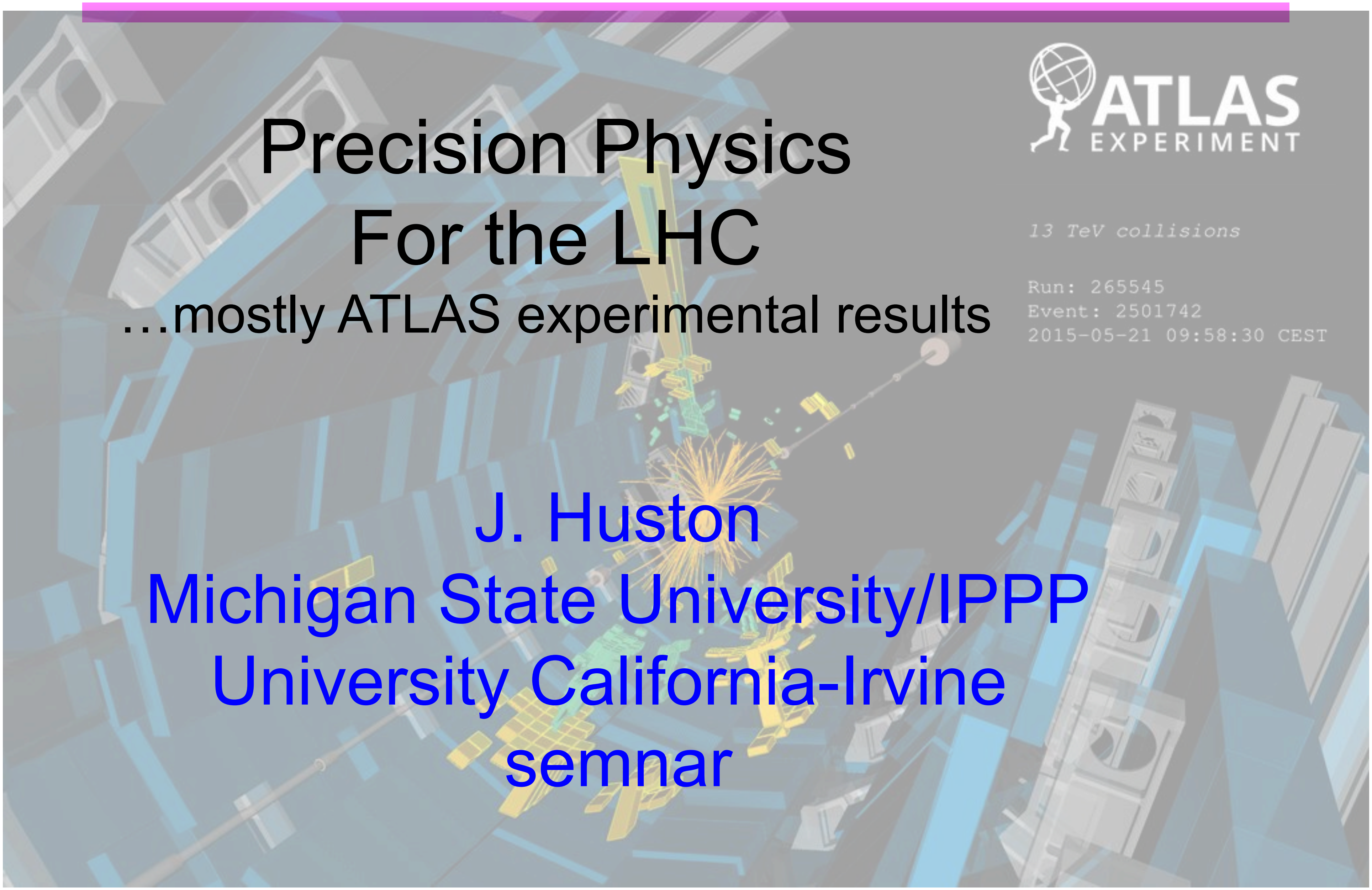


Precision Physics
For the LHC

…mostly ATLAS experimental results

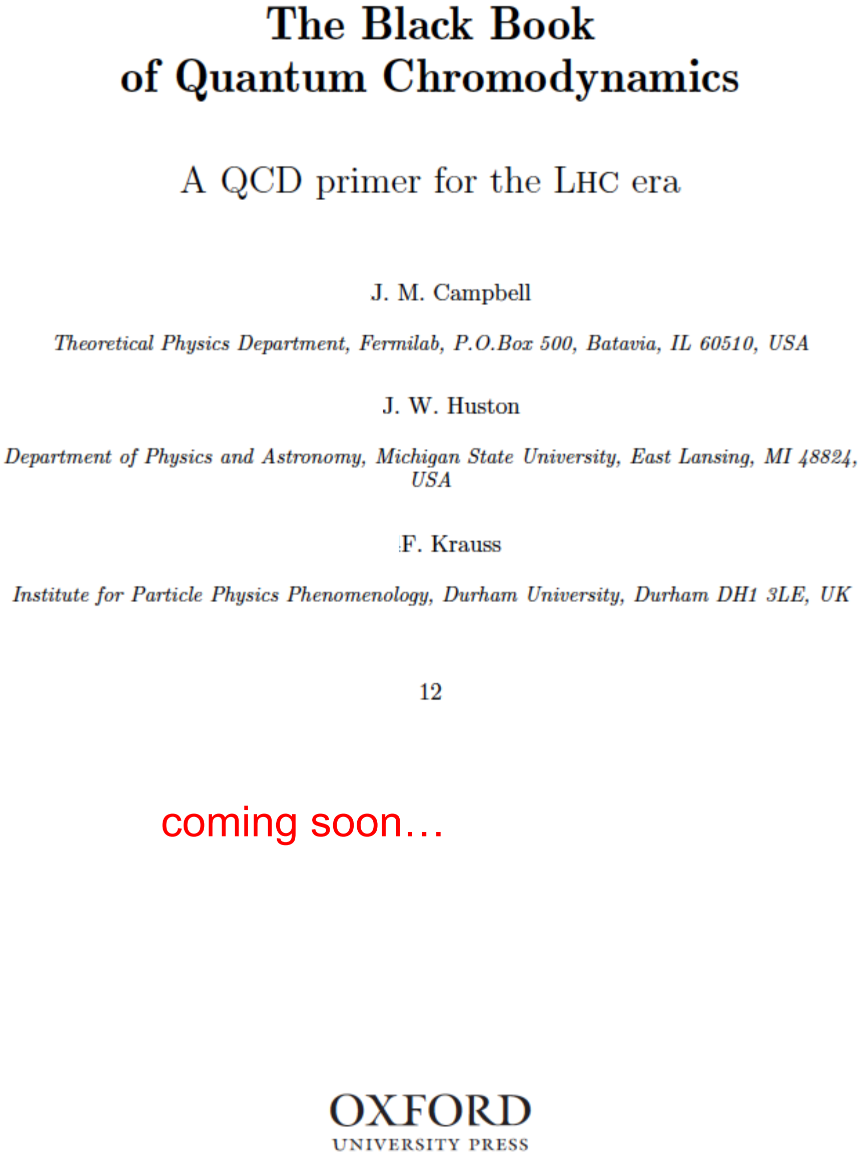
J. Huston

Michigan State University/IPPP

University California-Irvine

semnar

These lectures brought to you by



The Black Book of Quantum Chromodynamics

A QCD primer for the LHC era

J. M. Campbell

Theoretical Physics Department, Fermilab, P.O.Box 500, Batavia, IL 60510, USA

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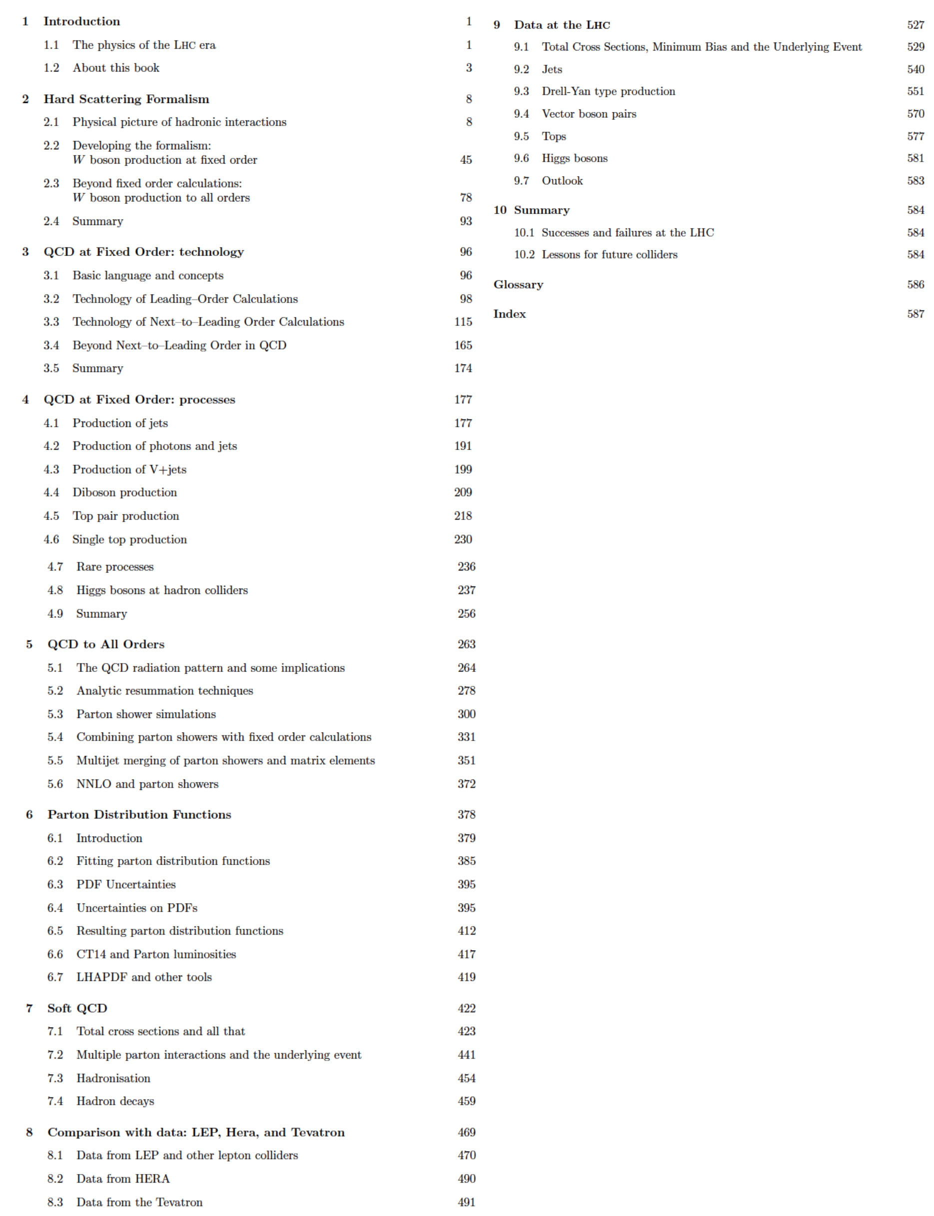
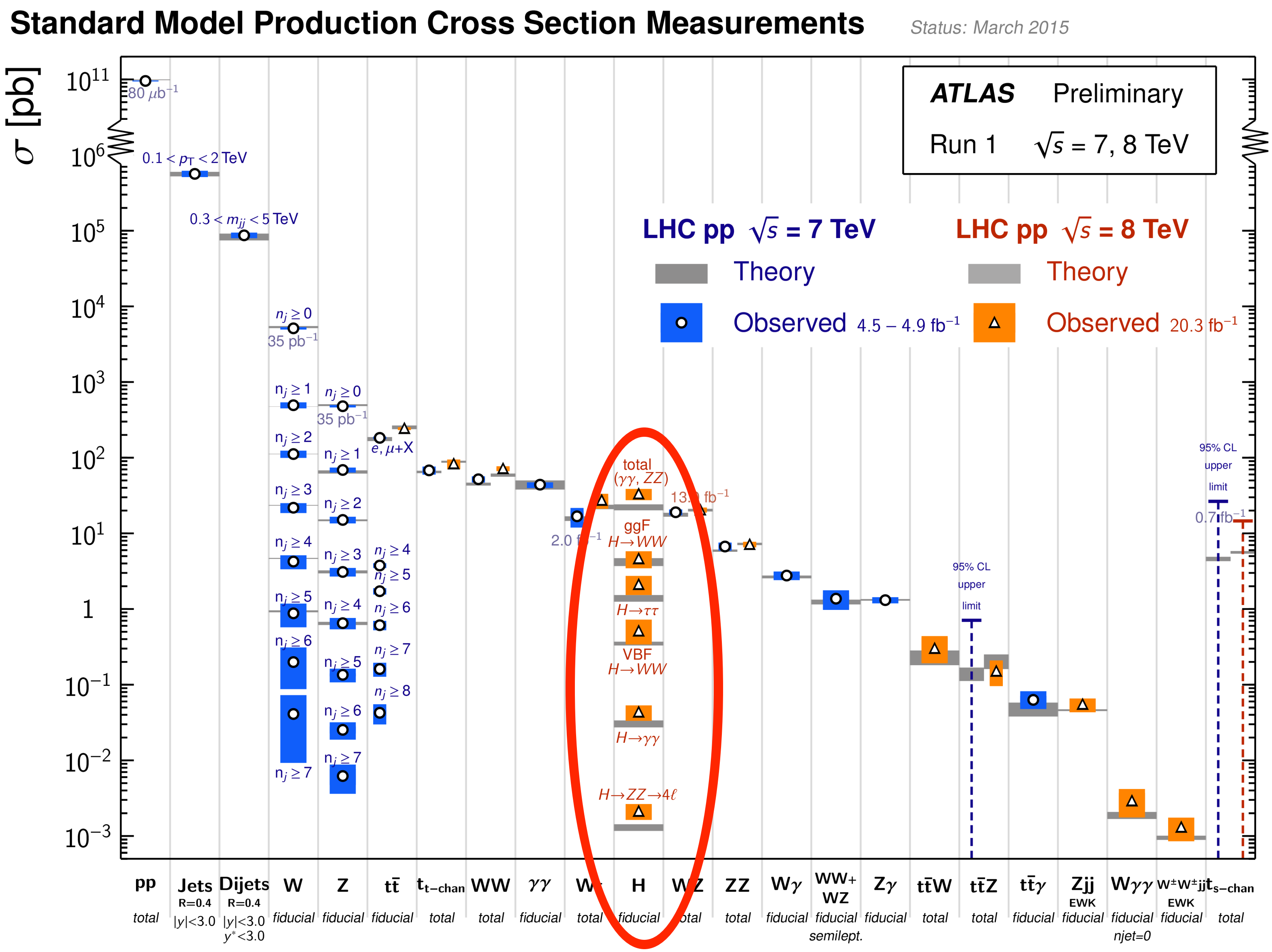
coming soon…



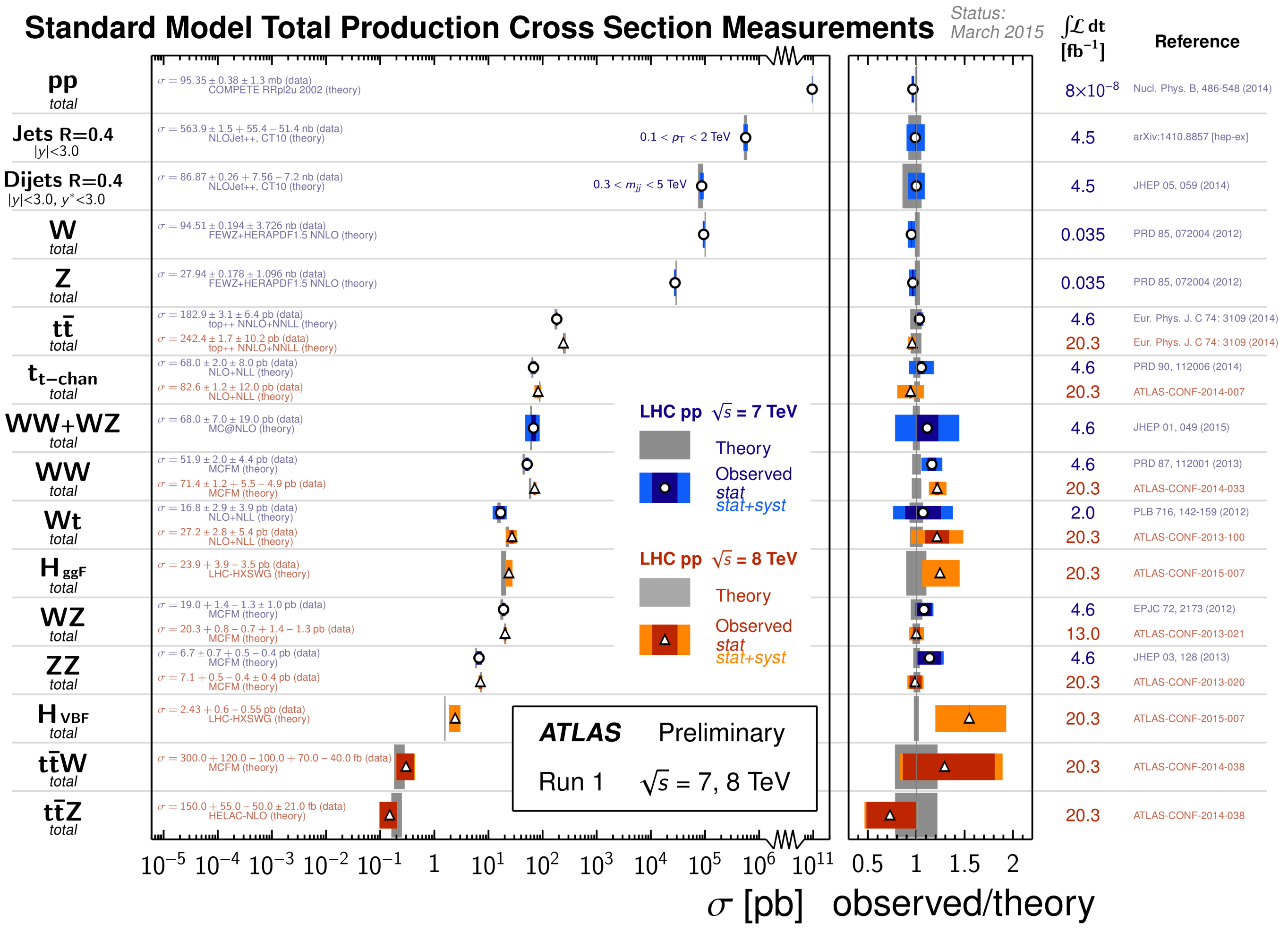
Les Houches 2015
...proceedings probably in March 2016

(SM) Physics from Run 1

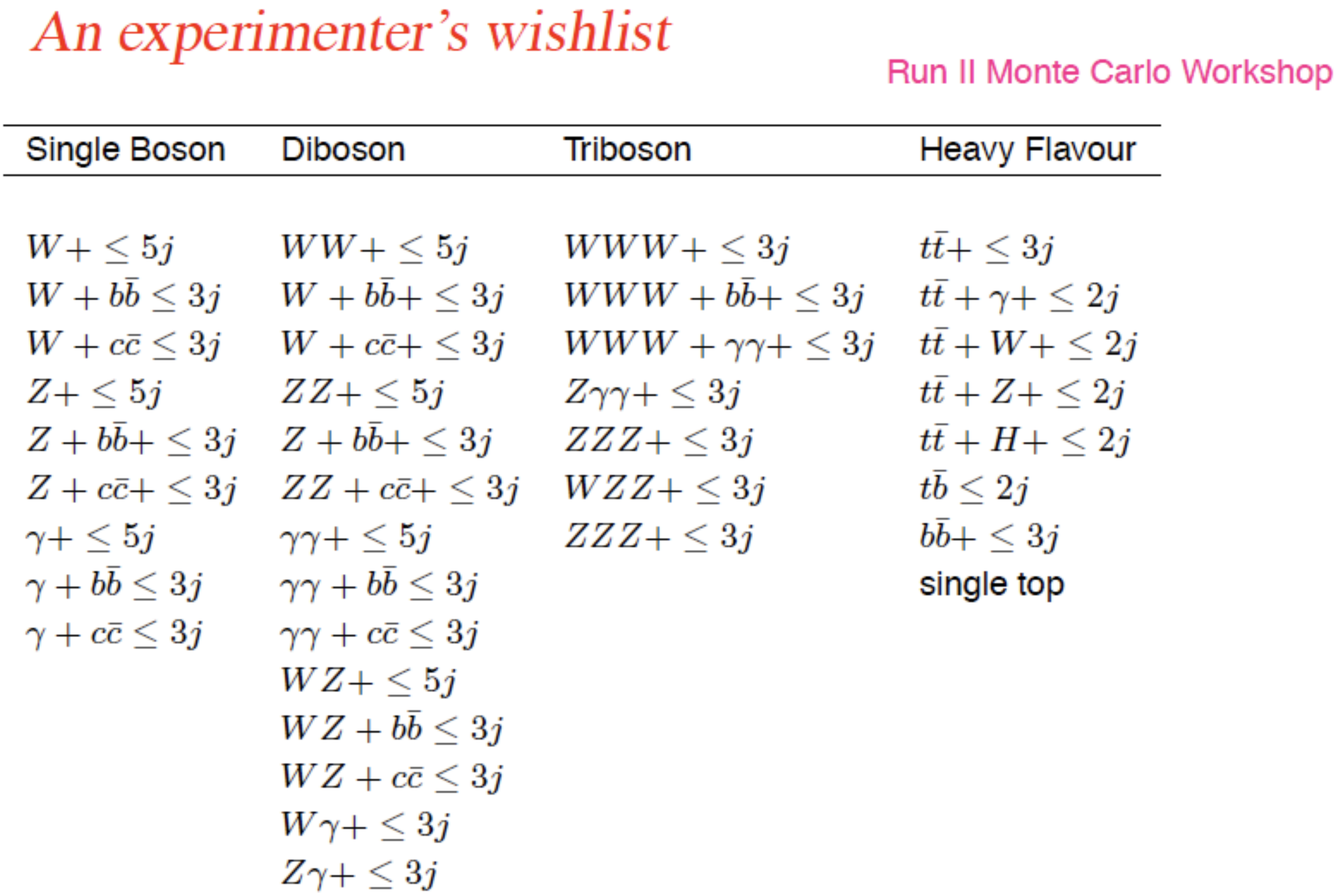


Physics from Run 1

…in most cases, good agreement with SM predictions (at NLO and higher). The SM will be tested more stringently (with hopefully BSM physics discovered) in Run 2. We need to have the predictions available to test data vs theory.



A similar need lead to the first wishlist (for the Tevatron)



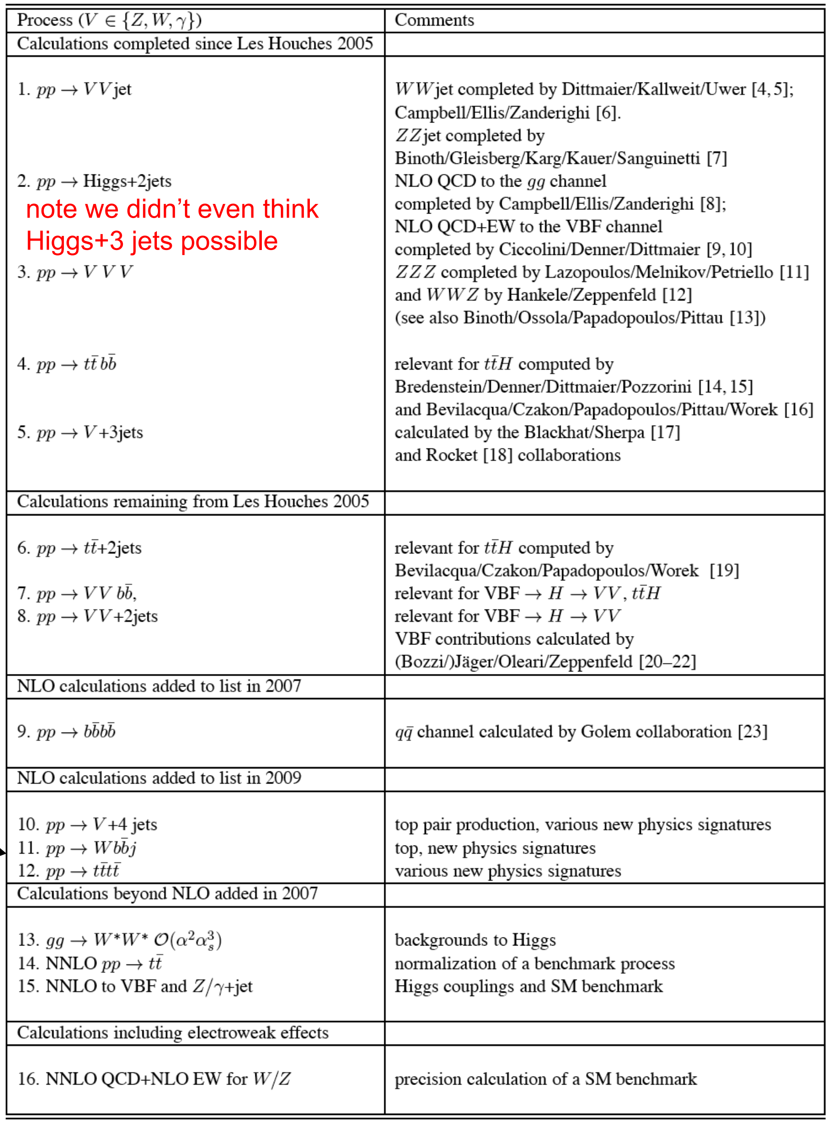
An experimenter's wishlist

Run II Monte Carlo Workshop

Single Boson	Diboson	Triboson	Heavy Flavour
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} \leq 3j$	$W + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} \leq 3j$	$W + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$Z + b\bar{b} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{b} \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$	$ZZZ + \leq 3j$	$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} \leq 3j$	$\gamma\gamma + b\bar{b} \leq 3j$		single top
$\gamma + c\bar{c} \leq 3j$	$\gamma\gamma + c\bar{c} \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} \leq 3j$		
	$WZ + c\bar{c} \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

Realistic wishlist

- Was developed at Les Houches in 2005, and expanded in 2007 and 2009
- Calculations that are important for the LHC AND do-able in finite time
- In 2009, we added tttt, Wbbj, W/Z+4j plus an extra column for each process indicating the level of precision required by the experiments
    - to see for example if EW corrections may need to be calculated
- In order to be most useful, decays for final state particles (t,W,H) need to be provided in the codes as well
- With the calculation of tttt, all processes on the wishlist have been calculated
- The wishlist has been retired since new techniques allow for the semi-automatic generation of new (reasonable) NLO cross sections



Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [4, 5]; Campbell/Ellis/Zanderighi [6]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9, 10]
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14, 15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \to VV\,b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [20–22]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*\ \mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

note we didn't even think Higgs+3 jets possible

Table 1: The updated experimenter's wishlist for LHC processes

Note that we have ticked off one cross section from the first list

An experimenter's wishlist

Run II Monte Carlo Workshop

Single Boson	Diboson	Triboson	Heavy Flavour
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}\leq 3j$	$W+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}\leq 3j$	$W+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$Z+b\bar{b}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{b}\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$	$ZZZ+\leq 3j$	$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}\leq 3j$	$\gamma\gamma+b\bar{b}\leq 3j$		single top
$\gamma+c\bar{c}\leq 3j$	$\gamma\gamma+c\bar{c}\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}\leq 3j$		
	$WZ+c\bar{c}\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

Going beyond the original wish list: a lot more complexity (loops and legs) required to keep it interesting

A new Les Houches high precision wishlist

- From the 2013 proceedings
  - arxiv:1405.1067
- NB: The counting of orders is done relative to LO QCD independent of the absolute power of α_s in cross section
- $\alpha \sim \alpha_s^2$ so that NNLO QCD and NLO EW effects are naively of the same size
- $d\sigma$ represents full differential cross sections
- The list is very ambitious, but possible to do over the remainder of the LHC running

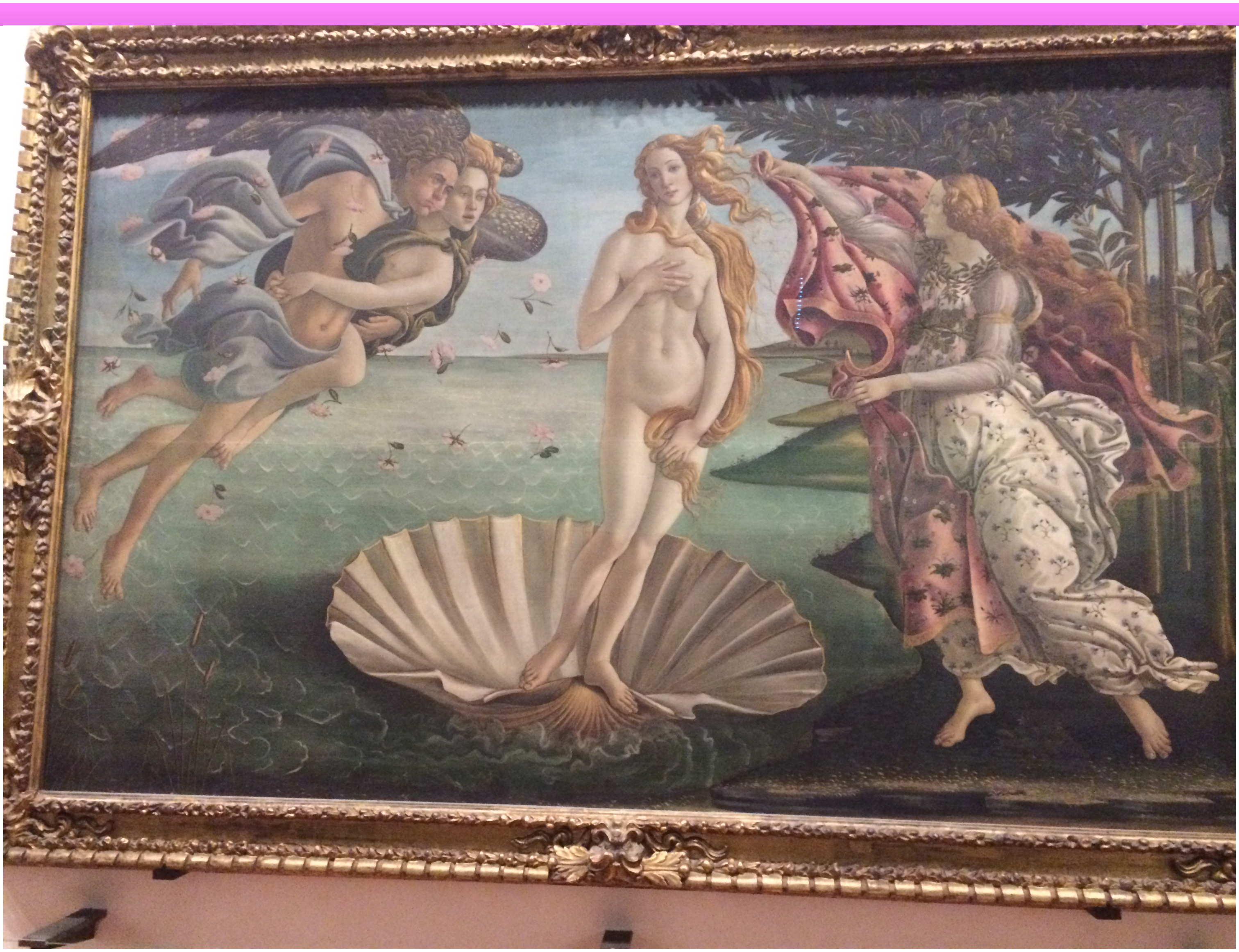
- $\text{LO} \equiv \mathcal{O}(1)$,
- $\text{NLO QCD} \equiv \mathcal{O}(\alpha_s)$,
- $\text{NNLO QCD} \equiv \mathcal{O}(\alpha_s^2)$,
- $\text{NLO EW} \equiv \mathcal{O}(\alpha)$,
- $\text{NNNLO QCD} \equiv \mathcal{O}(\alpha_s^3)$,
- $\text{NNLO QCD+EW} \equiv \mathcal{O}(\alpha_s \alpha)$.

…and of course, as much as possible, we would like matching to a parton shower for fully exclusive final states

Costas: “δεν υπάρχει πρόβλημα”

In this notation, $d\sigma$@NNLO QCD+NLO EW indicates a single code computing the fully differential cross section including both order α_s^2 and order α effects. Where possible, full resonance production, including interference with background should be taken into account.

Many of these calculations require the use of on-shell techniques

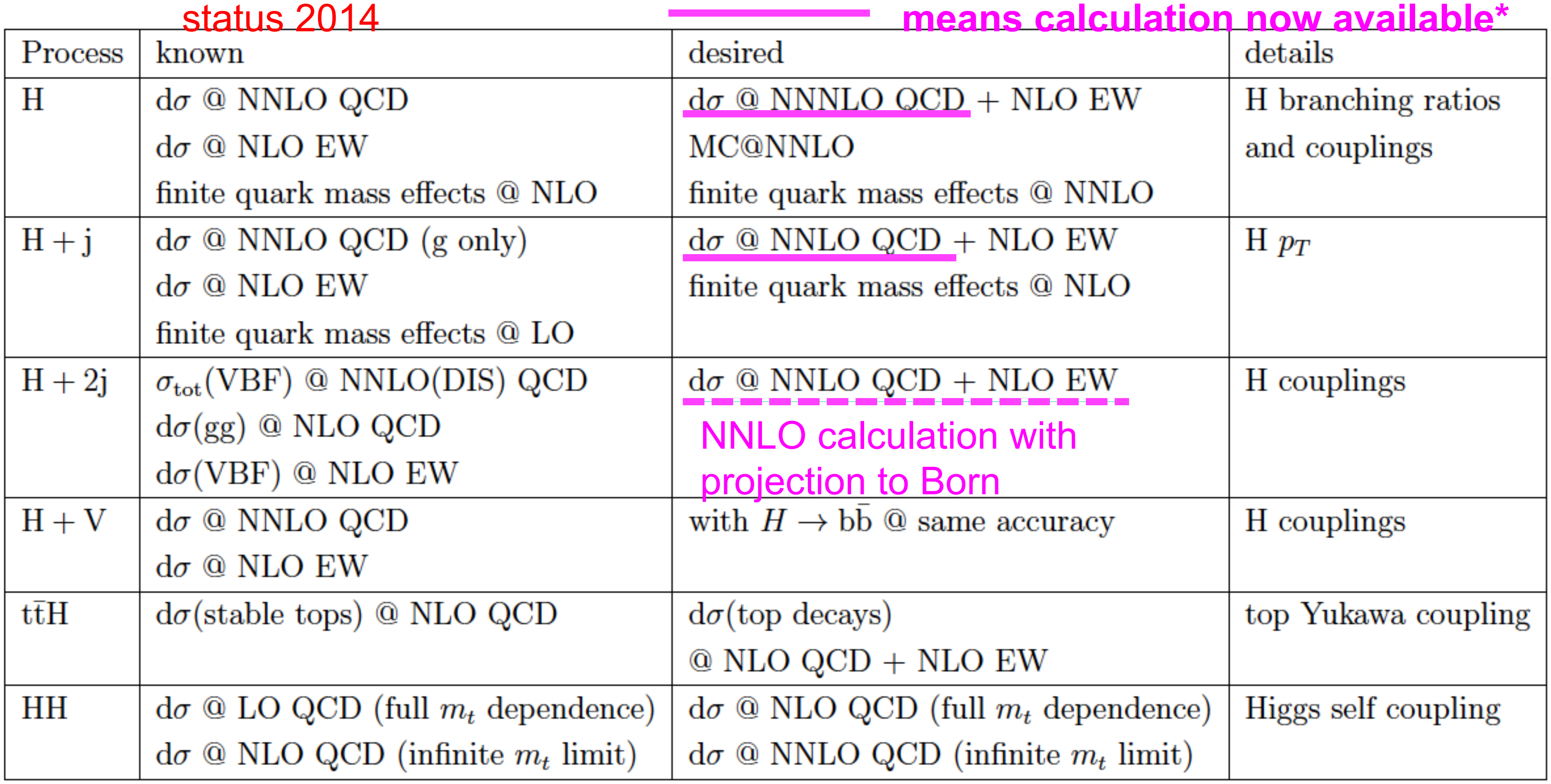


…which have been around longer than we realized

Wishlist: Higgs sector

status 2014

means calculation now available*



Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW NNLO calculation with projection to Born	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)

justify the requested precision based on current/extrapolated experimental errors

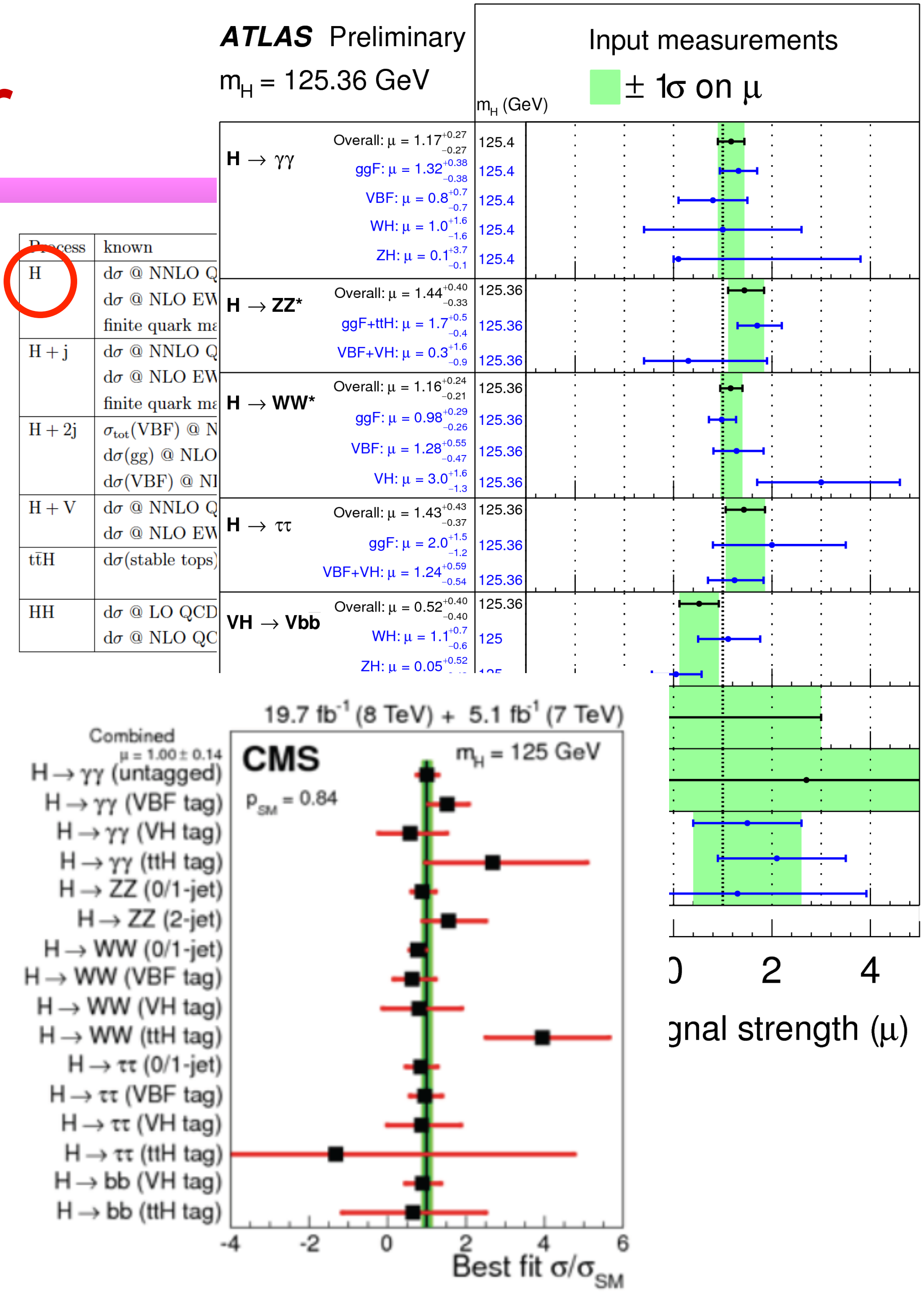
***my apologies if your calculation is not yet noted; let me know and I'll add it**

Higgs sector

- We currently know the production cross section for gg fusion to NNNLO QCD in the infinite m_t limit, including finite quark mass effects at NLO QCD and NLO EW.
- Current ATLAS (and CMS) experimental uncertainties are of the order of 20-40%->consistency with SM at that level
- NB: signal strength parameters make use of state-of-art calculations of Higgs cross sections and kinematics
- Theory error is competitive with other errors**->theory improvements needed**

CMS: μ = 1.00 ± 0.09 (stat) ± 0.07 (syst) ± 0.08 (theory)

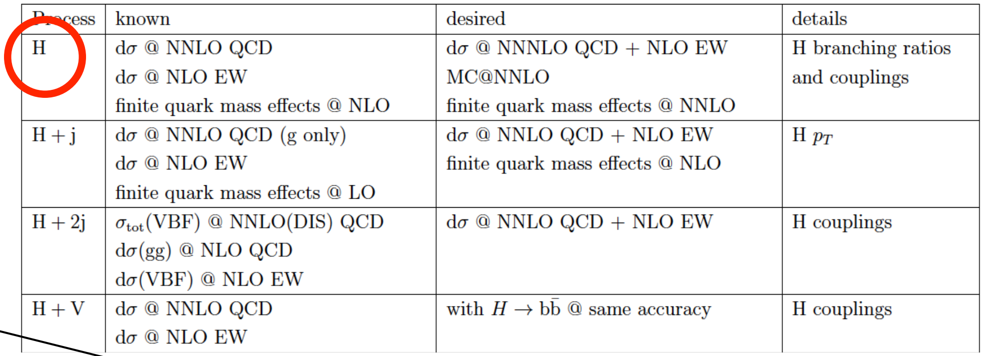
ATLAS: μ = 1.30 ± 0.12 (stat) ± 0.09 (syst) ± 0.10 (theory)



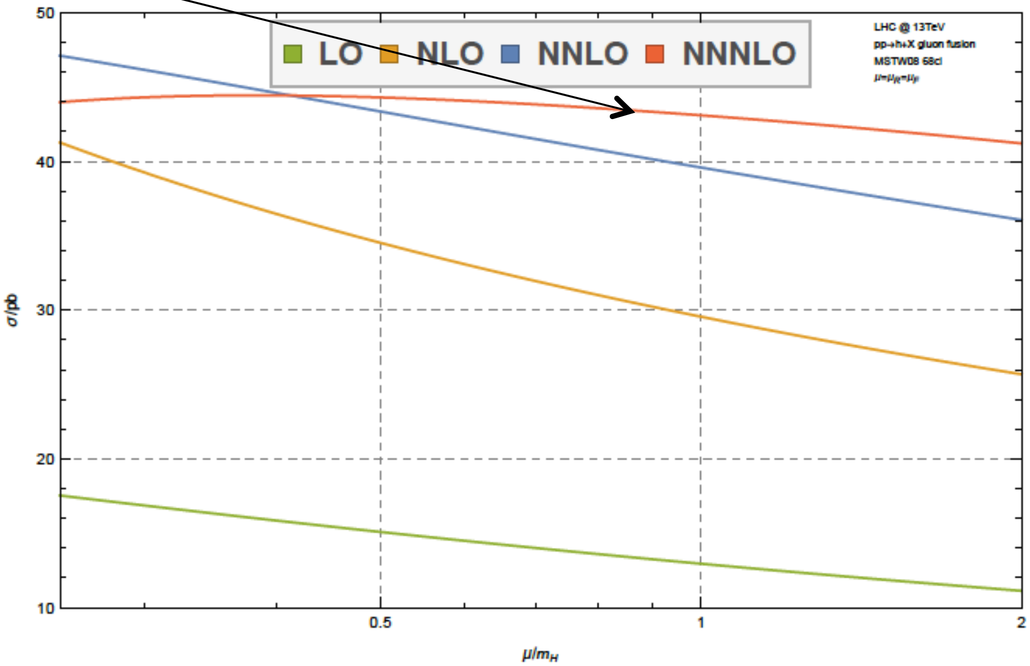
Process	known
H	dσ @ NNLO Q dσ @ NLO EW finite quark ma
H + j	dσ @ NNLO Q dσ @ NLO EW finite quark ma
H + 2j	σ_{tot}(VBF) @ N dσ(gg) @ NLO dσ(VBF) @ NI
H + V	dσ @ NNLO Q dσ @ NLO EW
$t\bar{t}$H	dσ(stable tops)
HH	dσ @ LO QCD dσ @ NLO QC

Higgs sector

- Previously, uncertainty was of order of 15% with PDF+α_s and higher order uncertainties, both being on the order of 7-8%
  - scale uncertainty now reduced to 2-3%
  - PDF+α_s uncertainty now dominant
  - see next few slides, however
- Expect total experimental error to decrease to <10% in Run 2
- So ultimately may want to know NNNLO QCD and mixed NNLO QCD+EW contributions maintaining finite top quark mass effects

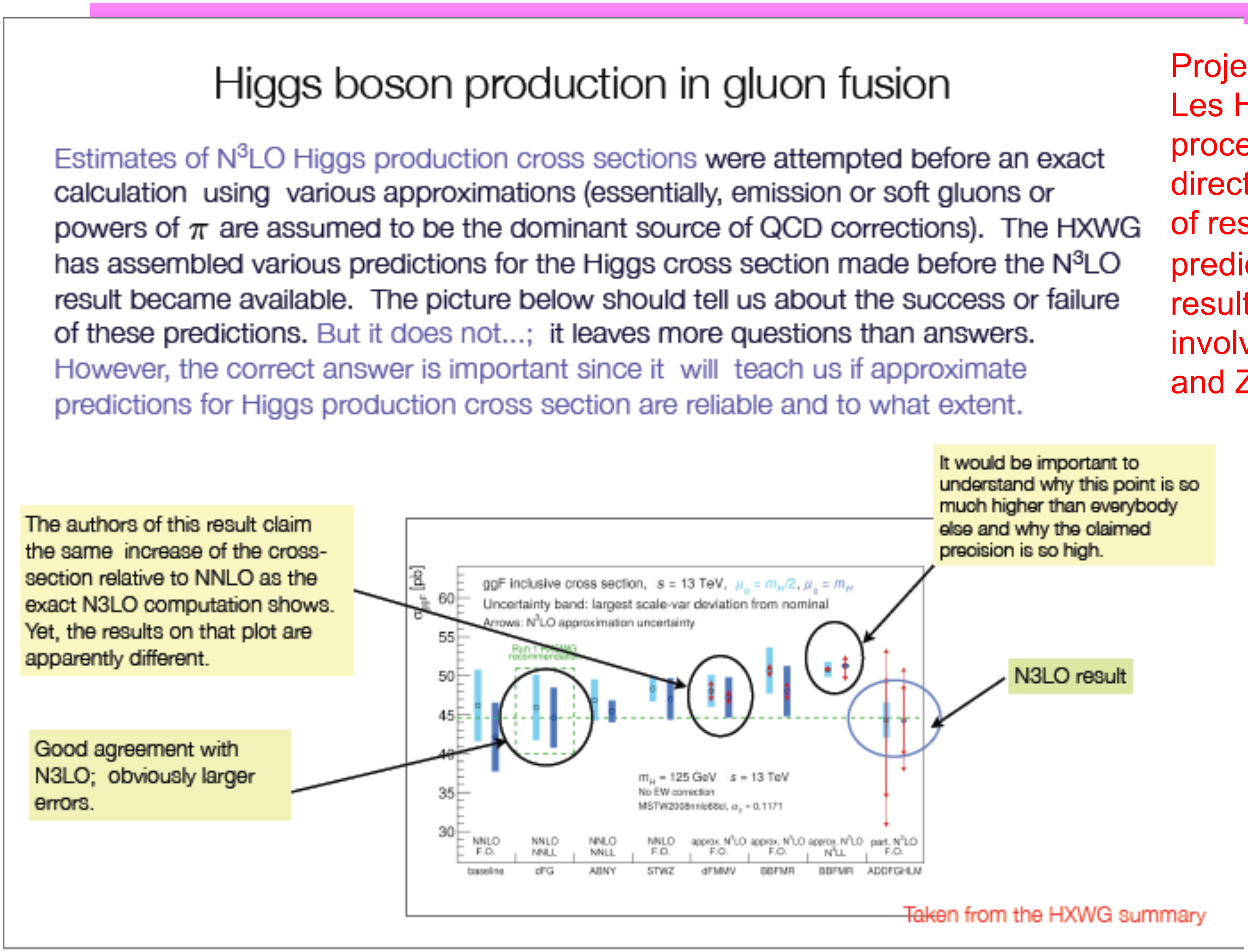


Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings



2 NNLO+PS simulations for ggF have already been developed; expect improvements/refinements.

Kirill Melnikov: LHCP 2015



Higgs boson production in gluon fusion

Estimates of N^{3}LO Higgs production cross sections were attempted before an exact calculation using various approximations (essentially, emission or soft gluons or powers of π are assumed to be the dominant source of QCD corrections). The HXWG has assembled various predictions for the Higgs cross section made before the N^{3}LO result became available. The picture below should tell us about the success or failure of these predictions. But it does not...; it leaves more questions than answers. However, the correct answer is important since it will teach us if approximate predictions for Higgs production cross section are reliable and to what extent.

The authors of this result claim the same increase of the cross-section relative to NNLO as the exact N3LO computation shows. Yet, the results on that plot are apparently different.

Good agreement with N3LO; obviously larger errors.

It would be important to understand why this point is so much higher than everybody else and why the claimed precision is so high.

N3LO result

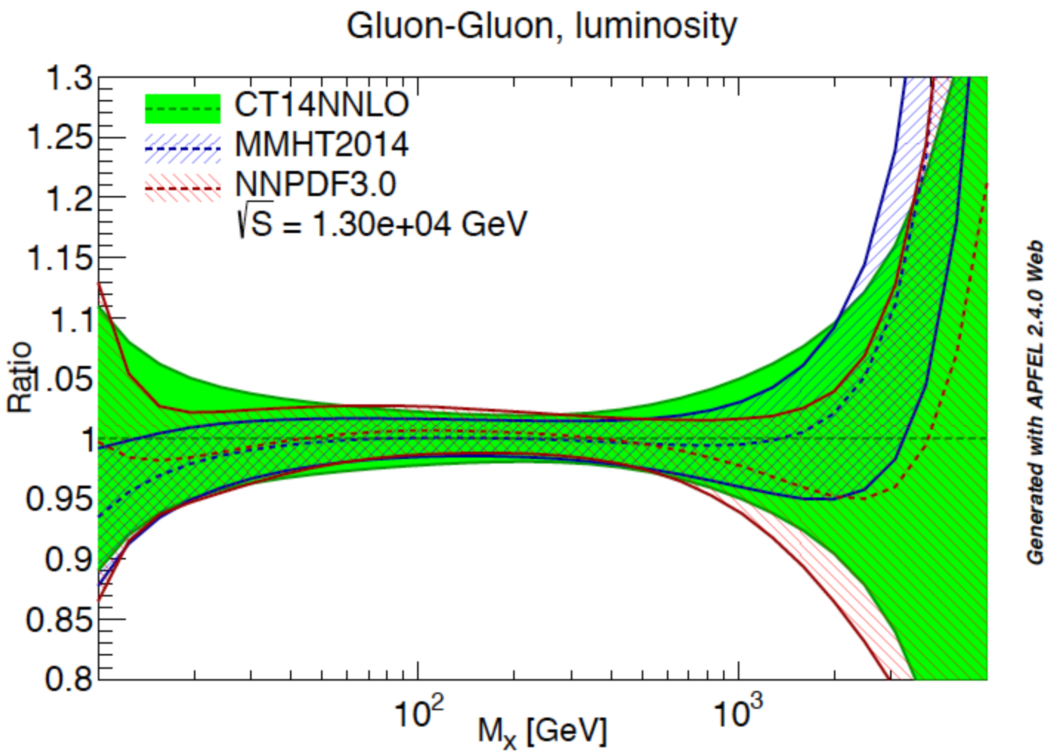
Taken from the HXWG summary

Tuesday, September 1, 15

Project underway for Les Houches proceedings with direct comparisons of resummed predictions and results of N^3LO, involving resummers and Zurich group

PDFs: the next generation

- NNPDF3.0 (arXiv:1410.8849)
- MMHT14 (arXiv:1412.3989)
- CT14 (arXiv:1506.07443))
- HERAPDF2.0
- The gg PDF luminosities for the first three PDFs are in good agreement with each other in the Higgs mass range
- PDF uncertainty using the CT14, MMHT14, CT14 PDFs would be 2-2.5%, comparable to new scale dependence at NNLO, and comparable to the as uncertainty



NNPDF down by 2-2.5%, CT14 up by ~1%, MMHT14 down by ~0.5%

partially data, partially corrections in fitting code, partially changes in fitting procedures

new PDF4LHC recommendation; see extra slides

A comparison of ggF at NNLO

scale = m_H	**CT14**	**MMHT2014**	**NNPDF3.0**
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

The PDF uncertainty using this new generation of PDFs is similar in size to the NNNLO scale uncertainty and to the $\alpha_s(m_Z)$ uncertainty.

THE VALUE OF α_s

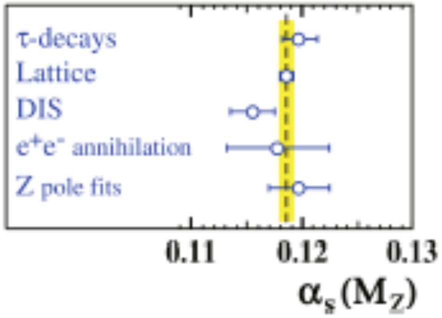
PDG VALUE (AUGUST 2014): $\alpha_s(M_Z) = 0.1185 \pm 0.0006$

COMMENTS (S.F.)

- LATTICE UNCERTAINTY CURRENTLY ESTIMATED BY FLAG (arXiv:1310.8555) TO BE TWICE THE PDG VALUE (± 0.0012)

to account for perturbative truncation errors

- IT IS AN AN AVERAGE OF AVERAGES
- SOME SUB-AVERAGES (E.G. DIS) INCLUDE MUTUALLY INCONSISTENT/INCOMPATIBLE DATA/EXTRACTIONS



- SOME SUB-AVERAGES (E.G. τ OR JETS) INCLUDE DETERMINATIONS WHICH DIFFER FROM EACH OTHER BY EVEN FOUR-FIVE σ
- AVERAGING THE TWO MOST RELIABLE VALUES (GLOBAL EW FIT & τ, BOTH N^{3}LO, NO DEP. ON HADRON STRUCTURE) GIVES

$$\alpha_s = 0.1196 \pm 0.0010$$

NEW PDF4LHC AGREEMENT

- PDG UNCERTAINTY CONSERVATIVELY MULTIPLIED BY 2
- CENTRAL VALUE & UNCERTAINTY ROUNDED: PDF SETS USUALLY GIVEN IN STEPS OF $\Delta\alpha_s(M_z) = 0.001$

$$\alpha_s(M_Z) = 0.118 \pm 0.0015$$

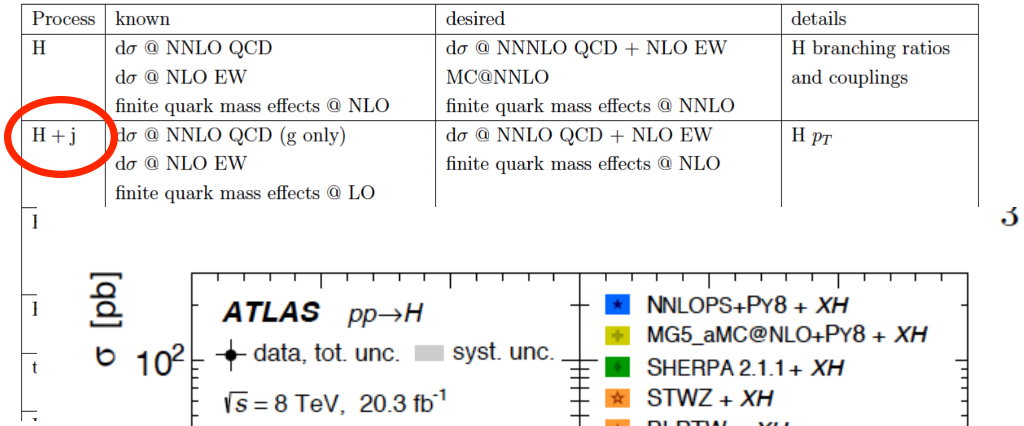
-PDFs all evaluated at same value of α_s (0.118).
−α_s uncertainty added in quadrature with PDF uncertainty
-α_s uncertainty is one of the dominant errors now

How aggressive should we be on $\alpha_s(m_Z)$ uncertainties?

S. Forte Higgs XSWG meeting
June 8, 2015

Higgs sector

- First attempts to measure differential Higgs+jets measurements made in diphoton (ZZ*) channel at ATLAS
    - JHEP 1409(2014)112; (Phys. Lett. B738(2014)234)
- Combination with ZZ*
    - arXiv:1504.05833



Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
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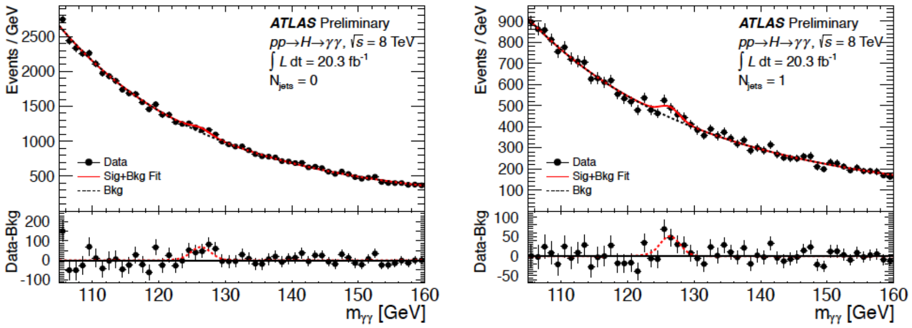
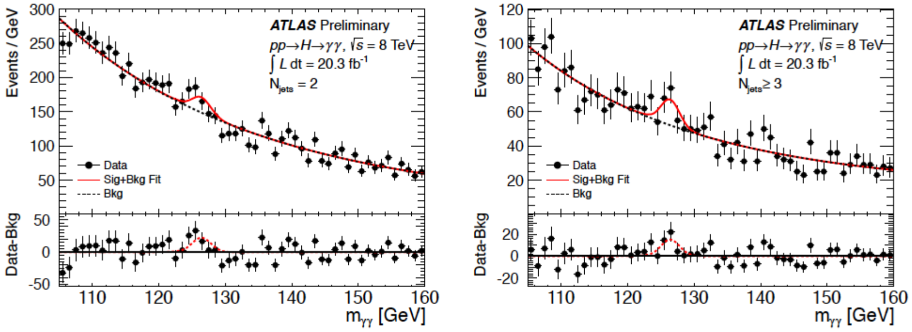
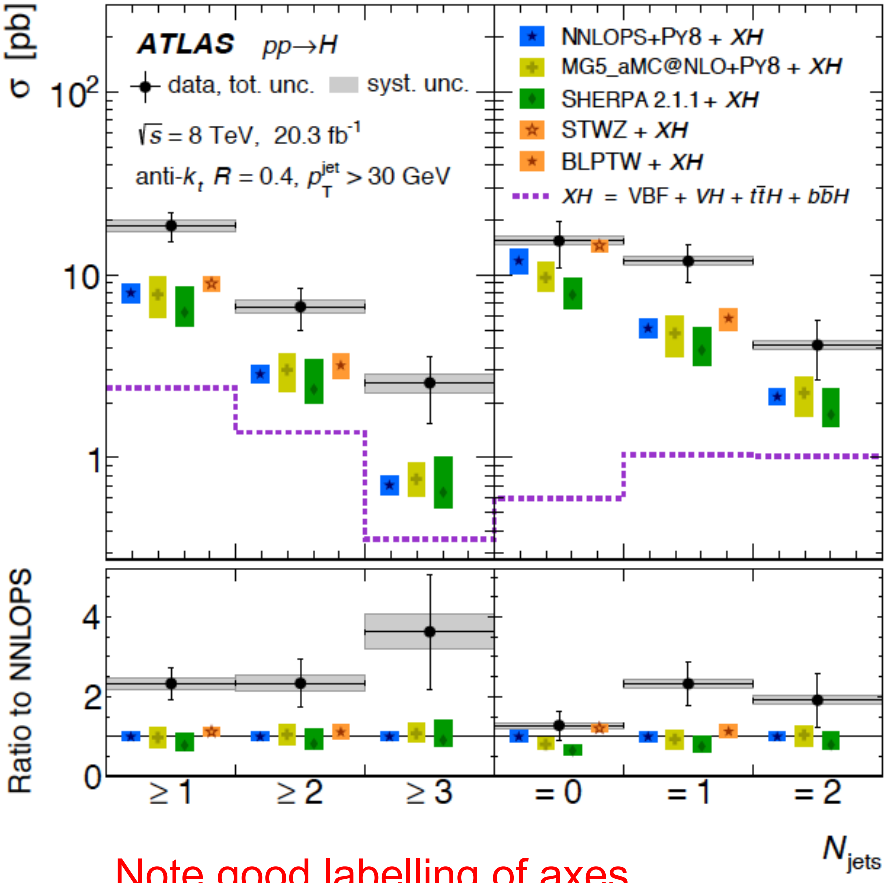
I			
t			



(a) $N_{\text{jets}} = 0$ (b) $N_{\text{jets}} = 1$



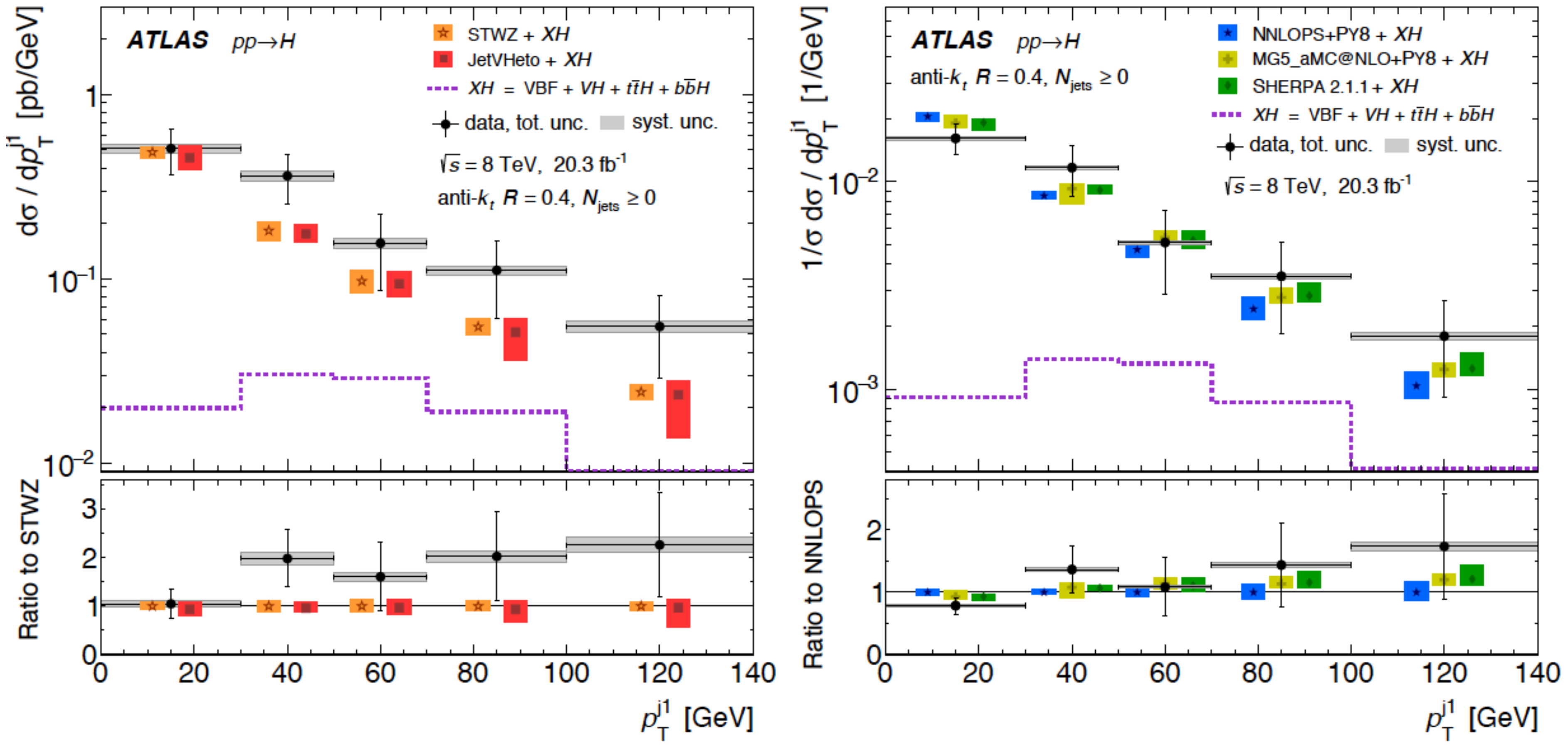
(c) $N_{\text{jets}} = 2$ (d) $N_{\text{jets}} \geq 3$



Note good labelling of axes

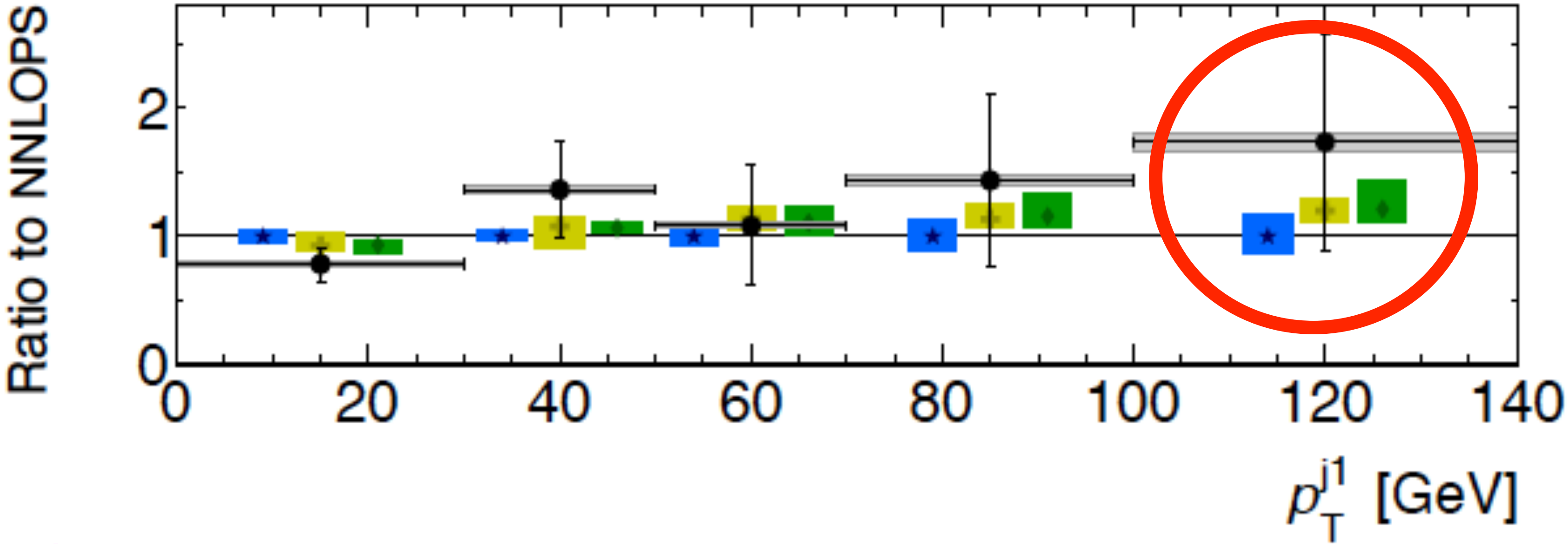
ATLAS Higgs+>=1 jet

- Comparisons to a wide number of resummation/ME+PS predictions…**but not to fixed order!** (with appropriate non-perturbative corrections)



ATLAS Higgs+>=1 jet

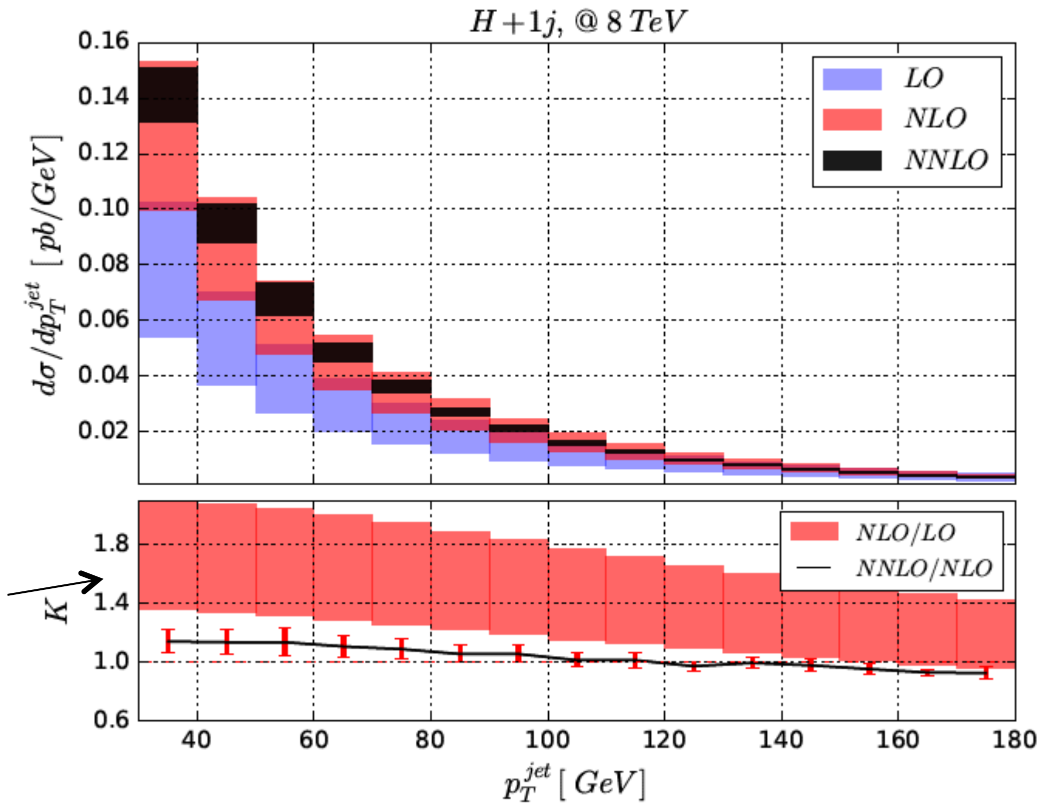
- Comparisons to a wide number of resummation/ME+PS predictions…**but not to fixed order**!
- **Les Houches:compare each prediction to each other, to fixed NLO/NNLO in detailed framework**
  - **wide variety of observables relating to Higgs+jets; Rivet routine available; ntuplereader modification available to talk to Rivet**
- **How well do the resummation calculations anticipate/reproduce the NNLO results**?



We're going to be looking at much higher p_T values with smaller errors in Run 2. We need to have a better quantitative handle on this.

Higgs + jet

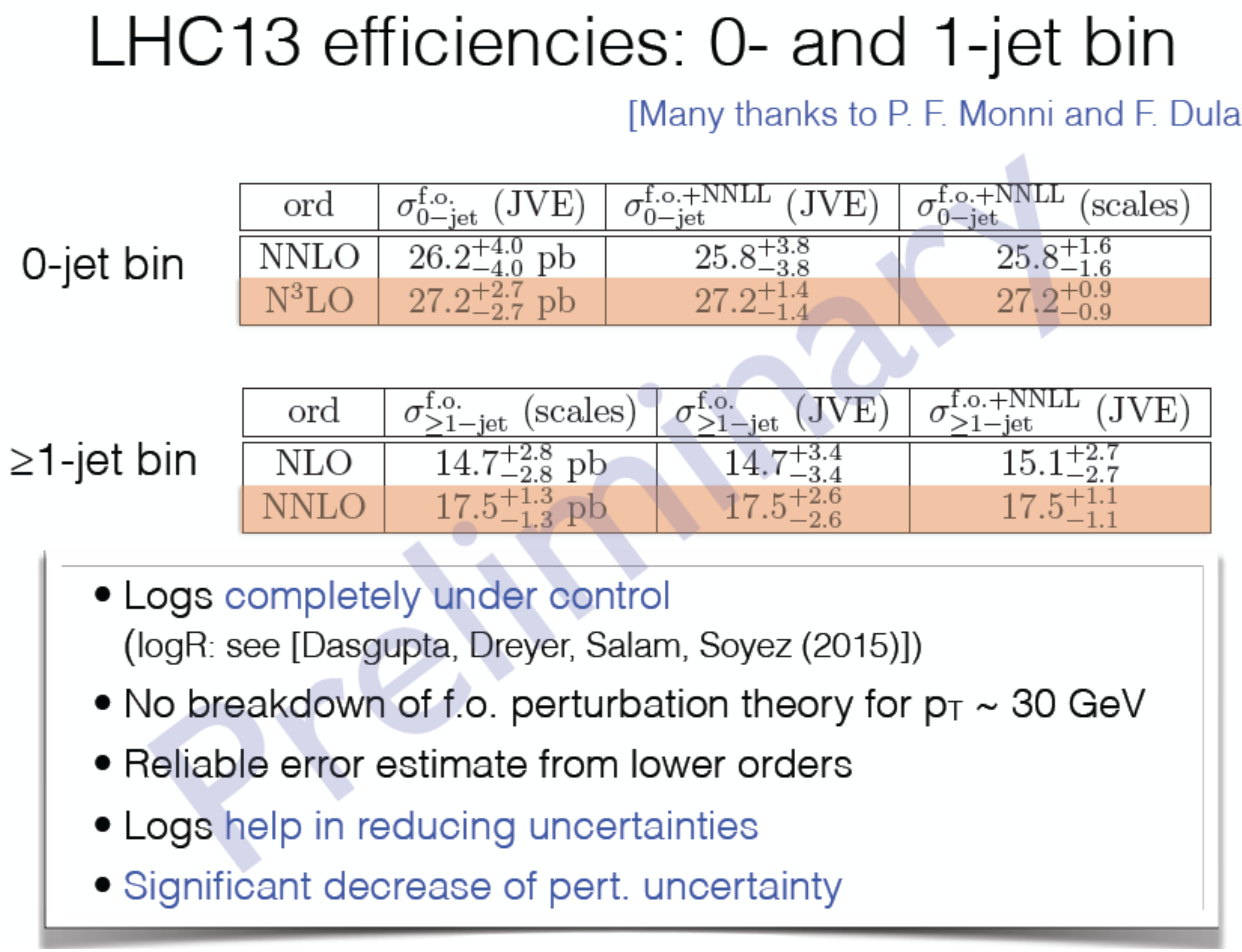
- At 14 TeV, with 300 fb^{-1}, there will be a rich variety of differential jet measurements with on the order of 3000 events with jet p_T above the top quark mass scale, thus probing inside the top quark loop
- H+j cross section now known to NNLO
  - using *conventional* techniques: arXiv:1504.07922
  - using n-jettiness: arXiv: 1505.03893
  - this cross section will be used to improve comparisons with Run 2 data
- LO (one-loop) QCD and EW corrections with top mass dependence known, but finite mass contributions at NLO QCD+NLO EW may also be needed



Can n-jettiness be successfully used for other processes, for example Higgs+>=2 jets at NNLO (once appropriate virtual terms are known)?

Is this the start of a NNLO revolution?

F. Caola: HXSWG meeting May 7, 2015



LHC13 efficiencies: 0- and 1-jet bin

[Many thanks to P. F. Monni and F. Dulat]

0-jet bin

ord	$\sigma^{\rm f.o.}_{0-\rm jet}$ (JVE)	$\sigma^{\rm f.o.+NNLL}_{0-\rm jet}$ (JVE)	$\sigma^{\rm f.o.+NNLL}_{0-\rm jet}$ (scales)
NNLO	$26.2^{+4.0}_{-4.0}$ pb	$25.8^{+3.8}_{-3.8}$	$25.8^{+1.6}_{-1.6}$
$\rm N^3LO$	$27.2^{+2.7}_{-2.7}$ pb	$27.2^{+1.4}_{-1.4}$	$27.2^{+0.9}_{-0.9}$

≥1-jet bin

ord	$\sigma^{\rm f.o.}_{\geq 1-\rm jet}$ (scales)	$\sigma^{\rm f.o.}_{\geq 1-\rm jet}$ (JVE)	$\sigma^{\rm f.o.+NNLL}_{\geq 1-\rm jet}$ (JVE)
NLO	$14.7^{+2.8}_{-2.8}$ pb	$14.7^{+3.4}_{-3.4}$	$15.1^{+2.7}_{-2.7}$
NNLO	$17.5^{+1.3}_{-1.3}$ pb	$17.5^{+2.6}_{-2.6}$	$17.5^{+1.1}_{-1.1}$

- Logs completely under control
  (logR: see [Dasgupta, Dreyer, Salam, Soyez (2015)])
- No breakdown of f.o. perturbation theory for $p_T \sim 30$ GeV
- Reliable error estimate from lower orders
- Logs help in reducing uncertainties
- Significant decrease of pert. uncertainty

preliminary; paper in progress

What is the effect of jet binning on a reasonably inclusive cross section, i.e. H+>=1 jet?

According to this result, the effects are small.

Can we (I) get a better understanding of this? How exclusive can you go?

arXiv:1511.02886

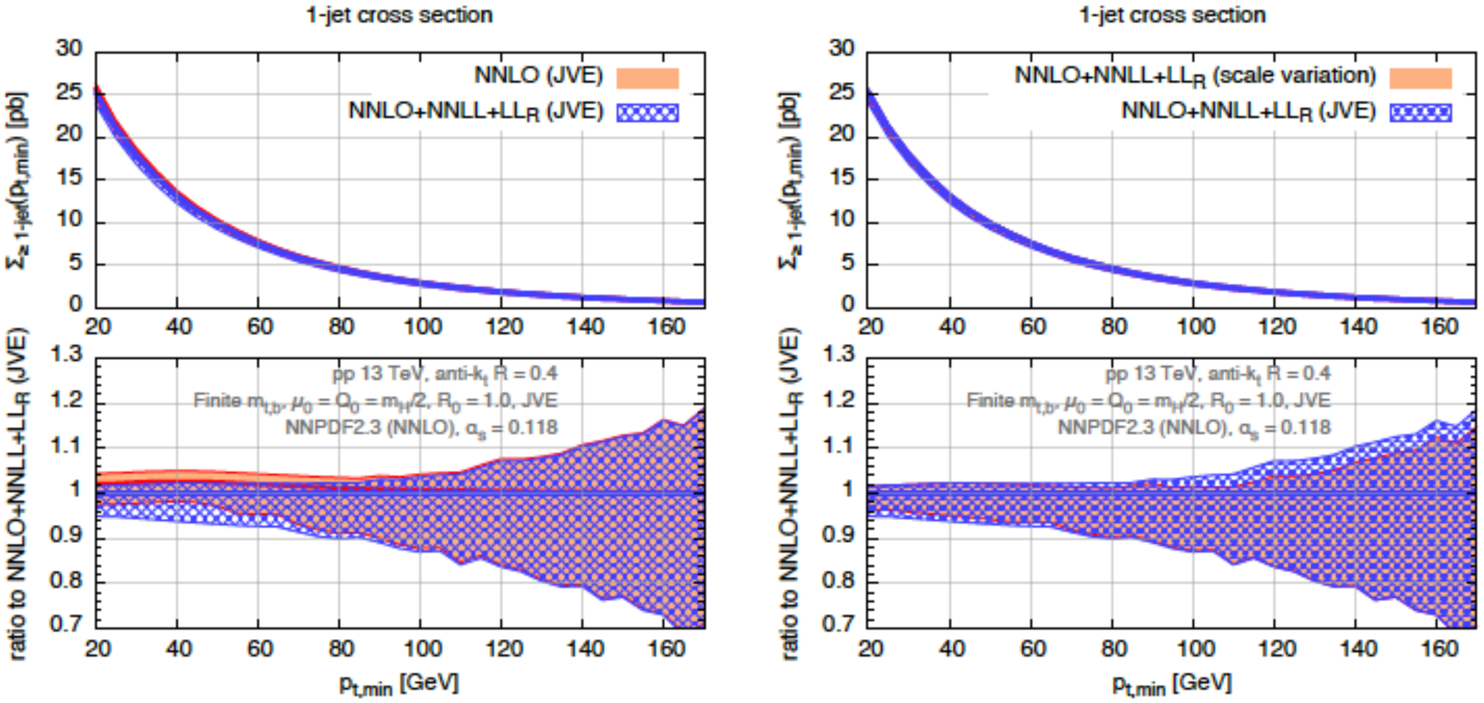


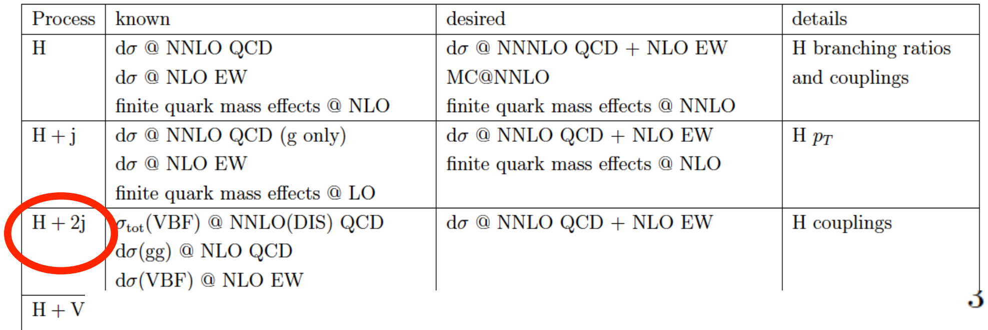
Figure 7. Matched NNLO+NNLL+LL$_R$ prediction for the inclusive one-jet cross section (blue/hatched) compared to fixed-order at NNLO (left) and to the matched result with direct scale variation for the uncertainty (right), as explained in the text.

LHC 13 TeV	$\Sigma^{\text{NNLO+NNLL+LL}_R}_{\geq 1\text{-jet}}$ [pb]	$\Sigma^{\text{NNLO}}_{\geq\ 1\text{-jet}}$ [pb]
$p_{t,\min} = 25\,\text{GeV}$	$21.2^{+0.4}_{-1.1}$	$21.6^{+0.5}_{-1.0}$
$p_{t,\min} = 30\,\text{GeV}$	$18.0^{+0.3}_{-1.0}$	$18.4^{+0.4}_{-0.8}$

difference is from small R resummation

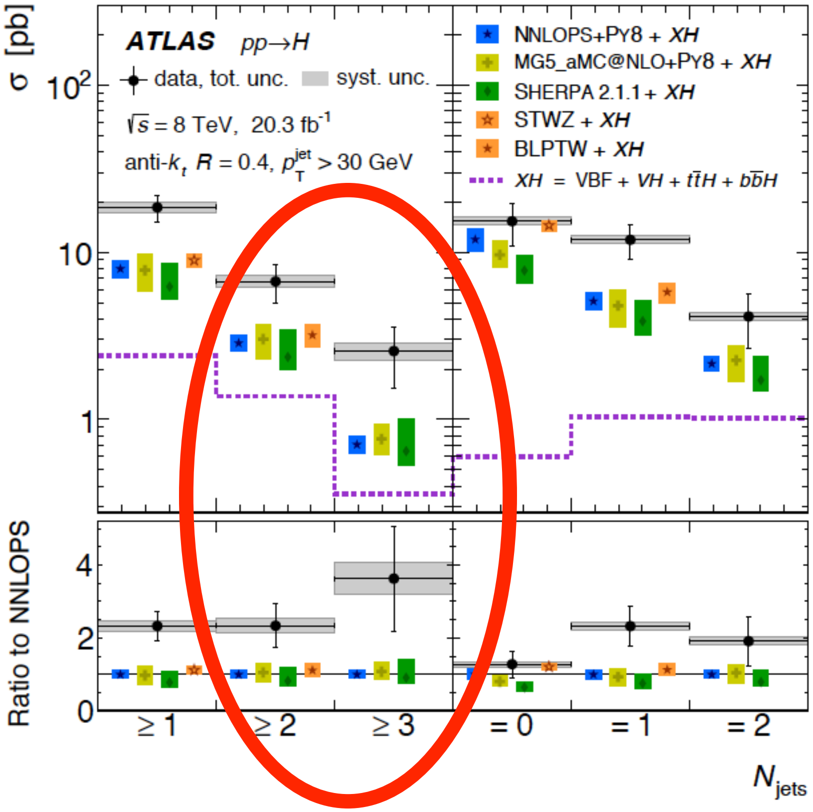
Higgs sector

- Higgs +>= 2 jets crucial to understand Higgs coupling, in particular through VBF
- VBF production previously known to NNLO QCD in double-DIS approximation together with QCD and EW effects at NLO; **now known to NNLO in projection-to-Born method**
- ggF known to NLO in infinite top mass limit and to LO QCD retaining top mass effects
- With 300 fb^{-1}, there is the possibility of measuring HWW coupling strength to order of 5%
- This would require both VBF and ggF Higgs + 2 jets cross sections to NNLO QCD and finite mass effects to NLO QCD and NLO EW



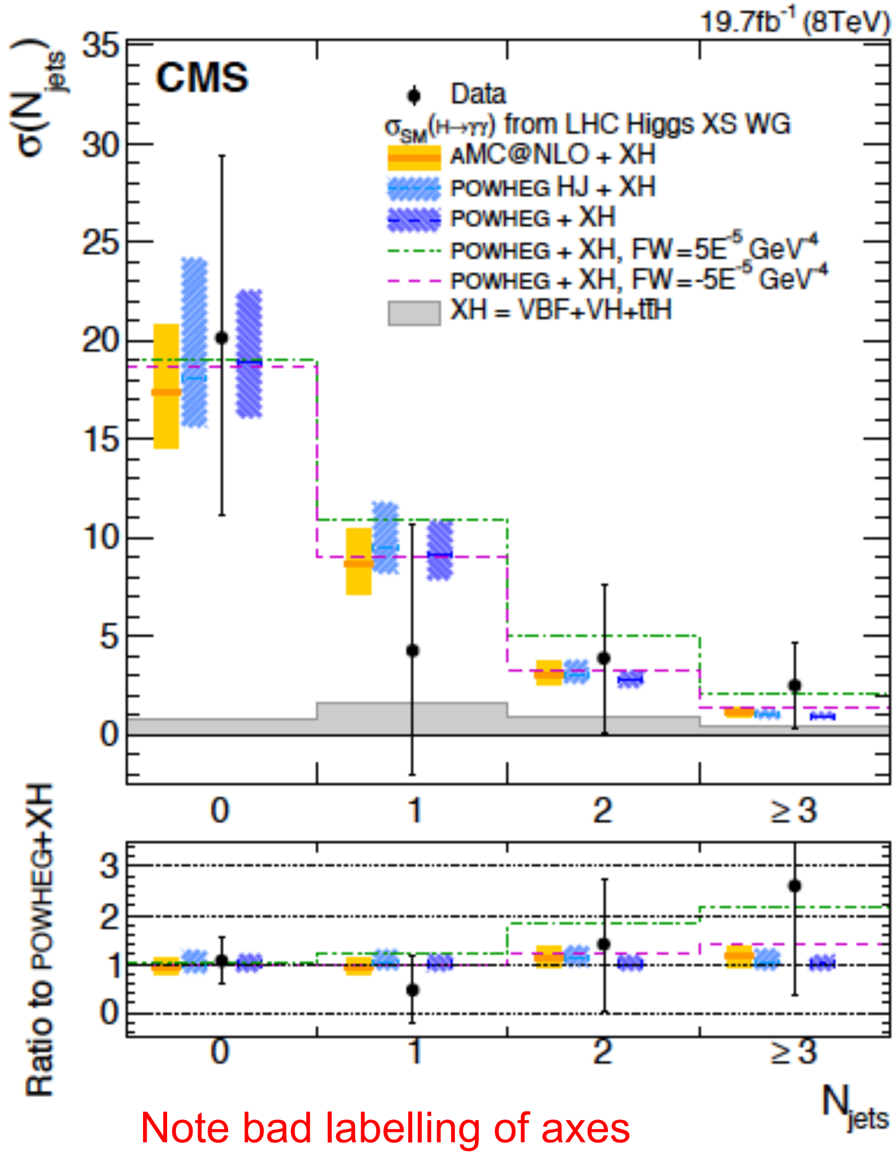
Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V			
$t\bar{t}$H			
HH			

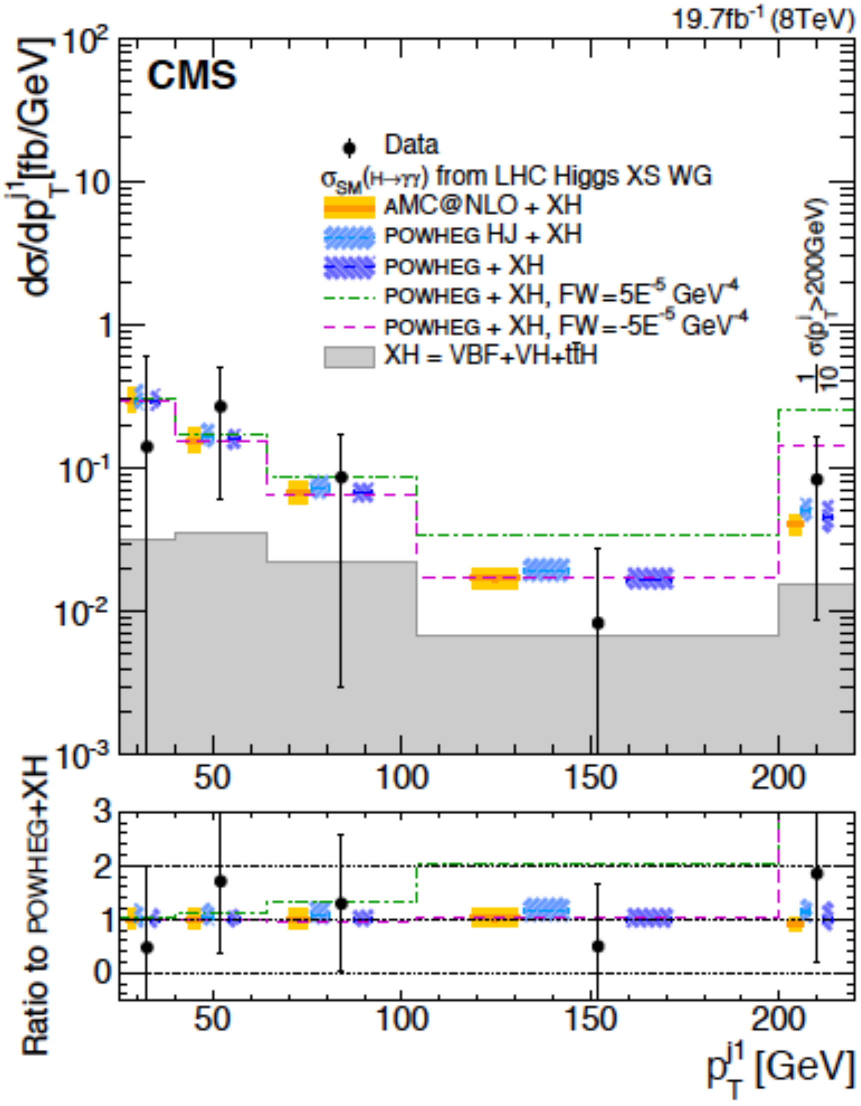
3



interesting that the (statistically limited) results seem to show a jettier final state than predicted…**but**

…alas, arXiv:1508.07819





Note bad labelling of axes

arXiv:1506.02660: VBF at NNLO, projection to Born

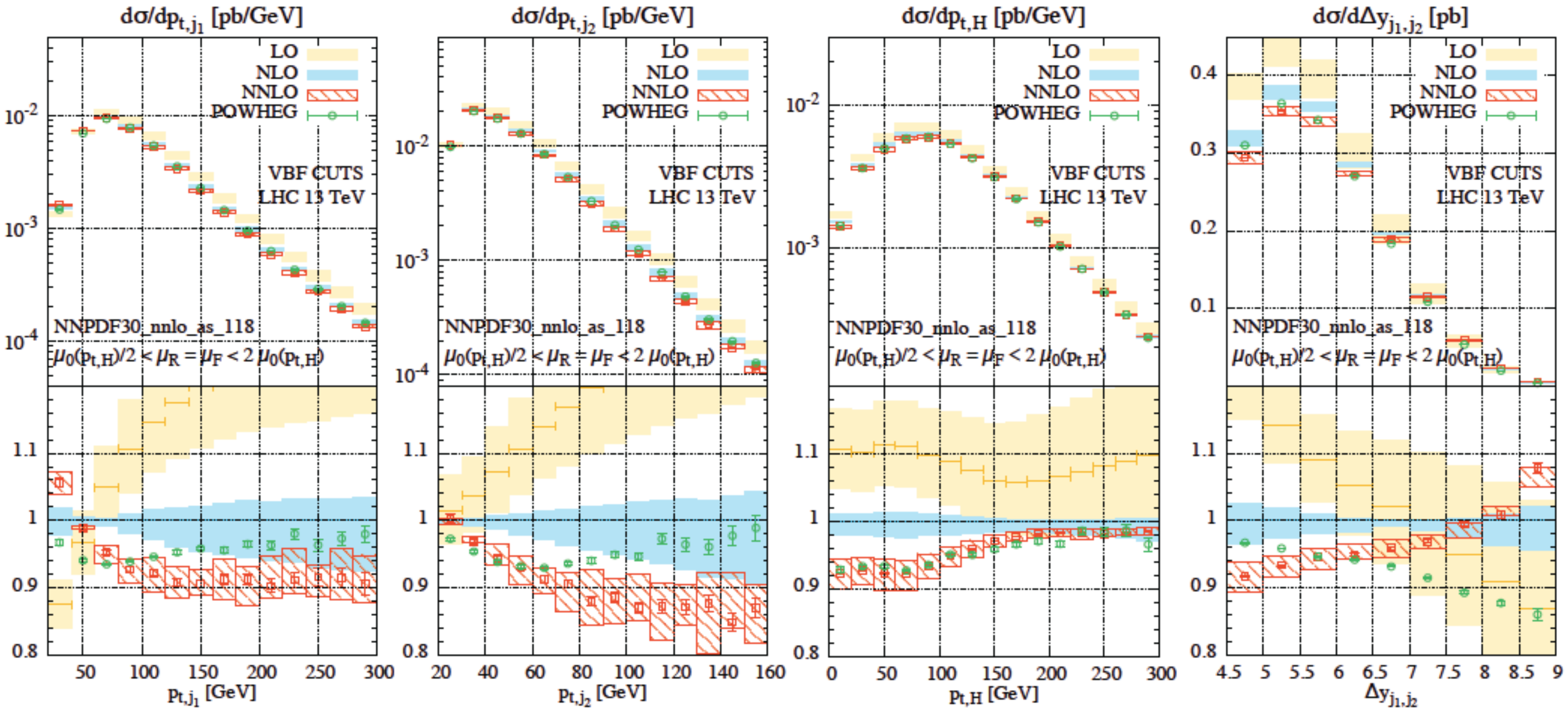
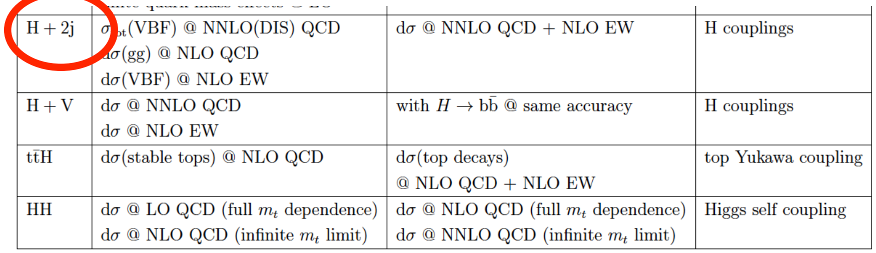


FIG. 2: From left to right, differential cross sections for the transverse momentum distributions for the two leading jets, p_{t,j_1} and p_{t,j_2}, for the Higgs boson, $p_{t,H}$, and the distribution for the rapidity separation between the two leading jets, $\Delta y_{j_1,j_2}$.

Differences between NLO and NNLO need to be better understood

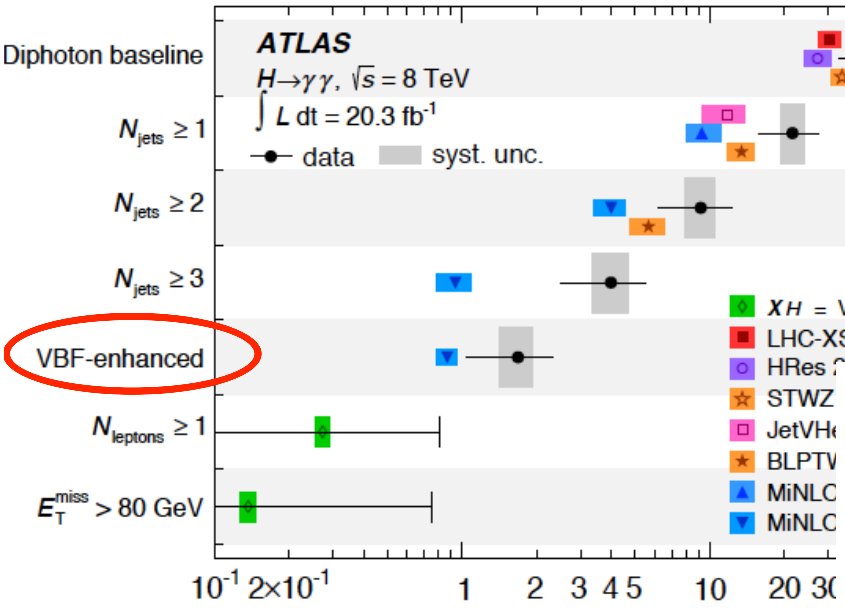
Higgs sector

- Higgs +>= 2 jets crucial to understand Higgs coupling, in particular through VBF



H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD dσ(gg) @ NLO QCD dσ(VBF) @ NLO EW	dσ @ NNLO QCD + NLO EW	H couplings
H + V	dσ @ NNLO QCD dσ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	dσ @ LO QCD (full m_t dependence) dσ @ NLO QCD (infinite m_t limit)	dσ @ NLO QCD (full m_t dependence) dσ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)



study from Les Houches 2013; will be extended in 2015

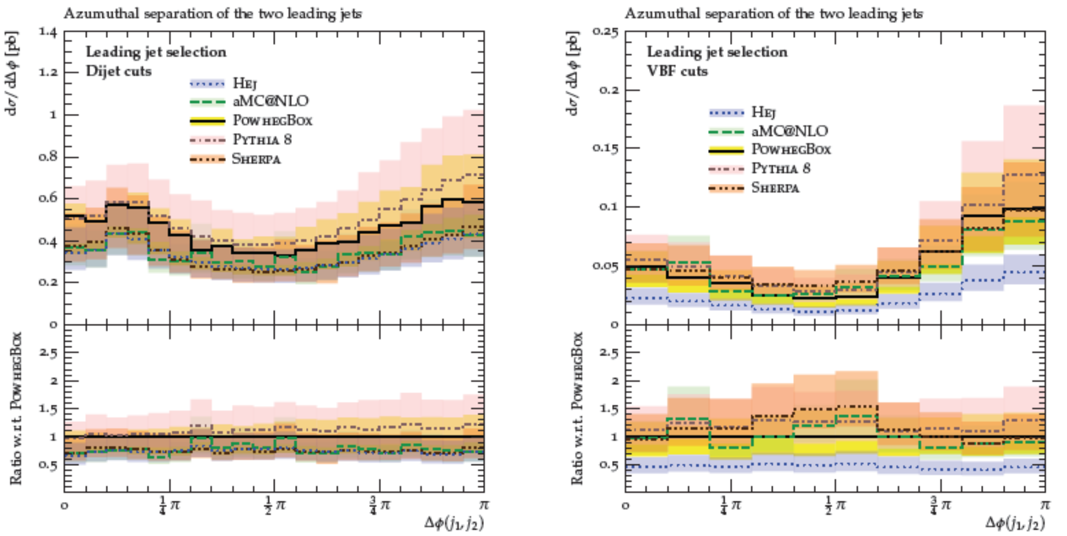
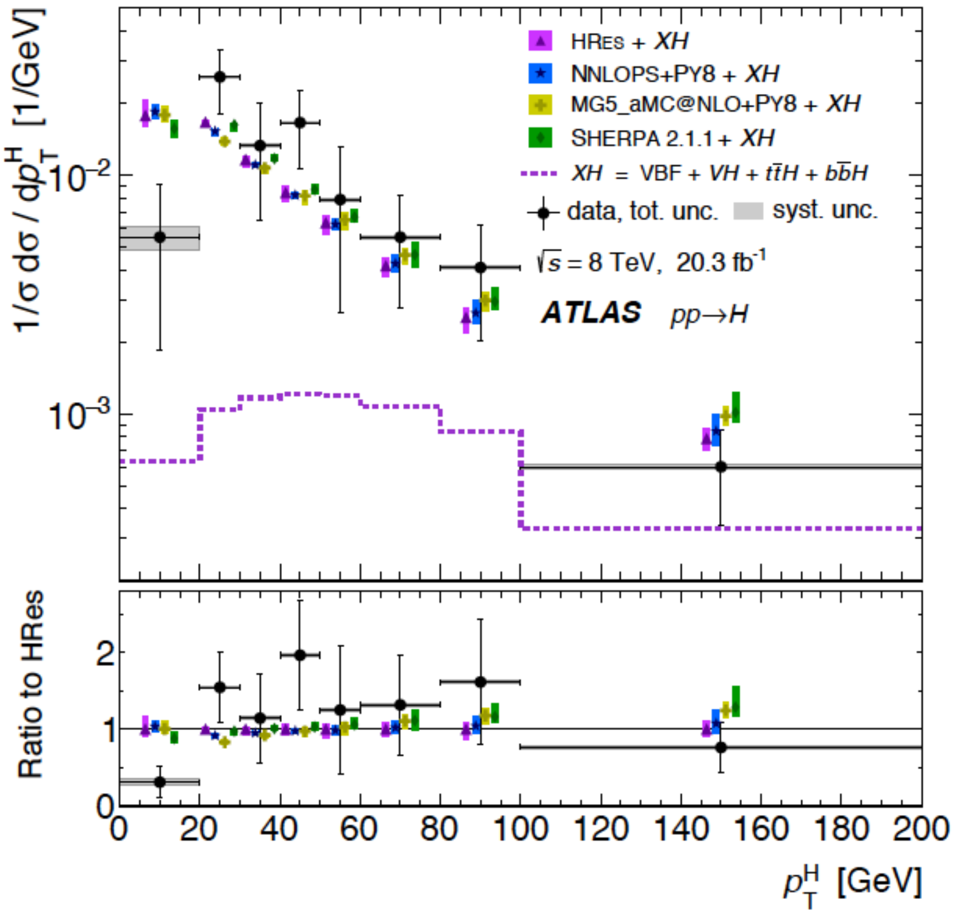


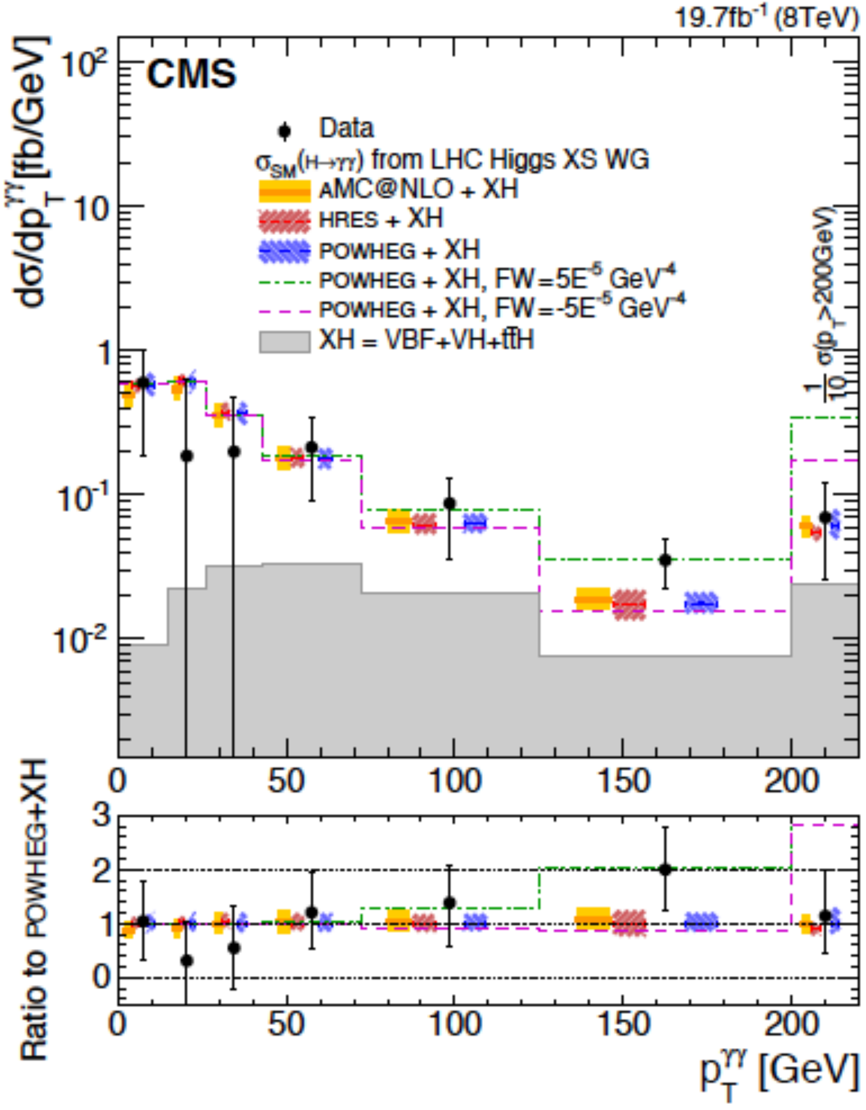
Fig. III.29: Azimuthal separation of the tagging jets before (left) and after (right) the application of the VBF selection cuts in the leading jet selection as predicted by the different generators. The individual sources of uncertainties used to generate the respective bands are described in Sec. 6.2.

can we gain a better quantitative understanding/reduction of ggF contamination in VBF region? It's not enough to say they agree within uncertainties. Many of those uncertainties are in common.

Higgs p_T distribution

…better statistics in Run 2 will make things more interesting with the comparisons

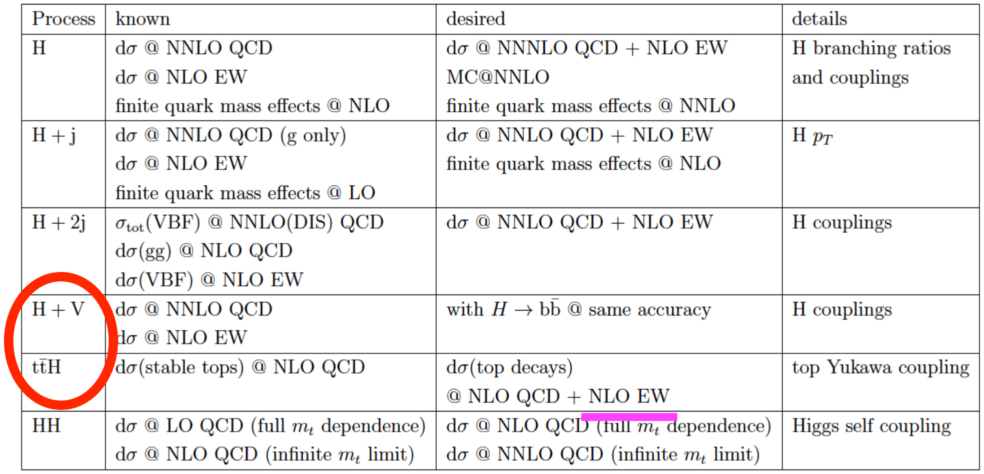




Higgs sector

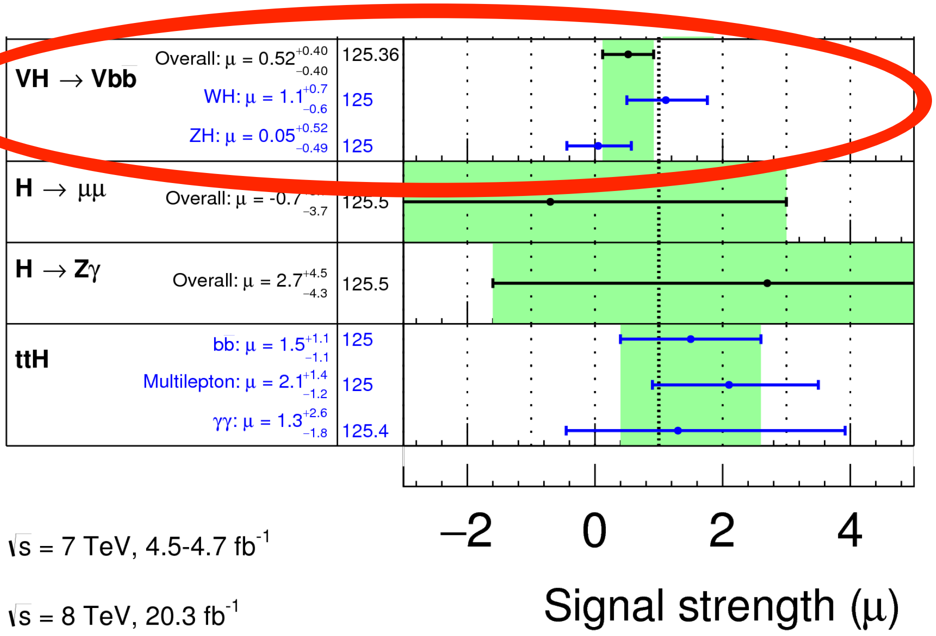
- Coupling of Higgs to top and bottom quarks poorly known
  - 50% for bottom
  - 100% for top
- H->bB primarily measured through asociated production, known currently at NNLO QCD and at NLO EW
- bB decay currently in NLO QCD production in narrow-width approximation; desirable to combine Higgs production and decay processes to same order, NNLO in QCD and NLO in EW for Higgs-strahlung process
- With 300 fb^{-1} at 14 TeV, signal strength for H->bB should be measured to 10-15% level, shrinking to 5% for 3000 fb^{-1}

- NB: gg->ZH at NLO critical component; currently beyond state of art



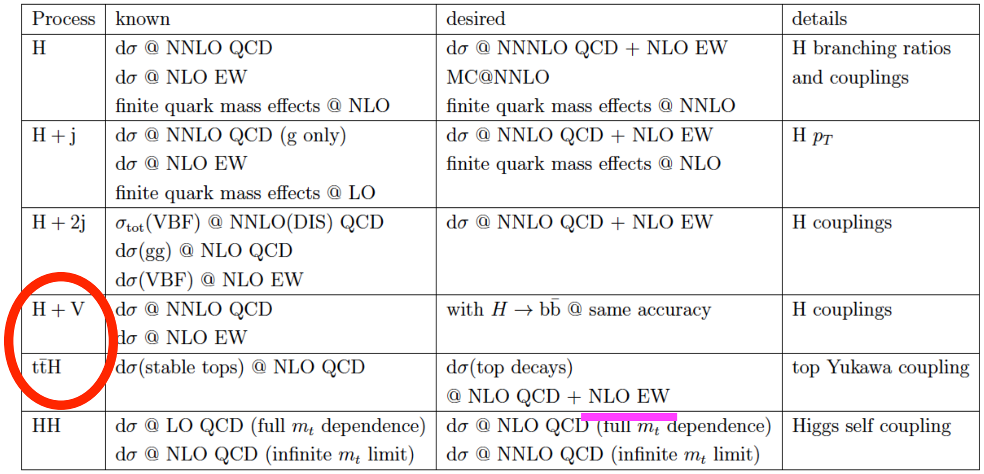
Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD dσ(gg) @ NLO QCD dσ(VBF) @ NLO EW	dσ @ NNLO QCD + NLO EW	H couplings
H + V	dσ @ NNLO QCD dσ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}H$	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	dσ @ LO QCD (full m_t dependence) dσ @ NLO QCD (infinite m_t limit)	dσ @ NLO QCD (full m_t dependence) dσ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)



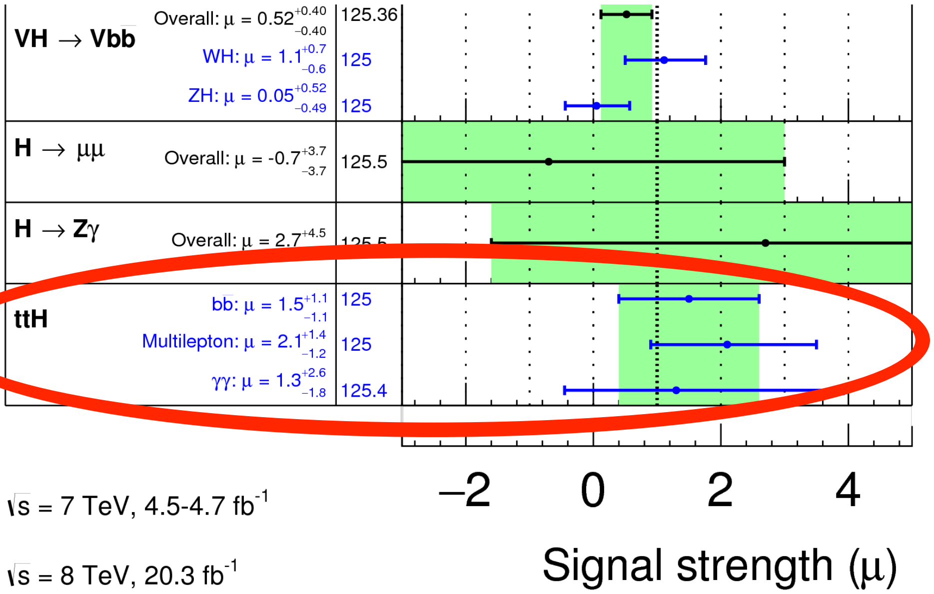
Higgs sector

- Coupling of Higgs to top and bottom quarks poorly known
  - 50% for bottom
  - 100% for top
- Higgs-top couplings may have both scalar and pseudo-scalar components (in presence of CP violation)
- Can be probed in measurements of Higgs production in association with tT or t
- tH (tTH) known to LO (NLO) QCD wth stable tops
- Need to know the cross section (with top decays) at NLO QCD, possibly including NLO EW effects



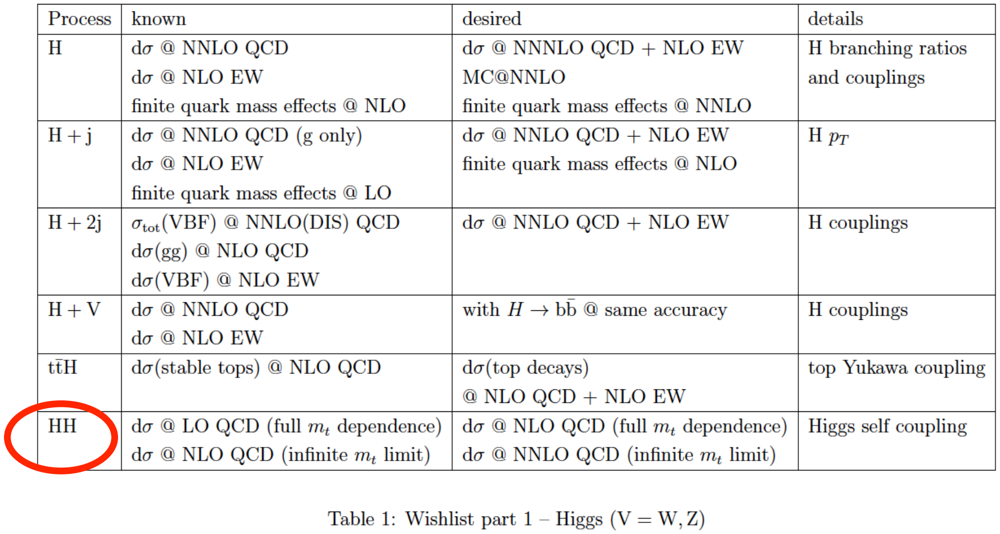
Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD dσ(gg) @ NLO QCD dσ(VBF) @ NLO EW	dσ @ NNLO QCD + NLO EW	H couplings
H + V	dσ @ NNLO QCD dσ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	dσ @ LO QCD (full m_t dependence) dσ @ NLO QCD (infinite m_t limit)	dσ @ NLO QCD (full m_t dependence) dσ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)



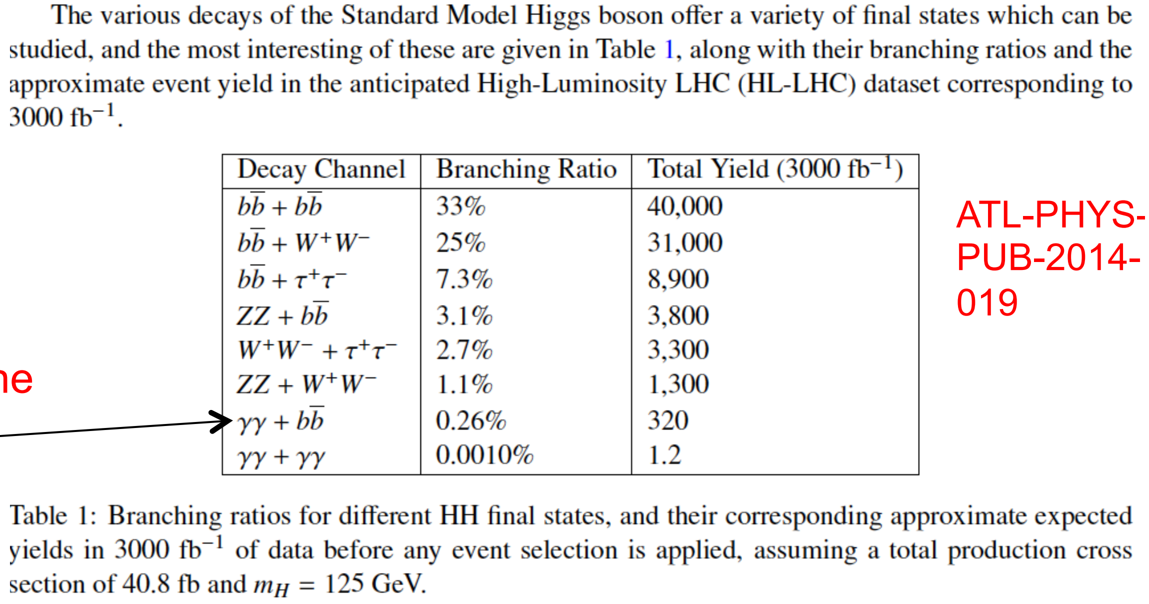
Higgs sector

- Self-coupling of the Higgs one of the holy grails of extended running at the LHC
    - directly probes EW potential
- HH production through ggF currently known at LO with full top mass dependence, at NLO with leading finite mass terms, and at NNLO in the infinite top-mass limit
- It may be necessary to compute full top mass dependence at NLO QCD
- With 3000 fb^{-1} at 14 TeV, hope for a 50% precision on self-coupling parameter



Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD dσ(gg) @ NLO QCD dσ(VBF) @ NLO EW	dσ @ NNLO QCD + NLO EW	H couplings
H + V	dσ @ NNLO QCD dσ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
t$\bar{\mathrm{t}}$H	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	dσ @ LO QCD (full m_t dependence) dσ @ NLO QCD (infinite m_t limit)	dσ @ NLO QCD (full m_t dependence) dσ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)



The various decays of the Standard Model Higgs boson offer a variety of final states which can be studied, and the most interesting of these are given in Table 1, along with their branching ratios and the approximate event yield in the anticipated High-Luminosity LHC (HL-LHC) dataset corresponding to 3000 fb^{-1}.

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

Table 1: Branching ratios for different HH final states, and their corresponding approximate expected yields in 3000 fb^{-1} of data before any event selection is applied, assuming a total production cross section of 40.8 fb and m_H = 125 GeV.

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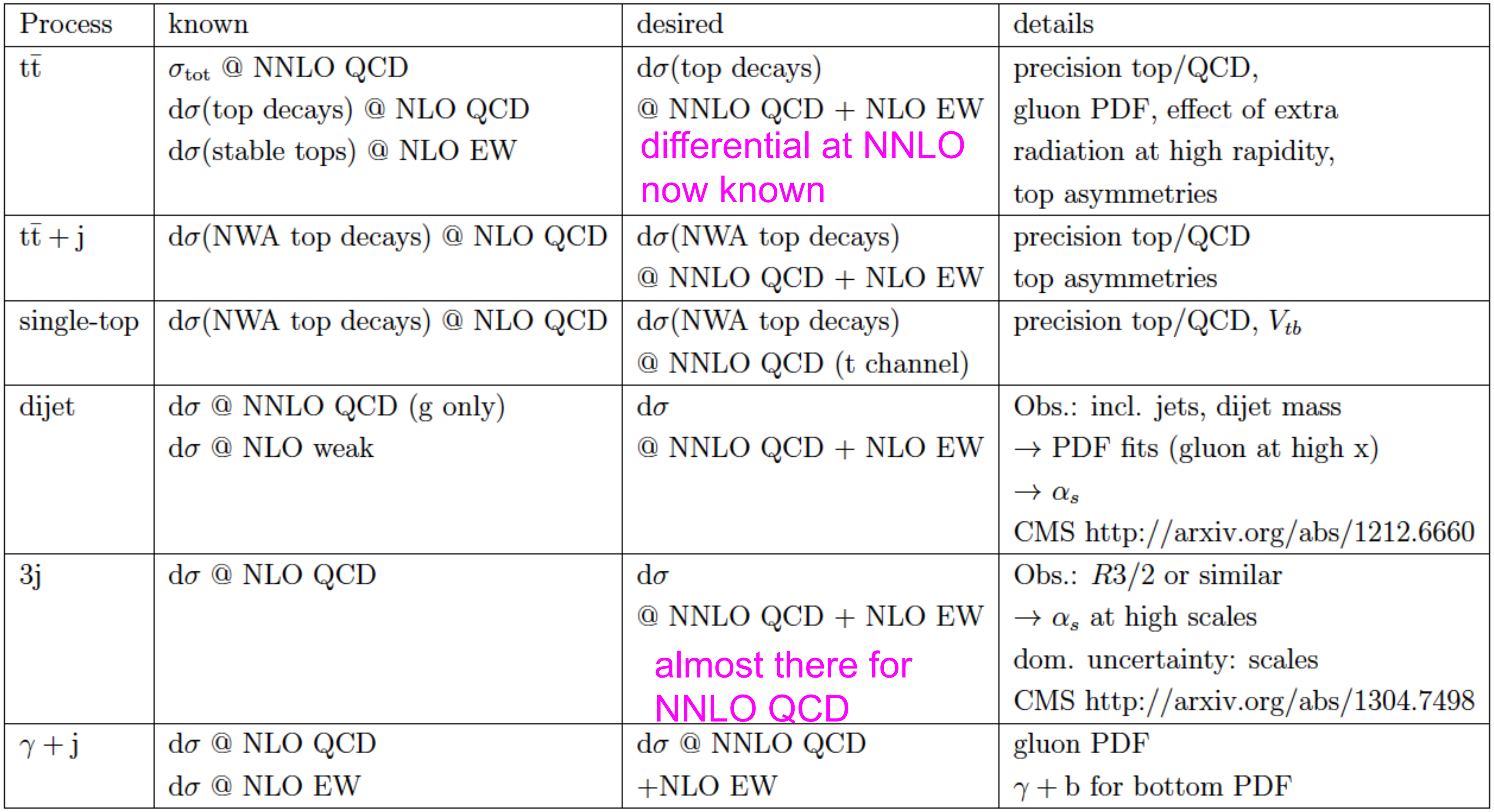
despite small BR, one of the most promising channels; best significance using boosted regime

heavy quarks, photons, jets

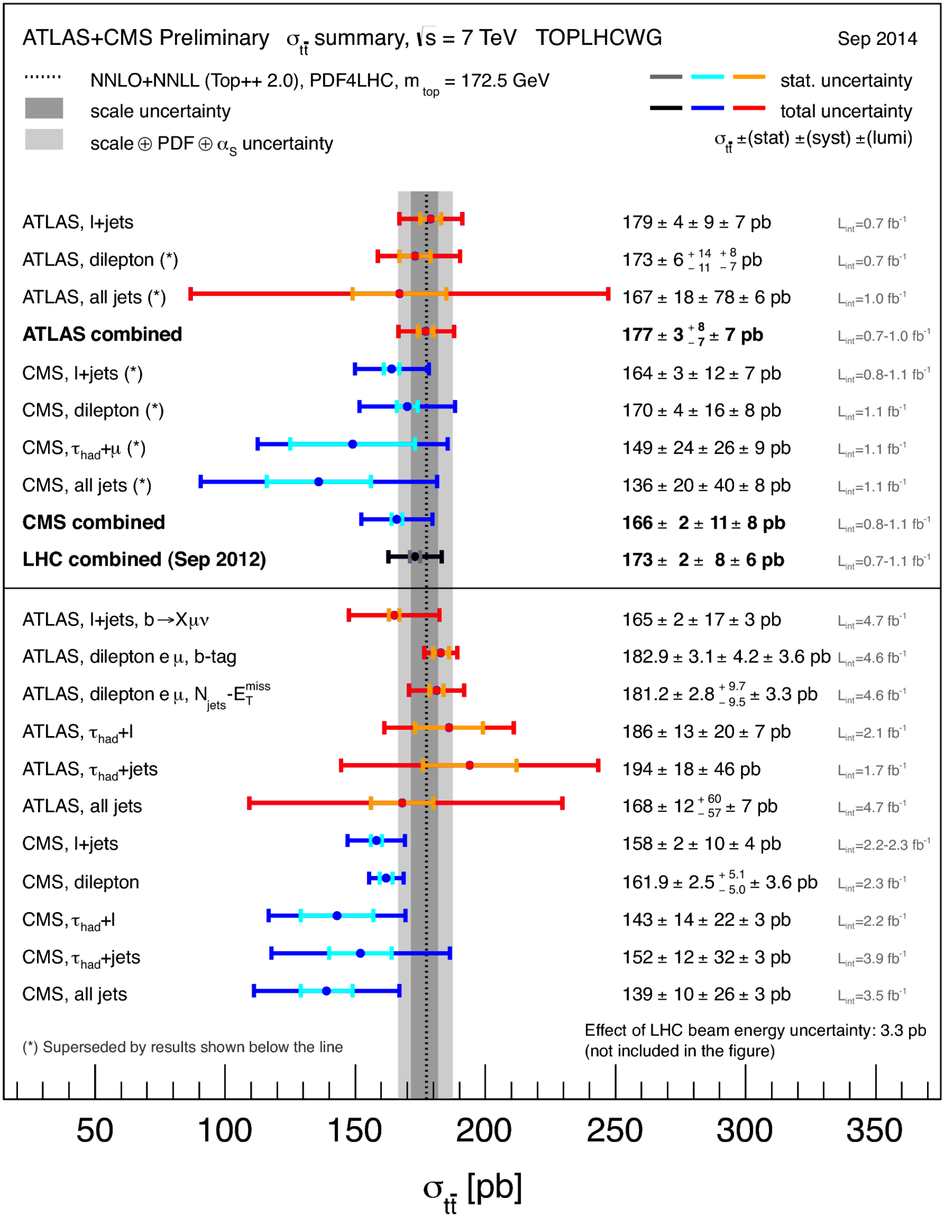


Process	known	desired	details
$t\bar{t}$	σ_{tot} @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW differential at NNLO now known	precision top/QCD, gluon PDF, effect of extra radiation at high rapidity, top asymmetries
$t\bar{t}+j$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW	precision top/QCD top asymmetries
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD (t channel)	precision top/QCD, V_{tb}
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO weak	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: incl. jets, dijet mass → PDF fits (gluon at high x) $\rightarrow \alpha_s$ CMS http://arxiv.org/abs/1212.6660
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW almost there for NNLO QCD	Obs.: $R3/2$ or similar $\rightarrow \alpha_s$ at high scales dom. uncertainty: scales CMS http://arxiv.org/abs/1304.7498
$\gamma+j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD +NLO EW	gluon PDF $\gamma+b$ for bottom PDF

Table 2: Wishlist part 2 – jets and heay quarks

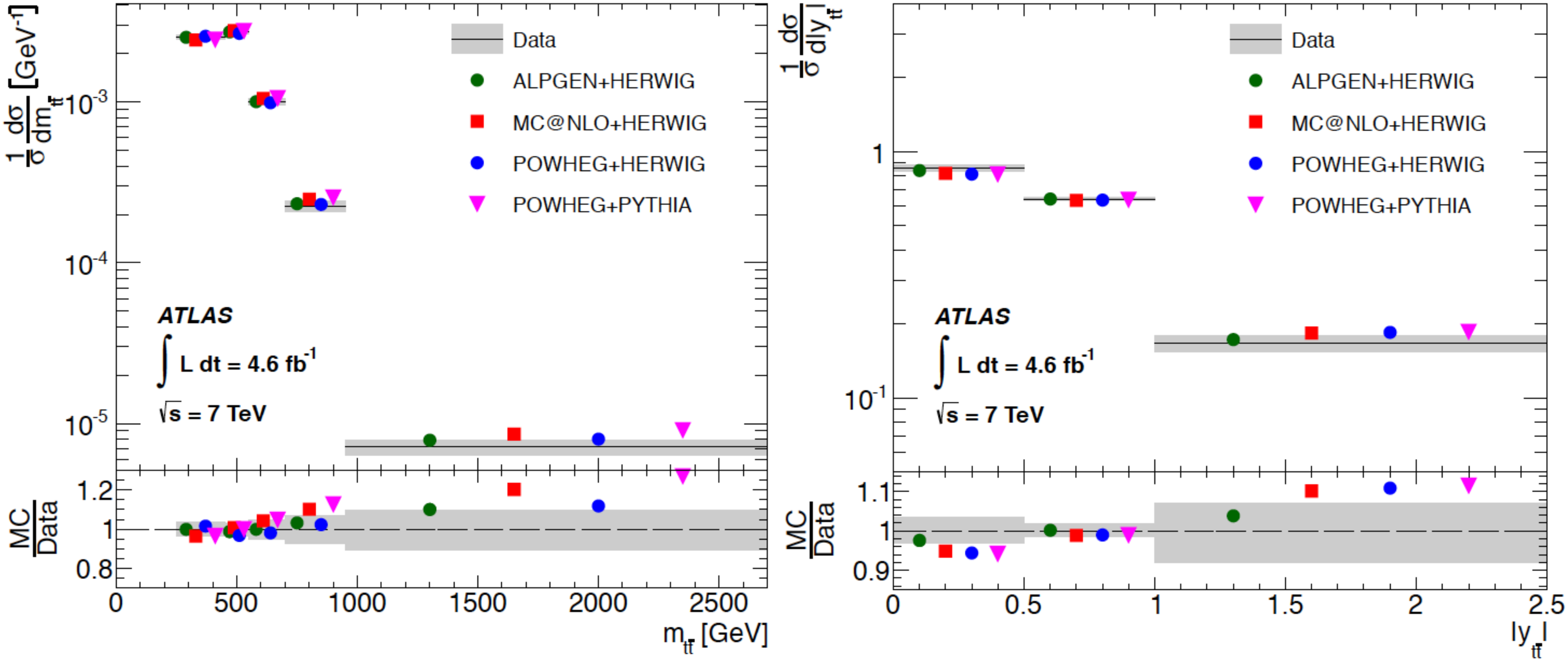
Top pair production

- Top production is important both as a possible venue for new physics as well as for more mundane purposes such as the determination of the gluon PDF at high x
- Currently, the dilepton final state is known to an experimental uncertainty of 4% and the uncertainty for the leptons+jets final state should be of the same order in Run 2
  - a sizeable portion of that error is due to the luminosity uncertainty
- Currently know total top cross section to NNLO QCD and NLO EW
  - 4% uncertainties
- Need differential top cross section to NNLO QCD (with decays) including NLO EW effects

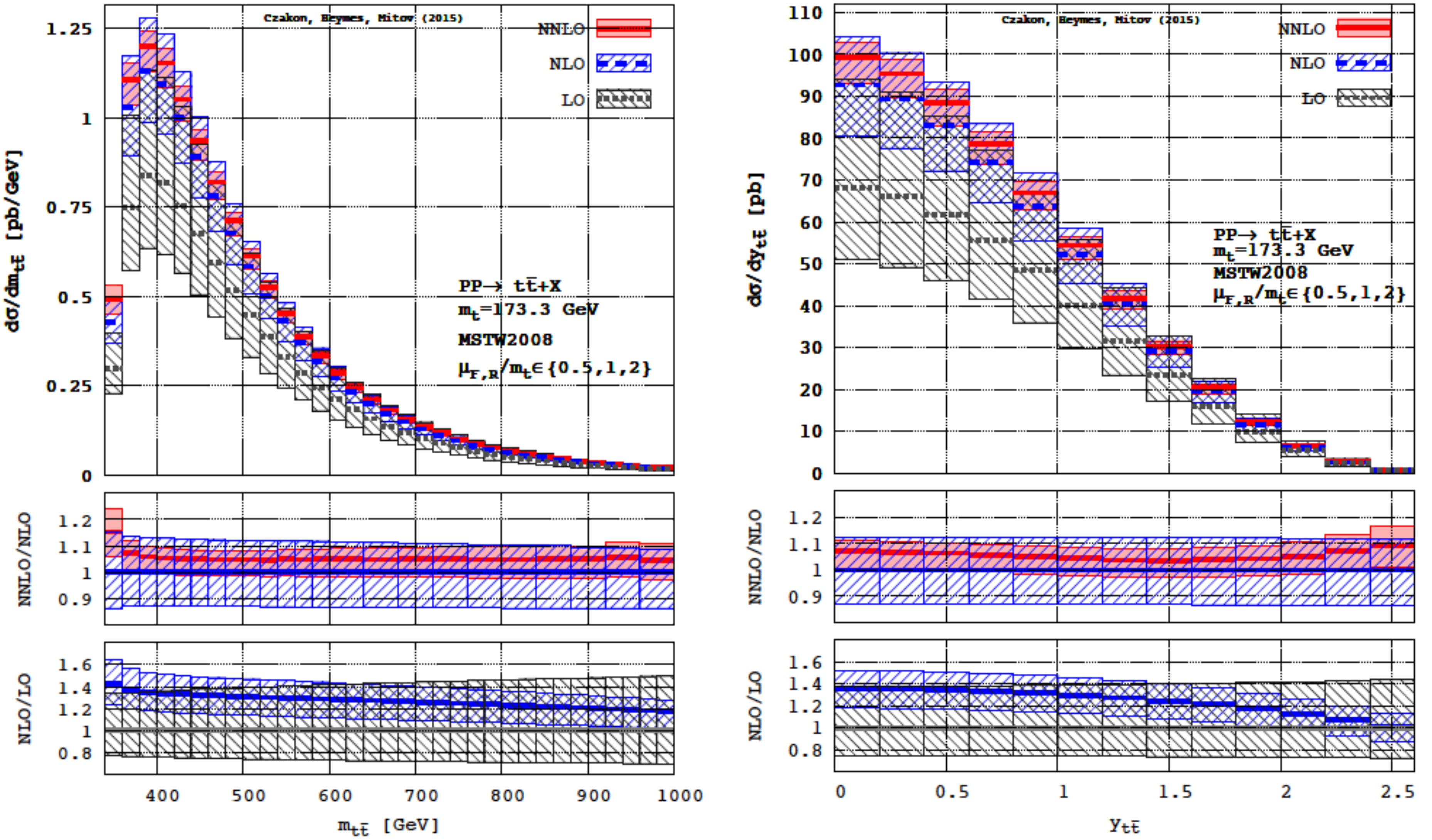


Mass and rapidity distributions

- gg channel is dominant; differential predictions at NNLO will help constrain high x gluon distribution
  - weaker gluon at high x than needed for jet production?
- …but, NLO EW corrections also important

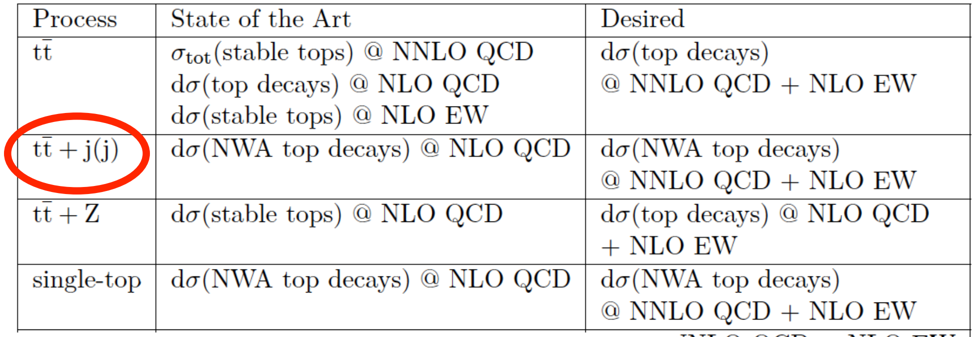


arXiv:1511.00549



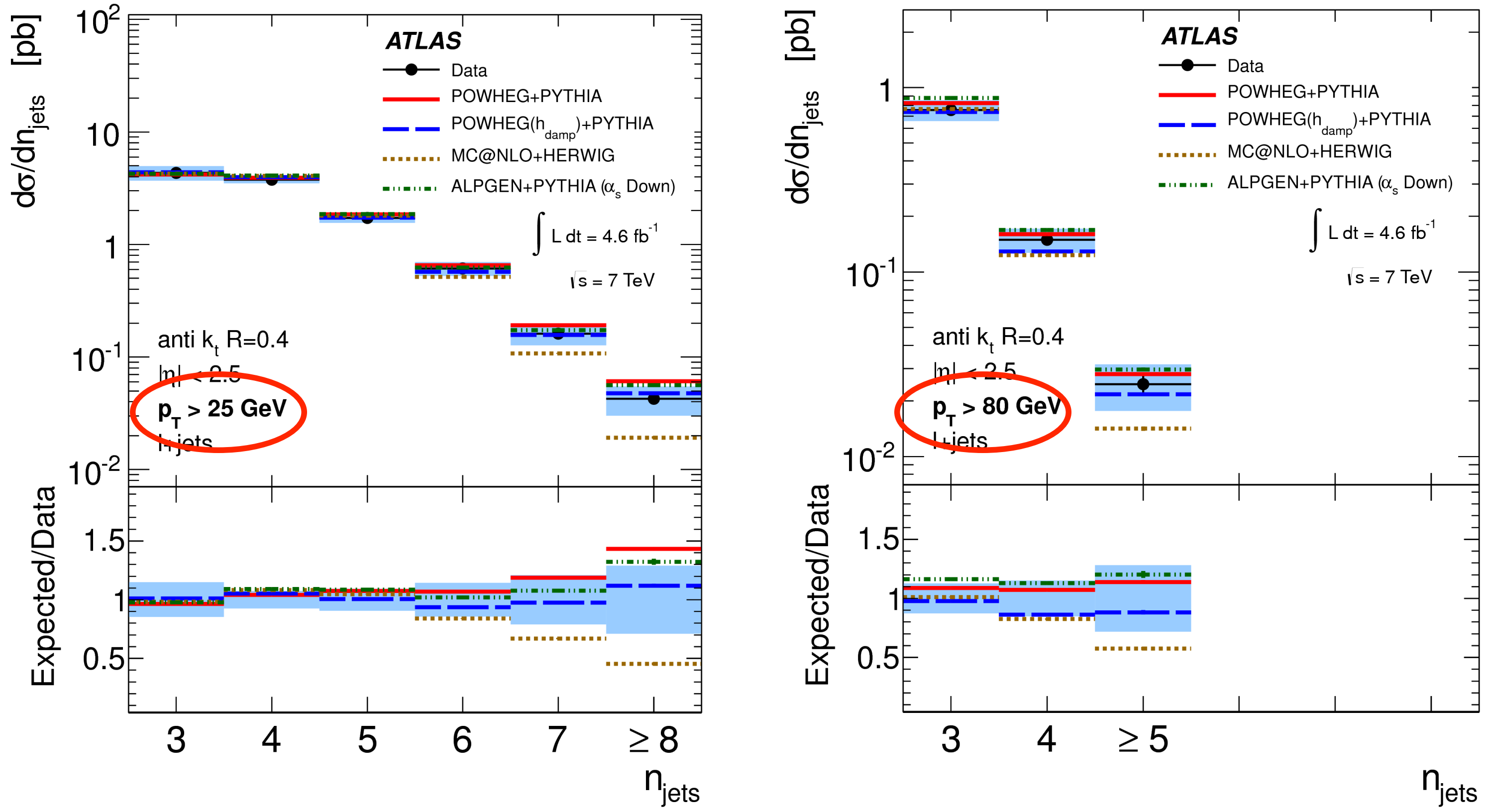
tT+jets

- Due to dominance of gg initial state, basically every tT event is a tTj event
- Currently known at NLO QCD
- Desired to know (with decays) at NNLO QCD with NLO EW effects



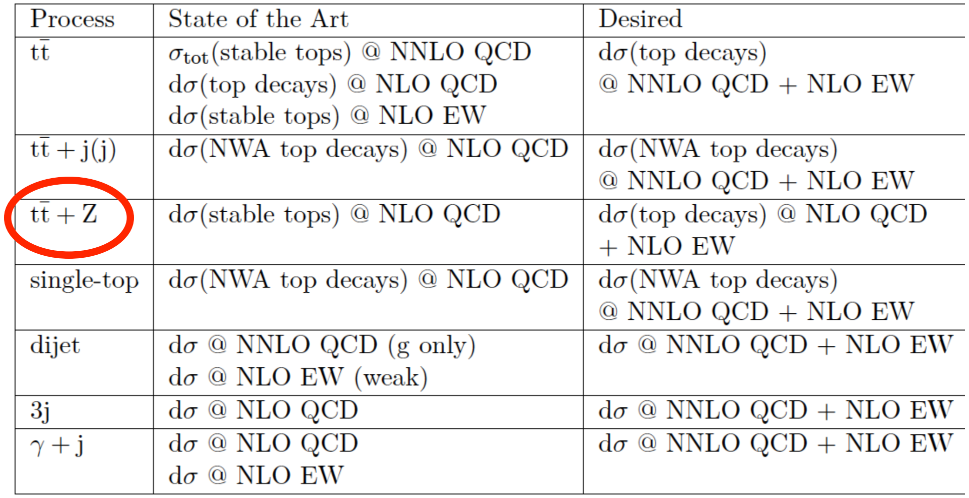
Process	State of the Art	Desired
$t\bar{t}$	$\sigma_{\rm tot}$(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t} + j(j)$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t} + Z$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW

NLO QCD + NLO EW
NLO QCD + NLO EW
NLO QCD + NLO EW

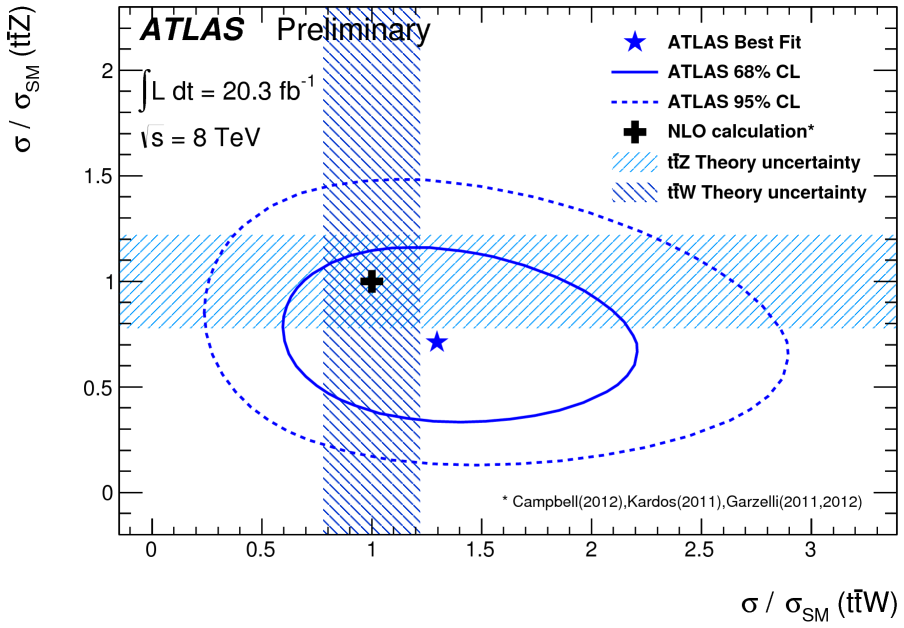


tTZ

- Important process to compare to tTH production, but also for measuring coupling of top quark with Z (or W)
- Currently known to NLO with on-shell top decays
- Need to be able to study hard radiation effects in top decays



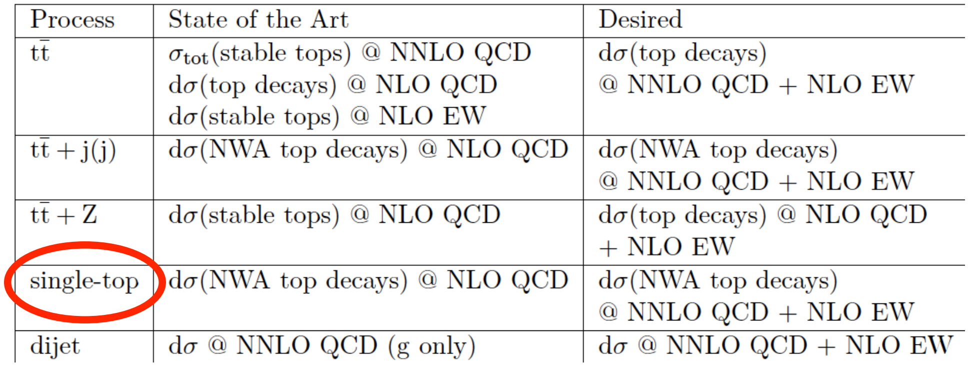
Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t}+j(j)$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}+Z$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW
$\gamma+j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW



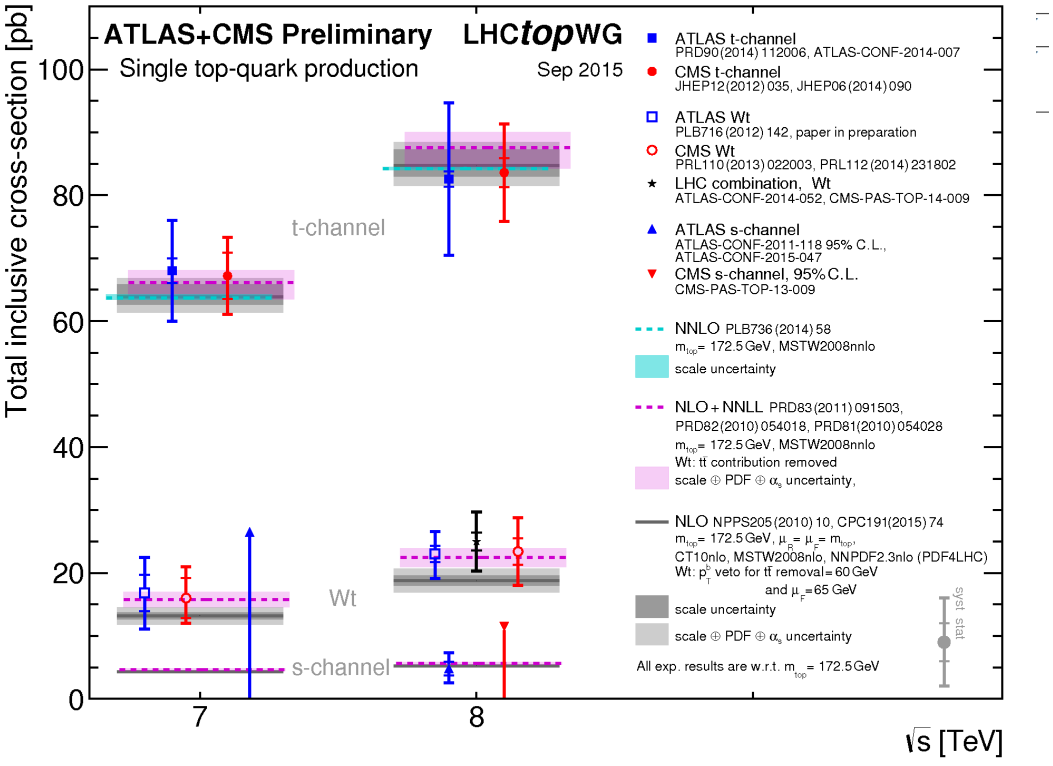
agreement (within large uncertainty) with the standard model prediction

Single top

- Important for precision top physics and in particular the measurement of Vtb
- Current experimental precision is on the order of 10% and a precision of the order of 5% desireable/possible in Run 2
- Both ATLAS and CMS have observed tW, with approximately 20% uncertainties (dominated by statistics)
    - <10% for Run 2
- Currently single top cross section known to NNLO in QCD
    - arXiv:1404.7116
- tW known theoretically to within 10% and tZ to within 5%
- Would like single top cross section to NNLO QCD including NLO EW effects

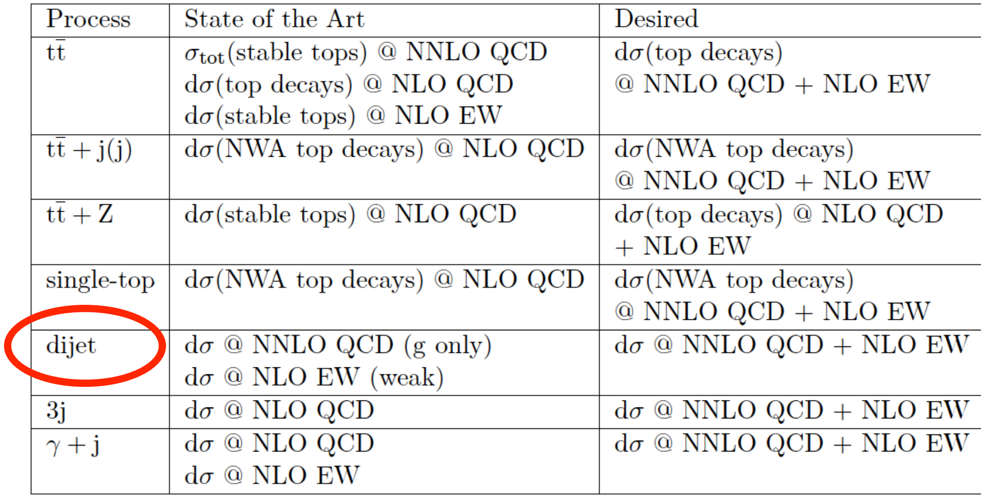


Process	State of the Art	Desired
$t\bar{t}$	$\sigma_{\rm tot}$(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t}+j(j)$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}+Z$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only)	$d\sigma$ @ NNLO QCD + NLO EW



Dijets

- One of key processes for perturbative QCD
    - covers largest kinematic range with jets produced in the multi-TeV range
    - EW effects very important in this range
- Only process currently included in global fits not known at NNLO
    - gg,qQ, gq channels have been calculated; only qq remains
- Current experimental precision on the order of 5-10% for jets from 200 GeV/c to 1 TeV/c
- Would like better precision for theory
    - so need NNLO QCD and NLO EW



Process	State of the Art	Desired
$t\bar{t}$	$\sigma_{\rm tot}$(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t}+j(j)$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}+Z$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW
$\gamma+j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW

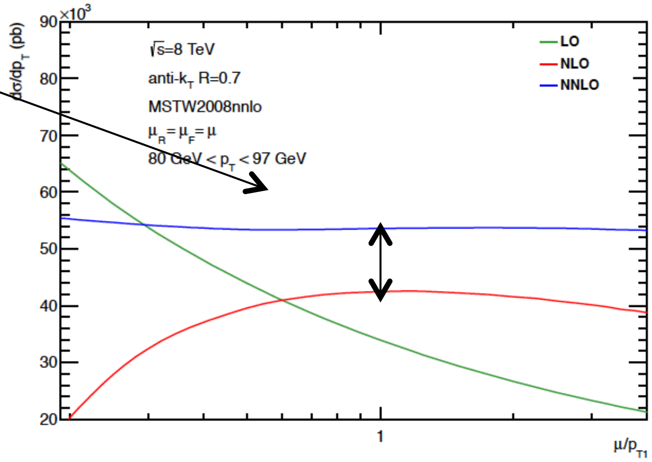
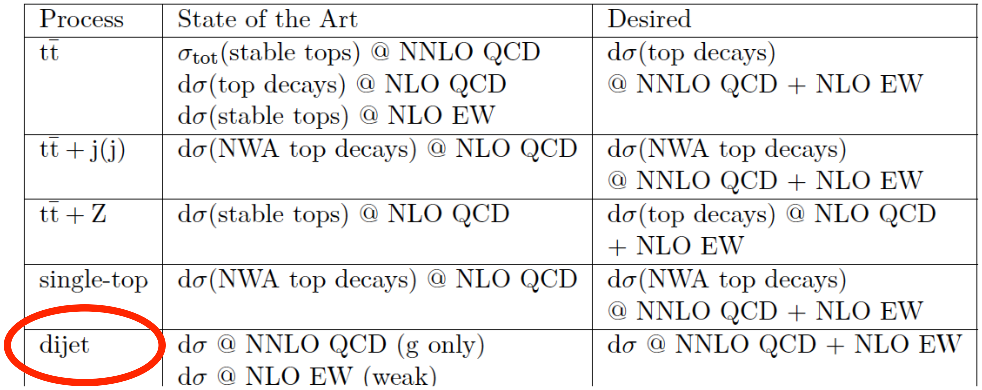


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

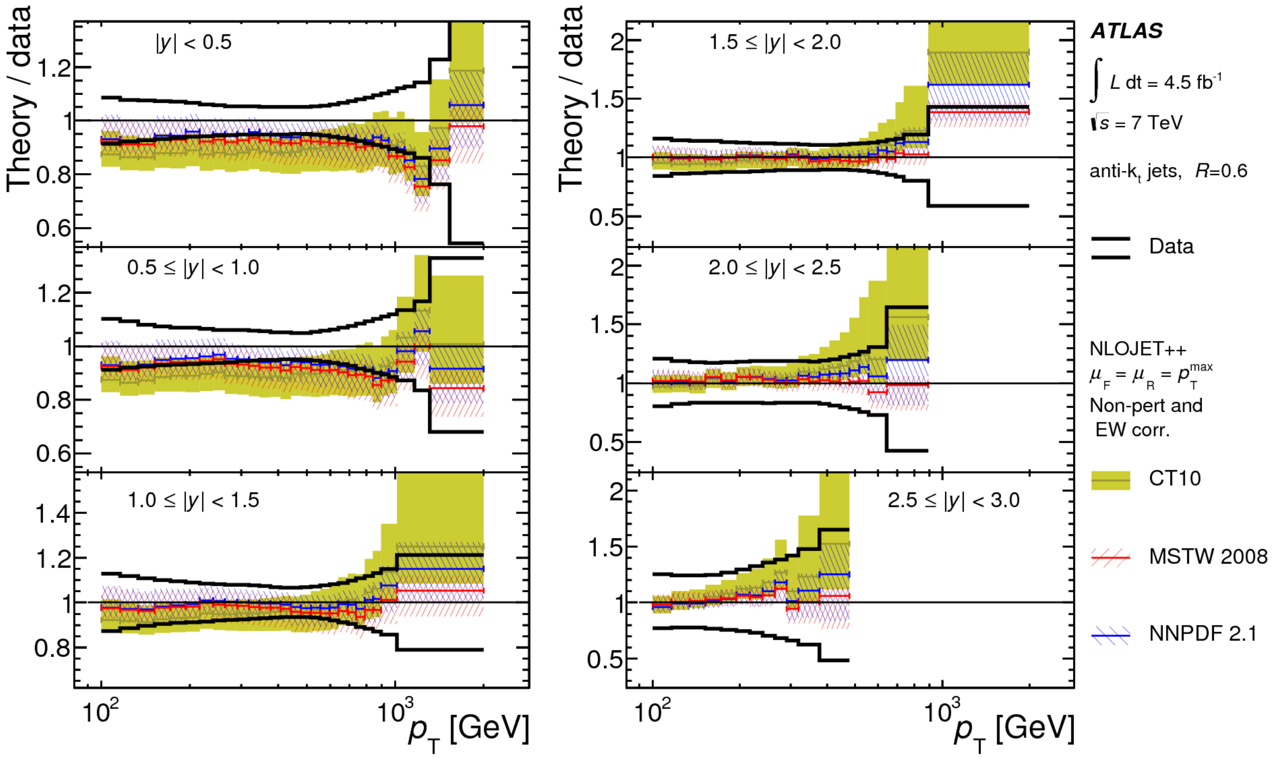
NB: relatively large corrections

Dijets

- One of key processes for perturbative QCD
  - covers largest kinematic range with jets produced in the multi-TeV range
  - EW effects very important in this range



Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t} + j(j)$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t} + Z$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW



…but, arXiv:1407.7031

- NNLO/NLO corrections smaller (on the order of 5%) and flat as a function of jet p_T if scale of inclusive jet p_T is used rather than p_T of the lead jet
- …which is what should be used in any case
- expect corrections for other subprocesses to be of similar order

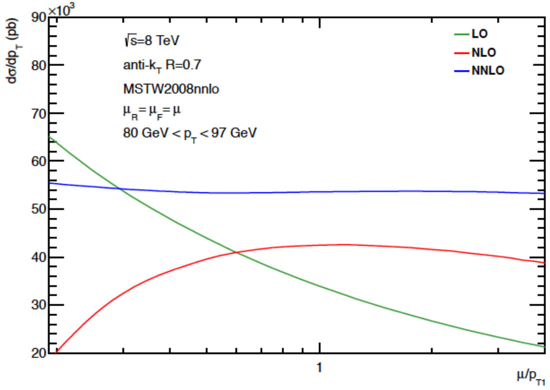


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

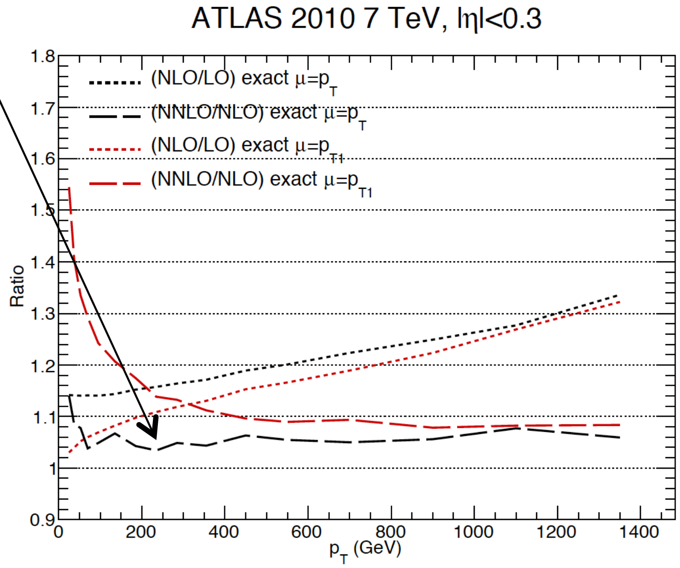
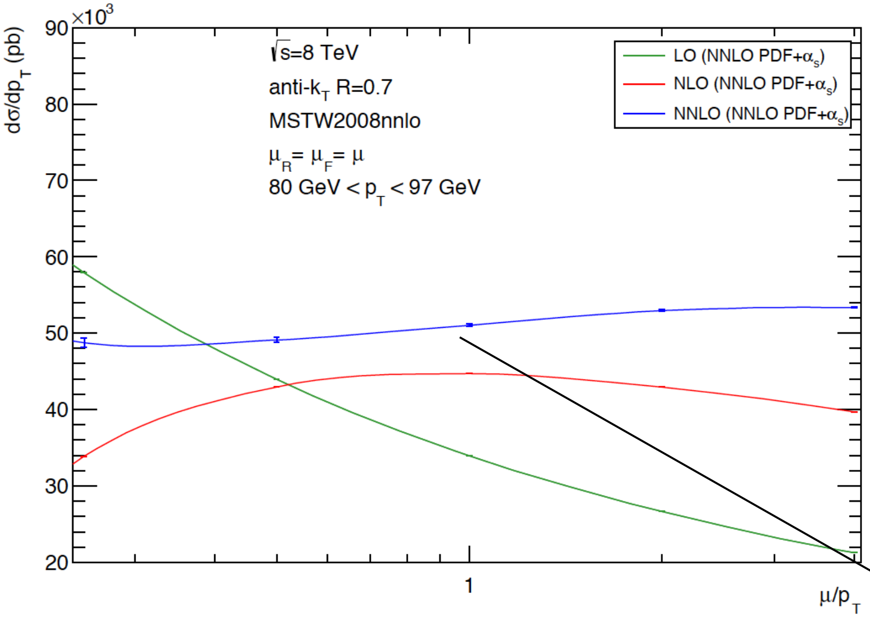


Figure 8: NLO/LO and NNLO/NLO exact k-factors for the gg-channel evaluated with the renormalisation and factorisation scales $\mu_R = \mu_F = p_T$ and $\mu_R = \mu_F = p_{T1}$.

…and, revision of the paper

- The referee made the same request I did, to show the plot to the right using a scale of p_T, rather than p_{T1}



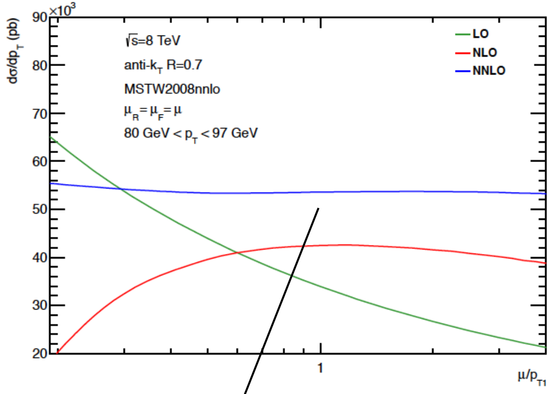


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

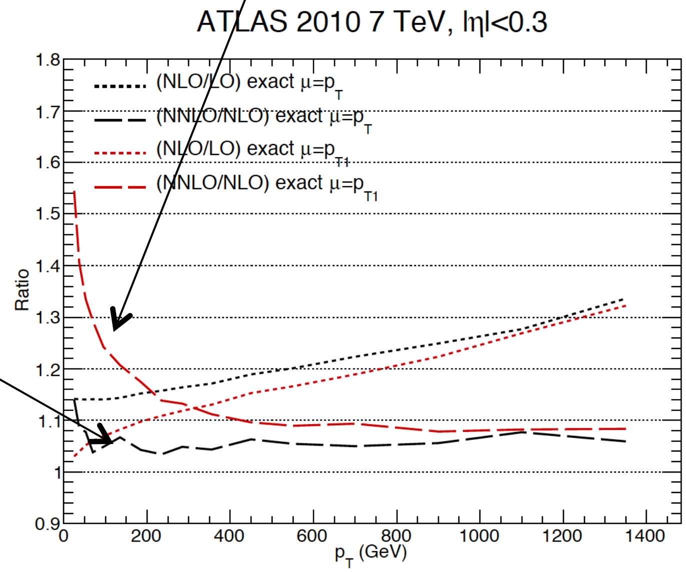

ATLAS 2010 7 TeV, |η|<0.3

Figure 8: NLO/LO and NNLO/NLO exact k-factors for the gg-channel evaluated with the renormalisation and factorisation scales $\mu_R = \mu_F = p_T$ and $\mu_R = \mu_F = p_{T1}$.

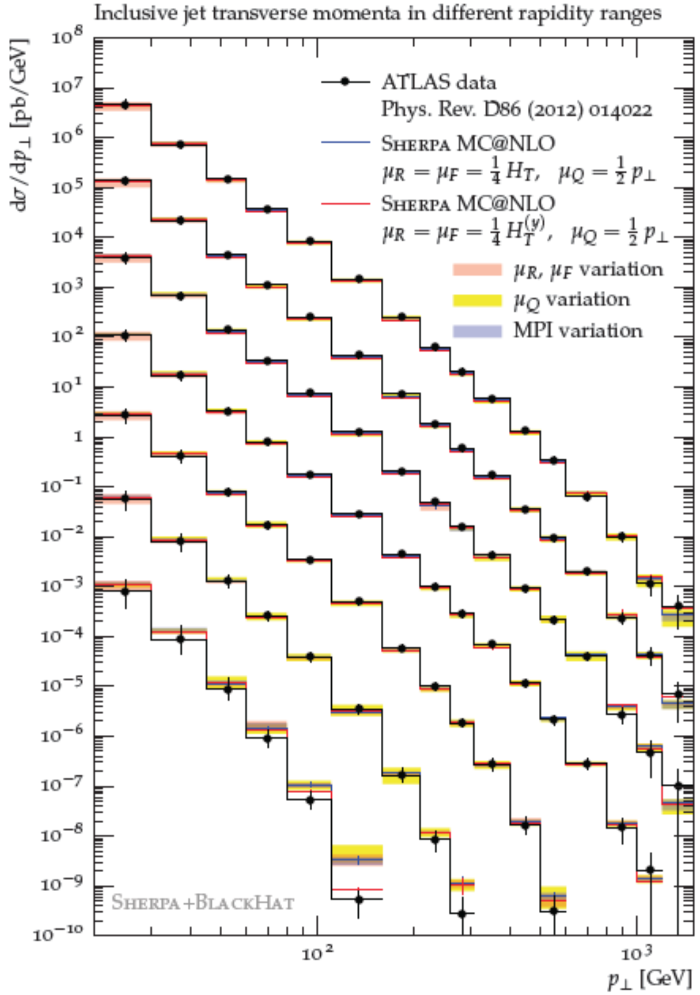
- Note that NLO goes up (as expected) but NNLO also comes down…and a bit more scale dependence

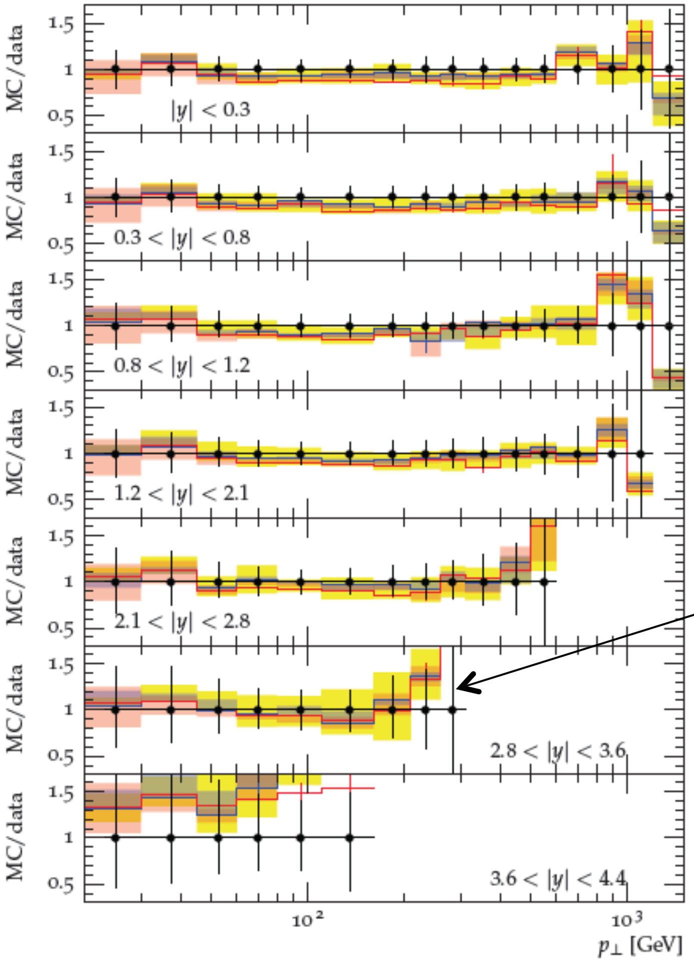
Inclusive jet production

- **We also need a better understanding of the impact of parton showers on the fixed order cross section**

Sherpa MC@NLO seems to do a good job in describing ATLAS data (but PDF dependent statement)

Compare to fixed order with same PDF



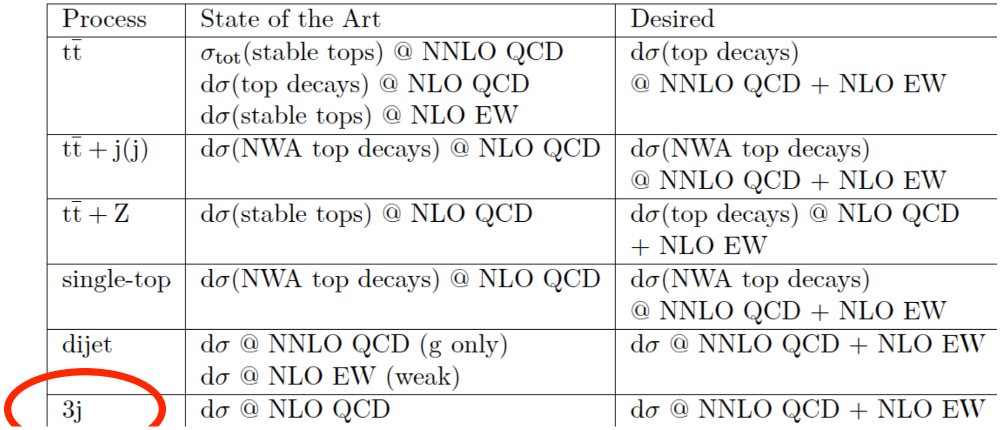


S. Hoeche, Marek Schoenherr for Sherpa; would be useful for other MC's as well

resummation scale uncertainties seem small except at extremes of phase space (as expected)

3 jets

- Useful for determination of the running of the strong coupling constant over a wide dynamic range
- Many experimental uncertainties cancel in the ratio of 3j/2j
    - for example jet energy scale uncertainty for ratio can be reduced to <1%
- Largest theoretical uncertainty is residual scale dependence at NLO
    - 5% at high p_T
- So like the dijet case, would like to know 3j production at NNLO QCD +NLO EW



Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
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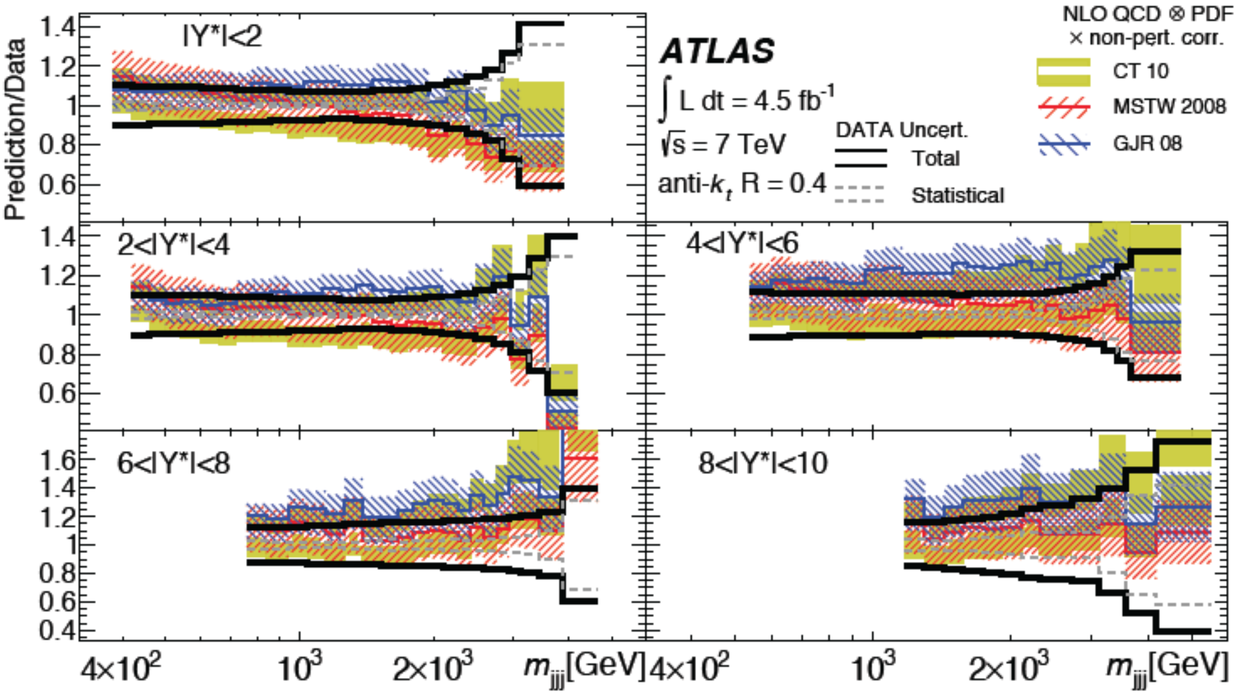
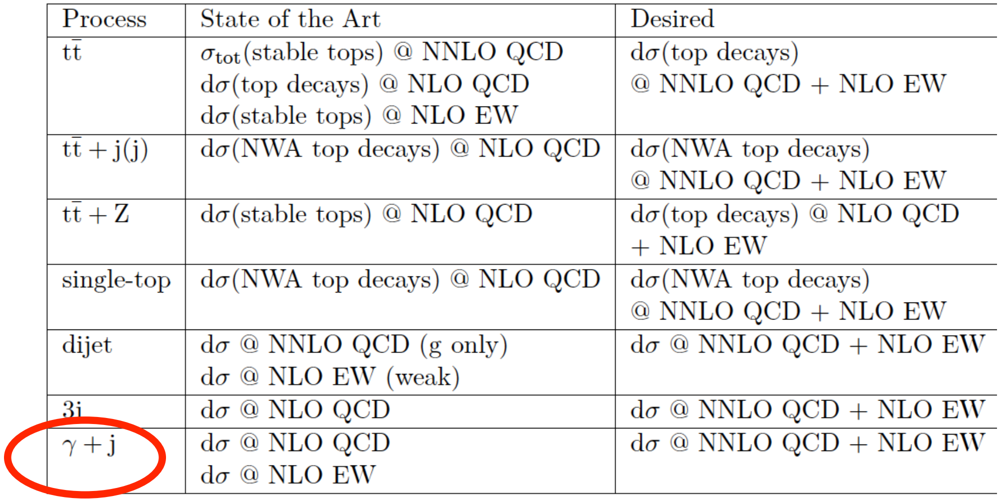
$t\bar{t}+Z$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW

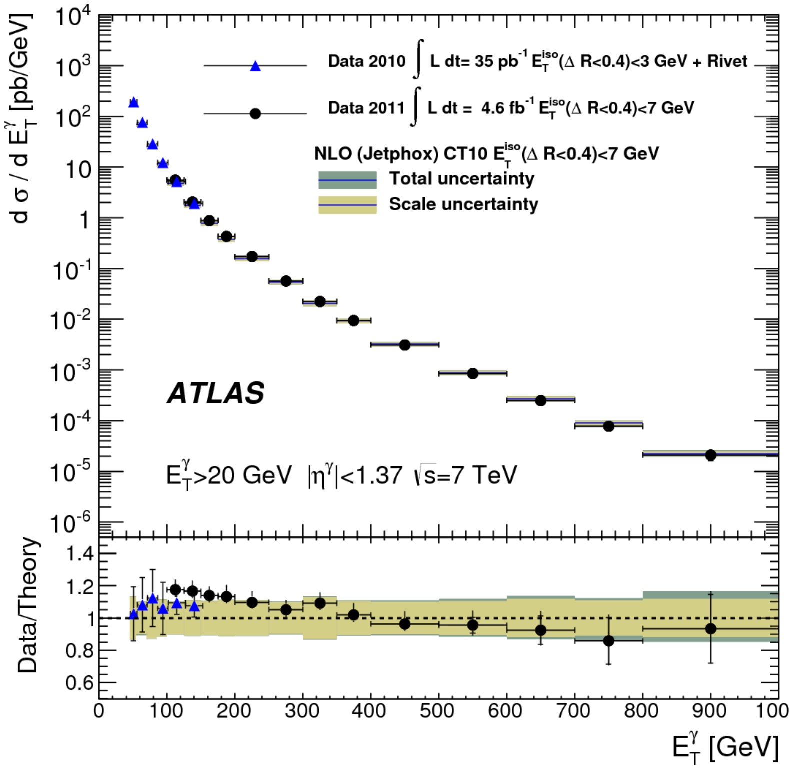


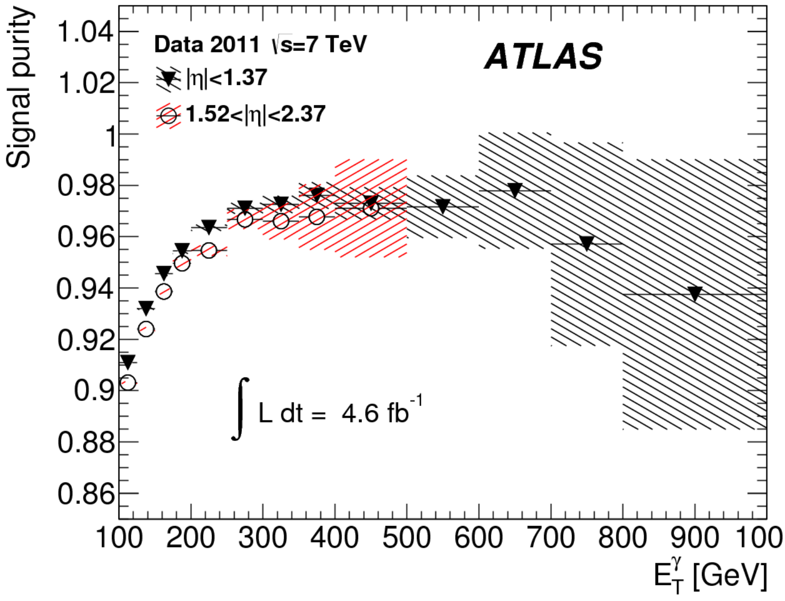
Inclusive photons

- Useful for determination of the gluon distribution, especially at high x
- Final state cleaner than dijet production (at high p_T)
- So like the dijet case, would like to know γ+j production at NNLO QCD +NLO EW



Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t}$ + j(j)	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}$ + Z	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW
γ + j	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW





Note any isolated high p_T EM object is a photon …if not in your analysis, then why not

L. Cieri: Paris photon workshop

Les Houches accord 2013

[Les Houches 2013: Physics at TeV Colliders: Standard Model Working Group Report]

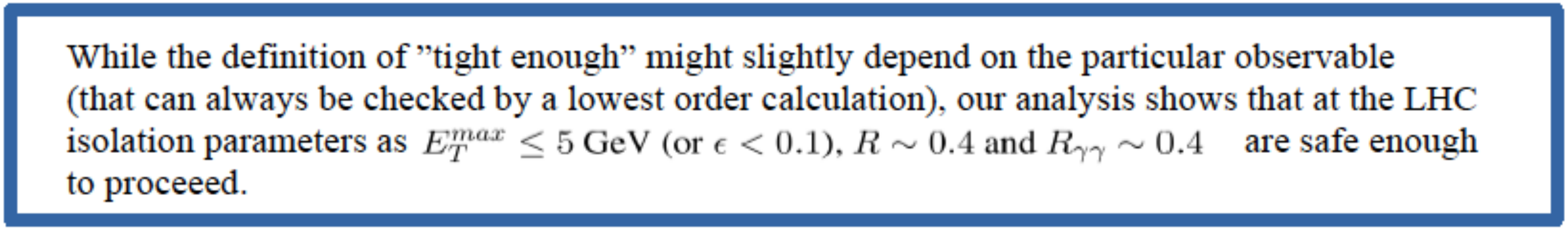
"LH tight photon isolation accord"

Can we explore this with more processes?
->Les Houches project

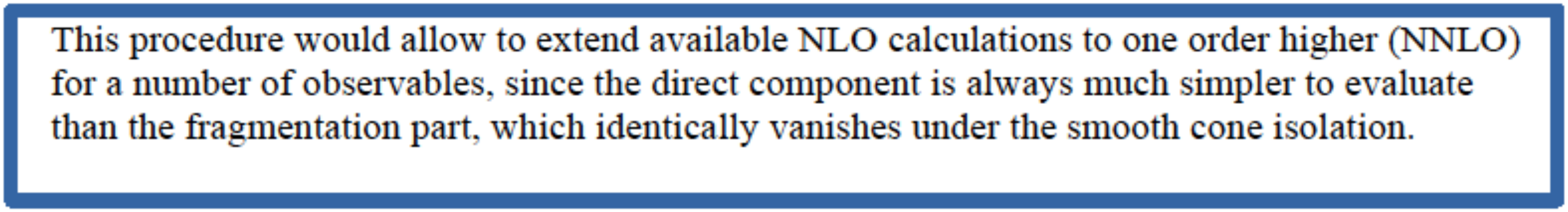
- EXP: use (tight) Cone isolation — solid and well understood
- TH: use smooth cone with same R and $E_{T\max}$ — accurate, better than using cone with LO fragmentation

Estimate TH isolation uncertainties using different profiles in smooth cone

should work to 1% if fragmentation contribution less than 20%



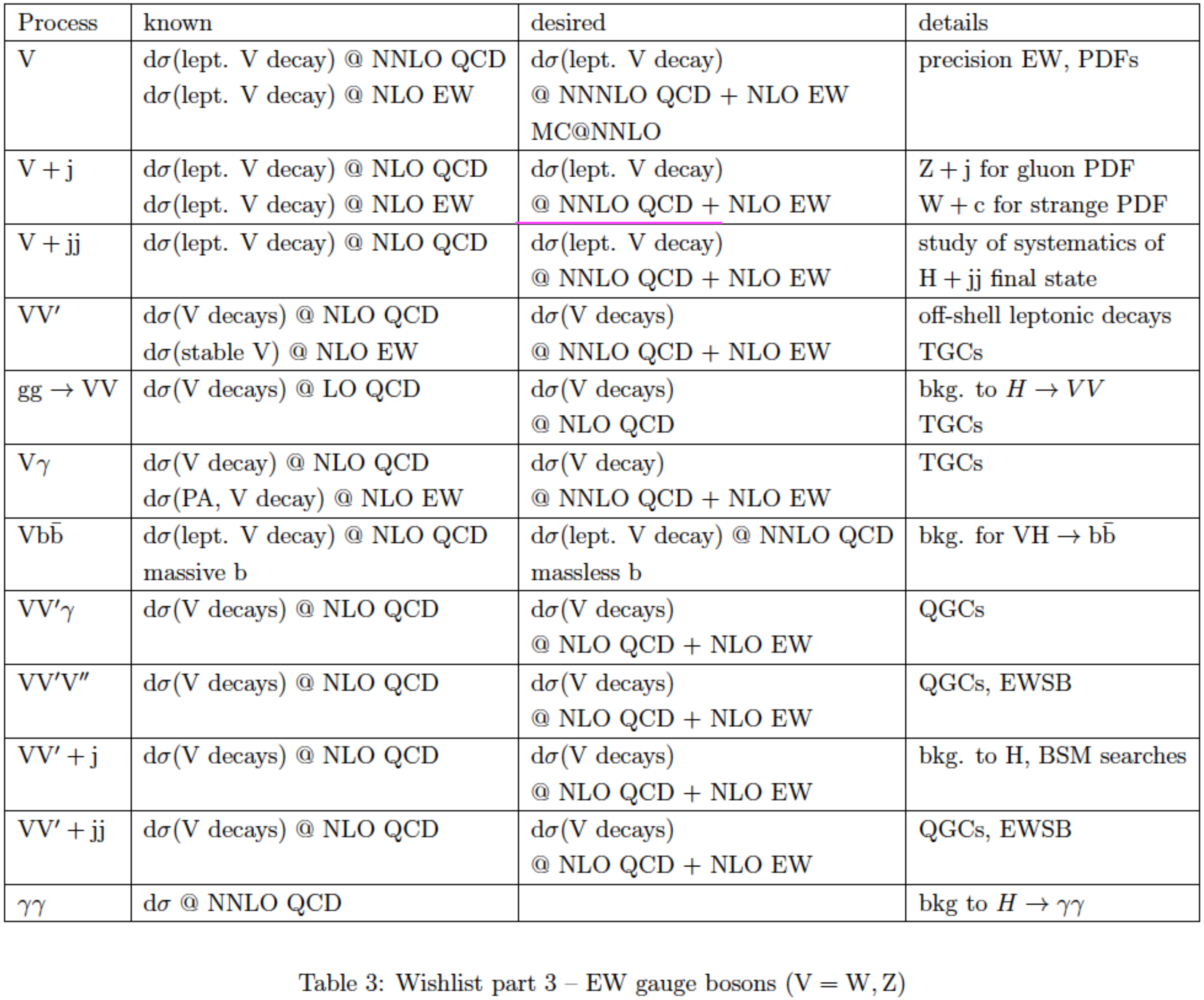
While the definition of "tight enough" might slightly depend on the particular observable (that can always be checked by a lowest order calculation), our analysis shows that at the LHC isolation parameters as $E_T^{max} \leq 5$ GeV (or $\epsilon < 0.1$), $R \sim 0.4$ and $R_{\gamma\gamma} \sim 0.4$ are safe enough to proceeed.



This procedure would allow to extend available NLO calculations to one order higher (NNLO) for a number of observables, since the direct component is always much simpler to evaluate than the fragmentation part, which identically vanishes under the smooth cone isolation.

Vector bosons

Vector bosons

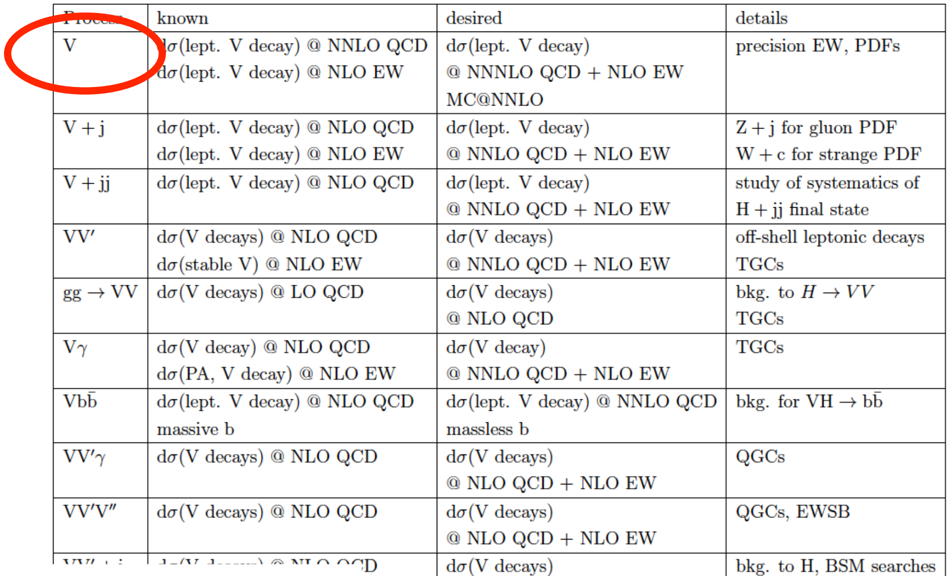


Process	known	desired	details
V	dσ(lept. V decay) @ NNLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
$\mathrm{V+j}$	dσ(lept. V decay) @ NLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNLO QCD + NLO EW	$\mathrm{Z+j}$ for gluon PDF $\mathrm{W+c}$ for strange PDF
$\mathrm{V+jj}$	dσ(lept. V decay) @ NLO QCD	dσ(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of $\mathrm{H+jj}$ final state
$\mathrm{VV'}$	dσ(V decays) @ NLO QCD dσ(stable V) @ NLO EW	dσ(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
$\mathrm{gg} \to \mathrm{VV}$	dσ(V decays) @ LO QCD	dσ(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
$\mathrm{V}\gamma$	dσ(V decay) @ NLO QCD dσ(PA, V decay) @ NLO EW	dσ(V decay) @ NNLO QCD + NLO EW	TGCs
$\mathrm{Vb\bar{b}}$	dσ(lept. V decay) @ NLO QCD massive b	dσ(lept. V decay) @ NNLO QCD massless b	bkg. for $\mathrm{VH} \to \mathrm{b\bar{b}}$
$\mathrm{VV'}\gamma$	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	QGCs
$\mathrm{VV'V''}$	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\mathrm{VV'+j}$	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
$\mathrm{VV'+jj}$	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	dσ @ NNLO QCD		bkg to $H \to \gamma\gamma$

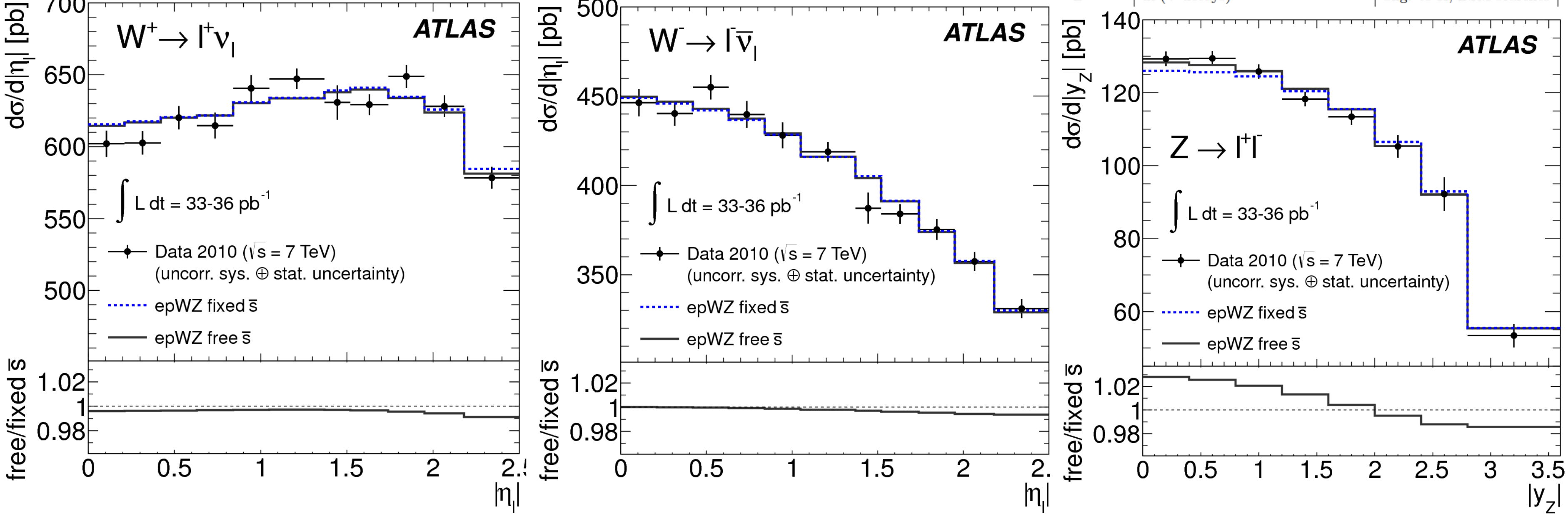
Table 3: Wishlist part 3 – EW gauge bosons ($\mathrm{V = W, Z}$)

Vector boson production

- Perhaps key collider benchmark process
- Known experimentally to 1-2% (excluding luminosity uncertainties)
- To take full advantage, would like to know process to NNNLO QCD and NNLO QCD+EW

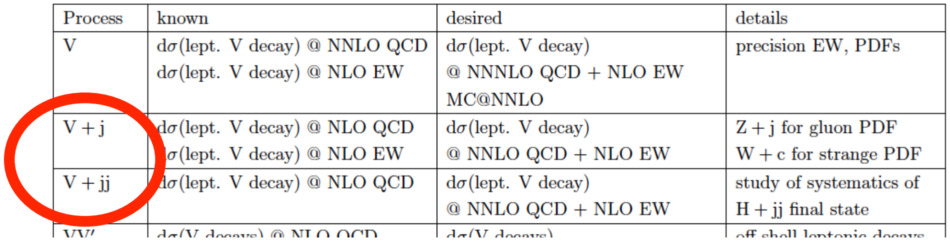


Process	known	desired	details
V	dσ(lept. V decay) @ NNLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	dσ(lept. V decay) @ NLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj	dσ(lept. V decay) @ NLO QCD	dσ(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of H + jj final state
VV′	dσ(V decays) @ NLO QCD dσ(stable V) @ NLO EW	dσ(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
gg → VV	dσ(V decays) @ LO QCD	dσ(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
Vγ	dσ(V decay) @ NLO QCD dσ(PA, V decay) @ NLO EW	dσ(V decay) @ NNLO QCD + NLO EW	TGCs
Vbb̄	dσ(lept. V decay) @ NLO QCD massive b	dσ(lept. V decay) @ NNLO QCD massless b	bkg. for VH → bb̄
VV′γ	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	QGCs
VV′V″	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
[illegible]	dσ(V decays) @ NLO QCD	dσ(V decays)	bkg. to H, BSM searches

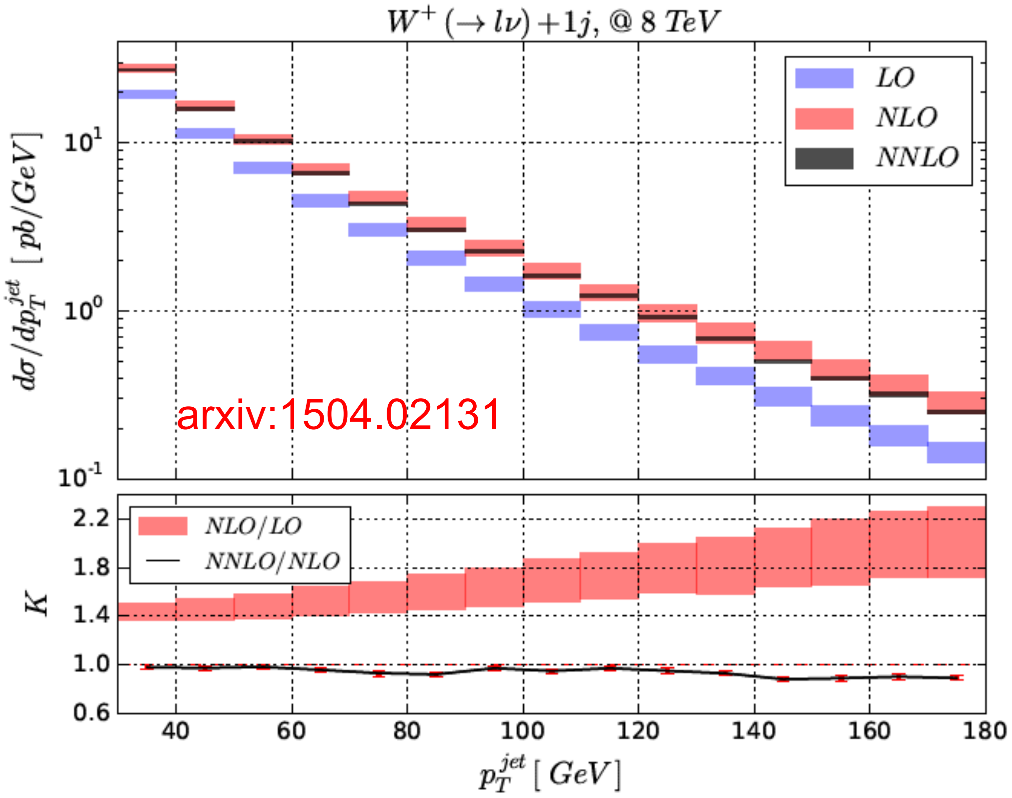


Vector bosons+jets

- Useful for PDF determination
    - Z+jet for gluon determination
    - W+c for strange quark determination
- Useful to study systematics of multiple jet production in a system with a large mass (->Higgs), with a wide accessible kinematic range
- Currently know W+>=1 jet to NNLO QCD
    - cross section seems very stable
- V+1-5 jets to NLO QCD; NLO EW corrections known for V+1 jet, including V decays and off-shell effects
- For Z+2 jets, NLO EW corrections known for on-shell, and are in progress for off-shell
- Differential theoretical uncertainties can reach 10-20% for high jet momenta, exceeding experimental uncertainties



Process	known	desired	details
V	dσ(lept. V decay) @ NNLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	dσ(lept. V decay) @ NLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj	dσ(lept. V decay) @ NLO QCD	dσ(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of H + jj final state

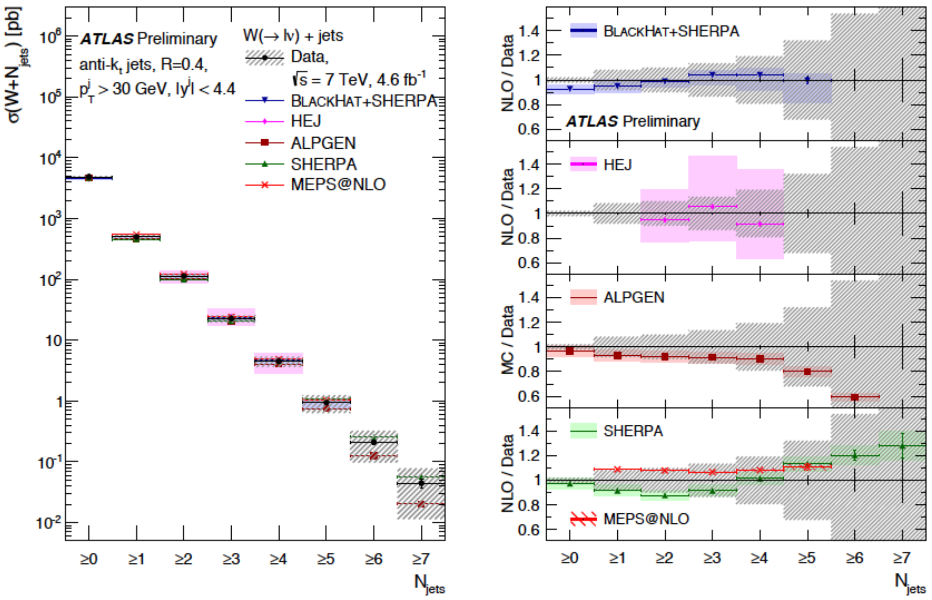


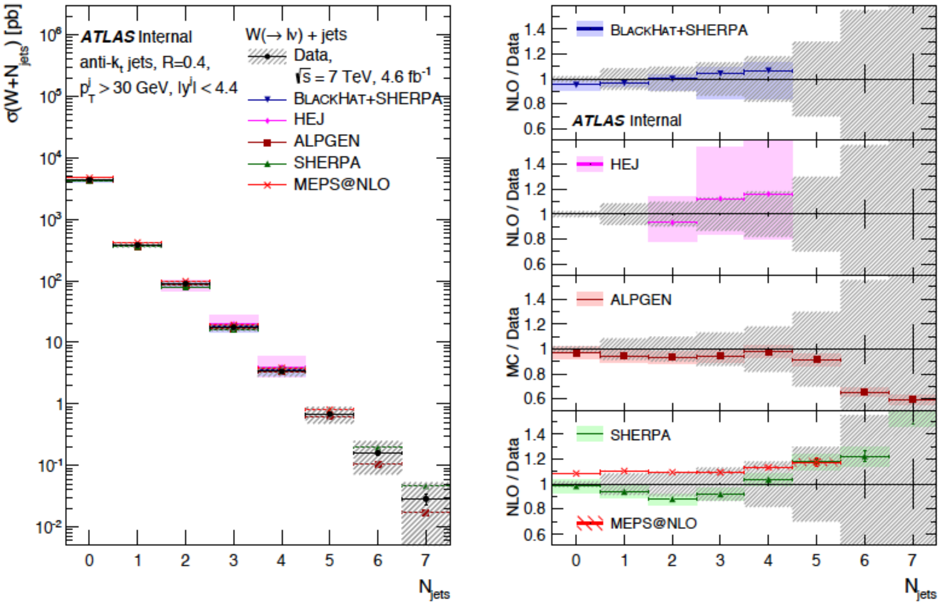
arxiv:1504.02131

Would like to know both cross sections at NNLO QCD+NLO EW

W+jets

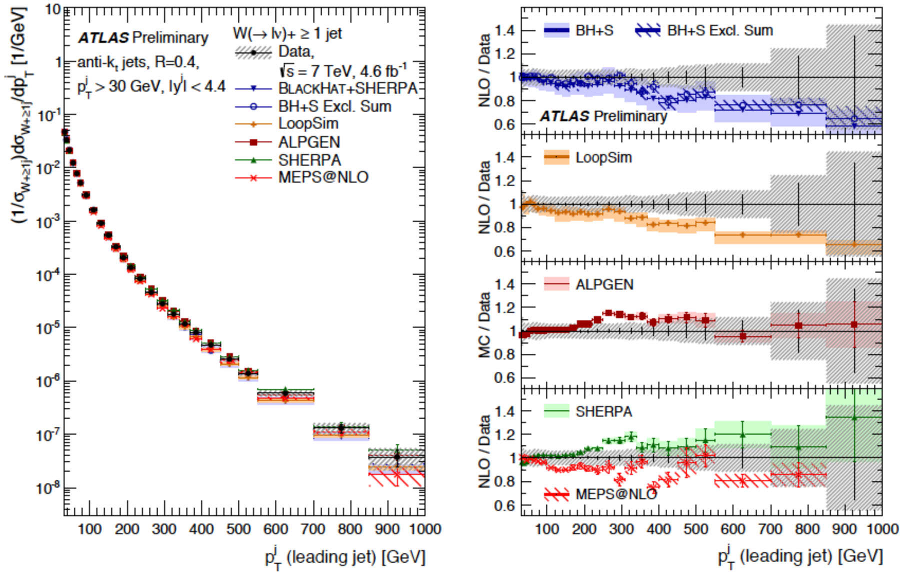
- ATLAS has measured up to 7 jets in the final state
    - ◆ both inclusive and exclusive final states
    - ◆ good agreement with Blackhat+Sherpa in general
        - ▲ with non-perturbative corrections
    - ◆ comparisons to a variety of predictions more thoroughly tests physics of process

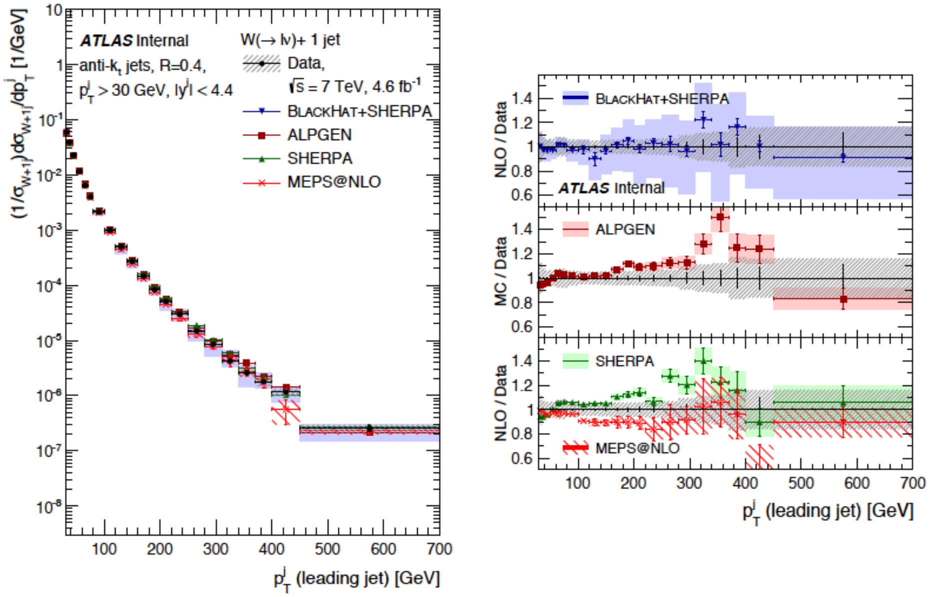


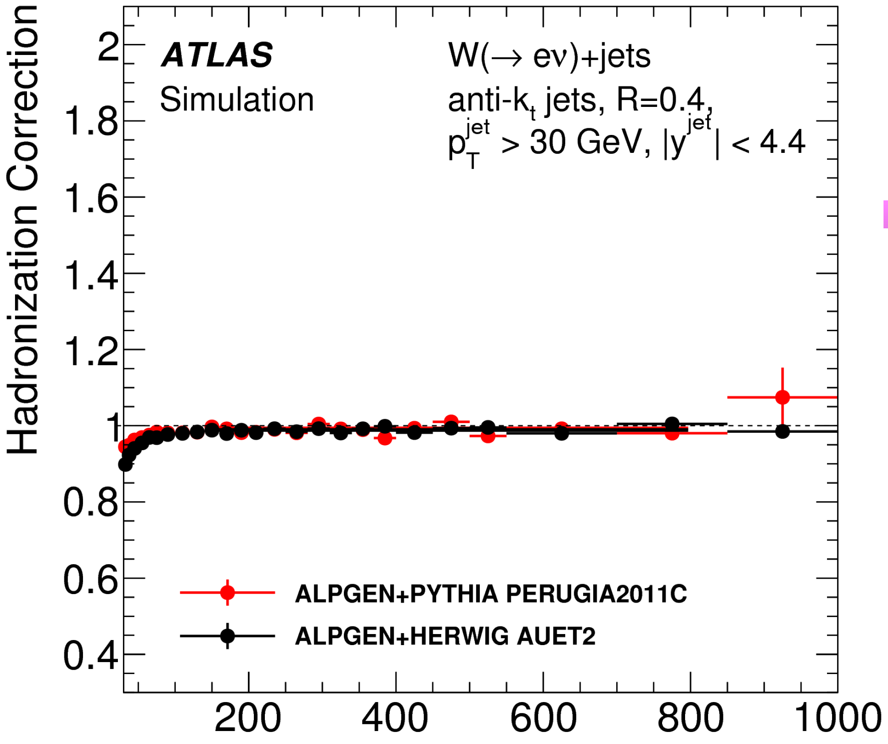


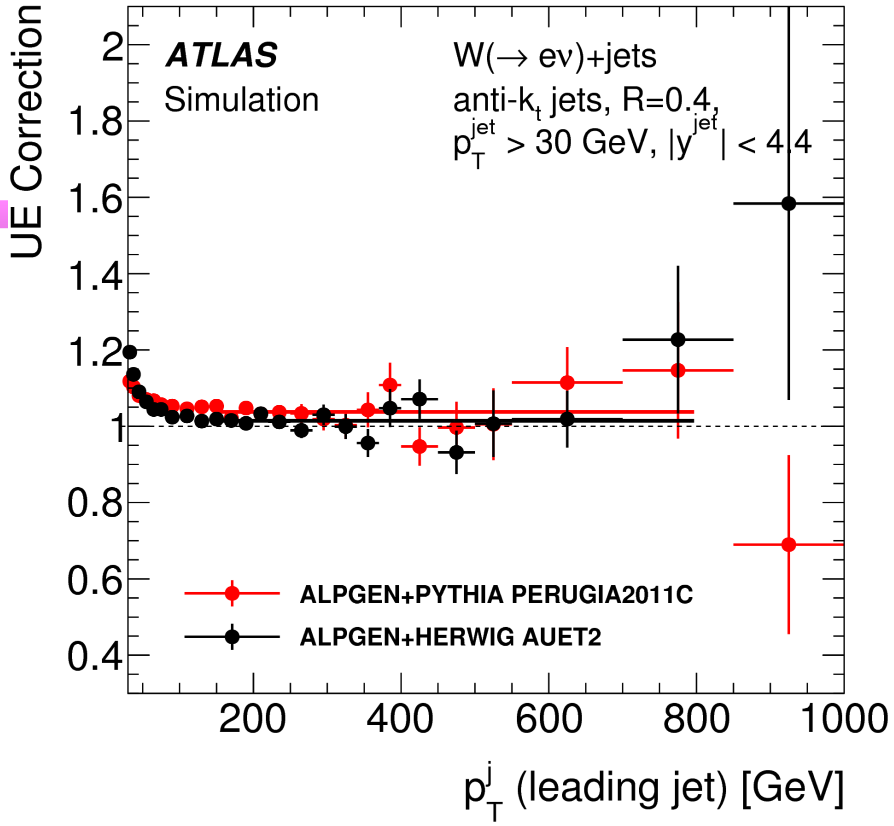
Leading jet p_T

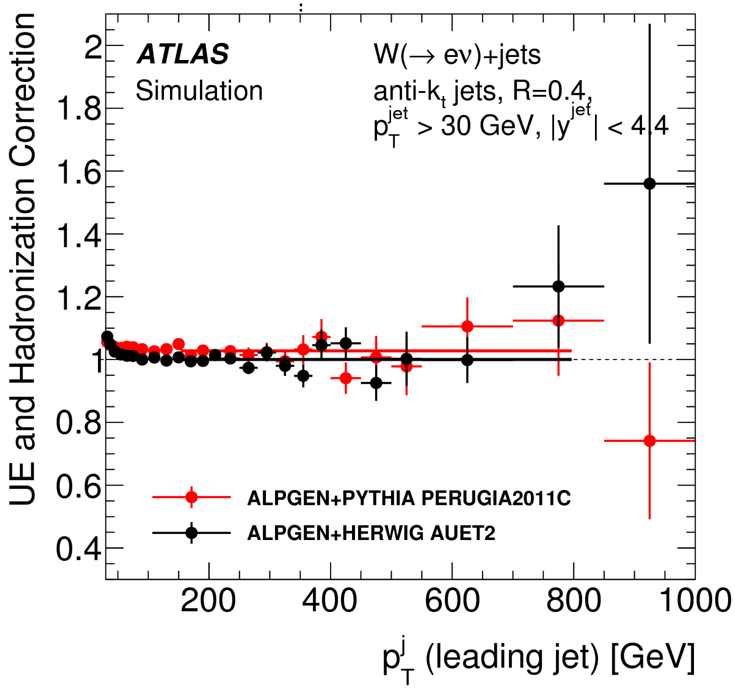
- Inclusive leading jet p_T distribution higher than NLO prediction at high transverse momentum
    - 1 TeV/c!
- Exclusive lead jet p_T agrees very well with NLO prediction up to 700 GeV/c
    - why should fixed order work so well when such an exclusive final state is probed?->jet veto logs
- arXiv:1501.01059
    - R. Boughezal et al
    - due to ATLAS analysis, additional jet allowed if it is collinear to a lepton









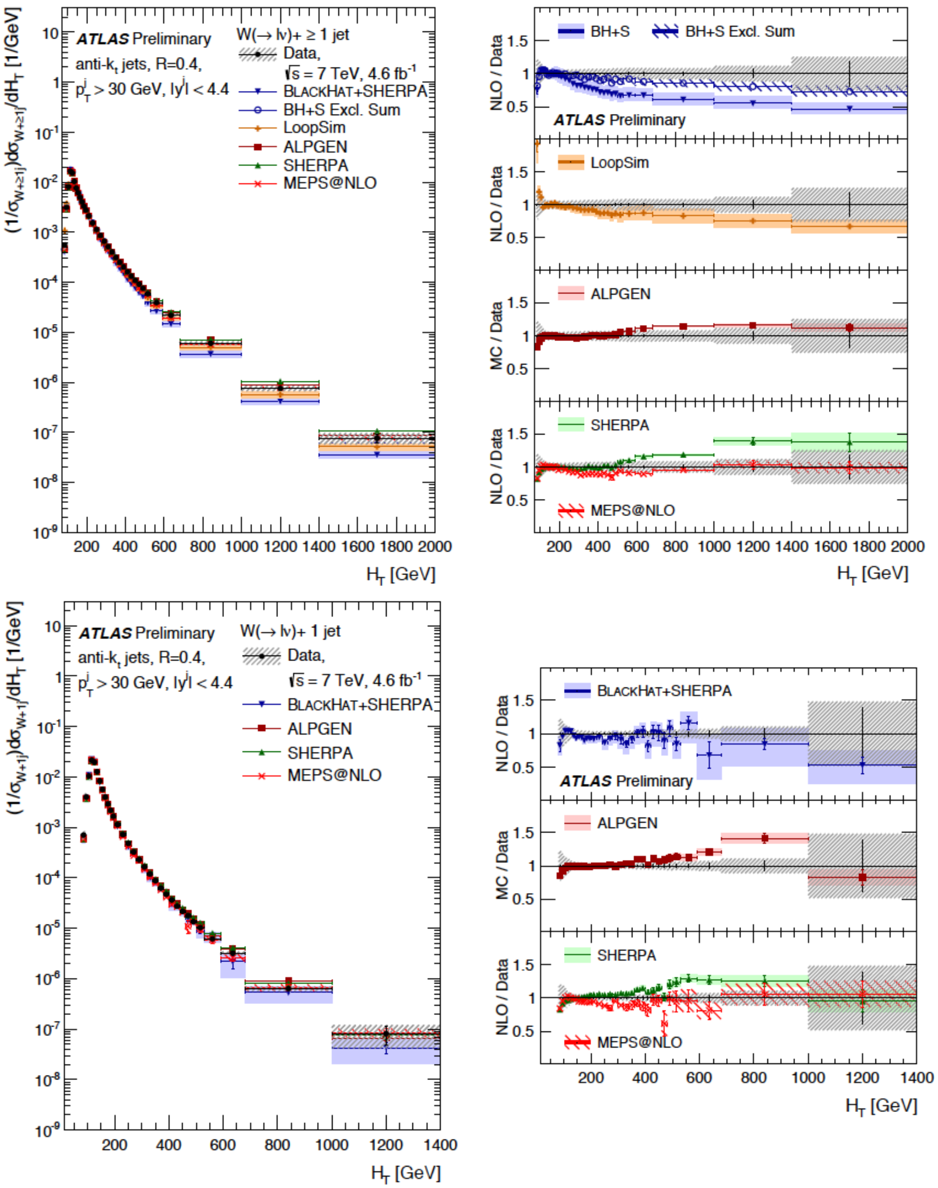


*The net correction is small and dies away quickly with increasing p_T, as expected for power corrections.

*Non-perturbative corrections for higher multiplicity final states are separately (UE and hadronization) but still cancel.

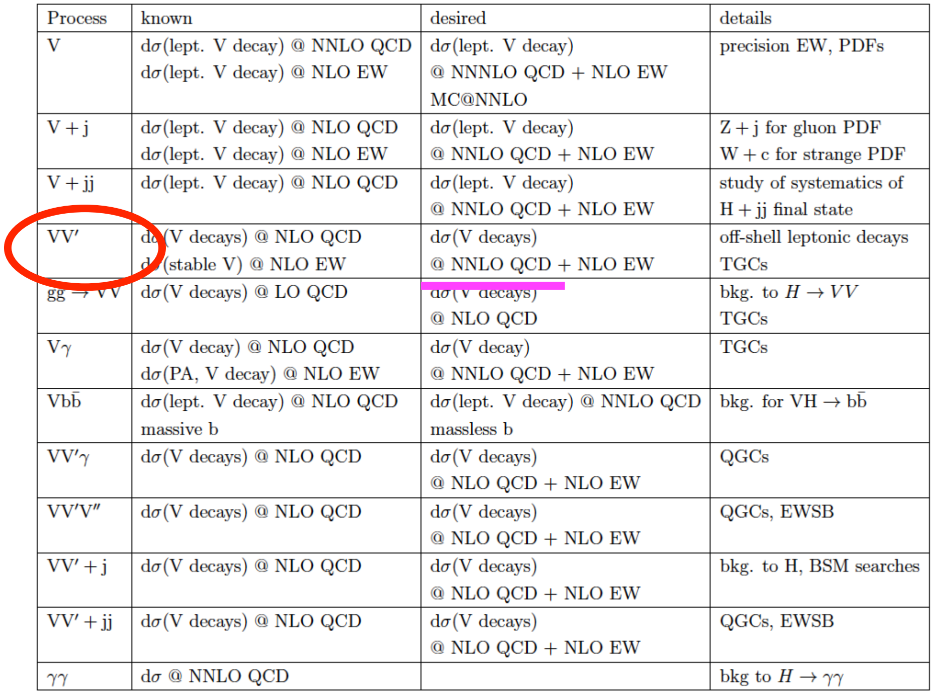
H_T

- NLO substantially below data at high H_T (50% discrepancy)
- Large contributions from qq->qq'W not fully taken into account in W+>=1 jet prediction
- Formalisms in which such contributions are added (LoopSim/exclusive sums) have better agreement with data
  - ◆ …now NNLO as well



Vector boson pairs

- Provides a handle on the determination of triple gauge couplings, and possible new physics
- Cross sections are known to NLO/ NNLO QCD (with V decays) and to NLO EW (with on-shell V's)
- WZ cross sections currently have a (non-luminosity) uncertainty of the order of 10%
    - will decrease in Run 2 of course
- Theoretical uncertainty is 6%
- Thorough knowledge of VV cross section is needed because of triple gauge couplings and backgrounds to Higgs measurements
- Non-luminosity errors for VV are of the order of 10% or less
- Experimental uncertainties will improve, so would like cross sections to NNLO QCD+NLO EW (with V decays)

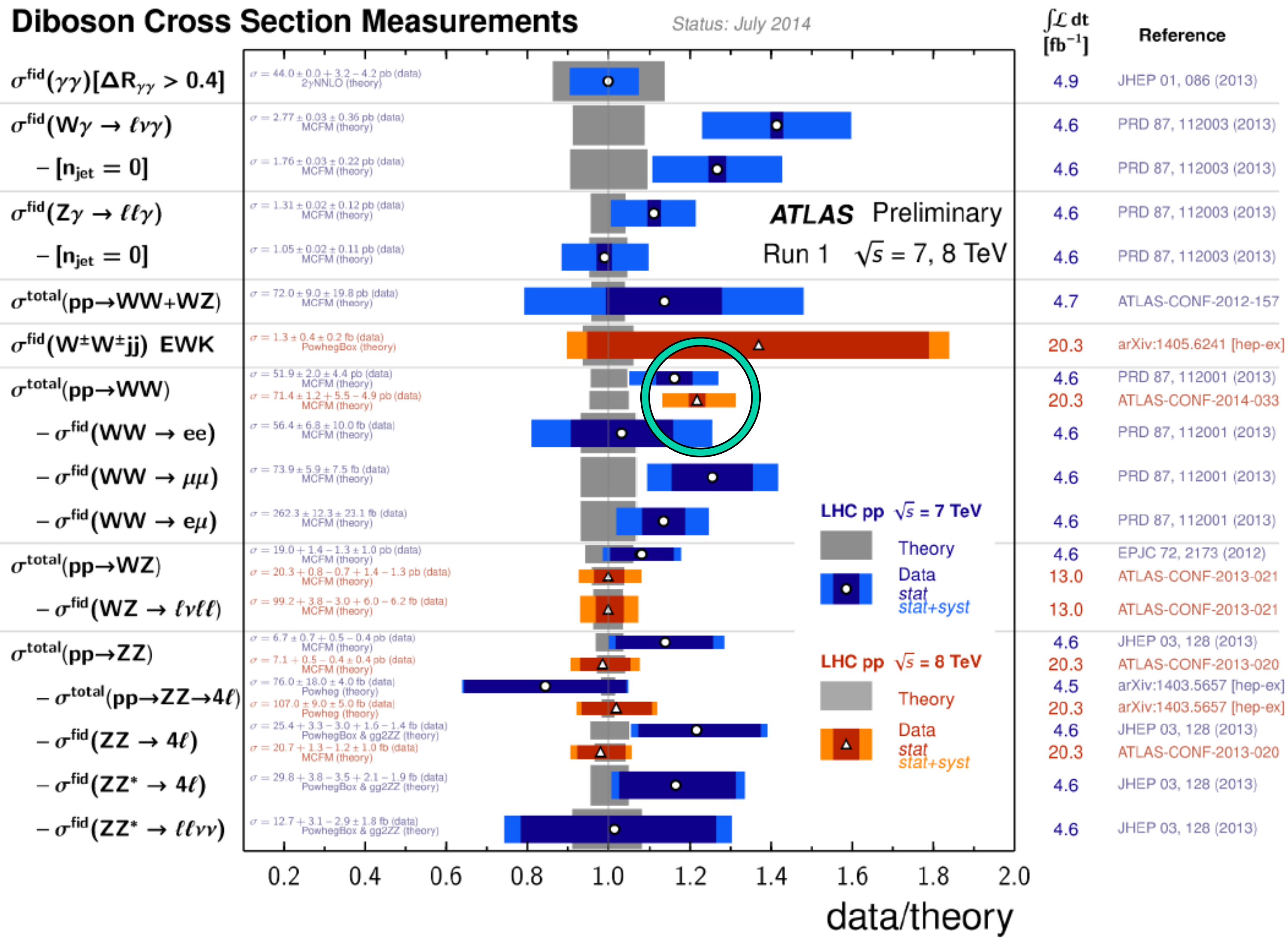


Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of H + jj final state
VV′	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
$gg \to VV$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
Vγ	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
V$b\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for VH $\to b\bar{b}$
VV′γ	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs
VV′V″	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
VV′ + j	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
VV′ + jj	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

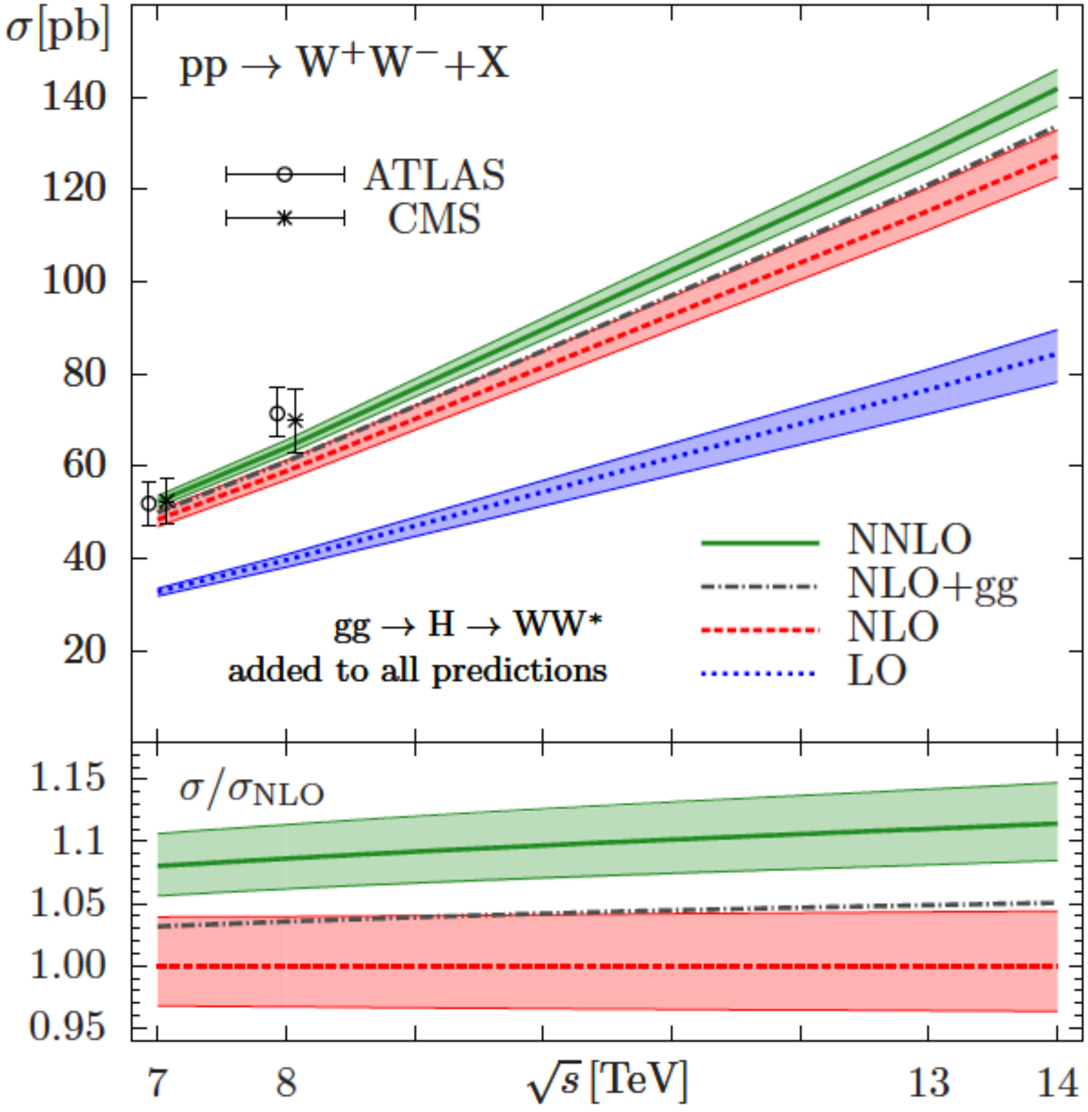
We also rely on theoretical predictions of VV* for Higgs measurements in that decay channel.

ATLAS diboson cross sections



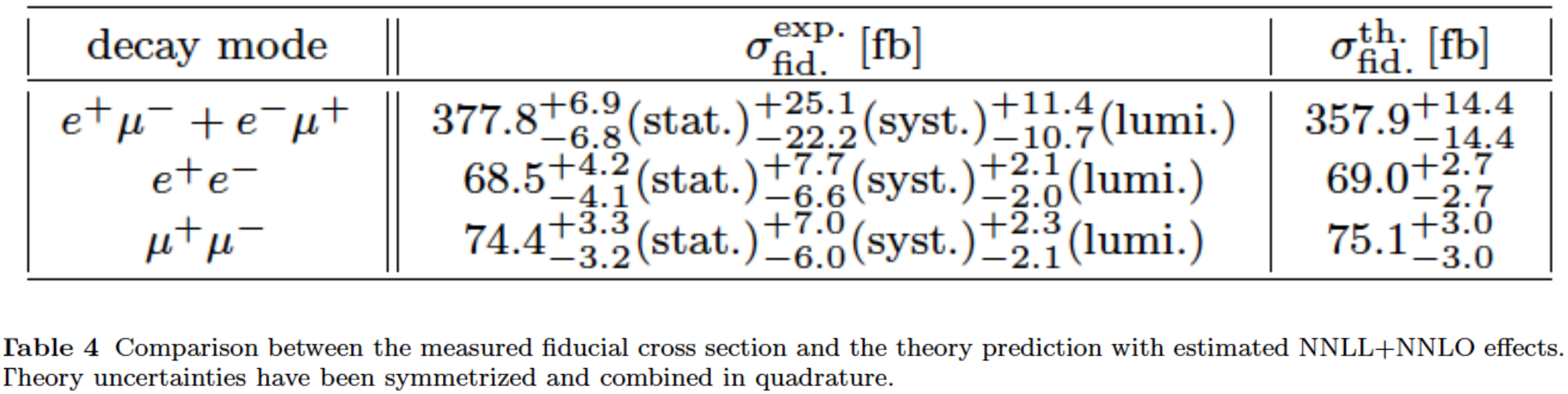
…but arxiv:1408.5243

- NNLO calculation of WW production recently completed
- Modest increase in size of cross section
- Decrease in size of excess
- QCD issues with extrapolation of jet vetoed cross section to full cross section mean that uncertainty is larger than assumed in experimental papers



arXiv:1410.4745

Fiducial cross sections in agreement with NNLO+NNLL. Powheg provides too large of an extrapolation from fiducial to full inclusive.

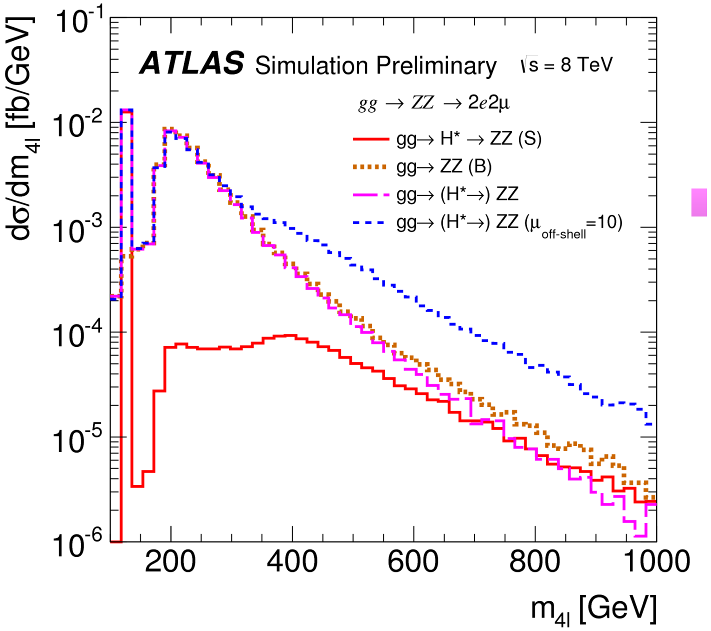


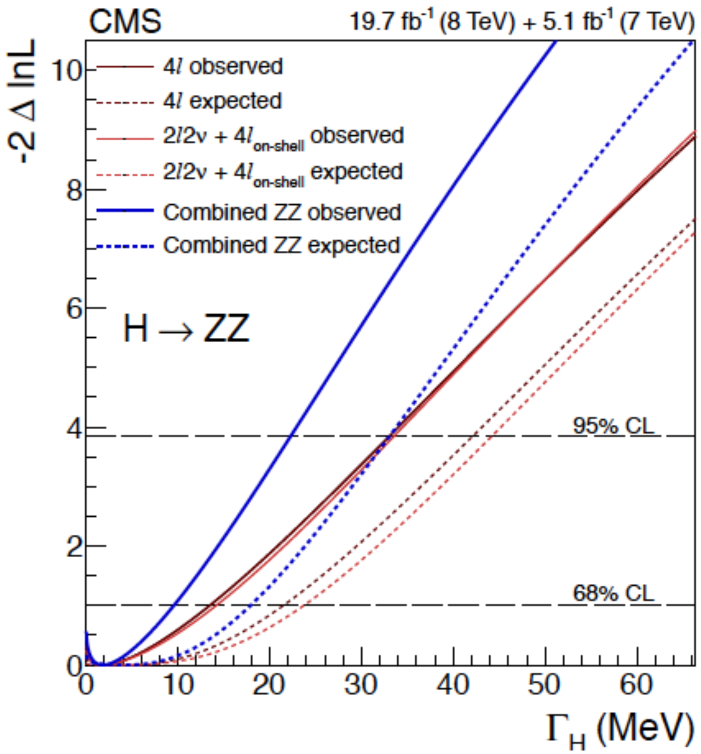
decay mode	$\sigma_{\text{fid.}}^{\text{exp.}}$ [fb]	$\sigma_{\text{fid.}}^{\text{th.}}$ [fb]
$e^+\mu^- + e^-\mu^+$	$377.8^{+6.9}_{-6.8}(\text{stat.})^{+25.1}_{-22.2}(\text{syst.})^{+11.4}_{-10.7}(\text{lumi.})$	$357.9^{+14.4}_{-14.4}$
e^+e^-	$68.5^{+4.2}_{-4.1}(\text{stat.})^{+7.7}_{-6.6}(\text{syst.})^{+2.1}_{-2.0}(\text{lumi.})$	$69.0^{+2.7}_{-2.7}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}(\text{stat.})^{+7.0}_{-6.0}(\text{syst.})^{+2.3}_{-2.1}(\text{lumi.})$	$75.1^{+3.0}_{-3.0}$

Table 4 Comparison between the measured fiducial cross section and the theory prediction with estimated NNLL+NNLO effects. Theory uncertainties have been symmetrized and combined in quadrature.

gg->VV

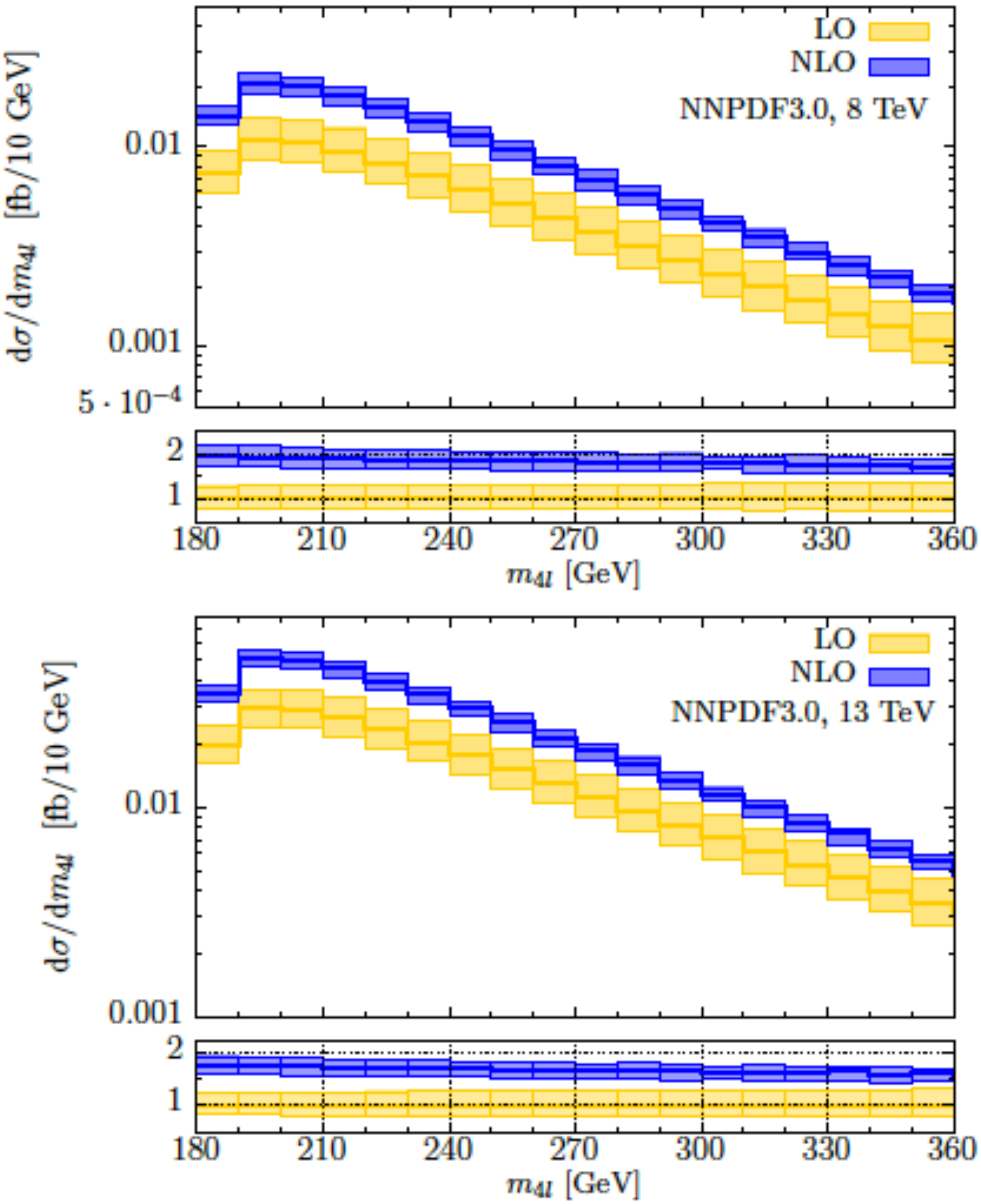
- Formally, this is suppressed by a factor of α_s^2 with respect to dominant q-qbar subprocess, but still contributes 5-10% to cross section due to large gluon flux
- For some Higgs background regions, it can be over 10%
- ZZ needed for determination of off-shell Higgs boson signal strength in high-mass ZZ final state
  - interferes with gg->H->ZZ$^{(*)}$
- Currently subprocess is known (with lepton decays) at LO QCD
- Need to know to NLO QCD
  - arXiv:1503.0127 for two loop gg->ZZ with heavy top mass
  - arXiv:1503.08759, arXiv:1503.08835 for two-loop massless case
  - **what about putting it all together?**





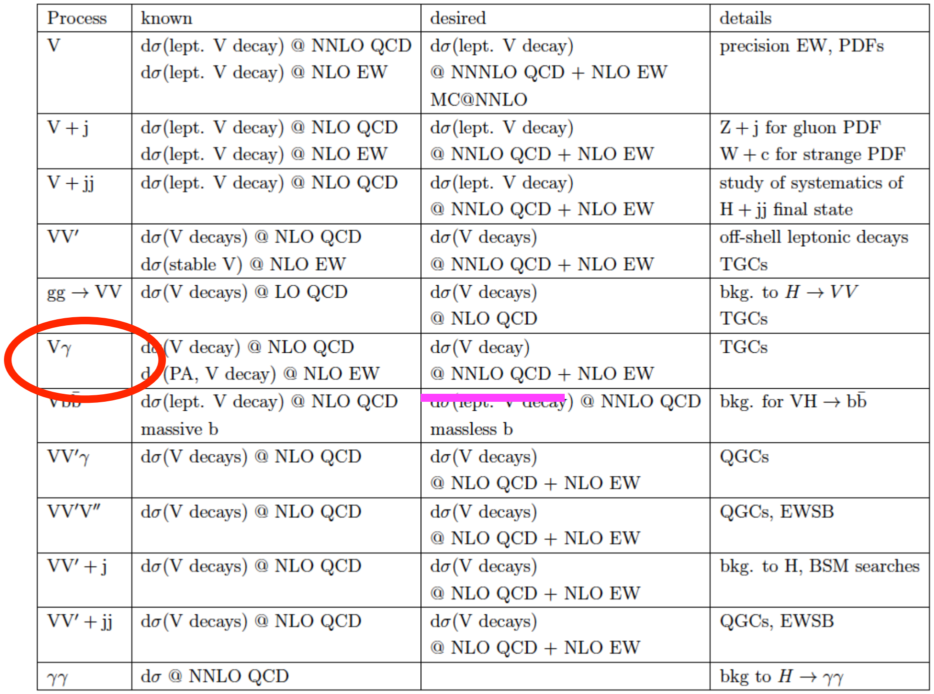
arXiV:1509.06734

- Would like to allow one of the Z’s to be virtual, for H->ZZ*



Vector boson + photon

- Serve as precision tests for EW sector and also a probe for possible new physics in triple gauge boson couplings, or in production of new vector meson resonances in Vγ
- Experimental uncertainties are on the order of 10% and theoretical errors on the order of 5-10%
- Currently, Wγ production is known (with decays) at NNLO QCD, Zγ production at NNLO QCD
- NLO corrections known in the pole approximation (resonant V bosons with decays)
- Need to know cross sections to NNLO QCD + NLO EW

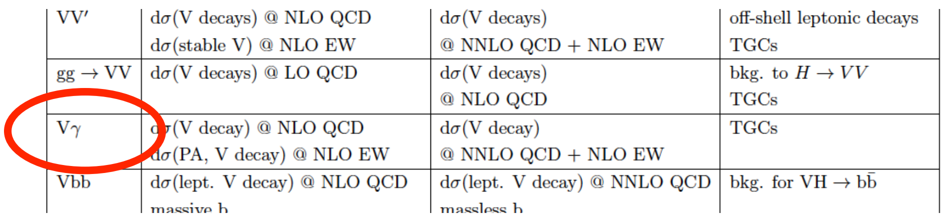


Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of H + jj final state
VV′	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
gg → VV	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
Vγ	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
Vb$\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for VH → b$\bar{b}$
VV′γ	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs
VV′V″	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
VV′ + j	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
VV′ + jj	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
γγ	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

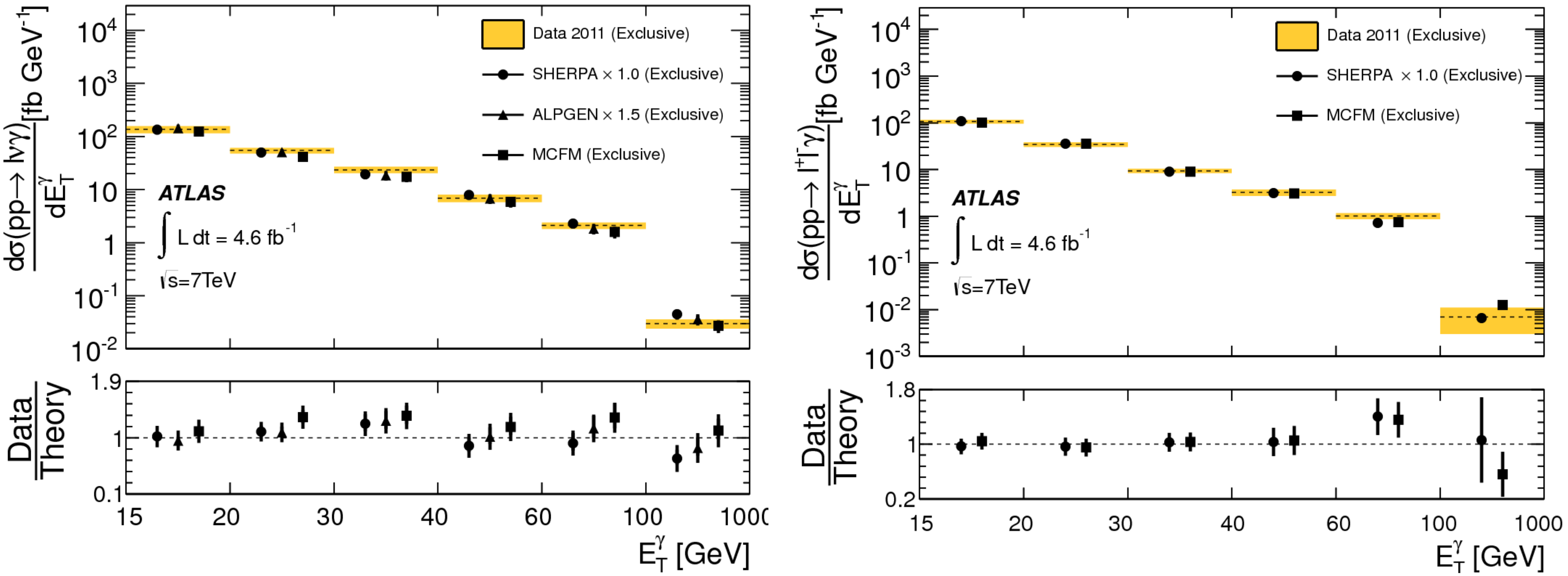
Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

Vector boson + photon

- Serve as precision tests for EW sector and also a probe for possible new physics in triple gauge boson couplings, or in production of new vector meson resonances in Vγ

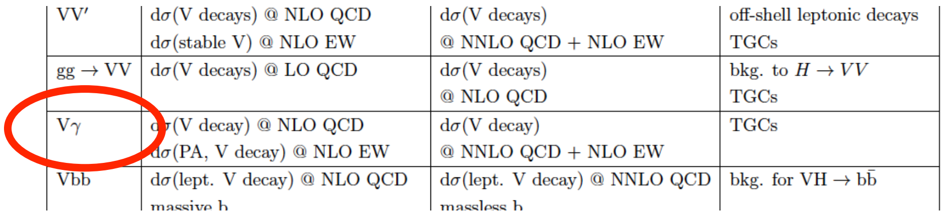


VV′	dσ(V decays) @ NLO QCD dσ(stable V) @ NLO EW	dσ(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
gg → VV	dσ(V decays) @ LO QCD	dσ(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
Vγ	dσ(V decay) @ NLO QCD dσ(PA, V decay) @ NLO EW	dσ(V decay) @ NNLO QCD + NLO EW	TGCs
Vbb	dσ(lept. V decay) @ NLO QCD massive b	dσ(lept. V decay) @ NNLO QCD massless b	bkg. for VH → $b\bar{b}$

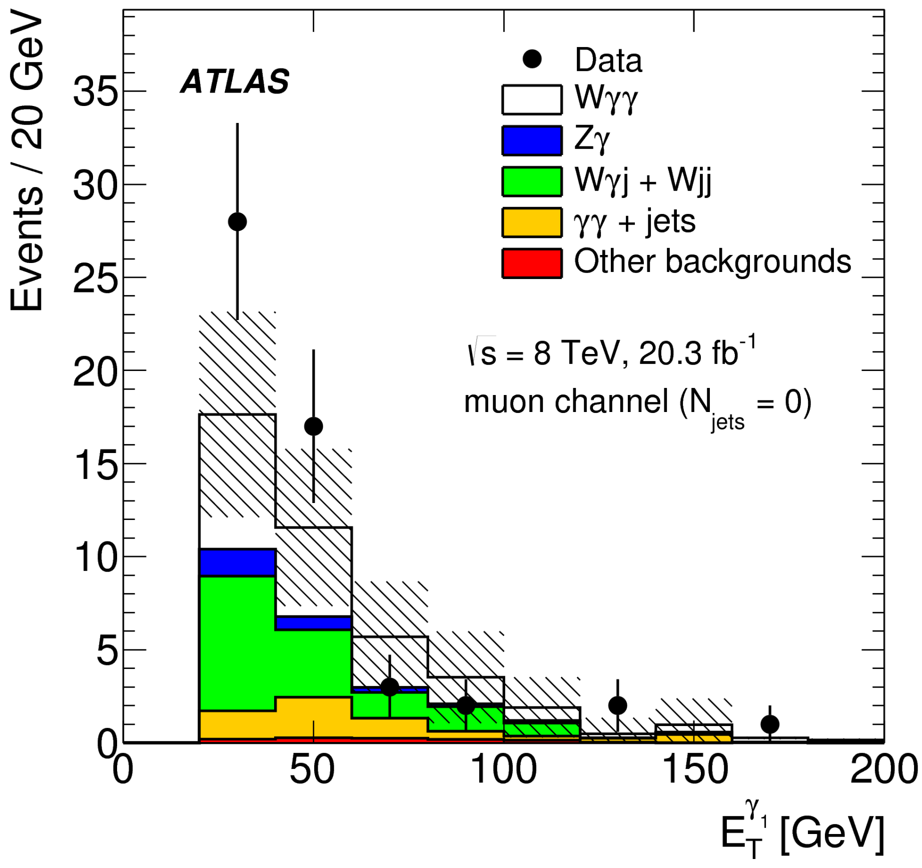


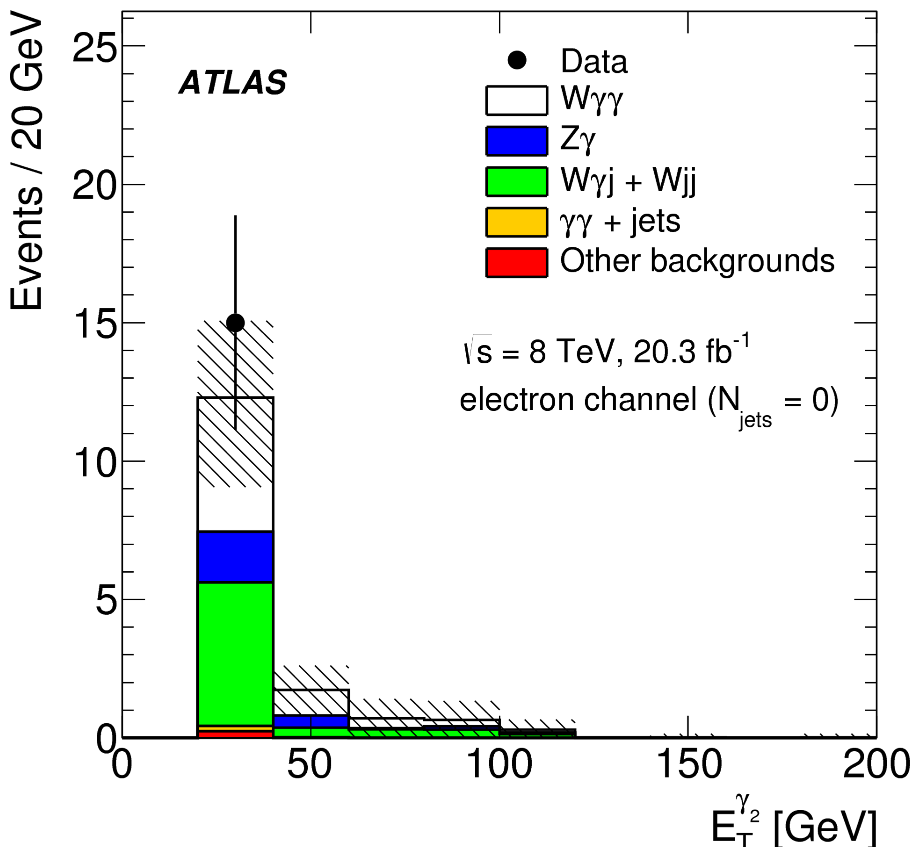
Vector boson + photons

- Evidence for Wγγ production



VV′	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
gg → VV	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
Vγ	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
Vbb	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for VH → b$\bar{\text{b}}$

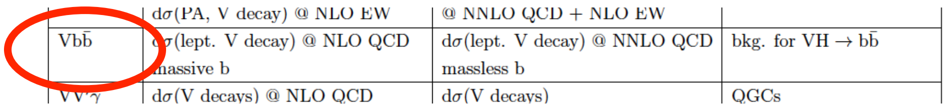




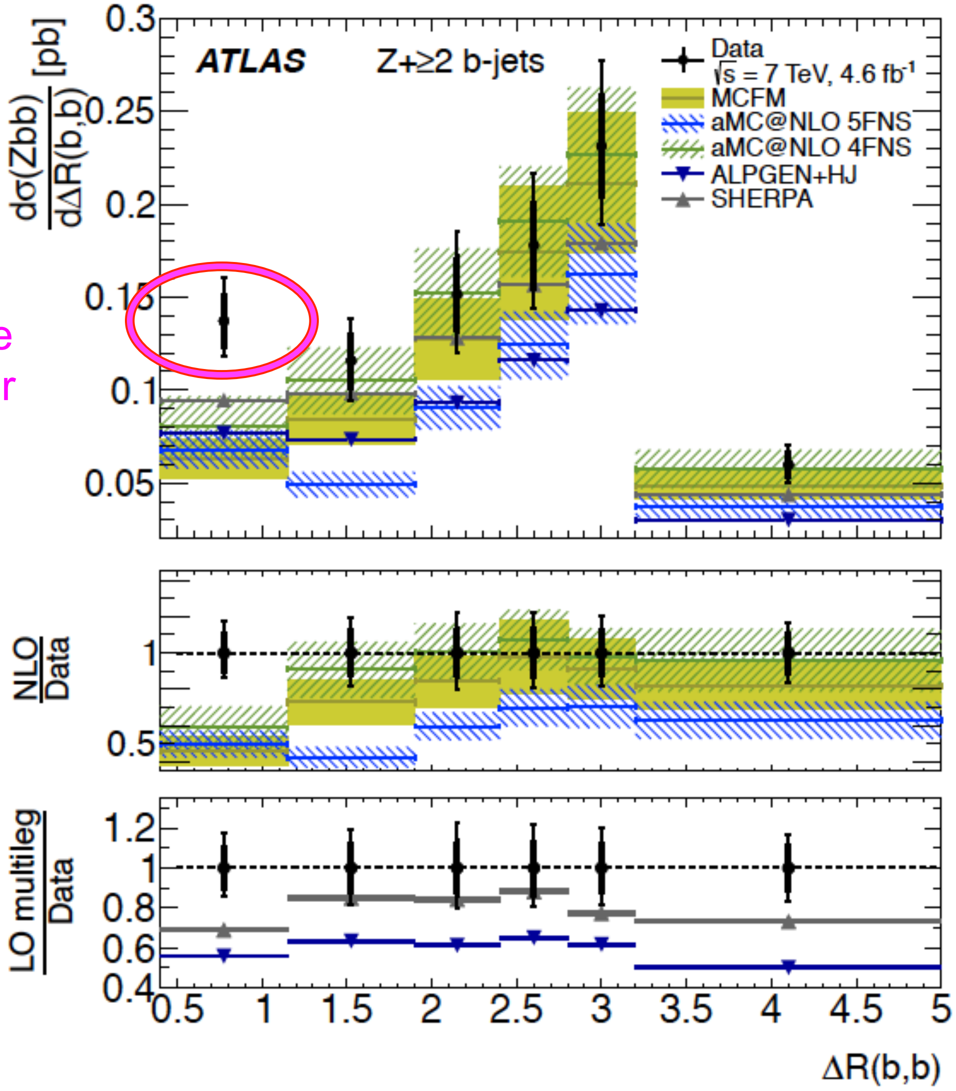
VbB

- Associated Higgs production, with Higgs decaying into bB is key to understanding Higgs couplings to b-quarks
- VbB is significant background
- Current state of the art is NLO QCD (including b-quark mass effects)
- Experimental and theoretical uncertainties are of the order of 20%
- As experimental uncertainties will improve with more data, crucial to extend the theoretical accuracy by extending the calculation to NNLO QCD (massless b quarks)
- Includes an understanding of uncertainties in 4-flavor vs 5-flavor approaches

better knowledge of collinear gluon splitting needed?

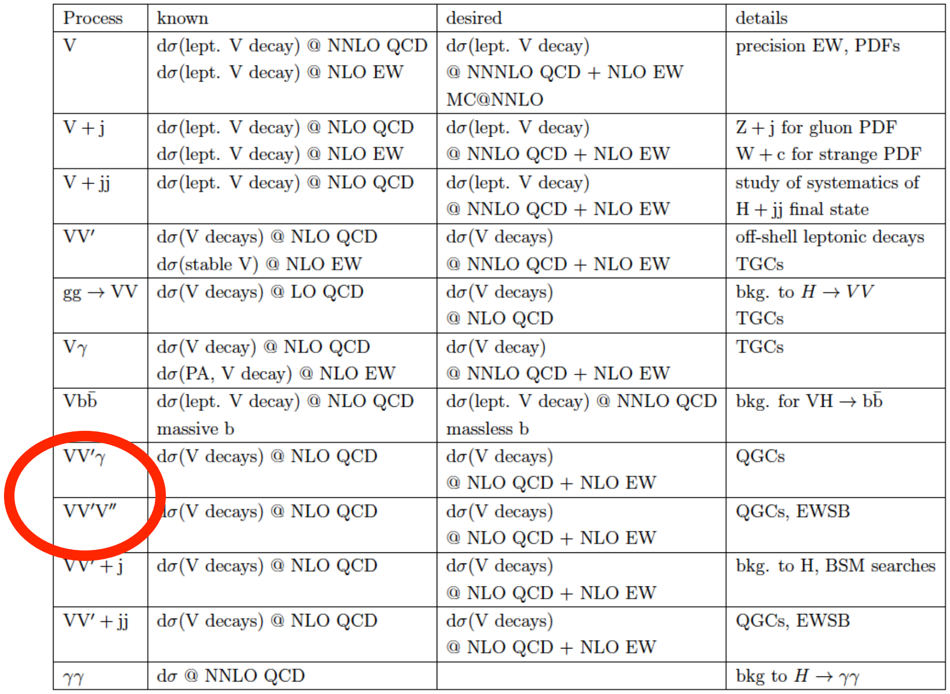


	$d\sigma$(PA, V decay) @ NLO EW	@ NNLO QCD + NLO EW	
V$b\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for VH → $b\bar{b}$
VV'γ	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays)	QGCs



VVV

- Cross sections currently known to NLO QCD, but NLO EW corrections only known for WWZ (in approximation of stable W and Z bosons)
- Triple gauge boson production processes serve as channels for determination of quartic gauge boson couplings and will allow for better understanding of EW symmetry breaking
- Analyses are currently statistically limited (no published results so far), but precision measurements will be possible in Run 2
- Desire calculation of final states to NLO QCD + NLO EW

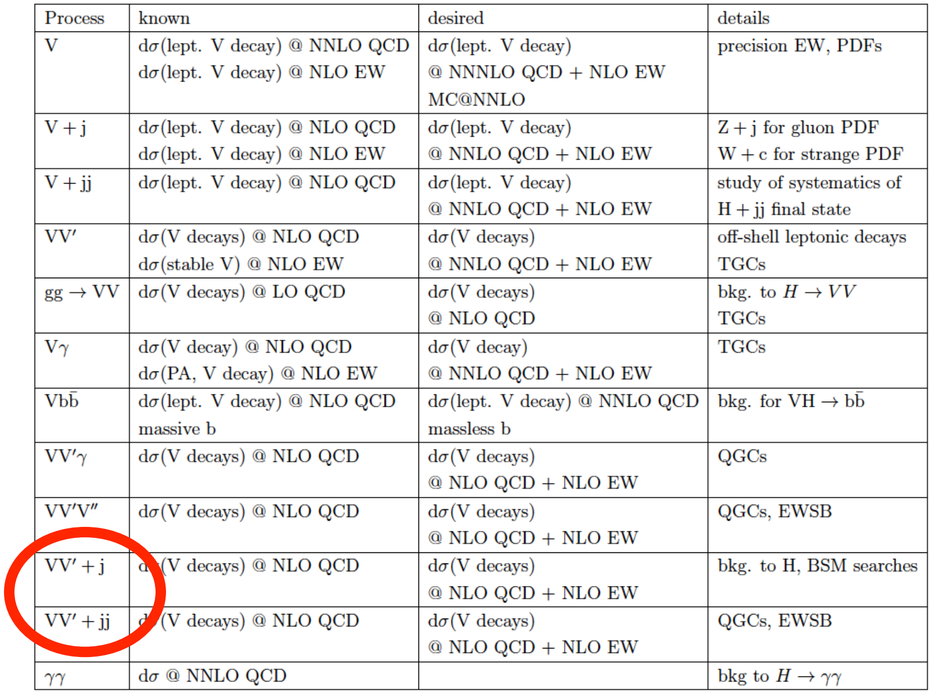


Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
$\mathrm{V+j}$	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	$\mathrm{Z+j}$ for gluon PDF $\mathrm{W+c}$ for strange PDF
$\mathrm{V+jj}$	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of $\mathrm{H+jj}$ final state
$\mathrm{VV'}$	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
$\mathrm{gg \to VV}$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
$\mathrm{V}\gamma$	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
$\mathrm{Vb\bar{b}}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for $\mathrm{VH \to b\bar{b}}$
$\mathrm{VV'}\gamma$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs
$\mathrm{VV'V''}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\mathrm{VV'+j}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
$\mathrm{VV'+jj}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons ($\mathrm{V = W, Z}$)

VVj(j)

- VV’+j(j) currently known to NLO QCD
- VV’+j useful as a background to Higgs boson production and for BSM searches
- VV’+jj production contains EW vector boson scattering subprocess that is particularly sensitive to EW quartic gauge couplings and to details of EW symmetry breaking
- EW corrections to these processes are unknown, although as important as QCD corrections in vector boson scattering channels

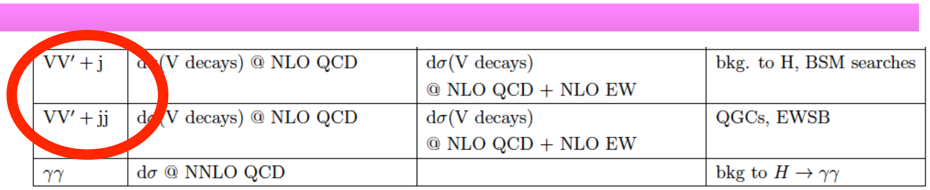


Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of H + jj final state
VV′	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
gg → VV	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
Vγ	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
V$b\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for VH → $b\bar{b}$
VV′γ	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs
VV′V″	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
VV′ + j	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
VV′ + jj	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

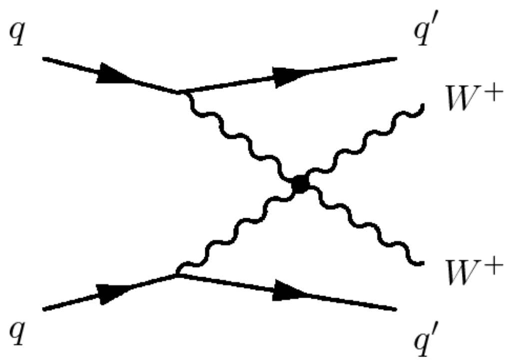
VV’jj

- VV’+jj production contains EW vector boson scattering subprocess that is particularly sensitive to EW quartic gauge couplings and to details of EW symmetry breaking



$VV' + j$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
$VV' + jj$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

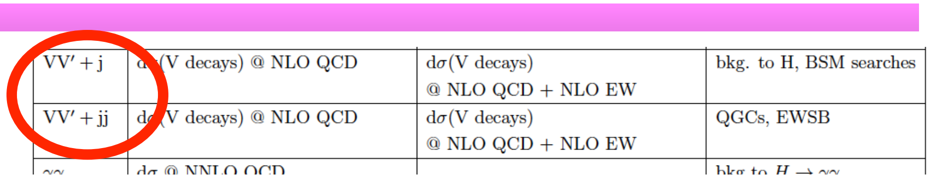
Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)



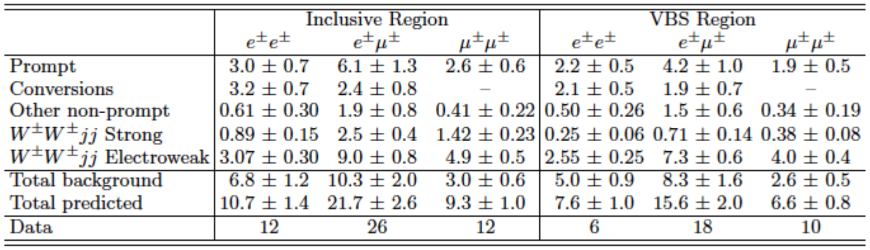
look for same-sign dileptons

VVj(j)

- VV’+jj production contains EW vector boson scattering subprocess that is particularly sensitive to EW quartic gauge couplings and to details of EW symmetry breaking

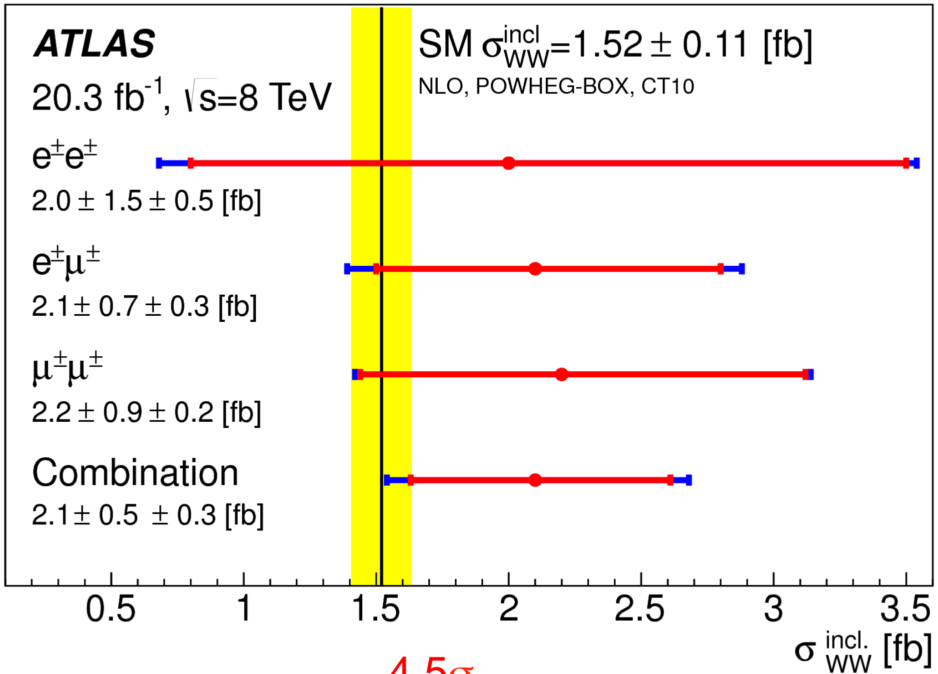


VV′ + j	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
VV′ + jj	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
γγ	dσ @ NNLO QCD		bkg to $H \to \gamma\gamma$

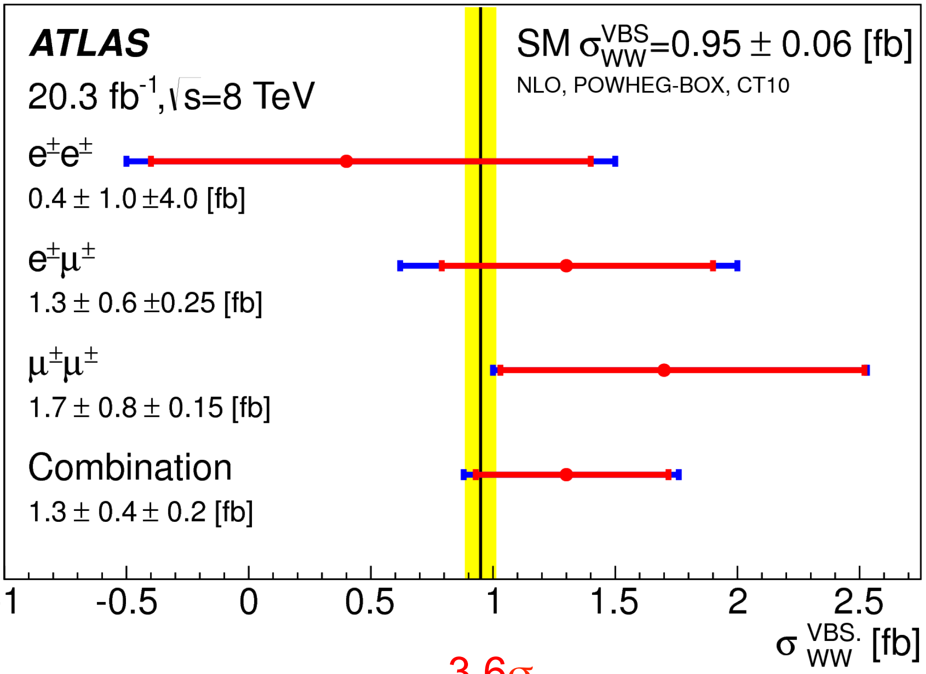


	Inclusive Region			VBS Region		
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^\pm W^\pm jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^\pm W^\pm jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

TABLE II: Estimated background yields, observed number of data events, and predicted signal yields for the three channels are shown with their systematic uncertainty. Contributions due to interference are included in the $W^\pm W^\pm jj$ electroweak prediction.



4.5σ

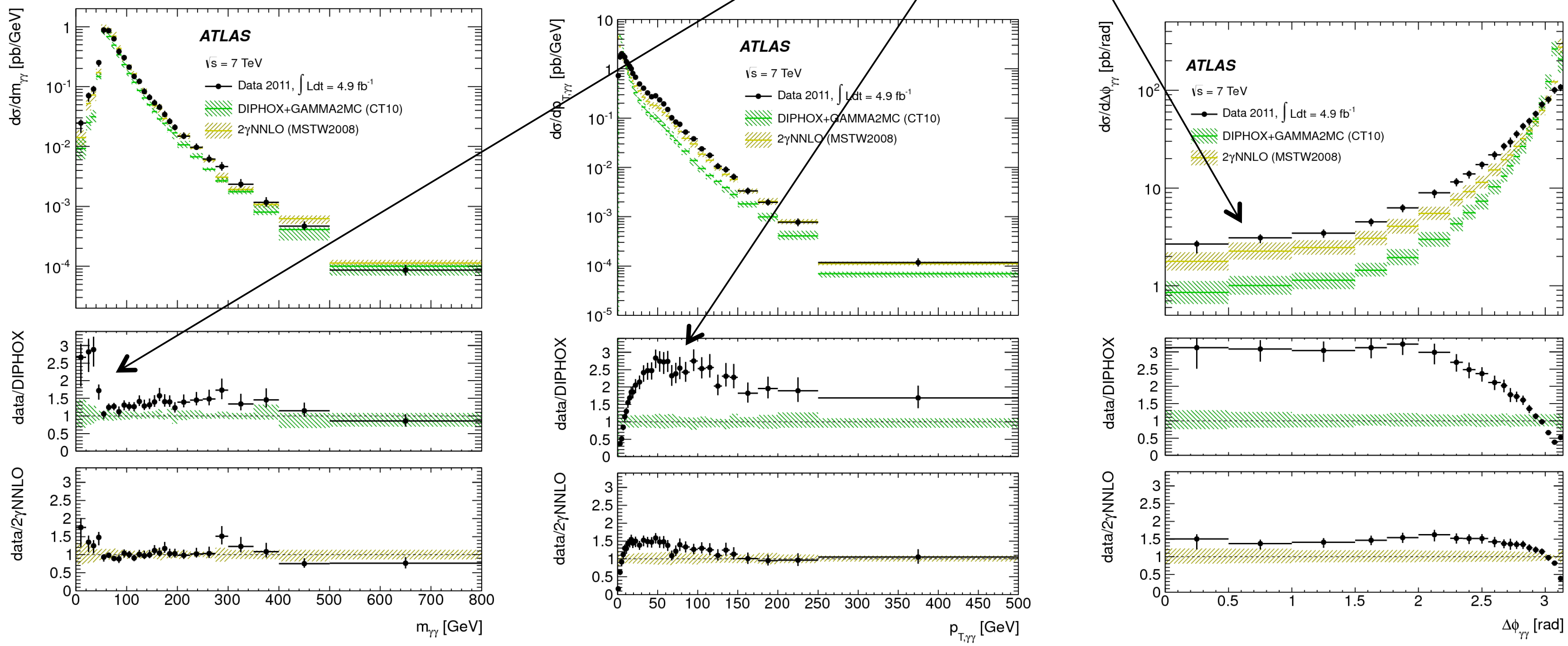


3.6σ

Diphoton production

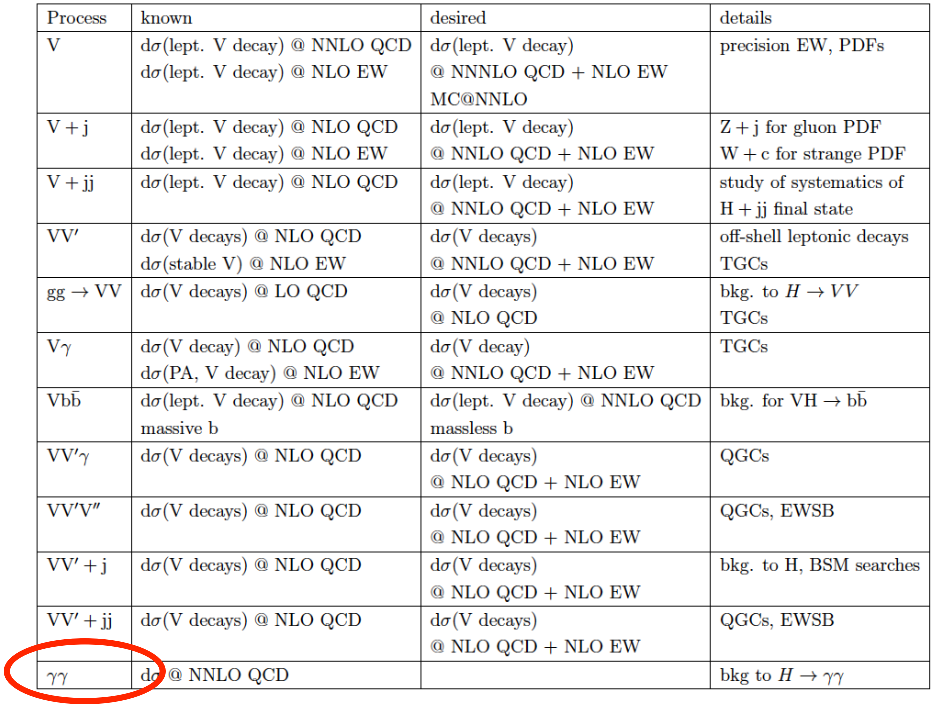
- Diphoton cross section known to NNLO QCD and to NLO EW
- Need q_T resummation at NNLL matched to the NNLO calculation
- If DY and Higgs production are known in fully differential form at NNNLO, then it should be possible to extend those calculations to $\gamma\gamma$

importance of higher multiplicity contributions clear in some corners of phase space



NNLO QCD + NLO EWK wishlist

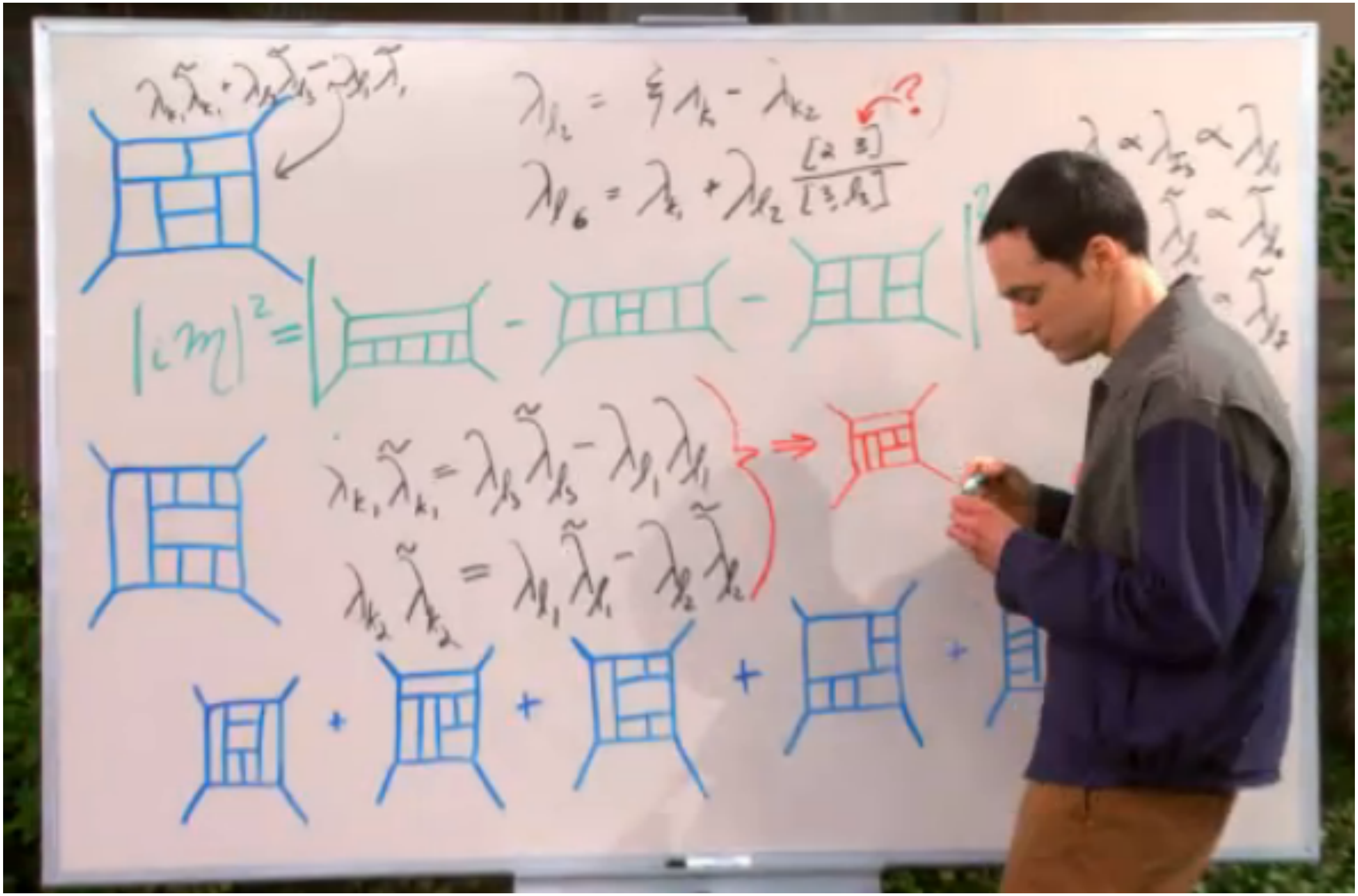
- Diphoton cross section known to NNLO QCD and to NLO EW
- Need q_T resummation at NNLL matched to the NNLO calculation
- If DY and Higgs production are known in fully differential form at NNNLO, then it should be possible to extend those calculations to $\gamma\gamma$
- …of course, the most complex calculations are being carried out by someone not present here, but whom I saw last night



Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of H + jj final state
VV′	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
gg → VV	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
Vγ	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
V$b\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for VH → $b\bar{b}$
VV′γ	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs
VV′V″	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
VV′ + j	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
VV′ + jj	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

The frontier

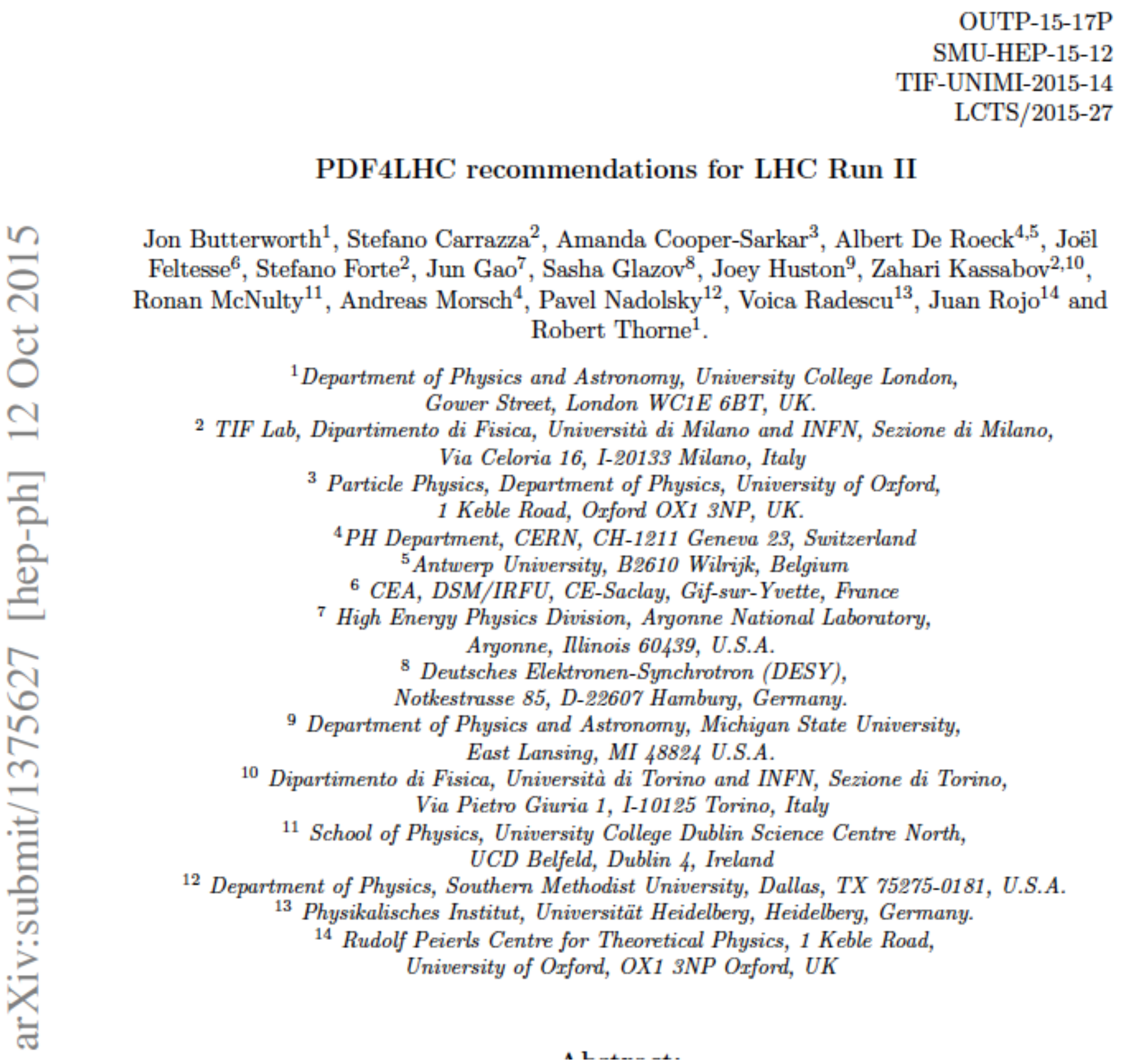


Summary

- The new high precision Les Houches wishlist presents some real (and important) challenges for QCD and EW calculators
    - **in 2015, we will take another look at the wishlist, setting some priorities, perhaps modifying some requests**
- The data to be taken in Run 2 by ATLAS and CMS requires the effort
- Don't delay

Summary

Because you know it's all about that Higgs, 'Bout that Higgs, no SUSY



OUTP-15-17P
SMU-HEP-15-12
TIF-UNIMI-2015-14
LCTS/2015-27

PDF4LHC recommendations for LHC Run II

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Abstract:

Progress with recent PDFs

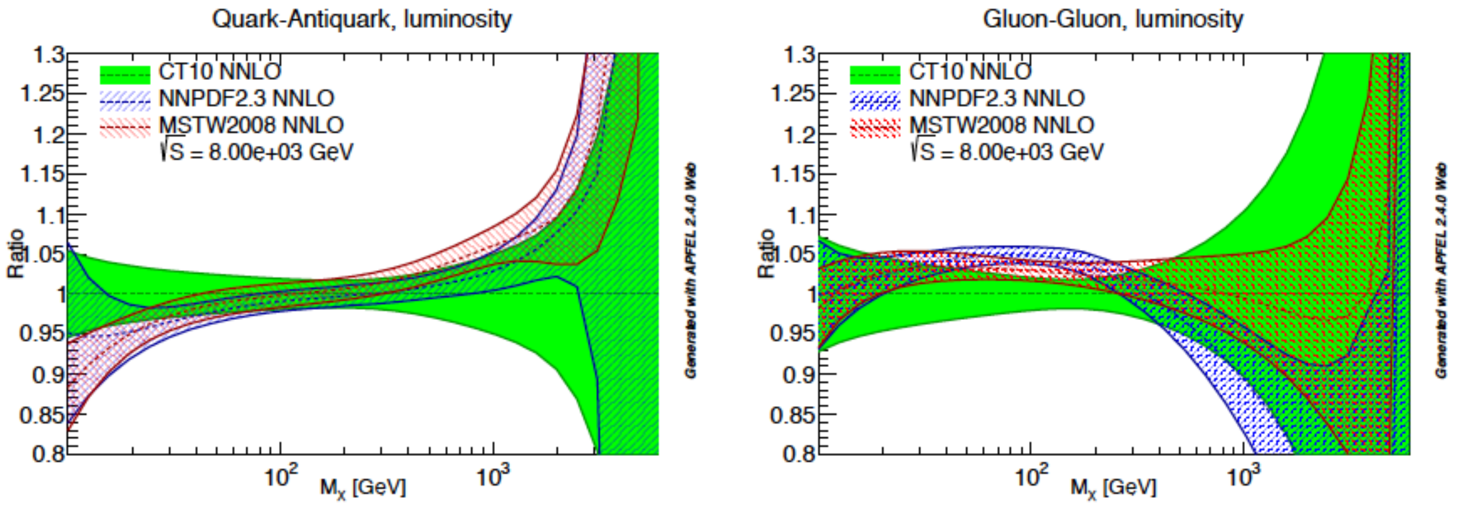
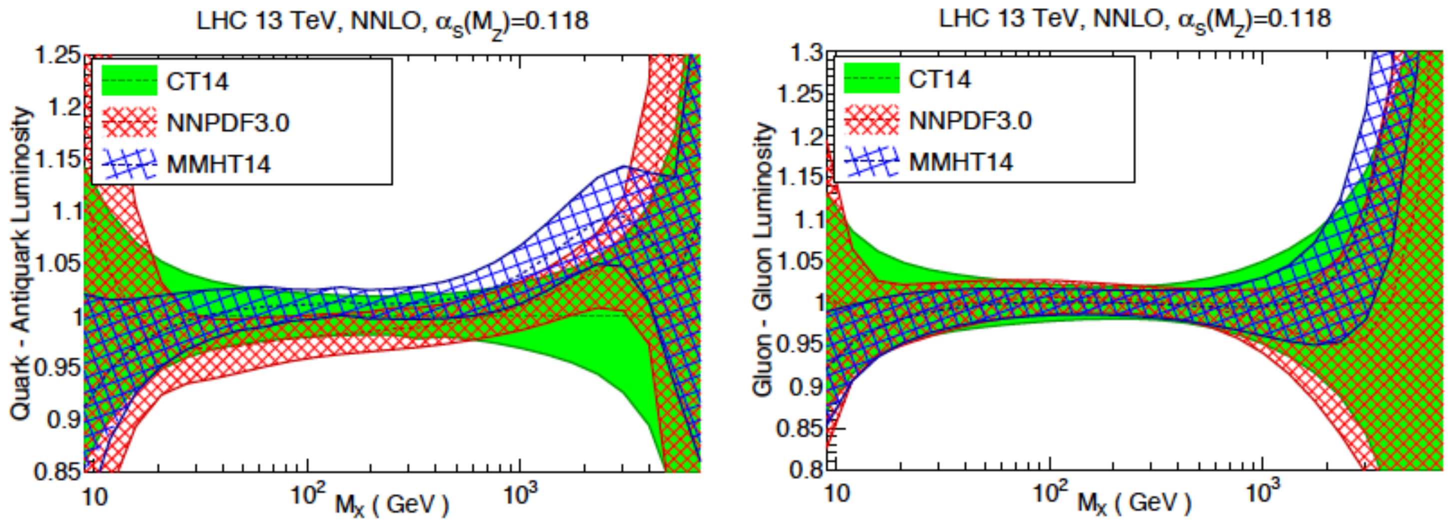


Figure 1: Comparison of the $q\bar{q}$ (left) and gg (right) PDF luminosities at the LHC 8 TeV for CT10, MSTW2008 and NNPDF2.3. Results are shown normalized to the central value of CT10.

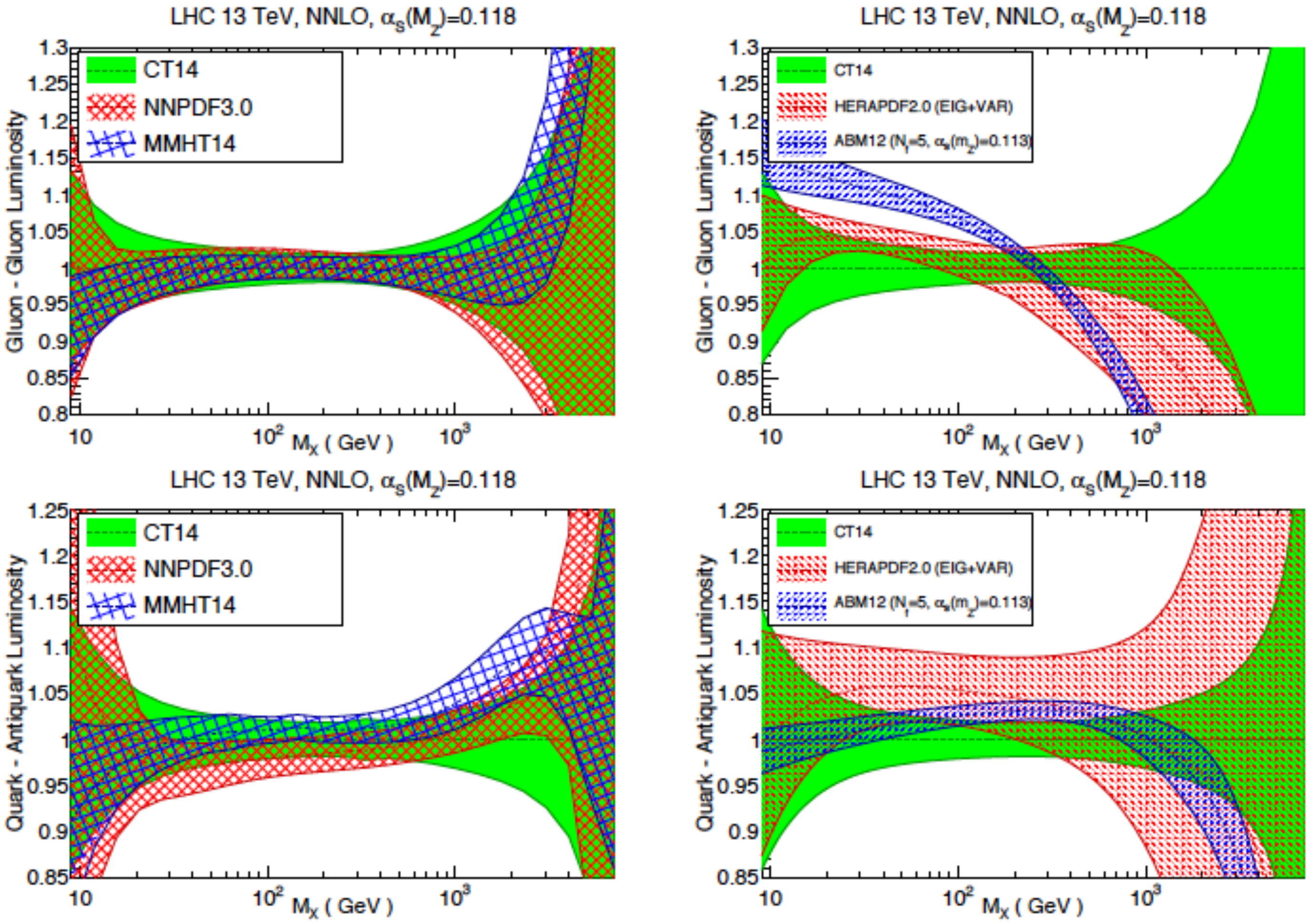


Note in particular the changes in the gg luminosity, especially important in the Higgs mass region

LHC data has been added for all 3 new PDFs, but most of change is due to changes in formalisms

Note also differences in high mass region remain

Other new sets out as well



behavior for HERAPDF2.0 and ABM12 somewhat different

HERAPDF2.0 uncertainties tend to be larger

Figure 5: Comparison of the gluon-gluon (upper plots) and quark-antiquark (lower plots) PDF luminosities from the CT14, MMHT14 and NNNPDF3.0 NNLO sets (left plots) and from the NNPDF3.0, ABM12 and HERAPDF2.0 NNLO sets (right plots), for a center-of-mass energy of 13 TeV, as a function of the invariant mass of the final state M_X.

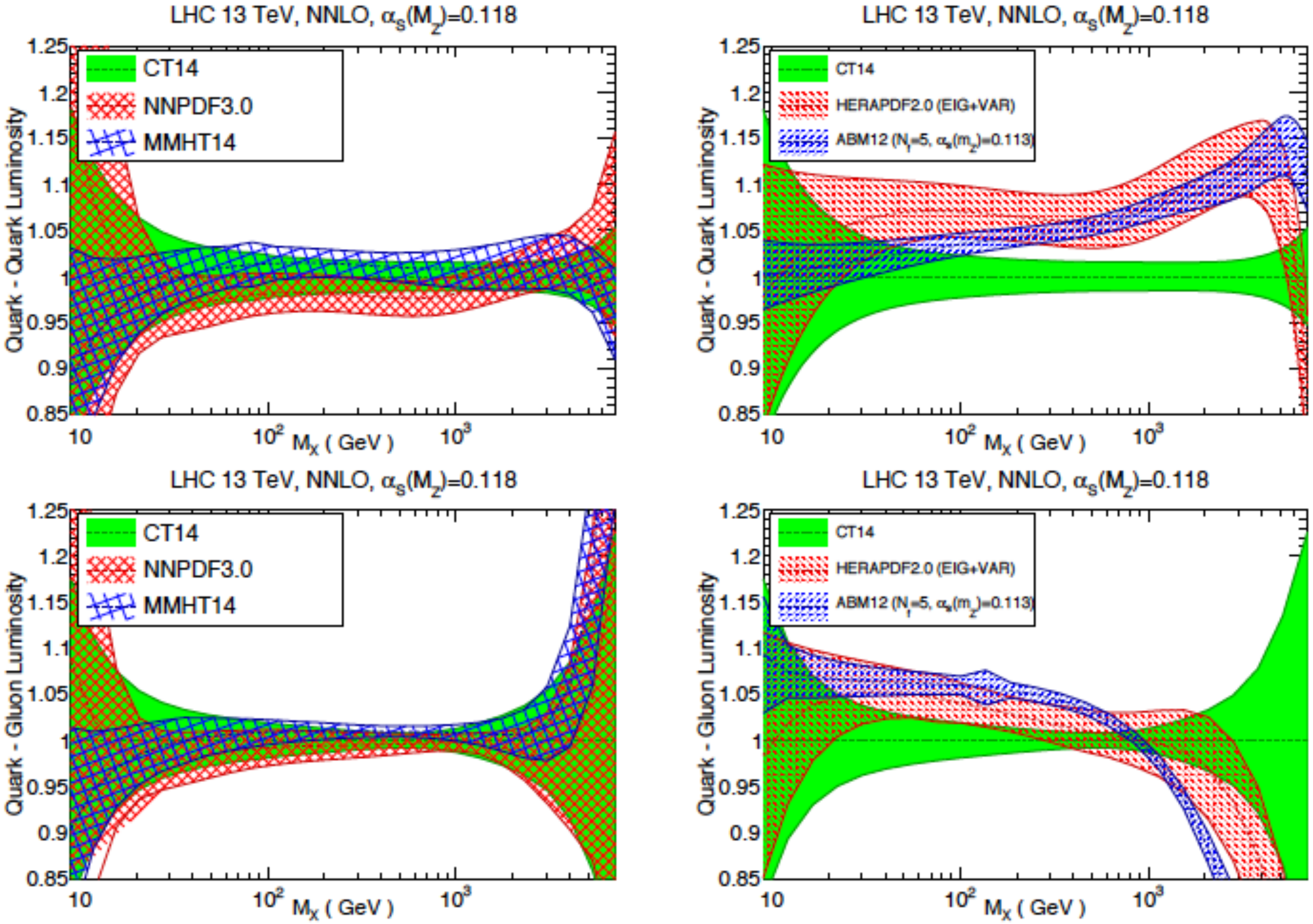
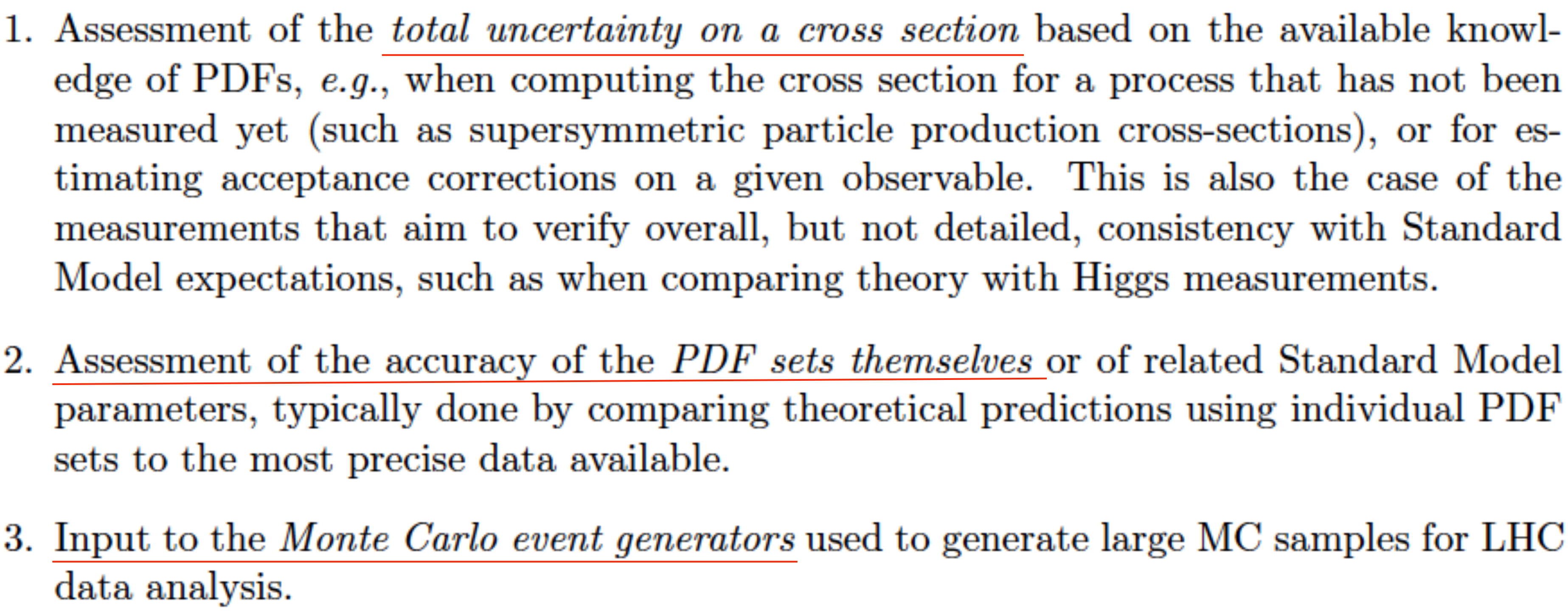


Figure 6: Same as Fig. 5 for the quark-quark (upper plots) and the quark-gluon (lower plots) PDF luminosities.

Three main uses of PDFs at LHC



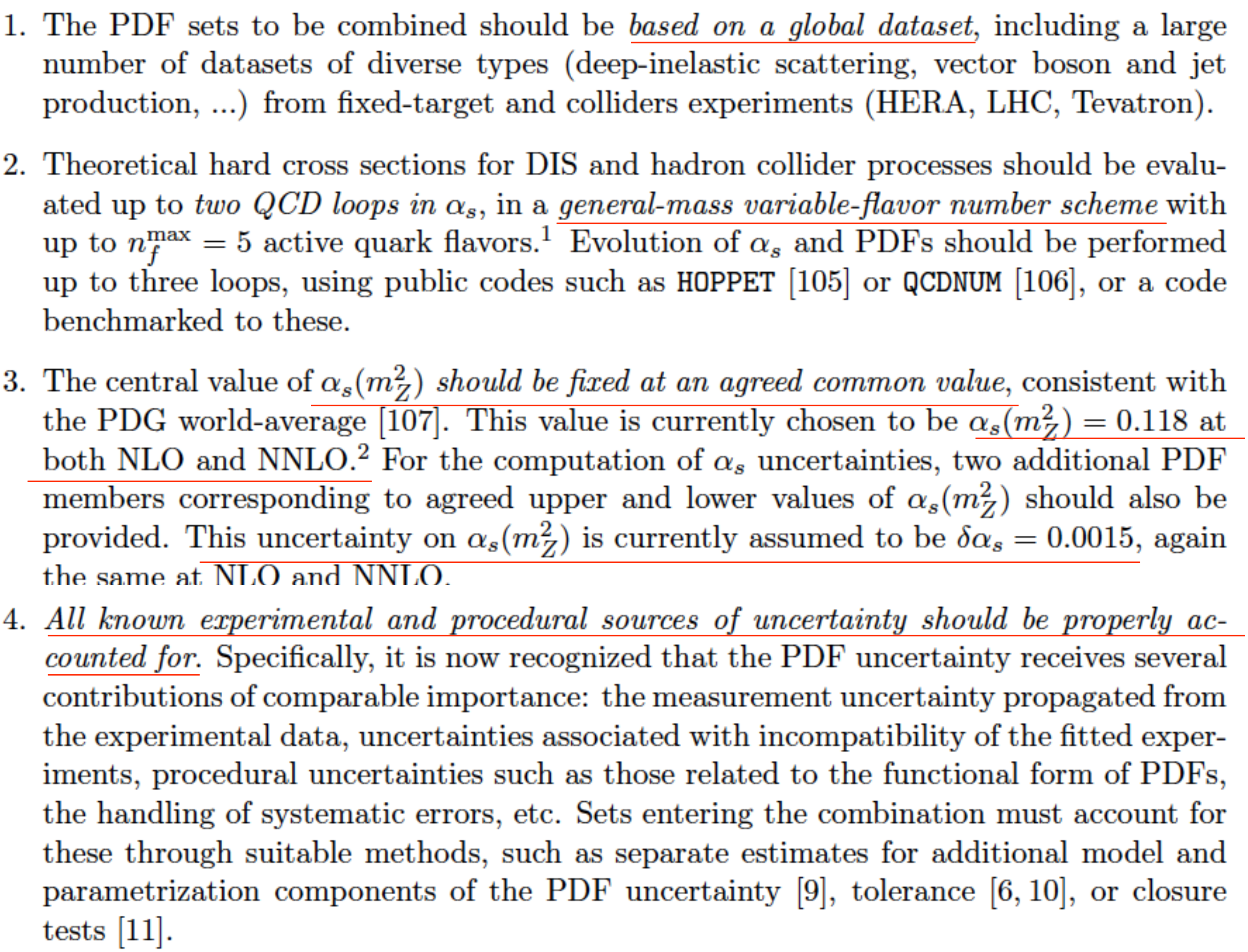
1. Assessment of the *total uncertainty on a cross section* based on the available knowledge of PDFs, *e.g.*, when computing the cross section for a process that has not been measured yet (such as supersymmetric particle production cross-sections), or for estimating acceptance corrections on a given observable. This is also the case of the measurements that aim to verify overall, but not detailed, consistency with Standard Model expectations, such as when comparing theory with Higgs measurements.
2. Assessment of the accuracy of the *PDF sets themselves* or of related Standard Model parameters, typically done by comparing theoretical predictions using individual PDF sets to the most precise data available.
3. Input to the *Monte Carlo event generators* used to generate large MC samples for LHC data analysis.

For 2), use individual PDF sets.

For 1), a more general uncertainty requires more than the use of 1 PDF set.

For 3), may want to use an average of PDF sets.

What PDFs to use?



1. The PDF sets to be combined should be *based on a global dataset*, including a large number of datasets of diverse types (deep-inelastic scattering, vector boson and jet production, ...) from fixed-target and colliders experiments (HERA, LHC, Tevatron).

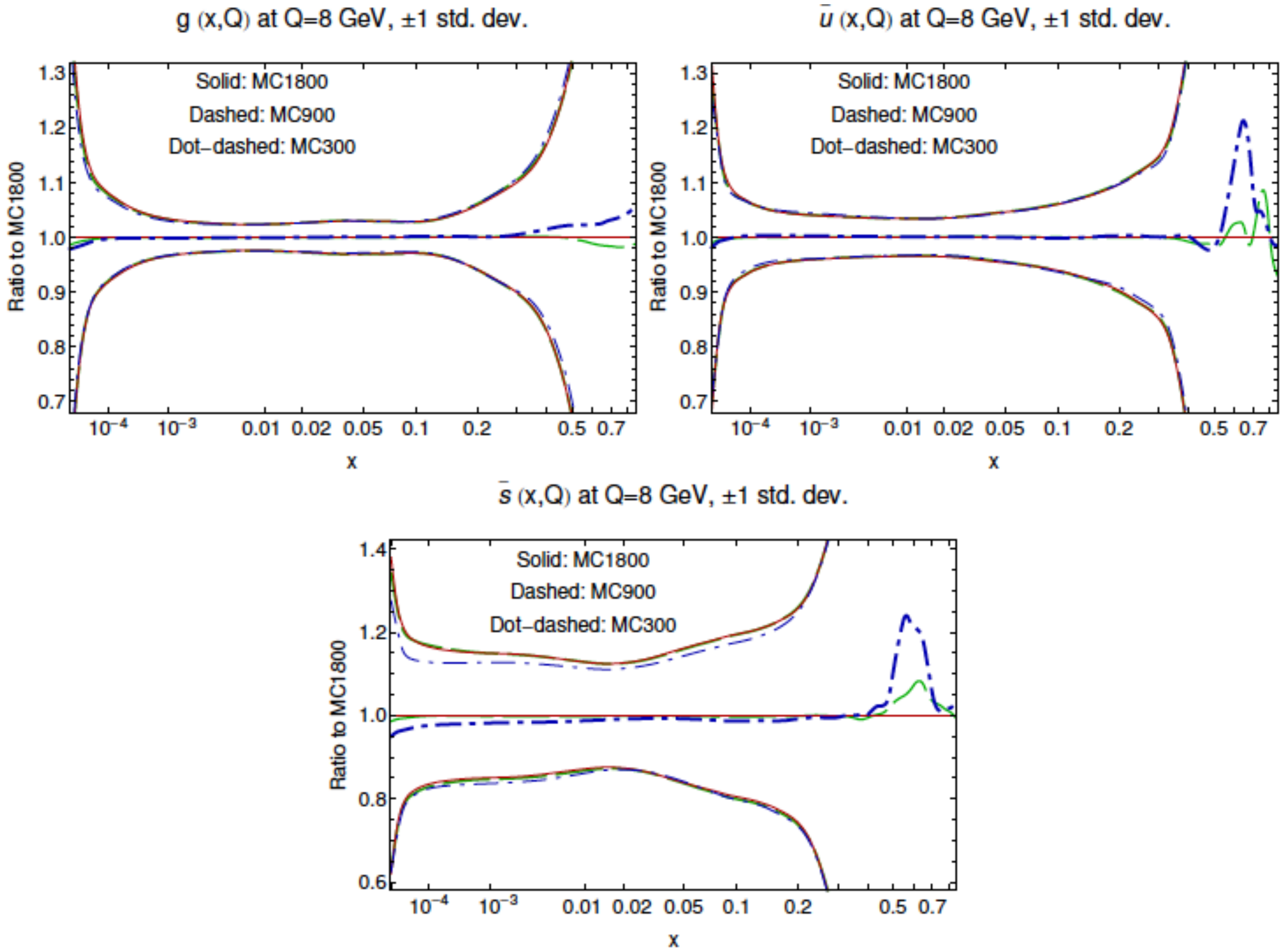
2. Theoretical hard cross sections for DIS and hadron collider processes should be evaluated up to *two QCD loops in α_s*, in a *general-mass variable-flavor number scheme* with up to $n_f^{\max} = 5$ active quark flavors.[1] Evolution of α_s and PDFs should be performed up to three loops, using public codes such as `HOPPET` [105] or `QCDNUM` [106], or a code benchmarked to these.

3. The central value of $\alpha_s(m_Z^2)$ *should be fixed at an agreed common value*, consistent with the PDG world-average [107]. This value is currently chosen to be $\alpha_s(m_Z^2) = 0.118$ at both NLO and NNLO.[2] For the computation of α_s uncertainties, two additional PDF members corresponding to agreed upper and lower values of $\alpha_s(m_Z^2)$ should also be provided. This uncertainty on $\alpha_s(m_Z^2)$ is currently assumed to be $\delta\alpha_s = 0.0015$, again the same at NLO and NNLO.

4. *All known experimental and procedural sources of uncertainty should be properly accounted for*. Specifically, it is now recognized that the PDF uncertainty receives several contributions of comparable importance: the measurement uncertainty propagated from the experimental data, uncertainties associated with incompatibility of the fitted experiments, procedural uncertainties such as those related to the functional form of PDFs, the handling of systematic errors, etc. Sets entering the combination must account for these through suitable methods, such as separate estimates for additional model and parametrization components of the PDF uncertainty [9], tolerance [6, 10], or closure tests [11].

Monte Carlo representation

- So based on the criteria on the previous slide, we use CT14, MMHT2014 and NNPDF3.0, with the option of adding additional sets in future upgrades if they satisfy the listed criteria
- In the previous recommendation, we used an envelope of 3 PDF sets; envelope determined by outliers
- Given the level of agreement of the 3 PDFs that will be used, try for a more relevant statistical approach
- Generate Monte Carlo replicas, equal numbers from error PDF sets of CT14, MMHT2014 and NNPDF3.0 using Thorne-Watt procedure



g (x,Q) at Q=8 GeV, ±1 std. dev.

$\bar{u}$ (x,Q) at Q=8 GeV, ±1 std. dev.

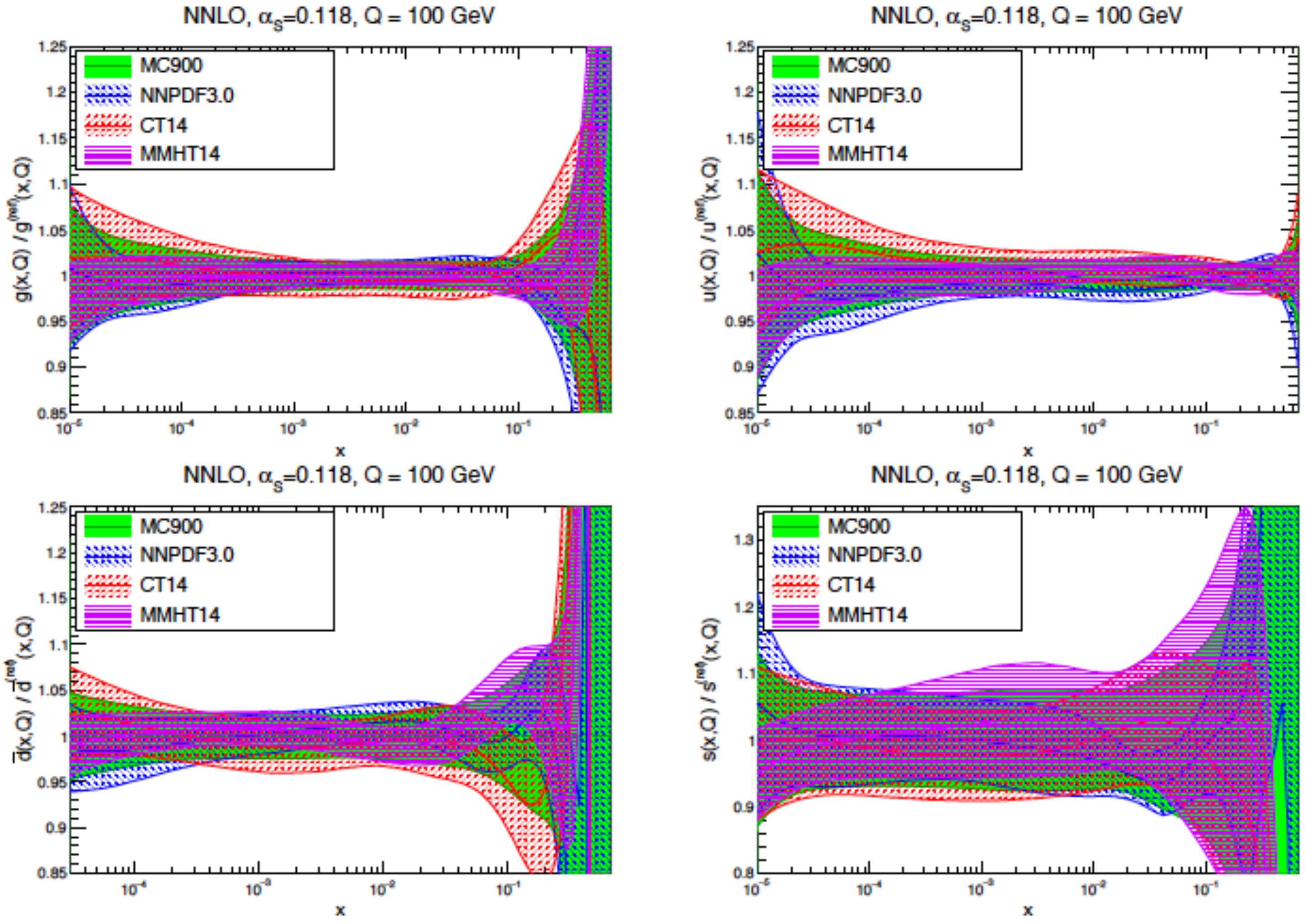
$\bar{s}$ (x,Q) at Q=8 GeV, ±1 std. dev.

900 replicas seems enough

->MC900
or
PDF4LHC_prior

Figure 7: Comparison of central values and uncertainties for the MC combination of CT14, MMHT14 and NNPDF3.0 for different values of N_{rep}, 300, 600 and 900, denoted by MC300, MC900 and MC1800 respectively.

MC900



Note that MC900 is not the envelope of the 3 PDF error bands

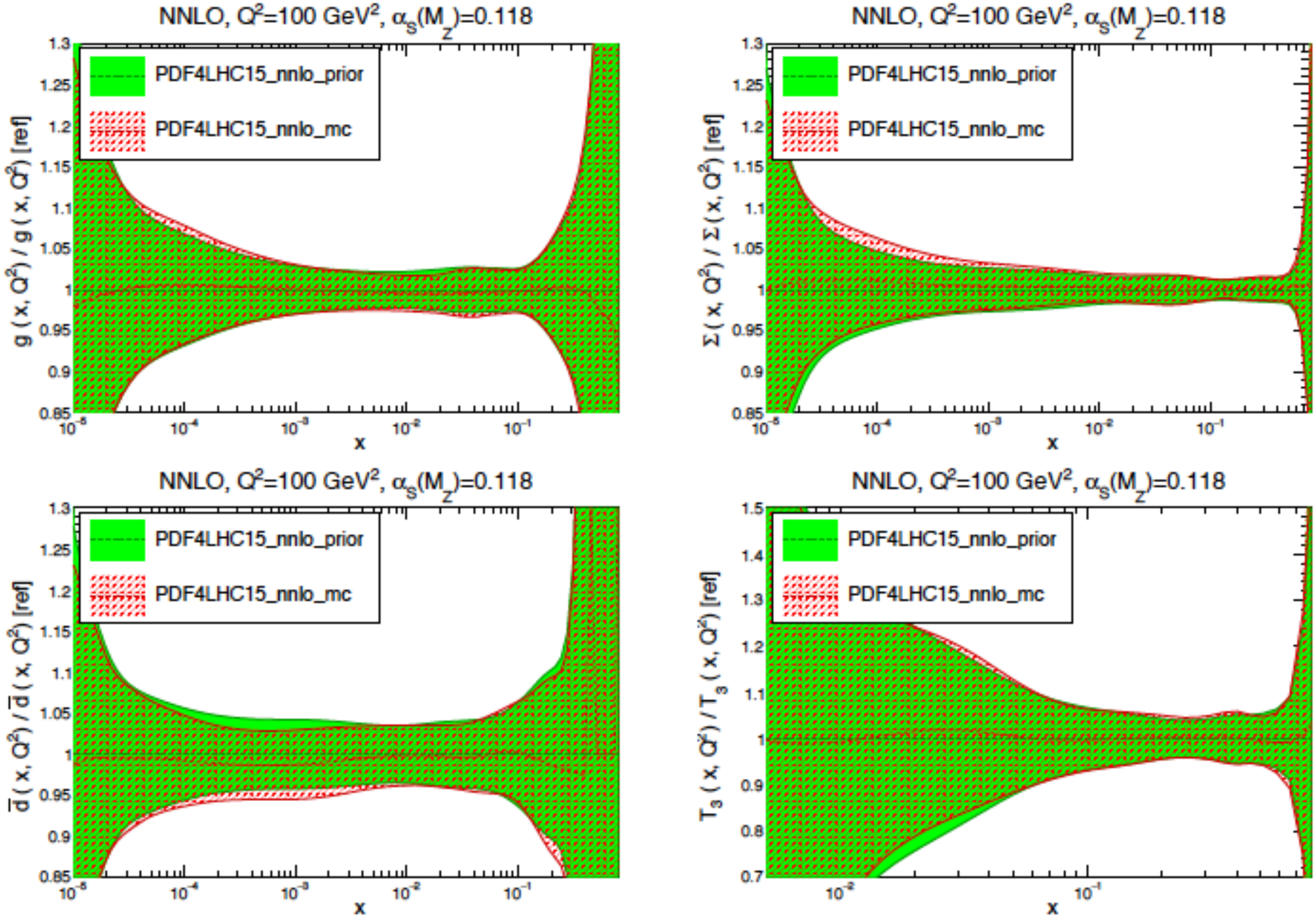
The PDF error bands themselves are similar for the precision physics region, but not for low mass/high mass

Figure 8: Comparison of the MC900 PDFs with the sets that enter the combination: CT14, MMHT14 and NNPDF3.0 at NNLO. We show the gluon and the up, anti-down and strange quarks at $Q = 100$ GeV. Results are normalized to the central value of MC900.

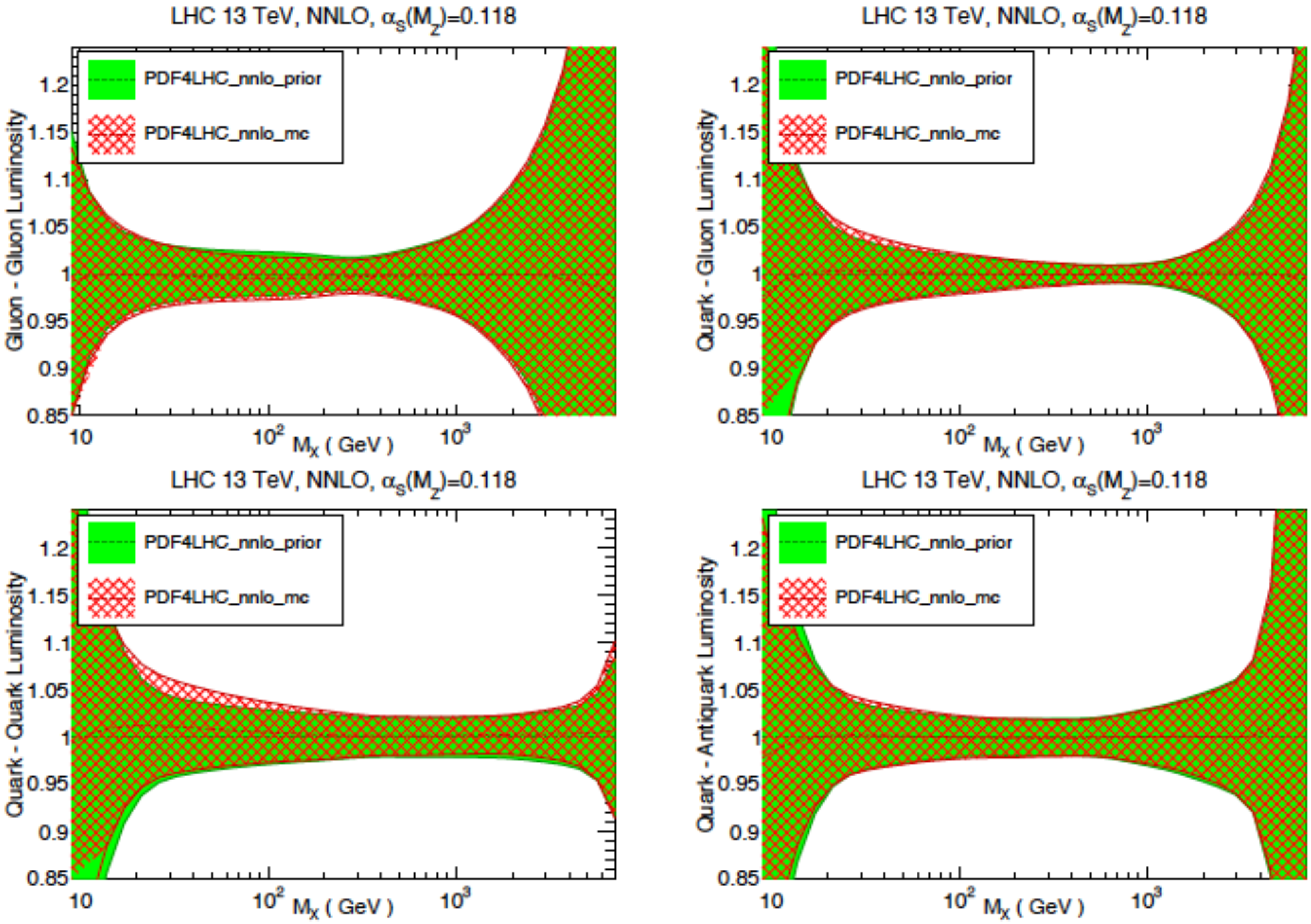
Reduced sets

- 900 error PDFs are too much for general use
- We would like to reduce this number while still maintaining as much information on the uncertainties and on correlations between PDF uncertainties as possible
- We have settled on 3 techniques/outputs
  - Compressed Monte Carlo PDFs (PDF4LHC15_nnlo(nlo)_mc)
    - 100 PDF error sets; preserve non-Gaussian errors
  - META Hessian PDFs (PDF4LHC15_nnlo(nlo)_30
    - 30 PDF error sets using METAPDF technique; Gaussian (symmetric) errors
  - MCH Hessian PDFs (PDF4lhc15_nnlo(nlo)_100
    - 100 PDF error sets using MCH technique; Gaussian (symmetric errors)
- The META technique is able to more efficiently reproduce the uncertainties when using a limited number (30) of error PDFs
- The MCH technique best reproduces the uncertainties of the 900 MC set prior

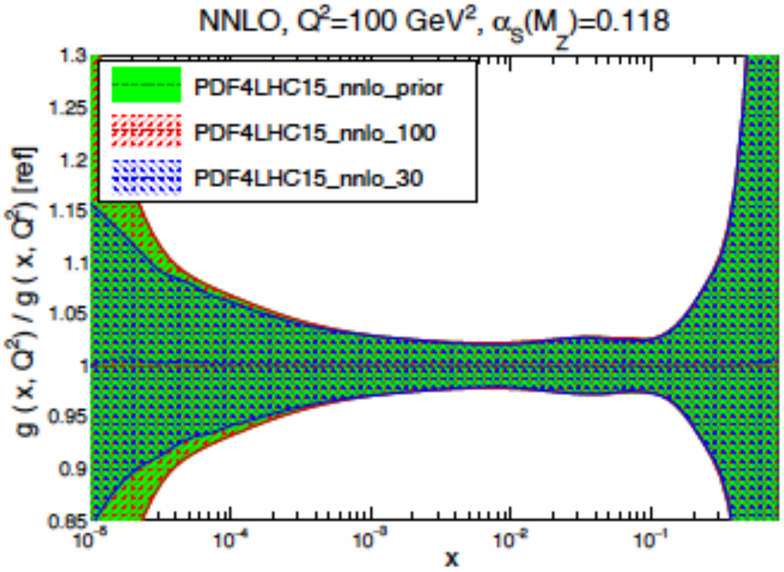
Some comparisons: mc PDFs

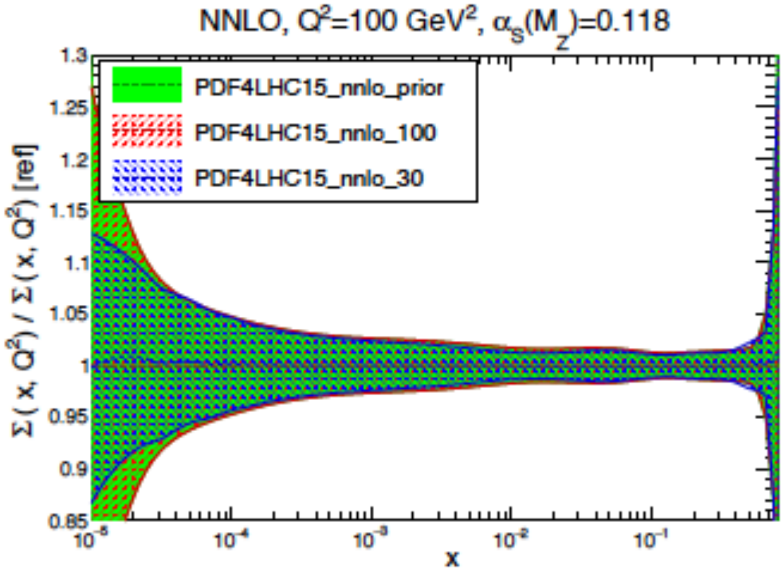


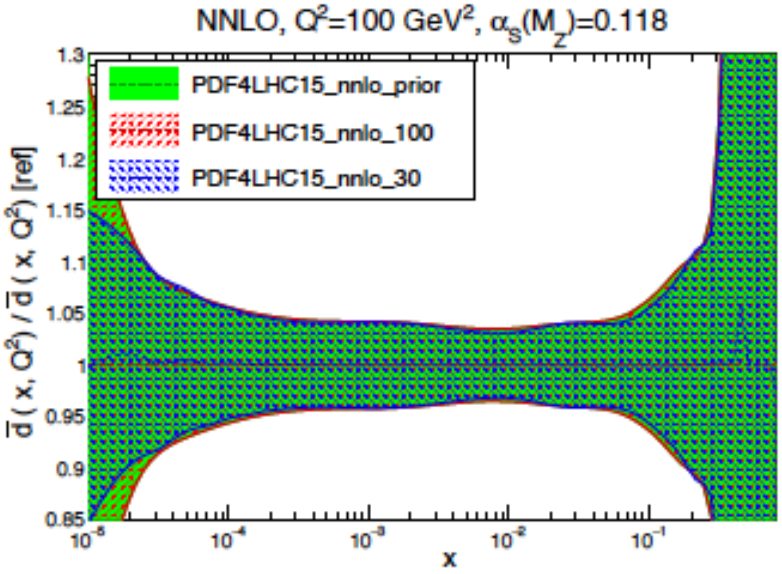
Some comparisons: mc PDFs

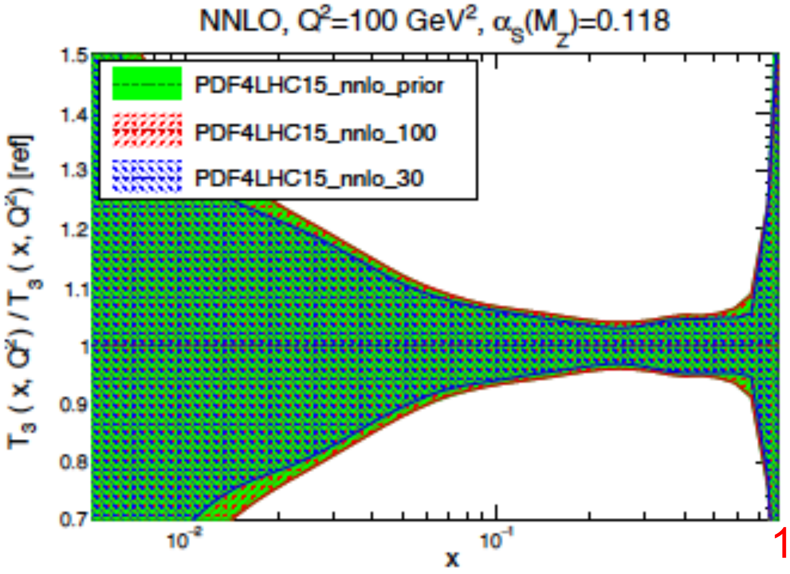


Some comparisons: Hessian sets

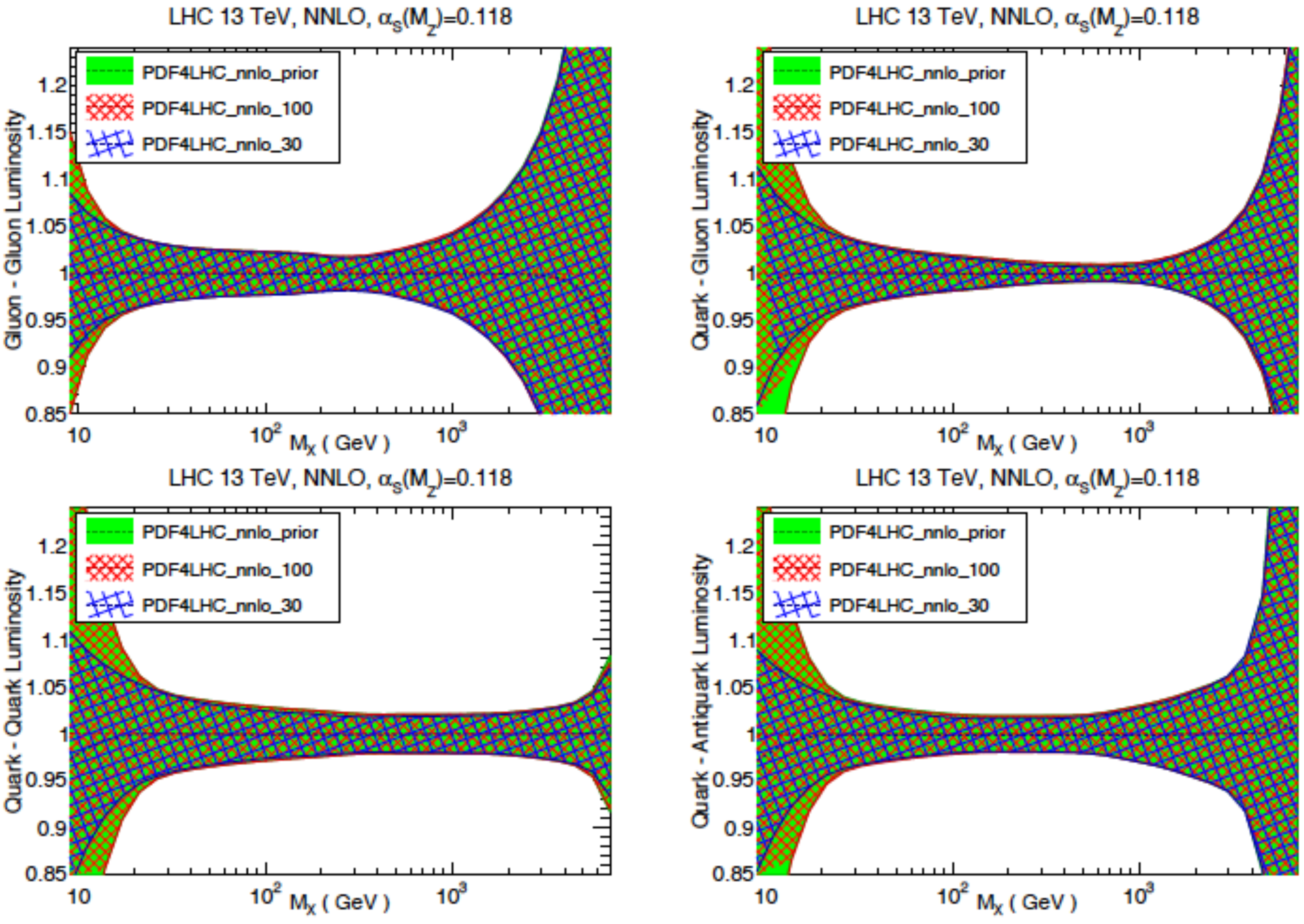




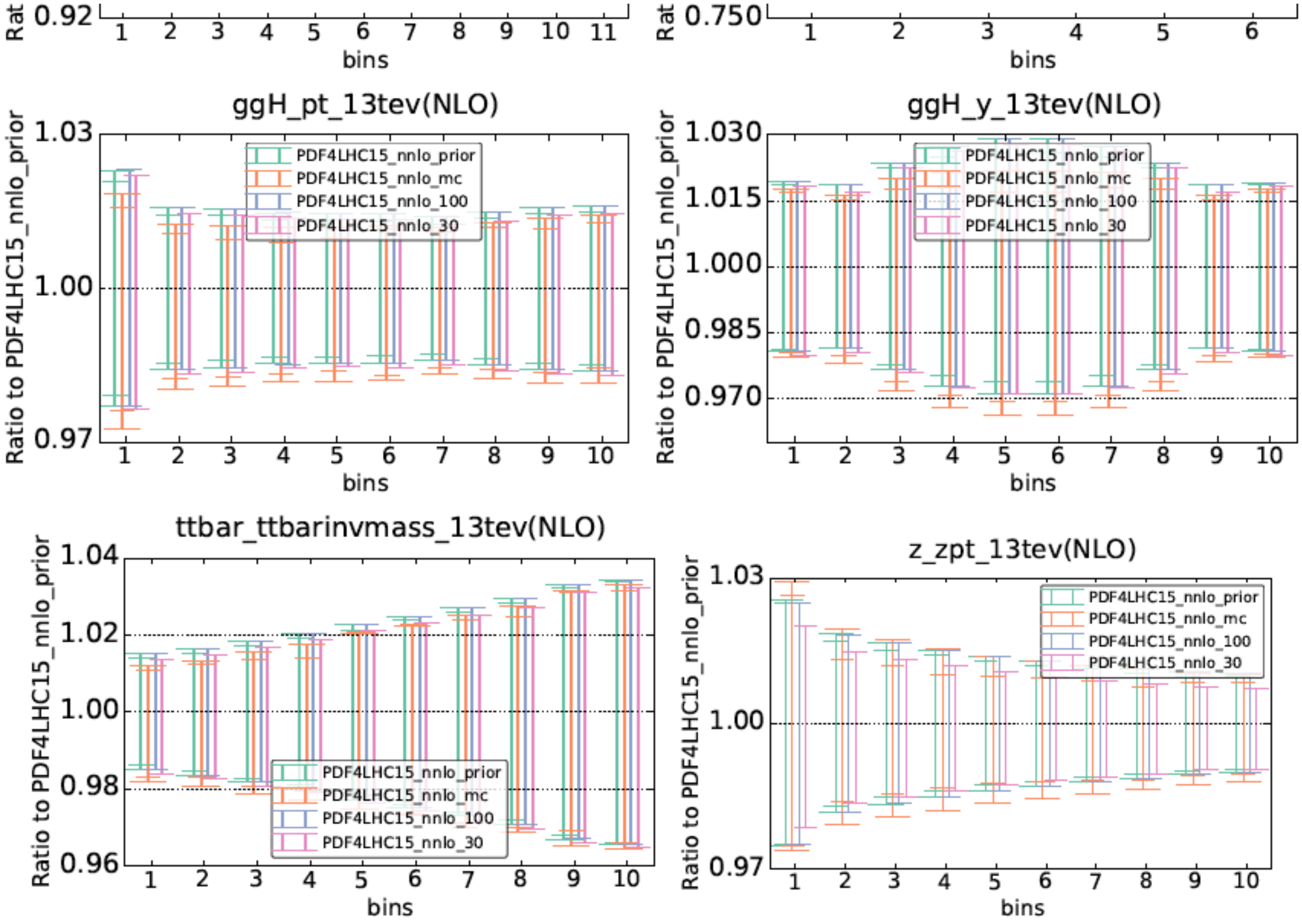


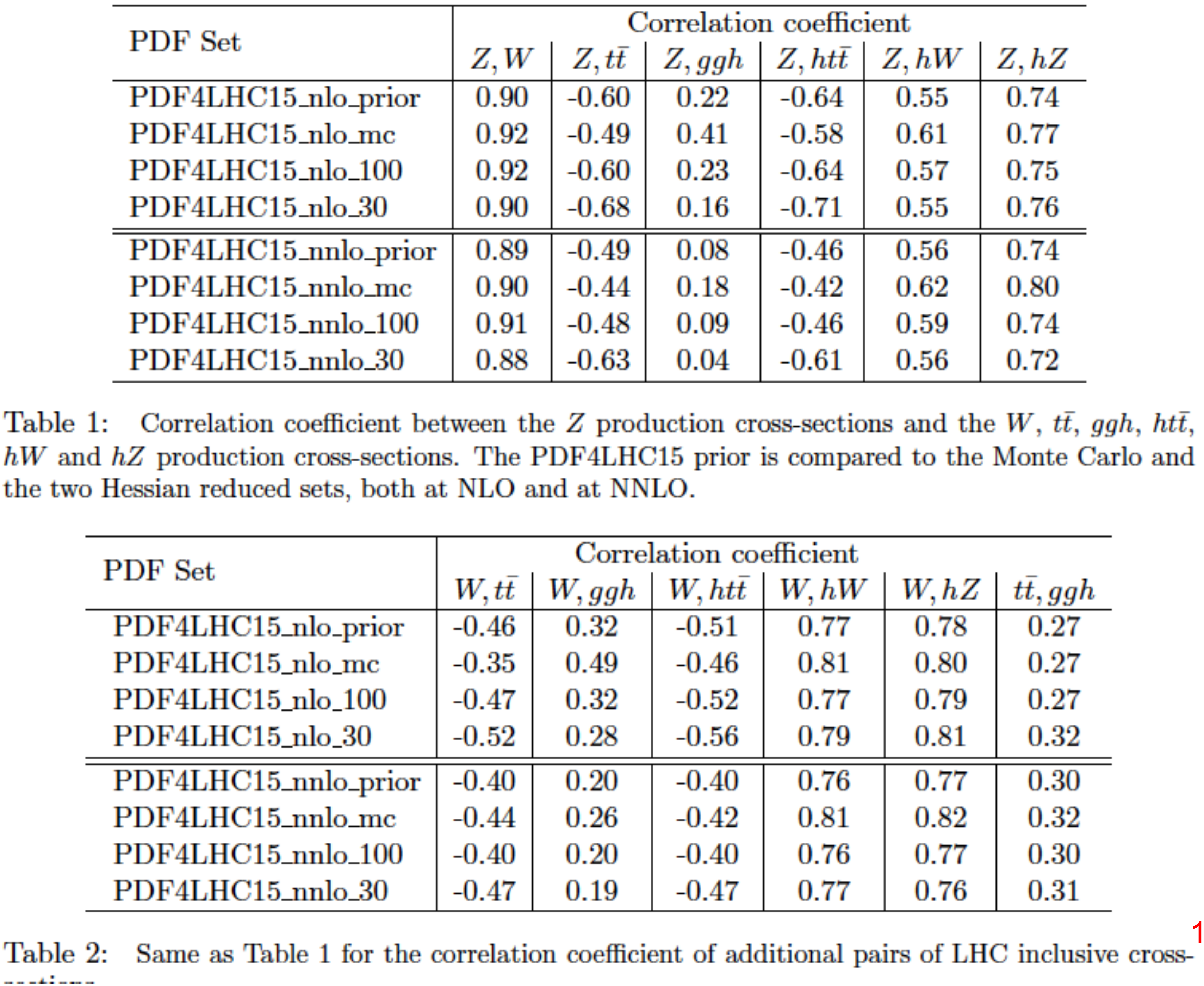


Some comparisons: Hessian sets



Application to cross sections





PDF Set	Correlation coefficient					
	Z, W	$Z, t\bar{t}$	Z, ggh	$Z, ht\bar{t}$	Z, hW	Z, hZ
PDF4LHC15_nlo_prior	0.90	-0.60	0.22	-0.64	0.55	0.74
PDF4LHC15_nlo_mc	0.92	-0.49	0.41	-0.58	0.61	0.77
PDF4LHC15_nlo_100	0.92	-0.60	0.23	-0.64	0.57	0.75
PDF4LHC15_nlo_30	0.90	-0.68	0.16	-0.71	0.55	0.76
PDF4LHC15_nnlo_prior	0.89	-0.49	0.08	-0.46	0.56	0.74
PDF4LHC15_nnlo_mc	0.90	-0.44	0.18	-0.42	0.62	0.80
PDF4LHC15_nnlo_100	0.91	-0.48	0.09	-0.46	0.59	0.74
PDF4LHC15_nnlo_30	0.88	-0.63	0.04	-0.61	0.56	0.72

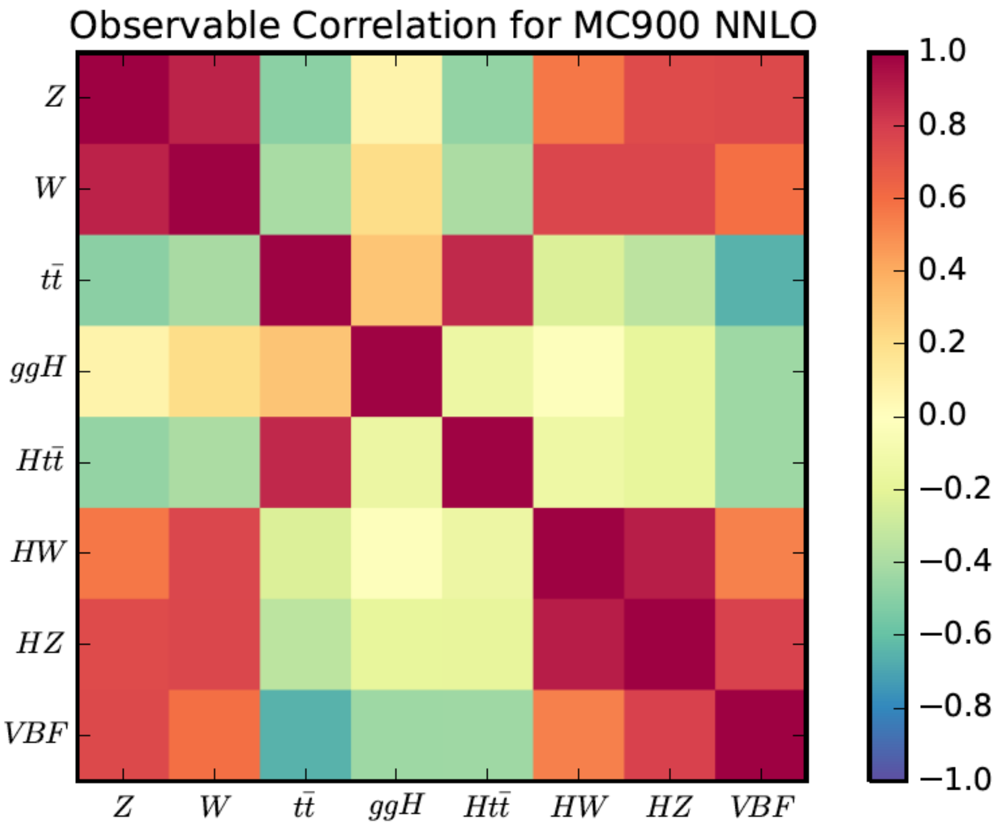
Table 1: Correlation coefficient between the Z production cross-sections and the W, $t\bar{t}$, ggh, $ht\bar{t}$, hW and hZ production cross-sections. The PDF4LHC15 prior is compared to the Monte Carlo and the two Hessian reduced sets, both at NLO and at NNLO.

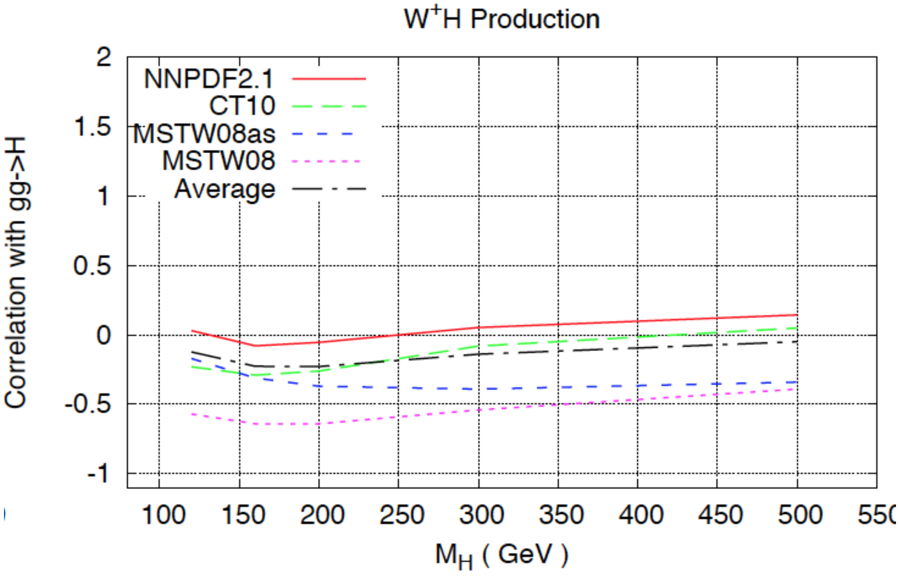
PDF Set	Correlation coefficient					
	$W, t\bar{t}$	W, ggh	$W, ht\bar{t}$	W, hW	W, hZ	$t\bar{t}, ggh$
PDF4LHC15_nlo_prior	-0.46	0.32	-0.51	0.77	0.78	0.27
PDF4LHC15_nlo_mc	-0.35	0.49	-0.46	0.81	0.80	0.27
PDF4LHC15_nlo_100	-0.47	0.32	-0.52	0.77	0.79	0.27
PDF4LHC15_nlo_30	-0.52	0.28	-0.56	0.79	0.81	0.32
PDF4LHC15_nnlo_prior	-0.40	0.20	-0.40	0.76	0.77	0.30
PDF4LHC15_nnlo_mc	-0.44	0.26	-0.42	0.81	0.82	0.32
PDF4LHC15_nnlo_100	-0.40	0.20	-0.40	0.76	0.77	0.30
PDF4LHC15_nnlo_30	-0.47	0.19	-0.47	0.77	0.76	0.31

Table 2: Same as Table 1 for the correlation coefficient of additional pairs of LHC inclusive cross-sections

Correlations

probably only 1 digit for the correlations is significant, so plot like on right is more relevant

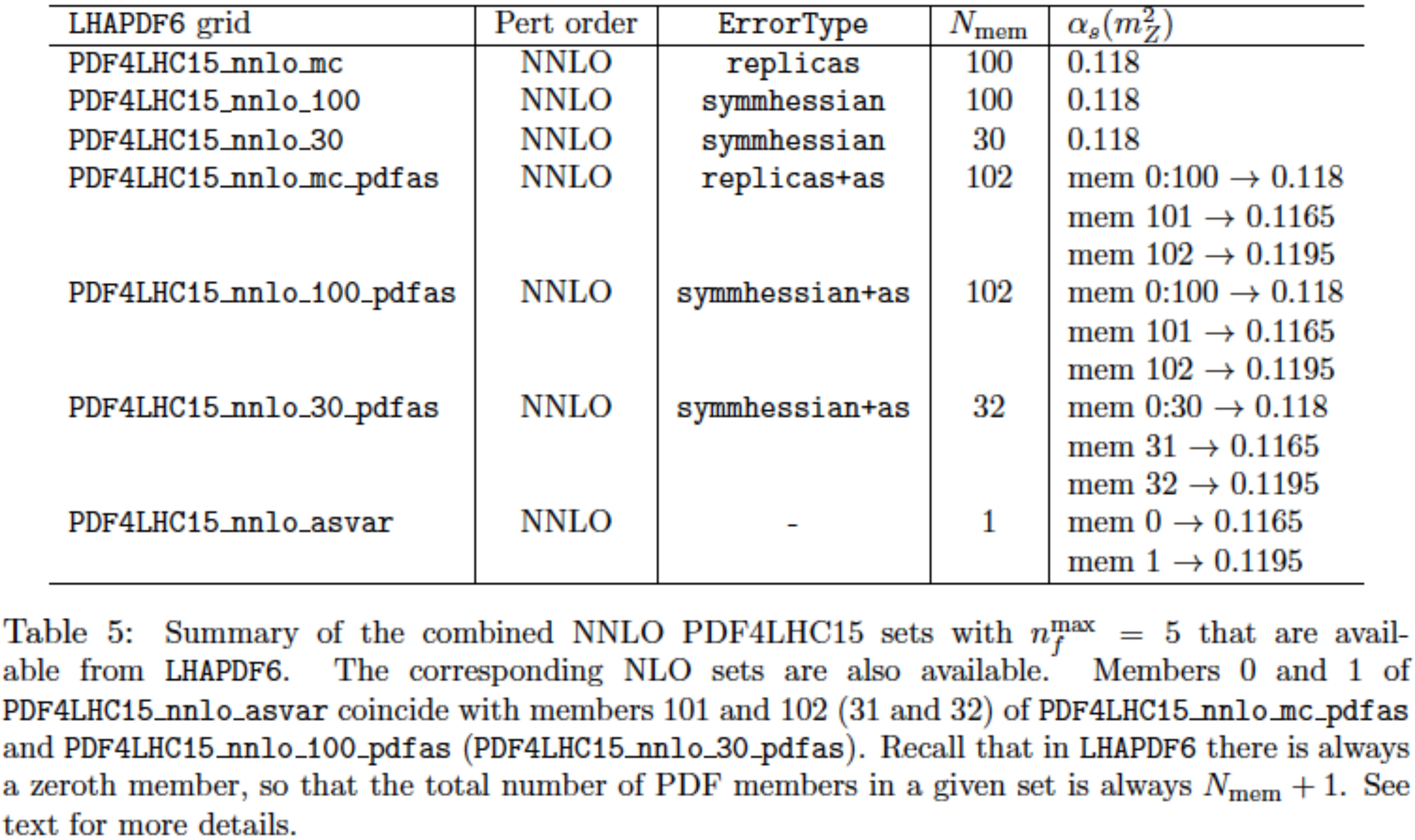




correlations can differ significantly for example from the individual PDFs

from YR2

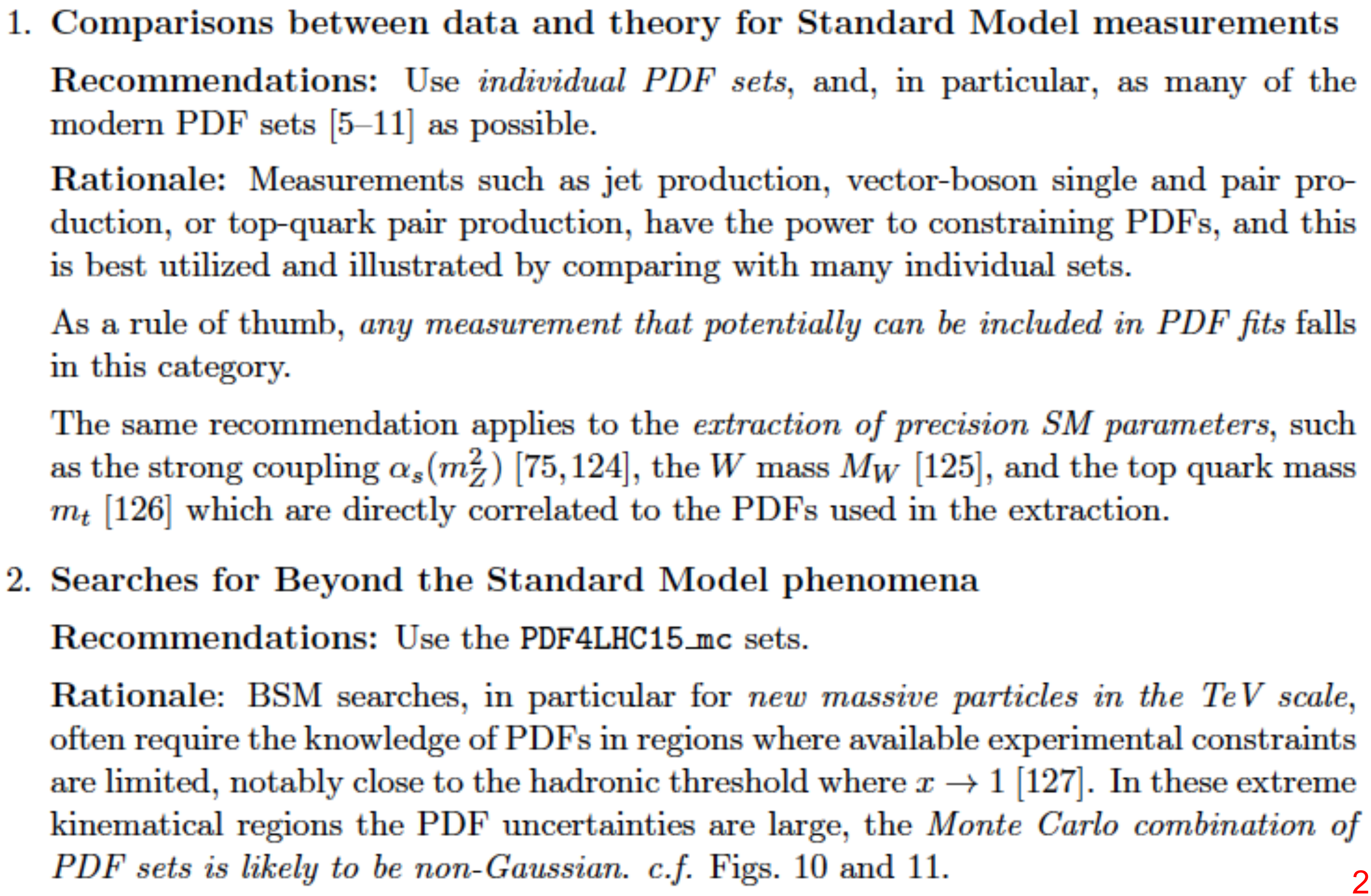
Now on LHAPDF



LHAPDF6 grid	Pert order	ErrorType	$N_{\rm mem}$	$\alpha_s(m_Z^2)$
`PDF4LHC15_nnlo_mc`	NNLO	`replicas`	100	0.118
`PDF4LHC15_nnlo_100`	NNLO	`symmhessian`	100	0.118
`PDF4LHC15_nnlo_30`	NNLO	`symmhessian`	30	0.118
`PDF4LHC15_nnlo_mc_pdfas`	NNLO	`replicas+as`	102	mem 0:100 → 0.118 mem 101 → 0.1165 mem 102 → 0.1195
`PDF4LHC15_nnlo_100_pdfas`	NNLO	`symmhessian+as`	102	mem 0:100 → 0.118 mem 101 → 0.1165 mem 102 → 0.1195
`PDF4LHC15_nnlo_30_pdfas`	NNLO	`symmhessian+as`	32	mem 0:30 → 0.118 mem 31 → 0.1165 mem 32 → 0.1195
`PDF4LHC15_nnlo_asvar`	NNLO	-	1	mem 0 → 0.1165 mem 1 → 0.1195

Table 5: Summary of the combined NNLO PDF4LHC15 sets with $n_f^{\rm max} = 5$ that are available from `LHAPDF6`. The corresponding NLO sets are also available. Members 0 and 1 of `PDF4LHC15_nnlo_asvar` coincide with members 101 and 102 (31 and 32) of `PDF4LHC15_nnlo_mc_pdfas` and `PDF4LHC15_nnlo_100_pdfas` (`PDF4LHC15_nnlo_30_pdfas`). Recall that in `LHAPDF6` there is always a zeroth member, so that the total number of PDF members in a given set is always $N_{\rm mem} + 1$. See text for more details.

Recommendations



1. **Comparisons between data and theory for Standard Model measurements**

   Recommendations: Use *individual PDF sets*, and, in particular, as many of the modern PDF sets [5–11] as possible.

   Rationale: Measurements such as jet production, vector-boson single and pair production, or top-quark pair production, have the power to constraining PDFs, and this is best utilized and illustrated by comparing with many individual sets.

   As a rule of thumb, *any measurement that potentially can be included in PDF fits* falls in this category.

   The same recommendation applies to the *extraction of precision SM parameters*, such as the strong coupling $\alpha_s(m_Z^2)$ [75,124], the W mass M_W [125], and the top quark mass m_t [126] which are directly correlated to the PDFs used in the extraction.

2. **Searches for Beyond the Standard Model phenomena**

   Recommendations: Use the `PDF4LHC15_mc` sets.

   Rationale: BSM searches, in particular for *new massive particles in the TeV scale*, often require the knowledge of PDFs in regions where available experimental constraints are limited, notably close to the hadronic threshold where $x \to 1$ [127]. In these extreme kinematical regions the PDF uncertainties are large, the *Monte Carlo combination of PDF sets is likely to be non-Gaussian. c.f.* Figs. 10 and 11.

3. **Calculation of PDF uncertainties in situations when computational speed is needed, or a more limited number of error PDFs may be desirable**

   Recommendations: Use the `PDF4LHC15_30` sets.

   Rationale: In many situations, PDF uncertainties may affect the extraction of physics parameters. From the point of view of the statistical analysis, it might be useful in some cases to *limit the number of error PDFs* that need to be included in such analyses. In these cases, use of the `PDF4LHC15_30` sets may be most suitable.

   In addition, the calculation of *acceptances, efficiencies or extrapolation factors* are affected by the corresponding PDF uncertainty. These quantities are only a moderate correction to the measured cross-section, and thus a mild loss of accuracy in the determination of PDF uncertainties in these corrections is acceptable, while computational speed can be an issue. In these cases, use of the `PDF4LHC15_30` sets is most suitable.

   However, in the cases when PDF uncertainties turn out to be substantial, we recommend to cross-check the PDF estimate by comparing with the results of the `PDF4LHC15_100` sets.

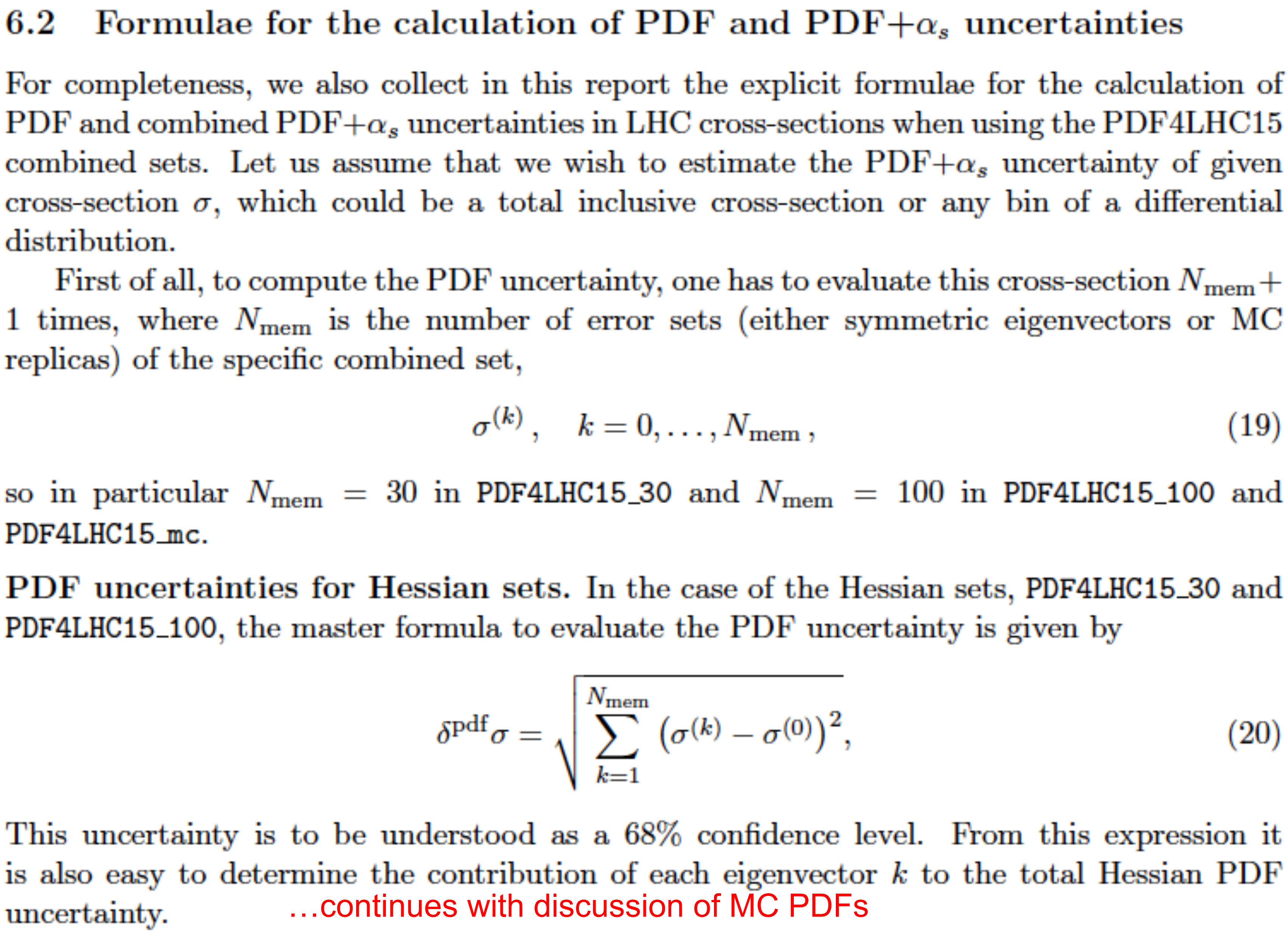
4. **Calculation of PDF uncertainties in precision observables**

   Recommendation: Use the `PDF4LHC15_100` sets.

   Rationale: For several LHC phenomenological applications, the highest accuracy is sought for, with, in some cases, the need to *control PDF uncertainties to the percent level*, as currently allowed by the development of high-order computational techniques in the QCD and electroweak sectors of the Standard Model.

   Whenever the highest accuracy is desired, the `PDF4LHC15_100` set is most suitable.

Pedagogical text about their use has been added



6.2 Formulae for the calculation of PDF and PDF+α_s uncertainties

For completeness, we also collect in this report the explicit formulae for the calculation of PDF and combined PDF+α_s uncertainties in LHC cross-sections when using the PDF4LHC15 combined sets. Let us assume that we wish to estimate the PDF+α_s uncertainty of given cross-section σ, which could be a total inclusive cross-section or any bin of a differential distribution.

First of all, to compute the PDF uncertainty, one has to evaluate this cross-section $N_{\rm mem}+1$ times, where $N_{\rm mem}$ is the number of error sets (either symmetric eigenvectors or MC replicas) of the specific combined set,

$$\sigma^{(k)}\,, \quad k=0,\ldots,N_{\rm mem}\,, \tag{19}$$

so in particular $N_{\rm mem}=30$ in `PDF4LHC15_30` and $N_{\rm mem}=100$ in `PDF4LHC15_100` and `PDF4LHC15_mc`.

PDF uncertainties for Hessian sets. In the case of the Hessian sets, `PDF4LHC15_30` and `PDF4LHC15_100`, the master formula to evaluate the PDF uncertainty is given by

$$\delta^{\rm pdf}\sigma = \sqrt{\sum_{k=1}^{N_{\rm mem}} \left(\sigma^{(k)}-\sigma^{(0)}\right)^2}\,, \tag{20}$$

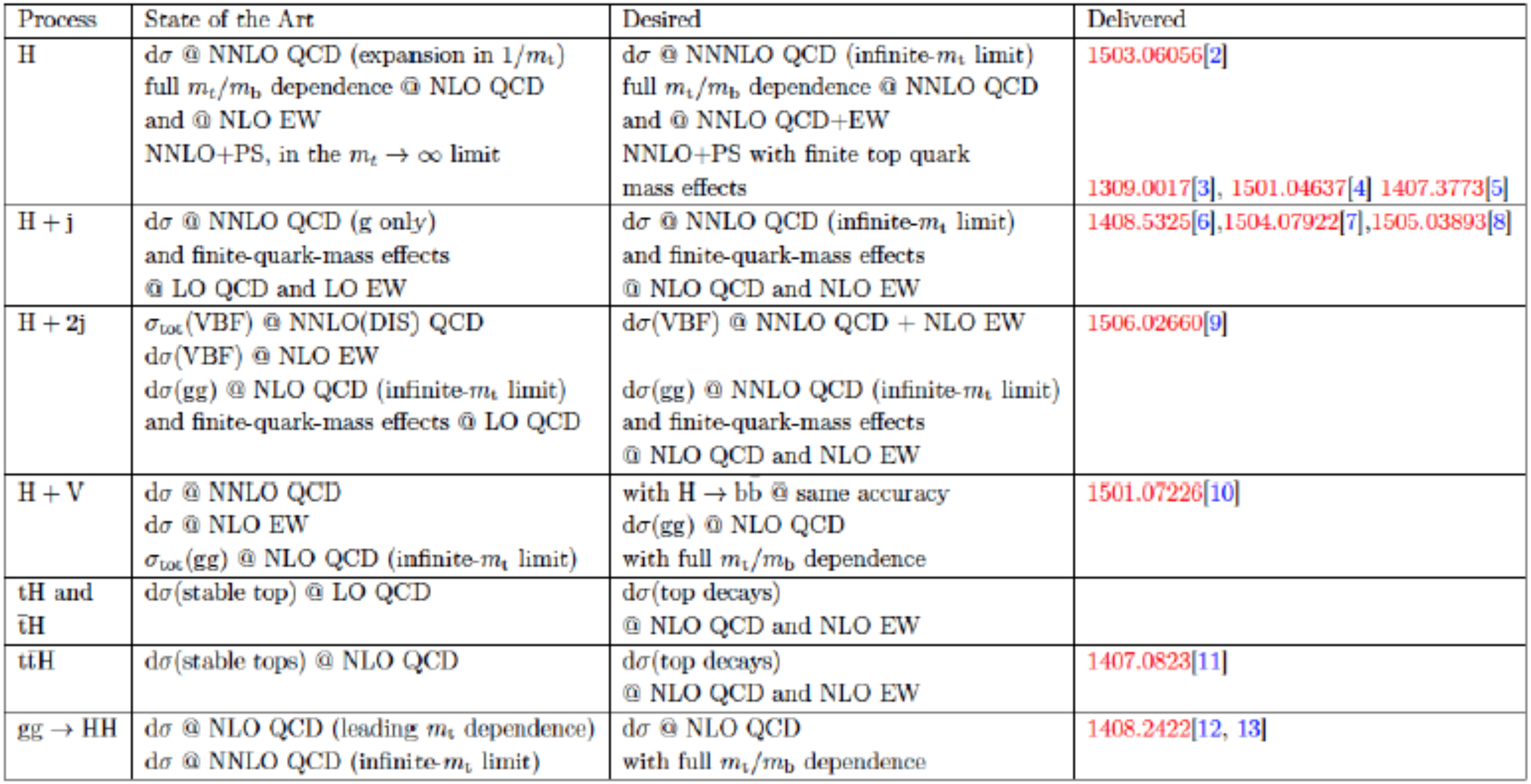
This uncertainty is to be understood as a 68% confidence level. From this expression it is also easy to determine the contribution of each eigenvector k to the total Hessian PDF uncertainty.

…continues with discussion of MC PDFs

Summary

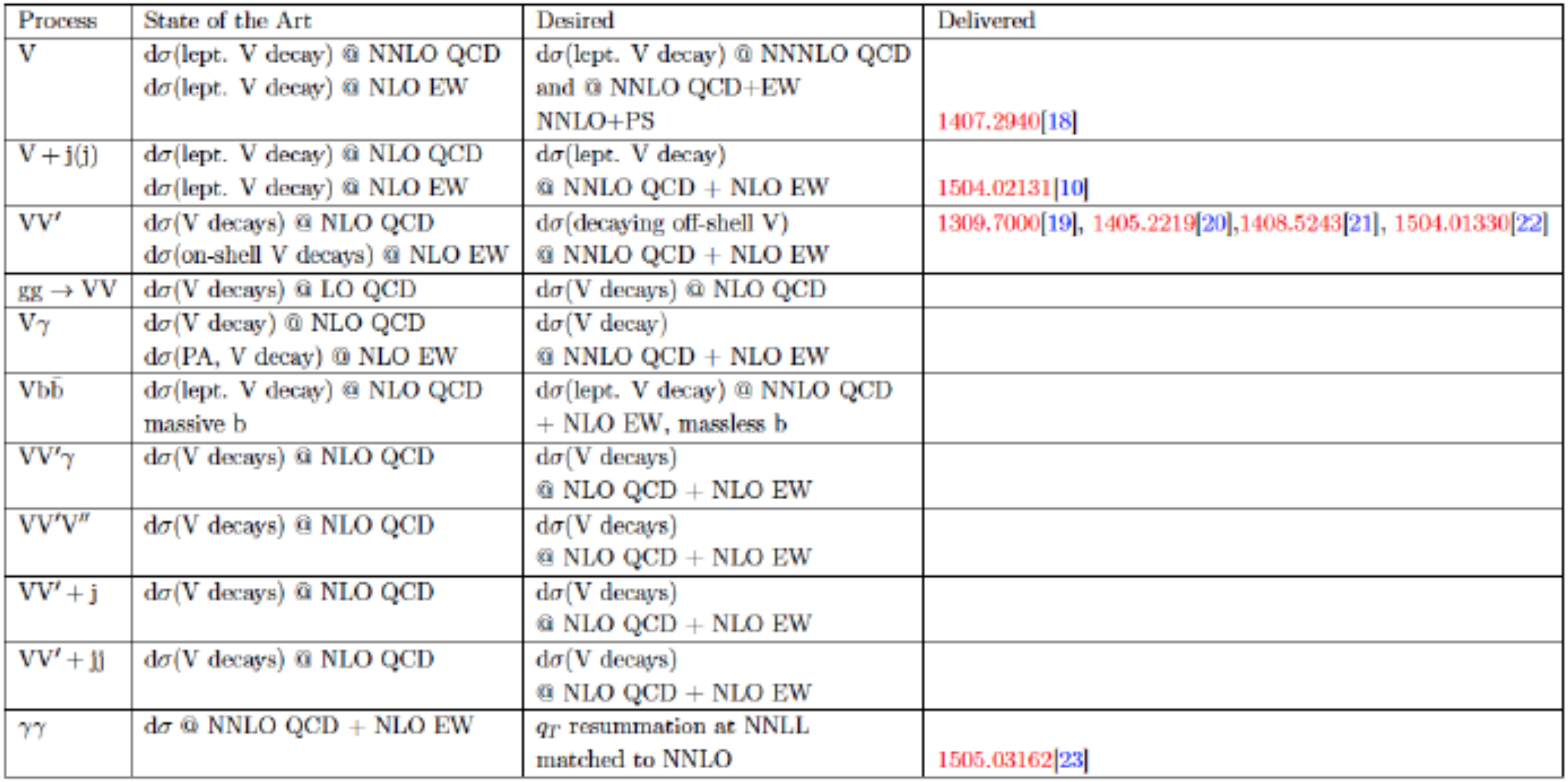
- New PDF4LHC recommendations are based on PDF combinations of CT14, MMHT2014 and NNPDF3.0
- Central PDF and uncertainties derived from 900 MC replicas of error PDFs of above 3 sets
- Three reduction techniques, with either 30 or 100 error PDFs, with uses as discussed previously
- With this recommendation also comes a new recommendation for the central value of $\alpha_s(m_Z)$ and its uncertainty
  - $\alpha_s(m_Z)=0.118$
  - $\delta\alpha_s(m_Z)=+/-0.0015$

Progress on wishlist



Process	State of the Art	Desired	Delivered
H	$d\sigma$ @ NNLO QCD (expansion in $1/m_t$) full m_t/m_b dependence @ NLO QCD and @ NLO EW NNLO+PS, in the $m_t \to \infty$ limit	$d\sigma$ @ NNNLO QCD (infinite-m_t limit) full m_t/m_b dependence @ NNLO QCD and @ NNLO QCD+EW NNLO+PS with finite top quark mass effects	1503.06056[2] 1309.0017[3], 1501.04637[4] 1407.3773[5]
$\mathrm{H}+\mathrm{j}$	$d\sigma$ @ NNLO QCD (g only) and finite-quark-mass effects @ LO QCD and LO EW	$d\sigma$ @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW	1408.5325[6],1504.07922[7],1505.03893[8]
$\mathrm{H}+2\mathrm{j}$	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(VBF) @ NLO EW $d\sigma$(gg) @ NLO QCD (infinite-m_t limit) and finite-quark-mass effects @ LO QCD	$d\sigma$(VBF) @ NNLO QCD + NLO EW $d\sigma$(gg) @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW	1506.02660[9]
$\mathrm{H}+\mathrm{V}$	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW σ_{tot}(gg) @ NLO QCD (infinite-m_t limit)	with $\mathrm{H} \to \mathrm{b\bar{b}}$ @ same accuracy $d\sigma$(gg) @ NLO QCD with full m_t/m_b dependence	1501.07226[10]
tH and $\bar{\mathrm{t}}$H	$d\sigma$(stable top) @ LO QCD	$d\sigma$(top decays) @ NLO QCD and NLO EW	
$\mathrm{t\bar{t}H}$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD and NLO EW	1407.0823[11]
$\mathrm{gg} \to \mathrm{HH}$	$d\sigma$ @ NLO QCD (leading m_t dependence) $d\sigma$ @ NNLO QCD (infinite-m_t limit)	$d\sigma$ @ NLO QCD with full m_t/m_b dependence	1408.2422[12, 13]

Process	State of the Art	Desired	Delivered
$\mathrm{t\bar{t}}$	σ_{tot}(stable tops) @ NNLO QCD dσ(top decays) @ NLO QCD dσ(stable tops) @ NLO EW	dσ(top decays) @ NNLO QCD + NLO EW	1411.3007[15]
$\mathrm{t\bar{t} + j(j)}$	dσ(NWA top decays) @ NLO QCD	dσ(NWA top decays) @ NNLO QCD + NLO EW	
$\mathrm{t\bar{t} + Z}$	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW	
single-top	dσ(NWA top decays) @ NLO QCD	dσ(NWA top decays) @ NNLO QCD + NLO EW	1404.7116[16]
dijet	dσ @ NNLO QCD (g only) dσ @ NLO EW (weak)	dσ @ NNLO QCD + NLO EW	1412.3427[17], 15xx.xxxx
3j	dσ @ NLO QCD	dσ @ NNLO QCD + NLO EW	
$\gamma + \mathrm{j}$	dσ @ NLO QCD dσ @ NLO EW	dσ @ NNLO QCD + NLO EW	



Process	State of the Art	Desired	Delivered
V	dσ(lept. V decay) @ NNLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNNLO QCD and @ NNLO QCD+EW NNLO+PS	1407.2940[18]
V + j(j)	dσ(lept. V decay) @ NLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNLO QCD + NLO EW	1504.02131[10]
VV$'$	dσ(V decays) @ NLO QCD dσ(on-shell V decays) @ NLO EW	dσ(decaying off-shell V) @ NNLO QCD + NLO EW	1309.7000[19], 1405.2219[20],1408.5243[21], 1504.01330[22]
gg $\to$ VV	dσ(V decays) @ LO QCD	dσ(V decays) @ NLO QCD	
Vγ	dσ(V decay) @ NLO QCD dσ(PA, V decay) @ NLO EW	dσ(V decay) @ NNLO QCD + NLO EW	
V$b\bar{b}$	dσ(lept. V decay) @ NLO QCD massive b	dσ(lept. V decay) @ NNLO QCD + NLO EW, massless b	
VV$'\gamma$	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	
VV$'$V$''$	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	
VV$'$ + j	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	
VV$'$ + jj	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	
$\gamma\gamma$	dσ @ NNLO QCD + NLO EW	q_T resummation at NNLL matched to NNLO	1505.03162[23]

Some more slides from Les Houches

Updating the PDF4LHC prescription

- We are working on an updated prescription, at NNLO and NLO, using information from CT14, MMHT14, NNPDF3.0, that have similar theoretical treatments/data sets
- We are currently examining two techniques for reducing the number of error PDFs needed
  - Hessian
    - META PDFs
    - MC2Hessian
  - Compression
    - CMC PDFs

Note that measurements should be compared to individual PDFs. Error PDFs derived in this way are useful when a more general definition of the PDF uncertainty is required.

Specialized PDFs can also be made available, i.e. to look at directions sensitive to Higgs physics, W mass, etc.

- See for example the presentation and discussion from PDF4LHC meeting in April
  - https://indico.cern.ch/event/355287/
- …and the one here last Thursday
  - https://indico.cern.ch/event/399439/
- Followup meeting later this month at CERN; paper in preparation

Scale determination (and uncertainty)

- We (almost universally) use a scale of $H_T/2$ for complex fixed order calculations, and the scale seems to work well, with variations a factor of 2 up and down to give uncertainties
- However, the optimal scale choice depends on kinematics and factors such as the jet size/algorithm
- **Can we understand this scale choice better for example through an implementation of the MINLO procedure in fixed order ntuples?**
  - **implementation in progress (S. Badger and D. Maitre)**
- **Can we adapt LoopSim to provide ~NNLO predictions for final states for which such calculations are not available?**
  - **implementation available for NLO ntuples (S. Badger)**
  - **how well does it work for states for which NNLO is available?**
    - **comparison with NNLO numbers from F. Petriello in progress**

Ntuple discussion

- As mentioned in the introductory talk, B+S ntuple format now universal among fixed order NLO calculations
- Want to be able to pipe Ntuples into Rivet, keeping track of correlated weight information; allows comparisons, for example Higgs+>=1 jet

New in twiki

Rivet for correlated weights

David Grellscheid and Daniel Maitre tested the feature of the new Rivet version that allows correlated weights to be taken into account correctly in Rivet analyses. This new feature allows to pipe nTuples directly into Rivet. An example implementation and the updated nTupleReader library is attached.

nTuple2Rivet program

nTupleReader library

The program can be called with

```
nTuple2Rivet RIVET_ANALYSIS_NAME nTupleFile1.root nTupleFile2.root ....
```

and will create a RIVET_ANALYSIS_NAME.yoda file with the analysis histograms.

This only works for a new version of Rivet.

Wu Ki Tung Award for Early Career Research on QCD

- See 2015 information at

http://tigger.uic.edu/~varelas/tung_award/

- 2014 winner: Stefan Hoeche
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