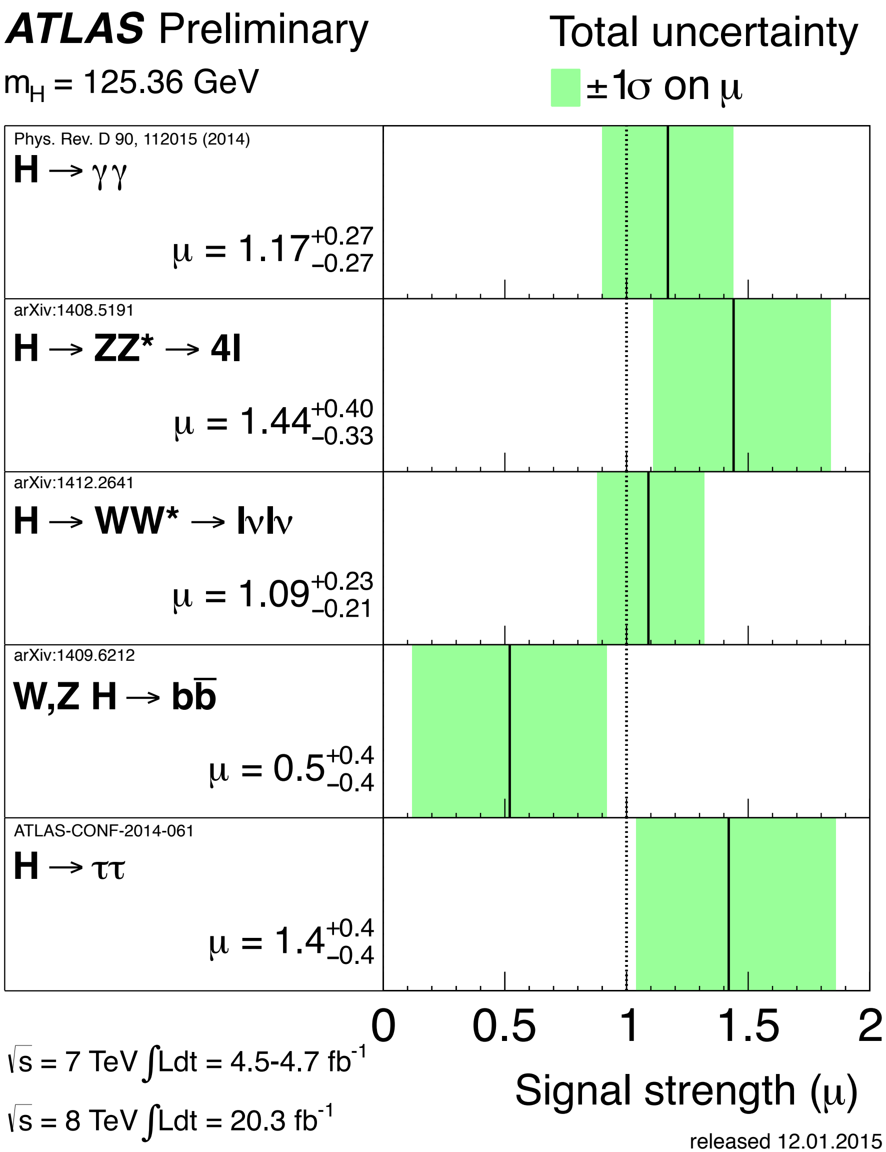
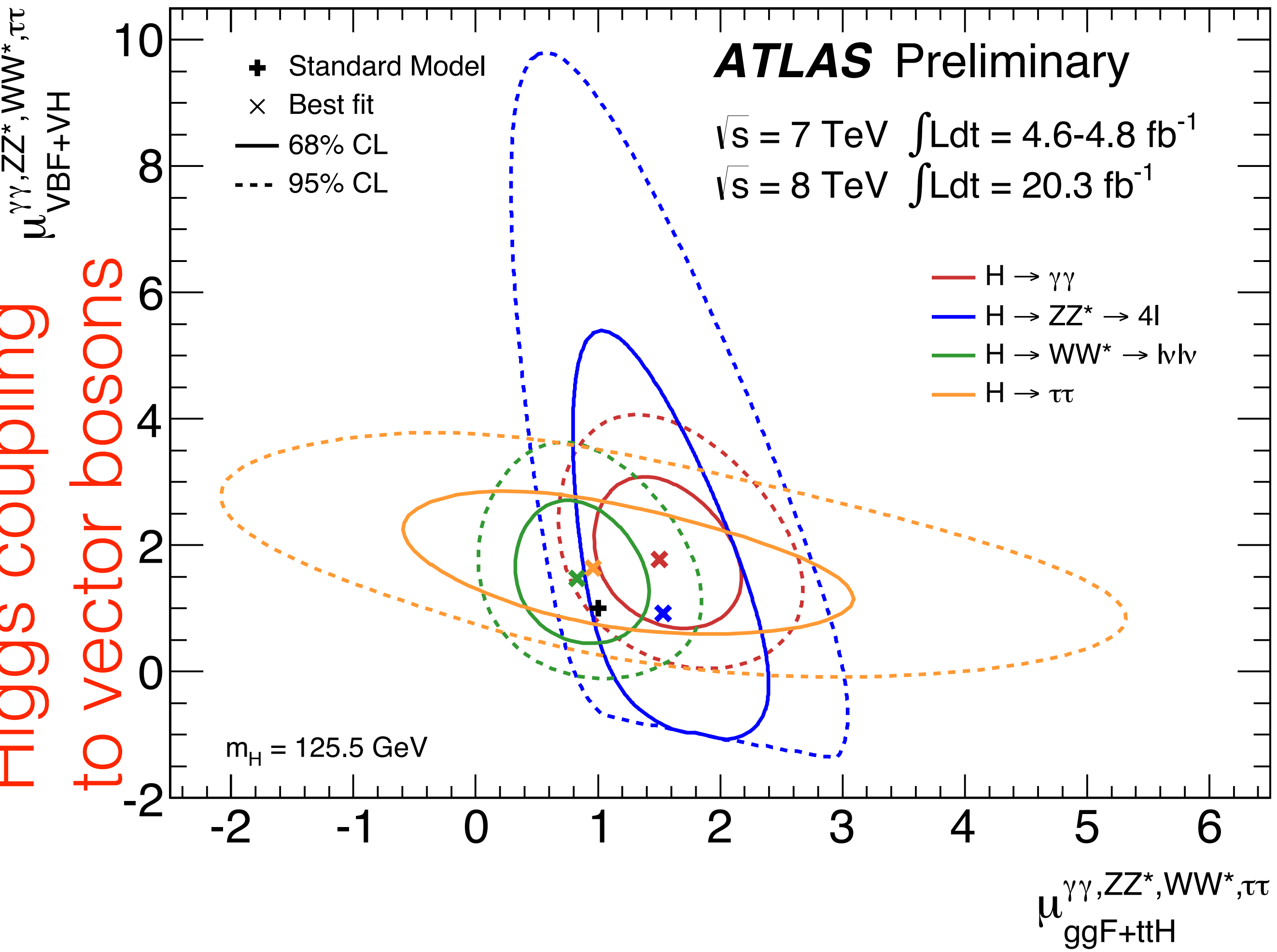
Searches for new physics at ATLAS using pair production of Higgs bosons



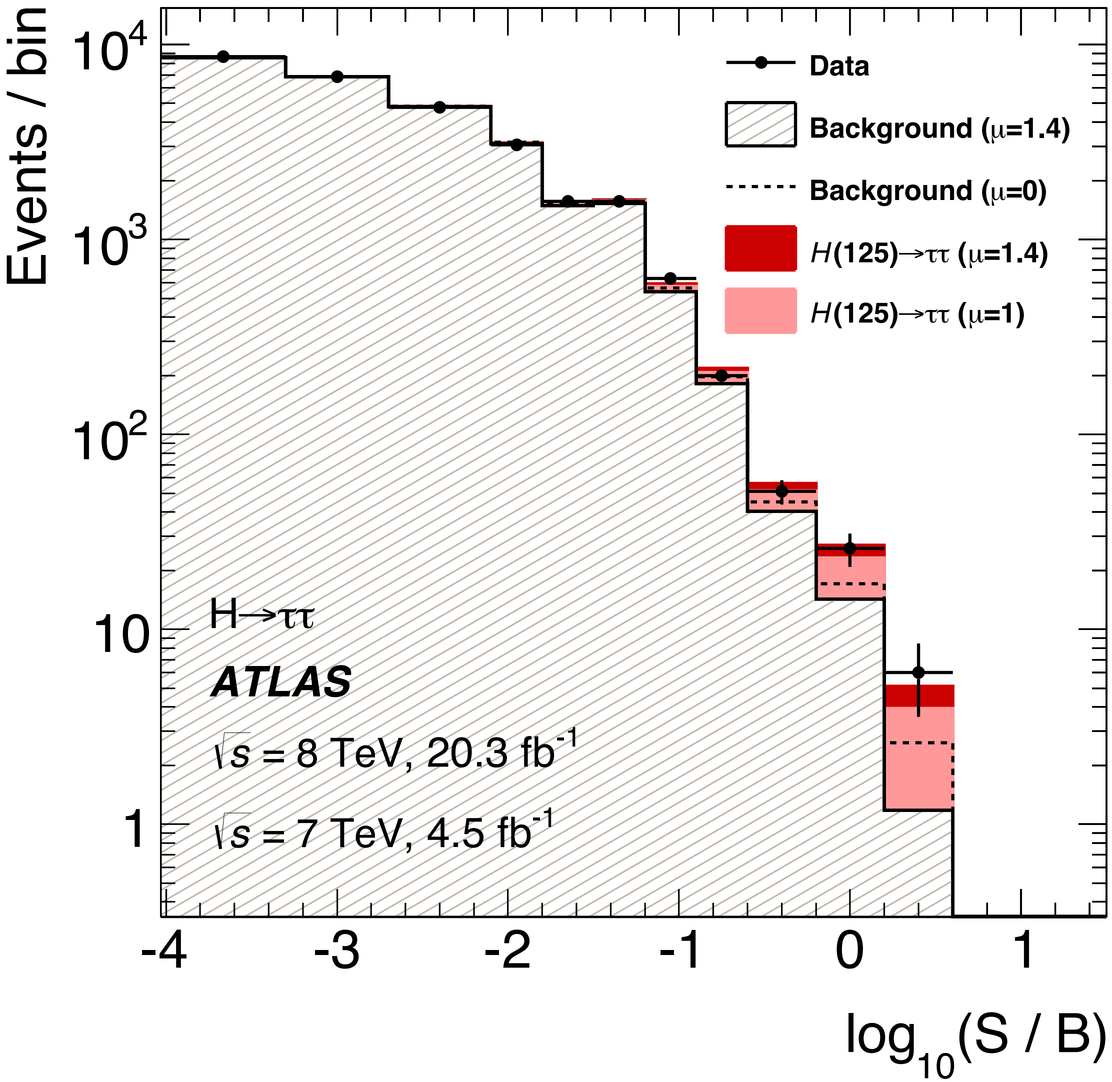
So far, no major discrepancies from SM predictions



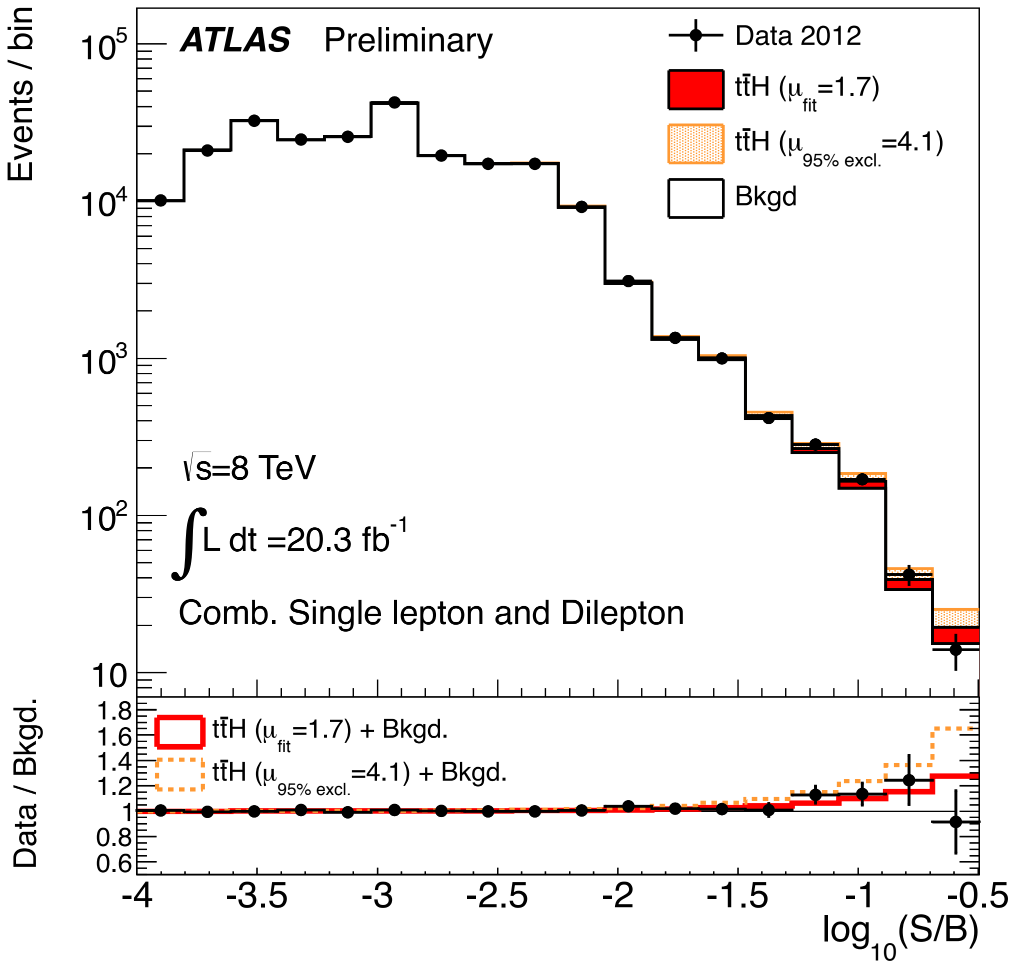
Higgs coupling to vector bosons

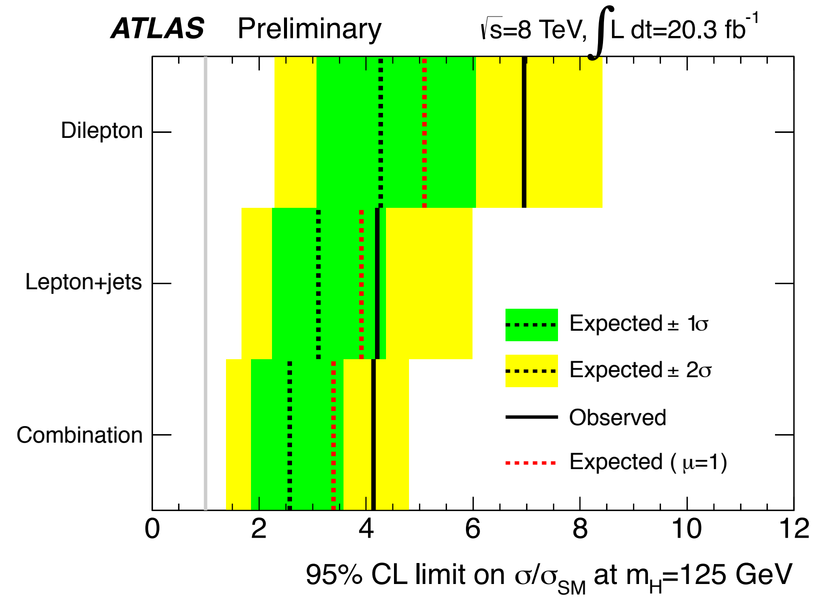
Higgs coupling to fermions

Higgs boson-like resonance really looks like the SM Higgs boson



4.5**σ** evidence for h→$\tau\tau$ decays





Limits of 4.1x SM expectation for ttH production, just from bb channel

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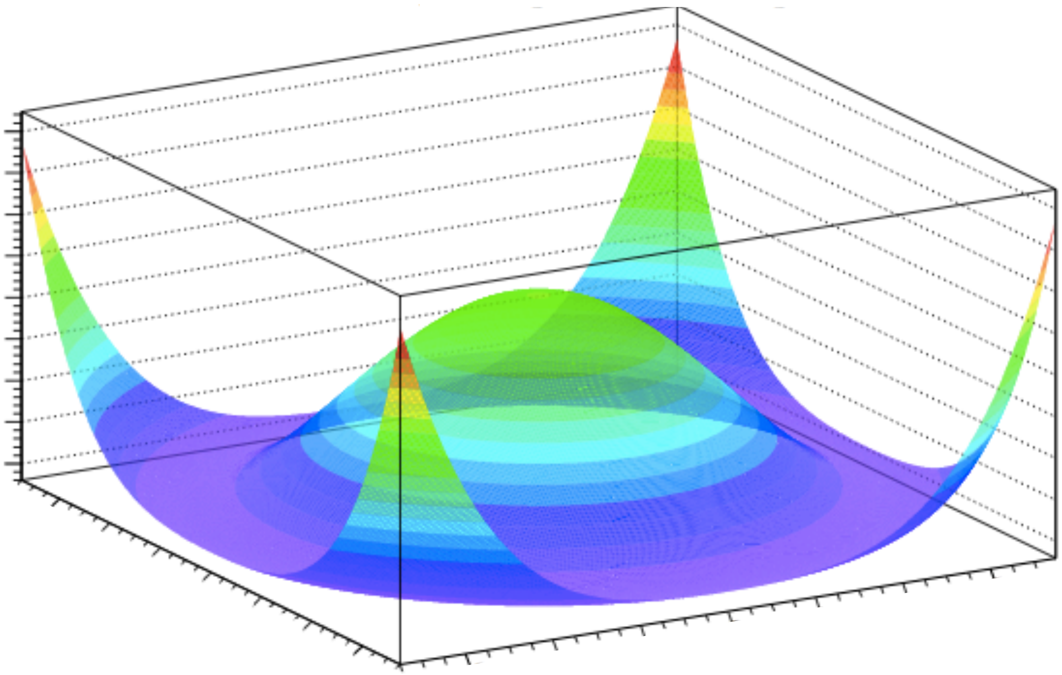
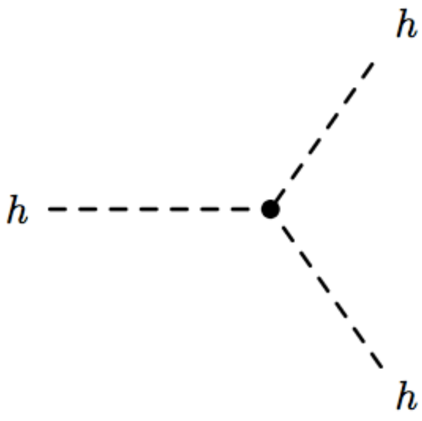
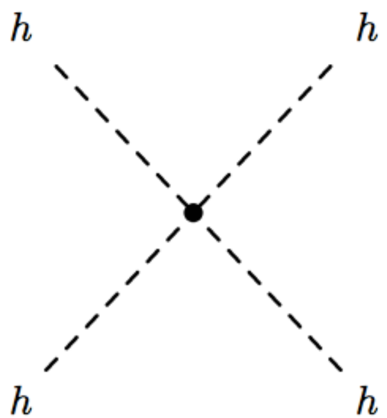
We are just being to probe and test this new particle arXiv:1212.5581 (Baglio et al), among many

Observe the Higgs boson self-coupling, crucial to testing if the Higgs potential is the one predicted in the SM

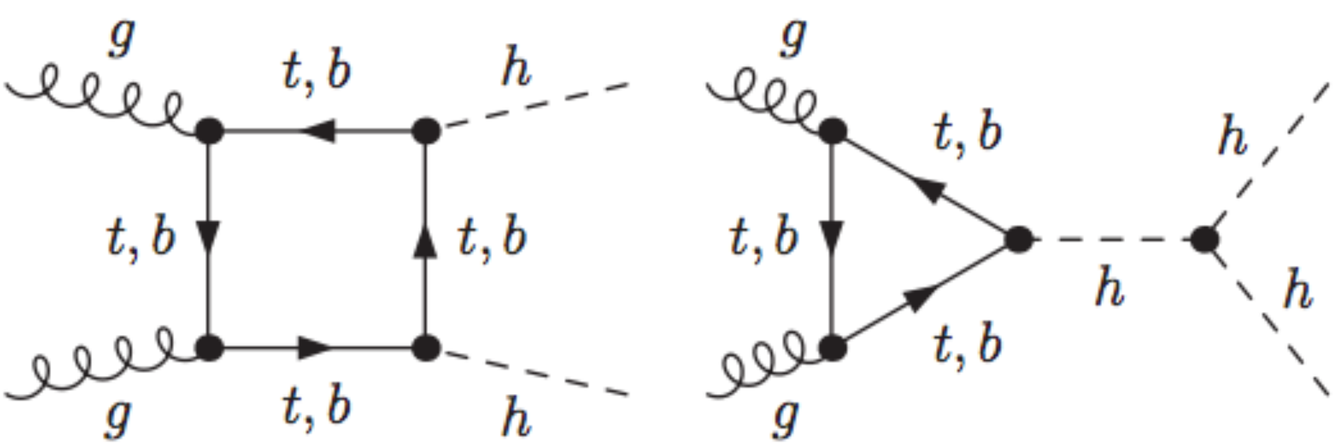






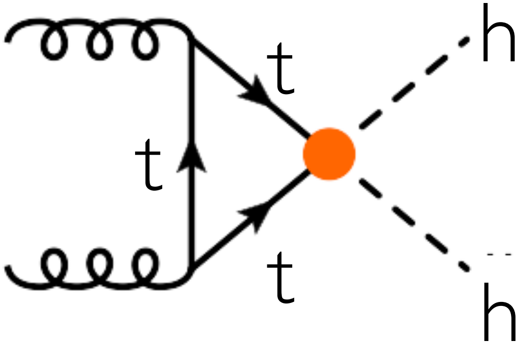
$$\mathcal{L}_V = -\lambda v^2 h^2 - \lambda v h^3 - \frac{\lambda}{4} h^4$$

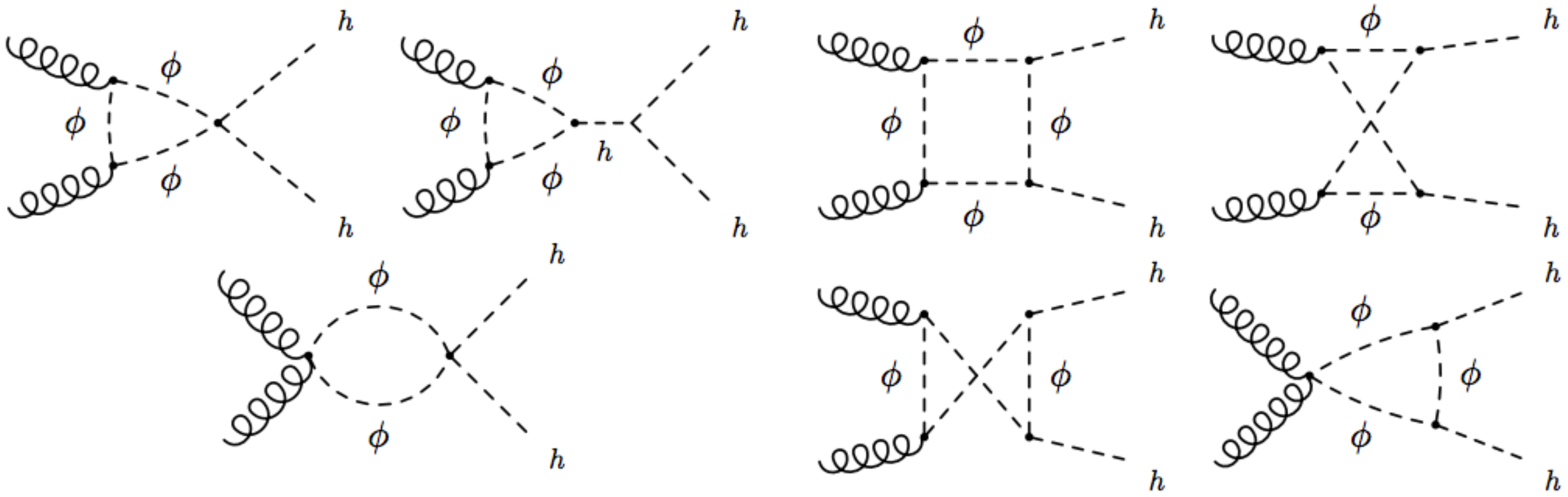
- SM hh production dominated by box diagram, not hh self-coupling, with destructive interference between the two
- Total SM hh cross section at 8 TeV ~9 fb not expected to be seen by us any time soon



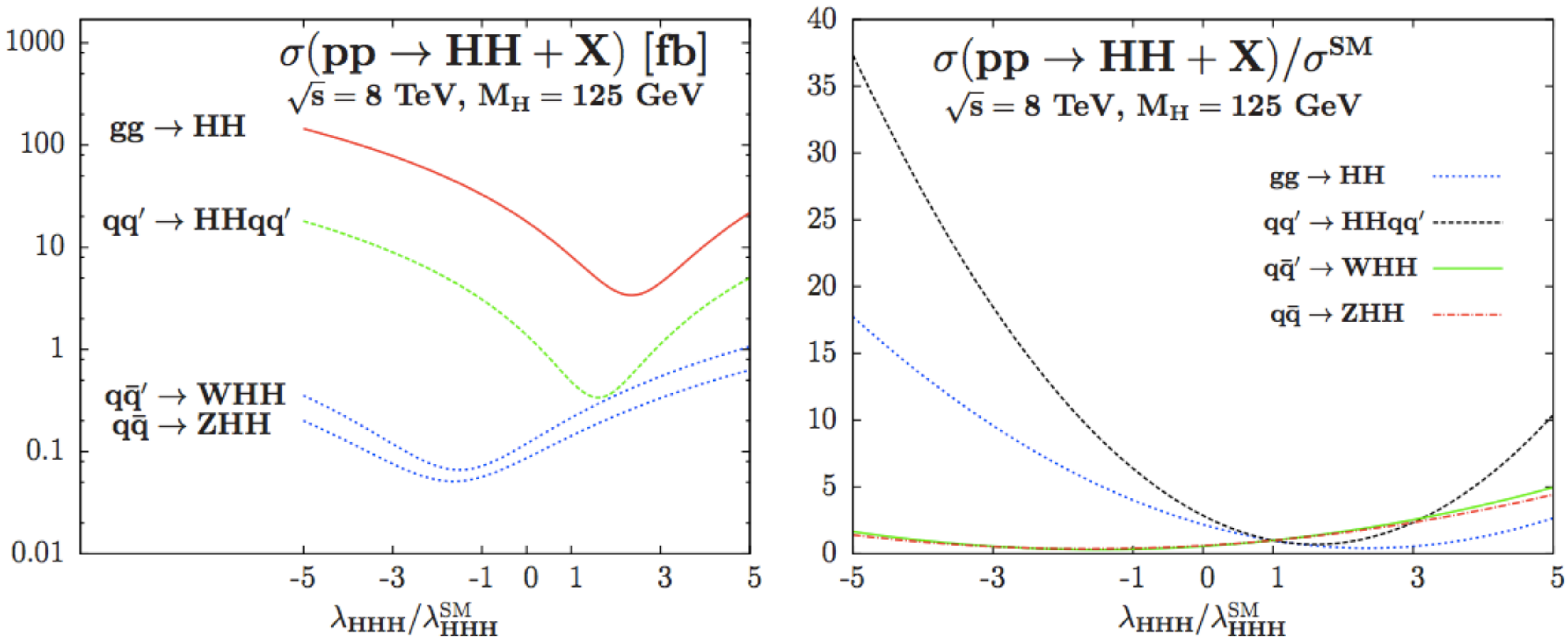
 arXiv:1205.5444 (Contino et al) 1207.4496 (Kribs and Martin), 1212.5581 (Baglio et al) among many

- Can enhance non-resonant hh production in many extensions to the SM
  - tthh interactions, light colored scalars, if Higgs boson self-coupling were altered, or if top quark had non-standard Yukawa coupling





arXiv:1212.5581 (Baglio et al)

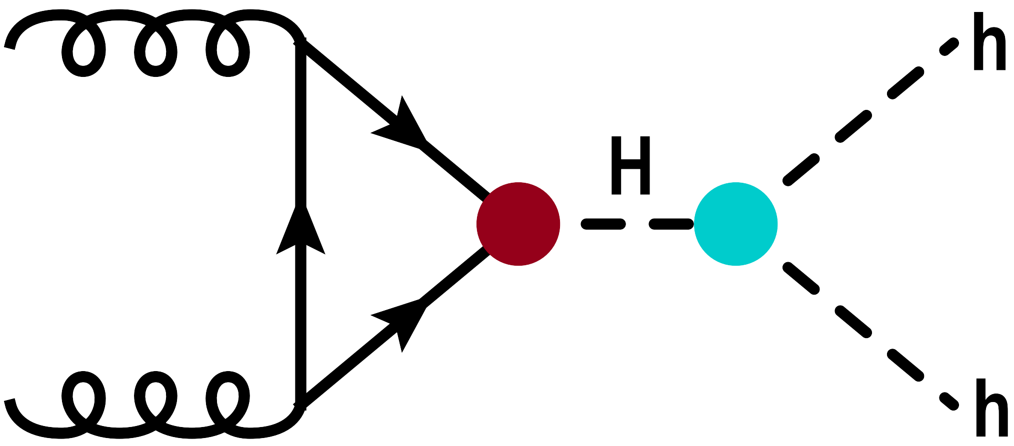


Altered self-coupling can significantly increase hh production rates

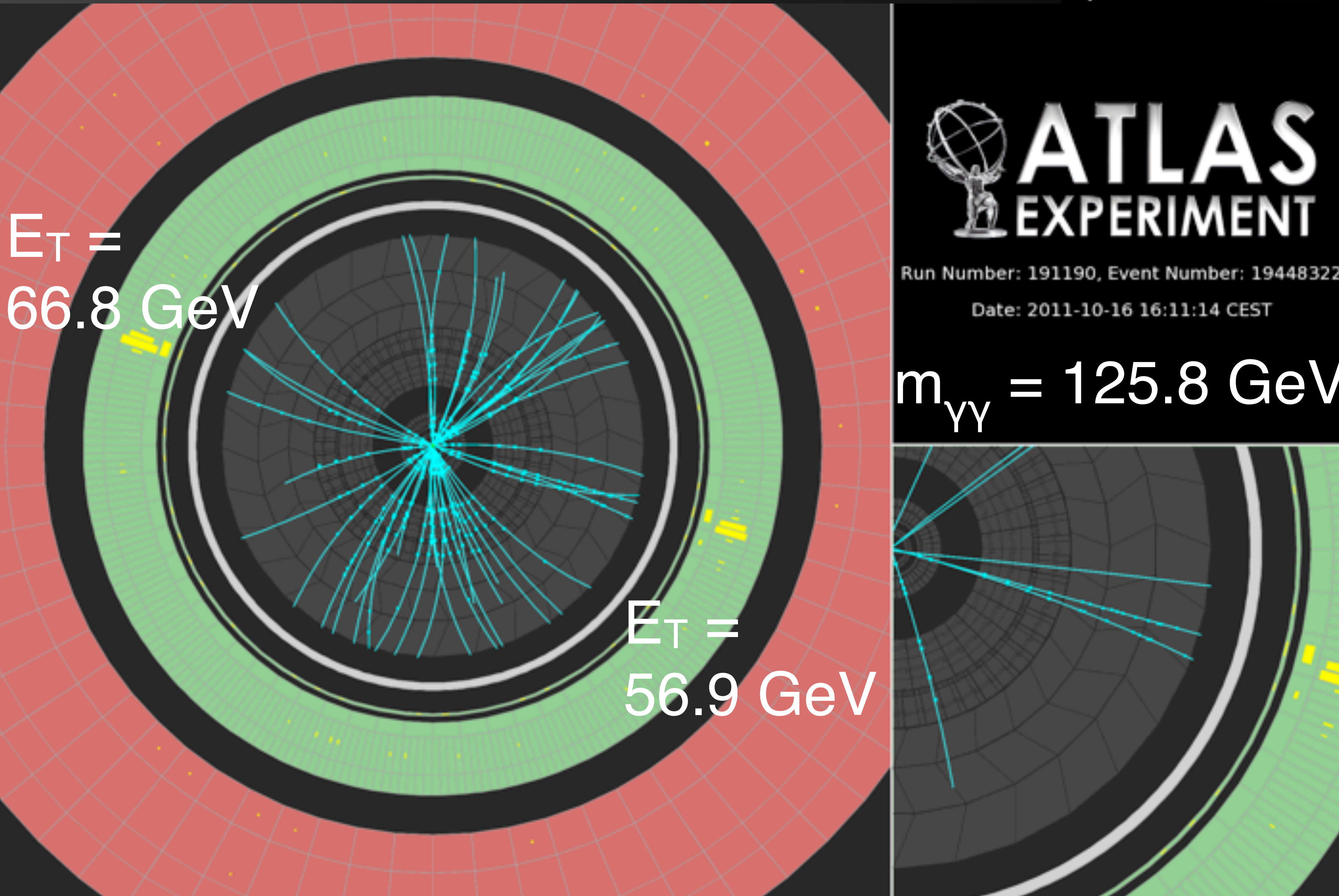
Resonant production?

arXiv:hep-ph/0009232 (Cheung), hep-ph/0503173 (Djouadi), 1210.8166 (Dolan et al), 1206.6949 (Tang), 1404.0996 (Kumar & Martin), among many

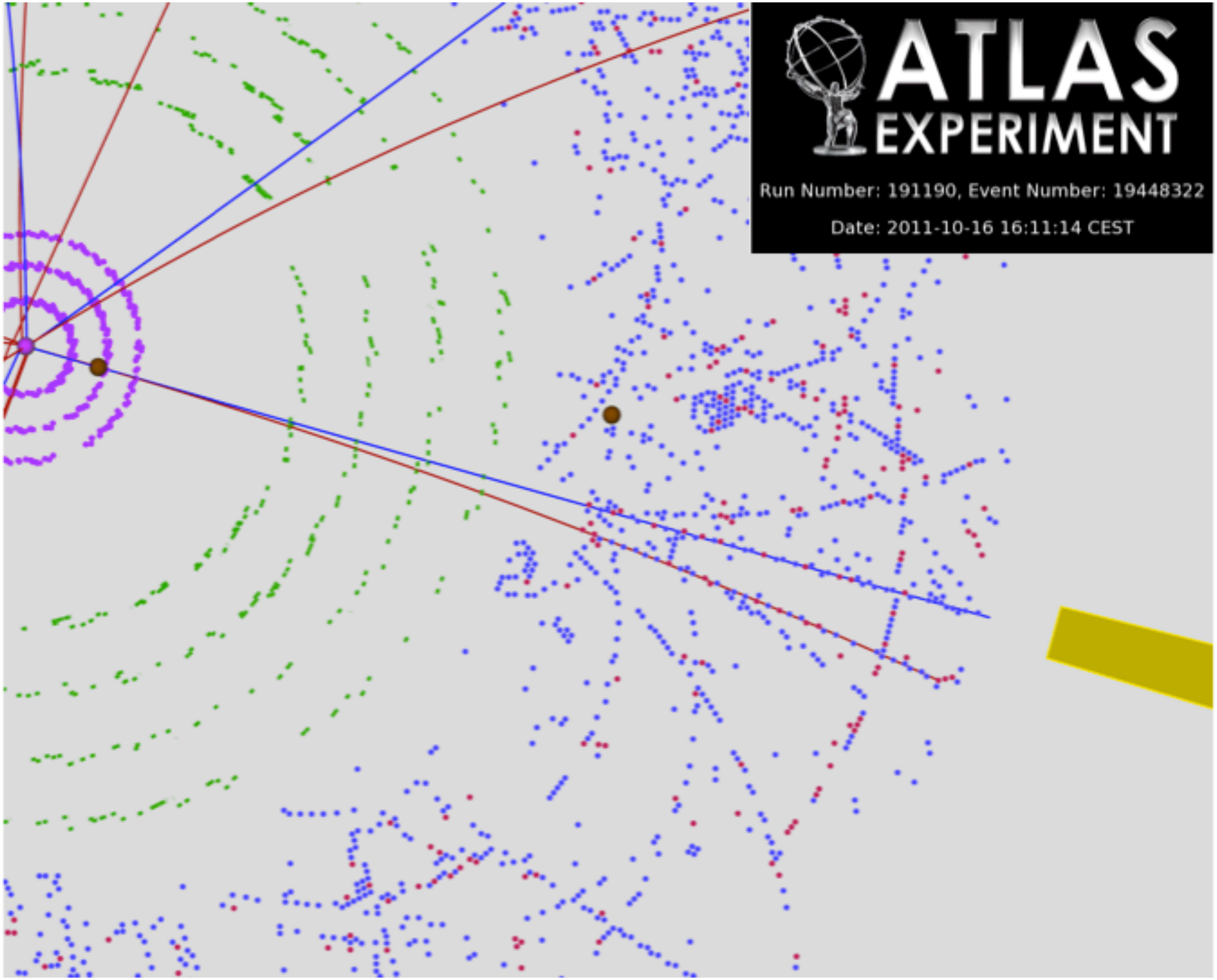
- Can enhance hh production resonantly as well
  - Two Higgs doublet models, Randall-Sundrum gravitons, radions, stoponium, ...



How to go about looking for Higgs bosons?



Zooming in on a converted photon



The calorimeters in action

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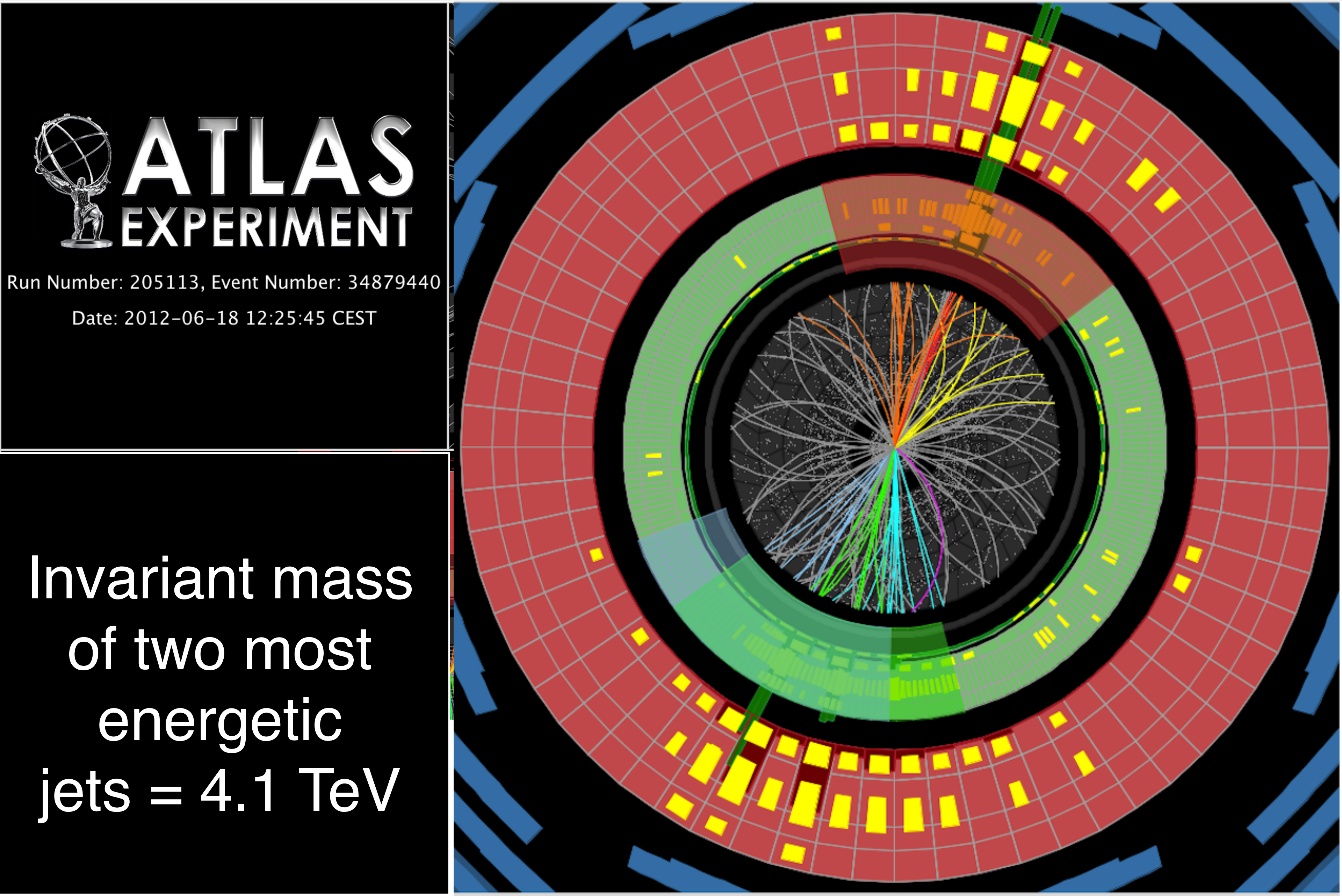
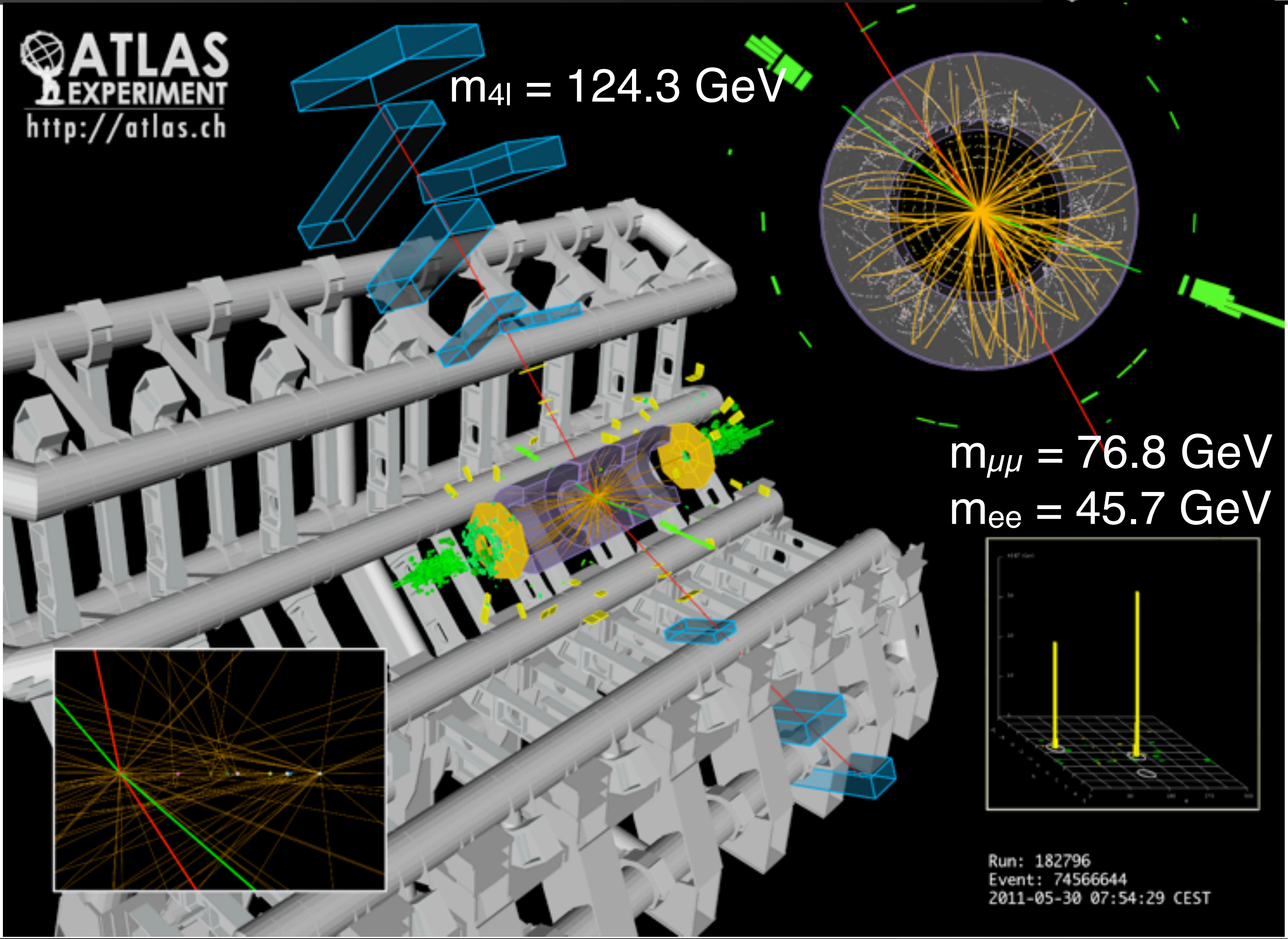
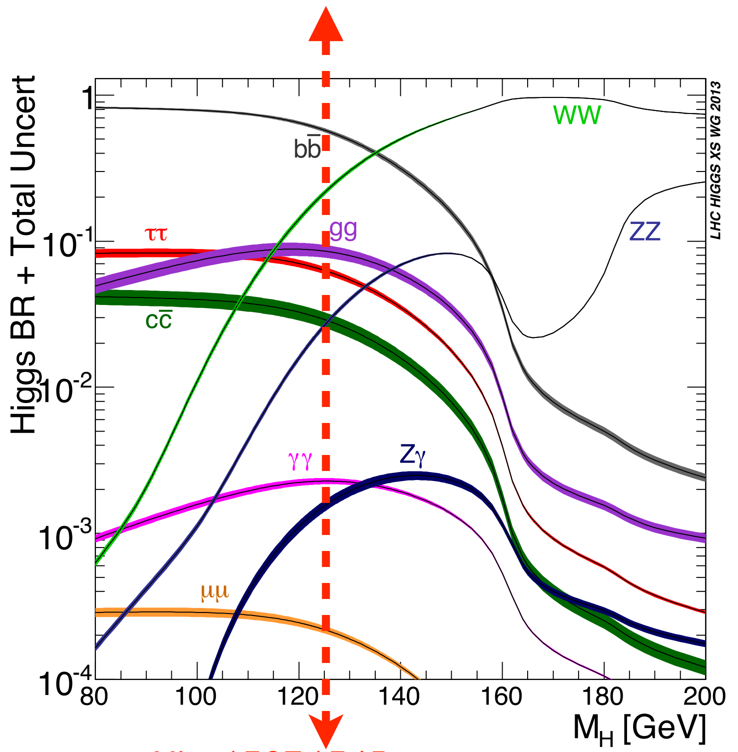


Invariant mass of two most energetic jets = 4.1 TeV

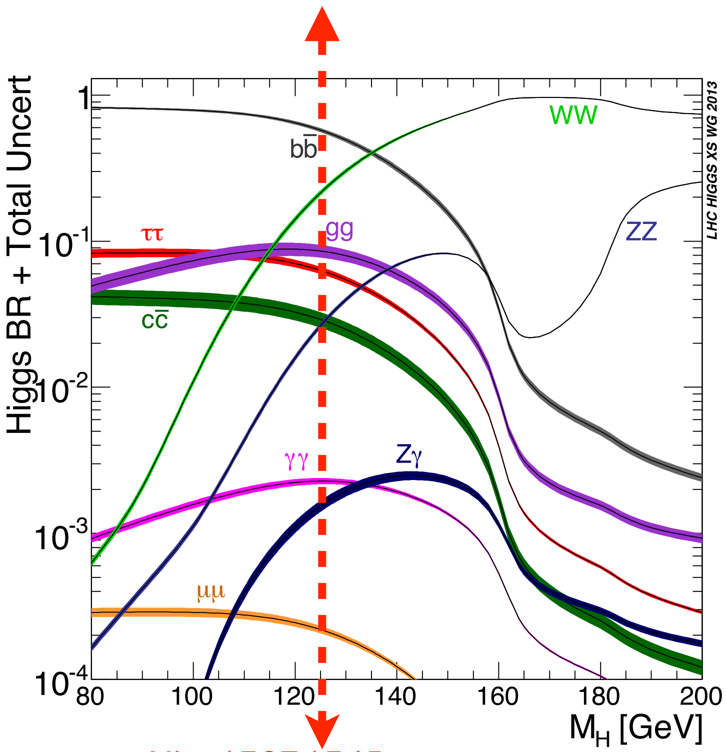

ATLAS EXPERIMENT
http://atlas.ch
m_{4l} = 124.3 GeV
$m_{\mu\mu}$ = 76.8 GeV
m_{ee} = 45.7 GeV
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

- At known $m_{H,}$ h→bb has highest Higgs BR (0.57)
- h→**γγ** has high efficiency and good mass resolution
  - Can perform full mass reconstruction
- h→$\tau\tau$ and h→WW have poor mass resolution vs **γγ**
- h→ZZ few events after require leptonic decays
- Sensitive to lower mass resonances and also the region testing hhh vertex



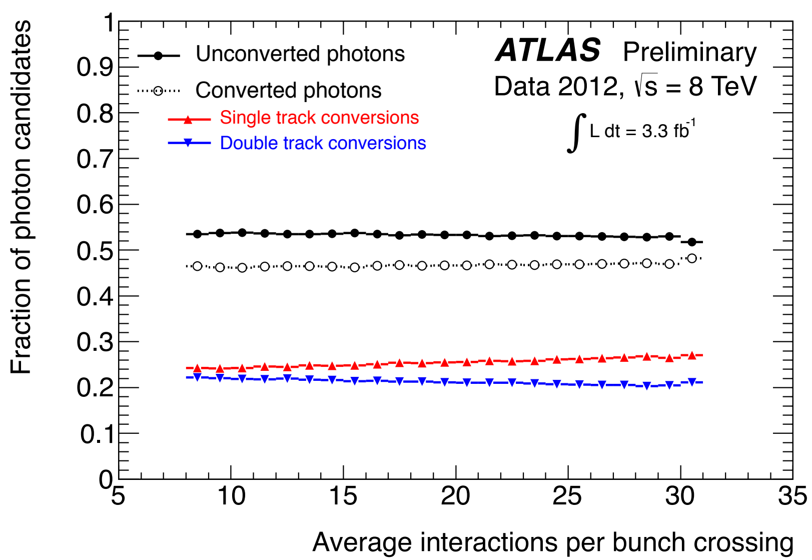
arXiv: 1307.1345

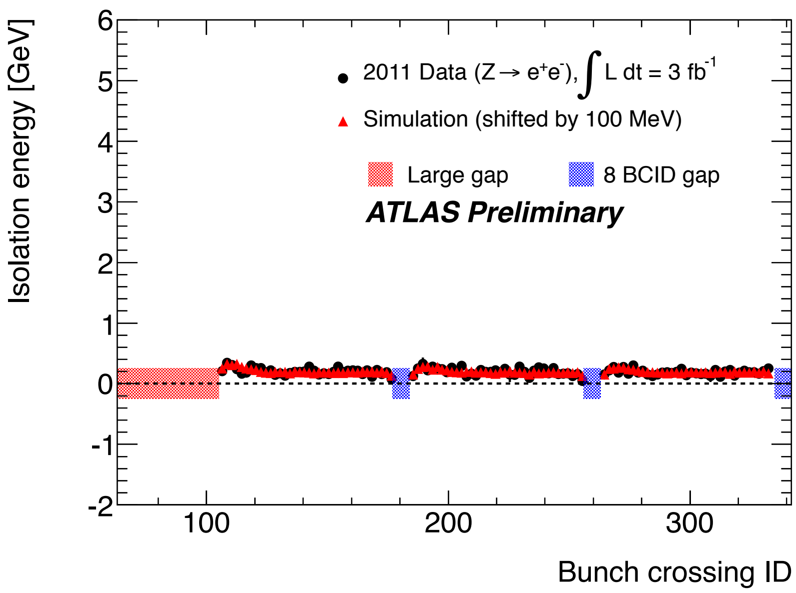
- Start with common ATLAS h→γγ selection
    - Loose diphoton trigger nearly 100% efficient for offline cuts
    - $E_T > 0.35(0.25) m_{\gamma\gamma}$ for leading (subleading) photon
    - $|\eta| < 2.37$ excluding $1.37 < |\eta| < 1.56$



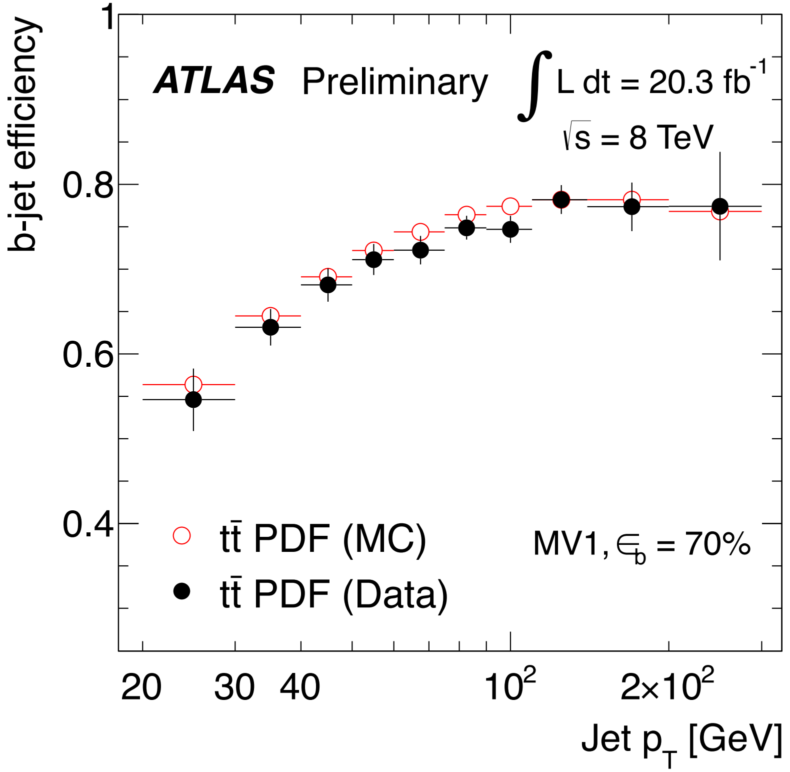
arXiv: 1307.1345

- Use "tight" photon ID. Can have unconverted, 1-track converted or 2-track converted photons, all isolated
  - Σp_T (tracks with pT > 1 GeV) in cone dR < 0.2 from photon < 2.6 GeV
  - ΣE_T (calorimeter) in cone dR < 0.4 from photon < 6 GeV, corrected for γ energy leakage and pileup





- Require two anti-k_T R=0.4 jets with $|\eta| < 2.5$
- Perform b-tagging using neural network tagger at 70% efficiency for b-jets in simulated ttbar events
  - Rejection factor 130x (4x) for light quark (charm) jets
  - Calibrate b-tag scale factors using dilepton ttbar events



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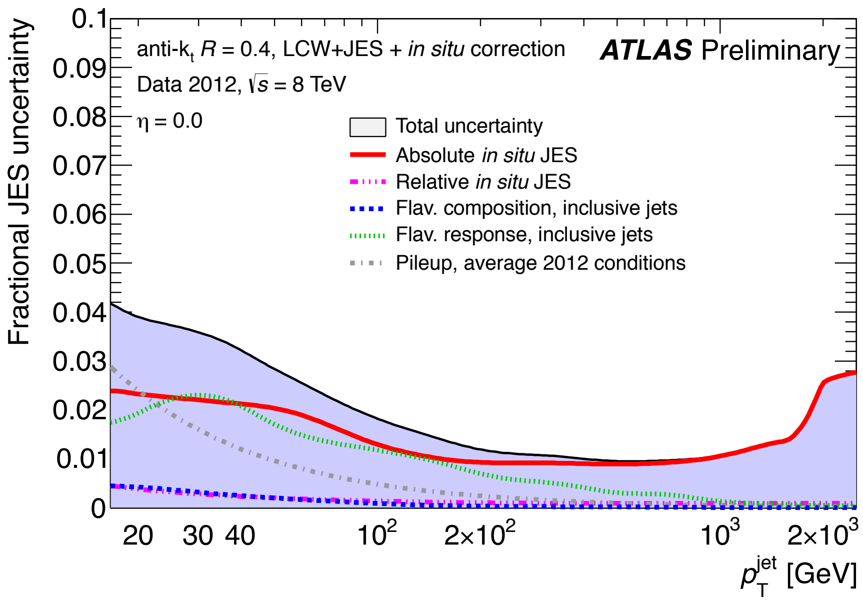
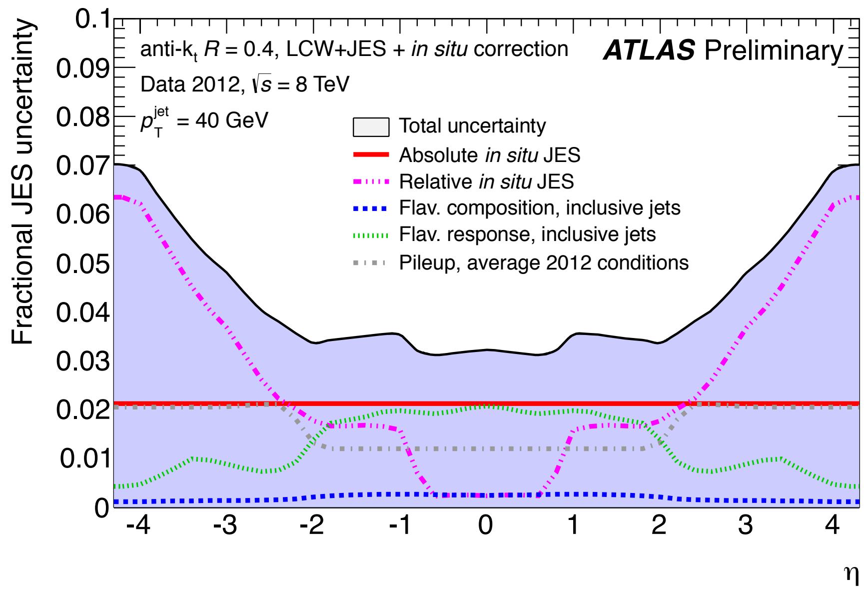
- Leading jet pT > 55 GeV, subleading pT > 35 GeV after adding in 4-vectors of any muons with pT > 4 GeV with dR < 0.4 to jet
- Require 95 < m_{bb} < 135 [GeV], 75% efficiency for hh
  - Asymmetric cut optimized in simulation and largely due to energies losses from escaping neutrinos





Strategy for hh→bbγγ

- Start by looking for non-resonant production of hh→bbγγ
  - Signal region is two photons with invariant mass consistent with m_h + two b-tagged jets with mass loosely consistent with m_h
- Cuts optimized for discovery while trying to maintain as simple a selection as possible at the same time

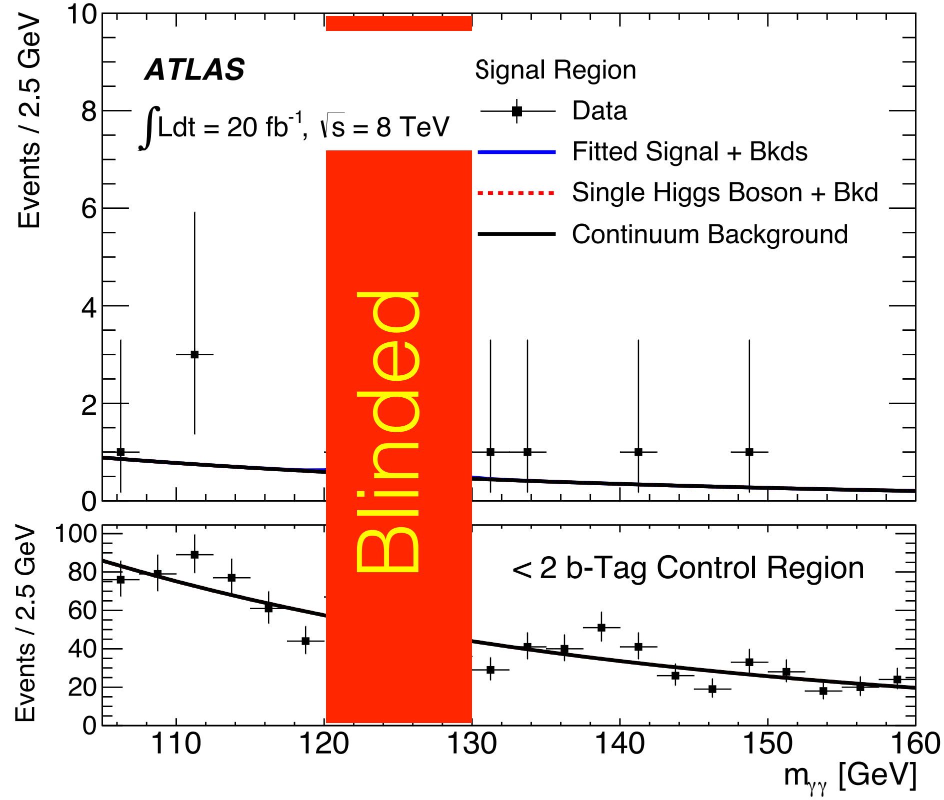
PRL Editors' Suggestion PDF HTML

Search for Higgs Boson Pair Production in the $\gamma\gamma b\bar{b}$ Final State Using pp Collision Data at $\sqrt{s} = 8$ TeV from the ATLAS Detector

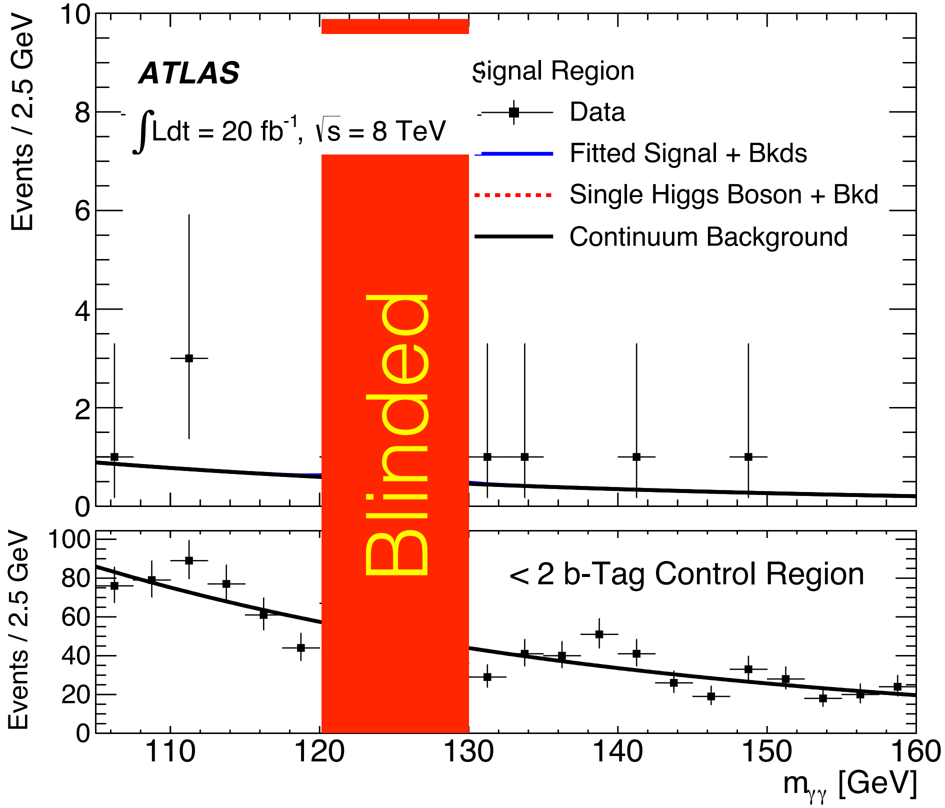
G. Aad *et al.* (ATLAS Collaboration)

Phys. Rev. Lett. **114**, 081802 (2015) – Published 26 February 2015

- All backgrounds without a Higgs boson estimated using m($\gamma\gamma$) sideband, which is fit to an exponential and extrapolated to signal region
  - Normalization comes from sidebands
  - Slope of the exponential constrained by fitting events with < 2 b-tags

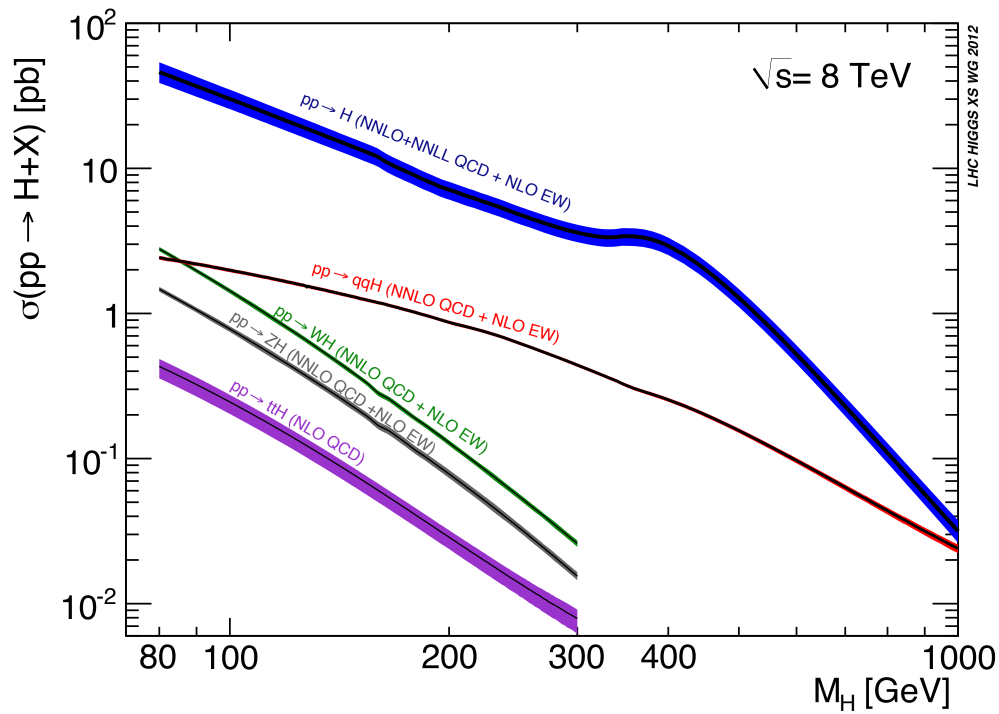


- Take advantage of good diphoton mass resolution ~1.6 GeV
- Note the normalization uncertainty of ~30-35% that cannot be avoided

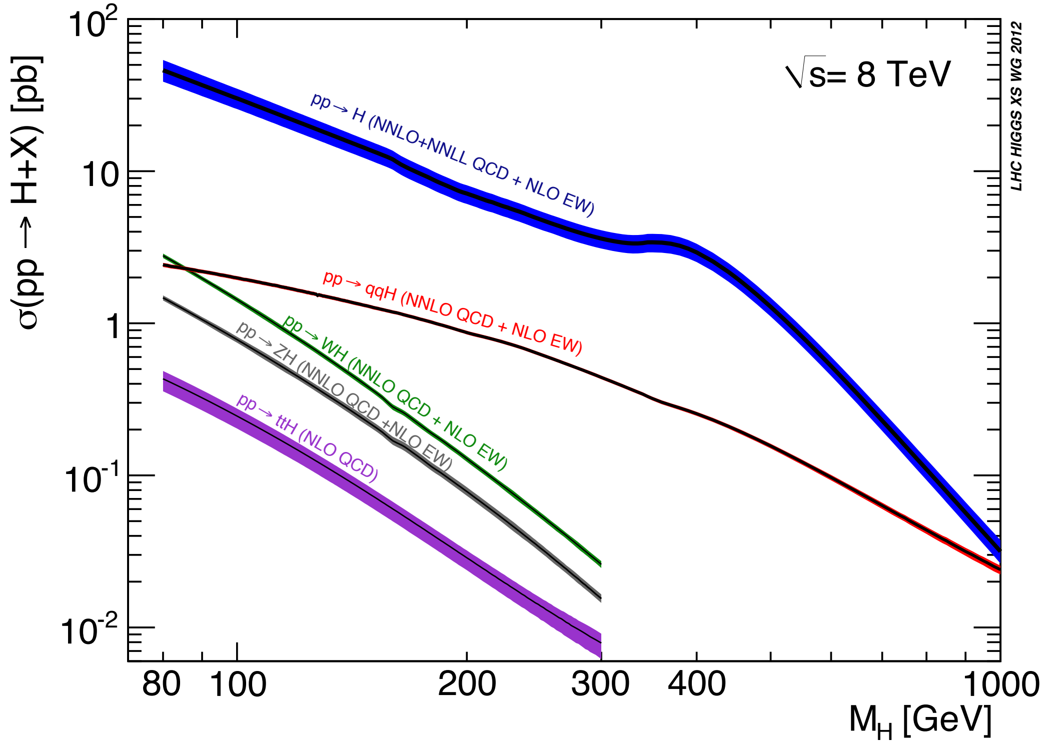


arXiv: 1307.1347
(LHC XS WG)

- Smaller backgrounds with single Higgs boson estimated from simulation
  - W/Z/tt + Higgs from Pythia8
    - WH xsec at NLO with EW corrections
    - ZH xsec at NNLO with EW corrections
    - ttH xsec at NLO



- gg and VV fusion with Powheg-Box
  - ggF xsec at NNLO+leading-log resummation and EW corrections
  - VV fusion at NLO+EW and approximate NNLO corrections
- bbH estimated to be negligible with our p_T and mass cuts



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- SM pair production of hh produced with Madgraph5+Pythia8, including interference between diagrams
- Resonant hh production modeled with a gluon-initiated spin-0 resonant state in a narrow-width approximation (NWA)
  - qq-initiated NWA signals give very similar kinematics and efficiencies
  - Radions would be in the NWA
  - Gravitons would not be in the NWA
  - Most interesting regions ($2m_h < m_H < 2m_t$) of 2HDM phase space are in the NWA

All small compared to statistical uncertainties

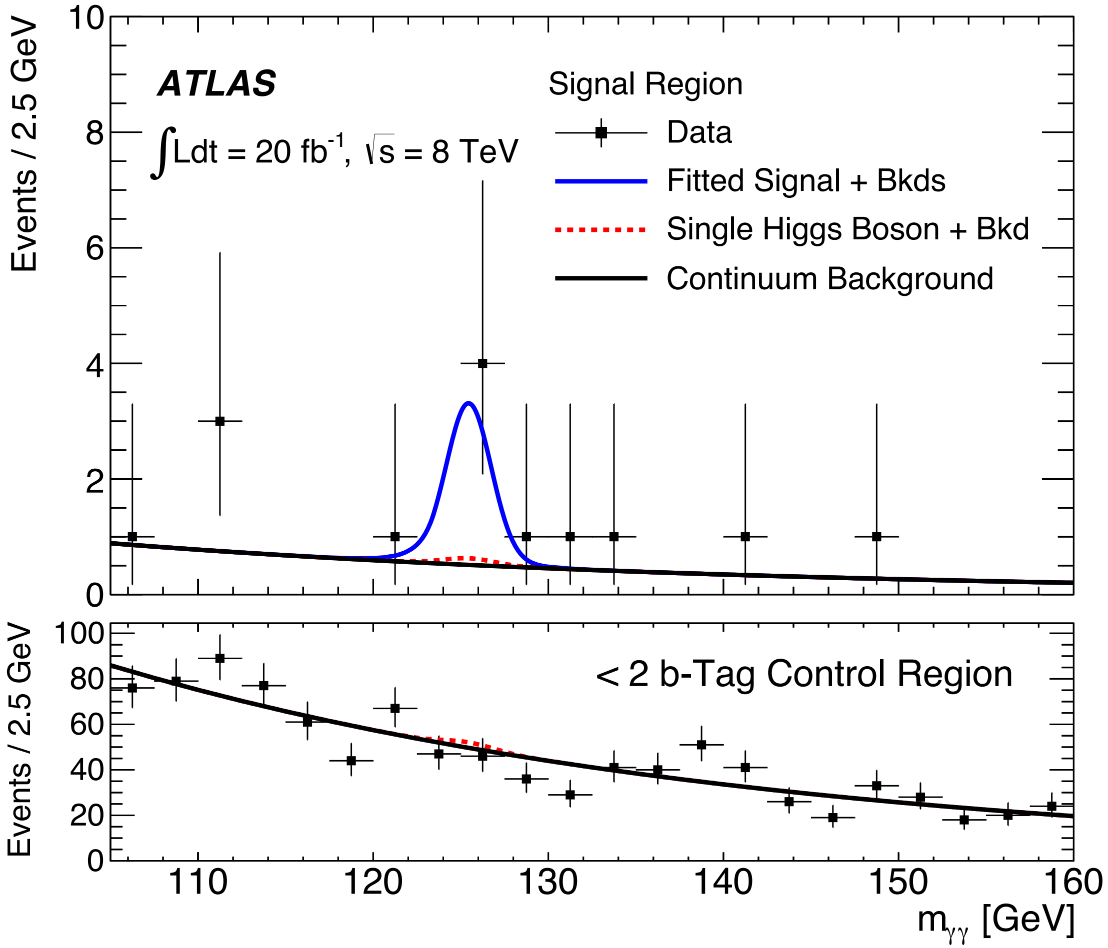
Systematic uncertainty		Non-Resonance Analysis Single h Bkgd	Non-Resonance Analysis hh Signal	Non-Resonance Analysis Continuum
Trigger [%]		0.5	0.5	–
Luminosity [%]		2.8	2.8	–
Photon	Identification [%]	2.4	2.4	–
	Isolation [%]	2	2	–
Mass	Resolution [%]	Resolution: 13	Resolution: 13	–
	Position	Value: +0.5/-0.6 GeV	Value: +0.5/-0.6 GeV	–
Shape	$m_{\gamma\gamma}$ Continuum Shape [%]	–	–	11
	$m_{\gamma\gamma b\bar{b}}$: Statistical [%]	–	–	–
	$m_{\gamma\gamma b\bar{b}}$: jj vs bb [%]	–	–	–
	$m_{\gamma\gamma b\bar{b}}$: Fit Model [%]	–	–	–
Jets	b-Tagging [%]	3.3	1.8	–
	Energy Scale [%]	6.5	1.4	–
	b-jet Energy Scale [%]	2.6	0.3	–
	Energy Resolution [%]	4.8	6.3	–
Theory	PDF+Scale [%]	8.4	–	–
	Single h+HF [%]	14	–	–

Fit sidebands to 0-tag data, 1-tag, data with non-isolated photons, and using flat function (largest=11%)

100% uncertainty on gg and VBF due to HF content

Process	Fraction of total
ggH	11%
qqH	2%
WH	1%
ZH	17%
$t\bar{t}H$	69%
Total	0.17 ± 0.04 Events

- Compares with 0.04 hh events and 1.3 events from continuum backgrounds in $\pm 2\sigma(m_{\gamma\gamma})$
- Continuum split evenly between $\gamma\gamma$jj and γjjj
  - j can be b, c or light
  - ttbar ~ 10% of the total

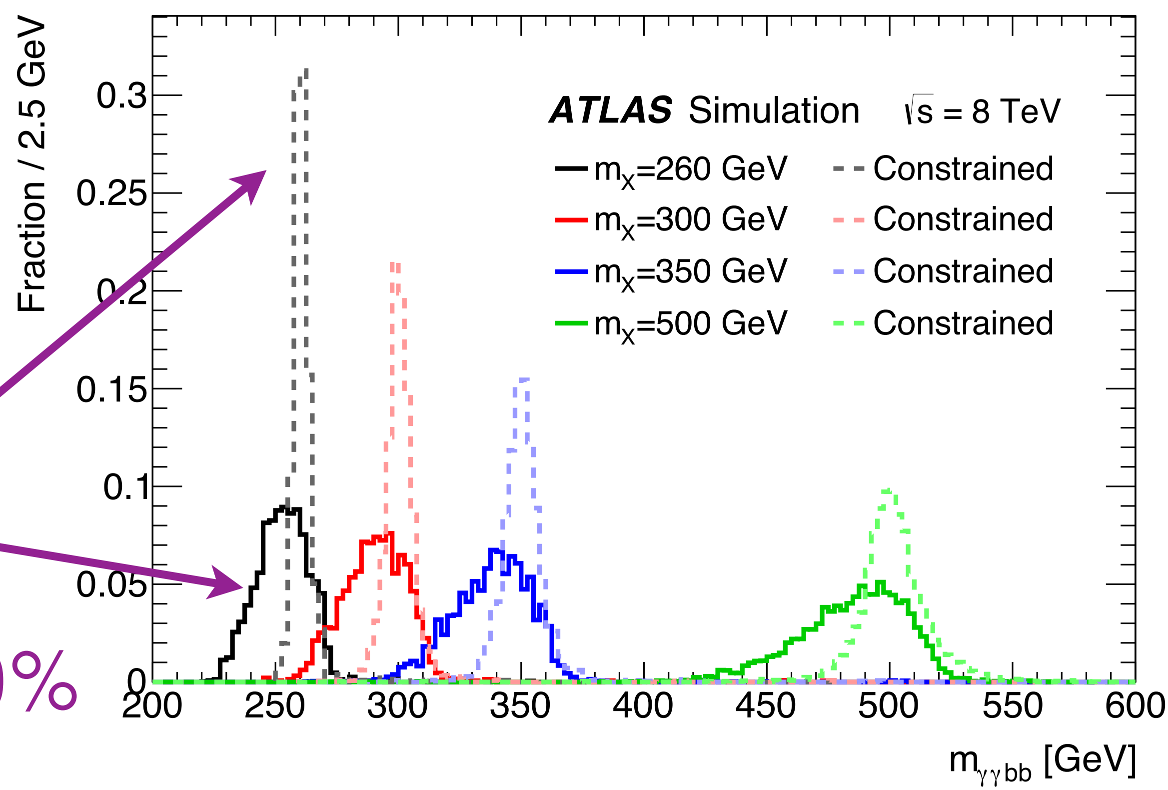


- Unbinned S+B fit
- 1.5 background events expected
- 5 events observed
  - 2.4**σ** from background-only hypothesis
- 95% CL upper limit on hh production of 2.2 pb (expected 1.0 pb)

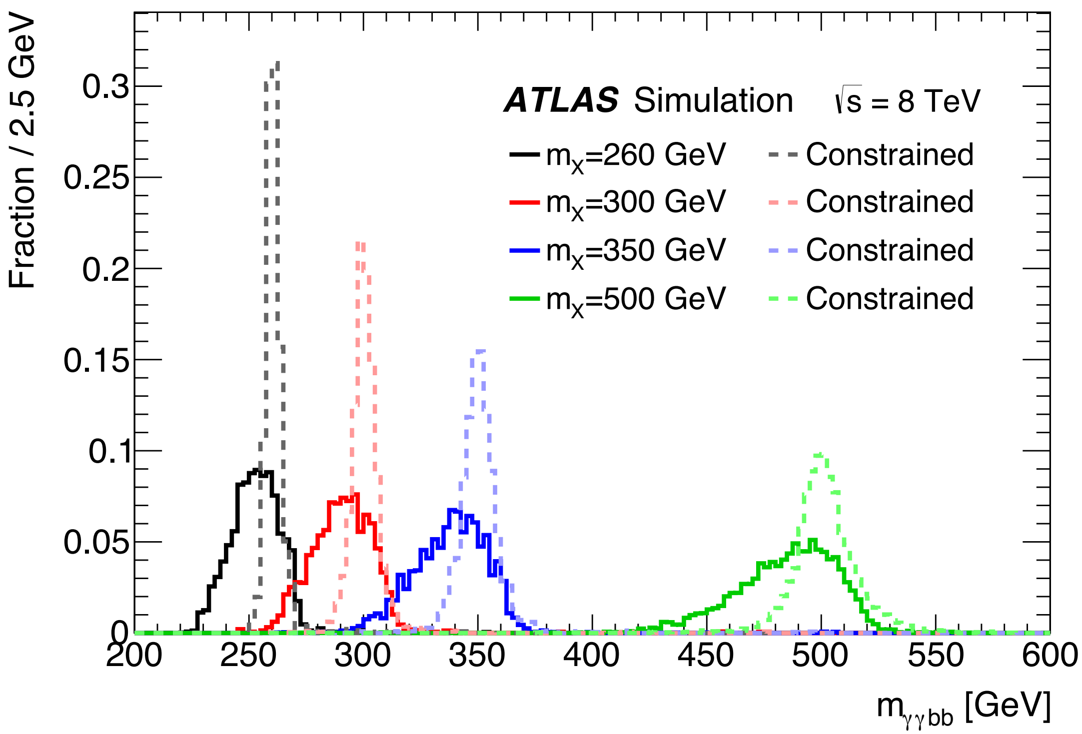
Continue with previous analysis but add additional feature of resonance in 4-object invariant mass

- Useful to improve 4-object invariant mass resolution as much as possible to reject background while maintaining signal efficiency
  - Once we select objects, require m_{bb} to give back 125 GeV (by scaling the combined bb 4-vector)

Improves mass resolution by 30-60%



- Require $m_{\gamma\gamma bb}$ to be within window around resonance mass m_H with 95% signal efficiency
  - Window varies from 17 GeV (m_X = 260 GeV) to 60 GeV (m_X = 500 GeV)



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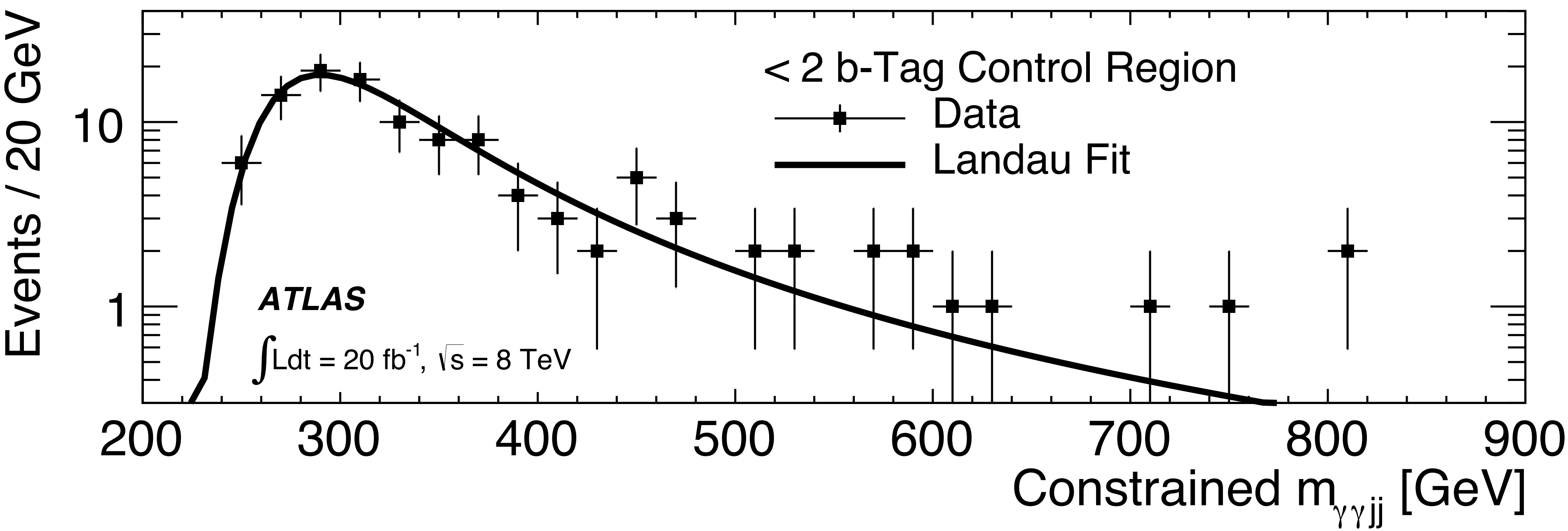
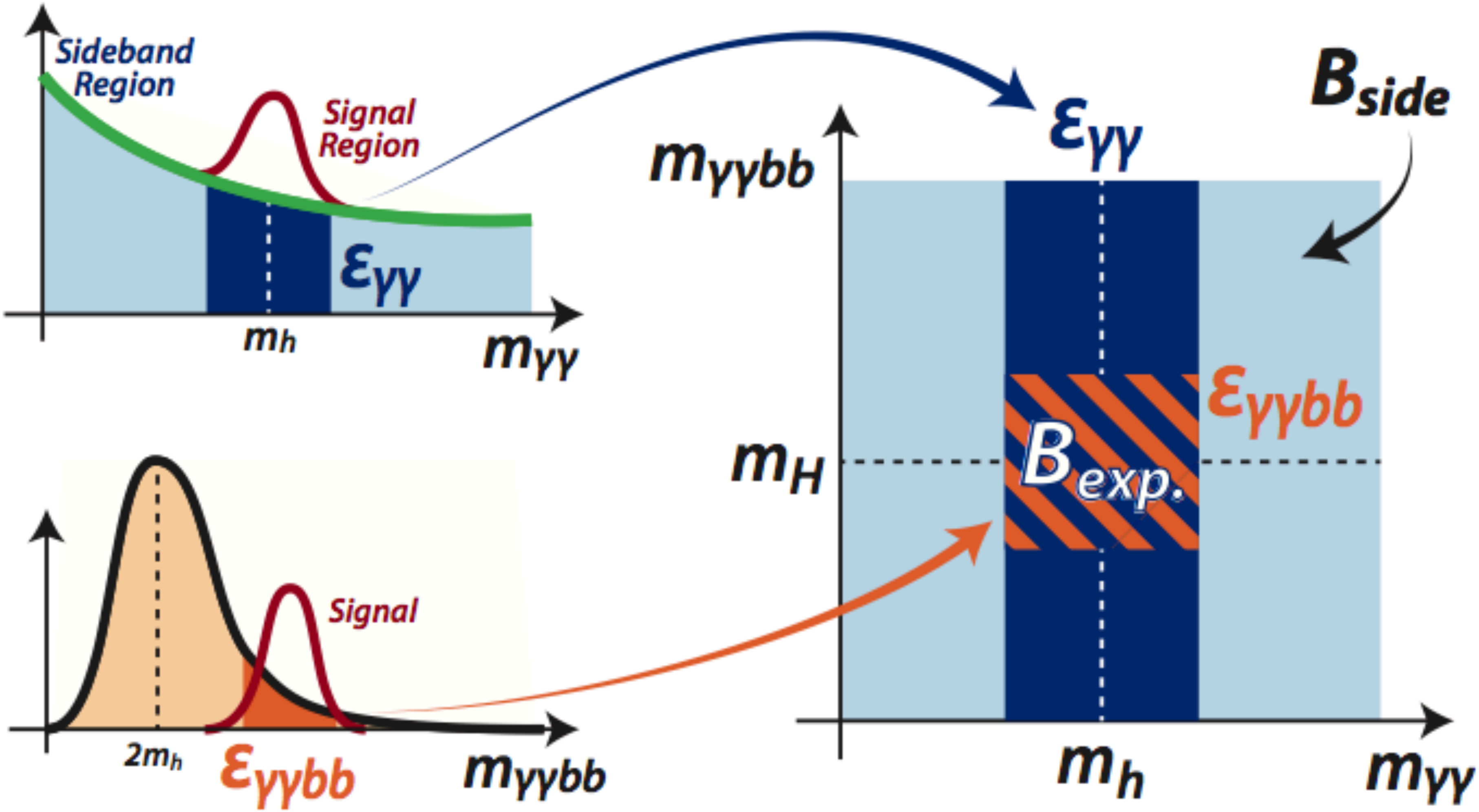
- Measure efficiency of continuum to pass this cut using events with <2 b-tags, fit with a priori Landau function
  - For m_X = low (260 GeV) and high (500 GeV) m_H, efficiency for continuum < 8%
  - For m_X = 300 GeV, 18% of continuum cut



Cannot fit sidebands after resonance selection (likely no events left)

Instead, perform cut-and-count analysis around $\pm 2\sigma$ of m_h (in $m_{\gamma\gamma}$) and in a given window of $m_{\gamma\gamma bb}$


Sideband Region
Signal Region
εγγ
mh
mγγ
Signal
2mh
εγγbb
mγγbb
Bside
mγγbb
εγγ
mH
εγγbb
Bexp.
mh
mγγ

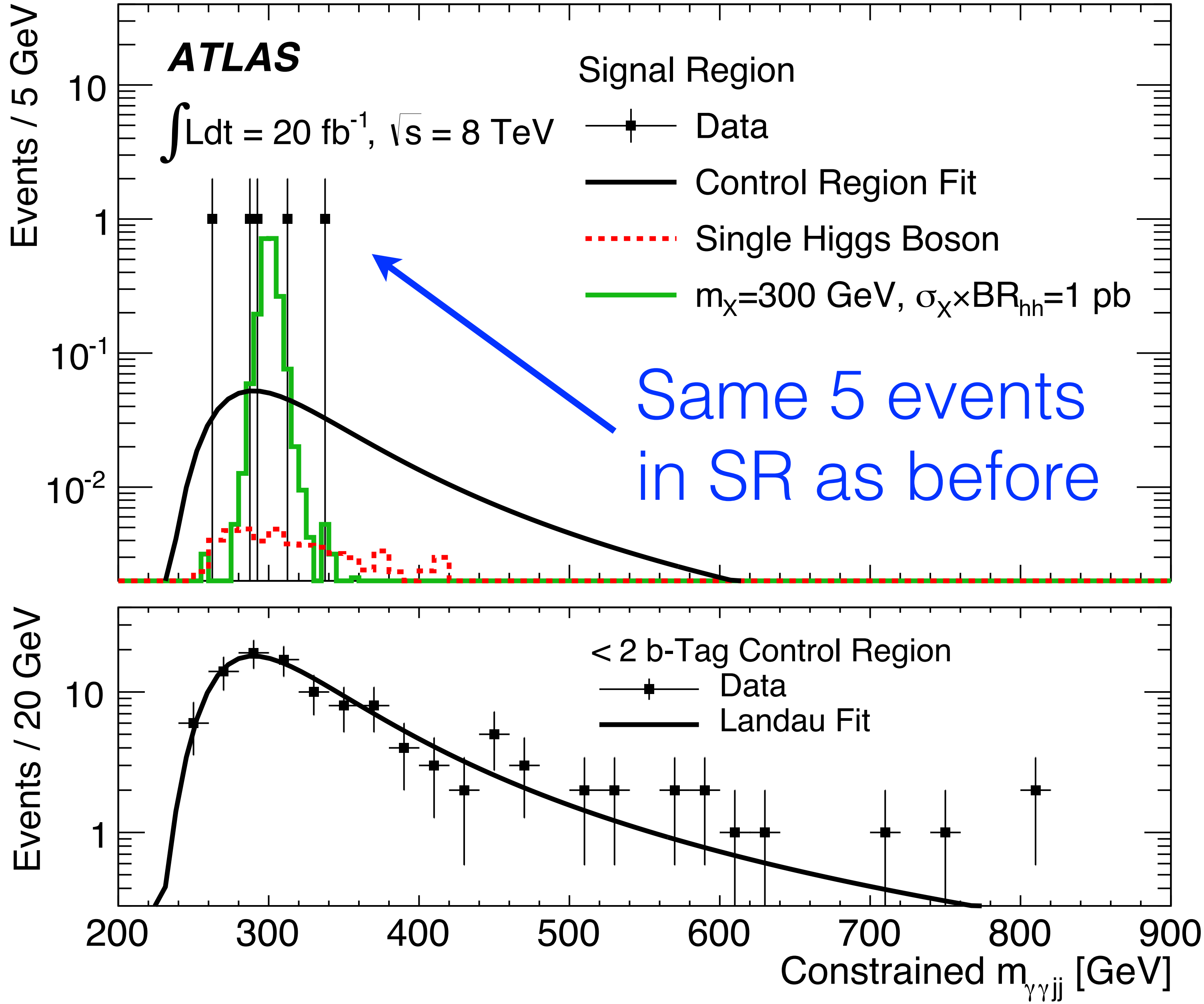
All very small compared to statistical uncertainties

Systematic uncertainty		Resonance Analysis		
		SM $h+hh$ Bkgd	$H\to hh$ Signal	Continuum
Trigger [%]		0.5		–
Luminosity [%]		2.8		–
Photon	Identification [%]	2.4		–
	Isolation [%]	2		–
Mass	Resolution [%]	Migration: 1.6		–
	Position	Migration: 1.7%		–
Shape	$m_{\gamma\gamma}$ Continuum Shape [%]	–		11
	$m_{\gamma\gamma b\bar{b}}$: Statistical [%]	–		3-18
	$m_{\gamma\gamma b\bar{b}}$: jj vs bb [%]	–		0-30
	$m_{\gamma\gamma b\bar{b}}$: Fit Model [%]	–		16-30
Jets	b-Tagging [%]	3.4	2.4	–
	Energy Scale [%]	19	3.8	–
	b-jet Energy Scale [%]	6.5	2.2	–
	Energy Resolution [%]	15	9.3	–
Theory	PDF+Scale [%]	+18/-15	–	–
	Single h+HF [%]	14	–	–

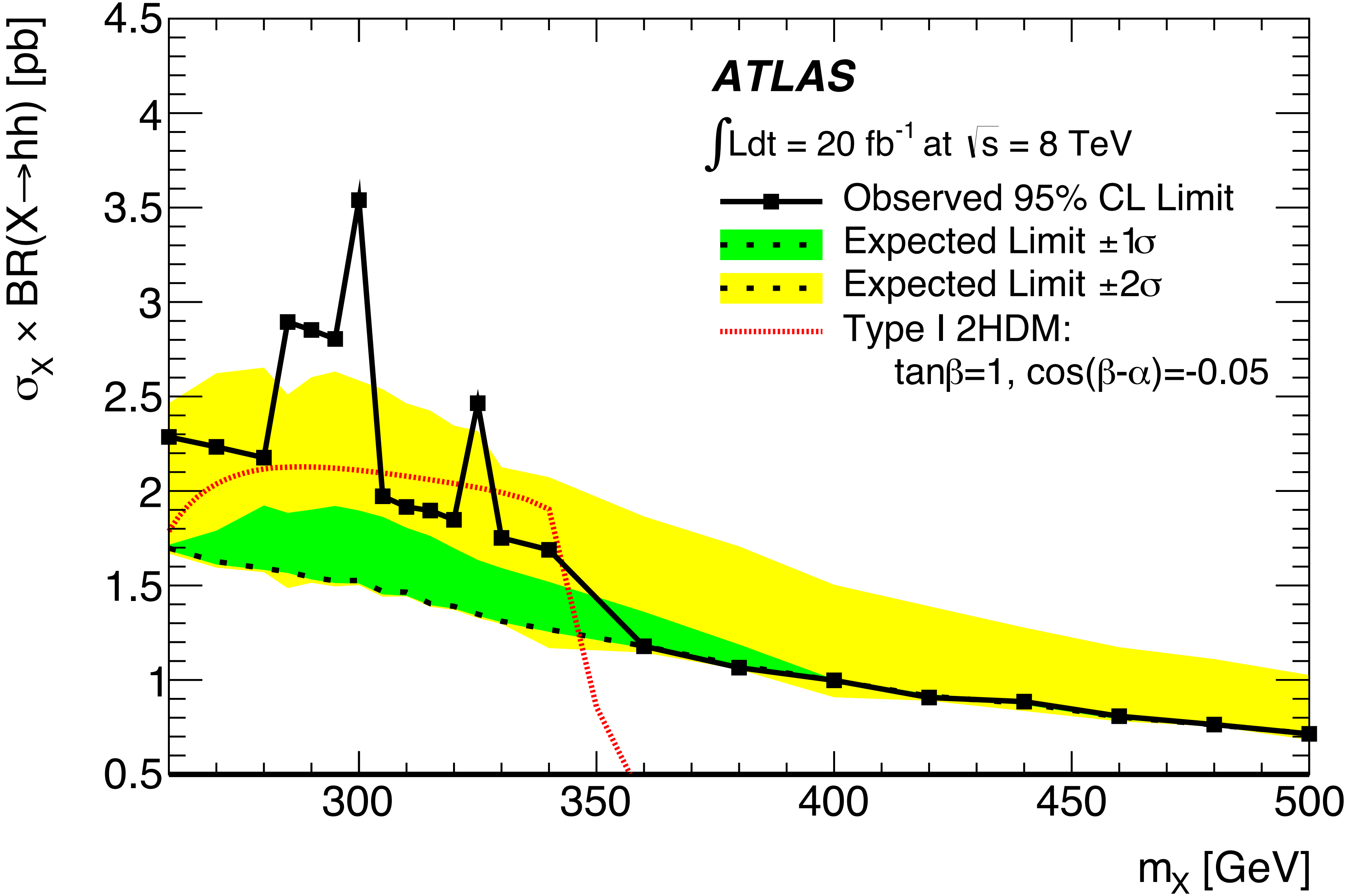
Use simulation to evaluate differences in shape between γγbb and γγjj masses

Use alternate fit functions to Landau distribution

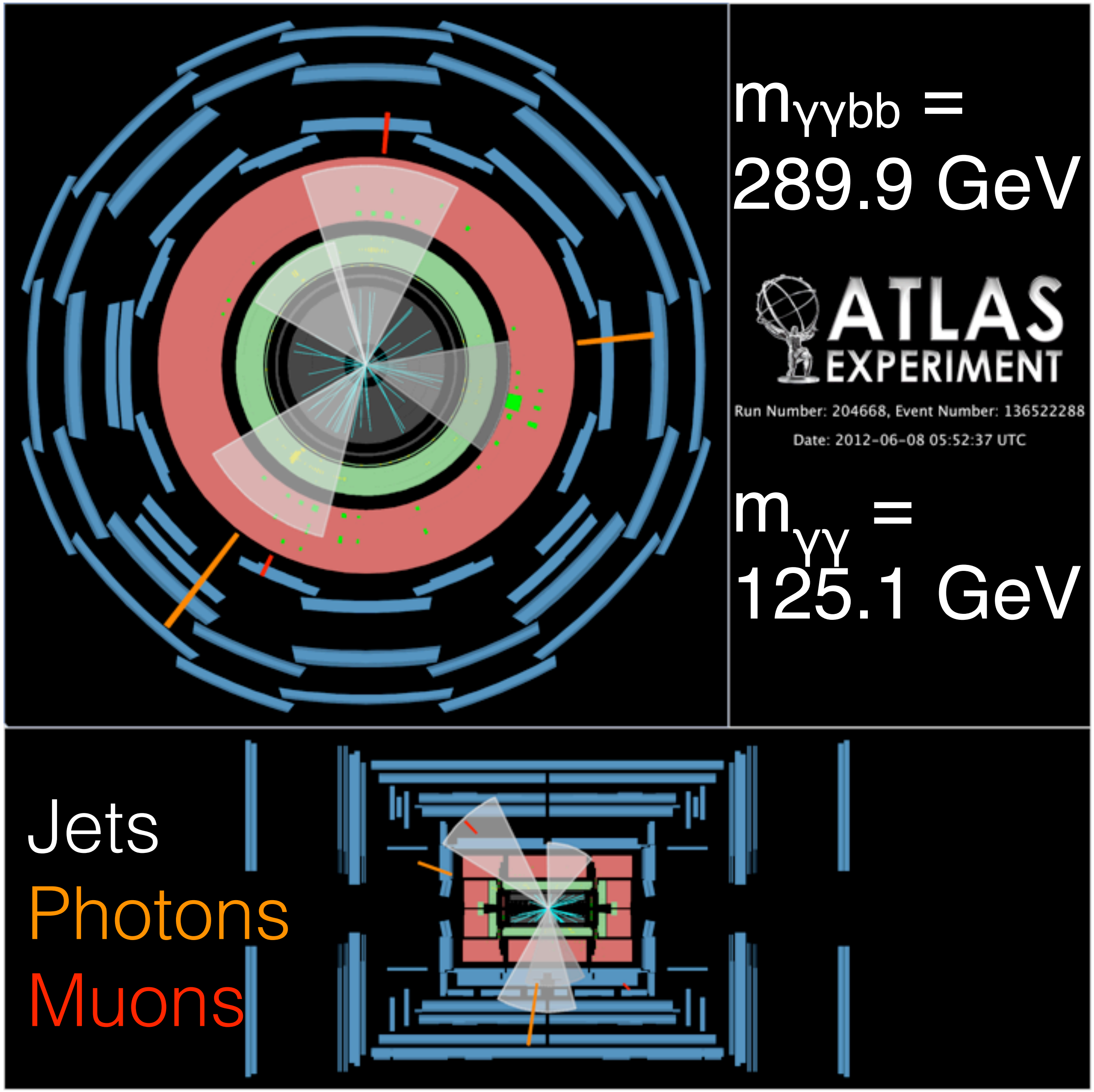
$m_{\gamma\gamma bb}$ mass in resonance search



Same 5 events in SR as before



ATLAS
∫Ldt = 20 fb⁻¹ at √s = 8 TeV
Observed 95% CL Limit
Expected Limit ±1σ
Expected Limit ±2σ
Type I 2HDM:
tanβ=1, cos(β-α)=-0.05
σX × BR(X→hh) [pb]
mX [GeV]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
300
350
400
450
500


$m_{\gamma\gamma bb}$ =
289.9 GeV
ATLAS
EXPERIMENT
Run Number: 204668, Event Number: 136522288
Date: 2012-06-08 05:52:37 UTC
$m_{\gamma\gamma}$ =
125.1 GeV
Jets
Photons
Muons

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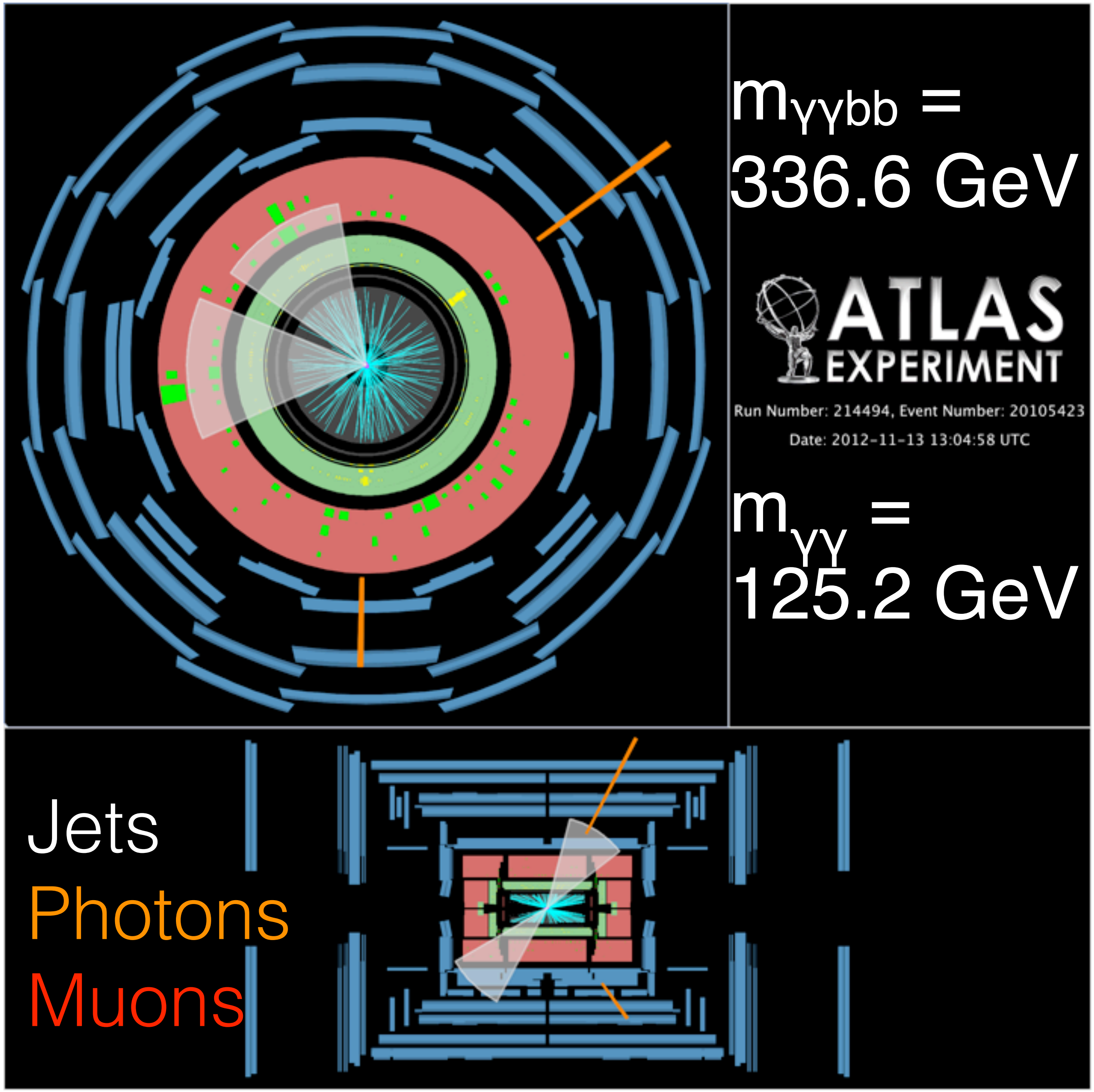

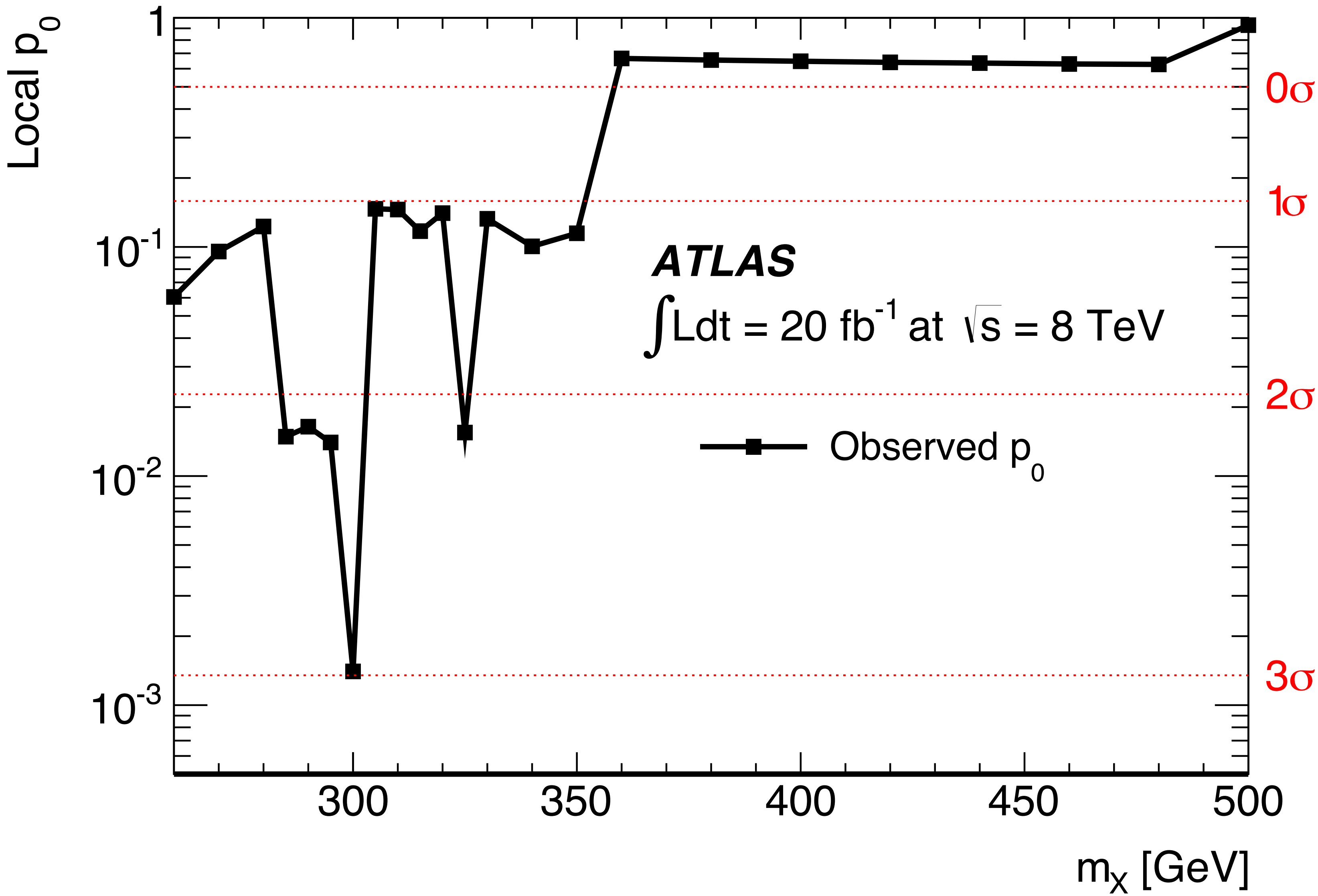

Global p-value = 2.1**σ**


Higgs
boson


Higgs
boson

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Search for resonant pair production of Higgs bosons via X→hh→bbbb

Dominant background is multi-jet background, subleading background is ttbar production

- 4b analysis much more sensitive at high m_X, where the backgrounds can be kept to a manageable rate
  - Look for m_X starting at 500 GeV
- Larger signals, but multijet backgrounds require data-driven methods to trust predictions
- Benchmark signal model: Randall-Sundrum graviton with a warped extra dimension
  - $k/\overline{M}_{pl}$ set to unity
  - Resonance smaller than 4j mass resolution
  - Modeled with Madgraph interfaced to Pythia8

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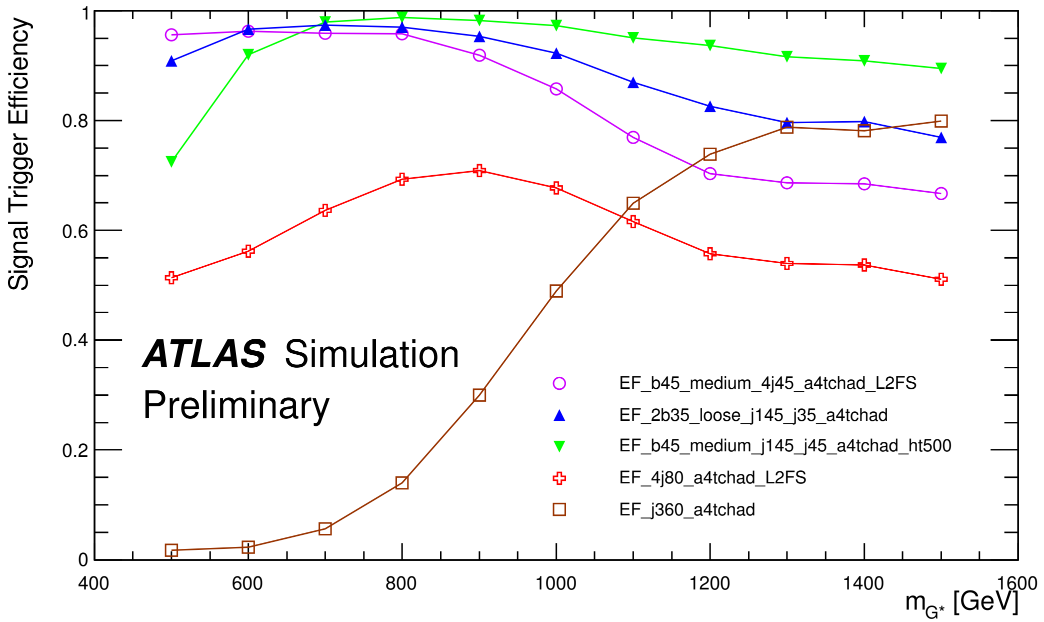


Combination of 5 non-prescaled triggers → >99.5% efficiency with respect to offline selection for mass range of interest

- Require 4 b-tagged jets with $p_T > 40$ GeV
- Look for dijet systems with pt(jj) > 200 GeV and dR(j,j) < 1.5
- Look for extra jets with pT > 30 GeV and dR(jj) < 1.2 to form ttbar system, and calculate:

$$X_{tt} = \sqrt{\left(\frac{m_W - \tilde{m}_W}{\sigma_{m_W}}\right)^2 + \left(\frac{m_t - \tilde{m}_t}{\sigma_{m_t}}\right)^2}$$

σ_{m_W}: $0.1m_W$ — σ_{m_t}: $0.1m_t$

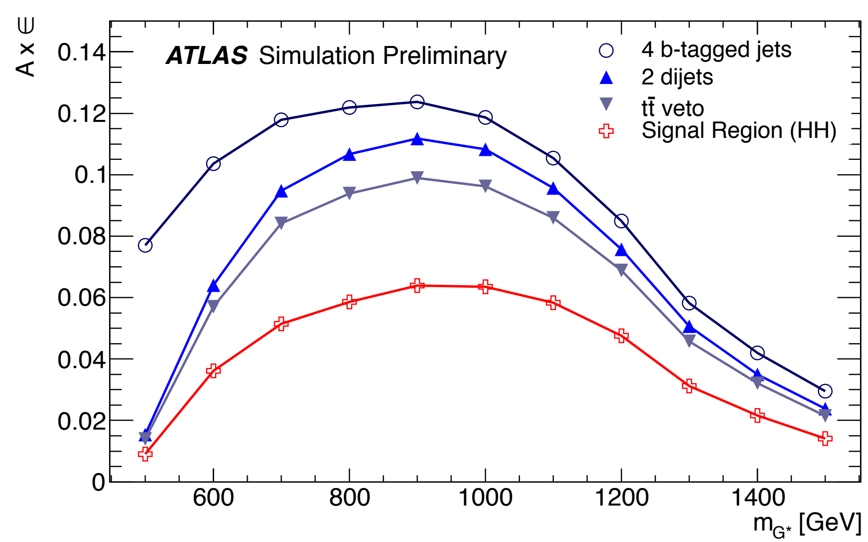
- m_t from 3-jet mass, m_W mass of extra jet and b-jet with lowest b-tag probability
- Reject events if $X_{tt} < 3.2$ (keeps 90% signal, rejects 60% ttbar background)

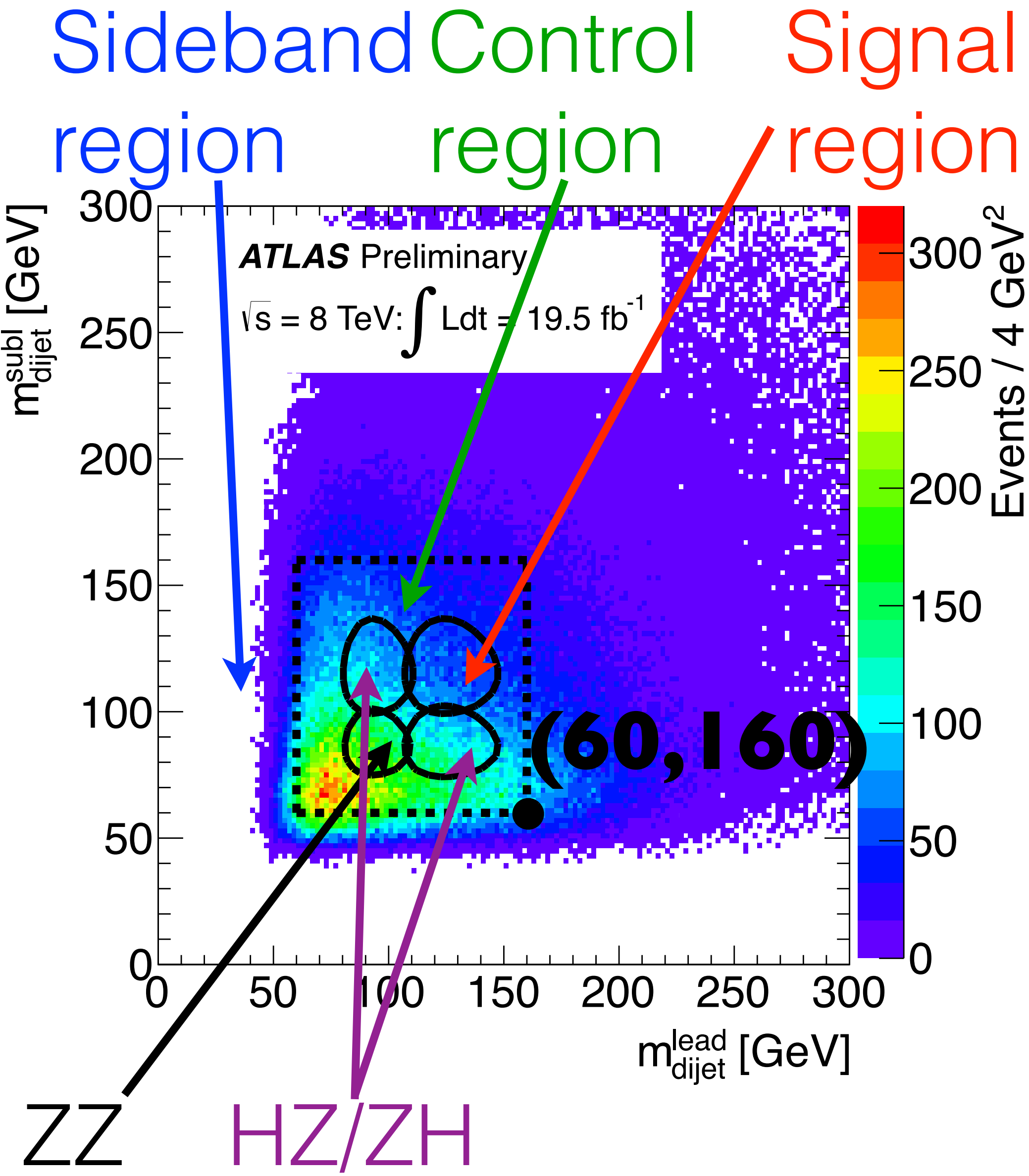
- Form X_{HH} from pairs of dijets:

$$X_{HH} = \sqrt{\left(\frac{m^{\text{lead}}_{\text{dijet}} - \tilde{m}^{\text{lead}}_{\text{dijet}}}{\sigma_{m^{\text{lead}}_{\text{dijet}}}}\right)^2 + \left(\frac{m^{\text{subl}}_{\text{dijet}} - \tilde{m}^{\text{subl}}_{\text{dijet}}}{\sigma_{m^{\text{subl}}_{\text{dijet}}}}\right)^2}$$

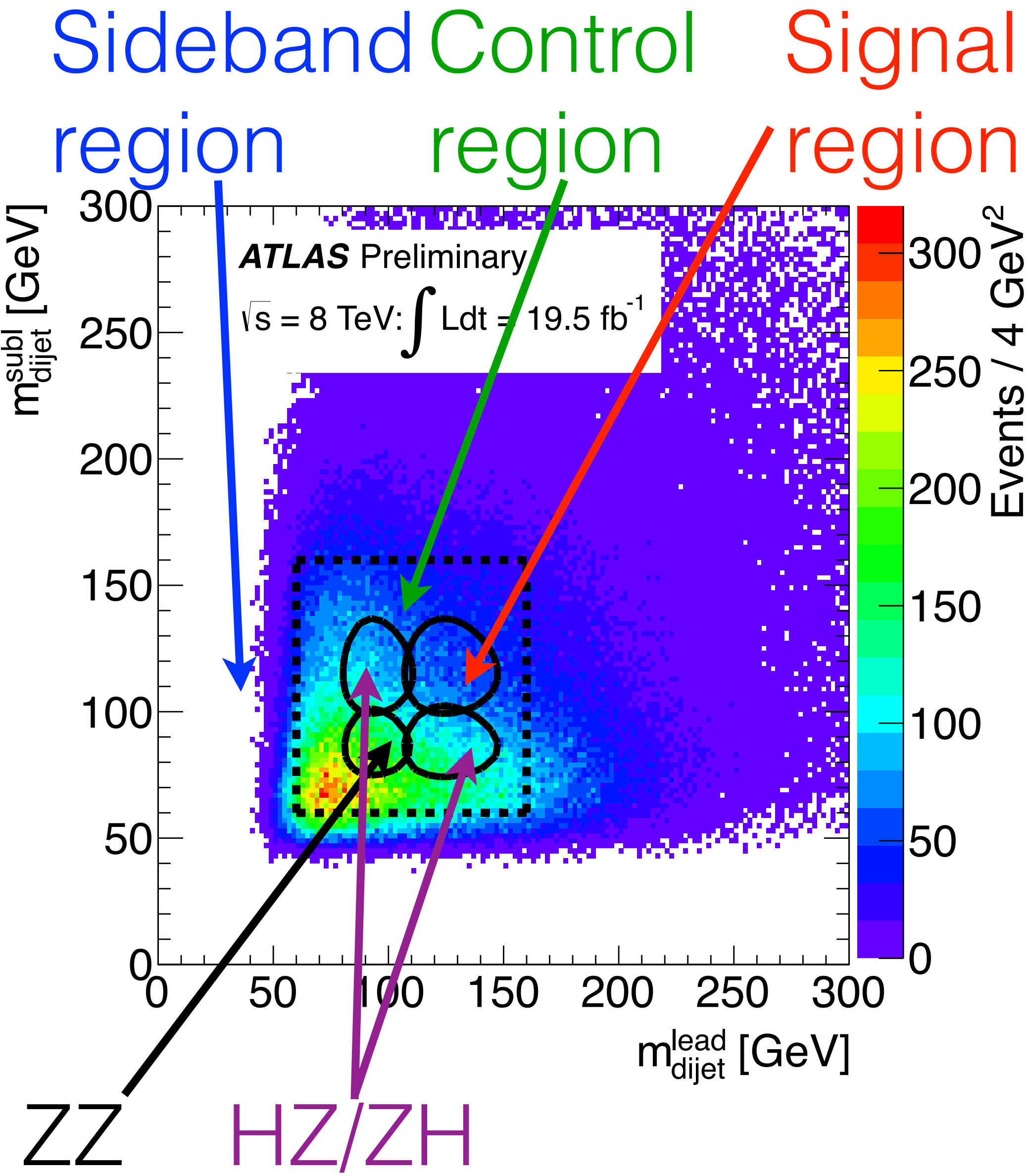
$0.1 m_{lead}$ $0.1 m_{subl}$

- $\tilde{m}^{lead}$ = 124 GeV, $\tilde{m}^{subl}$ = 115 GeV, optimized in simulation
- Require $X_{HH} < 1.6$ to be in signal region





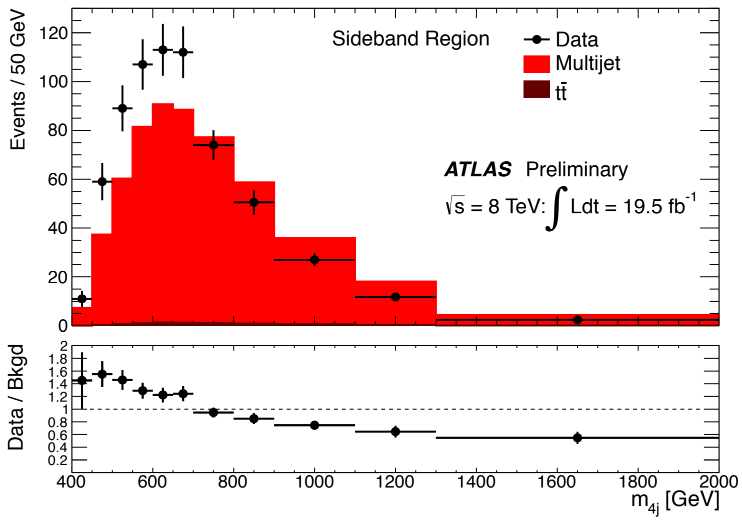
ZZ, HZ, ZH regions defined in same way as HH but with masses set for consistency with different final states



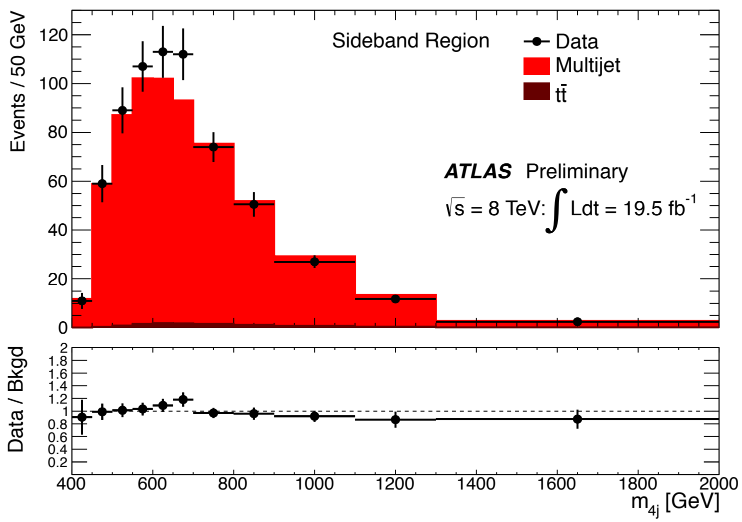
Two-tag data used to estimate multijet background in 4tag data

$$\mu_{\text{multijet}} = \frac{N^{\text{Sideband}}_{4\text{-tag}} - N^{\text{Sideband}}_{t\bar{t},4\text{-tag}} - N^{\text{Sideband}}_{Z+\text{jets},4\text{-tag}}}{N^{\text{Sideband}}_{2\text{-tag}}}$$

μ=0.0064 ± 0.0002



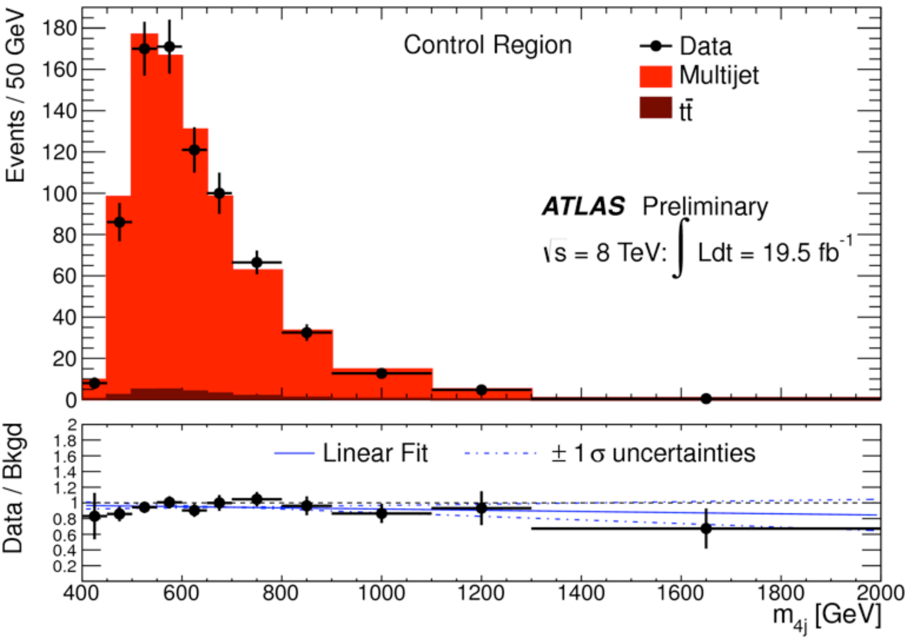
Before



After

Refine kinematics by reweighting from sideband events in leading dijet p_T, dR(j,j) in subleading dijet, dR(dijets)

4b check in control region

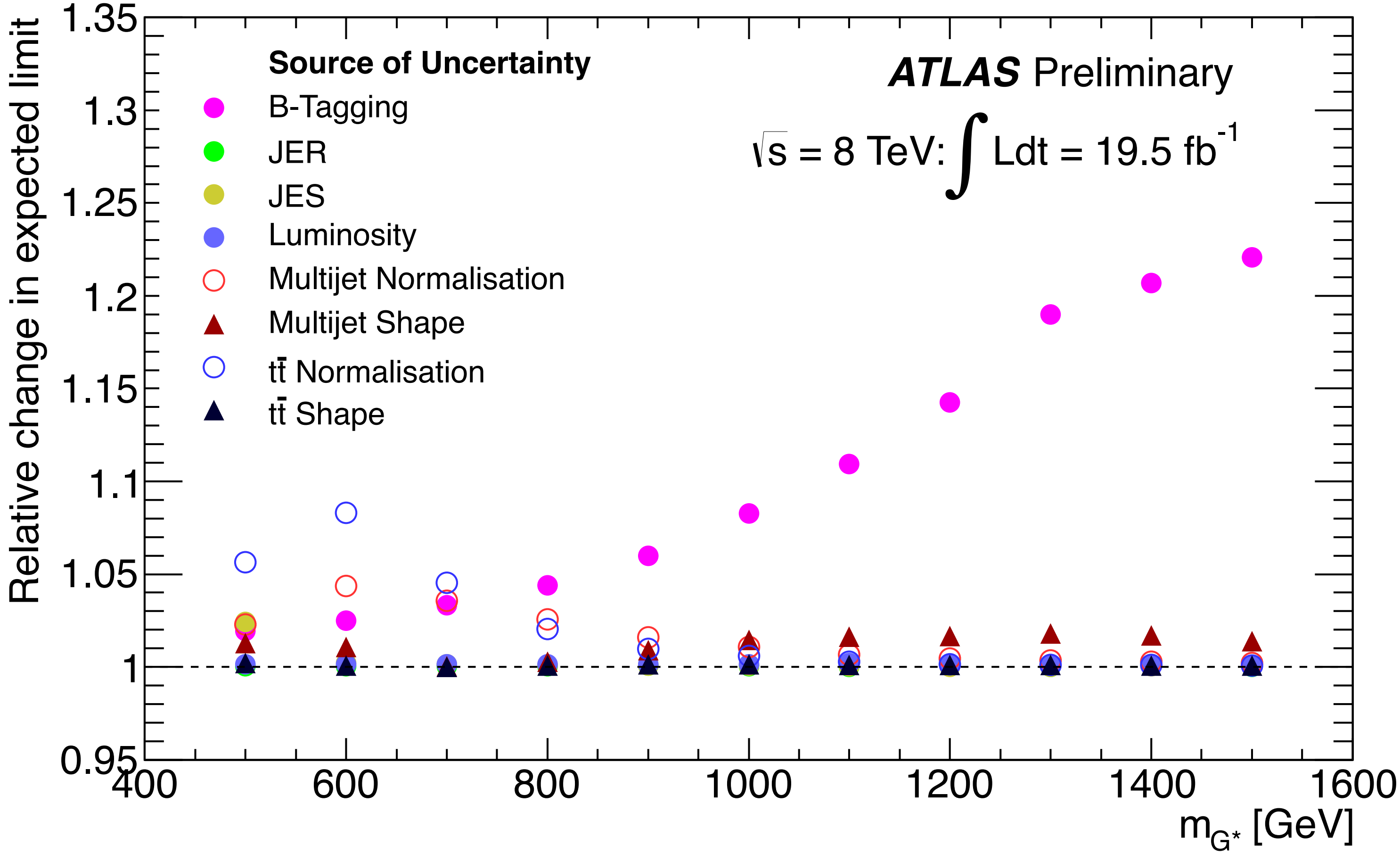


Type	Sideband Region	Control Region
Multijet	903 ± 3	935 ± 3
$t\bar{t}$	19.0 ± 0.2	26.7 ± 0.3
Z+jets	11 ± 1	17 ± 1
Total Bkgd	933 ± 3	979 ± 3
4-tag Data	933	933
G^* (m_{G^*} = 500 GeV)	0.75 ± 0.10	3.9 ± 0.2
G^* (m_{G^*} = 700 GeV)	0.48 ± 0.04	3.0 ± 0.1

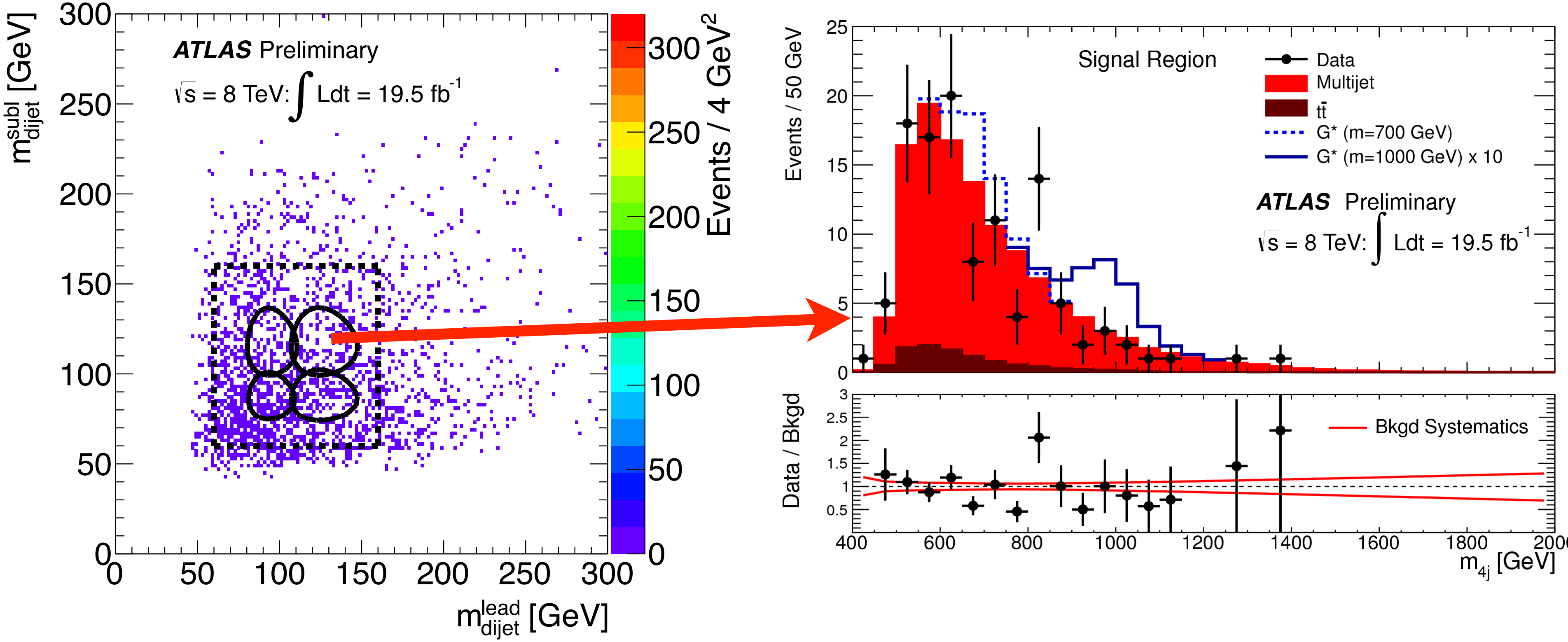
Residual normalization and shape differences taken as uncertainty

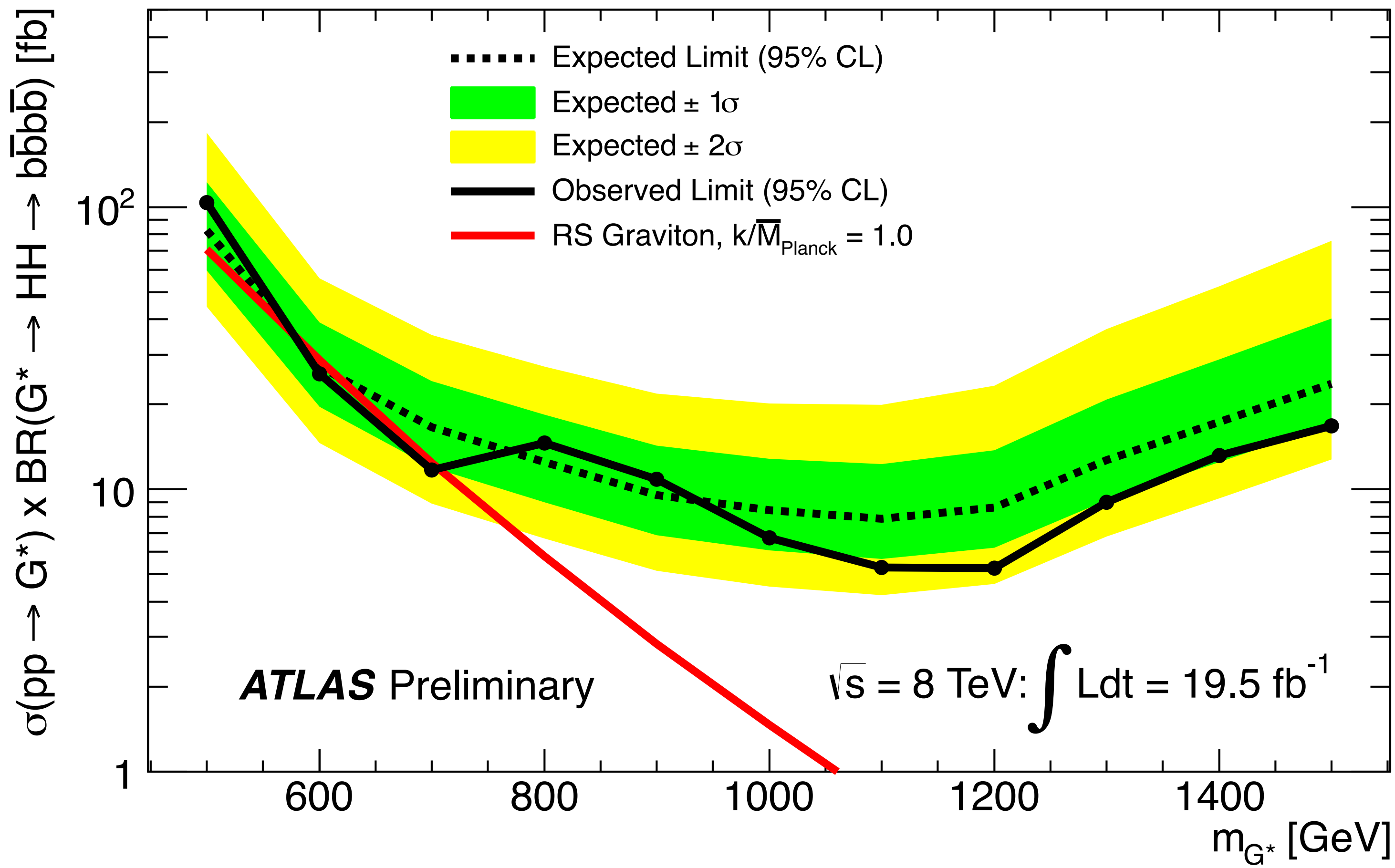
- ttbar contribution estimated from events where at least one dijet system fails X_{tt}
  - Extrapolation to signal region from semi-leptonic ttbar events in data
  - Large statistical uncertainties, but ttbar background is small compared to multijet background
- Shape of ttbar events taken from simulation

$$N_{t\bar{t}}^{Bkg} = \frac{\epsilon_{t\bar{t}}^2}{1-\epsilon_{t\bar{t}}^2} \times N_{t\bar{t}}^{CR}$$

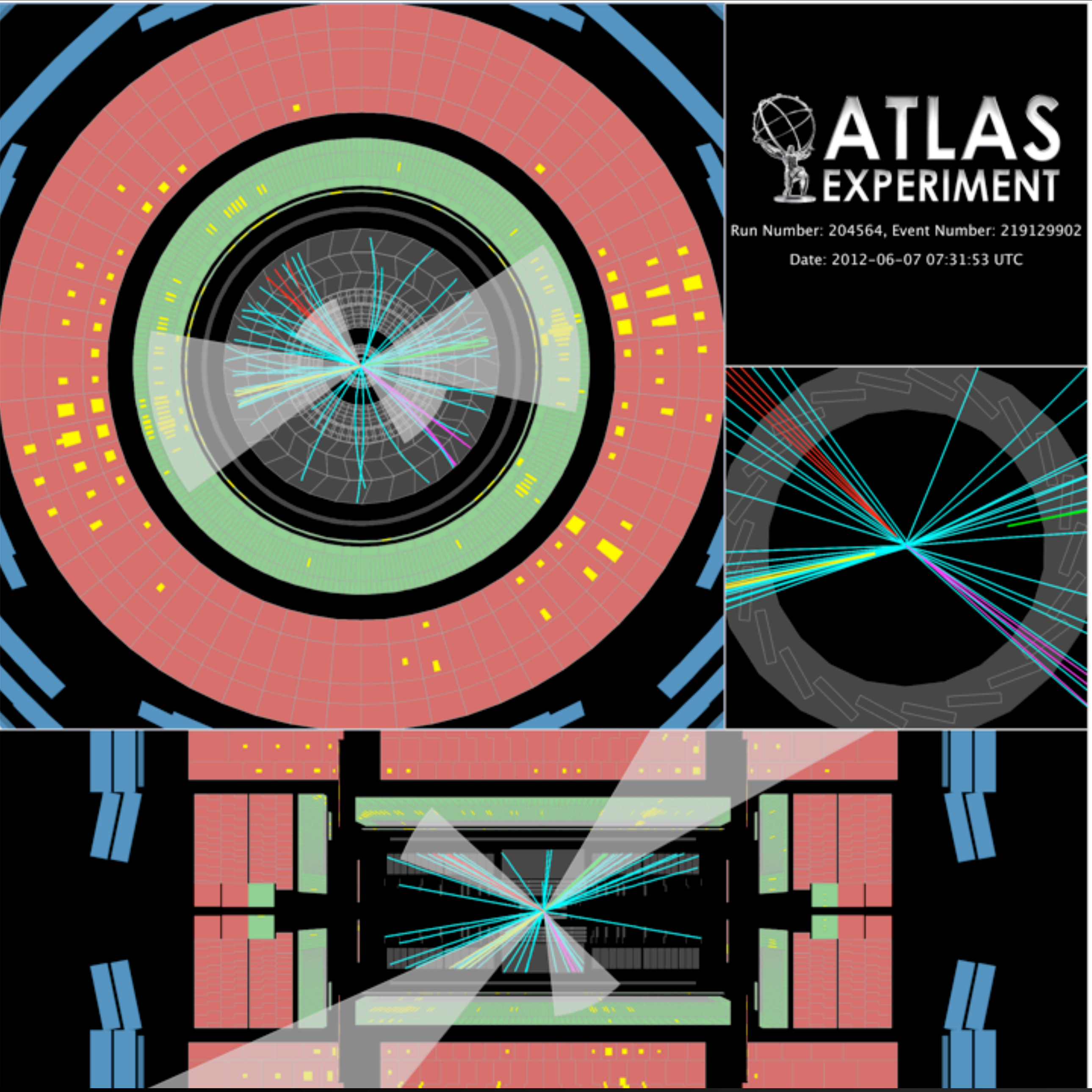


B-tagging scale factor uncertainties for jets with $p_T > 300$ GeV large (not enough data - estimated purely from simulation)


ATLAS Preliminary
√s = 8 TeV: ∫ Ldt = 19.5 fb⁻¹
m_dijet^subl [GeV]
m_dijet^lead [GeV]
Events / 4 GeV²
Signal Region
Data
Multijet
tt̄
G* (m=700 GeV)
G* (m=1000 GeV) x 10
ATLAS Preliminary
√s = 8 TeV: ∫ Ldt = 19.5 fb⁻¹
Events / 50 GeV
Data / Bkgd
Bkgd Systematics
m_4j [GeV]



Exclude gravitons at 95% CL with mass 590-710 GeV (expected 590-630 GeV)

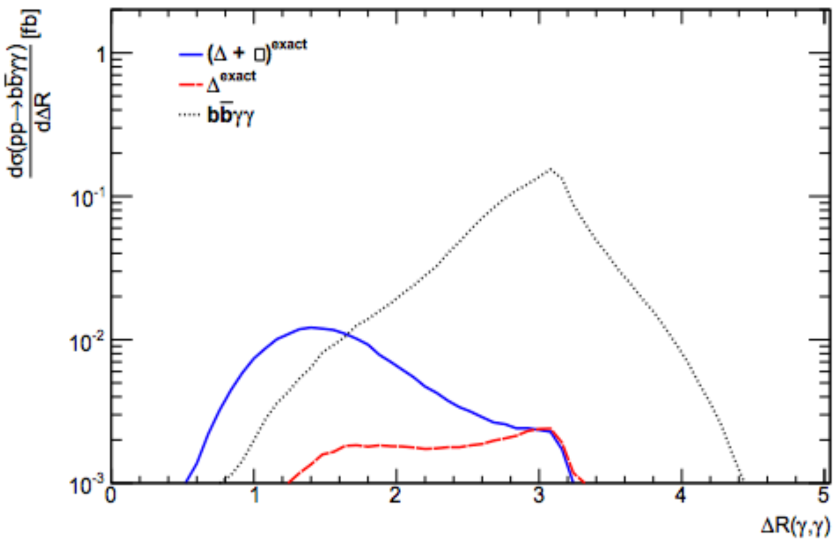


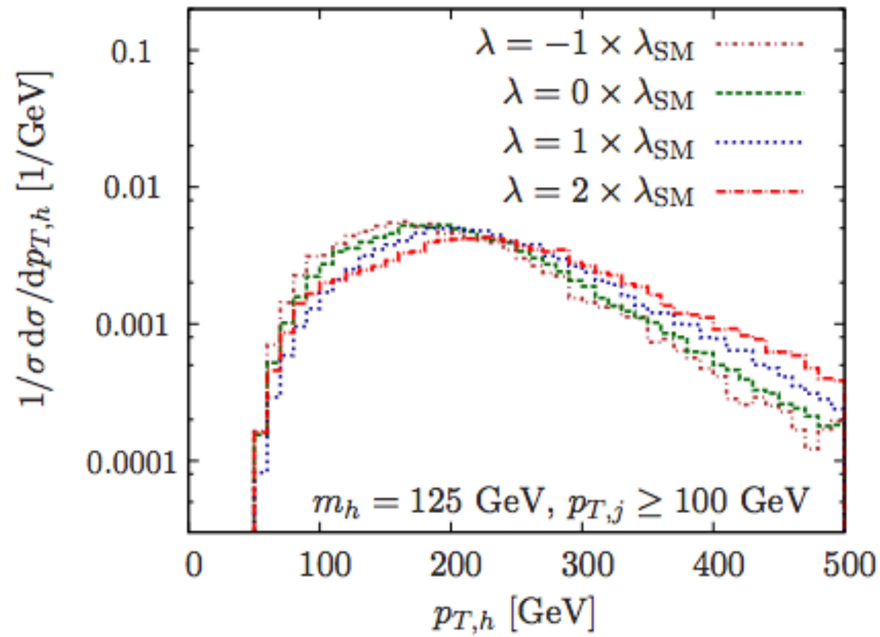
$m_{bb}(1) = 115$ GeV

$m_{bb}(2) = 112$ GeV

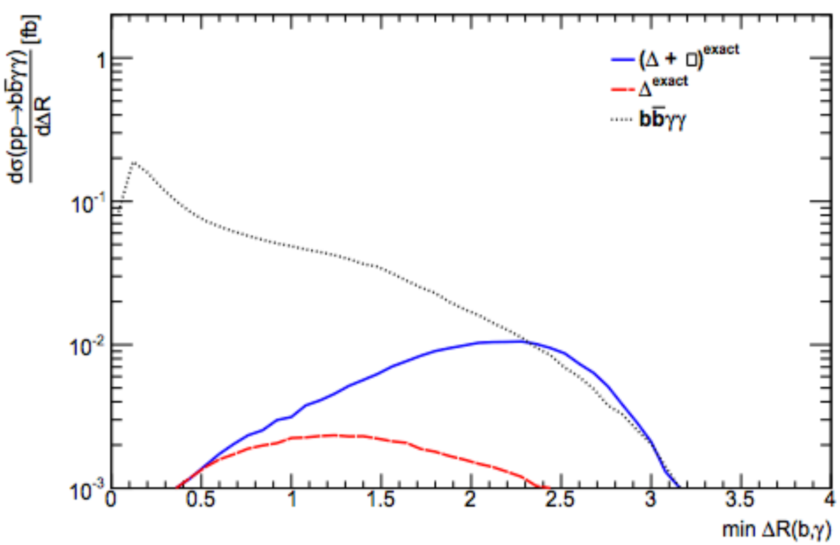
$m_{4b} = 834$ GeV

Last thoughts before concluding





arXiv: 1206.5001 (Dolan et al)



Can we use kinematics to separate out box and triangle diagrams?!

arXiv: 1408.5010 (Slawinska et al)

	HH	$b\bar{b}\gamma\gamma$	$t\bar{t}\gamma\gamma$	ZH	S/B	$S/\sqrt{B}$
Cross section NLO [fb]	8.92×10^{-2}	5.05×10^{3}	1.39	3.33×10^{-1}	1.77×10^{-5}	6.87×10^{-2}
Reconstructed Higgs from bs	4.37×10^{-2}	4.01×10^{2}	8.70×10^{-2}	1.24×10^{-3}	1.09×10^{-4}	1.20×10^{-1}
Reconstructed Higgs from γs	3.05×10^{-2}	1.78	2.48×10^{-2}	3.73×10^{-4}	1.69×10^{-2}	1.24
Cut on M_{HH}	2.73×10^{-2}	3.74×10^{-2}	7.45×10^{-3}	1.28×10^{-4}	6.07×10^{-1}	7.05
Cut on $P_{T,H}$	2.33×10^{-2}	3.74×10^{-2}	5.33×10^{-3}	1.18×10^{-4}	5.44×10^{-1}	6.17
Cut on η_H	2.04×10^{-2}	1.87×10^{-2}	3.72×10^{-3}	9.02×10^{-5}	9.06×10^{-1}	7.45
Cut on $\Delta R(b,b)$	1.71×10^{-2}	0.00	3.21×10^{-3}	7.44×10^{-5}	5.21	16.34
"Detector level"	1.56×10^{-2}	0.00	8.75×10^{-3}	8.74×10^{-3}	8.92×10^{-1}	6.46

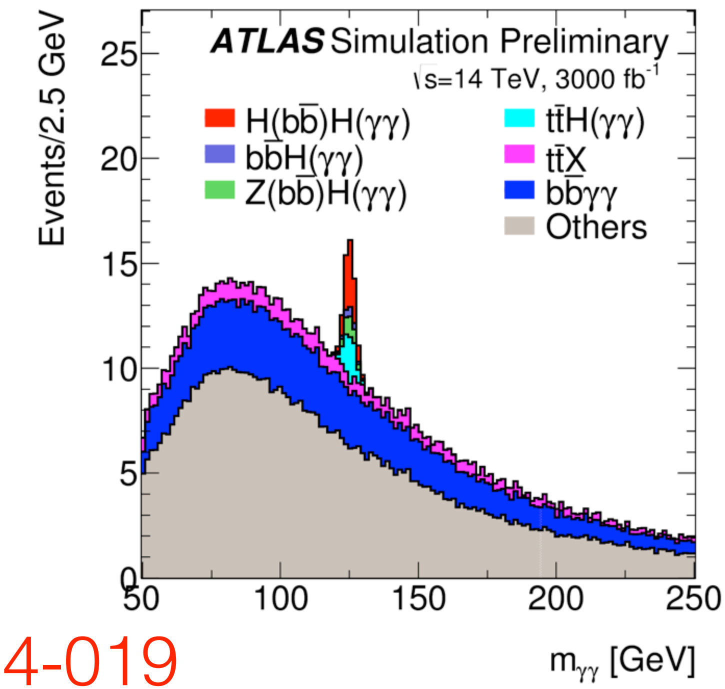
Table 7: Cross section values of the HH signal and the various backgrounds expected at the LHC at $\sqrt{s} = 14$ TeV, the signal to background ratio S/B and the significance $S/\sqrt{B}$ for $\int \mathcal{L} = 3000$ fb^{-1} in the $b\bar{b}\gamma\gamma$ channel after applying the cuts discussed in the text.

arXiv: 1212.5581 (Baglio et al)

$$\frac{S}{\sqrt{B}} = 1.3$$

vs

$$\frac{S}{\sqrt{B}} = 6.5$$



ATL-PHYS-PUB-2014-019

Northern Illinois University

- Key LHC goal to explore the Higgs boson potential and study the Higgs self-coupling
  - For the near future, we are searching for new physics
  - In the long-term, we hope to begin to make measurements (hopefully mostly of triangle!)
    - A difficult path, but also a fun one

Conclusions

Northern Illinois University

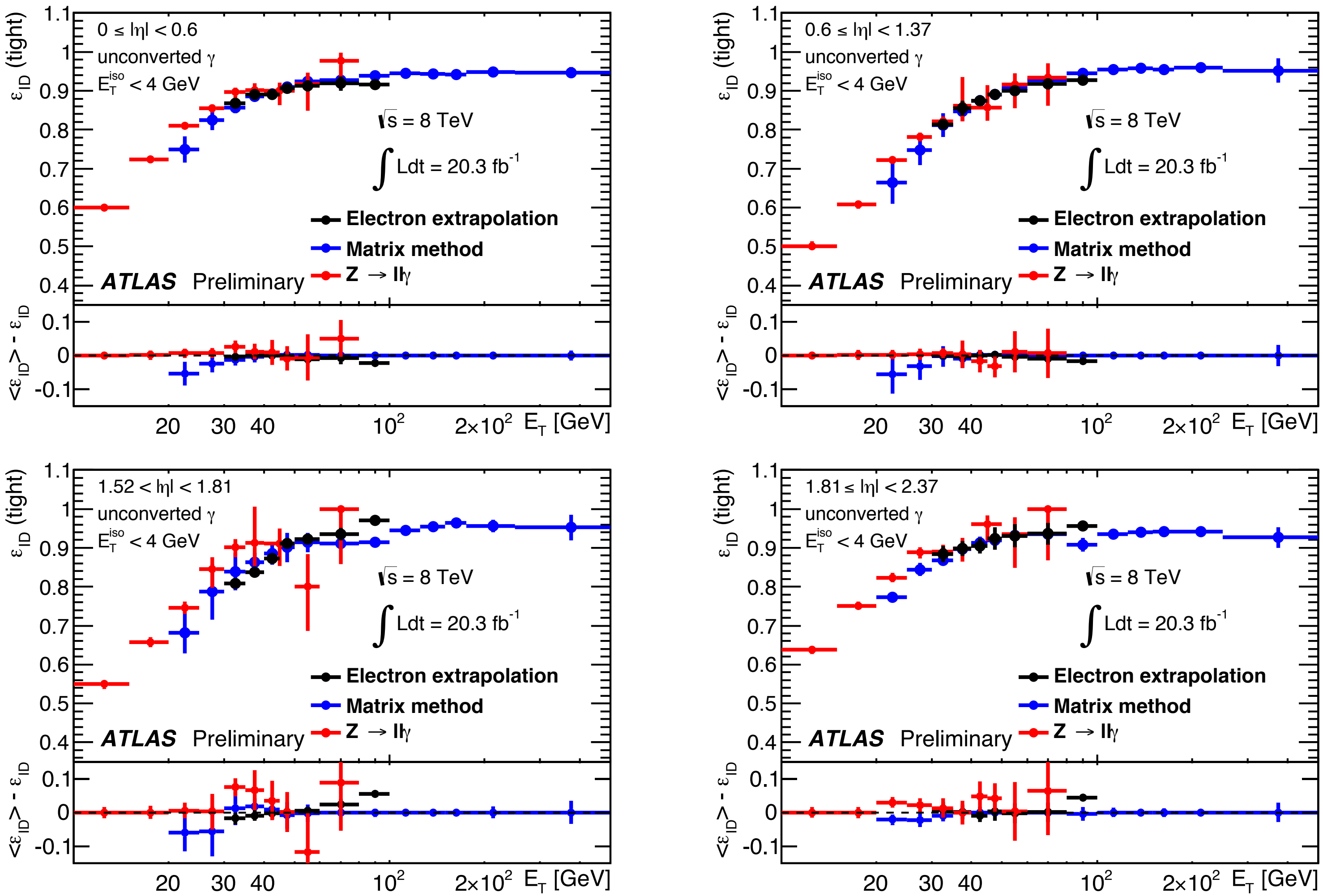
Look for Run 1 $\gamma\gamma$WW, $\tau\tau$bb and boosted-4b analyses (out very soon!) and a combination, and $\gamma\gamma$bb searches early in Run 2


Higgs
boson

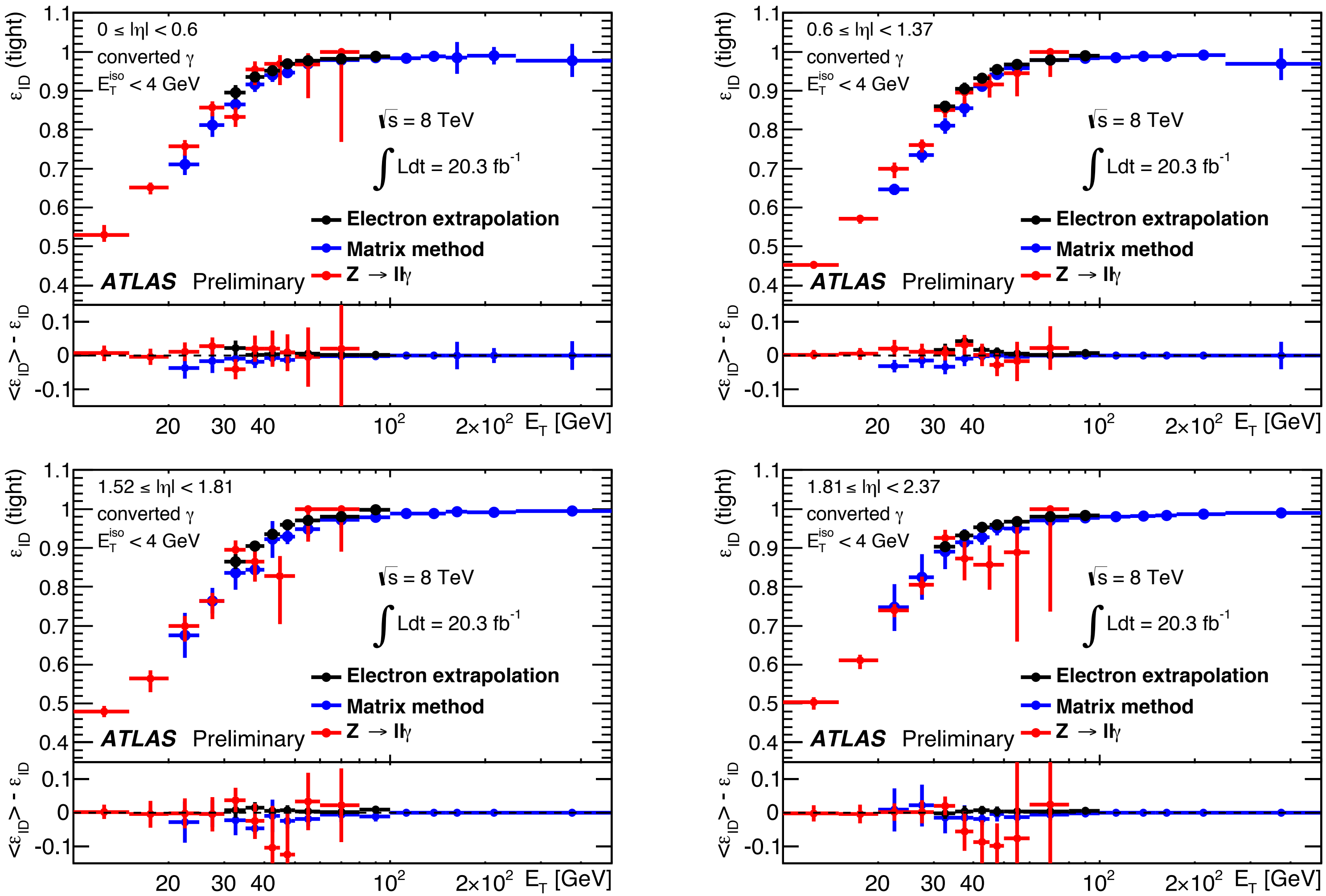

Higgs
boson

Backup

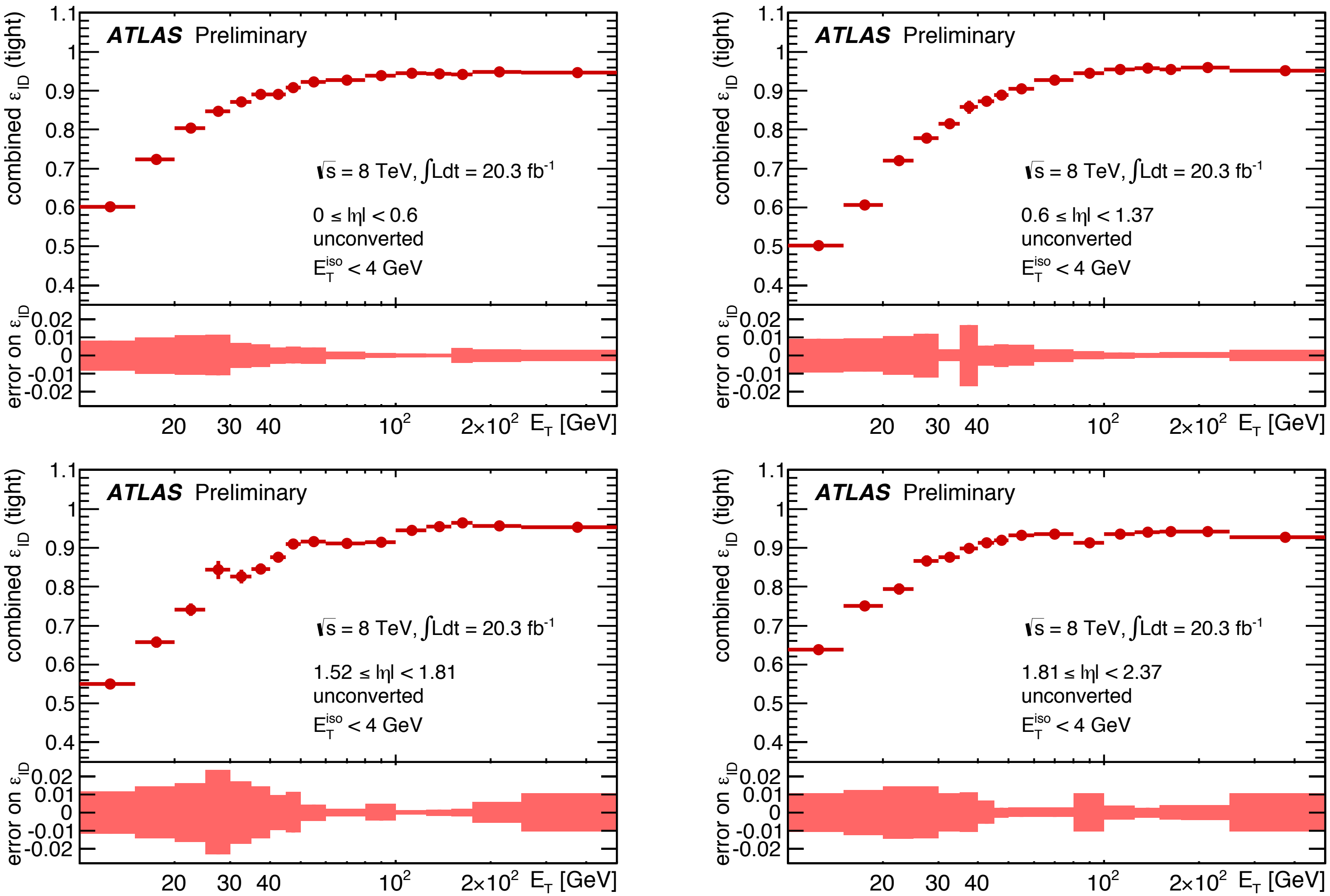
Photon ID


0 ≤ |η| < 0.6
unconverted γ
E_T^{iso} < 4 GeV
√s = 8 TeV
∫Ldt = 20.3 fb⁻¹
Electron extrapolation
Matrix method
Z → llγ
ATLAS Preliminary
0.6 ≤ |η| < 1.37
1.52 < |η| < 1.81
1.81 ≤ |η| < 2.37
ϵ_{ID} (tight)
$<\epsilon_{ID}> - \epsilon_{ID}$
E_T [GeV]
20
30
40
10^2
2×10^2

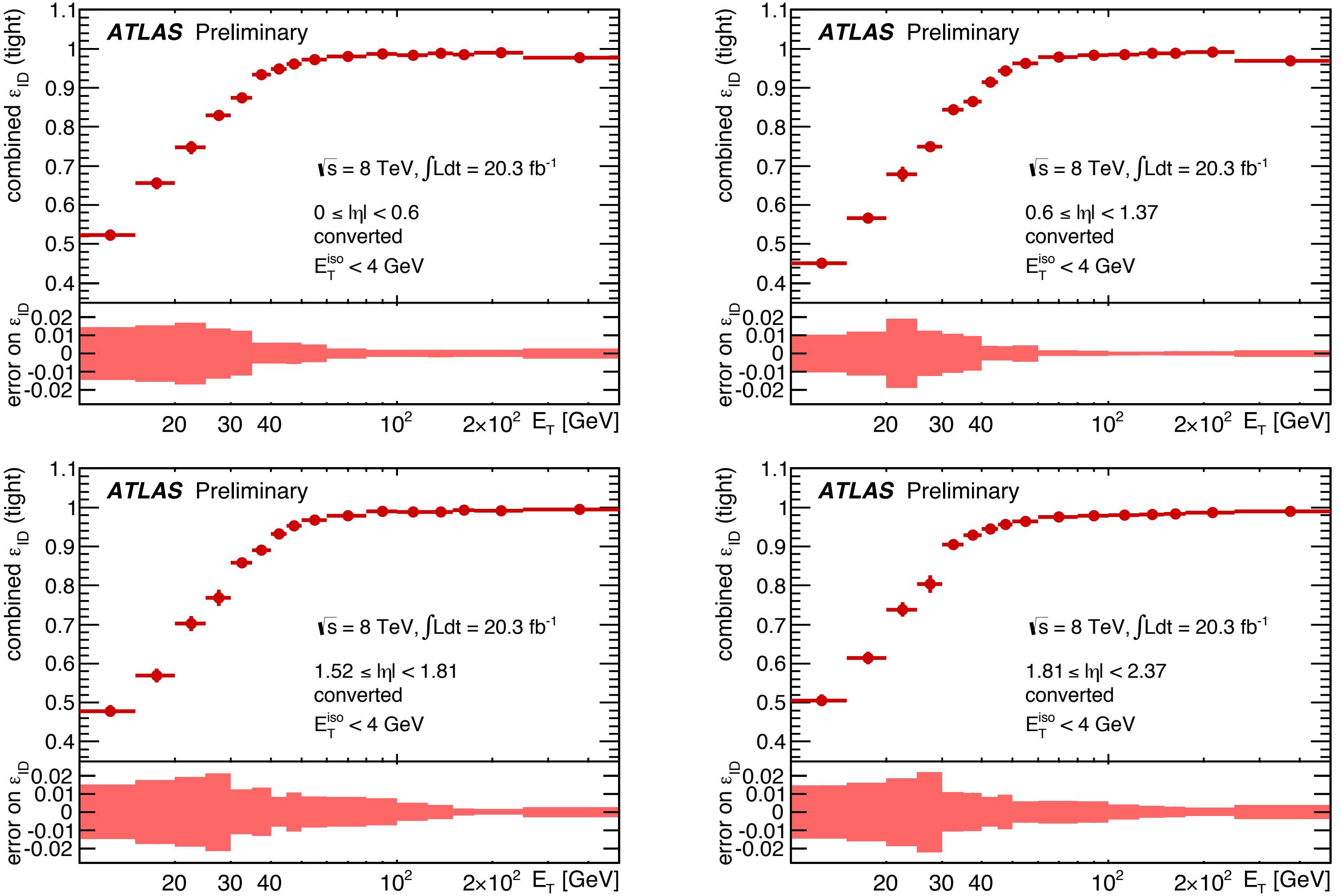
Photon ID


0 ≤ |η| < 0.6
0.6 ≤ |η| < 1.37
1.52 ≤ |η| < 1.81
1.81 ≤ |η| < 2.37
converted γ
E_T^{iso} < 4 GeV
√s = 8 TeV
∫Ldt = 20.3 fb⁻¹
Electron extrapolation
Matrix method
Z → llγ
ATLAS Preliminary
ε_{ID} (tight)
$<\varepsilon_{ID}> - \varepsilon_{ID}$
E_T [GeV]

Photon ID


ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, ∫Ldt = 20.3 fb^{-1}
0 ≤ |η| < 0.6
unconverted
E_T^{iso} < 4 GeV
0.6 ≤ |η| < 1.37
1.52 ≤ |η| < 1.81
1.81 ≤ |η| < 2.37
combined ε_{ID} (tight)
error on ε_{ID}
E_T [GeV]

Photon ID


ATLAS Preliminary
√s = 8 TeV, ∫Ldt = 20.3 fb-1
0 ≤ |η| < 0.6
converted
E_T^iso < 4 GeV
0.6 ≤ |η| < 1.37
1.52 ≤ |η| < 1.81
1.81 ≤ |η| < 2.37
combined ε_ID (tight)
error on ε_ID
E_T [GeV]

hh xsections in SM

http://arxiv.org/abs/1212.5581

$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}_{gg\to HH}$ [fb]	$\sigma^{\rm NLO}_{qq'\to HHqq'}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\rm LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82

Run/Event Number	214494/20105423	208261/19675029	205016/21379303	204668/136522288	204265/8266739
Leading γ ($p_{\mathrm{T}}/\eta/\phi$)	(110/0.5/0.6)	(73/-1.2/-1.3)	(52/-0.3/2.9)	(65/-0.1/-2.2)	(65/0.4/-2.6)
Subleading γ ($p_{\mathrm{T}}/\eta/\phi$)	(44/0.7/-1.6)	(34/0.6/-3.1)	(46/-2.3/-2.0)	(37/-1.7/0.1)	(42/-0.9/0.4)
$m_{\gamma\gamma}$	125.2	125.6	128.5	125.1	125.4
$p_{\mathrm{T}}^{\gamma\gamma}$	90.4	73.7	76.6	47.7	24.0
$m_{b\bar{b}}$ unconstrained	125.9	130.4	124.7	134.0	105.4
p_{T}^{bb} unconstrained	110.7	108.1	44.9	107.5	36.5
$m_{\gamma\gamma b\bar{b}}$ constrained	336.6	312.7	291.7	289.9	264.5
$m_{\gamma\gamma b\bar{b}}$ unconstrained	337.7	319.4	291.3	300.2	243.7
$p_{\mathrm{T}}^{\gamma\gamma bb}$ constrained	69.2	52.5	44.3	63.7	24.6
Leading jet ($p_{\mathrm{T}}/\eta/\phi$/E)	(68/-0.9/-3.1/100)*	(121/-1.1/1.4/196)*	(65/-1.5/1.0/157)*	(103/-0.8/1.5/140)*	(66/-0.6/1.9/80)*
Subleading jet ($p_{\mathrm{T}}/\eta/\phi$/E)	(58/0.6/2.1/71)*	(47/-1.9/0.4/157)	(65/-2.1/0.0/258)	(66/0.9/-2.0/97)	(43/-0.4/-0.7/48)*
3rd jet ($p_{\mathrm{T}}/\eta/\phi$/E)		(47/-1.0/-2.8/73)*	(59/-2.2/-1.5/273)*	(52/0.2/-0.2/53)*	
4th jet ($p_{\mathrm{T}}/\eta/\phi$/E)			(34/-0.7/2.5/43)	(36/0.4/2.2/39)	
$E_{\mathrm{T}}^{\mathrm{miss}}(E_{\mathrm{T}}/\phi)$	(26/-2.8)	(52/-0.8)	(4/-2.7)	(23/2.1)	(50/-0.1)

TABLE II: Kinematics of the five events in the non-resonant signal region. Units of GeV are assumed everywhere, as appropriate. The star (*) for a jet indicates a b-tag. Only jets above 30 GeV are considered. Unconstrained (constrained) refers to values before (after) constraining the $b\bar{b}$ mass to 125 GeV.

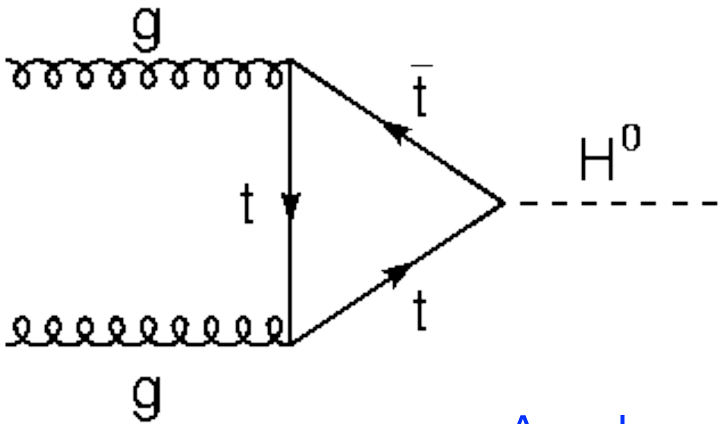
- Extend the Higgs sector to a second Higgs doublet
  - Type 1: All fermions couple to one doublet
  - Type 2: Up-type quarks couple to one doublet, down-type quarks and leptons to the second doublet
  - Type 3: Quarks couple to one doublet, leptons to second doublet
  - Type 4: Up-type quarks and leptons couple to one doublet, down-type quarks to the second doublet
  - tan β = ratio of vev of both doublets
  - α determines mixing between two neutral scalars

Φ	$g_{\Phi\bar{u}u}$		$g_{\Phi\bar{d}d}$		$g_{\Phi VV}$
	Type I	Type II	Type I	Type II	Type I/II
h	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
A	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\tan\beta$	0

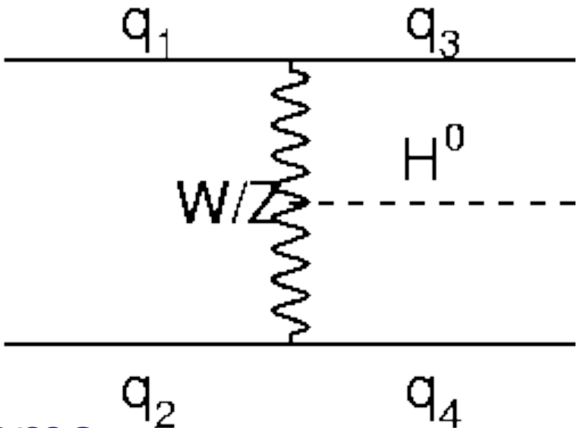
Table 1.4: The neutral Higgs couplings to fermions and gauge bosons in 2HDMs of Type I and II compared to the SM Higgs couplings. The $H^{\pm}$ couplings to fermions follow that of A.

Higgs boson production

(a)

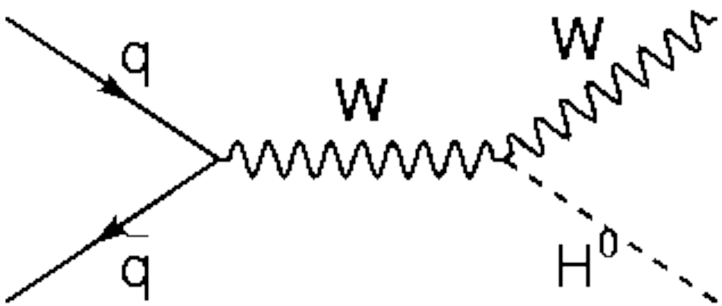


(b)

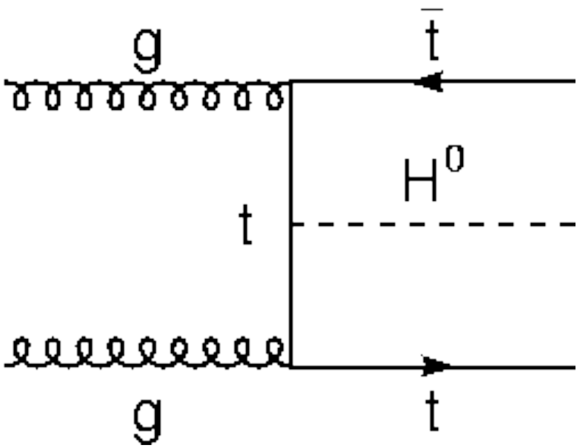


Analogous diagrams
for hh production, too!

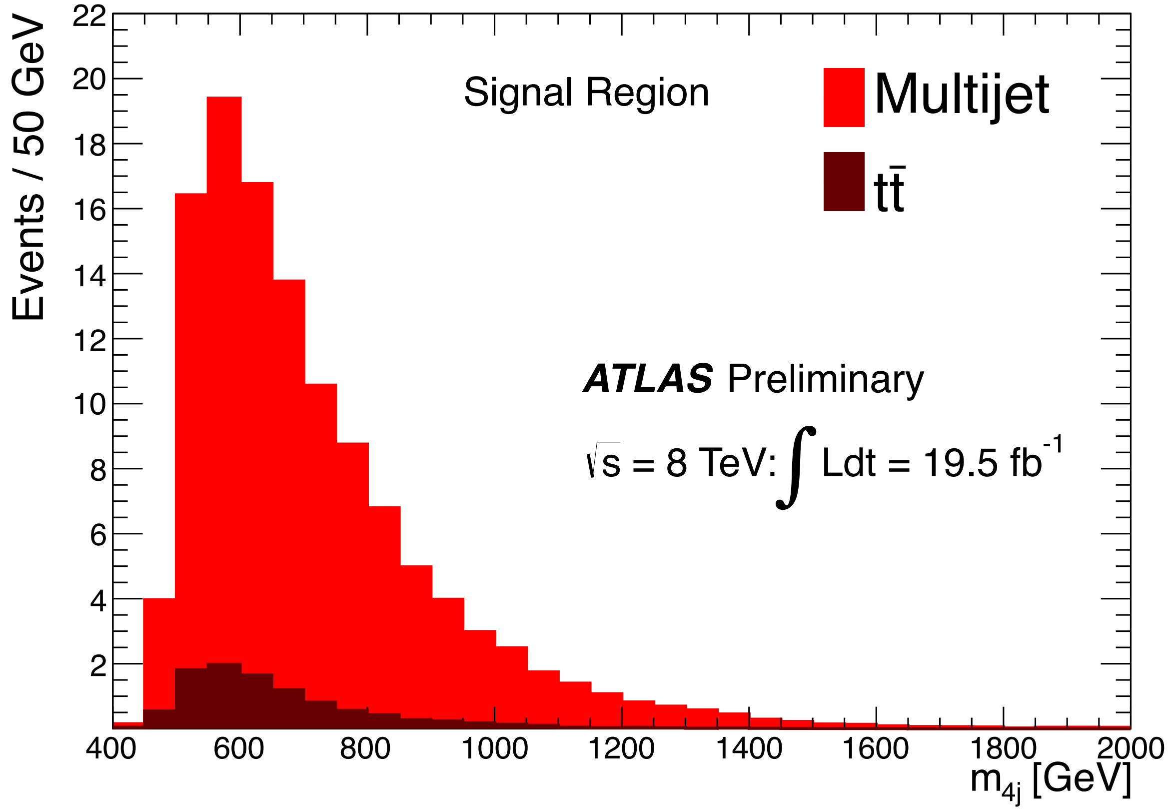
(c)

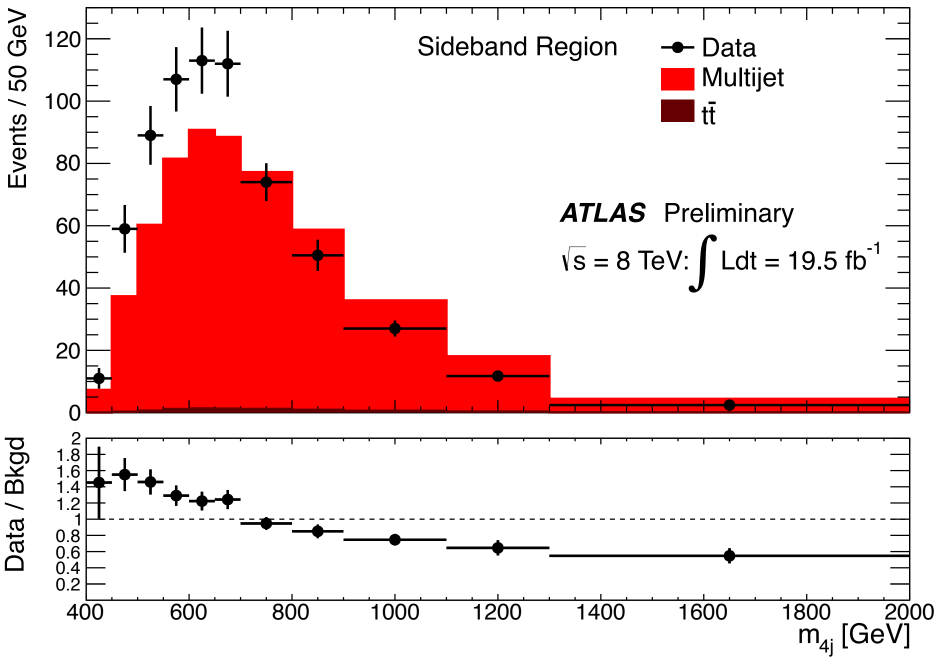


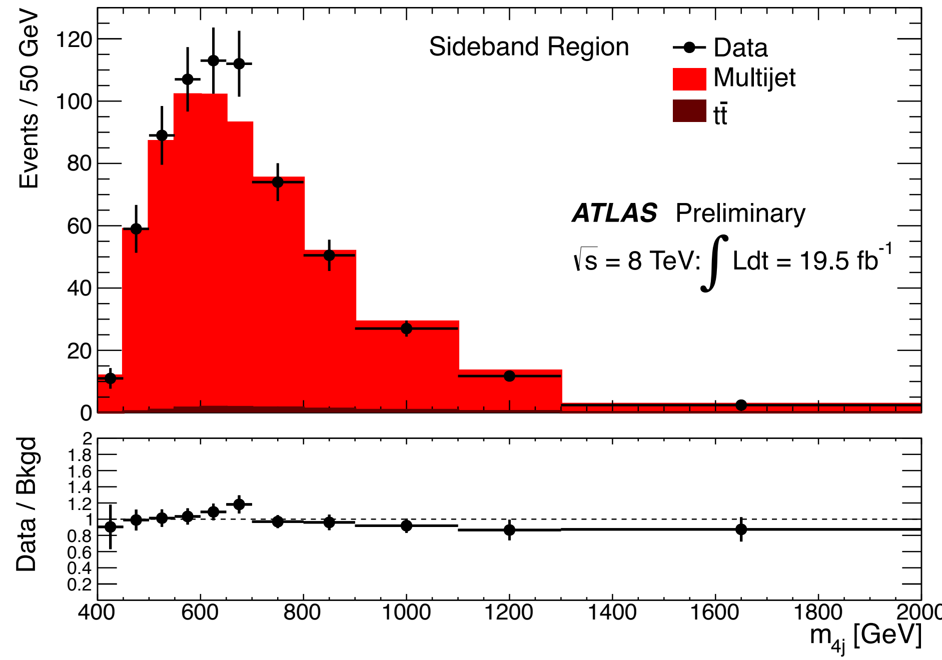
(d)



4b background

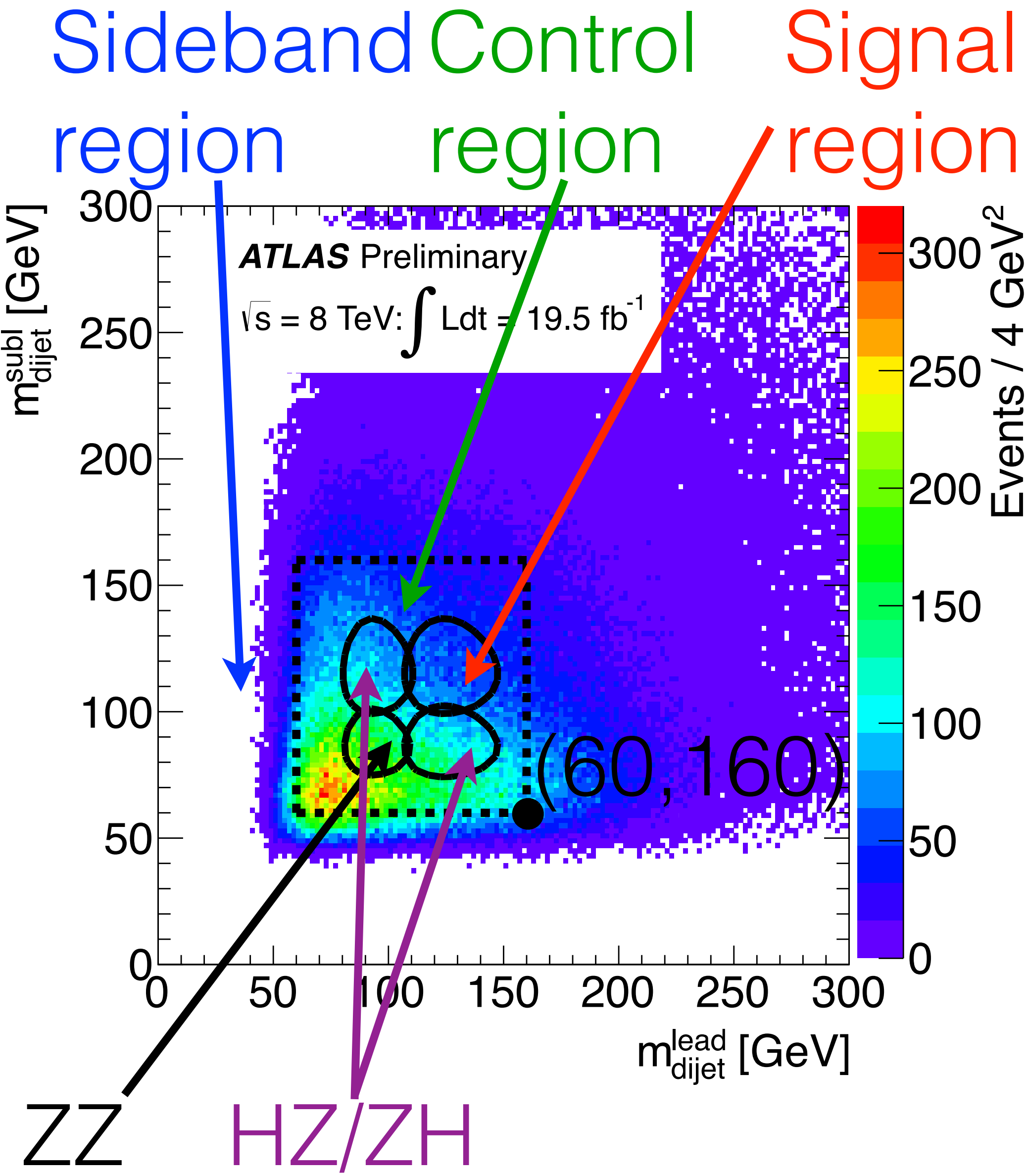






Before reweighting

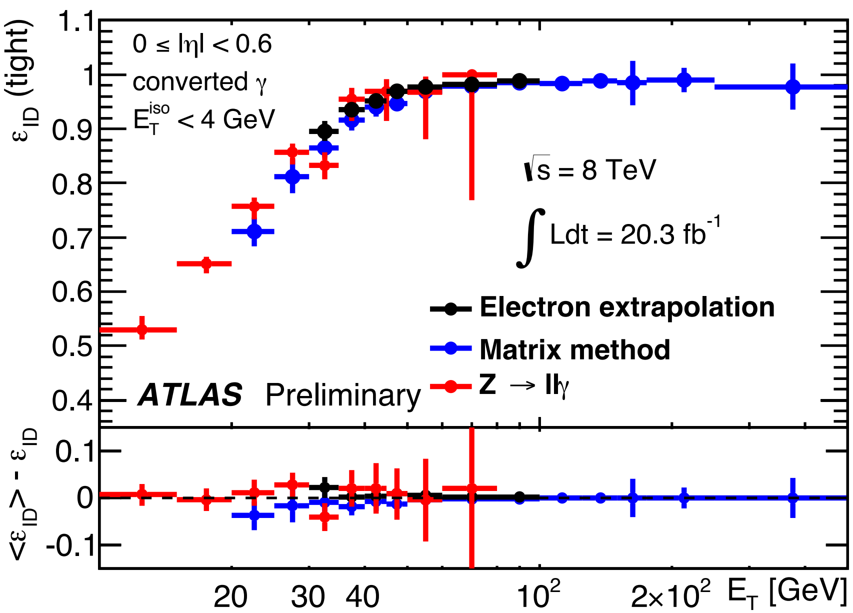
After reweighting



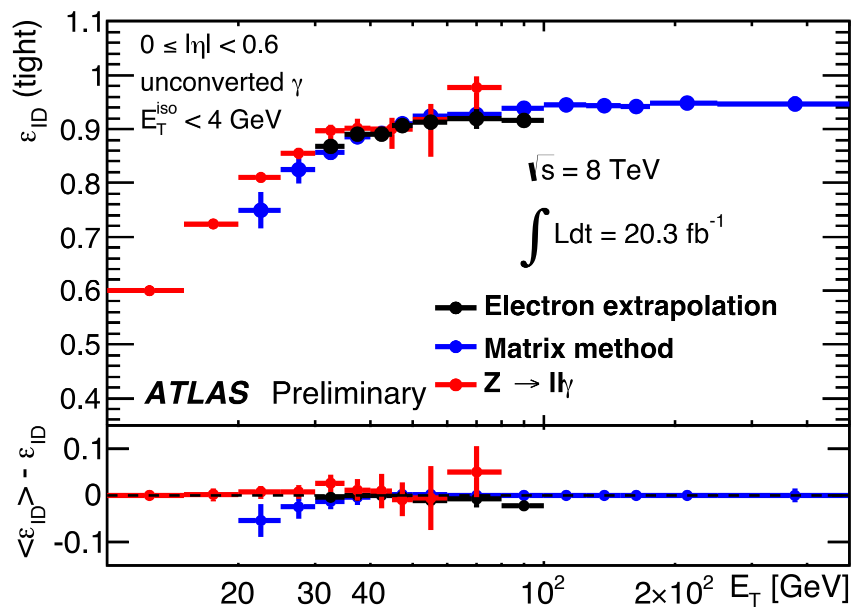
- ZZ region defined in same way as HH but with masses set to 86 and 93 GeV, and $X_{ZZ} < 1.5$
- HZ (ZH) region has mass windows set to 124/86 (93/115) GeV and $X < 1.6$
- Two-tag data used to estimate multijet background in 4tag data

Efficiency extrapolated from Z→ee and measured in Z→llγ + matrix method using track isolation sidebands

Converted central photons



Unconverted central photons



Those who pay attention to these things may have noticed that CMS also has a recent CONF note searching for hh resonances in the $\gamma\gamma$bb channel

Comparing ATLAS and CMS

CMS-PAS-HIG-13-032

Northern Illinois University

	ATLAS	CMS
Jet p_T	55/35 GeV	25 GeV
Tag requirement	≥ 2tag	Separate 1tag and ≥2tag regions for signal
m_{jj} range	95-135 GeV	85-155 GeV
m_{jj} method	4-vector scaling	Kinematic fit
Resonance limit method	Counting experiment	Sideband fit
Non-resonance limit	Yes	No
Signal at 300 GeV	CMS ~50% larger in 2-tag channel	
Background at 300 GeV	CMS ~400% larger in 2-tag channel	
Limit at 300 GeV	CMS ~50% better (expected)	