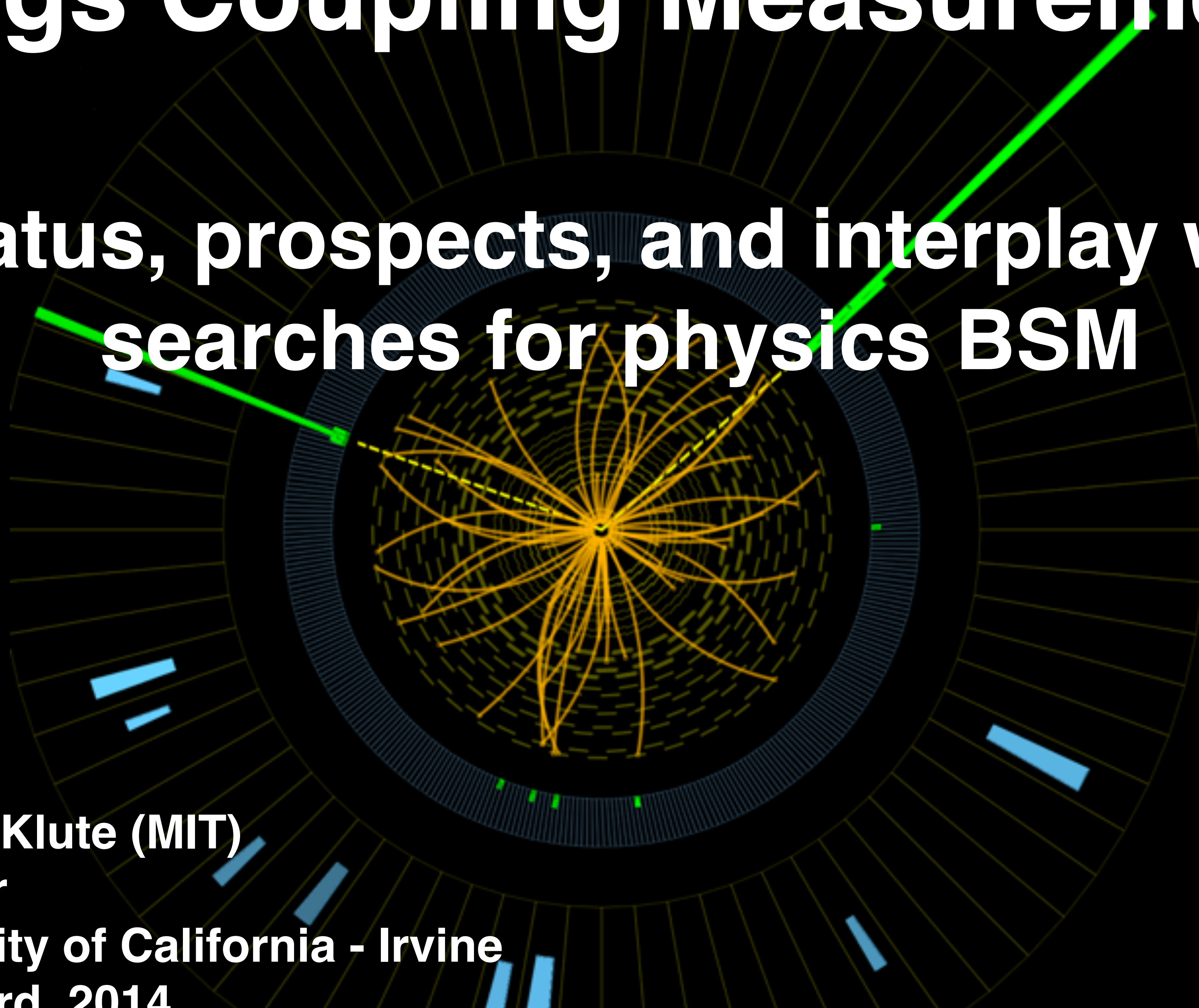
Higgs Coupling Measurements

Status, prospects, and interplay with searches for physics BSM



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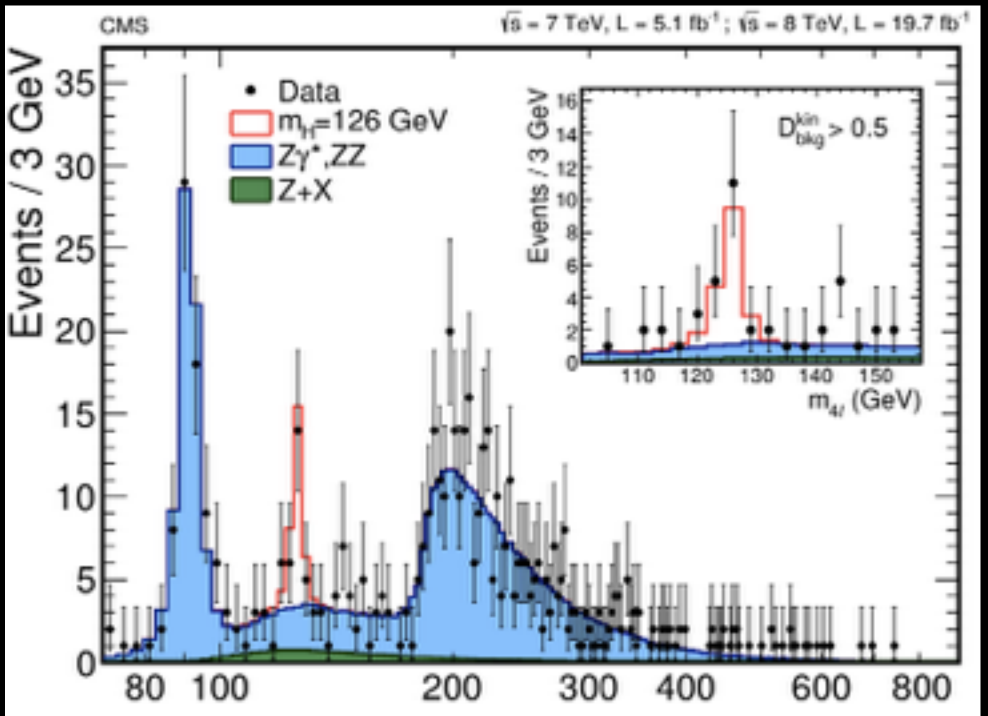
Seminar
University of California - Irvine

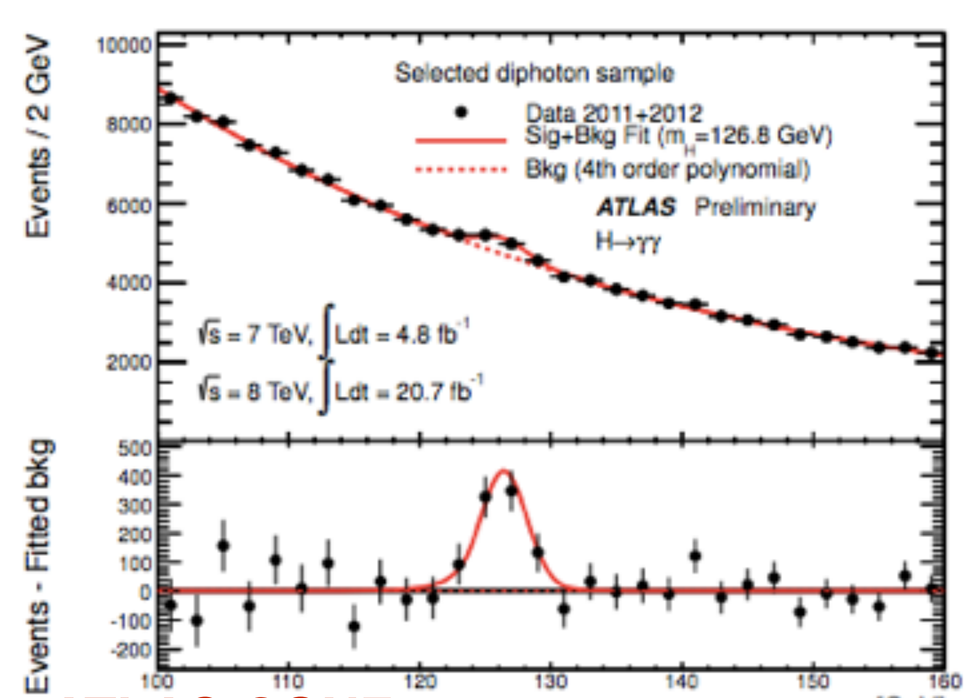
April 23rd, 2014

Introduction

- **Fantastic progress since discovery July 2012**
  - Observation in three boson channels
  - Evidence for fermion couplings
  - Precision mass measurement ~126 GeV
  - Spin determined
- **Looks more and more like the SM Higgs boson**
  - No evidence for non-SM decays
  - No evidence for additional Higgs bosons
- **ATLAS and CMS are finalizing final Run I papers and are preparing combinations**



arXiv:1312.5353



ATLAS-CONF-2013-012

Introduction

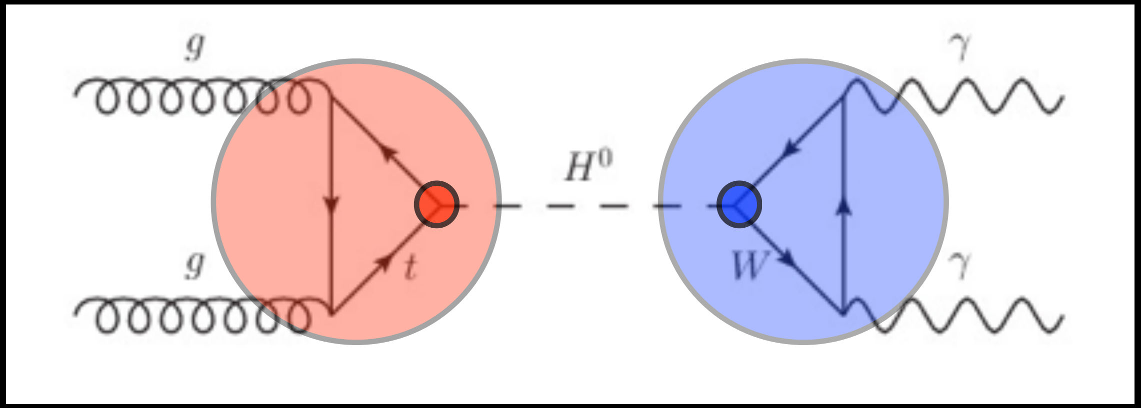
Is there BSM physics hidden in the “Higgs sector” ?

Experimental post-discovery approach

- Measure (126 GeV) Higgs properties
- Search for additional Higgs bosons
- Search for BSM in signatures with Higgs bosons
- Search for BSM Higgs decays

Introduction

- **Gateways to BSM physics in the 126 GeV Higgs**
  - Mixing
  - Loops
  - Decays



- **In general BSM physics modifies absolute value and tensor structure**
  - we factorize the problem, knowing that this is incorrect

Higgs coupling measurements

Coupling Measurements

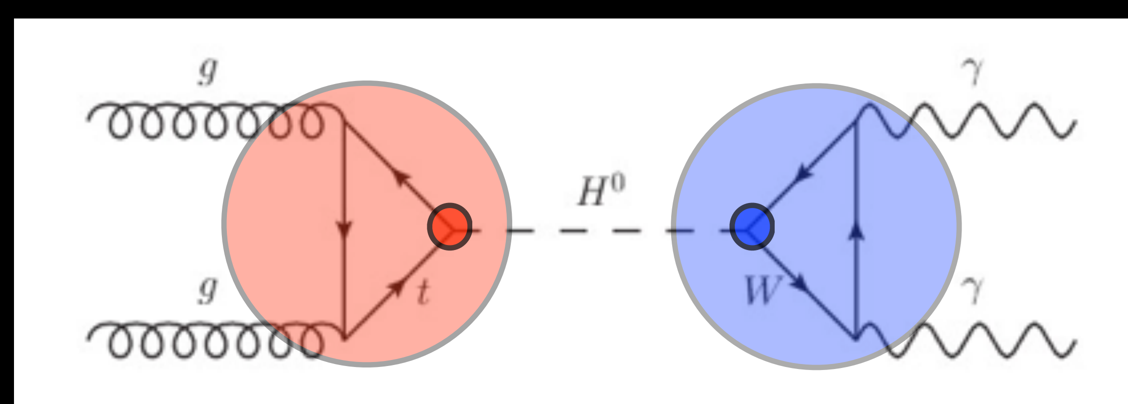
- **Strategy:** **narrow width approximation**

$$(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

- **Measurement:** **parametrize deviations** **wrt SM in production and decay**
  - implies precise knowledge of the SM prediction
  - BSM acceptance effects are not considered

$$\Delta_x \equiv \frac{g_x^{\mathrm{SM}}}{g_x} - 1$$

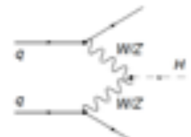
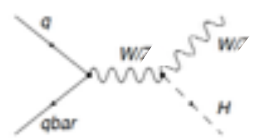
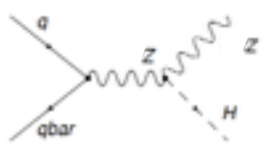
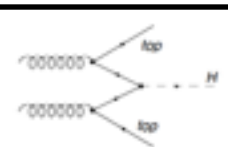
$$\kappa_x \equiv \frac{g_x}{g_x^{\mathrm{SM}}}$$

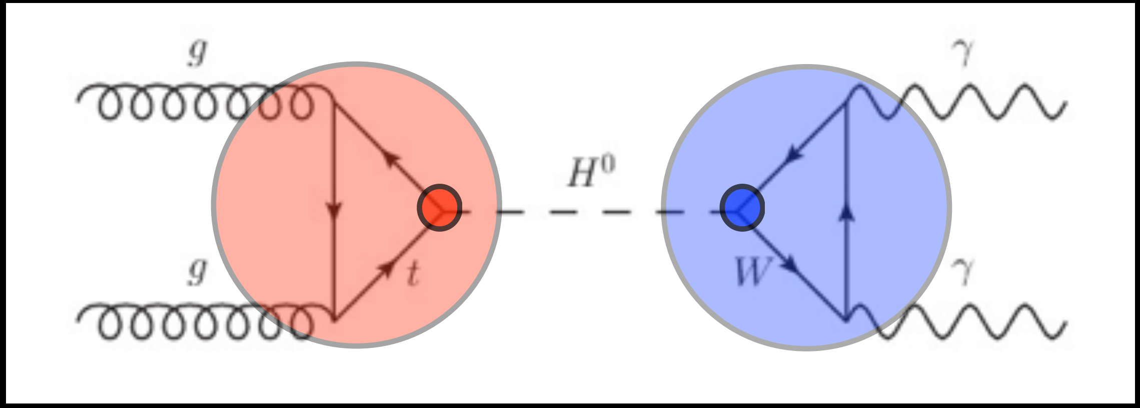


$$(\sigma \cdot \mathrm{BR})\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_{\mathrm{g}}^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}$$

LHC Higgs production and decay

m_H = 125 GeV, 8 TeV

Process	Diagram	Cross section [fb]
gluon-gluon fusion		19520
vector boson fusion		1578
WH		697
ZH		394
ttH		130



m_H = 125 GeV

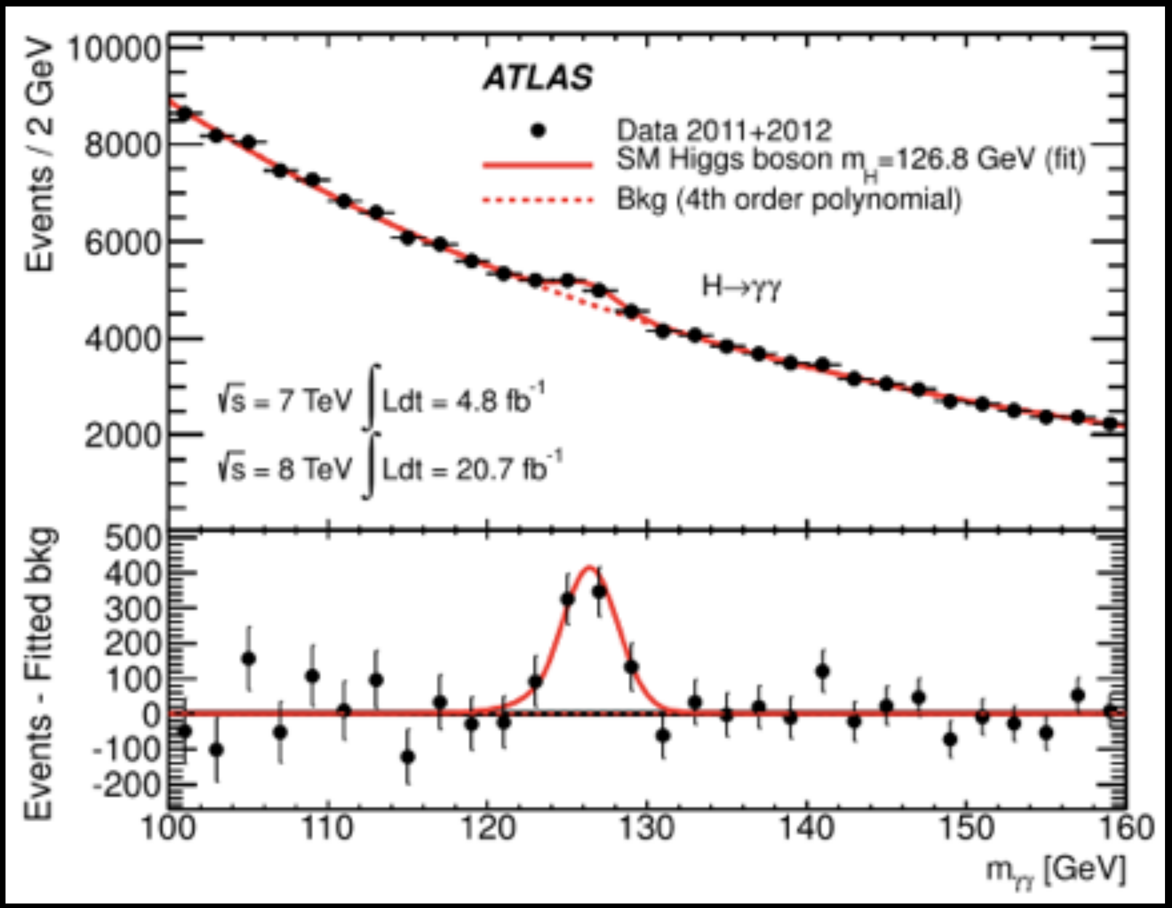
Decay	BR [%]
bb	57.7
ττ	6.32
cc	2.91
μμ	0.022
WW	21.5
gg	8.57
ZZ	2.64
γγ	0.23
Zγ	0.15
ΓH [MeV]	4.15

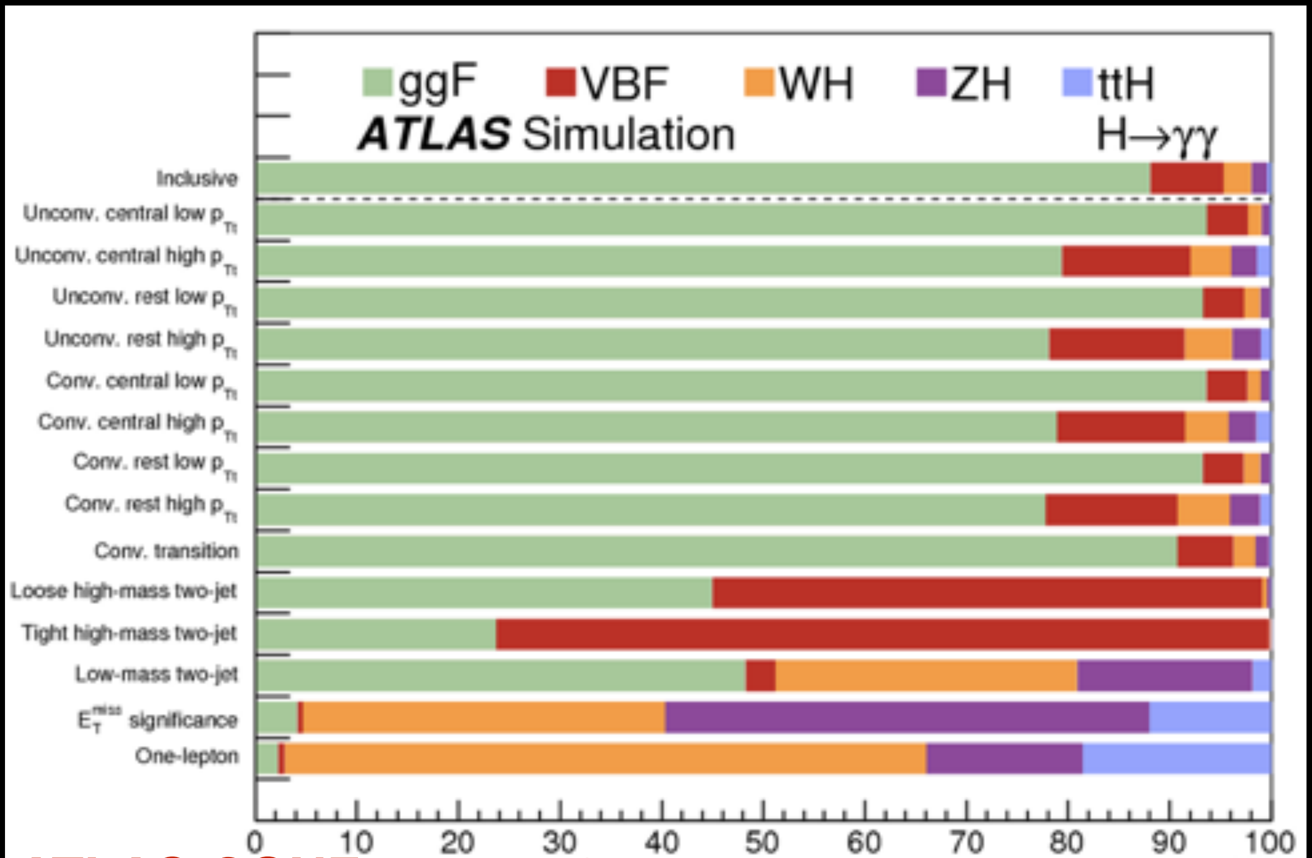
Available Channels

	untagged	jet-tag	VBF	VH	ttH
H ➔ γγ	used				
H ➔ WW ➔ 2l2ν					
H ➔ ZZ ➔ 4l		possible			
H ➔ bb					
H ➔ ττ					
H ➔ Zγ					
H ➔ μμ					
H ➔ invisible					

simplified view

Cross Contamination





ATLAS-CONF-2014-009

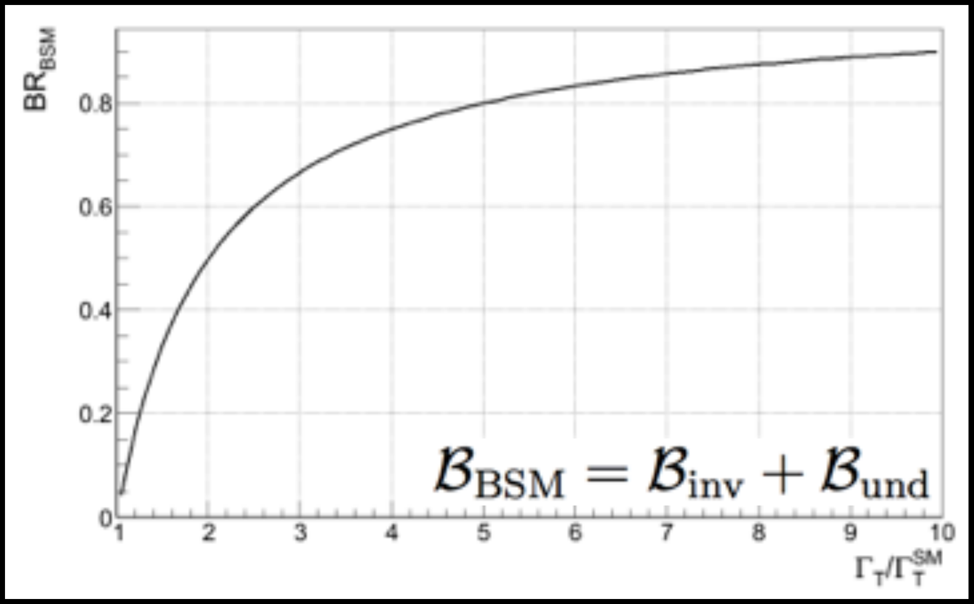
$$n_s^{c,f} = \sum_i (\sigma^i \times \mathcal{B}^f)_{SM} \times A_i^{c,f} \times \epsilon_i^{c,f} \times \mathcal{L} \times \frac{\kappa_i \cdot \kappa_f}{\kappa_H^2}$$

Total Width

- **SM Higgs total width $\Gamma_H \approx 4.2$ MeV**
- **Indirect constrained in coupling fits**
  - requires further assumptions

$$\kappa_H^2 \equiv \frac{\Gamma_H}{\Gamma_H^{SM}} \qquad \kappa_H^2 = \sum_f \kappa_f^2 \frac{\mathcal{B}_{\mathrm{SM}}(H \to ff)}{1 - \mathcal{B}_{\mathrm{BSM}}}$$

assuming SM Higgs coupling



- **Measurements at the LHC**
  - interference between Higgs signal $gg \to H \to \gamma\gamma$ and continuum $gg \to \gamma\gamma$ results in Higgs mass shift
  - off-shell H^* production in $H^* \to ZZ^{(*)}$ (more later)

Probing BSM

- Simultaneous fit of all couplings with several assumptions on total width
- Searches for new physics in loops: κ_g, κ_γ, BR_{BSM}
- Fermion vs vector boson couplings: κ_V, κ_f
- Search for asymmetries: λ_{WZ}, λ_{du}, λ_{lq}

$$\lambda_{xy} \equiv \frac{\kappa_x}{\kappa_y}$$

- Overall scaling of signal strength: μ

Effective Field Theory Approach

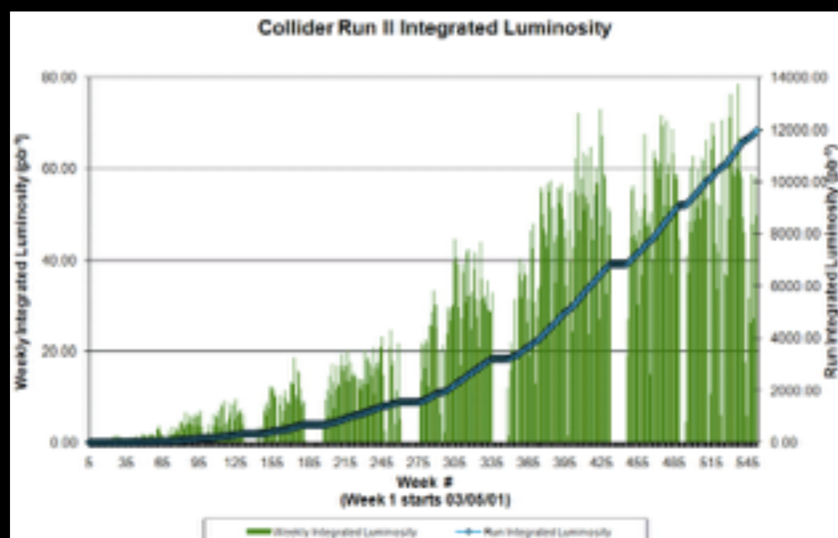
- Parametrize SM deviation by higher-dimensional operators

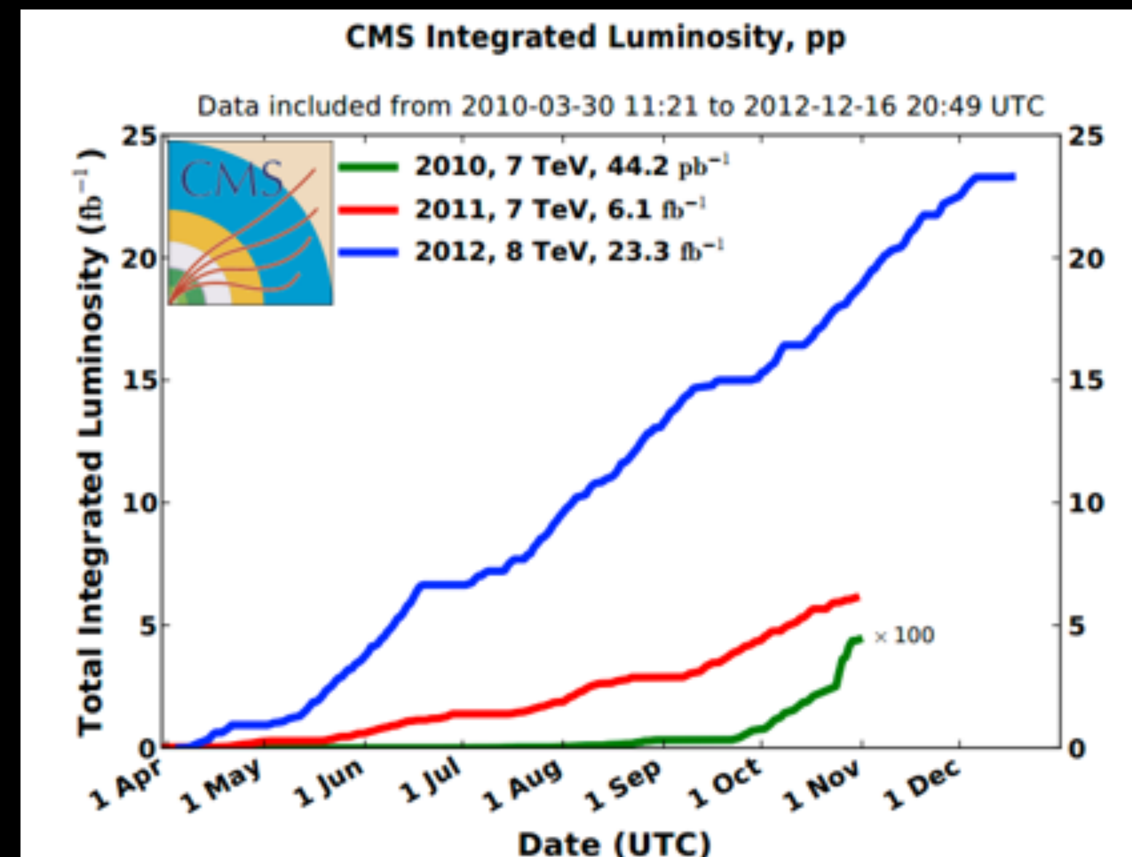
$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$

- Allows study of large class of BSM models
- Allows combination with electroweak precision data
- Does not account for effects of light particles in loops, but theses can be studied with specific BSM models
- No results from LHC experiments for now.

Experimental Status

Current Player





Future Player

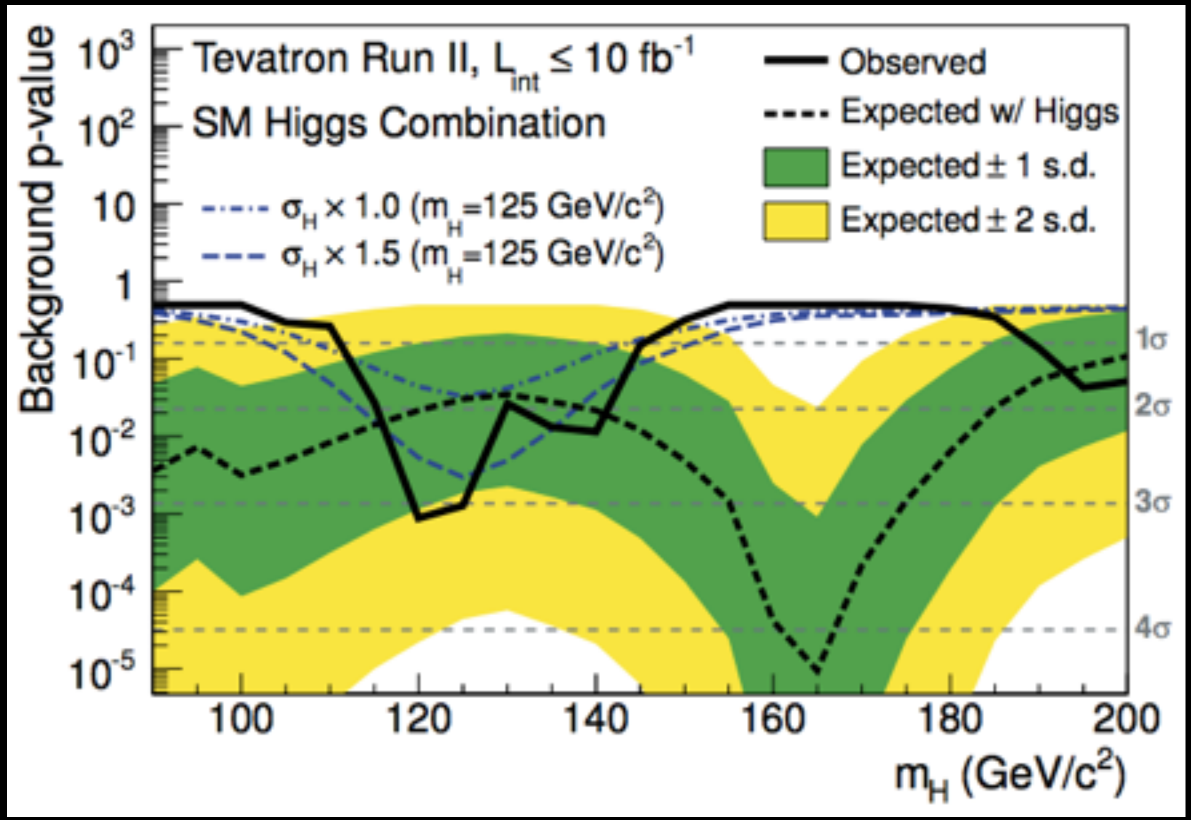
Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
$\int dt$ (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

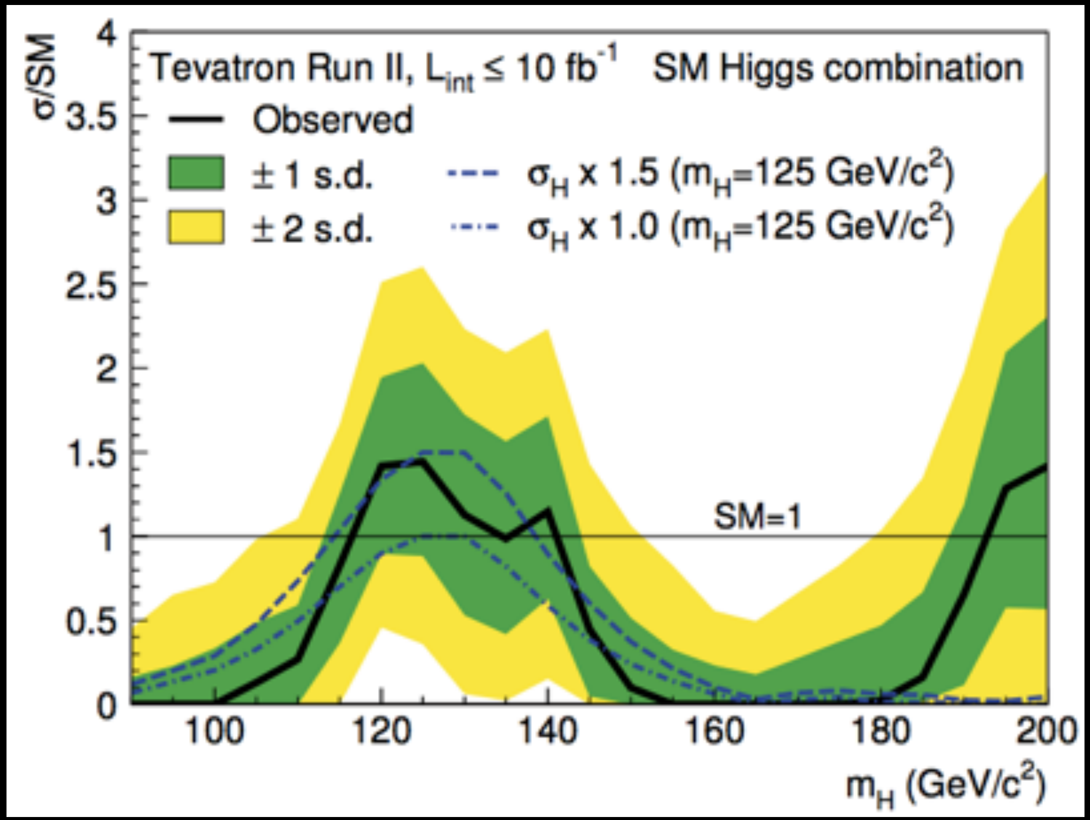
Status of LHC Higgs program

Channel	ATLAS Lumi [1/fb]	CMS Lumi [1/fb]	Specialty	Inclusive signature	σ Obs. (Exp.)	mass [GeV]	Signal Strength μ	Spin/ Parity
H ➜ ZZ ➜ 4l	4.6+20.7 ATLAS-CONF-2013-012	5.1+19.6 arXiv: 1312.5353	mass, discovery, spin/parity	4 leptons	6.6 (4.4) 6.8 (6.7)	124.3 ±0.6 (stat) ±0.5 (sys) 125.6 ±0.4 (stat) ±0.2 (sys)	1.7+0.5-0.4 0.93+0.29-0.25	√ √
H ➜ WW ➜ 2l2ν	4.6+20.7 ATLAS-CONF-2013-030	4.9+19.5 arXiv: 1312.1129	cross section, coupling	2 leptons, MET	3.8 (3.7) 4.3 (5.8)	consistent 125 ± 4	1.01 ± 0.31 0.72+0.20-0.18	√ √
H ➜ γγ	4.8+20.7 ATLAS-CONF-2013-012	5.1+19.6 CMS-PAS-HIG-13-001	mass, discovery, couplings	two photons	7.4 (4.3) 3.2 (4.2)	126.8 ±0.2 (stat) ±0.7 (sys) 125.4 ±0.5 (stat) ±0.6 (sys)	1.65+0.33-0.28 0.78+0.28-0.26	√ √
H ➜ bb	4.7+20.3 ATLAS-CONF-2013-079	5.0+18.9 arXiv: 1310.3687	total width, coupling to fermions	two b-jets	- 2.1 (2.1)	consistent consistent	0.2 ± 0.7 1.0 ± 0.5	- -
H ➜ ττ	20.3 ATLAS-CONF-2013-108	4.9+19.4 arXiv: 1401.5041	couplings to leptons	hadronic taus, leptons, MET	4.1 (3.2) 3.4 (3.6)	- 122 ± 7	1.4 + 0.5 - 0.4 0.78 ± 0.27	- -

Tevatron

- p-value 3.0σ (1.9σ expected) at m_H = 125 GeV
- Measurement of $H \to bb$ competitive with LHC





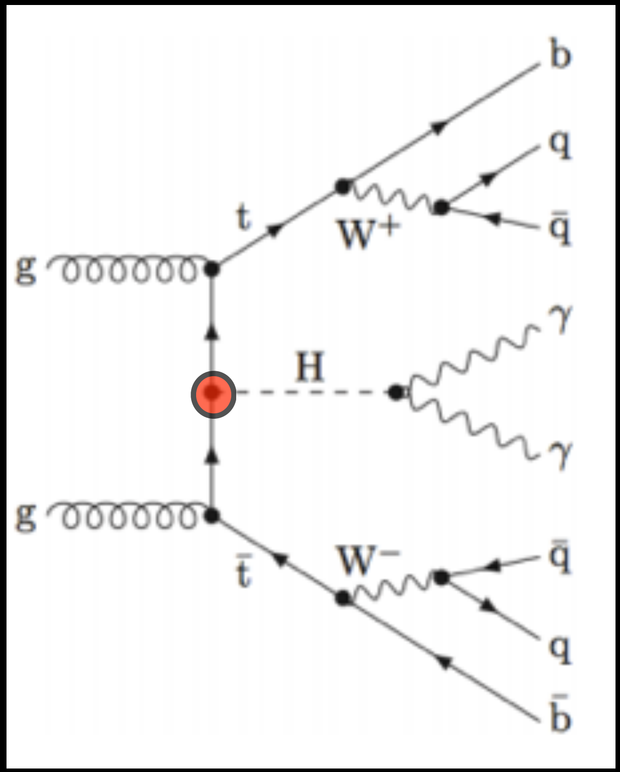
Progress on ttH

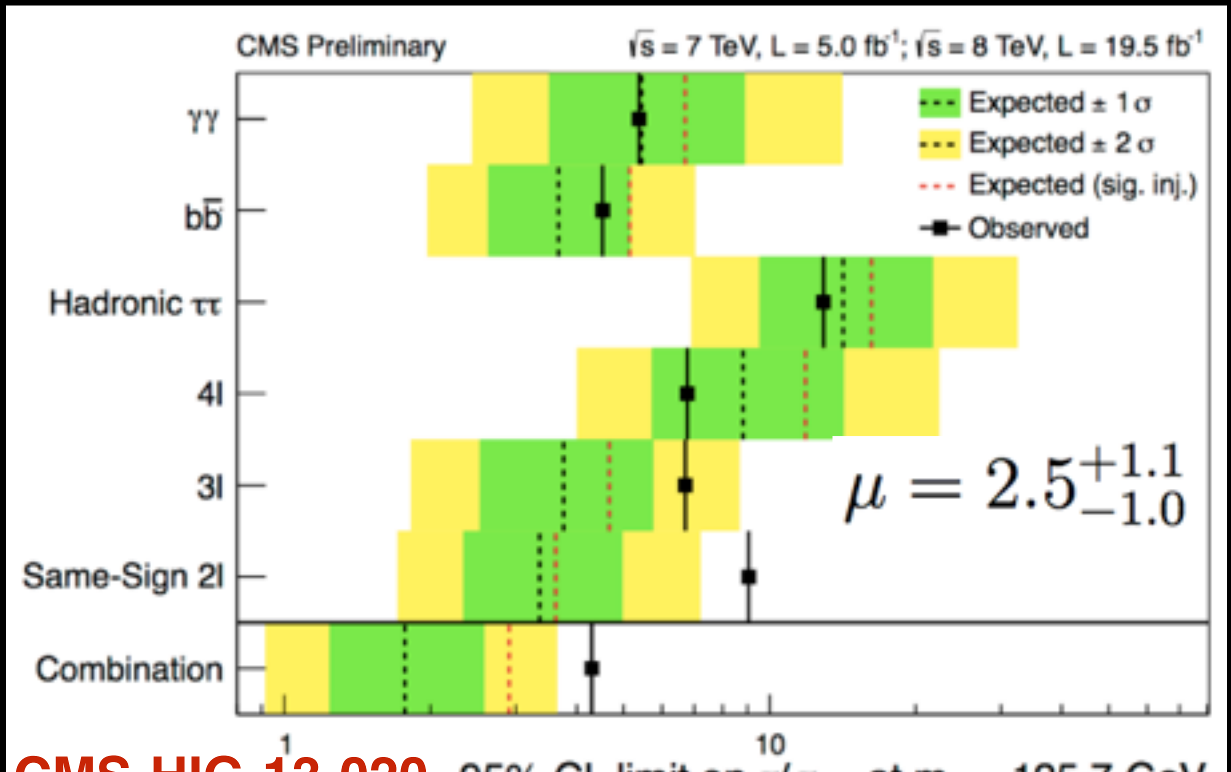
Direct study of top Yukawa coupling

CMS exploring all accessible Higgs decay modes

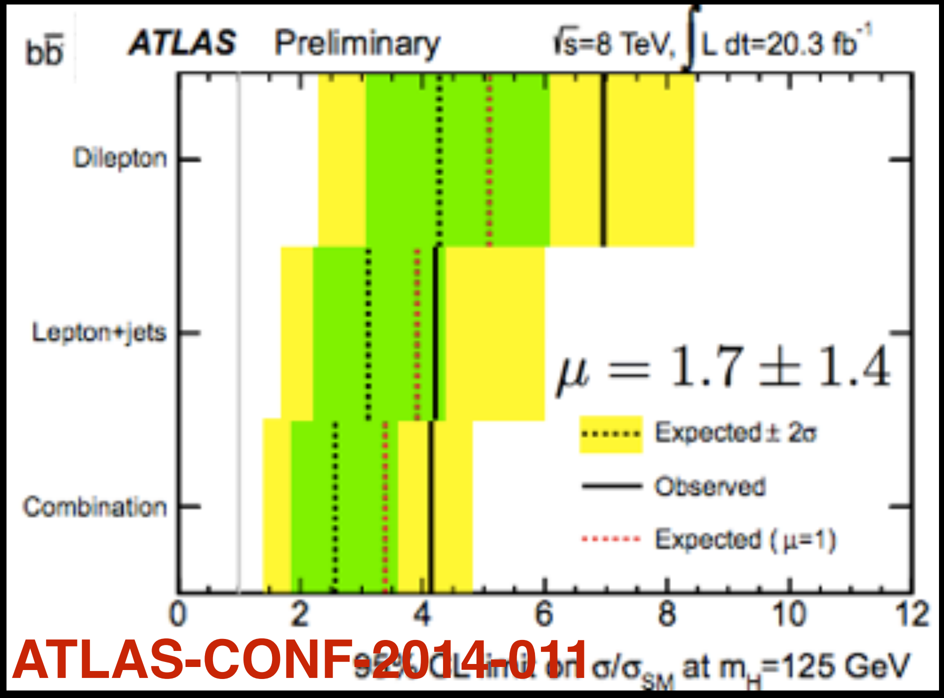
Full program on ttH underway in ATLAS

Approaching SM sensitivity in 8 TeV data





CMS-HIG-13-020

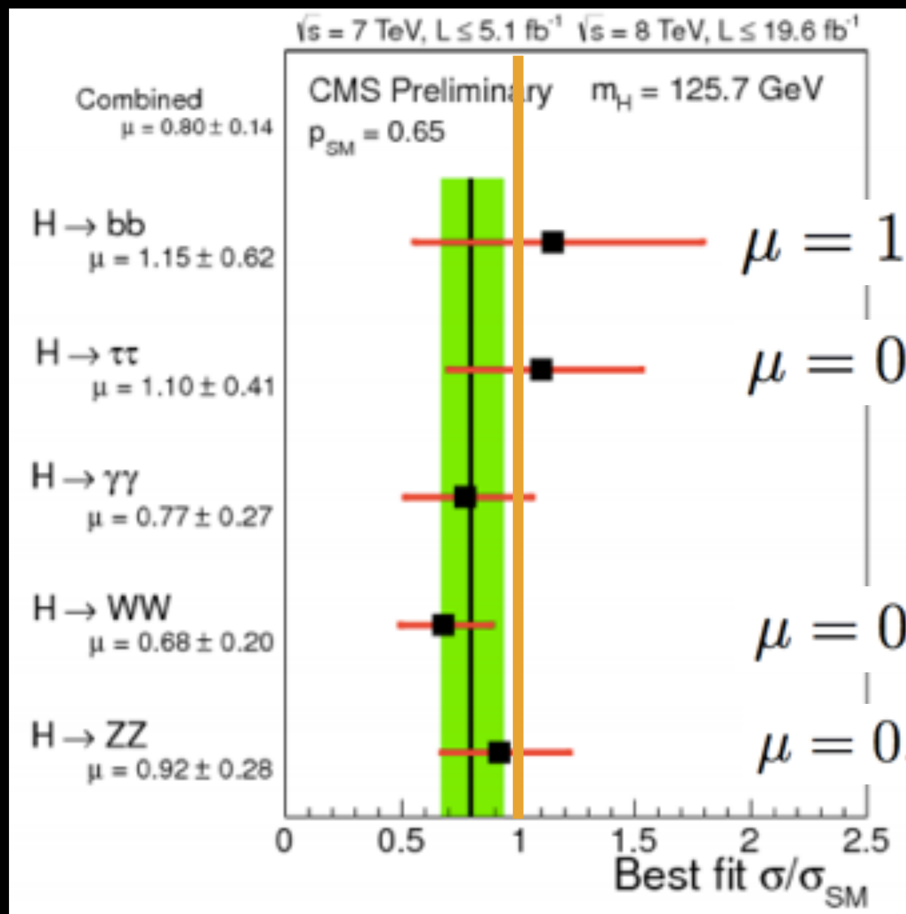


ATLAS-CONF-2014-011

Coupling Results

- CMS coupling fits (HIG-13-005) based on preliminary results released Moriond'13. Updated analyses are available.
- ATLAS coupling fits (ATLAS-CONF-2014-009) based on preliminary results released Moriond'14
- Tevatron results published in Phys.Rev.D88,052014

Summary of Signal Strength

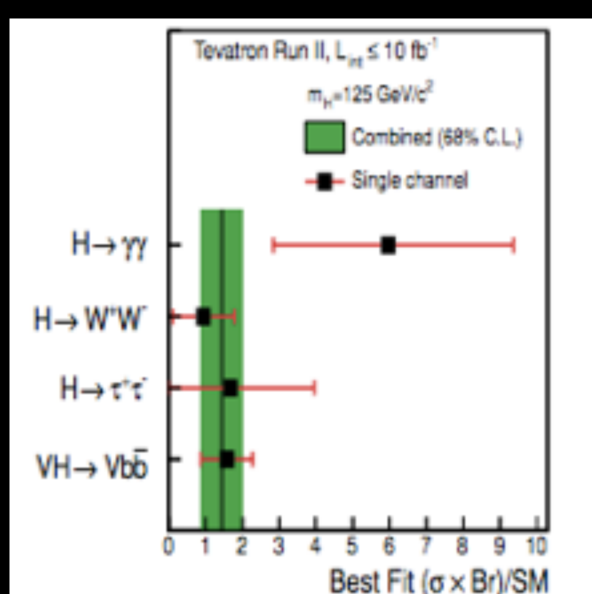


$\mu = 1.00 \pm 0.50$

$\mu = 0.78 \pm 0.27$

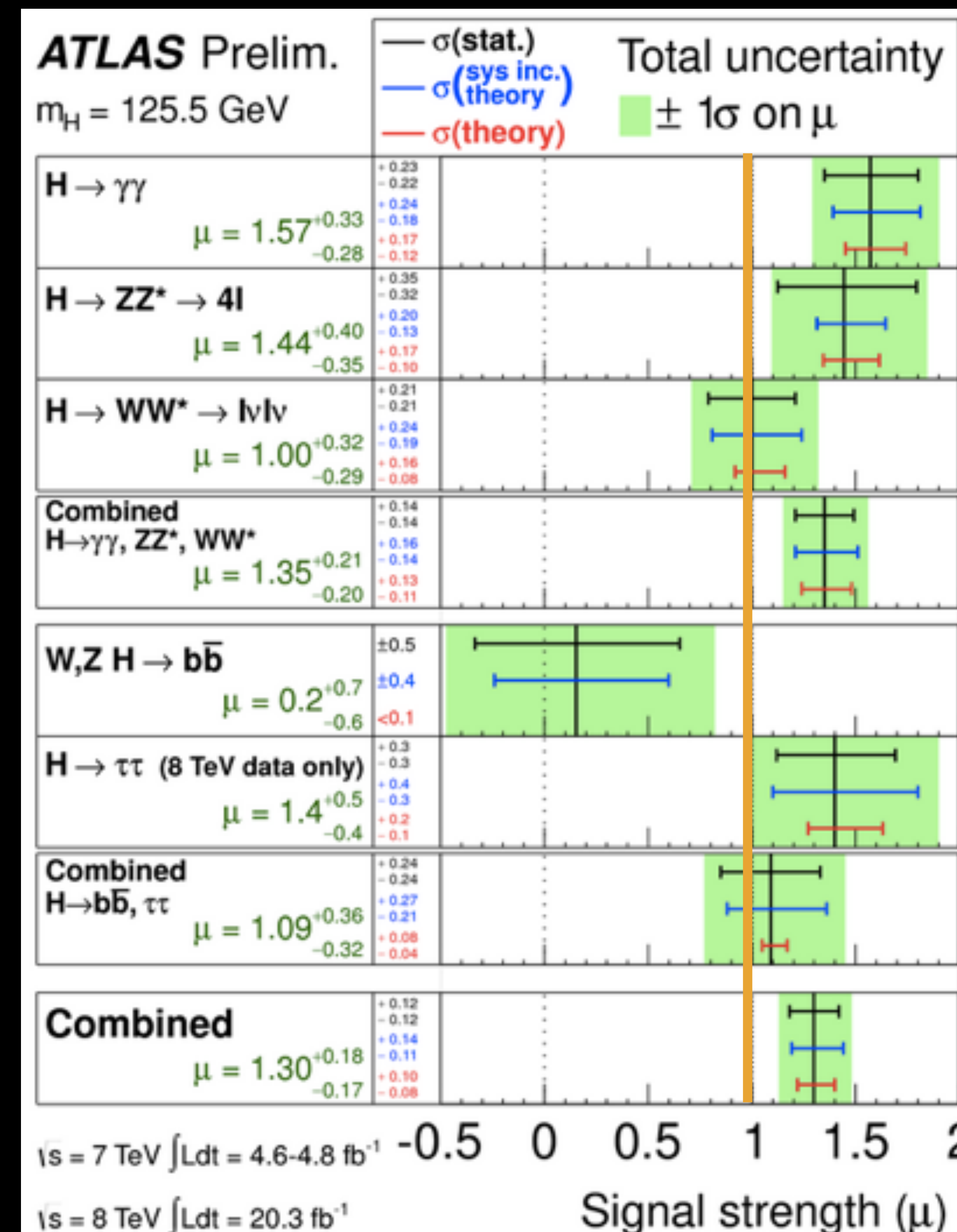
$\mu = 0.72^{+0.20}_{-0.18}$

$\mu = 0.93^{+0.25}_{-0.29}$

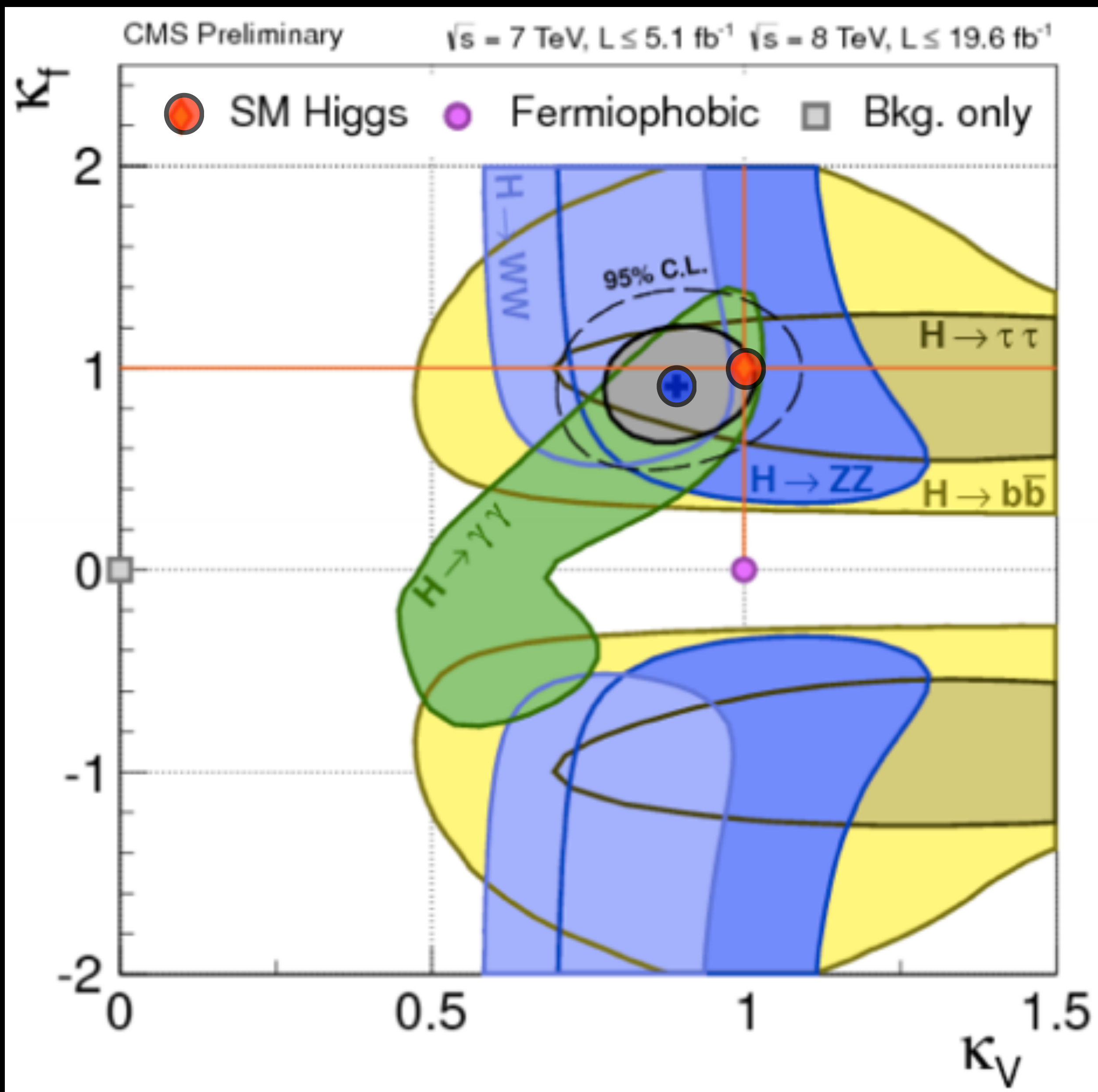


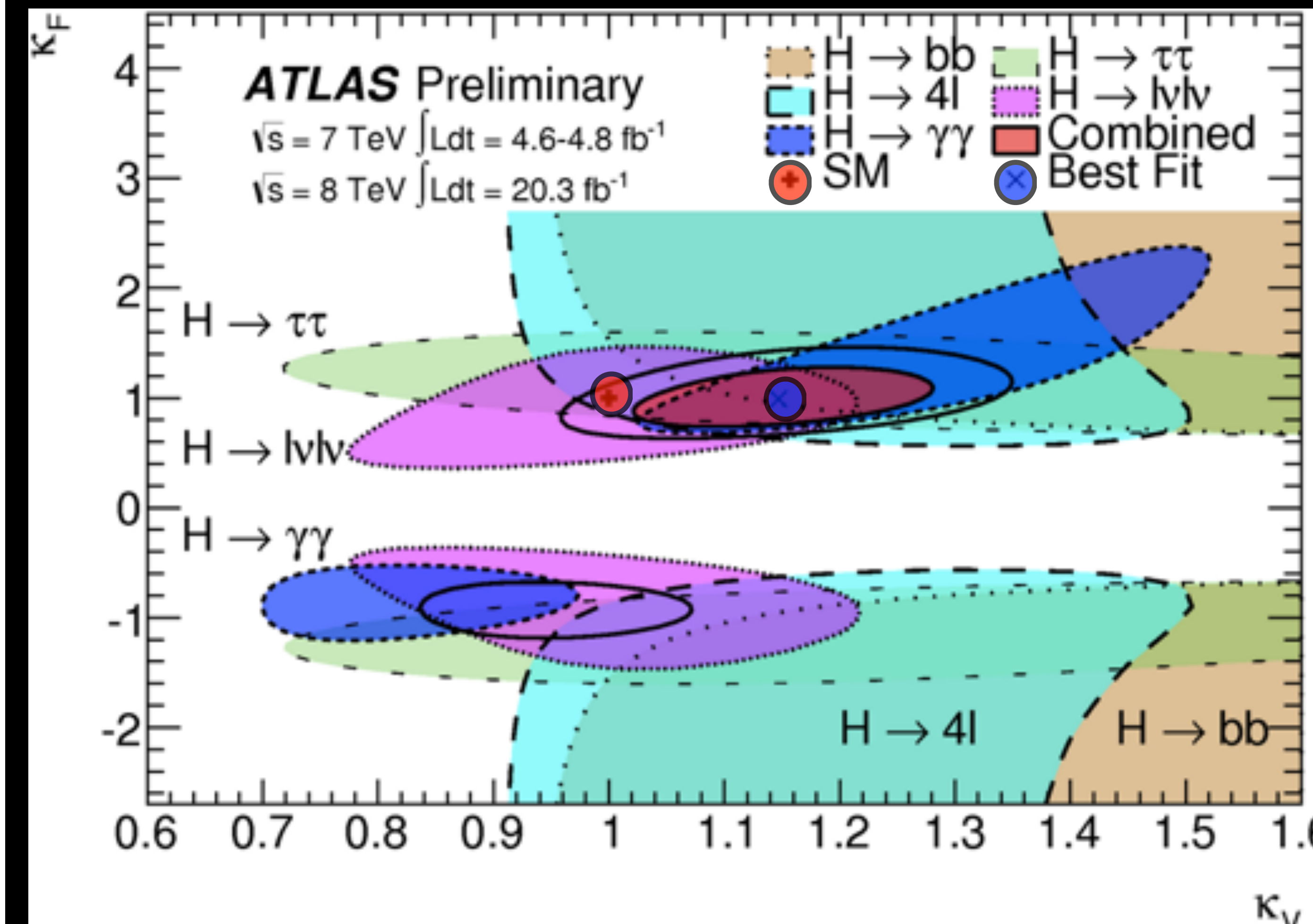
Combined:

$\mu = 1.44^{+0.59}_{-0.56}$



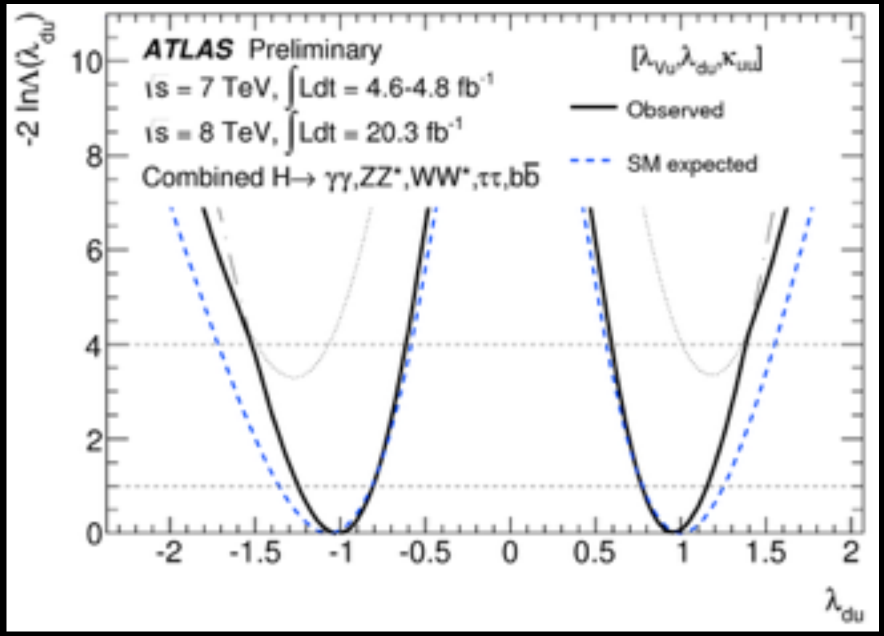
Vector and fermion coupling

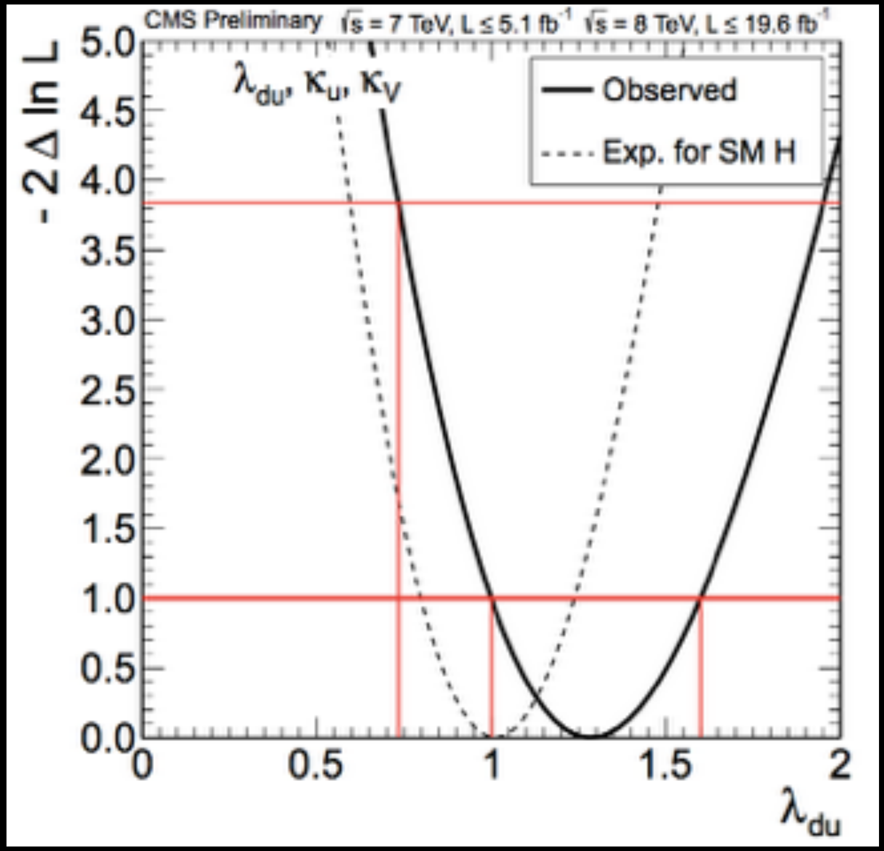




Fermion Coupling Asymmetry

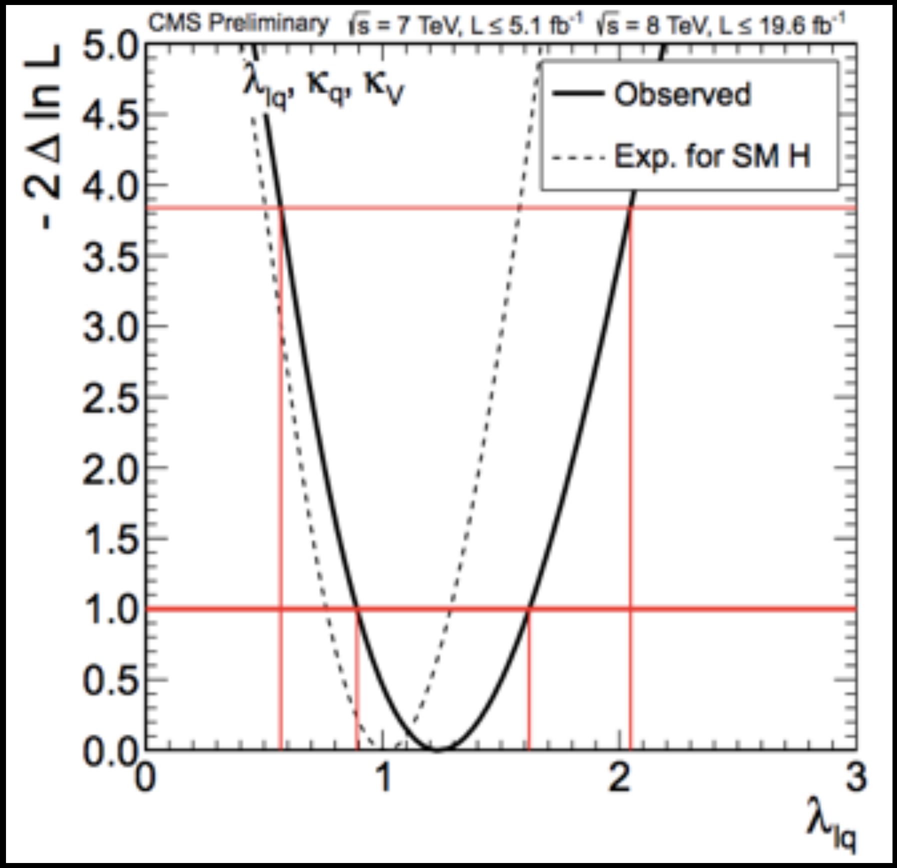
- BSM models (e.g. 2HDM) show asymmetries between up and down type or lepton and quark couplings
- Three parameter fits
- Measurement of κ_b and κ_τ coupling allows measurement of λ_{du}
- Measurement of κ_τ allows a measurement of λ_{lq}
- Downtype fermion couplings established by ATLAS (~3.6σ) and CMS (~4.0σ)





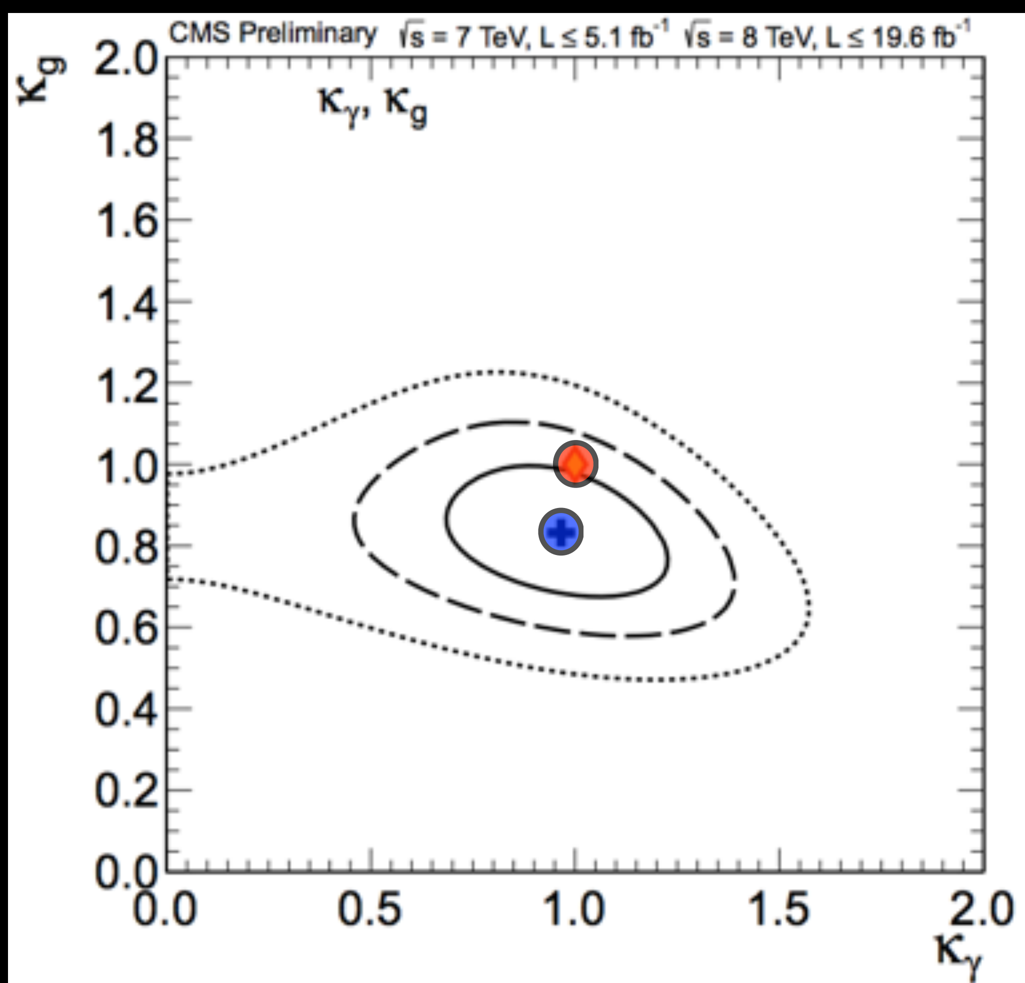
Lepton Quarks Asymmetry

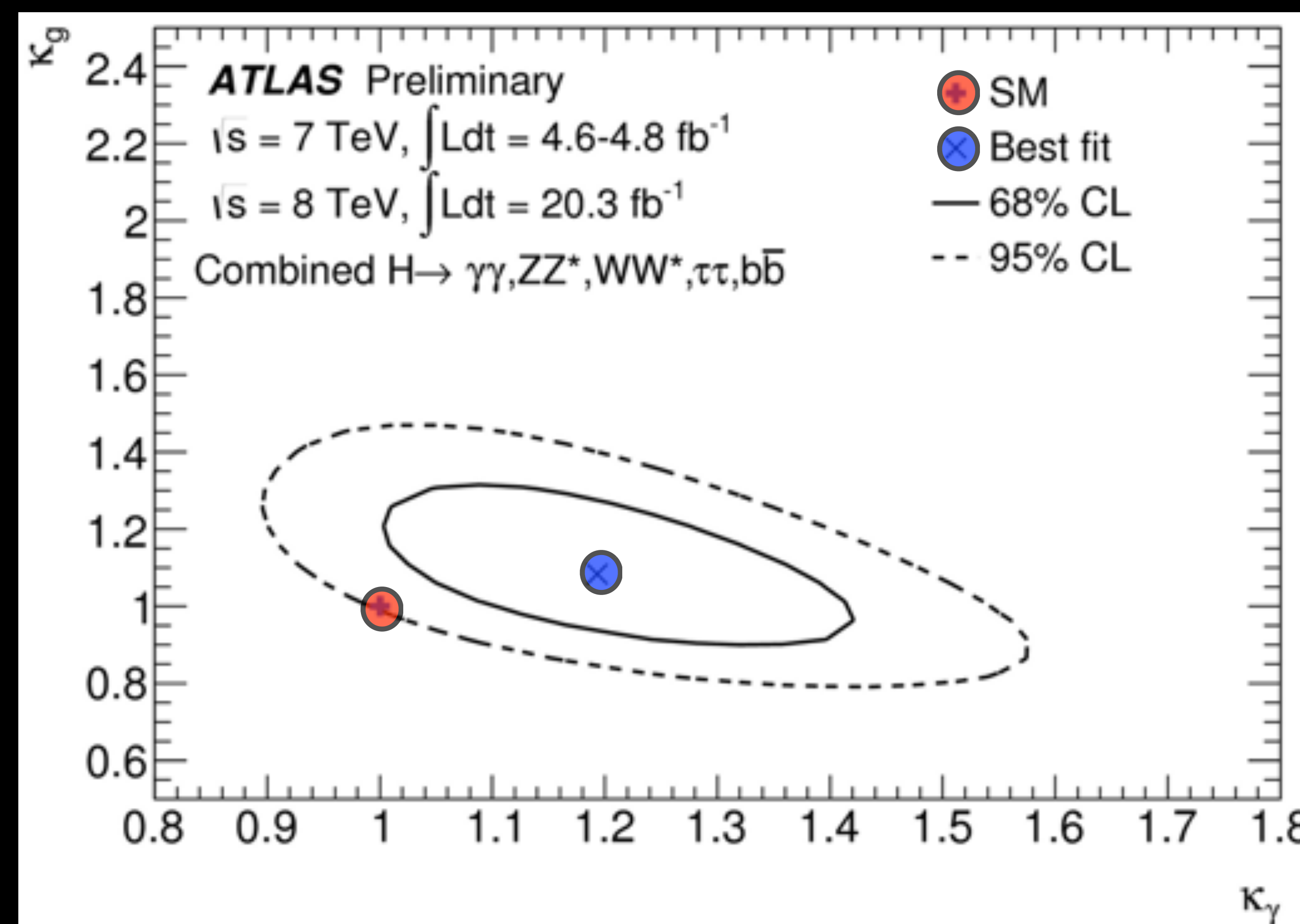
- BSM models (e.g. 2HDM) show asymmetries between up and down type or lepton and quark couplings
- Three parameter fits
- Measurement of κ_b and κ_τ coupling allows measurement of λ_{du}
- Measurement of κ_τ allows a measurement of λ_{lq}
- Downtype fermion couplings established by ATLAS (~3.6σ) and CMS (~4.0σ)



Probing BSM in Loops

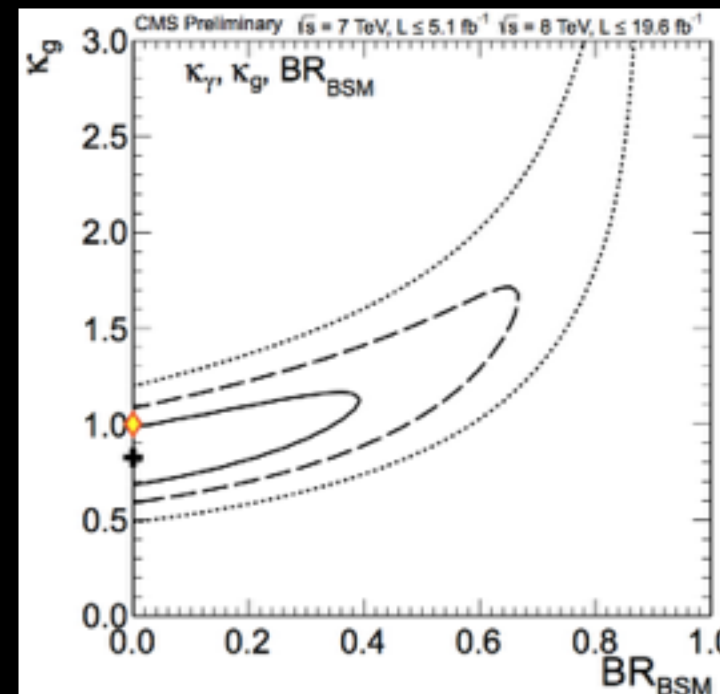
- Effective couplings to gluons and photons

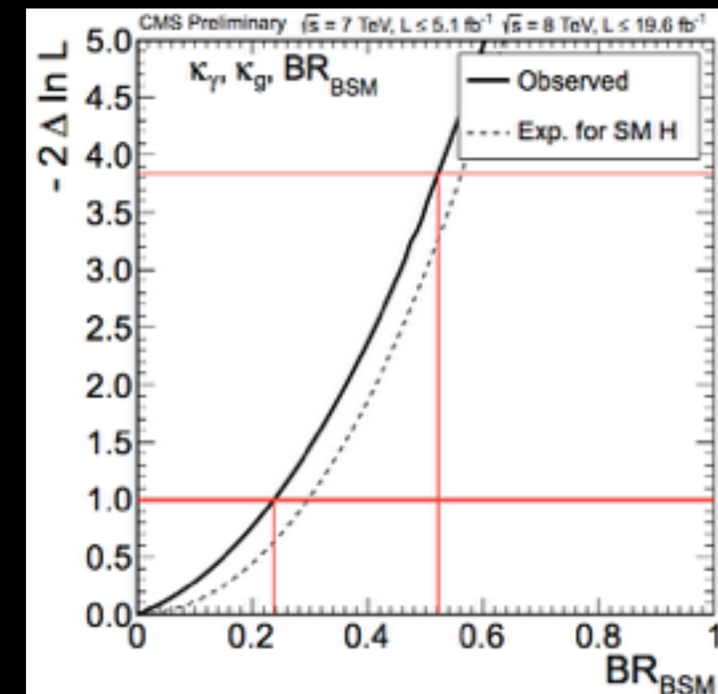


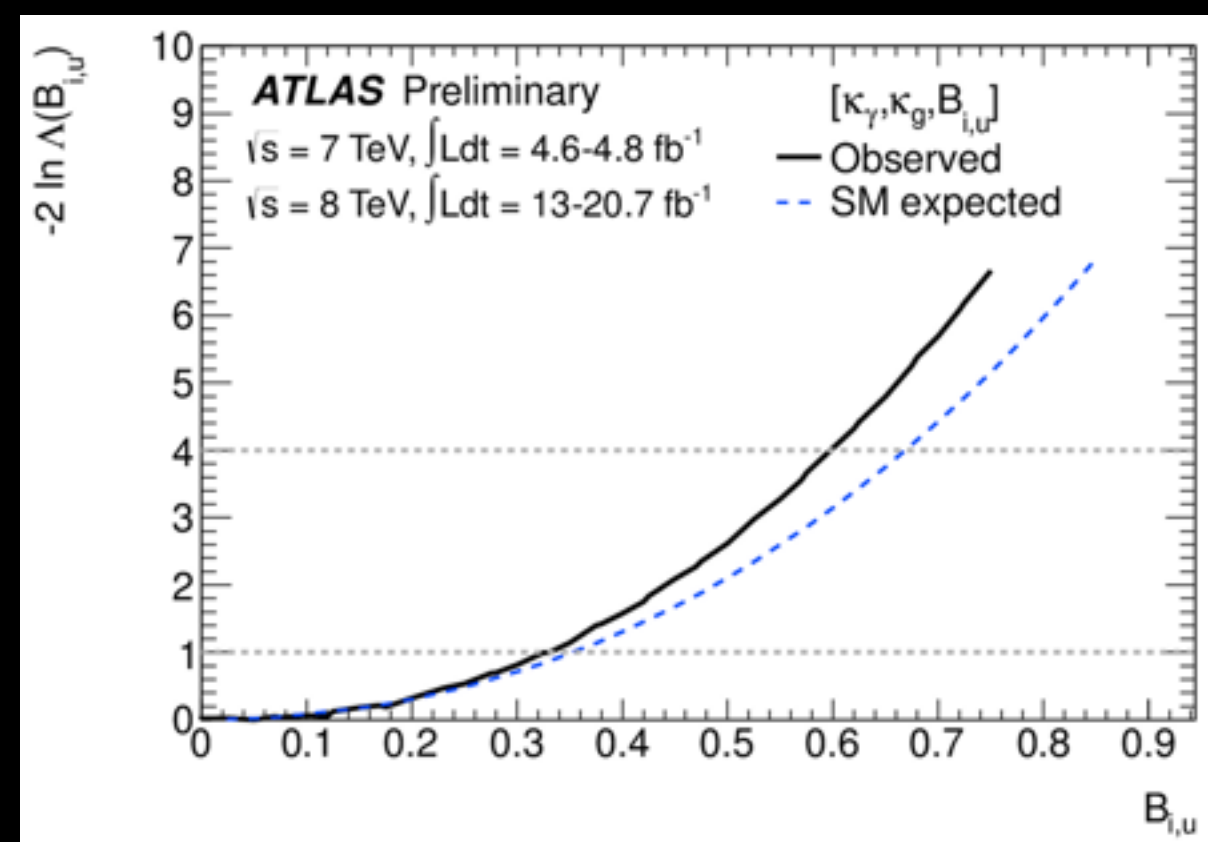


Probing BSM in Loops

- Constrain total width assuming SM Higgs tree-level couplings
- Degeneracy of BR_{BSM} with gluon coupling from $\sigma(gg \to H)$
- Direct search for invisible Higgs decays or total width measurements not included



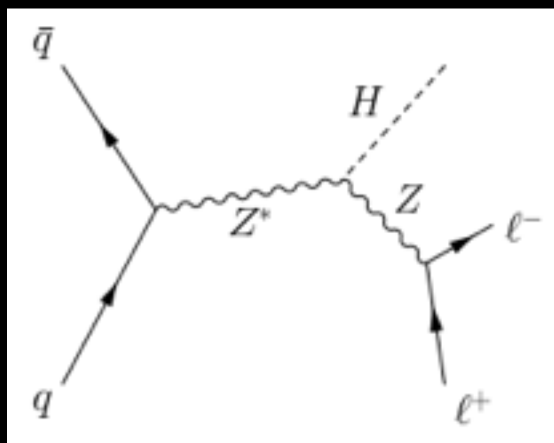


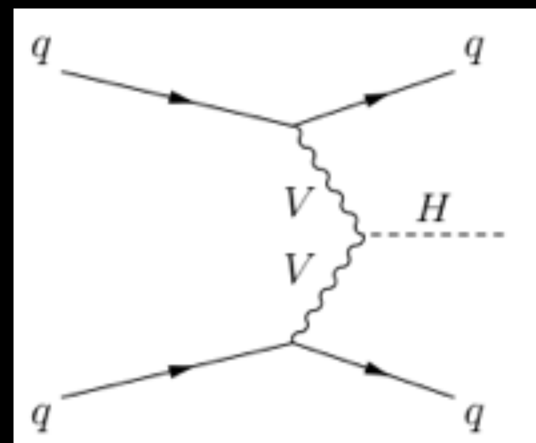


CMS: $\mathcal{B}_{BSM} < 0.52$ (0.58 expected) at 95% CL

ATLAS: $\mathcal{B}_{BSM} < 0.42$ (0.55 expected) at 95% CL

Invisible Higgs Decays

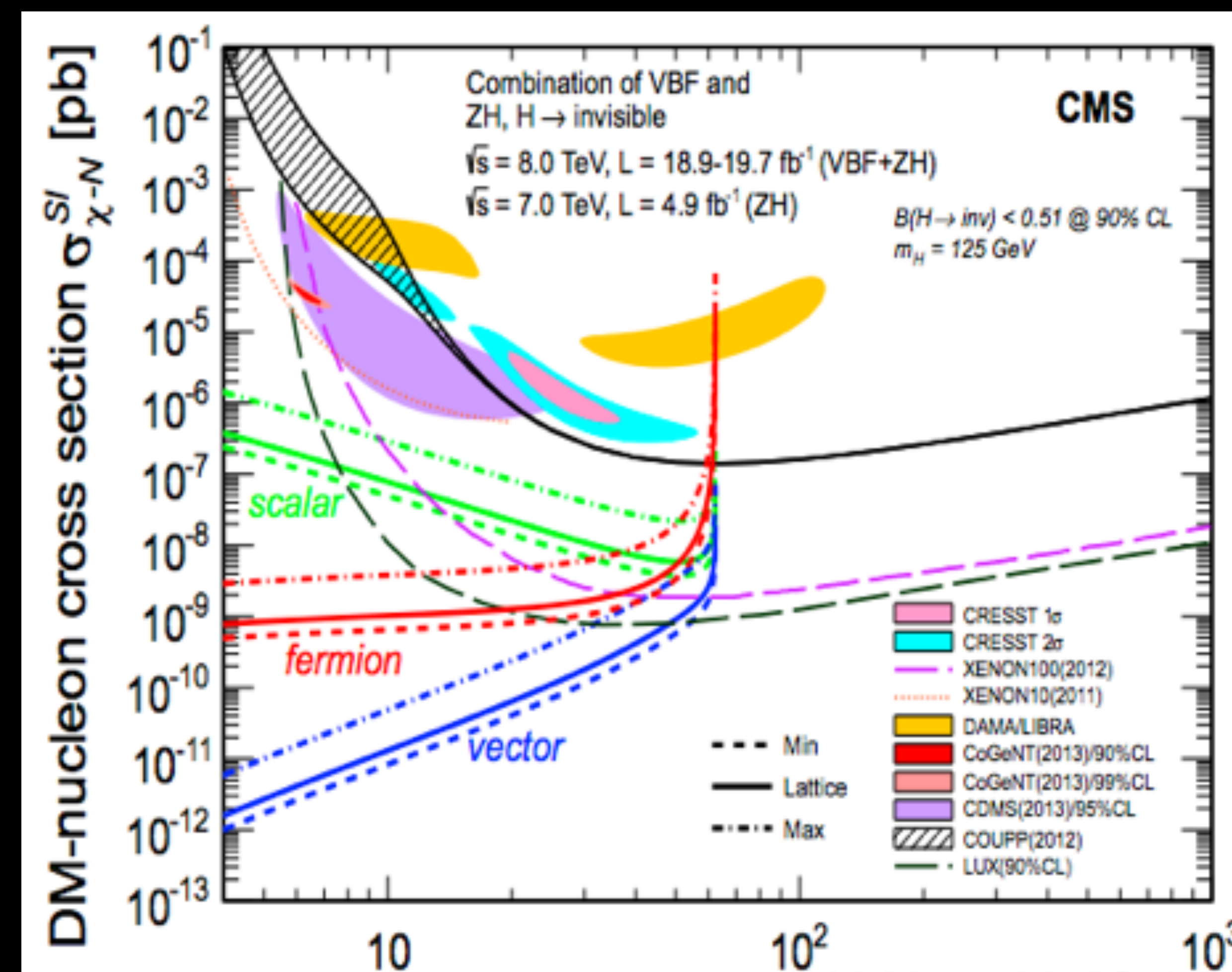




ATLAS ($H \to$ invisible): $\mathcal{B}_{\text{inv}} < 0.75$ (0.62 expected) at 95% CL

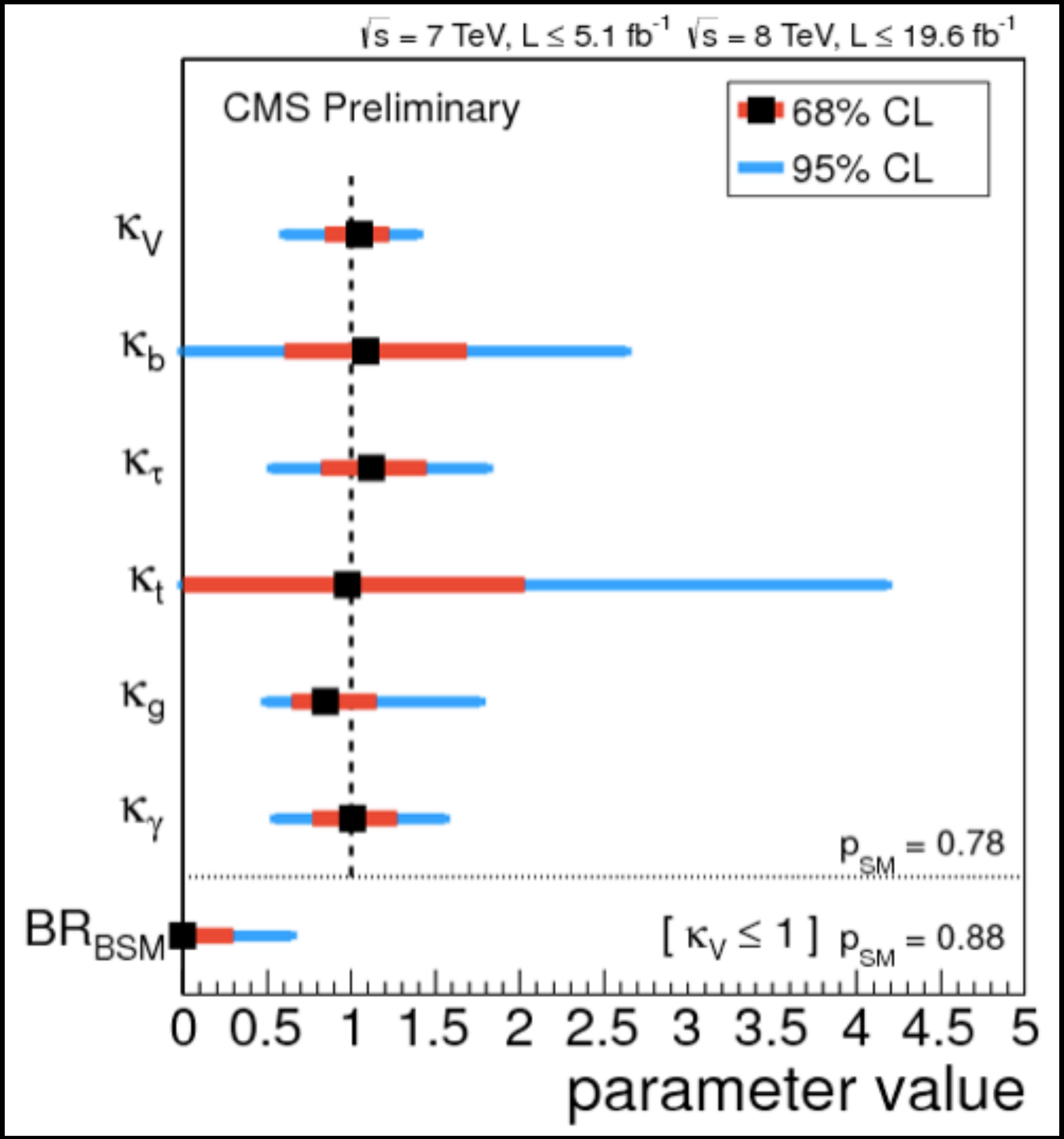
CMS ($H \to$ invisible): $\mathcal{B}_{\text{inv}} < 0.58$ (0.44 expected) at 95% CL

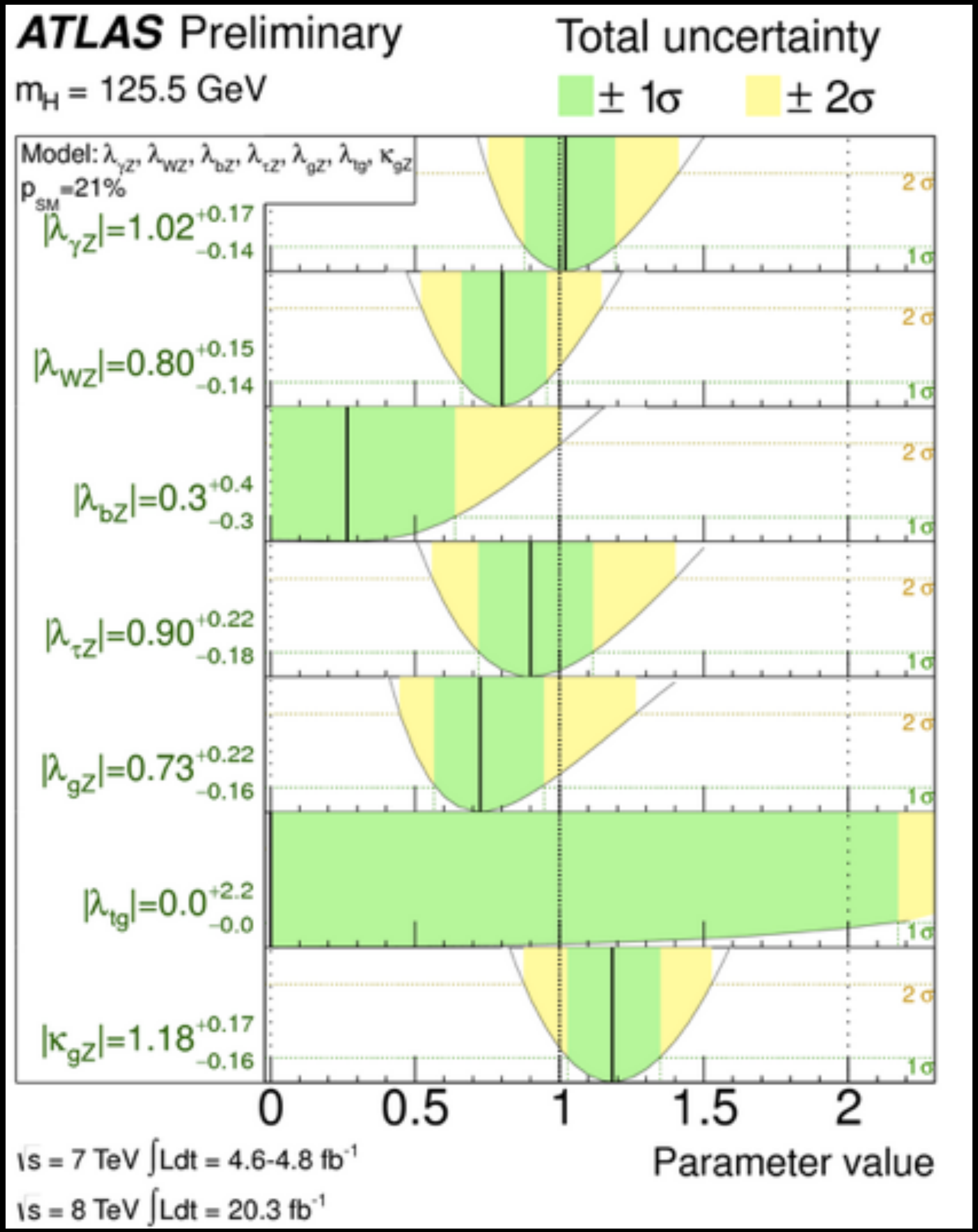
- Direct search for invisible Higgs decays
- VBF and ZH production modes used so far
- Gluon fusion production accessible
- DM interpretation complementary to direct searches



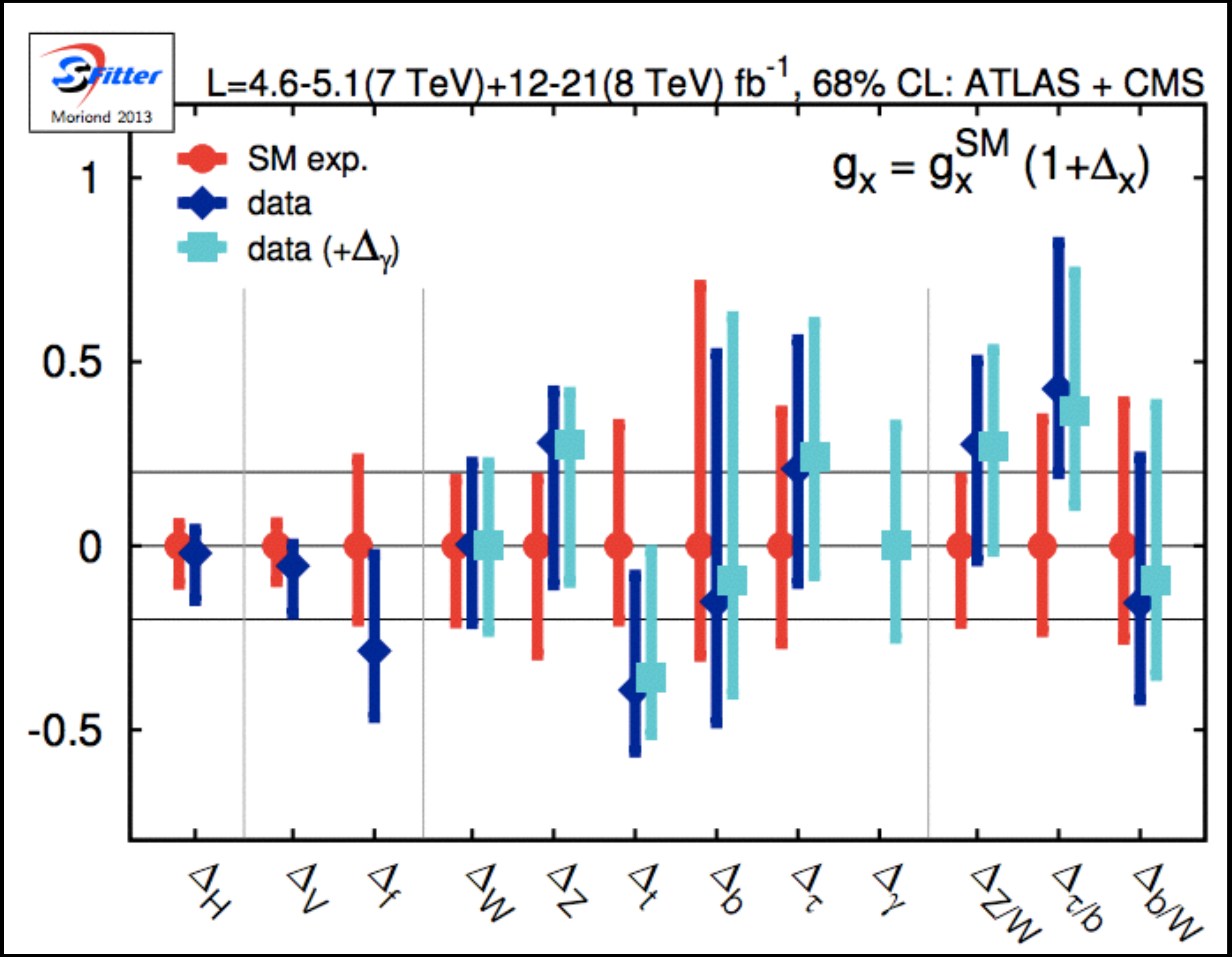
arXiv:1404.1344

Generic Fits



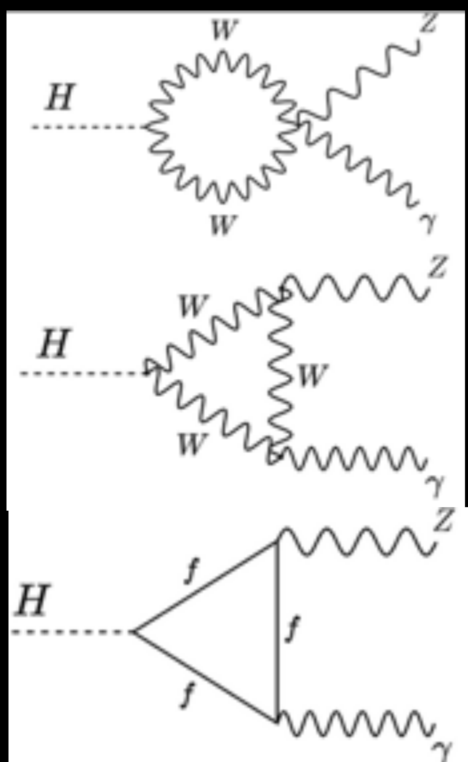


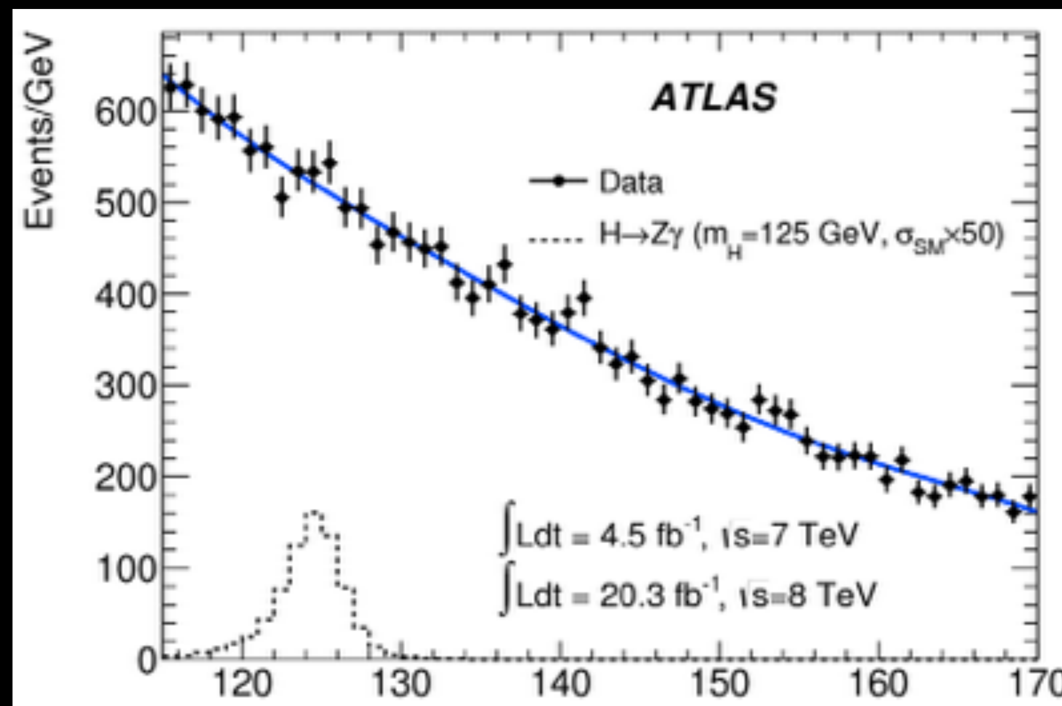
Generic Fits



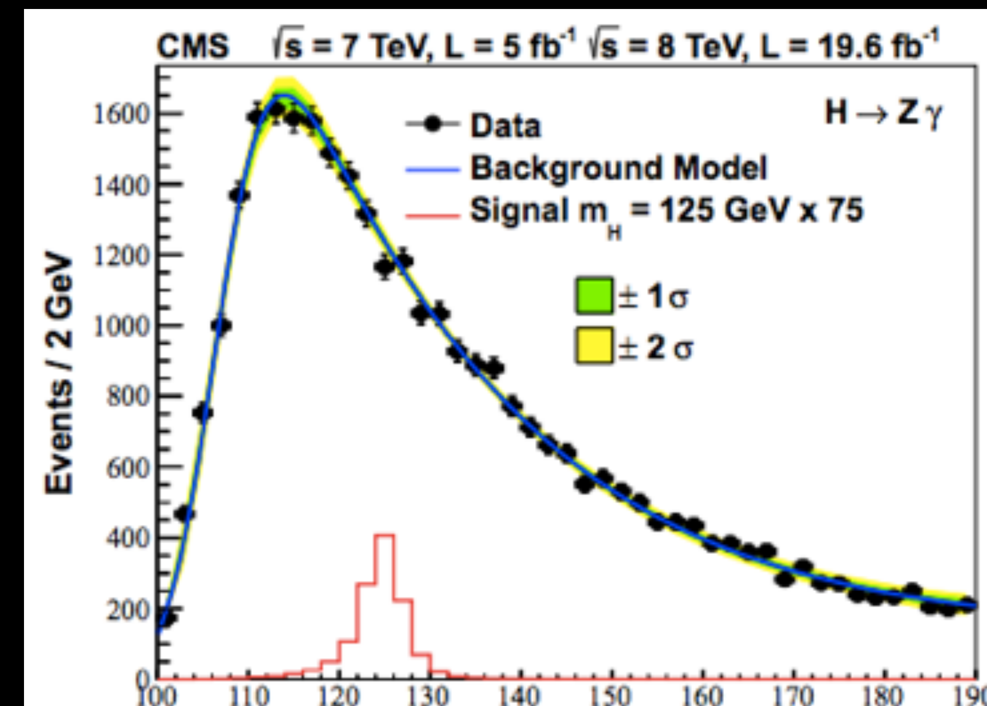
Rare SM Decay Channels

$H \to Z\gamma$ $H \to \gamma^*\gamma \to \mu^+\mu^-\gamma$





Phys.Lett.B732 (2014)



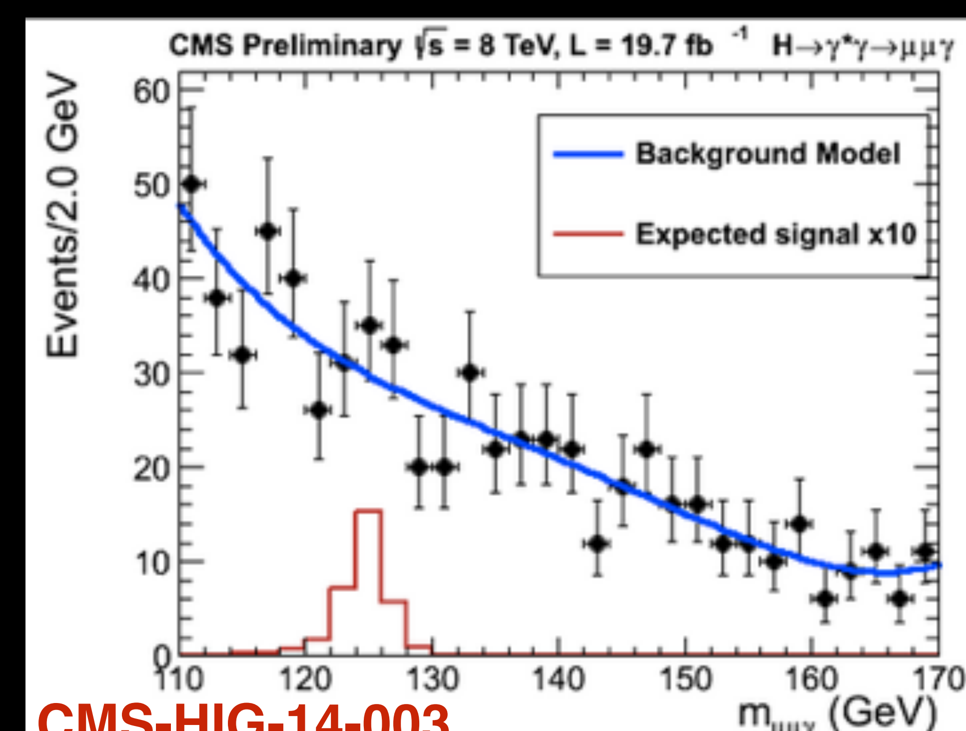
Phys.Lett.B726 (2013)

- Rare SM decay channels can be added to the general coupling fit
- No direct effect on other couplings, but other channel constrain production modes

$$\text{ATLAS } (H \to Z\gamma)\text{: } \mu < 11 \text{ (9 expected) at 95\% CL}$$

$$\text{CMS } (H \to Z\gamma)\text{: } \mu < 9 \text{ (9 expected) at 95\% CL}$$

$$\text{CMS } (H \to \gamma^*\gamma \to \mu^+\mu^-\gamma)\text{: } \mu < 12 \text{ (8 expected) at 95\% CL}$$



CMS-HIG-14-003

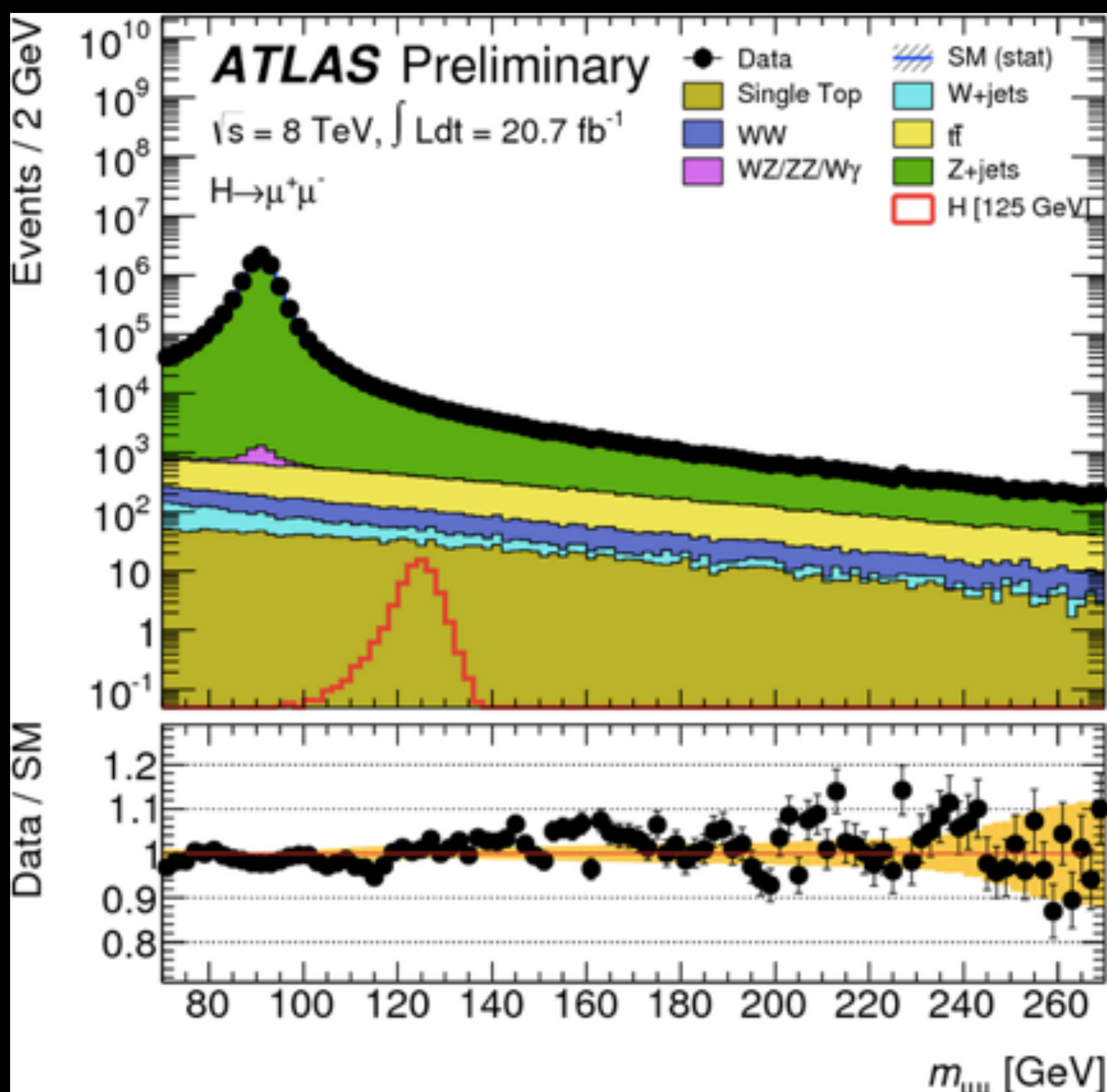
Rare SM Decay Channels

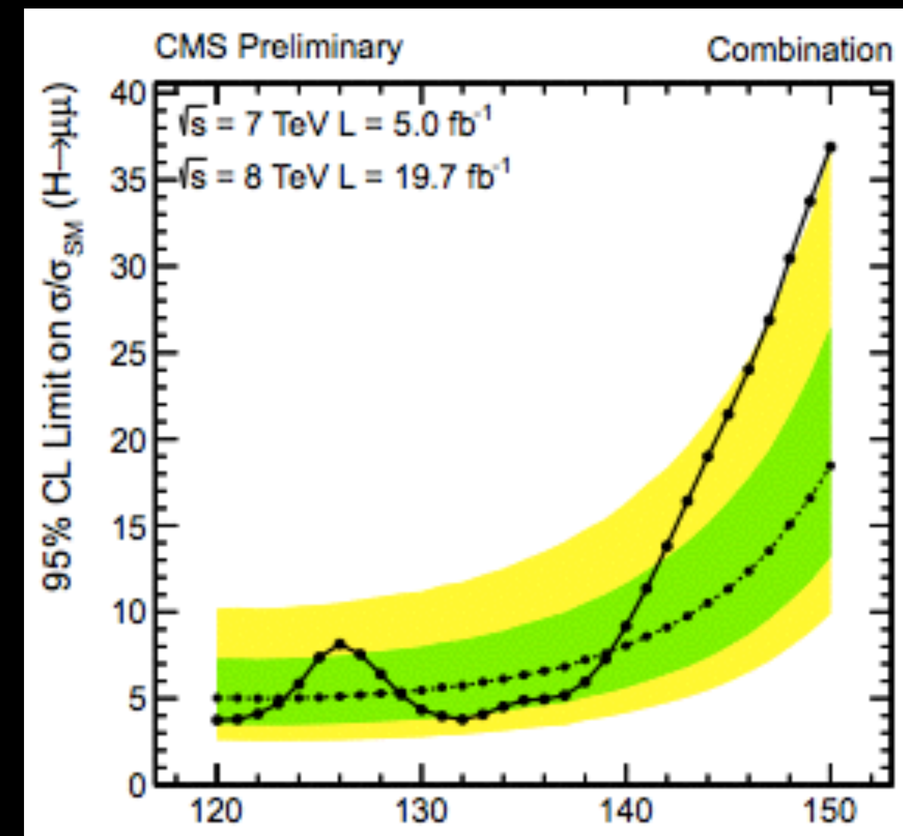
$H \to \mu\mu$

- $BR_{SM}(H\to\mu\mu) = 2.2 \times 10^{-4}$
- Good resolution, signal tiny, huge background
- Testing 2nd generation Higgs coupling

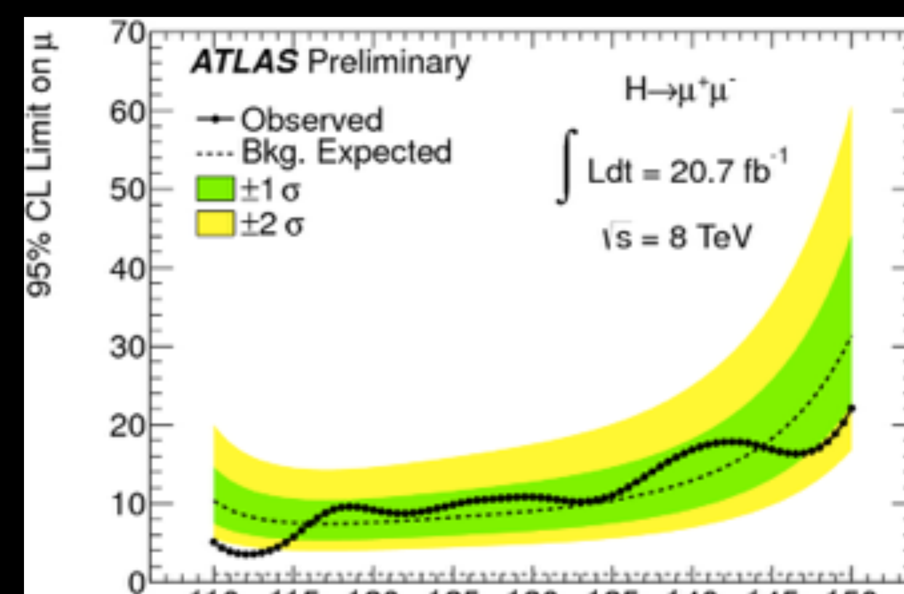
ATLAS $(H \to \mu\mu)$: $\mu < 9.8$ (8.2 expected)

CMS $(H \to \mu\mu)$: $\mu < 7.4$ (5.1 expected)





CMS-HIG-13-007



ATLAS-CONF-2013-010

Total Width Measurement

- Enhancement of cross section at high mass due to Higgs. ~8% in ZZ final state

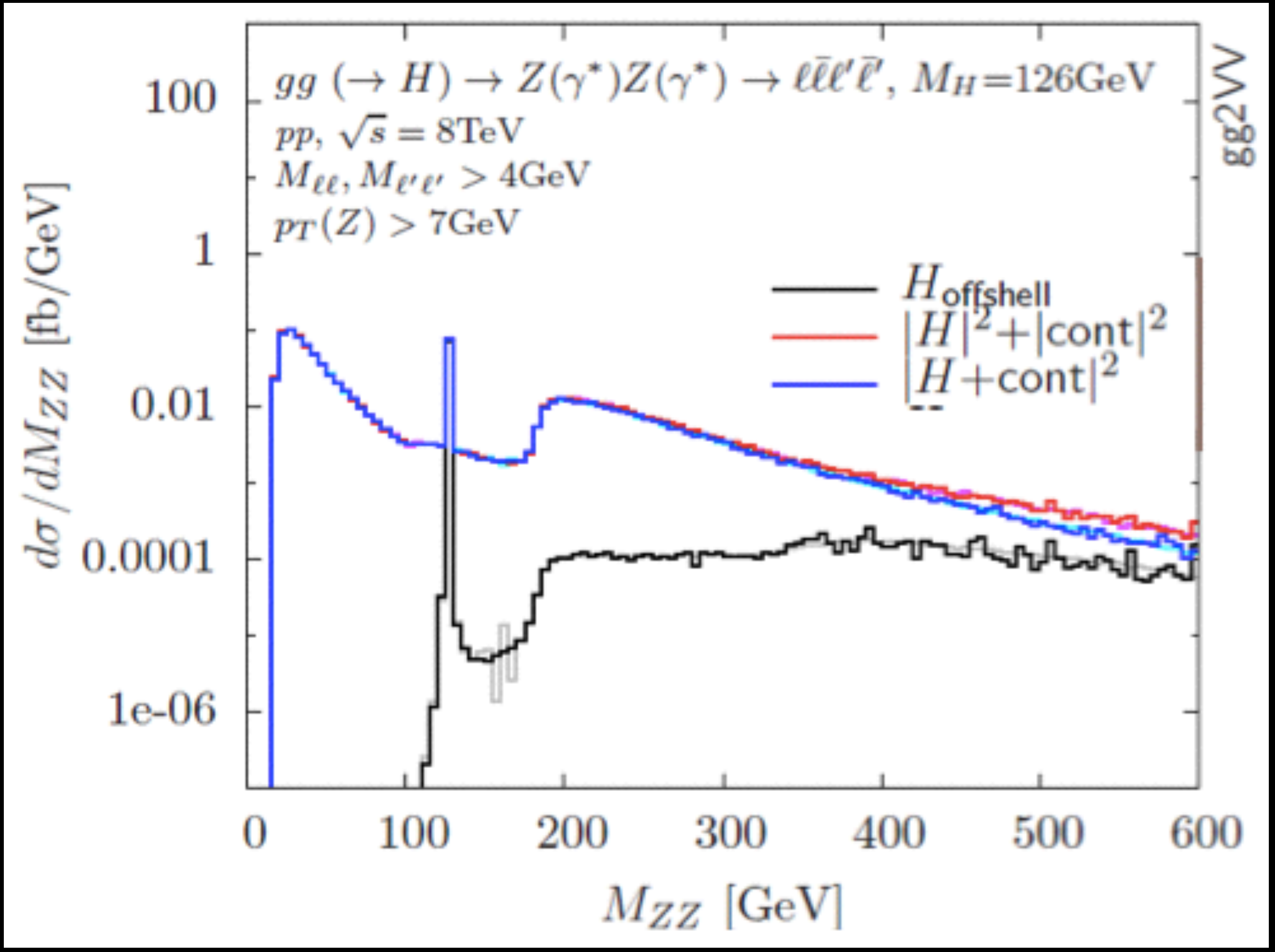
- Used to constrain Γ_H

$$r = \Gamma_{\rm H}/\Gamma_{\rm H}^{\rm SM}$$

$$\sigma^{\rm on-peak}_{\rm gg\to H\to ZZ} = \frac{\kappa_{\rm g}^2\kappa_{\rm Z}^2}{r}(\sigma\cdot\mathcal{B})_{\rm SM} \equiv \mu(\sigma\cdot\mathcal{B})_{\rm SM}$$

$$\frac{d\sigma_{\rm gg\to H\to ZZ}}{dm^2_{\rm ZZ}} \propto g^2_{\rm ggH}g^2_{\rm HZZ}\frac{F(m_{\rm ZZ})}{(m^2_{\rm ZZ}-m^2_{\rm H})^2+m^2_{\rm H}\Gamma^2_{\rm H}}$$

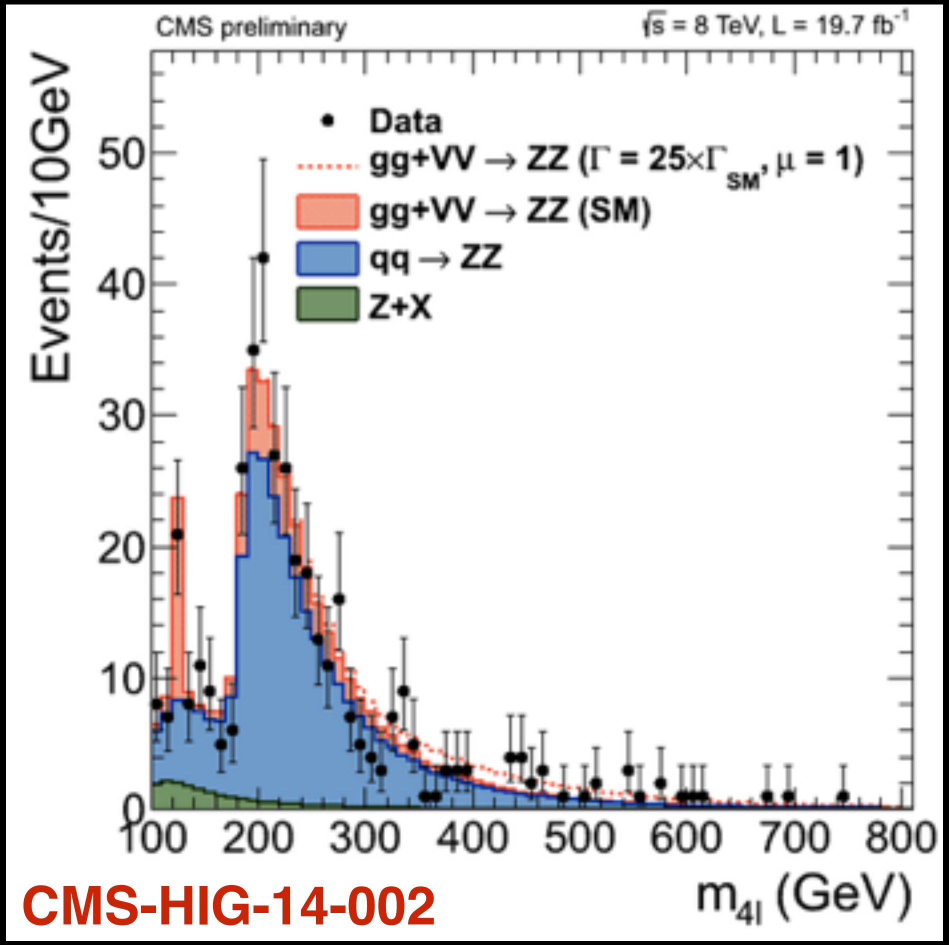
$$\frac{d\sigma^{\rm off-peak}_{\rm gg\to H\to ZZ}}{dm_{\rm ZZ}} = \kappa_{\rm g}^2\kappa_{\rm Z}^2\cdot\frac{d\sigma^{\rm off-peak,SM}_{\rm gg\to H\to ZZ}}{dm_{\rm ZZ}} = \mu r\frac{d\sigma^{\rm off-peak,SM}_{\rm gg\to H\to ZZ}}{dm_{\rm ZZ}}$$

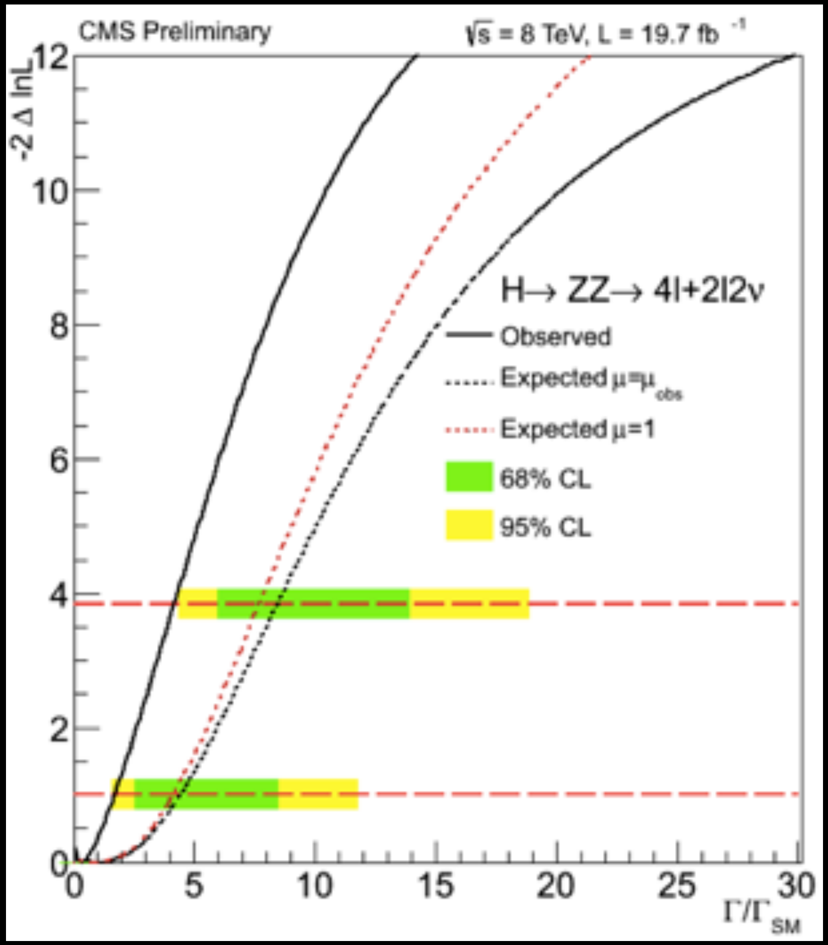


N. Kauer, G. Passarino, JHEP 08 (2012) 116
F. Koala, K. Melnikov, Phys. Rev. D88 (2013), 054024
J. Cambell et al, arXiv:1311.3589

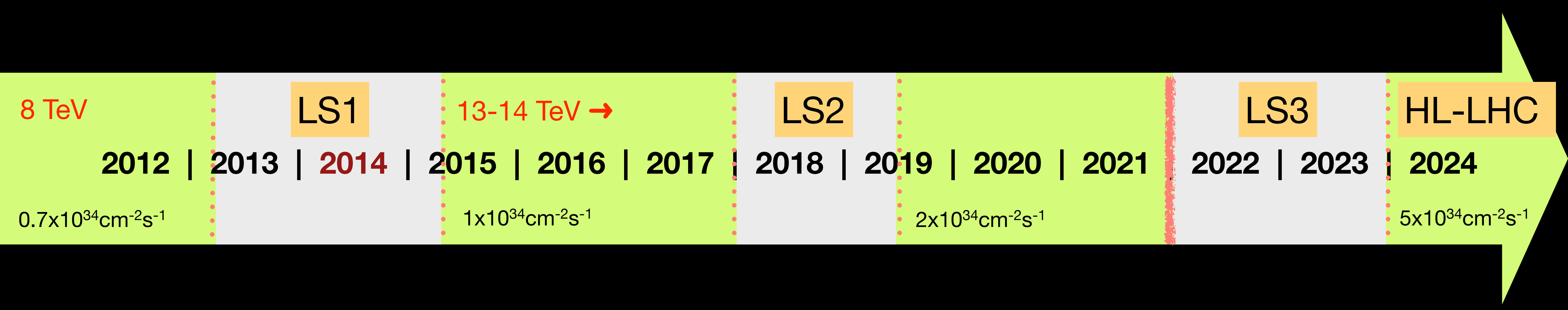
Total Width Measurement

- Experimental constraint on Higgs total width using $H^* \rightarrow ZZ$
- Combination of 4l and 2l2v final states
- **Results:**
  - **r < 4.2 (8.5 expected) @ 95% CL**
  - **Γ_H < 17 MeV (35 MeV expected) @ 95% CL**





Prospects at the HL-LHC and beyond

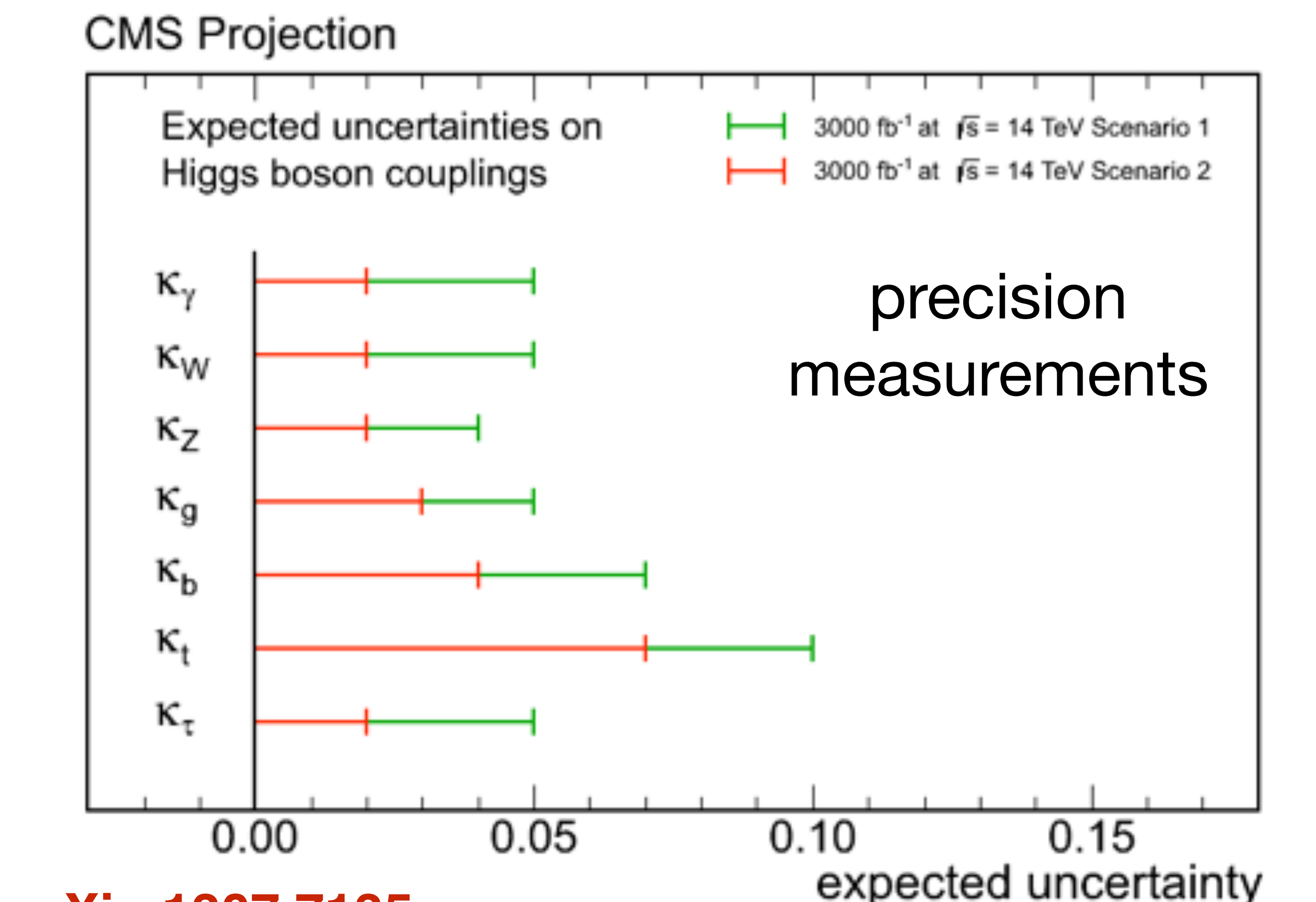


General Coupling Fits

κ_g, κ_γ, $\kappa_{Z\gamma}$: loop diagrams ➜ allow potential new physics
κ_W, κ_Z: vector bosons
κ_t, κ_b: up- and down-type quarks
κ_τ, κ_μ: charged leptons
total width from sum of partial widths

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ 1/√L

coupling precision 2-10 %
factor of ~2 improvement from HL-LHC



arXiv:1307.7135

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

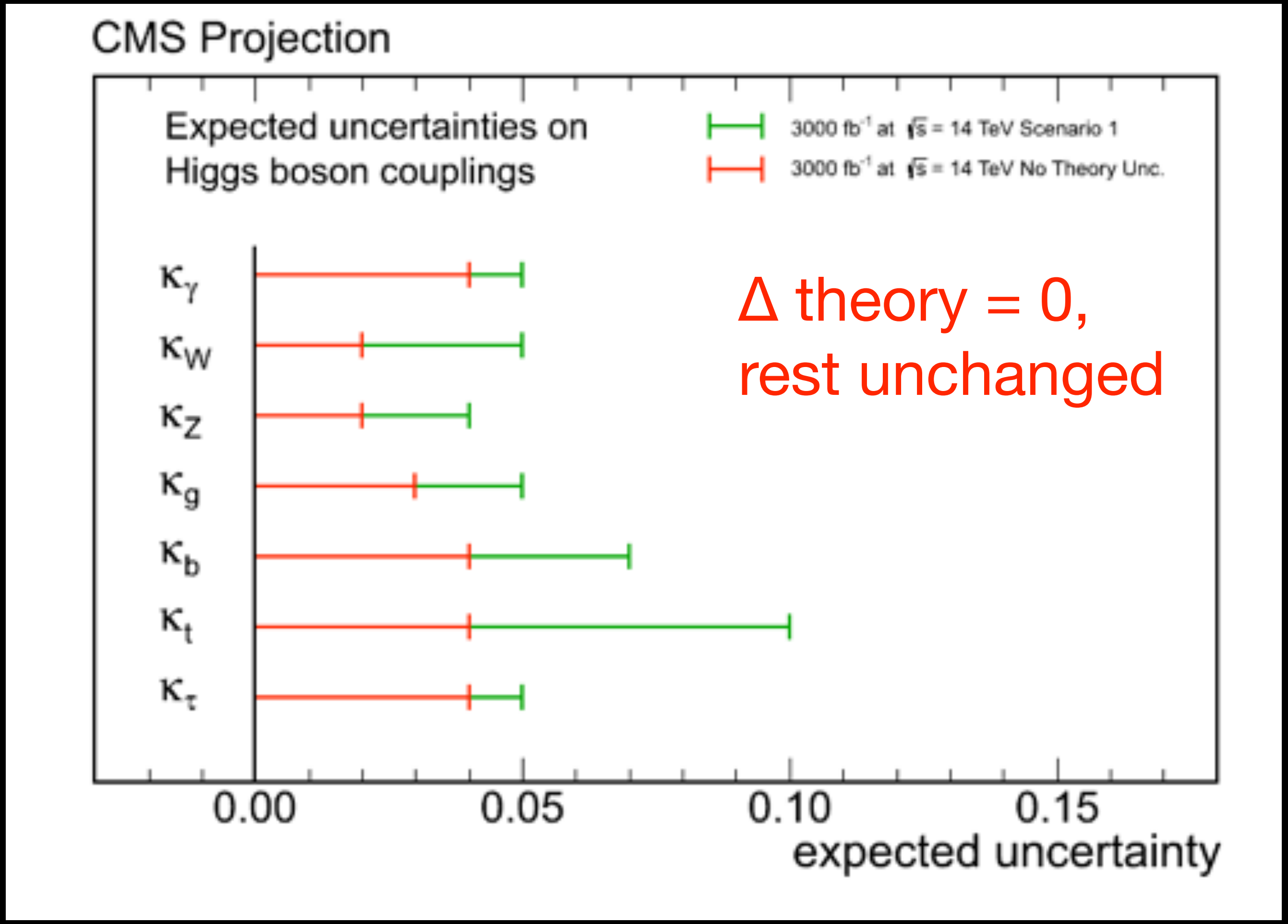
Theoretical Uncertainties

- To test the importance of theoretical uncertainties we show the effect of removing them.
- Theoretical uncertainties dominated by QCD scale and PDF uncertainties. Uncertainty on BR become relevant at few % precision.

arXiv:1310.8361

Process	Cross section (pb)	Relative uncertainty in percent: Total	Scale	PDF
Gluon fusion	49.3	$^{+19.6}_{-14.6}$	$^{+12.2}_{-8.4}$	$^{+7.4}_{-6.2}$
VBF	4.15	$^{+2.8}_{-3.0}$	$^{+0.7}_{-0.4}$	$^{+2.1}_{-2.6}$
WH	1.474	$^{+4.1}_{-4.4}$	$^{+0.3}_{-0.6}$	$^{+3.8}_{-3.8}$
ZH	0.863	$^{+6.4}_{-5.5}$	$^{+2.7}_{-1.8}$	$^{+3.7}_{-3.7}$

Channel	$\Delta\alpha_s$	Δm_b	Δm_c	Theory Uncertainty	Total Uncertainty
$H \to \gamma\gamma$	0%	0%	0%	$\pm1\%$	$\pm1\%$
$H \to b\bar{b}$	$\mp2.3\%$	$^{+3.3\%}_{-3.2\%}$	0%	$\pm2\%$	$\pm6\%$
$H \to c\bar{c}$	$^{-7.1\%}_{+7.0\%}$	$\mp0.1\%$	$^{+6.2\%}_{-6.1\%}$	$\pm2\%$	$\pm11\%$
$H \to gg$	$^{+4.2\%}_{-4.1\%}$	$\mp0.1\%$	0%	$\pm3\%$	$\pm7\%$
$H \to \tau^+\tau^-$	0%	0%	0%	$\pm2\%$	$\pm2\%$
$H \to WW^*$	0%	0%	0%	$\pm0.5\%$	$\pm0.5\%$
$H \to ZZ^*$	0%	0%	0%	$\pm0.5\%$	$\pm0.5\%$



Comparison of ATLAS and CMS prospects

L(fb^{-1})	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
300	ATLAS	[8,13]	[6, 8]	[7, 8]	[8, 11]	N/a	[20, 22]	[13, 18]	[78, 79]	[21, 23]
	CMS	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
3000	ATLAS	[5, 9]	[4, 6]	[4, 6]	[5, 7]	N/a	[8, 10]	[10, 15]	[29, 30]	[8, 11]
	CMS	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

Large differences in fits for coupling strength

- ATLAS connects Kτ with Kb to overcome H ➜ bb mode, but H ➜ ττ then becomes overall limitation in constraining total width.

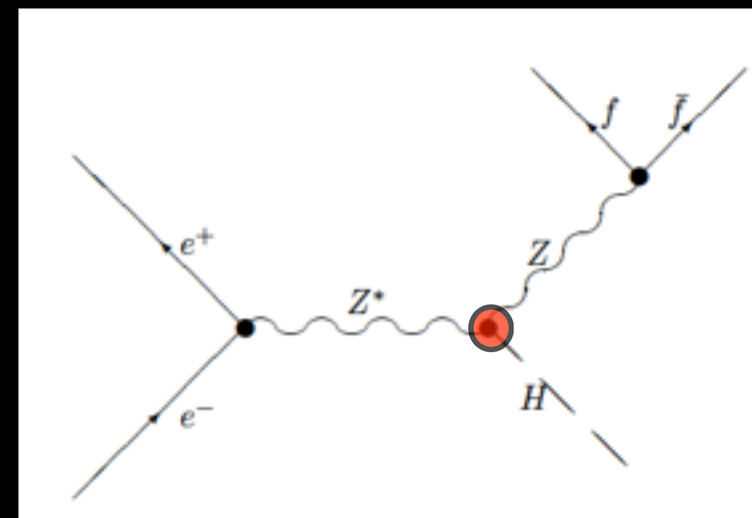
$$\kappa_H^2 = \sum_X \kappa_X^2 \mathrm{BR}_{\mathrm{SM}}(H \to X)$$

L(fb^{-1})	Exp.	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ/κ_Z	κ_W/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_Z/κ_g	κ_t/κ_g	κ_μ/κ_Z	$\kappa_{Z\gamma}/\kappa_Z$
300	ATLAS	[3,6]	[5,11]	[4,5]	N/a	[11,13]	[11,12]	[17,18]	[20,22]	[78,78]
	CMS	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	ATLAS	[2,5]	[2,7]	[2,3]	N/a	[7,10]	[5,6]	[6,7]	[6,9]	[29,30]
	CMS	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

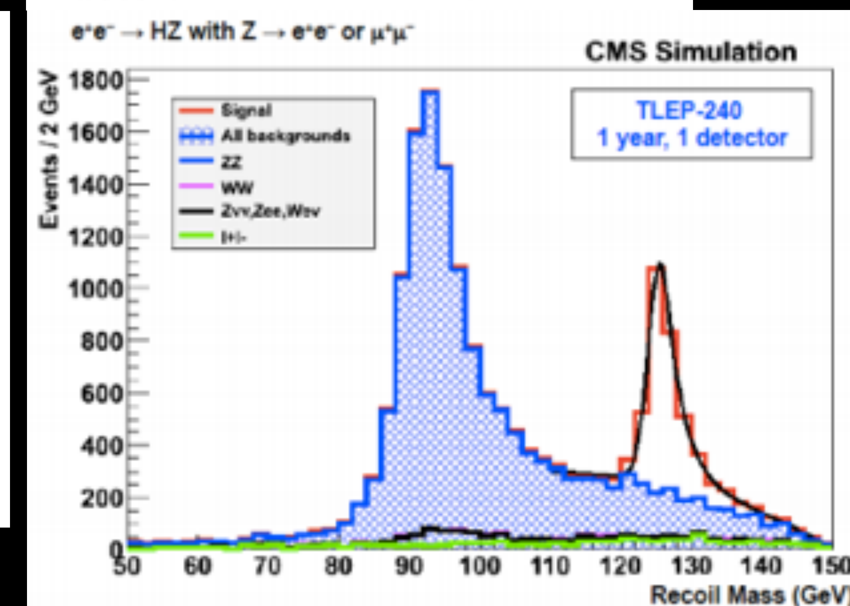
from: ATLAS-PHYS-PUB-2013-014

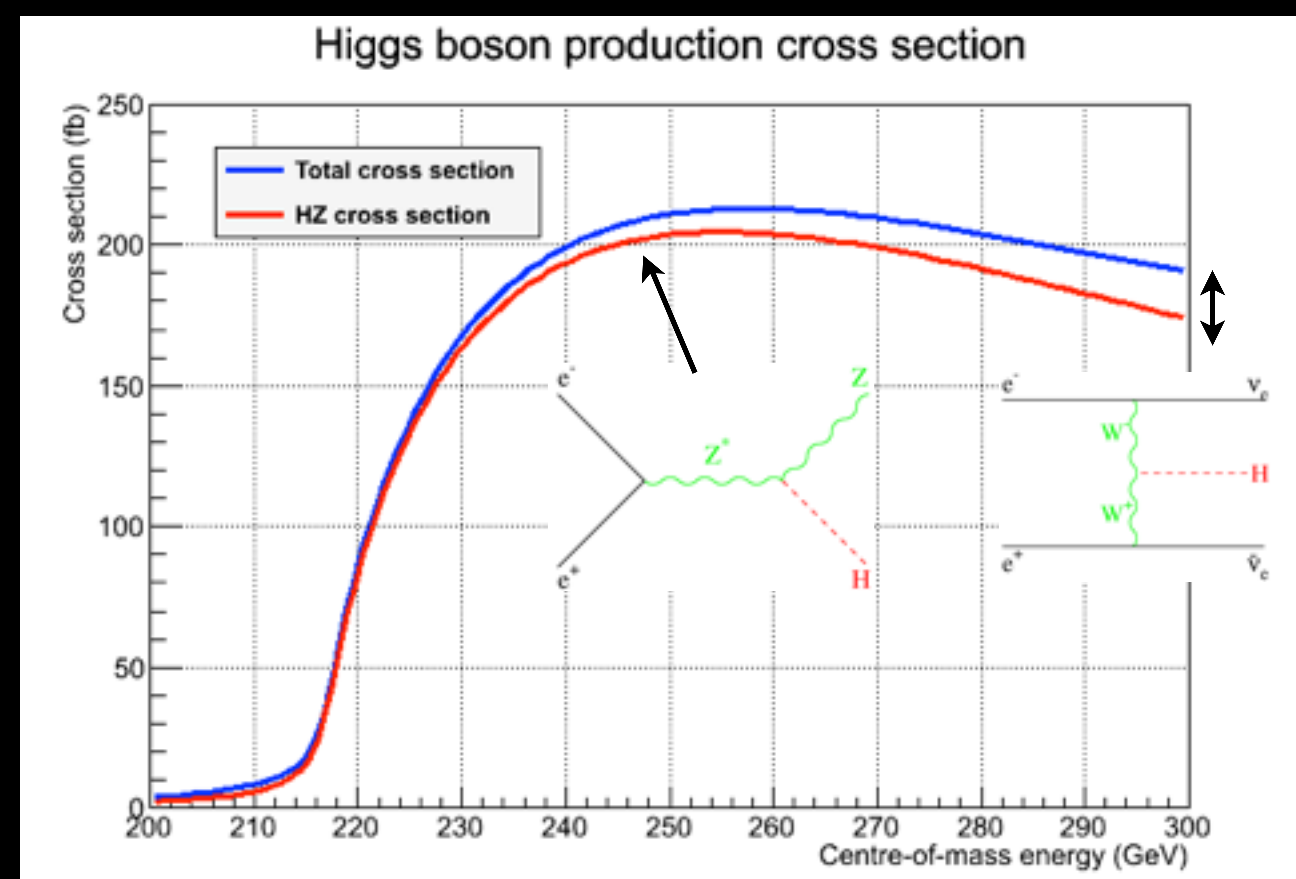
Higgs Couplings at Lepton Collider

- **Higgs-strahlung allows decay mode independent measurement**
  - performed on OPAL data
  - benchmark for lepton collider studies
- **Couplings**
  - model independent extraction of g_{ZZH} from σ_{ZH} in fit to recoil mass spectrum
  - other Higgs couplings extracted from σ_{ZH} x BR measurements and g_{ZZH}
  - total width extracted from combination of initial and final state measurements
  - precision limited by statistics

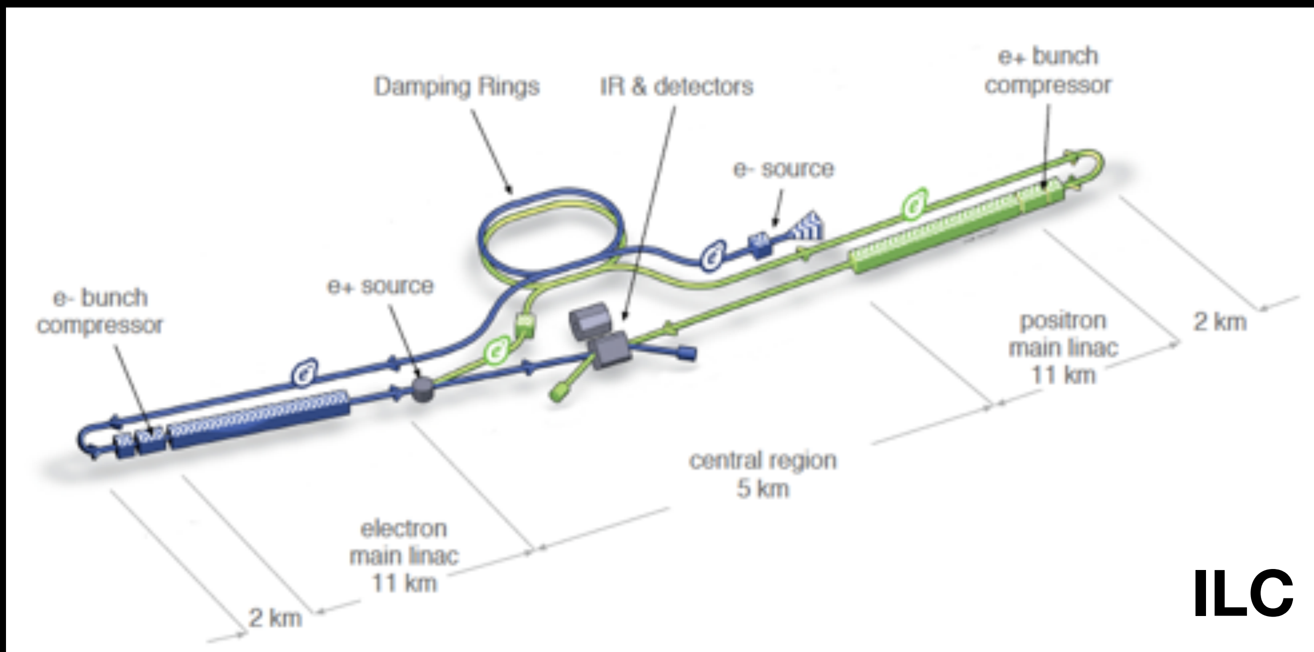


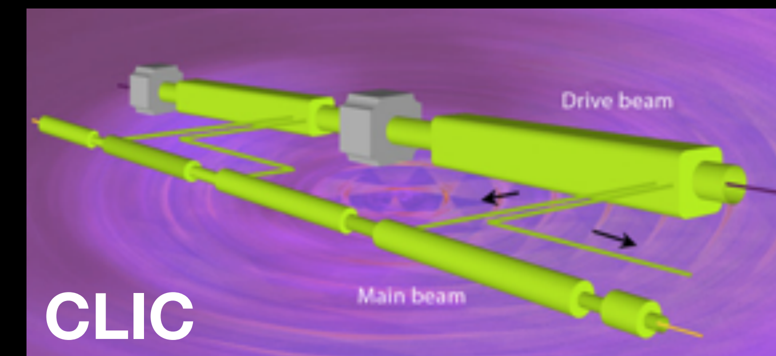
$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



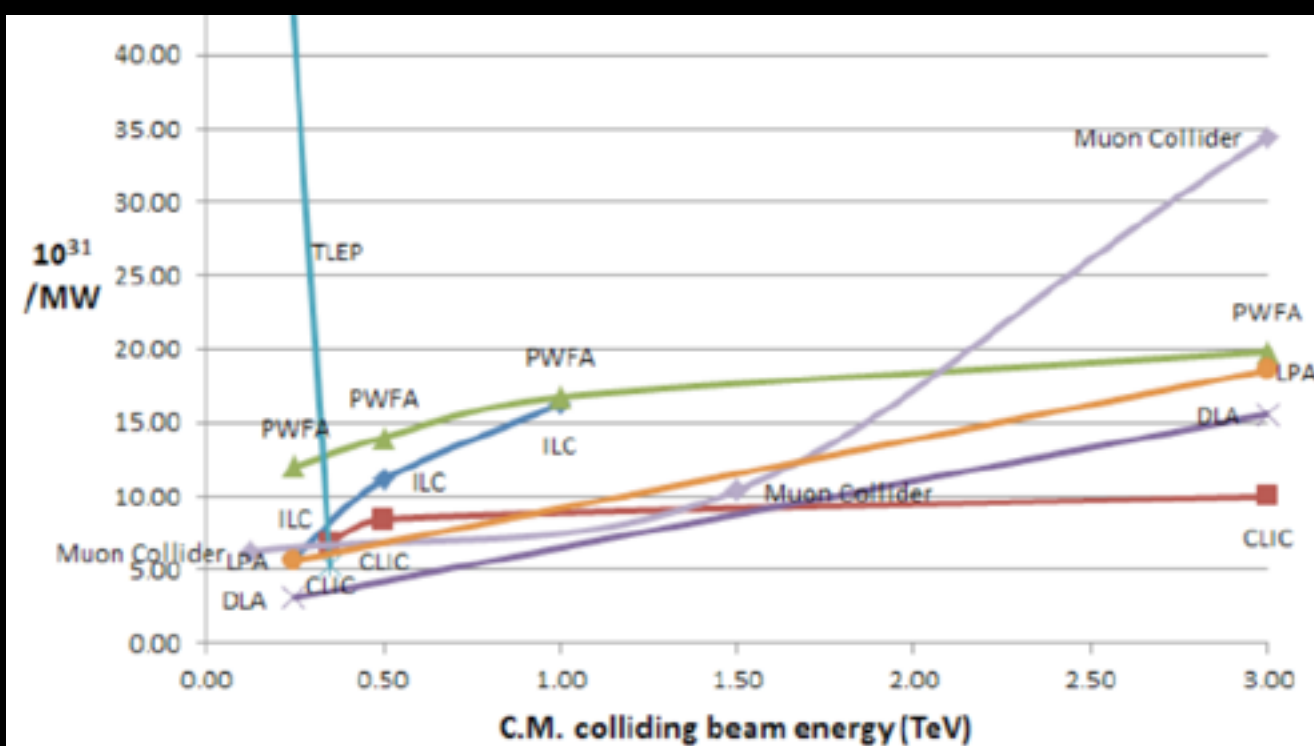


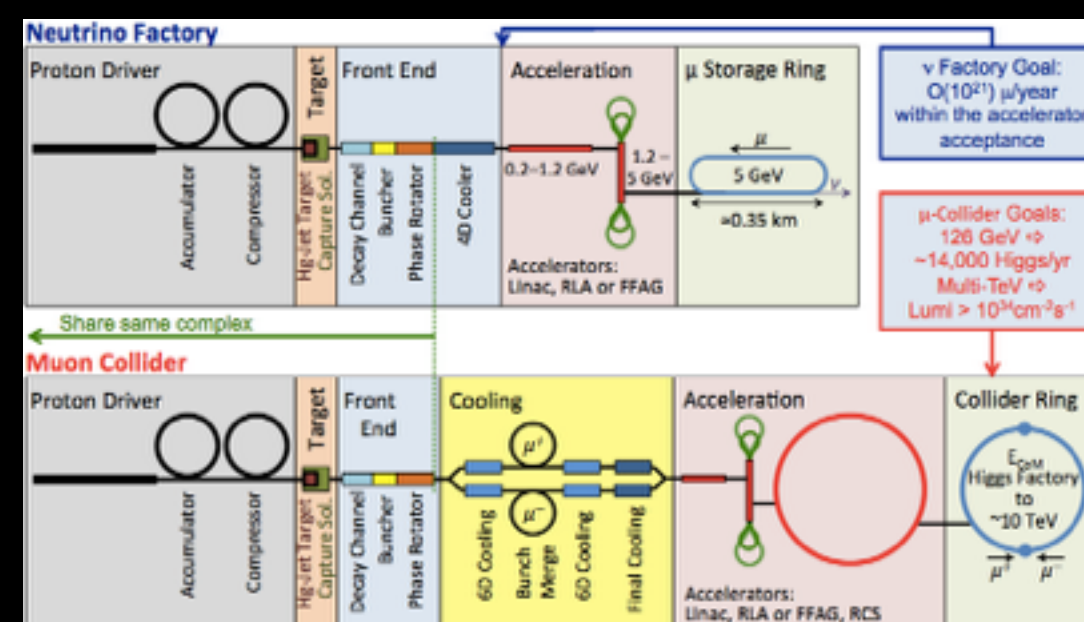
Potential Future Facilities





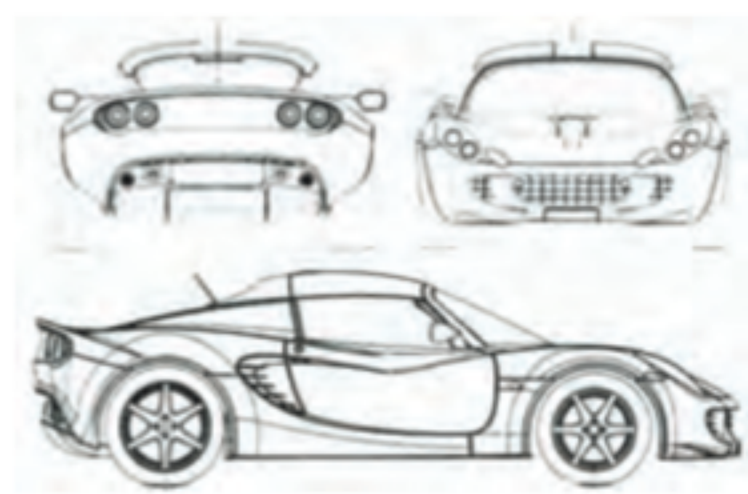
Future Circular Collider (FCC)





Potential Future Facilities

LHC 100/fb	LHC 300/fb	LHC 3/ab	ILC 250-500GeV	ILC 1TeV	CLIC >1TeV	MC	TLEP	VLHC
years beyond TDR	TDR	LOI	TDR	TDR	CDR			

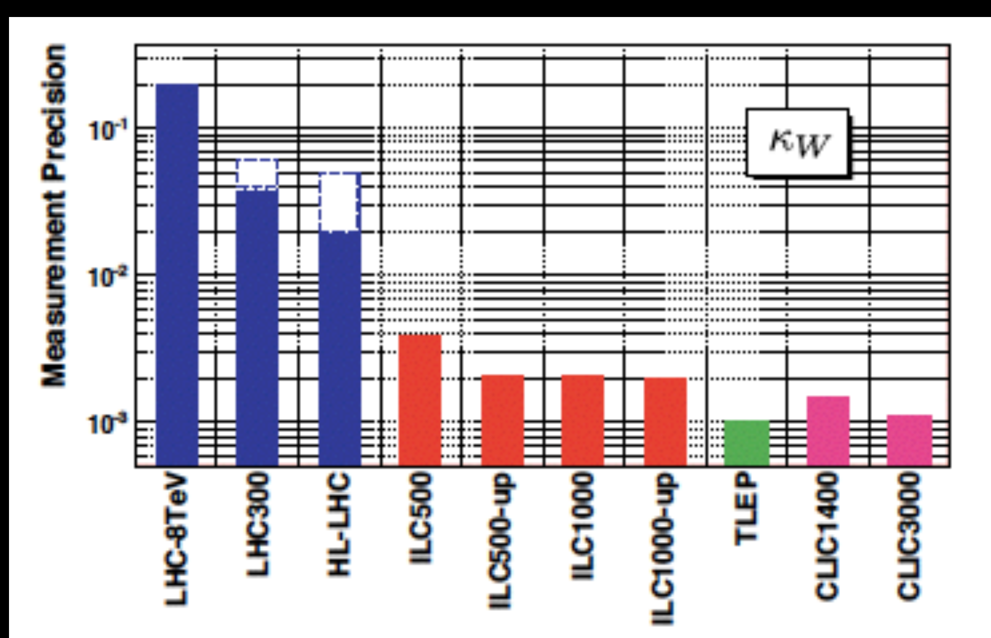


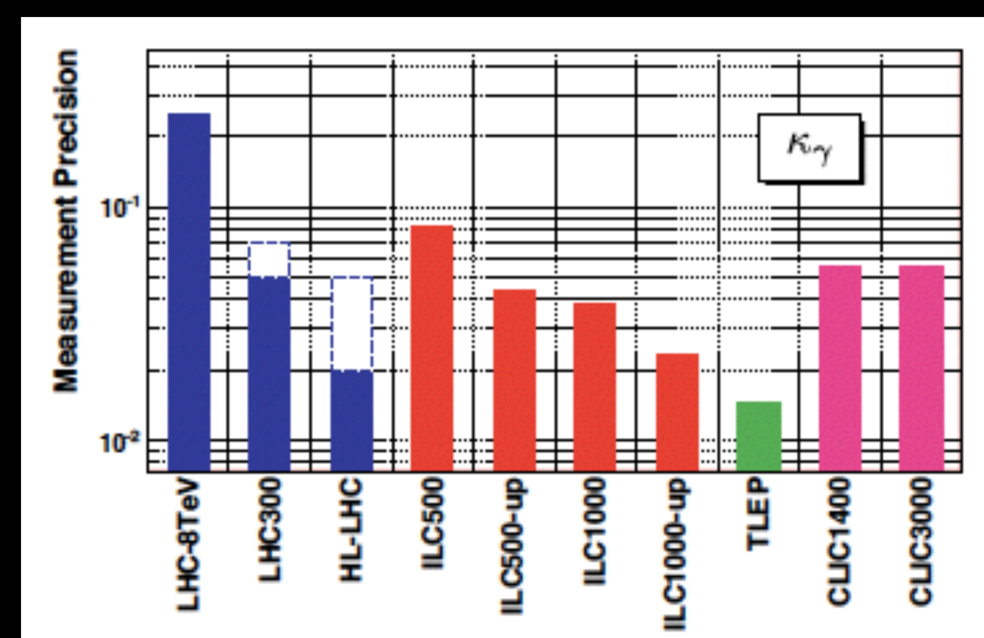
from Chip Brock

Higgs Couplings at Lepton Collider

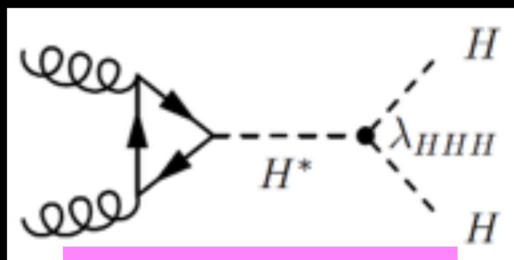
Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

arXiv:1310.8361

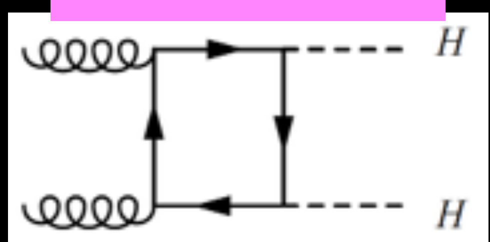




Higgs Self Coupling



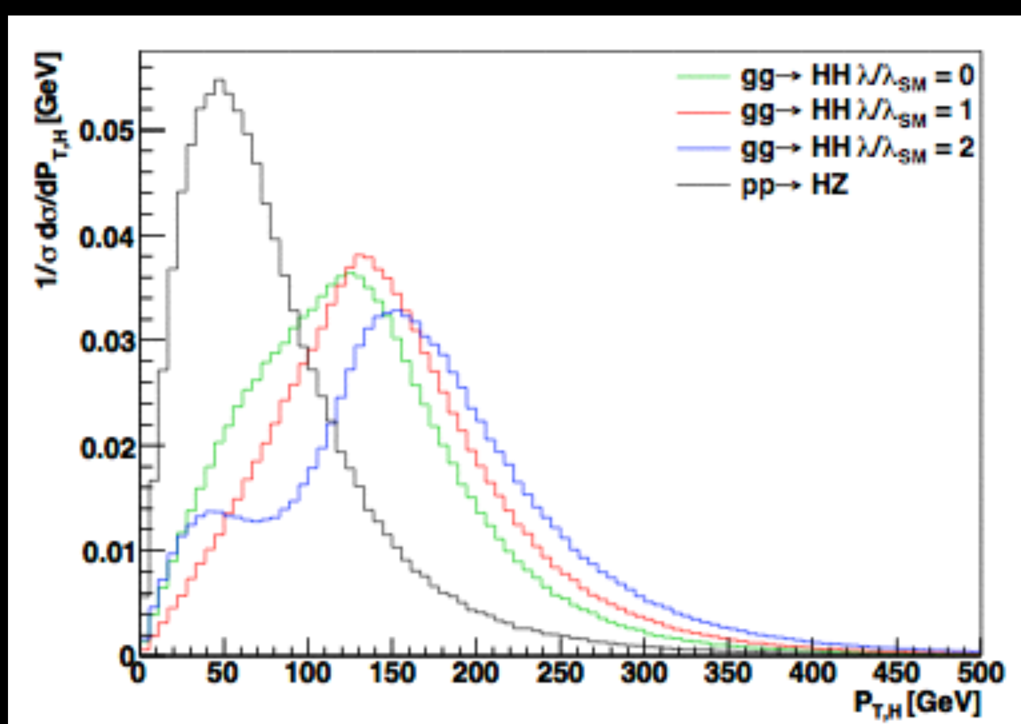
interference



Very challenging search / measurements

Cross section at NNLO
arXiv:1309.6594

E_{cm}	8 TeV	14 TeV
σ_{NNLO}	9.76 fb	40.2 fb
Scale [%]	$+9.0-9.8$	$+8.0-8.7$
PDF [%]	$+6.0-6.1$	$+4.0-4.0$
PDF+α_S [%]	$+9.3-8.8$	$+7.2-7.1$



Boosted Higgs bosons

HL-LHC required to reach SM sensitivity

BSM increase in yields can be substantial

Ebullient discussion of di-Higgs production by theory community

Experimentalists very conservative

References in backup

Channels and Sensitivity

- Promising final states at the LHC

$$HH \to b\bar{b}\gamma\gamma \qquad HH \to b\bar{b}\tau^+\tau^-$$

- Difficulties in background estimation
    - esp. fake rate or mistag estimates
- Expected sensitivity

$$\frac{\delta\lambda_{HHH}}{\lambda_{HHH}} = \mathcal{O}(30\%)$$

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	3000	3000
λ	50%	20%	8%

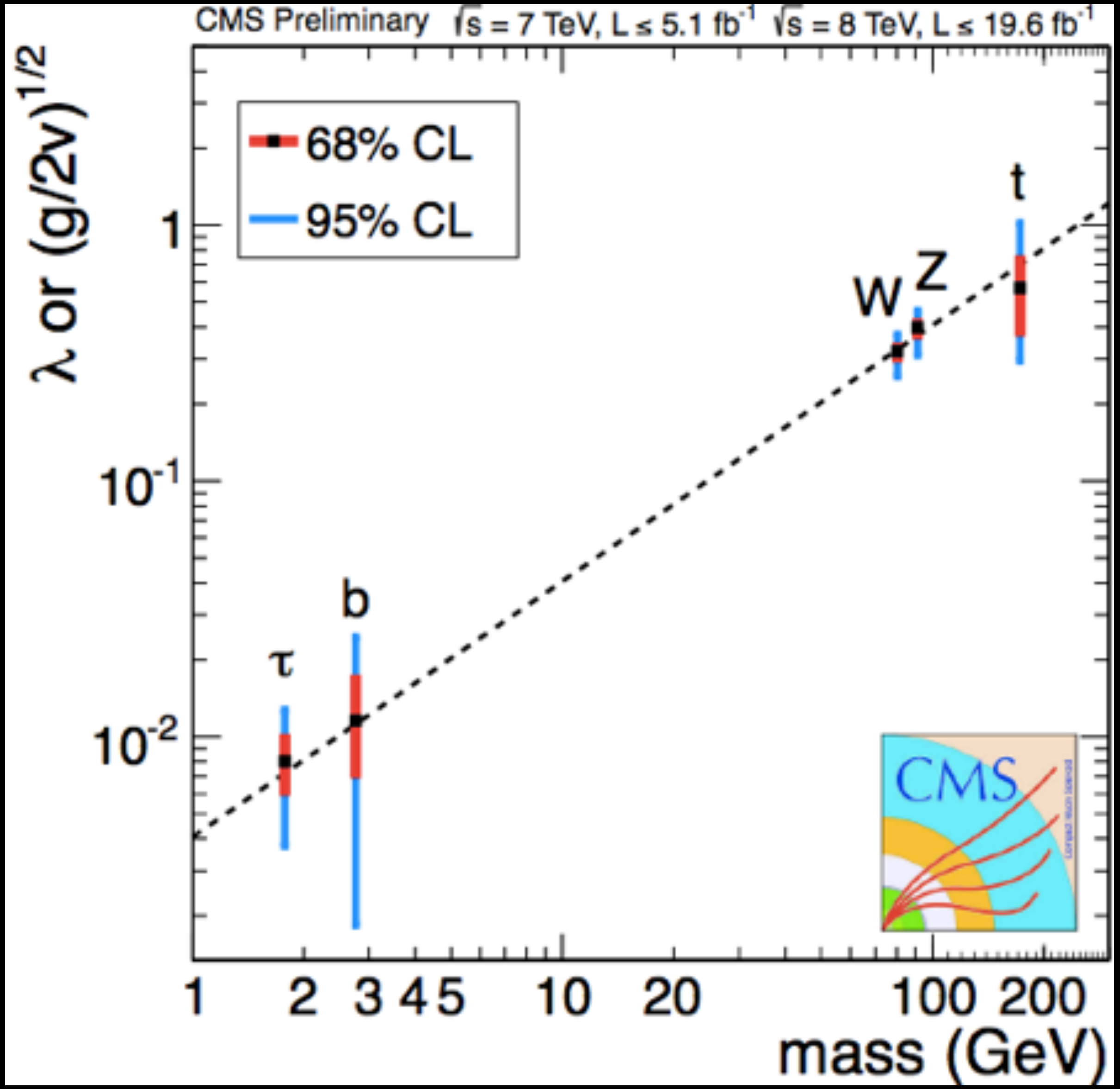
- Sensitivity enhanced using event shapes
- ATLAS & CMS are developing a program for HL-LHC di-Higgs measurements
- Lepton collider need very large datasets at high energy or extreme precision g_{ZH} measurements

	ILC500	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	500+1000	1600+2500‡	1500	+2000
λ	83%	21%	13%	21%	10%

Summary

Conclusion

- Higgs physics transitioned from searches to precision measurements
- **Signatures compatible with SM Higgs Boson**
    - Interpretation in numerous BSM model possible
    - Future precision measurements can unveil true nature of this beast
- Exciting experimental and theoretical research program ahead



Resources

- ATLAS public Higgs physics page
- CMS public Higgs physics page
- Tevatron Higgs page
- ATLAS & CMS Snowmass and ECFA reports
- Snowmass Higgs group summary report

Resources on Di-Higgs

1. LHC Physics Review
   - F. Gianotti, M.L. Mangano, T. Virdee (conveners), Eur. Phys. J. **C39** (2005) 293–333.
   - A. De Roeck, et al., Eur. Phys. J. **C66** (2010) 525–583.
2. Higgs Trilinear Coupling
   - E.W.N. Glover, J.J. van der Bij, Physics Letters **B219** (1989) 488–492.
   - S. Dawson, S. Dittmaier and M. Spira, Phys. Rev. **D58** (1998) 115012.
   - A. Djouadi, W. Kilian, M. Mühlleitner and P.M. Zerwas, Eur. Phys. J. **C10** (1999) 45–49 .
   - U. Baur,T. Plehn, and D. Rainwater, Phys. Rev. Lett. **89** (2002) 151801, Phys. Rev. **D67** (2003) 033003, Phys. Rev. **D68** (2003) 033001, Phys. Rev. **D69** (2004) 053004 .
   - T. Binoth, S. Karg, N. Kauer, and R. Rückl, Phys. Rev. **D74** (2006) 113008.
   - M.J. Dolan,C. Englert, and M. Spannowsky, arXiv:1206.5001.
   - J. Baglio, A. Djouadi, R. Grober, M. M. Muhlleitner, J. Quevillon, M. Spira, http://arxiv.org/abs/1212.5581
   - Florian Goertz, Andreas Papaefstathiou, Li Lin Yang, José Zurita http://arxiv.org/abs/1301.3492
3. Higgs Quartic Coupling
   - T. Plehn and M. Rauch, Phys. Rev. **D72** (2005) 053008.
4. BSM interpretation
   - M. Moretti, et al., JHEP **02** (2005)024.
   - A. Noble and M. Perelstein, Phys. Rev. **D78** (2008) 063518.
   - R. Gröber and M. Mühlleitner, JHEP **06** (2011) 020, ArXiv 1012.1562
   - Eibun Senaha http://arxiv.org/abs/1305.1563 on Baryogenisis
   - http://arxiv.org/abs/1207.4496 (enhanced di-Higgs production)

- incomplete list

Comparison of ATLAS and CMS

$L(fb^{-1})$	Exp.	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$
300	ATLAS	[9, 14]	[8, 13]	[6, 12]	N/a	[16, 22]	[145, 147]	[40,42]
	CMS	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]
3000	ATLAS	[4, 10]	[5, 9]	[4, 10]	N/a	[12, 19]	[54, 57]	[12,15]
	CMS	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[14,20]

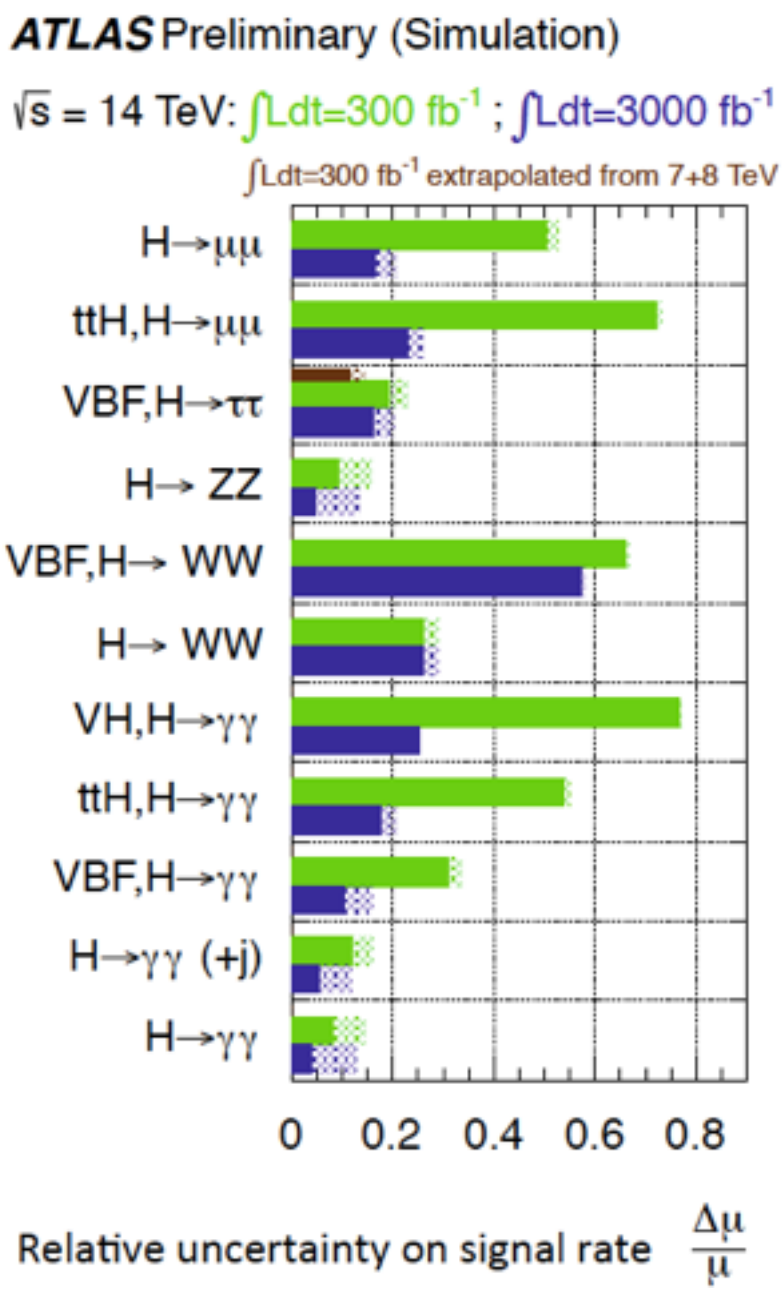
Uncertainty on signal strength

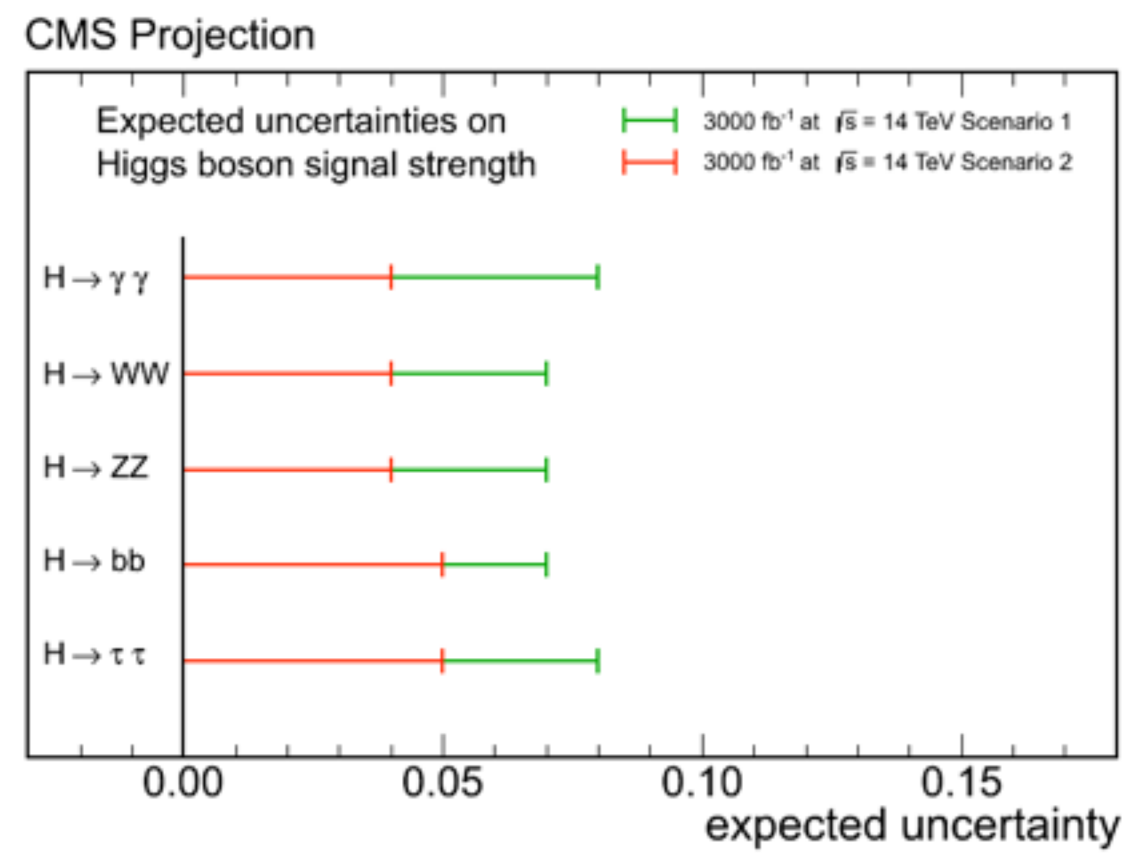
- Ranges [x,y] are not directly comparable
- ATLAS
  - [no theory uncertainty, Scenario 1]
- CMS
  - [Scenario 2, Scenario 1]

Overall reasonable agreement, but

- ATLAS does not include H ➜ bb mode
- CMS outperforms ATLAS H ➜ ττ mode
- Large differences in H ➜ Zγ mode due to photon id

Uncertainty on Signal Strength





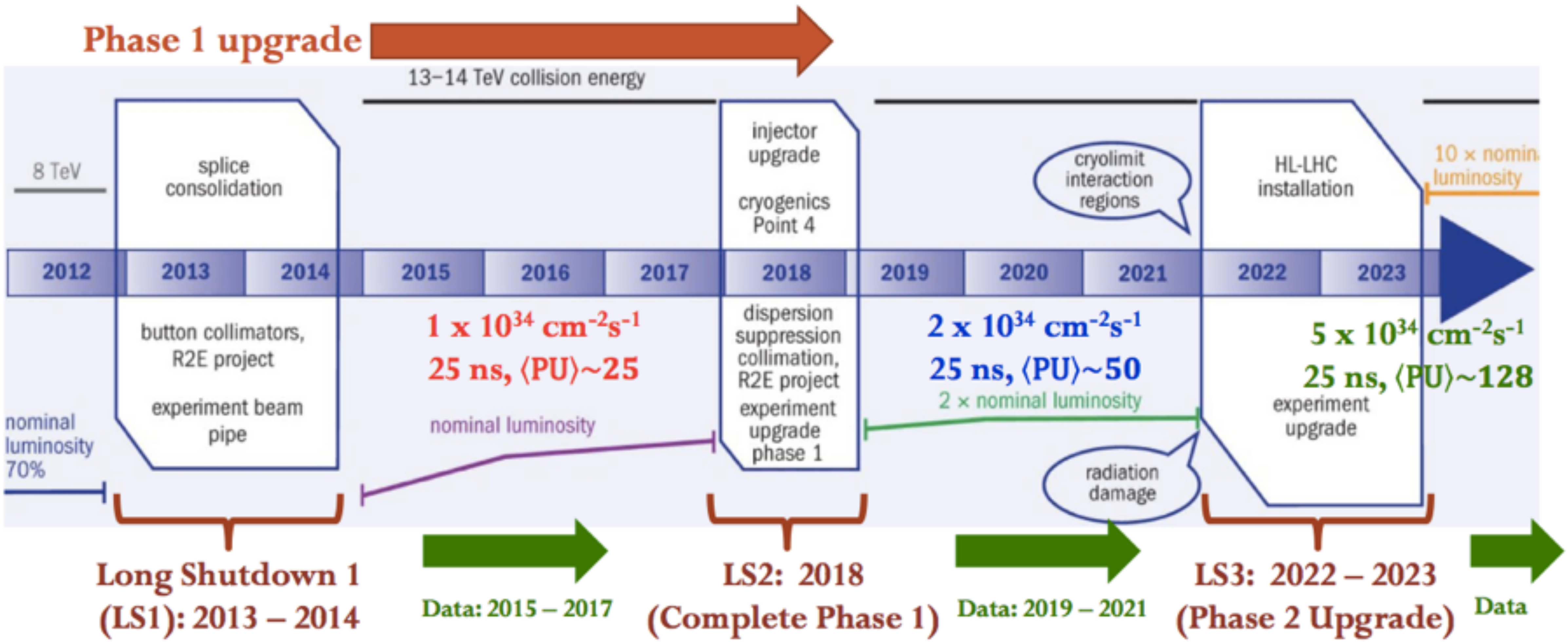
L (fb^{-1})	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to bb$	$H \to \tau\tau$	$H \to Z\gamma$	$H \to$ inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[6, 17]

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ $1/\sqrt{L}$

Based on parametric simulation

Extrapolated from 2011/12 results

LHC Upgrade Stages



LHC

Reach $10^{34}cm^{-2}s^{-1}$ by LS2, double by LS3 and integrate $300fb^{-1}$ by 2022

<PU> = 50

HL-LHC

Lumi-level 5x $10^{34}cm^{-2}s^{-1}$ and integrate $3000fb^{-1}$after L3

<PU> = 140

Higgs Couplings at Lepton Collider

- Higgs-strahlung is main production process
  - HZZ coupling observed at the LHC
  - Vector boson fusion give small contribution at 250 GeV
- Cross section plateau at 240-280 GeV
- Reasonable background level