Theory overview of Higgs physics

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The Lagrangian of Nature?

- With the discovery of a scalar particle having properties consistent with the SM Higgs boson, the Lagrangian of Nature appears complete.

$$\mathcal{L}_h^{SM} = |D_\mu H|^2 - \left(y_u \bar{Q}_L \tilde{H} u_R + y_d \bar{Q}_L H d_R + y_e \bar{L}_L H e_R + h.c.\right) - \lambda \left(H^\dagger H - \frac{v^2}{2}\right)^2$$

- The SM is *predictive*: given m_H, all couplings of the Higgs are now fixed.

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{scale}) \pm 0.02\,(\text{other}) \pm 0.01\,(\text{theory})\ \text{GeV},$$

(ATLAS+CMS, 1503.07589, fit to 4l+2γ)

Tree-level couplings:

$$g_{hf^i f^j} = -\frac{g m_f}{2 m_W} \delta^{ij}$$

$$g_{hVV} = g_V m_V$$

$$g_{hhh} = -\frac{3 m_H^2}{2 m_W}$$

Failures of the Standard Model I

- Numerous outstanding problems exist in the SM, both aesthetic and experimental, that demand explanation.

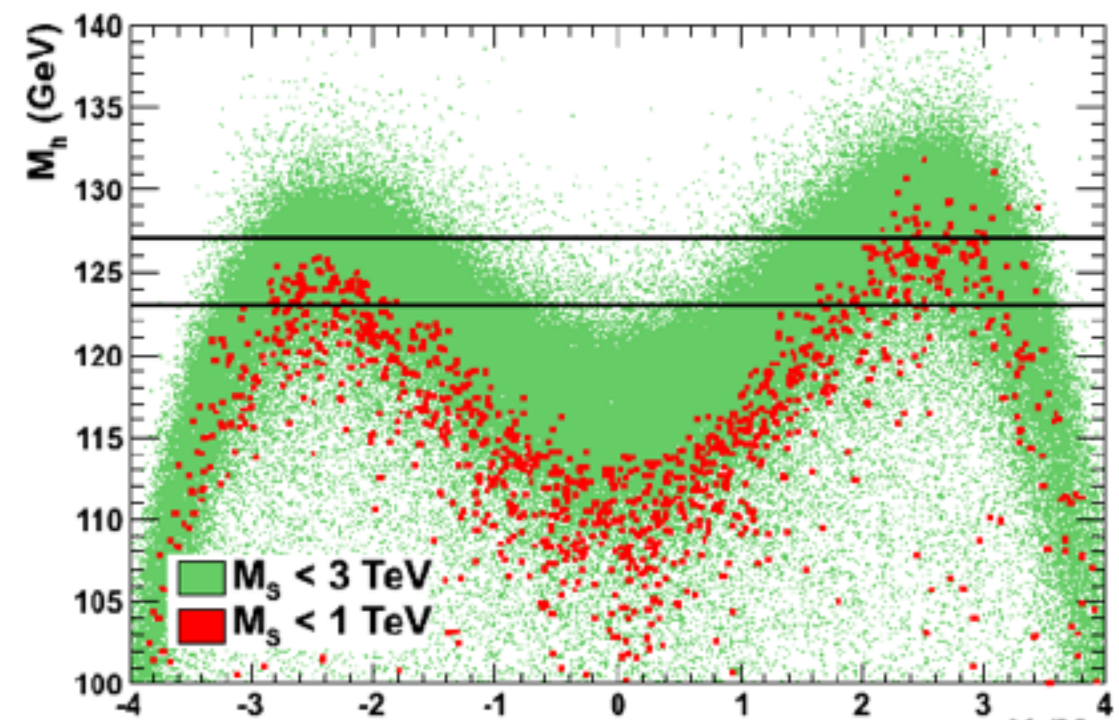
No hierarchy between input, "bare" value and quantum corrections ➪ *Naturalness*

- [x] True for gauge bosons ➪ gauge symmetry
- [x] True for the fermions ➪ chiral symmetry
- [ ] Not true for the Higgs!

$$M^{gauge,ferm} \sim M^{bare}\{1 + a \ln \Lambda/M\}$$

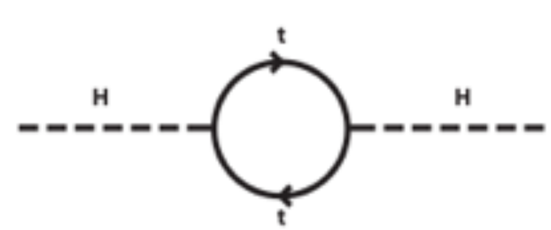
$$(M^{Higgs})^2 \sim (M^{bare})^2 + \Lambda^2$$

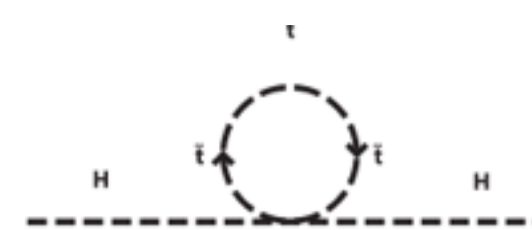
Does TeV-scale SUSY resolve this problem?



Arbey, Battaglia, Djouadi, Mahmoudi 1211.4004

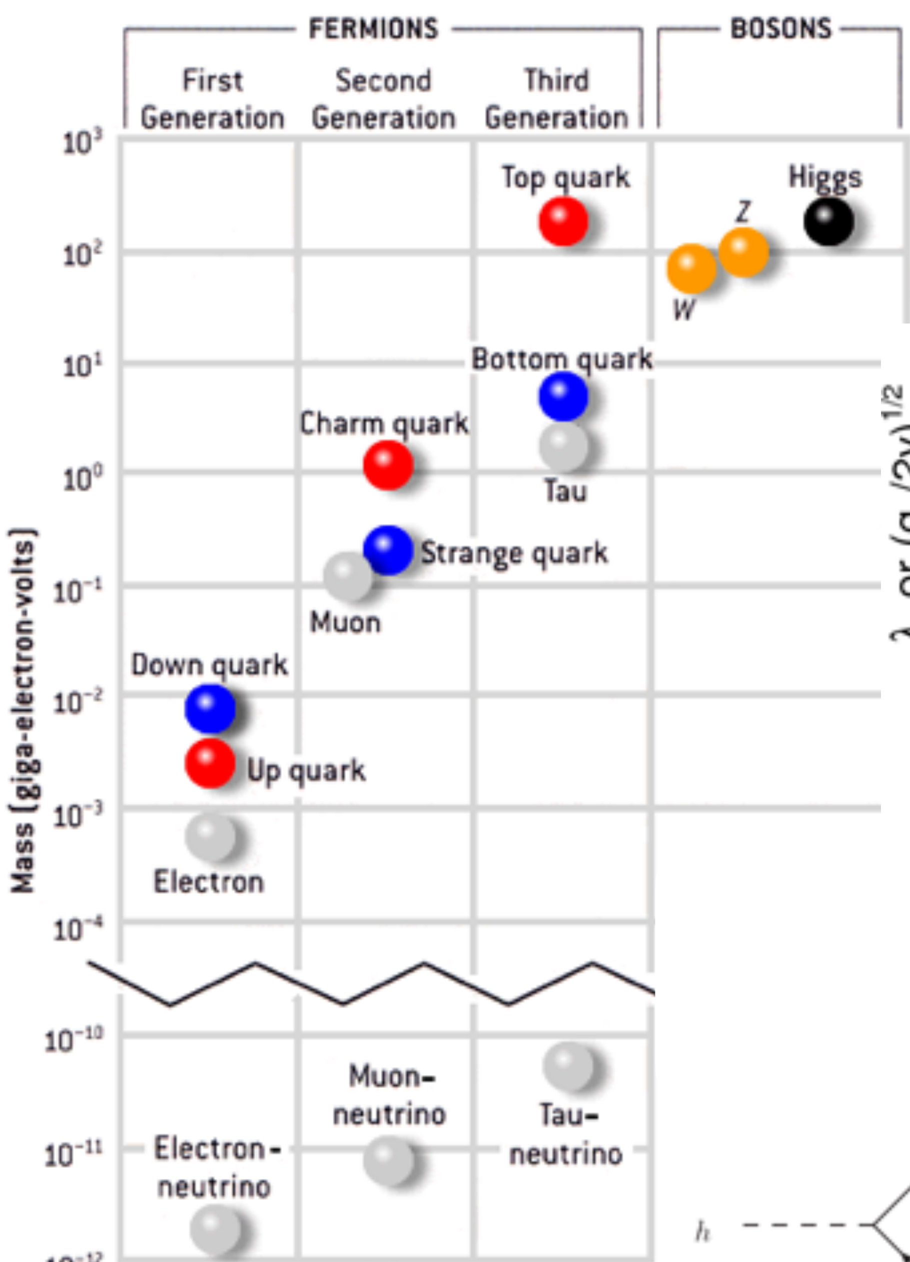
Precision Higgs mass measurement influencing our search for TeV-scale SUSY





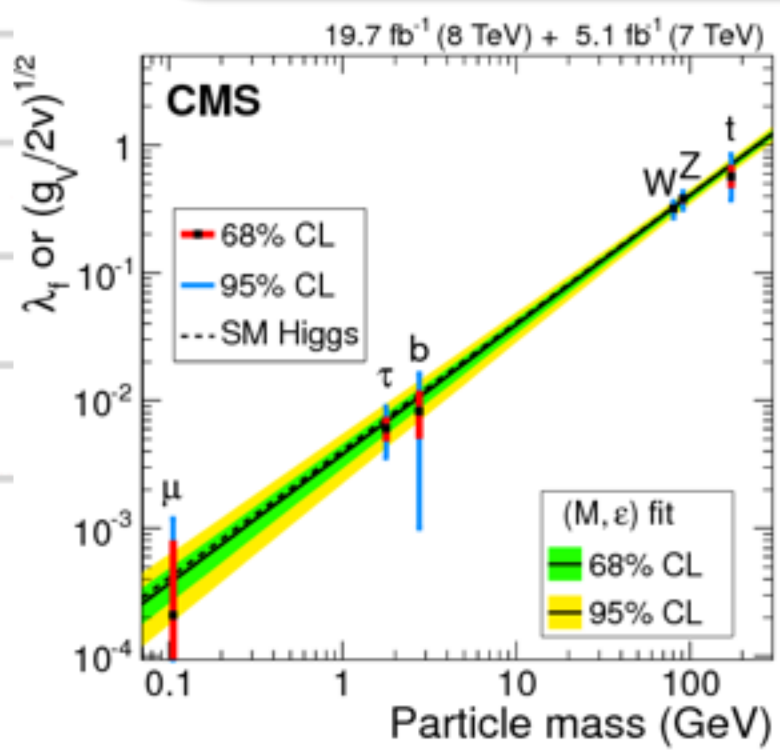
Failures of the Standard Model II

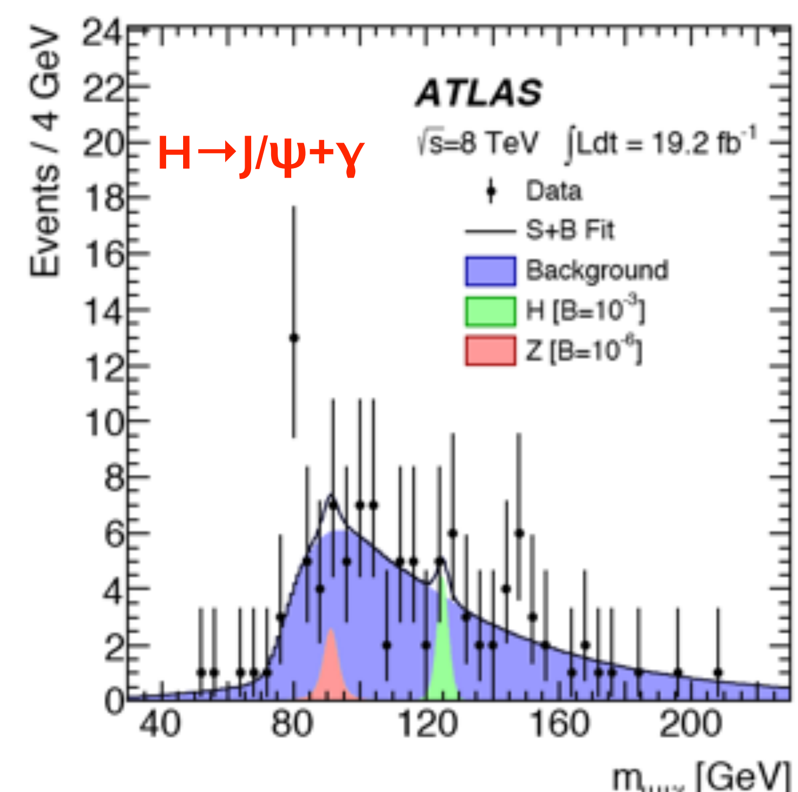
- Numerous outstanding problems exist in the SM, both aesthetic and experimental, that demand explanation.

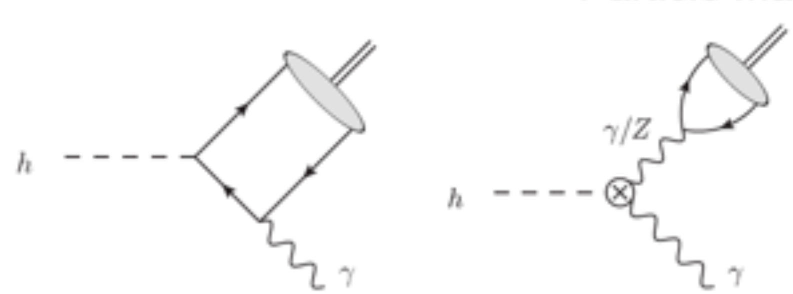


➪ The SM Higgs does not explain the observed masses and mixings of fermions.

Is insight hiding in the 1st-2nd generation couplings?





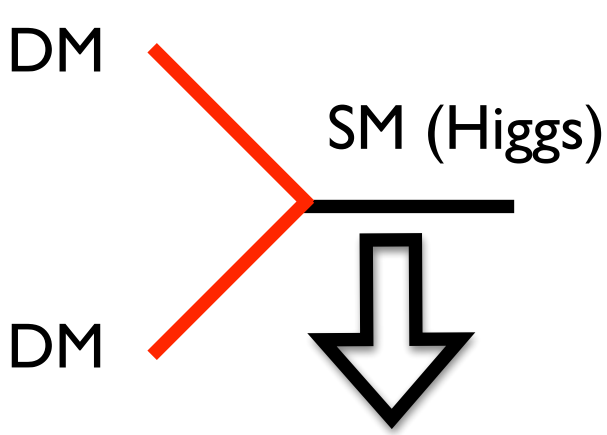


Use exclusive decays to constrain!

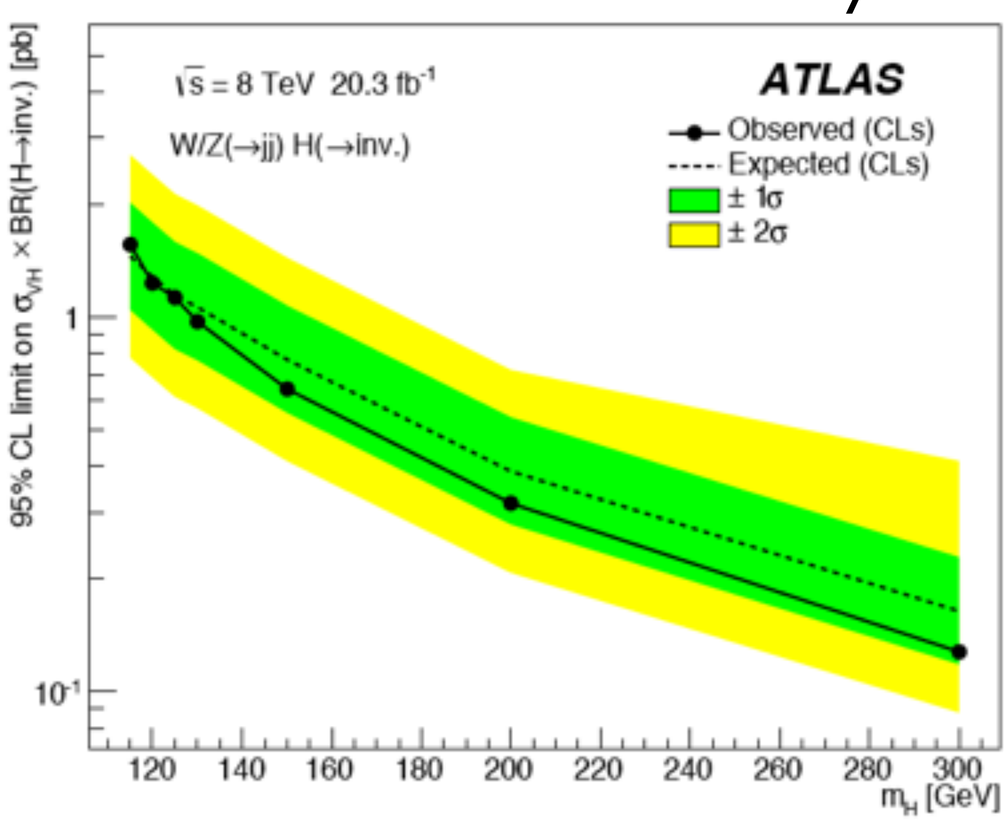
(Bodwin, FP, Stoynev, Velasco 1306.5570; Kagan et al. 1406.1722; Koenig, Neubert 1505.03870)

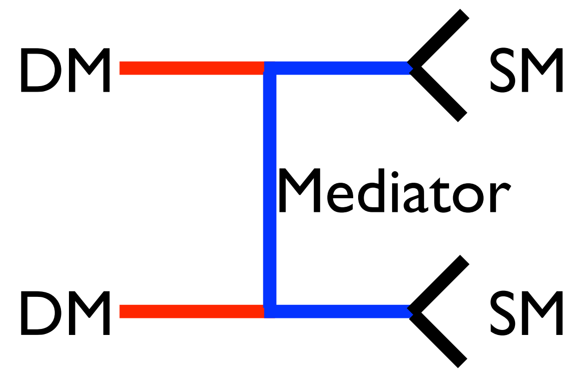
Failures of the Standard Model III

- Doesn't have dark matter! Assuming non-gravitational DM couplings, can imagine two possible scenarios for DM coupling to the SM.



Predicts invisible decays





Only three renormalizable possibilities, two involving the Higgs:

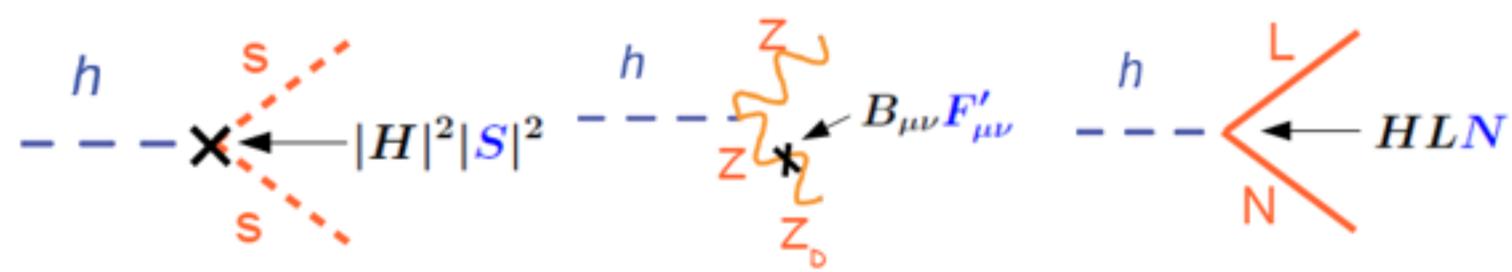
Schabinger, Wells hep-ph/0509209;
Patt, Wilczek hep-ph/0605188

$$\Delta\mathcal{L}_1 = |H|^2 S^2$$

$$\Delta\mathcal{L}_2 = HLN + h.c.$$

$$\Delta\mathcal{L}_3 = F'_{\mu\nu} B^{\mu\nu}$$

Hidden-sector dark matter leads to rich Higgs phenomenology (surveyed in Curtin et al, 1312.4992)

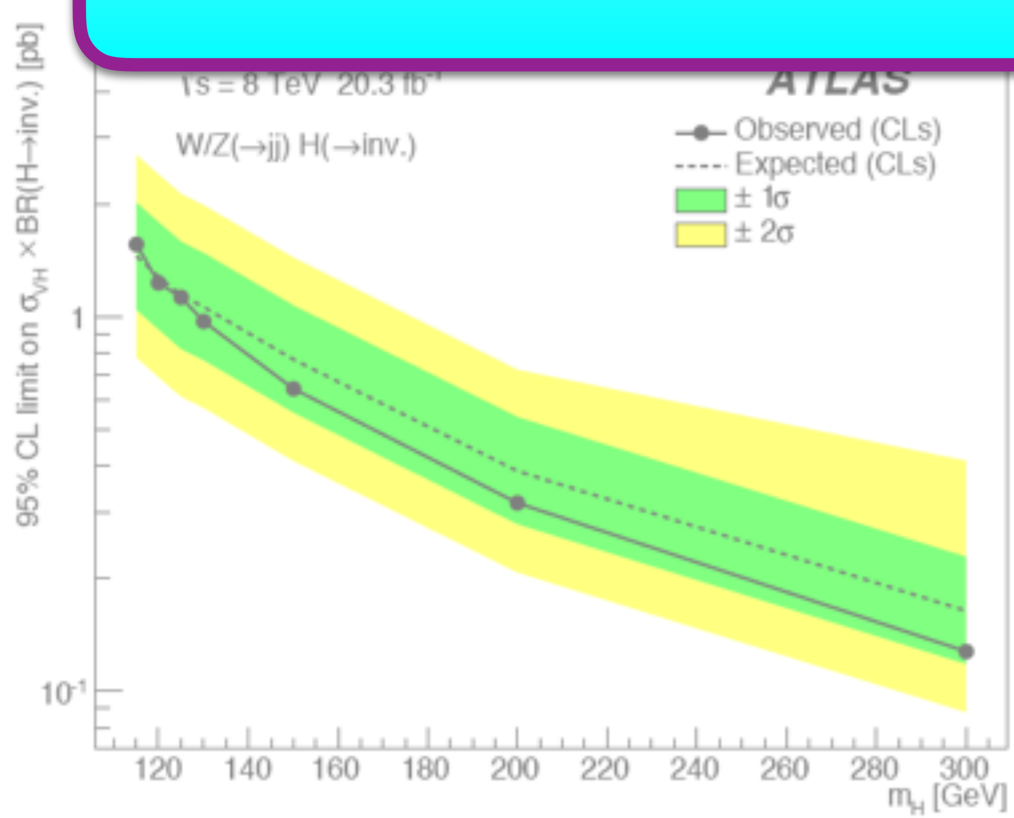


Failures of the Standard Model III

- Doesn't have dark matter! Assuming non-gravitational DM couplings, can imagine two possible scenarios for DM coupling to the SM.

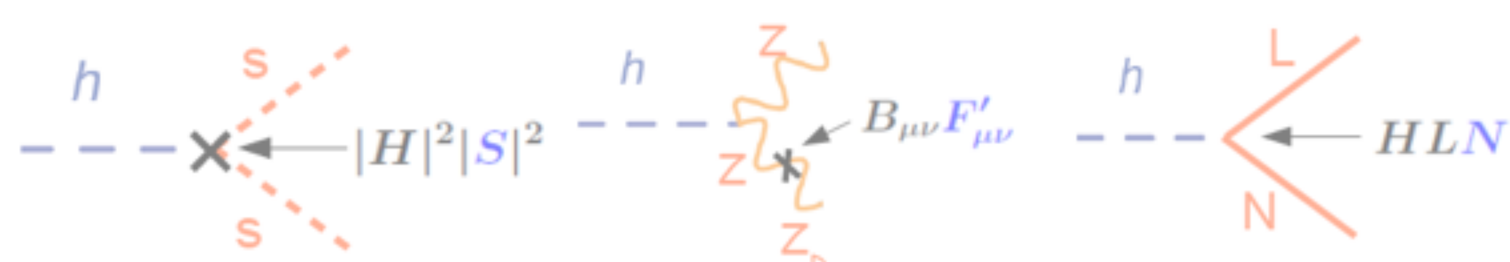
Understanding the properties of the Higgs is central to forming a new, more satisfactory Standard Model. To proceed:

- Measure the expected very precisely (m_H, couplings, CP, distributions,…)
- Leave no stone unturned (exotic decays, 1st+2nd generations,…)



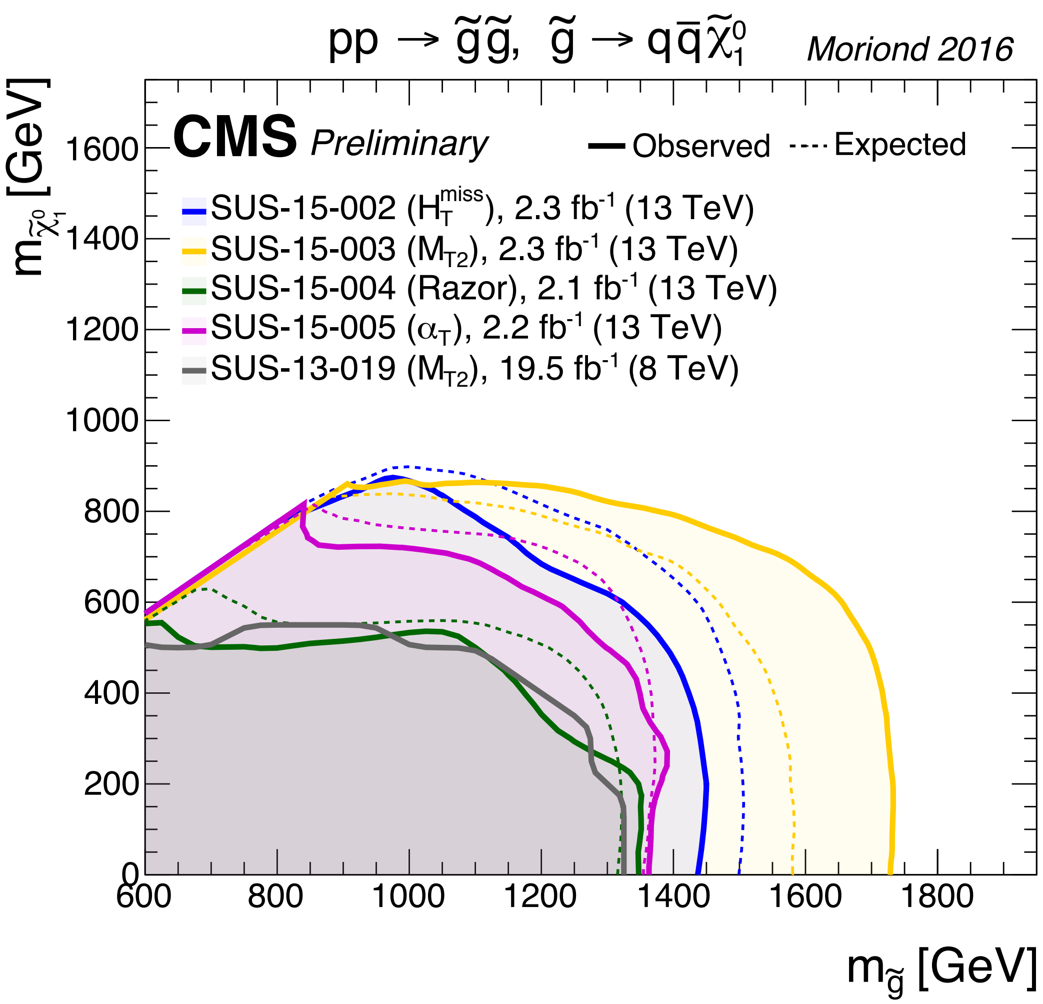
the Higgs: $\Delta\mathcal{L}_3 = F'_{\mu\nu}B^{\mu\nu}$

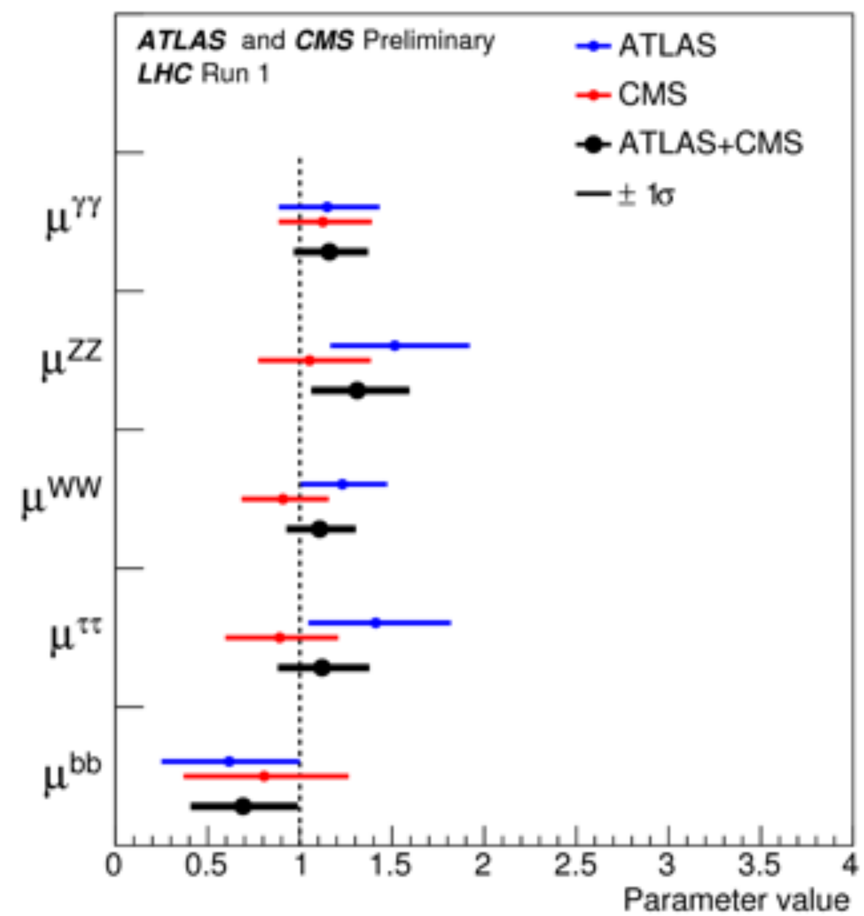
Hidden-sector dark matter leads to rich Higgs phenomenology (surveyed in Curtin et al, 1312.4992)



Framework for Run II Higgs studies

- We haven't yet seen anything beyond the SM, although hints exist. The Higgs appears SM-like. Motivates interpretation of Run II results in EFT framework.





$$\mathcal{L} = \mathcal{L}^{SM} + \mathcal{L}^{UV} \quad \Rightarrow \quad \mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{g_i^2}{\Lambda_{\mathrm{NP}}^2}\mathcal{O}_i$$

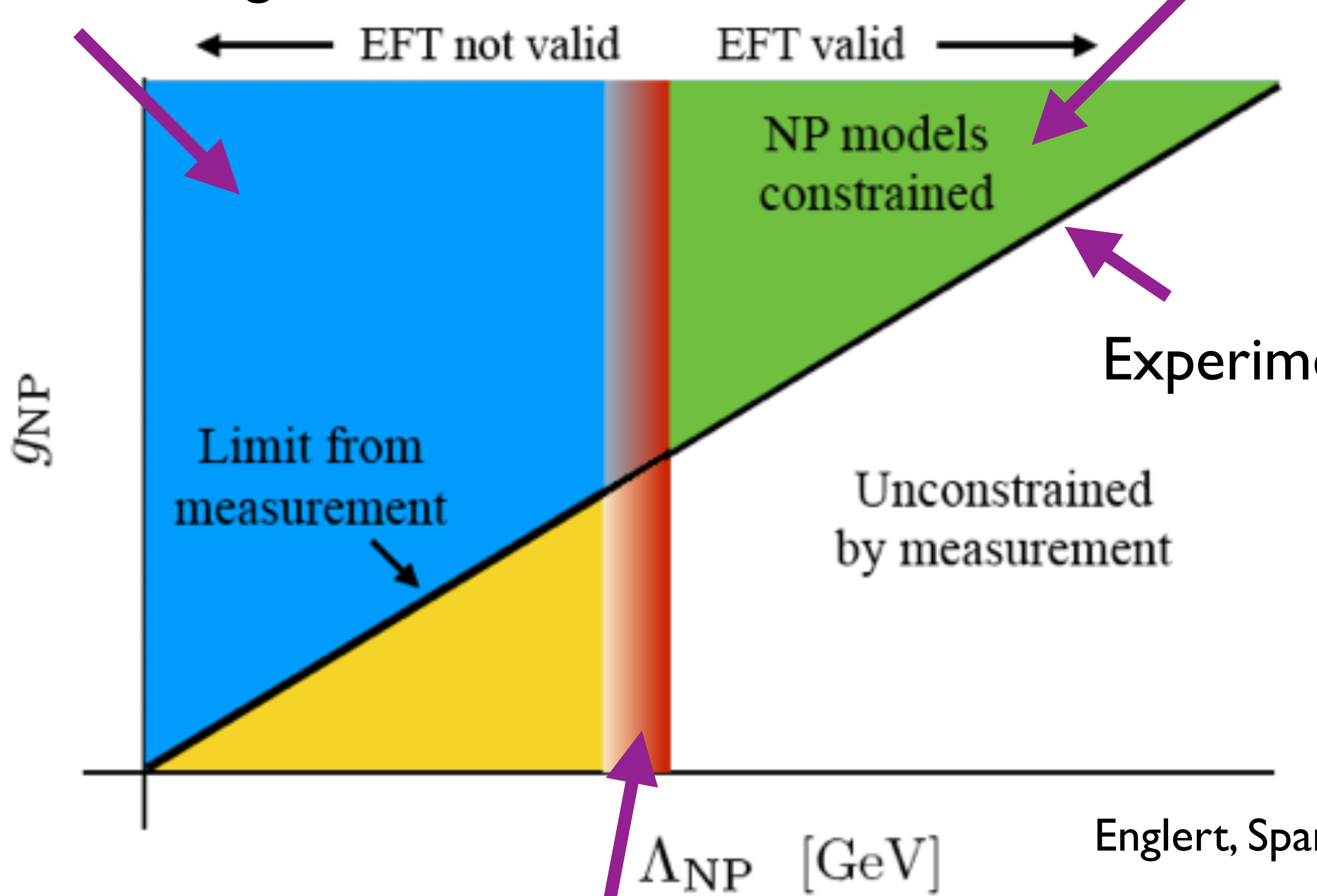
EFTs for Higgs physics

- Complete $N_F=1$, baryon-number conserving D=6 EFT contains 59 operators; $N_F=3$ contains 2499 operators (Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884); Alonso, Jenkins, Manohar, Trott 1312.2014). Various basis choices and simplifications have been discussed.
  - Warsaw basis (Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884)
  - SILH basis (Giudice, Grojean, Pomarol, Rattazzi hep-ph/0703164; Contino, Ghezzi, Grojean, Muhlleitner, Spira 1303.3876)
  - Higgs basis (Gupta, Pomarol, Riva 1405.0181)
  - Chiral EW Lagrangian (Buchalla, Cata, Krause 1307.5017)
- Higher-order corrections in EFT important to disentangle new physics effects from RG-running (Englert, Spannowsky 1408.5147). Full NLO EFT calculations appearing (Hartmann, Trott 1507.03568)
- Can investigate EFT validity in toy models (Contino, Falkowski, Goertz, Grojean, Riva 1604.06444)

Sketch of an EFT analysis

Must compare explicit UV models against data in the region

Can map heavy NP models into this constraint plane



Experiment bounds g^2/Λ^2

Englert, Spannowsky 1408.5147

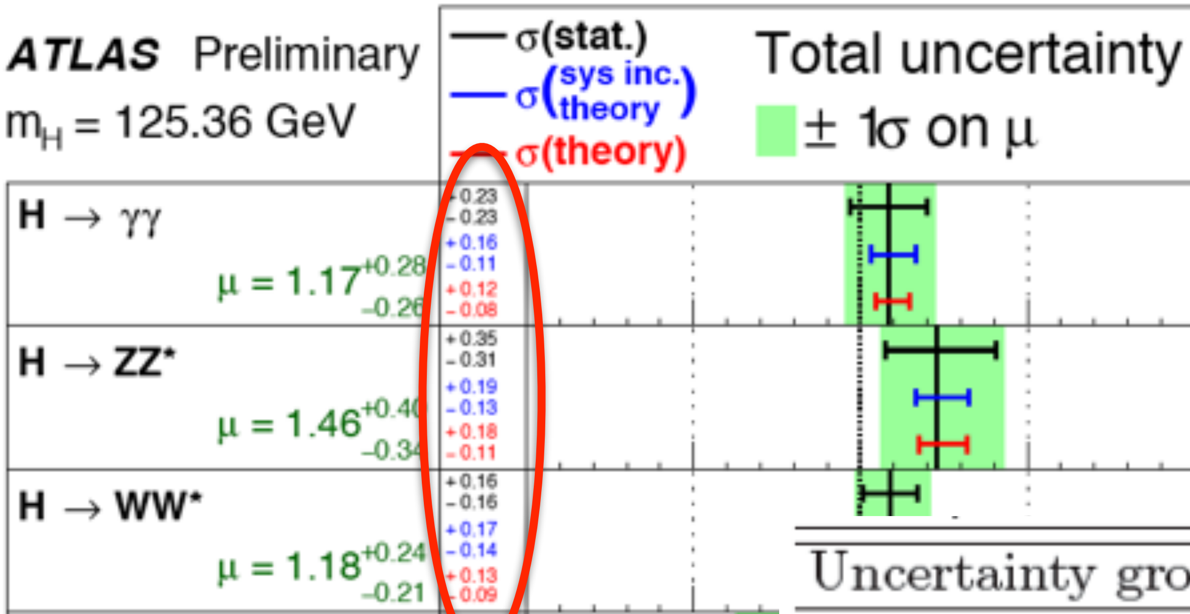
Measure maximum energy scale that goes into measurement to set lower limit on EFT region of validity

Sketch of an EFT analysis

Measurement — EFT

Several bridges between experiment and EFT interpretation have been proposed to simplify analyses:

- Pseudo-observables (Gonzalez-Alonso, Greljo, Isidori, Marzocca 1412.6038; Ghezzi, Gomez-Ambrosio, Passarino, Uccirati 1505.03706)
- Template cross sections (Duehrssen-Debling, Francavilla, Tackmann, Tackmann LHCHXSWG-2016-006)



Source of uncertainty	combined
Electron reconstruction and identification efficiencies	1.6%
Electron isolation and impact parameter selection	0.5%
Electron trigger efficiency	<0.2%
$\ell\ell + ee$ backgrounds	1.3%
Muon reconstruction and identification efficiencies	1.5%
Muon trigger efficiency	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.2%
QCD scale uncertainty	6.5%
PDF, α_s uncertainty	6.0%
$H \to ZZ^*$ branching ratio uncertainty	4.0%

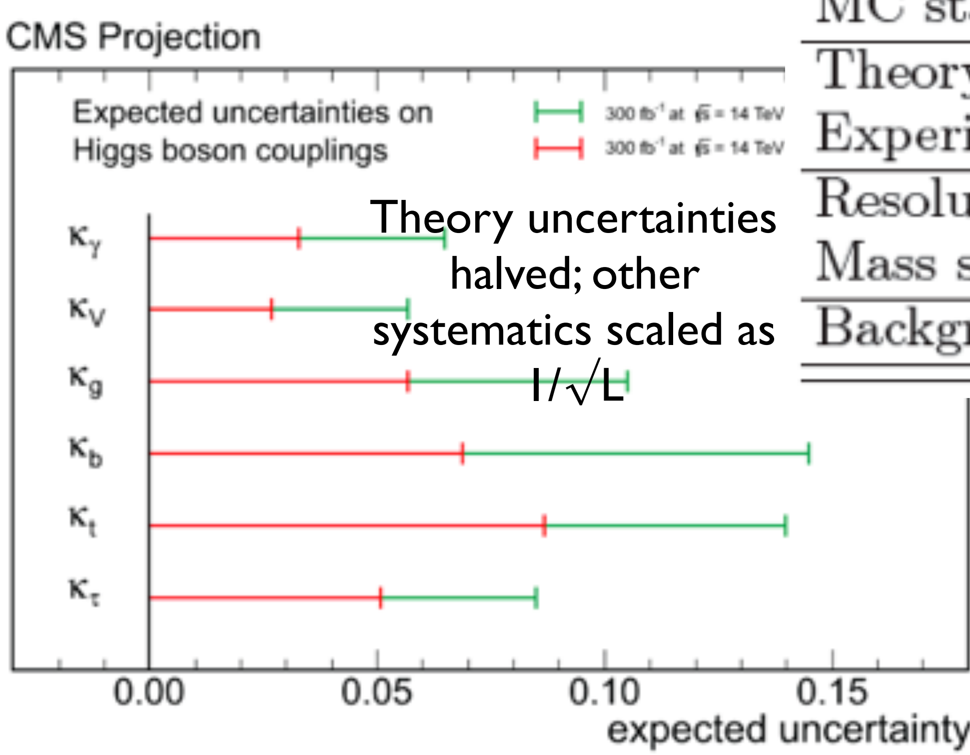
ZZ

Uncertainty group	$\sigma_\mu^{\text{syst.}}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02

YY

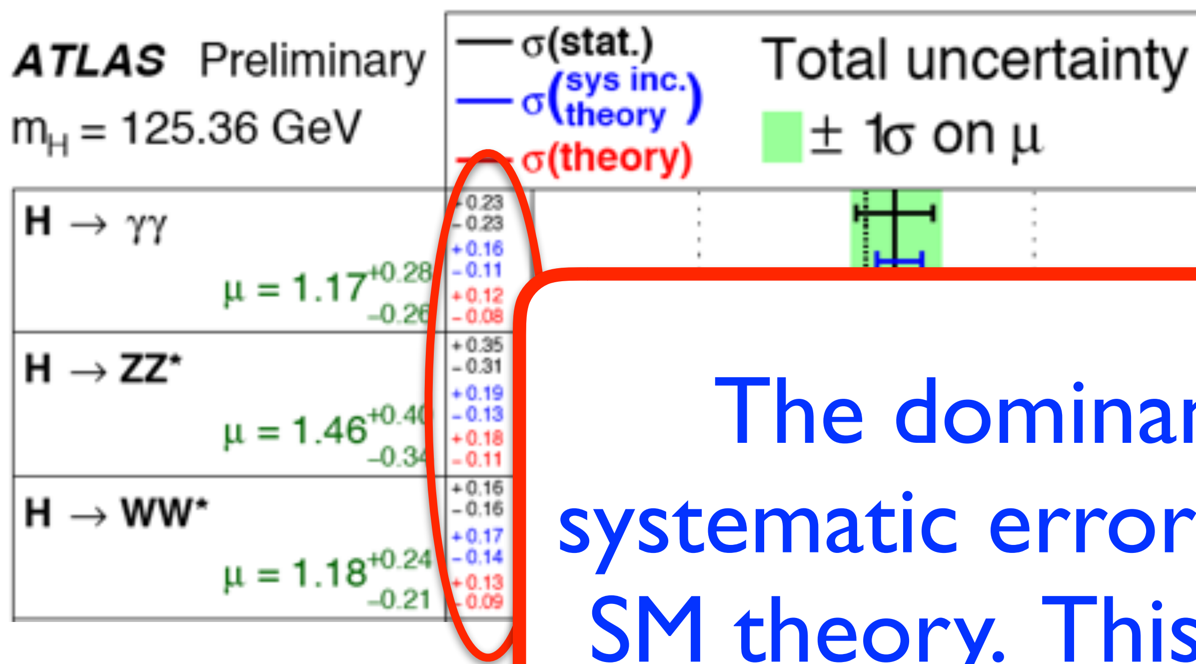
Source	Error +	Error −	Plot of error (scaled by 100)
Data statistics	0.16	0.15	
Signal regions	0.12	0.12	
Profiled control regions	0.10	0.10	
Profiled signal regions	-	-	-
MC statistics	0.04	0.04	
Theoretical systematics	0.15	0.12	
Signal $H \to WW^*$ $\mathcal{B}$	0.05	0.04	
Signal ggF cross section	0.09	0.07	
Signal ggF acceptance	0.05	0.04	
Signal VBF cross section	0.01	0.01	
Signal VBF acceptance	0.02	0.01	
Background WW	0.06	0.06	
Background top quark	0.03	0.03	
Background misid. factor	0.05	0.05	
Others	0.02	0.02	
Experimental systematics	0.07	0.06	
Background misid. factor	0.03	0.03	
Bkg. $Z/\gamma^* \to ee, \mu\mu$	0.02	0.02	
Muons and electrons	0.04	0.04	
Missing transv. momentum	0.02	0.02	
Jets	0.03	0.02	
Others	0.03	0.02	

WW



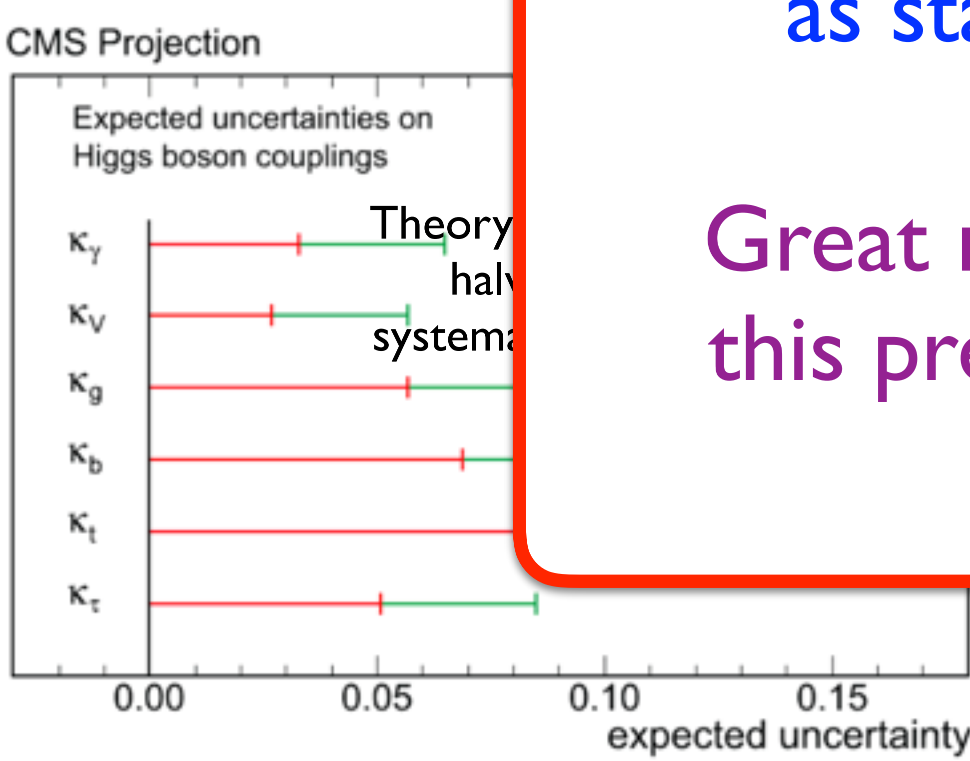
Theory uncertainties halved; other systematics scaled as $1/\sqrt{L}$

Source of uncertainty	combined
Electron reconstruction and identification efficiencies	1.6%
Electron isolation and impact parameter selection	0.5%
Electron trigger efficiency	<0.2%
$\ell\ell + ee$ backgrounds	1.3%
Muon reconstruction and identification efficiencies	1.5%
Muon trigger efficiency	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.2%
	6.5%
	6.0%
	4.0%



The dominant component of the systematic error on the signal strength is SM theory. This threatens to become a limiting factor in interpretation of Run II as statistical errors decrease.

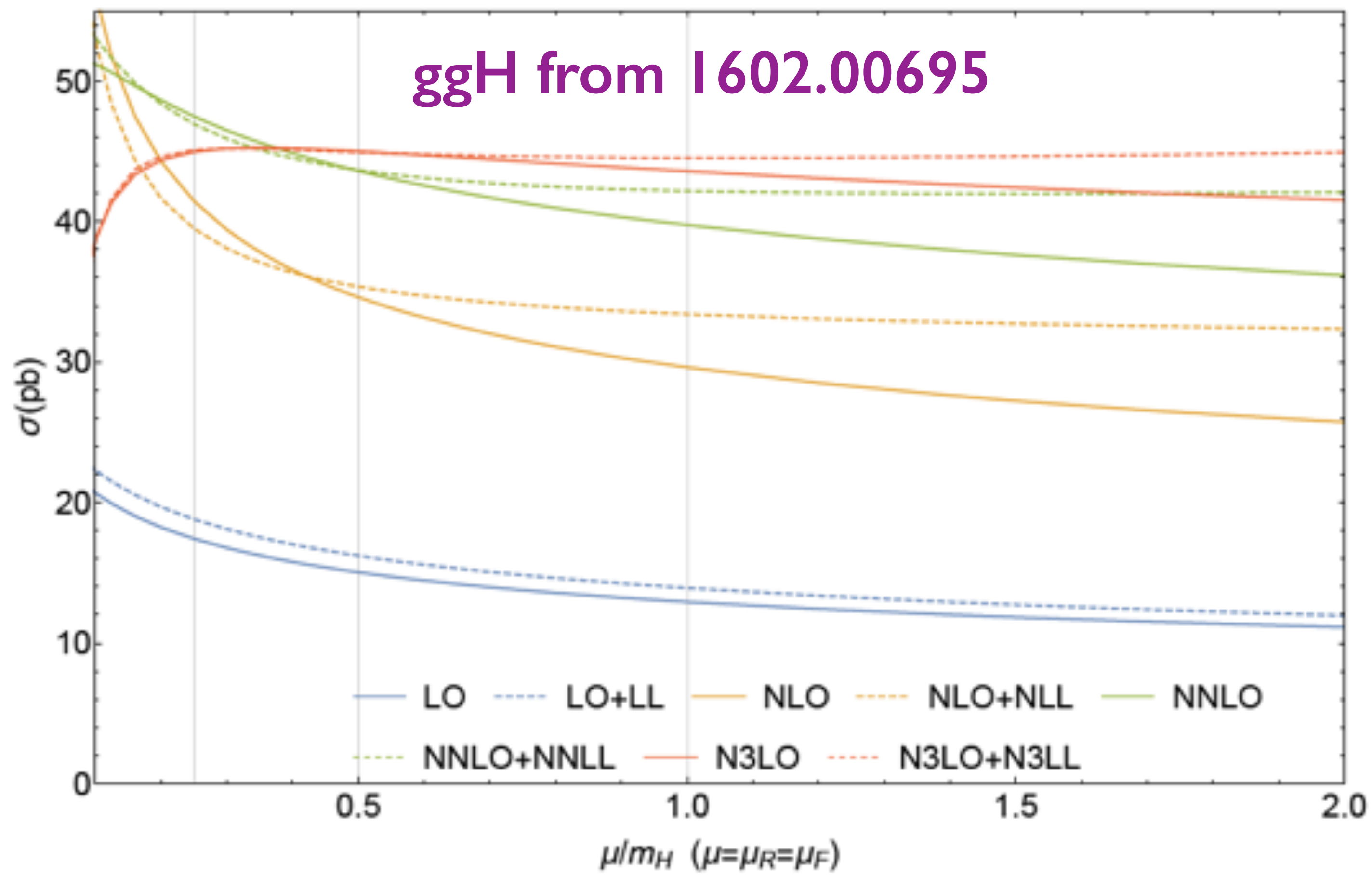
Great recent progress in meeting this precision challenge of Run II!



	...ror	Plot of error (scaled by 100)
	–	
		0.15
		0.12
		0.10
		-
		0.04
		0.12
		0.04
		0.07
		0.04
		0.01
		0.01
		0.06
		0.03
		0.05
		0.02
		0.06
		0.03
		0.02
Muons and electrons	0.04	0.04
Missing transv. momentum	0.02	0.02
Jets	0.03	0.02
Others	0.03	0.02

Higgs production in gluon-fusion and VBF

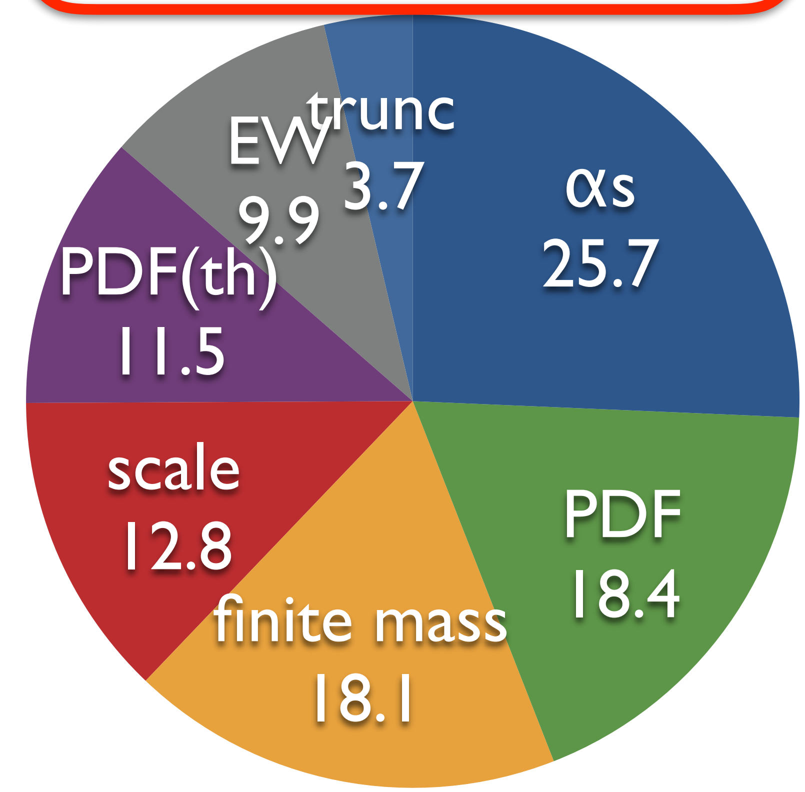
- Inclusive gluon-fusion Higgs production known at N^{3}LO! Important part of all coupling analyses (Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger 1602.00695)
- VBF production known at N^{2}LO differentially, and N^{3}LO inclusively (Cacciari, Dreyer, Karlberg, Salam, Zanderighi 1506.02660; Dreyer, Karlberg 1606.00840)



13 TeV:

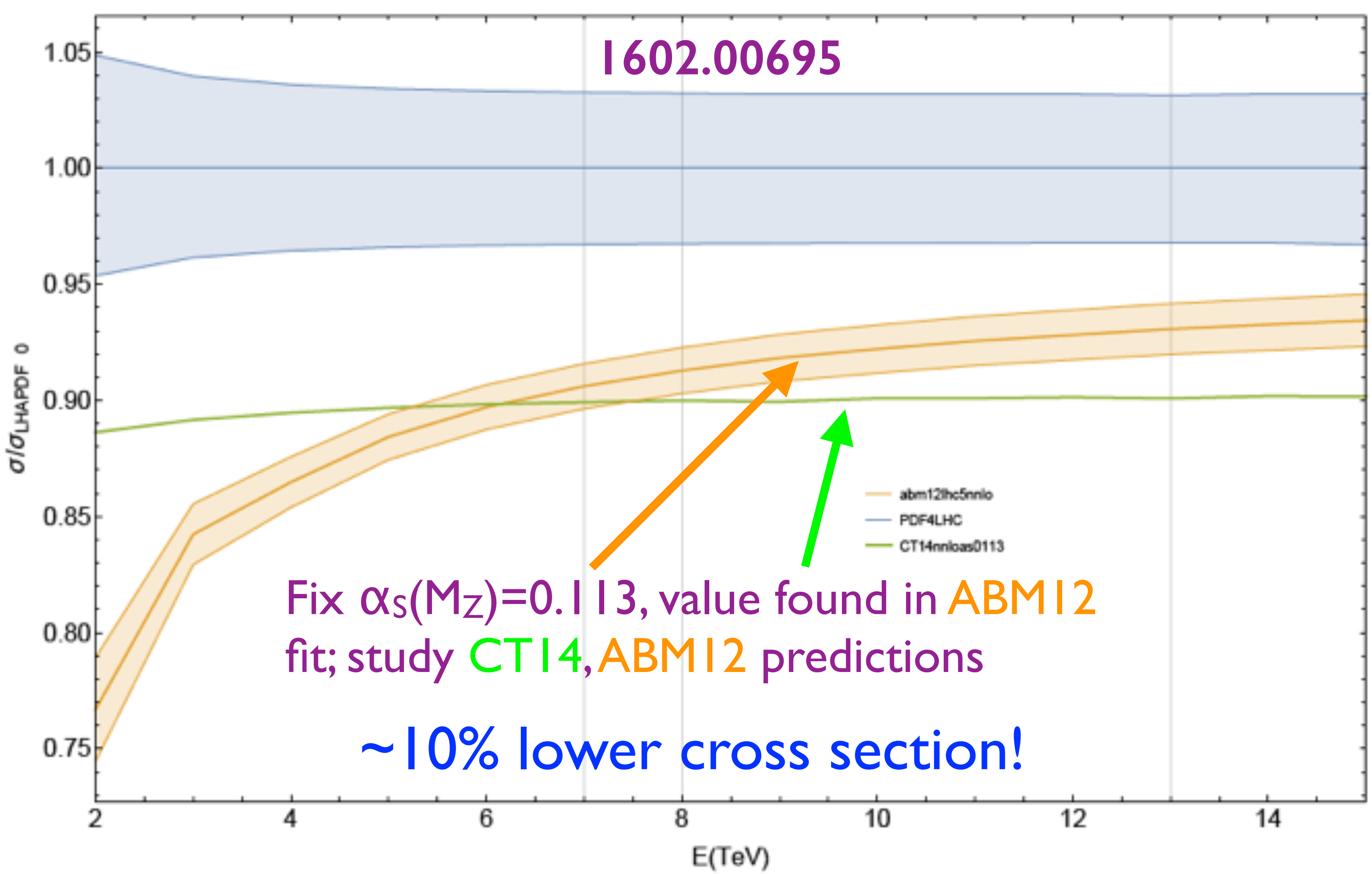
$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)\,.$$

Approximate error budget (percentage of total error):

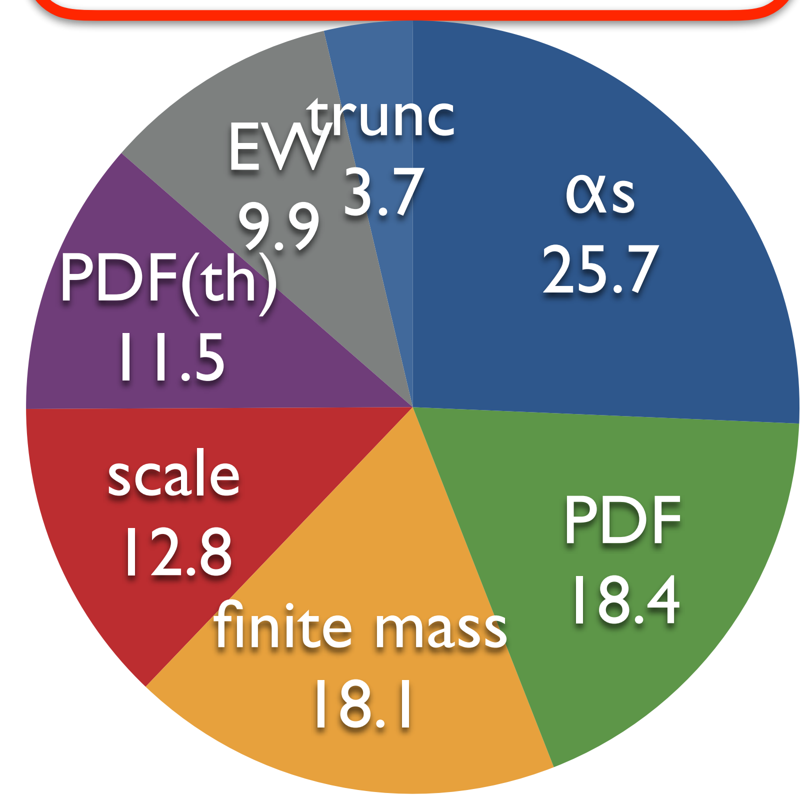


Higgs production in gluon-fusion and VBF

- This assumes PDF4LHC $\alpha_S(M_Z)$ recommendation: 0.1180±0.0015
- DIS fits prefer lower $\alpha_S(M_Z)$; LO ggH~α_S^2⇒strong parametric dependence!



Approximate error budget
(percentage of total error):

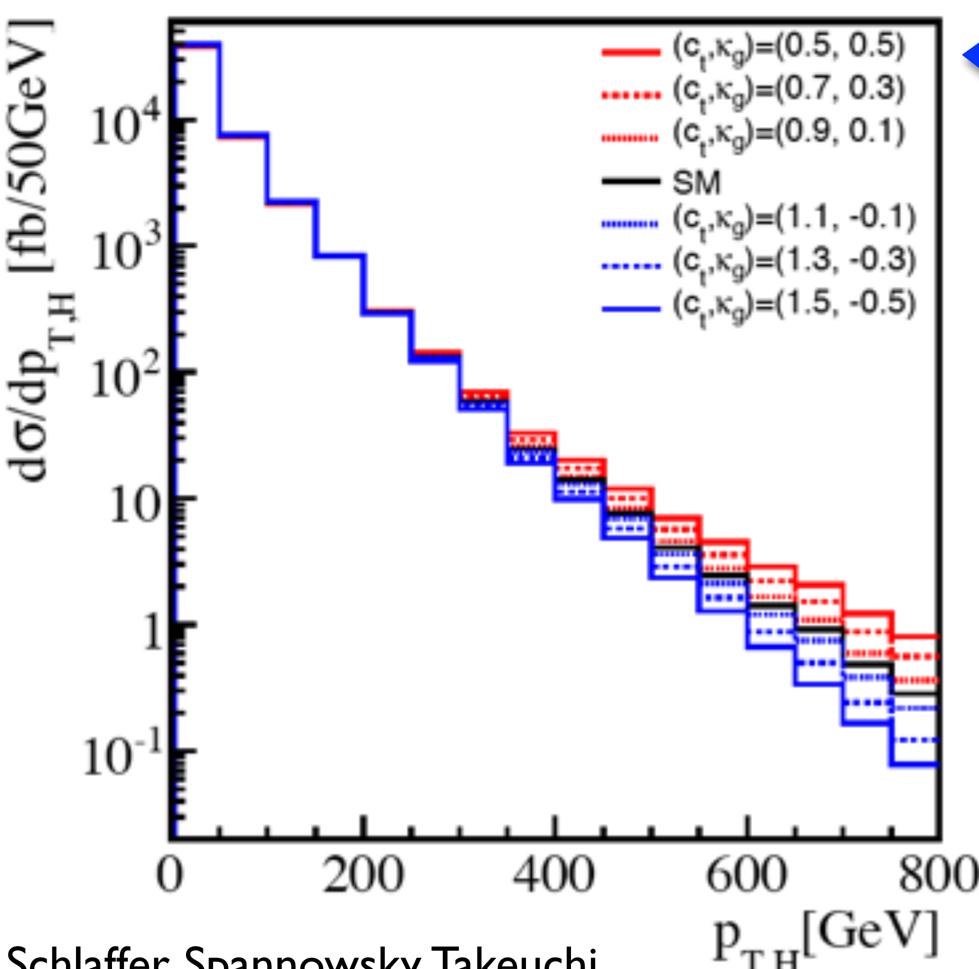


Would like resolution of α_s differences

Higgs+jet production

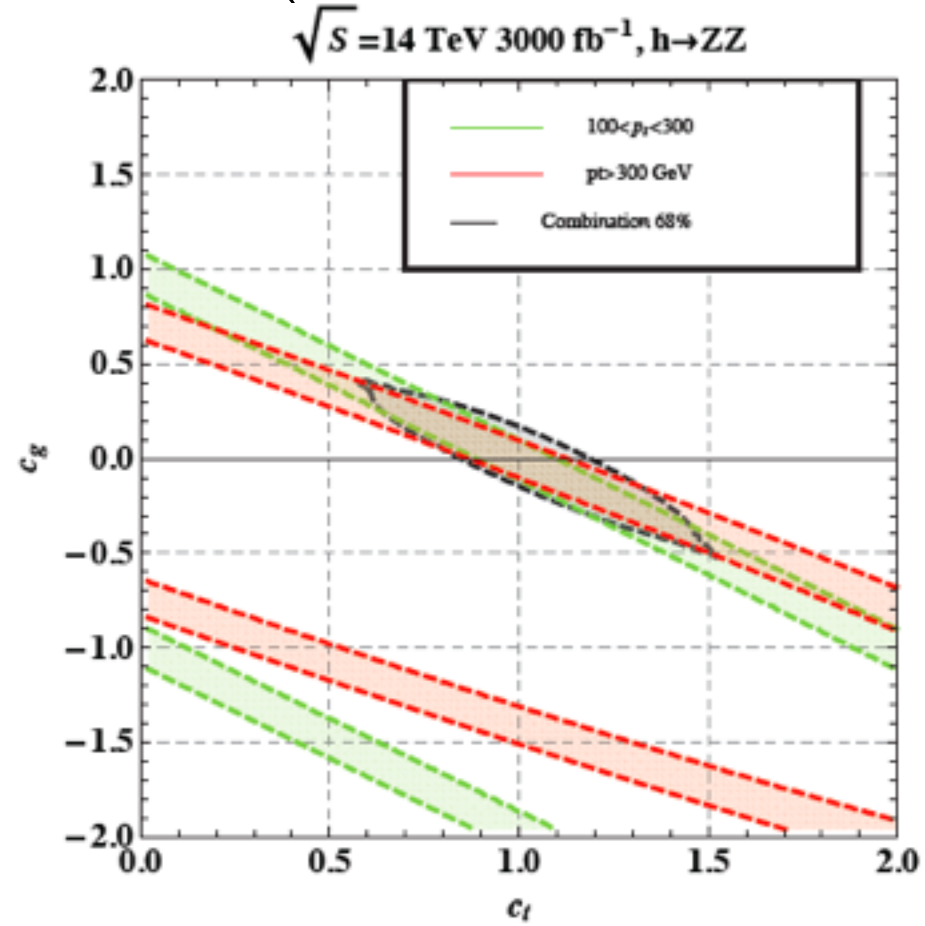
- Question: how can we disentangle the ggh and tth couplings? Direct tth production, but also through Higgs p_T spectrum.

$$\Delta\mathcal{L} = -c_t \frac{m_t}{v} + \kappa_g \frac{\alpha_s}{12\pi}\frac{h}{v} G^a_{\mu\nu} G^{a,\mu\nu} \Rightarrow \frac{\sigma(c_t,\kappa_g)}{\sigma_{\rm SM}} = (c_t+\kappa_g)^2$$



Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant 1405.4295

Inclusive production cannot distinguish these scenarios (must extend κ framework for Run II!)



Azatov, Paul 1309.5273 (see also Grojean et al. 1312.3317)

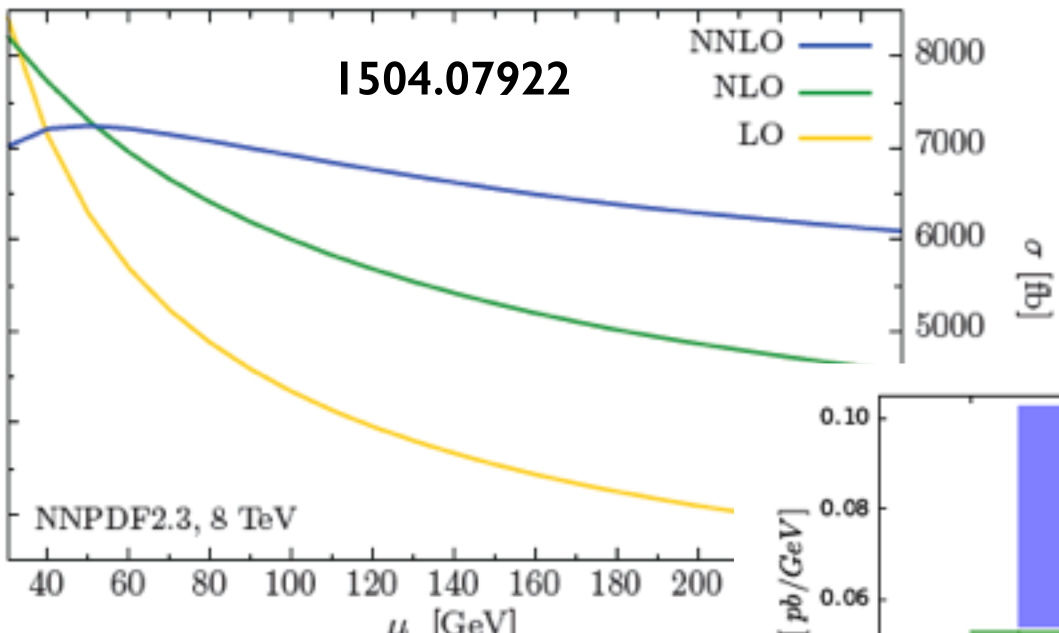
Precision p_{Th} calculation essential!

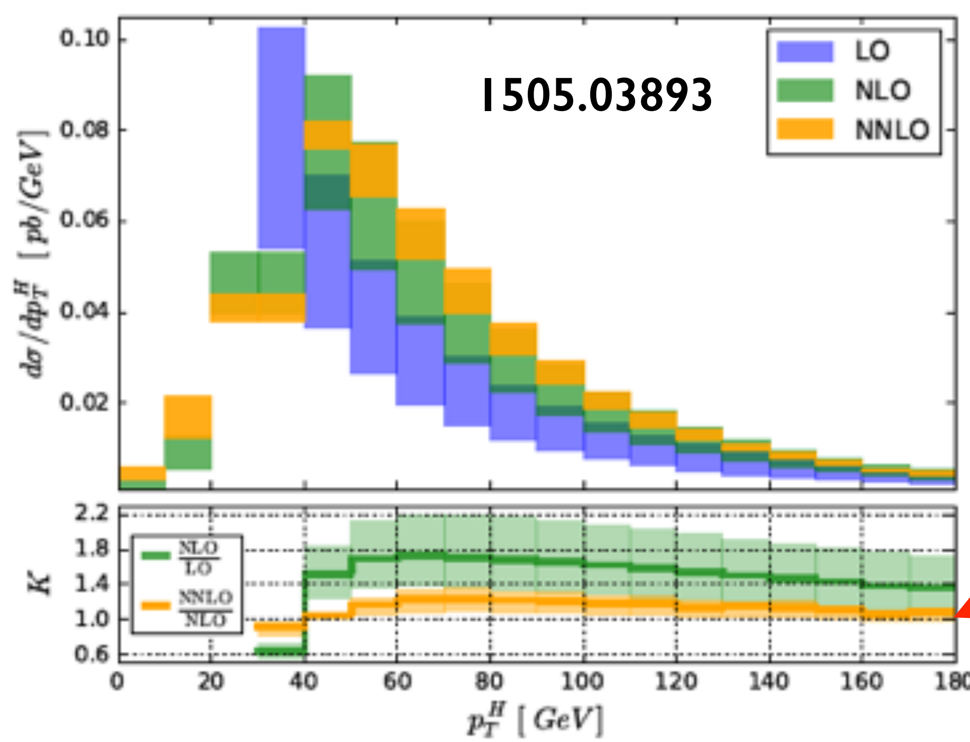
Higgs+jet production

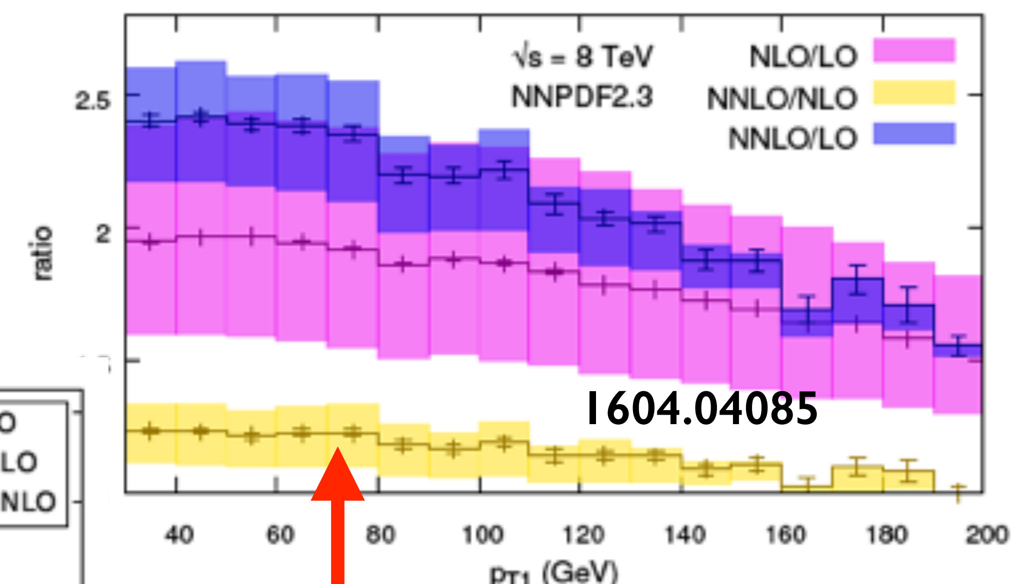
- Need precision theory improvements on two fronts:

Exact NLO m_t dependence for high p_{Th} (corrections to $1/m_t$ suppressed operators known Harlander, Neumann, Ozeren 1206.0157; Dawson, Lewis, Zeng 1409.6299)

NNLO QCD corrections in heavy-m_t limit for low p_{Th}. Now known from three independent calculations! (Boughezal, Caola, Melnikov, FP, Schulze 1504.07922; Boughezal, Focke, Giele, Liu, FP 1505.03893; Chen, Gehrmann, Glover, Jaquier 1604.04085)







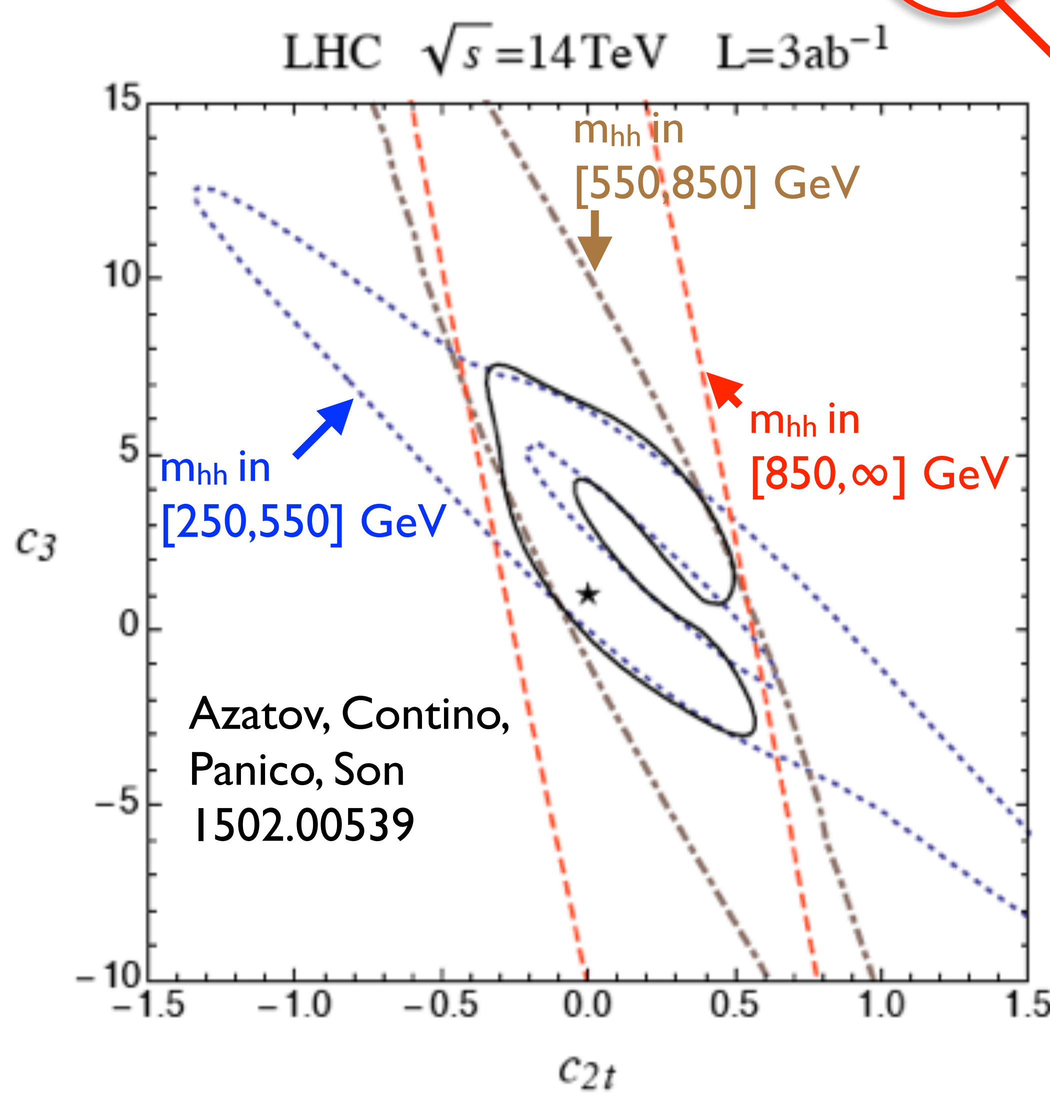
Non-trivial shape dependence of corrections!

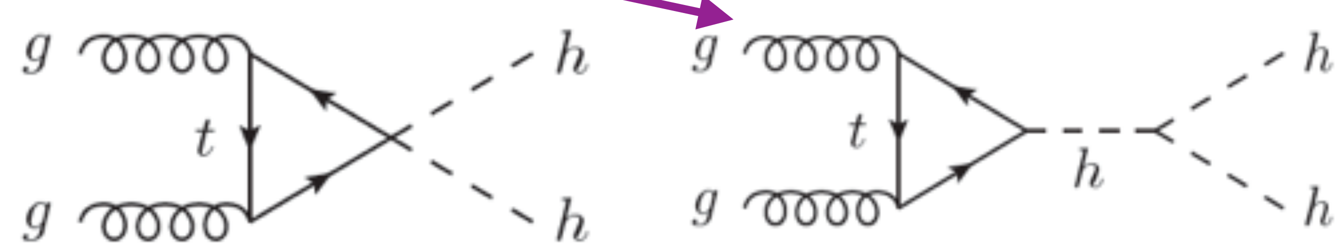
Di-Higgs production

- Question: Is the Higgs potential the one predicted in the SM, which depends only on m_h?

(These two c_i chosen for illustration)

$$\mathcal{L}_{non-lin} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t}\frac{h^2}{v^2}\right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2}\left(c_g \frac{h}{v} + c_{2g}\frac{h^2}{2v^2}\right) G^a_{\mu\nu}G^{a\,\mu\nu}$$



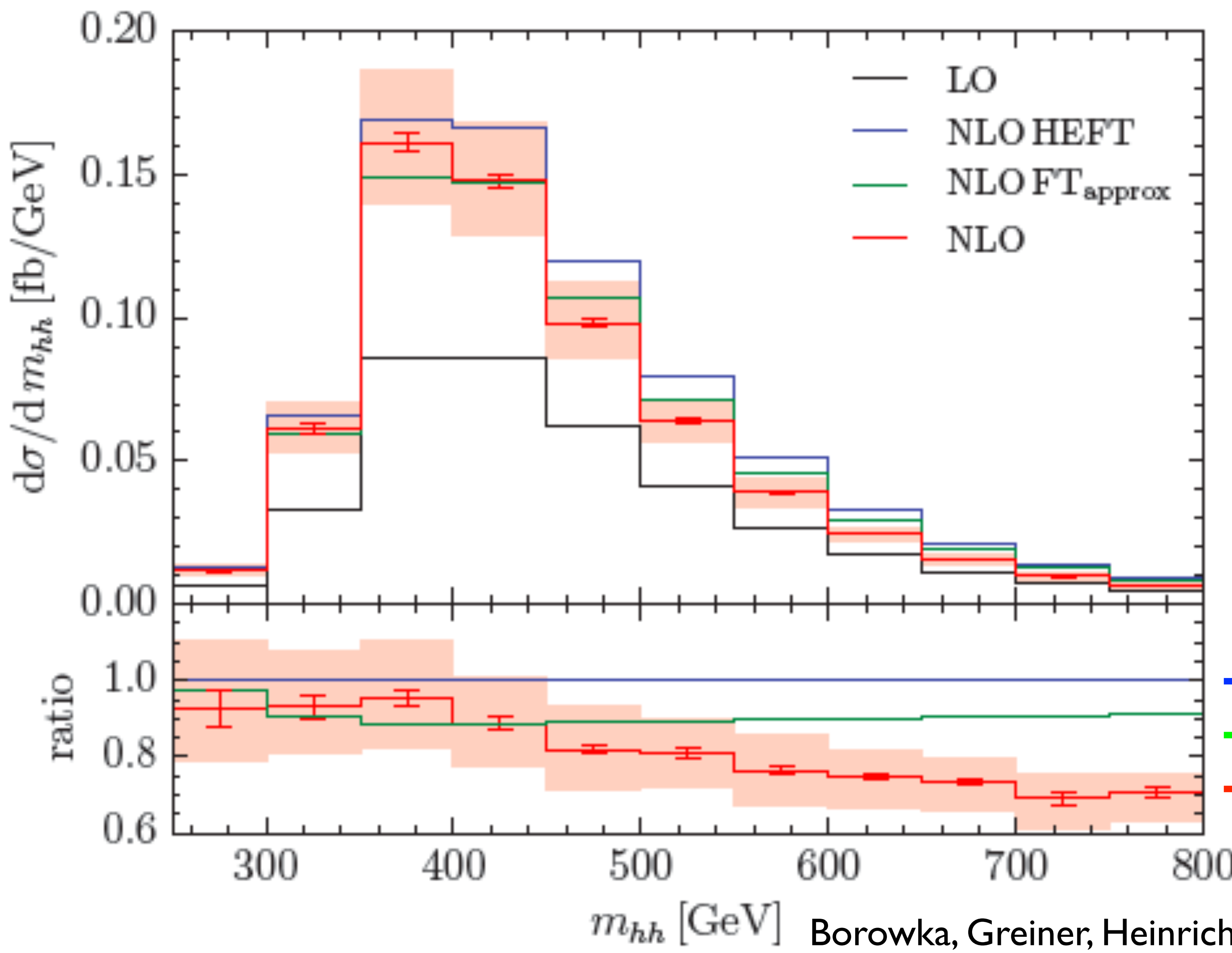


- Critical to use m_{hh} to break degeneracies between couplings. First higher-order QCD corrections were in heavy-m_t approximation

Plehn, Spira, Zerwas (1996); Dawson, Dittmaier, Spira (1998); Grigo, Hoff, Melnikov, Steinhauser (2013); Maltoni, Vryonidou, Zaro (2014); Degrassi, Giardino, Groeber (2016)

Di-Higgs production

- Large corrections not captured by heavy-m_t approximation! In particular, a strong dependence of the NLO corrections on m_{hh} is missed in the approximation approach



The full higher-order corrections are essential for interpretation of this measurement!

→ Heavy-m_t approximation

→ Exact m_t in real radiation only

→ Exact NLO result

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke 1604.06447

We eagerly await the answers to many questions during Run II

- Does SUSY, or another mechanism, stabilize the EW scale?
- Will the LHC measurements uncover the origin of flavor?
- Will the Higgs guide us to a new Standard Model?

Let's move beyond the desert!