Higgs Boson Production in the Standard Model

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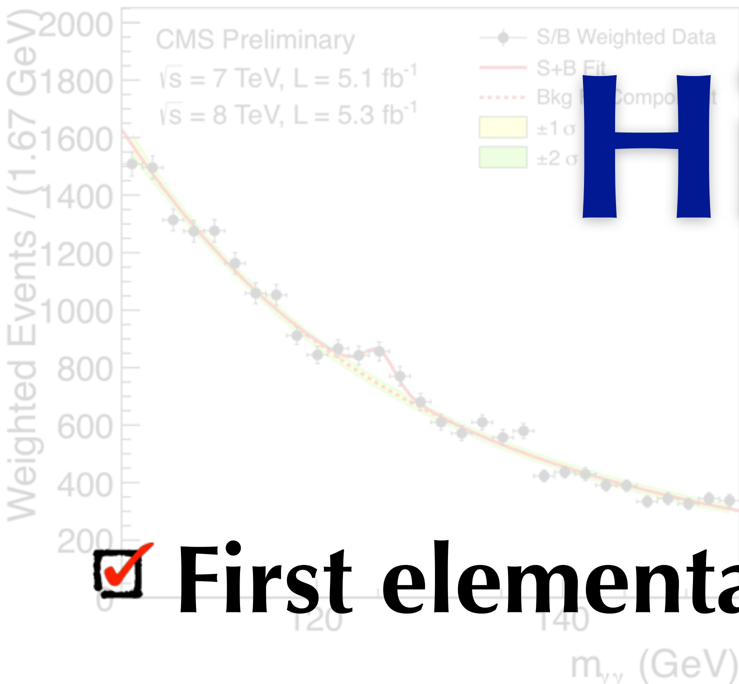
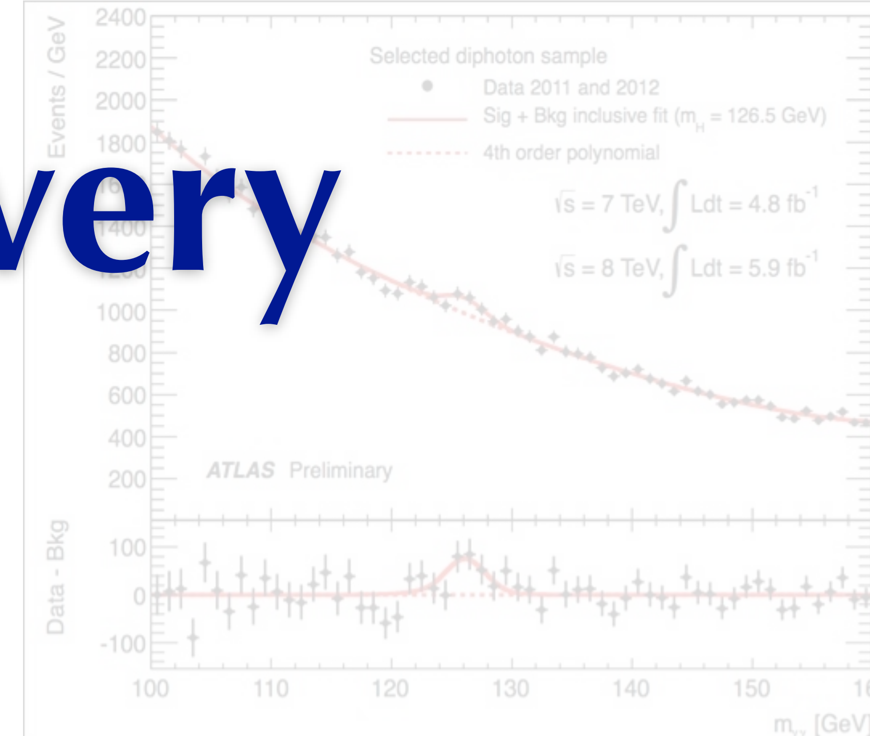
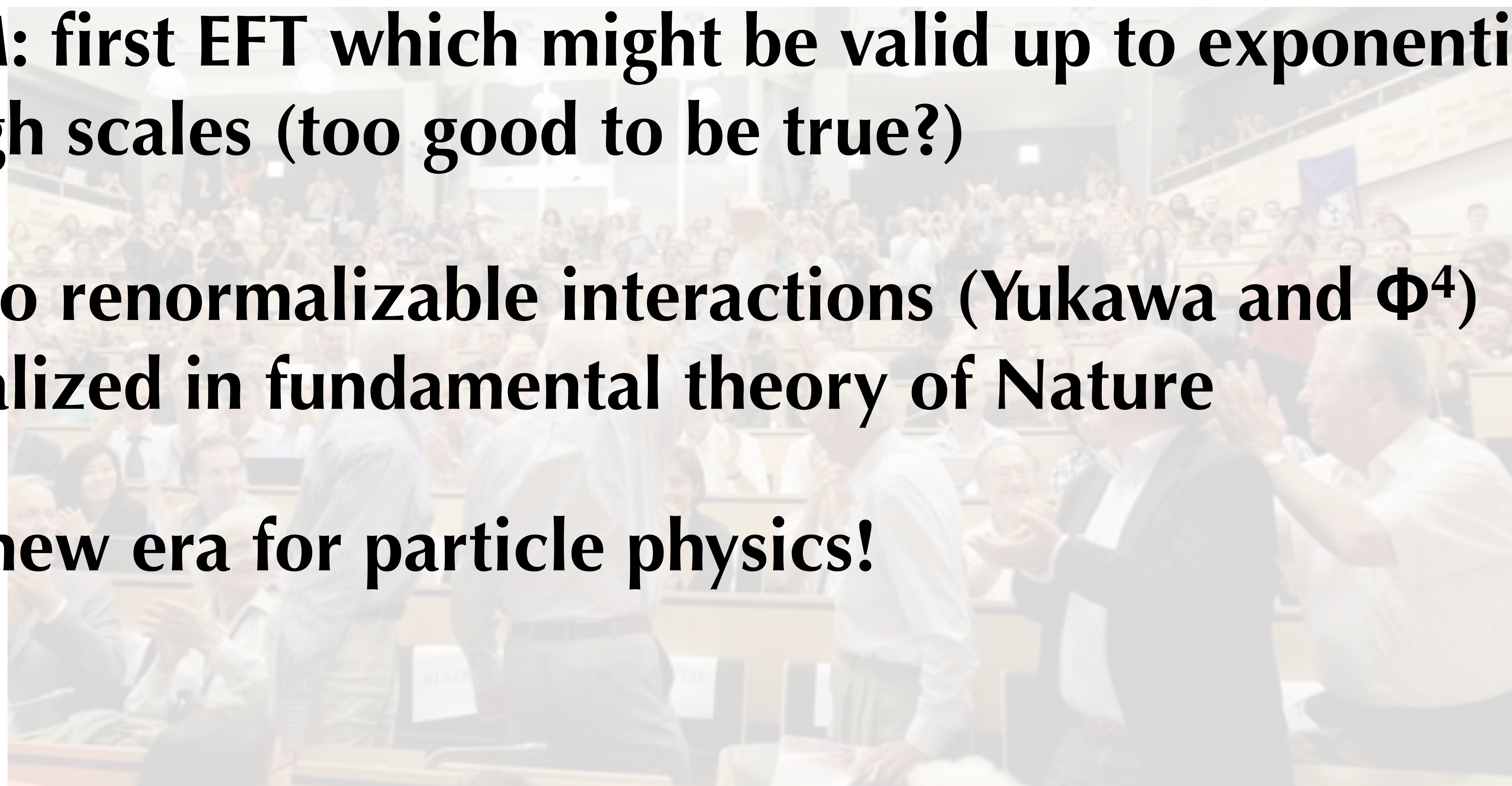
International Symposium on Higgs Boson and Beyond Standard Model Physics
Shandong University, Weihai

Higgs discovery





- ☑ First elementary(?) spin-0 particle
- ☑ SM: first EFT which might be valid up to exponentially high scales (too good to be true?)
- ☑ Two renormalizable interactions (Yukawa and Φ^4) realized in fundamental theory of Nature
- ☑ A new era for particle physics!



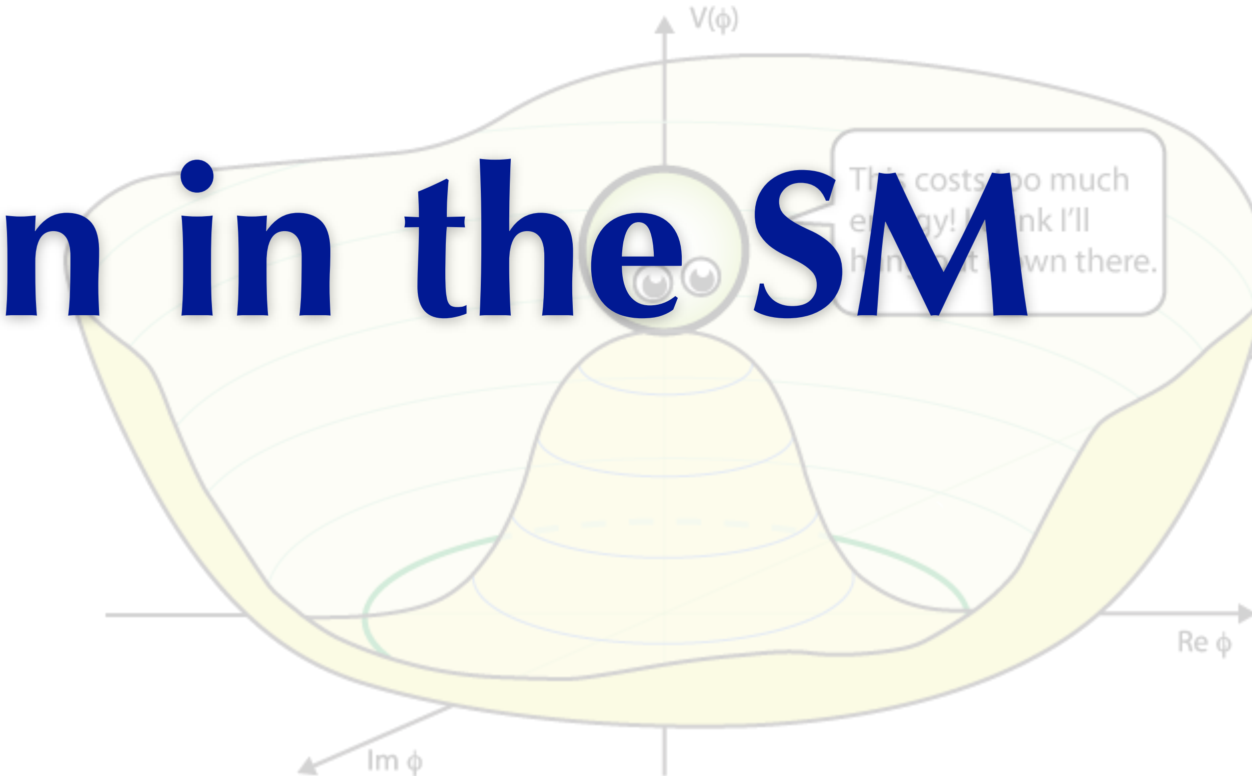
Open questions / hopes

* Is it (NOT) the SM Higgs?

Priority!

* Is it elementary or composite?
* Are there more than one Higgs?
* Phase transition? Vacuum stability? Naturalness?
* Relations to inflation / dark matter / matter-antimatter asymmetry / neutrino masses / … ?

Higgs boson in the SM



fermion $$\frac{m_f}{v}\bar{f}fh$$

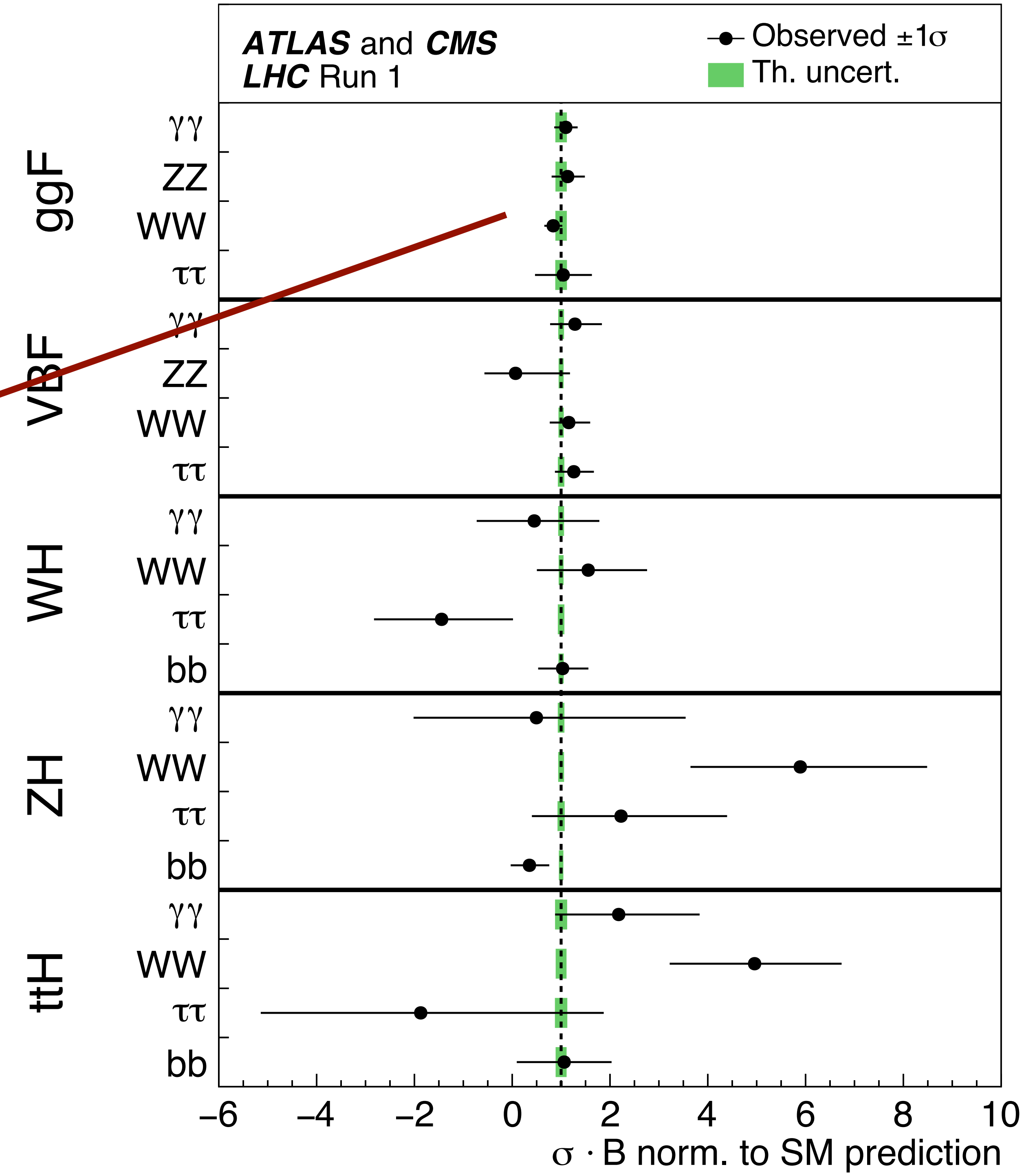
gauge $$\frac{m_W^2}{v^2}W_\mu^+W_-^\mu(v+h)^2+\frac{m_Z^2}{2v^2}Z_\mu Z^\mu(v+h)^2$$

potential $$\frac{m_h^2}{2}h^2+\frac{m_h^2}{2v}h^3+\frac{2m_h^2}{v^2}h^4$$

simple, elegant!
predictive, testable!

Theory vs. data

ATLAS and CMS: 1606.02266



Remarkable agreements based upon high precision **calculations** and **measurements**

Experimental error approaching theoretical uncertainty (NNLO+NNLL)

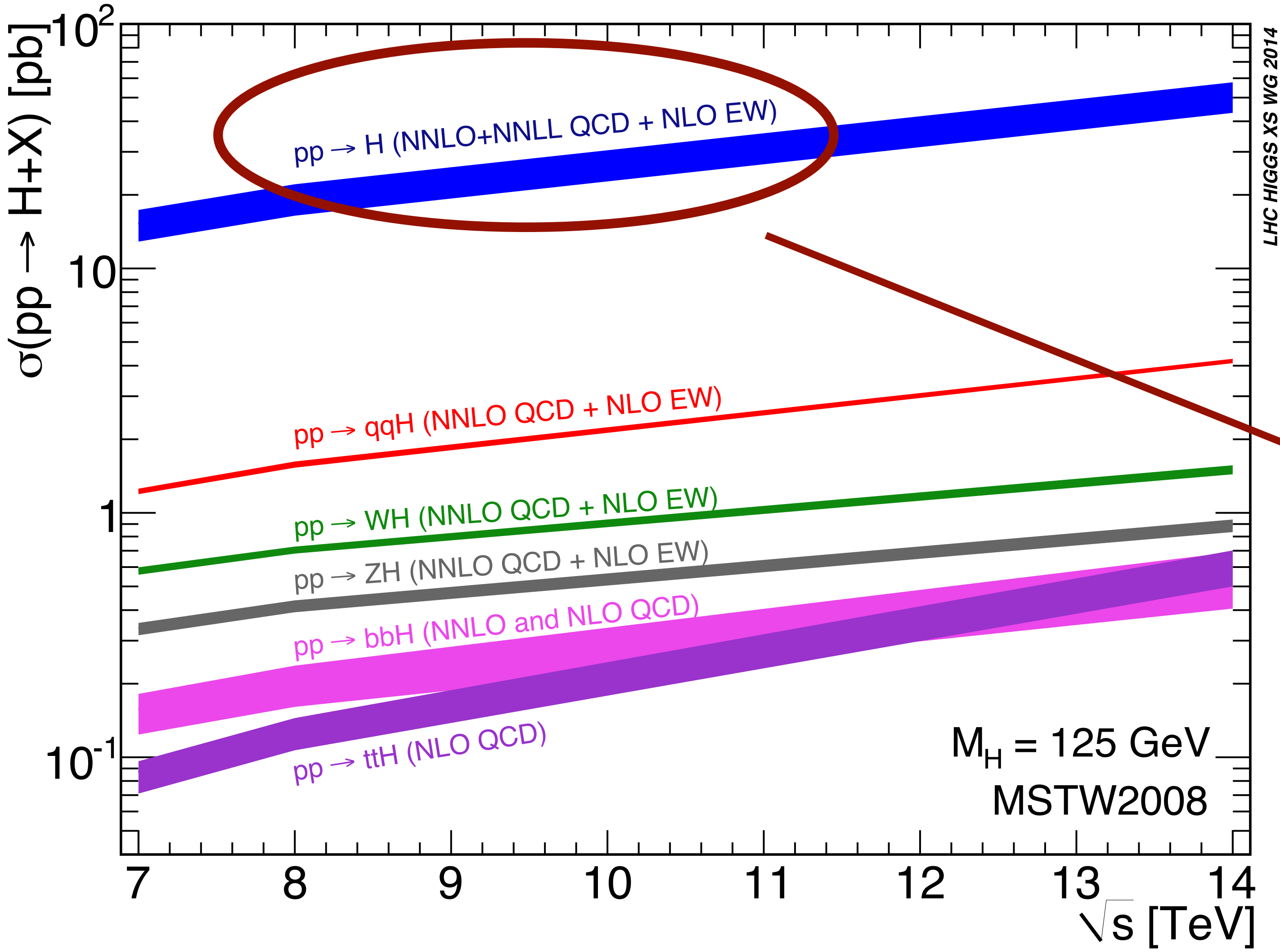
Run 2 updates in talks by Haifeng Li and Mingshui Chen!

Theoretical uncertainty

ATLAS and CMS: 1606.02266

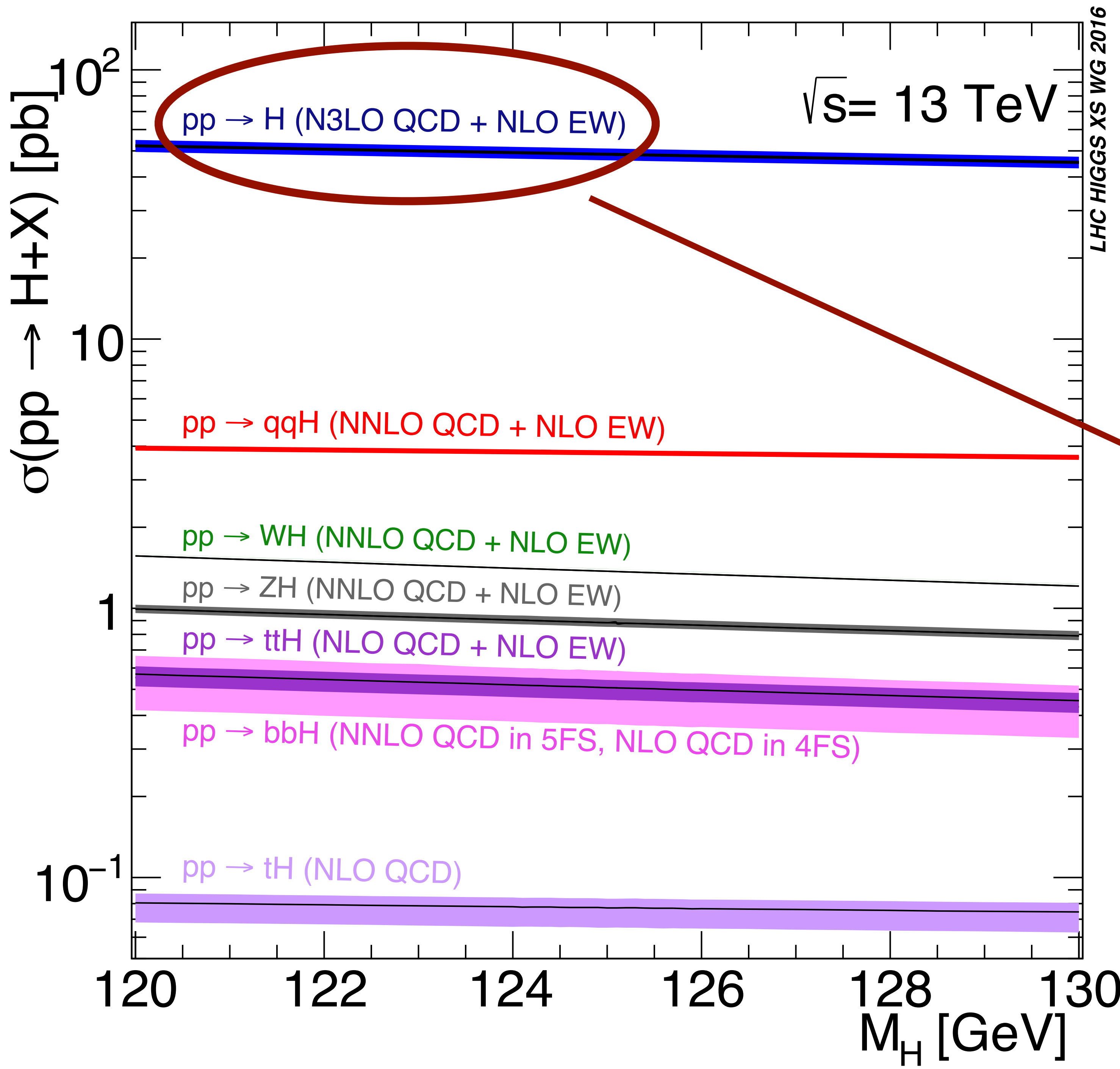
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,{}^{+0.04}_{-0.04}\,(\text{expt})\,\boxed{{}^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})}$$

LHC HXSWG report 3



Main source

Theoretical uncertainty



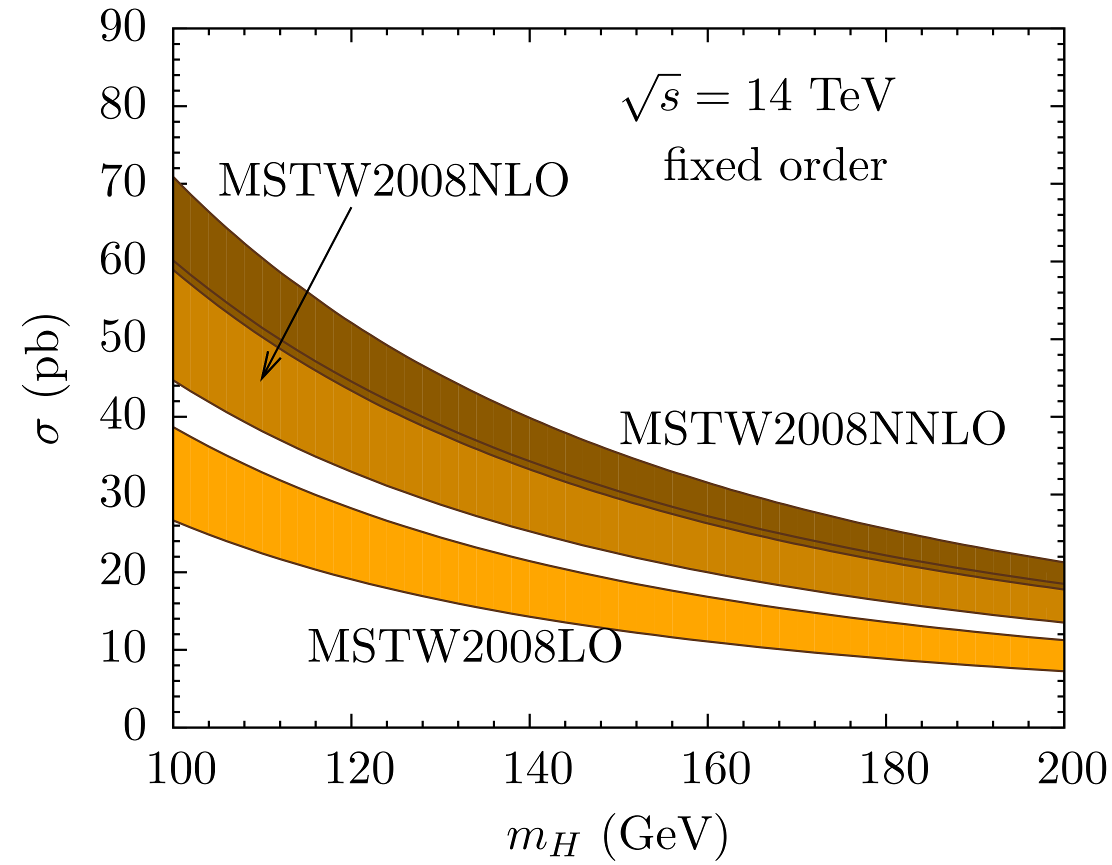
LHC HXSWG report 4 (to appear)

Improved precision!

gg→H

Huge QCD corrections

$$\frac{\sigma_{\rm NNLO}}{\sigma_{\rm LO}} \approx 200\%$$

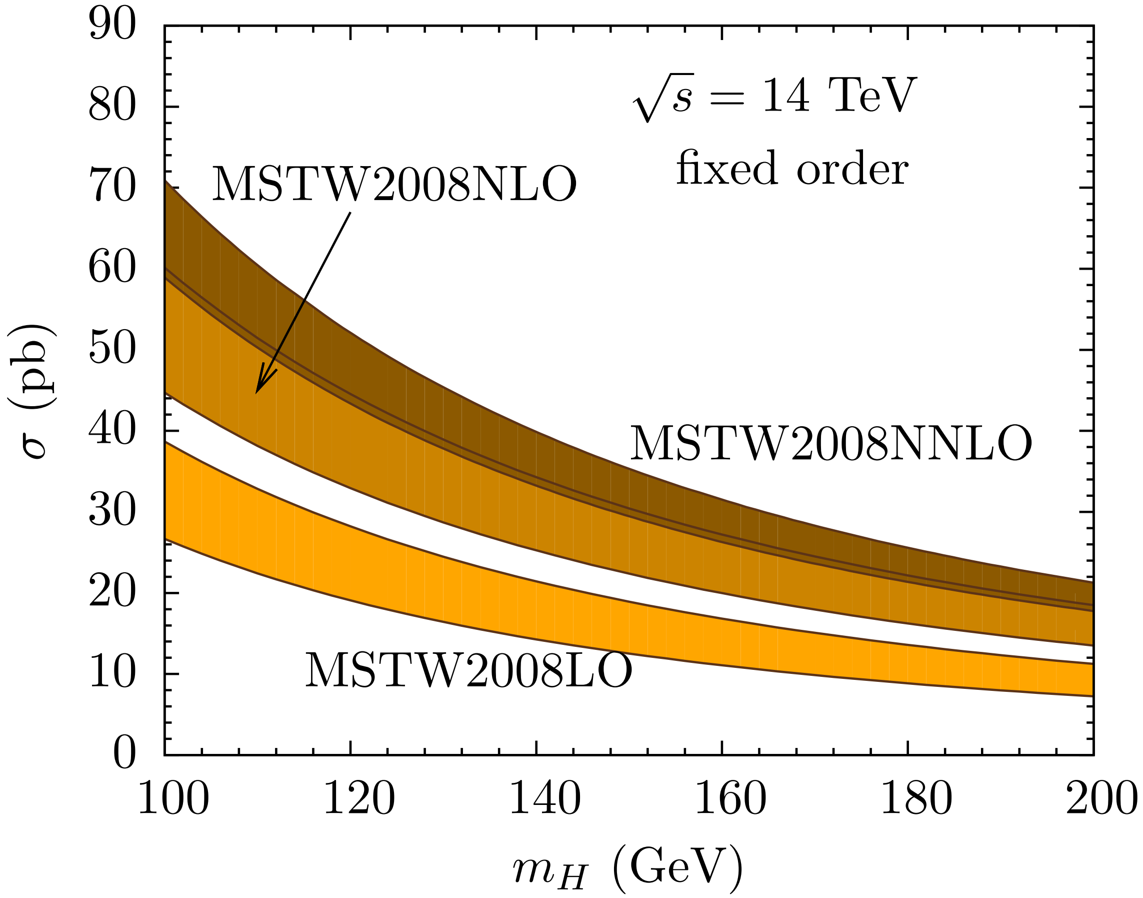


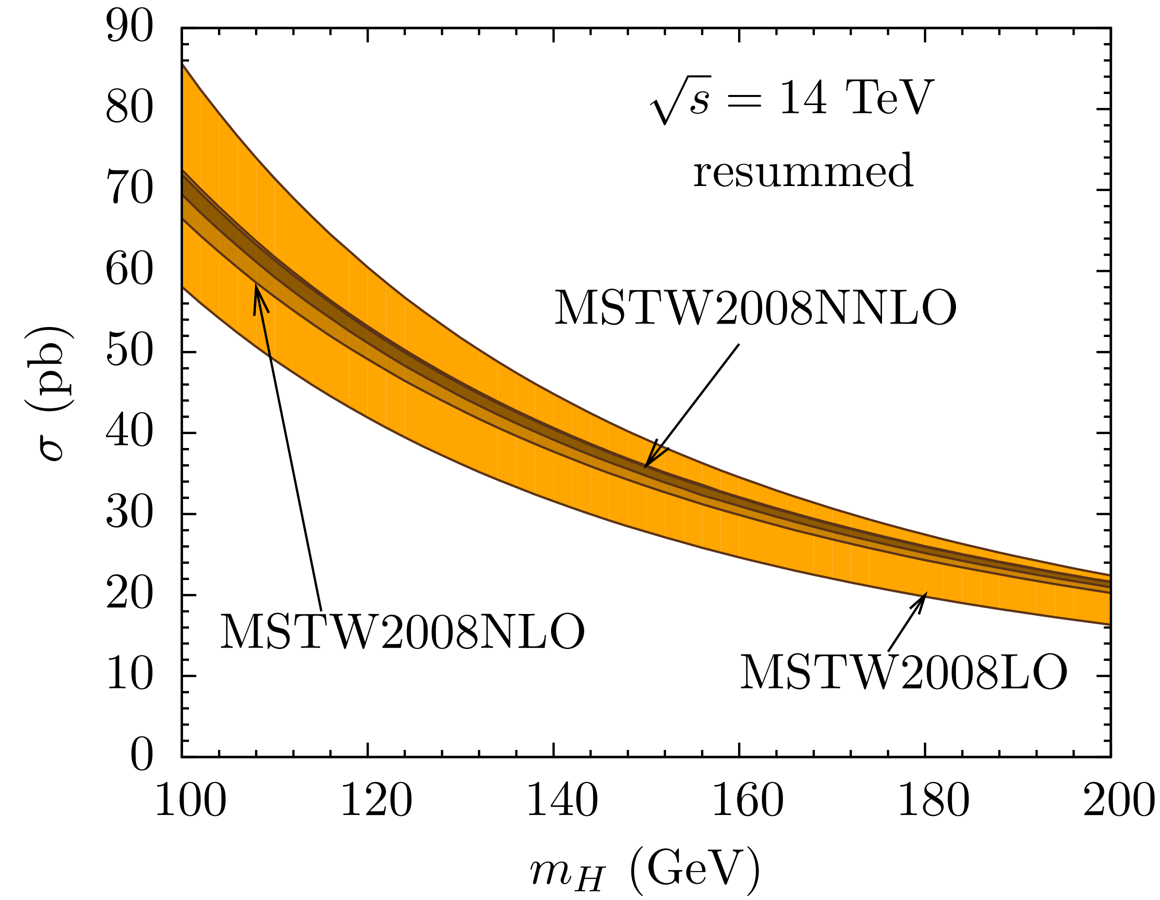
Reason well-understood: $$\left[\frac{\alpha_s}{2\pi} C_A \ln^2\left(\frac{-m_H^2}{m_H^2}\right)\right]^n$$

Ahrens, Becher, Neubert, **LLY**: 0808.3008

gg→H: NNLO+NNNLL +EW

Ahrens, Becher, Neubert, **LLY**: 0809.4283, 1008.3162



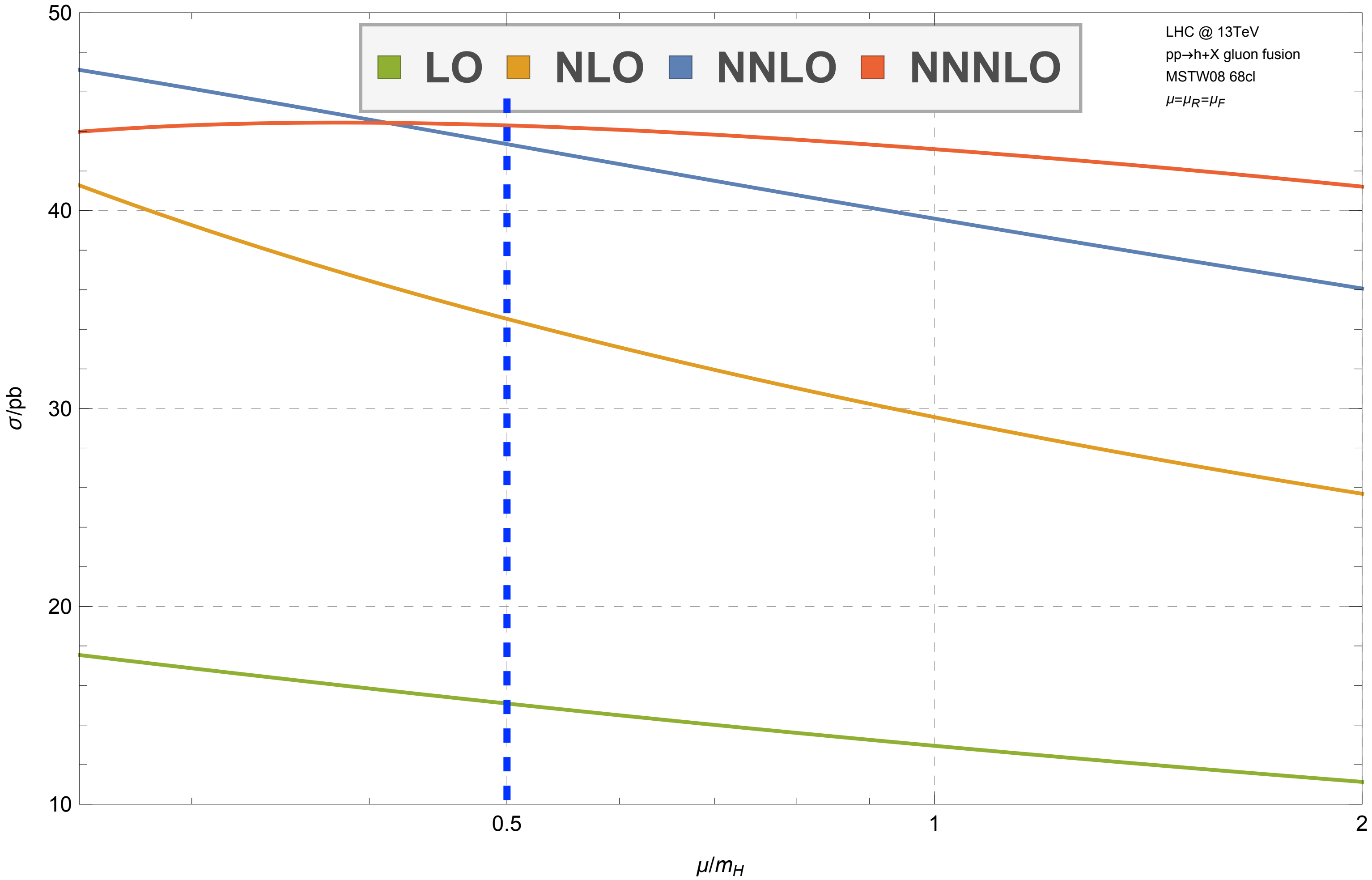


m_H [GeV]	Tevatron	LHC (7 TeV)	LHC (10 TeV)	LHC (14 TeV)
125	$0.950^{+0.022+0.113}_{-0.005-0.108}$	$15.43^{+0.44+1.23}_{-0.12-1.18}$	$29.0^{+0.8+2.2}_{-0.2-2.1}$	$50.4^{+1.4+3.8}_{-0.3-3.6}$

Resummed results hint at lower renormalization and factorization scales ($m_H/2$ instead of m_H) for fixed-order calculations; now widely adopted!

gg→H: NNNLO

Anastasiou, Duhr, Dulat, Herzog, Mistlberger: 1503.06056



σ/pb	2 TeV	7 TeV	8 TeV	13 TeV	14 TeV
$\mu = \frac{m_H}{2}$	$0.99^{+0.43\%}_{-4.65\%}$	$15.31^{+0.31\%}_{-3.08\%}$	$19.47^{+0.32\%}_{-2.99\%}$	$44.31^{+0.31\%}_{-2.64\%}$	$49.87^{+0.32\%}_{-2.61\%}$
$\mu = m_H$	$0.94^{+4.87\%}_{-7.35\%}$	$14.84^{+3.18\%}_{-5.27\%}$	$18.90^{+3.08\%}_{-5.02\%}$	$43.14^{+2.71\%}_{-4.45\%}$	$48.57^{+2.68\%}_{-4.24\%}$

- Well-consistent with NNLO+NNNLL
- Small correction and small uncertainty for $\mu=m_H/2$
- Theoretical error now dominated by other sources: PDF, α_s, top and bottom masses, etc.

Beyond SM: Higgs EFT

$$\mathcal{L} = \mathcal{L}_0 + \sum_{n,i} \frac{c_{n,i}}{\Lambda^{4+n}} O_{n,i}$$

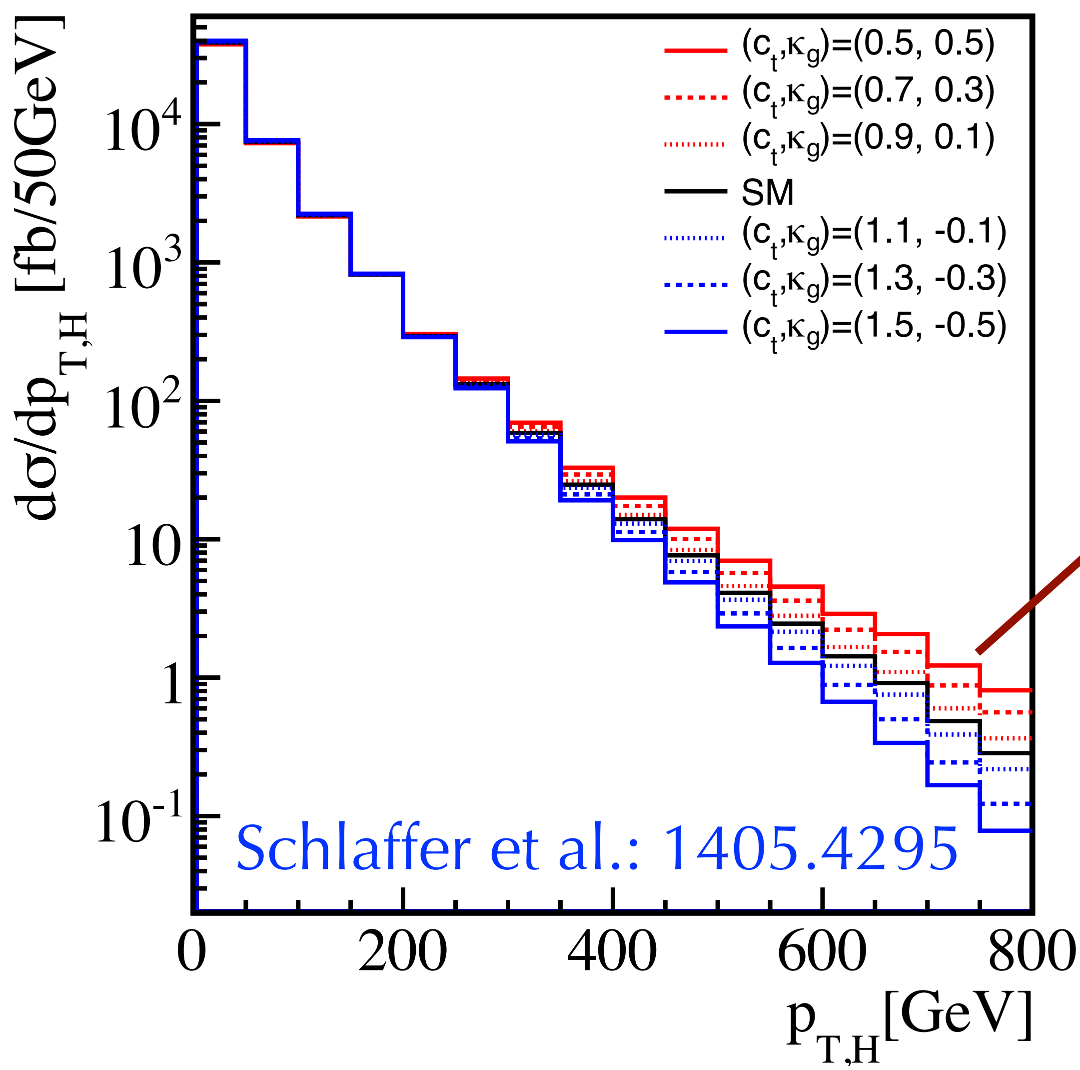
Buchmuller, Wyler (1986); Grzadkowski, Iskrzynski, Misiak, Rosiek: 1008.4884

$$\begin{aligned}
&+ \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda |H|^6 \\
&- \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \frac{c_\tau}{\Lambda^2} y_\tau |H|^2 \bar{L}_L H \tau_R + \text{h.c.} \right) \\
&+ \frac{\alpha_s c_g}{4\pi\Lambda^2} |H|^2 G^a_{\mu\nu} G^{\mu\nu}_a + \frac{\alpha' \, c_\gamma}{4\pi\Lambda^2} |H|^2 B_{\mu\nu} B^{\mu\nu} \\
&+ \frac{ig \, c_{HW}}{16\pi^2\Lambda^2} (D^\mu H)^\dagger \sigma_k (D^\nu H) W^k_{\mu\nu} + \frac{ig' \, c_{HB}}{16\pi^2\Lambda^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
&+ \frac{ig \, c_W}{2\Lambda^2} (H^\dagger \sigma_k \overleftrightarrow{D}^\mu H) D^\nu W^k_{\mu\nu} + \frac{ig' \, c_B}{2\Lambda^2} (H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu} \\
&+ \mathcal{L}_{\text{CP}} + \mathcal{L}_{\text{4f}} \, ,
\end{aligned}$$

A more consistent theoretical framework to quantify deviations from the SM than "anomalous couplings"

Higgs+jet: high p_T Higgs

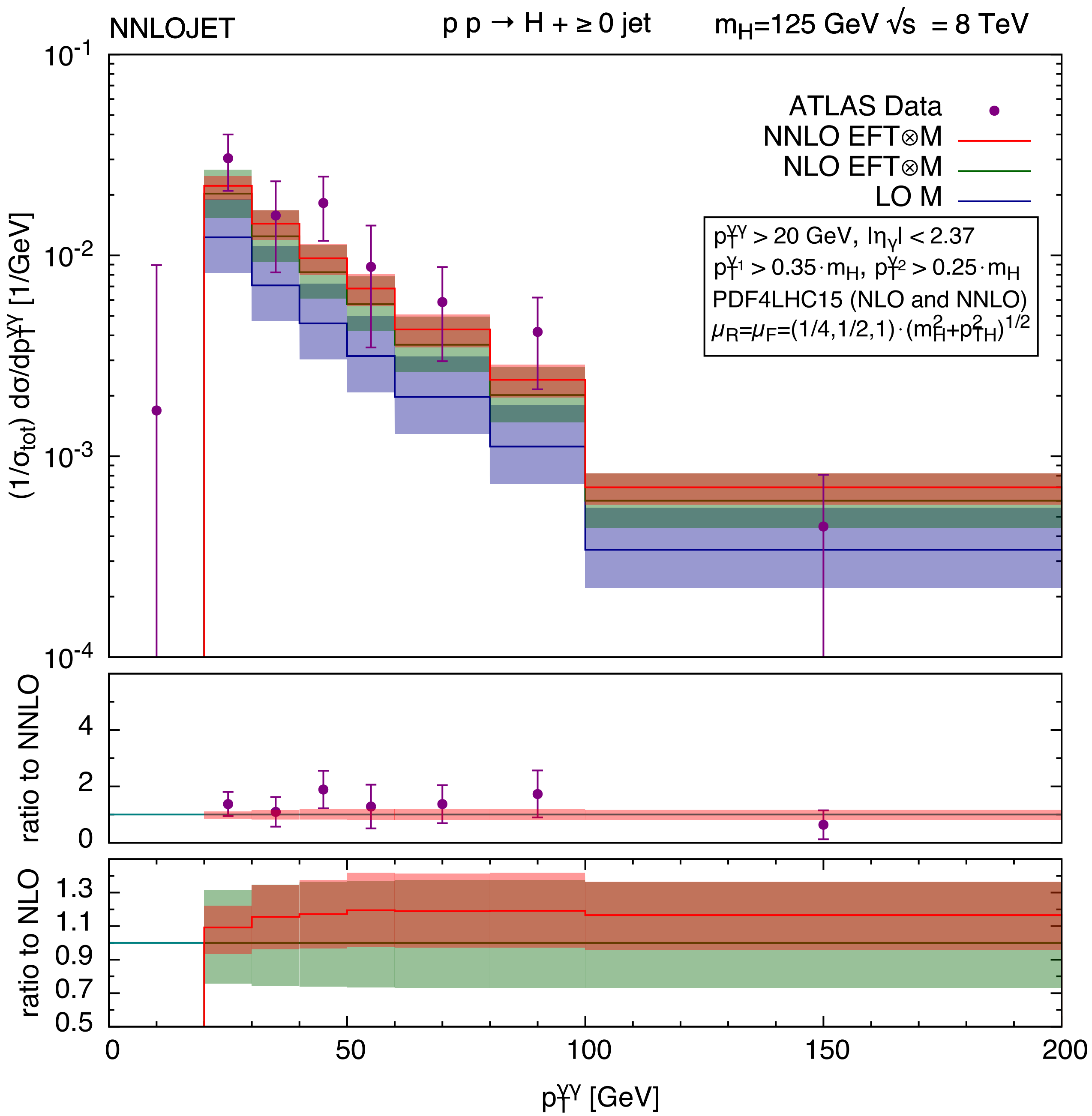
$$\mathcal{L} = \mathcal{L}_0 + \sum_{n,i} \frac{c_{n,i}}{\Lambda^{4+n}} O_{n,i}$$



- Tails of distributions sensitive to new physics
- High p_T Higgs resolves particles in the loop

Precise background modeling critical!

NNLO for Hj



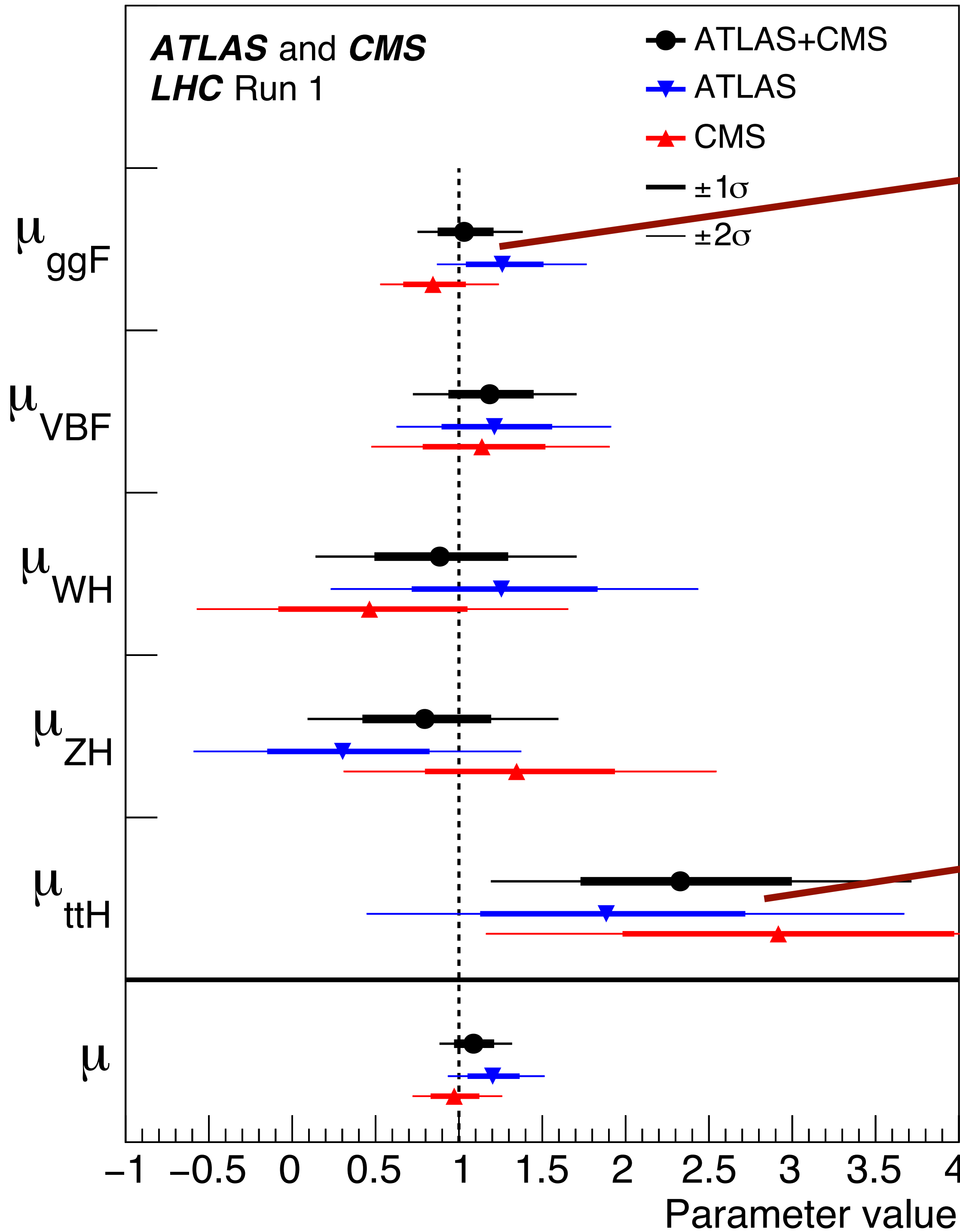
- Validation of various NNLO subtraction methods for colored final states
- Shape only changes slightly: good news for searches!

Boughezal, Caola, Melnikov, Petriello, Schulze: 1302.6216; 1504.07922;
Chen, Gehrmann, Glover, Jaquier: 1408.5325;
Boughezal, Focke, Giele, Liu, Petriello: 1505.03893;
Chen, Cruz-Martines, Gehrmann, Glover, Jaquier: 1607.08817

See talk by Dr. Xuan Chen

Top and Higgs

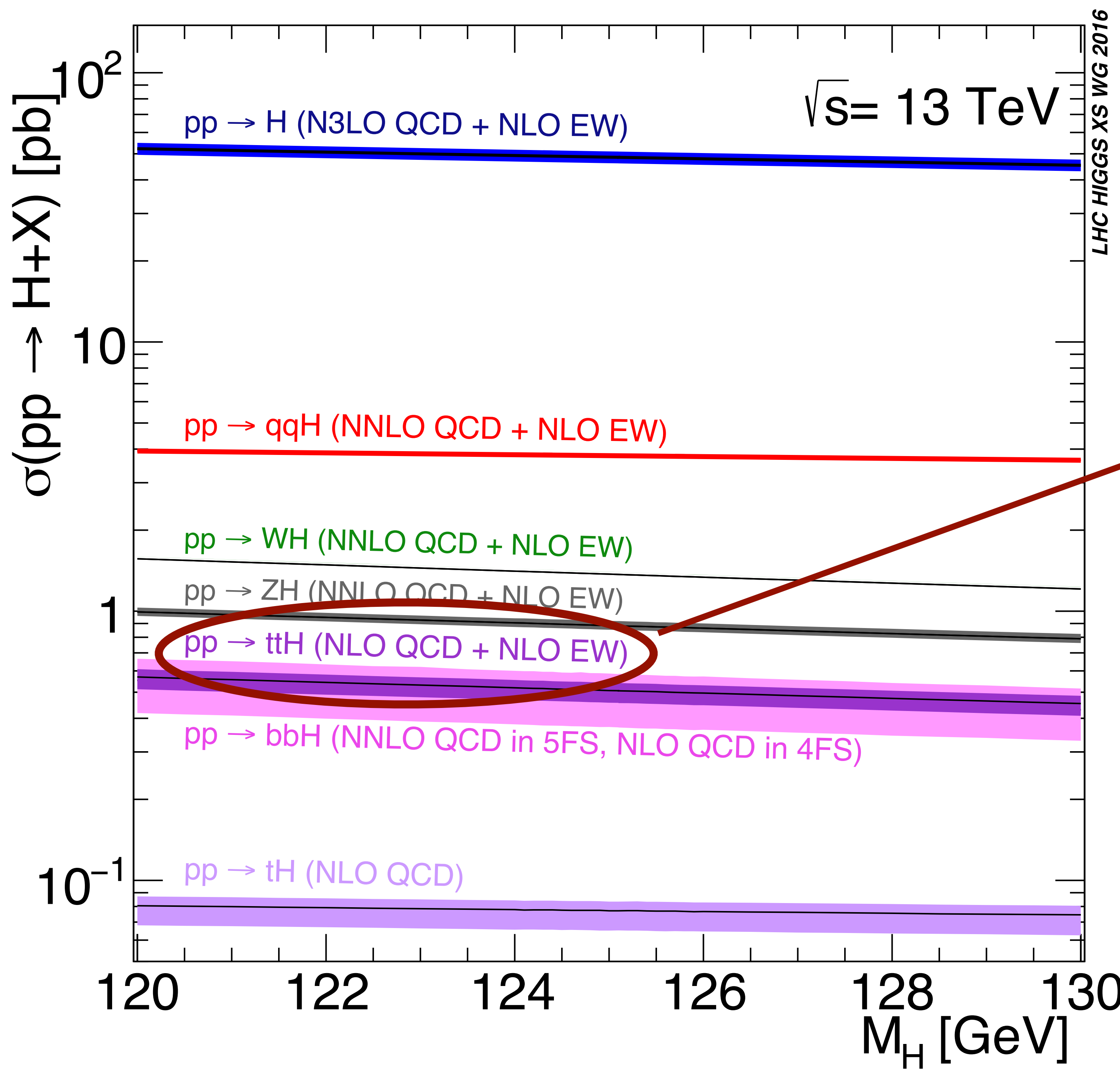
ATLAS and CMS: 1606.02266



gg→H cannot distinguish modified top Yukawa (c_t) vs. new particles in the loop (c_g)

- Direct information on top Yukawa
- Statistics limited (Run 2 physics)

Theoretical uncertainty (again)



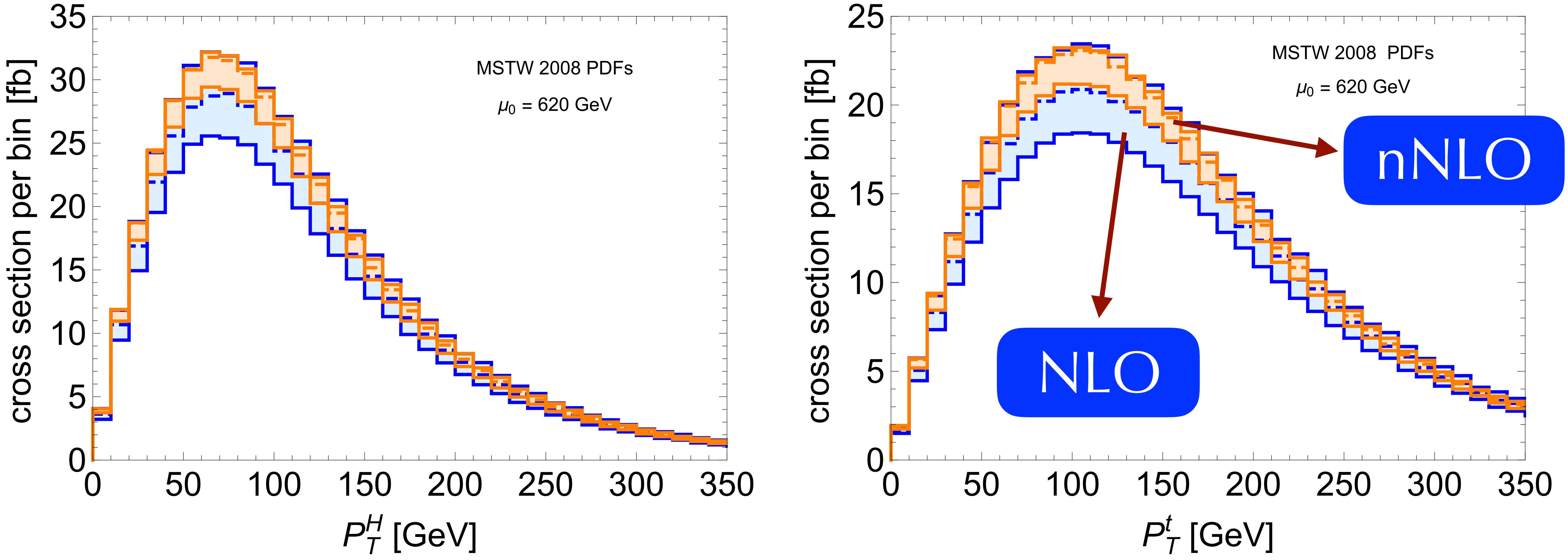
LHC HXSWG report 4 (to appear)

NLO only!

NLO EW: Zhang, Ma, Zhang, Chen, Guo (1407.1110)

ttH: approximate NNLO

Broggio, Ferroglia, Pecjak, Signer, **LLY**: 1510.01914



First fully differential prediction beyond NLO

It is unlikely that exact NNLO for ttH will become available very soon!

See also Kulesza, Motyka, Stebel, Theeuwes (1509.02780) for total rate

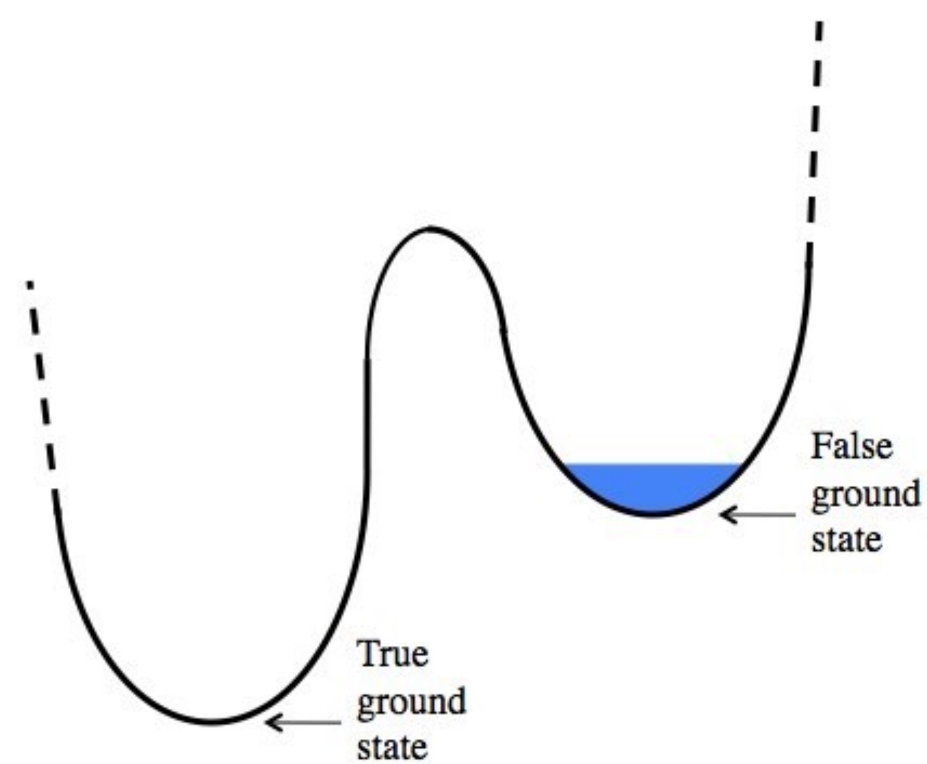
Higgs self-couplings

$$\frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{2m_h^2}{v^2}h^4$$

"6th force"

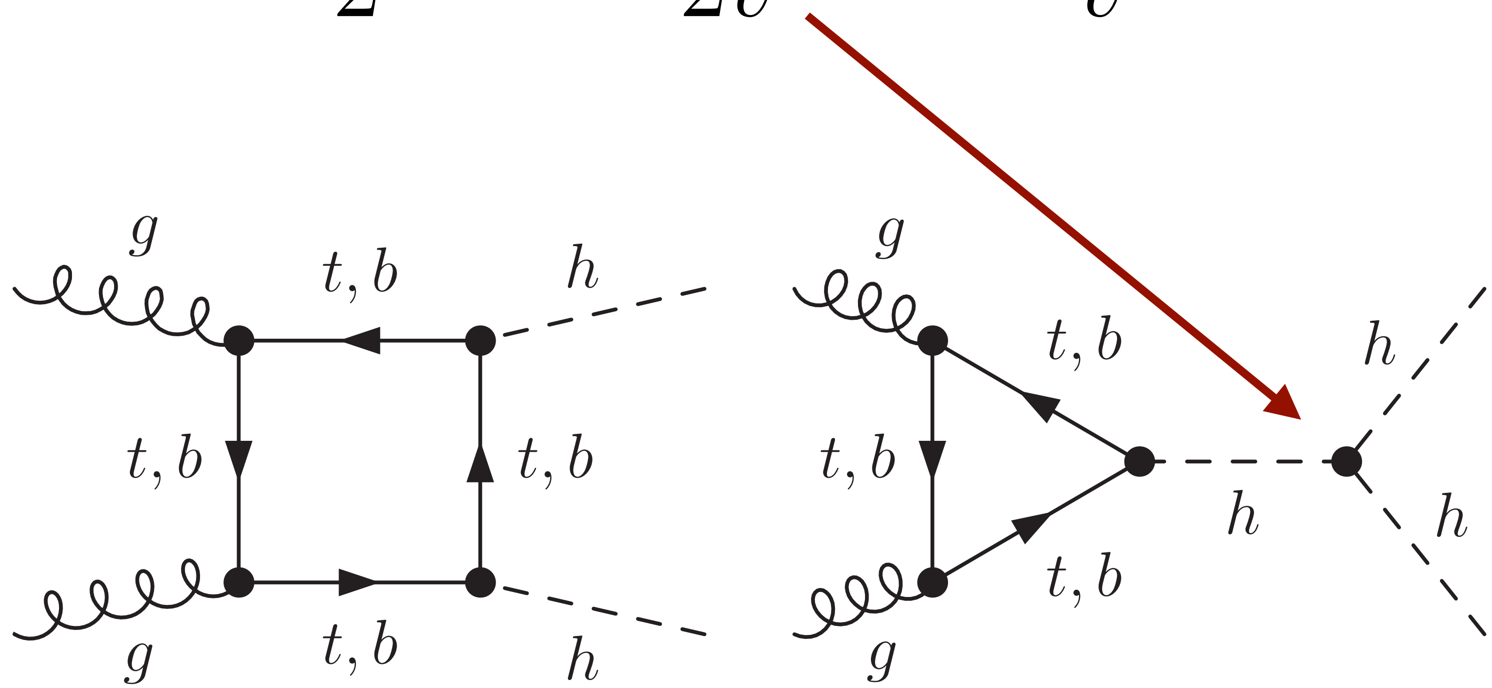
How can we verify these two interactions?

Important for EW phase transition as well as vacuum stability!



Higgs pair & self-coupling

$$\frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{2m_h^2}{v^2}h^4$$

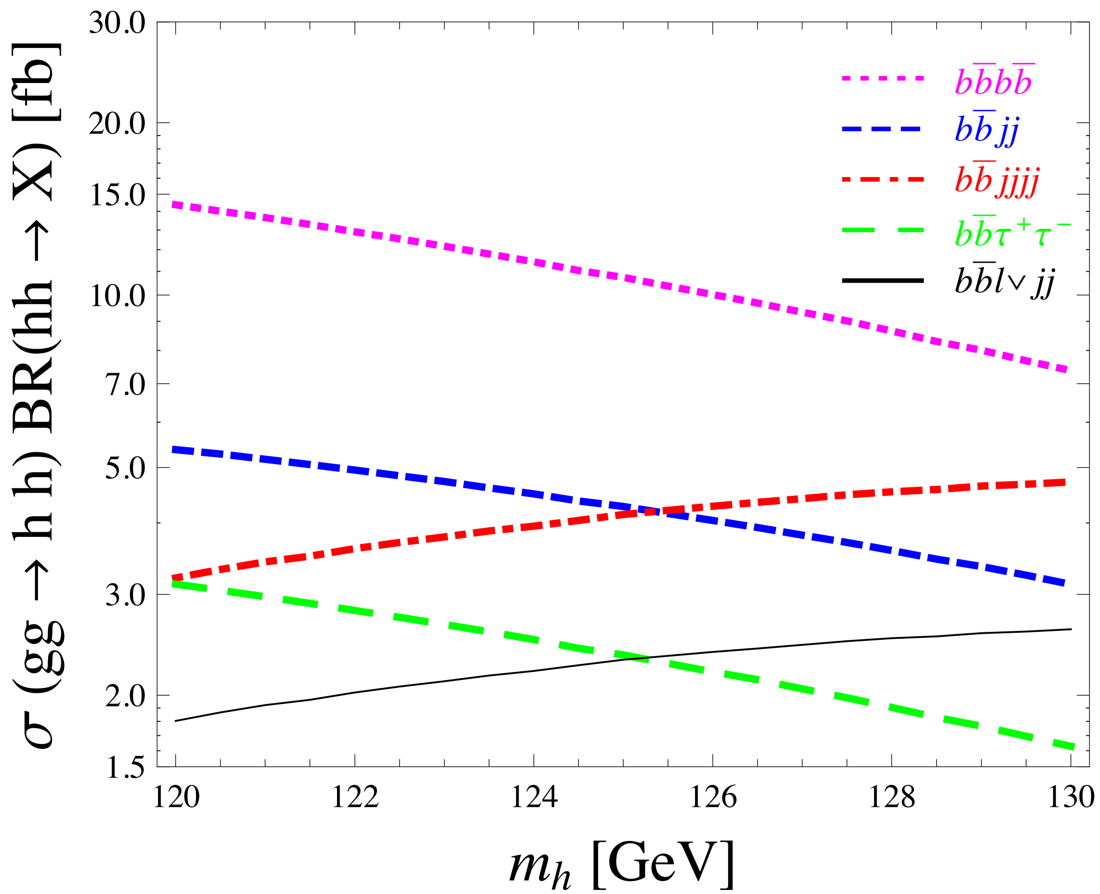


However, notoriously difficult to detect!

HL-LHC and 100 TeV physics!

Detecting HH production

Requires combination of various decay channels!



bbγγ bbWW bbττ

WWγγ ττττ

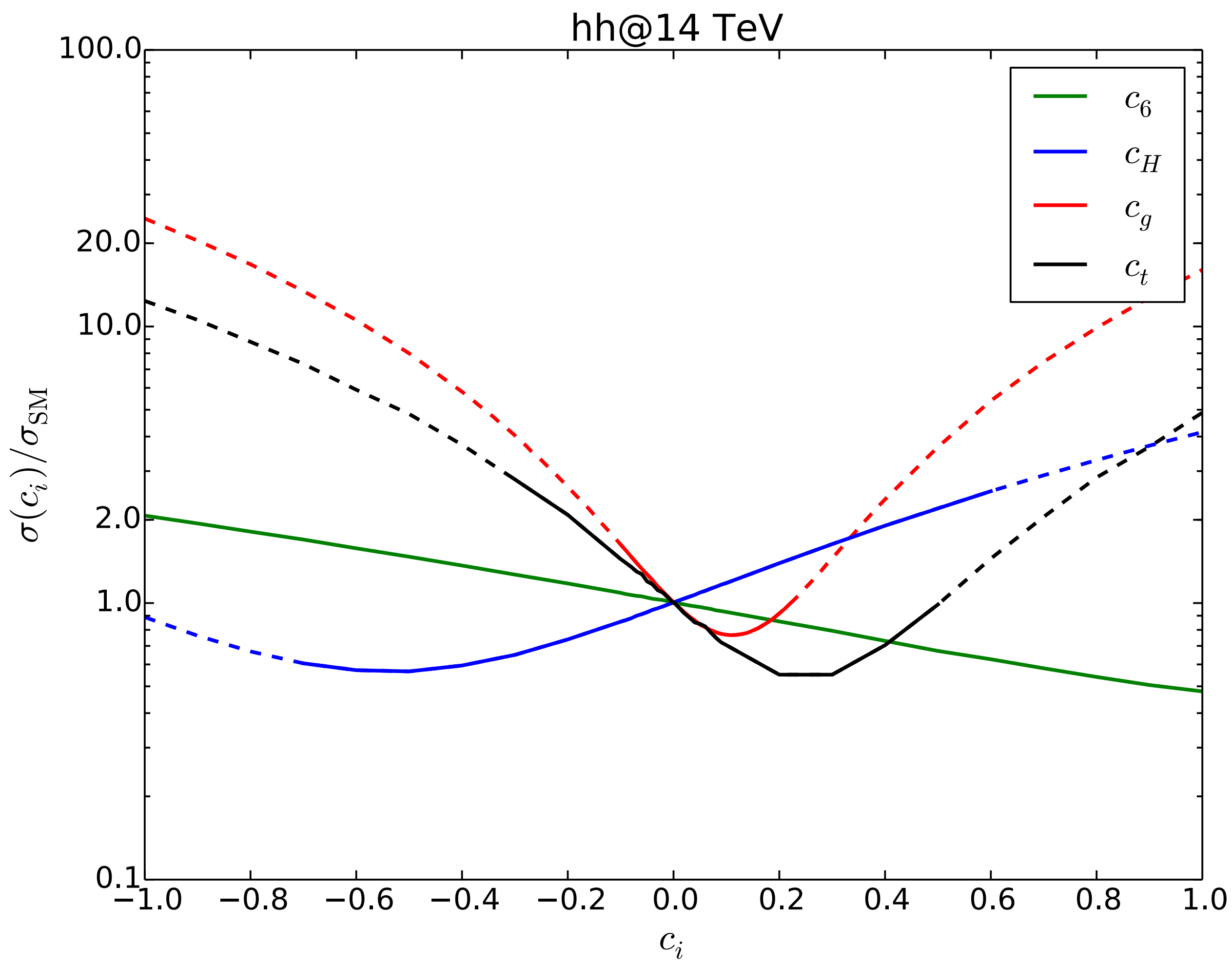
bbbb WWWW

Hot topic since Higgs discovery!

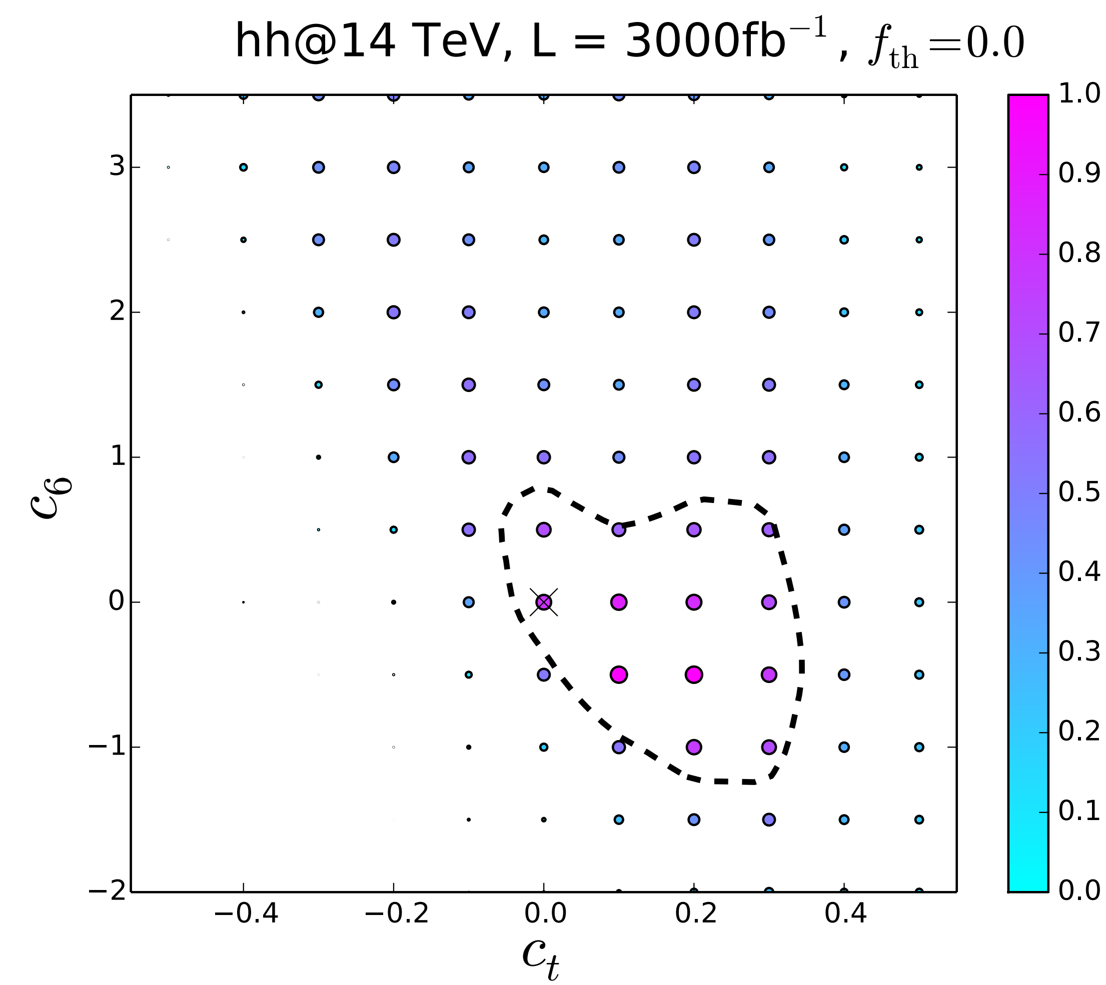
Dolan et al.: 1206.5001; Papaefstathiou, **LLY**, Zurita: 1209.1489; Baglio et al.: 1212.5581; Barr et al.: 1309.6318; de Lima et al.: 1404.7131; Barr et al.: 1412.7154; Li, Li, Yan, Zhao: 1503.07616; Papaefstathiou: 1504.04621; Kotwal et al.: 1504.08042; He, Ren, Yao: 1506.03302; Lü, Du, Fang, He, Zhang: 1507.02644; Zhao, Li, Li, Yan: 1604.04329; Kling et al.: 1607.07441; …; sorry for limited space!

HH constraints on EFT

Goertz, Papaefstathiou, **LLY**, Zurita: 1410.3471



Rate sensitive to new physics

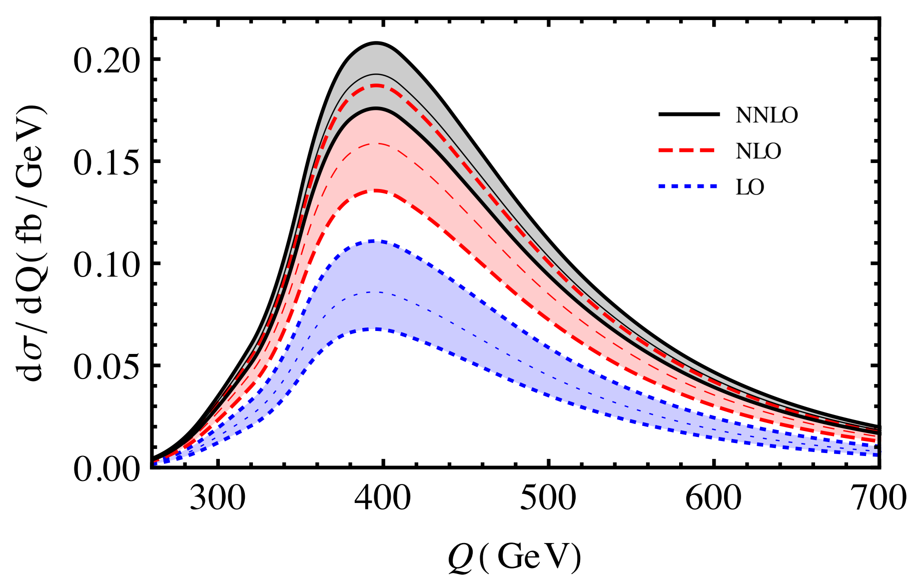


Can be used to constrain EFT parameters

See also: Azatov, Contino, Panico, Son (1502.00539); He, Ren, Yao (1506.03302); Cao, Yan, Zhang, Zhang (1508.06512)

NNLO for Higgs pair

de Florian, Mazzitelli: 1309.6594; de Florian, Grazzini et al.: 1606.09519;
See also Shao, Li, Li, Wang (1301.1245) for NLO+NNLL resummed prediction



$\sqrt{s}$ [TeV]	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]
13	$13.8059(13)\ ^{+31.5\%}_{-22.5\%}$	$25.829(3)\ ^{+17.8\%}_{-15.4\%}$	$30.38(3)\ ^{+5.2\%}_{-7.7\%}$
14	$17.0778(16)\ ^{+30.7\%}_{-22.1\%}$	$31.934(3)\ ^{+17.5\%}_{-15.1\%}$	$37.52(4)\ ^{+5.2\%}_{-7.6\%}$

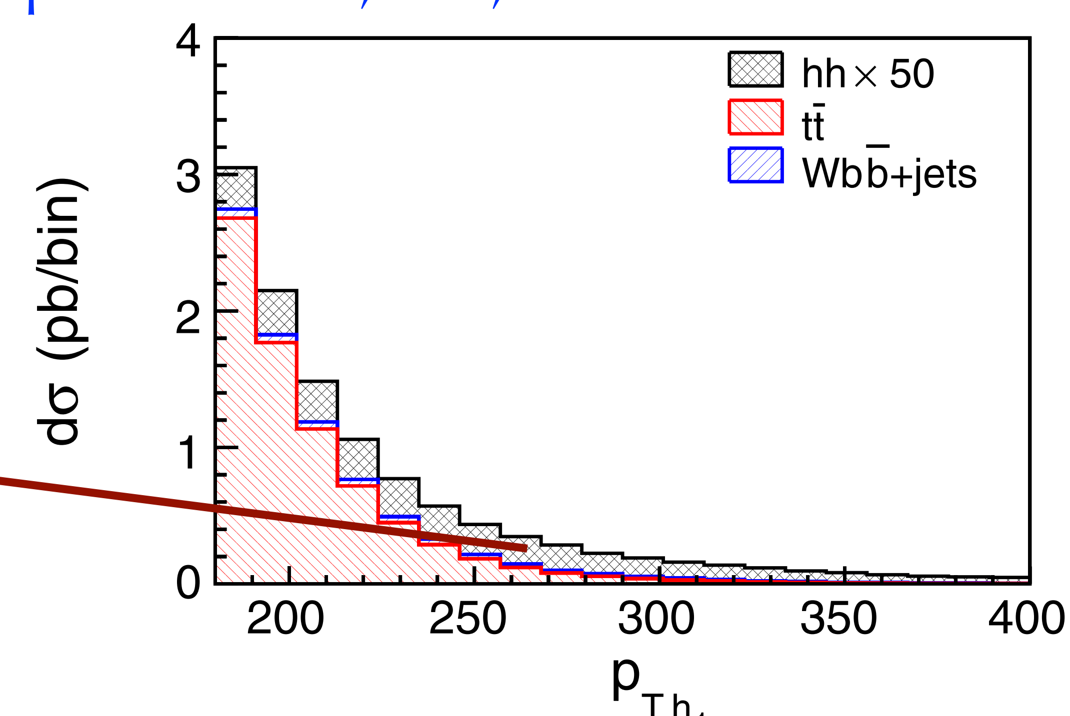
~20% correction

However, tagging H→bb typically requires jet substructure techniques!

High p_T to suppress QCD backgrounds

Validity of HEFT?

Papaefstathiou, **LLY**, Zurita: 1209.1489



Higgs pair at NLO with top-mass dependence

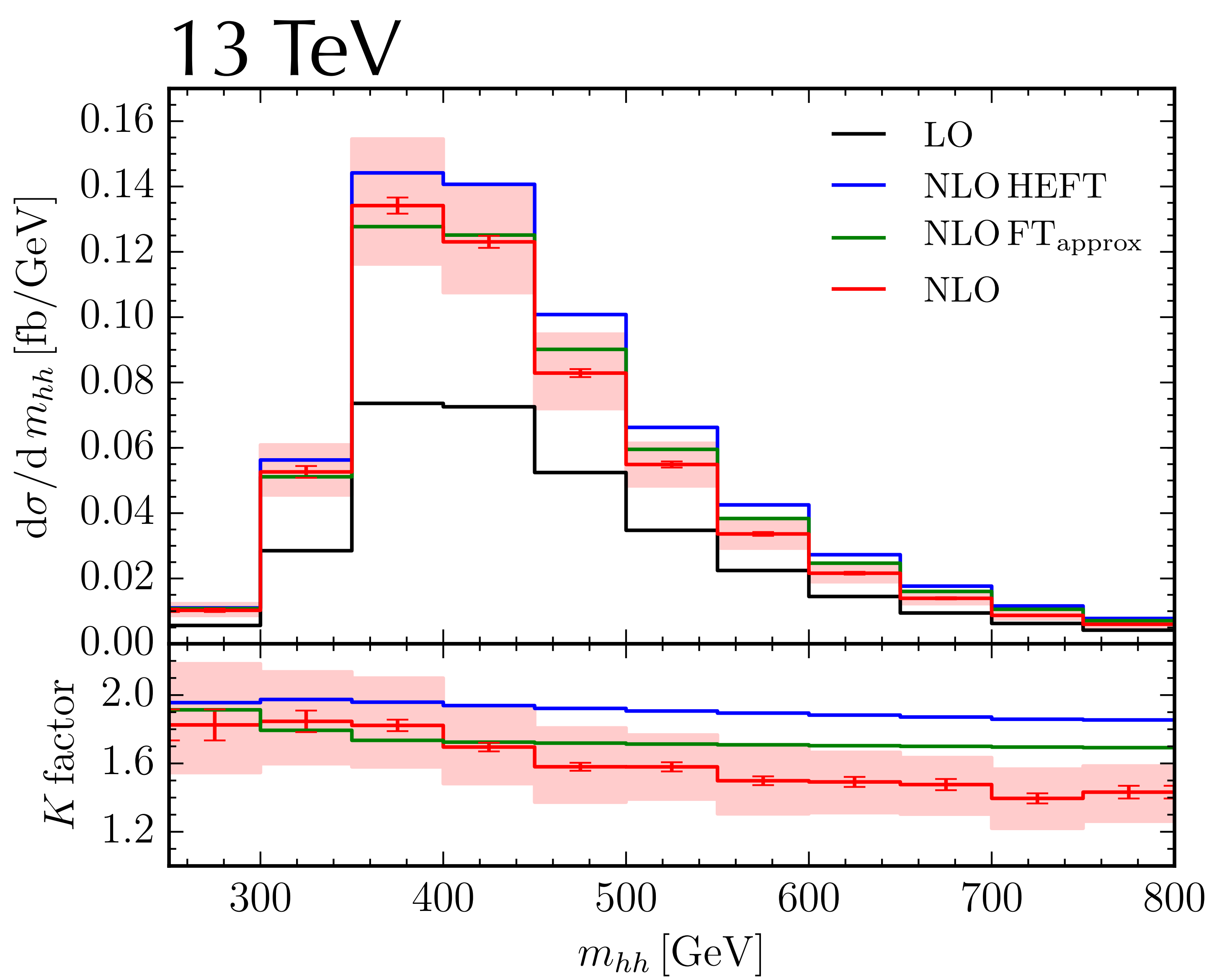
Borowka, Greiner, Heinrich et al.: 1604.06447

A highly non-trivial calculation!

$$\sigma^{\mathrm{NLO}} = 27.80^{+13.8\%}_{-12.8\%}\ \mathrm{fb}$$

14% smaller than Born-improved HEFT result

Prospect of observing this process at LHC reduced!

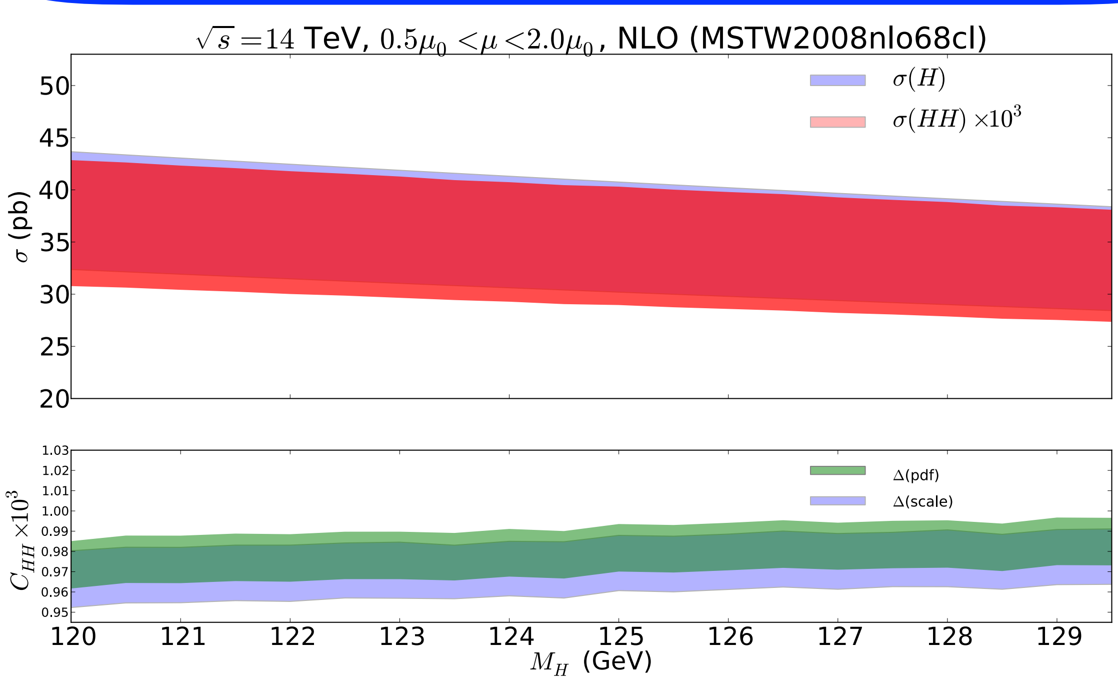


Higgs self-coupling from ratios of cross sections

Goertz, Papaefstathiou, **LLY**, Zurita: 1301.3492

- NNLO corrections to HH cross section are large, but suffer from uncertainties related to top-mass
- May use ratios of cross sections to reduce theoretical uncertainties!

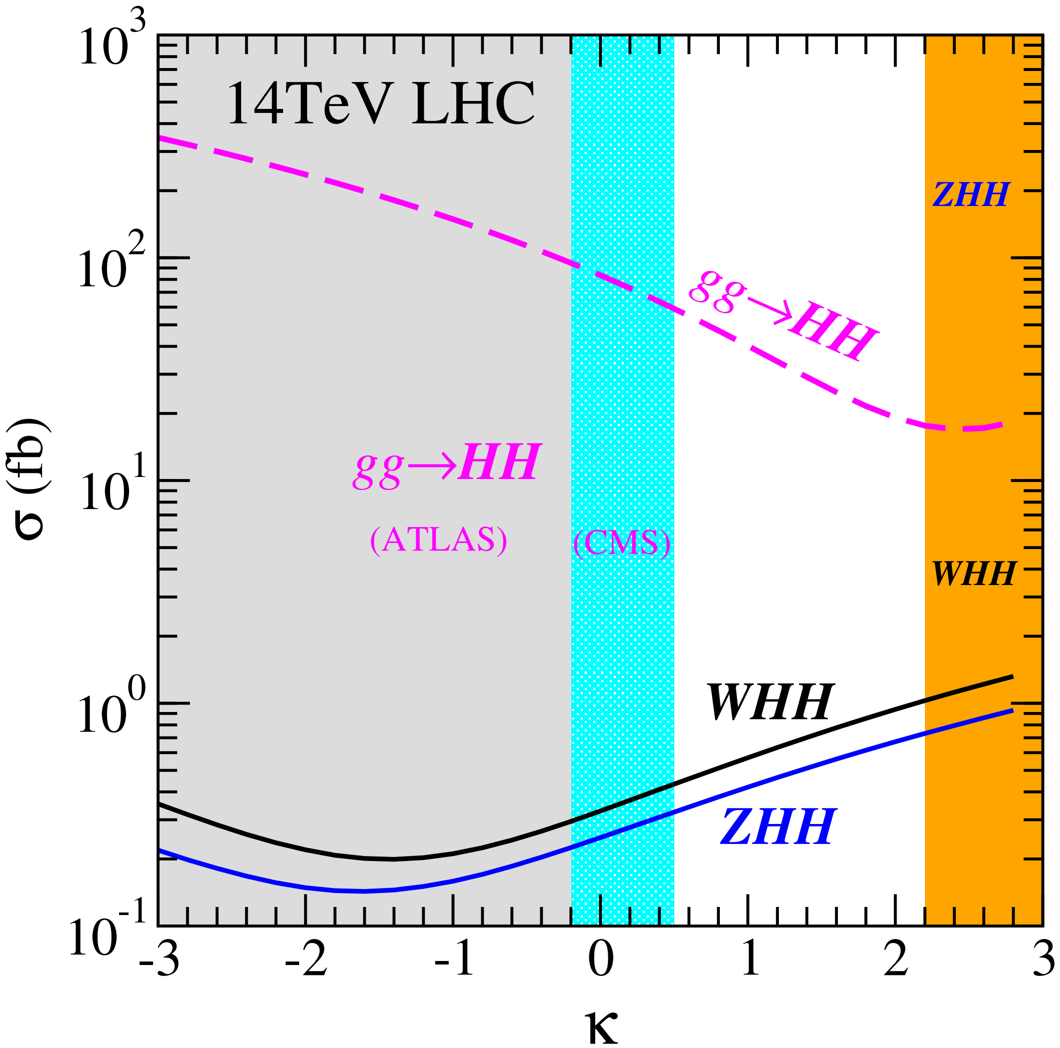
$$C_{HH} = \frac{\sigma(gg \to HH)}{\sigma(gg \to H)}$$



- Now known with exact top-mass dependence at NLO!
- Smaller higher order corrections and PDF/α_s dependences

Alternatives: HH+X

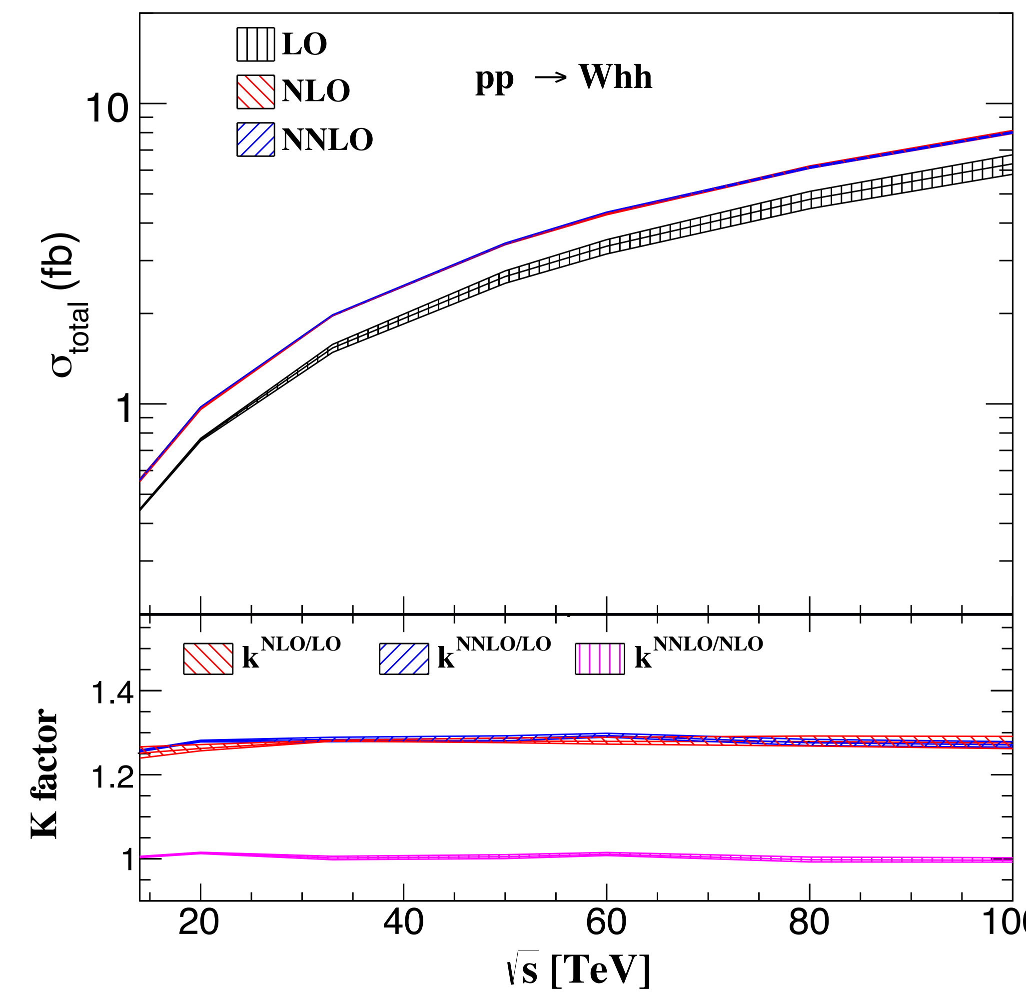
HH+V: Cao, Liu, Yan (1511.03311)



Complementary to gg→H

Additional handle: allows for bbbb final state (largest BR)

NNLO for WHH: Li, Wang (1607.06382)



Other possibilities (e.g., HHjj and HHtt): Dolan, Englert, Greiner, Spannowsky (1310.1084); Englert, Krauss, Spannowsky, Thompson (1409.8074); Liu, Zhang (1410.1855); Ling, Zhang, Ma, Guo, Li, Li (1410.7754); He, Ren, Yao (1506.03302)

Towards Higgs factories

High precision measurements of ZH cross section (and HZZ coupling) at CEPC

CEPC preCDR

Z decay mode	ΔM_H (MeV)	$\Delta\sigma(ZH)/\sigma(ZH)$	$\Delta g(HZZ)/g(HZZ)$
ee	14	2.1%	
$\mu\mu$	6.5	0.9%	
$ee+\mu\mu$	5.9	0.8%	0.4%
$q\bar{q}$		0.65%	0.32%
$ee+\mu\mu+q\bar{q}$		0.51%	0.25%

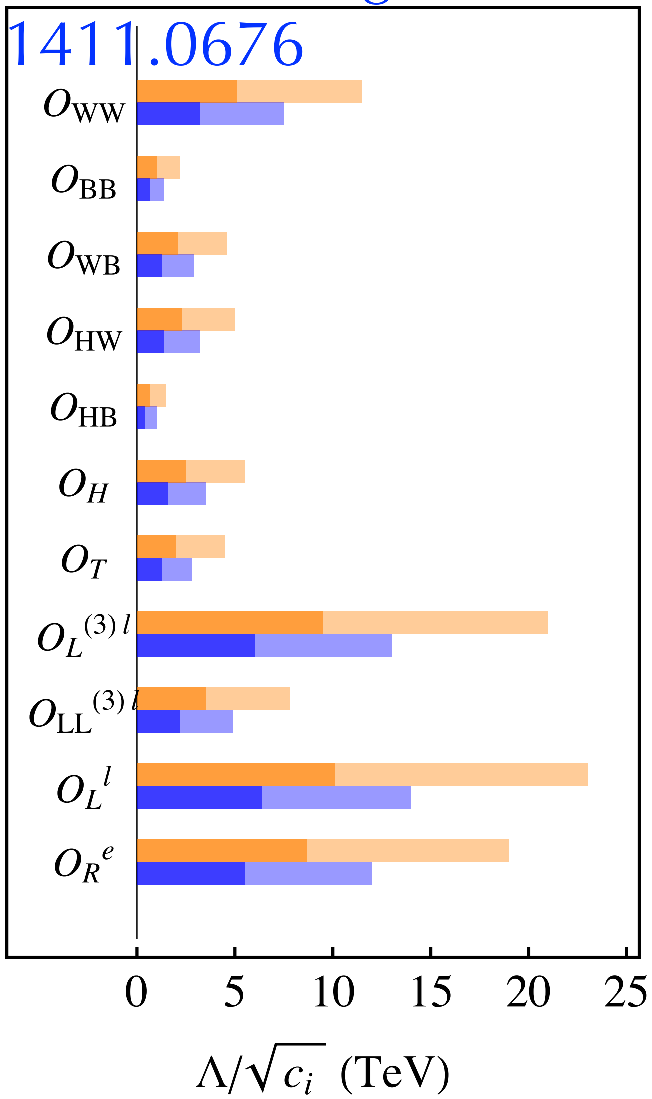
Even higher accuracies claimed by FCC-ee!

Bicer et al.: 1308.6176;
d'Enterria: 1601.06640; 1602.05043

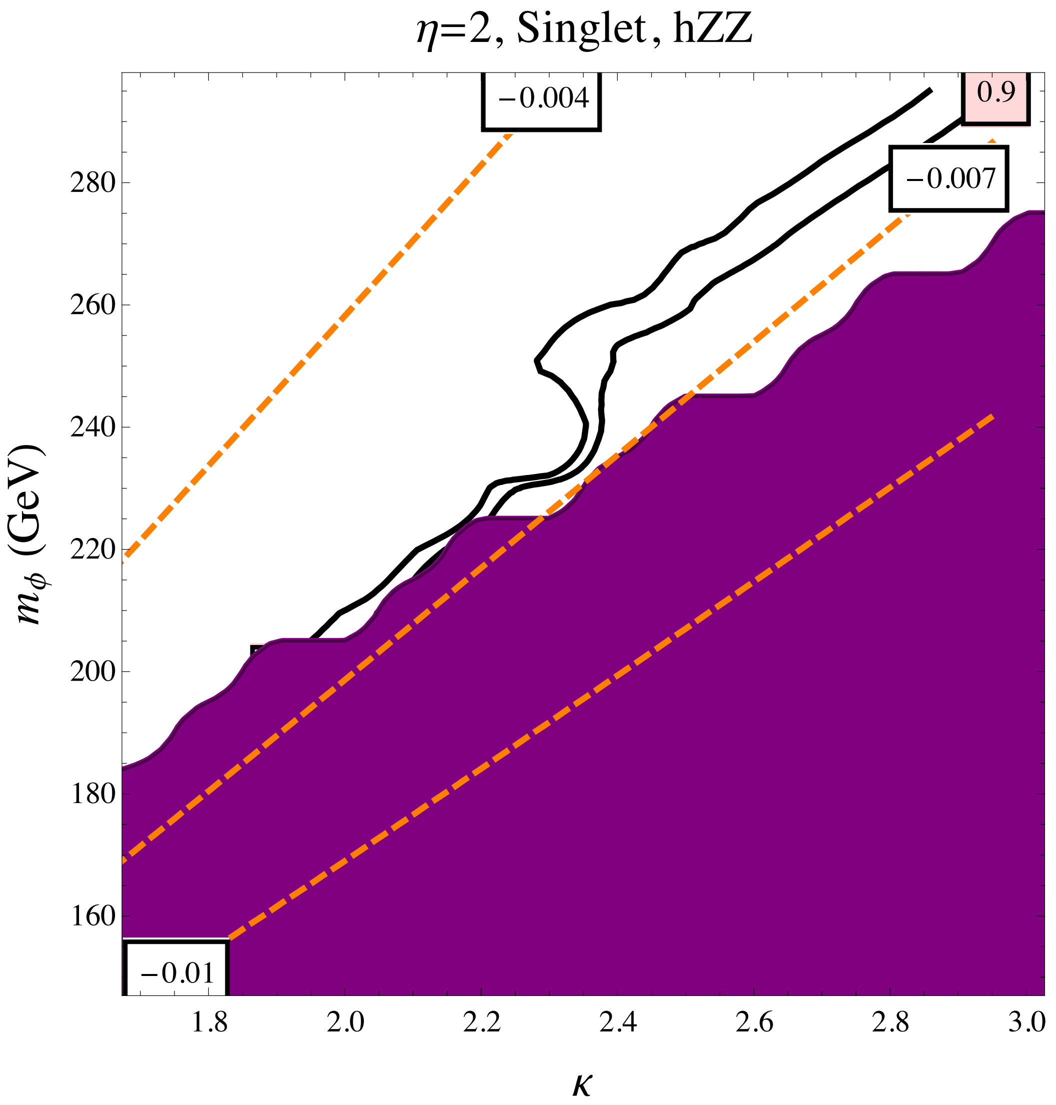
Precision measurements and new physics

Lots of discussions on probing new physics using precision measurements at Higgs factories; sorry that I can't cover all!

Craig, Farina, McCullough, Perelstein: 1411.0676



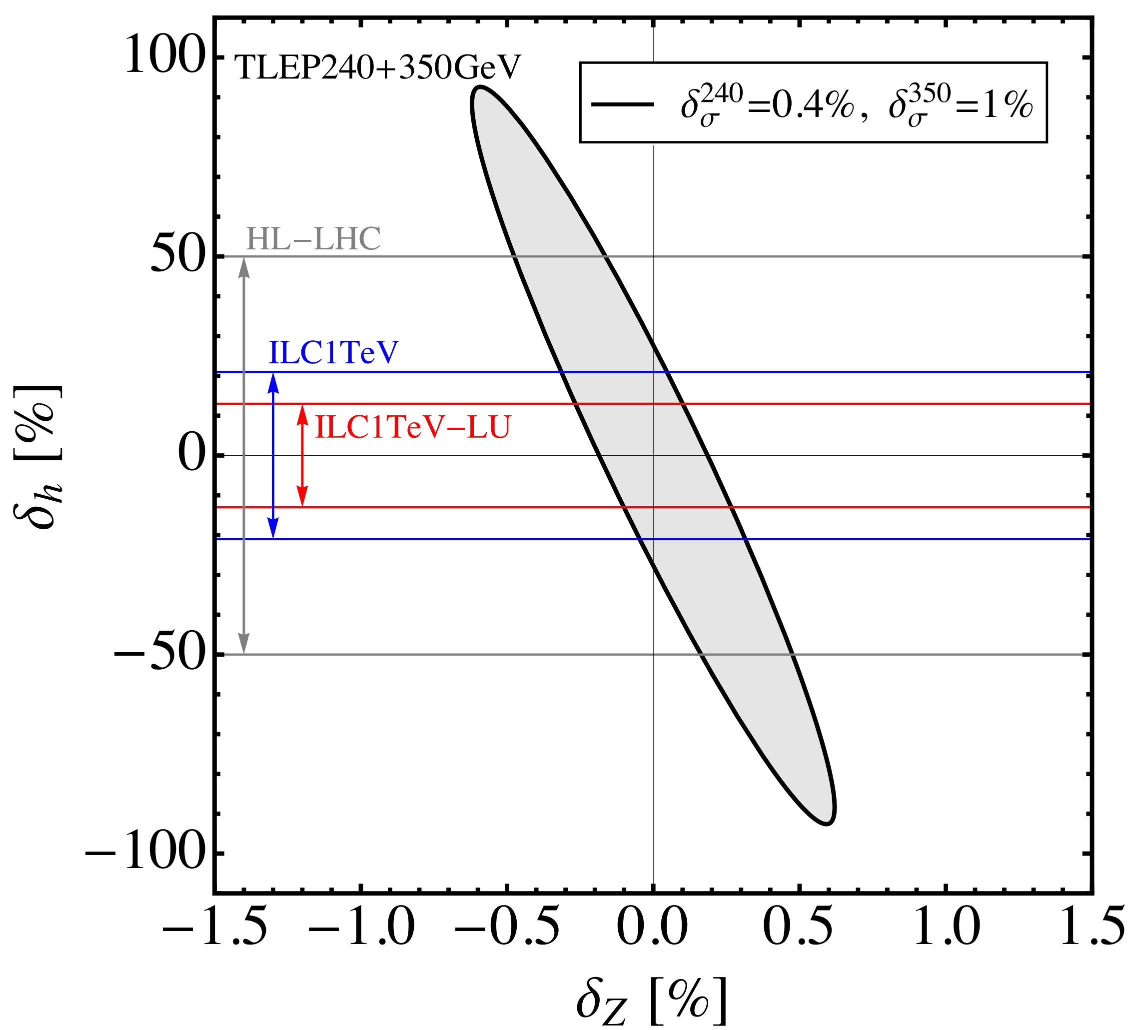
Katz, Perelstein: 1401.1827

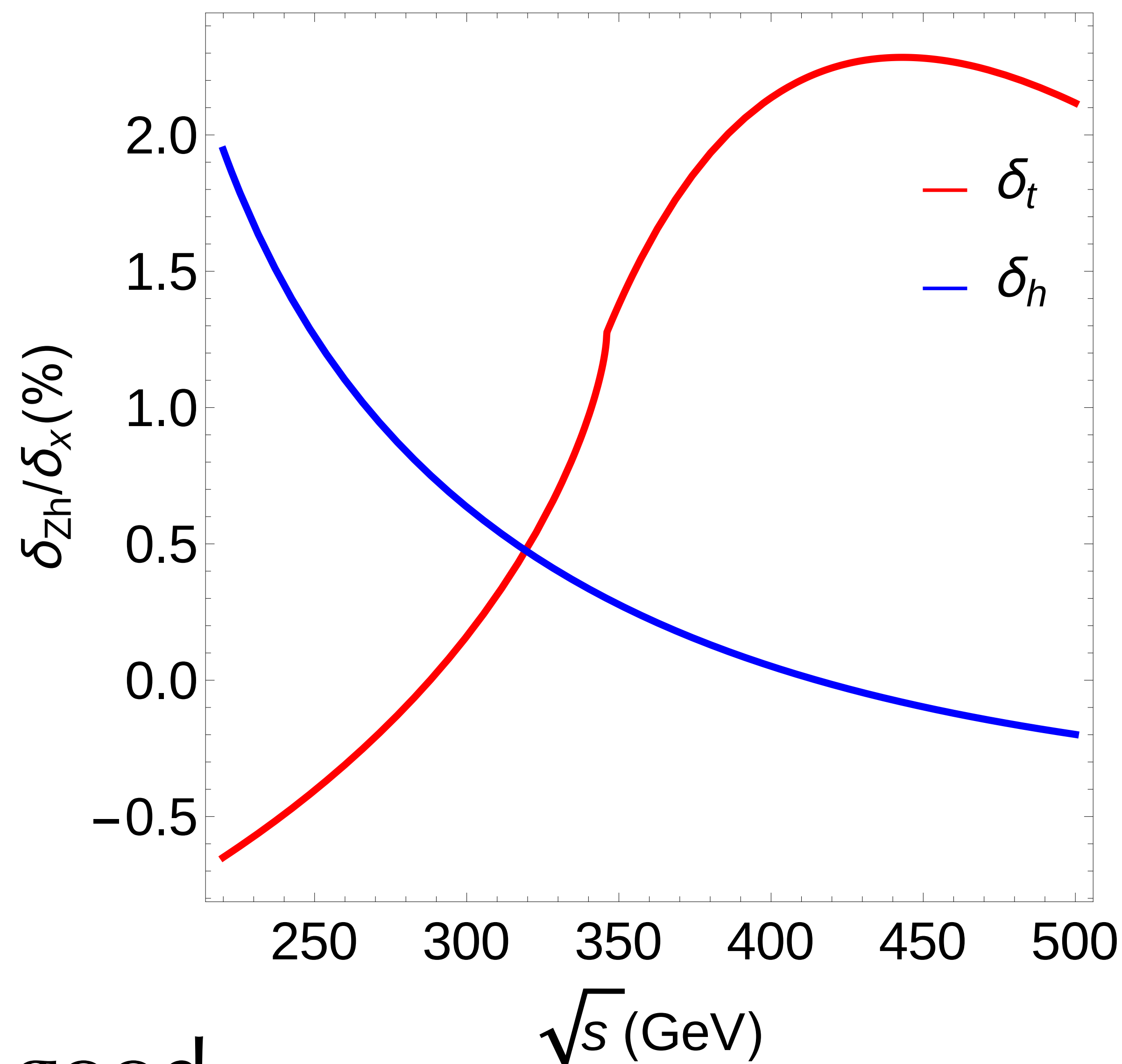


Indirect probe of Higgs self-coupling

McCullough: 1312.3322

Shen, Zhu: 1504.05626



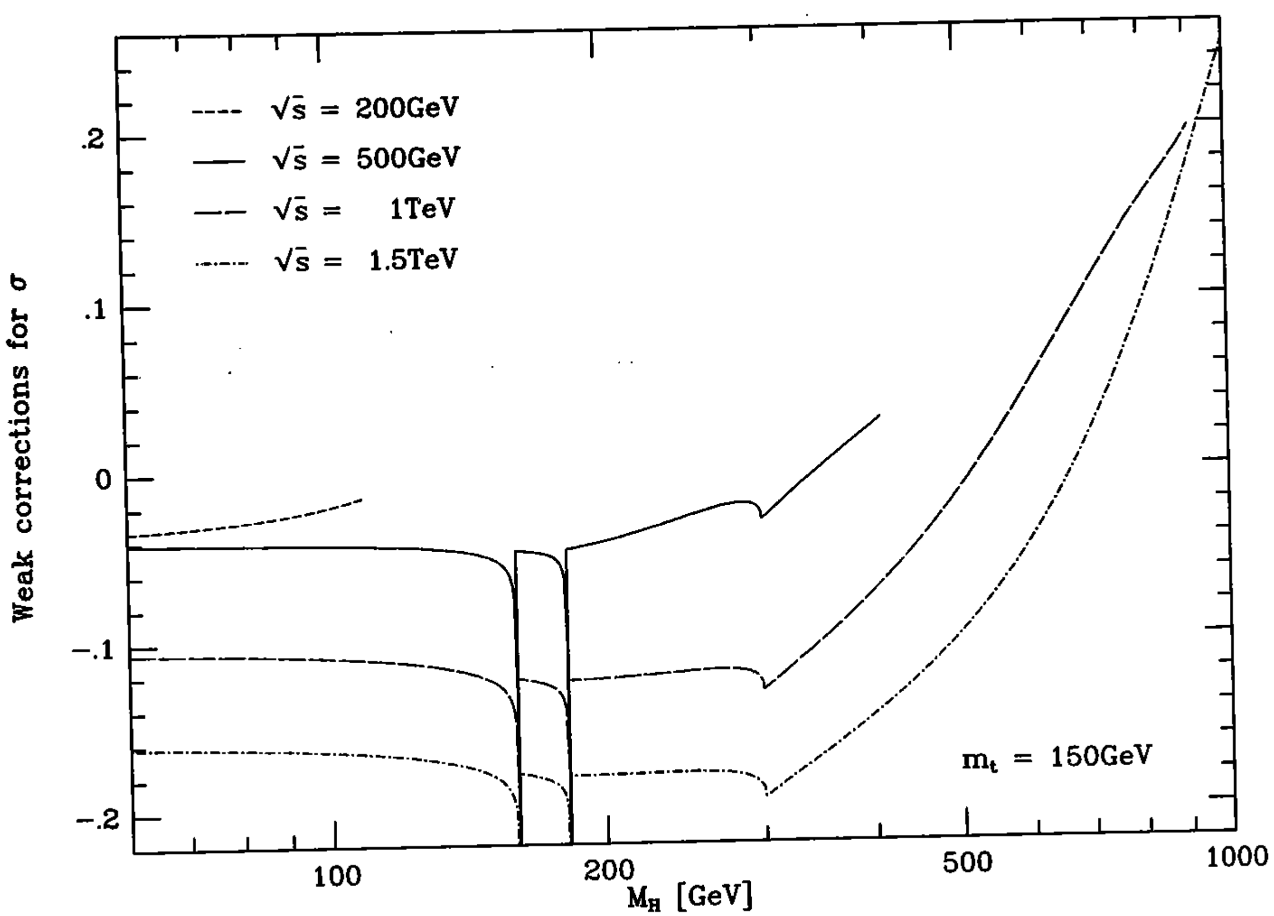


Model-dependent: requires good knowledges of HZZ and Htt couplings!

Precision theory for precision measurements

How well do we know σ(ZH) in the SM?

NLO weak corrections known for decades



Fleischer, Jegerlehner (1983); Kniehl (1992); Denner, Küblbeck, Mertig, Böhm (1992)

~-3% for 240 GeV

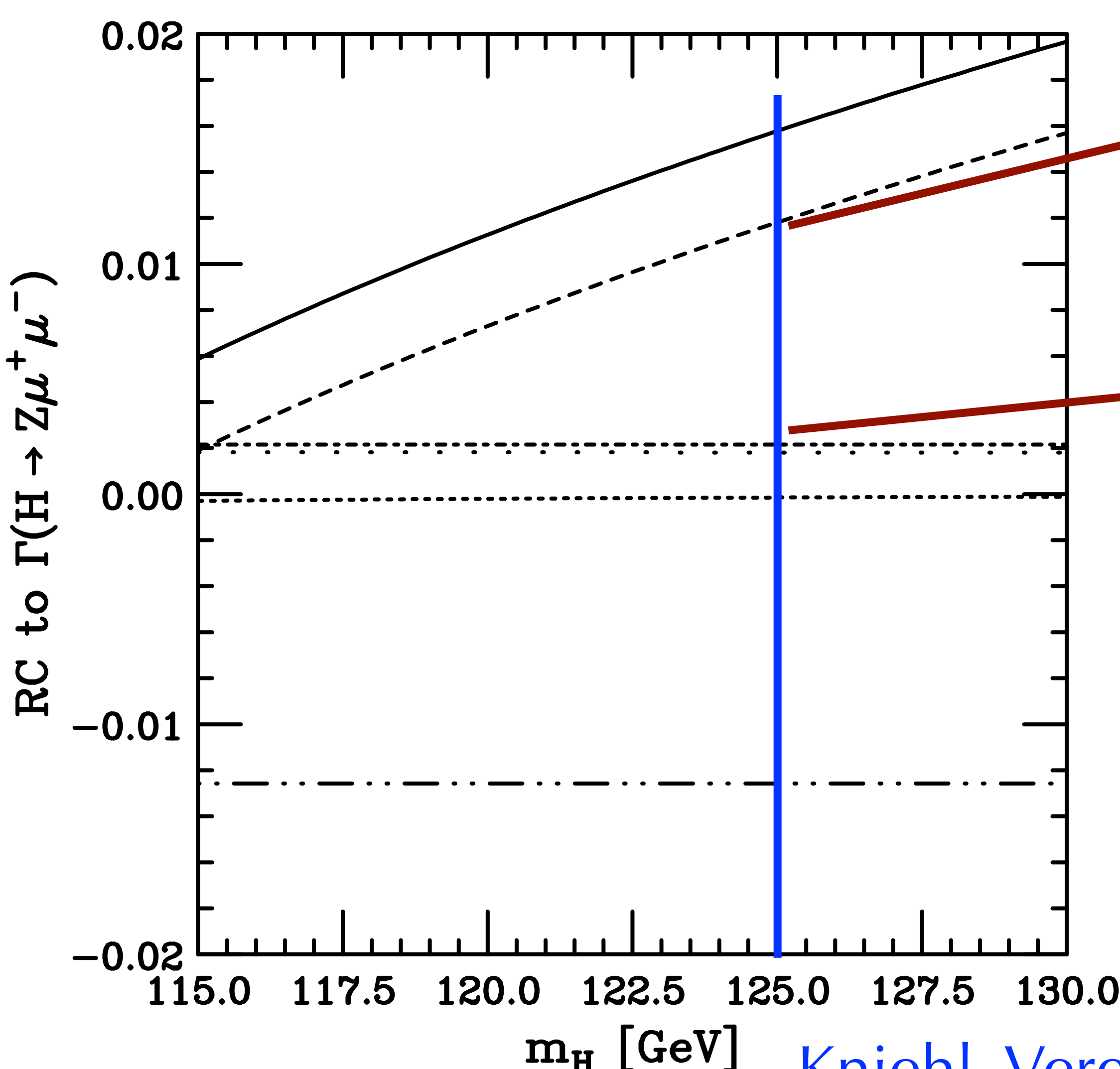
QED corrections also negative; size depends on cut on photon energy

No improvement was attempted since then (possibly because LEP2 didn't find the Higgs 😂)

Precision theory for precision measurements

How well do we know σ(ZH) in the SM?

Update for a closely related process: $H \rightarrow ZZ^* \rightarrow Zl^+l^-$



One-loop weak corrections

Top-mass enhanced higher-order contributions

For σ(ZH) need to go beyond large m_t!

Kniehl, Veretin: 1206.7110

Towards NNLO $\sigma(ZH)$

Gong, Li, Xu, **LLY**:1608.xxxxx

The "simpler": $O(\alpha\alpha_s)$

- 41 master integrals, many involve 4 mass scales
- Two methods:
  - Expansion in $1/m_t$
  - Numeric evaluation using sector decomposition

Agree well!

- **Preliminary result: ~1% for CEPC; important effect!**

The more difficult (but also important): $O(\alpha^2)$

Summary

- A new era for particle physics after Higgs discovery
- Many things waiting to be explored through various production and decay channels: gauge couplings, Yukawa couplings, Higgs self-couplings, Higgs width, CP, …
- New precision calculations for $gg\to H$, Hj, ttH, HH, WHH
- Precision $\sigma(e^+e^-\to ZH)$: fundamental theoretical input for Higgs factories

Thank you!