Precision Higgs Production

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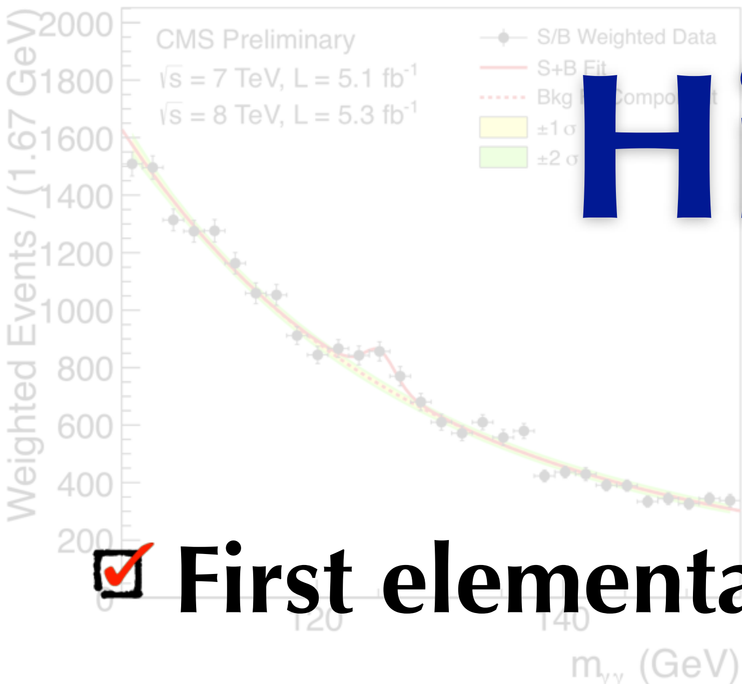
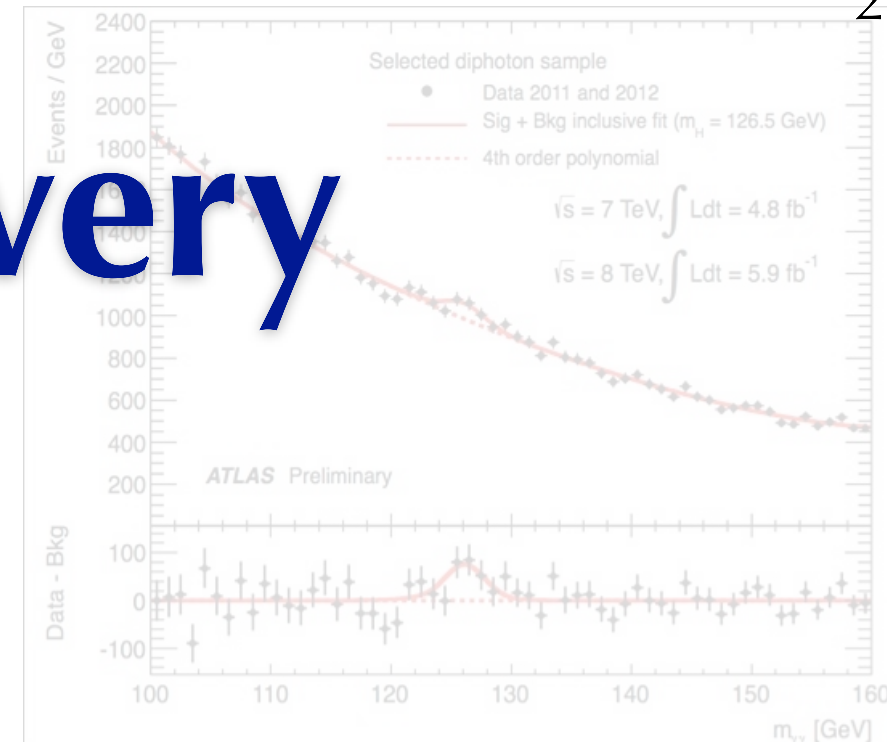
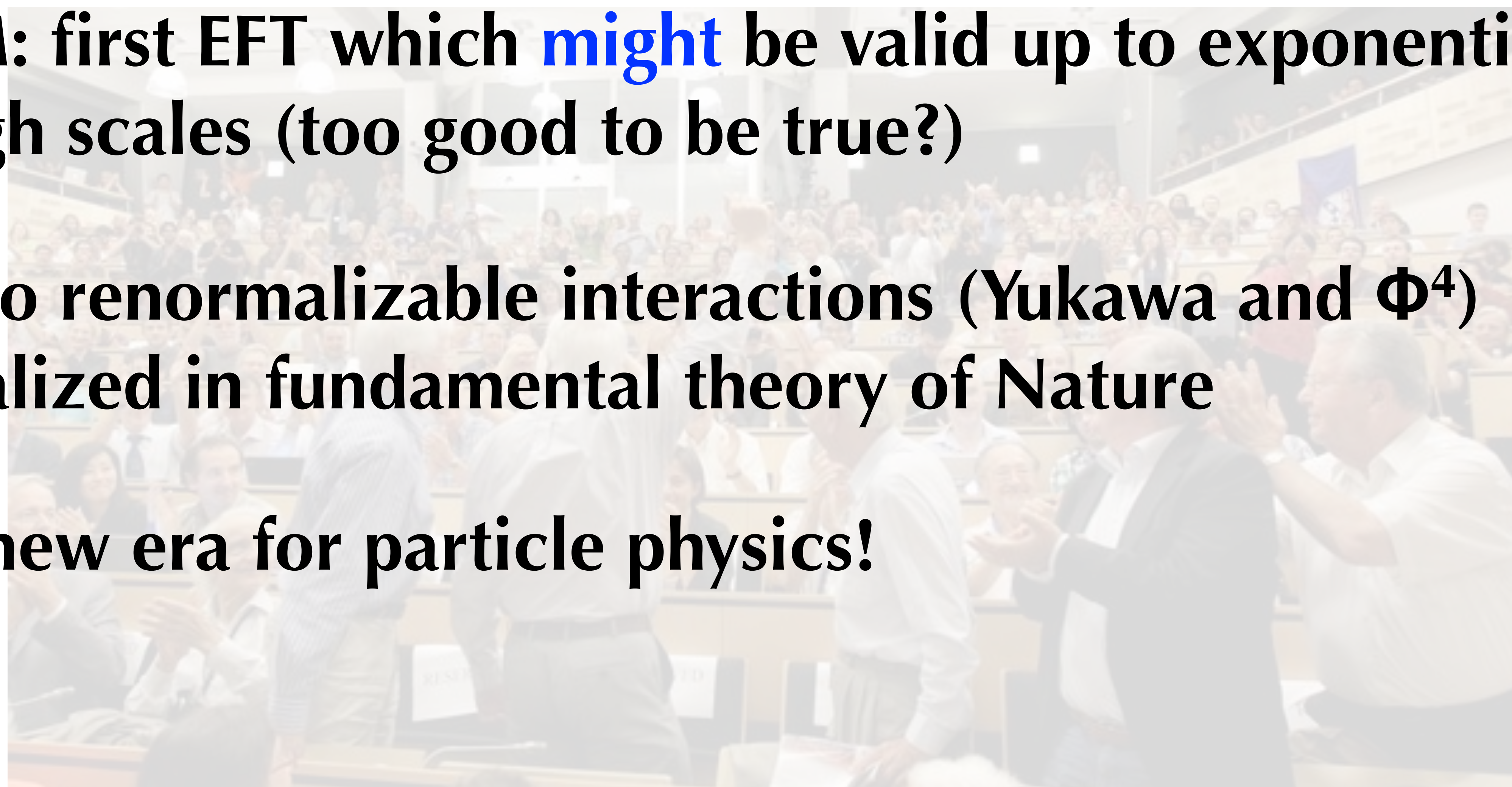
Higgs discovery







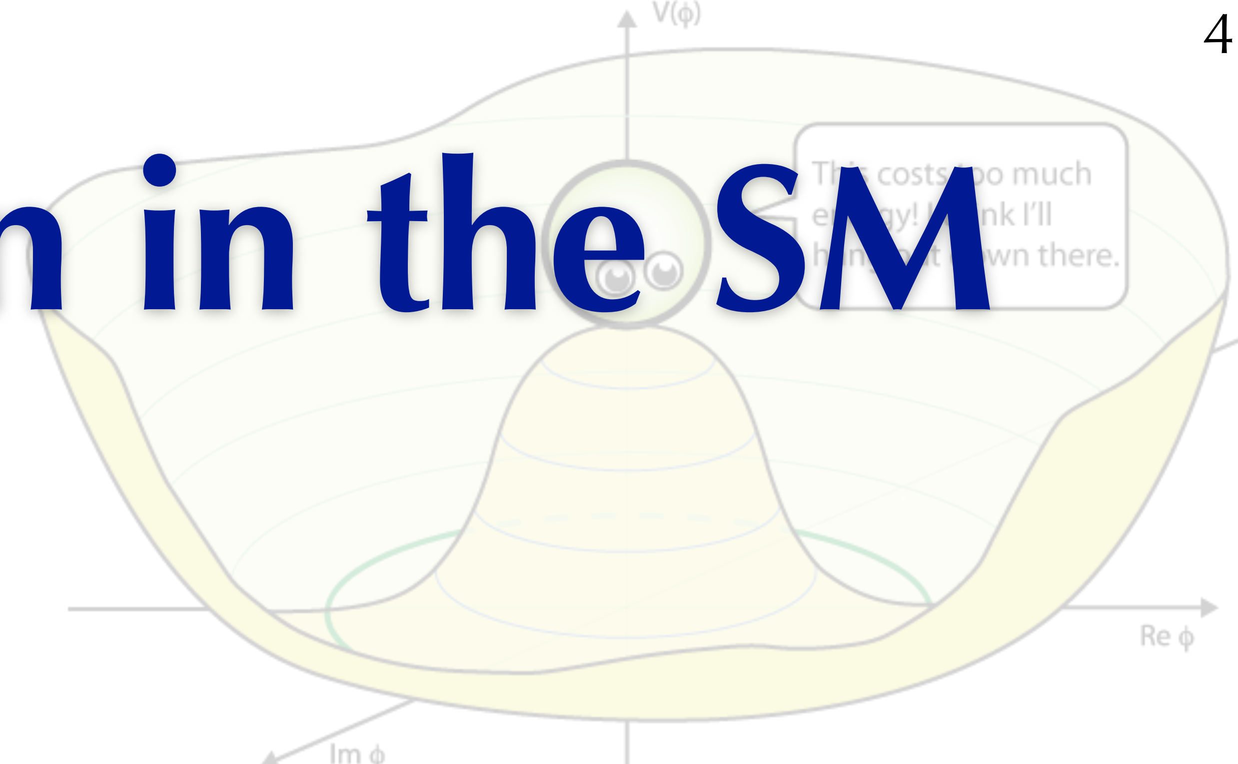
- ☑ First elementary(?) spin-0 particle
- ☑ SM: first EFT which *might* be valid up to exponentially high scales (too good to be true?)
- ☑ Two renormalizable interactions (Yukawa and Φ^4) realized in fundamental theory of Nature
- ☑ A new era for particle physics!

Open questions

- ✱ Is it (NOT) the SM Higgs? → Priority!
- ✱ Is it elementary or composite?
- ✱ Are there more than one Higgs bosons?
- ✱ Phase transition? Vacuum stability? Naturalness?
- ✱ Relations to inflation / dark matter / matter-antimatter asymmetry / neutrino masses / … ?

➡ **Precision measurements of Higgs properties!**

Higgs boson in the SM



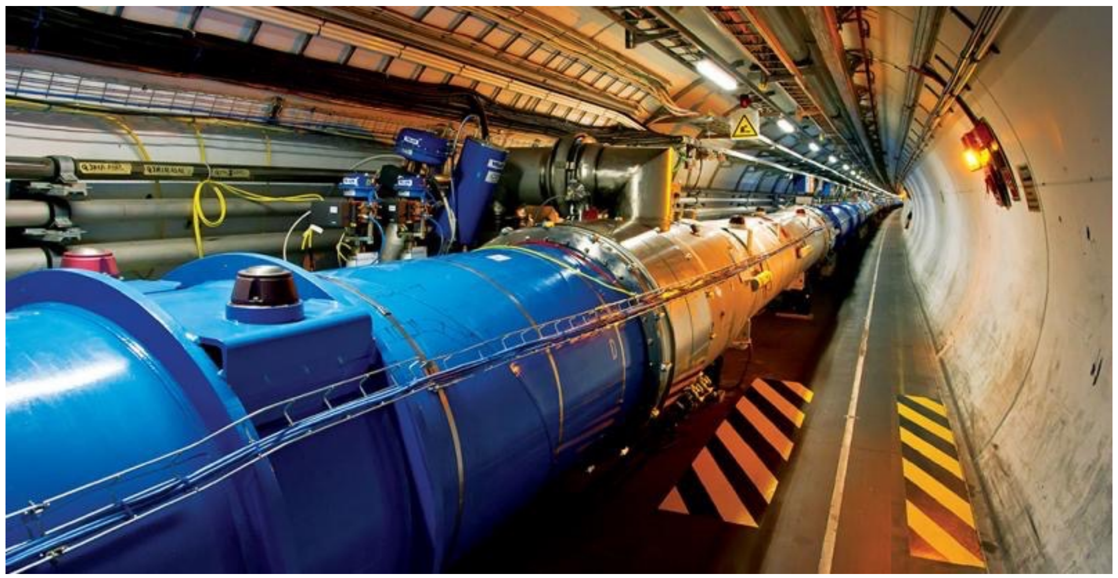
fermion $\frac{m_f}{v}\bar{f}fh$

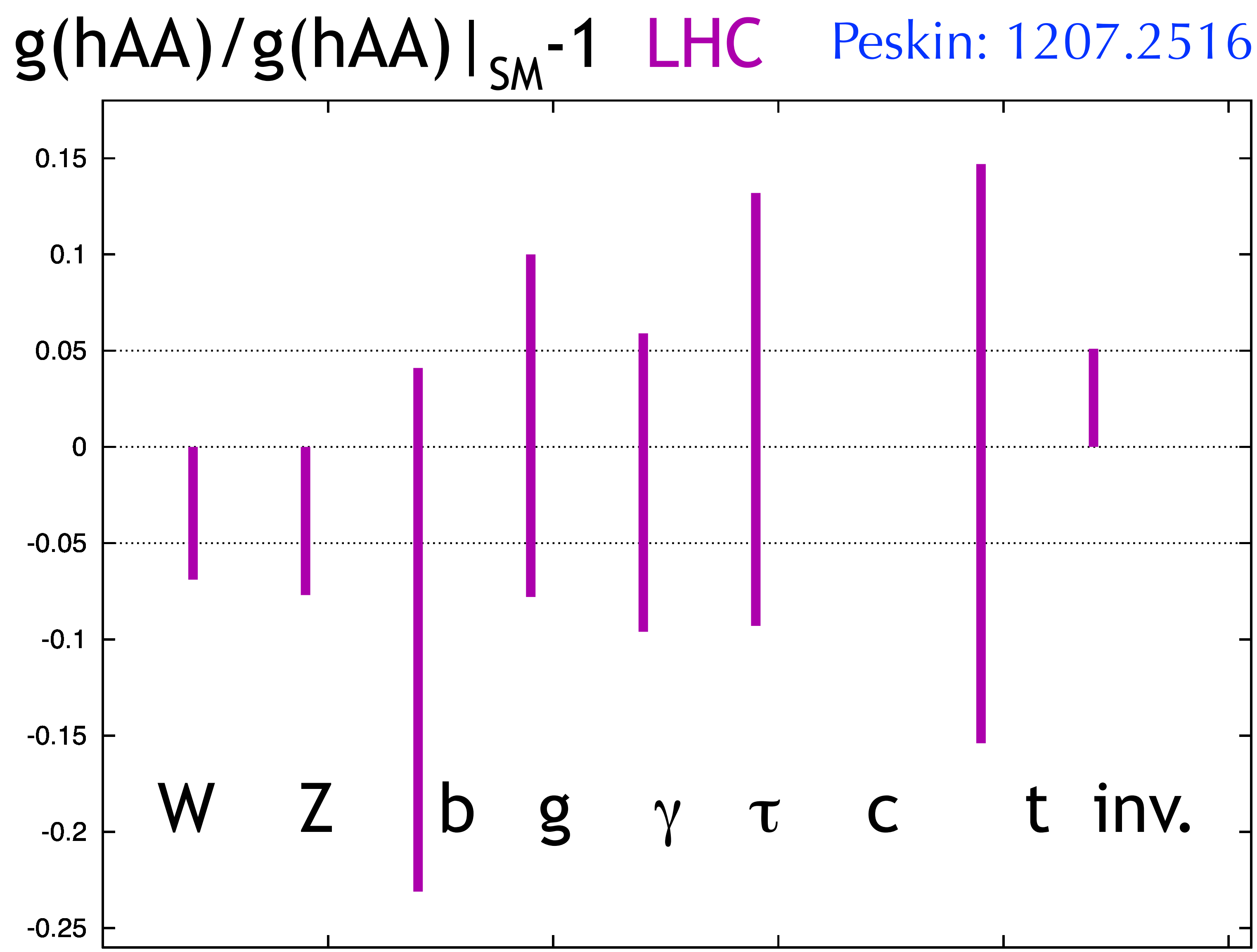
gauge $\frac{m_W^2}{v^2}W_\mu^+W_-^\mu(v+h)^2+\frac{m_Z^2}{2v^2}Z_\mu Z^\mu(v+h)^2$

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!

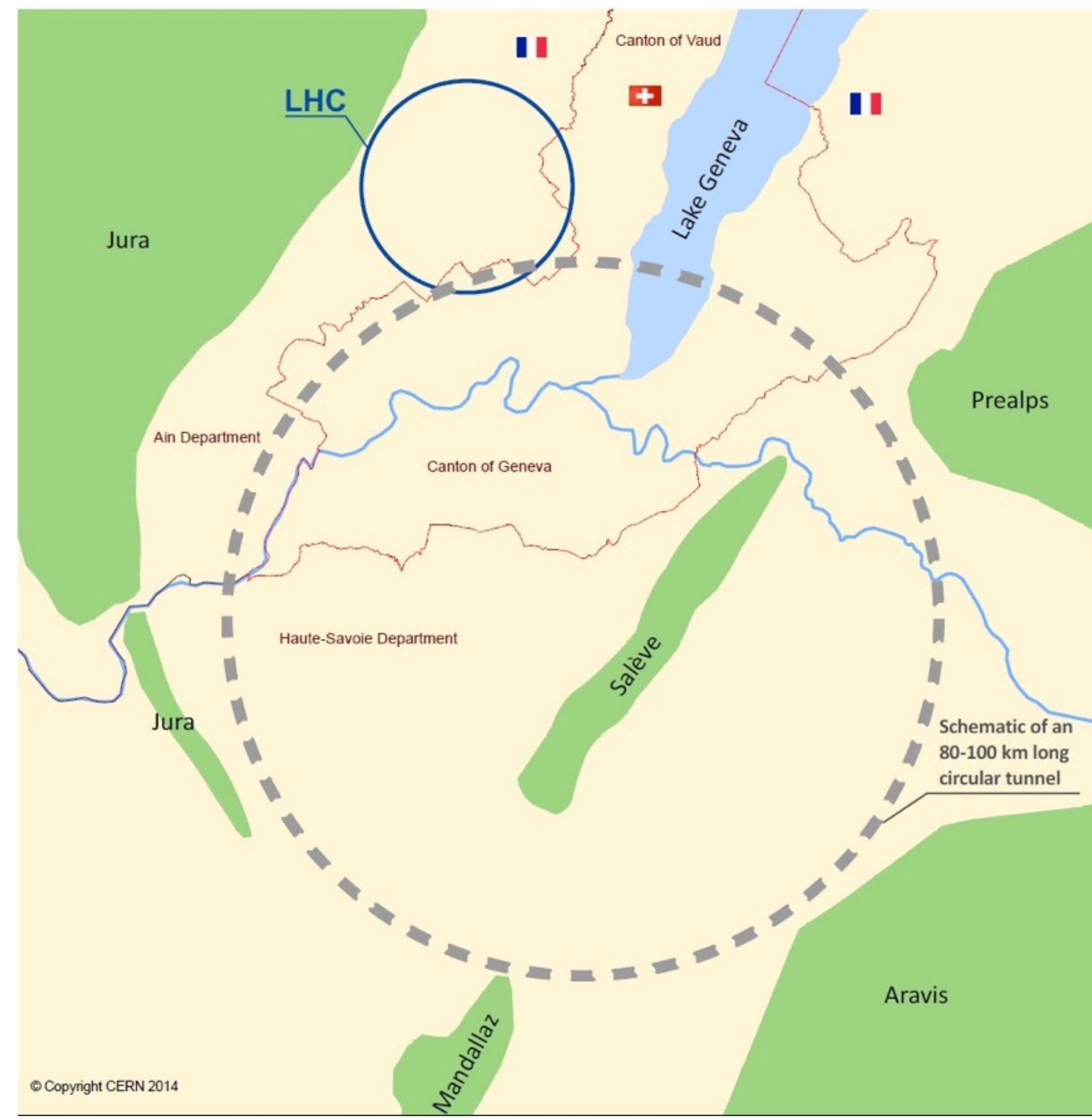
How to test: the LHC

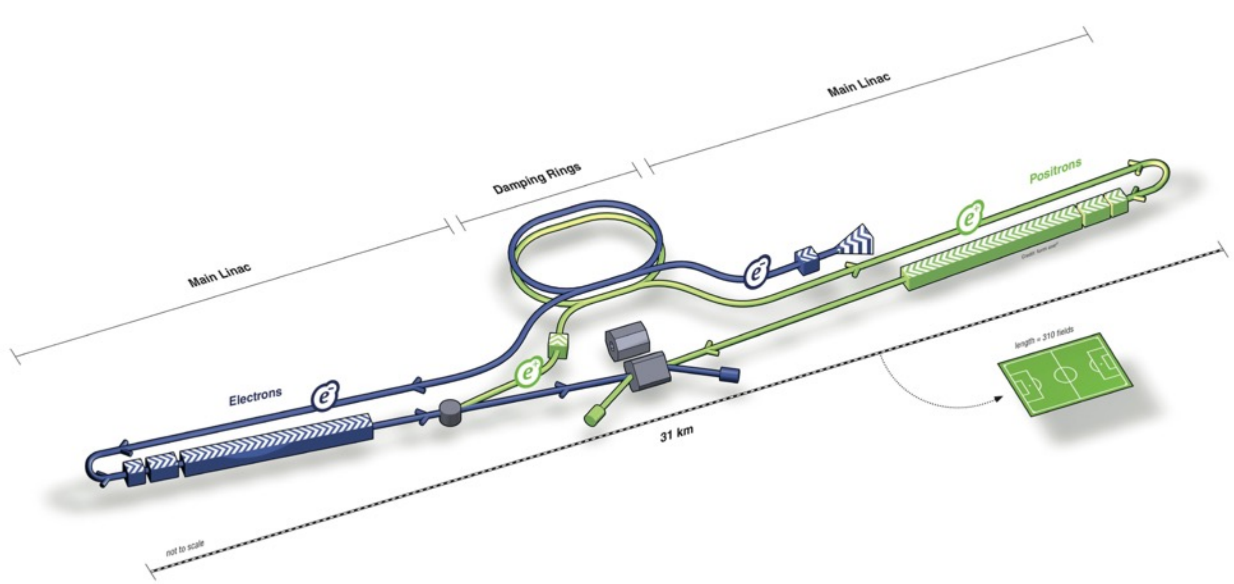




Not quite enough!

Beyond LHC: the future





HXS at CEPC

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%

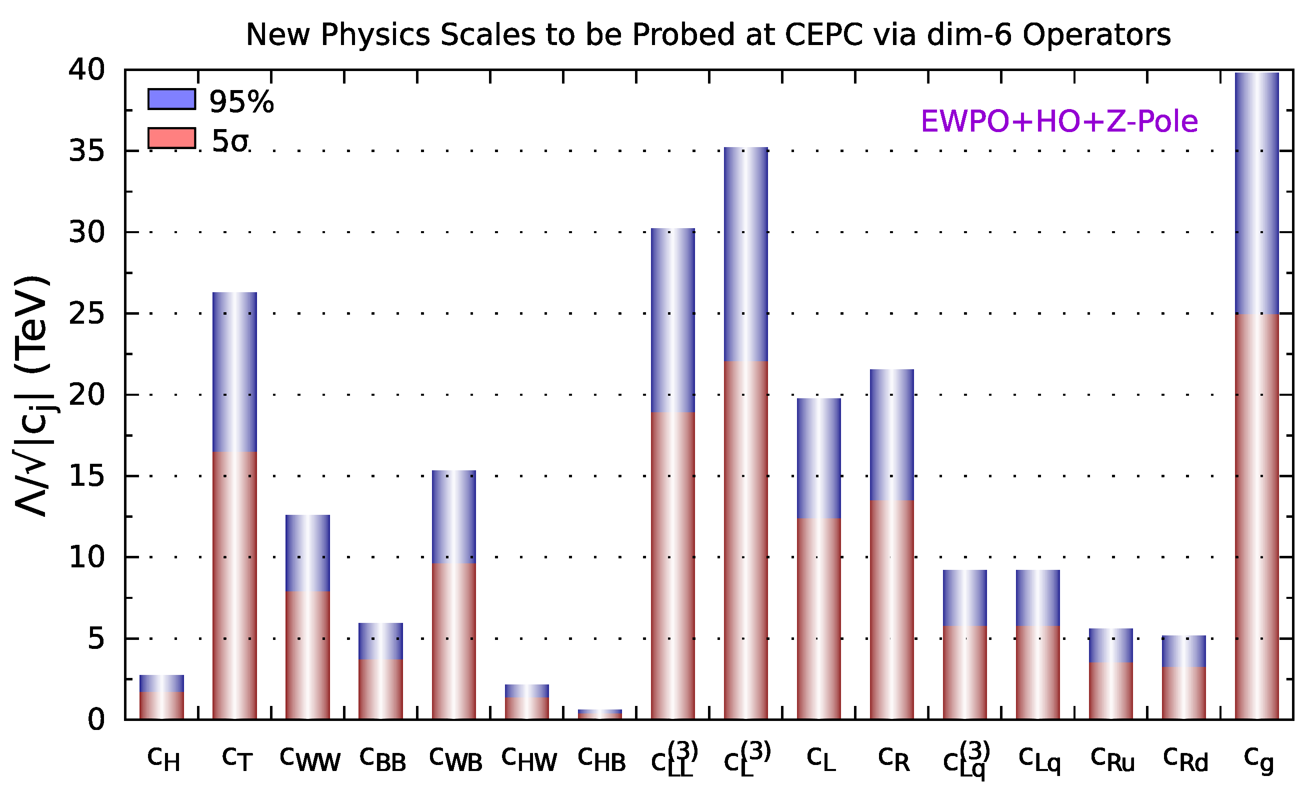
Even higher accuracies claimed by FCC-ee!

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

Precision measurements and new physics

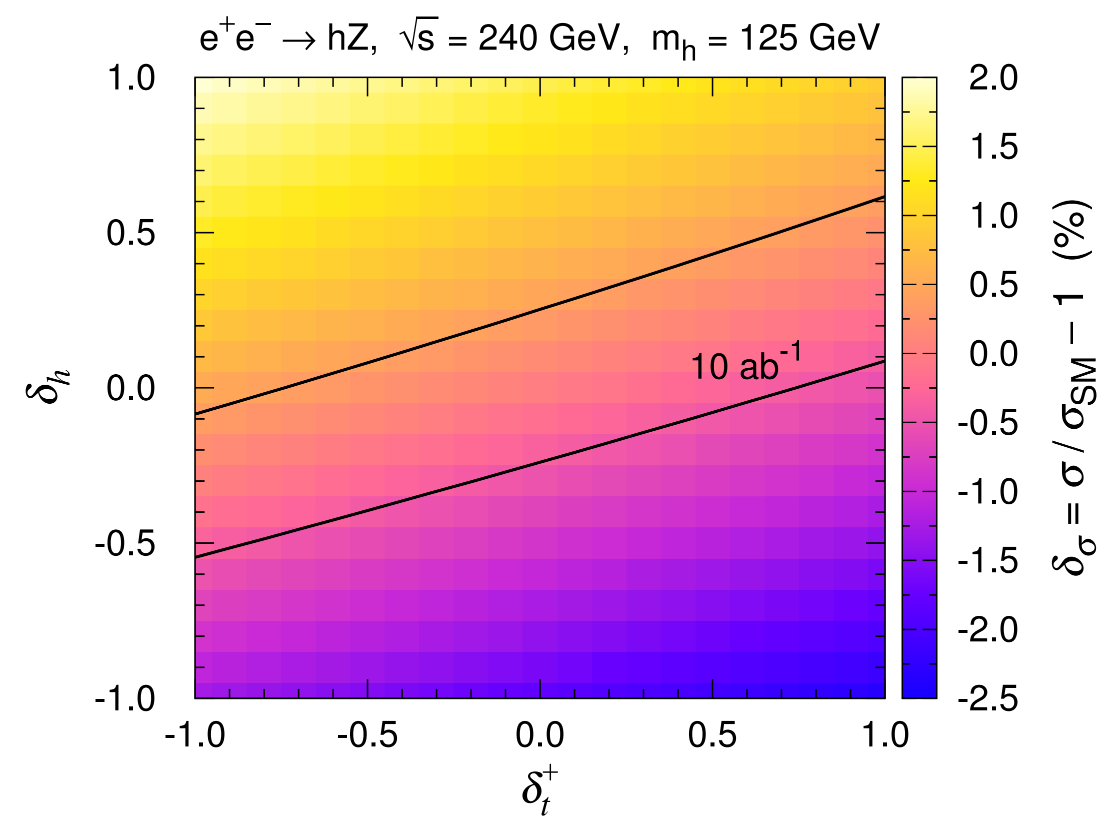
Lots of discussions on probing new physics using precision measurements at Higgs factories; sorry that I can't cover all!

Ge, He, Xiao: 1603.03385



Probing new physics scales

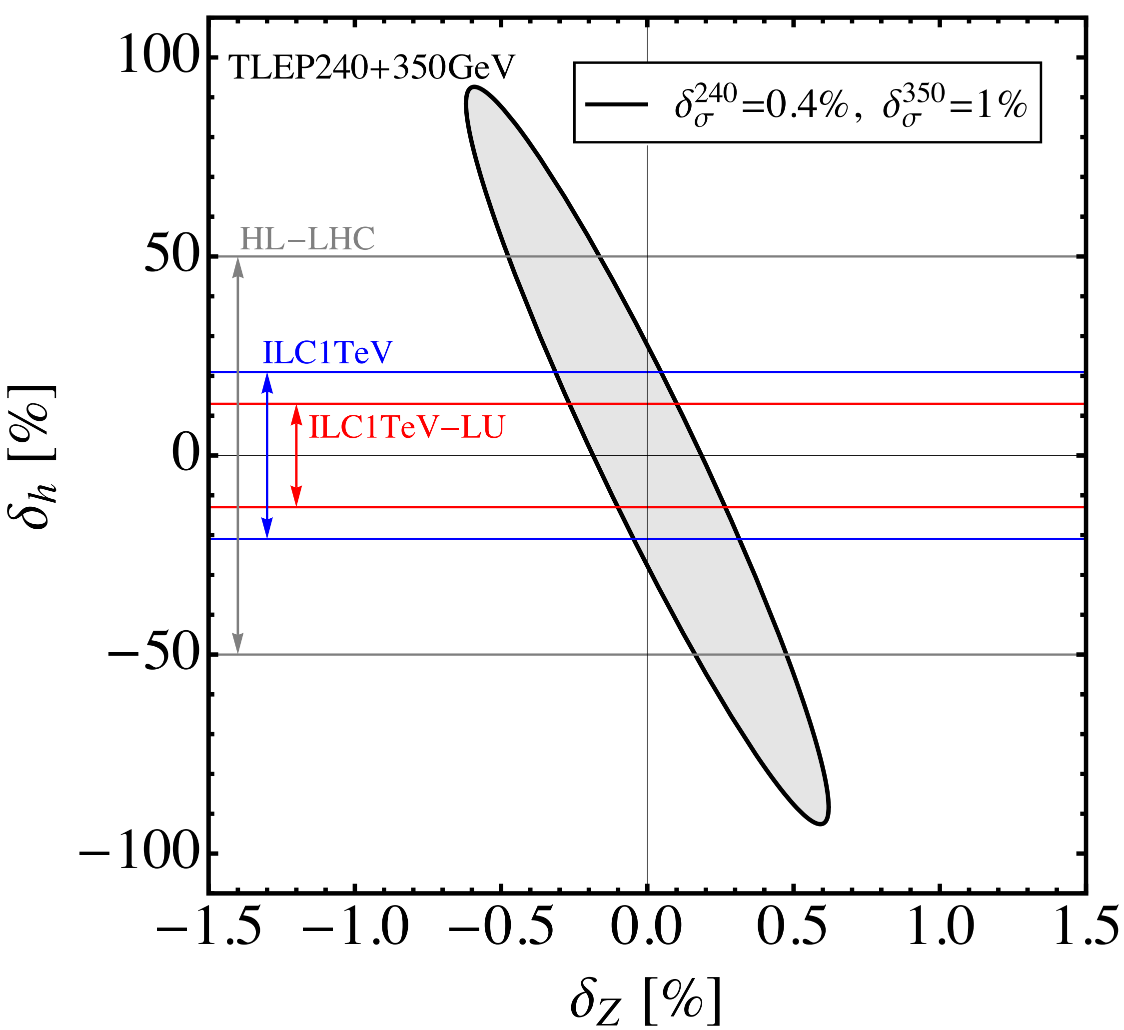
Huang, Gu, Yin, Yu, Zhang: 1511.03969



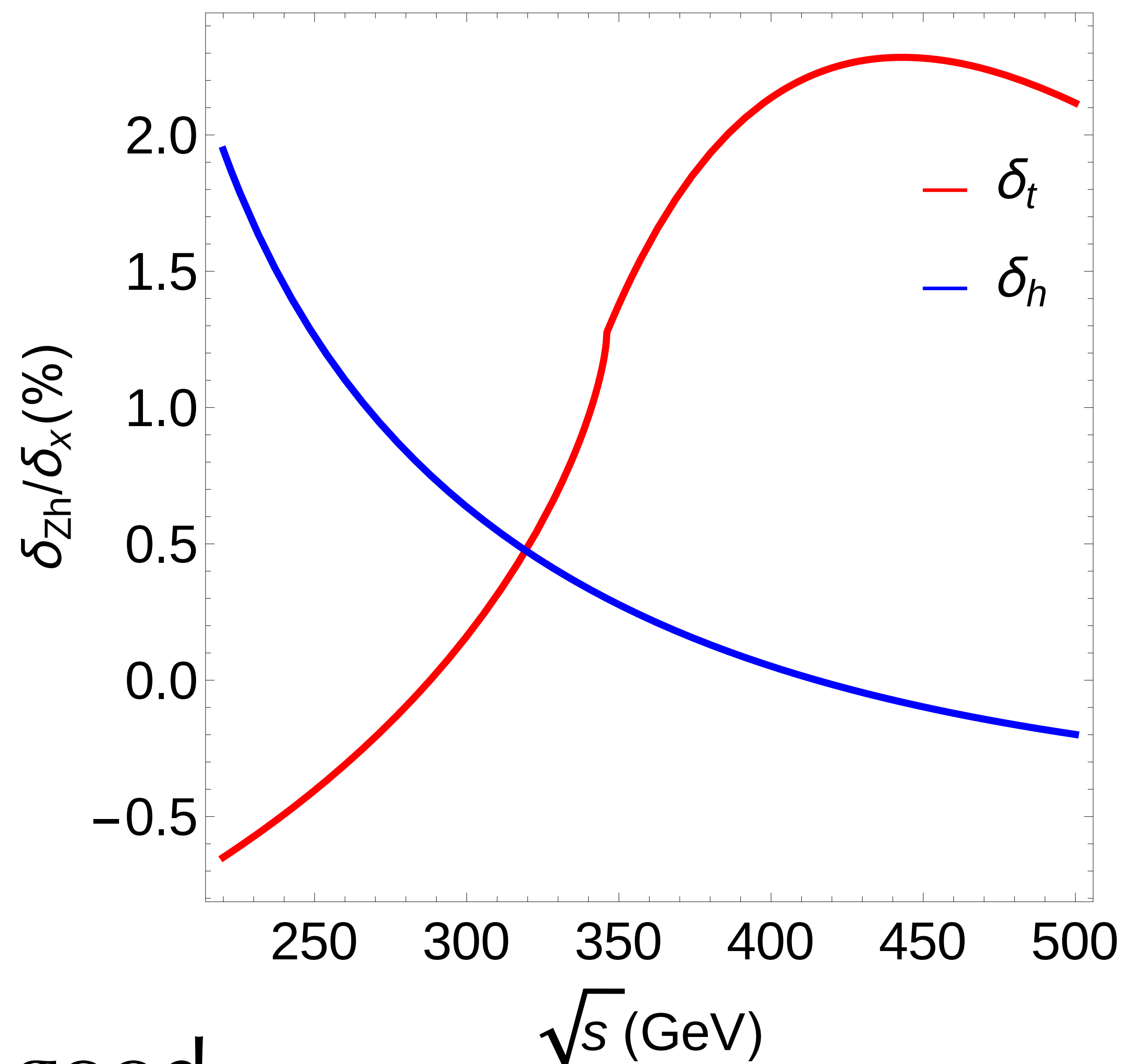
Testing EWPT

Indirect probe of Higgs self-coupling

McCullough: 1312.3322



Shen, Zhu: 1504.05626

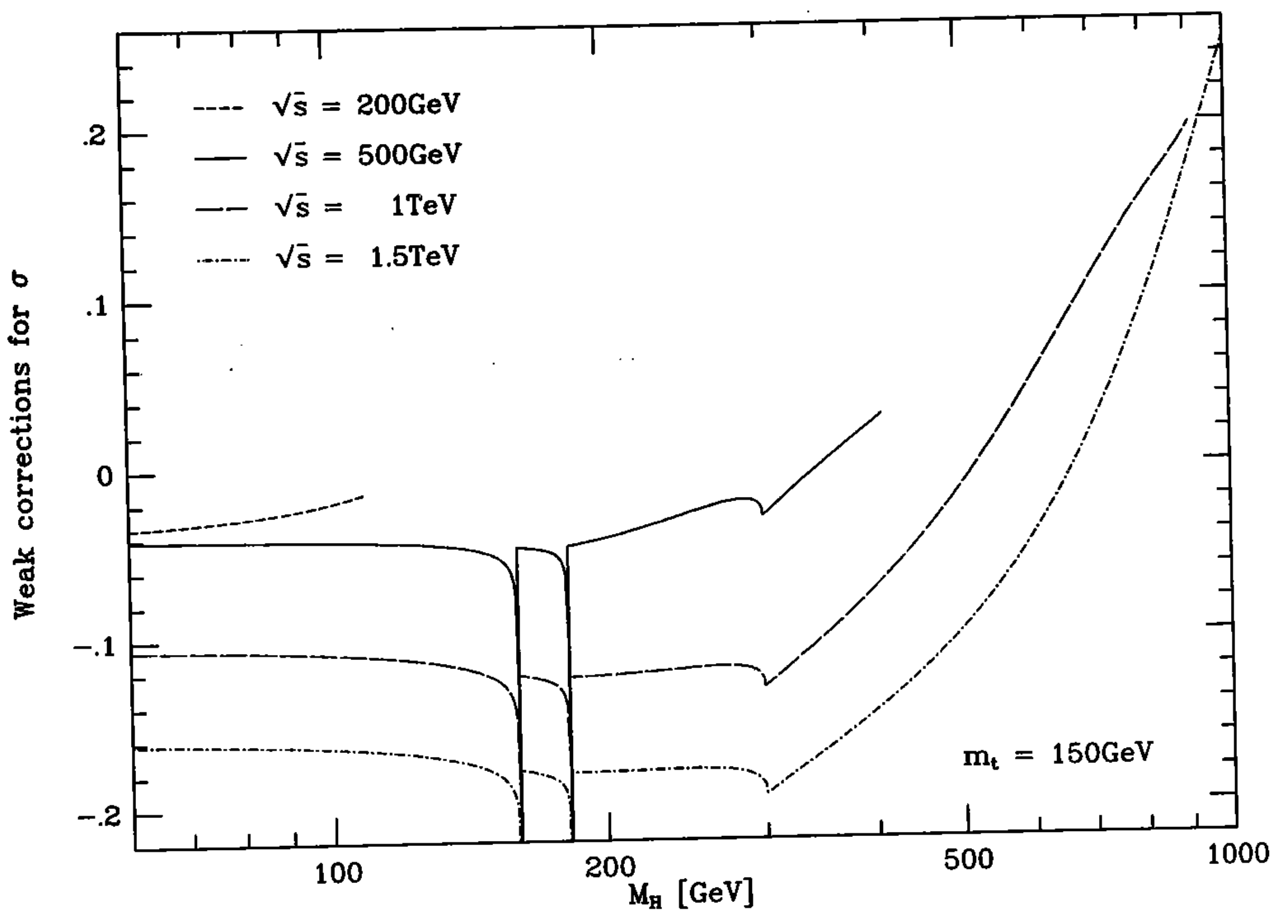


Model-dependent: requires good knowledges of HZZ and Htt couplings!

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

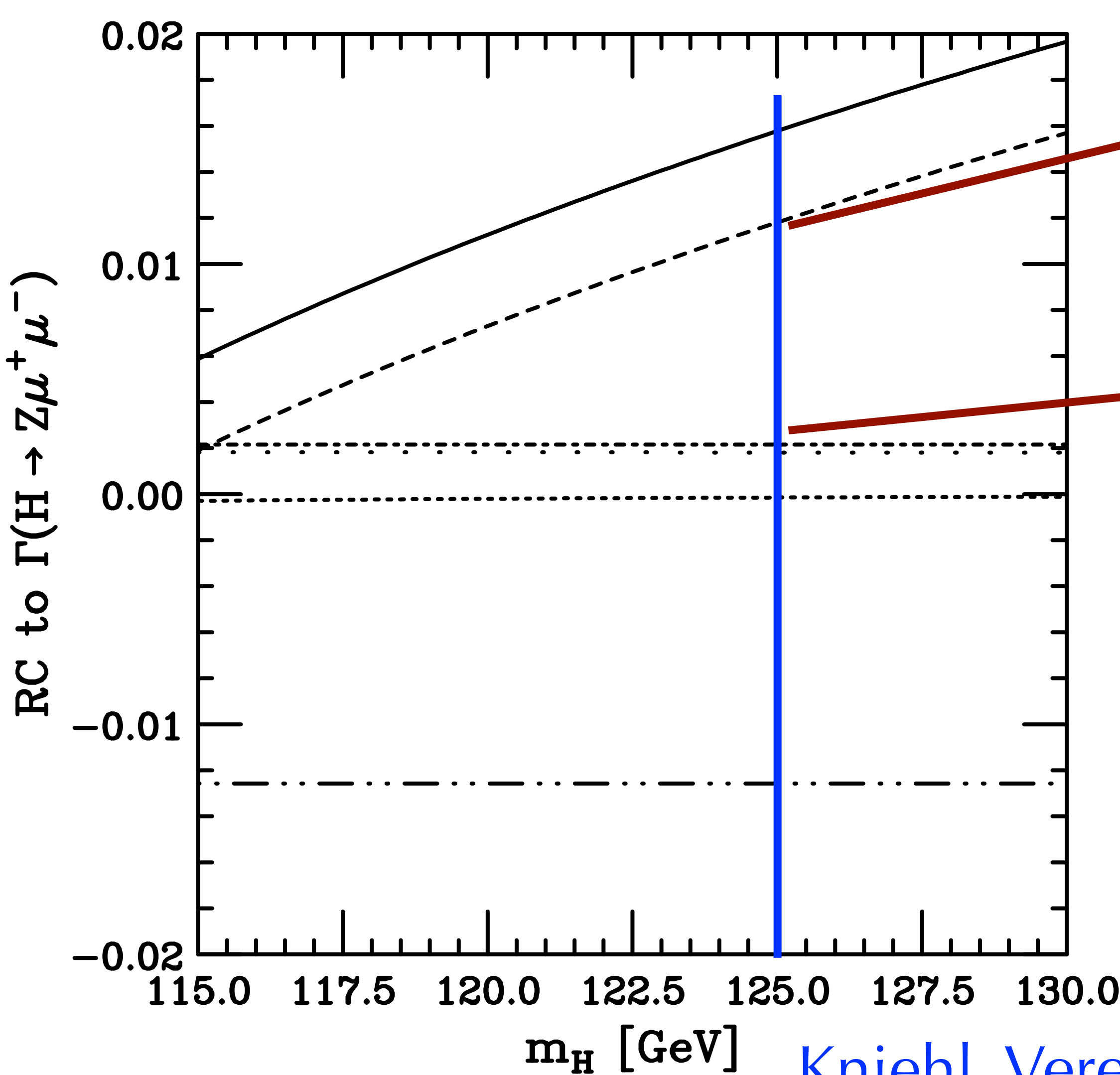
QED corrections also negative; size depends on cut on photon energy

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: $H \to ZZ^* \to Zl^+l^-$



One-loop weak corrections

Top-mass enhanced higher-order contributions

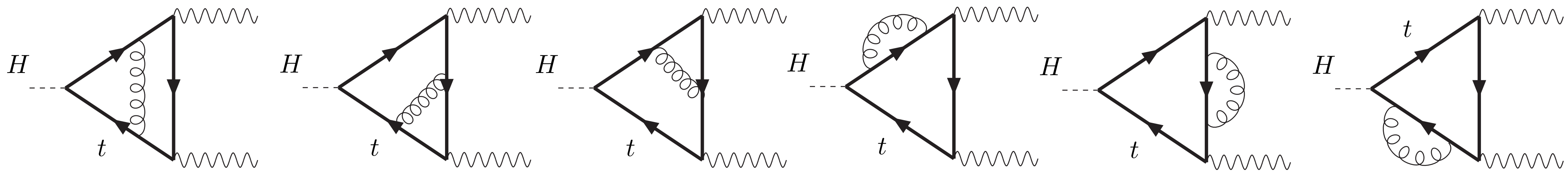
Kniehl, Veretin: 1206.7110

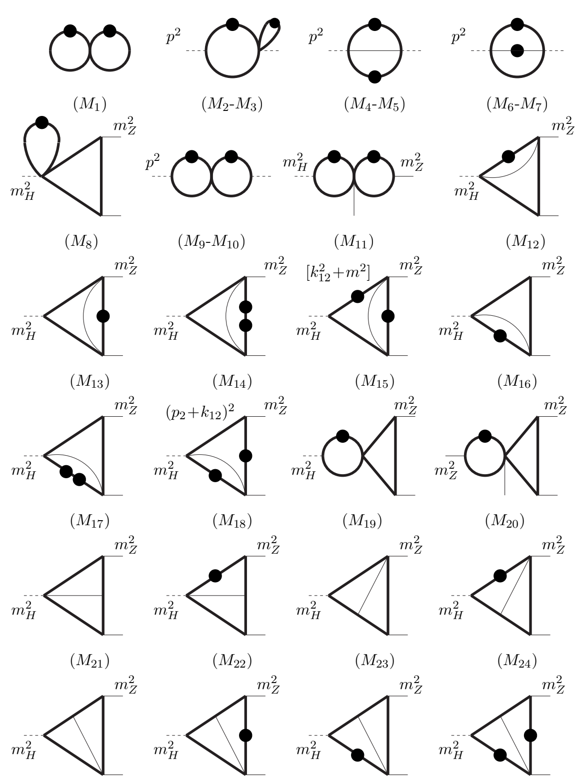
For σ(ZH) need to go beyond large m_t!

Towards NNLO σ(ZH)

Gong, Li, Xu, **LLY: 1609.xxxxx**

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





Figures from Bonciani et al. (1505.00567)

- 41 master integrals
- Many involve 4 mass scales: difficult to obtain analytic solutions

Sector decomposition

Binoth, Heinrich (hep-ph/0004013, hep-ph/0305234)

Efficient method for evaluating loop integrals in dimensional regularization

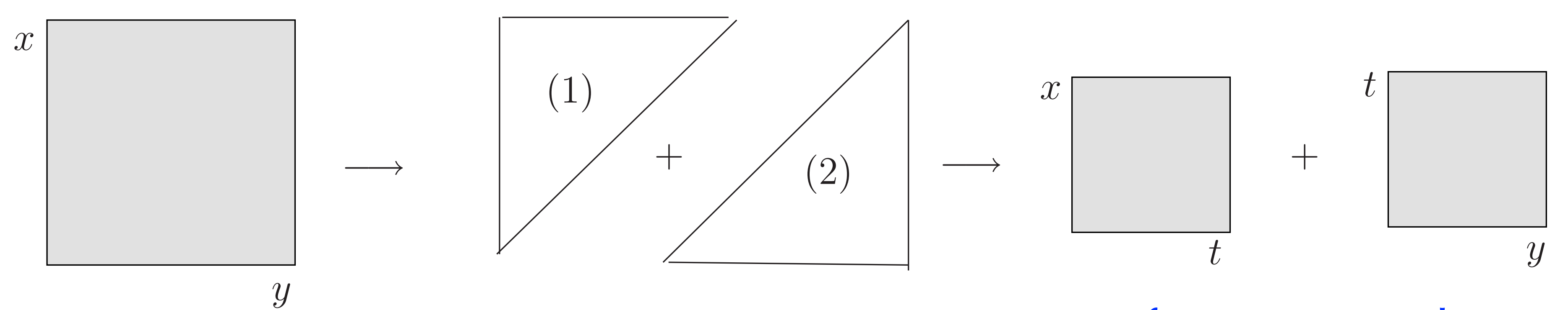


Figure from Heinrich (0803.4177)

Many public tools: FIESTA, SecDec, …

A new fast code:

Li, Wang, Yan, Zhao (1508.02512)

	Vegas/CPU	QMC/GPU
P_2	$-3.848 \pm 0.004 + 0.0005i \pm 0.003i$	$-3.8482 \pm 0.0007 + 0.0004i \pm 0.0003i$
P_1	$3.81 \pm 0.03 - 6.41i \pm 0.03i$	$3.83 \pm 0.02 - 6.40i \pm 0.02i$
P_0	$77.2 \pm 0.2 + 20.1i \pm 0.2i$	$77.2 \pm 0.1 + 19.9i \pm 0.1i$
Integration Time	54290s	20s

Result

Gong, Li, Xu, **LLY: 1609.xxxxx**

Correction ~ 1% for CEPC (240 GeV); important effect!

Alternative: expansion in $1/m_t$

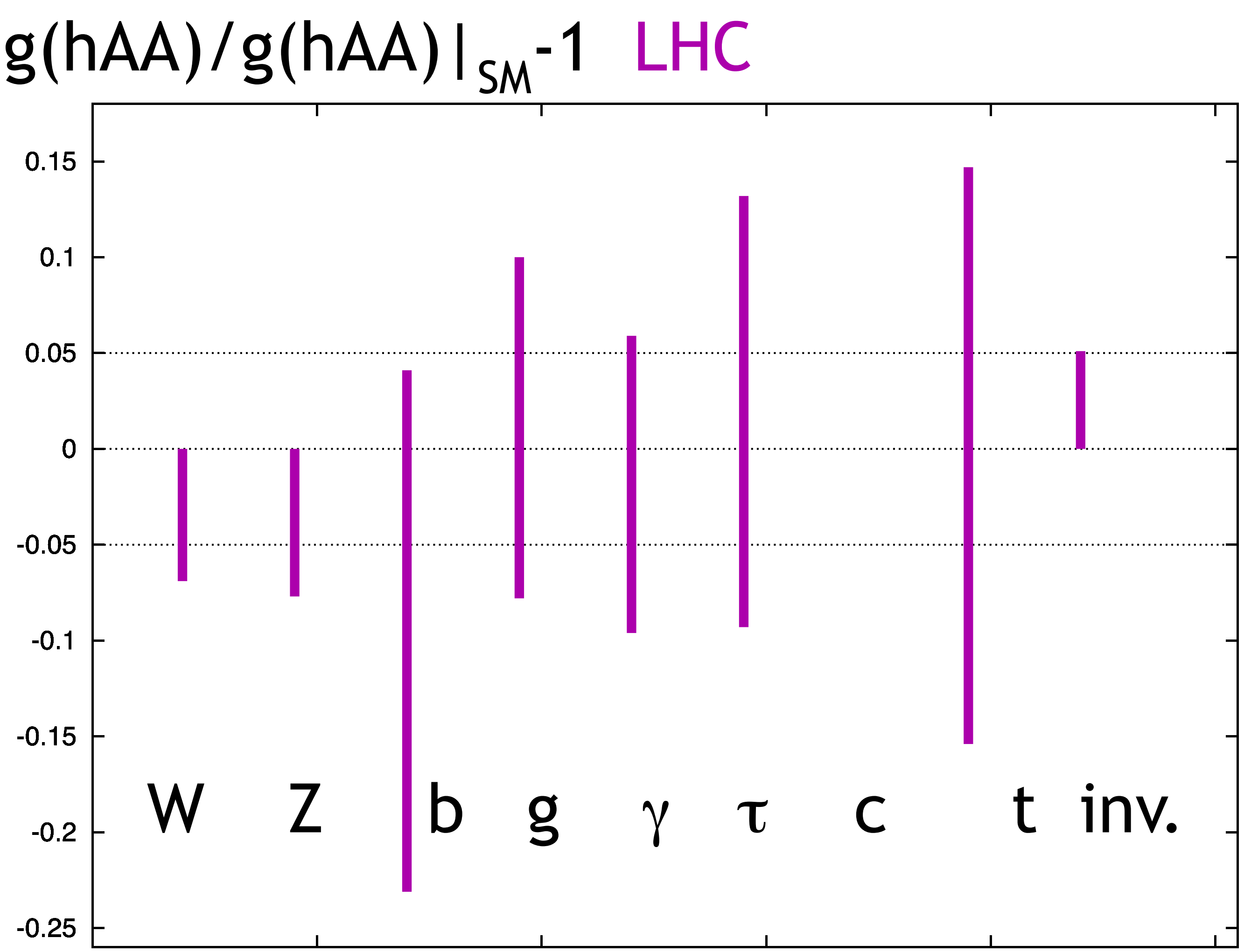
m_t^2	m_t^0	m_t^{-2}	m_t^{-4}
~ 82%	~ 16%	~ 1%	< 1%

Fast convergence

Expansion in $1/m_t$ will not work for higher energies (e.g. ILC and FCC-ee)!

Future: the more difficult (but also important) $O(\alpha^2)$ correction

Towards SppC

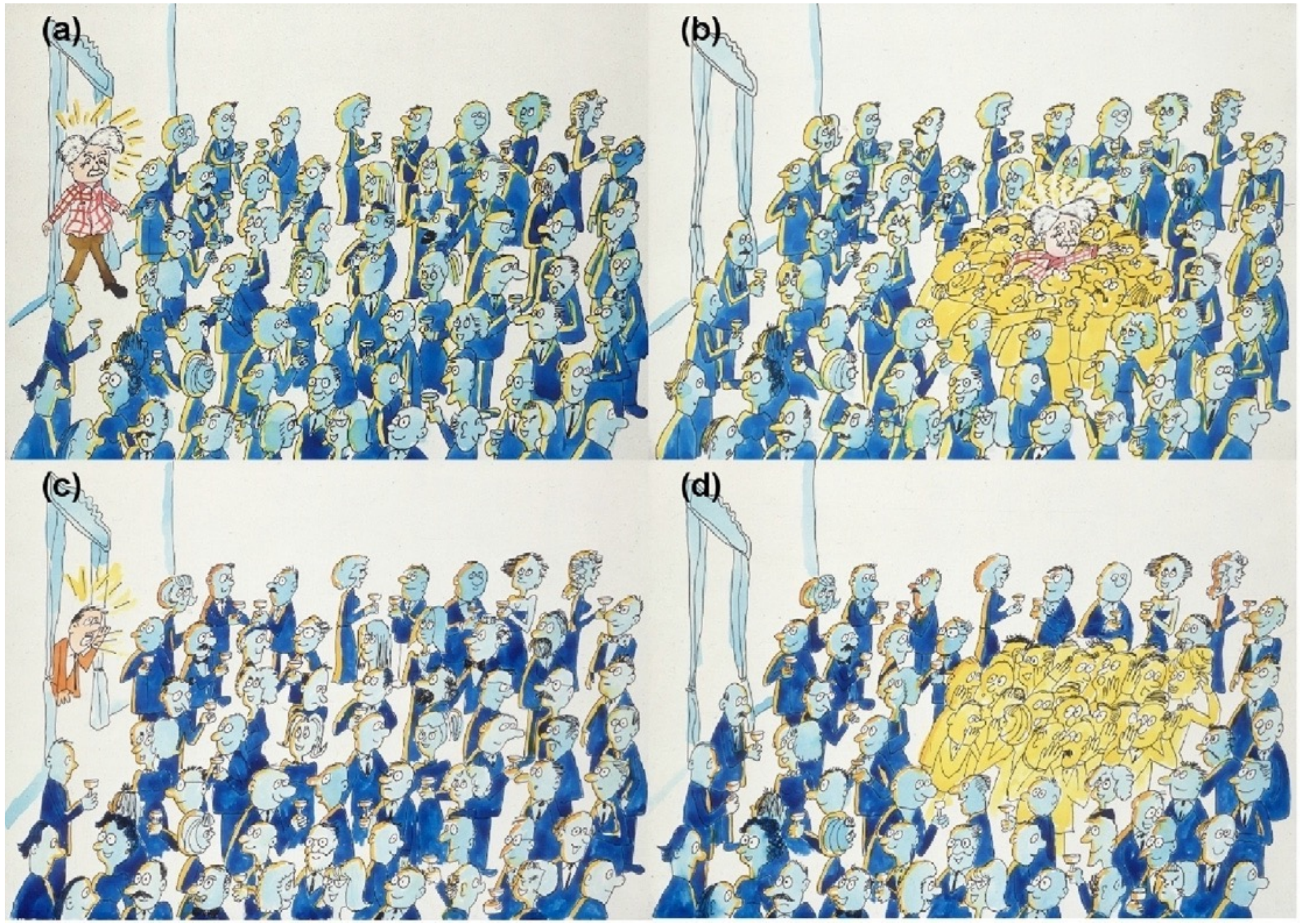


Peskin: 1207.2516

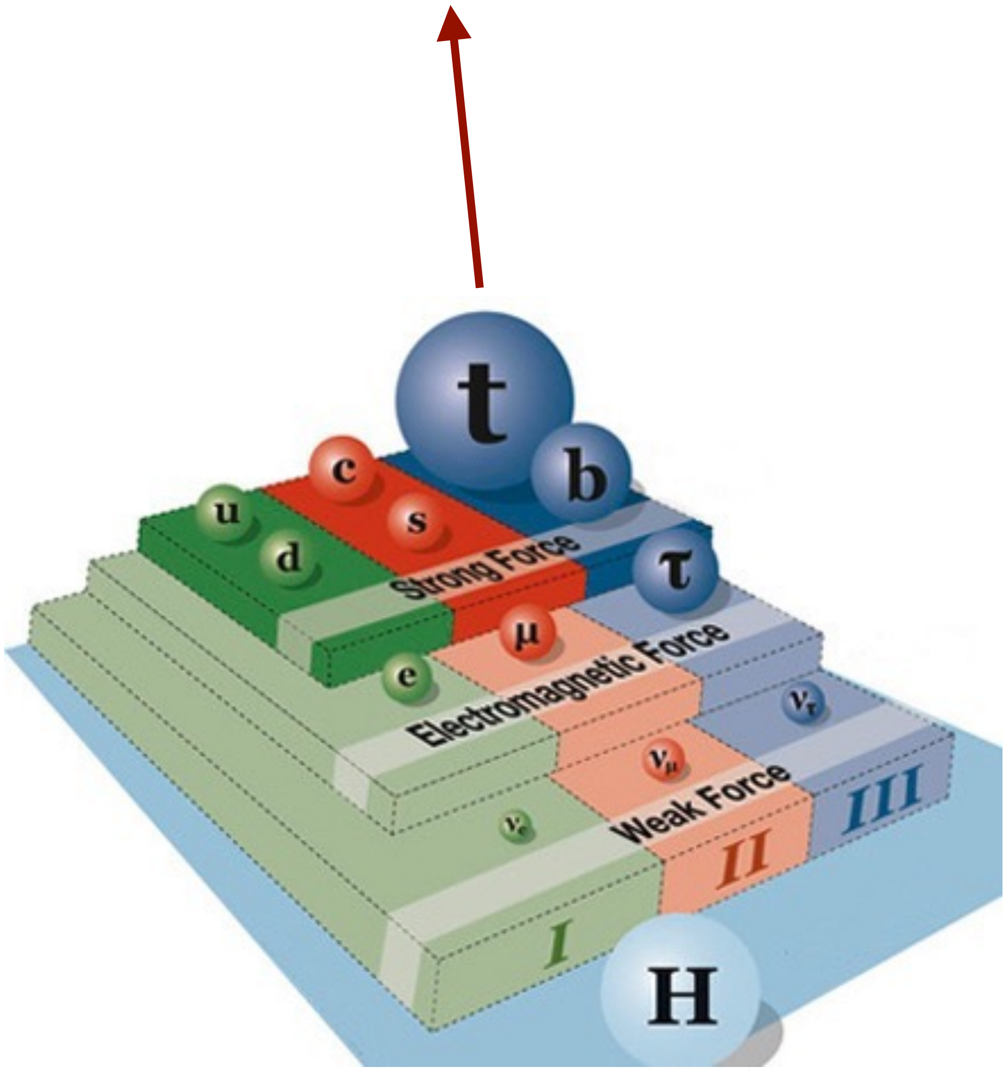
Two important things that LHC and CEPC will not tell us very precisely

- Top Yukawa coupling
- Higgs self-coupling

Top and Higgs

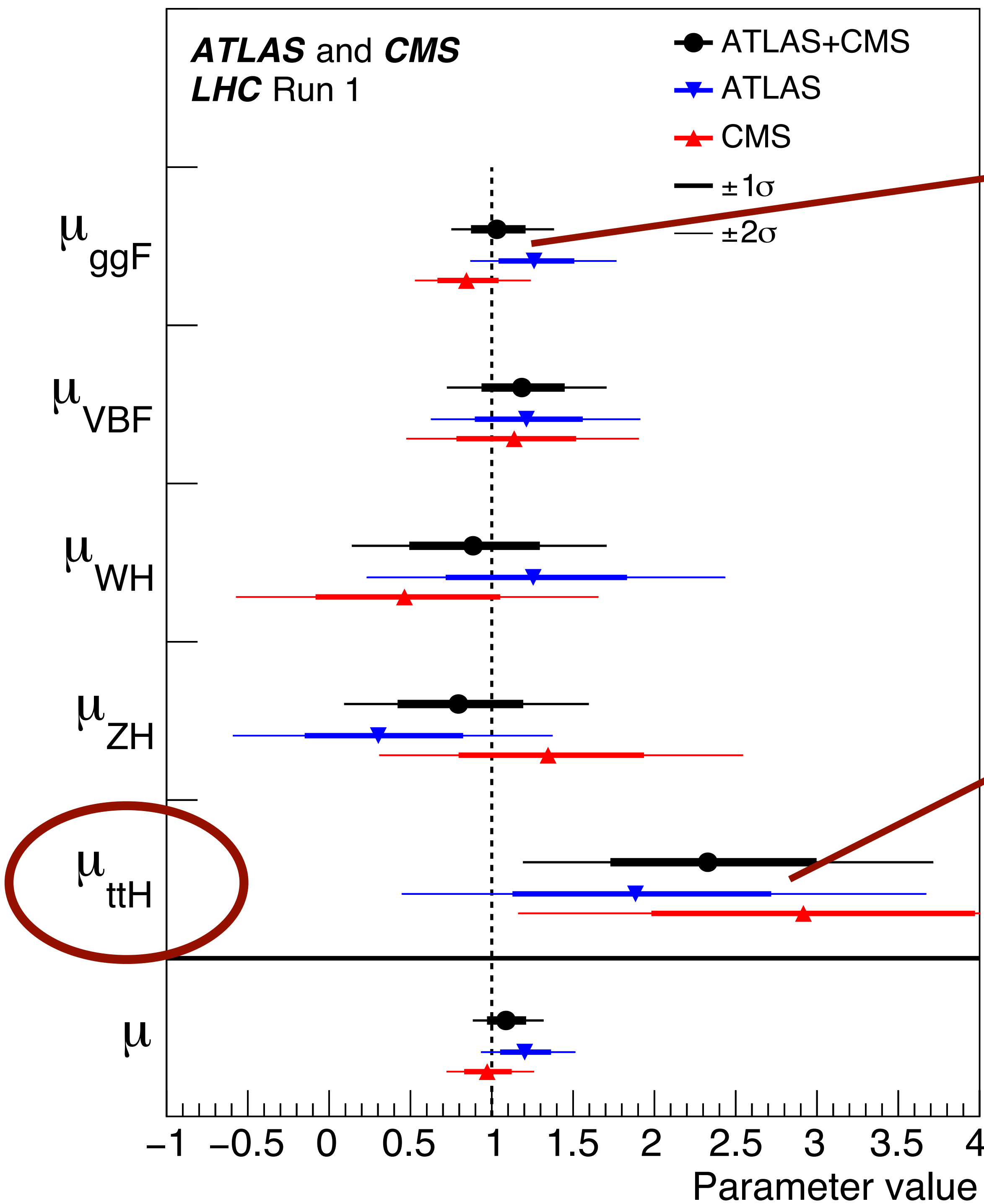


Strong Yukawa coupling!



Top Yukawa

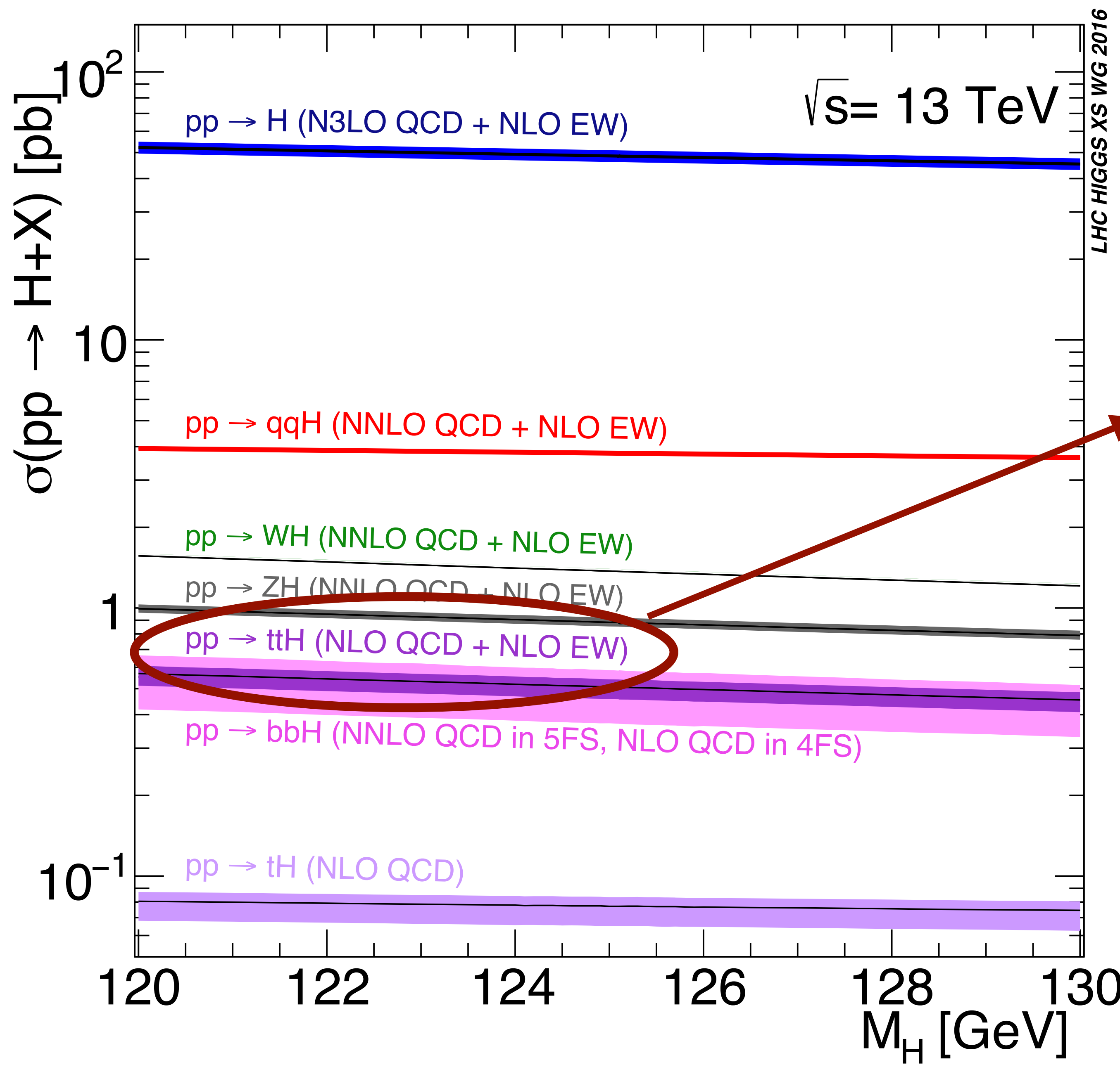
ATLAS and CMS: 1606.02266



gg→H cannot distinguish modified top Yukawa and new particles in the loop

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

Theoretical uncertainty (again)



LHC HXSWG report 4 (to appear)

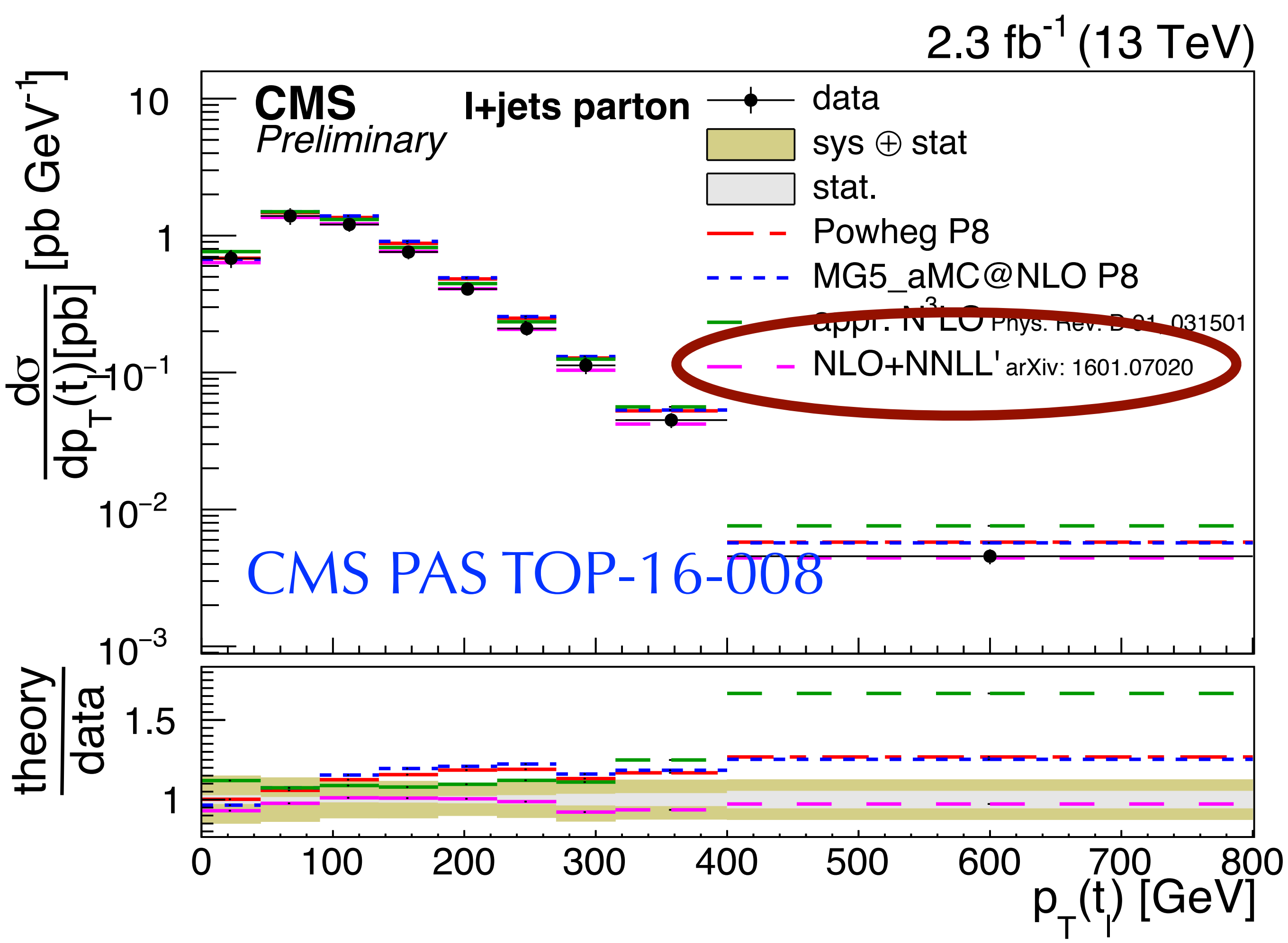
NLO only! Higher orders?

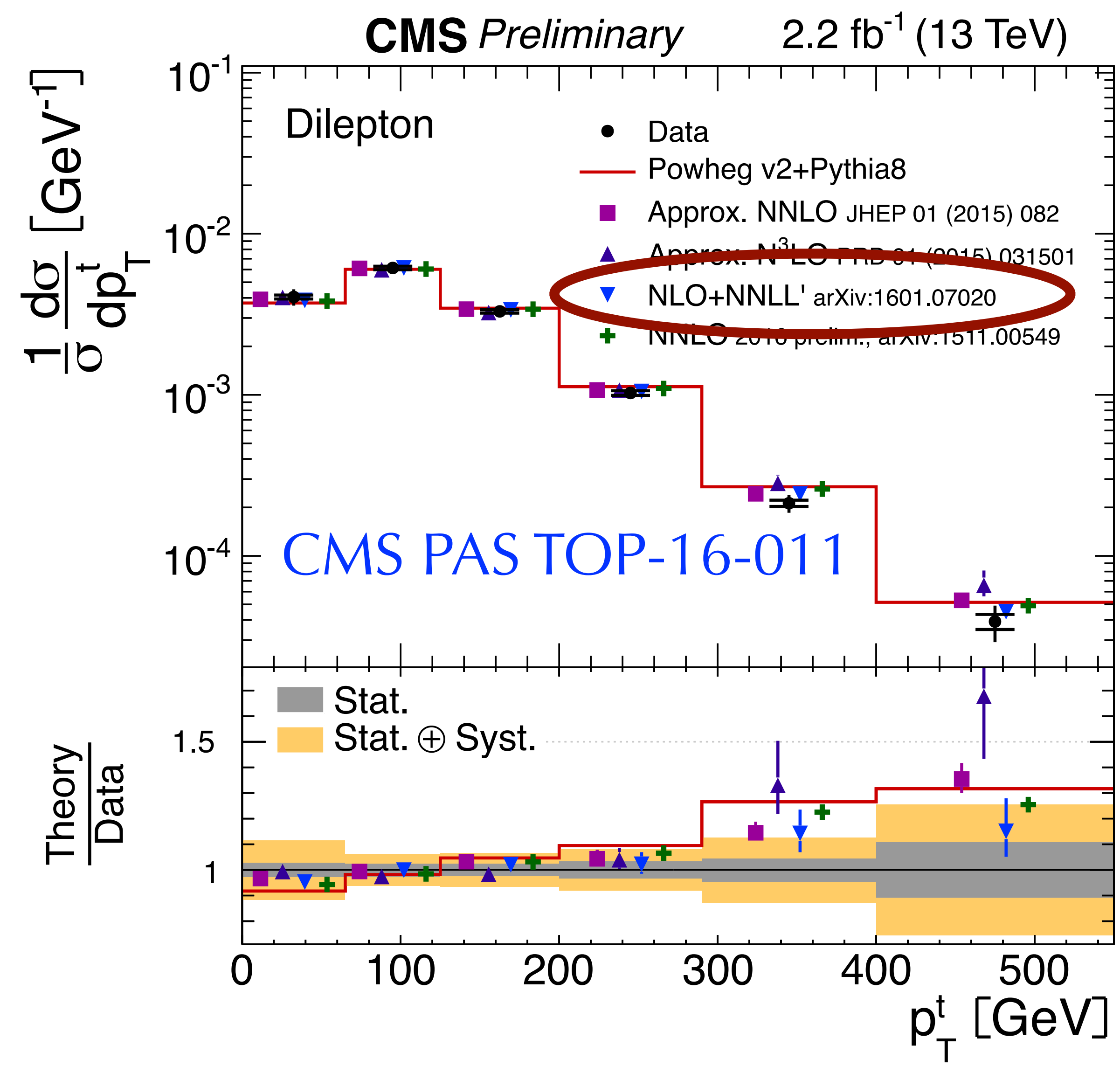
NNLO extremely difficult!

Resummation?

Resummation for top pairs

Ferroglia, Neubert, Pecjak, **LLY**: 0907.4791
Ahrens, Ferroglia, Neubert, Pecjak, **LLY**: 1003.5827; 1105.5824; 1106.6051
Ferroglia, Pecjak, **LLY**: 1205.3662; 1207.4798; 1306.1537
Zhu, **Li**, **Li**, **Shao**, **LLY**: 1208.5774; 1307.2464
Pecjak, Scott, Wang, **LLY**: 1601.07020





Essence of the calculation

Two dangerous contributions for production of highly-boosted top quarks at LHC and SppC

soft gluons

$$\ln \frac{\hat{s} - M_{t\bar{t}}^2}{M_{t\bar{t}}^2}$$

quasi-collinear gluons

$$\ln \frac{m_t^2}{M_{t\bar{t}}^2}$$

Double factorization

Ferroglia, Pecjak, **LLY**: 1205.3662

Boosted limit: $M \gg M/N,\ m_t$

$$\hat{\sigma}(N,\mu_f) \sim \mathrm{Tr}\big[\boldsymbol{H}(L_h,\mu_f)\,\boldsymbol{S}(L_s,\mu_f)\big]\,C_D^2(L_c,\mu_f)\,S_D^2(L_{sc},\mu_f)$$

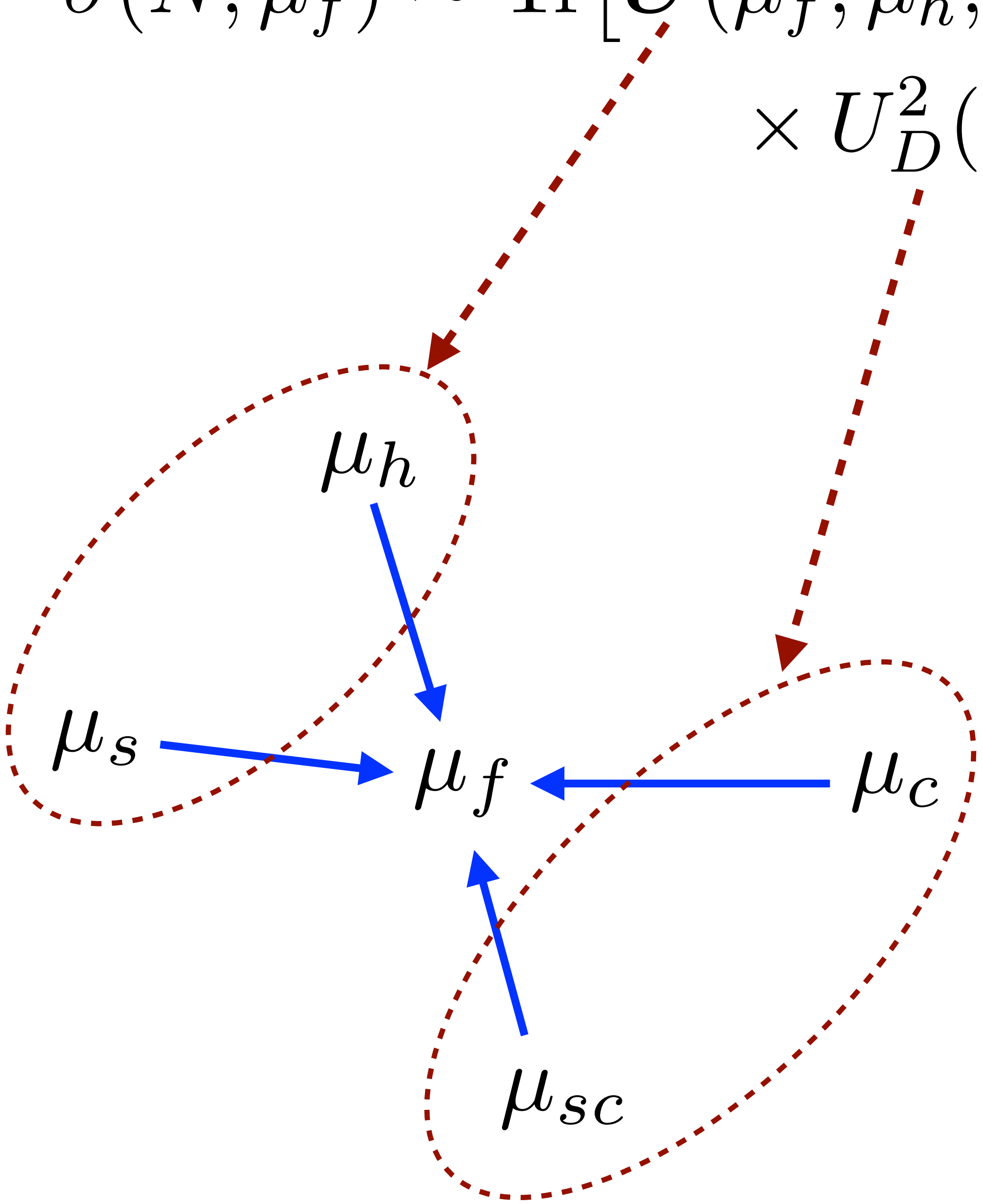
$$\ln\frac{M^2}{\mu_f^2} \qquad \ln\frac{M^2}{\bar{N}^2\mu_f^2} \qquad \ln\frac{m_t^2}{\mu_f^2} \qquad \ln\frac{m_t^2}{\bar{N}^2\mu_f^2}$$

Emergence of a soft-collinear scale m_t/N!

Resummation

Pecjak, Scott, Wang, **LLY**: 1601.07020

$$\hat{\sigma}(N,\mu_f) \sim \mathrm{Tr}\big[\boldsymbol{U}(\mu_f,\mu_h,\mu_s)\boldsymbol{H}(L_h,\mu_h)\boldsymbol{U}^\dagger(\mu_f,\mu_h,\mu_s)\boldsymbol{S}(L_s,\mu_s)\big]$$
$$\times\, U_D^2(\mu_f,\mu_c,\mu_{sc})C_D^2(L_c,\mu_c)S_D^2(L_{sc},\mu_{sc})$$

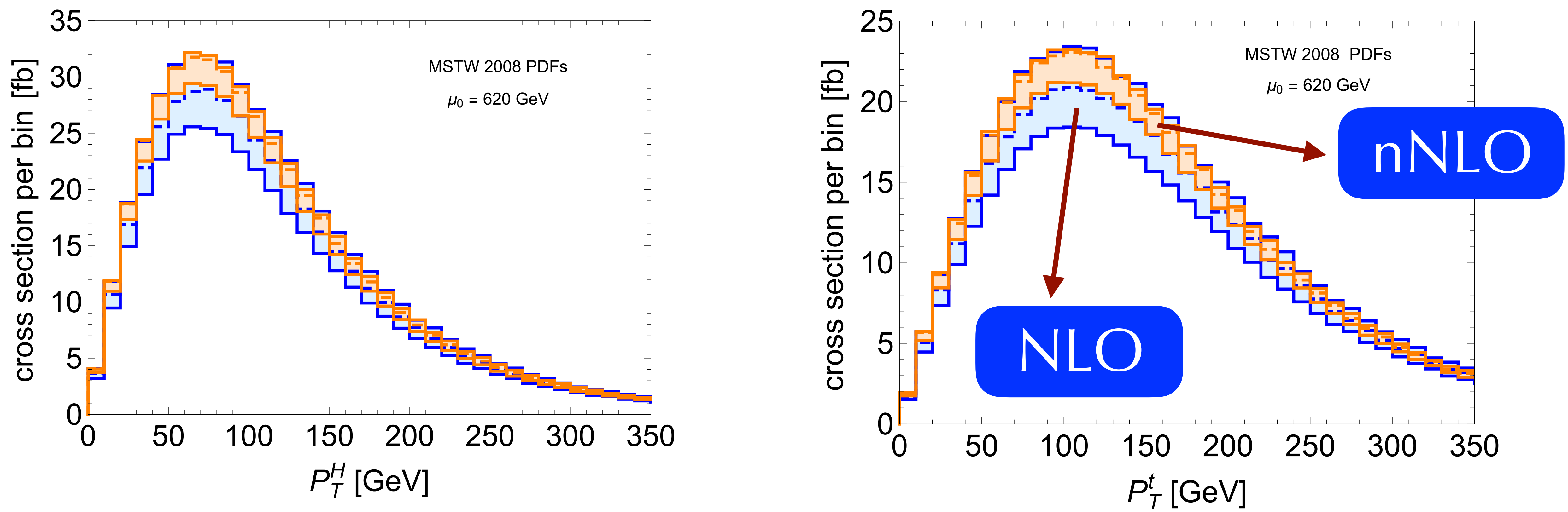


pp→ttH very similar to pp→tt, but some ingredients are missing: performing soft resummation first

ttH: approximate NNLO

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

Exact NNLO for ttH unlikely to be available very soon!



First fully differential prediction beyond NLO!

NLO+NNLL resummation in progress

Future: predictions for SppC (boosted tops and Higgs)

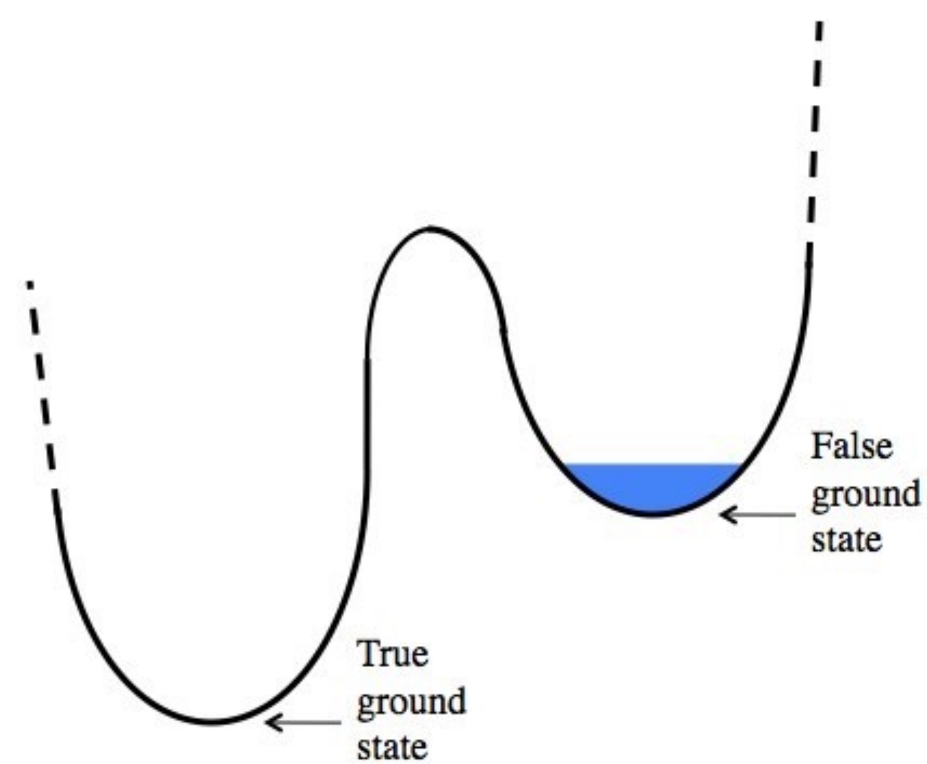
Higgs self-couplings

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

How can we verify these two interactions?

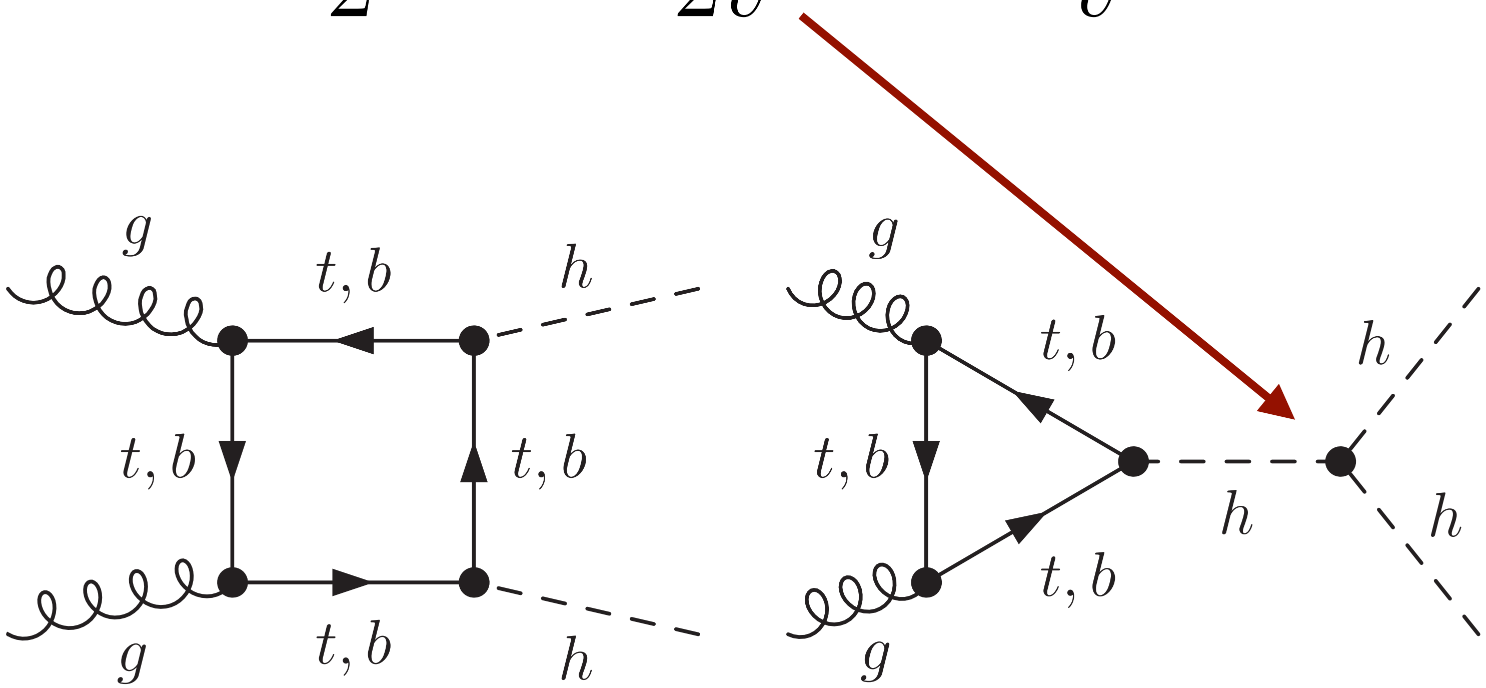
"6th force"

Important for EW phase transition as well as vacuum stability!



Higgs pair & self-coupling

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

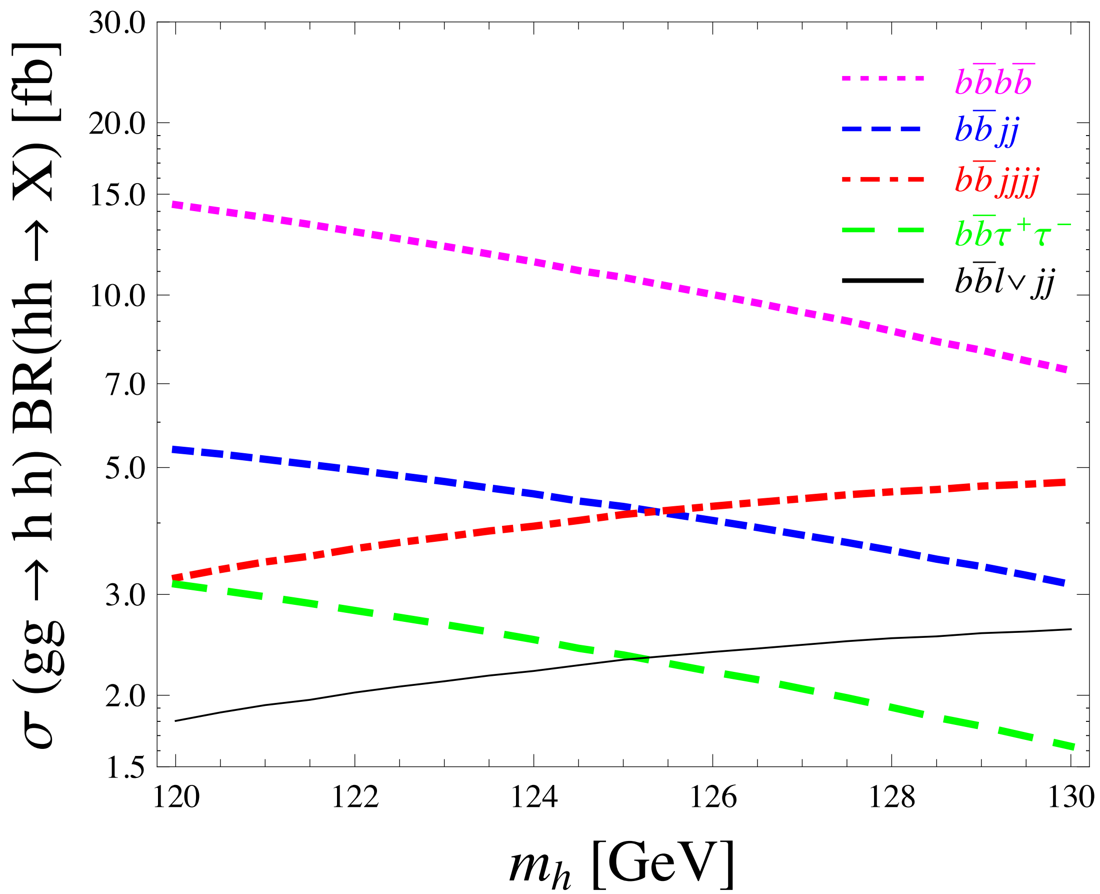


However, notoriously difficult to detect!

HL-LHC and 100 TeV physics!

Detecting HH production

Requires combination of various decay channels!



bbγγ bbWW bbττ

WWγγ ττττ

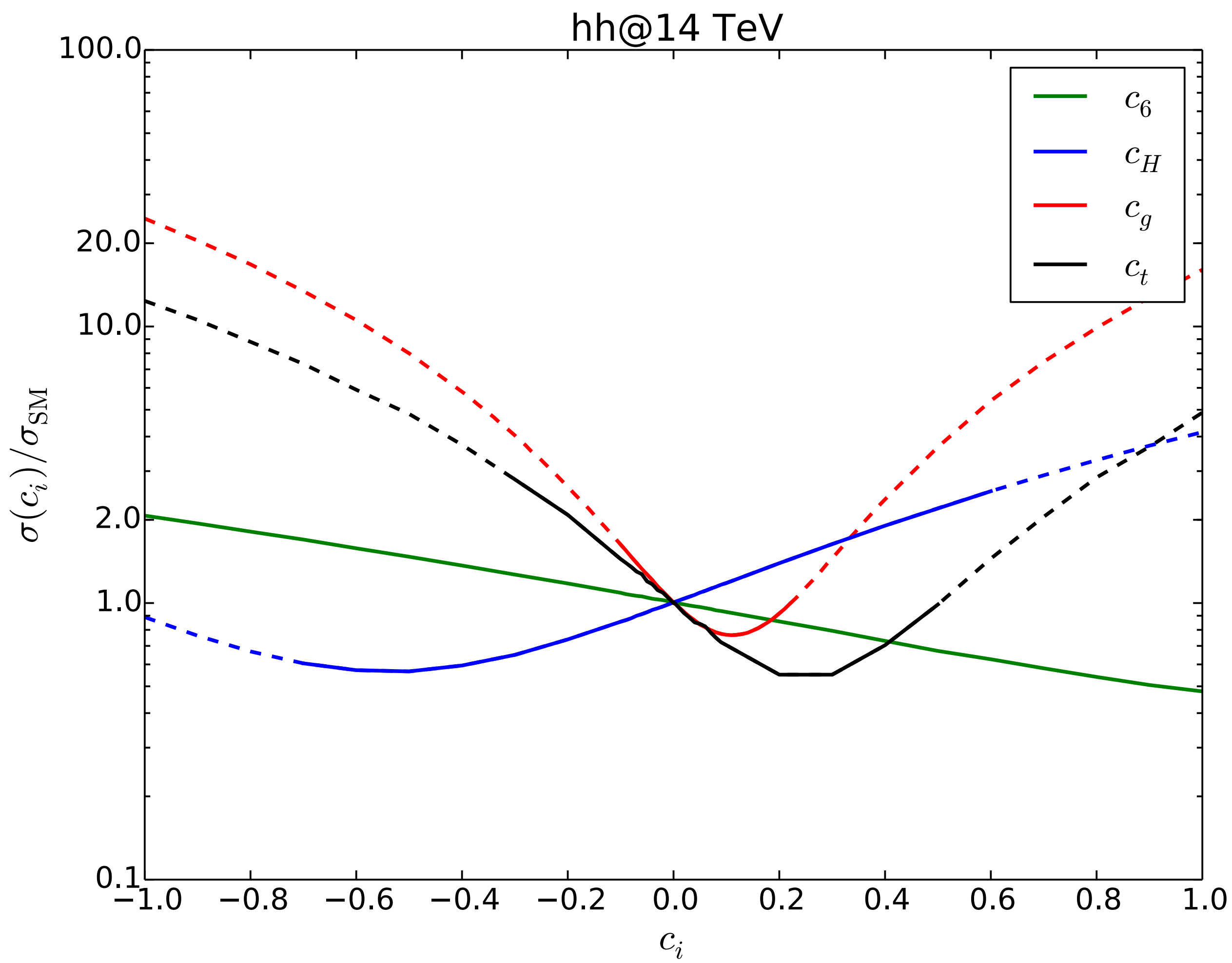
bbbb WWWW

Hot topic since Higgs discovery!

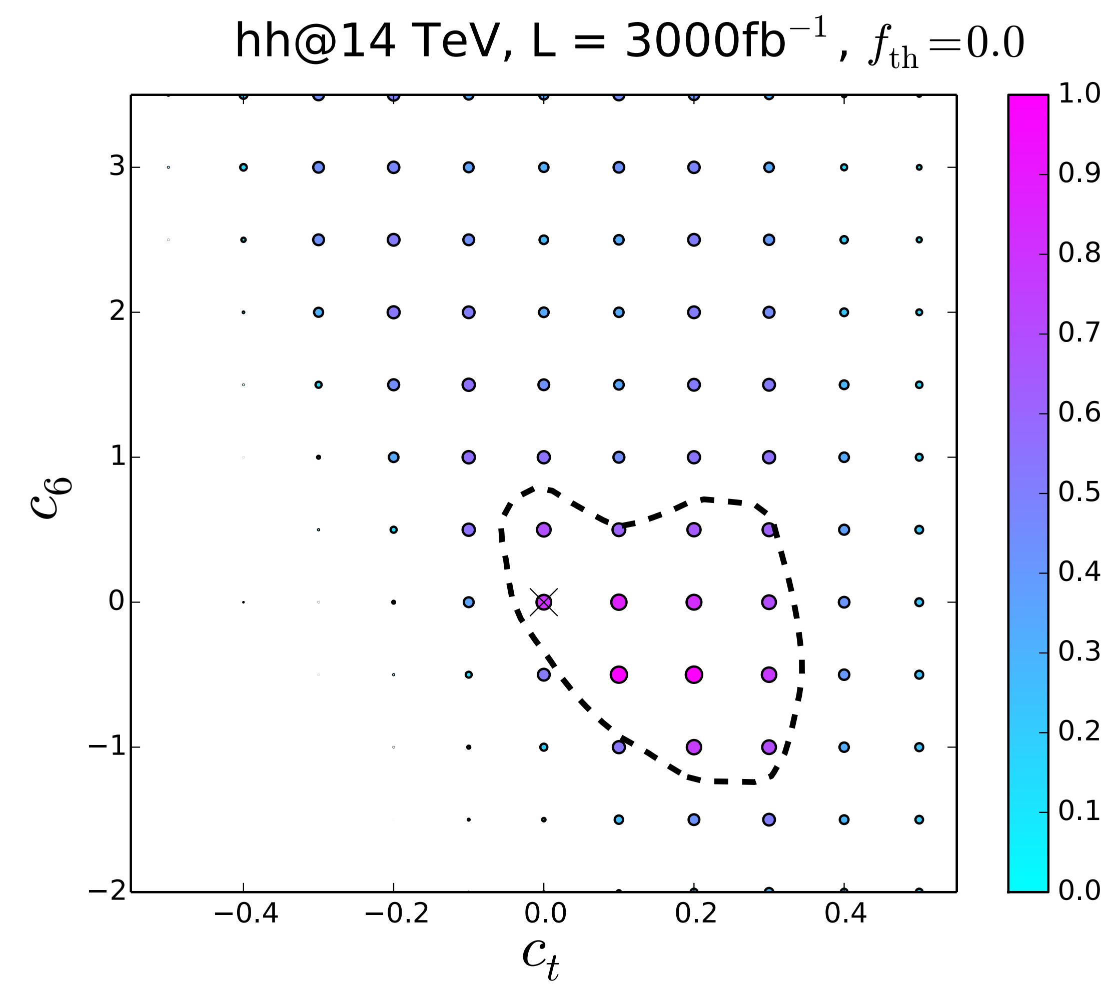
Dolan et al.: 1206.5001; Papaefstathiou, **LLY**, Zurita: 1209.1489; Baglio et al.: 1212.5581; Barr et al.: 1309.6318; de Lima et al.: 1404.7131; Barr et al.: 1412.7154; Li, Li, Yan, Zhao: 1503.07616; Papaefstathiou: 1504.04621; Kotwal et al.: 1504.08042; He, Ren, Yao: 1506.03302; Lü, Du, Fang, He, Zhang: 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

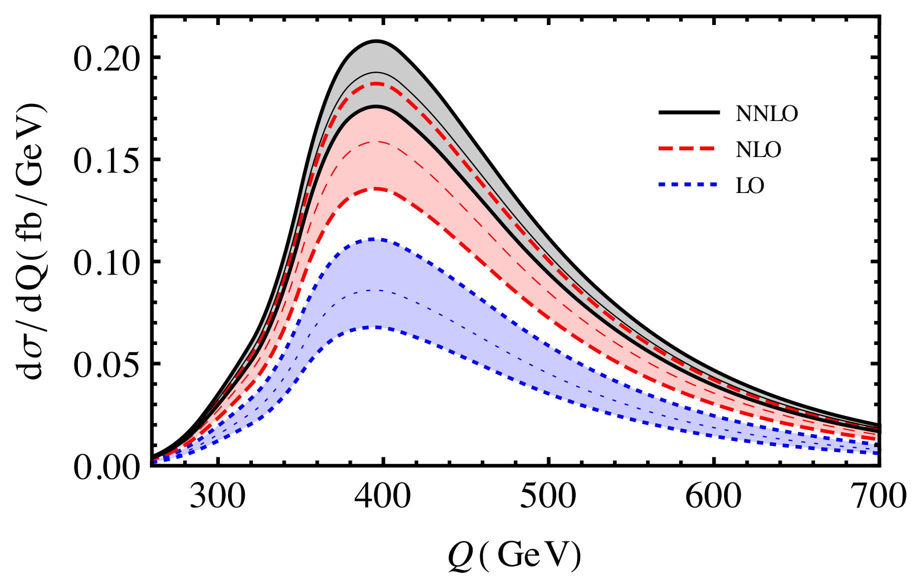


Can be used to constrain EFT parameters

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



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

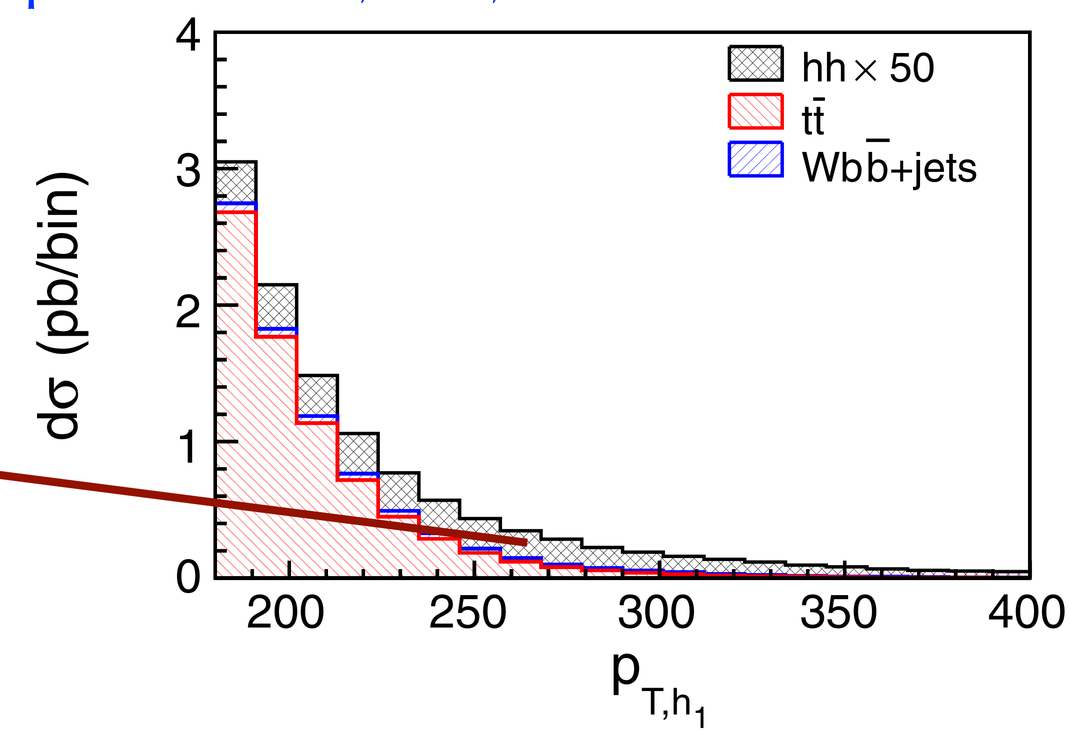
~20% correction

Papaefstathiou, **LLY**, Zurita: 1209.1489

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

High p_T to suppress QCD backgrounds

Validity of HEFT?



Higgs pair at NLO with top-mass dependence

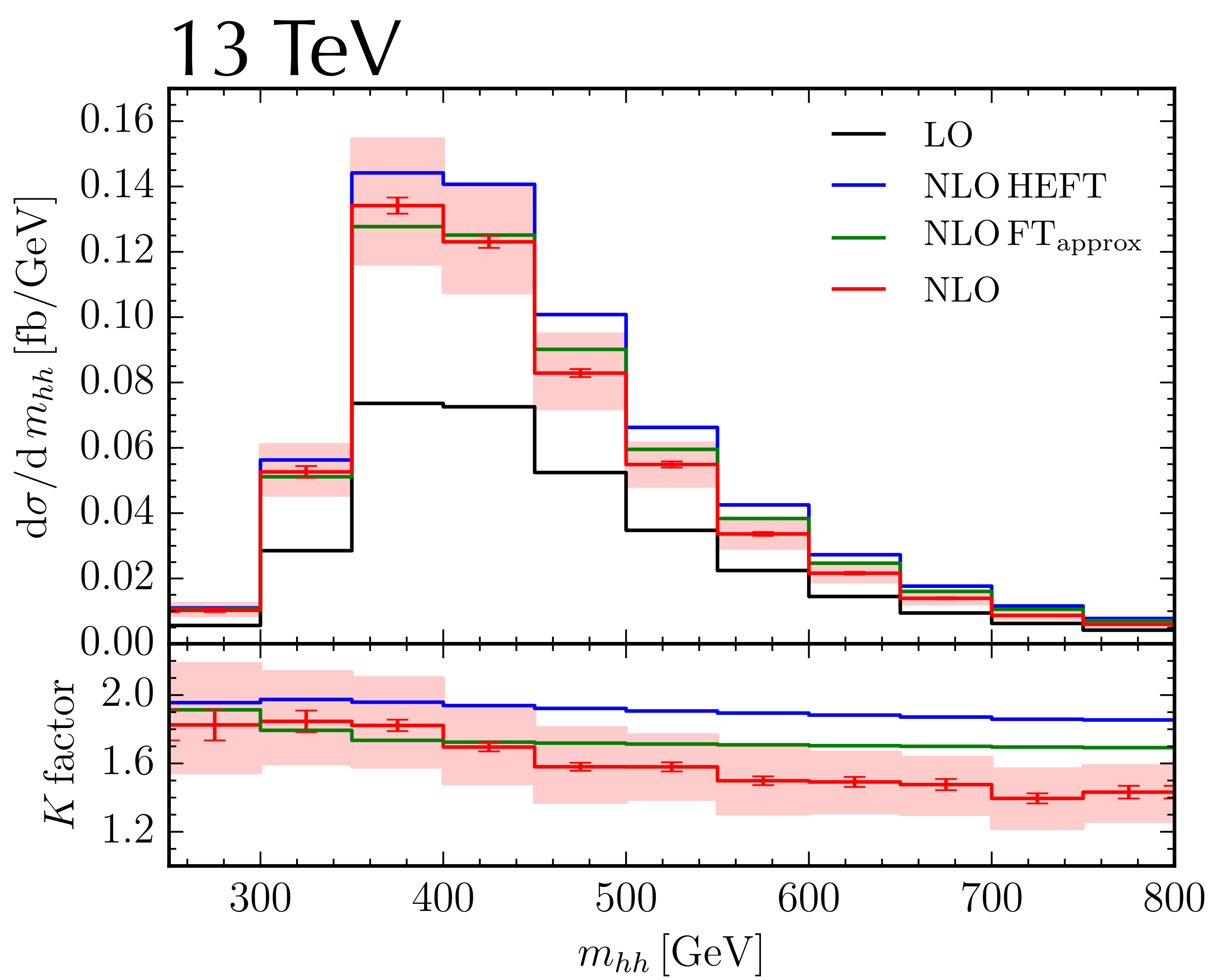
Borowka, Greiner, Heinrich et al.: 1604.06447

A highly non-trivial calculation!

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

14% smaller than Born-improved HEFT result

Prospect of observing this process at LHC reduced!

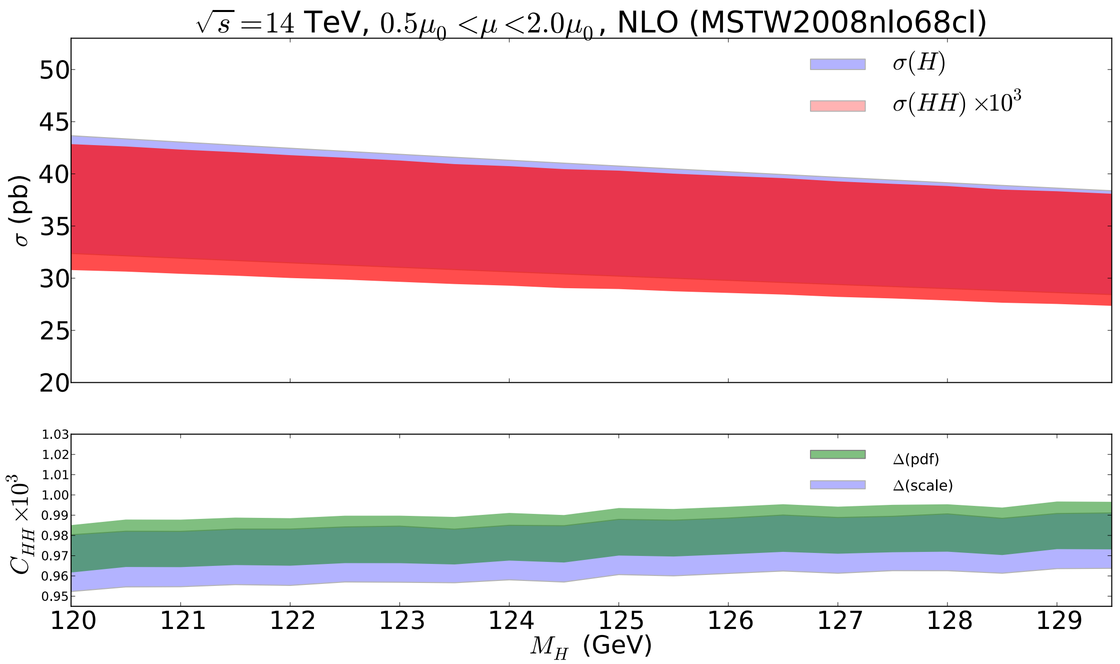


Higgs self-coupling from ratios of cross sections

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
- An idea worth reconsidering (and extending) for SppC!

Summary

* A new era for particle physics after Higgs discovery
* Many things waiting to be explored (gauge couplings, Yukawa couplings, Higgs self-couplings, ...): requires CEPC and SppC beyond LHC!
* Precision $\sigma(e^+e^- \rightarrow ZH)$: fundamental theoretical input for CEPC
* Precision observables to extract Htt and HHH couplings at SppC

Thank you!