Issues in Higgs Physics: A Theoretical Overview

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Mostly unanswered questions….

What will we want to know in *n* years?

- Higgs couplings
  - LHC will measure 3rd generation couplings to ~5% level (assuming central value is SM)
  - How well can HL-LHC measure 2nd generation couplings?
  - Does the Higgs mass come from a scalar potential?
- Are there rare Higgs decays that could hide at the LHC?
  - Are there flavor changing Higgs decays?
- Higgs spin/parity
  - Higgs is spin 0
  - What about admixtures?
- Are there more Higgs particles?
  - LHC will typically probe 1 TeV scale

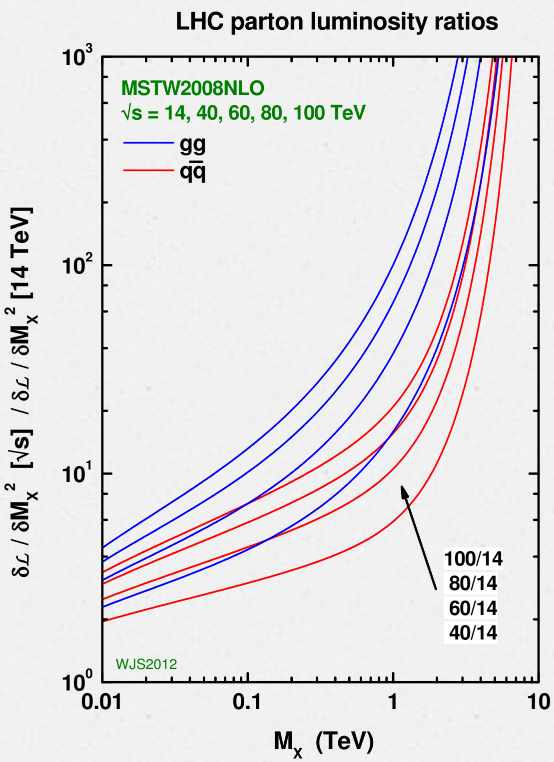
100 TeV makes a lot of SM Higgs

- Large cross sections at high energy pp
- Improvements in statistically limited measurements

	√S=14 TeV	√S=33 TeV	√S=100 TeV
ggF	50.4 pb	178 pb	740 pb
VBF	4.4 pb	17 pb	82 pb
WH	1.6 pb	4.7 pb	16 pb
ttH	.62 pb	4.6 pb	38 pb
HH	.034 pb	.2 pb	1 pb

[Higgs cross section working group]

PDFs



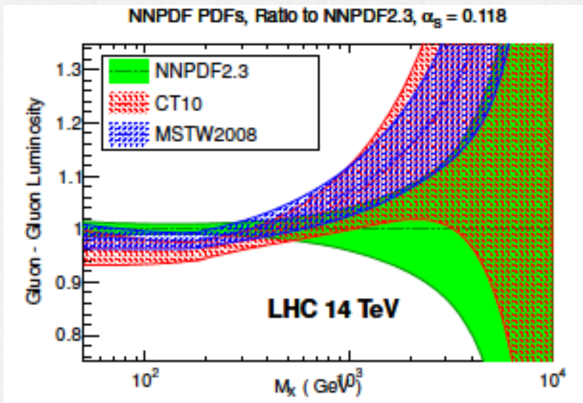
- Factor of 10 increase in luminosity for 100 GeV objects from gluon fusion at 100 TeV
- Factor of 100 increase in luminosity for 1 TeV objects from gluon fusion

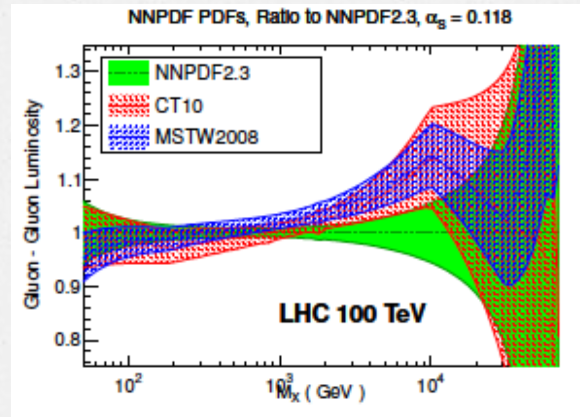
Large extrapolation of PDFs from current knowledge

[Stirling]

More PDFs

gg:





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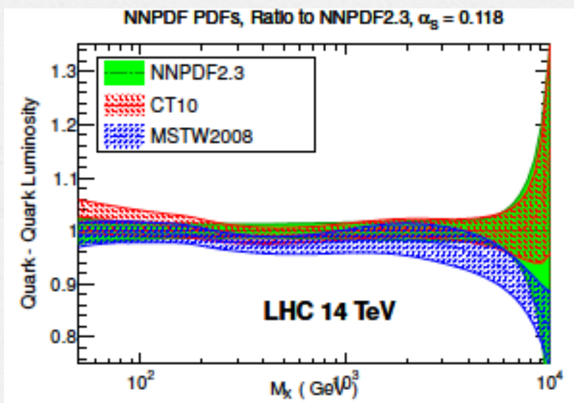
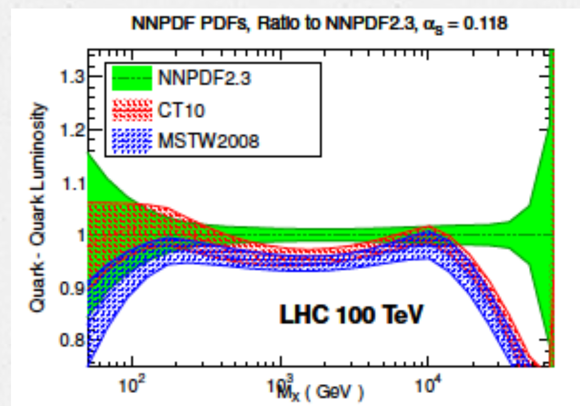


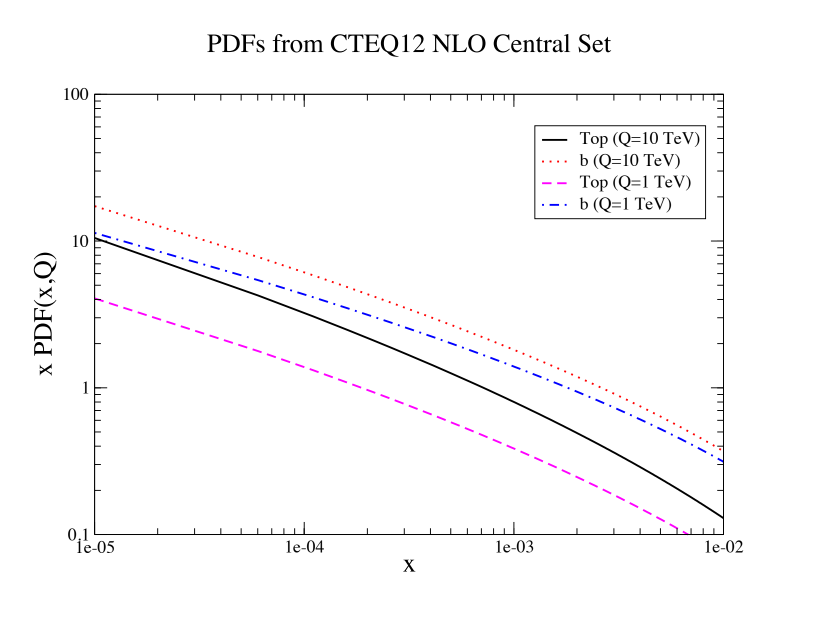


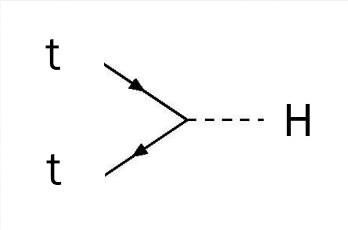
[Snowmass QCD, 1310.5189]

Is the top a parton?

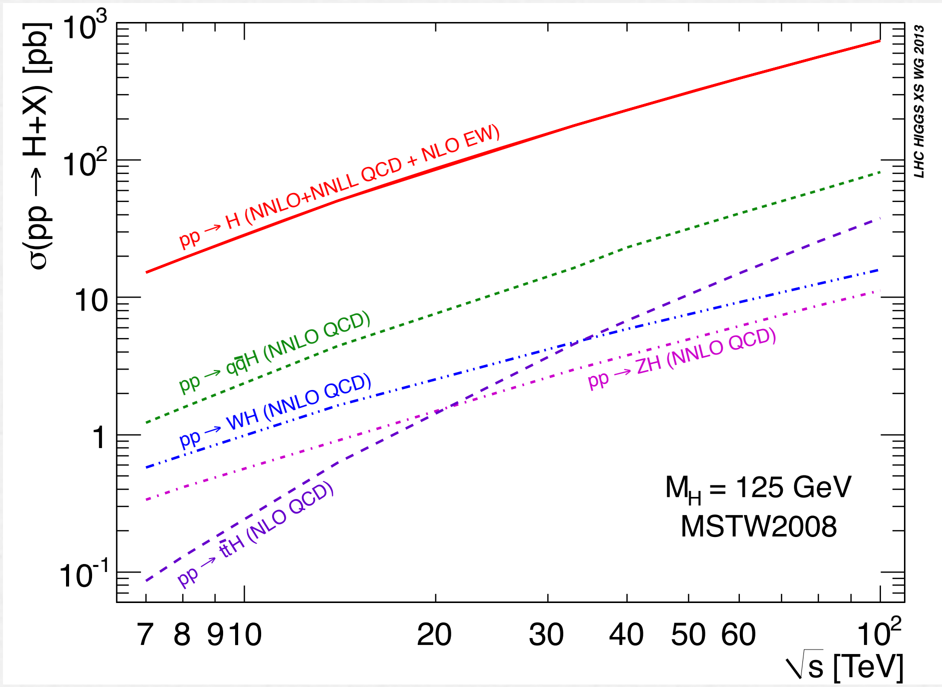
- Yes, but does it matter?

Gluon splitting to top quark pairs: $t(x,Q) \sim \frac{\alpha_s(Q)}{2\pi} \ln\left(\frac{Q^2}{m_t^2}\right) \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y,Q)$





Dominant process is gg→H

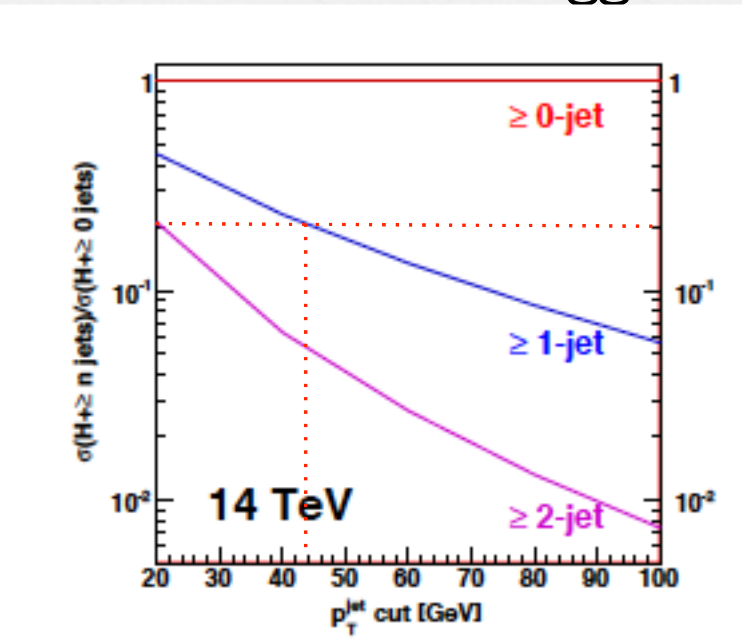


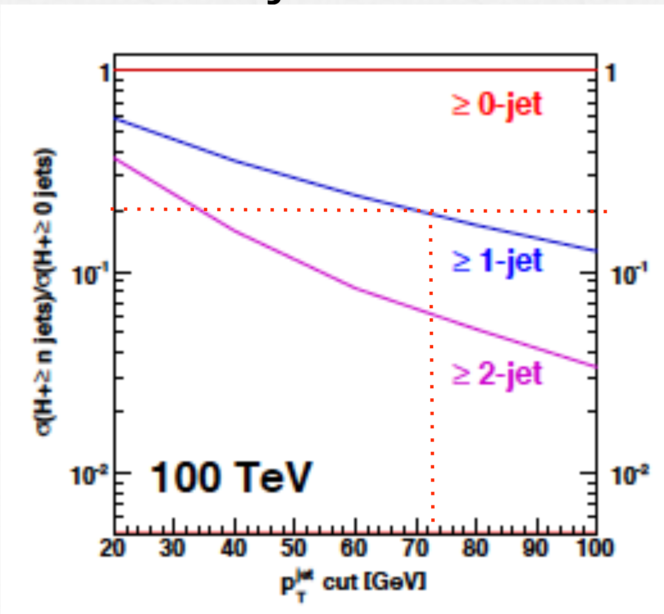
- Note rapid growth of ttH with √s
- For this process, highest possible energy is best

[Higgs cross section working group]

Gluon Fusion

- Fraction of Higgs events with > n jets

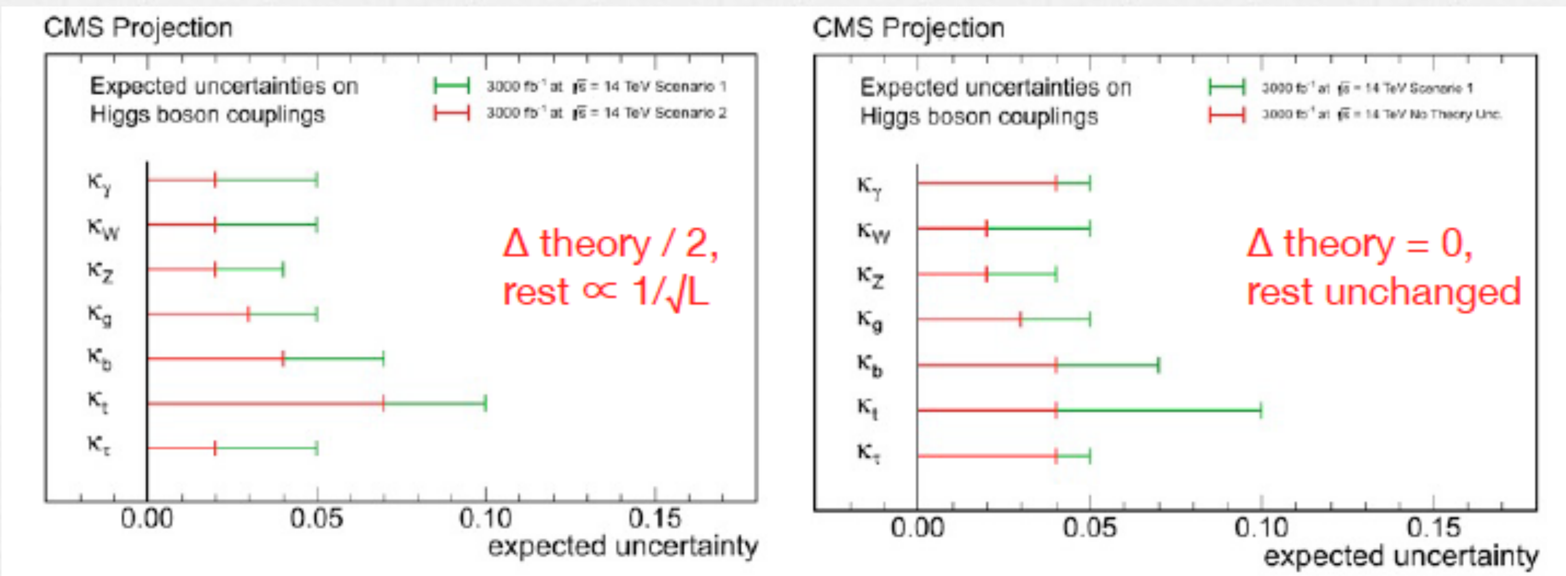




[Snowmass QCD]

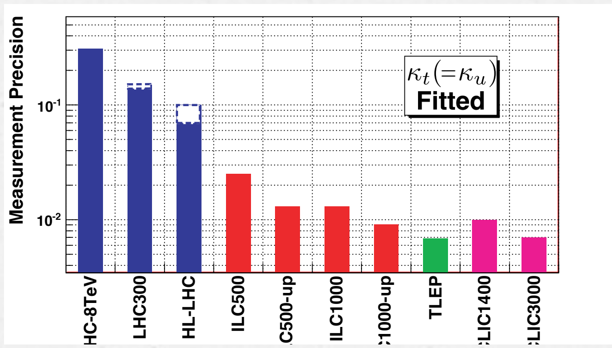
Needs Theory Improvements

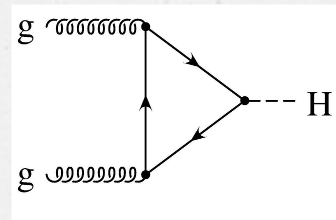
- Statistical improvements in Higgs measurements at 100 TeV need improved theory understanding
- At HL-LHC, improvements limited by theory

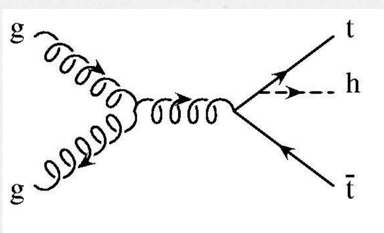


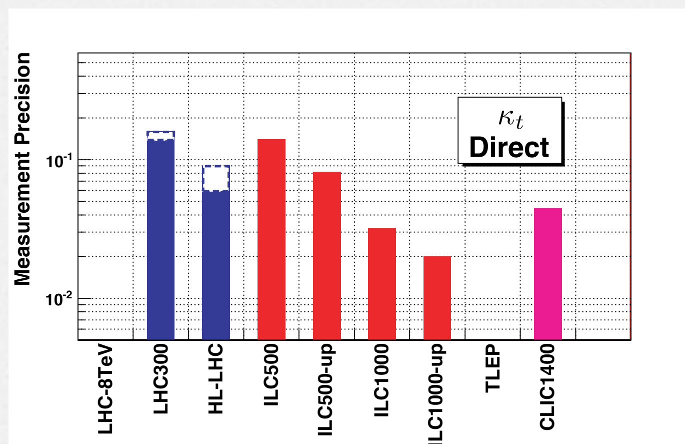
[Klute, Snowmass]

Top Yukawa Particularly Interesting









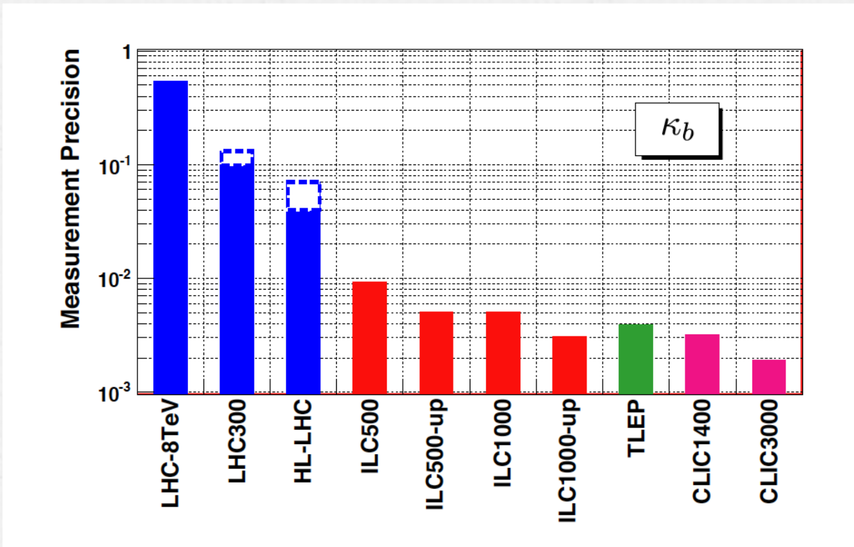
gg→ttH

- Because it has gg initial state, this process wants highest possible energy
- Measure non-SM top interactions directly
  - Example: dipole interaction

$$\bar{t}_L H \sigma^{\mu\nu} t_R t^a \cdot G^a_{\mu\nu}$$

  - Limited by ggH production rate, but can affect distributions

Understanding Higgs Couplings



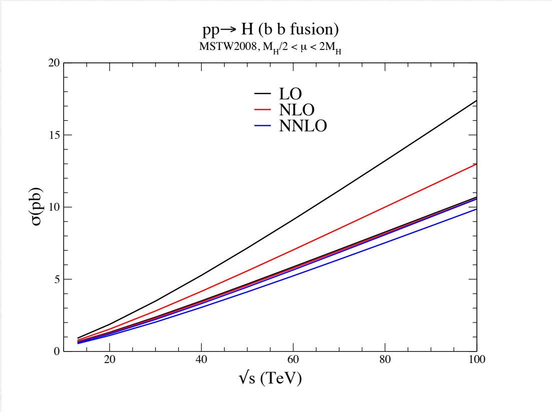
Tree level mixing:

$$\delta\kappa \sim \frac{v^2}{\Lambda^2}$$

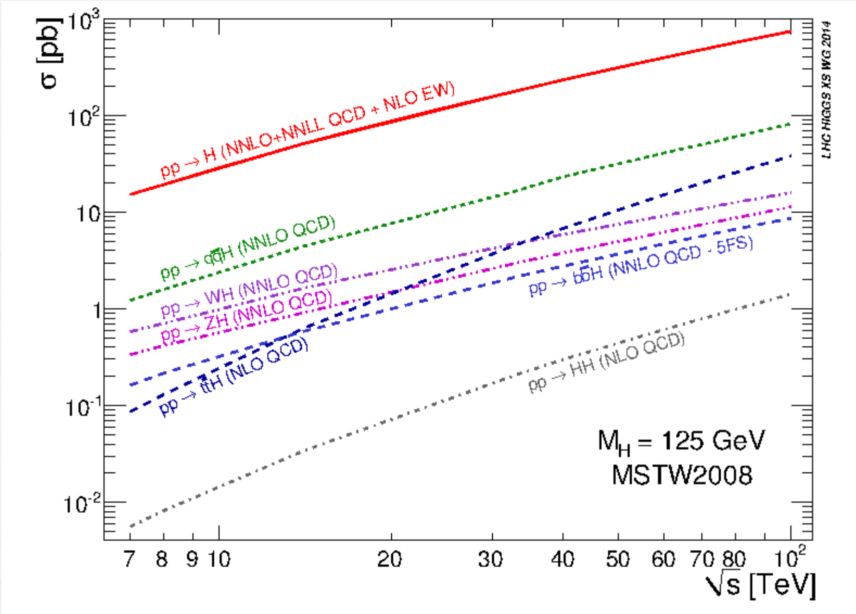
$$HL-LHC, \delta\kappa_b \sim 4-7\% \longrightarrow \Lambda \sim .9-1.2\ TeV$$

Theory uncertainty on BR(H→bb) is ~±3%

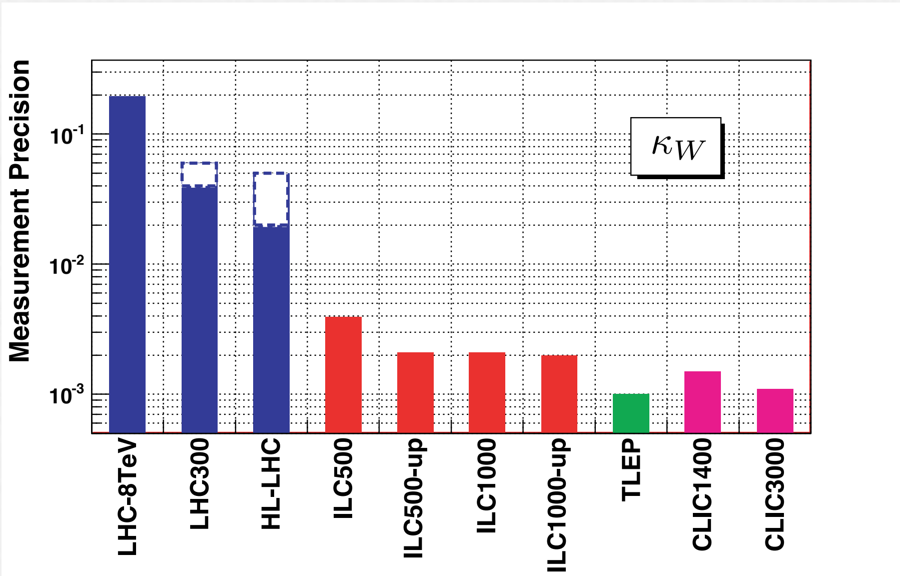
bbH



SM bbH is significant at 100 TeV



Couplings to Gauge Bosons

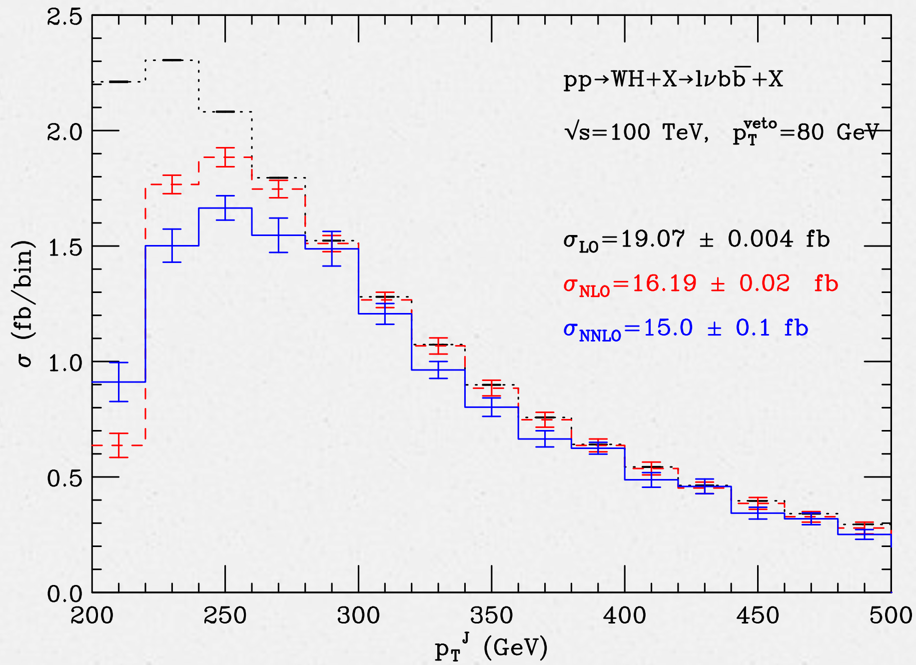


$$HL-LHC, \delta\kappa_W \sim 2-5\% \longrightarrow \Lambda \sim 1.1-1.7\ TeV$$

$$500\ GeV ILC, \delta\kappa_W \sim 1.2\% \longrightarrow \Lambda \sim 2.2\ TeV$$

Large rates

- Large samples at high p_T

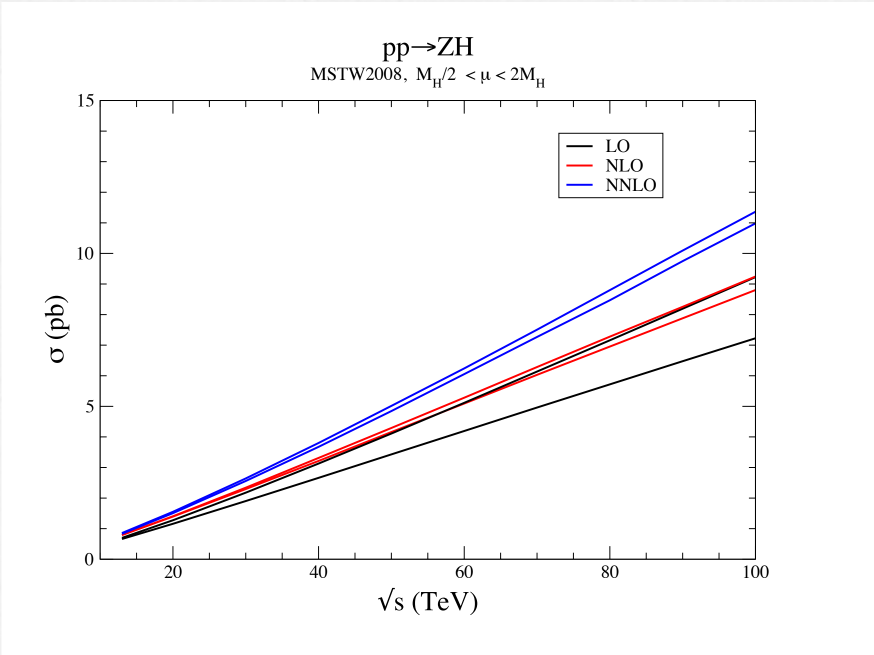


Can we look for new physics in tails of distributions?

[QCD Snowmass Report, arXiv:1310.5189]

ZH production

- Sensitive to ZZH Coupling



VH@NNLO "out of box"

Each curve uses appropriate PDF order

* In agreement with Higgs X-section working group

What about 2nd Generation?

- Are Higgs couplings to c,s,μ the same as t,b,τ?
- 3000 fb^{-1} at 14 TeV:
  - ATLAS: 7σ observation; 10% measurement of H$\mu\mu$ coupling
  - CMS: ~8% measurement of H$\mu\mu$ coupling

We need to do better!

Role of 100 TeV is to find Heavy New Particles

- Many extensions of SM have new Higgs particles
  - Higgs singlets
  - Multi-Higgs doublet models
  - MSSM
- Higgs particles are different because of connection to EWSB
  - Possibilities severely constrained

I consider only weakly interacting Higgs particles

Example: Additional Higgs Singlet

- Models to explain dark matter, flavor often have Higgs singlet
    - Simple example: SM Higgs mixed with electroweak singlet, S

$$V = \lambda_m \mid \Phi \mid^2 S^2 + \frac{\lambda_{SM}}{2} \mid \Phi \mid^4 + \frac{\lambda_S}{2} S^4$$

$$h = \cos\theta \phi_0 + \sin\theta S$$

$$H = -\sin\theta \phi_0 + \cos\theta S$$

- Universal rescaling of Higgs couplings, $\kappa_F = \kappa_V = \cos\theta$

Higgs Singlet

- Small mixing, $\theta \sim -\frac{\lambda_m}{\lambda_S}\left(\frac{v_{SM}}{v_S}\right)$
- Current limit, $\theta \sim .4$
- Mass eigenstates for small mixing:

$$M_h^2 = \lambda_{SM} v_{SM}^2 - M_H^2 \sin^2\theta$$
$$M_H^2 = \lambda_s v_s^2 + M_H^2 \sin^2\theta$$

$$M_H < \sqrt{2}\frac{M_h}{\sin\theta}$$

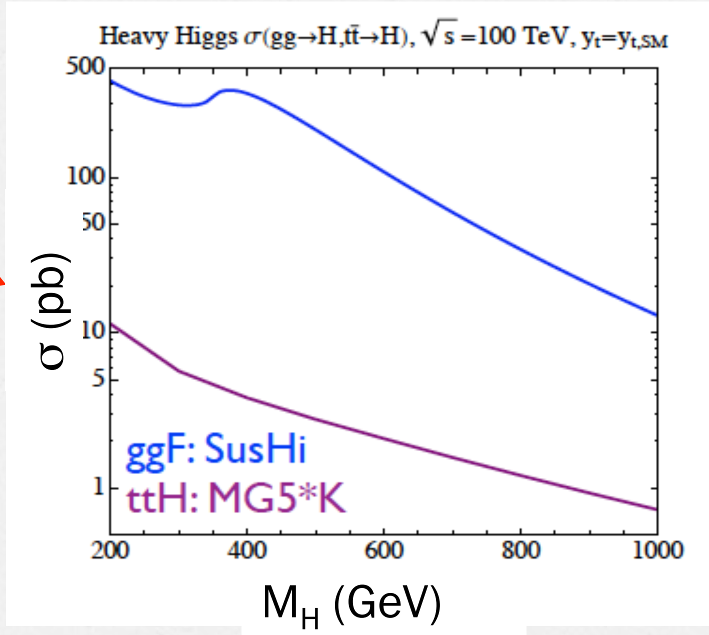
As coupling measurements at HL-LHC achieve % level, limit on M_H is O(1-2) TeV

Higgs Singlet

- Heavy state has small production rate

$$\Gamma_H \sim 500\ GeV \sin^2\theta \left(\frac{M_H}{1\ TeV}\right)^3$$

Multiply by $\sin^2\theta$



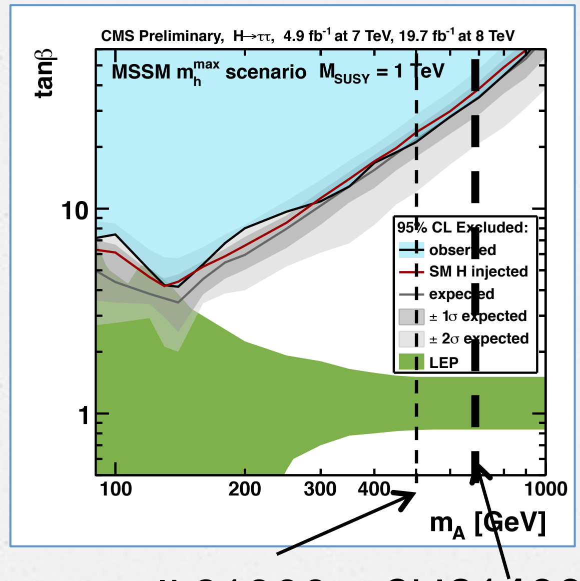
Unitarity violated at:

$$M_H \sim 43\ TeV \left(\frac{\sin\theta}{.02}\right)^2$$

[N. Craig, CERN 100 TeV BSM workshop]

Extended Higgs Sectors

- MSSM (motivated by naturalness arguments) has 5 Higgs particles
- $e^+e^- \rightarrow AH$ gets to roughly kinematic limit with few assumptions

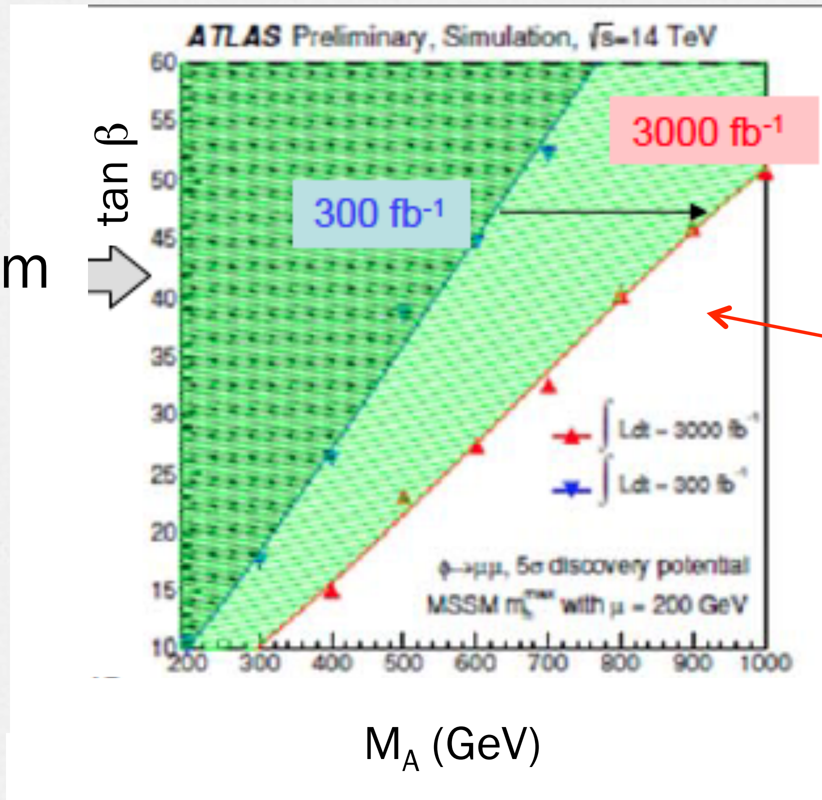


ILC1000 CLIC1400

How far out can 100 TeV machine push wedge?

Excluding Wedge

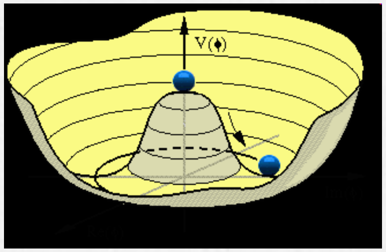
ATLAS: 5σ discovery from H/A➔ μμ



The 100 TeV region

Is the SM Potential Complete?

$$V = \frac{M_H^{\;2}}{2} H^2 + \frac{M_H^{\;2}}{2v} H^3 + \frac{M_H^{\;2}}{8v^2} H^4$$



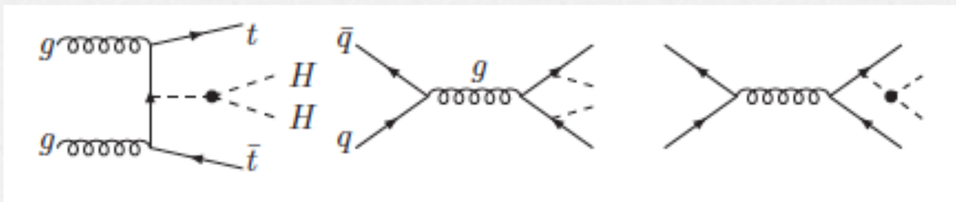
- Need to measure HHH and HHHH couplings
- HHH coupling can be measured with HH production

At 33 TeV, σ (gg→ HHH)~.3 fb
200 TeV, σ(gg→ HHH)~ 8 fb

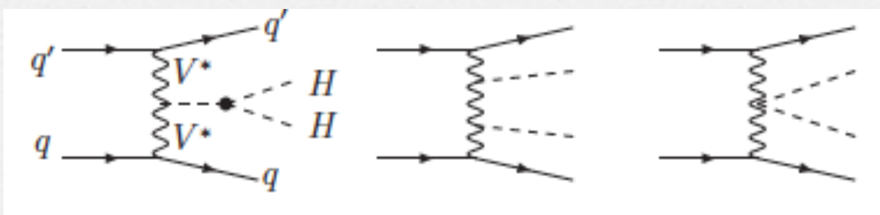
*Models are restricted by requiring single H production to have experimentally measured value

Production of HH

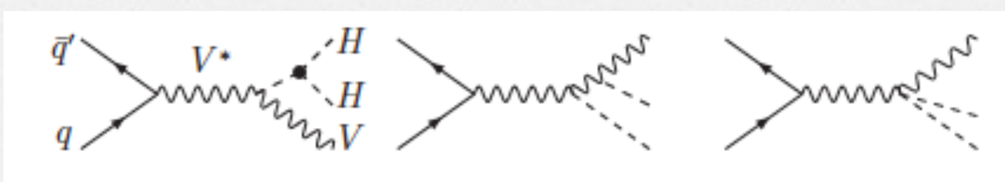
Sensitive to heavy colored particles (eg stops or top partners)



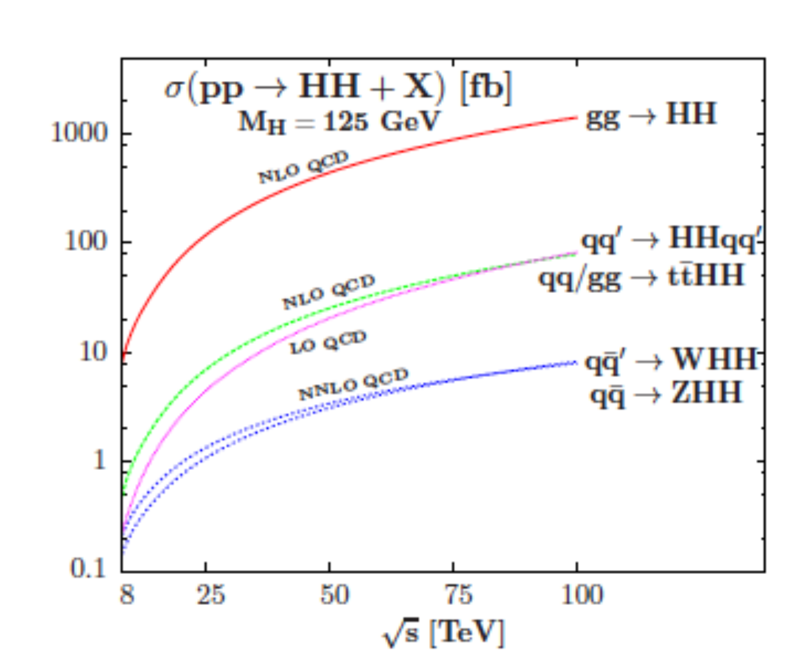
Sensitive to anomalous top-Higgs couplings



Sensitive to anomalous VVHH couplings



Small Rates



- gg rate increases by a factor of ~40 when going from 14 TeV to 100 TeV
- Gluon fusion is always the largest production channel

K factor ~ 2 for gg➔ HH

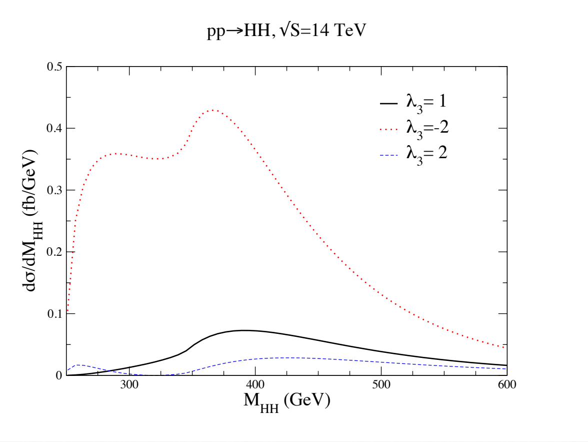
[Baglio et al, arXiv:1215.5581]

gg→HH

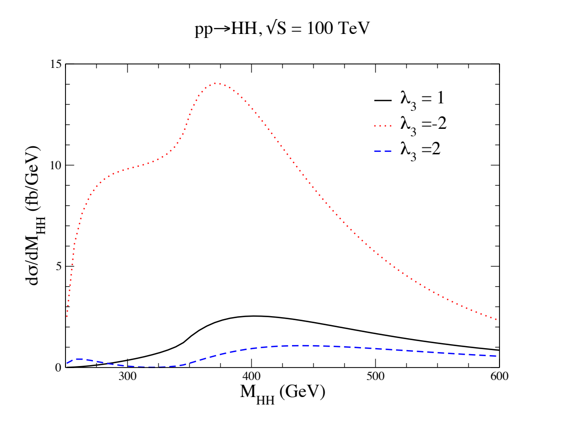
- Sensitive to HHH coupling and new particles in loops
  - Cancellation between box and triangle reduces sensitivity
- Small rates at LHC:
  - $bb\gamma\gamma$ gives 3σ with 3 ab^{-1} (270 events with 3 ab^{-1})
  - 30% measurement of λ_{HHH} with 2 experiments for SM
  - 8% with 100 TeV pp

[Guesstimate from Snowmass Higgs Report, arXiv:1310.8361; Yao, Snowmass study, arXiv: 1308.6302]

Double Higgs Production



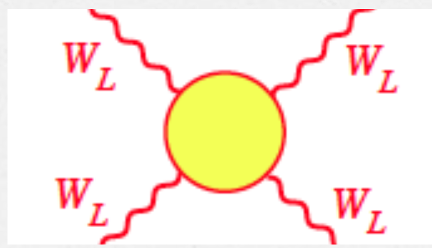
Can we find models with large enhancements of HH production which are not excluded by H production?



Distributions sensitive to sign(λ_3)

If no new particles at LHC

- Effective Lagrangians used to describe physics
  - Construct interactions which respect SU(2) x U(1) symmetry
  - Expand in powers of s/Λ^2: $L_{SM}+\Sigma f_i O_i/\Lambda^2+ \ldots$
- Effects grow with energy
- Precision measurements of VBF at high energy



[Electroweak Snowmass Report, arXiv: 1310.6708]

Toy Model

- Assume no new physics at the LHC at TeV scales
- Effective Lagrangian parameterizes high scale Higgs physics

$$V = \mu_0^2 \mid \Phi^\dagger \Phi \mid + \lambda_0 (\mid \Phi^\dagger \Phi \mid)^2 - \frac{f}{3\Lambda^2} (\mid \Phi^\dagger \Phi \mid)^3$$

- Only 1 new parameter, take it to be

$$\delta\kappa_W = \frac{f v^2}{2\Lambda^2}(1-\zeta) \sim .8 \left(\frac{1\ TeV}{\Lambda}\right)^2 \qquad \zeta = \frac{2v^2}{M_H^2} \sim 7.7$$

- All other coupling deviations predicted in terms of $\delta\kappa_W$

Toy Model Continued

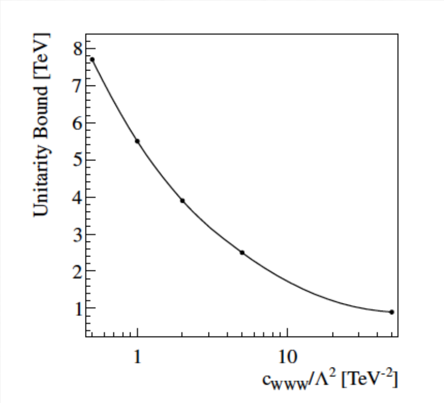
- HHH: $$\lambda_{HHH} = \frac{3M_H^2}{v}\Big(1+\delta_{HHH}\Big)$$
$$\delta_{HHH} = \left(1+\frac{2\zeta}{3(\zeta-1)}\right)\delta\kappa_W$$
- HHH and HHHH couplings are NOT free parameters

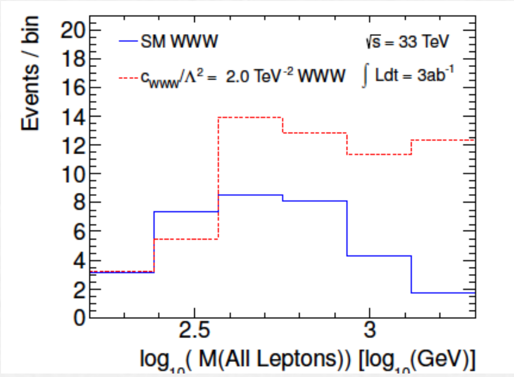
Test Case

- Consider dimension-4 operator:

$$L \sim \frac{c_{WWW}}{\Lambda^2} Tr\left(W_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho}\right)$$

- Look for all leptonic WWW final state
- Unitarity will be violated for large M_{WWW}



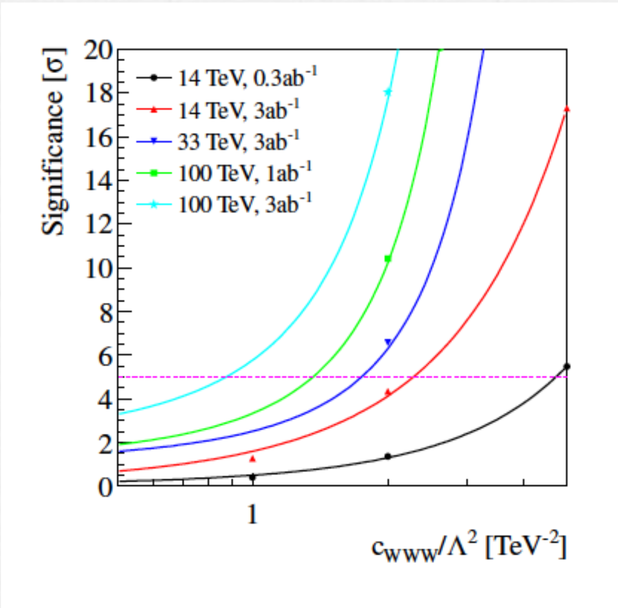


[Snowmass, hep-ph/1309.7453]

Bounds at High Energy

- 5σ discovery; #'s in () impose unitarity

Parameter	dim.	Luminosity [fb^{-1}]	14 TeV	33 TeV	100 TeV
c_{WWW}/Λ^2 [TeV^{-2}]	6	300	4.8 (8)	-	-
		1000	-	-	1.3 (1.5)
		3000	2.3 (2.5)	1.7 (2.0)	0.9 (1.0)



100 TeV ➔Λ~2.2 TeV

Conclusions

- The role of 100 TeV and Higgs physics
  - TeV scale weakly interacting Higgs scenarios largely explored at LHC
  - Unexplored corners for Higgs decays very restricted
  - In order to use large sample of SM Higgs bosons at 100 TeV machine, need improvement in theory
- PDFS!
  - Can we trust PDF extrapolations?
  - Data from LHC will improve PDFs