ISSUES IN HIGGS PHYSICS LECTURE 2

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Hadron Collider Summer School, August, 2018

Please send questions or corrections to dawson@bnl.gov

SM SATISFIES PERTURBATIVE UNITARITY

- Consider $2 \to 2$ particle elastic scattering

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|A|^2$$

- Partial wave decomposition of amplitude

$$A = 16\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) a_l$$

- a_l are the spin *l* partial waves

UNITARITY

- $P_l(\cos\theta)$ are Legendre polynomials:

$$\int_{-1}^{1} dx P_l(x) P_{l'}(x) = \frac{2\delta_{l,l'}}{2l+1}$$

$$\sigma = \frac{8\pi}{s} \sum_{l=0}^{\infty} (2l+1) \sum_{l'=0}^{\infty} (2l'+1) a_l a_{l'}^* \int_{-1}^{1} d\cos\theta P_l(\cos\theta) P_{l'}(\cos\theta)$$

$$= \frac{16\pi}{s} \sum_{l=0}^{\infty} (2l+1) |a_l|^2$$

Sum of positive definite terms

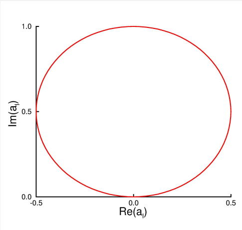
MORE ON UNITARITY

- Optical theorem $$\sigma = \frac{1}{s}\mathrm{Im}\left[A(\theta=0)\right] = \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)\left|a_l\right|^2$$

$$\mathrm{Im}(a_l) = \left|a_l\right|^2$$

Optical theorem derived assuming only conservation of probability

- Unitarity requirement:

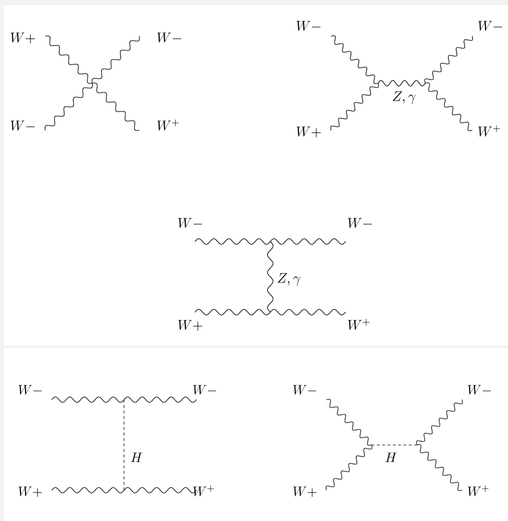


$$\left|\mathrm{Re}(a_l)\right| \le \frac{1}{2}$$

True for any 2→2 scattering amplitude

Unitarity is major restriction on any model of new physics

SM IS SPECIAL AT HIGH ENERGY



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

E^4 terms cancel between TGC and QGC

Terms which grow with energy cancel for E >> M_h

SM particles have just the right couplings so amplitudes don't grow with energy

EXPLORING THE HIGGS SECTOR

HIGGS PRODUCTION AT A HADRON COLLIDER

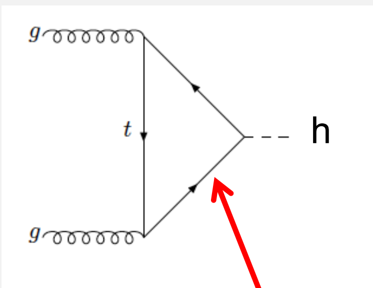
Most important processes:

$$gg \to h$$

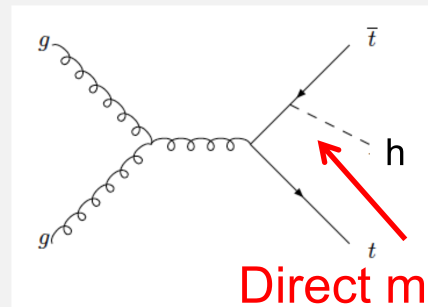
$$q\bar{q} \to q\bar{q}h$$

$$q\bar{q} \to q\bar{q}h$$

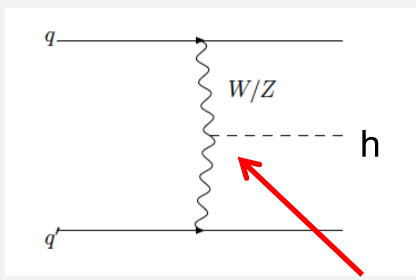
$$q\bar{q}, gg \to t\bar{t}h$$

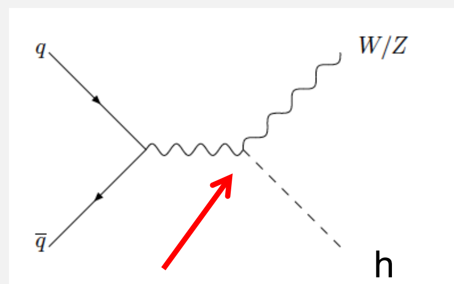


Depends on new physics in loop



Direct measurement of tth Yukawa

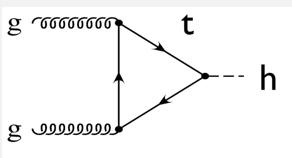




Vanishes if v=0: Fundamental test of EWSB mechanism

HOW DO WE MAKE A HIGGS BOSON?

- Largest production rate is from gluon fusion
- Largest contribution in SM is from top quarks
- Not a direct measurement of tth coupling since there could be new particles in loop



$$A(gg \to h) = -\frac{\alpha_s}{\pi v}\delta_{AB}\left(g^{\mu\nu}\frac{M_h^2}{2} - p^\nu q^\mu\right)\int dxdy\left(\frac{1-4xy}{1-M_h^2 xy/m_t^2}\right)$$

$$L \to -\frac{\alpha_s}{12\pi v} h G^A_{\mu\nu} G^{\mu\nu,A}$$

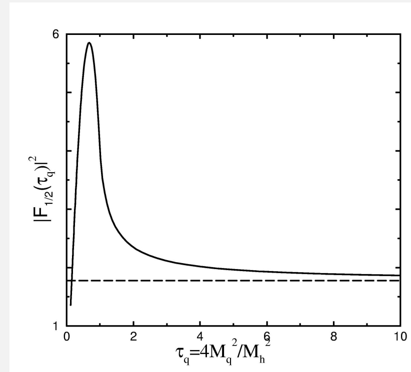
- Independent of m_t for $m_t >> M_h$: Form useful for radiative corrections

No decoupling of heavy top since coupling proportional to mass

GLUON FUSION

$$\sigma(gg \to h)(s) = \frac{\alpha_s^2}{1024\pi v^2} \mid \Sigma_q F_{1/2}(\tau_q) \mid^2 \delta\left(1 - \frac{M_h^2}{s}\right)$$

- Lowest order cross section:
  - $\tau_q = 4m_q^2/M_h^2$
  - Light Quarks: $F_{1/2} \to (m_b/M_h)^2 \log^2(m_b/M_h)$
  - Heavy Quarks: $F_{1/2} \to -4/3$



- Rapid approach to heavy quark limit: Counts number of heavy fermions

Heavy quarks don't decouple

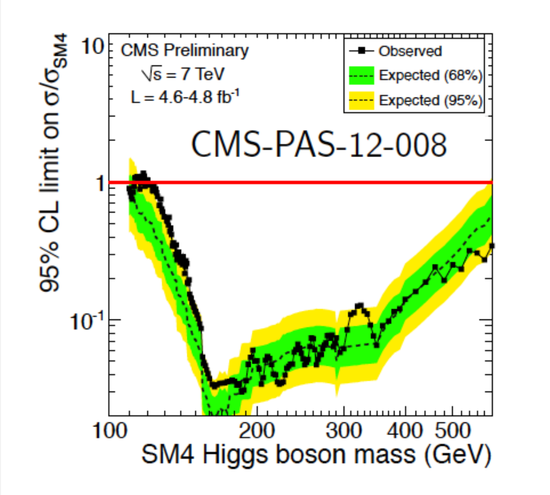
WHAT IF THERE WERE A SM 4TH GENERATION?

- Each fermion would contribute the same to gg→ h: t, T, B (in heavy fermion limit)

$$\sigma \to \sigma_{SM}(1+1+1)^2 \to 9\sigma_{SM}$$

Important: Contribution from chiral fermions roughly independent of fermion mass

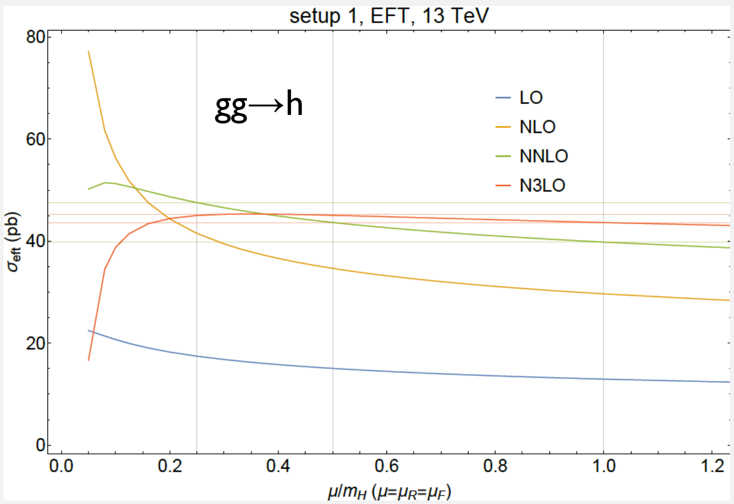
SM 4th generation is ruled out by Higgs observation!



* This logic doesn't hold for vector-like fermions

TREMENDOUS THEORY EFFORT

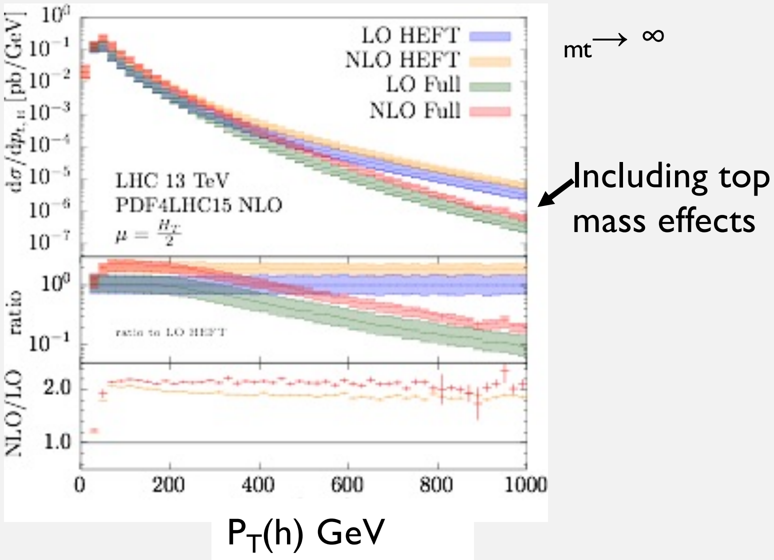
- MANY (!) Higgs processes calculated to NNLO and some further
- Since Higgs couplings are normalized by the SM expectations, theory and experimental precision must go hand in hand
- These higher order corrections are numerically significant



Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger, 1605.05761

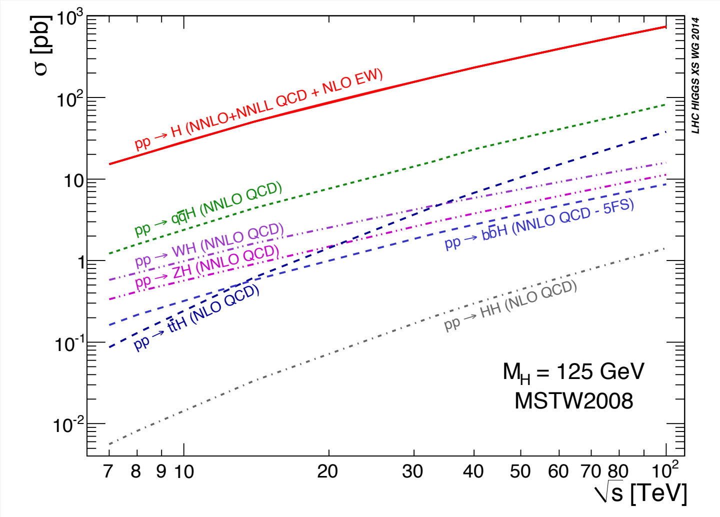
HIGGS PLUS JET PRODUCTION

- At lowest order Higgs has no p_T
- At high p_T, can't calculate using $m_t \to \infty$
- For $p_T > m_t$ top quark loop is resolved



Bagnaschi, Degrassi, Slavich, Vicini, 1111.2854

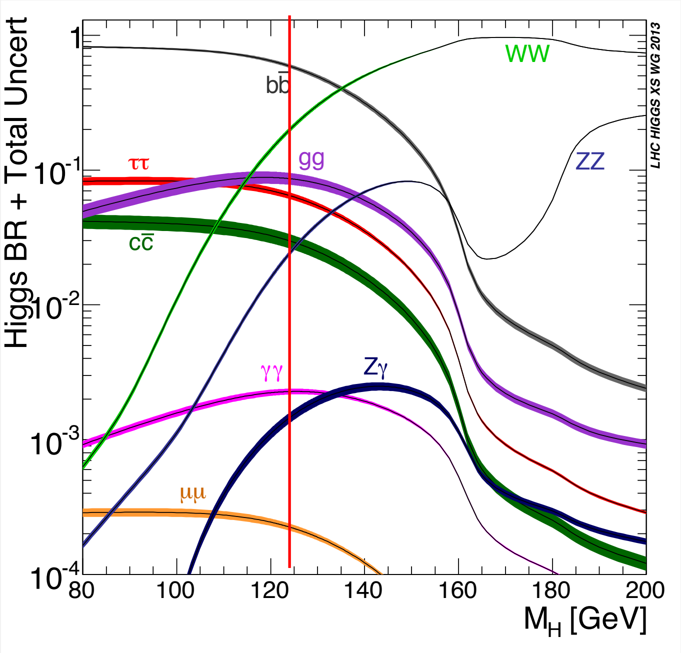
PRECISE PREDICTIONS FOR PRODUCTION AND DECAY



- Rates to NNLO or NLO
- Gluon fusion dominates
- Rates increase with energy
- tth and hh smallest rates

HIGGS DECAYS AND WIDTH

- Γ_{SM}=4 MeV << detector resolution
- Width is sensitive to light "invisible" particles



WHAT ARE THE MISSING PIECES?

- Fermion couplings to b, t, τ
- Gauge boson couplings to W/Z/g/γ
- Higgs is spin 0
- No measurements of hZγ, 2nd generation fermions, h^3, h^4 couplings….
- Higgs h^2 coupling (Mass)

What do we want to learn from future Higgs measurements?

WHAT DO WE LEARN FROM M_h?

- Free parameter in SM

(Run-1 combination)

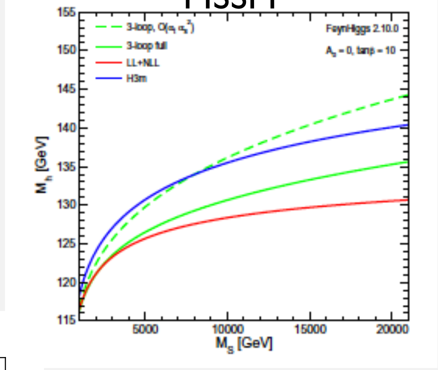
$$M_h = 125.09 \pm .21(stat) \pm .11(sys)\ GeV$$

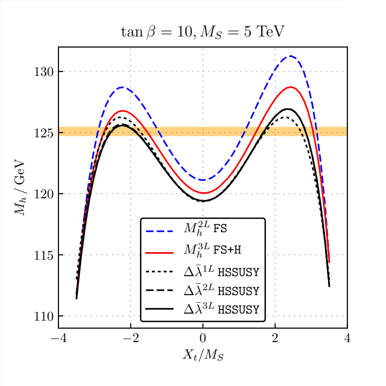
- Higgs self coupling is perturbative:

$$\lambda = \frac{M_h^2}{2v^2} = .13$$

- Consistent with predictions of weak scale MSSM

MSSM





Hahn, Heinemeyer, Hollik, Rzehak, Weiglein, 2016

Harlander, Klappert, Ochoa, Voigt, 1807.03509

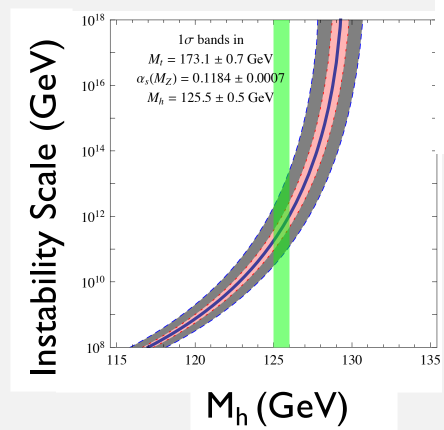
CAN CALCULATE RUNNING OF HIGGS SELF-COUPLING

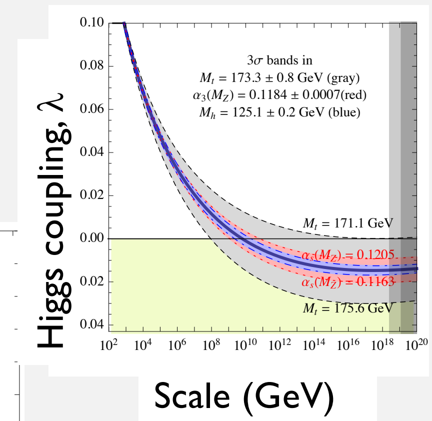
- Renormalization group scaling

$$16\pi^2 \frac{d\lambda}{d\log\mu^2} = 12\lambda^2 + 12\lambda y_t^2 - 12 y_t^4 + \dots.$$

- *Large λ (Heavy Higgs):* self coupling causes λ to grow with scale
- *Small λ (Light Higgs):* coupling to top quark causes λ to become negative

$$y_t = \frac{M_t}{v}$$



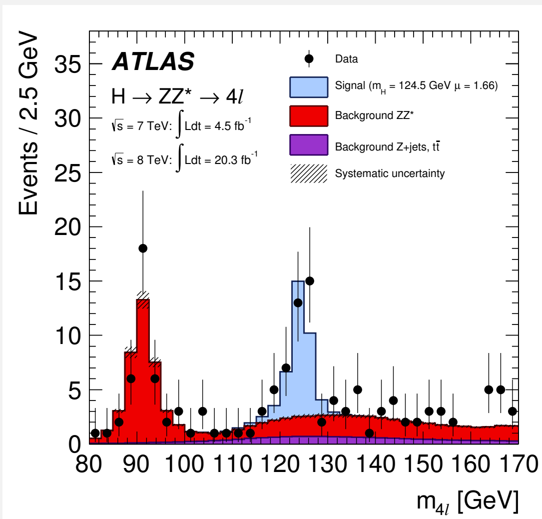


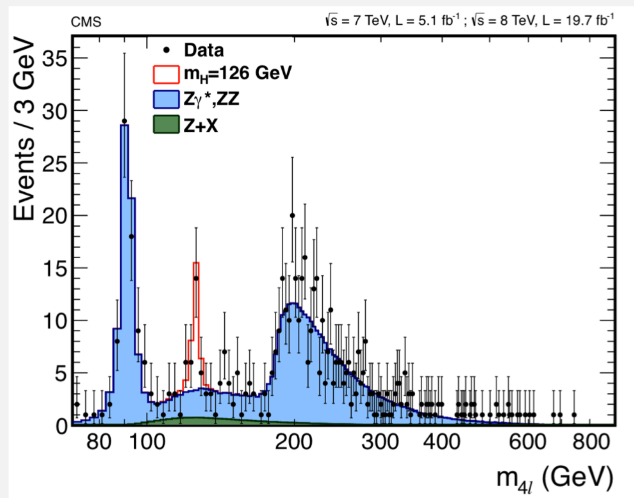
Buttazzo, Degrassi, Giardino, Guidice, Sala, Salvio, Strumia, 13073536

WHAT DOES THE HIGGS WIDTH TELL US?

$gg \rightarrow h \rightarrow ZZ$

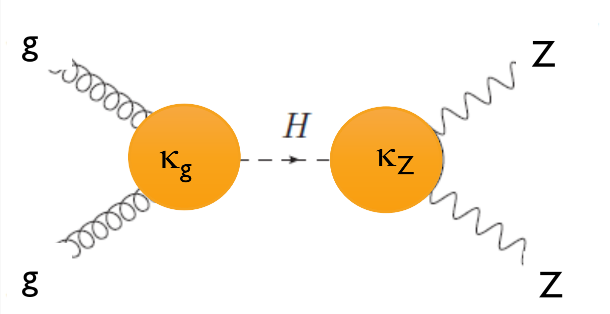
- Goal: Measure $gg \rightarrow h \rightarrow ZZ$ and use insights about resonances





HIGGS RESONANCE

$$\sigma \sim \int ds \frac{\kappa_g^2 \kappa_Z^2}{(s - M_h^2)^2 + M_h^2 \Gamma_h^2} \epsilon_Z^\mu(p) \cdot \epsilon_Z^{\mu *} \epsilon_Z^\nu(q) \cdot \epsilon_Z^{\nu *}(q)$$



Longitudinal Z polarization grows with energy: $\epsilon_L^\mu \sim \frac{p^\mu}{M_Z}$

Consider above pole, s >> M_h^2 $\sigma_{above} \sim \frac{\kappa_g^2 \kappa_Z^2}{M_h^2}$

No dependence on width

HIGGS RESONANCE

$$\sigma \sim \int ds \frac{\kappa_g^2 \kappa_Z^2}{(s - M_h^2)^2 + M_h^2 \Gamma_h^2} \epsilon_Z^{\mu}(p) \cdot \epsilon_Z^{\mu *} \epsilon_Z^{\nu}(q) \cdot \epsilon_Z^{\nu *}(q)$$

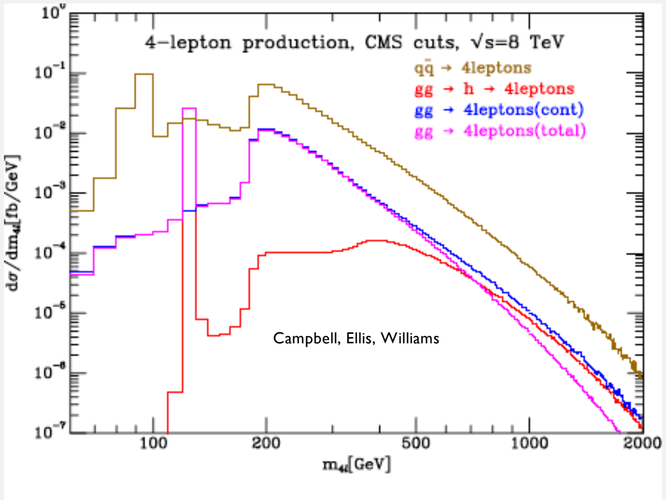
$$\int ds \frac{1}{(s - M_h^2)^2 + M_h^2 \Gamma_h^2} \to \frac{\pi}{\Gamma_h M_h} \delta(s - M_h^2)$$

On peak: $\sigma_{res} \sim \frac{\kappa_g^2 \kappa_Z^2}{\Gamma_h M_h}$

Resonance rate sensitive to total Higgs width

IDEA

- Measure above and below the peak:



$$\frac{\sigma_{above}}{\sigma_{res}} \sim \Gamma_h$$

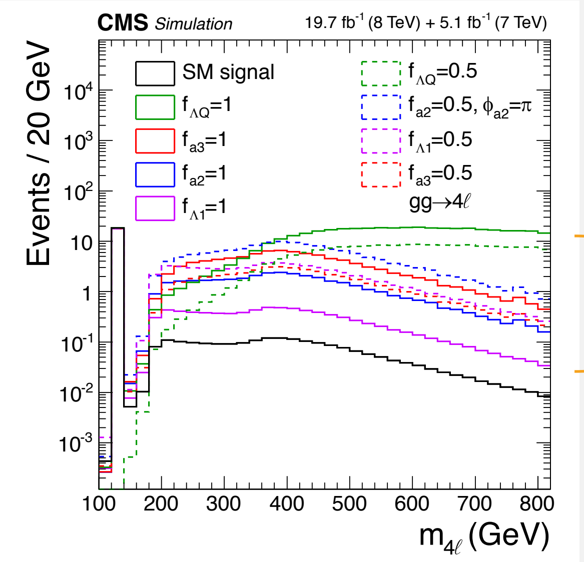
About 15% of total cross section in m_{4l}>140 GeV region above peak

$$ATLAS, CMS, \quad \Gamma_h < (4-5)\Gamma_{SM}$$

Caola, Melnkov; Kauer,Passarino, Campbell, Ellis, Williams

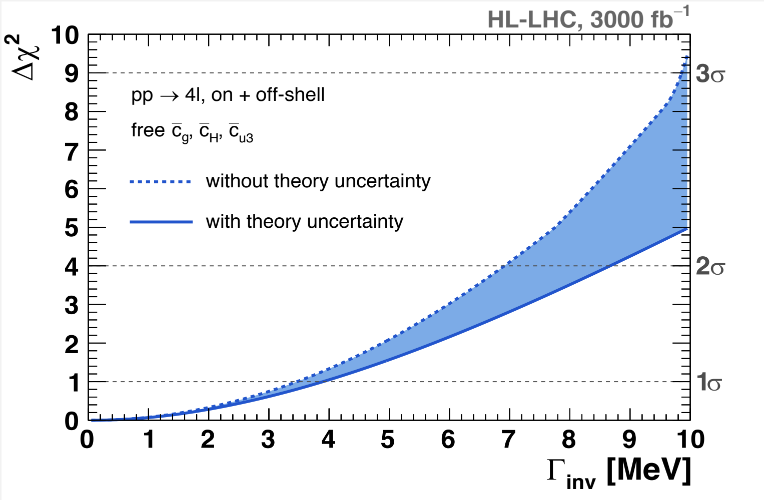
IMPLICIT ASSUMPTIONS IN HIGGS WIDTH EXTRACTION

- Assumes couplings are same on resonance and off resonance
- Assumes SM, ie no new higher dimension operators



Non-SM couplings

INVISIBLE HIGGS WIDTH



Interpret Higgs width limit as limit on invisible width, allowing non-SM couplings to vary

SM invisible width is BR (h→νννν)=10^{-3}

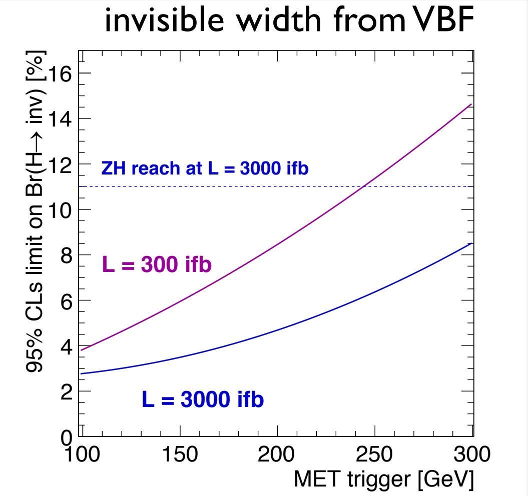
Englert, Kogler, Schulz, Spannowsky, 1708.03332

INVISIBLE WIDTH

- Sources of invisible width:
  - Light scalars, light axions, relaxions…. $h \to \phi_i \phi_i$
  - Neutralinos, fermionic dark matter… $h \to \chi\overline{\chi}$
- Limit comes from boosted Z recoiling against large missing energy

- Experimental limit is primarily from Zh, Z→leptons
- Future limits from VBF
- BR(h→ invisible) < 24%

Future limits on invisible width from VBF



Missing energy trigger in VBF

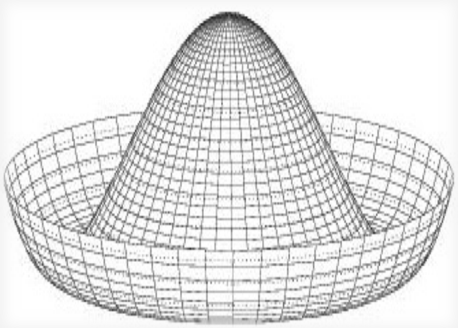
HIGGS SELF-COUPLING BIG MILESTONE

- We don't know that the Higgs comes from the scalar potential

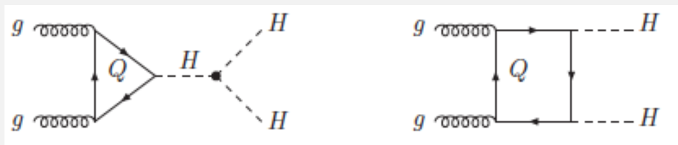
$$V = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$
$$= \frac{M_h^2}{2} h^2 + \lambda_3 h^3 + \lambda_4 h^4$$

- SM is perturbative

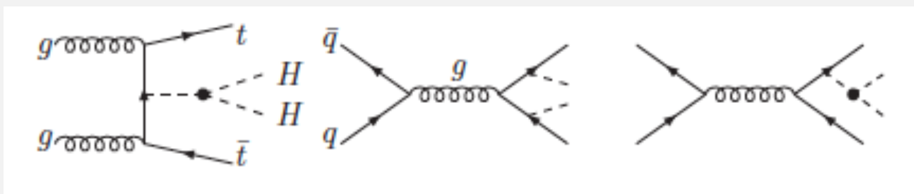
$$\lambda_3 = \frac{M_h^2}{2v} \sim .13v, \qquad \lambda_4 = \frac{M_h^2}{8v^2} = .03$$



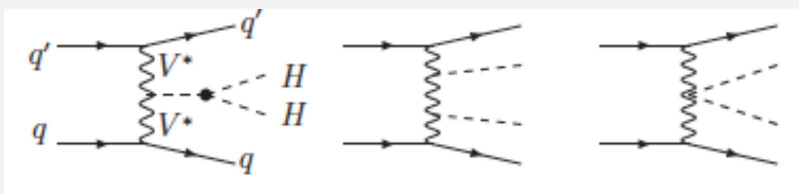
PRODUCTION OF hh



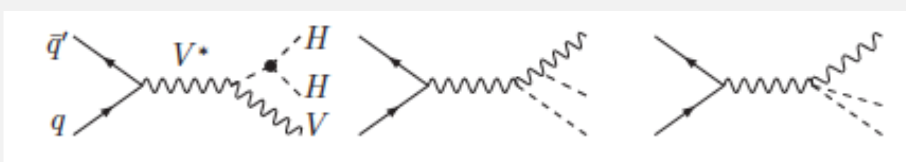
Sensitive to heavy colored particles (eg stops or top partners)



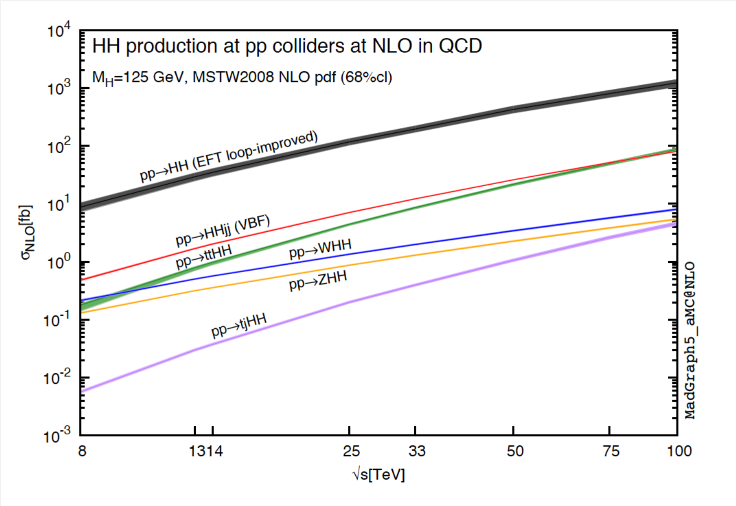
Sensitive to anomalous top-Higgs couplings



Sensitive to anomalous VVhh couplings



SMALL RATES FOR hh PRODUCTION



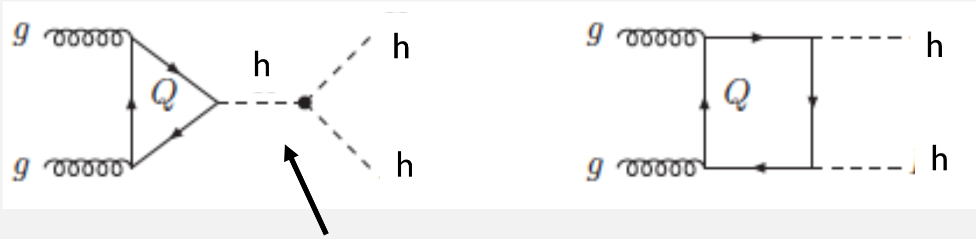
This is 3000 fb^{-1} physics and motivation for 100 TeV Collider!

Frederix et al, arXiv:1401.7440, Baglio et al, arXiv:1215.5581

MEASURING THE hhh COUPLING

- hh first occurs at one-loop

Large cancellation between diagrams



Goal: Measure λ_3

3 ab^{-1}

Theorists: $0.7 < \lambda_3/\lambda_{3,SM} < 7.7$
ATLAS: $0.2 < \lambda_3/\lambda_{3,SM} < 7.$ (bbbb)
ATLAS: $-0.8 < \lambda_3/\lambda_{3,SM} < 7.7$ ($bb\gamma\gamma$)

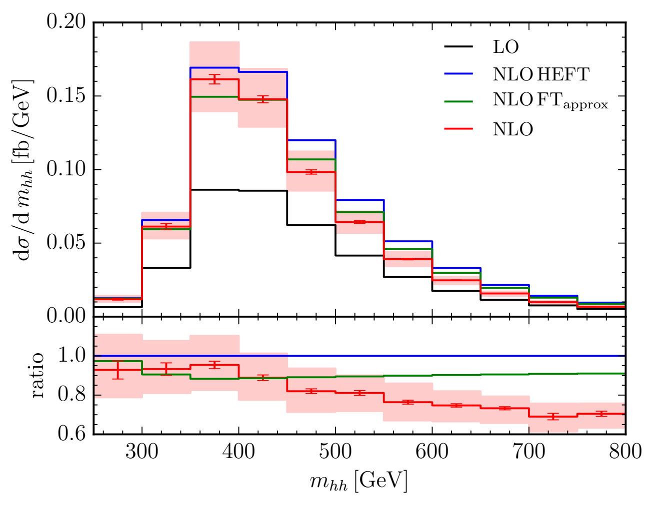
CURRENT

CMS: $\sigma/\sigma_{sm} < 19$ ($bb\gamma\gamma$)
ATLAS: $\sigma/\sigma_{sm} < 13.0$ (bbbb)
CMS: $\sigma/\sigma_{sm} < 28$ ($bb\tau\tau$)

Goncalves, Han, Kling, Plehn, Takeuchi, 1802.04319

PROGRESS IN HH CALCULATIONS

gg→hh @ 14 TeV



Result with full mass dependence 20-30% below HEFT ($m_t \to \infty$) for m_{hh} above 450 GeV

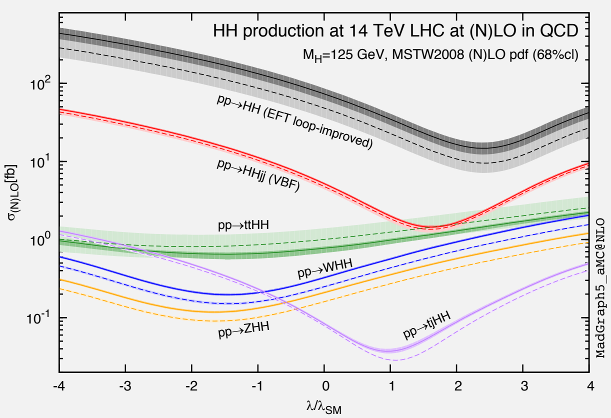
LO and $m_t \to \infty$ not accurate for tails of distributions

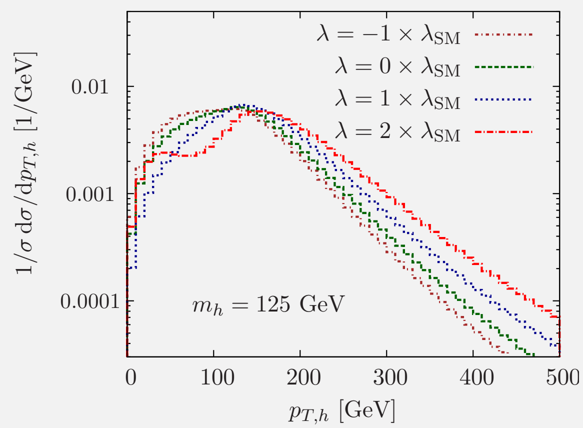
➡ Need higher order corrections

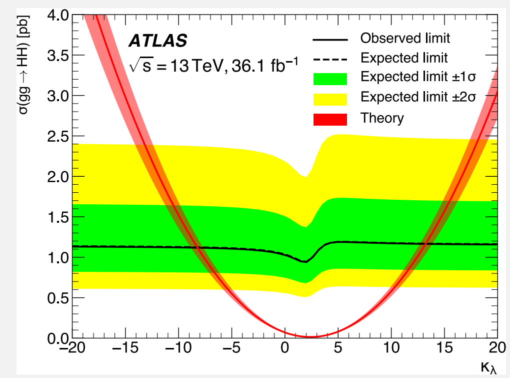
Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke, 1604.06447

MEASURING λ_3

- Corrections to λ_3 are typically $O(v^2/\Lambda^2)$, ie ~5% (for Λ= 1 TeV) (not factors of 2-3)
- Unitarity from hh →hh: $\lambda_3/\lambda_3(SM) < 6.5$





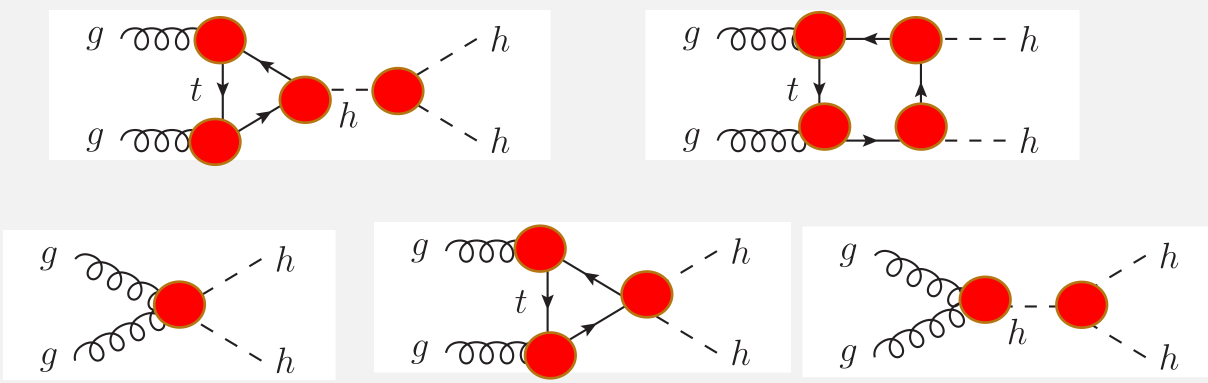


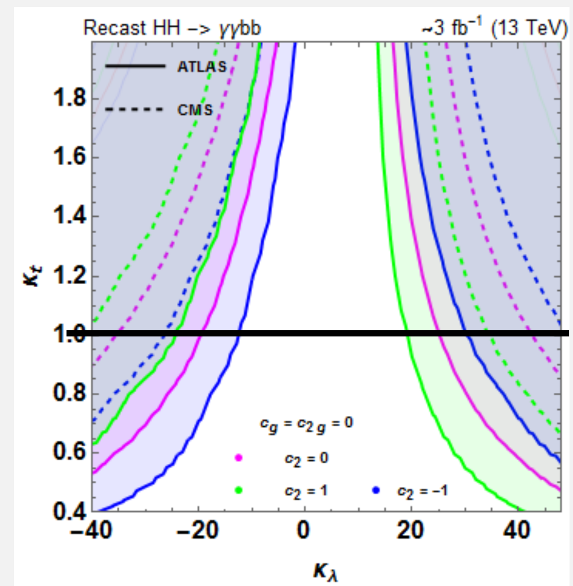
λ_3/λ_3 (SM)=κ_λ

Frederix, 1401.7340; Dolan, Englert, Spannowsky, 1206.5001

BUT SEE EFT SECTION……

- In any realistic model, other interactions than hhh are also changed
- Need global fit: Limits are correlated

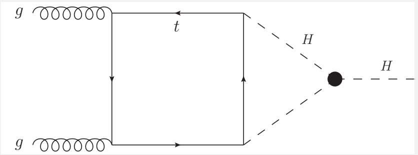


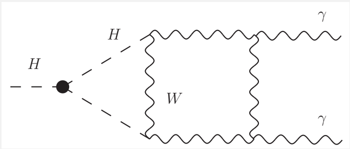


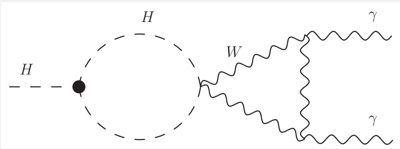
Carvalho, Goertz, Mimasu, Gouzevitch, Aggarwal, 1710.08261; Azatov, Contino, Panico, Son, 1502.00539

MEASURING THE HIGGS SELF COUPLING INDIRECTLY

- Higgs self coupling contributes to $gg \to h$, $h \to \gamma\gamma$, tth production
- Use measured single Higgs rates to limit: $-9.4 < \lambda_3/\lambda_3(SM) < 17$
- Similar order of magnitude as limit from hh production
- Include single Higgs production contribution to λ_3 in global fit
- (We don't yet have all the theory pieces to do this consistently … need full 2 loop electroweak corrections with all possible couplings)







Degrassi, 1607.04251; Gorbahn, Haisch, 1607.03773