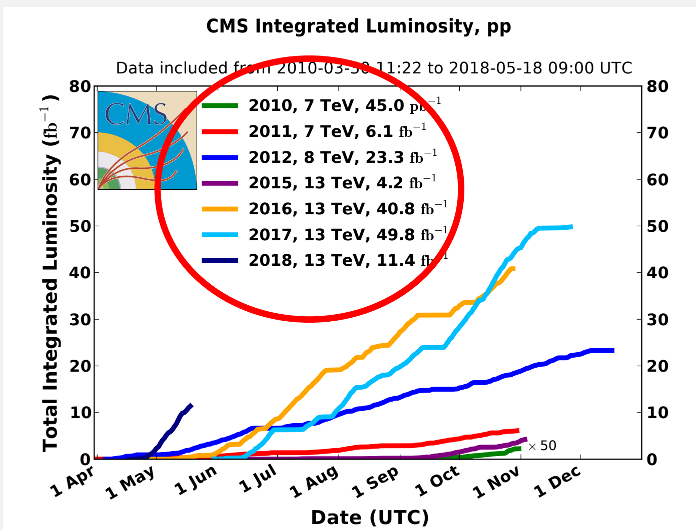
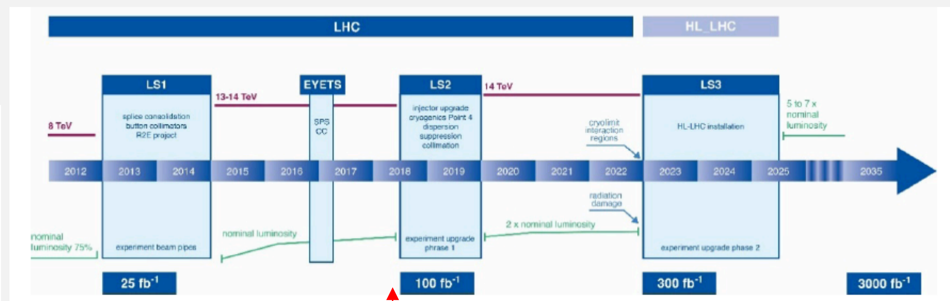
FRONTIERS OF ELECTROWEAK SYMMETRY BREAKING

Sally Dawson, BNL

CIPANP, May 2018

HIGGS PROGRAM IS JUST BEGINNING





We are here

A lot of Higgs physics ahead!

PDG-MAY, 2017

H^0 $J = 0$

Mass $m = 125.09 \pm 0.24$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

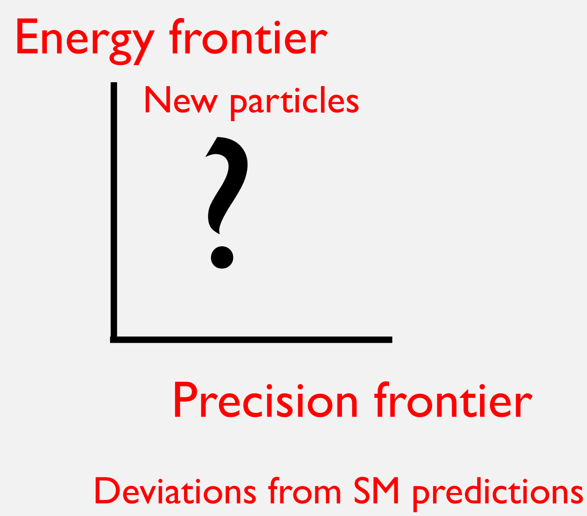
Combined Final States = 1.10 ± 0.11
$WW^* = 1.08^{+0.18}_{-0.16}$
$ZZ^* = 1.29^{+0.26}_{-0.23}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.82 \pm 0.30$ (S = 1.1)
$\mu^+\mu^- = 0.1 \pm 2.5$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 9.5$, CL = 95%
$t\bar{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

Rates normalized to Standard Model predictions

Relatively large uncertainties

GOALS OF HIGGS PROGRAM

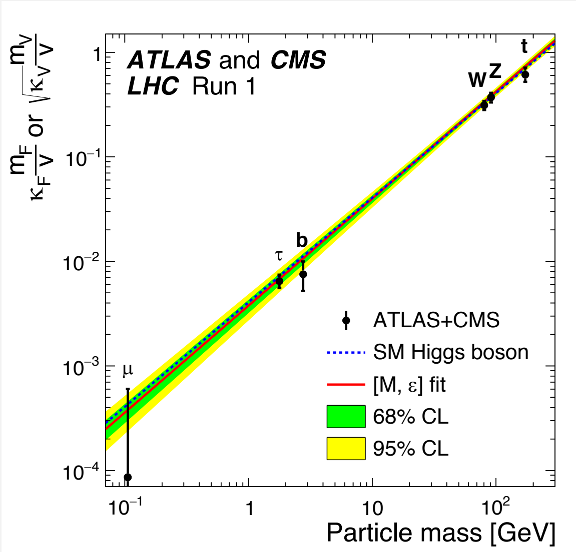
- Is it the Standard Model with nothing else?
  - Are there more Higgs particles?
- Are we closing in on new physics?
  - Can we predict the mass scale?
- Precision vs energy as tools
  - Deviations from SM often grow with energy



EVERY THING PREDICTED IN SM*

- Very precise predictions
  - Couplings to fermions proportional to mass
  - Couplings to gauge bosons proportional to mass
  - Higgs self-couplings proportional to M_H^2

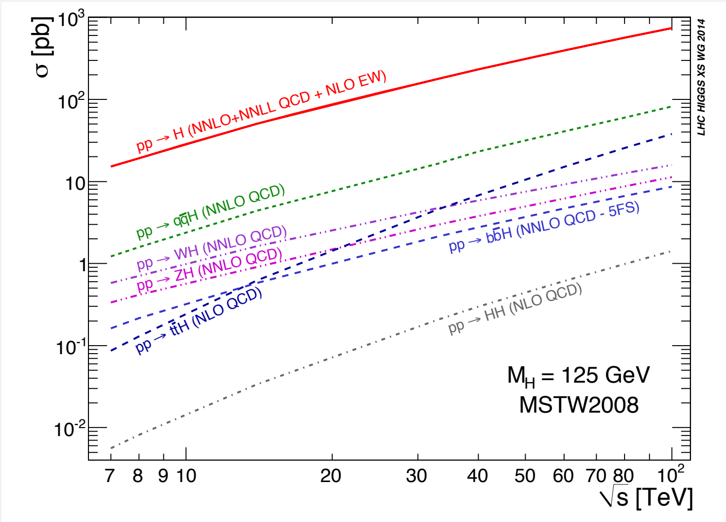
Couplings must have this pattern if model is correct



We know the μ has a different H coupling than the τ, but that's the only thing we know about the 2nd generation

* Except Higgs mass!

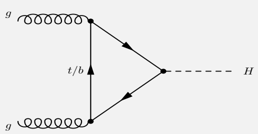
PRECISE PREDICTIONS FOR PRODUCTION AND DECAY



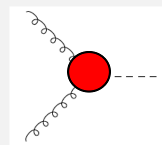
- Rates to NNLO or NLO
- Gluon fusion dominates
- Rates increase with energy
- ttH and HH smallest rates

SO FAR EVERYTHING LOOKS SM-LIKE

- The Higgs couples to top (or does it?)

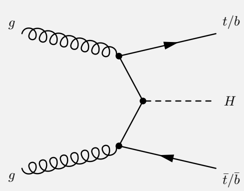


Could be other particles in loop

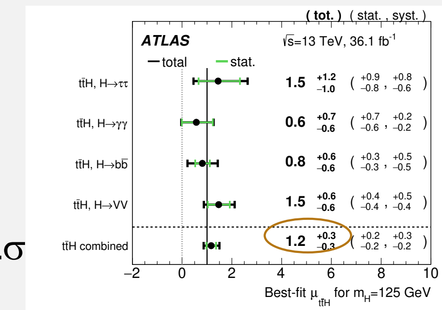


?

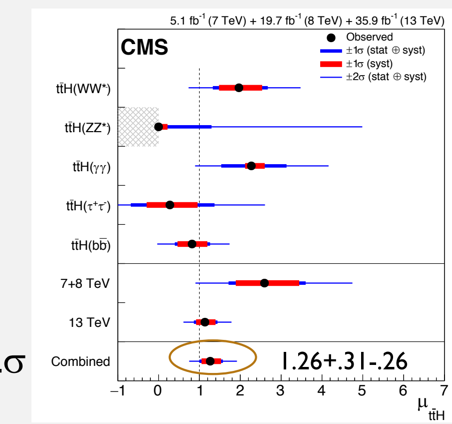
  - Gluon fusion production is indirect evidence
- 2018--observation of ttH production direct evidence for ttH coupling
  - ~50% deviations from SM allowed in ttH



ttH



4.2σ

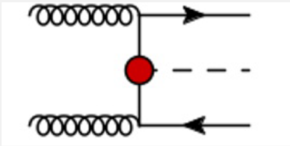


5.2σ

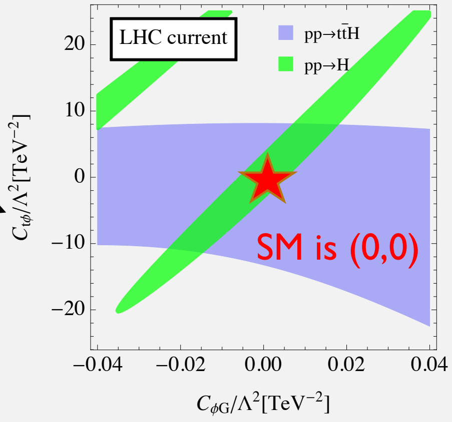
Always normalized to predictions

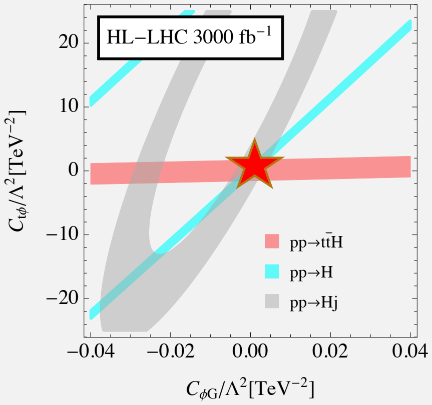
NEW PHYSICS IN THE TOP-HIGGS SECTOR

- Is the ttH coupling the Standard Model coupling?
- Non-SM contributions change rate/distributions



Non-SM ttH coupling





Non-SM ggH coupling

- Observation of gluon fusion production of Higgs at expected rate doesn't mean Higgs has SM ttH coupling
- Need ttH production
- High luminosity will pin down coupling

Maltoni, Vryonidou, Zhang, 1607.05339

IS THIS GOOD ENOUGH?

- Higgs mass known to .2%
- Couplings to gauge bosons known at ~20% level
- Couplings to 3rd generation observed and are SM-like at ~20%
- Nothing about 2nd generation couplings
  - Although we know $H\mu\mu$ coupling $\not\approx$ $H\tau\tau$ coupling
- Nothing about 1st generation couplings
- Very little about off-diagonal couplings
- Nothing about Higgs self-couplings

Just the beginning of the Higgs story!

ERA OF PRECISION CALCULATIONS

- New analytic and computational techniques
- Surprisingly large corrections to gluon fusion production:

LO → NLO → NNLO → NNNLO

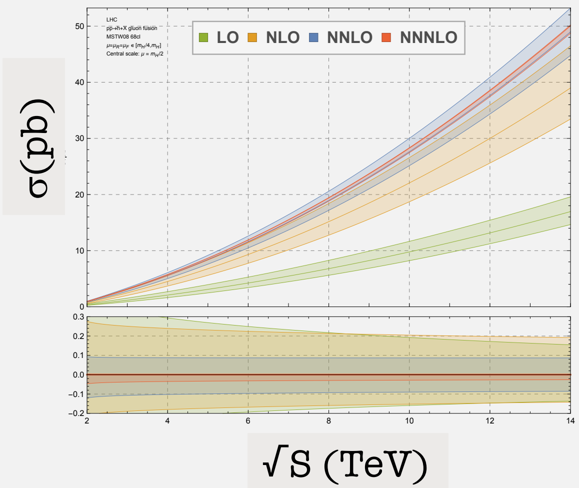
100% increase 20% increase 2% increase

1977 → 1995 → 2002 → 2015

See parallel talk by T. Neumann

GLOBAL PROGRAM OF CALCULATIONS

- Dominant Higgs production mechanism is gluon fusion
- Higgs production from gluon fusion known at NNNLO



Anastasiou, Duhr, Dulat, Herzog, Mistlberger, 1503.06056

Note stabilization at higher orders

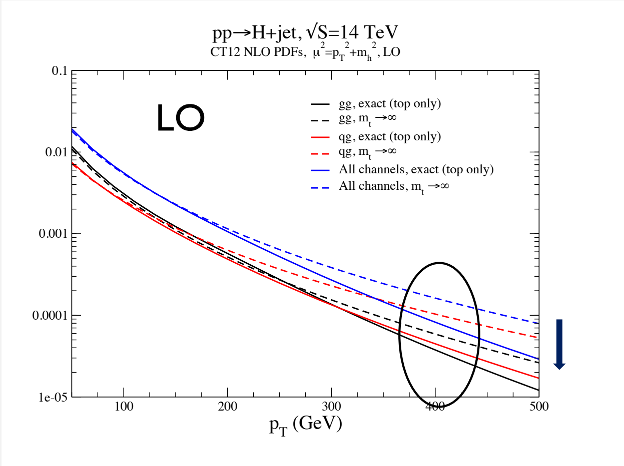
Exact results in $M_t \to \infty$ limit at NNNLO: [Mislberger, 1802.00833]

$$\sigma(13\ TeV) = 54.80\ pb \boxed{{}^{+4.28\ \%}_{-6.42\ \%}(theory)} \pm 1.96\ \%(PDF) \pm 2.7\%\ (\alpha_s)$$

Threshold expansion works well for gluon initiated contributions, poorly for quark initiated contributions

GLOBAL PROGRAM OF CALCULATIONS

- Higgs plus jet production at with top mass dependence
- $M_t \to \infty$ limit doesn't capture kinematics properly (especially at large p_T)



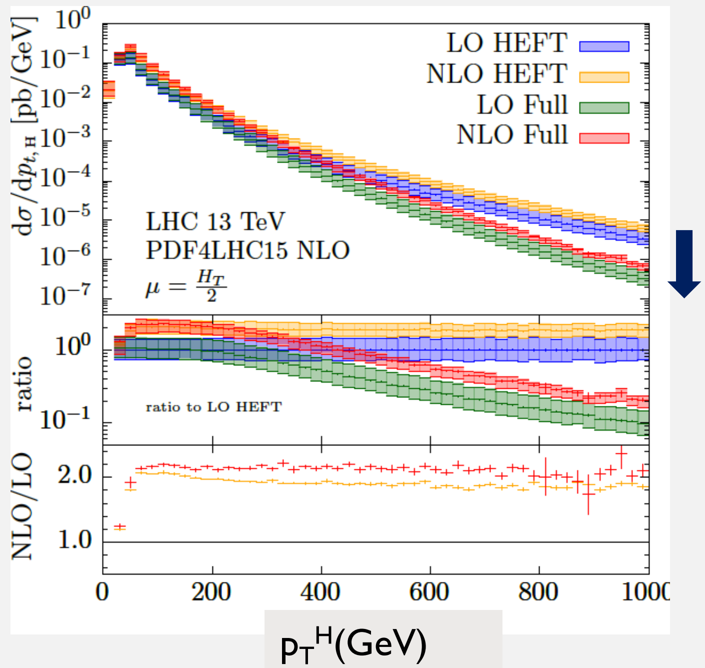
Dawson, Lewis, Zeng, 1409.629

GLOBAL PROGRAM OF CALCULATIONS

- Higgs plus jet at NLO with full top mass dependence
- Top mass effects order 9% at NLO

$$\sigma(13\ TeV) = 16.01^{+1.59}_{-3.73}\ pb\ (full\ M_t\ dependence)$$
$$= 14.63^{+3.3`}_{-2.54}\ pb\ (M_t \to \infty)$$

for p_T(jet) > 30 GeV



Jones, Kerner, Luisoni, 1802.00349

THEORY MATTERS

- Before we can use Higgs measurements to find new physics, we must understand the SM predictions
- Add all Higgs production and decay channels (ATLAS+CMS, 7-8 TeV data):

$$\frac{\sigma}{\sigma_{SM}} \equiv \mu = 1.09 \pm 0.07(stat) \pm .04(syst)$$
$$\boxed{\pm .03(th\ bckd)^{+.07}_{-.06}(th\ signal)}$$

Uncertainty from theory calculations dominates error!

STUDYING DEVIATIONS FROM THE SM

- Assume ***no new tensor structures, no new light particles***
- Define scaling factors κ

$$\sigma \cdot BR(ii \to H \to jj) = \frac{\sigma_{ii}\Gamma_{jj}}{\Gamma_H}$$

$$\boxed{\mu(gg \to H \to \tau^+\tau^-) = \frac{\sigma(gg \to H \to \tau^+\tau^-)}{\sigma(gg \to H \to \tau^+\tau^-)\mid_{SM}} = \frac{\kappa_g^2\kappa_\tau^2}{\kappa_h^2}}$$

- Approaches to loops: κ_γ, κ_g can be
  - Written as function of SM scaling factors: eg $\kappa_g=\kappa_g(\kappa_t,\kappa_b)$
  - Treated as free parameters to look for BSM contributions

SIMILARITY OF HIGGS PROPERTIES TO SM HIGGS PROPERTIES

- In general, BSM physics gives deviations in couplings from SM

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

κ=1 is SM

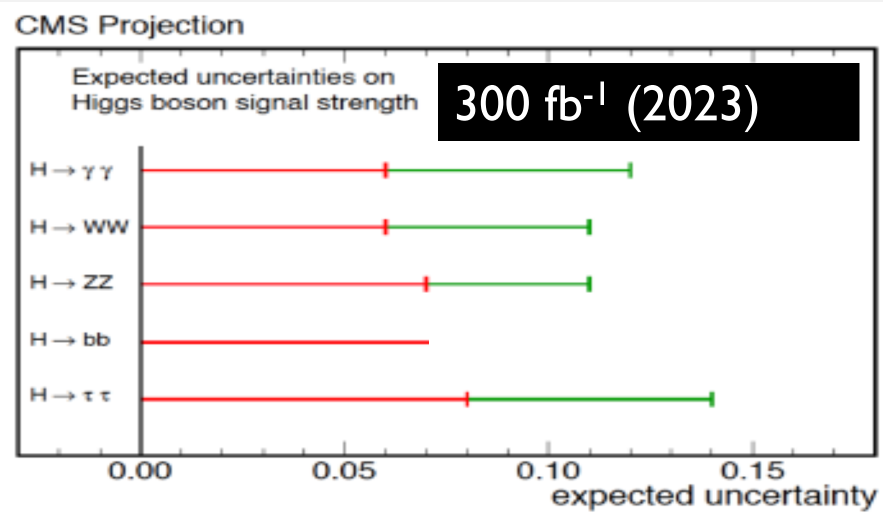
- LHC precision is typically ~20% on Higgs couplings
  - Coupling measurements sensitive to Λ ~ 800 GeV
- Direct searches restrict BSM physics to be above Λ ~ 1 TeV

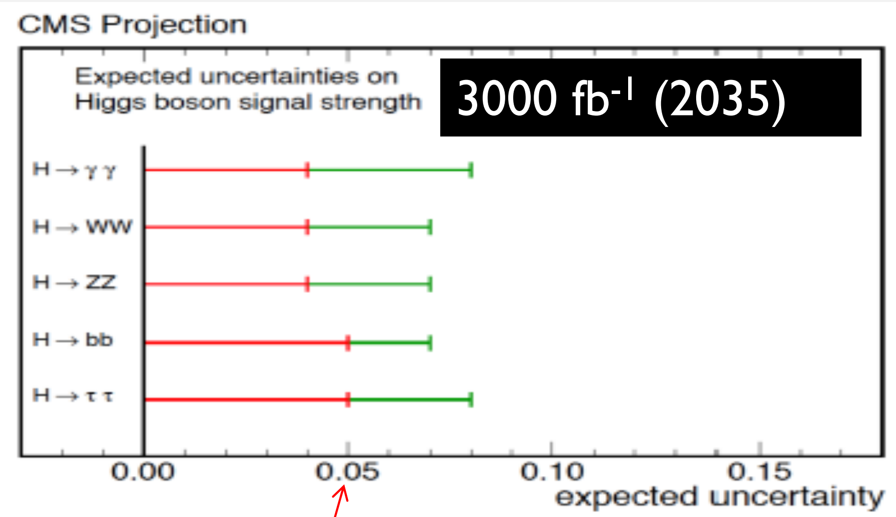
➡ We don't expect big deviations

Required precision is moving target as BSM search limits increase!

EXPECTATIONS FOR PRECISION

- Scenario 1: All systematic uncertainties same as now
- Scenario 2: theory uncertainty reduced by ½, experimental systematics by 1/√L





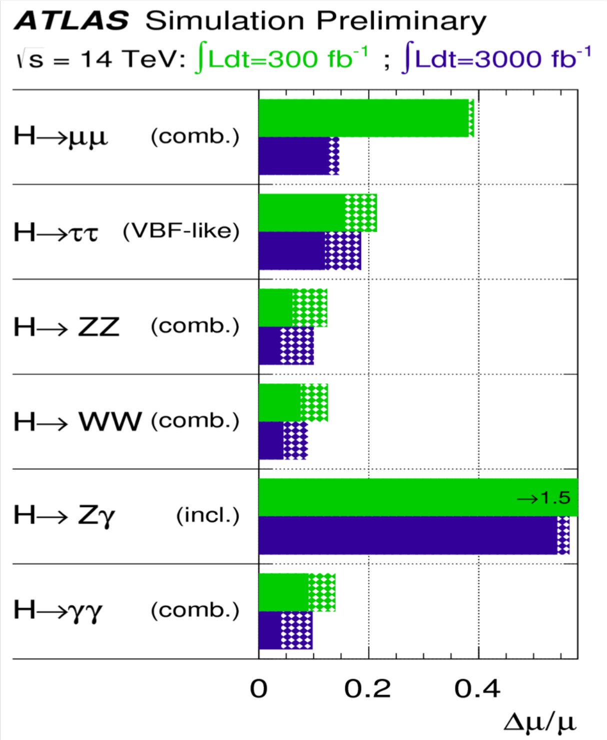
Updates in progress

Ultimate precision 5%

EXPECTATIONS FOR PRECISION

- Large impact of theory uncertainties (dashed)
- Theory will be limiting factor in understanding Higgs results

Updates in progress



THE PROBLEM WITH THE κ APPROACH

- SM Higgs couplings fixed—cannot be varied separately
  - Can test consistency of SM hypothesis
- Run 1 approach:
  - Rescale fundamental Higgs couplings: κ_W, κ_Z, κ_f and loop induced couplings, κ_γ, κ_g, $\kappa_{\gamma Z}$
  - Simple and easy to implement
  - Electroweak corrections not included exactly
  - No information from angular distributions
  - How to interpret deviations?

➡ *Rescaling breaks gauge invariance, renormalizability*

NEW PHYSICS IN HIGGS SECTOR

Use effective field theory

Can we determine source of new physics?

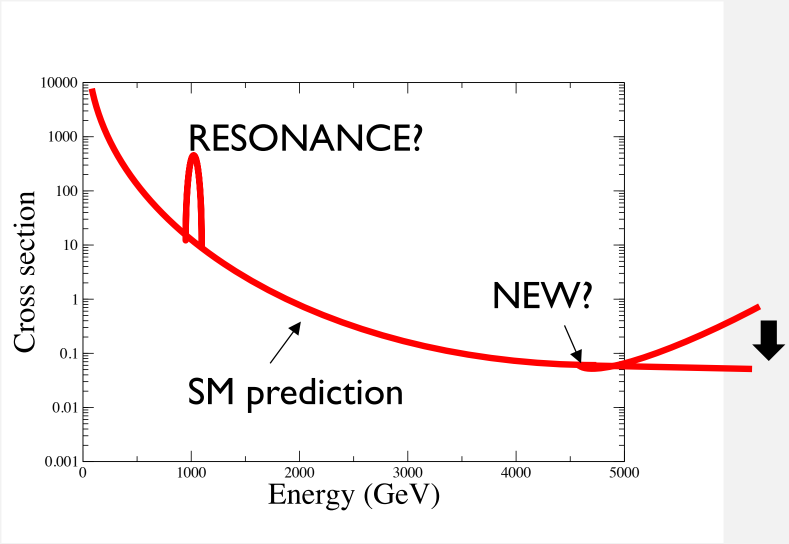
No resonance or light resonance

Find resonance!

Current limits are being strengthened at LHC-13

NO SIGN OF MORE HIGGS-LIKE PARTICLES

- No shortage of models predicting more Higgs particles
  - Singlet model, 2HDM, MSSM, NMSSM
- Models typically do **not** predict masses of new Higgs particles
- Models typically have a limit where all the new particles are heavy and all the Higgs couplings "look like" the SM



REQUIRES EFFECTIVE FIELD THEORY FRAMEWORK

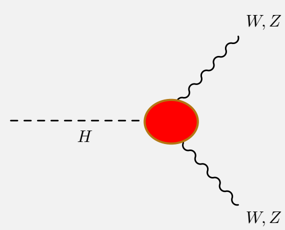
- Assume SU(3) x SU(2) x U(1) gauge theory with no new light particles
- Assume Higgs particle is part of SU(2) doublet
- SM is low energy limit of effective field theory with towers of higher dimension operators

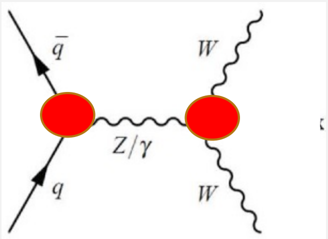
$$L = L_{SM} + \Sigma \frac{c_i}{\Lambda^2} O_i^{d=6} + \sigma \frac{c_i}{\Lambda^4} O_i^{d=8} + \ldots$$

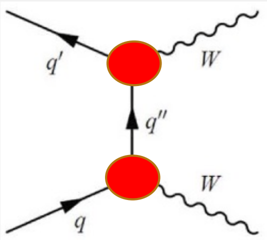
- Can calculate in controlled expansion in SMEFT
- Assume Λ>>v, only dimension-6 operators are important

CAN'T JUST FIT HIGGS COUPLINGS

- New physics that changes Higgs couplings typically changes 3- and 4- gauge boson couplings also



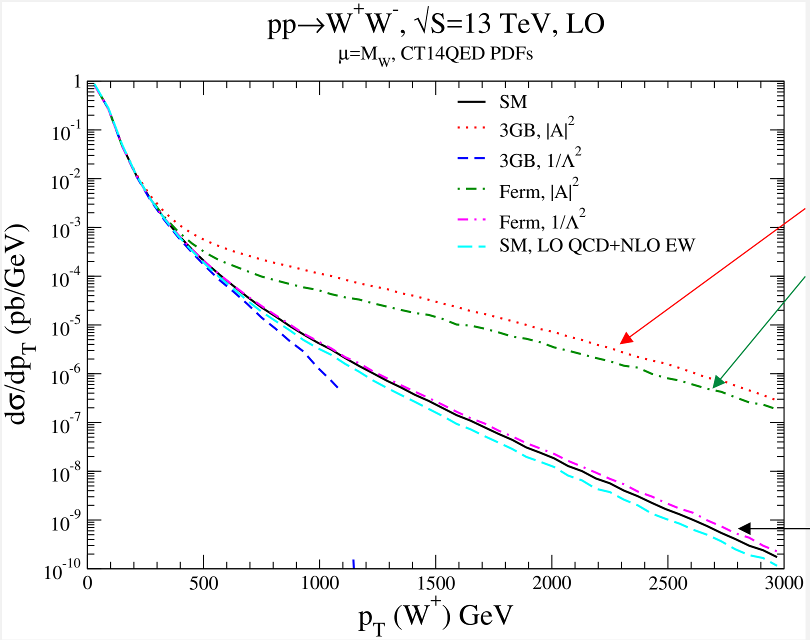




- Changing ZWW, γWW vertices spoils high energy cancellations between contributions
- Effective Field Theory effects enhanced at high energy, high p_T

EXAMPLE: W^+W^- PRODUCTION AT LHC

Effects of non-SM couplings enhanced at large p_T



….Anomalous 3 gauge boson couplings

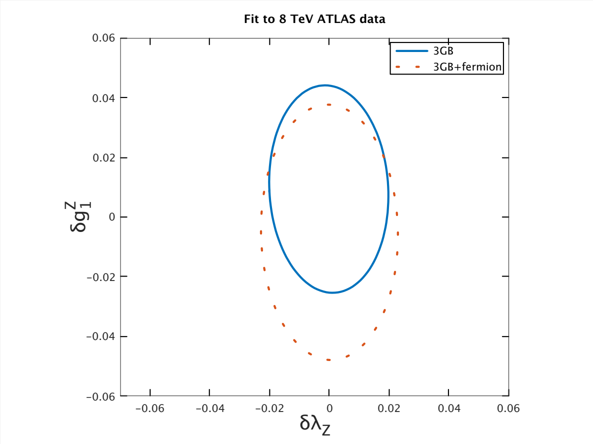
----Anomalous Z-fermion couplings allowed by LEP measurements

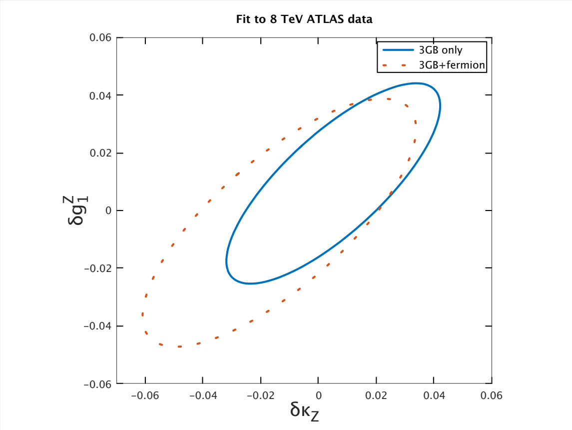
SM

Baglio, Dawson, Lewis , 1708.03332

EXAMPLE: WW PRODUCTION AT LHC

Allowed deviations from SM 3- gauge boson couplings





Fits change significantly when all allowed couplings included

Baglio, Dawson, Lewis , 1708.03332

FITS TO ANOMALOUS INTERACTIONS

- Finite number of relevant operators, can do global fits to Higgs couplings and WW interactions (no unique basis of operators)
  - Operators don't just rescale tree level interactions
  - Kinematic dependence of operators increases sensitivity

$$\begin{aligned}\mathcal{L} \supset \frac{h}{v}\Big[&\delta c_w \frac{g^2 v^2}{2} W_\mu^+ W^{-\mu} + \delta c_z \frac{(g^2+g'^2)v^2}{4} Z_\mu Z^\mu \\ &+ c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W^{-\mu\nu} + c_{w\Box} g^2 \left(W_\mu^- \partial_\nu W^{+\mu\nu} + \text{h.c.}\right) + \hat{c}_{\gamma\gamma}\frac{e^2}{4\pi^2} A_{\mu\nu}A^{\mu\nu} \\ &+ c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z^{\mu\nu} + \hat{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2\pi^2} Z_{\mu\nu}A^{\mu\nu} + c_{z\Box} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A^{\mu\nu}\Big] \\ &+ \frac{g_s^2}{48\pi^2}\left(\hat{c}_{gg}\frac{h}{v} + \hat{c}_{gg}^{(2)}\frac{h^2}{2v^2}\right) G_{\mu\nu}G^{\mu\nu} - \sum_f \left[m_f\left(\delta y_f \frac{h}{v} + \delta y_f^{(2)}\frac{h^2}{2v^2}\right)\bar{f}_R f_L + \text{h.c.}\right]\end{aligned}$$

$$\begin{pmatrix} \hat{c}_{gg} \\ \delta c_z \\ c_{zz} \\ c_{z\Box} \\ \hat{c}_{z\gamma} \\ \hat{c}_{\gamma\gamma} \\ \delta y_t \\ \delta y_b \\ \delta y_\tau \end{pmatrix} = \pm \begin{pmatrix} 0.07\ (0.02) \\ 0.05\ (0.01) \\ 0.05\ (0.02) \\ 0.02\ (0.01) \\ 0.09\ (0.09) \\ 0.03\ (0.02) \\ 0.08\ (0.02) \\ 0.12\ (0.03) \\ 0.11\ (0.09) \end{pmatrix}$$

1 σ bounds

Need more precision!

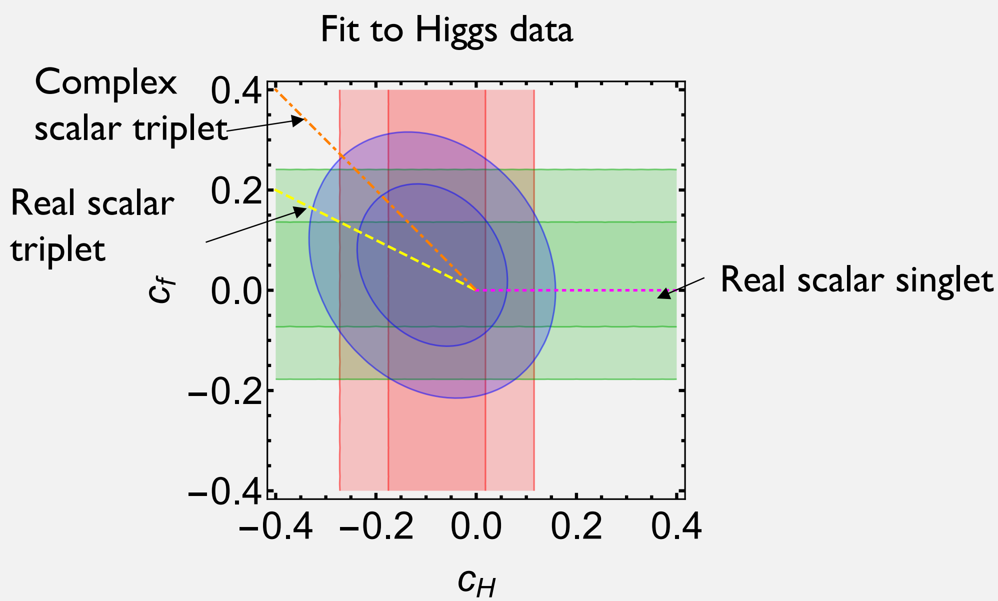
Di Vita, Grojean, Panico, Rimbau, Vantalon, 1704.01953

- ***Many groups doing fits!***

See parallel talk by C. Murphy for fit to 2018 data

WHAT DO WE LEARN BY FITTING HIGGS COUPLINGS?

- In any given high scale model, coefficients of EFT predicted in terms of small number of parameters
- Different coefficients are generated in different models
- By measuring the pattern of coefficients, information is gleaned about high scale physics



$$O_H = \frac{1}{2v^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)$$

$$O_f = \frac{(H^\dagger H)}{v^2} c_f Y_f (\Psi_L f_R H)$$

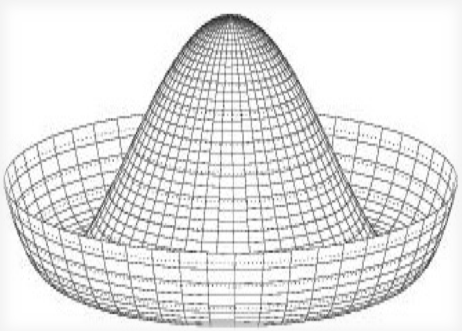
Dawson, Murphy, 1704.07851

HIGGS SELF-COUPLING BIG MILESTONE

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

$$V = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

$$V \to -\frac{M_H^2}{2}H^2 + \lambda_3 H^3 + \lambda_4 H^4$$



- SM is perturbative

$$\lambda_3 = \frac{M_H^2}{2v} \sim .13v \quad \lambda_4 = \frac{M_H^2}{8v^2} = .03$$

PROGRESS IN HH PREDICTIONS

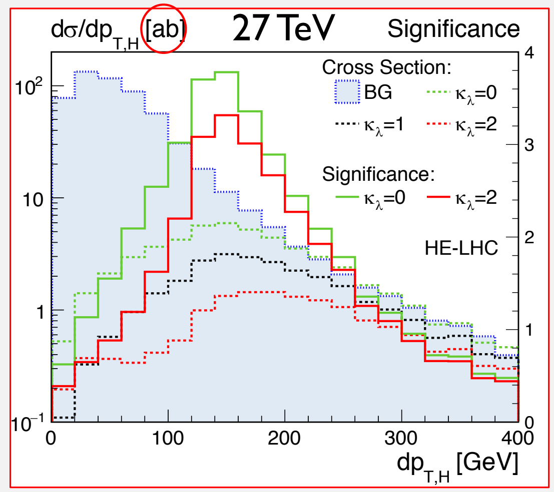
- HH first occurs at one-loop

Goal: Measure λ_3

- Currently, experimental limits are $\sigma/\sigma_{SM} \lesssim 19$
- HH is major goal of luminosity upgrades
- $-0.7 < \kappa_\lambda = \lambda_3/\lambda_{3,SM} < 7.7$ from rates at 3 ab^{-1}
- Improvement from distributions

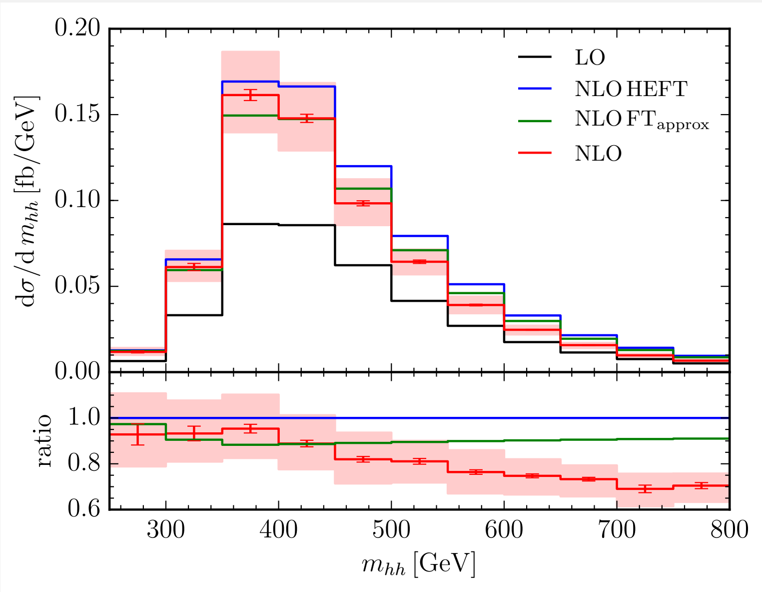
Goncalves, Han, Kling, Plehn, Takeuchi, 1802.04319

- Large cancellation between diagrams
- Reduces sensitivity to HHH coupling
- Small rate!



Effects enhanced at high p_T

PROGRESS IN HH CALCULATIONS



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

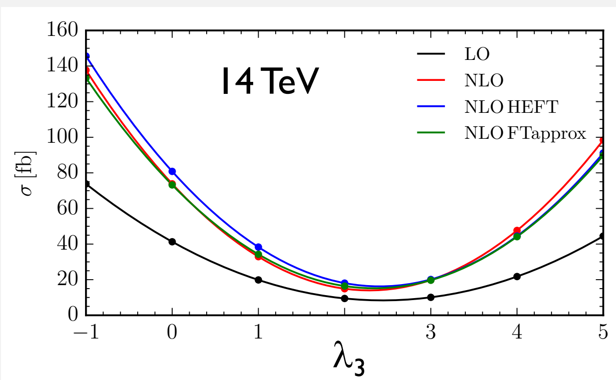
LO and $M_t \rightarrow \infty$ not accurate for tails of distributions

Need higher order corrections

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

PROGRESS IN HH CALCULATIONS

- Recently, NLO with full top mass dependence, combined with NNLO in large top mass dependence (Numerically significant effects of top mass)



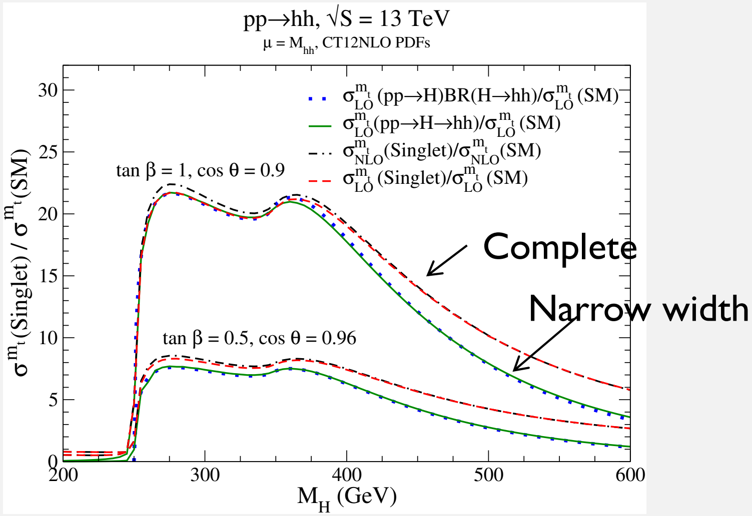
$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\text{NLO}_{\text{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
$\text{NNLO}_{\text{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
$\text{NNLO}_{\text{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$	$1406^{+0.5\%}_{-2.8\%}$
$\text{NNLO}_{\text{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$
M_t unc. $\text{NNLO}_{\text{FTapprox}}$	±2.6%	±2.7%	±3.4%	±4.6%
$\text{NNLO}_{\text{FTapprox}}/\text{NLO}$	1.118	1.116	1.096	1.067

$M_t \to \infty$

Grazzini, Heinrigh, Jones, Kallweit, Kerner, Lindert, Mazzitell, 1803.02463
Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke, 1608.04798

HH IS TEST CASE FOR NEW EWSB PHYSICS

- Add scalar singlet (simplest possible extension of SM)
- Large resonant effects when $M_H \sim 2M_h$



Can get factor of 20 enhancements

*Similar effects in MSSM, NMSSM models

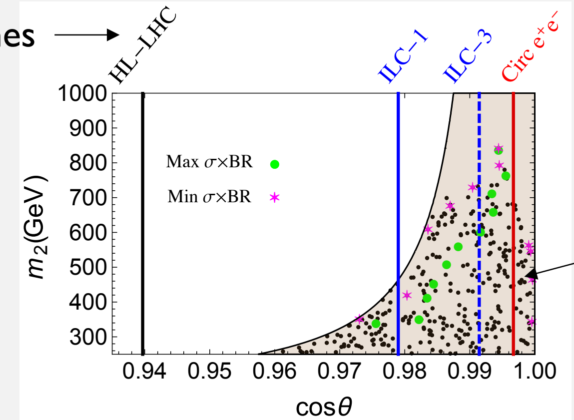
[Dawson, Lewis, arXiv:1508.05397]

HH CAN GIVE INFORMATION ON ELECTROWEAK PHASE TRANSITION

- Models with scalar singlets can allow first order electroweak phase transition

Limits from future machines →

Heavier scalar in singlet model



Suppression of SM Higgs couplings

- Motivation for high energy colliders
- Can probe region with EW phase transition in HH production

Kotwal, Ramsey-Musolf, No, Winslow, 1605.06123

IN THE FUTURE

- Higgs physics is just beginning!
- Precision measurements require precision calculations
  - Starting to see higher order corrections with full top mass dependence
- Many possibilities for extended Higgs sectors
  - Next few years will significantly improve limits on new Higgs particles