ISSUES IN HIGGS PHYSICS LECTURE 1

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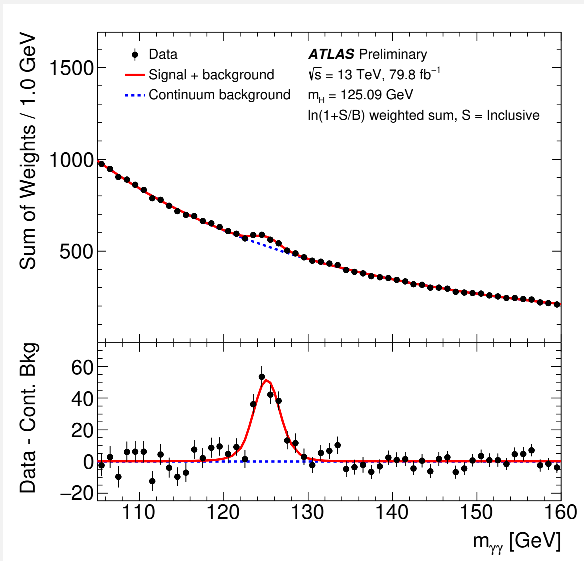
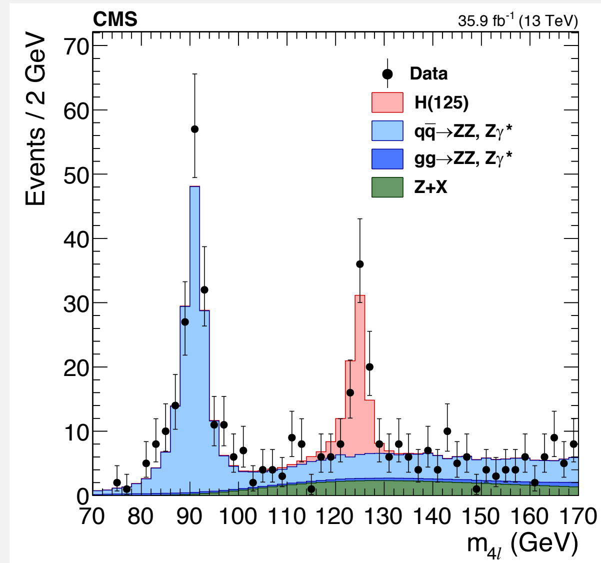
OUTLINE OF LECTURES

- 1. Introduction to Standard Model/Higgs Physics
  - Where are we now?
  - Personal (subjective) selection of interesting topices
- 2. Extended Higgs sectors
- 3. Effective field theory

See review: Higgs Physics (Dawson, Englert, Plehn)

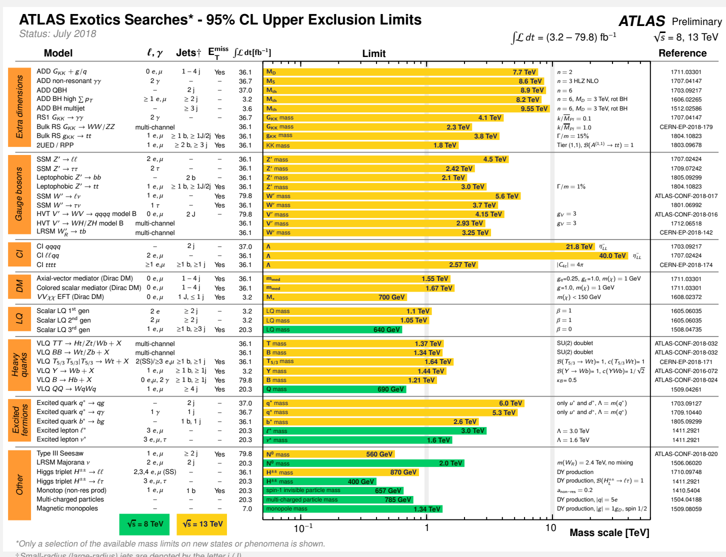
WE'VE DISCOVERED A "HIGGS-LIKE" PARTICLE

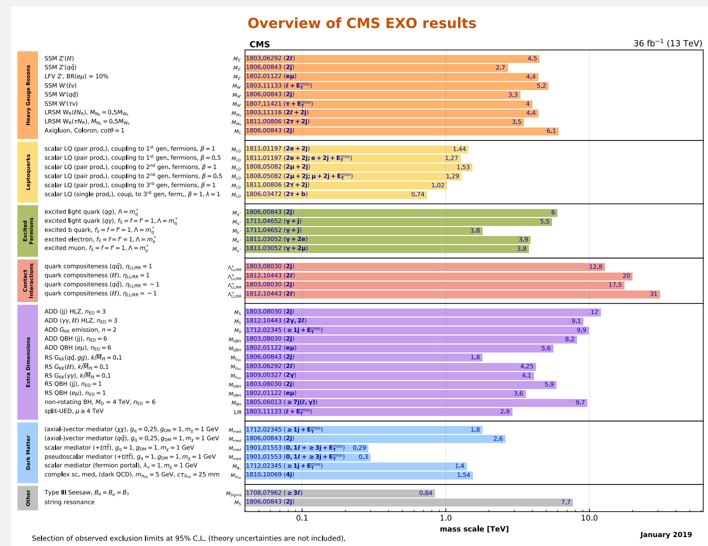




How do we prove it's the object predicted by the Standard Model, and not the low energy manifestation of some more complicated theory?

NO NEW PARTICLES DISCOVERED





Many limits exceed 1 TeV

Best limits at 13 TeV

IS THERE PHYSICS BEYOND THE SM?

- To the best of our knowledge…. The Higgs has no structure, no charge, no spin
- We know that the Higgs couples to fermions and gauge bosons at the 10-20% accuracy level
- We postulate that the Higgs interactions come from a scalar potential:

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

- The potential could just as easily be an effective theory:

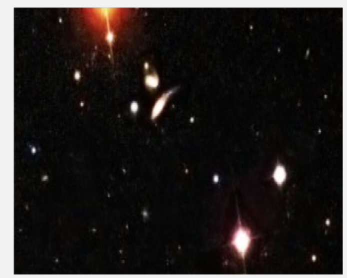
$$V \rightarrow -\frac{M_H^2}{2} H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

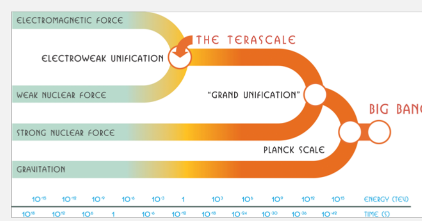
Must measure $\lambda_3 = \frac{M_H^2}{2v} = .13v$

We have no idea how to measure λ_4

WHY MIGHT NEW PHYSICS HIDE IN HIGGS SECTOR?

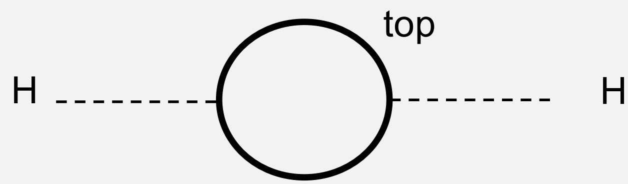
- Many *unanswered questions*: dark matter, the pattern of fermion masses (including neutrinos), baryogenesis, strong CP violation, EW hierarchy….
- Why does the SM only have one Higgs doublet?
  - No good answer to this question
- Higgs can be portal to dark matter
  - Motivates models with extra Higgs gauge singlet
- Higgs models can be constructed to have flavor violation such as $H\rightarrow\mu e$
  - Motivates 2HDM type models





WHY DO WE EXPECT SOMETHING NEW IN THE HIGGS SECTOR?

- The Higgs mass has quantum corrections that we can calculate:

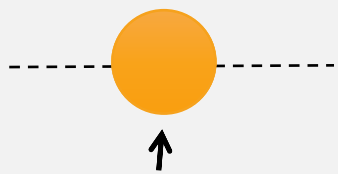


$$\delta M_H^2 = -\frac{3m_{top}^2}{8v^2\pi^2}\Lambda^2$$

- Λ is the largest mass scale in the theory, maybe $M_{planck} = 10^{18}$ GeV?
- Requires arranging counterterms to cancel
- Attractive solution is to add new states whose contribution cancels SM contribution to Higgs mass because of some symmetry

WHY DO WE EXPECT NEW PHYSICS IN LOOPS?

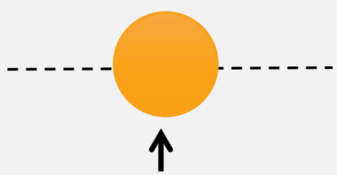
- Generically, solutions to ***naturalness*** involve new particles



SM particles

$$\delta M_h^2 \sim -(125\ GeV)^2 \left(\frac{\Lambda}{600\ GeV} \right)^2$$

Λ is scale of new physics



New stuff

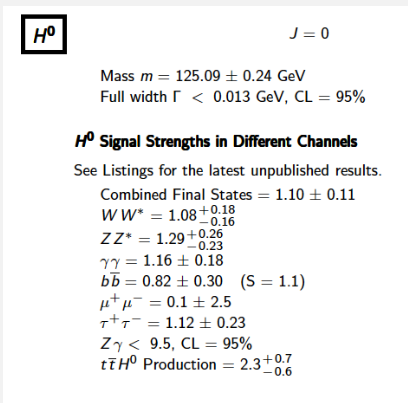
$$\delta M_h^2 \sim +(125\ GeV)^2 \left(\frac{\Lambda}{M_{new}} \right)^2$$

This argument appears to be wrong, or maybe just too simplistic

For this cancellation to work, new stuff can't be too much above TeV scale

WHERE ARE WE GOING?

PDG, 2017



H^0 $J = 0$

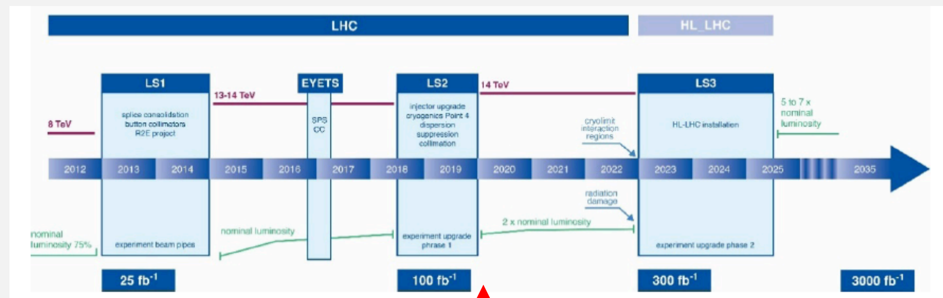
Mass $m = 125.09 \pm 0.24$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

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 = $2.3^{+0.7}_{-0.6}$

Normalized to SM



We are here

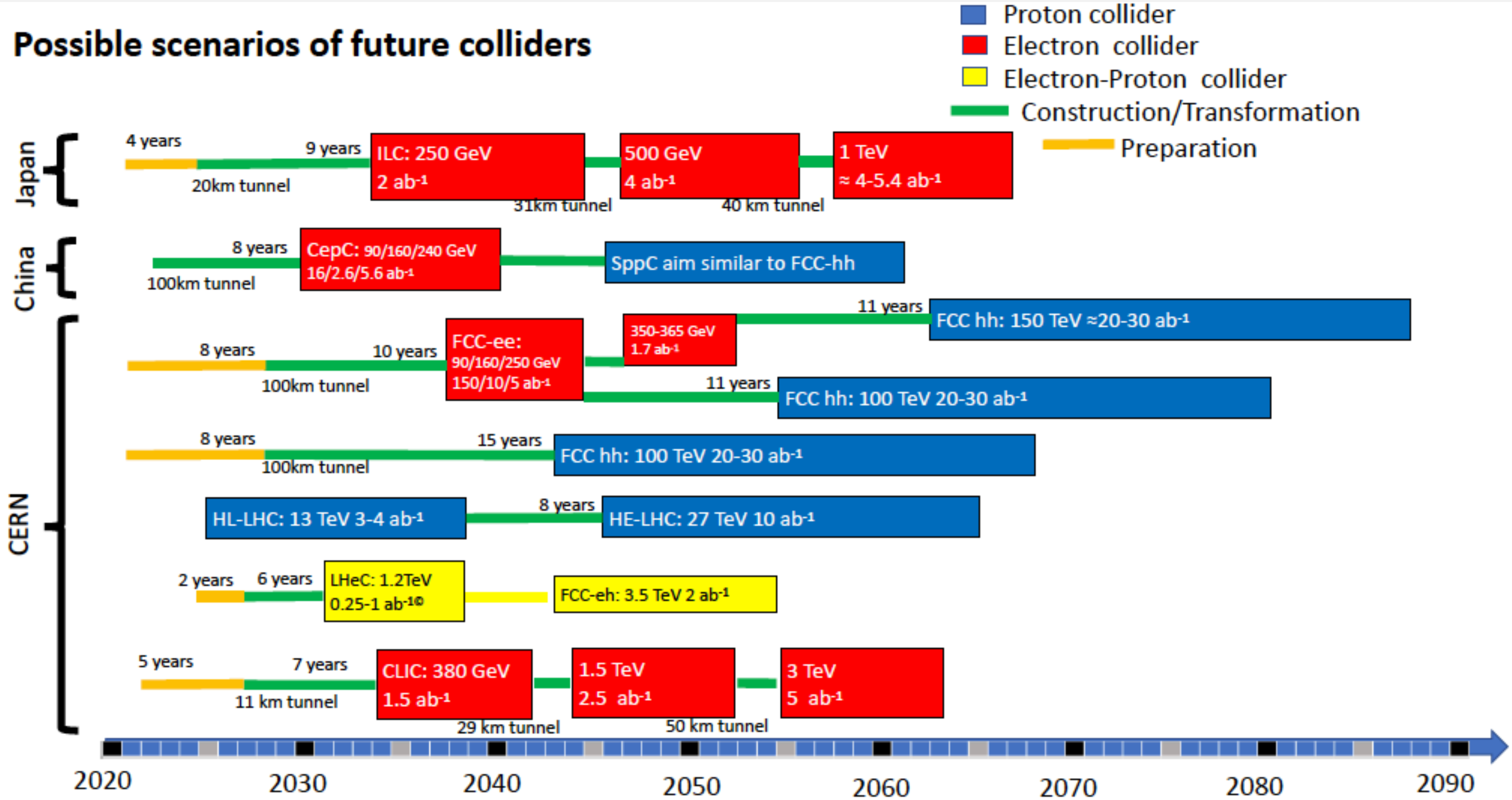
A good time to take stock of physics goals

If theory is incomplete, interpretations of Higgs results inaccurate

Future Colliders in a chart

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee_{240}
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee_{365}
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC_{250}
		350 GeV	±80/±30	1	1.6	0.2	1		ILC_{350}
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC_{500}
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC_{380}
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC_{1500}
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC_{3000}
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

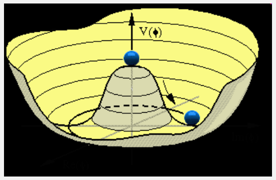
European Strategy Process


Possible scenarios of future colliders
Proton collider
Electron collider
Electron-Proton collider
Construction/Transformation
Preparation
Japan
4 years
9 years
20km tunnel
ILC: 250 GeV
2 ab-1
31km tunnel
500 GeV
4 ab-1
40 km tunnel
1 TeV
≈ 4-5.4 ab-1
China
8 years
100km tunnel
CepC: 90/160/240 GeV
16/2.6/5.6 ab-1
SppC aim similar to FCC-hh
CERN
11 years
FCC hh: 150 TeV ≈20-30 ab-1
8 years
10 years
100km tunnel
FCC-ee:
90/160/250 GeV
150/10/5 ab-1
350-365 GeV
1.7 ab-1
11 years
FCC hh: 100 TeV 20-30 ab-1
8 years
15 years
100km tunnel
FCC hh: 100 TeV 20-30 ab-1
HL-LHC: 13 TeV 3-4 ab-1
8 years
HE-LHC: 27 TeV 10 ab-1
2 years
6 years
LHeC: 1.2TeV
0.25-1 ab-1
FCC-eh: 3.5 TeV 2 ab-1
5 years
7 years
11 km tunnel
CLIC: 380 GeV
1.5 ab-1
29 km tunnel
1.5 TeV
2.5 ab-1
50 km tunnel
3 TeV
5 ab-1
2020
2030
2040
2050
2060
2070
2080
2090

EWSB IN A NUTSHELL

- Standard Model includes complex Higgs SU(2) doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$



- With SU(2) x U(1) invariant scalar potential

$$V_{SM} = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$

Invariant under $\varphi \to -\varphi$

- If $\mu^2 < 0$ (WHY???) then spontaneous symmetry breaking
- Minimum of potential at:

$$\phi = e^{\frac{\omega\cdot\sigma}{v}} \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix} \qquad \langle\phi\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

ω's correspond to longitudinal degrees of freedom– all the action is here!

- Choice of minimum breaks gauge symmetry

GAUGE SECTOR

- Couple φ to SU(2) x U(1) gauge bosons ($W^{\mu a}$, a=1,2,3; B^{μ})

$$L_\phi = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi)$$
$$D_\mu = \partial_\mu - i\frac{g}{2}\sigma^i W^i_\mu - i\frac{g'}{2}B_\mu$$

Couplings fixed by gauge invariance

- Gauge boson mass terms from:

$$(D_\mu \phi)^\dagger (D^\mu \phi) \rightarrow \frac{1}{8}(0, v)(gW^a_\mu \sigma^a + g' B_\mu)(gW^{b,\mu}\sigma^b + g' B^\mu)\begin{pmatrix} 0 \\ v \end{pmatrix} + \ldots$$
$$\rightarrow \frac{v^2}{8}\left[g^2 (W^1_\mu)^2 + g^2 (W^2_\mu)^2 + (-gW^3_\mu + g' B_\mu)^2\right] + \ldots$$

- Free parameters in gauge sector: g and g'

Potential fixed by gauge invariance and renormalizability

MORE ON SM HIGGS MECHANISM

- Massive gauge bosons:

$$W^{\pm}_{\mu} = \left(\frac{W^1_{\mu} \mp i W^2_{\mu}}{\sqrt{2}} \right)$$

$$Z^0_{\mu} = \left(\frac{g W^3_{\mu} - g' B_{\mu}}{\sqrt{g^2 + g'^{\,2}}} \right)$$

$$M_W = \frac{gv}{2}$$

$$M_Z = \sqrt{g^2 + g'^2}\,\frac{v}{2}$$

- Orthogonal combination to Z is massless photon

$$A^0_{\mu} = \frac{g' W^3_{\mu} + g B_{\mu}}{\sqrt{g^2 + g'^2}}$$

W, Z, HIGGS COUPLINGS

- Lagrangian in terms of massive gauge bosons and Higgs boson:

$$L = gM_W W^{+\mu} W_\mu^- h + \frac{gM_Z}{\cos\theta_W} Z^\mu Z_\mu h \qquad \cos\theta_W = \frac{M_W}{M_Z}$$

- Higgs couples to gauge boson mass
- Spontaneous symmetry breaking gives W/Z mass $\Rightarrow$ longitudinal polarization

No free parameters in couplings!

WHAT ABOUT FERMIONS?

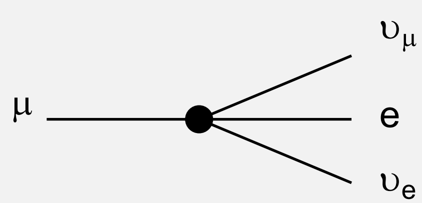
- Current-current interaction of 4 fermions

$$L_{FERMI} = -2\sqrt{2} G_F J_\rho^+ J^\rho$$

- Consider just leptonic current

$$J_\rho^{lept} = \overline{\nu}_e \gamma_\rho \left(\frac{1-\gamma_5}{2} \right) e + \overline{\nu}_\mu \gamma_\rho \left(\frac{1-\gamma_5}{2} \right) \mu + hc$$

- Only left-handed fermions feel charged current weak interactions
- This induces muon decay



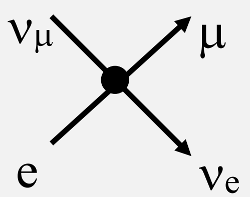
This structure known since Fermi

$G_F = 1.16637 \times 10^{-5}$ GeV $^{-2}$

MUON DECAY

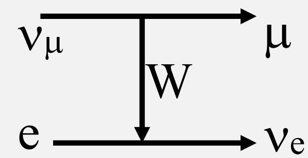
- Consider $\nu_\mu e \to \mu \nu_e$
- Fermi Theory:

$$-i2\sqrt{2}G_F g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$



- EW Theory:

$$\frac{ig^2}{2}\frac{1}{k^2-M_W^2}g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$



For $|k| << M_W$, $2\sqrt{2}G_F = g^2/2M_W^2$

$$M_W = \frac{gv}{2}$$

$$G_F = \frac{1}{\sqrt{2}v^2}$$

HIGGS PARAMETERS

- G_F measured precisely

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W{}^2} = \frac{1}{2v^2}$$

$$v^2 = (\sqrt{2}G_F)^{-1} = (246\,GeV)^2$$

- Higgs potential has 2 free parameters, μ^2, λ

$$V_{SM} = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$

$$v^2 = -\frac{\mu^2}{\lambda}$$

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

- Trade μ^2, λ for v^2, M_h^2

$$V = \frac{M_h^2}{2}h^2 + \frac{M_h^2}{2v}h^3 + \frac{M_h^2}{8v^2}h^4$$

  - Large M_h $\rightarrow$strong Higgs self-coupling
  - A priori, Higgs mass could have been anything

FERMION MULTIPLET STRUCTURE

- Left-handed fermions couple to $W^{\pm}$ (cf Fermi theory)
  - Put in SU(2) doublets
- Right-handed fermions don't couple to $W^{\pm}$
  - Put in SU(2) singlets (this is an assumptioned , but well tested experimentally)
- Fix weak hypercharge to get correct couplings to photon

$$Q = T_3 + \frac{Y}{2}$$

Put this in by hand

STANDARD MODEL IS VERY ECONOMICAL

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R, \quad d_R, \quad \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \quad e_R$$

$$\begin{pmatrix} c \\ s \end{pmatrix}_L \quad c_R, \quad s_R, \quad \begin{pmatrix} \nu \\ \mu \end{pmatrix}_L, \quad \mu_R$$

$$\begin{pmatrix} t \\ b \end{pmatrix}_L \quad t_R, \quad b_R, \quad \begin{pmatrix} \nu \\ \tau \end{pmatrix}_L, \quad \tau_R$$

Except for masses, the generations are identical

Reasons for flavor symmetry not understood

5 multiplets with 3 generations each: flavor symmetry (broken explicitly by Yukawas)

WHAT ABOUT FERMION MASSES?

- Left-handed fermions $SU(2)_L$ doublets, right-handed fermions $SU(2)_L$ singlets
- Dirac mass term forbidden by $SU(2)_L$ gauge invariance:

$$L = -m\overline{\psi}\psi = -m(\overline{\psi}_L\psi_R + \overline{\psi}_R\psi_L)$$

- Effective Higgs-fermion coupling is gauge invariant

$$L_Y = -\overline{Q}^i_L F^{ij}_u \tilde{\phi} u^j_R - \overline{Q}^i_L F^{ij}_d \phi d^j_R - \overline{l}^i_L F^{ij}_l \phi e^j_R + hc$$

i,j=1,2,3 =generation index

- Mass terms generated with $\phi^0=(h+v)/\sqrt{2}$
- Diagonalizing mass matrix diagonalizes Higgs Yukawa couplings

$$L \sim \overline{u}^i_L m^{ij}_u u^j_R + Y^{ij}_u \overline{u}^i_L u^j_R h + hc$$

$$m^{ij}_u = \frac{v}{\sqrt{2}} F^{ij}_u \qquad Y^{ij}_u = \frac{F^{ij}_u}{\sqrt{2}}$$

Higgs has no flavor changing couplings

REVIEW OF HIGGS COUPLINGS

- Couplings to fermions proportional to mass: $\frac{m_f}{v} h \overline{f} f$
- Couplings to massive gauge bosons proportional to (mass)^2 :

$$2M_W^2 \frac{h}{v} W_\mu^+ W^{-\mu} + M_Z^2 \frac{h}{v} Z_\mu Z^\mu$$

- Couplings to gauge bosons at 1-loop: *

$$F(m_f) \frac{\alpha_s}{12\pi} \frac{h}{v} G_{\mu\nu}^A G^{A,\mu\nu} + F(m_f, M_W) \frac{\alpha}{8\pi} \frac{h}{v} F_{\mu\nu} F^{\mu\nu} + F(m_f, M_W) \frac{\alpha}{8\pi s_W} \frac{h}{v} F_{\mu\nu} Z^{\mu\nu}$$

- Higgs self-couplings proportional to M_h^2:

$$V = \frac{M_h^2}{2} h^2 + \frac{M_h^2}{2v} h^3 + \frac{M_h^2}{8v^2} h^4$$

Only unpredicted parameter is M_h

* Normalization is such that F→1 for m_t, $M_W \to \infty$

SM PREDICTS M_W

- Inputs: g, g', v, $M_H \to M_Z$, G_F , α, M_H
  - Predict M_W

$$M_W^2 = \pi\sqrt{2}\,\frac{\alpha}{G_F}\left(1-\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F M_Z^2}}\right)^{-1}$$

  - Need to calculate beyond tree level

M_W predicted =80.935 GeV

M_W experimental =80.379 $\pm$ 0.012 GeV

M_W AT 1-LOOP

- Predict M_W

$$G_F = \frac{\pi\alpha}{\sqrt{2} M_W^2 \sin^2\theta_W} \frac{1}{(1-\Delta r)}$$

Δr contains all the radiative corrections

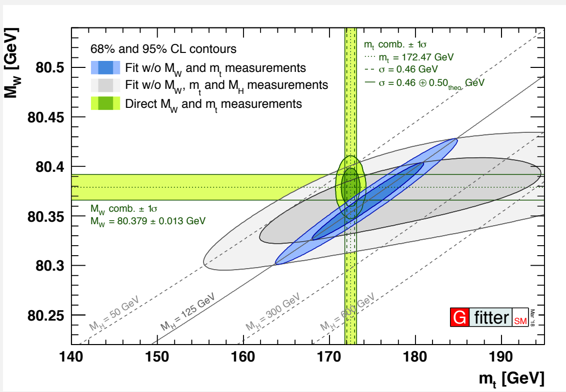
- Need to calculate beyond tree level

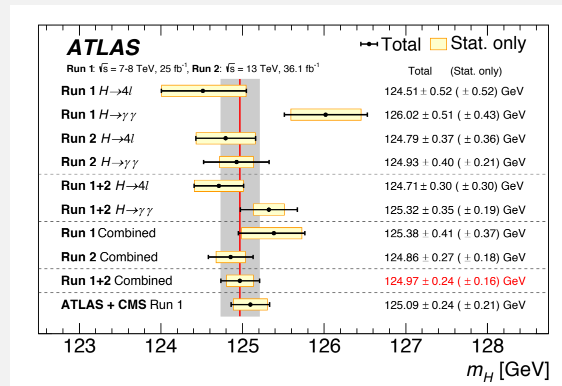
$$\Delta r^t = -\frac{3 G_F m_t^2}{8\sqrt{2}\pi^2}\left(\frac{\cos^2\theta_W}{\sin^2\theta_W}\right) \qquad \Delta r^h = \frac{11 G_F M_W^2}{24\sqrt{2}\pi^2}\left(\ln\frac{M_h^2}{M_W^2}\right)$$

In general: quadratic dependence on top mass, logarithmic dependence on Higgs mass

PRECISION CONSTRAINS NEW PHYSICS

- Use precision measurements to constrain BSM physics (long history starting with LEP)
- Higgs mass is precision observable





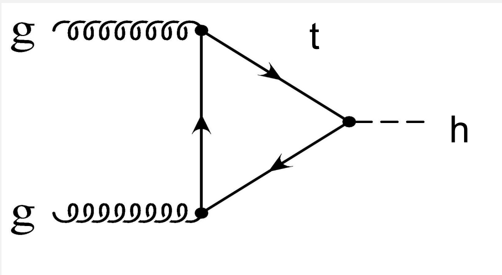
SM predicts relationship between v, λ, and M_H

HIGGS COUPLINGS TO GLUONS

- Largest contribution in SM is from top quarks
- (hff coupling ~ m_f/v)
- Not a direct measurement of tth coupling since there could be new particles in loop

$L \sim \overline{u}^i_L m^{ij}_u u^j_R + Y^{ij}_u \overline{u}^i_L u^j_R h + hc$

Contribution of b quark ~ - 6%



No direct ggh , γγh couplings since Higgs couples to mass

Independent of M_t in large top mass limit

HIGGS COUPLINGS TO PHOTONS

- Dominant contribution is W loops
- Contribution from top is small

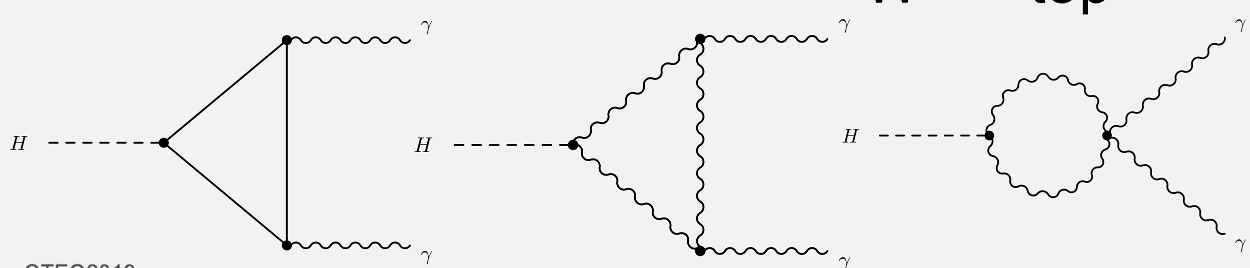
Note opposite signs of t/W loops: Sensitive to sign of top Yukawa

$$\Gamma(H \to \gamma\gamma) \sim \frac{\alpha^3}{256\pi^2 s_W^2} \frac{M_H^3}{M_W^2} \mid 7 - \frac{16}{9} + ... \mid^2$$

*limits are small M_h limit

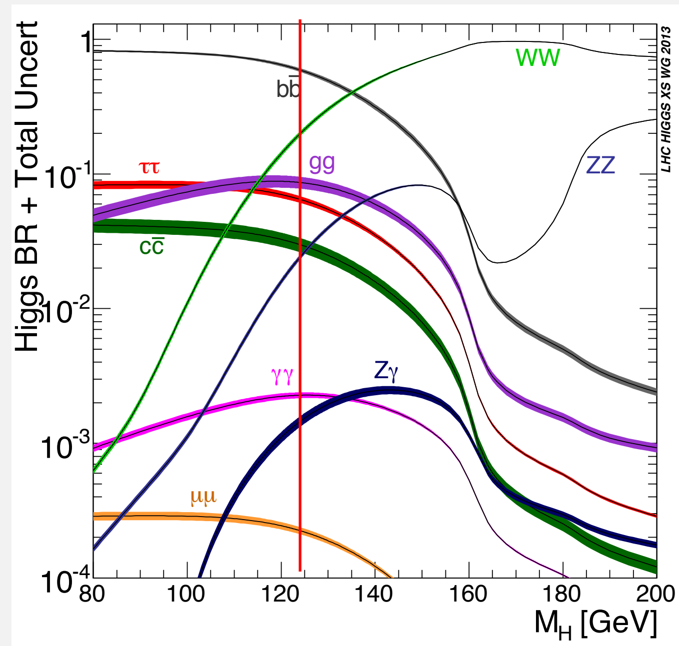
W top

Loops imply sensitivity to new physics

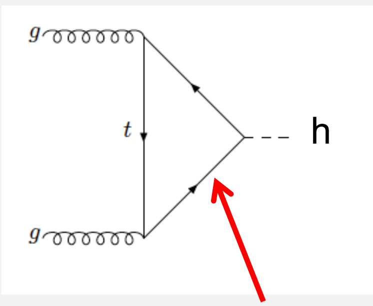


HIGGS DECAYS AND WIDTH

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



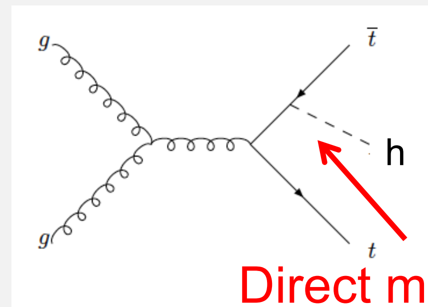
HIGGS PRODUCTION AT A HADRON COLLIDER



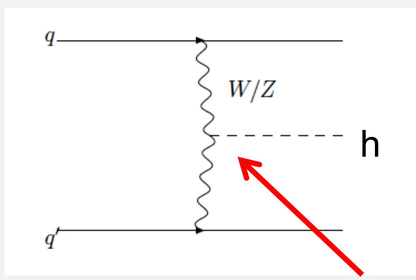
Depends on new physics in loop

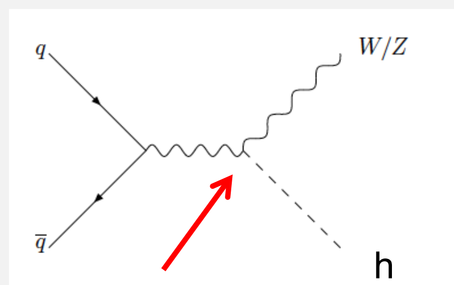
Most important processes:

$$gg \rightarrow h$$
$$q\overline{q} \rightarrow q\overline{q}h$$
$$q\overline{q} \rightarrow q\overline{q}h$$
$$q\overline{q}, gg \rightarrow t\overline{t}h$$



Direct measurement of tth Yukawa





Vanishes if v=0: Fundamental test of EWSB mechanism

ERA OF PRECISION CALCULATIONS

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

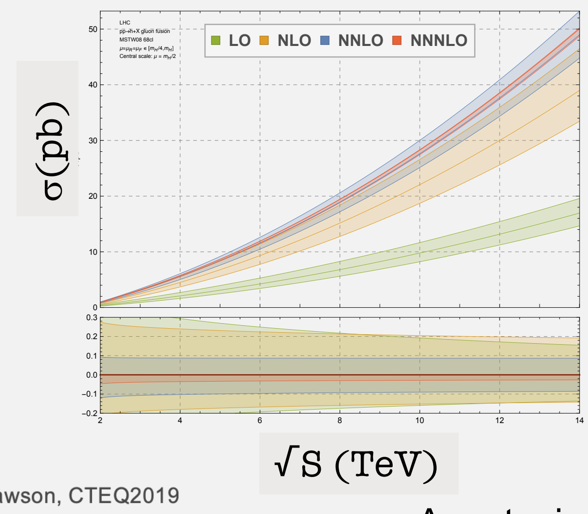
LO → NLO → NNLO → NNNLO

100% increase 20% increase 2% increase

1977 → 1995 → 2002 → 2015

GLOBAL PROGRAM OF CALCULATIONS

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



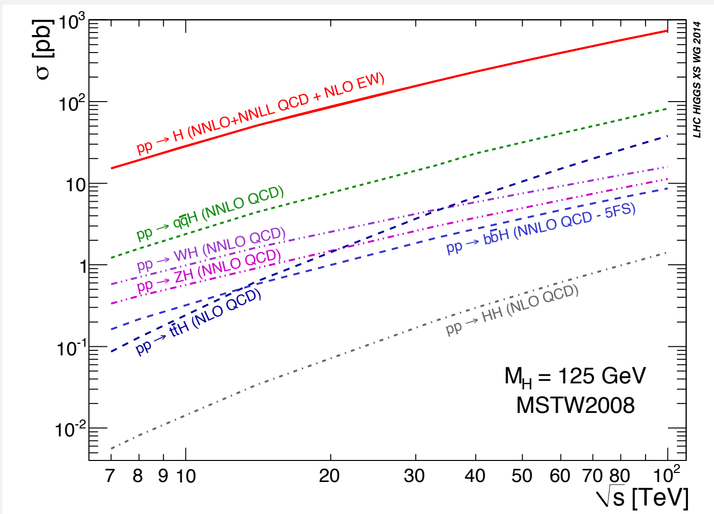
Note stabilization at higher orders

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

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

Anastasiou, Duhr, Dulat, Herzog, Mistlberger, 1503.06056

PRECISE PREDICTIONS FOR PRODUCTION AND DECAY

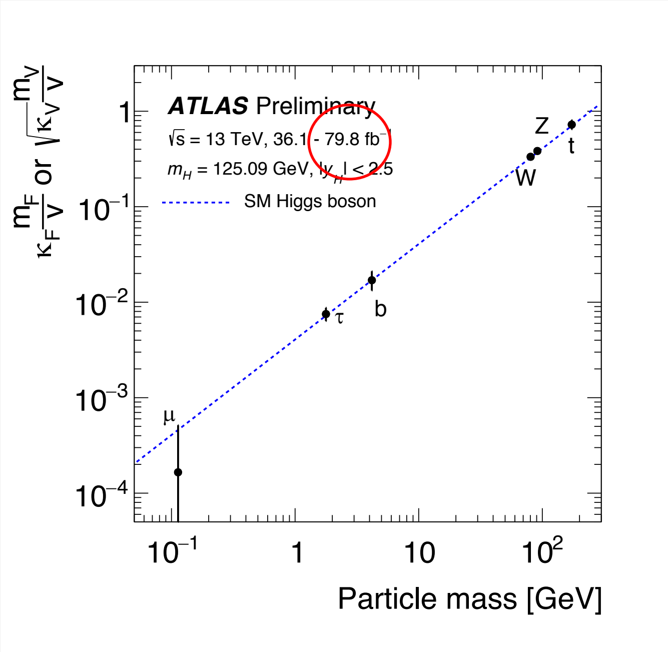


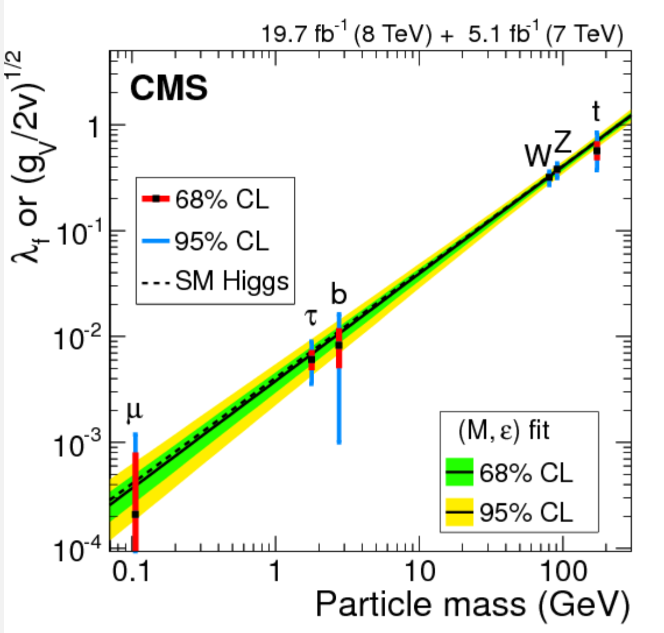
- Rates to NNLO or NLO
- Gluon fusion dominates
- Rates increase with energy
- tth and hh smallest rates

Higgs cross section working group

png

GENERICALLY, SM COUPLINGS





HIGGS COUPLING MEASUREMENTS

- Assume 1 resonance/zero width approx/no new tensor structures

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

- Define scaling factors κ

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

- 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

LHC Higgs Cross Section Working group, 1307.1347

FIRST STEP TO HIGGS COUPLINGS: κ APPROACH

- κ_i=(Higgs coupling to particle i)/(SM Higgs coupling to particle i)
  - Simple rescaling; no momentum dependence
  - Gauge invariance of SM requires κ=1
- Assuming loops resolved and no BSM:

- Couplings to gauge bosons at 8-12%
- Couplings to 3rd generation fermions at 15-20%

Current Limits

	CMS	ATLAS
k_Z	$.99^{+.11}_{-.12}$	$1.10^{+.08}_{-.08}$
k_W	$1.10^{+.12}_{-.17}$	$1.05^{+.08}_{-.08}$
k_t	$1.11^{+.12}_{-.10}$	$1.02^{+.11}_{-.10}$
k_b	$-1.10^{+.33}_{-.23}$	$1.06^{+.19}_{--.18}$
k_τ	$1.01^{+.16}_{-.20}$	$1.07^{+.15}_{-.15}$
k_μ	$.79^{+.58}_{-.79}$	<1.51 at 95% cl

We are just getting to the interesting regime: Generically expect deviations

$$\delta\kappa \sim \frac{v^2}{\Lambda^2} \sim 6\% \left(\frac{1000\ TeV}{\Lambda}\right)^2$$

CMS, arXiv:1809.10733
ATLAS, ATLAS-CONF-2019-005

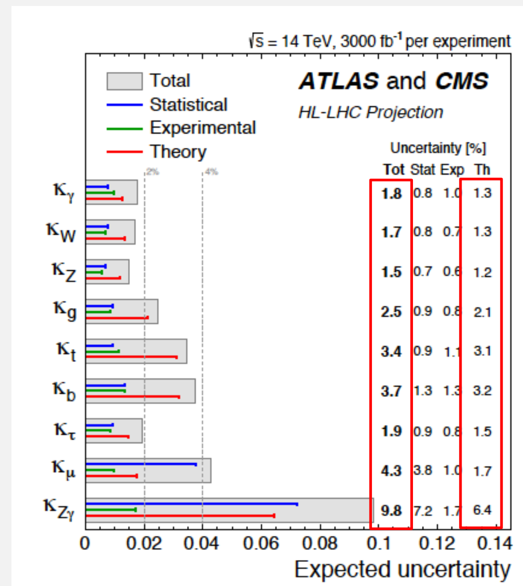
THEORY ERRORS DOMINATE EXPERIMENTAL EXTRACTIONS OF HIGGS PARAMETERS

ATLAS, Global Higgs signal strength

$$\mu = \frac{\sigma \cdot BR}{[\sigma \cdot BR]\,|_{SM}}$$

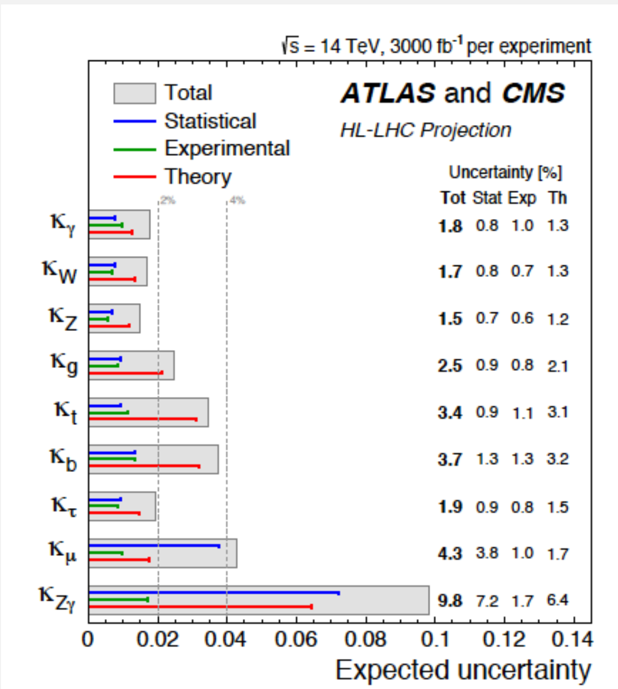
Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, E_T^{miss}	1.4
Flavour tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7
Total uncertainty	7.6

FUTURE



Lots of theoretical work needed!

PROJECTIONS FOR HIGGS COUPLINGS



Large theory errors at LHC

Uncertainties in % with 2 ab^{-1}

	ILC250	ILC500
κ_γ	1.1	1.0
κ_W	1.8	0.4
κ_Z	.38	0.3
κ_g	2.2	0.97
κ_b	1.8	0.60
κ_τ	1.9	0.80

* From ILC study, 1710.076210.80

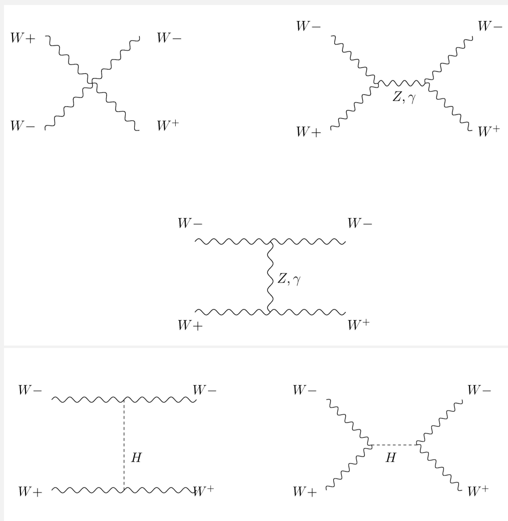
CLIC, uncertainties in %

	350 GeV, 1 ab^{-1}	3 TeV, 5 ab^{-1}
κ_γ	-	2.3
κ_W	0.8	0.1
κ_Z	0.4	0.2
κ_g	2.1	0.9
κ_b	1.3	0.2
κ_τ	2.7	0.9

* From CLIC study, 1812. 06018

Energy critical at e^+e^- machines;
negligible theory error

SM IS SPECIAL AT HIGH ENERGY



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

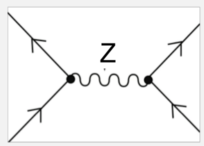
$$A \approx -g^2 \frac{E^2}{M_W^2}$$

E^4 terms cancel between TGC and QGC

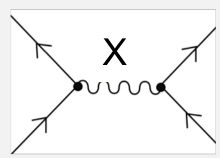
Terms which grow with energy cancel for E >> M_H

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

HIGH SCALE DECOUPLING

- Suppose there is a new particle X, with mass $M_X >> M_W$
- SM scattering: 

$$A_{SM} \sim \frac{g^2}{M_Z^2}$$

- Contribution from X: 

$$A_X \sim \frac{g_X^2}{M_X^2}$$

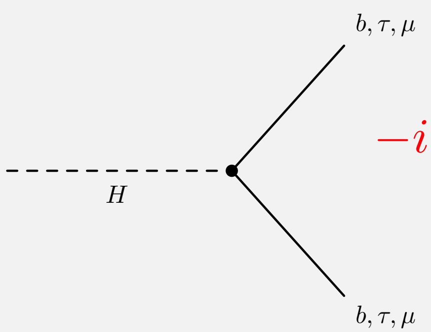
- Scattering rate:

$$\sigma \sim \sigma_{SM} + \frac{g^2 g_X^2}{M_X^2} \to \sigma_{SM}$$

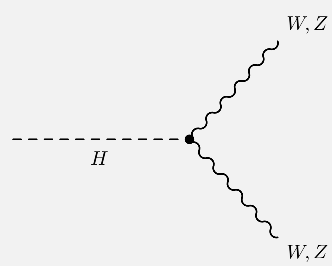
Effects of X vanish as $1/M_X^2$ for ***weak coupling***

THE HIGGS IS DIFFERENT

- Particles whose couplings are proportional to mass don't decouple



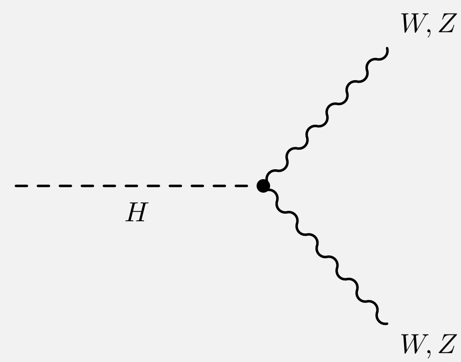
$$-i\frac{m_f}{v}$$



$$-2i\frac{M_V^2}{v}g^{\mu\nu}$$

- Longitudinal polarizations also change counting

EXAMPLE: $h \rightarrow W^+W^-$



- Rest frame of h:
  - $p_h = (M_h, 0, 0, 0)$
  - $p_{W+} = M_h/2(1, 0, 0, \beta)$
  - $p_{W-} = M_h/2(1, 0, 0, -\beta)$
  - $\varepsilon_\pm(W^+) = (0, 1, \pm i, 0)/\sqrt{2}$
  - $\varepsilon_\pm(W^-) = (0, 1, \mp i, 0)/\sqrt{2}$
  - $\varepsilon_L(W^+) = (M_h/2M_W)(\beta, 0, 0, 1)$
  - $\varepsilon_L(W^-) = (M_h/2M_W)(\beta, 0, 0, -1)$

$$A(h \rightarrow W^+W^-) = -gM_W \varepsilon(W^+) \cdot \varepsilon(W^-)$$

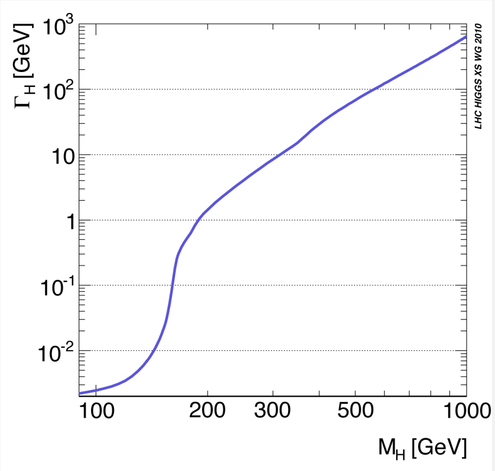
$$A(h \rightarrow W^+W^-)_{longitudinal} \approx g \frac{M_h^2}{4M_W}$$

$$A(h \rightarrow W^+W^-)_{transverse} \approx gM_W$$

The action is in the longitudinal sector!

$\beta^2 = 1 - 4M_W^2/M_h^2$

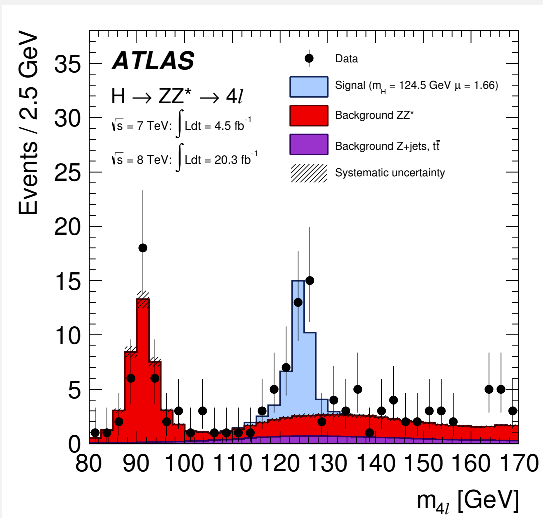
SM HIGGS IS NARROW



- How to measure Higgs width?
- A non-standard value would mean new physics
- Detector resolution a few GeV in $\gamma\gamma$ channel

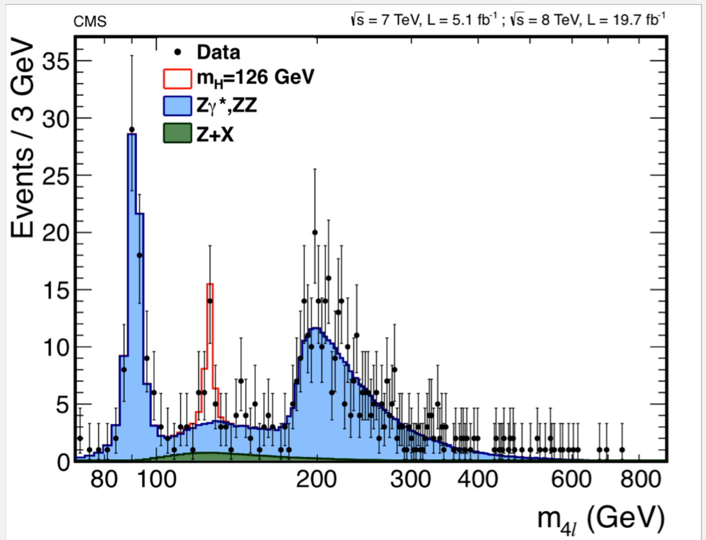
$$\Gamma_H(M_H = 125\ GeV) = 4\ MeV \pm 4\%$$

$$gg \to H \to ZZ$$



ATLAS
H → ZZ* → 4l
√s = 7 TeV: ∫Ldt = 4.5 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.3 fb⁻¹
Data
Signal (m_H = 124.5 GeV μ = 1.66)
Background ZZ*
Background Z+jets, tt̄
Systematic uncertainty
Events / 2.5 GeV
m_4l [GeV]

→H



CMS
√s = 7 TeV, L = 5.1 fb⁻¹ ; √s = 8 TeV, L = 19.7 fb⁻¹
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Events / 3 GeV
m_4l (GeV)

ASIDE ON HZZ COUPLINGS

- HZ_LZ_L couplings vestige of EWSB
  - Massless gauge theory has no longitudinal polarizations
  - On-shell HZ_LZ_L coupling ~ M_H^2/v

$$\epsilon_L(p_Z) \sim \frac{p_Z}{M_Z}$$ ➡ Enhanced at high energy

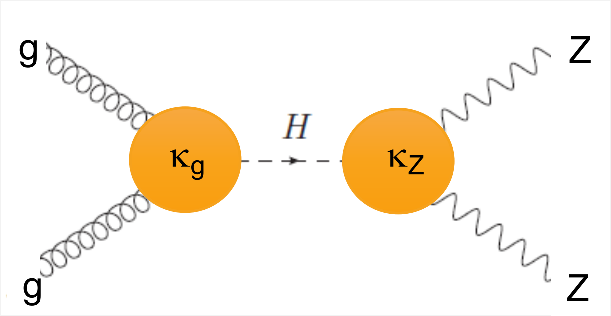
  - Expect resonance to have high energy tail

HIGGS RESONANCE

- Above resonance:

$$\sigma_{above} \sim \frac{\kappa_g^2 \kappa_Z^2}{s} \epsilon_Z^\mu \epsilon_Z^\nu$$

$$\epsilon_L^\mu \sim \frac{p^\mu}{M_Z}$$



$$I = \int \frac{1}{(s - M_H^2)^2 + (\Gamma_H M_H)^2} ds \rightarrow \frac{1}{s}$$

$$\sigma_{above} \sim \frac{\kappa_g^2 \kappa_Z^2}{M_Z^2}$$

No dependence on width

Longitudinal Z's give significant contribution above pole

ON THE HIGGS RESONANCE

- On the resonance: $\sigma_{res} \sim \frac{\kappa_g^2 \kappa_Z^2}{\Gamma_H M_H} \epsilon_Z^\mu \epsilon_Z^\nu$ $\quad \epsilon^\mu \to \mathcal{O}(1)$

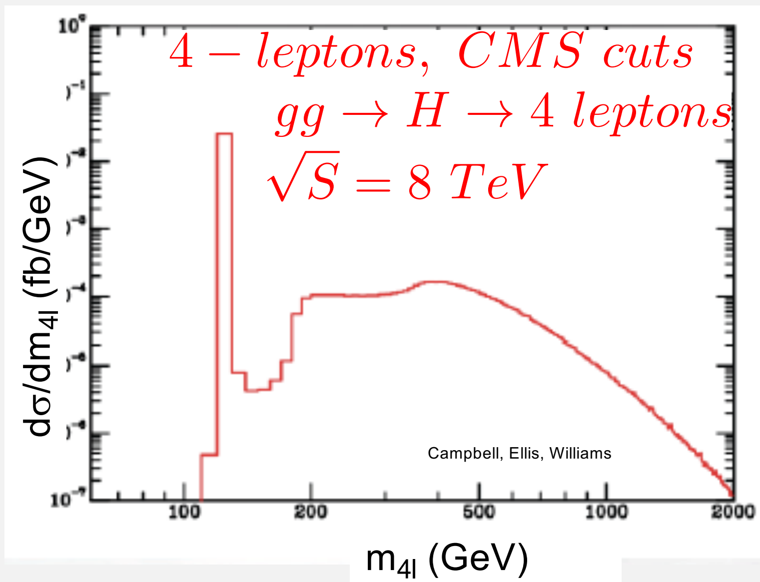
$$\frac{1}{(s - M_H^2)^2 + (\Gamma_H M_H)^2} \to \frac{\pi}{\Gamma_H M_H} \delta(s - M_H^2)$$

$$\sigma_{res} \sim \frac{\kappa_g^2 \kappa_Z^2}{\Gamma_H M_H}$$

Sensitive to resonance width

IDEA

- Measure above and below the peak: $\frac{\sigma_{above}}{\sigma_{res}} \sim \Gamma_H$



Dependence on couplings cancels

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

Caola, Melnkov, 1307.493; Kauer, Passarino,1305.2092

HOW IT WORKS

- On shell measurement of Higgs cross section consistent with SM expectations
- A larger Higgs width ➡ more off-shell events: $\Gamma_H \sim \sigma_{above}/\sigma_{res}$
- *Big assumption* is that couplings are same on and off the peak

ATLAS: $$\frac{\Gamma_H}{\Gamma_H(SM)} < 3.8$$

CMS: $$\frac{\Gamma_H}{\Gamma_H(SM)} < 3.2$$

ATLAS: 1808.01191
CMS:1901.00174

Example: Anomalous HZZ Coupling

$$O_1 = -M_Z^2 \frac{H}{v} Z_\mu Z^\mu$$

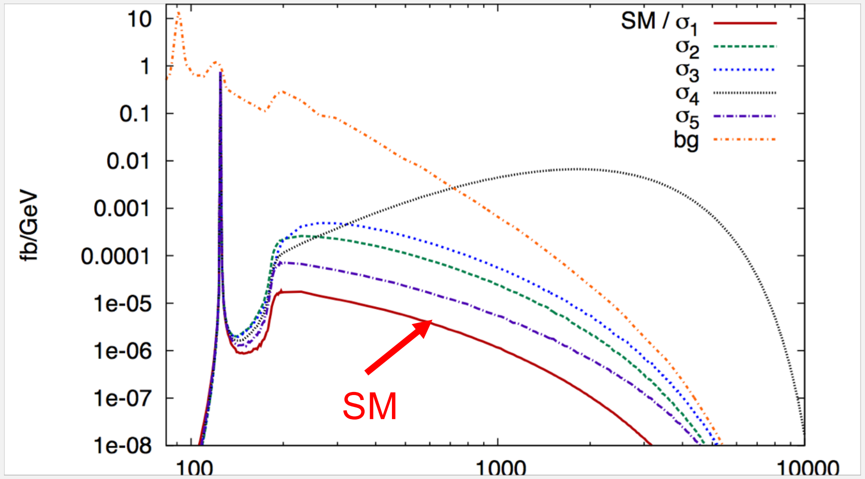
$$O_2 = -\frac{1}{2}\frac{H}{v} Z_{\mu\nu} Z^{\mu\nu}$$

$$O_3 = -\frac{1}{2}\frac{H}{v} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

$$O_4 = 2\frac{H}{v} Z_\mu \partial^2 Z^\mu$$

$$O_6 = -\frac{M_Z^2}{M_H^2 v} Z_\mu Z^\mu \partial^2 H$$

Anomalous HZZ couplings can lead to an increase in the number of events in the off-shell tail.

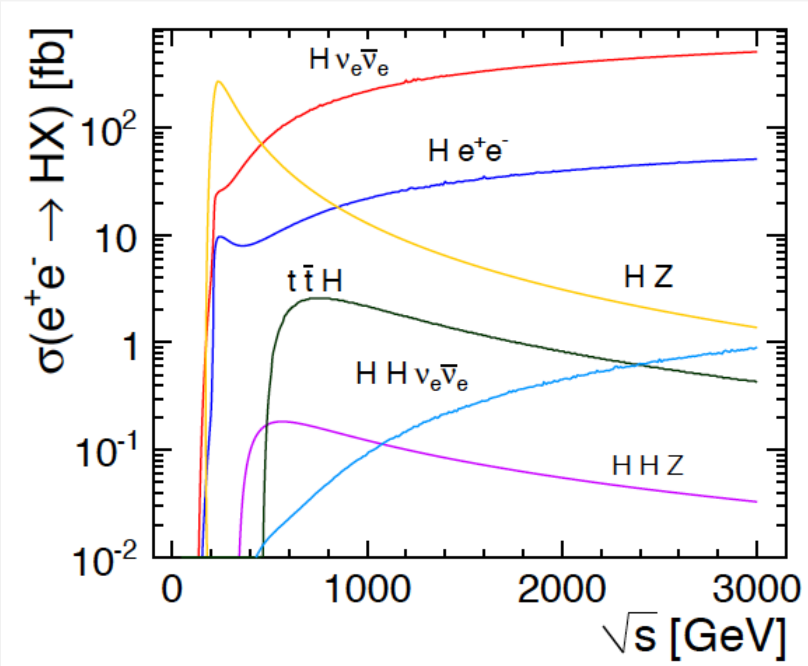


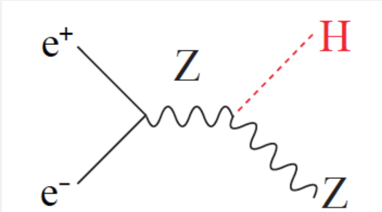
M_{4l} (GeV)

Strong modification of the M_{4l} shape

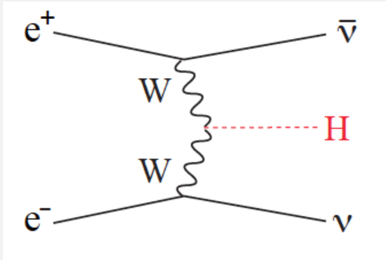
Gainer, Lykken, Matchev, Mrenna, Park, 1403.4951

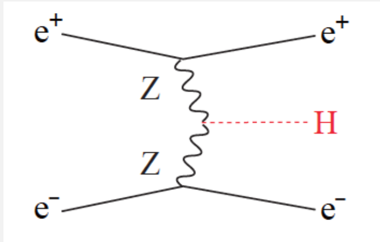
e^+e^- COLLIDERS





Note sharp threshold





HIGGS WIDTH AT e^+e^- COLLIDERS

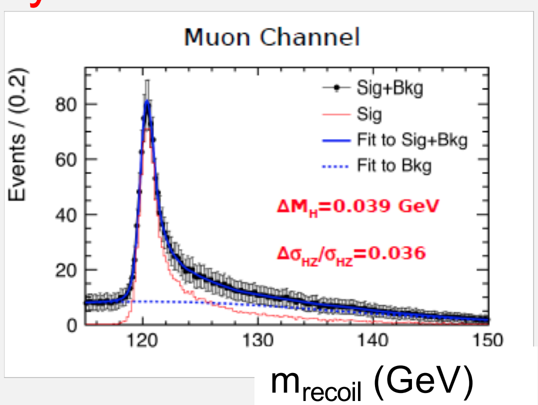
- Use recoil technique: $e^+e^- \to Zh$; tag $Z \to \mu^+\mu^-$, e^+e^-
  - Reconstruct recoil mass, $m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{l^+l^-})^2 - \mid \vec{p}_{ll} \mid^2$
  - Identify Higgs independent of decay
  - This gives: $\sigma(Zh) \sim (g_{hZZ})^2$
  - Classify the rest of the events to measure $BR(h \to XX)$

ILC250:

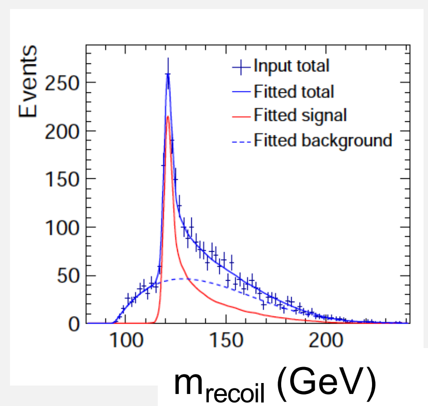
$\frac{\Delta\sigma}{\sigma} = 2.5\%$

$\frac{\Delta g_{hZZ}}{g_{hZZ}} = 1.3\%$

$\Delta\Gamma_h = 11\%$



$e^+e^- \to Zh$, ILC at $\sqrt{s}$=250 GeV, 250 fb^{-1}



$e^+e^- \to Zh$, CLIC at $\sqrt{s}$=350 GeV, 500 fb^{-1}

CLIC350:

$\frac{\Delta\sigma}{\sigma} = 4\%$

$\frac{\Delta g_{hZZ}}{g_{hZZ}} = 2\%$

HIGGS WIDTH AT e^+e^- COLLIDERS

- Recoil technique gives independent measurements of total width and branching ratios
- Get total Higgs width: $\Gamma_h = \frac{\Gamma(h \to ZZ)}{BR(h \to ZZ)} \sim \frac{\sigma(Zh)}{BR(h \to ZZ)}$
- At higher energies can also use $e^+e^- \to \nu\nu h$

$$\Gamma_h = \frac{\Gamma(h \to WW^*)}{BR(h \to WW^*)}$$

Advantage: Coupling extractions don't need assumptions about total width
Clean measurement of total width

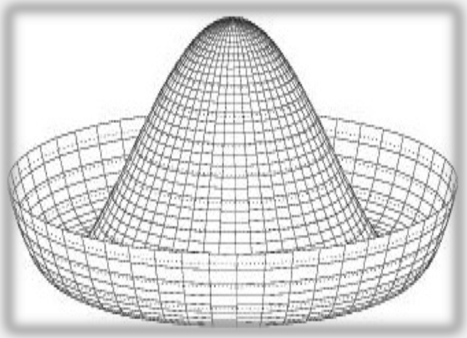
HIGGS SELF-COUPLING BIG MILESTONE

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

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

- SM is perturbative

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



TWO HIGGS PRODUCTION AT LHC

- Cross section has spin-0 and spin-2 contributions

$$\frac{d\sigma(gg\rightarrow HH)}{dt}=\frac{\alpha_s^2}{32768\pi^3 v^4}\left(\mid F_0\mid^2+\mid F_2\mid^2\right)$$

- $M_t^2 >> s, p_T^2$

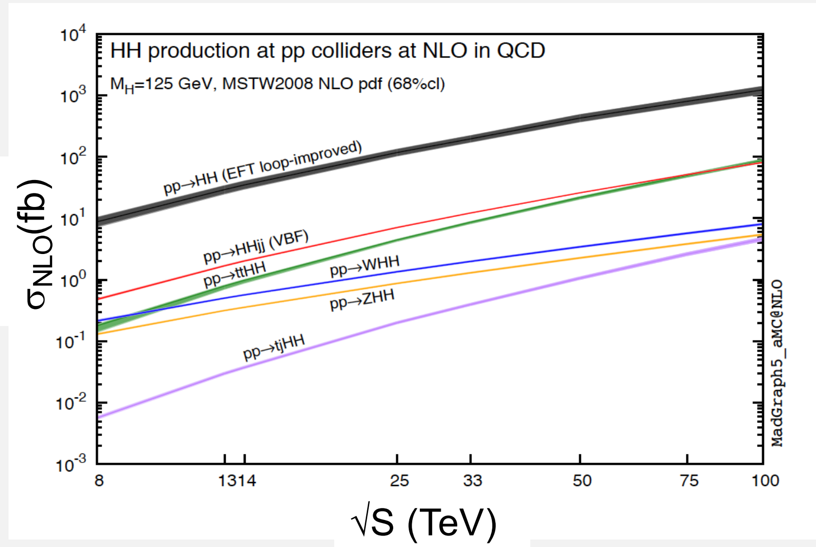
$$F_0\rightarrow -\frac{4}{3}+\frac{4M_H^2}{s-M_H^2}(\lambda_3)$$

$$F_2\rightarrow 0$$

HHH coupling (1 for SM)

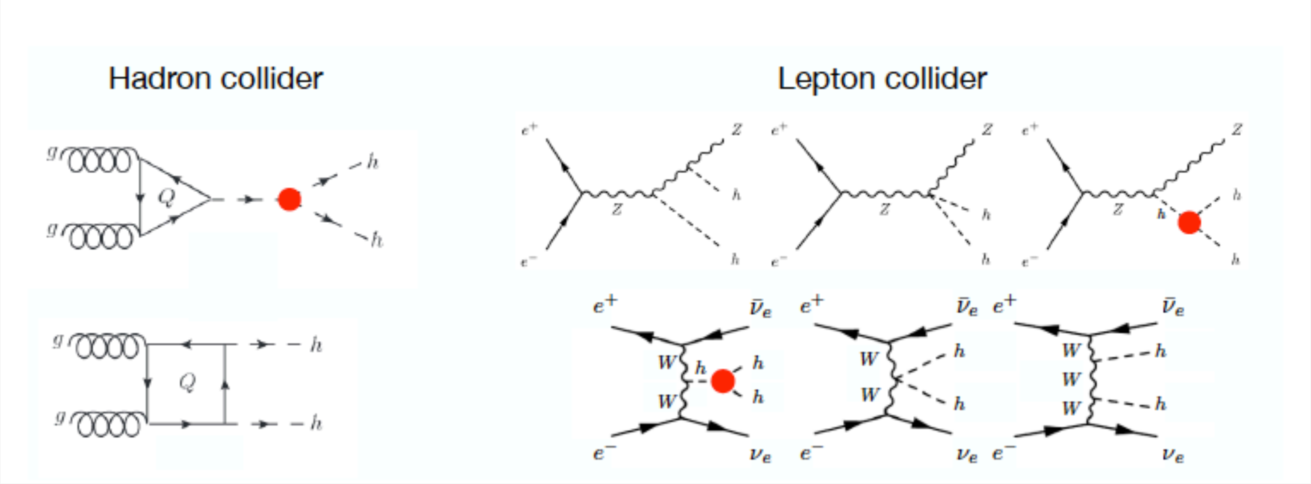
- For large s, dependence on λ_3 suppressed
- More sensitivity to negative λ_3
- Exact cancellation at threshold
- b quark contribution ~2%

SMALL RATES FOR HH



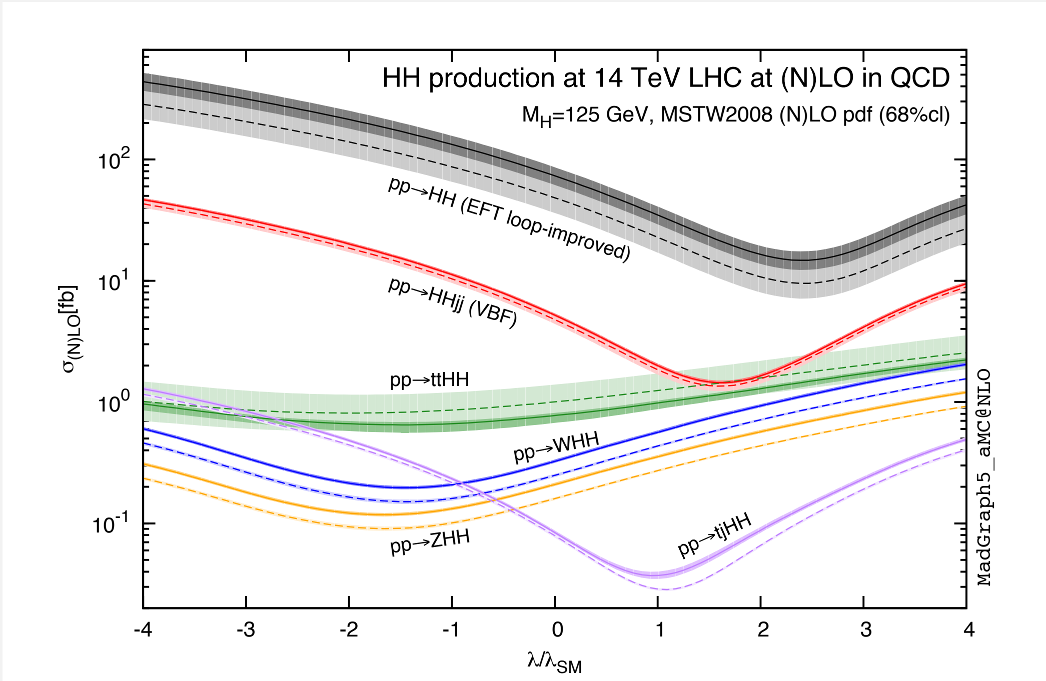
- Only gluon fusion likely to be relevant
- Large increase in hh rate at high energy

SCENARIO WHERE ONLY HHH COUPLING VARIES



250 GeV lepton colliders can't do this

DEPENDENCE ON HHH

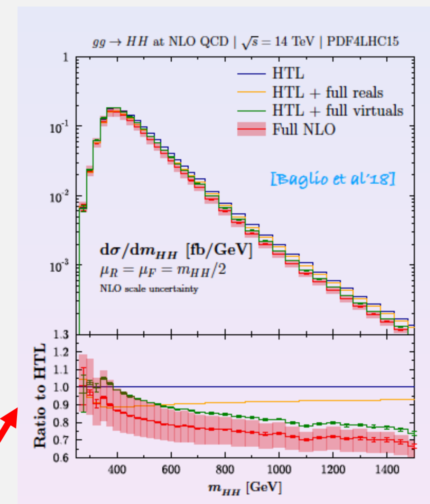


Everything SM except λ_3

SM THEORY UPDATE

- Now know NLO with full mass dependence (2-loop virtual)
  - Reduces rate by -14%; changes distributions
- NNLO+NNLL in large top mass limit
  - Increases NLO by +5%
- 14 Tev: σ_{hh}= 36.69 -4.9%+2.1% (fb)
- At high m_{HH}, large uncertainties
- Top mass uncertainties:

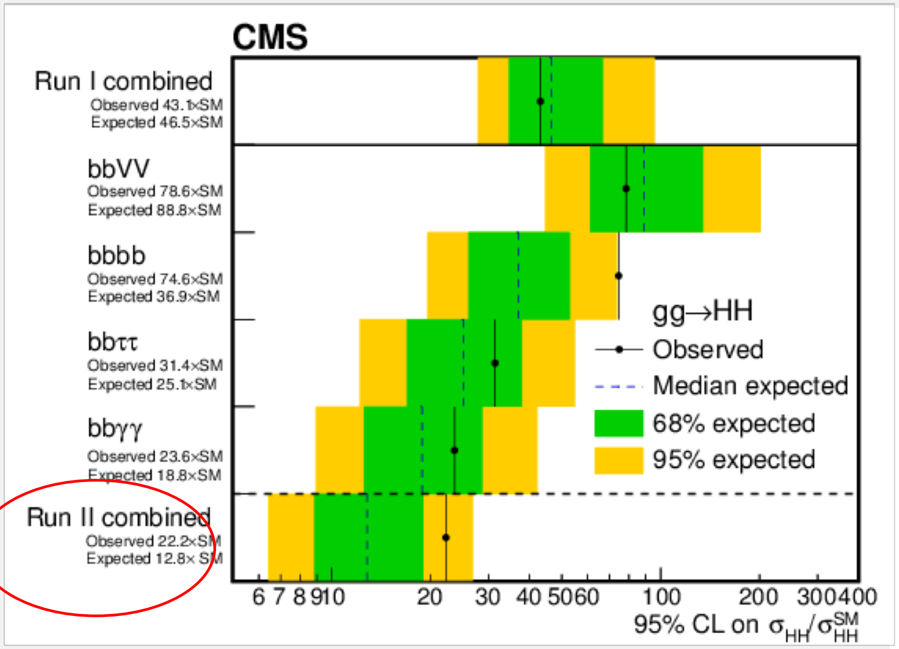
$$\frac{d\sigma(gg\to HH)}{dQ}\Big|_{Q=300\text{ GeV}} = 0.0312(5)^{+9\%}_{-23\%}\ \text{fb/GeV},$$



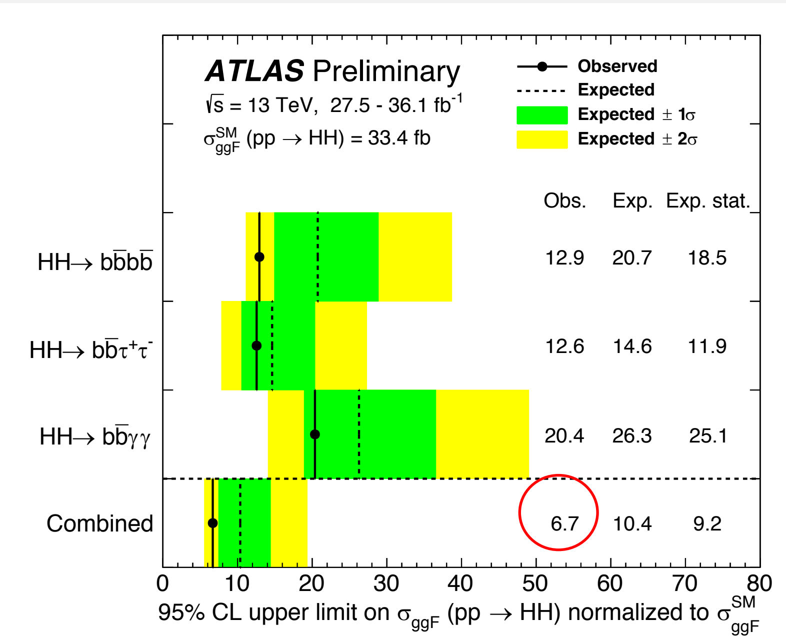
Relative to infinite top mass limit

Grazzini, Heinrich, Jones,Kallweit,Kerner, Lindert, Mazzitelli,Heinrich, Jones, arXiv:1803.02463; Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk,Zirke,arXiv:1608.04798; Baglio, Campanario, Glaus,Muhlleitner, Spira, Streicher, arXiv:1811.05692

CURRENT STATUS OF SM SEARCHES

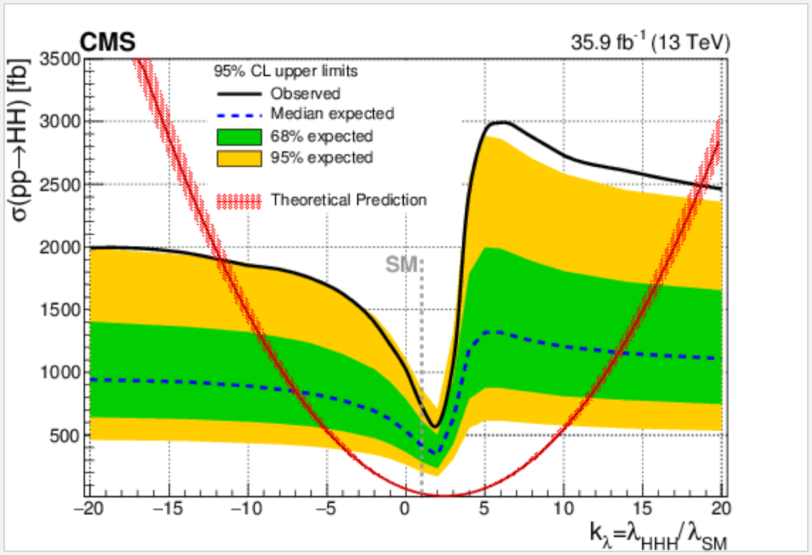


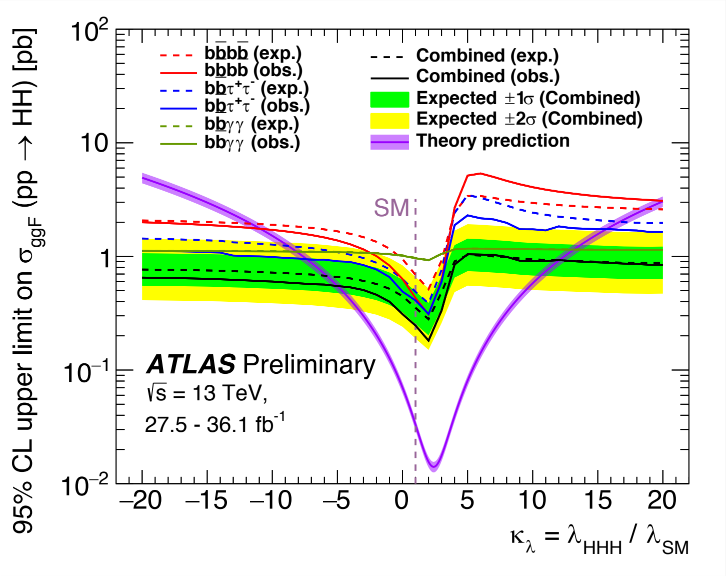
CMS, 1811.09689



ATLAS-CONF-2018-043

CURRENT LIMITS





Limits are asymmetric

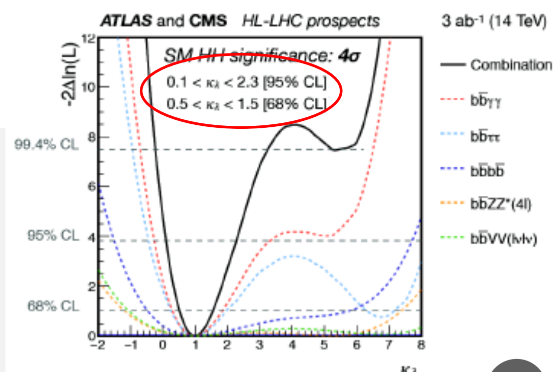
$-5 < \kappa_\lambda < 12$

HH AT HL-LHC

- Expected significance (SM) with and without systematics at HL-LHC

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

4σ expected with ATLAS+CMS!



PROJECTIONS AT FUTURE COLLIDERS

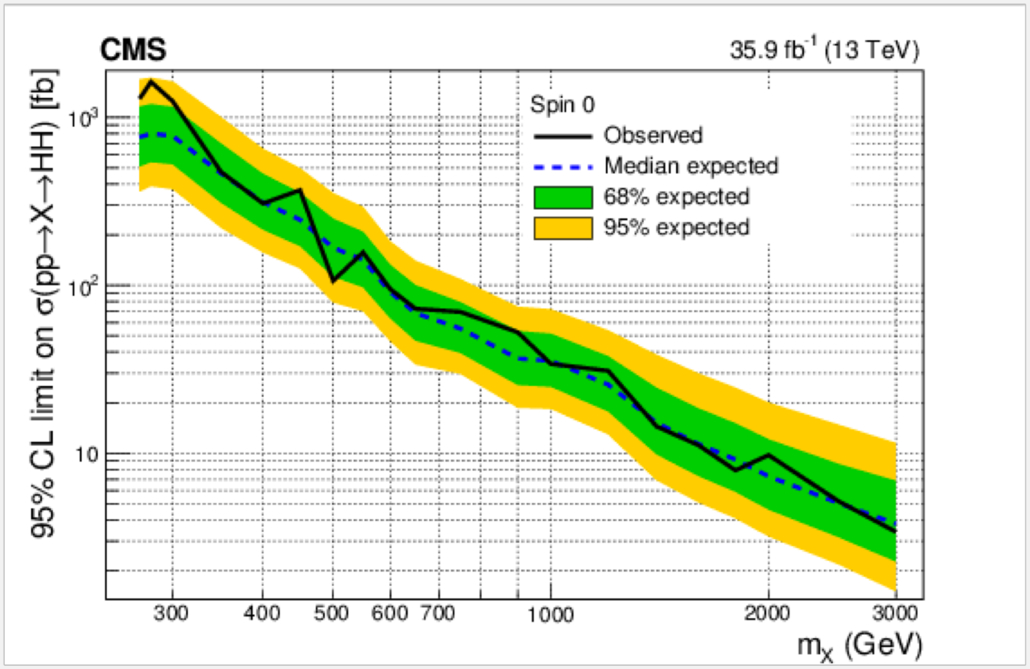
- Assuming only λ_3 non-zero

Numbers are from collaborations;
numbers in () independent calculation

collider	Error on λ_3	Running years
HL-LHC	$^{+60}_{-50}$% (50%)	12
HE-LHC	10-20% (n.a.)	20
ILC_{250}	–	
ILC_{350}	–	
ILC_{500}	27% (27%)	21
$CLIC_{380}$	–	
$CLIC_{1500}$	36% (36%)	15
$CLIC_{3000}$	$^{+11}_{-7}$% (n.a.)	23
FCC-ee_{240}	–	
FCC-ee_{365}	–	
FCC-ee/eh/hh	5% (5%)	13
CEPC	–	

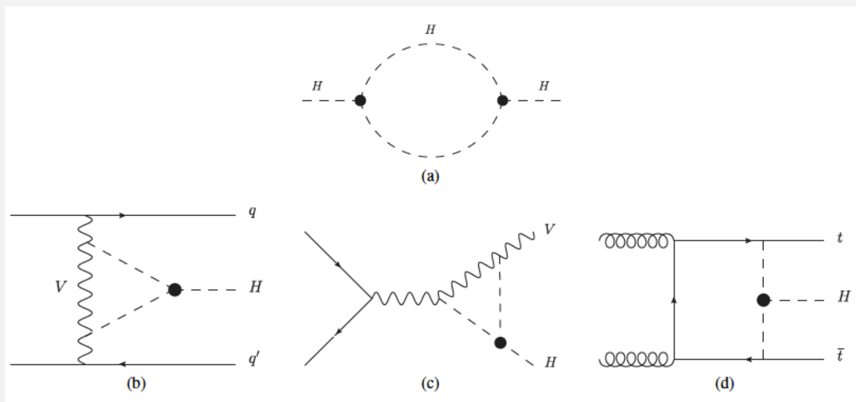
De Blas, et al, 1905.03764

LIMITS ON RESONANT PRODUCTION



COMPLEMENTARITY WITH SINGLE HIGGS PRODUCTION

- Implicit dependence on λ_3

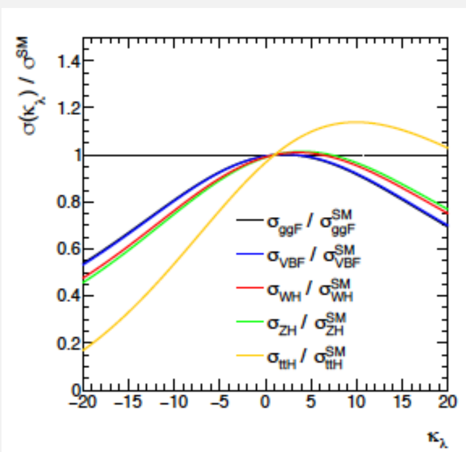


COMPLEMENTARITY WITH SINGLE HIGGS PRODUCTION

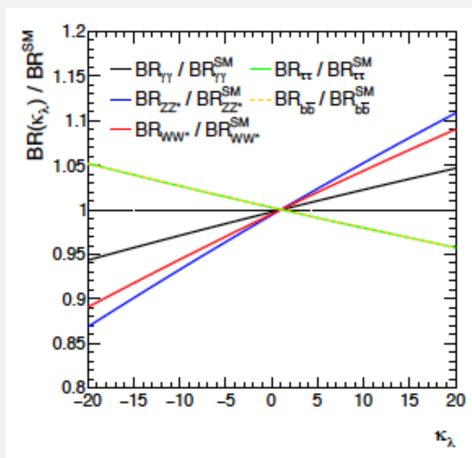
- ATLAS fit to single Higgs production with 80 fb^{-1} (2019)

$$\kappa_\lambda = 4.0^{+3.7}_{-3.6}(\text{stat.})^{+1.6}_{-1.5}(\text{exp.})^{+1.3}_{-0.9}(\text{sig.th})^{+0.8}_{-0.9}(\text{bkg.th})$$

$$-3.2 < \kappa_\lambda < 11.9 \quad @ \, 95\% \text{ CL}$$



Dawson, CTEQ2019



Similar to results from HH production