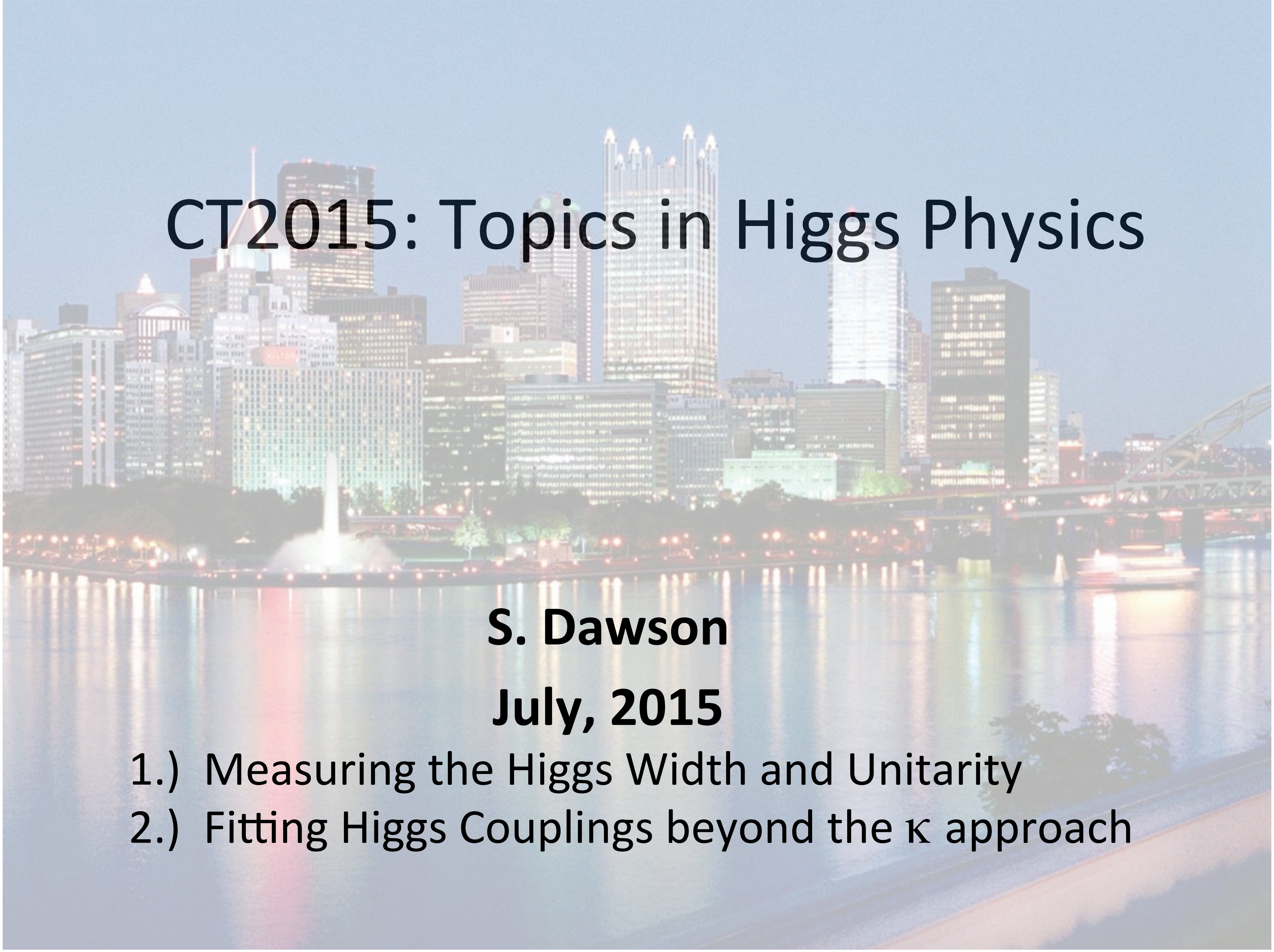


CT2015: Topics in Higgs Physics

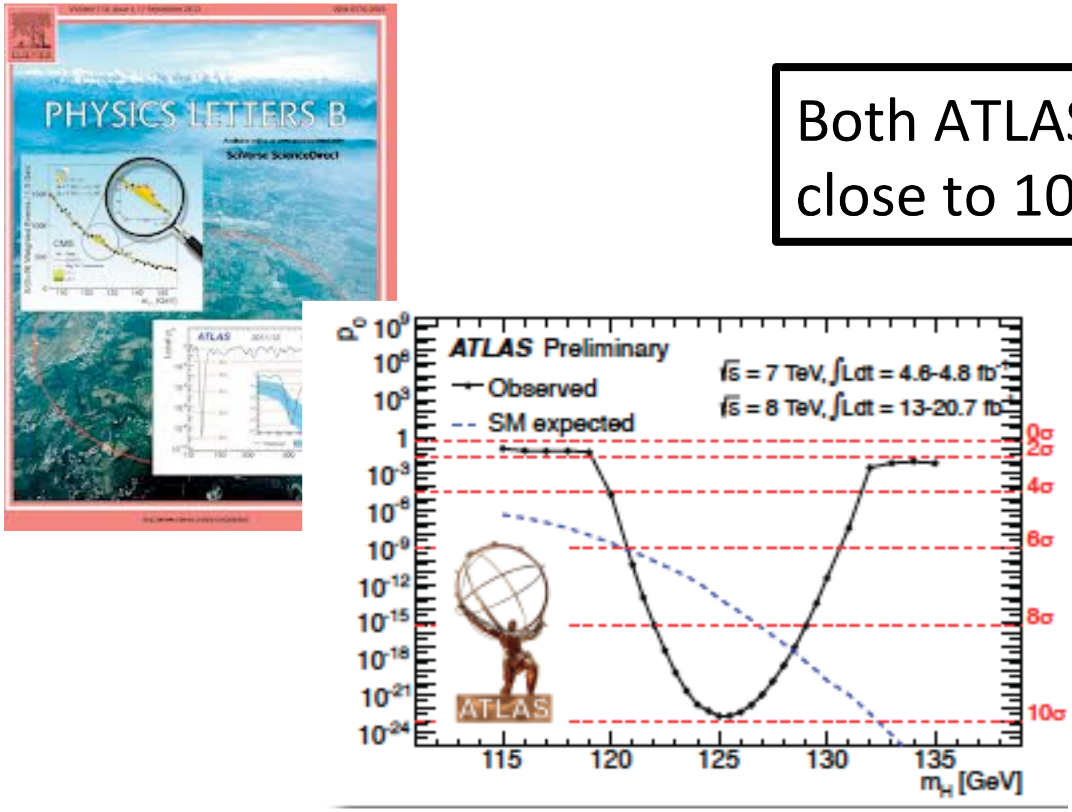
S. Dawson

July, 2015

1.) Measuring the Higgs Width and Unitarity
2.) Fitting Higgs Couplings beyond the κ approach

We discovered a Higgs boson!

- The Standard Model is very predictive *(testable!)*
- Only free parameter is M_H



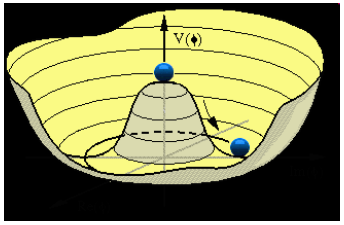
Both ATLAS and CMS have close to 10σ significance

Probability of 10 σ event being random is 10^{-23}

SM is Very Simple

- Standard Model includes complex Higgs SU(2) doublet

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$



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

$$V = \mu^2 \Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$ Invariant under $\Phi \rightarrow - \Phi$

- If $\mu^2 < 0$, then spontaneous symmetry breaking
- Minimum of potential at:

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \Phi = e^{\frac{i\omega\cdot\sigma}{v}}\begin{pmatrix} 0 \\ \frac{H+v}{\sqrt{2}} \end{pmatrix}$$

  - Choice of minimum breaks gauge symmetry

More on SM Higgs Mechanism

- Couple Φ to SU(2) x U(1) gauge bosons (W_i^μ, i=1,2,3; B^μ)

$$L_S = (D_\mu \Phi)^+ (D^\mu \Phi) - V(\Phi)$$

$$D_\mu = \partial_\mu - i\frac{g}{2}\sigma^i W^i{}_\mu - i\frac{g^{'}}{2}B_\mu$$

Couplings fixed by
gauge invariance

- Gauge boson mass terms from:

$$(D_\mu \Phi)^+ D^\mu \Phi \rightarrow \ldots + \frac{1}{8}(0,v)(gW_\mu^a\sigma^a + g'B_\mu)(gW^{b\mu}\sigma^b + g'B^\mu)\begin{pmatrix}0\\ v\end{pmatrix} + \ldots$$

$$\rightarrow \ldots + \frac{v^2}{8}\left(g^2(W_\mu^1)^2 + g^2(W_\mu^2)^2 + (-gW_\mu^3 + g'B_\mu)^2\right) + \ldots$$

Generated masses (ie longitudinal component) for W and Z

Recap of SM Higgs Mechanism

- Generate mass for W,Z using Higgs mechanism
  - Higgs VEV breaks SU(2) x U(1)
  - Single Higgs doublet is minimal case (singlet doesn't work)
- Before spontaneous symmetry breaking:
  - Massless W_i, B, Complex Φ
  - *(Massless gauge bosons have only transverse polarizations)*
- After spontaneous symmetry breaking:
  - Massive $W^{\pm}$,Z; massless γ; physical Higgs boson H

Spontaneous symmetry breaking generates longitudinal components of gauge bosons

* Count degrees of freedom

Higgs Parameters

- G_F measured precisely

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

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

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

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

- Trade μ^2, λ for v^2, M_H^2

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

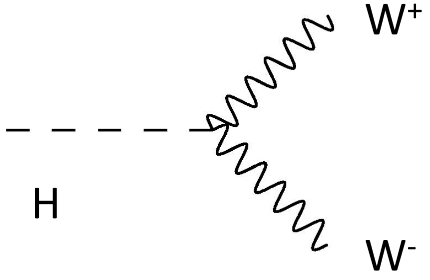
$$v^2 = -\frac{\mu^2}{2\lambda}$$

$$M_H^2 = 2v^2\lambda$$

  - Large M_H →strong Higgs self-coupling
  - A priori, Higgs mass can be anything

Example: $H \rightarrow W^+W^-$

- Rest frame of H:
  - $\varepsilon_\pm(W^+)=(0,1,\ \pm i,0)/\sqrt{2}$
  - $\varepsilon_\pm(W^-)=(0,1,\ \ i,0)/\sqrt{2}$
  - $\varepsilon_L(W^+)=(M_H/2M_W)(\beta,0,\ 0,1)$
  - $\varepsilon_L(W^-)=(M_H/2M_W)(\beta,0,\ 0,-1)$



$$A(H \to W^+W^-) = -gM_W\epsilon(W^+)\cdot\epsilon(W^-)$$

$$A(H \to W_L^+W_L^-) = g\frac{M_H^2}{4M_W}$$

$$A(H \to W_T^+W_T^-) = gM_W$$

The action is in the longitudinal sector!

Longitudinal interactions of gauge bosons with Higgs are enhanced at large $p^2=M_H^2$

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

What about fermion masses?

- Fermion mass term:

$$L = m\overline{\Psi}\Psi = m\left(\overline{\Psi}_L \Psi_R + \overline{\Psi}_R \Psi_L\right)$$

← Forbidden by SU(2)xU(1) gauge invariance

- Left-handed fermions are SU(2) doublets $Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$

- Scalar couplings to fermions: $L_d = -\lambda_d \overline{Q}_L \Phi d_R + h.c.$

- Effective Higgs-fermion coupling

$$L_d = -\frac{\lambda_d}{\sqrt{2}} (\overline{u}_L, \overline{d}_L) \begin{pmatrix} 0 \\ v + H \end{pmatrix} d_R + h.c.$$

Fermion Masses, 2

- M_u from $\Phi_c = i\sigma_2\Phi^*$ (not allowed in SUSY)

$$\Phi_c = \begin{pmatrix} \overline{\phi}^0 \\ -\phi^- \end{pmatrix} \qquad L = -\lambda_u \overline{Q}_L \Phi_c u_R + hc \qquad \boxed{\lambda_u = \frac{M_u\sqrt{2}}{v}}$$

- Higgs-fermion couplings proportional to mass
- No flavor violating Higgs fermion couplings

SUSY models always have at least 2 Higgs doublets

*tcH, μeH couplings etc smoking guns for new physics

Review of Higgs Couplings

- Very precise predictions
  - 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 massless gauge bosons at 1-loop

$$\kappa_g \frac{\alpha_s}{12\pi} \frac{H}{v} G^A_{\mu\nu} G^{A,\mu\nu} + \kappa_\gamma \frac{\alpha}{8\pi} \frac{H}{v} F_{\mu\nu} F^{\mu\nu} + \kappa_{Z\gamma} \frac{\alpha}{8\pi s_W} \frac{H}{v} F_{\mu\nu} Z^{\mu\nu}$$

  - Higgs self-couplings proportional to M_H^2

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

Only unpredicted parameter is M_H

Model Makes Predictions

- Four free parameters in gauge-Higgs sector (g, g’, μ, λ)
  - Conventionally chosen to be
    - α=1/137.0359895(61)
    - G_F =1.16637(1) x 10^{-5} GeV $^{-2}$
    - M_Z=91.1875 ± 0.0021 GeV
    - M_H=125.09 ±.21 ±.11 GeV
  - Express everything else in terms of these parameters

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{\pi\alpha}{2\left(1-\frac{M_W^2}{M_Z^2}\right)M_W^2} \quad \Rightarrow \text{Predicts } M_W$$

The Higgs and EW Fits

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

$$\frac{M_W}{M_Z} \equiv \cos\theta_W$$

- Δr is a physical quantity which incorporates 1-loop corrections

- Contributions to Δr from top quark and Higgs loops

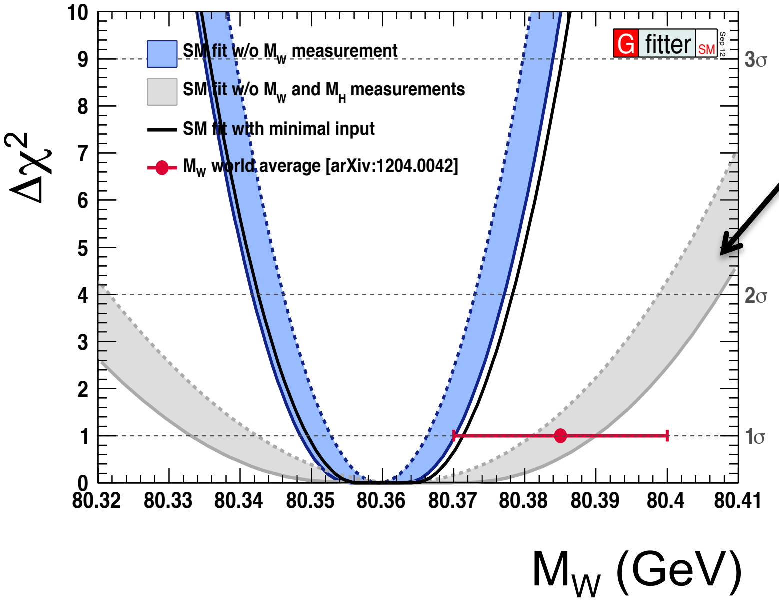
$$\Delta r^t = -\frac{3G_F M_t^2}{8\sqrt{2}\pi^2}\left(\frac{\cos^2\theta_W}{\sin^2\theta_W}\right)$$

Extreme sensitivity of precision measurements to M_t

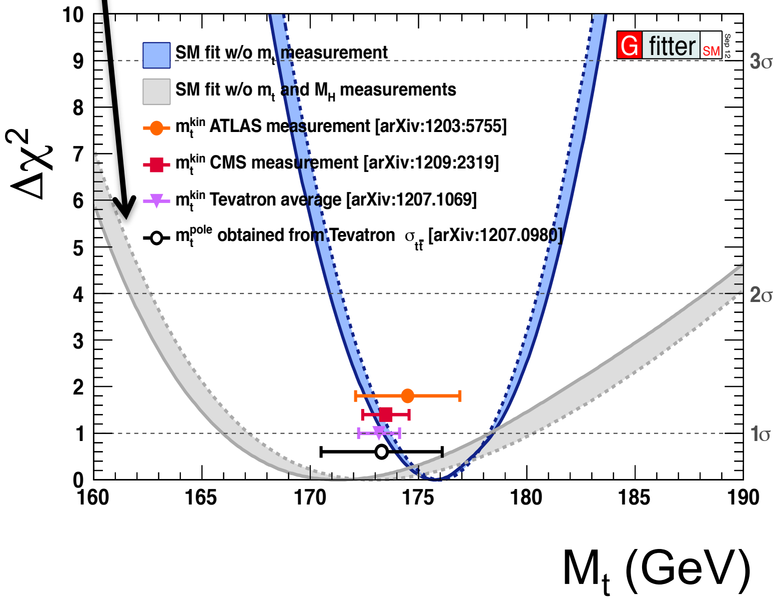
$$\Delta r^H = \frac{11G_F M_W^2}{24\sqrt{2}\pi^2}\left(\ln\frac{M_H^2}{M_W^2}\right)$$

If we removed the Higgs, this formula would be infinite

Precision Physics After Higgs Discovery

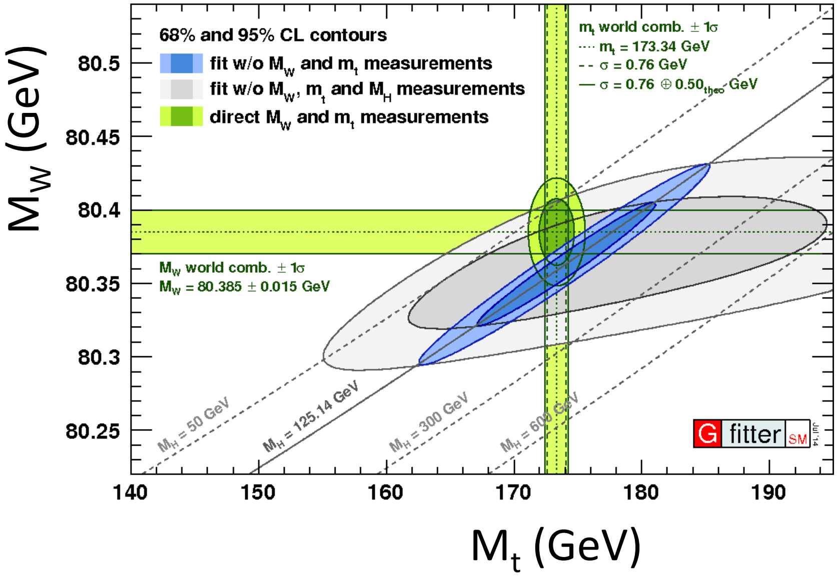


Fit without Higgs



EW fits improved by addition of Higgs

The SM Works!

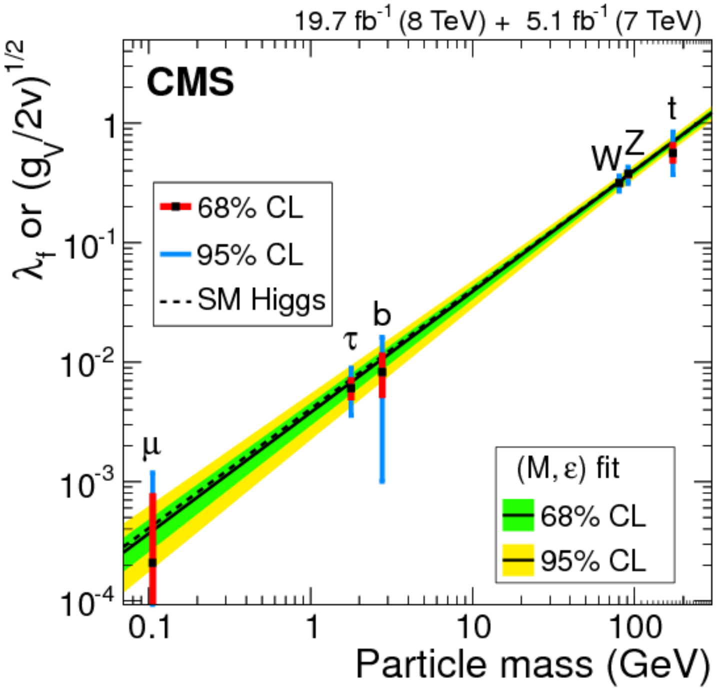


Measurements sensitive to $\ln(M_H)$ terms

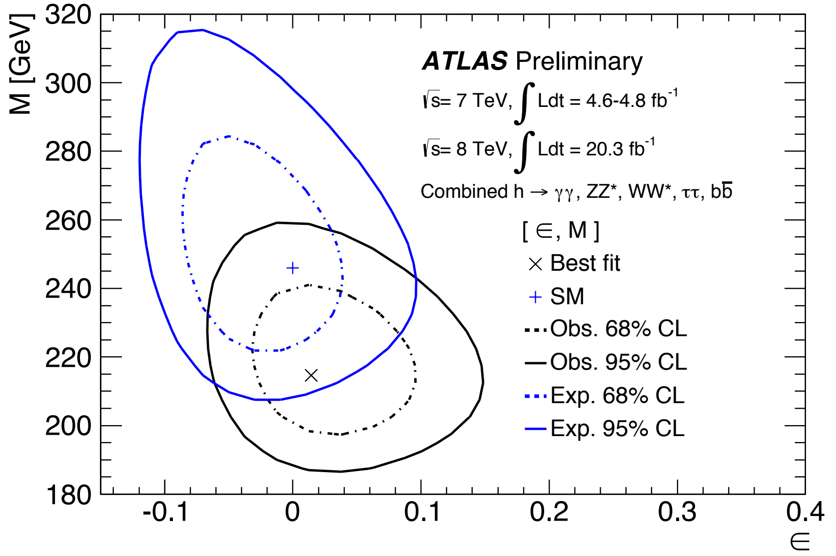
Corollary: New Physics highly restricted by data

**So why are we still talking about BSM physics in the Higgs sector?*

No Unknown Parameters in SM



$$L \sim \left(\frac{m_f}{M}\right)^{1+\epsilon} H\bar{f}f + \left(\frac{M_V^{2+2\epsilon}}{M^{1+2\epsilon}}\right) HV_\mu V^\mu$$



Everything looks reasonably consistent with SM

At the 10-30% level:

- Fermion couplings to b, t, τ ✔
- Gauge boson couplings to W/Z/g/γ ✔
- Higgs H^2 coupling ✔
- No information on HZγ, 2nd generation fermions, H^3, H^4 couplings….
- Generically, Higgs coupling deviations in BSM:

$$\mathcal{O}\left(\frac{v^2}{M^2}\right) \sim 5\%\left(\frac{1\ TeV}{M}\right)^2$$

Much work to do!

Things we need to know

- How close are Higgs couplings to SM predictions?
- Does the Higgs come from a scalar potential?
- Does the Higgs couple to things we don't see?
- What is the Higgs width? Spin? Parity? Mass?
- Are there more Higgs particles?

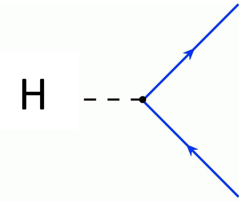
These questions will be at the center of the 13 TeV Higgs physics program

Higgs Decays

- At tree level Higgs mostly decays to heaviest particle allowed
  - Coupling proportional to mass
  - Largest uncertainty on Higgs branching ratios comes from M_b
  - BSM models often have enhanced Hbb couplings (e.g. SUSY at large tan β)
- At loop level: $H \rightarrow \gamma\gamma$ important
  - Precision discovery channel
  - Sensitive to new physics

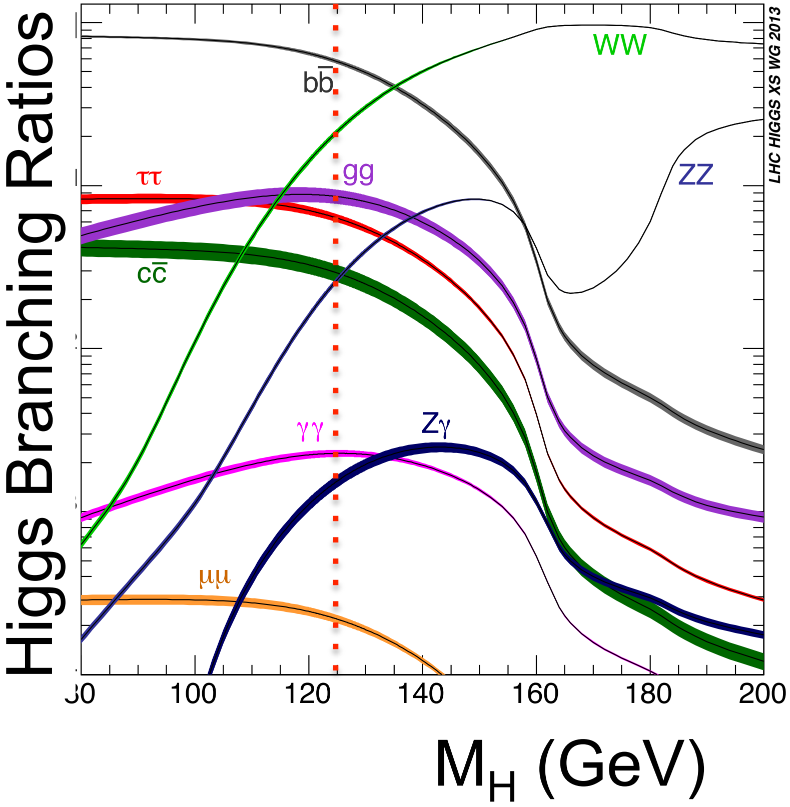
Higgs Decays

- $H \to f\bar{f}$ proportional to M_f^2



$$\frac{BR(H \to b\bar{b})}{BR(H \to \tau^+\tau^-)} \sim N_c \left(\frac{M_b^2}{M_\tau^2} \right)$$

$$\Gamma_{ff} = N_c \frac{G_F}{4\sqrt{2}\pi} M_H M_f^2 \left(1 - \frac{4M_f^2}{M_H^2} \right)^{3/2}$$



For $M_H < 2M_W$, decays to $b\bar{b}$ dominate

[Higgs Cross Section working group]

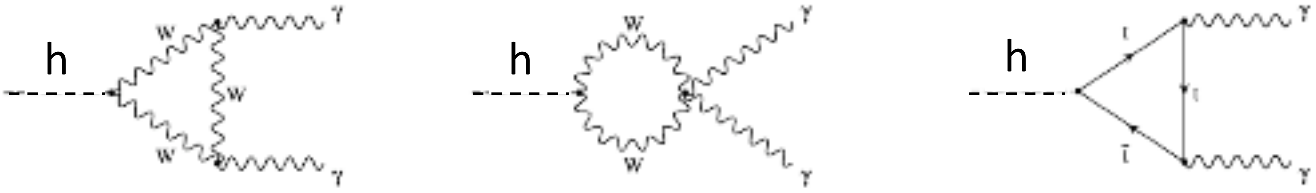
Higgs Decays to Photons

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

Note opposite signs of t/W loops

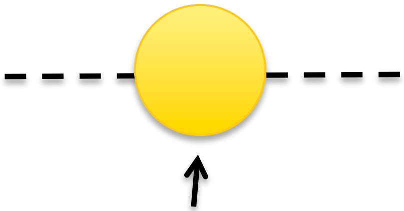
$$\Gamma(H\to\gamma\gamma)\sim\frac{\alpha^3}{256\pi^2 s_W^2}\frac{M_H^3}{M_W^2}\,|\,7-\frac{16}{9}+\ldots\,|^2$$

W top



Why do we expect BSM in Loops?

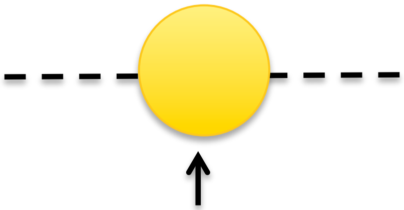
- Generically, solutions to naturalness involve new particles



SM particles

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

Λ is scale of new physics



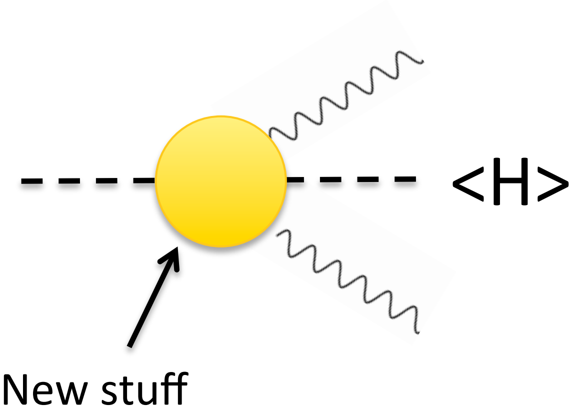
New stuff

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

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

Why care about H→ γγ?

- New particles lead to deviations in Higgs couplings



MSSM light stops generically contribute (no mixing):

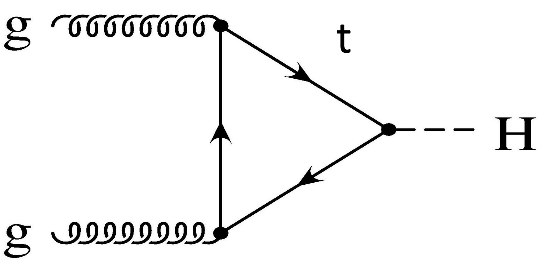
$$\kappa_g^2 = \frac{\sigma(gg \to H)}{\sigma(gg \to H)\,|_{SM}} \sim 1 + \left(\frac{700\ GeV}{\tilde{m}_t}\right)^2 3\%$$

Target precision < 3%

As LHC limits on new particles increase, target precision decreases

How do we make a Higgs boson?

- Largest production rate is from gluon fusion
- 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



For large M_t

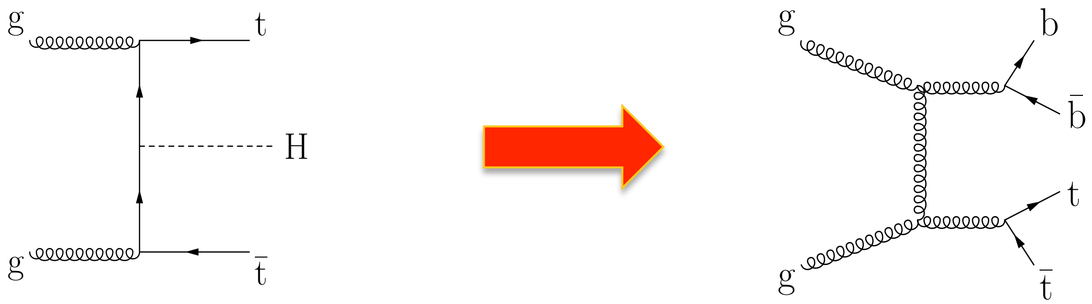
$$L \rightarrow -\frac{\alpha_s}{12\pi v} H G^A_{\mu\nu} G^{A,\mu\nu}$$

Gluon fusion sensitive to new strongly interacting particles: Ex: squarks or heavy colored fermions

*Heavy chiral fermions don't decouple since coupling is proportional to mass

ttH Production

- Can unambiguously measure ttH Yukawa coupling
- Small rates, large backgrounds

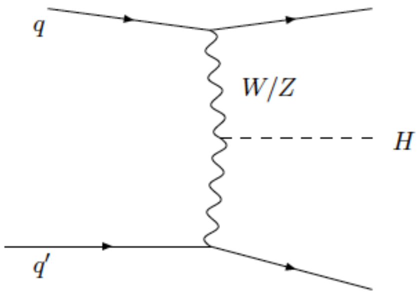


- Most of ttH cross section at LHC is from gluon initial states

*CMS significance for observation of ttH final state in Run 1 is σ=3.5

Vector Boson Scattering

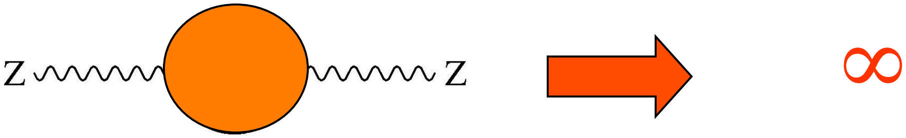
- Outgoing jets peaked in forward direction
- Large jet-jet invariant mass, large angular separation
- Cuts are effective in separating from gluon fusion background



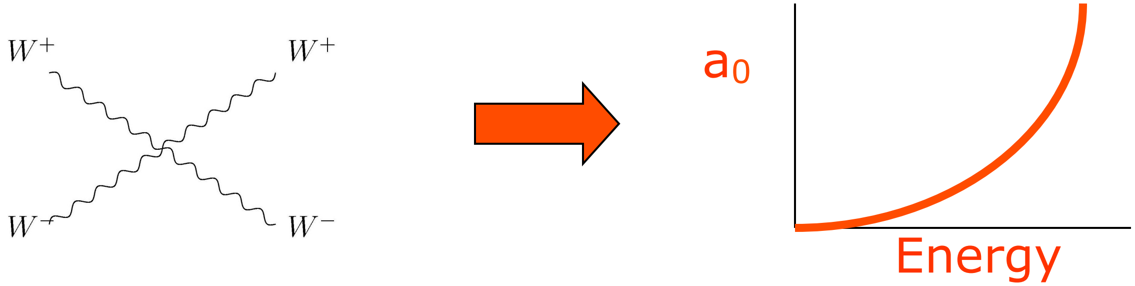
- $W^+W^- \rightarrow W^+W^-$ is a physical process!
- Without a Higgs, this process would grow with energy (unitarity violation)

Higgs has special job in SM

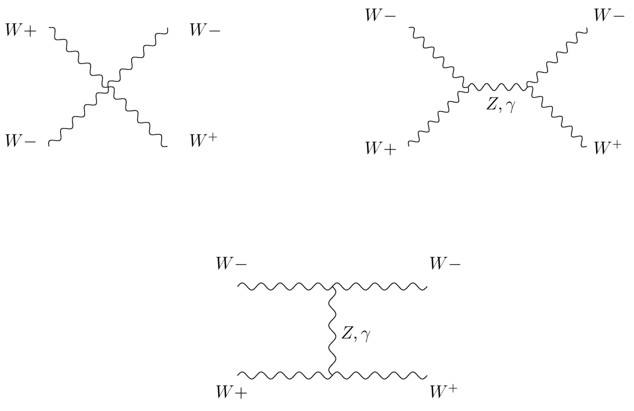
- Massive W and Z's have longitudinal polarizations
- Longitudinal interactions spoil nice properties of gauge theories:
  - Loops are not finite without Higgs



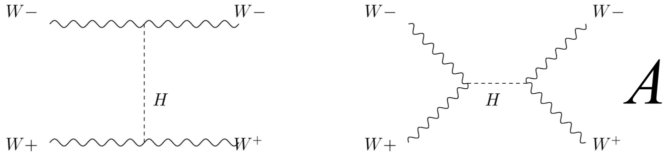
  - Scattering amplitudes grow with energy



VV Scattering



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



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

E^4 terms cancel between TGC and QGC

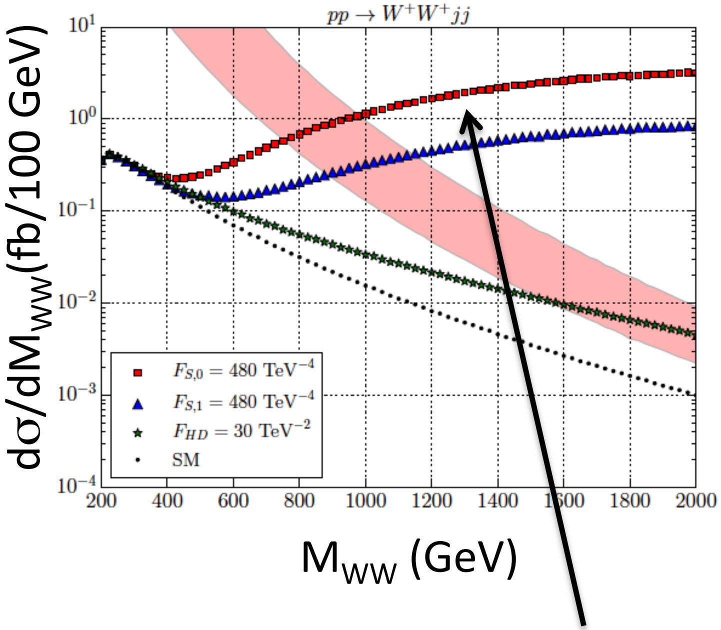
Terms which grow with energy cancel for $E >> M_H$

This cancellation requires $M_H < 800$ GeV

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

VBF Scattering: W^+W^+jj

- New physics effects grow like s/Λ^2, spoils cancellations
- Unitarity violation above red band (region of validity) of theory

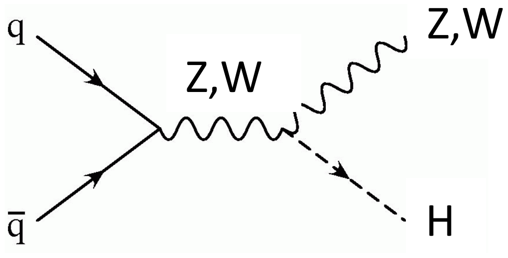


Note growth of new physics effects with M_{WW}

[Kilian,Ohl,Reuter Sekulla]

Higgstrahlung

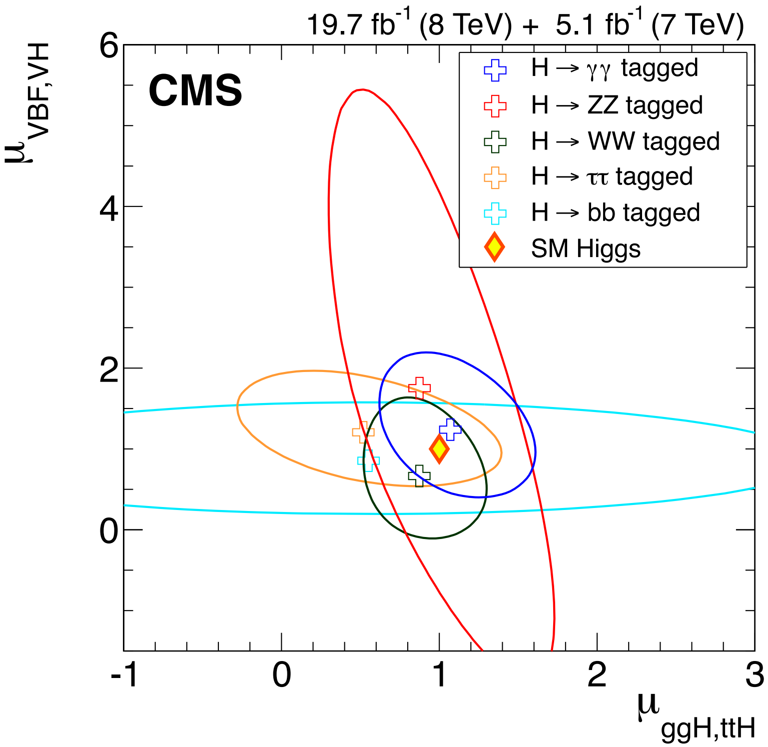
- Small rate, clean signal
- High p_T tails sensitive to new physics



Sensitive to same couplings as VBF

Separate initial states

Separate quark and gluon initial states



Simplistic cheat sheet:

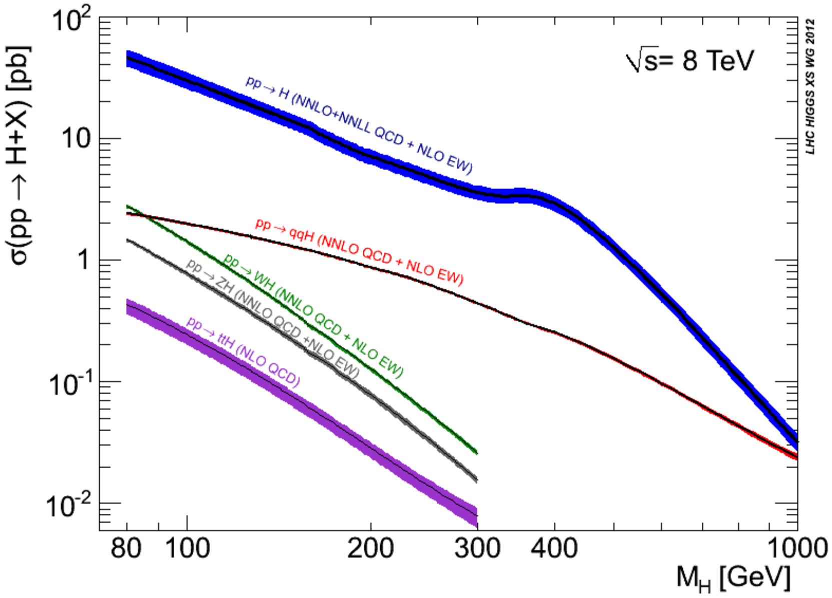
Gluon fusion: Laboratory for higher order QCD; sensitive to new heavy colored states

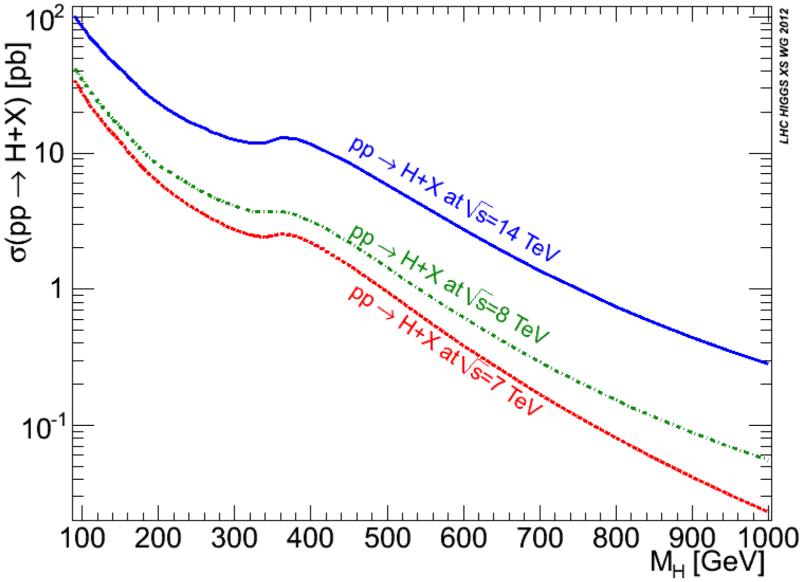
VBF: Probes Higgs role in unitarity cancellations (no growth with energy)

ttH: Direct measurement of top quark Yukawa coupling

VH: Sensitive to new physics in high p_T tail

Higgs Production



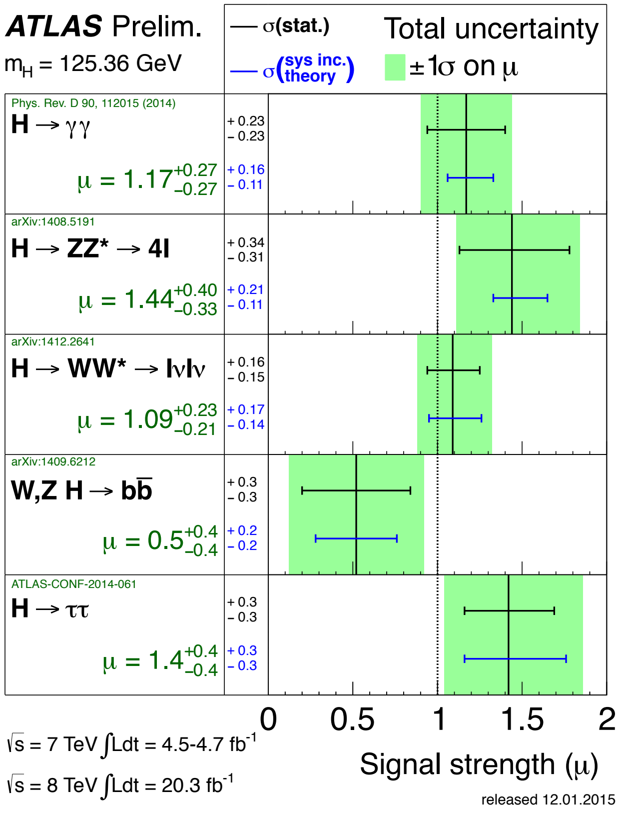


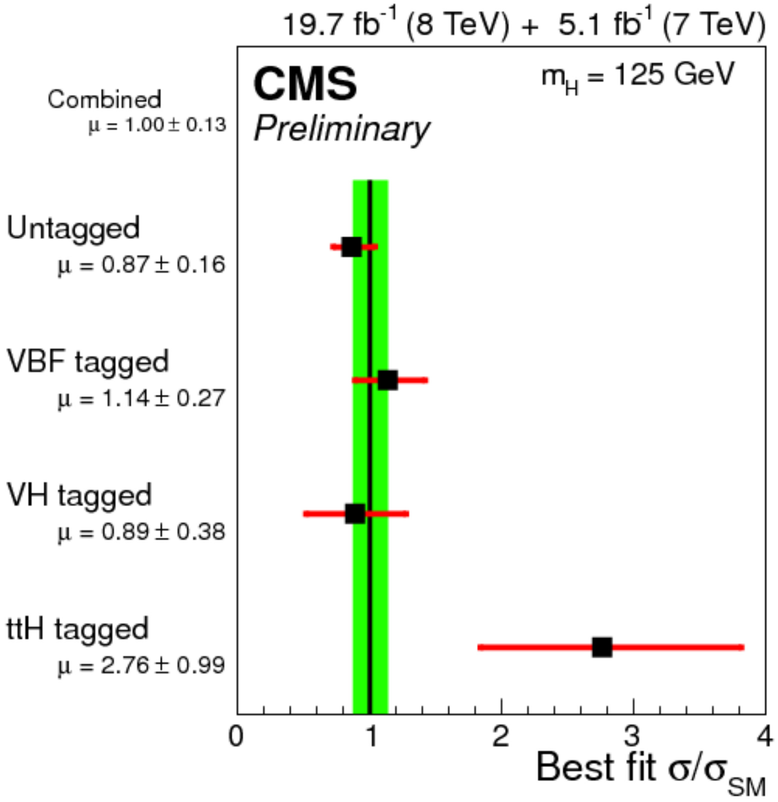
Reduction of scale uncertainty at N^3LO:
13 TeV $\sigma(M_H=125$ GeV$)=43.14$ pb $^{+2.71\%}_{-4.45\%}$
Increase of +2.2% from NNLO rate

3 Loops!

[Anastasiou, Duhr, Dulat, Herzog, Mistlberger, arXiv:1503.06056]

Production Strengths





Always normalized to SM *(Theory matters!)*

Higgs Production Increases at 13 TeV

	σ(pb) at 13 TeV	σ(pb) at 8 TeV
Gluon Fusion	43.9	19.27
Vector Boson Fusion	3.748	1.578
WH	1.38	.70
ZH	.87	.42
ttH	.51	.13
HH	.034	.008

Factors of 2-4 increases in rates

Note large increase in ttH rate!

[Higgs Cross Section Working Group]

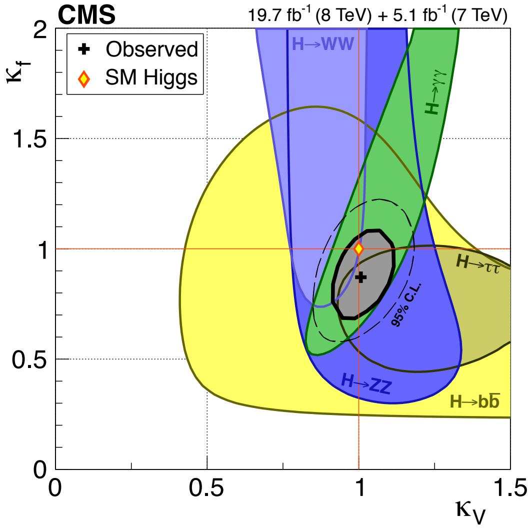
Testing Higgs Couplings

- Higgs couplings unambiguously predicted
- Simplest approach:

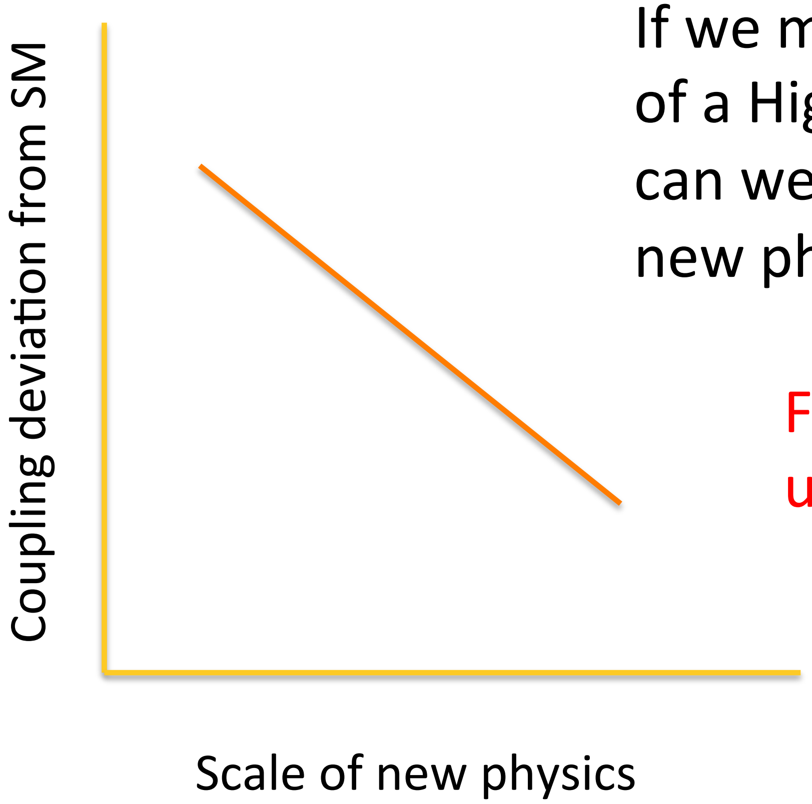
$$L_F \to (\kappa_F)\frac{M_f}{v} f\bar{f}H$$

$$L_V \to \frac{M_V^2}{v}(\kappa_V) V^\mu V_\mu$$

- SM, κ_i=1
- In a particular model, there will be relationships among κ' s



What we hope for



If we measure a large deviation of a Higgs coupling from the SM, can we associate it with a scale of new physics?

For this to work, we have to understand the SM first

Small Corrections Expected in BSM

If new physics is at 1 TeV:

	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	~6%	~6%	~6%
2HDM	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%
Composite	~-3%	~-(3-9)%	~-9%
Top Partner	~-2%	~-2%	~1%

Patterns of deviations can pinpoint specific BSM physics

[Snowmass Higgs report, 1310.8361]

Higgs Couplings (STILL!) Interesting

- Precision measurements of Higgs couplings rigorous tests of SM
  - NNLO QCD, NLO EW, resummation all needed!
  - Flavor structure of Higgs sector untested so far
- Models with TeV scale new physics give small corrections to κ parameters

- We would expect deviations from SM to be $O(v^2/TeV^2)$
- *Just starting to probe interesting region*

Testing Higgs Couplings

- 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

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

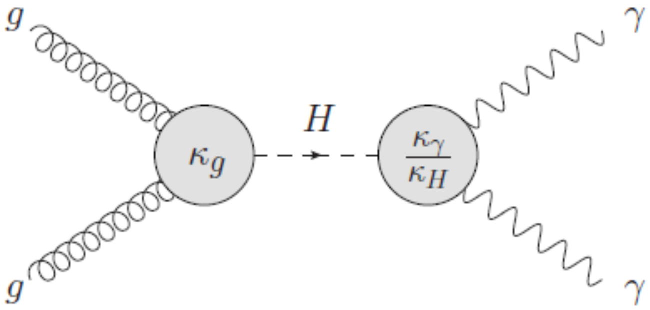
- Approaches to loops: κ_γ, κ_g can be
  - Written as function of SM scaling factors: eg $\kappa_g=\kappa_g(\kappa_t,\kappa_b)$
  - Treated as free parameters to look for BSM contributions

[LHC Higgs Cross Section Working group, arXiv1307.1346]

Higgs Couplings

Example:

$gg \rightarrow H \rightarrow \gamma\gamma$



$$(\sigma \cdot BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \left[\sigma(gg \rightarrow H) \cdot BR(H \rightarrow \gamma\gamma)\right]_{SM} \times \boxed{\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}}$$

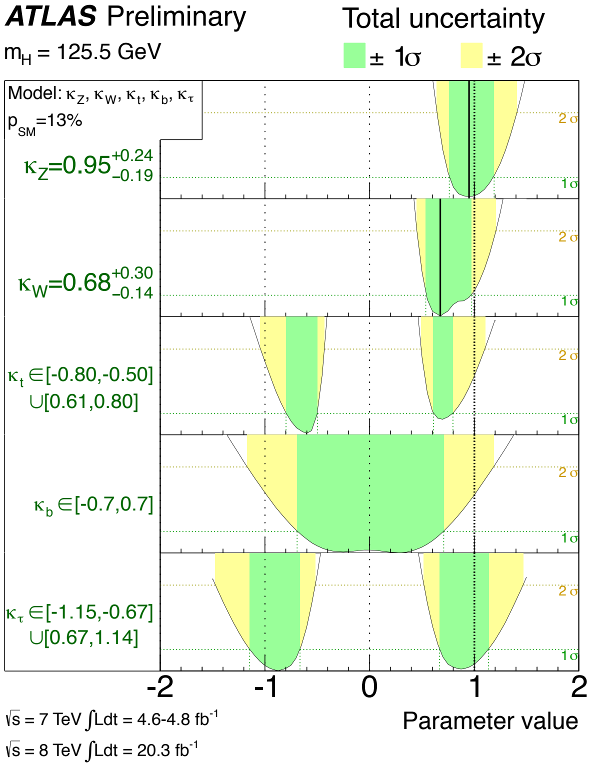
κ_H^2 is the scale factor to the total Higgs decay width

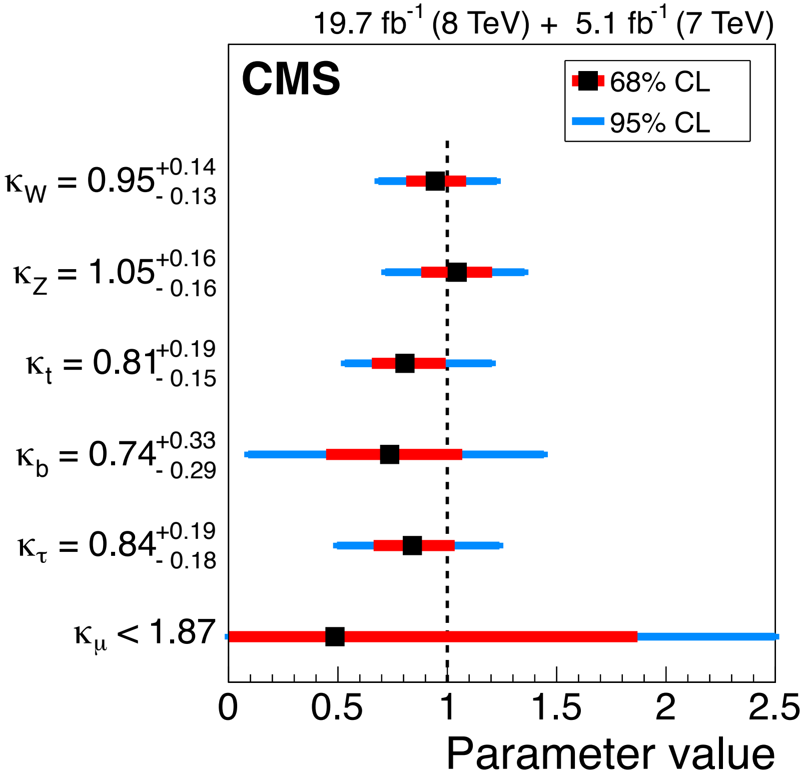
$$\kappa_H^2 = \sum_x \kappa_x^2 \cdot BR(H \rightarrow xx) \xrightarrow{\text{No BSM decays}} \kappa_H^2 = \sum_x \kappa_x^2 \cdot BR_{SM}(H \rightarrow xx)$$

*BSM decays really just means unobserved decays

κ Fits (miniature subset)

Plenty of room for non-SM physics at 10-20% level





Only SM particles in loops; no invisible decays in these fits

**** Read the fine print in fits***

Invisible width

- Invisible is just stuff you don't observe

$$\Gamma_H = \kappa_H^2 \Gamma_H^{SM} = \Sigma_i \kappa_i^2 \Gamma(H \to X_i X_i)^{SM} + \Gamma(H \to invisible)$$

$$\kappa_H^2 = \Sigma_i \kappa_i^2 \frac{\Gamma(H \to X_i X_i)}{\Gamma_H^{SM}} + \frac{\Gamma(invisible)}{\Gamma_H^{SM}}$$

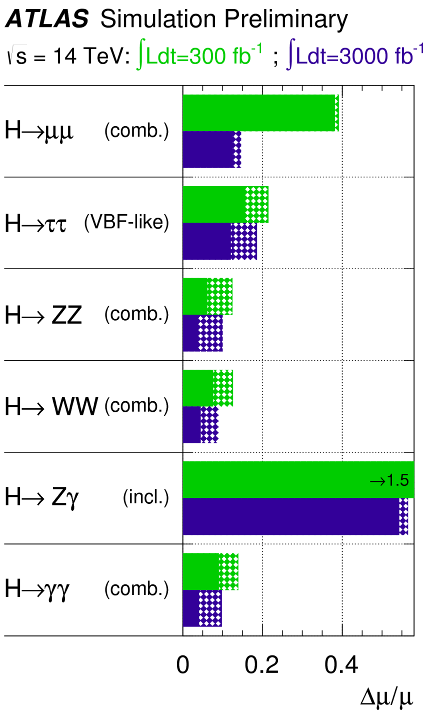
$$= \Sigma_i \kappa_i^2 BR(H \to X_i X_i) + \kappa_H^2 BR(H \to invisible)$$

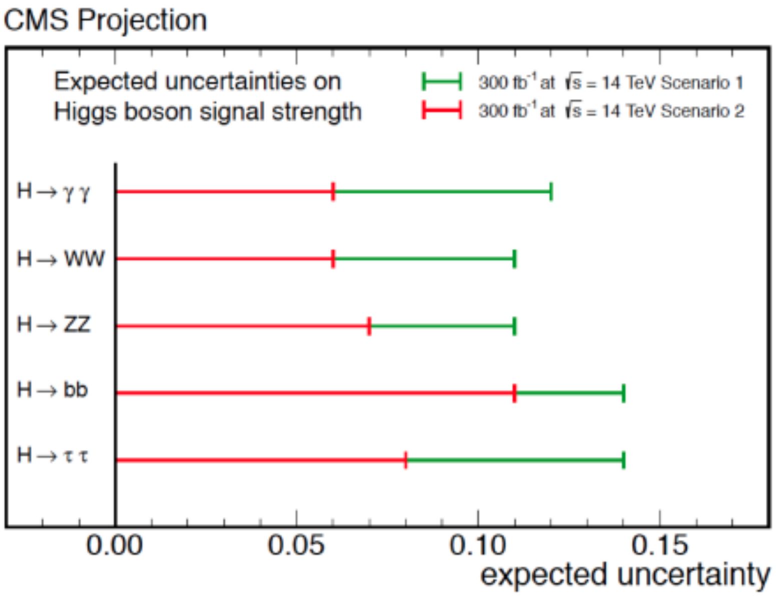
- Can do fits allowing for H → invisible
- CMS: BR(H→invisible)< .49 at 95%
- Similar limits from ZH production, H→ invisible

Invisible could be new dark matter particles,
could be unobserved decays to charm….

Projections

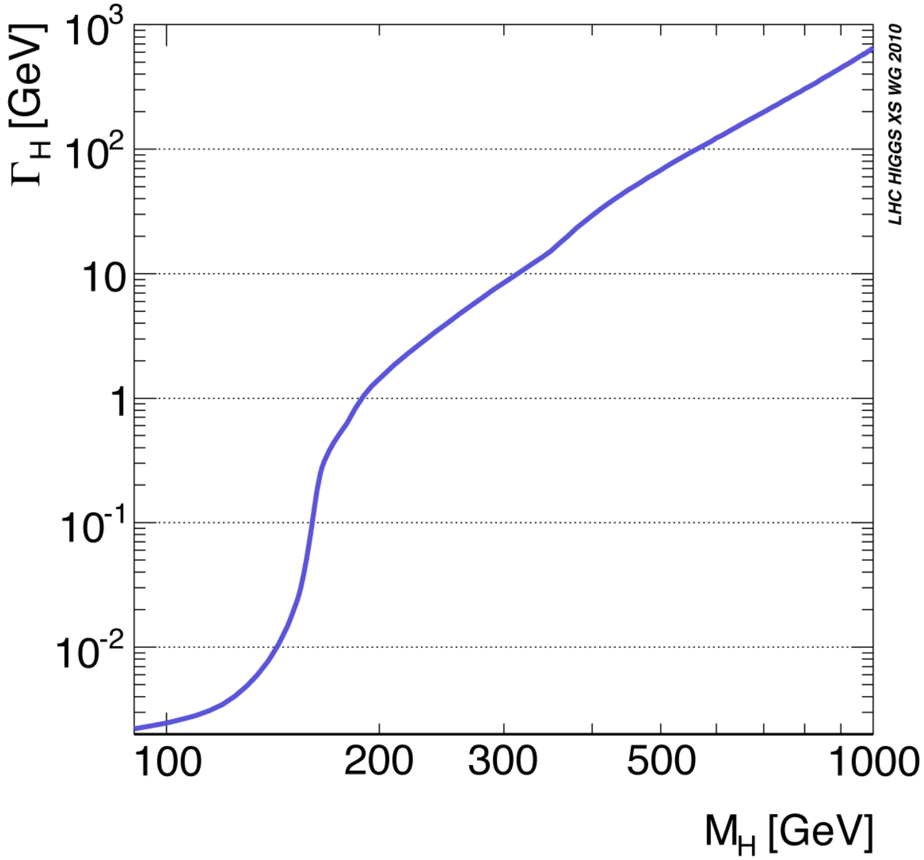
Lumi	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	κ_{Zg}	κ_μ
300 fb^{-1}	ATLAS	9%	9%	8%	11-14%	22-23%	20-22%	13-14%	24%	21%
	CMS	5-7%	4-6%	4-6%	6-8%	10-13%	14-15%	6-8%	41%	23%
3000 fb^{-1}	ATLAS	4-5%	4-5%	4%	5-9%	10-12%	8-11%	9-10%	14%	7-8%
	CMS	2-5%	2-5%	2-4%	3-5%	4-7%	7-10%	2-5%	10-12%	8%





* Projections allow loop factors, κ_γ, κ_g to vary independently

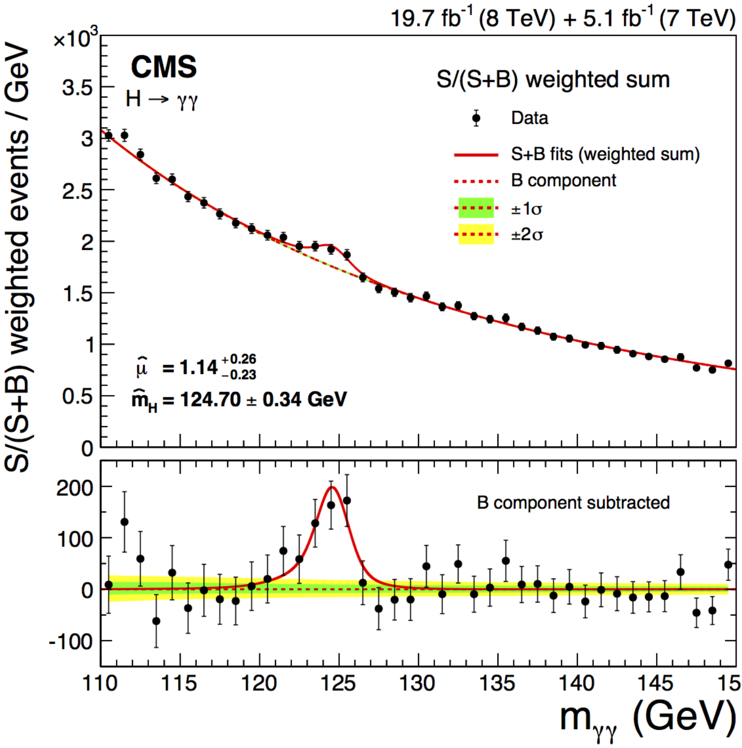
SM Higgs is Narrow



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

Direct Measurement of Higgs width

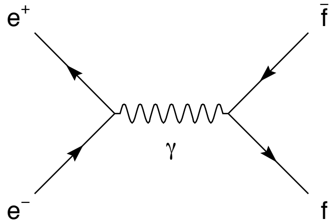
- Detector resolution a few GeV in γγ channel
- Limits are weak: $\Gamma_H < 6.9$ GeV ($1600\ \Gamma_H^{SM}$) at 95% CL

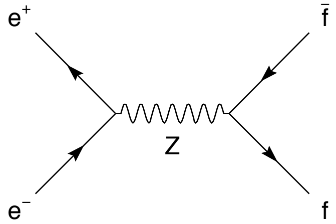


Z-Resonance

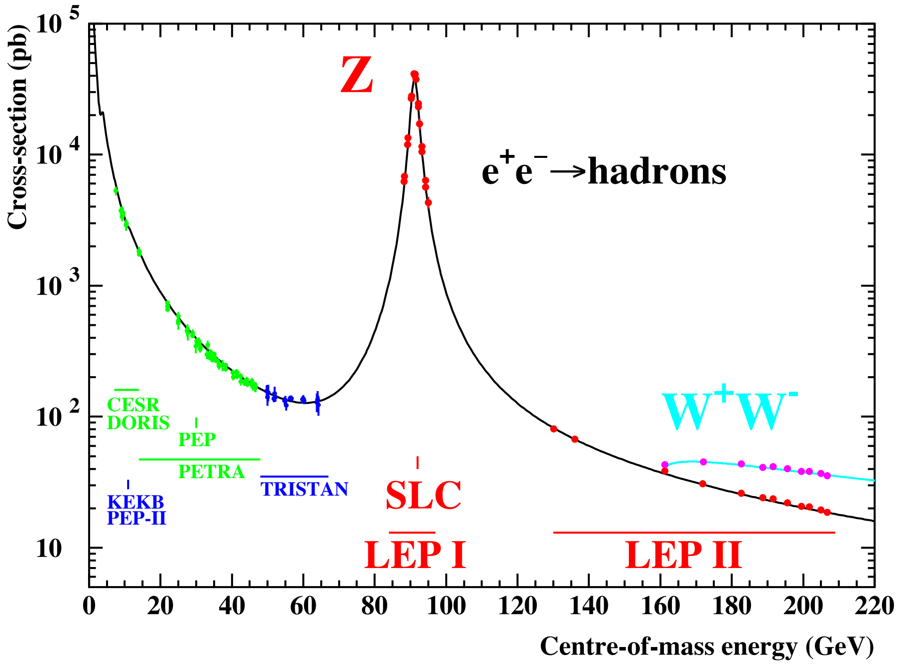
$$e^+e^- \to f\overline{f}$$

$$A \sim g_{Zff}\, g_{Zee} \frac{1}{s - M_Z^2 + iM_Z\Gamma_Z}$$





- Narrow resonance: Γ_Z=2.495 ± .0023GeV



Narrow width approximation

- Integral near resonance:

$$I = \int \frac{1}{(s - M_Z^2)^2 + (\Gamma_Z M_Z)^2} ds$$

$$\tan\ \theta = \frac{s - M_Z^2}{\Gamma_Z M_Z} \qquad I = \int \frac{d\theta}{\Gamma_Z M_Z} \qquad \theta_{min} \sim -\pi, \theta_{max} \sim 0$$

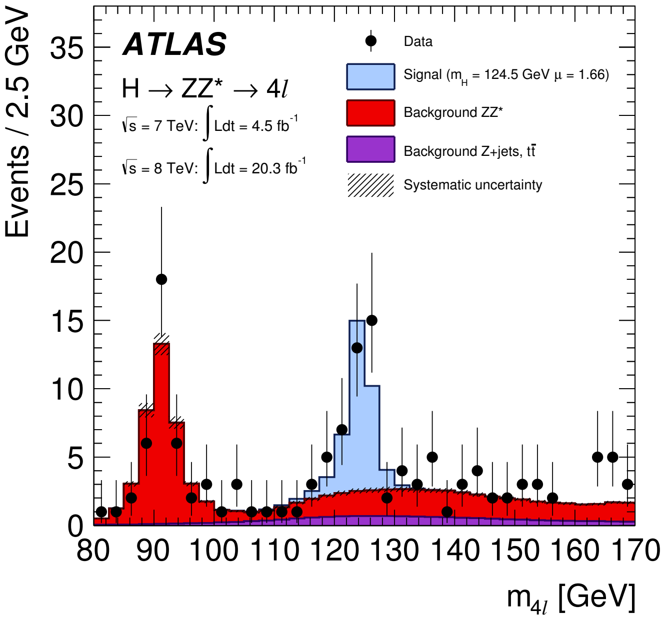
$$\frac{1}{(s - M_Z^2)^2 + (\Gamma_Z M_Z)^2} \rightarrow \frac{\pi}{\Gamma_Z M_Z} \delta(s - M_Z^2)$$

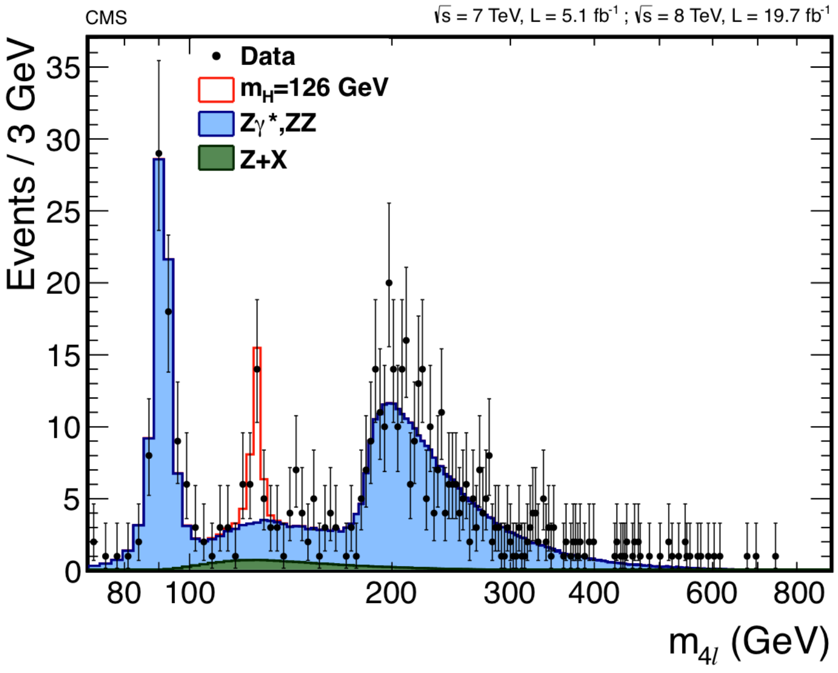
$$\boxed{\sigma_{res} \sim \frac{(g_{Zff} g_{Zee})^2}{\Gamma_Z}}$$

Sensitive to resonance width

$gg \to H \to ZZ$

- Goal: Measure gg → H → ZZ and use insights about resonances





Aside on HZZ couplings

- HZ_LZ_L couplings vestige of EWSB
  - Massless gauge theory has no longitudinal polarizations
  - HZ_LZ_L coupling ~ M_H^2/v
  - Expect resonance to have high energy tail

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

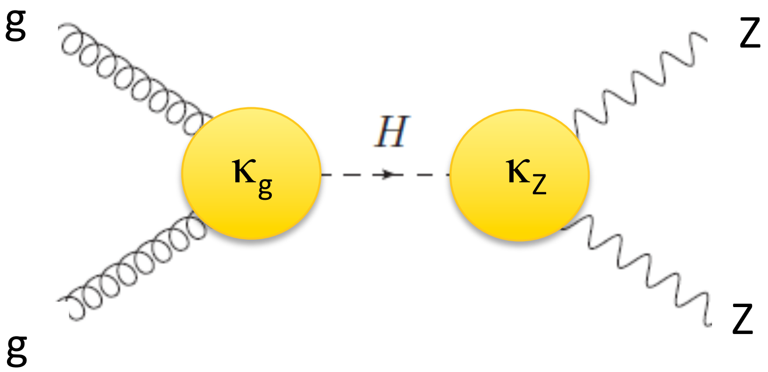
Higgs Resonance

- Above resonance:

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

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

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



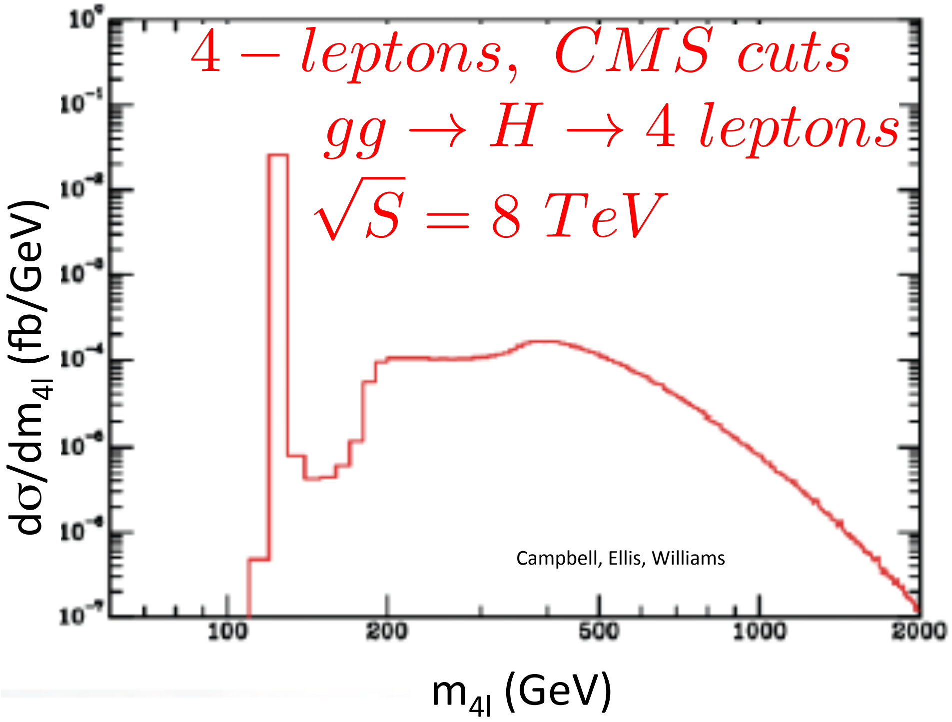
$$I = \int \frac{1}{(s - M_H^2)^2 + (\Gamma_H M_H)^2} ds \to \frac{1}{s}$$

No dependence on width

Longitudinal Z polarization grows with energy

Idea

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



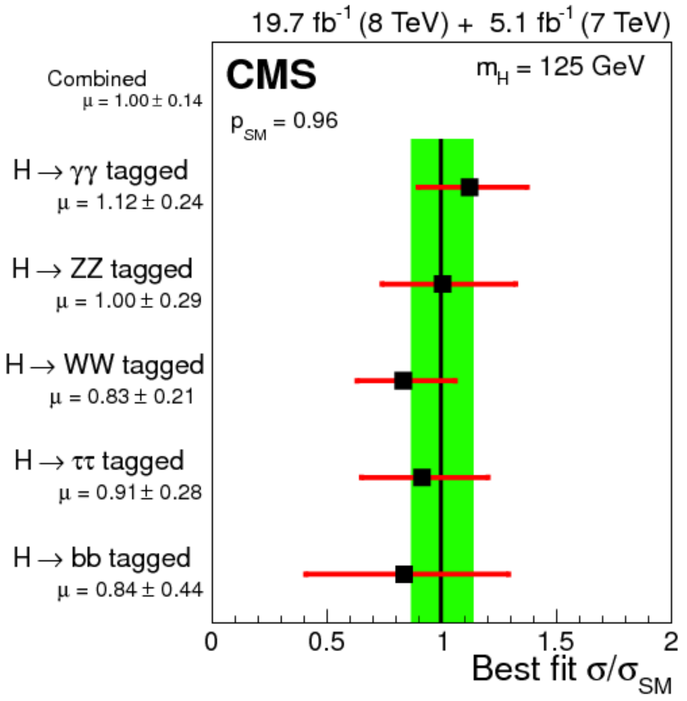
Campbell, Ellis, Williams

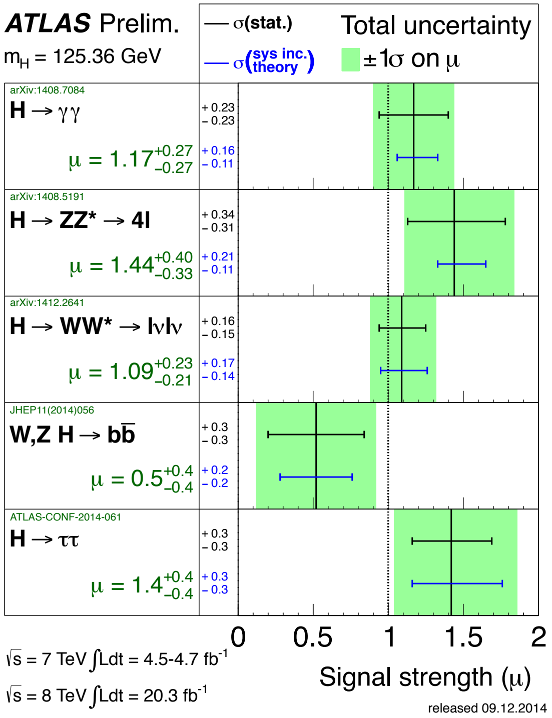
About 15% of total cross section in m_{4l}>140 GeV region above peak

[Caola, Melnkov; Kauer,Passarino]

Technique

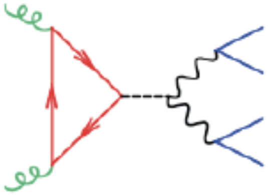
- On shell measurement of Higgs cross section consistent with SM expectations
- A larger Higgs width → more off-shell events: $\Gamma_H \sim \sigma_{above}/\sigma_{res}$



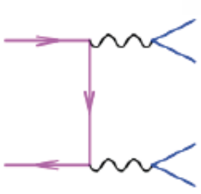


Other contributions to 4 leptons

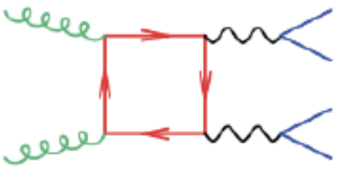
- Not just the Higgs



$gg \to H \to ZZ \to l^+l^-l^+l^-$



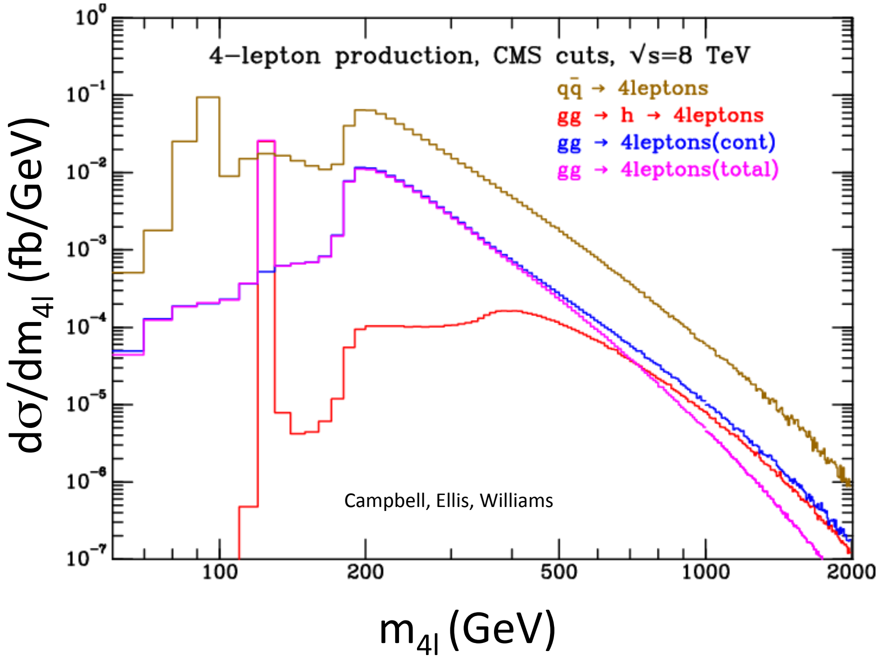
$SM : \quad q\bar{q} \to ZZ \to l^+l^-l^+l^-$



Box diagram can interfere with Higgs contribution

Separation into "signal" and "background" misses interference

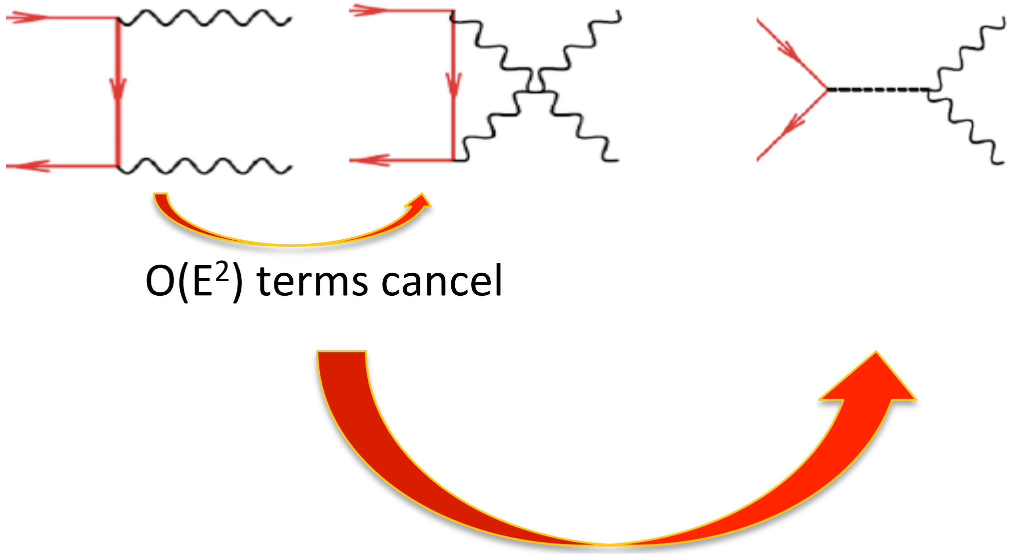
Observe destructive Interference



- Note destructive interference
- Quark channel >> Higgs contribution

Unitarity and the Higgs Width

$t\bar{t} \to Z_L Z_L$



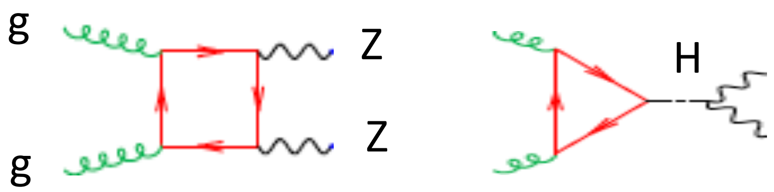
O(E^2) terms cancel

O(EM_t) terms cancel

A naïve separation into signal and background would miss this effect

Observation of this cancellation shows that Higgs boson is enforcing unitarity cancellations: No effects which grow with energy

Unitarity and the Higgs width



- Interference small on peak, but significant above peak

Averaging 7/8 TeV data:

$$\frac{\sigma(m_{4l} > 130\ GeV)}{\sigma_{peak}} \sim 2.8\frac{\Gamma}{\Gamma_{SM}} - 6\sqrt{\frac{\Gamma}{\Gamma_{SM}}}$$

Interference is destructive and weakens bound

$$CMS:\ \ \Gamma_H < 4.2\Gamma_H^{SM}$$

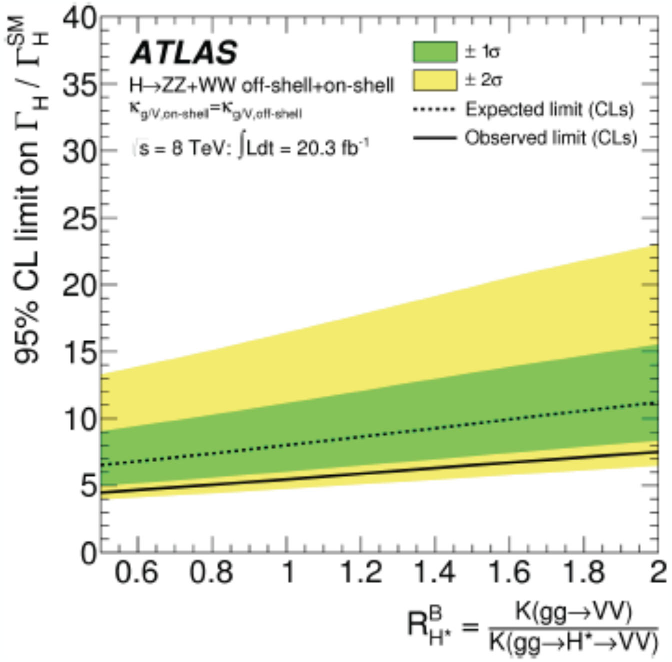
$$ATLAS:\ \ \Gamma_H < (4.5 - 7.5)\Gamma_H^{SM}$$

Sign of interference predicted by unitarity conservation

[Campbell, Ellis, Williams, arXiv:1311.3589]

Counting Orders

- Destructive interference computed at LO (even though it's a loop)
- Need K factor for gg contributions (unknown)
  - Assume similar to that for gg→ Higgs (~2)



Resonance contribution known at N^3LO

Box contribution only known at LO

Are we really measuring Γ_H?

- On-shell measurement:

$$\mu_{peak} = \frac{\sigma_{peak}}{\sigma_{peak}^{SM}} \sim \frac{\kappa_g^2 \kappa_Z^2}{(\Gamma_H/\Gamma_H^{SM})} \sim 1$$

  - Since μ_{peak}~1 a value $\Gamma_H > \Gamma_H^{SM}$ implies $\kappa_g^2\ \kappa_Z^2 > 1$
  - i.e. BSM physics
- Measurement above peak is $\sigma_{above} \sim \kappa_g^2 \kappa_Z^2$
  - Consistency check
  - Assumes correlation between κ on-shell and above peak

New Physics Changes κ's

- With BSM physics $\kappa(m_{ZZ}^2) \neq \kappa(M_H^2)$ in general
- Simple example: Add a colored scalar (as in the MSSM)

$$L \sim -\kappa_s \frac{2m_s^2}{v} H s^* s$$

- For a color triplet scalar

$$\kappa_g(\hat{s}) = 1 + \frac{\kappa_s A_s(\tau_s)}{(A_t^{SM}(\tau_t) + A_b^{SM}(\tau_b))} \qquad \tau_i = \frac{\hat{s}}{4m_i^2}$$

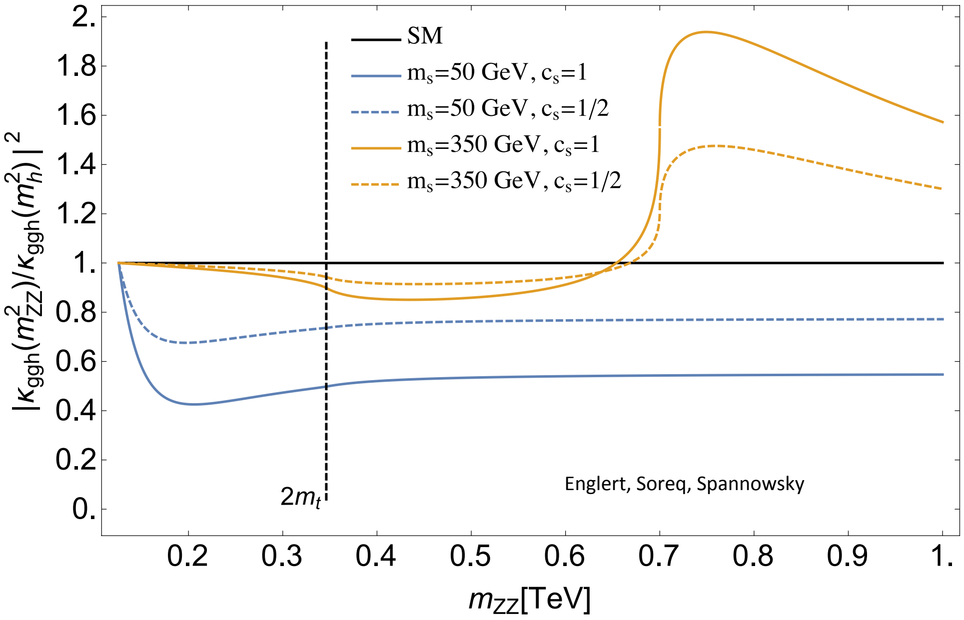
- Relation of off-shell couplings to on-shell couplings depends on dynamics of model

Colored scalar changes gg→H production rate

[Englert, Soreq, Spannowsky]

Effects can be large

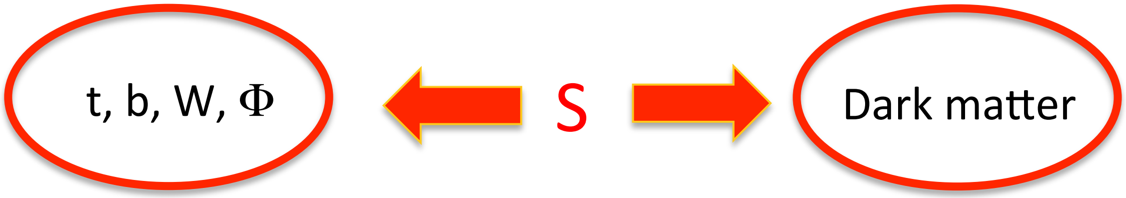
- Look at: $\dfrac{\kappa_g(m_{ZZ}^2)}{\kappa_g(M_H^2)}$
- Can have either enhancement or suppression



Interpretation requires assumptions about model

Example: Additional Higgs Singlet

- Dark matter models often have Higgs singlet



- Communication with SM particles through mixing
  - SM Higgs mixed with electroweak singlet, S

$$V_4 = \lambda_m \mid \Phi \mid^2 S^2 + \frac{\lambda_{SM}}{2} \mid \Phi \mid^4 + \frac{\lambda_S}{2} S^4$$

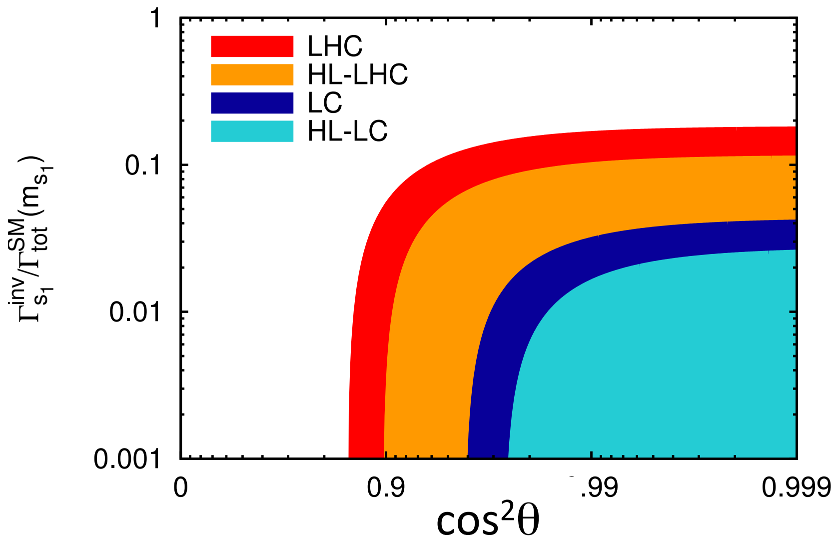
$$h = \cos\theta \phi_0 + \sin\theta S$$

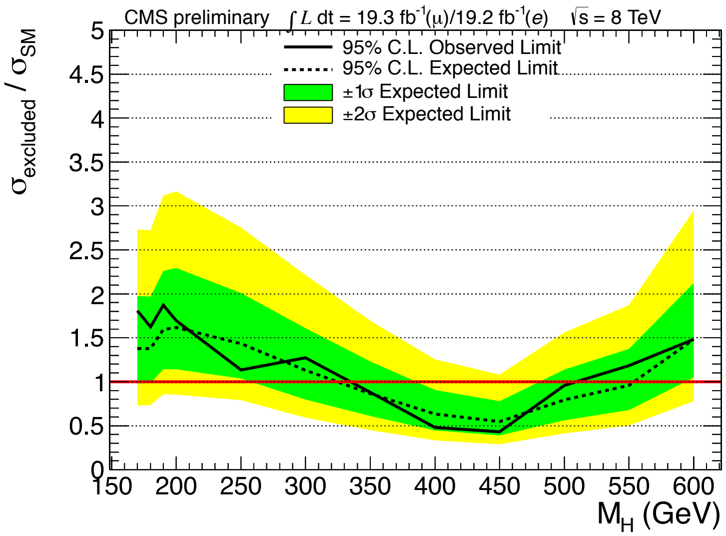
$$H = -\sin\theta \phi_0 + \cos\theta S$$

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

Complementarity of Approaches

- Find heavier Higgs and measure deviations in couplings
- $\sin^2\theta < .12$ (with no invisible BR) from H couplings
  - – Need increased sensitivity in direct searches



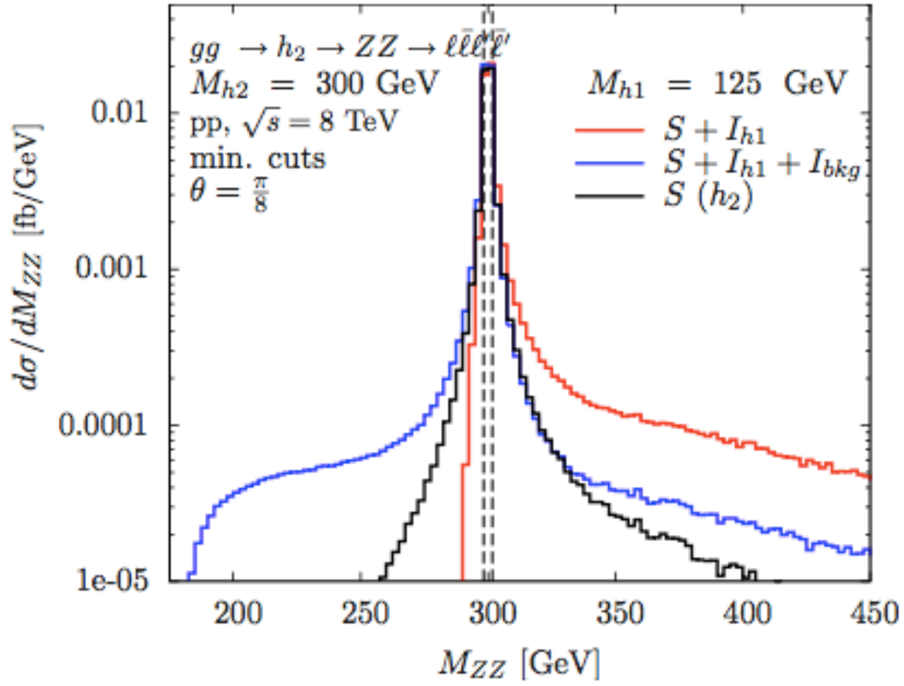


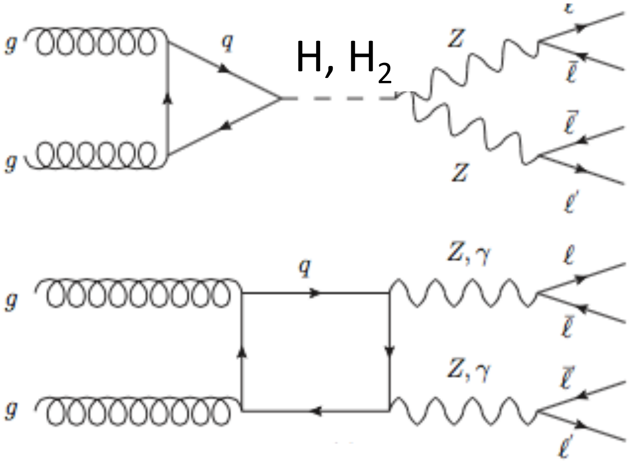
These simple studies are very important for limiting EWSB models

[Englert et al, arXiv:1403.7191]

Higgs Width in Singlet Model

- Large interference effects from new scalar, H_2
- Quantitatively different results from SM





[Kauer, O'Brien]

Example: Two Higgs Doublets

- Many models have extended Higgs sectors
  - Two Higgs doublet models can be used as effective theories for many of these models
  - 5 Higgs bosons: h, H, A, $H^{\pm}$
  - 4 types of 2HDM models which avoid tree level FCNCs
  - Classified in terms of tan $\beta = v_2/v_1$, α, m_h=125 GeV

$$\sin 2\alpha = -\sin 2\beta \left(\frac{M_H^2 + m_h^2}{M_H^2 - m_h^2} \right)$$

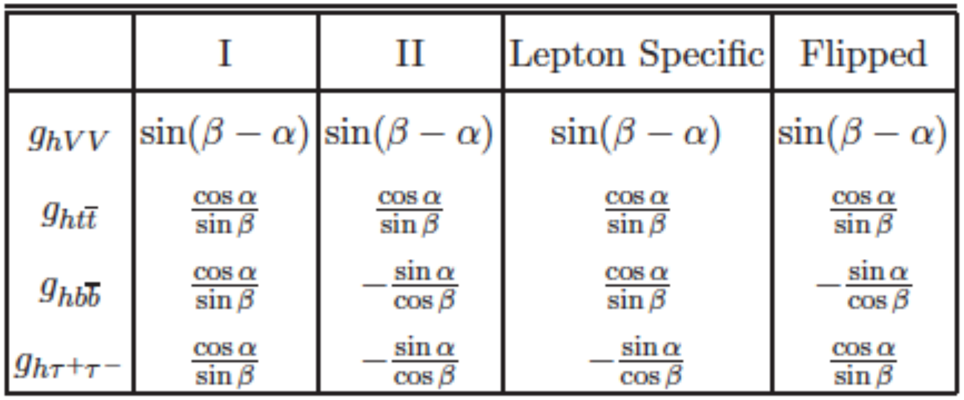
  - Predictive models (MSSM is special case)

Rich Phenomenology

Higgs Couplings: 2 Parameters

- 2 Higgs doublet models with no FCNC
  - Parameters are α (mixing in neutral h), tan β, $M_{H,}$ $M_{A,}$ M_{H+}
  - 4 possibilities for Higgs coupling assignments

$$L = -g_{hii}\frac{m_i}{v}\overline{f}_i f_i h - g_{hVV}\frac{2M_V^2}{v}V_\mu V^\mu h$$



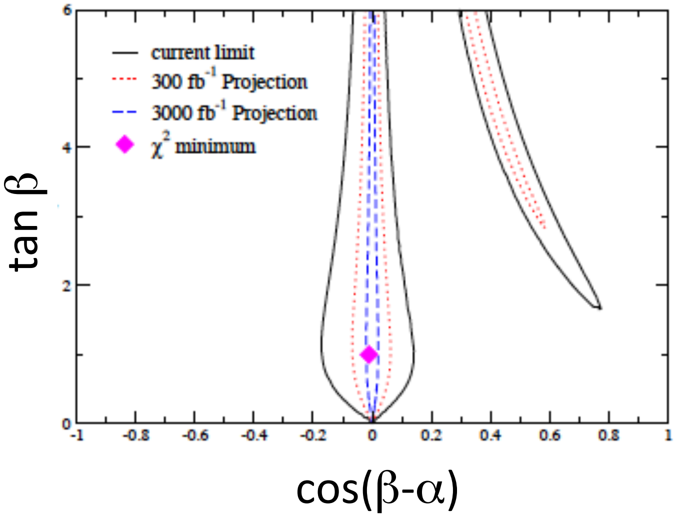
	I	II	Lepton Specific	Flipped
g_{hVV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
$g_{ht\bar{t}}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
$g_{hb\bar{b}}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
$g_{h\tau^+\tau^-}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

Type II is MSSM – like 2 Higgs doublet model

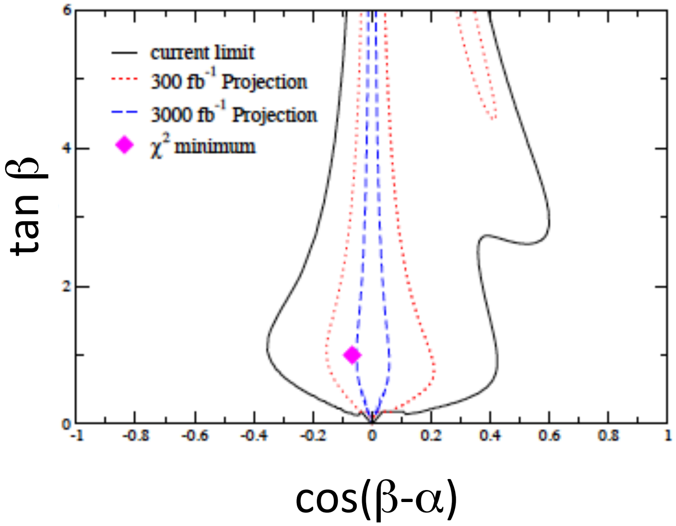
Decoupling Limit

- 2HDMs approach SM when $\cos(\beta-\alpha) \rightarrow 0$
- Current limits allow non-SM like couplings
- $\tan\beta < .4$ excluded by ΔM_{Bd} for $M_{H+} < 2$ TeV
  - Higgs coupling measurements sensitive probes of theory even if new Higgs particles too heavy to be produced
  - Prefer small $\tan\beta$

MSSM-like model



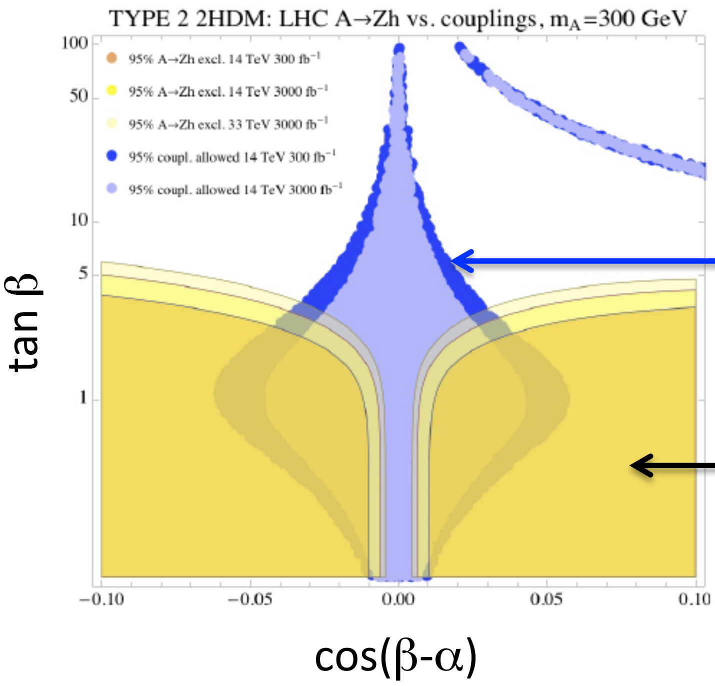
Lepton specific model



New Higgs Bosons → New Signatures

- 2HDM example: gg→ A → ZH_1
  - Complementary limits from direct search/coupling measurements

14 TeV projections:



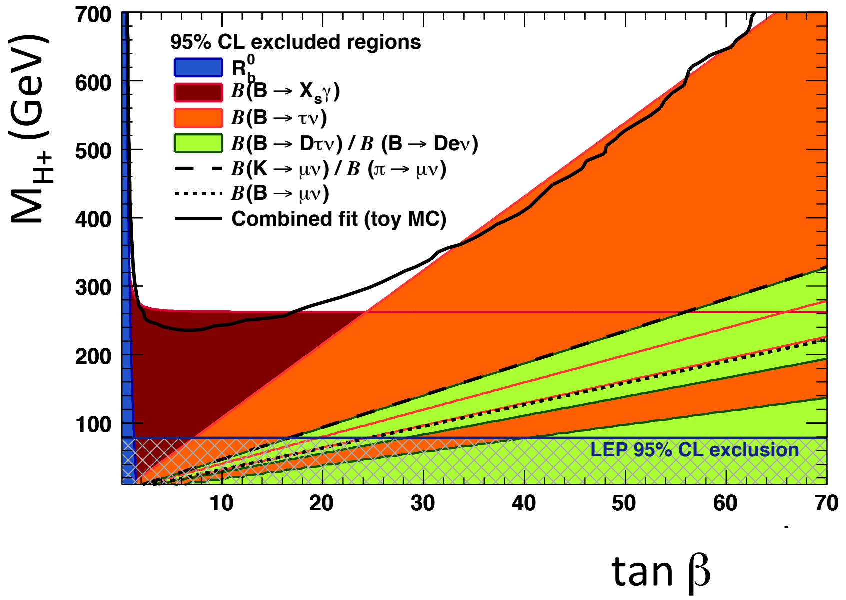
Limits from H coupling measurements

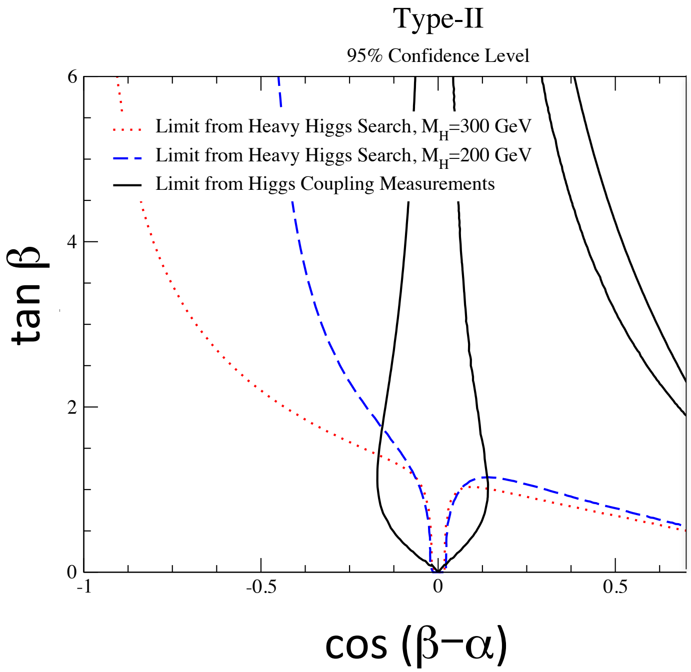
Limits from direct search, gg→A→ZH_1

[Brownson, 1308.6334]

Again…. Complementarity

- Many limits on 2HDM besides Higgs parameters
- Precision EW, B physics…..





[Gfitter, arXIv0811.0009, Chen, Dawson, Sher, 1305.1624]

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*

Need to Use Effective Field Theory

- Many possible parameterizations:
  - HISZ (no fermions), Buchmuller/Wyler (59 operators before flavor), SILH,…..
  - Operators related by equations of motion
  - Need to simplify and make assumptions!
  - Assume: Higgs comes from doublet
    - Always have combination $(H+v)^n$
    - Assume CP conservation, no flavor violation in Higgs sector

BIG ASSUMPTION

Higgs Couplings & Effective Field Theory

- Operators obey symmetry of SM

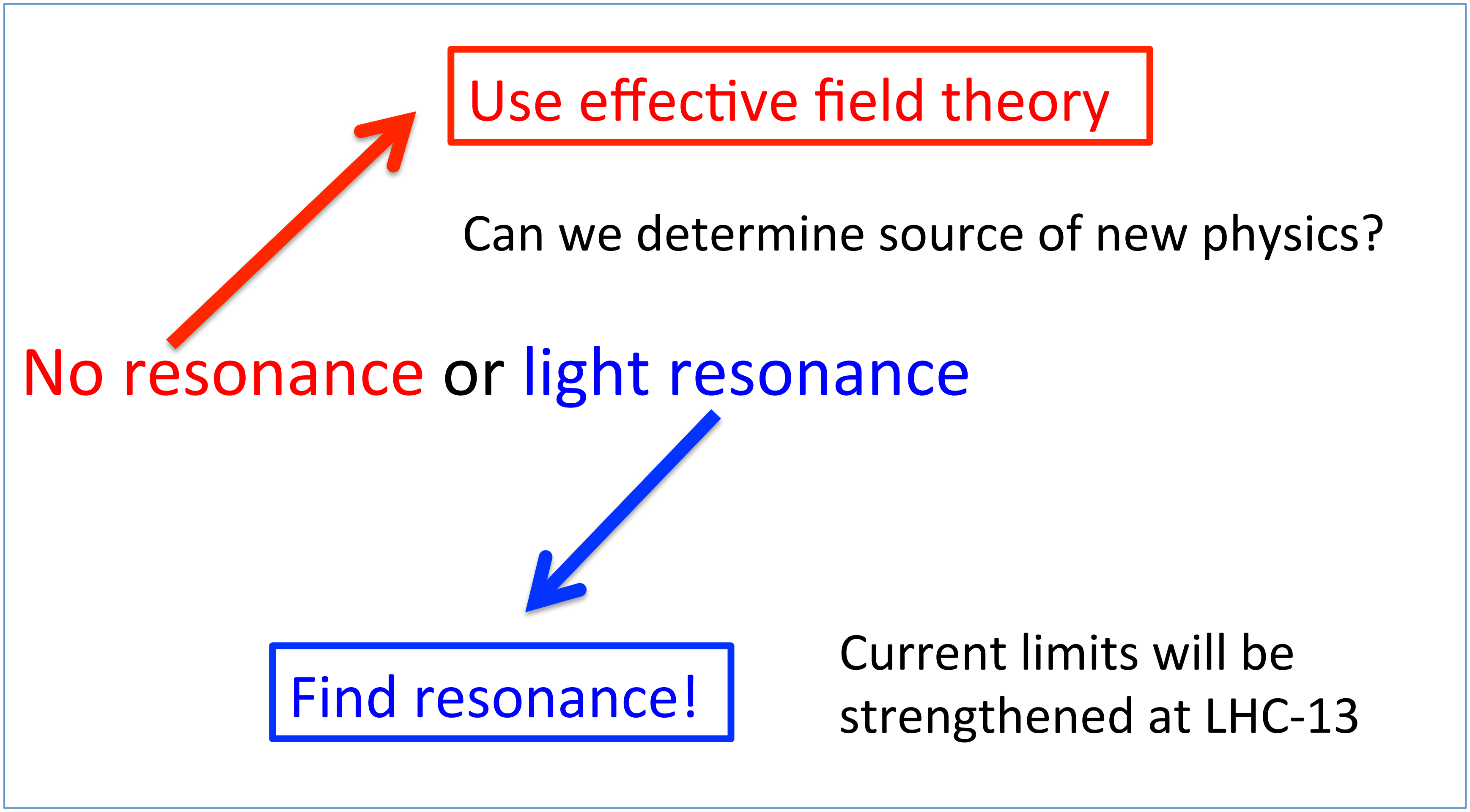
$$L \sim L_{SM} + \Sigma_i \frac{C_i}{\Lambda^{n-4}} O_n$$

Consistent expansion

- New physics decouples at high scales
  - ***No new light particles***
  - n=6 operators expected to give dominant contribution
  - Λ is scale of new physics >> v
  - EFT valid at E << Λ
  - Consider all n=6 operators that can be constructed from SM fields

Looking for new physics in tails of distributions, but have to make sure EFT is valid

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 will be
strengthened at LHC-13

Construct EFT for Higgs

- Take SM operators and add $\Phi^{+}\Phi$

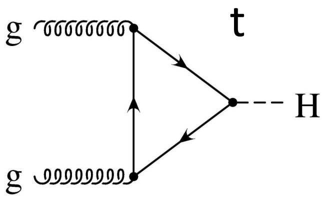
g_s	$(\Phi^\dagger\Phi)G^A_{\mu\nu}G^{A,\mu\nu}$	$gg \to H$
g	$(\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	$H \to \gamma\gamma$
g’	$(\Phi^\dagger\Phi)W^a_{\mu\nu}W^{a,\mu\nu}$	$H \to Z\gamma$ *UNKNOWN*
M_W	$(\Phi^\dagger\Phi) \mid D_\mu\Phi \mid^2$	$H \to VV^*$
M_H	$(\Phi^\dagger\Phi)^3$	λ_3 *UNKNOWN*
M_f	$(\Phi^\dagger\Phi)\overline{f}_L\Phi f_R + h.c.$	$H\tau\tau, Hbb, Htt$

Here, I am only concerned with effective operators that affect Higgs production

Effective Theory Example

- Very simple EFT:

$$L \sim L_{SM} + \frac{\alpha_s}{12\pi v} c_g G^{\mu\nu,A} G^{A}_{\mu\nu} H - \delta Y_t \frac{M_t}{v} \bar{t} t H$$



  – gg→H sensitive to $|c_g + \delta Y_t|^2$

$$A(gg \to H) = A^{SM}\left(\frac{M_H^2}{M_t^2}\right)\left[1 + \delta Y_t\right] + A^{SM}(0) c_g$$

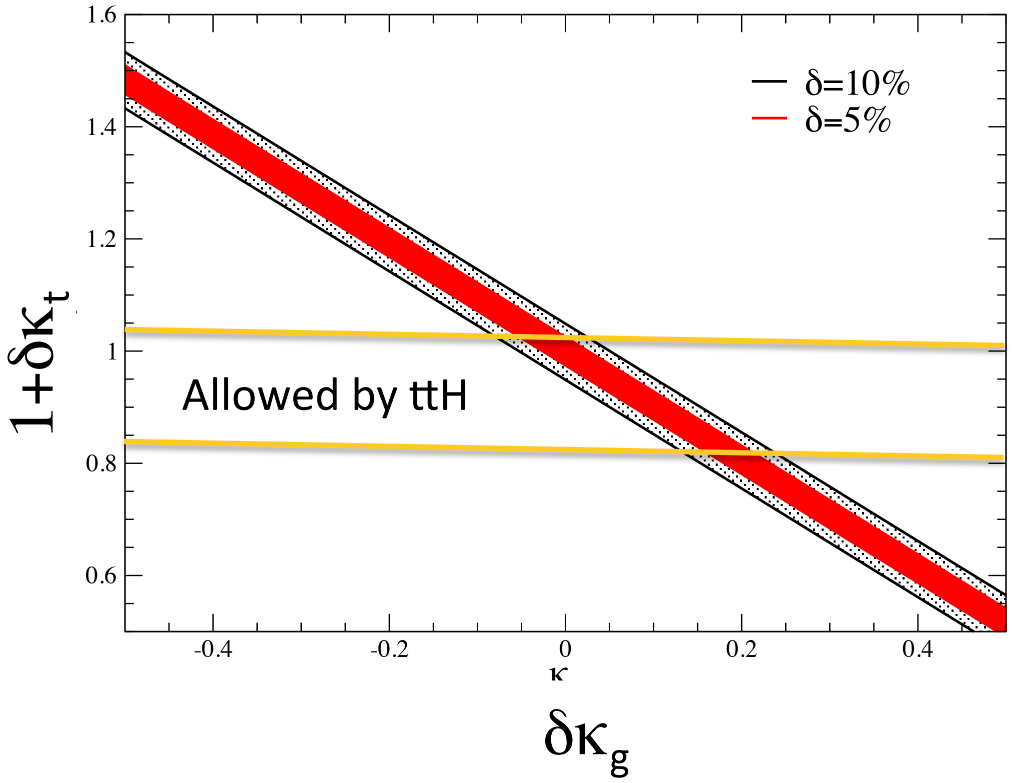
Almost equal in SM

Can't distinguish *long distance* physics (δY_t) from *short distance* physics (new particles in loops, c_g nonzero)

[Delauney, Grojean, Perez, 1309.090;
Chen, Dawson, Lewis, 1406.3349]

How to break κ_t -κ_g degeneracy?

gg➔ H rate within δ of SM prediction



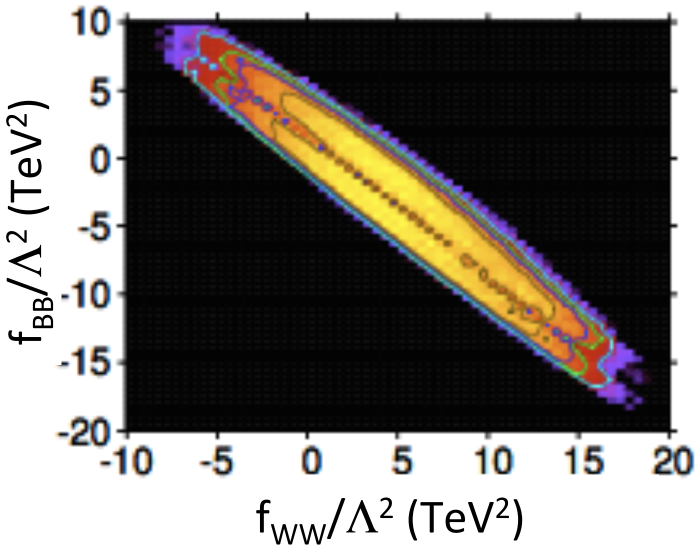
- ttH production proportional to $(1+\delta\kappa_t)^2$
- (very small dependence on κ_g neglected in ttH)
- Assume

$$\frac{\delta\sigma_{ttH}}{\sigma_{ttH}} \sim .2$$

Need global fits

Many Global Fits to EFT Parameters

- Limits on EFT coefficients are correlated



Fit to Higgs rates

95% cl f_{ww}/Λ^2: (-3.7, 13.7)

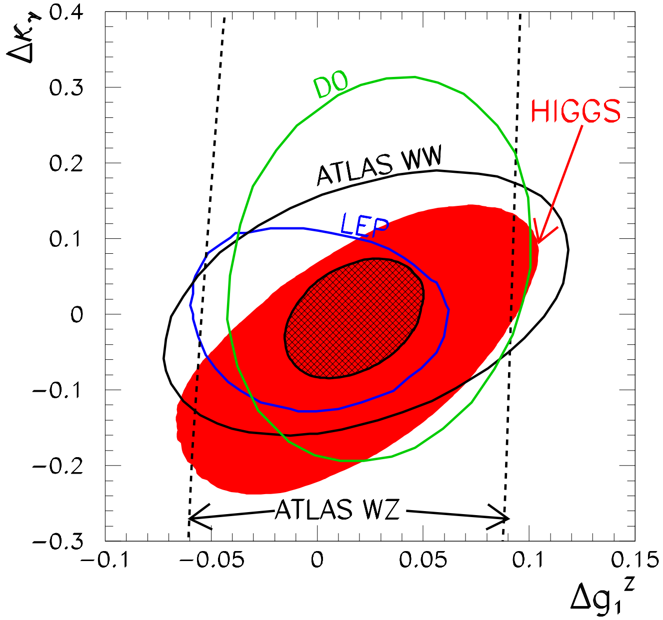
[Corbett et al, arXiv:1505.05516]

Complementarity

- Effective operators contribute to precision electroweak interactions
- Some operator coefficients known to be small from M_W, ρ…
- W^+W^- production probes complementary coupling space to Higgs coupling limits

$$\Delta\kappa_\gamma = \frac{M_W^2}{2\Lambda^2}(f_W + f_B)$$

$$\Delta g_1^Z = \frac{M_Z^2}{2\Lambda^2} f_W$$

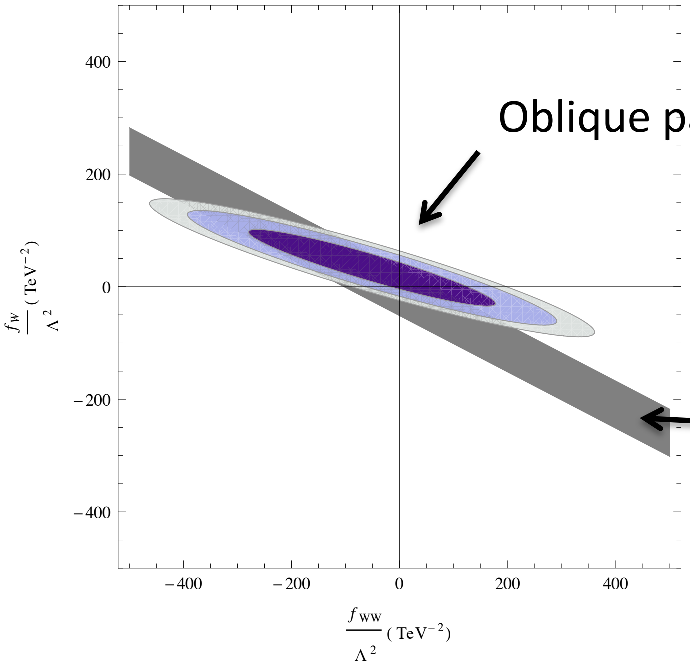


[Corbett et al, arXiv:1304.1151]

Limits highly correlated

EFT: Need Global FIts

$$\frac{\Gamma(H\to W^+W^-)}{\Gamma(H\to W^+W^-)_{SM}}\sim 1+\left[.0086 f_{WW}+.017 f_W\right]\left(\frac{1\ TeV}{\Lambda}\right)^2$$



Oblique parameters

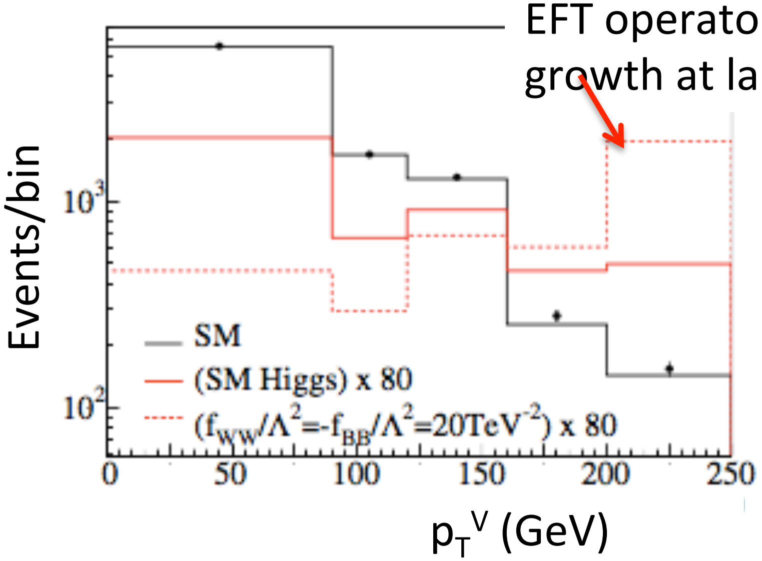
Higgs data

Complementary data from oblique parameters and Higgs data

EFTs change kinematic distributions

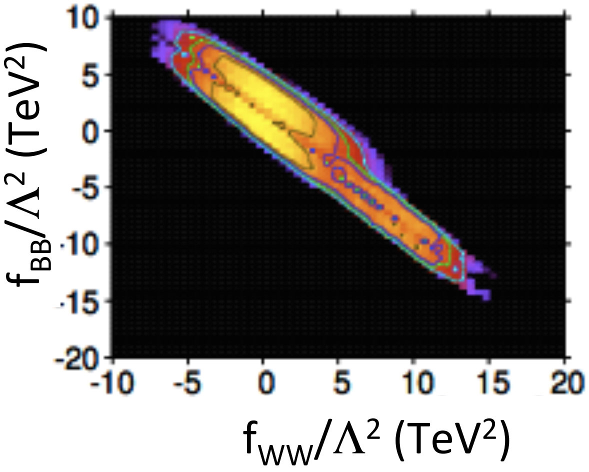
- Dimension-6 operators contribute terms ~E^2/Λ^2

VH (single lepton) production at 8 TeV



EFT operators cause growth at large p_T^V

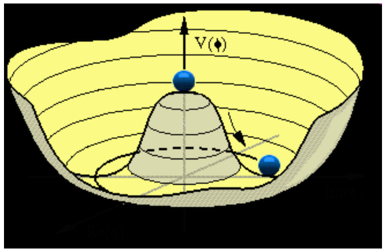
- Can improve fits by including kinematic distributions



95% cl. f_{ww}/Λ^2: (-4.3, 4.4)

Does the Higgs come from the SM Potential?

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



We know the the Higgs self interactions are weak: $\frac{M_H^2}{2v^2} \sim .13$

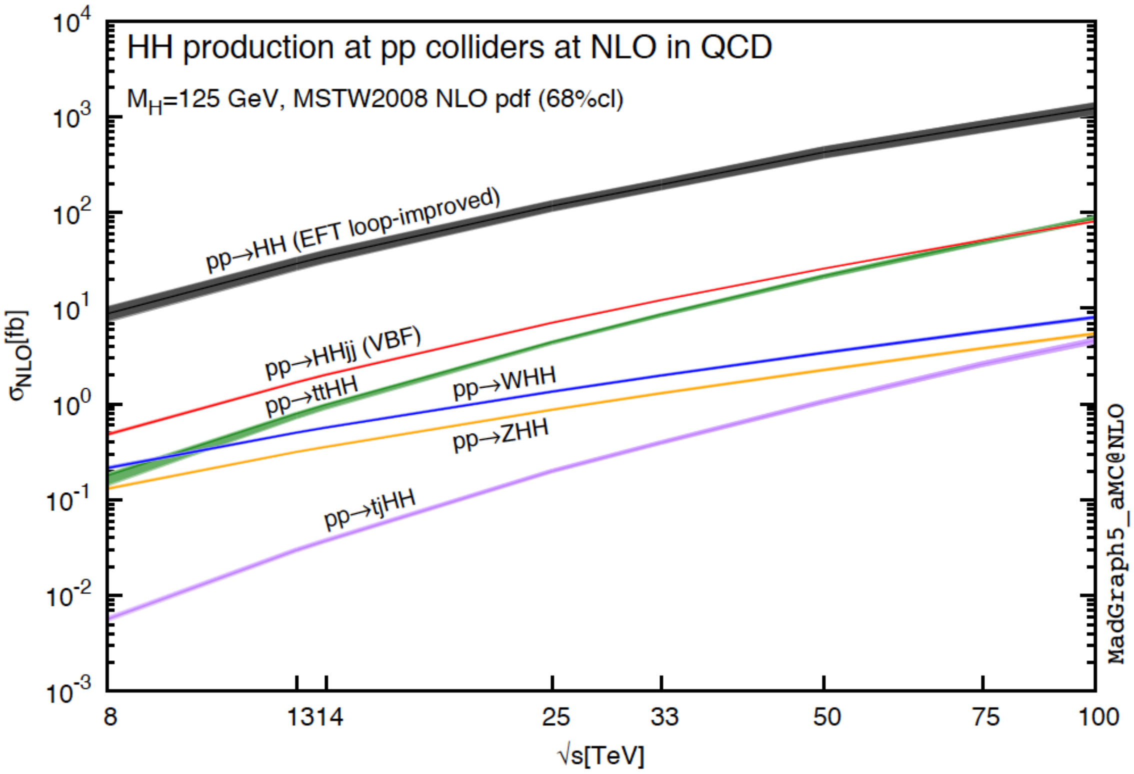
- Need to measure HHH and HHHH couplings
- HHH coupling can be measured with HH production

$$14\ TeV: \quad \sigma(gg \to HH) \sim 34 fb$$
$$\sigma(gg \to HHH) \sim .04 fb$$

BSM models can change the HHH and HHHH couplings

M_H is a free parameter of the theory

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]

Two Higgs Production at LHC

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

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

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

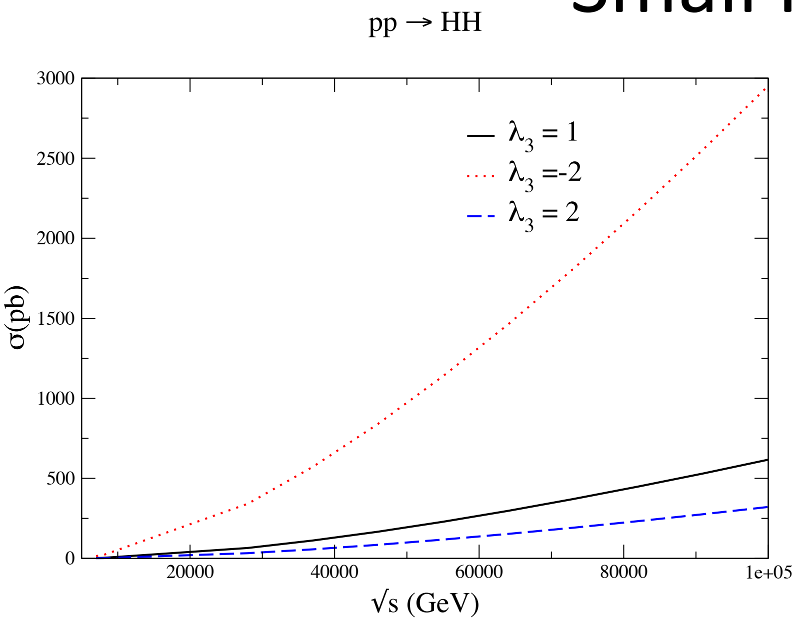
$$F_0 \to -\frac{4}{3} + \frac{4M_H^2}{s - M_H^2}(\lambda_3)$$

$$F_2 \to 0$$

HHH coupling (1 for SM)

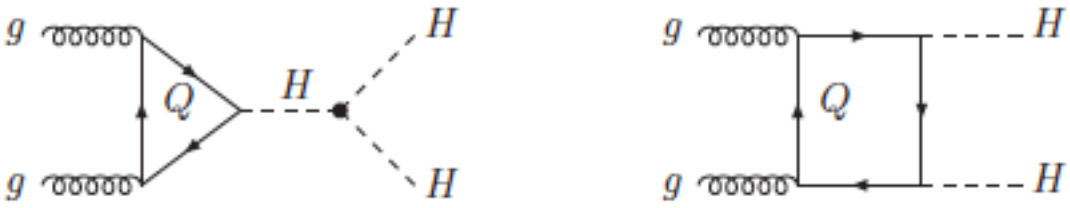
- For large s, dependence on λ_3 suppressed
- More sensitivity to negative λ_3
- Exact cancellation at threshold

Small Rates



For √ S=14 TeV,
K ~ 2 in $m_t \rightarrow \infty$ limit
(not in plot)

Sensitivity to HHH coupling; also to sign(λ_3)

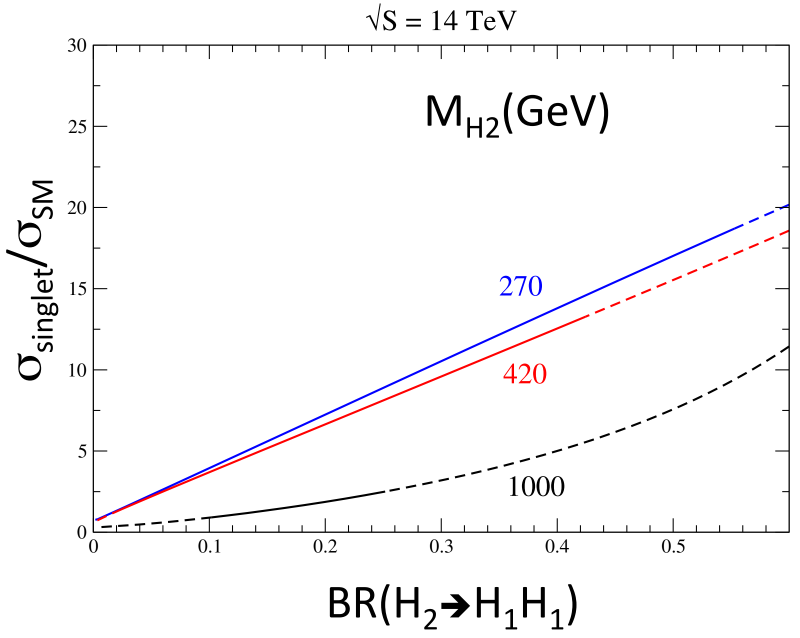


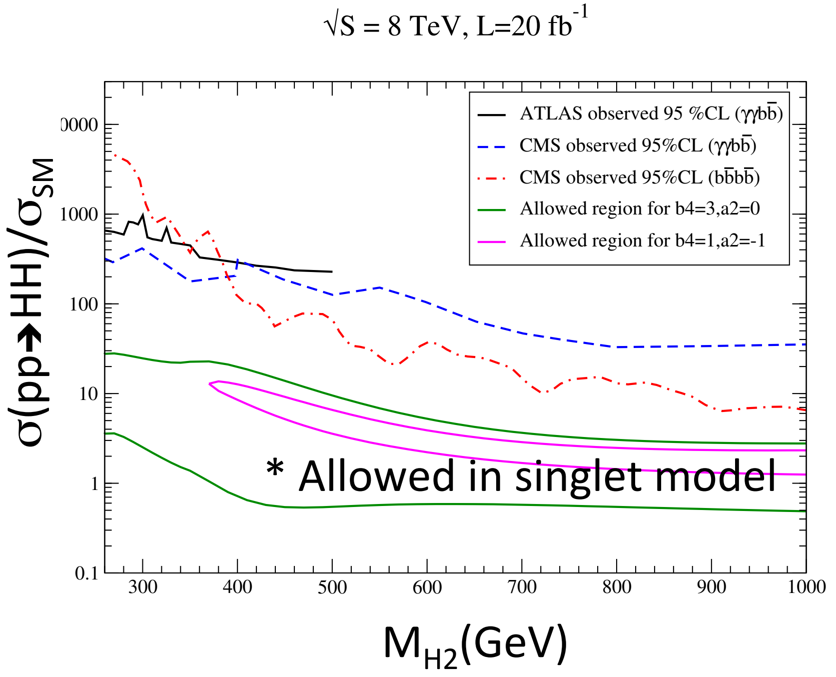
Double Higgs Production

- Can we measure it?
  - Small rate!
- Can we construct models where it is enhanced?
  - Non-SM couplings (λ_3 or ttHH vertex, eg)
  - New particles in loops
  - Resonances: gg→X→HH (MSSM, eg)

Creativity restricted by requiring single H production to have experimentally measured value and by precision EW measurements

Enhanced HH in Singlet Model





- Enhancements of H_1H_1 rate of factors 10-15 if M_{H2} < 400 GeV
- Easy to arrange in many models…. Major constraint is gg➔ h needs to have observed rate

[Chen, Dawson, Lewis, arXiv:1410.5488]

The Story is Just Beginning

We are just starting the exploration of weak scale physics

- We know that deviations from SM predictions cannot be too large

- *But there is lots of room for discovery of new Higgs particles, measurements of Higgs signals in new channels, precision measurements of Higgs properties*

Big questions remain: Flavor, dark matter, hierarchy….

Lots of Higgs Physics to do in Run 2!