Finding the (a) Higgs Boson

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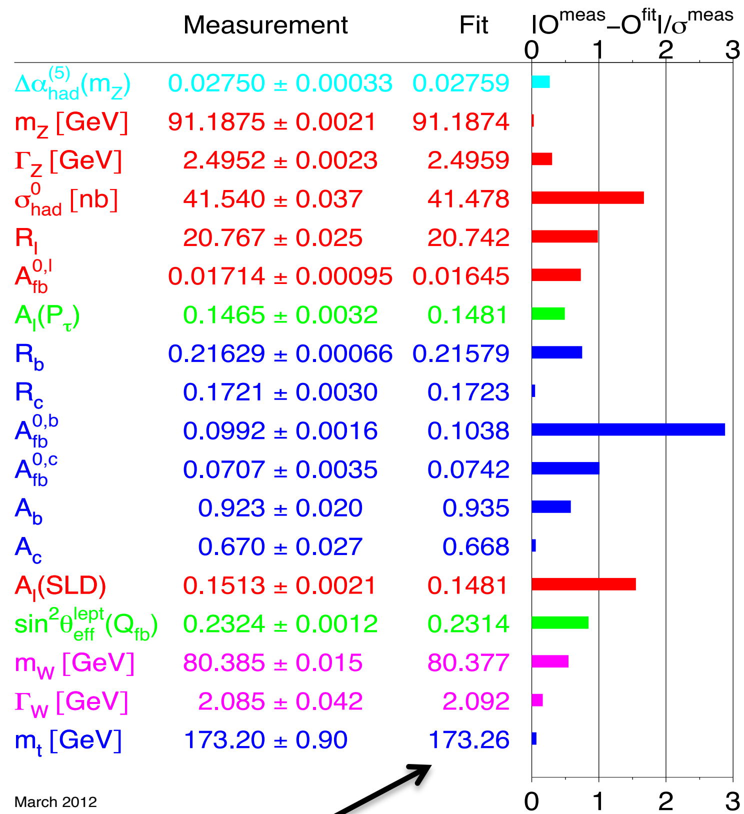
Fermilab 2012, Lecture 2

- Production of a Higgs boson
  - How much freedom do we have to change the Standard Model predictions
  - What are the theory uncertainties?
  - Which channels are important?

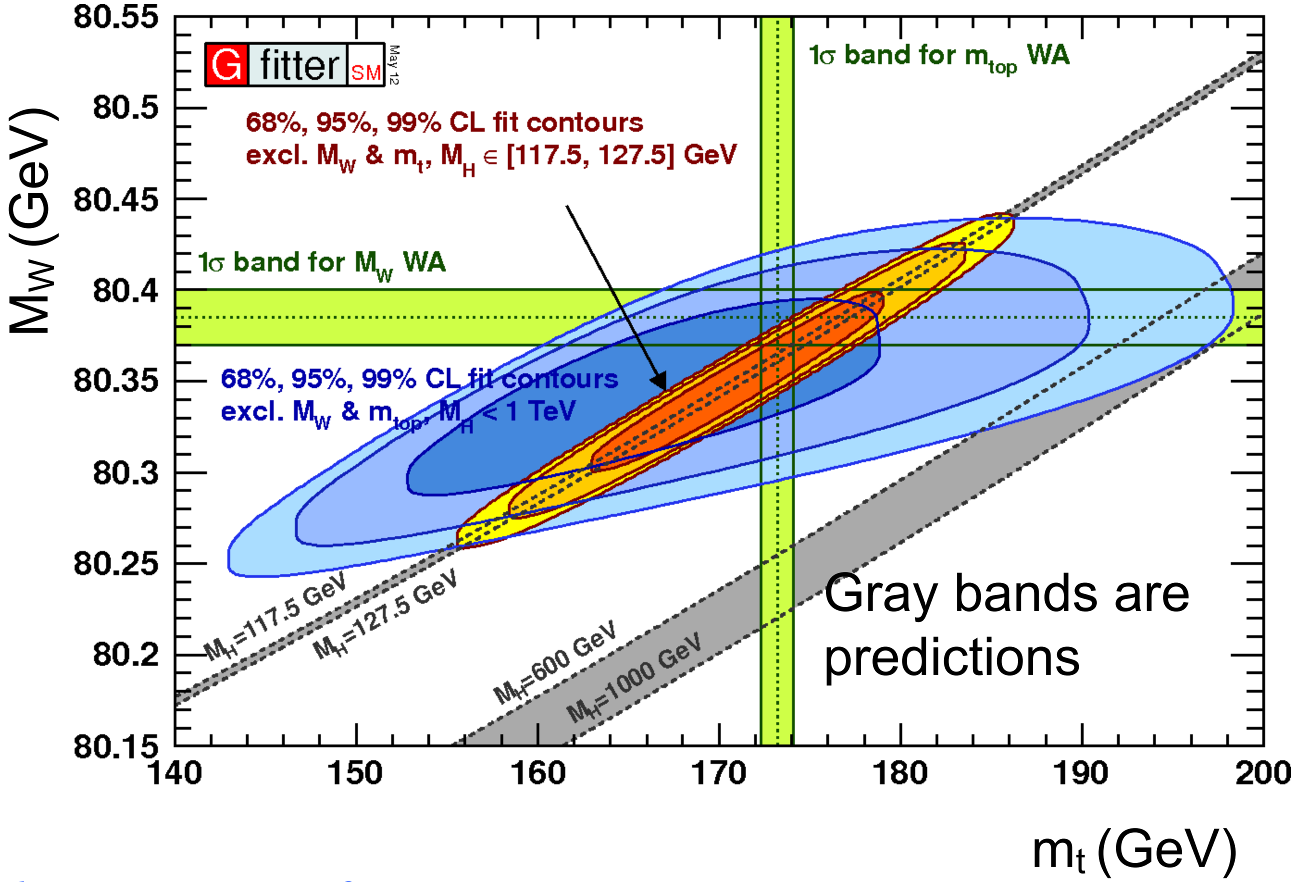
Recap

- Standard Model is simple
  - 4 input parameters (G_F, α, M_Z, M_h)
- All Higgs couplings predicted
- *Only unknown is Higgs mass*
- Many things put in by hand
  - Which gauge group, left-handed doublets, number of generations, fermion masses
- Pretty much everything works (experimentally)



Fits m_t too using radiative corrections!

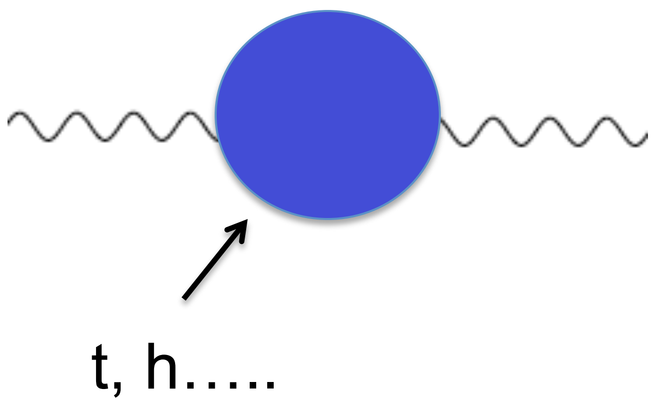
Global Fits to Electroweak Data

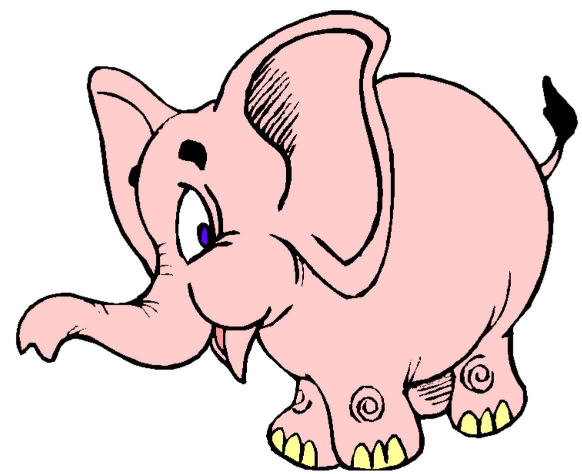


Observation of M_h=125 GeV Higgs in agreement with global fits is triumph for Standard Model… consistent theory!

Indirect Limits

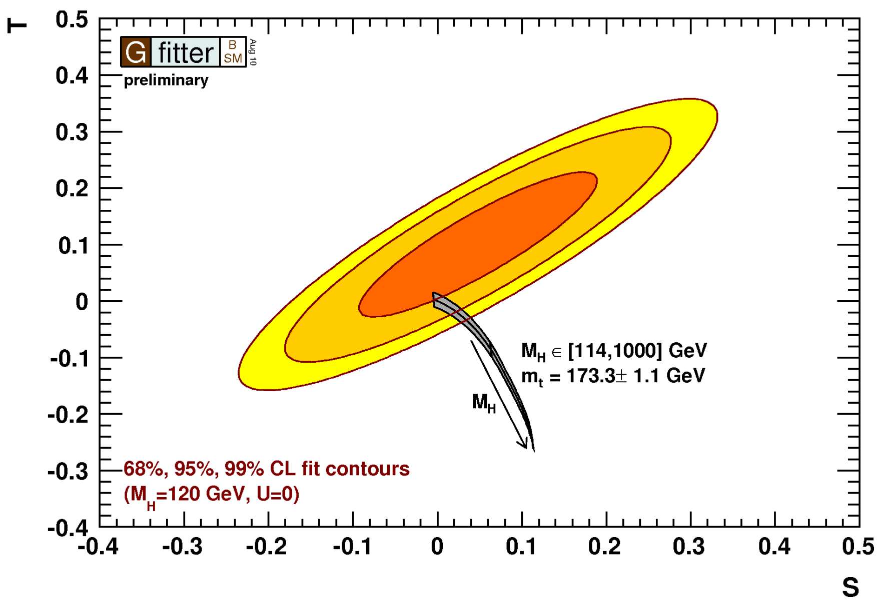
- They come from loops
  - *Test consistency of SM*
- Good: Sensitive to new physics in loops
- Bad: Lots of possibilities





Indirect Limits

- Used to be able to play off M_h vs new physics effects
- BSM physics strongly restricted by light Higgs

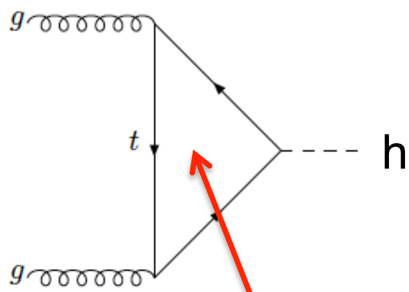


New Physics tends to pull you out of the ellipse

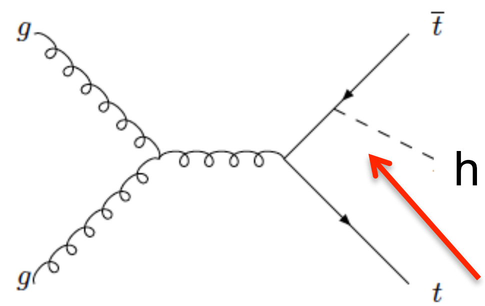
Higgs Production at a Hadron Collider

Most important processes:

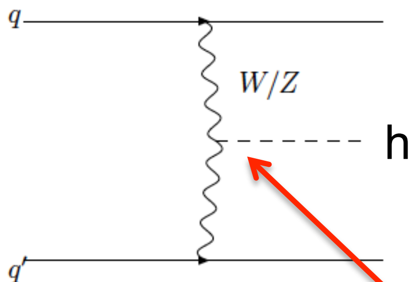
$$gg \to h$$
$$q\bar{q} \to q\bar{q}h$$
$$q\bar{q} \to Vh$$
$$q\bar{q}, gg \to t\bar{t}h$$

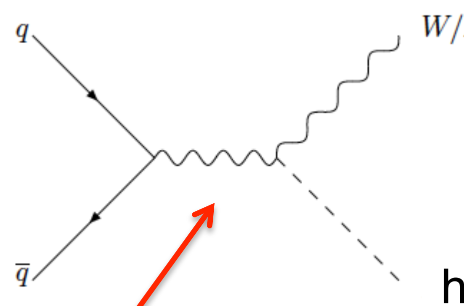


Depends on new physics in loop



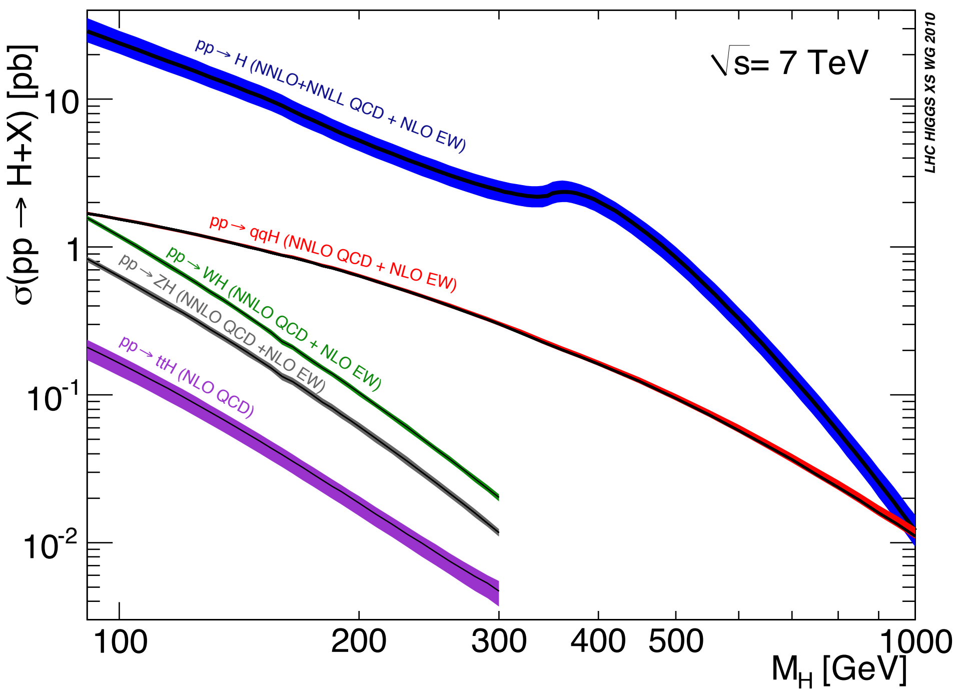
Direct measurement of tth Yukawa





Vanishes if v=0: Fundamental test of EWSB mechanism

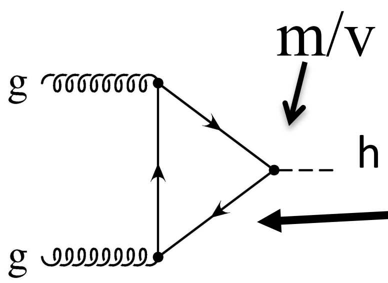
Higgs at the LHC



M_h=125 GeV, σ (gg➔H) at 7 TeV: 15.3 pb
at 8 TeV: 19.5 pb
at 14 TeV: 49.9 pb

Production Mechanisms in Hadron Colliders

- Gluon fusion
  - Largest rate for all M_h at LHC and Tevatron
  - Gluon-gluon initial state
  - Sensitive to top quark Yukawa λ_t



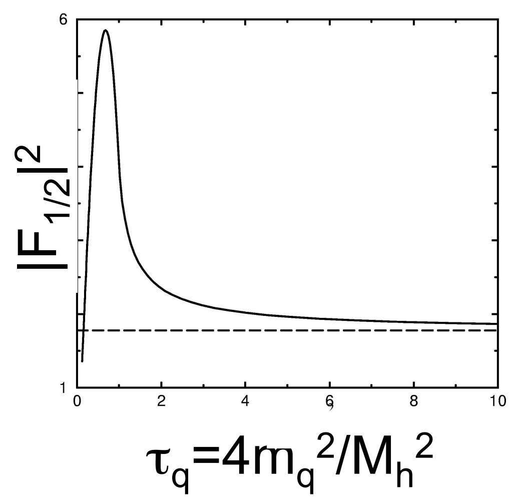
Largest contribution is top loop

In Standard Model, b-quark loop contribution small

Gluon Fusion

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

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



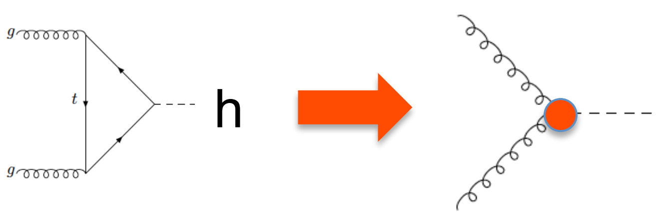
- Rapid approach to heavy quark limit: Counts number of heavy fermions
- NNLO corrections calculated in heavy top limit

Gluon Fusion

- Heavy fermions give mass independent contribution to gluon fusion……*no decoupling*
- This statement tests source of fermion mass from Yukawa

$$L_t = -\frac{m_t}{v}\bar{t}t\left(h+v\right)$$

- ggh described by effective Lagrangian (which can be used for higher order corrections)



$$L_{eff} = \frac{\alpha_s}{12\pi v} G^A_{\mu\nu} G^{A\mu\nu} h$$

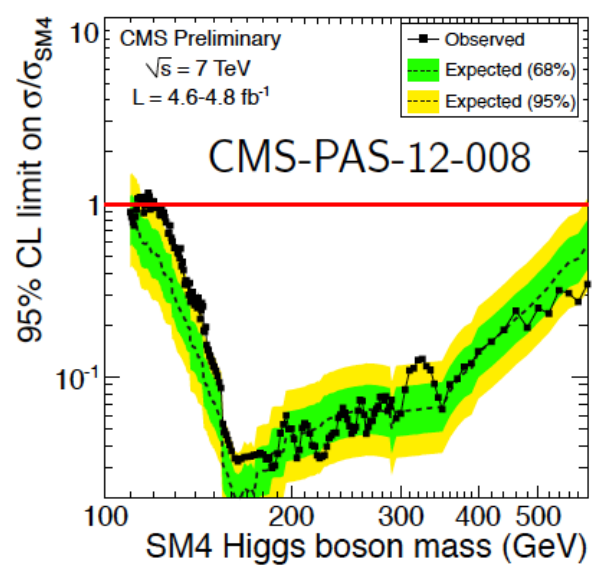
What if there were a SM 4th generation?

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

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

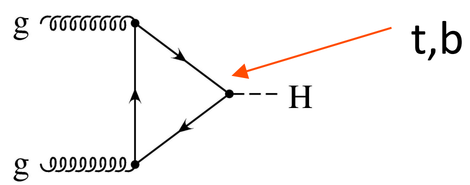
Important: Contribution from chiral fermions roughly independent of fermion mass

SM 4th generation is ruled out by Higgs observation!



Gluon Fusion at Higher Order

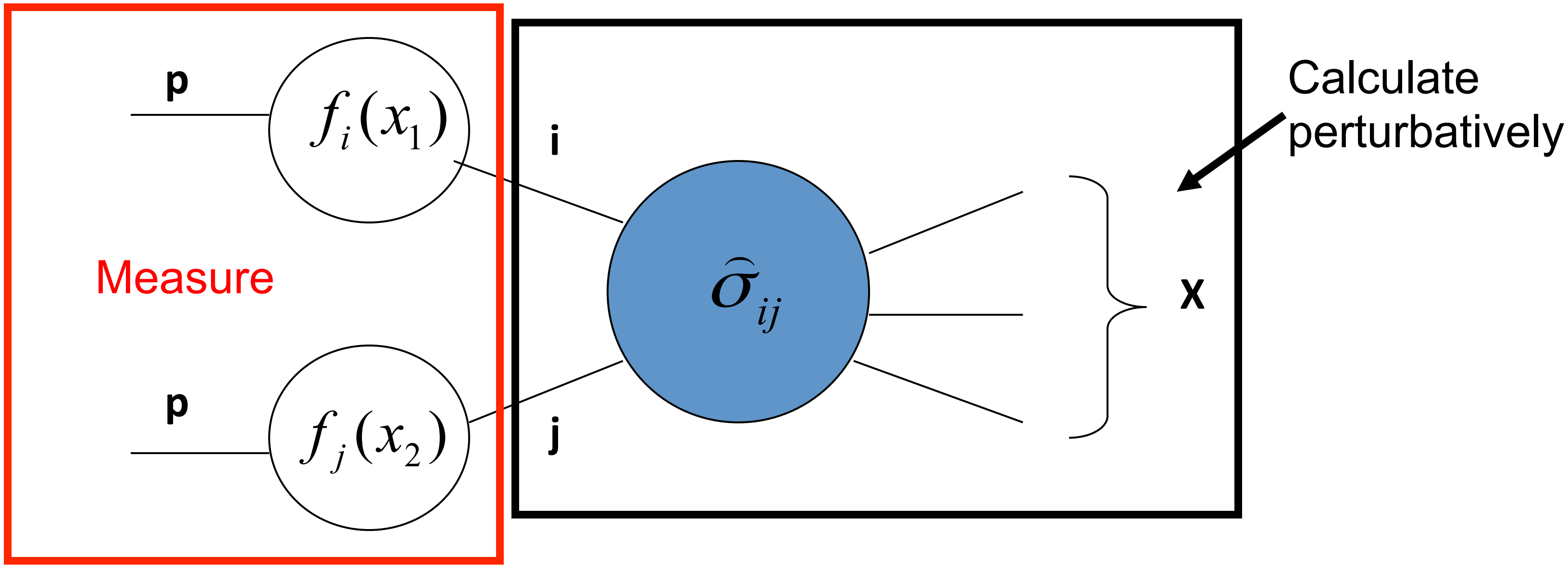
- Dominant production mode is $gg \rightarrow h$



  - NNLO in heavy m_t limit (checked in M_h/m_t expansion)
  - Exact t,b loops at NLO
  - N^3LL resummation
  - EW and mixed EW/QCD corrections

⇒ **Precise predictions allow us to trust error estimates**

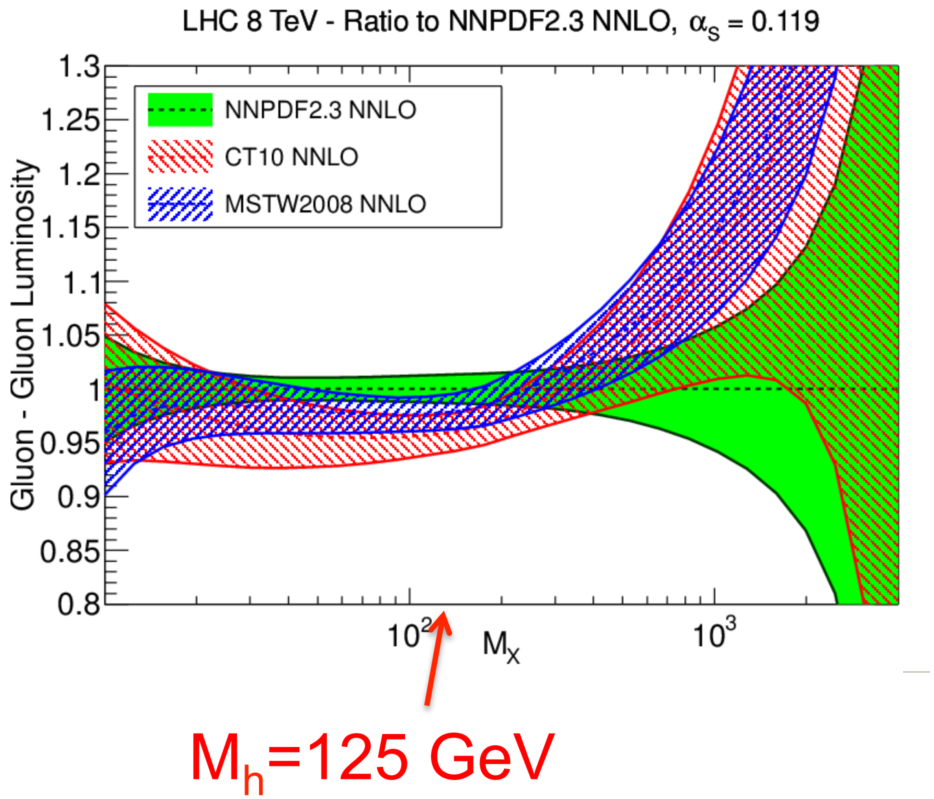
Hadronic Collisions



$$\sigma(pp \to X) = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu_F) f_j(x_2, \mu_F) \widehat{\sigma}(ij \to X)$$

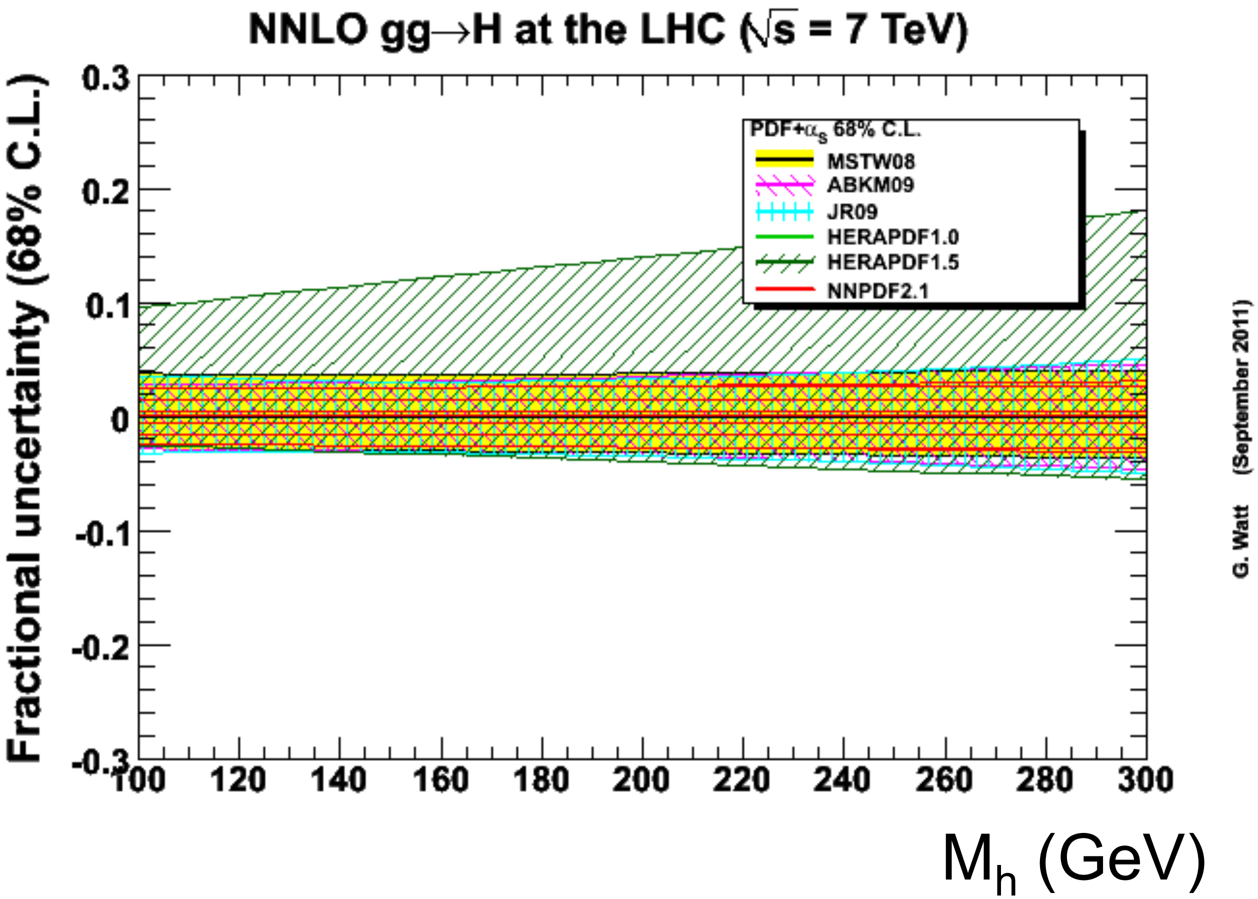
Dominant Higgs contribution is gg→h

- PDFs to NNLO
- NNPDFs, CT10, MSTW are global fits



Differences between sets larger than PDF errors of a given set

PDF sets give consistent NNLO predictions



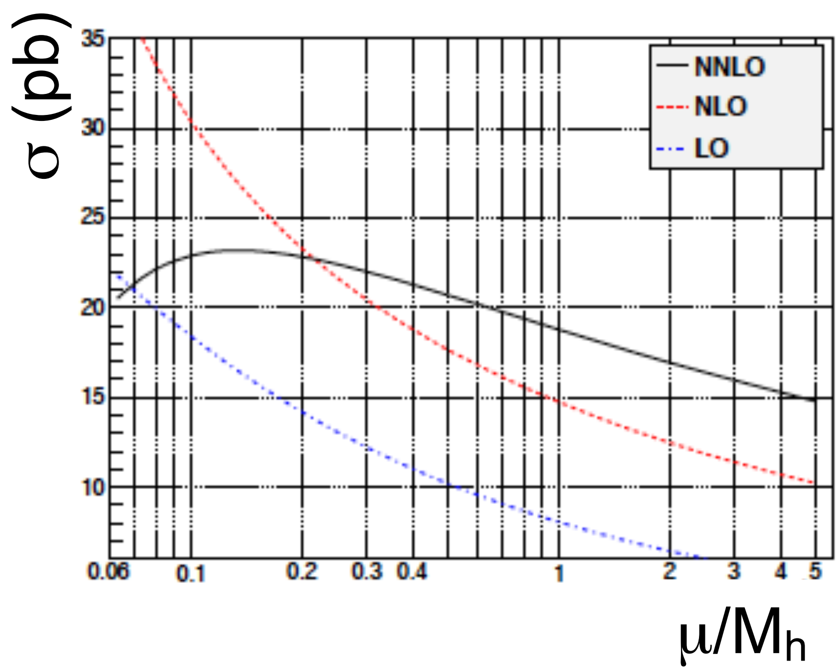
Scale variations

- 2 unphysical scales in hadronic cross sections
- Renormalization scale μ_R : $\alpha_s(\mu_R)$, $\log(\mu_R/M_h)$
- Factorization scale μ_F: $f_i(x,\mu_F)$
- To any given order in α_s, μ dependence vanishes
- *Hence scale dependence often used as estimate of theory uncertainty*
    - No "right" scale
    - Want to pick scale to minimize logarithms

Radiative Corrections are Large

LHC at 8 TeV, M_h=125 GeV

$gg \rightarrow h$

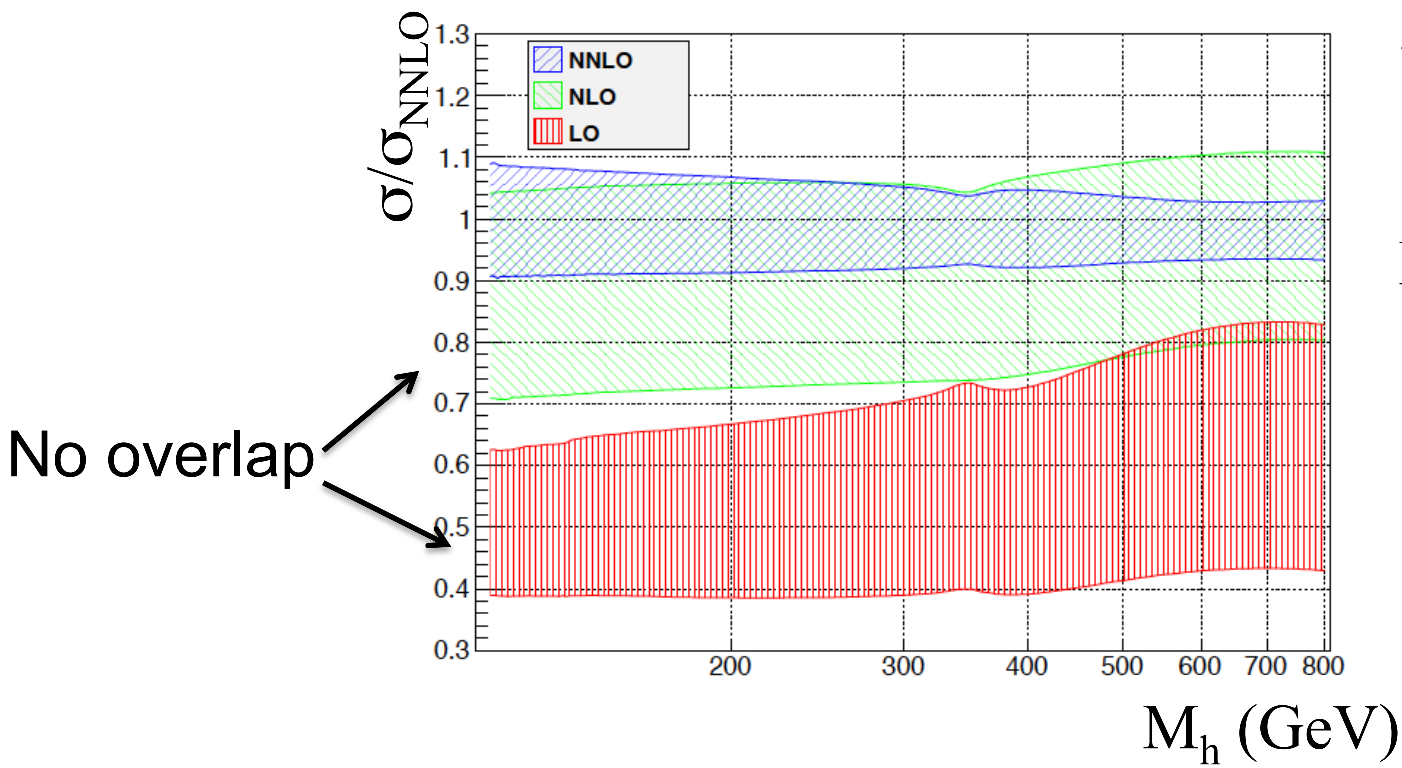


K_{NNLO} ~2.5

[Anastasiou, et al, arXiv: 1202.3608]

Scale Dependence

- μ dependence would cancel in all orders result
- Scale variation can underestimate uncertainties



$\sqrt{s}$=8 TeV

$M_h/4<\mu<M_h$

[Anastasiou]

Exclusive Higgs Cross Sections

- Classify Higgs signal by number of jets
  - Require $p_T^{jet} < p_T^{cut}$
  - $pp \rightarrow h + 0$ jets
  - $pp \rightarrow h + 1$ jet
  - $pp \rightarrow h + 2$ jets
  - Backgrounds vary with number of jets
    - Optimize analysis for different jet bins

p_T^{cut} introduces new uncertainties

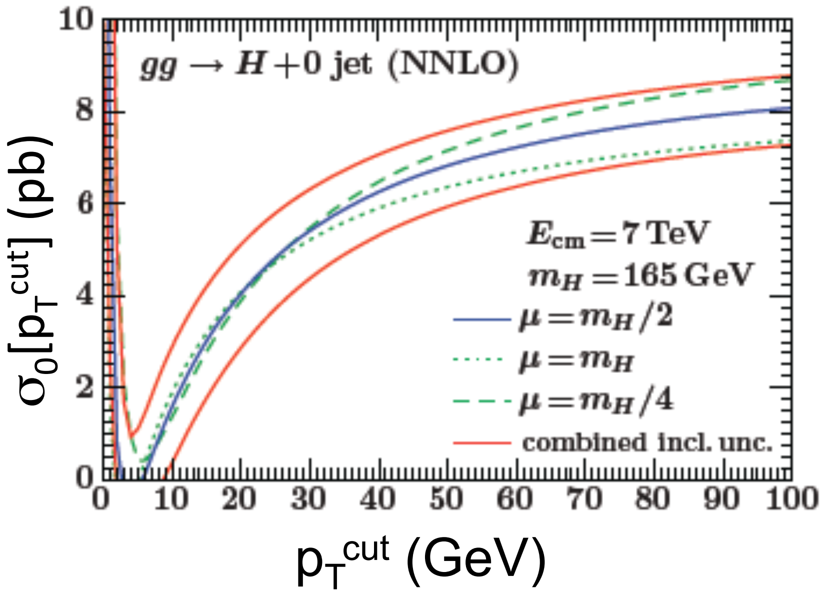
Vetoing Jets

- Jet veto changes form of perturbation theory

$$\sigma(0\ Jet) = \sigma(p_T^{cut}) \sim \sigma_B \left(1 - (..)\alpha_s \ln^2 \frac{p_T^{cut}}{M_H} + \ldots\right)$$

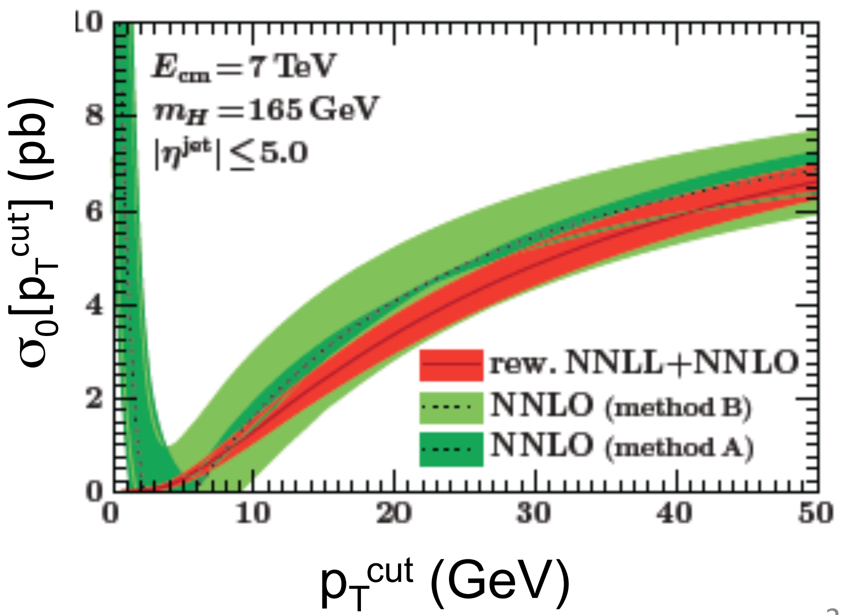
- Logarithms can be large
- Varying scale in total cross sections underestimates scale uncertainties due to cancellations
- Better estimate: treat inclusive cross section errors as independent: $\Delta_{total},\ \Delta_{\geq 1}, \Delta_{\geq 2}$

Fixed Order Predictions Have Large Uncertainties



FeHiP NNLO fixed order

NNLL resummation of $\mathrm{Log}(p_T^{cut}/M_h)$



[Stewart, Tackmann, 1107.2117]

Where do uncertainties come from?

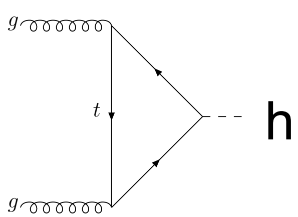
- Unknown higher order terms (TH)
- Scale dependence (TH)
- PDFs/α_s (TH + EXP)
- Other parameters: m_b, …. (TH+EXP)
- Effects of cuts (TH + EXP)
  - Do cuts script the result?
- BSM effects (TH)

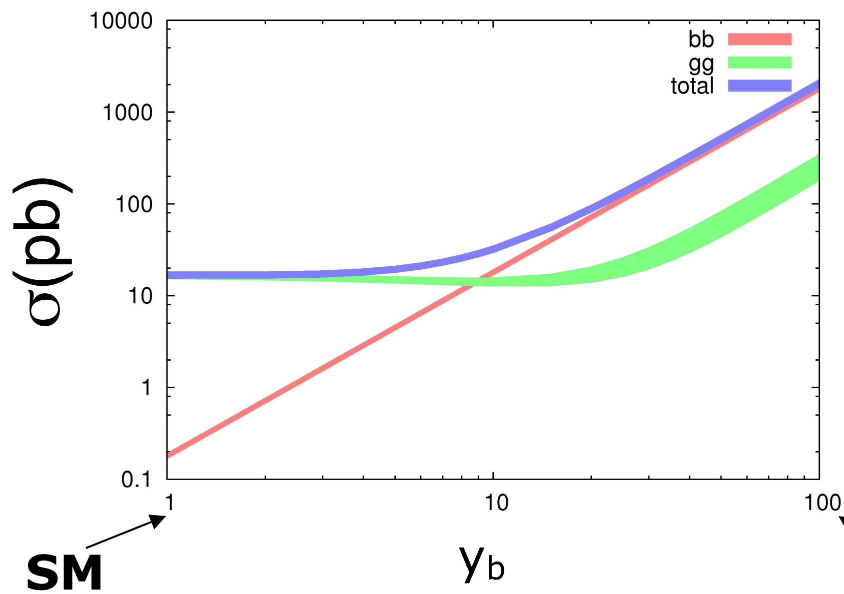
$$\sigma = \sum_{ij} f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}\left(\hat{s}, \alpha_k, M_n, cuts\ldots\right)$$

The Role of b-loops

Gluon fusion rate mostly depends on top yukawa

b loops are ~5% of SM gg→h





M_h=120 GeV
$\sqrt{s}$=7 TeV

SM

gg "only" NLO

[Anastasiou, Buehler, Herzog, Lazopoulos]

Bottom line on gg $\rightarrow$h

- Largest production mode
- Well understood theoretically
  - ± 7% scale uncertainty
  - ± 7% PDF as uncertainty
  - Total uncertainty ~ ±25% when jet veto uncertainty included
- Could be sensitive to new colored states
  - Production is (almost all) proportional to tth Yukawa coupling
  - Measured rate looks “SM like”