Higgs Cross Sections

S. Dawson, BNL

Triumf

December, 2011

What's it all mean?

Questions to my experimental friends

- If the Higgs indications are real, where will you be next summer?
- What do you need us (theorists) to calculate?
  - Is Higgs cross section working group still relevant?
    - Or are the challenges experimental?
  - Do you need backgrounds (ZZ?) to higher order?
    - These are a lot of theory work!
  - What kind of model building is useful?
    - Are there still missing signatures?
  - Can we be cleverer at the way we think about studying Higgs properties?

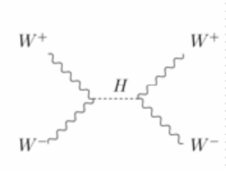
Who Needs a Higgs Boson?

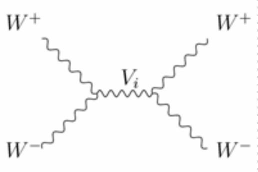
- To give mass to W/Z and fermions
  - W mass is predicted in terms of $G_{F,}$ α, M_Z
  - Fermion masses are free parameters
- To unitarize vector boson scattering
  - $VV \rightarrow VV$ grows with energy unless $M_H < 700$ GeV
  - Theory is strongly interacting at TeV scale without Higgs Boson

We expect something "Higgs-like"

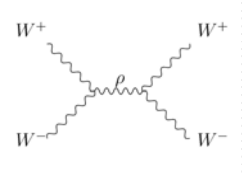
What unitarizes WW scattering?

- Symmetry breaking could be weakly coupled
  - SUSY (and beyond MSSM), Higgs Portal (lots of singlets), Extra-D with multiple vector bosons…..



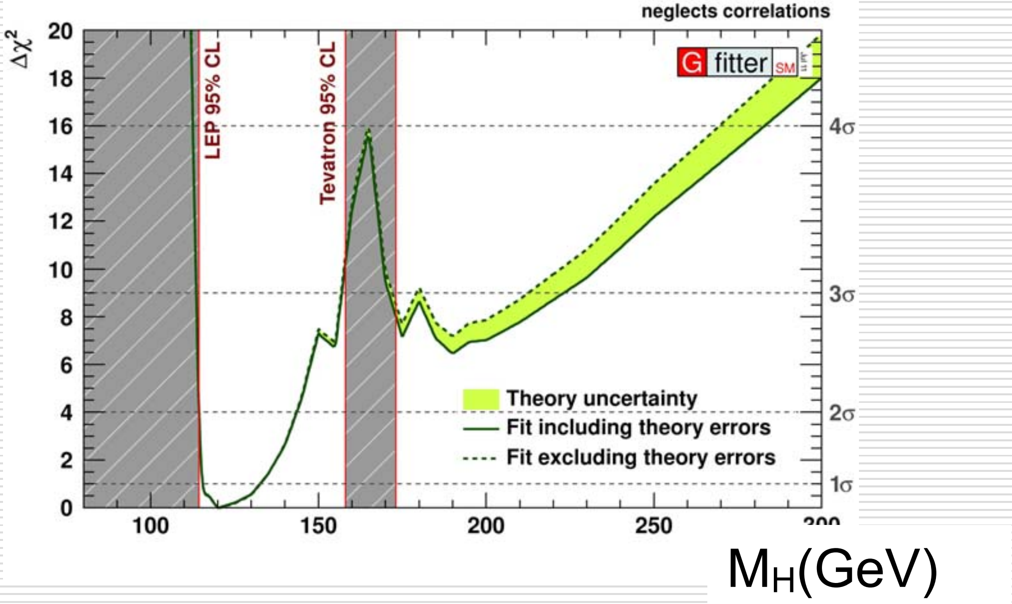


- Symmetry breaking could be strongly coupled
  - Technicolor, QCD like models, Higgsless, composite Higgs…..



Higgs Boson

- Standard Model Higgs expected to be light



- This assumes the Standard Model!

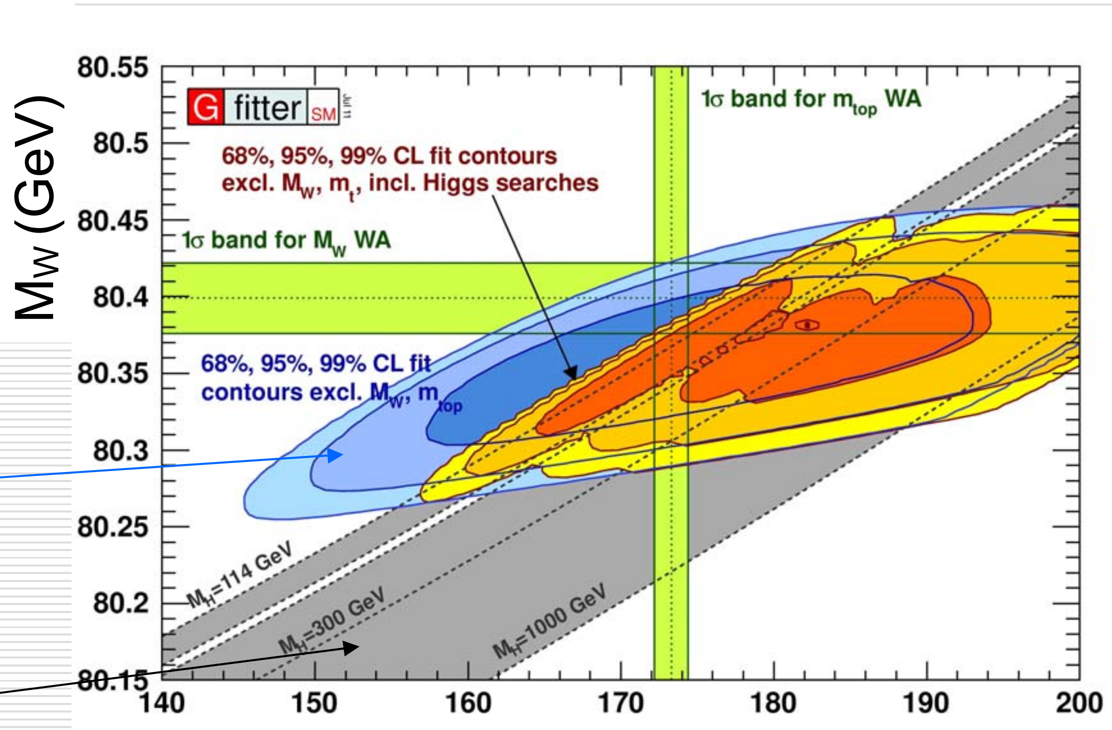
$\Delta\chi^2=4$ gives 95% confidence level limit

M_W versus m_t

Masses inferred from precision measurements and Higgs searches*

Masses inferred from precision measurements

SM Predictions



m_t (GeV)

Higgs boson wants to be light

* Includes LHC searches

Higgs Limits

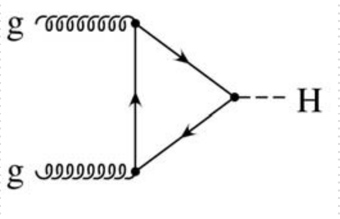
- From Gfitter (2011)
  - If you don't include direct search limits for Higgs, 95% CL upper bound: $M_H < 169$ GeV
  - If you include LEP, Tevatron, LHC limits, 95% CL upper bound: $M_H < 143$ GeV
  - ***Test of consistency of Standard Model***

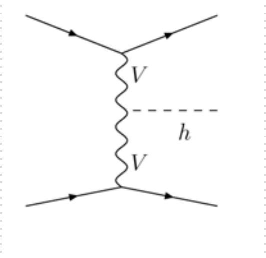
Not hard to fit bounds with new physics

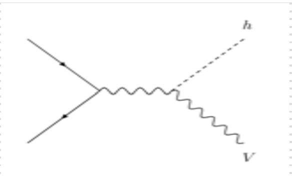
http://gfitter.desy.de/

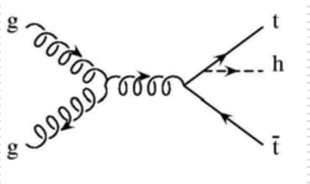
***before yesterday**

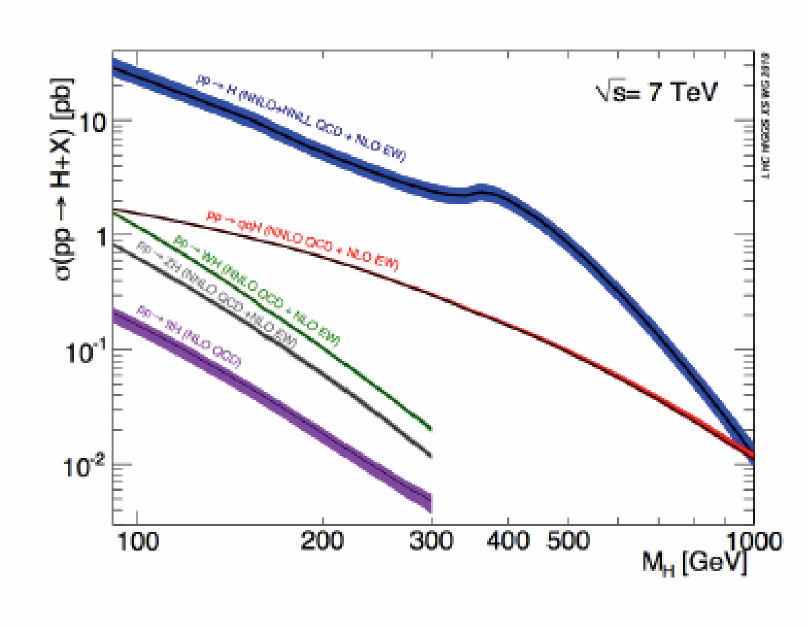
Higgs at the LHC











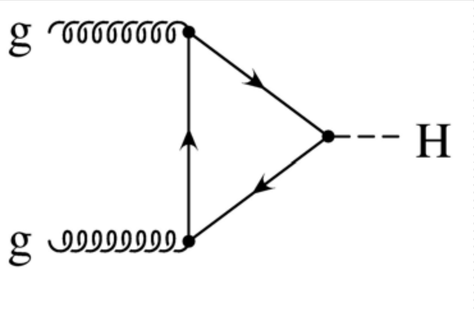
Reliable estimates of uncertainties

Largest uncertainties on gluon initiated processes

Standard Model Higgs

- SM fermion couplings to Higgs are fixed

$$L_Y = -m_f\left(\overline{\Psi}_L\Psi_R + \overline{\Psi}_R\Psi_L\right)\left(1+\frac{H}{v}\right)$$



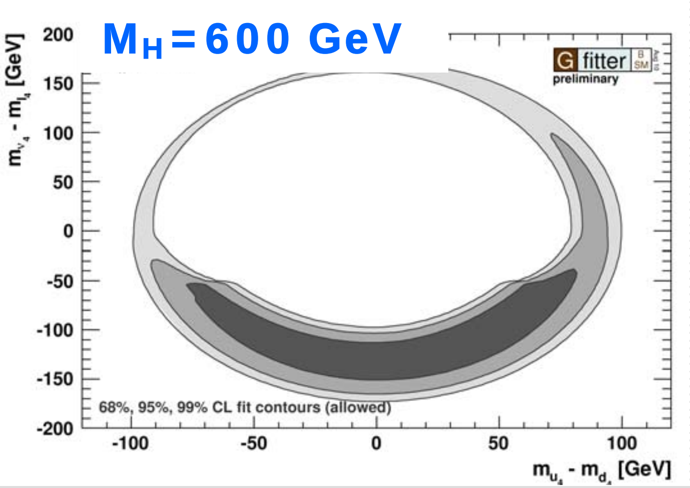
Largest contribution is top loop

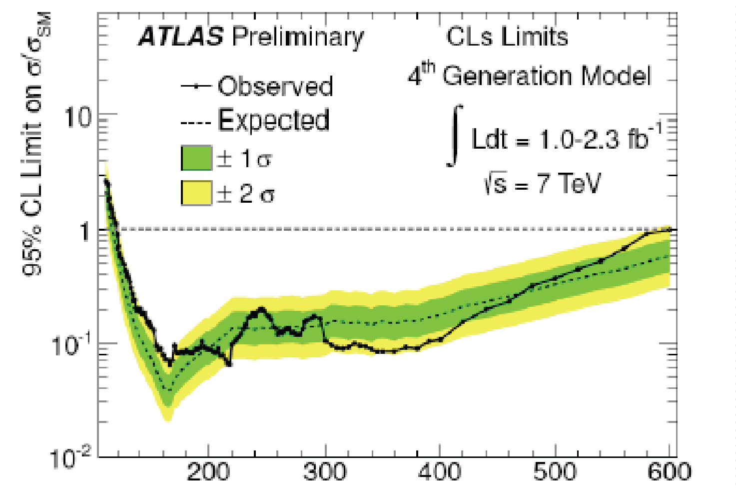
b-loop contributes ~2-5%

Extremely sensitive to BSM Physics

Many models can have a heavy Higgs Boson

- SM 4th generation almost gone





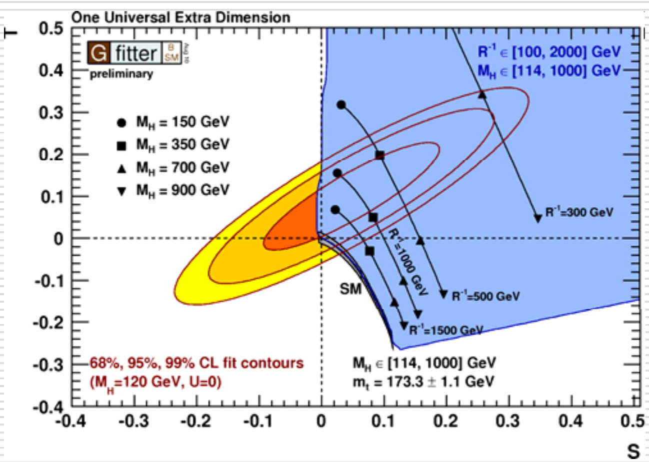
M_H(GeV)

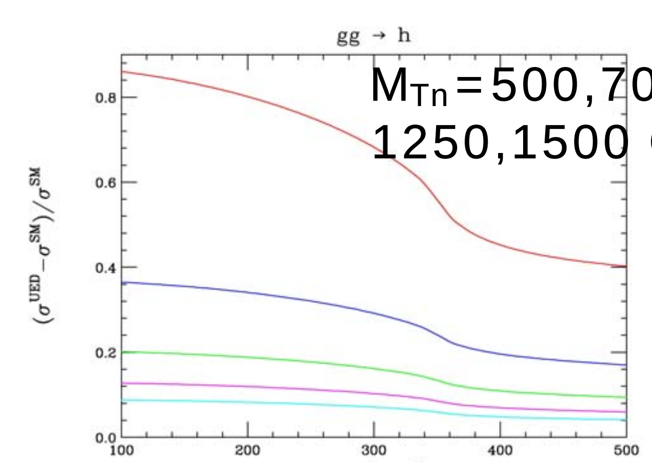
gg→H enhanced by ~9 in 4G model

H→γγ decay suppressed in 4G model

Many Models can have a Heavy Higgs Boson

- Universal extra dimension models can have a heavy Higgs boson
  - Models have heavy copies of top quark, T_n
  - Higgs couplings of $T_n \sim (m_t/v)(m_t/M_{Tn})$
  - Gluon fusion Higgs cross section enhanced





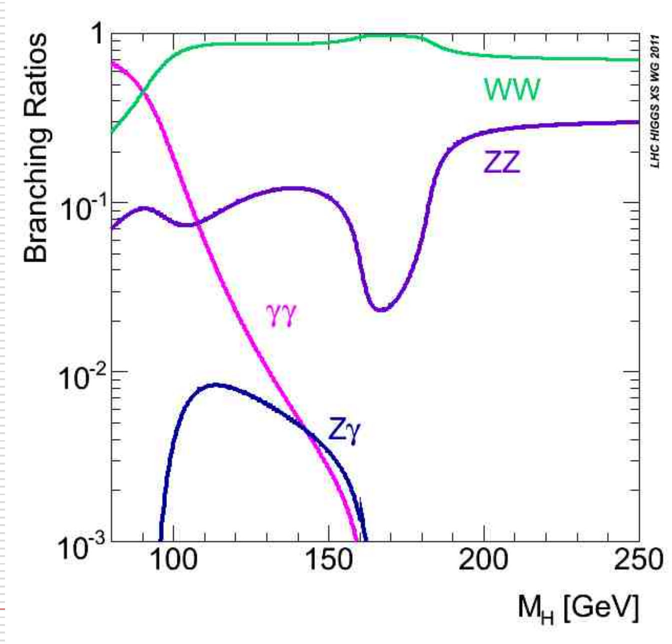
M_{Tn}=500,700,1000, 1250,1500 GeV

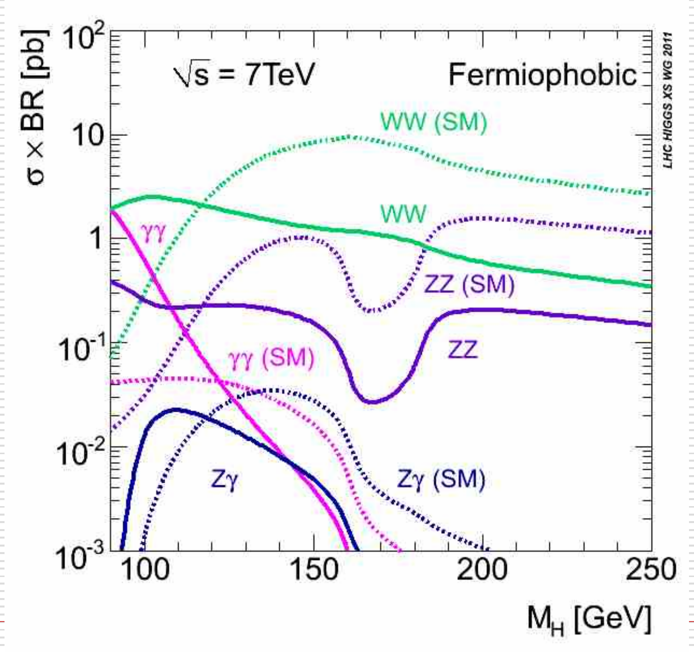
M_H (GeV)

[Matchev, Petriello]

Many Possibilities: Fermiophobic Higgs

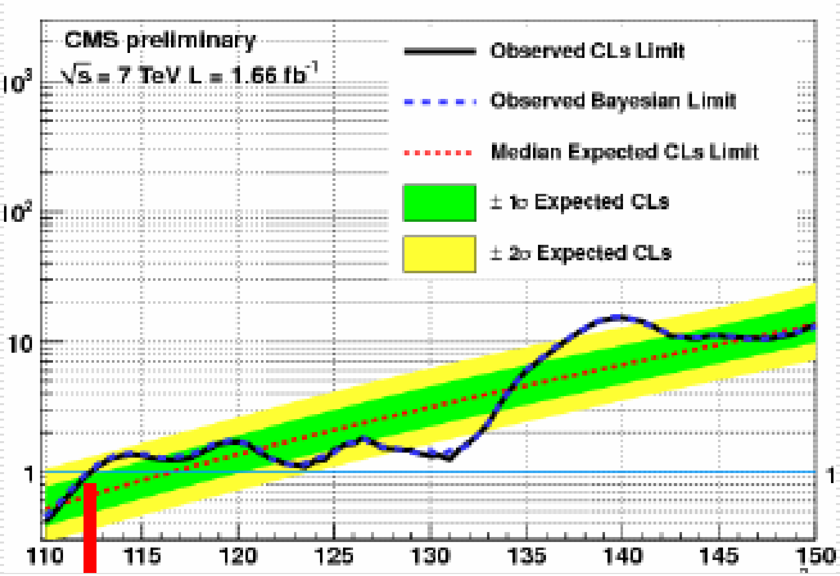
- Higgs produced from VBF, VH
- Branching ratio to vector bosons much larger than SM





Fermiophobic Limits

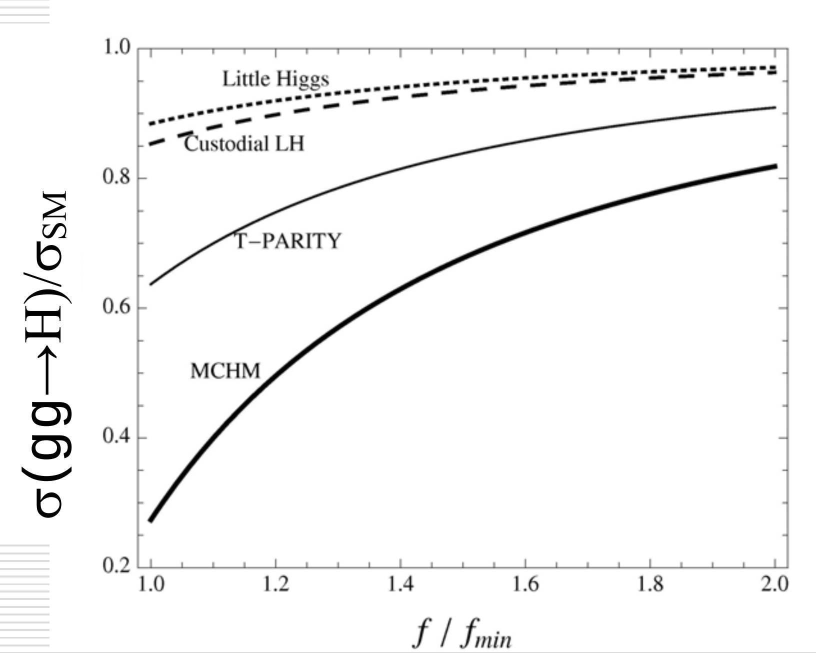
- In $\gamma\gamma$ mode, CMS excludes fermiophobic Higgs with M_H<112 GeV



M_H(GeV)

Of course, rate can be suppressed

- Little Higgs like models
  - Higgs is Goldstone Boson of broken global symmetry
  - Top quark has a weak singlet partner which mixes with top
  - Higgs production can be significantly suppressed



Note decoupling for large f

f_{min} is minimum scale allowed by precision EW (500 -1200 GeV)

[Low & Vichi]

Higgs Cross Section is window to BSM

- Gluon fusion to NNLO for models with new fermions
  - If fermions mix with top, rate tends to be suppressed by ~ 20% [Composite Higgs models, Little Higgs]
- New channels in MSSM (and others)
- Hard to quantify this kind of uncertainty

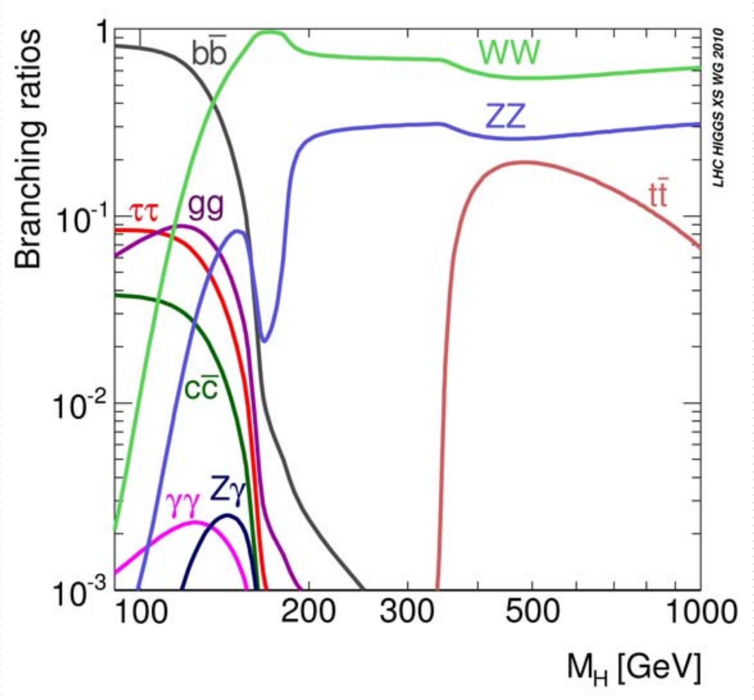
Largest uncertainty in Higgs cross sections is unknown BSM physics

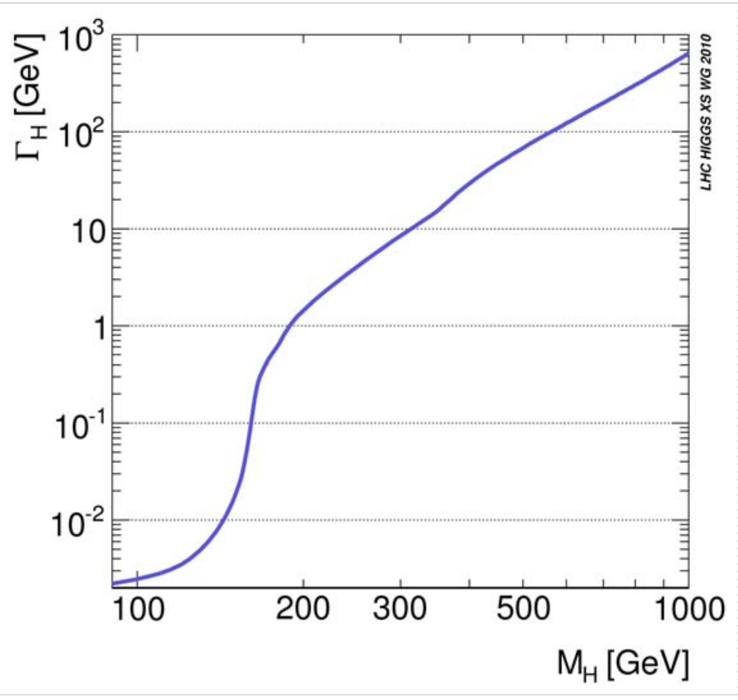
See Y. Bai talk

[Furlan]

SM Higgs Theory is predictive

- Branching ratios known in SM

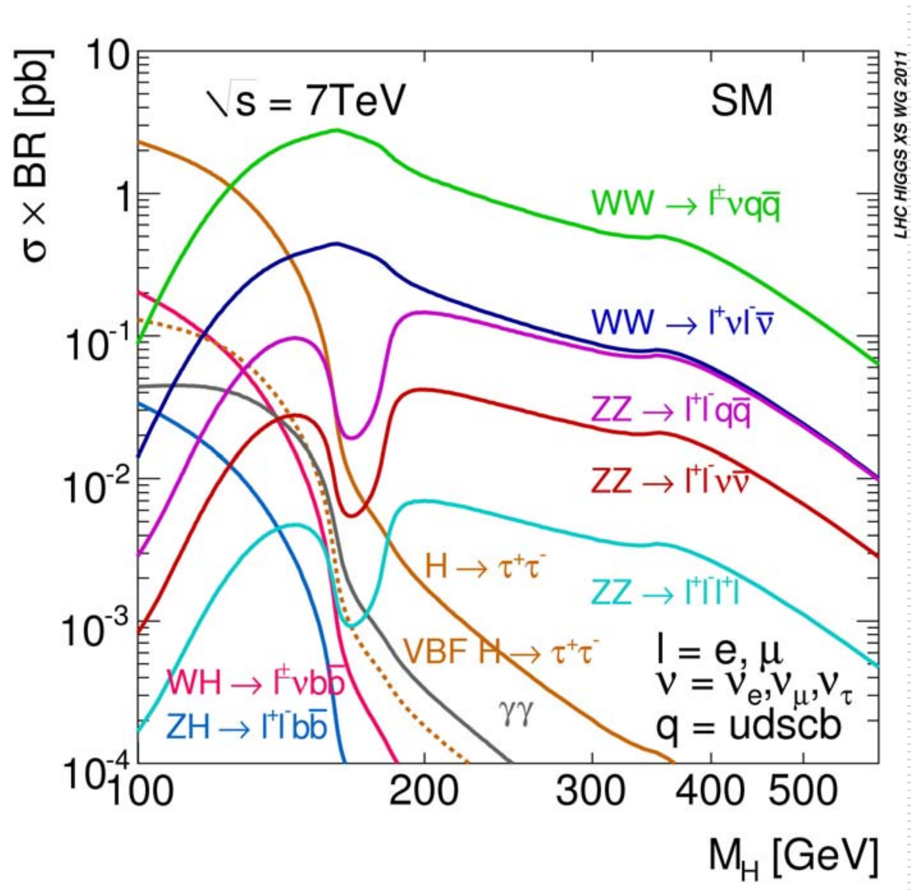




Branching Ratio Uncertainties are Small

- Largest uncertainty is on $H \to bb$ of O(3-4%) coming from uncertainty on m_b
- Other uncertainties on BRs are O(1%)
  - (Except $H \to tt$)
- Use HIGLU plus Prophecy4f (includes $H \to V^*V^* \to 4f$)
  - Off-shell effects matter near WW, ZZ thresholds

Higgs Theory is predictive



Where do uncertainties come from?

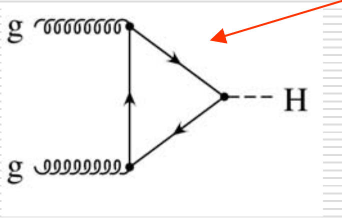
- Unknown higher order terms (TH)
- Scale dependence (TH)
- PDFs/α_s (TH + EXP)
- Other parameters: m_b, ... (TH+EXP)
- Effects of cuts (TH + EXP)
  - Do cuts script the result?
- BSM effects (TH)

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

SM calculations in great shape

- Dominant production mode is gg→H

t,b

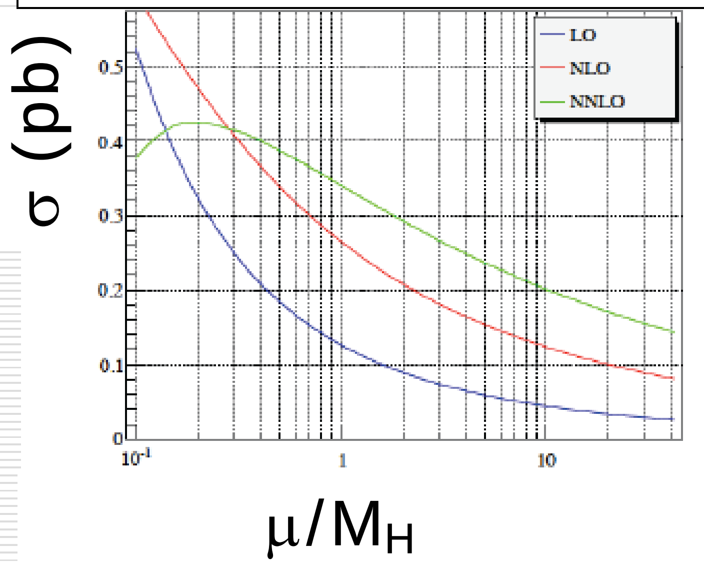


  - NNLO in heavy M_{top} limit (checked in M_H/M_{top} expansion)
  - Exact t,b loops at NLO
  - N^3LL resummation
  - EW and mixed EW/QCD corrections

⇒ Precise predictions allow us to trust error estimates

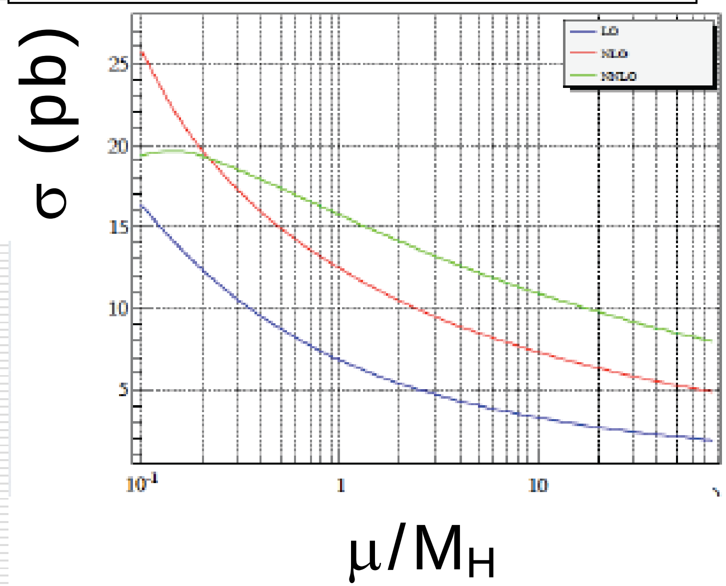
Radiative Corrections are Large

Tevatron, M_H=165 GeV



K_{NNLO} ~3

LHC, M_H=120 GeV

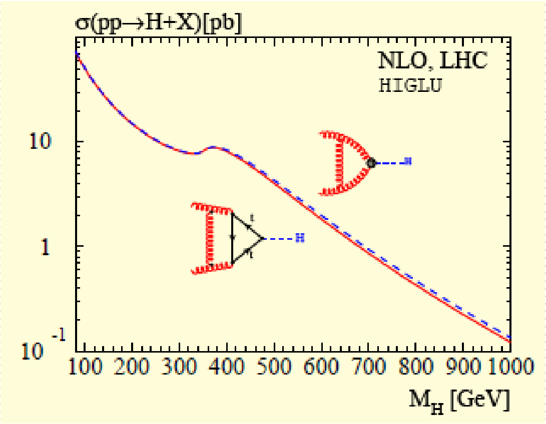


K_{NNLO} ~2.5

[Anastasiou, Moriond 2011]

What do we mean by NNLO?

- It is computed in limit $M_H^2/4M_t^2 \to 0$
- How can this work for heavy Higgs?
  - Can analytically check approximation at NLO
  - At NNLO can compute corrections in low x limit, $x=M_H^2/s$
  - They look big, but after weighting by PDFs give 2% effect to hadronic cross section

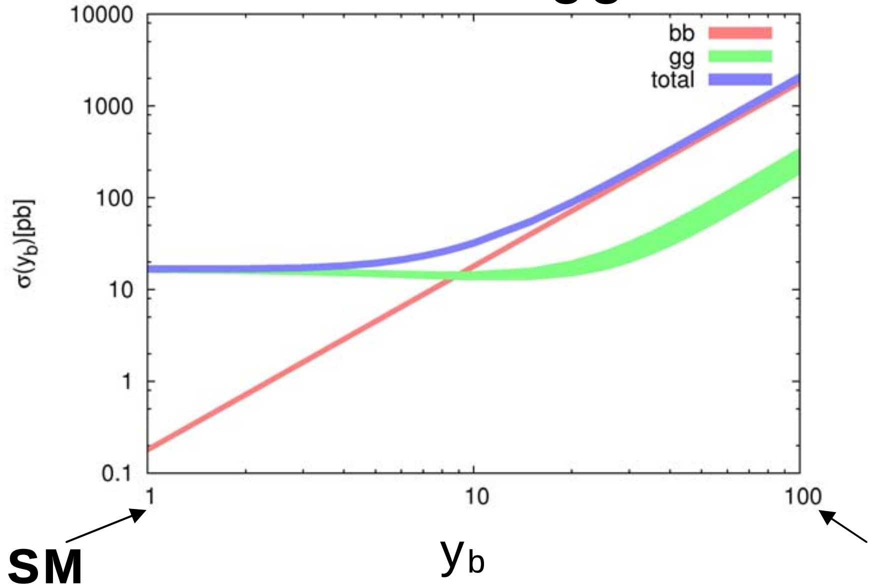


At NLO, 5% accuracy at M_H=1 TeV

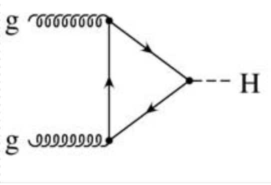
[Caola, Forte, Marzani, Harlander, Pak, Steinhauser, Ozeren]

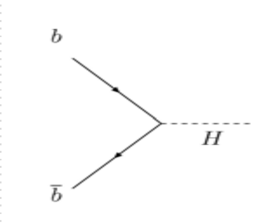
The Role of b-loops

- K factor for b loops smaller than for top loops
  - Known “only” at NLO
- b loops are 2-5% of SM gg→H



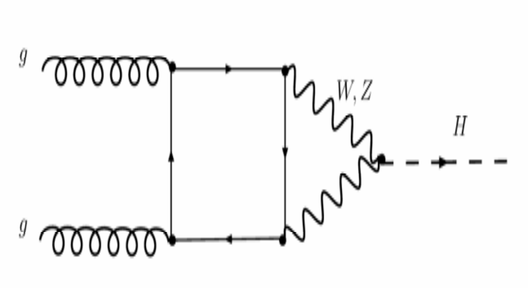
gg “Only” NLO





[Anastasiou, Buehler, Herzog, Lazopoulos]

Electroweak Contributions



$$L_{eff} = \frac{\alpha_s}{12\pi}\frac{H}{v} C_1 G_{\mu\nu}{}^A G^{\mu\nu A}$$

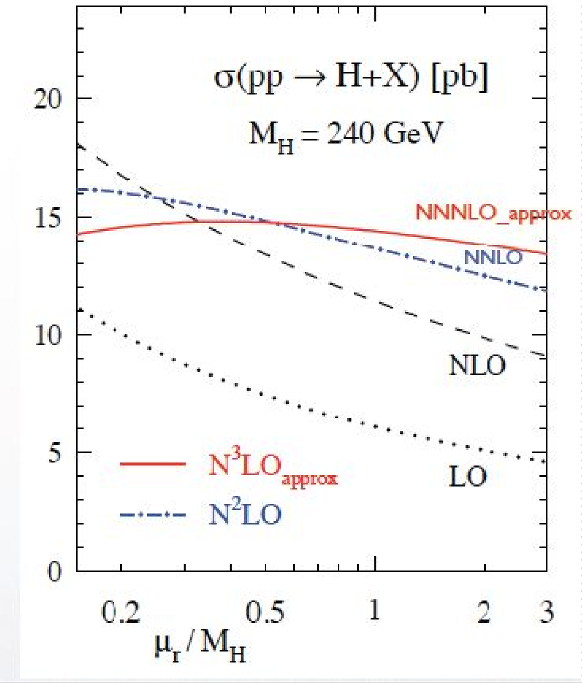
Enhanced by N_{lf}, No Yukawa suppression

$$C_1 = 1 + \alpha_S C_a + \alpha_S{}^2 C_b + \delta_{EW}\left(1 + \alpha_S C_{a,EW} + \alpha_S{}^2 C_{b,EW}\right)$$

Do EW terms factor?

$$C_1 = (1 + \delta_{EW})(1 + \alpha_S C_a + \alpha_S{}^2 C_b)$$

Small scale gives better convergence

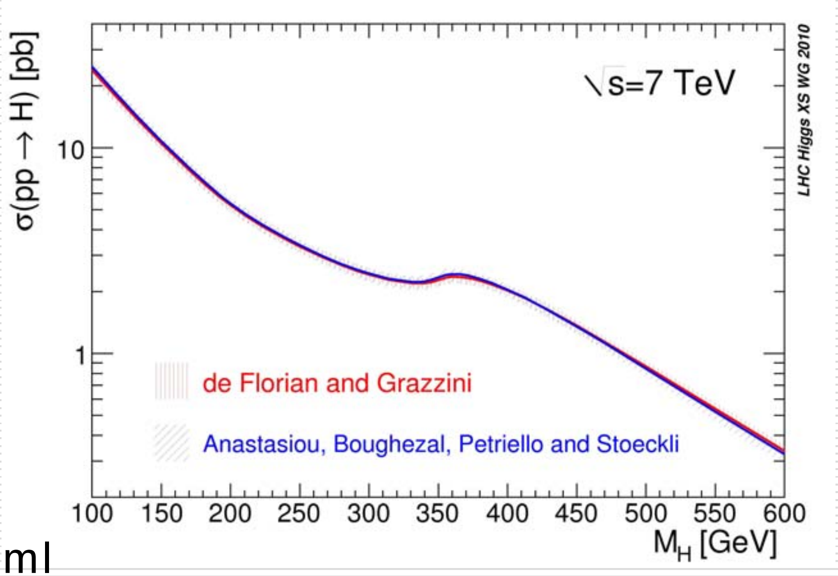


- Taking $\mu_0 = M_H/2$ minimizes effect of logs
- Increases cross section by about 10% from $\mu_0 = M_H$

[Moch and Vogt]

Scale uncertainty for gg→H

- Scale uncertainty O(6-8%) for M_H~ 100-300 GeV
- Slightly different approaches
  - ABPS
    - Exact NLO/NNLO in large M_t limit
    - No resummation
    - EFT estimate of EW/QCD
  - dFG
    - NNLO for large M_t+NNLL
    - Exact t/b to NLO
    - Exact EW



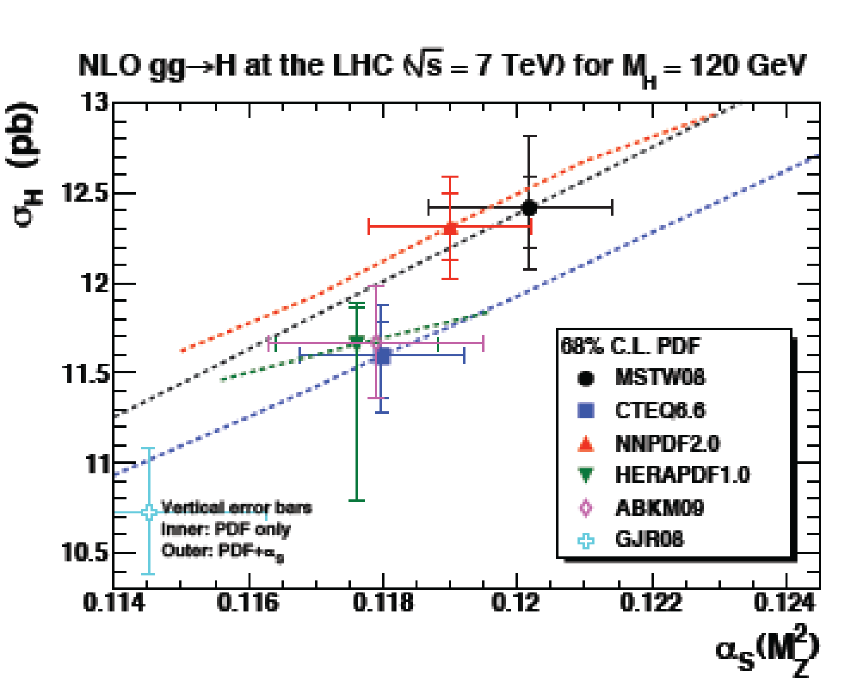
Online calculator:
http://theory.fi.infn.it/grazzini/hcalculators.html

PDF Uncertainties

- Experimental uncertainty
  - Choice of data sets
  - Statistical treatment of errors
  - α_s (correlated with PDFs)
    - PDFs have different central values
- Theory uncertainty
  - Parametrization of PDFs
  - Only ABKW, HERAPDF, MSTW at NNLO
  - CTEQ NNLO PDFs not public, but soon....

Each PDF has different central α_s

- α_s enters PDF evolution and cross section



NNLO PDF sets tend to have smaller α_s (ABKM: α_s =.1147)

→ ABKM gives 20% smaller σ

→ Djouadi suggests larger uncertainty

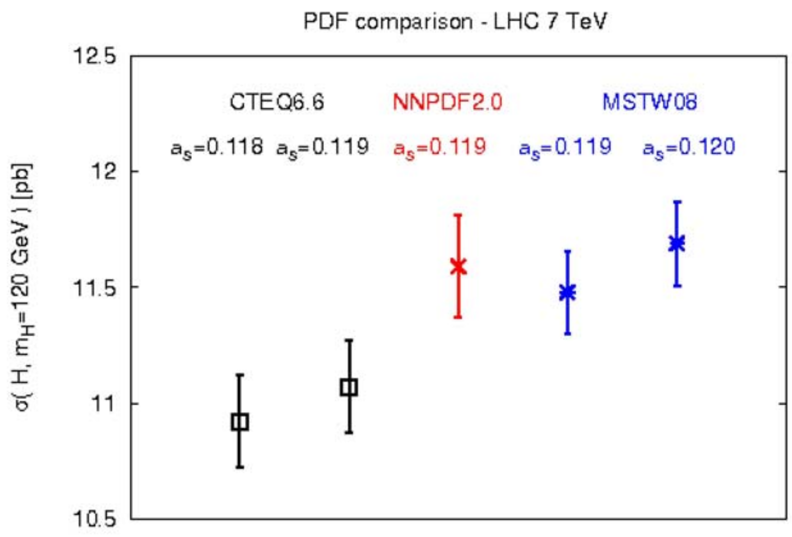
→ Need PDFs which include Tevatron di-jet data for gluons at high x

PDF differences

- Differences not entirely due to α_s

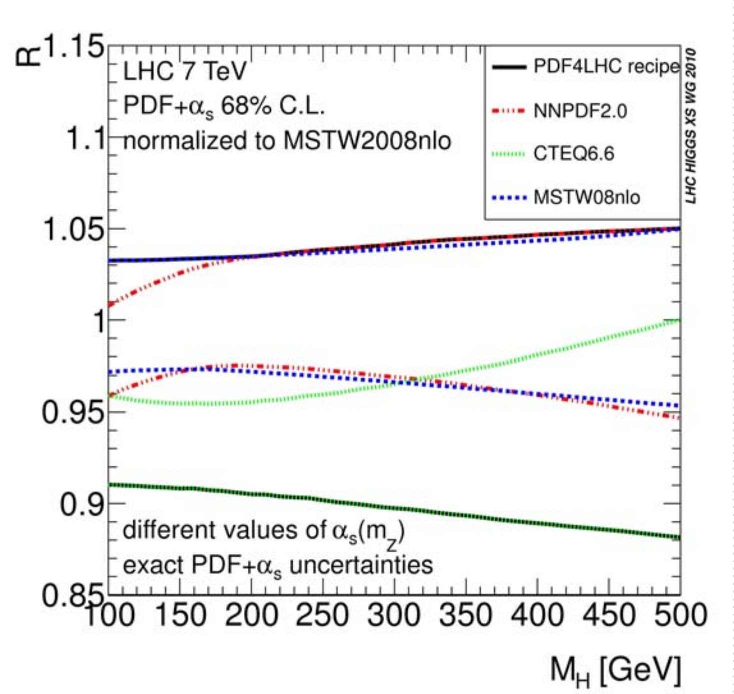
Even when evaluated at the same α_s, PDF sets give predictions which differ by more than purported PDF error

NLO $gg \to H$



PDF4LHC Recipe for NLO

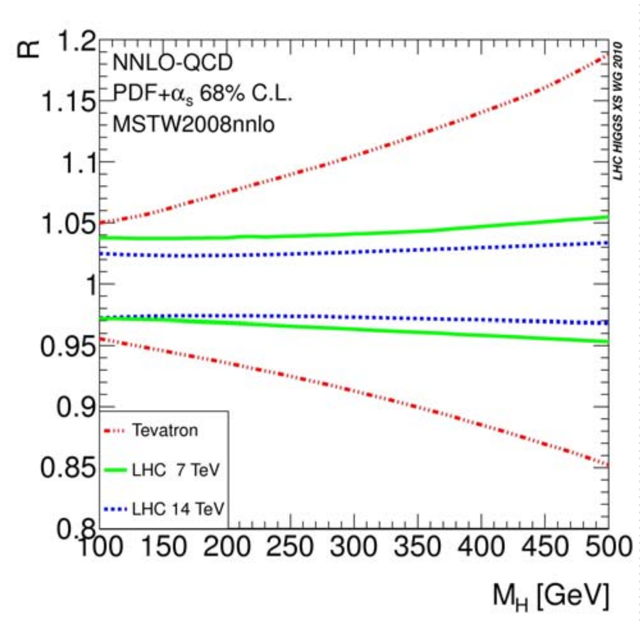
- Calculate PDF+α_s uncertainties from CTEQ, MSTW, NNPDF PDF sets at 68% confidence level
- Use envelope



PDF4LHC

- At NNLO use MSTW rescaled by NLO uncertainty
  - Roughly amounts to doubling MSTW NNLO errors

Note larger PDF + α_s errors at Tevatron

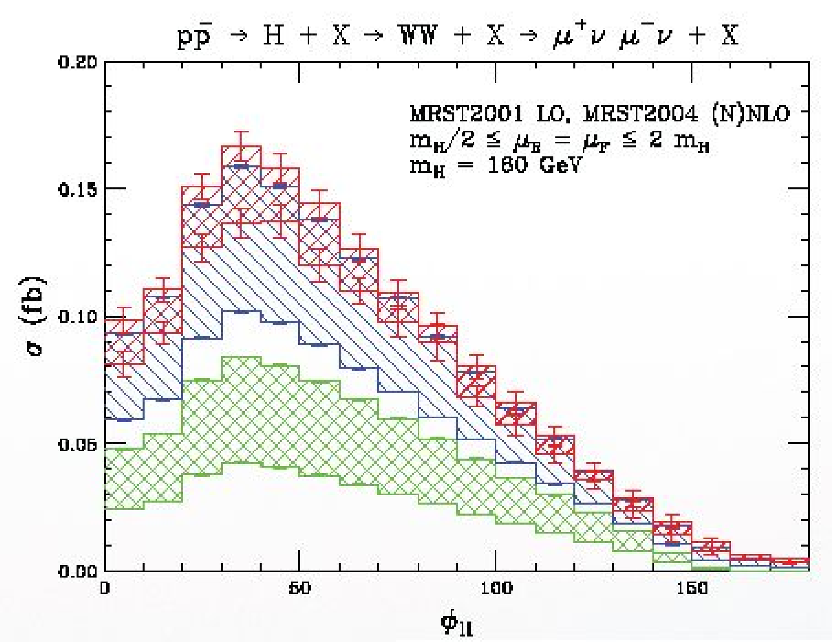


The Bottom Line

- PDF + α_s , other parametric uncertainties, added in quadrature
  - Gaussian distribution
- Scale, theory uncertainties ~ not statistical
  - Flat distribution
- Add scale uncertainties + parametric uncertainties linearly (Higgs Xsection WG prescription)
- gg $\rightarrow$H, M_H=120 GeV, (+20%, -15%) uncertainty at 7 TeV
  - Scale & PDF/α_s uncertainties roughly equal

gg→ H

- Fully differential NNLO rates
- K factor isn't a constant



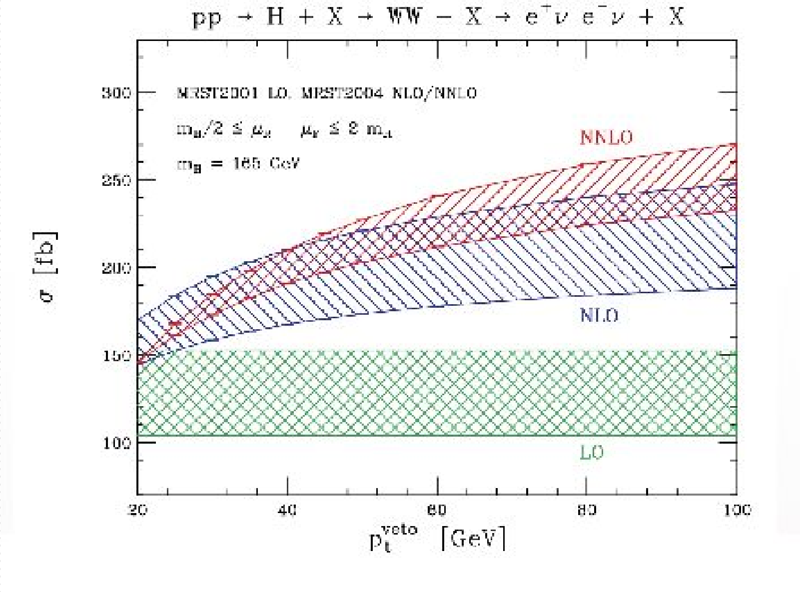
FEHIP, HNNLO

[Anastasiou, Melnikov, Petriello; Catani, Grazzini]

Compare theory/experiment

- Experiments separate Higgs rate into 0, 1, 2 jet bins
- Theory precision degrades from 0 to 1 to 2 jet bins

Higgs @ LHC



Theory uncertainties depend on cuts & binning

$gg \to H \to WW^*$

- Tevatron looks for lν lν + 0, 1, 2 jets
- Uncertainties vary by bin: M_H~160 GeV

$$\sigma_{gg\to H} = \sigma_{gg\to H}^{0\,jets} + \sigma_{gg\to H}^{1\,jets} + \sigma_{gg\to H}^{2\,jets}$$

	[60%	29%	11%]
	NNLO	NLO	LO
Scale:	(+5,-9%)	(+24,-23%)	(+91,-44%)

Correlated!

Scale uncertainty depends on cuts

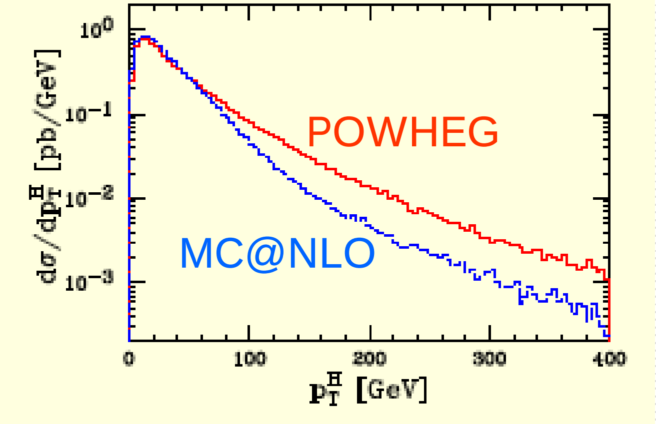
[Anastasiou, Dissertori, Grazzini, Stockli 0905.3529]

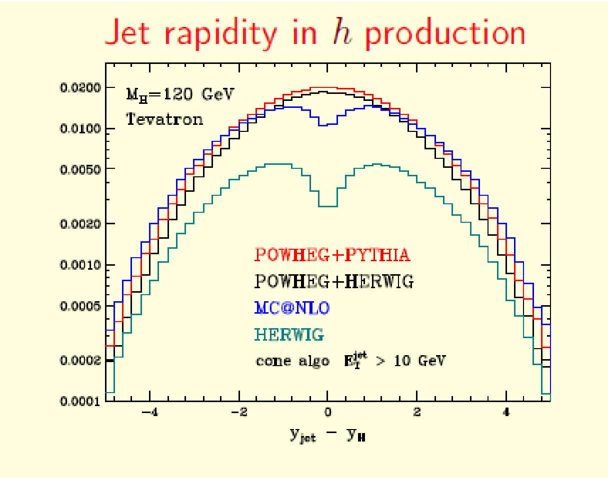
Interface with NLO Monte Carlos

- Only 2 public NLO MCs: POWHEG & MC@NLO
  - Hardest jet with LO accuracy, other jets generated by shower in collinear/soft approximations
- MC@NLO tied to HERWIG
- POWHEG
  - Can switch shower models
  - No issues with improper cancellations of higher order effects
  - Automation: new processes should be faster
  - NEW: Exact quark mass effects at NLO

gg→H in MC@NLO & POWHEG

- Harder p_T spectrum in POWHEG than MC@NLO
  - (large) K factor multiplies all p_T in POWHEG, not in MC@NLO
- Dip in MC@NLO understood
  - Incomplete cancellation (NNLO effect)





➡ Differences understood

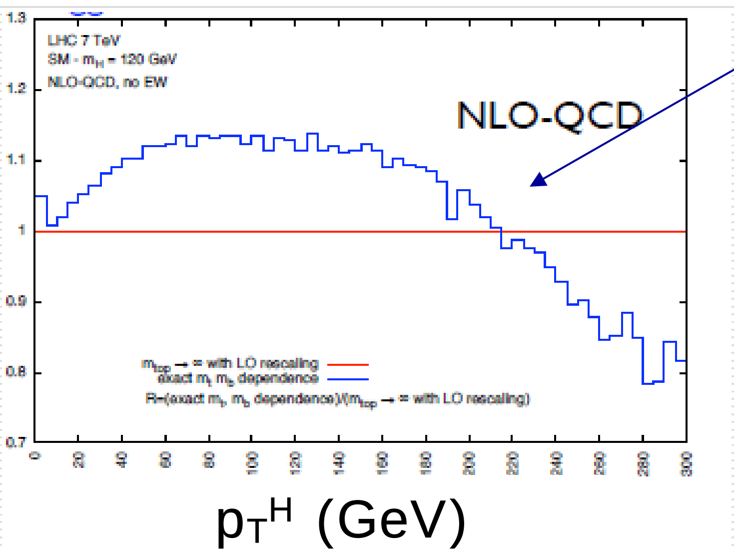
[Nason, Oleari]

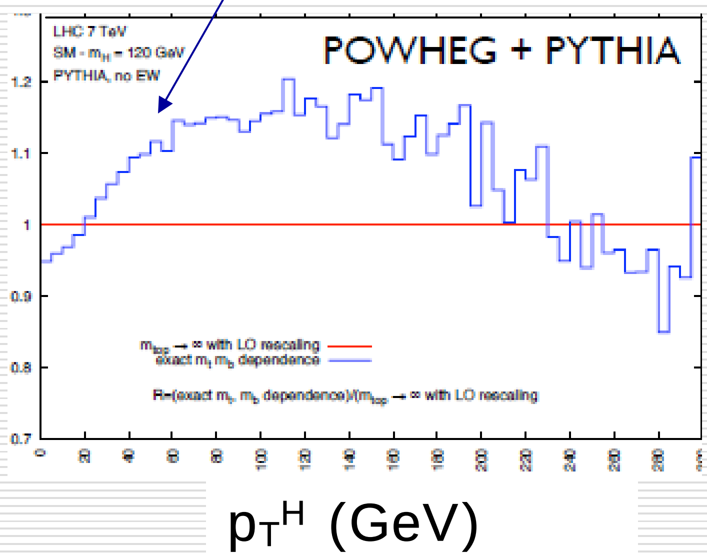
Finite Mass Effects at NLO in POWHEG

Fixed order (NLO) diverges at $p_T \to 0$

POWHEG vanishes at $p_T \to 0$

Exact m_b, m_t at NLO normalized to $m_t \to \infty$ limit for $gg \to H$

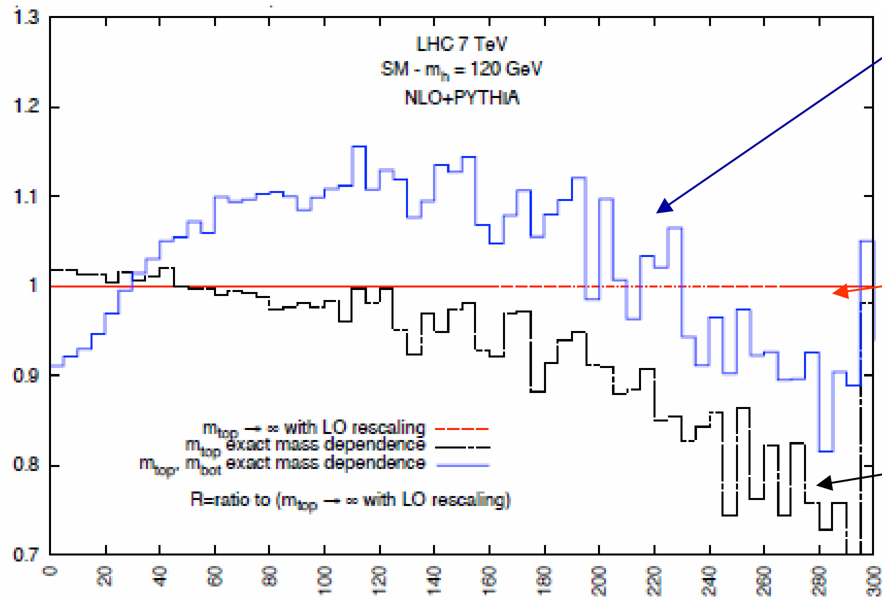




~10% effects

The role of the b-quark

- POWHEG with finite mass effects



m_t, m_b exact mass dependence

$m_t \to \infty$

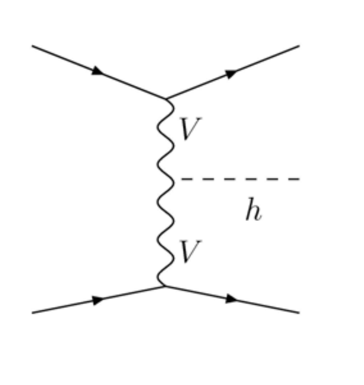
m_t exact mass dependence, no b

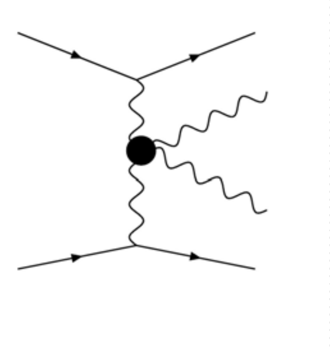
p_T^H (GeV)

[Vicini]

Vector Boson Fusion

- Discovery channel
  - 2^{nd} largest cross section over entire M_H range
- VBF: $H\rightarrow\tau^+\tau^-$ and $H\rightarrow WW$ give H couplings
- Probes new vector boson interactions

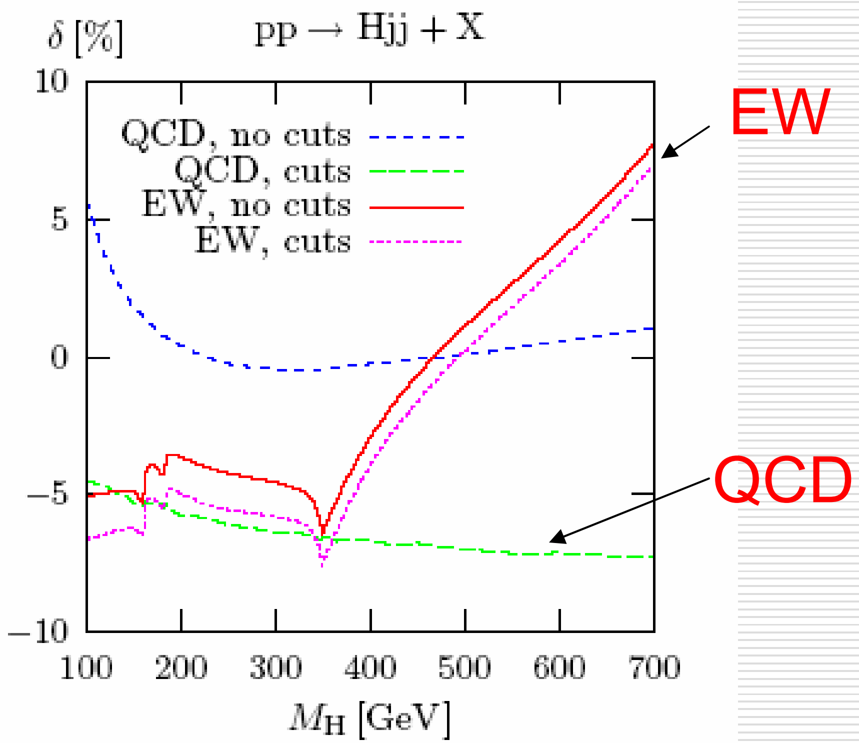




VBF with NLO QCD + EW

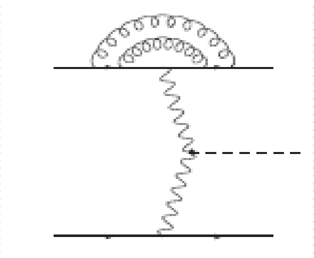
- Electroweak corrections to vector boson fusion are of similar size as QCD corrections (-4% , -7%)
- QCD contributions very sensitive to cuts
- Partial cancellation between EW & QCD

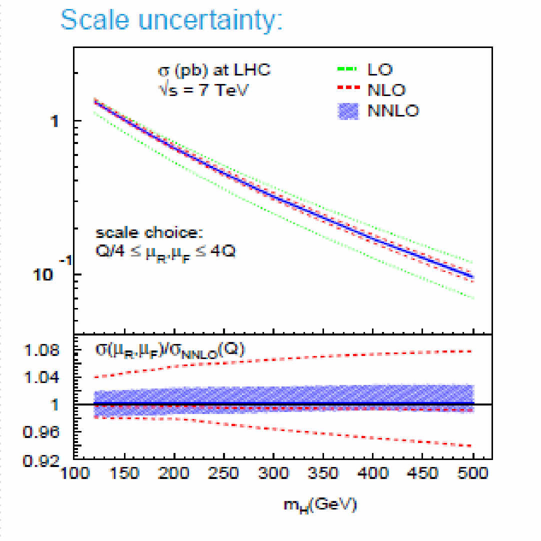
NLO distributions in VBFNLO and HAWK

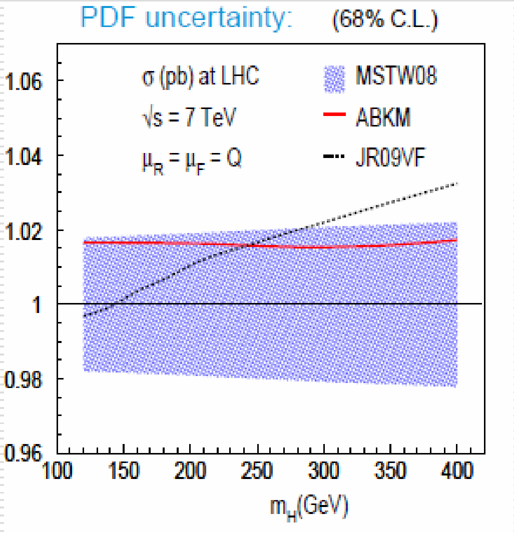


VBF at (partial) NNLO

- NNLO corrections in DIS approximation
  - Prediction for total rate under excellent control







→ Scale uncertainty ~ PDF uncertainty ~ 2%

[Bolzoni, Maltoni, Moch, Zaro]

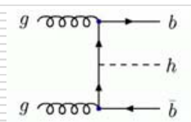
New modes in MSSM: bbH production

Reduced ↓ Background

- Inclusive mode: No tagged b's
- Semi-inclusive mode: At least one tagged b
- Exclusive mode: Two tagged b's

Larger ↑ Signal

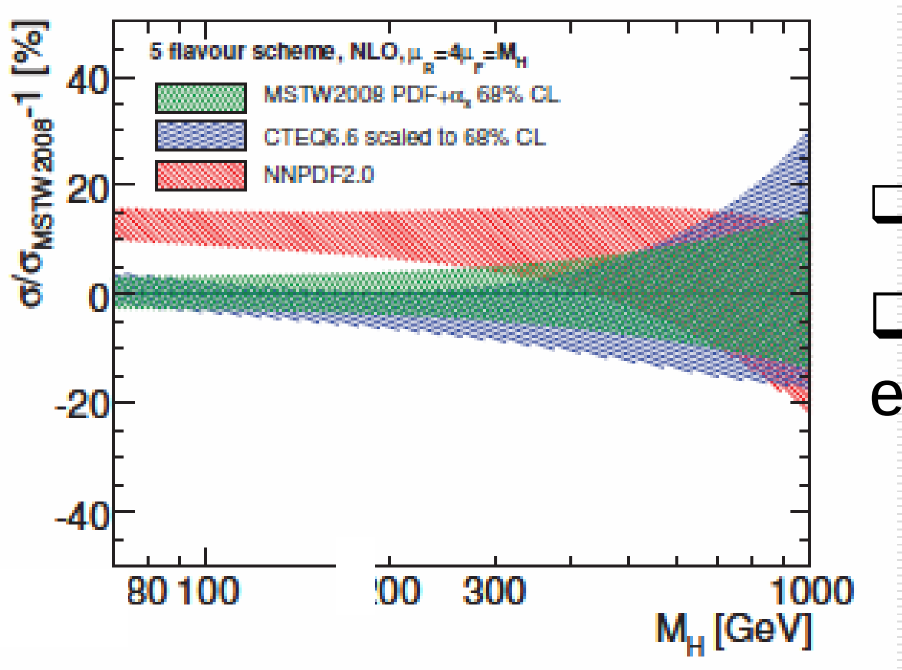
- Treating b quarks inclusively leads to large collinear logarithms from integration over phase space



$$\ln\left(\frac{\mu_F^{\,2}}{m_b^{\,2}}\right), \qquad \mu_F \approx M_H$$

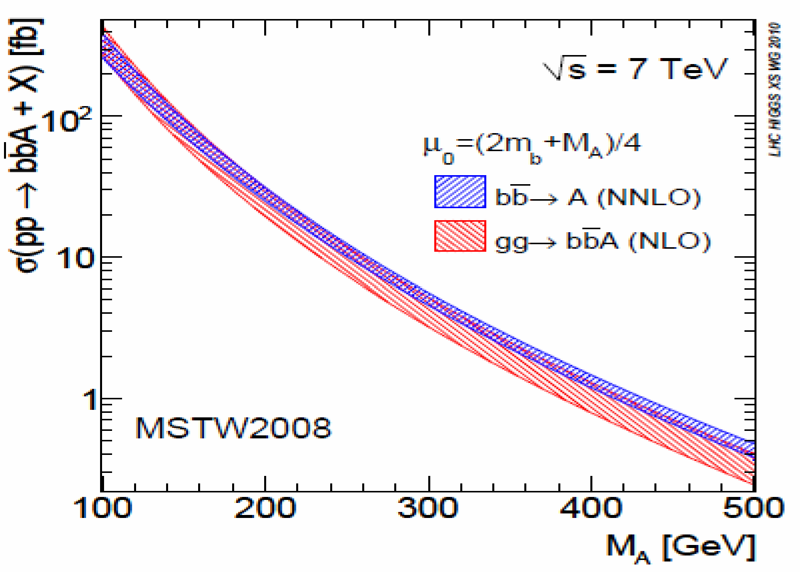
- Expansion parameter becomes $\alpha_s \log(m_b/M_H)$
- Absorb large logs into b PDFS
  - Relevant process is then $bg \rightarrow bH$ or $b\bar{b} \rightarrow H$

PDF Uncertainties on bH

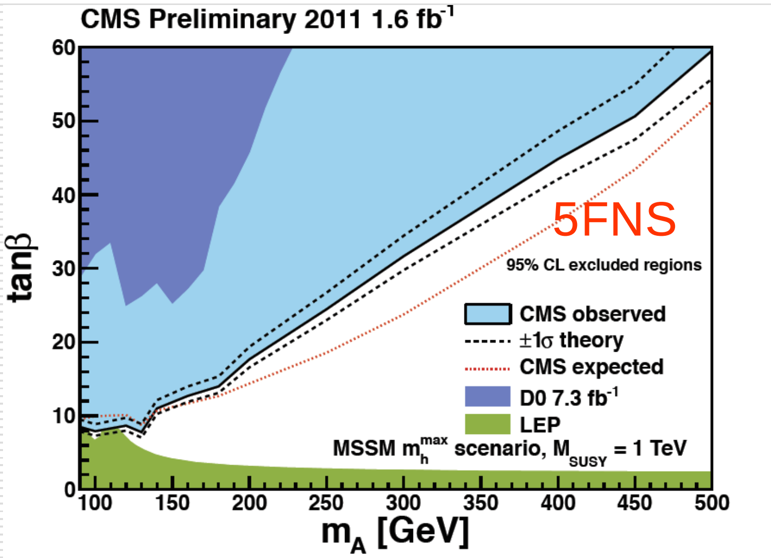


- Different b masses used
- b PDFs calculated from evolution equations

Differences between PDF sets larger than proponents claims of PDF uncertainties



Needed: Scheme to combine best features of 4FNS and 5FNS



- Theory error bands are scale/PDF uncertainties
- Large effects from choice of SUSY parameters

Conclusions

- Higgs Hunting in an exciting phase!
  - Theory/experimental dialog critical
  - Total cross section predictions under good control with theory uncertainty ~ 20% at LHC
  - The hard part is understanding theory uncertainties for cuts/distributions
  - Uncertainties for large p_T (boosted Higgs) still a work in progress
  - ***BSM uncertainty***