Higgs Cross Sections

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University of Washington
Workshop on Higgs Cross Sections
April, 2011

A status report on higher order corrections to Higgs production rates

LHC Higgs Cross Section Working Group

- Chartered by CMS & ATLAS
  - Many theorists involved
- Dittmaier, Mariotti, Passarini, Tanaka
  - arXiv:1101.0594*
- Yellow report with total cross sections and “best understanding” of uncertainties
- Next: Include decays/cuts
  - This is much harder!

* Not a report of this group, but my own views

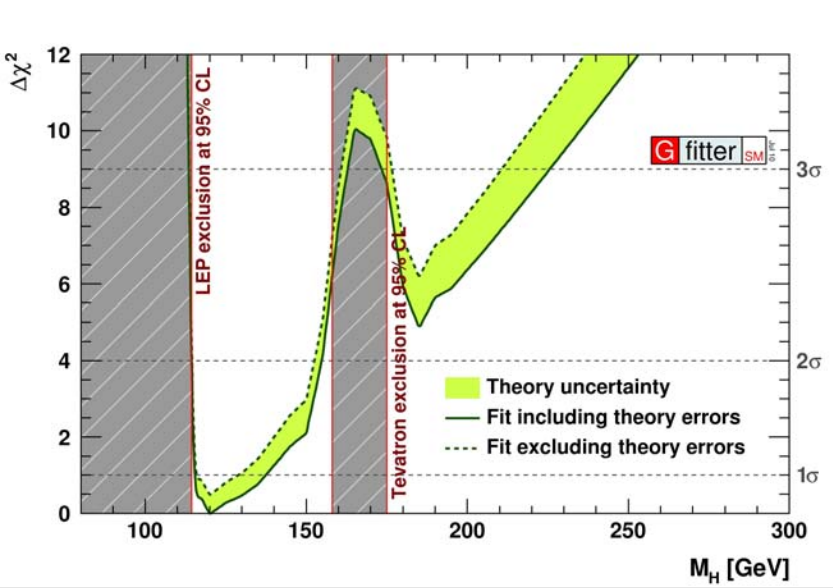
Where do uncertainties come from?

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

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

Higgs Boson(s)

- SM Higgs expected to be light

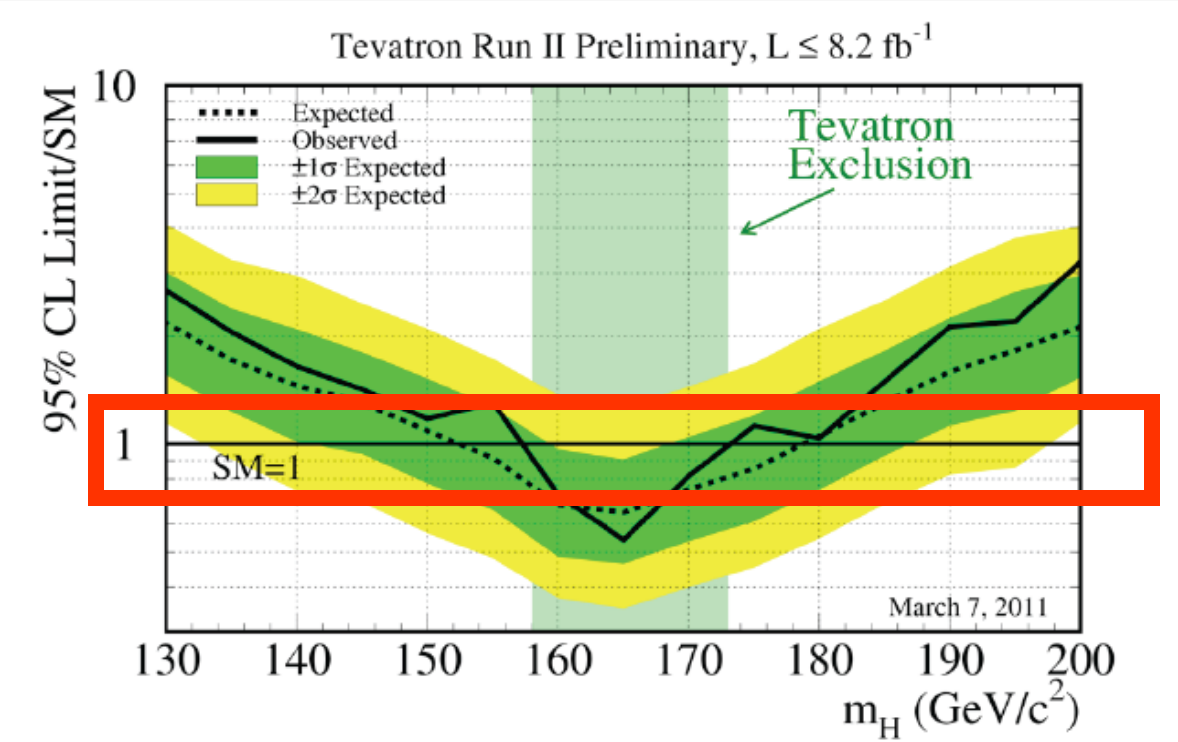


Note importance of theory uncertainties

- This assumes the SM!

SM prefers light (M_H < 158 GeV) Higgs boson

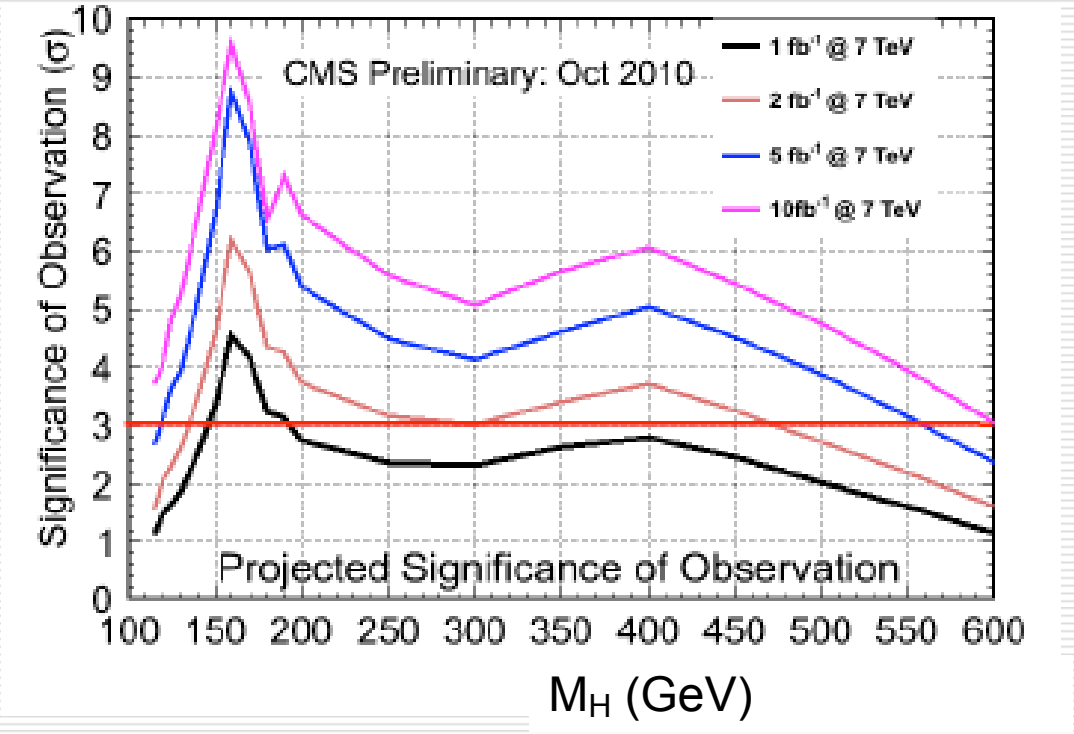
Tevatron Higgs Exclusion



Theory uncertainties on both background and signal

Tevatron Exclusion: [158 GeV < M_H < 173 GeV]

Higgs Discovery Soon



CMS: 10 fb^{-1} gives 3σ discovery for M_H=115-600 GeV

Higgs Discovery

$\sqrt{s}$=7 TeV

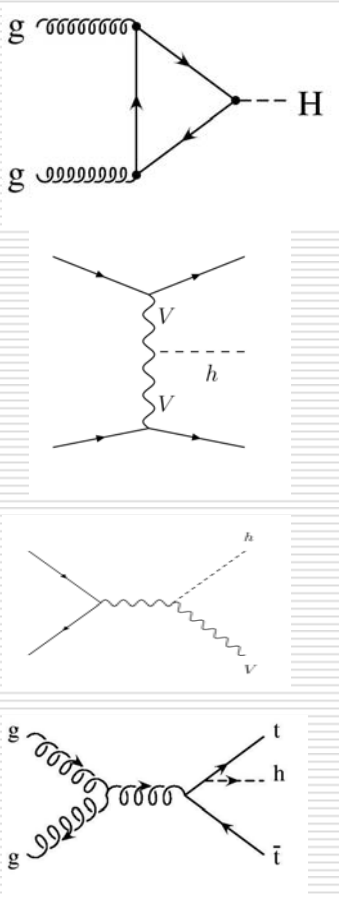
ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

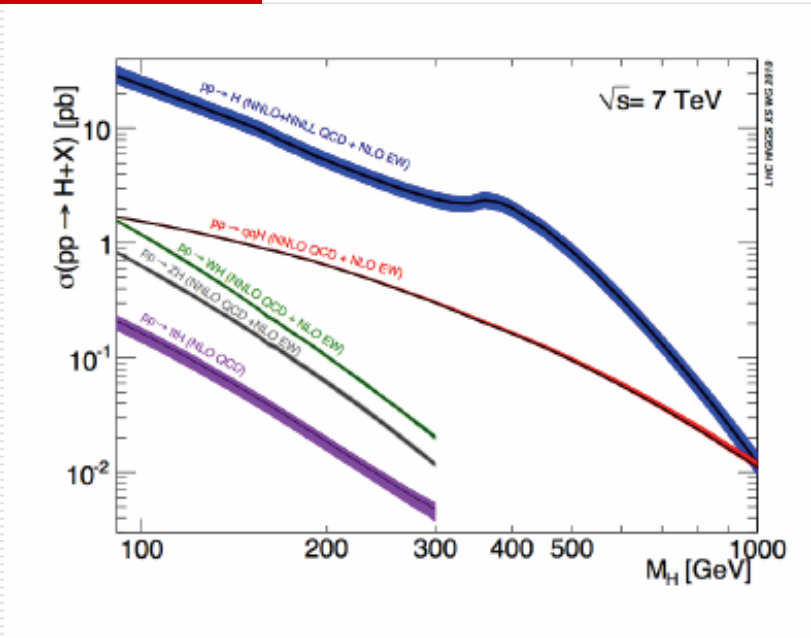
2011

2012

If the SM Higgs exists, we'll know its mass soon

Higgs at the LHC





Reliable estimates of uncertainties

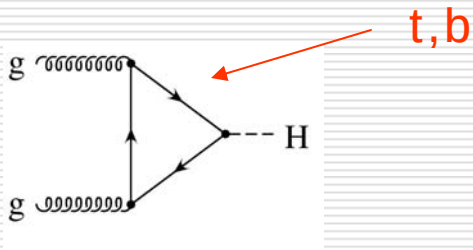
Largest uncertainties on gluon initiated processes

Many *public* tools available

- gg→H
  - NNLO QCD +EW (total and differential)
  - Resummation (threshold)
- Vector Boson Fusion
  - NLO QCD + EW with decays, NNLO QCD
- VH
  - NLO QCD + EW
- ttH
  - LO QCD (NLO private code)
- NLO event generators
  - MC@NLO, POWHEG
- Decays
  - NLO QCD+EW

SM calculations in great shape

- Dominant production mode is gg→H

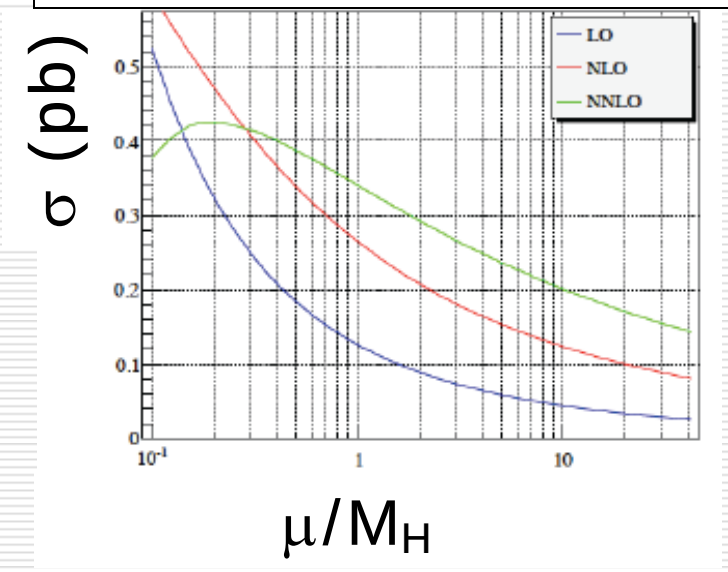


  - NNLO in heavy M_{top} limit (checked in M_H/M_{top} expansion)
  - Exact t,b loops at NLO
  - N^3LL resummation
  - EW and mixed EW/QCD corrections

Precise predictions allow us to trust error estimates

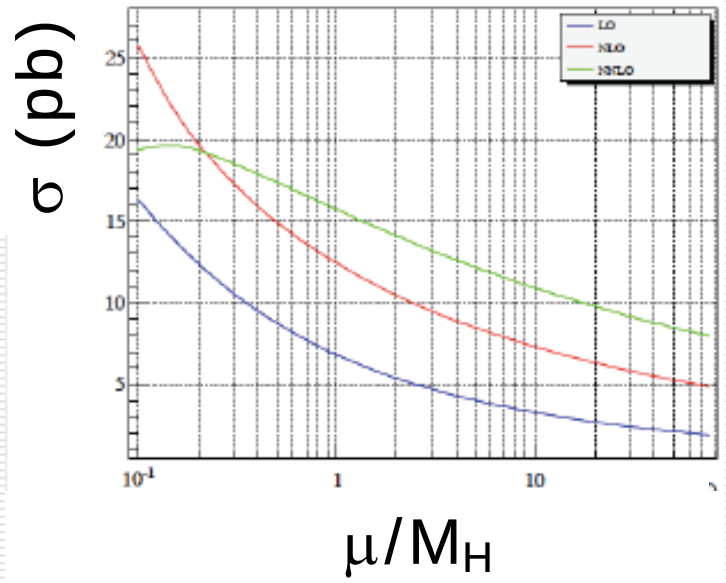
Radiative Corrections are Large

Tevatron, $M_H = 165$ GeV



$K_{NNLO} \sim 3$

LHC, $M_H = 120$ GeV

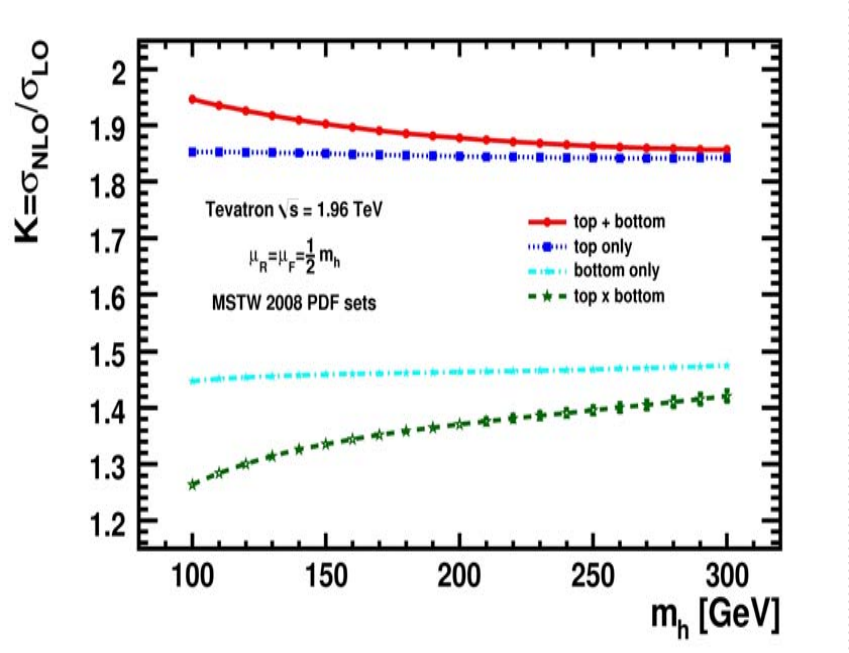


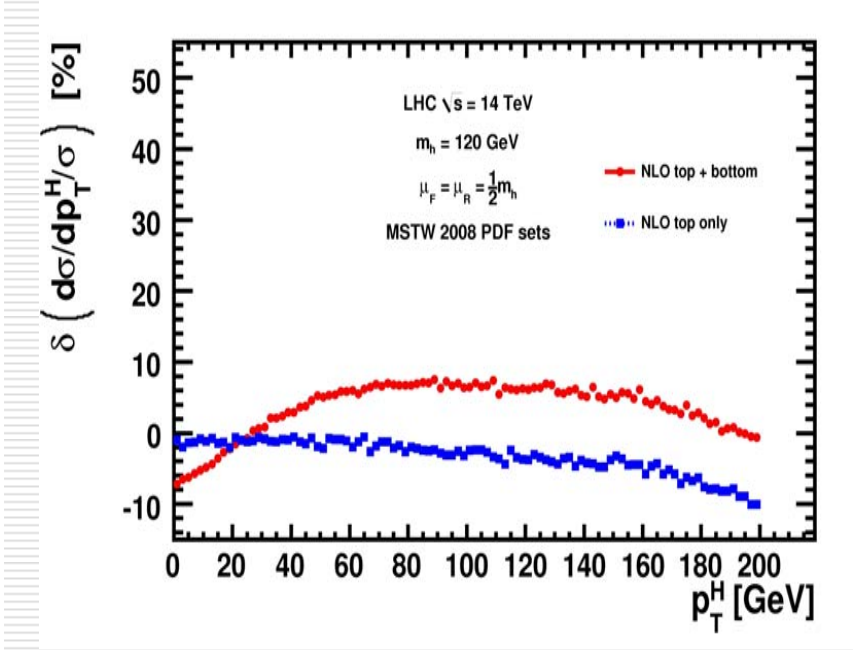
$K_{NNLO} \sim 2.5$

[Anastasiou, Moriond 2011]

The Role of b-loops

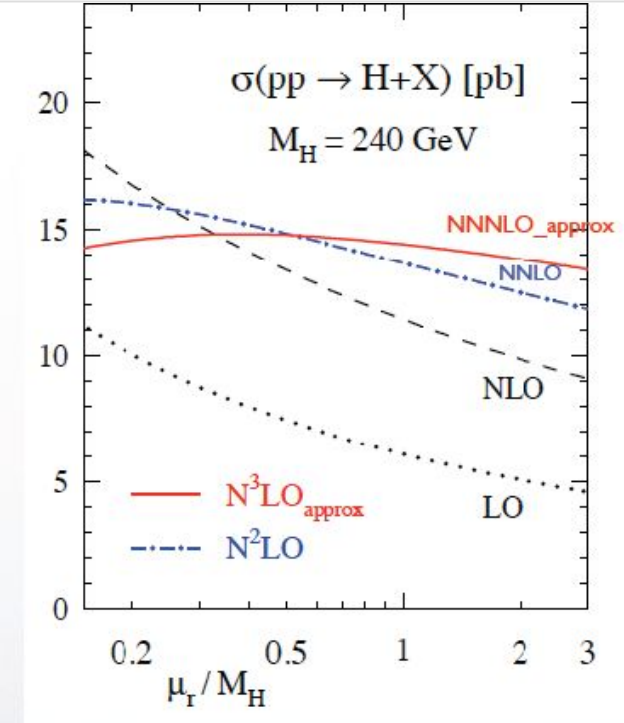
K factor for b loops smaller than for top loops





[Anastasiou, Bucherer,Kunszt, 0907.2362]

Small scale gives better convergence



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

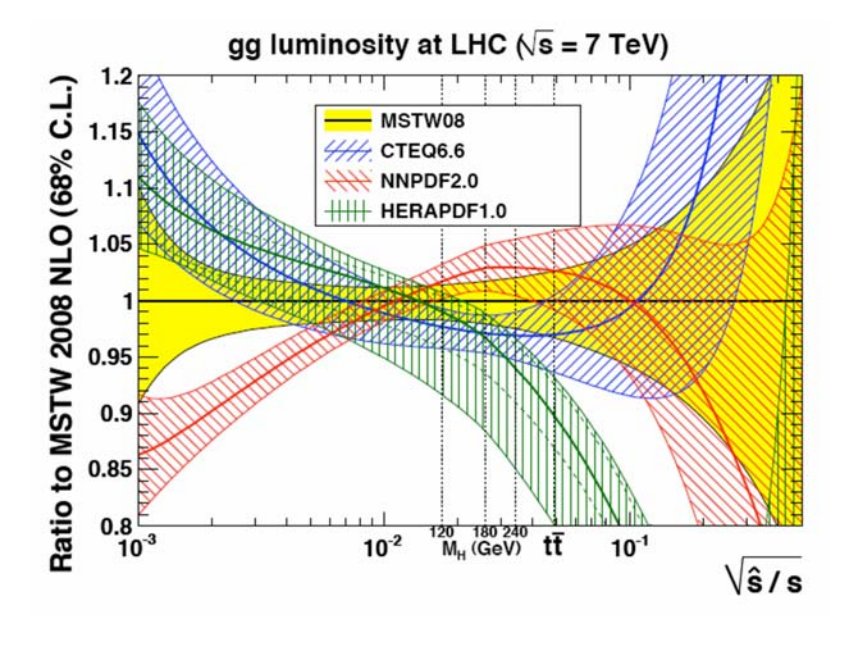
[Moch and Vogt]

PDF Uncertainties

- Experimental uncertainty
  - Choice of data sets
    - CTEQ, MSTW, NNPDF include electroproduction, Drell-Yan, jets @Tevatron…
    - HERAPDF, ABKW don't include jet data
  - 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

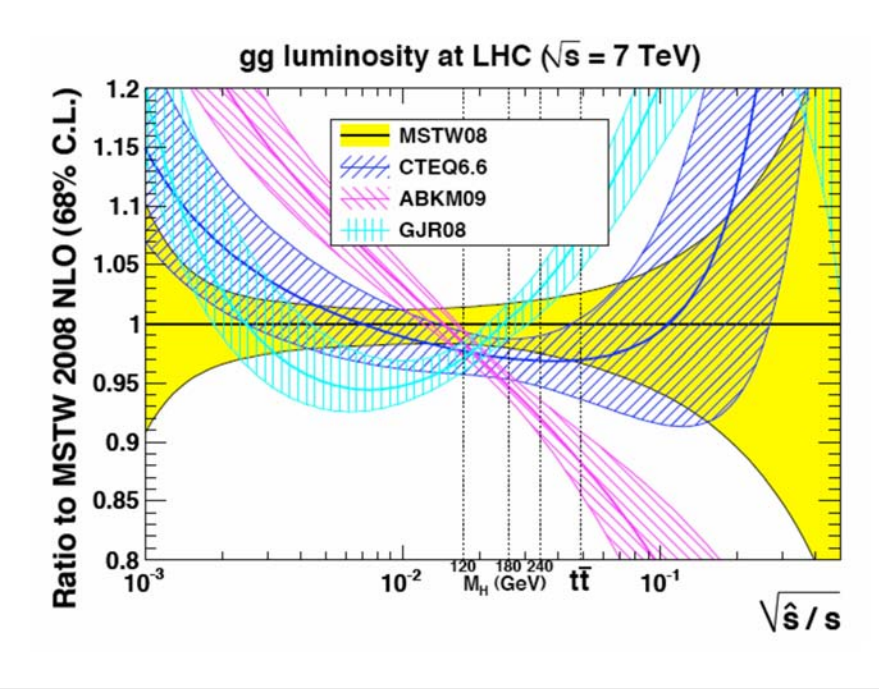
PDF Issues

- HERAPDFS don't include Tevatron di-jet data$\Rightarrow$ Not used by Higgs Xsection group
- Reasonable agreement among MSTW, CTEQ, NNPDFs



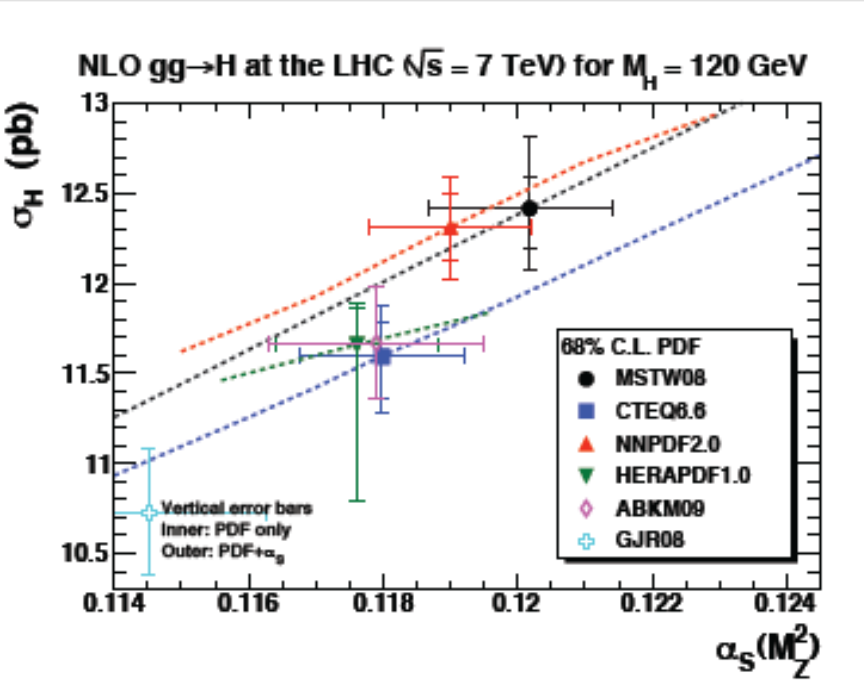
PDFs

- ABKM, HERAPDFs differ at large x from MSTW, CTEQ, NNPDF



Each PDF has different central α_s

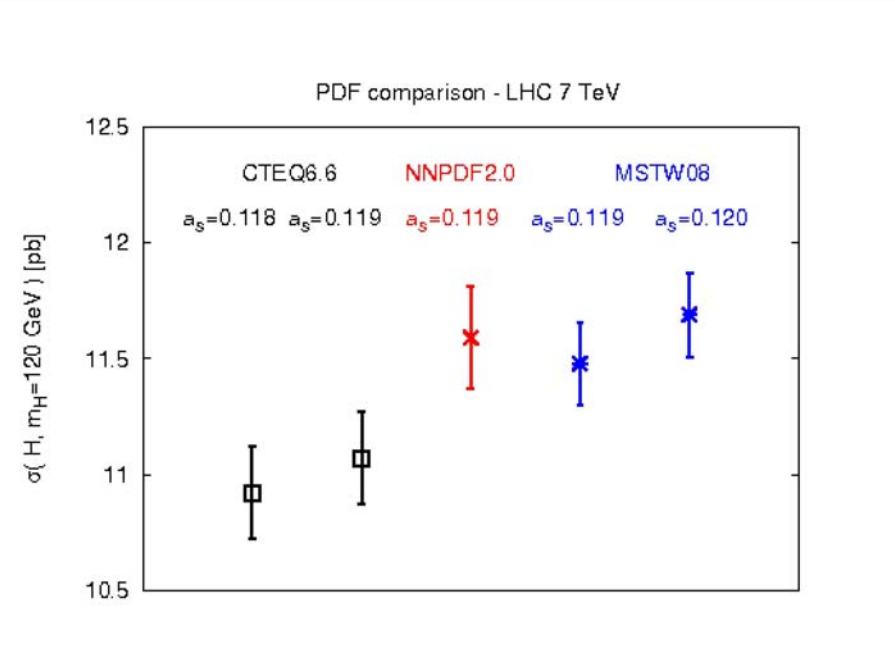
- α_s enters PDF evolution and cross section
- Differences not entirely due to α_s



PDF differences

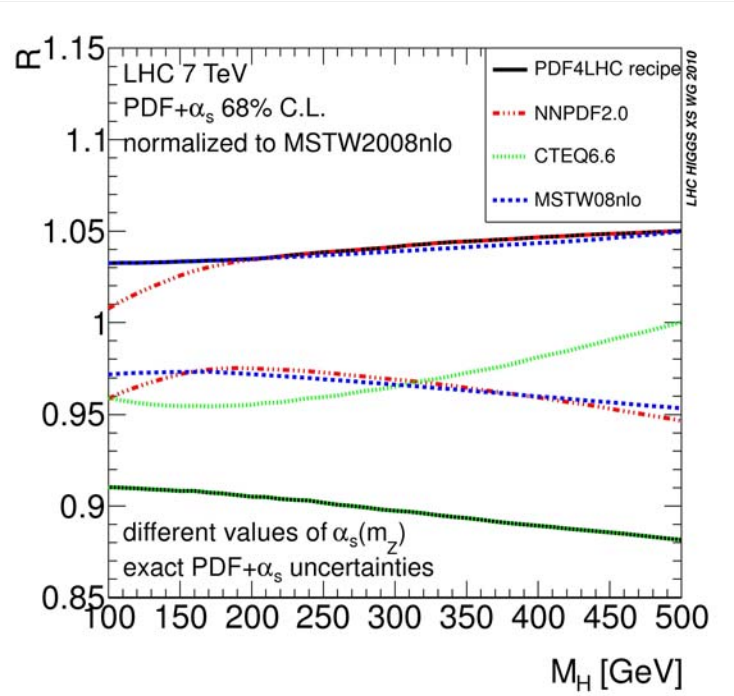
NLO gg→H

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



PDF4LHC Recipe for NLO

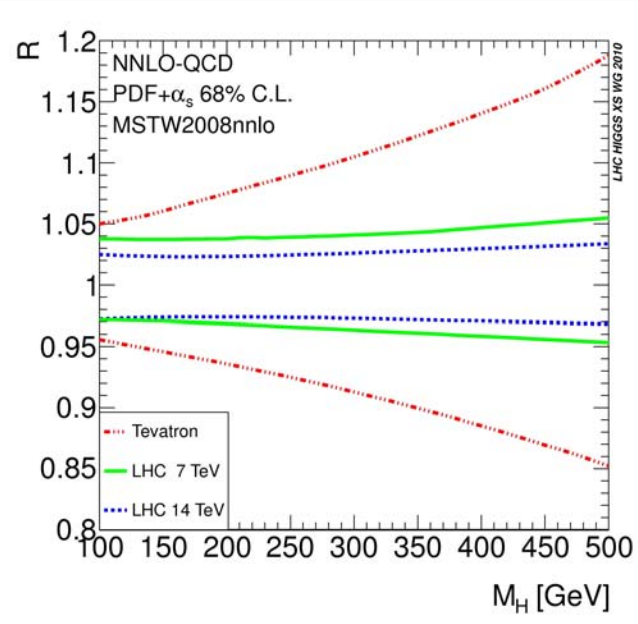
- Calculate PDF+α_s uncertainties from CTEQ, MSTW, NNPDF PDF sets at 68% confidence level
- Use envelope



PDF4LHC

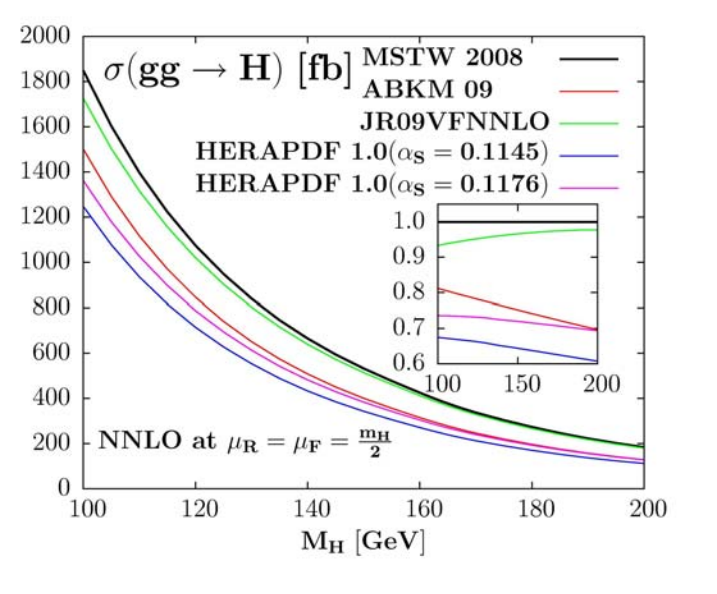
- At NNLO use MSTW rescaled by NLO uncertainty
  - Roughly amounts to doubling MSTW NNLO errors

Note larger PDF + α_s errors at Tevatron



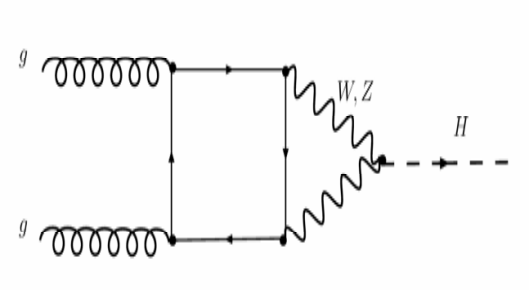
Is this procedure conservative?

- Tevatron MSTW σ is 35% higher than ABKM at $M_H = 165$ GeV
- Preliminary ABKM results with Run II di-jet data have larger Higgs rate



[Baglio, Djouadi, Ferrag, Godbole, 1101.1832, Alekhin DIS 2011]

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

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

Unknown

Do EW terms factor? $\boxed{C_1 = \left(1+\delta_{EW}\right)\left(1 + \alpha_S C_a + \alpha_S{}^2 C_b\right)}$?

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)
  - Something to think about at this workshop
- $gg \rightarrow H$, M_H=120 GeV, (+20%, -15%) uncertainty at 7 TeV

The Bottom Line

- Tevatron:

$$\sigma(M_h = 165\,GeV)_{Tevatron} = 389.0\ fb\ ^{+8.1\%}_{-11.7\%}\ (scale)\ ^{13.6\%}_{-12.0\%}\ (\alpha_s + PDF)$$

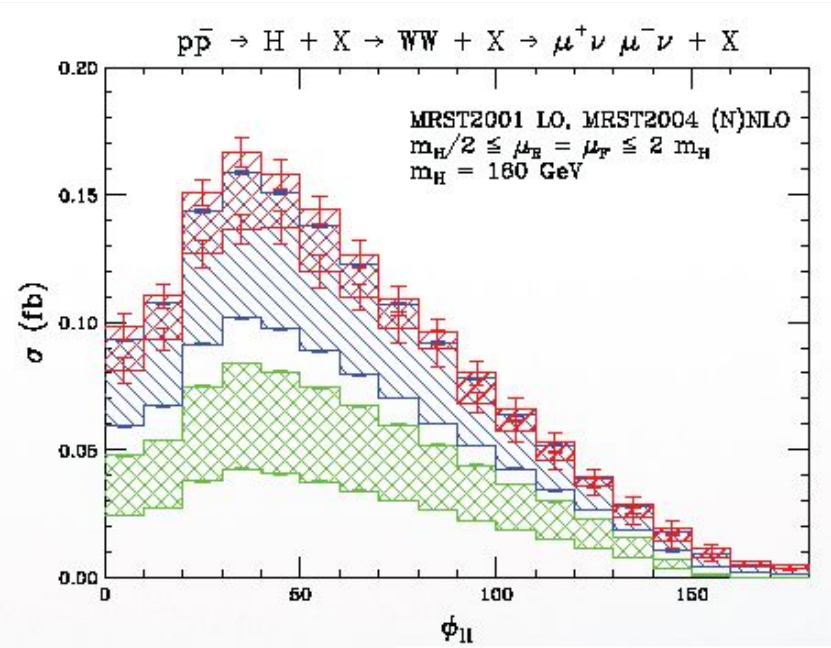
  - PDF4LHC: double MSTW NNLO PDF errors
  - Higgs Xsection WG: Combine PDF/theory linearly
  - Baglio/Djouadi: Uncertainty from EFT~5%
    - Think about at this workshop
  - Uncertainty ~ +(8.1+2*13.6+5)% ~ 40%
    - (11.7+2*12+5)% ~ - 31%

Larger than CDF/D0 assumptions

[Cross sections from Anastasiou,Moriond 2011 & deFlorian & Grazzini, 0901.2427; Baglio & Djouadi, 1012.0530]

gg→ H

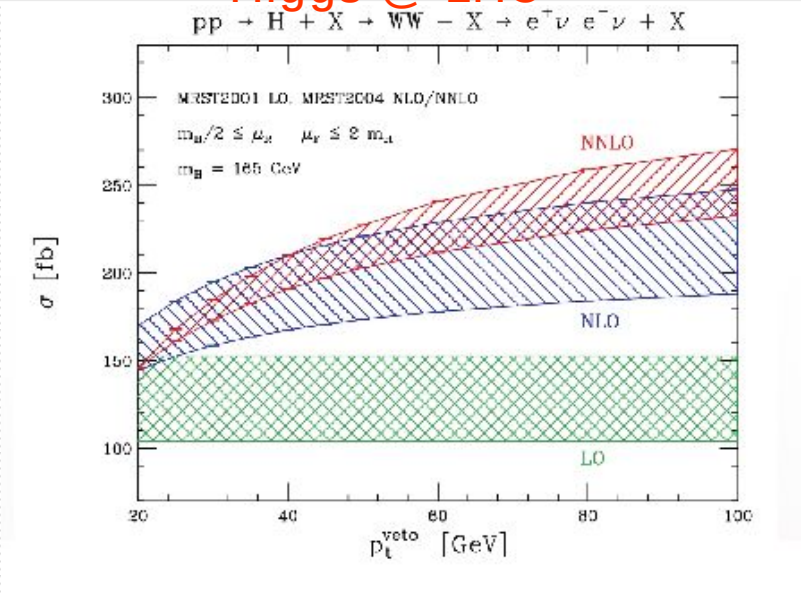
- Fully differential NNLO rates
- K factor isn't a constant



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 $l\nu\, l\nu$ + 0, 1, 2 jets
- Uncertainties vary by bin: $M_H \sim 160$ 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%)

Scale uncertainty depends on cuts

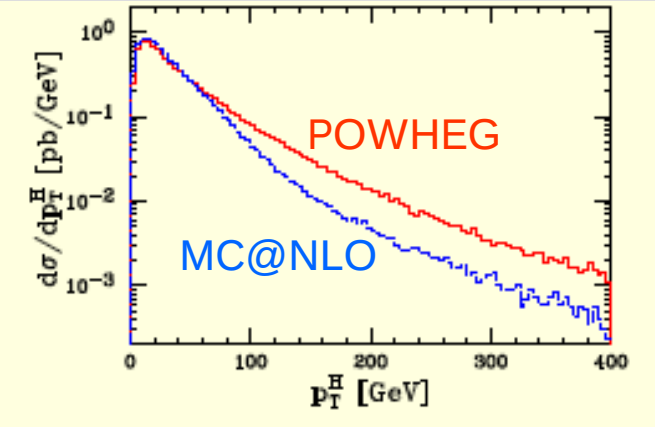
[Anastasiou, Dissertori, Grazzini, Stockli 0905.3529]

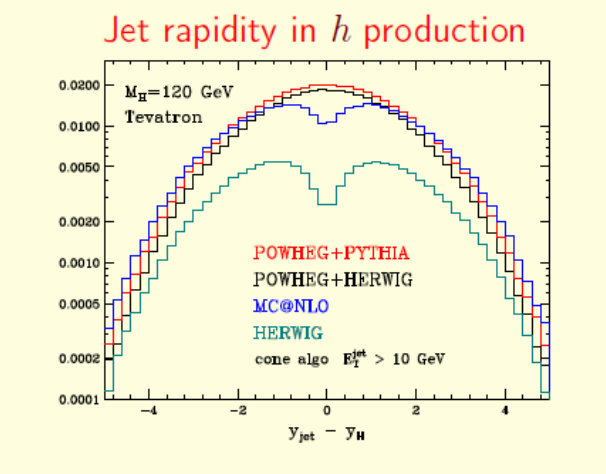
Interface with NLO Monte Carlos

- 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

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]

Many Alternatives to SM

- MSSM
  - A favorite
  - Still a lot of work to do to have reliable predictions
  - Beyond the MSSM….
- Multi-Higgs
  - NMSSM has 1 extra singlet
- Higgsless
- Composite Higgs
- Multiple fermion generations
- TBD….

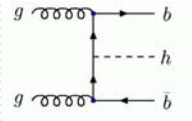
Example: bbH production

Reduced ↓ Background

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

Larger ↑ Signal

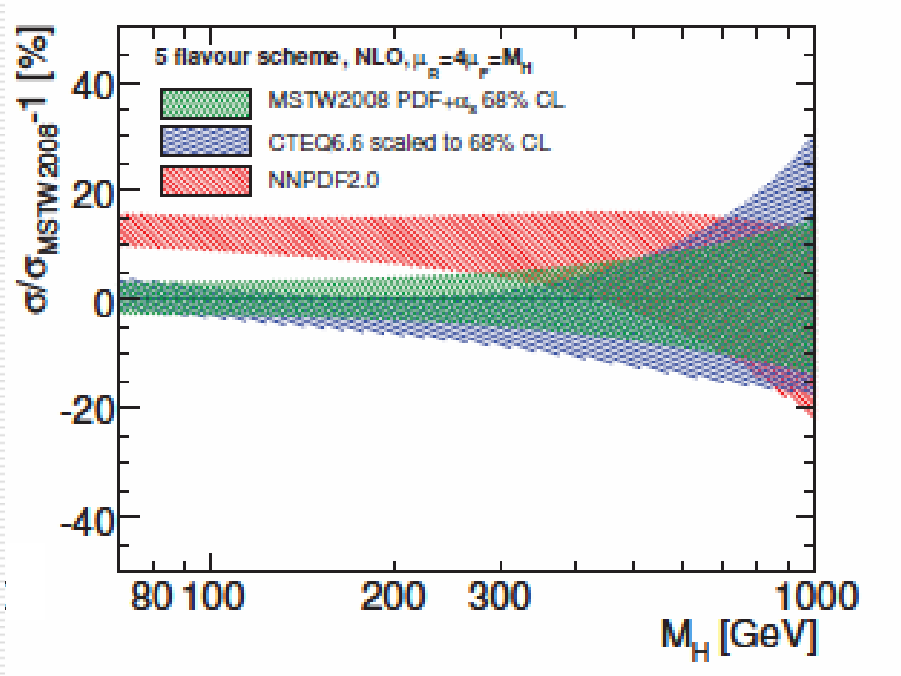
- Treating b quarks inclusively leads to large collinear logarithms from integration over phase space



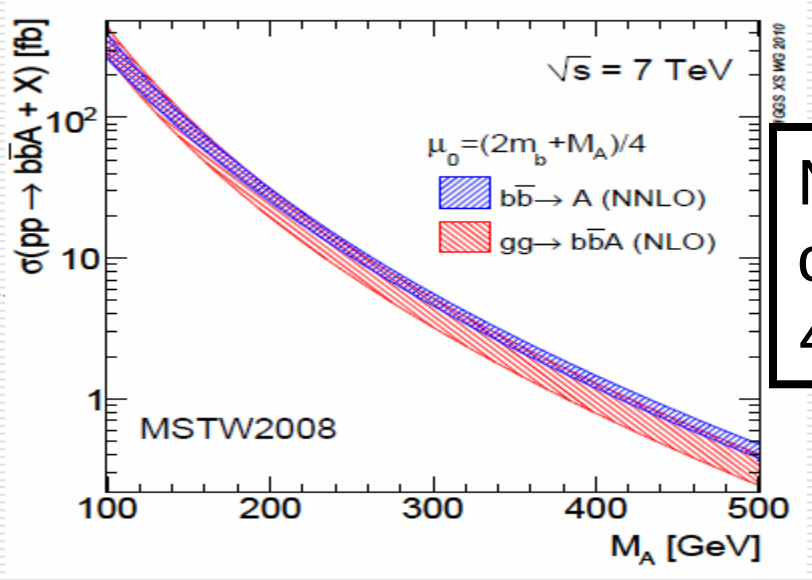
$$\ln\left(\frac{\mu_F^2}{m_b^2}\right), \qquad \mu_F \approx M_H$$

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

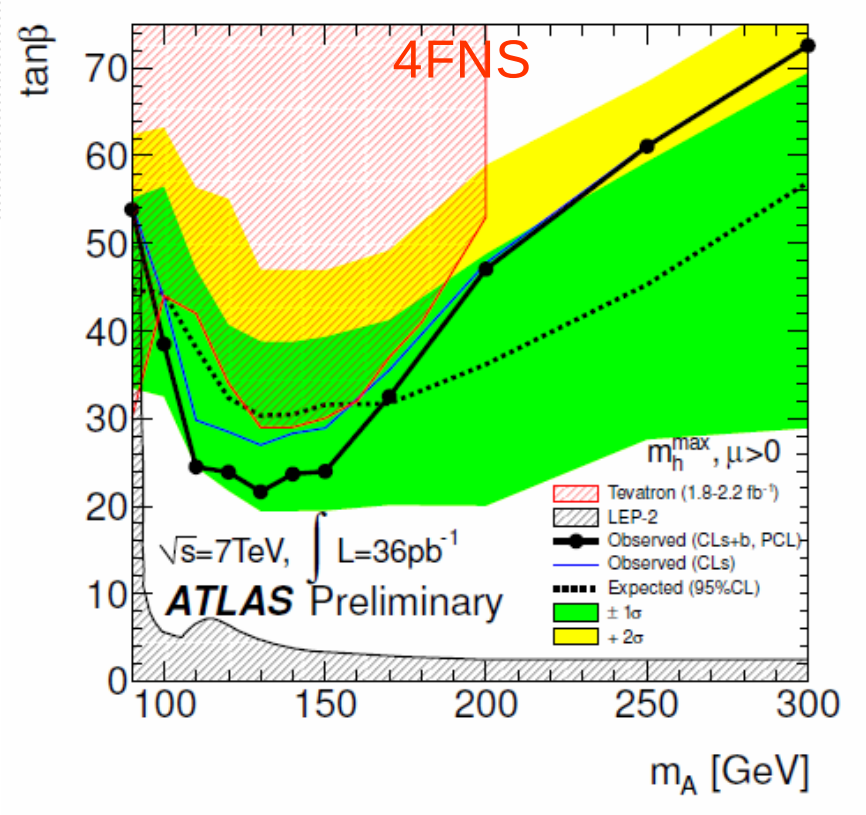
PDF Uncertainties on bbH

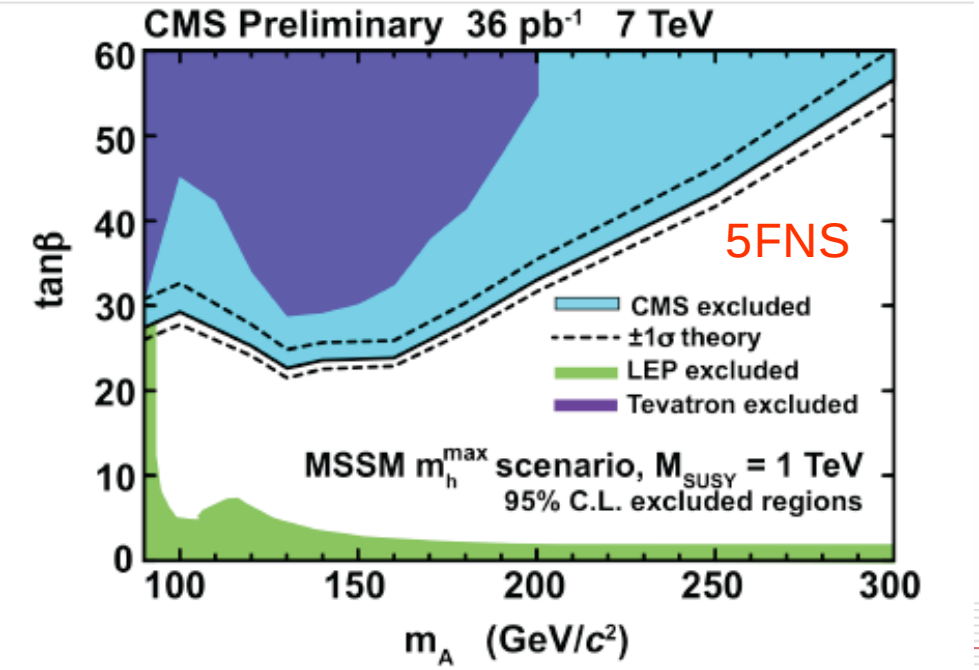


Differences between PDF sets larger than proponents claims of PDF uncertainties



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





Conclusions

- Higgs Hunting just starting
  - Theory/experimental dialog critical
  - PDFs, PDFs, PDFs....