Electroweak Symmetry Breaking and the LHC

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Oct. 7, 2010

LHC Theory Initiative Fellows Meeting

A status report on higher order corrections to Higgs production rates

What are the criteria?

- Electroweak symmetry breaking needs to explain:
  - Non-zero mass of W and Z gauge bosons
  - Non-zero mass of fermions
  - Unitarity conservation at 1 TeV
- Must be consistent with all data
  - Precision electroweak data
  - Tevatron searches
  - Flavor changing neutral currents
  - Little hierarchy
    - Much possible physics required to be at >> TeV scale

The Little Hierarchy

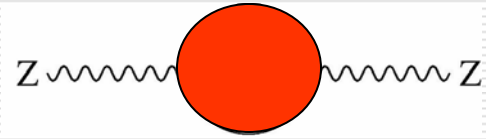
- L ~ (dimension-6 operator) /Λ^2

	Λ_{min}
$H^+\sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$10\ TeV$
$\left\lvert H^+ D_\mu H \right\rvert^2$	$5\ TeV$
$iH^+ D_\mu H \bar{L}\gamma^\mu L$	$9\ TeV$
$\bar{e}\gamma_\mu e \bar{l}\gamma^\mu l$	$6\ TeV$
$\bar{e}\gamma_\mu\gamma_5 e \bar{b}\gamma^\mu\gamma_5 b$	$4\ TeV$

Scale of new physics often greater than 5-10 TeV

Unitarity

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



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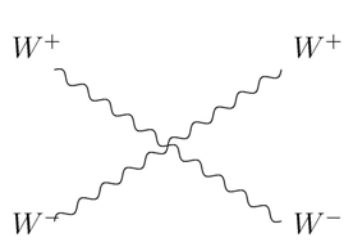
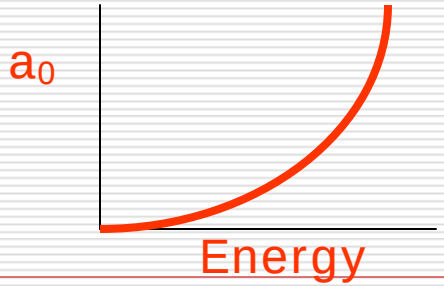
  - Scattering amplitudes grow with energy





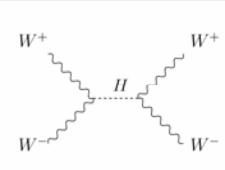
The TeV Scale

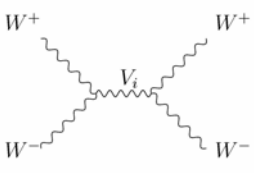
- We expect the Higgs or unitarity restoring action to be around 1 TeV
- Symmetry breaking mechanism must:
  - Give mass to vector bosons
  - Not have massless Goldstone boson
  - Be part of a renormalizable quantum field theory

→ Simplest possibility is weakly coupled Higgs boson

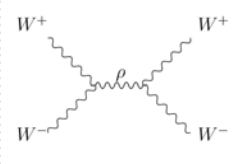
What unitarizes WW scattering?

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



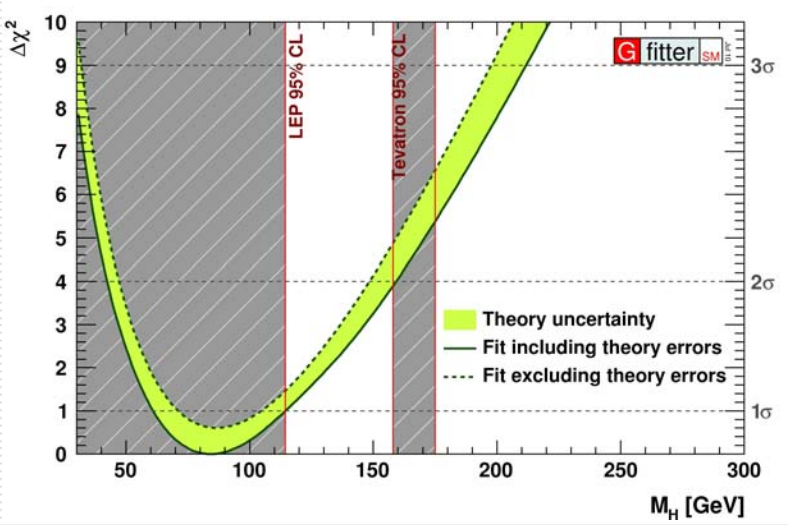


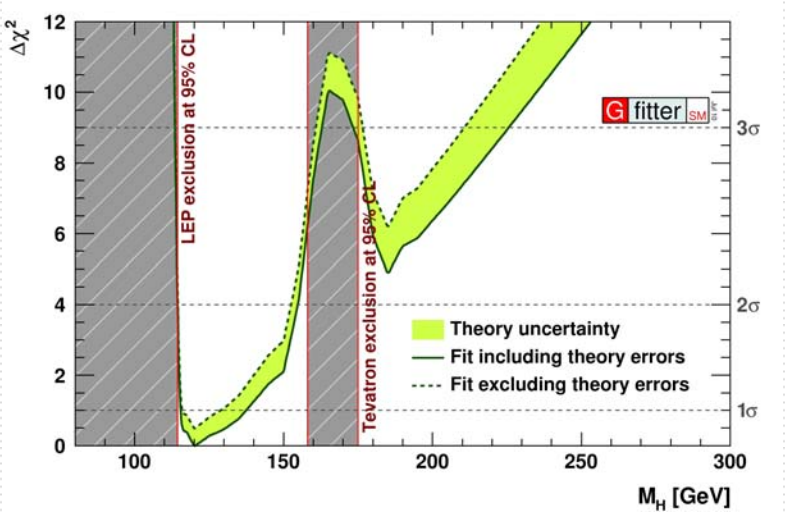
- Symmetry breaking could be strongly coupled
  - Technicolor, QCD like models, Higgsless, composite Higgs…..



Precision EW Data

- Prefer light (M_h < 158 GeV) SM Higgs
- Quality of fit is good—doesn't require new physics



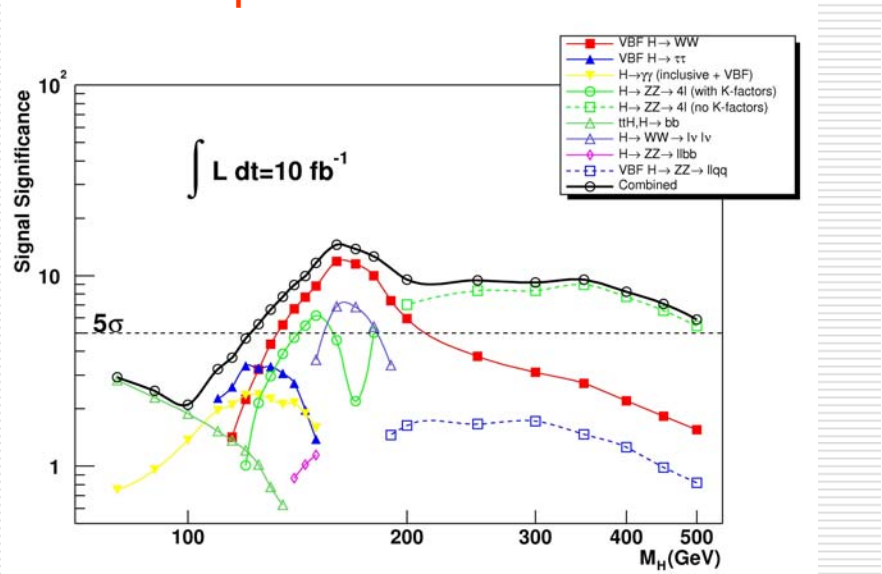


Includes direct search limits

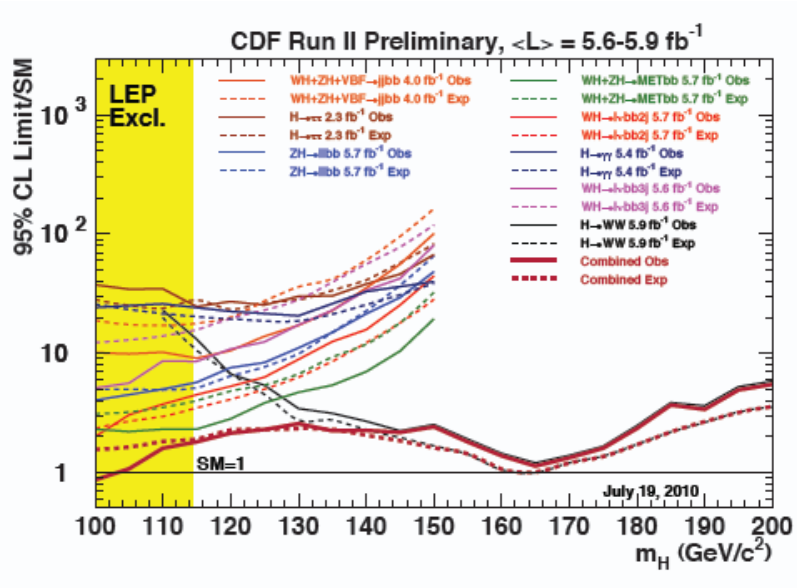
Updated

Higgs Searches

Not updated

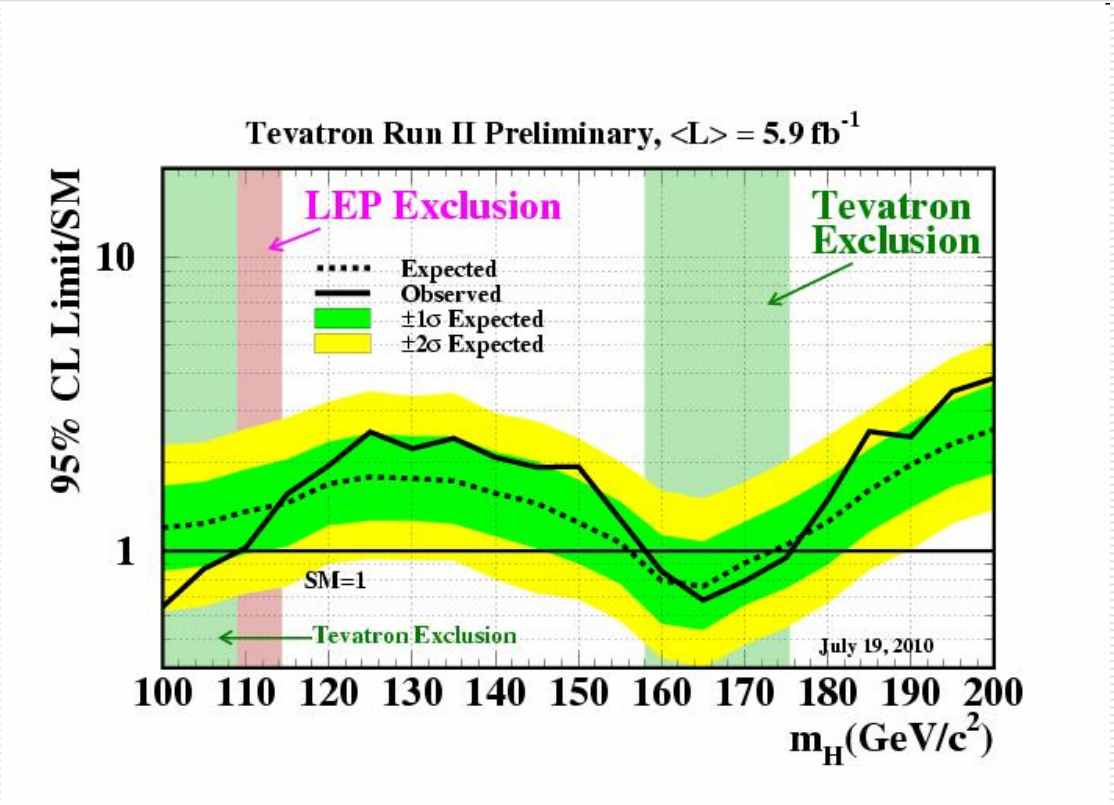


Updated



Need reliable predictions for many channels

Allowed parameter space shrinking

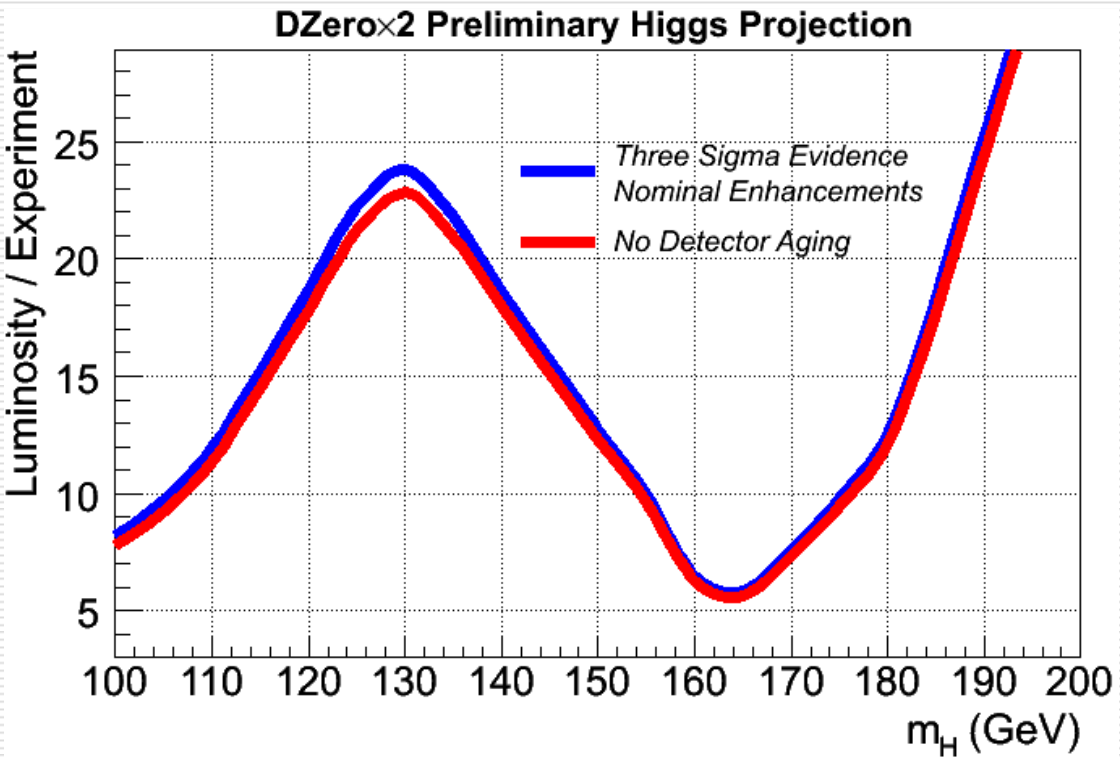


What is error on SM line?

Tevatron excludes M_h: [100-109; 158-175 GeV]

How far can the Tevatron go?

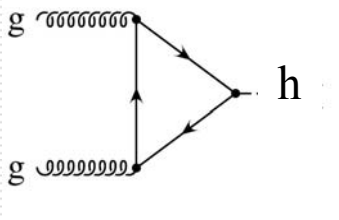
- Presentation to Fermilab PAC, Aug, 2010

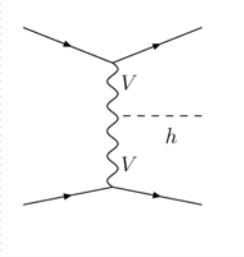


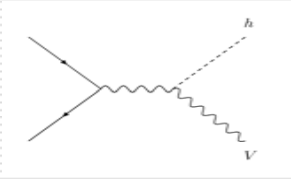
LHC Higgs Cross Section Working Group*

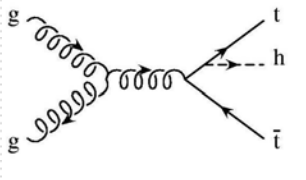
- Higgs exclusion requires reliable predictions for many channels
- Need to understand theory uncertainties
  - From PDFs
  - From unknown higher order corrections
  - From scale and α_s variations
  - From ….

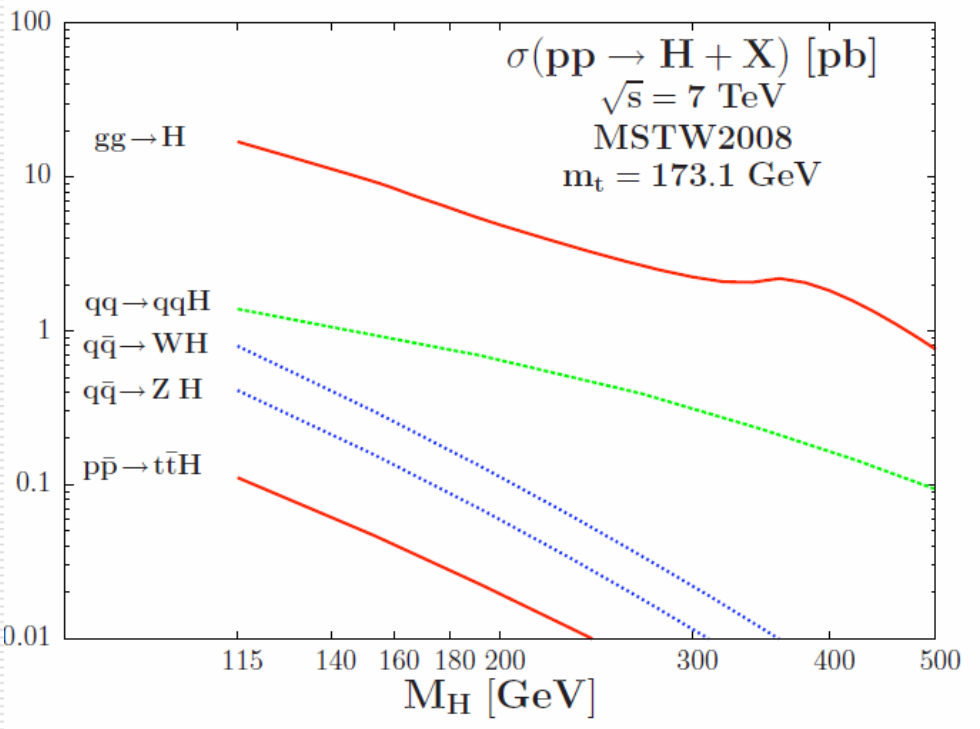
Higgs at the LHC











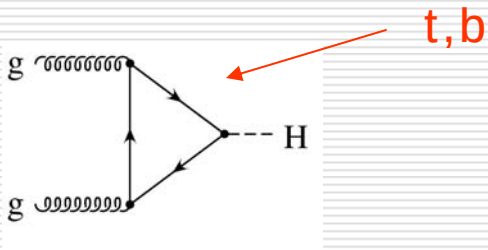
Goal: Update with comparison of PDFs and reliable estimates of uncertainties

Many *public* tools available

- gg→h
  - NNLO QCD +EW
  - Resummation (threshold)
- Vector Boson Fusion
  - NLO QCD + EW with decays, NNLO QCD
- Vh
  - NLO QCD
- tth
  - LO QCD
- NLO event generators
  - MC@NLO, POWHEG
- Decays
  - NLO QCD+EW

SM calculations in great shape

- Dominant production mode is gg→h



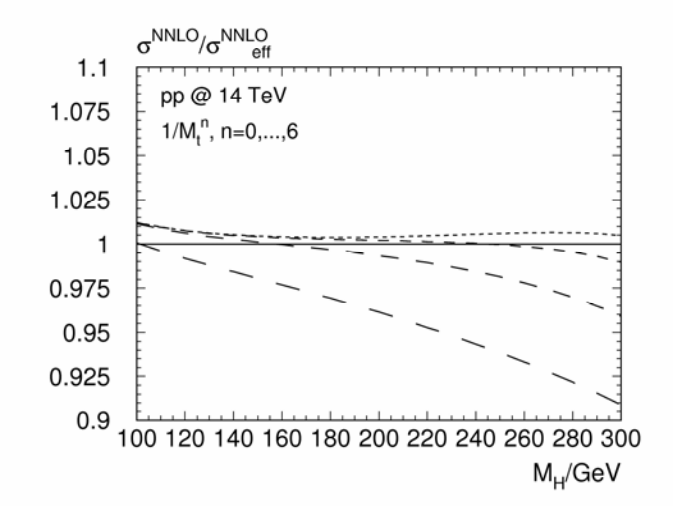
  - NNLO in heavy M_{top} limit
  - Exact t,b loops at NLO
  - N^3LL resummation
  - EW and mixed EW/QCD corrections

→ Precise predictions allow us to trust error estimates

NNLO for Finite Top Mass

- Previous calculations done in effective field theory where $M_t^2 >> s, M_h^2$
  - Include powers of $(s/M_t^2)^k$

$$L \approx c \frac{h}{v} G^A_{\mu\nu} G^{A\mu\nu}$$



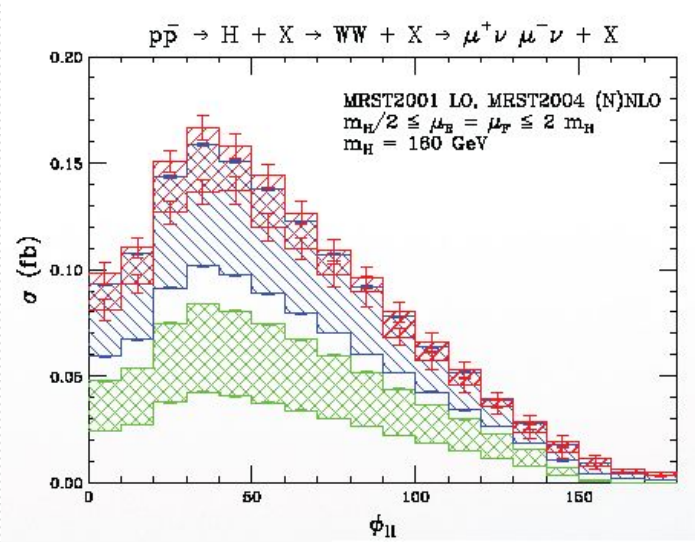
Increasing k

EFT excellent approximation (~1%)

Harlander, Mantler, Marzani, Ozeren; Pak, Rogal, Steinhauser

$gg \to h$

- Fully differential NNLO rates



The issues:

How to chose central scale / scale variation?

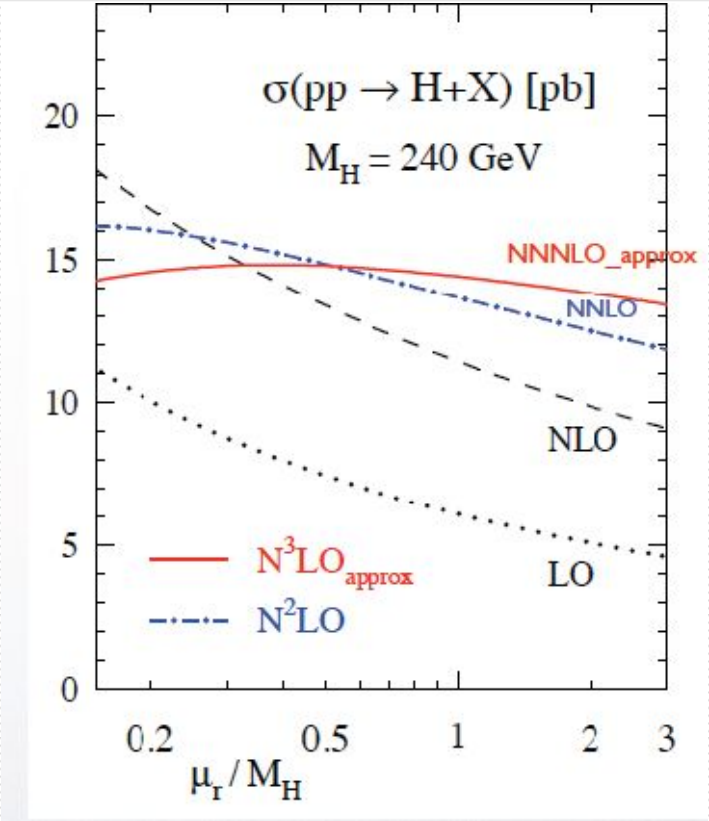
How to combine PDF & scale uncertainties?

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

Similar size

Anastasiou, Melnikov, Petriello

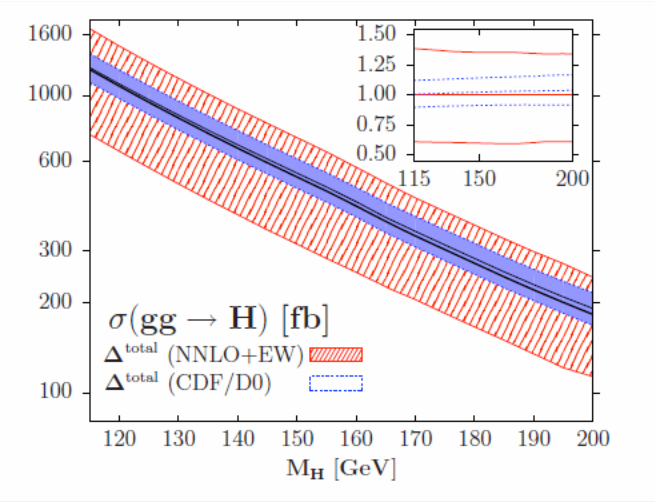
Small scale gives better convergence



Moch and Vogt

How big is uncertainty on gg→h?

- Baglio & Djouadi uncertainty on gg→h: ~±38%
- Roughly 2x's Anastasiou uncertainty: mainly due to method of combining scale and PDF/α_s uncertainties, along with larger variation of scale, $M_h/3 < \mu < 3M_h$



Tevatron

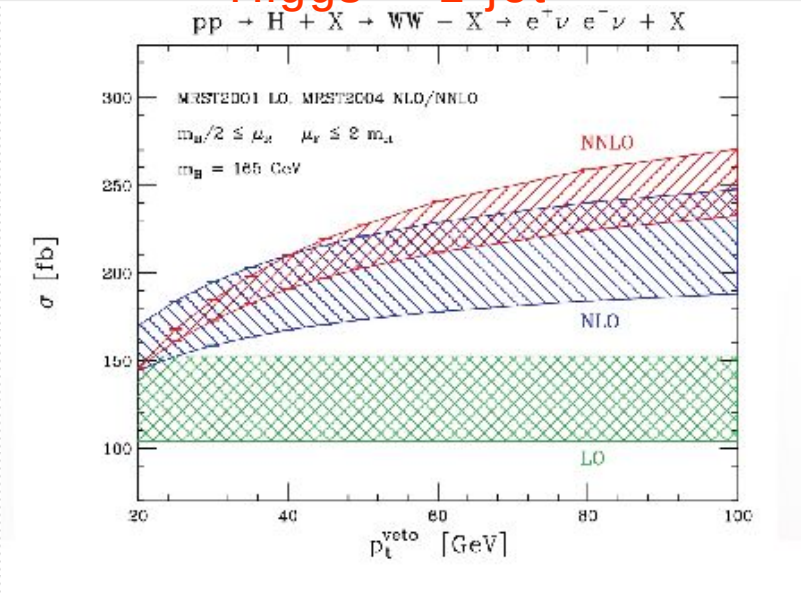
Tevatron assumes ±17.5% theory uncertainty on gg→h

Baglio, Djouadi

Compare theory/experiment

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

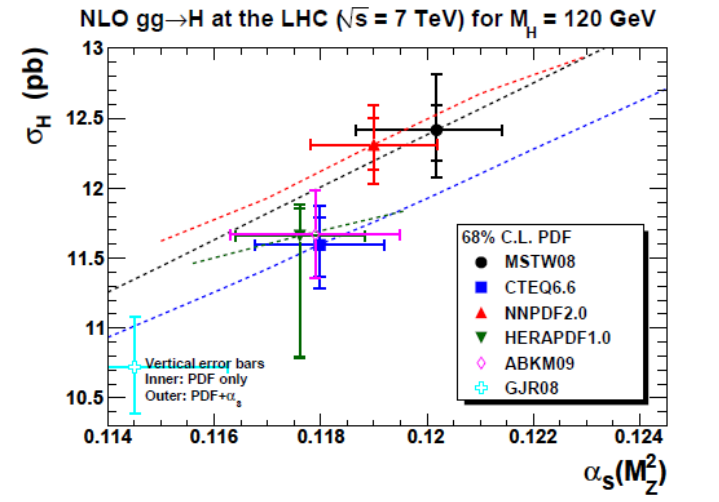
Higgs + 1 jet



Theory uncertainties depend on cuts & binning

PDF errors are complicated….

- Prescription for PDF errors:
  - Errors quoted by PDF fitters typically smaller than variations between sets
  - PDF4LHC: Use envelope of MSTW,CTEQ,NNPDF predictions
- Effectively amounts to doubling MSTW error



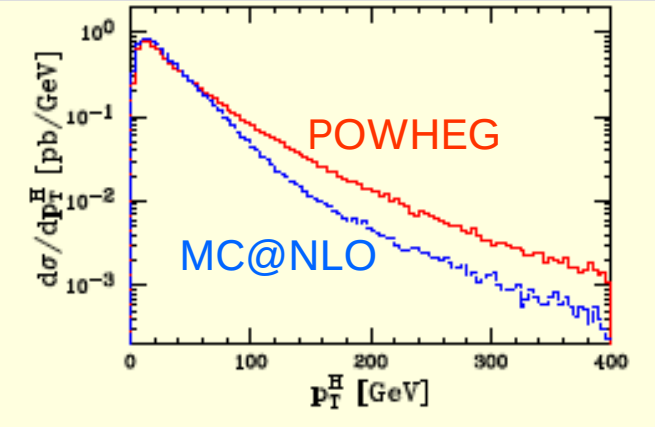
Thorne

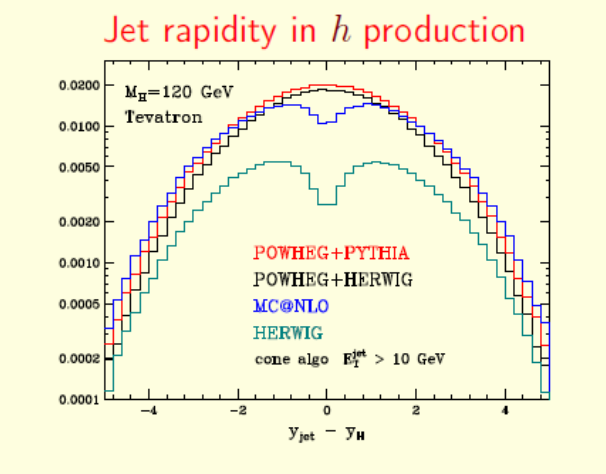
Interface with NLO Monte Carlos

- 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)

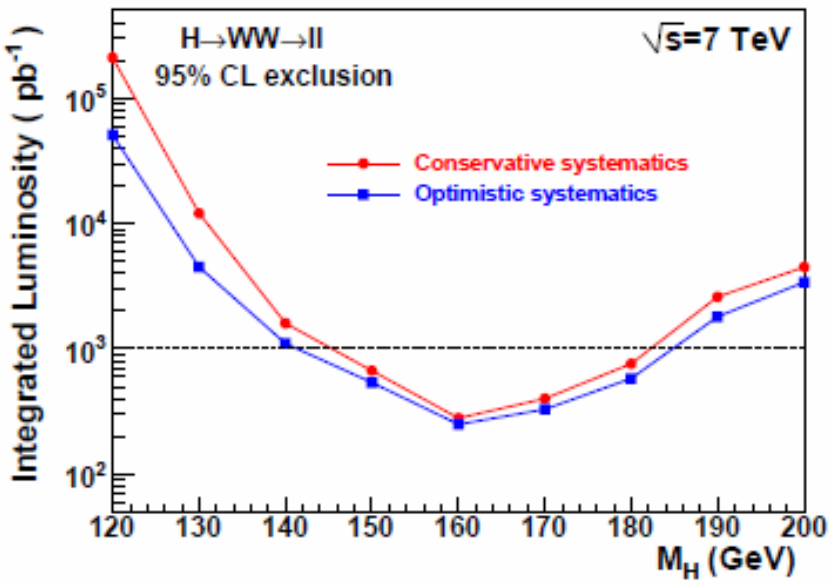




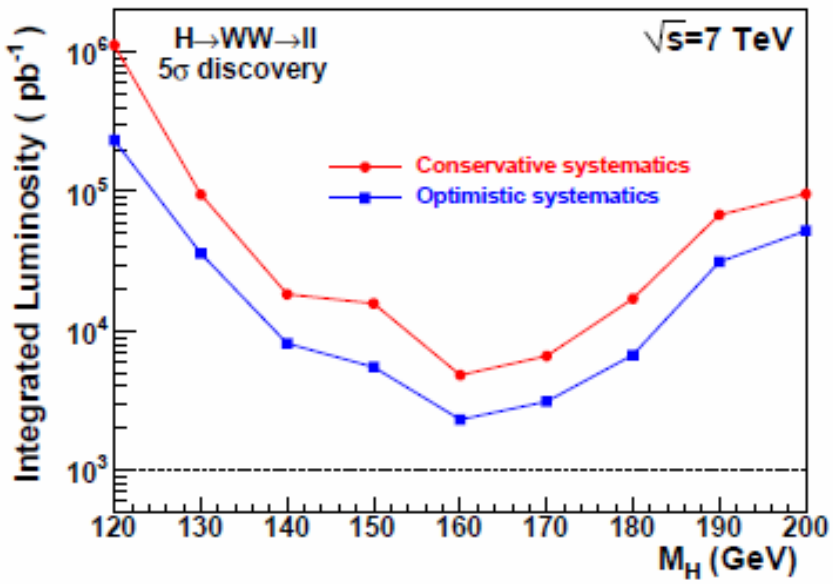
Differences understood

7 TeV Higgs Reach with 1 fb^{-1}

CMS



95% C.L. Exclusion

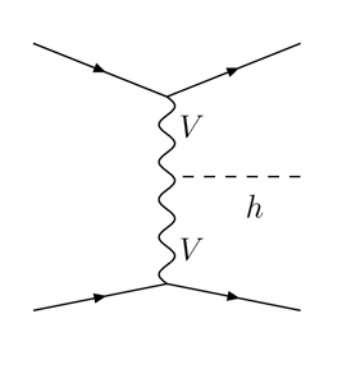


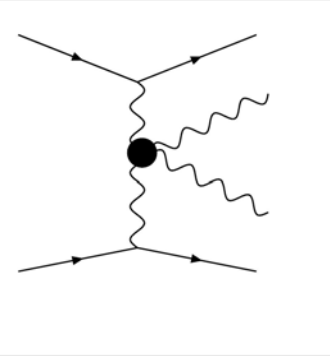
5σ Discovery

- This mass region dominated by gg initial channel
- LHC 7 could exclude 140 GeV < M_H < 185 GeV
- No Higgs discovery in 1 fb^{-1}

Vector Boson Fusion

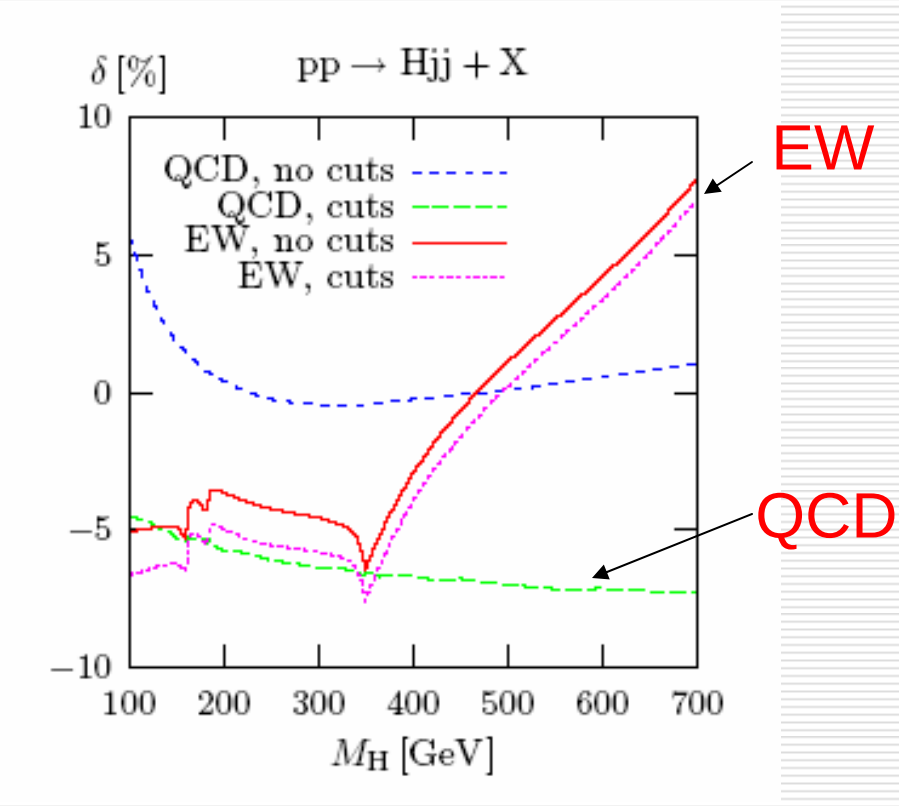
- Discovery channel
  - 2nd largest cross section over entire M_h range
- VBF: $h \to \tau^+\tau^-$ and $h \to WW$ give h couplings
- Probes new vector boson interactions





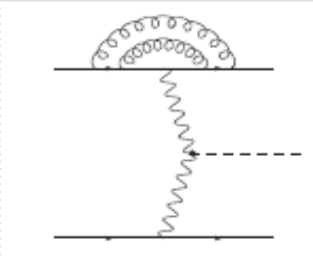
VBF with NLO QCD + EW

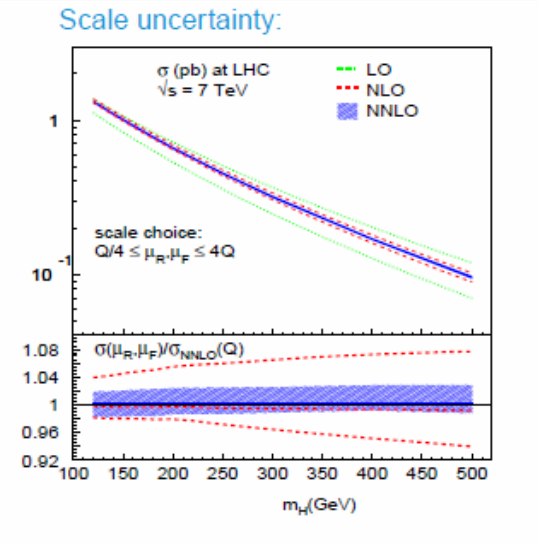
- Electroweak corrections to vector boson fusion are of similar size as QCD corrections (-4% , -7%)
- QCD contributions very sensitive to cuts
- Partial cancellation between EW & QCD

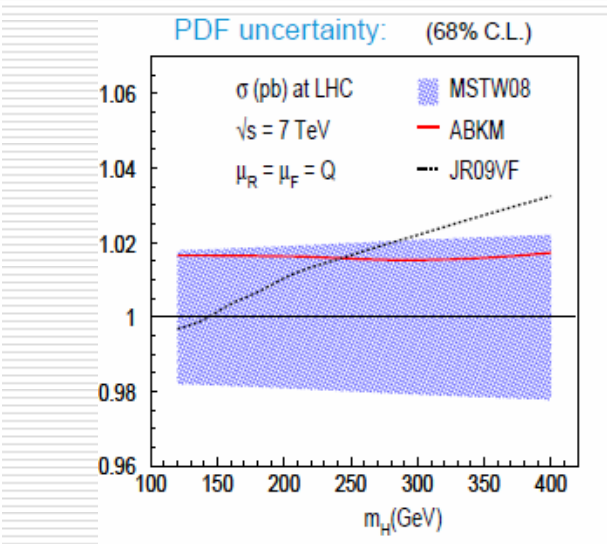


VBF at (partial) NNLO

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





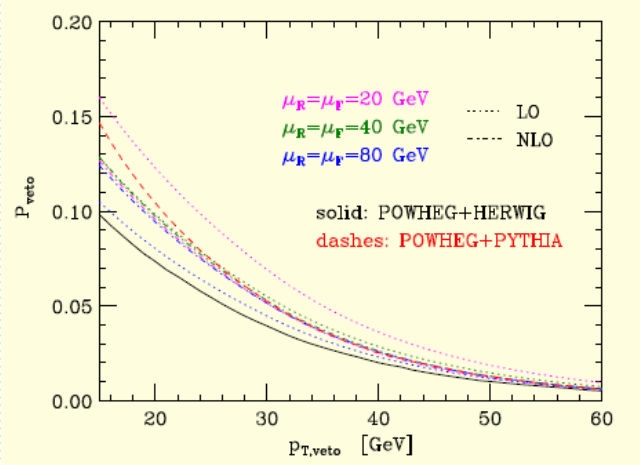


Scale uncertainty ~ PDF uncertainty ~ 2%

Bolzoni, Maltoni, Moch, Zaro

VBF in POWHEG

- 3rd jet generated by shower
  - Not accurate in central region as needed for p_T veto
- As p_T veto gets smaller, shower/hadronization as important as NLO scale variation

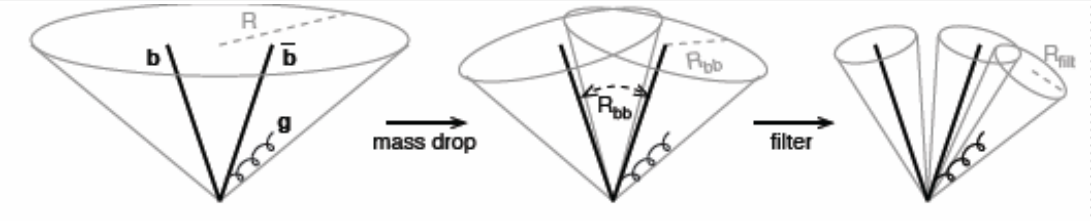


← p_T veto on 3rd jet

Nason, Oleari

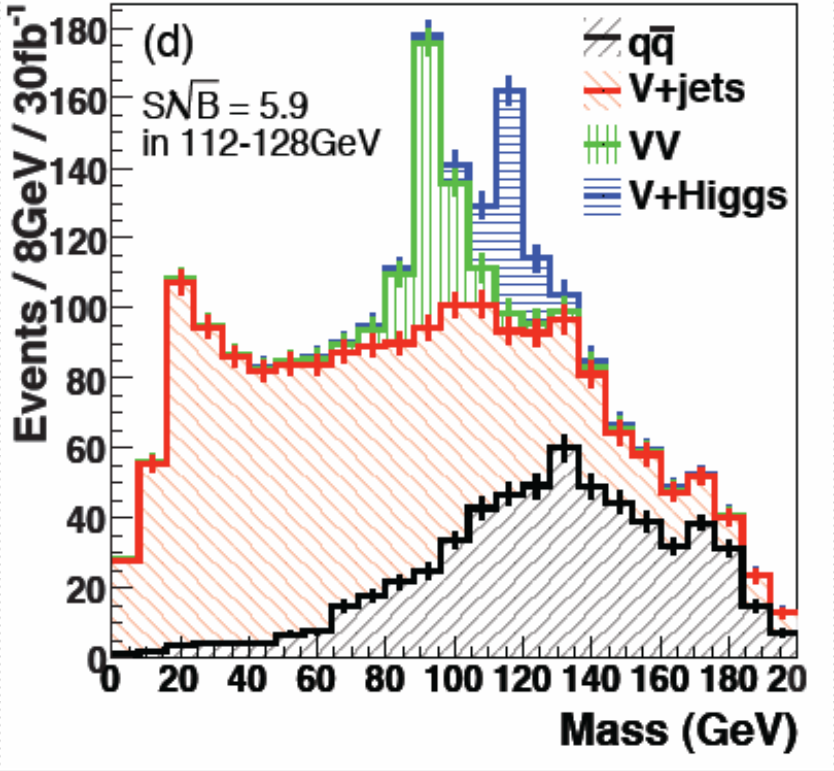
Jet Substructure

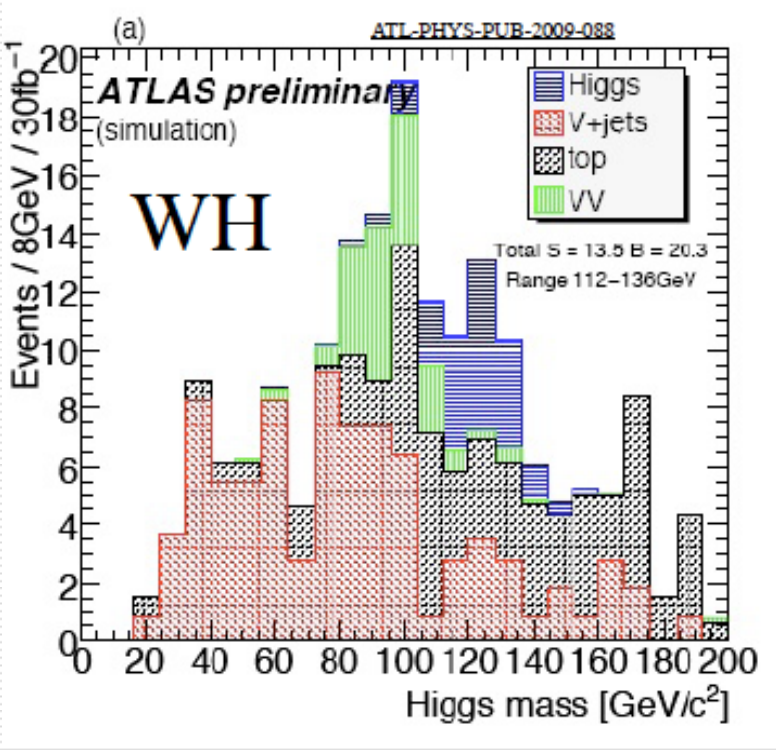
- At LHC energy, electroweak scale physics (W,Z,h,t) inside jets
  - Distinguish between QCD generated jets and those due to heavy object decays
  - Algorithms for unclustering jets
  - Apply technique to Wh, Zh, h→bb
    - Important to get y_b
  - Require h & V have high p_T (>200 GeV)
  - Decay products collimated, subjet techniques useful



Butterworth,Davison, Rubin, Salam

Subjets and Vh, h→bb





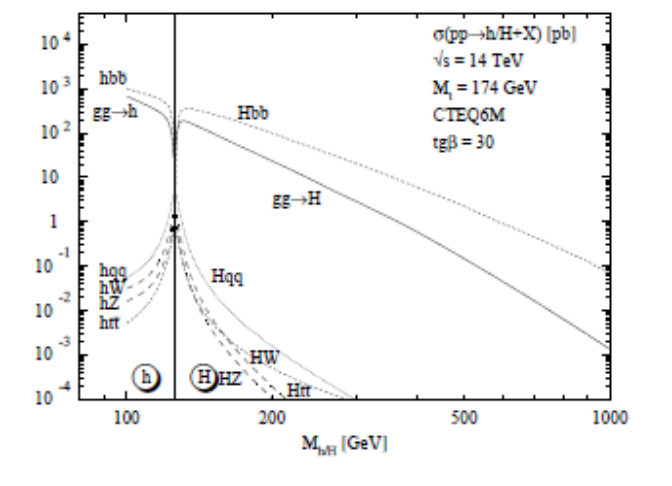
3.5 σ, 30 fb^{-1}, 14 TeV

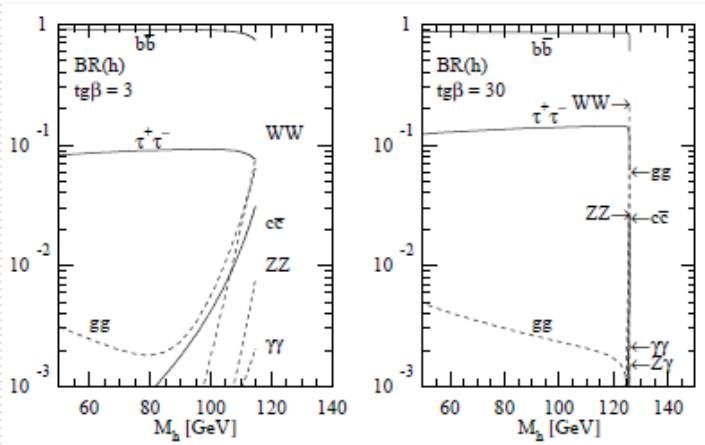
Many Alternatives to SM

- 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
- TBD….

MSSM

- 5 Higgs bosons. h, H, A, $H^{\pm}$
- Rates affected by change in couplings
  - For tan β > 10, largest rate is bbϕ at LHC
  - Need NLO generator for bbϕ
  - h decays 90% to bb, 10% to $\tau^+\tau^-$





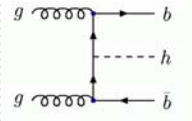
Theoretical Issues in $b\bar{b}\Phi$ production

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

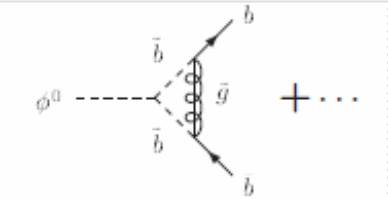


$$\ln\left(\frac{\mu_F^2}{m_b^2}\right), \qquad \mu_F \approx M_h$$

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

MSSM & Tevatron Limits

- $b\bar{b} \to \phi \to \tau^+\tau^+$ (NNLO QCD)
  - MSSM corrections included using Δm_b approximation
  - Resums large effects to get effective couplings
  - Accurate to < 1%



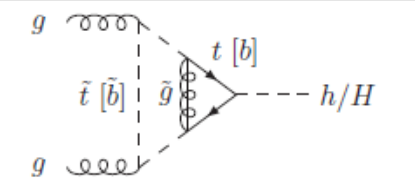
$$g_{hbb} = \frac{M_b}{v_{SM}(1+\Delta_b)}\left(-\frac{s_\alpha}{c_\beta}\right)\left(1-\frac{\Delta m_b}{t_b t_\alpha}\right)$$

$$\Delta m_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}})$$

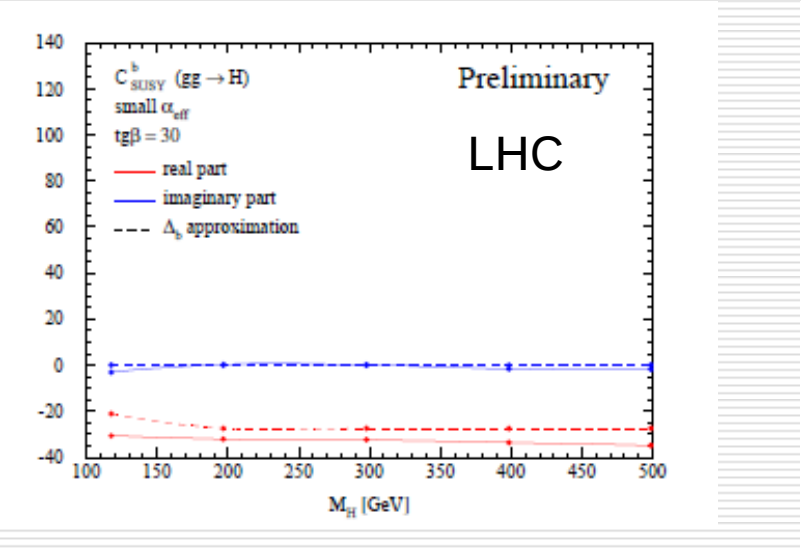
- $bg \to \phi b \to \tau^+\tau^- b$, bbb (NLO QCD)
  - $bb\phi$ vertex corrections included in Δm_b approximation

MSSM Higgs production rates

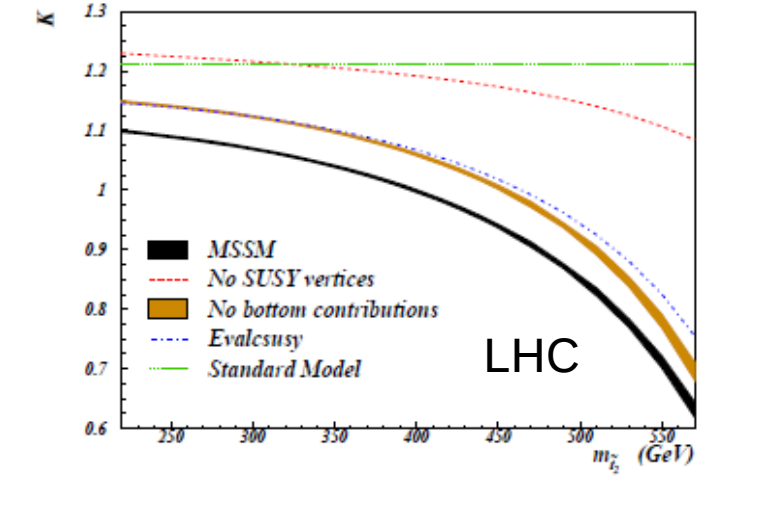
- Squark/gluino loops important for gg→ϕ
  - Rate significantly reduced



SQCD corrections
(relative to LO b loop)

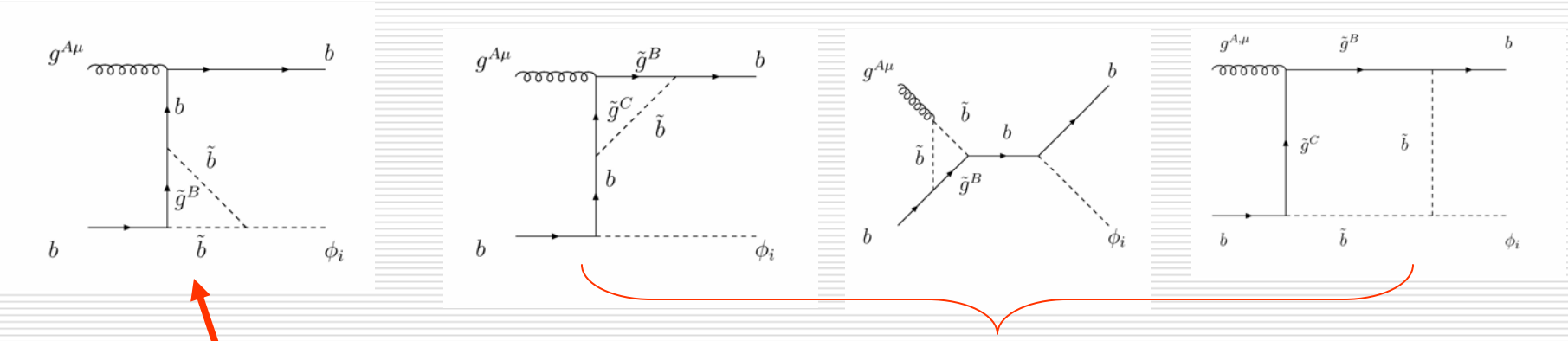


tan β = 20



Calculate SUSY QCD Corrections to $bg \to b\Phi$

- $O(\alpha_s^2)$ NLO SUSY QCD calculation
  - Use g_{hbb} as above, so subtract off double counting
  - Include all contributions from squarks/gluinos



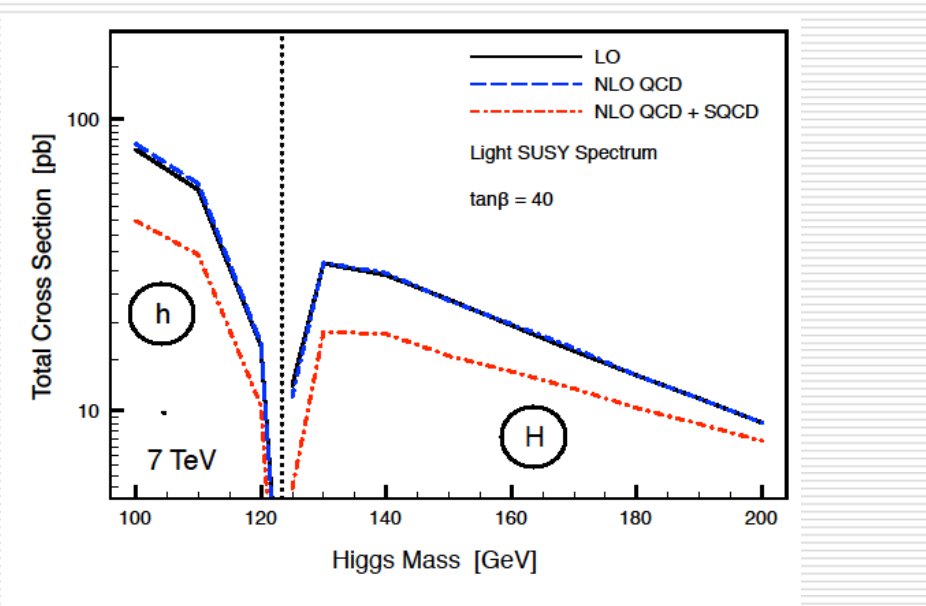
Δm_b approximation puts $bb\Phi$ vertex on shell

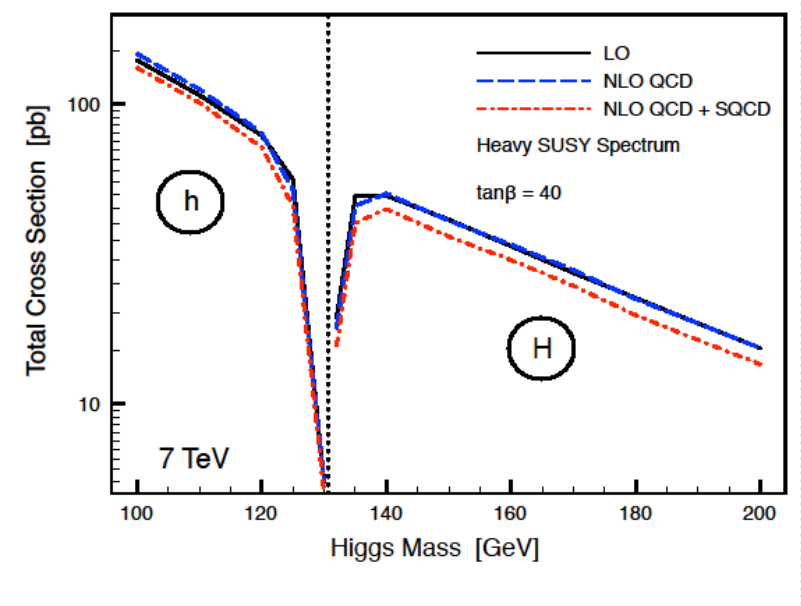
Many contributions not included in IBA

Jackson, Dawson

Can't neglect SQCD Effects on $bg \to b\Phi$

$\sqrt{s} = 7$ TeV





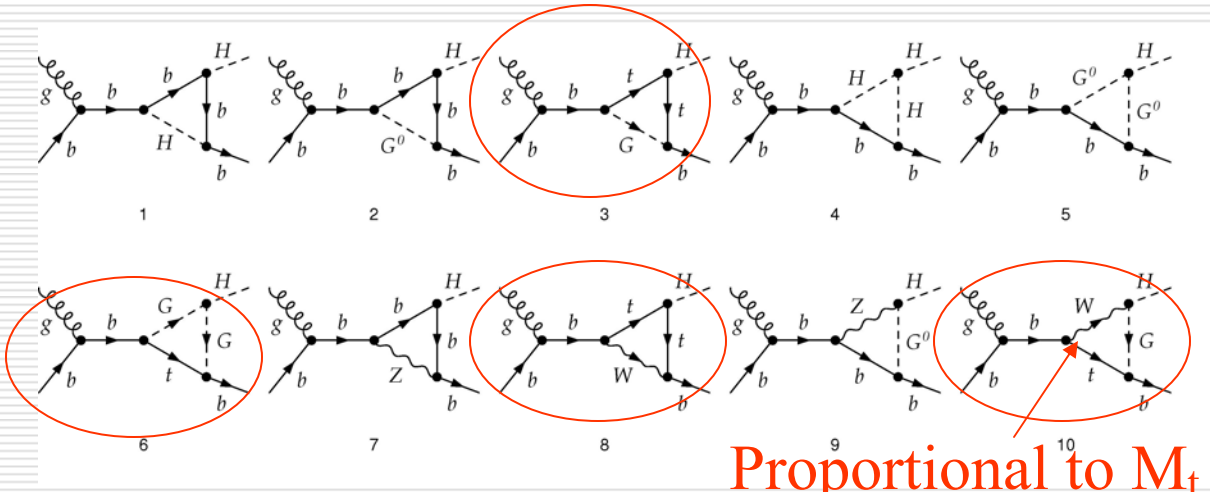
$M_{squark}=M_{gluino}=250$ GeV

$M_{squark}=M_{gluino}=1$ TeV

SQCD effects large for light SUSY and large tan β

Do Electroweak Corrections Matter?

- Lowest order rate for bg→bh vanishes for $m_b=0$
- At 1-loop, there are diagrams which do NOT vanish in $m_b=0$ limit
- Full electroweak calculation



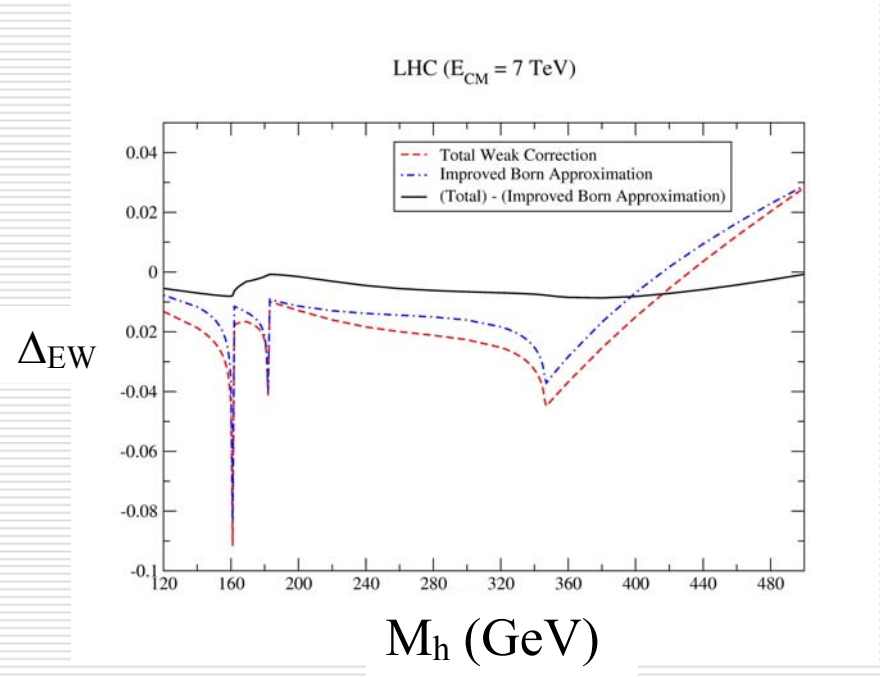
Proportional to M_t not m_b

Standard Model: EW Corrections to pp → b h

$$\sigma(pp \to bh) = \sigma_0 \left(1 + \Delta_{QCD} + \Delta_{SQCD} + \Delta_{EW}\right)$$

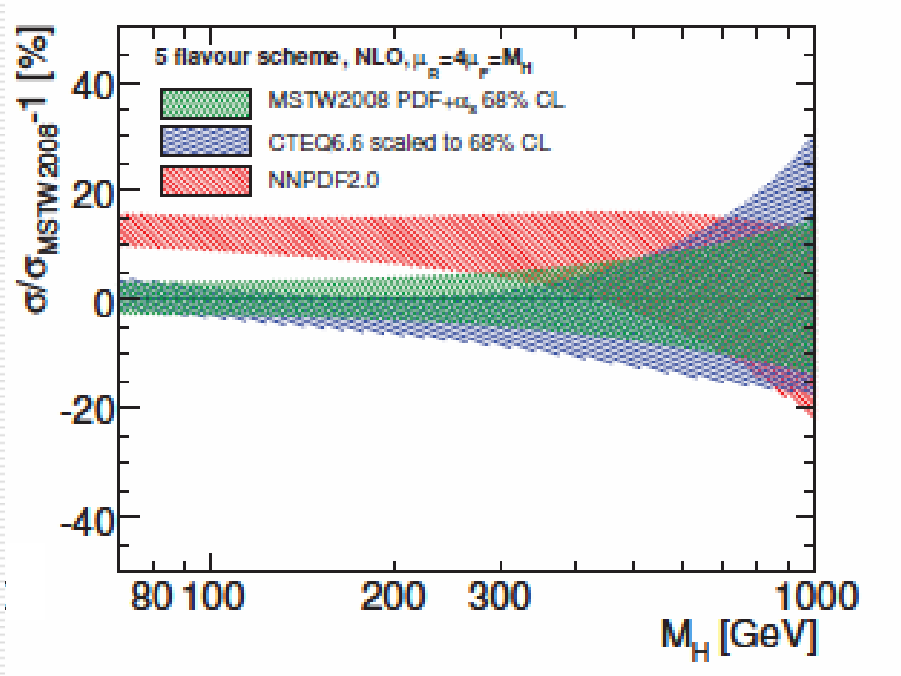
For M_h ~ 400 GeV corrections 2-4%

IBA captures weak corrections accurately



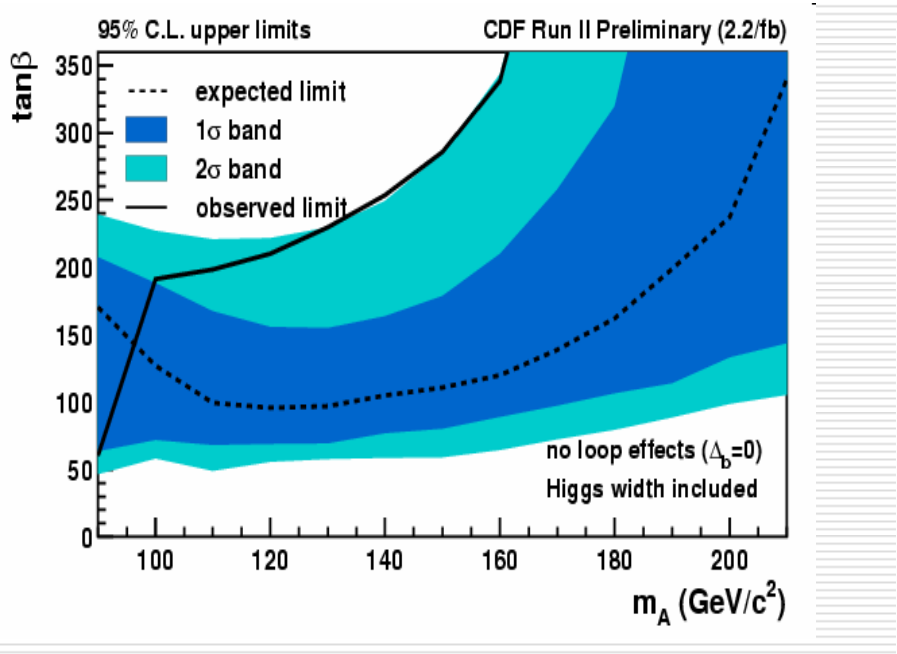
Dawson, Jaiswal [arXiv:1002.2672]

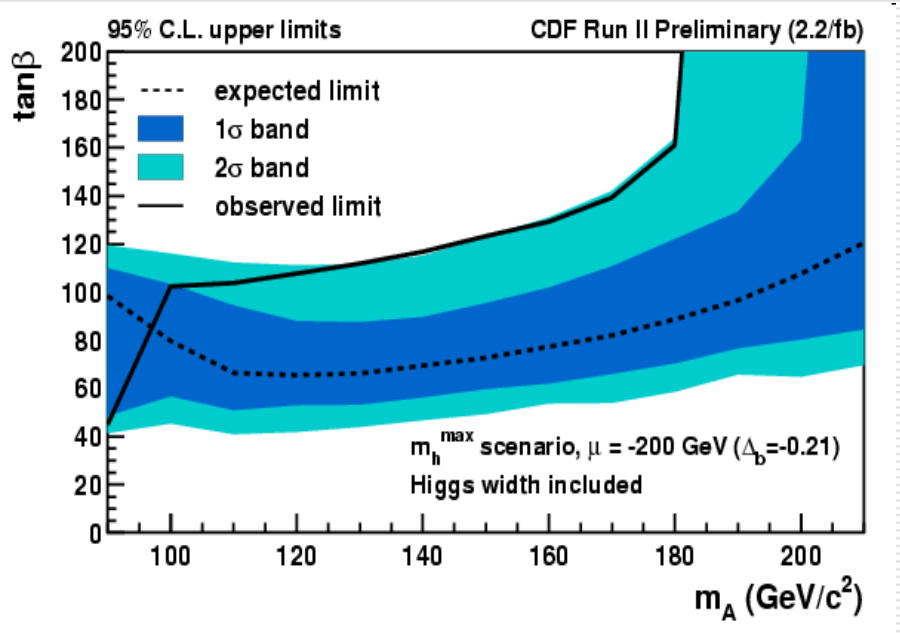
PDF Uncertainties on bbΦ



Differences between PDF sets larger than proponents claims of PDF uncertainties

Limits from Tevatron

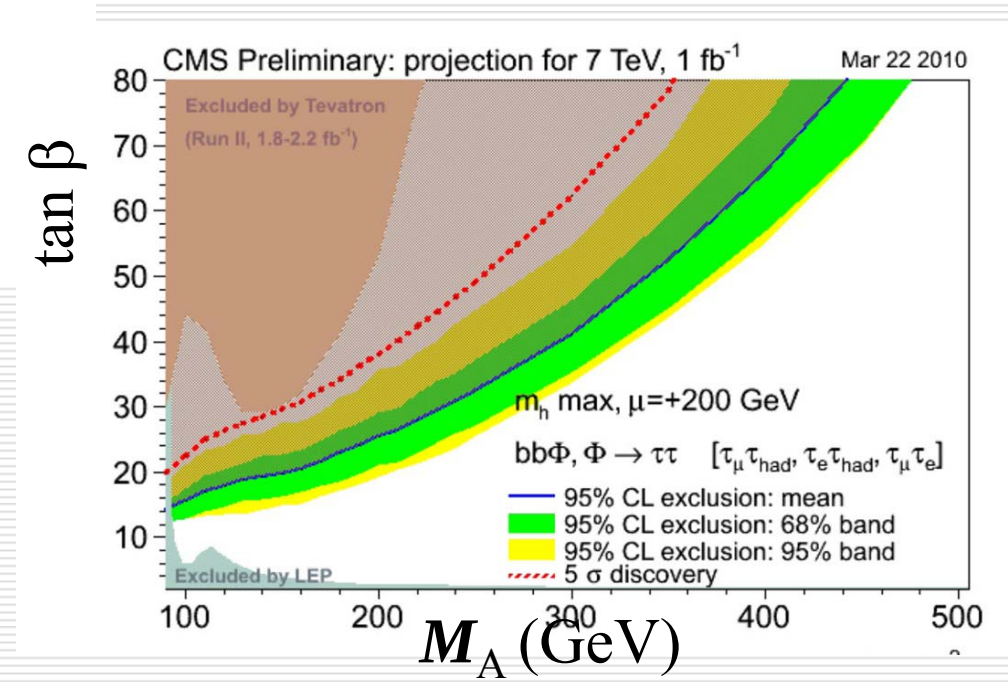




$b\Phi \rightarrow bbb$

Note dependence of limits on assumptions about loop (Δm_b) effects

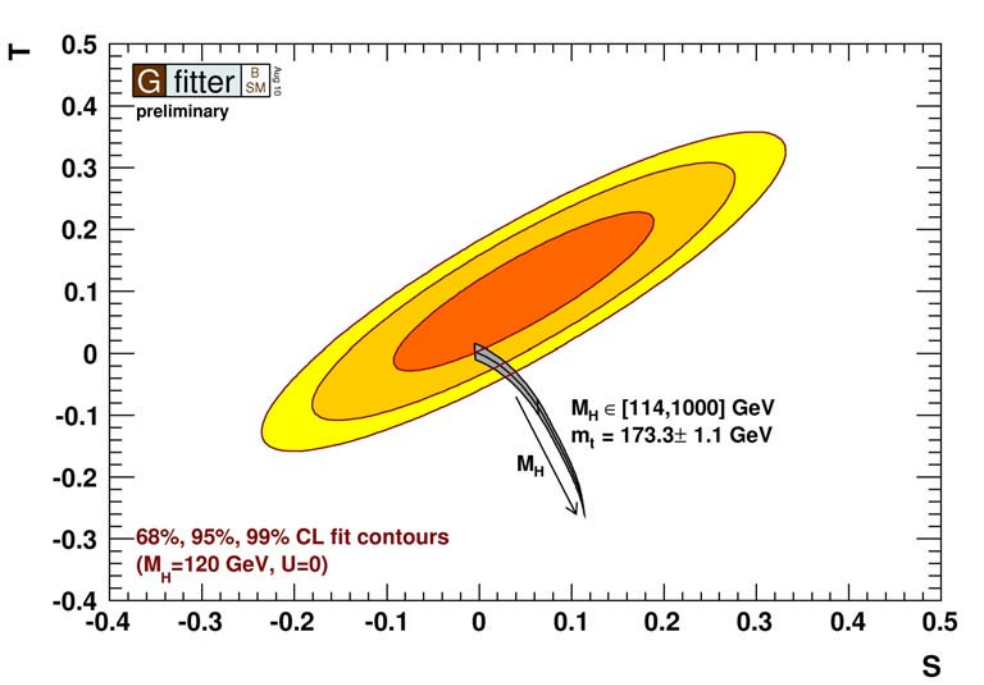
LHC Expectations



- Higgs Discovery Channel

STU

- If new physics is at scale $\Lambda >> M_Z$, then STU describe precision electroweak measurements

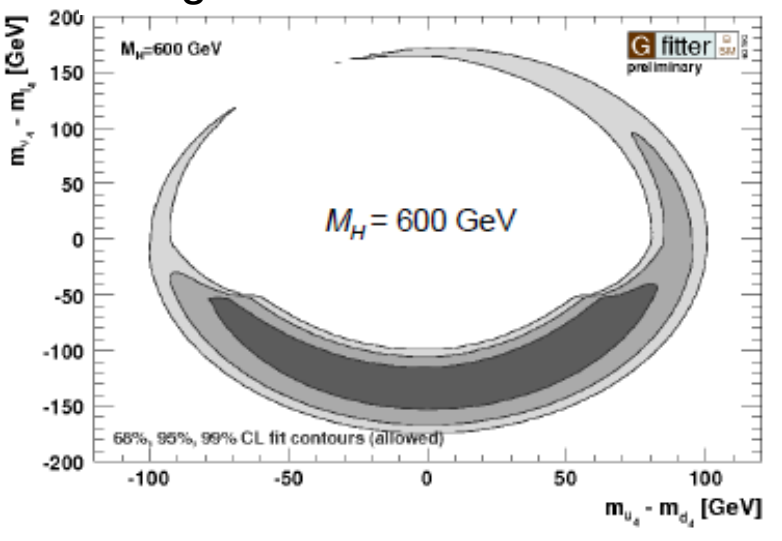


Precision data restrict BSM scenarios

- General 2 Higgs doublet
- Kaluza Klein particles
- Little Higgs with T parity
- MSSM
- 4 generations

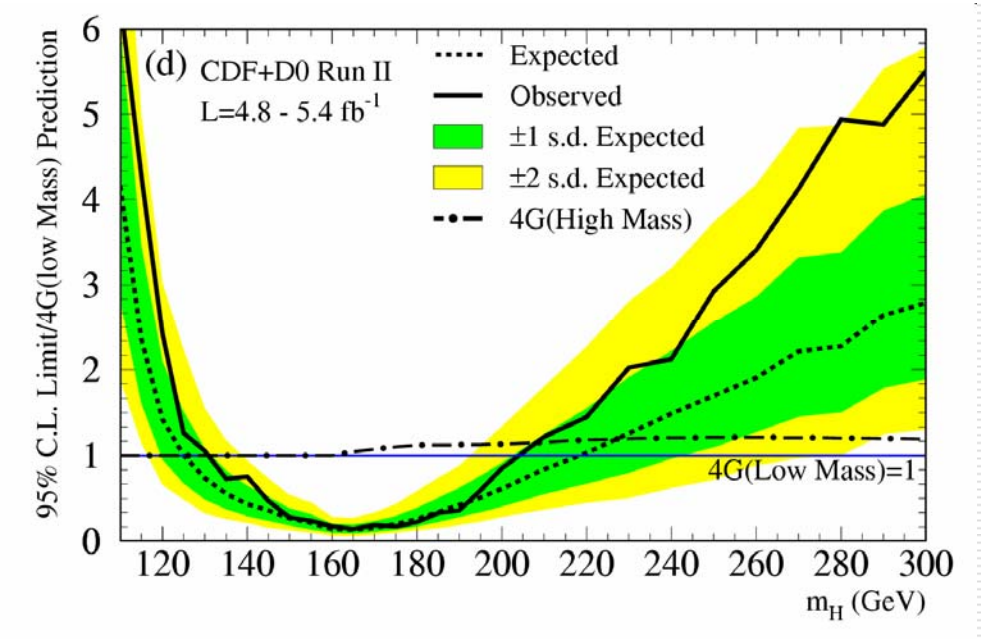
Can accommodate heavy Higgs with some types of new physics

4th generation



Light Higgs and 4th Generation

- Heavy fermions decouple from gg→h production

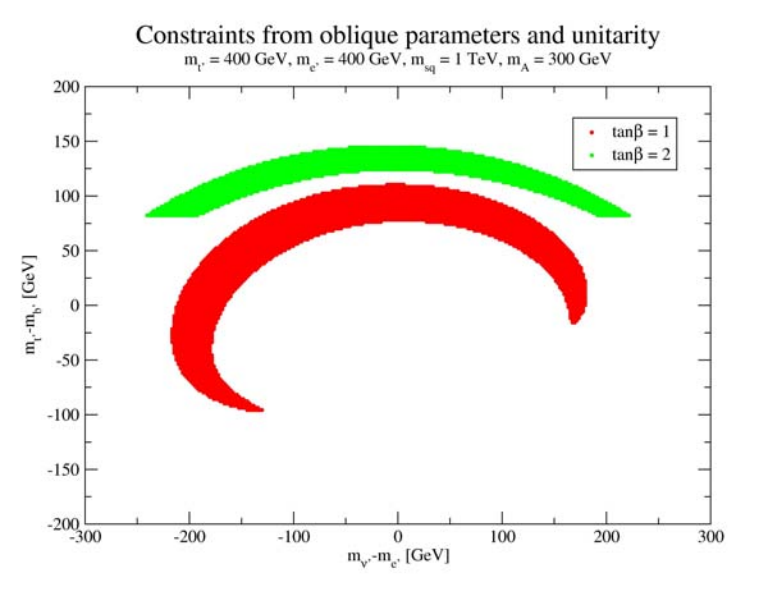


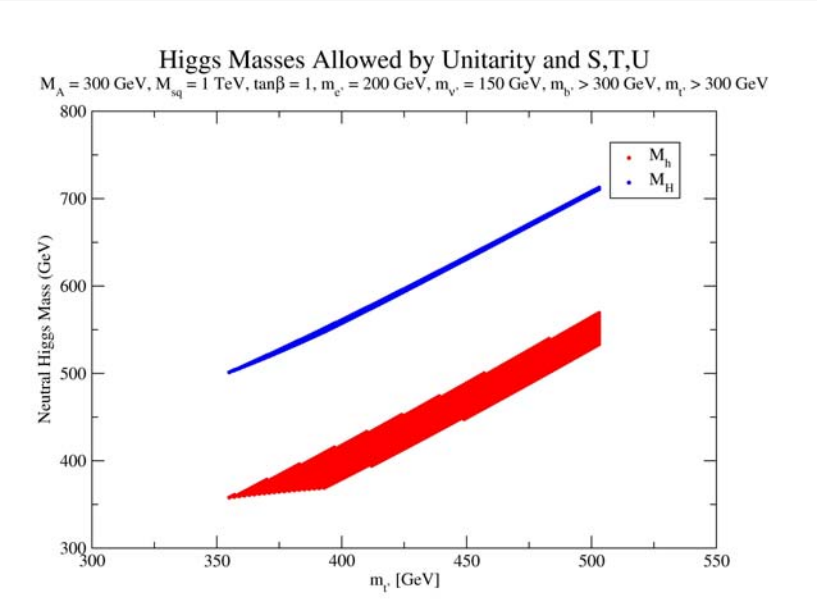
Tevatron excludes 4G and M_h : [131-204 GeV]

Anastasiou, Boughezal, Furlan, arXiv:1003.4677

4th Generation with MSSM

- Arrange parameters carefully
  - Requires tan β~1





Dawson, Jaiswal, arXiv:1009.1099

Conclusions

- Higgs Hunting just starting
  - Theory/experimental dialog critical
  - Theory calculations under excellent control for SM
  - Need to come to consensus about treatment of theoretical uncertainties
  - BSM scenarios need more work to obtain reliable predictions