Finding the Source of Electroweak Symmetry Breaking: Theoretical Summary

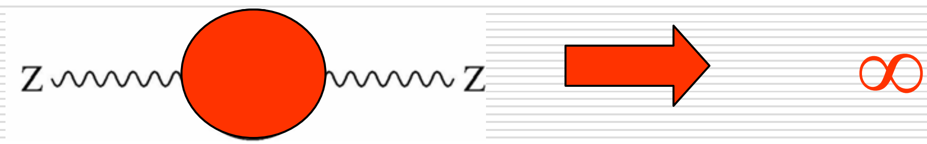
S. Dawson, BNL, July 31, 2010

What are the criteria?

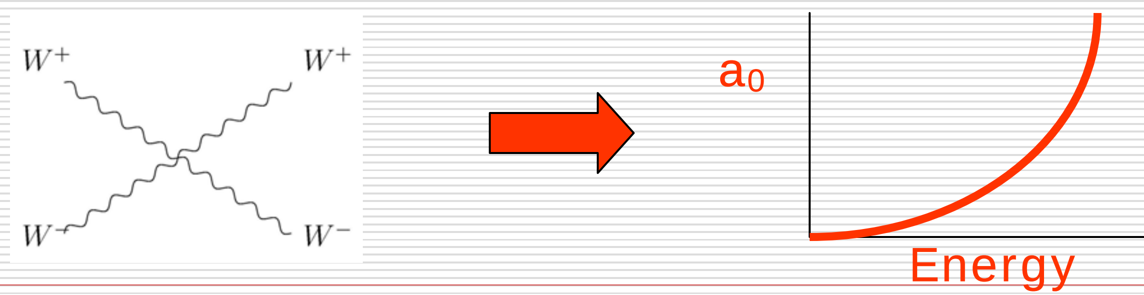
- Electroweak symmetry breaking needs to explain:
  - Non-zero mass of W and Z gauge bosons
  - Non-zero mass of fermions
  - Unitarity at 1 TeV
- Must be consistent with all data
  - Precision electroweak data
  - Tevatron searches
  - Flavor changing neutral currents
  - Little hierarchy
    - Much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

Unitarity

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

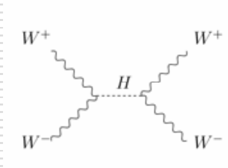


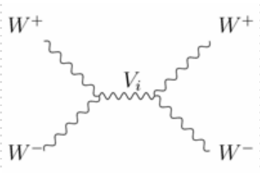
  - Scattering amplitudes grow with energy



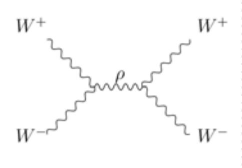
What unitarizes WW scattering?

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





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



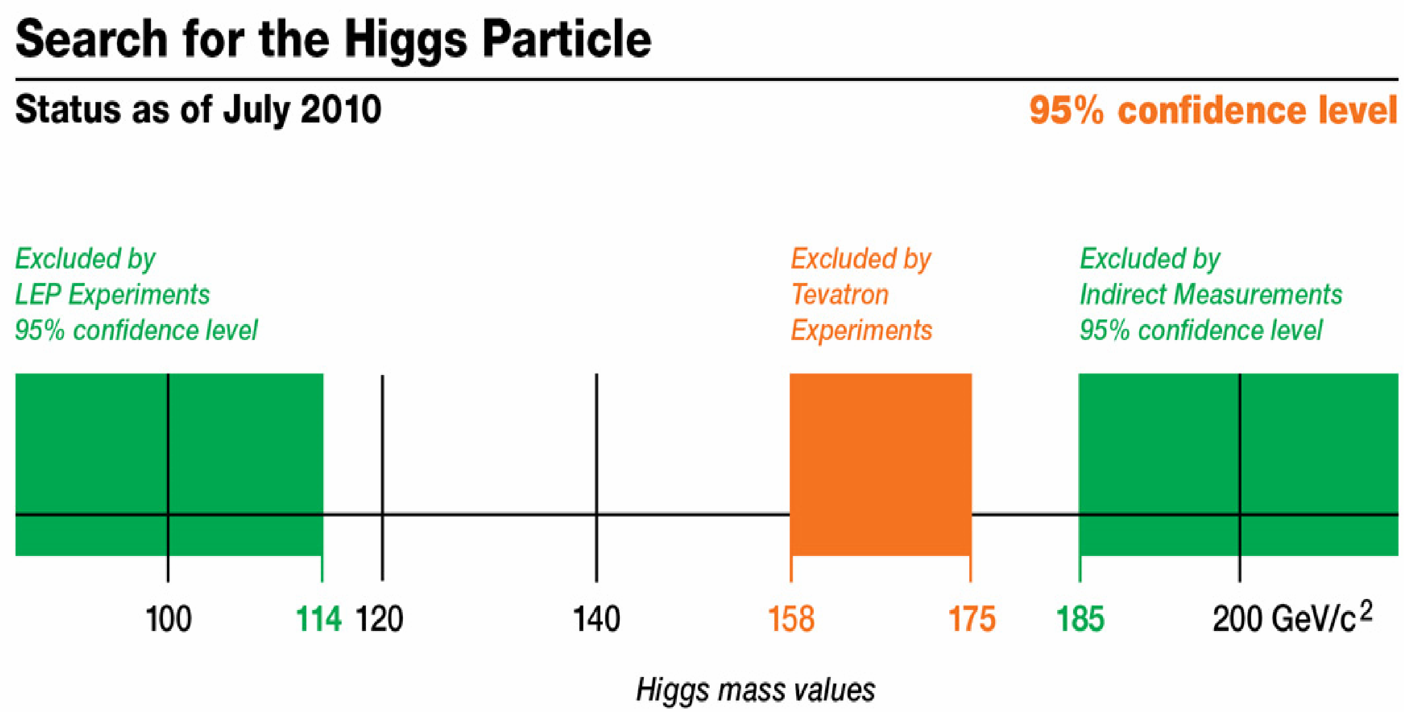
[Rychkov]

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
  - History: Zinn-Justin

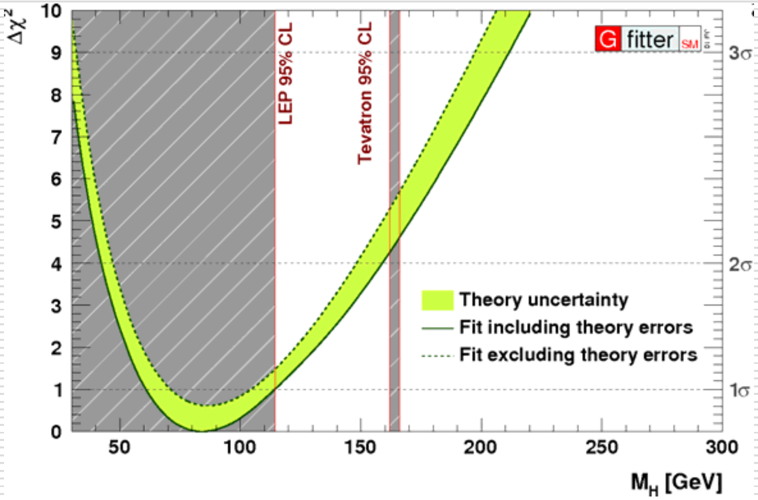
→ Simplest possibility is weakly coupled Higgs boson

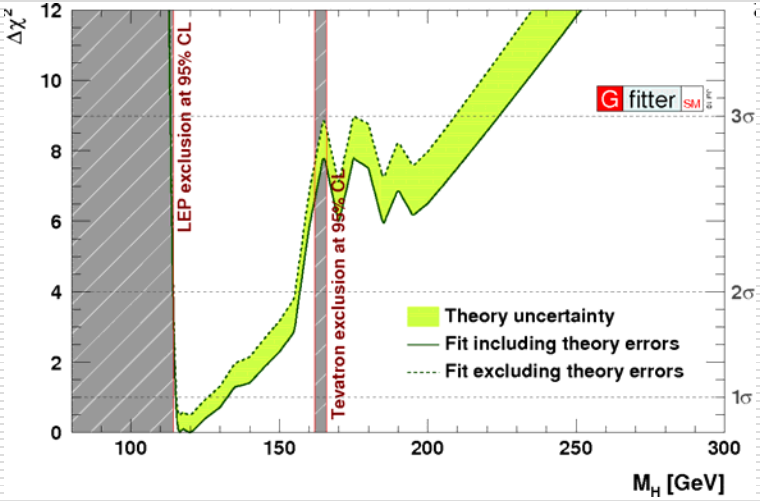
Allowed parameter space shrinking



Precision EW Data

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





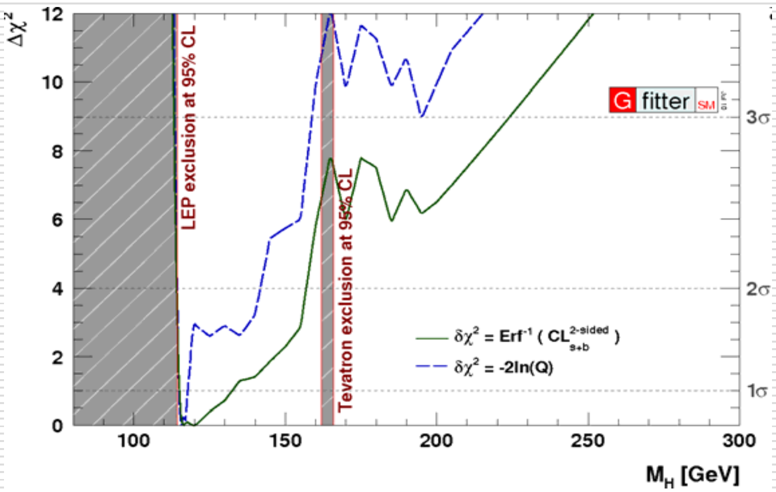
Includes direct search limits

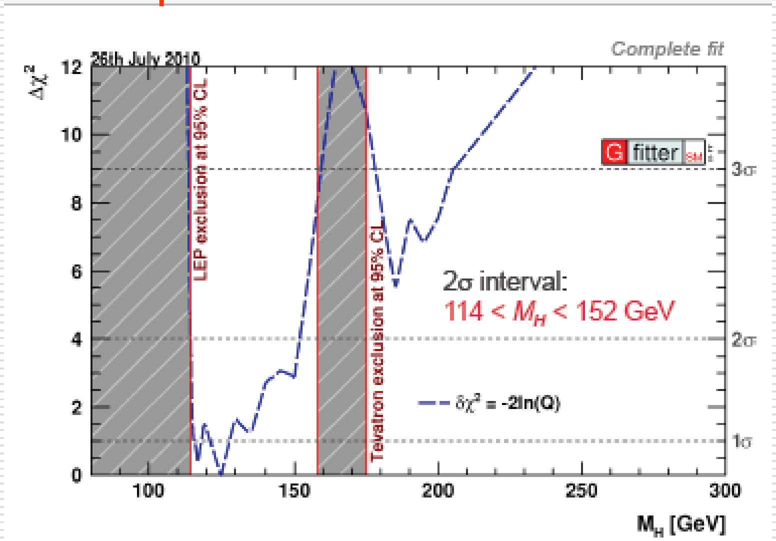
Not updated

[Hoecker]

Understanding Statistics....

Updated from ICHEP





- 2-sided confidence level of direct search limits from LEP & Tevatron

- Log likelihood interpretation of experiments

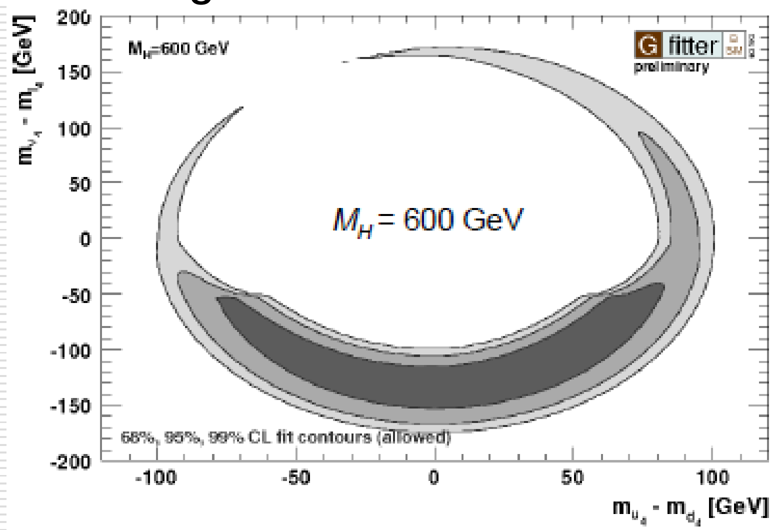
[Hoecker]

Precision data restrict BSM scenarios

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

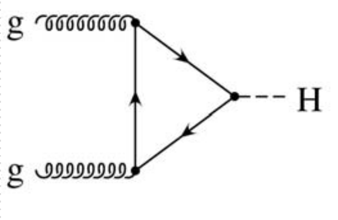
Can accommodate heavy Higgs with some types of new physics

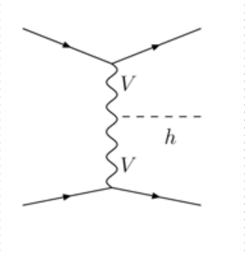
4th generation

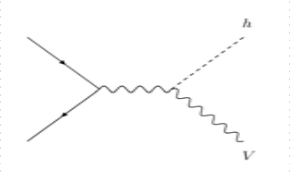


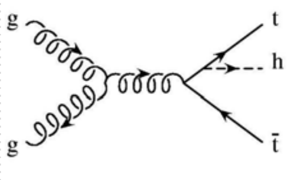
[Hoecker]

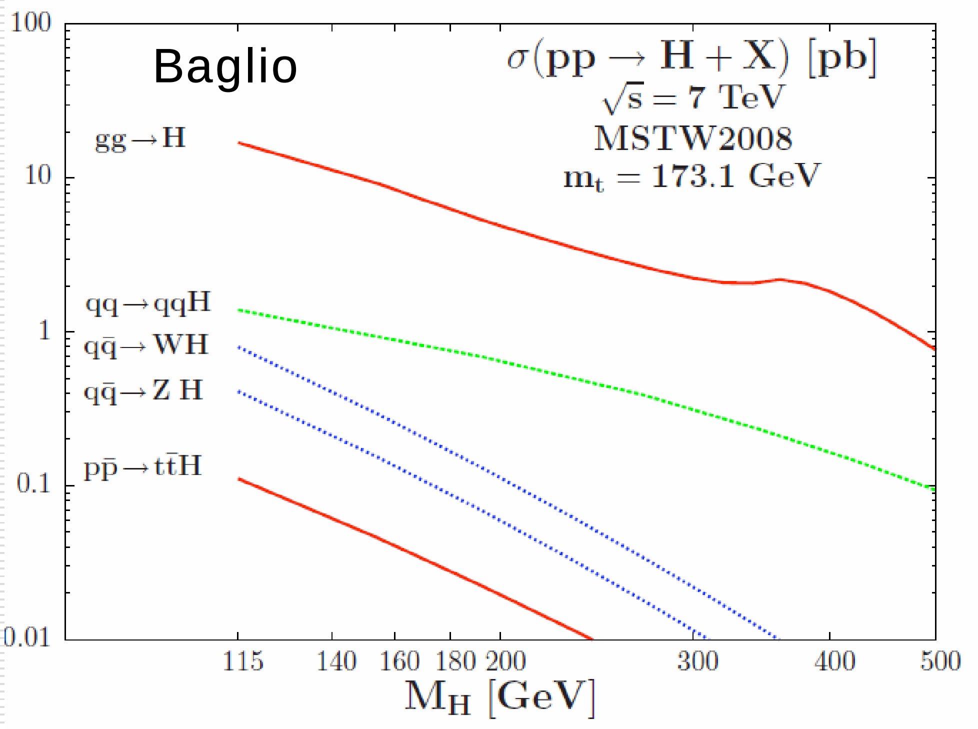
Higgs at the LHC







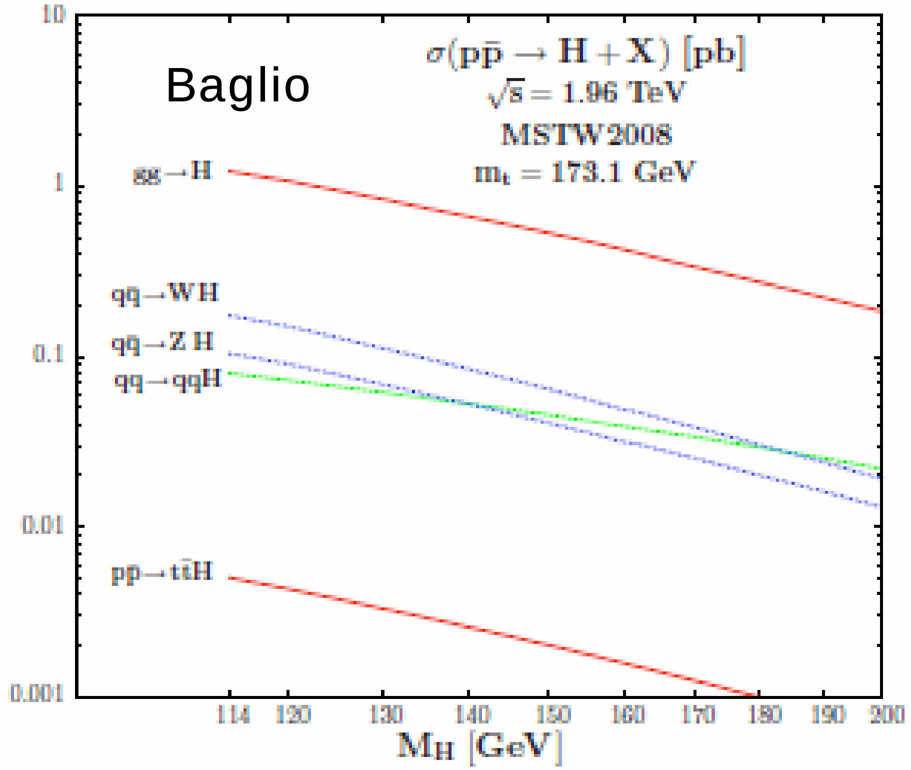




Goal: Update with comparison of PDFs and reliable estimates of uncertainties

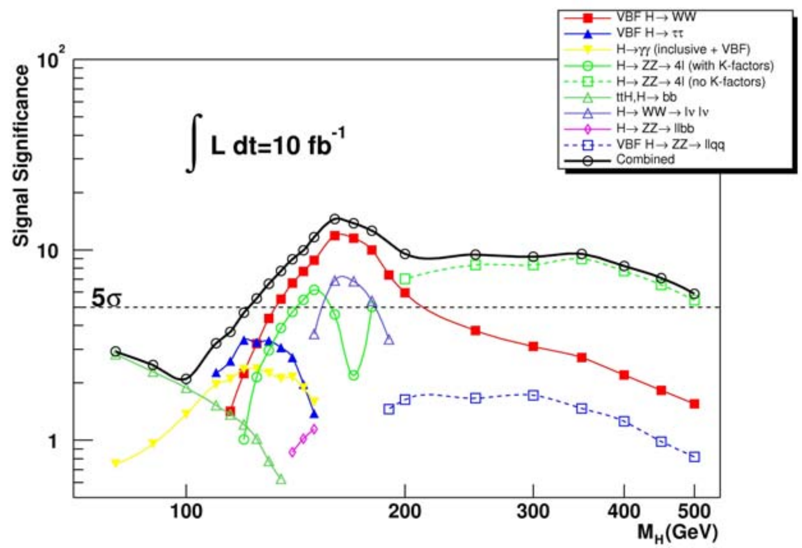
Higgs at the Tevatron

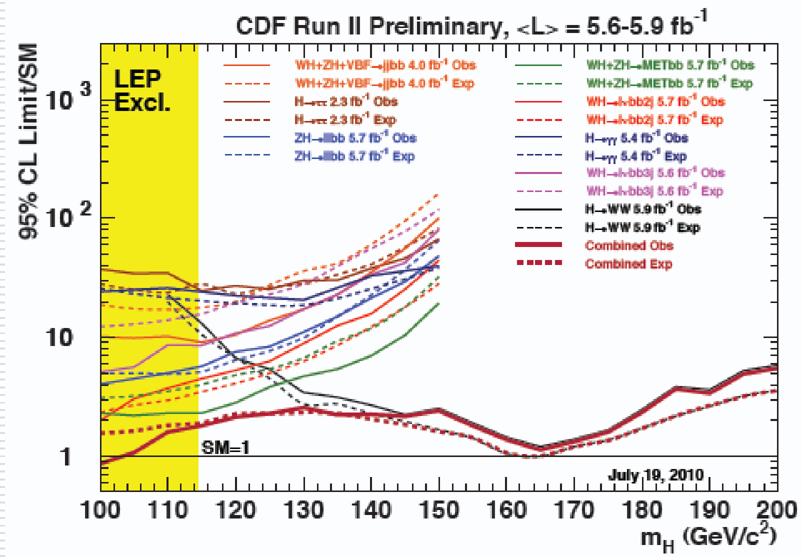
Do we need update of Tev4LHC plots?



Higgs Searches

Updated





➡ Need reliable predictions for many channels

Many tools available

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

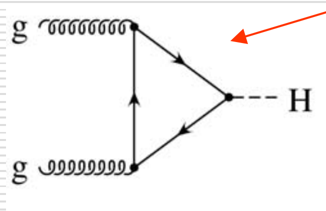
Plea to experimentalists: Help theorists make their tools useful!

[Tanaka]

SM calculations in great shape

- Dominant production mode is gg→h

t,b



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

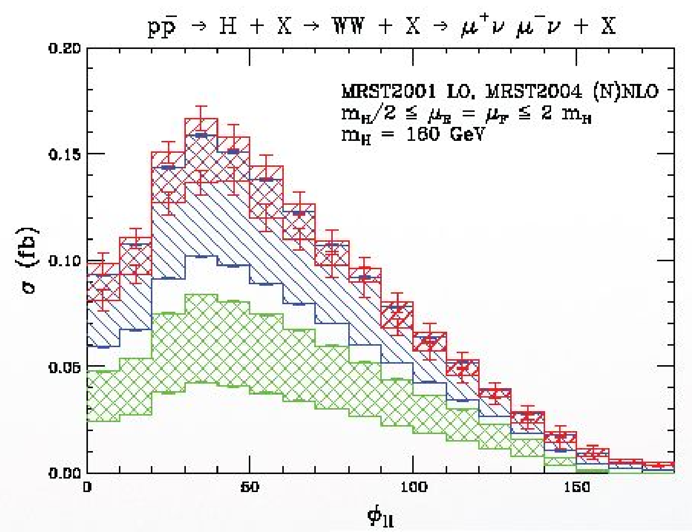
Precise predictions needed for error estimates

[Anastasiou]

gg→ h

- Fully differential NNLO rates

Anastasiou, Melnikov, Petriello



The issues:

How to chose central scale / scale variation?

How to combine PDF & scale uncertainties?

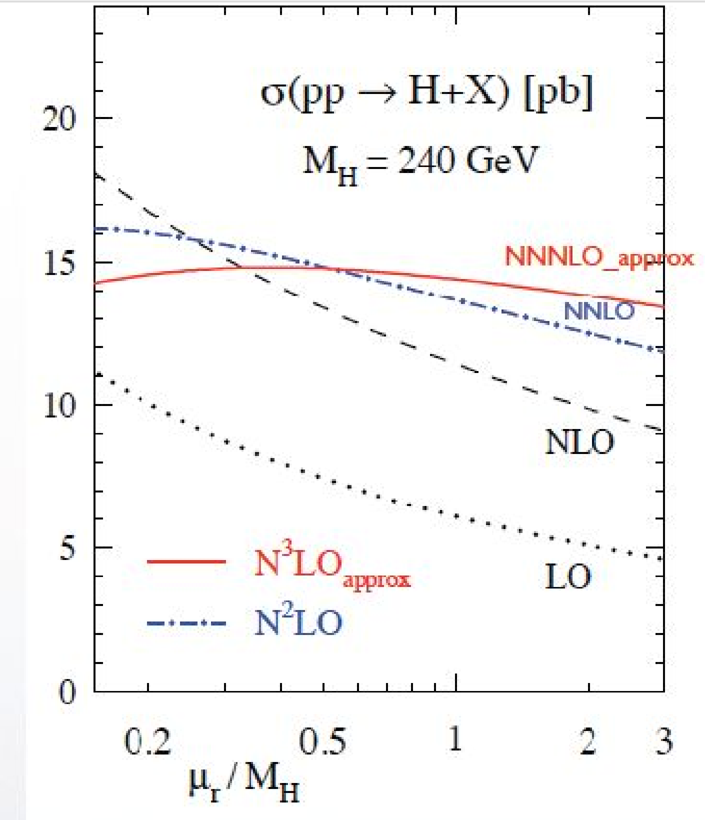
$$\sigma(M_h = 165\,GeV)_{Tevatron} = 389.0\ fb\ ^{+8.1\%}_{-11.7\%}\ (scale)\ ^{13.6\%}_{-12.0\%}\ (\alpha_s + PDF)$$

Similar size

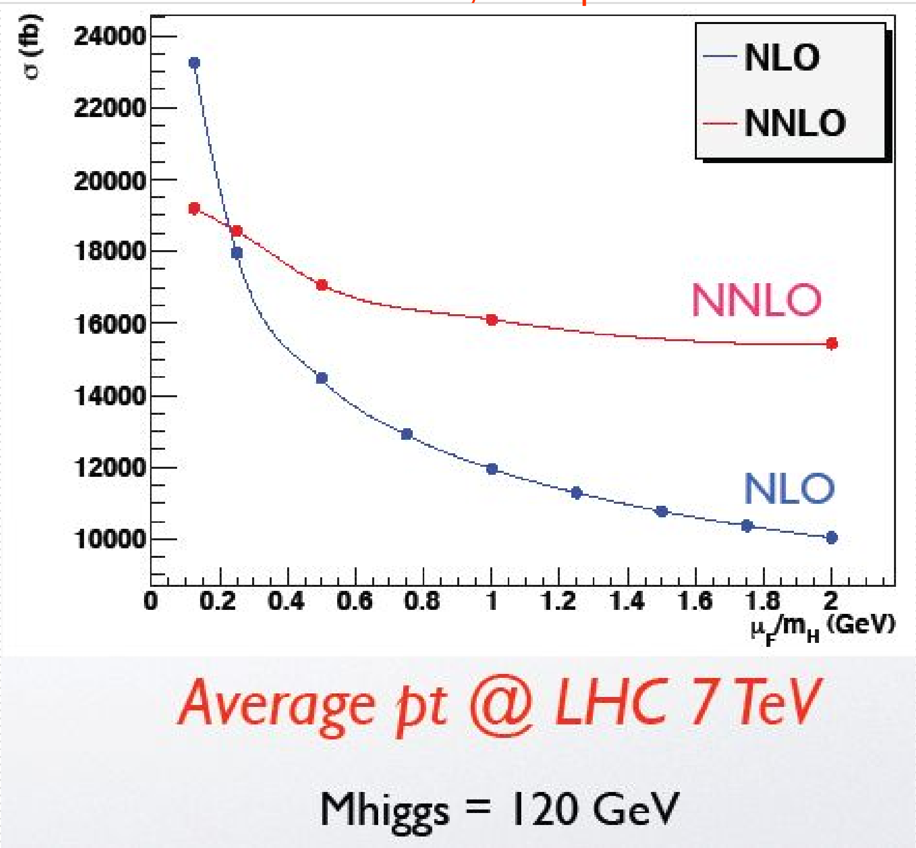
[Anastasiou]

Small scale gives better convergence

Moch and Vogt

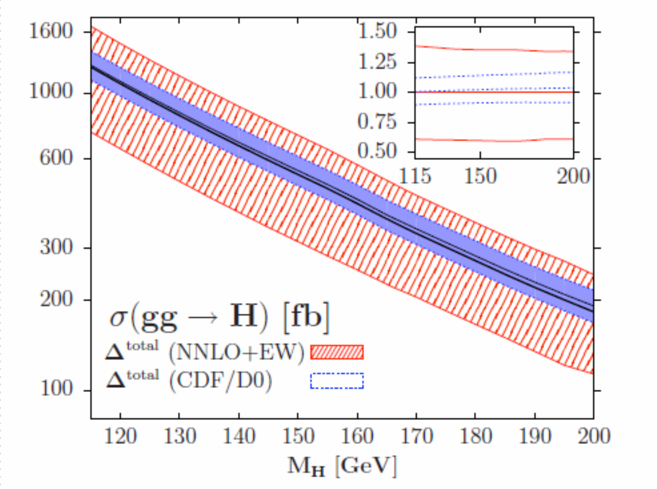


Anastasiou, Lazopoulos



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 uncertainty, along with larger variation of scale, $m_h/3 < \mu < 3m_h$



Tevatron

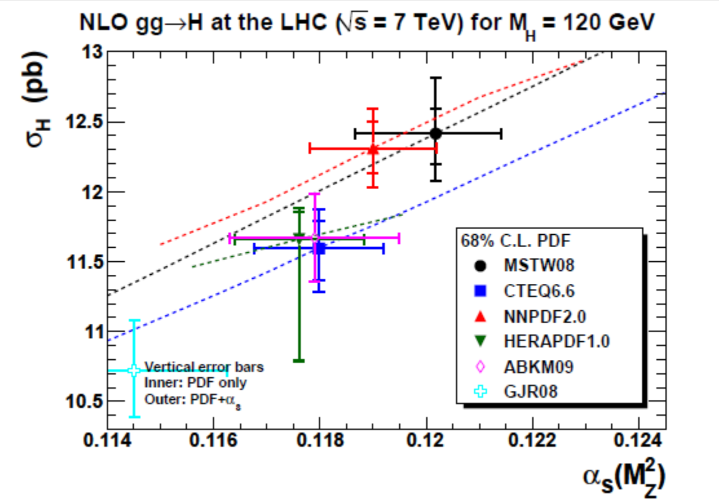
Tevatron assumes ±17.5% theory uncertainty on gg→h

[Baglio]

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

Differences not just α_s

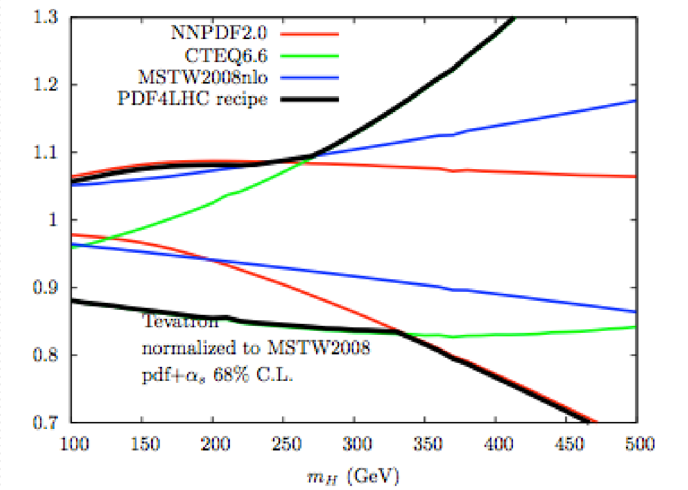


[Thorne]

Higgs Cross Section Working Group

- Attempt to clarify uncertainties on Higgs rates
- Total rates now; differential rates with cuts coming
- Working towards ATLAS/CMS combination

PDF4LHC recipe for NLO gg→h

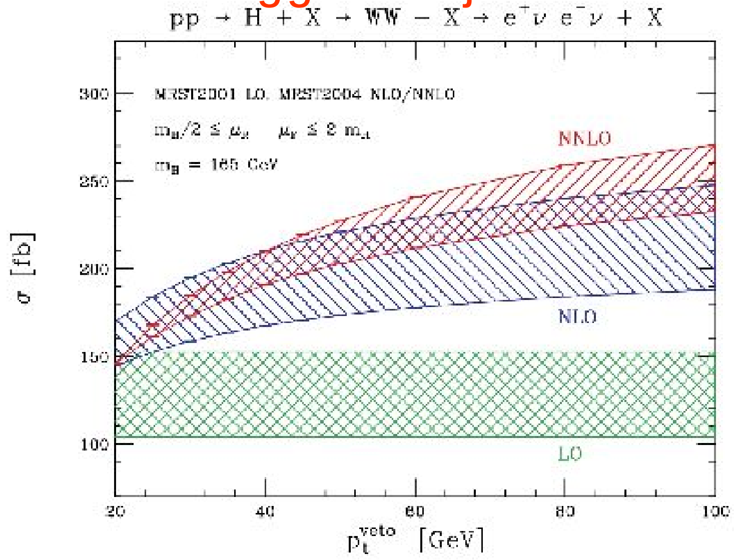


[Mariotti]

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

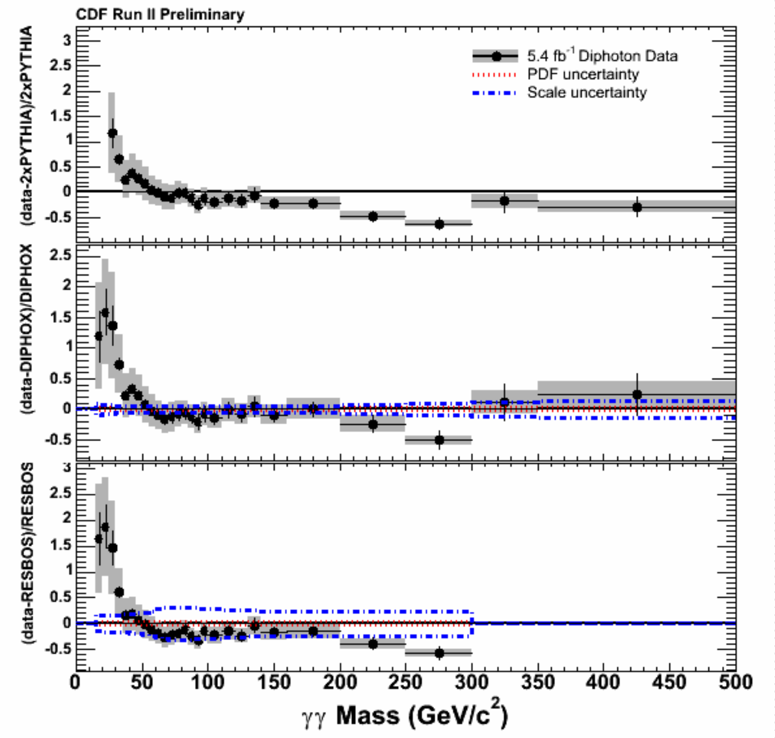


Theory uncertainties depend on cuts & binning

[Anastasiou]

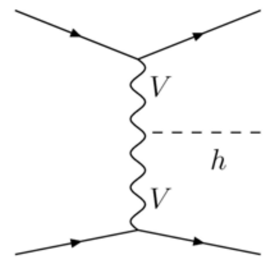
h→γγ: Discovery channel for light Higgs

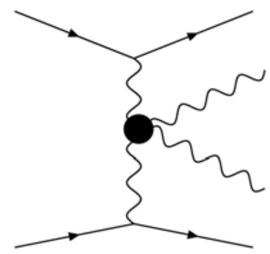
- Single γ production: experiment/theory differences seem to be sorted out
- Understanding double photon production necessary before Higgs discovery
  - Low γγ differences could be theory/experiment miscommunication about isolation cuts



Vector Boson Fusion

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



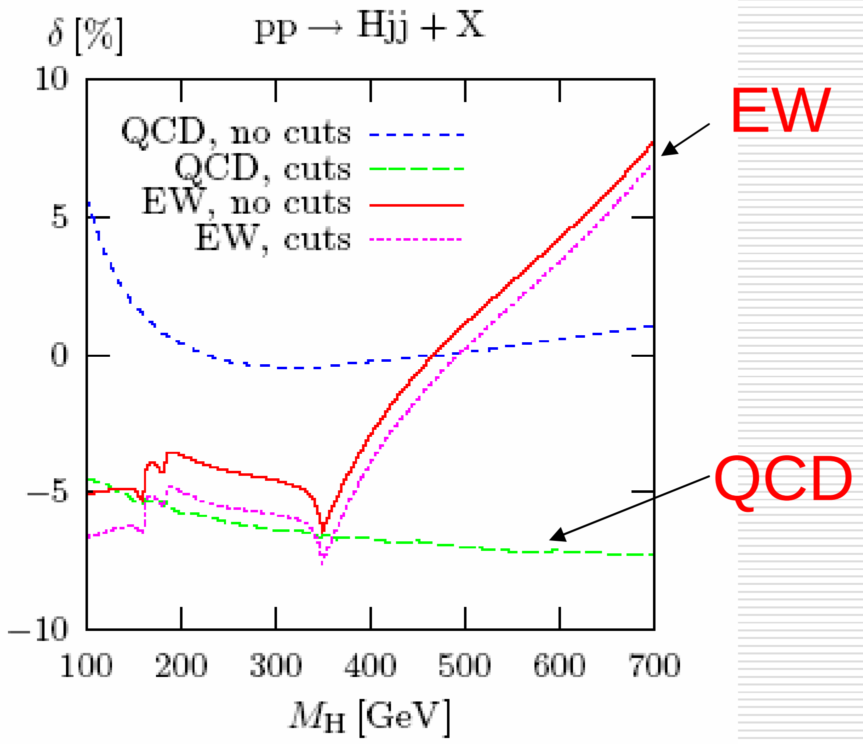


[Dittmaier]

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

Ciccolini, Denner, Dittmaier

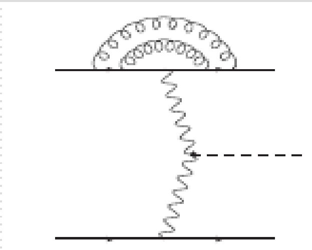


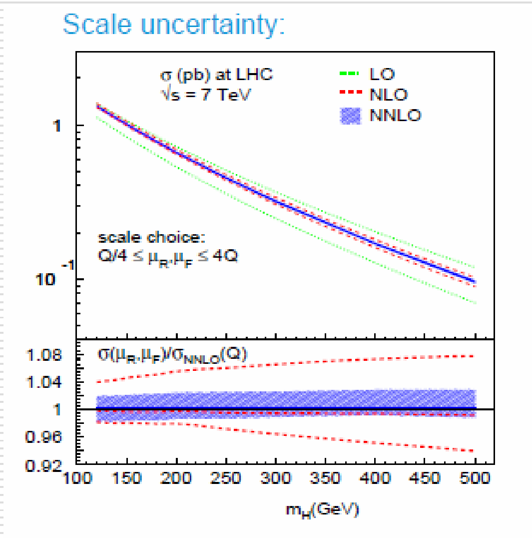
[Dittmaier]

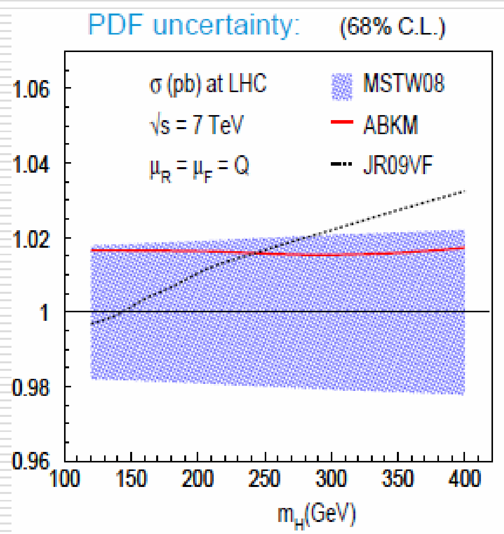
VBF at (partial) NNLO

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

Bolzoni, Maltoni, Moch, Zaro







→ Scale uncertainty ~ PDF uncertainty ~ 2%

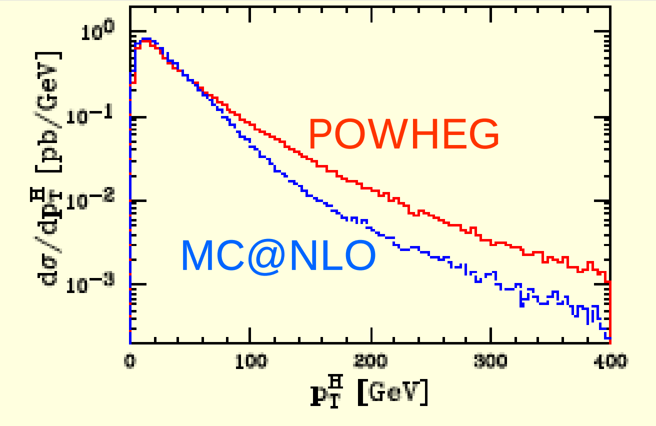
Interface with NLO Monte Carlos

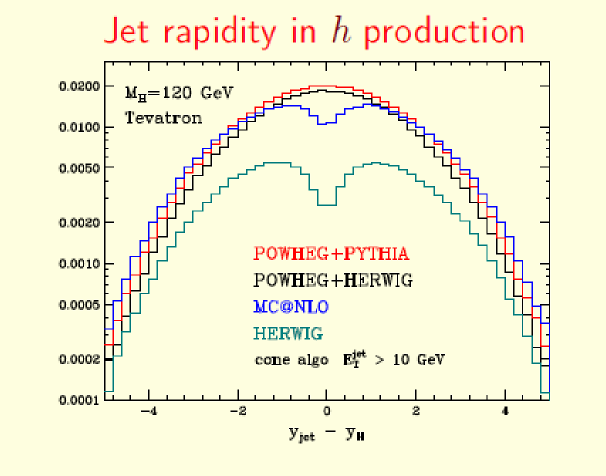
- Only 2 NLO MCs: POWHEG & MC@NLO
  - Hardest jet with LO accuracy, other jets generated by shower in collinear/soft approximations
- MC@NLO tied to HERWIG
- POWHEG
  - Can switch shower models
  - No issues with incomplete cancellations of higher order effects
  - Automation: new processes should be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

[Nason]

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)



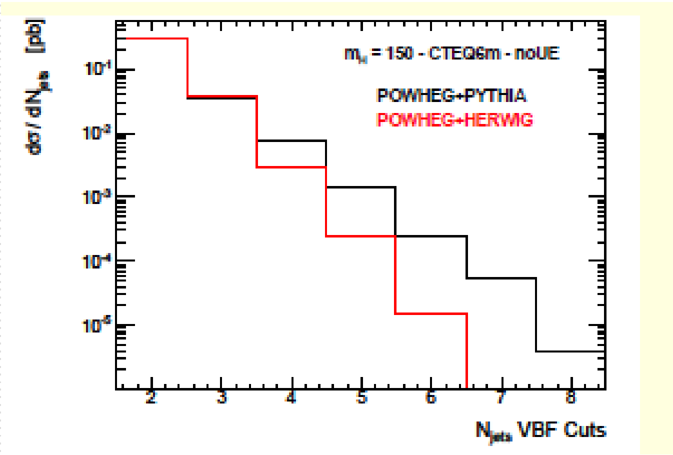


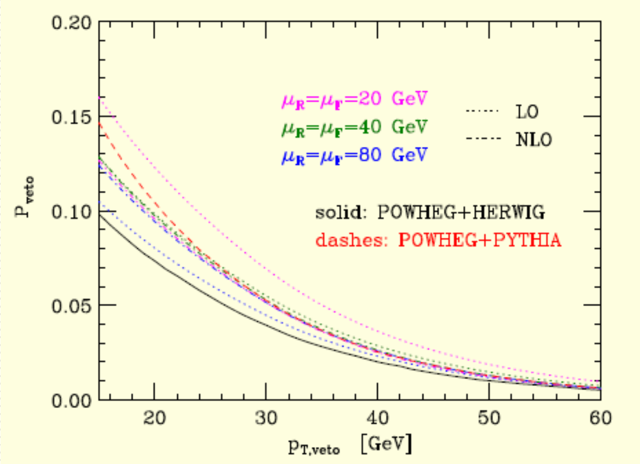
→ Differences understood

[Nason]

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]

Step 2: Extract parameters

- Measure couplings to fermions & gauge bosons

$$\frac{\Gamma(h \to b\overline{b})}{\Gamma(h \to \tau^+\tau^-)} \approx 3\frac{m_b^{\ 2}}{m_\tau^{\ 2}}$$

- Measure spin/parity

$$J^{PC} = 0^{++}$$

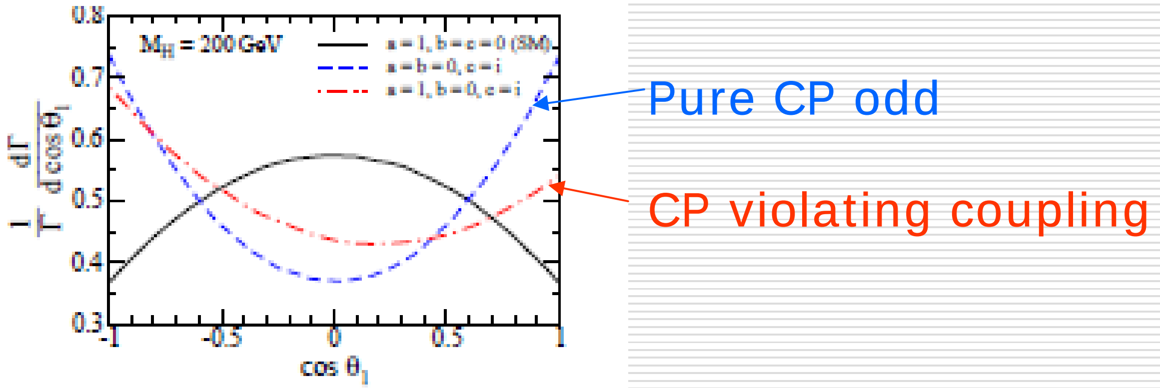
- Measure self interactions

$$V = \frac{M_h^{\ 2}}{2}h^2 + \frac{M_h^{\ 2}}{2v}h^3 + \frac{M_h^{\ 2}}{8v^2}h^4$$

← Need good ideas here!

CP Higgs Studies

- Study CP of spin-0 particle in model independent way
- Simple observables sensitive to spin
  - Differential width for $h \rightarrow ZZ \rightarrow 4f$
  - Depending on parameters need~100 fb^{-1}



[Godbole]

Determining Spin/Parity

- Suppose we find a resonance $X \rightarrow ZZ \rightarrow l^+l^-l^+l^-$
  - What is it?
- Helicity amplitudes with most general ZZX couplings for X= spin 0,1,2
- Amplitude depends on 5 angular variables
- Can distinguish between various spin parity assumptions with small number of events
  - Monte Carlo simulation of signal/background with detector effects
  - For M_h=250 GeV and 30 signal events (corresponds to 5 fb^{-1} for SM rate), have 4σ discrimination between 0^+ and 0^-

[Tran]

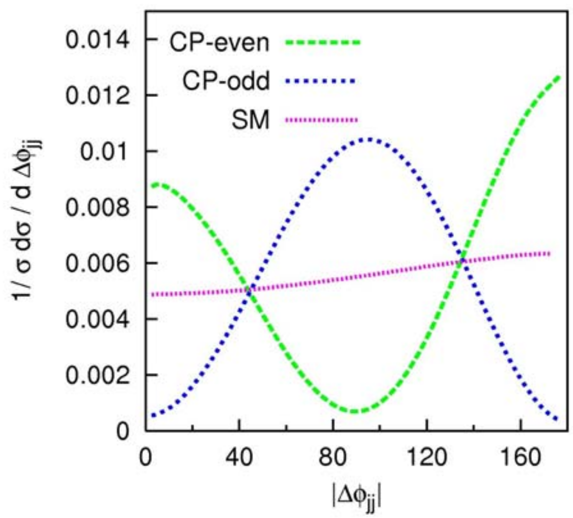
Is *the Higgs* a Scalar?

- VBF sensitive to HVV tensor structure

$$T^{\mu\nu} = c_1 g^{\mu\nu} + c_2 \left(p_1 \cdot p_2 g^{\mu\nu} - p_1^{\ \mu} p_2^{\ \nu} \right) + c_3 \varepsilon^{\mu\nu\alpha\beta} p_{1\alpha} p_{2\beta}$$

SM CP even CP odd

Hankele, Klamke, Zeppenfeld, Figy

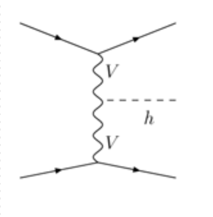


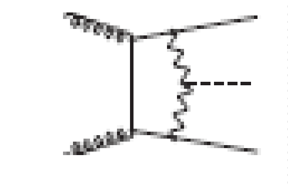
Azimuthal angle between tagging jets

[Dittmaier]

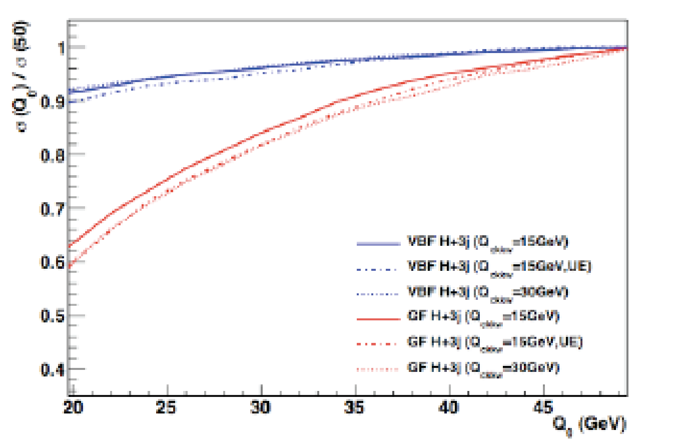
Higgs couplings from VBF

- Signal: VBF, $h \to \tau\tau$
- Idea: vary central jet veto scale to extract gg and VBF separately
- Large theoretical uncertainty in normalization & shape of gg rate



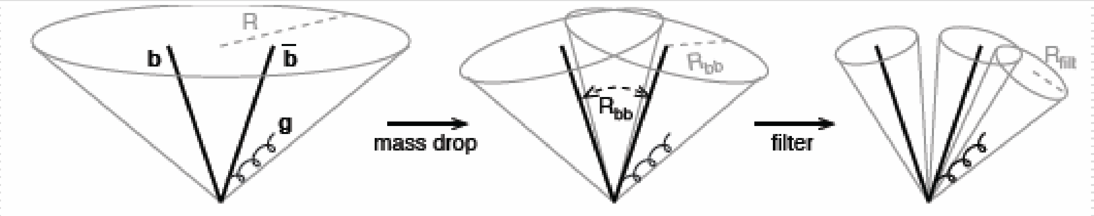


60 fb^{-1} gives ~ 30% measurement of VBF couplings



Jet Substructure

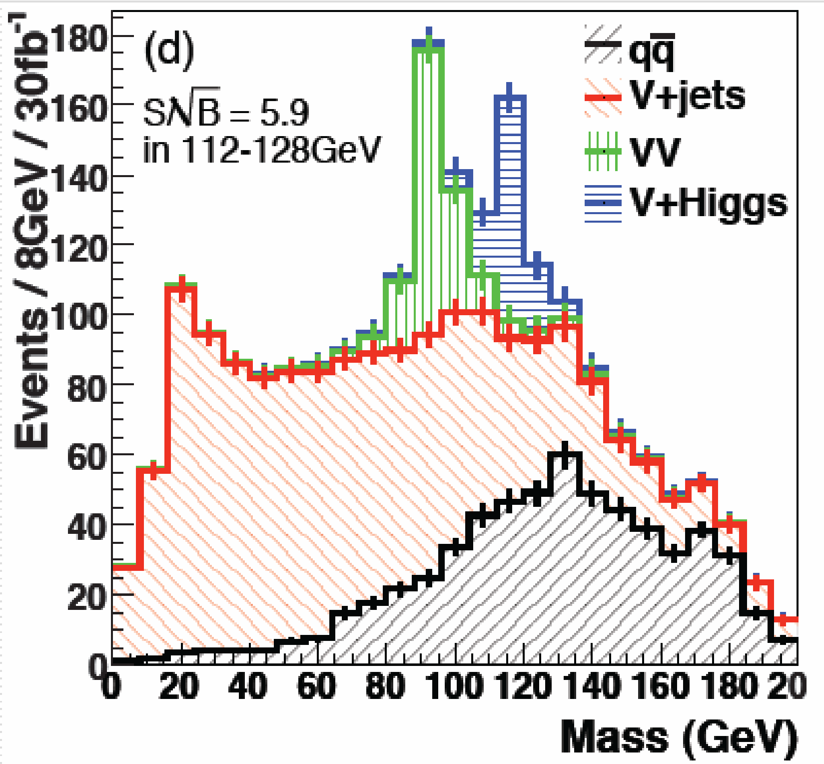
- At LHC energy, electroweak scale physics (W,Z,h,t) inside jets
  - Distinguish between QCD generated jets and those due to heavy object decays
  - Algorithms for unclustering jets
  - Apply technique to Wh, Zh, $h \rightarrow bb$
    - Important to get y_b
  - Require h & V have high p_T (>200 GeV)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

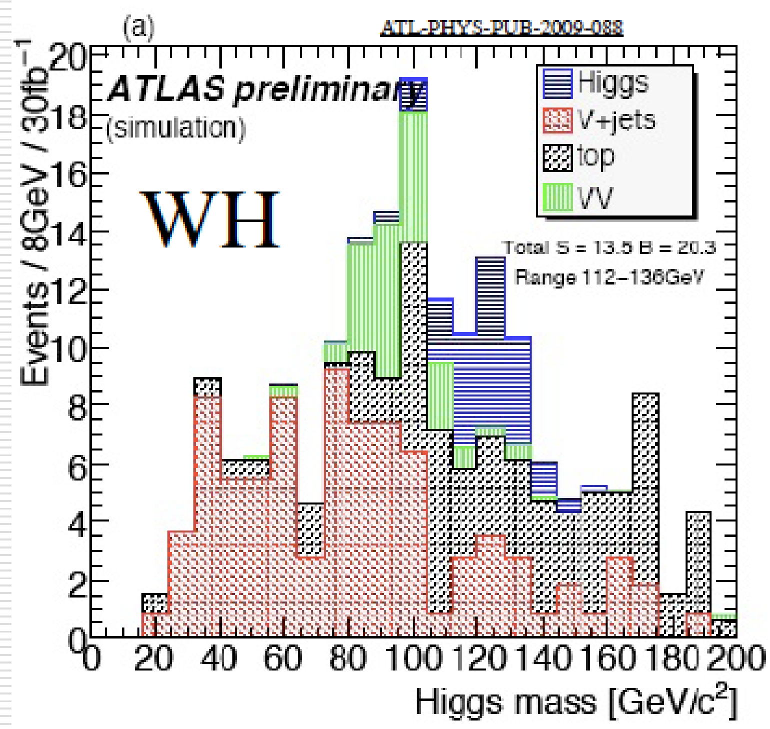


[Butterworth]

Subjets and Vh, h→bb

Butterworth, Davison, Rubin, Salam





3.5 σ, 30 fb^{-1}, 14 TeV

[Butterworth]

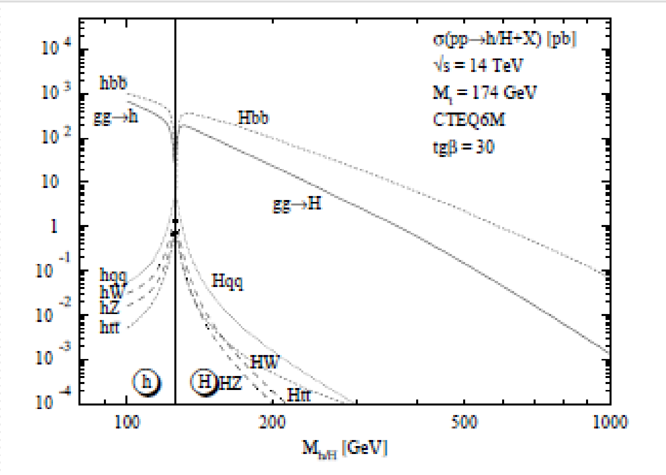
Many alternatives to SM

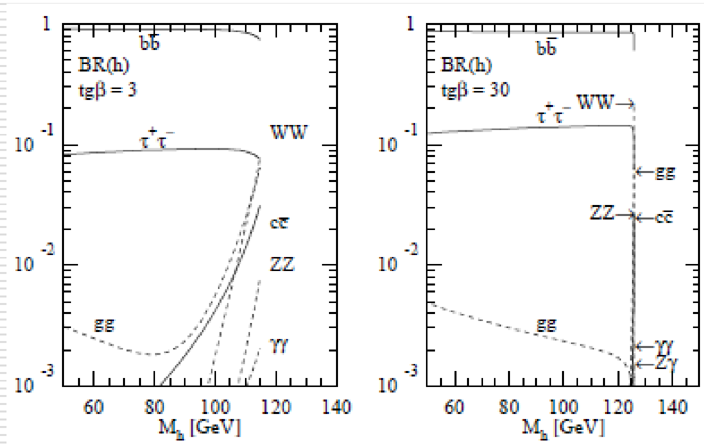
- MSSM
  - A favorite
  - Still a lot of work to do to have reliable predictions
- Multi-Higgs
  - NMSSM has 1 extra chiral superfield
- Higgsless
- Composite Higgs
- TBD....

Requires > 100 fb^{-1} (Higgsless, Composite Higgs)

MSSM

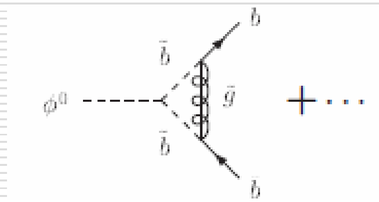
- 5 Higgs bosons. h, H, A, $H^{\pm}$
- Rates affected by change in couplings
  - For tan β > 10, largest rate is bbϕ at LHC
  - Need NLO generator for bbϕ
  - h decays 90% to bb, 10% to $\tau^+\tau^-$





MSSM & Tevatron Limits

- bb→ϕ→$\tau^+\tau^+$ (NNLO QCD)
  - MSSM corrections included using Δm_b approximation
  - Resums large effects to get effective couplings
  - Accurate to < 1%



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

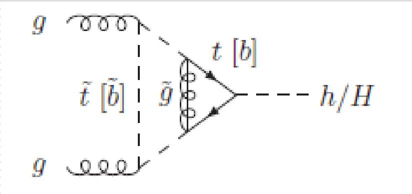
$$\Delta m_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}})$$

- bg→ϕb→$\tau^+\tau^-$b, bbb (NLO QCD)
  - bbϕ vertex corrections included in Δm_b approximation
  - Remaining squark/gluon loop contributions neglected in limits
    - O(±20%) for m_{SUSY}~500 GeV

[Spira]

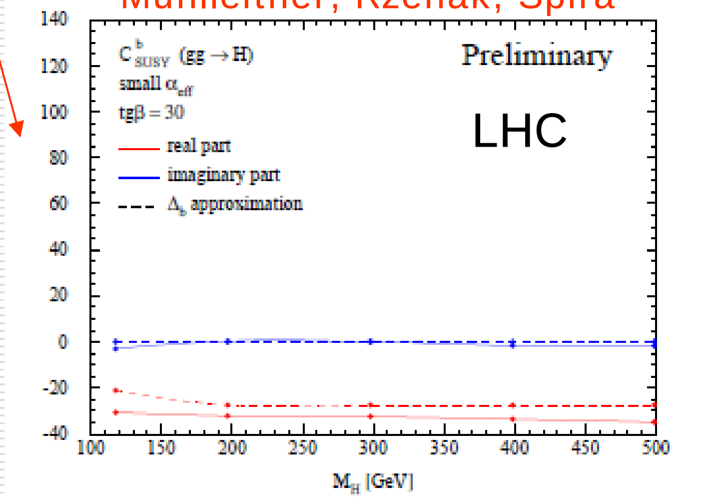
MSSM Higgs production rates

- Squark/gluino loops important for $gg \to \phi$
  - Rate significantly reduced

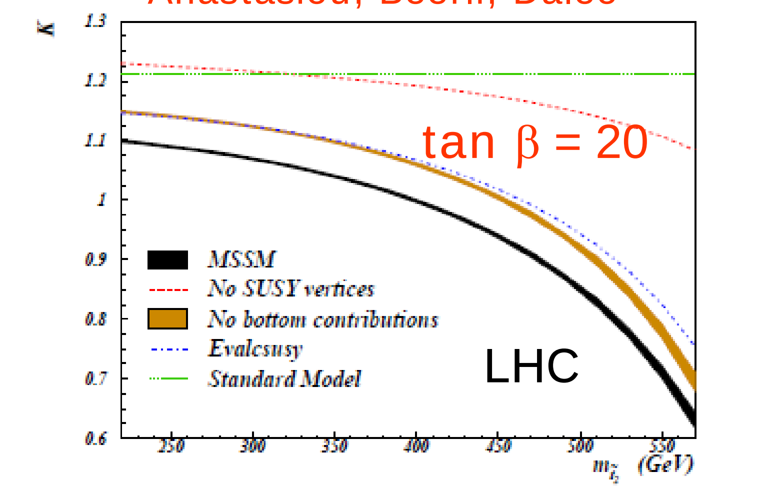


SQCD corrections
(relative to LO b loop)

Muhlleitner, Rzehak, Spira



Anastasiou, Beerli, Daleo



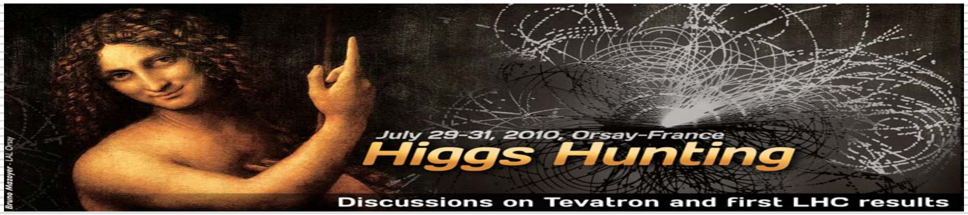
[Spira]

NMSSM

- Add gauge singlet superfield
  - Rich phenomenology: 3 neutral Higgs, 2 pseudoscalars, 5 neutralinos
- Severely limited by ALEPH/B physics/Tevatron Higgs limits
  - Some regions allowed where lightest neutralino can be dark matter
  - New signature: $h \rightarrow aa$

[Gunion]

Conclusions



- ***Thanks to the organizers!***
  - Theory/experimental dialog critical
  - Theory calculations for Higgs signal under excellent control for SM
    - Still need work on theoretical uncertainties on background
  - Need to come to consensus about treatment of theoretical uncertainties
    - Higgs cross section working group can do this!
  - BSM scenarios need more work