Electroweak Symmetry Breaking at the Terascale

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October, 2008

XIII Mexican School of Particles and Fields

The Standard Model is Phenomenally Successful

- SM breaks electroweak symmetry and generates mass for the W and Z with a single scalar doublet, Φ

$$V = \lambda\left(\left|\Phi^{+}\Phi\right| - v^{2}\right)^{2}$$

$$\lambda = \frac{M_h^2}{2v^2}$$

$$v = \left(\sqrt{2}G_F\right)^{-1/2}$$

- Minimal approach
- Higgs couplings to fermions and gauge bosons fixed in terms of masses

EW Measurements test SM

We have a model….
And it works to the
1% level

- Consistency of precision measurements at multi-loop level used to constrain models with new physics

This fit ASSUMES SM

Higgs Couplings Fixed

- Standard model is chiral theory
  - t_L is SU(2) doublet, t_R is SU(2) singlet
- Quark and lepton masses are forbidden by SU(2) x U(1) gauge symmetry
  - Mass term connects left and right-handed fermions: $L \approx m \bar{f}_L f_R$
  - SU(2) Higgs allows gauge invariant coupling

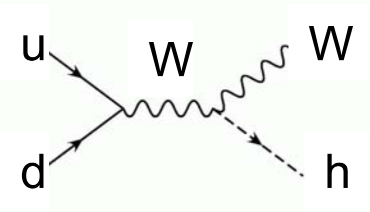
$$L \approx \frac{m_f}{v} \bar{f}_L \Phi f_R$$

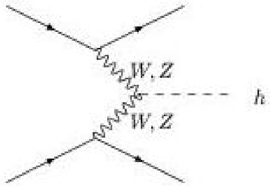
Gauge Higgs Couplings

- Higgs couples to gauge boson masses

$$\left(D_\mu \Phi\right)^{+}\left(D_\mu \Phi\right) \rightarrow \left(\frac{gv}{2}\right)^2 W^{+\mu} W_\mu^{-}\left(1+\frac{h}{v}\right)+\ldots.$$

- WWh coupling vanishes for v=0! Tests the connection of M_W to non-zero VEV





No Experimental Evidence for Higgs

- SM requires scalar particle, h, with unknown mass
  - M_h is ONLY unknown parameter of EW sector
- Observables predicted using: M_Z, G_F, α, M_h
- Higgs and top quark masses give quantum corrections:

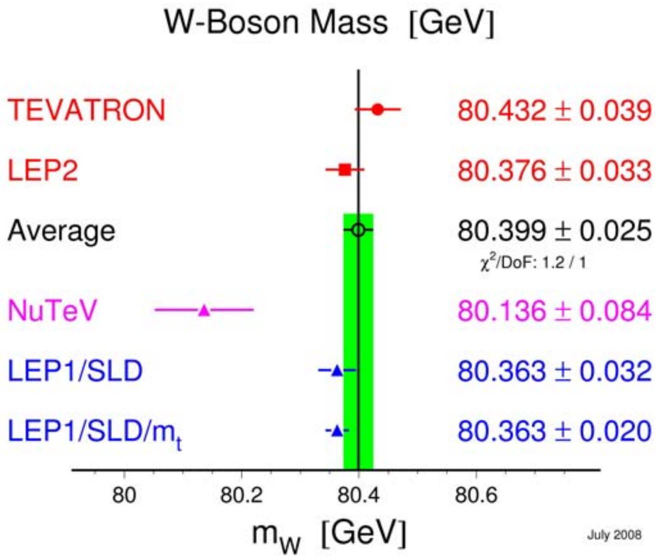
  $\approx M_t^2, \log(M_h)$

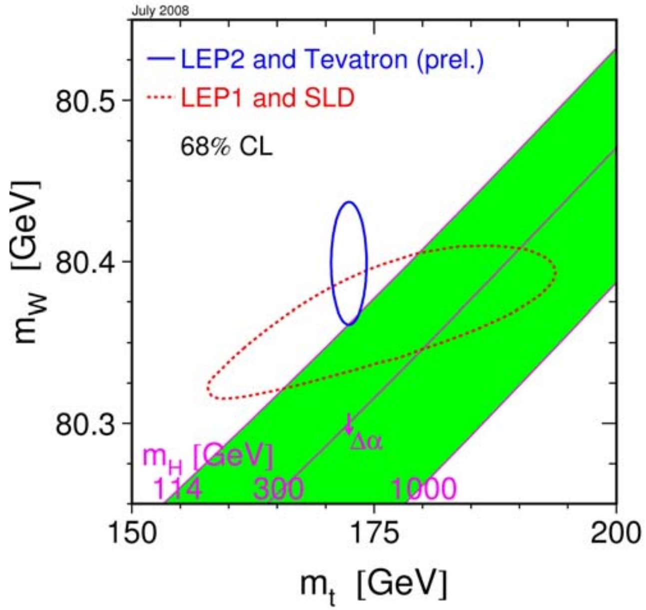
Everything is calculable….***testable theory***

Understanding Higgs Limit

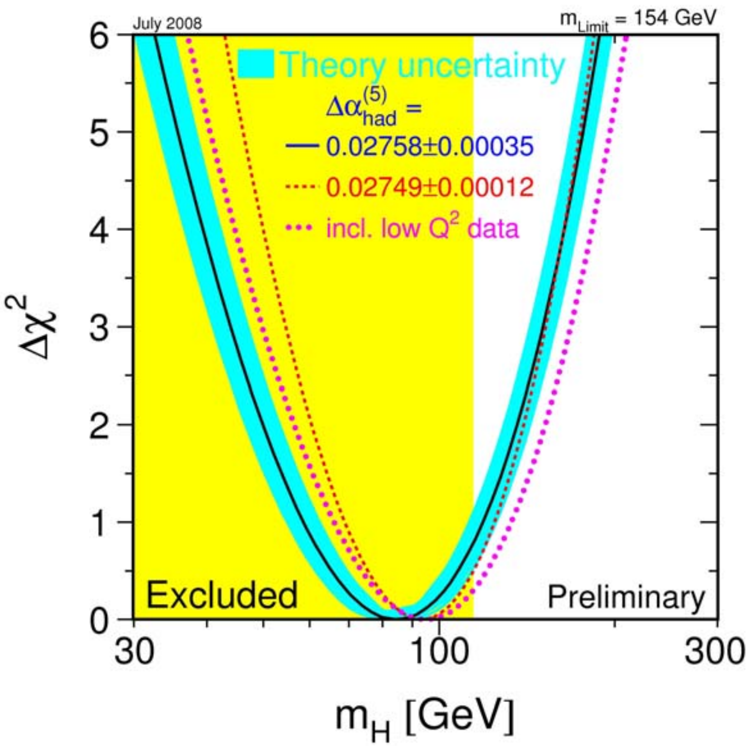
Theory: Input M_Z, G_F, α

$\rightarrow$ Predict M_W





Precision Measurements Limit M_h

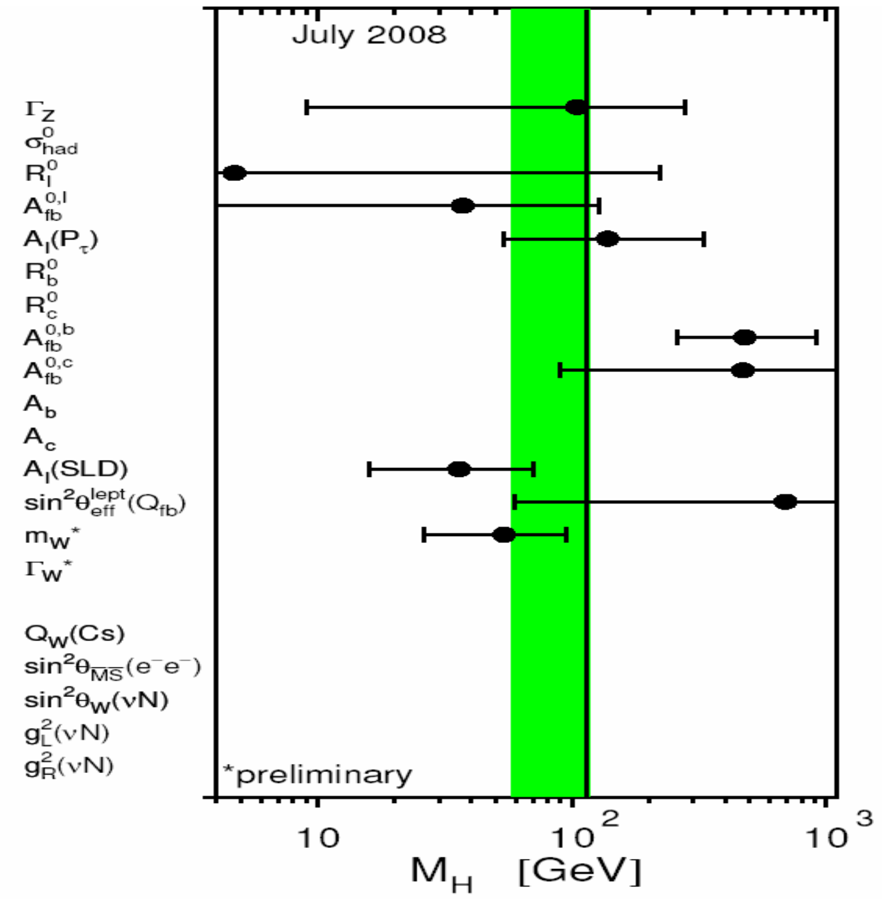


- LEP EWWG (July, 2008):
  - M_t=172.4 ± 1.2 GeV
  - M_h=84^{+34}_{-26} GeV
  - M_h < 154 GeV (one-sided 95% cl)
  - M_h < 185 GeV (Precision measurements plus direct search limit)

Best fit in region excluded by direct searches

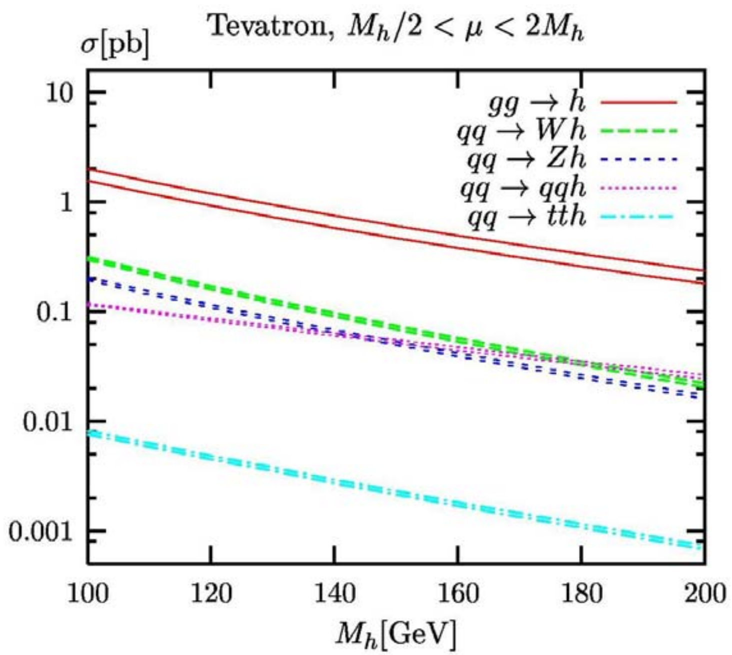
Higgs Mass From Individual Measurements

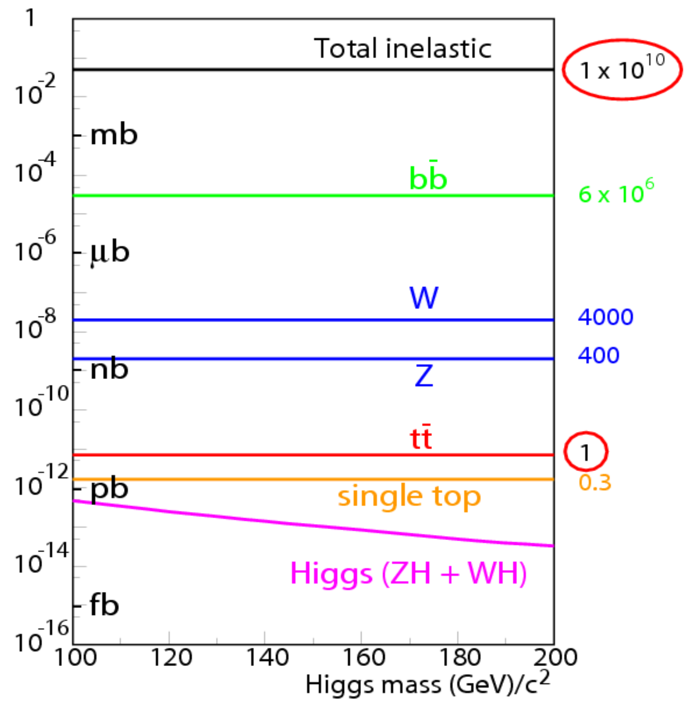
Consistent?



LEPEWWG

Higgs at the Tevatron



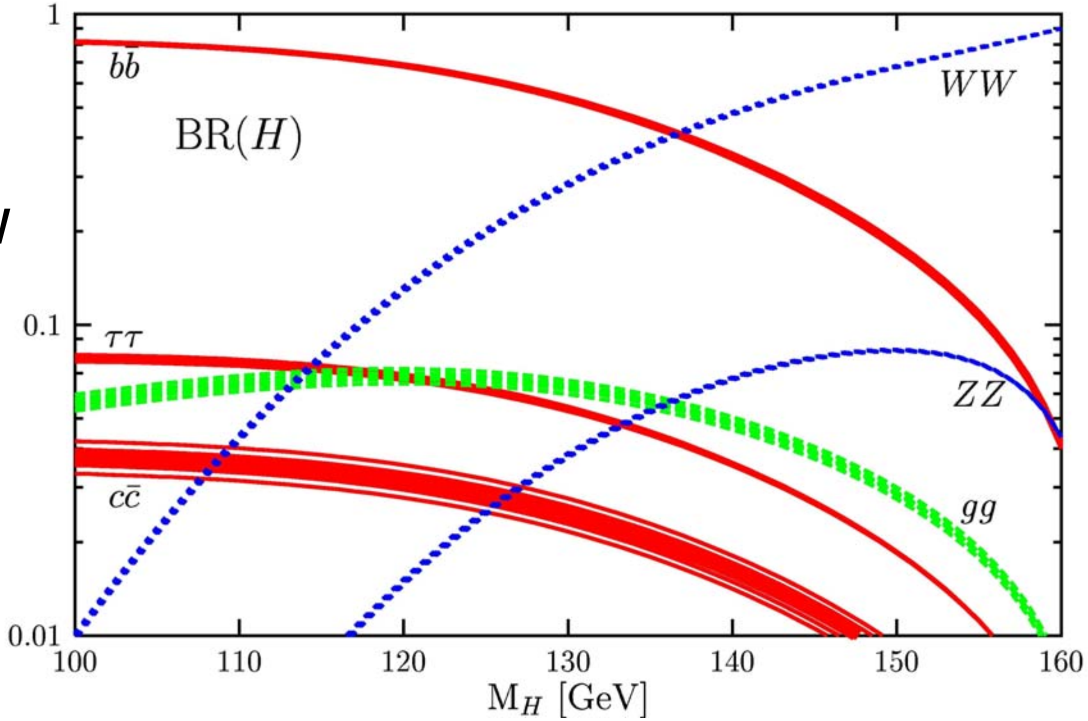


NNLO or NLO rates

$M_h/2 < \mu < M_h/4$

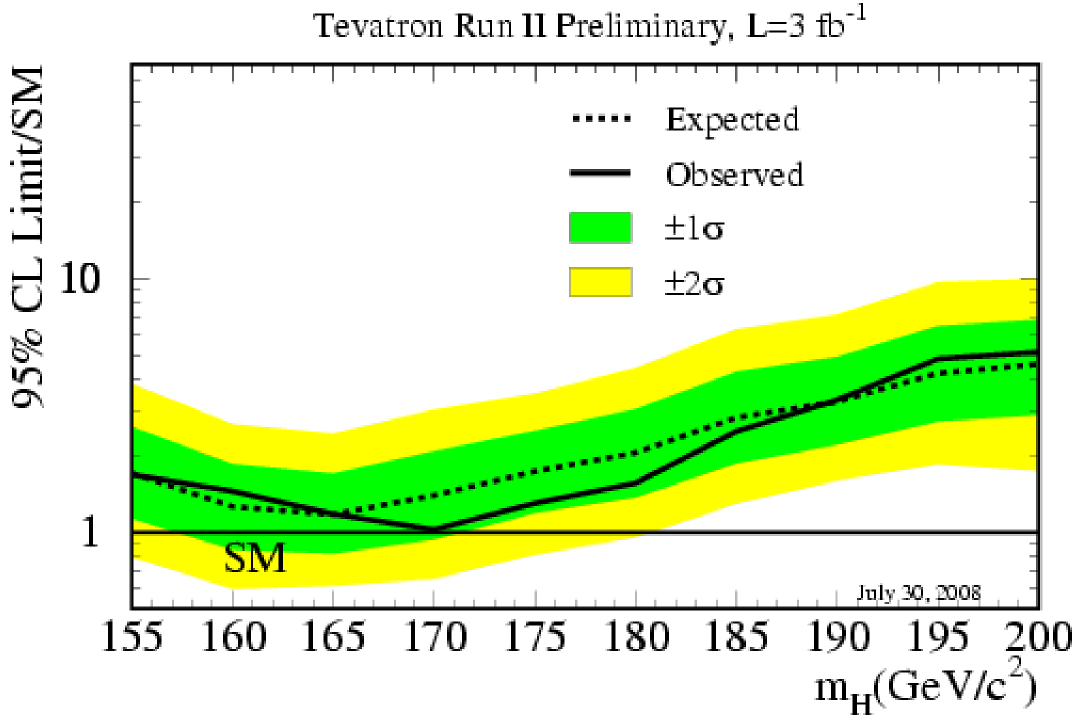
Higgs Branching Ratios

Use $q\bar{q} \rightarrow Vh$, $h \rightarrow b\bar{b}$ at low Higgs mass



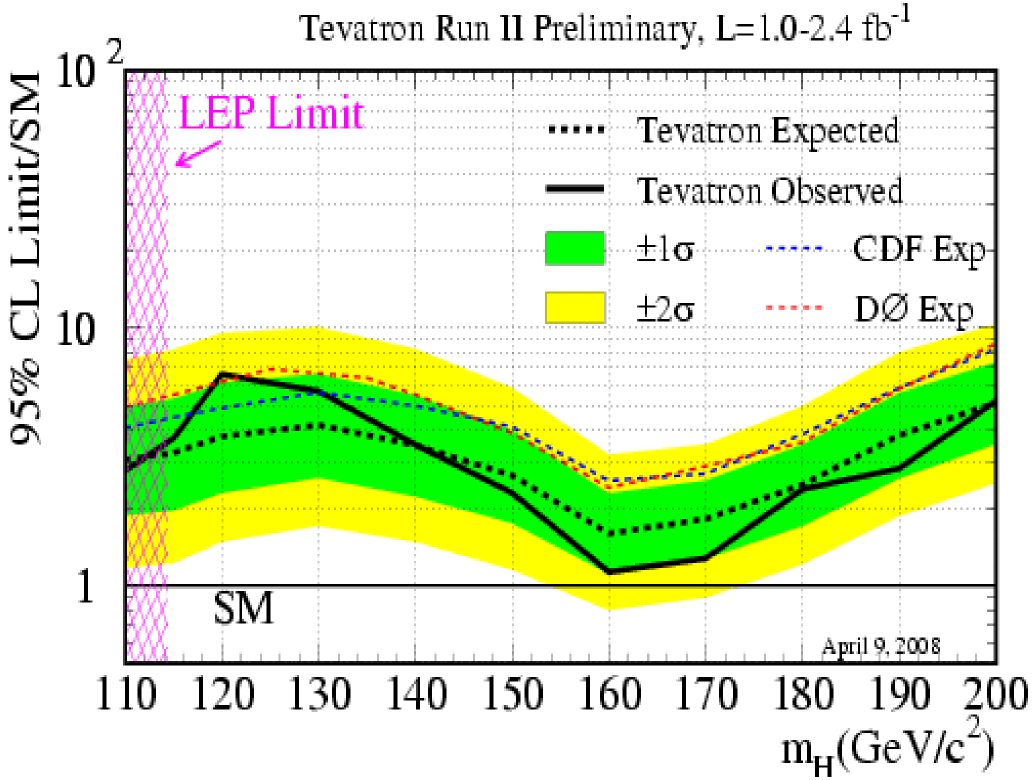
Use $gg \rightarrow h$, $h \rightarrow WW$ at high Higgs mass

SM Higgs Searches at Tevatron



95% CL exclusion of SM Higgs at 170 GeV

SM Higgs Searches at Tevatron

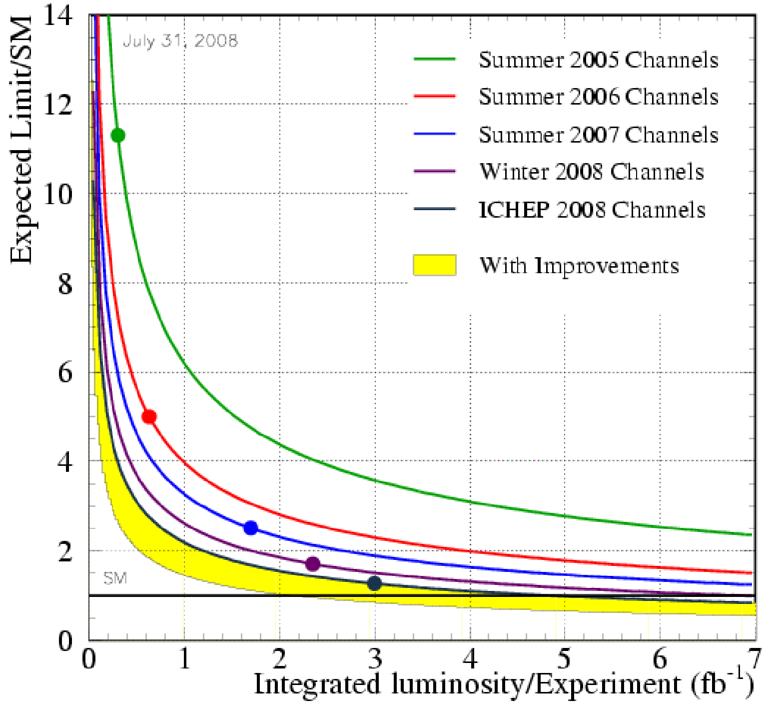


CDF/D0 combination with 3 fb^{-1} coming.

Expected sensitivity < 3 x SM @ M_h=115 GeV

Will Fermilab find the Higgs?

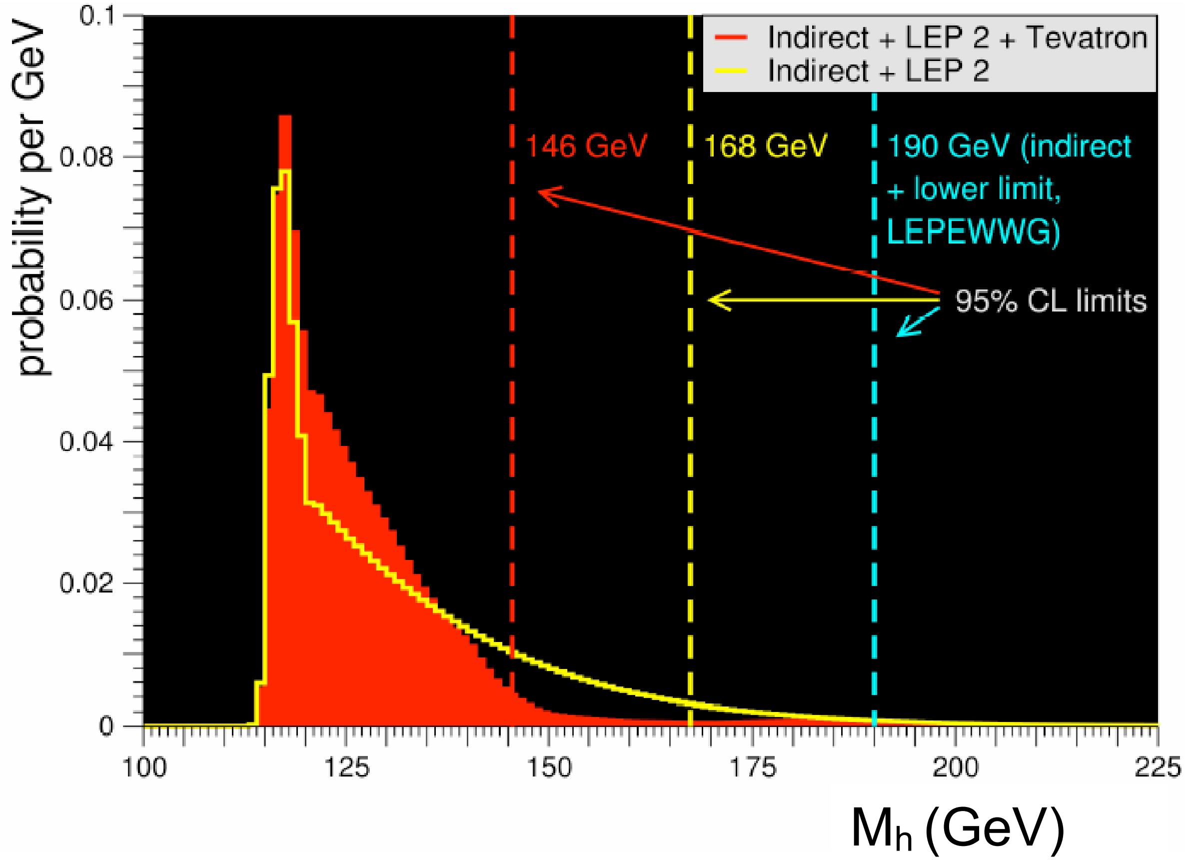
M_h=160 GeV



- ➢It's not just luminosity

Herndon, ICHEP 2008

Tevatron Results Starting to Limit M_h



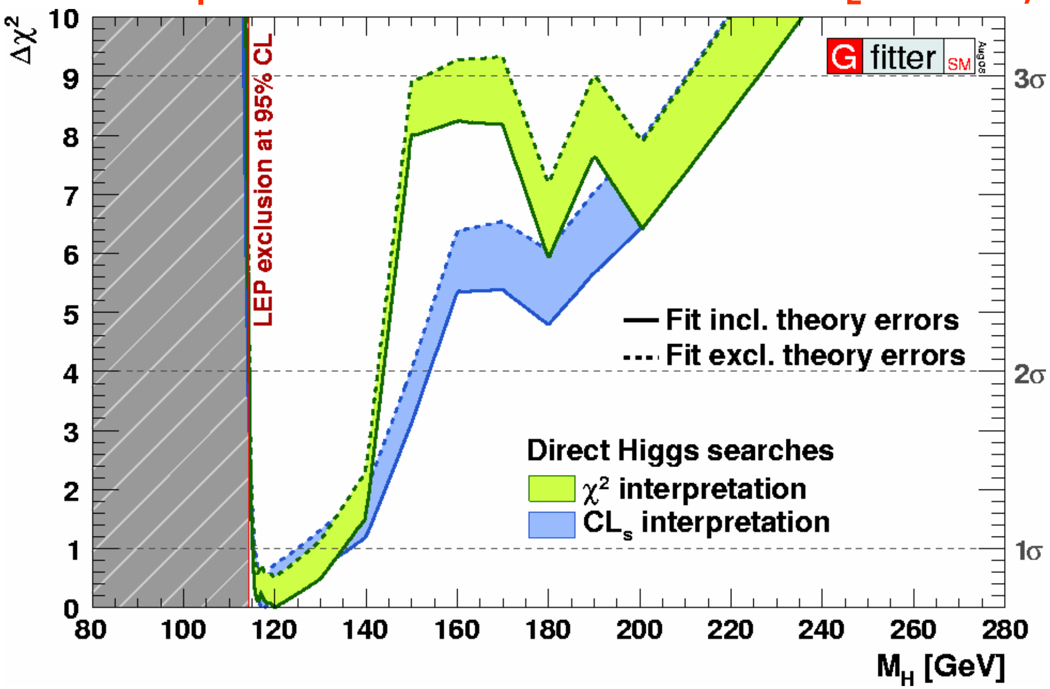
Erler, ICHEP08, arXiv:0809.2366

Tevatron Limits Have Impact on M_h

Higgs limit including Tevatron and LEP direct search:

- χ^2 2σ interval: [114.4, 144] GeV

CL_S-like interpretation 2σ interval: [114.2, 154] GeV

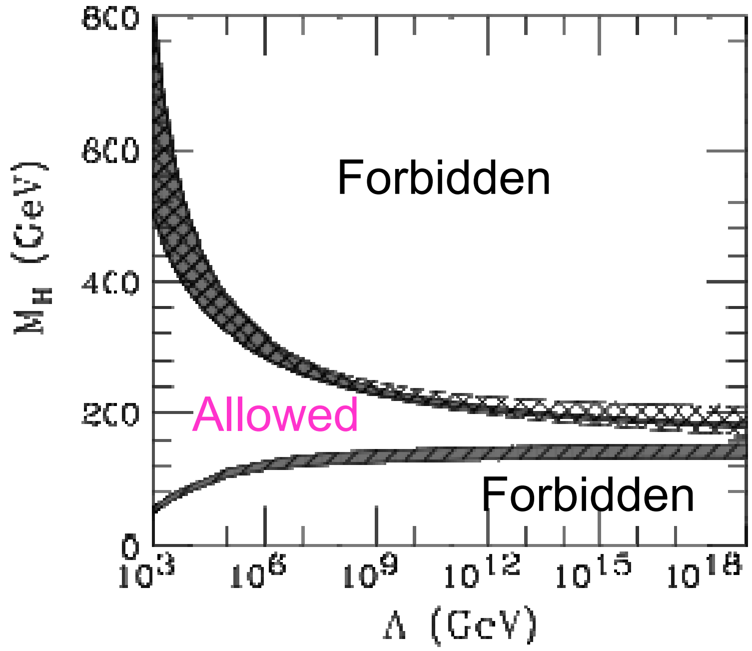


Haller, ICHEP08, Gfitter analysis

Light Higgs Theoretically Attractive

- Extrapolate Higgs potential to high scale Λ

$$V = \lambda\,(\Phi^{+}\Phi - v^{2})^{2}$$



- Standard Model is only consistent to Planck scale for 130 GeV < M_h < 180 GeV

- Heavy Higgs implies new physics at some low scale

The signs

- All the evidence points towards a light Higgs boson
  - Consistency of precision EW measurements with measured M_W and M_t
  - Theoretical prejudices also suggest that if there is a SM Higgs boson, it will be light
- Will we find it at the LHC?

Eagerly Awaiting the LHC

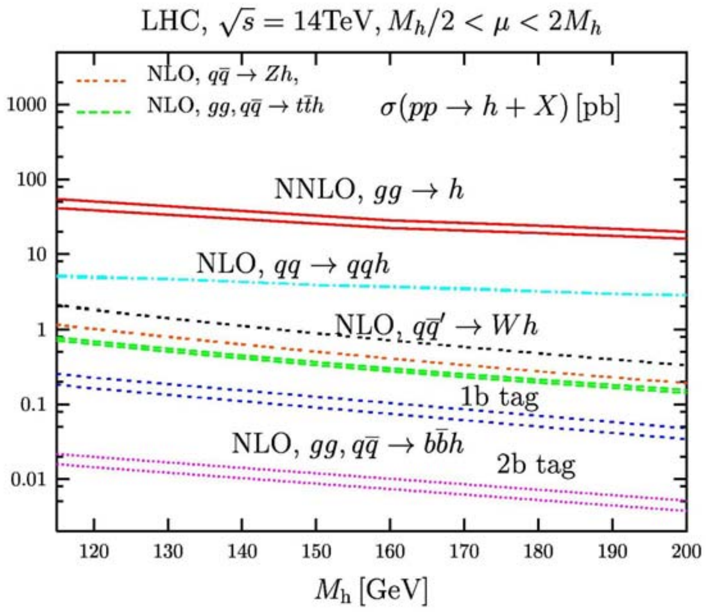
- Sept 10, first particles injected in LHC
- Collisions in spring, 2009
- What can we learn from early data sets? (10 fb^{-1})

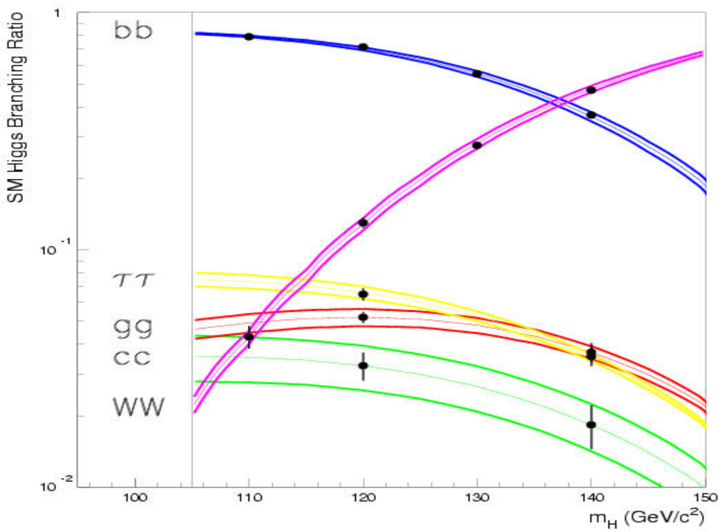
LHC Higgs Theory Challenges

- Precise predictions for Higgs production & backgrounds
- Understanding uncertainties on predictions
  - PDFs, scale uncertainties, model dependence
- Implementing NLO/NNLO in useful Monte Carlo programs
  - Including distributions
- Can we distinguish the Standard Model Higgs from all other possibilities?

Tremendous progress on all these fronts

Large Rates for Higgs at the LHC

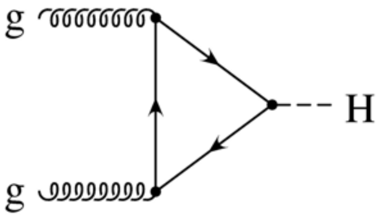




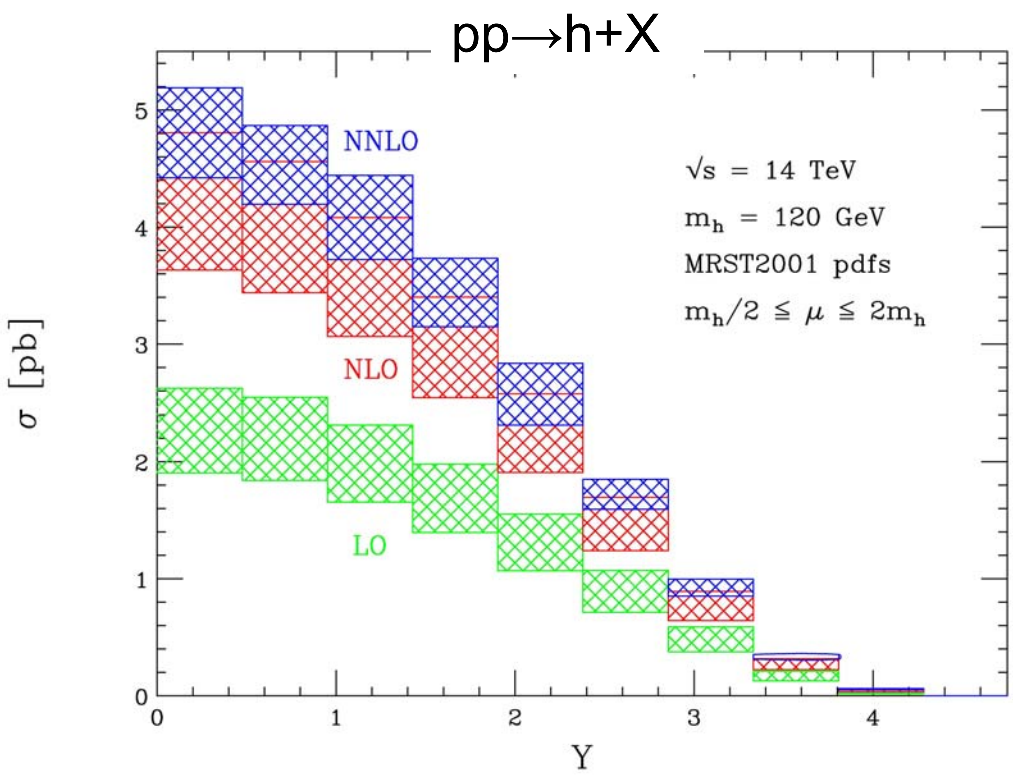
- ➢ Total cross sections known to NLO or NNLO

Production Mechanisms in Hadron Colliders

- Gluon fusion
  - Largest rate for all M_h at LHC and Tevatron
  - Rate known to NNLO in large M_t limit
    - Effect is 15-20% for $M_h < 200$ GeV
  - Soft gluon resummation increases rate +6%
  - EW 2-loop effects increase rate 5-8%



Need to go beyond Total Cross Sections



- ➢ Higgs production from gluon fusion known at NNLO, including some distributions and summation of large logarithms

Our estimates of scale dependence are inadequate

Anastasiou, Dixon, & Melnikov, hep-ph/0211141, hep-ph/0501130

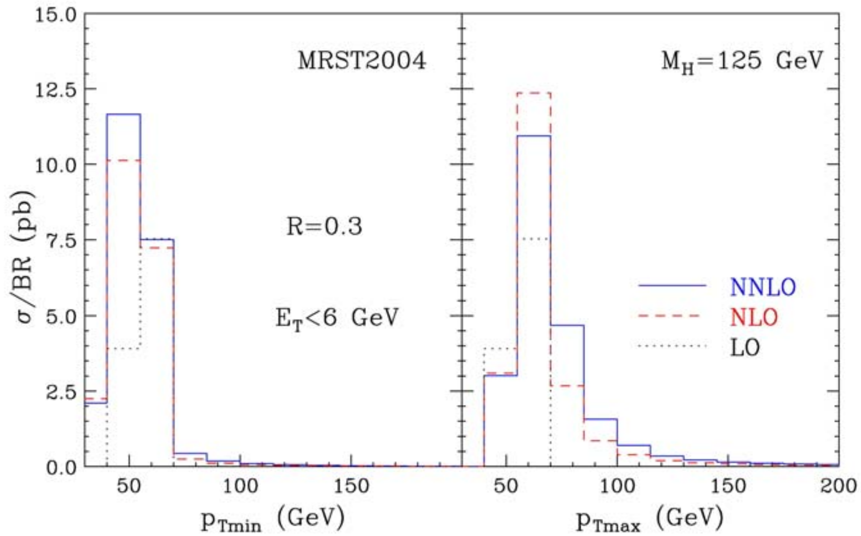
NNLO Monte Carlos

- NNLO MC for gg→h→γγ and h→WW

- Photons isolated: Total energy in cone of ΔR=.3 less than 6 GeV

- Note impact of NNLO corrections

LHC



Catani & Grazzini, hep-ph/0703012

Anastasiou, Melnikov, & Petriello, hep-ph/0501130

Gluon Fusion in Large M_t Limit

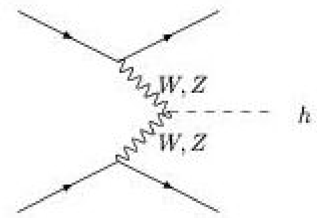
- Good approximation for small transverse momenta of accompanying jets and for parton energy << M_t
  - h+ 1 Jet, h+ 2 Jets at NLO known
- New: approximate NNLO gluon fusion total rate for finite M_t

	K^{NLO}	K^{NNLO}
$m_H = 130$ GeV		
pointlike	1.800	2.140
exact	1.797	n.a.
appr.	1.796	2.136
$m_H = 280$ GeV		
pointlike	1.976	2.420
exact	1.958	n.a.
appr.	1.959	2.394

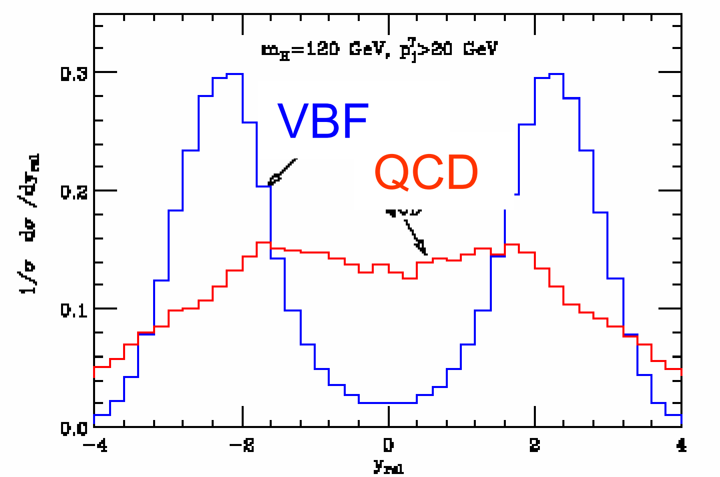
Marzani et al, arXiv: 0809.4934

Vector Boson Fusion

- QCD corrections increase LO rate by 5-10%
- Implemented for distributions
- Important channel for extracting couplings
- Need to separate gluon fusion contribution from VBF
  - Central jet veto
  - Many of the backgrounds known at NLO (Zeppenfeld et al)



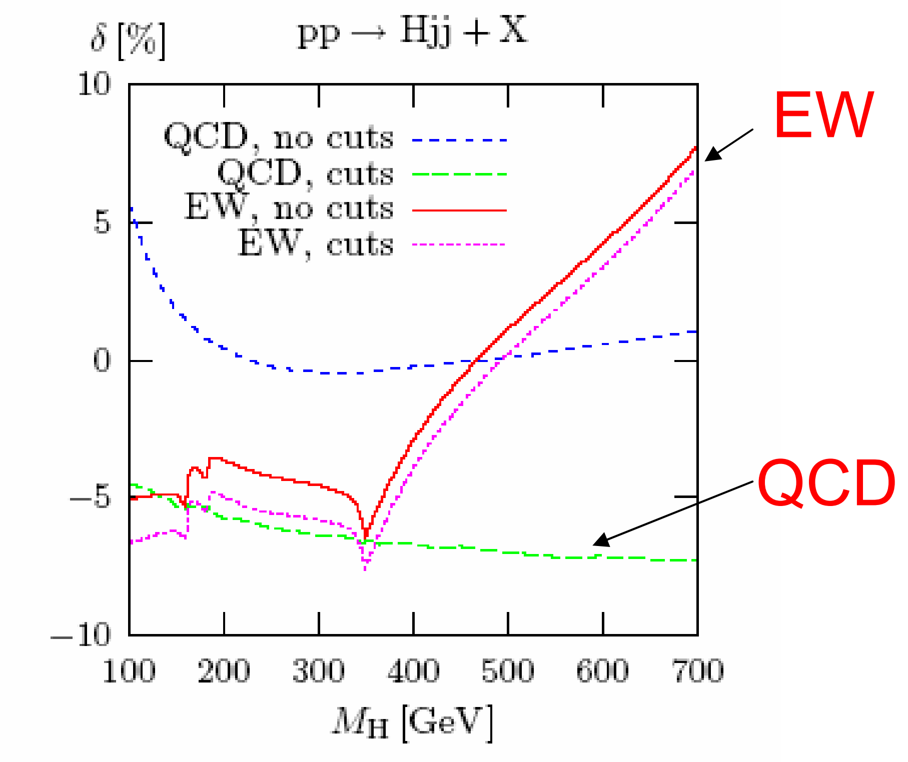
Azimuthal distribution of 3[rd] hardest jet



Del Duca, Frizzo, Maltoni, JHEP05 (2004) 064

When are EW Corrections Needed?

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



Ciccolini, Denner, Dittmaier, arXiv:0710.4749

Much work done computing backgrounds

- $\gamma\gamma$ directly measured from sidebands
  - Calculated at NLO
- $WW \rightarrow l\nu l\nu$
  - NLO, NLO+soft gluon resummation, spin correlations in MC@NLO
  - gluon fusion at NNLO
- $ZZ \rightarrow 4l$ can be measured from sidebands
  - NLO known
- tt, tt+jet known at NLO
- VV pair production from VBF at NLO

More Backgrounds Needed @ NLO

- $t\bar{t}$ with finite width effects
- VV+jets
- $Vt\bar{t}$
- $VVb\bar{b}$
- $t\bar{t}jj$
- $t\bar{t}b\bar{b}$

Much progress made

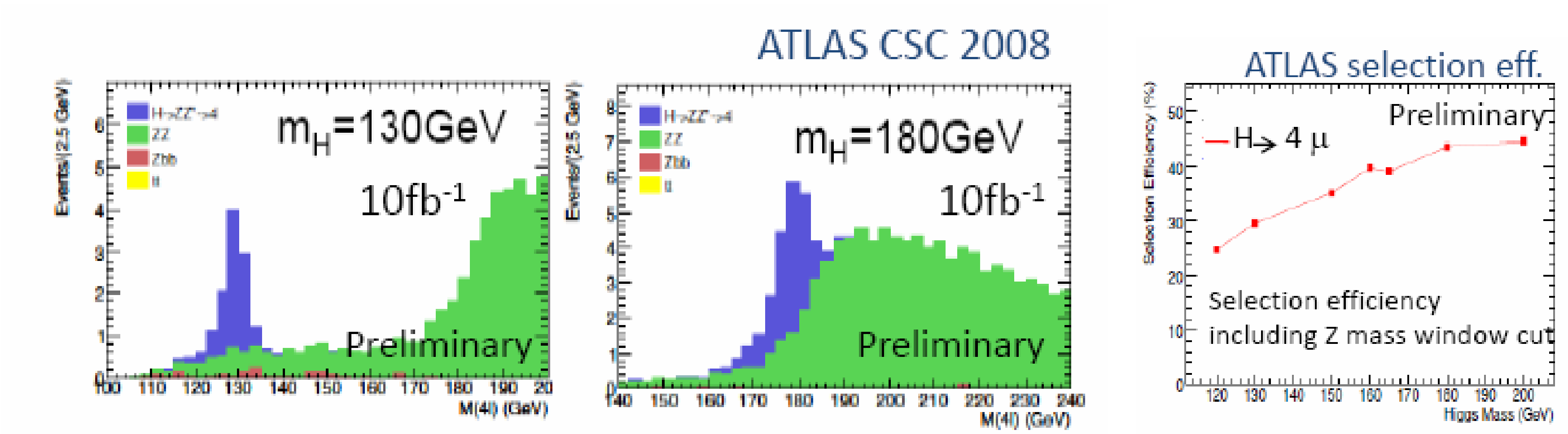
I haven't reviewed the status of implementation of higher order corrections in Monte Carlos

Improvement in LHC Higgs Studies

- Many analyses with full GEANT simulations
- New (N)NLO Monte Carlos for signal and background
- New approaches to match parton showers and matrix elements

Golden Channel: $h \to ZZ \to 4$ leptons

- Need excellent lepton ID

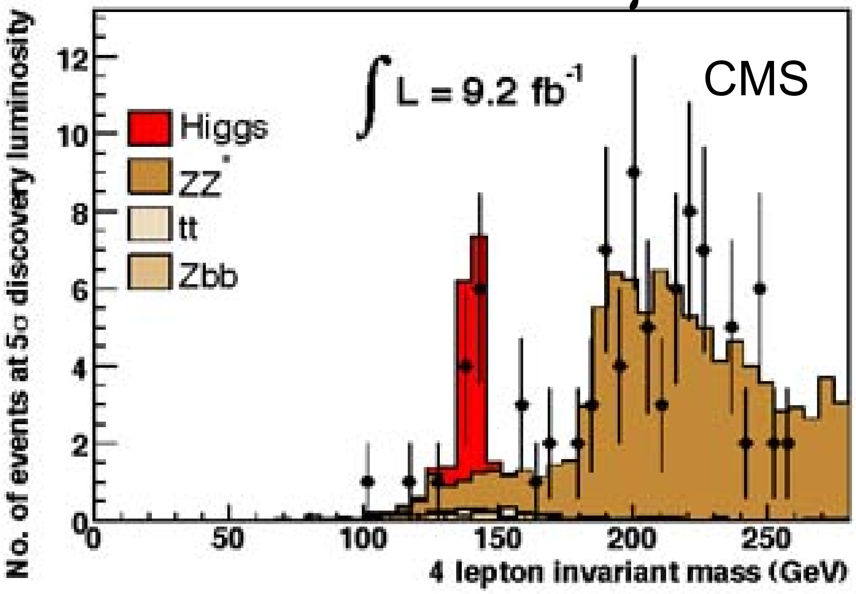


- Below M_h ~130 GeV, rate is too small for discovery

$H \to ZZ^* \to 4l$

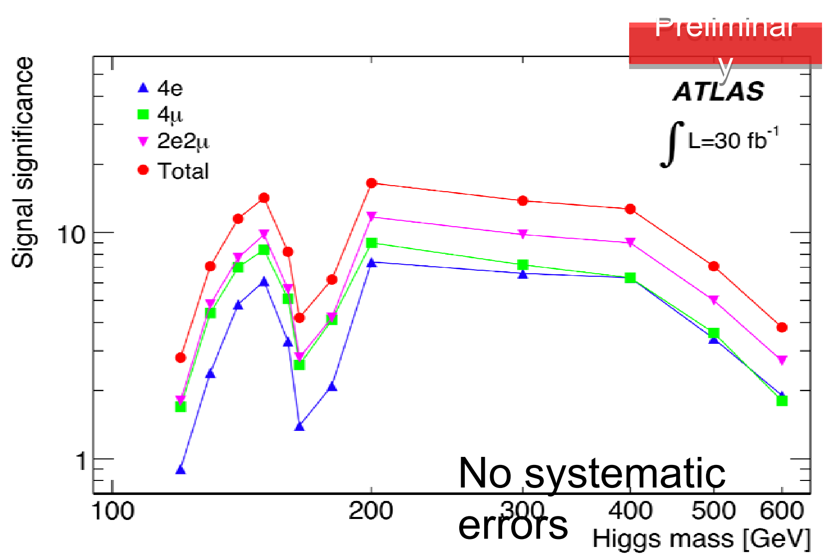
- Could be early discovery!

$$H \to 2e2\mu$$

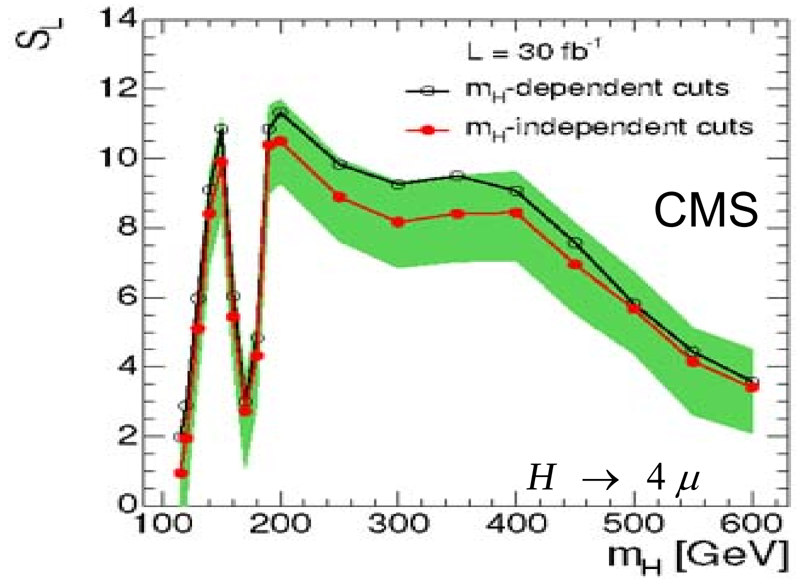


$H \to ZZ^* \to 4l$

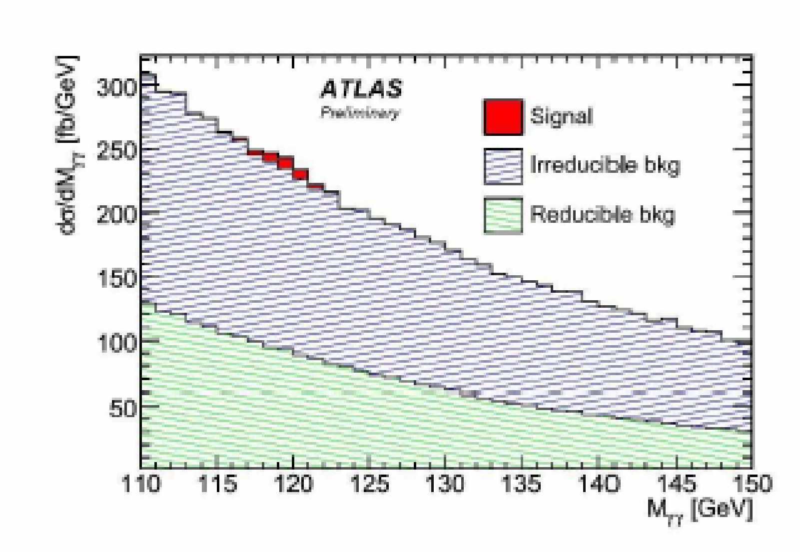
- Data-driven methods to estimate backgrounds
- 5σ discovery with less than 30 fb^{-1}

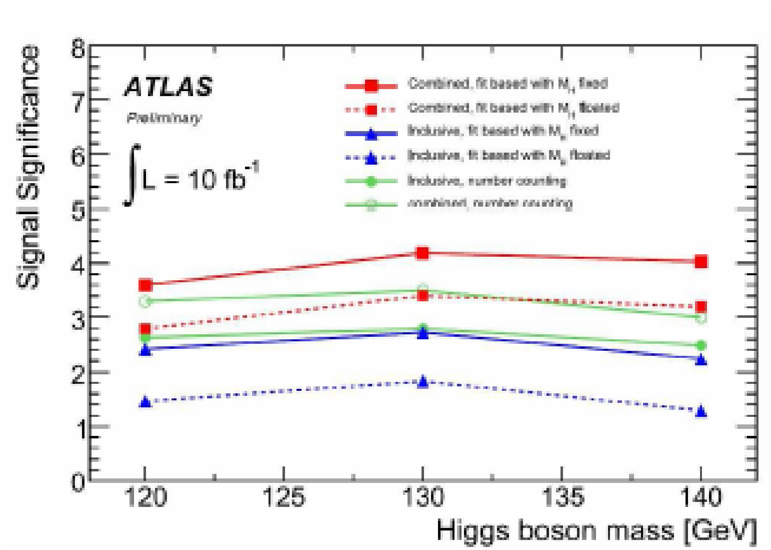


No systematic errors



h→γγ

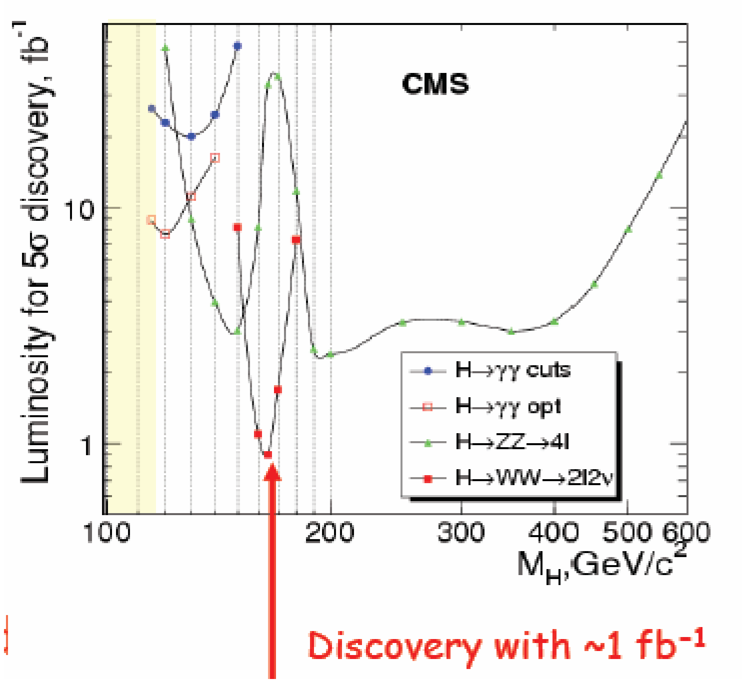




Higgs plus jet production may provide better Signal/Background

ATL-PHYS-PROC-2008-014

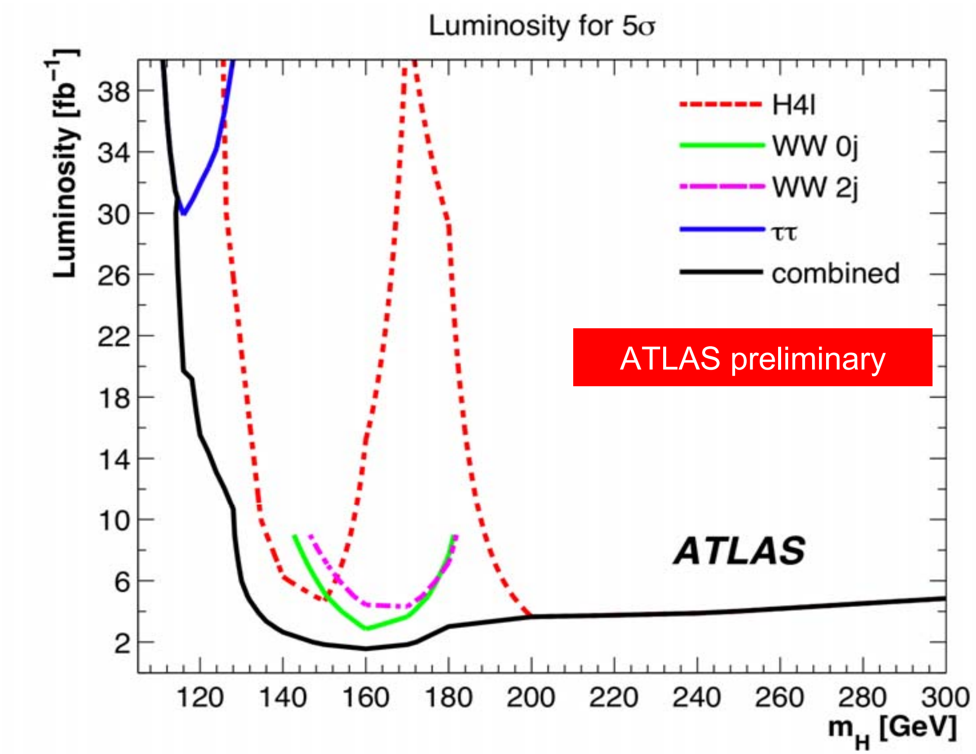
CMS SM Higgs, 2008



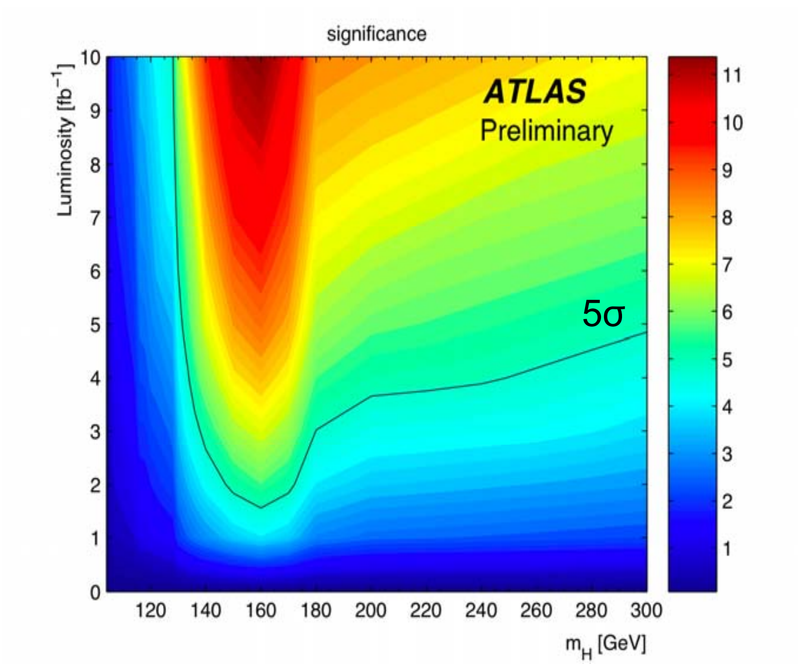
- ➢Improvement in $\gamma\gamma$ channel from earlier studies
- ➢Note: no tth discovery channel

ATLAS SM Higgs, 2008

- Observation: $gg \to h \to \gamma\gamma$, VBF $h \to \tau\tau$, $h \to WW \to l\nu l\nu$, and $h \to ZZ \to 4l$



ATLAS SM Higgs, 2008



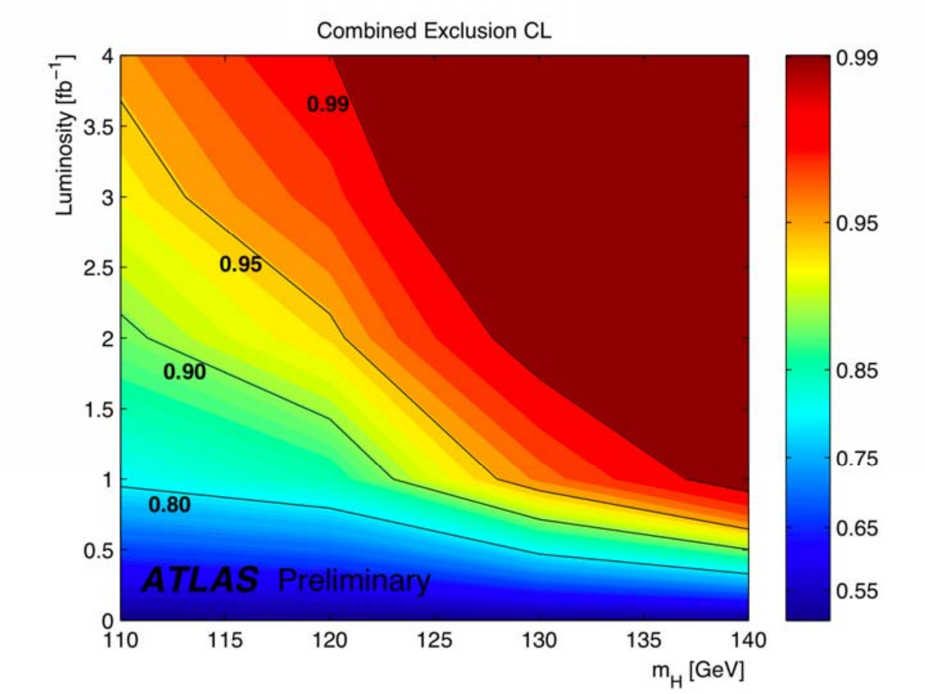
Discovery:

- Need ~20 fb^{-1} to probe M_h=115 GeV
- 10 fb^{-1} gives 5σ discovery for 127< M_h< 440 GeV
- 3.3 fb^{-1} gives 5σ discovery for 136< M_h 190 GeV

Luminosity numbers include estimates of systematic effects and uncertainties

Herndon, ICHEP 2008

ATLAS SM Higgs, 2008



Exclusion:

- 2.8 fb^{-1} excludes at 95% CL M_h = 115 GeV
- 2 fb^{-1} gives exclusion at 95% CL for 121< M_h < 460 GeV

Is it ***the*** Higgs?

- Measure couplings to fermions & gauge bosons

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

- Measure spin/parity

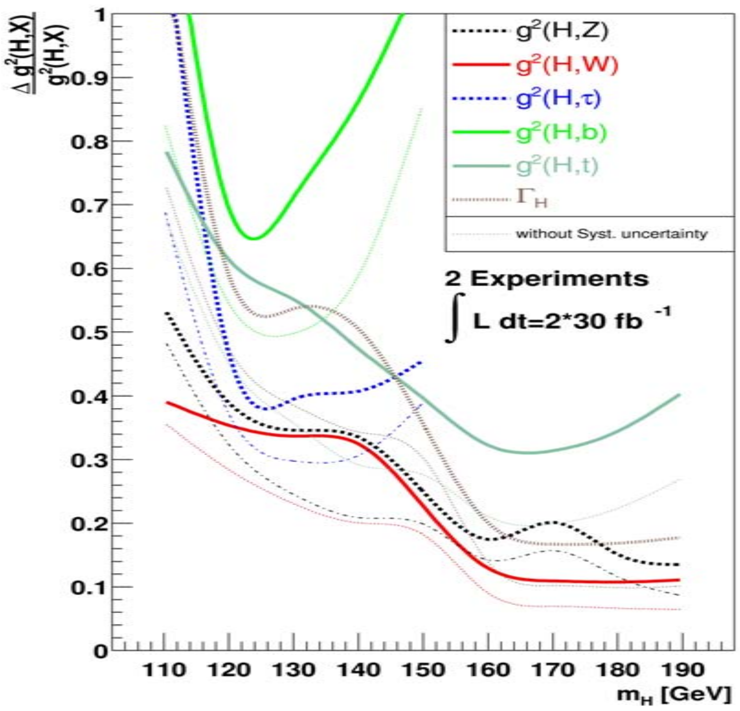
$$J^{PC} = 0^{++}$$

- 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!

Higgs Couplings Difficult

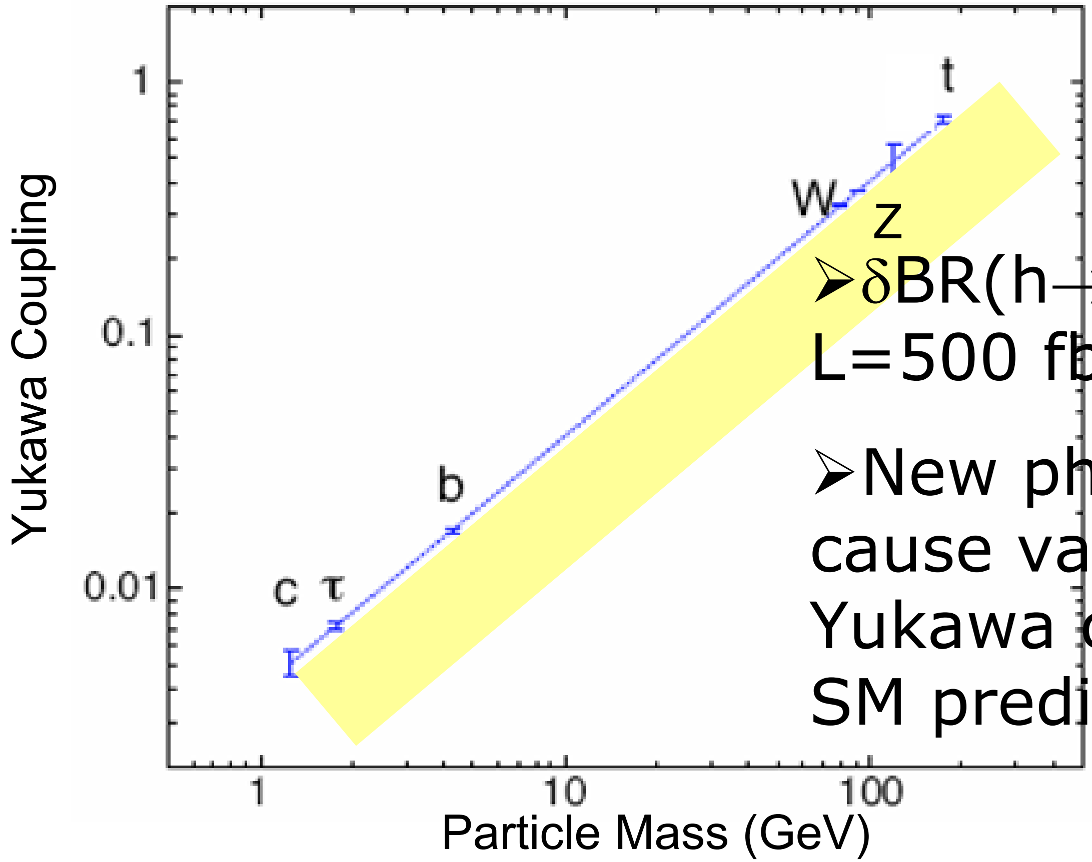


Extraction of couplings requires understanding NLO QCD corrections for signal & background

Ratios of couplings easier

Logan, hep-ph/0409026

ILC Goal: Precision Measurements of Yukawa Couplings



- δBR(h→bb)~2% with L=500 fb^{-1}
- New phenomena can cause variations of Yukawa couplings from SM predictions

On Very General Grounds…..

- We expect a Higgs boson or something like it….

$$A\left(W_L^+W_L^- \rightarrow Z_L Z_L\right) = -\frac{G_F E^2}{8\sqrt{2}\pi}\left(\frac{M_h{}^2}{E^2 - M_h^2}\right)$$

Unitarity → Light Higgs: M_h < 800 GeV

No Higgs: $\Lambda_c \sim 1.2$ TeV ← Unitarity violation

- ***Expect a light Higgs or New Physics below 1 TeV***

Lee, Quigg, Thacker, PRD16, 1519 (1977)

Standard Model is Effective Low Energy Theory

- We don't know what's happening at high energy
  - We haven't found the Higgs!
- Effective theory approach: $L \approx L_{SM} + \sum_i f_i \frac{O_i}{\Lambda^2} + \ldots$
- Compute deviations from SM due to new operators and compare with experimental data

LHC job is to probe physics which generates these operators

Little Hierarchy Problem

- Unitarity arguments suggest new physics is at 1 TeV scale
- Much possible new physics is excluded at this scale
  - Look at possible dimension 6 operators
    - Many more operators than shown here
  - Limits depend on what symmetry is violated

New operators	Experimental limits
$\frac{(\bar{d}s)(\bar{d}s)}{\Lambda^2}$	$\Lambda > 1000\ TeV$
$\frac{m_b(\bar{s}\sigma_{\mu\nu}F^{\mu\nu}b)}{\Lambda^2}$	$\Lambda > 50\ TeV$
$\frac{(h^+D_\mu h)^2}{\Lambda^2}$	$\Lambda > 5\ TeV$
$\frac{(D^2h^+D^2h}{\Lambda^2}$	$\Lambda > 5\ TeV$

New Physics must be at scale $\Lambda > 5$ TeV

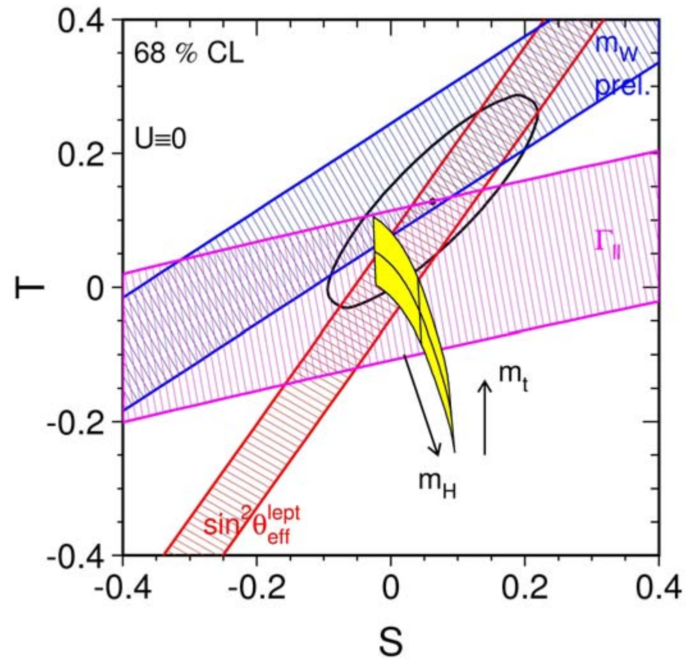
Schmaltz, hep-ph/0502182

Many New Models…

- Supersymmetry
  - Trusty standard
  - NMSSM, MSSM with CP violation….
- Little Higgs
  - Higgs is pseudo Goldstone boson
- Extra dimensions
  - Higgs is component of gauge field in extra-D
  - Higgsless: Symmetry breaking from boundary conditions
- Strong electroweak symmetry breaking
  - Technicolor, top-color
  - …..

Higgs Mass Limits *ASSUME* Standard Model

- It's easy to construct models which evade Higgs mass limits
- All you need is large $\Delta\rho = \alpha\Delta T$
  - Models typically have new particles…..



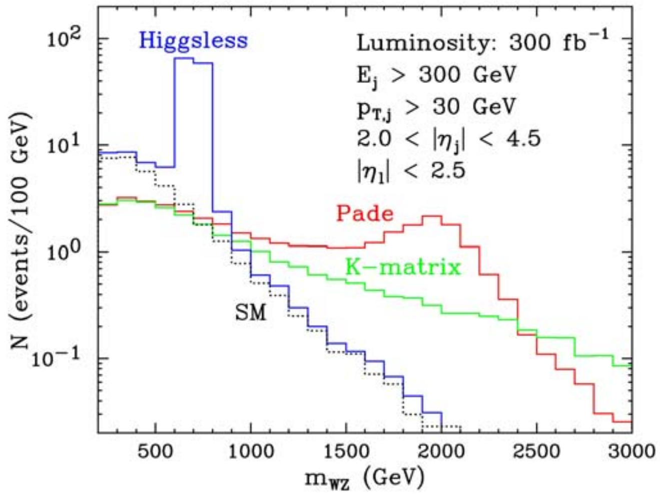
What if no Higgs?

- Technicolor models unitarize WW scattering with ρ-like particle
- Extra dimension models have new possibilities for EWSB
  - Higgs could be 5th dimension of gauge field
  - Or….generate EWSB from boundary conditions on branes (Higgsless)
- Models generically have "tower" of Kaluza Klein particles (massive vector particles): V_n

Experimental Signatures of Extra-D Higgsless Models

- Look for massive W, Z, γ like particles in vector boson fusion
  - Need small couplings to fermions to avoid precision EW constraints
  - Narrow resonances in WZ channel

LHC: pp→WZ + X



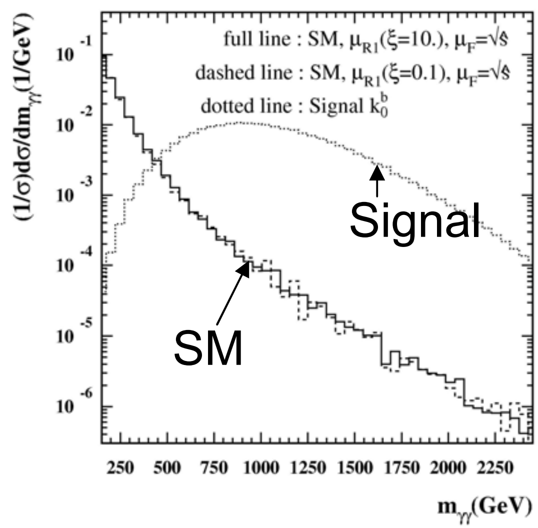
Different resonance structure from SM!

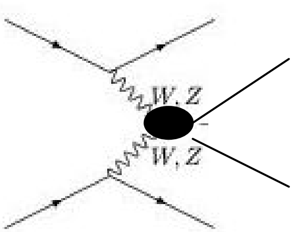
Birkedal, Matchev, Perelstein, hep-ph/0412278

WW Scattering without a Higgs

- Construct effective Lagrangian without Higgs
  - Gauge boson interactions grow with energy
  - This Lagrangian violates unitarity
- This is counting experiment
  - Example: Search for anomalous $WW\gamma\gamma$ vertex through gauge boson fusion

LHC





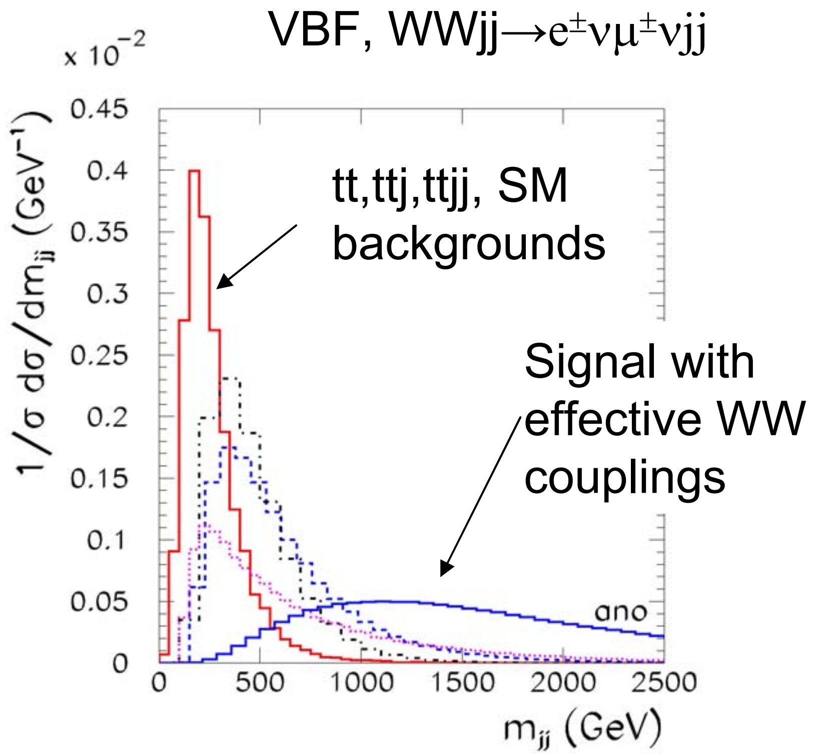
Hard!

Normalized to show difference in shape of signal and background

Eboli et al, hep-ph/0310141

No light Higgs/No KK particles/No techni-ρ Scenario

- No resonance
  - Effective Lagrangian couplings grow with energy
- Counting experiments
- Very hard!



Eboli, Gonzales-Garcia, Mizukoshi, hep-ph/0606118, Zeppenfeld et al

Conclusion

- Theory challenges relate to understanding predictions for signal and background and implementing them in Monte Carlo programs
- Waiting for data!
- Electroweak symmetry breaking sector is win-win