Electroweak Symmetry Breaking at the Terascale

S. Dawson (BNL)

October, 2008

XIII Mexican School of Particles and Fields

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

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

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

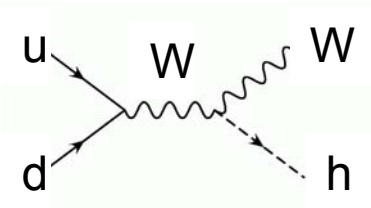
$$L \approx \frac{m_f}{v} \bar{f}_L \Phi f_R$$

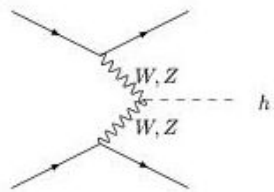
Gauge Higgs Couplings

- 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:

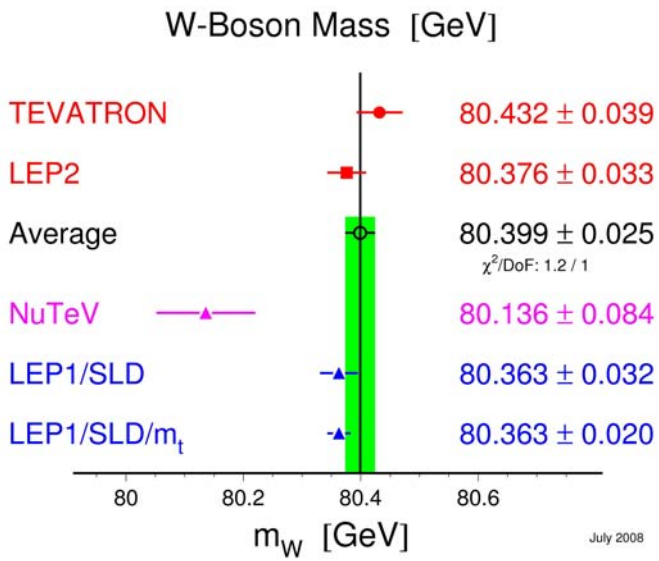
  $\approx M_t^2$, log (M_h)

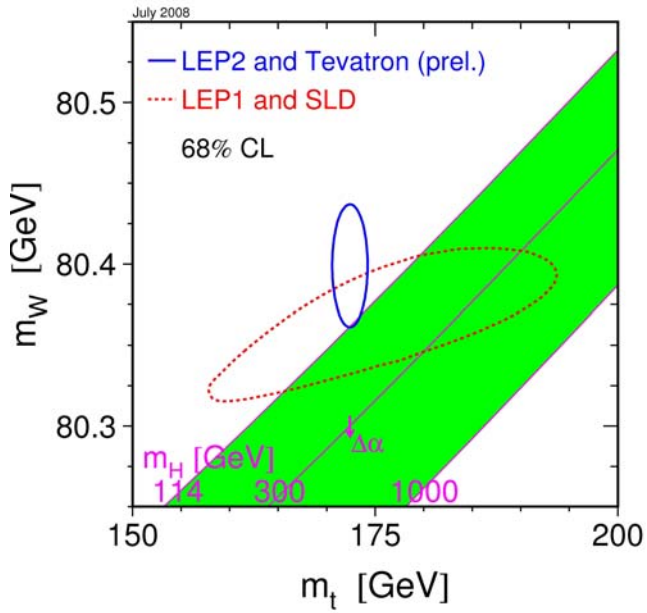
Everything is calculable….***testable theory***

Understanding Higgs Limit

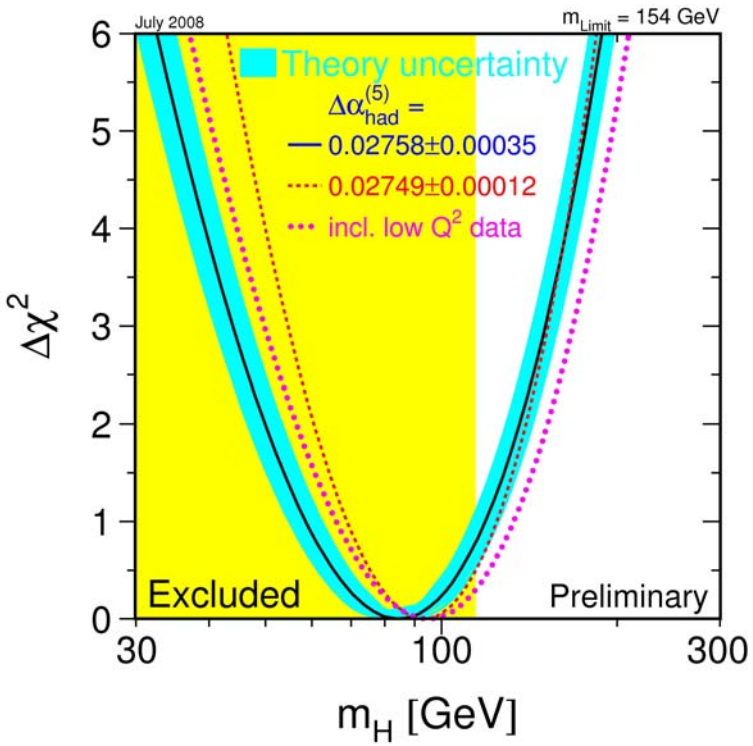
Theory: Input M_Z, G_F, α

$\rightarrow$ Predict M_W





Precision Measurements Limit M_h

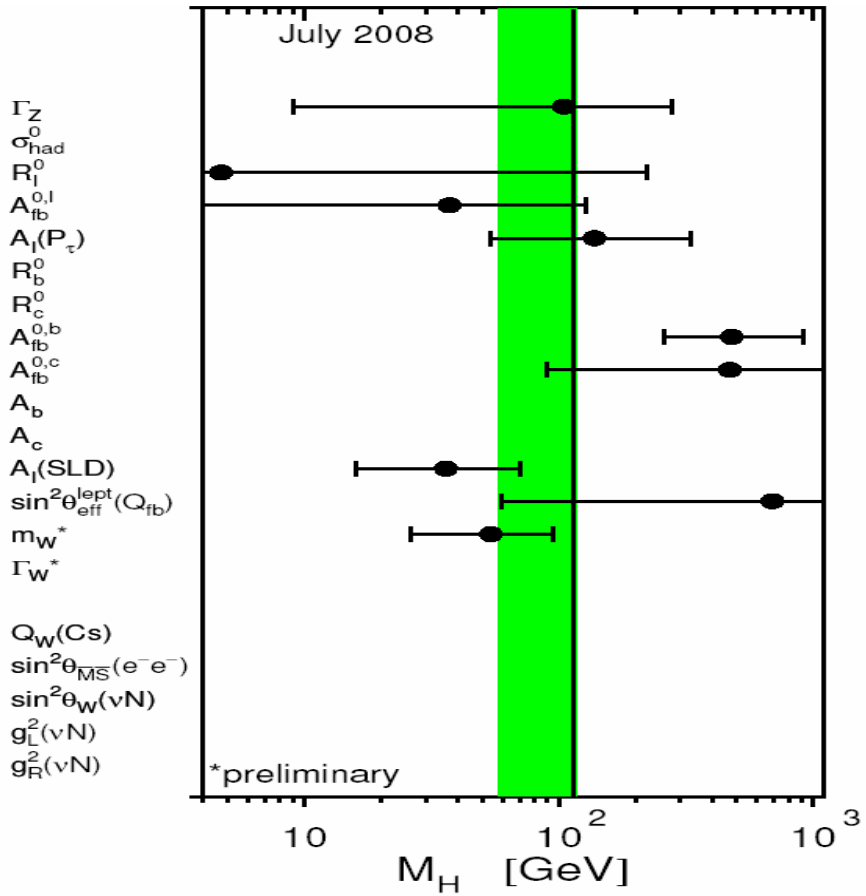


- LEP EWWG (July, 2008):
  - $M_t = 172.4 \pm 1.2$ GeV
  - $M_h = 84^{+34}_{-26}$ GeV
  - $M_h < 154$ GeV (one-sided 95% cl)
  - $M_h < 185$ GeV (Precision measurements plus direct search limit)

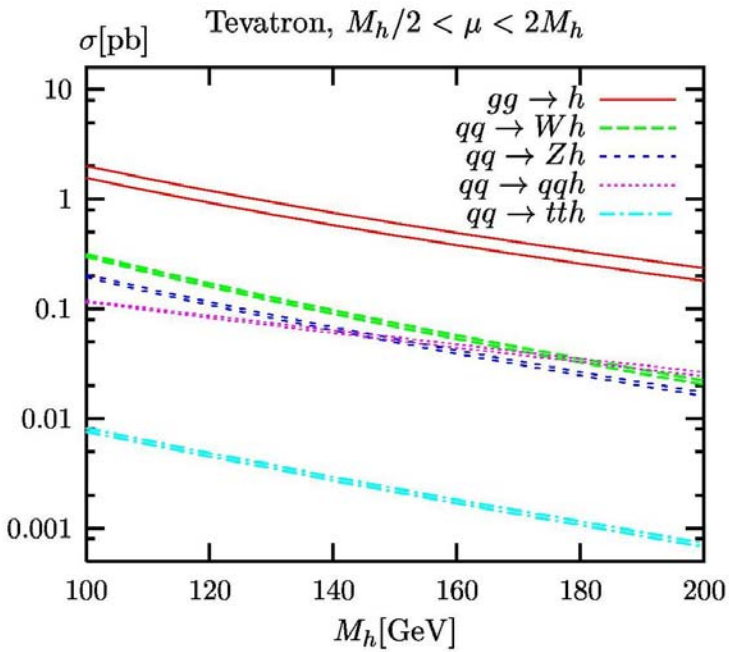
Best fit in region excluded by direct searches

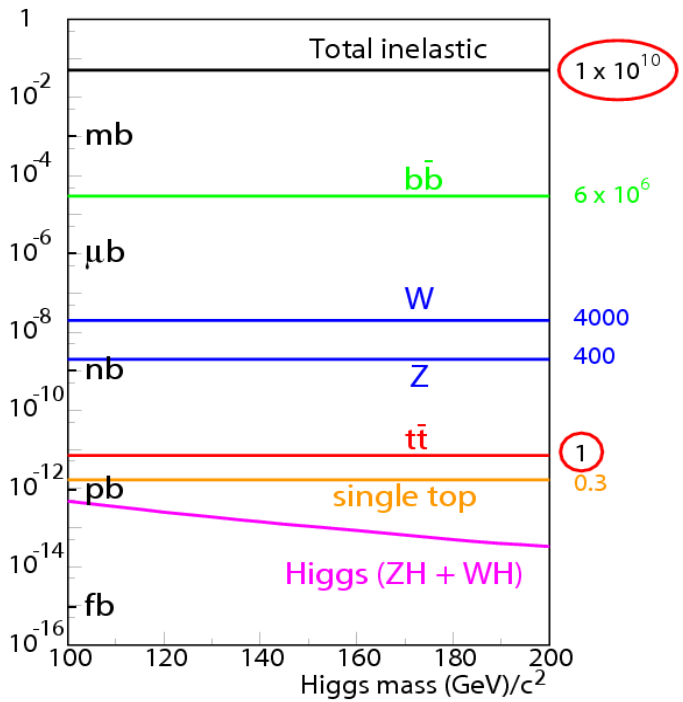
Higgs Mass From Individual Measurements

Consistent!



Higgs at the Tevatron



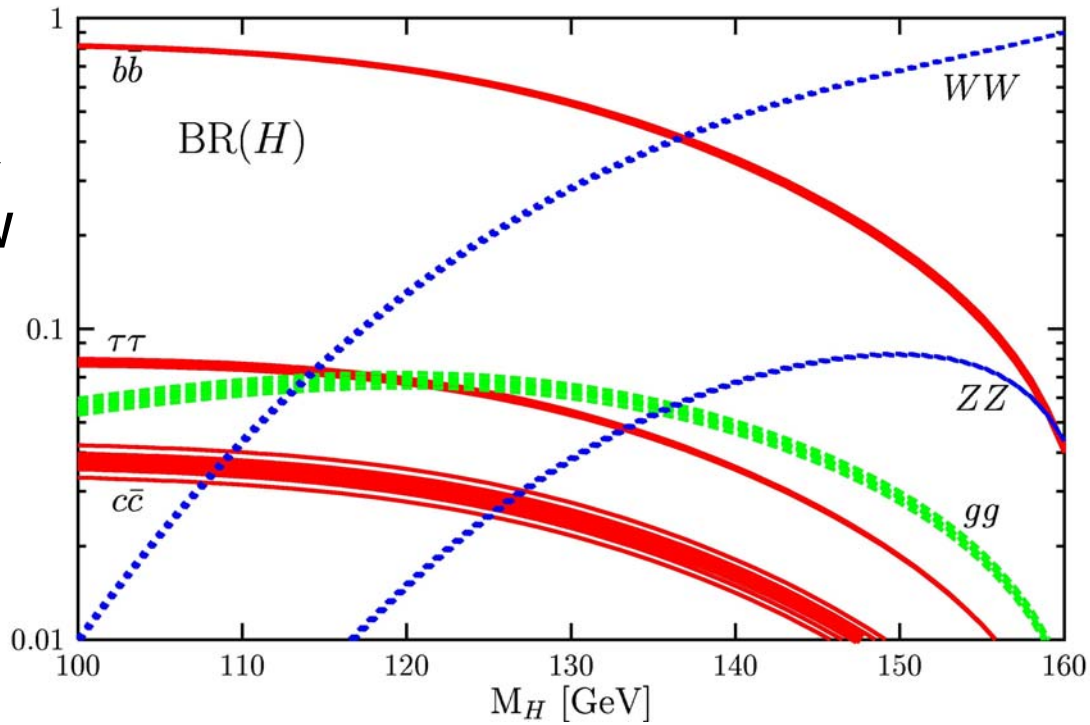


NNLO or NLO rates

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

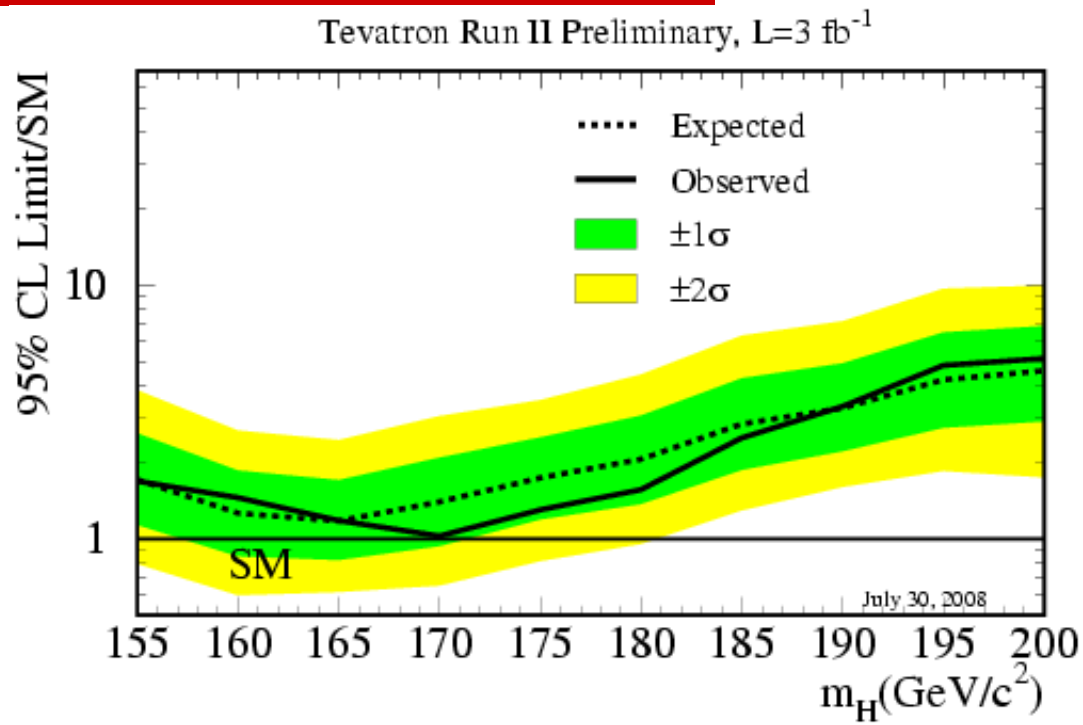
Higgs Branching Ratios

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



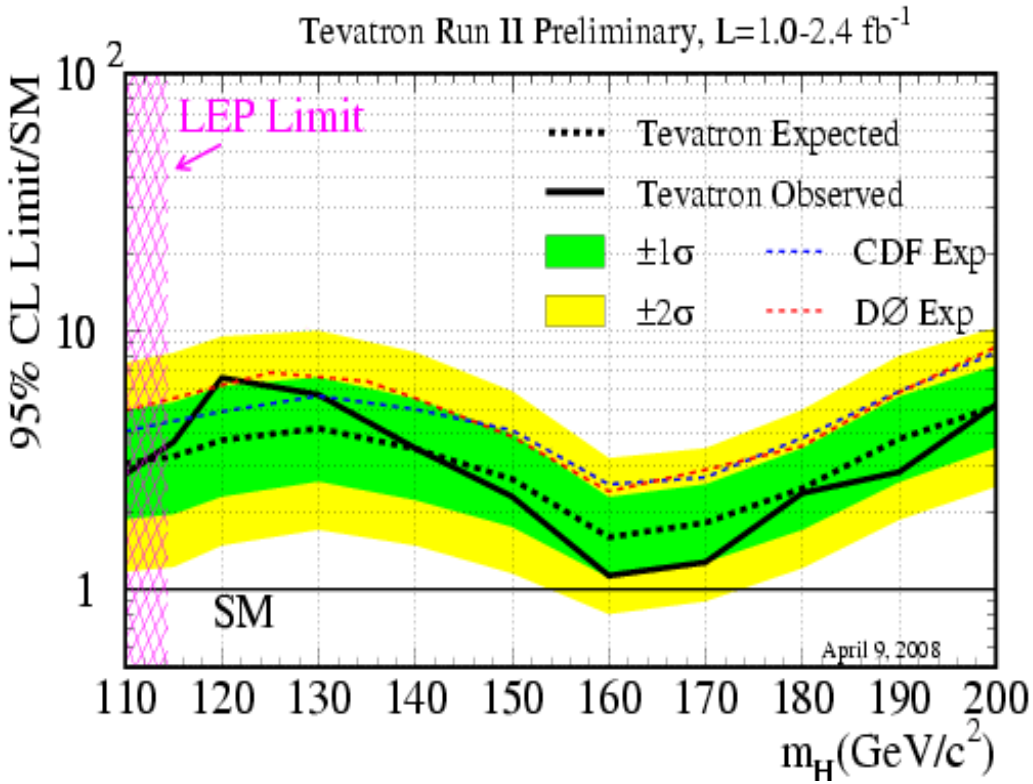
Use $gg \rightarrow h$, $h \rightarrow WW$ at high Higgs mass

SM Higgs Searches at Tevatron



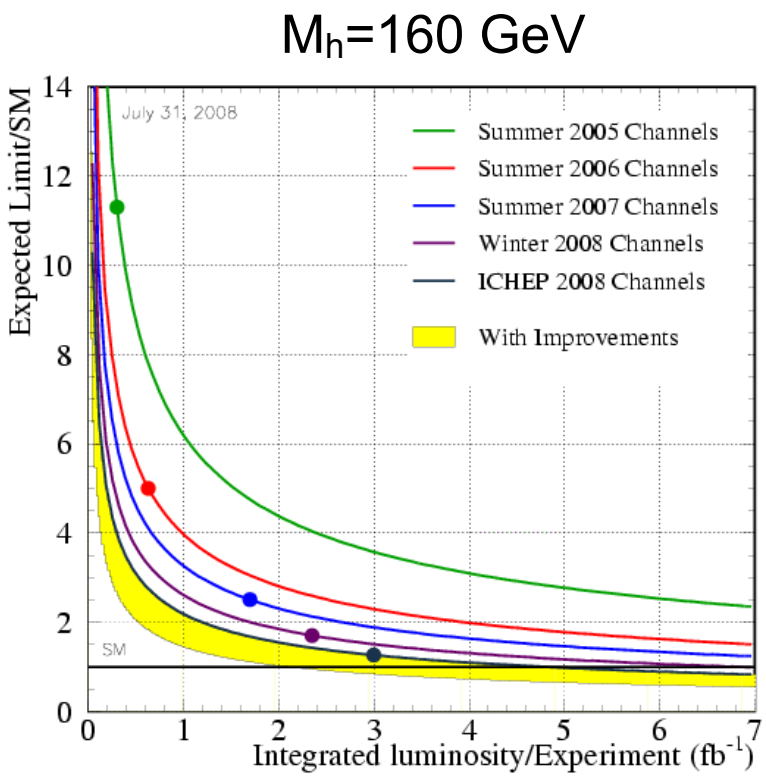
95% CL exclusion of SM Higgs at 170 GeV

SM Higgs Searches at Tevatron



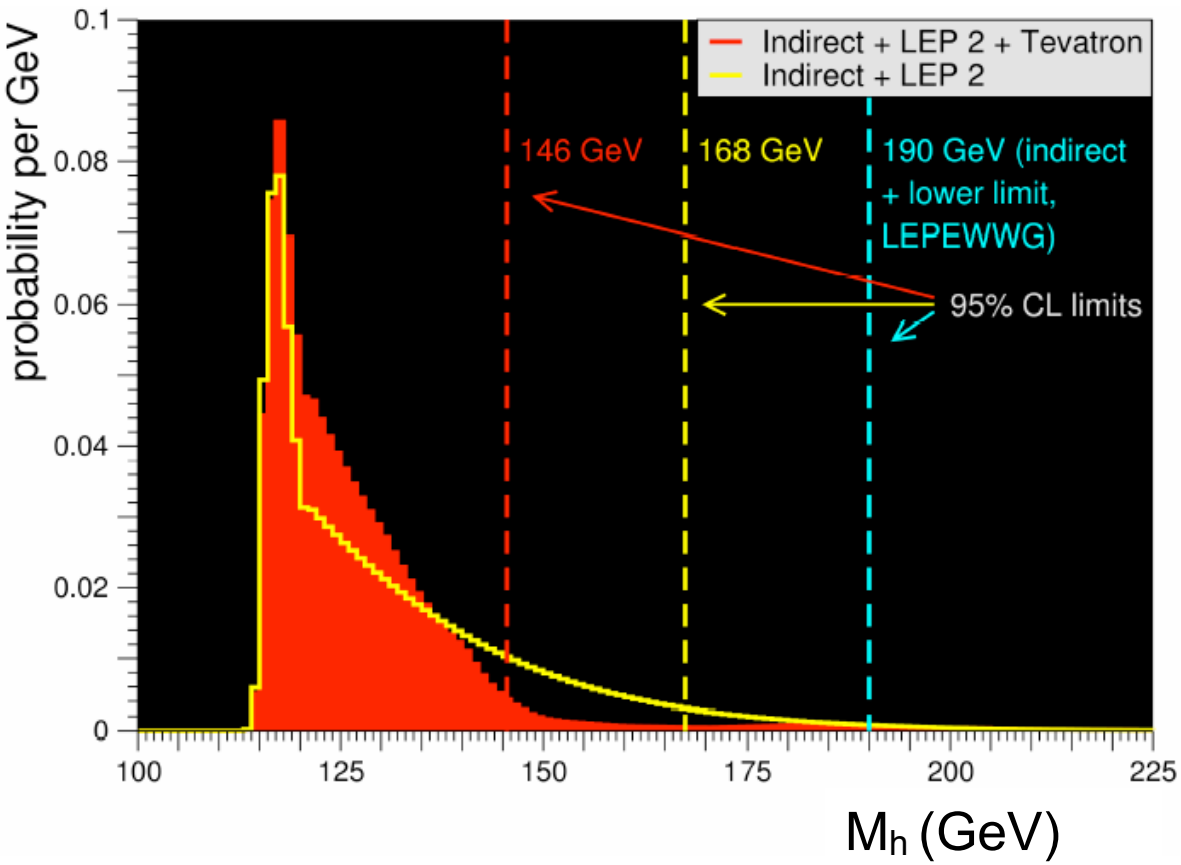
CDF/D0 combination with 3 fb^{-1} coming.
Expected sensitivity < 3 x SM @ M_h=115 GeV

Will Fermilab find the Higgs?



- It's not just luminosity

Tevatron Results Starting to Limit M_h



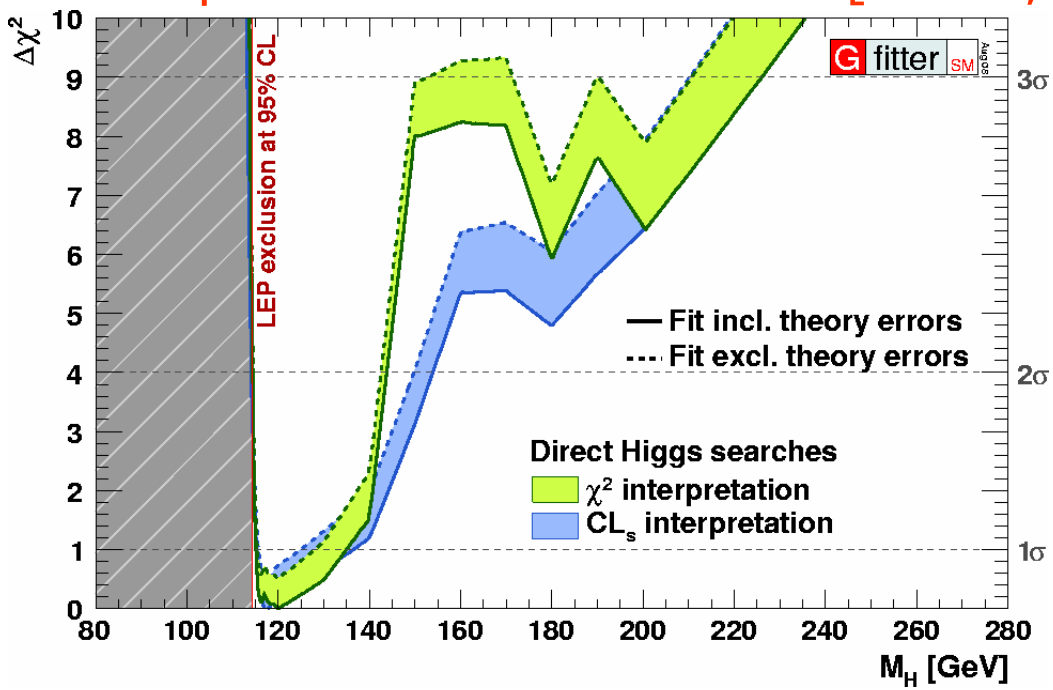
Erler, ICHEP08, arXiv:0809.2366

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

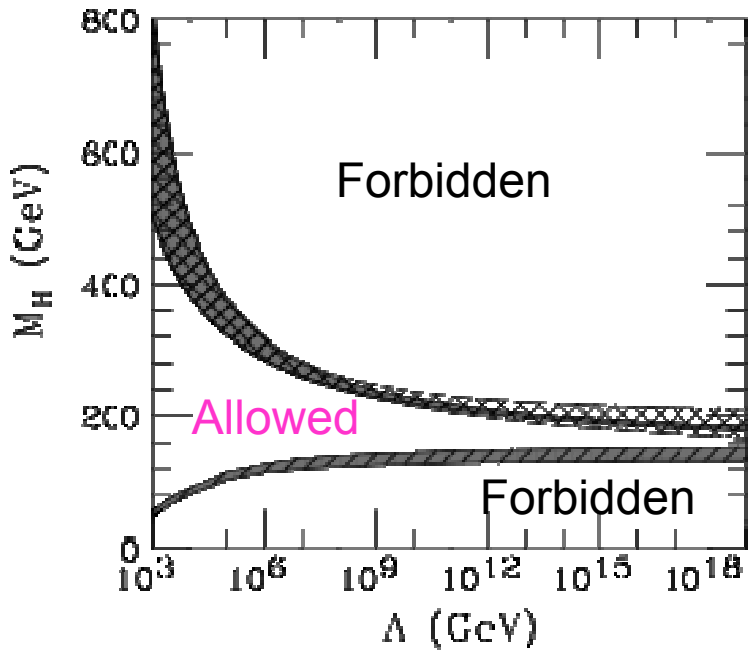


Haller, ICHEP08, Gfitter analysis

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

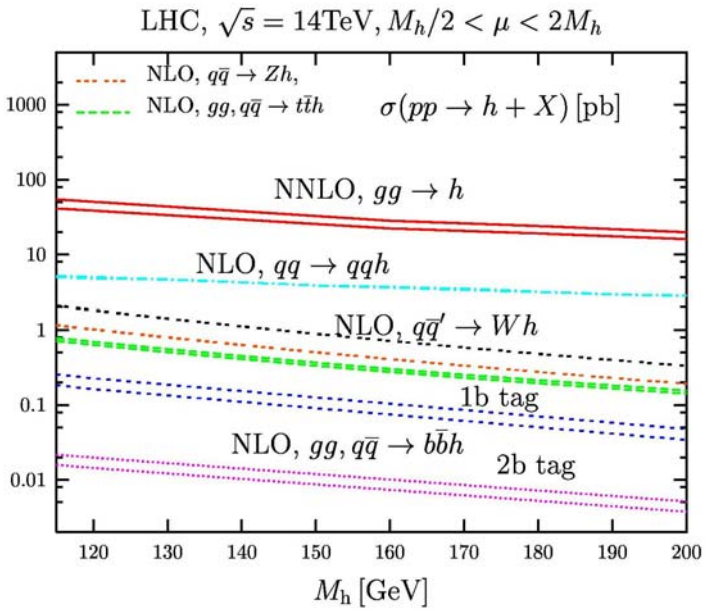
- Sept 10, first particles injected in LHC
- Collisions in spring, 2009
- What can we learn from early data sets? (10 fb^{-1})

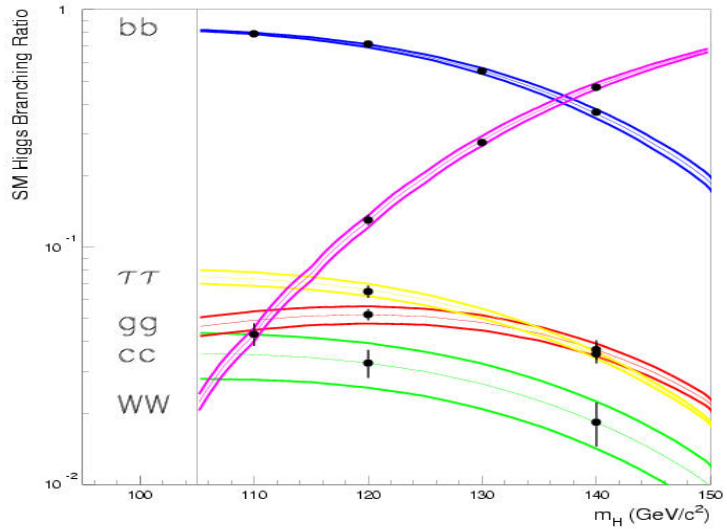
LHC Higgs Theory Challenges

- 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

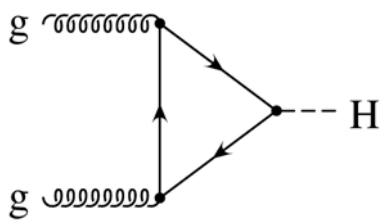




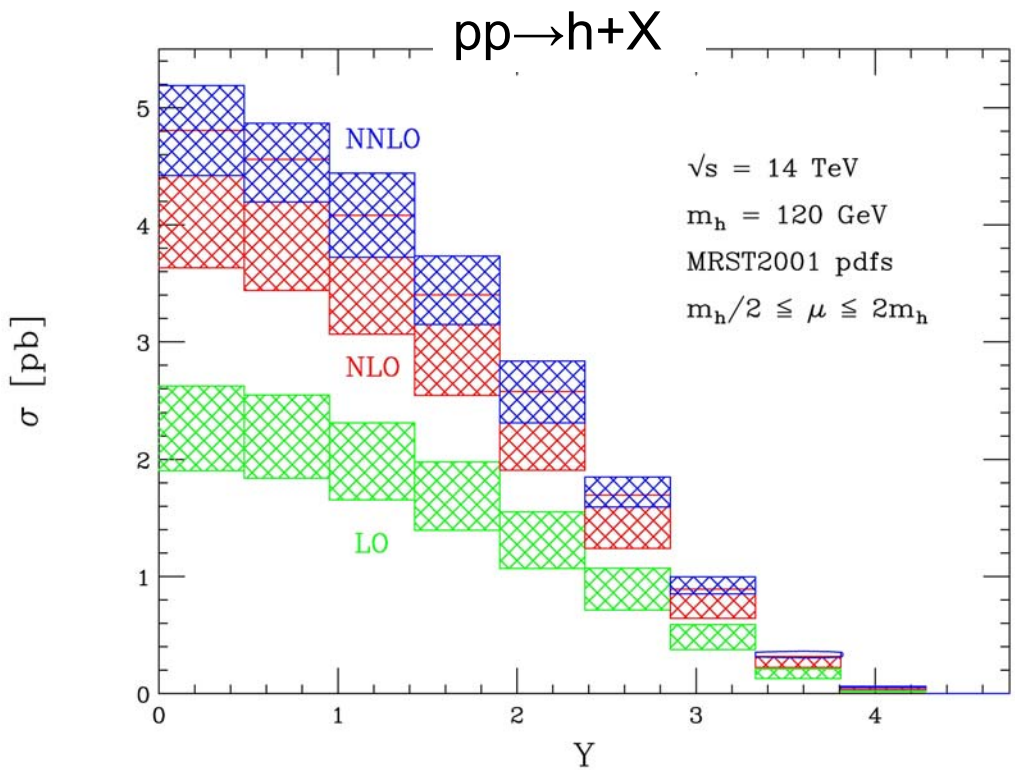
- Total cross sections known to NLO or NNLO

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

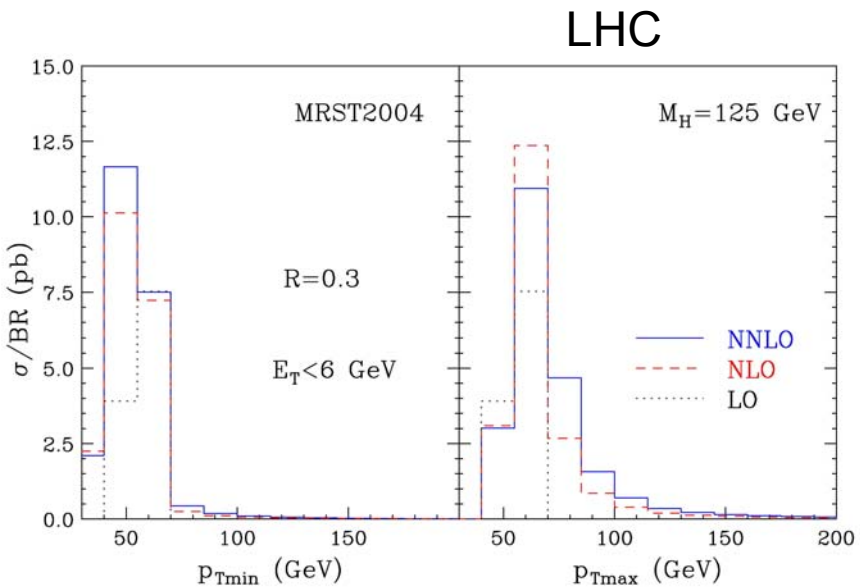
Anastasiou, Dixon, & Melnikov, hep-ph/0211141, hep-ph/0501130

NNLO Monte Carlos

- NNLO MC for $gg \rightarrow h \rightarrow \gamma\gamma$ and $h \rightarrow WW$

- Photons isolated: Total energy in cone of $\Delta R = .3$ less than 6 GeV

- Note impact of NNLO corrections



Catani & Grazzini, hep-ph/0703012

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

Gluon Fusion in Large M_t Limit

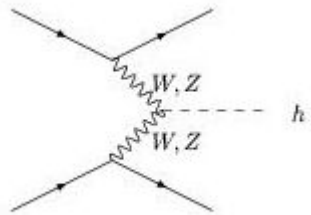
- Good approximation for small transverse momenta of accompanying jets and for parton energy << M_t
  - h+ 1 Jet, h+ 2 Jets at NLO known
- New: approximate NNLO gluon fusion total rate for finite M_t

	$K^{\rm NLO}$	$K^{\rm NNLO}$
$m_H = 130$ 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

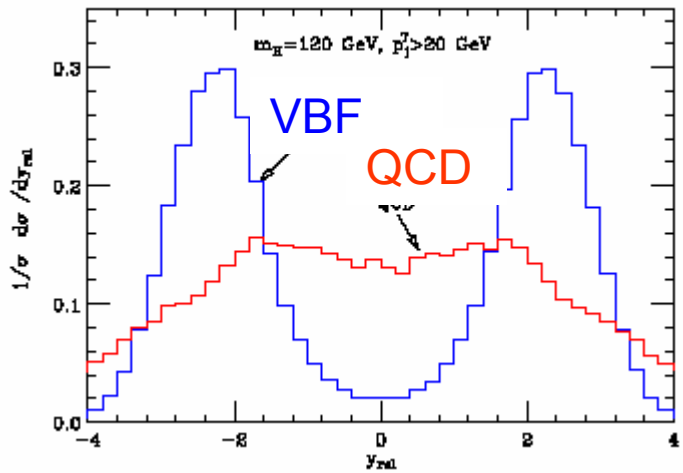
Marzani et al, arXiv: 0809.4934

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)



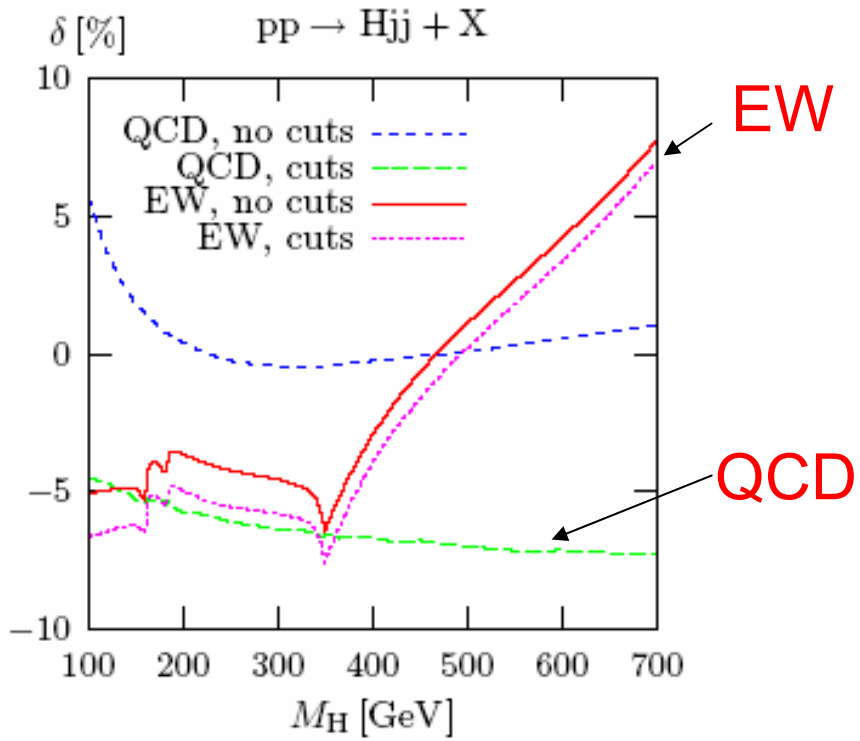
Azimuthal distribution of 3rd hardest jet



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

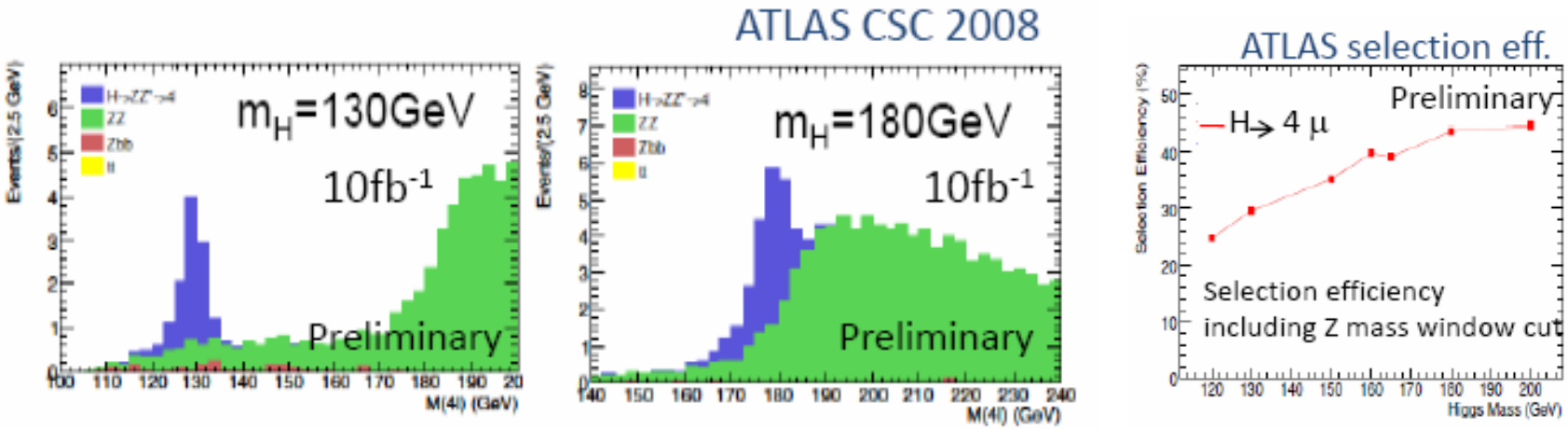
I haven't reviewed the status of implementation of higher order corrections in Monte Carlos

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→ZZ→4 leptons

- Need excellent lepton ID

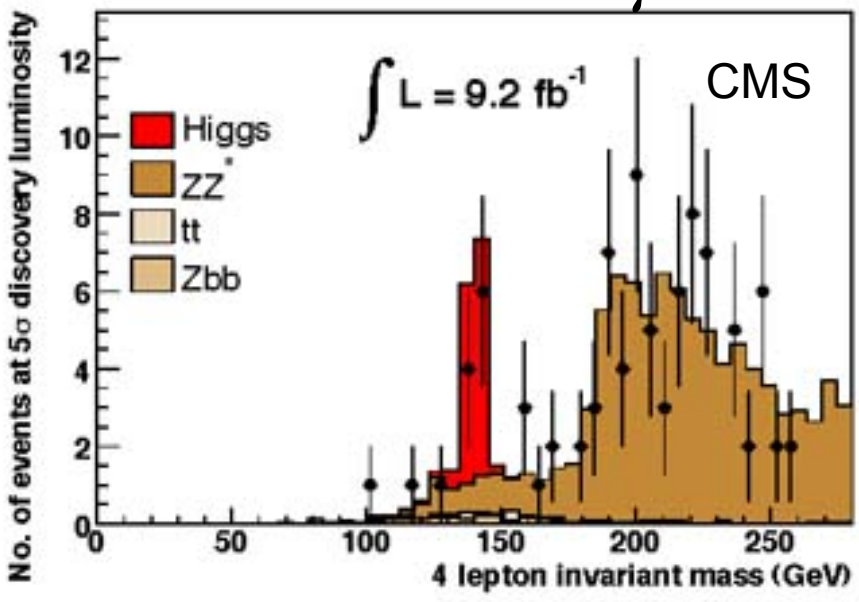


- Below M_h ~130 GeV, rate is too small for discovery

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

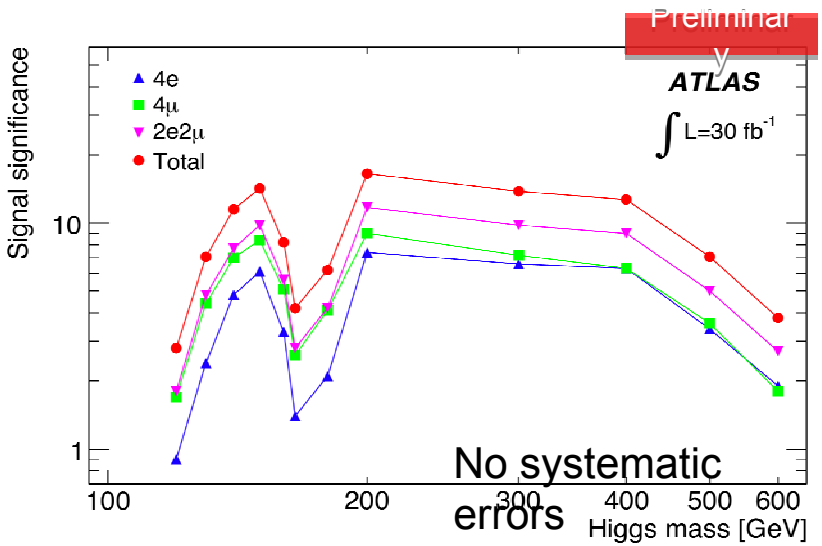
- Could be early discovery!

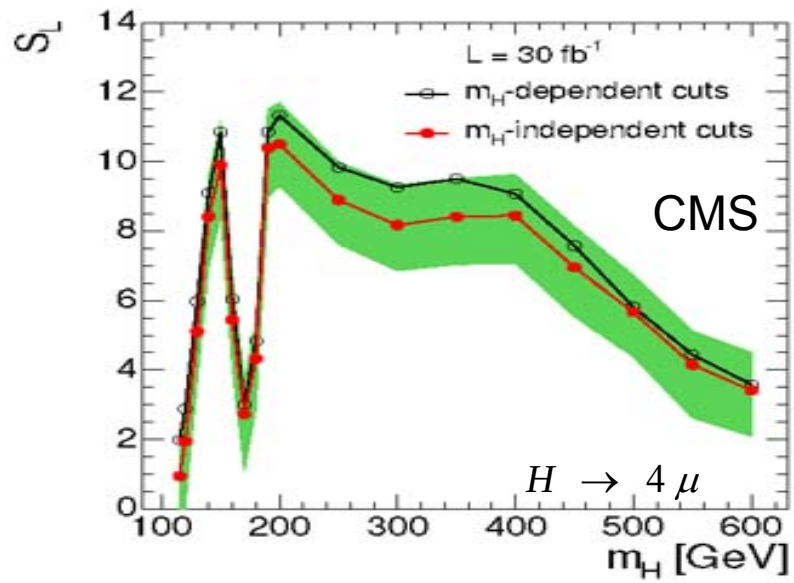
$$H \to 2e2\mu$$



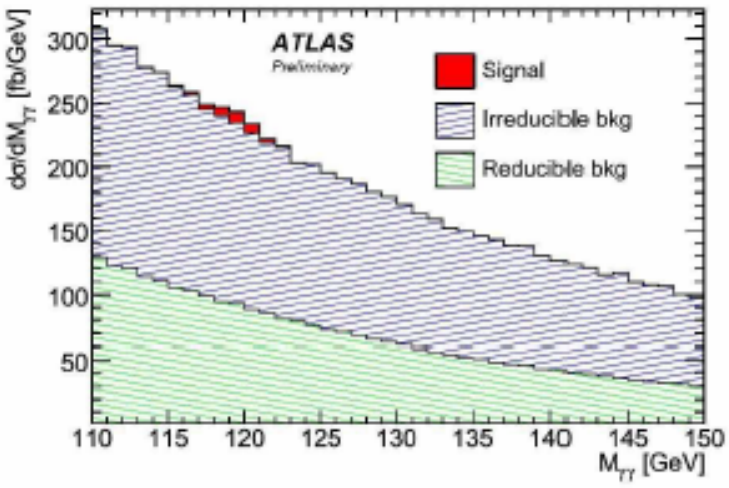
$H \rightarrow ZZ^{*} \rightarrow 4l$

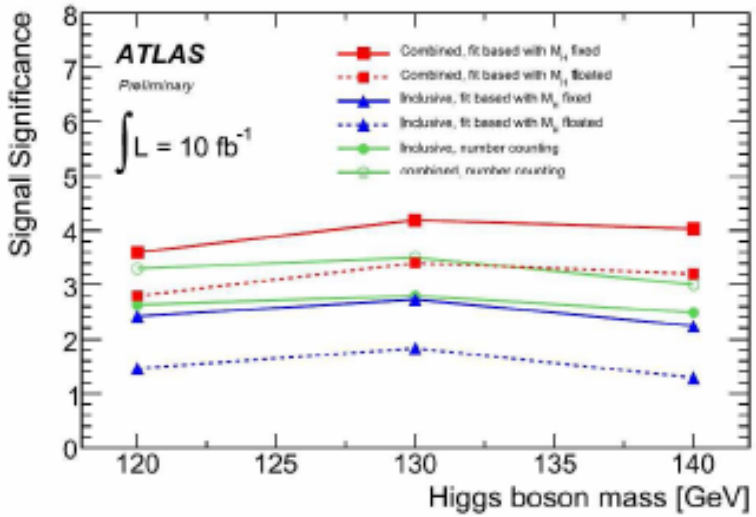
- Data-driven methods to estimate backgrounds
- 5σ discovery with less than 30 fb^{-1}





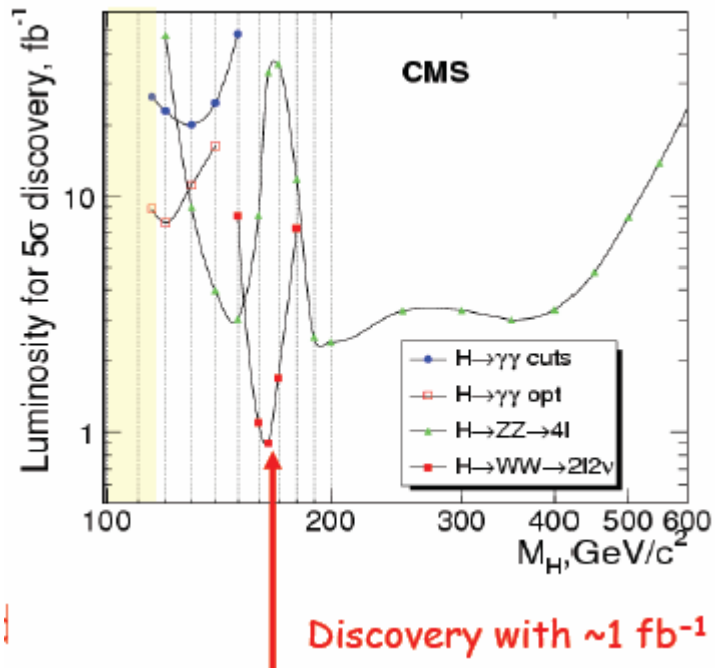
h→γγ





ATL-PHYS-PROC-2008-014

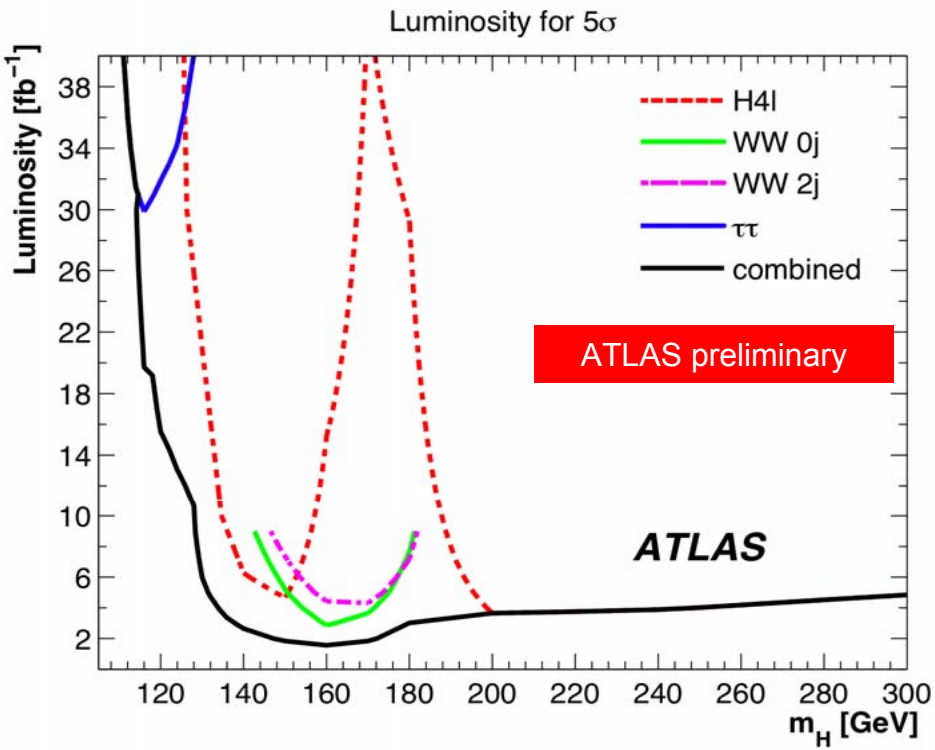
CMS SM Higgs, 2008



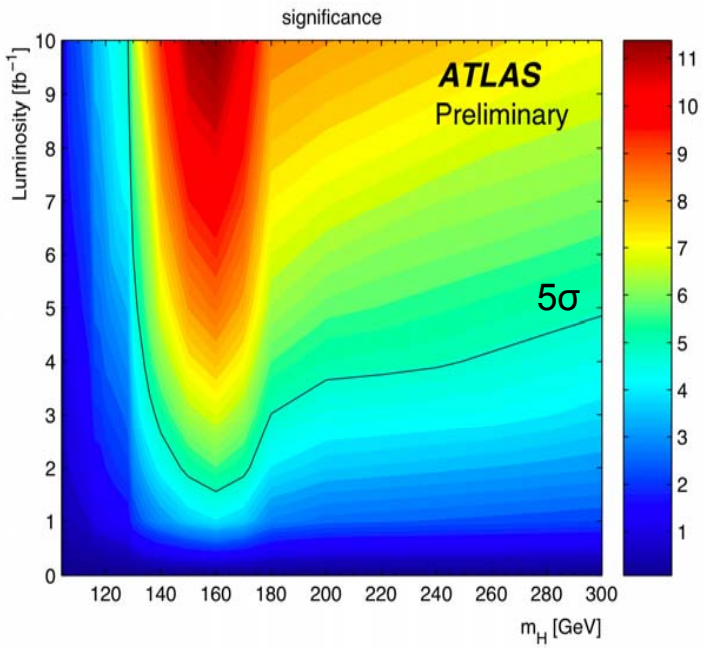
- Improvement in $\gamma\gamma$ channel from earlier studies
- Note: no tth discovery channel

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



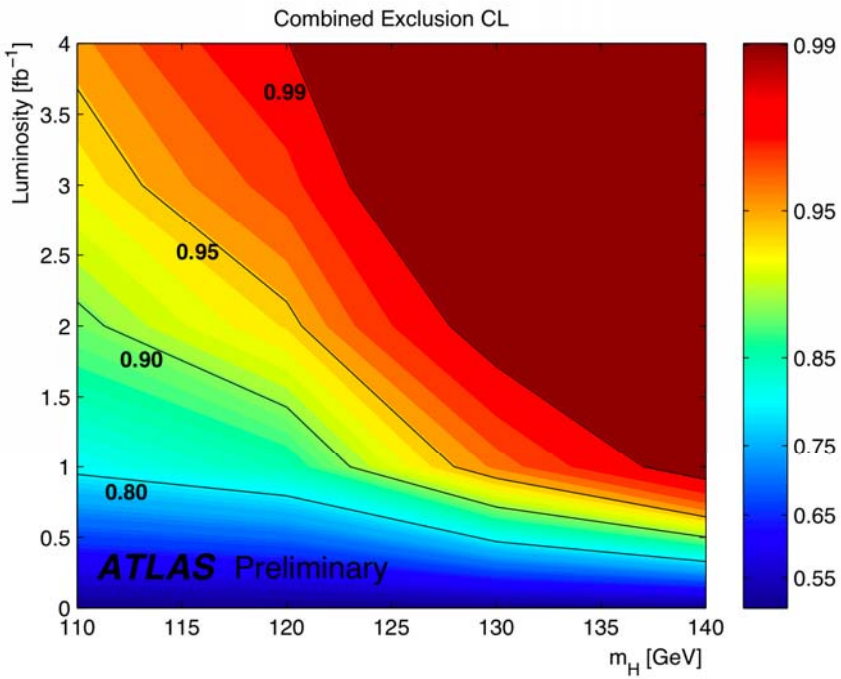
Discovery:

- 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

Herndon, ICHEP 2008

Is it ***the*** Higgs?

- Measure couplings to fermions & gauge bosons

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

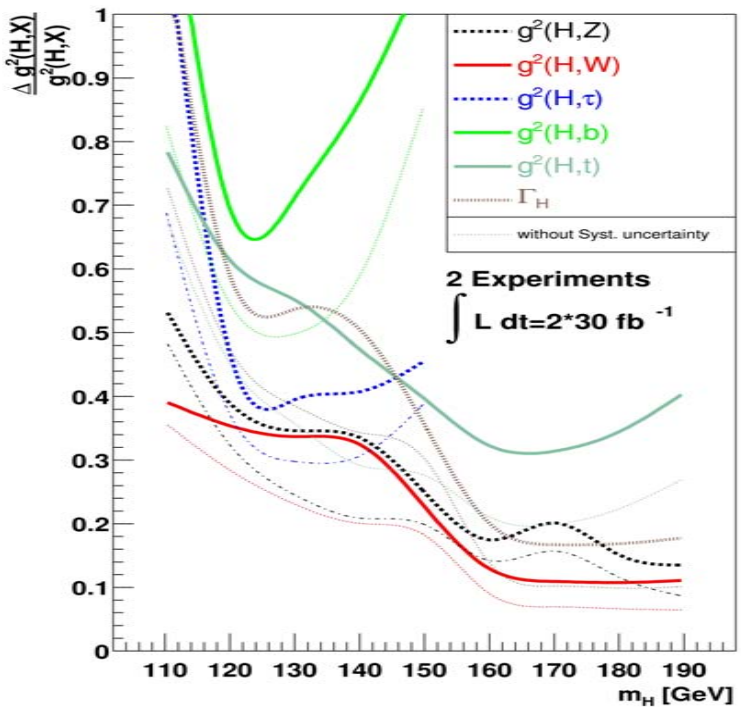
- Measure spin/parity $J^{PC} = 0^{++}$

- 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

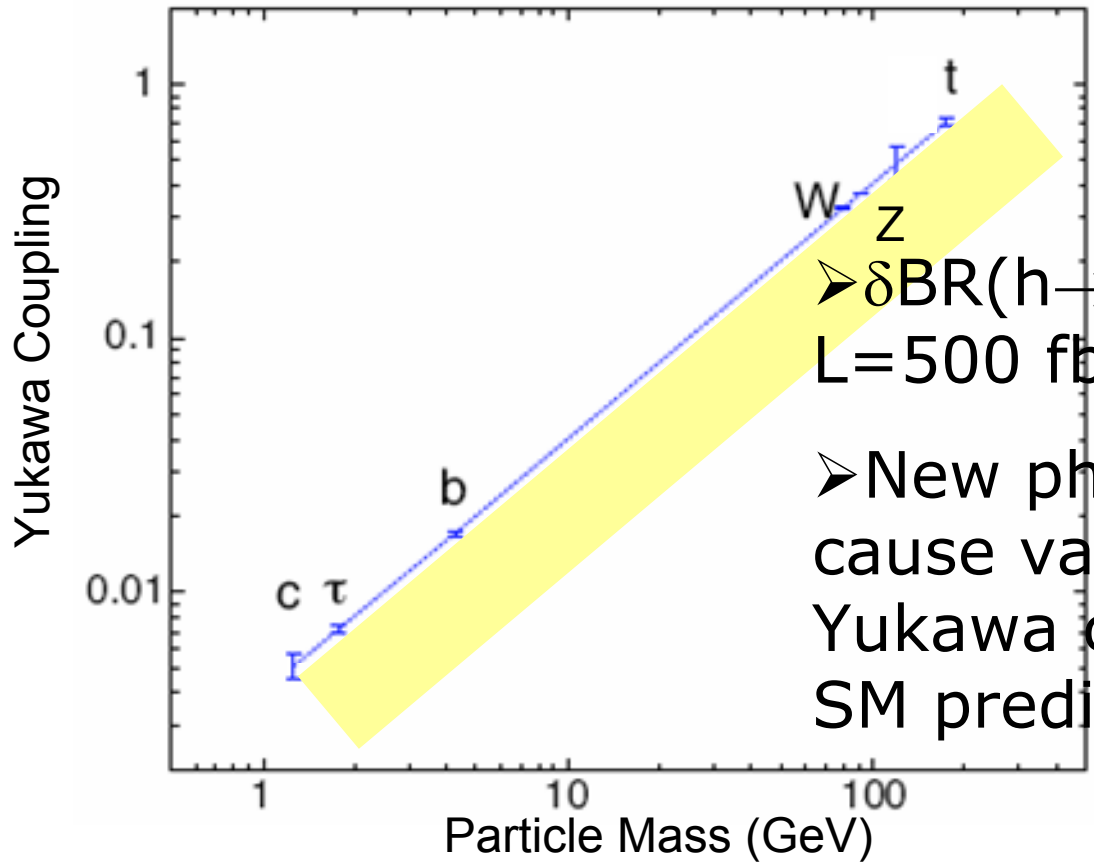


Extraction of couplings requires understanding NLO QCD corrections for signal & background

Ratios of couplings easier

Logan, hep-ph/0409026

ILC Goal: Precision Measurements of Yukawa Couplings



- δBR(h$\rightarrow$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….

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

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

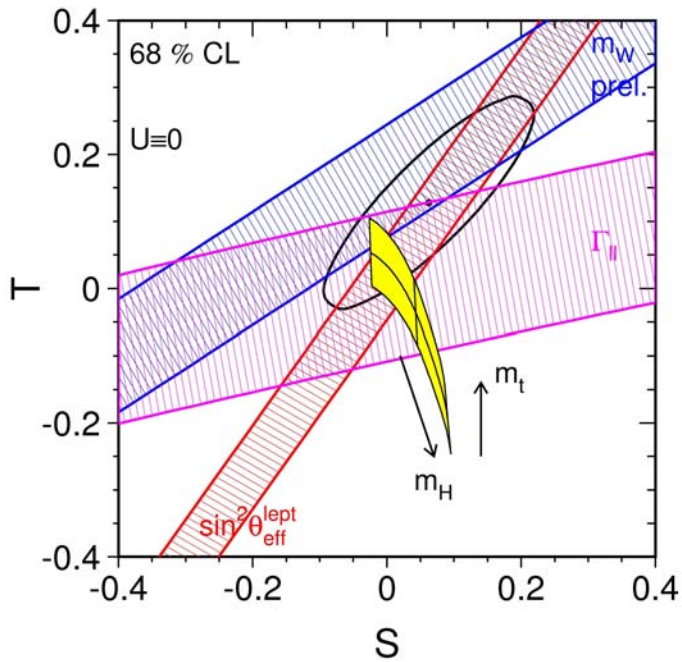
Schmaltz, hep-ph/0502182

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…..



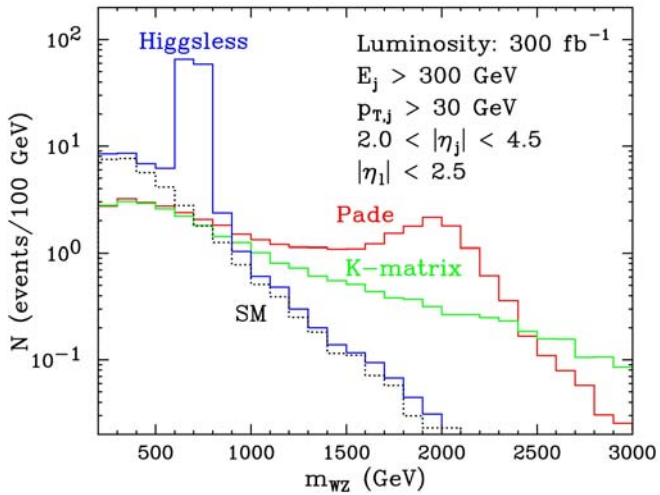
What if no Higgs?

- Technicolor models unitarize WW scattering with ρ-like particle
- Extra dimension models have new possibilities for EWSB
  - Higgs could be 5^{th} 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: $pp \rightarrow WZ + X$



Different resonance structure from SM!

Birkedal, Matchev, Perelstein, hep-ph/0412278

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