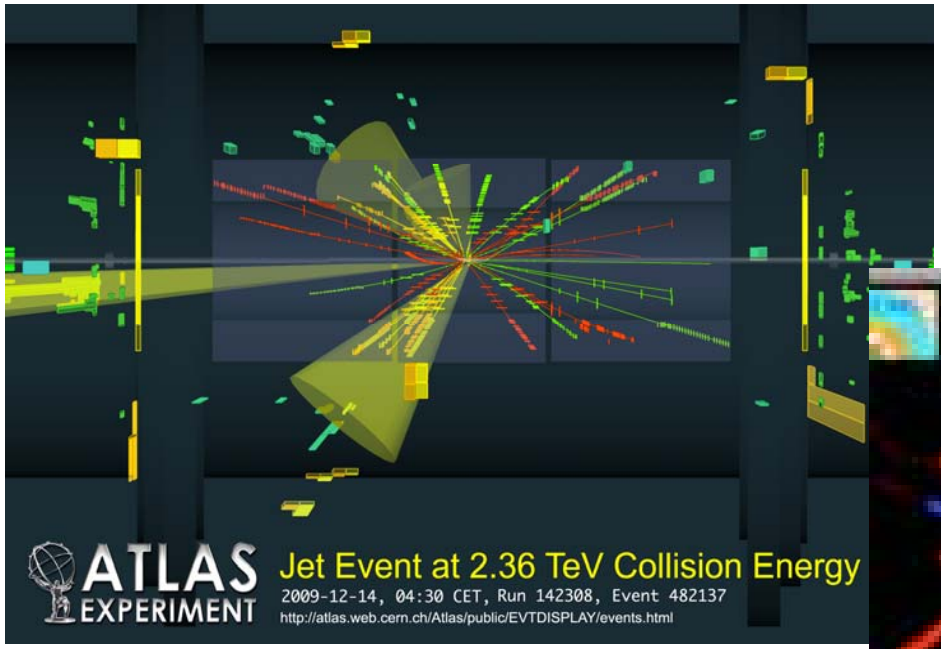
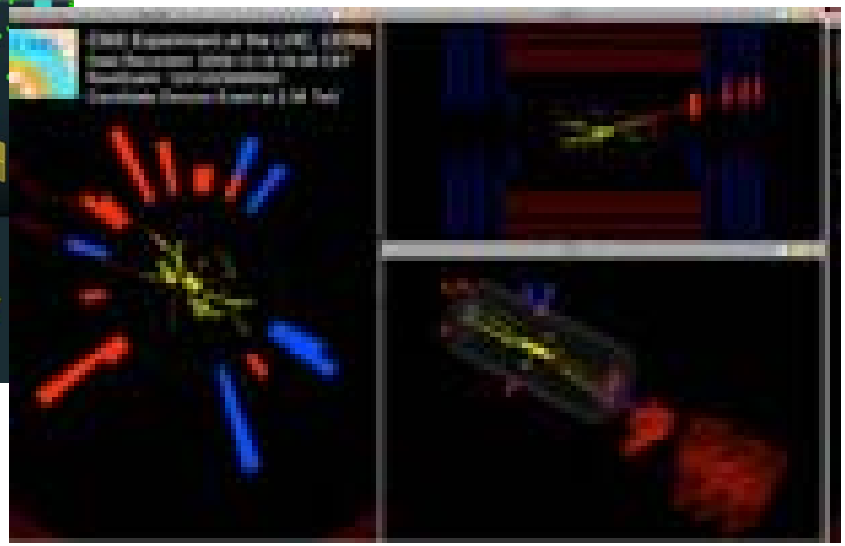
The LHC and Beyond
Spring, 2010

Sally Dawson, BNL





Large Hadron Collider (LHC)

- proton-proton collider at CERN
  - First collisions, March 30, 2010!
- Goal: 14 TeV energy
  - 7 mph slower than the speed of light
  - *cf*. 2TeV @ Fermilab

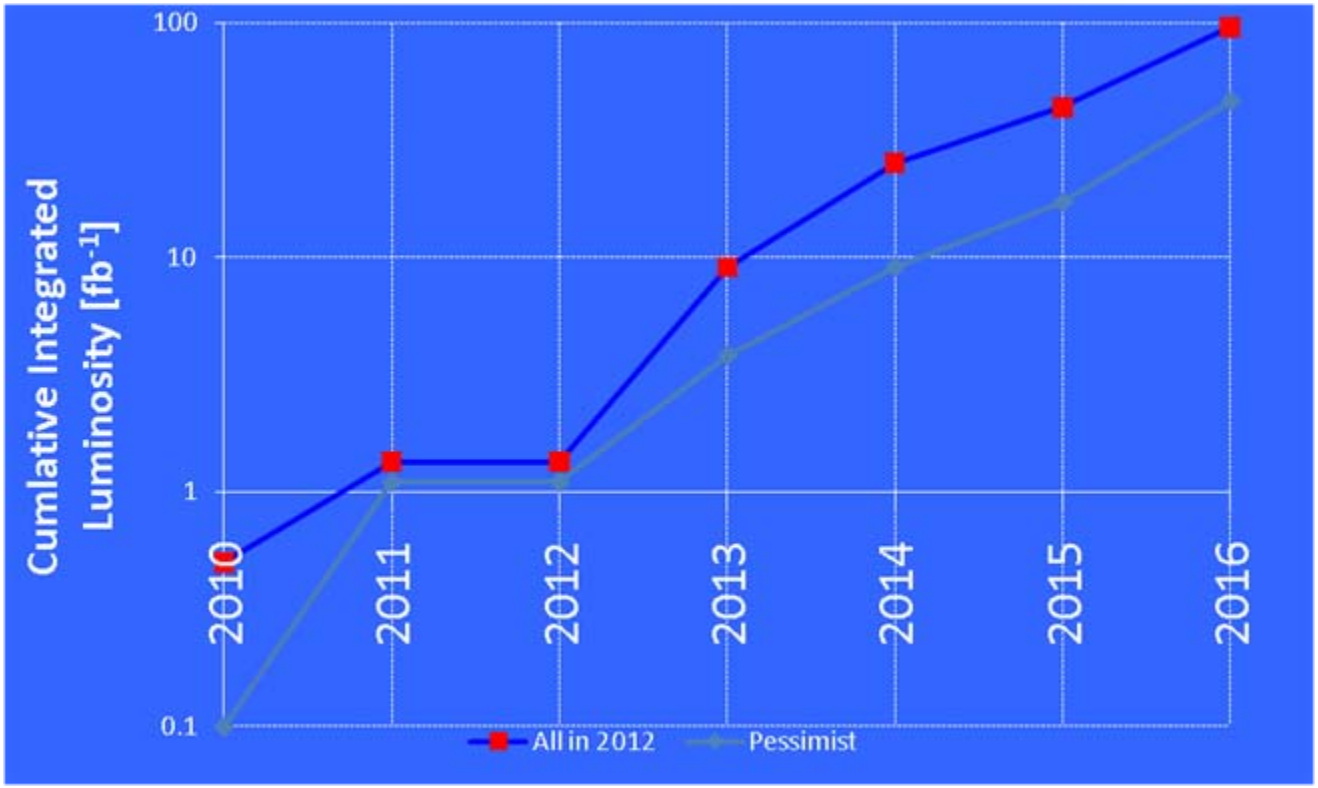
    (307 mph slower than the speed of light)
- Typical energy of quarks and gluons 1-2 TeV

We have been waiting a long time

- SSC (pp @ 40 TeV) cancelled in 1993
  - Physics of the LHC is the physics of the SSC
- LHC is running at $\sqrt{s}$=7 TeV until 1 fb^{-1} of data collected
  - What will we learn from this?
  - What's next?
  - The importance of precision calculations

LHC Plan

- Run for 1 year at $\sqrt{s}$=7 TeV to get 1 fb^{-1}
- Shut down for a year, then $\sqrt{s}$=12-14 TeV

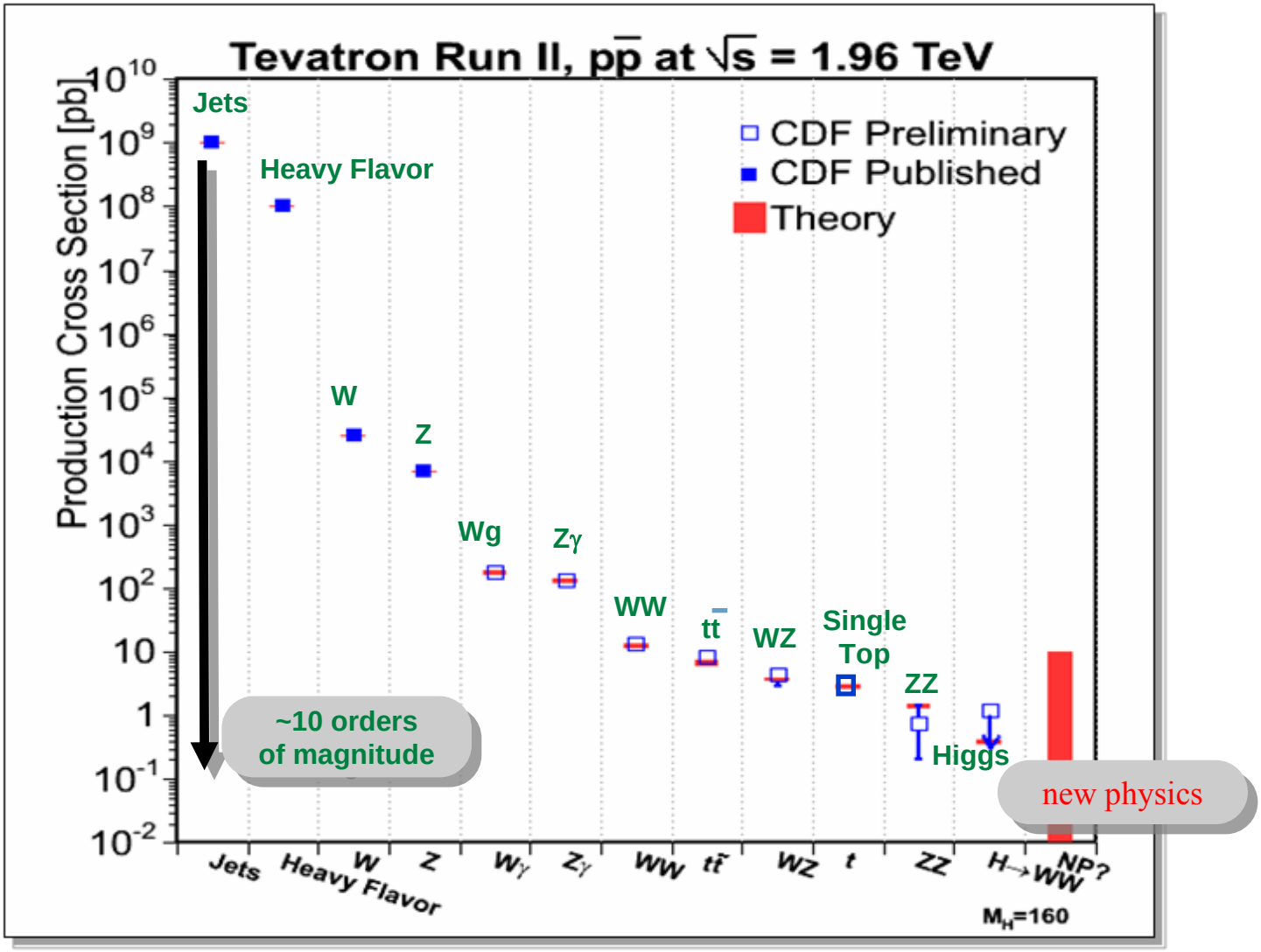


Many Discoveries in Last Decade

- Tevatron discovered the top quark
- Precision measurements from LEP/SLD/Tevatron limit new physics
- Dark matter and dark energy
- Calculational tools greatly improved

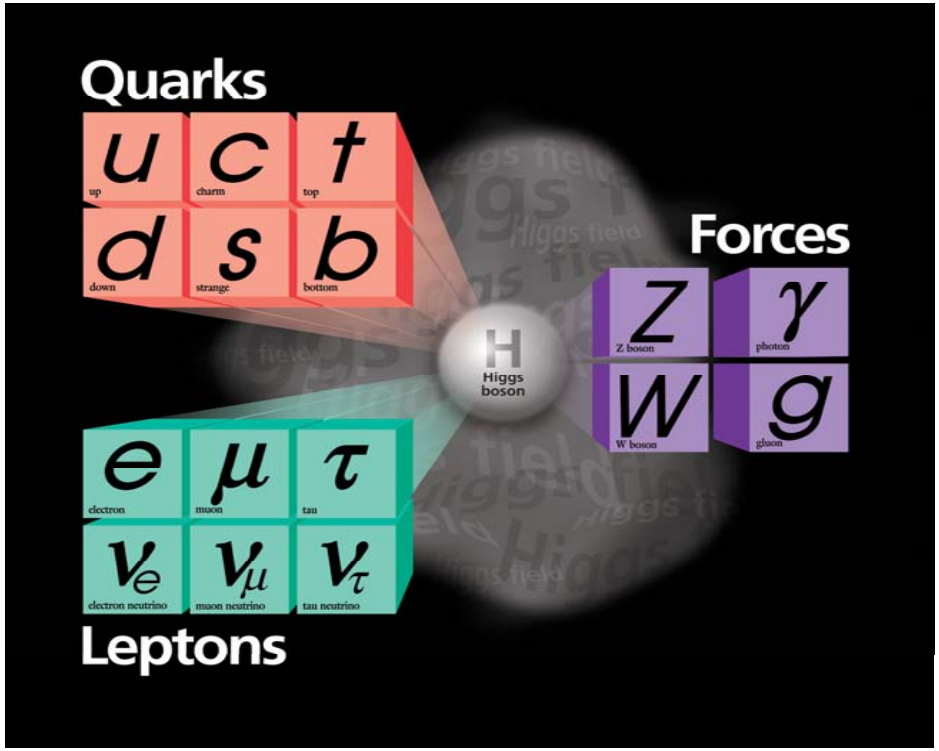
MANY PREDICTIONS
FOR LHC PHYSICS

Many Discoveries at the Tevatron



Standard Model

- Particle physics has a “Standard Model” of particles and their interactions



Quarks come in pairs with charge 2/3 e and -1/3 e

Each lepton has its own neutrino

Force carriers communicate between quarks and leptons

Forces

- Strong, weak, electromagnetic, gravity
- Force carriers: gluon, W/Z bosons, photon
- Standard Model is SU(3) x SU(2) x U(1) gauge theory
- Gluon and photon are massless
- W/Z are very heavy…..WHY?????

Masses for Gauge Bosons

- Why are the W and Z boson masses non-zero?
- U(1) gauge theory with single spin-1gauge field, A_μ

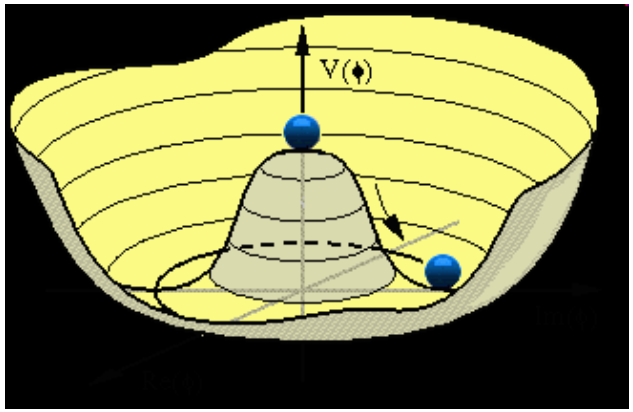
$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \qquad F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

- U(1) local gauge invariance: $A_\mu(x) \to A_\mu(x) - \partial_\mu \eta(x)$
- Mass term for A would look like: $L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2 A_\mu A^\mu$
- Mass term violates local gauge invariance
- We understand why $M_A = 0$

Gauge invariance is guiding principle

Wanted

- Wanted….gauge invariant way to give mass to W/Z
- Solution is “Higgs Mechanism”
- Relies on broken symmetry



Choice of minimum breaks symmetry

Higgs Mechanism in a Nutshell

- Add a complex scalar Higgs doublet (4 free parameters)
- Couple Higgs doublet to gauge fields
- 3 degrees of freedom are absorbed to give longitudinal degrees of freedom to W^+, W^-, Z
- 1 scalar degree of freedom remains
  - This is physical Higgs boson, H
  - Necessary consequence of Higgs mechanism

Gauge invariant mechanism to give mass to W and Z

Standard Model is Inconsistent Without a Higgs boson

- n
n
- s

Solution requires physical scalar particle: THE HIGGS BOSON

M_H is ***ONLY*** unknown parameter

No evidence (yet) for existence of Higgs boson

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

Higgs Couplings Fixed

- Higgs couples to fermion mass
  - Largest coupling is to heaviest fermion
  - Top-Higgs coupling plays special role?
  - No Higgs coupling to neutrinos
- Higgs couples to gauge boson masses
- Only free parameter is Higgs mass!
- Everything is calculable….***testable theory***

Theory is Predictive

Theory has only a few free parameters

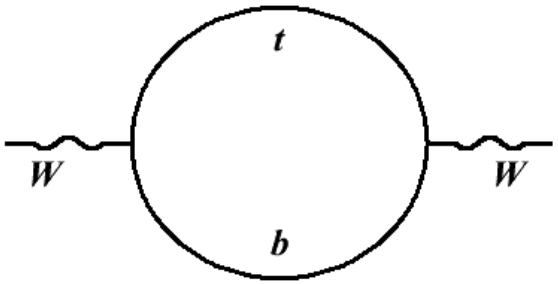
- Mass of the Z boson, M_Z=91.1875 $\pm$ .0021 GeV
- Strength of the coupling of the photon to the electron, α=1/137.0359895(61)
- Strength of the weak interactions (measured in muon decay) G_F=1.16637(1) x 10^{-5} GeV^{-2}
- Then the W mass is predicted

W Boson Mass

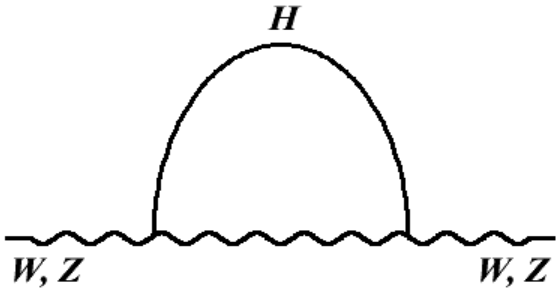
$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F\,(1 - M_W^2/M_Z^2)(1 - \Delta r)}$$

Δr: Quantum corrections dominated by top/bottom and Higgs loops

$\Delta M_W \propto M_t^2$



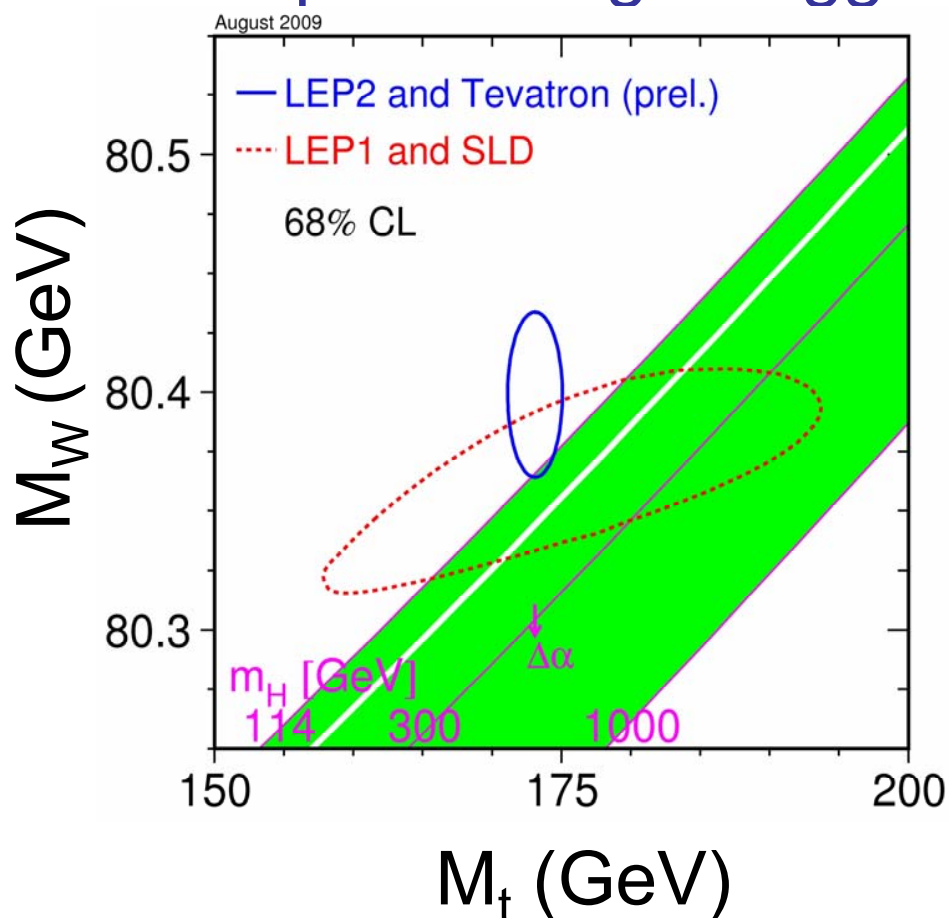
$\Delta M_W \propto \ln (M_H/M_Z)$



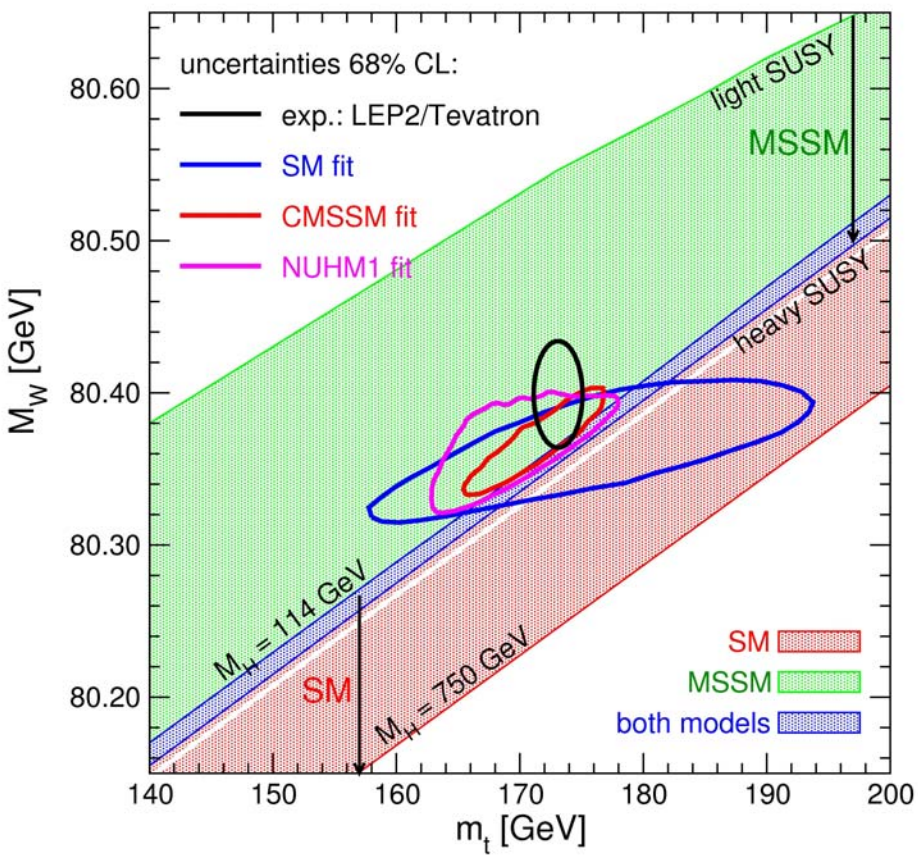
Top Quark Mass Restricts Higgs Mass

- Direct observation of W boson and top quark (blue)
- Inferred values from other measurements (red)

Data prefer a light Higgs



Supersymmetry is favorite alternative

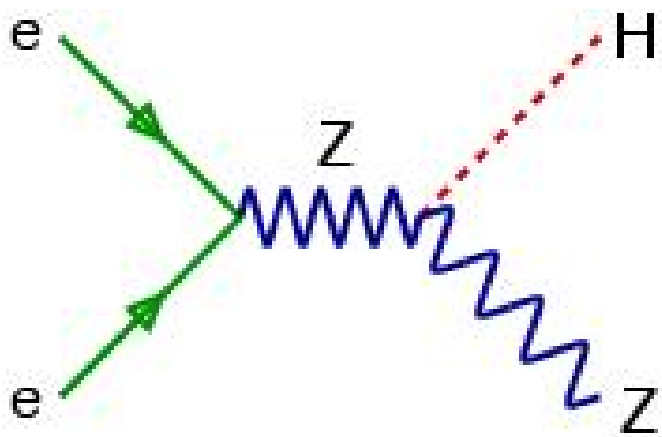


SUSY is slightly better fit than SM

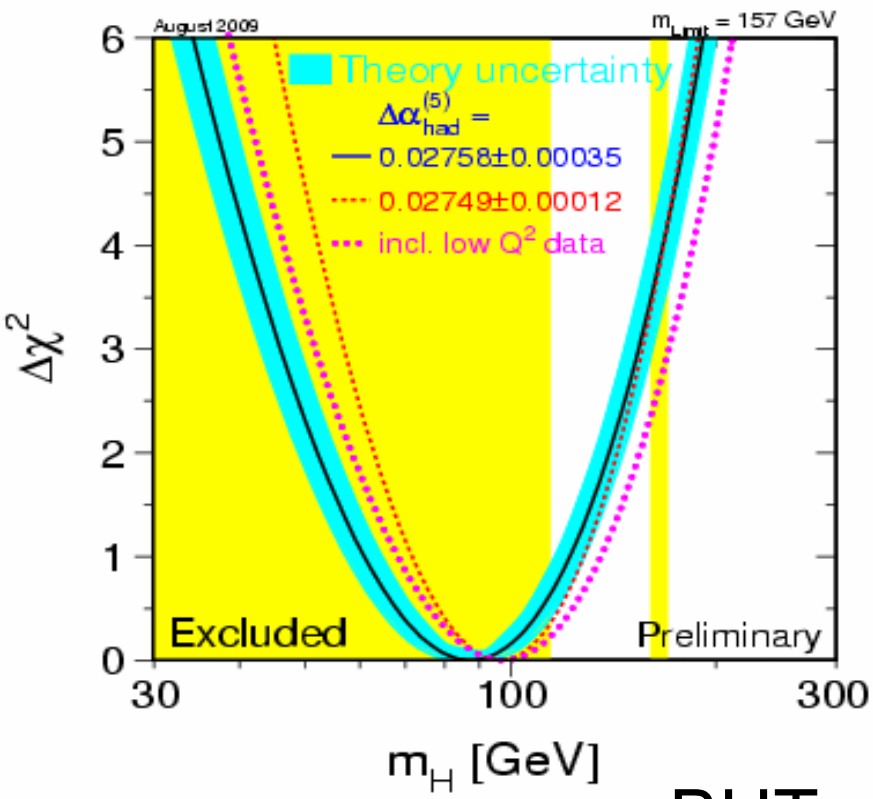
Buchmueller et al, arXiv:0912.1036

LEP Looked for the Higgs

- Looked for $e^+e^- \rightarrow Z\,H$
- Excluded a Higgs boson up to M_H=114 GeV
- This limit assumes a Higgs boson with the properties predicted by the Standard Model



EW measurements suggest light Higgs

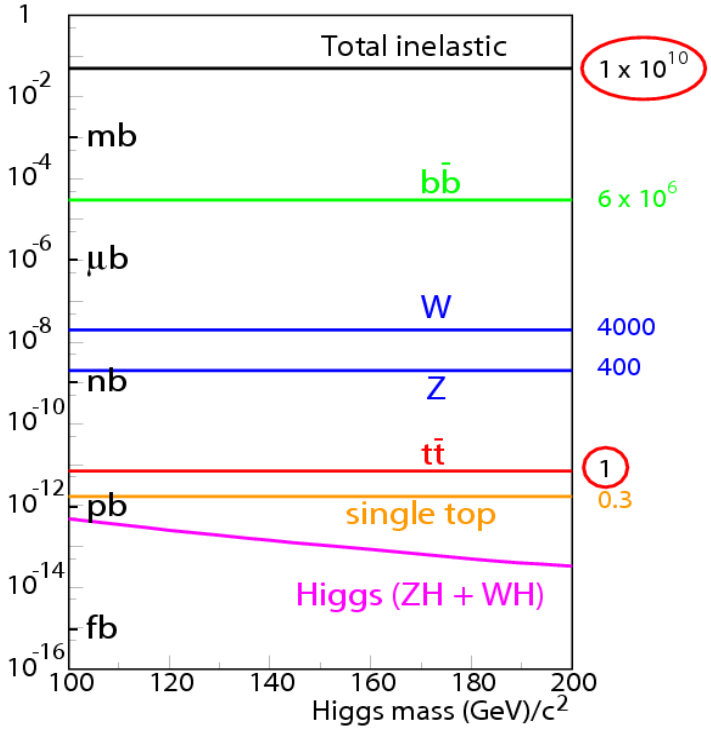


- $M_H = 87^{+35}_{-26}$ GeV (68% CL)
- M_H < 186 GeV (Precision measurements plus direct search limit)

BUT…..Fits assume SM with weakly interacting Higgs boson

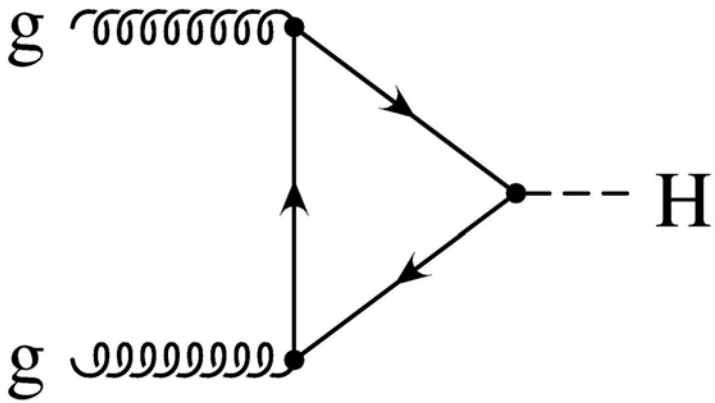
Higgs at the Tevatron

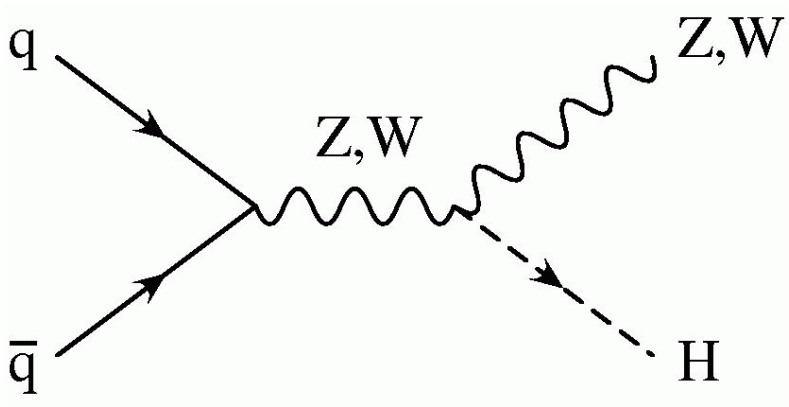
- Largest rate, gg→H, H $\rightarrow b\bar{b}$, is overwhelmed by background

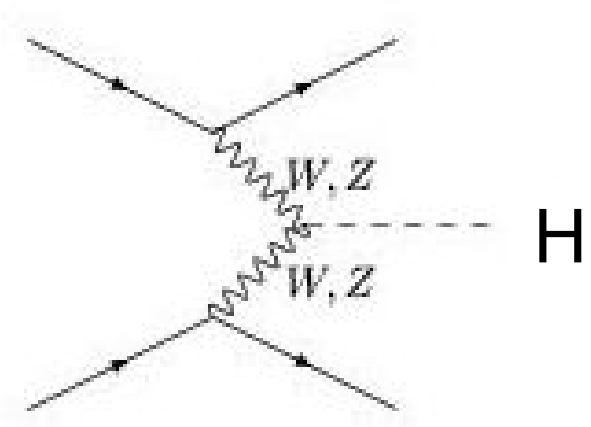


$$\sigma(gg\rightarrow H)\sim 1\ \text{pb} << \sigma(b\bar{b})$$

Higgs Production

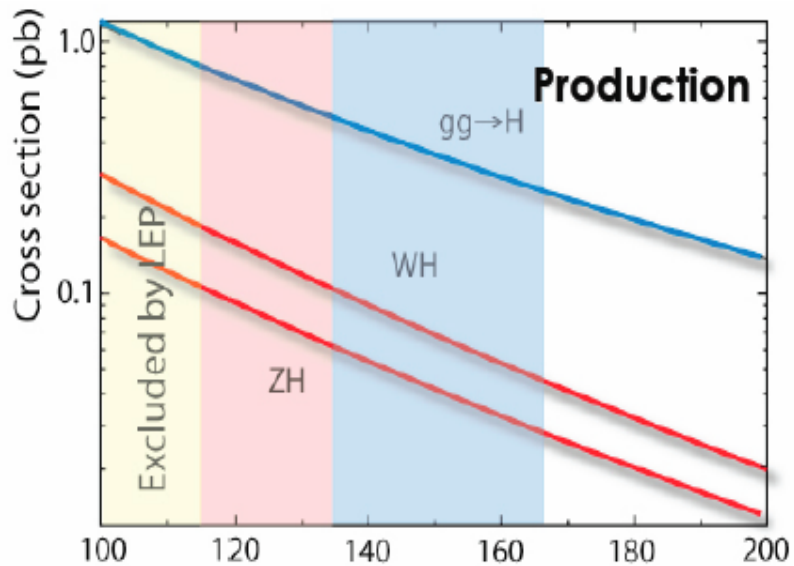


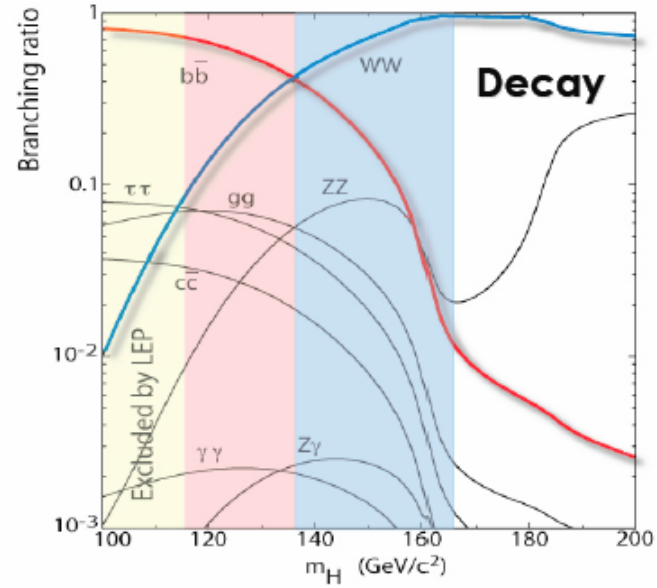




Different mechanisms important for different M_H

Higgs at the Tevatron





High mass: Look for $H \to W^+W^- \to l\nu l\nu$

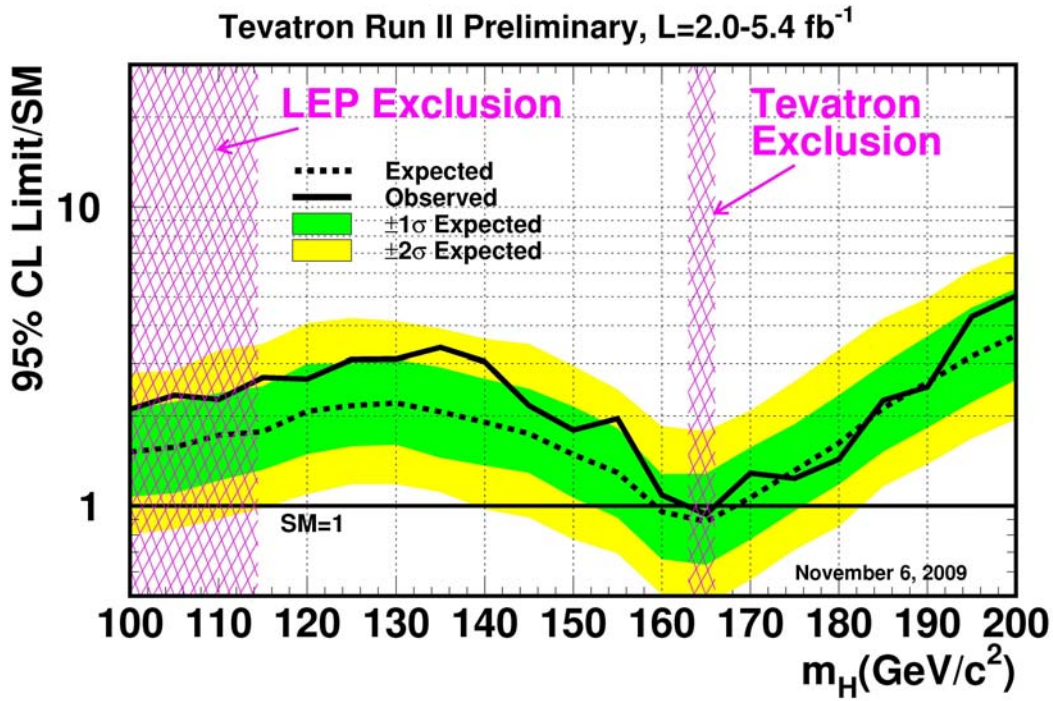
Large gg→H production rate

Low Mass: $H \to b\bar{b}$, Huge QCD $b\bar{b}$ background

Use associated production with W or Z

What's Wrong with the SM?

- We haven't seen the Higgs

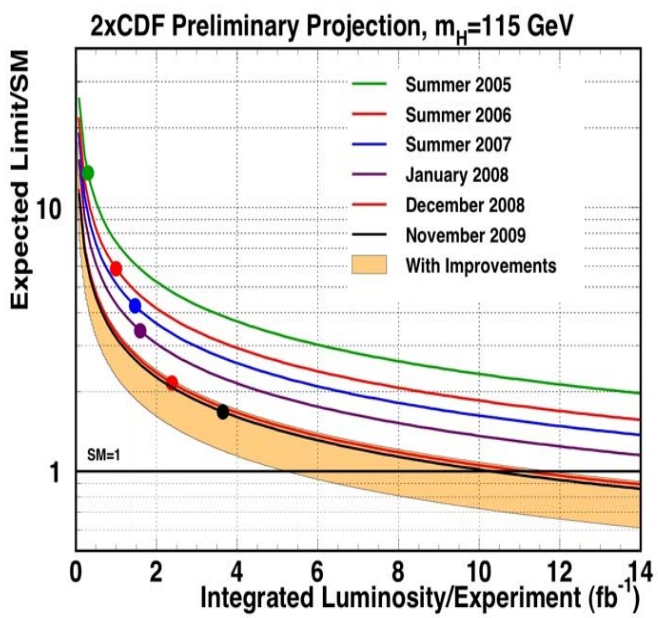


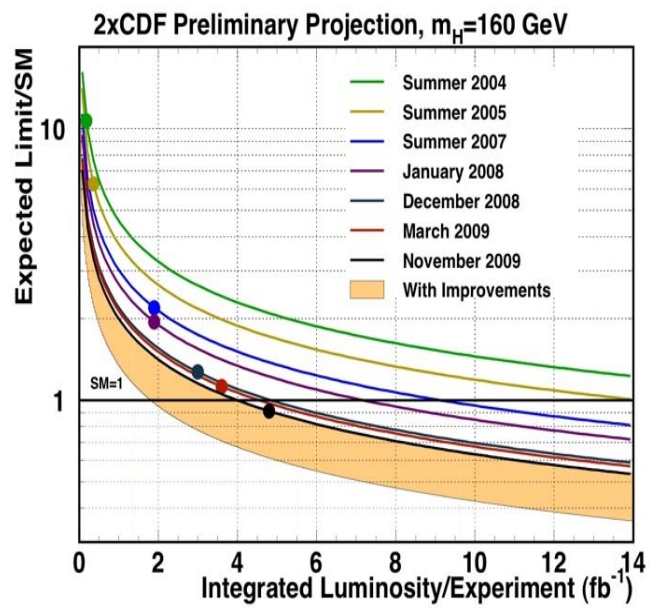
$$M_H = 165\,GeV \rightarrow \sigma = 389.0\ fb^{+8.1\%}_{-11.7\%}\ (scale)^{+13.6\%}_{-12.0\%}(\alpha_s + PDF)$$

Need theory for exclusion!

Tevatron Limit

- Combines many channels
- Current limit 163 GeV < M_H < 166 GeV

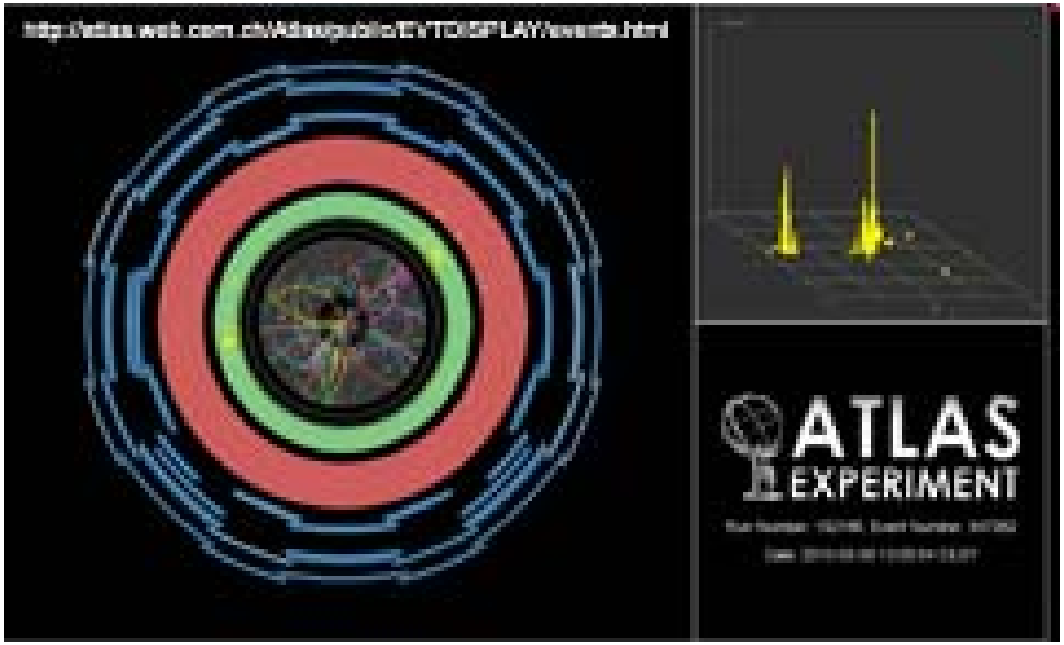




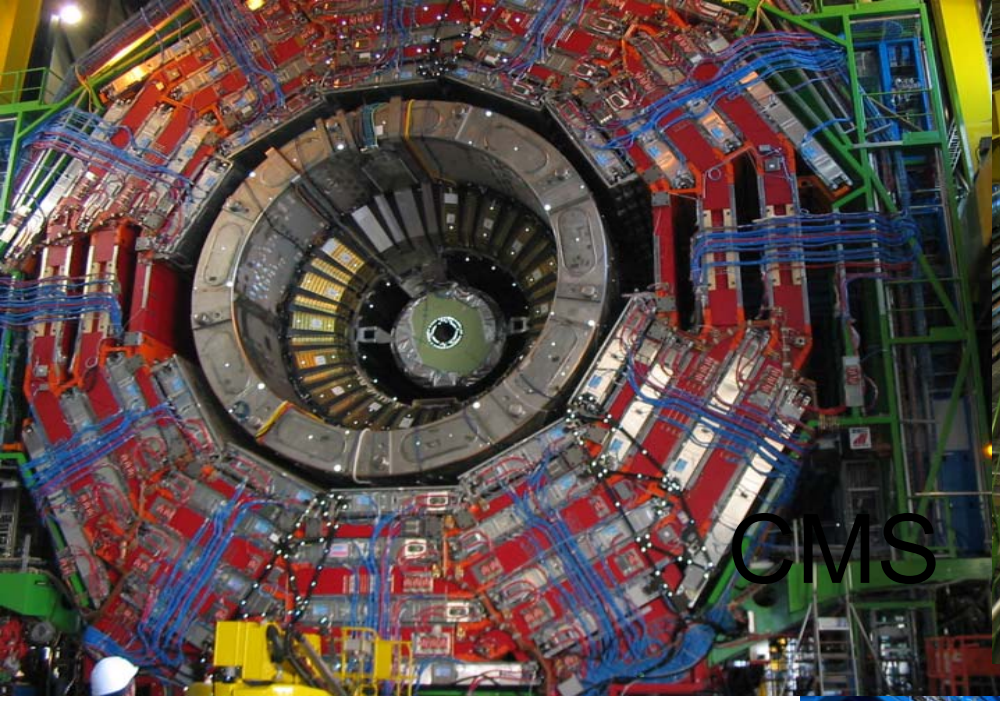
Anticipate 10 – 12 fb^{-1}…..Stay tuned….

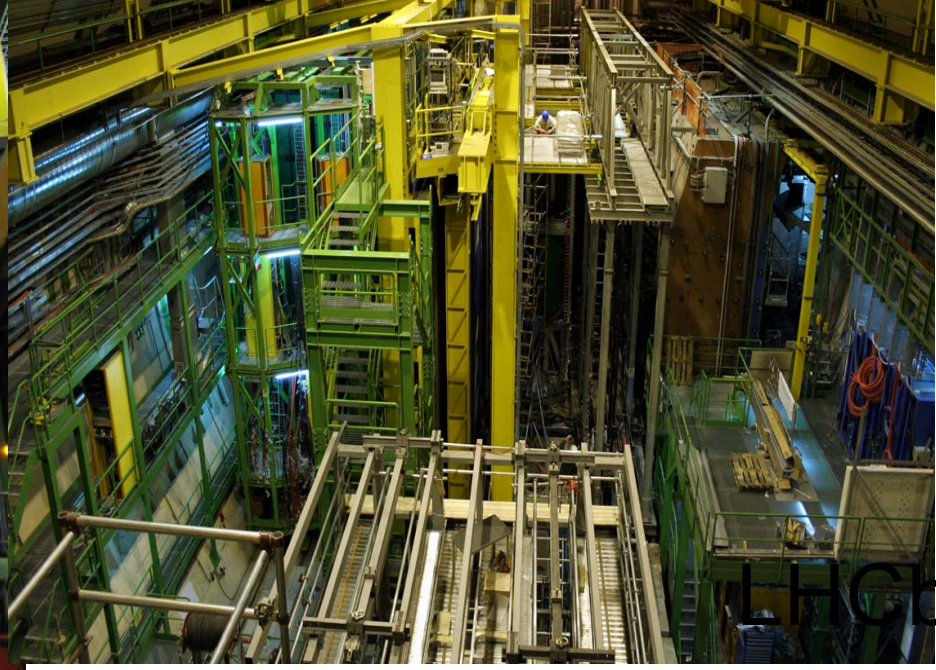
Forward to the LHC

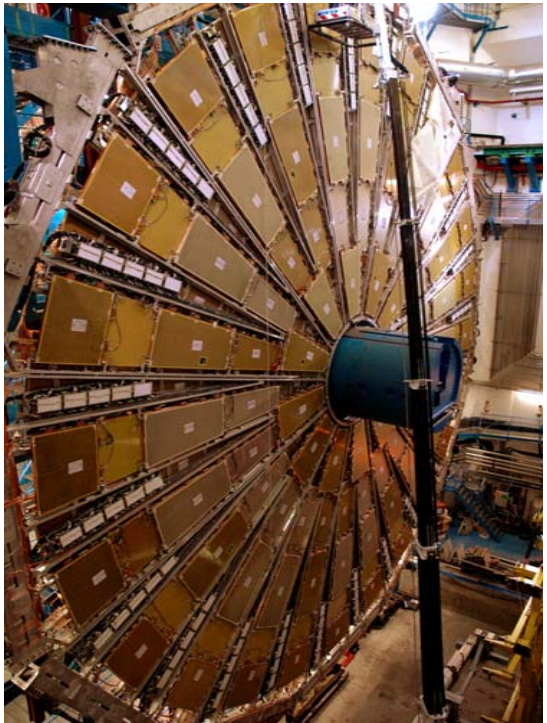
- LHC probes many new types of physics
- I will focus on the potential for discovering (or excluding) a Standard Model Higgs boson

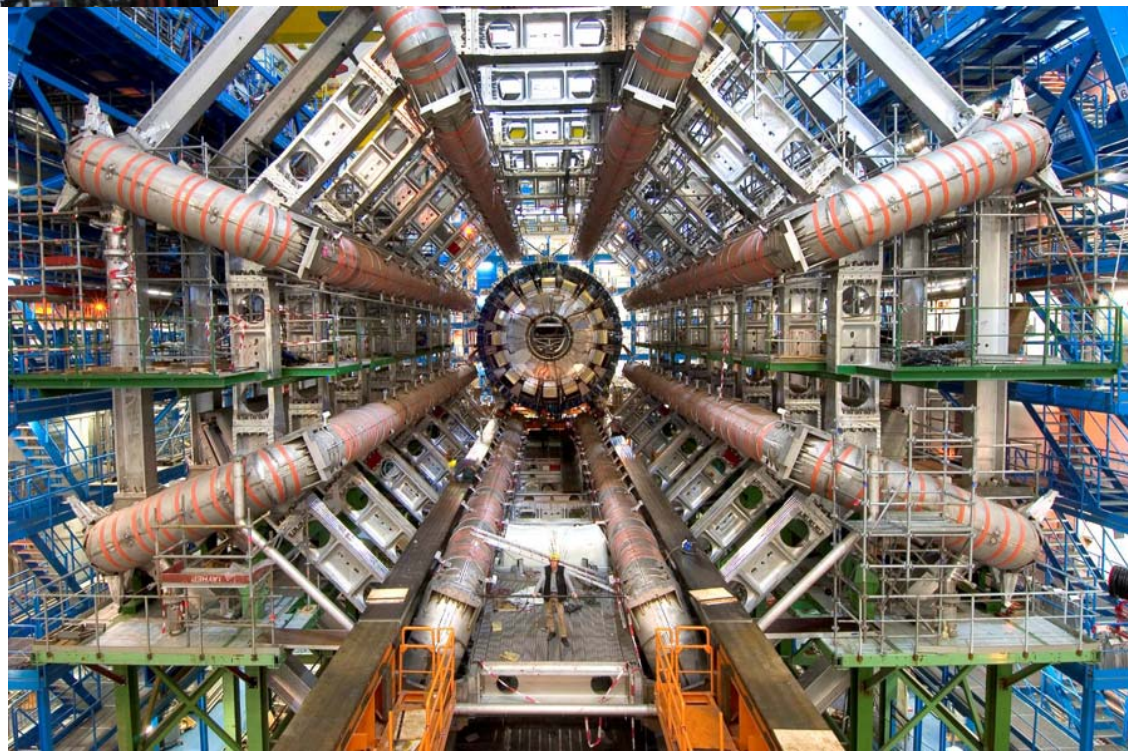


Jet event

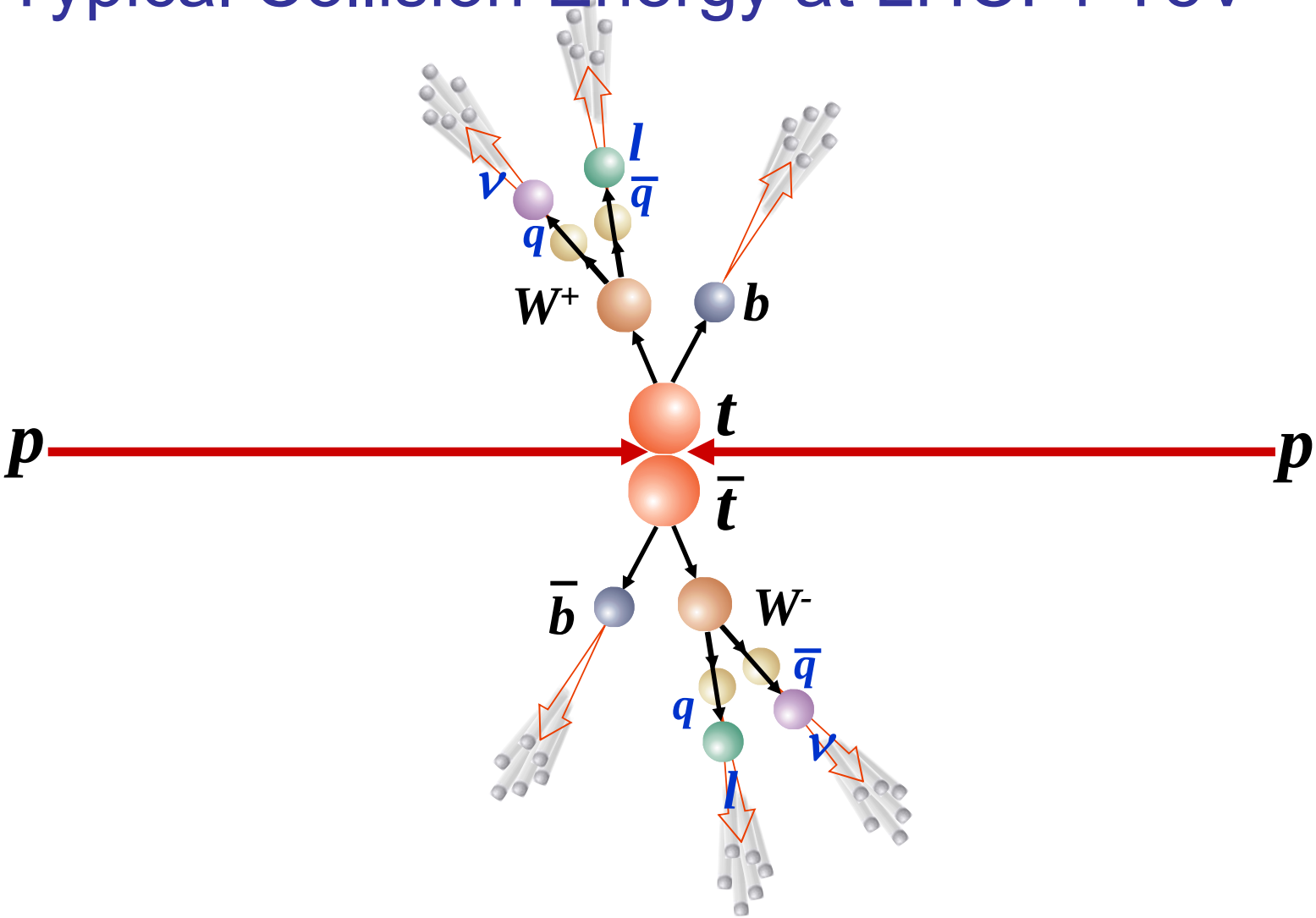

CMS


LHCb

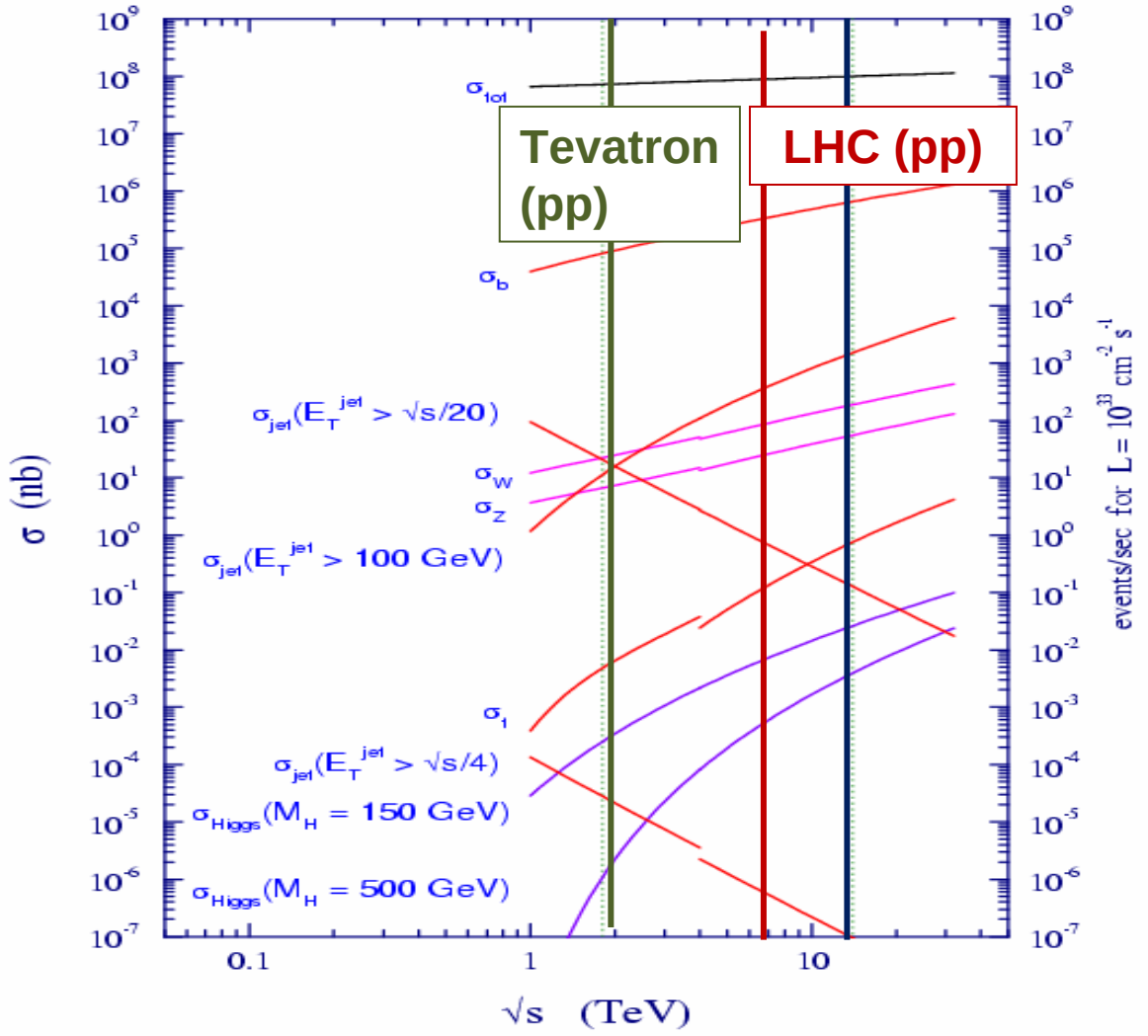




Typical Collision Energy at LHC: 1 TeV



From the Tevatron to the LHC



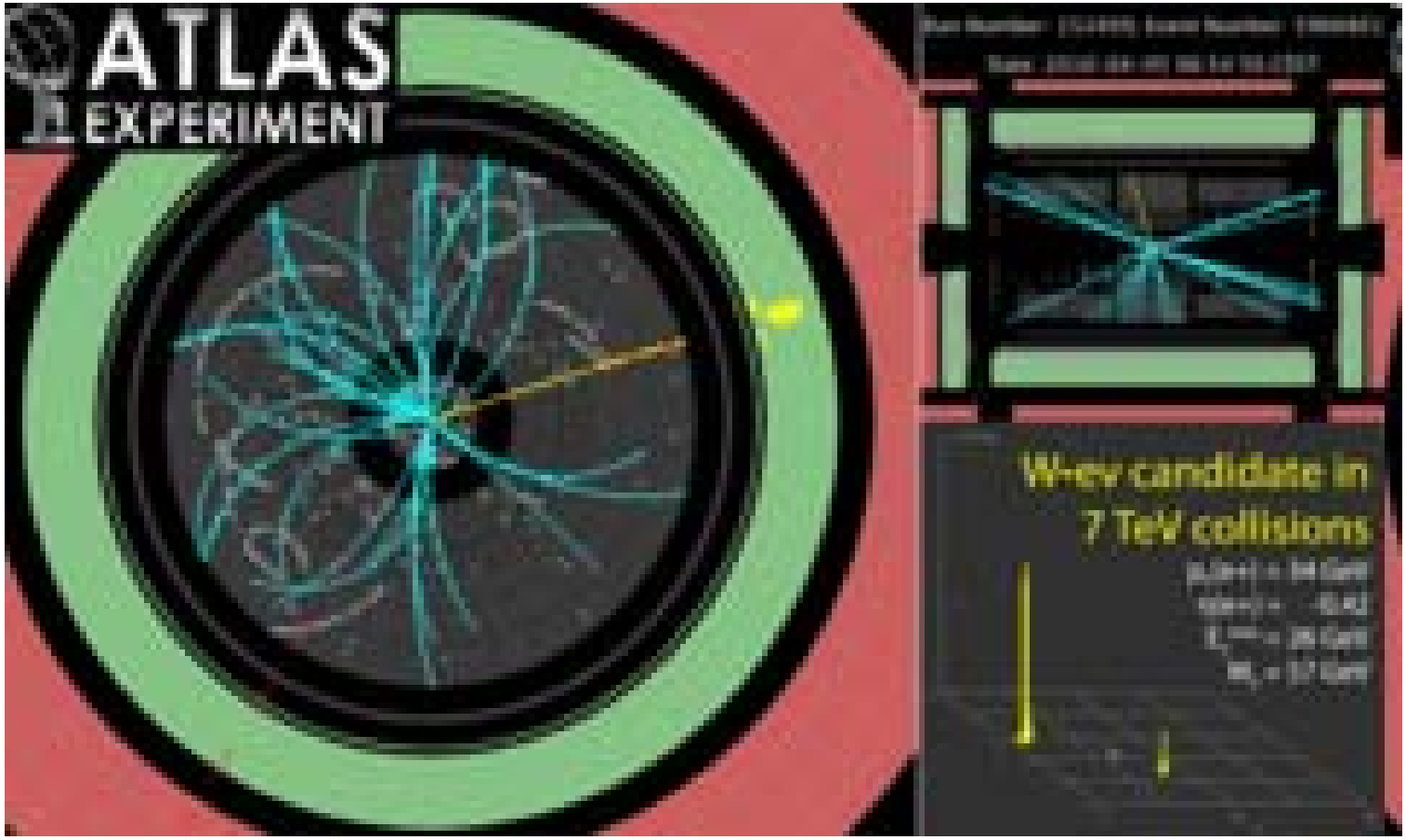
Large increase in cross sections as we go from the Tevatron to the LHC

Early Physics at the LHC

Channel	Events/fb^{-1} At 14 TeV LHC	Previous # of Events
$W \rightarrow \mu\nu$	10^6	10^4 LEP, 10^6 Tevatron
$Z \rightarrow e^+e^-$	10^6	10^7 LEP, 10^5 Tevatron
$t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow \mu\nu X$	10^5	10^4 Tevatron
QCD jets, p_T>1 TeV	$>10^4$	☺
1 TeV Gluino pairs	500	☺

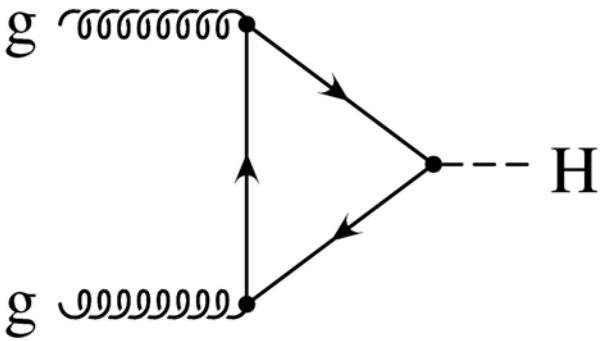
Rediscover SM physics: W, Z, top, QCD

Already observed W candidates



Also have W→μν candidates

Finding the Higgs at the LHC

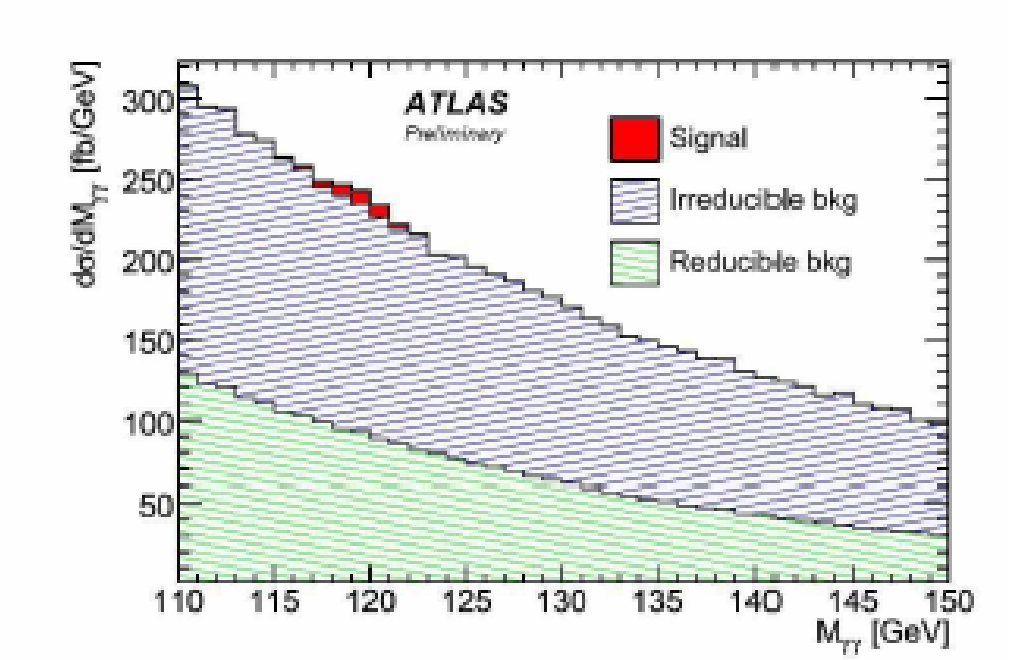


Largest rate

- Rate calculated to next-to-next to leading order
- Inclusion of many small effects
- Uncertainties from parton distribution effects, scale choices, strong coupling uncertainty

Theory uncertainty is ~10%

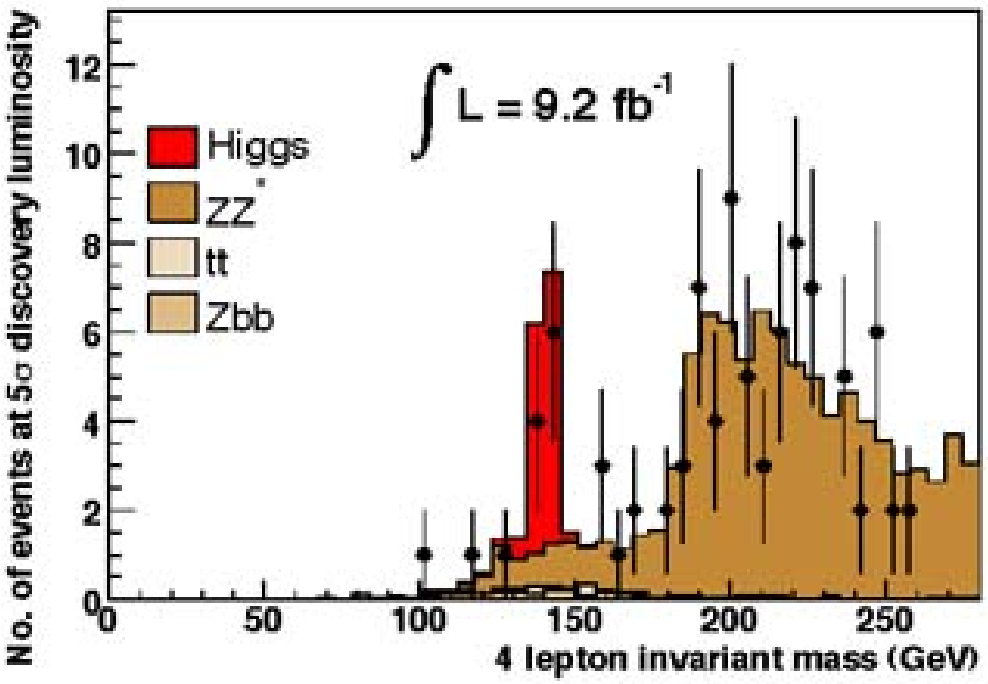
$gg \rightarrow H \rightarrow \gamma\gamma$



- Important for $M_H < 140$ GeV
- Don't need precision theory for resonances….measure background
- Light Higgs is VERY hard at LHC

14 TeV

gg → H→ZZ→(4 leptons)



Golden Mode

Possible discovery with < 10 fb^{-1}

14 TeV

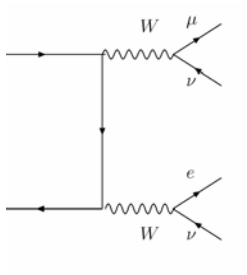
Discovery Signals

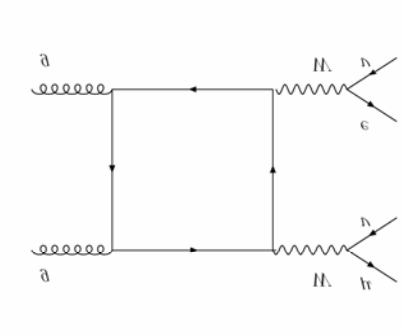
- Mass peaks
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ \rightarrow (\mu^+\mu^-)\ (e^+e^-)$
- Excess of events or anomalous shapes of distributions
  - $H \rightarrow W^+W^- \rightarrow (\mu\nu)\ (e\nu)$
  - No Higgs mass peak because of neutrinos in final state
  - Large QCD background from $q\bar{q} \rightarrow W^+W^-$
  - Need theory here!

Measure backgrounds from sidebands

$H \rightarrow W^+W^- \rightarrow (\mu\nu)(e\nu)$

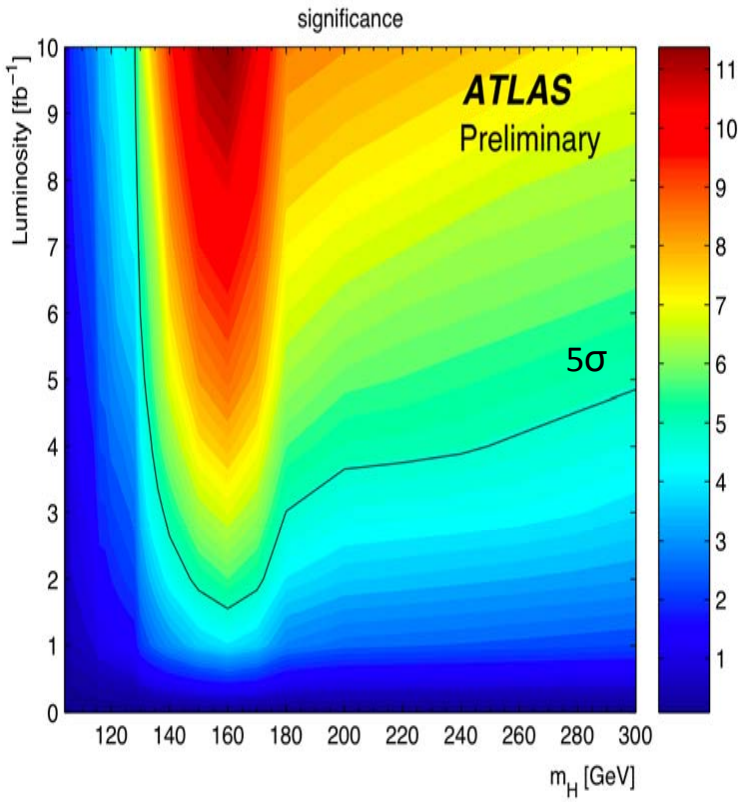
- Experimental cuts sometimes enhance the importance of higher order effects to background





- Formally, higher order, but contributes 30% correction to lowest order prediction for background

ATLAS Discovery with √s=14 TeV

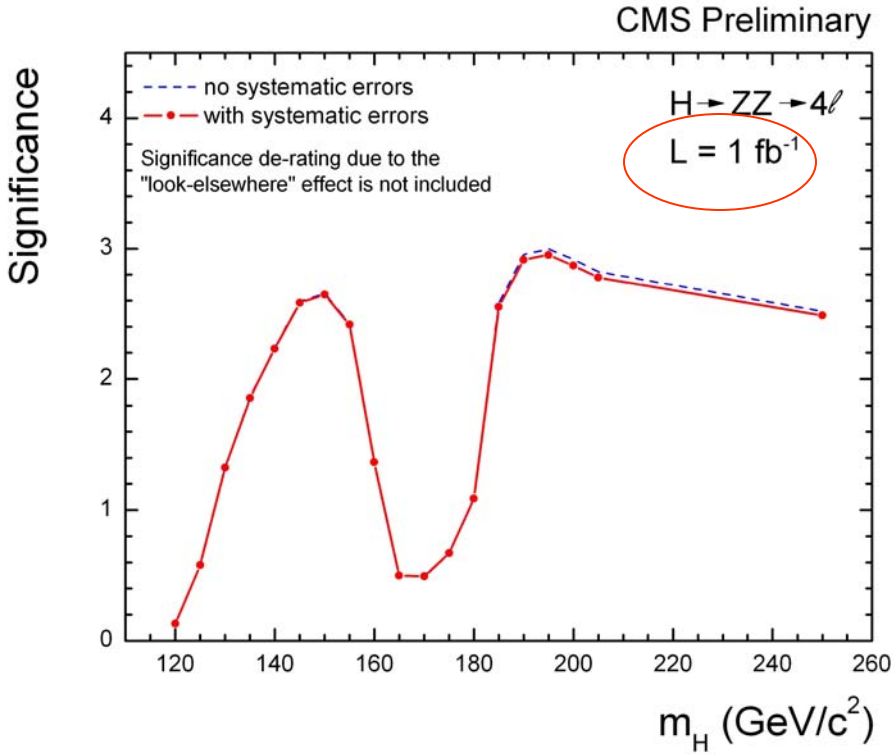


Discovery:

- 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

Significance = 5 is defined as discovery

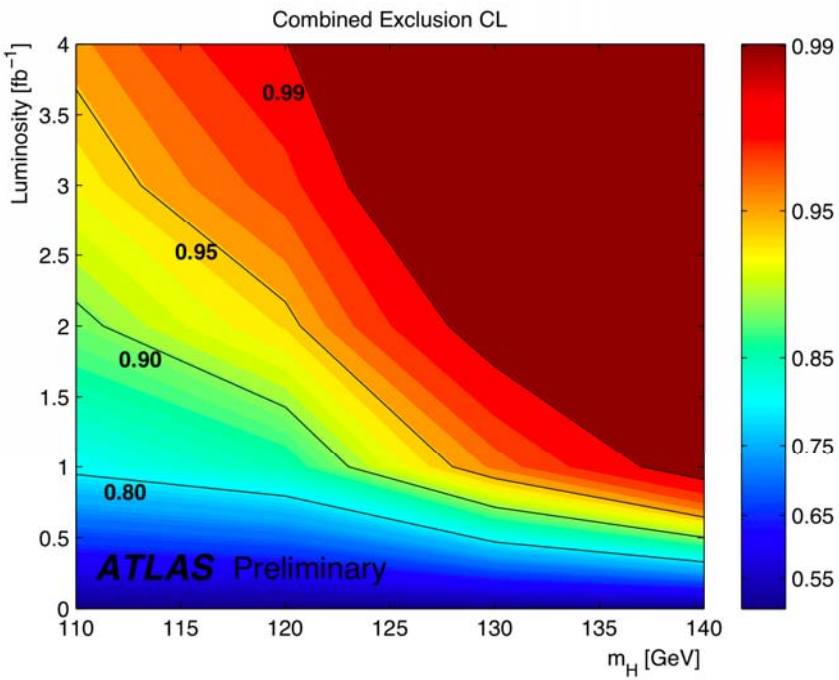
Early LHC Data



Higgs discovery comes later

14 TeV

Exclusion is Easier



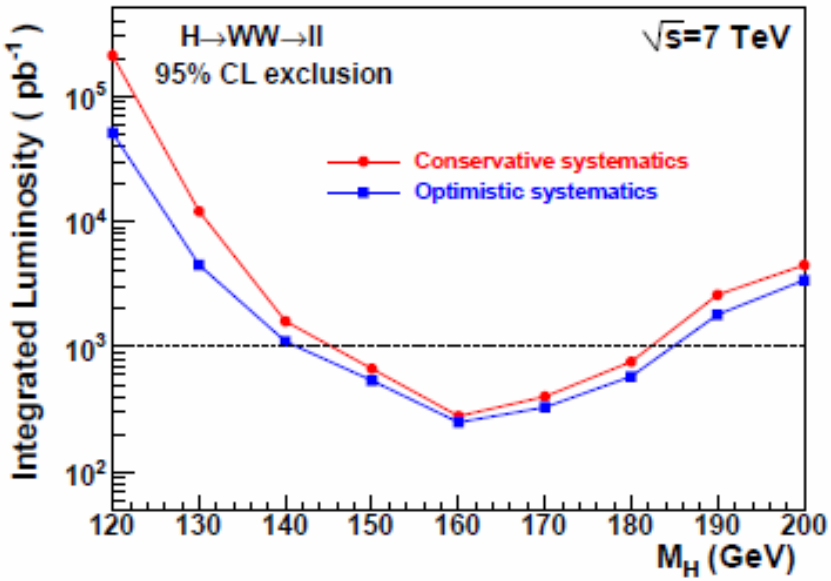
Exclusion:

- 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

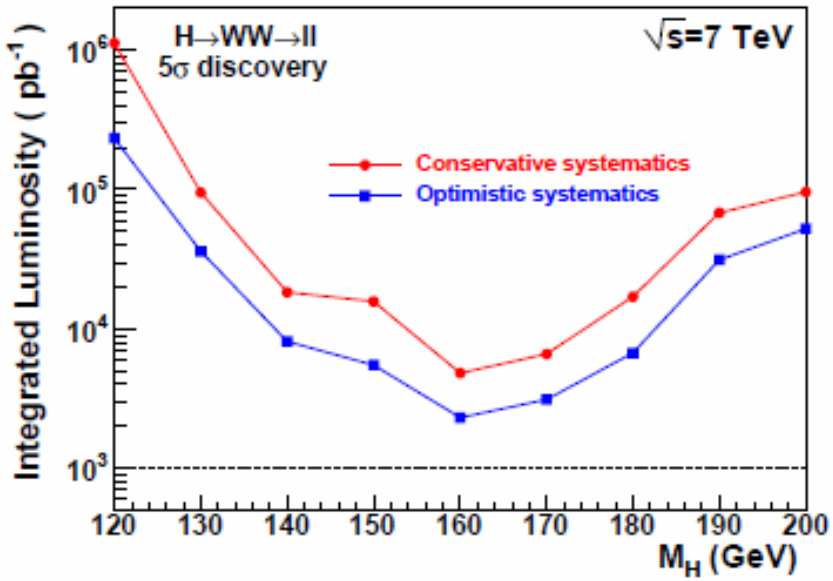
LHC rapidly overtakes Tevatron limit

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

CMS



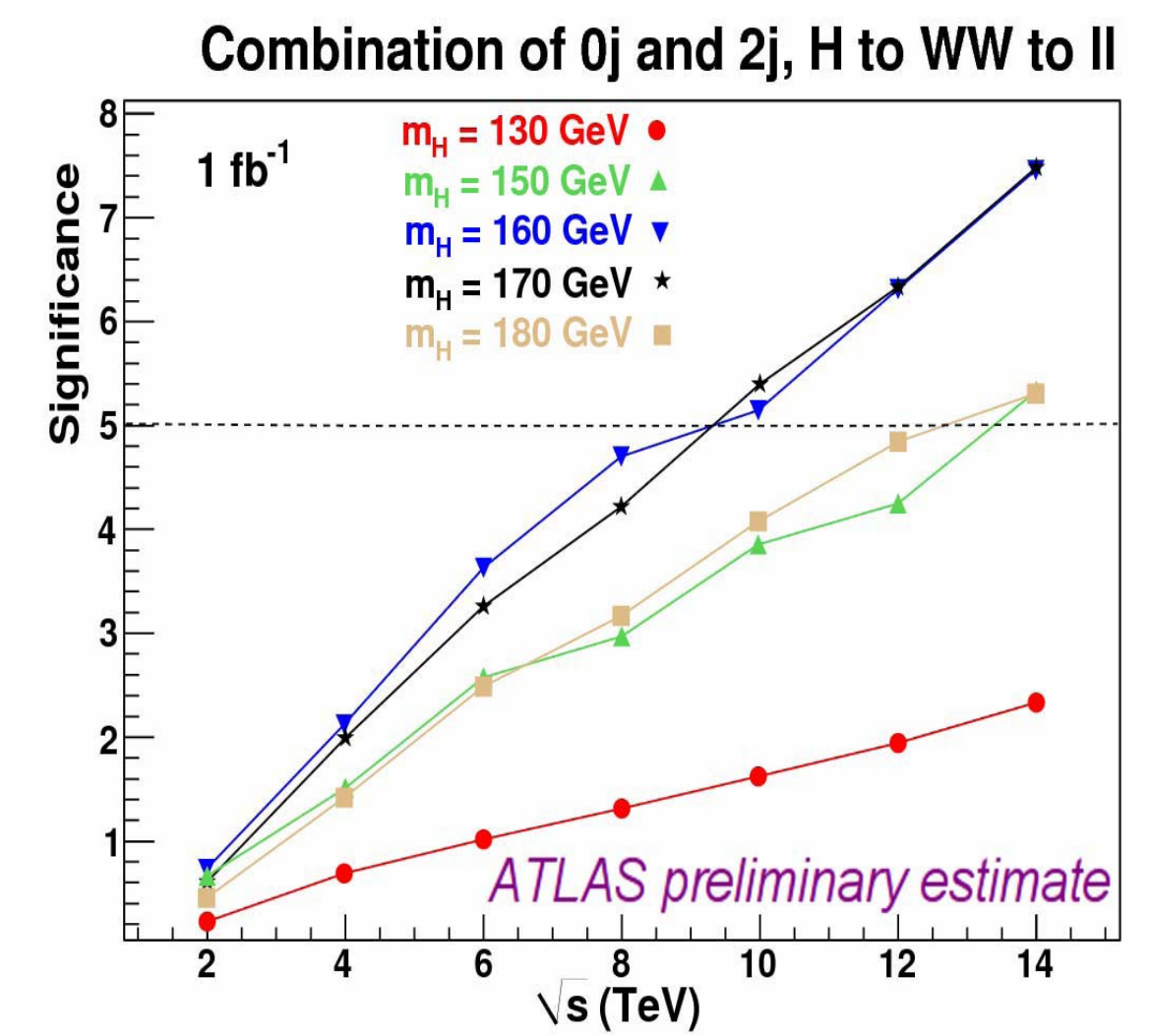
95% C.L. Exclusion



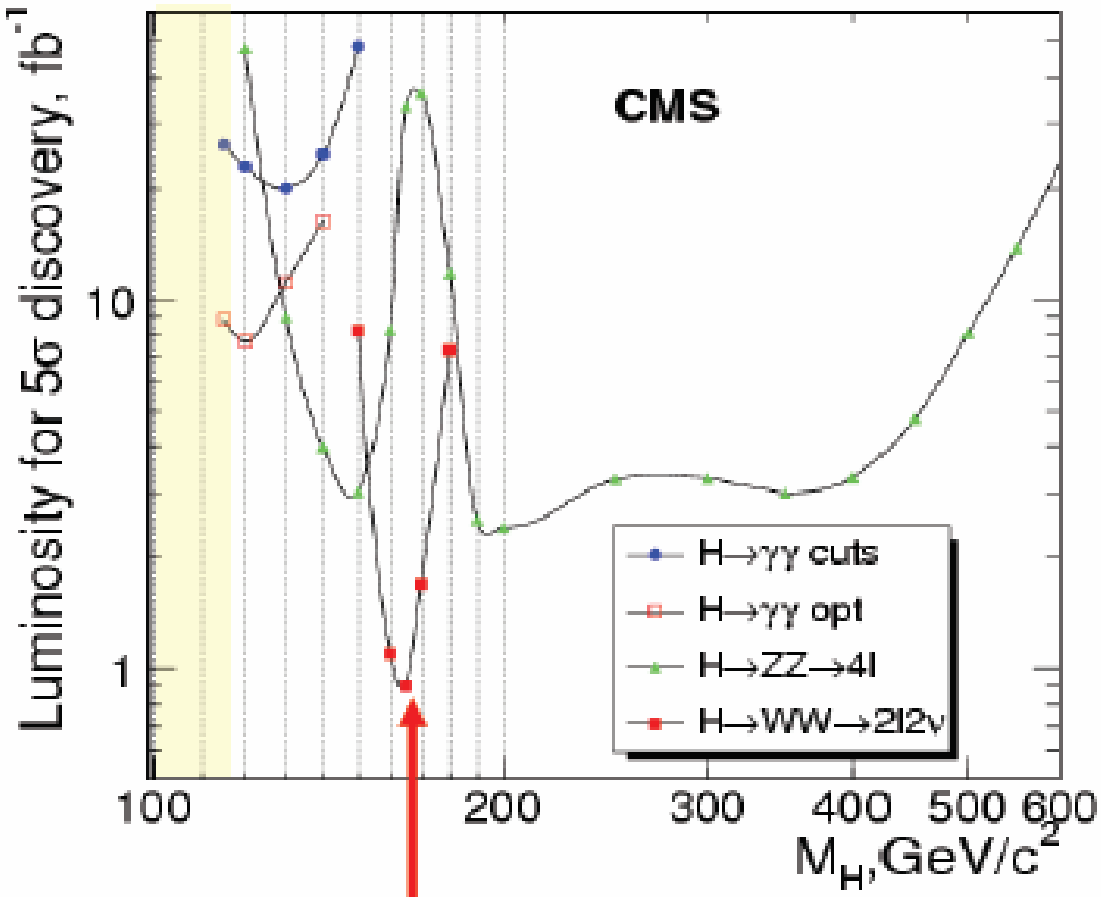
5σ Discovery

- Exclude 140 GeV < M_H < 185 GeV
- Big improvement over Tevatron

With 1 fb^{-1}


Combination of 0j and 2j, H to WW to ll
1 fb-1
mH = 130 GeV
mH = 150 GeV
mH = 160 GeV
mH = 170 GeV
mH = 180 GeV
Significance
√s (TeV)
ATLAS preliminary estimate

Eventually, expect to find Higgs regardless of mass*



Discovery with ~1 fb^{-1}

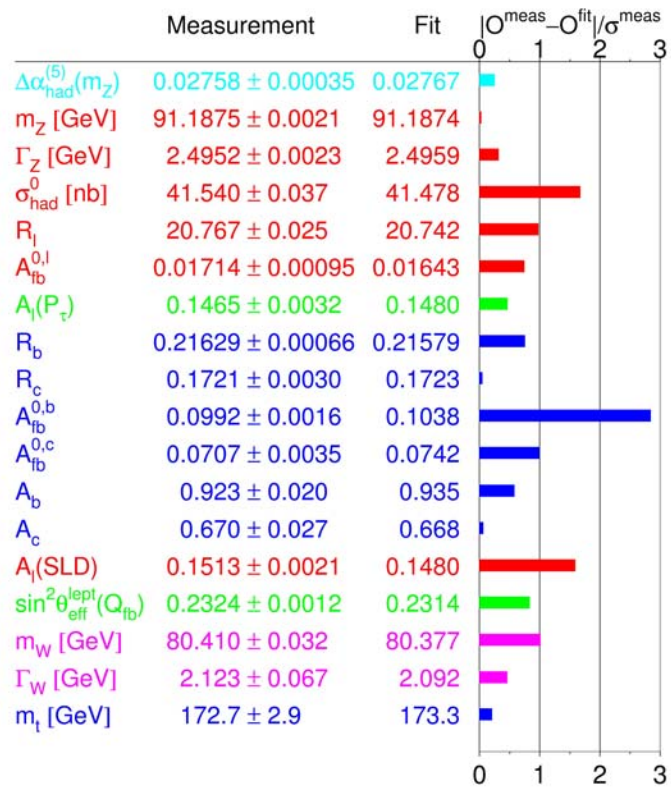
14 TeV

* If it exists!

But the model isn't completely satisfactory…..

- Many *theoretical* reasons why we expect more physics than *just* a standard model Higgs

Experimental data consistent with Standard Model with single Higgs boson



Quantum Corrections to Higgs Mass

- Higgs mass grows quadratically with scale of new physics, Λ

$$\delta M_H^2 \approx -\left(\frac{\Lambda}{0.7\,\mathrm{TeV}}\,200\,\mathrm{GeV}\right)^2$$

$M_H \leq 200$ GeV requires $\Lambda \sim$ TeV

Points to 1 TeV as scale of new physics

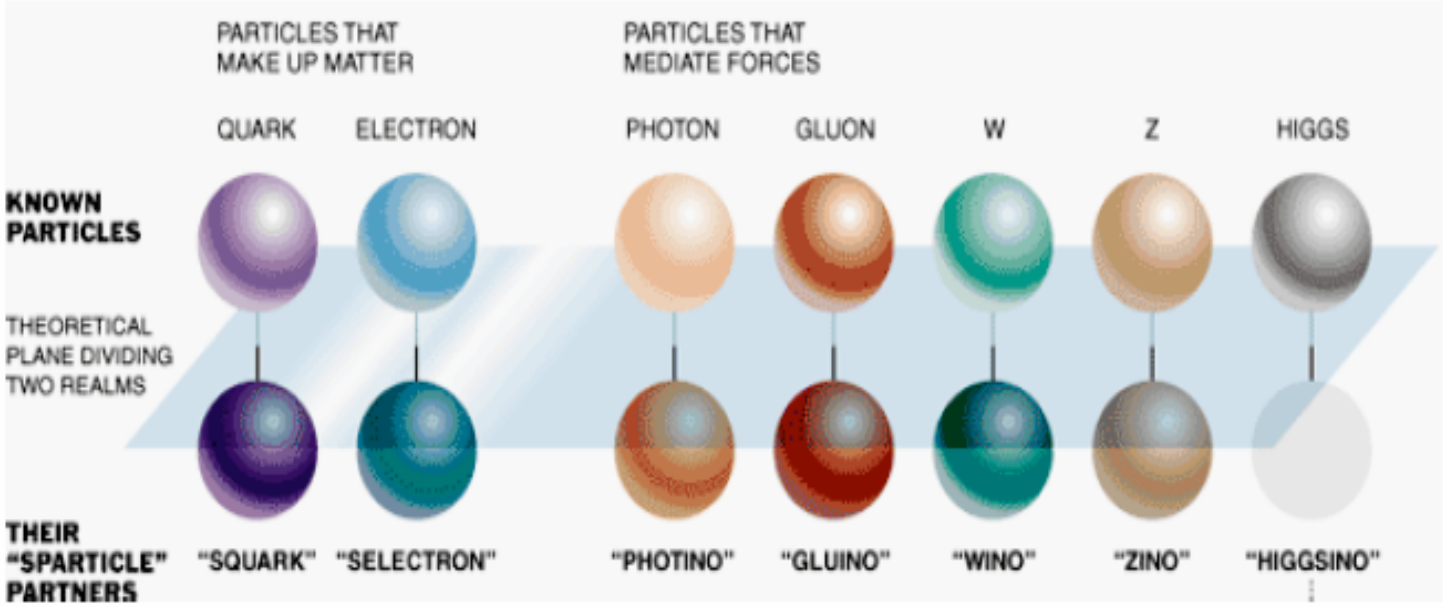
We expect much at the TeV Scale

- Maybe a Higgs (or something like it)
- Maybe supersymmetry (lots of new particles)
  - Supersymmetric models have at least 5 Higgs particles!
- Maybe extra dimensions
- Maybe other new symmetries

We're not sure what will be there, but we're sure there will be something!

supersymmetry

fermions ⟷ **bosons**

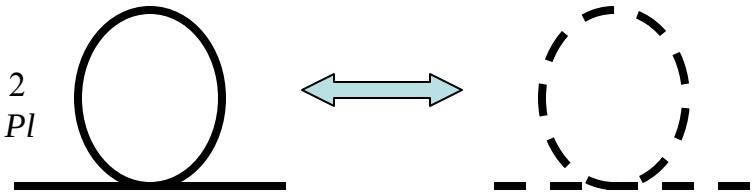


Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Quantum Corrections and Supersymmetry

$$\delta M_H^2 \approx -M_{Pl}^2$$



$$\delta M_H^2 \approx M_{Pl}^2$$

Tevatron/LHC Energies

Quantum corrections cancel order by order in perturbation theory

Supersymmetric Theories

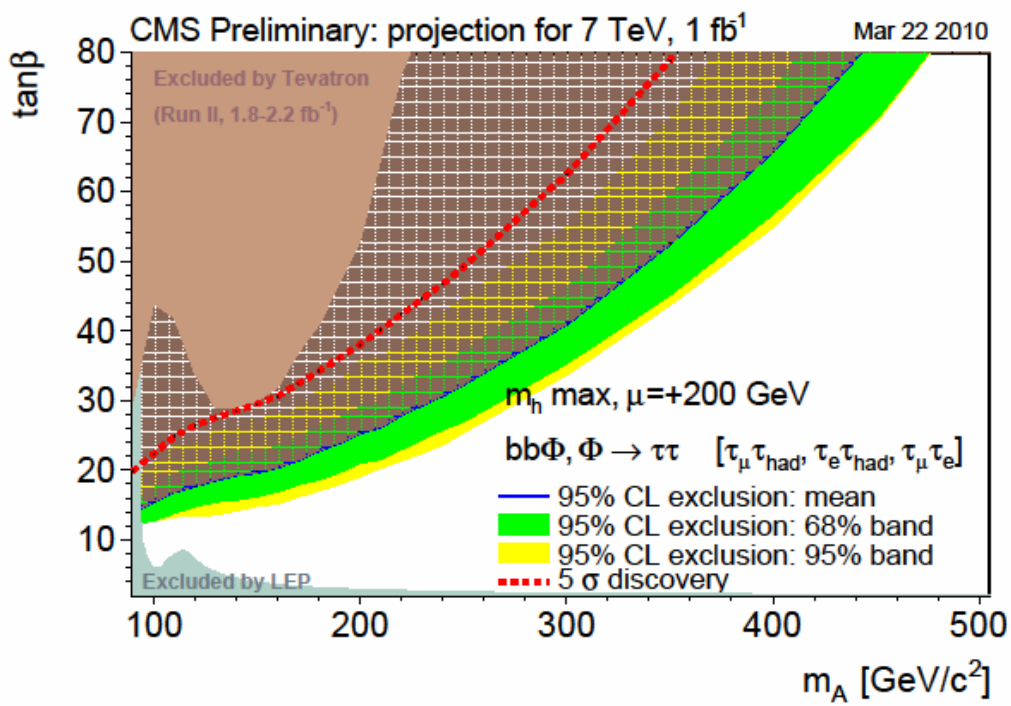
- Predict many new undiscovered particles (>29!)
- 5 Higgs-like particles to look for
  - New signatures
- Very predictive models
  - Can calculate particle masses, interactions, everything you want in terms of a few parameters

- In Standard Model, Higgs mass is free parameter
- In simplest supersymmetric model, $M_H < 130$ GeV

Supersymmetric Higgs produced with b's

$$(b)bH,\ H \rightarrow \tau\tau$$

- In SM, Higgs coupling to b quark very small
- In SUSY, b-Higgs coupling enhanced



New signatures!

Discovery isn't Enough

- Is this a Higgs or something else?
- We must answer critical questions
  - Does the Higgs generate mass for the W,Z bosons?
  - Does the Higgs generate mass for fermions?
  - Does the Higgs generate its own mass?

Is it a Higgs?

- Measure couplings to fermions & gauge bosons

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

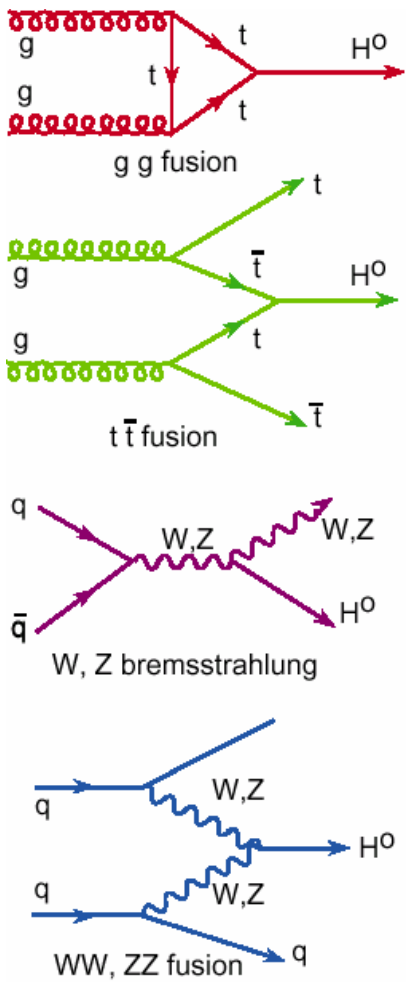
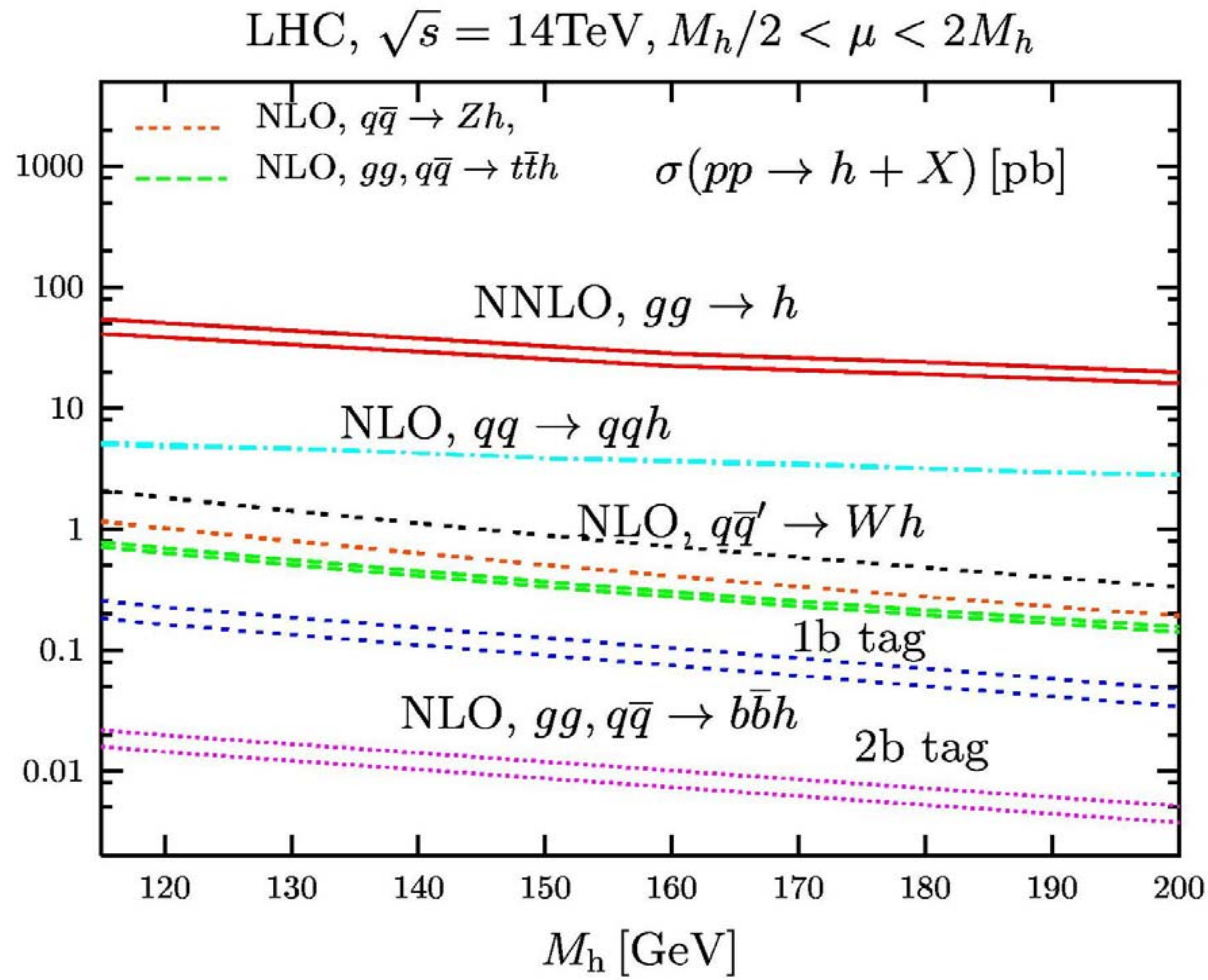
- Measure spin/parity

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

- Measure self interactions

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

Conclusions

A new era of particle physics has begun

Higgs at the LHC