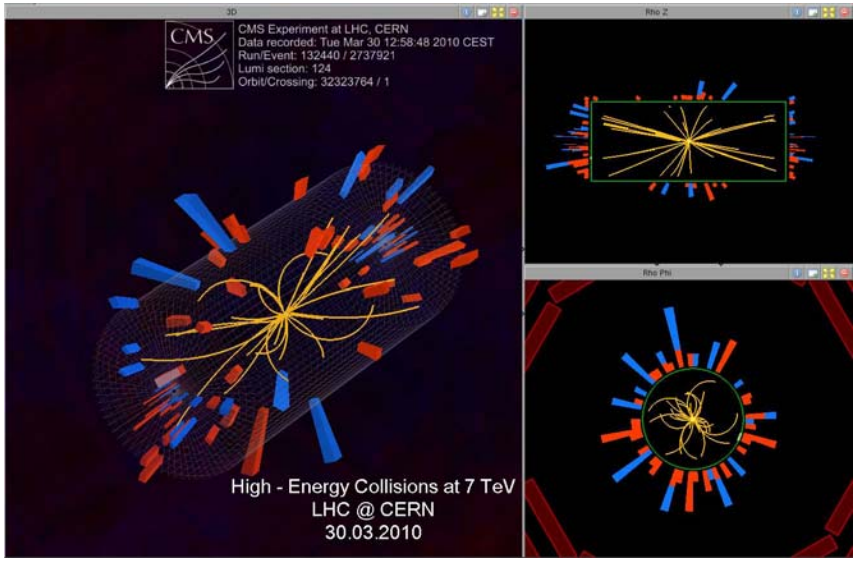
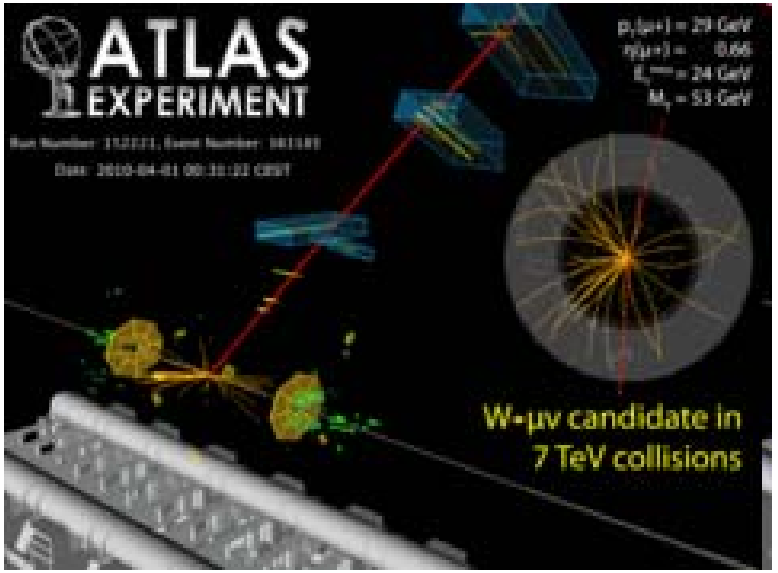
Frontiers in Particle Physics
90/50/10 Celebration

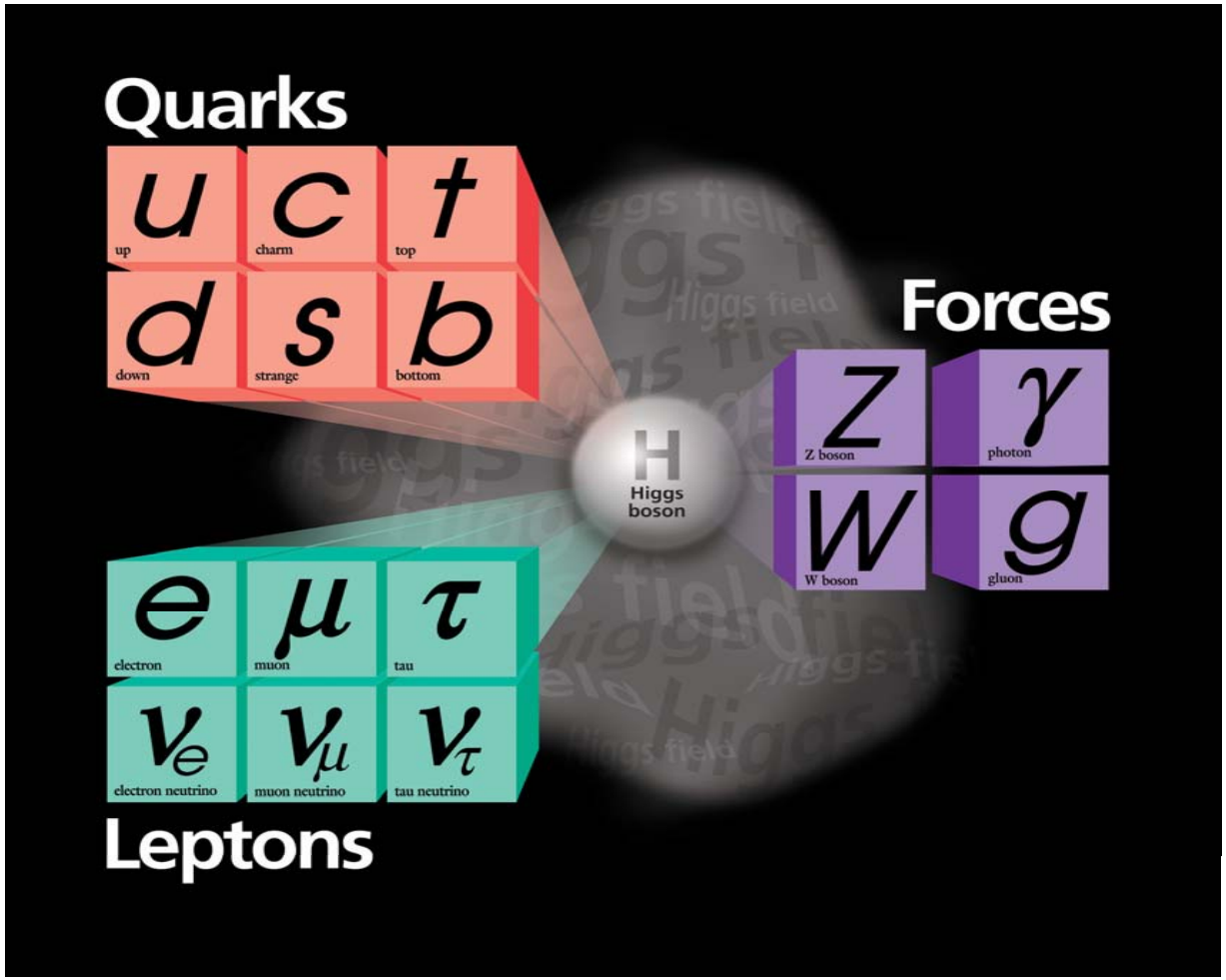
Sally Dawson, BNL





A New Era for Particle Physics has begun

We have a *Standard Model*



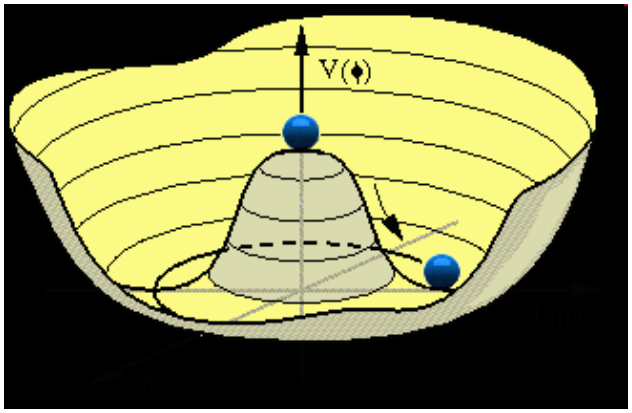
Standard Model Works

- Standard model provides excellent interpretation of experimental data starting with LEP/SLD
- Where is electroweak symmetry breaking?

Experimental data consistent with Standard Model with single scalar boson, H

Wanted

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



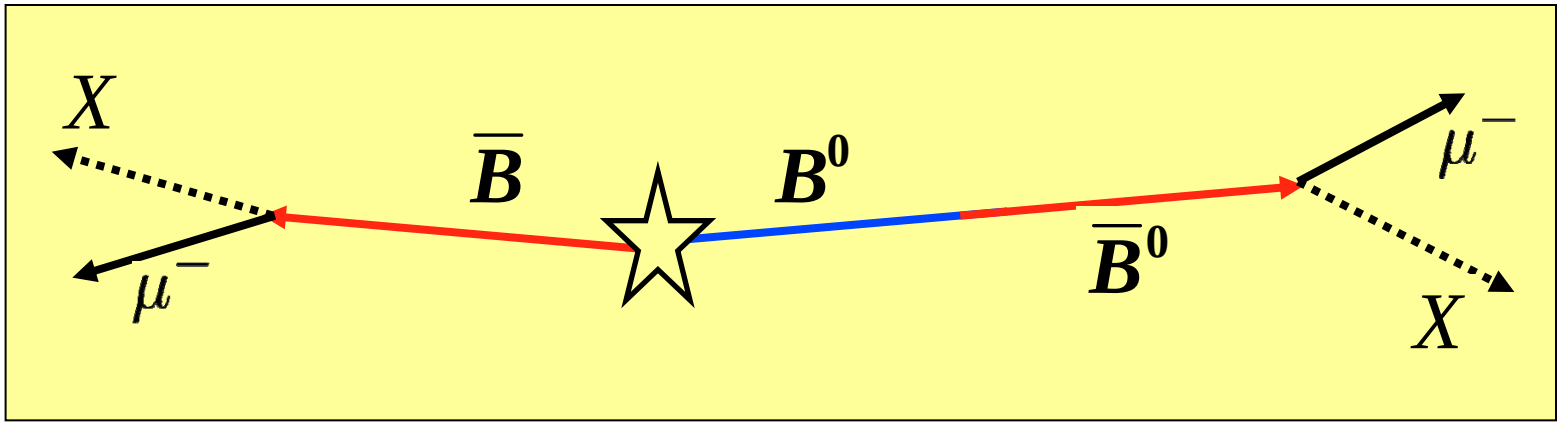
- Physical particle (the Higgs) is result of symmetry breaking
- Missing link is Higgs boson

Choice of minimum breaks symmetry

Tevatron still surprising us

Just recently at D0

- Measurement of di-muon asymmetry: $A_{sl}^{b} \equiv \dfrac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$



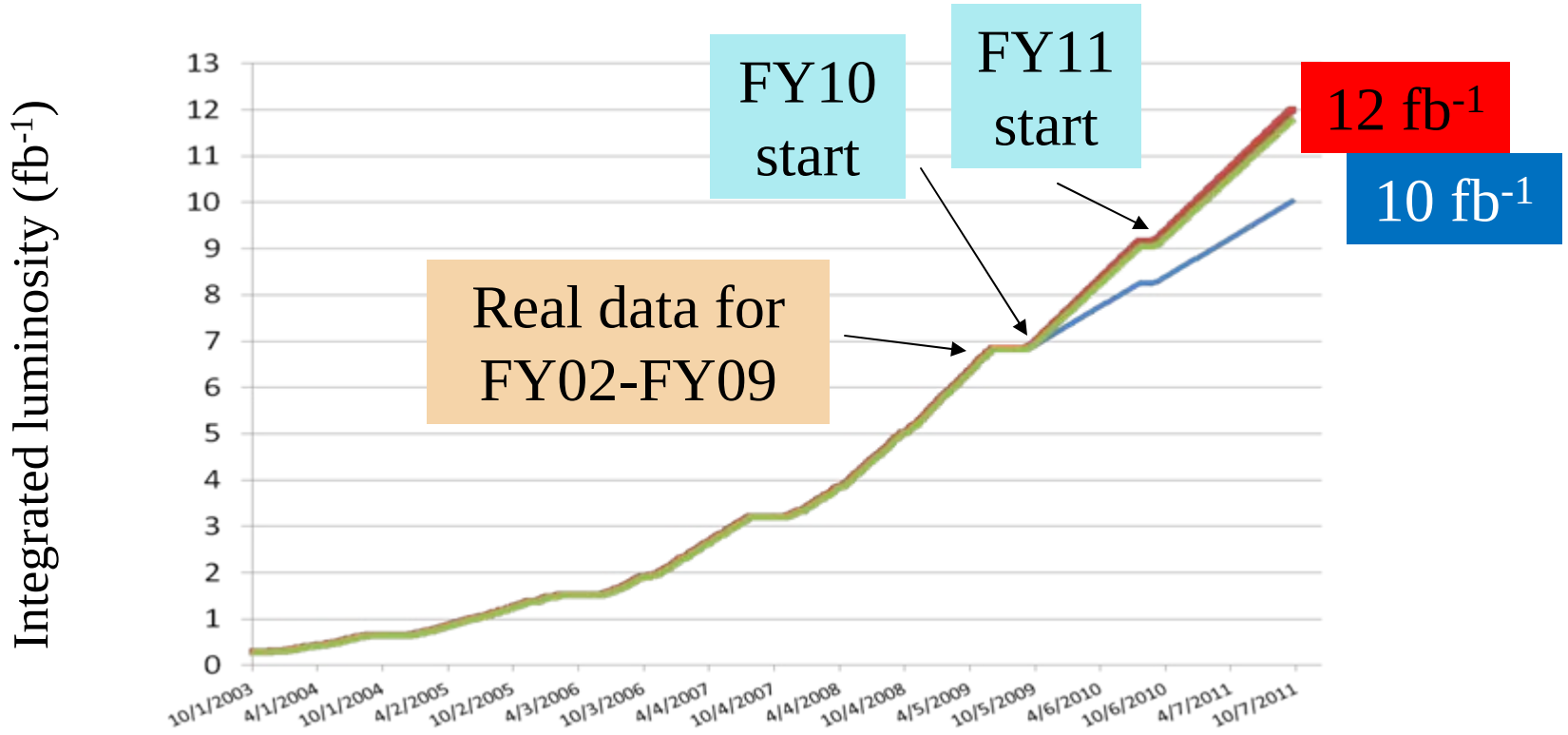
$$A_{sl}^{b} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$

$$A_{sl}^{b}(SM) = (-0.023^{+0.005}_{-0.006})\%$$

3.2σ

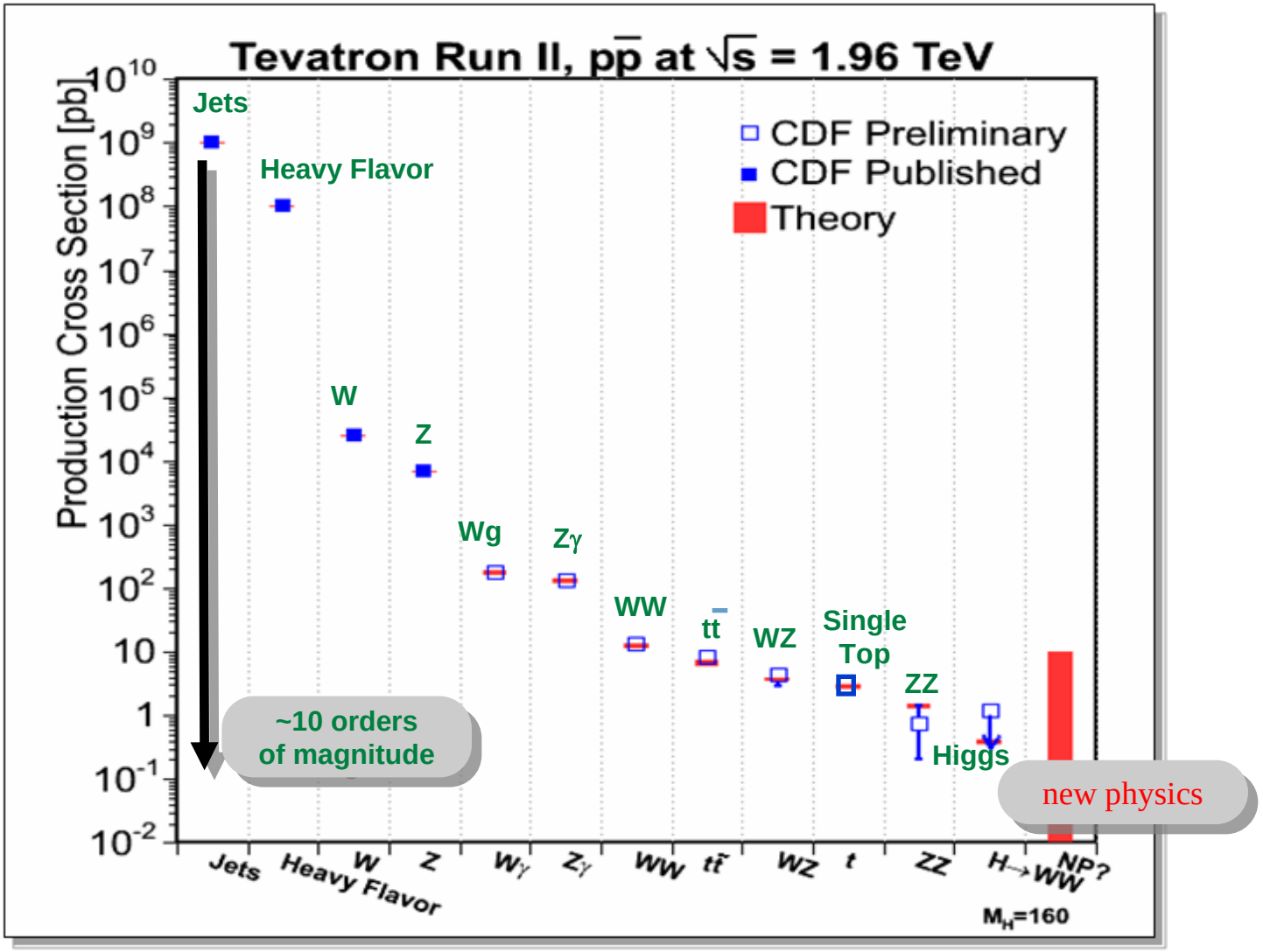
Is there a new source of CP violation?

The Tevatron is still going strong!

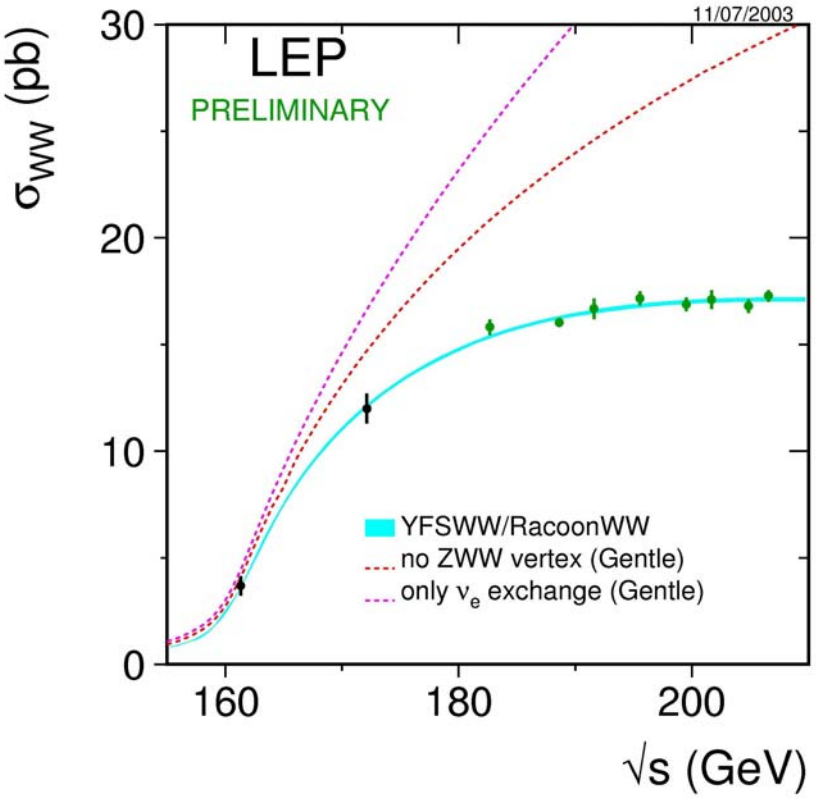


Planned shut-down end of FY11

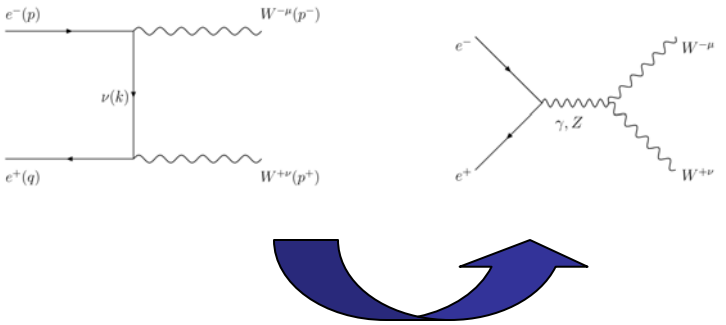
Many Discoveries at the Tevatron



Tevatron measured 3 Gauge Boson Couplings

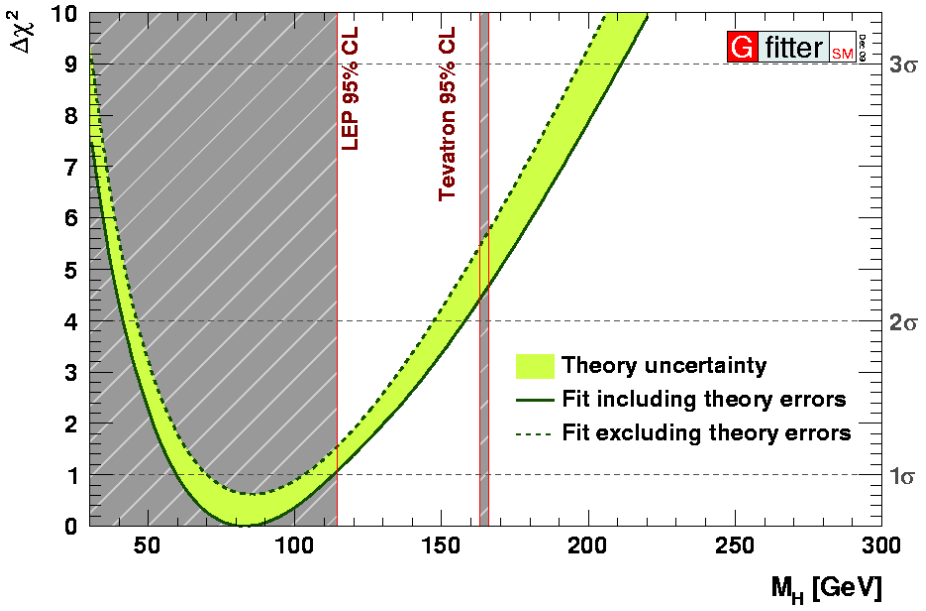


No evidence for non-SM 3 gauge boson vertices

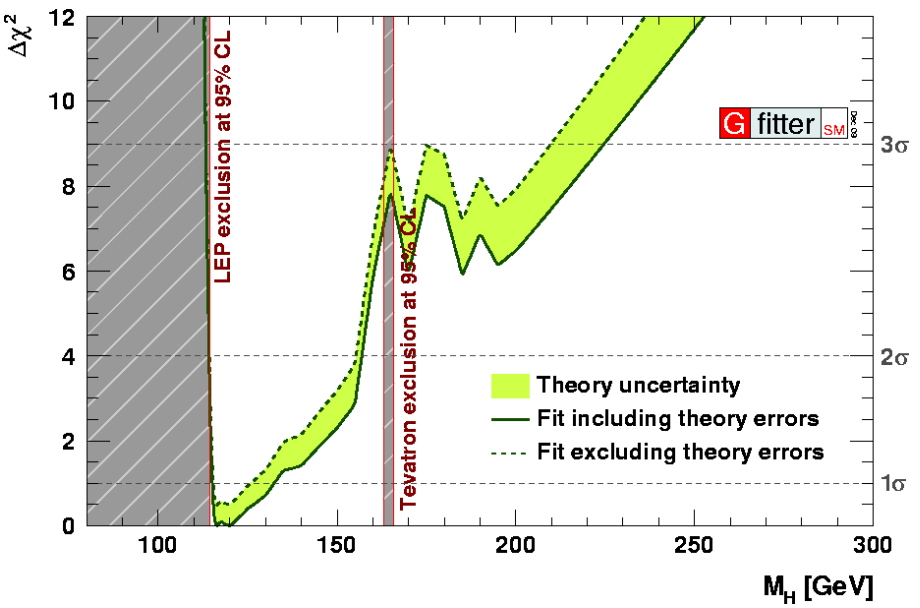


Cancellation of terms which grow with energy experimentally verified

Minimal SM Very Constrained



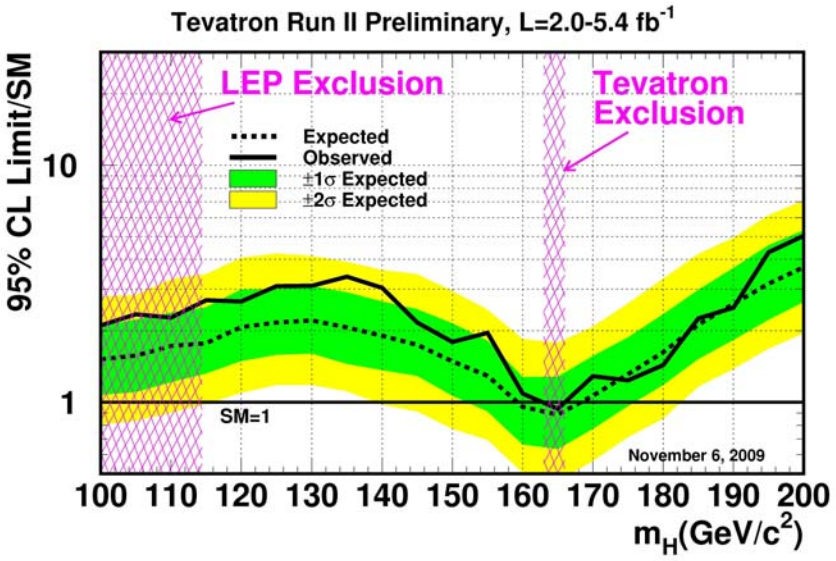
Direct search limits from LEP/Tevatron not included



Direct search limits from LEP/Tevatron included

What's Wrong with the SM?

- We haven't seen the Higgs….***Maybe we're just seeing the low energy limit of some more complicated scenario***

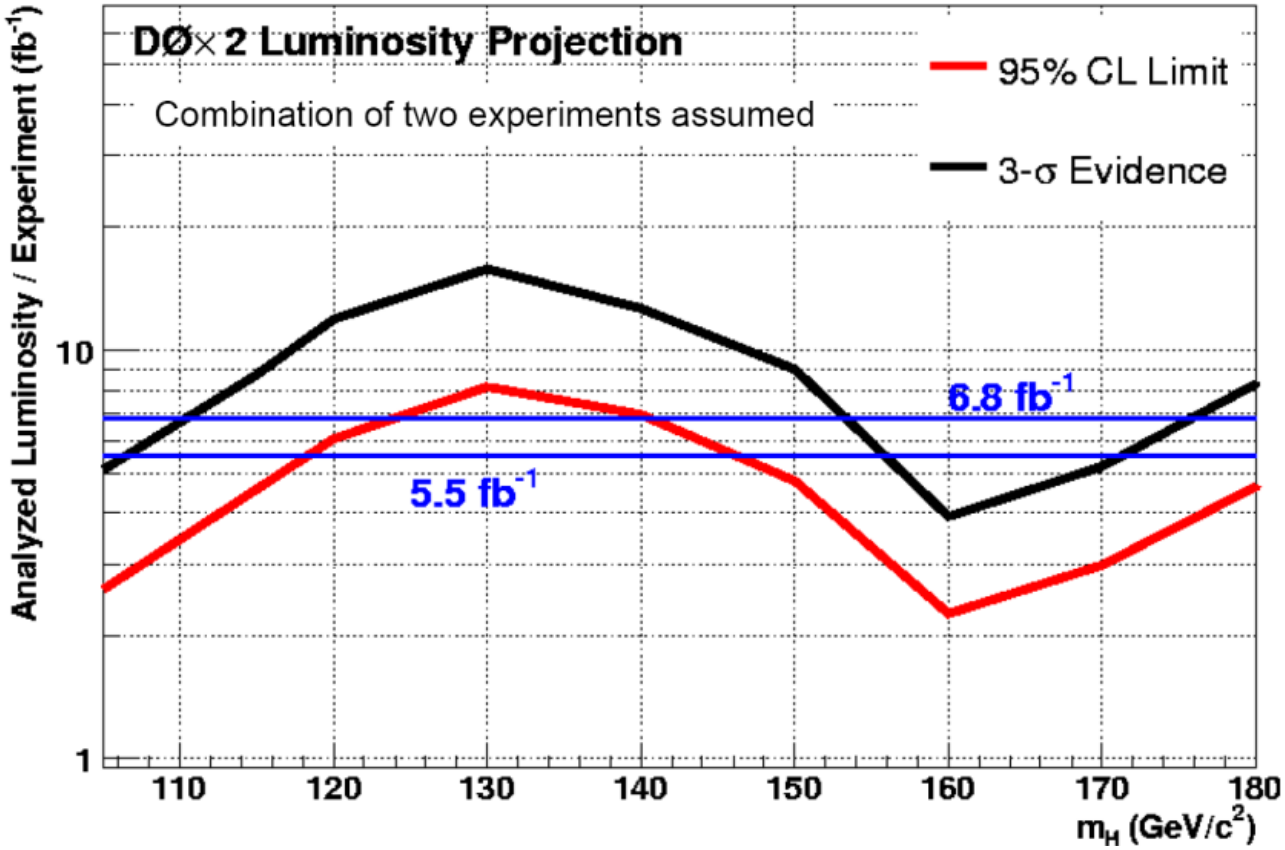


- 163 GeV < M_H < 166 GeV excluded
- This is *easy* region where $gg \rightarrow H$, $H \rightarrow W^+W^-$

$$M_H = 165\,GeV \rightarrow \sigma = 385.4\ fb\ \ (\pm 9\%\ PDF)$$

Need theory for exclusion!

Will the Tevatron Find the Higgs?



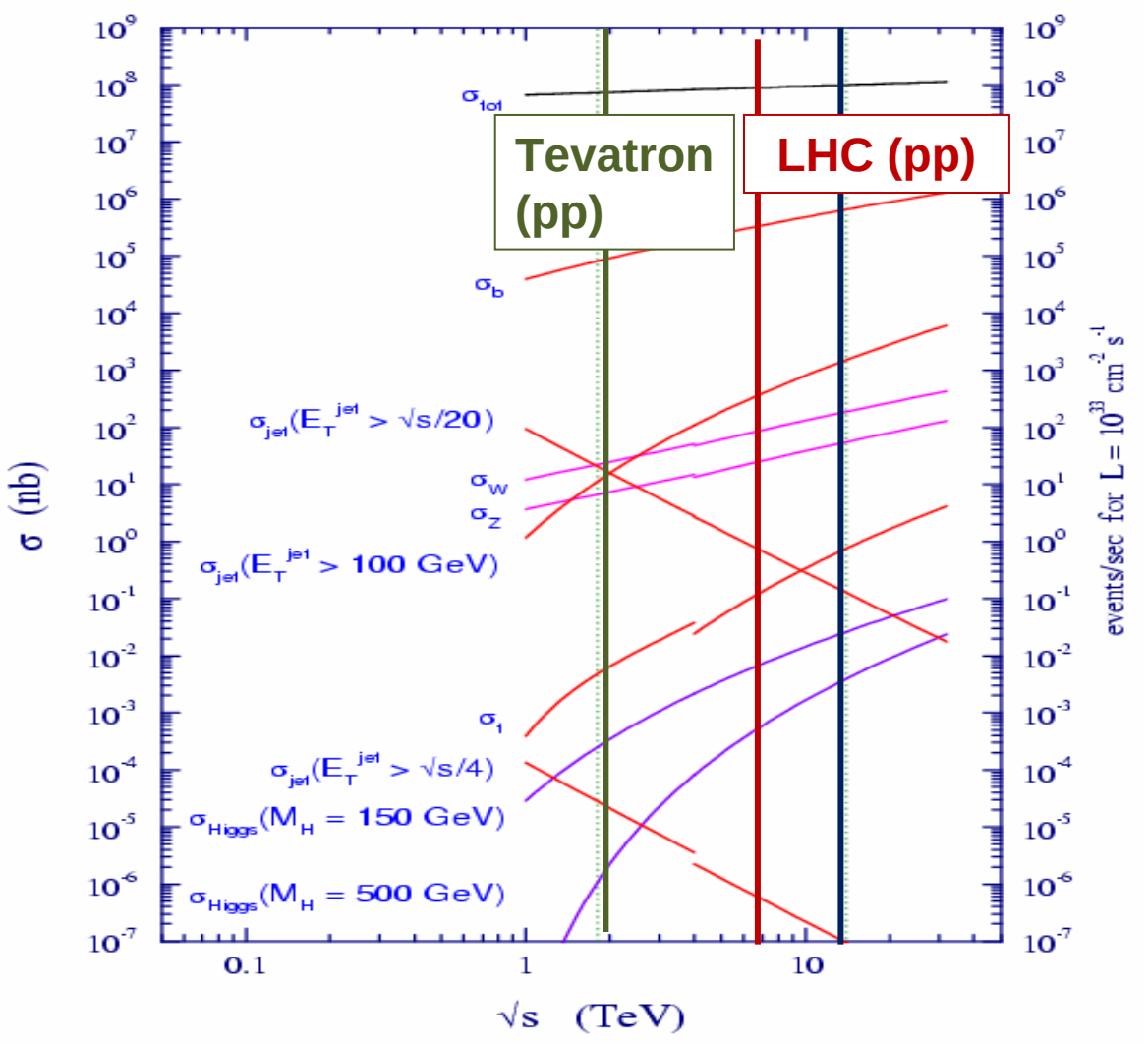
~8 fb gives exclusion over entire mass region below M_H~180 GeV

Many Discoveries in Last Decades

- Tevatron discovered the top quark
- Precision measurements from LEP/SLD/Tevatron limit new physics possibilities
  - Many new physics scenarios excluded
- Dark matter and dark energy discovered
  - Informed (inspired?) model building
- Neutrino masses aren't zero
- Calculational tools greatly improved
  - Much better handle on backgrounds
- ….. + much more

MANY PREDICTIONS, SPECULATIONS, & HOPES FOR LHC PHYSICS

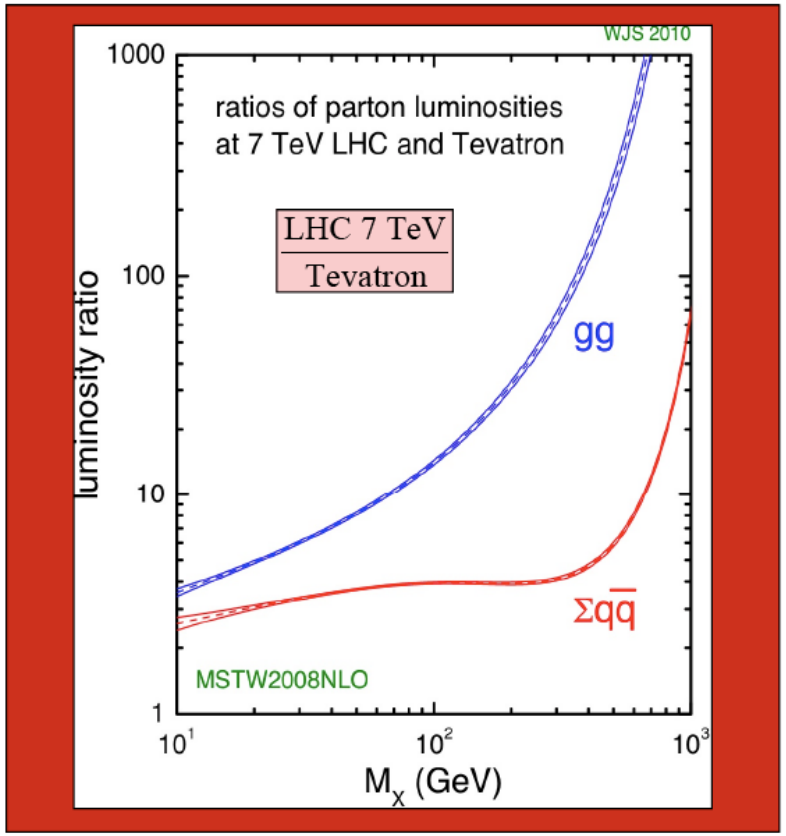
From the Tevatron to the LHC



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

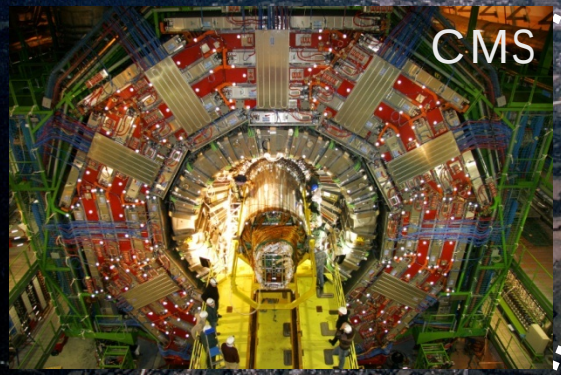
By the end of 2010, same number of tops at LHC as Tevatron

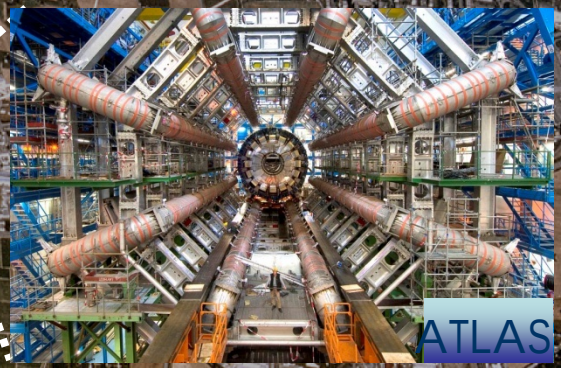
LHC is a gluon collider



Cross-section	Tevatron	LHC@7TeV/Tevatron	LHC@14TeV/Tevatron
W/Z → lν, ll	2.5/0.25 nb per family	~ 5	~ 10
tt production	7.2 pb	~ 20	~ 100

Large Hadron Collider will probe the TeV Energy Scale

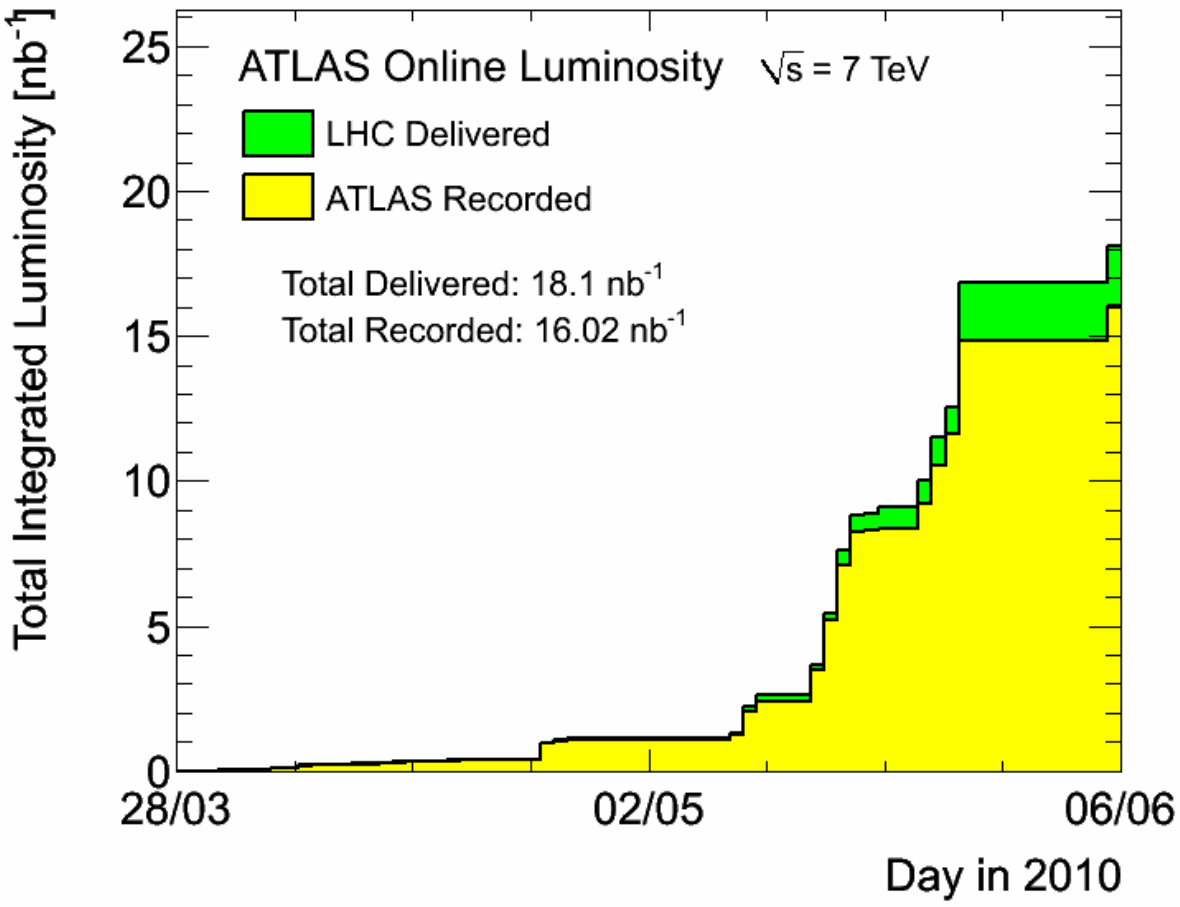




We have been waiting a long time

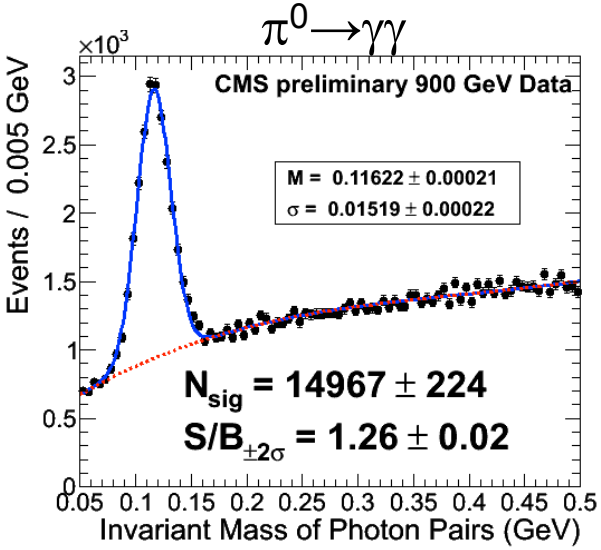
- SSC (pp @ 40 TeV) cancelled in 1993
  - Physics of the LHC is much the same as the physics of the SSC
    - Is there supersymmetry at the TeV scale?
    - What is the source of electroweak symmetry breaking?
    - Are there new Z bosons?
  - Of course there are new questions too
    - Are there extra dimensions?
    - What is the source of dark matter?
    - What do neutrino masses tell us?

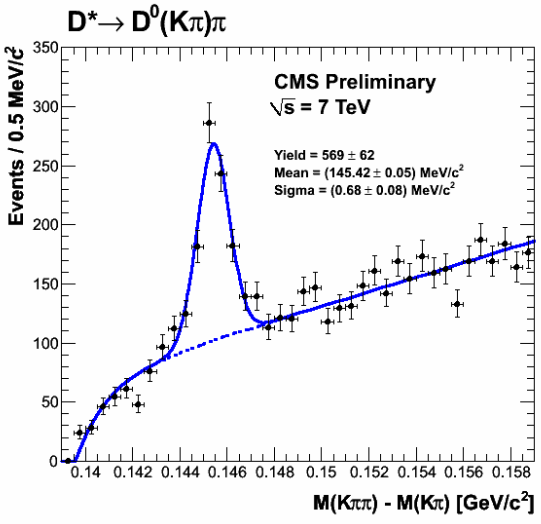
The Frontier is at the LHC Now

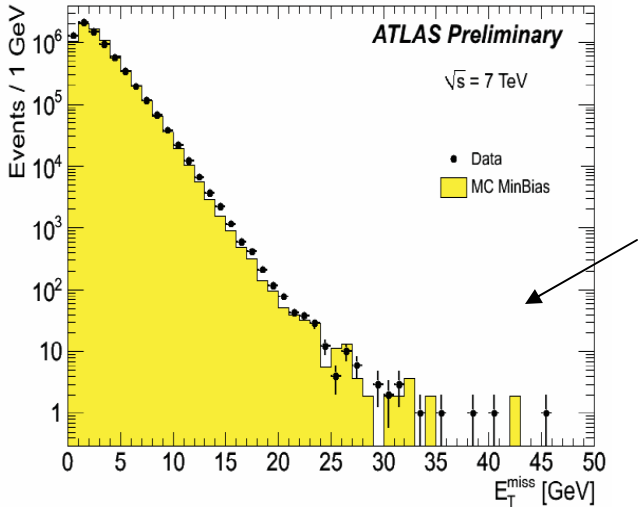


Exciting Times

- Both ATLAS and CMS have ~16 nb^{-1}
  - More data coming quickly ($L \sim 10^{29}/cm^2/s$)
- Both experiments have W's, Z's, are rediscovering D decays, ψ's,….
- Detectors working well







Critical for new physics searchs

Today's status

- LHC is running at $\sqrt{s}$=7 TeV until 1 fb^{-1} of data collected
  - 2010: L ~10^{27} -10^{32} cm^{-2} s^{-1} → total of 100-200 pb^{-1}
  - 2011: L ~10^{32} cm^{-2} s^{-1} → ≥ 100 pb^{-1}/month
  - Two heavy ion runs at the end of 2010 and 2011

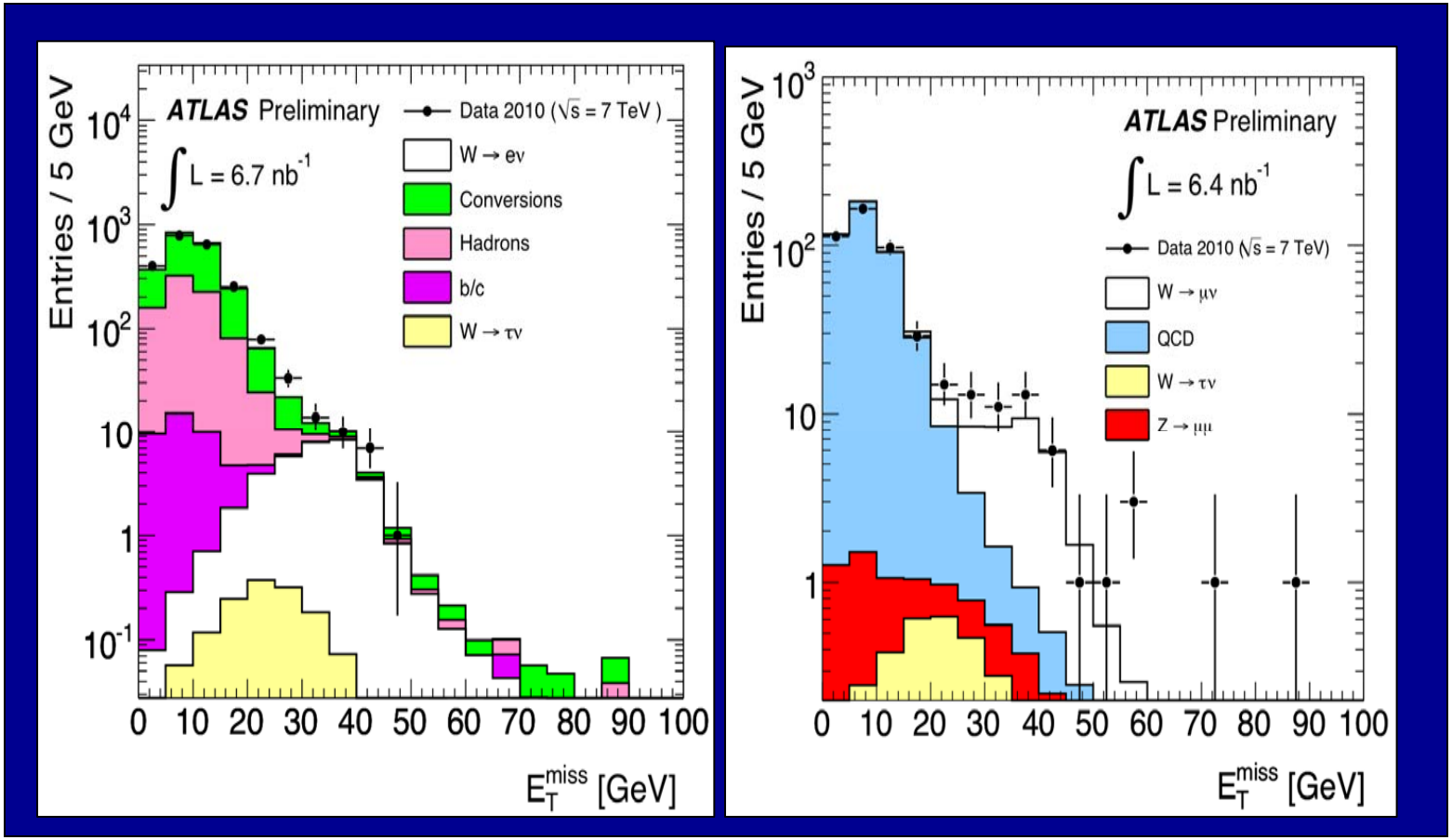
  - What's next?
    - 100 fb^{-1} by 2016 at $\sqrt{s}$=13-14 TeV
    - Many questions will likely remain even with large data sets from the LHC
    - How do we decide the long term future?
    - Next year at this time we will be in a very different position

Early LHC Physics uses SM for Calibration

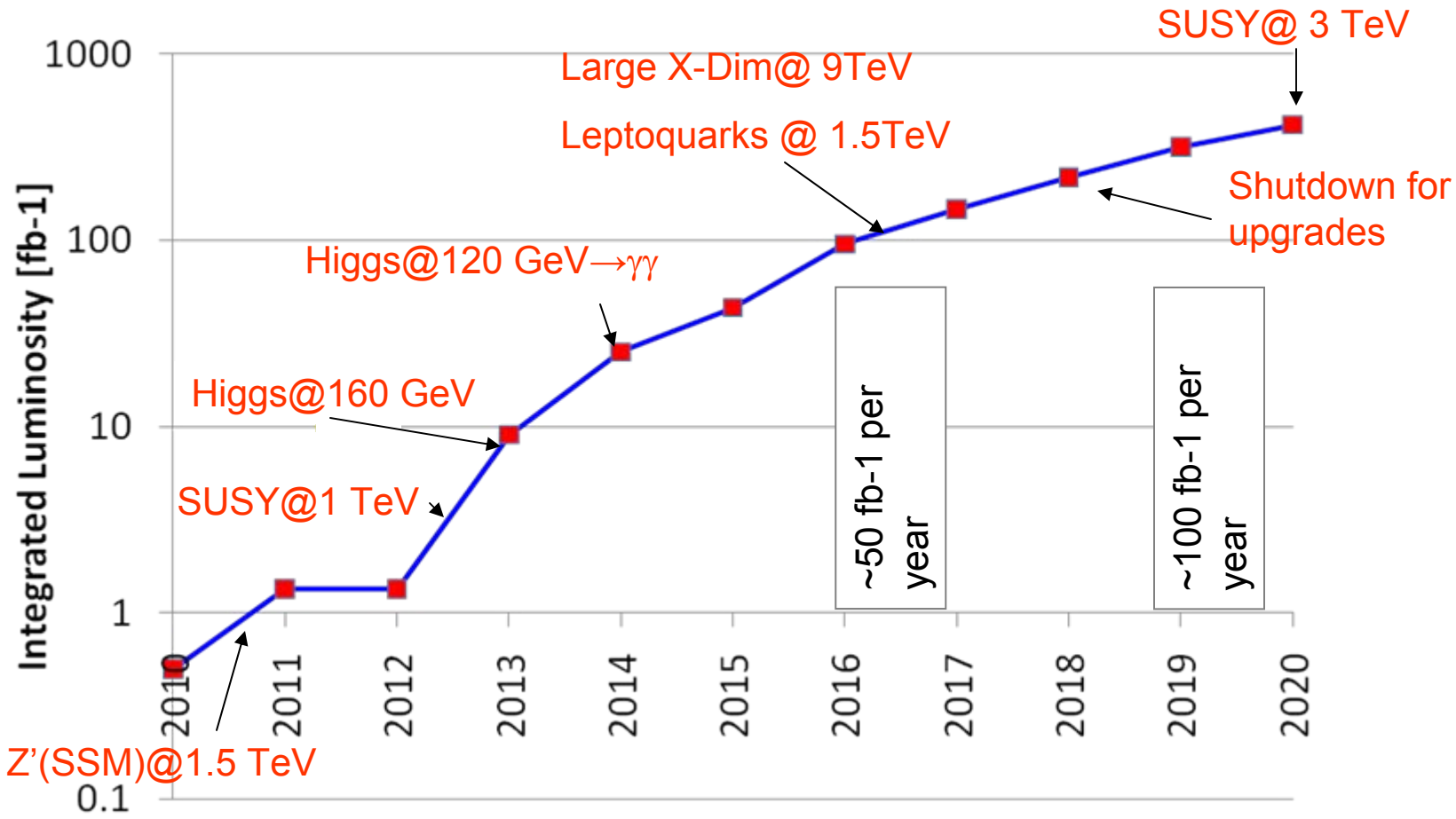
- 1 pb^{-1}
  - 5000 $W \rightarrow e\nu$, $\mu\nu$ — l + E_T^{miss}
  - 500 $Z \rightarrow e^+e^-$, $\mu^+\mu^-$ — e/μ ID
- 20 pb^{-1}
  - $t\bar{t}$ — jet energy calibration, b tagging, E_T^{miss}
- 100 pb^{-1}
  - 500,000 $W \rightarrow e\nu, \mu\nu$
  - 50,000 $Z \rightarrow e^+e^-$, $\mu^+\mu^-$

Re-discover the Standard Model

Already have W's



We expect great things at the LHC

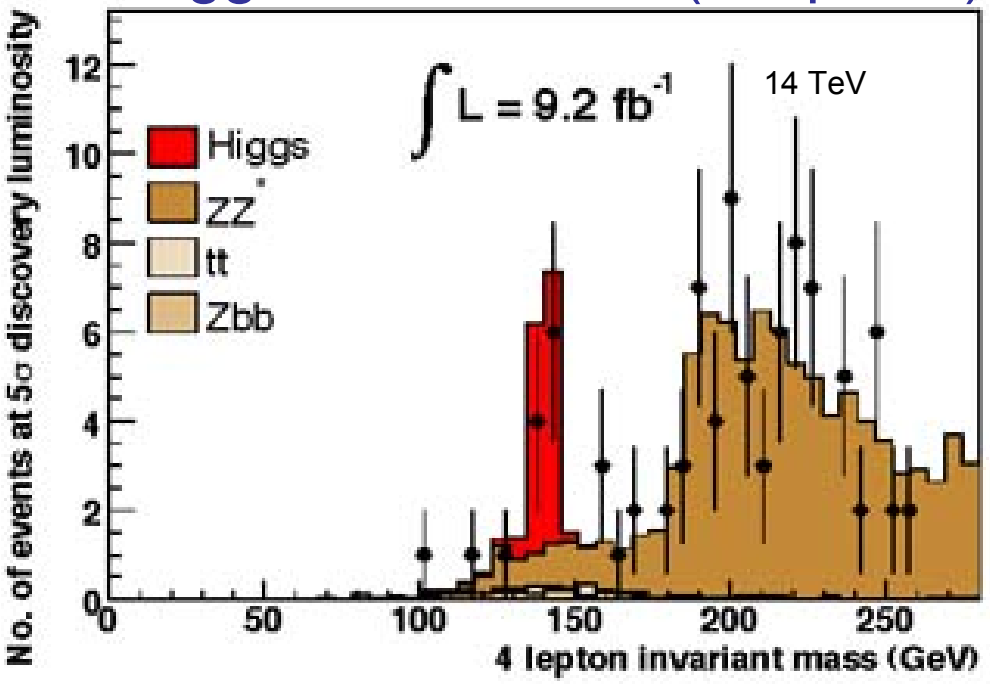


Physics updated from De Roeck

Luminosity projections from Jenni, 3/10

First we look for the Higgs

$gg \rightarrow H \rightarrow ZZ \rightarrow$ (4 leptons)

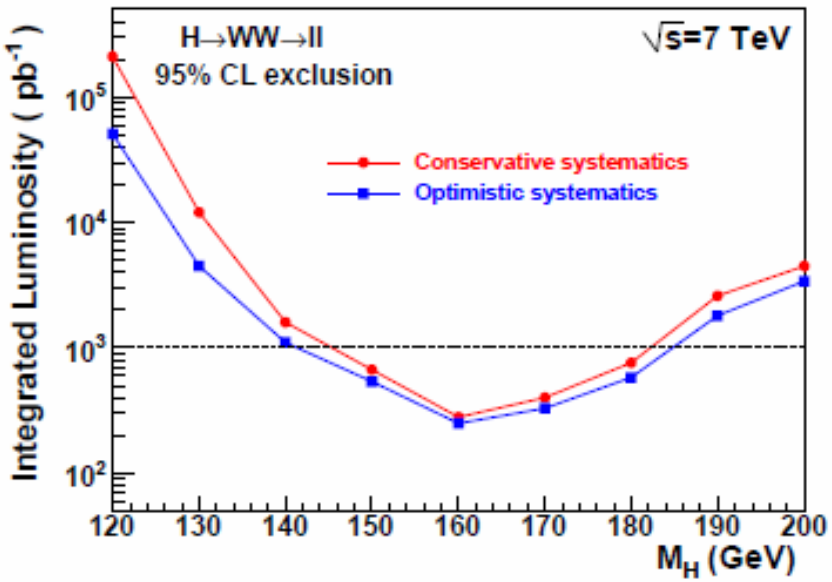


Golden Mode

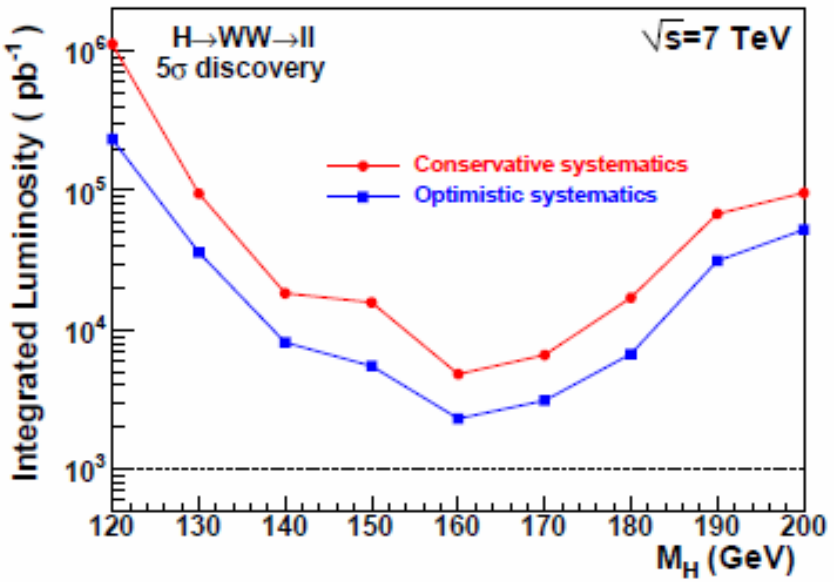
Possible discovery with < 10 fb^{-1}

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

CMS



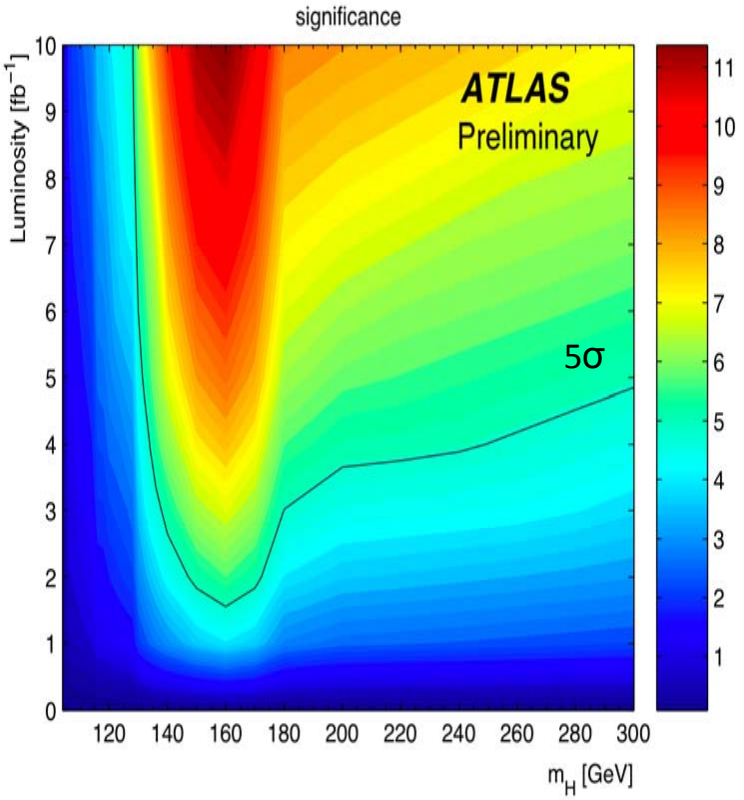
95% C.L. Exclusion



5σ Discovery

- LHC 7 excludes 140 GeV < M_H < 185 GeV
- No Higgs discovery in 1 fb^{-1}

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

If the SM Higgs is there…..the LHC will find it!

Is it *the* Higgs?

- Measure couplings to fermions & gauge bosons

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

Substructure/fat jet methods help pull out H→bb

- Measure spin/parity

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

Angular correlations of decays $H \to ZZ \to \mu^+\mu^- e^+ e^-$ help (but only for $M_H > 140$ GeV)

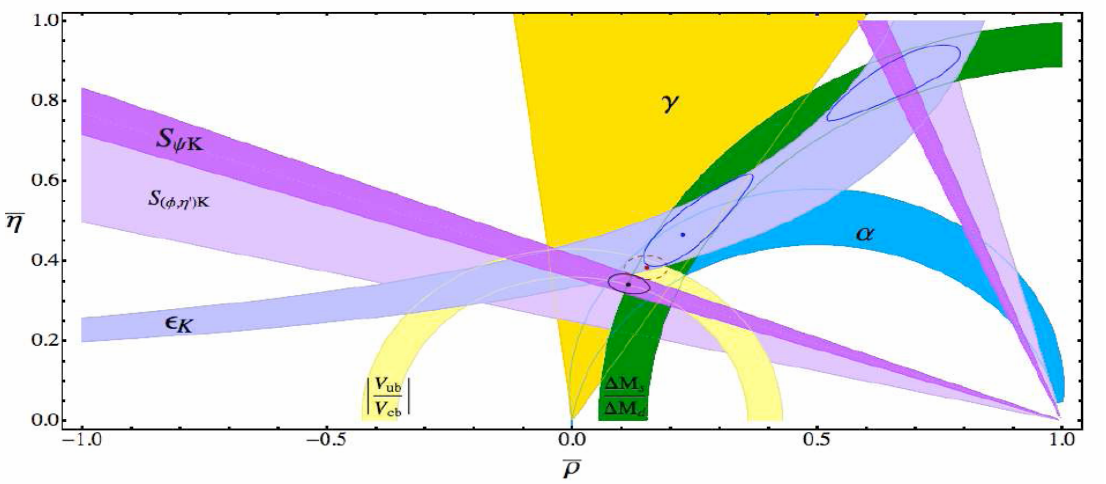
- Measure self interactions

$$V = \frac{M_H^{\,2}}{2} H^2 + \frac{M_H^{\,2}}{2v} H^3 + \frac{M_H^{\,2}}{8v^2} H^4$$

Need some good ideas here

Why go beyond the SM?

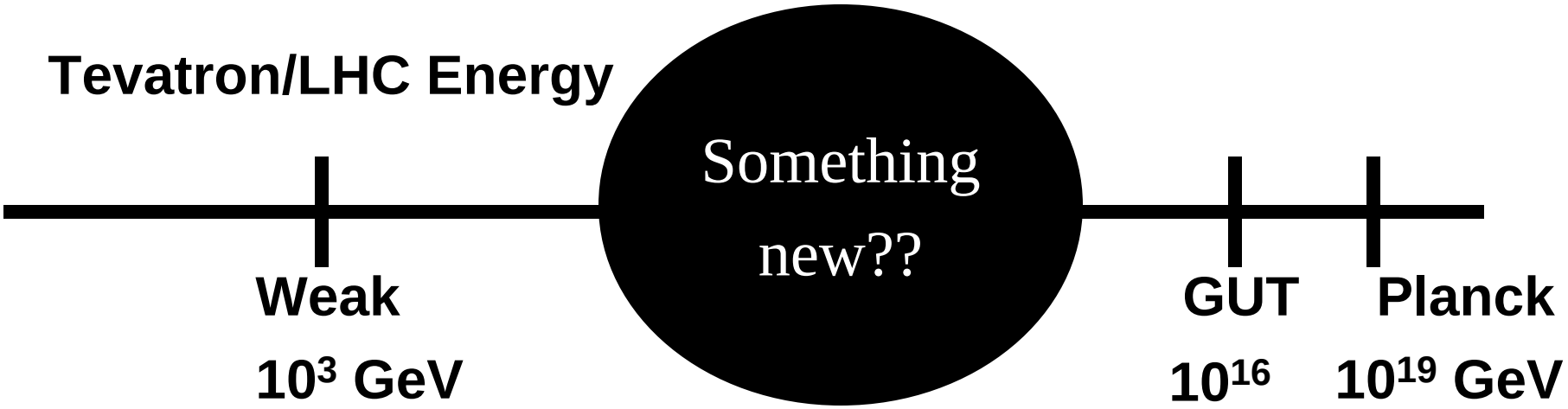
Tensions in fitting unitarity triangle



mode	w/out V_{ub}	with V_{ub}
$S_{\psi K_S}$	$2.4\,\sigma$	$2.0\,\sigma$
$S_{\phi K_S}$	$2.2\,\sigma$	$1.8\,\sigma$
$S_{\eta' K_S}$	$2.6\,\sigma$	$2.1\,\sigma$
$S_{(\phi+\eta')K_S}$	$2.9\,\sigma$	$2.5\,\sigma$

Lunghi and Soni, PL B666 (2008) 162

Quantum Corrections Connect Weak and Planck Scales



Quantum corrections drag weak scale to Planck scale

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

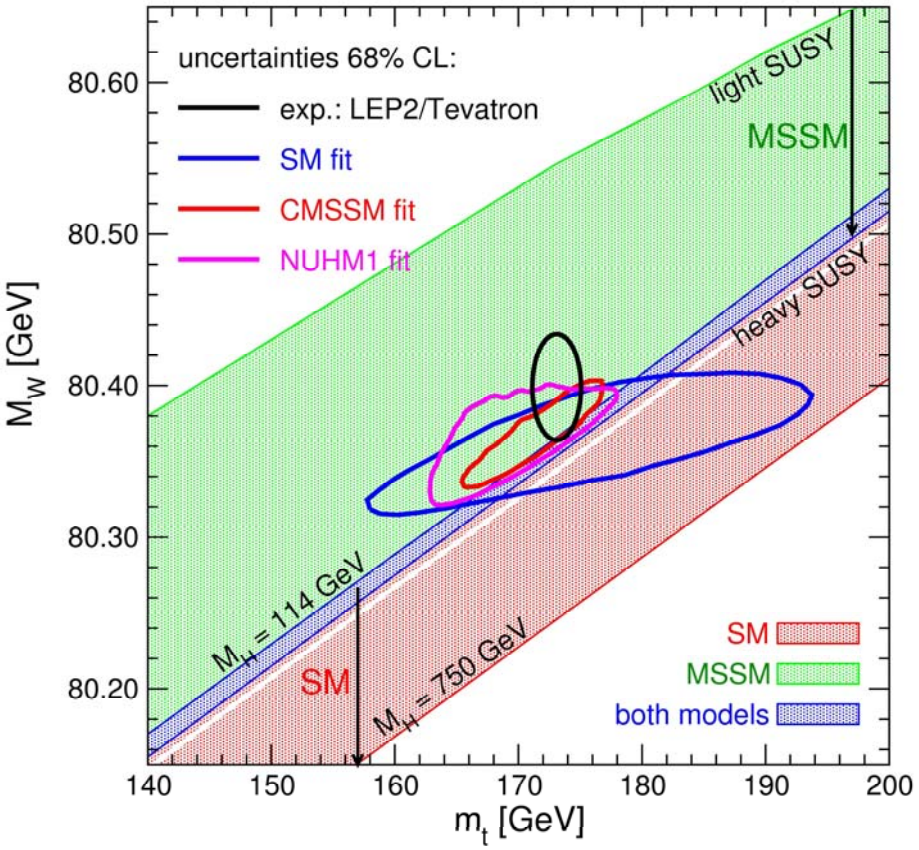
Points to 1 TeV as scale of new physics

We expect much at the TeV Scale

- Maybe a Higgs (or something like it)
- Maybe supersymmetry (lots of new particles)
  - SUSY particles can cancel quadratic growth of Higgs mass
  - SUSY particles strongly produced
  - Supersymmetric models have at least 5 Higgs particles!
- Maybe extra dimensions
  - First signal likely to be Z' like object
- Maybe other new symmetries

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

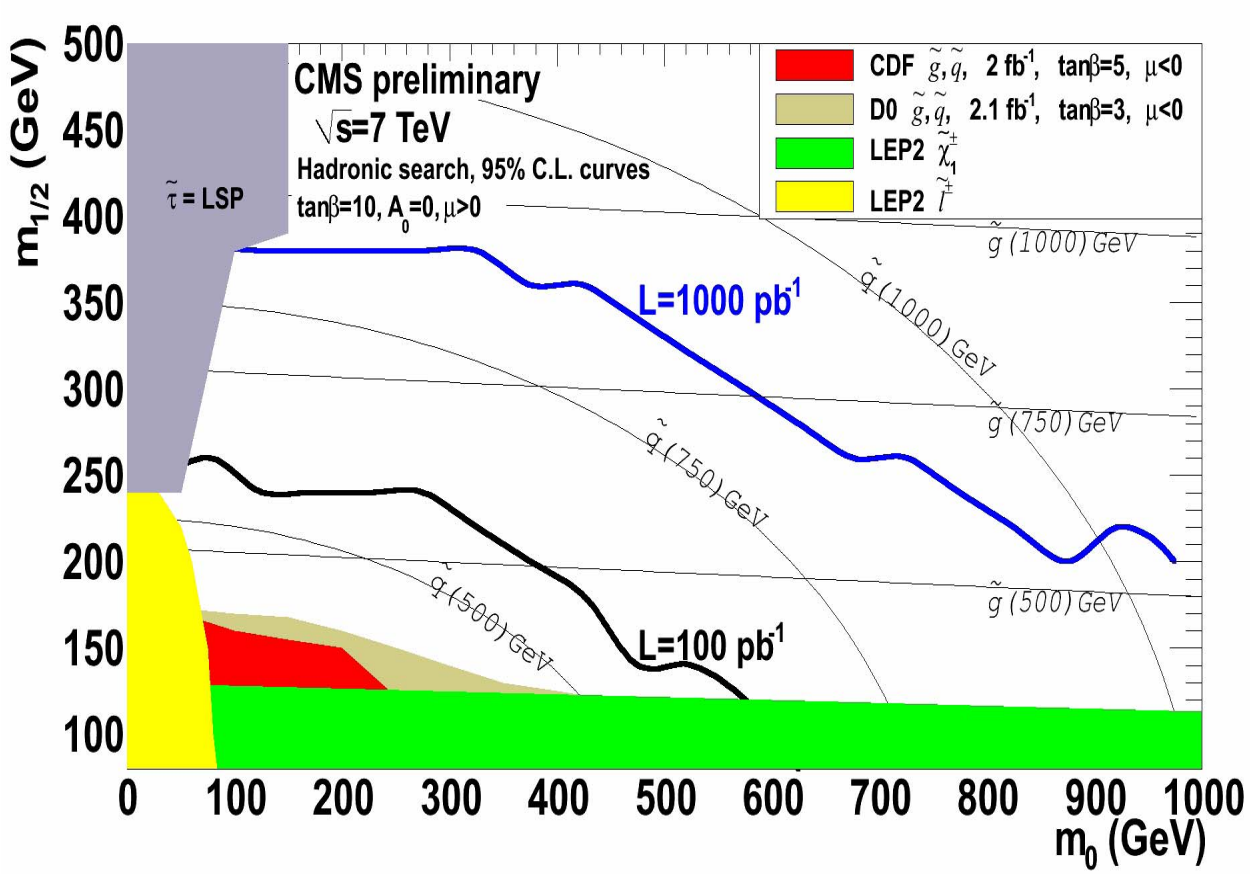
Supersymmetry is Favorite Alternative to SM



SUSY is slightly better fit than SM

SM predicts W mass in terms of M_Z, G_F,α, M_H, M_t

100 pb^{-1} LHC Exceeds Tevatron Reach



CMS Note 2010/008

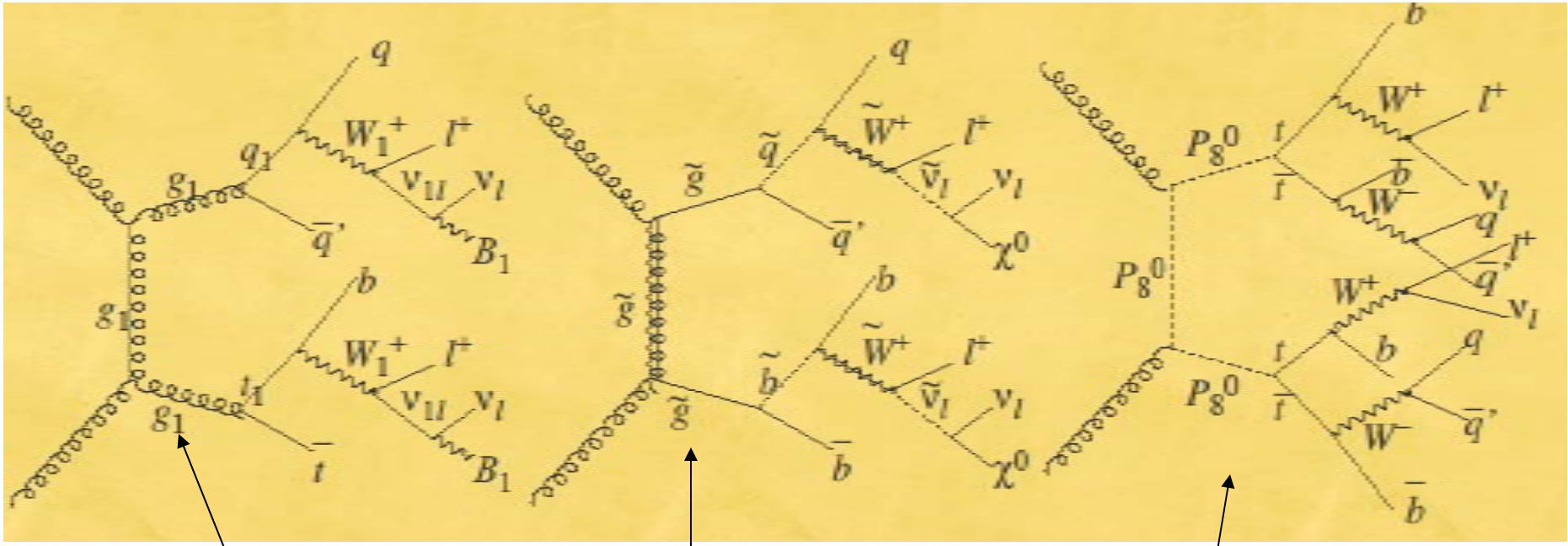
Suppose we find….

- Missing E_T, tri-leptons, same sign leptons
  - Classic SUSY signatures
- Have to probe mass spectrum
  - Usual method is using kinematic endpoints, M_{T2}
  - Large QCD corrections to shapes
- Prove couplings have SUSY relations
  - This is another motivation for future collider

Understanding new discoveries will be the frontier

A lot of new physics looks alike!

Missing E_T, jets, b's, same sign di-leptons



UED: Spin 1 bosons

SUSY: Spin ½ gluinos

Technicolor: Spin 0 techni-pions

Conclusions

The LHC will only begin the exploration of the TeV Scale

Expect a golden age for particle physics