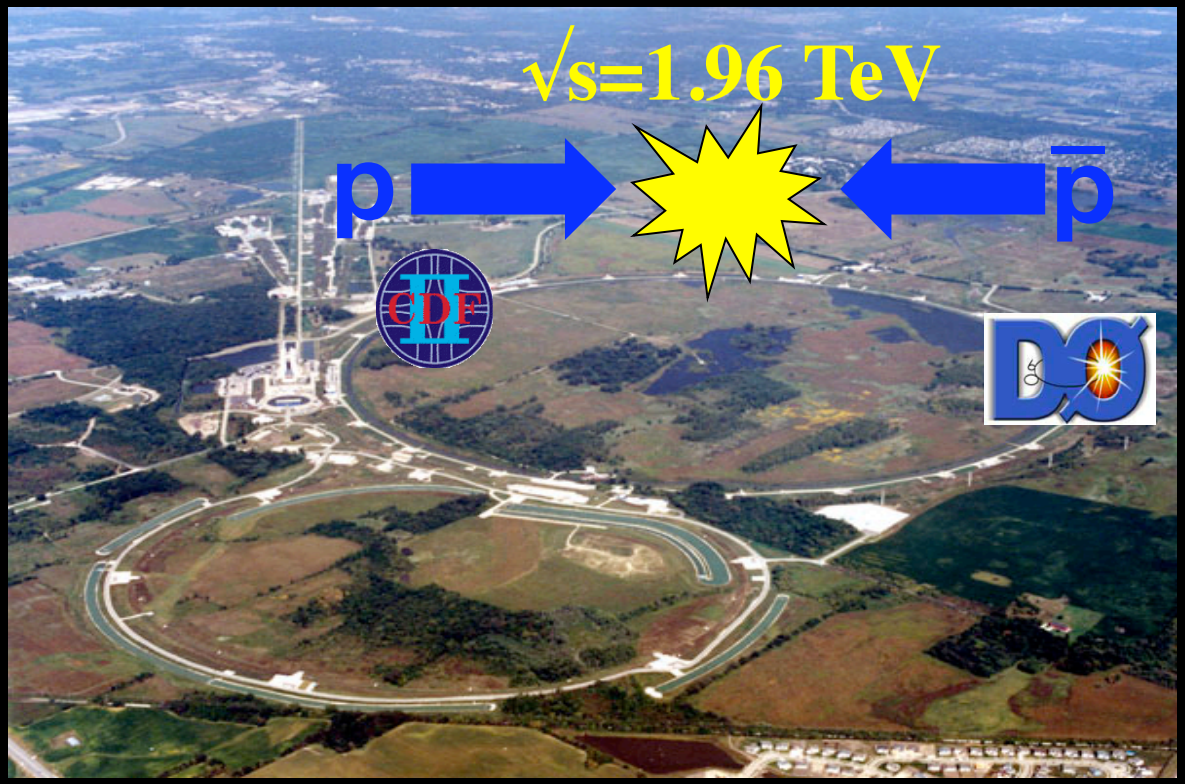
Physics Lessons from the Tevatron



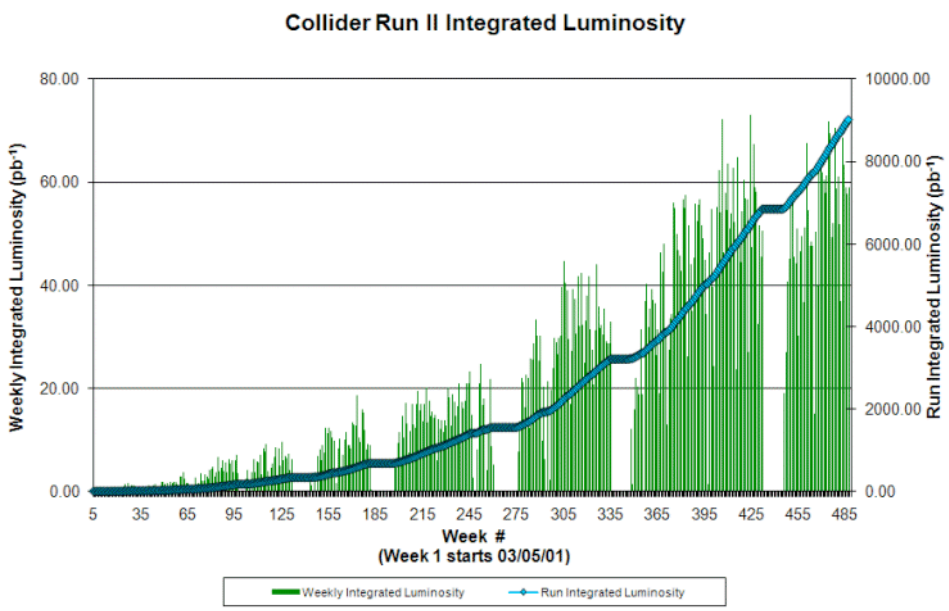
Beate Heinemann

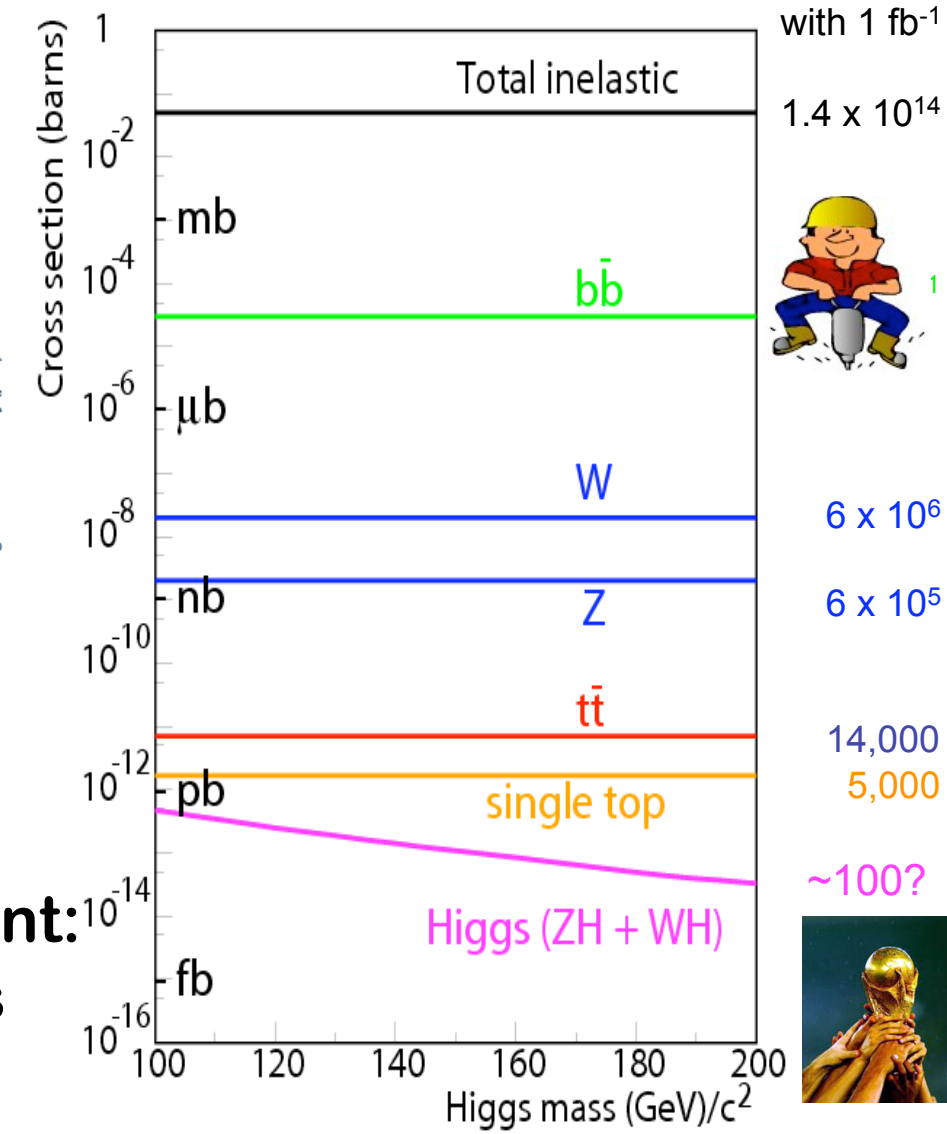
University of California at Berkeley and Lawrence Berkeley National Laboratory

Zuoz, August 2010

Luminosity and Cross Sections

Run 2: $\int Ldt = 9\ fb^{-1}$

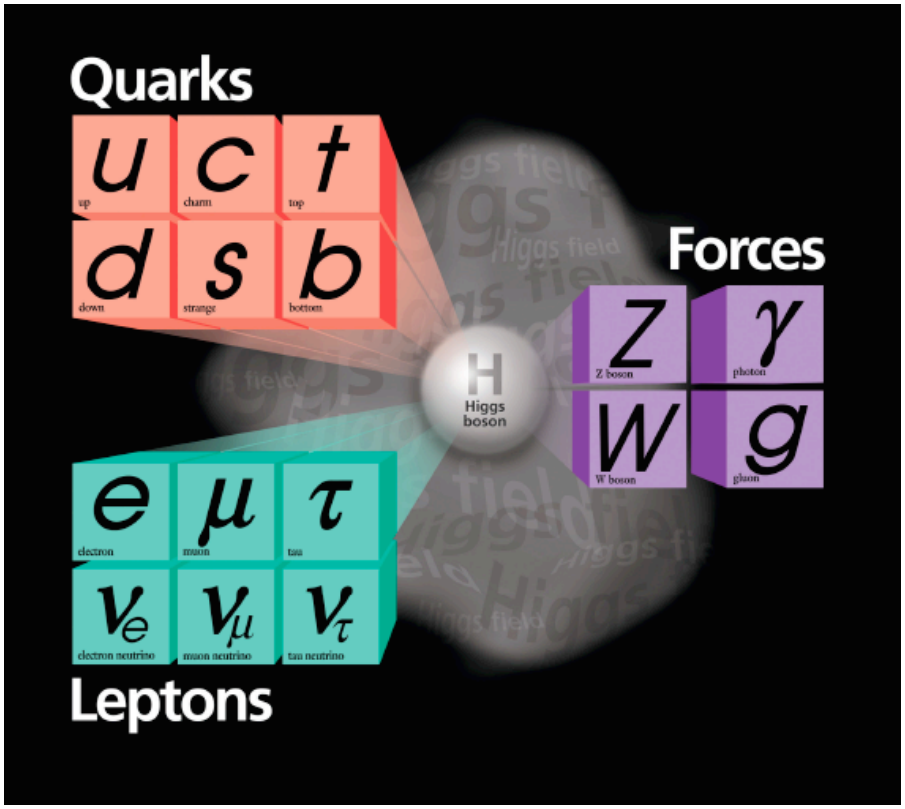




Experiments are ~85% efficient:
up to 6.7 fb^{-1} used for physics
Analyses presented today

At peak luminosity ~1 W boson per second produced!

The Standard Model and the Standard Questions We Have

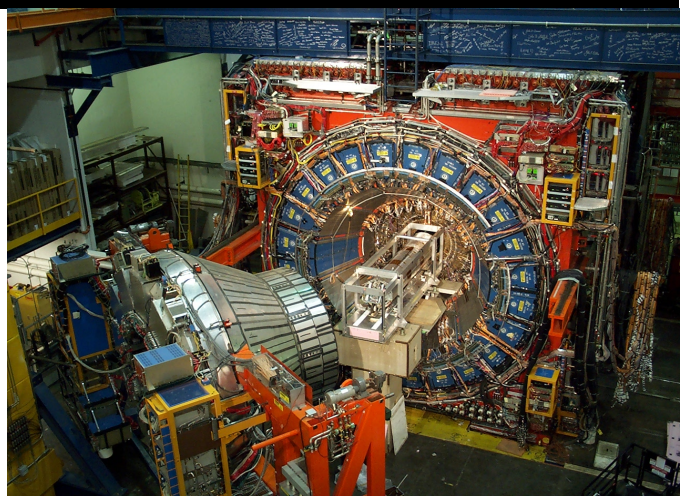


- Is QCD the right theory for the strong force?
  - Are the calculations adequate?
- What is the origin of electroweak symmetry breaking?
  - Is there a Higgs boson?
- Is the CKM matrix the only source of CP violation?
- What is the Dark Matter?
  - Is it produced it at colliders?
- Are there new dimensions of space?
  - Or e.g. extended gauge sectors, more gauge bosons,…?

- Is there anything maybe that no one has thought of and no one has looked for and we missed it?

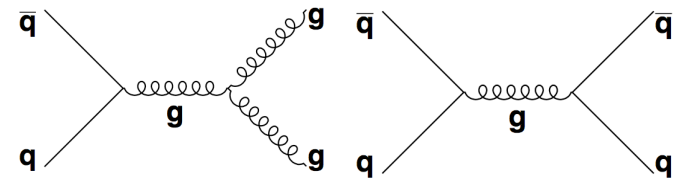
Outline

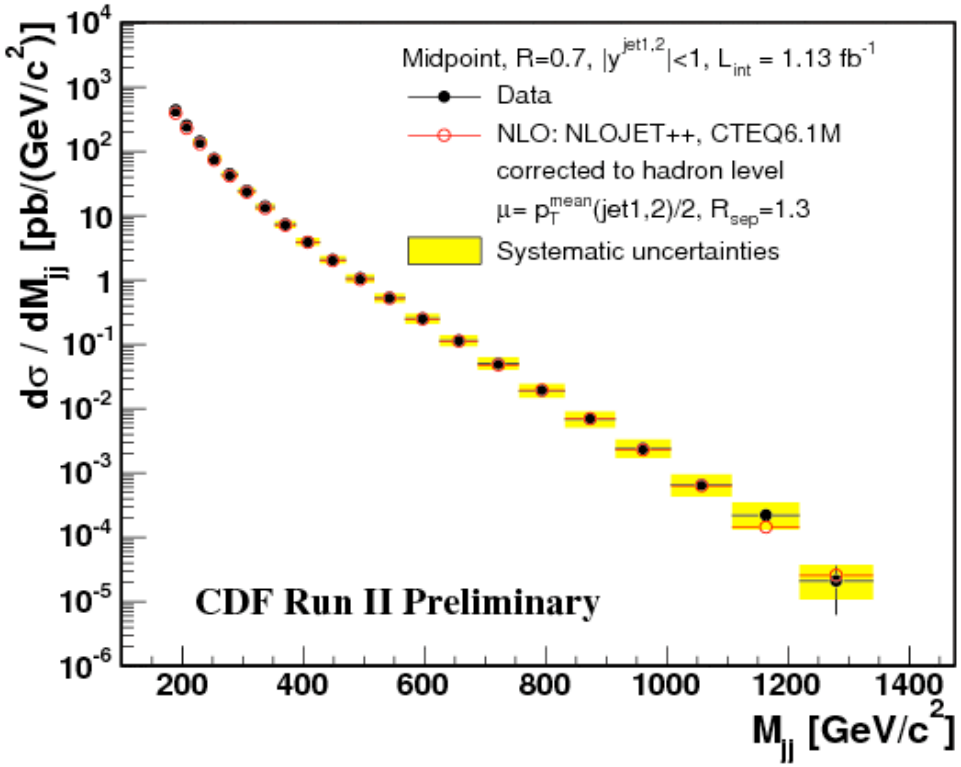
- **Testing Particle Production**
  - Jets, W's and Z's, top quarks
- **Electroweak Symmetry Breaking**
  - W boson mass and width
  - Top quark mass
  - Higgs boson search
- **Beyond the Standard Model**
  - Supersymmetry and beyond
- **Flavor physics:**
  - B lifetimes, mixing and Rare Decays

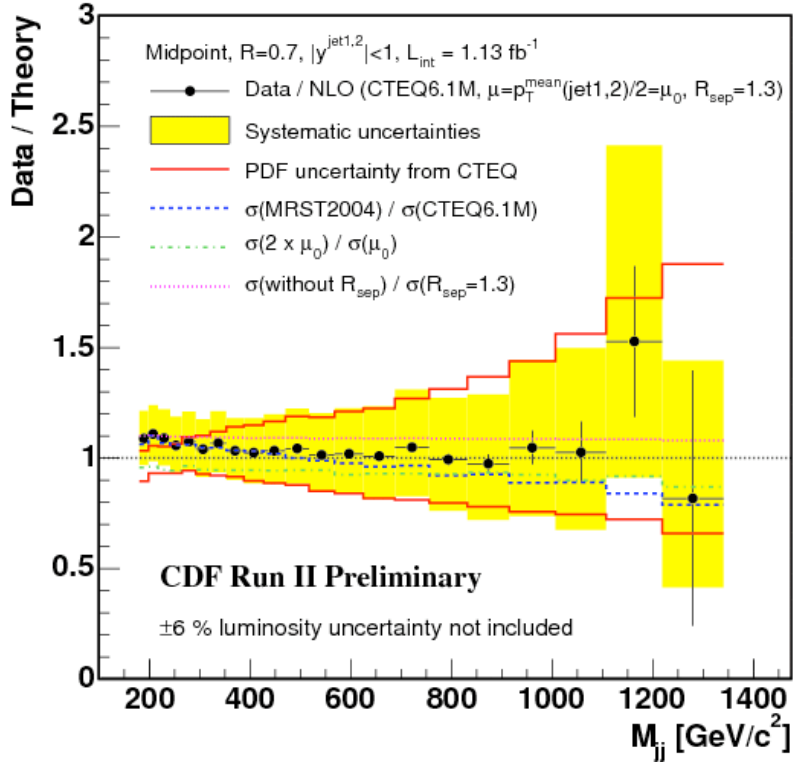


Production of Particles

Jet Cross Sections

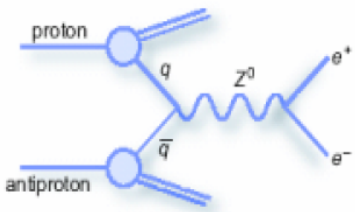


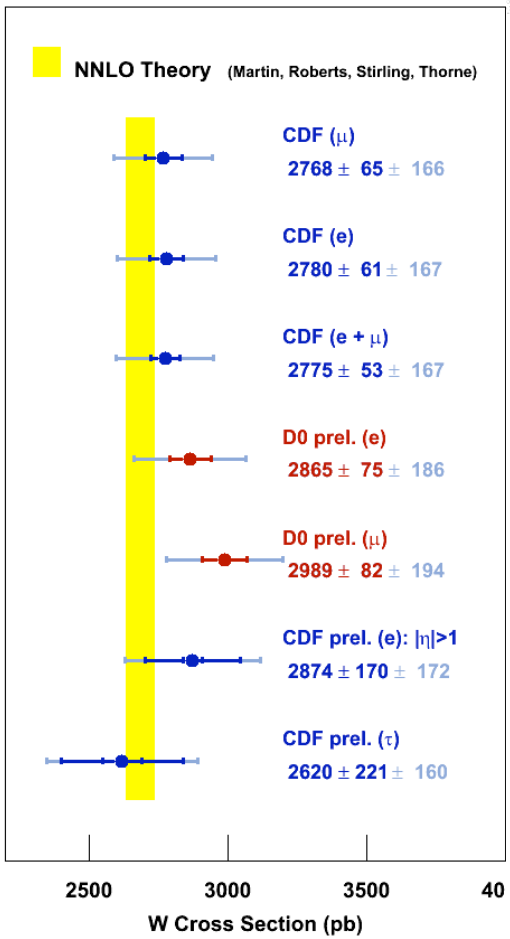


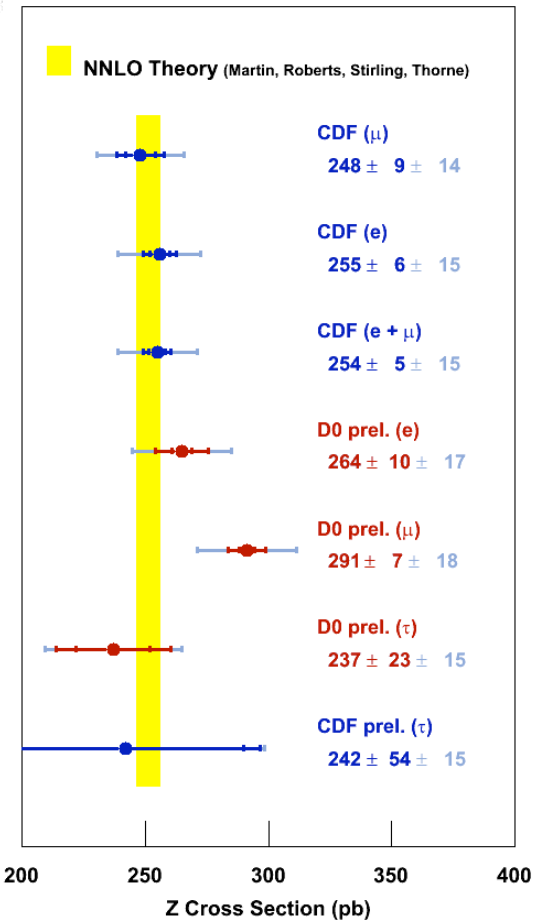


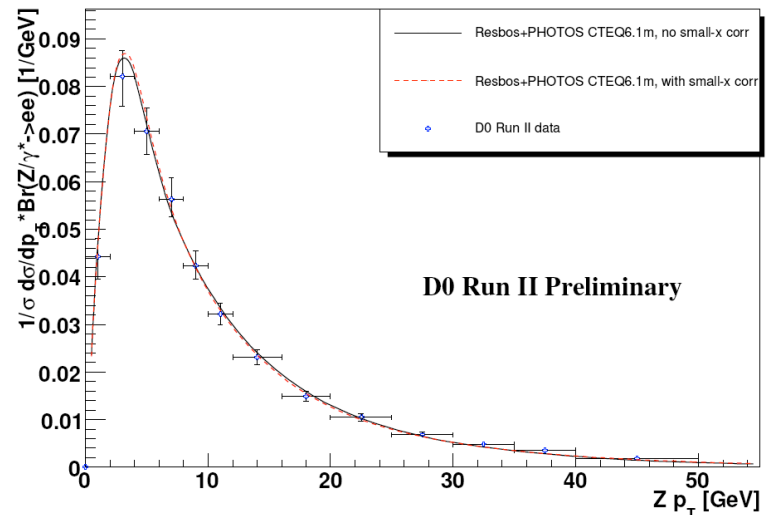
- Cross section measured over 7 orders of magnitude
- Data well described by Standard Model prediction up to masses of 1.2 TeV

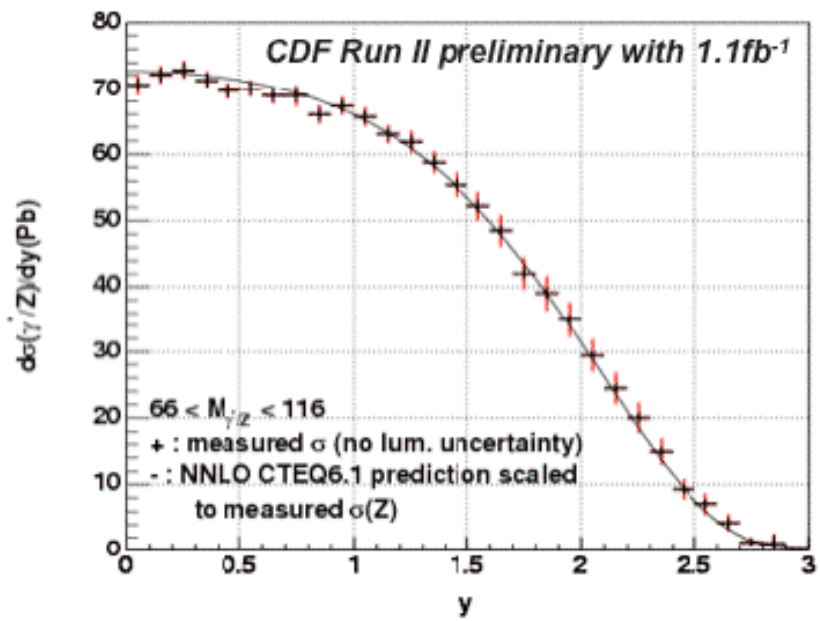
W and Z production





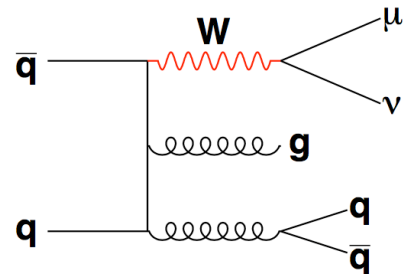




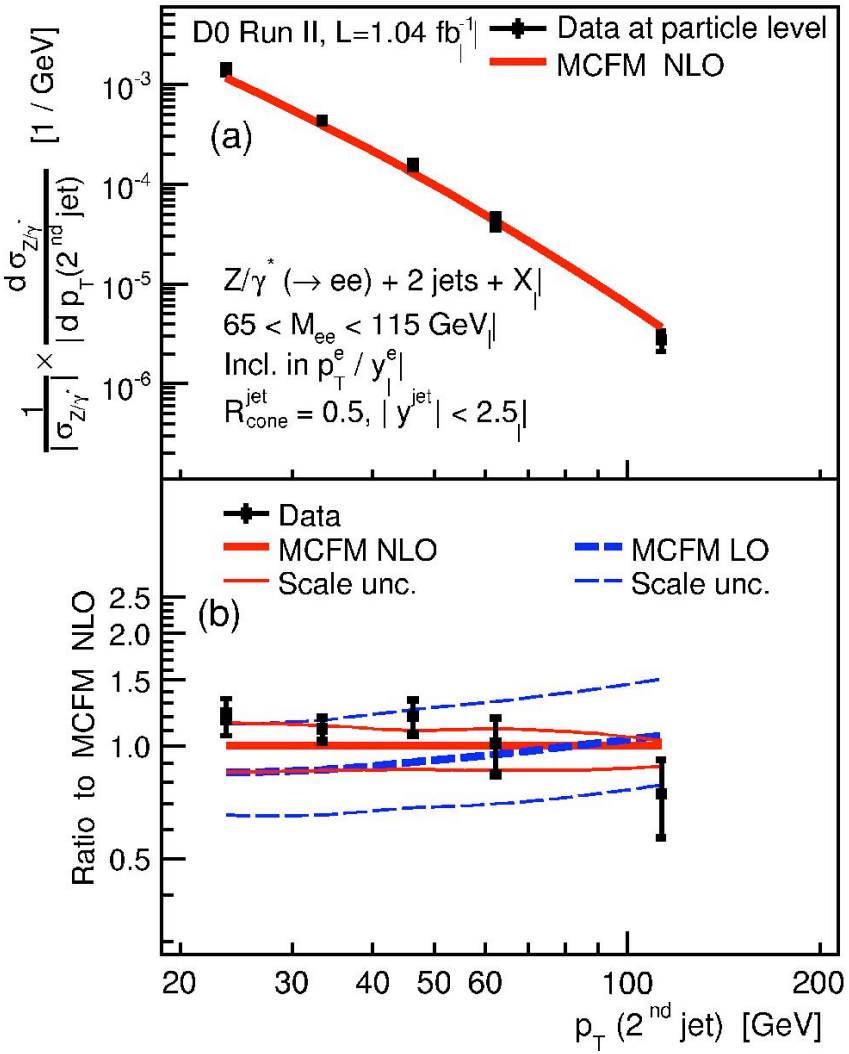


- High precision measurements
  - test NNLO QCD predictions

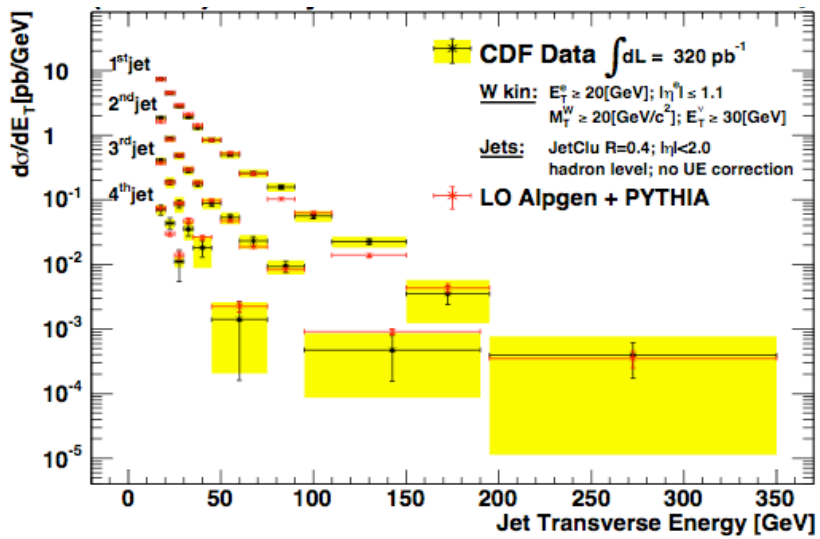
W/Z + Jets Production



Z + n jets

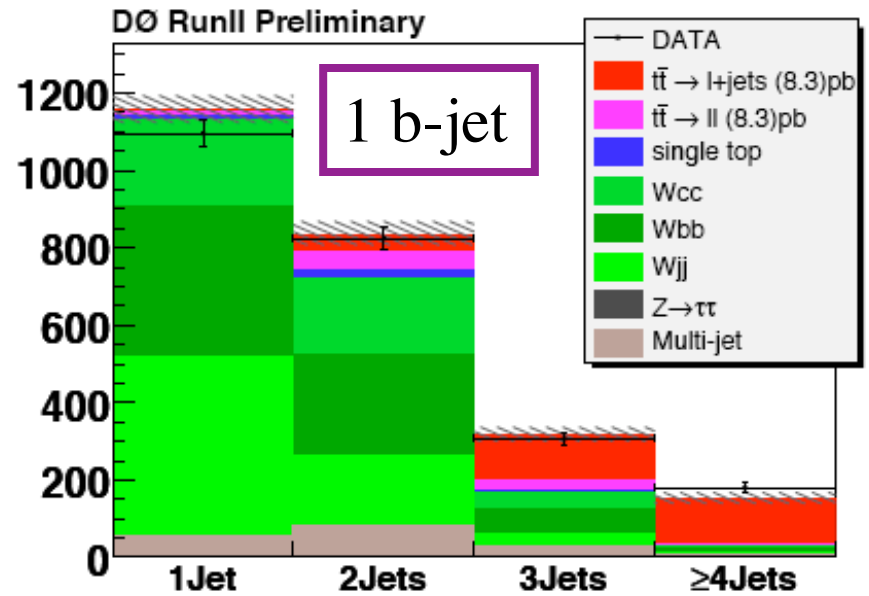


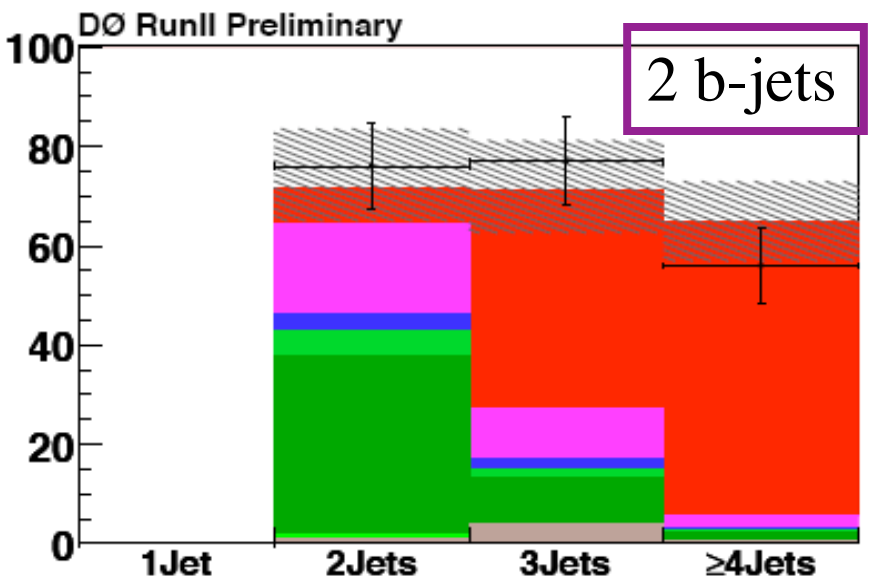
W + n jets

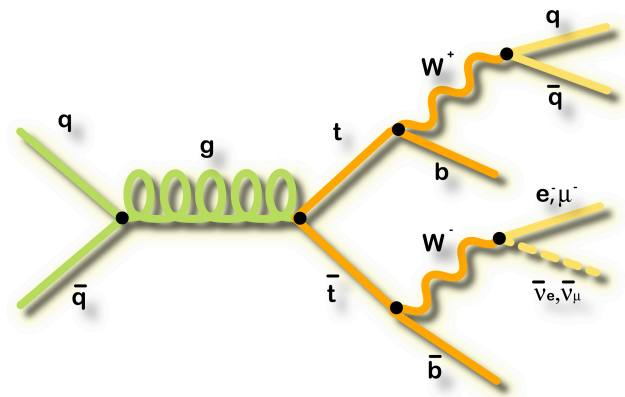


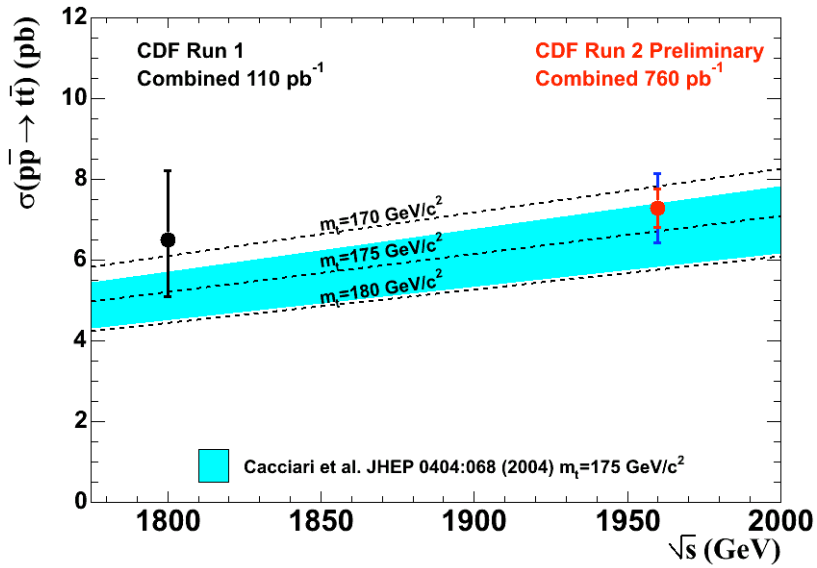
- Data agree well with QCD calculations

Top Quark Production



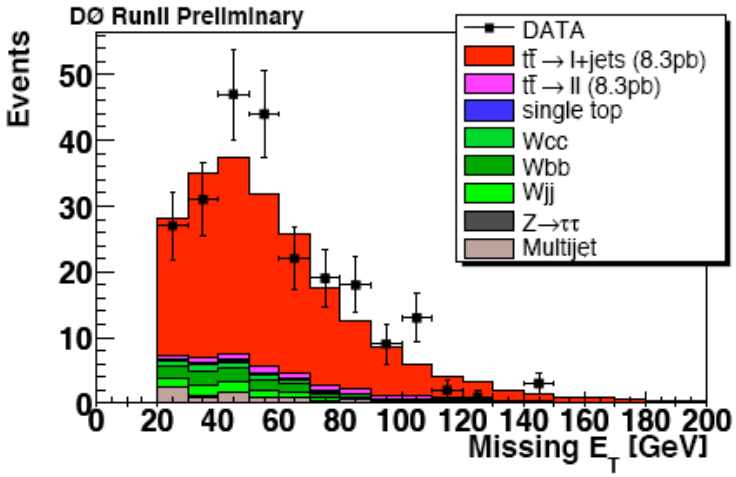


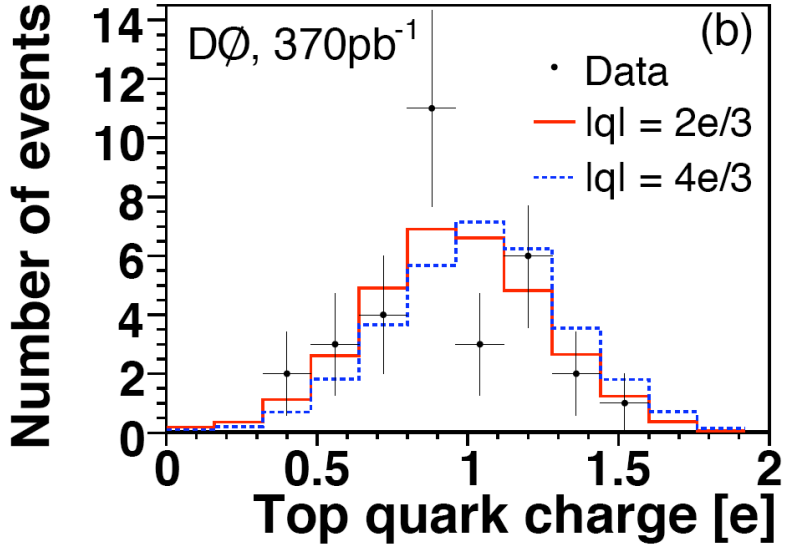




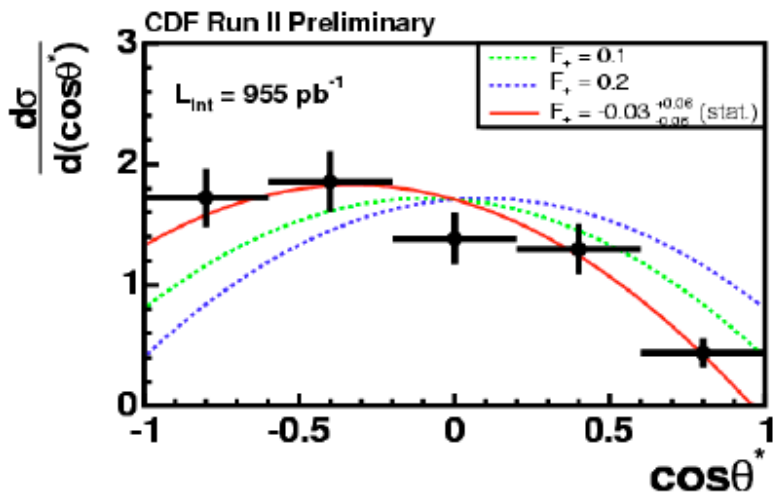
- Measurements consistent with theory

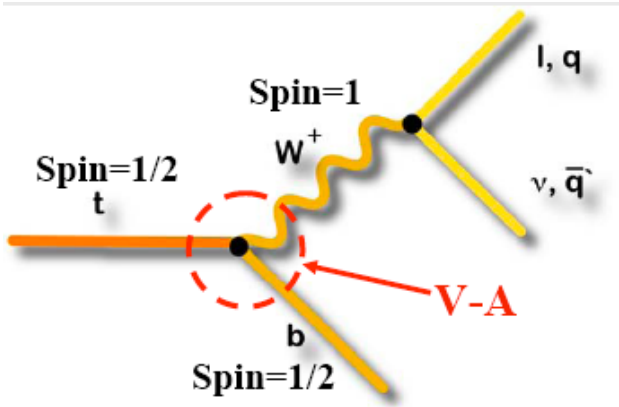
Top Quark: Kinematics+Properties





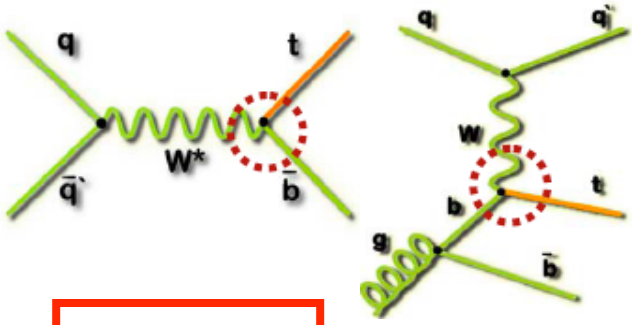
q_{top}=+2/3?



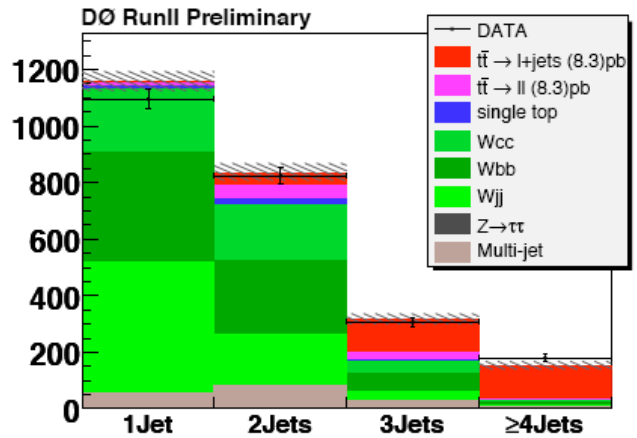


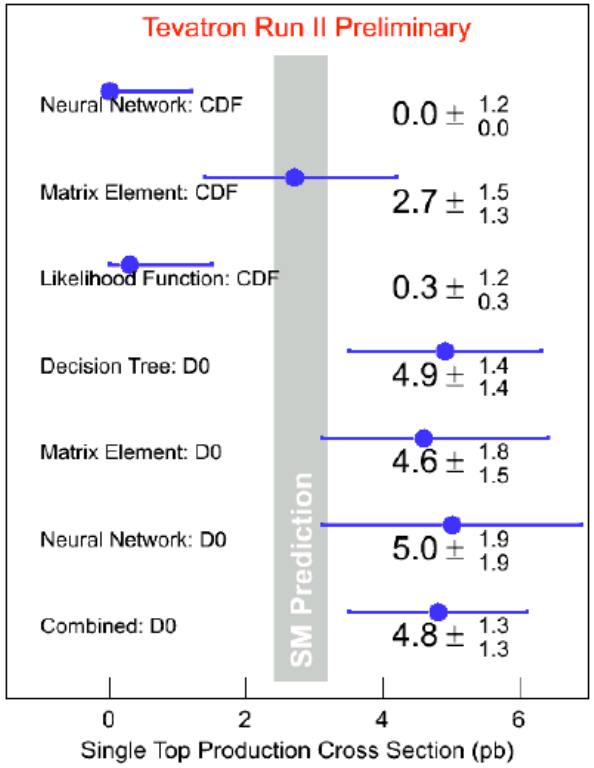
- Kinematic properties, couplings and charge consistent with Standard Model top prodiction so far

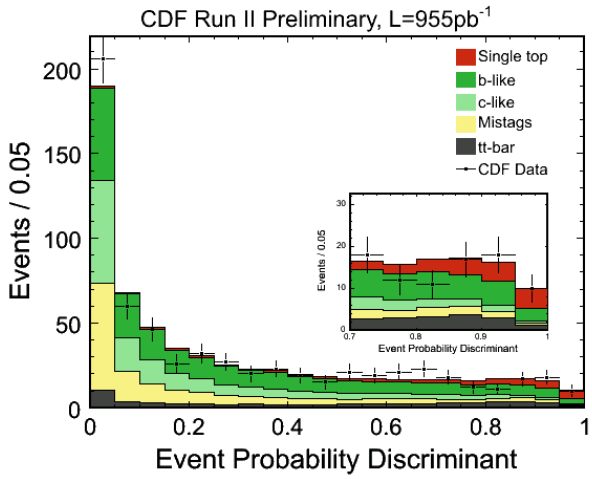
Single Top Production

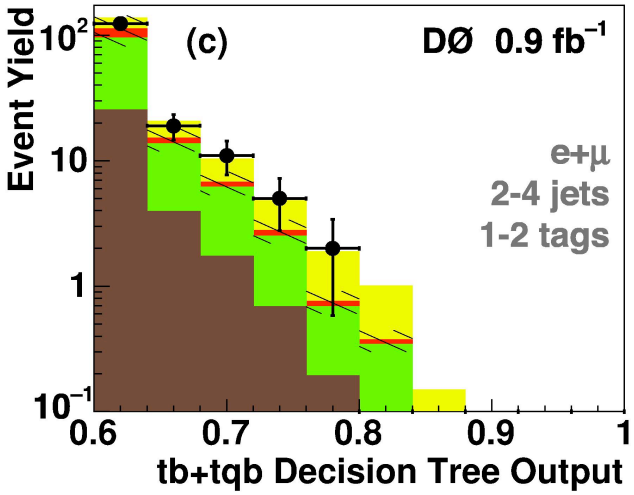


$$\sigma \propto V_{tb}^2$$







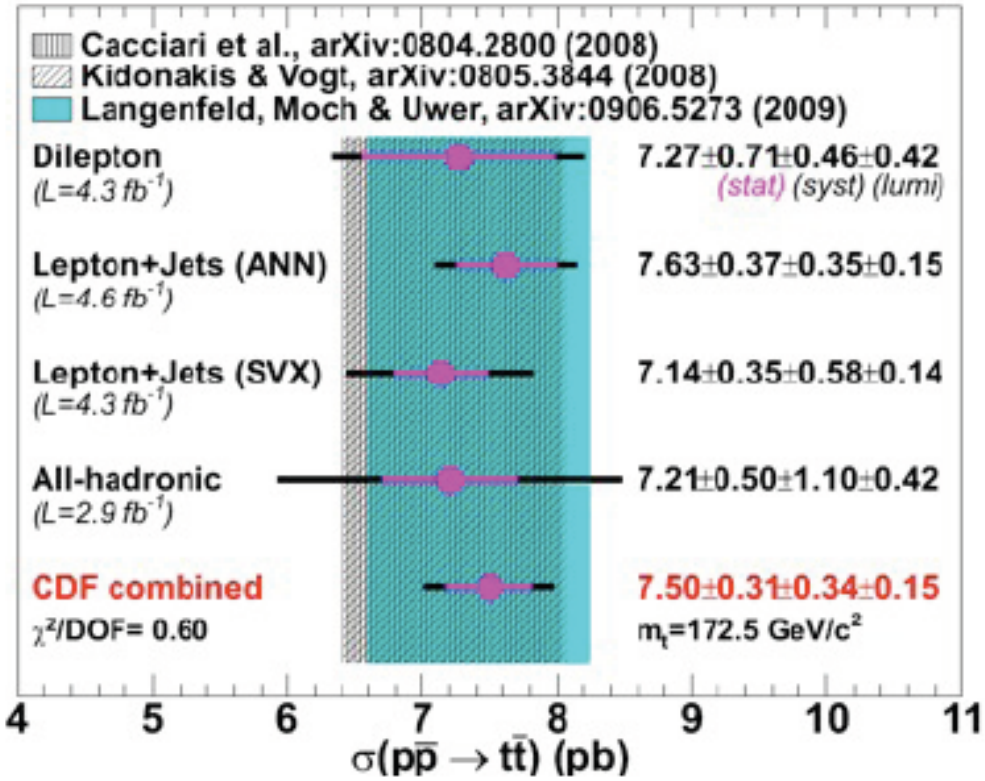


From DØ σ result:

V_{tb}>0.68 @ 95% CL

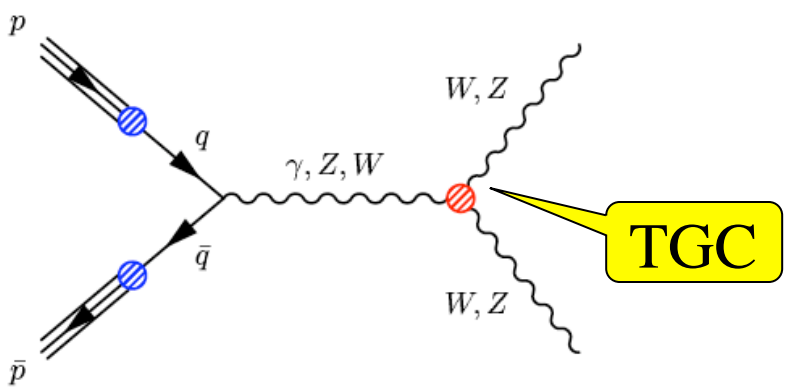
- Recently DØ announced first evidence for single top production
  - still rather poor precision and further data needed to clarify situation

The Top Cross Section

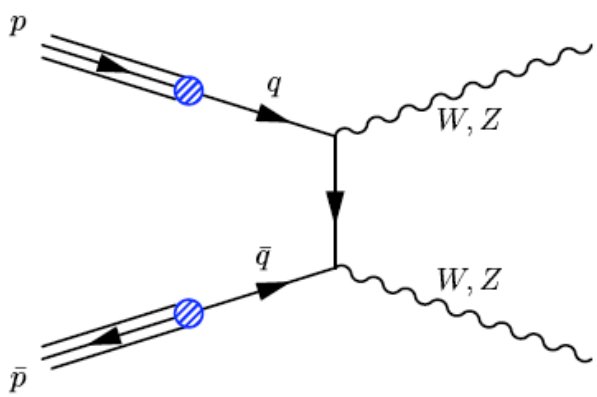


- Many measurements that use different techniques
- Good agreement
  - between all measurements
  - between data and theory
- Experimental Precision: ~6%
  - Better than theoretical precision

Diboson Production



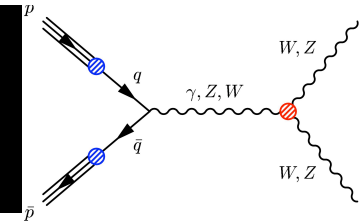
s-channel

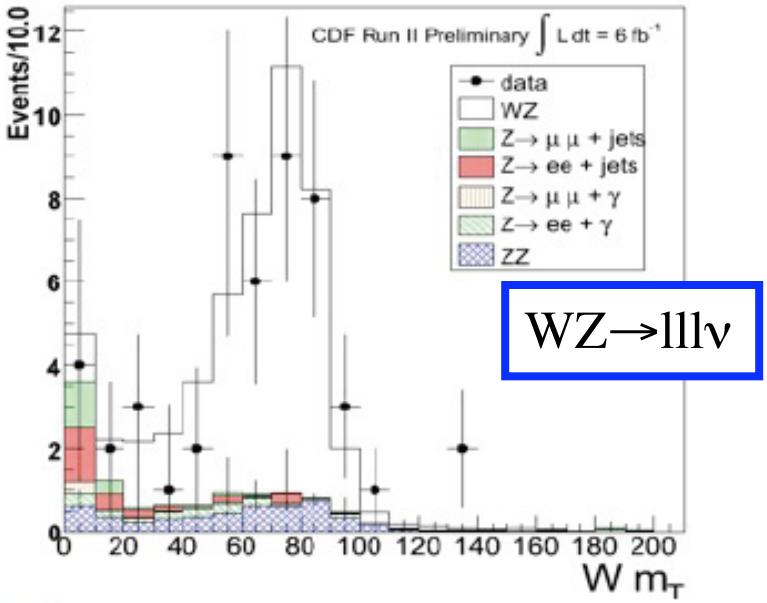


t-channel

- Diboson production probes trilinear couplings among the gauge bosons (TGC)
  - Direct prediction from SU(2)xU(1) gauge group
  - New physics could lead to anomalous couplings
- WW, Wγ, Z γ observed some time ago:
  - Agree with SM prediction
- Focus today:
  - WZ cross section: σ_{SM}=3.7 ± 0.3 pb
  - ZZ cross section: σ_{SM}=2.1 ± 0.2 pb

Diboson Production: WZ,ZZ





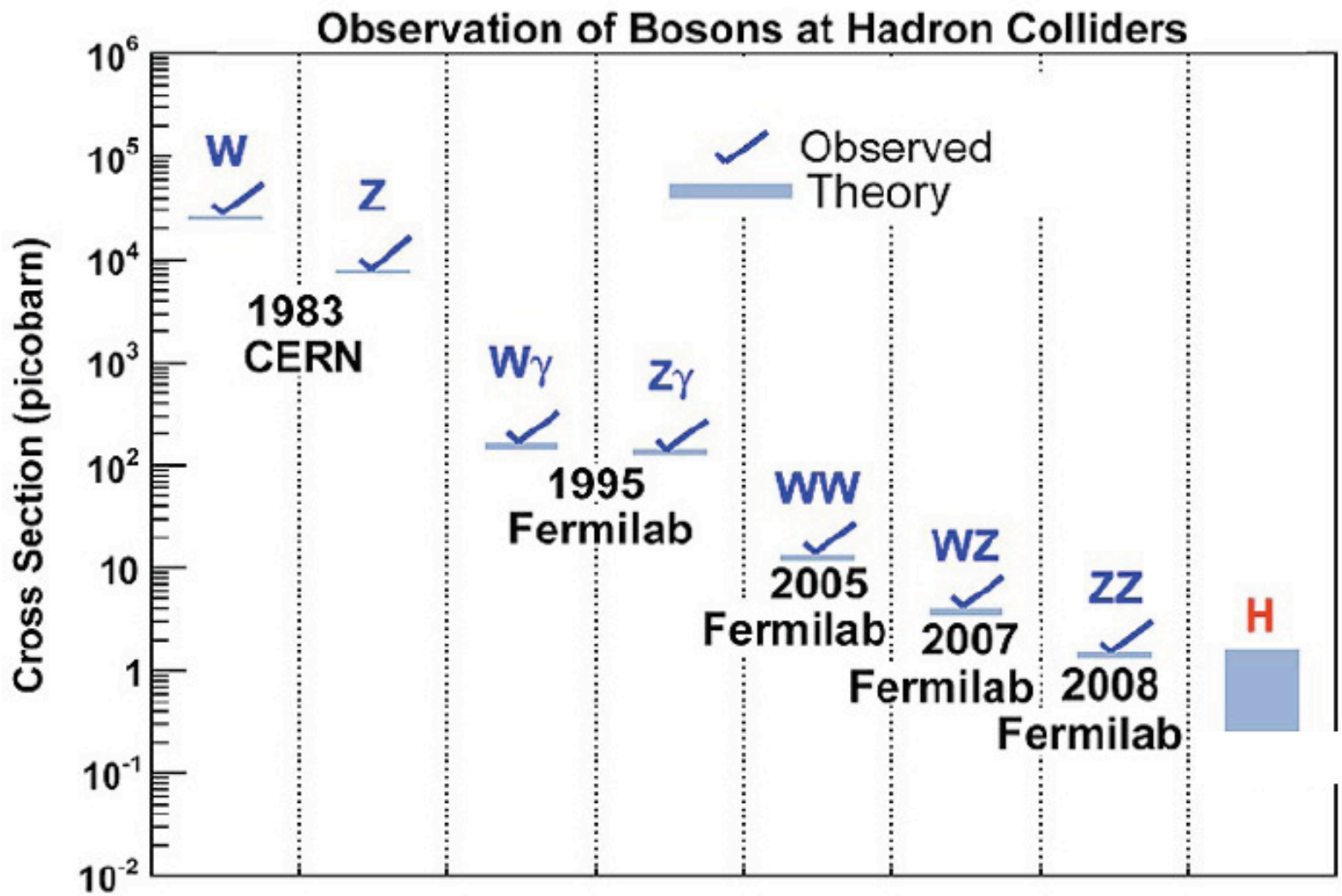
- WZ cross section:
  - CDF: 4.1±0.7 pb
  - DØ: $3.9^{+1.1}_{-0.9}$ pb
  - Theory: 3.46 ± 0.21 pb
- ZZ:
  - 3.0σ evidence
    - llll mode: 2.2σ
    - llνν mode: 1.9σ

DØ

ZZ→llll

	WZ cross section (pb)	ZZ
CDF	4.1±0.7	
D0	$3.9^{+1.1}_{-0.9}$	
Theory	3.46 ± 0.21	

Diboson Production Summary



Higgs Boson is next in line (at Fermilab or CERN…)

Electroweak Symmetry Breaking

The Electroweak Precision Data

- **Precision measurements of**
  - muon decay constant and α
  - Z boson properties (LEP,SLD)
  - W boson mass (LEP+Tevatron)
  - Top quark mass (Tevatron)

Measured to 0.015%

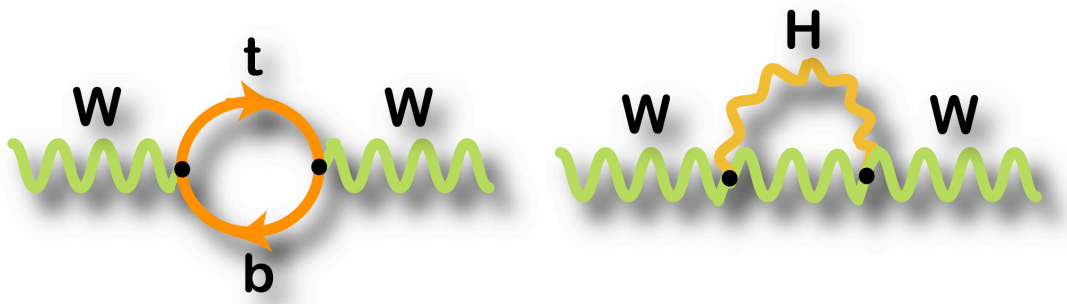
Measured to 0.002%

Measured to 0.036%

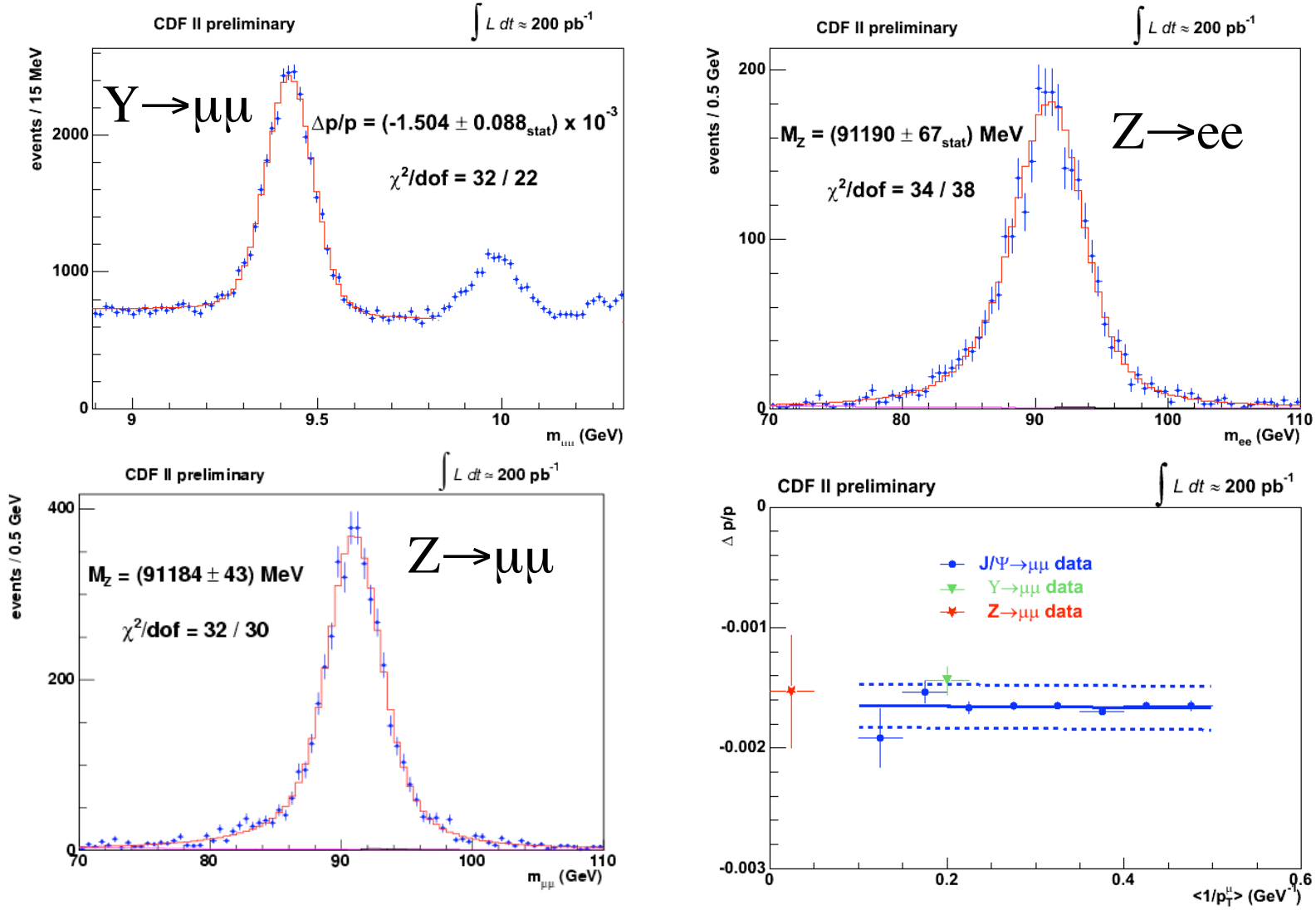
$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F}\frac{1}{(1-(M_W^2/M_Z^2))}\frac{1}{(1-\Delta r)}$$

Measured to 0.0009%

Δr: O(3%) radiative corrections dominated by *tb* and Higgs

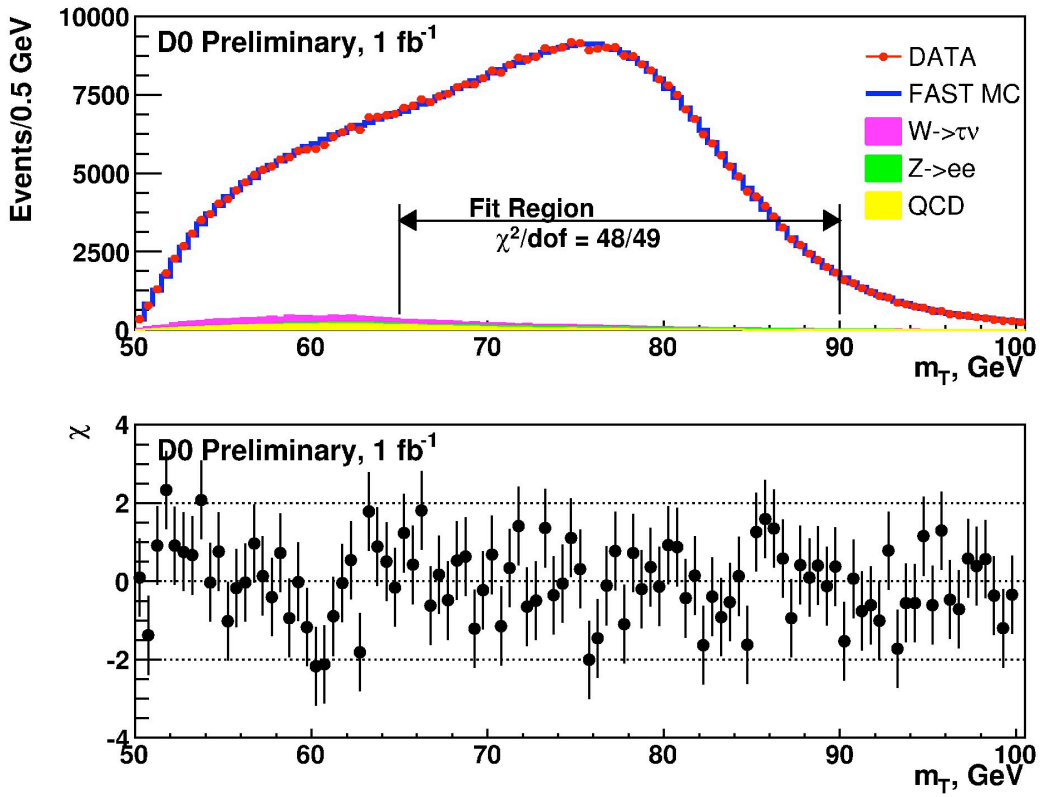


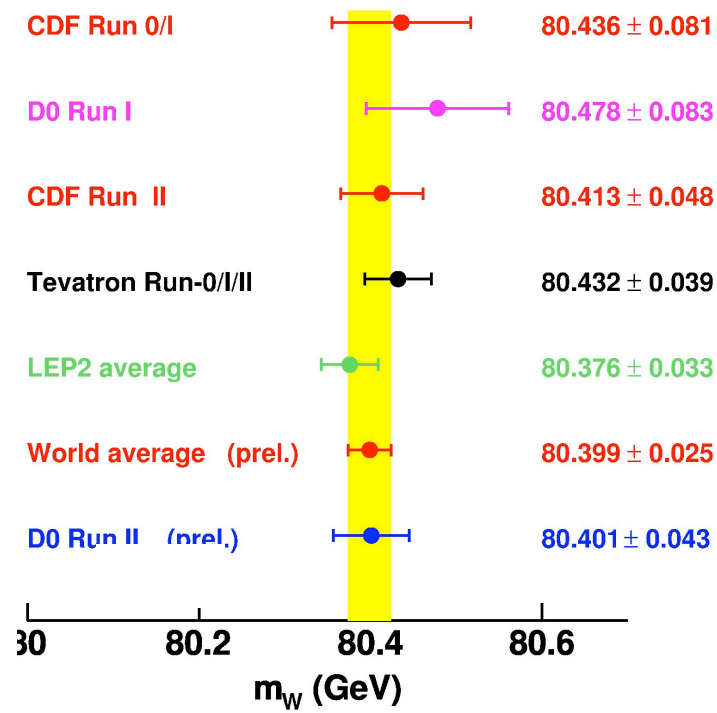
Lepton Energy Scale and Resolution



- Systematic uncertainty on momentum scale: 0.04%

W Boson Mass





World average:

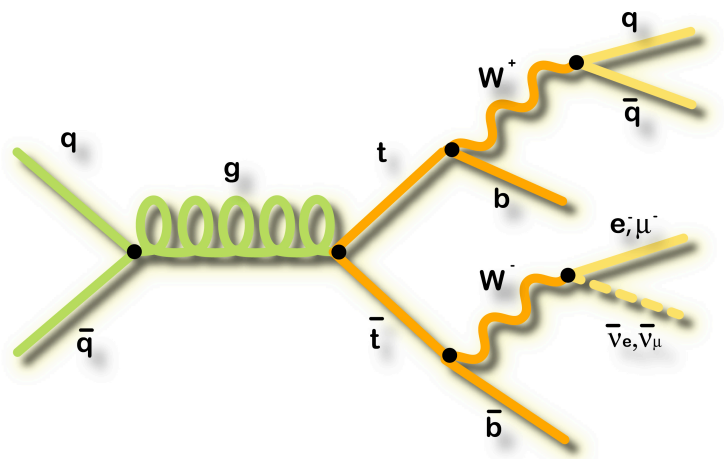
M_W=80399 ± 23 MeV

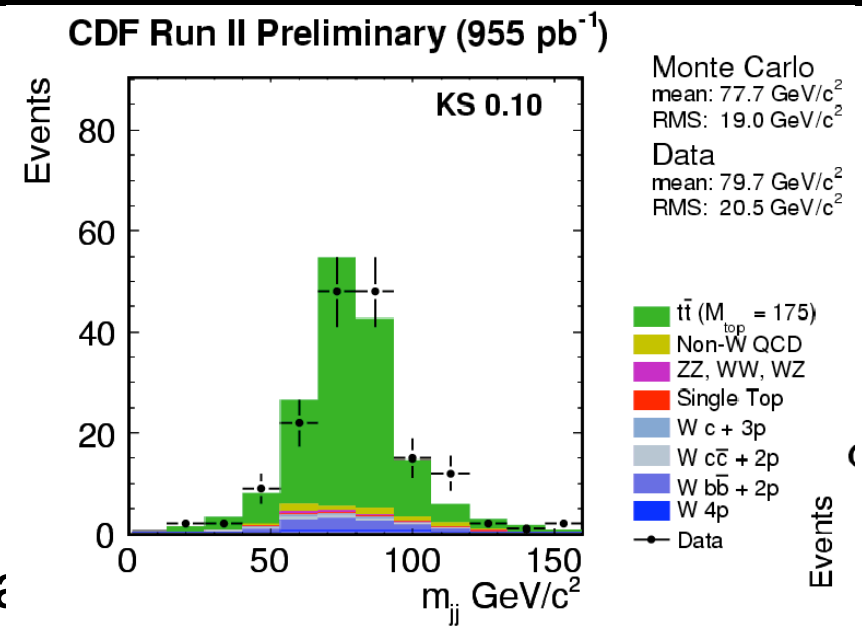
Ultimate precision:

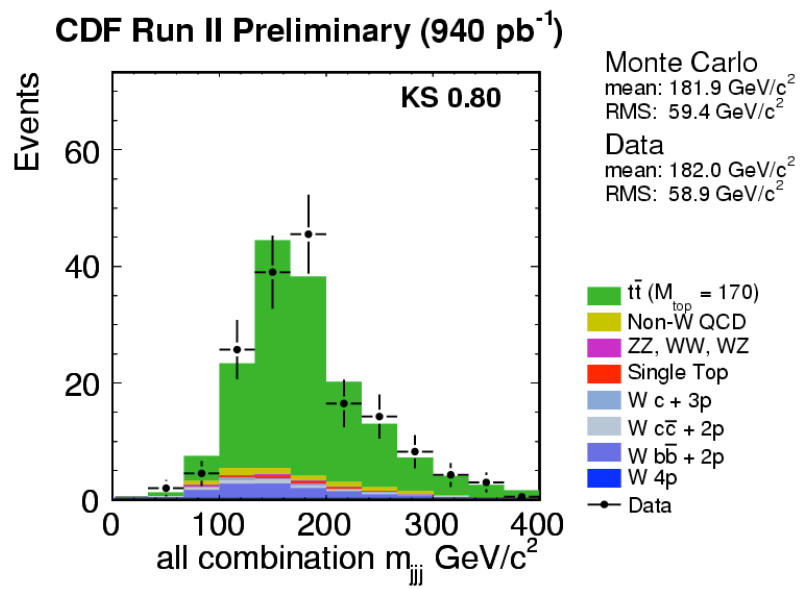
Tevatron: 15-20 MeV

LHC: unclear (5 MeV?)

Top Quark Mass

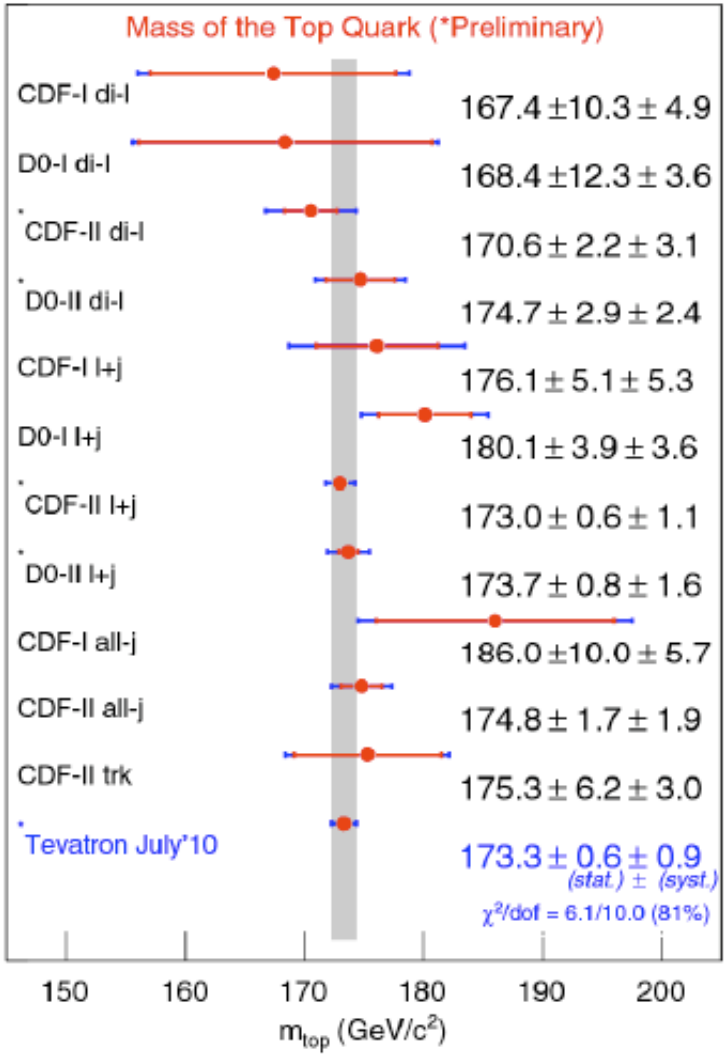






- Rather large pure samples availa
  - 166 events: S/B=4/1
- Perform simultaneous fit for
  - Top quark mass
  - Jet energy scale (M_W=M_{jj})
    - dominant systematic uncertainty

Top Quark Mass Results

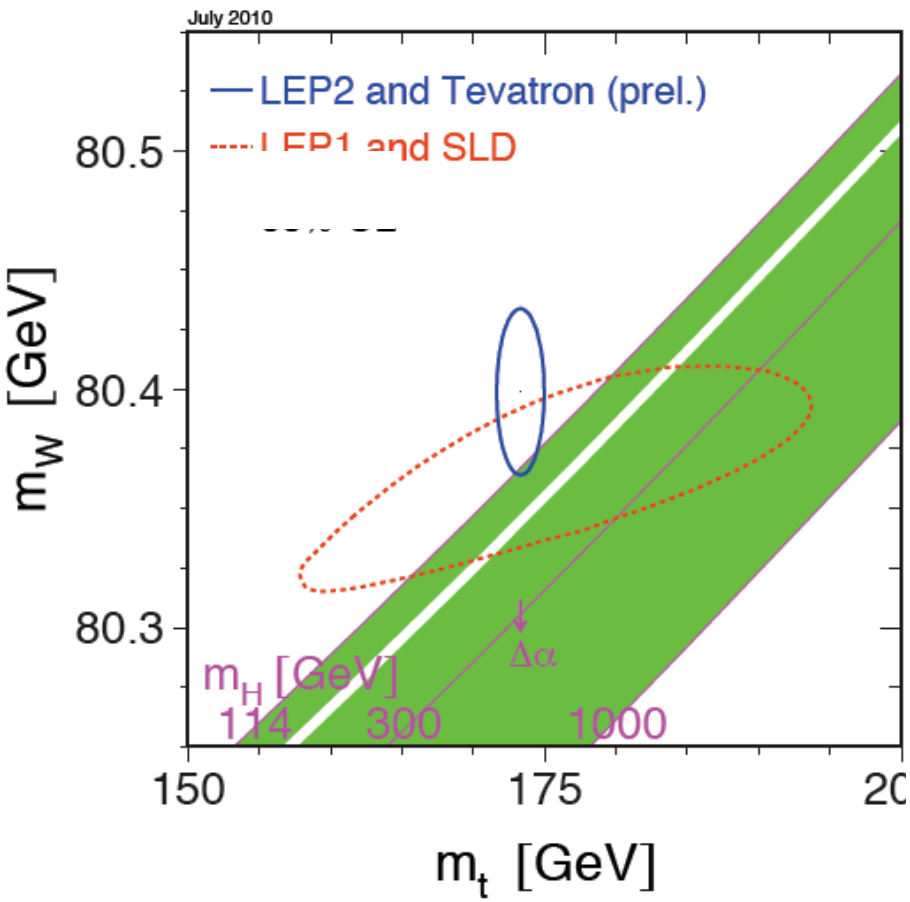


m_{top}=173.3± 0.6 GeV/c^2

Prediction from LEP1, SLD, M_W,Γ_W: 178.9 $^{+11.7}_{-8.6}$ GeV/c^2

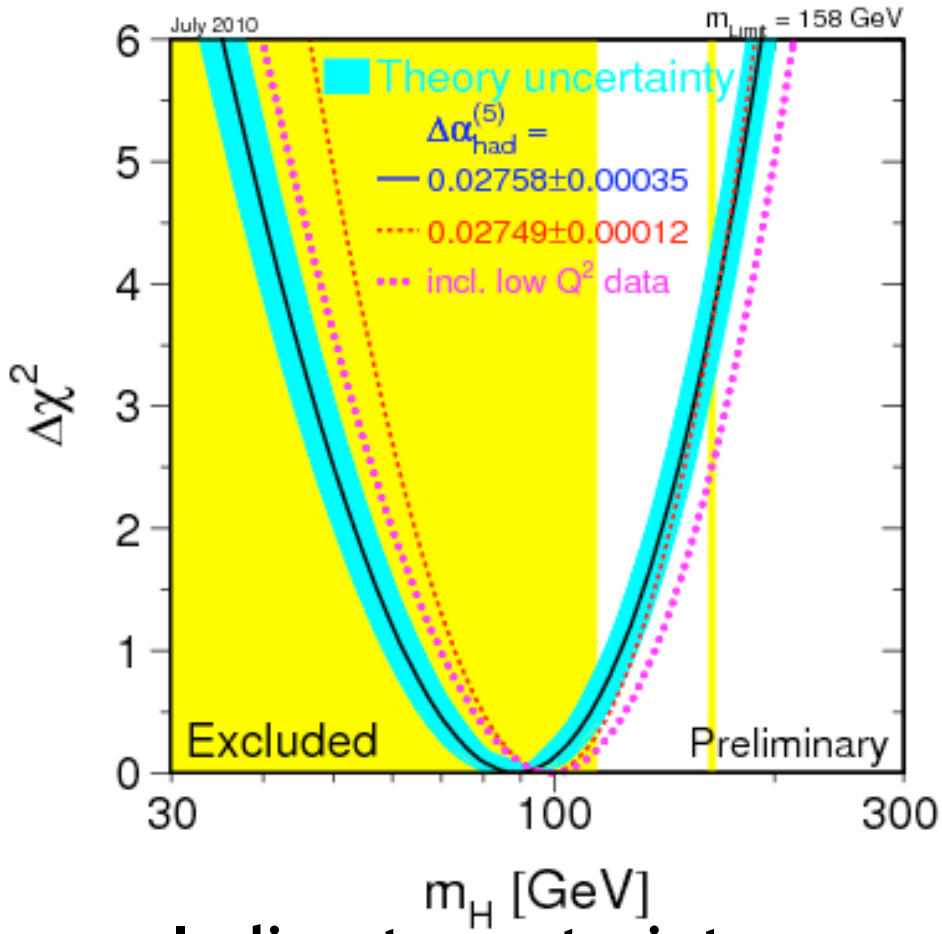
Implications for the Higgs Boson

Relation: M_W vs m_{top} vs M_H



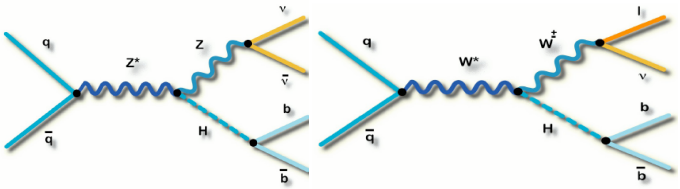
Standard Model still works!

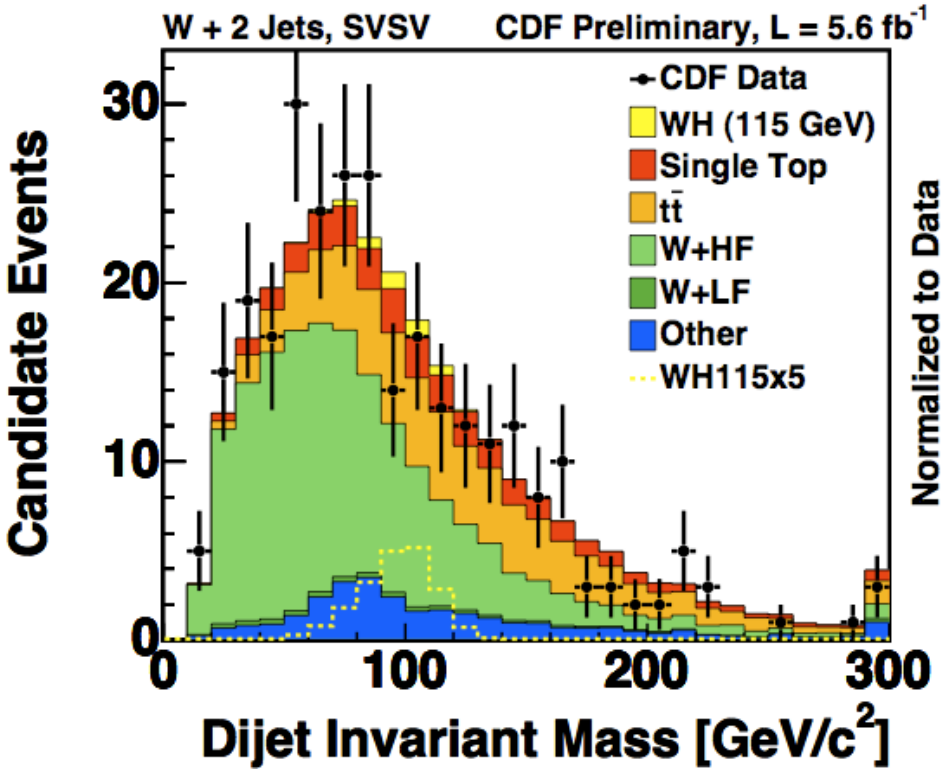
$m_H = 89^{+35}_{-26}$ GeV

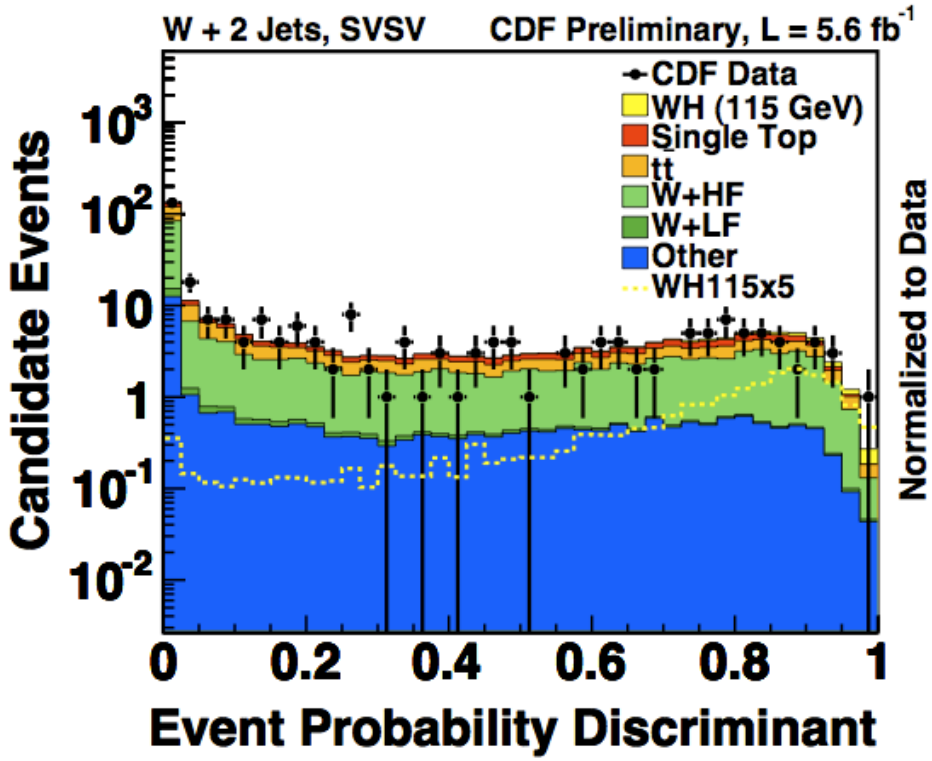


Indirect constraints:
m_H<158 GeV @95%CL

W/Z+Higgs with H→bb



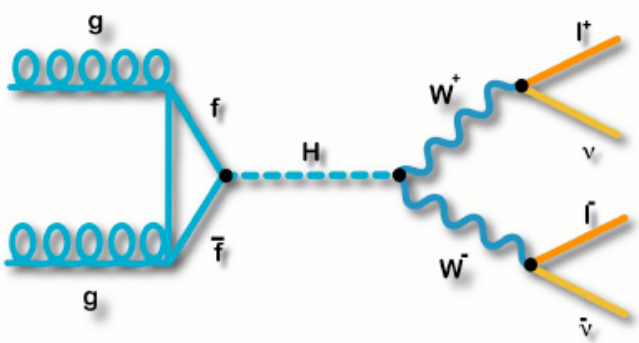


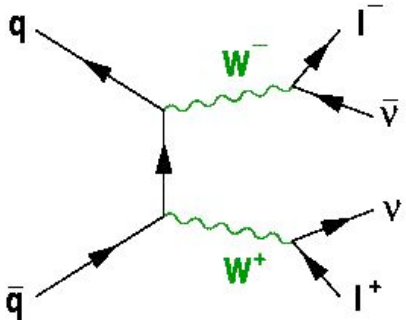


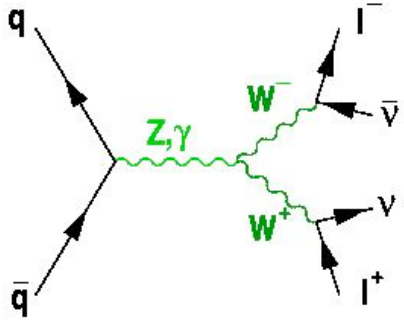
- For m_H<135 GeV/c^2:
  - WH→lνbb, ZH →llbb, ZH →ννbb
- Higgs causes peak in dijet mass
- Analyses make use of full event correlations to improve separation from background

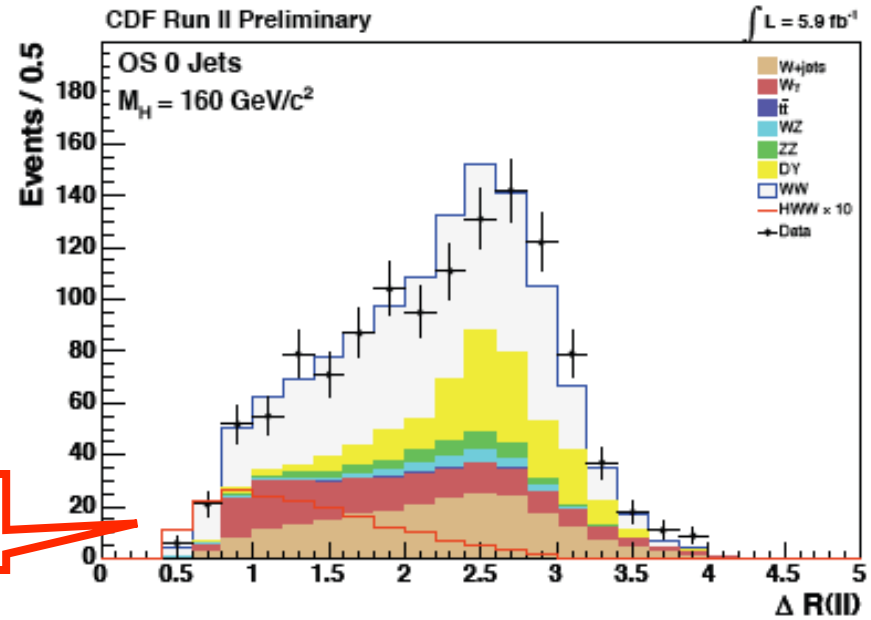
$H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$

- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs has spin=0
  - leptons in $H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$ are collinear
- Main background: WW production



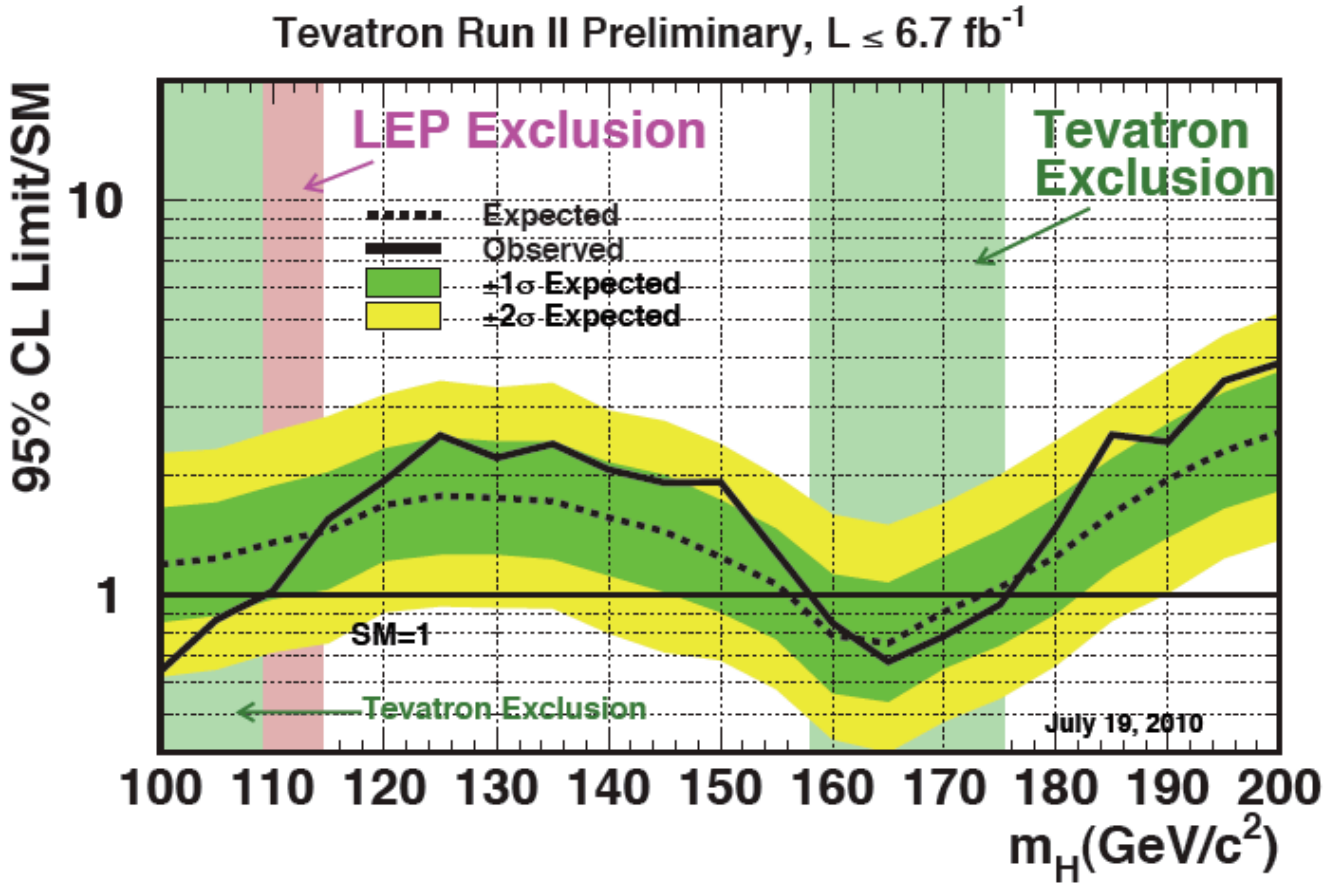






160 GeV Higgs

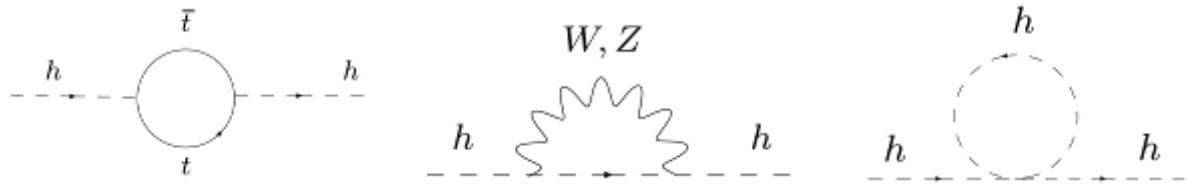
Tevatron Higgs Limit



- Combine CDF and DØ analyses from all channels at low and high mass
  - Exclude m_H=158-175 GeV/c^2 at 95% C.L.
  - m_H=120 GeV/c^2: limit/SM ≈ 1.5

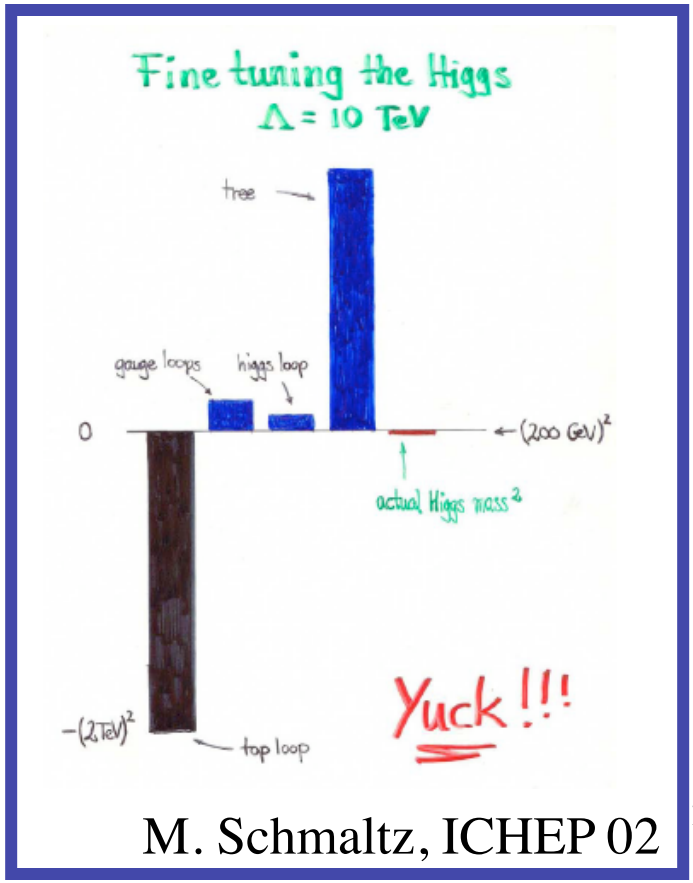
Beyond the Standard Model

Problems of the Standard Model



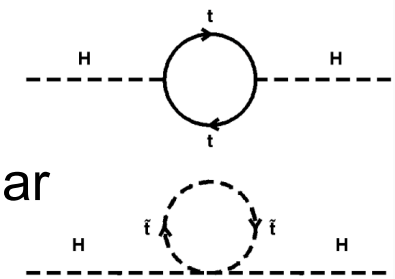
$$m^2_H \approx (200\ \text{GeV})^2 = m^2_H{}^{tree} + \delta\, m^2_H{}^{top} + \delta\, m^2_H{}^{gauge} + \delta\, m^2_H{}^{higgs}$$

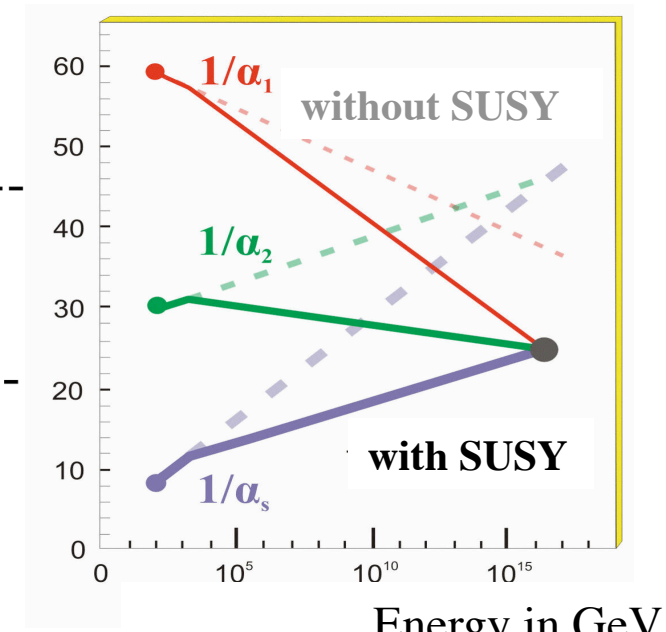
- Large fine-tuning required:
  - $m_H \ll m_{Pl}$
- Accounts for just 5% of the matter on the Universe
  - No dark matter candidate
- No prediction for
  - fundamental constants, unification of forces, number of generations, mass values and hierarchy of SM particles, anything to do with gravity



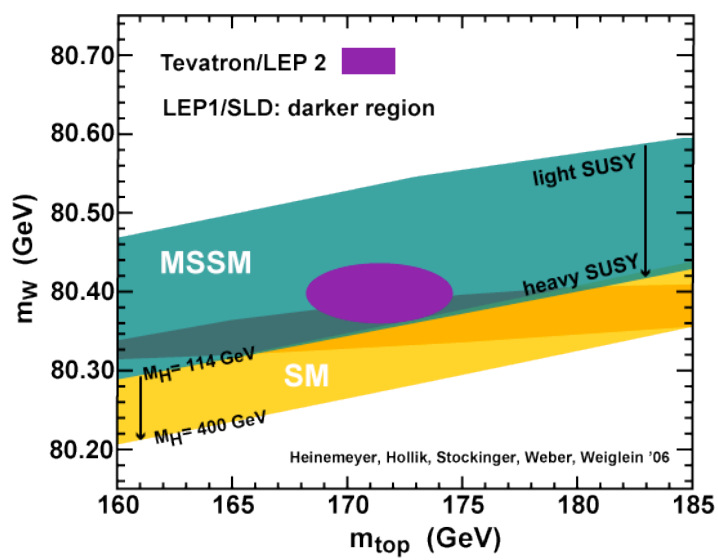
What's Nice about SUSY?

- Radiative corrections to Higgs acquire SUSY corrections:
  - No/little fine-tuning required
  - Particles masses must be near EWK scale

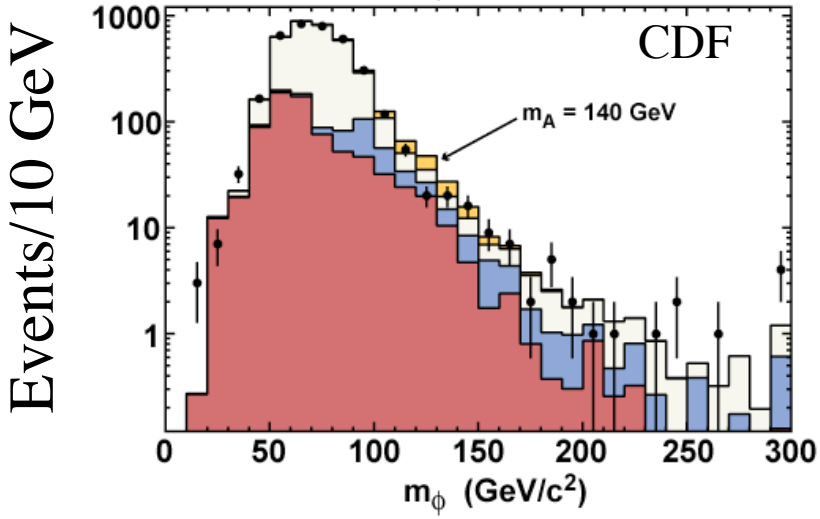


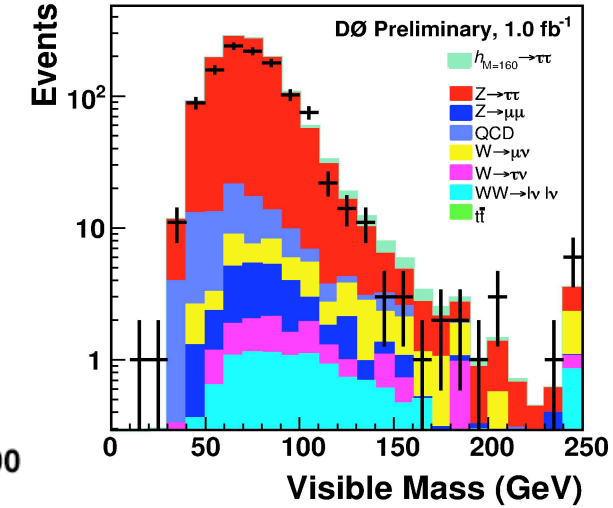


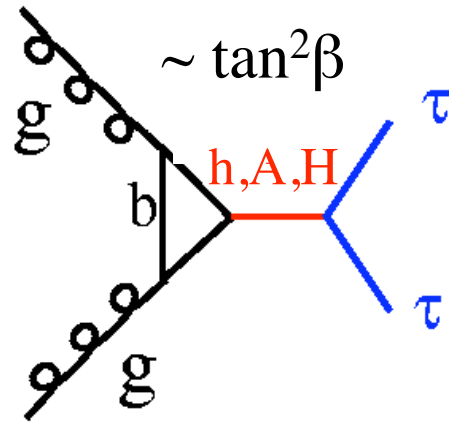
- Unification of forces possible
- Dark matter candidate exists:
  - lightest neutral gaugino
- Changes relationship between m_W, m_{top} and m_H:
  - Also consistent with precision measurements of M_W and m_{top}
- SUSY particles must be near EWK scale (~TeV) for SUSY to actually solve these problems

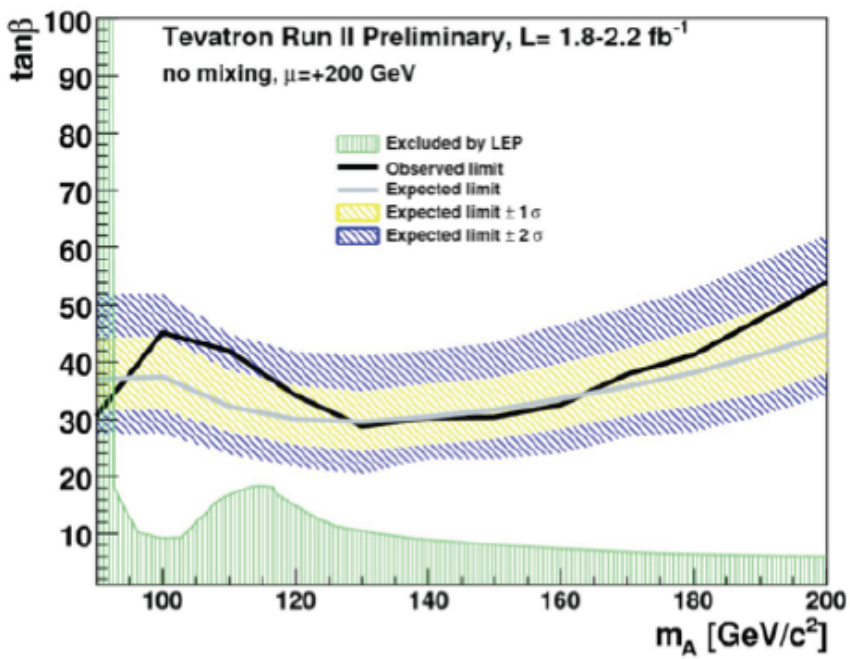


MSSM Higgs Boson Search



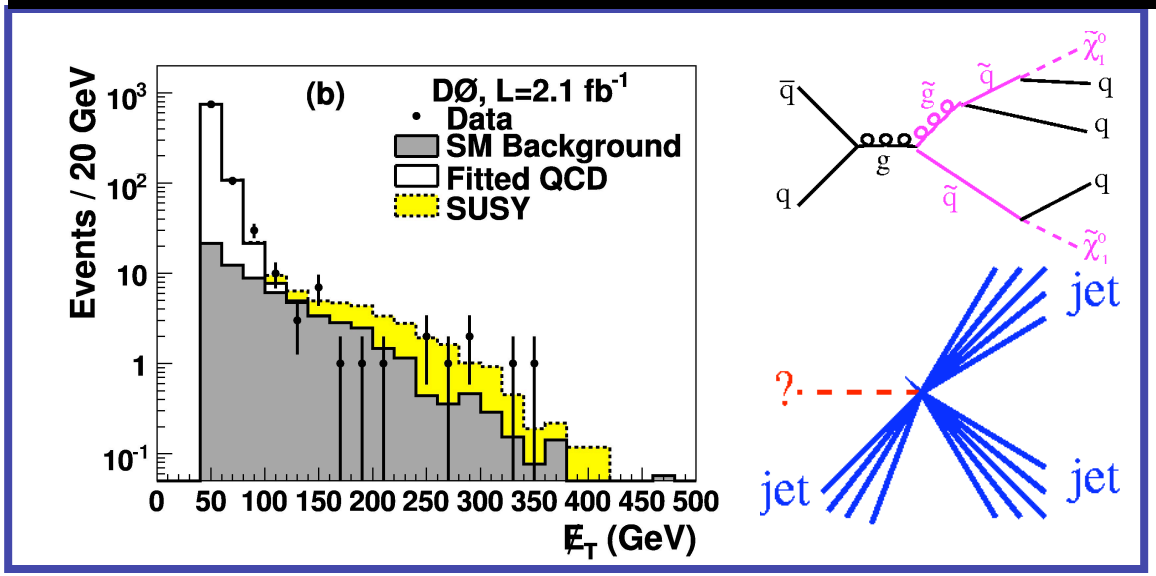


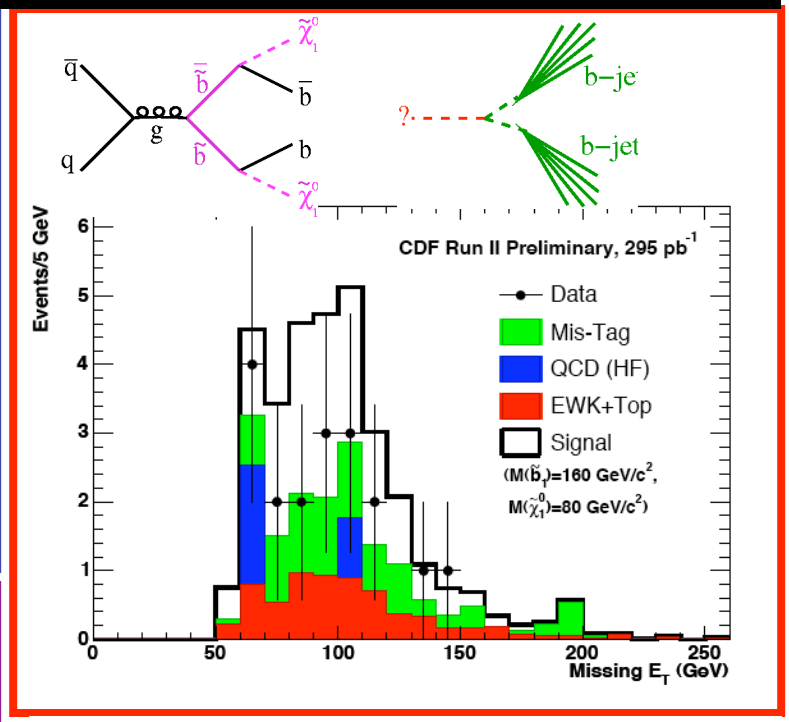


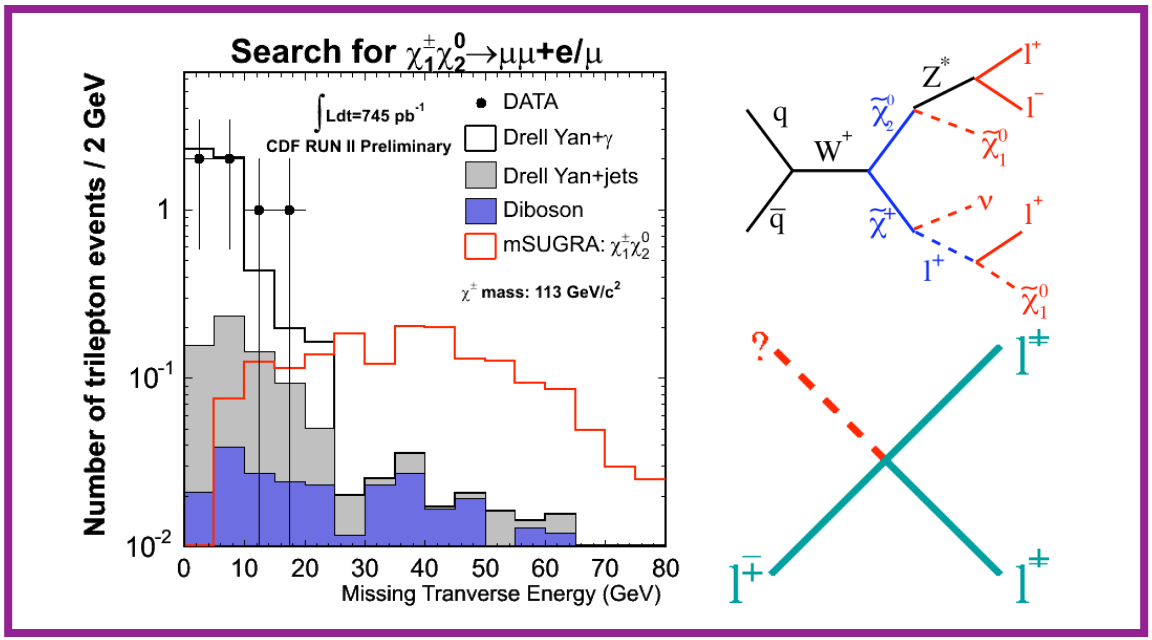


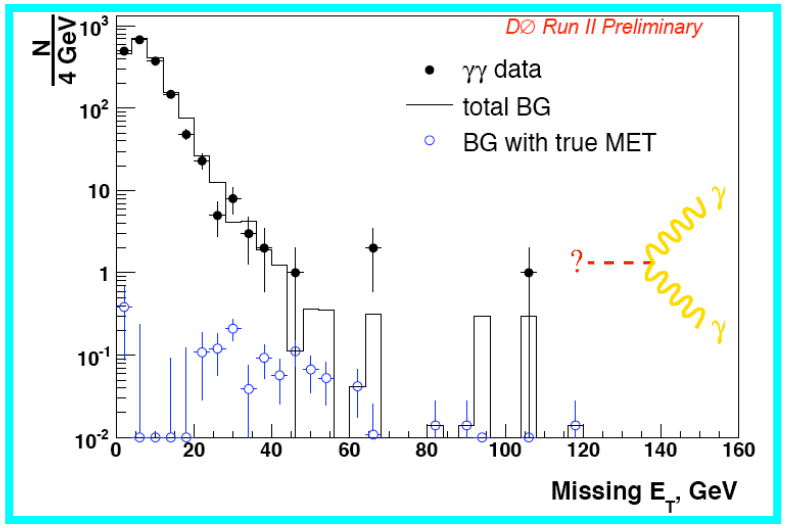
- Data mass distribution agrees with SM expectation
- Limits placed on such supersymmetric Higgs bosons

Supersymmetry Searches

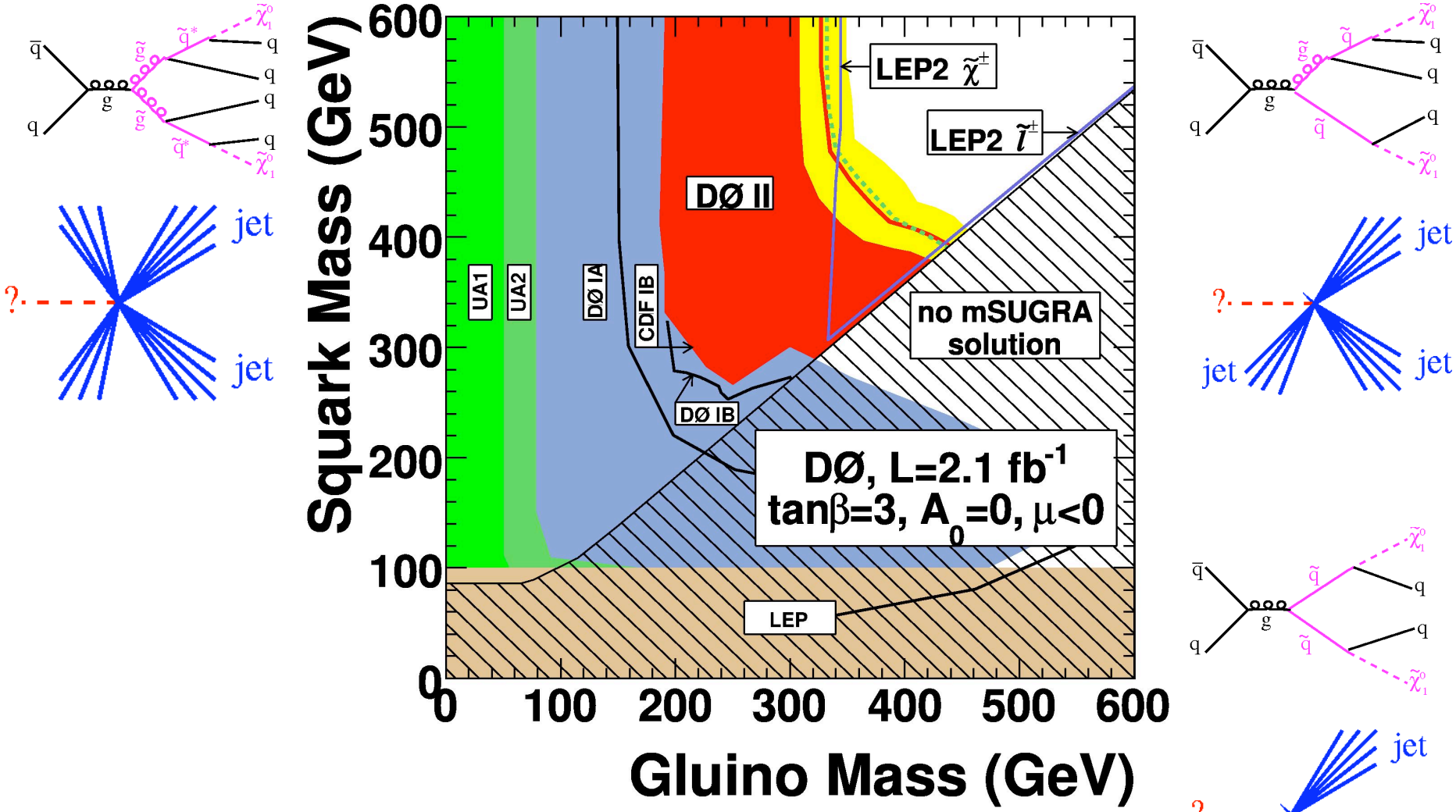








Supersymmetry Parameter Space



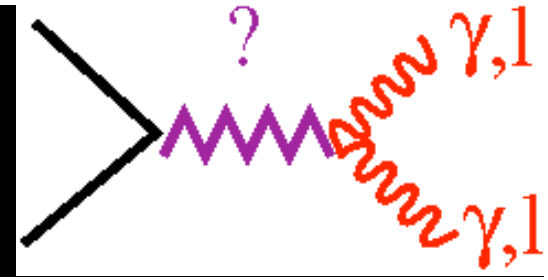
M($\tilde{g}$)>308 GeV and M($\tilde{q}$)>379 GeV

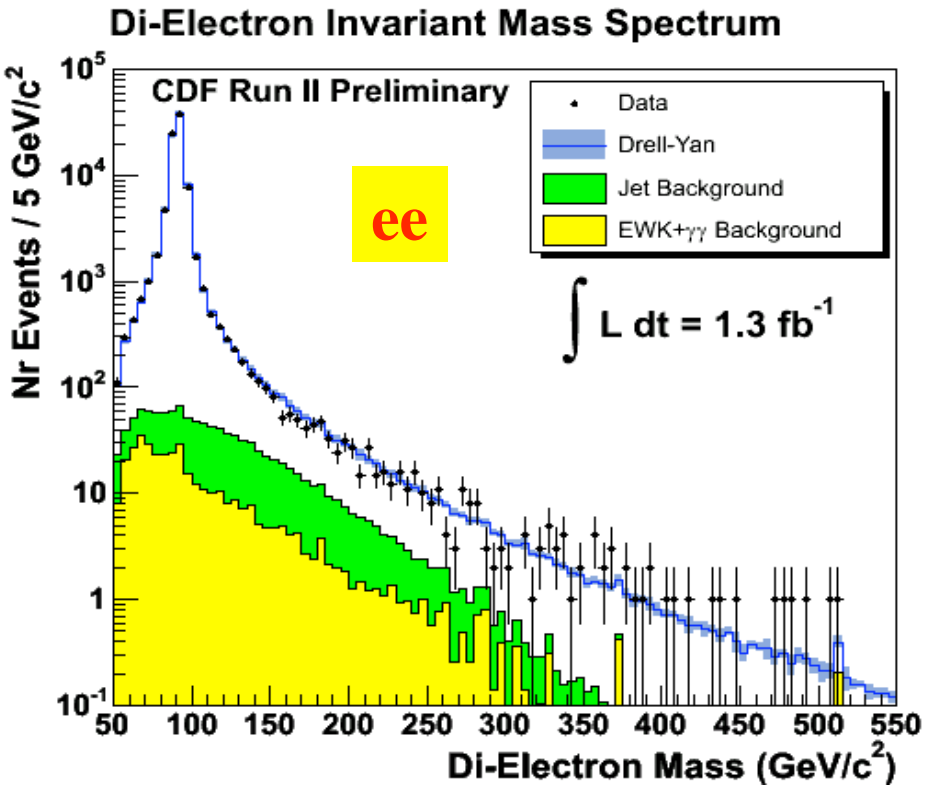
Beyond SUSY

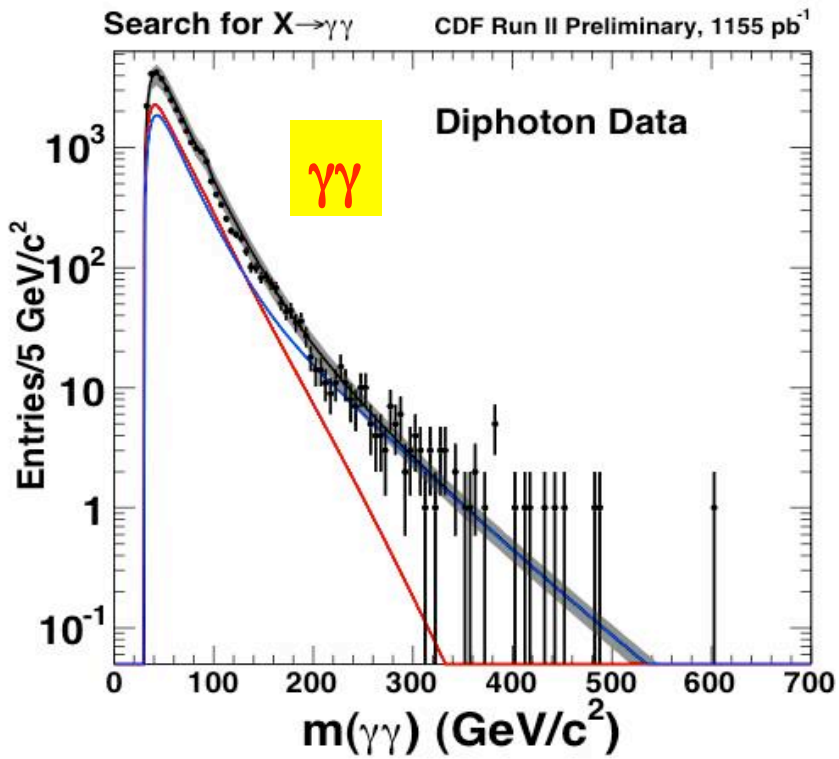
What else could be there?

- Strong theoretical prejudices for SUSY being true
  - However, we need to keep our eyes open
  - particularly due to the lack of SUSY observation…
- There could be many other theories/particles, e.g.:
  - Extra spatial dimensions:
    - "Solve" hierarchy problem by making gravity strong at TeV scale
  - Extra gauge groups: Z', W'
    - Occur naturally in GUT scale theories
  - Leptoquarks:
    - Would combine naturally the quark and lepton sector
  - ????

ee and γγ Mass Spectra

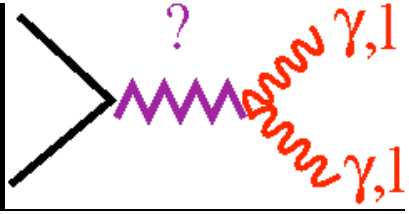




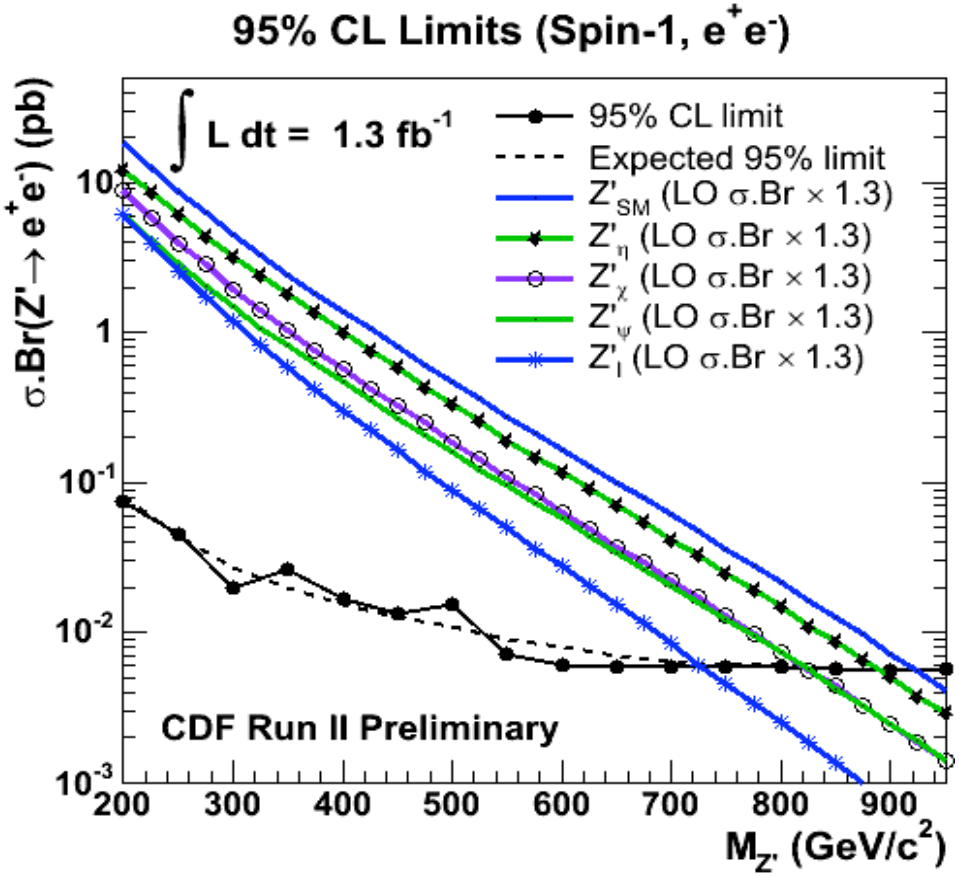


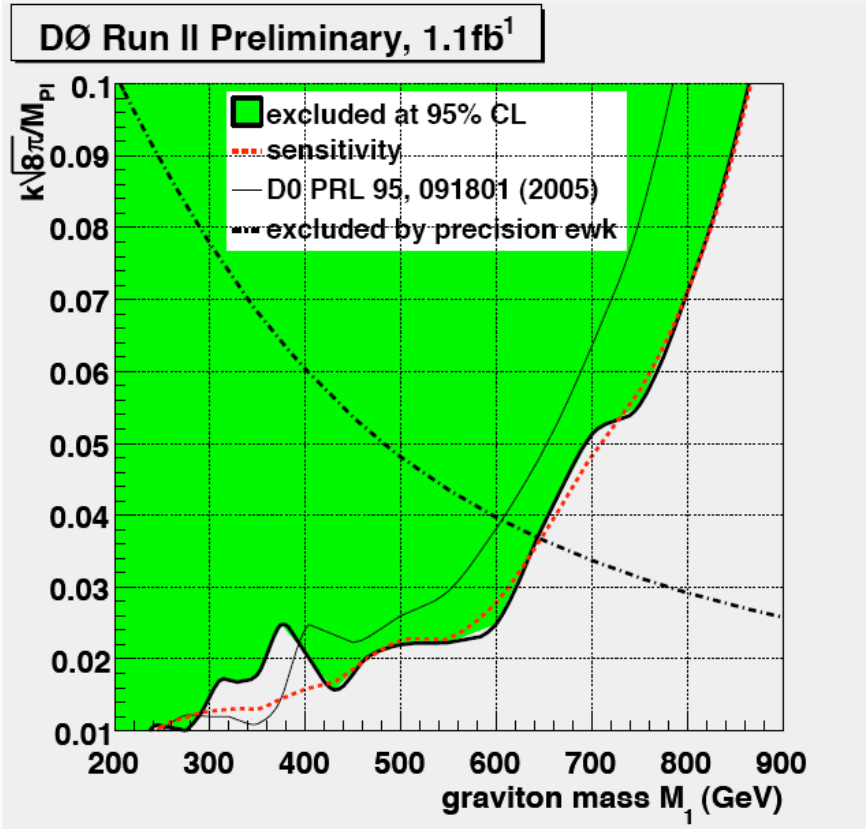
- Dielectron mass spectrum and diphoton mass distributions
  - Data agree well with Standard Model spectrum
  - No evidence for mass peak or deviation in tail

High Mass ee and γγ



- Resonance in diphoton or dielectron mass spectrum predicted in
  - Z' models (ee only): Spin 1
  - Randall-Sundrum graviton (ee and γγ): Spin 2



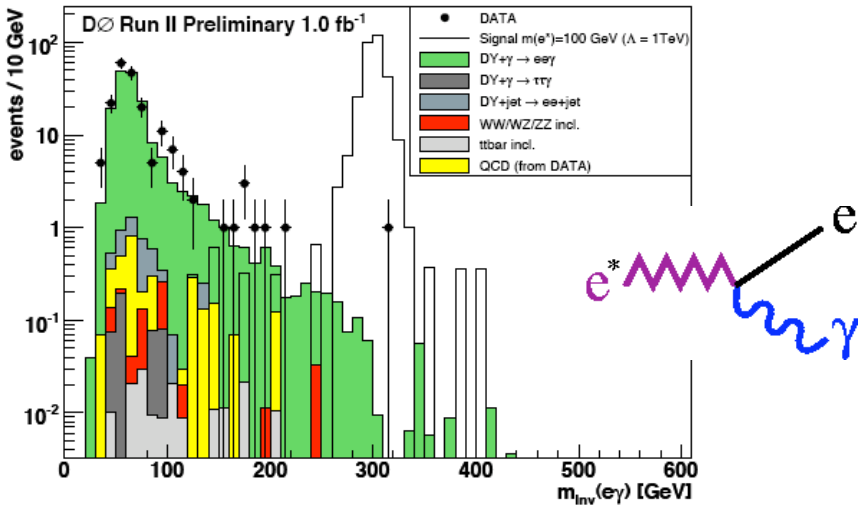


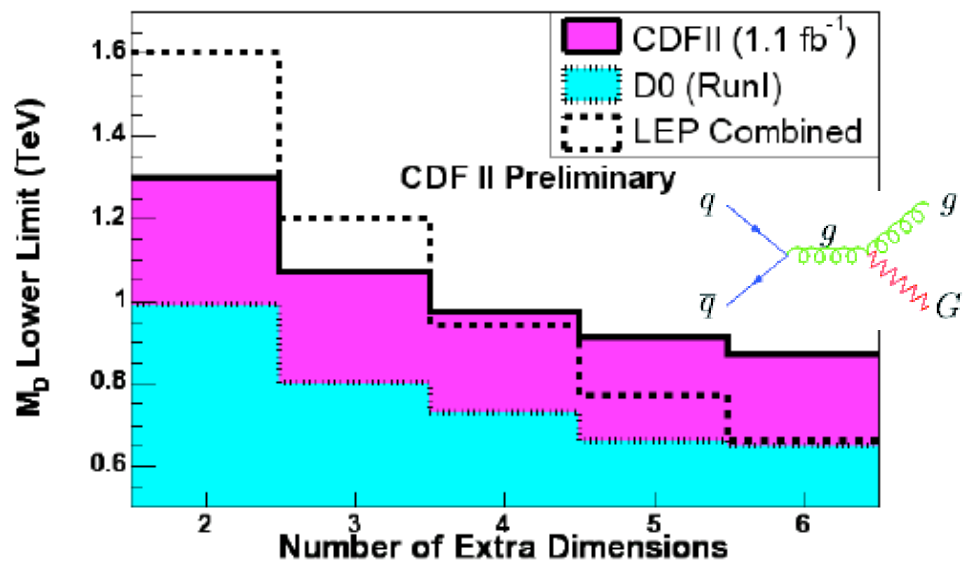
$M_{Z'}$>923 GeV for SM-like Z'

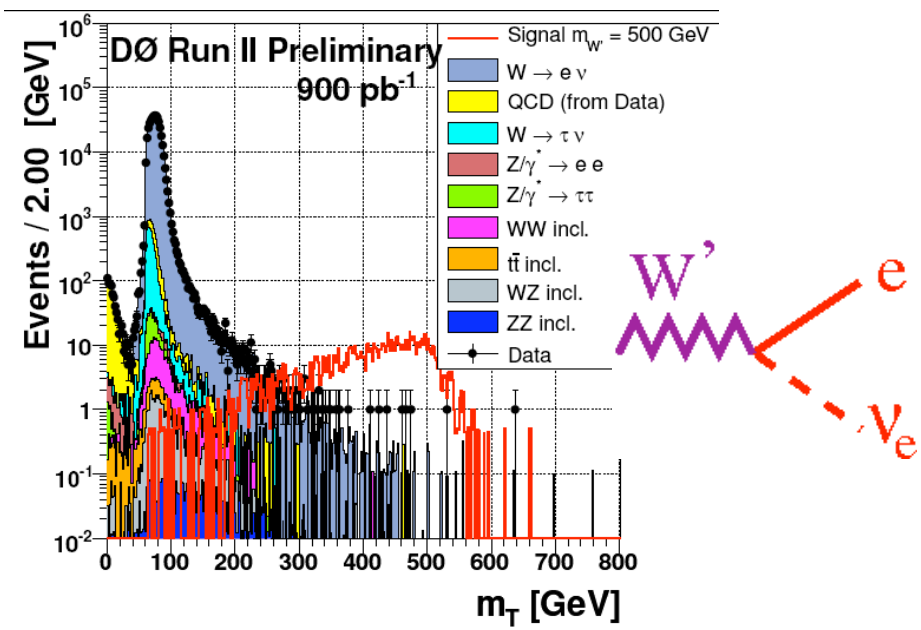
CDF: M_G>889 GeV for k/M_{Pl}=0.1

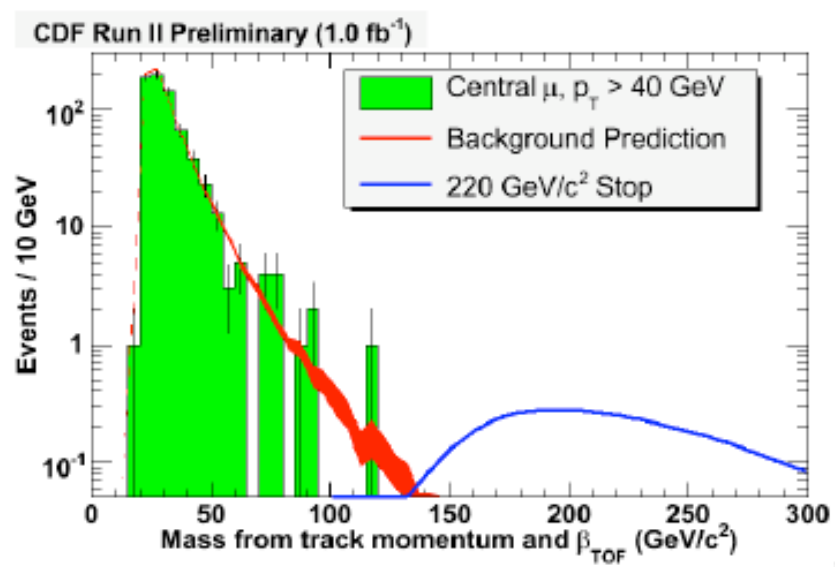
DØ: M_G>865 GeV for k/M_{Pl}=0.1

Many More Searches



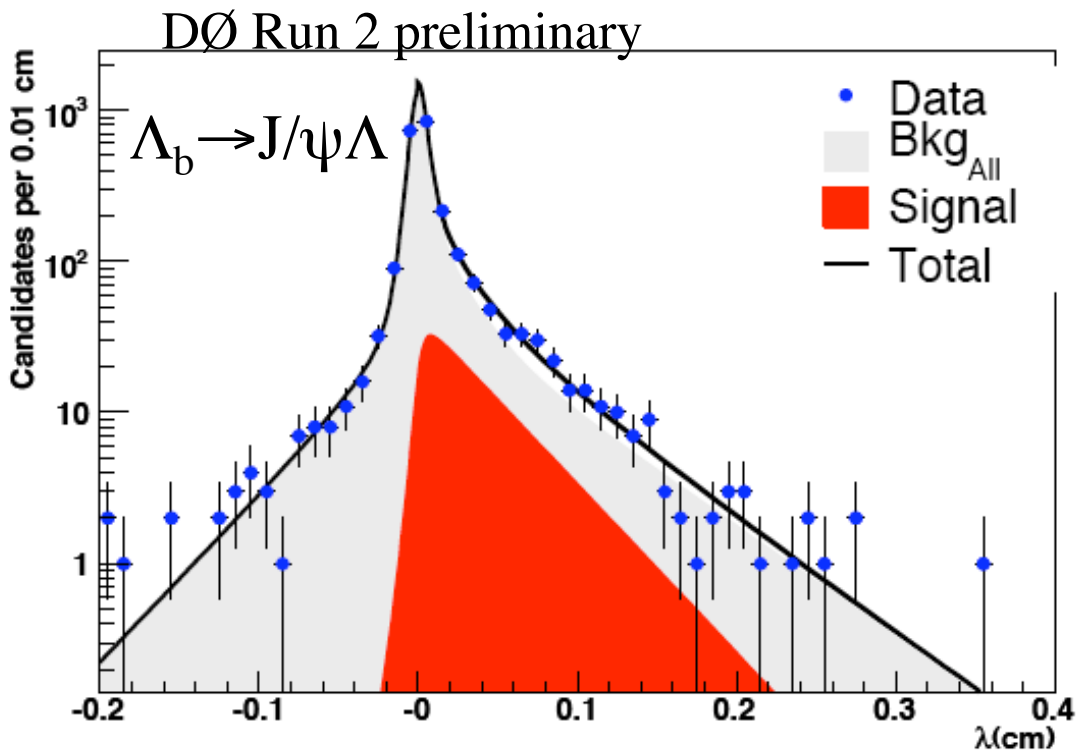


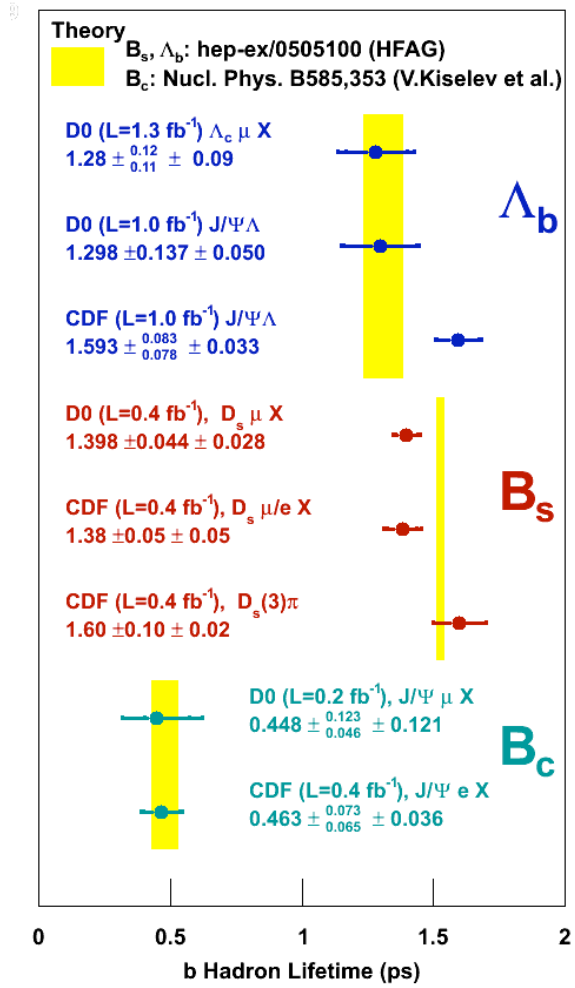




The Flavor Sector

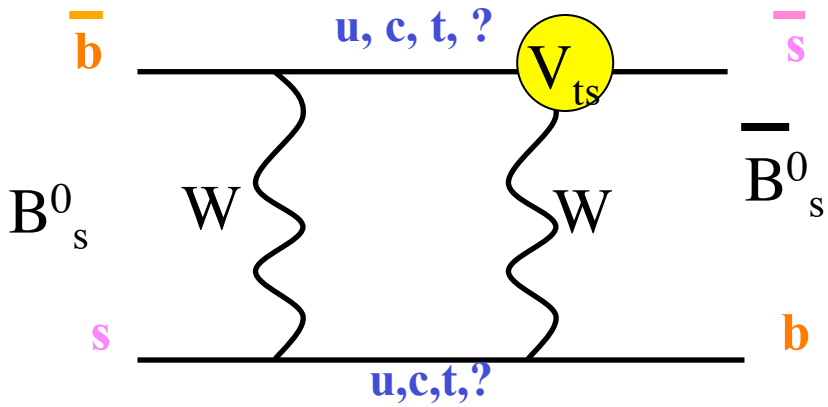
Lifetimes: B_s, Λ_b, B_c





Precision tests of Heavy Quark Effective Theory with heavy B states

B_s -$\overline{B}_s$ Oscillation Frequency



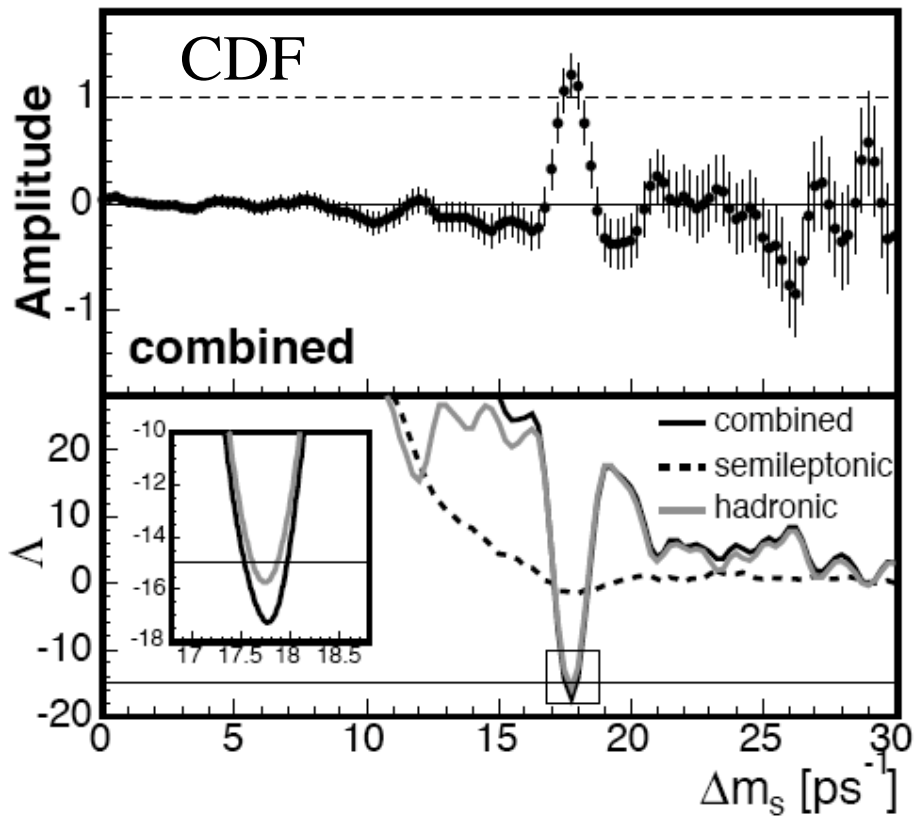
CP-odd: $B_H = pB + q\overline{B}$
CP-even: $B_L = pB - q\overline{B}$
with $|p|^2+|q|^2=1$

$$P^{B_s}_{unmix} = \frac{1}{2}\Gamma_{B_s} e^{-\Gamma_{B_s} t}\left(1 + A\cos\Delta m_s t\right)$$

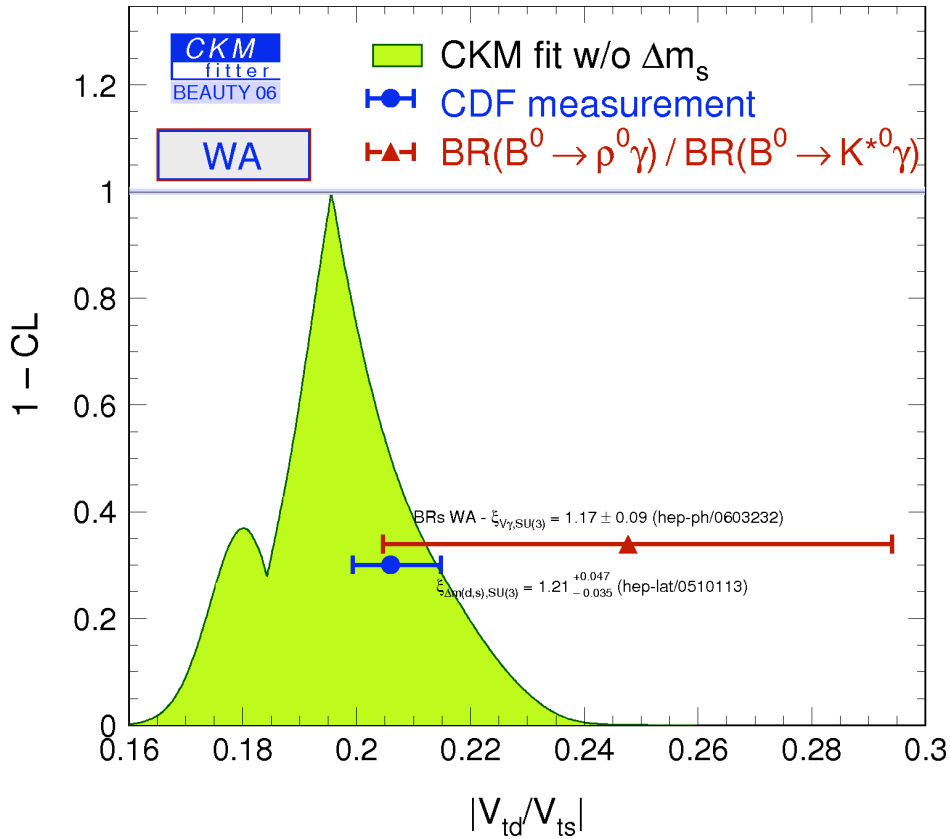
$$P^{B_s}_{mix} = \frac{1}{2}\Gamma_{B_s} e^{-\Gamma_{B_s} t}\left(1 - A\cos\Delta m_s t\right)$$

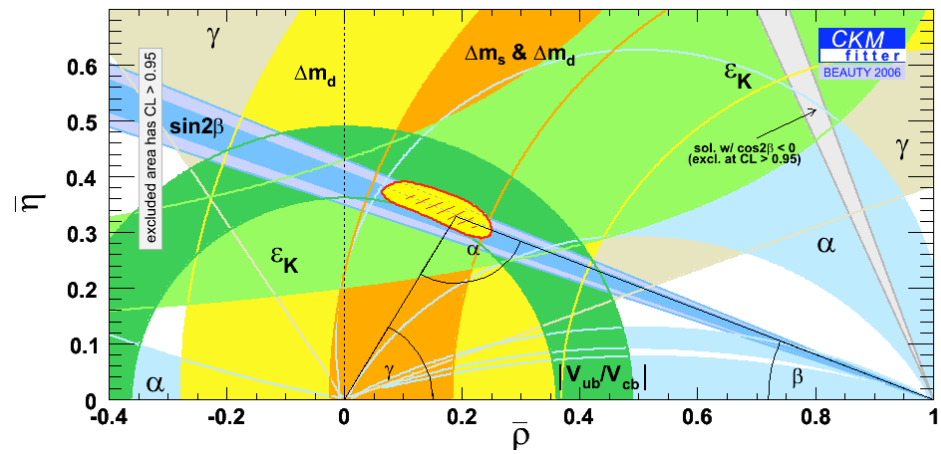
H. G. Moser, A. Roussarie, NIM **A384** (1997)

- **CDF Measurement:**
  - Prob. of stat. fluctuation: 8×10^{-8}
  - **Δm_s=17.77 ± 0.10 ±0.07 ps^{-1}**
  - $|V_{td}/V_{ts}|=0.2060\pm0.0007\ ^{+0.008}_{-0.006}$ (th.)
- **DØ:** $17<\Delta m_s<21$ ps^{-1}

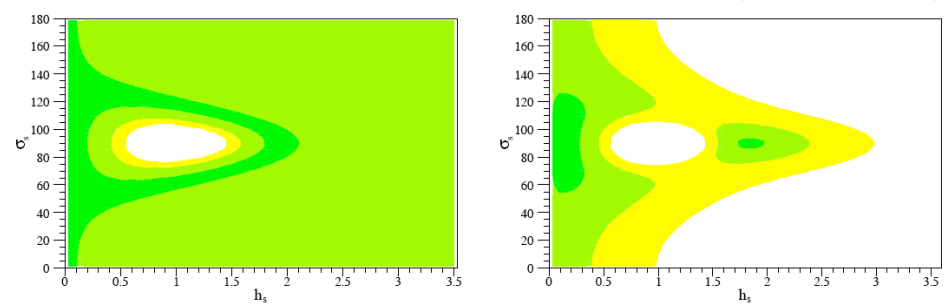


Δm_s Measurement: Impact on Unitarity Triangle





$$\Delta m_q = \Delta m_q^{SM} \left|1 + h_q e^{2i\sigma_q}\right|$$

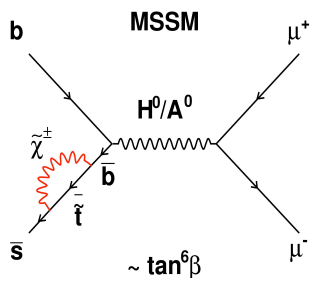


Z. Ligeti *et al.*, PRL97:101801,2006

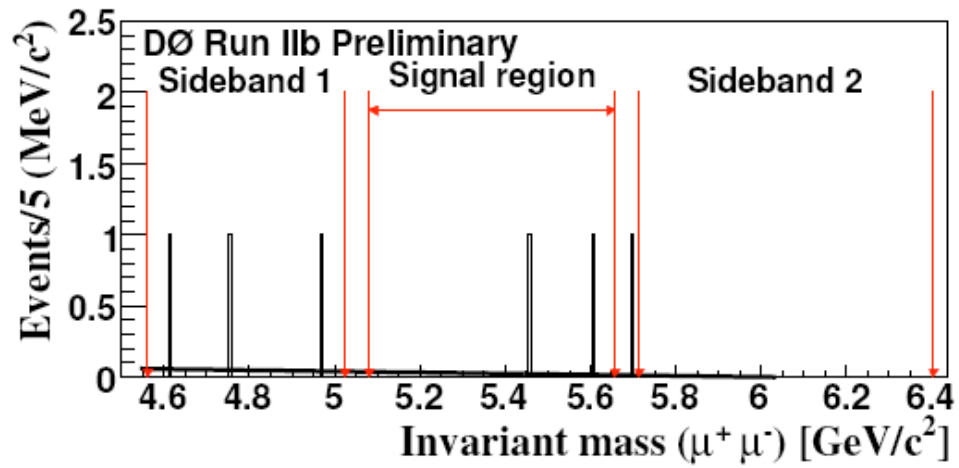
- Significant impact on unitarity triangle
- Some new physics constrained tightly

$B_s \to \mu^+\mu^-$ Branching Ratio

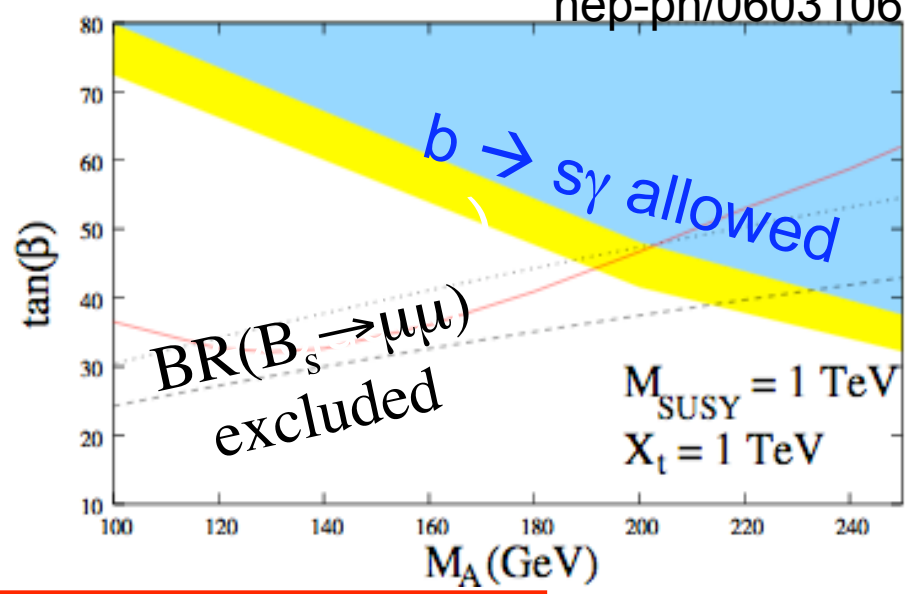
- Standard Model prediction:
  BR=(3.42±0.54) x 10^{-9}
  A.J. Buras Phys.Lett.B 566, 115 (2003)
- Large enhancements e.g. in Supersymmetry possible



$\sim \tan^6\beta/m_A^4$

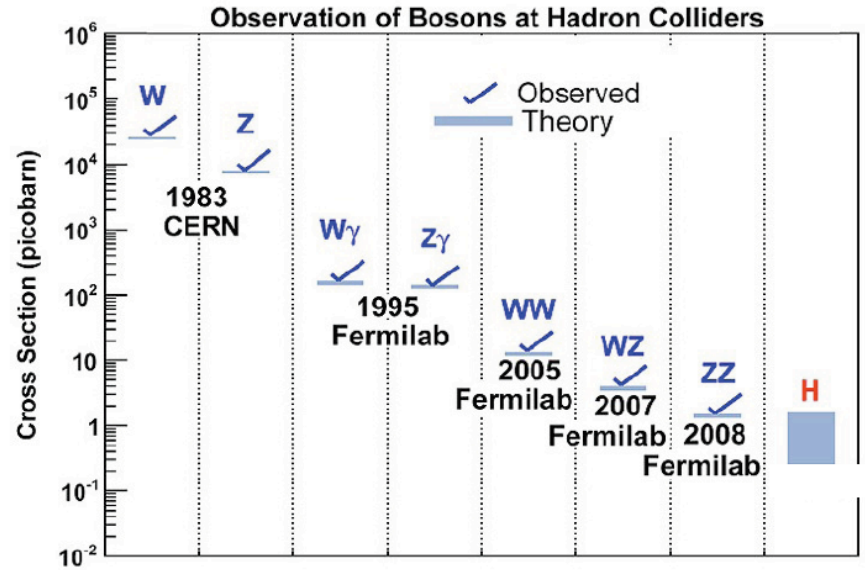
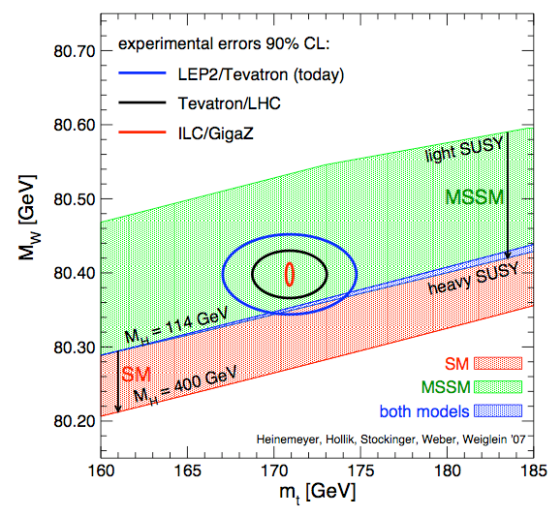


hep-ph/0603106



	CDF L=0.8 fb^{-1}	DØ L=2.0 fb^{-1}
N_{exp}	**1.47**	**2.3**
N_{obs}	**0**	**3**
Limit at 95%CL	**<10 x 10^{-8}**	**<9.3 x 10^{-8}**

Severe constraints on SUSY parameter space

Conclusions and Outlook

- **Tevatron + experiments operating well**
  - Analyses mostly based on ~5 fb^{-1}
  - 9 fb^{-1} delivered by Tevatron
- **Physics result cover broad range:**
  - **QCD** thoroughly being tested:
    - works very well even in complicated final states!
  - **Electroweak** precision data getting more and more precise:
    - Indirect : m_H<158 GeV
    - Direct: 114<m_H<158 GeV or m_H > 175 GeV
  - **Flavor physics**:
    - Unitarity triangle closes
    - no signs of new physics yet
  - **Searches** beyond the Standard Model
    - Many searches but no sign of new physics yet