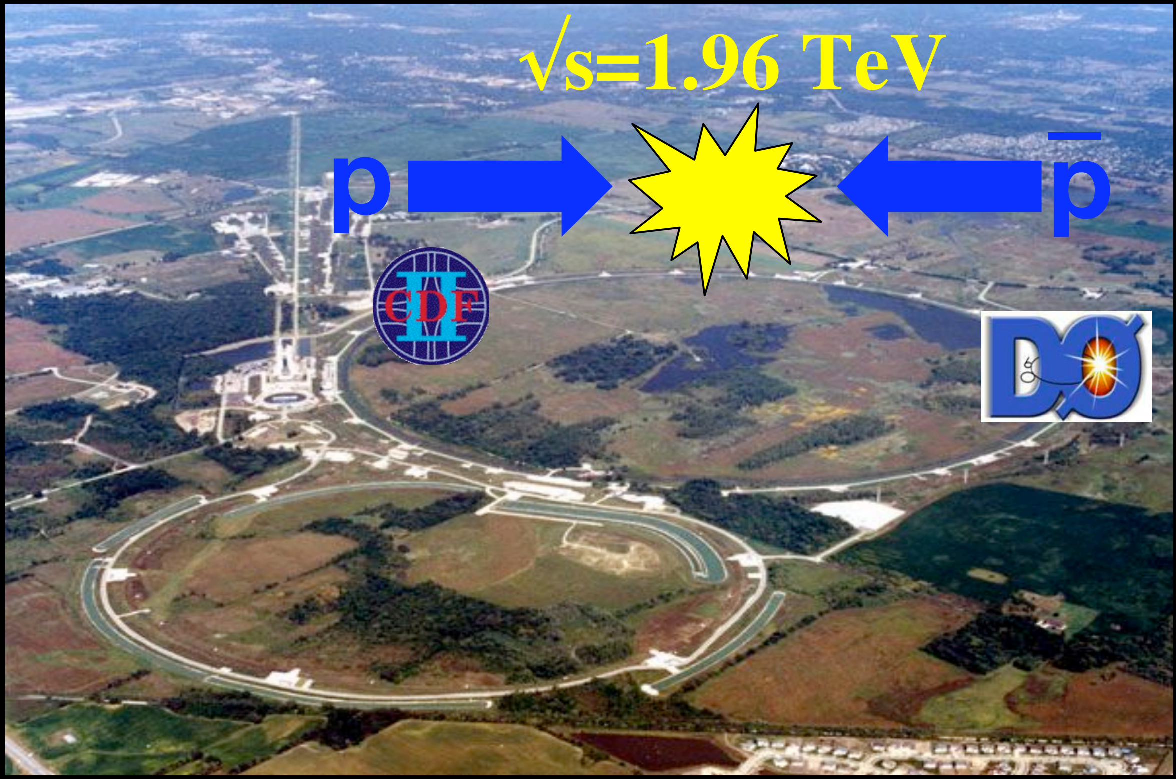
Recent Results from the Tevatron



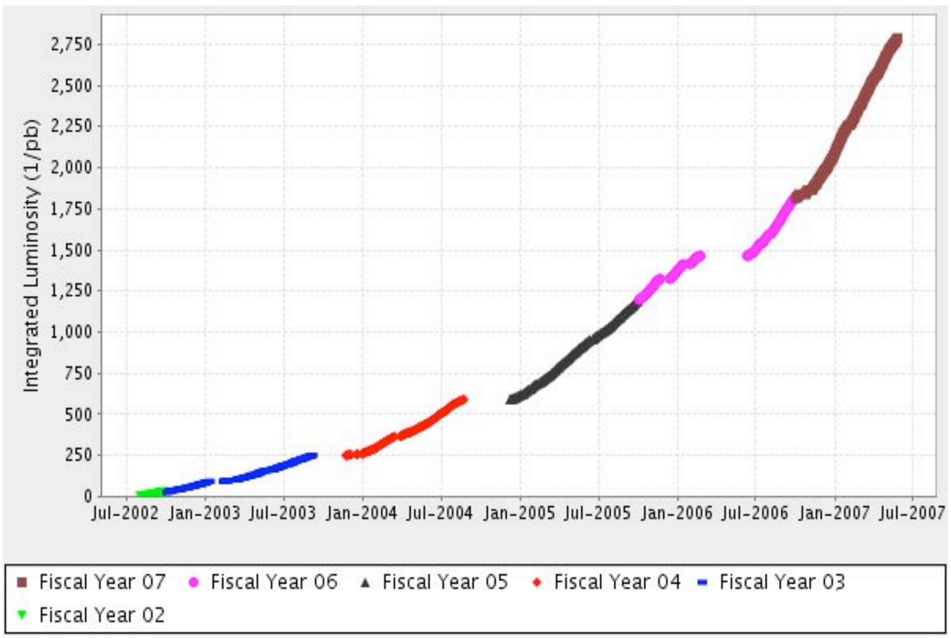
Beate Heinemann

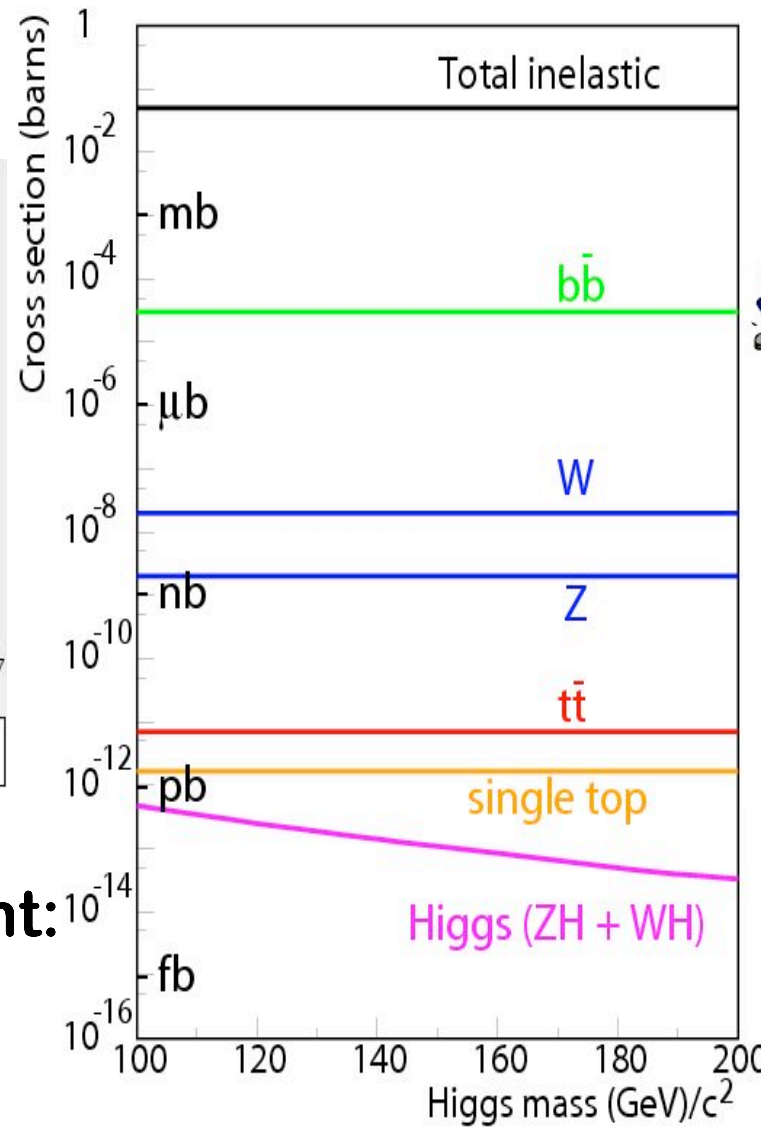
University of California at Berkeley and Lawrence Berkeley National Laboratory

LCWS Workshop, DESY, May 2007

Luminosity and Cross Sections

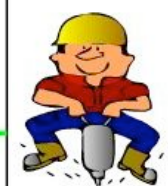
Run 2: $\int L dt = 2.8\ fb^{-1}$





with 1 fb^{-1}

1.4×10^{14}



1

6×10^6

6×10^5

14,000

5,000

~100?

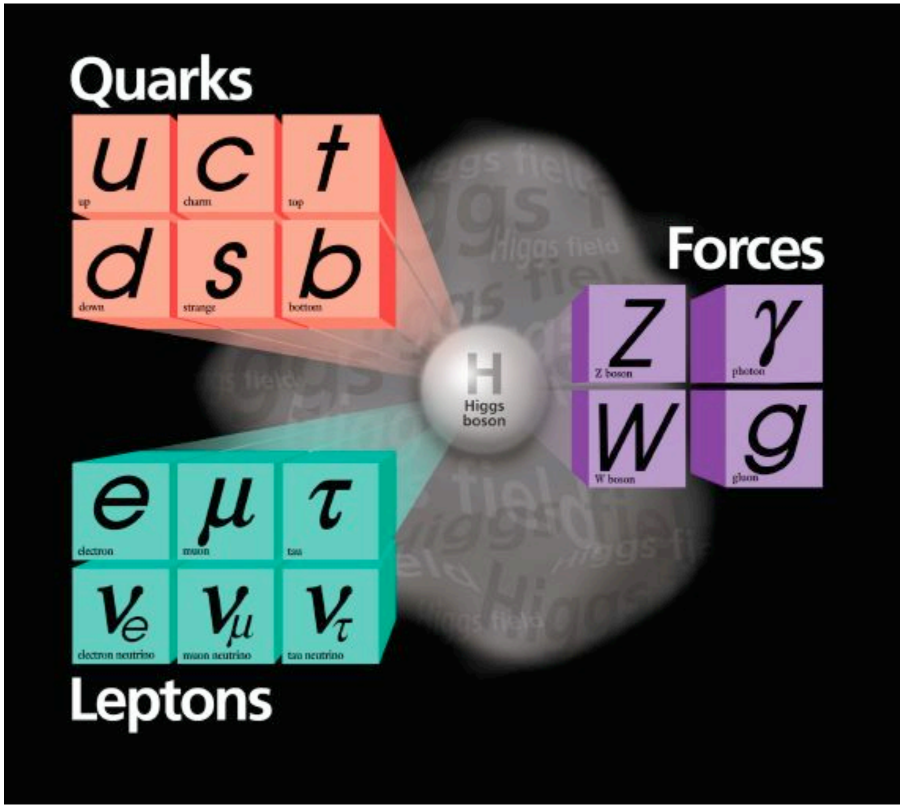
Experiments are ~85% efficient:

-2.2 fb^{-1} for physics analyses

-Most analyses use 1.3 fb^{-1}

At peak luminosity ~1 W boson per second produced!

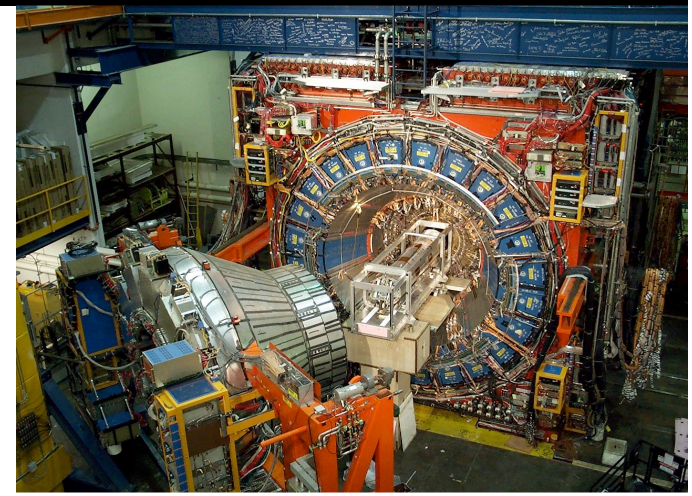
The Standard Model and the Standard Questions We Have



- 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?

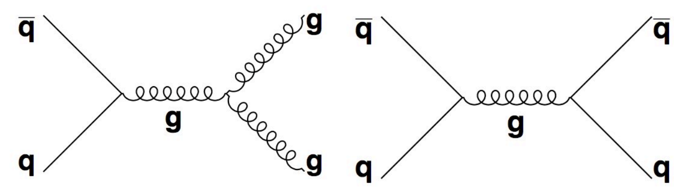
Outline

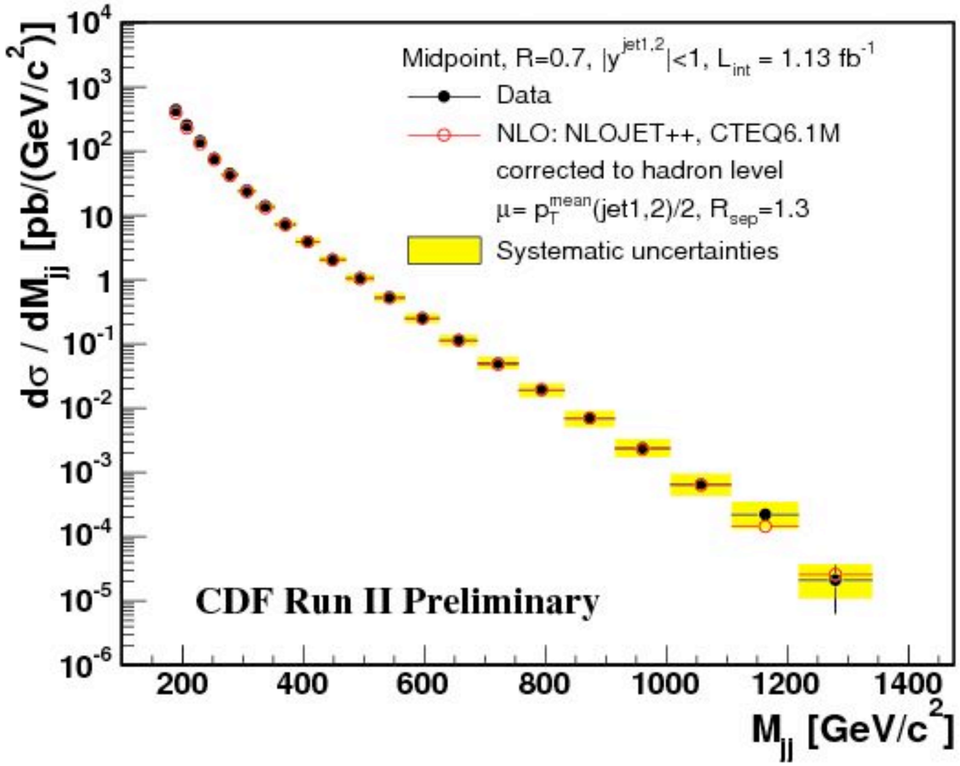
- **Testing Particle Production**
  - Jets, W’s and Z’s, b-jets, top quarks
- **Electroweak Symmetry Breaking**
  - W boson mass and width
  - Top quark mass
  - Higgs boson search
- **Beyond the Standard Model**
  - Supersymmetry and beyond
- **Flavor physics:**
  - B lifetimes, mixing and Rare Decays

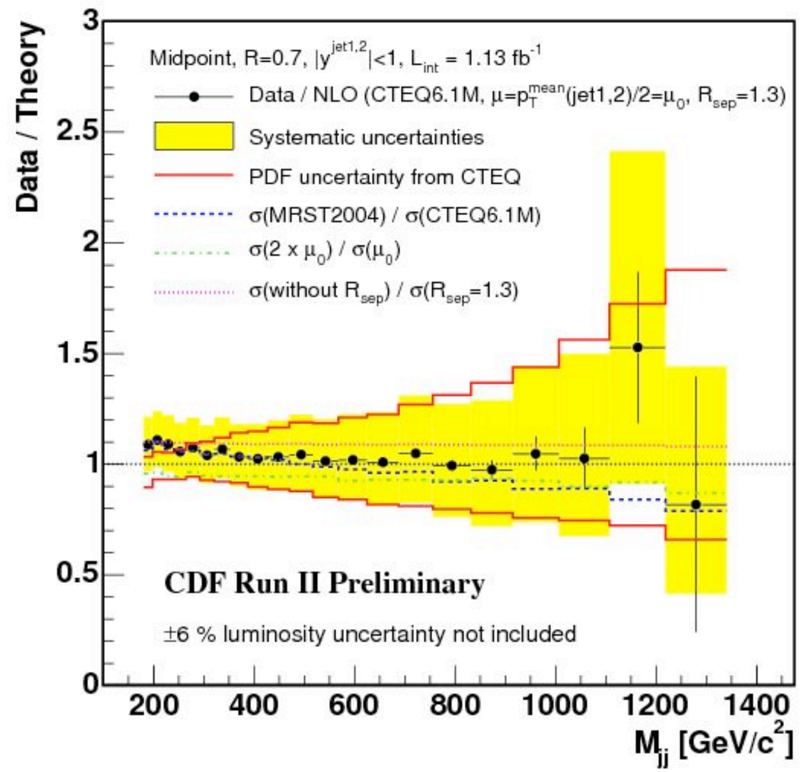


Production of Particles

Jet Cross Sections

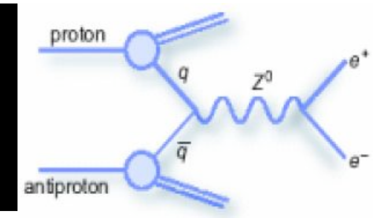


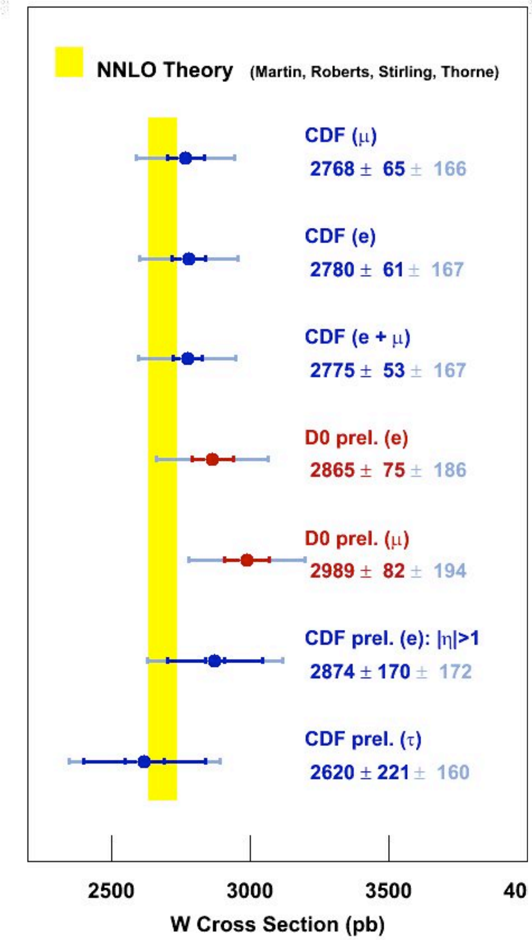


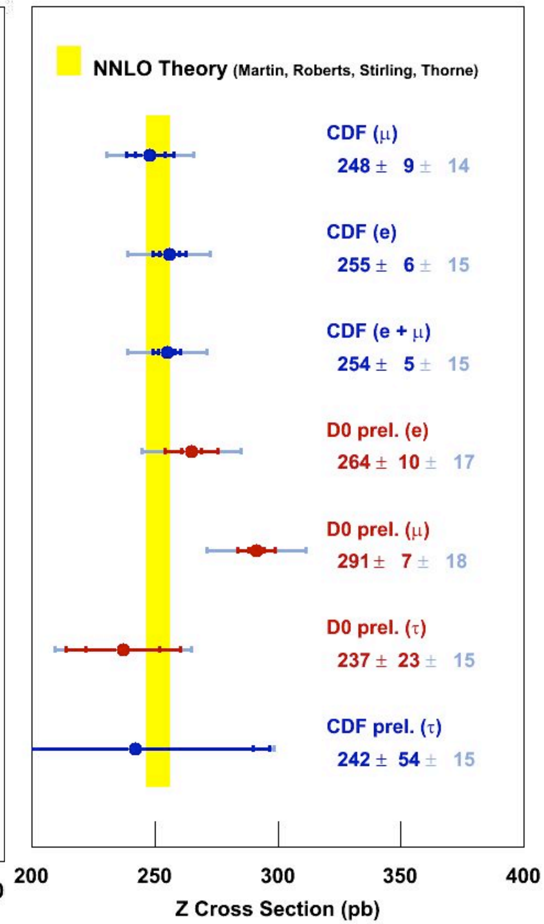


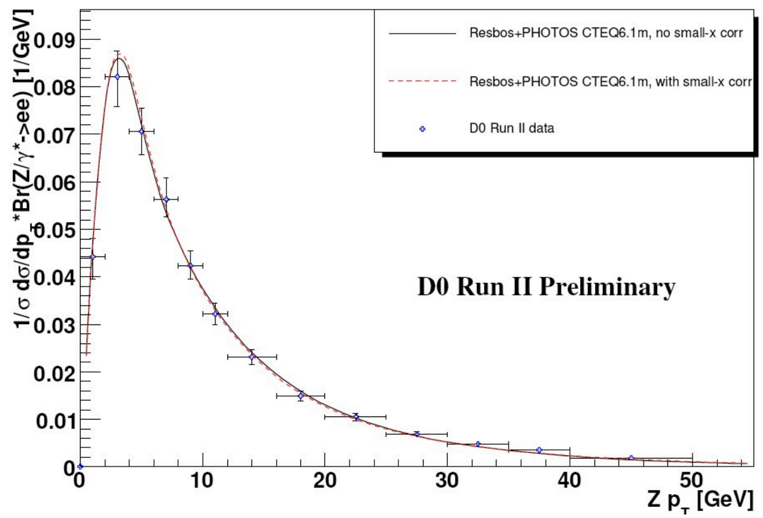
- Cross section measured over 7 orders of magnitude
- Data well described by Standard Model prediction up to masses of 1.2 TeV

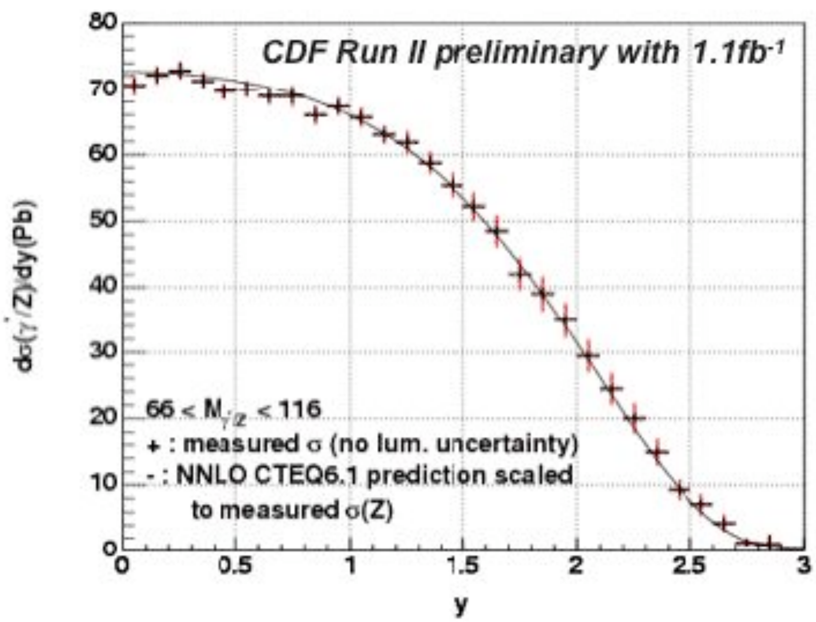
W and Z production





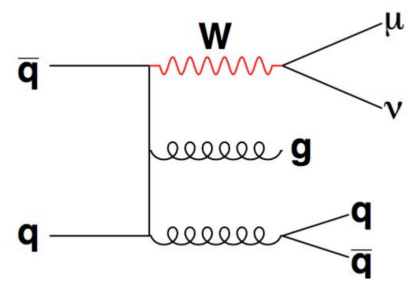






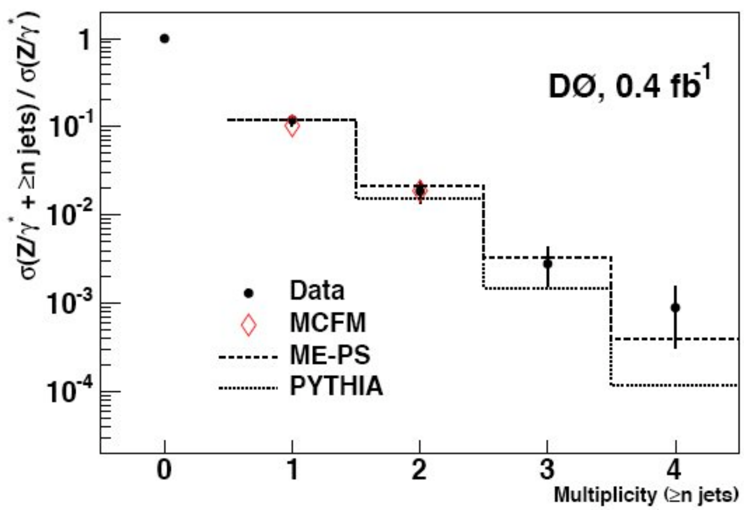
- High precision measurements
  - test NNLO QCD predictions

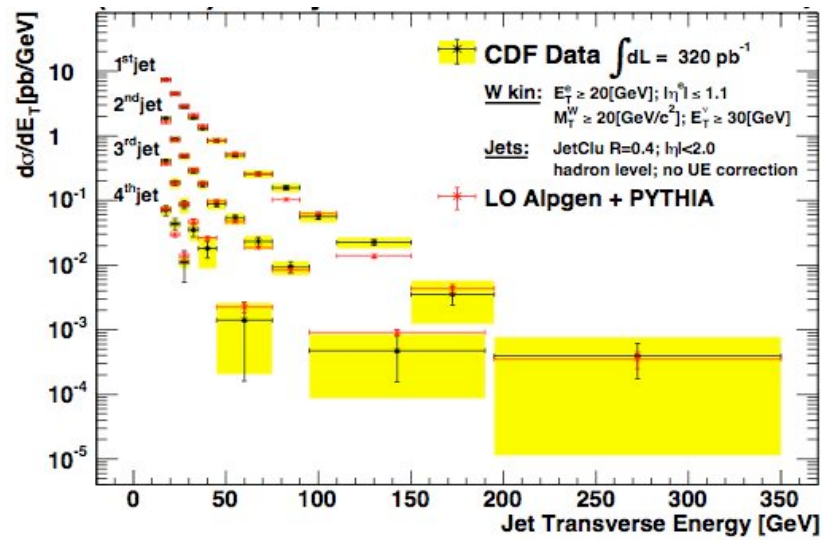
W/Z + Jets Production

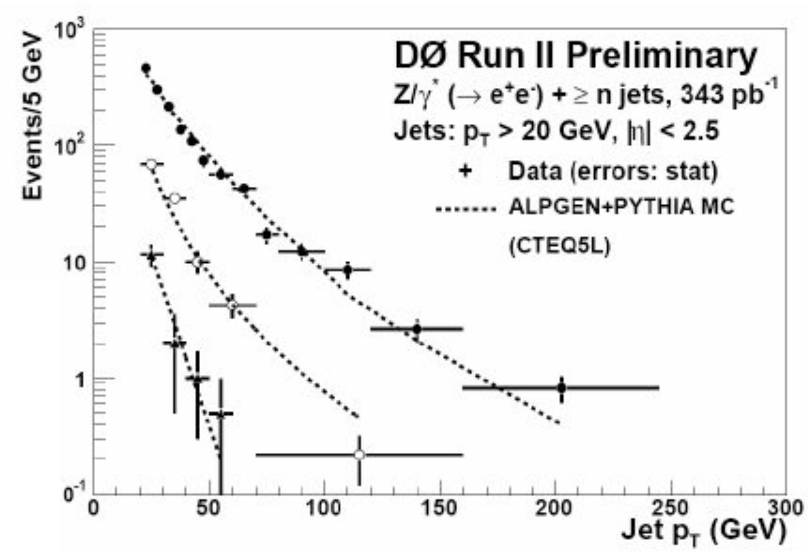


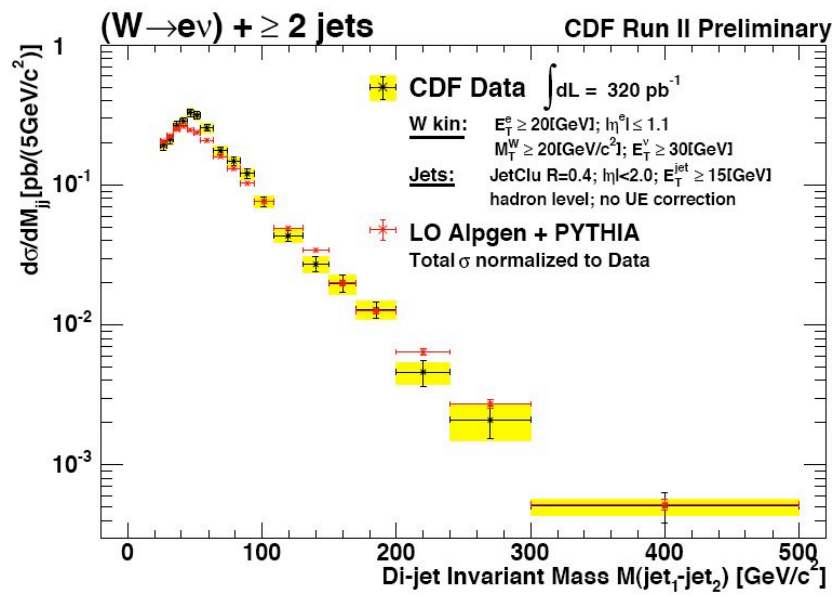
Z + n jets

W + n jets

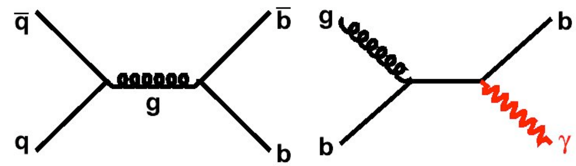


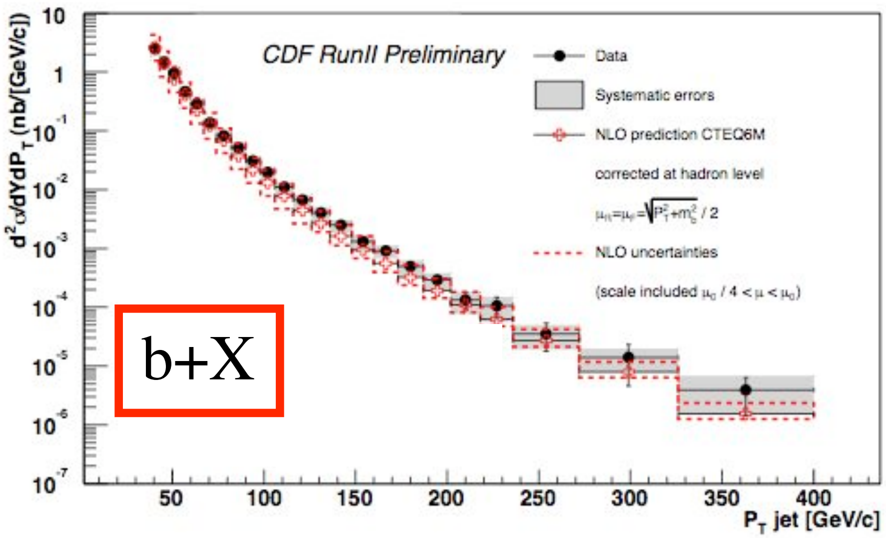


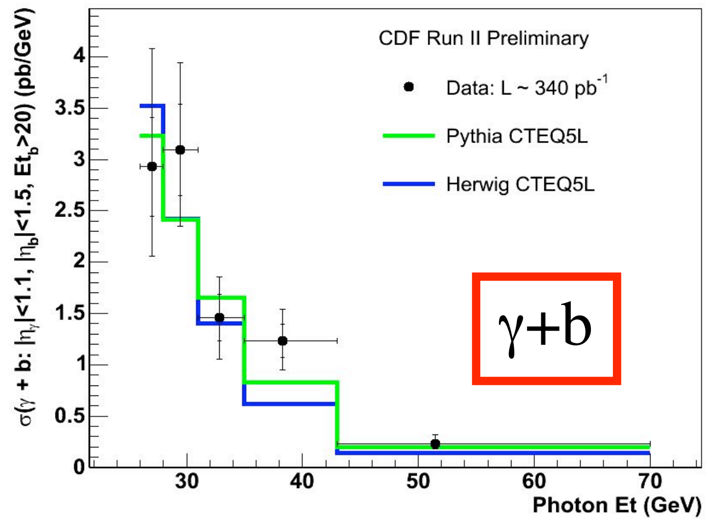


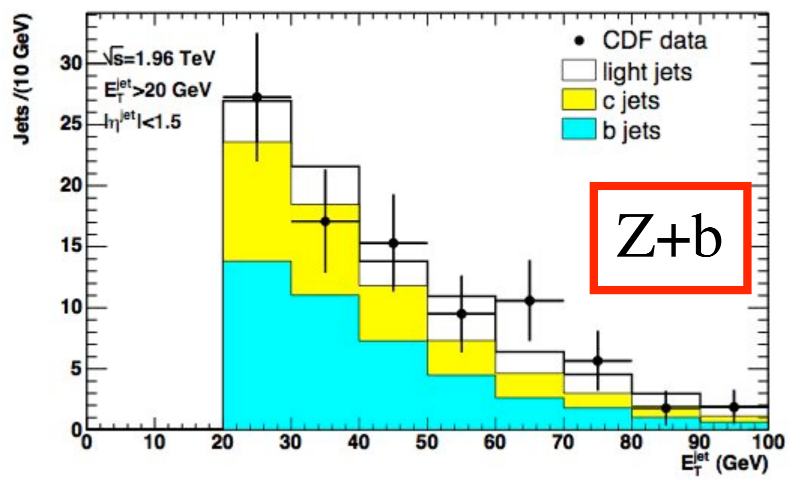


B-quark Production



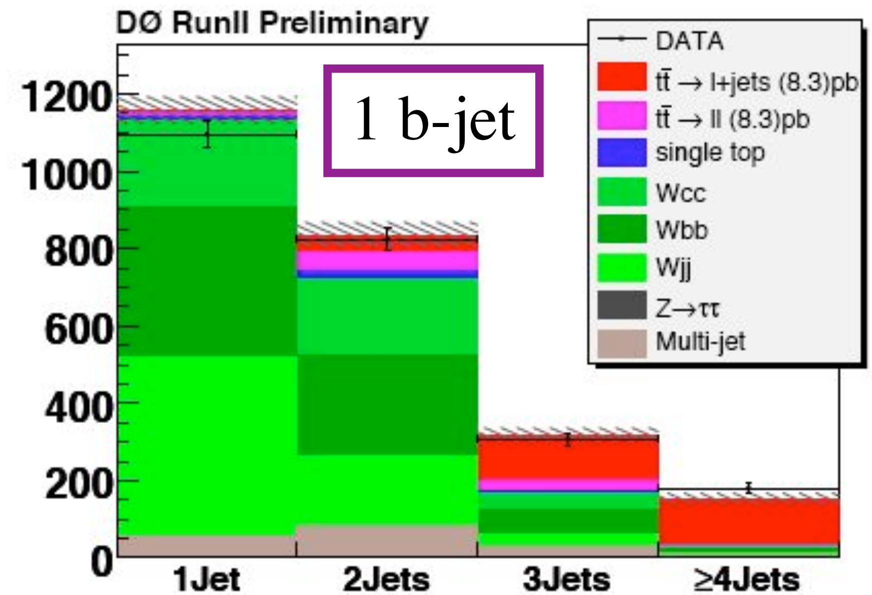


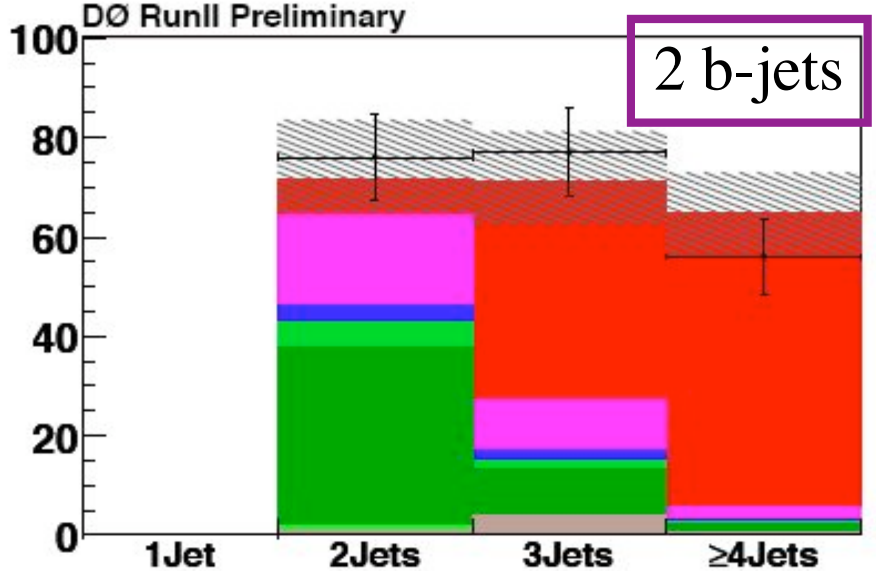


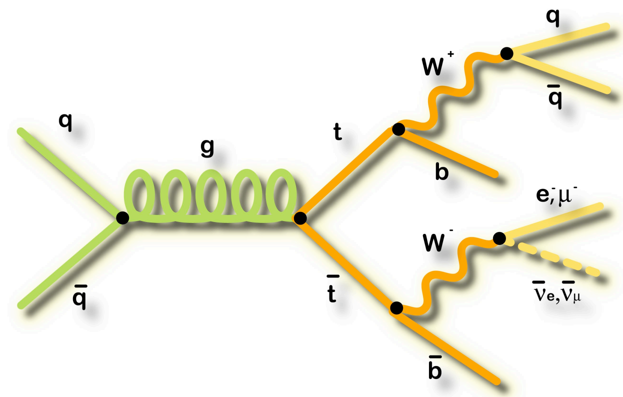


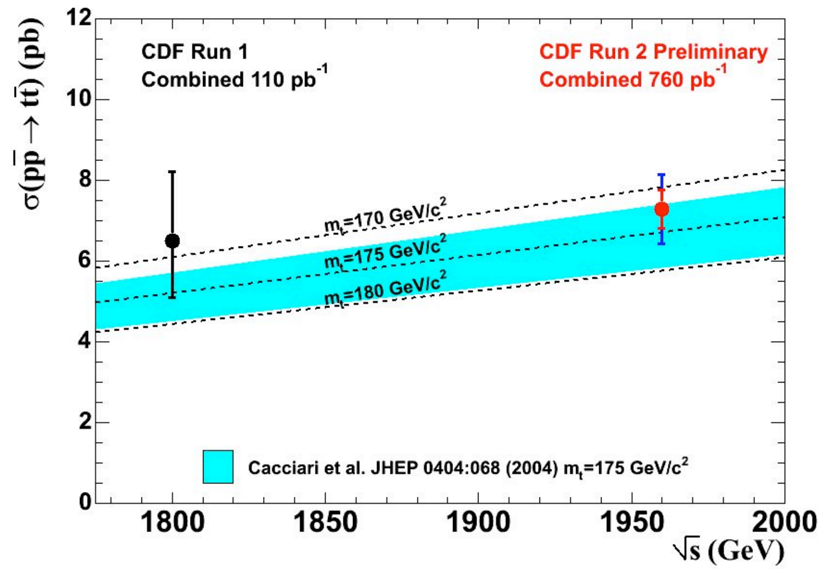
- Measurements of b-jet production in good agreement with theoretical predictions

Top Quark Production



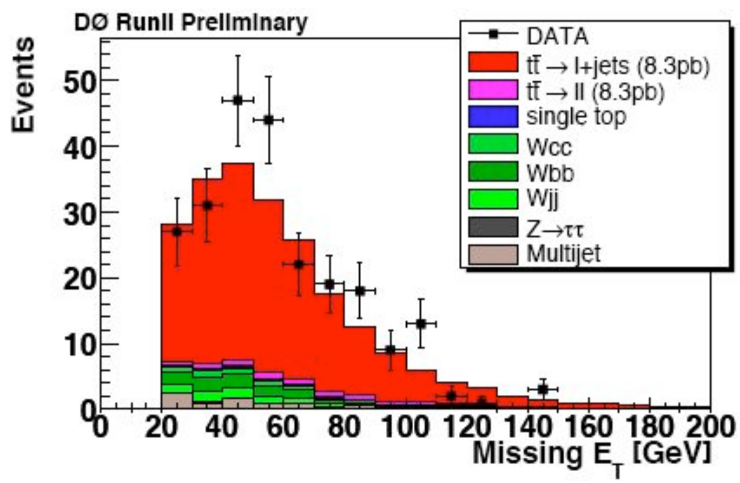


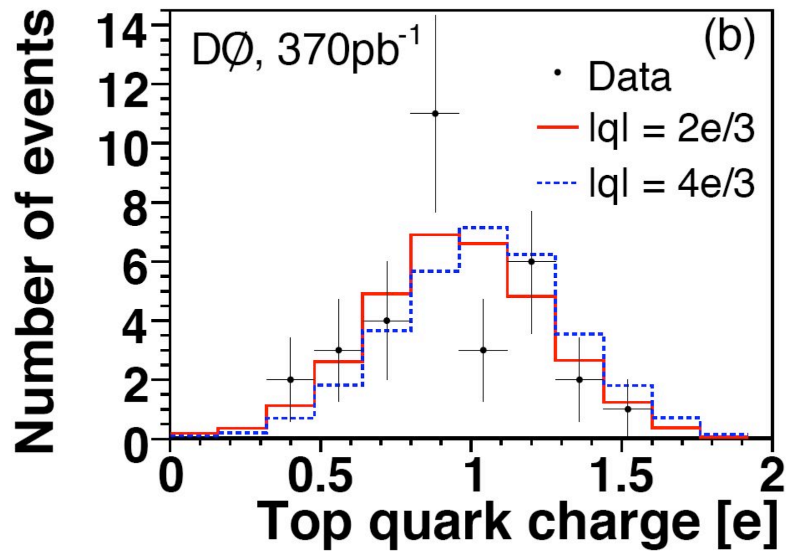




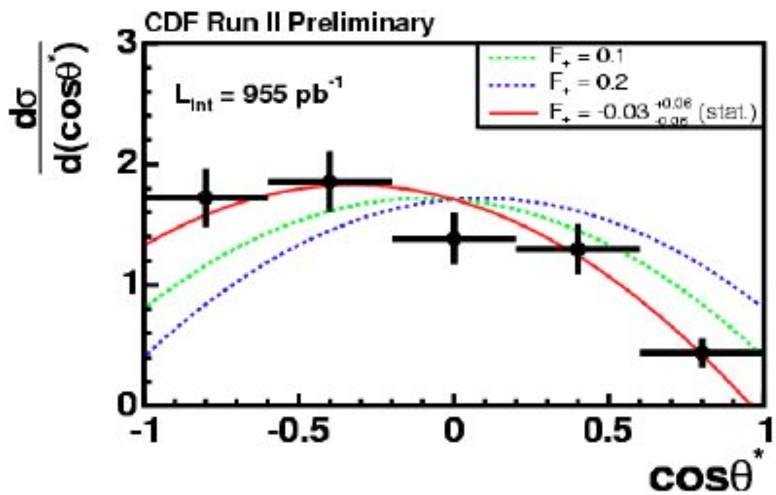
- Measurements consistent with theory

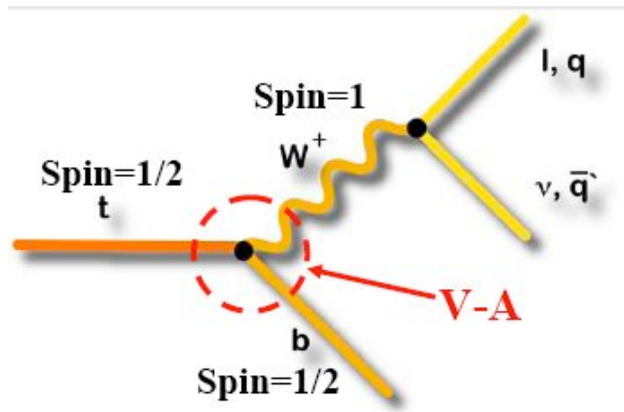
Top Quark: Kinematics+Properties





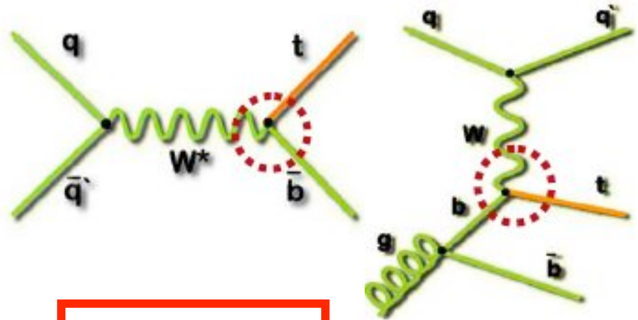
q_{top}=+2/3?



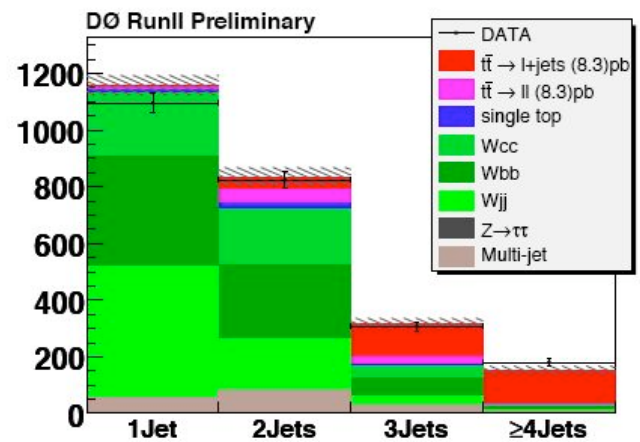


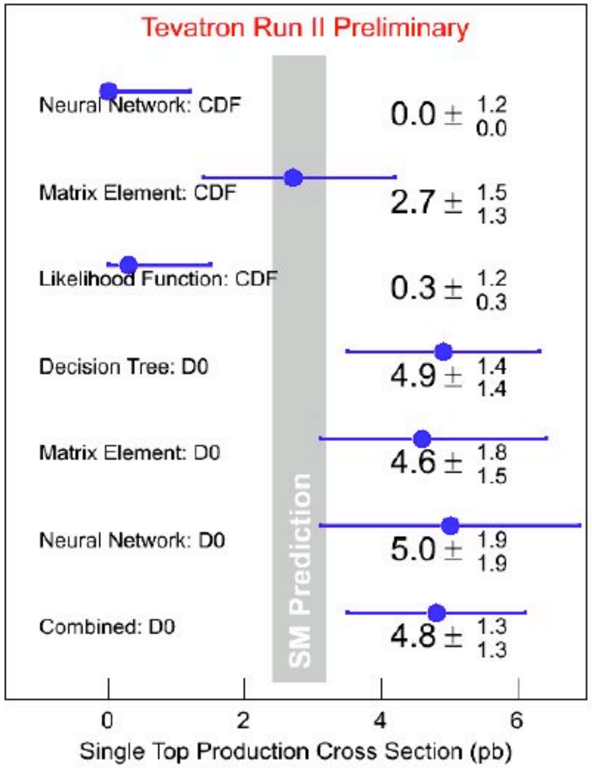
- Kinematic properties, couplings and charge consistent with Standard Model top prodiction so far

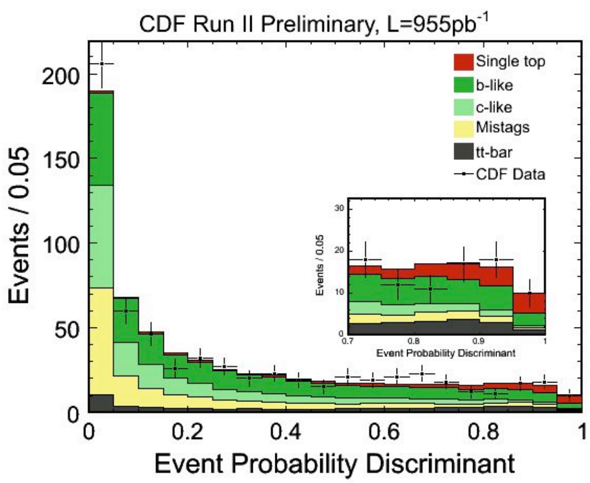
Single Top Production

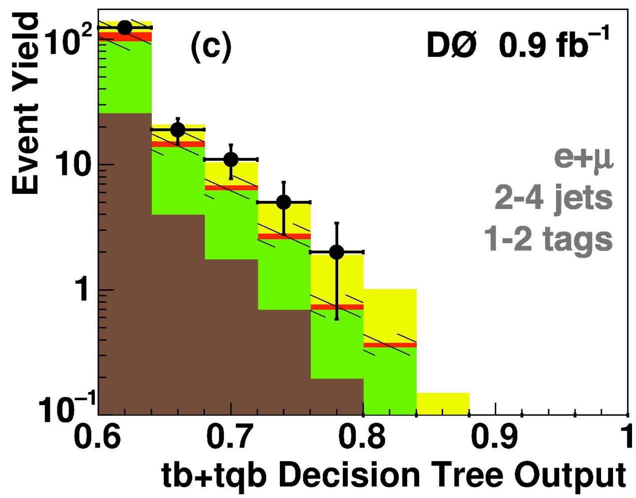


$\sigma \propto V_{tb}^2$







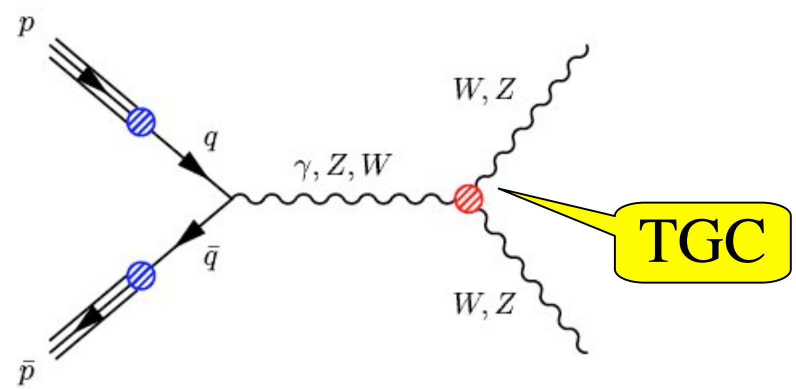


From DØ σ result:

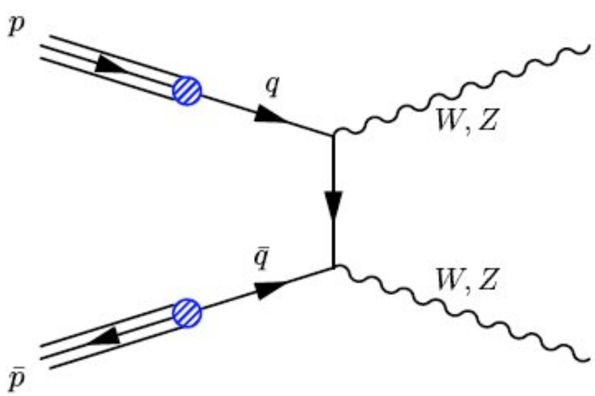
$V_{tb} > 0.68$ @ 95% CL

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

Diboson Production



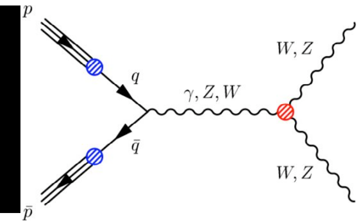
s-channel

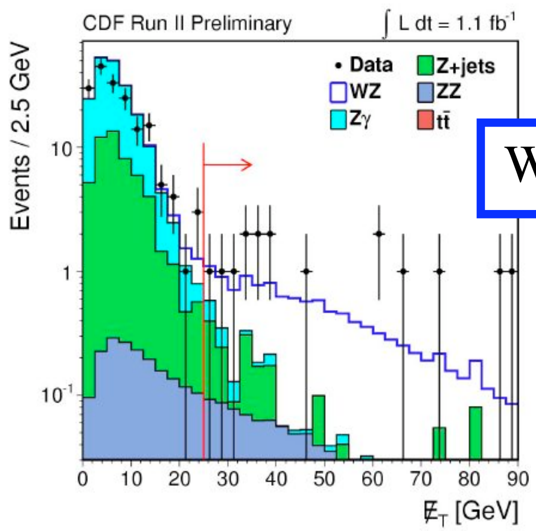


t-channel

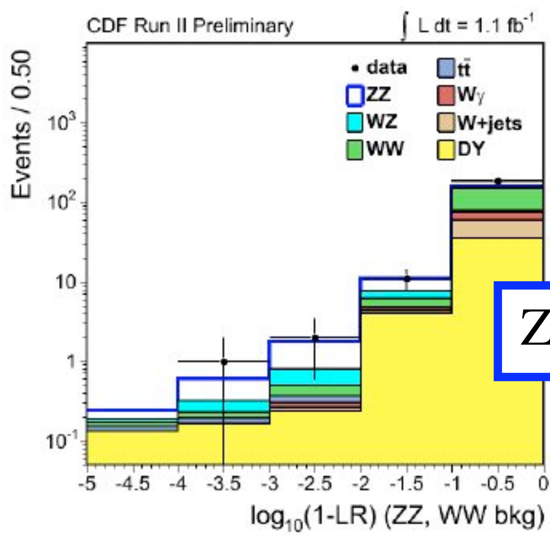
- Diboson production probes trilinear couplings among the gauge bosons (TGC)
  - Direct prediction from SU(2)xU(1) gauge group
  - New physics could lead to anomalous couplings
- WW, Wγ, Z γ observed some time ago:
  - Agree with SM prediction
- Focus today:
  - WZ cross section: σ_{SM}=3.7 ± 0.3 pb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

Diboson Production: WZ,ZZ





WZ→lllν



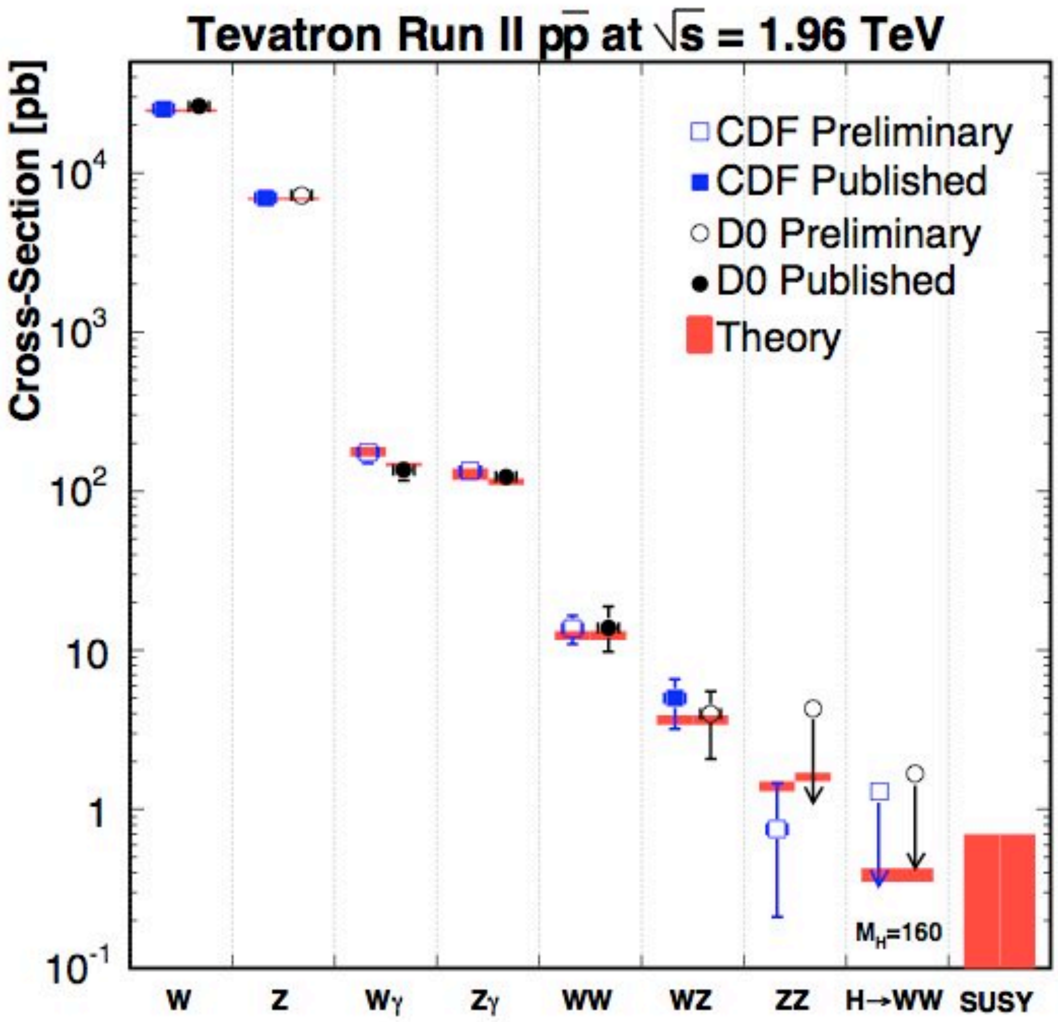
ZZ→llνν

- WZ:
  - 5.9σ observation
  - Cross section: $5.0^{+1.8}_{-1.6}$ pb
- ZZ:
  - 3.0σ evidence
    - llll mode: 2.2σ
    - llνν mode: 1.9σ

CDF DØ ZZ→llll

CDF	DØ	
2.51+-0.16	1.71+-0.11	ZZ expected
0.029+-0.021	0.17+-0.04	Bkg expected
1 (4μ)	1 (eeμμ)	Yield observed

Diboson Production Summary



Higgs Boson is next in line

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% → $\pi\alpha(M_Z^2)$

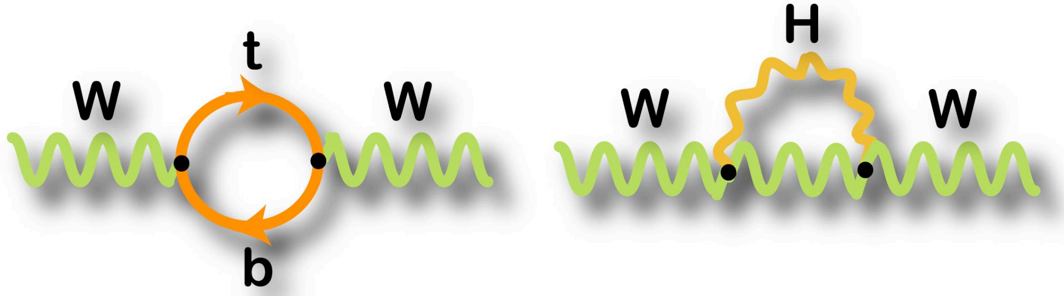
Measured to 0.002% → M_Z^2

Measured to 0.036% → M_W^2

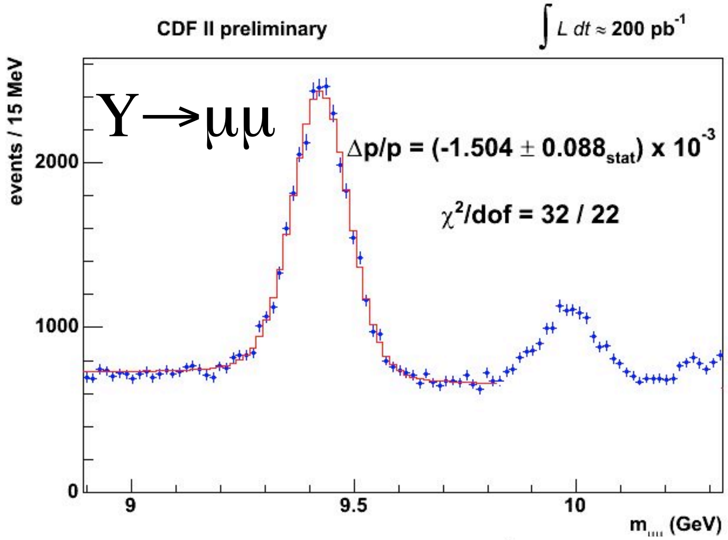
$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F}\frac{1}{(1-(M_W^2/M_Z^2))}\frac{1}{(1-\Delta r)}$$

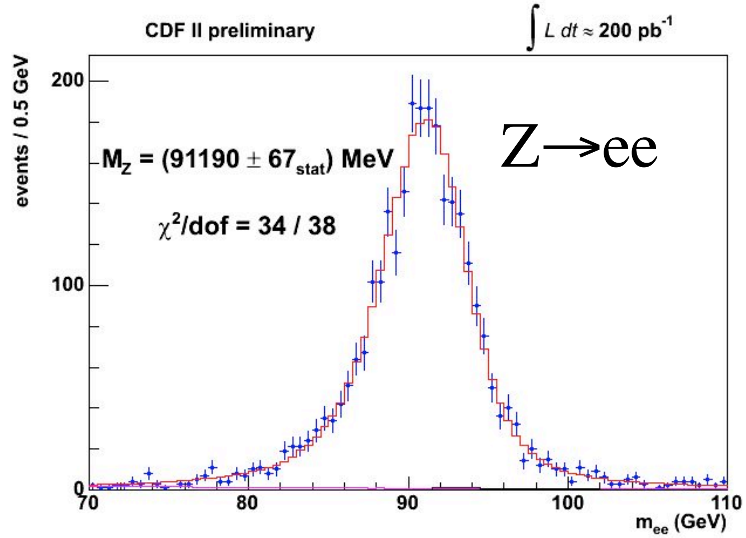
Measured to 0.0009% → G_F

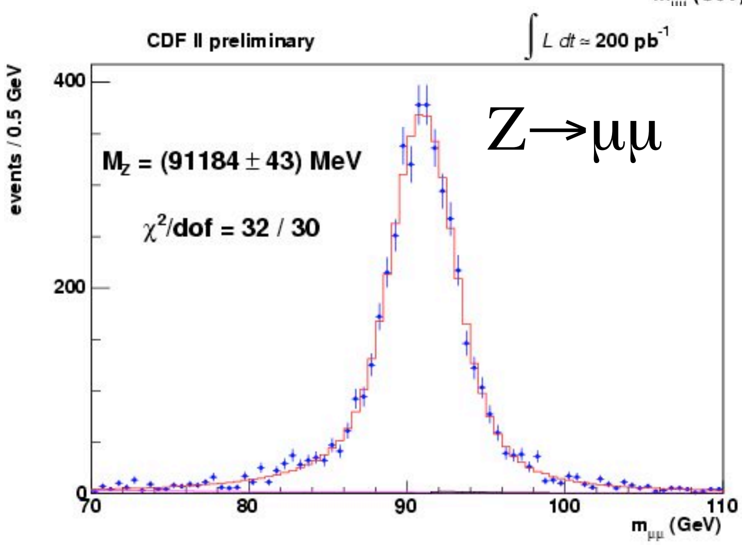
Δr: O(3%) radiative corrections dominated by *tb* and Higgs

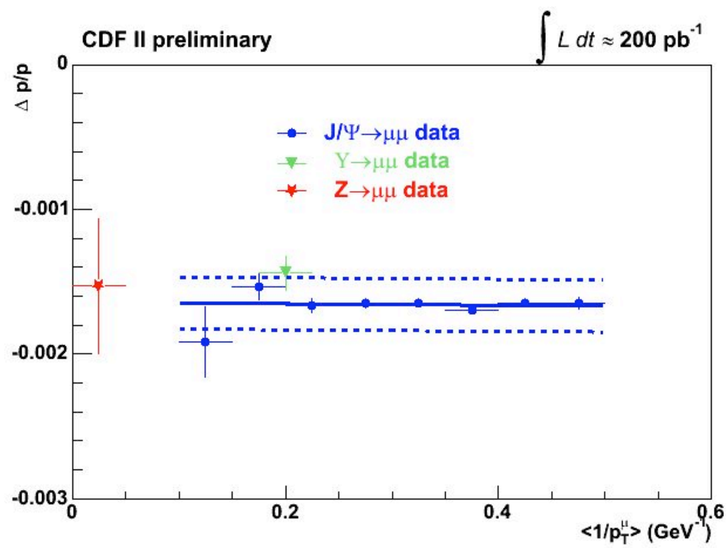


Lepton Energy Scale and Resolution



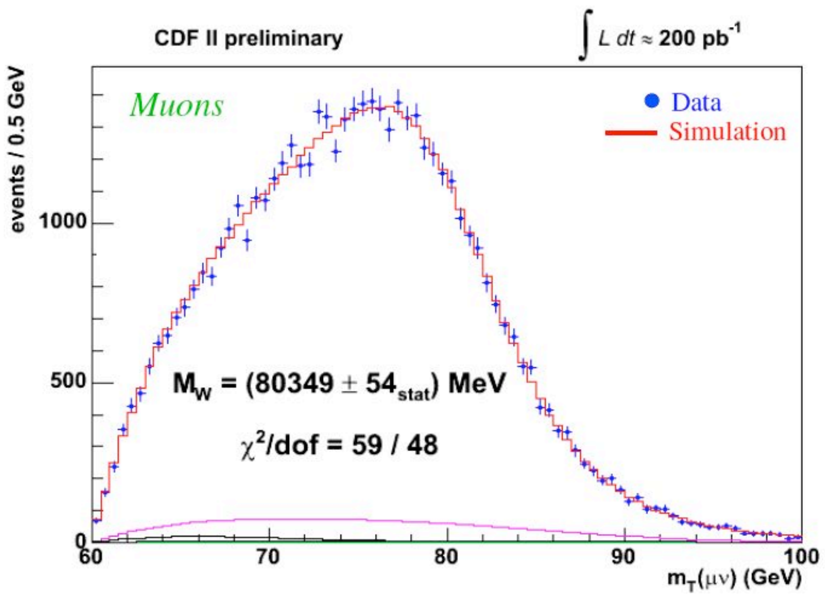


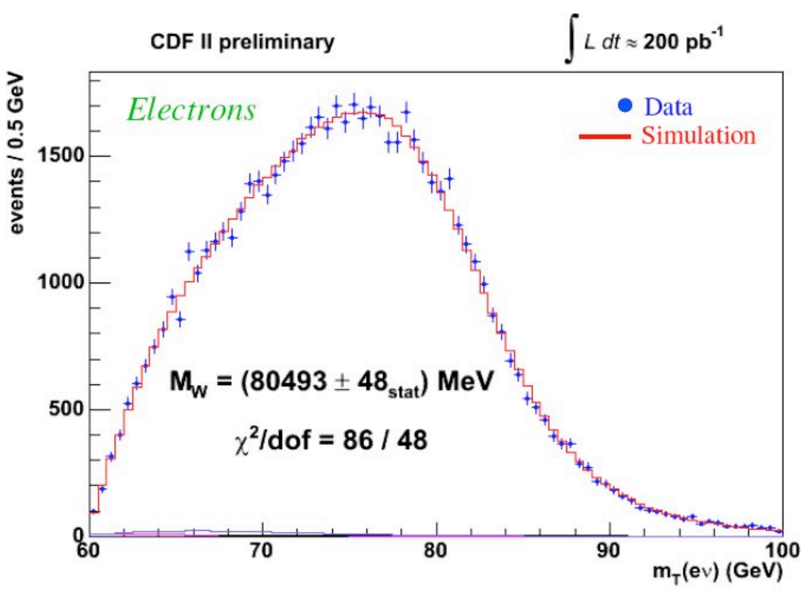


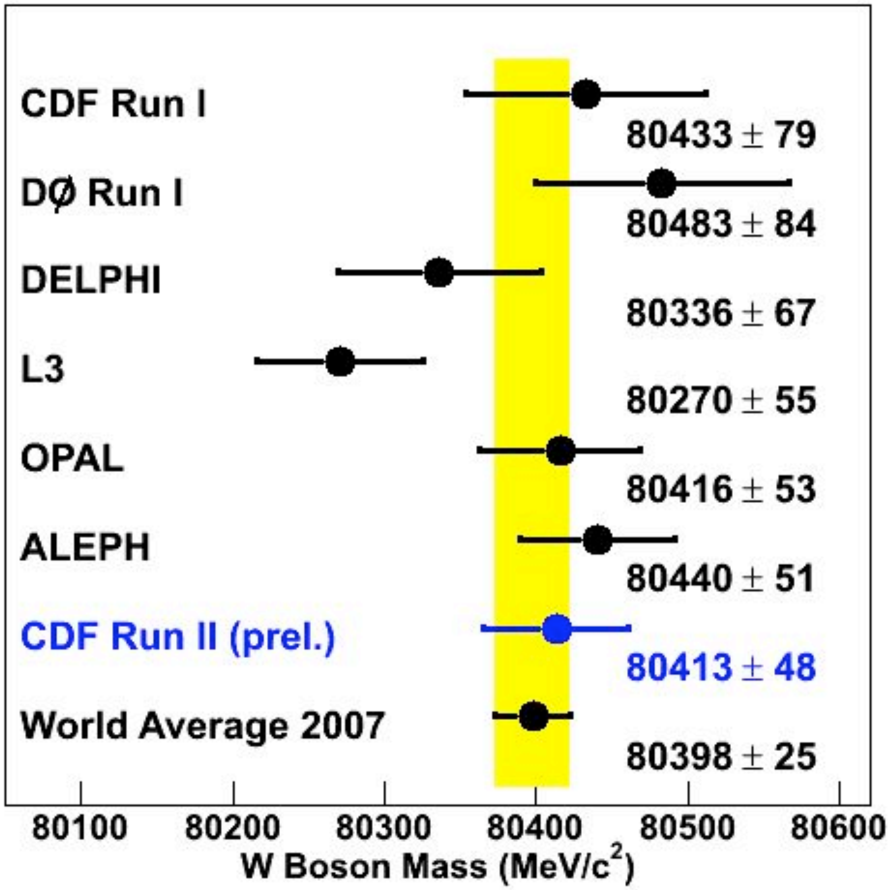


- Systematic uncertainty on momentum scale: 0.04%

W Boson Mass





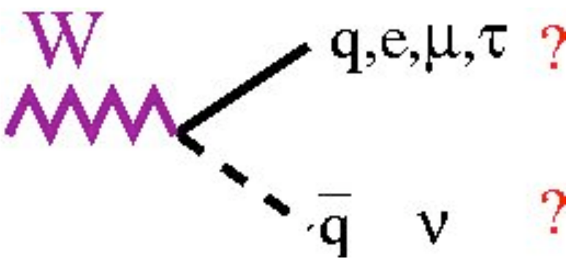


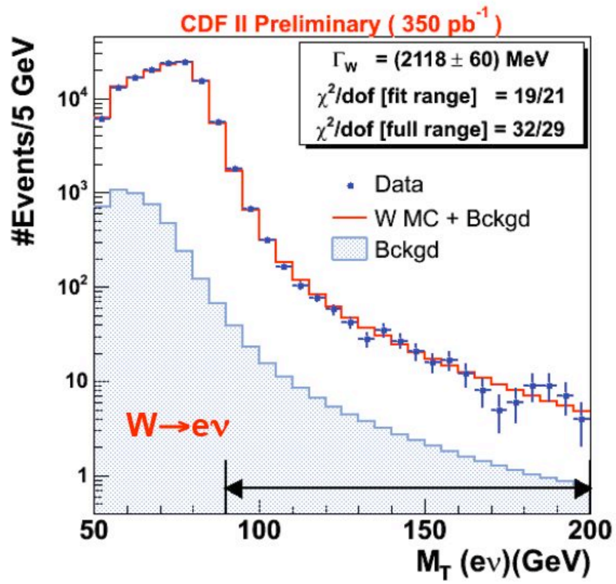
- New world average:

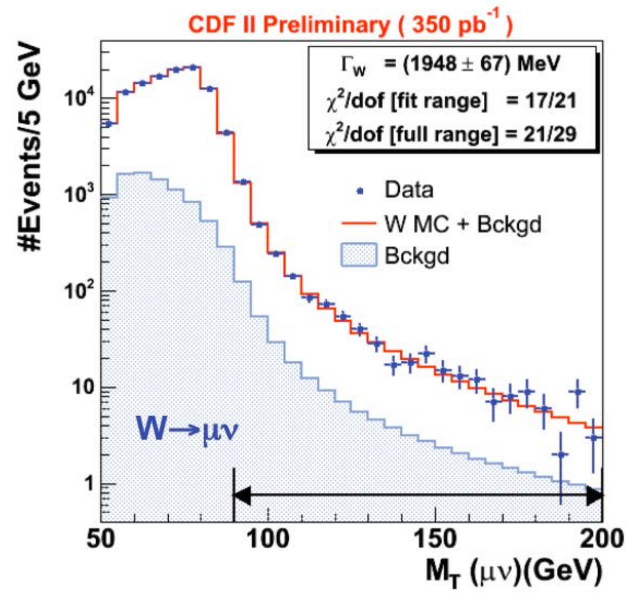
  M_W=80398 ± 25 MeV
- Ultimate Run 2 precision:

  ~15 MeV

W Boson Width



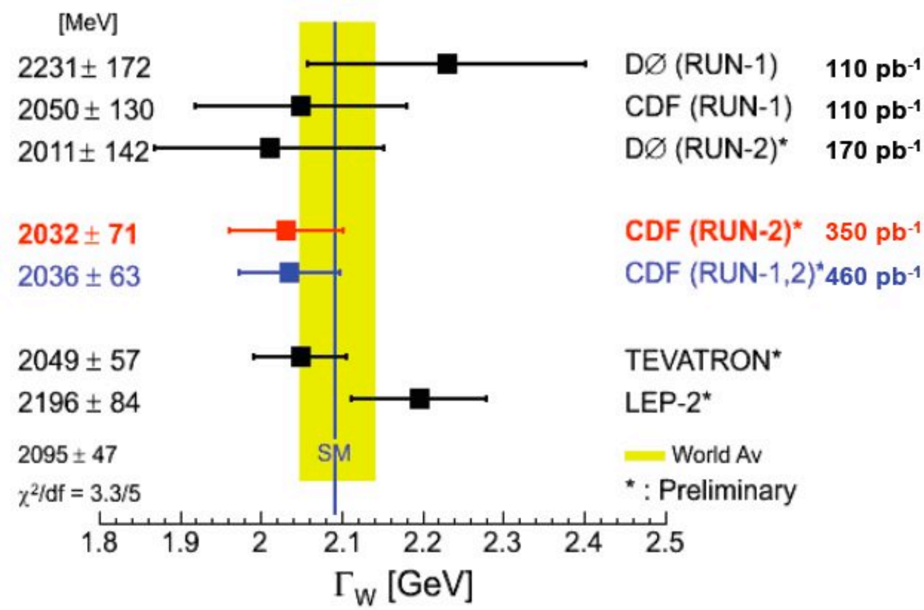




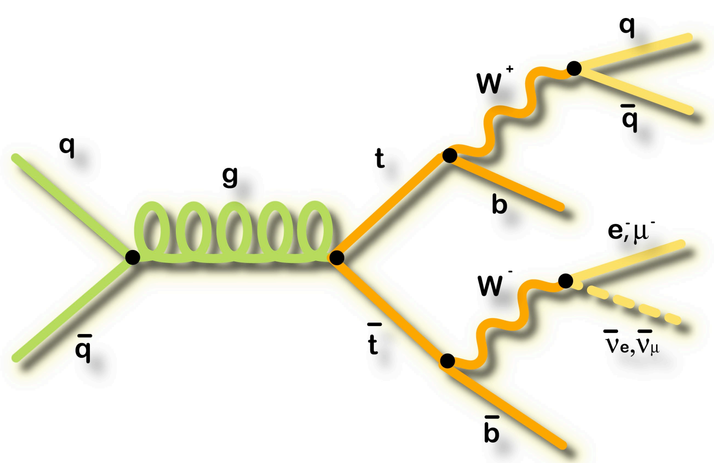
- New world average:
  Γ_W=**2095 ± 47 MeV**

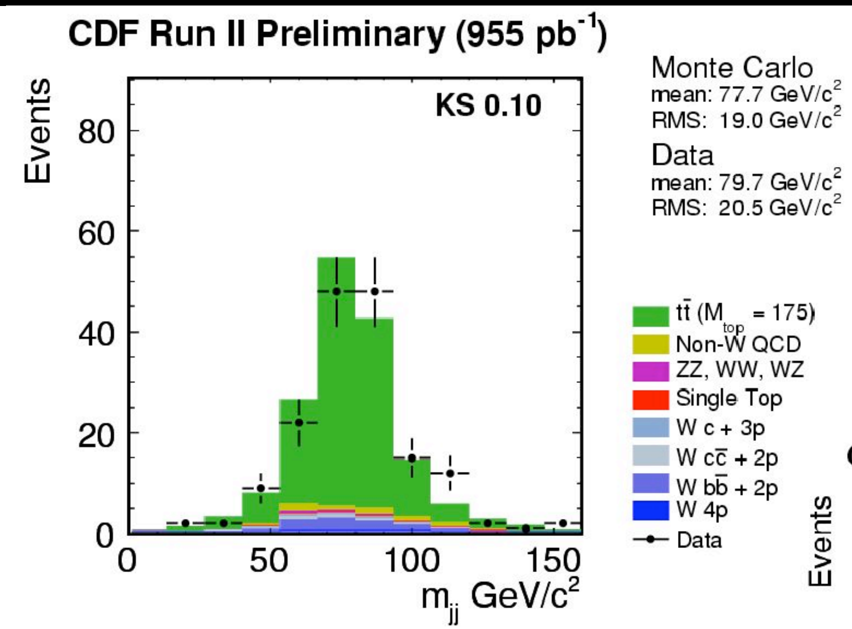
- Standard Model prediction:
  Γ_W =**2091 ± 2 MeV**

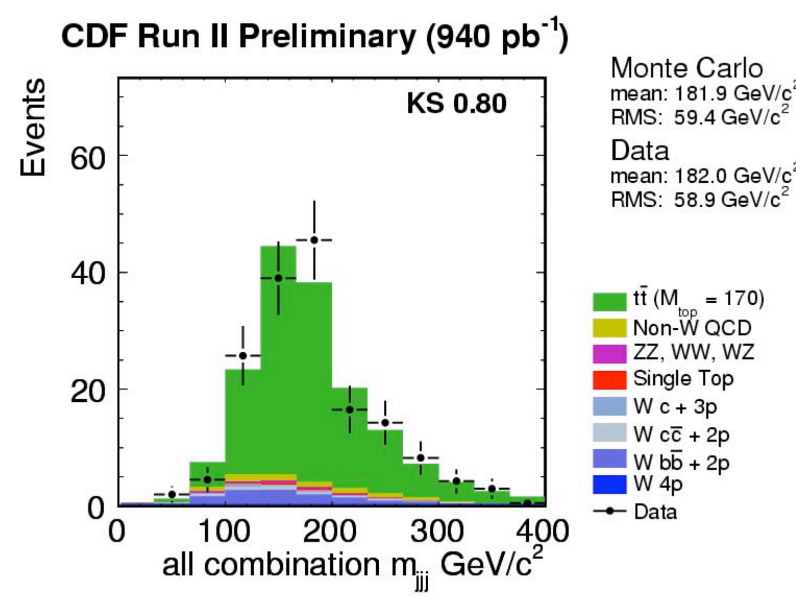
  [PRL 94, 091803 (2005)]



Top Quark Mass

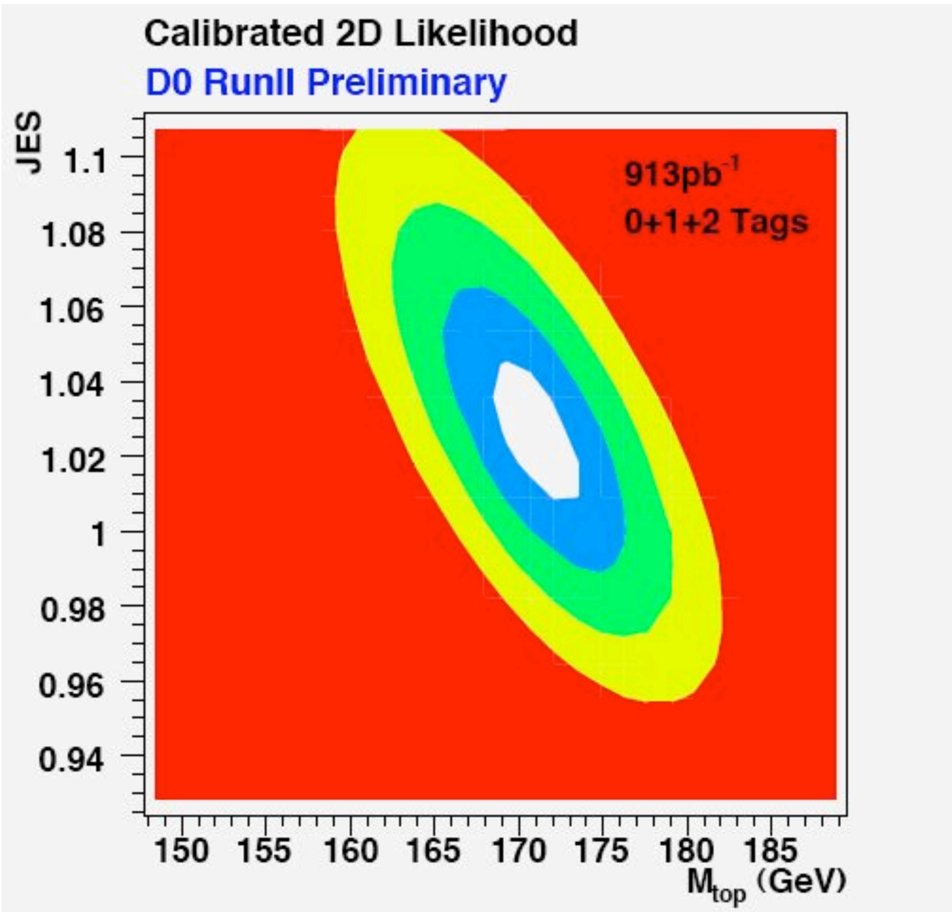


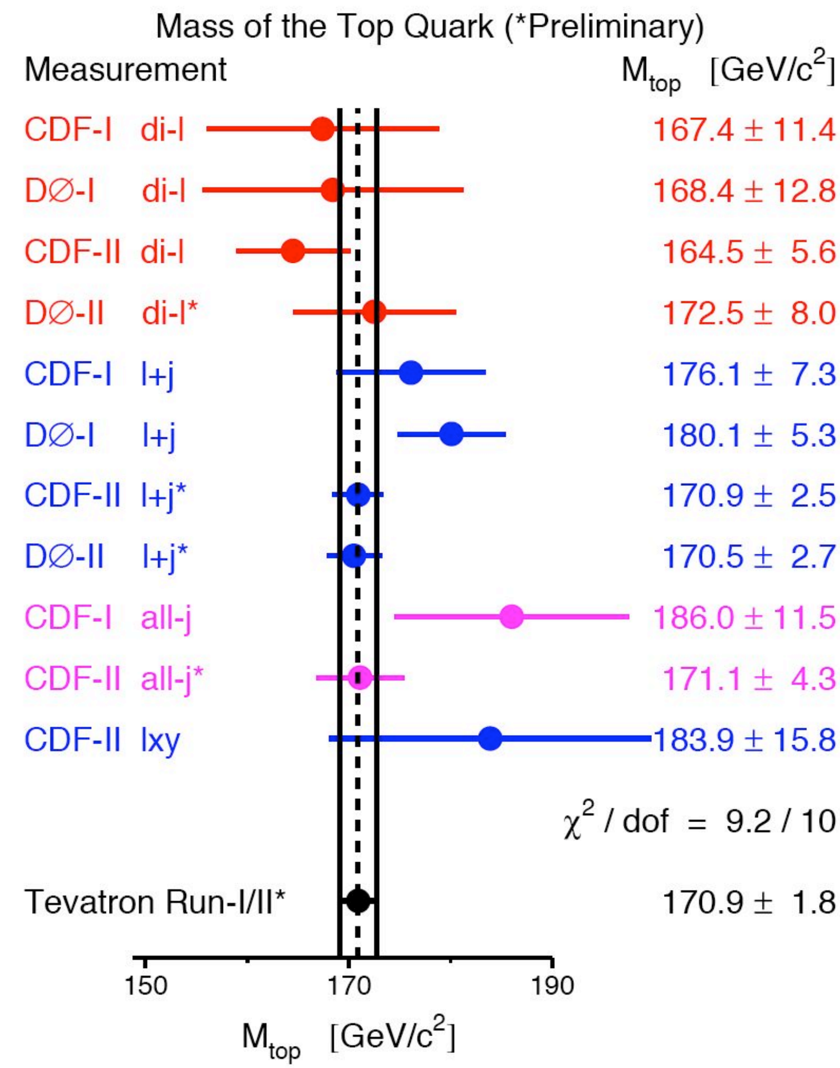




- Rather large pure samples available:
  - 166 events: S/B=4/1
- Perform simultaneous fit for
  - Top quark mass
  - Jet energy scale ($M_W = M_{jj}$)
    - dominant systematic uncertainty

Top Quark Mass Results

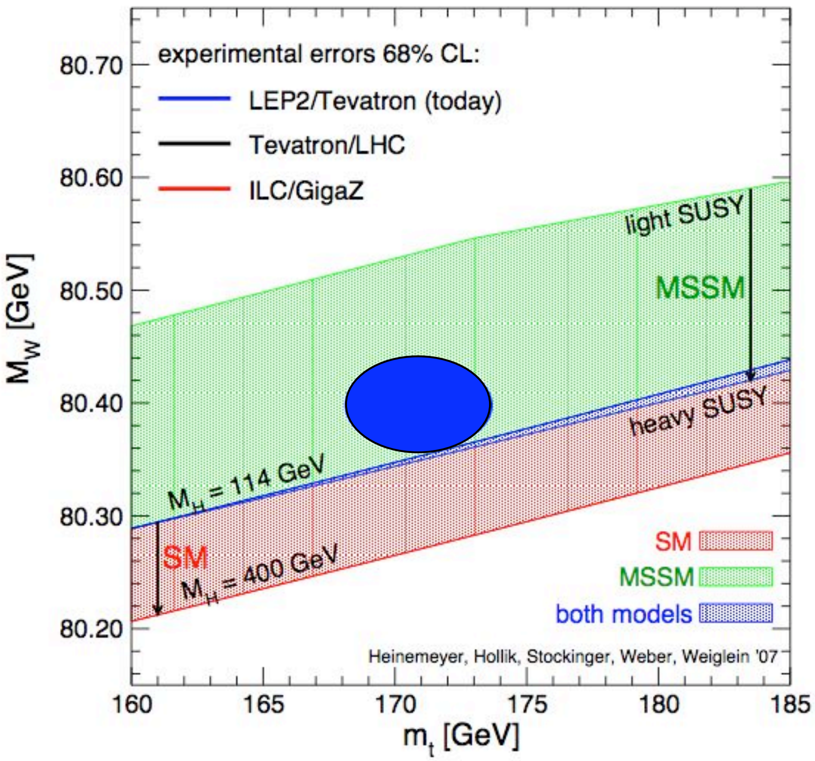


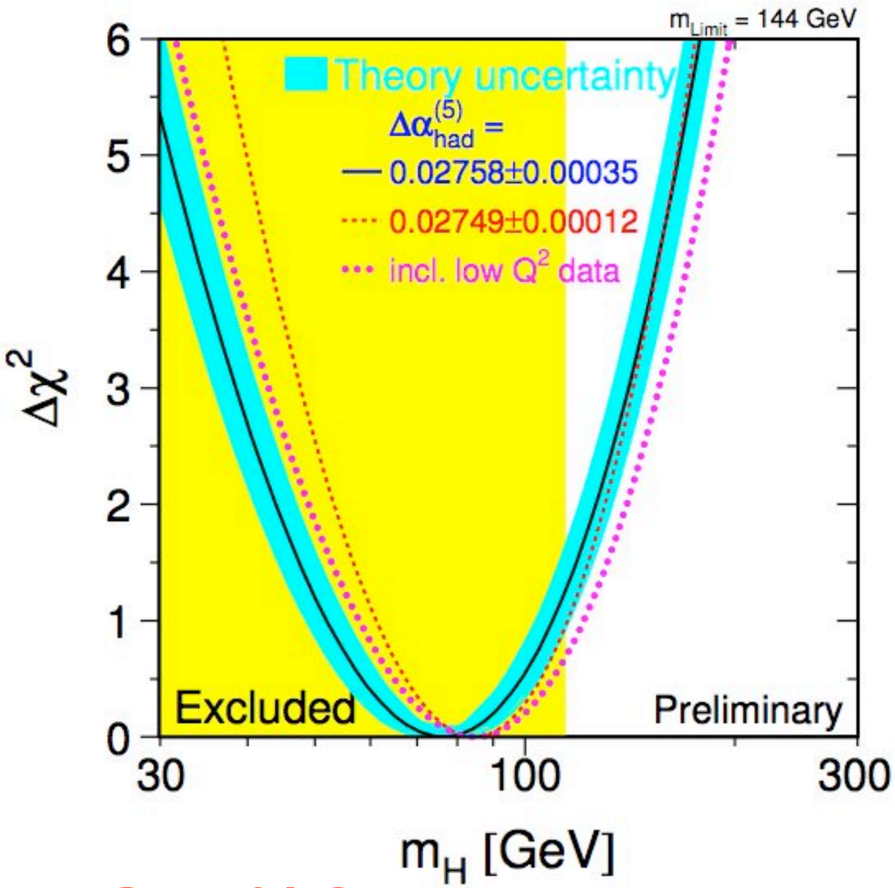


m_{top}=170.9± 1.8 GeV/c^2

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

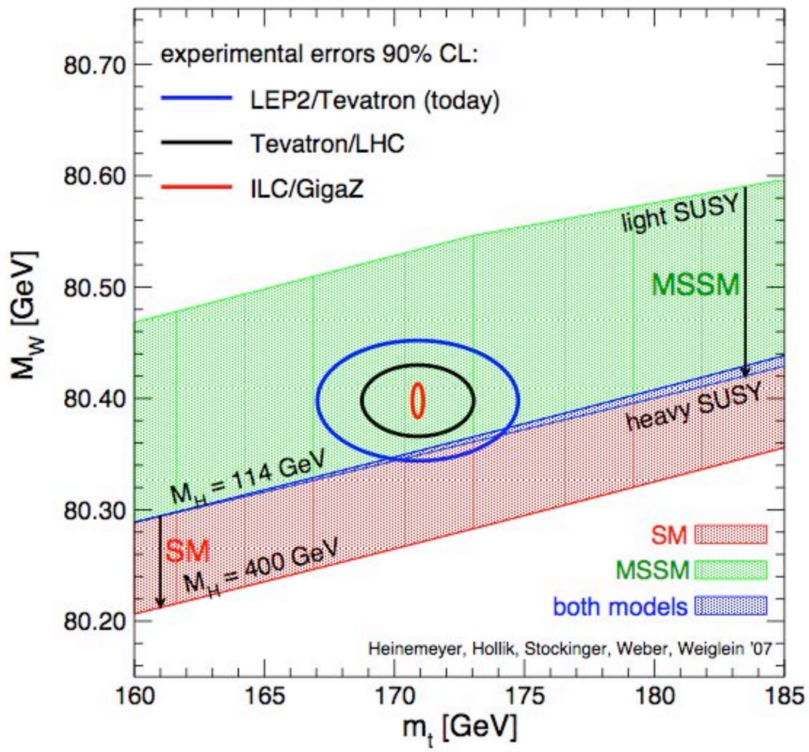
M_W, m_{top} and m_{Higgs}

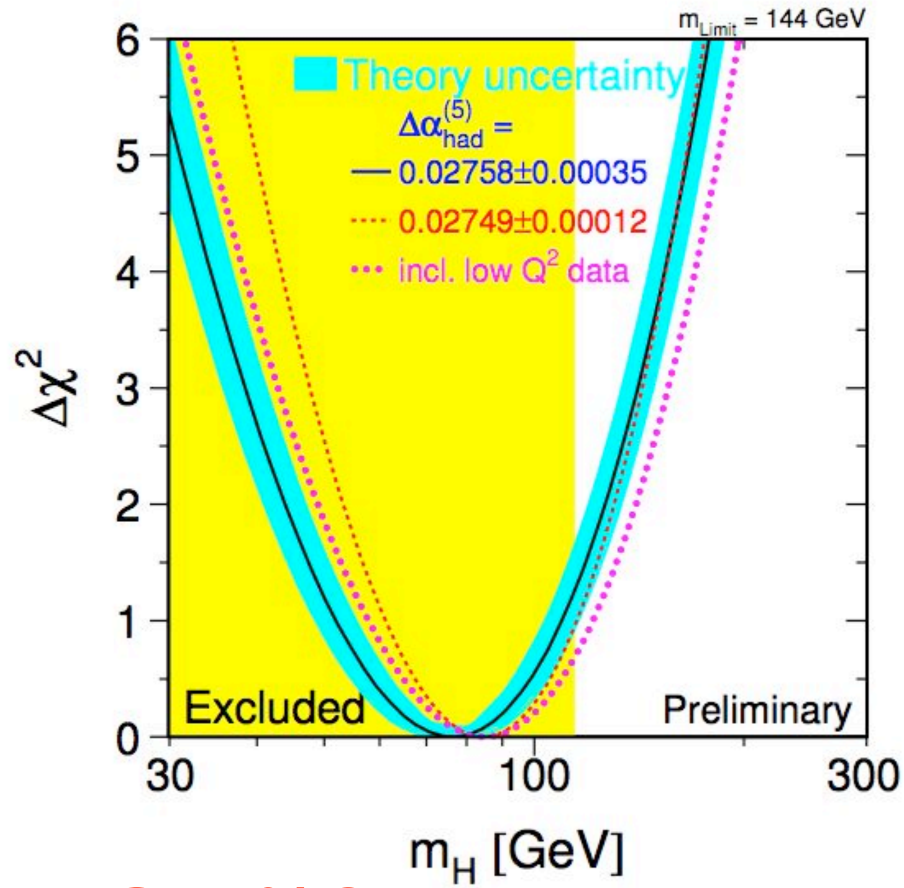




- **Indirectly: m_H<144 GeV@95%CL**
- **Directly (LEP): m_H>114 GeV@95%CL**
  – Standard Model excluded at 68% CL

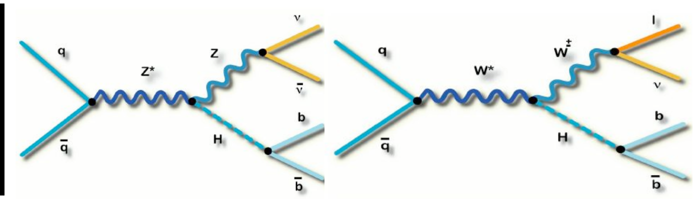
M_W, m_{top} and m_{Higgs}

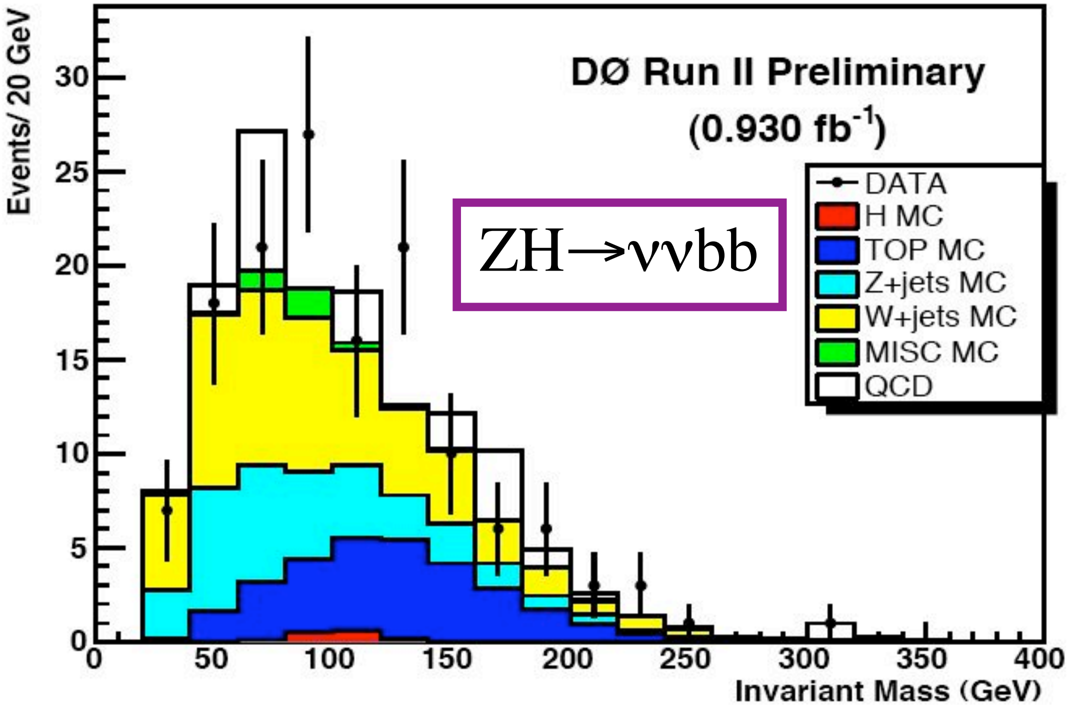


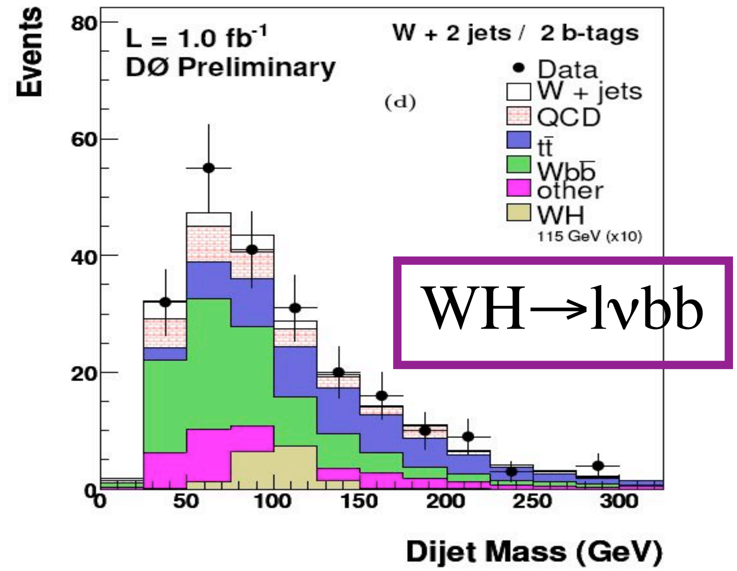


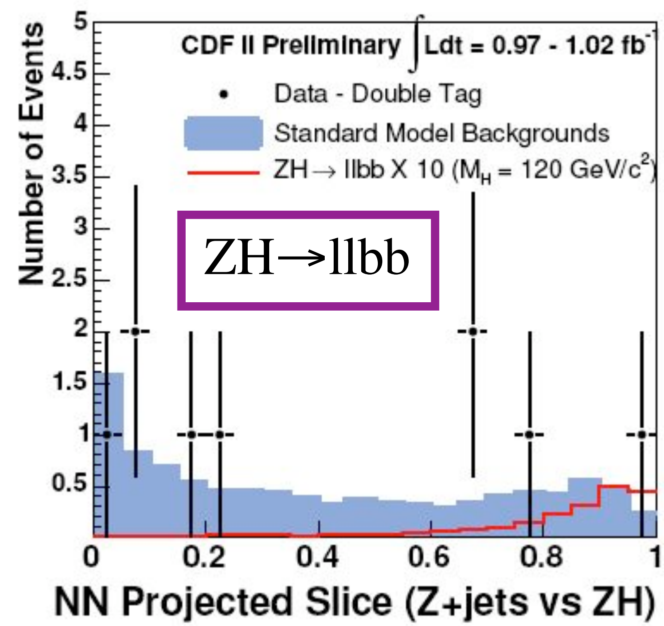
- **Indirectly: m_H<144 GeV@95%CL**
- **Directly (LEP): m_H>114 GeV@95%CL**
  - Standard Model allowed at 95% CL

W/Z+Higgs with H→bb



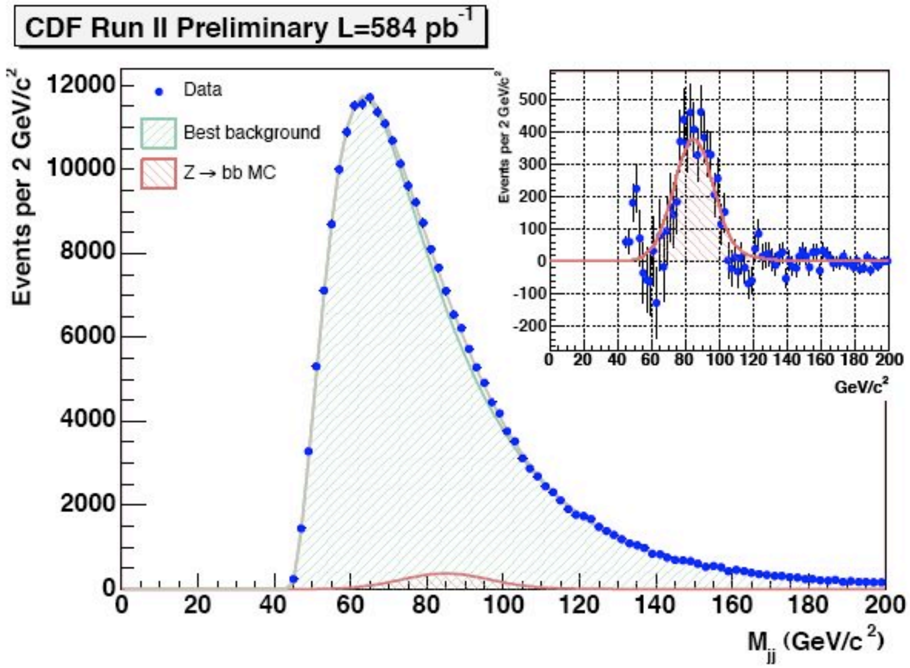


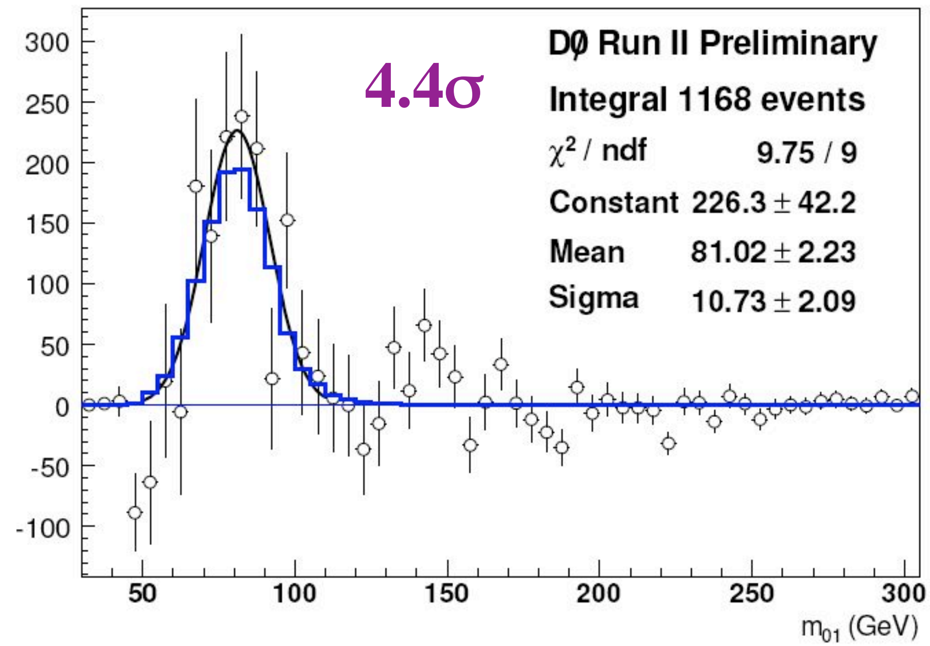




- For m_H<135 GeV/c^2:
  - WH→lνbb, ZH →llbb, ZH →ννbb
- Both collaborations have analyzed 1 fb^{-1} in for all three modes:

Z→bb resonance

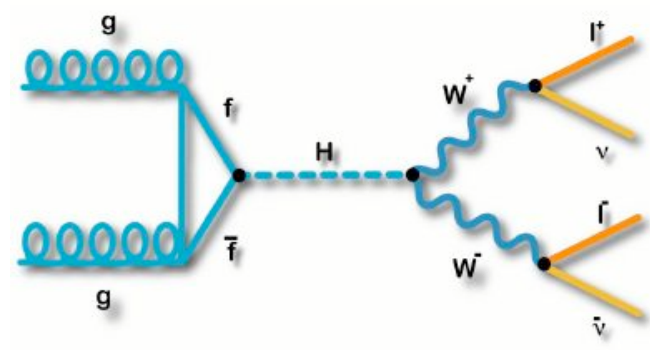


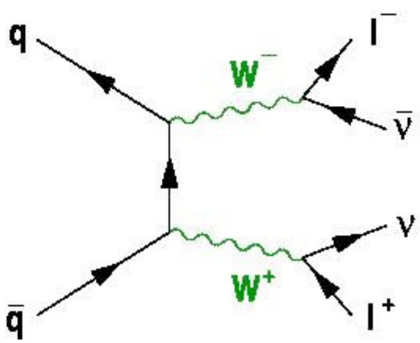


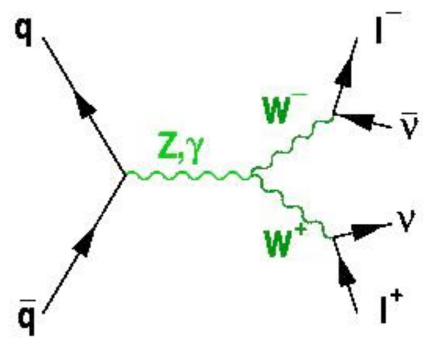
- Both collaboration succeeded in extracting a signal consistent with Z->bb out of an enormous QCD bb background
  - Energy scale and resolution so far consistent with simulation

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

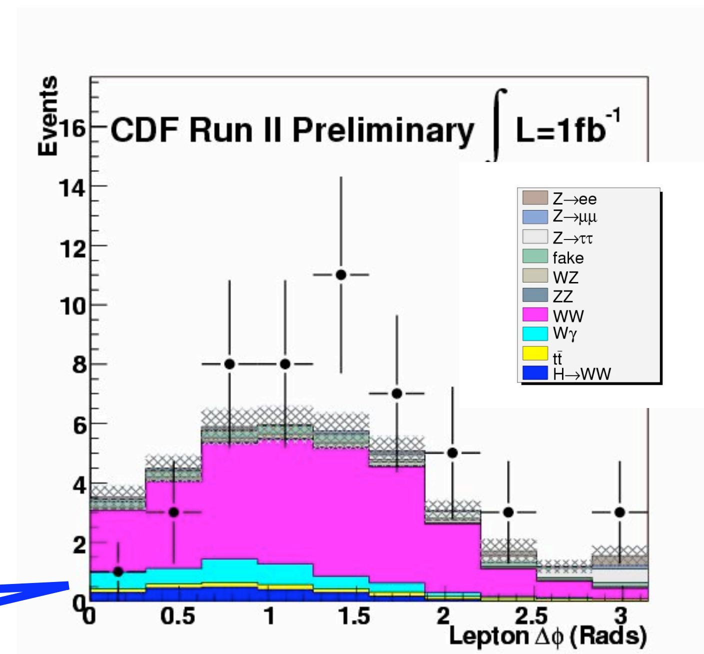
- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs has spin=0
  - leptons in $H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$ are collinear
- Main background: WW production



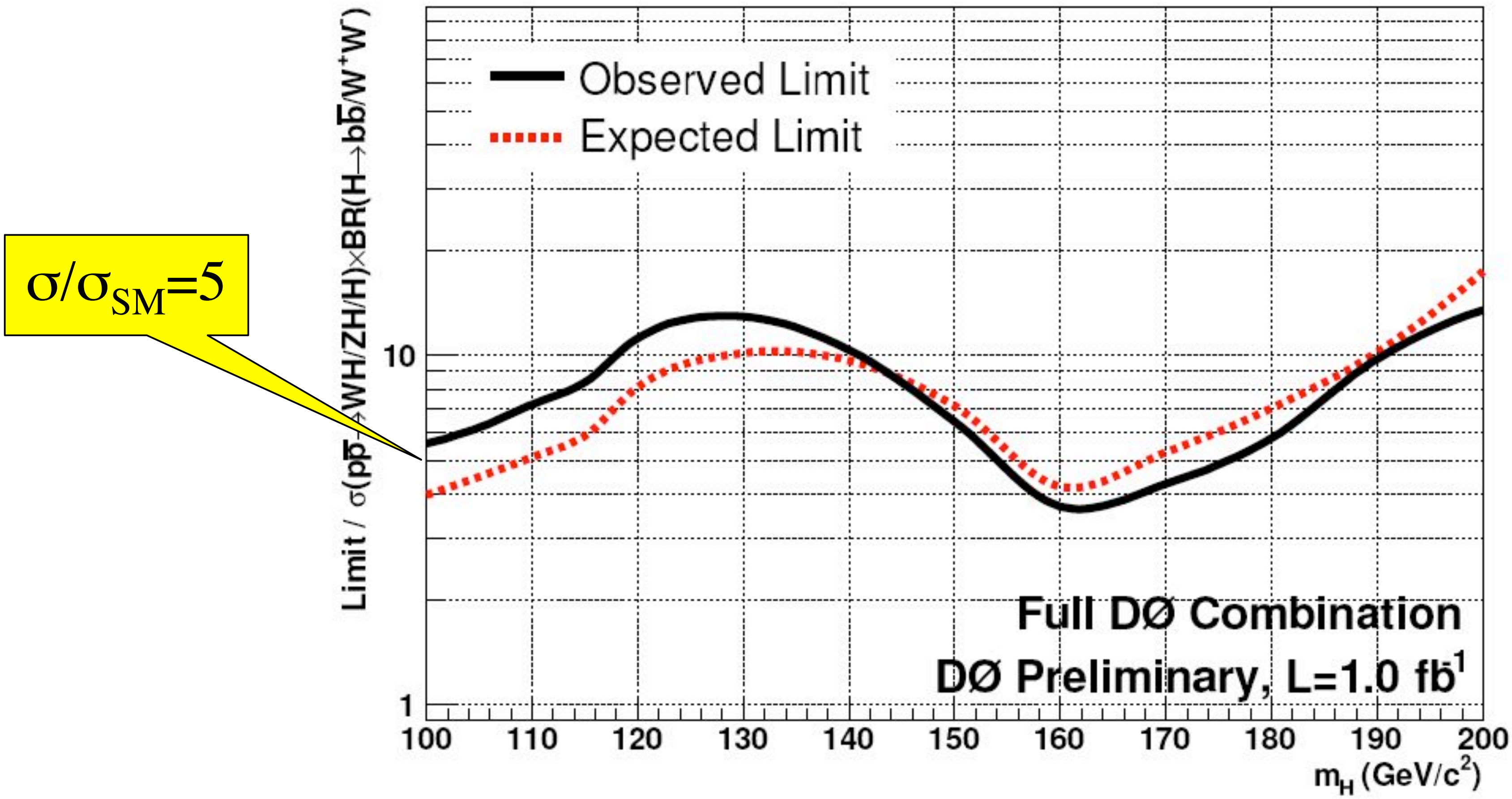




160 GeV Higgs



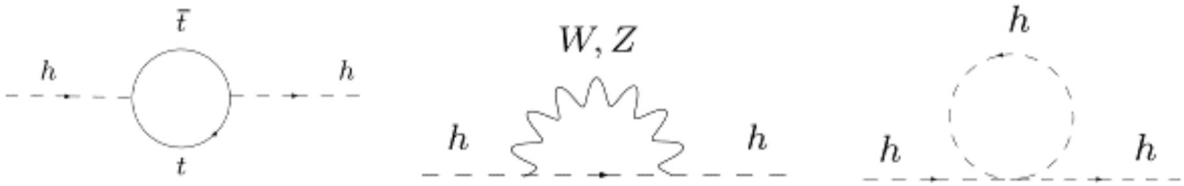
Higgs Cross Section Limit



- Ratio of limit to SM about 5-10 with 1 experiment with 1 fb^{-1}
  - CDF+D0 combination ongoing
  - more data coming
  - experimental improvements ongoing

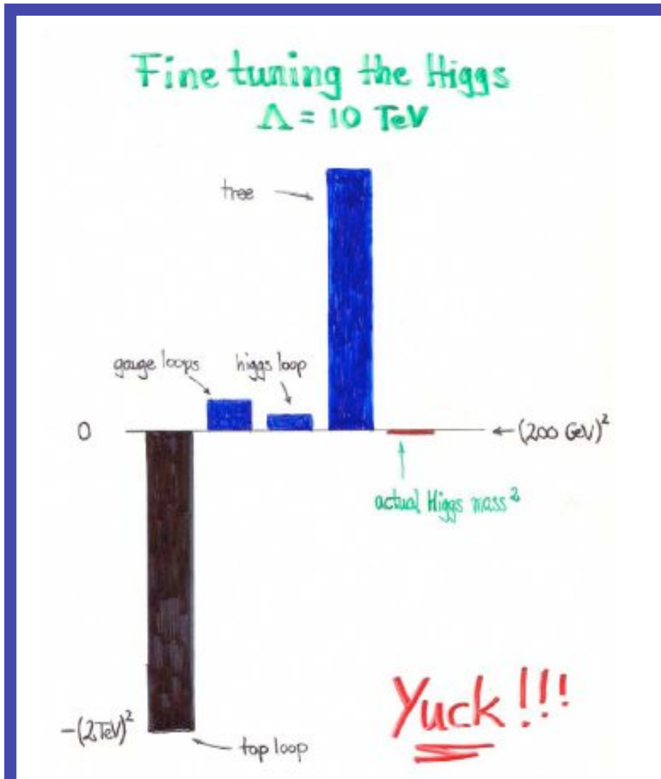
Beyond the Standard Model

Problems of the Standard Model



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

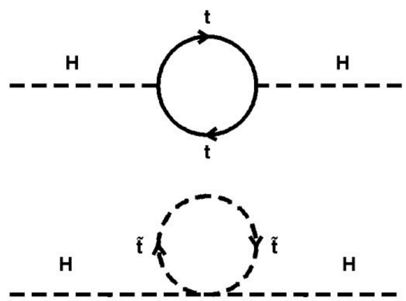
- Large fine-tuning required:
  - $m_H \ll m_{Pl}$
- Accounts for just 4% of the Universe
  - No dark matter candidate
  - Cosmological constant problem
- No prediction for
  - fundamental constants, unification of forces, number of generations, mass values and hierarchy of SM particles, anything to do with gravity



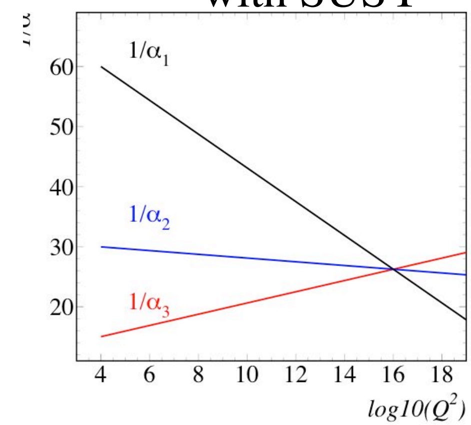
M. Schmaltz, ICHEP 02

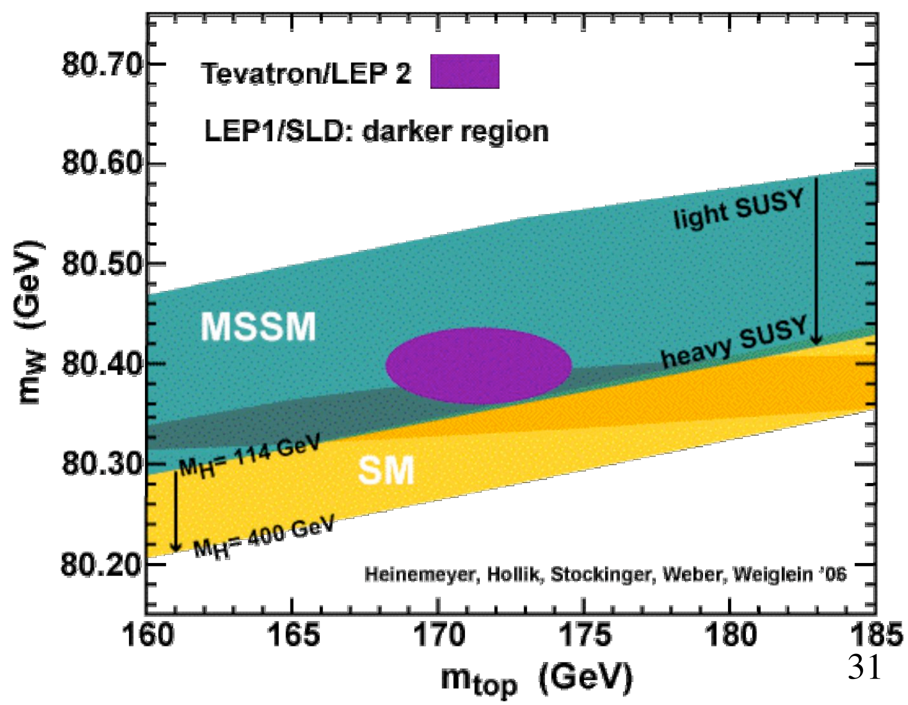
What’s Nice about SUSY?

- 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}

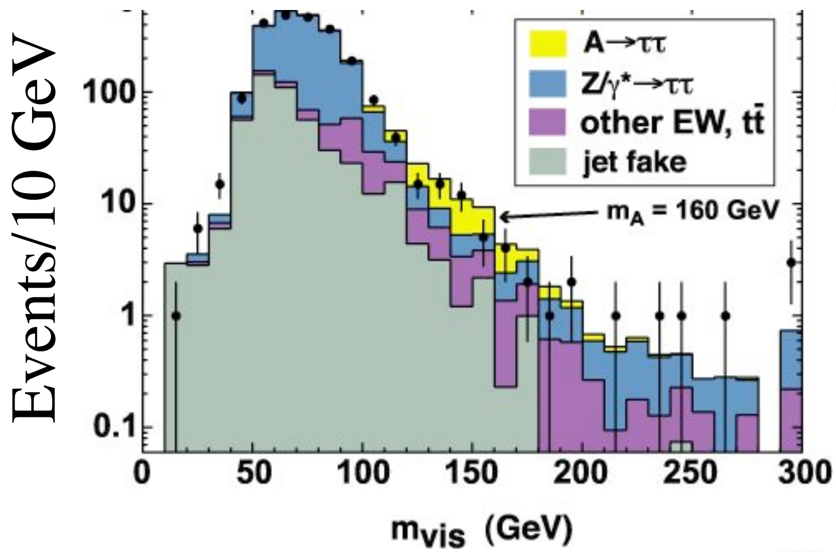


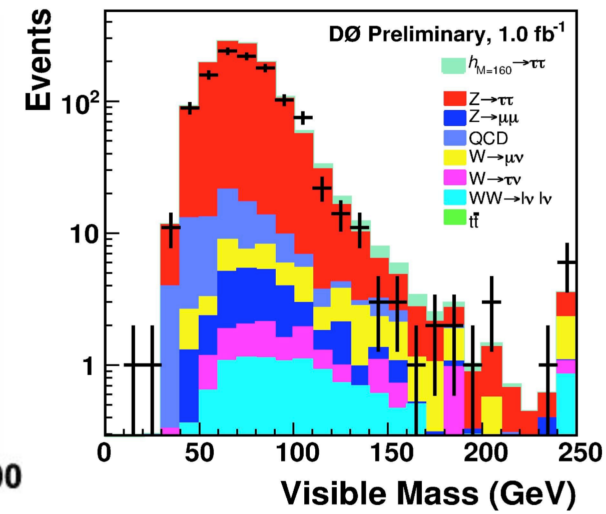
with SUSY

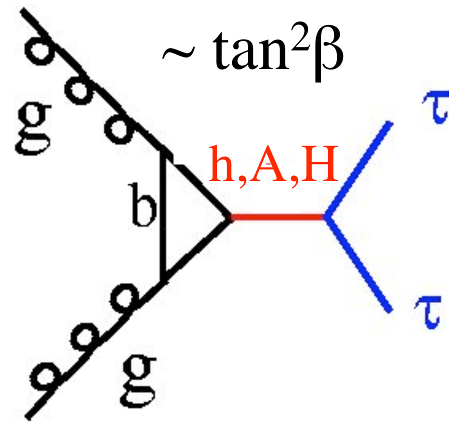


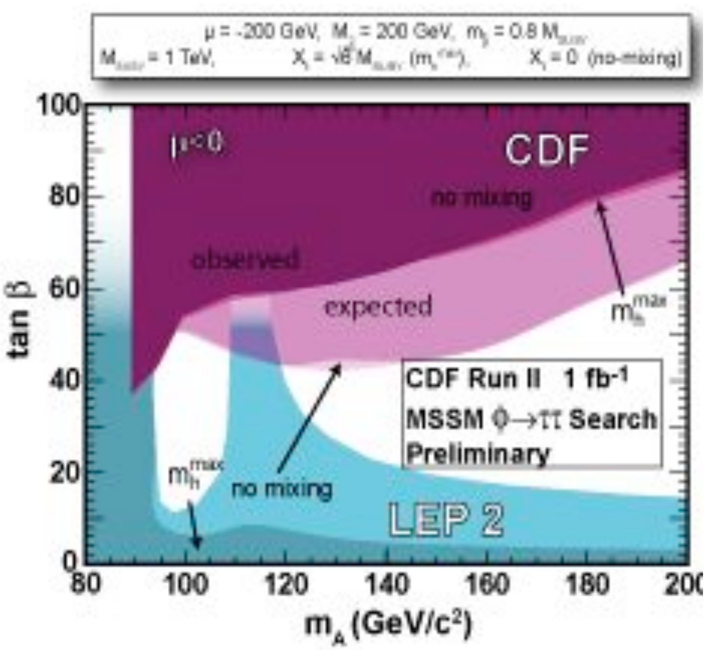


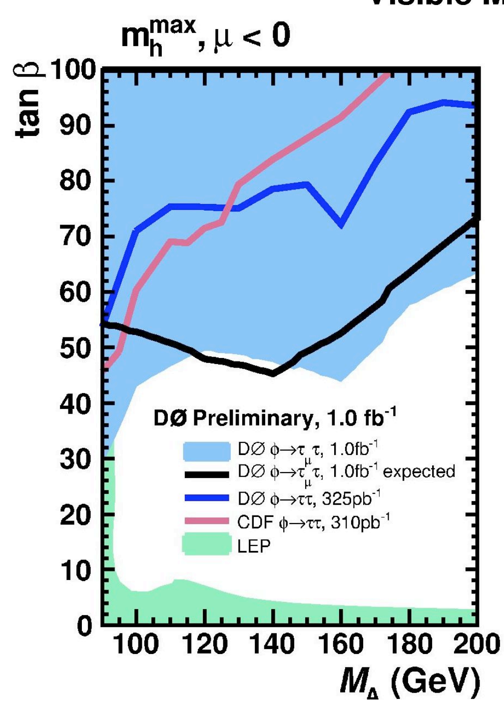
MSSM Higgs Boson Search





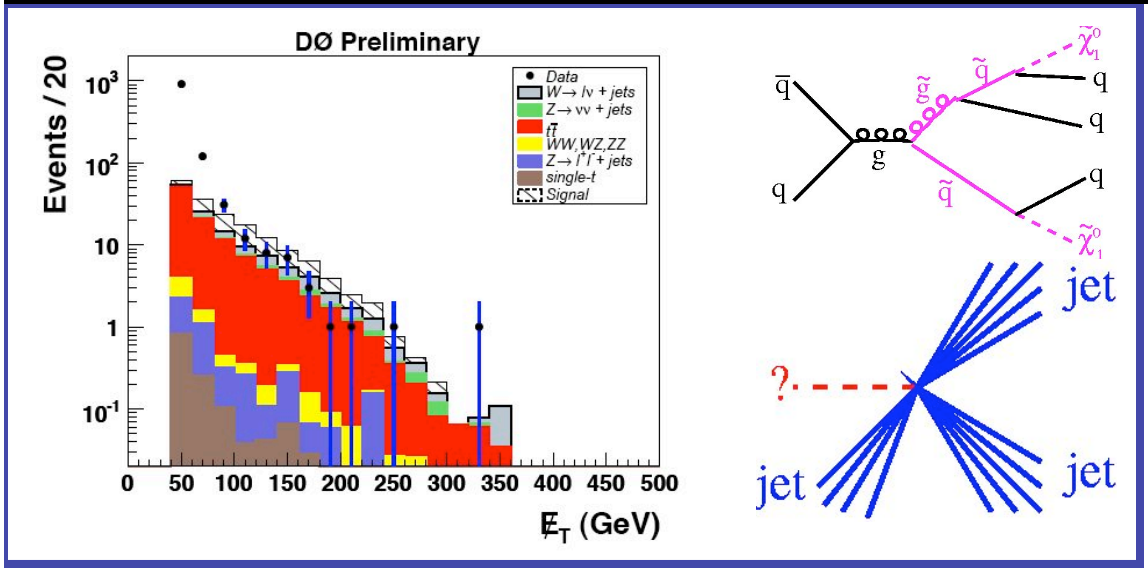


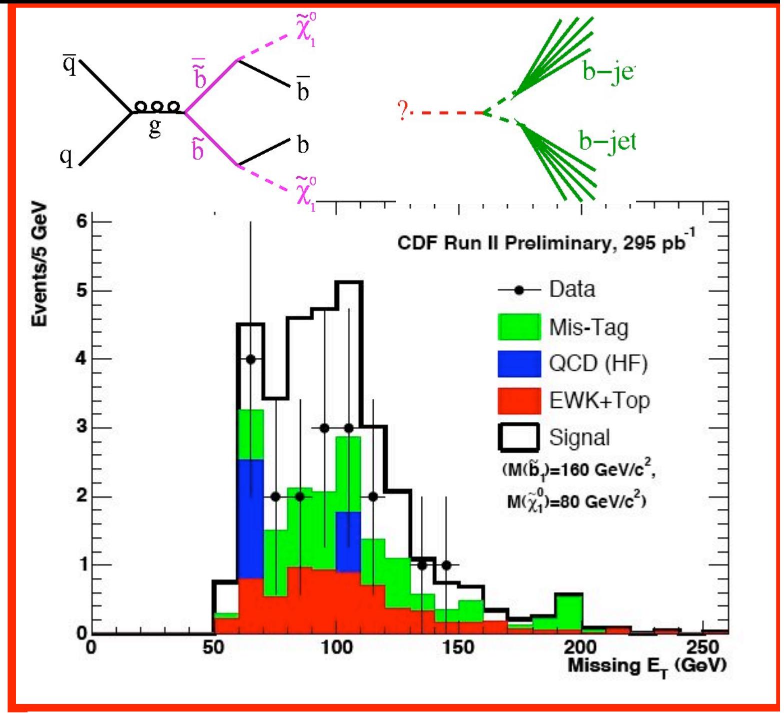


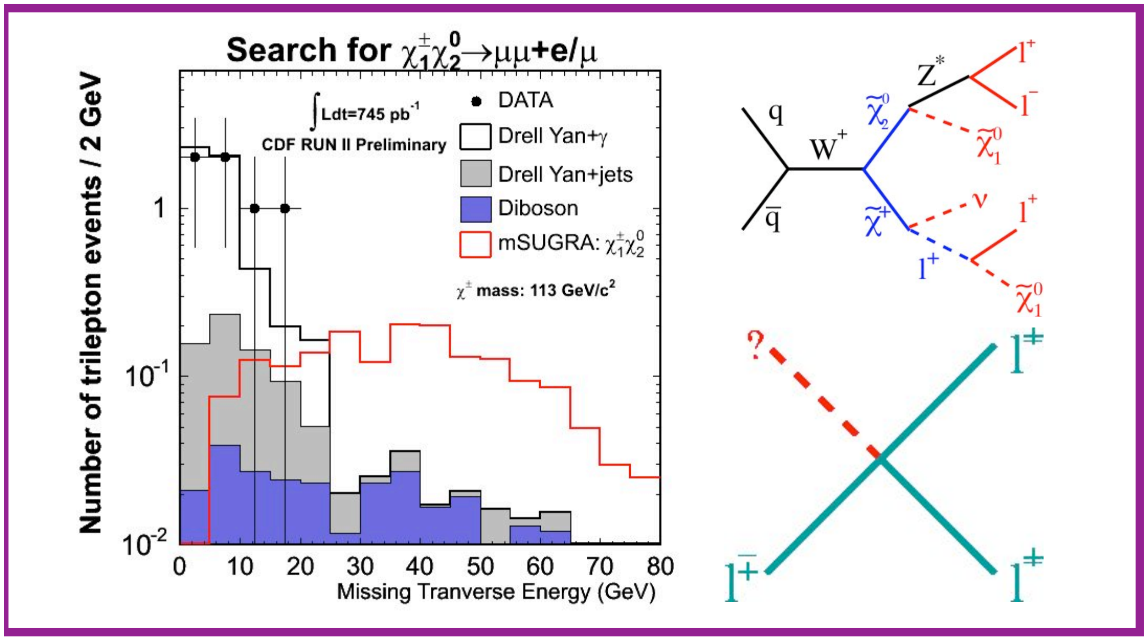


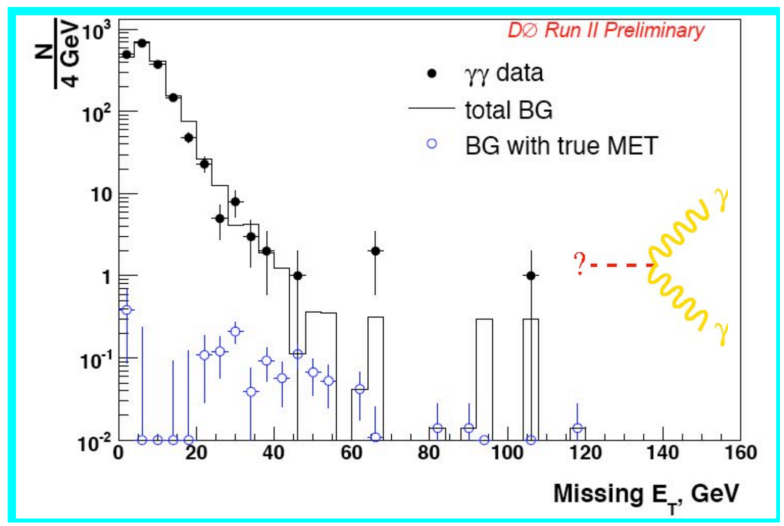
- Data mass distribution agrees with SM expectation mostly:
  - CDF: Slight excess has a significance of 2.1σ (cross section about 2 pb)
  - DØ: slight deficit in that region

Supersymmetry Searches

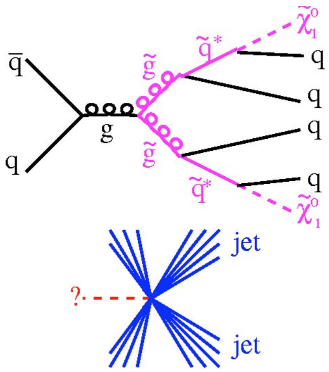


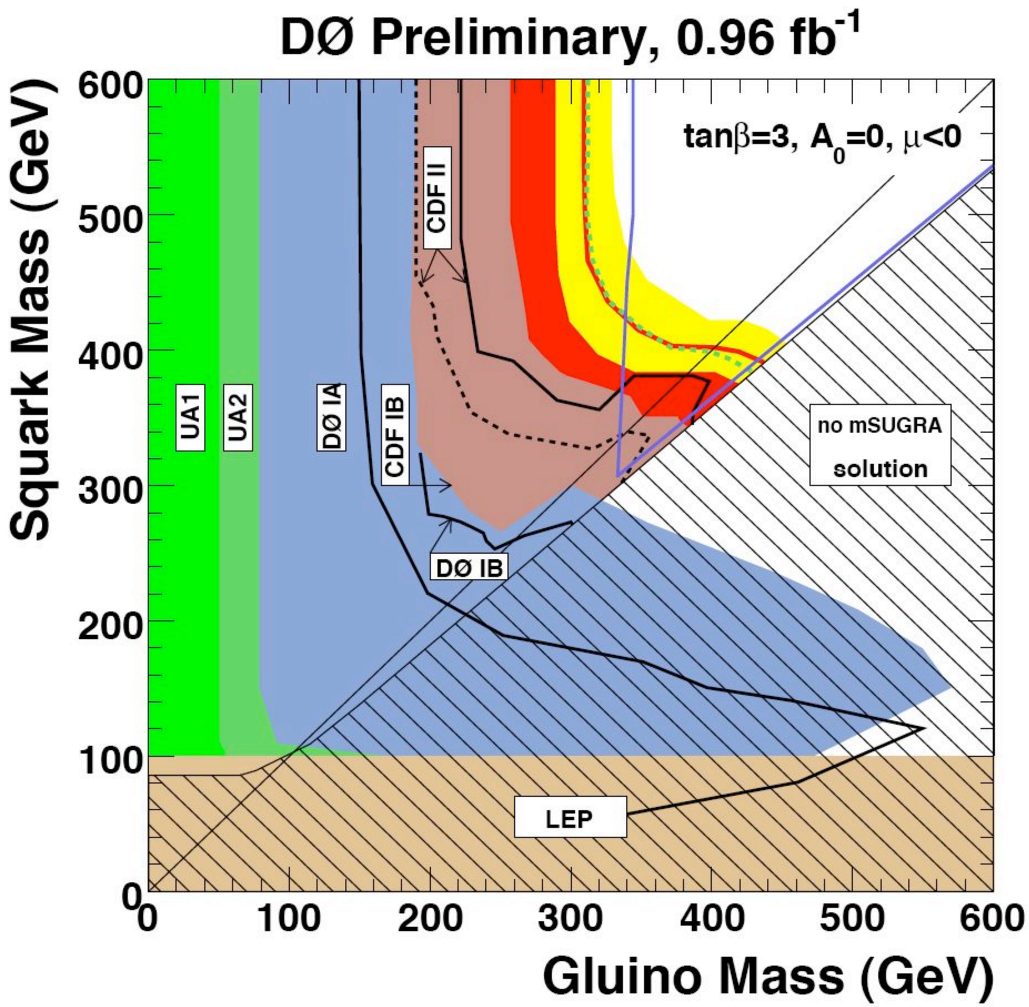


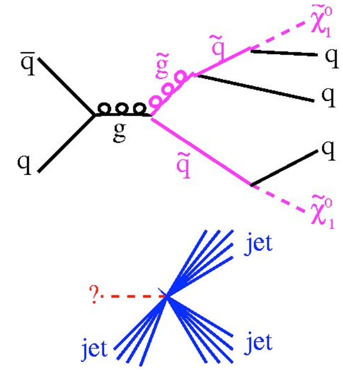


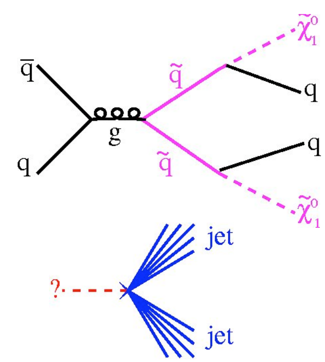


Supersymmetry Parameter Space



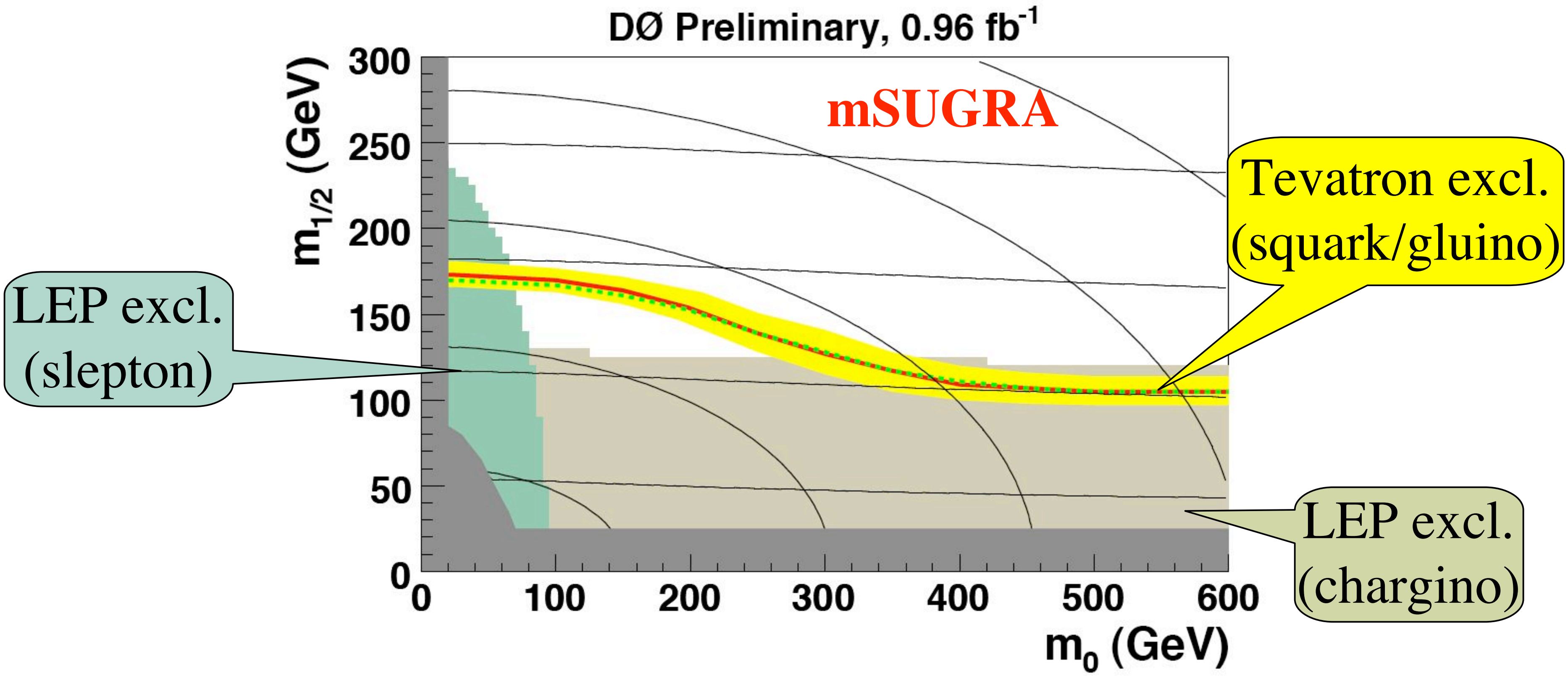






- $M(\tilde{g}) > 289$ GeV
- for $M(\tilde{q}) \approx M(\tilde{g})$: $M(\tilde{q}) > 375$ GeV, $M(\tilde{g}) > 410$ GeV

Exclusion of GUT scale parameters



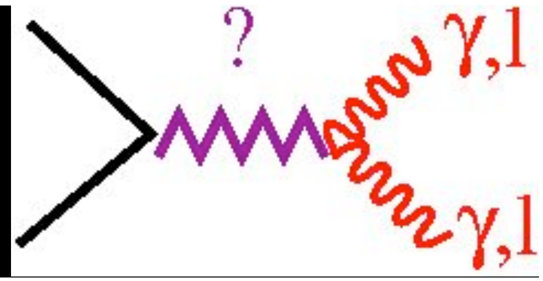
- Nice interplay of hadron colliders and e^+e^- colliders:
  - Similar sensitivity to same high level theory parameters via very different analyses

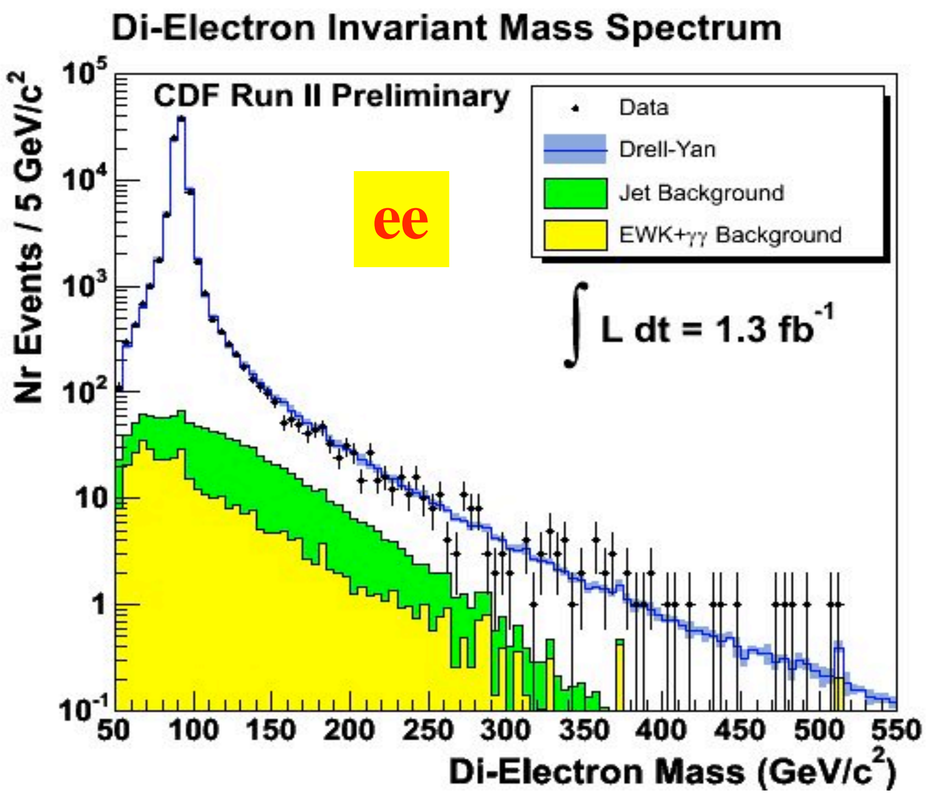
Beyond SUSY

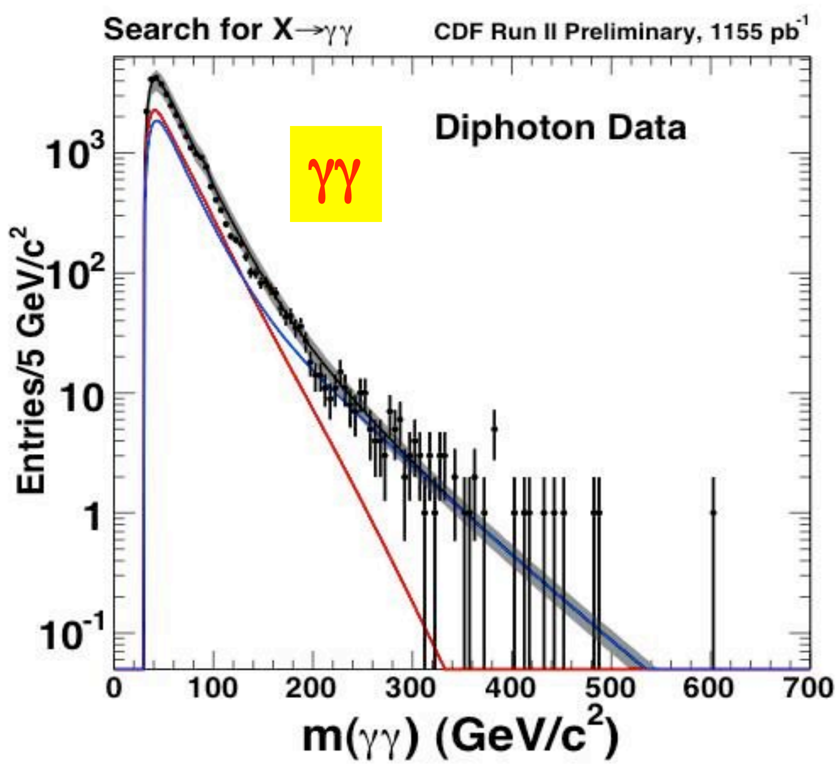
What else could be there?

- 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

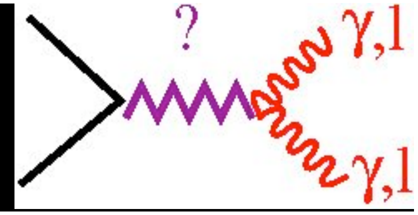




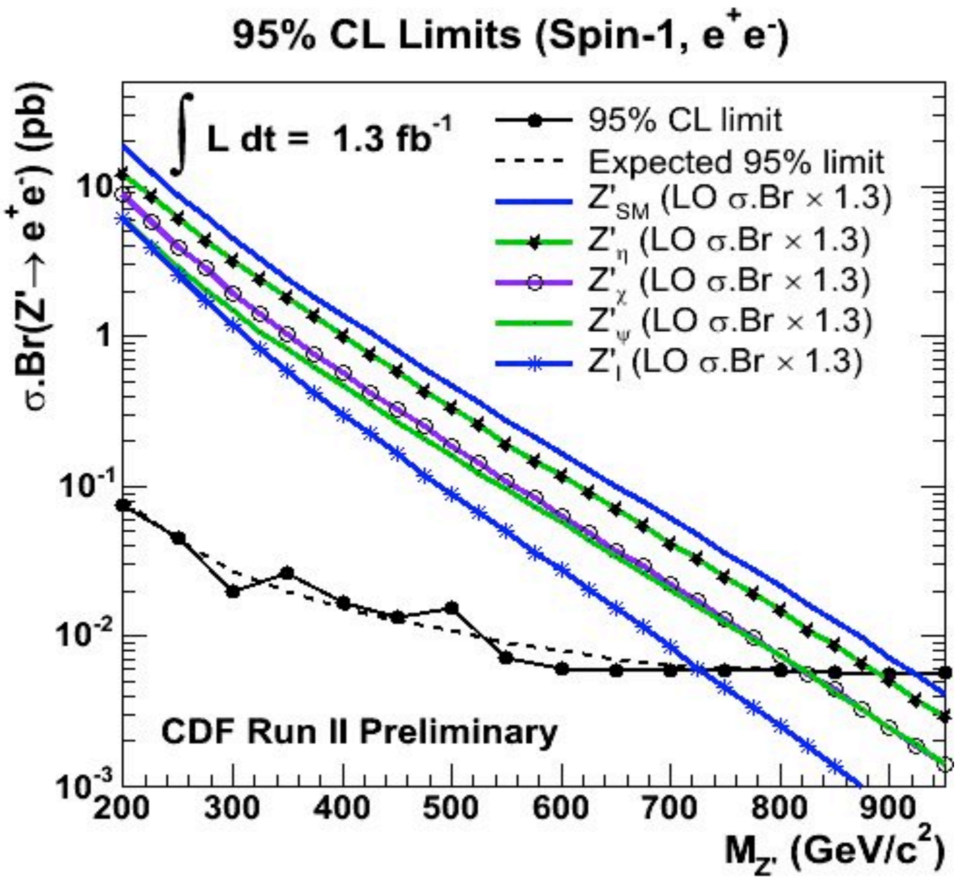


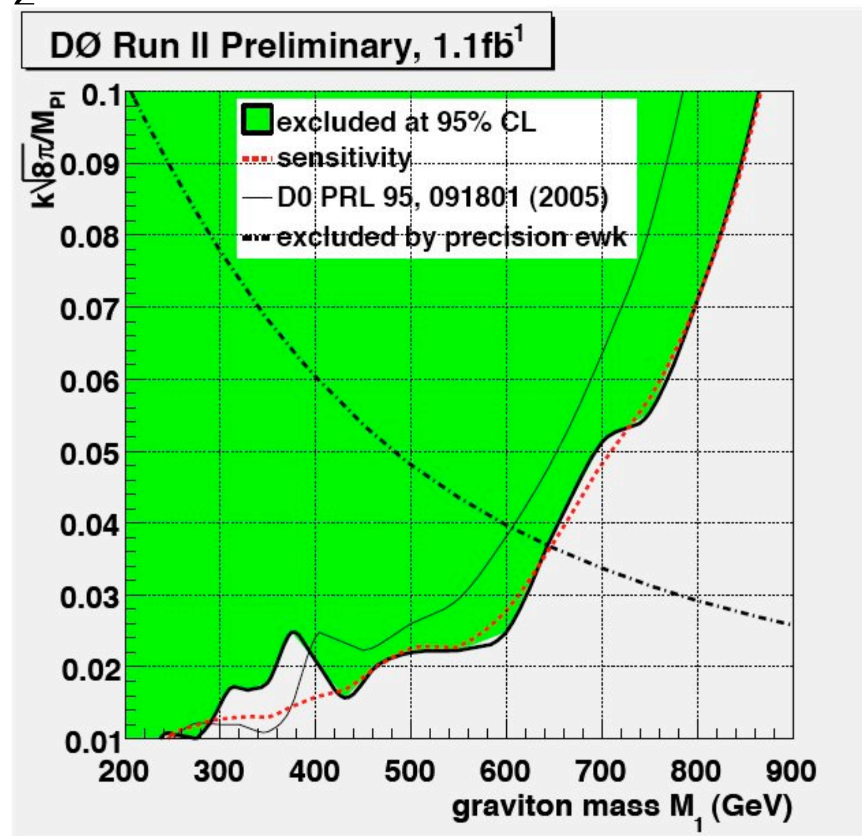
- Dielectron mass spectrum and diphoton mass distributions
  - Data agree well with Standard Model spectrum
  - No evidence for mass peak or deviation in tail

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



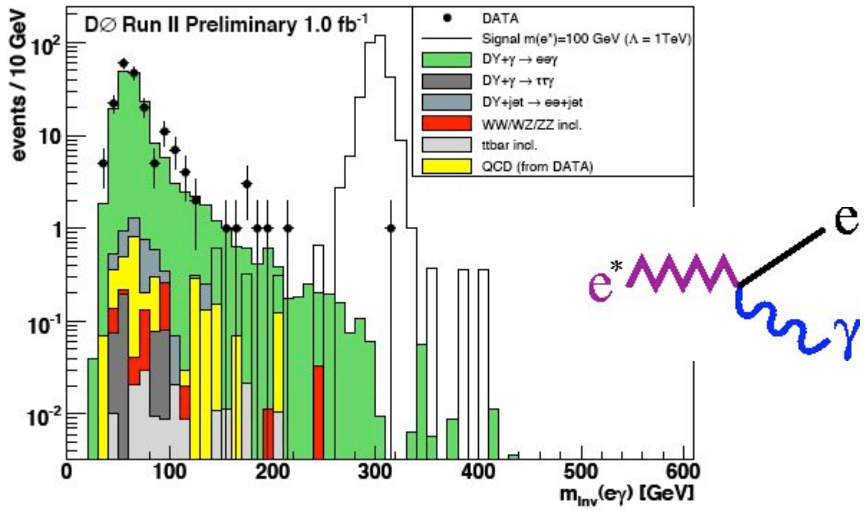


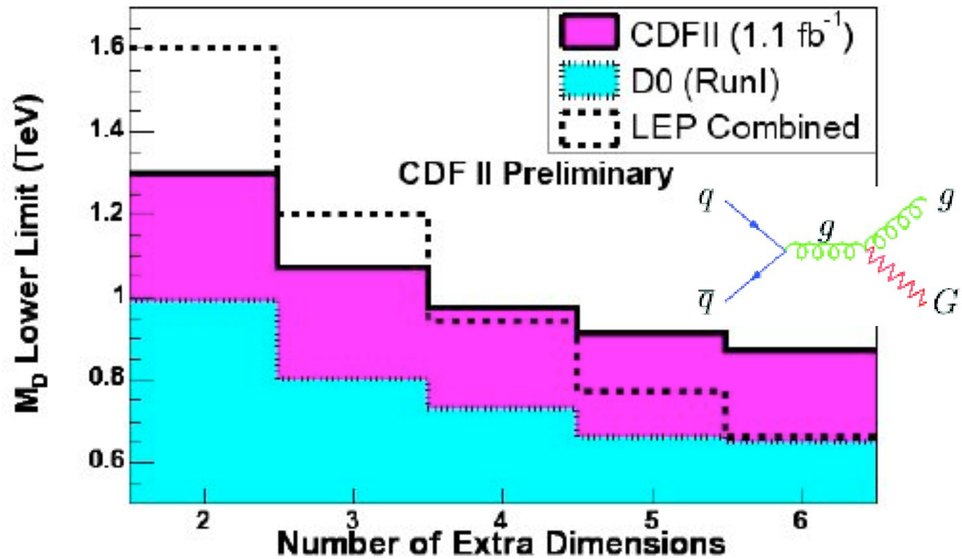
$M_{Z'}$>923 GeV for SM-like Z'

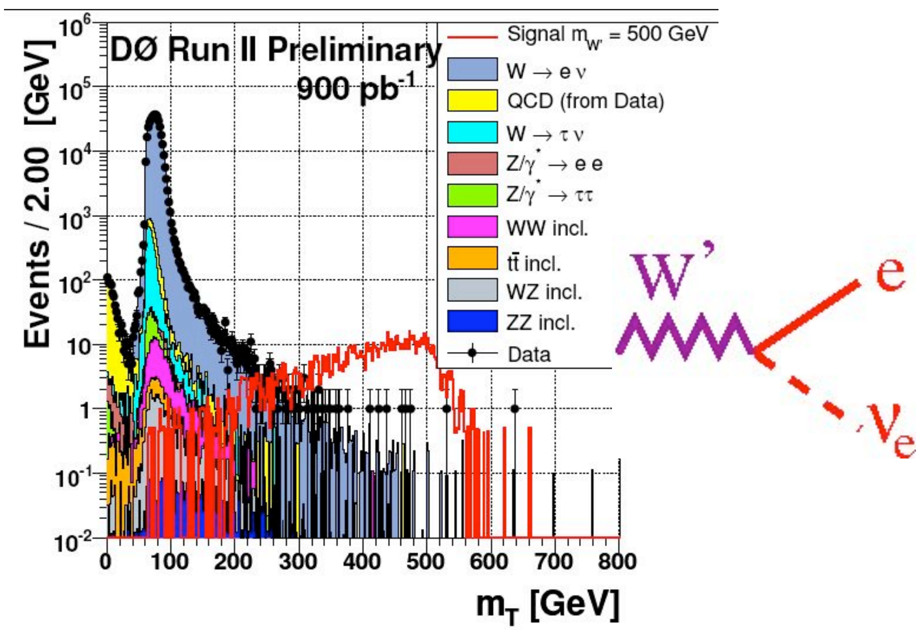
CDF: M_G>889 GeV for k/M_{Pl}=0.1

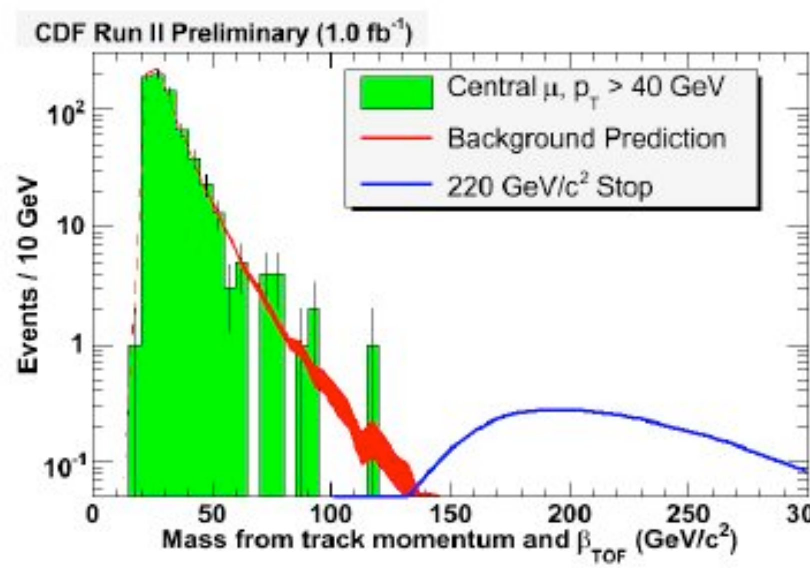
DØ: M_G>865 GeV for k/M_{Pl}=0.1

Many More Searches



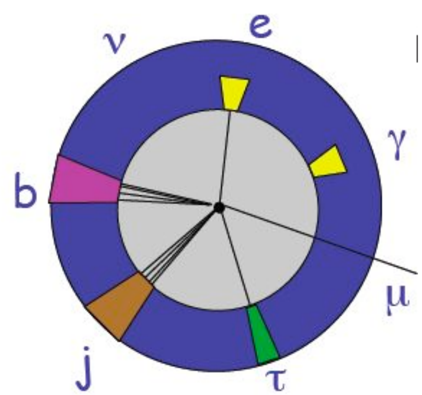


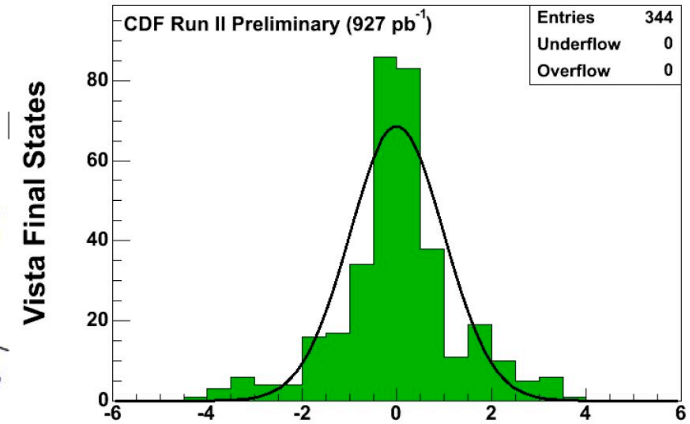




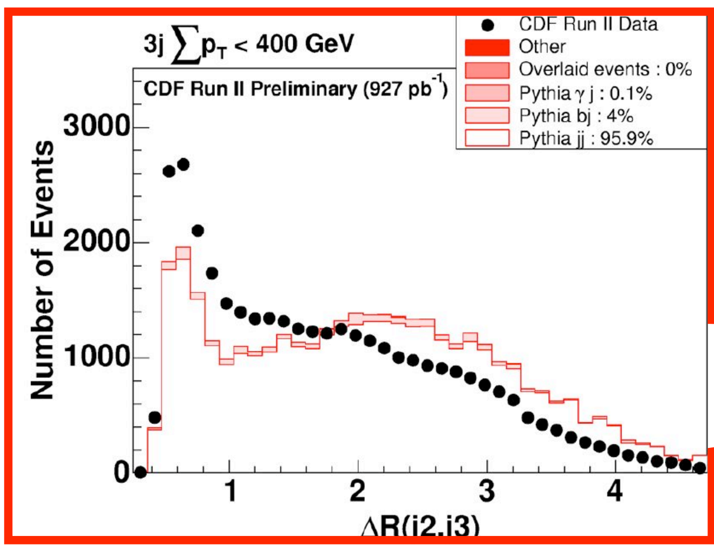
Inclusive Survey of High P_T Data

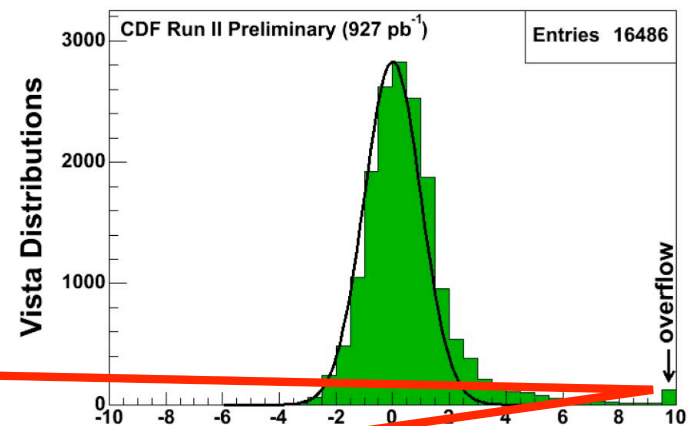
- Look for new physics in "all" event topologies, e.g.:
  - Photon+jet+muon
  - Photon+jet+electron
  - …
  - 344 final states, 16,486 distributions!





$(N_{data}-N_{SM})/\ \delta$

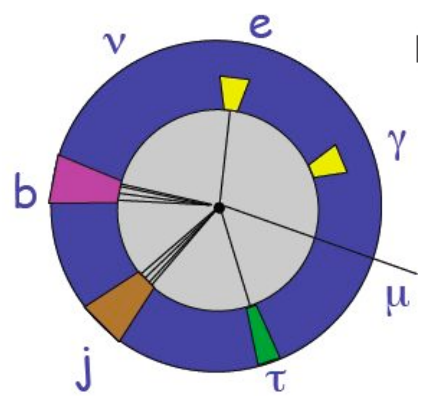


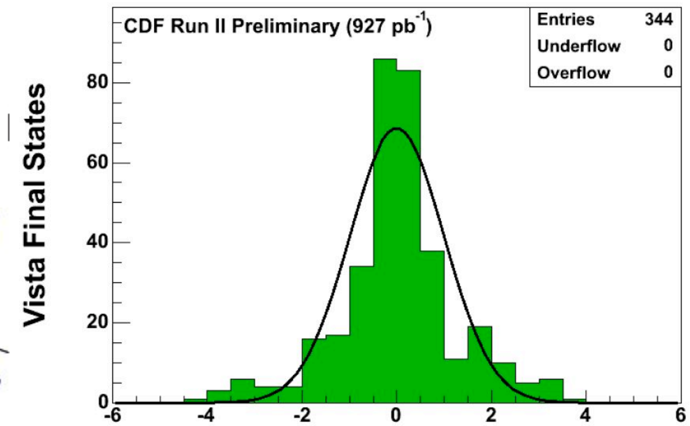


$(N^i_{data}-N^i_{SM})/\delta^i$

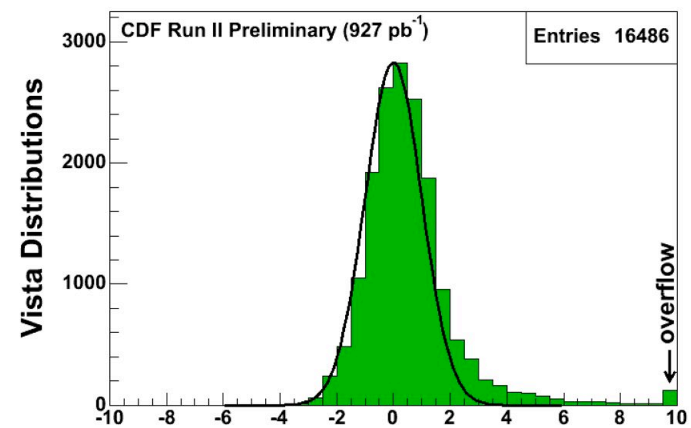
Inclusive Survey of High P_T Data

- Look for new physics in “all” event topologies, e.g.:
  - Photon+jet+muon
  - Photon+jet+electron
  - …
  - 344 final states, 16,486 distributions!
- Only sensitive if new physics is large and at high P_T
  - Good for looking for “the unexpected”
  - Typically less sensitive than dedicated searches
    - E.g. for WZ discovery 3 times more data needed than in dedicated search





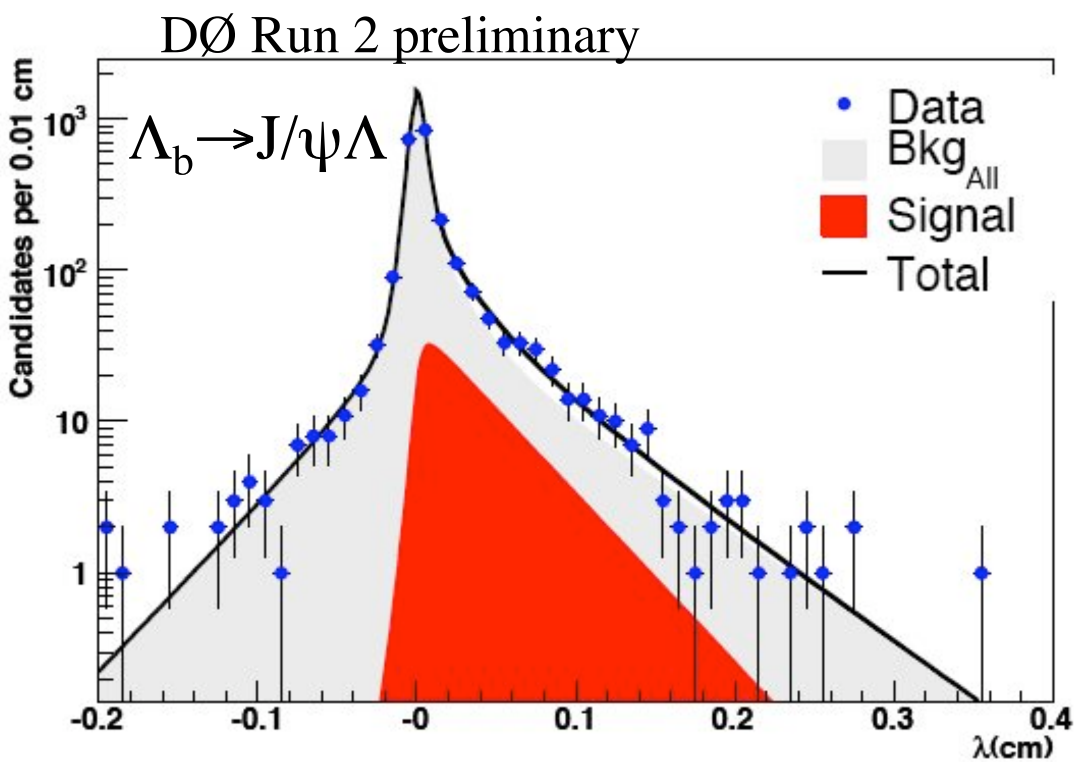
$(N_{data}-N_{SM})/\ \delta$

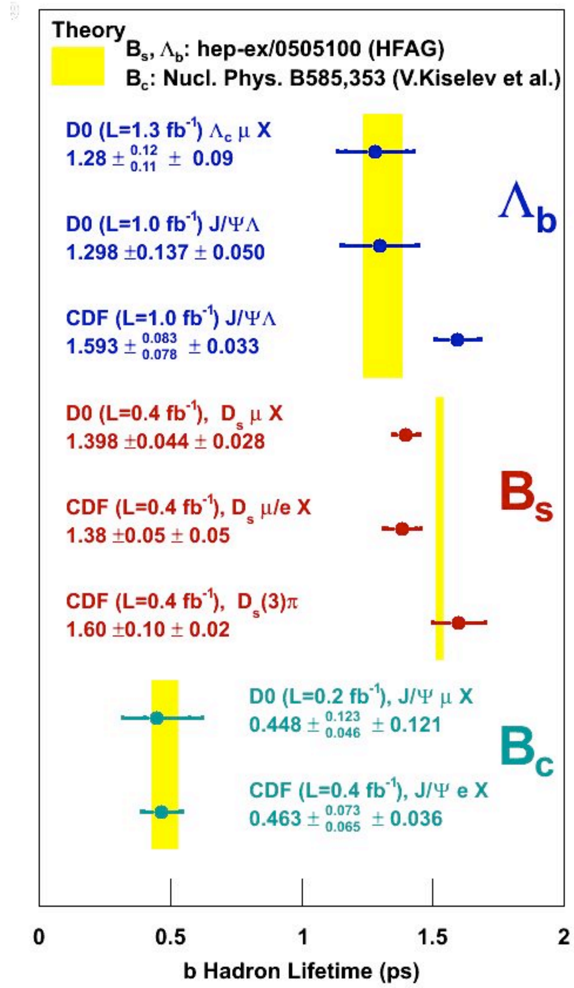


$(N^i_{data}-N^i_{SM})/\delta^i$

The Flavor Sector

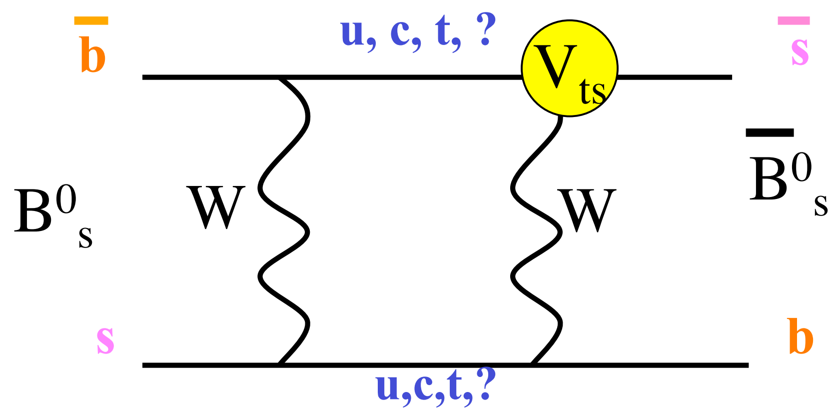
Lifetimes: B_s, Λ_b, B_c





Precision tests of Heavy Quark Effective Theory with heavy B states

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



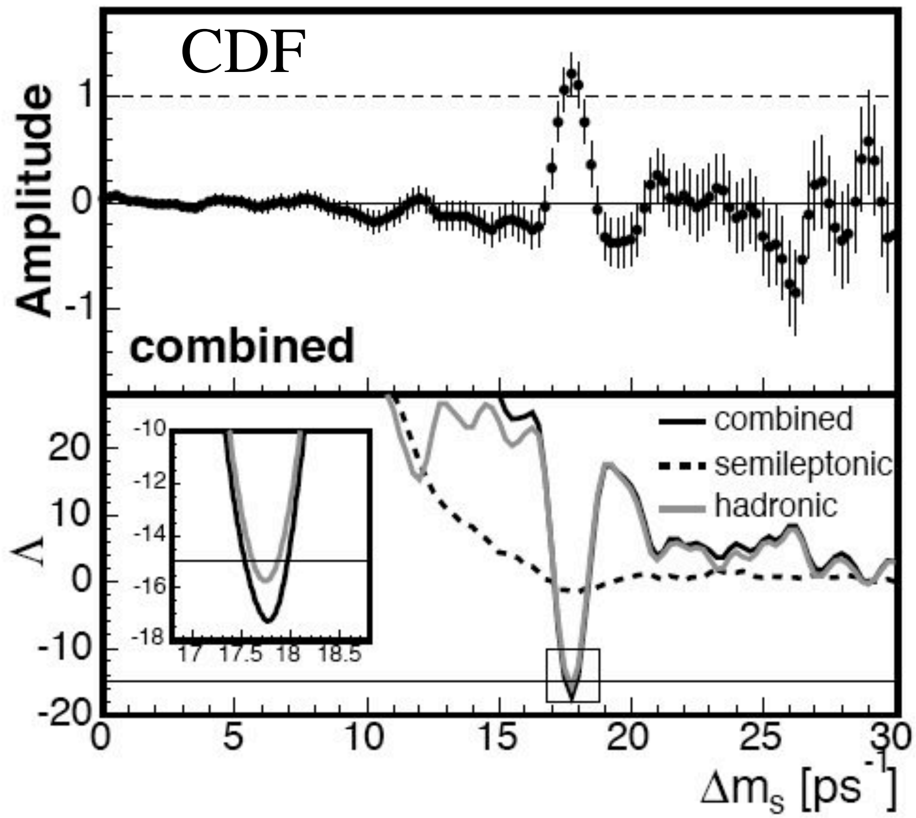
CP-odd: $B_H = pB + q\overline{B}$
CP-even: $B_L = pB - q\overline{B}$
with $|p|^2 + |q|^2 = 1$

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

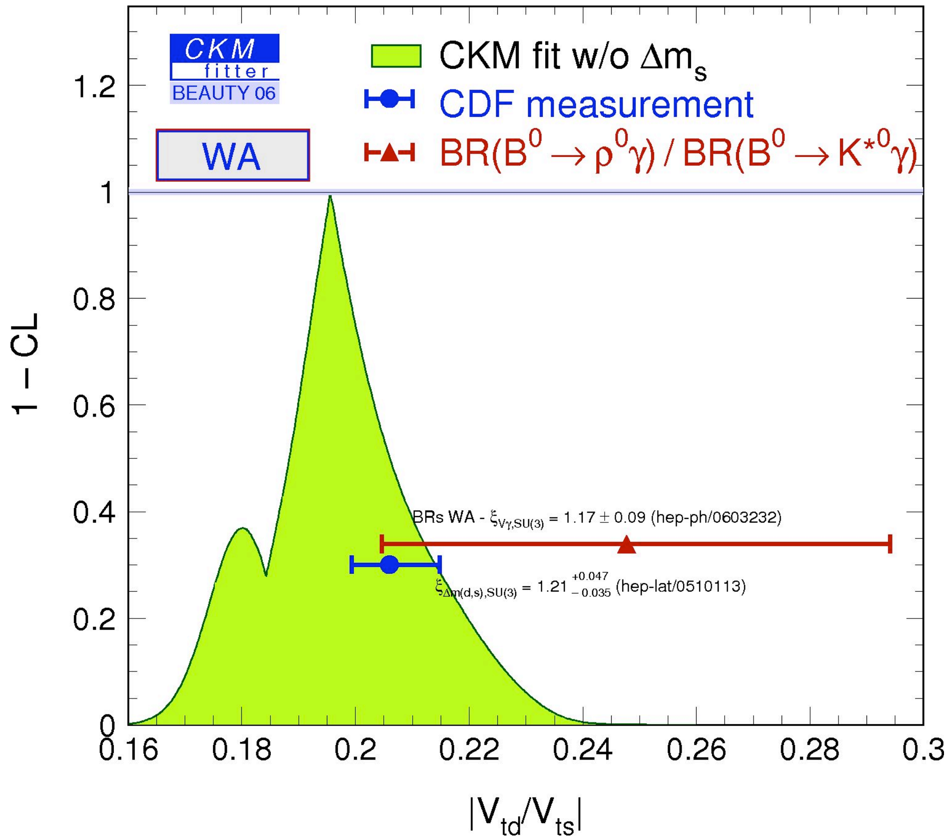
$$P_{mix}^{B_s} = \frac{1}{2}\Gamma_{B_s} e^{-\Gamma_{B_s} t}\left(1 - A\cos\Delta m_s t\right)$$

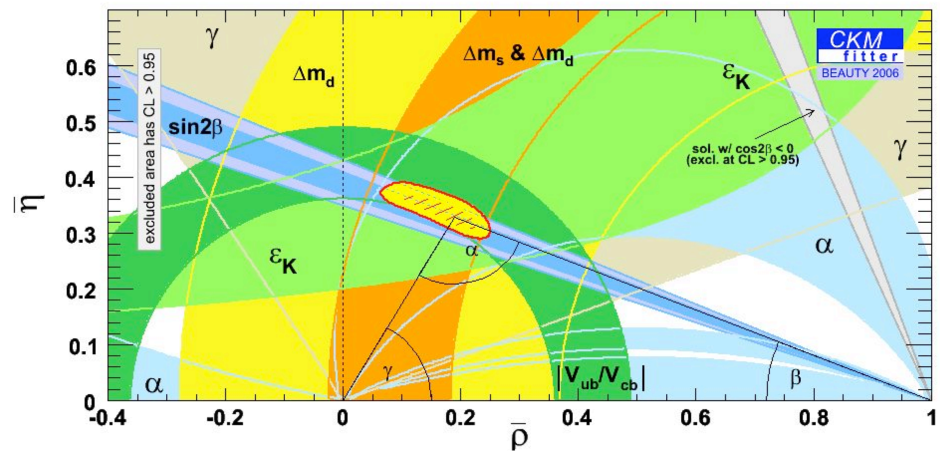
H. G. Moser, A. Roussarie, NIM **A384** (1997)

- **CDF Measurement:**
  - Prob. of stat. fluctuation: 8×10^{-8}
  - **$\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$**
  - $|V_{td}/V_{ts}| = 0.2060 \pm 0.0007\ ^{+0.008}_{-0.006}$ (th.)
- **DØ:** $17 < \Delta m_s < 21\ ps^{-1}$

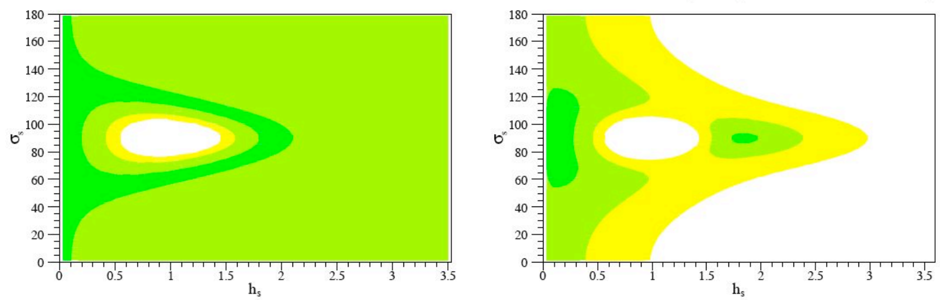


Δm_s Measurement: Impact on Unitarity Triangle





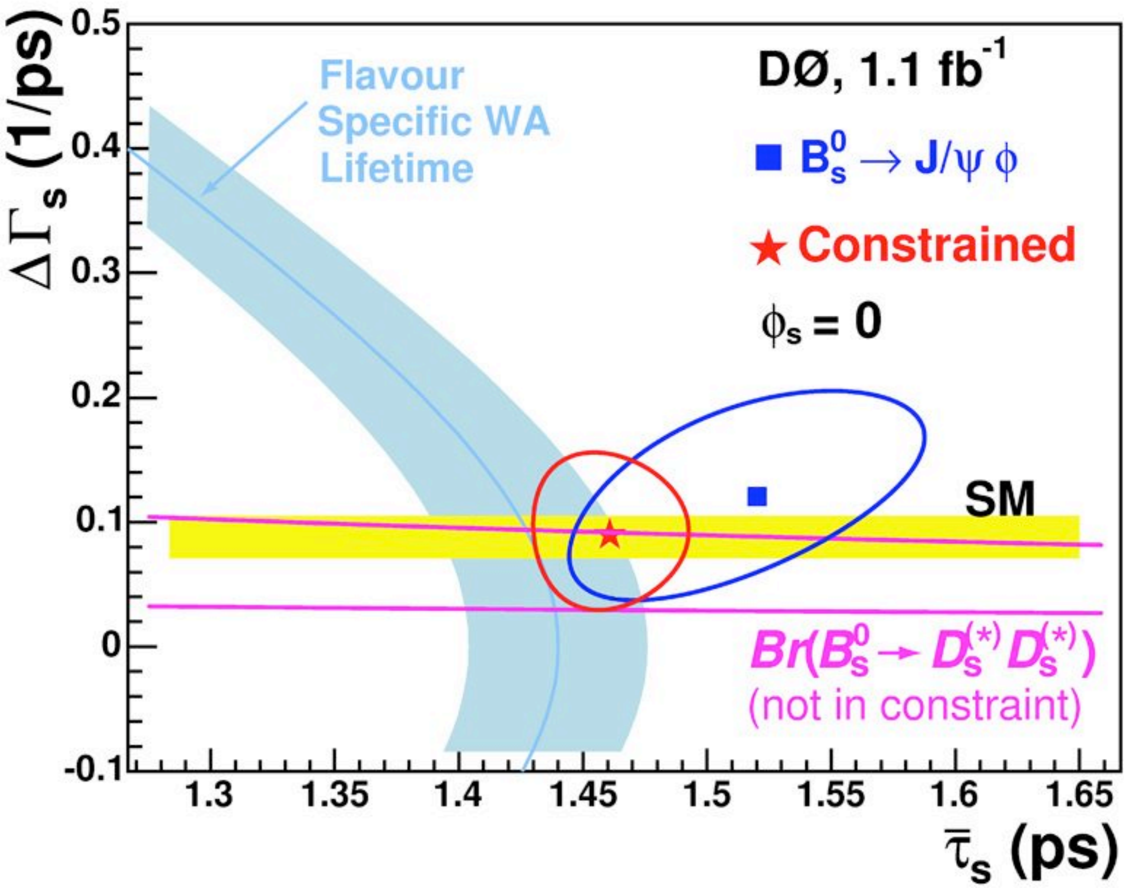
$$\Delta m_q = \Delta m_q^{SM} \left|1 + h_q e^{2i\sigma_q}\right|$$



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

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

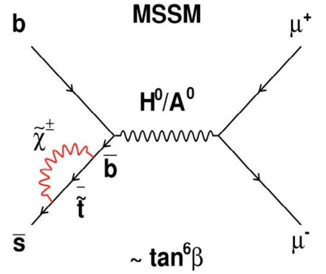
Lifetime Difference: $\Delta\Gamma_s$



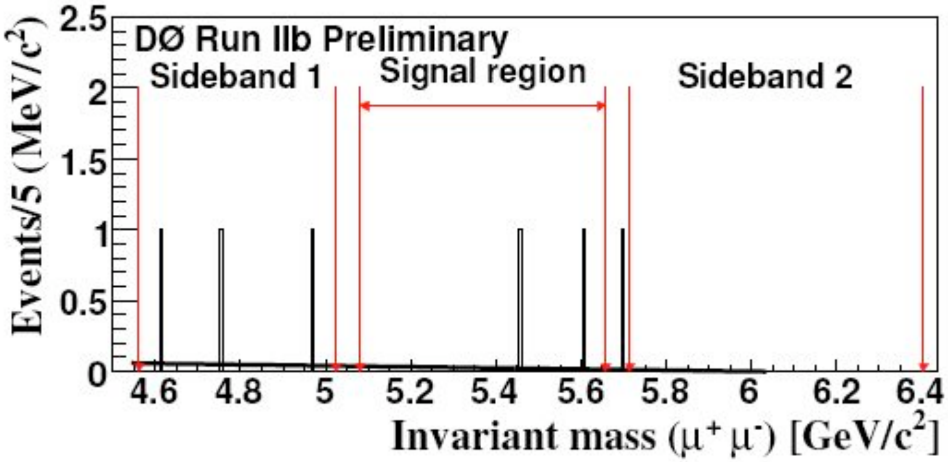
- Lifetime difference also consistent with Standard Model

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

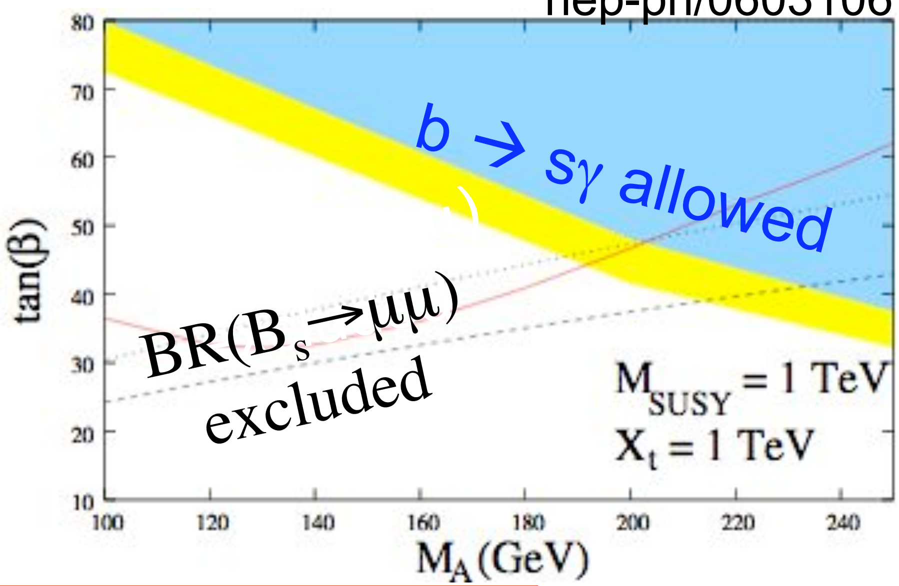
- Standard Model prediction:
  BR=(3.42±0.54) x 10^{-9}
  A.J. Buras Phys.Lett.B 566, 115 (2003)
- Large enhancements e.g. in Supersymmetry possible



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



hep-ph/0603106

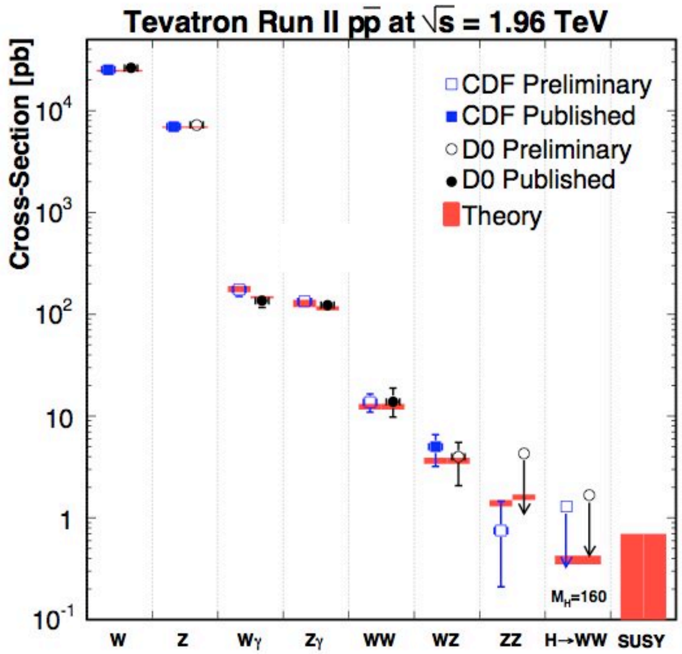


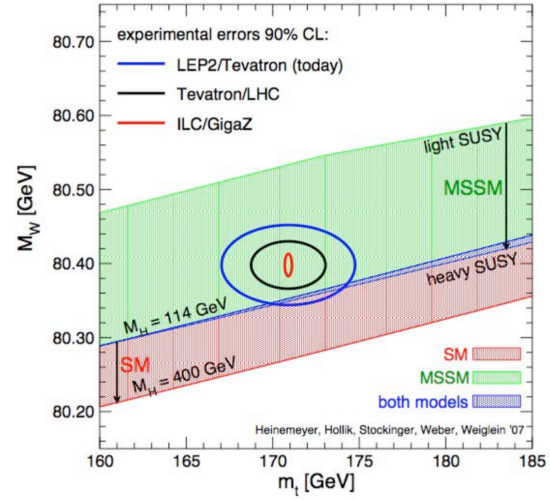
	CDF L=0.8 fb^{-1}	DØ L=2.0 fb^{-1}
N_{exp}	**1.47**	**2.3**
N_{obs}	**0**	**3**
Limit at 95%CL	**<10 x 10^{-8}**	**<9.3 x 10^{-8}**

Severe constraints on SUSY parameter space

Conclusions and Outlook

- **Tevatron + experiments operating well**
  - Analyses mostly based on 1 fb^{-1}
  - Already >2 fb^{-1} on tape
- **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:
    - m_H<144 GeV/c^2
  - **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
- **Anticipate 4.4-8.6 fb^{-1} by 2009**
  - Hope now for a **discovery** of the Higgs boson…. or something even more exciting!
  - Continue **precision measurements** in QCD, flavor and electroweak sectors





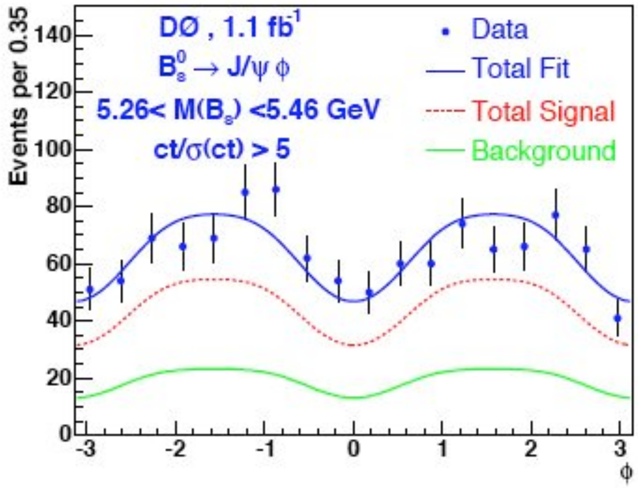
Backup Slides

B_s Lifetime Difference $\Delta\Gamma_s$ and Phase ϕ_s

$$\left|M(t)\right\rangle_1 = \left(g^+(t)\left|M\right\rangle + g^-(t)e^{-2i\phi}\left|\overline{M}\right\rangle\right)$$

$$\left|M(t)\right\rangle_2 = \left(g^-(t)e^{2i\phi}\left|M\right\rangle + g^+(t)\left|\overline{M}\right\rangle\right)$$

$$\left|g^\pm(t)\right|^2 = \frac{e^{-\Gamma t}}{2}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) \pm \cos(\Delta m t)\right]$$

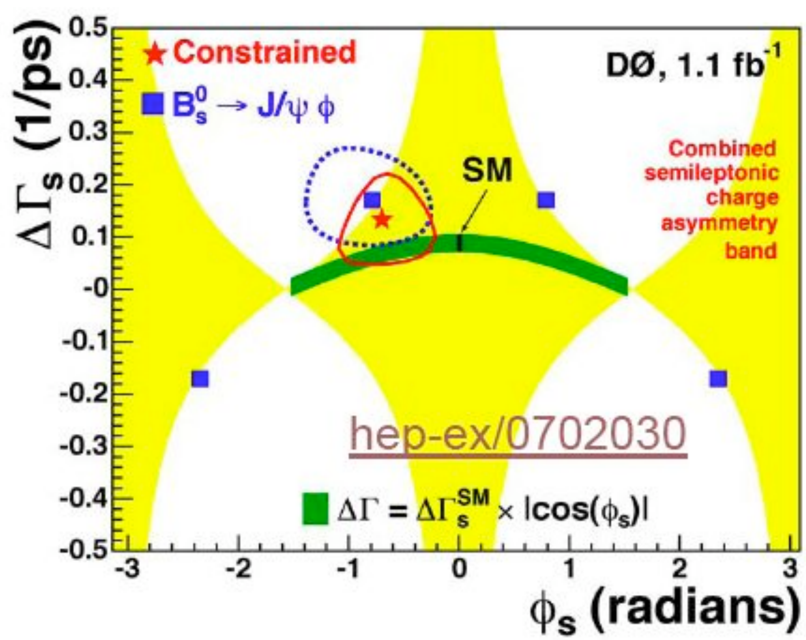


Using $B_s \to J/\psi\phi$, $A_{SL}(\mu^\pm\mu^\pm)$ DØ obtains:

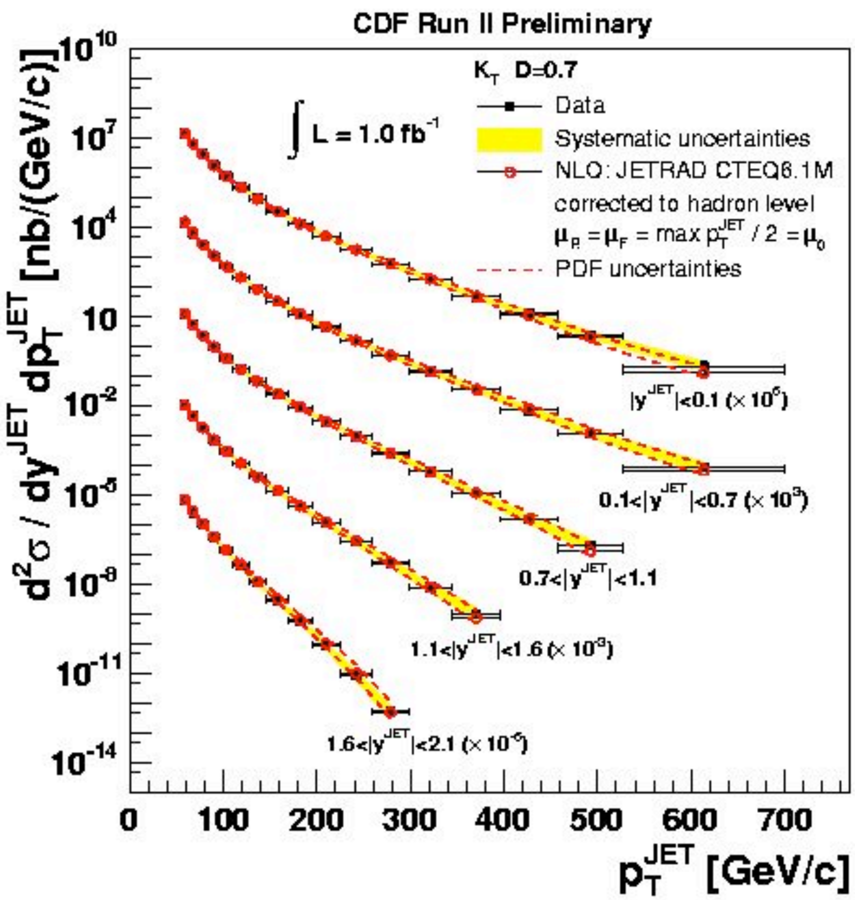
$$\Delta\Gamma_s = 0.13 \pm 0.09\, ps^{-1}$$

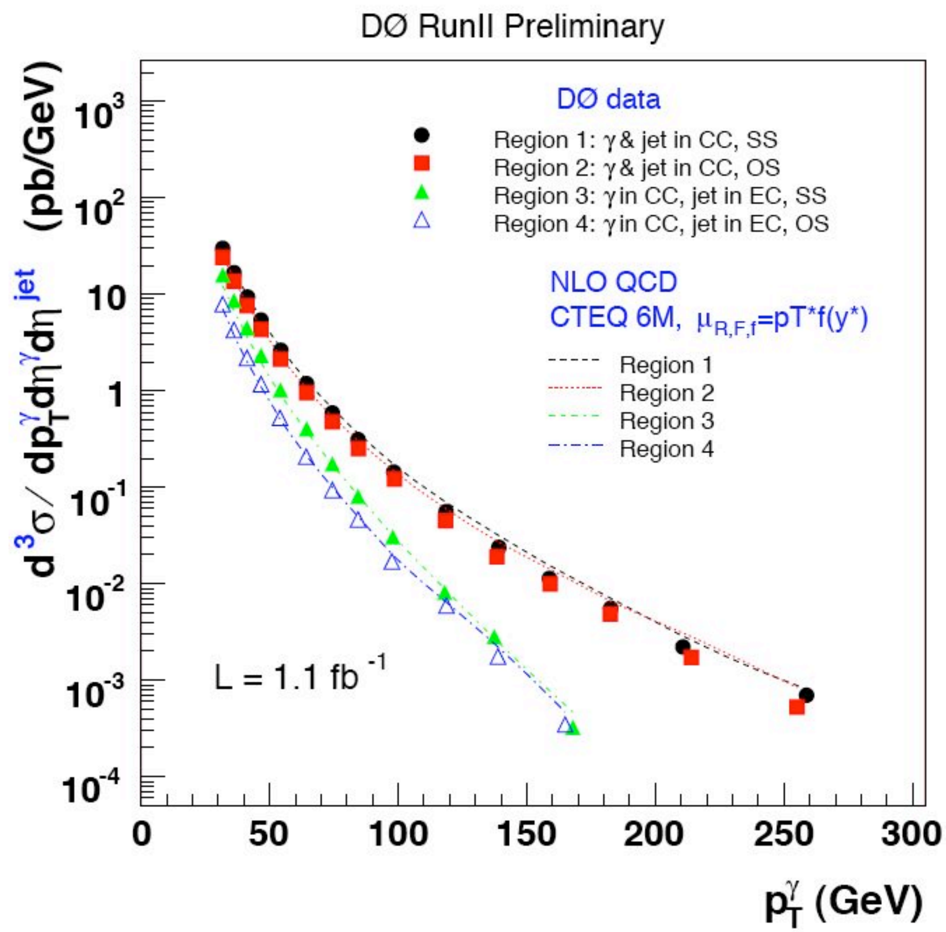
$$\phi_s = -0.70^{+0.47}_{-0.39}$$

- In agreement with SM prediction but ~1.5σ off



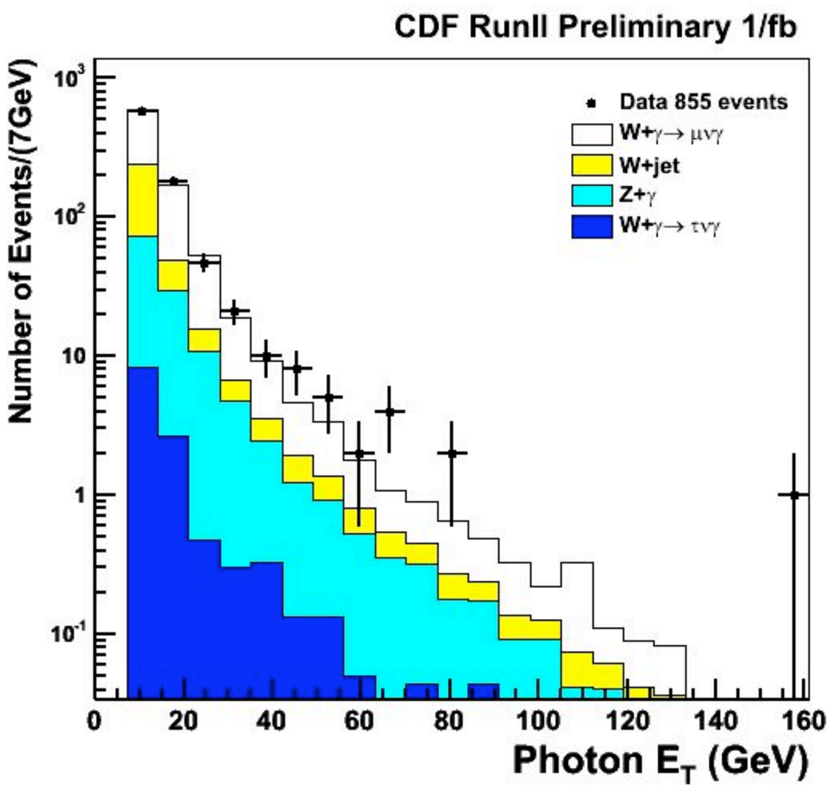
Jet and Photon Cross Sections

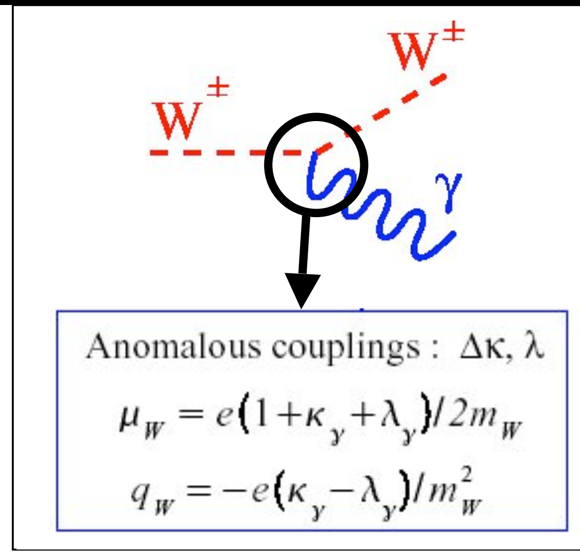


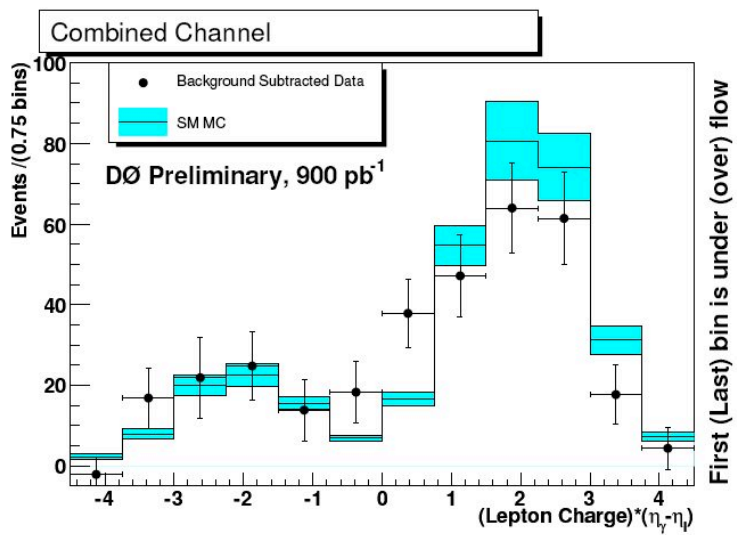


- Cross sections measured over wide kinematic and angular ranges

Diboson Production: Wγ and Zγ

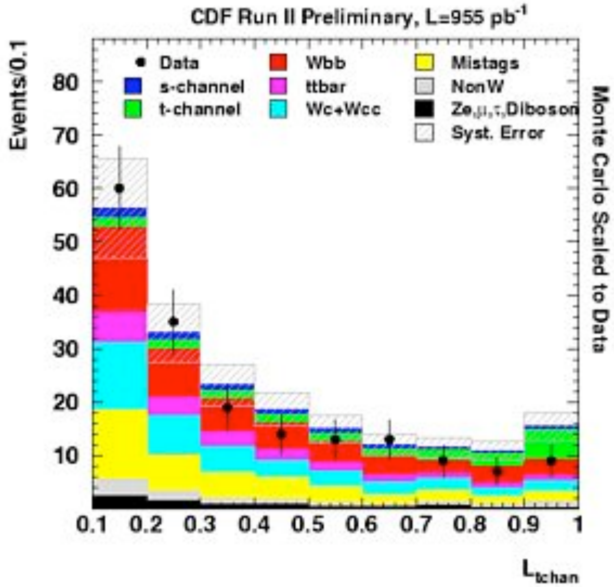


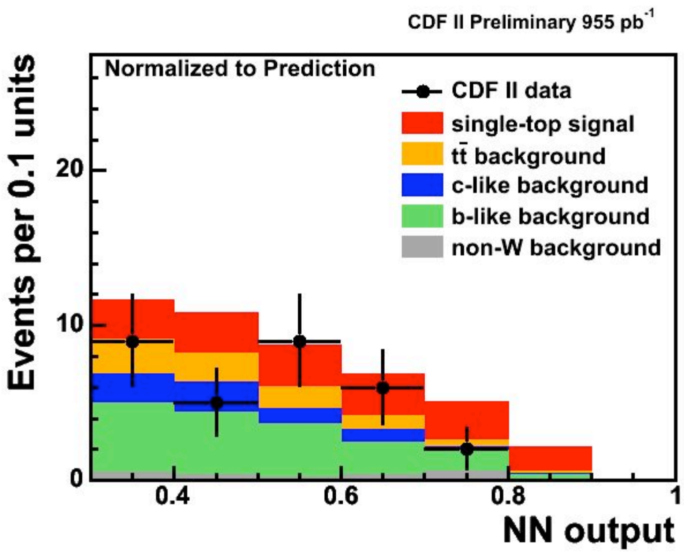


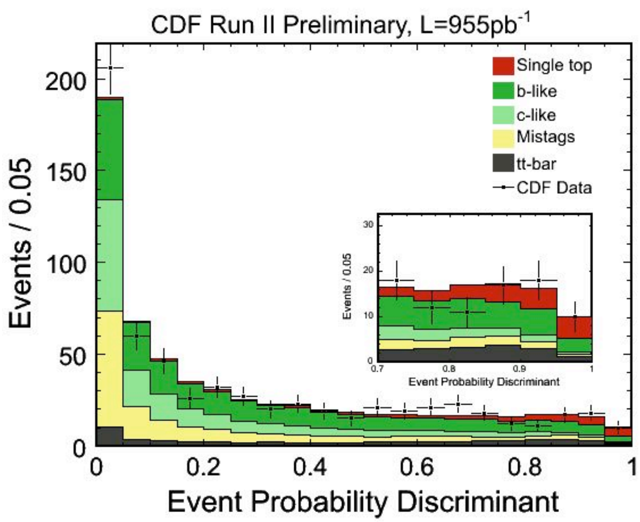


- Probe anomalous couplings of the electroweak gauge bosons

CDF Single Top Analyses



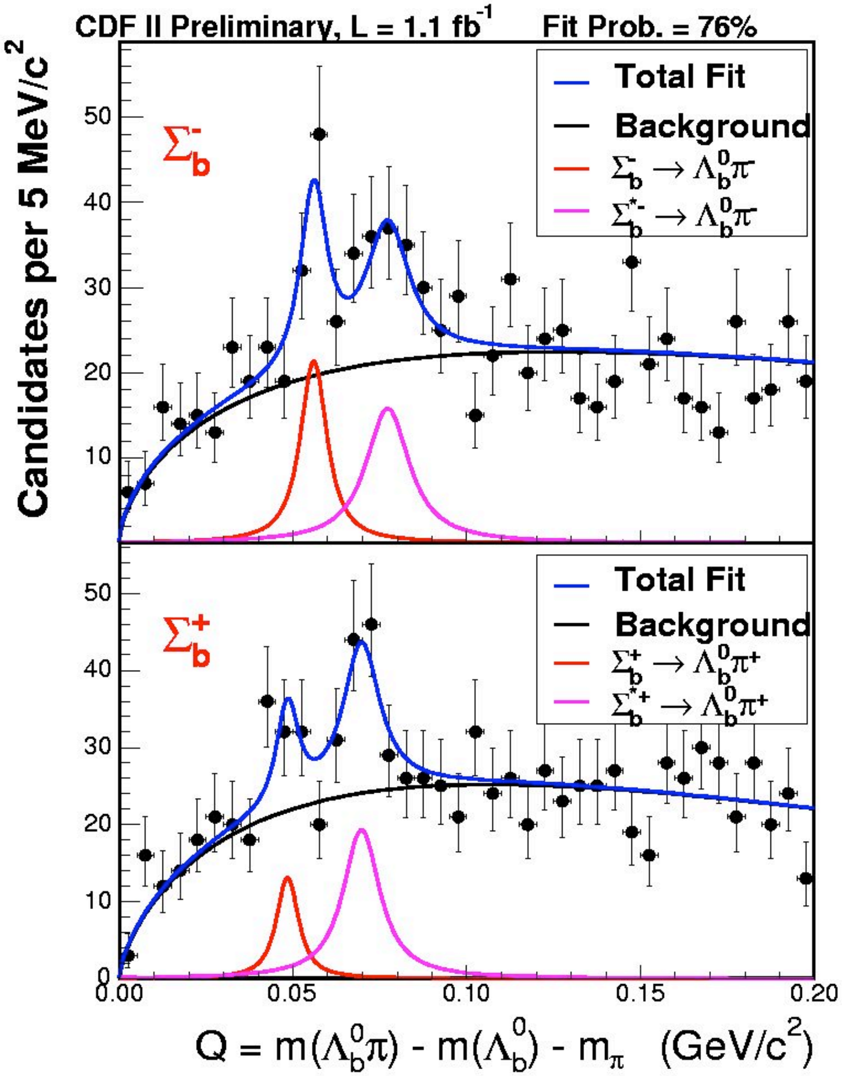


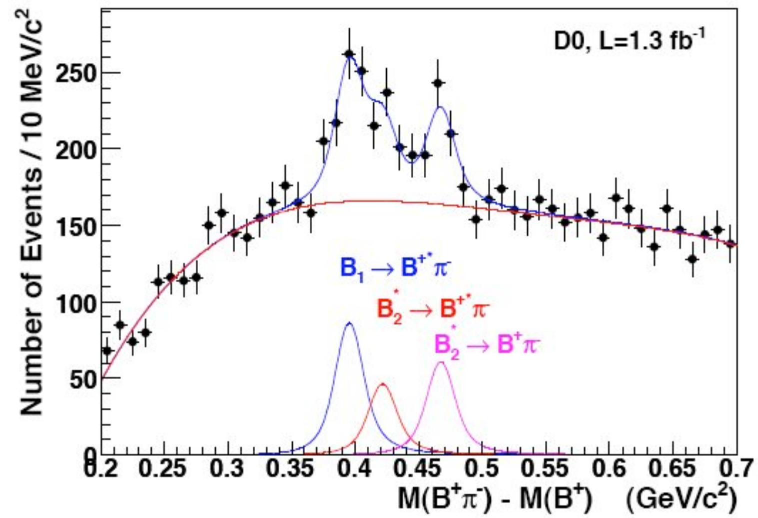


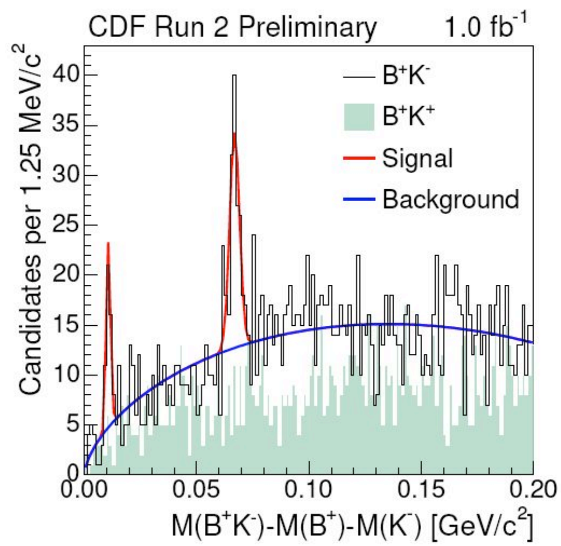
W Mass Systematic Uncertainties

m_T Systematic (MeV)	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
Lepton Removal	8	5	5
Backgrounds	9	9	0
$p_T(W)$ model	3	3	3
Parton Distributions	11	11	11
QED radiation	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total Uncertainty	62	60	26

New B states







Observations of new b-states and excited B mesons