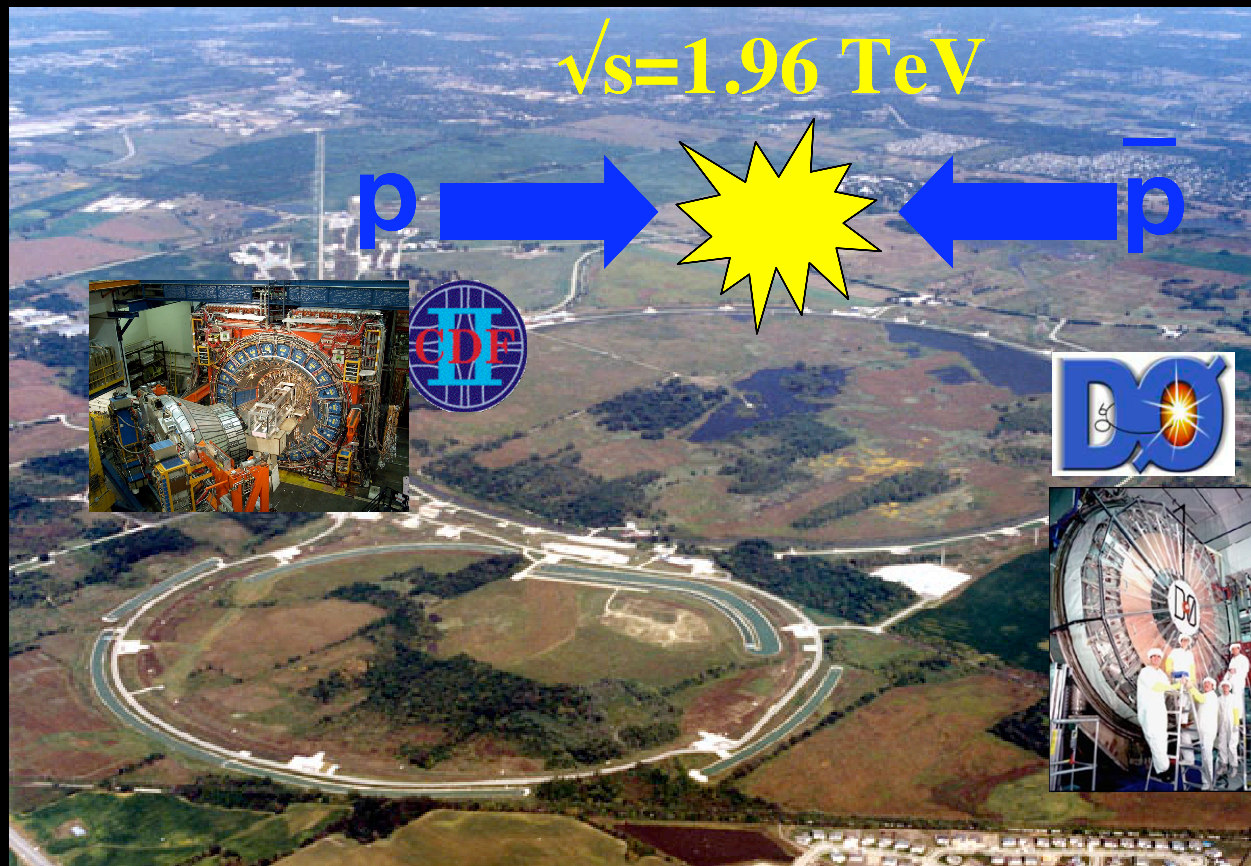
(Recent) Physics Highlights from the Tevatron



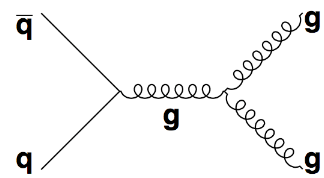
Beate Heinemann

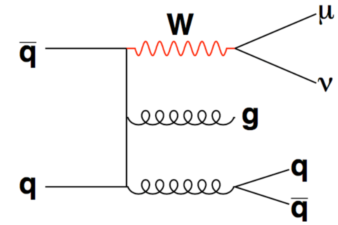
University of California at Berkeley and Lawrence Berkeley National Laboratory

UK Theory meeting, Durham, December 2008

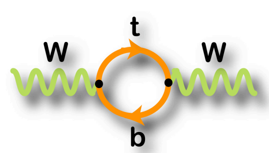
Outline

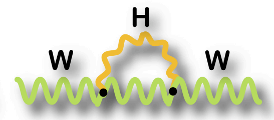
- **Testing Particle Production**
  - Jets, W's and Z's, top quarks

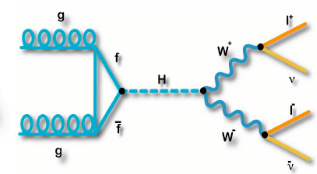




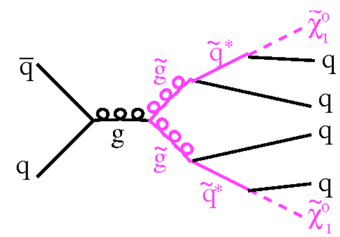
- **Electroweak Symmetry Breaking**
  - W boson and top quark mass
  - Higgs boson search

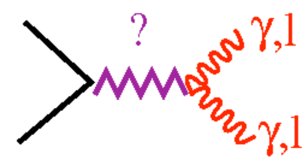




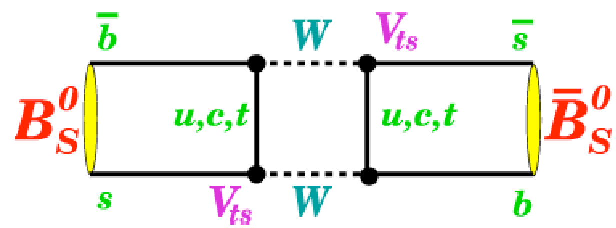


- **Beyond the Standard Model**
  - Supersymmetry and beyond



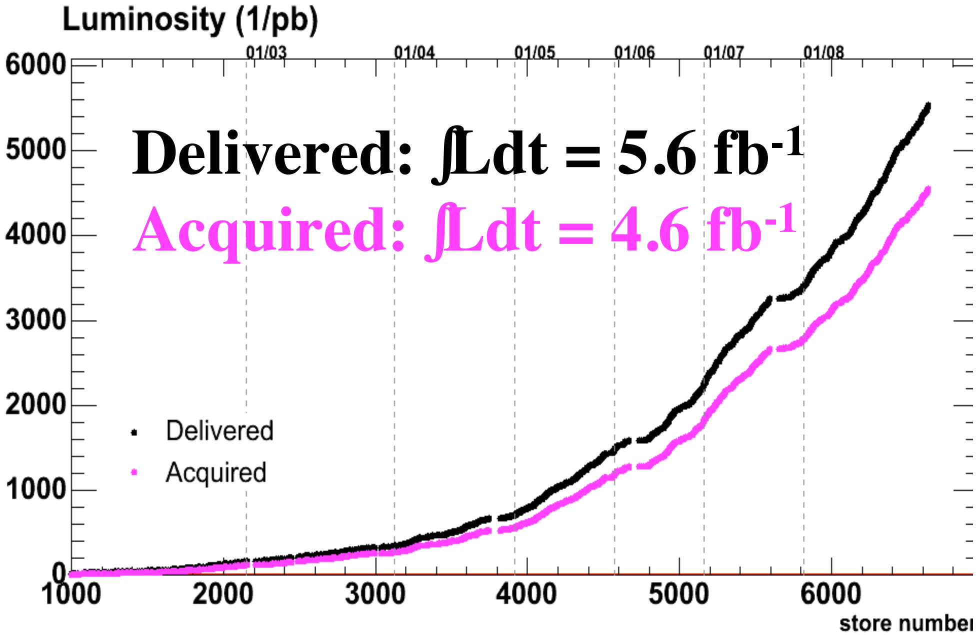


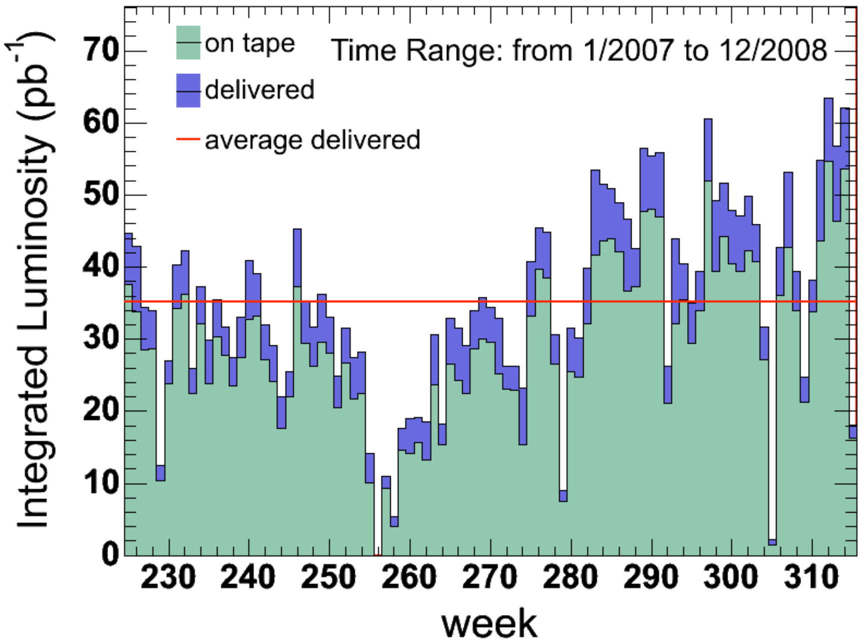
- **Flavour Sector**
  - Lifetimes
  - CP violating phase β_s



- **Conclusions and Outlook**

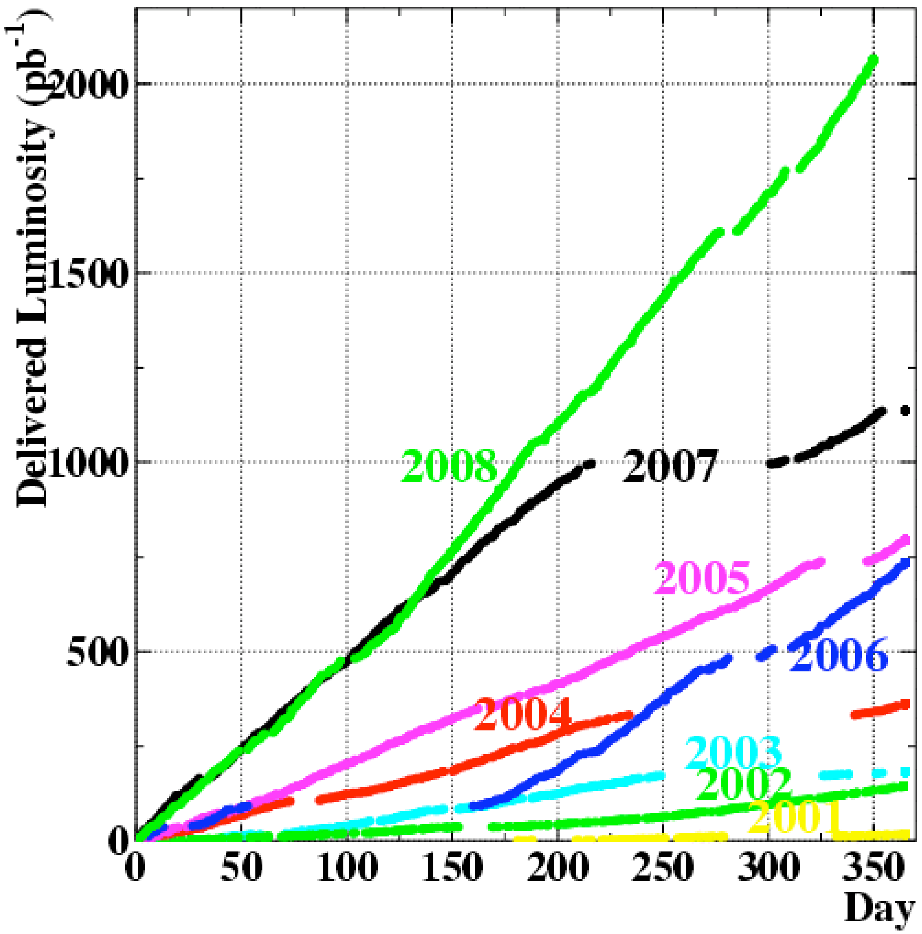
Tevatron Luminosity





- **Excellent Performance**
  - Luminosity / week: ~60 pb^{-1}
  - Luminosity in 2008 alone: 2 fb^{-1}
  - Peak luminosity $3.5 \times 10^{32}\ cm^{-2}\ s^{-1}$
  - Data taking efficiency of CDF and DØ: ~85%

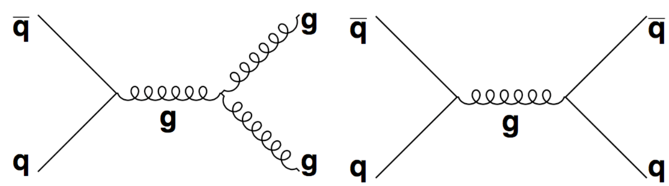
Annual Integrated Luminosity



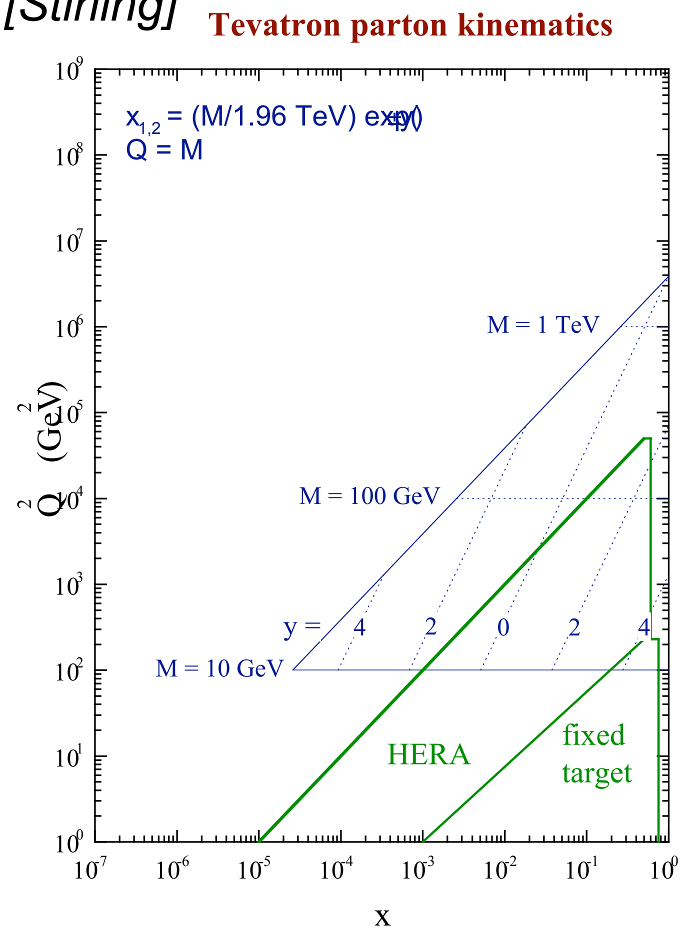
- Significant improvement year by year!
  - Even between 2007 and 2008

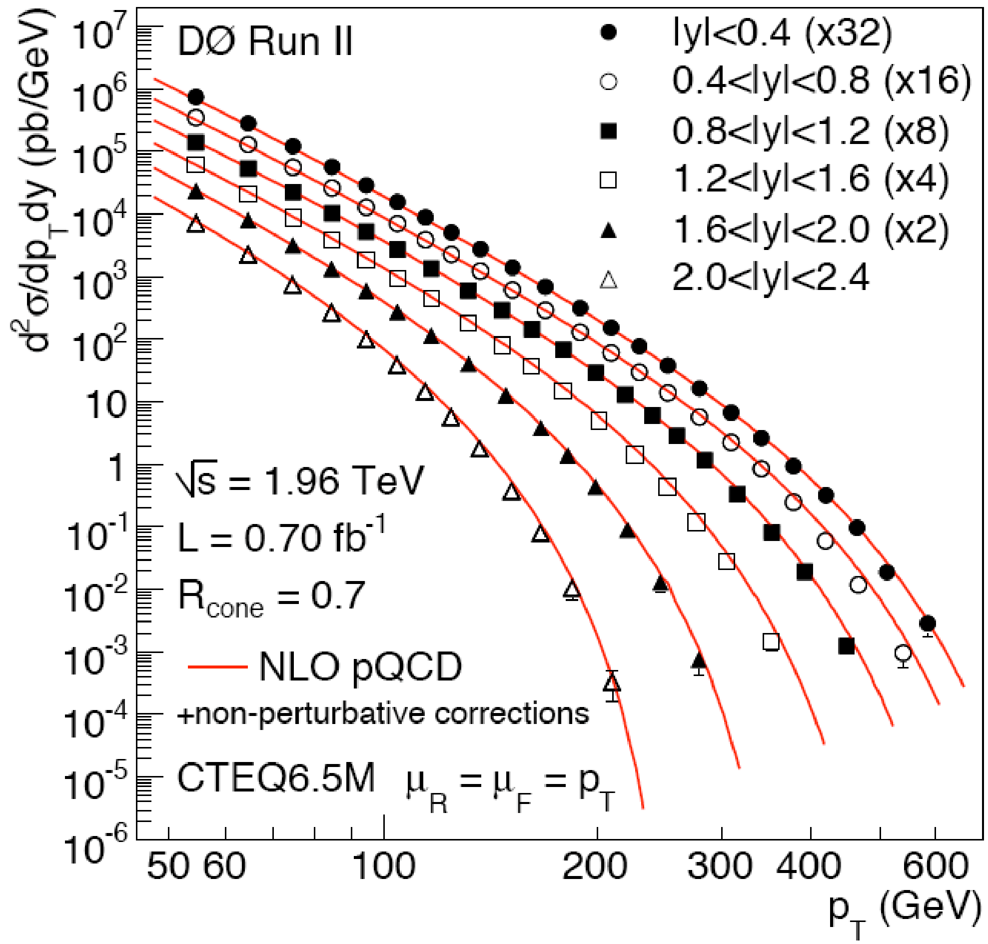
Production of Particles

Jet Cross Sections



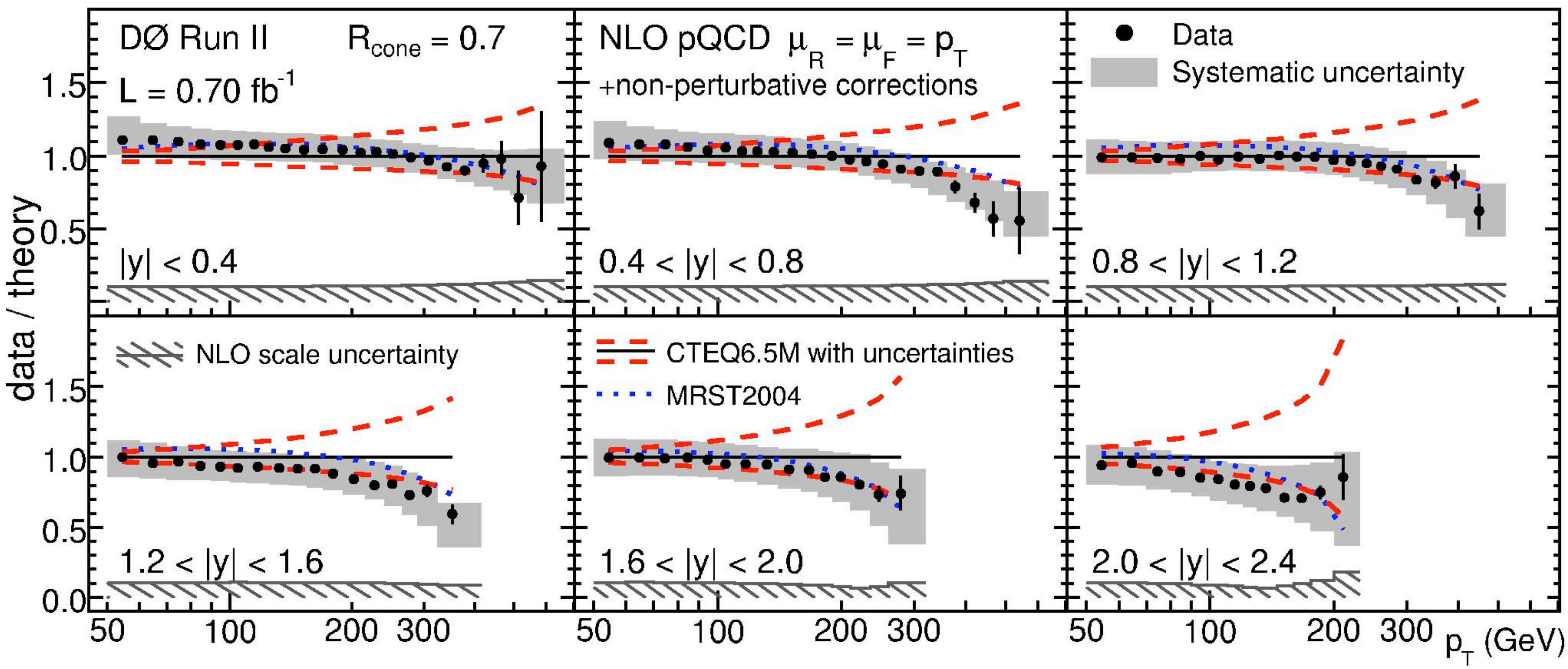
[Stirling]





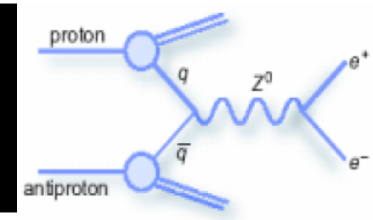
- Cross section measured over 9 orders of magnitude double-differentially in y and p_T (related to x and Q^2)

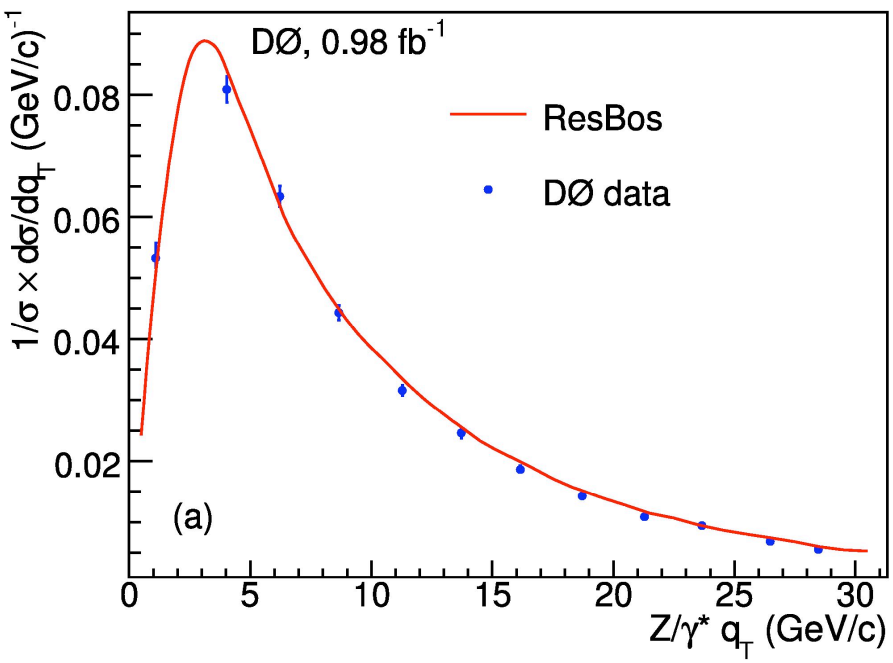
Jet Cross Section: Ratio to Theory

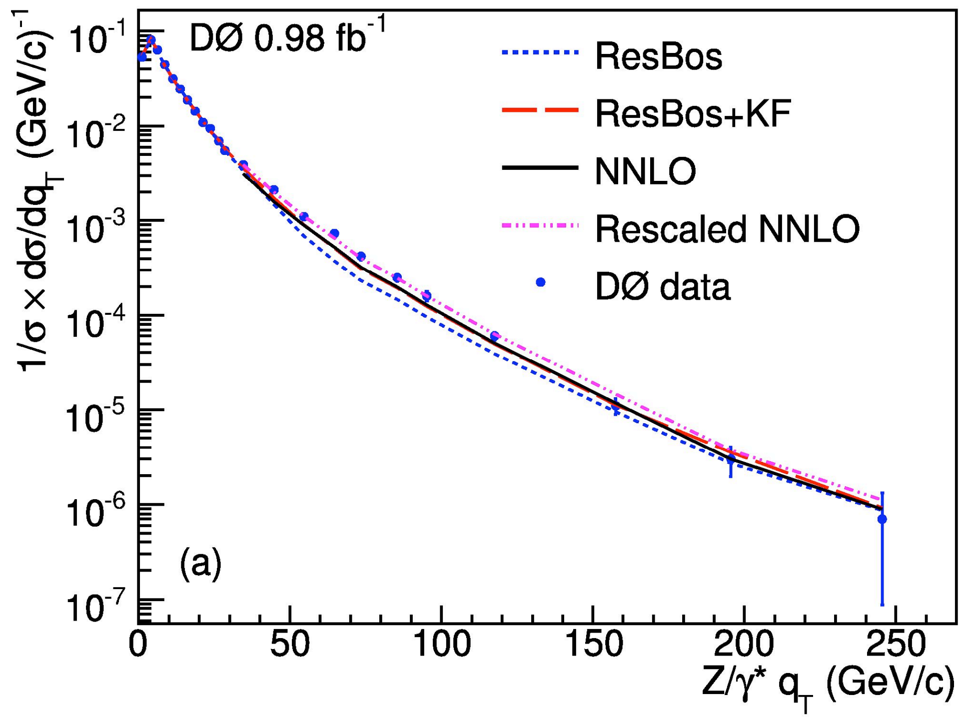


- Data precision higher than pdf uncertainties
  - Data uncertainties between 10% and 25%
    - Due to high precision jet energy scale understanding
  - Data will further constrain pdf's
    - They tend to agree better with MRST2004 than CTEQ6.5
    - In particular sensitive to gluon at high x

Z production

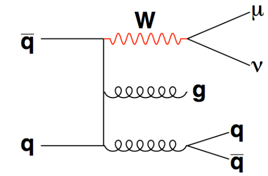


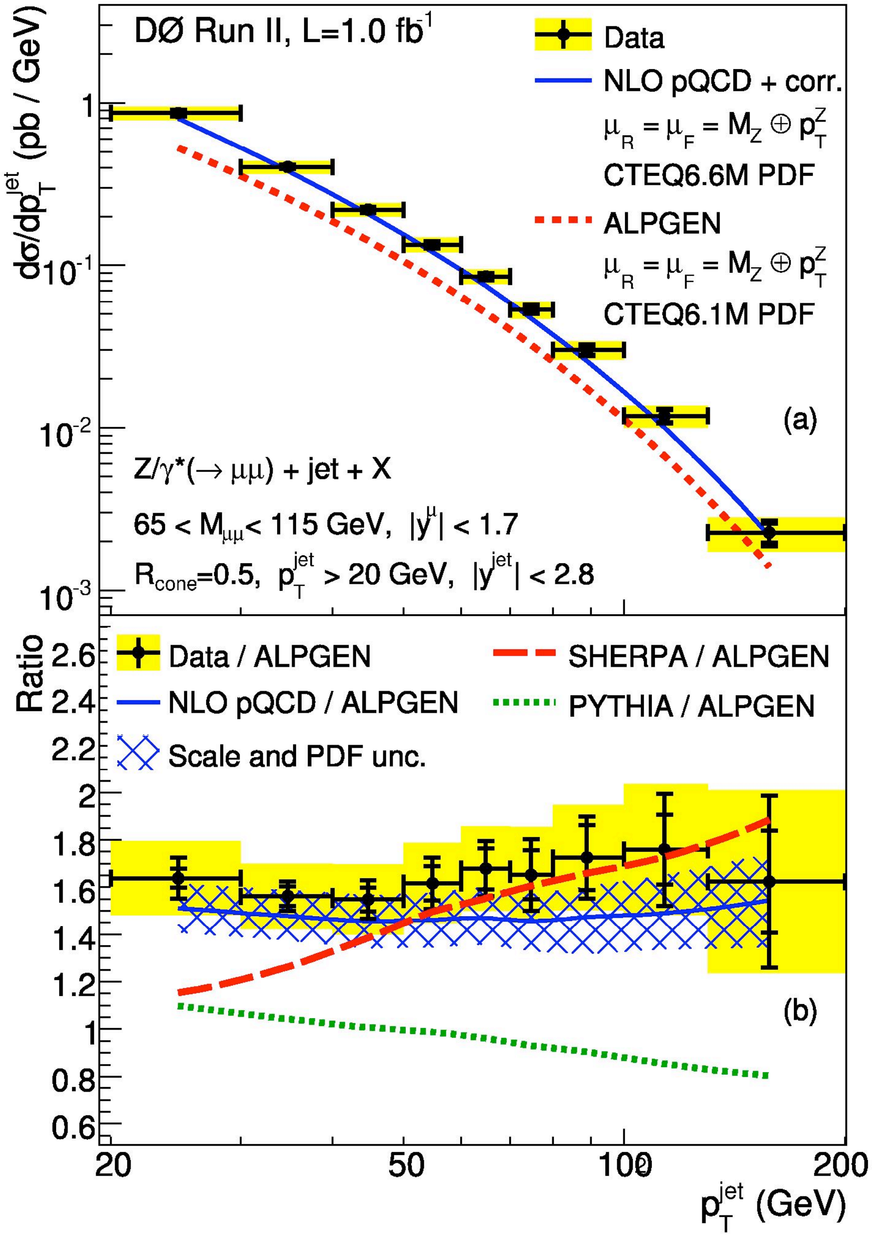


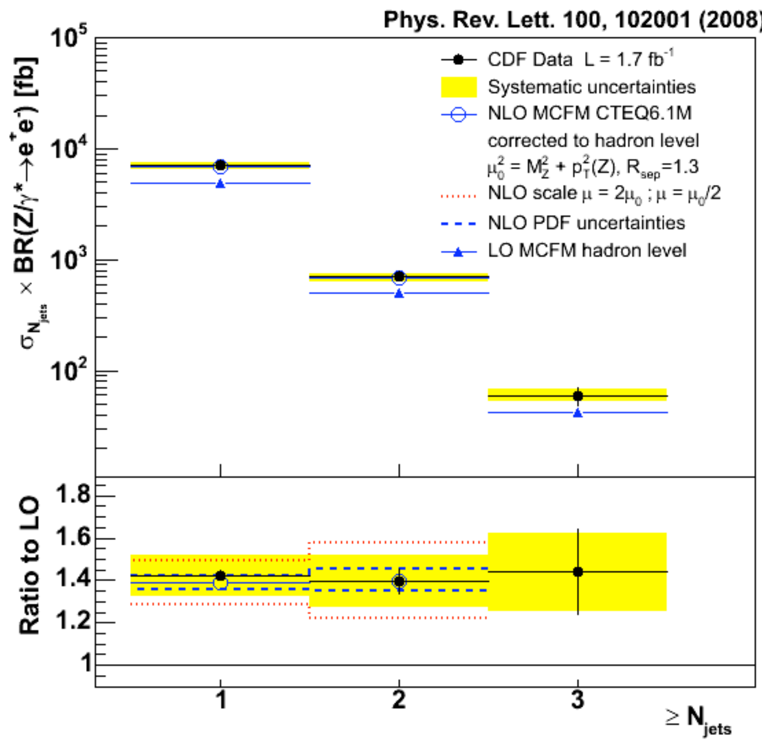


- High precision measurement challenges hard and soft QCD predictions
  - At low $p_T(Z)$: soft non-perturbative effects dominate
    - Important for W boson mass measurement
  - At high $p_T(Z)$: perturbative regime
    - Important for understanding background to new physics searches

Z + Jets Production

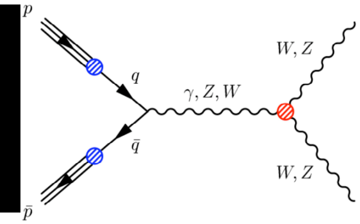


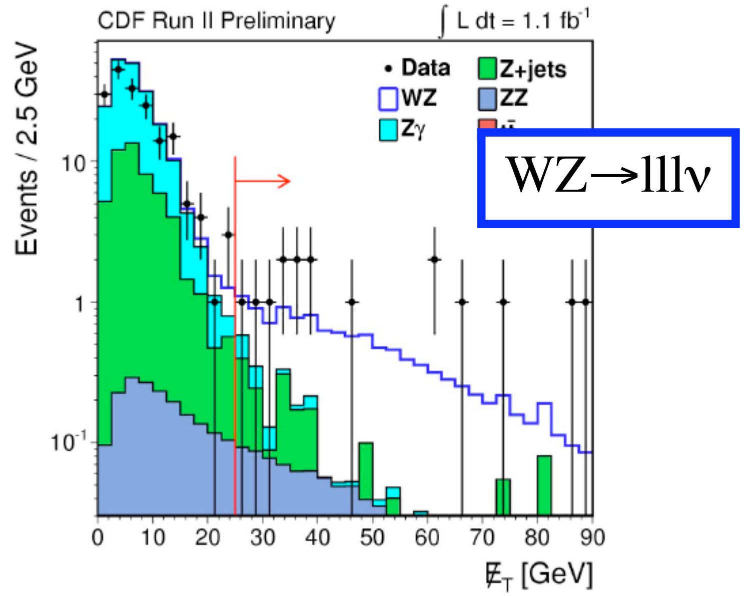


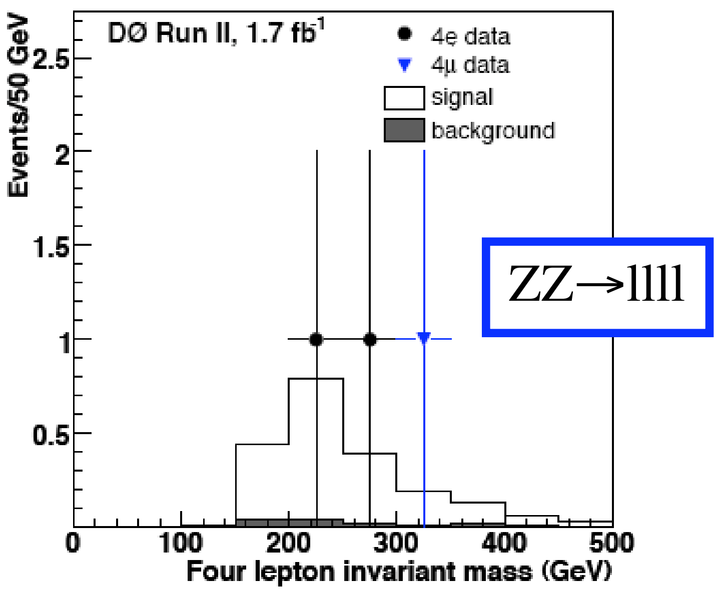


- W/Z+jets are important backgrounds:
  - Top production
  - SUSY
  - Higgs boson
- Data agree with NLO within ~15%
  - MC models more or less successful

Diboson Production: WZ,ZZ

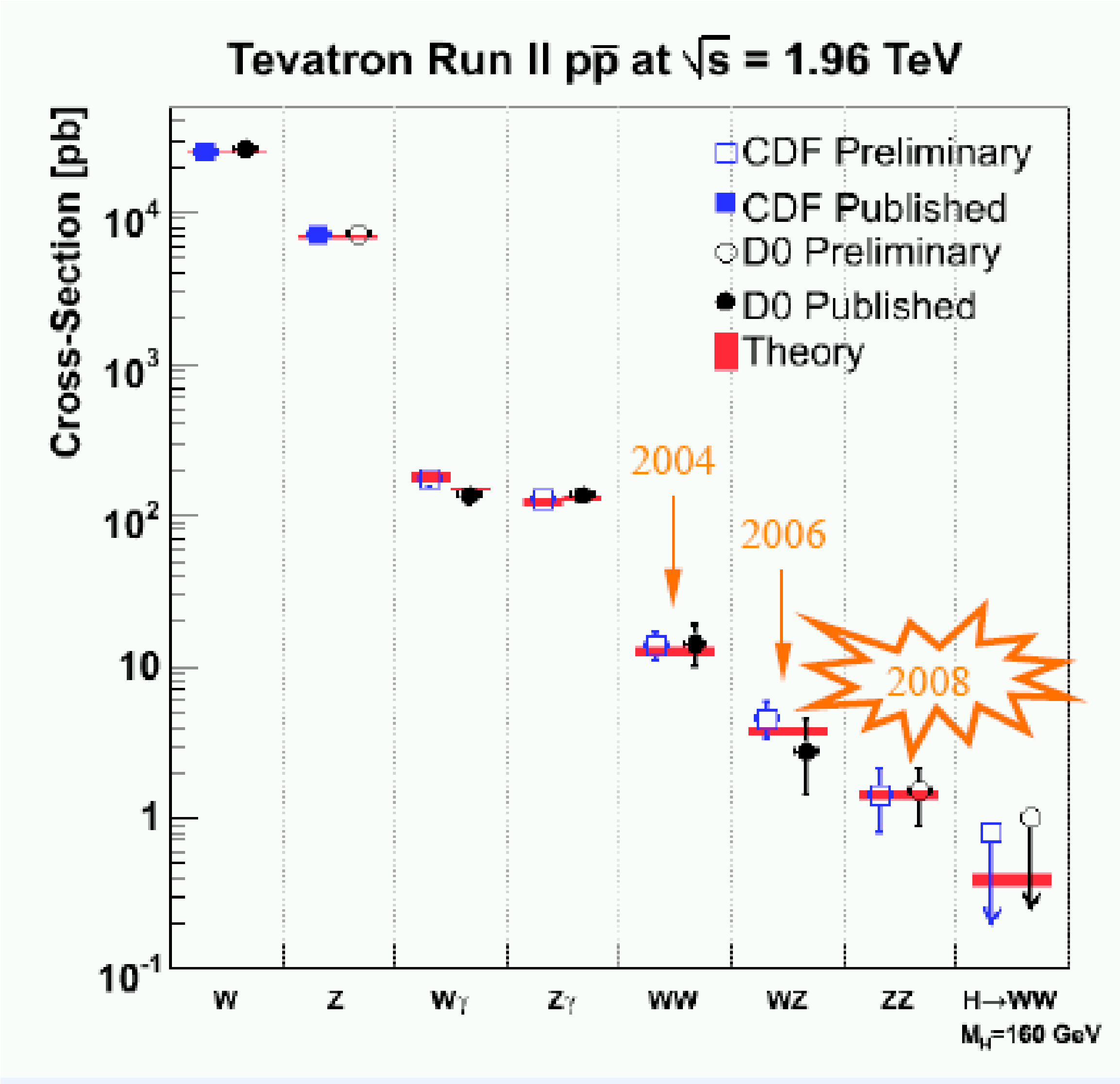




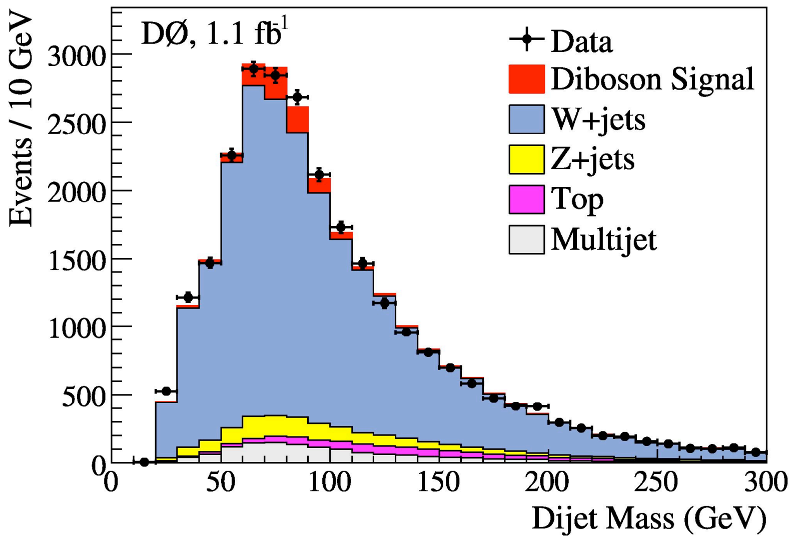


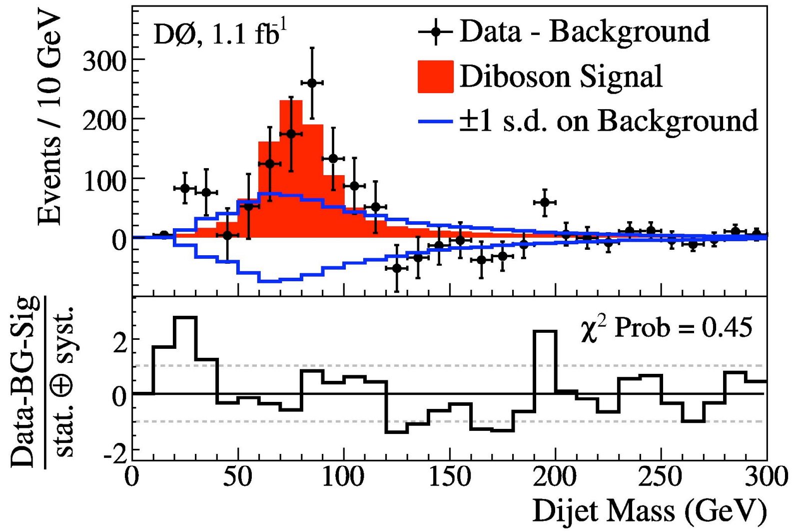
- Diboson production
  - Sensitive to trilinear couplings among gauge bosons
  - Direct consequence of SU(2)xU(1) gauge group
- Recent highlights:
  - WZ:
    - 5.9σ observation
    - Cross section: $5.0^{+1.8}_{-1.6}$ pb
  - ZZ:
    - 5.7σ observations
    - Cross section: 1.60±0.65 pb
- All diboson measurements in agreement with SM prediction

Summary of Electroweak Cross Section Measurements



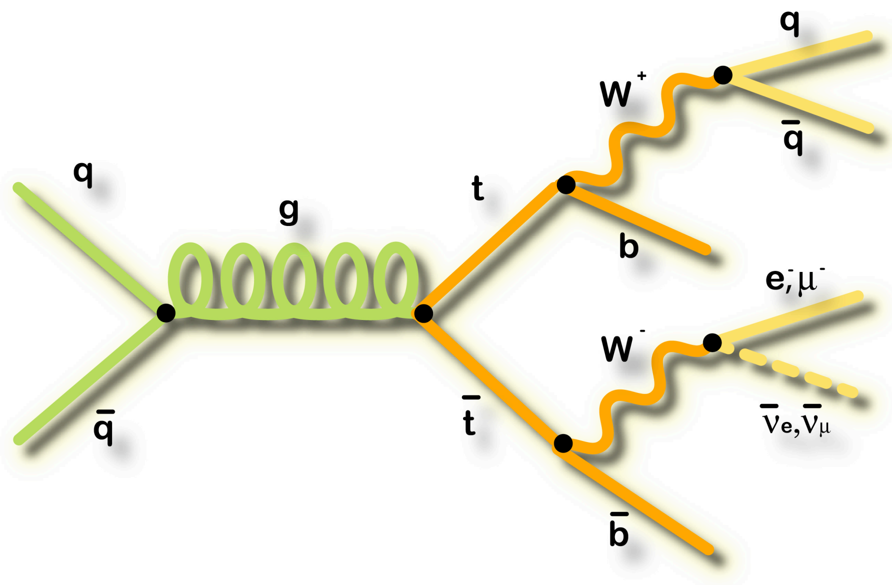
Evidence at 4.4σ for WW+WZ →lνjj

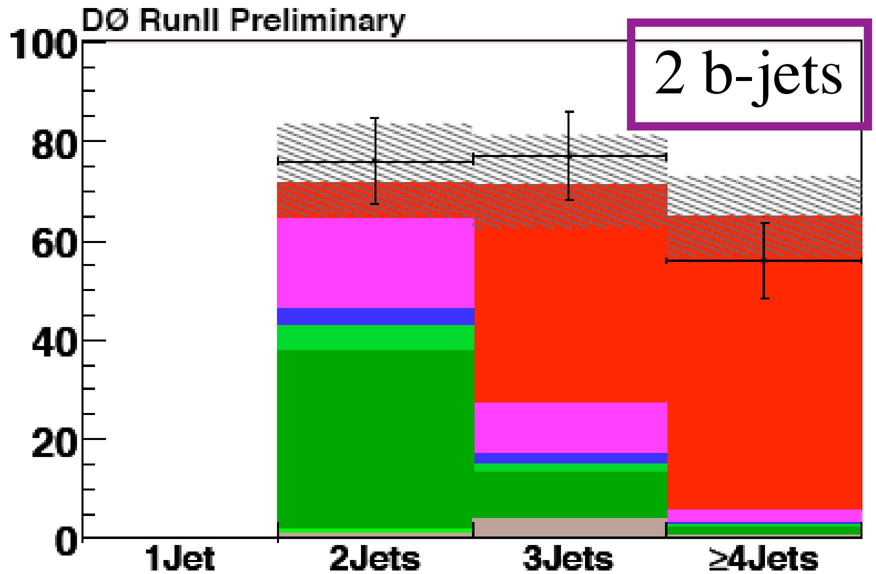


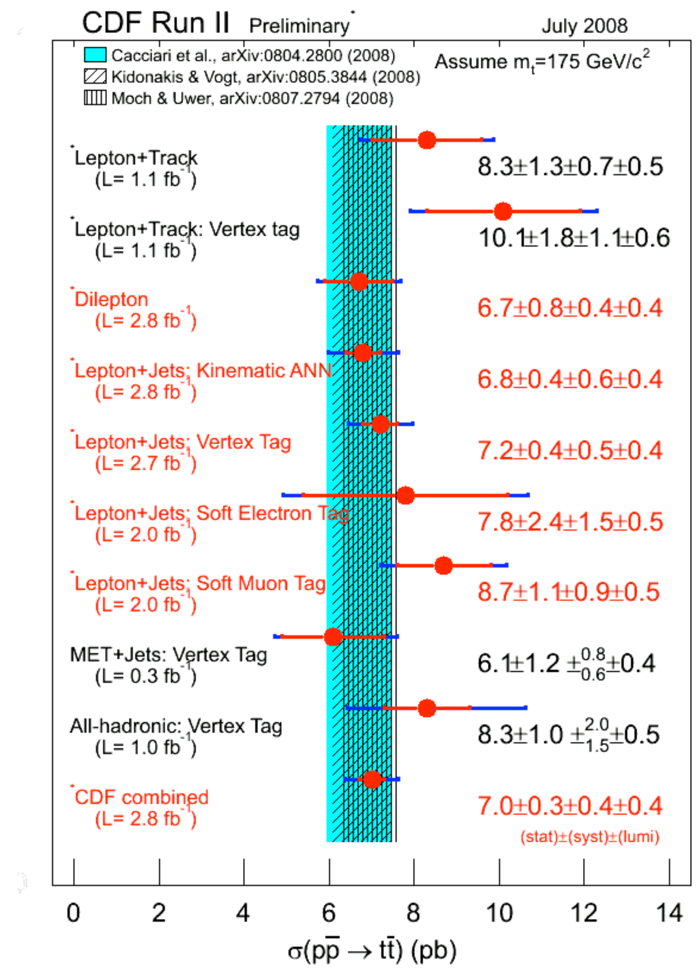


- Very similar analysis to Higgs search (see later)
  - Needs to find a peak on a huge (sculpted) background
    - Great that this has now succeeded
  - Cross section: σ(WW+WZ)=20.2 +/- 4.5 pb
    - in agreement with NLO calculation (16 pb)

Top Quark Production

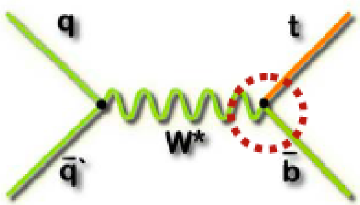




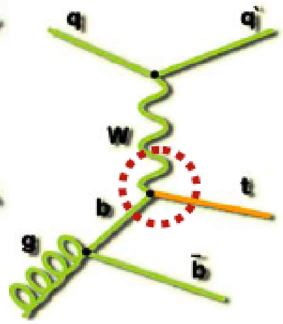


- **Measured cross section consistent with theory**
  - **Precision ~8%**

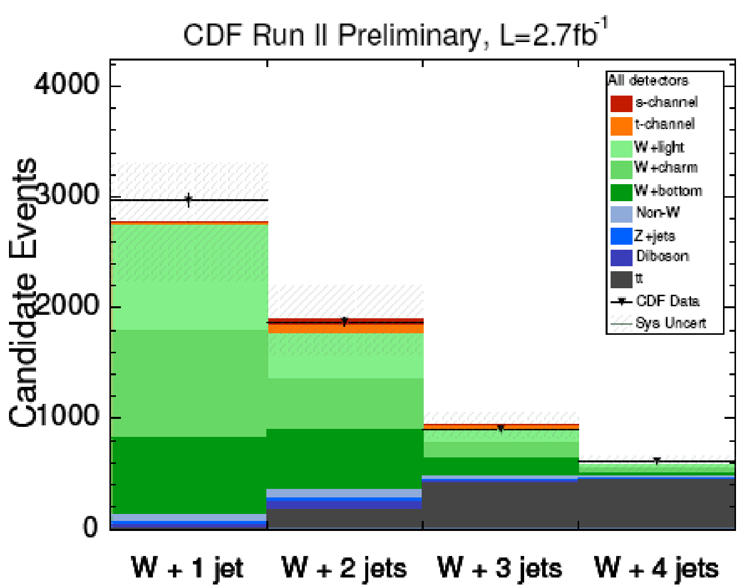
Single Top Production

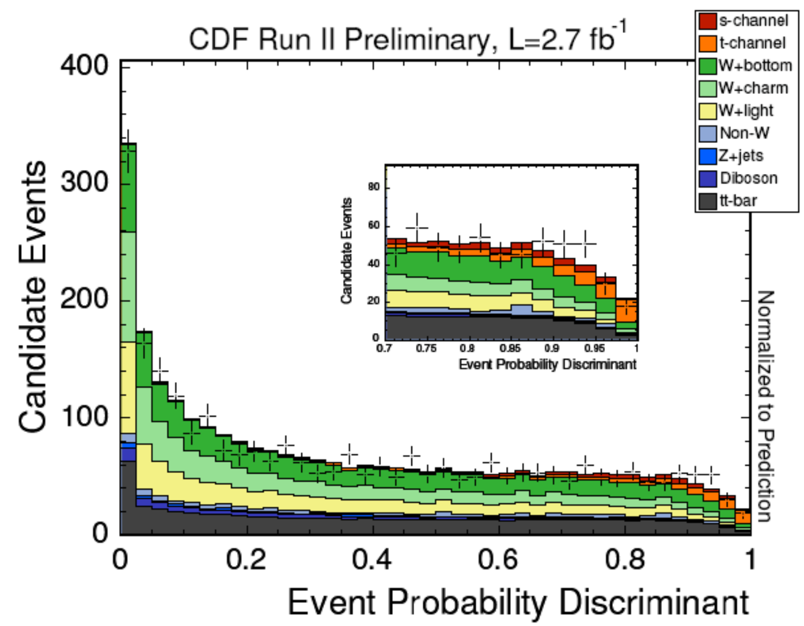


$$\boxed{\sigma \propto V_{tb}^{2}}$$



- Evidence for single top established by CDF and DØ:
  - CDF: σ=2.2 ± 0.7 pb ($V_{tb}=0.88^{+0.13}_{-0.12}$)
  - DØ: σ=4.7 ± 1.3 pb ($V_{tb}=1.31^{+0.25}_{-0.21}$)
  - Theory: σ=2.86 ± 0.36 pb (V_{tb}=1)





- Very difficult analysis
  - Signal / background small and backgrounds uncertain
  - Important "practice" for Higgs boson: σ(single top) / σ(WH)~10

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%

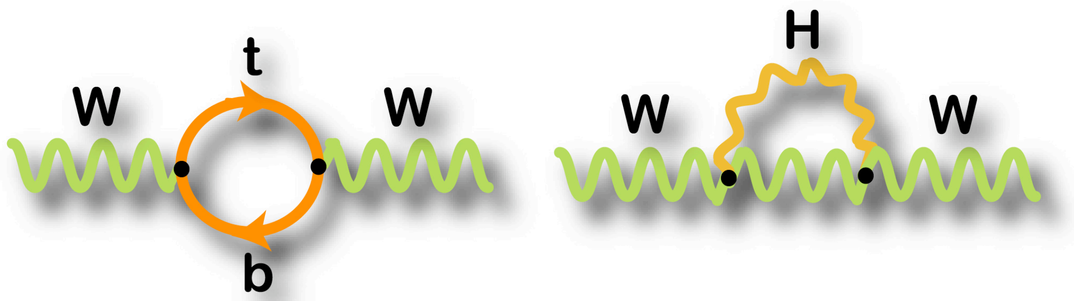
Measured to 0.002%

Measured to 0.036%

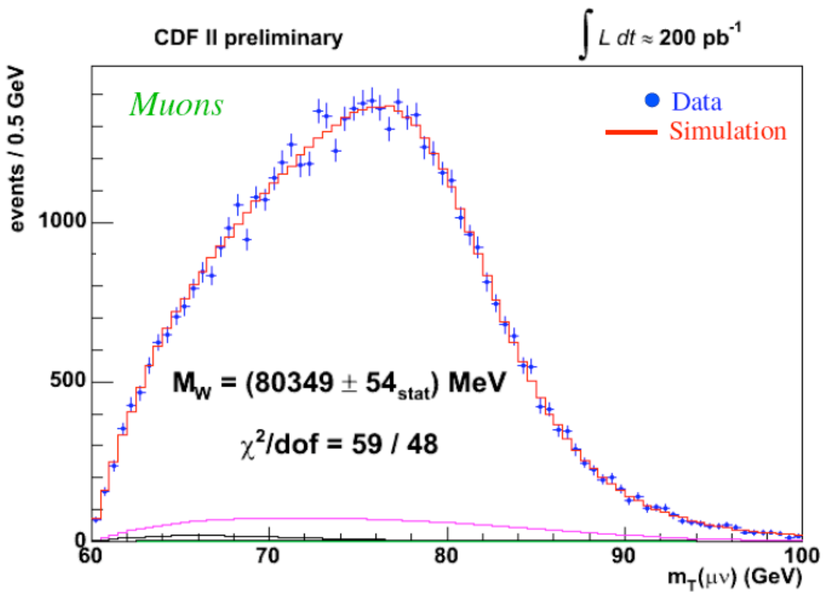
$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F}\frac{1}{(1-(M_W^2/M_Z^2))}\frac{1}{(1-\Delta r)}$$

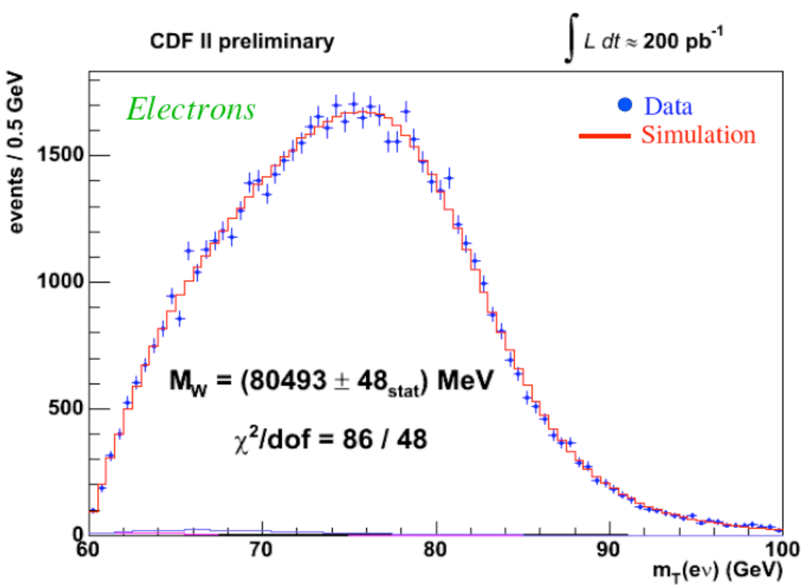
Measured to 0.0009%

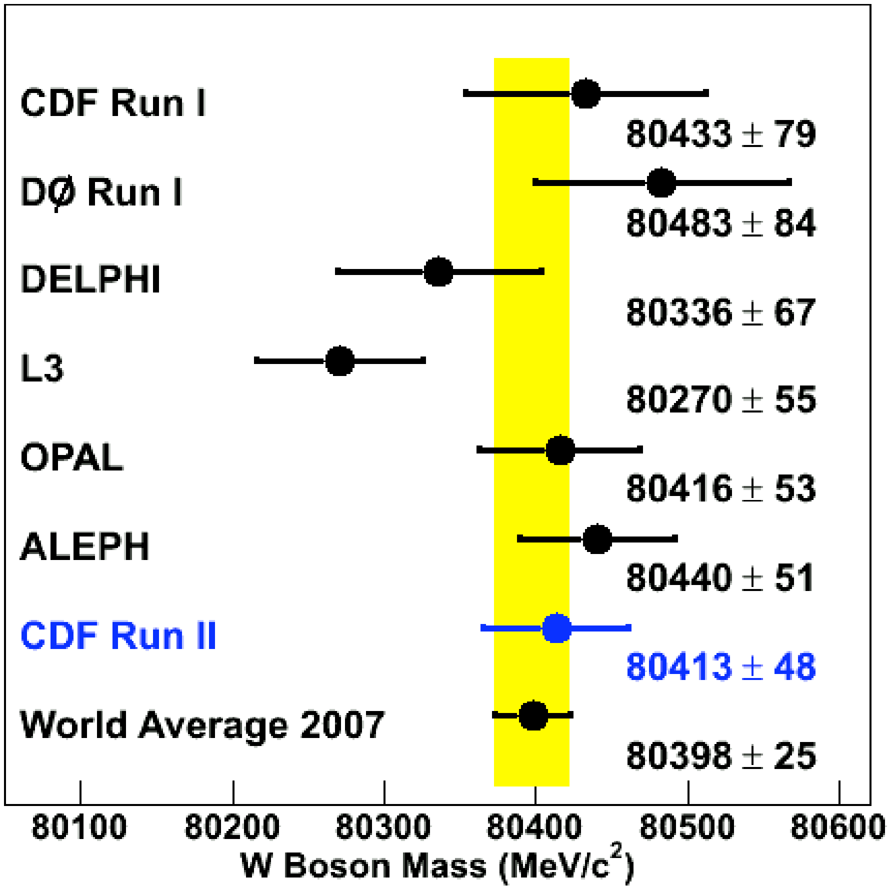
Δr: O(3%) radiative corrections dominated by *tb* and Higgs



W Boson Mass





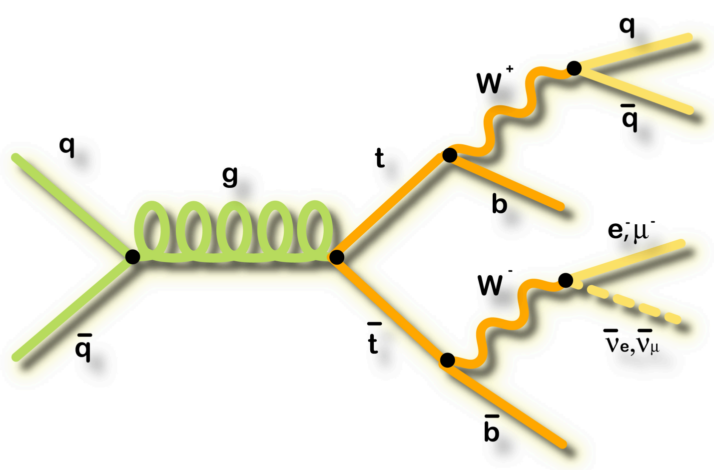


- World average:

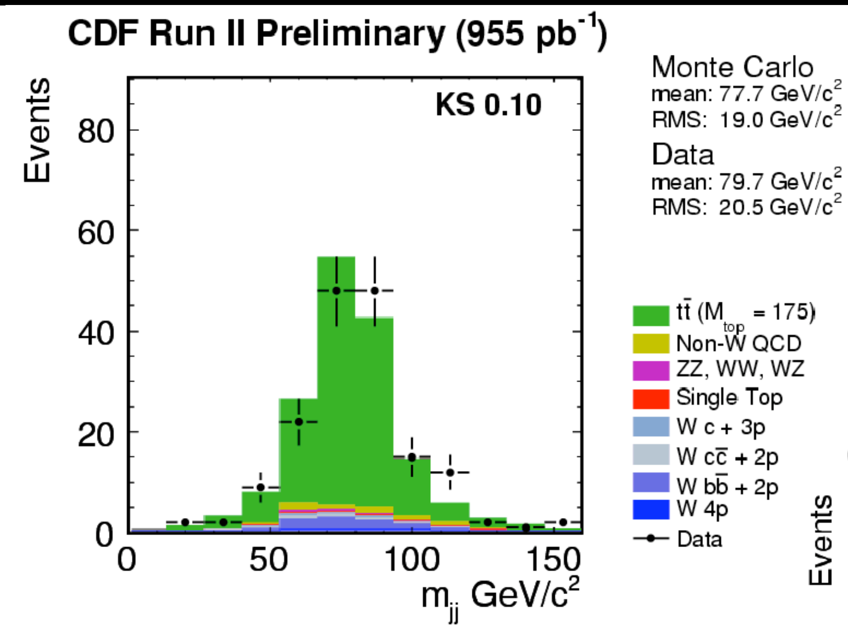
  M_W=80398 ± 25 MeV
- Ultimate Run 2 precision:

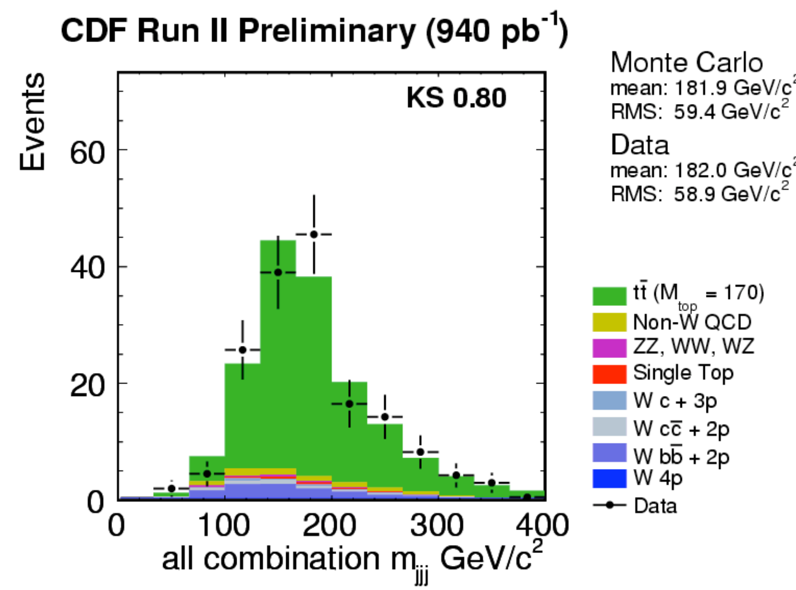
  ~15 MeV

Top Quark Mass

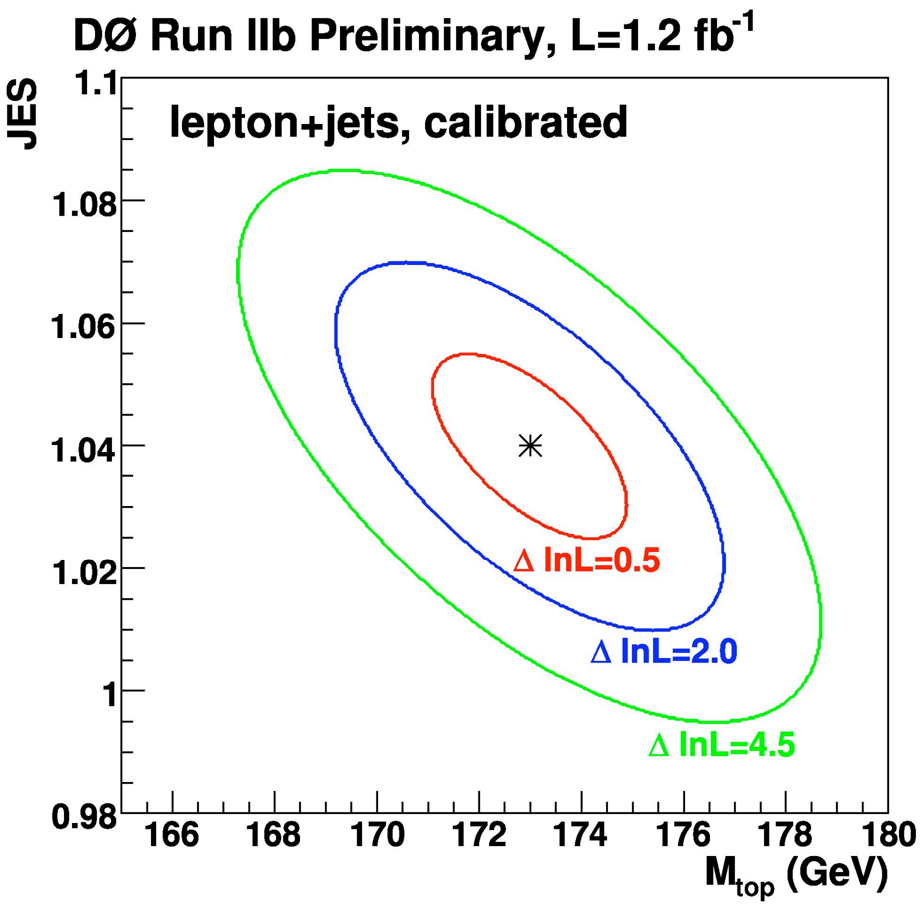


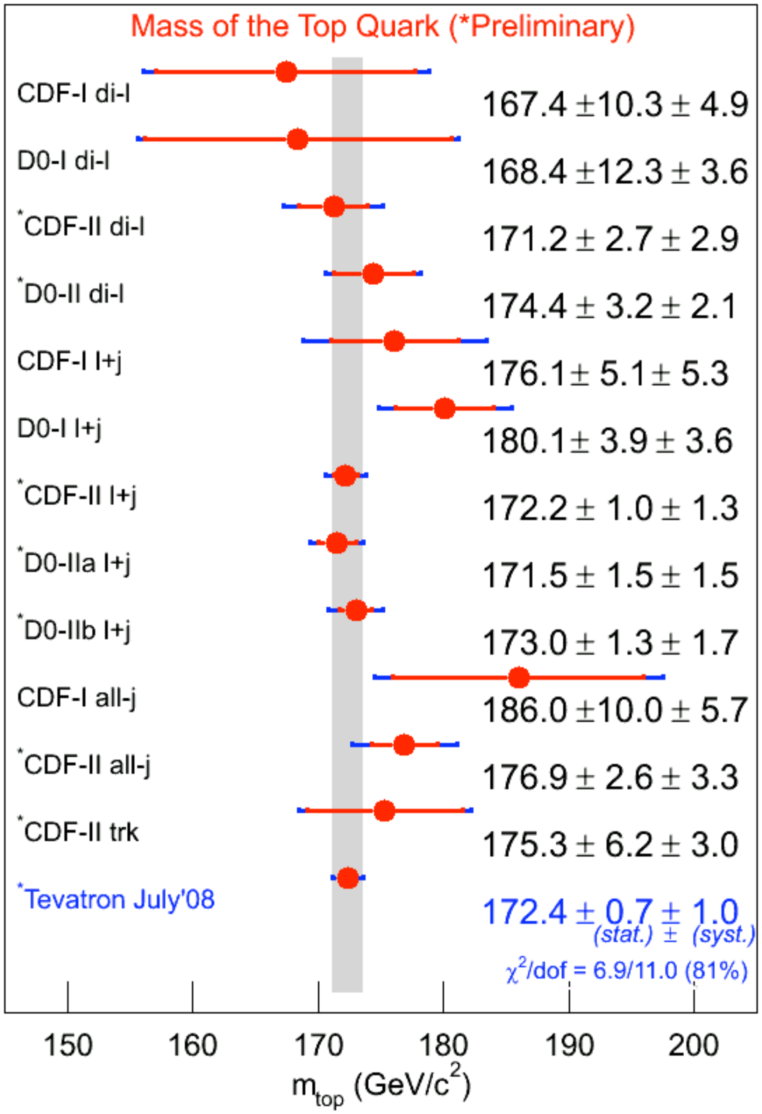
- Rather large pure samples available:
  - 166 events: S/B=4/1
- Perform simultaneous fit for
  - Top quark mass
  - Jet energy scale (M_W=M_{jj})
    - dominant systematic uncertainty





Top Quark Mass Results



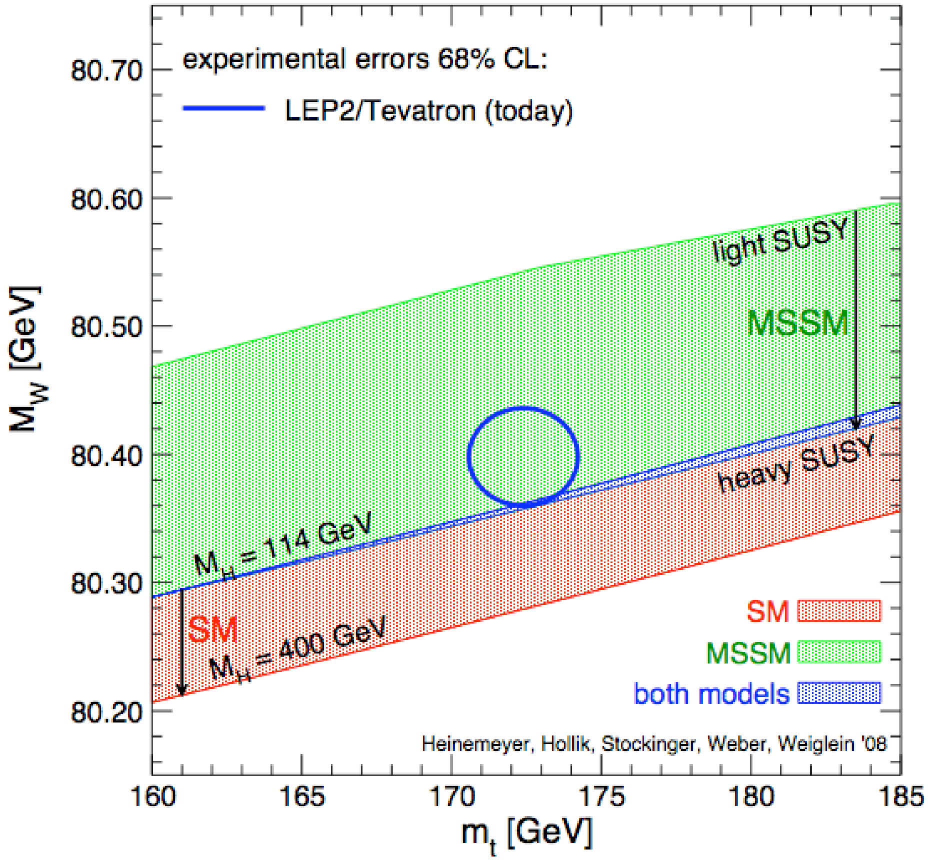


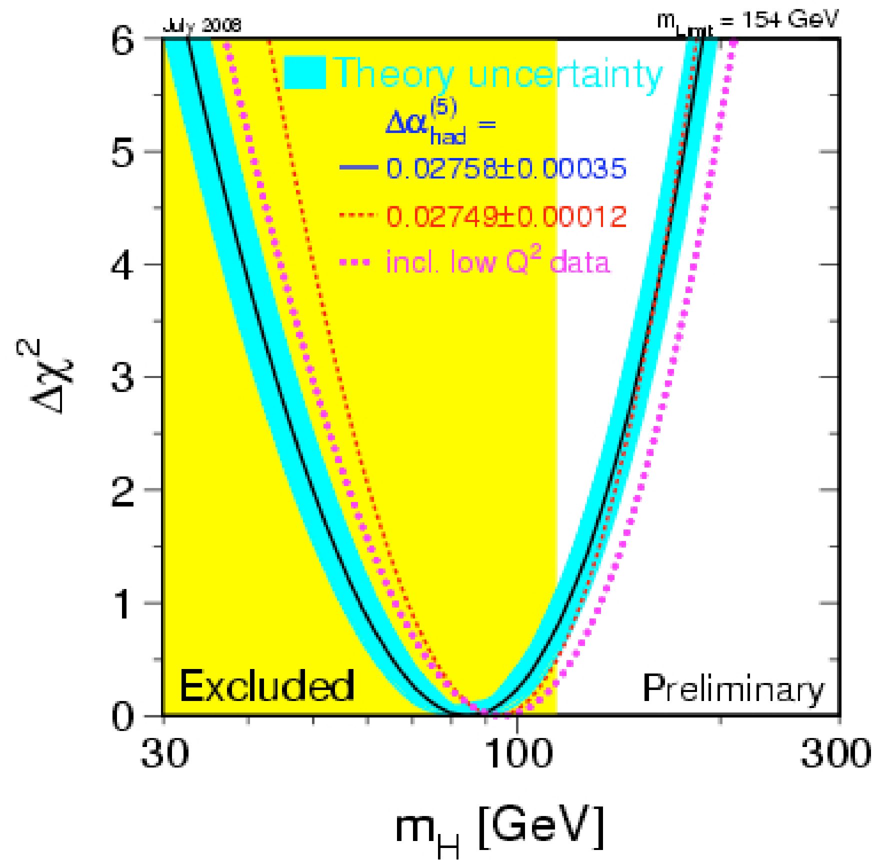
$\boxed{m_{top}=172.4 \pm 1.2 \text{ GeV}/c^2}$

Dominant systematic uncertainties:

MC modelling and jet energy calibration for b-jets

M_W, m_{top} and m_{Higgs}



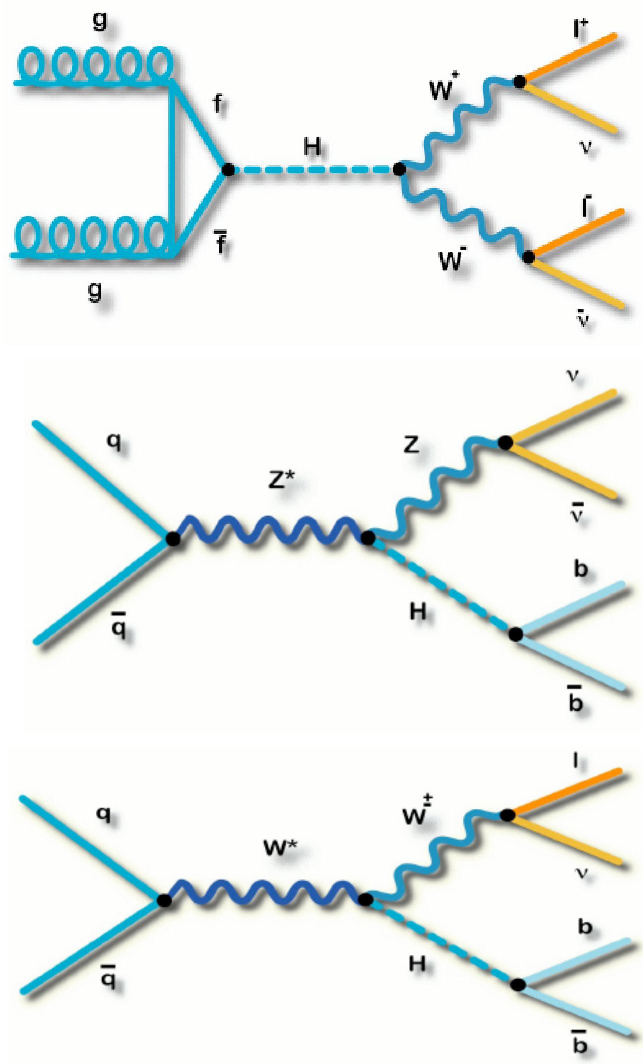


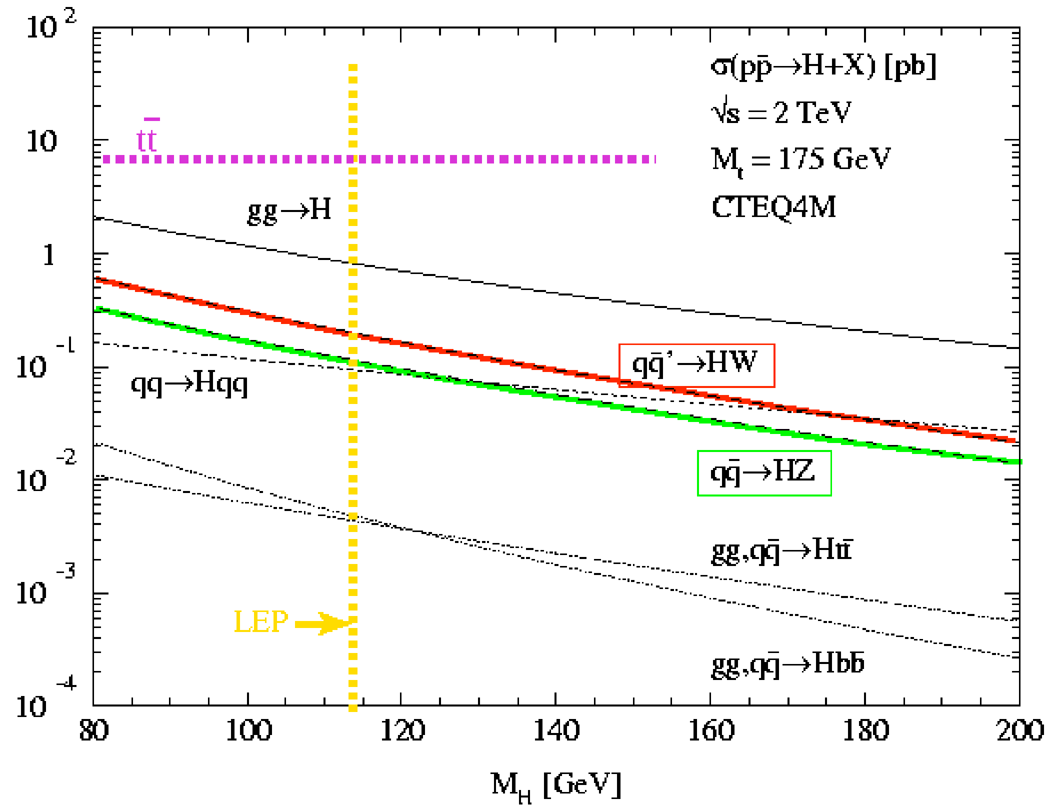
- **Indirectly: m_H<154 GeV@95%CL**

(caveat: is the measured top mass the pole mass?)

- **Directly (LEP): m_H>114 GeV@95%CL**

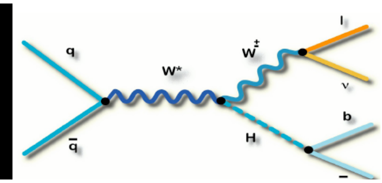
Higgs Production at the Tevatron

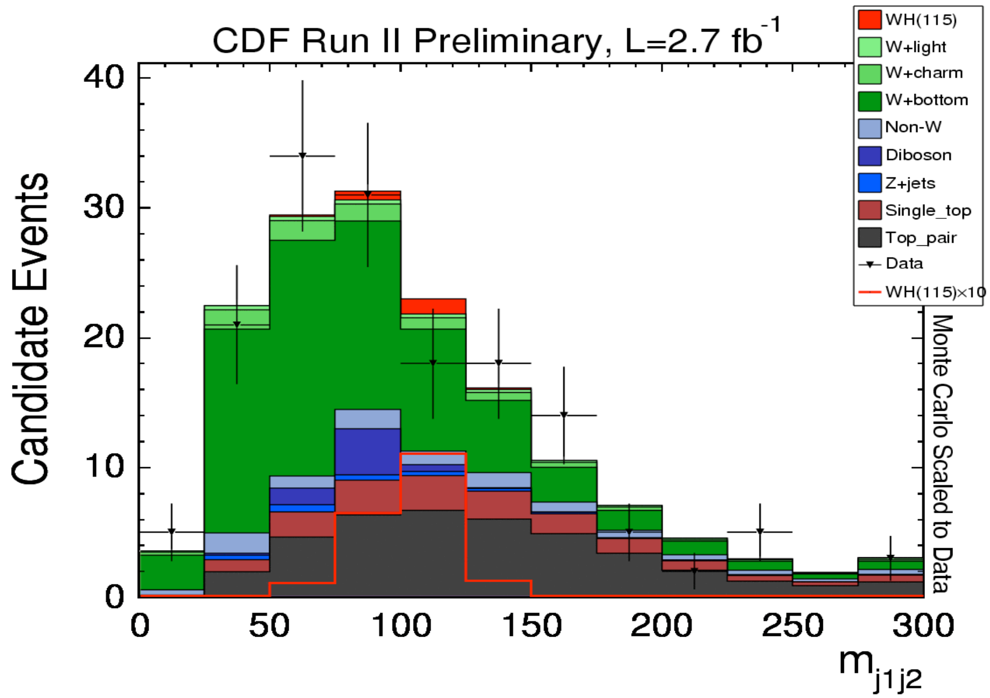


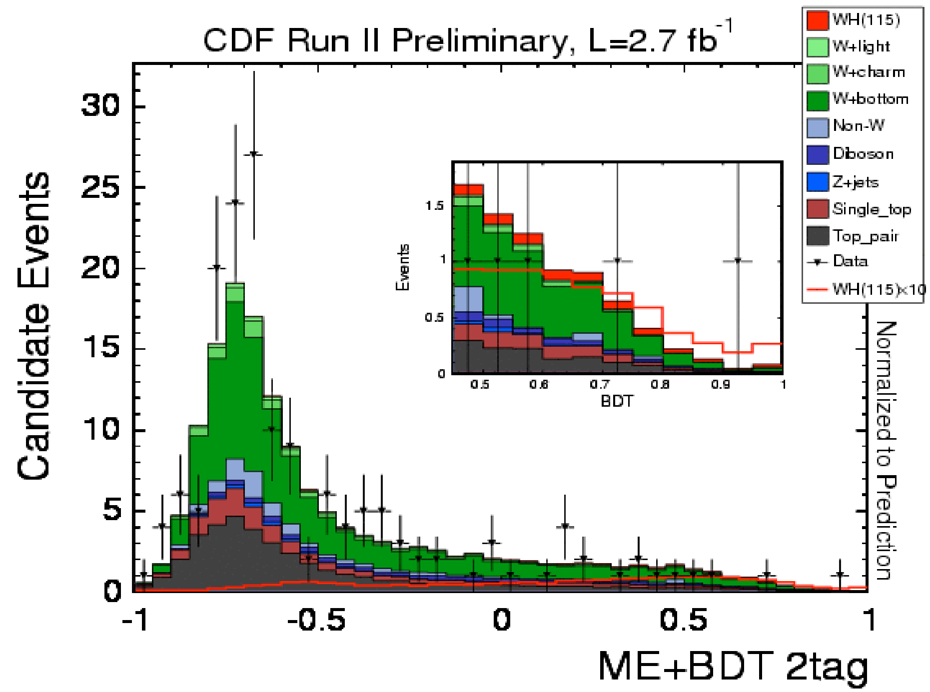


- Dominant **gg->H**
- Subdominant **WH**, ZH

W+Higgs with H→bb



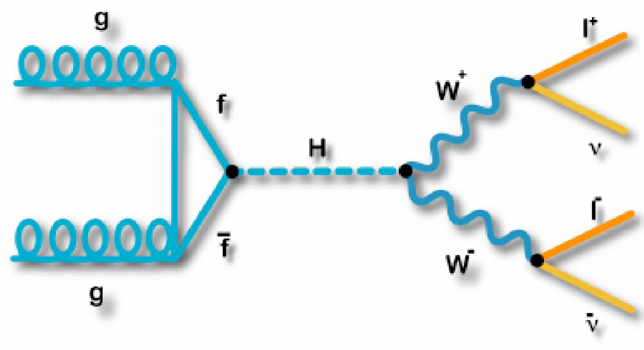


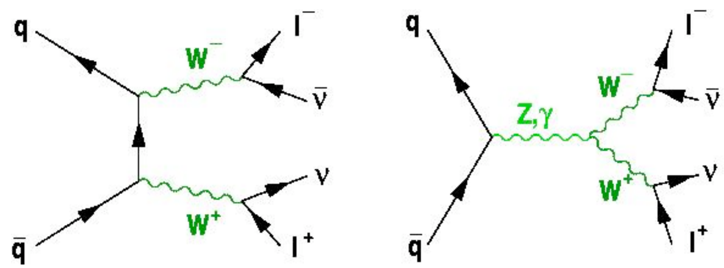


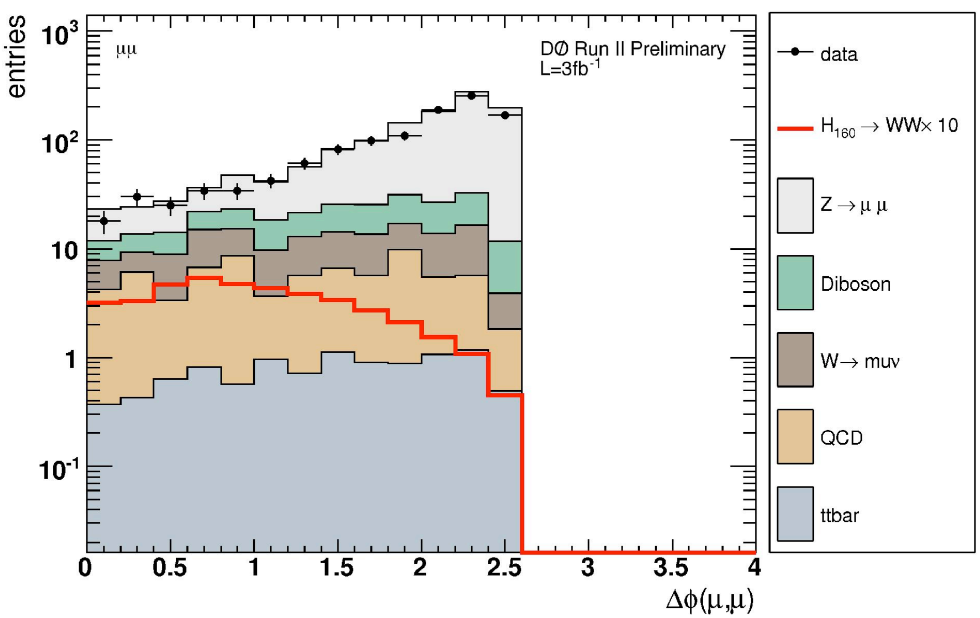
- Search for really small signal on top of difficult backgrounds:
  - Peak in invariant mass of two b-jets not sufficient to discriminate
  - Analyses based on advanced analysis techniques
    - Neural Networks, Boosted Decision trees, etc
- Both collaborations have analyzed nearly 3 fb^{-1} in for all three modes:
  - WH→lνbb, ZH →llbb, ZH →ννbb

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

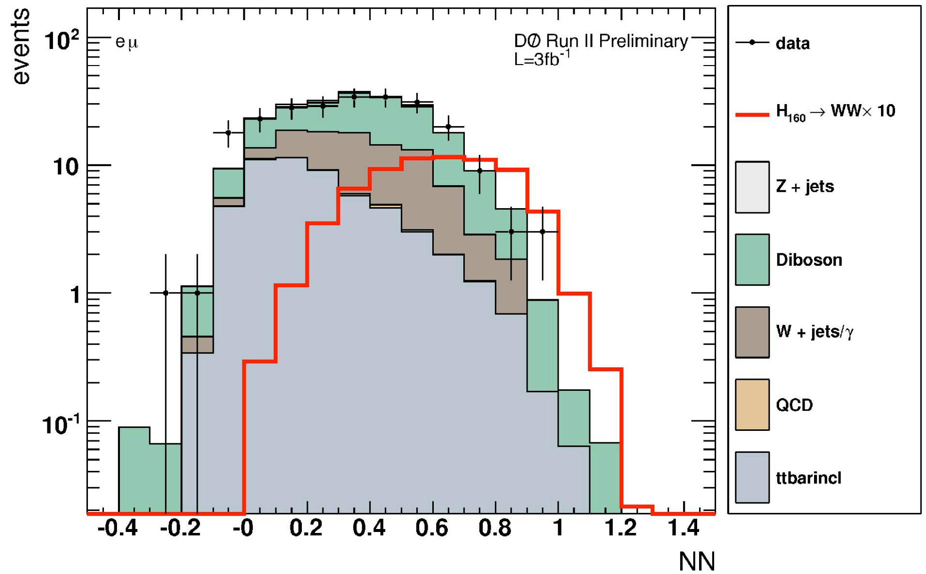
- Main background:
  - WW production
- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs has spin=0
  - leptons in $H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$ are collinear
- Use advanced techniques (NN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

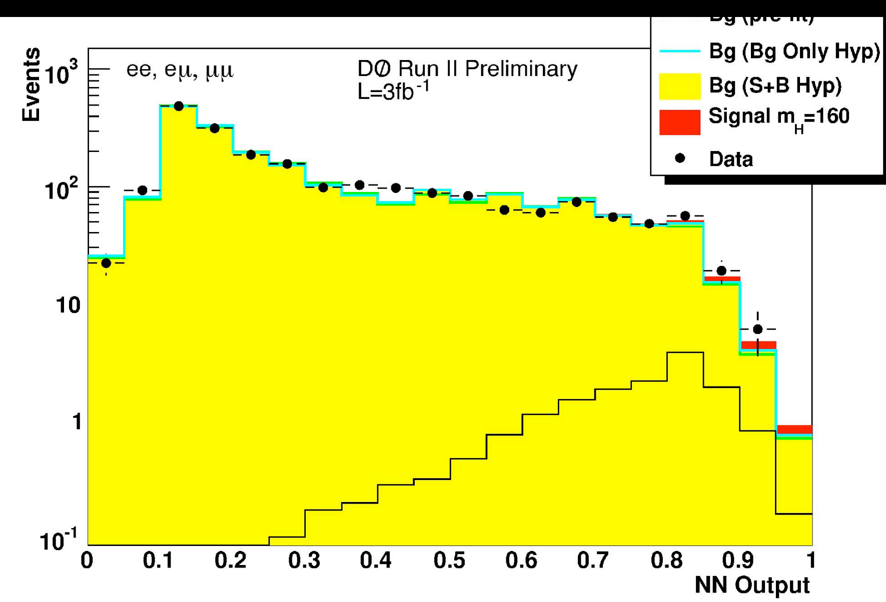






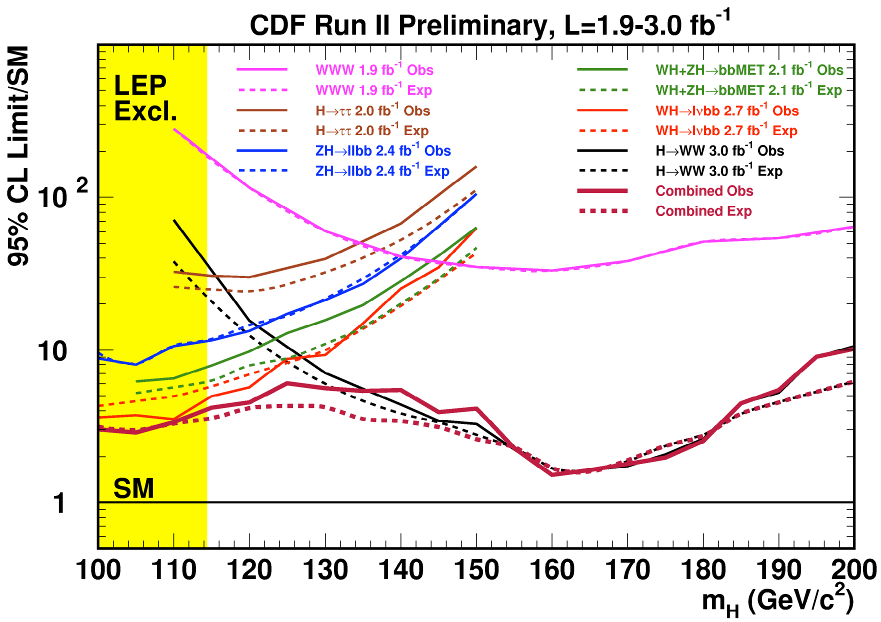
$H \rightarrow WW^{(*)} \rightarrow l^+l^-\nu\nu$

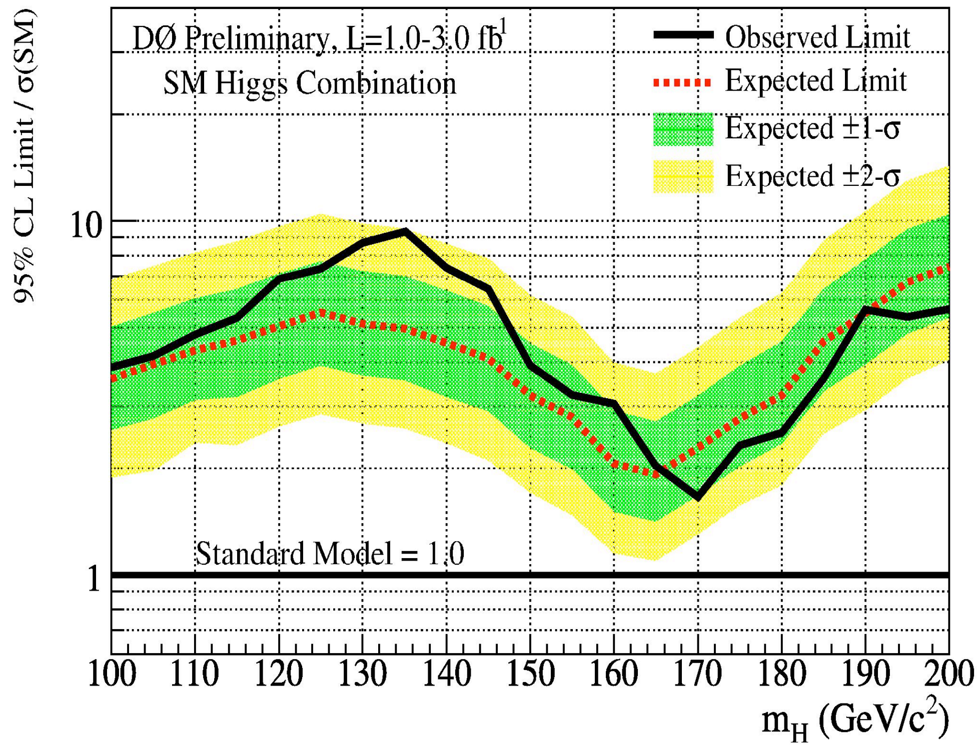




- Neural Network separates signal from background rather well
  - Data well described in background dominated region
  - No sign of excess in the data
- Data used to set limits on Higgs boson cross section

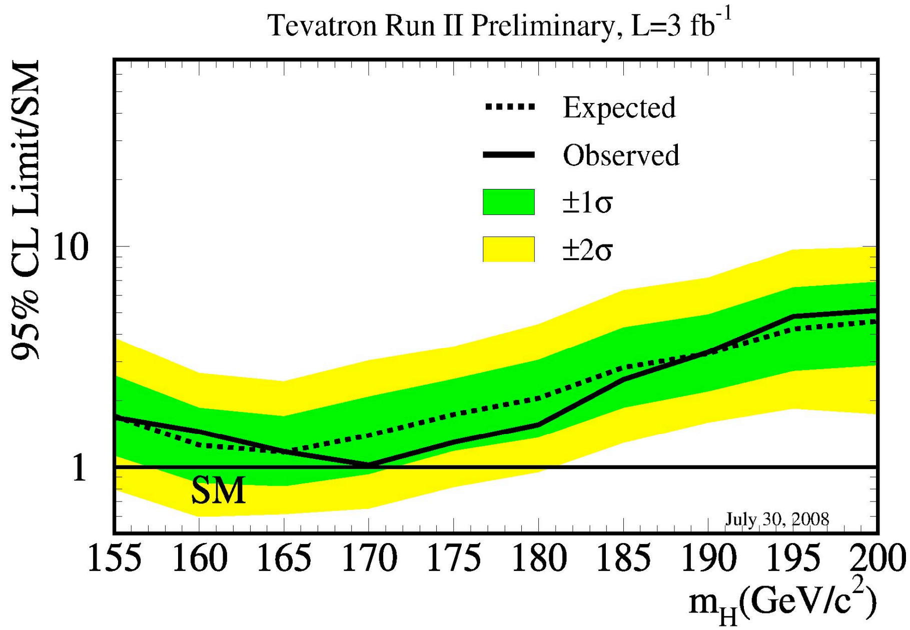
Higgs Cross Section Limit per Experiment

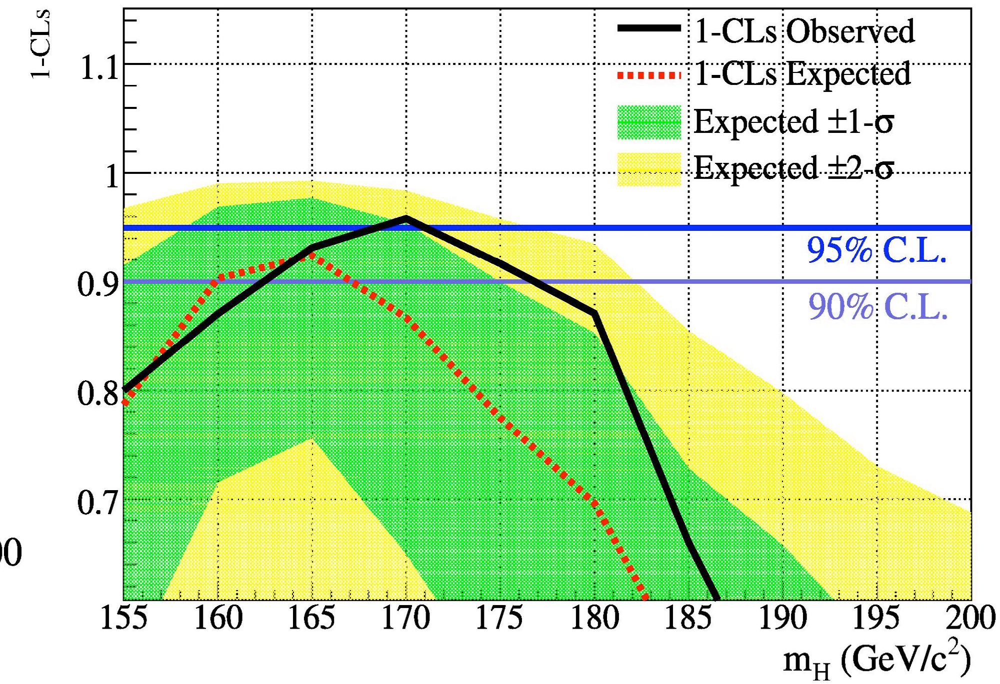




- Cross Section limits from each experiment
  - M_H=115 GeV: σ_{limit} factor 4.2 (CDF)-5.3 (DØ) above the SM
  - M_H=165 GeV: σ_{limit} factor 1.8 (CDF)-1.7 (DØ) above the SM
    - Note the 1σ downward fluctuation by DØ at 170 GeV

High Mass Higgs Combination

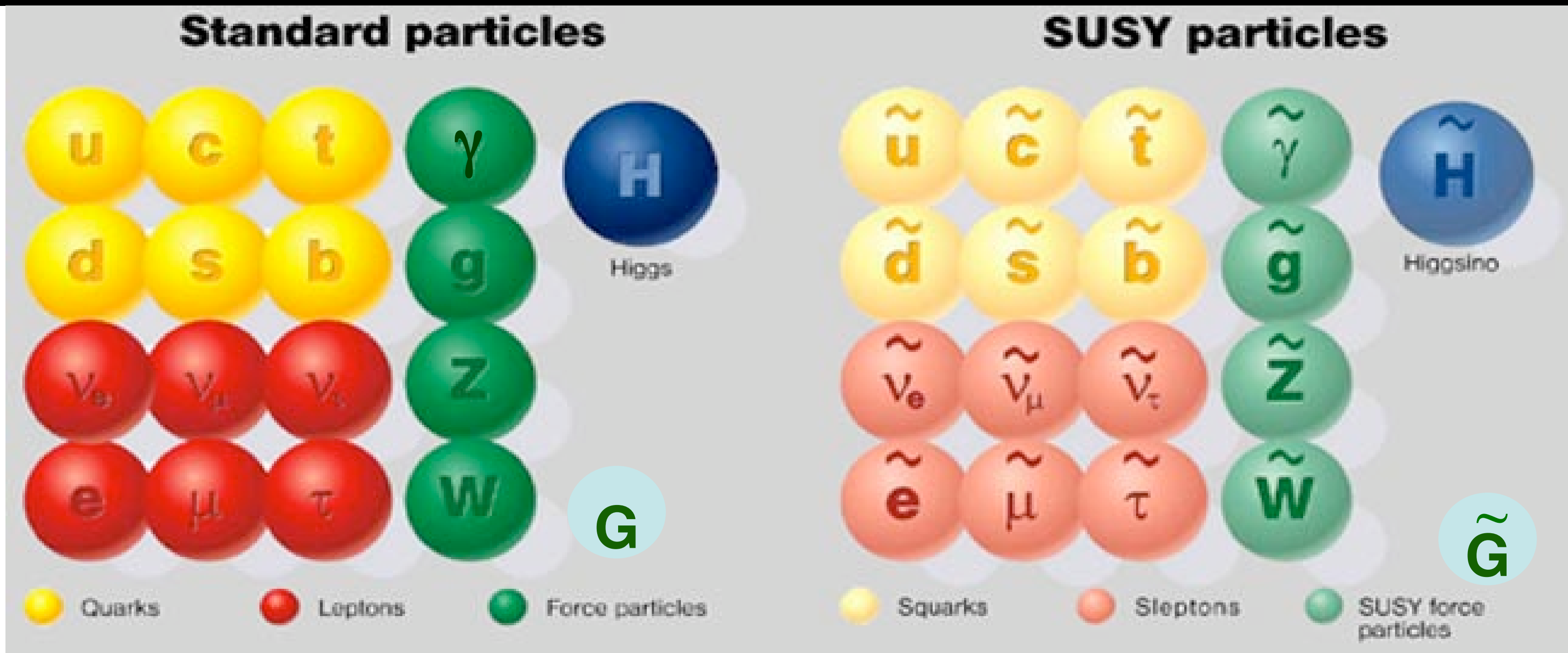




- Higgs excluded at 95% CL at 170 GeV
  - Still debates ongoing about the theoretical cross section value
  - Anastasiou *et al.* (arXiv: 0811.3458) show the theoretical cross section is 10% higher
    - Increasing it by 10% would enlarge the exclusion mass window by up to 5 GeV

Beyond the Standard Model

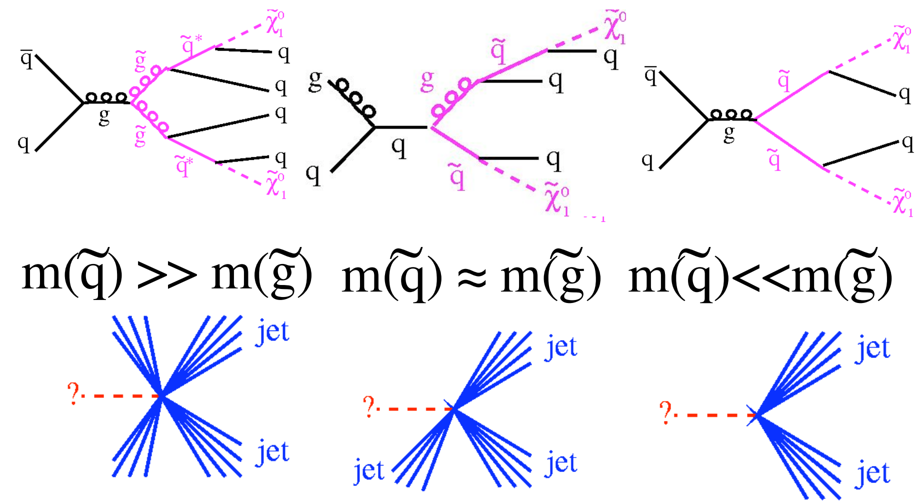
Supersymmetry (SUSY)

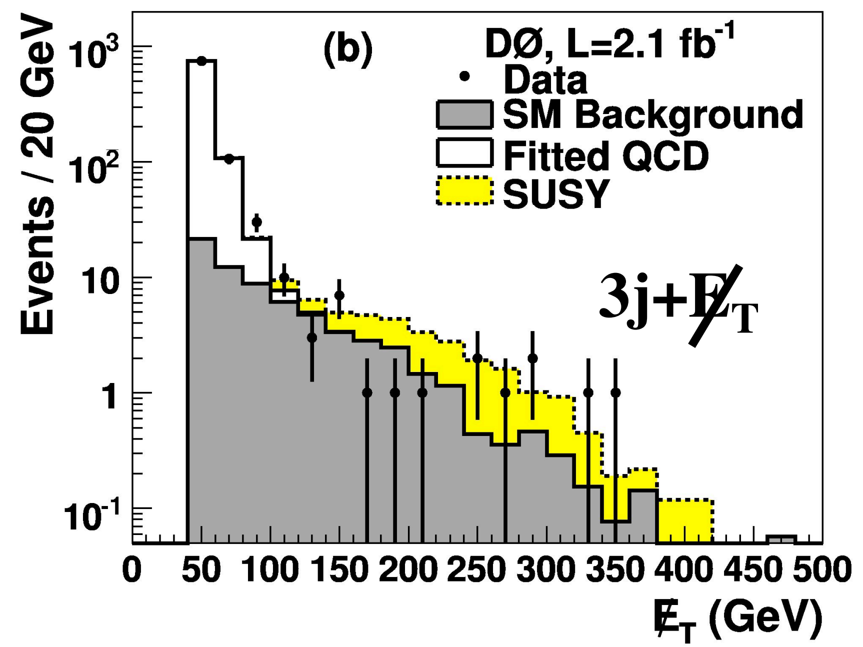


- **SM particles have supersymmetric partners:**
  - **Differ by 1/2 unit in spin**
    - **Sfermions (squarks, selectron, smuon, ...): spin 0**
    - **gauginos (chargino, neutralino, gluino,…): spin 1/2**
- **No SUSY particles found as yet:**
  - **SUSY must be broken: breaking mechanism determines phenomenology**
  - **More than 100 parameters even in “minimal” models!**

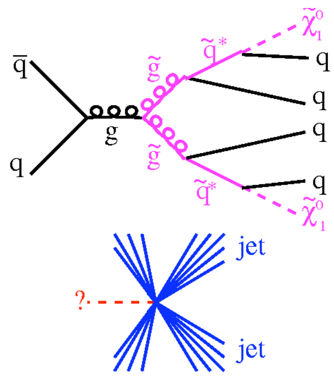
Squarks and Gluinos

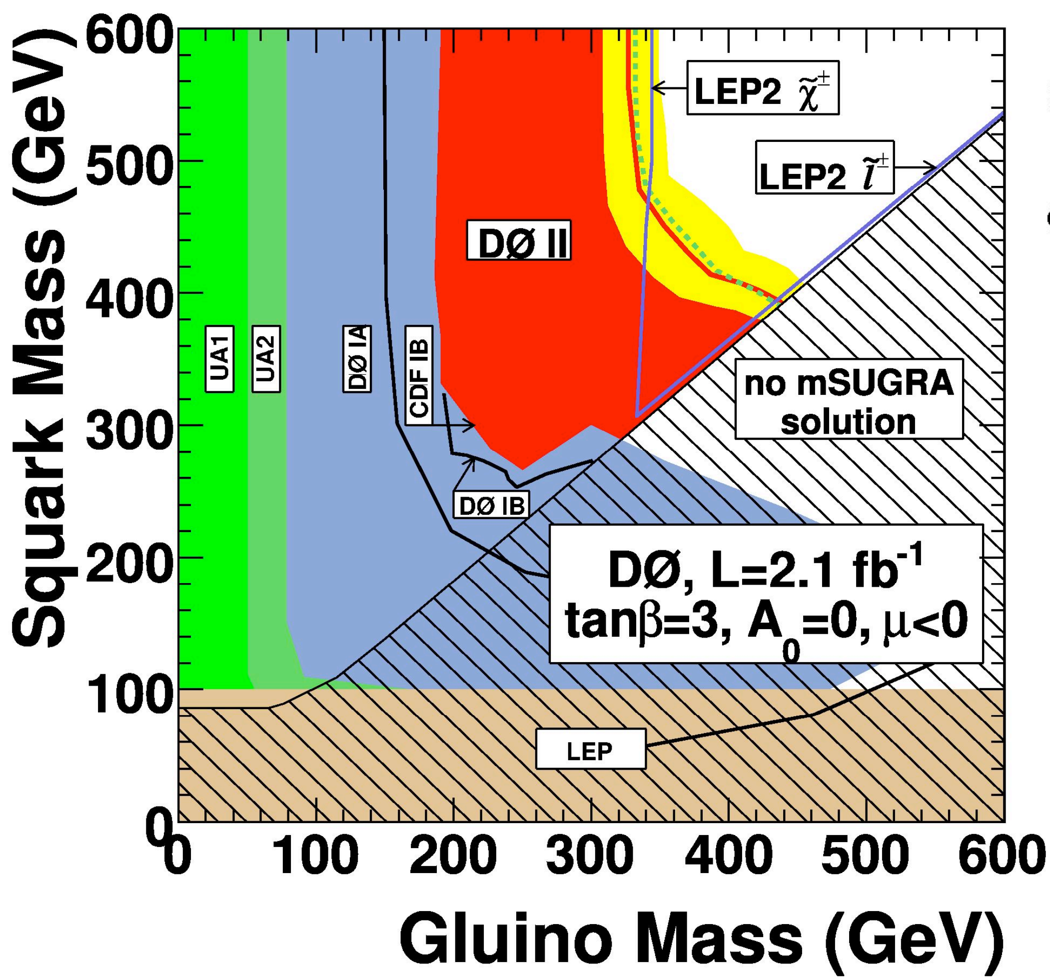
- Squark and Gluino production:
  - Signature: jets and E_T^{miss}
  - At Tevatron no long cascades to leptons expected:
    - Lepton veto applied
- Strong interaction => large production cross section
  - for M(g) ≈ 300 GeV/c^2:
    - 1000 event produced/ fb^{-1}
  - for M(g) ≈ 500 GeV/c^2:
    - 1 event produced/ fb^{-1}
  - Relatively little gain expected with more data
    - Need LHC!
- Analysis optimized depending on mass hierarchy

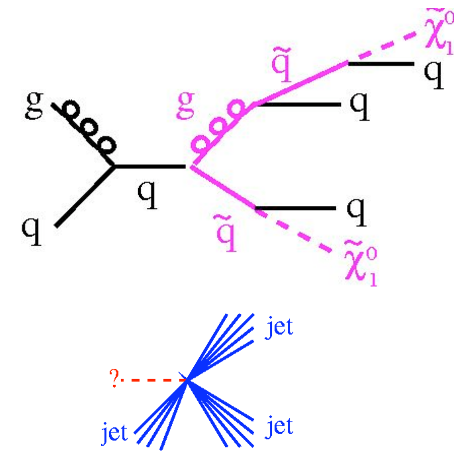


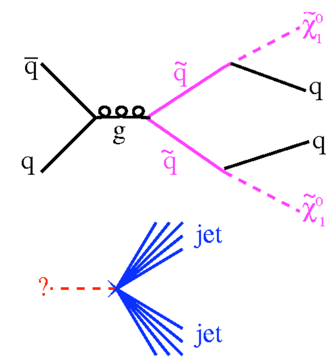


Supersymmetry Parameter Space





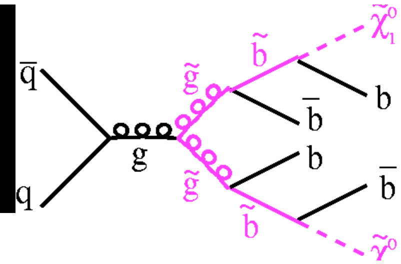




$M(\tilde{g})>308$ GeV, $M(\tilde{q})>379$ GeV

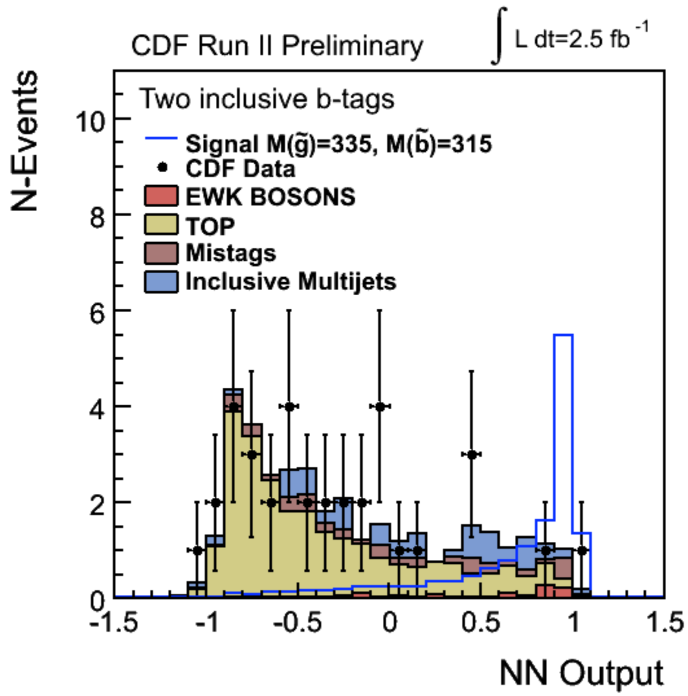
NB: up to 10 GeV differences depending on treatment of theoretical cross section uncertainties

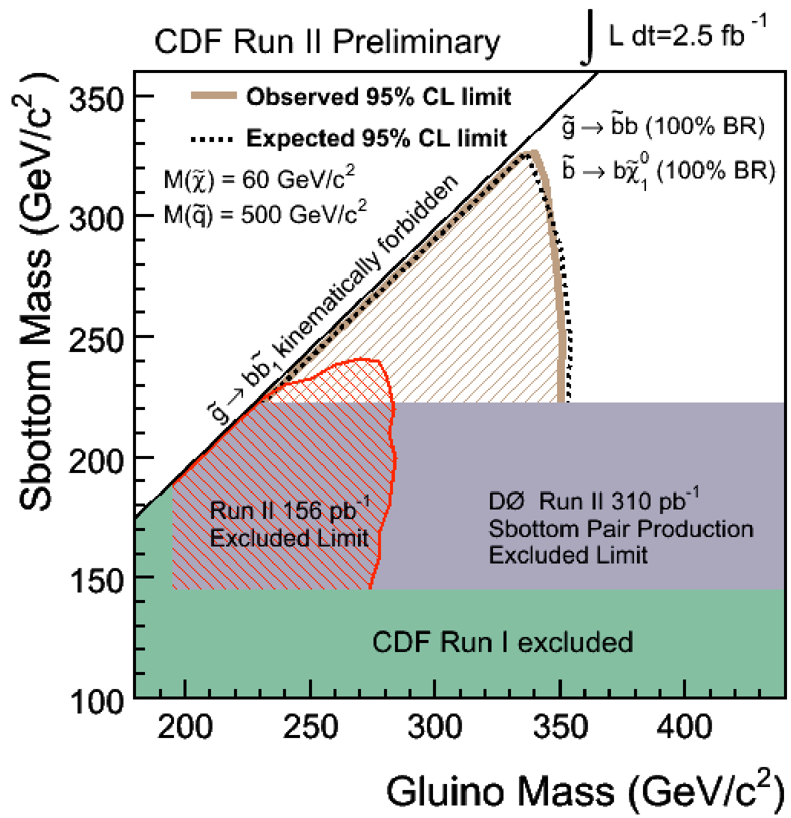
3rd generation Squarks



- 3rd generation is special:
  - Masses of one can be very low due to large SM mass
  - Particularly at high tanβ
- Search for sbottom quarks from gluino decays
  - 2 b-jets and E_T^{miss}

$$m^2_{\tilde{b}_{1,2}} = \frac{1}{2}\left(m^2_{\tilde{b}_L} + m^2_{\tilde{b}_R}\right) \mp \frac{1}{2}\sqrt{\left(m^2_{\tilde{b}_L} - m^2_{\tilde{b}_R}\right)^2 + \boxed{4m_b^2(A_b - \mu\tan\beta)^2}}$$

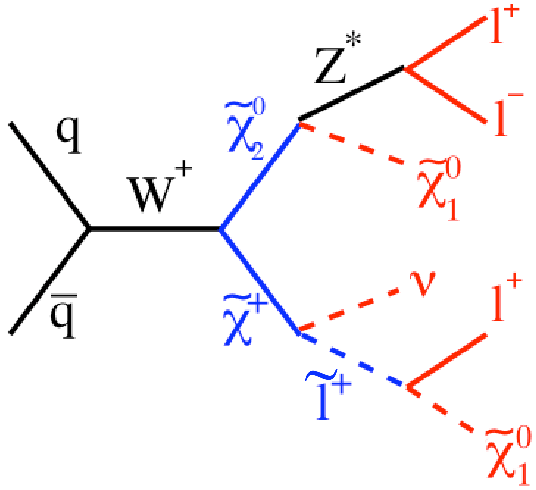


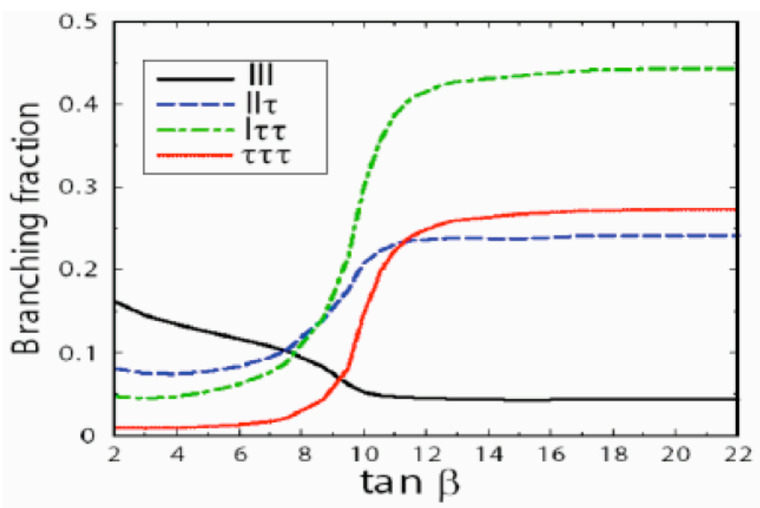


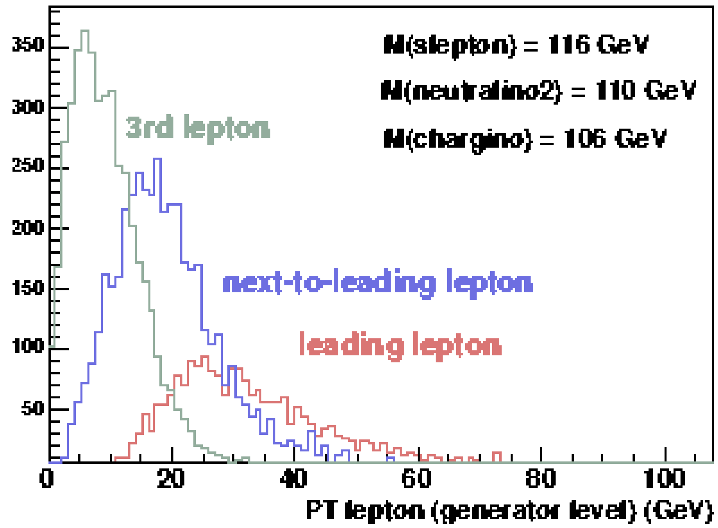
Searches in stop sector also performed and no signal found

Trileptons: Another Look for SUSY

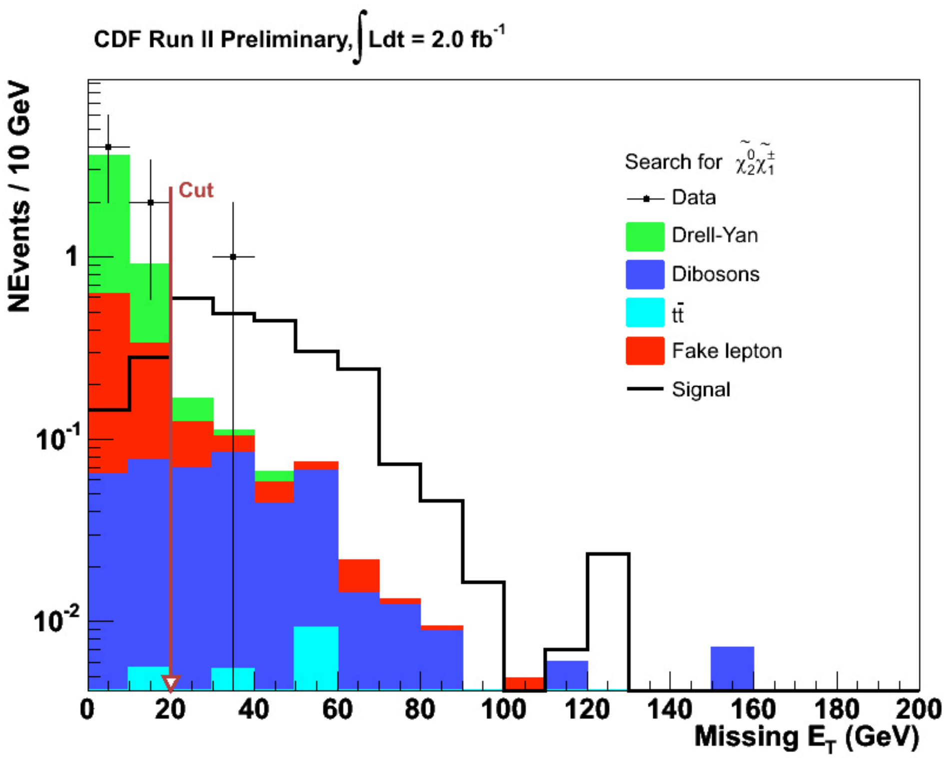
- Search for partners of W and Z boson
  - Decaying via leptons
- Signal:
  - 3 leptons and missing E_T
- Challenges
  - Lepton p_T low
  - Tau final states difficult
    - Analysis most sensitive at low tanβ

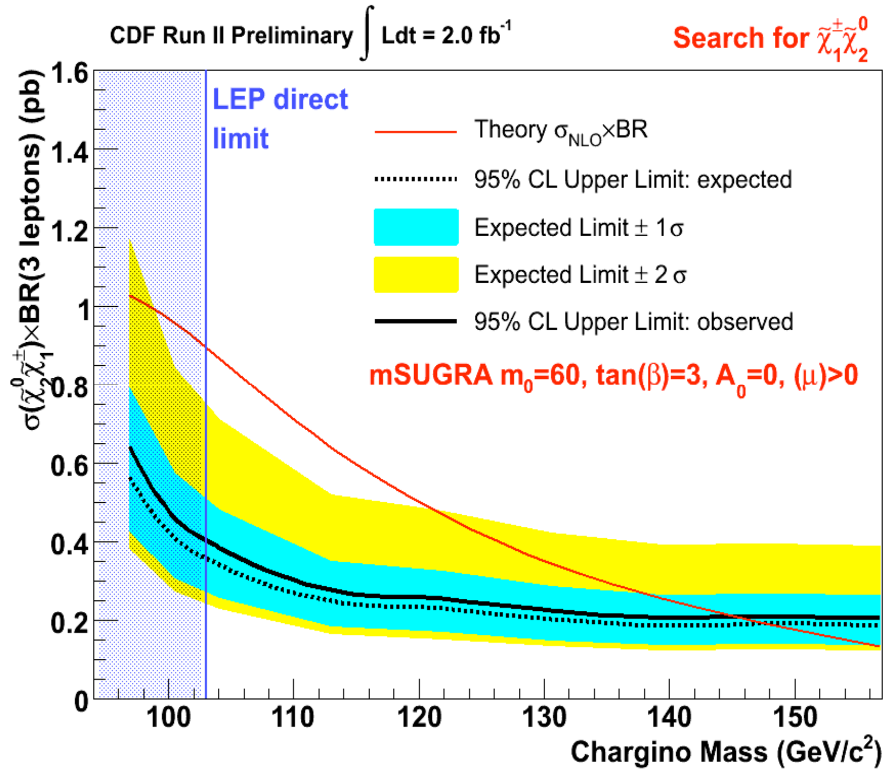






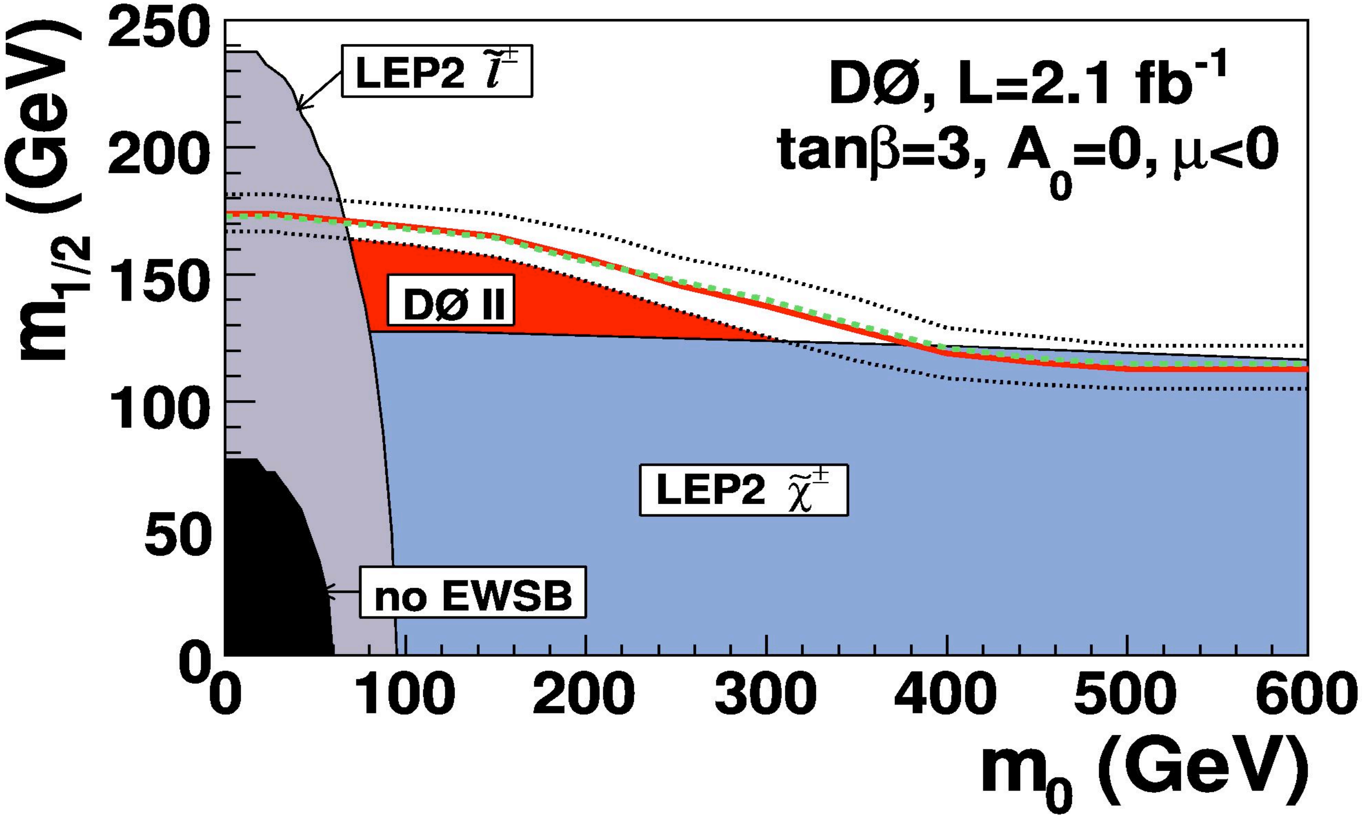
The Trilepton Data





- Data consistent with background expectations
  - M(chargino)>140 GeV/c^2 at 95% confidence level in certain parameter space
  - rather model-dependent though

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
  - Tevatron has started to probe beyond LEP in mSUGRA type models

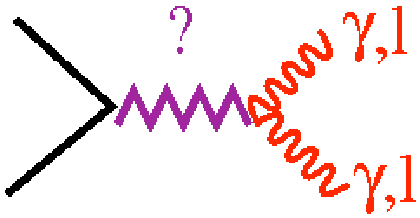
Confusion among Theorists?

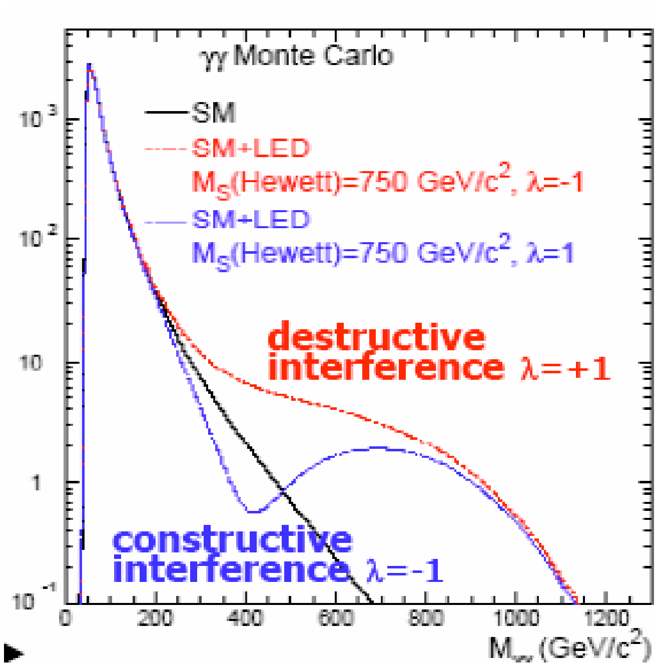
[Hitoshi Murayama]

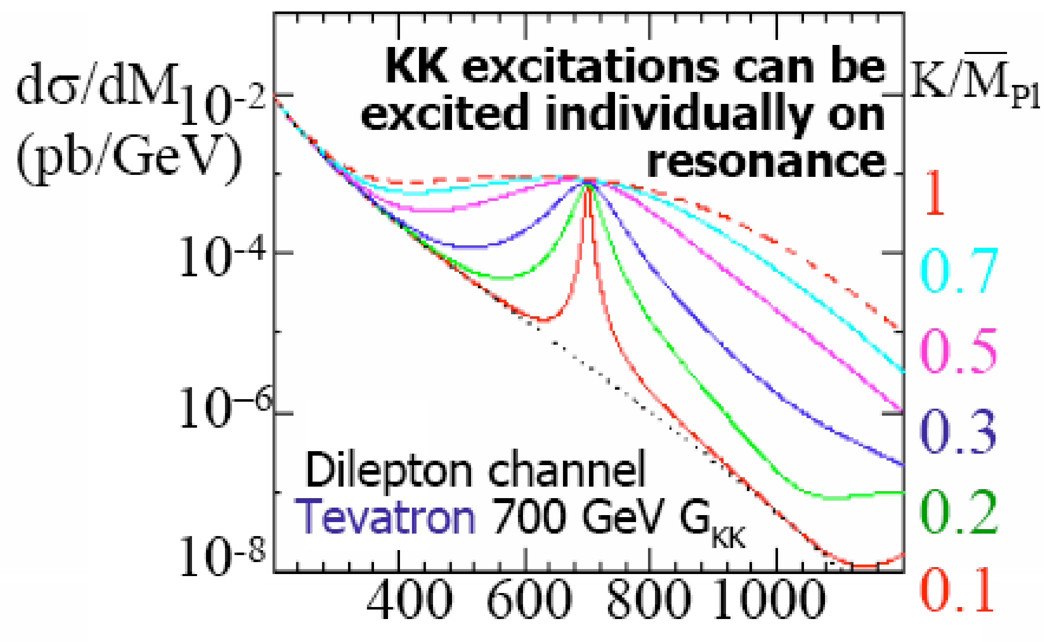
- Need to keep our experimental eyes open!

Possible Signatures in Dilepton Mass Spectra

- Resonant production of new particle
  - (Narrow) peak in mass spectrum, e.g. Z', Randall-Sundrum Graviton, RPV sneutrino
- Virtual exchange or KK tower
  - Contact interaction or ADD model

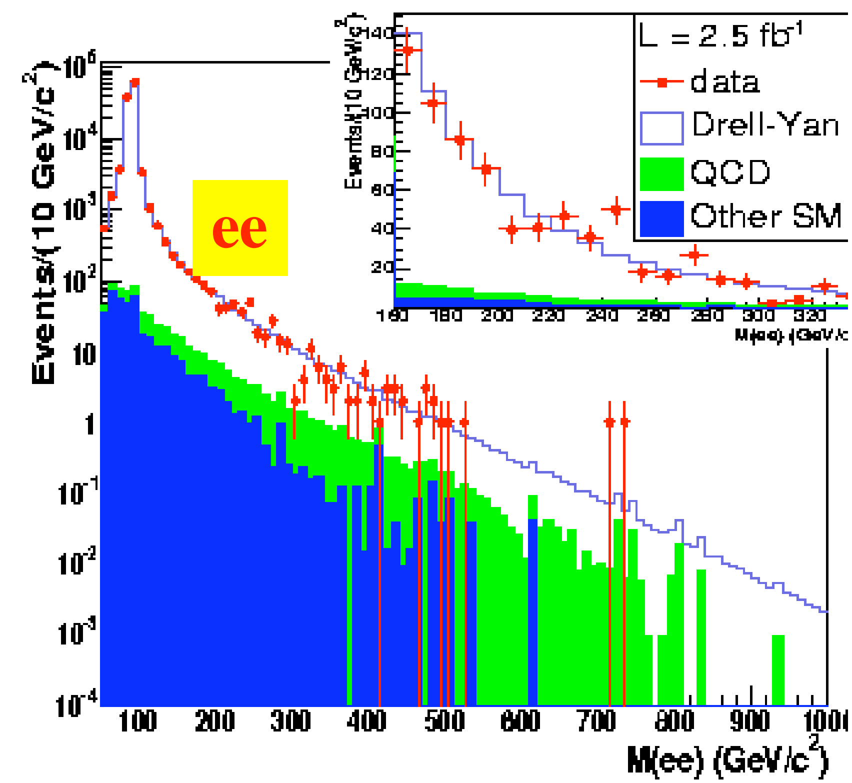


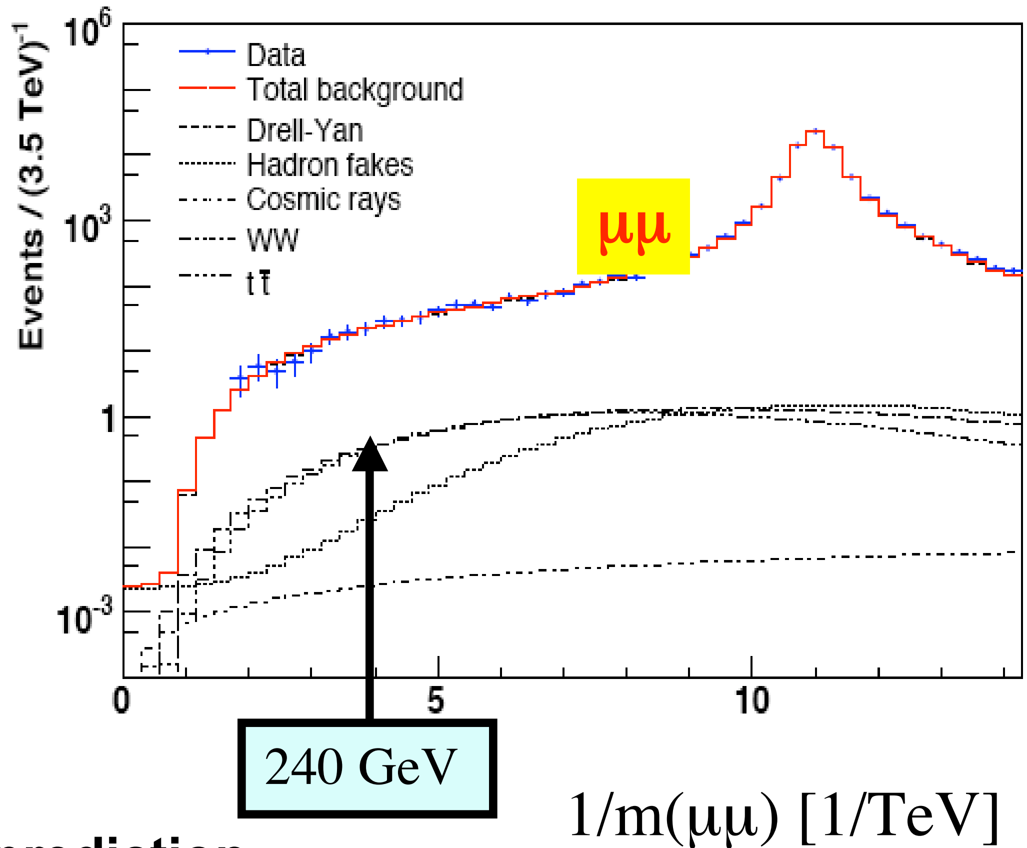




Dielectron and Dimuon Mass Spectra

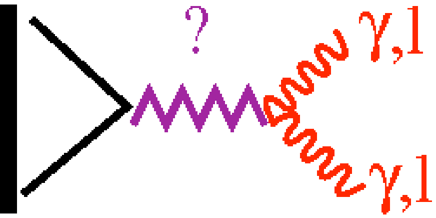
CDF Run II Preliminary



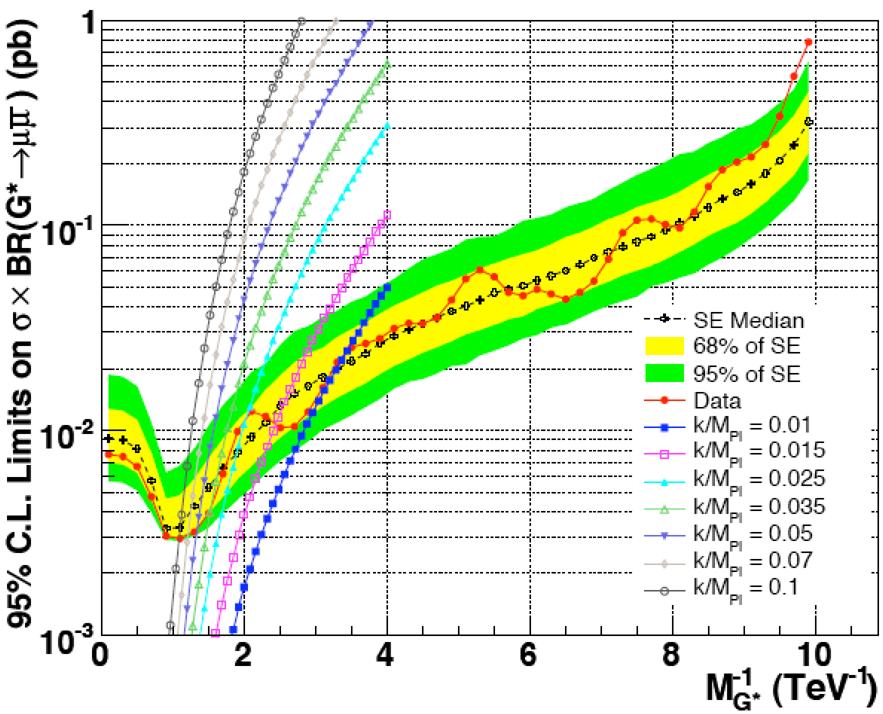


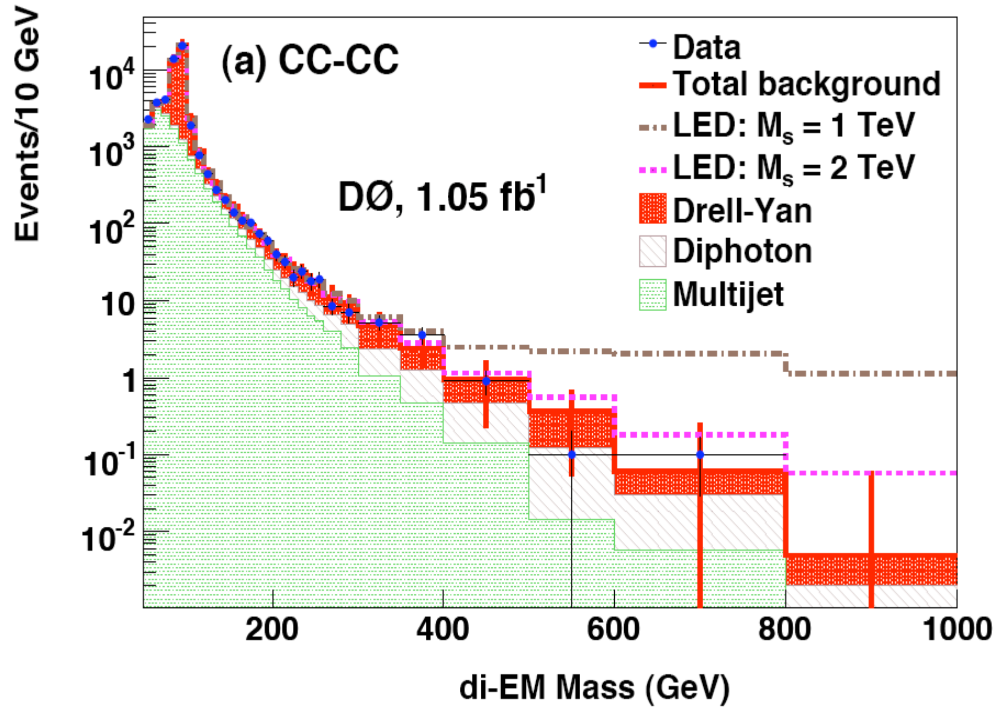
- **Data agree with background prediction**
  - Slight excess in CDF ee spectrum at 240 GeV (prob.~0.6%)
    - 50 events on a background of 27
  - No excess seen in dimuon data
  - No recent analysis by DØ available

High Mass dilepton and $\gamma\gamma$



- Anomalous in diphoton or dielectron mass spectrum predicted in
  - Resonance: Z´ models (spin 1) and Randall-Sundrum Graviton (spin 2)
  - Hard tail: large ED model (ADD)





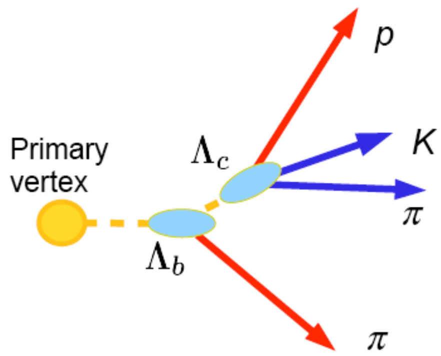
$M_{Z'}$>1.03 TeV for SM-like Z´

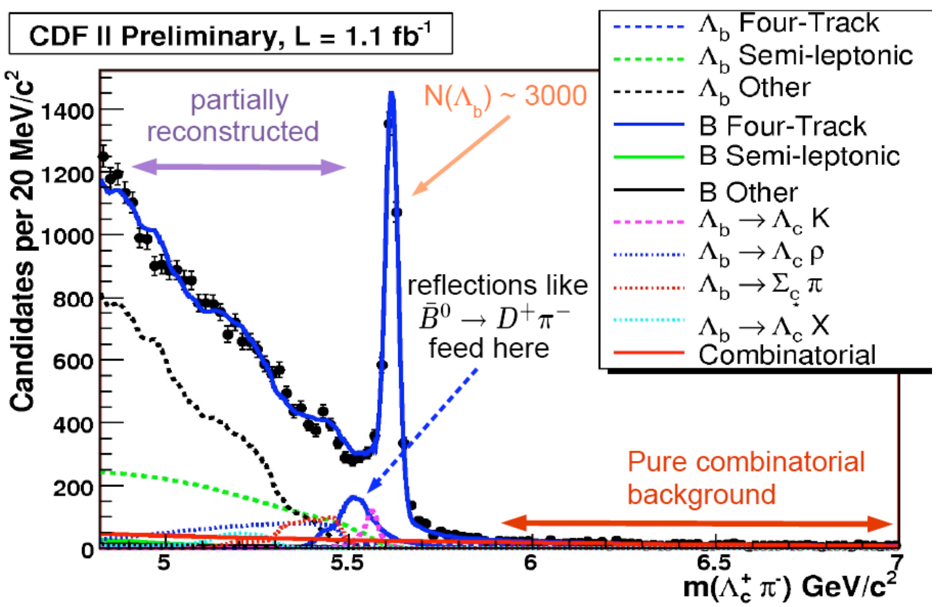
M_G>0.92 TeV for k/M_{Pl}=0.1

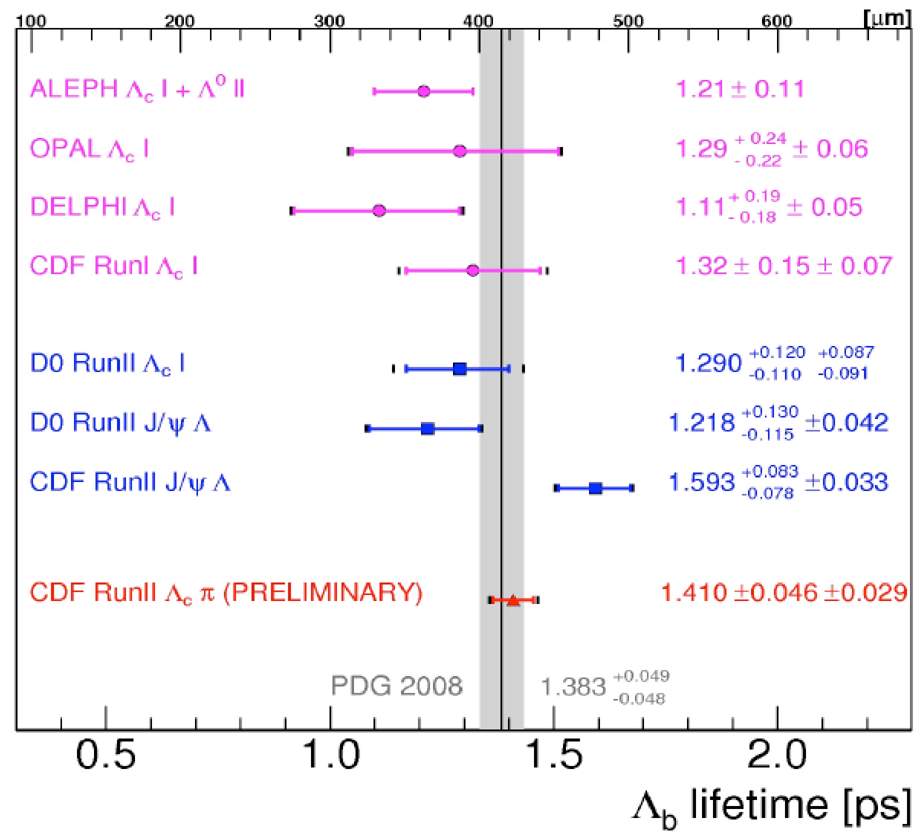
M_s>2.1-1.3 TeV for N_{dim}=1-7

Flavour Physics

Lifetime of the Λ_b Baryon

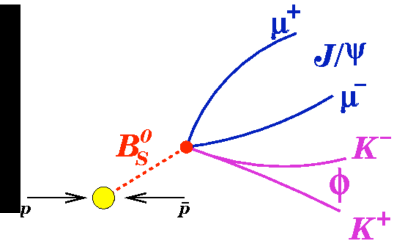




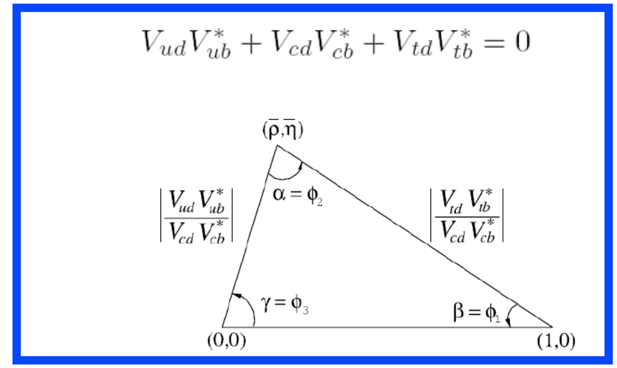


- Brand new measurement in fully reconstructed mode
- Consistent with world-average: $\tau(\Lambda_b)/\ \tau(B^0)=0.922$ +/- 0.039

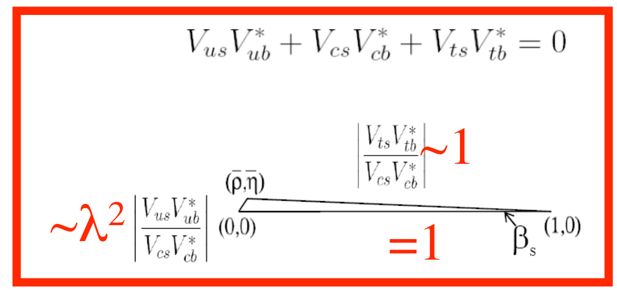
CP violating Phase: β_s



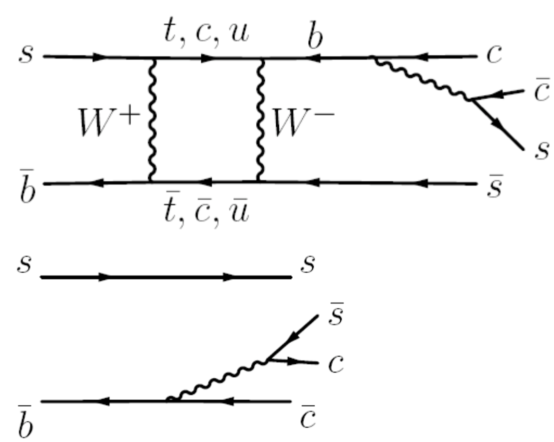
- Size of angle β_s in unitarity angle quantifies CP violation
  - Measured very precisely at Belle/BaBar in B_d system using $B_0 \rightarrow J/\psi K_s^0$



- Equivalent measurement in B_s sector
  - Uses $B_s \rightarrow J/\psi\phi$
  - Theoretical prediction:
    - 0.02 (very small, not observable a Tevatron)



- Interference of decays with and without mixing ($B_s^0 \leftrightarrow \overline{B}_s^0$): extract from angular distributions
  - Average lifetime: Γ
  - Lifetime difference between light and heavy state ($\Delta\Gamma$)
  - Phase β_s



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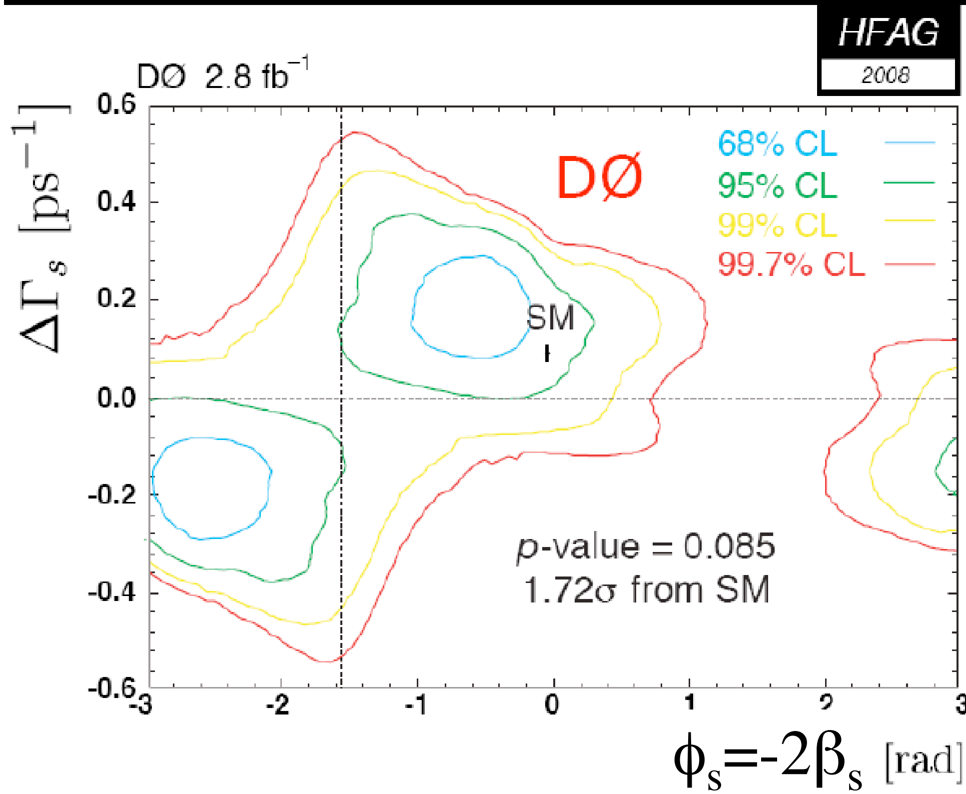

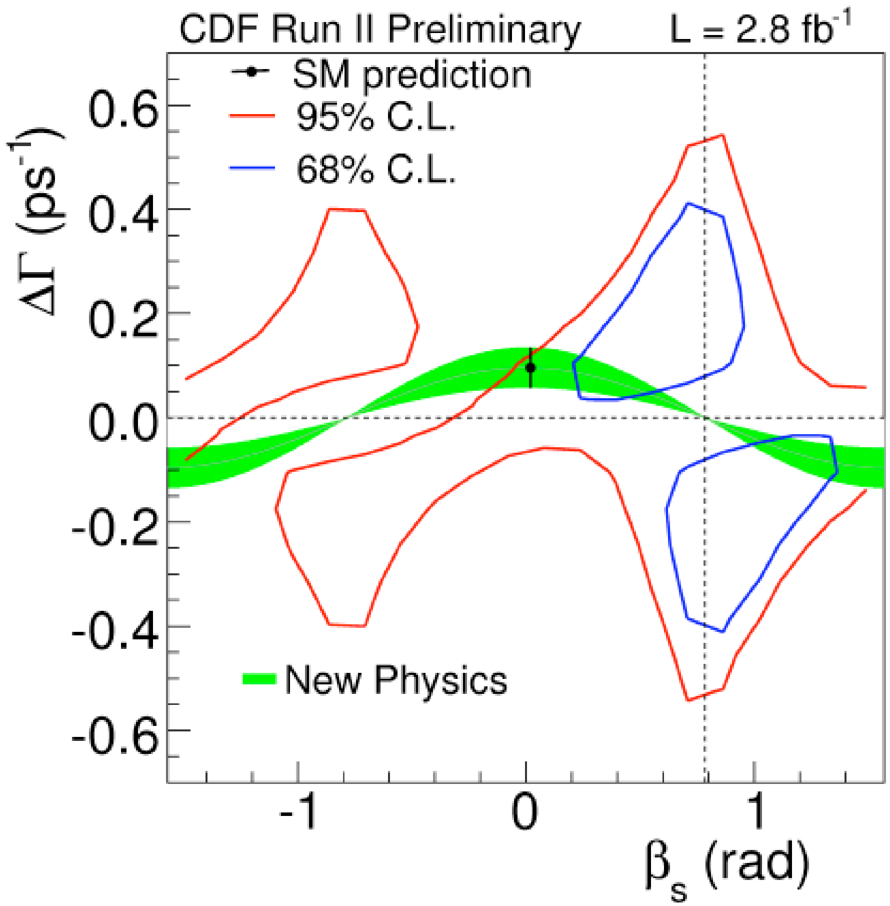

- Difference between data and SM nearly 2σ in each experiment
  - Combined value 2.2σ
- Will need to watch development with more data

Conclusions and Outlook

- **Tevatron, CDF and DØ are operating well**
  - Tevatron delivered 2 fb^{-1} in 2008!
  - About 4.5 pb^{-1} of analysis data on tape
  - Running guaranteed until summer '09
- **Physics results cover broad range:**
  - **QCD** thoroughly being tested:
    - Precision between 2 and 50%
  - **Higgs boson constraints at 95% CL**:
    - Indirect (m_W and m_{top}): m_H<154 GeV/c^2
    - Direct searches: $m_H \neq 170$ GeV/c^2
  - **Searches** beyond the Standard Model
    - no sign of new physics yet
  - **Flavour Physics**
    - Puzzle about Λ_b lifetime resolved
    - Interesting fluctuation in phase β_s
- **Tevatron also provides valuable experience for LHC**
  - Test MC models / QCD calculations
  - Test analysis techniques

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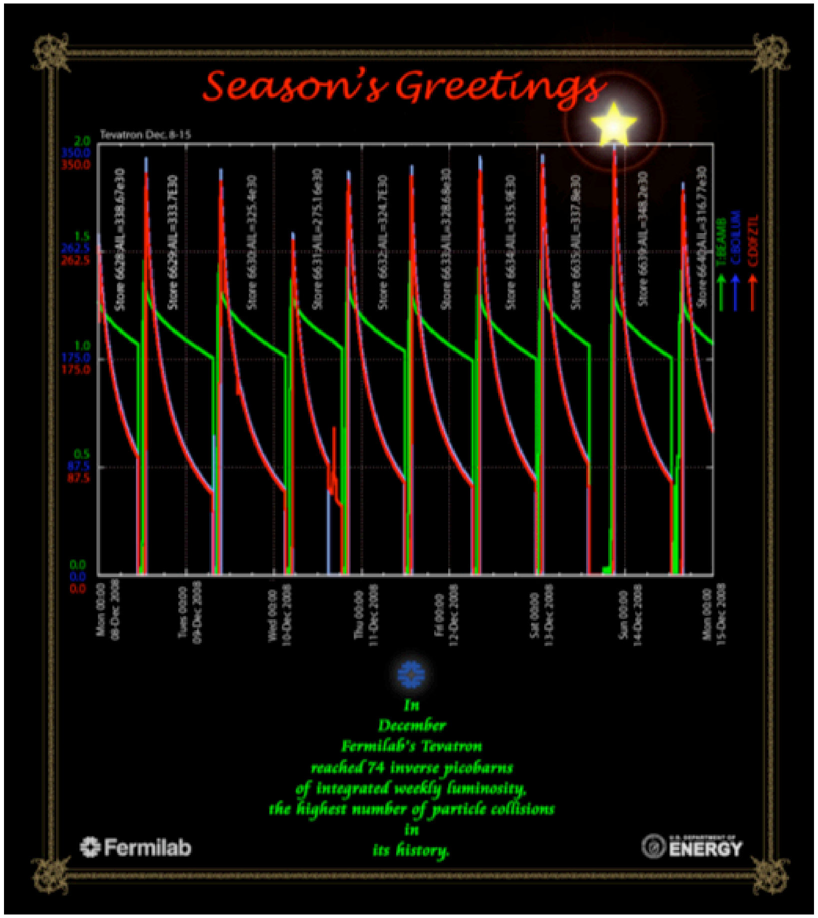
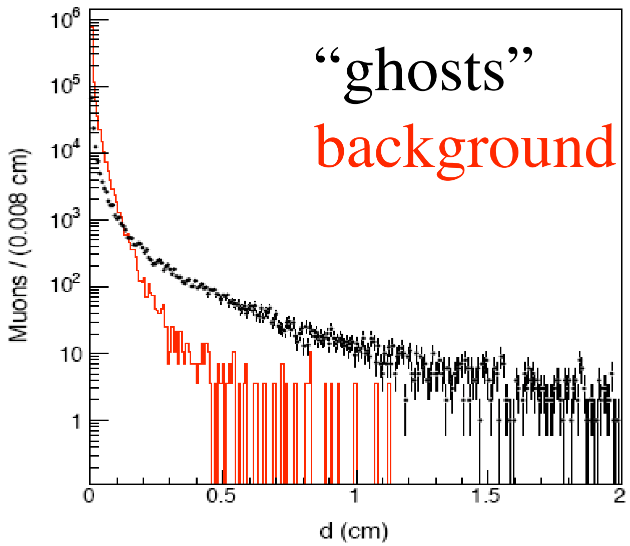


Hopefully either Tevatron or LHC will find something soon!

Backup Slides

CDF “Ghosts” I

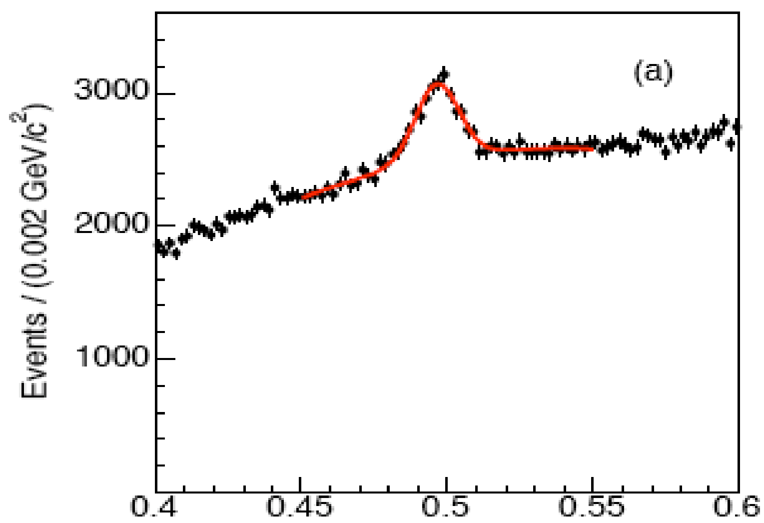


	Data	Background
N(extra μ)≥0	1.42×10^6	1.13×10^6
N(extra μ)≥1	1.41×10^5	0.94×10^5
N(extra μ)≥2	1.02×10^4	0.39×10^4

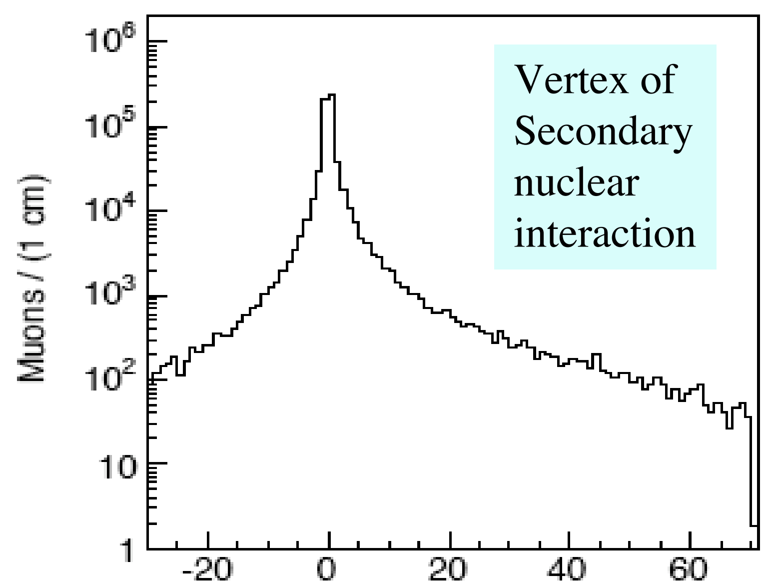
- Recent preprint (0810.5357) discusses excess of muons
  - Muons have anomalously high impact parameters:
    - Lifetime: $\tau \approx 20$ ps (N_{data}=154,000, N_{BG}=69,000)
  - There are extras muons in these events
  - Controversial within CDF (1/3 of default authors withdrew name)

CDF “Ghosts” II

- Unclear if this is due to a signal or a miscalculated background
  - Considered backgrounds due to
    - Muons from
      - b-decays and
      - decay-in-flight (pions/kaons)
    - Punch-through from pions from
      - Primaries
      - Secondaries due to (inelastic) nuclear interactions
      - Pions from secondary decays (e.g. Kshort of Lambda decay)
    - The size of these backgrounds did not account for the ghosts
  - Further studies ongoing in CDF
  - DØ (and maybe HERA also) is having a look as well

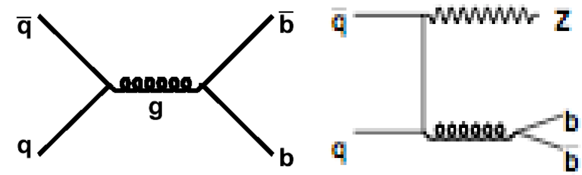


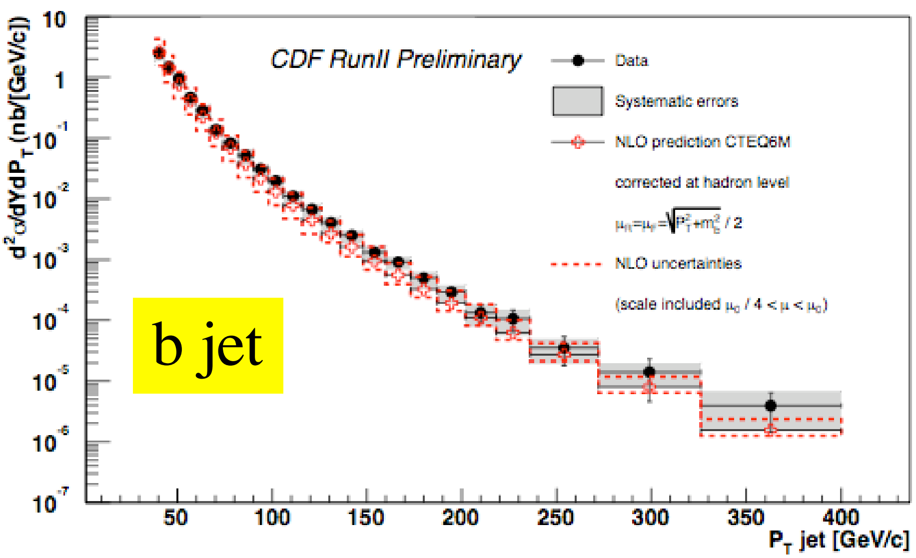
di-muon candidate mass (GeV/c^2)

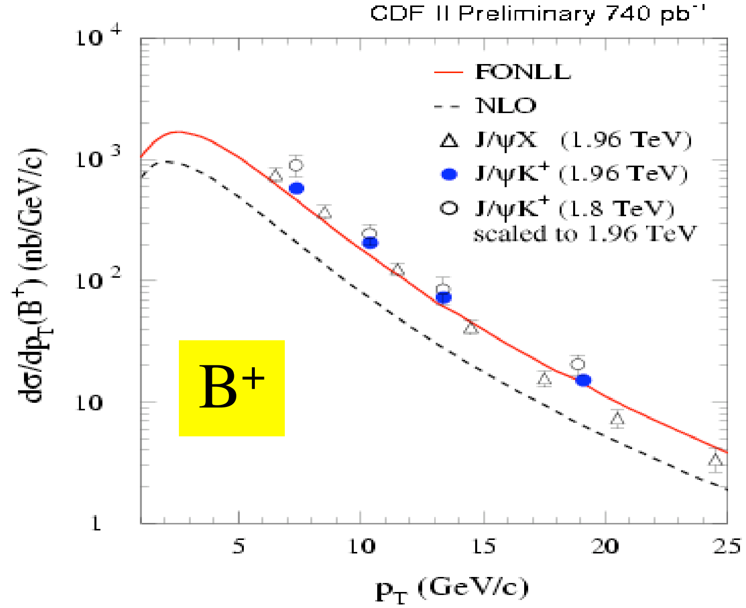


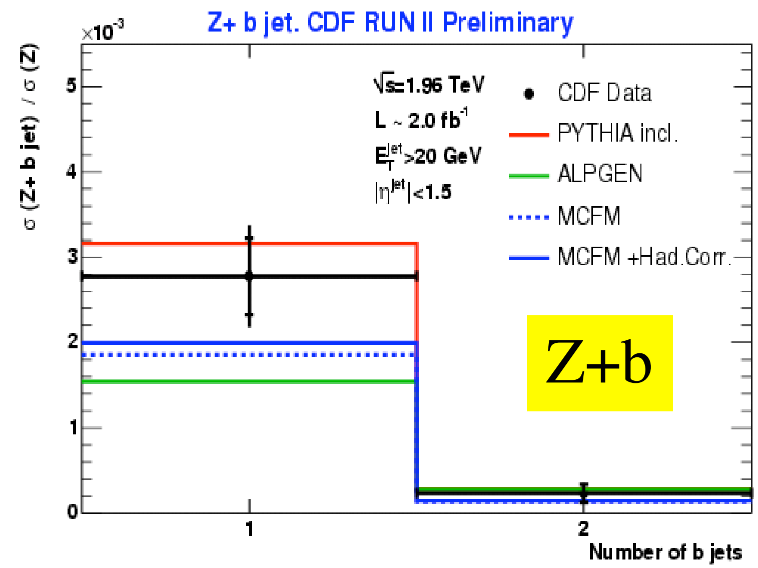
Radial distance of vertex (cm)

b-quark Production









- Measurements of b-jet production in variety of processes
  - Data agree with theoretical predictions within large uncertainties
  - Typical theoretical uncertainties are ~50%

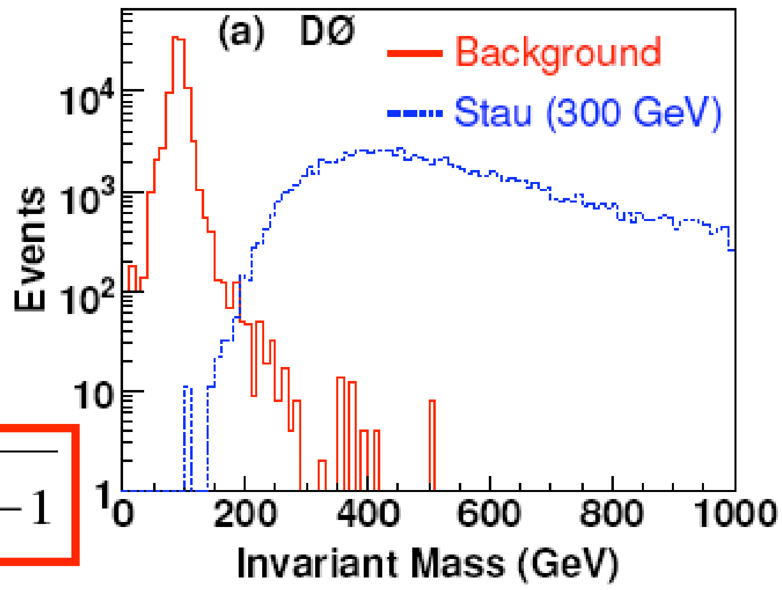
CHAMPS: Charged Massive Stable Particles

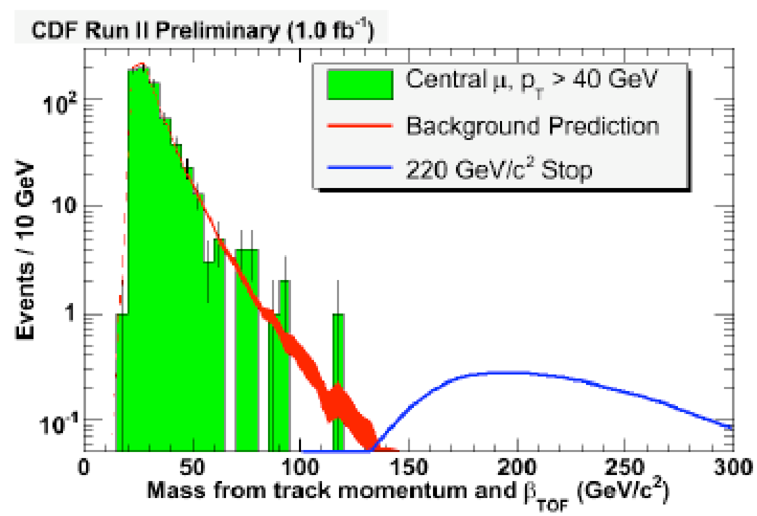
- Scenario:
  - Escape detector completely
- Experimentally:
  - Search for "muons" that travel at β<<1
    - CDF: Time-Of-Flight detector and drift chamber
    - D0: muon system
  - Reconstruct mass from p and β

$$\boxed{m = p\sqrt{1/\beta^2 - 1}}$$

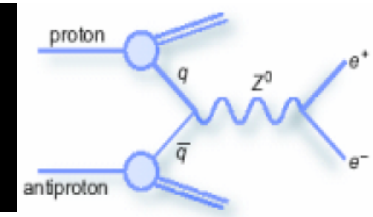
- Cross Section Limits
  (for p_T>40 GeV and $|\eta|$<1, 0.4<β<0.9)
  - Weakly interacting ($\tilde{\tau}$, $\tilde{\chi}_1^{\pm}$):
    - σ<10 fb at 95% CL
  - Strongly interacting (stop):
    - σ <48 fb at 95% CL
    - Assumes stop stays charged up to muon system with P=43±7%

CDF: m($\tilde{t}$)>250 GeV
DØ: m($\tilde{\chi}_1^{\pm}$)>169-204 GeV

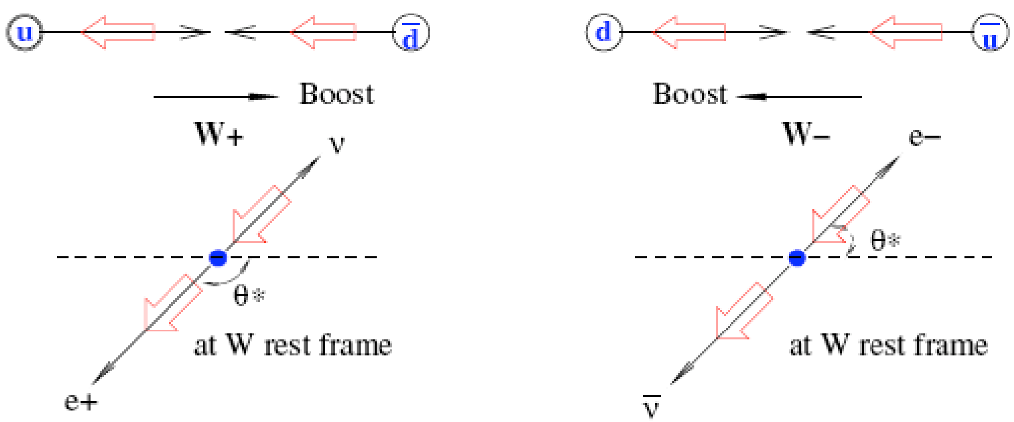


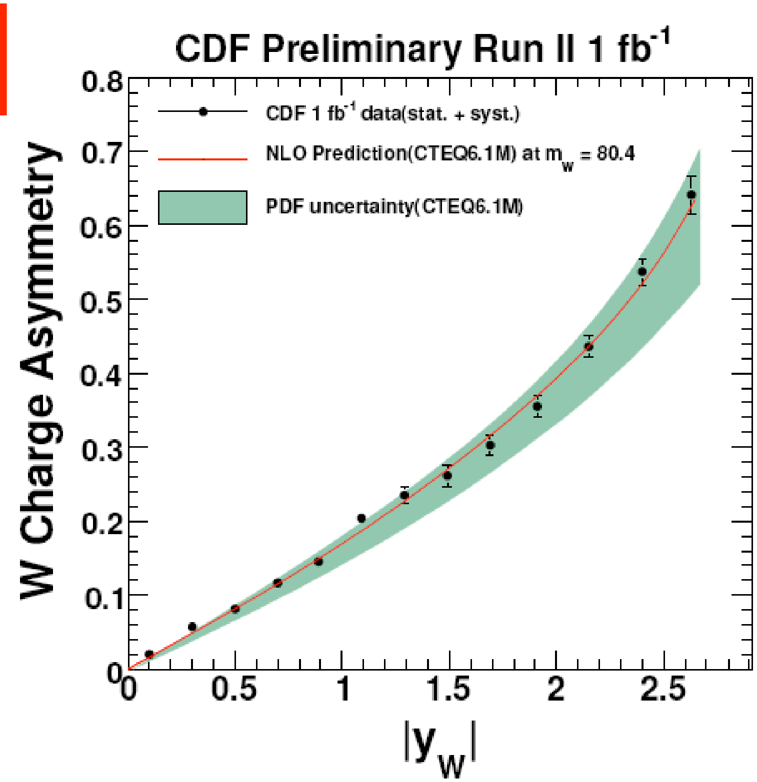


W boson charge asymmetry



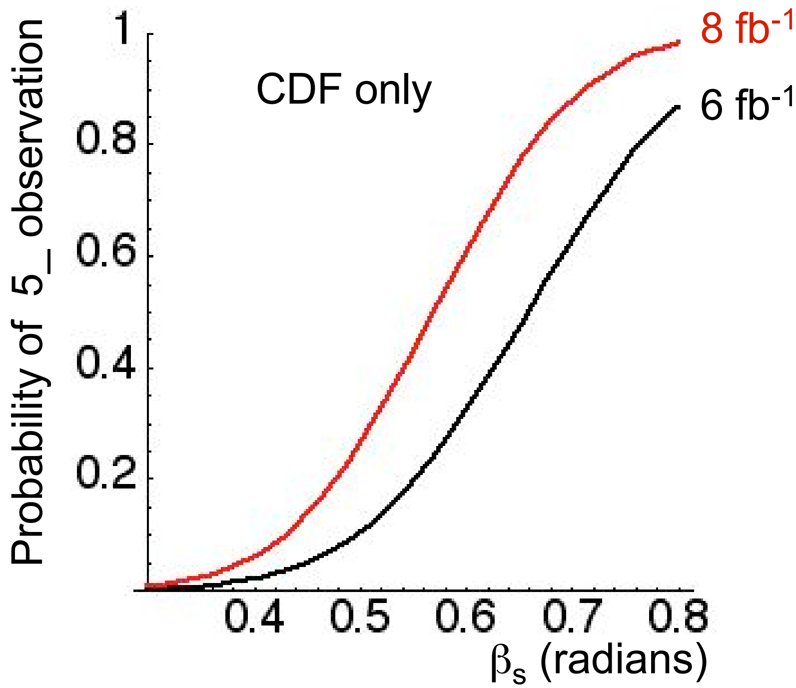
$W^{\pm}$ boost depends on pdf's: $d\ /\ \bar{u}$

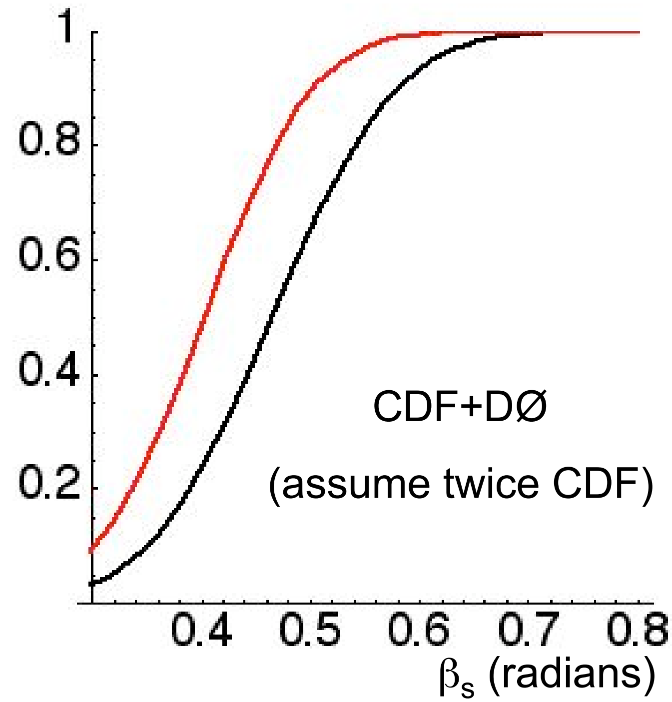




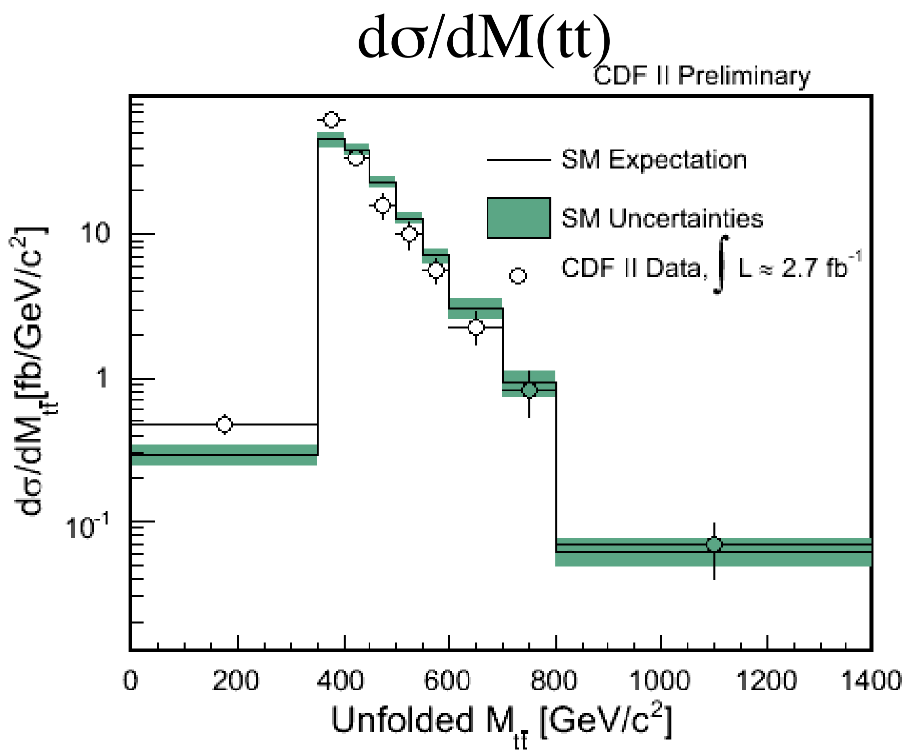
- High precision measurement
  - Constrains parton distribution functions: $d/\bar{u}$
  - Important for measurement of W boson mass

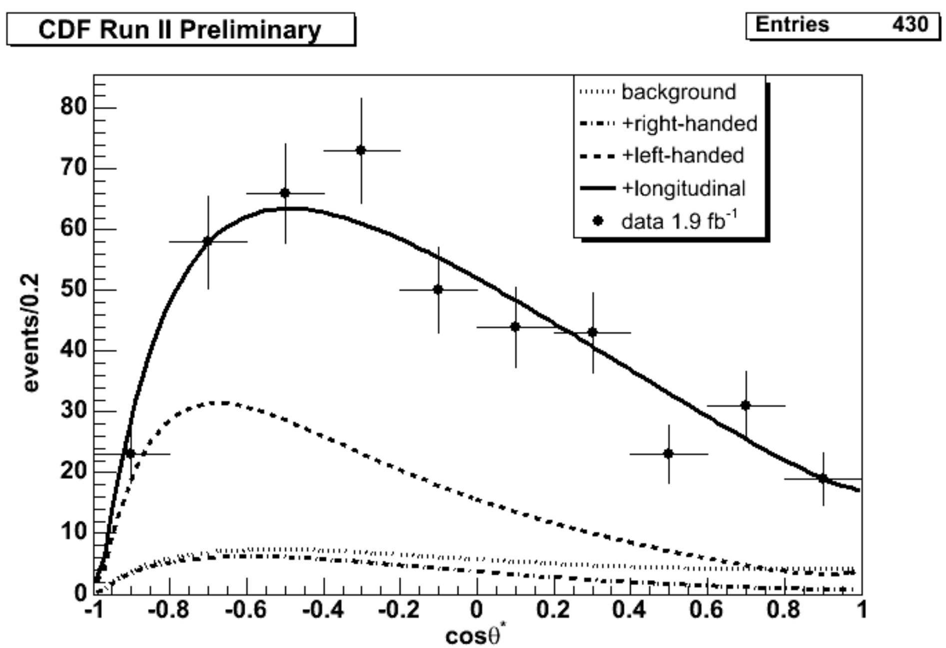
Prospects for Observation β_s

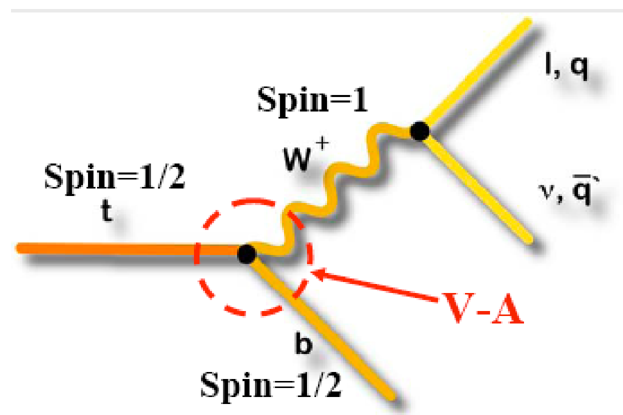




Top Quark: Kinematics+Properties







- Kinematic properties, couplings and charge consistent with Standard Model top production so far
  - Precision typically 10%

H$\rightarrow$WW Cross Section Details

- Still debates ongoing about the theoretical cross section value
  - Used NNLO calculation by Catani *et al.* (JHEP 0307, 028 (2003))
  - With electroweak corrections by Aglietti *et al.* (hep-ph/0610033)
- Anastasiou, Boughezal and Petriello show (0811.3458) that the cross section increases by 11% due to
  - 6%: better knowledge of the top- and b-loop k-factors
  - 3%: better treatment of HF in the most recent CTEQ and MRST pdf's
  - 2%: new calculations of electroweak effects
- There is also a recent paper by T. Becher *et al.* (0809.4283): "resummed NNLO"
  - Increases cross section by 13%
- Any help with sorting this out would be very much appreciated!

Diffractive Dijets