Tevatron Electroweak Results and Top Quark Properties

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On behalf of the CDF and DØ Collaborations

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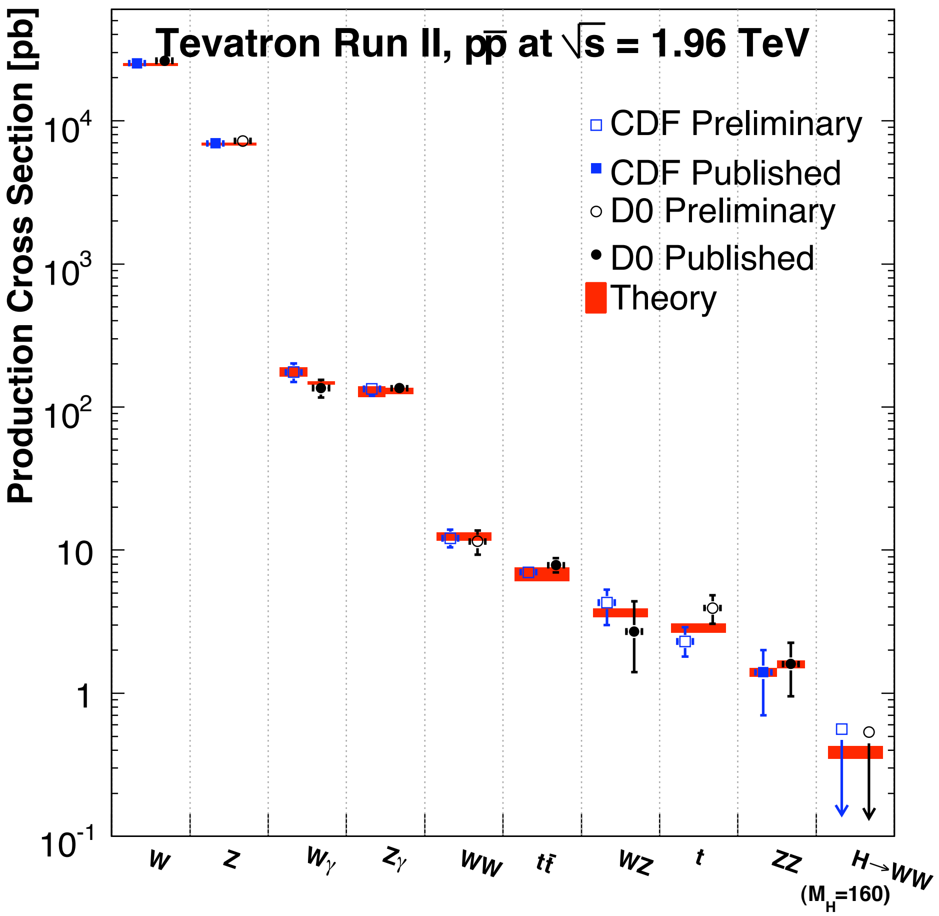
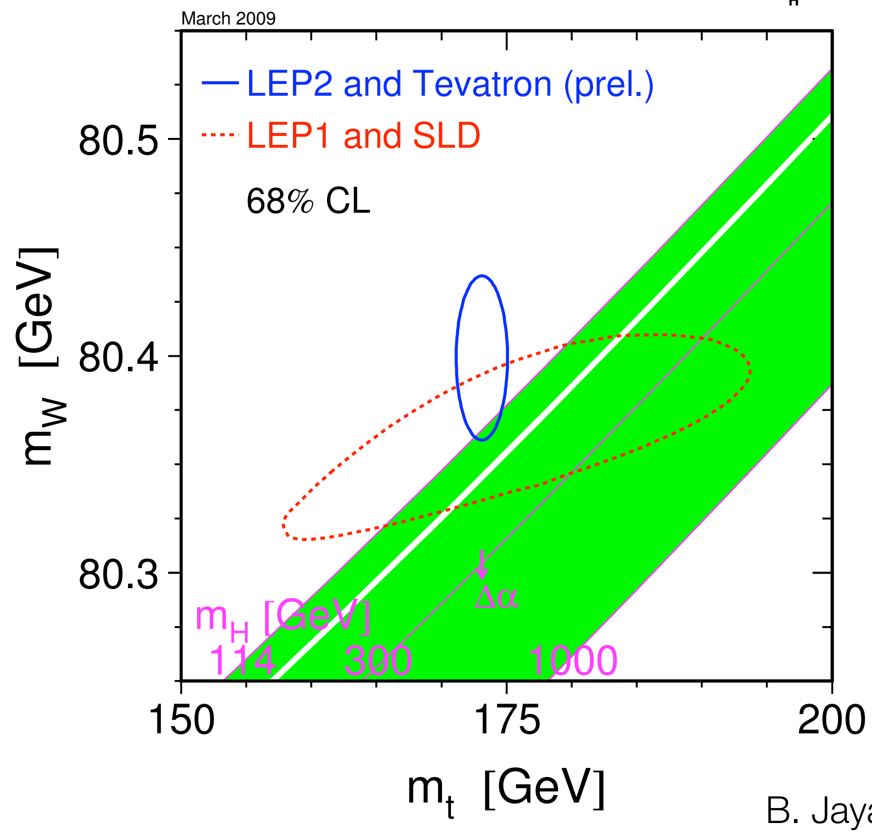
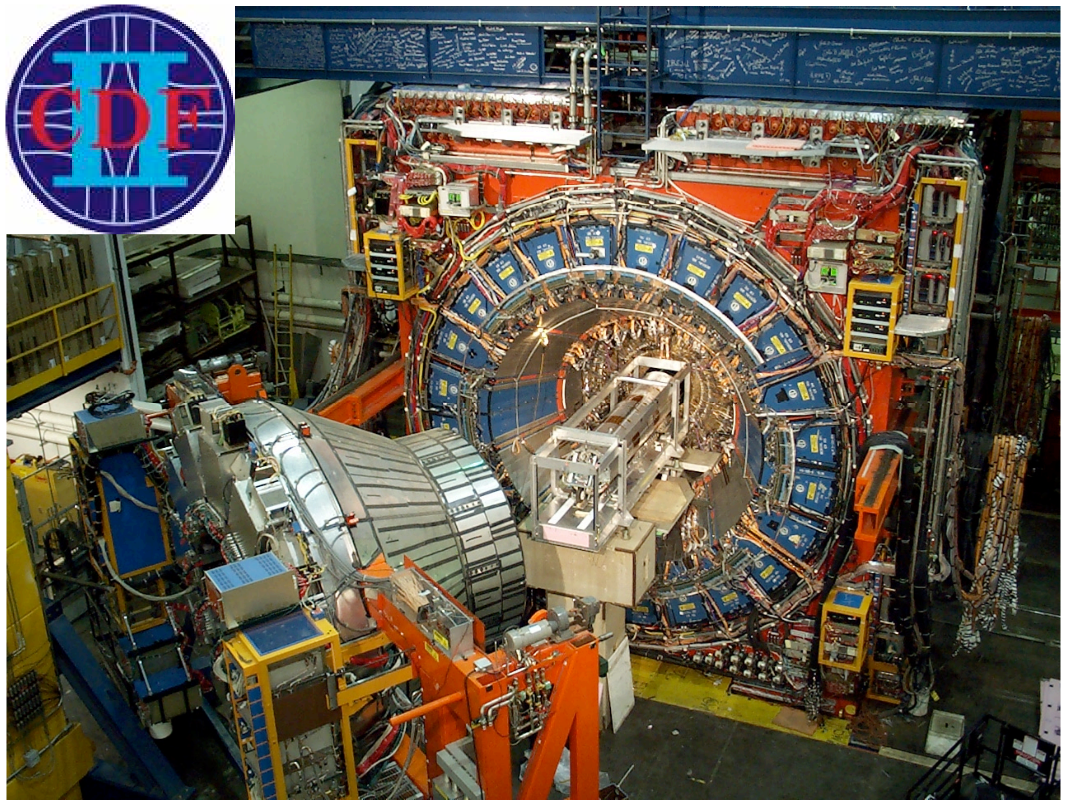
High p_T physics at the Tevatron

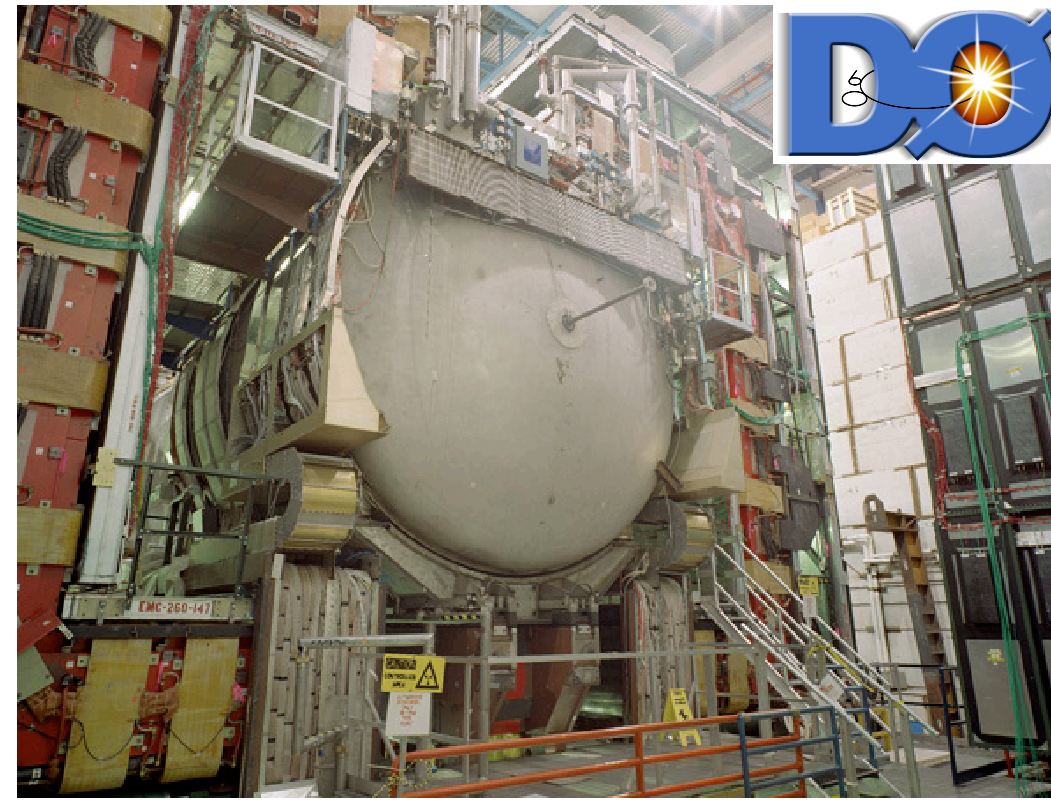
- Robust high-p_T physics program spanning a wide range of cross sections
  - High precision measurements to recent discoveries
- Measurements allow us to probe the standard model
  - Top quark gone from discovery to precision measurement in a decade
  - All SM diboson modes observed in Run II
- Sets us up to look for the Higgs
  - Top and *W* masses constrain the mass of the SM Higgs
  - Measurements shown here are important backgrounds for Higgs searches
  - See W. Fisher's talk for latest on Higgs searches





The experiments

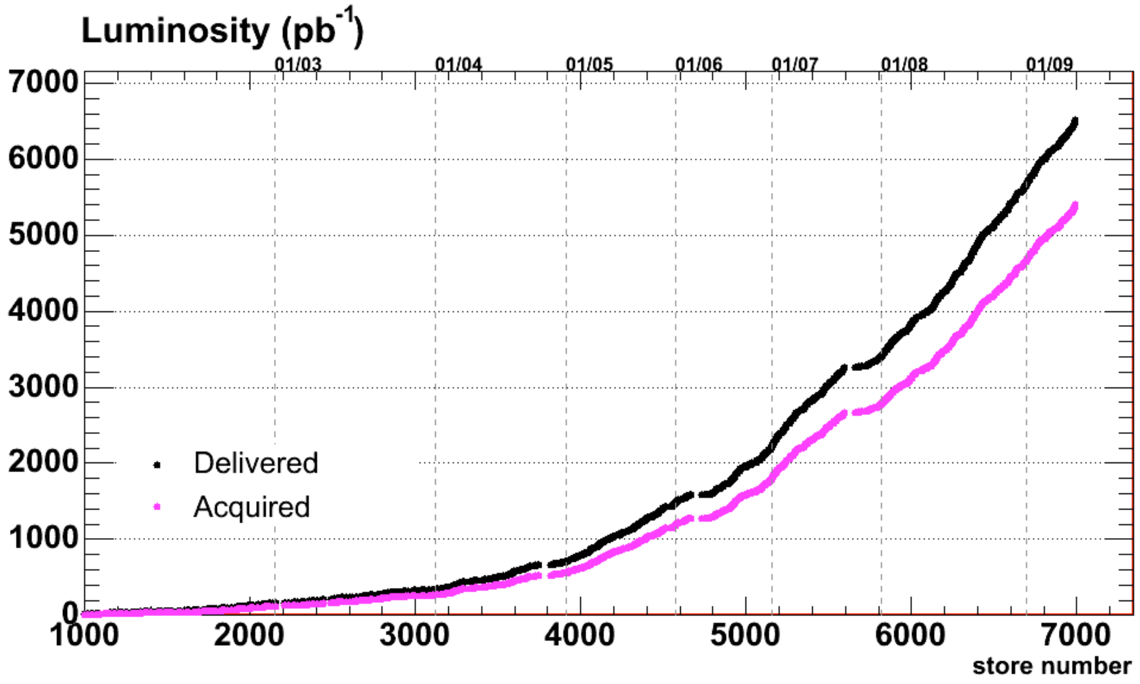




- General purpose detectors
  - Nearly all aspects used in electroweak and top physics analyses
- “Mature” experiments
  - Stable running and no major upgrades
  - Allows us to focus on acquiring data and analyzing it

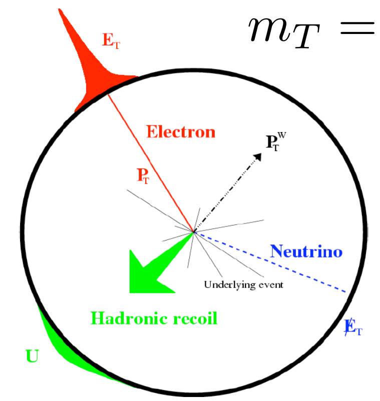
Speaking of data...

- Excellent accelerator performance
  - Inst. lum. exceeding 3×10^{32} $cm^{-2}s^{-1}$
  - Over 6 fb^{-1} delivered to each experiment
  - Results shown today use ≤ 3.6 fb^{-1}
- Every bit of data helps
  - Even analyses with "abundant" statistics (*e.g. W* mass)
- Many thanks to the Fermilab accelerator division!



Precision physics: measuring the *W* mass

$$m_T = \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos \Delta\phi_{\ell\nu})}$$



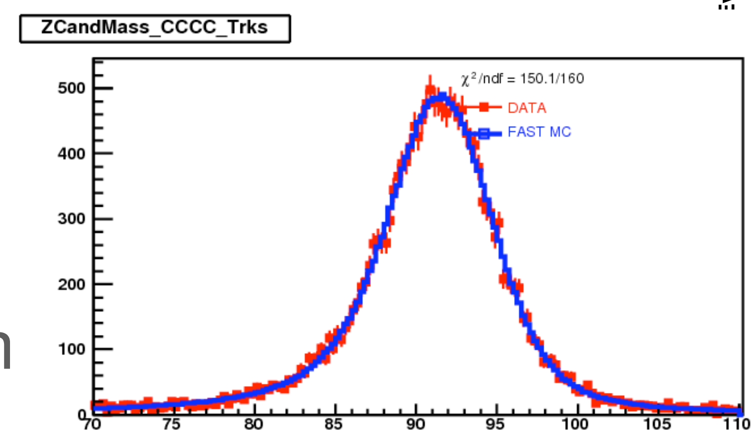
- At hadron colliders, rely on transverse mass, m_T
  - Requires precise measure of charged lepton p_T and hadronic recoil
- Use well-measured resonances to calibrate
  - *Z* boson, *J*/ψ, ϒ
  - Requires detailed knowledge of detectors
- Perform fits to templates generated from calibrated simulation
- First Run II result from CDF using 200 pb^{-1}

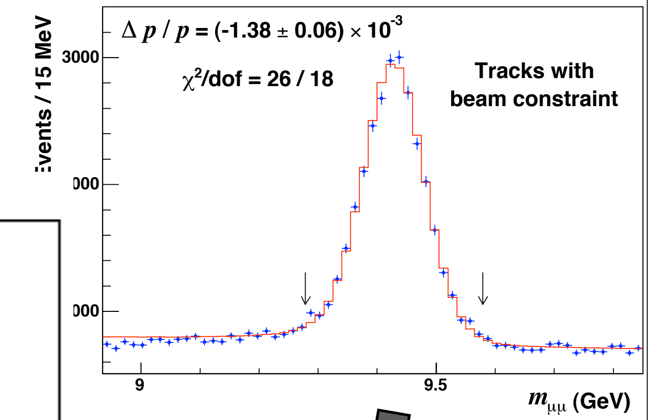
m_W=80413±34(stat)±34(syst) MeV/c^2

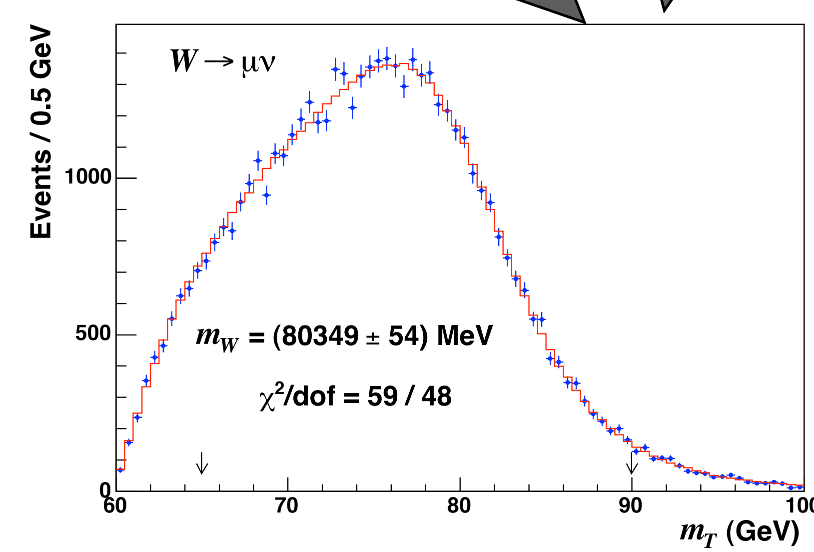
Published:

Phys. Rev. Lett. **99**, 151801 (2007)

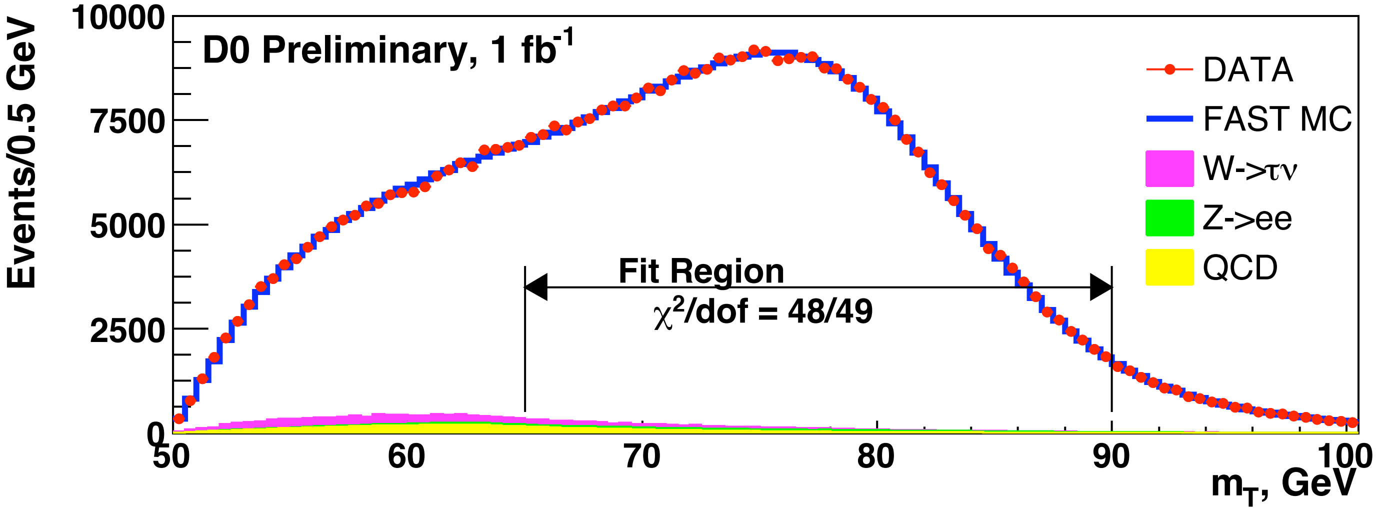
Phys. Rev. D. **77**, 112001 (2008)

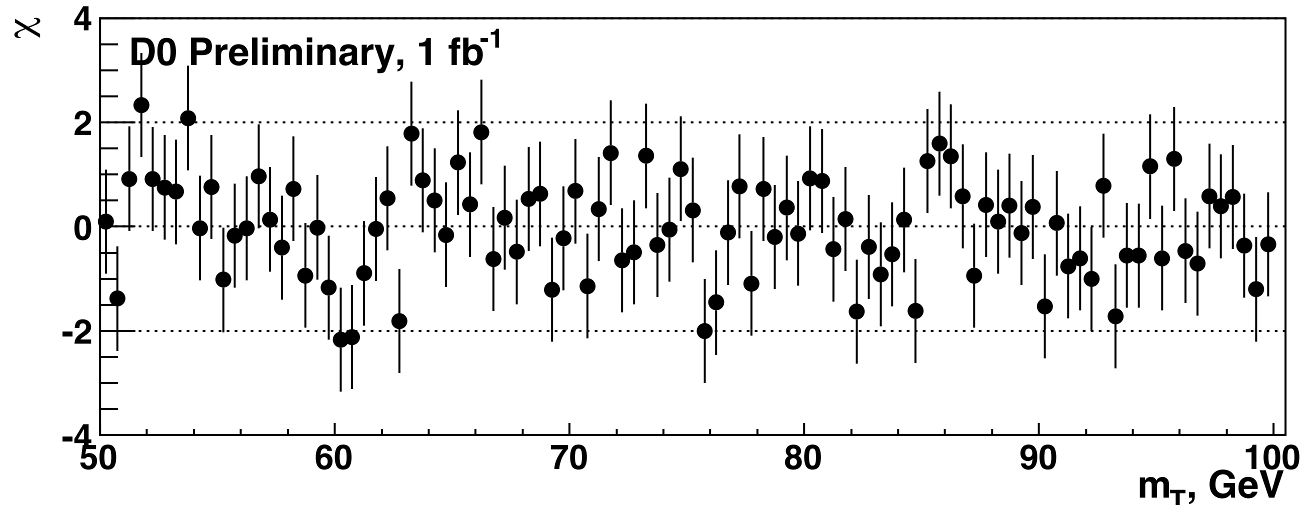






W mass measurement: DØ





m_T	80.401±0.044 GeV
p_T	80.400±0.048 GeV
missE_T	80.402±0.050 GeV

See J. Zhu's talk

Source	$\sigma(m_W)$ MeV m_T
Experimental	
Electron Energy Scale	34
Electron Energy Resolution Model	2
Electron Energy Nonlinearity	4
W and Z Electron energy loss differences	4
Recoil Model	6
Electron Efficiencies	5
Backgrounds	2
Experimental Total	35
W production and decay model	
PDF	9
QED	7
Boson p_T	2
W model Total	12
Total	37

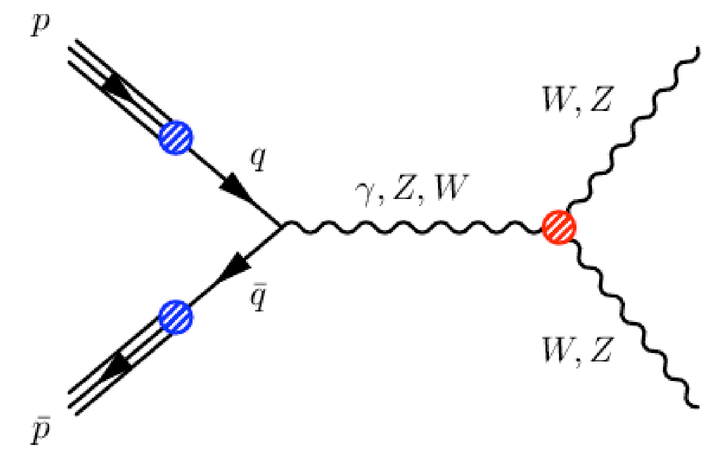
- Electron channel with 1 fb^{-1}
- Combines all 3 fits

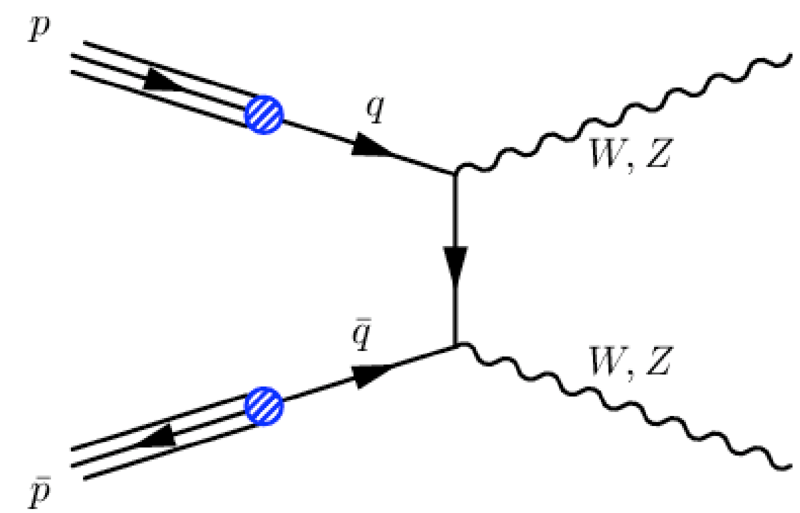
m_W=80401±21(stat)±38(syst) MeV/c^2

- **Single best** measurement of m_W
- Both CDF and DØ looking at larger datasets
  - ~25 MeV precision

Diboson physics

- Important test of standard model
  - Production rates would be altered by anomalous triple guage couplings
    - *ZZZ, ZZγ, Zγγ* not permitted in SM
- Critical for SM Higgs search
  - Similar final state to dominant decays of both light and heavy SM Higgs bosons
- Provided a series of natural benchmarks for Run II analyses in the electroweak sector
  - *WW*, *WZ*, and *ZZ* **all observed** with 5σ significance at Tevatron



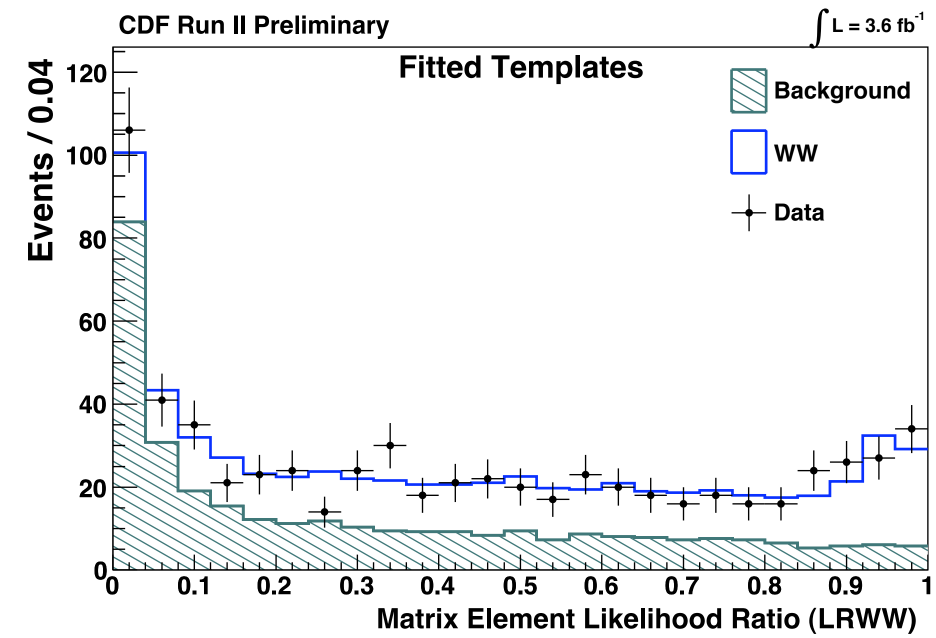


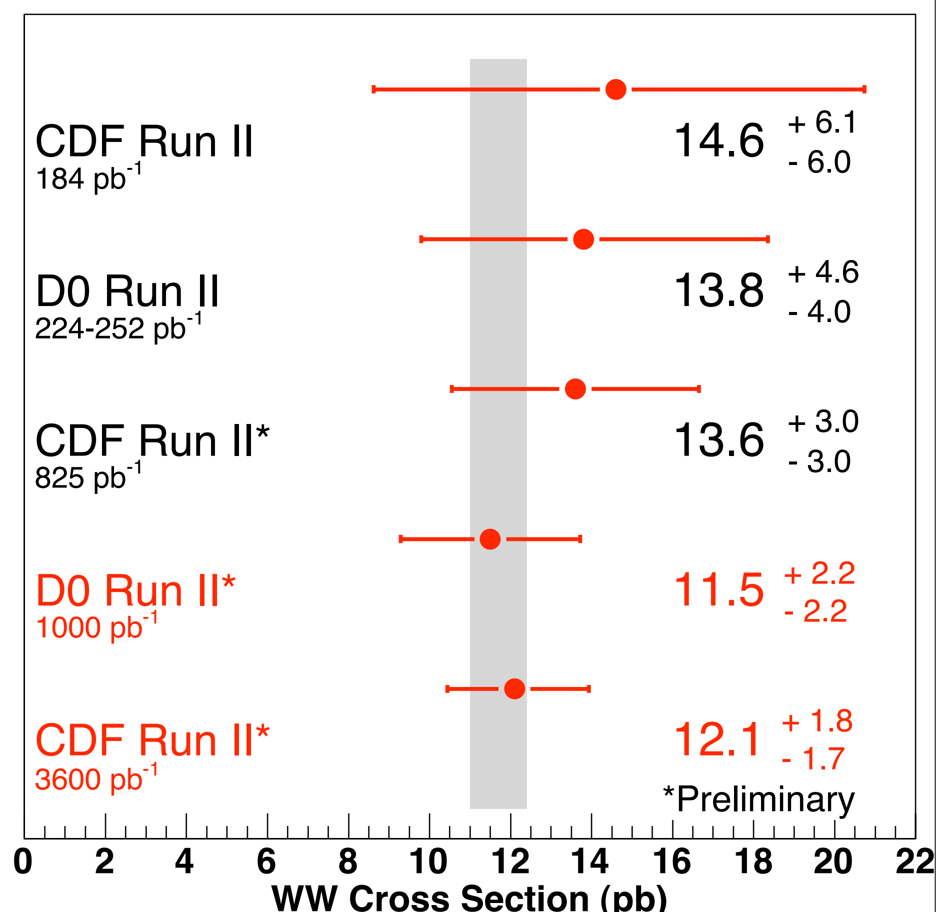
WW production

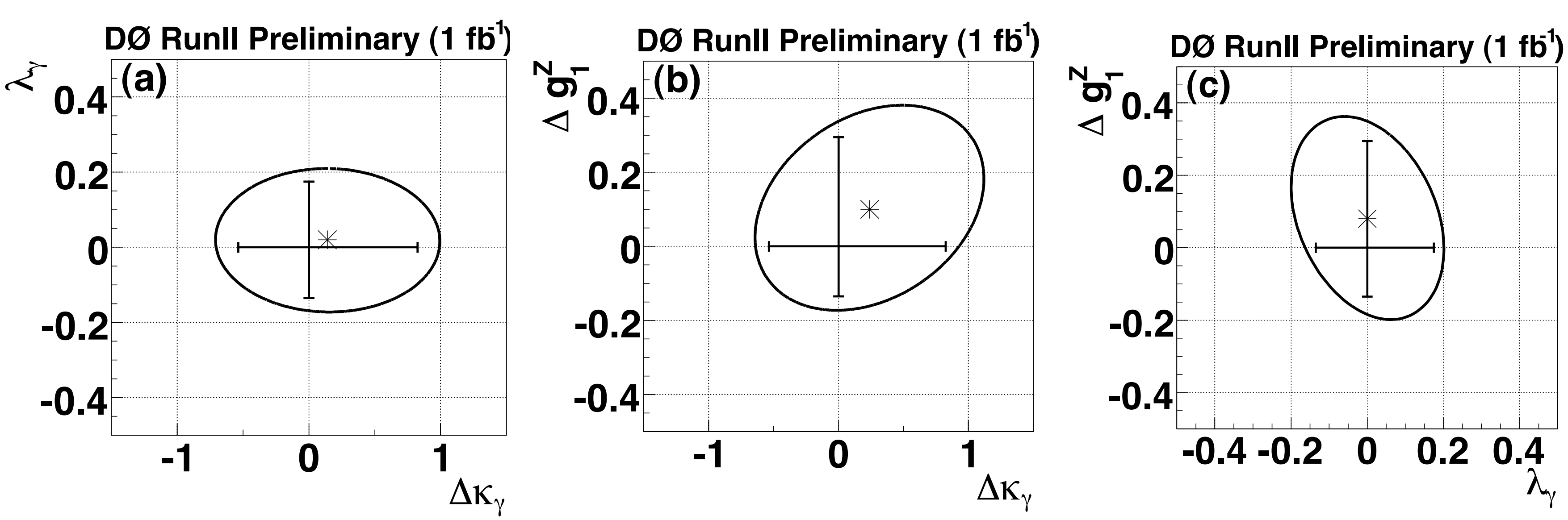
- Offers a clean and relatively high statistics final state
  - 2 charged leptons and missing E_T
- CDF analysis uses matrix element-based likelihood
  - Based on $H \to WW$ analysis
- Most precise measurement **twice** in April:

  DØ(1.0 fb^{-1}) σ_{WW}=11.5±2.1(stat)±0.7(syst) pb

  CDF(3.6 fb^{-1}) $\sigma_{WW}=12.1\pm0.9(\mathrm{stat})^{+1.6}_{-1.4}(\mathrm{syst})$ pb
- DØ analysis places new limits on anomalous TGCs



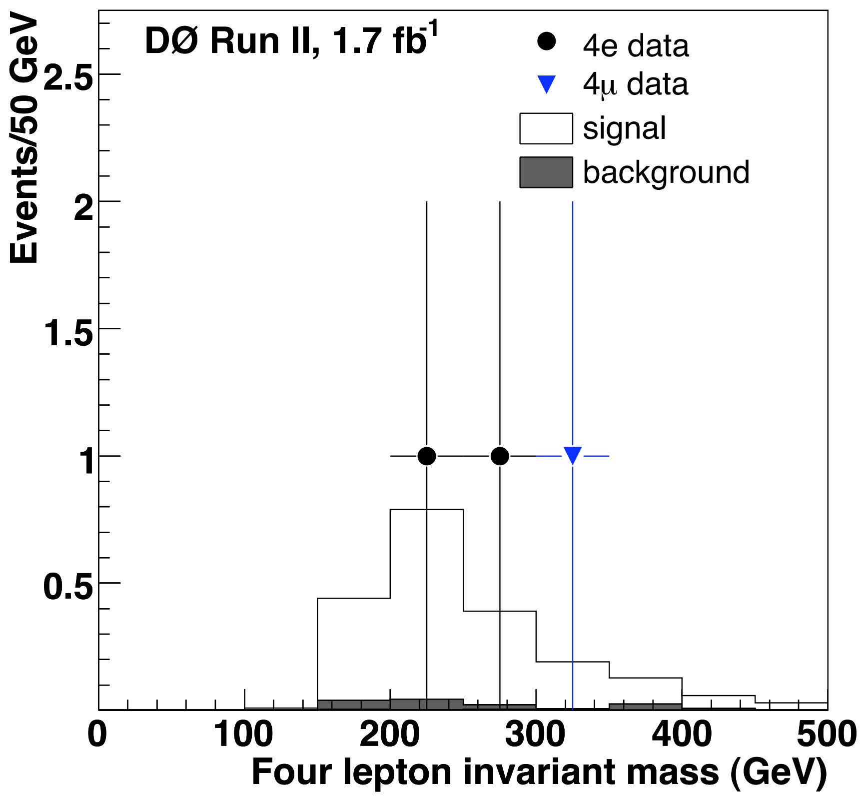




ZZ production

- Smallest cross-section of SM diboson states
  - 4 charged leptons: unmistakable signature
  - 2 charged leptons+2 neutrinos: added statistics
- SM prediction: $\sigma_{ZZ} = 1.4 \pm 0.1$ *pb*
- Last year
  - CDF: $\sigma_{ZZ} = 1.4^{+0.6}_{-0.7}$ pb (4.4σ)
- DØ
  - 4l (1.7 fb^{-1}, Run 2b): $\boldsymbol{\sigma_{ZZ} = 1.75^{+1.27}_{-0.86}}$ **pb (5.3σ)**
  - 2l+2ν (2.7 fb^{-1}): **σ_{ZZ}=2.01±0.93(stat)±0.29(syst)pb (2.6σ)**
- Combined (includes 1 fb^{-1} Run 2a 4l analysis):

  σ_{ZZ}=1.60±0.63(stat)±0.17(syst) pb
  - Significance of **5.7σ** First observation!



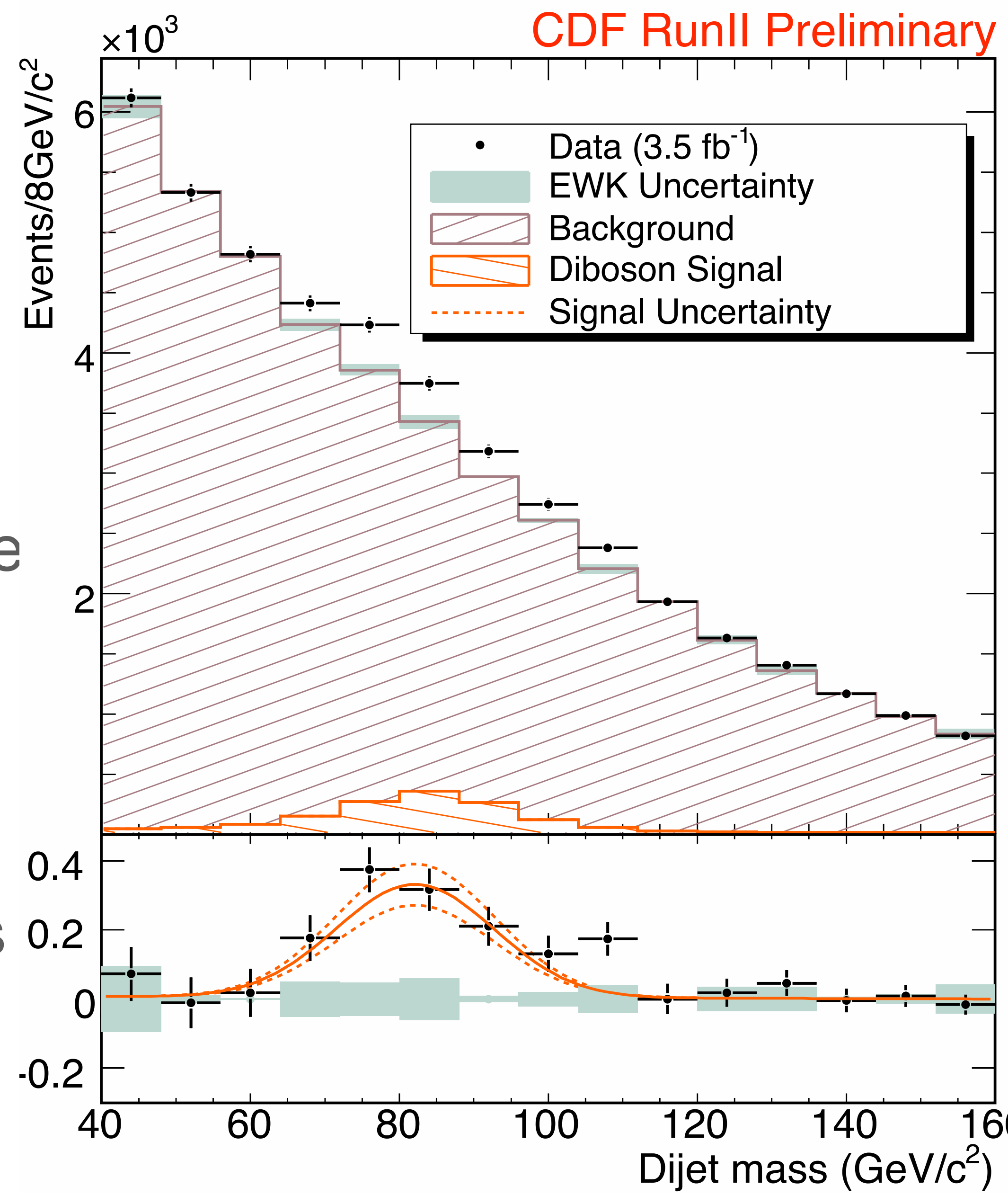
Phys. Rev. Lett. **101**, 171803 (2008)

WW/WZ/ZZ with a hadronic final state

- Search for *VV* (*V*=*W*,*Z*) where one boson decays hadronically
  - Much larger background
  - Topologically very similar to low mass SM Higgs (*WH* and *ZH*)
- Evidence presented by DØ using 1 fb^{-1}
  - Require one charged lepton: *lνqq'* final state
  - σ_{VV}=20.2±4.5 pb (4.4σ)
- CDF analysis using 3.5 fb^{-1}
  - No charged lepton requirement
  - Allows for νν*qq'* as well as *lνqq'* final states
- Observe 1516±239(stat)±144(syst) diboson events

σ_{VV}=18.0±2.8(stat)±2.4(syst)±1.1(lumi) pb

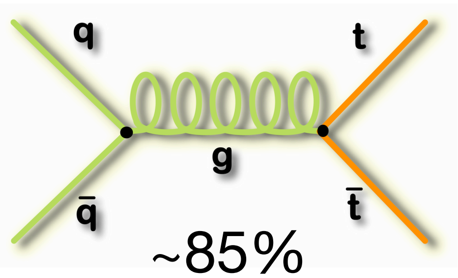
  - Significance of **5.3σ** First observation!
  - Theory: σ_{VV}=*16.8±0.5pb*

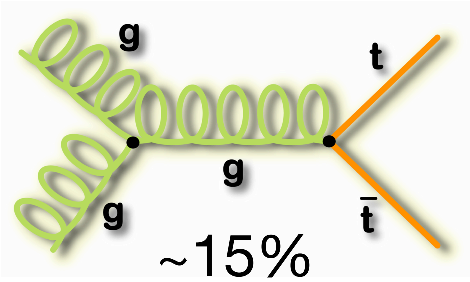


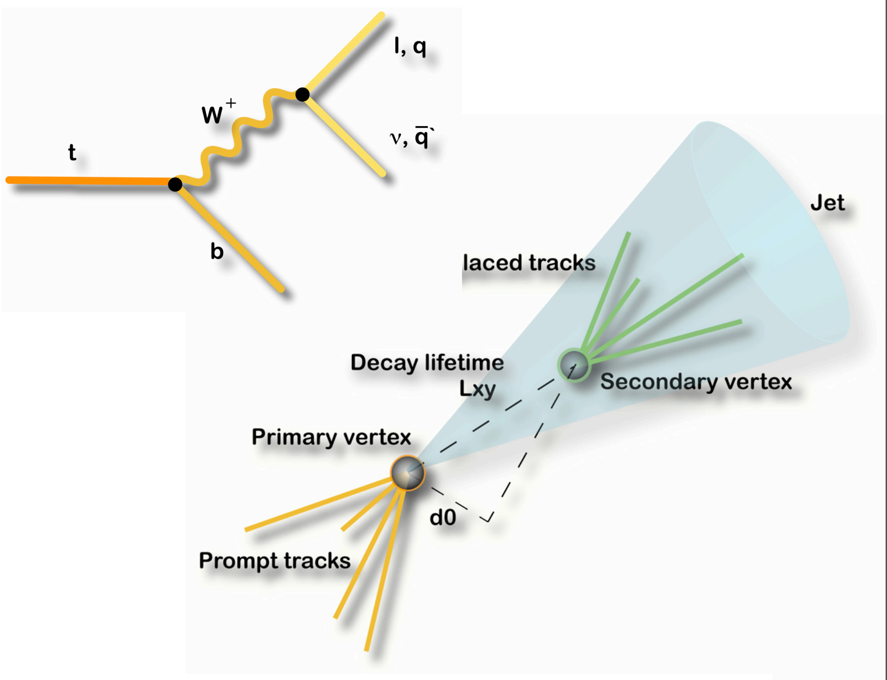
W&C seminar this Friday

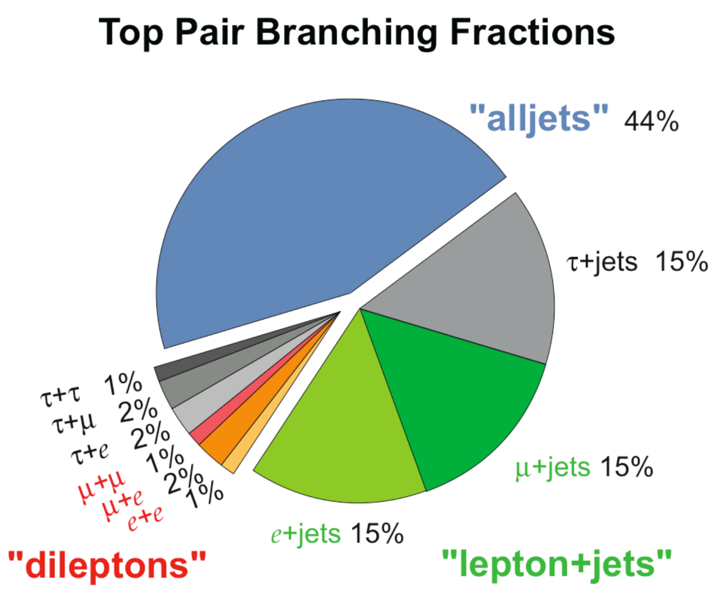
Top pair production and decay at the Tevatron

- QCD pair production
  - Dominant source of top quarks for study [σ=6.7±0.8pb @175 GeV]
- Decay
  - Top quark decays before hadronization
  - *t* → *Wb* ~100%
    - Can identify *b* quarks from secondary decay
  - Top pair decays defined by decay of *W*
    - “dilepton”: both *W*s decay leptonically
    - “lepton+jets”: one *W* to quarks and other to leptons
    - “all jets/hadronic”: both *W*s to quarks
- Cross section measurements
  - Inconsistency across channels could indicate new physics
  - Provides sample compositions for other measurements







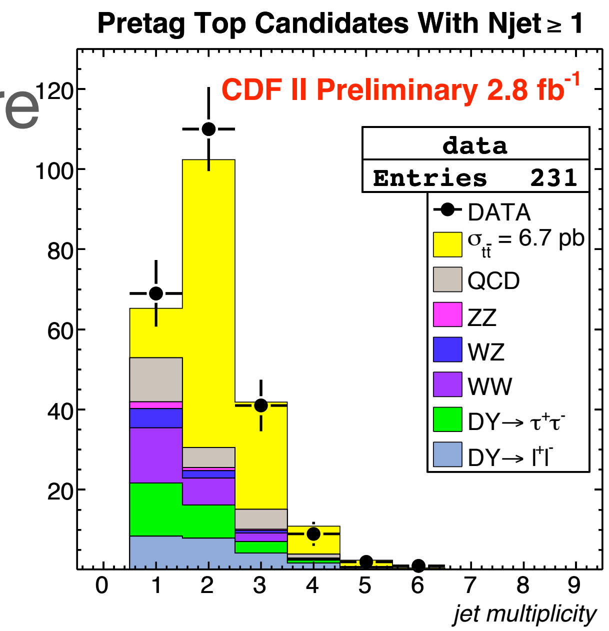


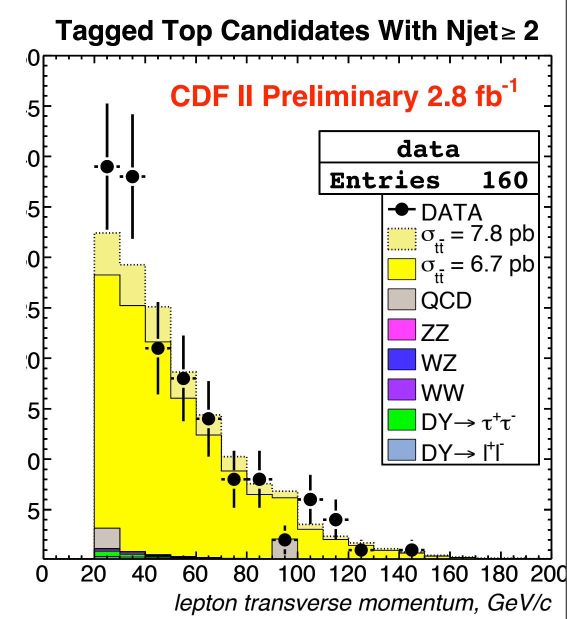
Top pair cross section: dilepton channel

- Two well-identified charged leptons (*e* or μ)
  - *b*-tagging not required to have relatively pure sample
  - Requiring a tag results in almost pure signal sample
- CDF analysis in 2.8 fb^{-1} in both samples

σ_{pre}=6.7±0.8(stat)±0.4(syst)±0.4(lumi)pb

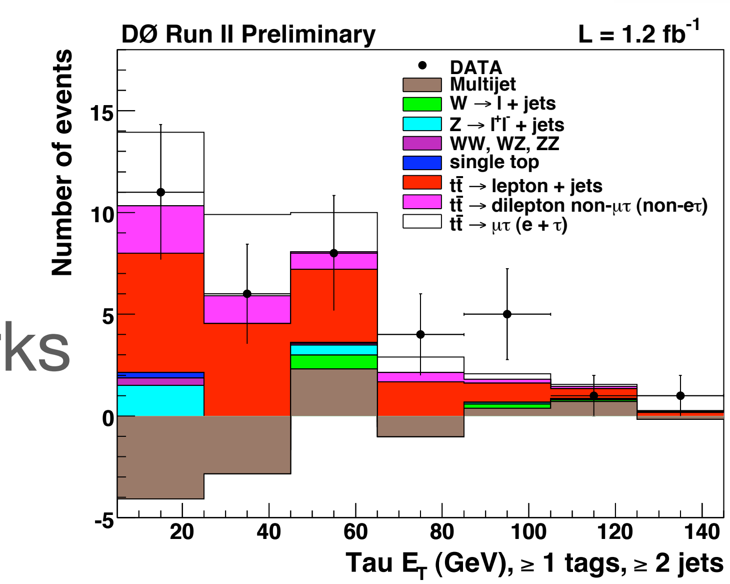
σ_{tag}=7.8±0.9(stat)±0.7(syst)±0.4(lumi)pb

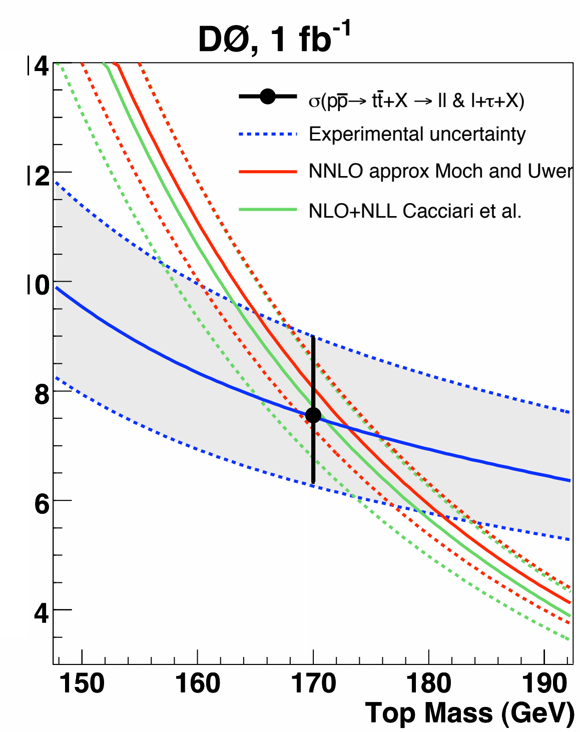




- Exclusive sample: one τ and one *e* or μ
  - Search for hadronically decaying τ
  - NN tagging algorithm to identify *b* quarks
- DØ analysis with 2.1 fb^{-1}
- $\sigma_{l+\tau}=7.32^{+1.34}_{-1.32}$ (stat)$^{+1.20}_{-1.06}$(syst)±0.45(lumi)pb
  - Combined with other dilepton results [1fb^{-1}]:

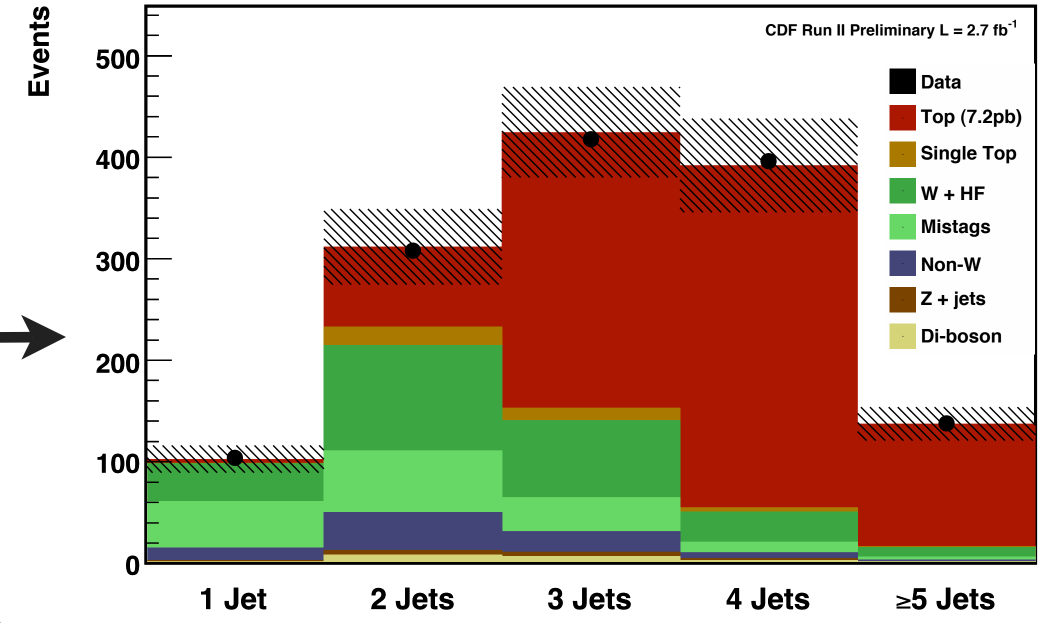
$\sigma_{ll}=7.1\pm1.0$(stat)$^{+0.7}_{-0.6}$(syst)$^{+0.6}_{-0.5}$(lumi)pb





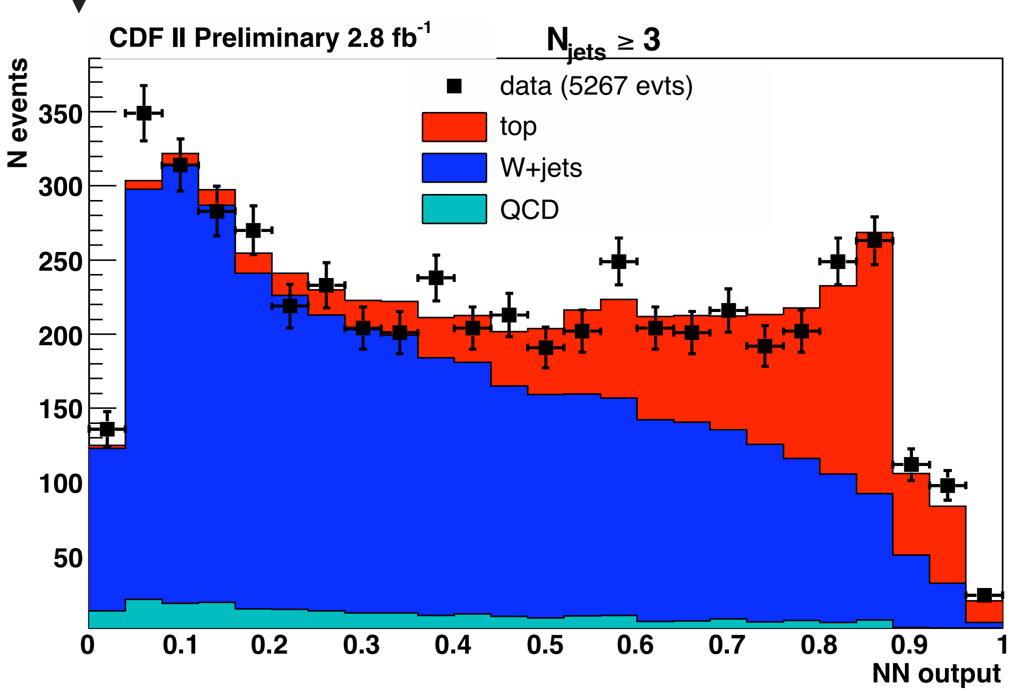
Top pair cross section: lepton+jets

- One lepton, 3 or more jets: “golden channel”
- Reducing background
  - Identify *b*-jets via tags, or
  - Topological separation of signal and background via neural net



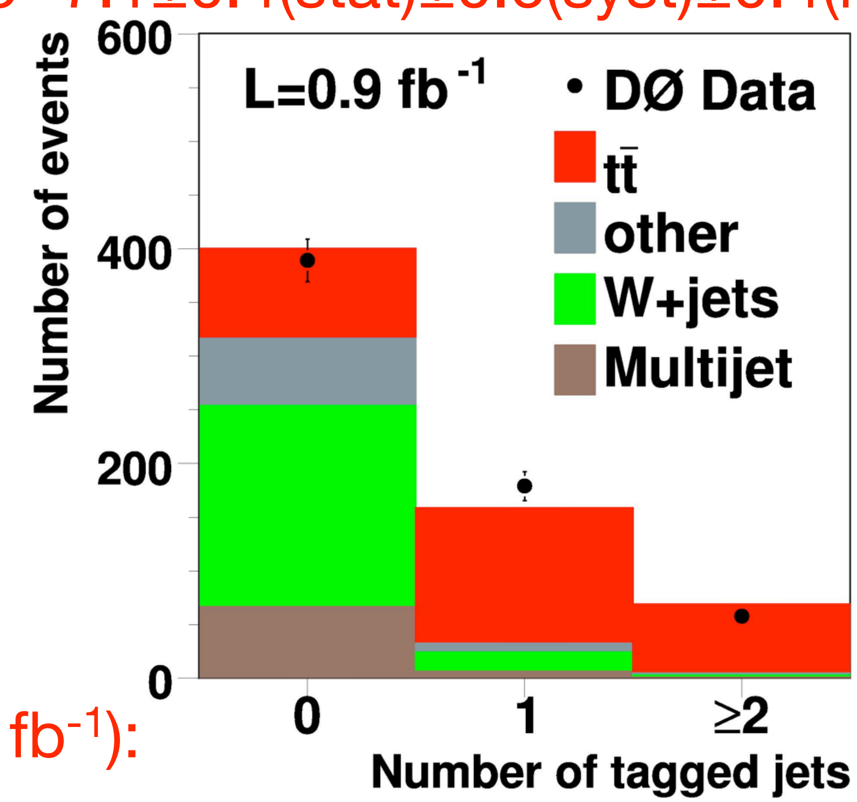
CDF (2.7 fb^{-1}): **Δσ/σ~12%**

σ=7.1±0.4(stat)±0.6(syst)±0.4(lumi)pb



CDF (2.8 fb^{-1}): **Δσ/σ~10%**

σ=7.1±0.4(stat)±0.4(syst)±0.4(lumi)pb



DØ (0.9 fb^{-1}):

σ=7.4±0.5(stat)±0.5(syst)±0.5(lumi)pb

Δσ/σ~12%

Reducing systematic uncertainty

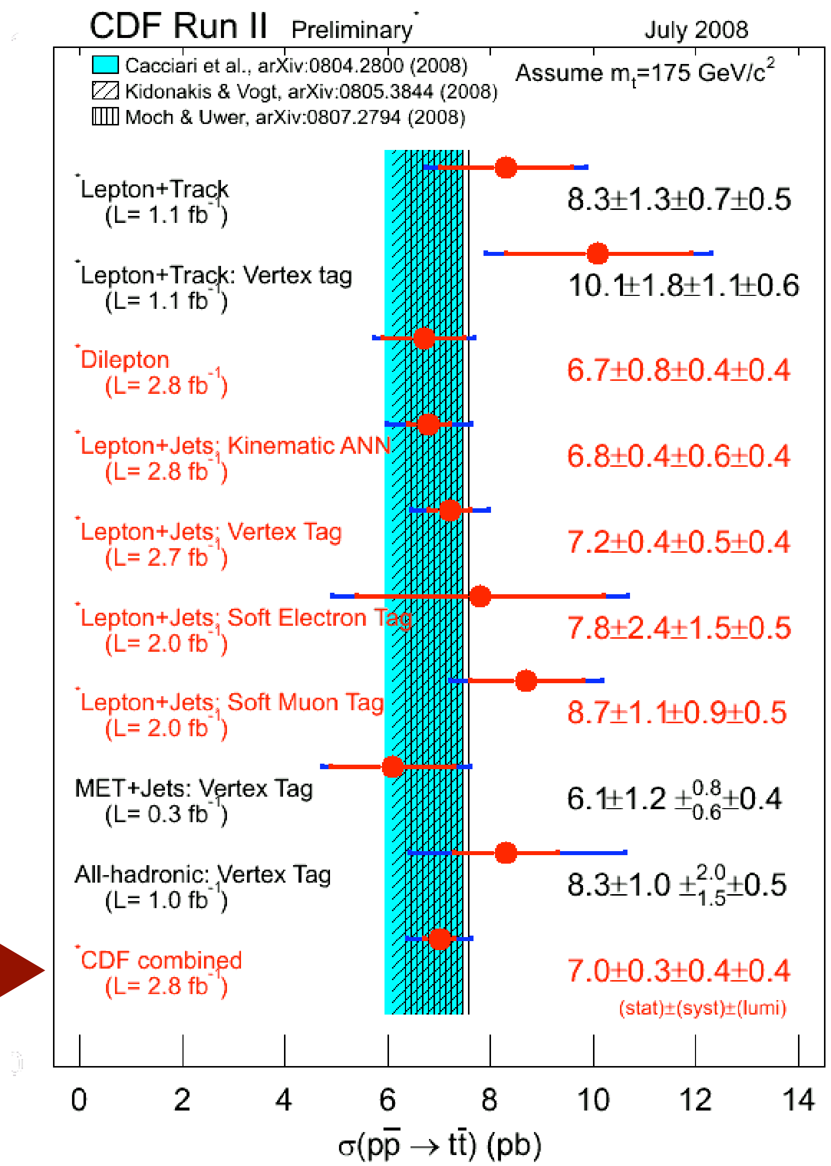
- Uncertainty from luminosity begins to dominate
  - σ=7.1±0.4(stat)±0.4(syst)±0.4(lumi) pb
- Reduce by normalizing to *Z* cross section

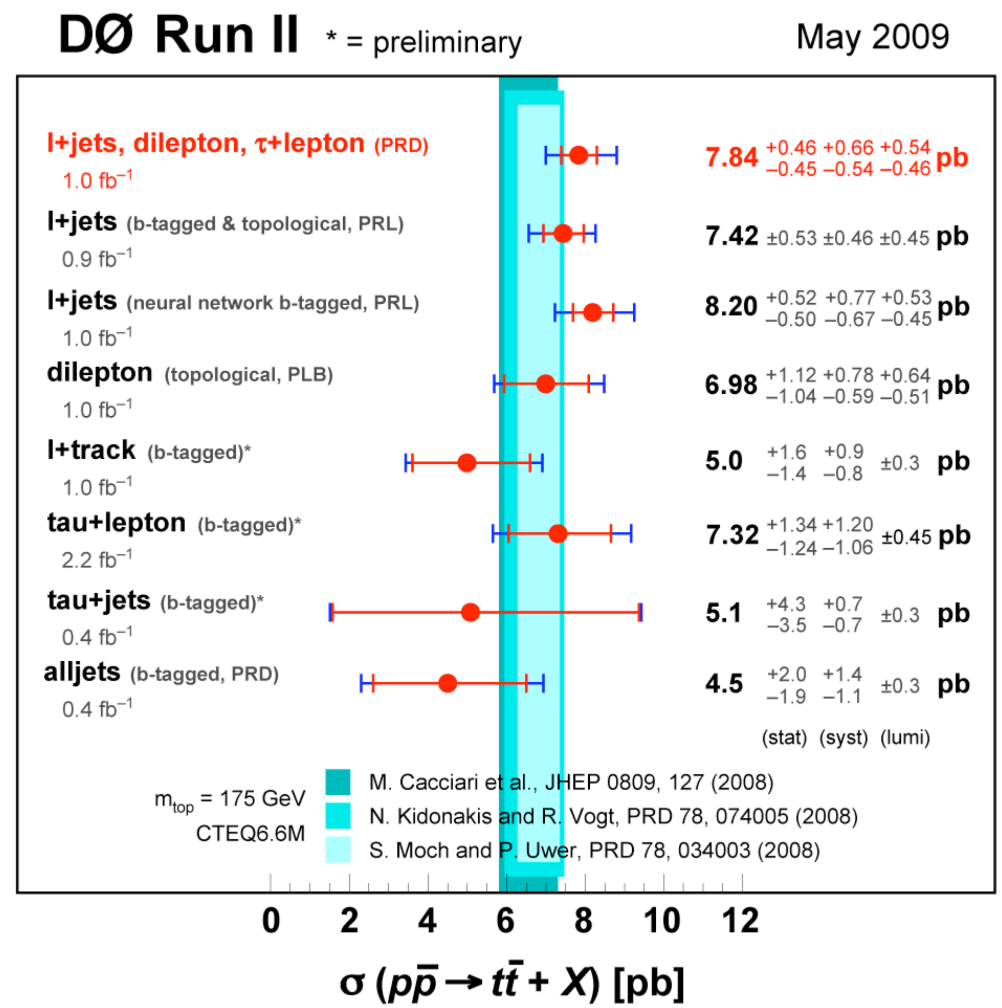
$$\sigma_{t\bar{t}} = R \cdot \sigma_Z^{theory}$$

  - Measure *R* in ttbar data sample and multiply by *Z* cross section from theory
  - theory: σ_Z= 251.3 ± 5.0 pb [J. Phys. G: Nucl. Part. Phys. 34 (2007) 2457]

- Results:
  - Topological (NN): σ=6.9±0.4(stat)±0.4(syst)±0.1(theory)pb
  - b-tagged: σ=7.0±0.4(stat)±0.6(syst)±0.1(theory)pb
- Relative error on NN cross-section is **8.3%**
  - Comparable with error from theory

Cross section summary

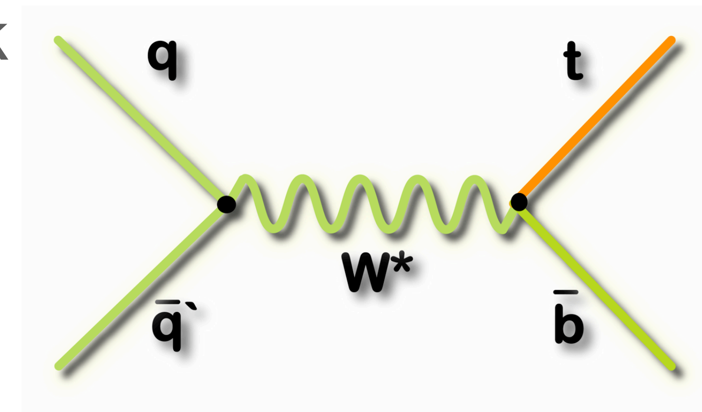


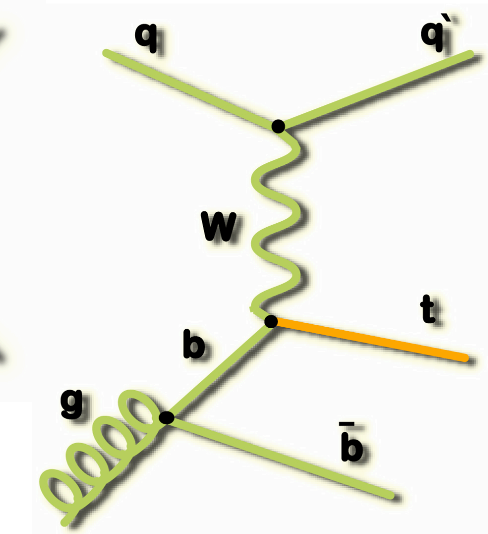


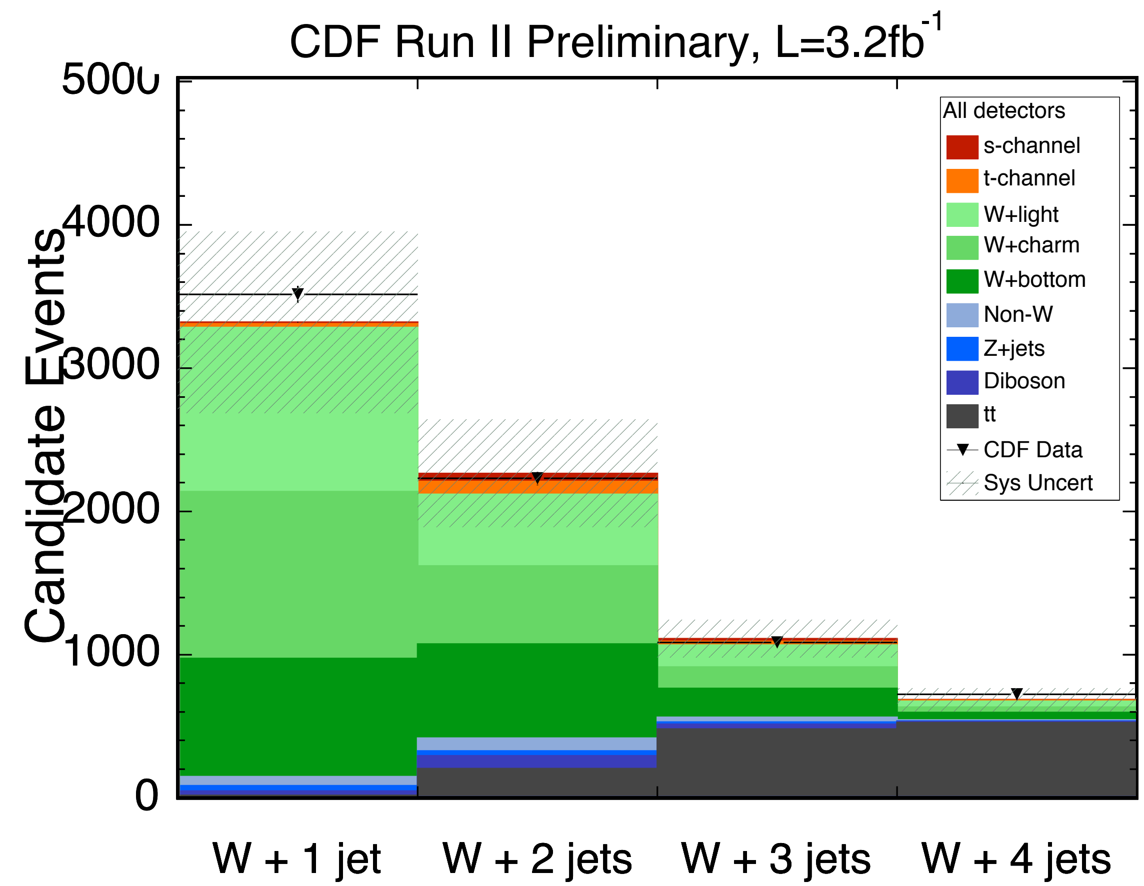
- Cross section measurements consistent across channels and experiments
- Tevatron combination underway

Single top

- Electroweak production of single top quark
  - s-channel: σ_{NLO} = 1.98 ± 0.21 pb
  - t-channel: σ_{NLO} = 0.88 ± 0.07 pb
- Allows for
  - Direct probe of *t-b* vertex
  - Several BSM phenomena (W', charged Higgs, etc.)
  - Similar final state as $WH \rightarrow l\nu bb$
- Not as "easy" as top pair measurement
  - Large backgrounds with large systematics
    - Makes counting experiment difficult
  - **Rely on multivariate techniques**

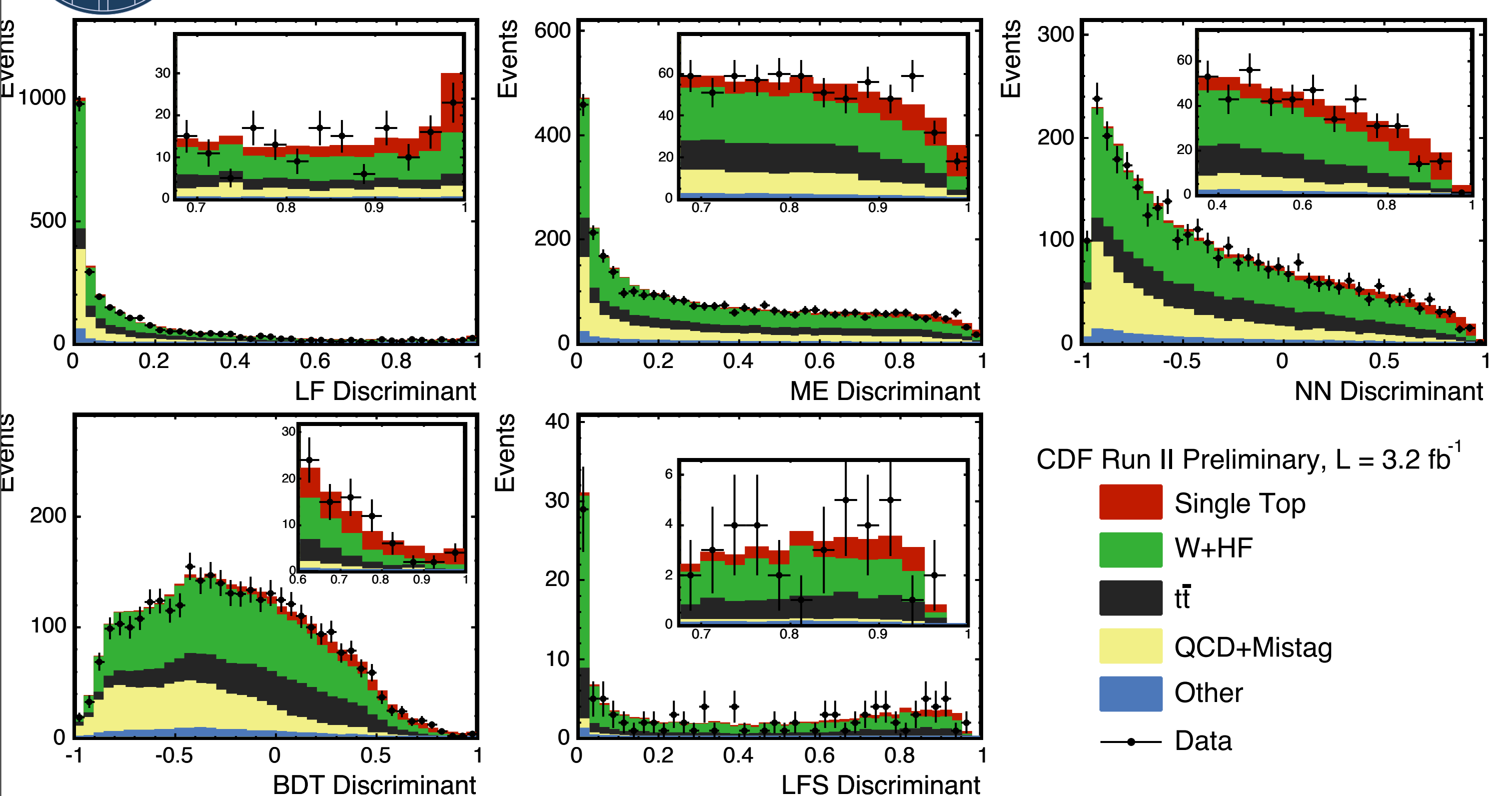


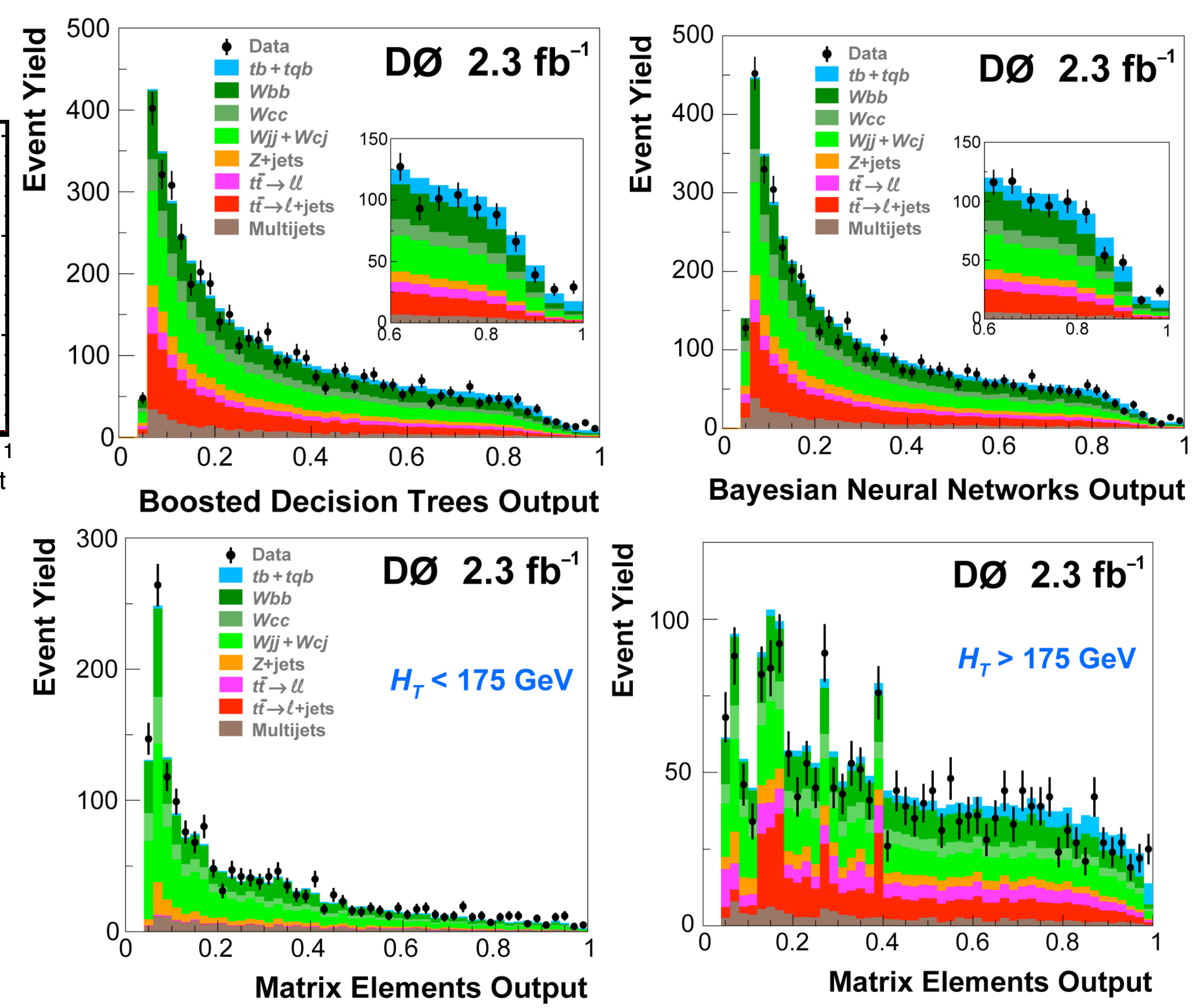




Extracting a signal

- Both CDF and DØ use a range of multivariate techniques to extract a single top signal
  - Likelihoods based on SM matrix elements
  - Decision trees
  - Neural networks
- Combine all methods for maximal statistical power





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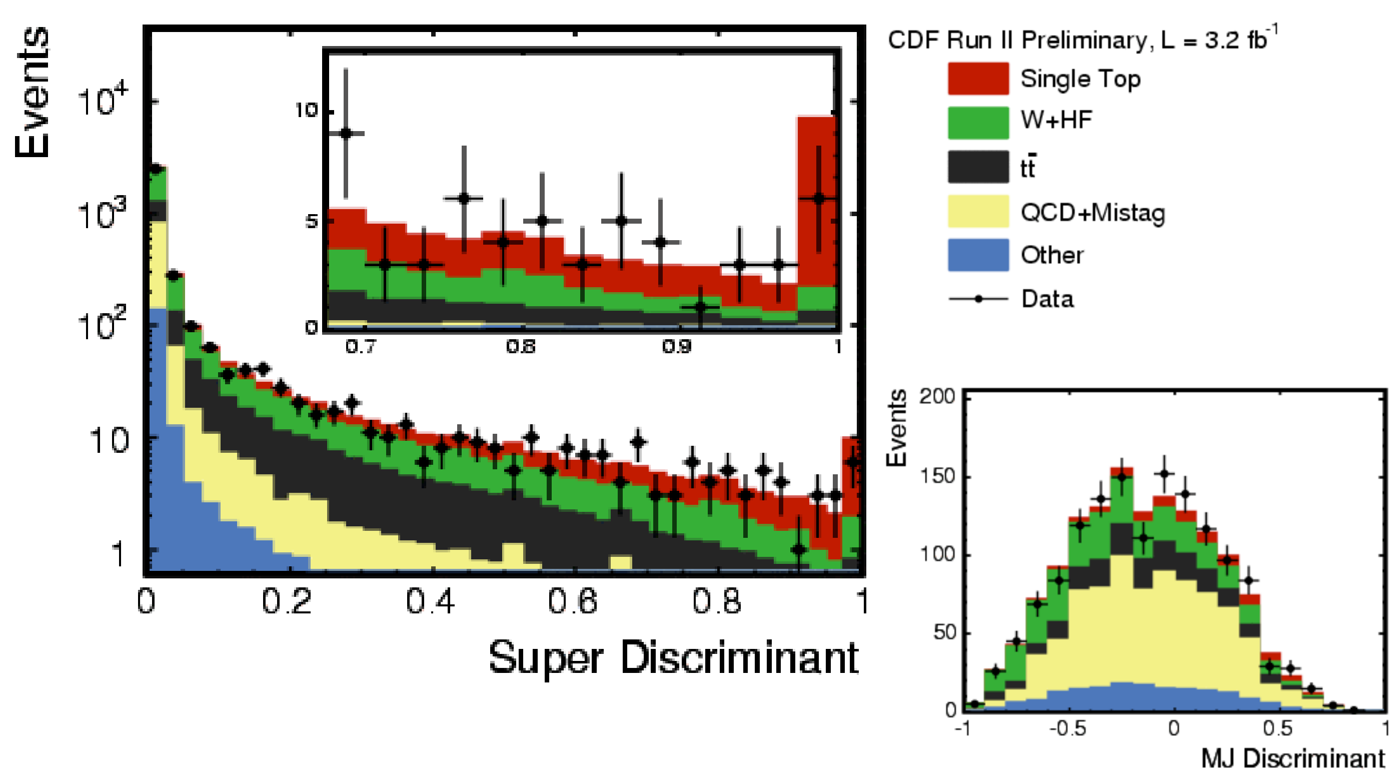
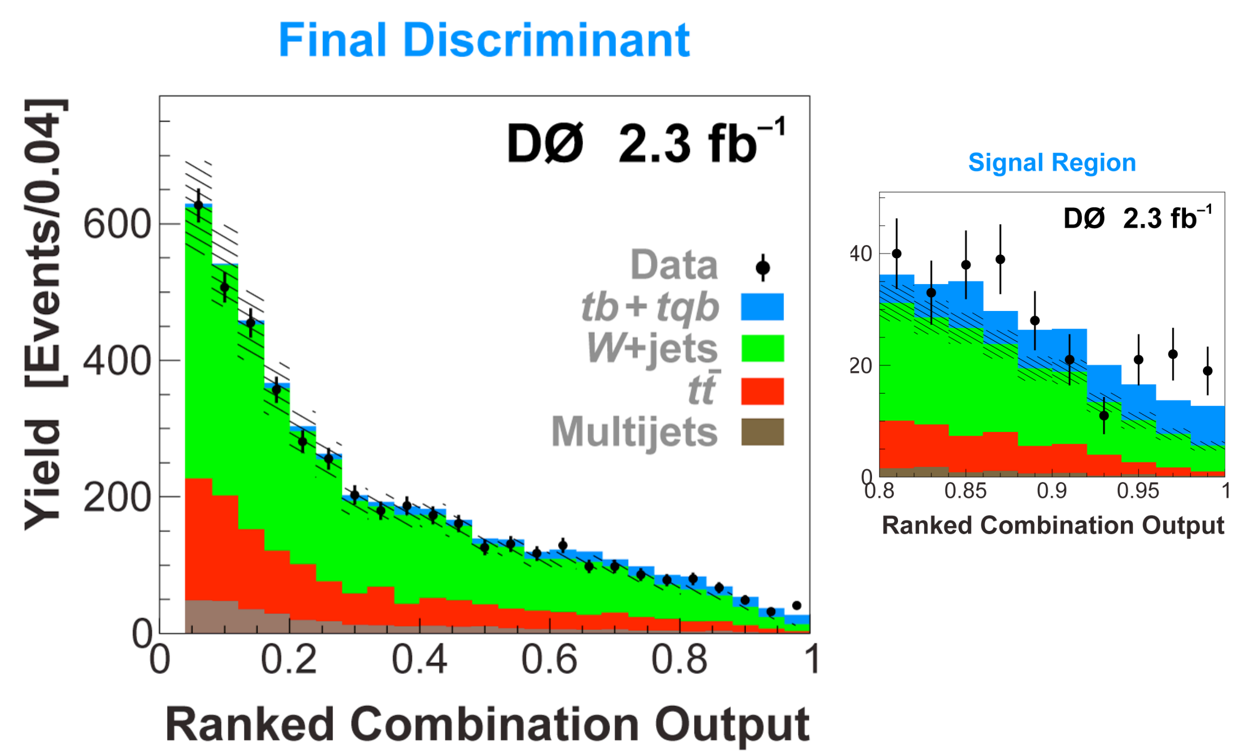
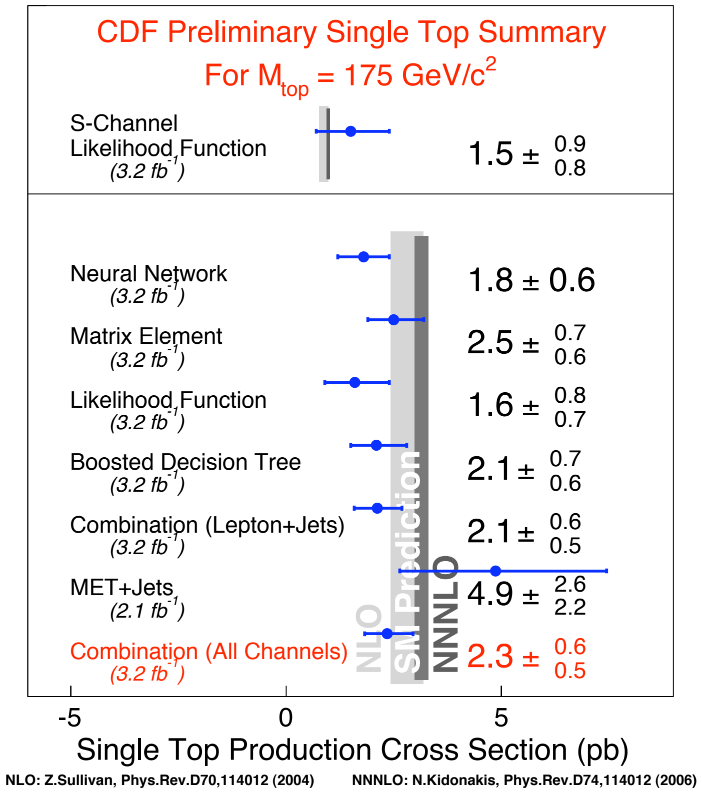
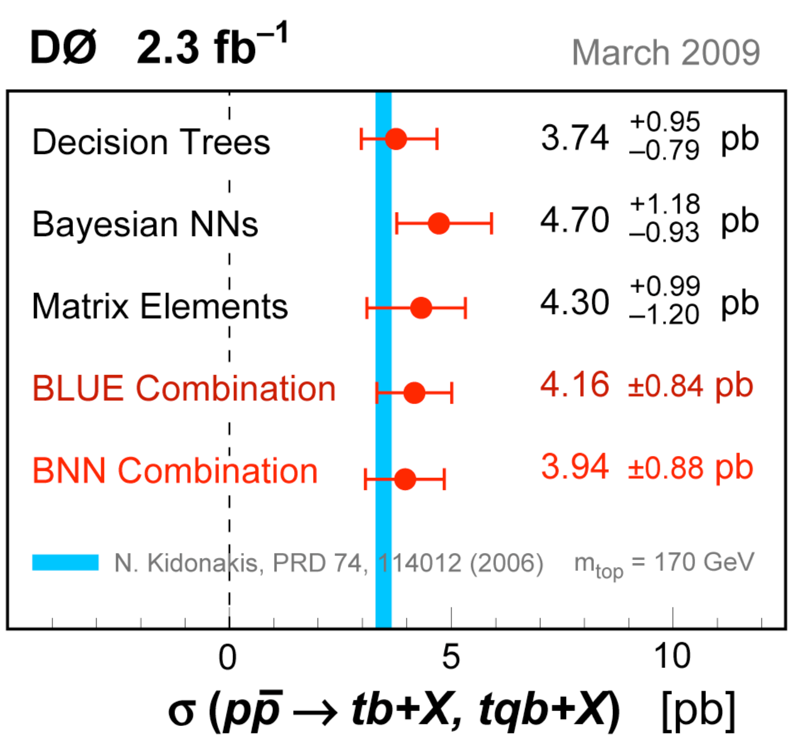




Single top: result



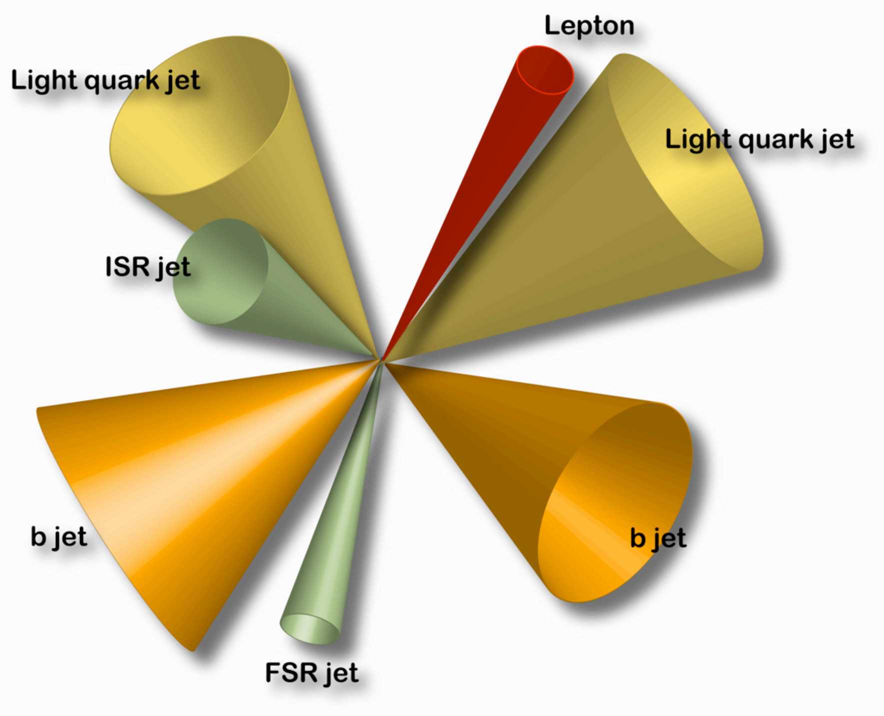


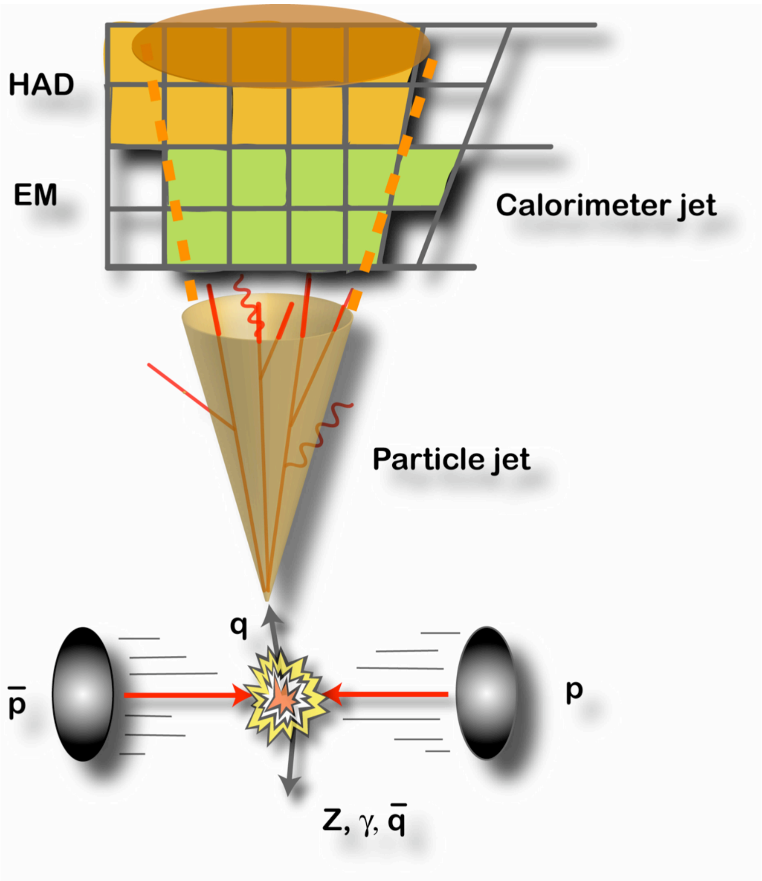
Single Top Cross Section	Signal Significance Expected	Signal Significance Observed	CKM Matrix Element V_{tb}
CDF (3.2 fb^{-1}) *March 2009* [m_t=175 GeV/c^2] *arXiv:0903.0885*			
$2.3^{+0.6}_{+0.5}$ pb	>5.9σ	5.0σ	$\lvert V_{tb}\rvert$>0.71 @95%CL $\lvert V_{tb}\rvert$=0.91±0.13
DØ (2.3 fb^{-1}) *March 2009* [m_t=170 GeV/c^2] *arXiv:0903.0850*			
3.94±0.88 pb	4.5σ	5.0σ	$\lvert V_{tb}\rvert$>0.78 @95%CL $\lvert V_{tb}\rvert$=1.07±0.12

5σ Observation from both CDF and DØ!

More precision physics: measuring the top mass

- Difficult measurement
  - Most information carried in quarks
    - Can only measure jets resulting from quarks
    - Jet-parton assignment
    - QCD radiation
  - Jet energy scale (JES) uncertainty dominates [~3%]
    - Can be reduced via *in situ* measurement from hadronic *W*
- Mass measurement techniques
  - Matrix element: form probabilities as function of m_t and JES from SM MEs, convolute with detector resolution functions and integrate
  - Template: form templates as function of m_t and JES from fully simulated events



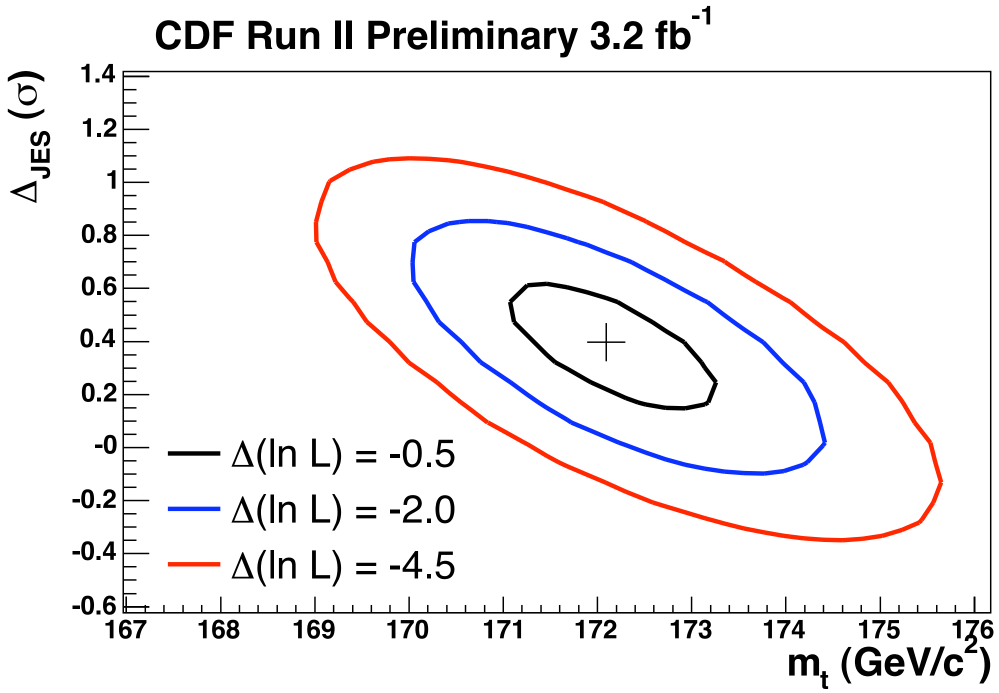


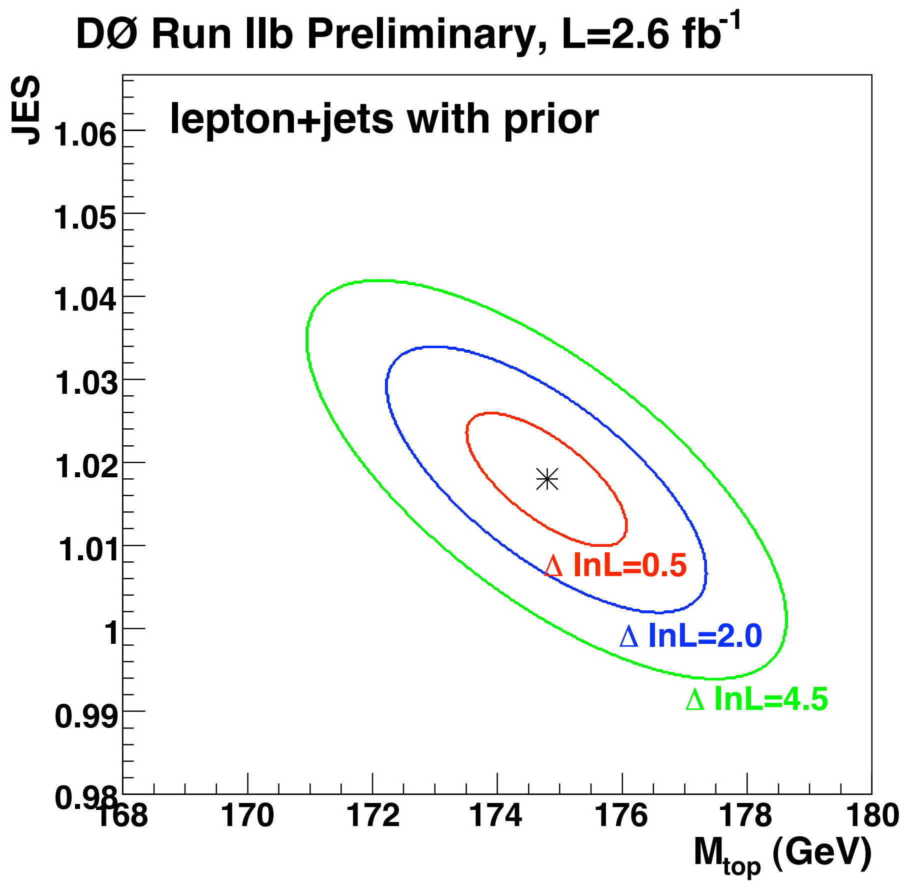
Top mass: lepton+jets channel

- Fully reconstructable final state
  - Reduce jet combinatorics and background by requiring ≥1 *b*-tag
- Matrix element technique for probabilities
- *In situ* JES calibration
  - Form 2D likelihood as function of top mass and shift in JES error
- CDF (3.2 fb^{-1})

  m_t=172.1±0.9(stat)±1.3(syst) GeV/c^2
  - Single best measurement, precision **<1%**
- DØ (3.6 fb^{-1})

  m_t=173.7±0.8(stat)±1.6(syst) GeV/c^2





Top mass: dilepton channel

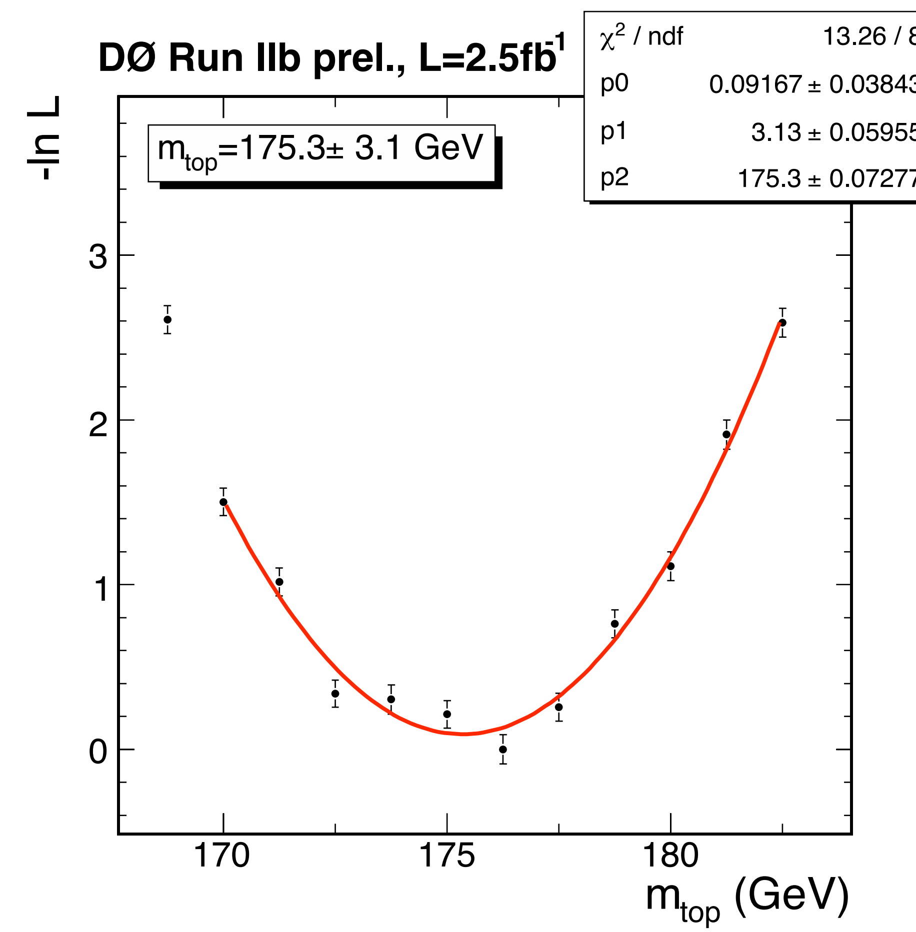
- Two neutrinos result in kinematically under-constrained system
  - Requires integration over at least one variable
- DØ (3.6 fb^{-1})
  - eμ channel and matrix element technique

m_t=174.8±3.3(stat)±2.6(syst) GeV/c^2

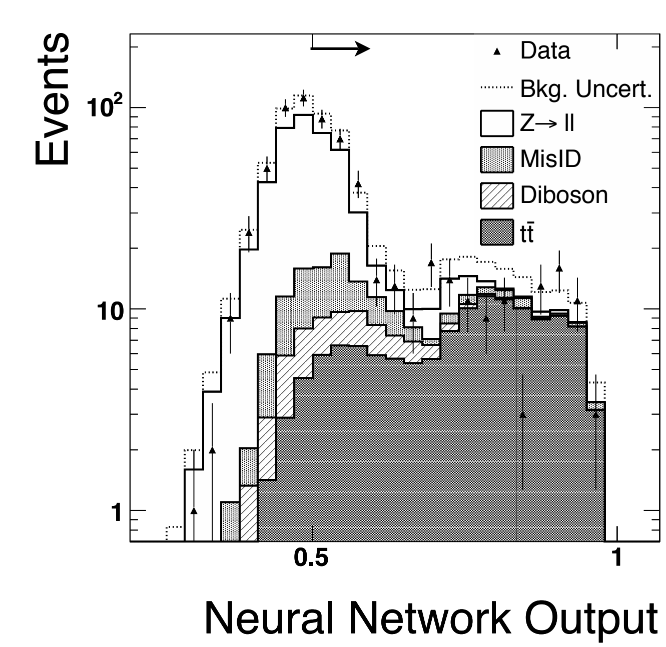
  - Combine with template measurement from 1 fb^{-1}

m_t=174.7±2.9(stat)±2.4(syst) GeV/c^2 **$\Delta m_t/m_t$~8%**

  - Single best measurement in channel, precision~2.2%



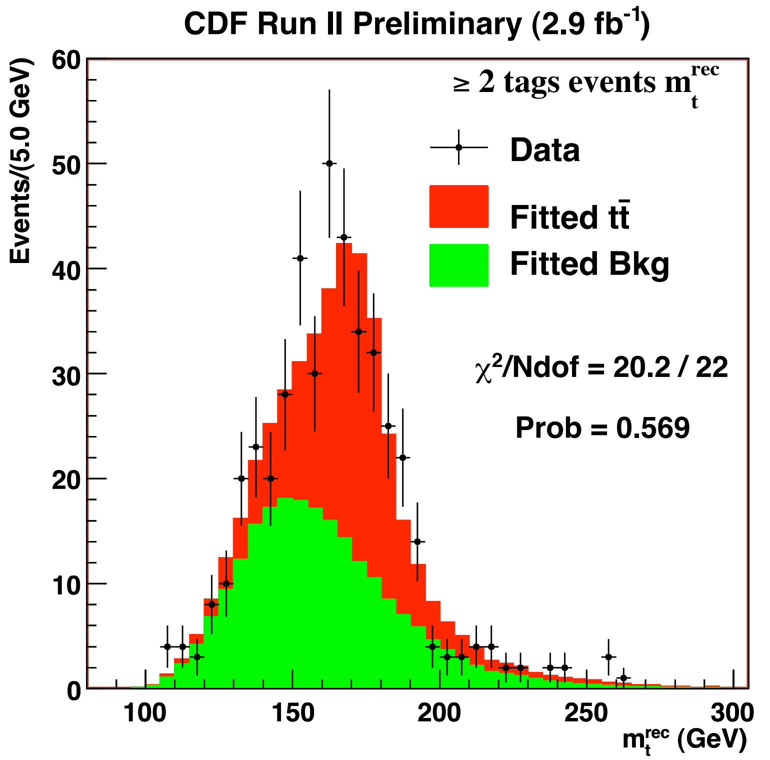
- CDF (2.0 fb^{-1})
  - Evolutionary neural network to optimize selection for top mass
  - m_t=172.1±2.7(stat)±2.9(syst) GeV/c^2 **$\Delta m_t/m_t$~9%**
    - Phys. Rev. Lett. **102**, 152001 (2009)

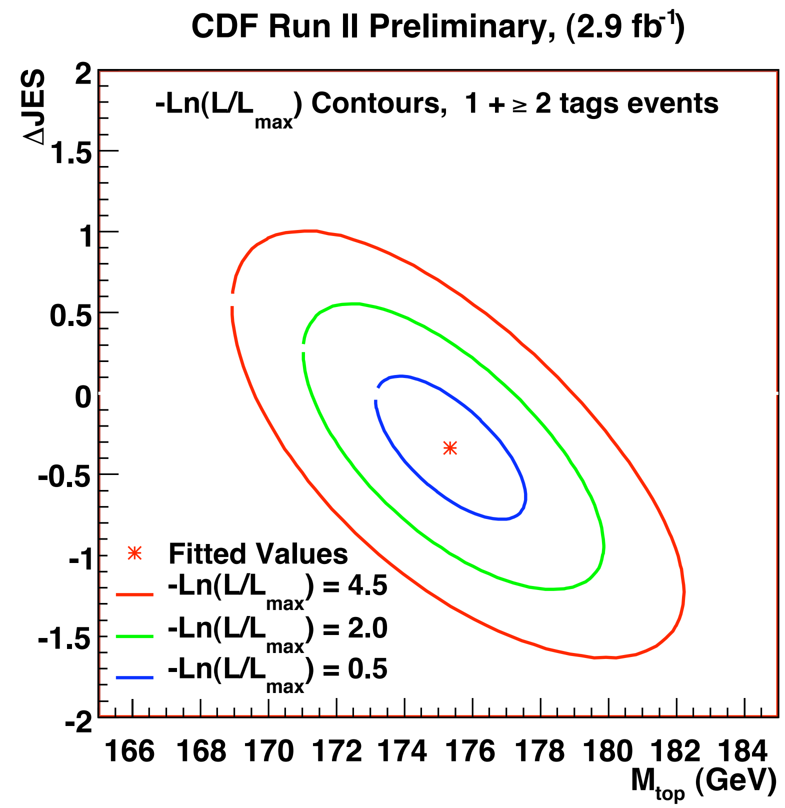


Top mass: all hadronic

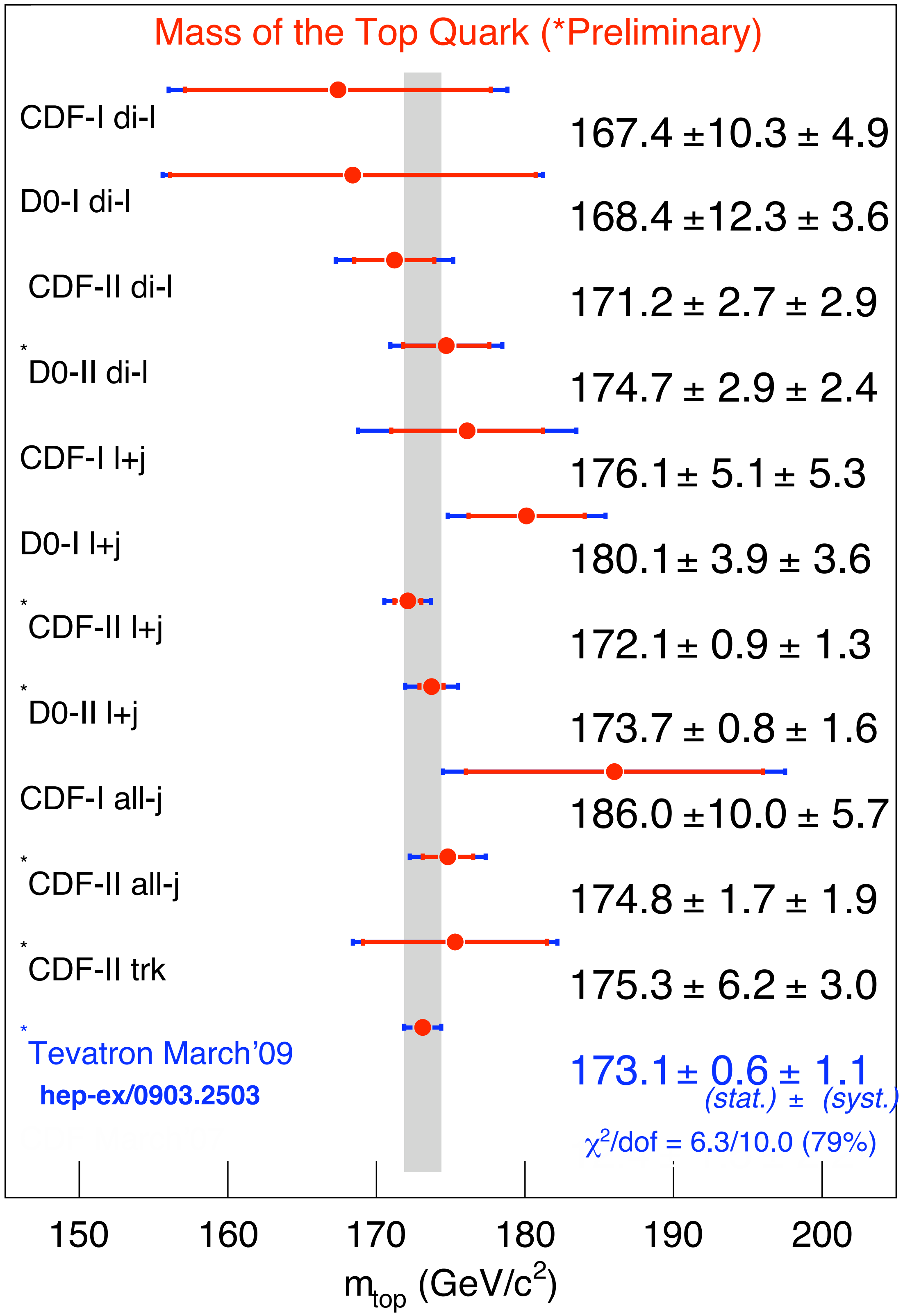
- Final state entirely measured (6 jets)
  - Very large QCD background
  - Require ≥1 *b*-tag or 2 *b*-tags
  - Further reduce background with neural net trained to identify non-top background
- Template method for mass measurement
  - Calibrate for JES *in situ* as in lepton+jets
- CDF (2.9 fb^{-1})

  m_t=174.8±1.7(stat)±1.9(syst) GeV/c^2
  - Precision of ~1.5%

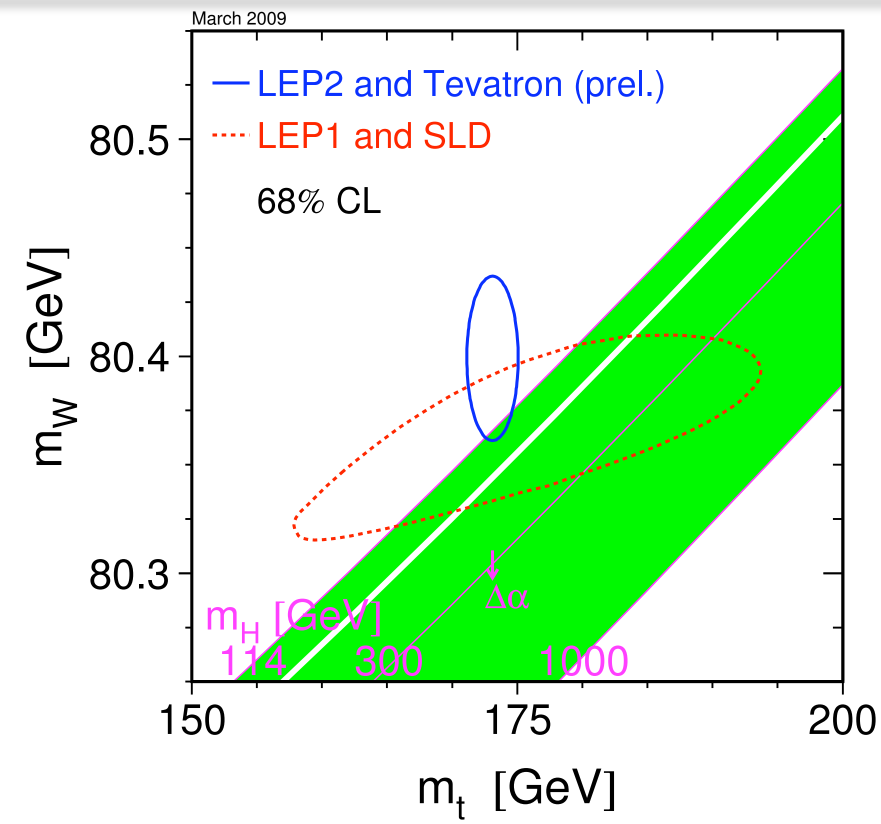




Tevatron top mass combination



m_t=173.1±0.6(stat)±1.1(syst) GeV/c²

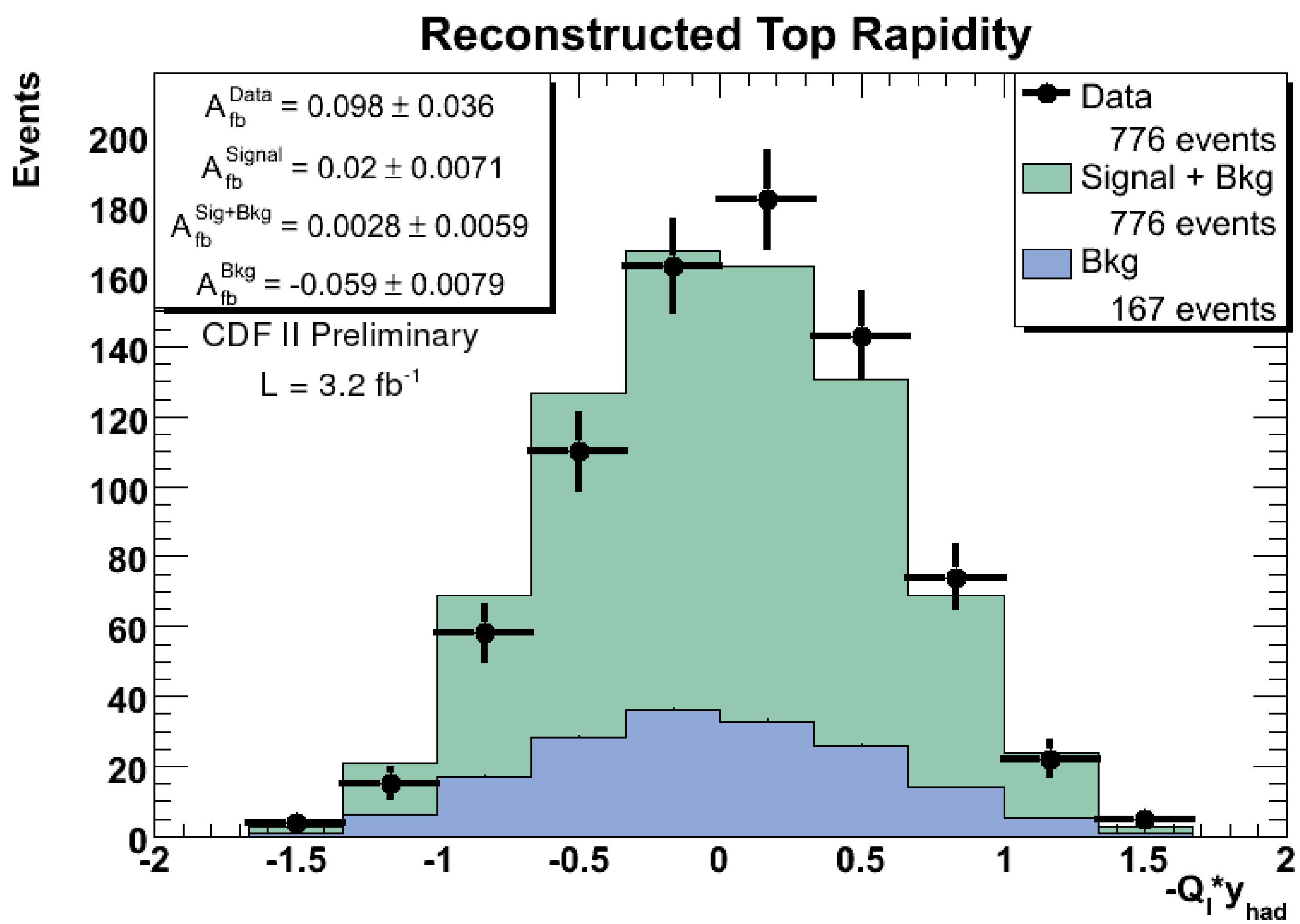


Combine using best measurement per channel, per experiment: **0.75% uncertainty**

New electroweak fit incorporating **new top mass combination** and **W mass measurement**: **m_H<163 GeV/c² @95% CL**

Both experiments working to better understand systematics

Forward-backward asymmetry



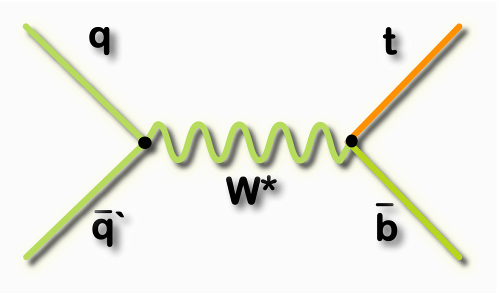
- New physics could result in large A_{FB} asymmetry
  - NLO QCD calculations predict A_{FB}=5±1.5%
- Measure in lepton+jets channel
  - ≥4 jets, ≥1 *b*-tag
- Use rapidity of hadronically decaying top
  - Correct for detector effects
- CDF (3.2 fb^{-1})

  A_{fb}=19.3±6.5(stat)±2.4(syst)%

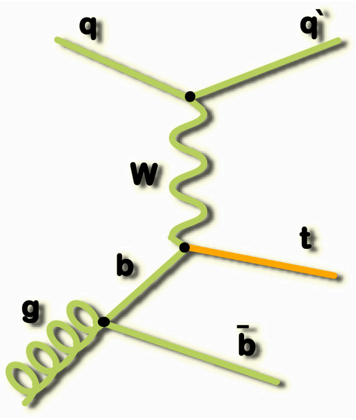
Anomalous couplings of the *tbW* vertex

- General form of *tbW* vertex:

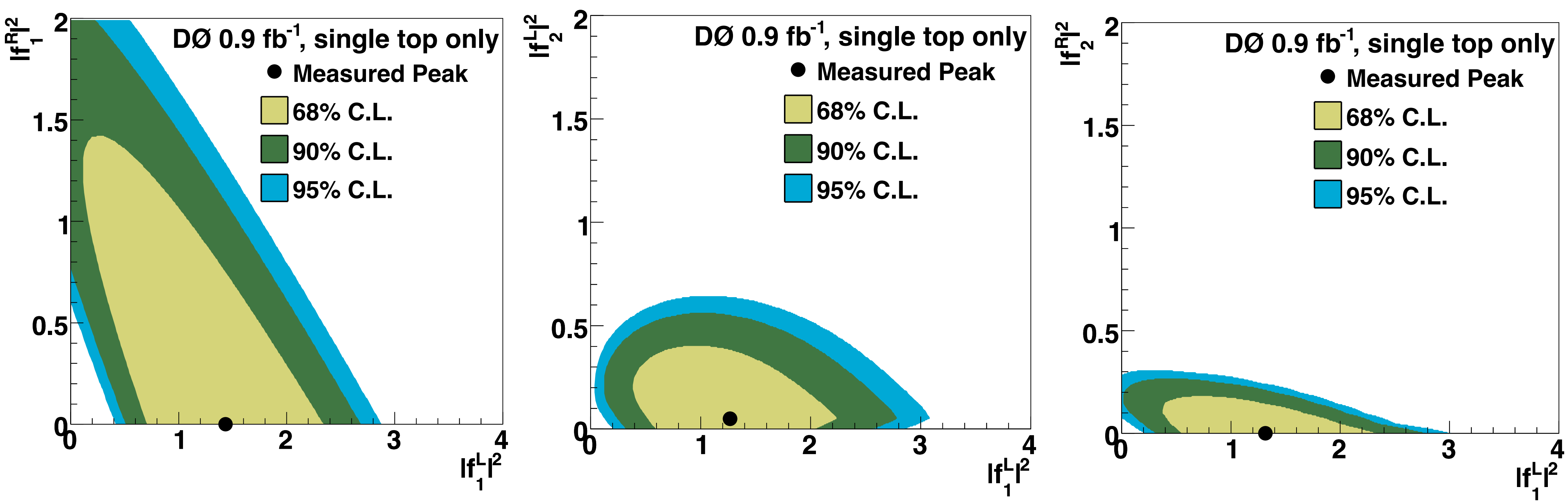
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_1^L P_L + f_1^R P_R)tW_{\mu}^{-}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}V_{tb}}{M_W}(f_2^L P_L + f_2^R P_R)tW_{\mu}^{-} + h.c.$$



  - =1 and =0 in SM
- DØ: search for deviations from SM



0.9 fb^{-1} of single top data

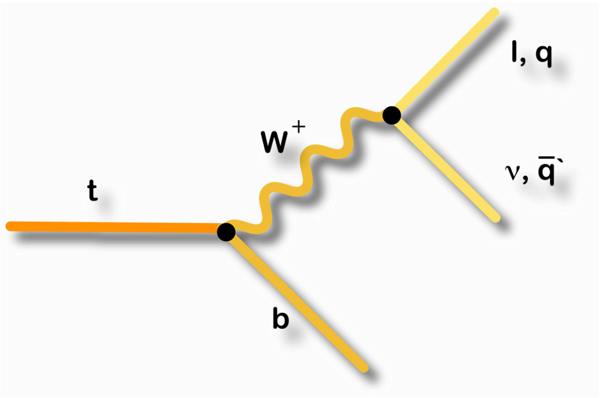


Anomalous couplings of the *tbW* vertex

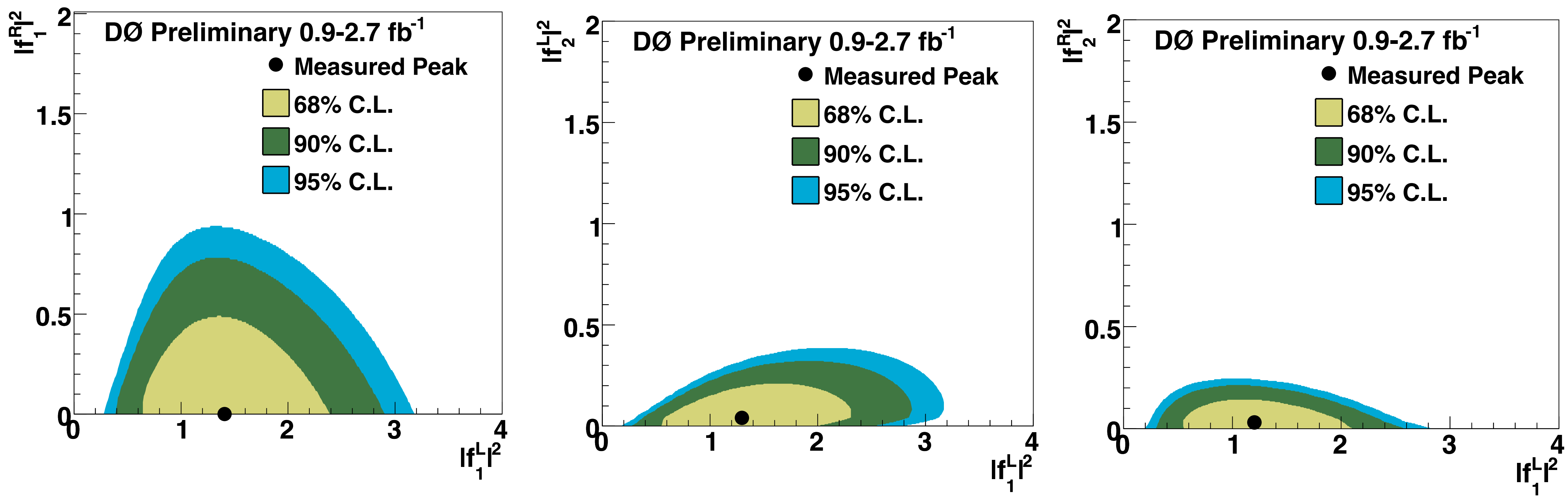
- General form of *tbW* vertex:

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_1^L P_L + f_1^R P_R)tW_{\mu}^{-}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}V_{tb}}{M_W}(f_2^L P_L + f_2^R P_R)tW_{\mu}^{-} + h.c.$$

  - =1 and =0 in SM
- DØ: search for deviations from SM



Add 2.7fb^{-1} of top pair data from helicity fraction measurement

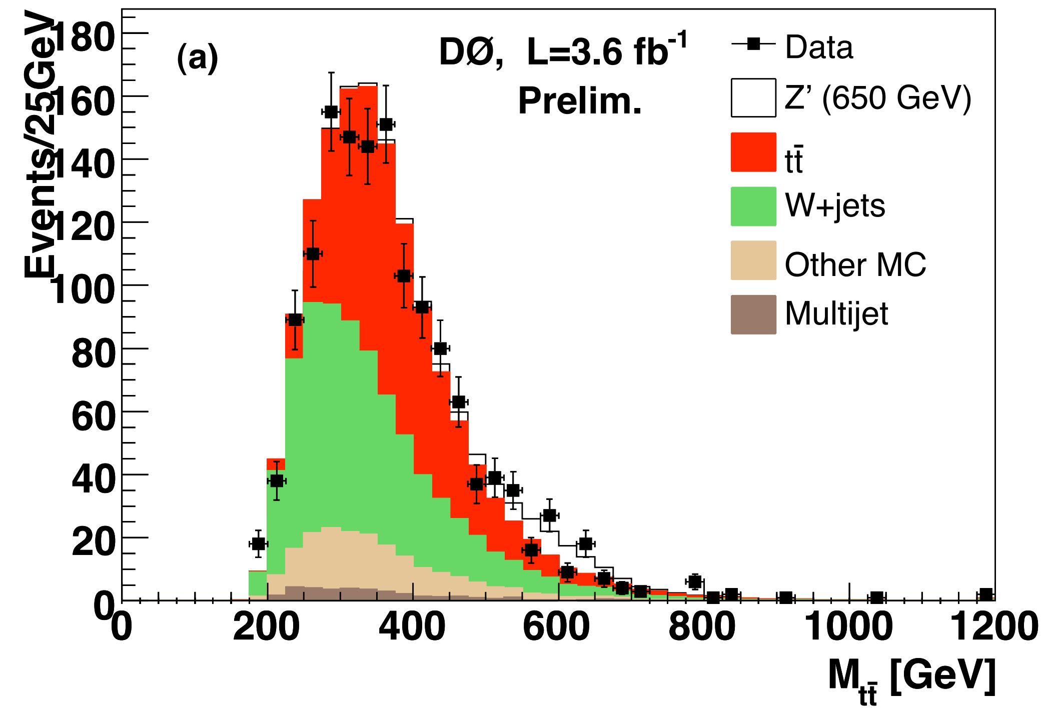


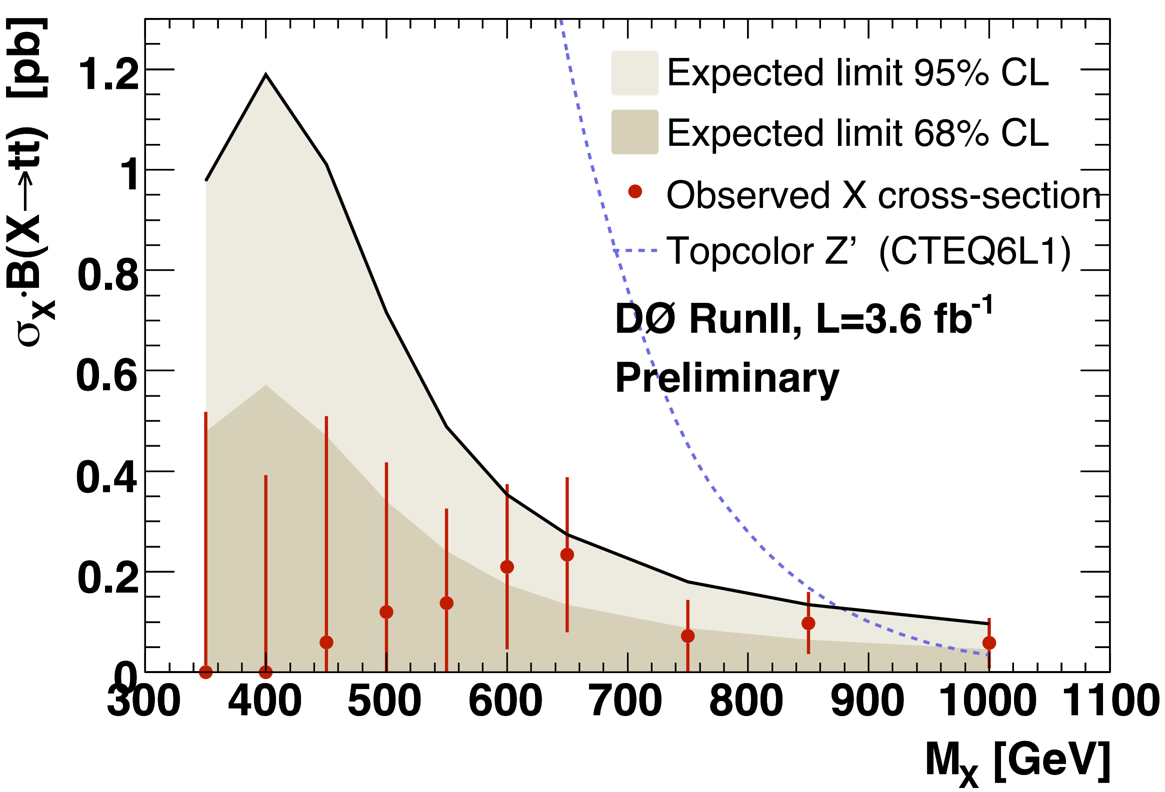
Resonant production in top sample

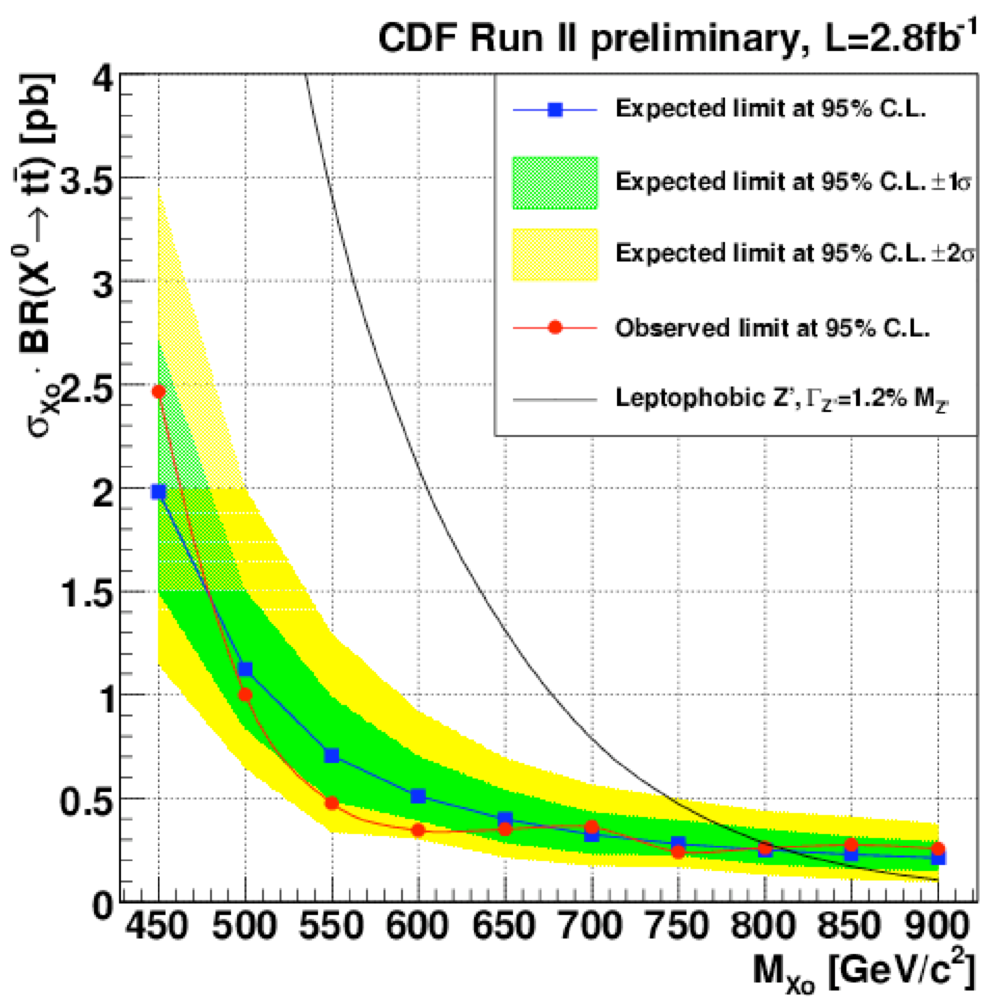
- Search for narrow resonances decaying to top pairs
- DØ (3.6 fb^{-1})
  - Lepton+jets channel

    $m_{Z'} < 820$ GeV/c^2 excluded @95%CL
- CDF (2.8 fb^{-1})
  - All hadronic channel [leptophobic Z']

    $m_{Z'} < 800$ GeV/c^2 excluded @95%CL







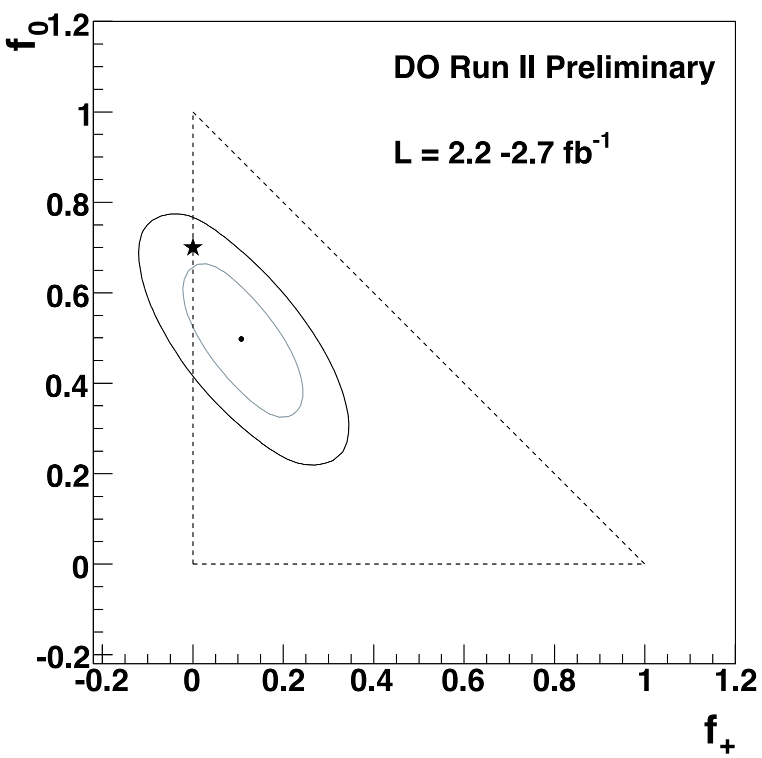
Conclusion

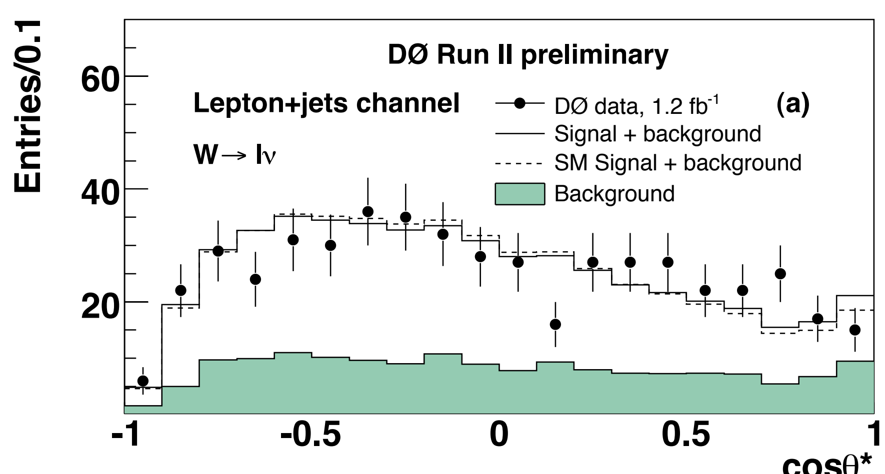
- Just a sampling of results
  - http://www-cdf.fnal.gov/physics/physics.html (CDF)
  - http://www-d0.fnal.gov/Run2Physics/WWW/results.htm (D0)
  - Numerous publications and PhD theses from both experiments
- Top and electroweak sectors reaching realm of precision physics
  - Two measurements of *W* mass more precise than any single LEP result
  - Top mass uncertainty to <1%
- Checking off remaining standard model business
  - All SM diboson states observed
  - Single top production observed
- Much more data on the way
  - >5 fb^{-1} already on tape
- *Stage is set to find the Higgs*
  - Lets do it!

Backup

W Helicity

- In SM, *t Wb* with 100% BR
- Due to V-A, expect:
  - Left handed: f_{-}=0.3
  - Longitudinal f_0=0.7
  - Right handed: suppressed
- cos θ^* - angle between *d*-type fermion and *W* rest frame wrt *t* direction

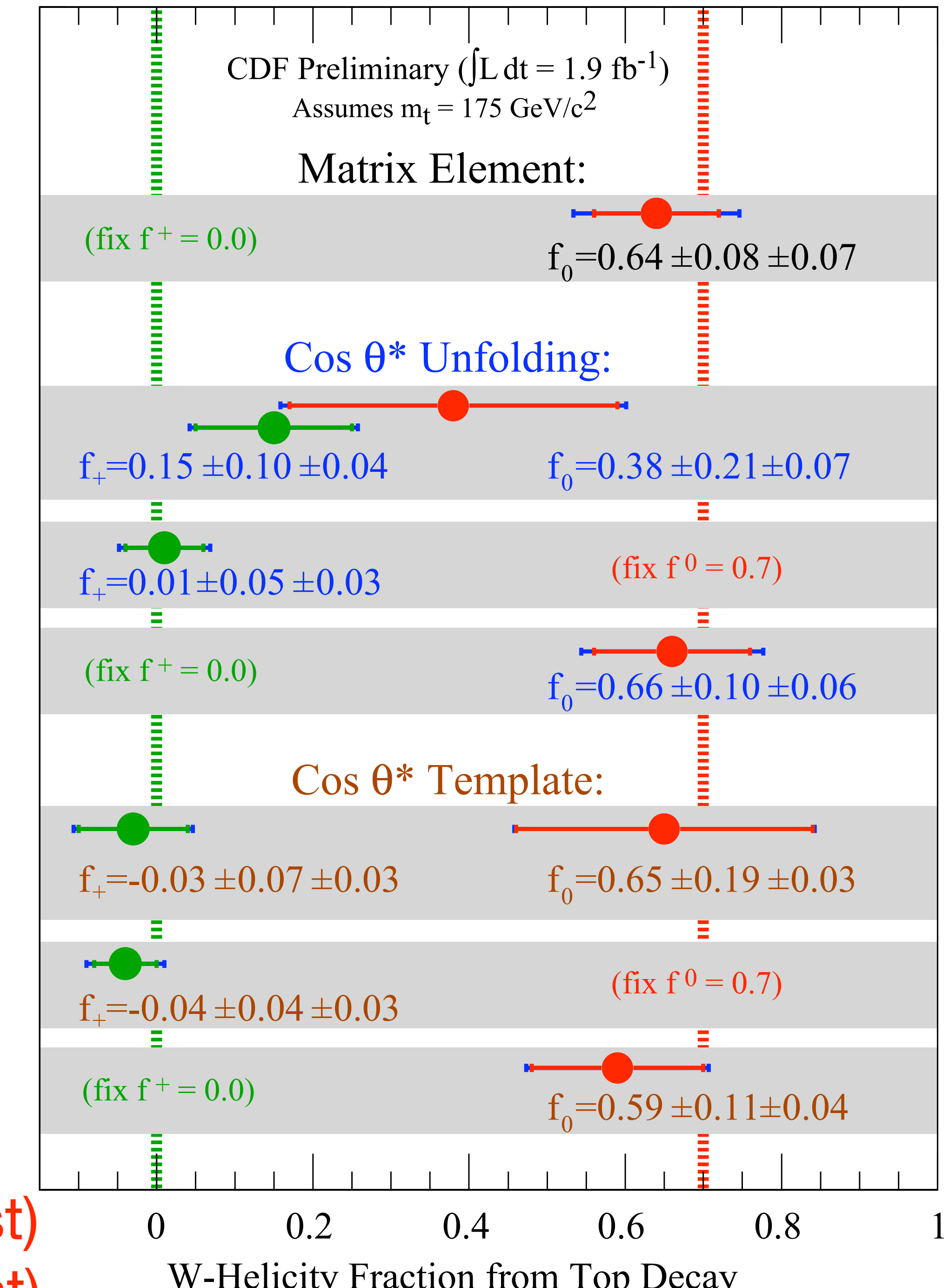




DØ (2.7 fb^{-1})

f_0=0.490±0.106(stat)±0.085(syst)

f_+=0.110±0.059(stat)±0.052(syst)

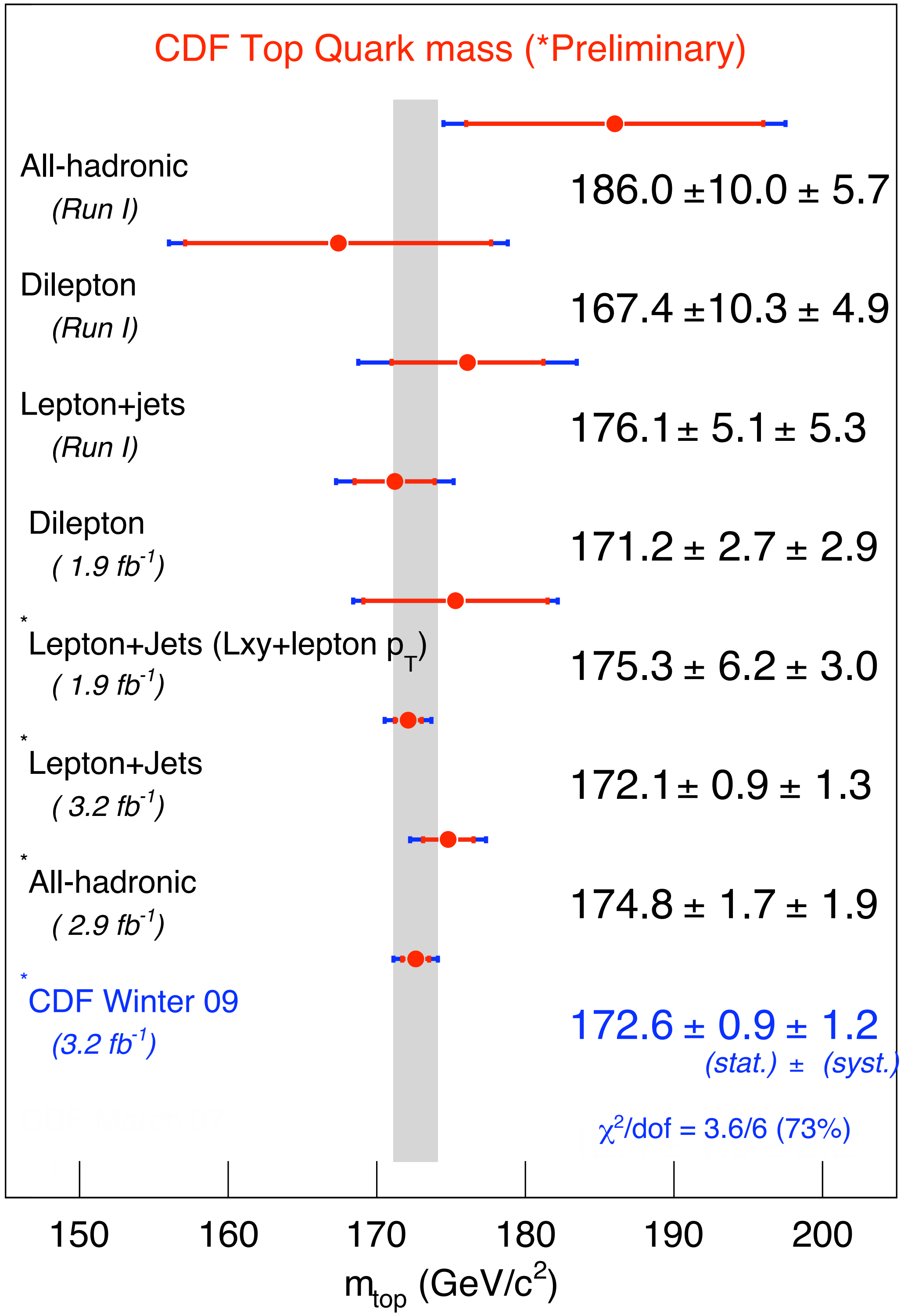


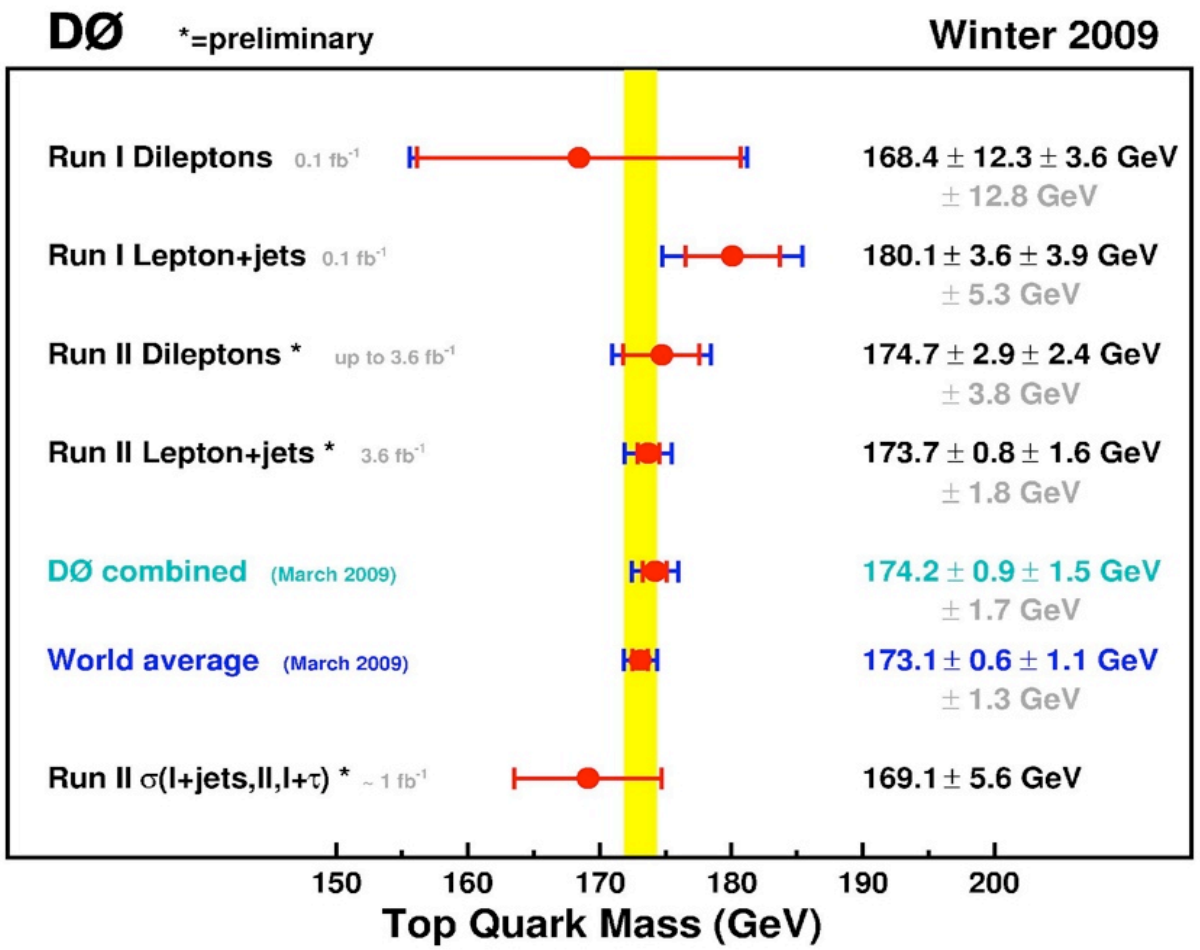
CDF (1.9 fb^{-1})

f_0=0.62±0.10(stat)±0.05(syst)

f_+=-0.04±0.04(stat)±0.03(syst)

Top mass summary





- Consistent results across channels and experiments
- Combine using most precise measurement per channel per experiment