The Top Quark We Observe

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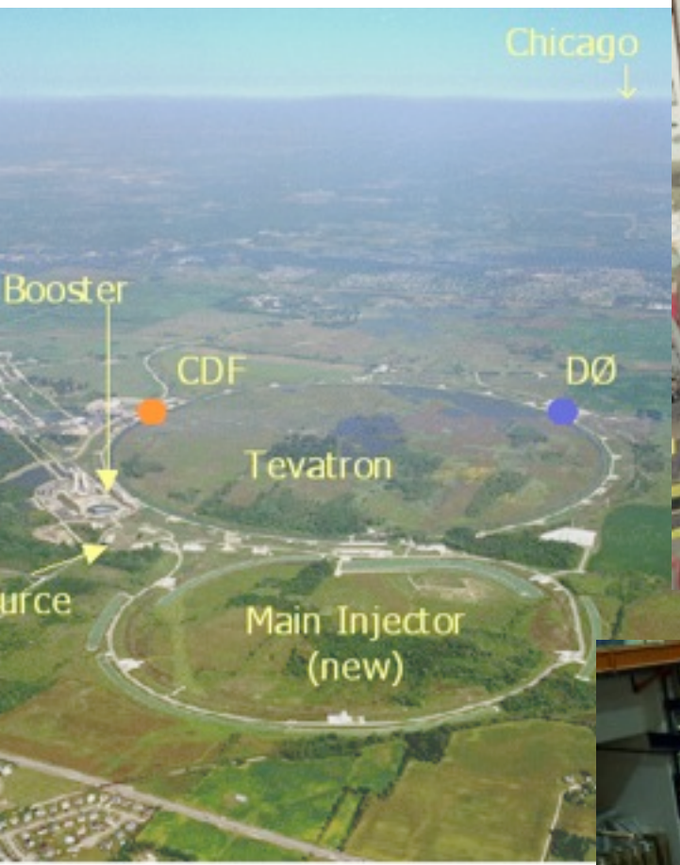
Indirect Searches for New Physics at the Time of the LHC
The Galileo Galilei Institute, March 23rd, 2010

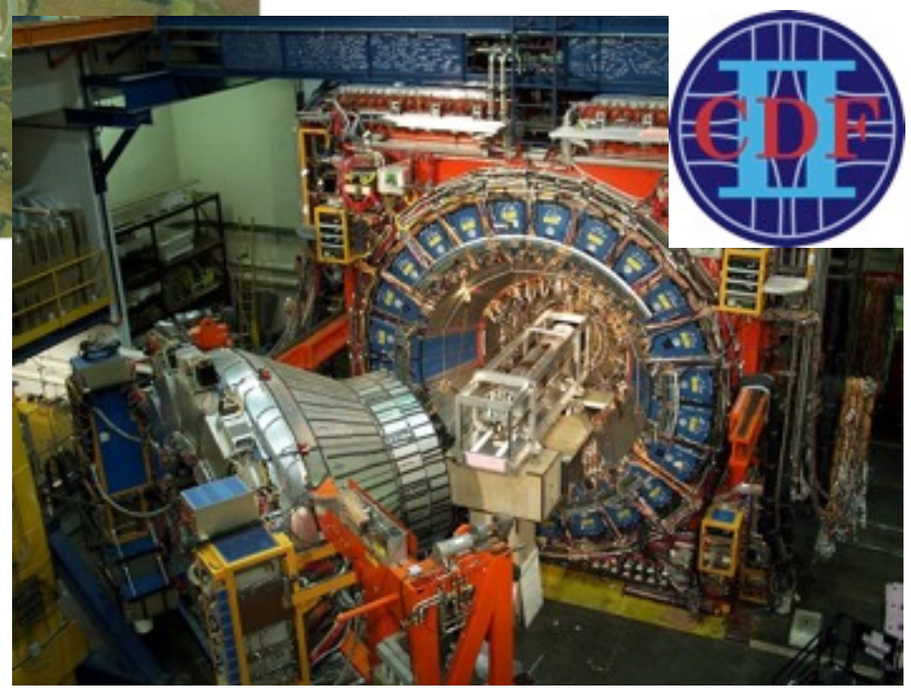
- Top Quark Properties from Decays
  - Mass
  - Branching Ratios & V_{tb}
  - V_{tb} from Single Top
  - W Helicity
  - Top Quark Charge and Width
- Top Quark Production
  - Cross-Section
  - Spin Correlations
  - Forward-backward asymmetry

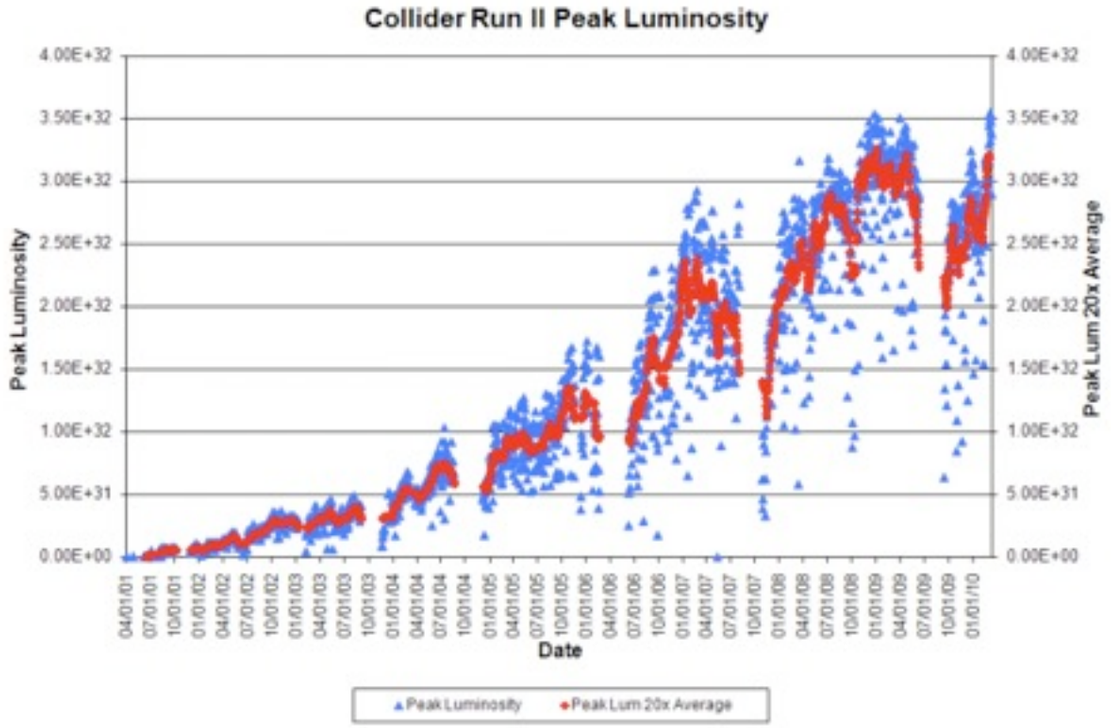
Top History

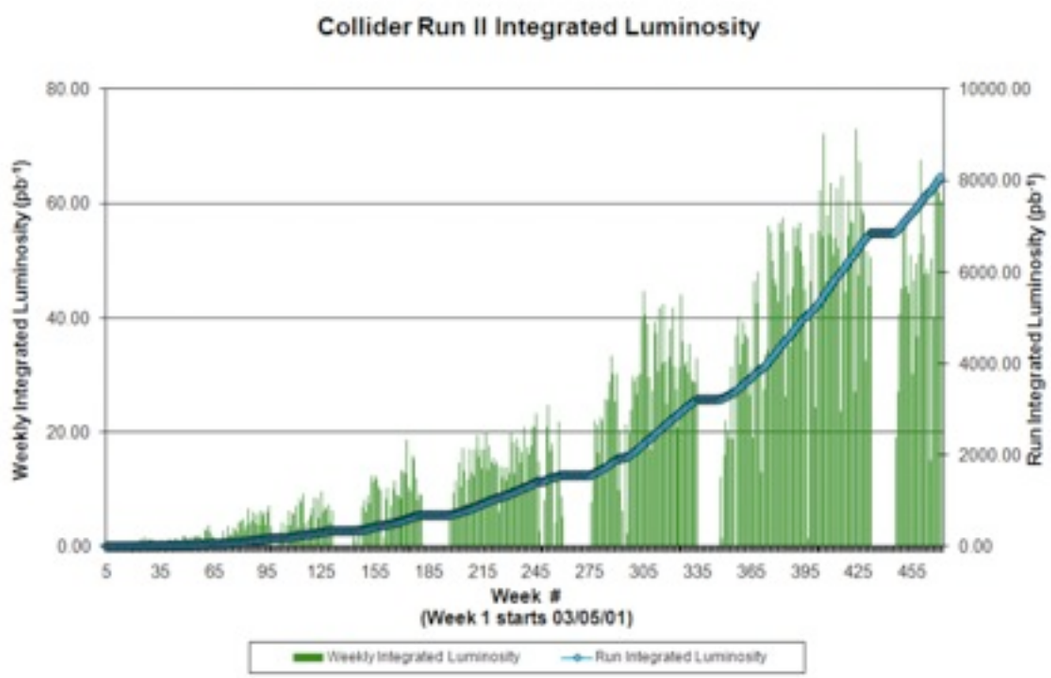
Date	Milestone	Statistics	Luminosity	√s
1995	Observation	10's	50 pb^{-1}	1.8 TeV
1997	Properties	~100	120 pb^{-1}	1.8 TeV
2009	Precision Properties	100's - 1k	few fb^{-1}	1.96 TeV
2009	Single Top Observation	10's (?)	2 fb^{-1}	1.96 TeV
2011	Observation	5 k?	~1 fb^{-1}	7 TeV
2014	Precision Differential	100 k?	10 (?) fb^{-1}	14 (?) TeV

Tevatron


Chicago
Booster
CDF
DØ
Tevatron
Main Injector
(new)



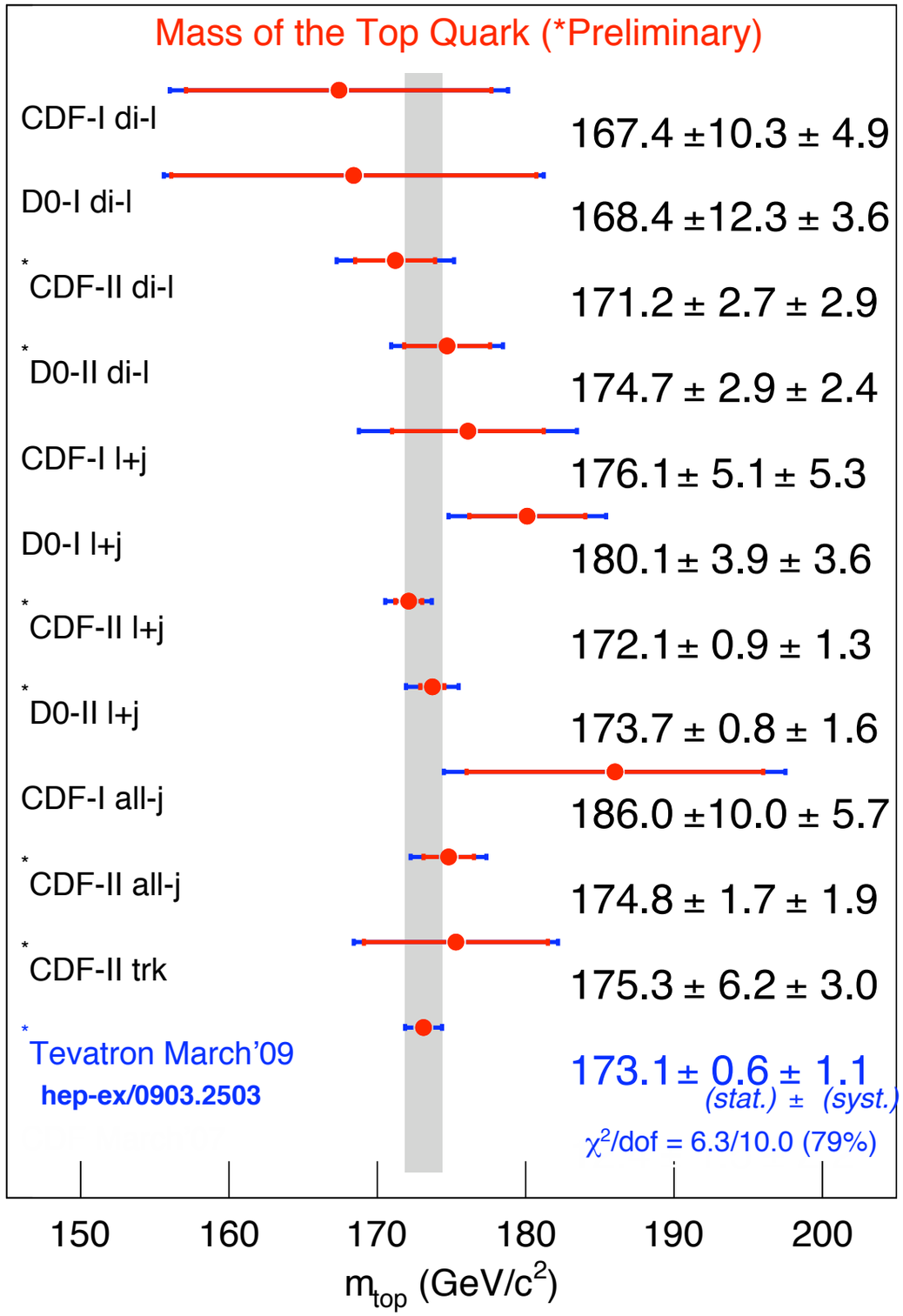

Collider Run II Peak Luminosity
Peak Luminosity
Peak Lum 20x Average
Date
4.00E+32
3.50E+32
3.00E+32
2.50E+32
2.00E+32
1.50E+32
1.00E+32
5.00E+31
0.00E+00


Collider Run II Integrated Luminosity
Weekly Integrated Luminosity (pb⁻¹)
Run Integrated Luminosity (pb⁻¹)
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity
80.00
60.00
40.00
20.00
0.00
10000.00
8000.00
6000.00
4000.00
2000.00
0.00

Decays

Top Mass

- Top quark's existence established 18 years after bottom quark
  - Long road to discovery due to surprisingly large mass
    - Now known to better than 1%
    - Interestingly, $y_{top}(m_{top}) \cong 1$
- Precise measurement with low Tevatron statistics driven by experimenters' resourcefulness



Matrix Element Analyses

- Currently yield the most precise measurement of the top quark mass, also
  - Major contribution to the observation of single top
  - Big contribution in Higgs searches
- Basically unbinned maximum likelihood fits
  - Event-by-event measured uncertainties
    - More weight for more signal-like event
    - Determine event's "signal probability":

Transfer functions: generated → measured momenta

b-tag prob

matrix element

$$\sum_{\text{perm}} w_i \int_{q_1,q_2,y} \sum_{\text{flavors}} dq_1 dq_2 f(q_1) f(q_2) \frac{(2\pi)^4 \left|\mathcal{M}(q\bar{q} \to t\bar{t} \to y)\right|^2}{2q_1 q_2 s} d\Phi_6 W(x, y; JES)$$

- Caveats:
  - LO matrix elements (typically madevent):
    - (Initially) require exact number of jets
    - Evaluation of NLO systematic not so easy
  - Recent development: add NN to discriminate further against background
  - Calibration, i.e. determination of transfer functions done by full simulation with pythia
    - What's really measured is basically PMAS(6,1)
    - Group trying to figure out what that really means
      - Because with current precision, that is an important question!

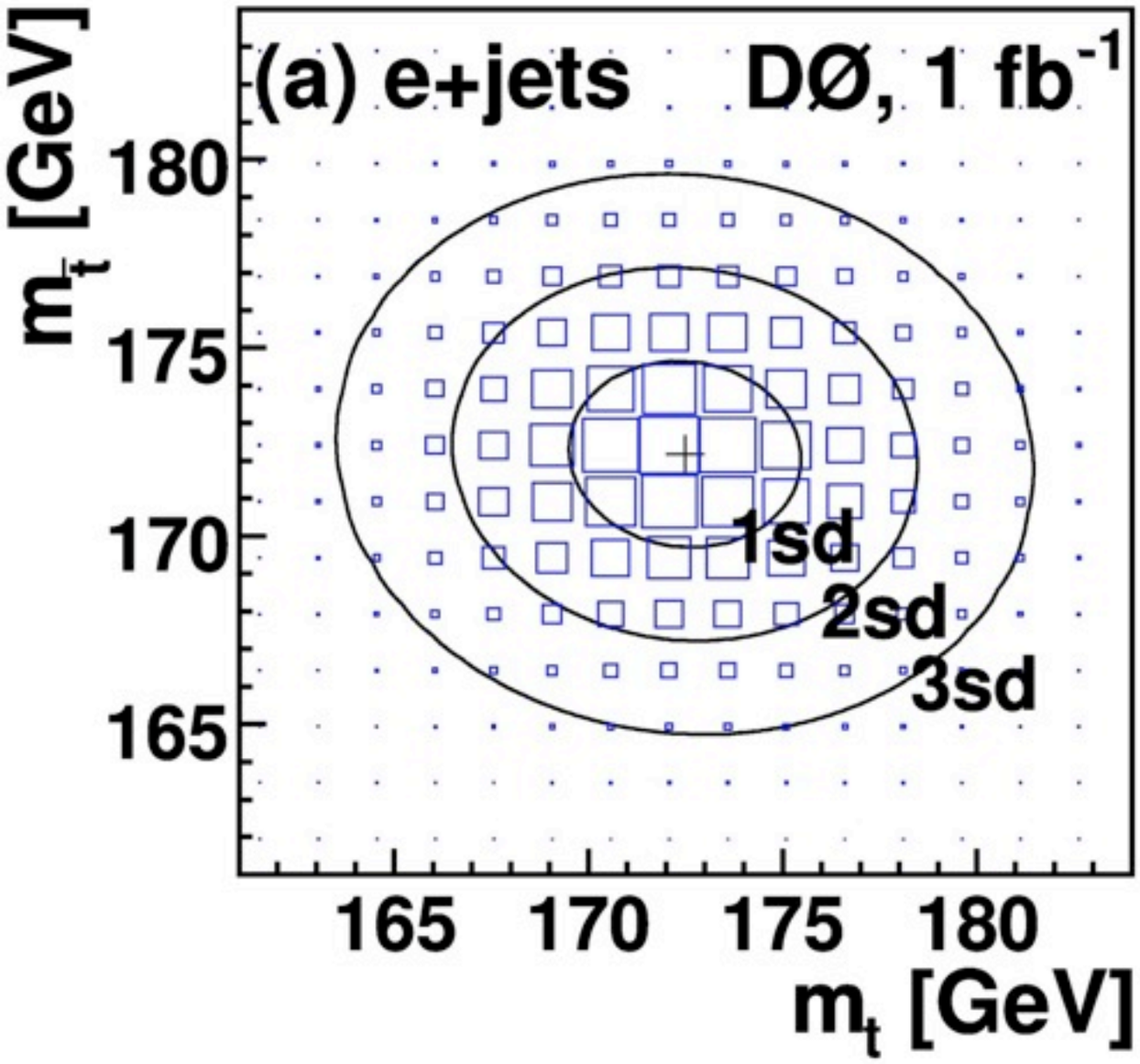
Top Mass @ LHC

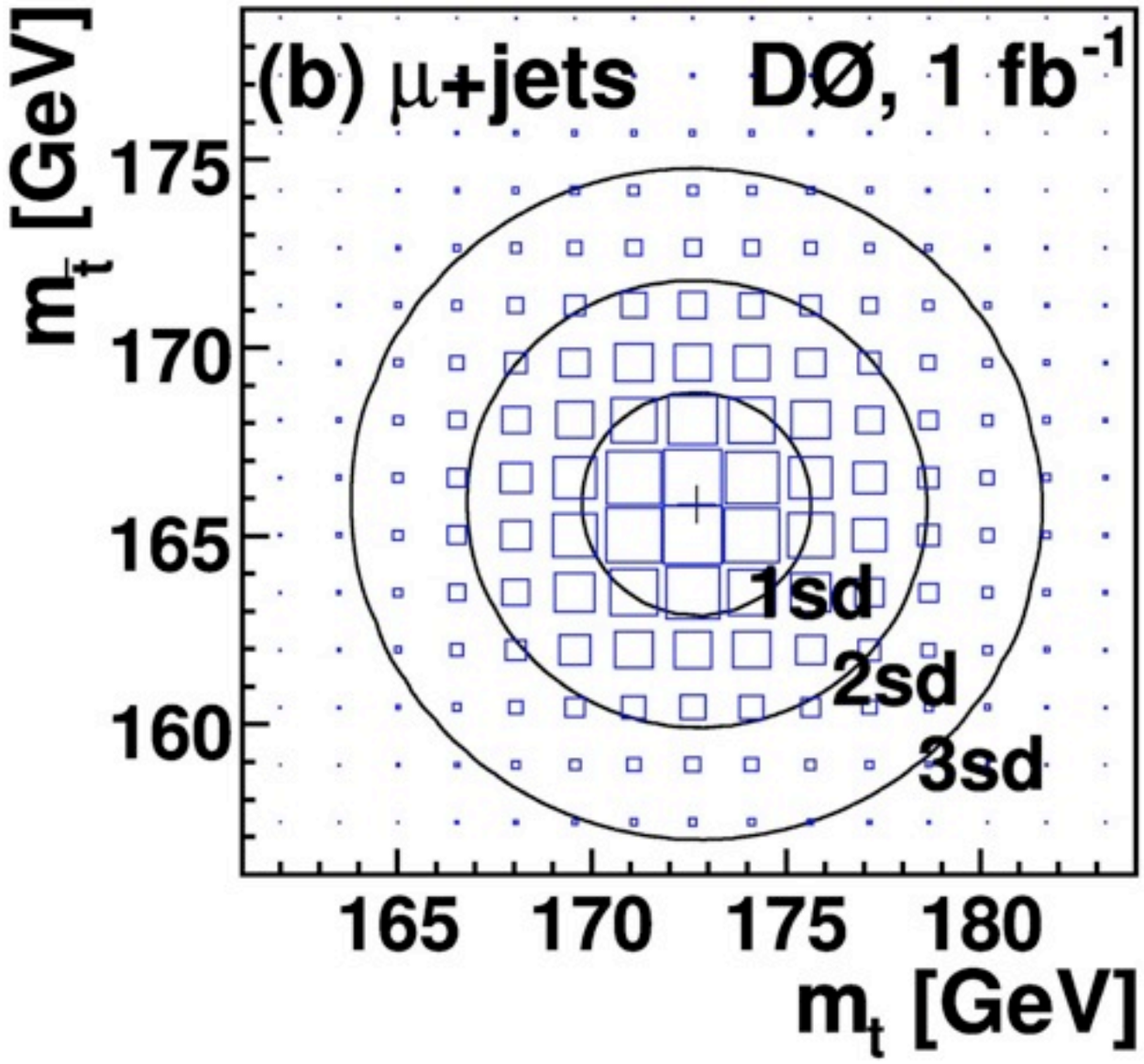
- Use statistics to beat down the systematics
  - Will be very challenging to do better than Tevatron
  - ... but ultimately expect to get there
- Intrinsic limit from measurement in final state
  - Can't beat Λ_{QCD}!
  - Can we hope for ~500 MeV precision?
- Only way to do better is probably threshold scan at lepton collider

Mass: CPT Test

- Mass difference top - antitop: 3.8 ± 3.7 GeV

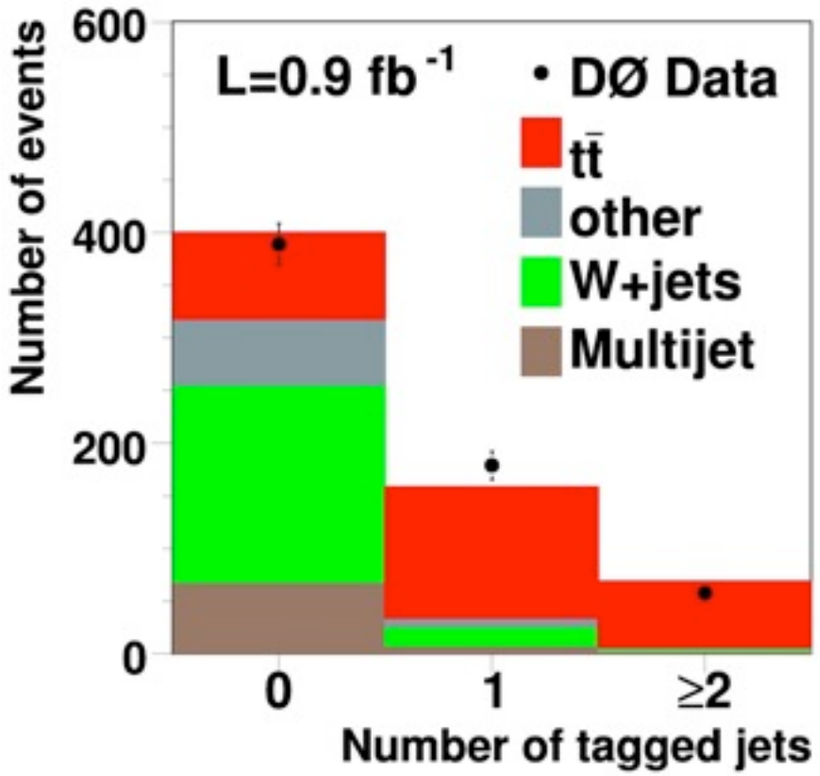
DØ:[Phys.Rev.Lett.103:132001,2009]

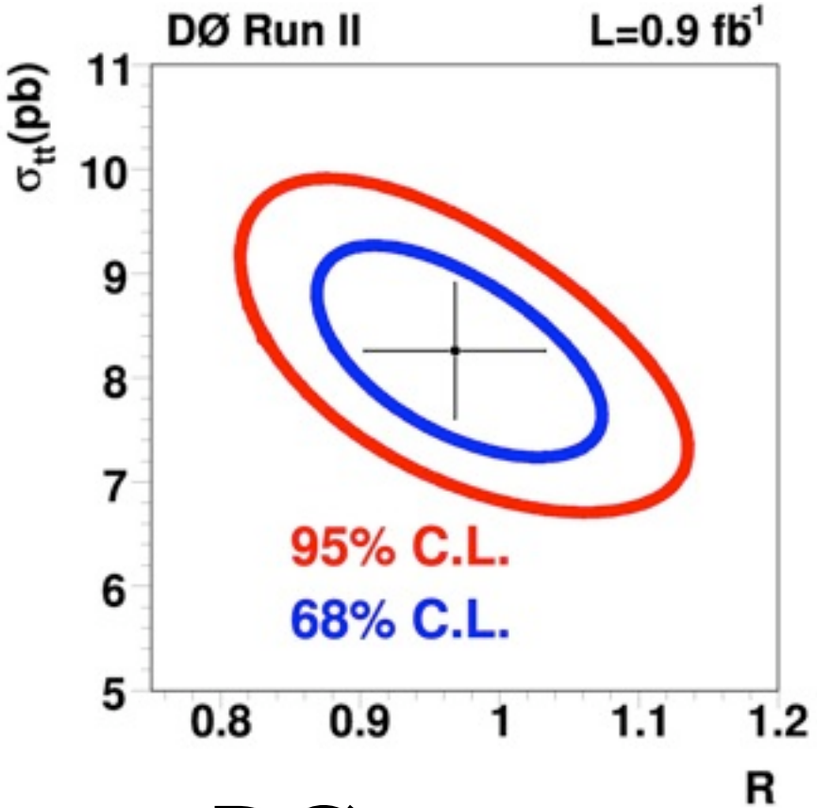




Is It Top?

- Top ≡ weak isospin partner of bottom
  - "Partner" in the sense of having the largest EWK/CKM coupling to *b*
  - Measure $R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$
  - ...from fraction of b-tagged jets in pair production



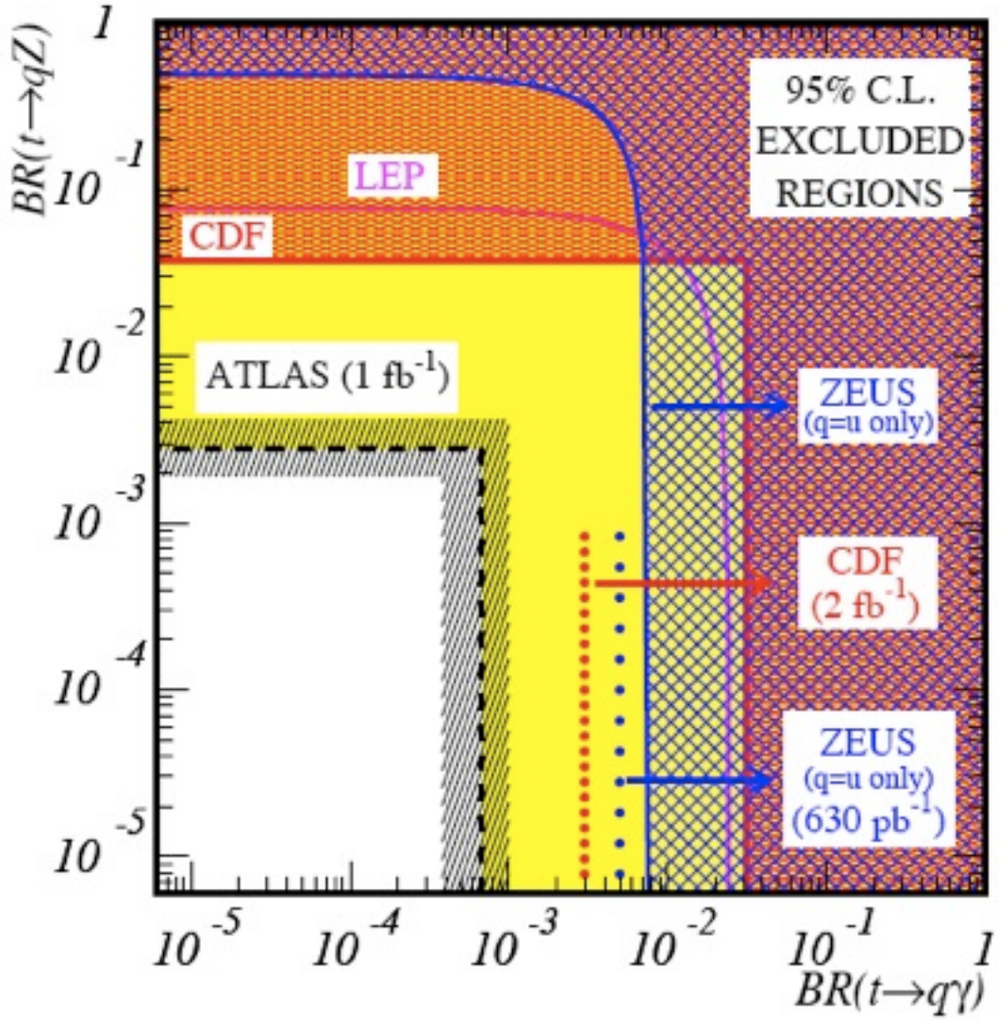


If unitary CKM matrix with 3 generations:
$|V_{tb}| > 0.89$
@ 95% CL

DØ: Phys. Rev. Lett. 100 , 192003 (2008)

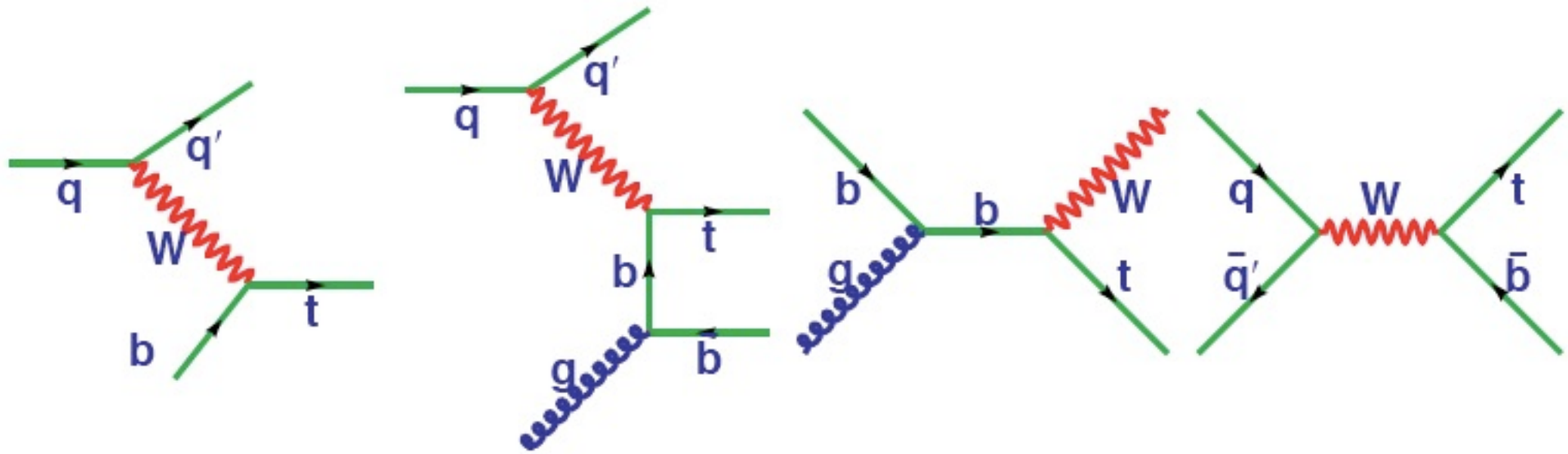
- Rare decays
  - $t \rightarrow Zc$: < 3.7% @ 95% CL (CDF: PRL 101 192002)
  - $t \rightarrow H^+b$: < 10-30% @ 95% CL (CDF:PRL 103 101803, DØ: Phys.Lett.B682:278-286,2009, **Phys.Rev.D80:051107(R),2009**)
  - LHC prospects (ATLAS):
    - $t \rightarrow H^+b$: < ~3%, then systematics limited?
    - $t \rightarrow Zq, \gamma q$: sensitive to ~$10^{-4}$ with 100 fb^{-1}
    - $t \rightarrow gq$: sensitive to ~7 10^{-3}
    - Radiative $t \rightarrow WbZ$ (predicted at ~5 10^{-7} in SM) out of LHC reach

ATLAS CSC Book: arXiv:0901.512

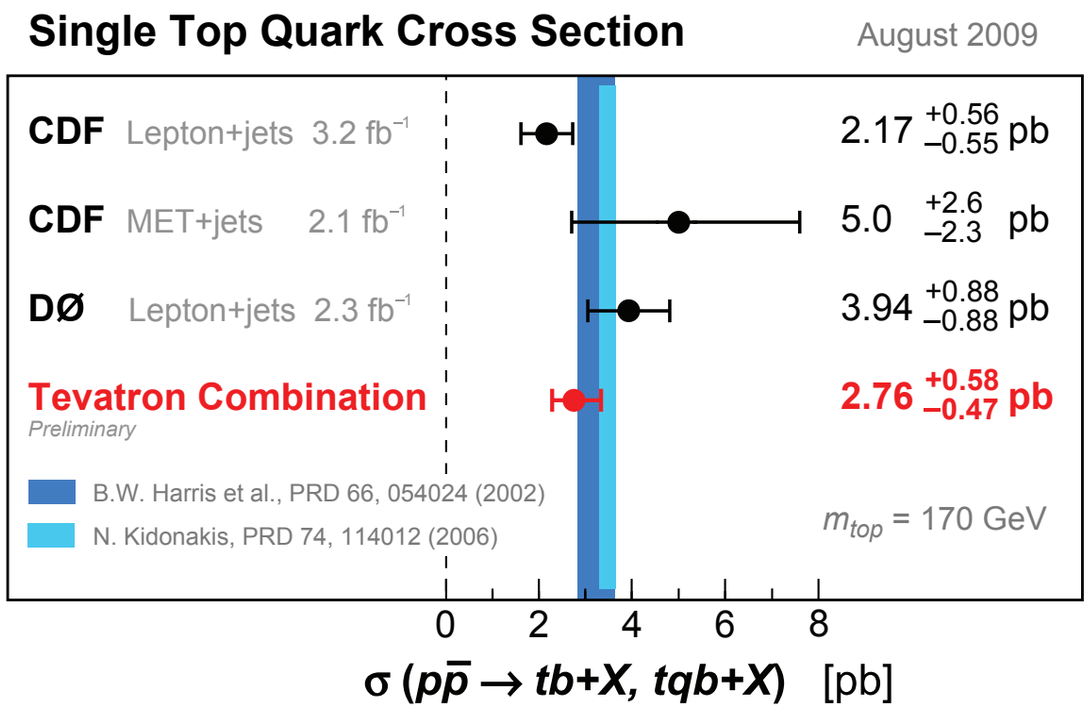


Single Top

- Probe the top's EWK coupling through production



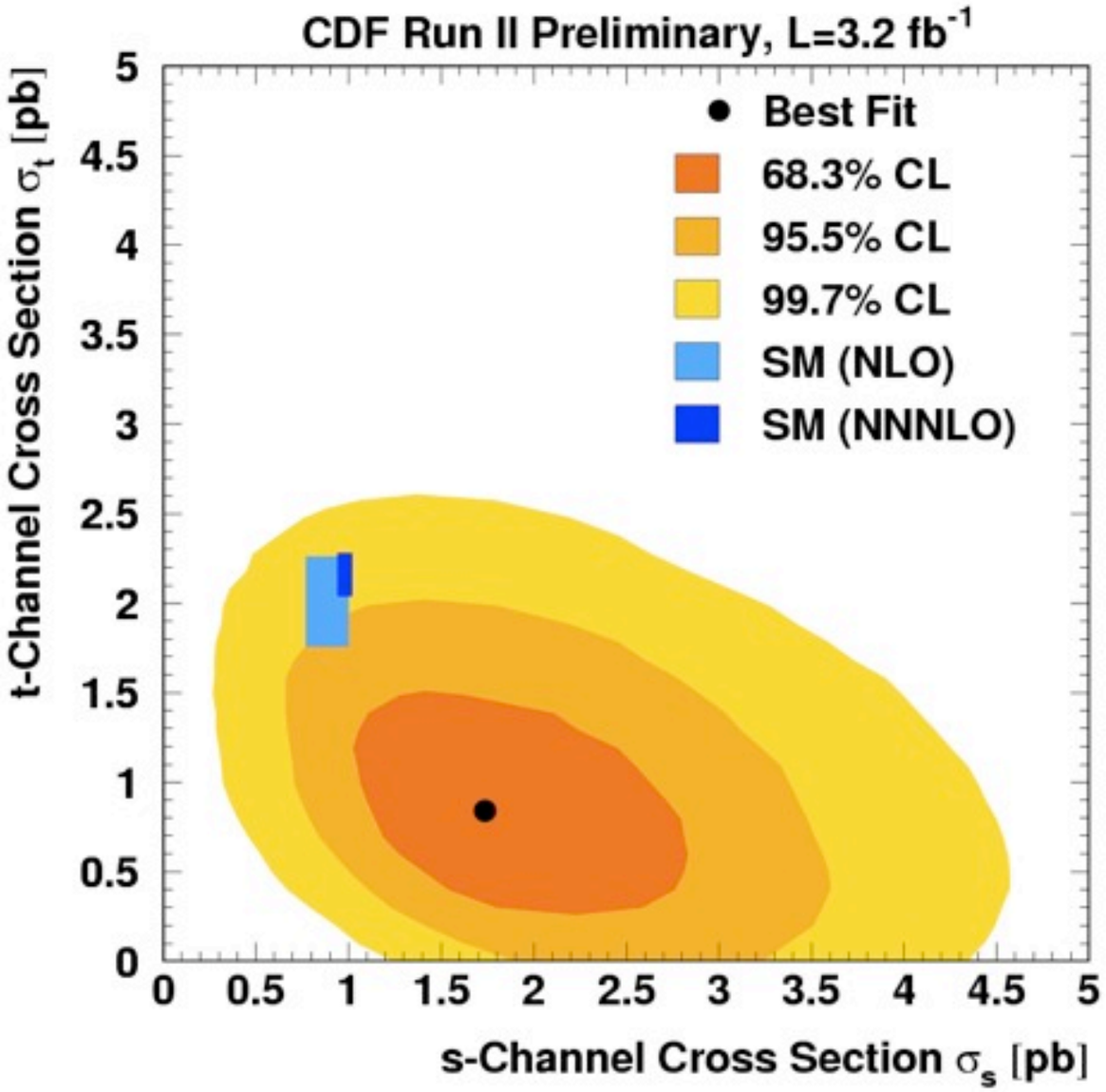
- Process now well-established at the Tevatron:

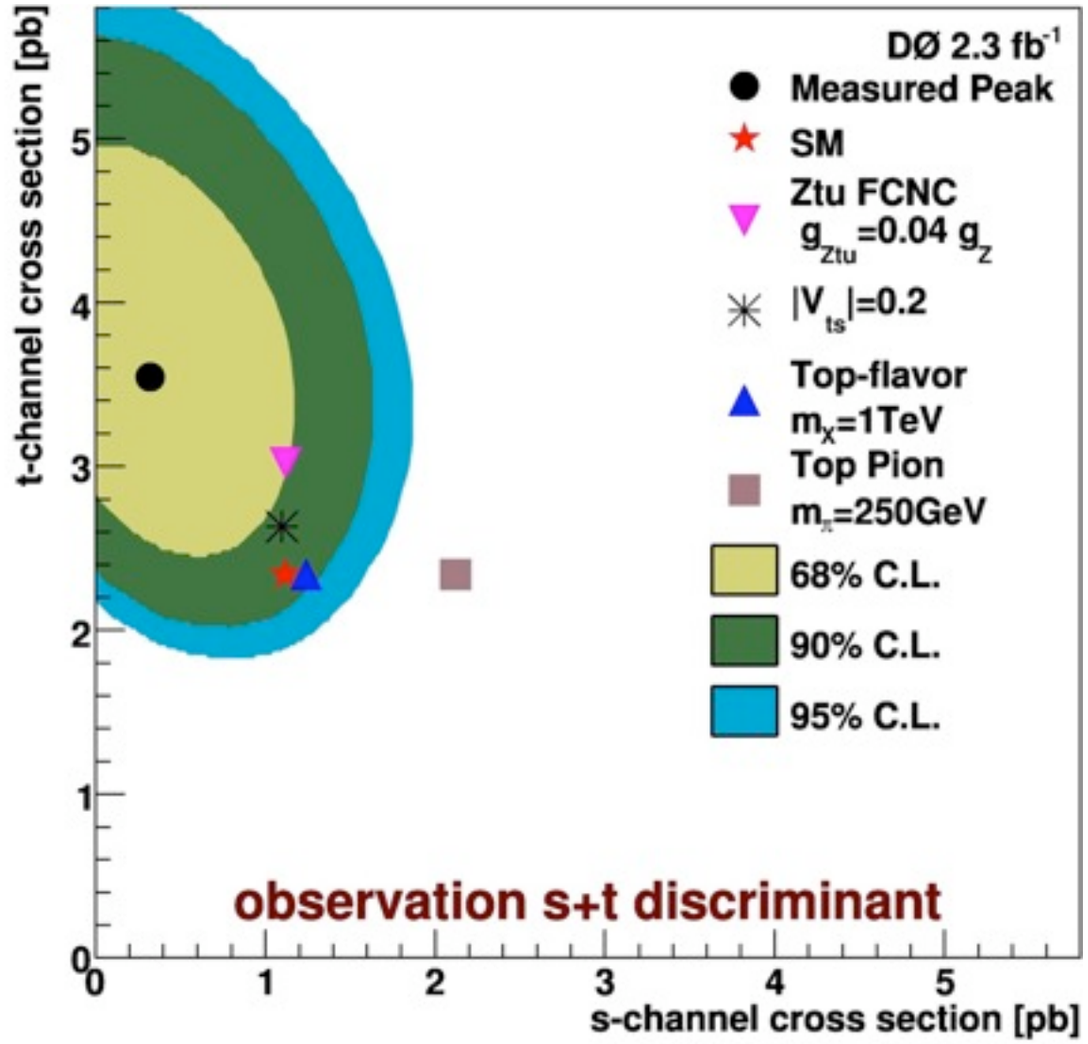


CDF: PRL 103 092002

DØ: Phys. Rev. Lett. 103 , 092001 (2009)

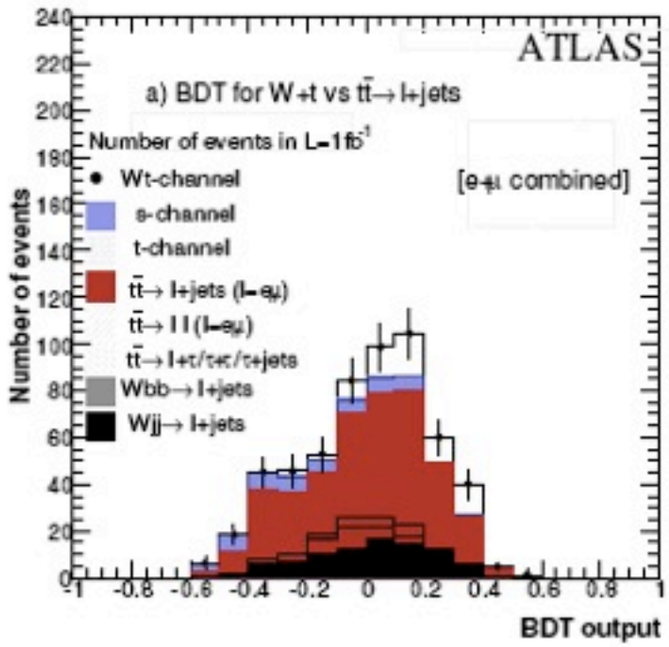
- Extracted measurements:
  - $|V_{tb}| > 0.71/0.78$ @ 95% CL (CDF/DØ)

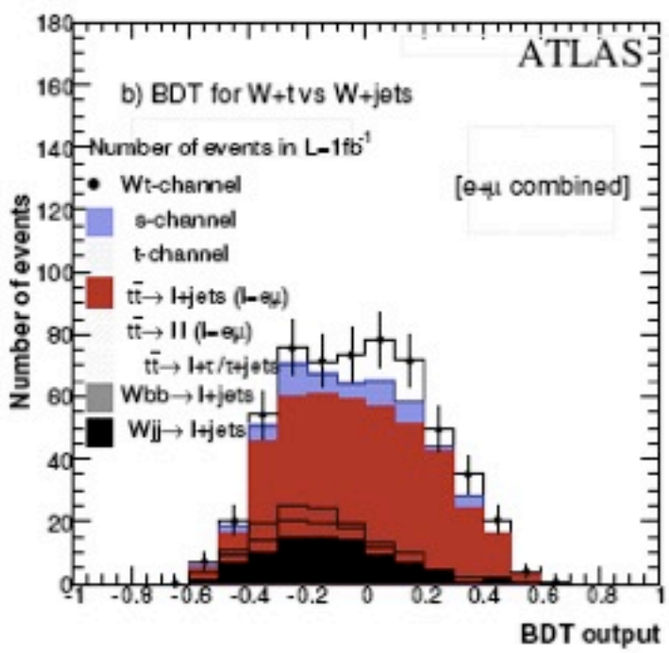




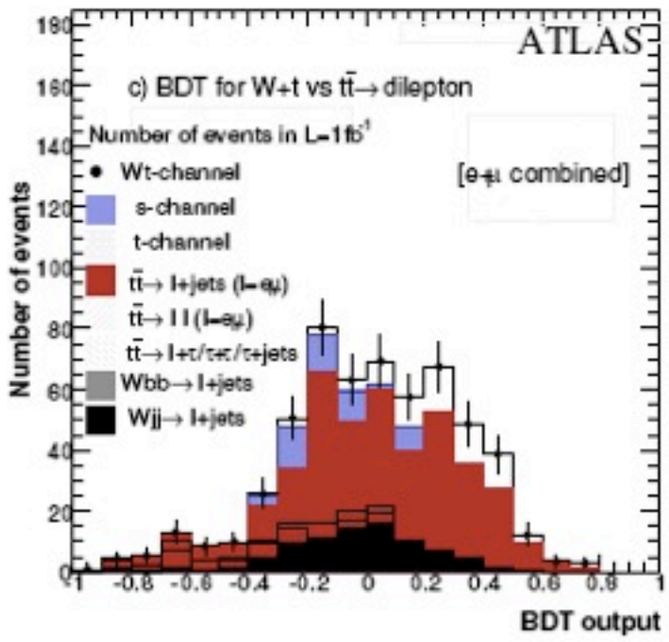
Single Top @ LHC

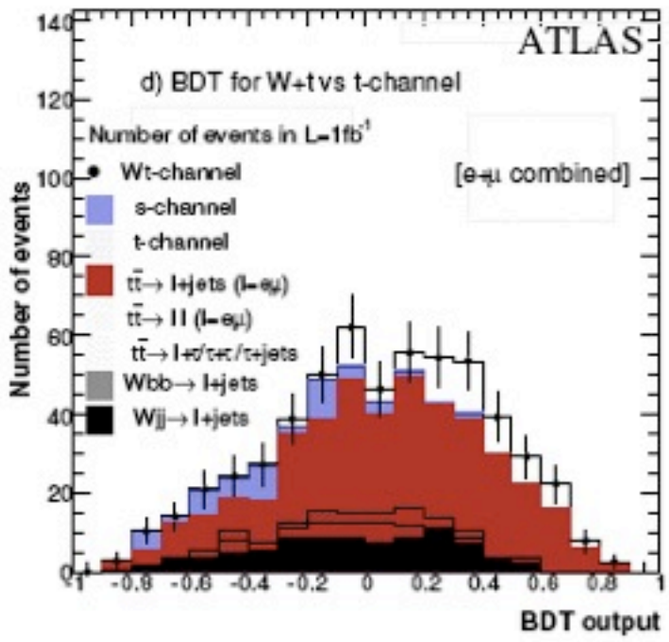
- t-channel and Wt measurable with a few fb^{-1}, more needed for s-channel





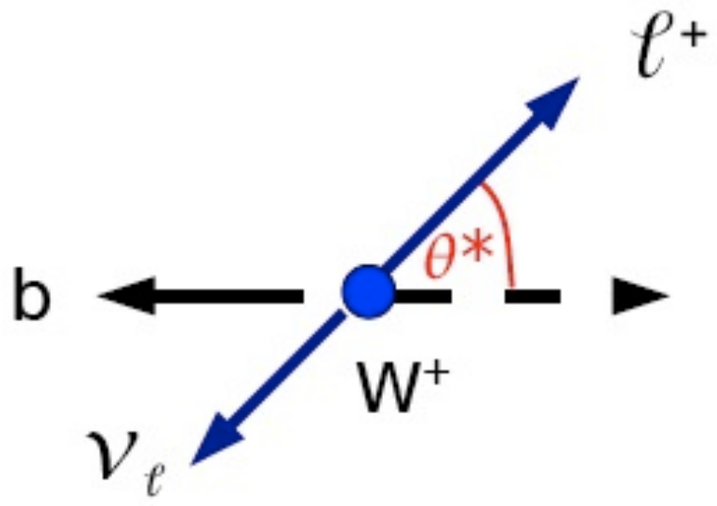
ATLAS CSC Book: arXiv:0901.512

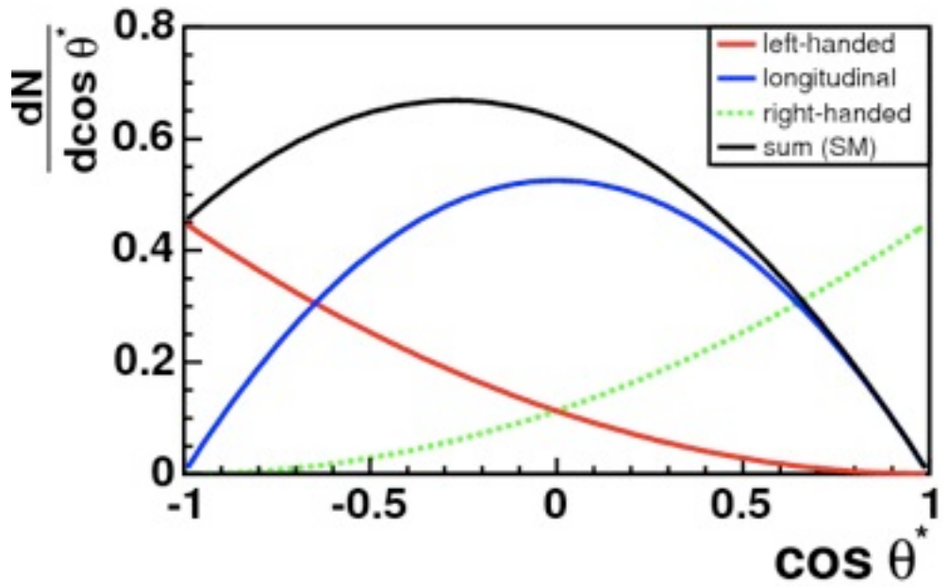




W Boson Helicity

- But is the tWb coupling EWK?
  - Study angular distribution of the decays





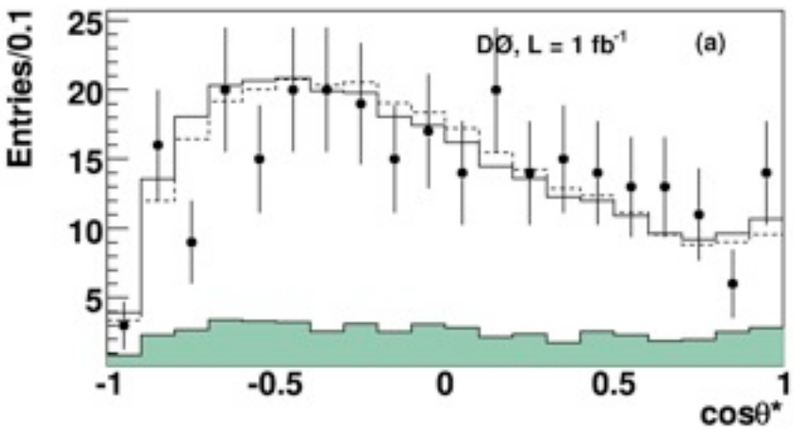
$$\frac{dN}{d\cos\theta^*} = F_- \cdot \frac{3}{8}(1-\cos\theta^*)^2 + F_0 \cdot \frac{3}{4}(1-\cos^2\theta^*) + F_+ \cdot \frac{3}{8}(1+\cos\theta^*)^2$$

LH Contribution
≈ 0.3 in SM

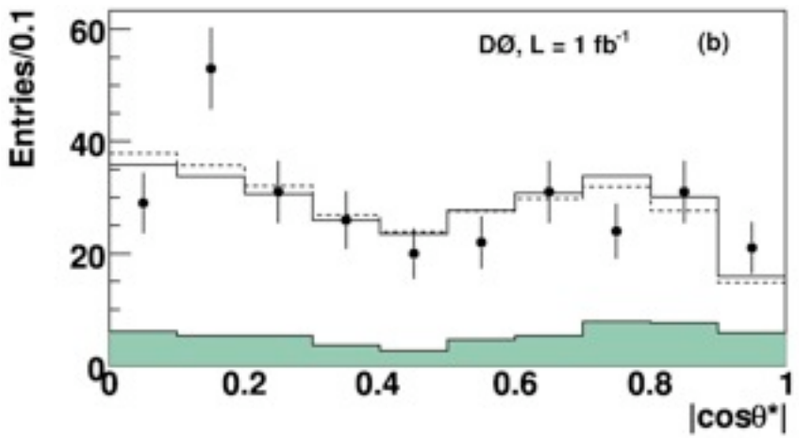
Longitudinal
Contribution
≈ 0.7 in SM

RH Contribution
≈ 0.0 in SM

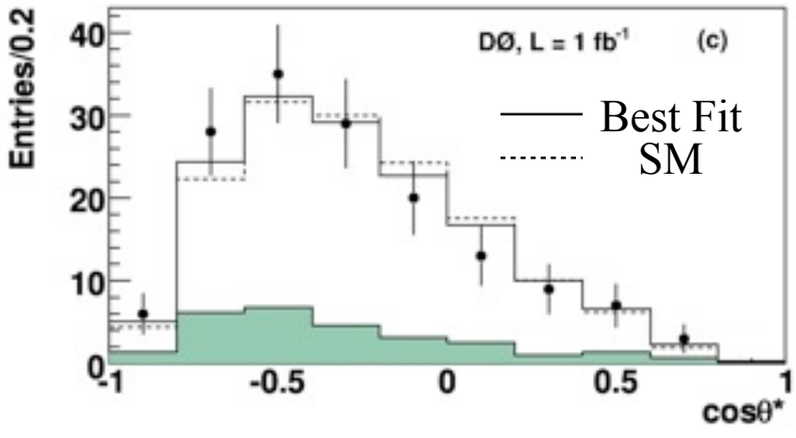
- Two approaches:
  - Reconstruct $\cos\theta^*$ directly in l+jets and/or dilepton events, then use template or unfolding



Leptonic W in l+jets



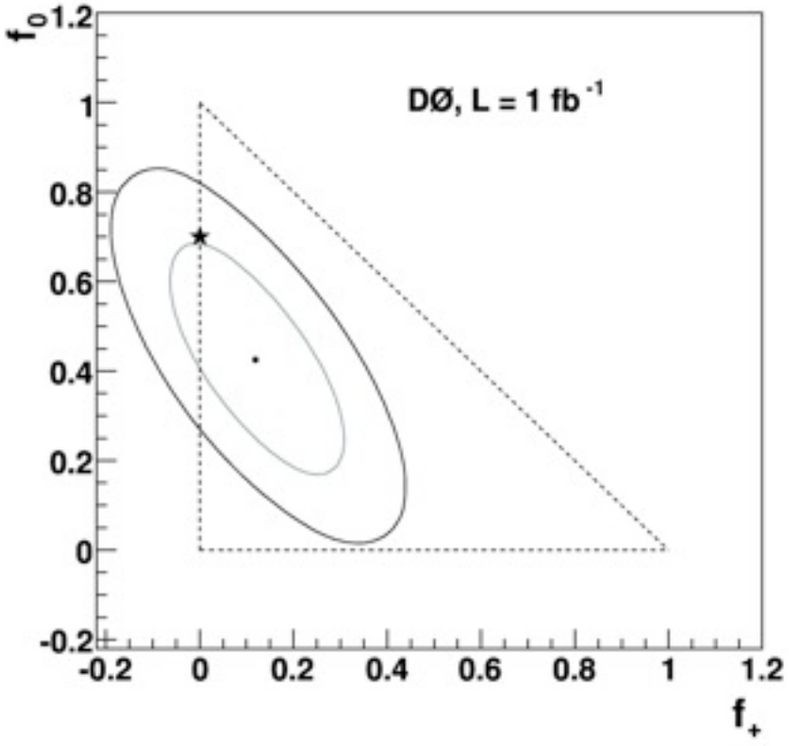
Hadronic W in l+jets

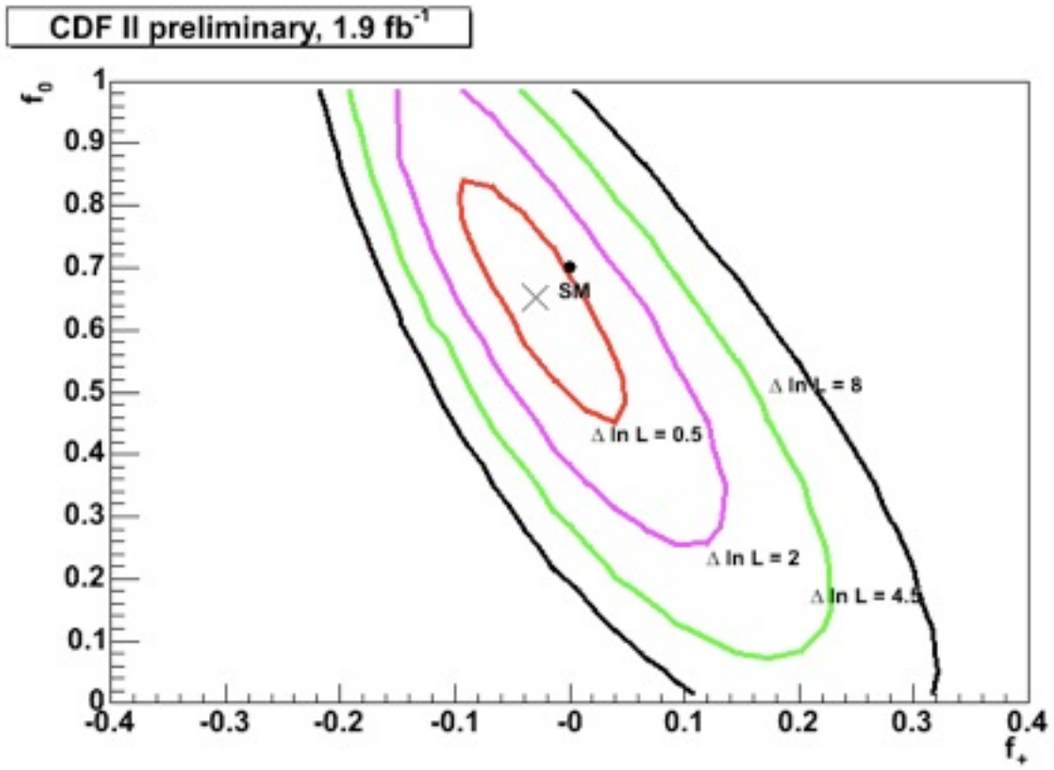


Dileptons

2-D likelihood fit to templates

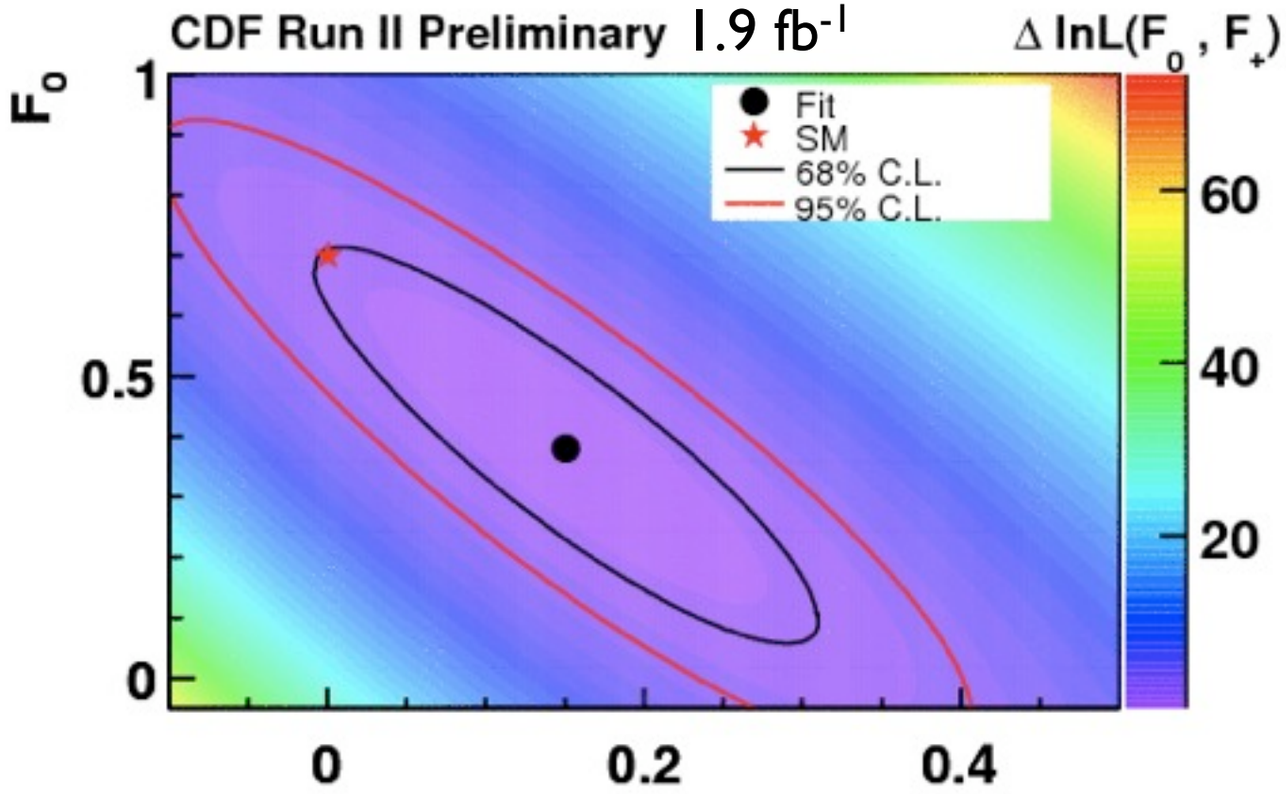
Phys. Rev. Lett. 100 , 062004 (2008)





CDF Templates

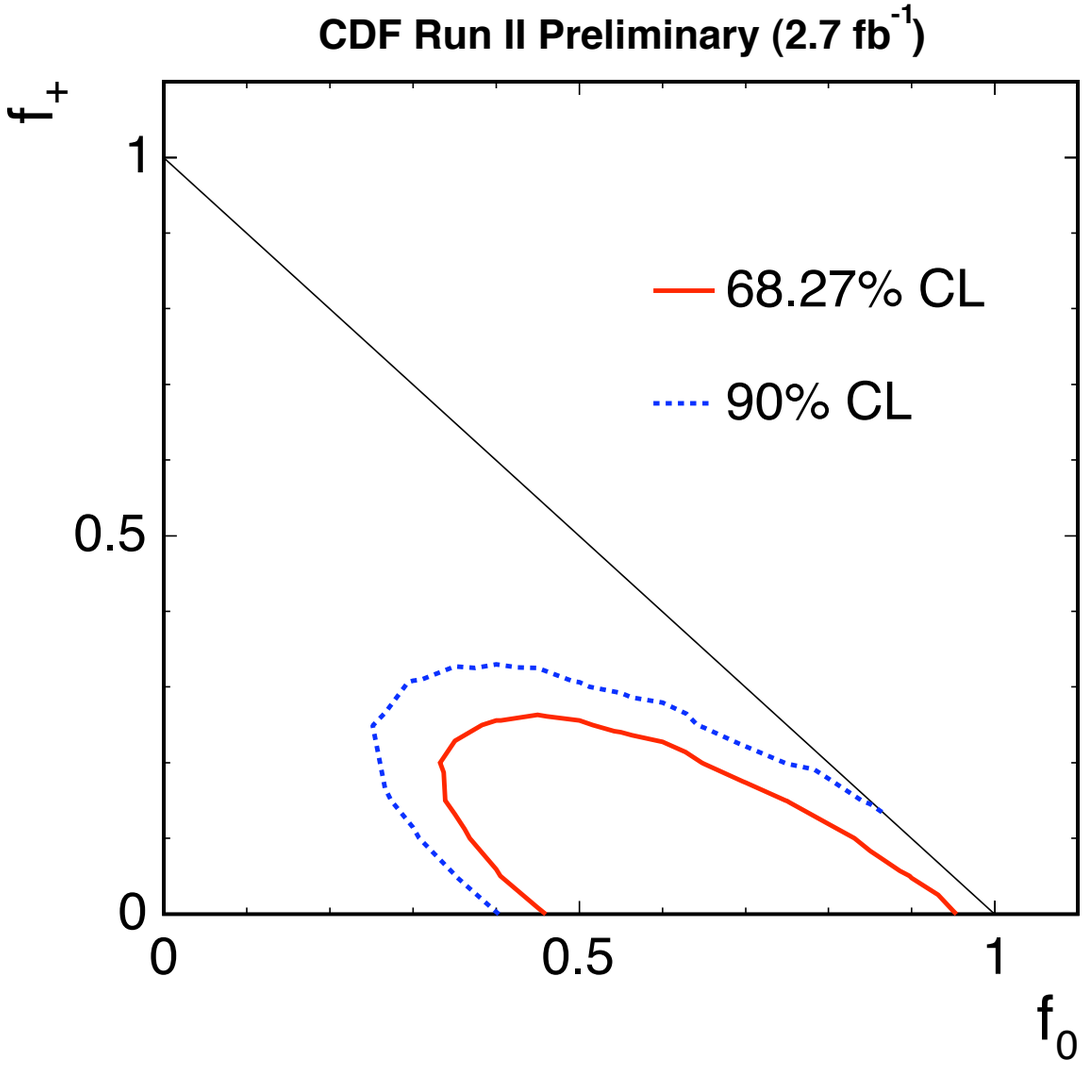
Conf. Note 9215



CDF Unfolding

Conference Note 9114

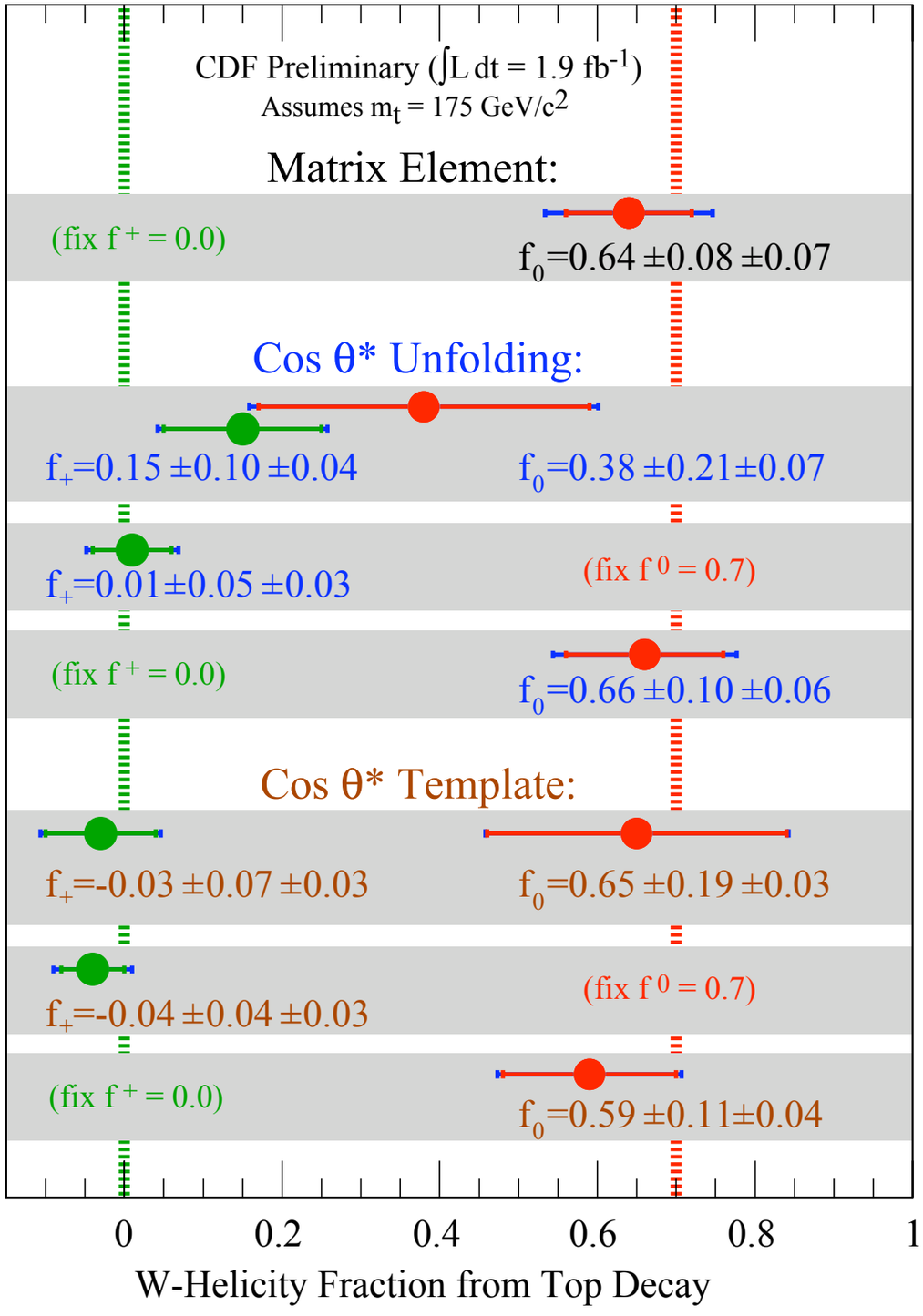
- Or, use matrix-element technique



$f_0 = 0.88 \pm 0.11\ (stat) \pm 0.06\ (syst)$

$f_+ = -0.15 \pm 0.07\ (stat) \pm 0.06\ (syst)$

Conf. Note 10004

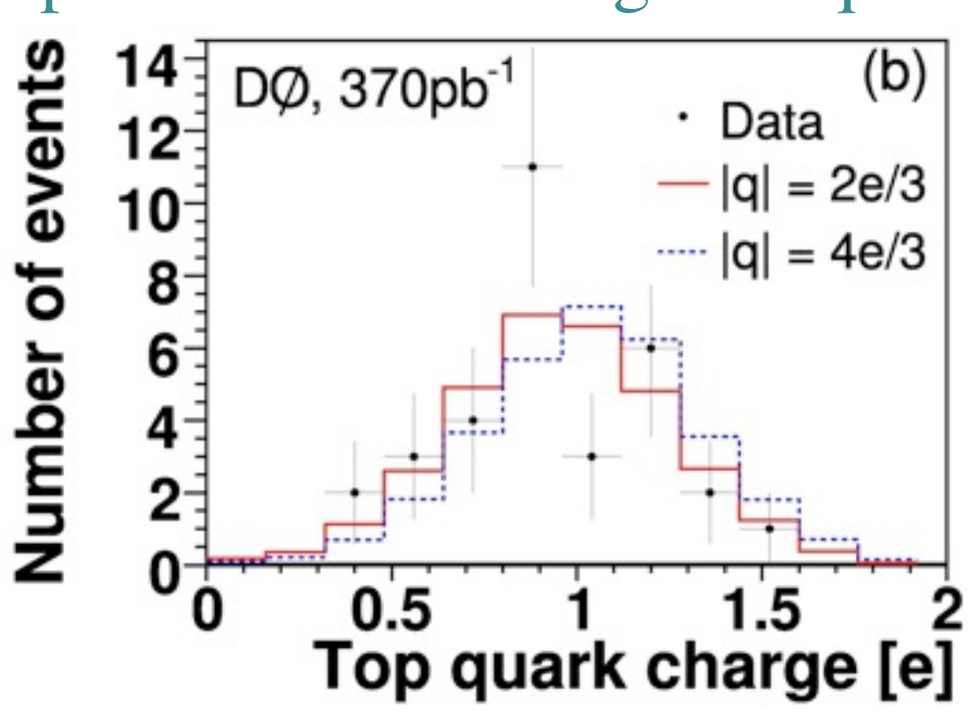


➡ All measurements statistics-limited....

Top Charge

- Does it have charge +2/3? Look at the charge of the b associated with the W
  - Jet charge (CDF & DØ)
    - CDF Conf. Note 8967: exclude 4/3 @ 87% CL
    - DØ: exclude complete sample is made of charge 4/3 quarks @ 92% CL

Phys. Rev. Lett. 98 , 041801 (2007)



  - Soft lepton tag (CDF)
    - 45 events, 29 events best fit 2/3, 16 events 4/3 → 4/3 excluded @ 95% CL

Conf. Note 9939

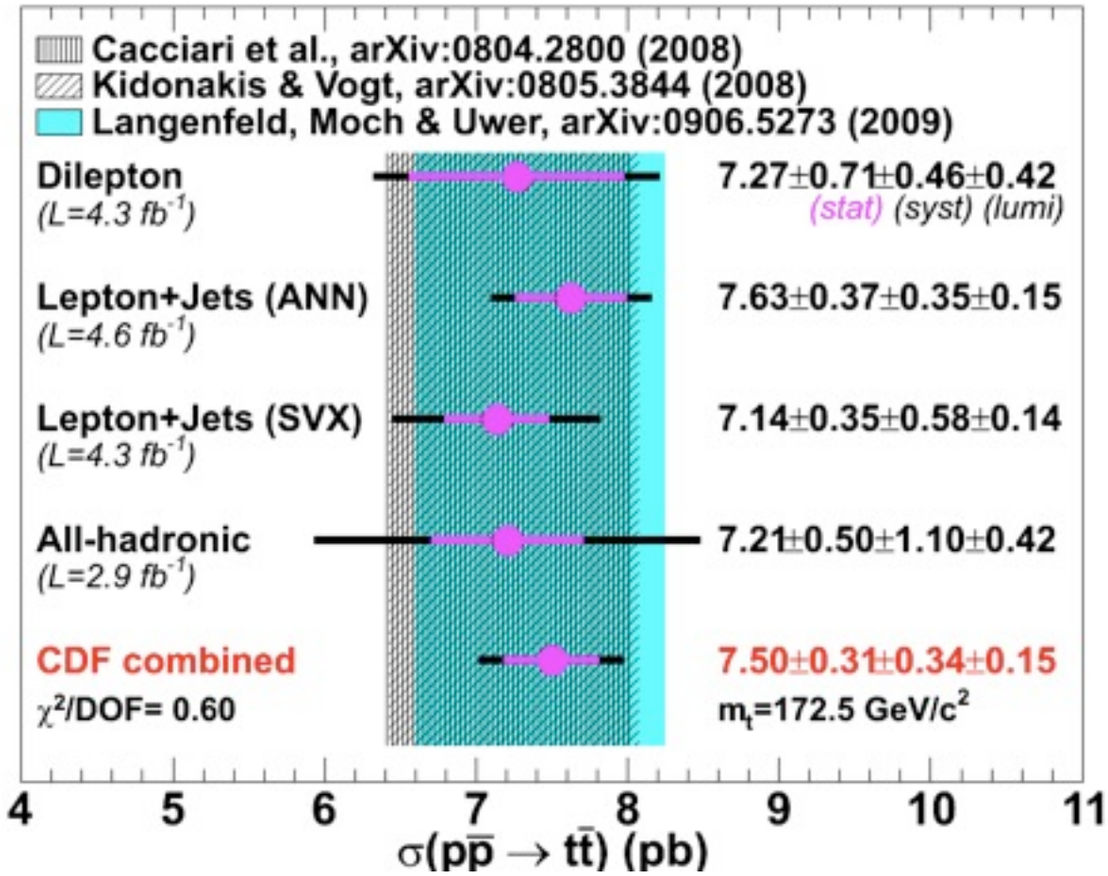
Top Width

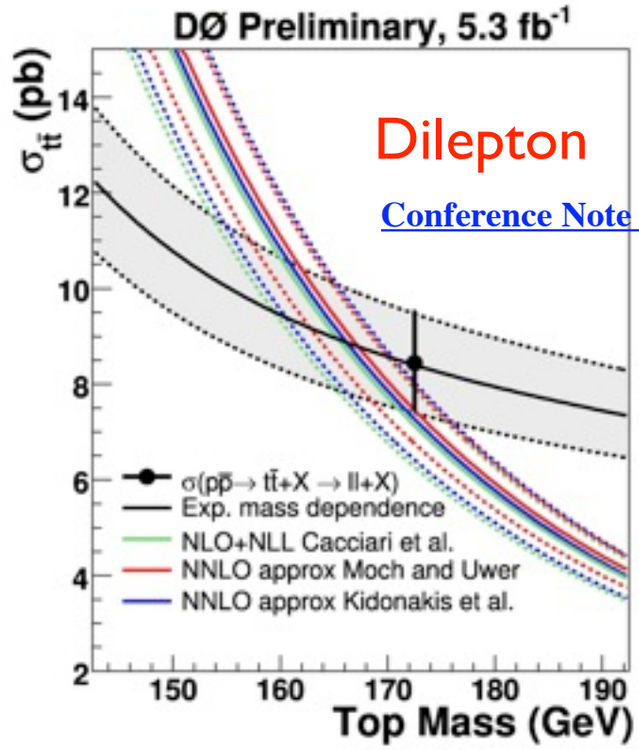
- SM: $\Gamma_t \sim 1.4$ GeV
- Combine $\Gamma(t \to Wb)$ (from single top) and $B(t \to Wb)$ and assume $B(t \to Wq) = 1$:
  - $\Gamma_t = 2.1 \pm 0.6$ GeV DØ: Conference Note D0 Note 6034-CONF
  - i.e. $\tau_t = (3 \pm 1)\ 10^{-25}$ s
- Using only $\Gamma(t \to Wb)$:
  - $\Gamma_t > 1.2$ GeV @ 95% CL
  - $\tau_t < 5\ 10^{-25}$ s @ 95% CL
- CDF direct measurement from m_t, m_{jj}:
  - $\Gamma_t < 7.5$ GeV @ 95% CL (Conf. Note 10035)

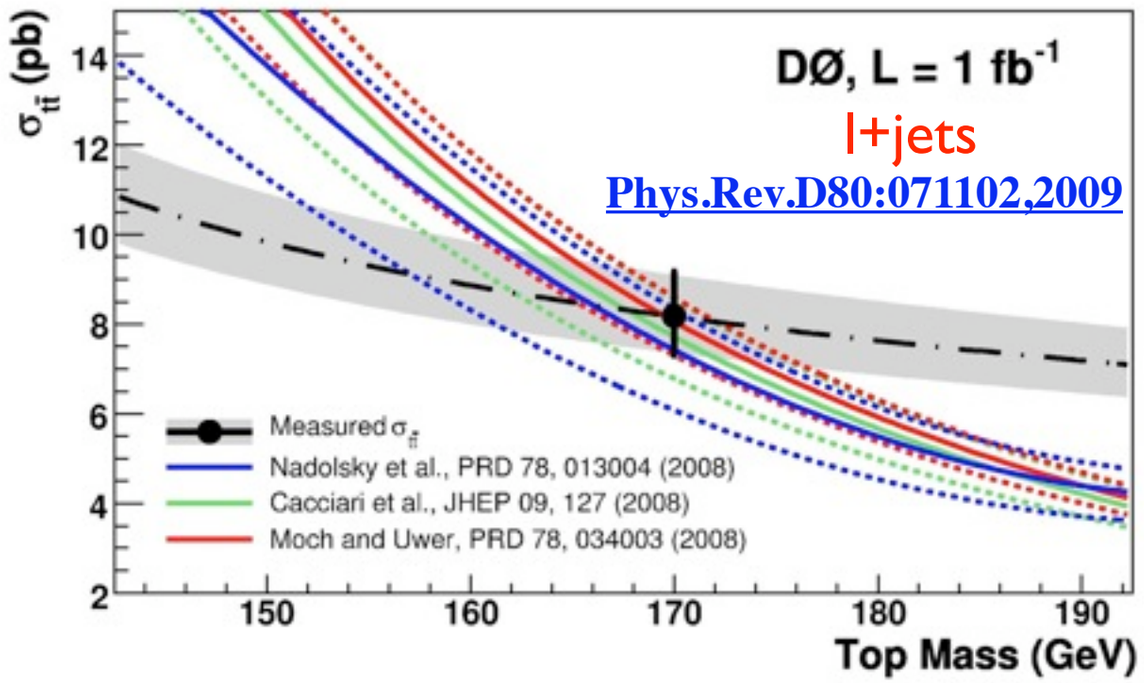
Production

Top Pair Production

CDF Conf. Note 9913



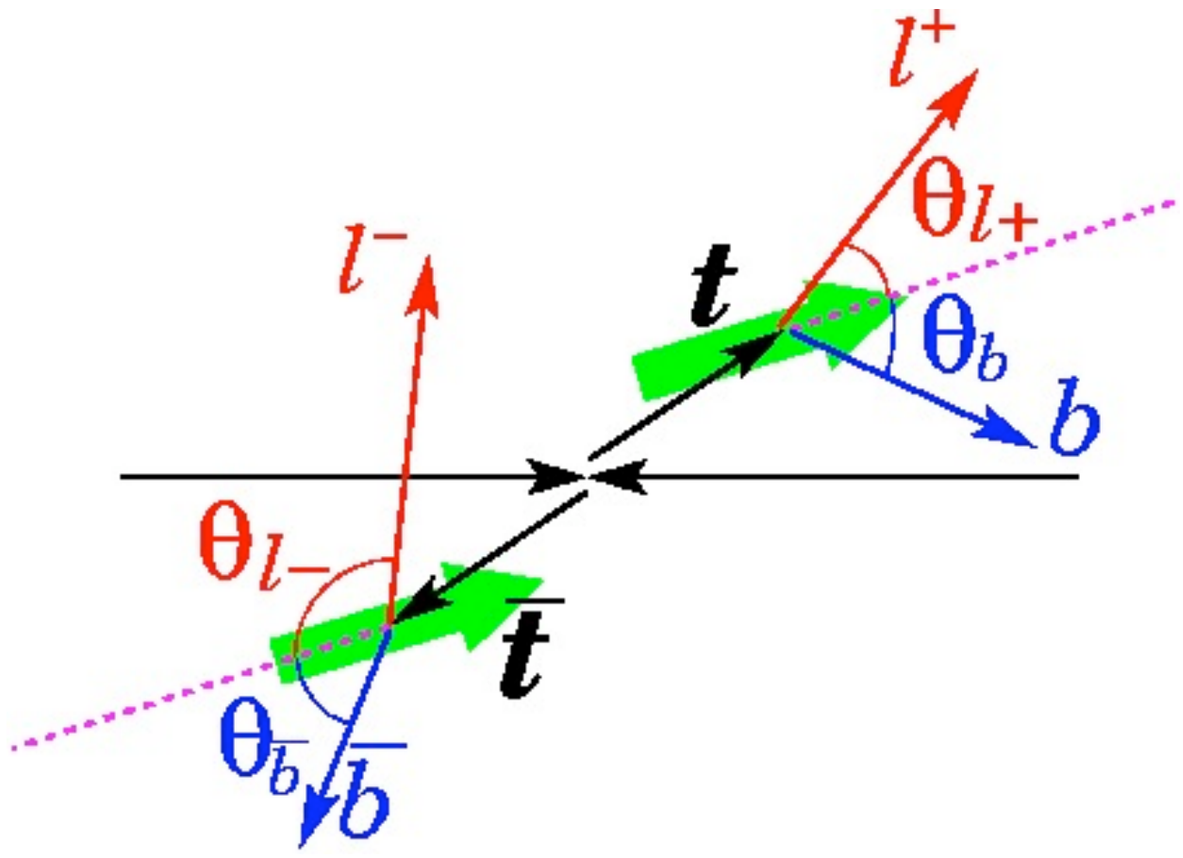




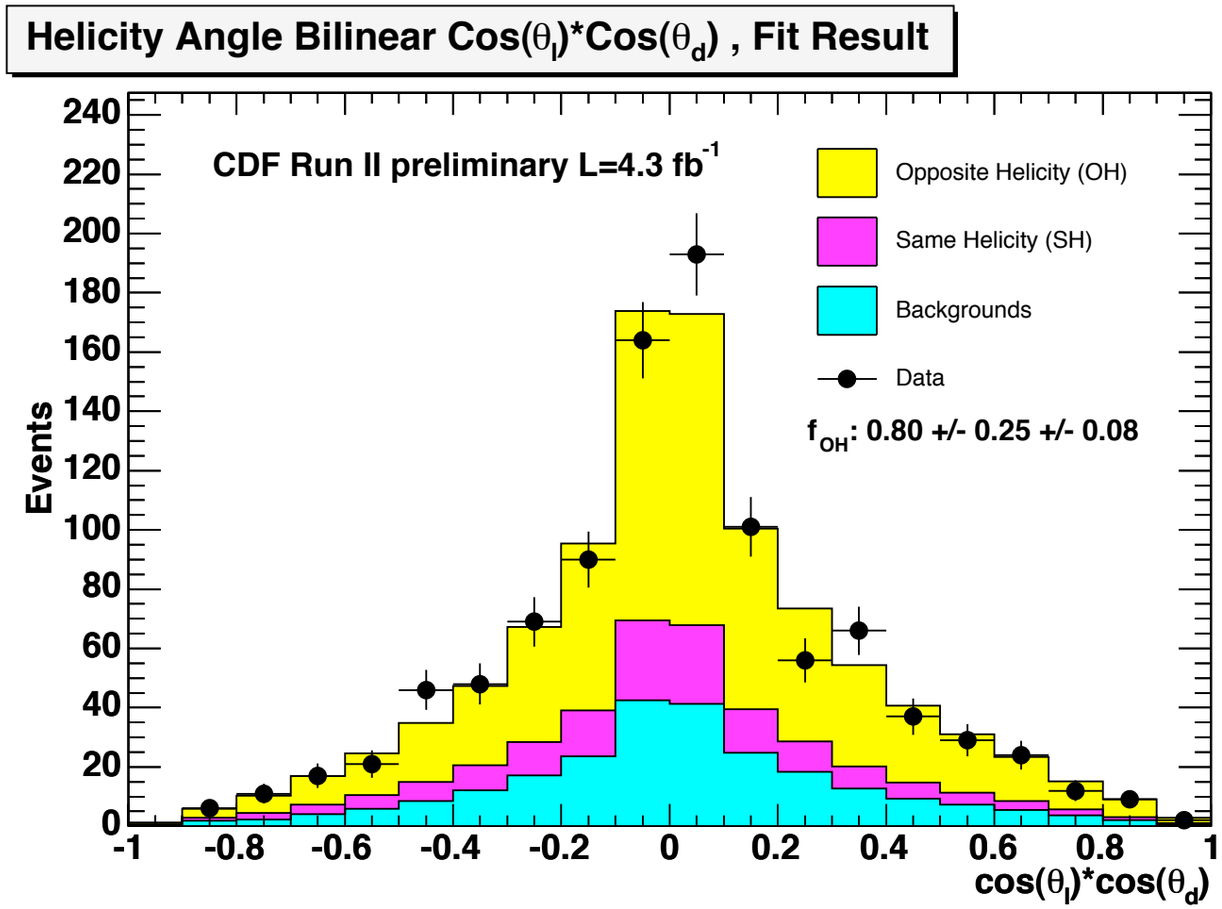
➡ Not much room for anomalous production…

Spin Correlations

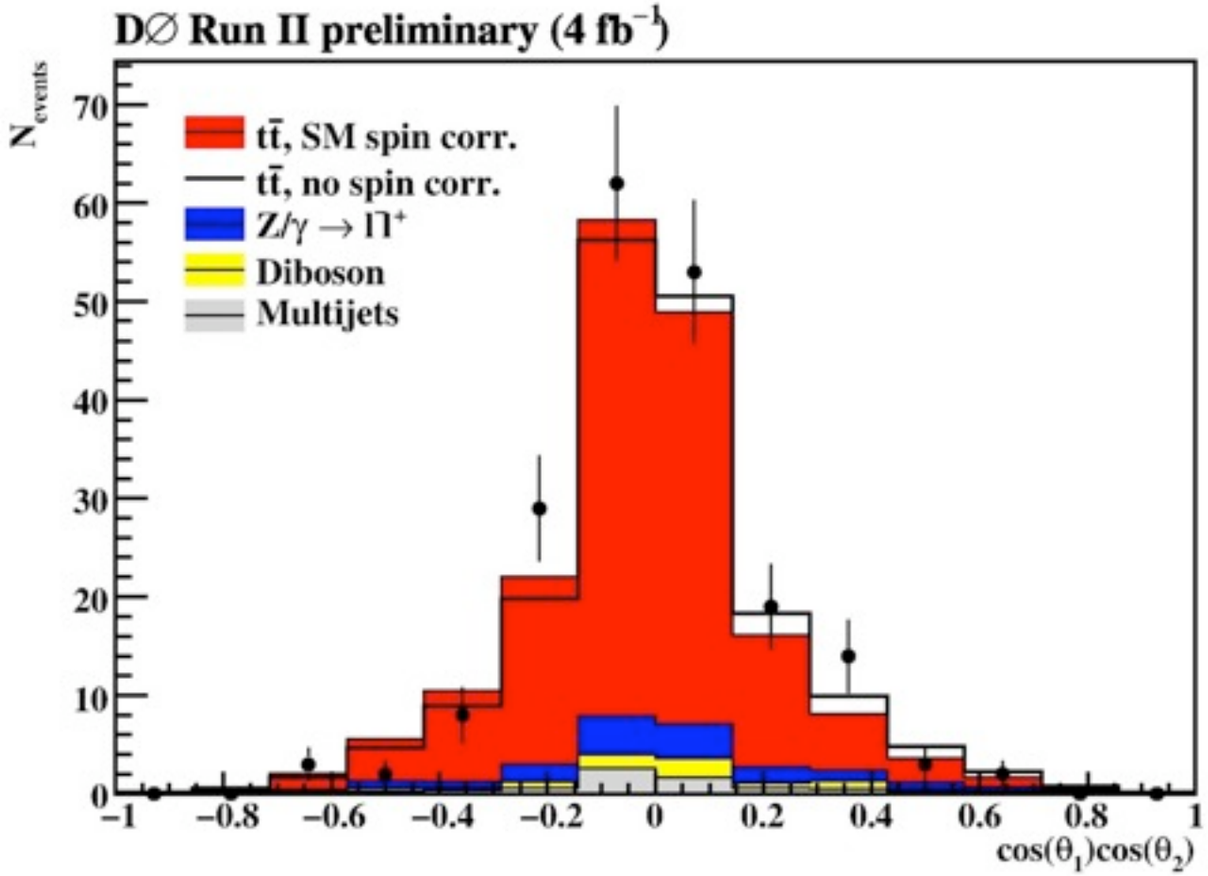
- Top decays before hadronization → initial polarization information is reflected in top decay products
  - Tops have opposite/same helicity in $q\bar{q}$/gg production
  - Measure angles of down-type fermions from W/top decay in top rest-frame wrt quantization axis (top in $t\bar{t}$ rest frame or beam axis)



- It's a difficult measurement:



Conf. Note 10048



Conference Note 5950-CONF

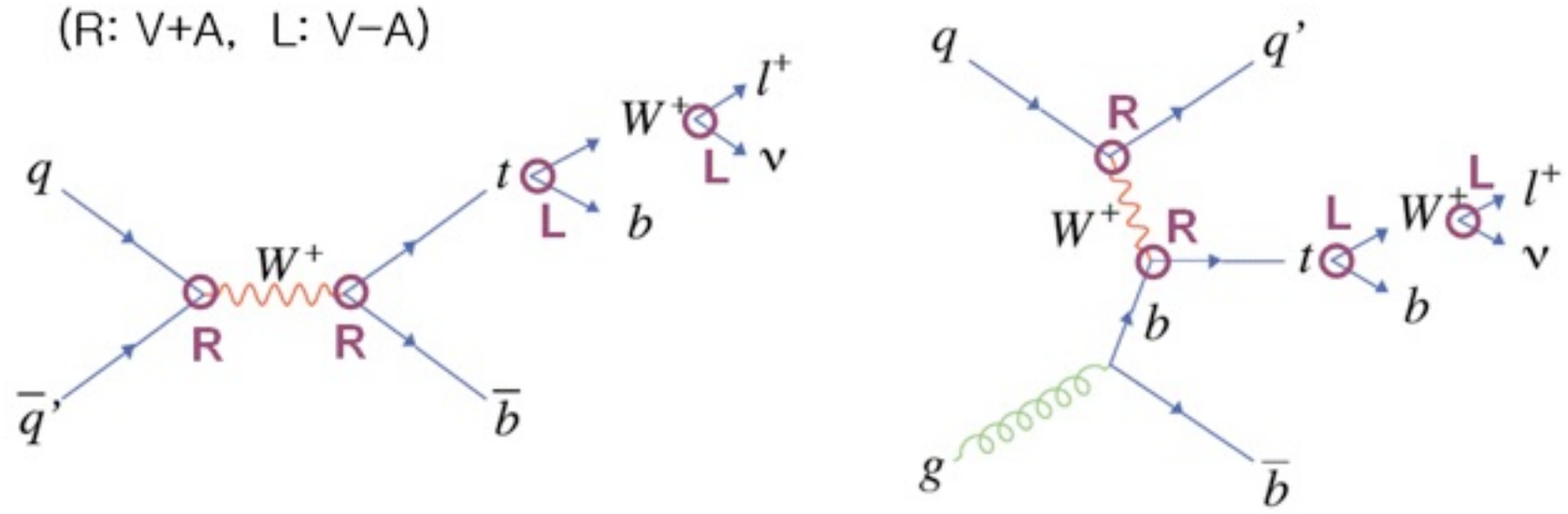
CDF: C = 0.60 ± 0.50 (stat) ± 0.16 (syst) (l+jets)

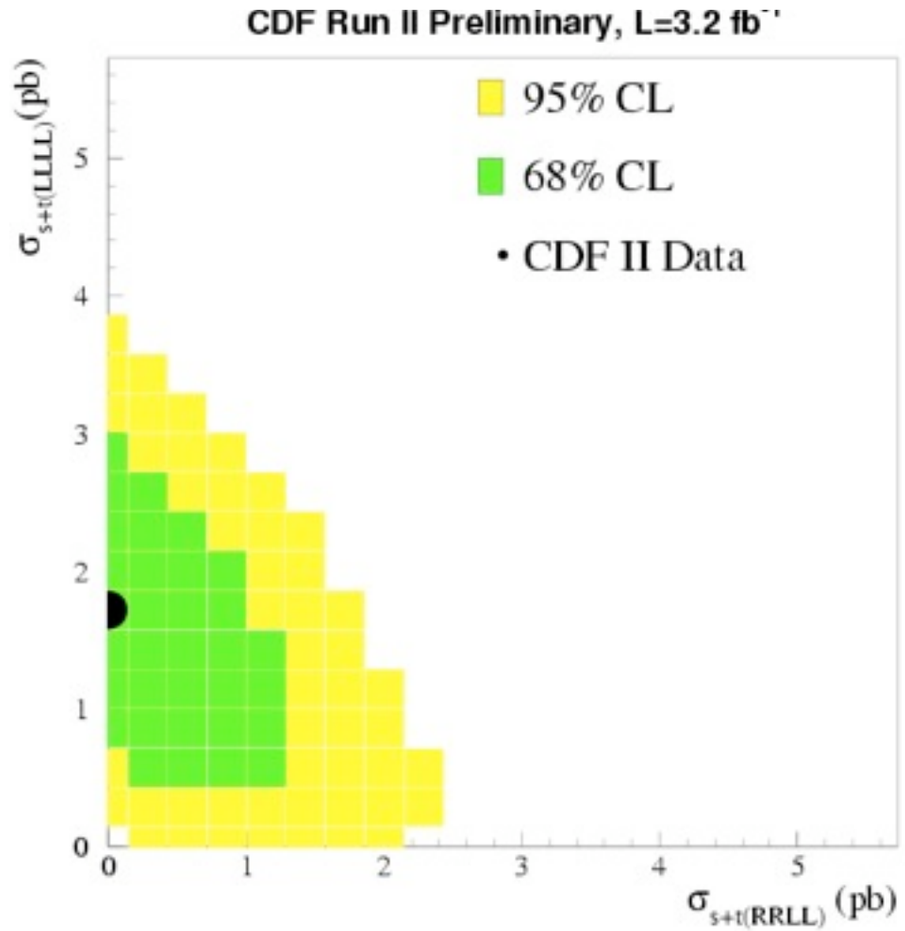
CDF: C = 0.32 $^{+0.55}_{-0.78}$ (stat + syst) (dilepton)

DØ: C = -0.17 $^{+0.65}_{-0.53}$ (stat + syst) (dilepton)

SM: 0.78 (NLO)

Polarization in Single Top



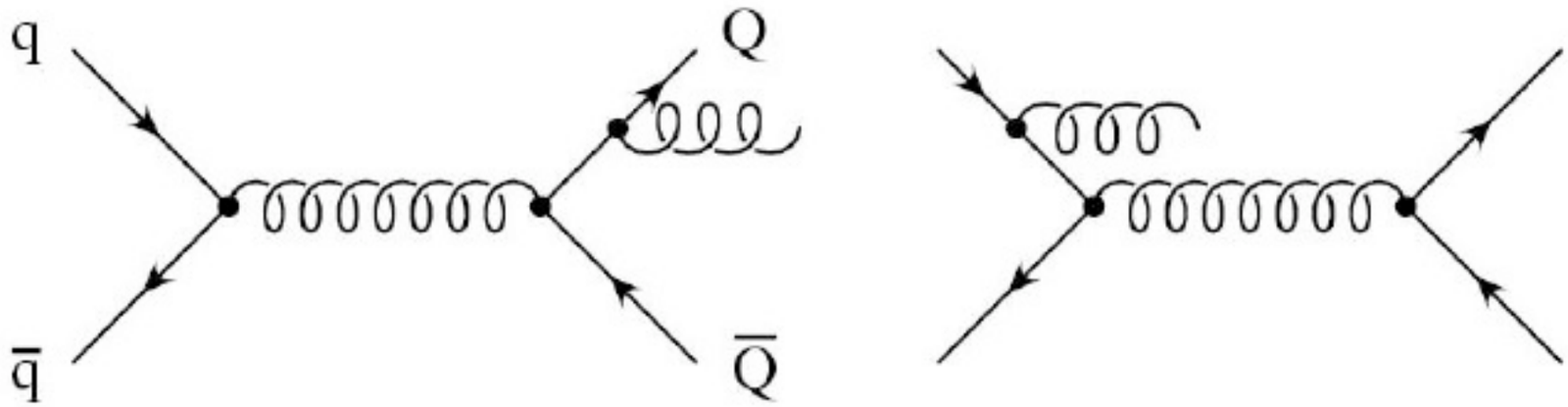


Conf. Note 9920

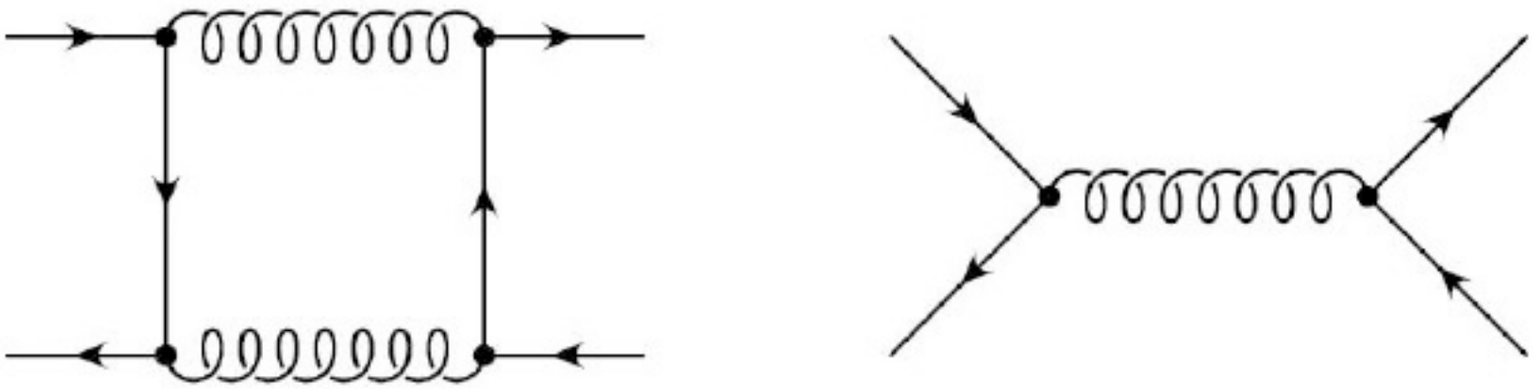
- Something for the LHC!

Forward-Backward Asymmetry

- Arises at NLO from interference between diagrams:
  - FSR & ISR

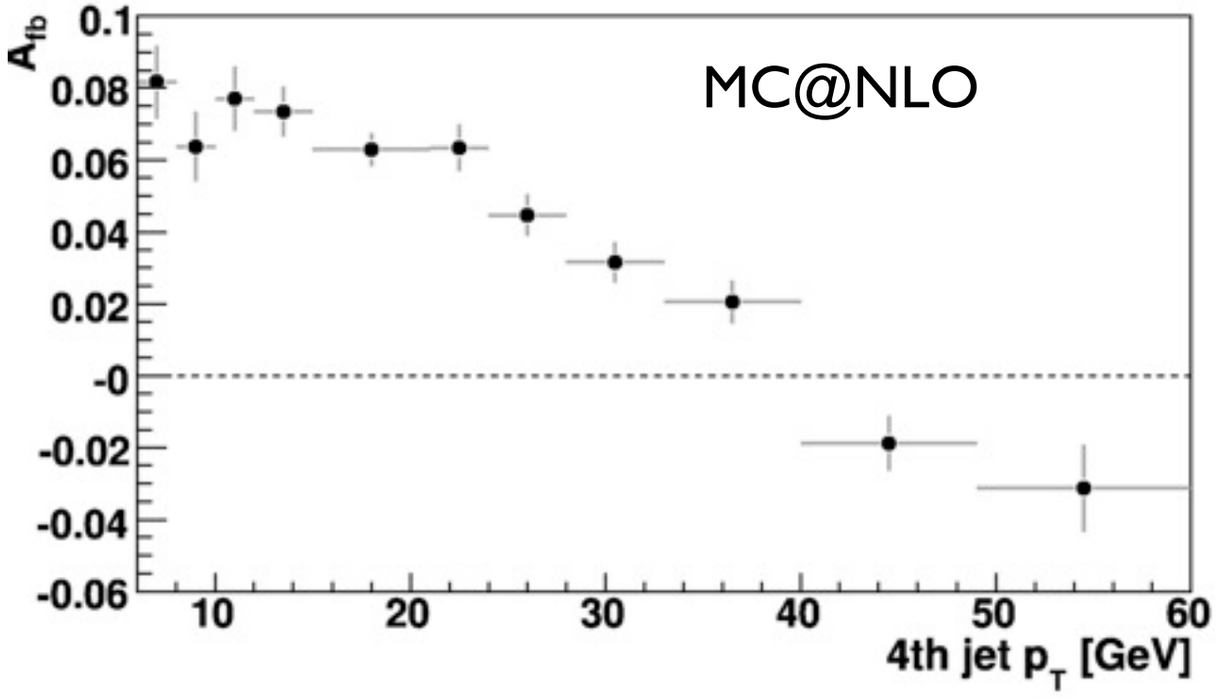


  - Box & Born



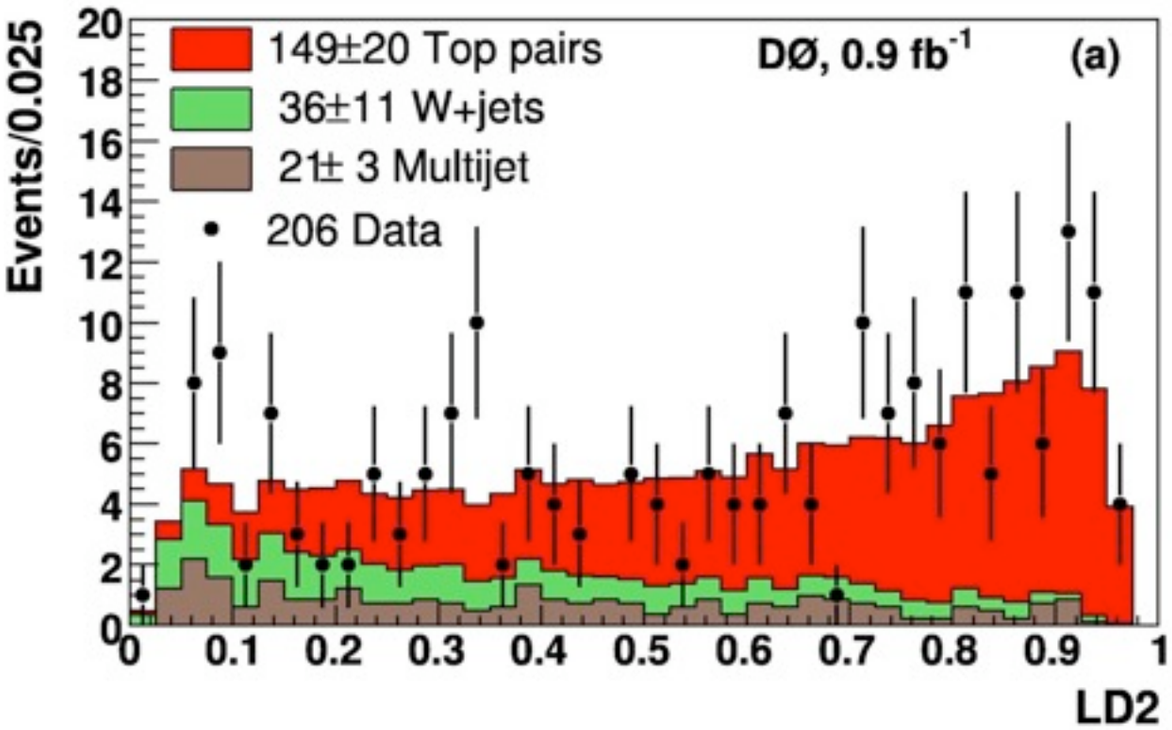
Measurement

- Fit events to determine $\Delta y = y_t - y_{\bar{t}}$, $\begin{cases} N_f = \#\{y_t > y_{\bar{t}}\} \\ N_b = \#\{y_t < y_{\bar{t}}\} \end{cases}$
- Define $A_{fb} = \dfrac{N_f - N_b}{N_f + N_b}$
- Careful!
  - Strong phase-space dependence
  - NNLO?
- Use kinematic fit
  - And minimize acceptance corrections

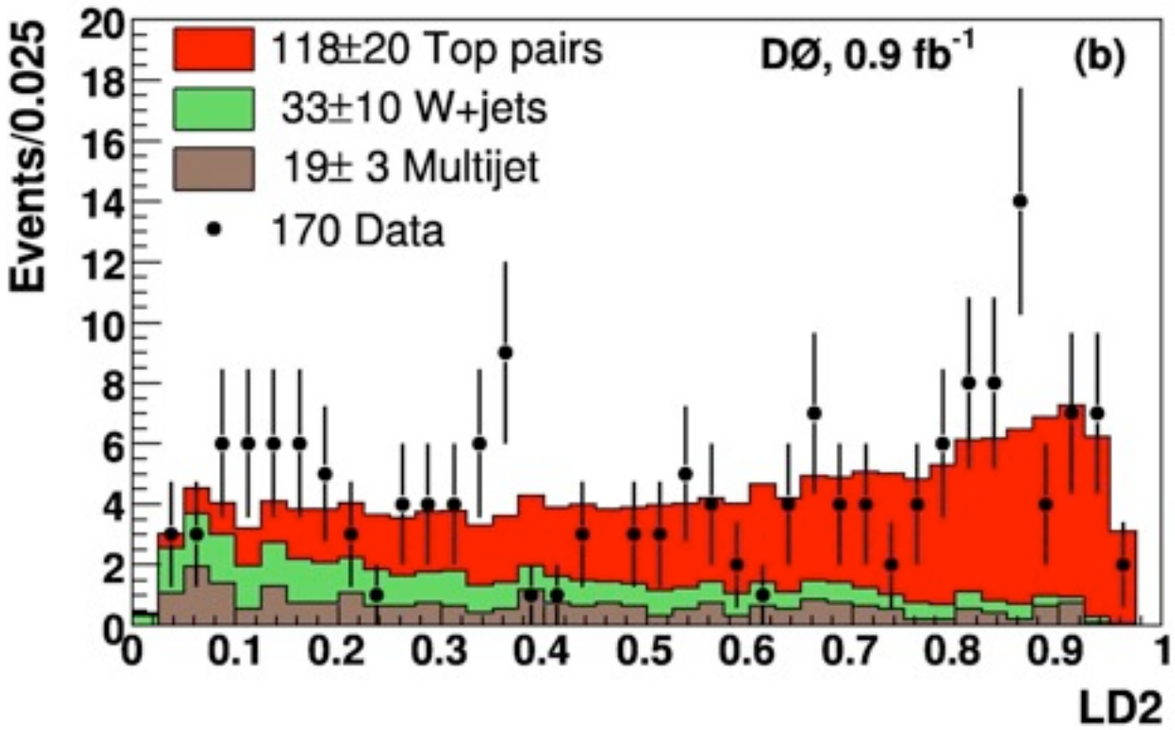


- DØ:

Forward



Backward



A_{fb}^{obs} = 0.12 ± 0.08 (stat)
± 0.01 (syst)
(Integrated over Δy)

Equiv MC@NLO pred:
A_{fb} = 0.08 ± 0.02 ± 0.1

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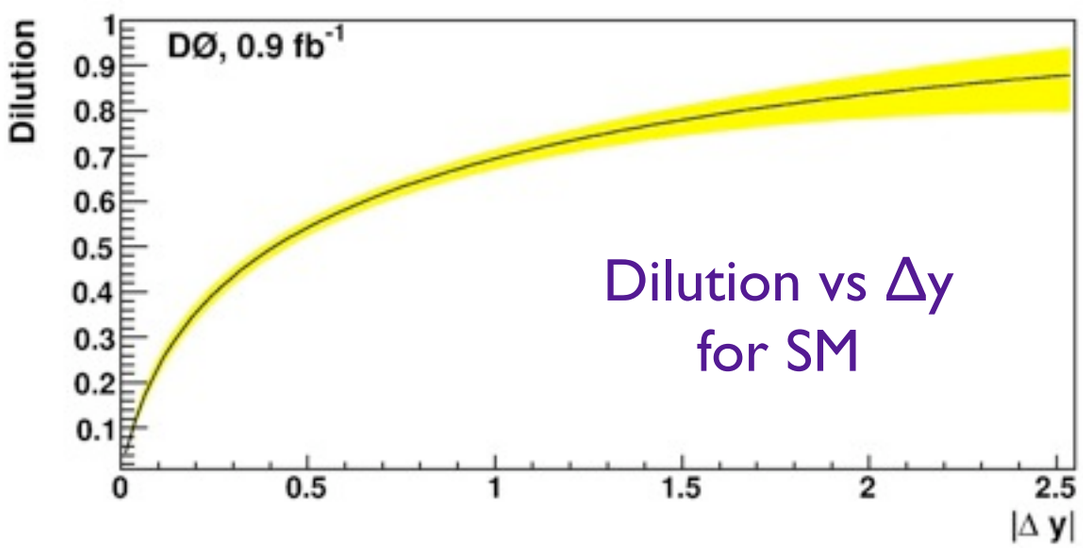
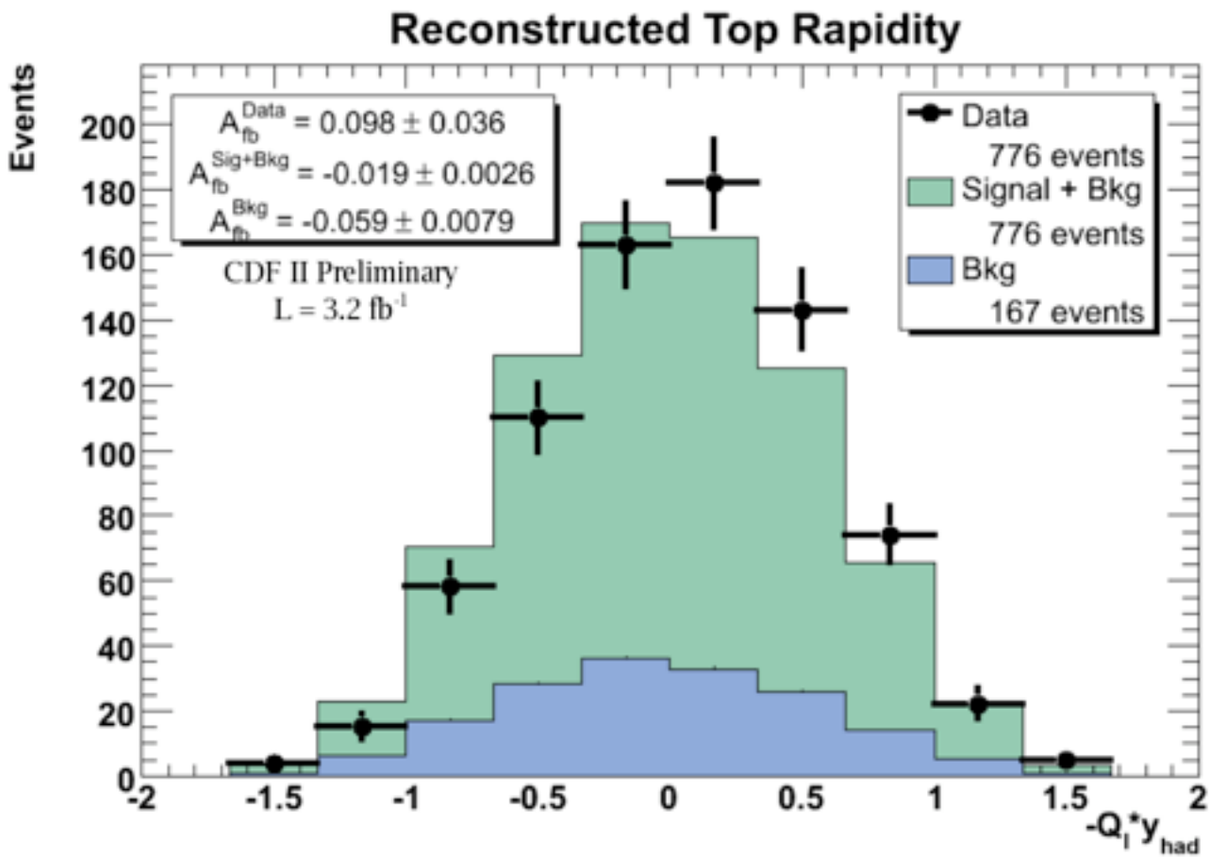
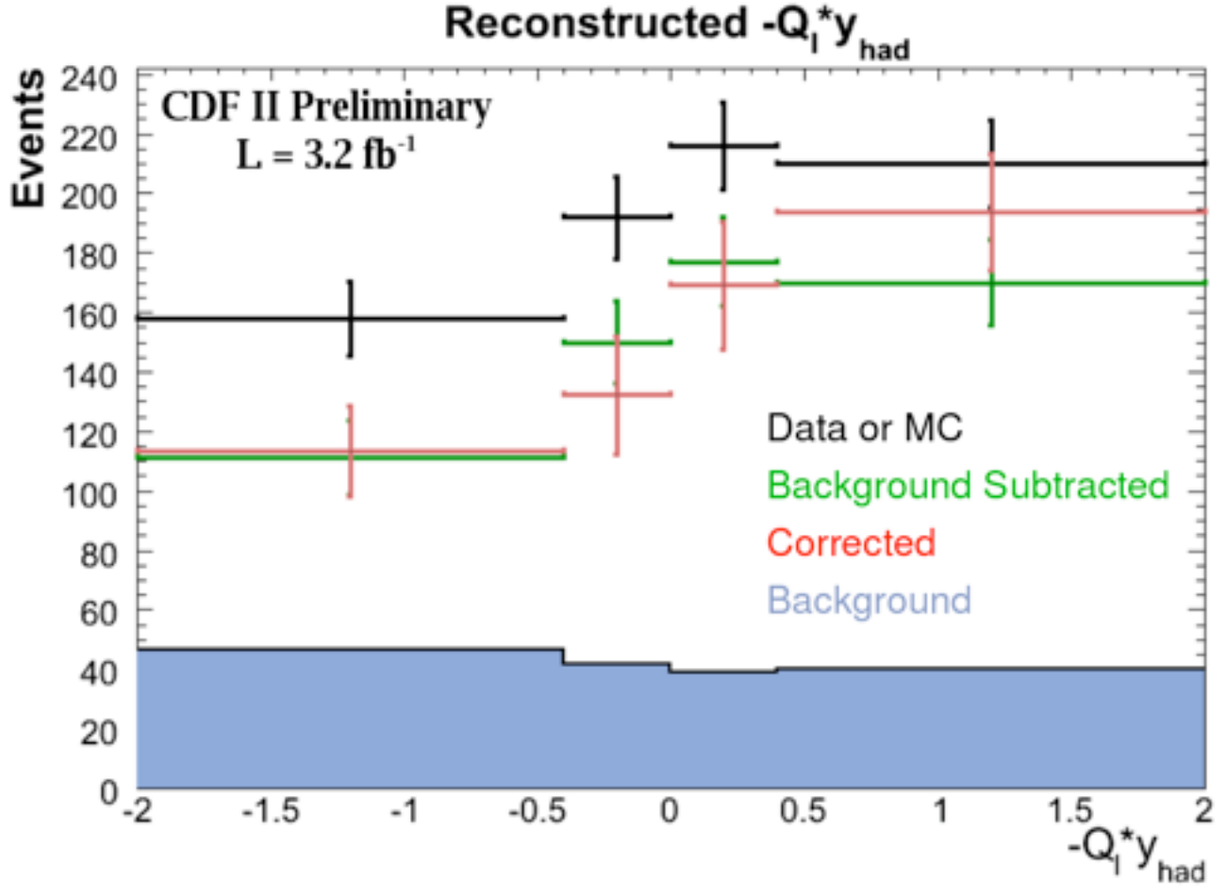


Dilution vs Δy for SM

- CDF:





$A_{fb} = 0.19 \pm 0.065\ (syst) \pm 0.024\ (stat)$

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SM (NLO): $A_{fb} = 0.04 \pm 0.01$

New Physics? See e.g. Cao et al. http://arxiv.org/abs/1003.3461

Conclusion

- The top quark observed at the Tevatron looks very much like the weak isospin partner of the *b* quark
  - High precision measurements with small statistics
  - A_{fb} may be hinting at a new production mechanism
    - But most 2σ deviations go away after a while....
- The LHC is a top-factory
  - Systematics will be just as difficult to control
  - But large statistics open new doors
    - Study of CP-violation etc.
  - Beams now accelerated to 3.5 TeV!