Top Physics Results from Tevatron

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on behalf of the

CDF and D0 Collaborations

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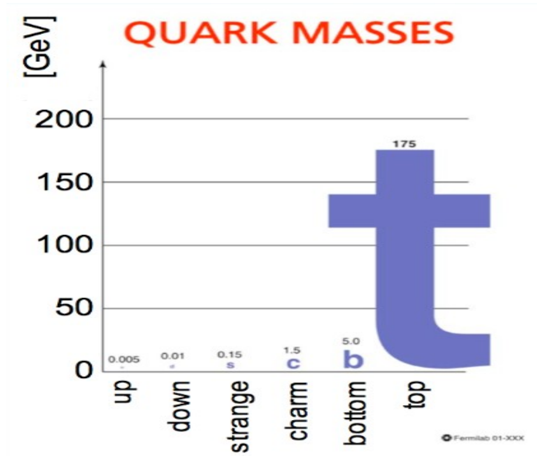
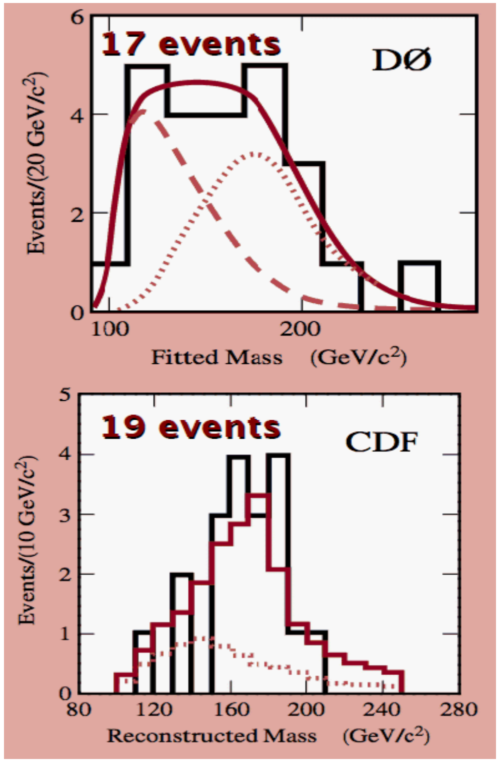
Top Quarks in a Nutshell

- discovered in 1995 at the Tevatron
- heaviest known elementary particle:
  - 173.2 ± 0.9 GeV
  - large coupling ~1 to Higgs boson

  → special role in electroweak symmetry breaking ?
- short lifetime of $5 \cdot 10^{-25}$ s less than $1/\Lambda_{QCD}$

  → top quarks decay before hadronization
  → observation of a bare quark
- started with a handful of events in 1995; now 1000s of them
  - precision measurements
  - excellent tool to search for new physics

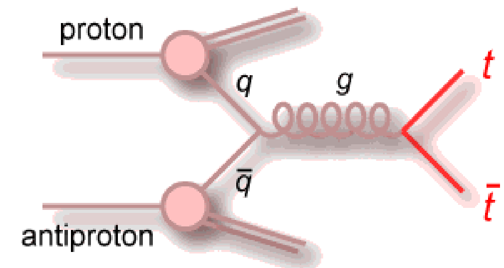


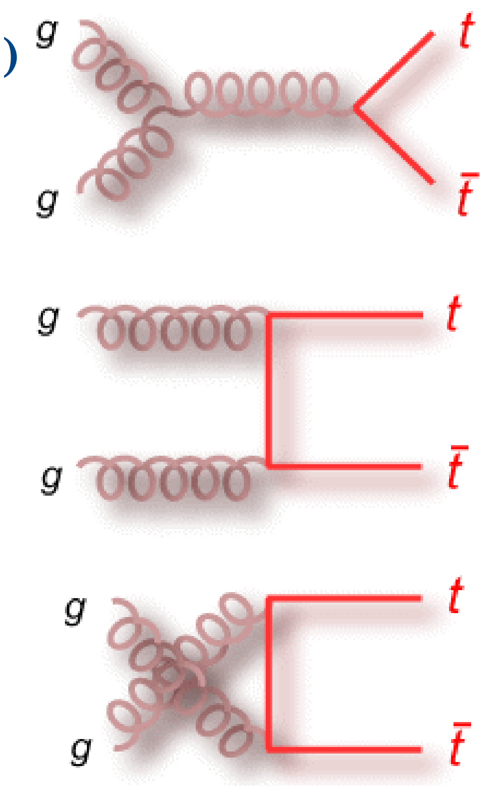


- top quark pairs are produced in strong interaction via
  - quark-antiquark annihilation (85%)
  - gluon-gluon fusion (15%)

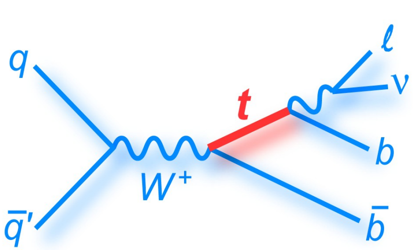
  with a theoretical $\text{NNLO}_{\text{approx}}$ cross section of

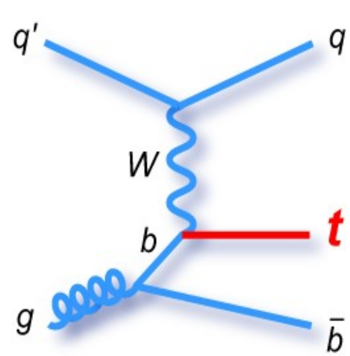
  σ_{top} = 7.46 pb @ m_{top} = 172.5 GeV (PRD 78, 034003 (2008))

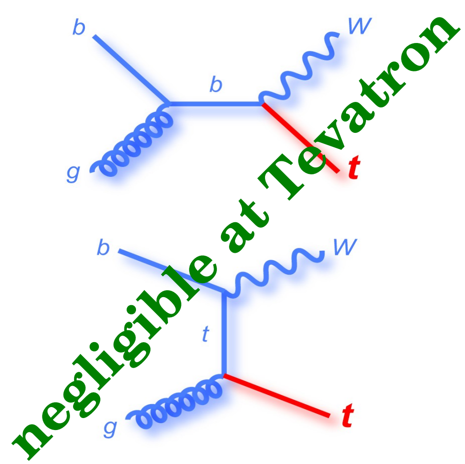




- single tops arise in weak interaction (PRD 74, 114012 (2006))
  - s - channel : σ_{top} = 1.04 pb @ m_{top} = 172.5 GeV
  - t - channel : σ_{top} = 2.26 pb @ m_{top} = 172.5 GeV
  - tW - channel : σ_{top} = 0.30 pb @ m_{top} = 172.5 GeV

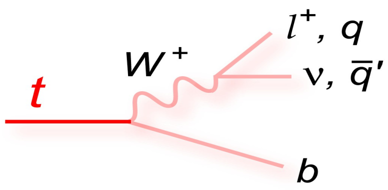






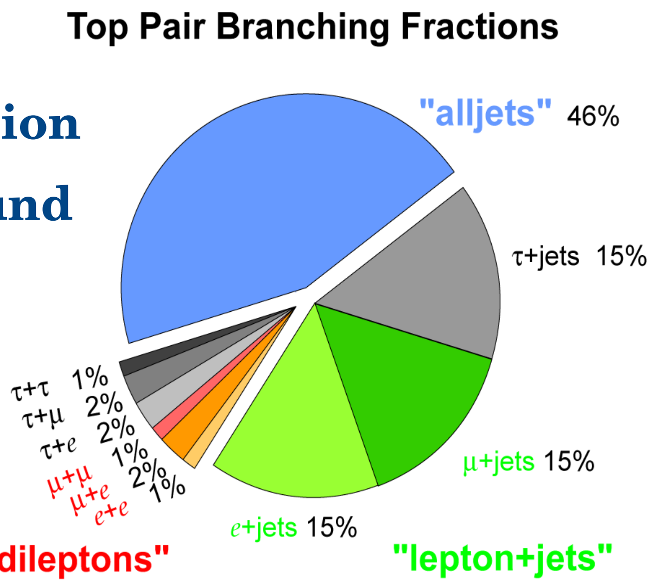
Top Quark Decay

as **Br(t->Wb) ≅ 100%** final states classified according to W decay



alljet channel :

- largest branching fraction
- huge multijet background



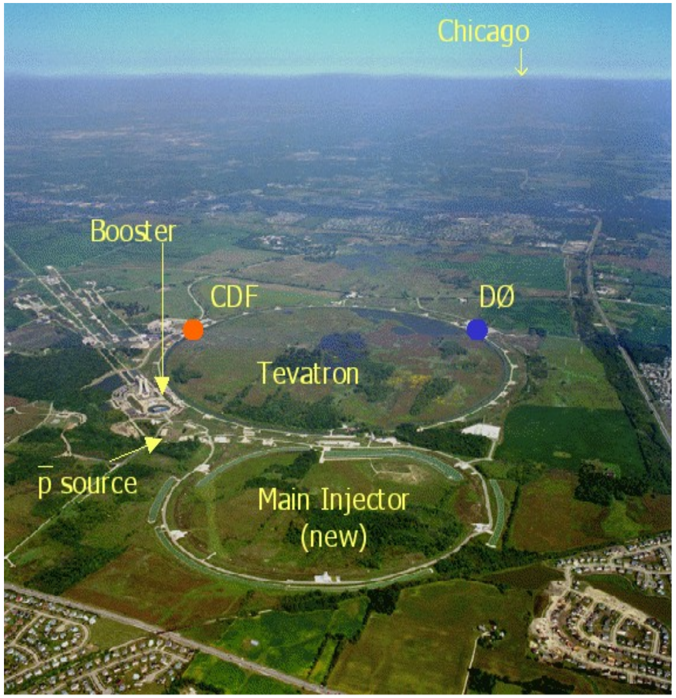
lepton+jets channel :

- good branching fraction of ~35%
- moderate background
- mainly W+jets and multijet events
- "golden channel"

dilepton channel :

- smallest branching fraction of ~5%
- small background, mainly Z+jets events, misidentified leptons

Tevatron Balance



- after 26 years of operation, **Tevatron** turned **off** 30th September 2011
  - 10 years of data at $\sqrt{s}$=1.96 TeV
  - **~10 fb^{-1}** recorded **per experiment**
- birthplace of top quark
- **14 years** later discovery of **single top**
- but compared to LHC
  - 20 times more top pair events then at the Tevatron

→ What can we still learn from the Tevatron?

Outline

- Top Quark Production at $\sqrt{s}$=1.96 TeV
- Measuring and Understanding the Top Quark Mass
- Unique Top Properties at the Tevatron
- Exploring New Aspects in Top Quark Events

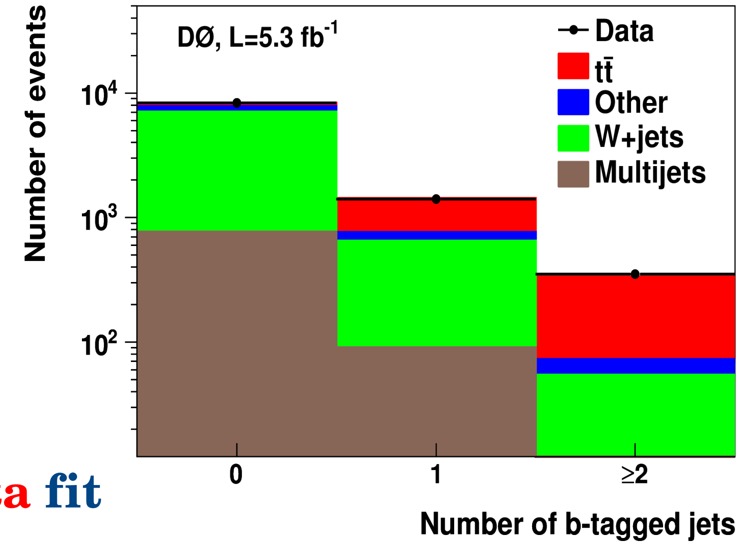
Probing Tops at a Different Center-of-Mass Energy: Top Quark Production at $\sqrt{s}$=1.96 TeV

Top Pair Production Cross Section

- measure if production rate is as predicted by NLO QCD
- measurement requires:
  - well understood background
  - clean signal region to extract cross section

  → divide samples using b-tagging or multivariate techniques
- additional tricks:
  - constrain systematic uncertainties from data fit
  - consider ratio R of $Z \to l\bar{l}/t\bar{t}$ cross section

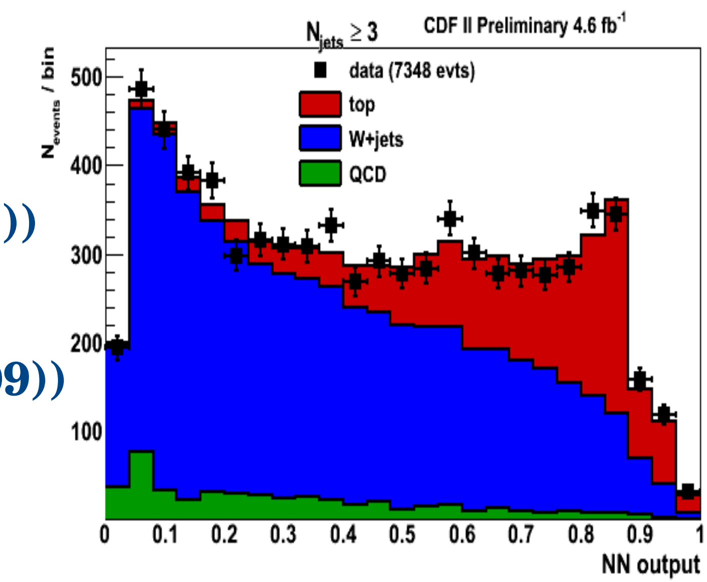
$$\sigma_{t\bar{t}} = R \cdot \sigma_Z^{theo}$$



- D0 l+jets 5.3fb^{-1}:

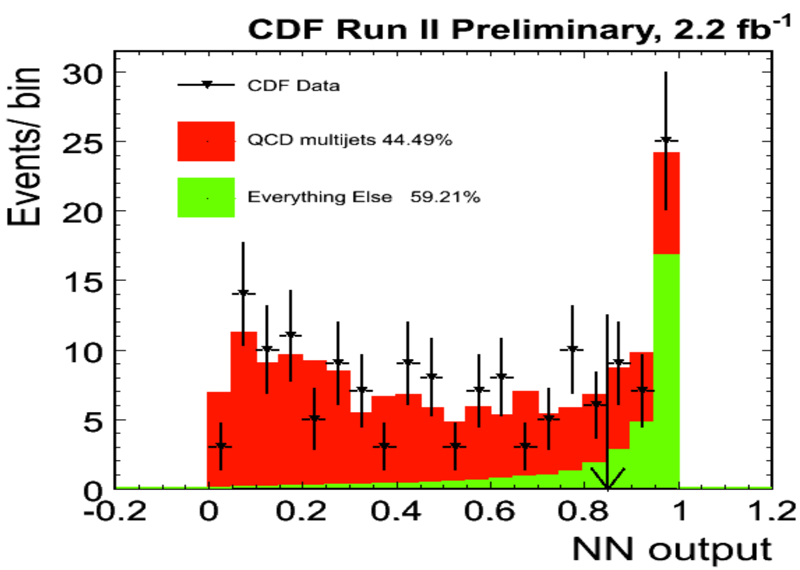
  $\sigma_{t\bar{t}} = 7.78\,^{+0.77}_{-0.64}$ (stat+sys) pb (PRD 84,012008 (2011))
- CDF l+jets 4.6 fb^{-1}:

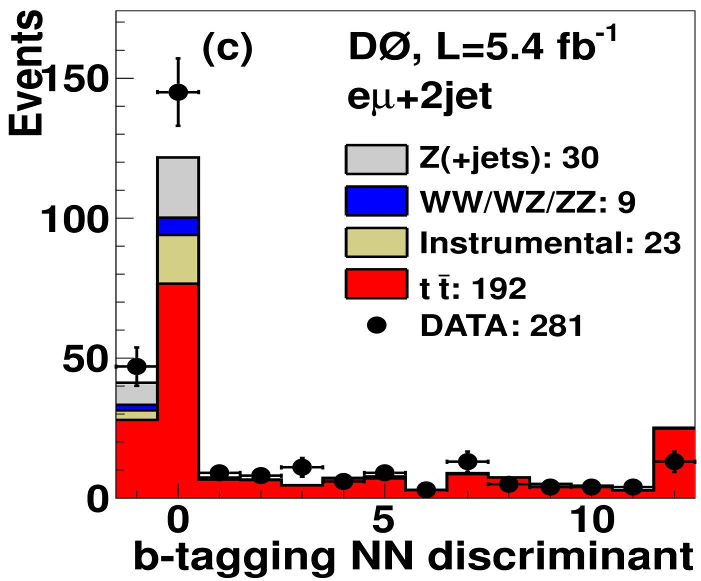
  $\sigma_{t\bar{t}} = 7.82 \pm 0.55$ (stat+sys) pb (PRL 105,012001 (2009))
- limited by systematic uncertainty
- total uncertainty comparable to theoretical one



Comparing Different Final States

- **cross check** of different final states interesting
  - **new physics** may affect different final states in a different way
  - different parts of **phase space**
  - different kinds of **background**





2.2 fb^{-1} τ+jets events:

$\sigma_{t\bar{t}}$ = 8.8 ± 4.3 (stat+sys) pb

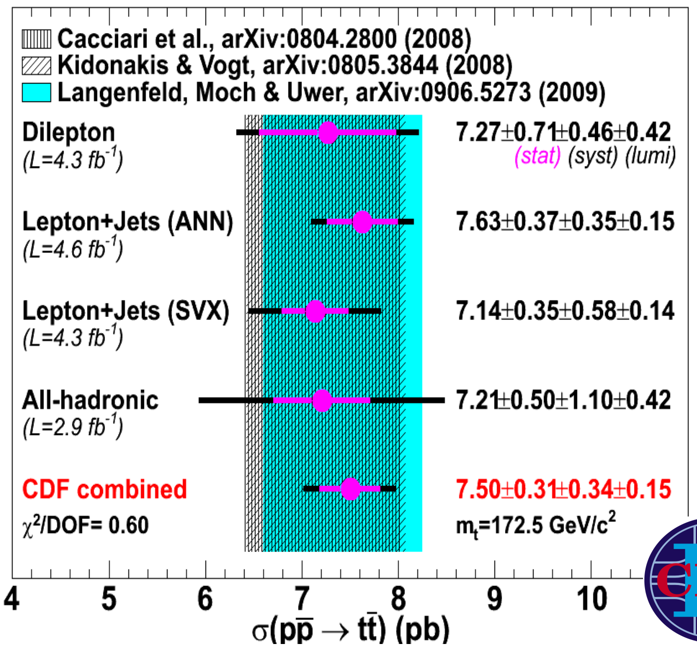
5.4 fb^{-1} dilepton events:

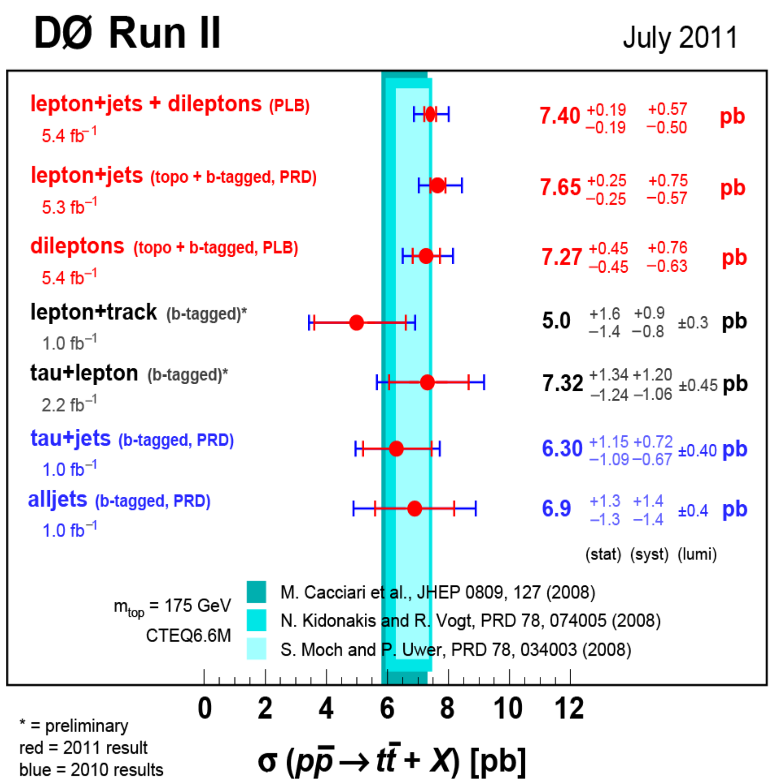
$\sigma_{t\bar{t}} = 7.36^{+0.90}_{-0.79}$ (stat+sys) pb

(PLB 704,403 (2011))

Top Pair Cross Section @ 2 TeV

- experimental results **well consistent** with theoretical predictions
- main systematic uncertainties from:
  - $t\bar{t}$ modeling
  - luminosity (~6%)
  - PDFs for theory
- **CDF/D0 combination** will have a precision of **5%**



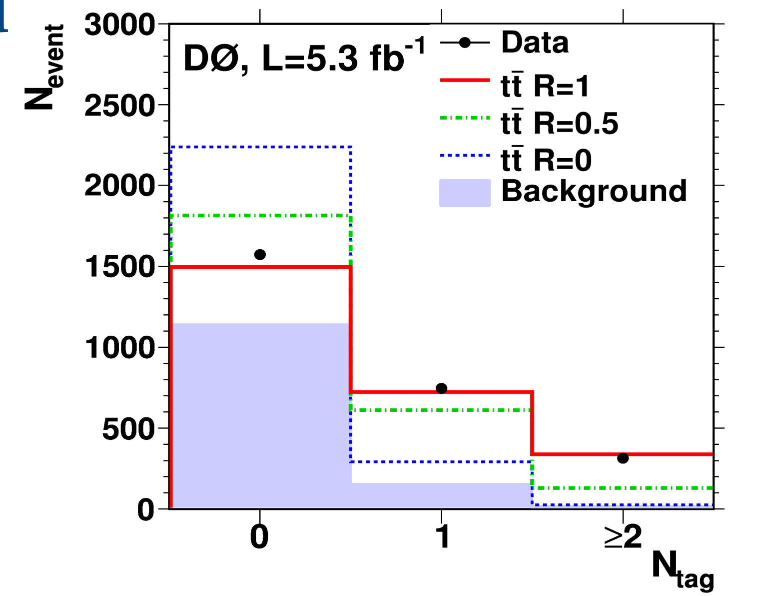


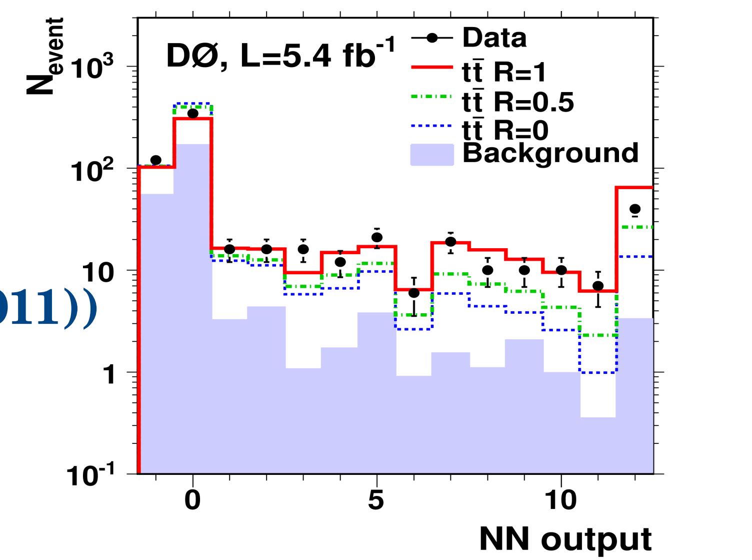
Measurement of Branching Ratios

- cross section measurements can be extended to extract R

$$R=\frac{BR(t\rightarrow Wb)}{BR(t\rightarrow Wq)}=\frac{|V_{tb}|^2}{|V_{td}|^2+|V_{ts}|^2+|V_{tb}|^2}$$

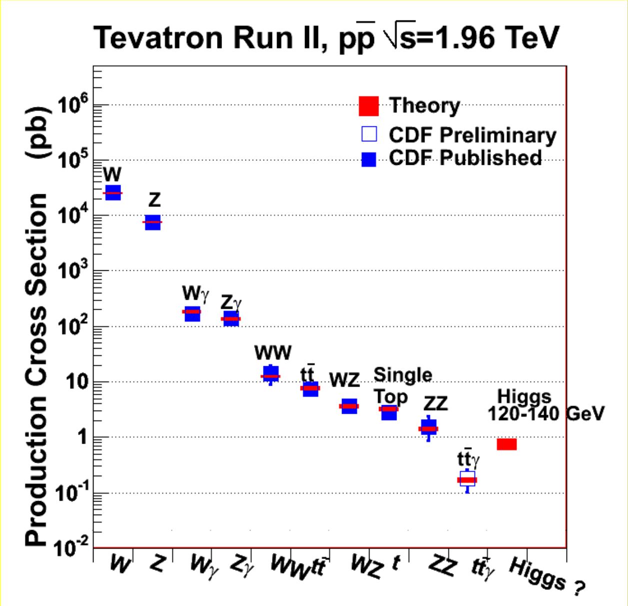
- SM predicts R=1 (unitarity of CKM, BR(t->Wb) ≅ 100%)
- smaller values could indicate new physics e.g. 4th generation quarks
- strategy
  - l+jets: split into 0,1 and ≥ 2 b-tagged jets
  - dilepton: use b-tagging NN distribution
- D0 5.4 fb^{-1}:
  R = 0.90 ± 0.04 (stat+syst) (PRL 107,121802 (2011))
- limited by systematic uncertainty
  - main from b-jet identification
- worlds best measurement of R

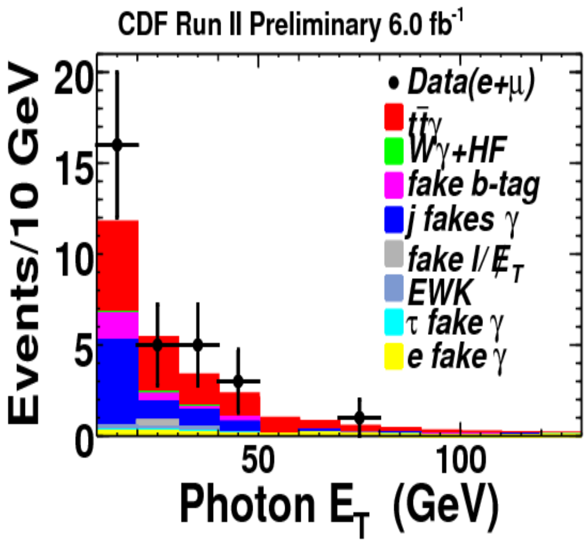




Evidence for $t\bar{t}+\gamma$ Production

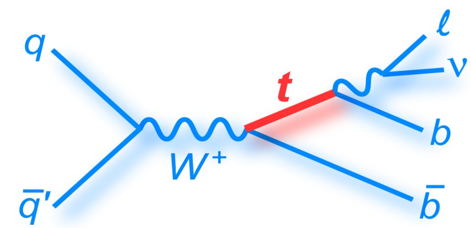
- first measurement of $t\bar{t}+\gamma$ cross section
- order of magnitude smaller than top pair production rate
- well understood photon identification and background modeling required
- CDF 6.0 fb^{-1} of l+jets events:
  - 30 $t\bar{t}+\gamma$ candidates where 26.9 ± 3.4 are expected
  - $\sigma_{t\bar{t}+\gamma}$ = 0.18 ± 0.08 pb (PRD 84, 031104 (2011))
- result well consistent with prediction of $\sigma_{t\bar{t}+\gamma}$ = 0.17 ± 0.03 pb (arXiv:0907.1324)
- 3 SD for background-only hypothesis (0.15%)

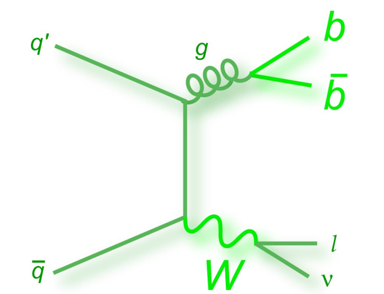




Single Top Quark Production

- took **14 years** from tops to single tops:
  - needed **multivariate techniques** to extract small signal from large background

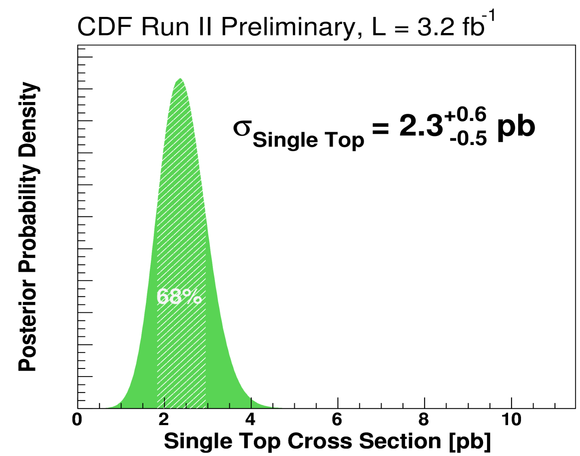




- direct **probe** of **Wtb** electroweak interaction

  D0 5.4 fb^{-1}: σ (s+t) = 3.4 ± 0.7 pb

  CDF 3.2 fb^{-1}: σ (s+t) = 2.3 ± 0.6 pb



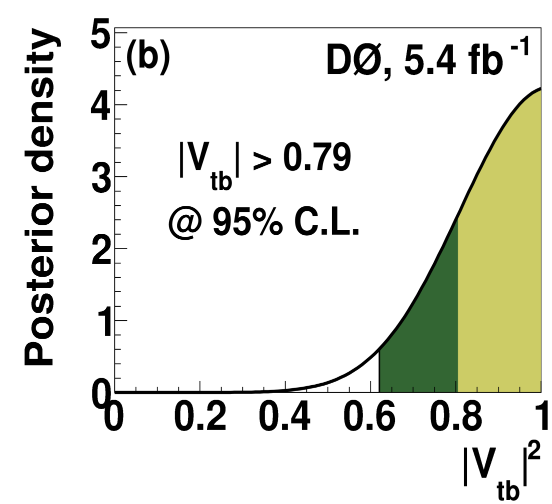
- $|V_{tb}|$ extraction
  - σ (s+t) ~ $|V_{tb}|^2$, assuming only SM sourcing single tops and $|V_{ts}|^2 + |V_{td}|^2 << |V_{tb}|^2$

    D0 5.4 fb^{-1}:

    $|V_{tb}|$ = 1.02 ± 0.11 (PRD 84, 112001 (2011))

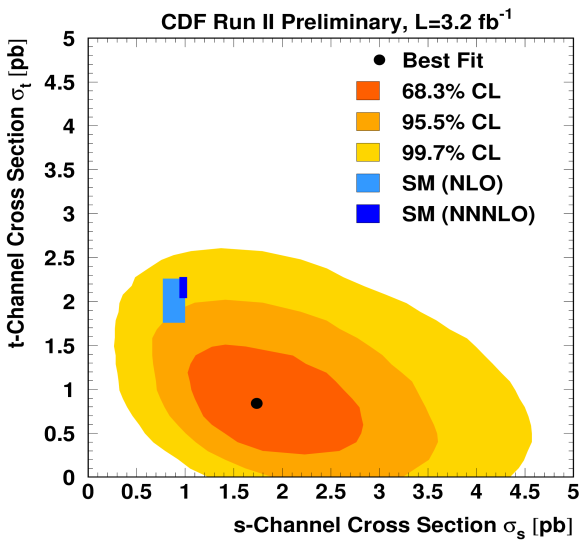
    CDF 3.2 fb^{-1}:

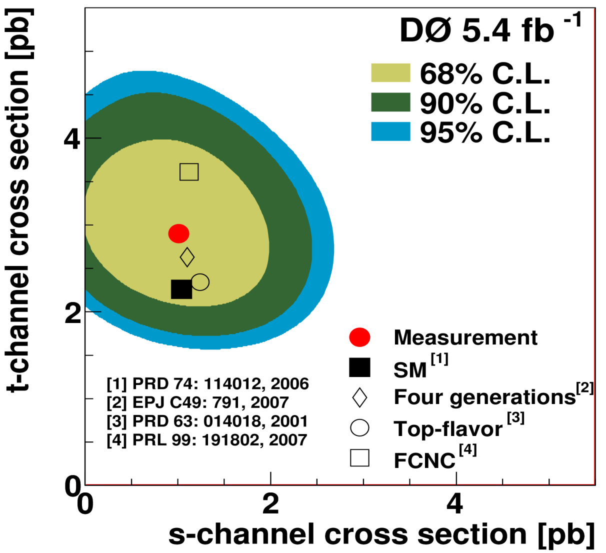
    $|V_{tb}|$ = 0.91 ± 0.13 (PRL 103, 092002 (2009))



Separate t- and s- Channel Production

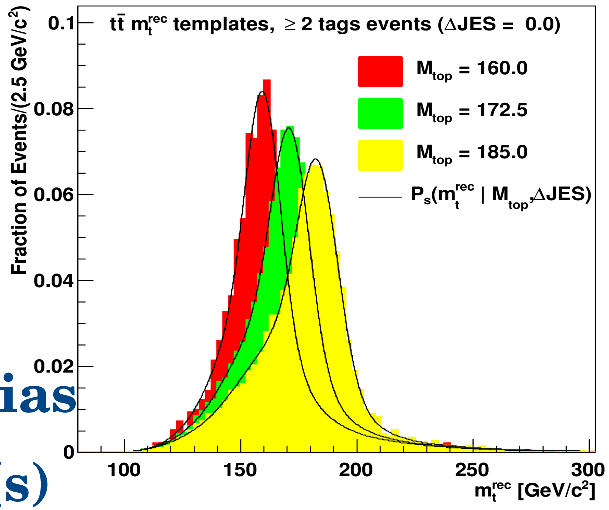
- 2-dimensional measurement of s- and t-channel
  - t-channel sensitive to anomalous couplings
  - s-channel sensitive to resonances
- strategy: train separately for s- and t-chanel
- CDF 3.2 fb^{-1}:
  - σ (t) = 0.8 ± 0.4 pb (PRD 82, 112005 (2009))
  - σ (s) = $1.8^{+0.7}_{-0.5}$ pb
- D0 5.4 fb^{-1}:
  - σ (t) = 2.90 ± 0.59 pb (PLB 705, 313 (2011))
  - σ (s) = 0.98 ± 0.63 pb
- t-channel observation with 5.5 σ at D0
  - main systematics from background
- s-channel evidence with full data set
- part of Tevatrons legacy
  - s-channel (~4x) not as enhanced as others (>25x)
  - more challenging at LHC



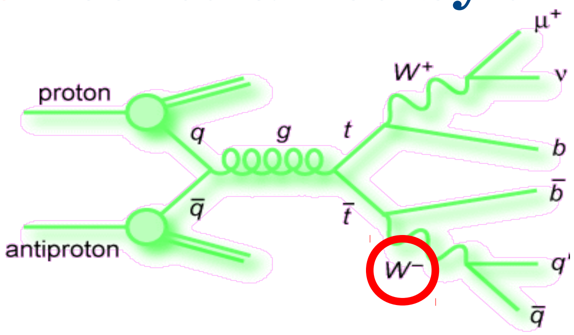


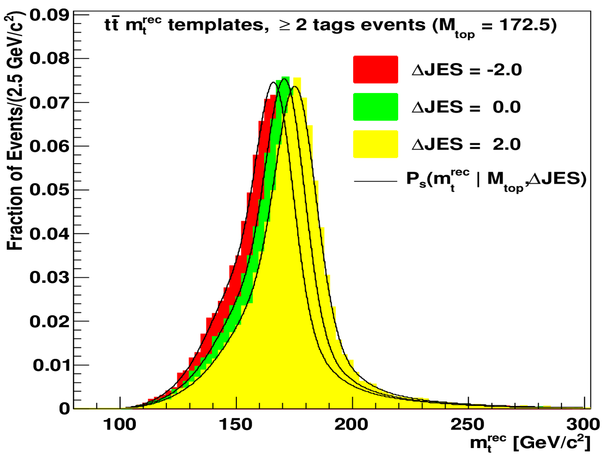
Very Challenging:
Measuring and Understanding the Top Quark Mass

- idea:
  - construct mass dependent templates using MC simulated events
  - determine mass from a comparison to data



- apply calibration from MC to correct for any bias
- channels with hadronically decaying W boson(s) allow in addition to fit a global jet energy scale correction constrained by the W mass

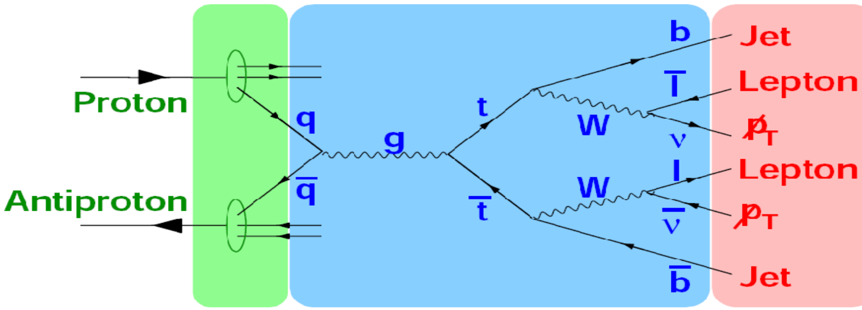




- l+jets energy correction can be applied in dilepton events to reduce main systematic

Matrix Element Method

- **calculate per event the probability to arise from LO $t\bar{t}$ production for different hypotheses of mass/JES**

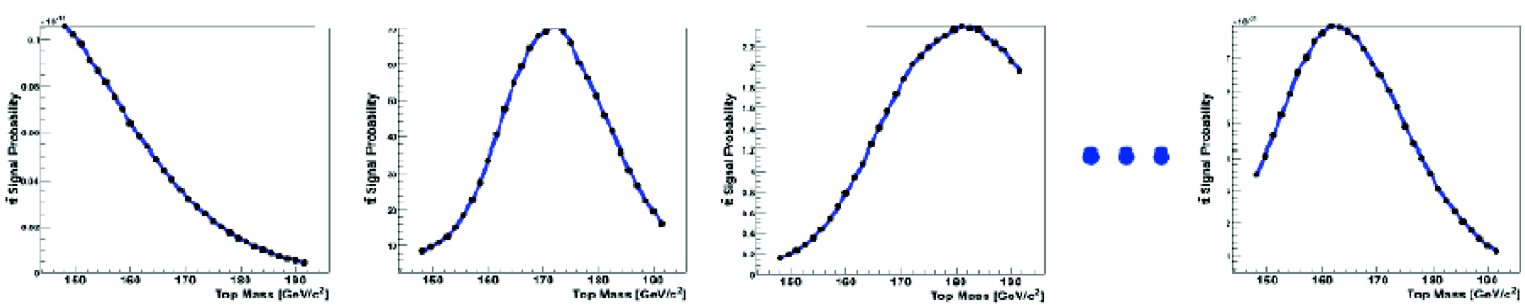


$$P_{t\bar{t}}(x;H) \propto \int d\epsilon_1 d\epsilon_2 f_{PDF}(\epsilon_1) f_{PDF}(\epsilon_2) \frac{|M(y;H)|^2}{\epsilon_1 \epsilon_2 s} W(x,y) d\phi_6$$

f_{PDF}: *parton density functions*
$M(y;H)$: *ME under hypothesis H for partons y*
$W(x,y)$: *transfer functions for measuring y as x*

- **calculate main background probability similarly and combine them**

$$P_{evt}(x; m_{top}, JES) = f_{sgn} P_{sgn}(x; m_{top}, JES) + (1 - f_{sgn}) P_{bkg}(x; JES)$$



Event 1 **Event 2** **Event 3** **Event n**

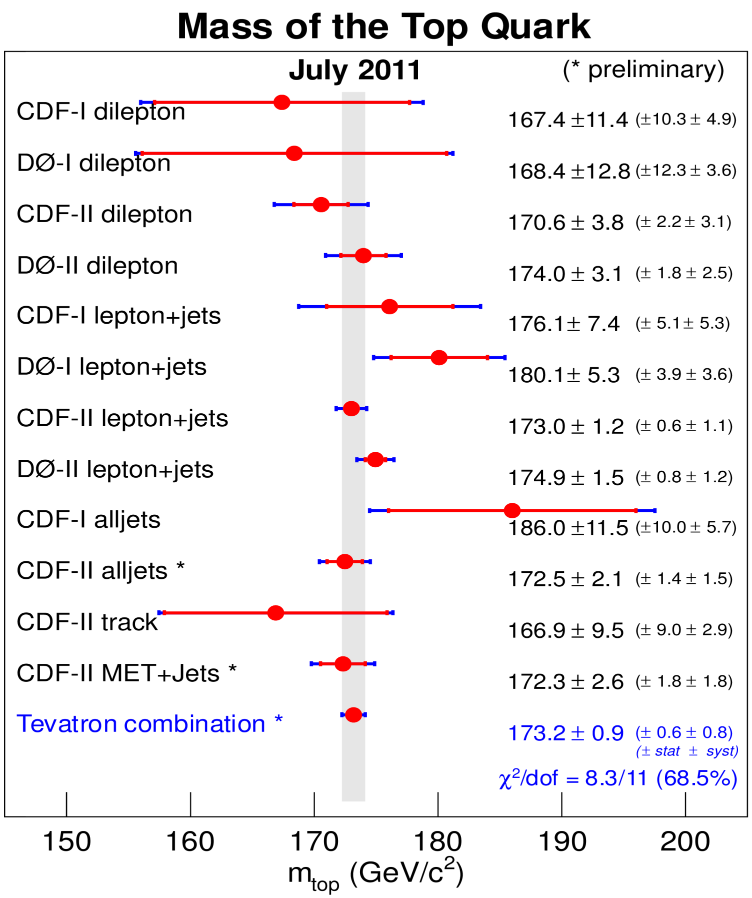
Latest Mass Results

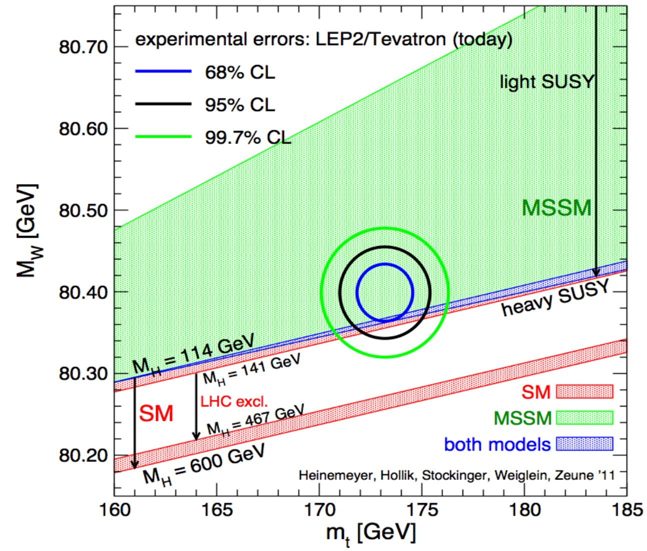
- Template method:
  - CDF l+jets 8.7 fb^{-1} ($m_{top}^{(1)}$, $m_{top}^{(2)}$, m_{jj}): m_{top} = 172.8 ± 0.7 (stat+JES)± 0.8 (syst)
  - CDF all jets 5.8 fb^{-1} ($m_{top}^{(rec,\chi 2}$, $m_W^{(rec,\chi 2)}$): m_{top} = 172.5 ± 1.7 (stat+JES) ± 1.1 (syst)
  - CDF dilepton 5.6 fb^{-1} ($m_{top}^{(\nu wA)}$): m_{top} = 170.3 ± 2.0 (stat) ± 3.1 (syst)
  - D0 dilepton 5.4 fb^{-1} ($w_{\nu wA}$): m_{top} = 174.0 ± 2.4(stat) ± 1.4(syst)
- Matrix Element method:
  - D0 dilepton 5.4fb^{-1} : m_{top} = 174.0 ± 1.8(stat) ± 2.4(syst)
  - D0 l+jets 3.6 fb^{-1} : m_{top} = 174.9 ± 1.1(stat+JES) ± 1.0(syst)
  - CDF l+jets 3.6fb^{-1} : m_{top} = 172.4 ± 1.4(stat+JES) ± 1.3(syst)

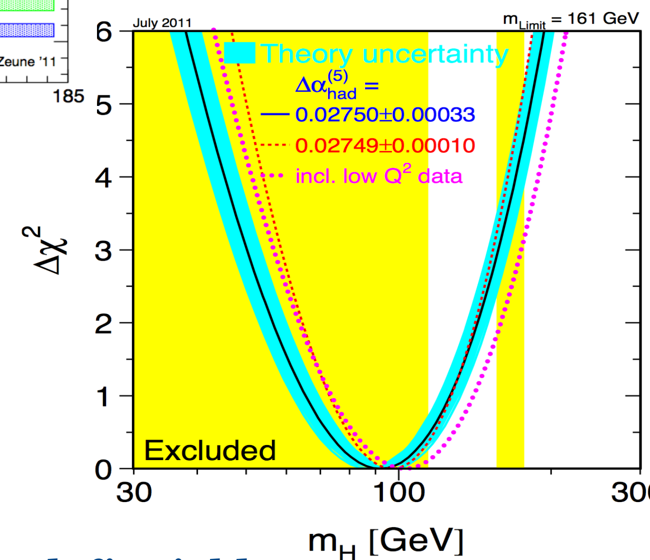
- almost all results limited by systematics
- true challenge: understanding systematic effects
  - remaining jet uncertainties
  - $t\bar{t}$ modeling (hadronization and UE, NLO, ISR/FSR, CR)

combination as by summer 2011

- all results **consistent**
- total uncertainty **< 1 GeV**







electroweak fit yields:

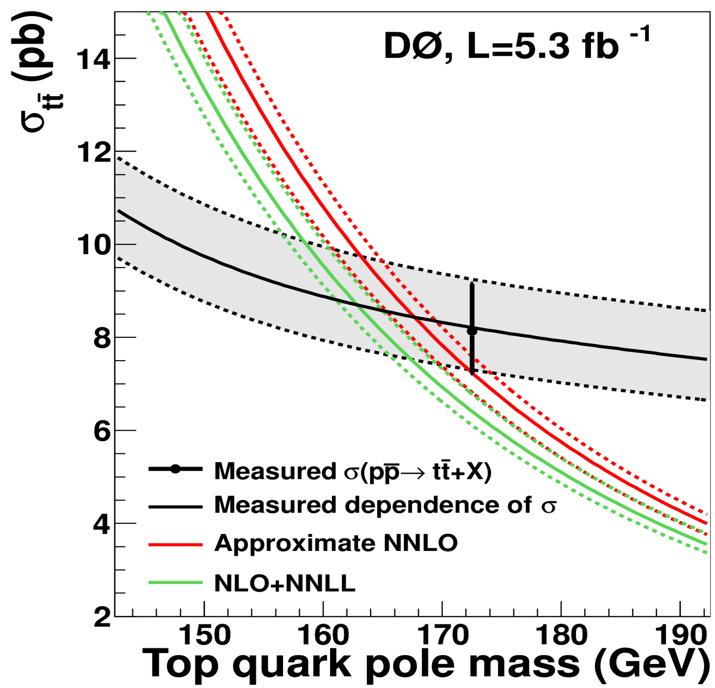
m_{Higgs} < 161 GeV @ 95% C.L.

(w./ new CDF W mass: 145 GeV)

$m_{Higgs} = 92 + 34 - 26$ GeV

Mass Interpretation

- second challenge: theoretical interpretation
  - How close is the measured mass relying on MC to the pole mass?
- different approach:
  - assume MC mass to be once pole, once $\overline{\text{MS}}$ mass
  - calculate cross section as a function of well-defined mass
  - compare result with measured cross section function



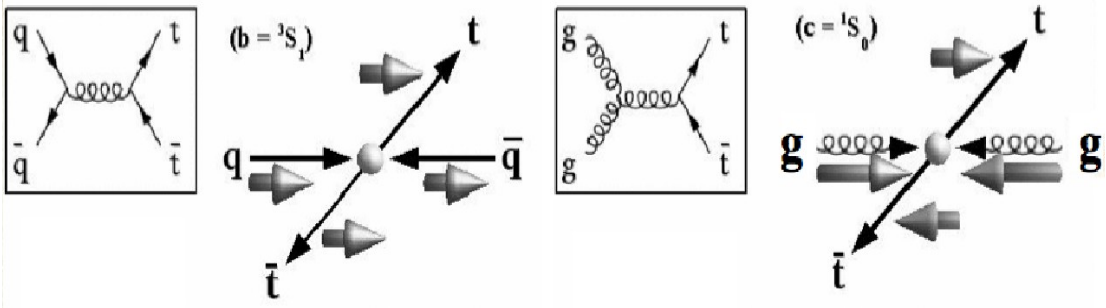
- D0 5.3 fb^{-1} l+jets:
  - $m_{top}^{pole} = 167.5^{+5.2}_{-4.7}$ GeV (PLB 703, 422 (2011))
  - $m_{top}^{\overline{MS}} = 160.0^{+4.8}_{-4.3}$ GeV
- pole mass closer to direct results

$p\bar{p}$ is not pp :
Unique Top Properties at the Tevatron

Spin Correlation

- even **tops** are **not** produced in **polarized** state, the **spins** are **correlated**
- the correlation strength A

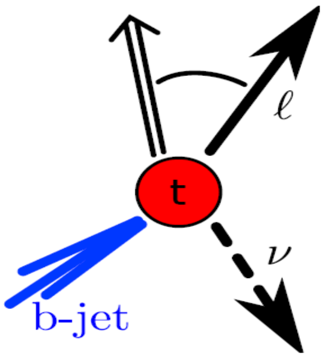
$$A=\frac{N_{\uparrow\uparrow}+N_{\downarrow\downarrow}-N_{\uparrow\downarrow}-N_{\downarrow\uparrow}}{N_{\uparrow\uparrow}+N_{\downarrow\downarrow}+N_{\uparrow\downarrow}+N_{\downarrow\uparrow}}$$



  - depends on the **production mode** → different for Tevatron and LHC
  - choice of **spin basis** (here beam basis)
- due to the short top lifetime the **spin** does **not flip** and is **reflected** in the **angular** distributions of the **decay products**

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i}=\frac{1}{2}(1+\alpha_i\cos\theta_i)$$

with **α = 1** for charged leptons and down-type quarks



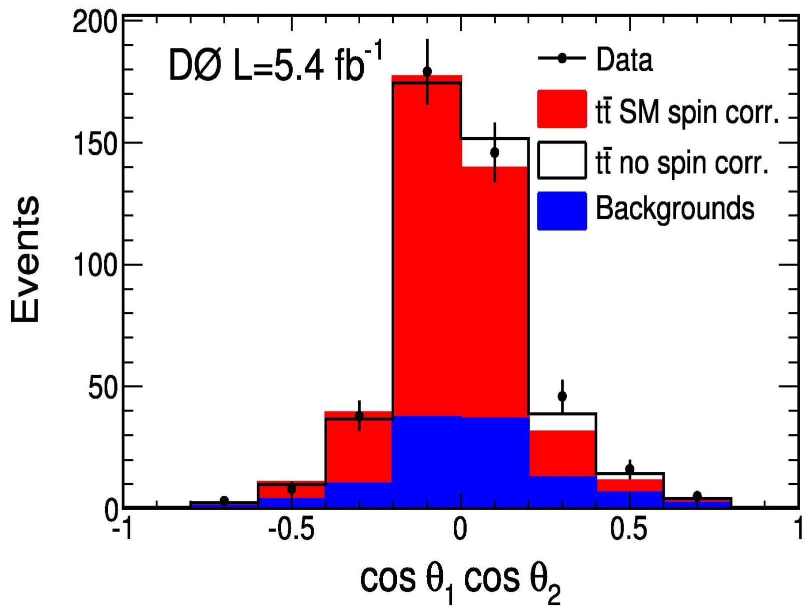
- thus spin correlation can be measured by studying e.g.

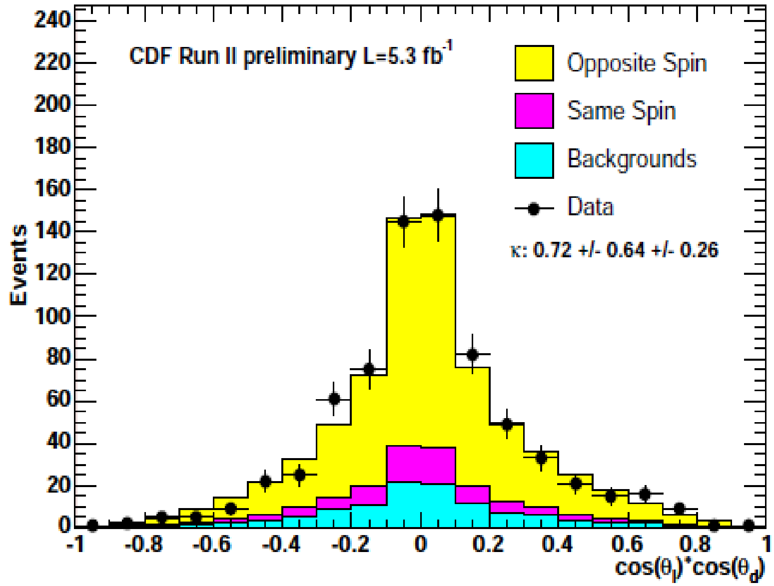
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2}=\frac{1}{4}(1-C\cos\theta_1\cos\theta_2)$$

$$where\ C=A\alpha_1\alpha_2$$

Angular Template Based Results

- **D0 5.4 fb^{-1} dilepton :**
  C_{beam} = 0.10 ± 0.45 (stat+syst)
  (PLB 702,16 (2011))
- **CDF 5.1 fb^{-1} dilepton :**
  C_{beam} = 0.04 ± 0.56 (stat+syst)
- **CDF 5.3 fb^{-1} l+jets :**
  C_{beam} = 0.72 ± 0.69 (stat+syst)
- **all measurements limited by statistical uncertainty**
- **results consistent with SM expectation of**
  C_{beam} = 0.78 ± 0.04 @NLO QCD
  (Nucl. Phys. B 690,81 (2004))





Matrix Element Approach

- MEs can be used to discriminate no correlation (H=0) and SM spin correlation (H=1)

$$P_{t\bar{t}}(x;H) \propto \int d\epsilon_1 d\epsilon_2 f_{PDF}(\epsilon_1) f_{PDF}(\epsilon_2) \frac{|M(y;H)|^2}{\epsilon_1 \epsilon_2 s} W(x,y) d\phi_6$$

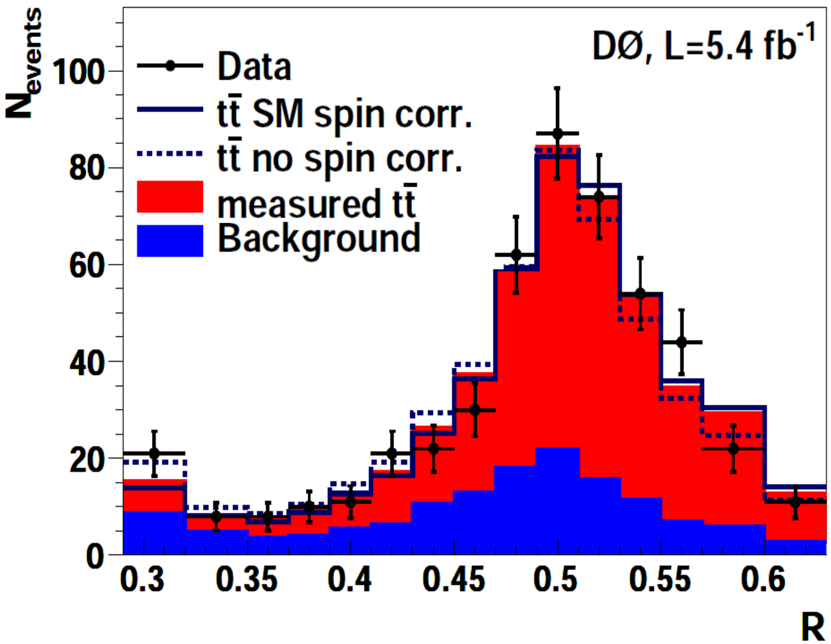
- as correlation needs set of events, construct discrimination variable from MEs :

$$R(x) = \frac{P_{t\bar{t}}(x, H=1)}{P_{t\bar{t}}(x, H=0) + P_{t\bar{t}}(x, H=1)}$$ (PLB 700, 17 (2011))

- D0 5.4 fb^{-1} dilepton :
  C_{beam} = 0.57 ± 0.31 (stat+syst)
- D0 5.3 fb^{-1} l+jets :
  C_{beam} = 0.89 ± 0.33 (stat+syst)
- 30% increased sensitivity
- excellent agreement with SM
- combining statistically independent results:

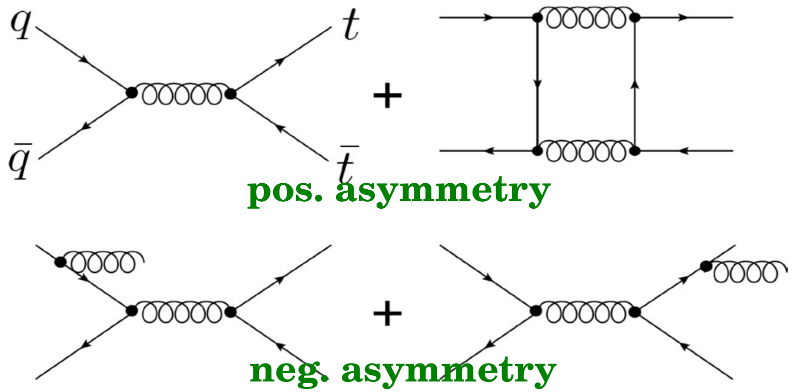
  C_{beam} = 0.66 ± 0.23 (stat+syst)

  - C < 0.26 @ 95% C.L. and C < 0.04 @ 99.7% C.L.
  - C= 0 @ 3.1 σ SD (PRL 108, 032004 (2012))

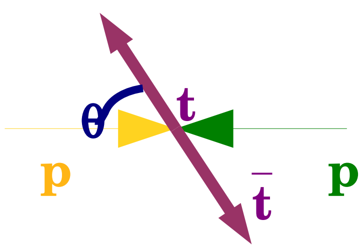


=> first evidence for non-vanishing spin correlation !

Top Asymmetry A_{fb}



- at NLO top pair production is supposed to be asymmetric because of interferences from contributions symmetric and asymmetric under top exchange
- measurement sensitive to new physics:
  - SM extension with Z' and warped extra dimension increase, axi-gluons decrease the asymmetry
- different definitions (frames, objects) but all go back to the same idea:
  - count the number of tops (anti-tops) into the direction of the proton and see whether there is any difference or not



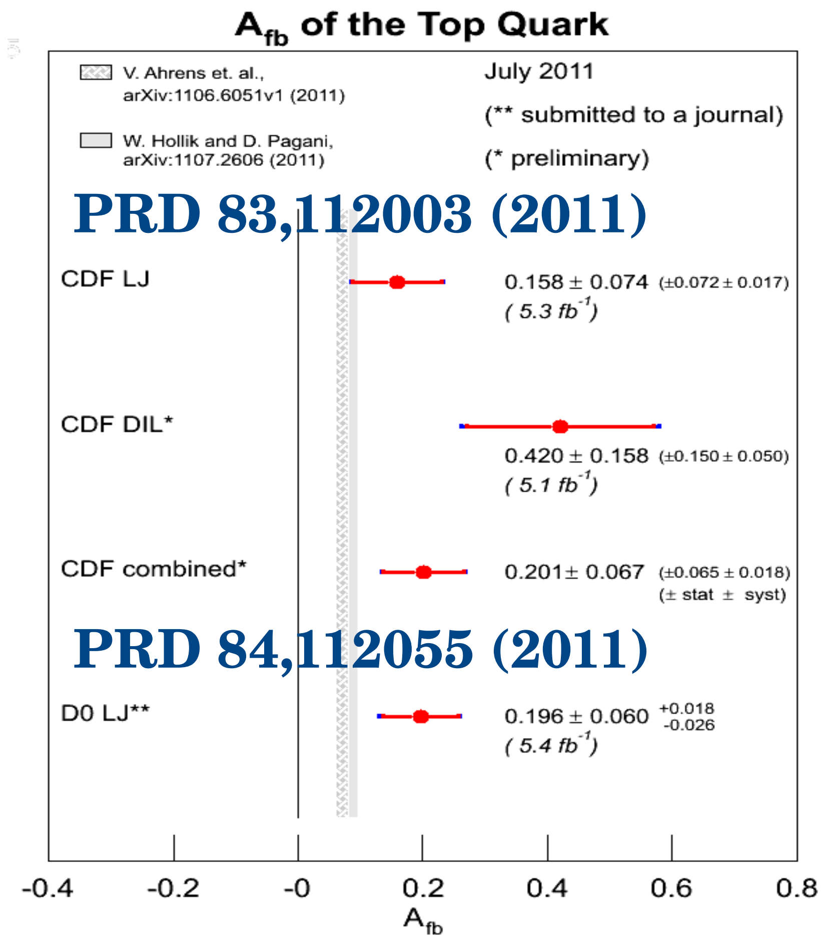
$$A_{fb}^{t\bar{t}} = \frac{N_f - N_b}{N_f + N_b} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)}$$

$$with\; y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right)$$

  - less resolution dependent: lepton based definition

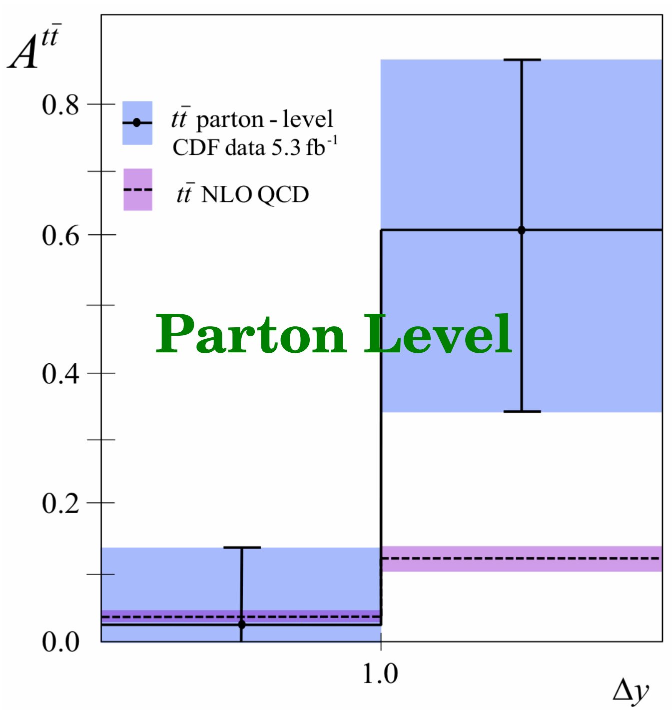
$$A_{fb}^{l} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

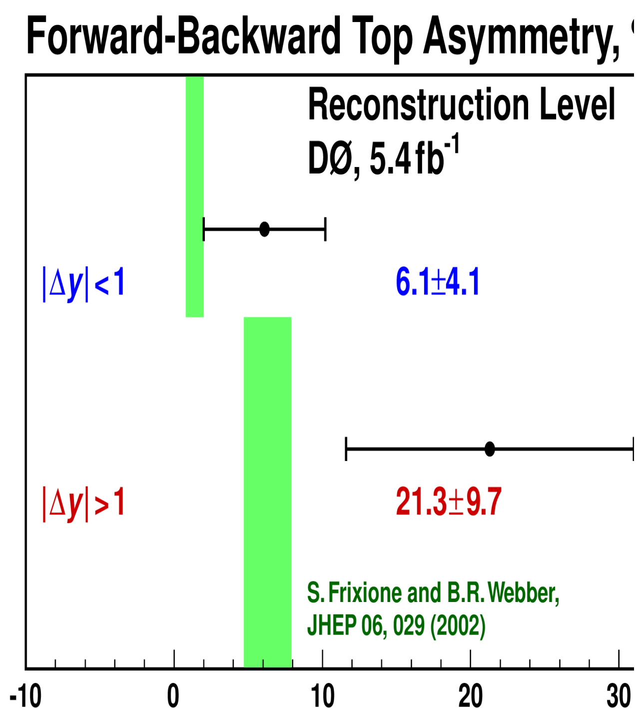
- **kinematic fitters** used to reconstruct event
- background asymmetry subtracted from data
- raw value **unfolded**
  - correcting for reconstruction and selection
  - CDF: 4x4 matrix-inversion
    D0: regularized unfolding (50→26 bins)
- results can **directly** be **compared**:
  - MC@NLO: ~5%
  - Ahrens et. al. (NLO+NNLL): ~7% (arXiv:1106.6051)
  - Holik et. al. (NLO+ QED cor.) : ~9% (arXiv:1107.2606)
- measurements higher than prediction
- even larger difference for A_{fb}^{l}:
  - D0 l+jets: $A_{fb}^{l} = 14.2 \pm 3.8$ % where MC@NLO : $A_{fb}^{l} = 0.8 \pm 0.6$ %
  - CDF dilepton: $A_{fb}^{\Delta\eta(l)} = 21 \pm 7$ %

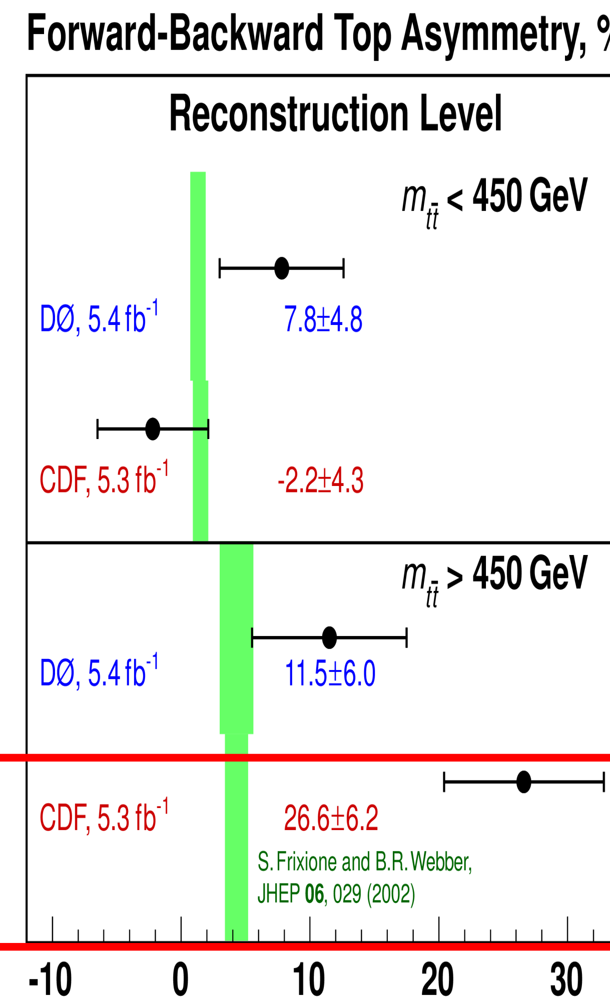


Dependencies of A_{fb}

- asymmetry **depends** on several variables like $m_{t\bar{t}}$, |y|
  - e.g. new physics could lead to a different mass dependency



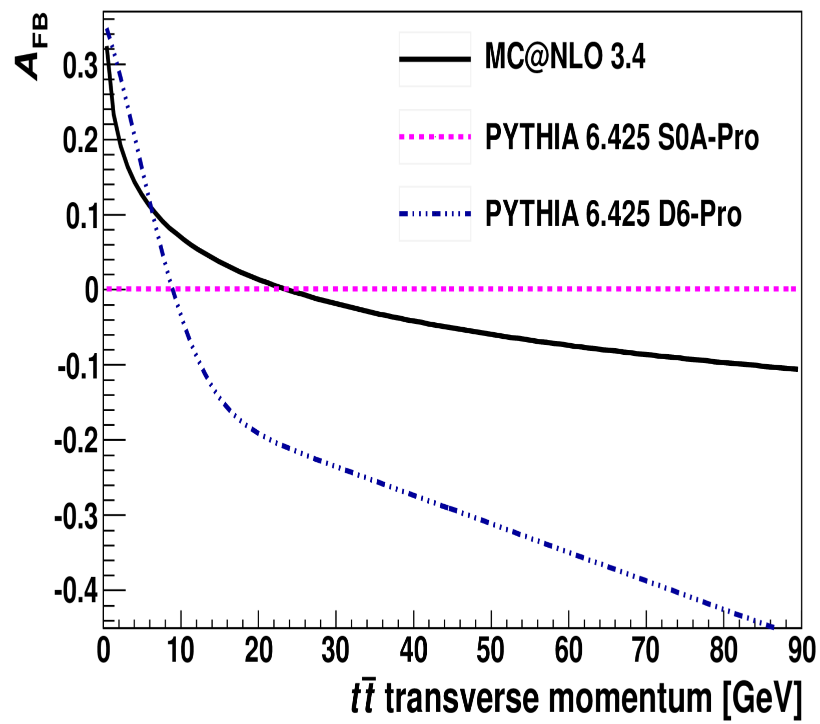




3 σ from MC@NLO

New Physics and Prospects

- prediction is sensitive to **modeling** e.g. transverse $t\bar{t}$ momentum
  → better understanding needed
- in addition to SM corrections, many **new models** try to explain discrepancy (see e.g. S. Westhoff)
  - **axigluons** (FCNC at tree level)
  - **Z'** (excluded by CMS same sign $t\bar{t}$ production limit)



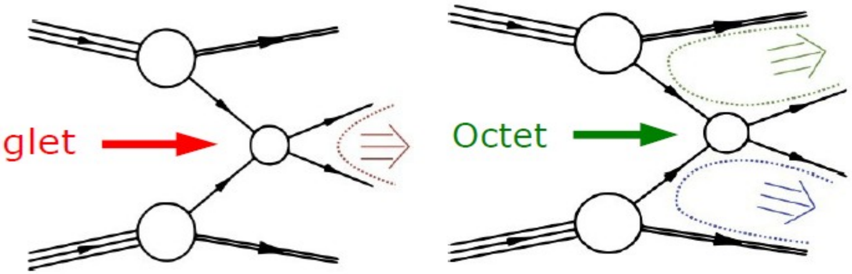
- to better understand asymmetry:
  - many models predict very different $A_{fb}^{t\bar{t}}$ and A_{fb}^{l}
    → need to measure both with full data set in l+jets and dilepton
  - many models couple only to right-handed top quarks
    → need to study **top polarization**

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1}{2}\left(1 + P_{top}\,\alpha_i \cos\theta_i\right)$$

Taking Advantage of the Clean Environment: Exploring New Aspects in Top Events

Color Flow in $t\bar{t}$ Events

- **pairing** of color **connections** in decays depends on **decaying particle** (singlet e.g. W,H,.. or octet, gluons)



→ good to separate e.g. **ZH → $Zb\bar{b}$** from **Z+jets**

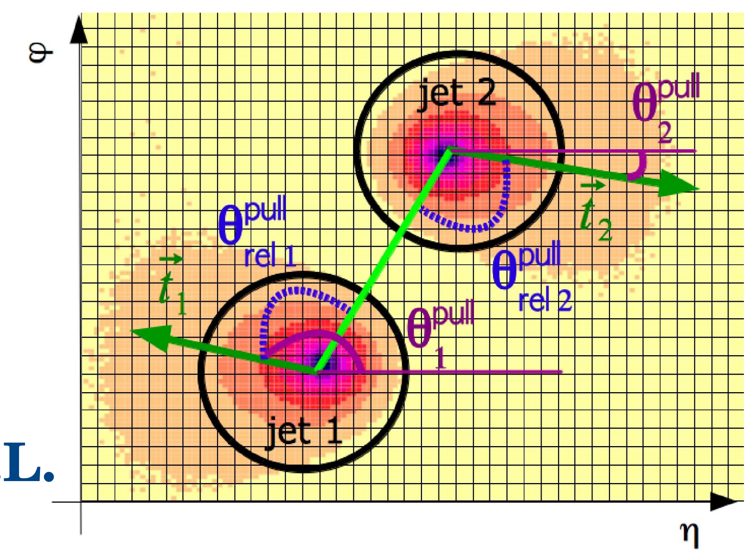
- jet pull (vectorial sum of all calorimeter cells within a jet) useful to describe color-flow (PRL 105 022001)

$$\vec{p} = \sum_i \frac{E_T^i |r_i|}{E_T^{jet}} \vec{r}_i$$

- jet **pulls point** more towards **each other** for jets from **singlets**
- study how often hadronic W boson is identified as color singlet
- D0 5.3 fb^{-1} l+jets :

  $f_{Singlet} = 0.56 \pm 0.42$ (stat+syst)

  (PRD 83, 092002 (2011))

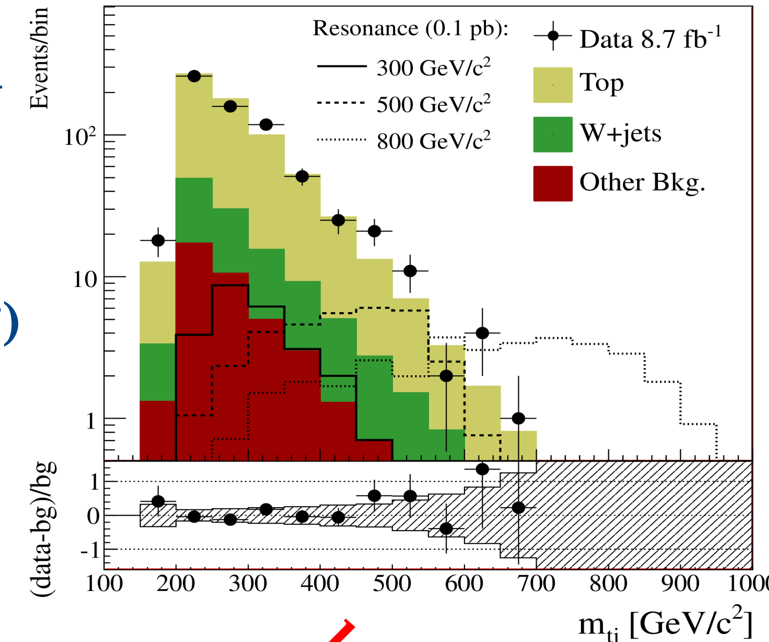


- expected: W boson octet exclusion @ 99% C.L.

  observed: can't be excluded @ 95% C.L.

Searches and Exotics

- well understood $t\bar{t}$ events allow to search for
  - resonant $t\bar{t}$ production (e.g. Z') by studying invariant $t\bar{t}$ spectrum
  - heavy new particles decaying to tops (e.g. t',b',W')
  - tops decaying to new particles (H^+)
  - new couplings (e.g. FCNC, vector/tensor couplings)
- all searches well consistent with SM

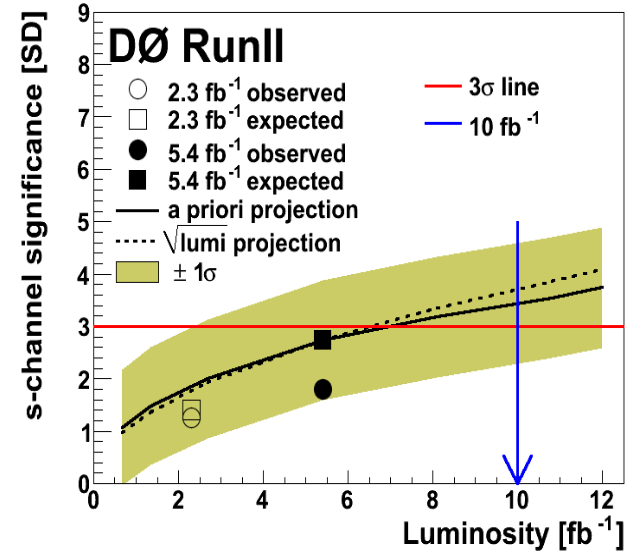


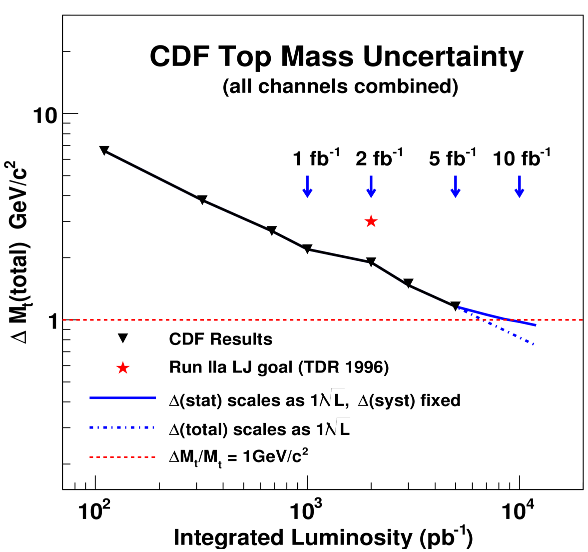
latest results

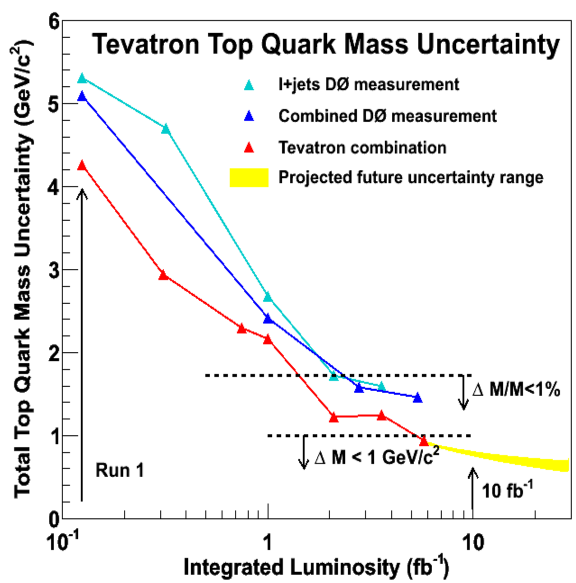
FCN	D0	4.1 fb^{-1}	BR($t \rightarrow Zq$, q=u,c) < 3.2%
Z'	D0	5.3 fb^{-1}	$m_{Z'}$ < 835 GeV excluded @ 95% C.L.
t'	D0	5.3 fb^{-1}	$m_{t'}$ < 285 GeV excluded @ 95% C.L.
Z' → ttj	CDF	8.7 fb^{-1}	0.02 pb < σ < 0.61 pb for 200 < $m_{Z'}$ < 800
t'	CDF	5.7 fb^{-1}	$m_{t'}$ < 400 GeV excluded @ 95% C.L.

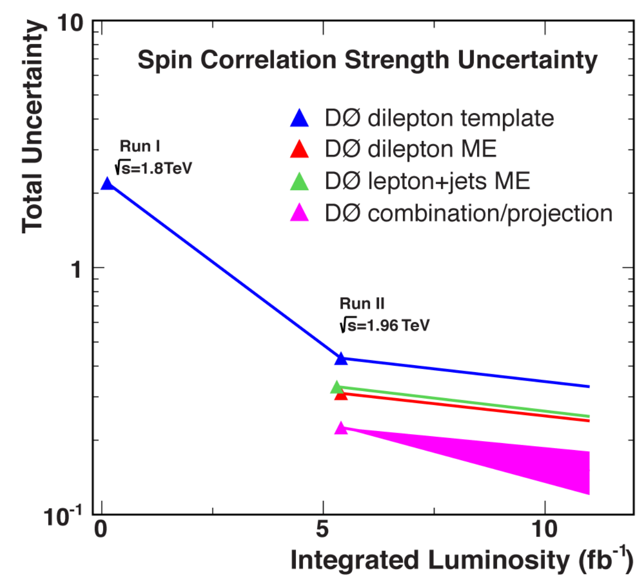
Prospects

- legacy still needs to be written
  - most analyses use only half the data
- many analyses different between LHC and Tevatron
- more highlights expected with full data set



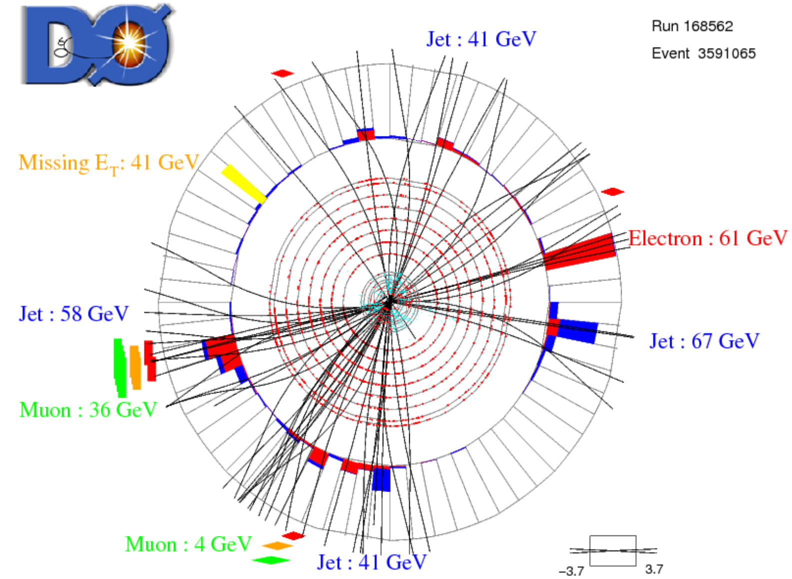






Summary

- after 17 years:
  - many aspects very precisely measured (e.g. Δm_{top}<1 GeV)
  - many new aspects of top quark physics pioneered
  - excellent environment to search for extensions of the SM
- so far everything consistent
- only small tensions: A_{fb}
  - statistical issue, underestimated effect or new physics?
- many things I couldn't cover (e.g. width, charge, W helicity):
  - CDF
  - D0



→ Tevatron still an interesting place for top quark physics!