Recent Top Quark Results from the Tevatron

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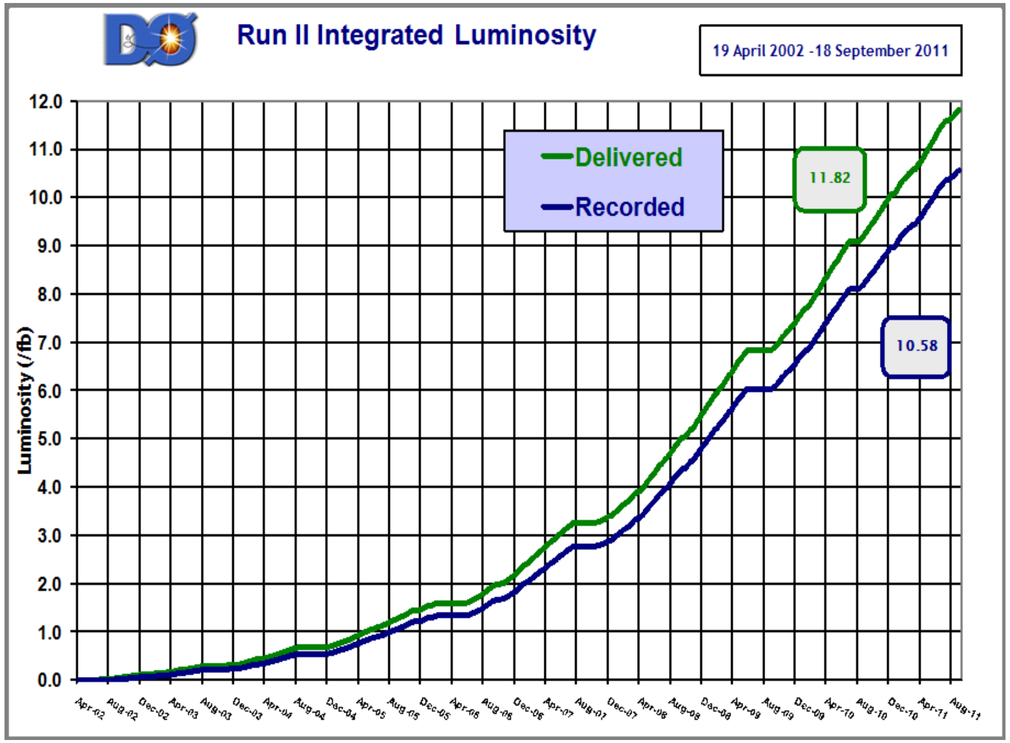
University of Manchester & Fermilab

on behalf of CDF & DØ

MANCHESTER 1824

The Tevatron

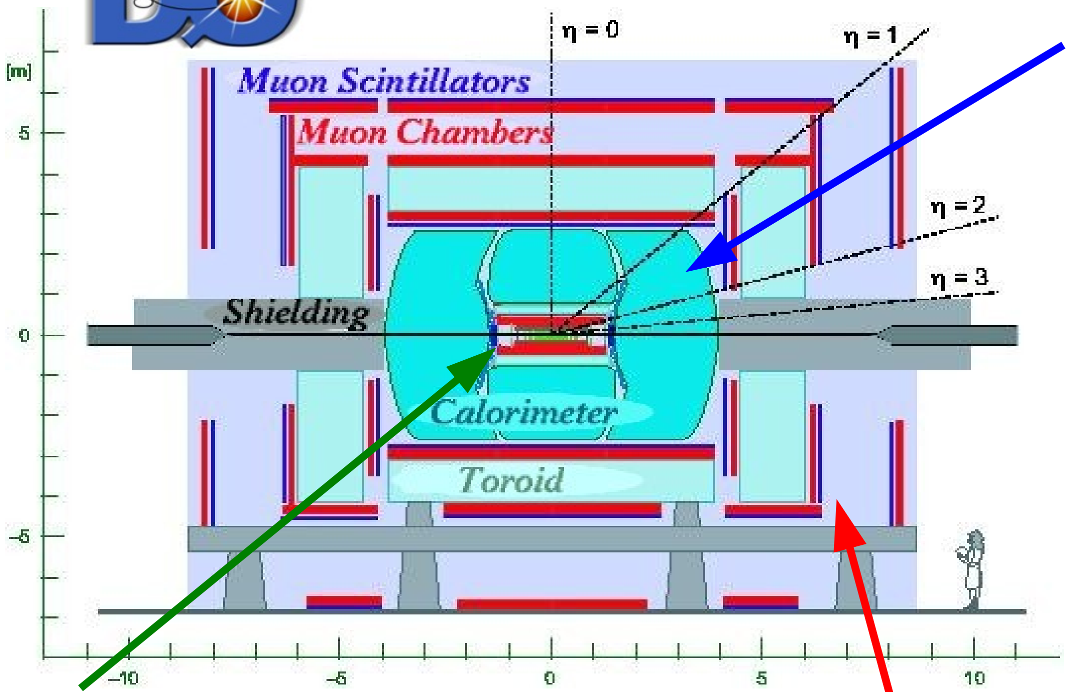


~11.5fb^{-1} delivered

>10.5fb^{-1} on disk per experiment

Tevatron will end operation
next friday (30.09.2011, 2pm CDT)

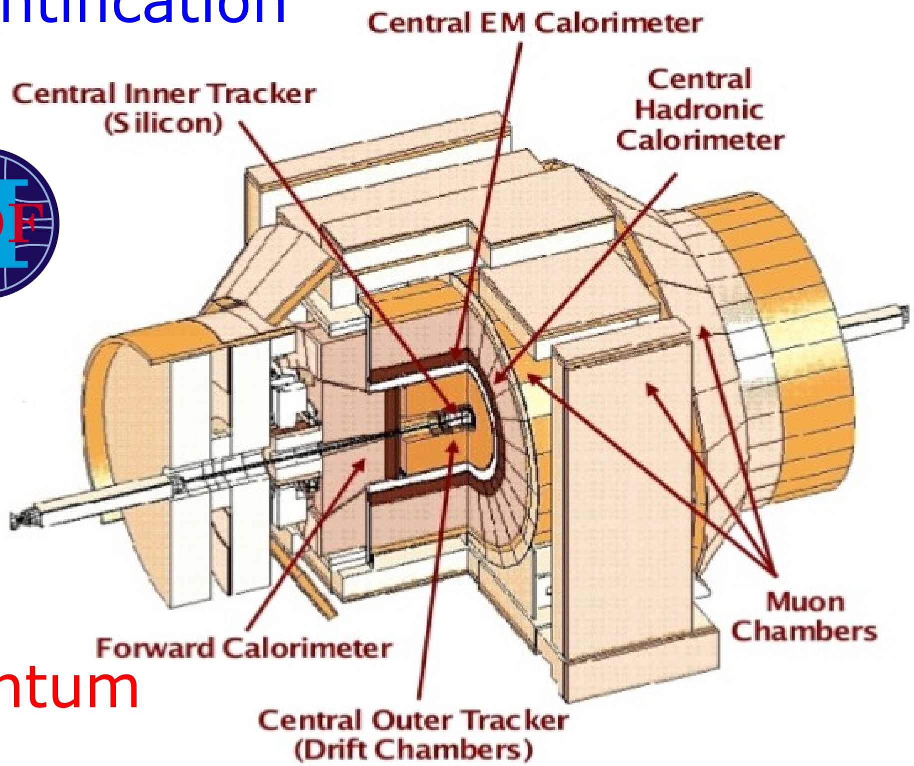
The CDF & DØ Detectors



Calorimeter: Identification and energy measurement of jets and electrons; tau identification

Tracker: Detection and momentum measurement for charged particles

Muon chamber: Identification and momentum measurement of muons



The Top Quark

- Heaviest known elementary particle:

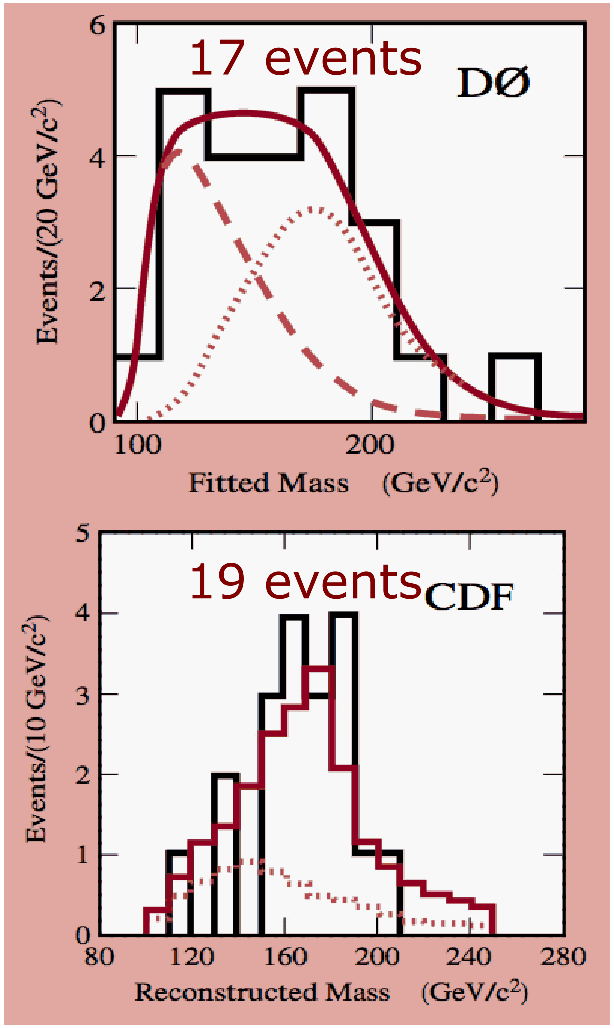
$$m_t = 173.2 \pm 0.9 \text{GeV}$$

arXiv:1007.3178

- Standard Model:
  - Single or pair production
  - Electric charge +2/3 e
  - Short lifetime 0.5×10^{-24}s
    - Bare quark - no hadronization
  - ~100% decay into Wb
  - Large coupling to SM Higgs boson

Top: The TevatrOn Particle

Discovered in 1995 by CDF and DØ at Fermilab (with few events)



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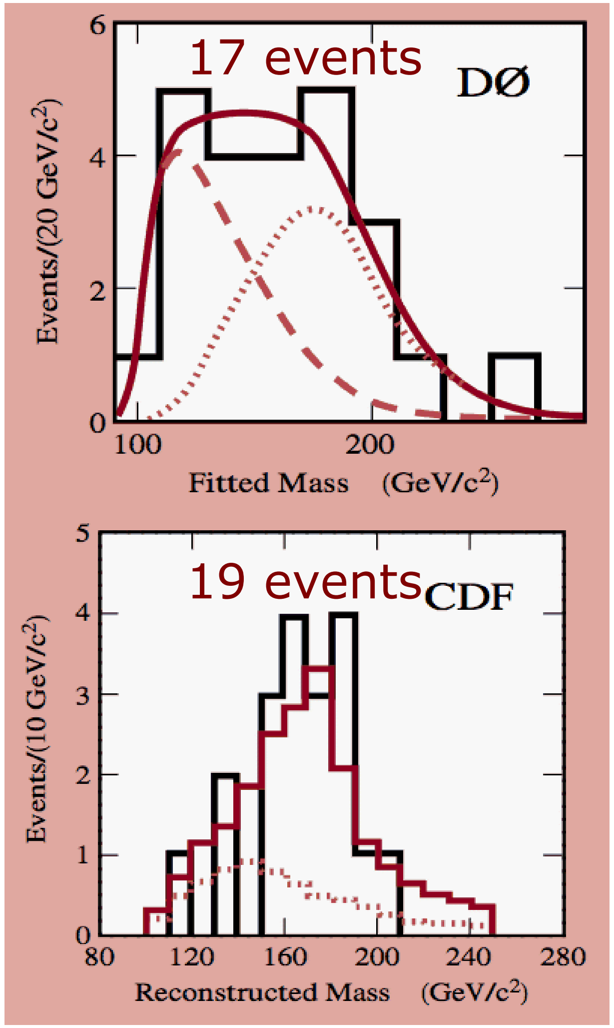
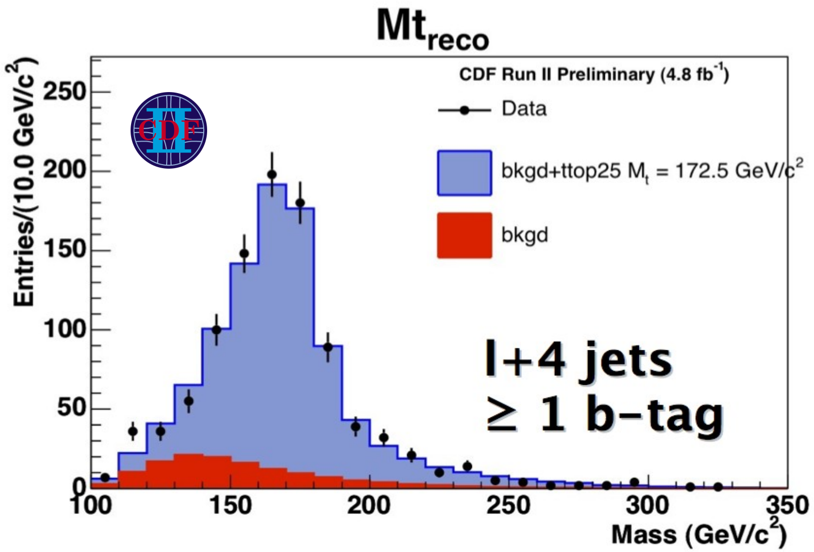
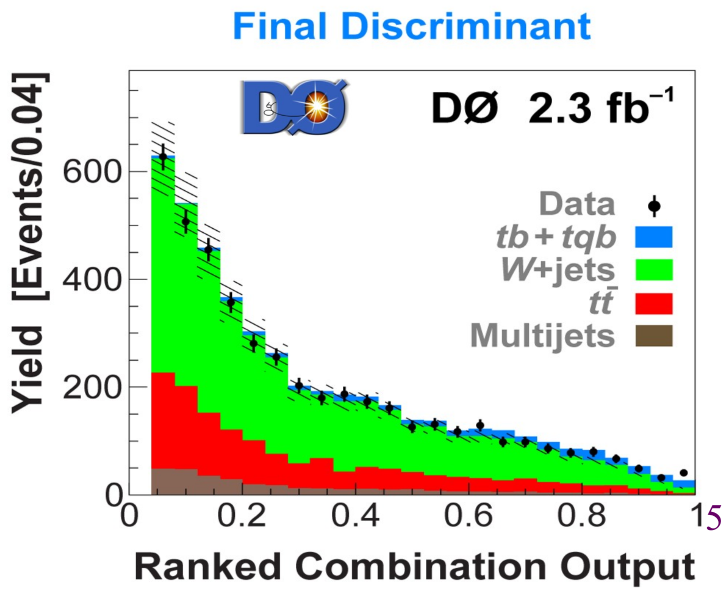


Situation today:

1000s of events!



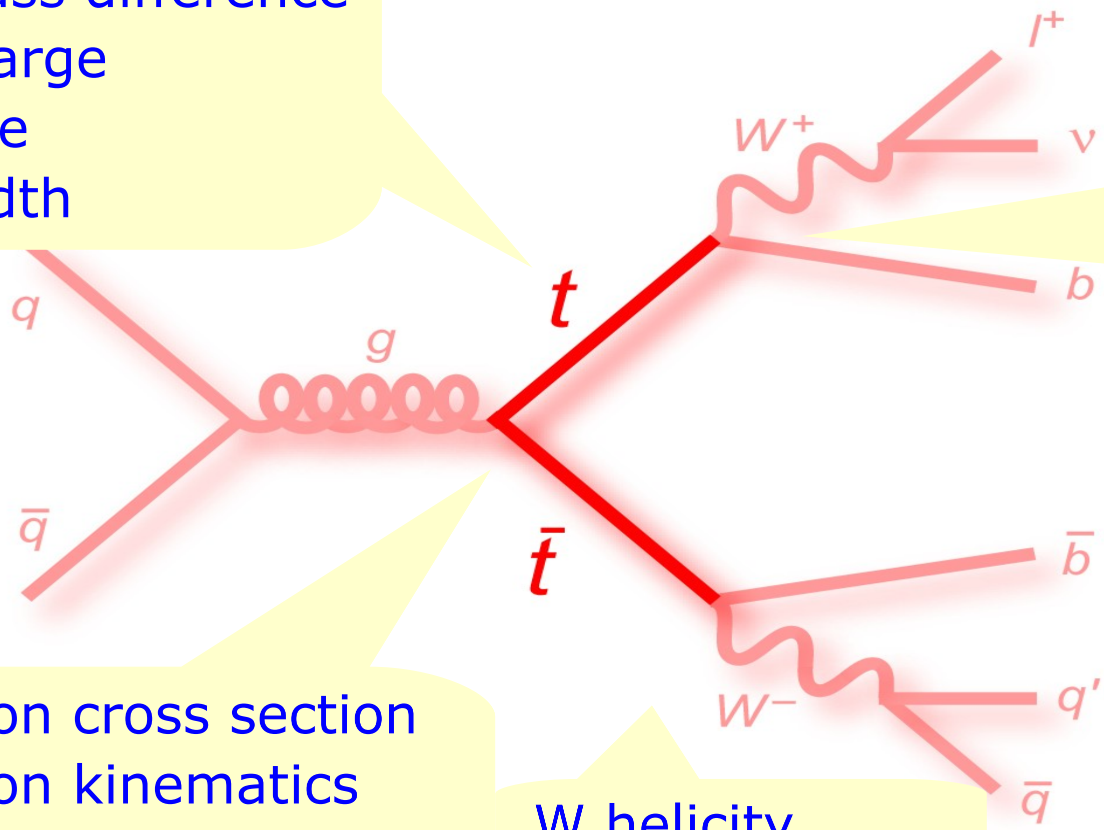
Rediscovered in 2009 in single top production



Since 2010 LHC operating → top quark factory

All we study about the Top

- Top mass
- Top mass difference
- Top charge
- Lifetime
- Top width



- Branching ratios
- $|V_{tb}|$
- Anomalous coupling
- New/Rare decays

- Spin correlation
- Charge asymmetry
- Color Flow

- Production cross section
- Production kinematics
- Production via resonance
- New particles

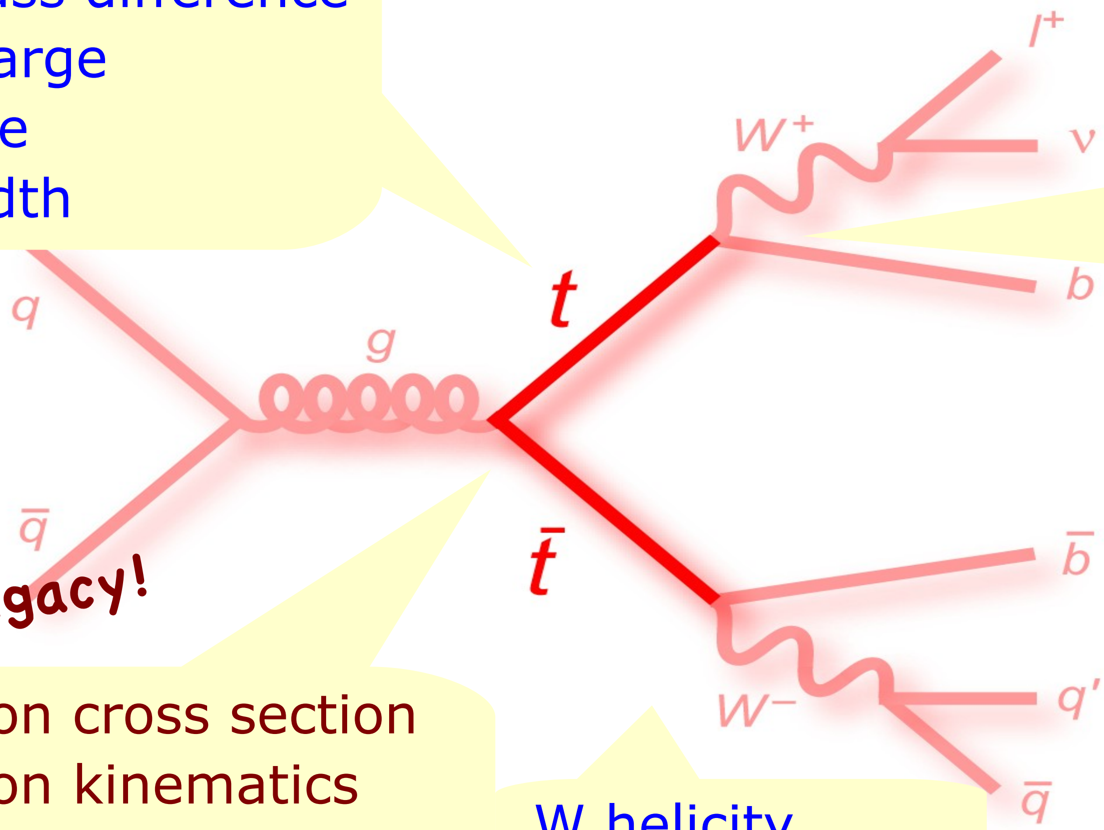
- W helicity

s- & t- channel production, properties and searches in single top events

What we learned from the Tevatron

Tevatron Legacy!

- Top mass
- Top mass difference
- Top charge
- Lifetime
- Top width



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(Still) competitive to LHC!

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- $|V_{tb}|$
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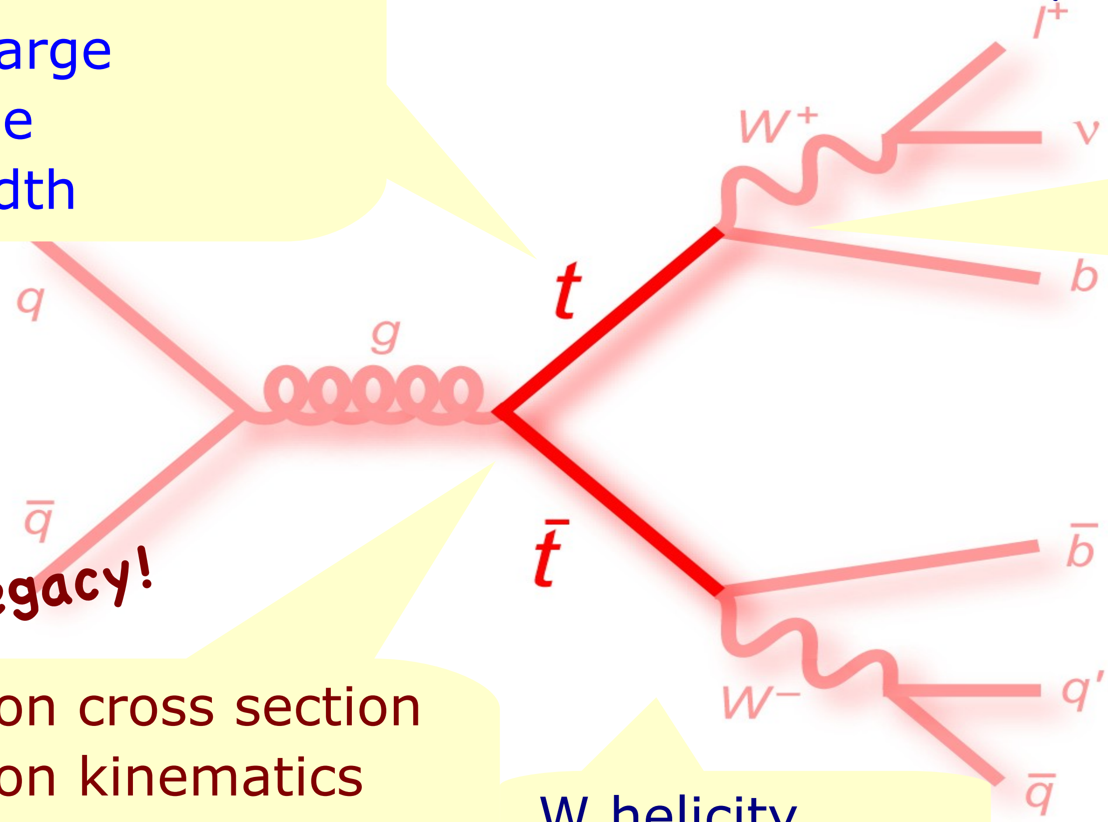

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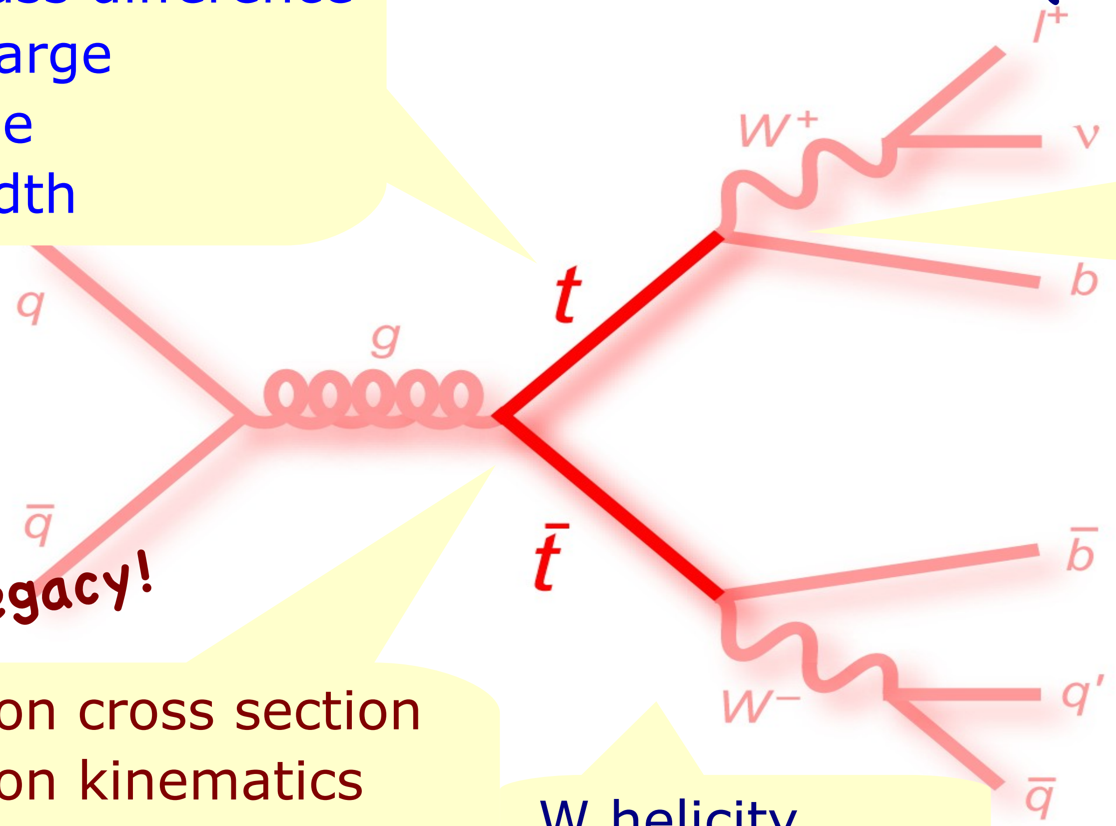

Complementary to LHC!

- Spin correlation
- Charge asymmetry
- Color Flow

Tevatron Legacy!

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What we learned from the Tevatron

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(Still) competitive to LHC!

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- pin correlation
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- Color Flow

Not to forget:
New ideas
Sensitive, new methods
→ All developed during almost 20 years of top quark physics at the Tevatron!

Tevatron Legacy

- Production cross section
- Production kinematics
- Production via resonance
- New particles

- W helicity

(Still) competitive to LHC!

- s- & t- channel production, properties and searches in single top events

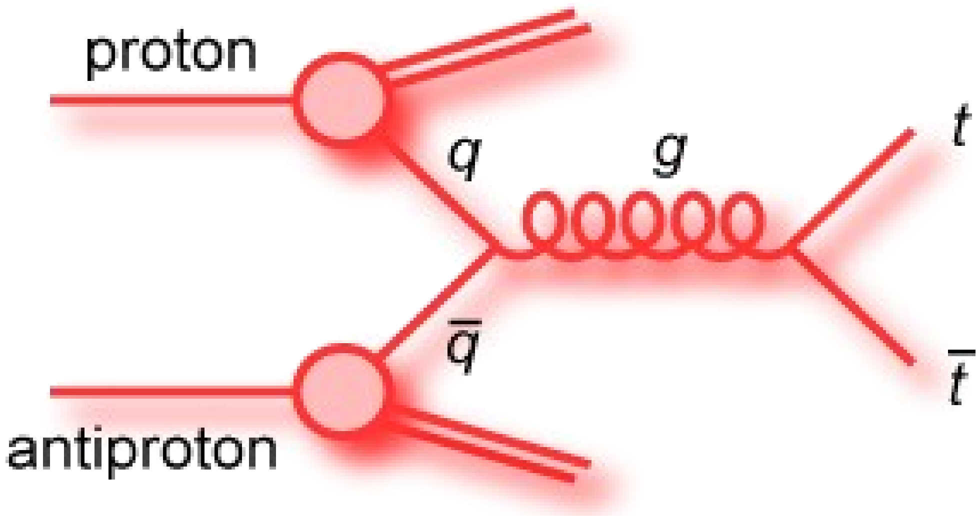
Outline

Part I: Production

Part II: Properties

Part I: Production

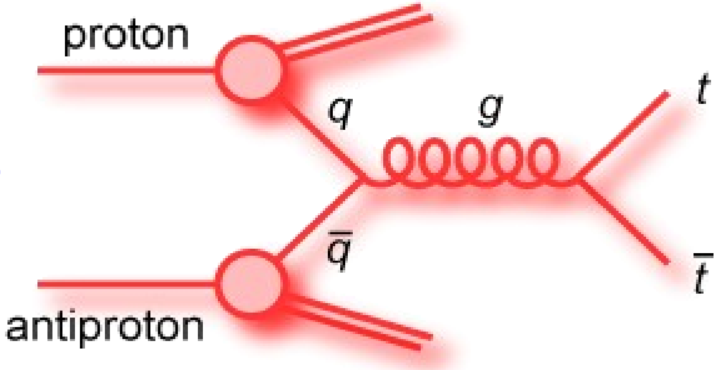
- $t\bar{t}$ production
- Single top production



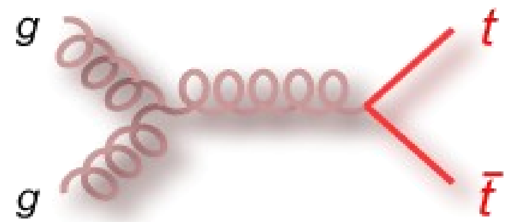
Top Quark Pair Production

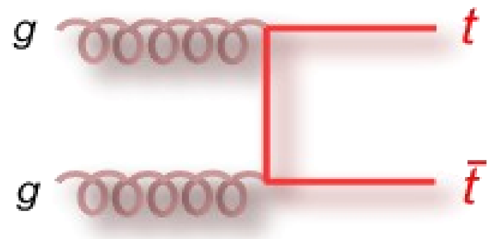
- Via strong interaction
- At the Tevatron:

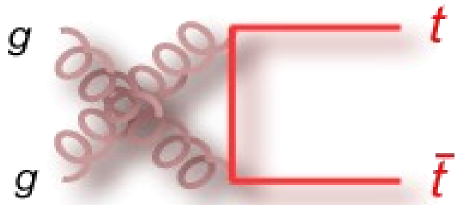
85%



+ 15%







At LHC:

14 TeV: 10% + 90%

7 TeV: 15% + 85%

- Production cross section (@Tevatron):

approximate NNLO: $\sigma = 7.46^{+0.48}_{-0.67}\, pb$ @ m_t=172.5GeV

Moch, Uwer, PRD 78, 034003 (2008)

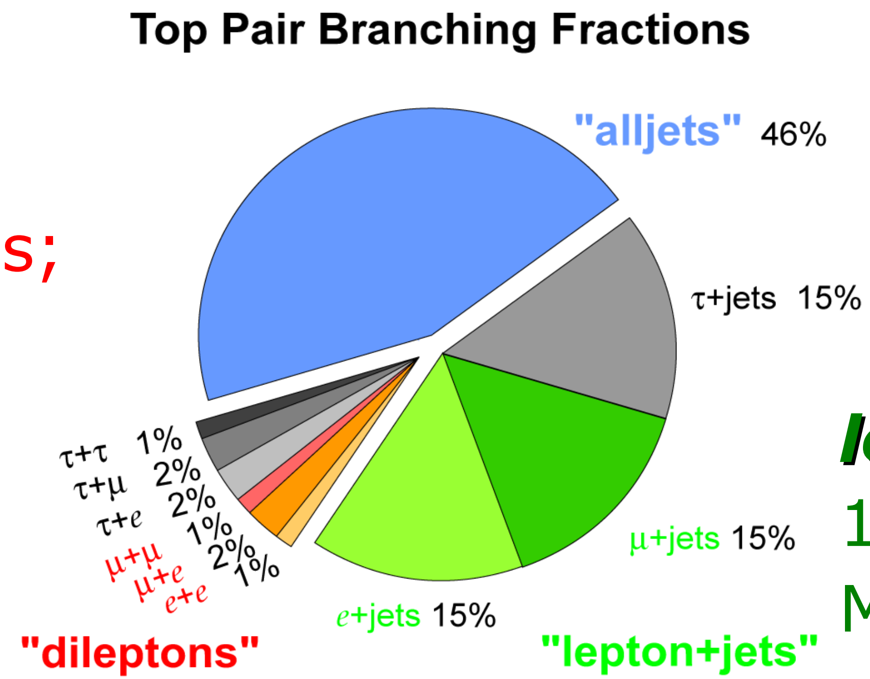
Final States in $t\bar{t}$

$t\bar{t} \rightarrow W^+bW^-\bar{b}$: Final states are classified according to W decay

$B(t \rightarrow W^+b) = 100\%$

pure hadronic:
≥6 jets (2 b-jets)

dilepton:
2 isolated leptons;
High missing E_T from neutrinos;
2 b-jets

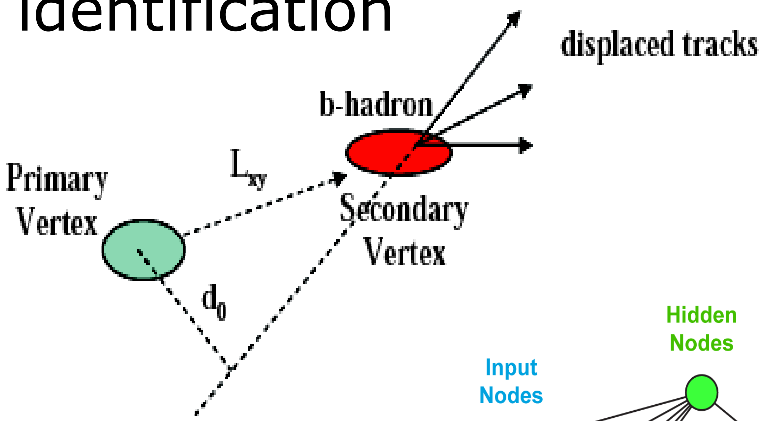


lepton+jets:
1 isolated lepton;
Missing E_T from neutrino;
≥4 jets (2 b-jets)

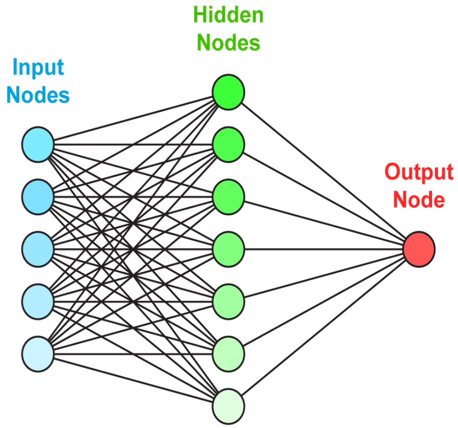
Cross Section Measurement: Methods

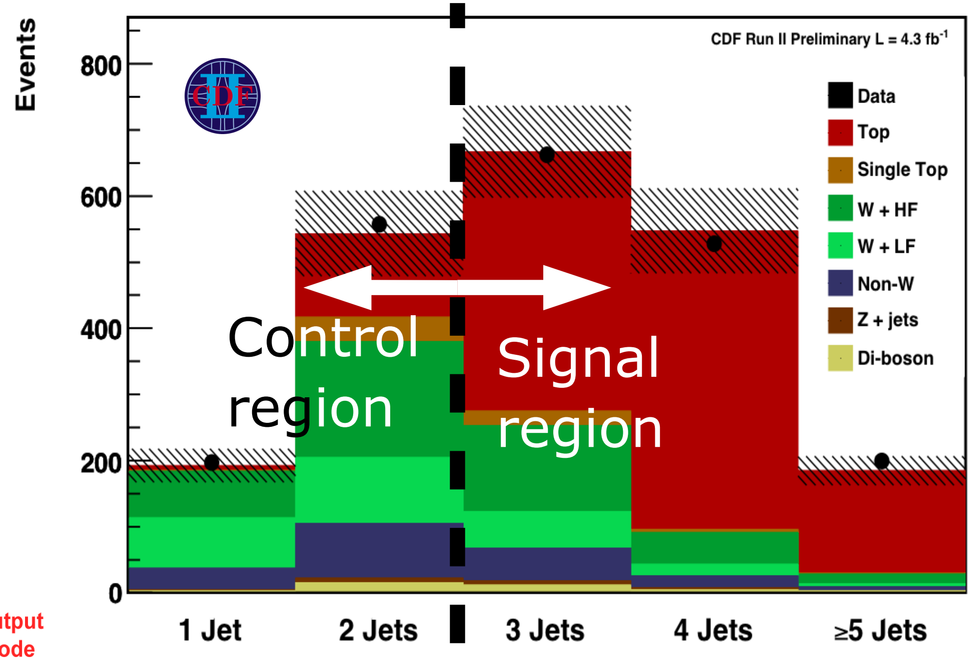
- Use knowledge of signal and background signature to enrich data sample in $t\bar{t}$ events

- Important tools:
  - B-jet identification



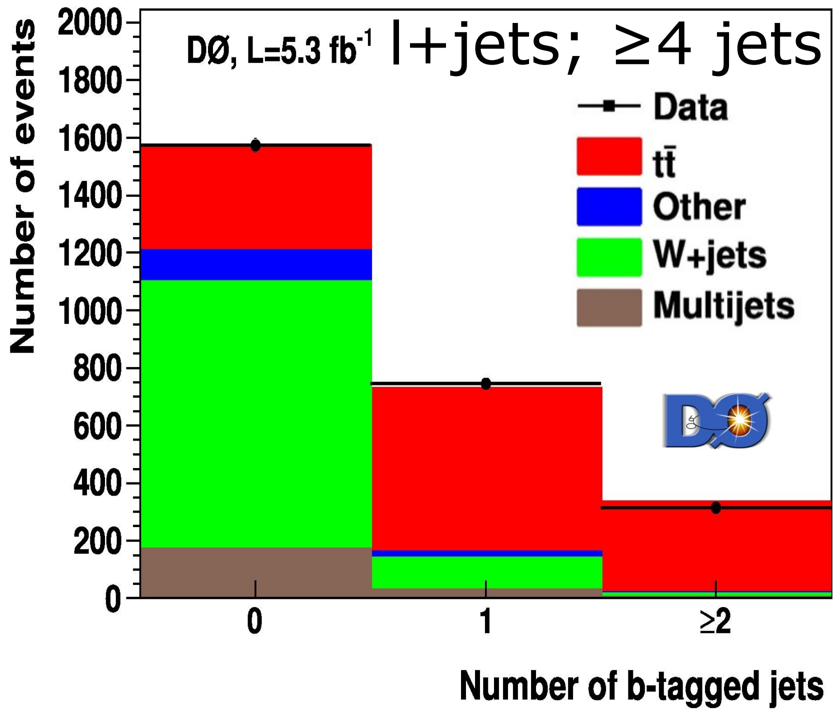
  - Multivariate analysis techniques



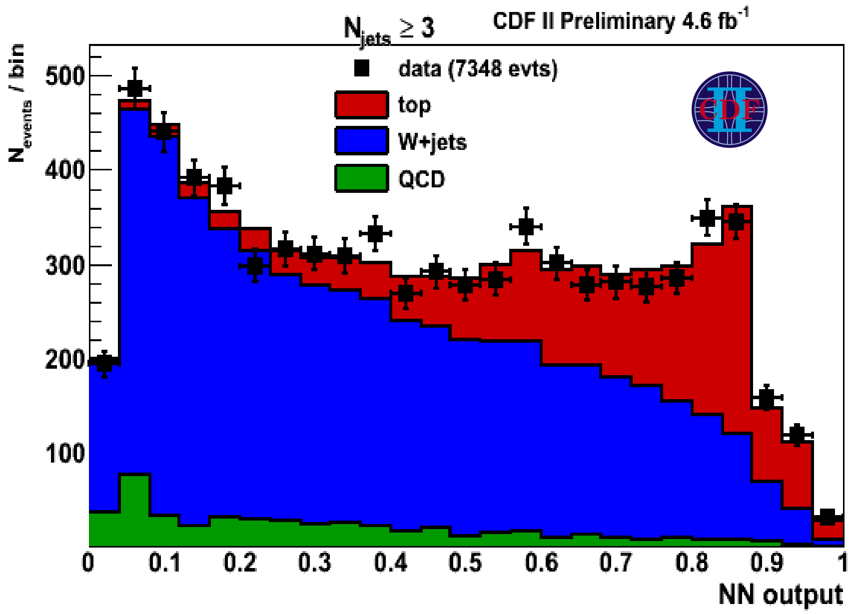


$\sigma_{t\bar{t}}$ in l+jets

- Split events counting b-jets
  - More b-jets → higher purity



- Construct discriminant
  - Combine variables discriminating signal and background in NN/BDT

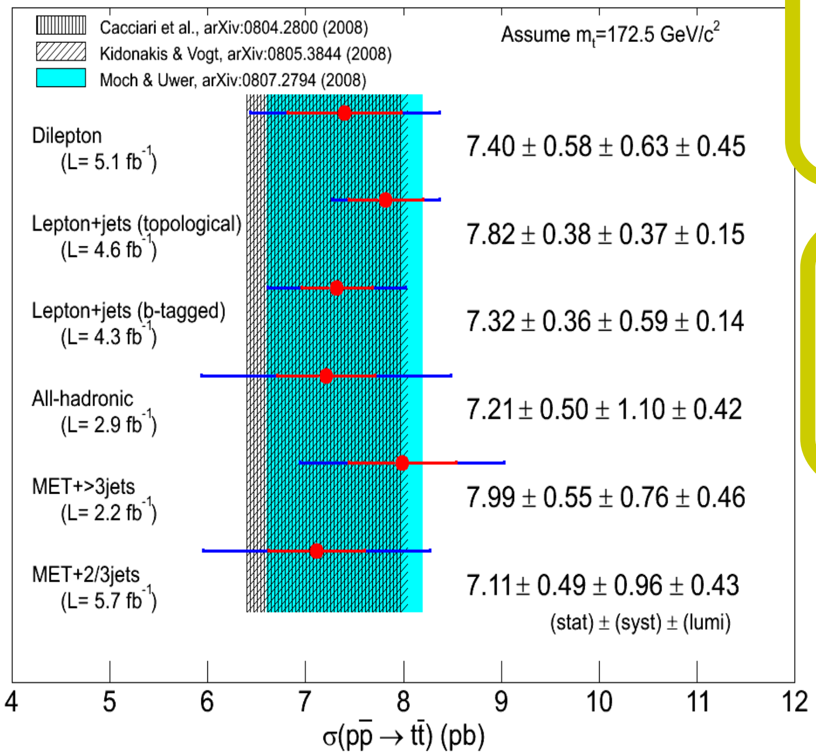


$D0: \quad \sigma = 8.13^{+1.02}_{-0.90}(stat + syst)\ pb$ PRD 84, 012008 (2011) $\sigma = 7.68^{+0.71}_{-0.64}(stat + syst)\ pb$

$CDF: \quad \sigma = 7.22 \pm 0.80\,(stat + syst)\ pb$ PRL 105:012001 (2010) $\sigma = 7.52 \pm 0.66\,(stat + syst)\ pb$

Other Channels & Combination

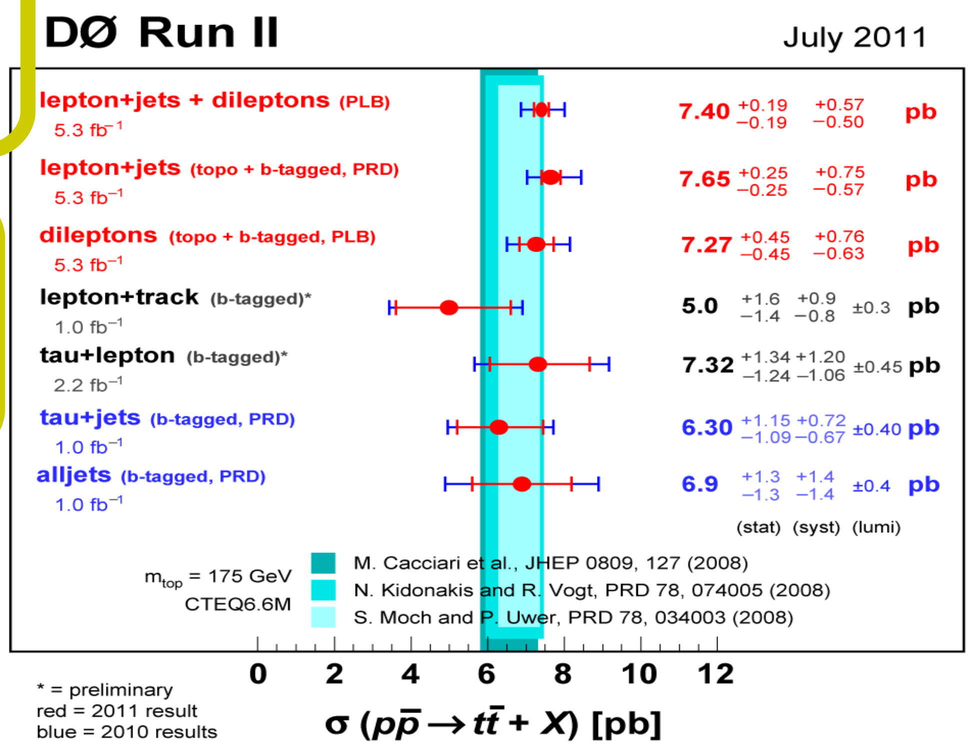
- $\sigma_{t\bar{t}}$ measured in various other channels



$\not{E}_T$ +(lepton/jets): interesting for Higgs search

τ+(lepton/jets): Interesting for H^+ search @ high tanβ

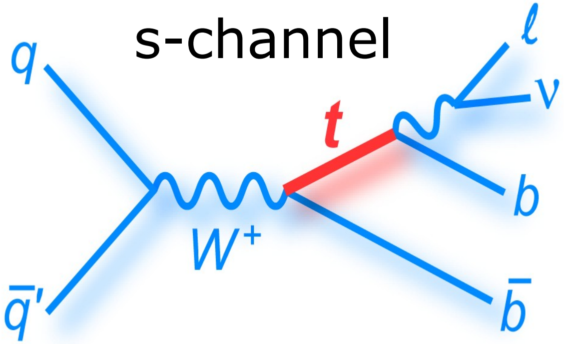
All hadronic: no $\not{E}_T$



- Deviation of $\sigma_{t\bar{t}}$ from SM or between channel could indicate new physics
  - Everything consistent with each other and SM prediction
  - Now most measurements systematically limited

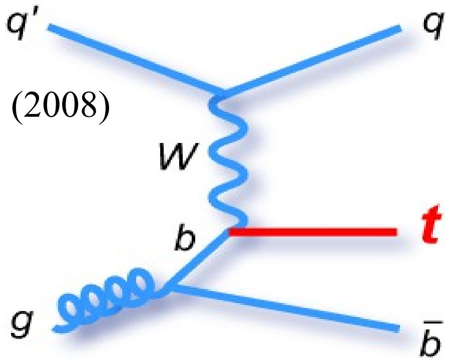
Single Top: Cross Section Measurement

- Single top quark production via electroweak interaction



Kidonakis, Vogt, PRD 78, 074005 (2008)

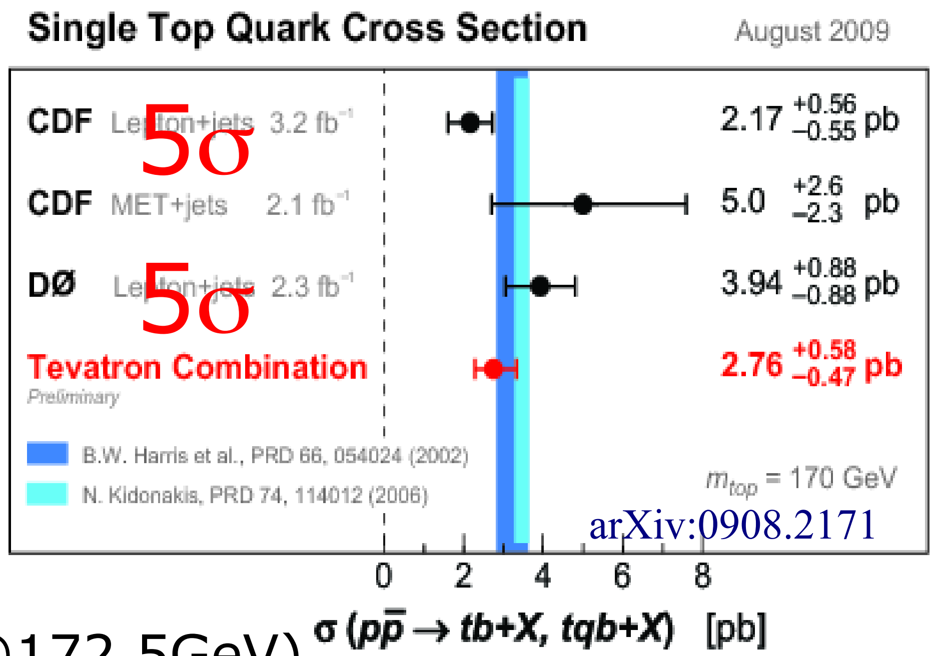
$\sigma_{tb} = 1.04 \pm 0.04$ pb
$NNNLO_{approx}$, $m_{top} = 172.5$ GeV



t-channel

$\sigma_{tqb} = 2.26 \pm 0.12$ pb
$NNNLO_{approx}$, $m_{top} = 172.5$ GeV

- Very challenging:
  - Low signal: similar signature like W+jets!
  - Counting only: Uncertainty on background larger than expected signal
- Use multivariate techniques
  - WH similar to single top → use methods
- Observation in 2009

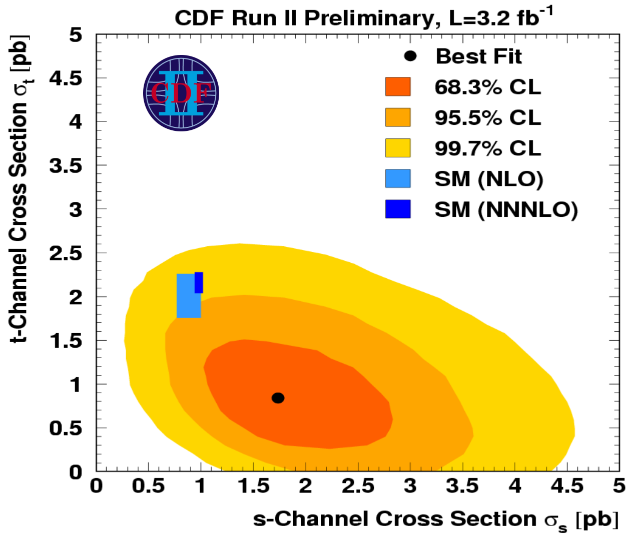


arXiv:1108.3091

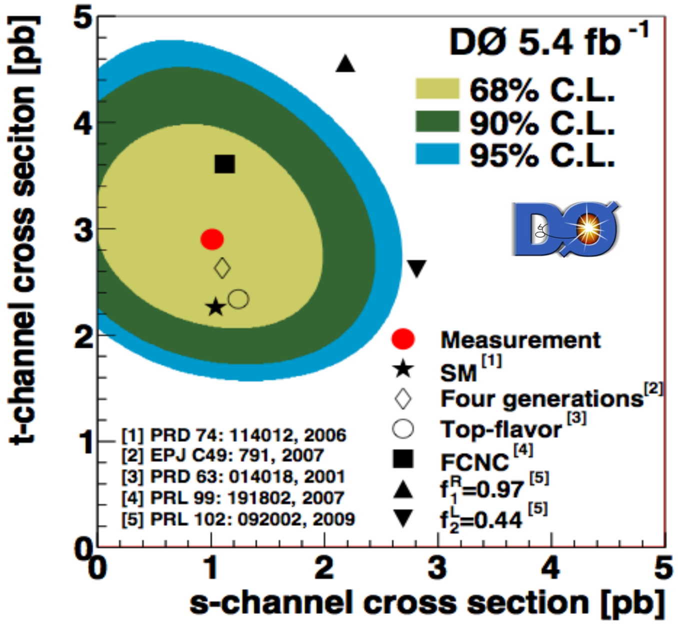
- DØ update 2011: $\sigma(tb,tqb)=3.43^{+0.73}_{-0.74}$ pb (@172.5GeV)

Single top t-channel

- Measure s- and t-channel simultaneously
  → no assumption of SM ratio



In agreement with SM prediction

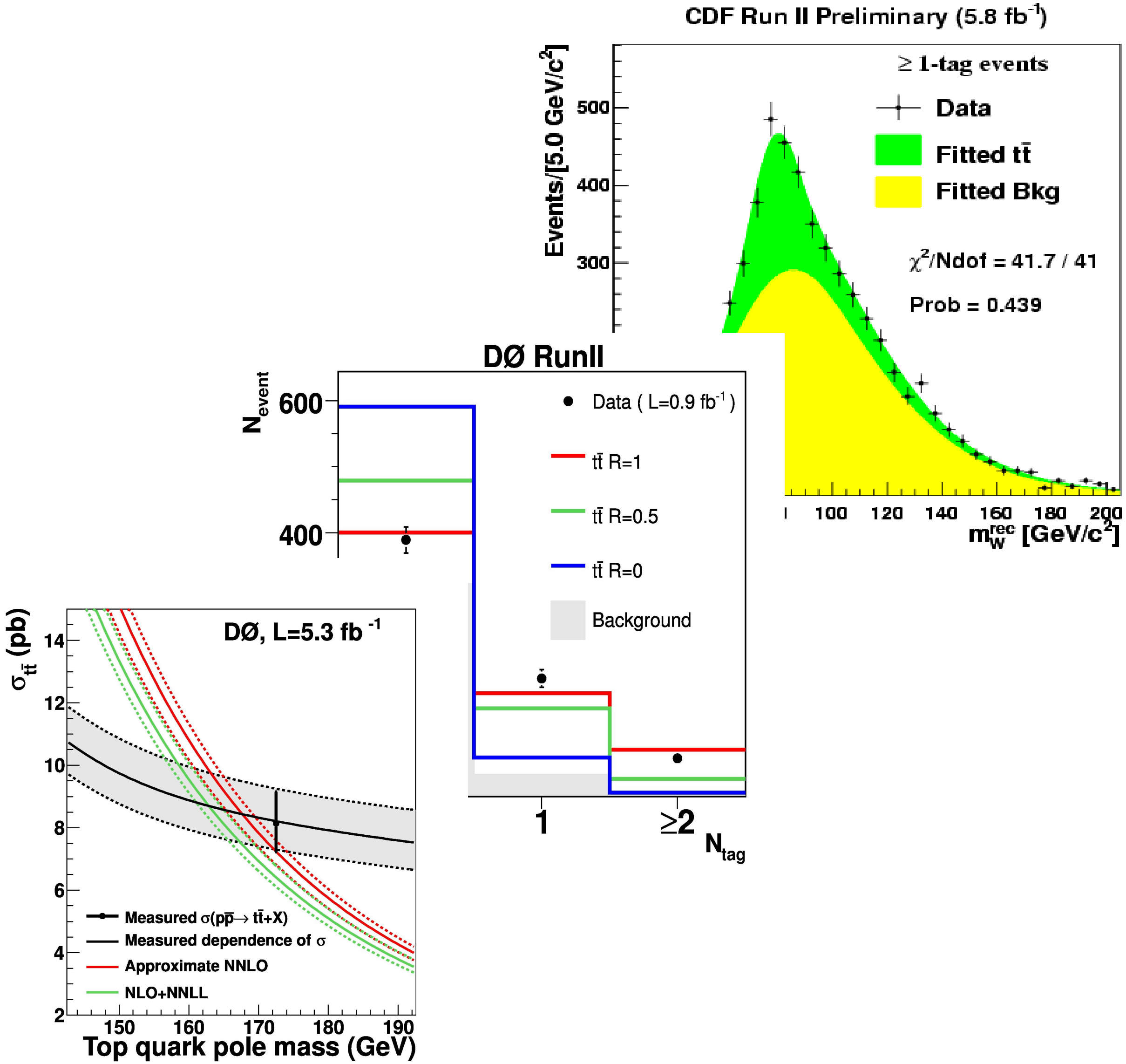


- Train with t-channel as signal and integrate over s-channel: t-channel cross section
- DØ: observation of t-channel (5.5 sigma)

$$D0: \quad \sigma = 2.90 \pm 0.59 \,(stat + syst)\; pb$$

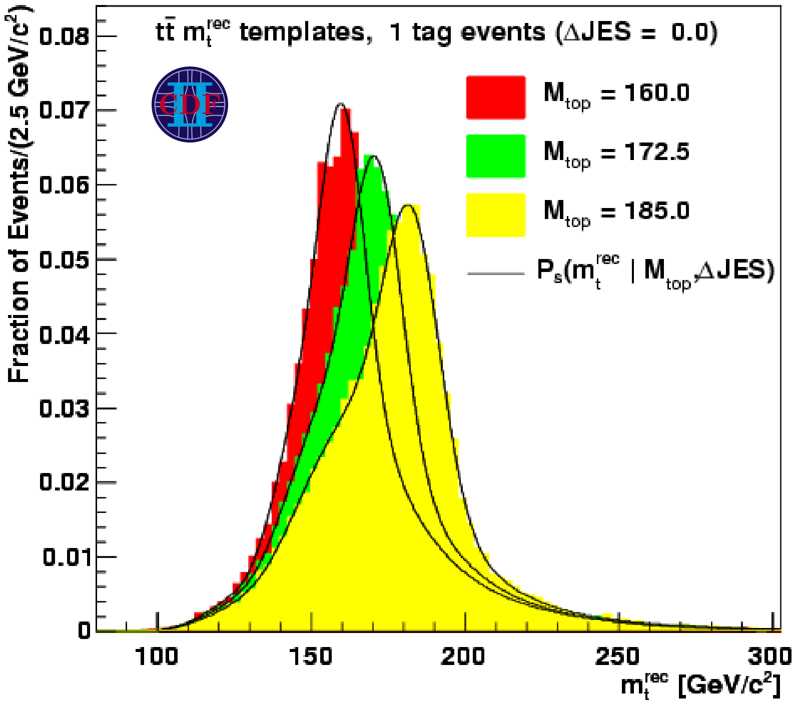
Part II: Properties

- Mass
- Mass from cross section
- Mass difference
- W helicity
- Spin correlations
- Color charge asymmetry

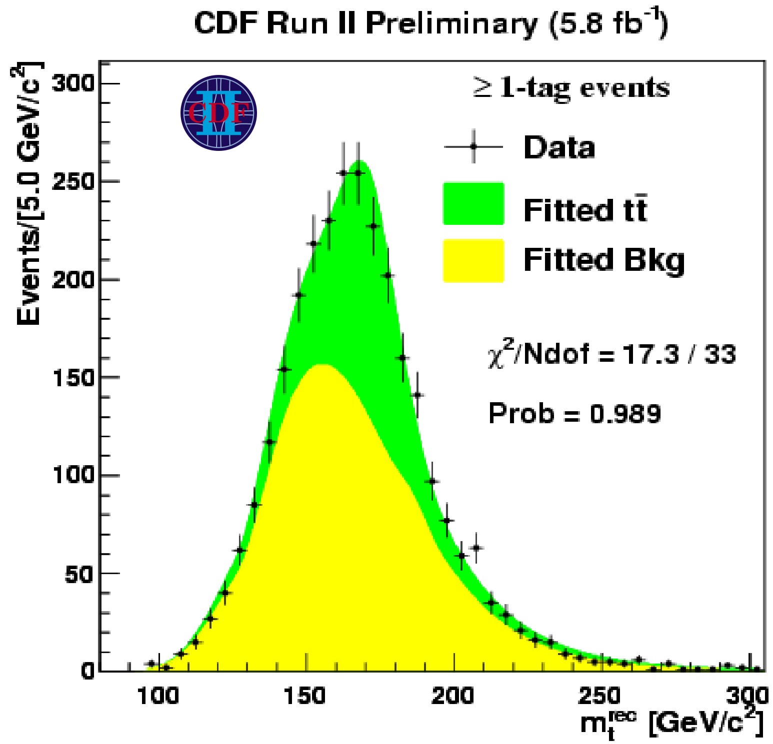


Top Quark Mass

- Motivation: free parameter of the SM & constraint on Higgs
- Several methods: Template method, matrix element, etc.
  - Methods also used for other analyses, e. g. W helicity & spin correlations
- Template method: construct mass dependent template, fit to data



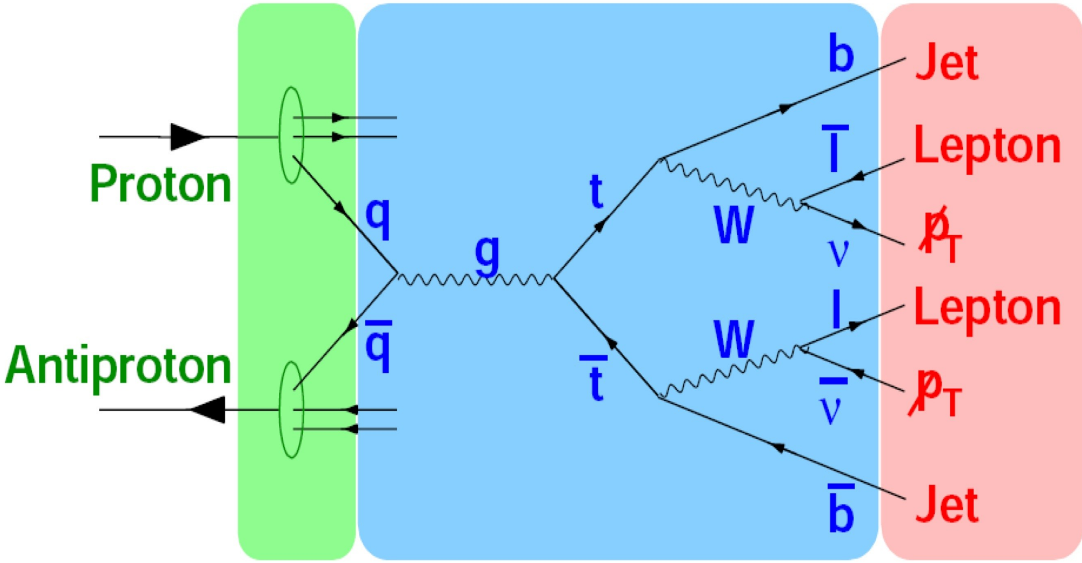
Additionally: Take info from W mass to constrain jet energy scale



Top Quark Mass: Matrix Element Method

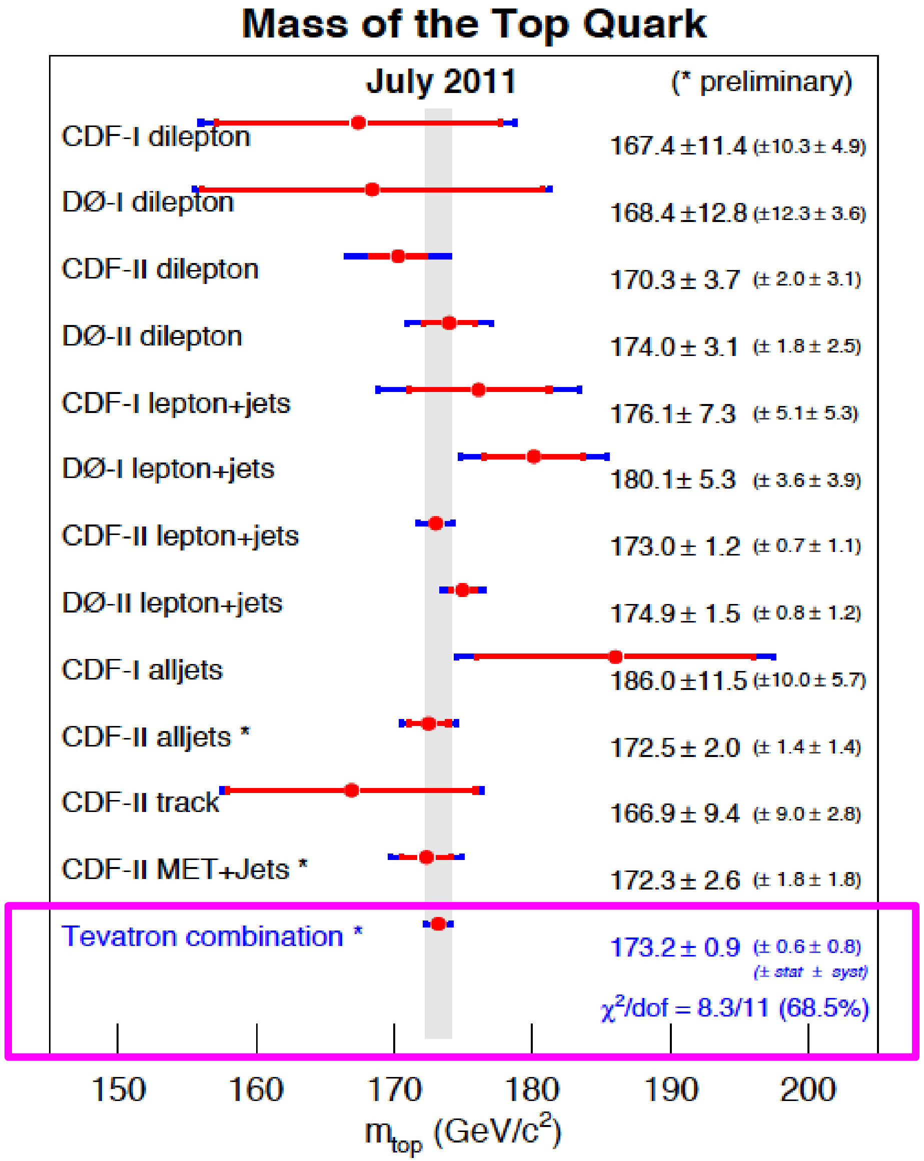
- Use the full event kinematics → most precise method
- For each event calculate probability to belong to certain top mass

$$P_{sig}(x;m_t) \propto \int \text{PDF x Matrix element x Transfer function}$$



- Perform likelihood fit of event probabilities
- Probability dependent on top mass (& JES for in-situ fit)

Top Quark Mass: All Methods & Combinations

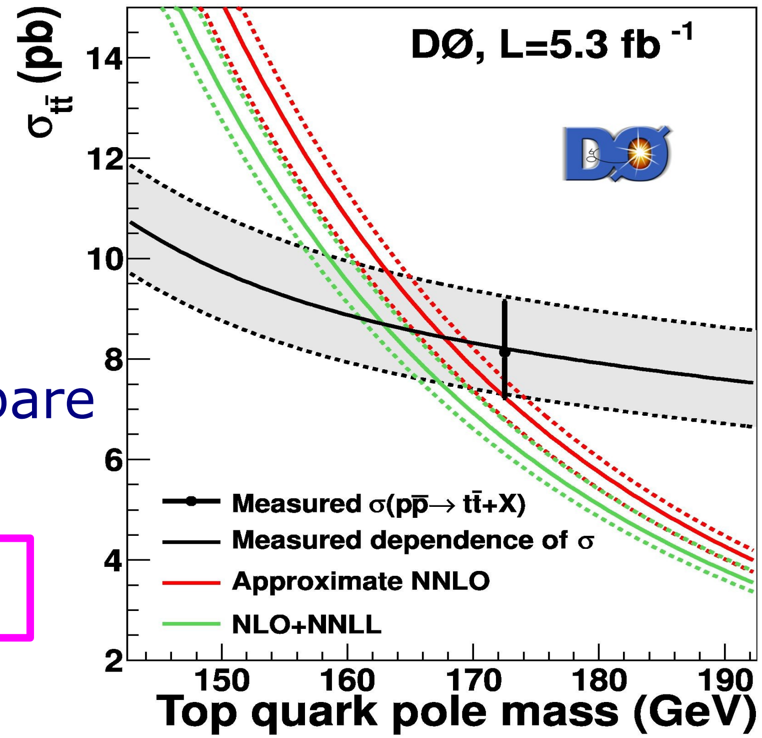


- Tevatron combination: first time uncertainty below 1GeV!
- Systematics limited!
  - Main effort for experiments: detailed understanding of systematics
  - Main systematics at Tevatron: JES-related & signal modeling

arXiv:1007.3178

Top Quark Mass: Be aware

- Ongoing discussion:
  What is theoretical interpretation of the measured parameter?
  - We extract the top mass based on Monte Carlo → Is it the pole mass?
- Alternative method: Extract m_t from measurement of $t\bar{t}$ cross section
  - Assuming MC mass =pole or $\overline{\text{MS}}$ mass
    - Take difference as systematics
    - Calculate $\sigma_{t\bar{t}}$ as function of pole mass; compare to measured $\sigma_{t\bar{t}}$ as function of pole mass
      → Extract pole mass: $m_t = 167.5^{+5.2}_{-4.7}\,GeV$
- Assuming $\overline{\text{MS}}$ mass leads to ~7GeV smaller value
- World average more compatible with pole mass



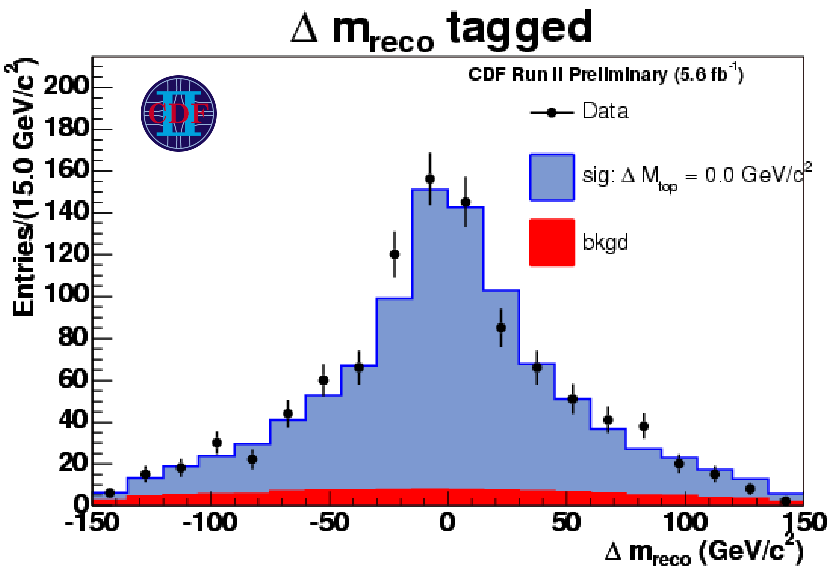
arXiv:1104.2887

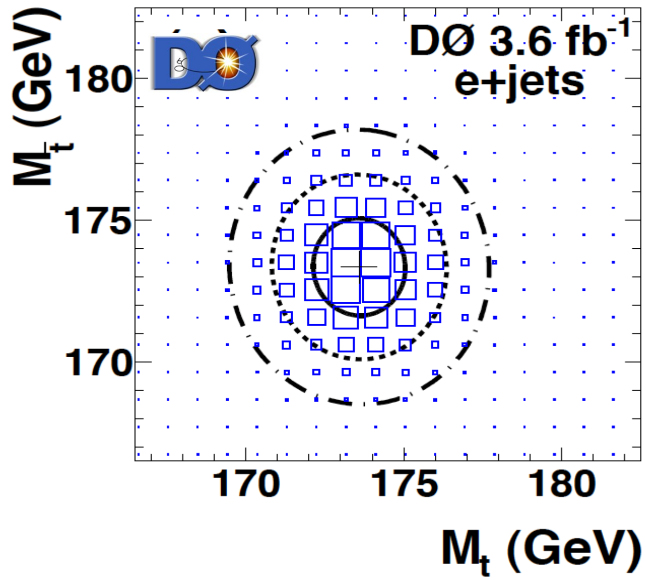
Top Quark Mass Difference

- Are top and anti-top equally heavy?
  - If not: CPT violation!
- CDF: Using template technique
  - Assume average top mass of 172.5GeV

    $m_t - m_{\bar{t}} = -3.3 \pm 1.7\,\text{GeV}$ PRL 106, 161801
- DØ: Using Matrix Element technique
  - $P_{sig}(x; m_t, m_{\bar{t}})$ instead of $P_{sig}(x; m_t)$

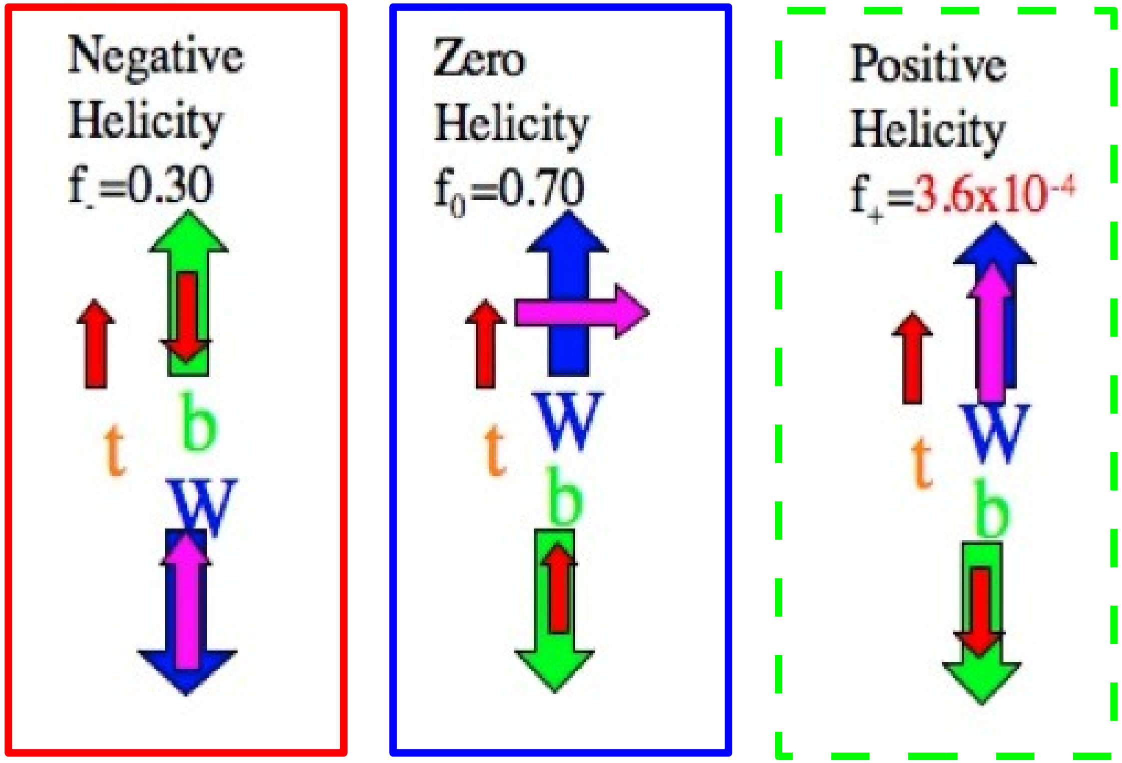
    $m_t - m_{\bar{t}} = 0.8 \pm 2.0\,\text{GeV}$ PRD 84, 052005
- Statistics limited
- Good agreement with the SM!

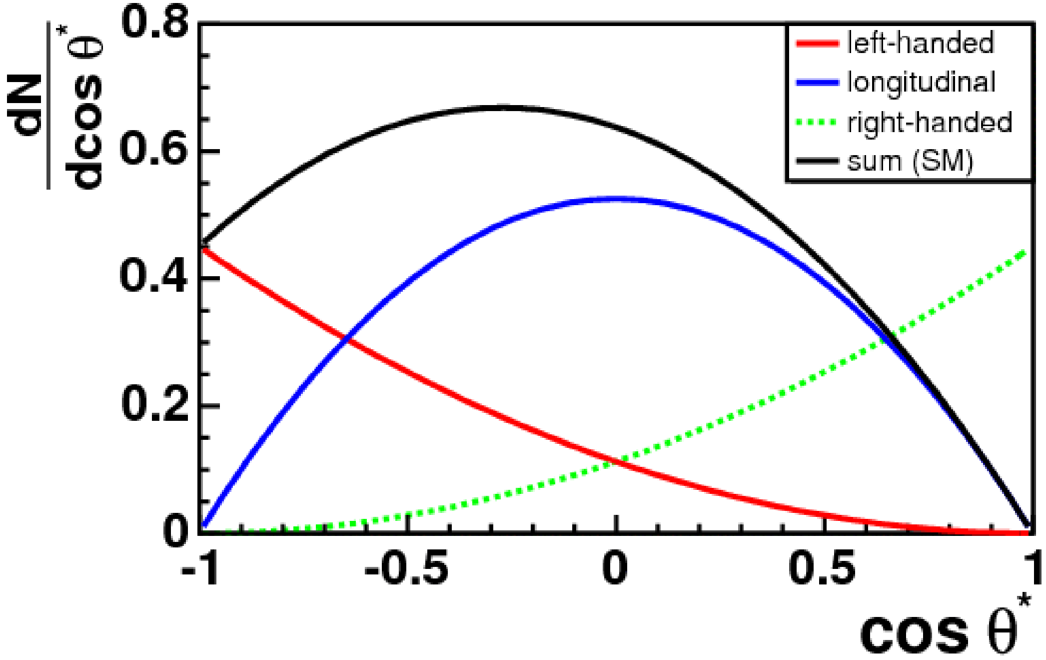




W Helicity in Top Quark Decays

- Left handed coupling of W-boson to fermions:
  Not every combination of spin for W and b-quark is allowed

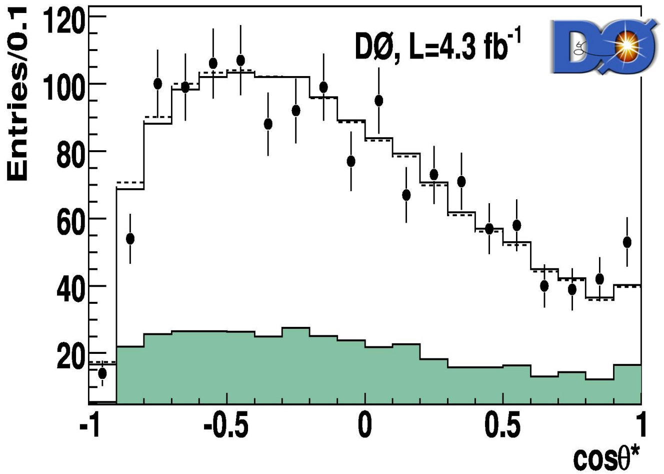




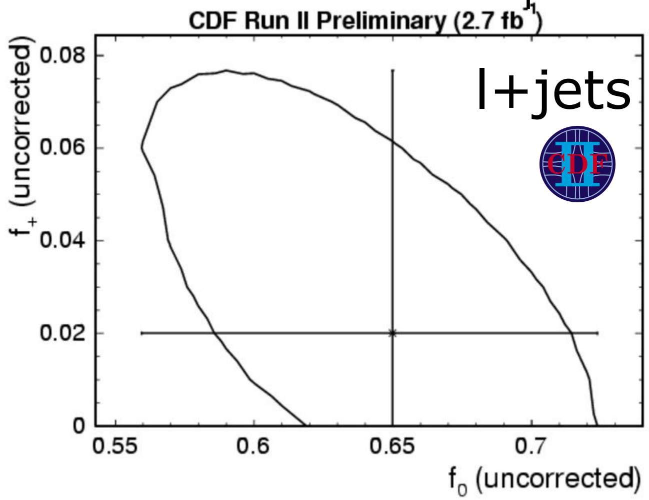
- Measure angle θ^* between down-type decay product (lepton, d-, s-quark) of W and top quark in W rest frame

W Helicity in Top Quark Decays

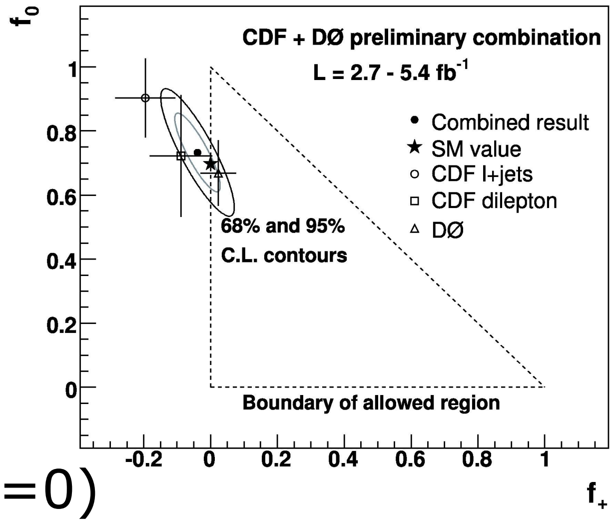
- Template method: Fit fraction of cosθ* templates to data



- Matrix Element Method: use method as for mass, replace m_T with f_0 & f_+



- Tevatron: Combination of DØ & CDF l+jets & dilepton results
  - Model independent (fit f_+, f_-, f_0 with $f_-+f_0+f_+=1$):
    f_0=0.732±0.063(stat)±0.052(syst)
    f_+=-0.039±0.034(stat)±0.030(syst)

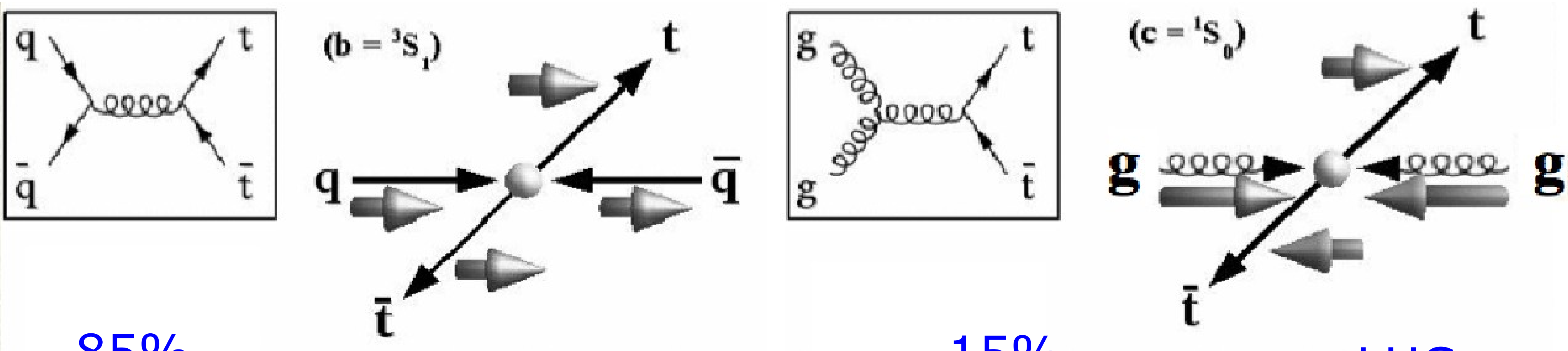


- So far all in agreement with SM values (f_0=0.7,f_+=0)

$t\bar{t}$ Spin Correlations

- Top quarks decay before fragmentation
  - Spin information is preserved
- Spin correlation depends on production mode

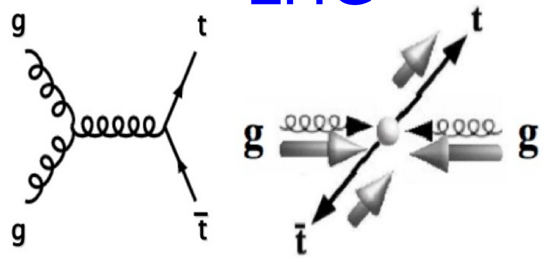
Complementary to LHC



85%

15%

LHC



- We use two methods to explore spin correlations
  - Template based using angular distribution
  - Matrix element based

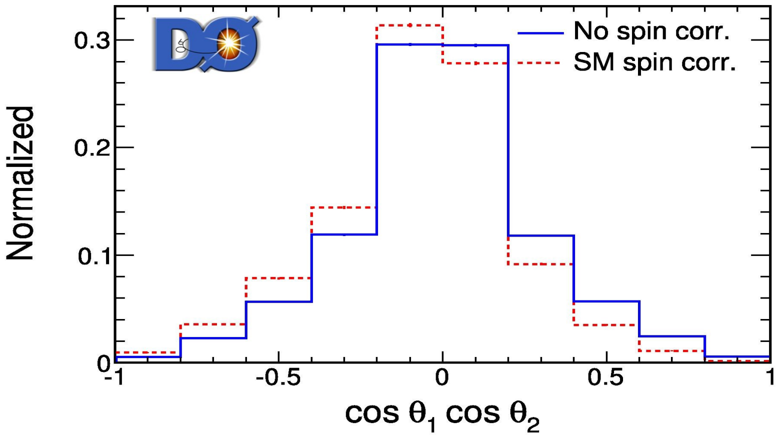
$t\bar{t}$ Spin Correlations: Methods

Angular Distributions

- Use angles between decay products and beam axis
- Differential cross section:

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

  - C: spin correlation strength
  - NLO SM: C≈0.78

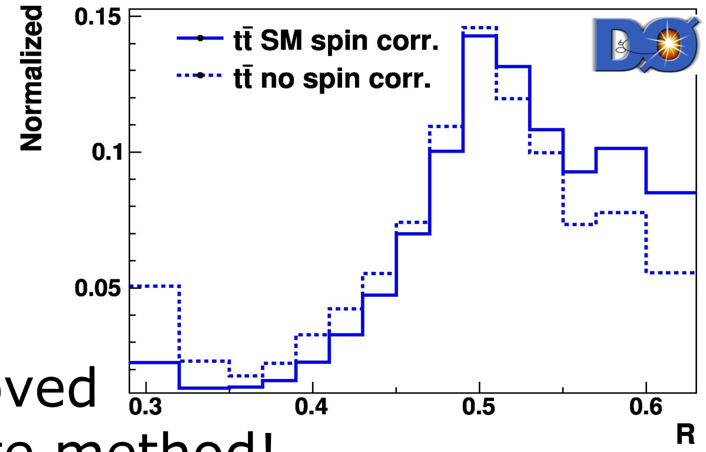


Matrix Elements

- Test hypothesis of spin correlation (H=1) versus no correlation (H=0)
- Calculate signal probability P_{sgn} for H=0 and H=1, define discriminator:

$$R = \frac{P_{\rm sgn}(H=1)}{P_{\rm sgn}(H=0)+P_{\rm sgn}(H=1)}$$

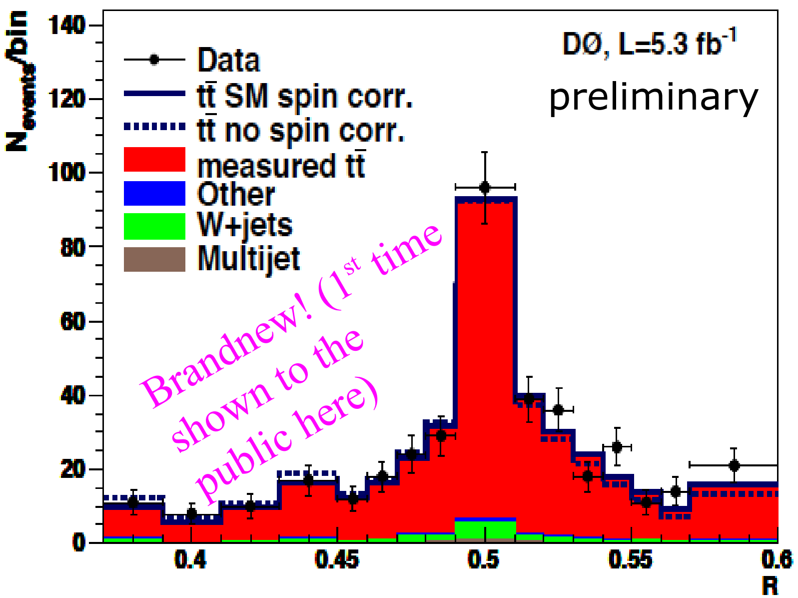
- Fit fraction $f = N_{t\bar{t}}(\text{with spin})/N_{t\bar{t}}(\text{total})$



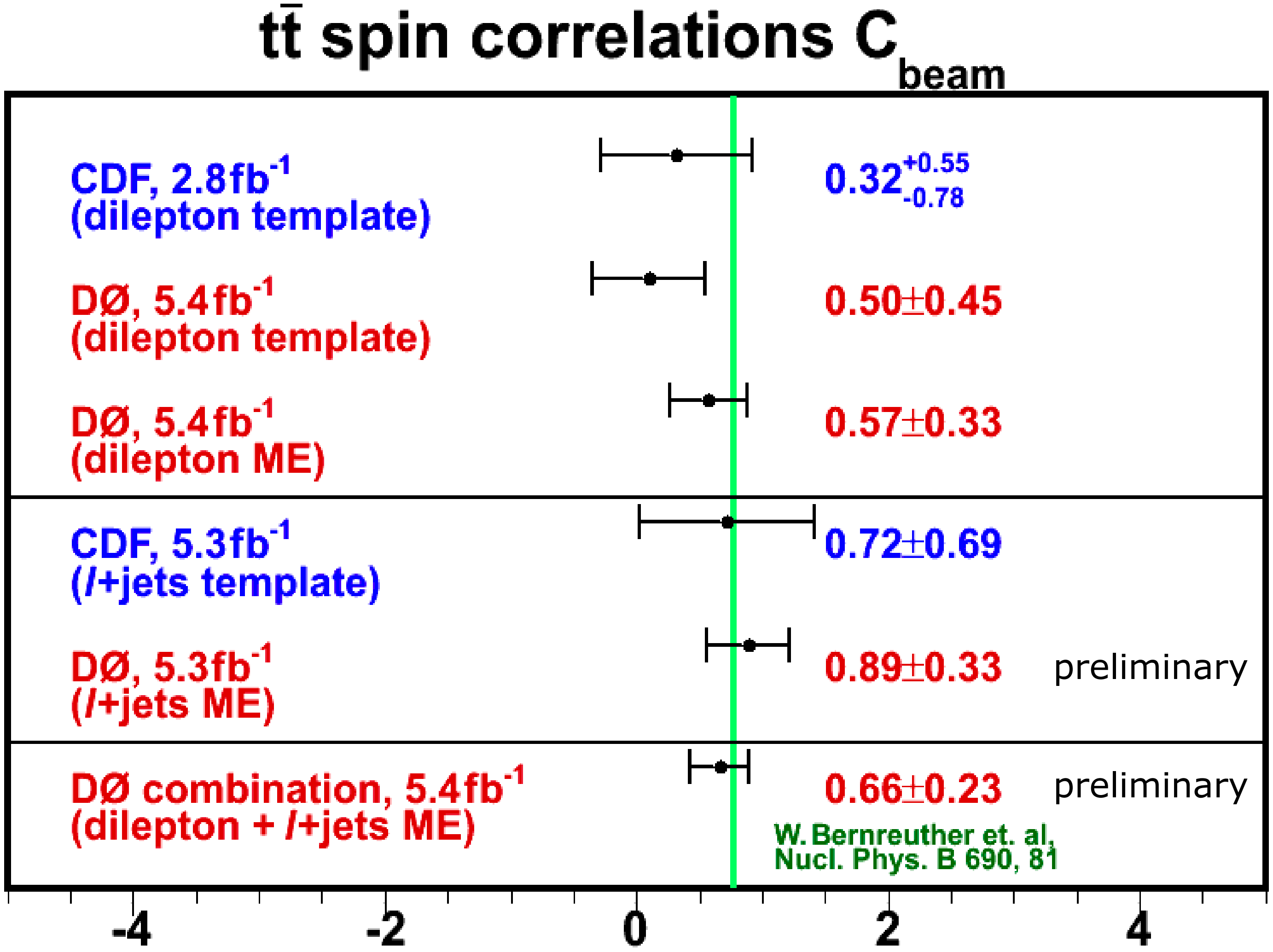
- ~30% improved over template method!

$t\bar{t}$ Spin Correlations: Results

- Since summer 2009 several new results on spin correlations!
  - Before: 6 events in RunI $\rightarrow$ not sensitive



l+jets & dilepton combination



First evidence for non-vanishing $t\bar{t}$ spin correlations!

$t\bar{t}$ Forward Backward Asymmetry

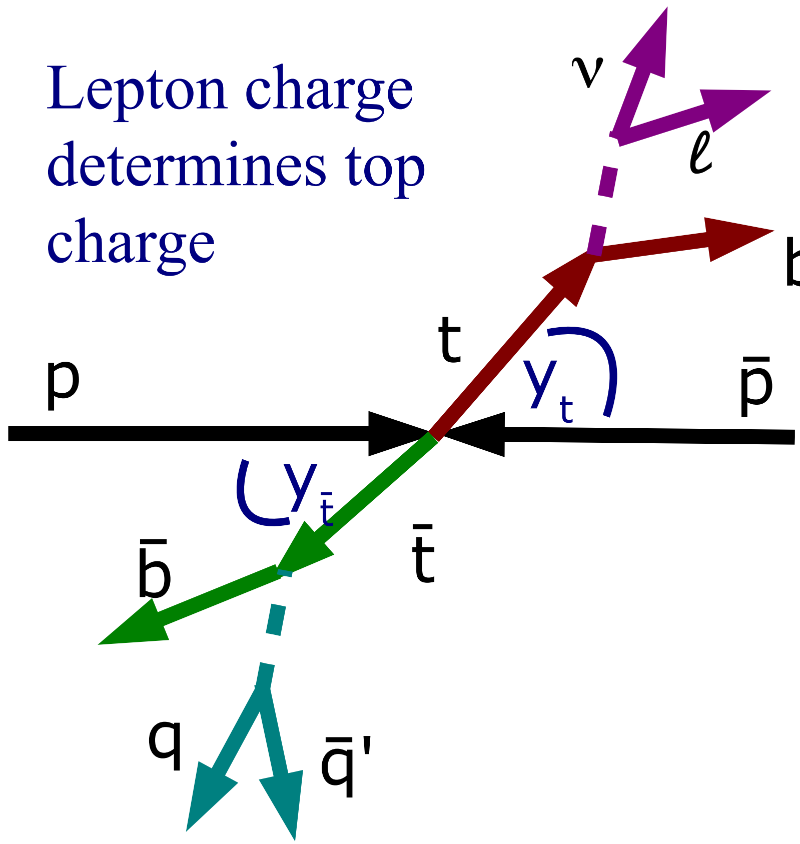
- Asymmetry definition in $t\bar{t}$ rest frame:

$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right) \qquad \Delta y = y_t - y_{\bar{t}}$$

  - Requires reconstruction of $t\bar{t}$ system
    $\rightarrow$ Kinematic fitter

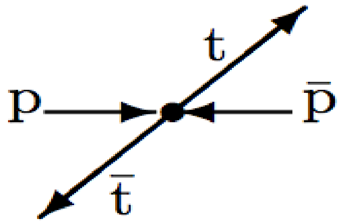
Lepton charge determines top charge

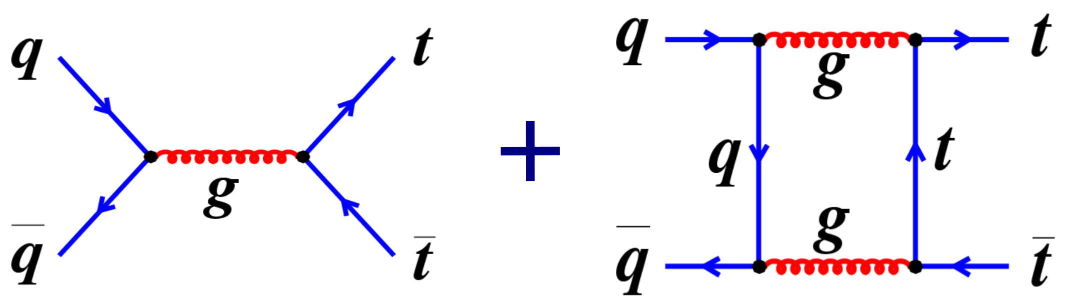


- We have results in l+jets (CDF & DØ) and dilepton (CDF)

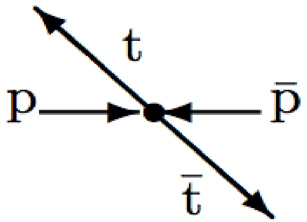
$t\bar{t}$ Forward Backward Asymmetry

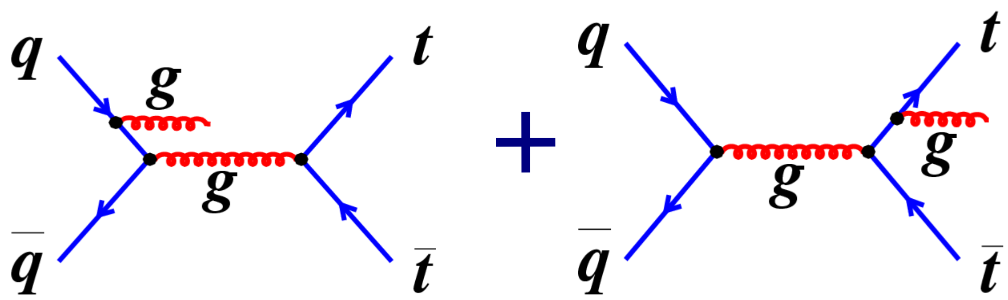
- LO: No charge asymmetry expected
- NLO QCD: Interference between $q\bar{q}$ diagrams
- Tree level and box diagrams:
  - Positive asymmetry





- Initial and final state radiation:
  - Negative asymmetry

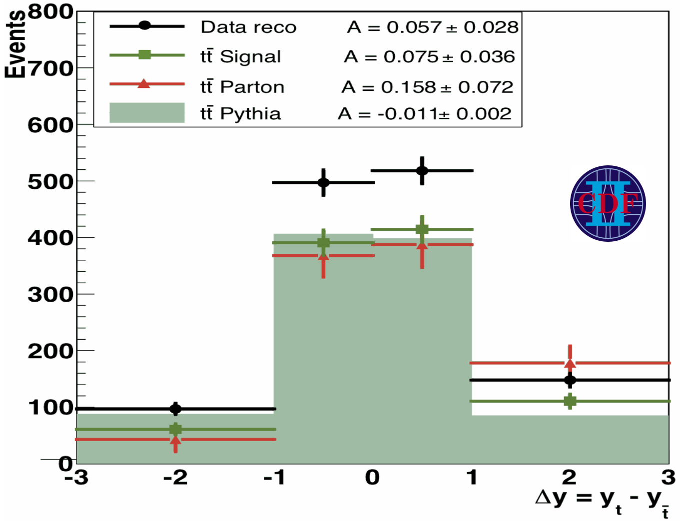


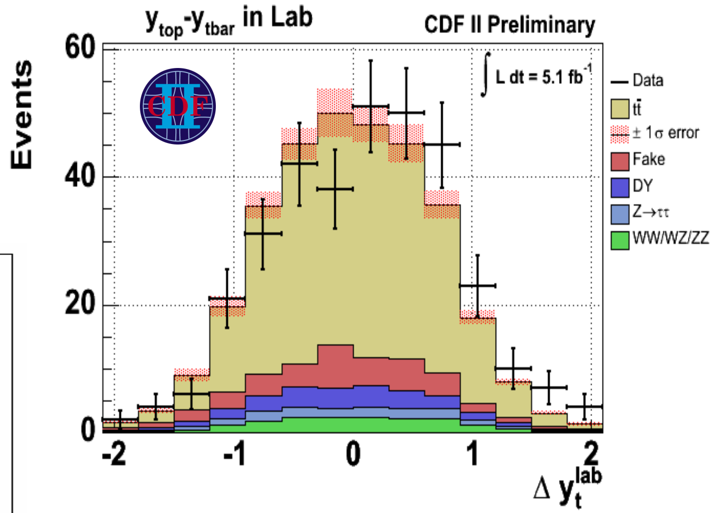


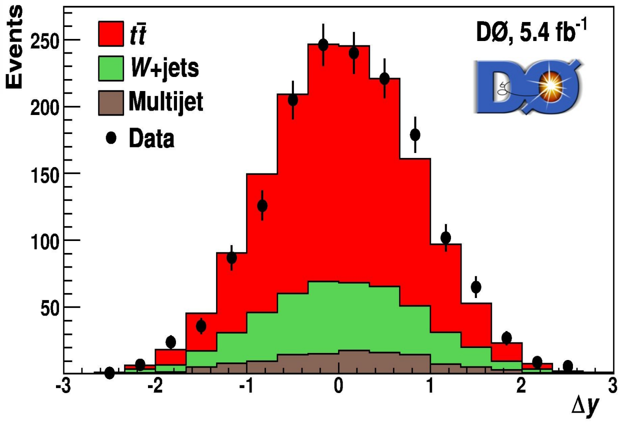
- Sensitive to new physics, e. g. Z' & sensitive to theory modeling

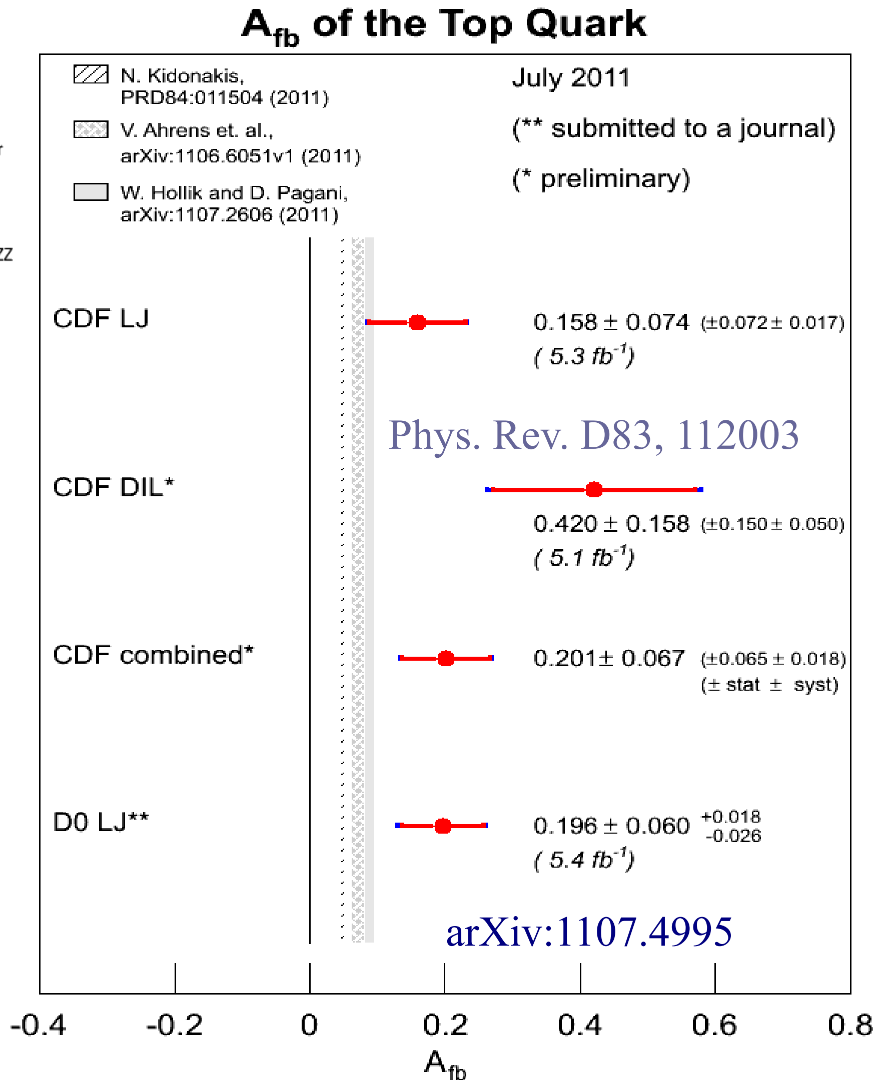
$t\bar{t}$ Forward Backward Asymmetry

- Unfolding via bin-by-bin (CDF) or regularized unfolding (DØ)
- Prediction from MC@NLO MC



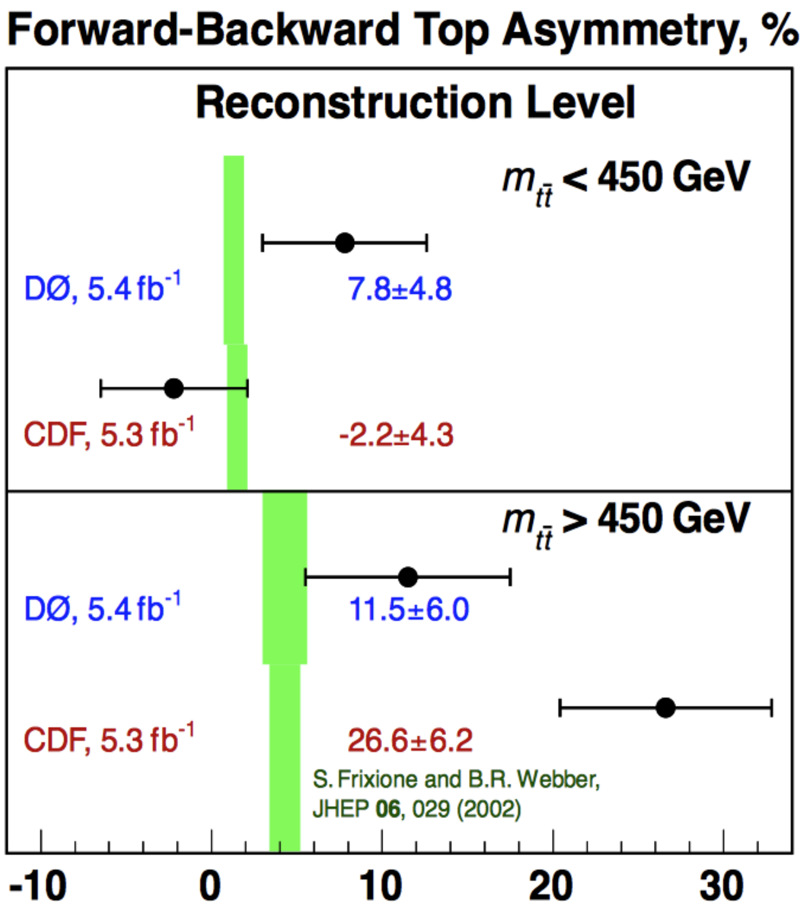




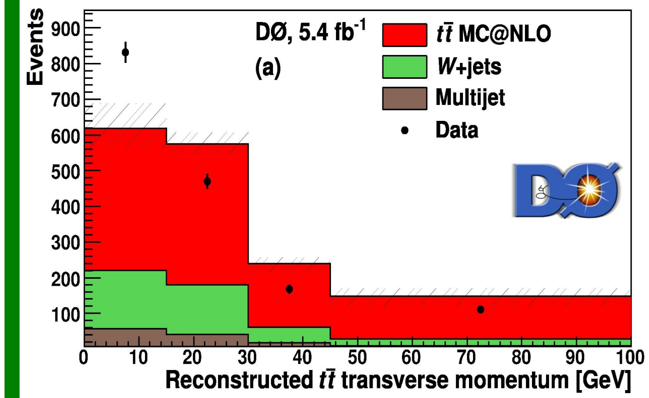


$t\bar{t}$ Forward Backward Asymmetry

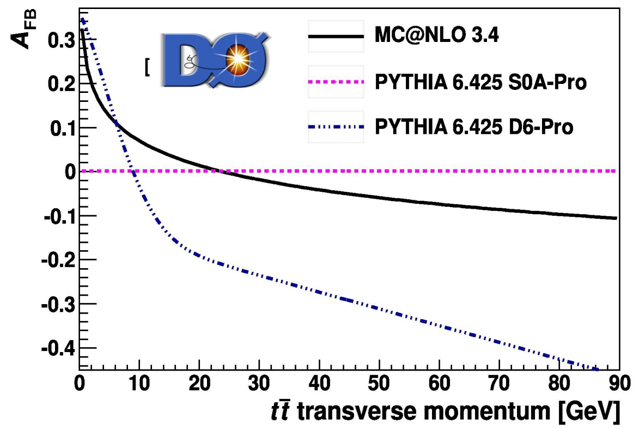
- Asymmetry depends on several variables
- CDF: $m_{t\bar{t}}$ dependency seen



~3σ away from MC@NLO prediction



Prediction sensitive to modeling, e. g. $t\bar{t}$ p_T



Measurement Overview

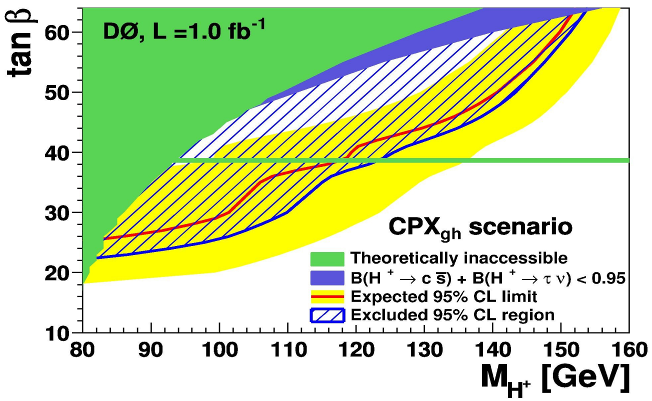
- Other recent results: top charge, color flow, R, width

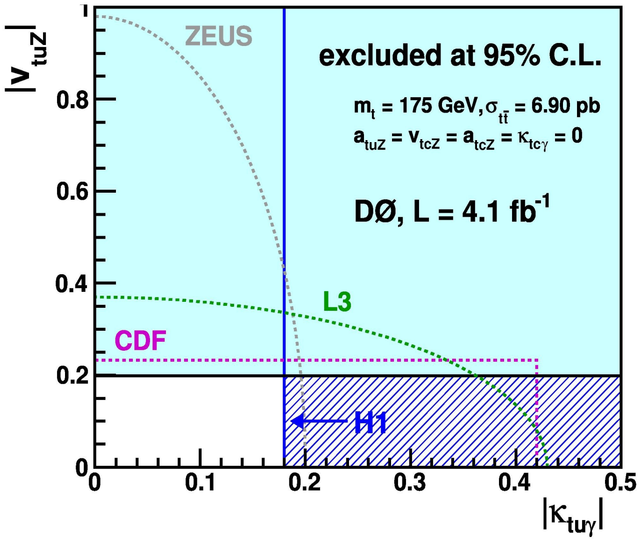
Property	Measurement	SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
	D0: 2.90 ± 0.59 pb		5.4
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
	D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	5.3
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\lvert V_{tb} \rvert$	CDF: $\lvert V_{tb} \rvert = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	3.2
	D0: $\lvert V_{tb} \rvert = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	0.2
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3

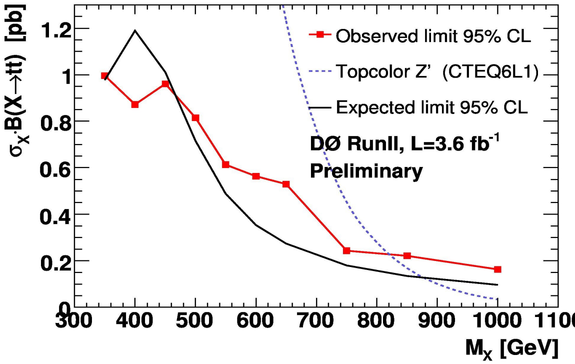
The neglected Part III: Searches in the Top Sector

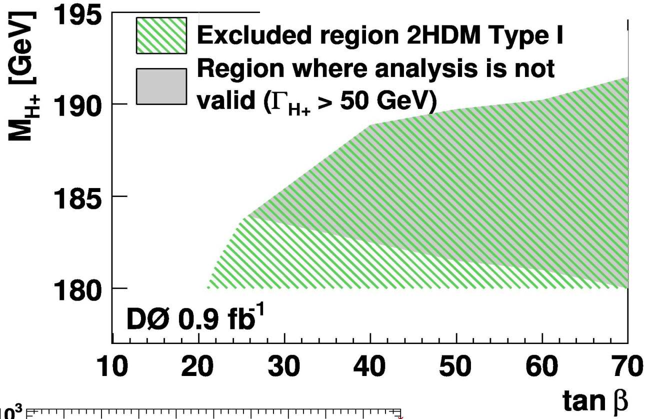
- Many sensitive searches: b', t', Z', W', H^+, FCNC, boosted top, ttH,…

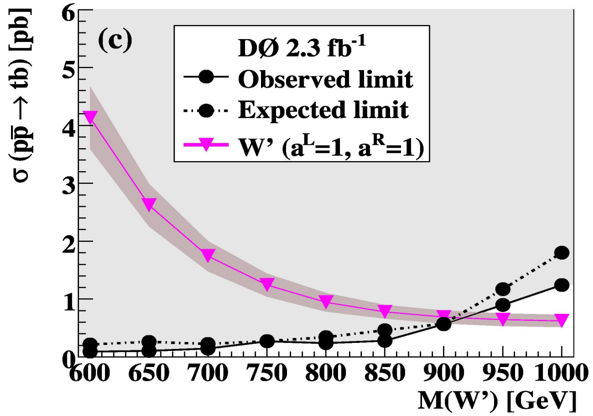
  → some are world's best limits

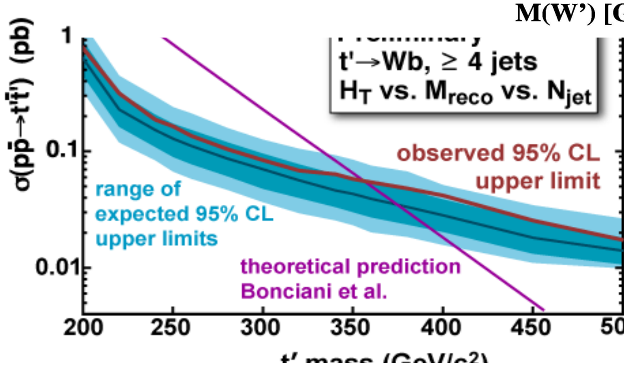


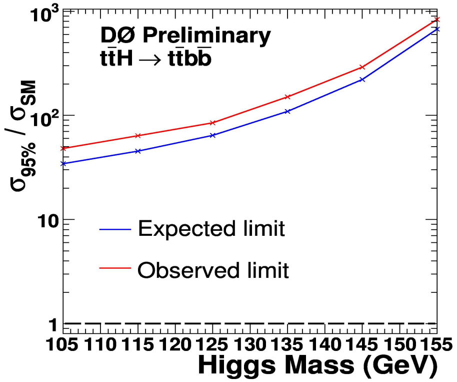


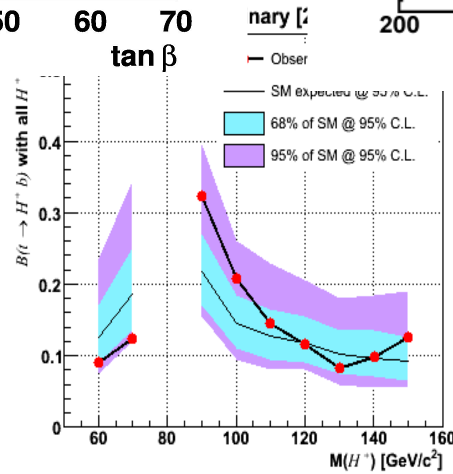


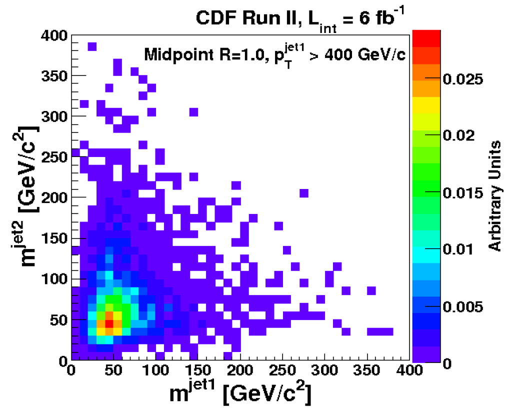












Summary and Outlook

- Rich top quark program at CDF & DØ
  - Precision measurements (cross section, mass)
  - Many new properties analyzed for the first time (e. g. color flow, spin correlation)
  - Sensitive searches, e. g. , t', charged Higgs
  - Many analyses complementary to LHC

- Full beauty of top results:

DØ: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

CDF: http://www-cdf.fnal.gov/physics/new/top/top.html

- Tevatron's legacy still to be written!

→ More to explore in the top sector

Backup

$\sigma_{t\bar{t}}$ in l+jets: Fancy Extensions

- Combined method: combine b-tag and topological information
  - Use topological discriminant in low purity channels

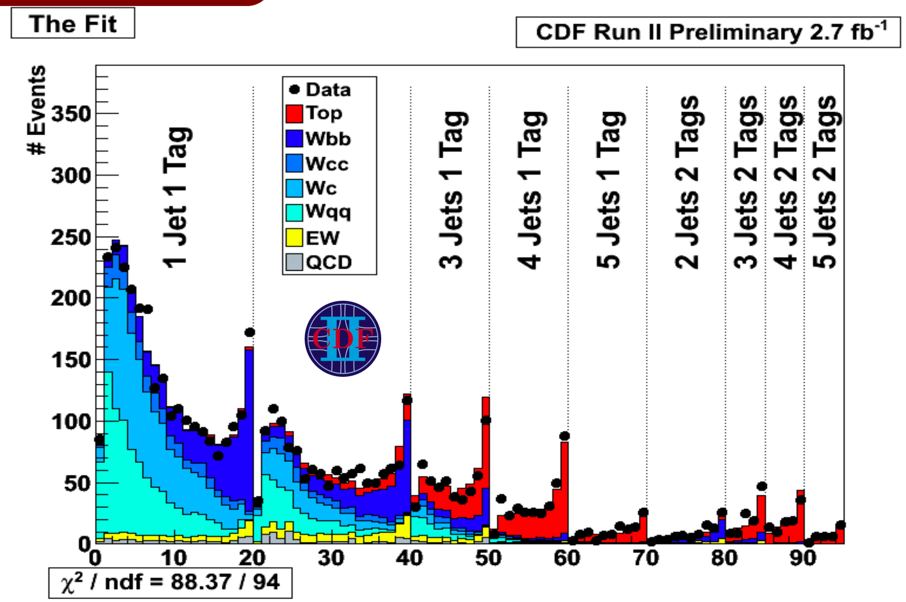
arXiv:1101.0124

$$D0: \quad \sigma = 7.78^{+0.77}_{-0.64}\,(stat + syst)\ pb$$

- Float systematic uncertainties

$$CDF: \quad \sigma = 7.64 \pm 0.57\,(stat + syst) \pm 0.45\,(lumi)\ pb$$

arXiv:1103.4821



- Reduce luminosity error by taking ratio to Z cross section (for b-tag & topological combined)

$$CDF: \quad \sigma = 7.70 \pm 0.52\,(stat + syst + theory)\ pb$$

PRL 105:012001,2010

Anomalous Couplings on Wtb Vertex

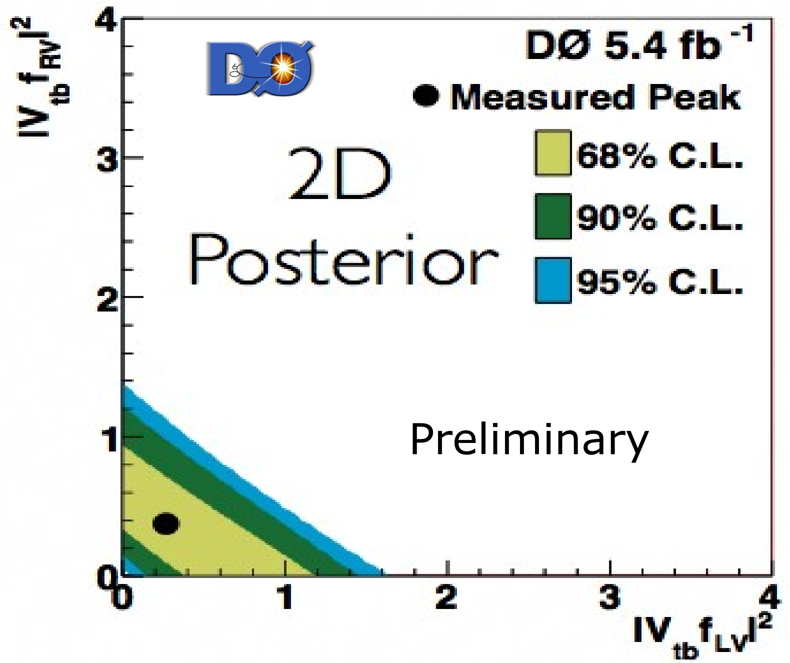
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \text{h.c.}$$

- SM: $V_L=1$; $V_R=g_L=g_R=0$
- Extract constraints on couplings of Wtb vertex

$$|V_R|^2 < 0.93 @ 95\,\%\,CL$$

$$|g_R|^2 < 0.06 @ 95\,\%\,CL$$

$$|g_L|^2 < 0.13 @ 95\,\%\,CL$$



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Other recent Results

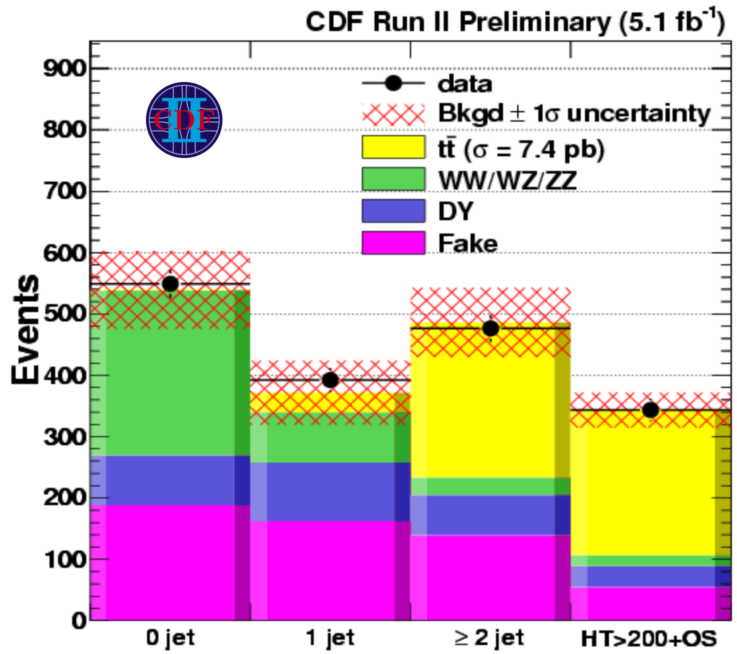
- Top charge: Exotic model with top charge -4/3 e could be possible
  - Use l+jets event; extract top charge from lepton charge & jet charge
  - Exclude exotic model at 95% CL
- Ratio of branching fractions: $R = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$
  - SM: R=1, constrained by CKM unitarity → R<1 could indicate new physics
  - Results: R=0.90±0.04(stat+syst) → $|V_{tb}|$=0.95±0.02(stat+syst)
    → Most precise determination of R to date! PRL 107, 121802
- Color flow: Jets carry color, and are thus color connected to each other
  - Pull variable to distinguish singlet from octet
  - Use it for new physics searches (e. g. ZH)
  - Study color flow in l+jets $t\bar{t}$ events => clean W → jj sample
  - Result for $f_{Singlet} = N_{singlet}/N_{total}$ =0.56±0.38(stat+syst)±0.19(MC stat)

First study of color flow in $t\bar{t}$ events

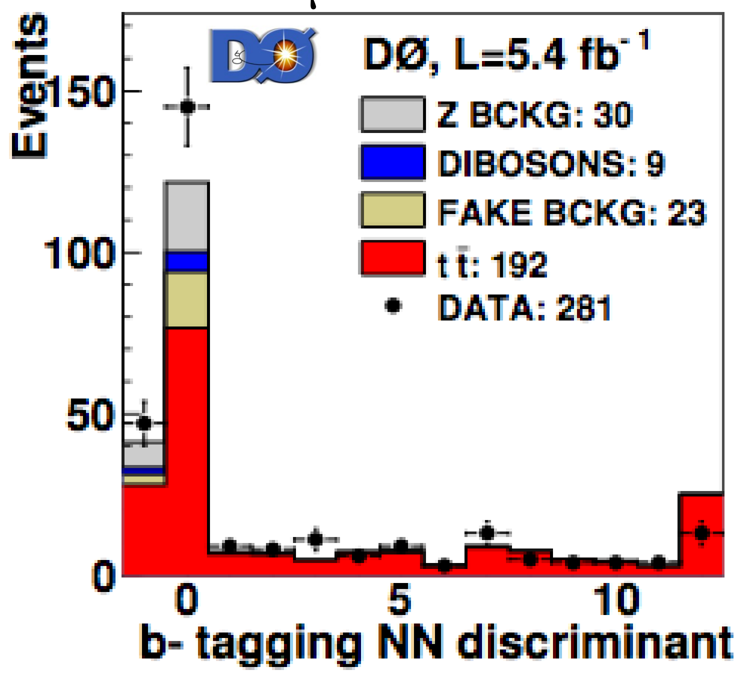
PRD 83, 092002 (2011)

$\sigma_{t\bar{t}}$ in Dilepton

- Very clean channel → use b-jet identification or pure counting
- DØ: Use b-tag NN output as discriminant



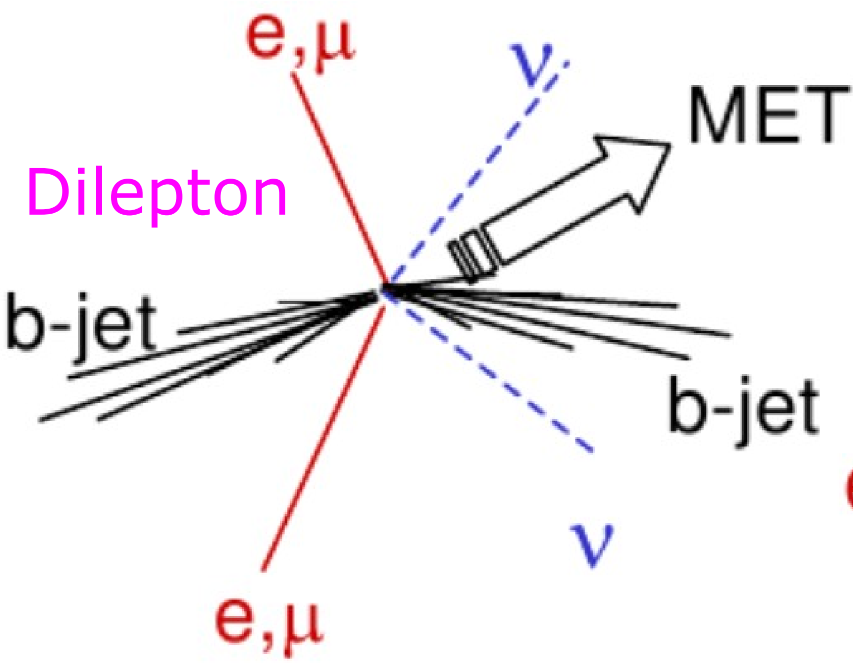
eμ channel



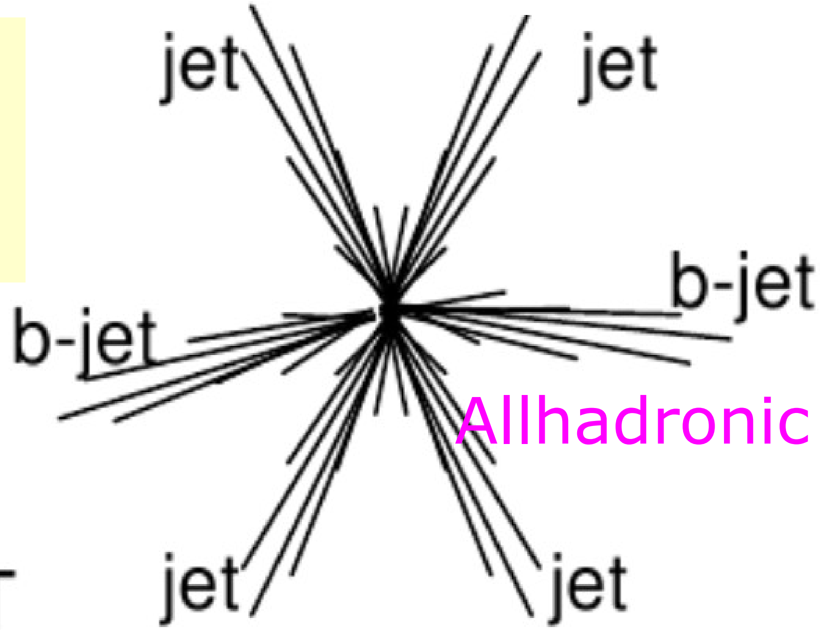
$$D0: \quad \sigma = 7.4^{+0.9}_{-0.8} (stat + syst)\ pb$$

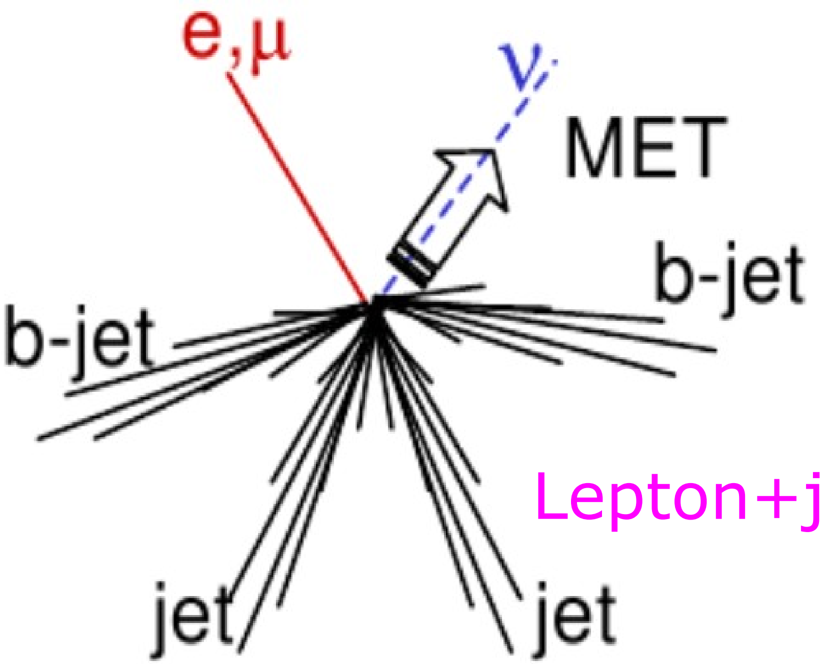
$$CDF: \quad \sigma = 7.25 \pm 0.66 (stat) \pm 0.47 (sys) \pm 0.44 (lumi)\ pb$$

Event selection: Use the signature!



High $\not{E}$ for the neutrino



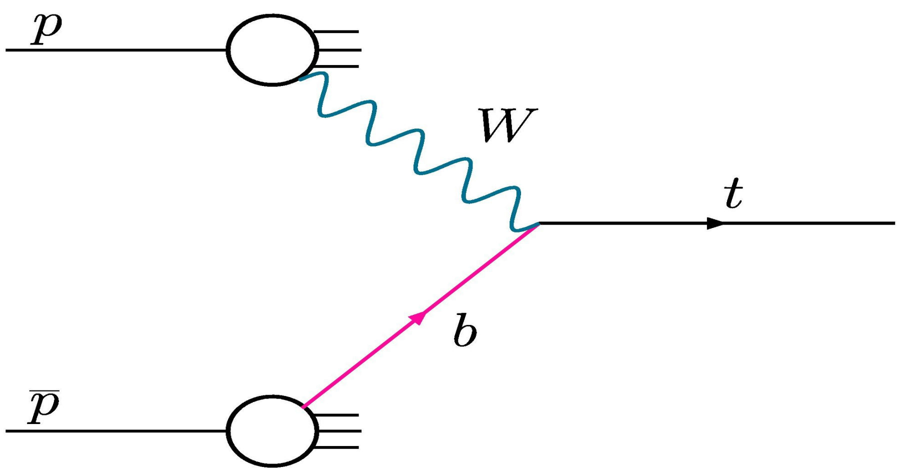


Isolated, high momentum leptons

High momentum (b-)jets

Limit on $|V_{tb'}|$

- Example for new physics affecting the top width
- Use the total width determination to constrain coupling to a fourth generation b' quark, with $m_{b'} > m_t - M_W$
  - Will only affect the production
  - Low probability density of b' in proton & antiproton
  - Assume $|V_{tb}|^2+|V_{tb'}|^2=1$, $|V_{ts}|,|V_{td}|<<1$



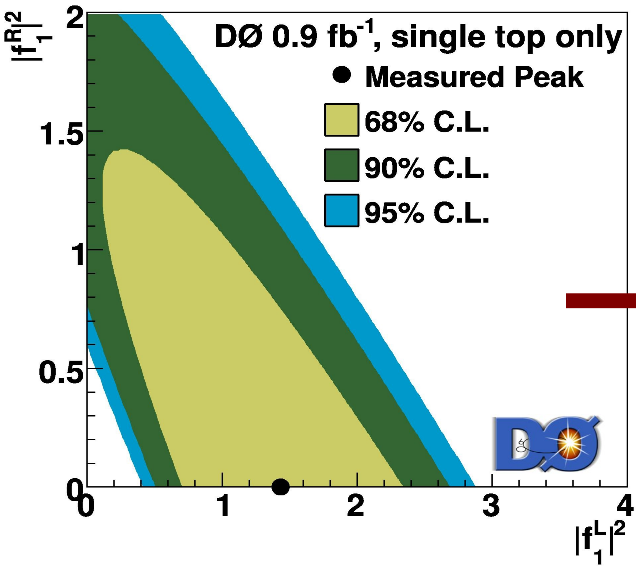
First limit on W boson coupling to top and b' quark

$$|V_{tb'}| < 0.63$$ @ 95% C.L.

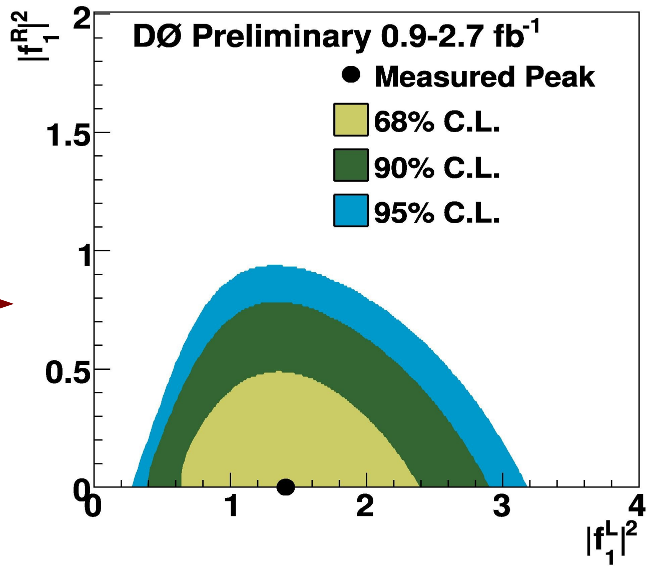
W helicity and anomalous couplings

- Form factors f_1^L, f_1^R, f_2^L, f_2^R: Can be extracted in single top channel
- Single top and W helicity measurement:
  - Usage of all applicable top quark measurements

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



Single top alone



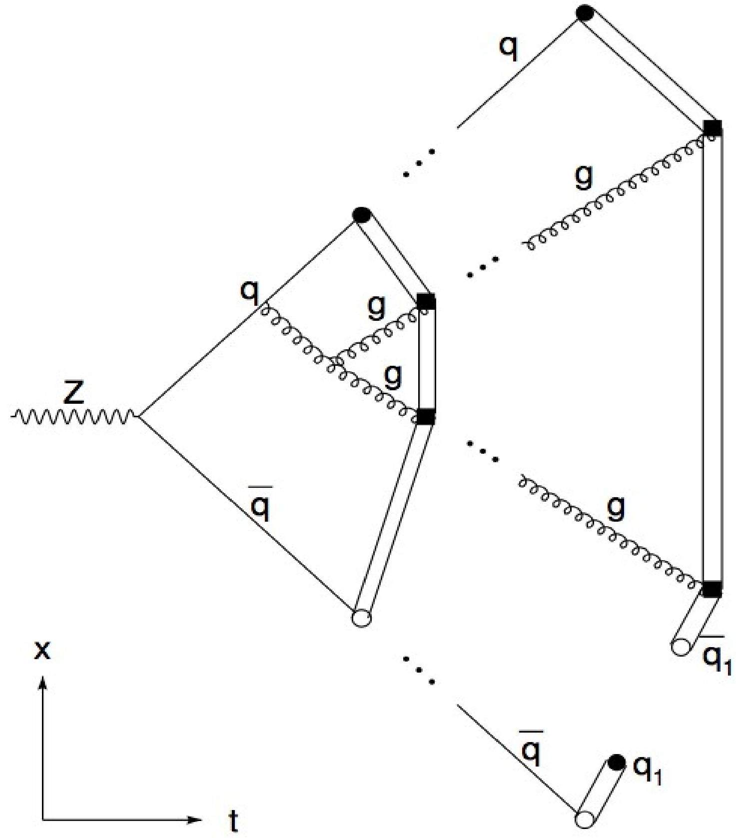
Single top and W helicity

W helicity: Systematics

Source	Uncertainty (f_+)	Uncertainty (f_0)
Jet energy scale	0.007	0.009
Jet energy resolution	0.004	0.009
Jet ID	0.004	0.004
Top quark mass	0.011	0.009
Template statistics	0.012	0.023
$t\bar{t}$ model	0.022	0.033
Background model	0.006	0.017
Heavy flavor fraction	0.011	0.026
b fragmentation	0.000	0.001
PDF	0.000	0.000
Analysis consistency	0.004	0.006
Muon ID	0.003	0.021
Muon trigger	0.004	0.020
Total	0.032	0.060

String Fragmentation Model

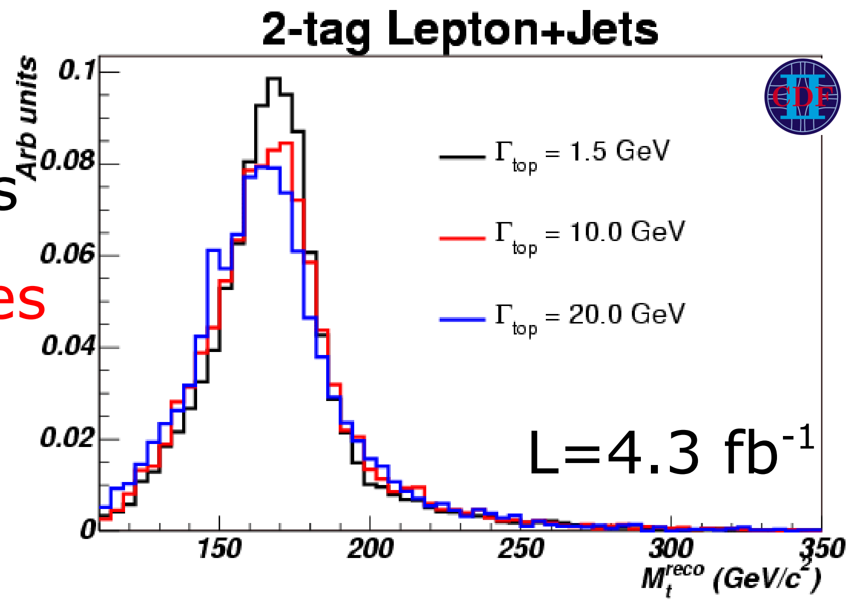
- Color string building up between the color connected particles
- Color string has constant energy density (1GeV/fm)
- When quark-antiquark pair separates, potential energy in string increases
  - New $q\bar{q}$ pair can be built out of the vacuum once energy is large enough
  - Arise along the lines of color string!
- Alternative hadronization models exist, all having the idea of color connection in common



Top Quark Width

- Top lifetime ~5x10^{-25}s
  => Top quark decay width is 1.4 GeV
- Top width determination using l+jets events
- Direct: Reconstruct top mass → fit templates

0.3<Γ<4.4 GeV @68% CL
Γ<7.6 GeV @95% CL



PRL 105 232003

- Indirect: Extract partial and total width from combination of R measurement and t-channel cross section
  - Partial width from t-channel cross section

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)}$$

$$\Gamma_t = 1.99^{+0.69}_{-0.55}\, GeV$$

$$\tau_t = \frac{1}{\Gamma_t} = (3.3^{+1.3}_{-0.9}) \times 10^{-25}\, s$$

Most precise determination of top width!

PRL 106, 022001 (2011)

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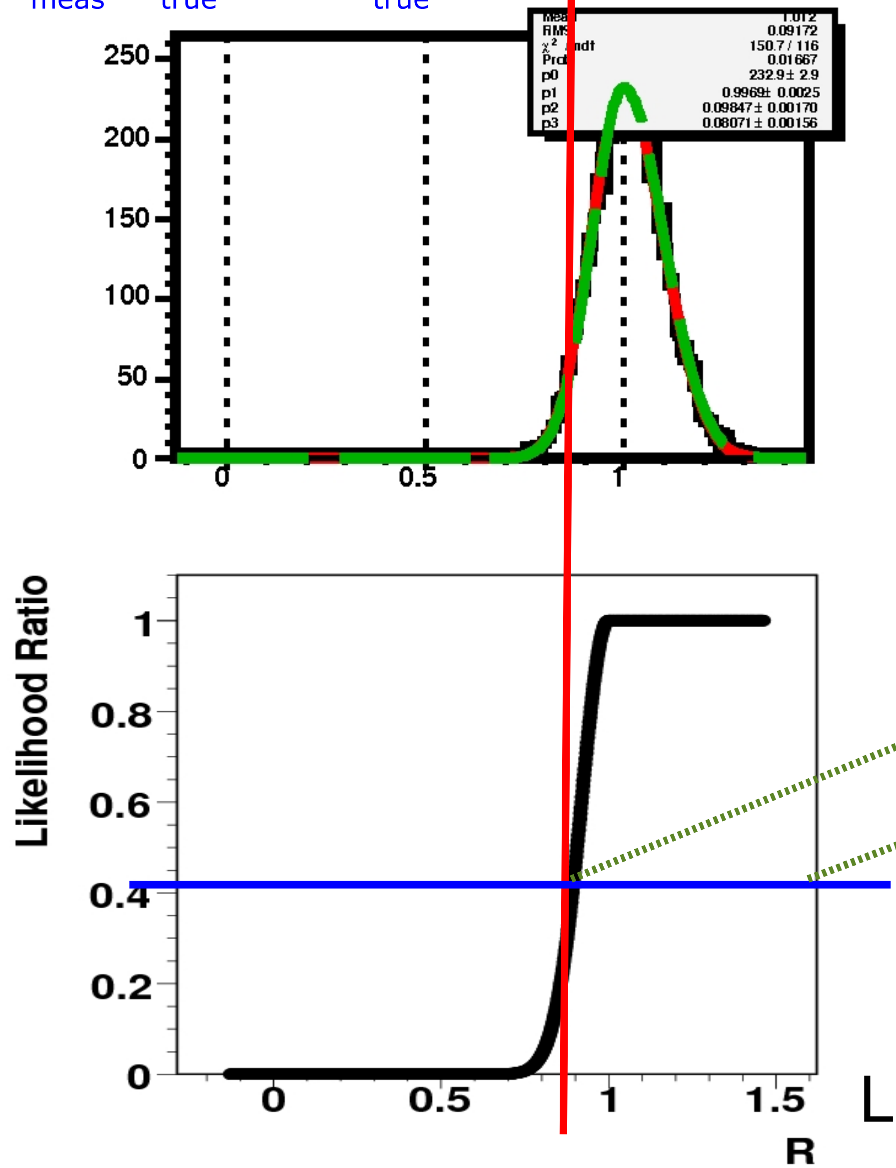
Feldman & Cousins Limits

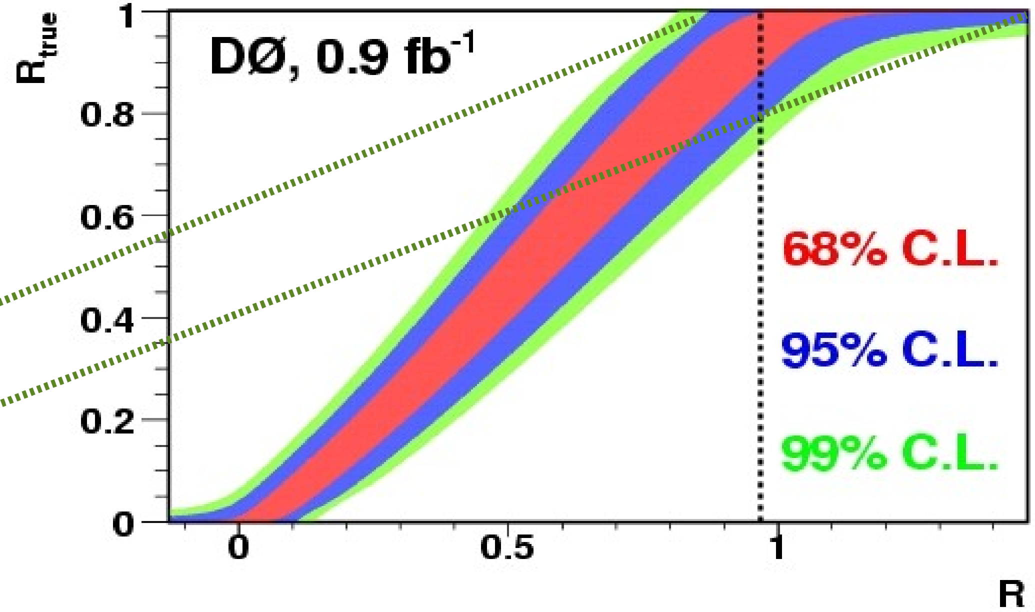
- Feldman & Cousins method for calculation of limits:
  - Pseudo-experiments for various true R (R_{true})
    - Number of events is chosen randomly within a Poisson distribution
    - All systematic uncertainties are varied randomly within a Gaussian distribution
  - For each true R one obtains a distribution of measured values R_{meas}: normalized distributions are $P(R_{meas}|R_{true})$
  - Application of the "likelihood ratio ordering":
    - calculation of $$r_{likeli}(R_{meas}) = \frac{P(R_{meas} \backslash R_{true})}{P(R_{meas} \backslash R_{best})}$$
    - R_{best}: R_{true} for which $P(R_{meas}|R_{true})$ is maximal
      - has to be within the physically allowed region

Feldman & Cousins Limits

$P(R_{meas}|R_{true})$ for $R_{true}=1$



Variation of the blue line until the area of $P(R_{meas}|R_{true})$ is 95% within the interactions points with r_{likeli} (red line) is 95%



Likelihood ratio for $R_{true}=1$

Color Flow: Toy MC

- Toy MC study of calorimeter effects:
  - Granularity: 0.1x0.1 in e x p towers
- Calorimeter noise floor per cell: 150MeV
  - 500MeV threshold for hadron
- Charged particles with <75MeV are ignored due to being bent by magnetic field
- Energy resolution: MC tower is smeared with 50%/sqrt(E[GeV])
  - Resolution in hadronic calorimeter
- Noise/pile-up: Each MC tower has a chance of 7% to have added noise to it
  - p_T: Exponential distribution around mean 360MeV

Some props: Jet Energy Scale