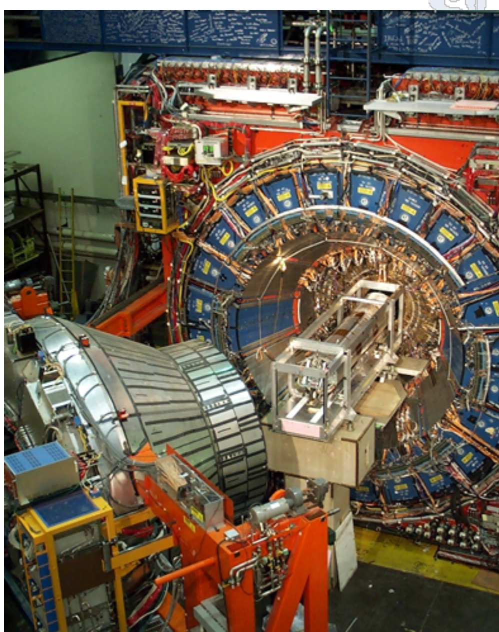
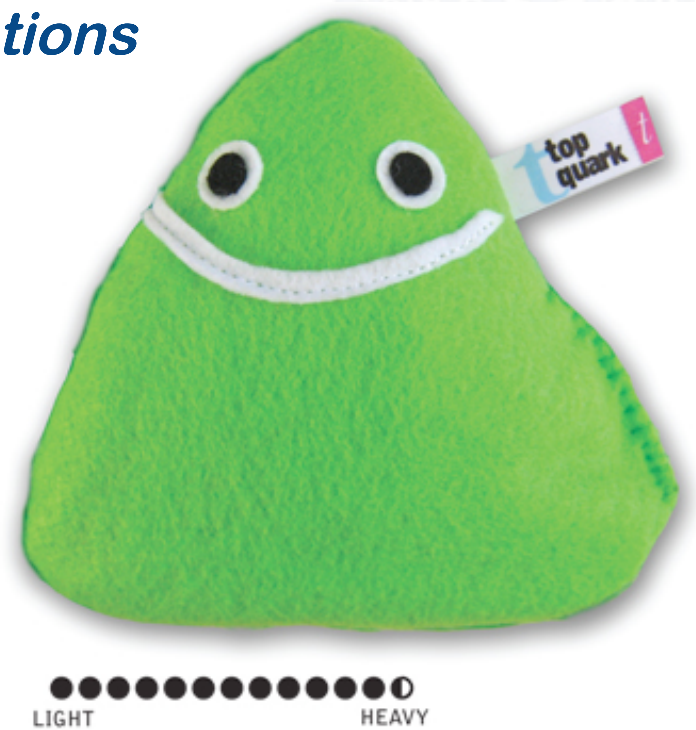
Top Properties at the Tevatron

Oleg Brandt on behalf of the CDF and DØ collaborations
II. Physikalisches Institut, Georg-August-Universität Göttingen



What makes top so interesting?

- Compelling arguments that new physics can show up in the top sector:
  - Top is the heaviest quark discovered so far
  - Its Yukawa coupling is 0.996±0.006
    - Special role in EWSB?
  - Since 17 years, our measurements have been *consistent with SM predictions* in the top sector *within uncertainties*
  - D0 and CDF collected thousands of $t\bar{t}$ events, enabling precise studies of top properties
    - There are recent measurements displaying tension between Tevatron data and the SM predictions (A_{FB}, R-ratio)



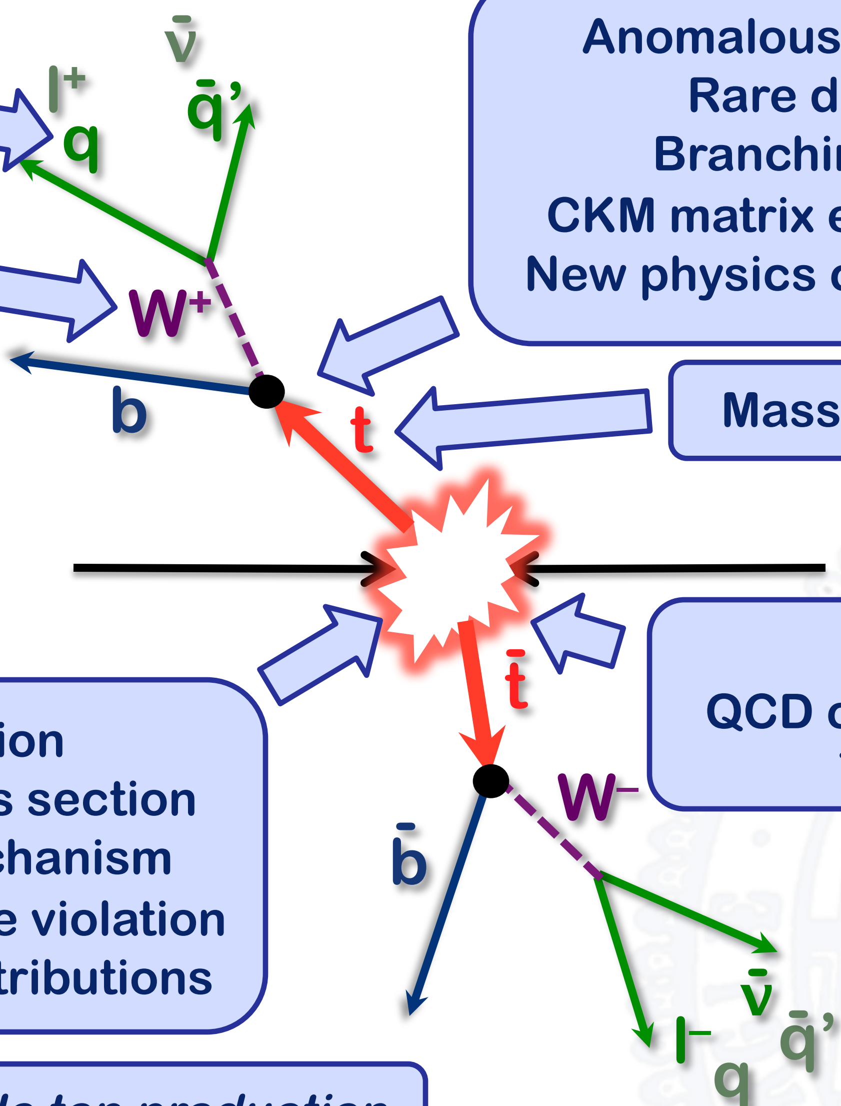
A wealth of top properties

Color flow

W helicity

Anomalous couplings
Rare decays
Branching ratio
CKM matrix element $|V_{tb}|$
New physics contributions

Mass, charge, width



Spin correlation
QCD charge asymmetry A_{FB}
Top polarisation

Cross section
Differential cross section
Production mechanism
Lorentz invariance violation
New physics contributions

+ electroweak single top production

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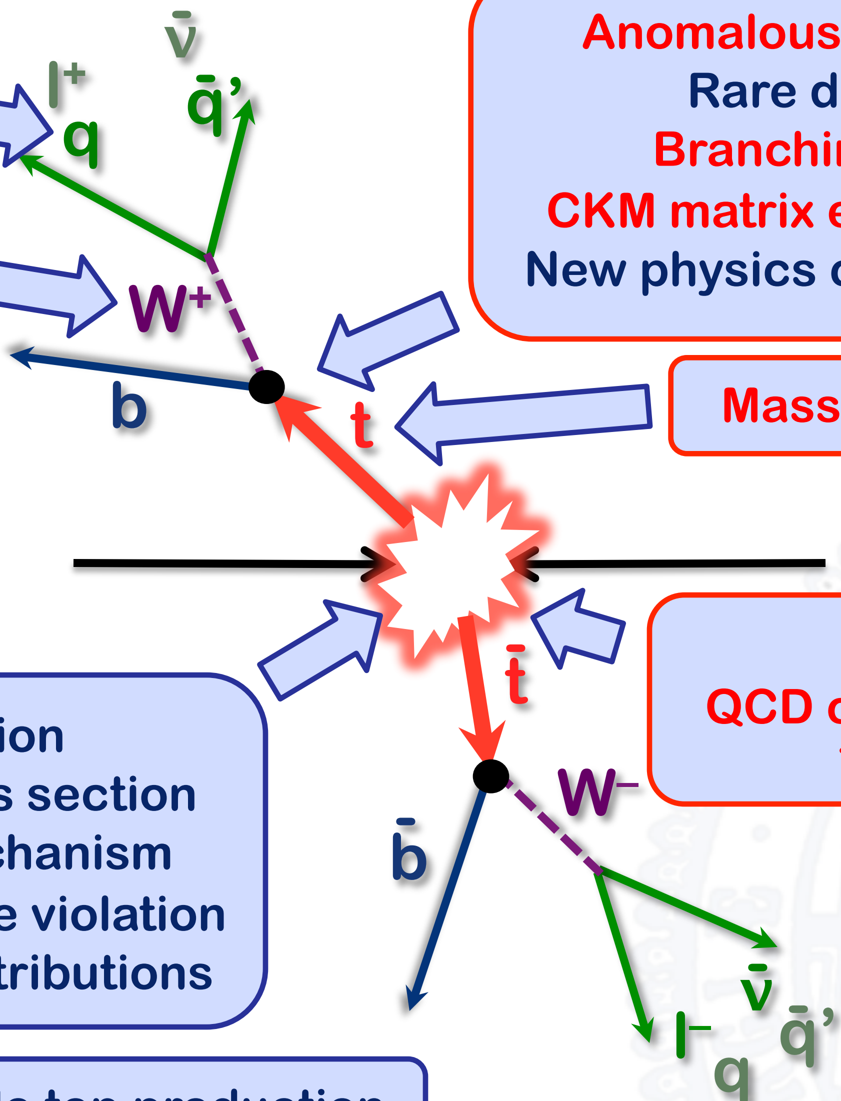

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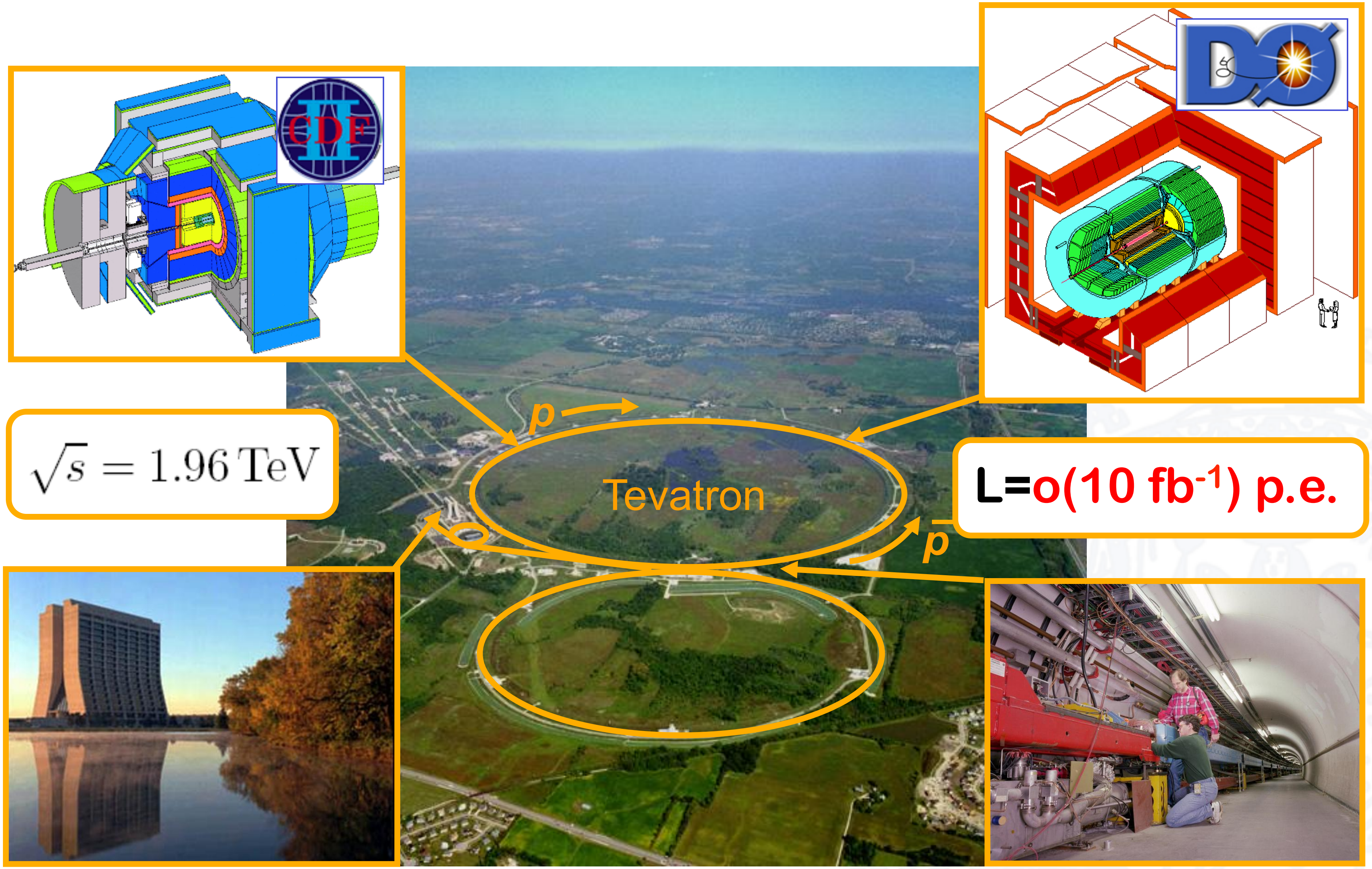
← *cf. talk Yun-Tse Tsai*

More about the top birth place…



$$\sqrt{s} = 1.96\,\mathrm{TeV}$$

L=o(10 fb^{-1}) p.e.

Initial state @ Tevatron (and LHC)

- **Initial state for top-antitop pair-production rather different between Tevatron and LHC:**

Tevatron	LHC
$p\bar{p}$ initial state → *CP* eigenstate	pp initial state
centre-of-mass energy: 1.96 TeV	centre-of-mass energy: 7 (8) TeV
Initial state: qq (~85%), gg (~15%)	Initial state: qq (~25%), gg (~75%)

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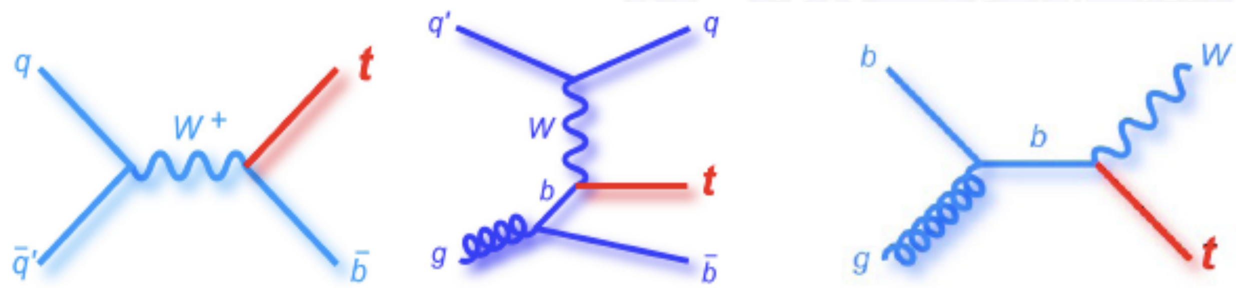
- **Dramatic differences for single top production:**



Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.04 pb	2.26 pb	0.28 pb
LHC: pp (7 TeV)	4.6 pb	64.6 pb	15.7 pb

Top mass in ll final states

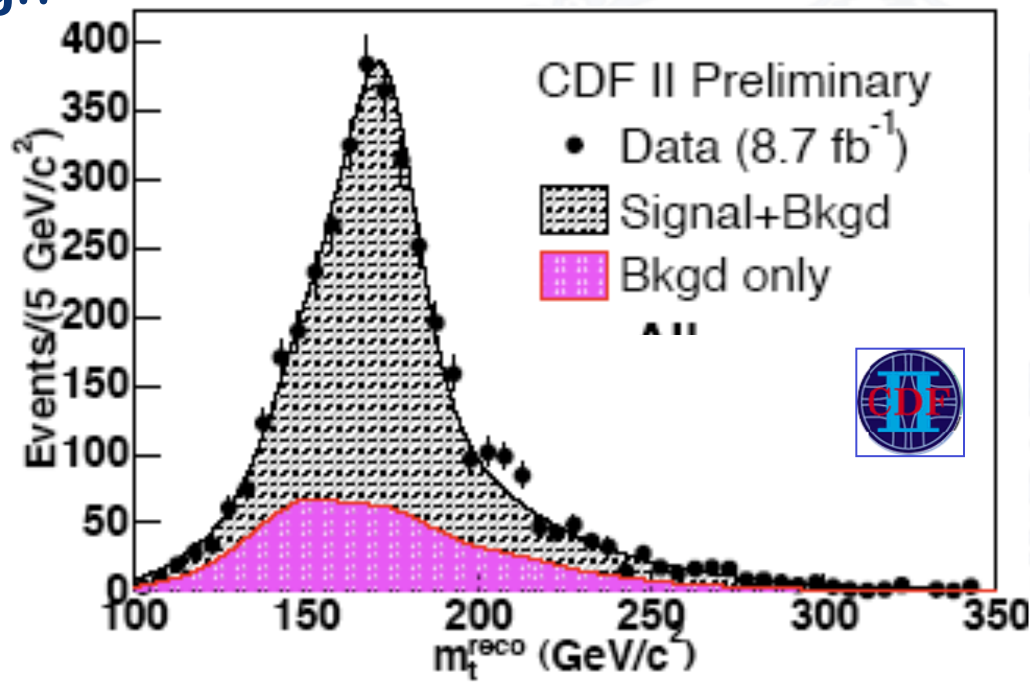
- **Top mass in dilepton final states with, D0 (5.4 fb^{-1})**
  - **Dilepton final states provide a clean signature**
    - Measure m_{top} in this clean experimental environment
    - Transfer the in-situ JES calibration from l+jets channel
      - Properly account for event topology, run period dependence, etc.
  - Extract m_{top} using:
    - Neutrino-weighting technique
    - Matrix Element technique
  - Properly combine the two methods (60% statistical correlation) to maximise statistical sensitivity!
  - Final result:

$$m_t = 173.9 \pm 1.9\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})\ \mathrm{GeV}$$

Most precise m_{top} measurement in ll final states @ Tevatron!

Phys. Rev. D ***86****, 051103(R) (2012)*

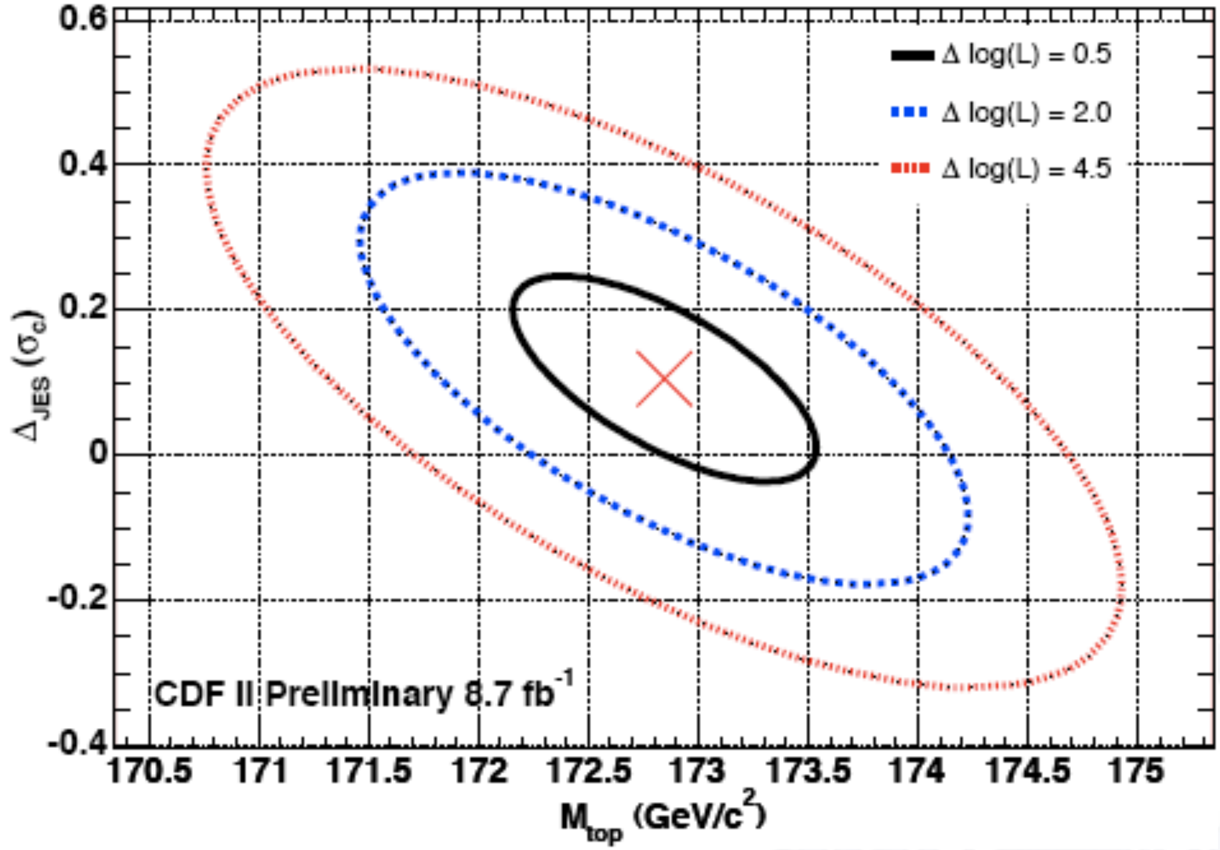
- **Template method in lepton+jets final states, CDF (8.7 fb^{-1})**
  - Reconstruct the event kinematics by minimising a χ^2-like quantity depending on e.g.:
    - matching between reconstructed and fitted momenta
    - *W* mass constraint for in-situ JES extraction
    - top quark mass constraint for m_{top} extraction
  - Consider jet-parton assignments consistent with b-tagging
  - **Form templates from:**
    - m_t^{reco} : best jet-parton assignment
    - $m_t^{reco(2)}$: second-best assignment
    - m_{jj}



Phys. Rev. Lett. ***109***, *152003 (2012)*

m_{top} with templates in l+jets

- **Final result:**

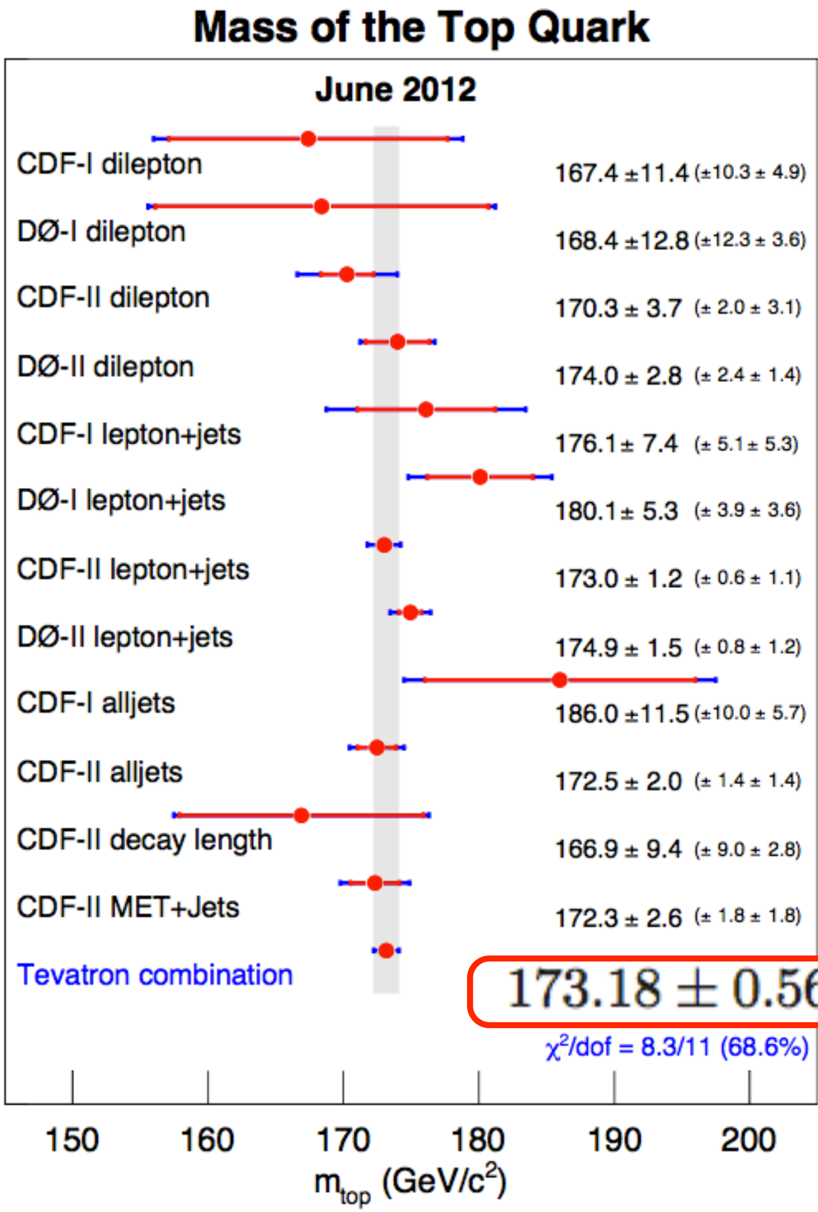


$$M_{top} = 172.85 \pm 0.71\ (\text{stat.}) \pm 0.84\ (\text{syst.})\ \text{GeV}$$

Most precise m_{top} measurement @ Tevatron

Phys. Rev. Lett. ***109****, 152003 (2012)*

Phys. Rev. D ***86***, *092003 (2012)*



$$173.18 \pm 0.56\,(\mathrm{stat}) \pm 0.75\,(\mathrm{syst})$$

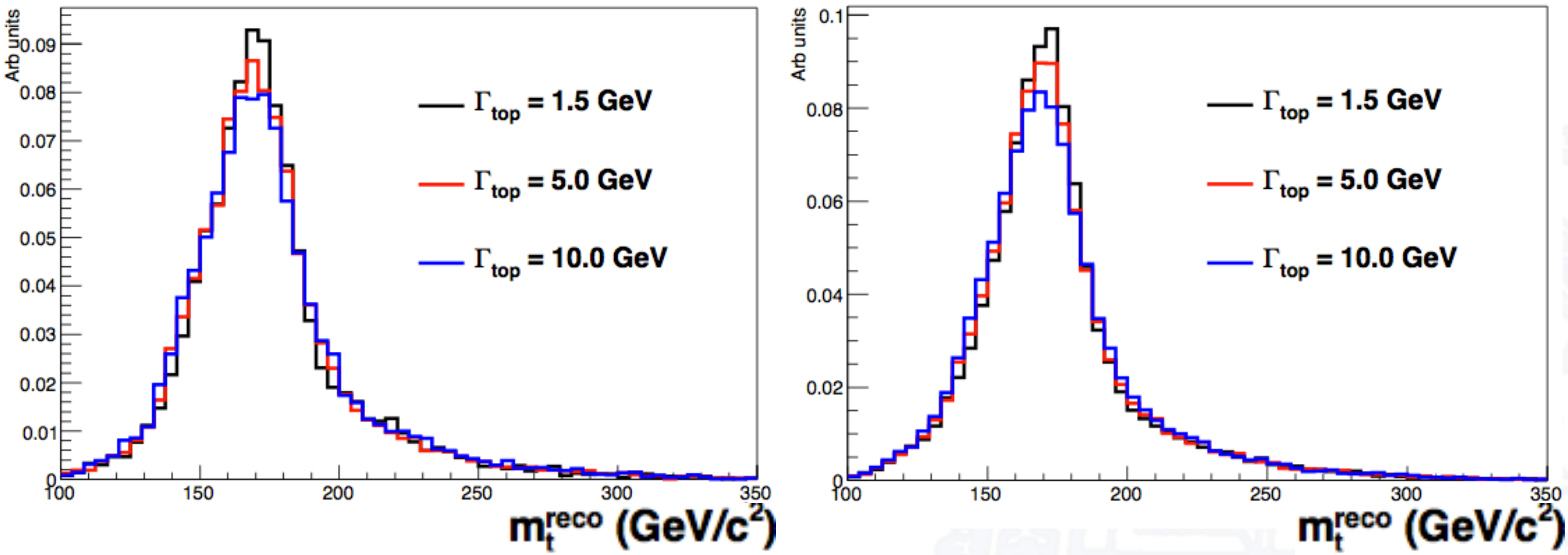
Dominant uncertainties:

- **In-situ JES calibration:**
  - **0.39 GeV, ~ 1/√N**
- **Residual JES calibration:**
  - **0.19 GeV, ~ 1/√N**
- **b quark jets energy scale:**
  - **0.12 GeV, ~ √brain effort**
- **Signal modeling:**
  - **0.51 GeV, ~ √brain effort**

World's **most precise m_{top} measurement!**

Relative uncertainty: 0.54%

- **Direct measurement of Γ_{top}, CDF (8.7 fb^{-1}):**
  - **Ansatz:**
    - **reconstructed distribution in m_{top} is sensitive to Γ_{top}:**

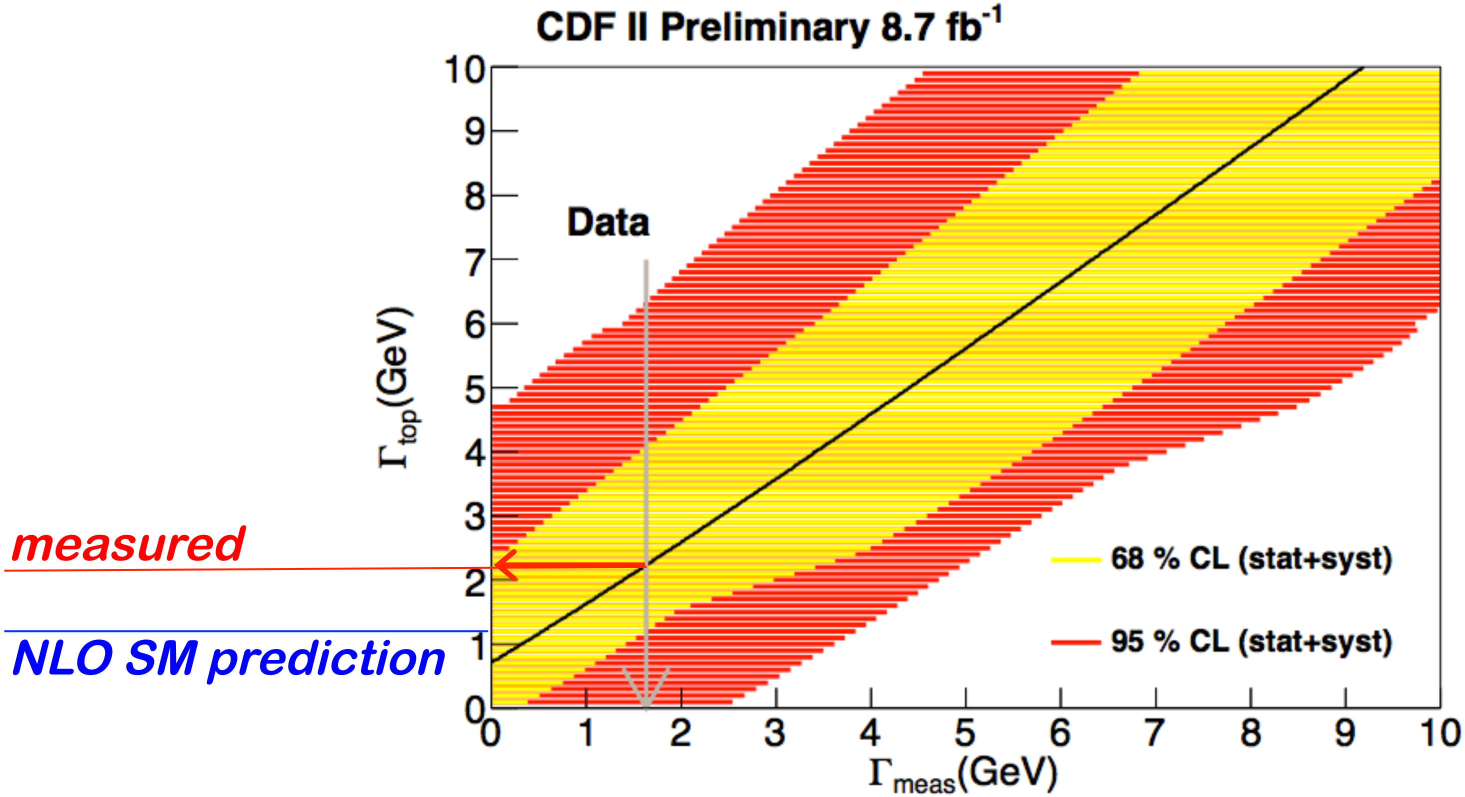


  - **Use same χ^2-based reconstruction as for m_{top}**

CDF Note 10936

Direct measurement of Γ_{top}

- **Final result:**



$$\Gamma_{top} = 2.21^{+1.46}_{-0.92}(\text{stat})^{+1.12}_{-0.62}(\text{syst})\,\text{GeV}$$

The only direct measurement of Γ_{top} to date

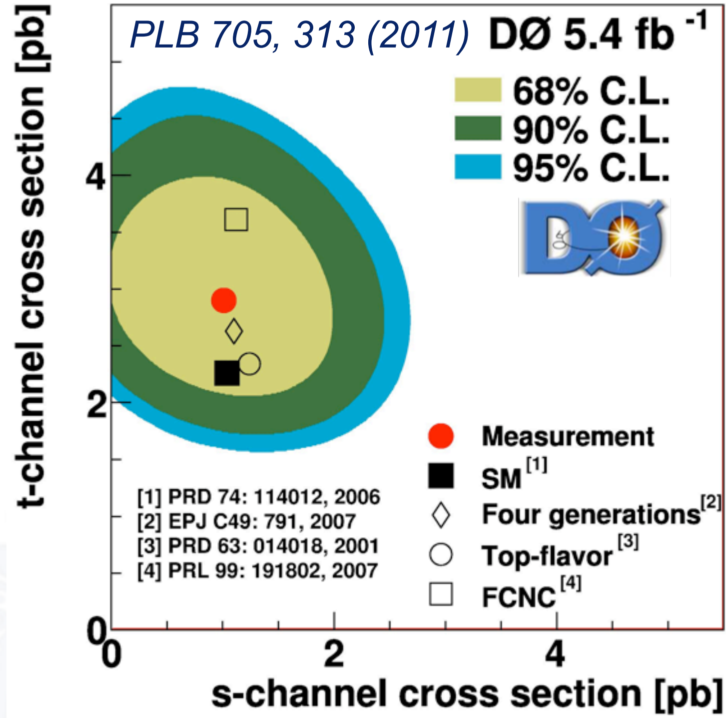
CDF Note 10936

Indirect measurement of Γ_{top}

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)} \longleftarrow \Gamma(t \to Wb) = \sigma(t\text{-channel}) \frac{\Gamma(t \to Wb)_{SM}}{\sigma(t\text{-channel})_{SM}}$$

Assume:

Wtb coupling identical in production & decay



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$\mathcal{B}(t \to Wb)$ ⟵ measured in $t\bar{t}$ events

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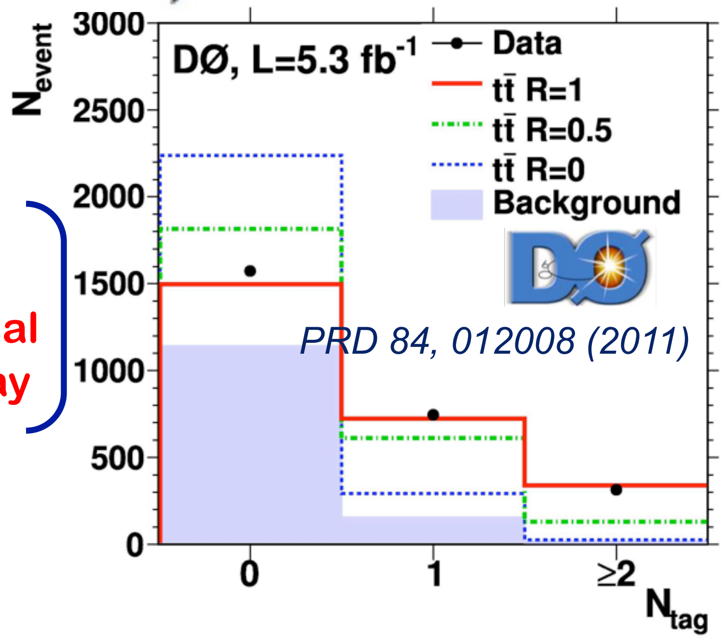

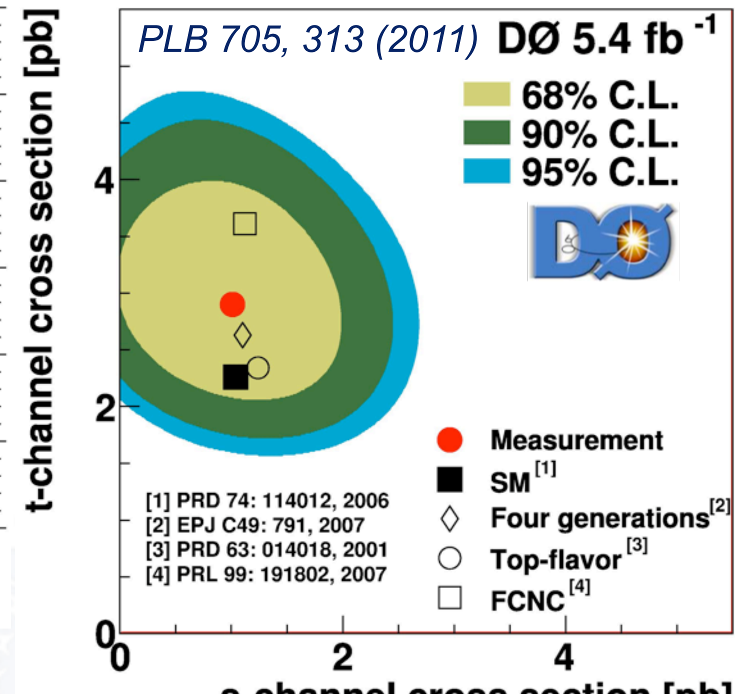

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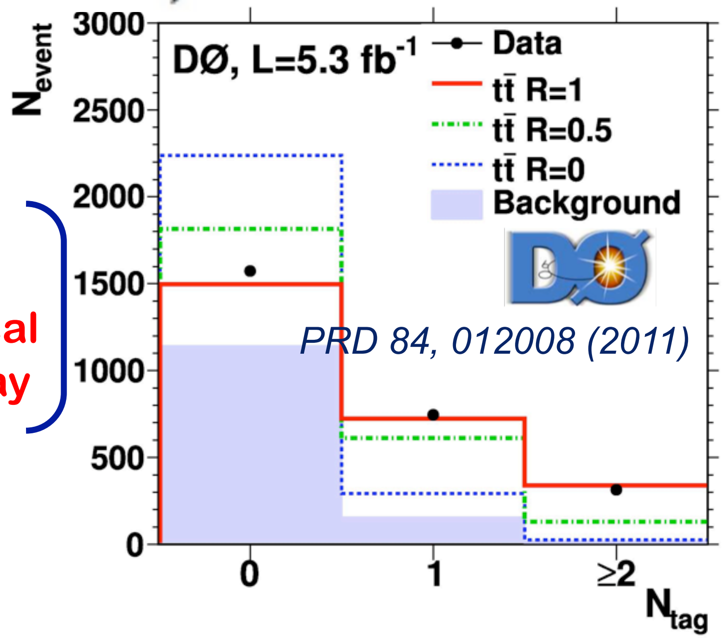

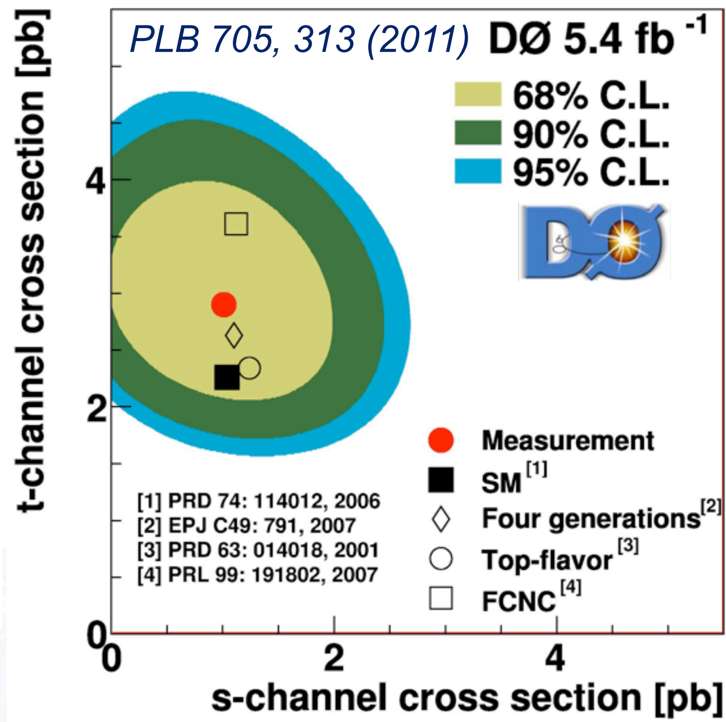

Properly correlate $\sigma(t\text{−channel})$, $\mathcal{B}(t \to Wb)$ → measure Γ_t from LH based on *t*-channel discriminant

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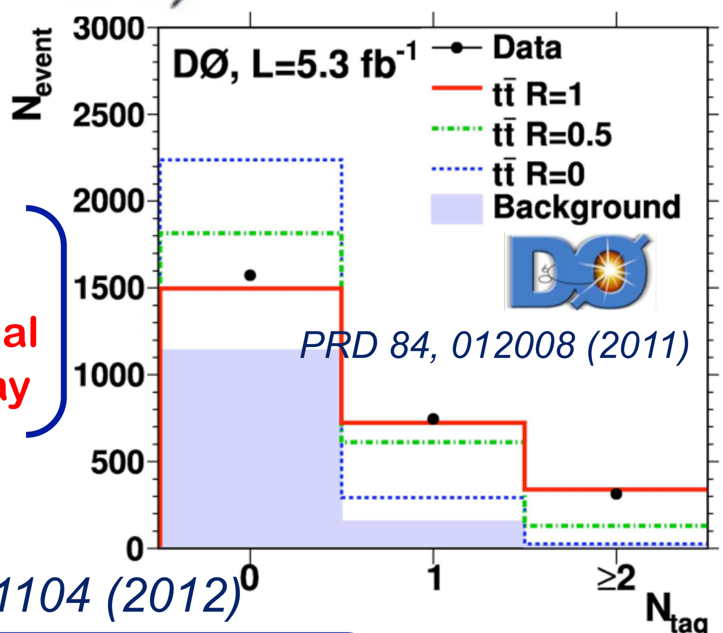
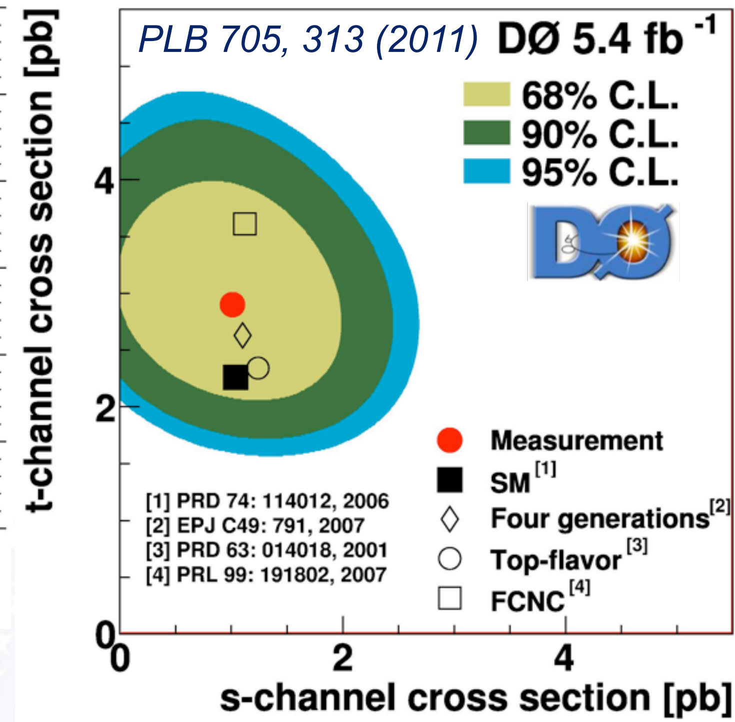


Phys. Rev. D **85**, 091104 (2012)



World's most precise (indirect) determination of Γ_t to date

$$\Gamma_t = 2.00^{+0.47}_{-0.43}\ \text{GeV}$$

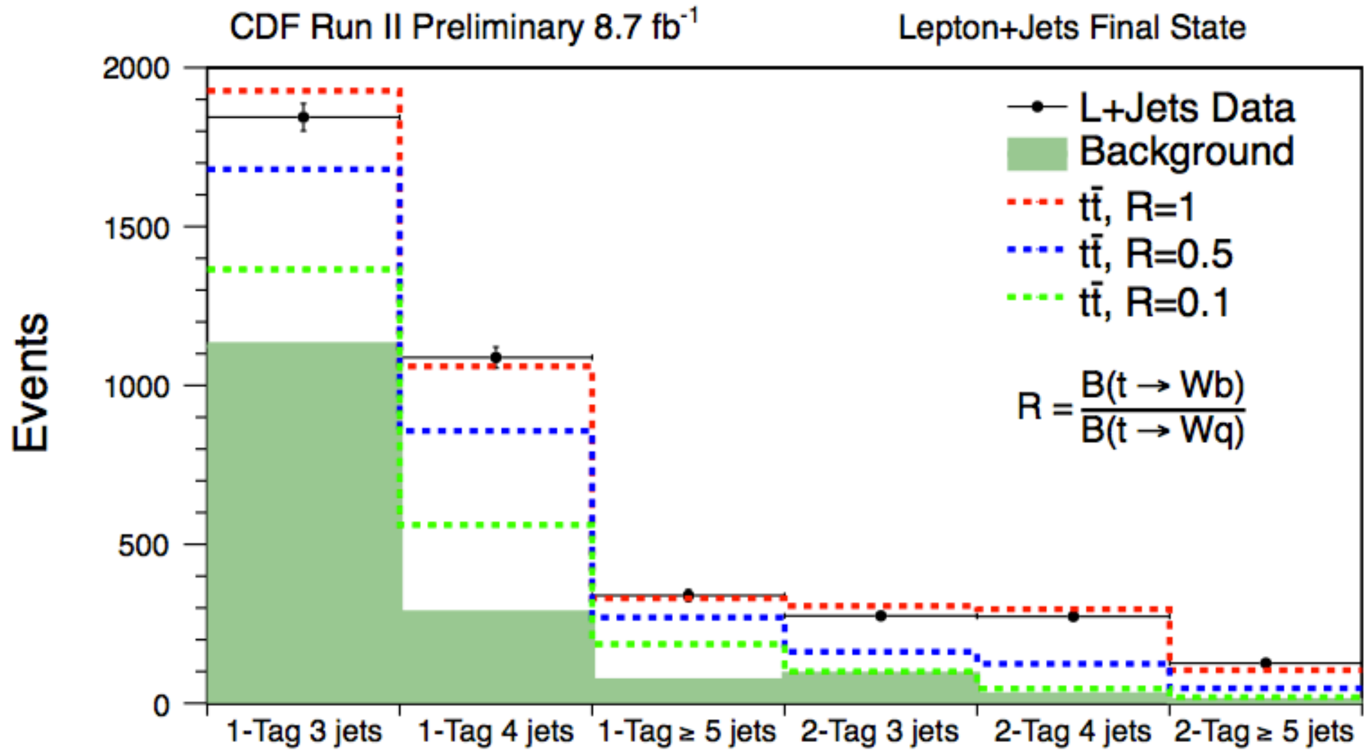
$$\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}\ \text{s}$$

Properly correlate $\sigma(t\text{−channel})$, $\mathcal{B}(t \to Wb)$ → measure Γ_t from LH based on *t*-channel discriminant

- **Measurement of *R*-Ratio in l+jets, CDF (8.7fb^{-1})**
  - **Defintion *R*-Ratio:**

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

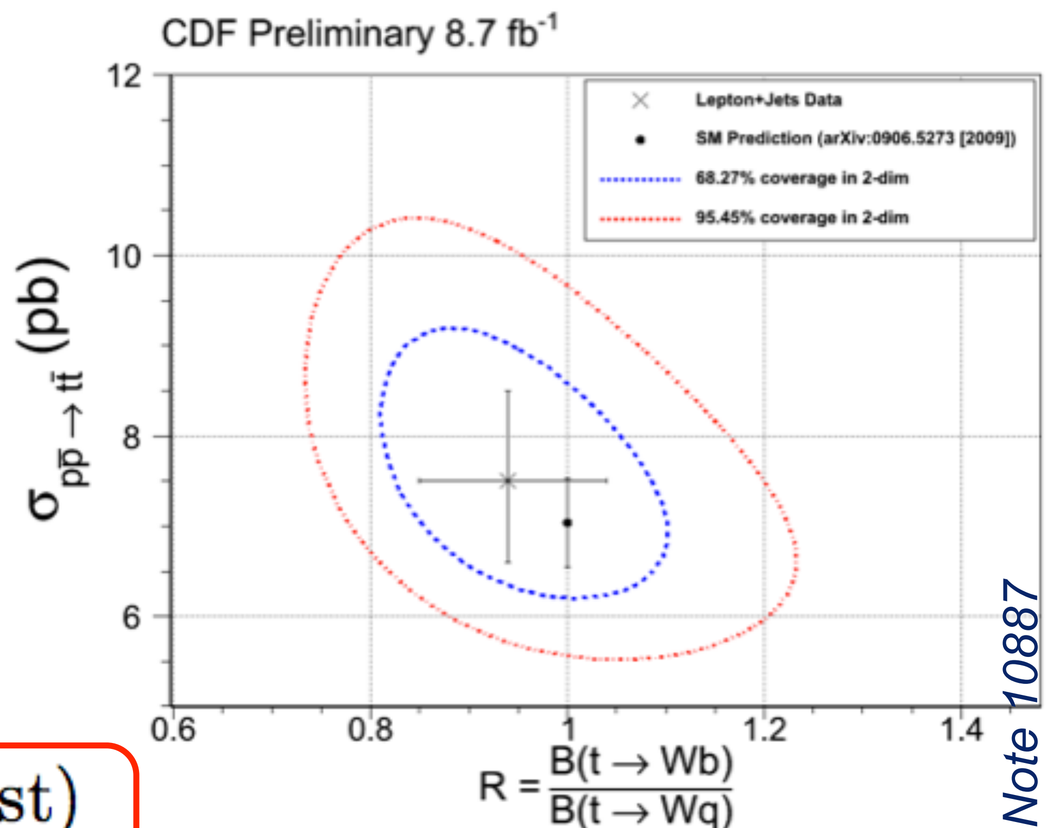
  - **Ansatz:**
    - Use **relative yields in different *b*-tagging bins**



CDF Note 10887

$R = BR(t \to Wb) / BR(t \to Wq)$

- Relative changes in b-tagging bins also affect the **total $t\bar{t}$ cross** section:
  - → simultaneously fit *R*-ratio and *tt* cross section!
  - Take systematic uncertainties into account via nuisance parameters in the final LH fit



CDF Note 10887

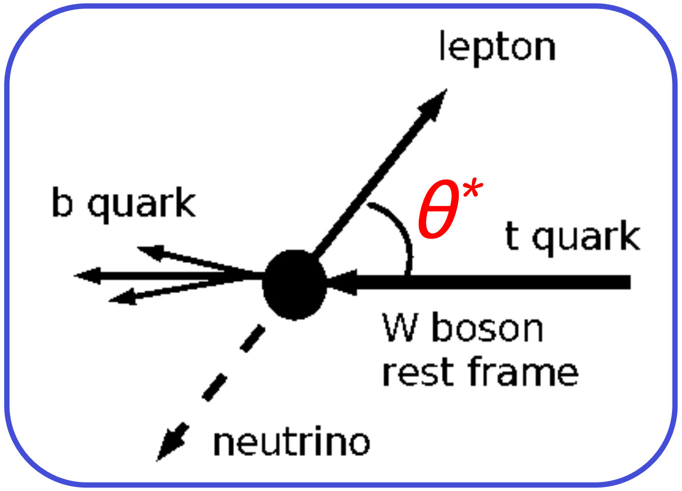
- Final result:

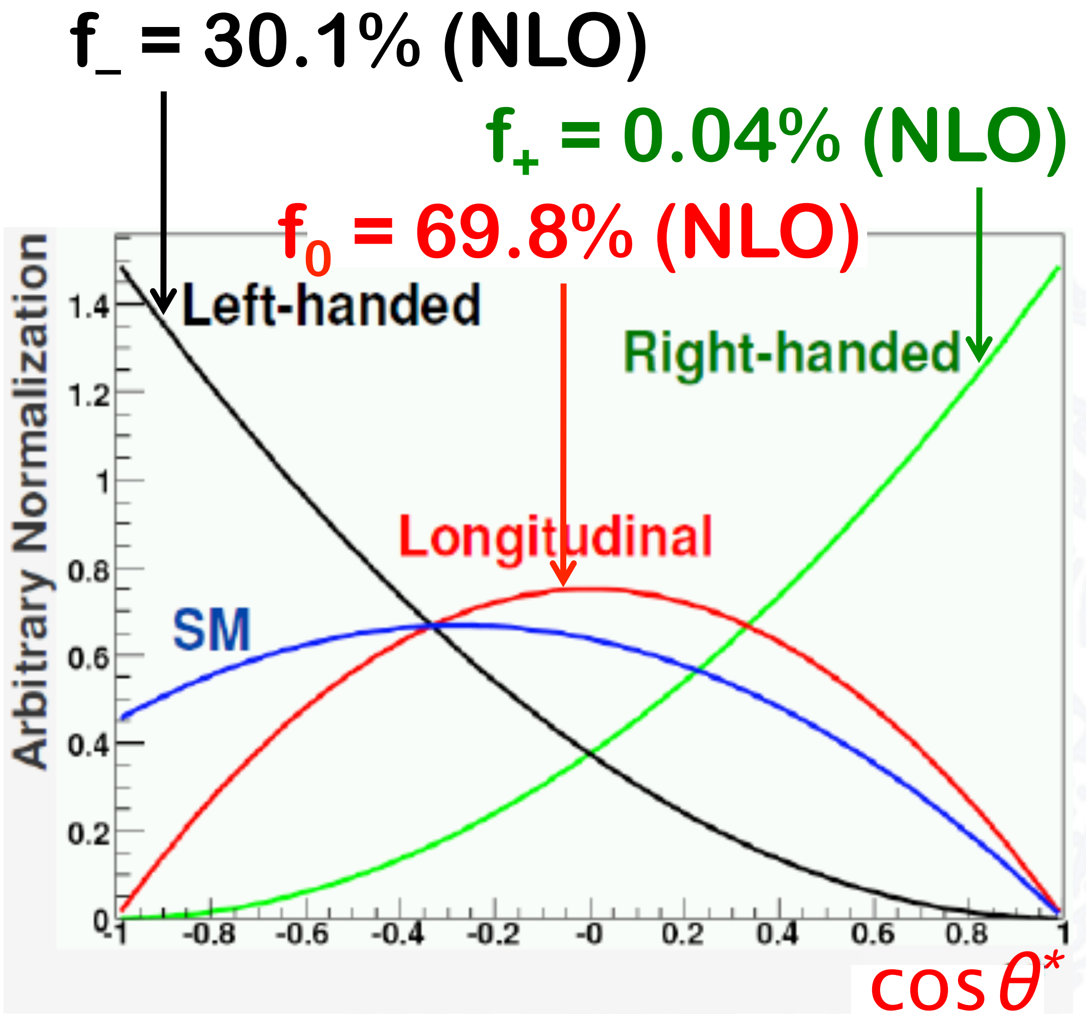
$$R = 0.94 \pm 0.1(\text{stat+syst})$$
$$\sigma_{t\bar{t}} = 7.5 \pm 0.95 \text{ pb.}$$

$$|V_{tb}| > 0.89 \text{ at } 95\% \text{ C.L.}$$

W boson helicity

- Study the *V-A* nature of the *Wtb* coupling
  - Deviations from SM would indicate new physics





W boson helicity

- **W helicity measurement in l+jets, CDF (8.7 fb^{-1}):**
  - Use the matrix element technique
    - Include not only the $\cos\theta^*$ of the leptonic W decays, but also in the hadronic decays despite the sign ambiguity!
  - Extract the polarisation fractions by maximising the LH:

$$L(f_0, f_+, C_s) = \prod_{i=1}^{N}[C_s \frac{P_s(x; f_0, f_+)}{\langle A_s(x; f_0, f_+)\rangle} + (1 - C_s)\frac{P_b(x)}{\langle A_b(x)\rangle}],$$

  - The clue:
    - Use the LO matrix-element

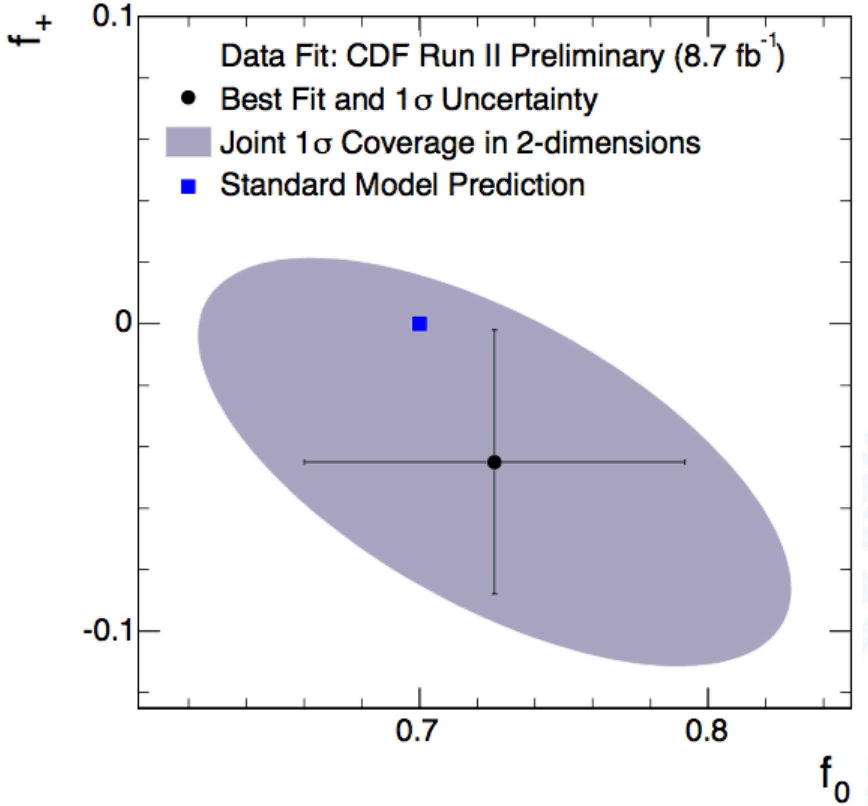
$$|M|^2 = \frac{g_s^4}{9} F_\ell \bar{F}_h (2 - \beta^2 \sin^2\theta_{qt})$$

      - to express P_{sig}
      - to introduce the dependence on the W boson polarisation!

$$F_\ell = \frac{2\pi g_W^4 m_{\bar{\ell}\nu}^2}{3 m_t \Gamma_t}(2E_b^{*2} + 3E_b^* m_{\bar{\ell}\nu} + m_b^2)(\frac{3}{8}(1 + \cos\theta^*)^2 f_+ + \frac{3}{4}(1 - \cos^2\theta^*) f_0 + \frac{3}{8}(1 - \cos\theta^*)^2(1 - f_0 - f_+)).$$

CDF Note 10855

- **Final result:**



$$f_0 = 0.726 \pm 0.066(\text{stat}) \pm 0.067(\text{syst})$$
$$f_+ = -0.045 \pm 0.043(\text{stat}) \pm 0.058(\text{syst})$$

CDF Note 10855

- **Most general, lowest-dim, *CP*-conserving *Wtb* vertex**

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

Underlined couplings are 0 in SM!

Phys. Lett. B **703**, 21 (2012)

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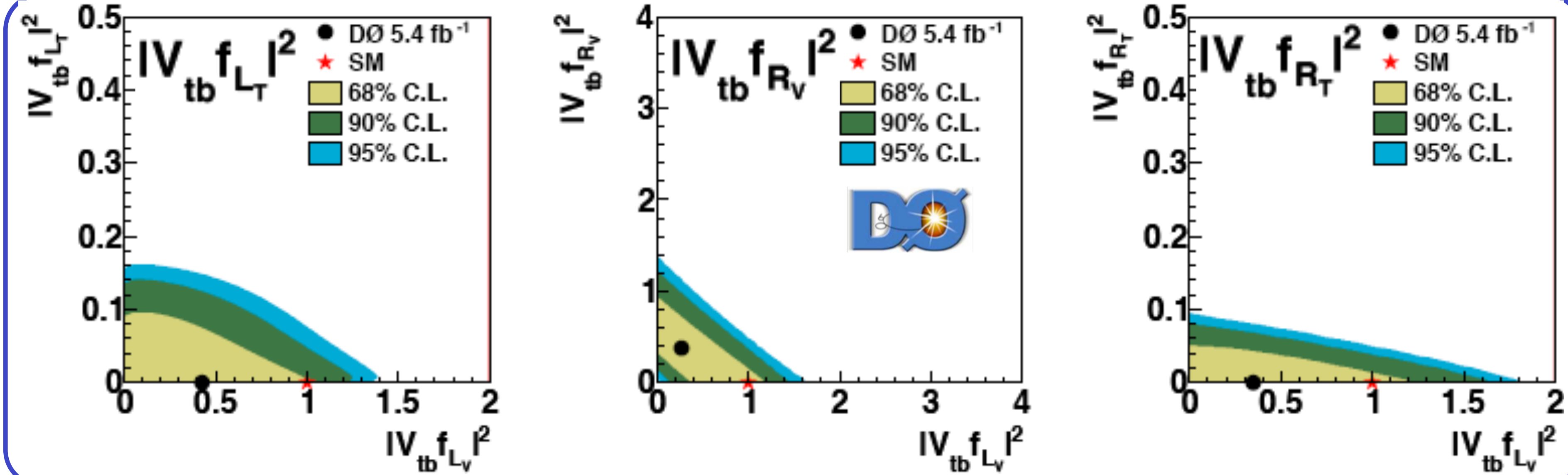
Underlined couplings are 0 in SM!

- Extract *Wtb* AC from single top production using:
  - shapes of kinematic distributions
  - event rate (overall, *s*-channel vs *t*-channel)
- Few assumptions:
  - Single top quarks produced exclusively via a *W* boson
  - $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$

Phys. Lett. B **703**, 21 (2012)

- **Obtained limits:**

Limits on Wtb AC from single top production



Phys. Lett. B ***703****, 21 (2012)*

- ***Wtb*** **AC will alter:**
  - **single top production (see previous slides)**
  - **fractions of W bosons in the 3 helicity states**

*Phys. Lett. B **713**, 165 (2012)*

Wtb AC from single top + *W* helicity

- ***Wtb* AC will alter:**
  - single top production (see previous slides)
  - fractions of W bosons in the 3 helicity states

combine!

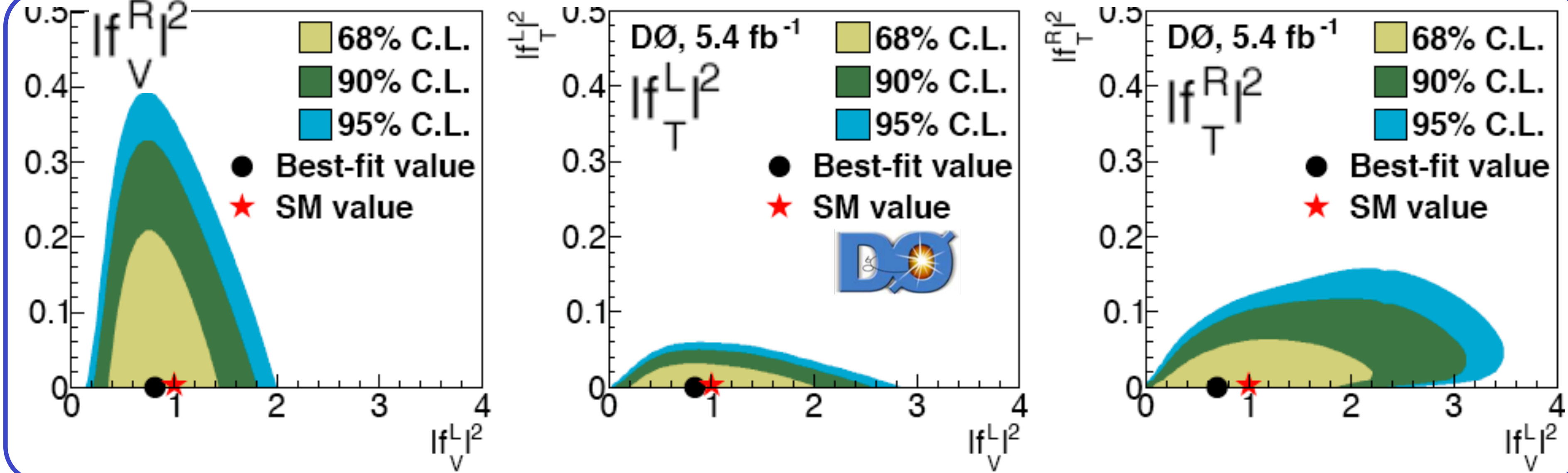
- **Assume:**
  - Single top production through *Wtb* vertex exclusively
  - $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$

- Use the LH from *W* helicity meas't as prior for single top
  - Compute LH over all possible analysis channels
  - Remove overlap between selections

Phys. Lett. B ***713***, *165 (2012)*

Wtb AC from single top + *W* helicity

Combination of single top + *W* helicity



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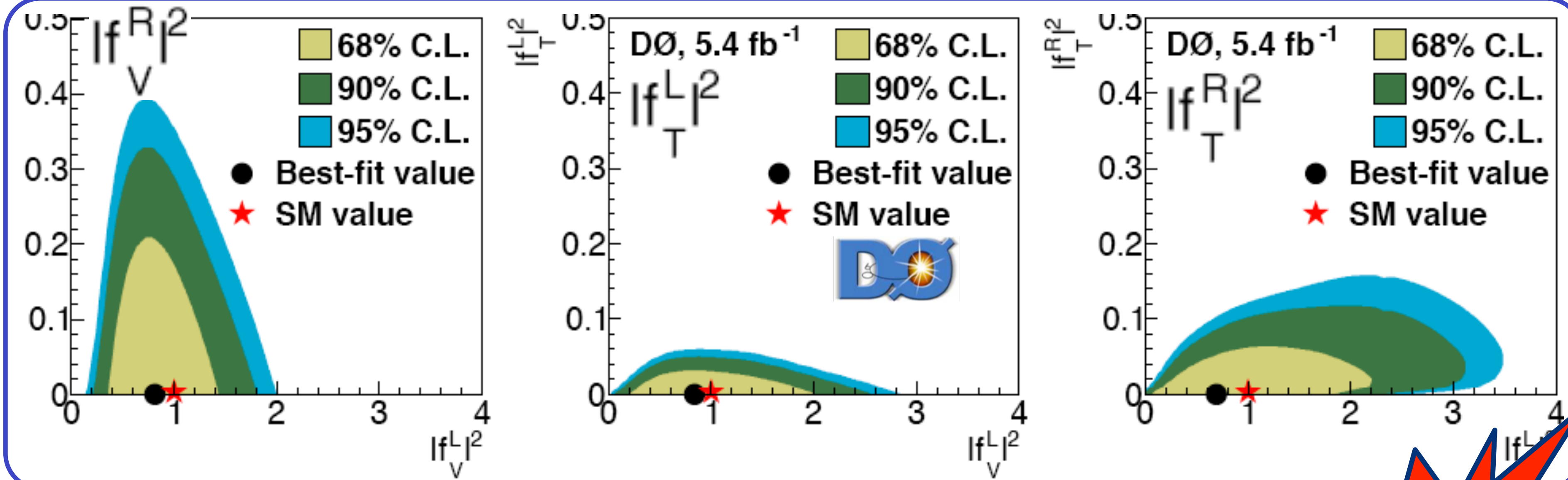
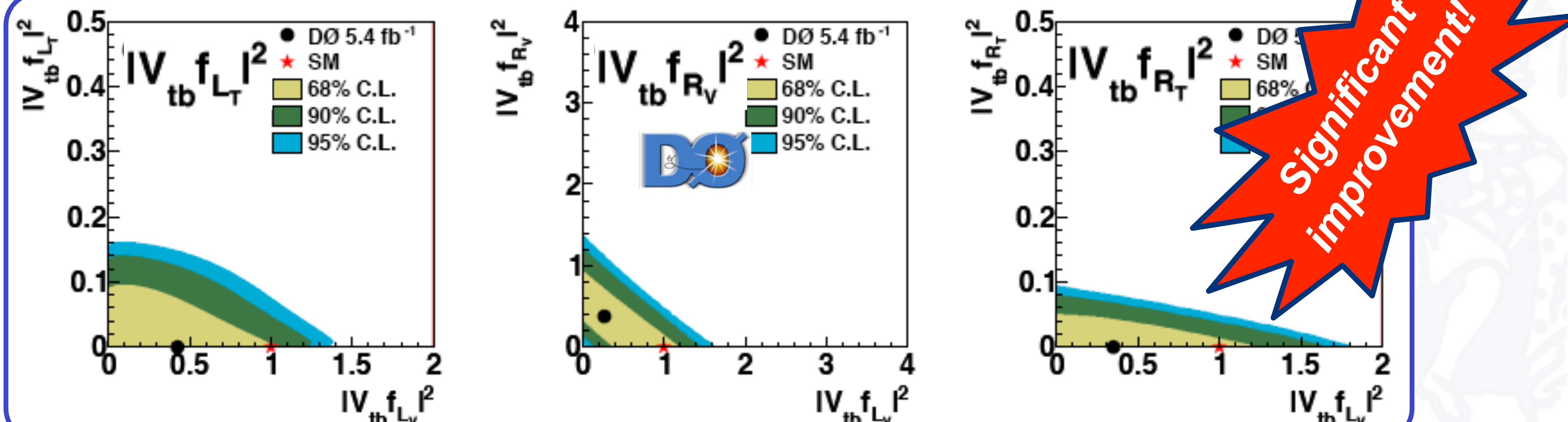
Combination of single top + *W* helicity

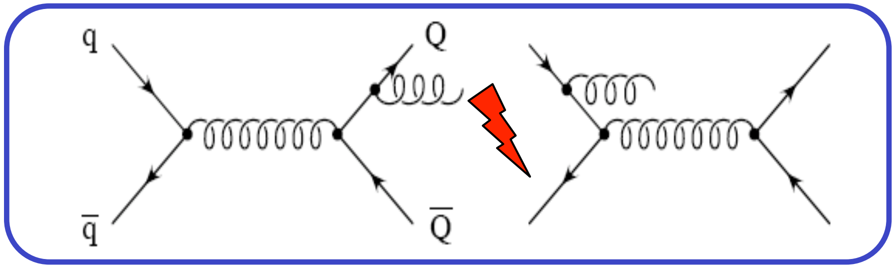


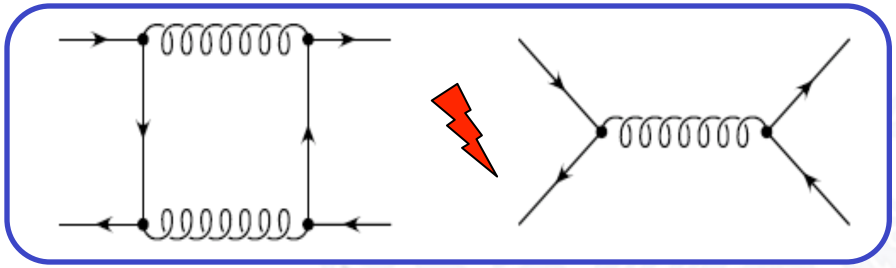


single top production **ONLY**

Colour charge asymmetry, l+jets

- Theoretical predictions (Tevatron-specific!):
  - At LO, completely symmetric
  - At higher orders, interference terms influence t and tbar production asymmetrically, e.g.:





Colour charge asymmetry @ CDF → cf. talk by J. Wilson

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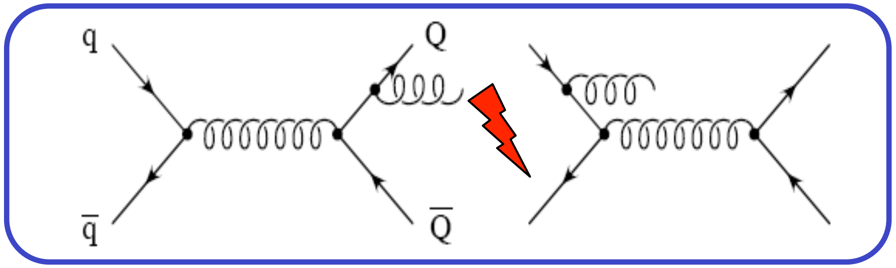

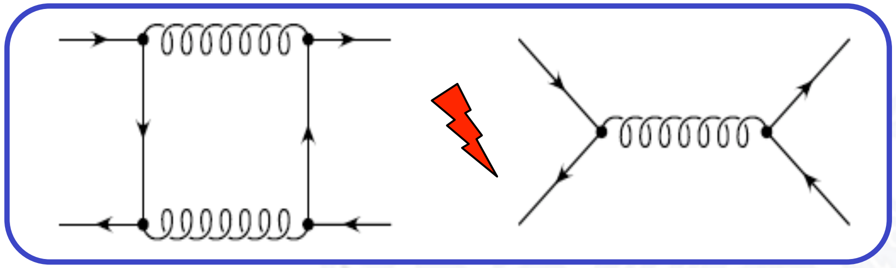

  - New physics contributions to enhance asymmetry?
    - Massive axial vector gluons
    - Massive vector gluons
    - Z', W'
    - Technicolour
    - ?

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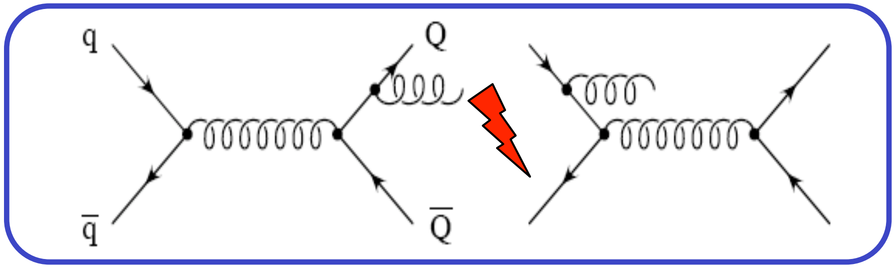

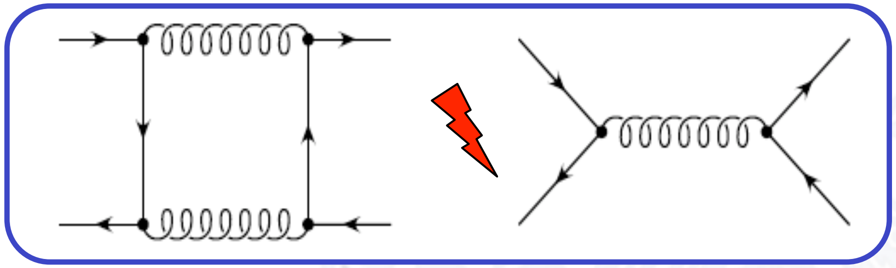

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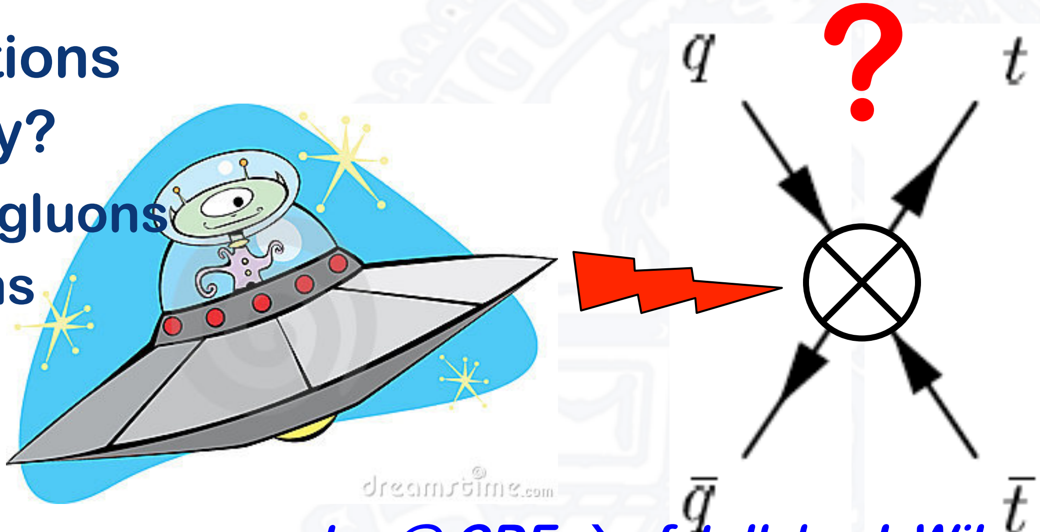


Colour charge asymmetry @ CDF → cf. talk by J. Wilson

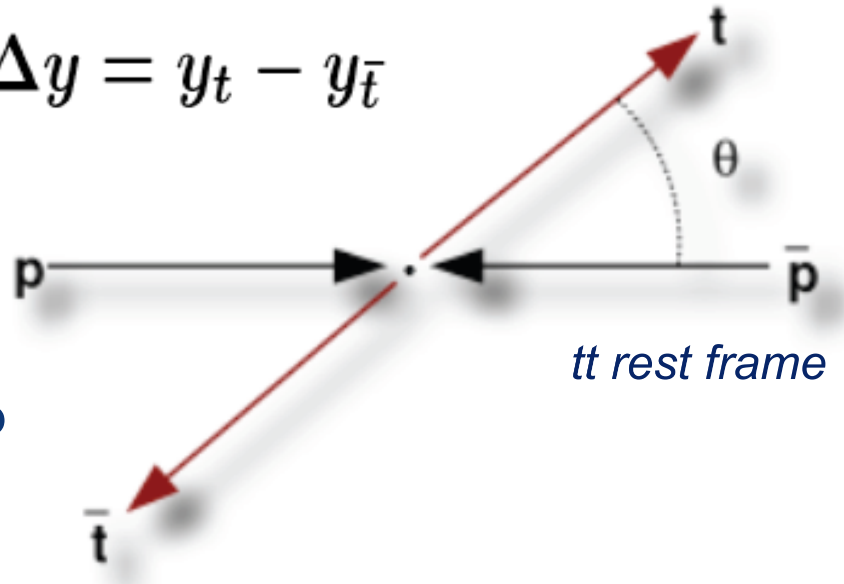
Colour charge asymmetry, l+jets

- **Form observable:**

$$\Delta y = y_t - y_{\bar{t}}$$

$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$

  - Use b-tagged events
  - Use kinematic fitter for reco



Phys. Rev. D ***84****, 112005 (2011)*

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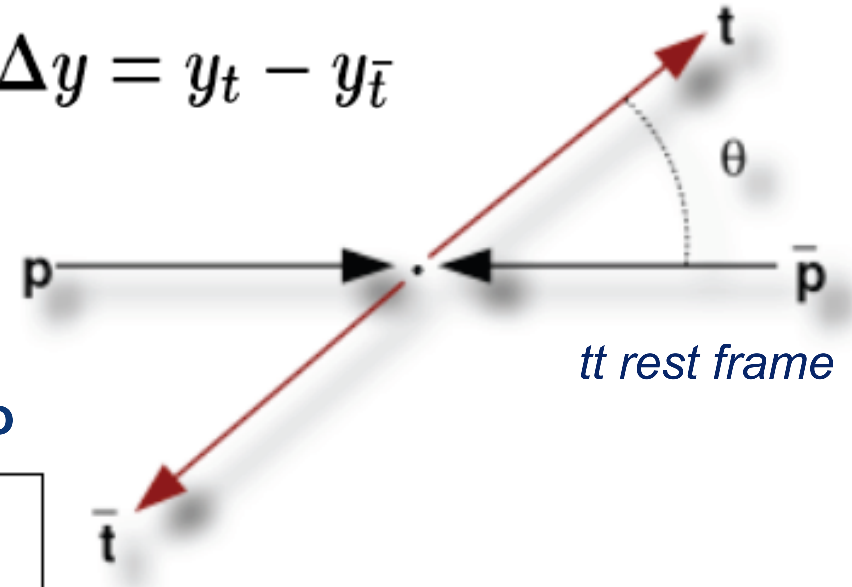
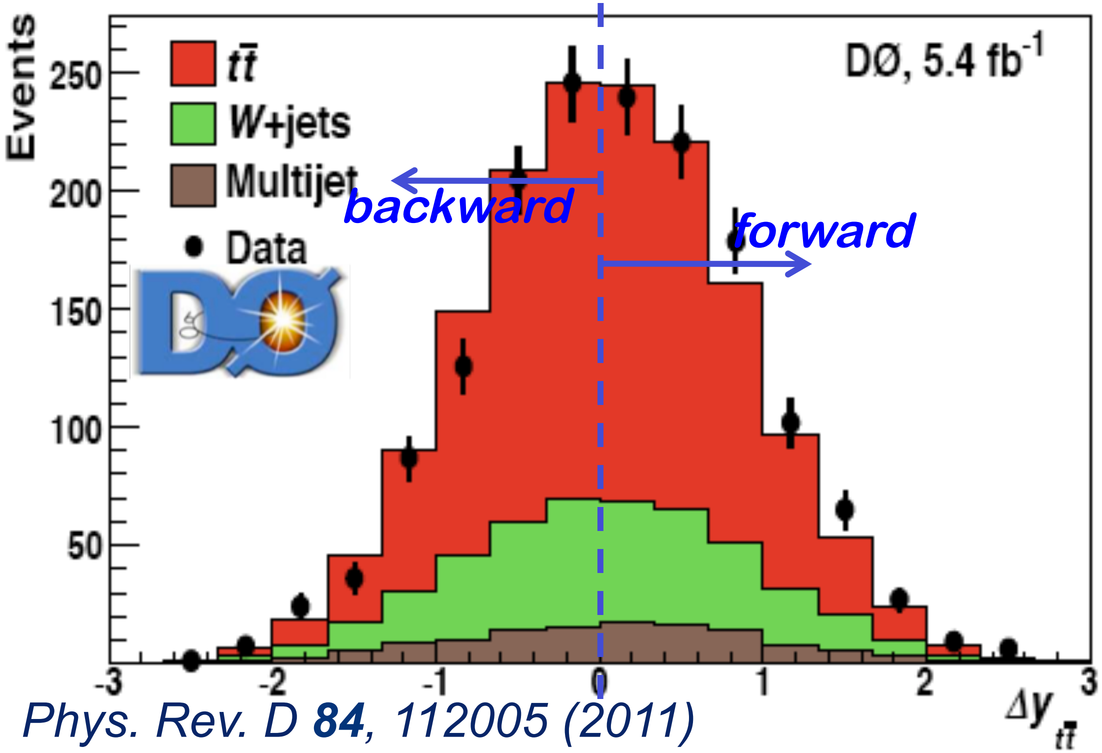




*Phys. Rev. D **84**, 112005 (2011)*

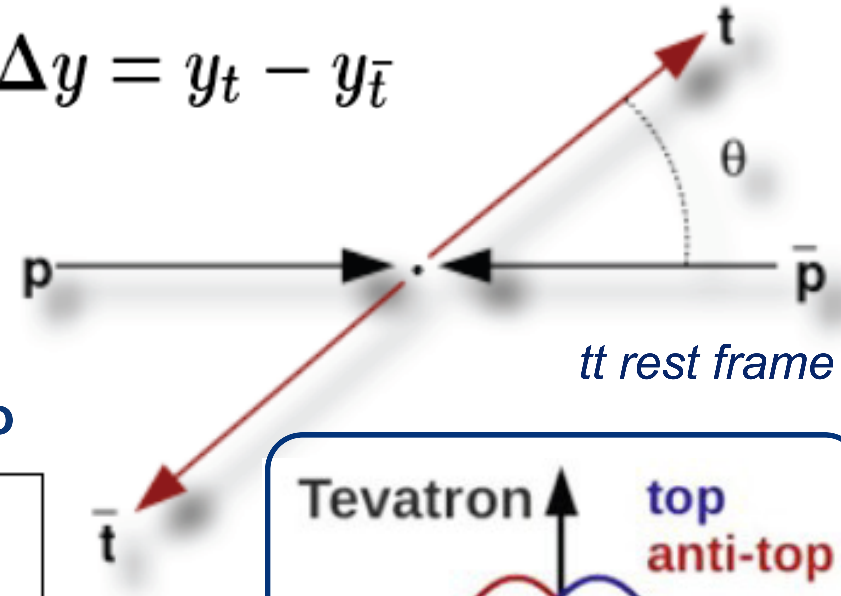
Colour charge asymmetry, l+jets

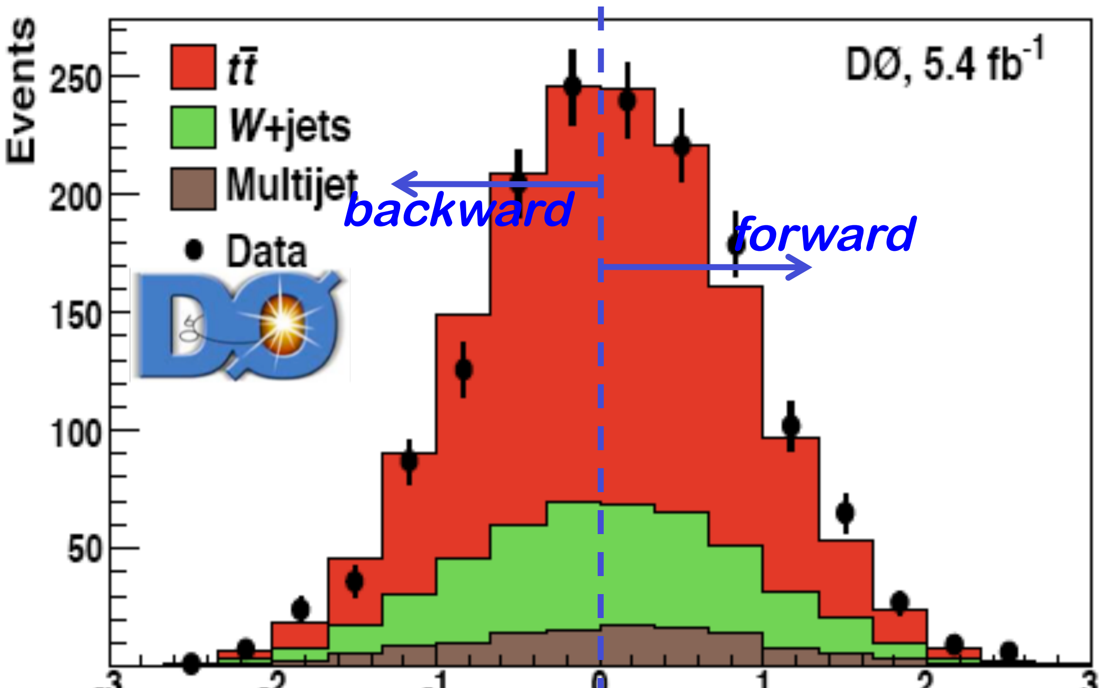
- **Form observable:**

$$\Delta y = y_t - y_{\bar{t}}$$

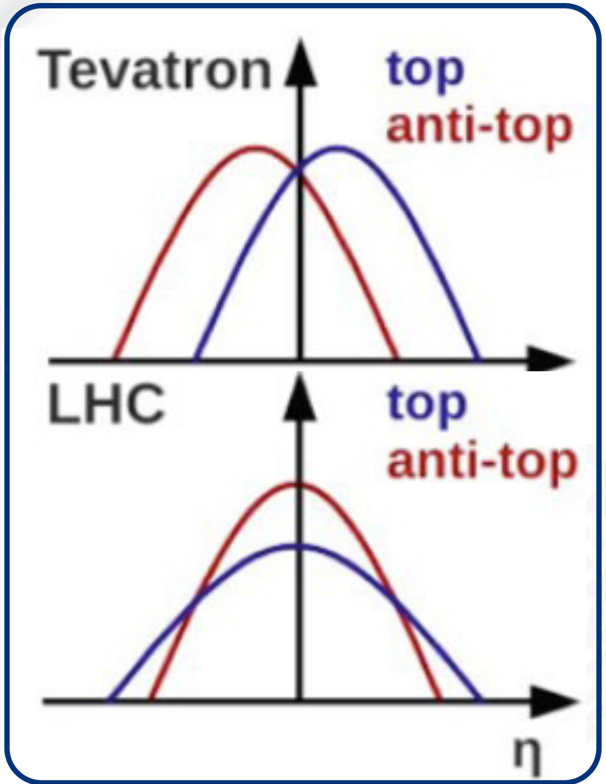
$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$

  - Use b-tagged events
  - Use kinematic fitter for reco





*Phys. Rev. D **84**, 112005 (2011)*



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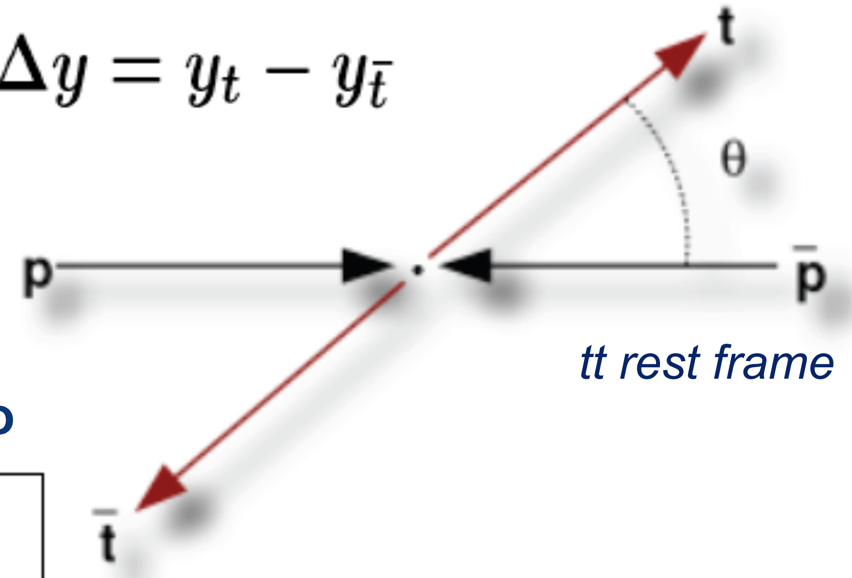

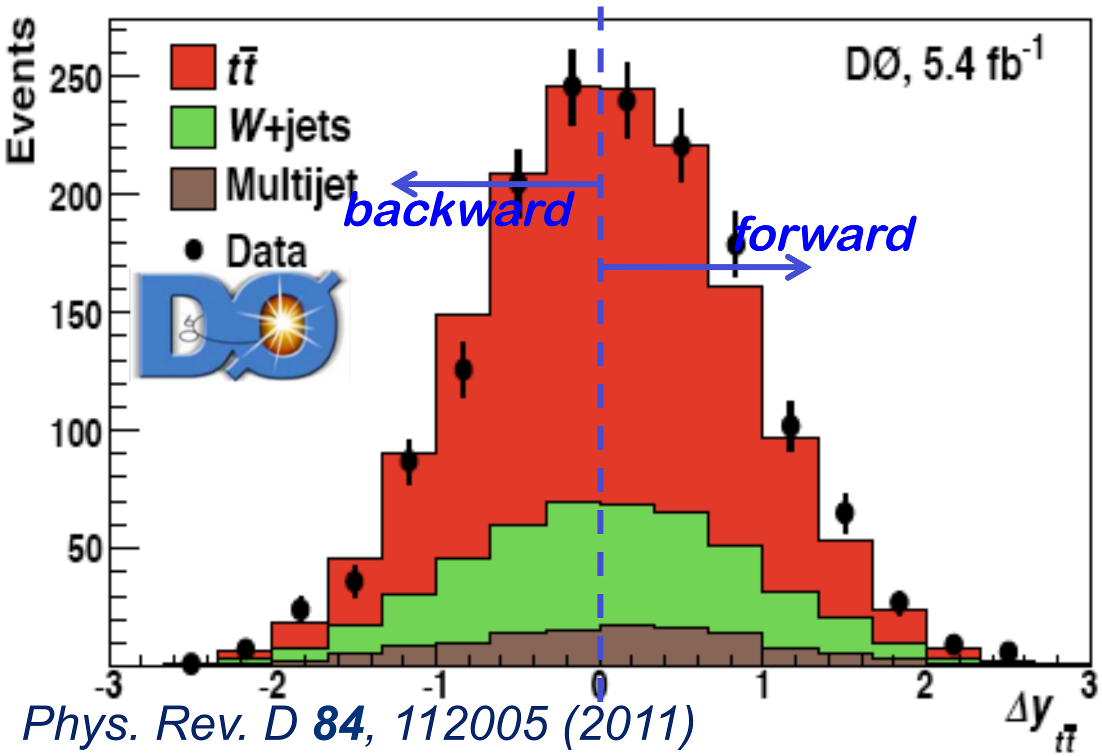

Phys. Rev. D ***84****, 112005 (2011)*

Raw result (not unfolded), after background subtraction:
$A_{\mathrm{FB}} = 9.2 \pm 3.7\ \%$

MC@NLO prediction:
2.4 ± 0.7

Colour charge asymmetry, l+jets

- **Asymmetry would be enhanced:**
  - For high m_{tt} for an *s*-channel resonance
  - For high |Δy| for a *t*-channel anomaly

	A_{FB} (%)	
Subsample	Data	MC@NLO
$m_{t\bar{t}} < 450$ GeV	7.8 ± 4.8	1.3 ± 0.6
$m_{t\bar{t}} > 450$ GeV	11.5 ± 6.0	4.3 ± 1.3
$\lvert\Delta y\rvert < 1.0$	6.1 ± 4.1	1.4 ± 0.6
$\lvert\Delta y\rvert > 1.0$	21.3 ± 9.7	6.3 ± 1.6

*Phys. Rev. D **84**, 112005 (2011)*

Colour charge asymmetry, l+jets

- Typically, A_{FB} at generator level will be diluted at reconstruction level due to
  - Limited detector acceptance
  - Limited resolution on Δy (≈0.7)
- → Unfold Δy to generator level
  - Bin migrations particularly relevant close to Δy = 0
    - Use sufficiently fine binned, regularised unfolding
    - Correct for possible biases with ensemble tests
    - (Cross-check with coarse-binned unfolding consistent)

	A_{FB} (%)	
	Reconstruction level	Production level
Data	9.2 ± 3.7	19.6 ± 6.5
MC@NLO	2.4 ± 0.7	5.0 ± 0.1

Phys. Rev. D ***84****, 112005 (2011)*

Colour charge asymmetry, l+jets

- **Migrations** around $\Delta y=0$ are **tiny if lepton-based observables are used**
  - → define forward, backward events via $q_\ell y_\ell < 0$, $q_\ell y_\ell > 0$

Phys. Rev. D **84**, 112005 (2011)

Colour charge asymmetry, l+jets

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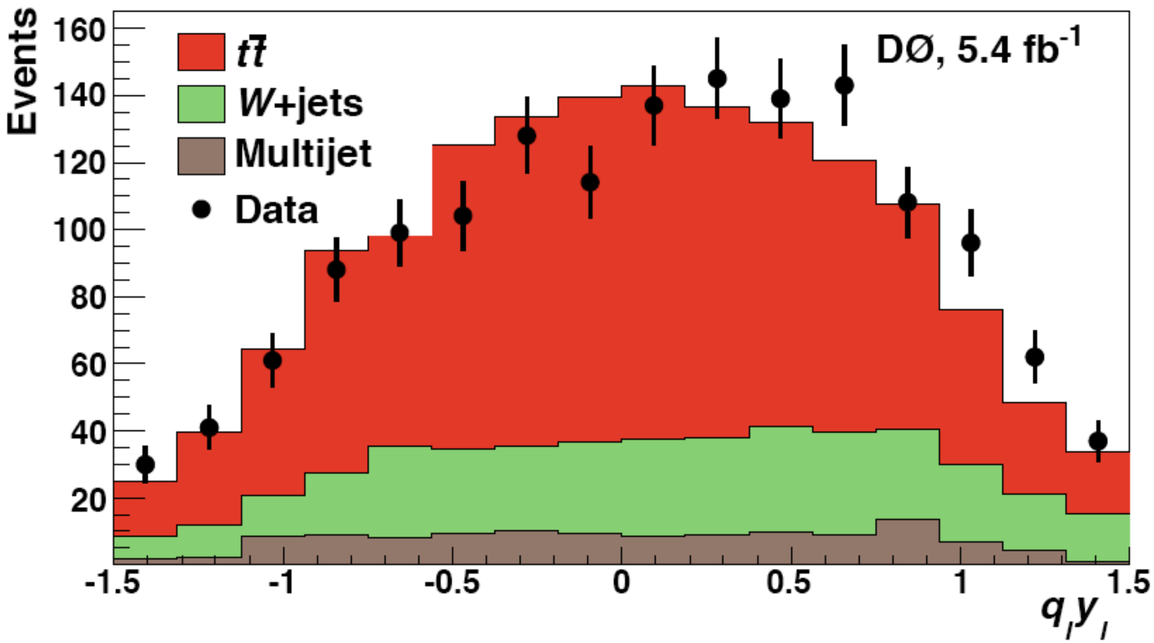


	A^l_{FB} (%)	
	Reconstruction level	Production level
Data	14.2 ± 3.8	15.2 ± 4.0
MC@NLO	0.8 ± 0.6	2.1 ± 0.1

Phys. Rev. D 84, 112005 (2011)

- **Colour charge asymmetry in $\ell\ell$ channel, D0 (5.4 fb^{-1})**
  - Use lepton-based observables:
    - Experimentally more robust
    - No full kinematic reconstruction of $t\bar{t}$ system necessary
  - "Classical" forward-backward asymmetry:

$$A^{\ell}_{\mathrm{FB}} = \frac{N_{\ell}(Q \cdot \eta > 0) - N_{\ell}(Q \cdot \eta < 0)}{N_{\ell}(Q \cdot \eta > 0) + N_{\ell}(Q \cdot \eta < 0)}$$

  - Longitudinal asymmetry in spin orientation relative to proton beam direction:

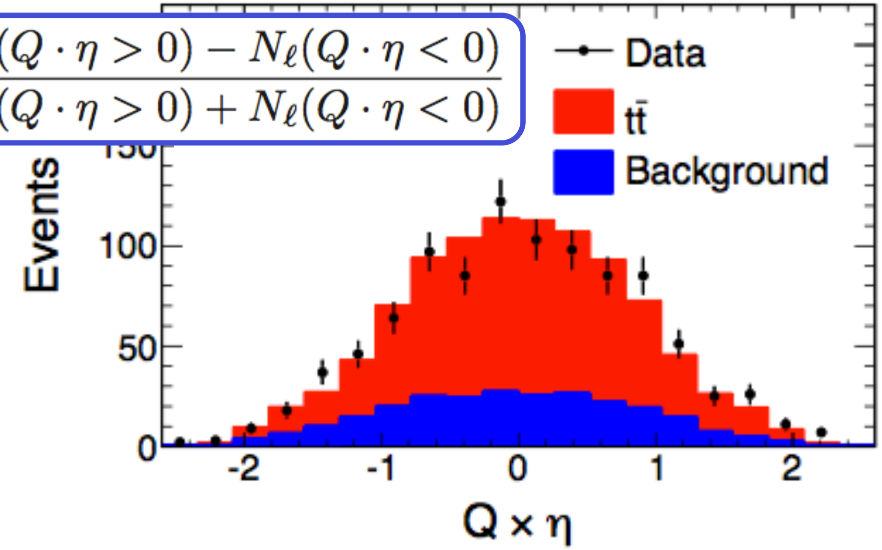
$$A^{\ell}_{\mathrm{CP}} = \frac{N_{\ell+}(\eta > 0) - N_{\ell-}(\eta < 0)}{N_{\ell+}(\eta > 0) + N_{\ell-}(\eta < 0)}$$

    - Sensitive to *s*-channel exchanges of heavy non-scalar resonances with *CP*-violating couplings to quarks
    - Not sensitive to possible *P* and *CP*-violating effects from an *s*-channel exchange of Higgs bosons

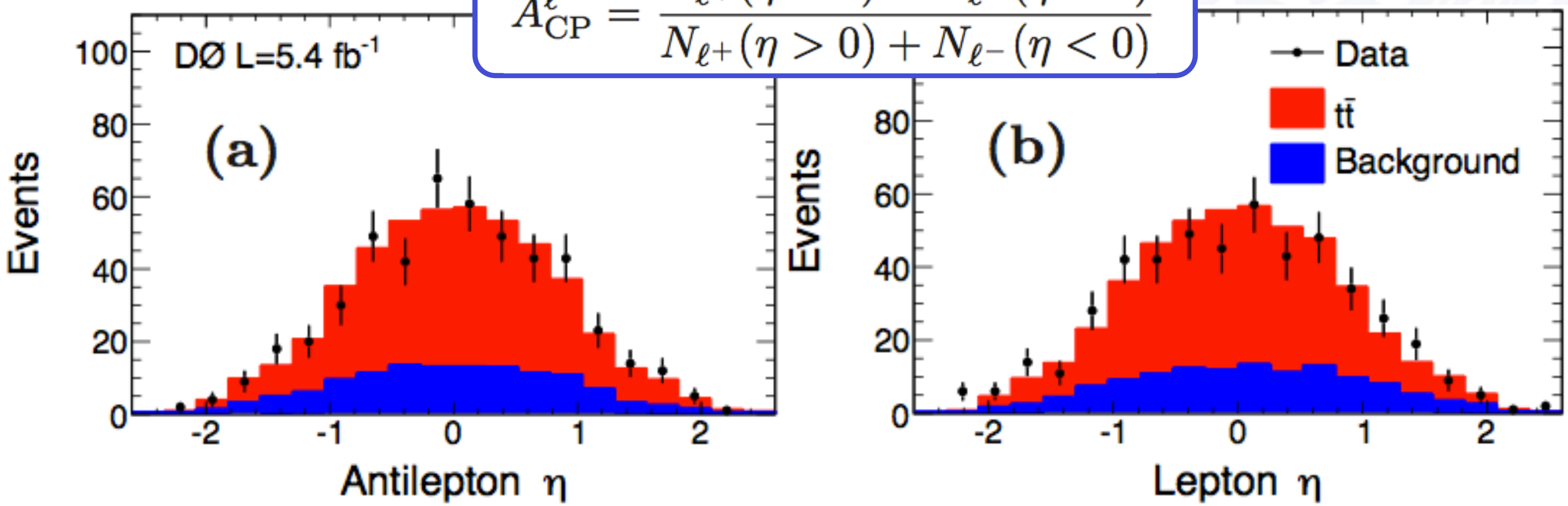
arXiv:1207.0364 [hep-ex] (2012)

Colour charge asymmetry, $\mathcal{U}$

$$A^{\ell}_{\rm FB} = \frac{N_\ell(Q\cdot\eta>0) - N_\ell(Q\cdot\eta<0)}{N_\ell(Q\cdot\eta>0) + N_\ell(Q\cdot\eta<0)}$$



$$A^{\ell}_{\rm CP} = \frac{N_{\ell+}(\eta>0) - N_{\ell-}(\eta<0)}{N_{\ell+}(\eta>0) + N_{\ell-}(\eta<0)}$$



arXiv:1207.0364 [hep-ex] (2012)

Colour charge asymmetry, $\mathcal{U}$

- **Final results:**

Predictions at NLO in pQCD + EW corrections: Bernreuter and Si, Nucl. Phys. B ***837****, 90 (2010)*

	Raw	Unfolded	Predicted
$A^\ell_{\rm FB}$	$3.1 \pm 4.3 \pm 0.8$	$5.8 \pm 5.1 \pm 1.3$	4.7 ± 0.1
$A^\ell_{\rm CP}$	$1.8 \pm 4.3 \pm 1.0$	$-1.8 \pm 5.1 \pm 1.6$	-0.3 ± 0.1

- **Combine with the l+jets channel:**

$$A^\ell_{\rm FB} = (11.8 \pm 3.2)\%$$

$$A^\ell_{\rm FB}(\text{predicted}) = (4.7 \pm 0.1)\%$$

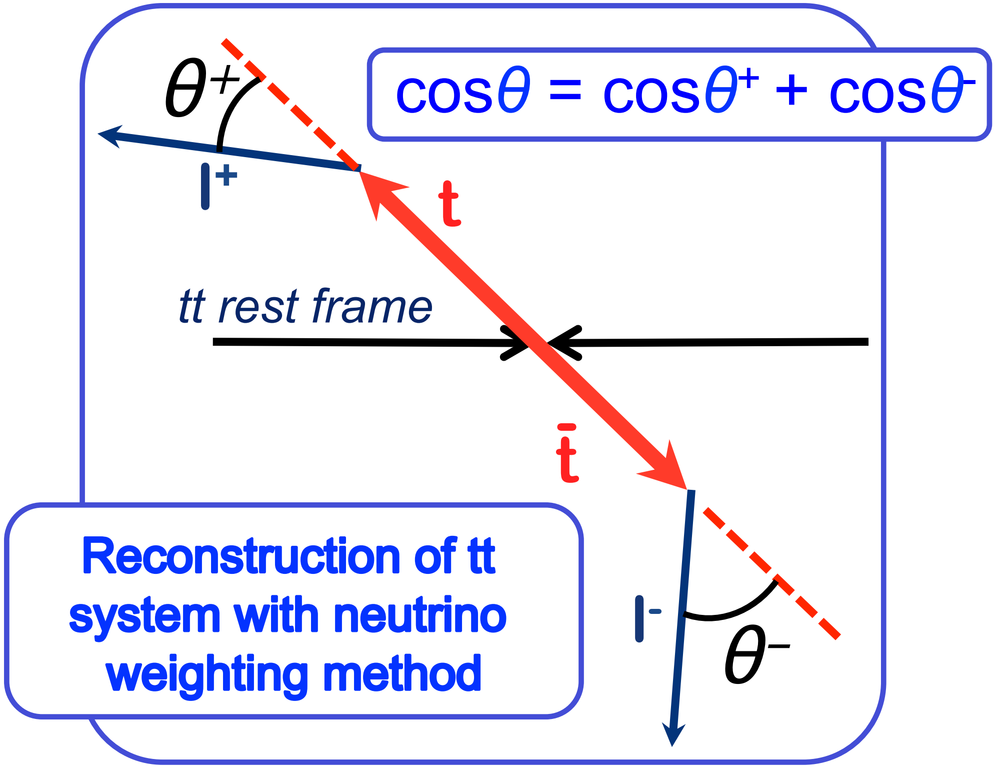
Predictions in l+jets updated to include EW corrections

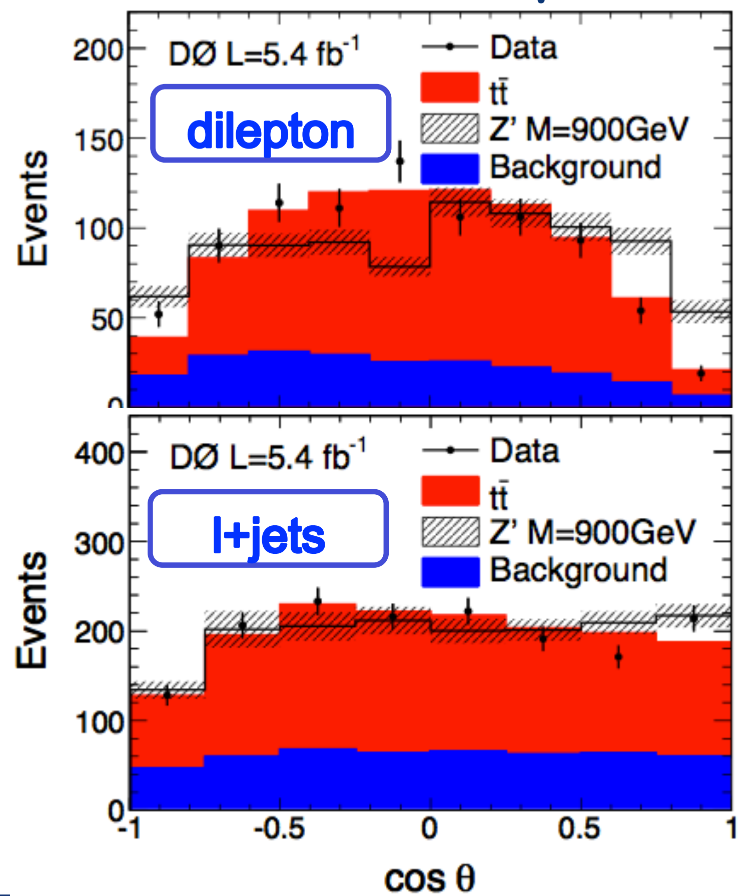
- **Relative contributions: 64% / 36% for l+jets / dilepton**
- **Consistency: 68%**
- **Disagreement with prediction: 2.2 SD**

arXiv:1207.0364 [hep-ex] (2012)

Colour charge asymmetry, ll

- **Study of the longitudinal polarisation of top quark:**
  - In the SM, top quarks unpolarised in $t\bar{t}$ events
  - Many BSM models with enhanced A_{FB} also predict non-vanishing longitudinal polarisation of the top





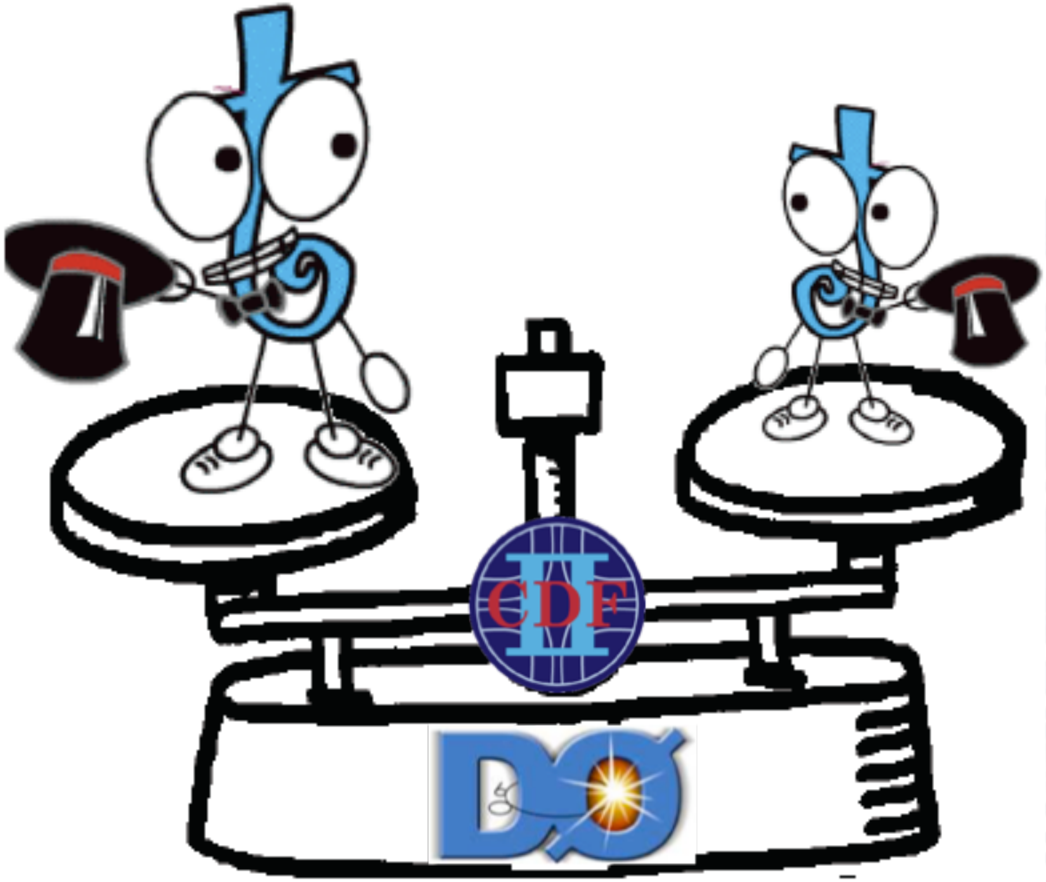
arXiv:1207.0364 [hep-ex] (2012)

Summary & Outlook

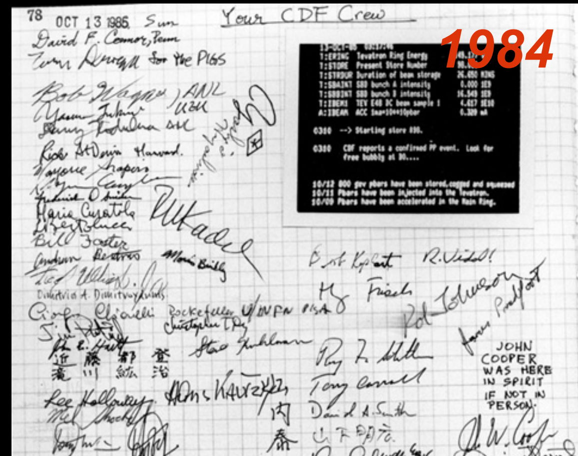
- The era of **precision measurements in the top quark sector** has begun!
- Many exciting new/updated analyses:
  - World's most precise m_{top} comes from the Tevatron
  - Competitive limits on anomalous *Wtb* couplings
  - The only measurements of top decay width
  - Further steps towards pinning down strong colour charge asymmetry A_{FB}
  - First study of top quark polarisation
- We are looking ahead to more exciting measurements from the Tevatron:
  - Final, most precise measurement of m_{top}
  - Detailed measurement of $t\bar{t}$ production in $p\bar{p}$ collisions
  - …


GAME OVER
... FOR THE TEVATRON (2011)

We are looking ahead to more exciting measurements from the Tevatron!




1983


78
OCT 13 1985 Sun
Your CDF Crew
1984
JOHN COOPER WAS HERE IN SPIRIT IF NOT IN PERSON

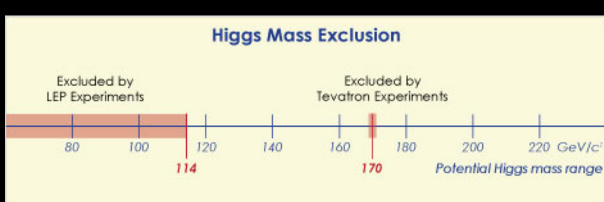

1985

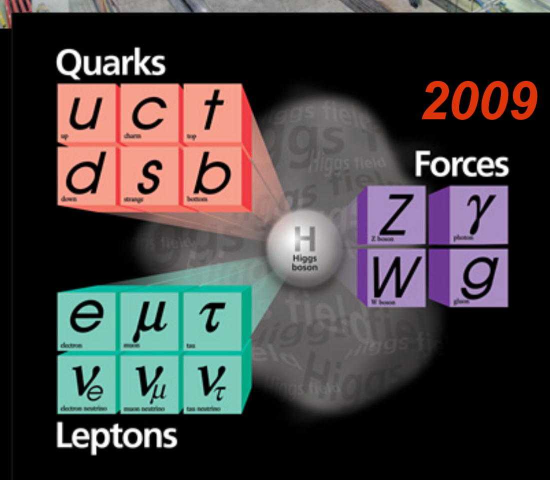

1991

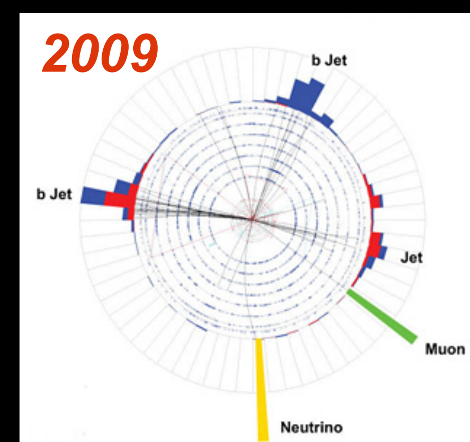

1992


1995
Cultura e Spettacoli
CORRIERE DELLA SERA
Dove vai, cacciatore di quark?
Batavia is center of universe
Alles Quark, oder was?
I predatori del quark perduto
Nation
For physicists, last piece of a puzzle
RICERCA ITALIANA
Truth by Consensus

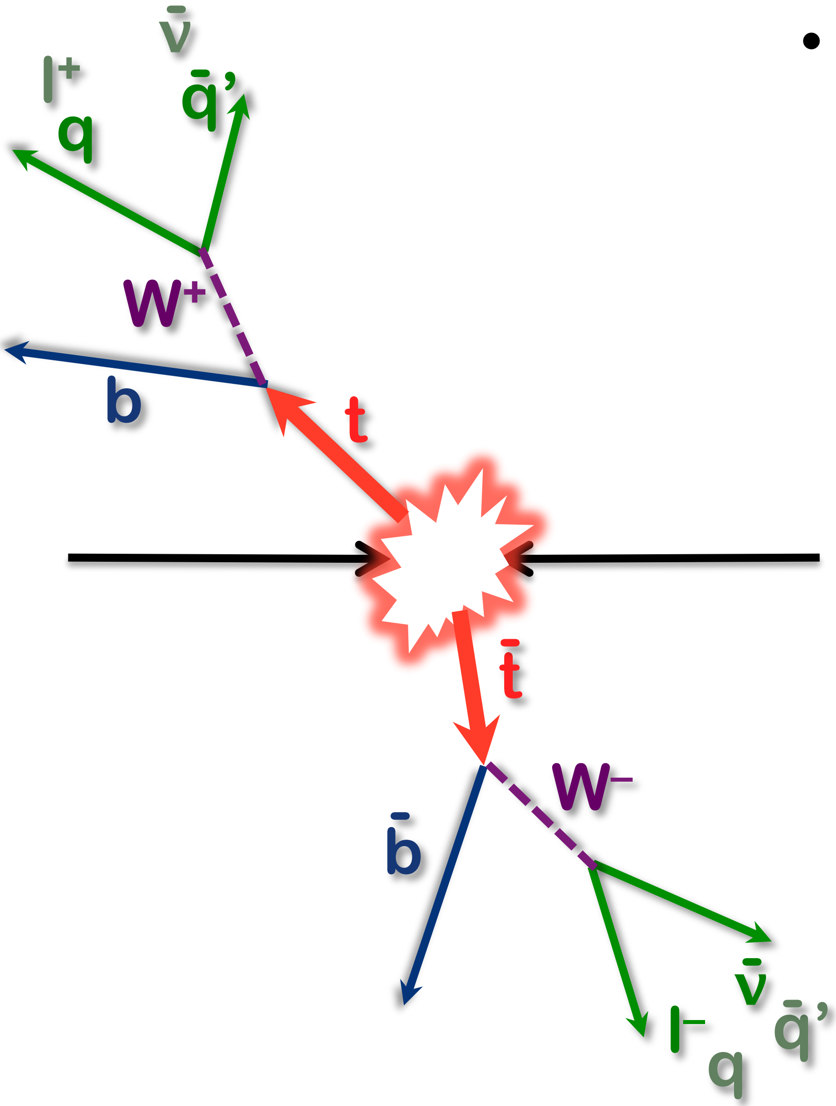
2008


Higgs Mass Exclusion
Excluded by LEP Experiments
Excluded by Tevatron Experiments
80
100
120
140
160
180
200
220 GeV/c²
114
170
Potential Higgs mass range


Quarks
2009
u c t
d s b
Forces
Z γ
W g
H
Higgs boson
e μ τ
νe νμ ντ
Leptons

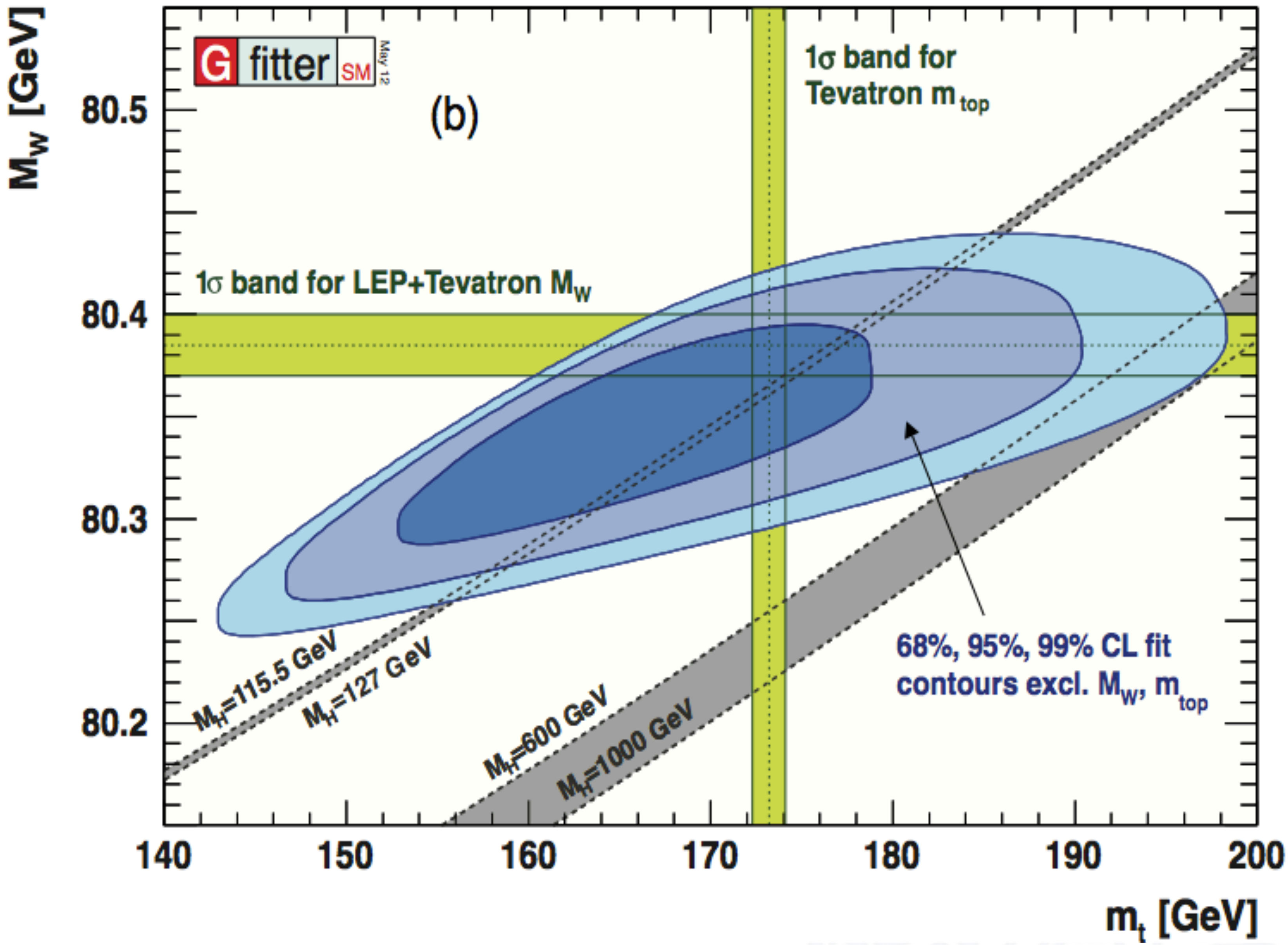

2009
b Jet
b Jet
Jet
Muon
Neutrino

A wealth of top properties



- Typically: we measure top properties in tt events
  - Dilepton channel: low backgrounds, but underconstrained kinematics and low rate
  - l+jets channel: good compromise between kinematic reconstr'n, high rate, and backgrounds
  - All-hadronic channel: highest branching ratio, very high backgrounds from QCD multijet production
  - \+ other orthogonal channels…

Single top: high backgrounds, moderate rate, direct access to some observables (e.g. V_{tb})


Gfitter SM
May 12
(b)
1σ band for
Tevatron m top
1σ band for LEP+Tevatron MW
68%, 95%, 99% CL fit
contours excl. MW, mtop
MH=115.5 GeV
MH=127 GeV
MH=600 GeV
MH=1000 GeV
MW [GeV]
80.5
80.4
80.3
80.2
140
150
160
170
180
190
200
mt [GeV]

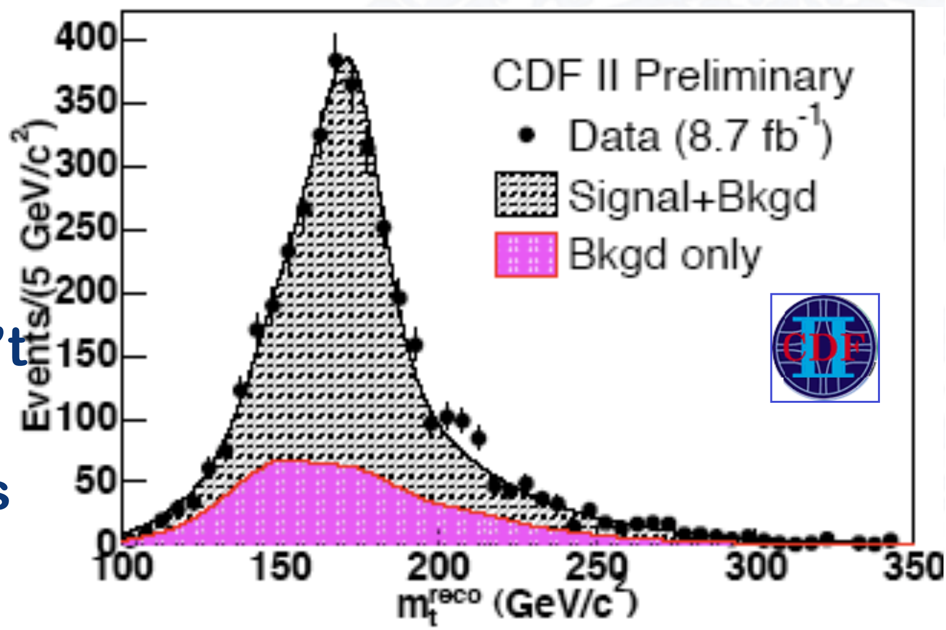
m_{top} with templates in ll and l+jets

- **Template method in lepton+jets final states, CDF (8.7 fb^{-1})**
  - Reconstruct the event kinematics by minimising:

$$\chi^2 = \Sigma_{i=\ell,4jets}\frac{(p_T^{i,fit}-p_T^{i,meas})^2}{\sigma_i^2} + \Sigma_{j=x,y}\frac{(U_j^{fit}-U_j^{meas})^2}{\sigma_j^2}$$

$$+ \underbrace{\frac{(M_{jj}-M_W)^2}{\Gamma_W^2}}_{\text{JES constraint}} + \underbrace{\frac{(M_{\ell\nu}-M_W)^2}{\Gamma_W^2}}_{\text{MET constraint}} + \underbrace{\frac{(M_{bjj}-m_t^{\rm reco})^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu}-m_t^{\rm reco})^2}{\Gamma_t^2}}_{m_{top}\text{ extraction}}$$

  - Consider jet-parton assignments consistent with b-tagging
  - **Form templates** from:
    - $m_t^{\rm reco}$: best jet-parton ass't
    - $m_t^{\rm reco(2)}$: second-best ass't
    - $m_{\rm jj}$: dijet invariant mass



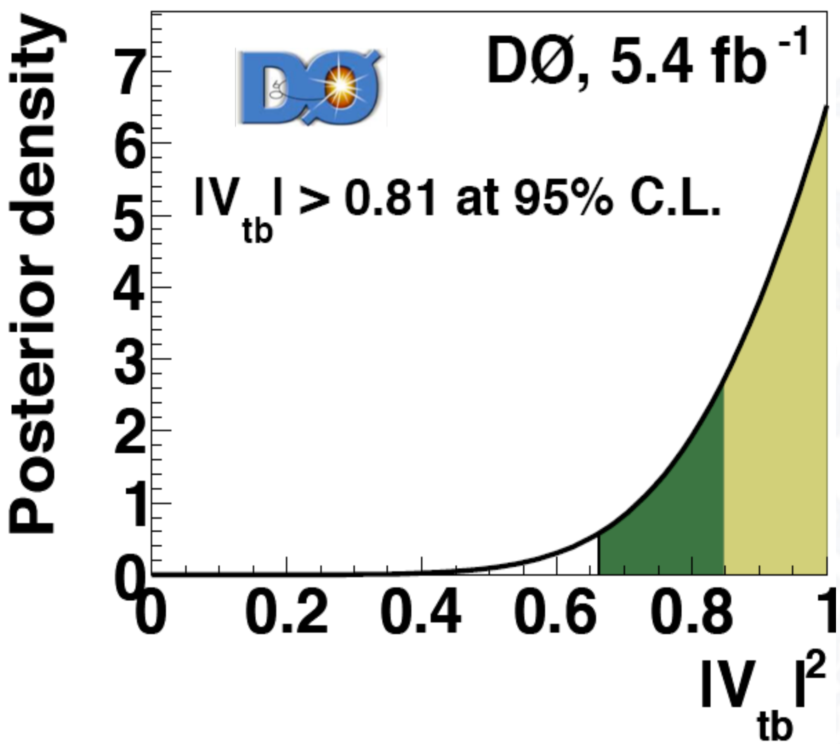
Phys. Rev. Lett. ***109****, 152003 (2012)*

Measurement of $|V_{tb}|$

- To **extract $|V_{tb}|$**, use again ***t*-channel discriminant**
- Form the LH as before but analyse

$$|V_{tb}|^2\mathcal{B}(t \to Wb)\sigma(t\text{−channel})_{SM,|V_{tb}|=1}$$

- Form Bayesian posterior density:



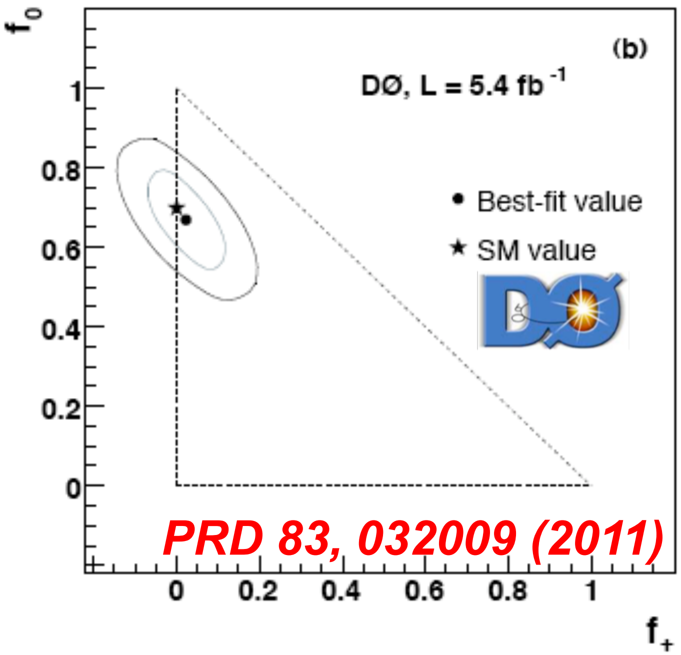
$$|V_{tb}| > 0.81 \text{ at 95\% C.L.}$$

No assumption that t→Wb exclusively or on relative *t* to *s* channel rates

Phys. Rev. D ***85****, 091104 (2012)*

Dilepton & l+jets comb'd

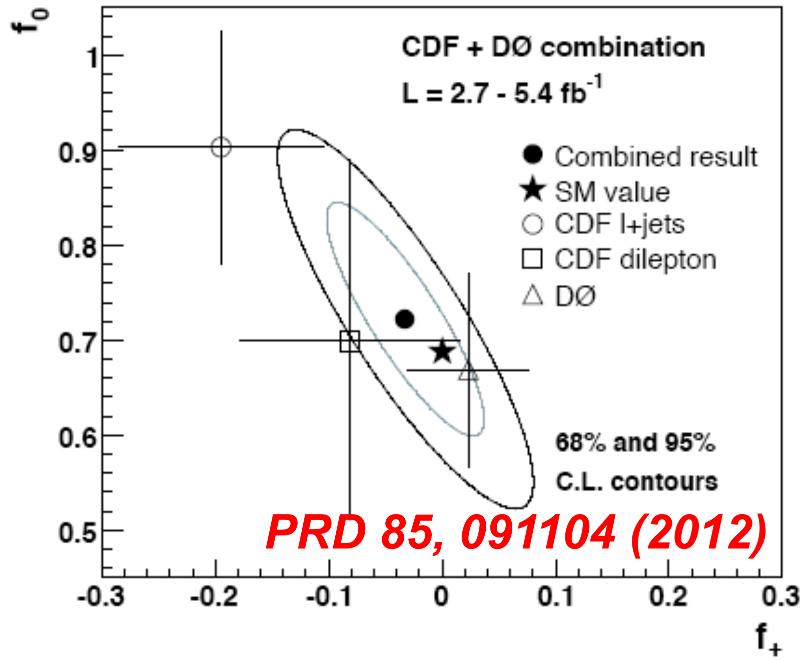
Define channel-dependent templates in cosθ* (leptonic W) and |cosθ*| (hadronic W) + LH fit



Simultaneous 2-D fit results:

$$f_0 = 0.669 \pm 0.078\ (\text{stat.}) \pm 0.065\ (\text{syst.})$$
$$f_+ = 0.023 \pm 0.041\ (\text{stat.}) \pm 0.034\ (\text{syst.})$$

Tevatron combination:

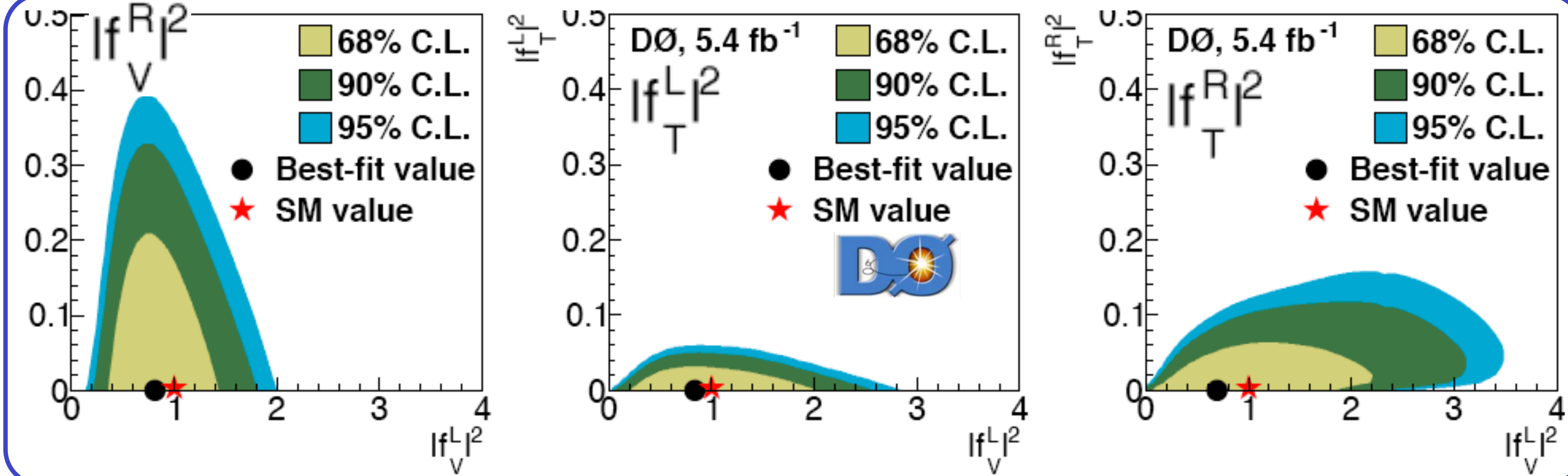


$$f_0 = 0.722 \pm 0.062\ (\text{stat.}) \pm 0.052\ (\text{syst.})$$
$$f_+ = -0.033 \pm 0.034\ (\text{stat.}) \pm 0.031\ (\text{syst.})$$

χ^2/N_{DOF} = 8.82/4, p-value = 6%

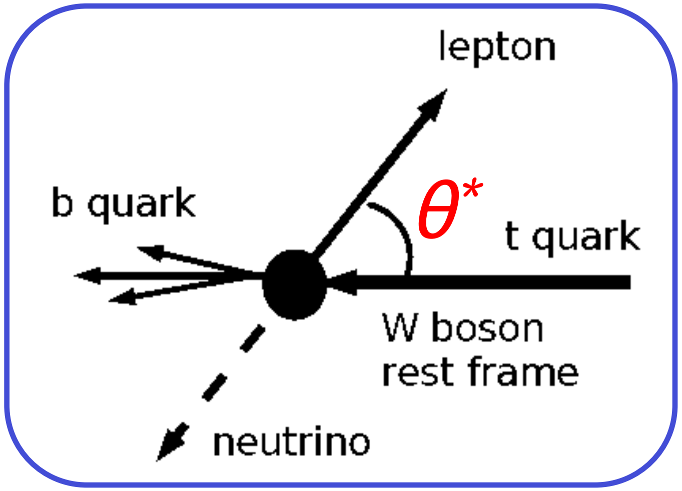
Wtb AC from single top + W helicity

Combination of single top + W helicity



Scenario	only W helicity	only single top	combination
$\|f_V^R\|^2$	0.62	0.89	0.30
$\|f_T^L\|^2$	0.14	0.07	0.05
$\|f_T^R\|^2$	0.18	0.18	0.12

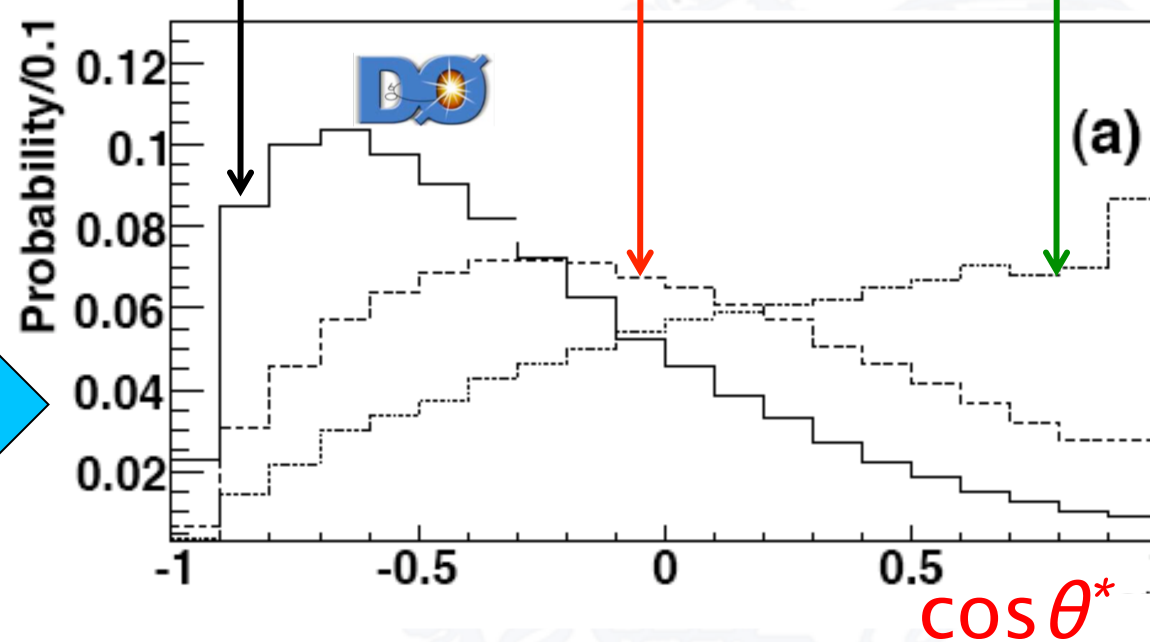
- Study the *V-A* nature of the *Wtb* coupling
  - Deviations from SM would indicate new physics



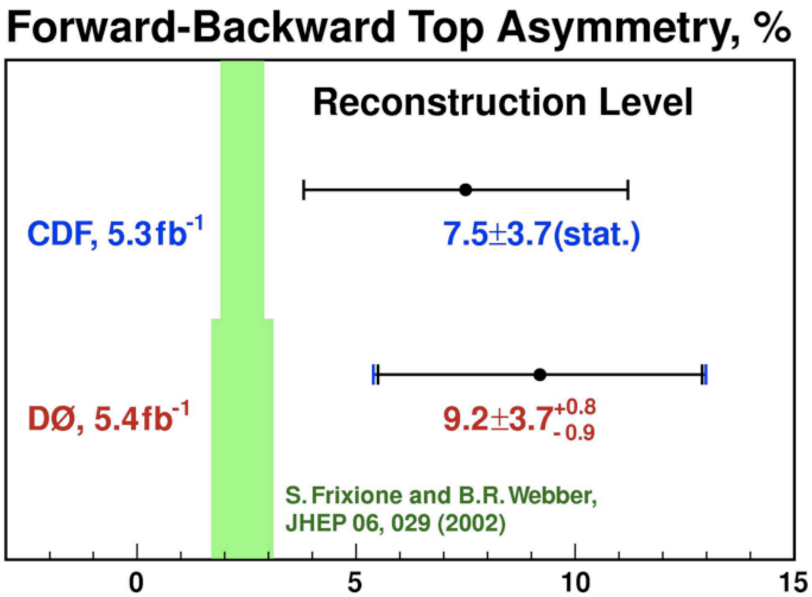
$f_- = 30.1\%$ (NLO)

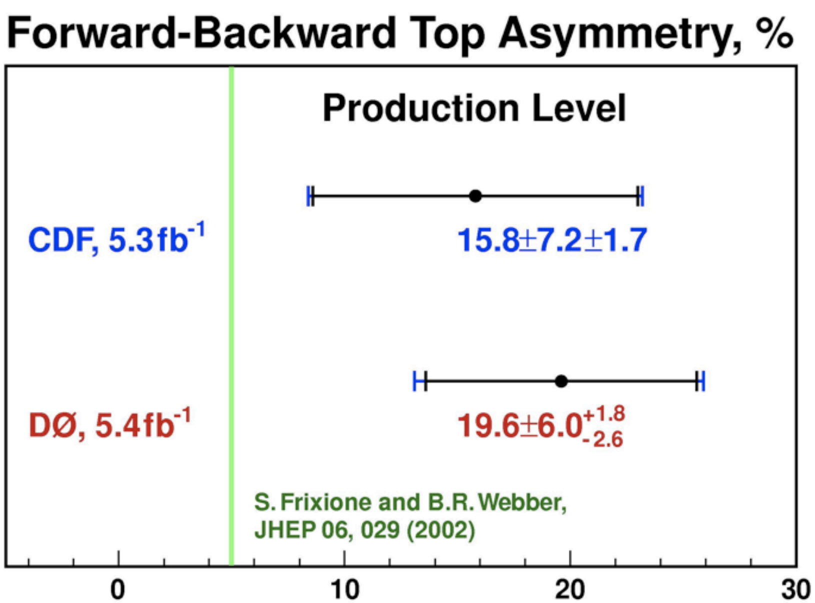
$f_+ = 0.04\%$ (NLO)

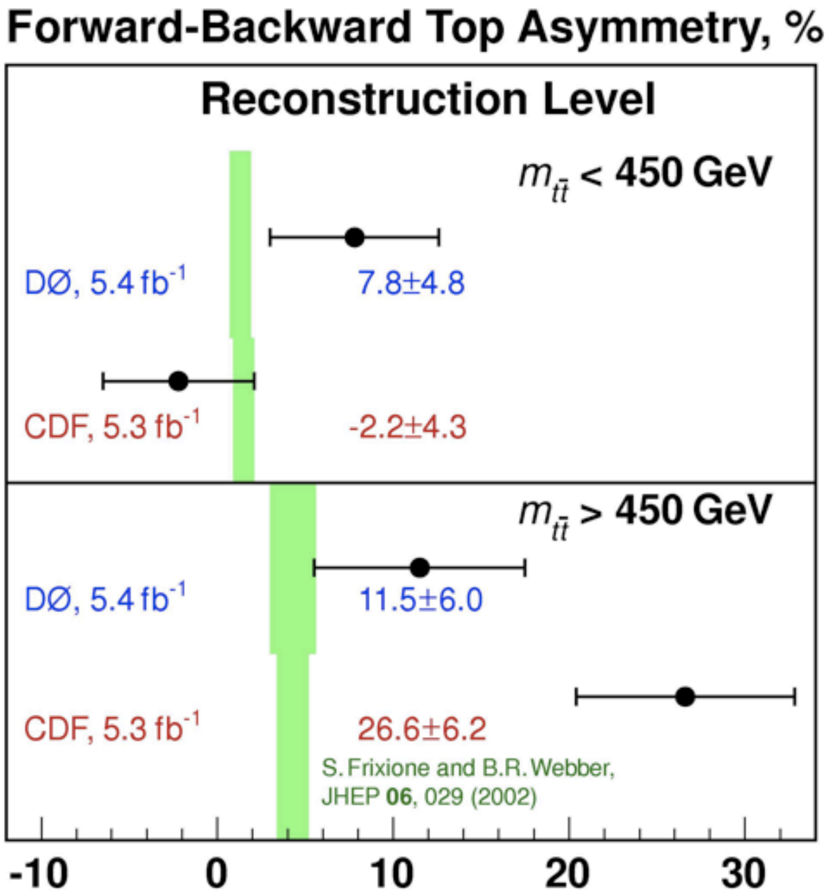
$f_0 = 69.8\%$ (NLO)



Colour Charge Asymmetry (A_{FB})







There is a new measurement of A_{FB} by CDF (arXiv:1211.1003, 9.3 fb^{-1})
→ comparison plots are not available yet

- **Invariance** under **Lorentz** transformation is a **fundamental property of the SM**
  - Thoroughly tested in the leptonic sector and for first generation, some tests for second generation, b-system
  - Quantify **Lorentz invariance violation (LIV)** in the top sector using in the **SM Extension formalism**:

$$|\mathcal{M}|^2_{\rm SME} = PF\bar{F} + (\delta P)F\bar{F} + P(\delta F)\bar{F} + PF(\delta\bar{F})$$

P *@ prod'n vertex* F *@ decay vertex* δ *Dependence on SM extension coefficiencts*

[D. Colladay and V.A. Kostelecky, Phys. Rev. D 58, 116002 (1998)]
[V.A. Kostelecky, Phys. Rev. D 69, 105009 (2004)]

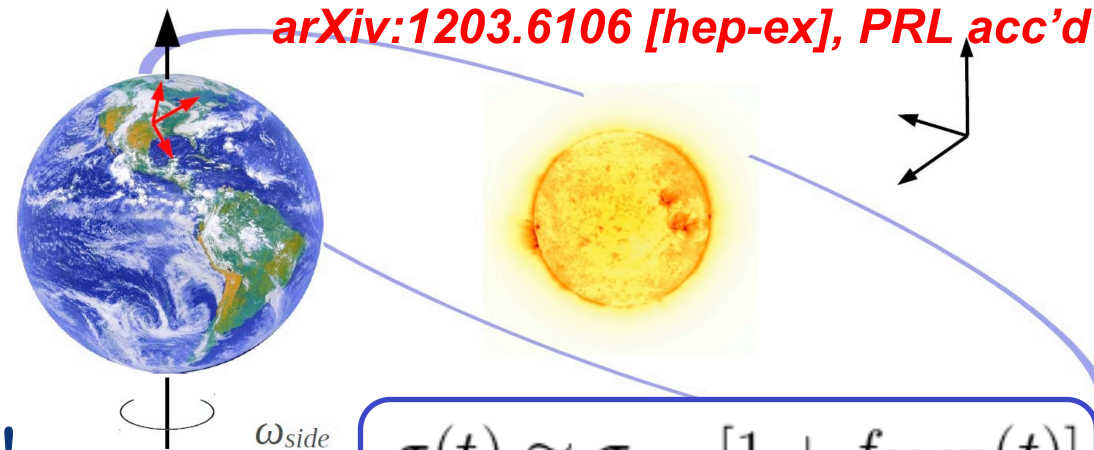
  - Parametrise LIV $f_{\rm SME}(t)$ in terms of coefficients $C_{\mu\nu}$:
    - $f_{\rm SME}(t) = C_{\mu\nu} R^{\mu}_{\alpha}(t) R^{\nu}_{\beta}(t) A^{\alpha\beta}$
  - Non-zero $C_{\mu\nu}$ will result in **time dependent *tt* production** due to the **rotation of the Earth!**

arXiv:1203.6106 [hep-ex], PRL acc'd

Lorentz invariance violation

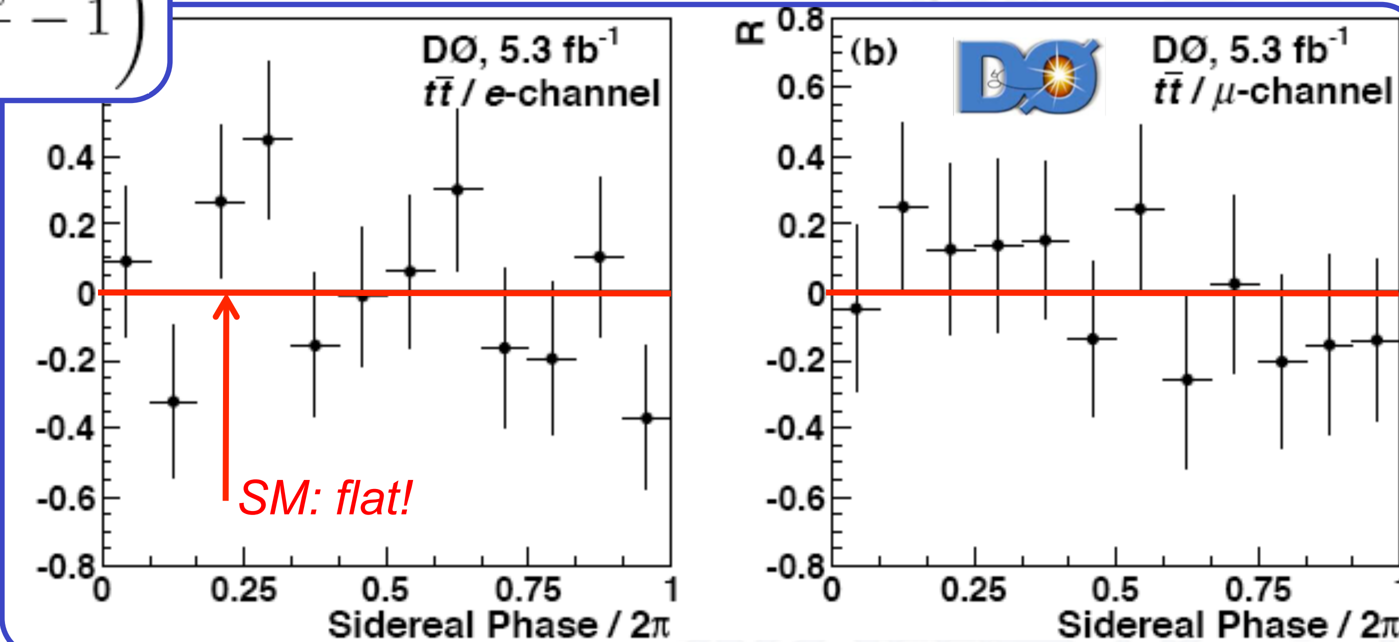
arXiv:1203.6106 [hep-ex], PRL acc'd

- The period is 1 or ½ siderial day
  - 1 Solar day $\approx$ 0.997 siderial day
  - Use time stamp to check perodicity!

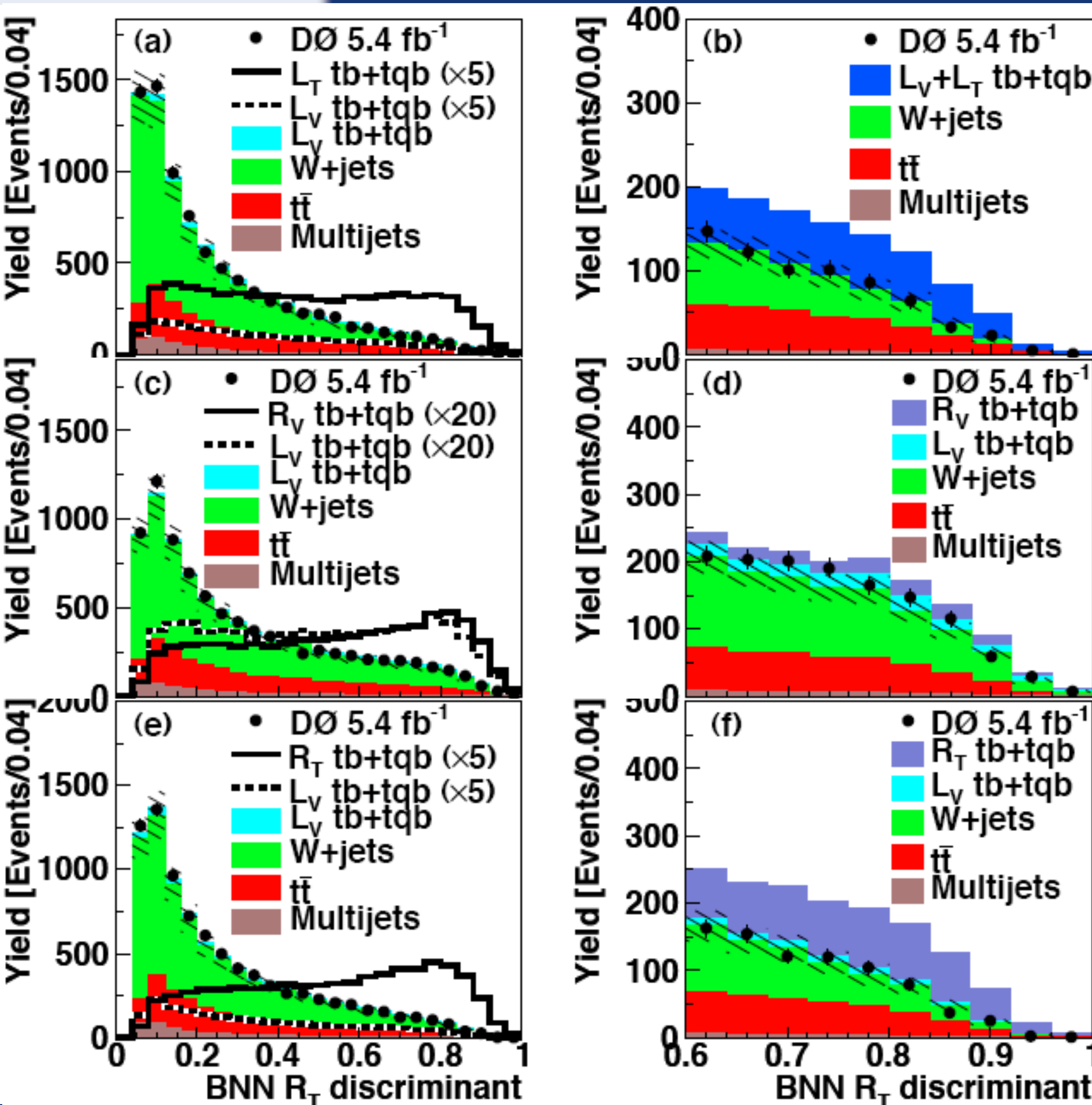


$$\sigma(t) \approx \sigma_{\text{ave}} \left[1 + f_{\text{SME}}(t)\right]$$

$$R_i \equiv \frac{1}{f_S} \left(\frac{N_i / N_{\text{tot}}}{\mathcal{L}_i / \mathcal{L}_{\text{int}}} - 1 \right)$$



Wtb AC from single top prod’n

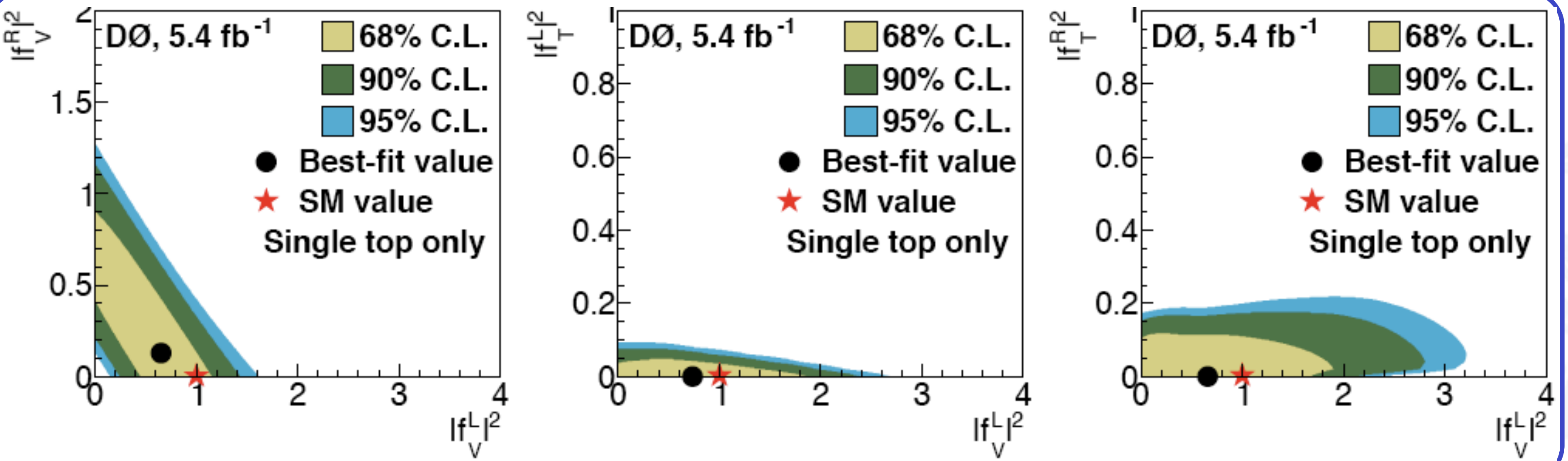


[arXiv:1110.4592]

Wtb AC from single top prod'n

- **Obtained limits:**

Limits on Wtb AC from single top production

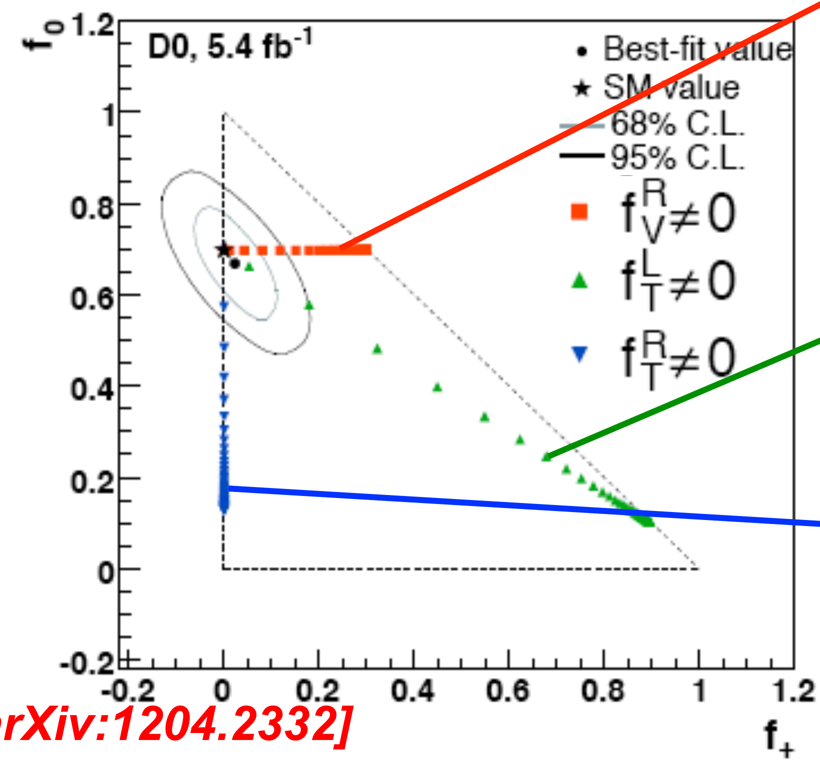


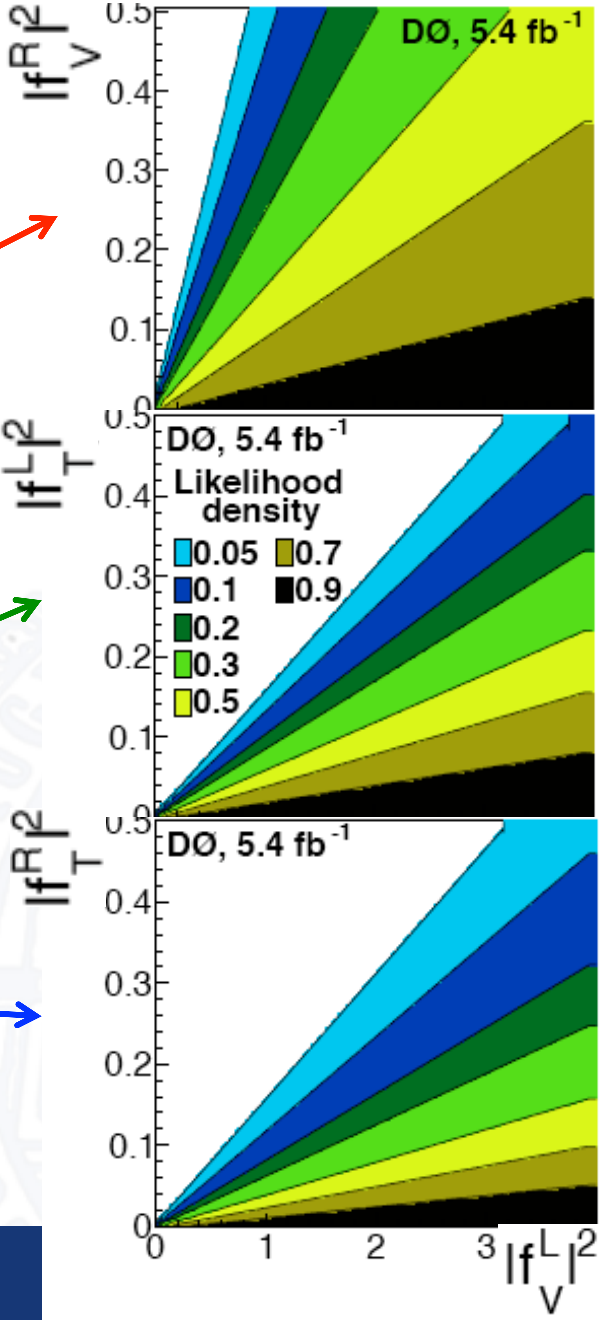
Using events orthogonal to W helicity meas't ONLY

[arXiv:1110.4592]

Wtb AC from single top + W helicity

- **Wtb AC will alter:**
  - single top production (see previous slides)
  - fractions of W bosons in the 3 helicity states:



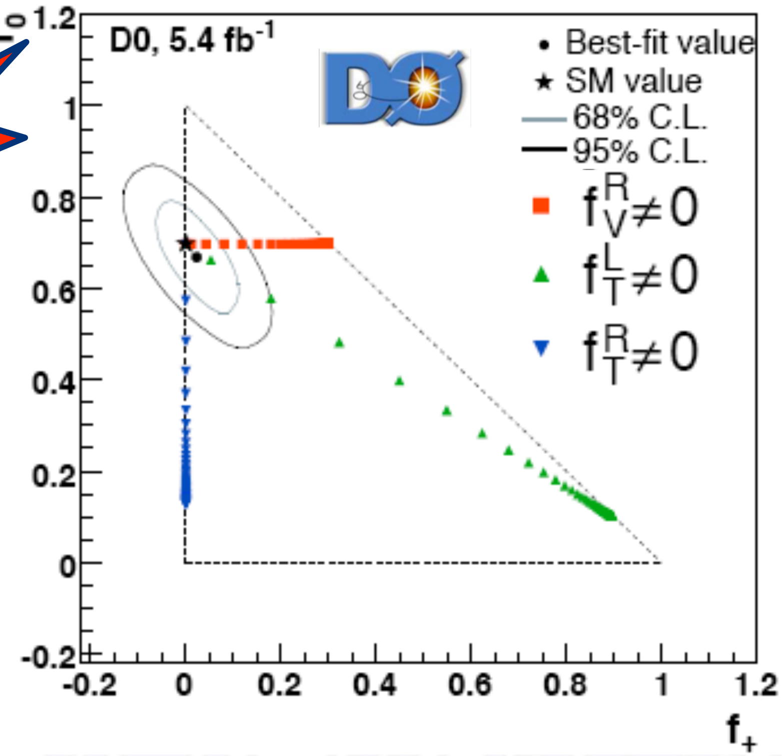


[arXiv:1204.2332]

Wtb AC from single top + W helicity

- ***Wtb* AC will alter:**
  - single top production (see previous slides)
  - fractions of W bosons in the 3 helicity states

combine!



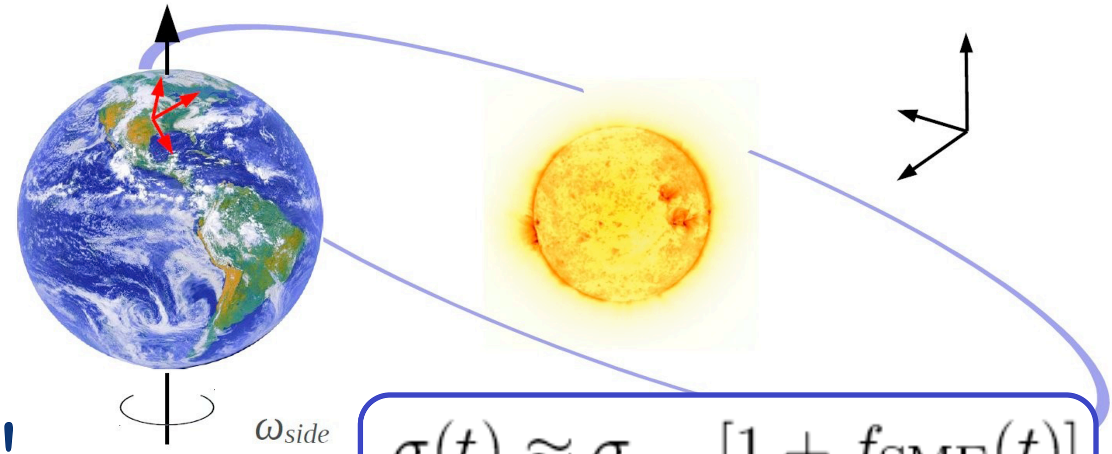
- **Assume:**
  - Single top production through *Wtb* vertex exclusively
  - $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$

- Use the LH from W helicity meas't as prior for single top
  - Compute LH over all possible analysis channels
  - Remove overlap between selections

arXiv:1204.2332 [hep-ex], PLB acc'd

Lorentz invariance violation

- The period is 1 or ½ siderial day
  - 1 Solar day $\approx$ 0.997 siderial day
  - Use time stamp to check perodicity!



$$\sigma(t) \approx \sigma_{\text{ave}}\left[1 + f_{\text{SME}}(t)\right]$$

TABLE III: Limits on SME coefficients at the 95% C.L., assuming $(c_U)_{\mu\nu} \equiv 0$.

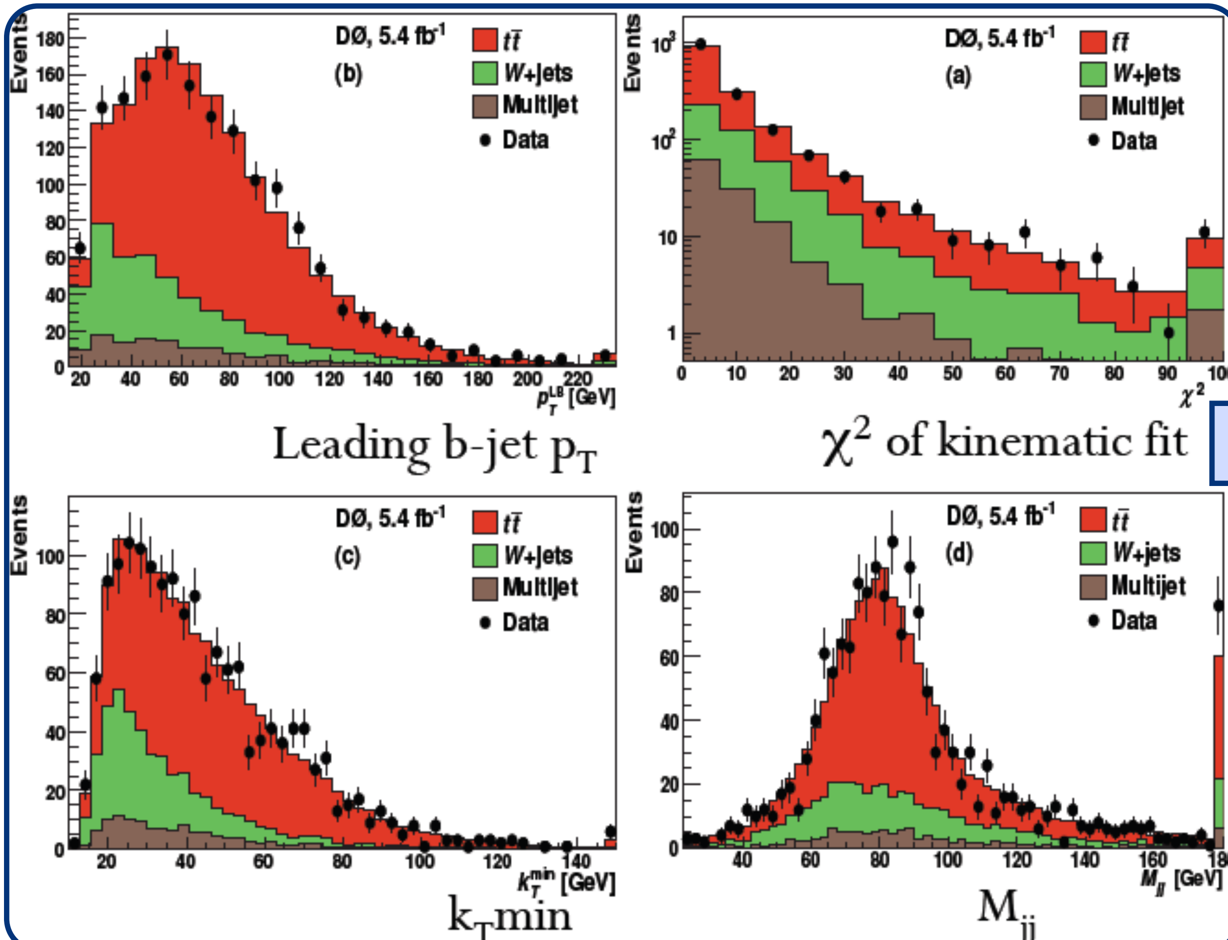
Coefficient	Value ± Stat. ± Sys.	95% C.L. Interval
$(c_Q)_{XX33}$	$-0.12 \pm 0.11 \pm 0.02$	$[-0.34, +0.11]$
$(c_Q)_{YY33}$	$0.12 \pm 0.11 \pm 0.02$	$[-0.11, +0.34]$
$(c_Q)_{XY33}$	$-0.04 \pm 0.11 \pm 0.01$	$[-0.26, +0.18]$
$(c_Q)_{XZ33}$	$0.15 \pm 0.08 \pm 0.02$	$[-0.01, +0.31]$
$(c_Q)_{YZ33}$	$-0.03 \pm 0.08 \pm 0.01$	$[-0.19, +0.12]$

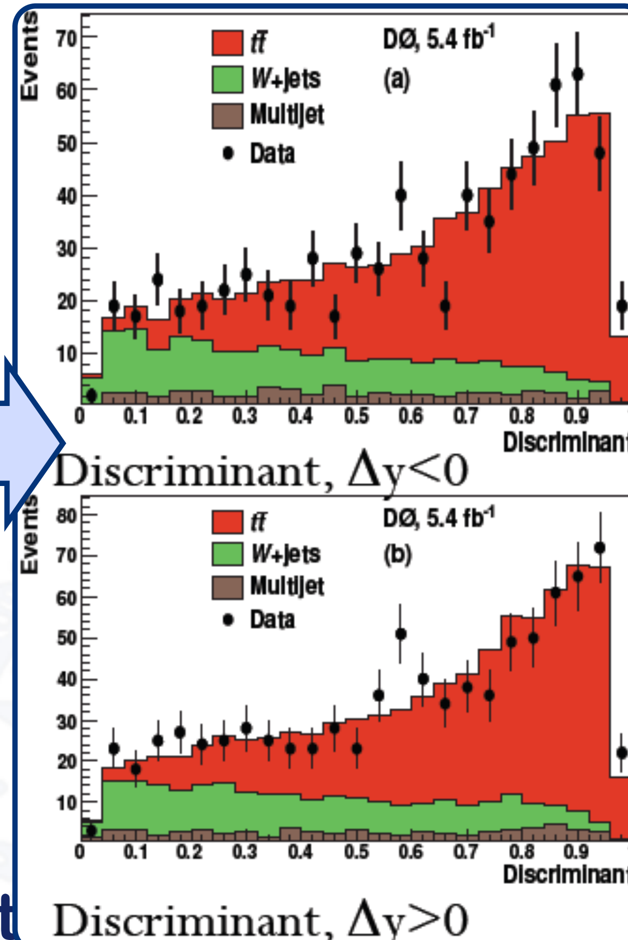
TABLE IV: Limits on SME coefficients at the 95% C.L., assuming $(c_Q)_{\mu\nu} \equiv 0$.

Coefficient	Value ± Stat. ± Sys.	95% C.L. Interval
$(c_U)_{XX33}$	$0.10 \pm 0.09 \pm 0.02$	$[-0.08, +0.27]$
$(c_U)_{YY33}$	$-0.10 \pm 0.09 \pm 0.02$	$[-0.27, +0.08]$
$(c_U)_{XY33}$	$0.04 \pm 0.09 \pm 0.01$	$[-0.14, +0.22]$
$(c_U)_{XZ33}$	$-0.14 \pm 0.07 \pm 0.02$	$[-0.28, +0.01]$
$(c_U)_{YZ33}$	$0.01 \pm 0.07 \pm < 0.01$	$[-0.13, +0.14]$

[arXiv:1203.6106]

- **Strong Colour charge asymmetry (D0, 5.4 fb^{-1})**





$$\Delta y>0 \qquad \Delta y<0$$

$$A = (9.2 \pm 3.6^{+0.8}_{-0.9})\% \Leftrightarrow A(MC@NLO) = (2.4 \pm 0.3^{+0.7}_{-0.5})\%$$

	$l+\geq4$ jets	$e+\geq4$ jets	$\mu+\geq4$ jets	$l+4$ jets	$l+\geq5$ jets
Raw N_{F}	849	455	394	717	132
Raw N_{B}	732	397	335	597	135
$N_{t\bar{t}}$	1126 ± 39	622 ± 28	502 ± 28	902 ± 36	218 ± 16
$N_{W+\mathrm{jets}}$	376 ± 39	173 ± 28	219 ± 27	346 ± 36	35 ± 16
N_{MJ}	79 ± 5	56 ± 3	8 ± 2	66 ± 4	13 ± 2
$A_{\mathrm{FB}}(\%)$	9.2 ± 3.7	8.9 ± 5.0	9.1 ± 5.8	12.2 ± 4.3	-3.0 ± 7.9
MC@NLO A_{FB} (%)	2.4 ± 0.7	2.4 ± 0.7	2.5 ± 0.9	3.9 ± 0.8	-2.9 ± 1.1

	$l+\geq4$ jets	$e+\geq4$ jets	$\mu+\geq4$ jets	$l+4$ jets	$l+\geq5$ jets
Raw N^{l}_{F}	867	485	382	730	137
Raw N^{l}_{B}	665	367	298	546	119
$N_{t\bar{t}}$	1096 ± 39	622 ± 28	474 ± 27	881 ± 36	211 ± 16
$N_{W+\mathrm{jets}}$	356 ± 39	173 ± 28	198 ± 27	323 ± 36	31 ± 16
N_{MJ}	79 ± 5	56 ± 3	8 ± 2	66 ± 4	14 ± 2
A^{l}_{FB} (%)	14.2 ± 3.8	16.5 ± 4.9	9.8 ± 5.9	15.9 ± 4.3	7.0 ± 8.0
MC@NLO A^{l}_{FB} (%)	0.8 ± 0.6	0.7 ± 0.6	1.0 ± 0.8	2.1 ± 0.6	-3.8 ± 1.2

m_{top} in dilepton channel (DØ)

- **Template method, 4.7 fb^{-1} (DØ):**
  - m_{top} free parameter → dilepton events are kinematically underconstrained
  - Use the so-called neutrino-weighting algorithm:
    - Postulate eta-distributions of neutrinos from MC
    - Calculate weight distribution vs. m_{top}
    - Use 1st and 2nd moment of this distribution to form templates
  - Apply in-situ JES calibration from l+jets channel:

$$1.013 \pm 0.008(\text{stat})$$

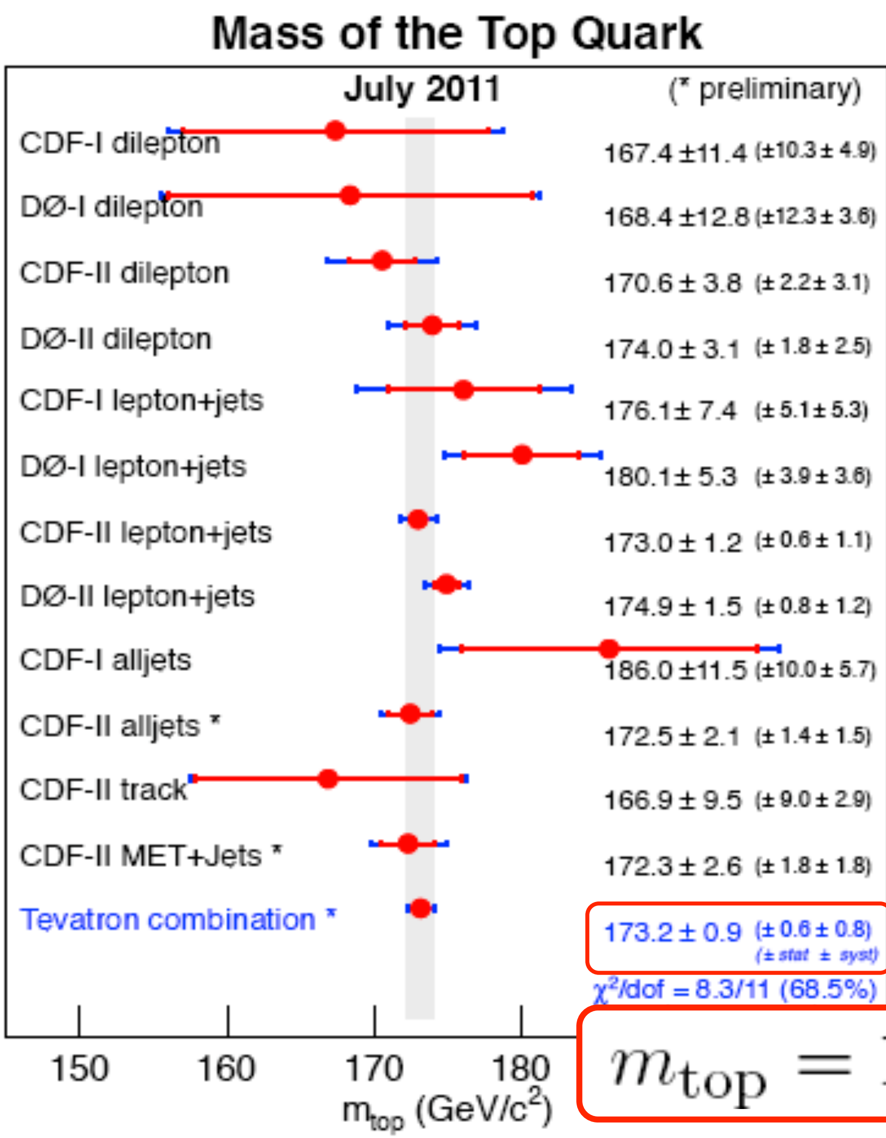
    - Caveat:
      k_{JES} can be final state-dependent, so we derive a dedicated response correction
  - Final result:

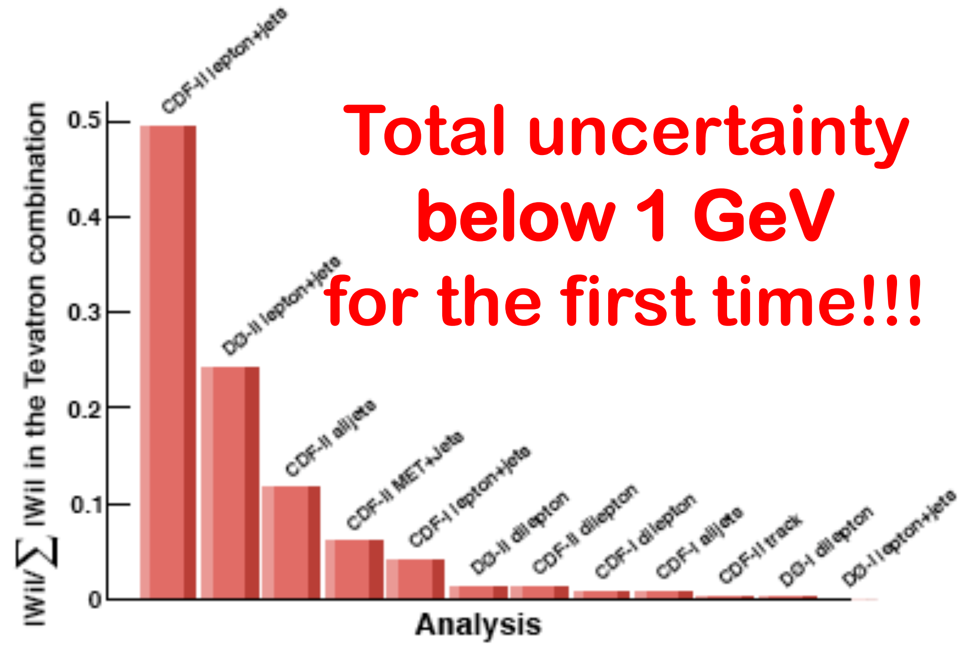
$$m_t = 174.0 \pm 2.4(\text{stat}) \pm 1.4(\text{syst})\ \text{GeV}$$

arXiv:1201.5172 [hep-ex] (2011)

Best Tevatron dilepton result!

Tevatron Combination





Total uncertainty below 1 GeV for the first time!!!

$$m_{\text{top}} = 173.2 \pm 0.6\,(\text{stat}) \pm 0.8\,(\text{syst})$$

arXiv:1107.5255 [hep-ex]

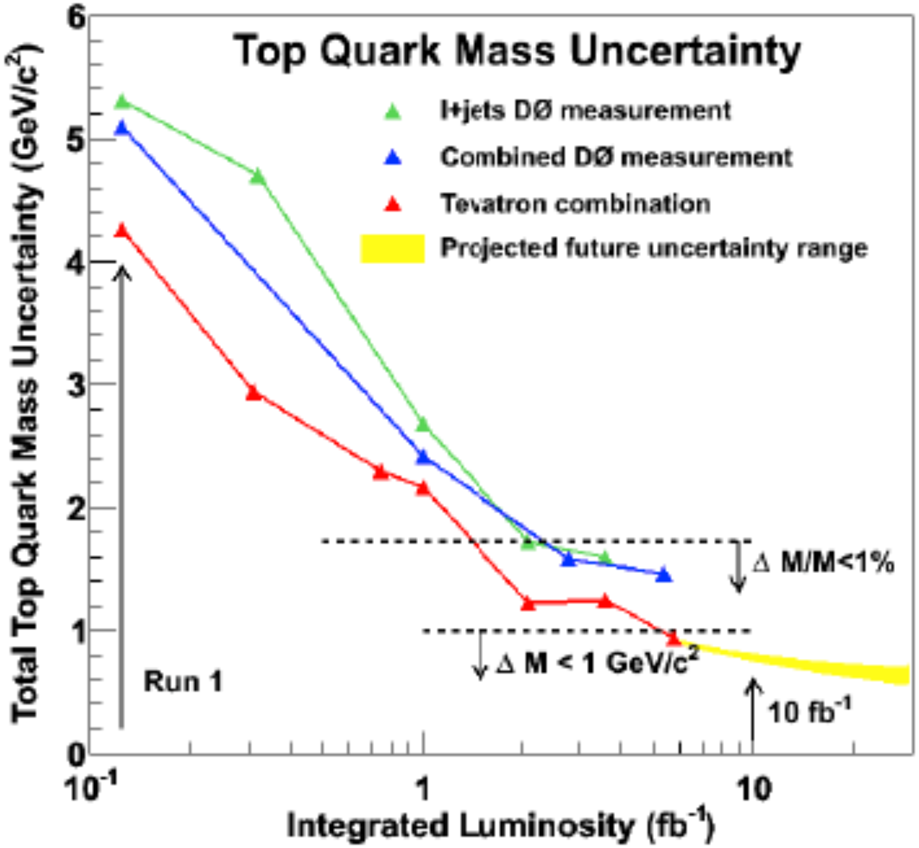
Tevatron Combination

	Tevatron combined values (GeV/c^2)
m_t	173.18
iJES	**0.39**
aJES	0.09
bJES	0.15
cJES	0.05
dJES	**0.20**
rJES	0.12
Lepton p_T	0.10
Signal	**0.51**
Detector Modeling	0.10
UN/MI	0.00
Background from MC	0.14
Background from Data	0.11
Method	0.09
MHI	0.08
Systematics	0.75
Statistics	0.56
Total	0.94

In-situ JES calibration ~ 1/√N (iJES)

Size of calibration samples ~ 1/√N (dJES)

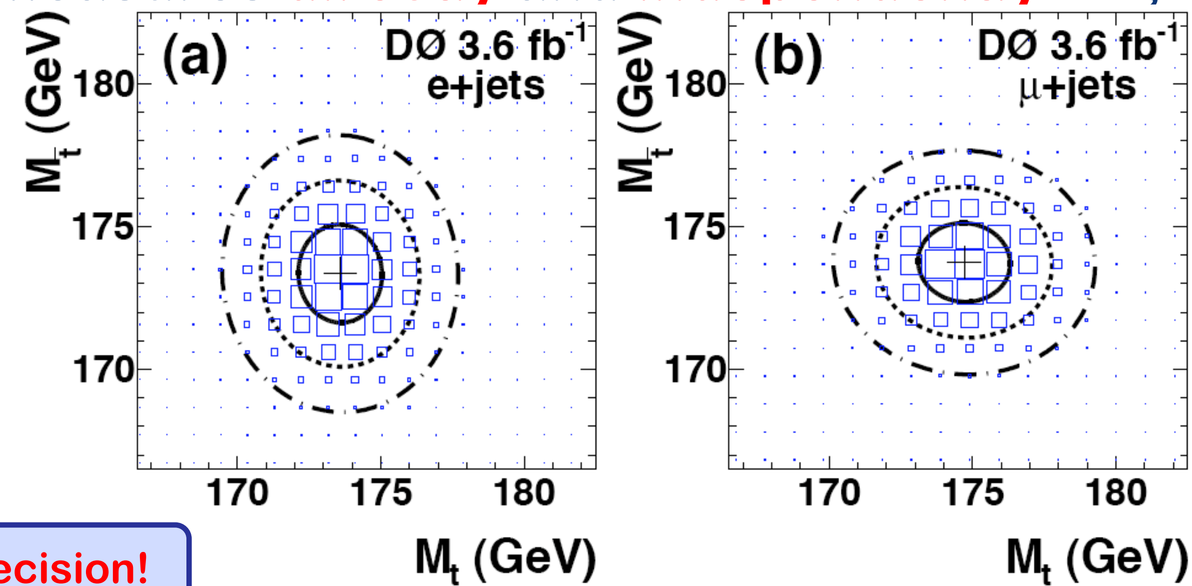
Various signal modeling uncert. ~ √brain effort (Signal)



Relative uncertainty: 0.54%
Expect this limit to be improved…

Top-antitop mass difference meas't

- **CPT is essential for a locally Lorentz-invariant QFT**
  - $m_{particle}$!= $m_{antiparticle}$ → CPT violated!
    - Top is the only quark where this test is pc $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s
  - DØ measures directly and independe m_t, $m_{\bar{t}}$, (ME):



<1% relative precision!

$$\Delta m \equiv m_t - m_{\bar{t}} = 0.8 \pm 1.8\ (\text{stat}) \pm 0.5\ (\text{syst})\ \text{GeV}$$

$$\Delta m \qquad \frac{m_t + m_{\bar{t}}}{2} \equiv 172.5\ \text{GeV}$$

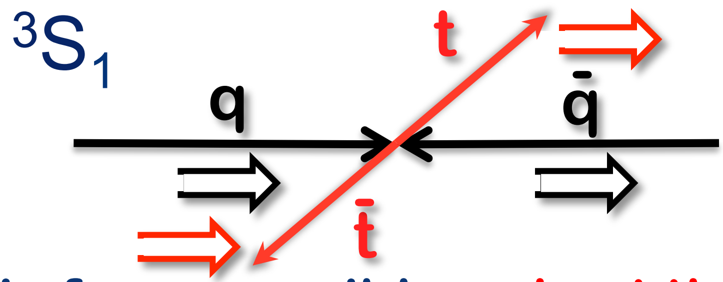
$$\Delta m = -1.95 \pm 1.11\ (\text{stat}) \pm 0.59\ (\text{syst})\ \text{GeV}$$ (8.7 fb^{-1})

  - CDF measures directly with

D0: Phys. Rev. D **84**, 052005 (2011)
CDF: Conf-Note 10777 (2012)

Top-antitop spin correlations

- $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s < hadronisation time
  - Decay products carry info about spin of tt system

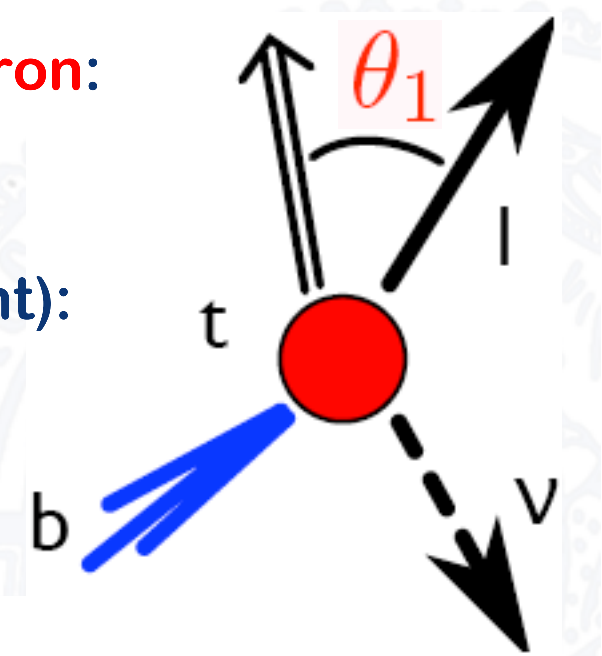


$+\ ^1S_0$ (15%)

  - In this form possible only at the Tevatron:
    - High qq fraction (LHC: ~10%)
    - production at threshold dominates
  - Correlation strength (frame dependent):

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

  - Analyse it using angular info:



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

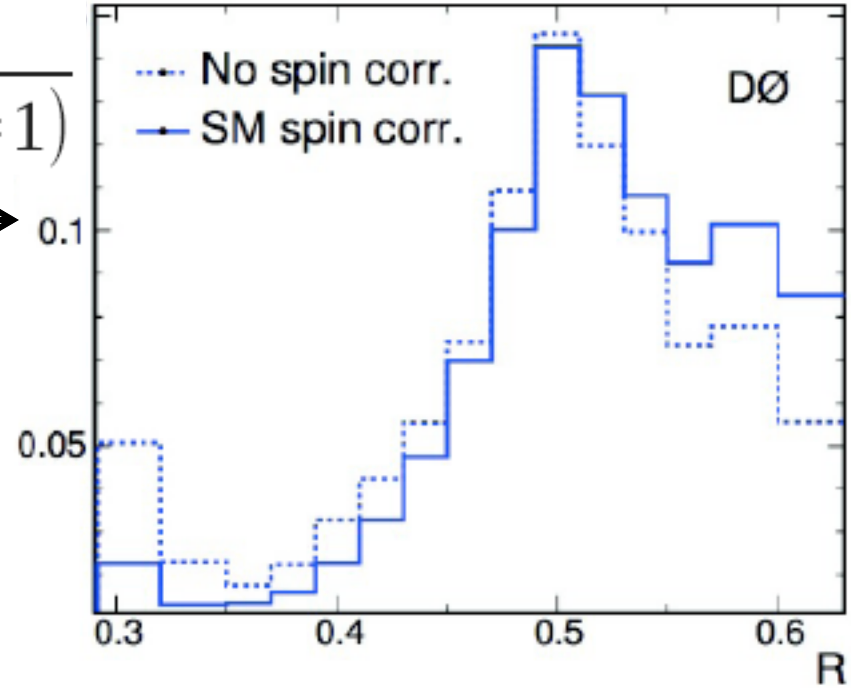
(for dilepton channel case)

Spin correlations w. matrix element

- **How can we adopt the superior matrix element* (ME) technique for the spin correlation measurement?**
  - **Melnikov and Schulze (PLB 700, 17 (2011)):**

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

  - **Construct templates in R** →



  - **Observable:**
    - **Fraction of events with spin corr.:**

$$f = \frac{N_{t\bar{t}}(w./spin\,correlation)}{N_{t\bar{t}}(all)}$$

  - **Translates into C → f * C_{SM}**
    - **i.e. SM pred'n is f = 1**

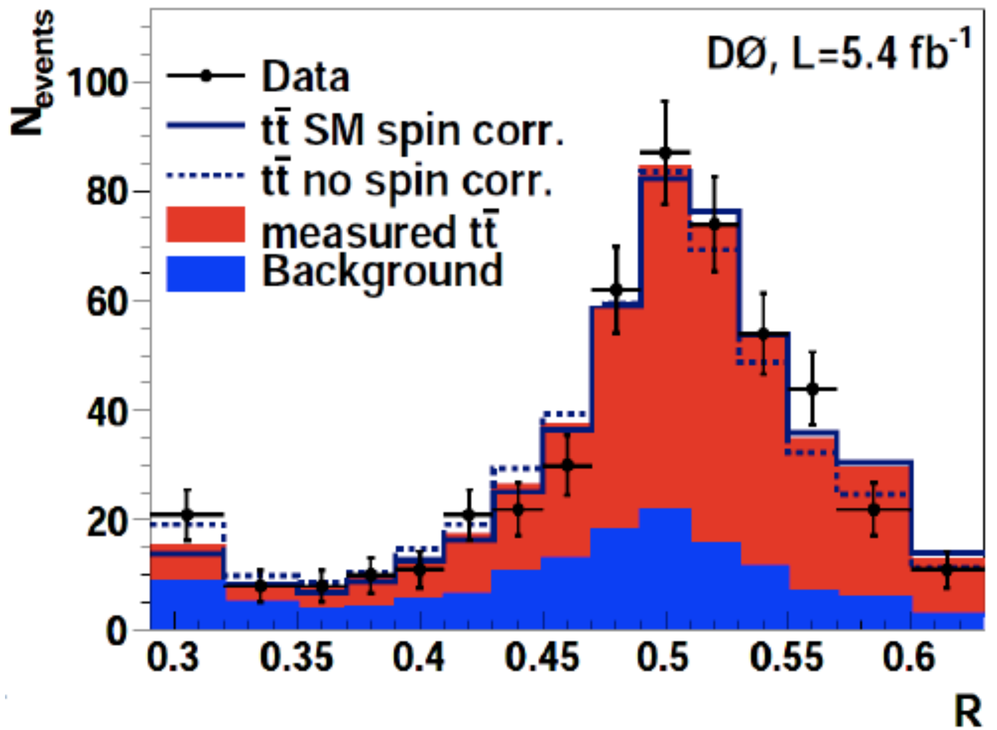
** I will discuss the ME technique in detail in the context of m_{top} meas't*
Here: it gives probability P(x,H) that a given event came from the process described by the ME, given observed kinematics x and hypothesis H

Spin correlations w. matrix element

- Take ME from Mahlon & Parke (PLB 411, 173 (1997)):

$$\sum |(M)|^2 = \frac{1+H}{2}\frac{g_s^4}{9}F\overline{F}(2-\beta^2 s_{qt}^2) - H\frac{g_s^4}{9}F\overline{F}\Delta$$

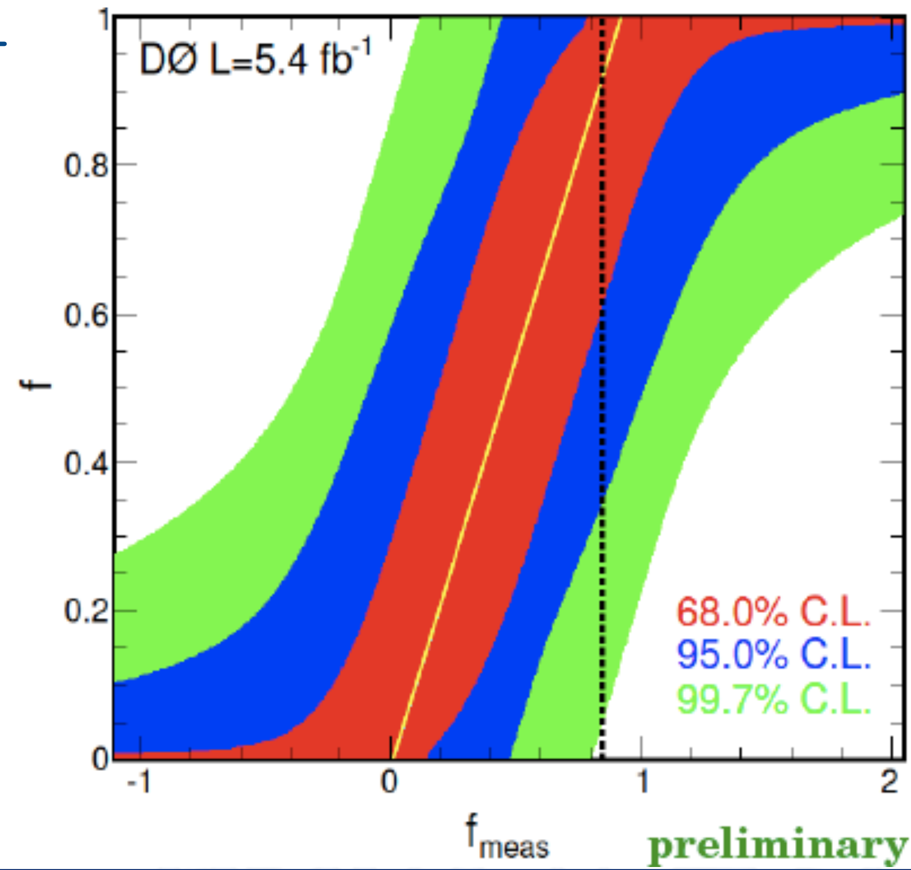
  - H=1: correlated spins
  - H=0: uncorrelated spins
- Perform measurement:
  - Dilepton channel
  - mc@nlo generator
  - dataset as 2 slides ago
- Use binned LH fit with nuisance parameters



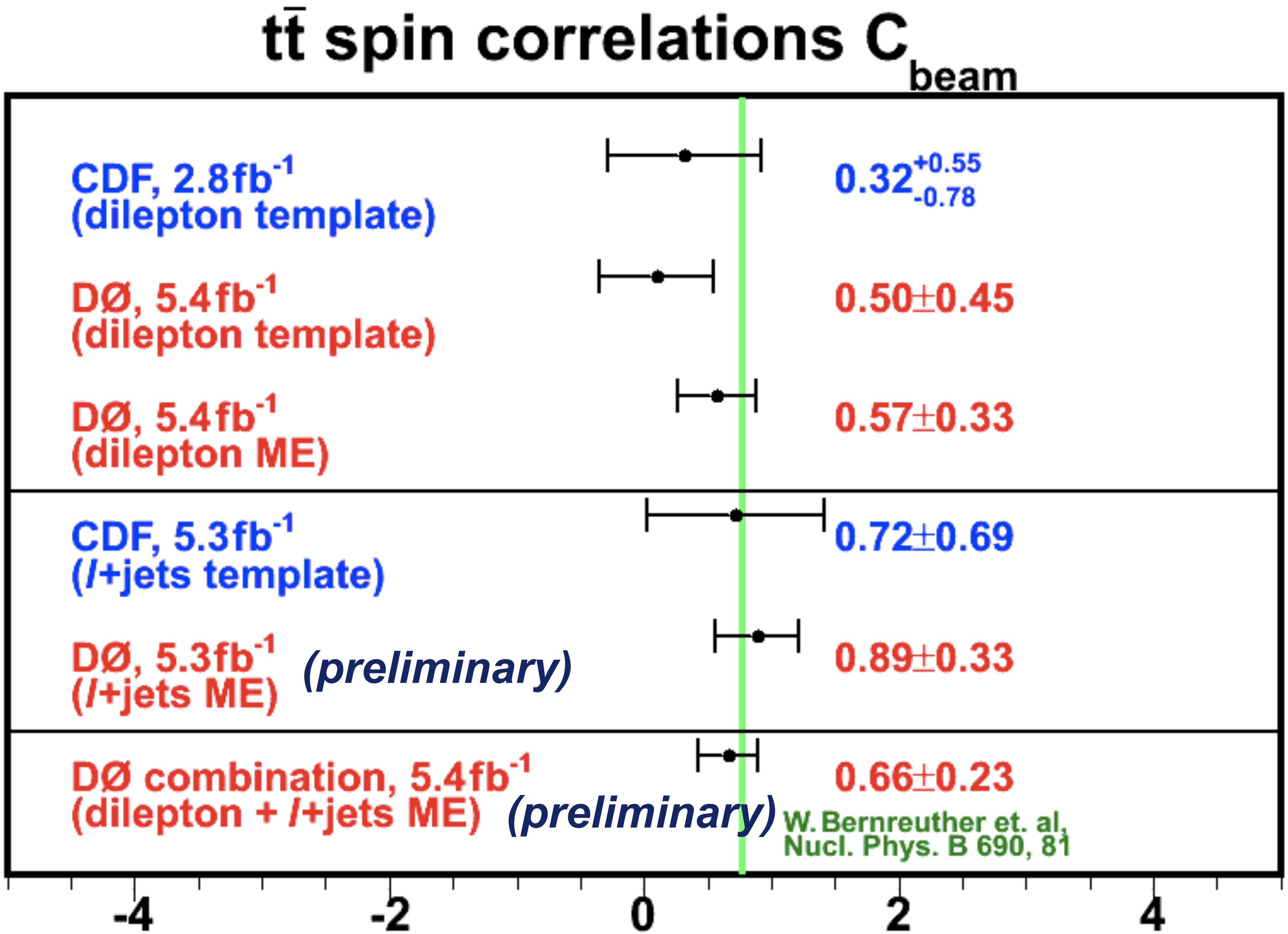
- We obtain:
  - f = 0.74 ± 0.41 (stat+syst)
  - f > 0.14 @ 95% CL
  - f=0 excluded at 97.7% CL (99.6% exp.)
    - 30% more sensitivity!
      - But still statistically dominated (0.27)

Spin correlations w. matrix element

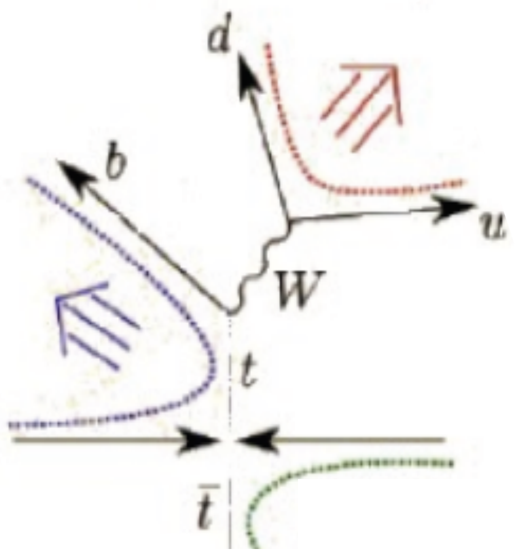
- Straight forward to extend the lepton+jets channel:
  - Same ME, mc@nlo as generator
  - Split in 4 and 4+ jet bins
  - Require two b-tags to reduce combinatorics (+ purity 90%)
  - Regard the other two hightes p_T jets as light jets
  - → four permutations
- Combine with dilepton result:
  - $f = 0.85 \pm 0.29$ (stat+syst)
  - $f < 0.34$ @ 95% CL
  - $f < 0.05$ @ 99.7% CL
  - $f = 0$ @ 3.1 SD !!!
    - First evidence for non-vanishing spin correlations!



Spin correlations Tevatron

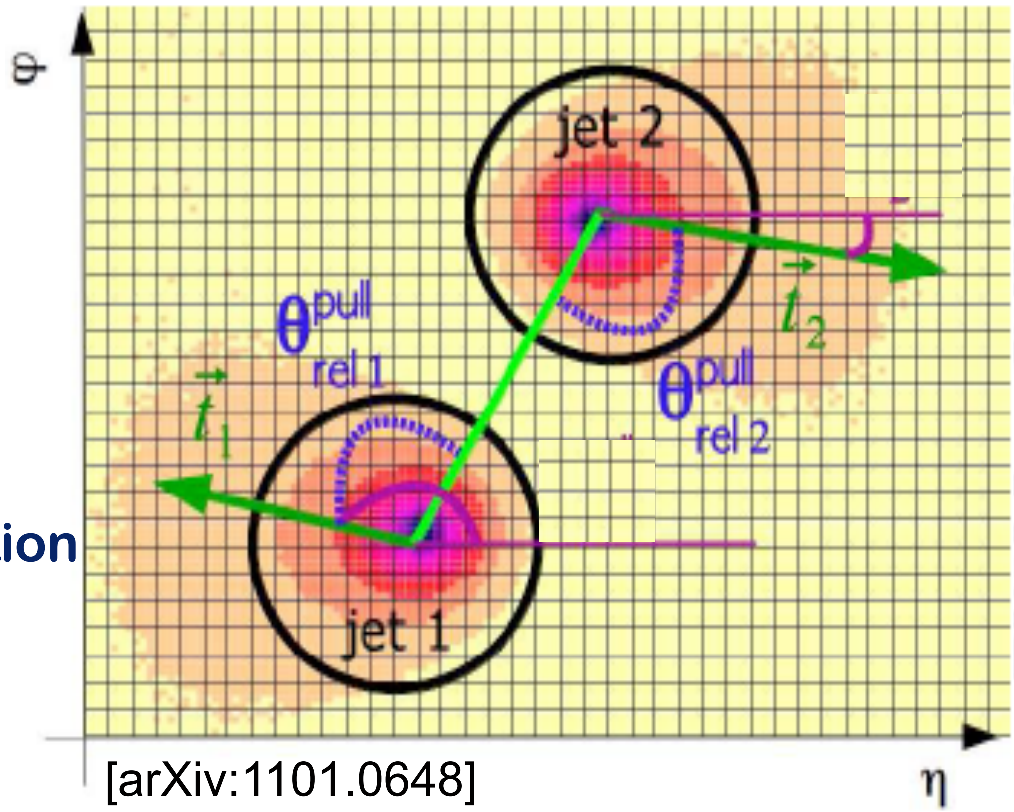


- **Use colour-connections as selection tool**
  - $H \rightarrow b\bar{b}$: colour singlet, $g \rightarrow b\bar{b}$ colour octet
  - tt events provide clean samples of W bosons (colour-singlet) and b-jets (colour-octet)



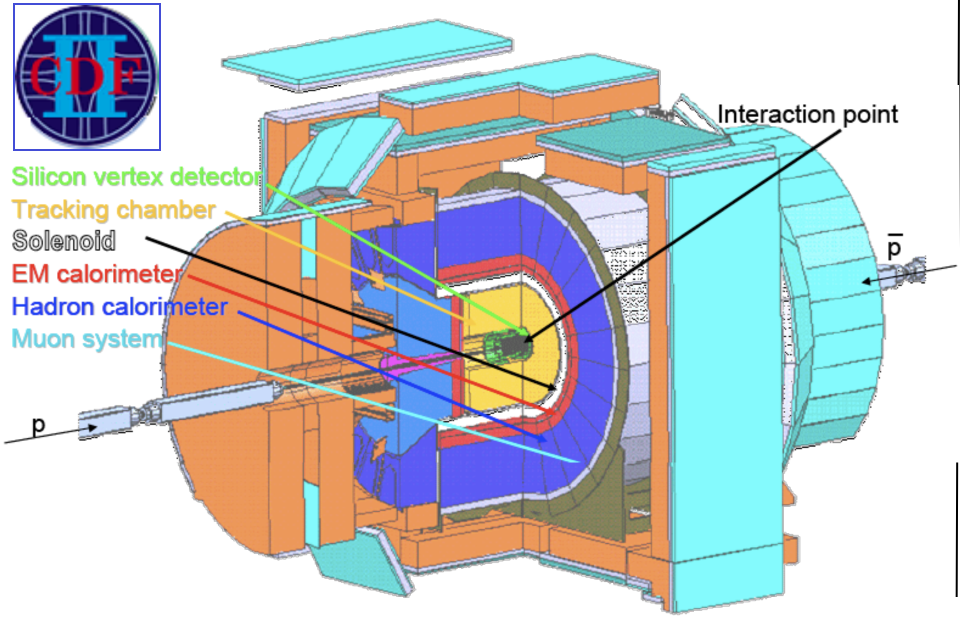
Fraction of W in singlet configuration

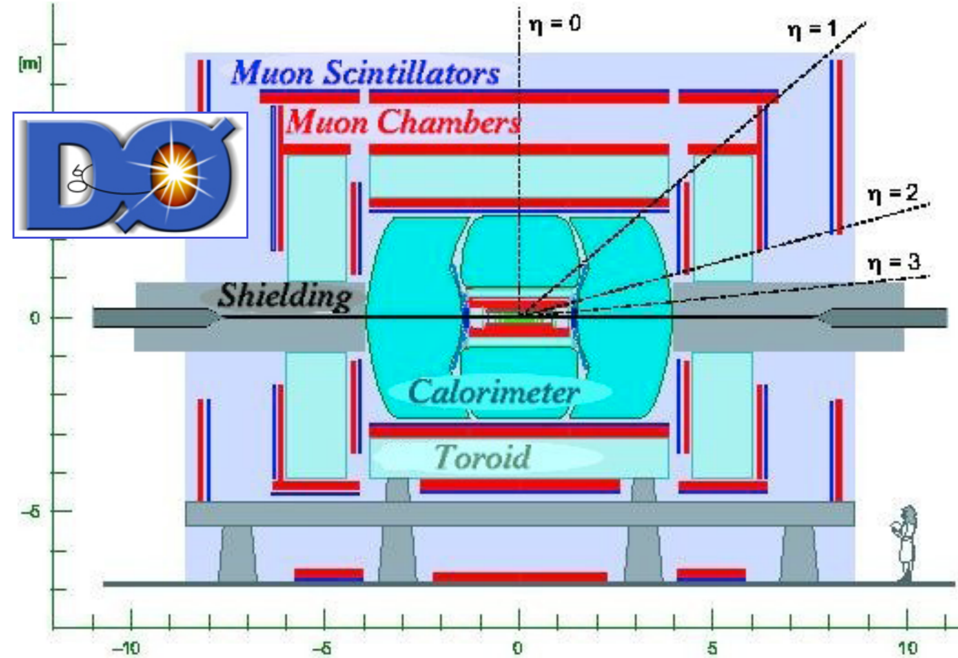
$$f_{\text{Singlet}} = 0.56 \pm 0.42$$
$$f_{\text{Singlet}} = 1 \text{ (SM)}$$



[arXiv:1101.0648]

The CDF and D0 detectors





	CDF	DØ
EM calorimeter	14%/√E + 1%	22%/√E + 4%
Hadronic calorimeter	70%/√E + 5%	68%/√E + 5%

The birth size

- 24 Feb. 1995:
  - Simultaneous PRL submission by CDF and DØ
- CDF (67 pb^{-1}) :
  - $\sigma=6.8^{+3.6}_{-2.4}$ pb,
  - observed 19 events, expected 6.9 bkg
    - bkg-only hypothesis rejected at 4.8σ
  - m_{top}=176±13 GeV
- D0 (50 pb^{-1}):
  - σ=6.4±2.2 pb,
  - observed 17 events, expected 3.8 bkg
    - → bkg-only hypothesis rejected at 4.6σ
  - m_{top}=199±30 GeV

The birth weight

- 24 Feb. 1995:
  - Simultaneous PRL submission by CDF and DØ
- CDF (67 pb^{-1}) :
  - $\sigma=6.8^{+3.6}_{-2.4}$ pb,
  - observed 19 events, expected 6.9 bkg
    - bkg-only hypothesis rejected at 4.8σ
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- D0 (50 pb^{-1}):
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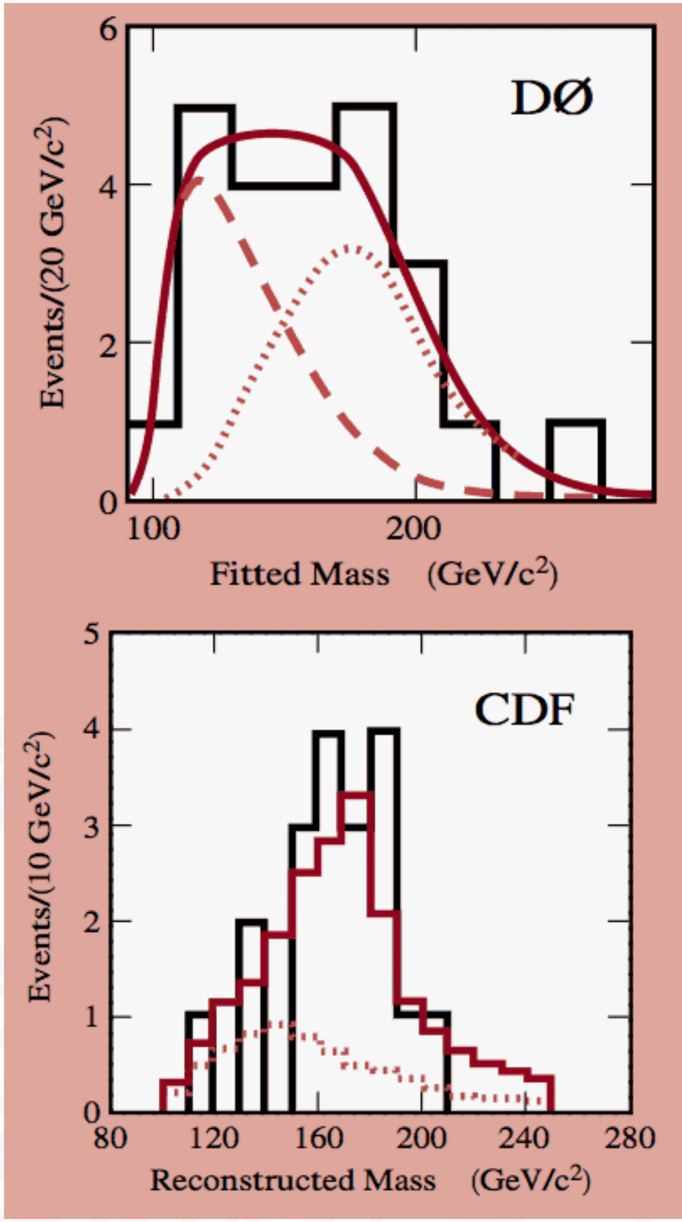
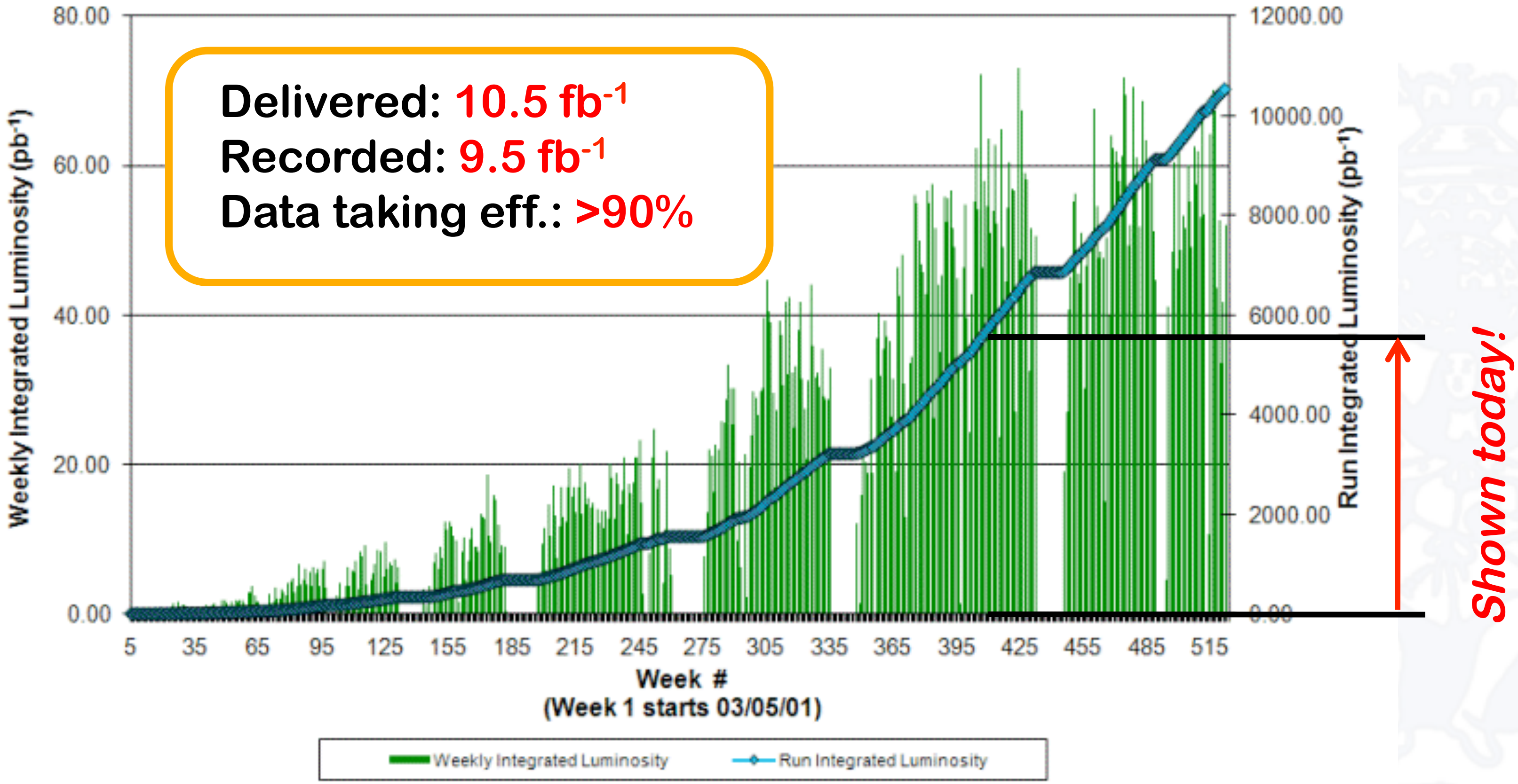


Analyzed dataset

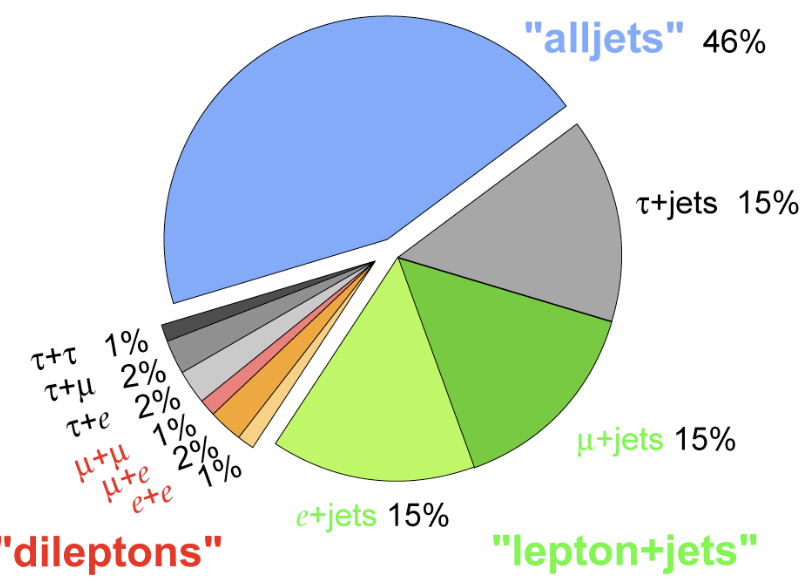
- Tevatron has shown a great performance in FY 2010!
- We keep enlarging our calibration samples
  - Better handles on experimental uncertainties:
    - e.g. Jet Energy Scale (JES), Jet Energy Resolution, etc.

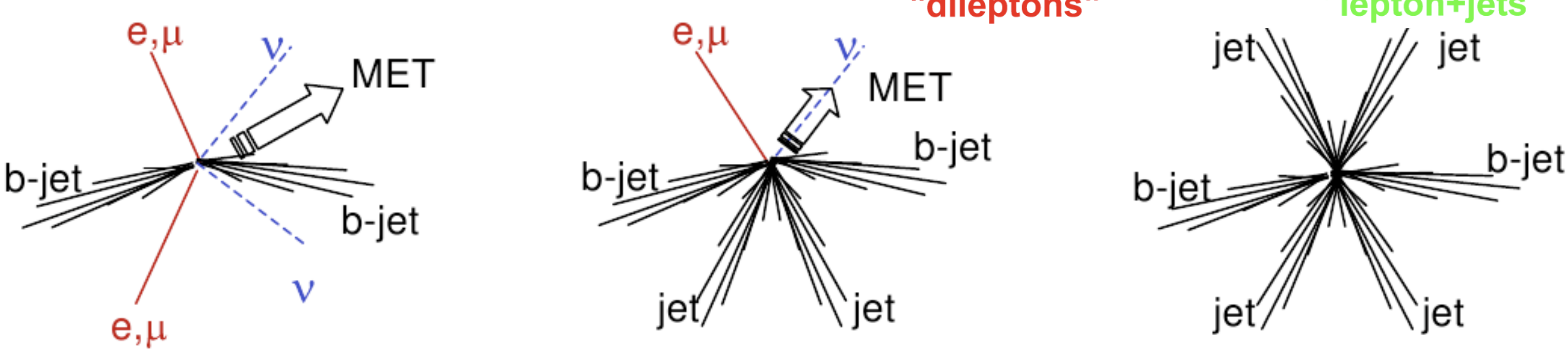


… and Decay

- **In the SM:**
  - **$|V_{tb}|$ = 0.9990-0.9992 @ 95% C.L. assuming 3 CKM generations**
- **Characterise tt final states by top decays!**

Top Pair Branching Fractions





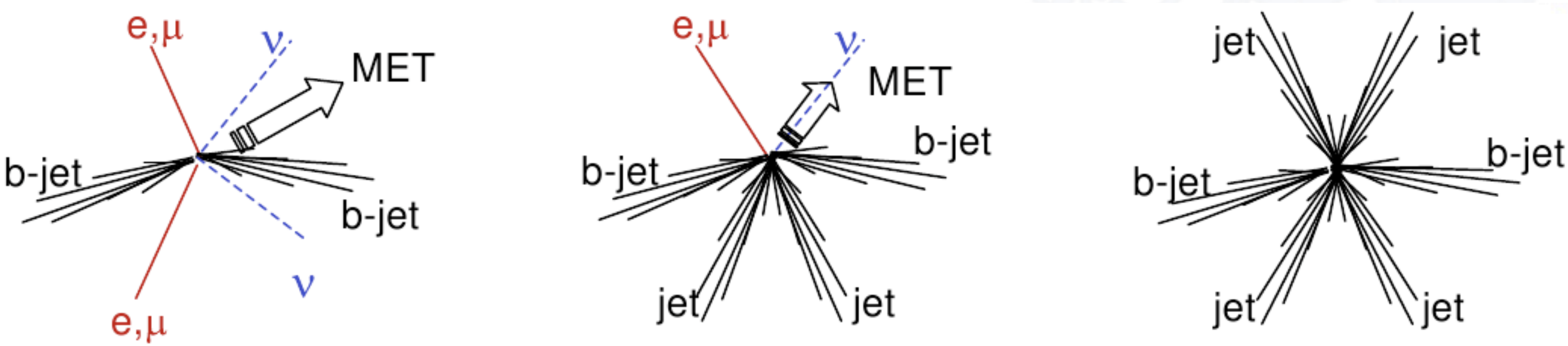
Dilepton (BR~5%, low bckg)

Lepton+jets (BR~30%, moderate bckg)

All-hadronic (BR~46%, huge bckg)

Typical ttbar preselection

Dilepton	Lepton+jets	All-hadronic
2 high-p_T leptons	1 high-p_T lepton (>20 GeV)	No leptons
Missing E_T	Missing E_T (>40 GeV)	No missing E_T
2 jets	4 jets (> 20GeV)	6 jets
≥ 0 b-tags	≥ 1 b-tag	≥ 1 b-tag
S/B:		



Dilepton
(BR~5%, low bckg)

Lepton+jets
(BR~30%, moderate bckg)

All-hadronic
(BR~46%, huge bckg)

Experimental Challenges

- We are interested in parton-level quantities for our top measurements
  - Map the energies of reco-level jets particle jets (D0) / partons (CDF)
  - This is referred to as a Energy Scale (JES) corr'n
  - With the current size of samples:
    - s(JES)/JES ~ 1.5% (D0)
    - s(JES)/JES ~ 3% (CDF)
- And many more:
  - Lepton ID, p_T scale