Top property measurements at the Tevatron

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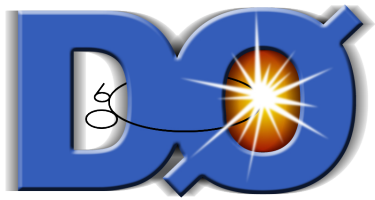
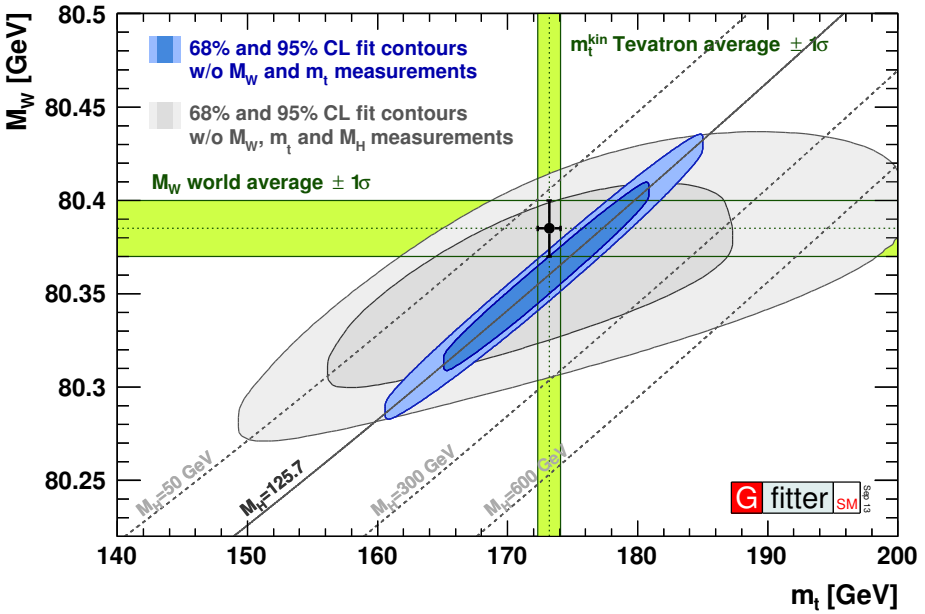


Today's measurements

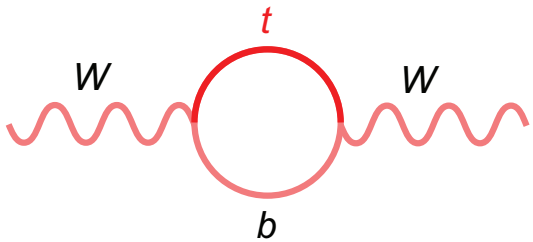
1. Top quark mass
2. $t\bar{t}$ production asymmetry

The top quark and its mass

- top quark is the heaviest among the observed particles
- it can be measured "naked": it decays before hadronizing
- its mass, m_t, is a free parameter of Standard Model:
  - present in loop corrections of W mass
  - with t, W and H masses, the SM predictions are severely tested
- a precise measurement helps understanding our models



Global fit of measurements in the SM [Oth1]



Measurement on dilepton decay channel

[Mass1]

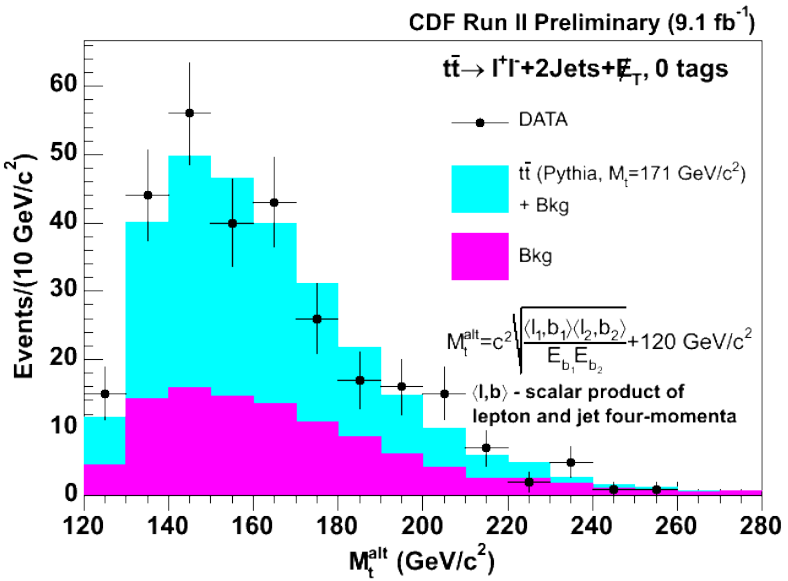
- process: $t\bar{t} \to b\ell\nu\, b\ell\nu$ (POWHEG)
- observable distributions compared to models with set m_t (*templates*):

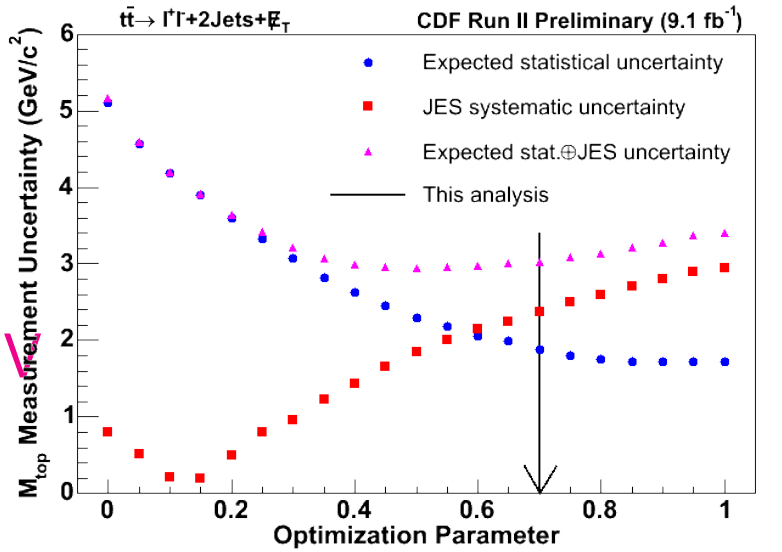
  M_t^{reco} most likely mass from kinematic reconstruction, sampling the whole $\nu \times \bar{\nu}$ undetected space

  M_t^{alt} based on ℓ/b directions and ℓ energies: independent of jet energy scale

  weighted to minimize uncertainty:
  $M_t = w\, M_t^{\text{reco}} + (1-w)\, M_t^{\text{alt}}$

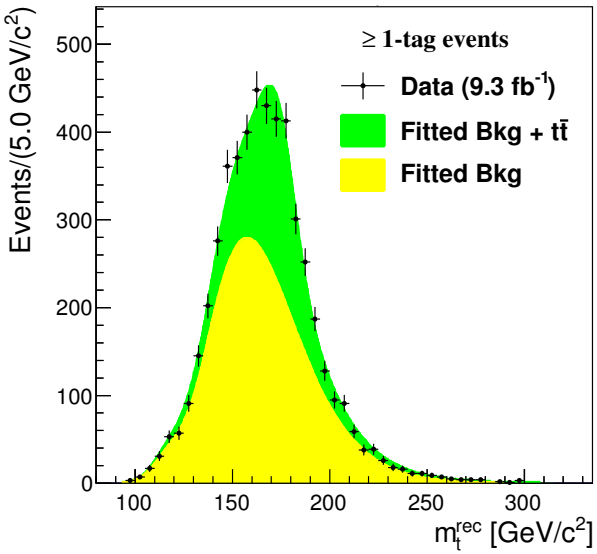
- 9.1 fb^{-1} of CDF data, 520 events:
  $170.80 \pm 1.83\ (stat) \pm 2.69\ (syst)$ GeV
- dominant uncertainty: JES
  (2.49 GeV, -20% thanks to M_t^{alt})

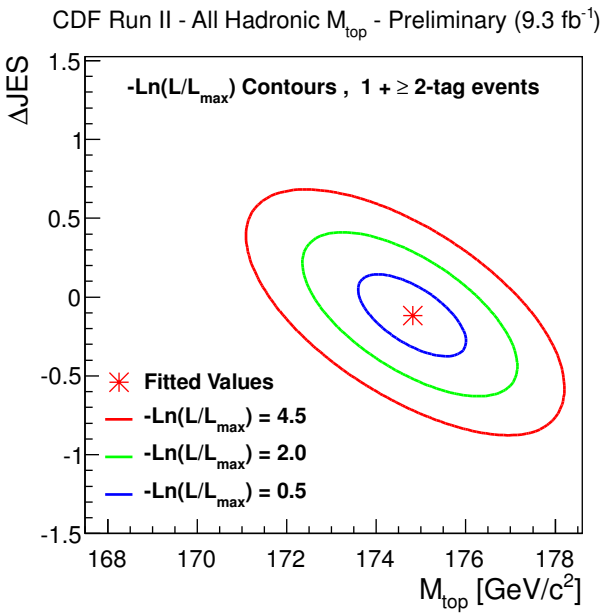




Measurement on all hadronic channel

[Mass2]





- process: $t\bar{t} \to bqq'\, bqq'$ (PYTHIA)
- NN discriminant achieves S:B up to 4:3
- observables (*templates* method):

  M_t^{rec} using the assumption $m_t = m_{\bar{t}}$

  M_W^{rec} constraining jet energies thanks to the known W mass

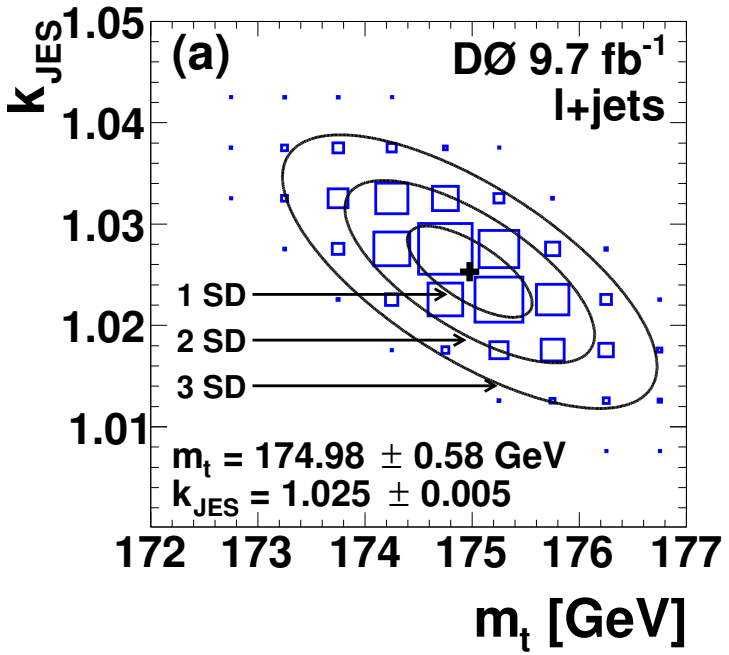
- from 901 (≥ 2 b-tags) and 4130 events (1 b-tag) in 9.3 fb^{-1} of CDF data:
  $175.07 \pm 1.19\ (stat) \pm 1.56\ (syst)$ GeV

  and observed JES shift: $\Delta JES = -0.28 \pm 0.55$

- leading systematics: JES (0.57 GeV), trigger simulation (0.61 GeV)

Measurement with Matrix Element method [Mass3]

- process: $t\bar{t} \to bqq' b\ell\nu$ (ALPGEN)
- based on probability of being signal ($t\bar{t}$) with a set m_t or background ($W + 4$ partons) for each event
- optimization of code facilitated more detailed study of uncertainties, e.g.:
  - → re-derivation of ISR/FSR
  - → disentanglement of JES and hadronization uncertainties
- 9.7 fb^{-1} of DØ data with 2592 events:
  $174.98 \pm 0.58\ (stat) \pm 0.49\ (syst)$ GeV



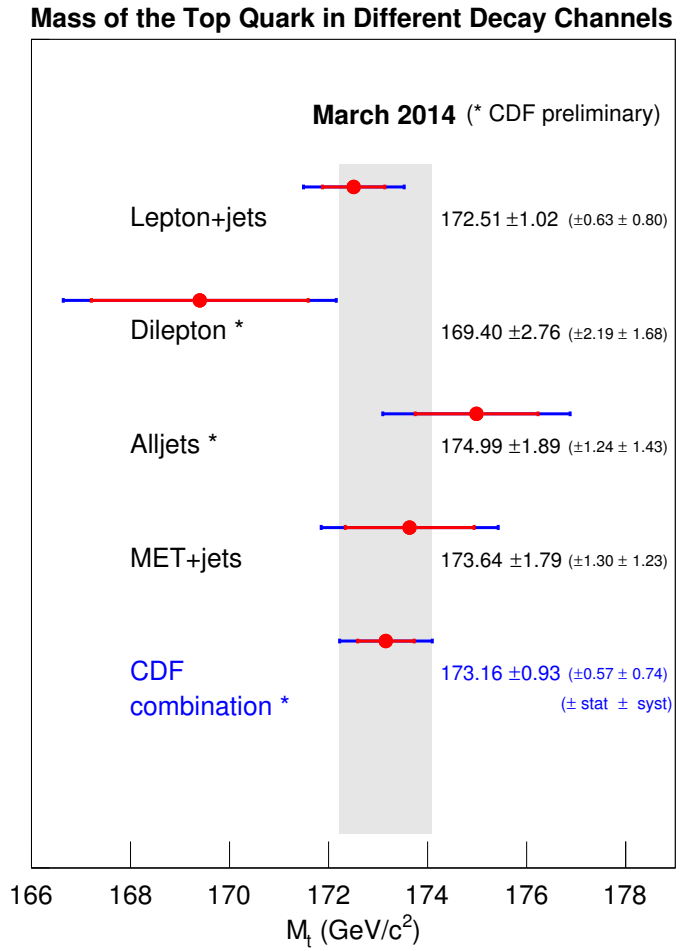
signal modelling		*detector modelling*	
Hadronization and U.E.	±0.26	Residual JES	±0.21
Higher orders	±0.15	Flavour JES	±0.16
PDF	±0.11	*b*-tagging	±0.10
Colour reconnection	±0.10		
ISR/FSR	±0.09		

CDF final result

[Mass4]

CDF mass measurements are complete: time to wrap up with a **final combination**!

- using Best Linear Unbiased Estimator
  → *requires knowledge of the correlation of uncertainties between measurements*
- 8 CDF measurement from RunI and II
- uncertainties split in 13 categories, half of them about jet energy
  → *designed to be either uncorrelated or fully correlated*
- systematic distributions are assumed (symmetric) Gaussian



Final mass measurement from CDF

$m_t = 173.16 \pm 0.57\,(stat.) \pm 0.74\,(syst.)\ \mathrm{GeV}/c^2$

$= 173.16 \pm 0.93\ \mathrm{GeV}/c^2$ *(rel. 0.54%)*

Today's measurements

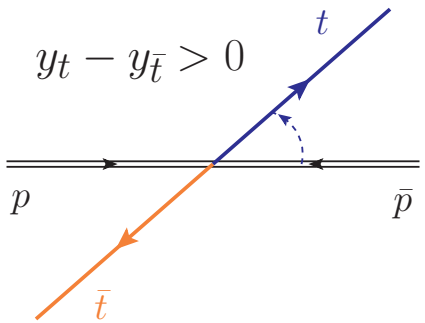
1. Top quark mass
2. $t\bar{t}$ production asymmetry

Asymmetry of $t/\bar{t}$ production

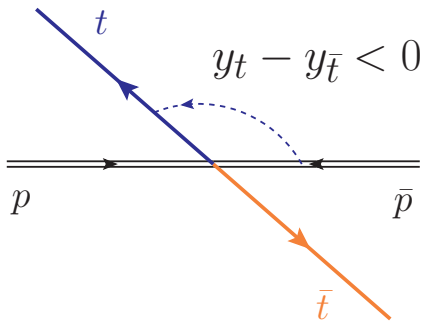
We describe whether t quark was produced more forward than $\bar{t}$ by:

$$A_{\mathrm{FB}} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)}$$

$$(\Delta y_{t\bar{t}} \equiv y_t - y_{\bar{t}})$$

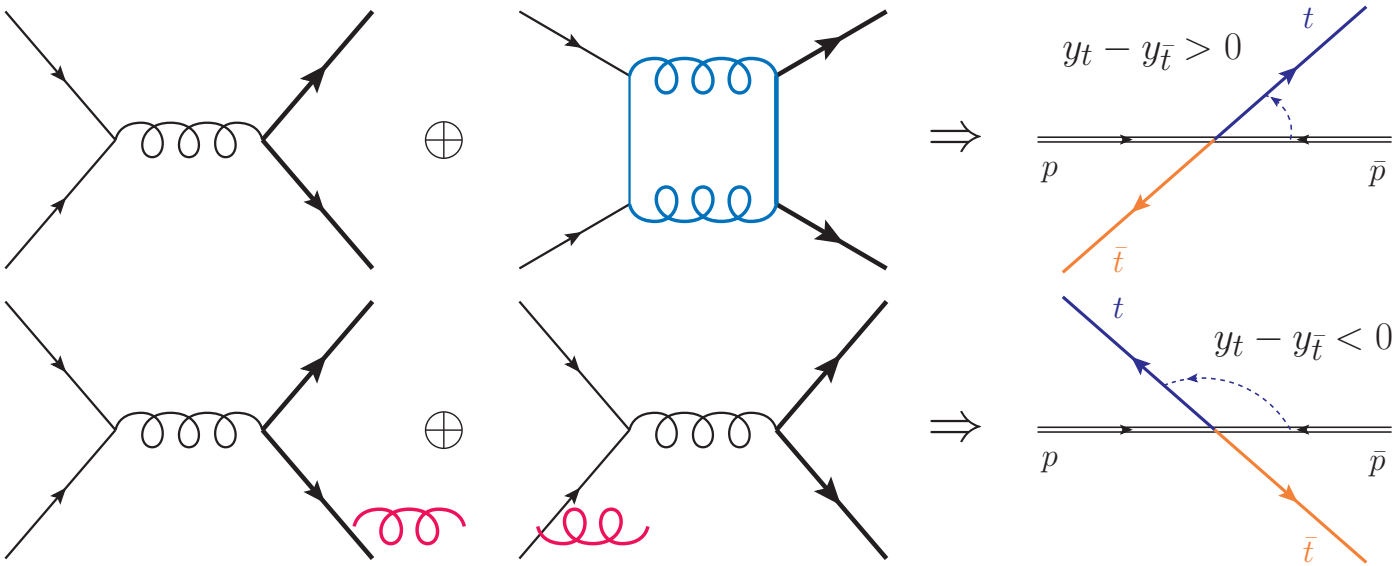


"forward"



"backward"

At Leading Order, symmetry is expected. But with NLO interference...



higher $m_{t\bar{t}}$

higher jet multiplicity, larger $p_{\mathrm{T}}(t\bar{t})$

The total asymmetry depends on the phase space of the final state.

Asymmetry measurements

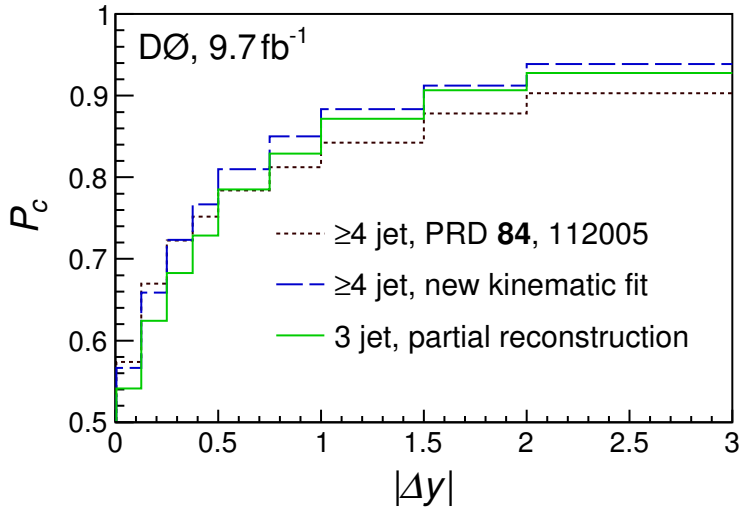
- ✓ QCD NLO prediction with electroweak corrections: $A_{FB} = 5.0 - 8.8\%$ *[Asym5]*
- ✓ uncertainty from higher orders is believed to be as large as $\pm 25\%$
- – different choices (e.g. scales) yield sensibly different predictions
- – CDF measures $A_{FB} = (16.4 \pm 4.5)\%$ on 9.4 fb^{-1} *[Asym6]*
- – previous DØ measurement: $A_{FB} = (19.6 \pm 6.5)\%$ on 5.4 fb^{-1} *[Asym7]*
- – LHC $pp \to t\bar{t}$ events are also sensitive to production asymmetries, but not as A_{FB}

In general, asymmetries larger than predicted have been observed.

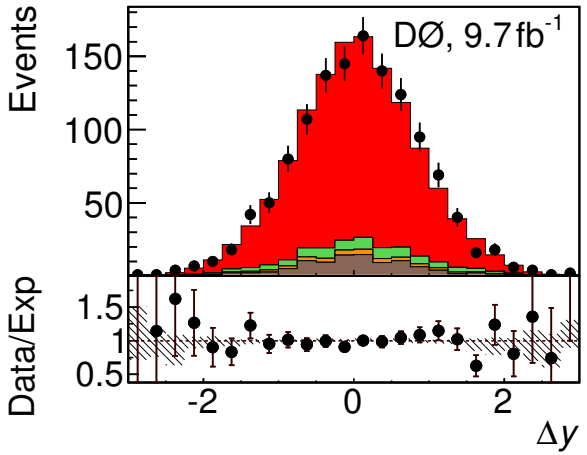
- analyse events with one charged lepton and jets:
  - $\Rightarrow$ full reconstruction of t and $\bar{t}$
  - $\Rightarrow$ high purity to reduce background contribution (W+jets, multijet)
- DØ analysis includes in separate subsamples *also* events with
  - \+ 3 jets to reduce selection biases
  - \+ no b-tag, to characterise background contribution
- kinematic reconstruction:

4 jets average 3 different reconstruction algorithms

3 jets ignore missed jets (usually low p_T)



Reconstruction efficiency for sign $\Delta y_{t\bar{t}}$



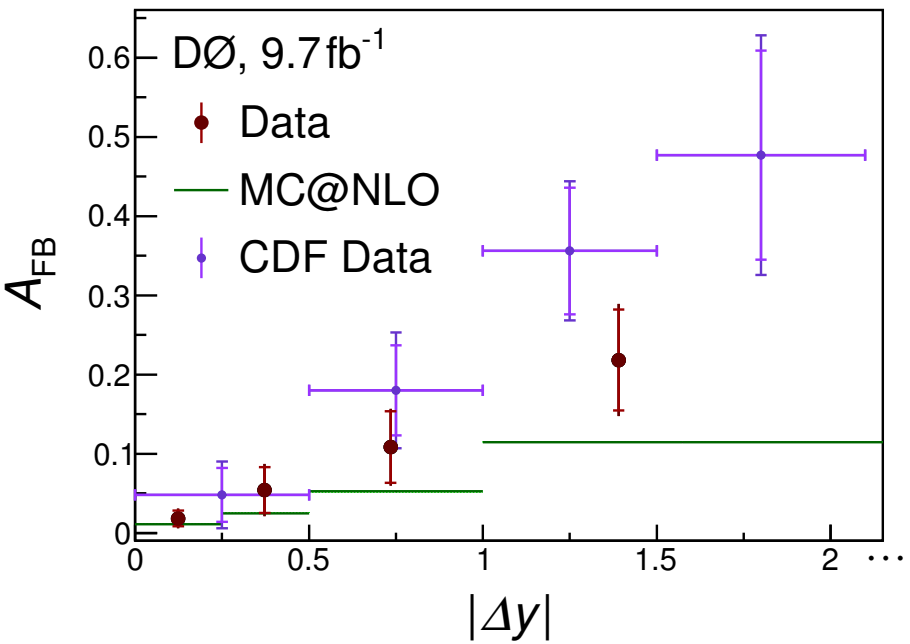
$\Delta y_{t\bar{t}}$ *for 4-jet, 2-b-tags sample*

Results are "unfolded" to production level, differential in $\Delta y_{t\bar{t}}$ and $\Delta y_{t\bar{t}} \otimes m_{t\bar{t}}$, *simultaneously* extracted from the 4 b-tagged subsamples.

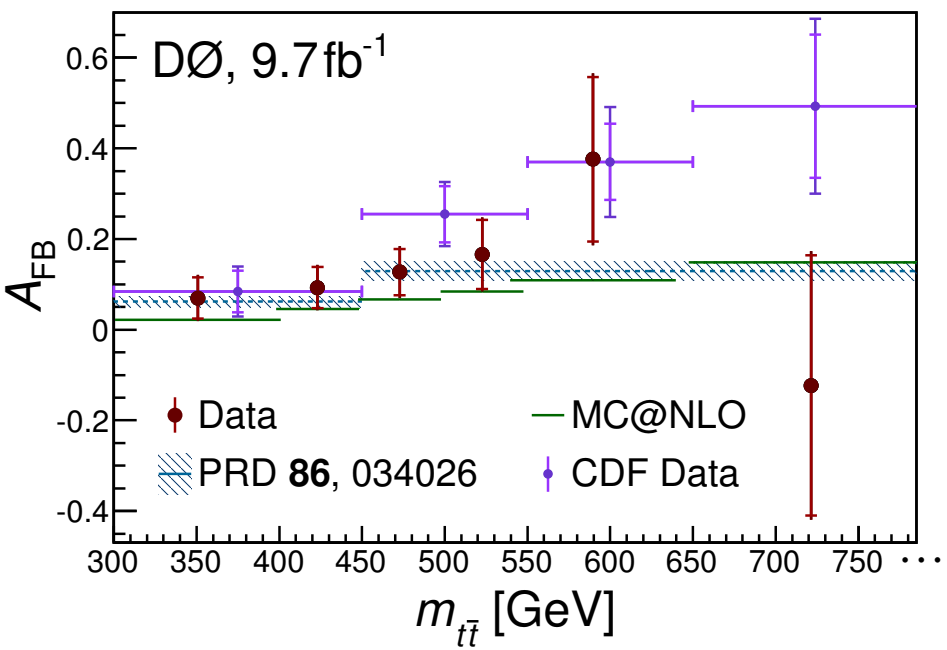
A_{FB} results

From 9.7 fb^{-1} of DØ data we measure $A_{FB} = 10.6 \pm 3.0$ *(in percent)*

Differential in $\Delta y_{t\bar{t}}$:
slope: $(15.4 \pm 4.3) \cdot 10^{-2} \Delta y_{t\bar{t}}$
(MC@NLO: 8.0, negligible uncertainty)



Differential in $m_{t\bar{t}}$:
$(3.9 \pm 4.4) \cdot 10^{-2} m_{t\bar{t}} + (11.9 \pm 3.6)$
(MC@NLO: $3.8 \cdot 10^{-2} m_{t\bar{t}} + 5.3$)



- dominant systematic from background model ($\pm 1\%$ on $A_{FB}(\Delta y)$)
- in between MC@NLO prediction and CDF measurement
- *compatible with both*

Asymmetry from leptons

We can also measure an asymmetry from leptons:

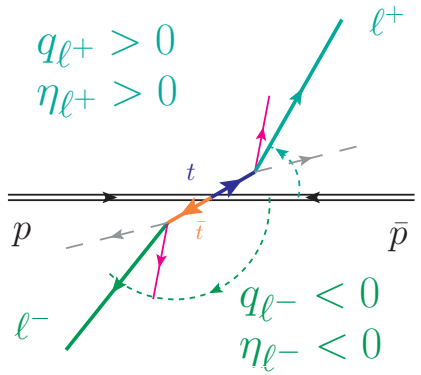
- correlated to A_{FB}, but less sensitive
- simpler in reconstruction and unfolding
- available for $t\bar{t} \to b\ell\nu\, b\ell\nu$ too
- sensitive to top spin effects
- from lepton charge times pseudorapidity ($q\eta_\ell$):

$$A_{FB}^{\ell} = \frac{N(q\eta_\ell > 0) - N(q\eta_\ell < 0)}{N(q\eta_\ell > 0) + N(q\eta_\ell < 0)}$$

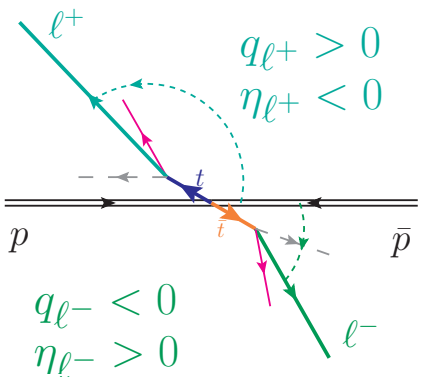
($q\eta_\ell > 0$: ℓ^+ following p direction, ℓ^- following $\bar{p}$)

- for events with two charged leptons ($\Delta\eta_{\ell\ell} \equiv \eta_{\ell^+} - \eta_{\ell^-}$):

$$A_{FB}^{\ell\ell} = \frac{N(\Delta\eta_{\ell\ell} > 0) - N(\Delta\eta_{\ell\ell} < 0)}{N(\Delta\eta_{\ell\ell} > 0) + N(\Delta\eta_{\ell\ell} < 0)}$$



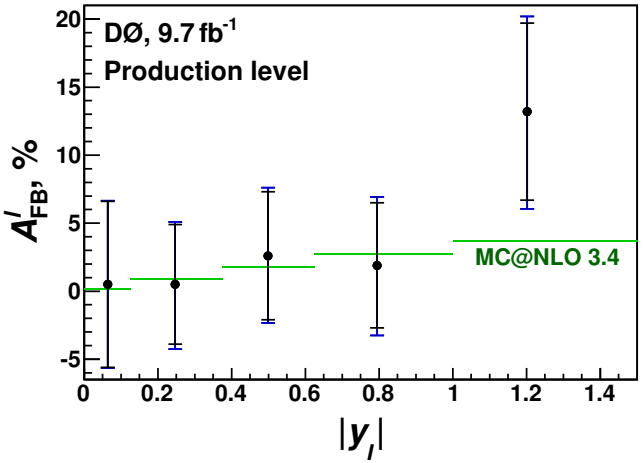
$q\eta_\ell > 0$ *("forward")*



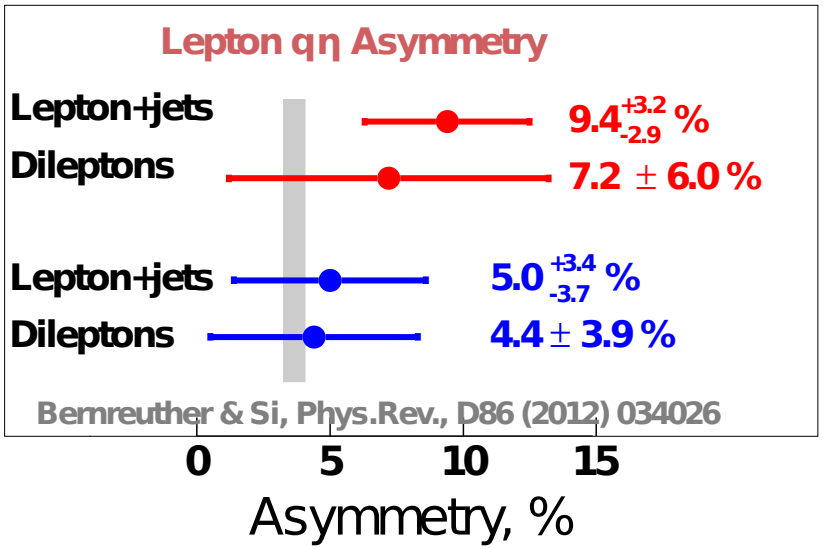
$q\eta_\ell < 0$ *("backward")*

A_{FB}^{ℓ} measurements

DØ combination ($\lvert y_\ell \rvert < 1.5$)	$4.2 \pm 2.0 \pm 1.4$
$bqq'\ b\ell\nu$ ($\lvert y_\ell \rvert < 1.5$) *[Asym3]*	$4.2 \pm 2.3\ ^{+1.7}_{-2.0}$
$b\ell\nu\ b\ell\nu$ ($\lvert y_\ell \rvert < 2$) *[Asym4]*	$4.1 \pm 3.5 \pm 1.0$



A_{FB}^{ℓ} *vs.* $|y_\ell|$ *from [Asym4]*



Summary of A_{FB}^{ℓ} with full y_ℓ coverage:

CDF *[Asym2]*	$9.0^{+2.8}_{-2.6}$
$bqq'\ b\ell\nu$ *[Asym6]*	$9.4 \pm 2.4\ ^{+2.2}_{-1.7}$
$b\ell\nu\ b\ell\nu$ *[Asym2]*	$7.2 \pm 5.2 \pm 3.0$
DØ *[Asym3]*	$4.7 \pm 2.3 \pm 1.5$
NLO QCD+EW [Asym5]	3.8 ± 0.3

↖ *extrapolation applied to DØ as in [Asym3]*

CDF result is significantly higher than the expectation, while DØ is again in between and compatible with both.

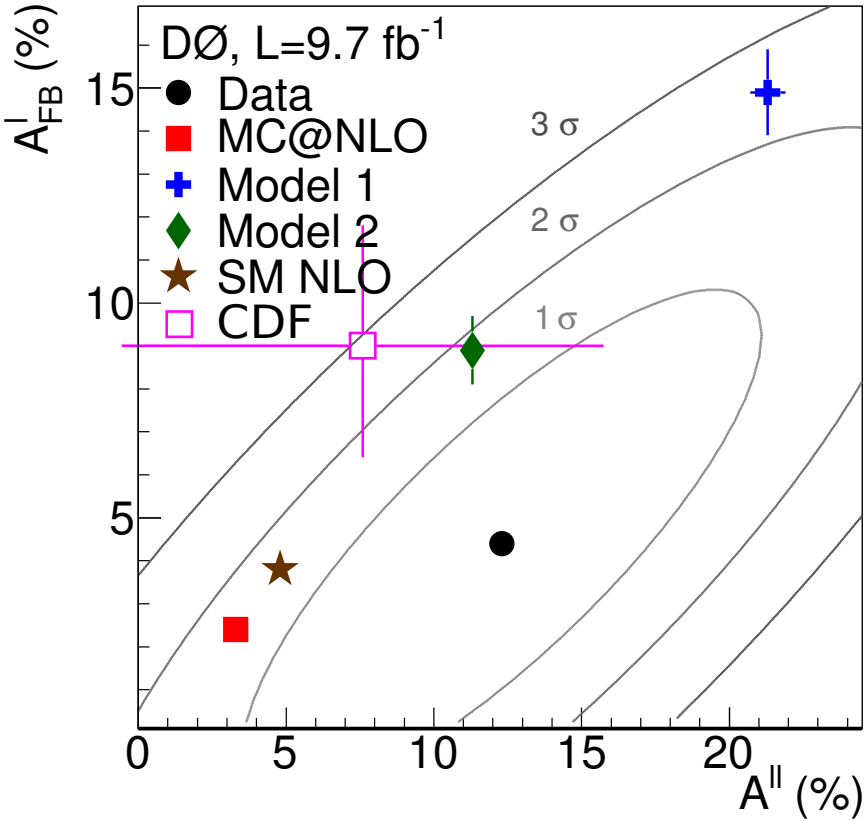
$A_{FB}^{\ell\ell}$ measurements

In events with two leptons we describe a model by both A_{FB}^{ℓ} and $A_{FB}^{\ell\ell}$.
Included in the plot:

DØ A_{FB}^{ℓ}, $A_{FB}^{\ell\ell}$ (with contours) from $b\ell\nu\ b\ell\nu$ (9.7 fb^{-1} *[Asym3, Asym4]*)

CDF $A_{FB}^{\ell\ell}$ from $b\ell\nu\ b\ell\nu$ (9.1 fb^{-1} *[Asym2]*)

CDF A_{FB}^{ℓ} combined: $b\ell\nu\ b\ell\nu$ (*ibid.*) and $bqq'\ b\ell\nu$ (9.4 fb^{-1} *[Asym6]*)



Also shown two models with a color-octet vector boson G ("axigluon") coupling only to right-handed quarks:

(1) $0.8g_s$ ($g_s \equiv \sqrt{\alpha_s/4\pi}$) *to all quarks* ($M_G = 0.2$ TeV, $\Gamma_G = 50$ GeV)

(2) $6g_s$ *to t quark and* $-1.5g_s$ *to the other quarks* ($M_G = 2$ TeV, $\Gamma_G = 670$ GeV)

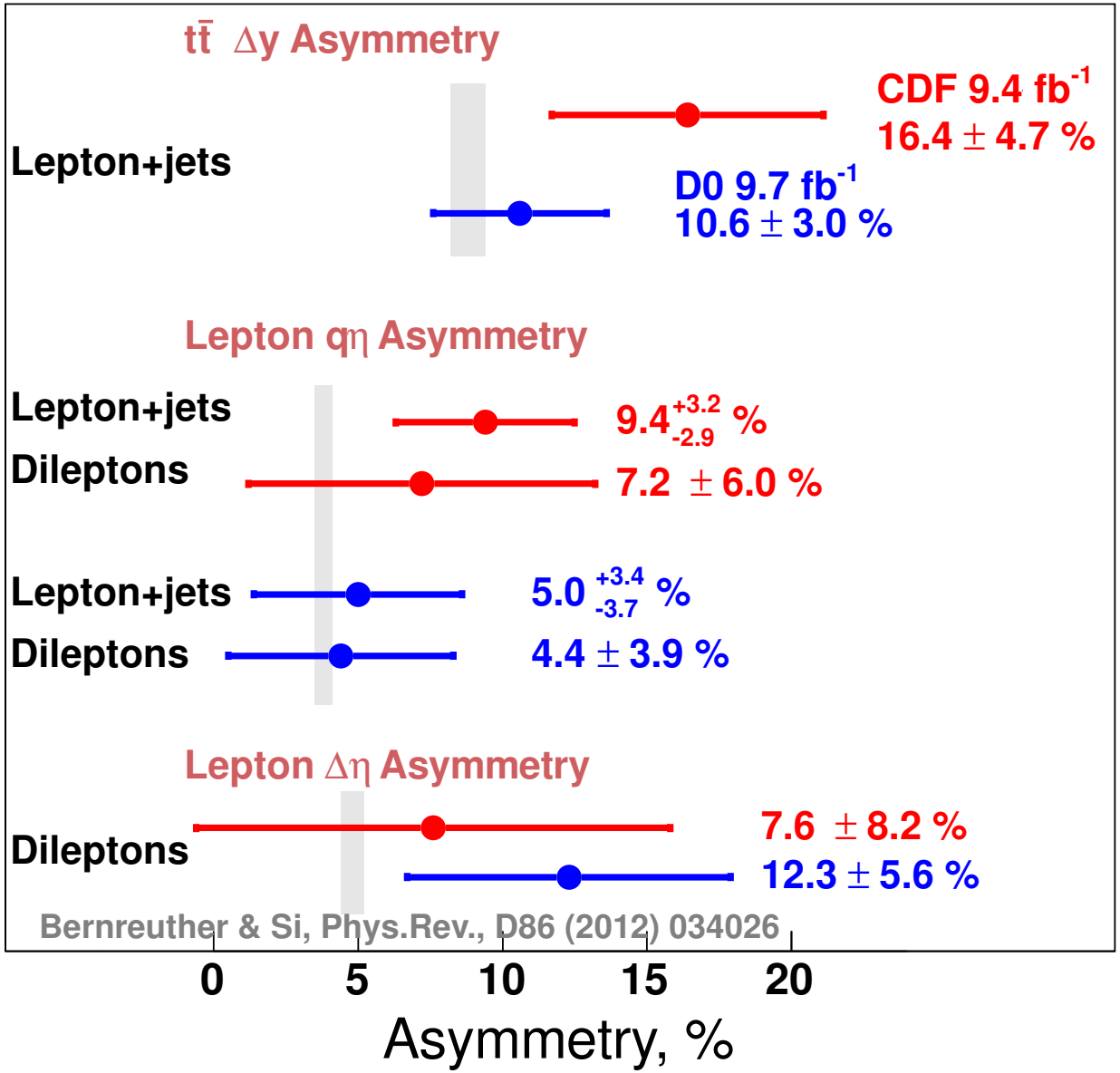
↖ *CDF result added by hand, uncorrelated uncertainty only*

Summary

- we are squeezing the last drops of information from Tevatron data
- we measure the top quark mass at better than 0.5%
- the latest mass measurements (and a few more coming soon from DØ) will have heavy weight in a combination with LHC
- measurements of $t/\bar{t}$ production asymmetry are unfortunately not conclusive, but suggestive
- theory predictions are still a somehow moving target

References and supplemental material

Summary of asymmetry measurements by Tevatron

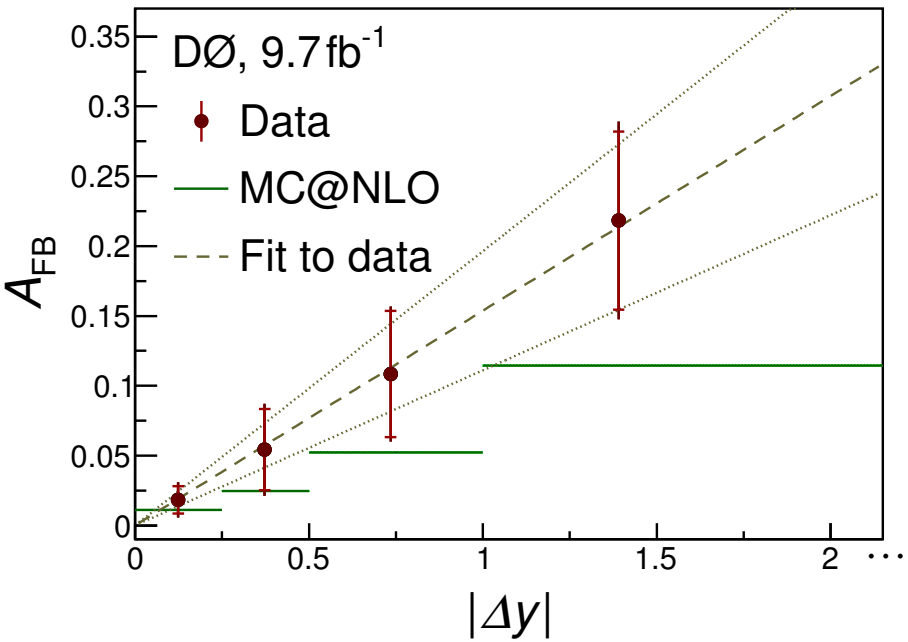


All measurements are at production level.

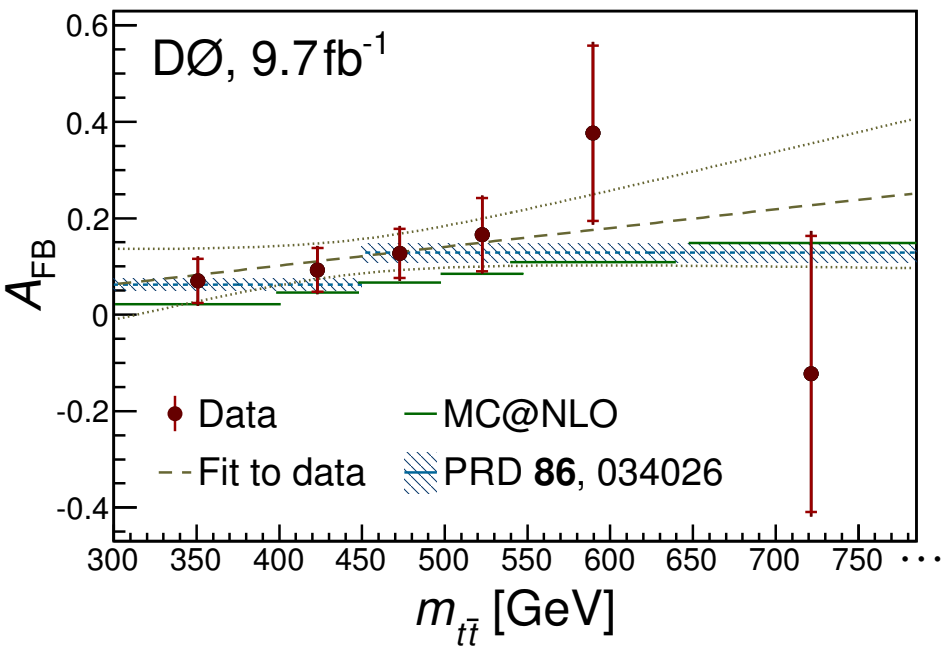
Differential A_{FB} results (CDF and DØ)

These plots show both DØ measurements from slide 12 and linear fits:

Differential in $\Delta y_{t\bar{t}}$:
slope: $(15.4 \pm 4.3) \cdot 10^{-2} \Delta y_{t\bar{t}}$
(MC@NLO: 8.0, negligible uncertainty)



Differential in $m_{t\bar{t}}$:
$(3.9 \pm 4.4) \cdot 10^{-2} m_{t\bar{t}} + (11.9 \pm 3.6)$
(MC@NLO: $3.8 \cdot 10^{-2} m_{t\bar{t}} + 5.3$)



References to new Tevatron mass measurements

[Mass1] The CDF Collaboration,
"Top Quark Mass Measurement in the Dilepton Channel Using the Full CDF Data Set",
CDF note 11072, 01/2014

[Mass2] The CDF Collaboration,
"Measurement of the top quark mass with in situ jet energy scale calibration in the all-hadronic channel using the Template Method with 9.3 fb^{-1}",
CDF note 11084, 03/2014

[Mass3] The DØ Collaboration,
"Precision measurement of the top-quark mass in lepton+jets final states",
submitted to PRL, arxiv:1405.1756 [hep-ex], 05/2014

[Mass4] The CDF Collaboration,
"Final combination of the CDF results on top-quark mass",
CDF note 11080, 01/2014

[Mass5] The CDF and DØ Collaborations,
"Combination of CDF and DO results on the mass of the top quark using up to 8.7 fb^{-1} at the Tevatron",
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[Mass6] The ATLAS, CDF, CMS and DØ Collaborations,
"First combination of Tevatron and LHC measurements of the top-quark mass",
arxiv:1403.4427 [hep-ex], 03/2014

References to new Tevatron A_{FB} measurements

[Asym1] The DØ Collaboration,
"Measurement of the forward/backward asymmetry in top quark/antiquark production in $p\bar{p}$ collisions using the lepton+jets channel",
submitted to PRD, 04/2014

[Asym2] The CDF Collaboration,
"Measurement of the Leptonic Forward-Backward Asymmetry of $t\bar{t}$ Production and Decay in the Dilepton Final State and Combination of Charge Weighted Leptonic A_{FB} at CDF",
CDF note 11035, 03/2014

[Asym3] The DØ Collaboration,
"Measurement of the forward-backward asymmetry in the distribution of leptons in $t\bar{t}$ events in the lepton+jets channel",
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[Asym4] The DØ Collaboration,
"Measurement of the asymmetry in angular distributions of leptons produced in dilepton $t\bar{t}$ final states in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV",
PRD **88**, 112002 (2013), arXiv:1308.6690 [hep-ex], 12/2013

Additional references

[Asym5] W. Bernreuther, Z.-G. Si,
"Top quark and leptonic charge asymmetries for the Tevatron and LHC",
PRD **86**, 034026 (2012)

[Asym6] The CDF Collaboration,
"Measurement of the top quark forward-backward production asymmetry and its dependence on event kinematic properties",
PRD **87**, 092002 (2013) [arxiv:1211.1003 [hep-ex]]

[Asym7] The DØ Collaboration,
"Forward-backward asymmetry in top quark-antiquark production",
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[Oth1] from the GFitter collaboration,
Standard Model plots on September 2013
(http://gfitter.desy.de/Standard_Model)

[Oth2] The CDF Collaboration,
"Measurement of $R = B(t \to Wb)/B(t \to Wq)$ in the $t\bar{t}$ dilepton decay channel at CDF",
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