A_{FB}s in $t\bar{t}$ production at the Tevatron

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On behalf of the DØ and CDF collaborations

Rencontres de Moriond – EW session

La Thuile, Italy

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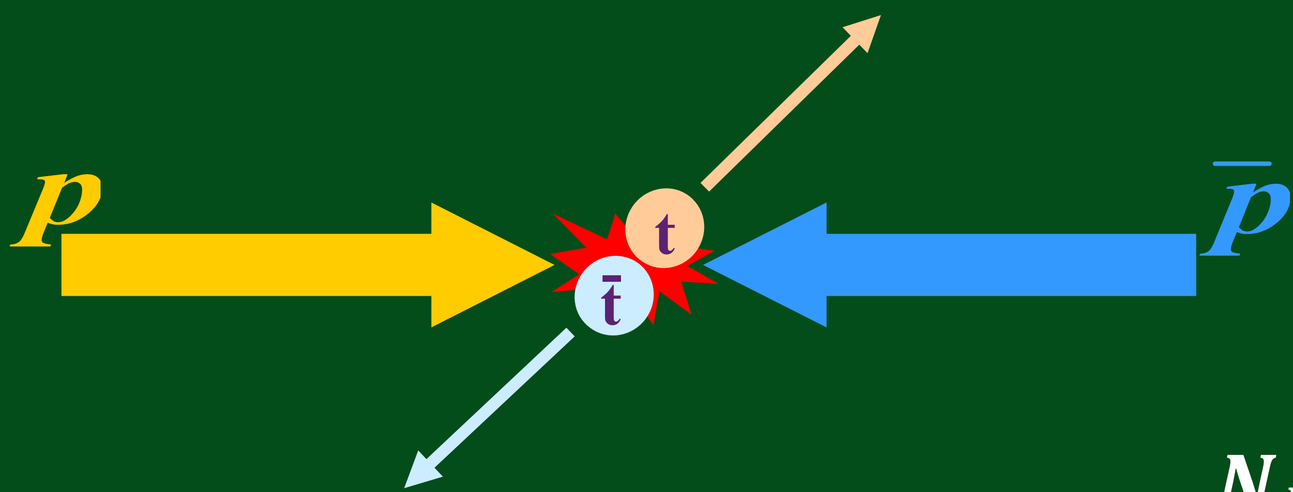
Forward – Backward

Is it the top or the antitop that is produced preferentially in the direction (hemisphere) of the incoming proton?



Choose an angular variable x and define: $A_{\mathrm{FB}} = \frac{N_F - N_B}{N_F + N_B}$

Three observables "x" in today's talk:

- $\Delta y = y_t - y_{\bar{t}}$: combines both tops, invariant to boosts in z

$N_F = N(x > 0)$

$N_B = N(x < 0)$

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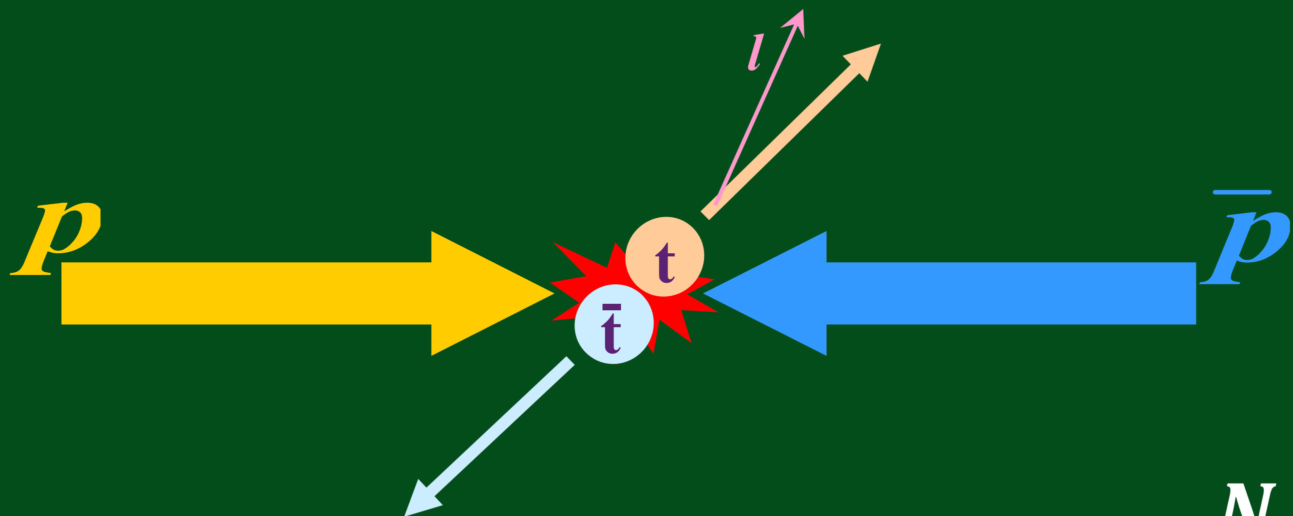

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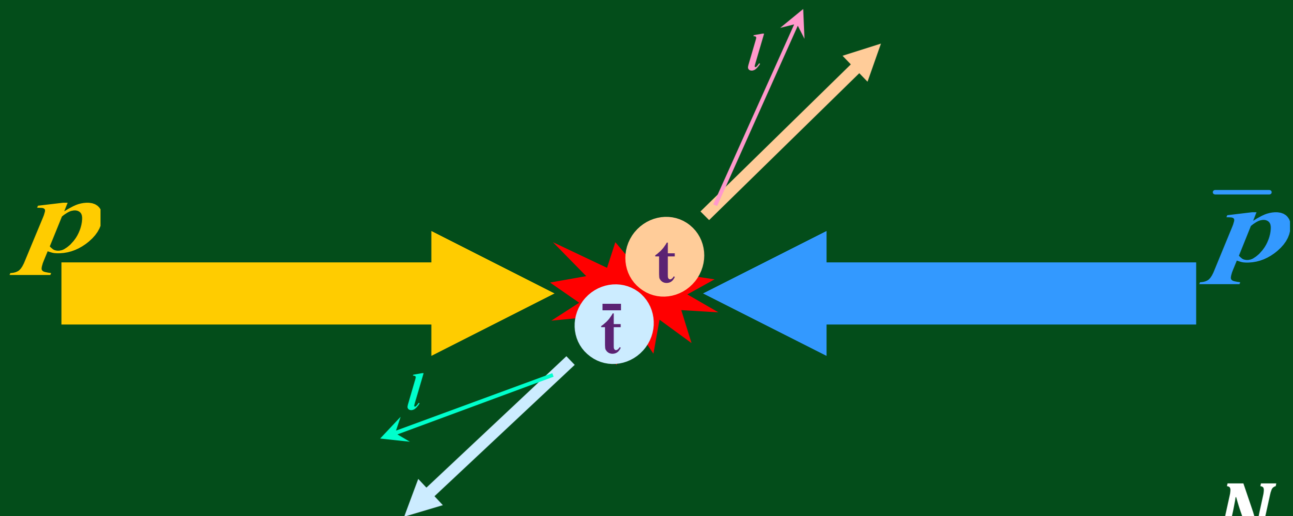

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- $\Delta y = y_t - y_{\bar{t}}$: combines both tops, invariant to boosts in z
- qy_l: trivial reconstruction, simple corrections
- $\Delta\eta = \eta_{l^+} - \eta_{l^-}$: combined both tops in dilepton events

$$N_F = N(x > 0)$$
$$N_B = N(x < 0)$$

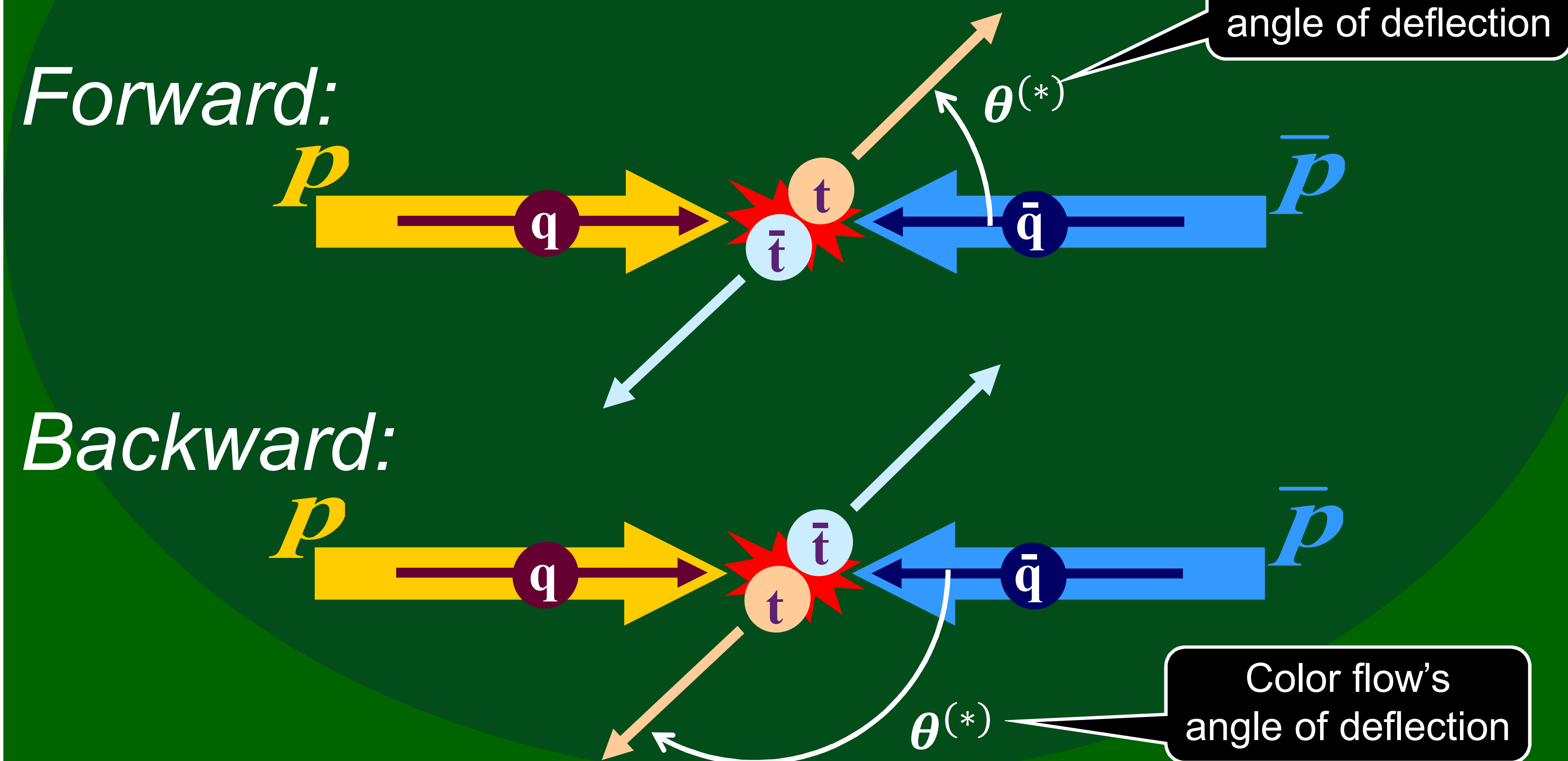
At the Tevatron

“charge asymmetry”

It’s not about the incoming protons

It’s about the incoming quarks and their QCD charges

- at the Tevatron: $85\%\ q\bar{q} \to t\bar{t} + 15\%\ gg \to t\bar{t}$



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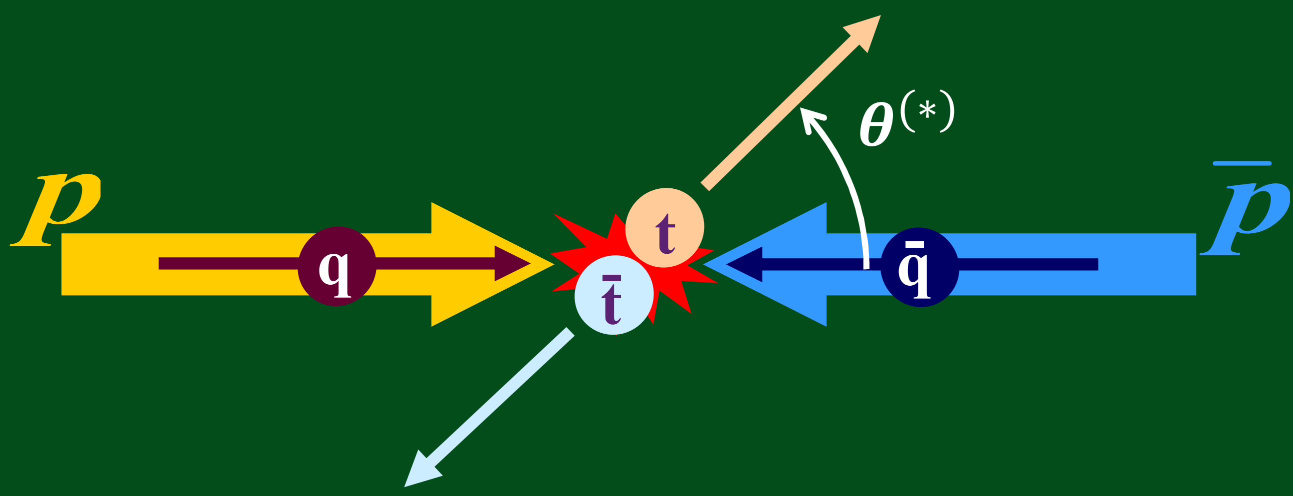


At the LHC:

- 90% $gg \rightarrow t\bar{t}$, a charge symmetric background
- No valence anti-quarks → no pre-defined forward direction

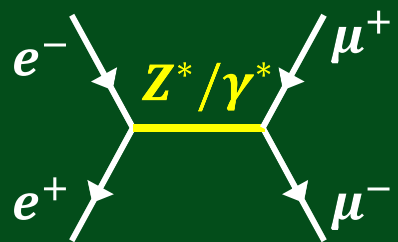
The first motivation

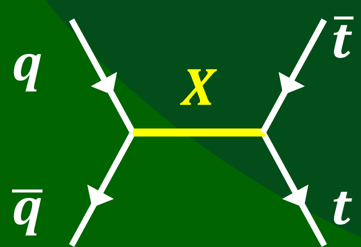
Small SM predictions → can identify new physics

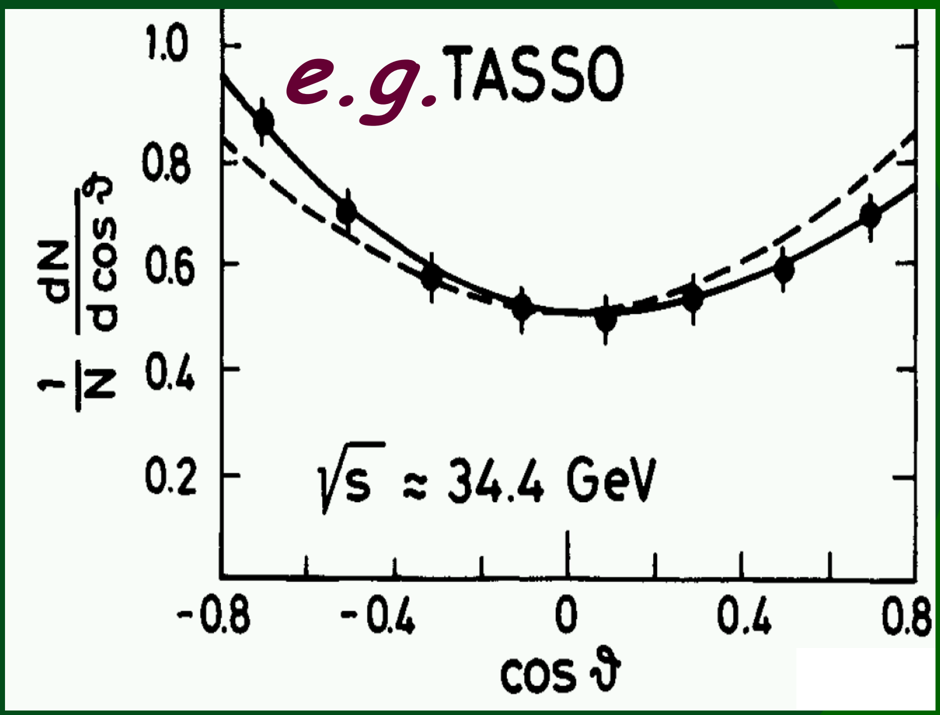
Back to the 80s?

A_{FB} in $e^+e^- \to \mu^+\mu^-$ indicated the Z resonance with an E_{cm} of only 35 GeV

[e.g. PRL 48 (1982) 1701]







With X some strongly interacting particle, e.g. an axigluon

The main motivations

Small SM predictions → can identify new physics

Back to the 80s?
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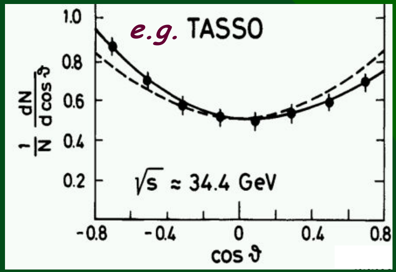

Experimental work on $p\bar{p} \to t\bar{t}$ followed Kühn & Rodrigo [PRL **81** (1998) 49]

First experimental paper, DØ in l+jets, 0.9 fb^{-1} [PRL **100** (2008) 142002]
Quickly followed by CDF paper in l+jets, 1.9 fb^{-1} [PRL **100** (2008) 202001]

Both found higher than expected asymmetries, which raised some interest

The main motivations

Small SM predictions → can identify new physics

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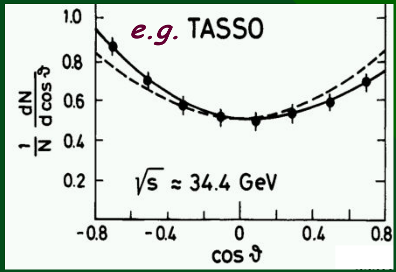
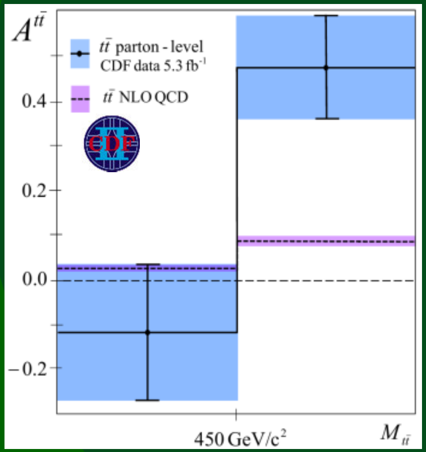




In 2011 CDF found [PRL **83** (2011) 112003]

$A_{\rm FB}(m(t\bar{t}) > 450{\rm GeV}) = 47.5 \pm 11.4\%$ $> 3\sigma$!?

- vs. MCFM prediction of only 8%

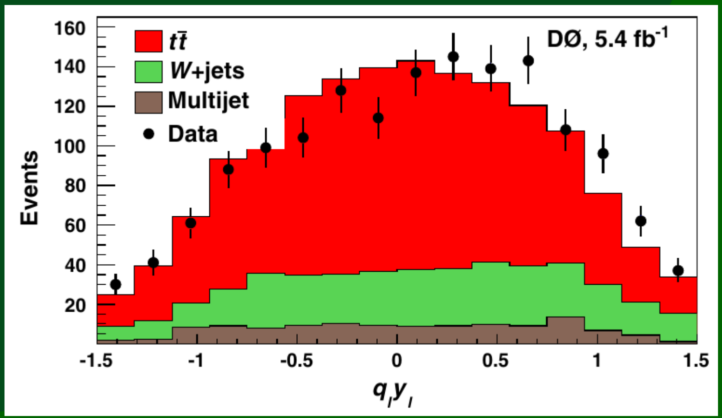
This got the community's attention…

- >350 citations

2011 D0 found [PRD **84** (2011) 112005]

$A^{l}_{\rm FB} = 15.2 \pm 4.0\%$ $> 3\sigma$!?

- vs. MC@NLO prediction of only 2.1%



The new measurements

- A_{FB}^{l} in l+jets channel – preliminary shown last year
- Preliminary result: A_{FB}^{l} and $A_{\mathrm{FB}}^{\Delta\eta}$ in dilepton channel

  www-cdf.fnal.gov/physics/new/top/2013/DiLAFBLep

- A_{FB}^{l} and $A_{\mathrm{FB}}^{\Delta\eta}$ in dilepton channel
- A_{FB}^{l} in l+jets channel
- Brand new preliminary: A_{FB} in l+jets channel

  www-d0.fnal.gov/Run2Physics/WWW/results/prelim/TOP/T100

SM predictions

A_{FB}:	$\mathbf{5-6.5\%}$	$\mathbf{6-7.5\%}$	$\mathbf{8\ -9\%}$	$\mathbf{12.7\%}$
from Δy	$\frac{@\alpha_s^3}{@\alpha_s^3}$	$\frac{@\alpha_s^3}{@\alpha_s^2}$, **resum**	**+EW**	MCP??
	MC@NLO, POWHEG	e.g. Ahrens et al.	e.g. Bernreuther&Si	Brodski et al.

Scale uncertainties ~1%.

With only LO, perturbative uncertainty at least 1%(absolute)

SM predictions

A_{FB}: **from** Δy

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Scale uncertainties ~1%.

With only LO, perturbative uncertainty at least 1%(absolute)

A_{FB}^{l}:

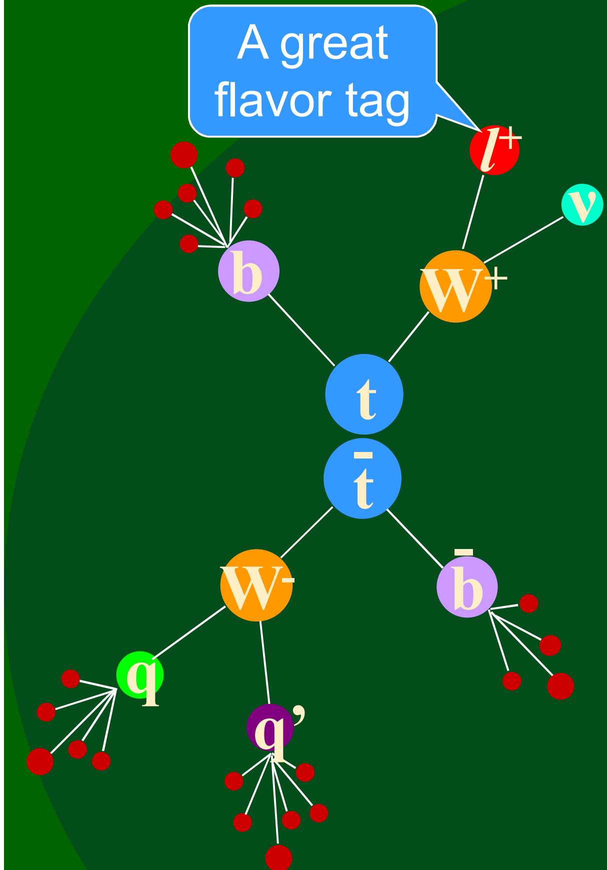
$\mathbf{2-2.4\%}$	$\mathbf{3.8\%}$
$\frac{@\alpha_s^3}{@\alpha_s^3}$	$\frac{@\alpha_s^3}{@\alpha_s^2}$ **+ EW**
MC@NLO, POWHEG	Bernreuther&Si

$A_{\mathrm{FB}}^{\Delta\eta}$: $\mathbf{3-3.3\%}$

SM (CP conservation) predicts no longitudinal t polarization

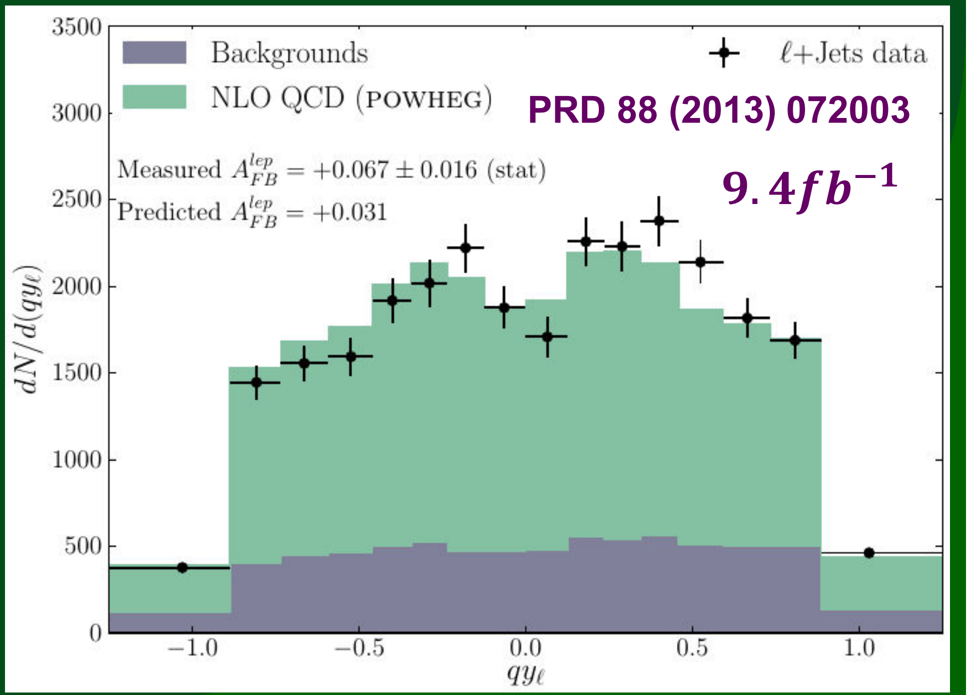
→ Leptonic asymmetries are merely a result of A_{FB} and smaller

A^l_{FB} in l+jets



- select objects with $p_T > 20\ \mathrm{GeV}$
- e/μ within $|\eta| < 1.25$
- ≥ 4 jets
  - but 4th jet $> 12\ \mathrm{GeV}$ → improved acceptance
- p_T imbalance (MET)

Select ~2800 $t\bar{t}$ events with a purity of ~72%



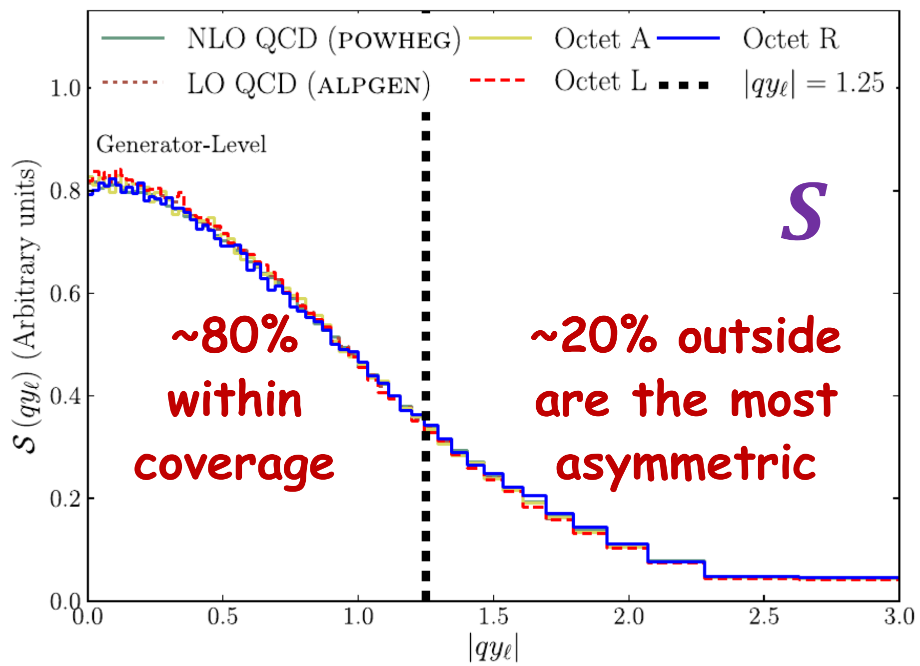
l+jets

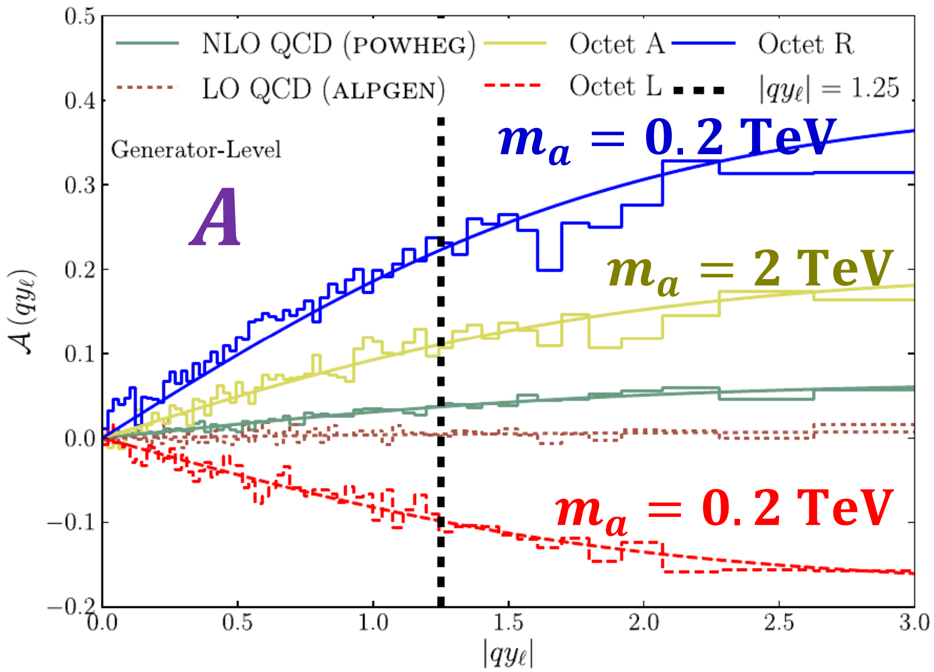
Extrapolating A_{FB}^{l}

$N(qy_l)$

$$S(qy_l) = \frac{N(qy_l) + N(-qy_l)}{2}$$

$$A(qy_l) = \frac{N(qy_l) - N(-qy_l)}{N(qy_l) + N(-qy_l)}$$





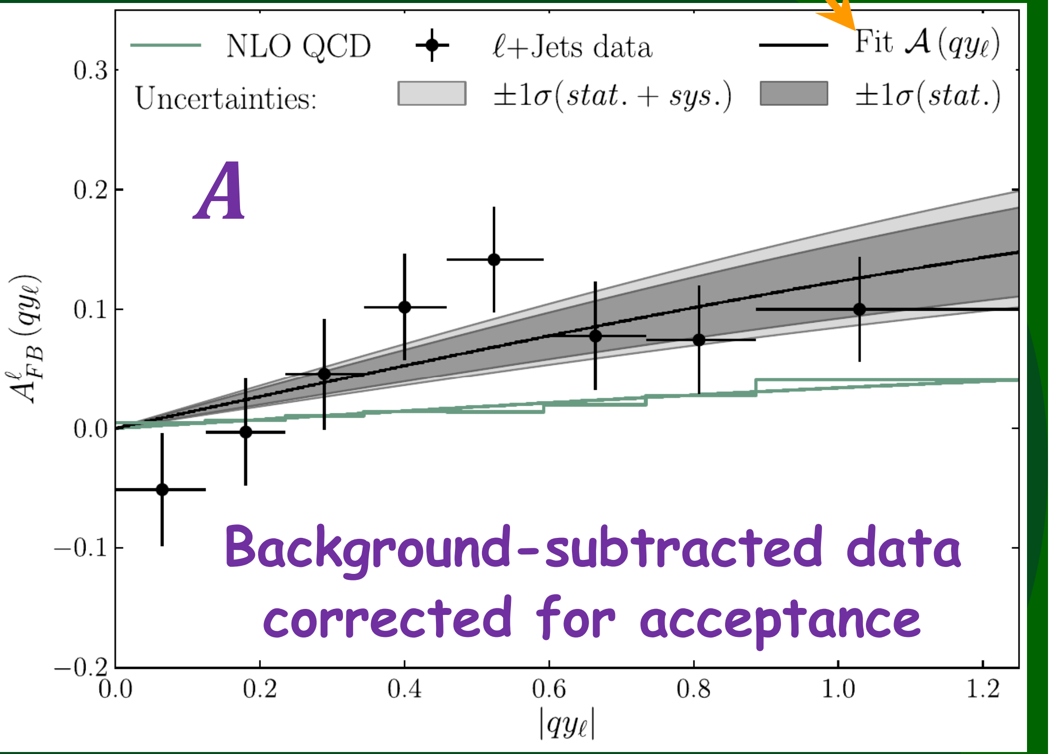
Looks the same for the different SM and BSM simulations

- Other BSM cases in PRD **83** (2011) 114027

$A(qy_l)$ is nicely described by the functional form $f(|qy_l|) = a \tanh \frac{|qy_l|}{2}$

Results

$f(|qy_l|) = a \tanh \frac{|qy_l|}{2}$



Measured:

$a = 0.266 \pm 0.068(\text{stat.})$

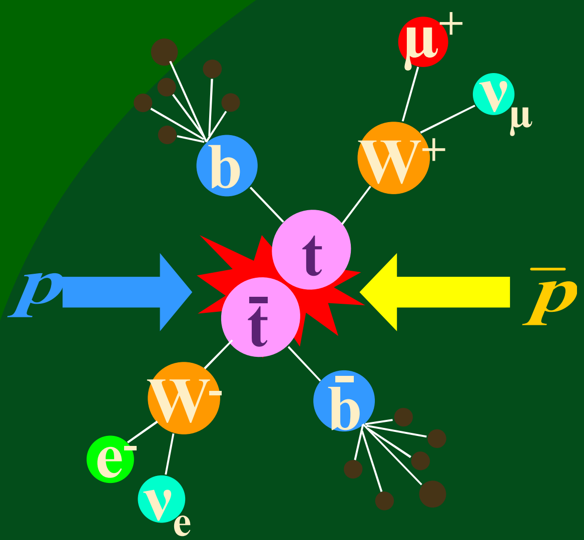
Integrate with simulated $\boldsymbol{S(qy_l)}$ to find the extrapolated A^l_{FB}

The dominant systematic uncertainties are due to:

- Background modeling
- Modeling of the recoil $p_T(t\bar{t})$, which arises from ISR

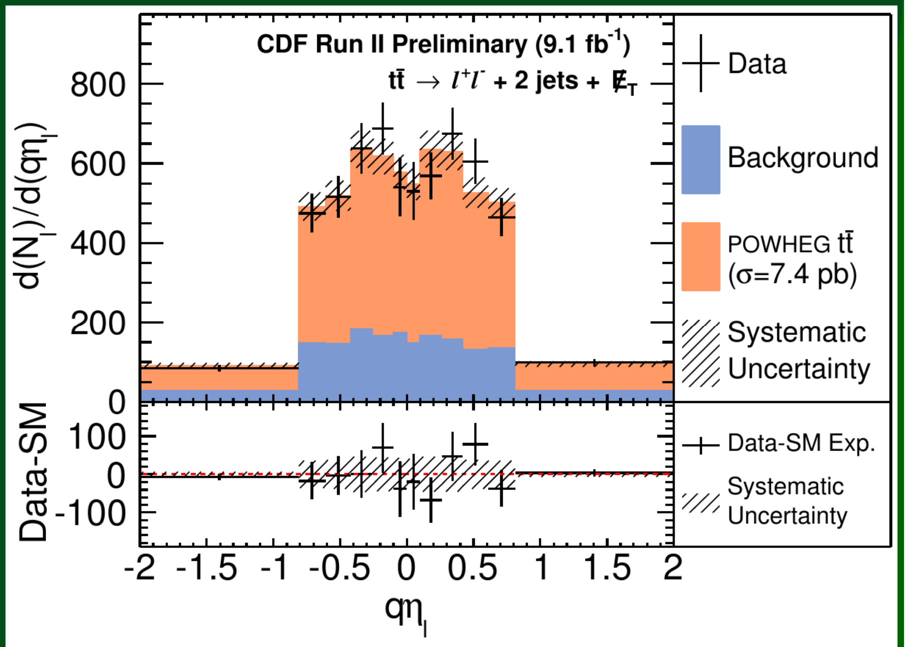
$$\boldsymbol{A^l_{\text{FB}} = 0.094 \pm 0.024(\text{stat.})^{+0.022}_{-0.017}(\text{syst.})}$$

A_{FB}^{l} in dileptons



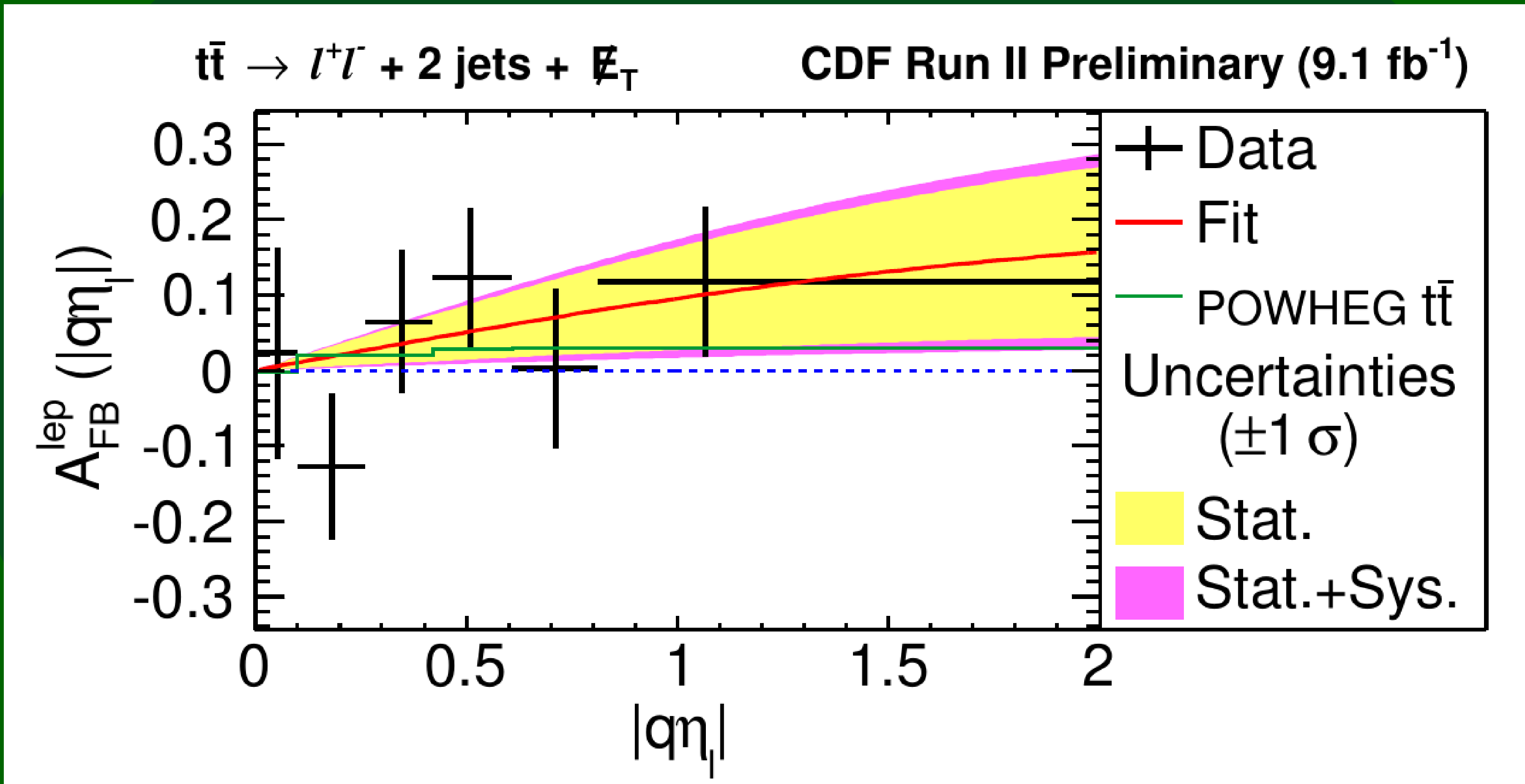
- $|\eta_e| < 1.1, |\eta_\mu| < 2.0$
- $\geq$ 2 jets with $p_T > 15$ GeV
- p_T imbalance (MET)
  - > 25 / 50 GeV depending on topology
  - cut on significance>4 near Z peak ($e^+e^-/\mu^+\mu^-$)
- $m(l^+l^-) > 10$ GeV

Select ~410 $t\bar{t}$ events with a purity of ~72%



A^{l}_{FB} in dileptons

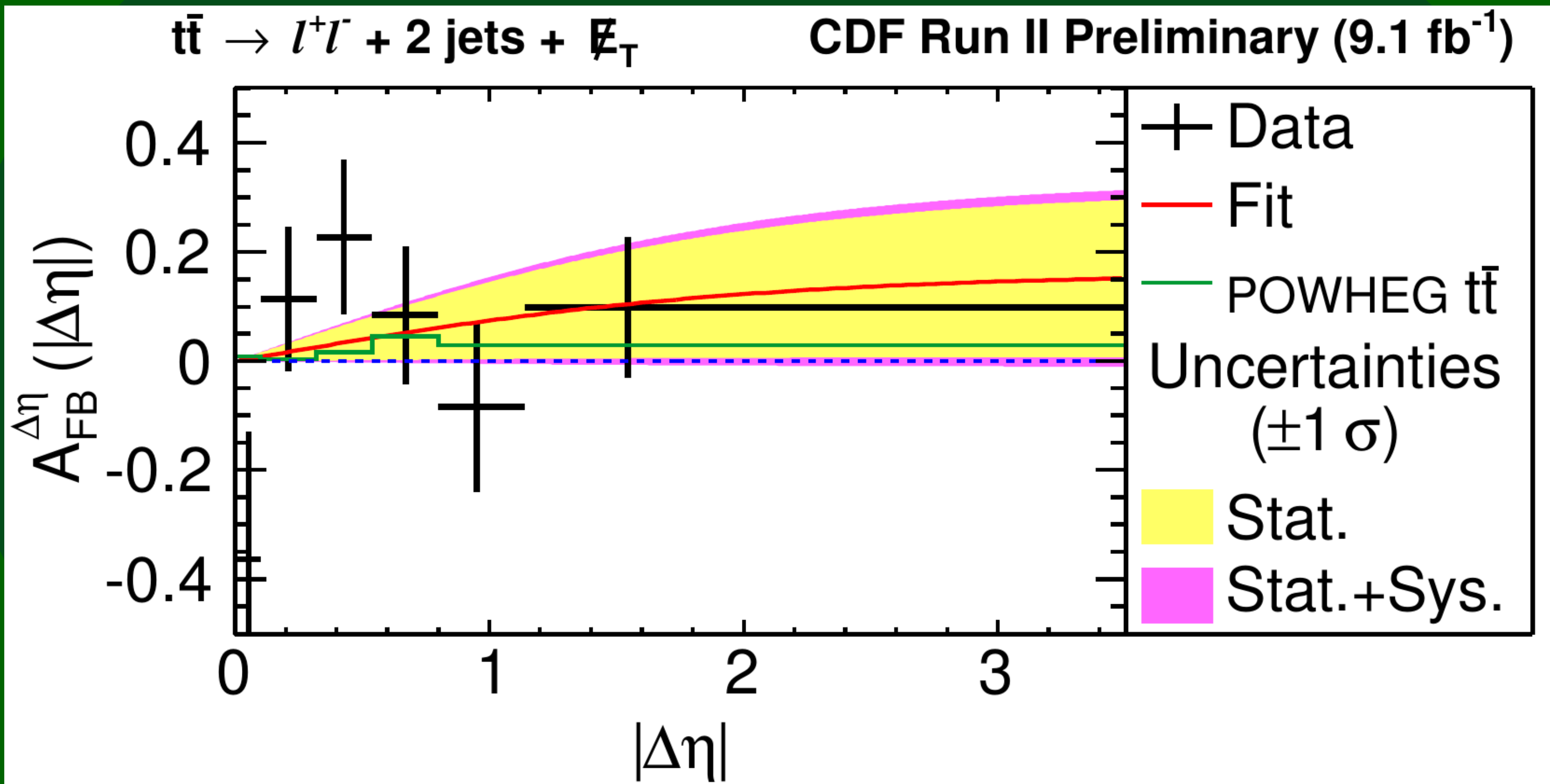
Similar measurement and extrapolation



$$A^{l}_{\mathrm{FB}} = \mathbf{0.072} \pm \mathbf{0.052}(\text{stat.}) \pm \mathbf{0.030}(\text{syst.})$$

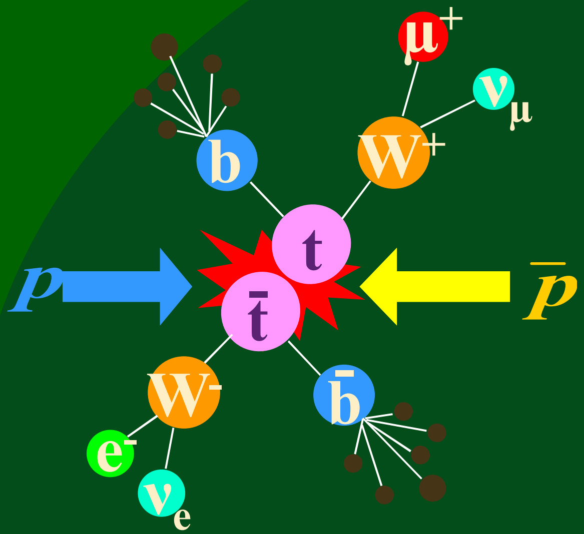
$A_{\mathrm{FB}}^{\Delta\eta}$ in dileptons

Similar measurement and extrapolation



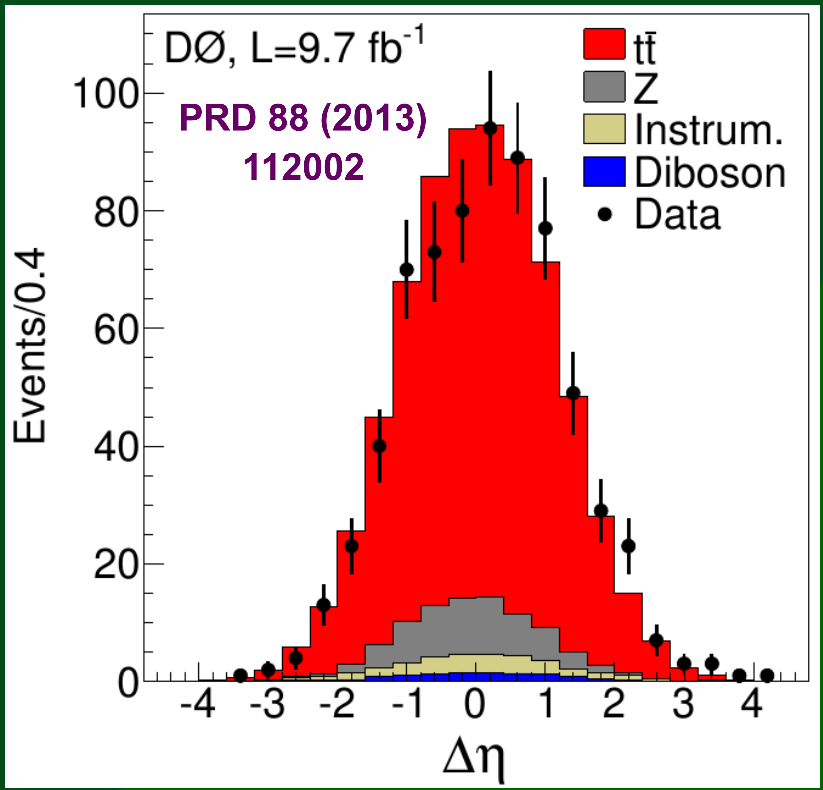
$$A_{\mathrm{FB}}^{\Delta\eta} = 0.076 \pm 0.072(\mathrm{stat.}) \pm 0.037(\mathrm{syst.})$$

Dilepton selection



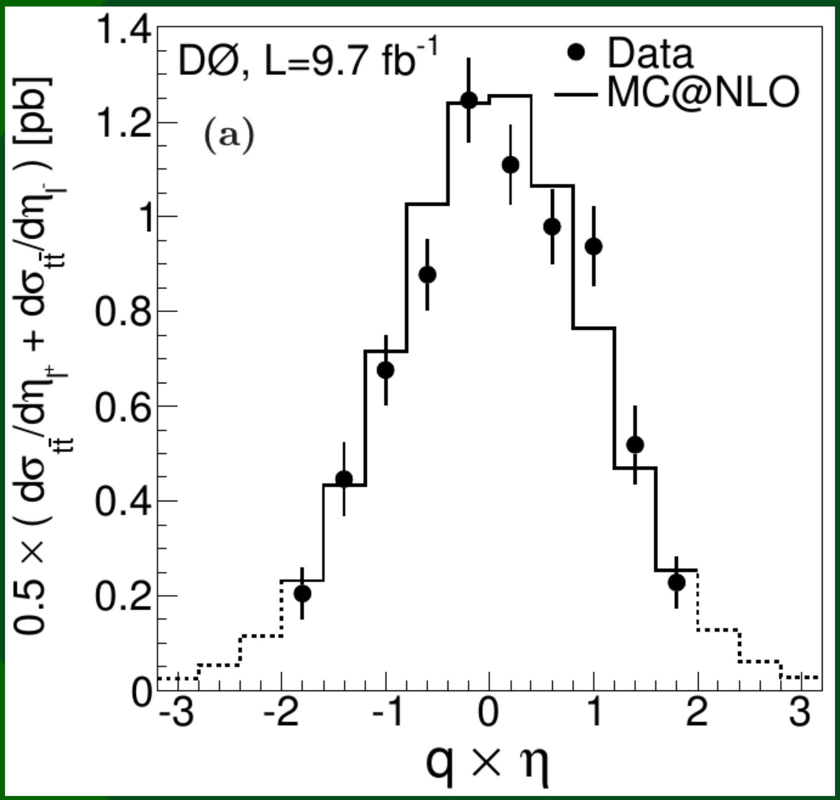
- $|\eta_e| < 1.1$,or $\mathbf{1.5 < |\eta_e| < 2.5}$, $|\eta_\mu| < 2.0$
  - $|\Delta\eta| < 2.4$
- ≥ 2 jets with $p_T > 20$ GeV, w. 1jet in $e\mu$
- p_T imbalance (MET) in ee and $\mu\mu$ channels
- b tagged jet

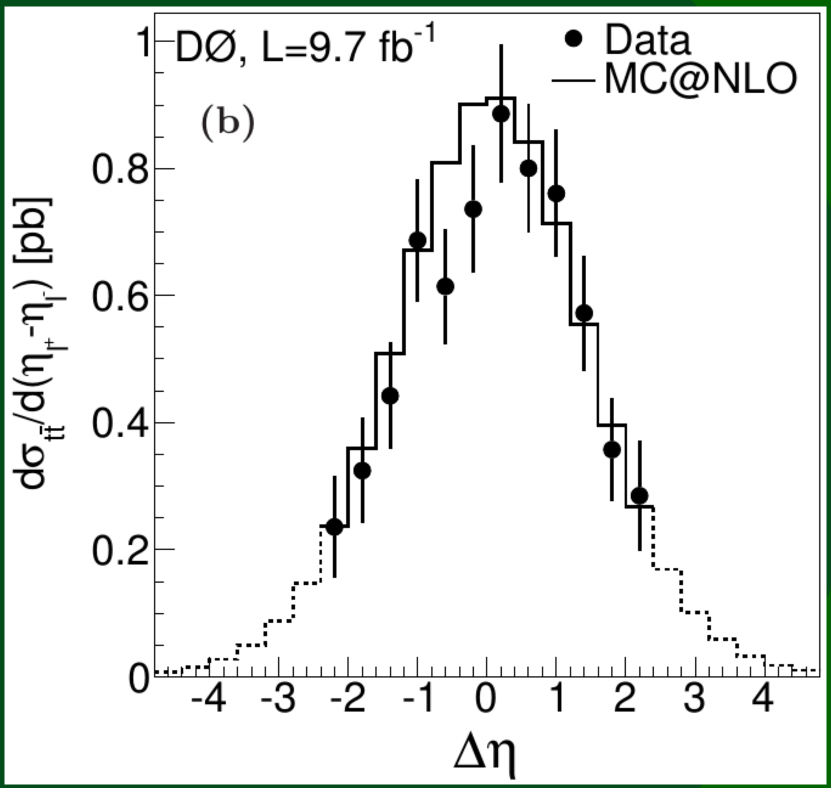
Select ~590 $t\bar{t}$ events with a purity of ~86%



A_{FB}^{l} and $A_{\mathrm{FB}}^{\Delta\eta}$ in dileptons

Extensive η_l coverage → a simple multiplicative extrapolation suffices

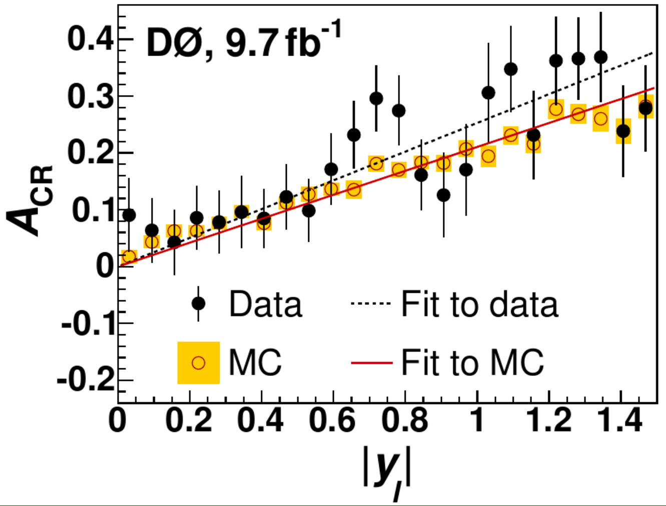




$$A_{\mathrm{FB}}^{l} = 0.044 \pm 0.037(\text{stat.}) \pm 0.011(\text{syst.})$$

$$A_{\mathrm{FB}}^{\Delta\eta} = 0.123 \pm 0.054(\text{stat.}) \pm 0.015(\text{syst.})$$

A_{FB}^{l} in l+jets

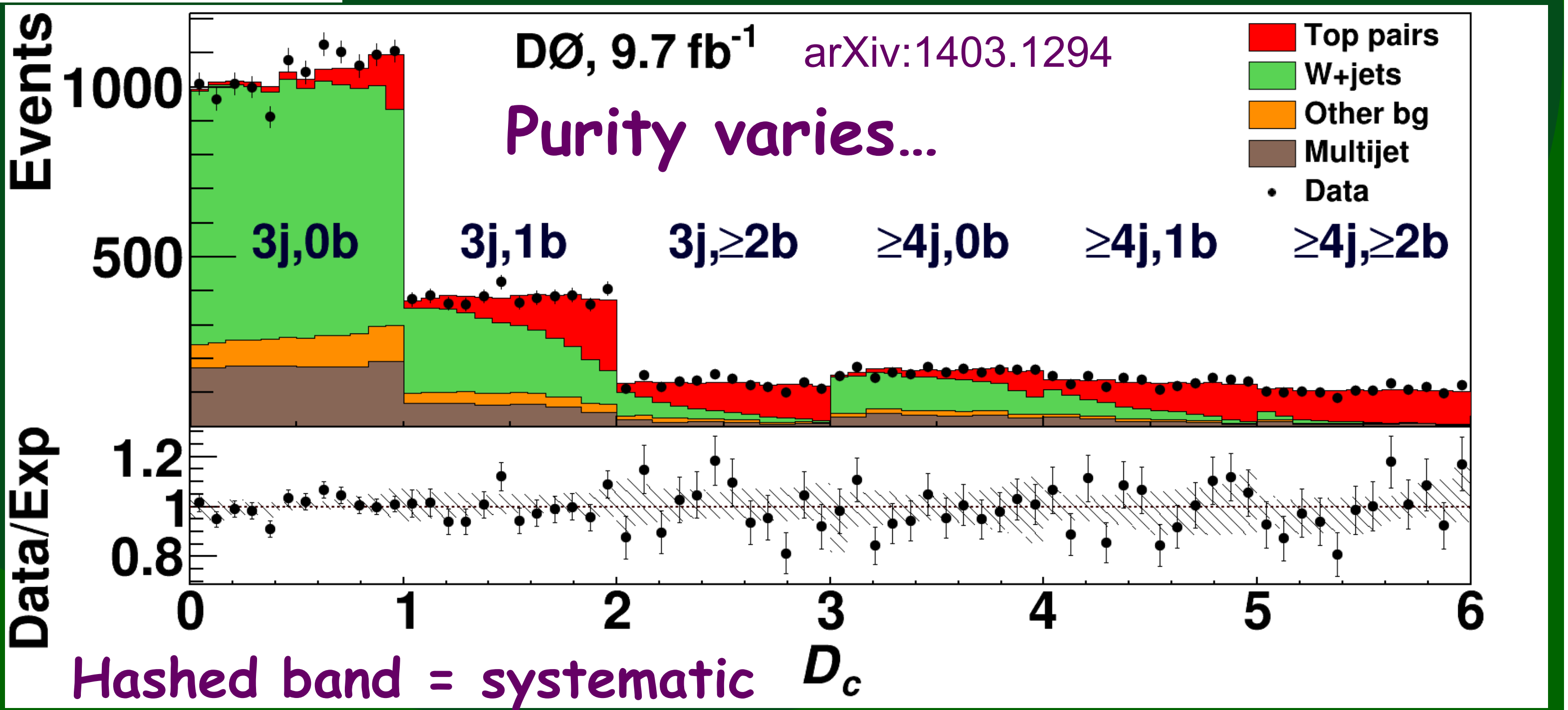


- select objects with $p_T > 20$ GeV
- $|\eta_e| < 1.1, |\eta_\mu| < 1.5$
- **$\geq$ 3 jets**
- p_T imbalance (MET)

→ 4400 signal events (w. ≥1 *b* tag)

Fit for W+jets A_{FB}^{l} in 3j0b control region

Basically doubles PDF uncertainties



l+jets

Results

Data corrected for acceptance within $|y_l| < 1.5$

$$A_{\mathrm{FB}}^{l} = 0.042 \pm 0.023(\mathrm{stat.})^{+0.017}_{-0.020}(\mathrm{syst.})$$

Quite different from 2011 result.
See “Discussion” section of paper.

Combinations with dilepton:

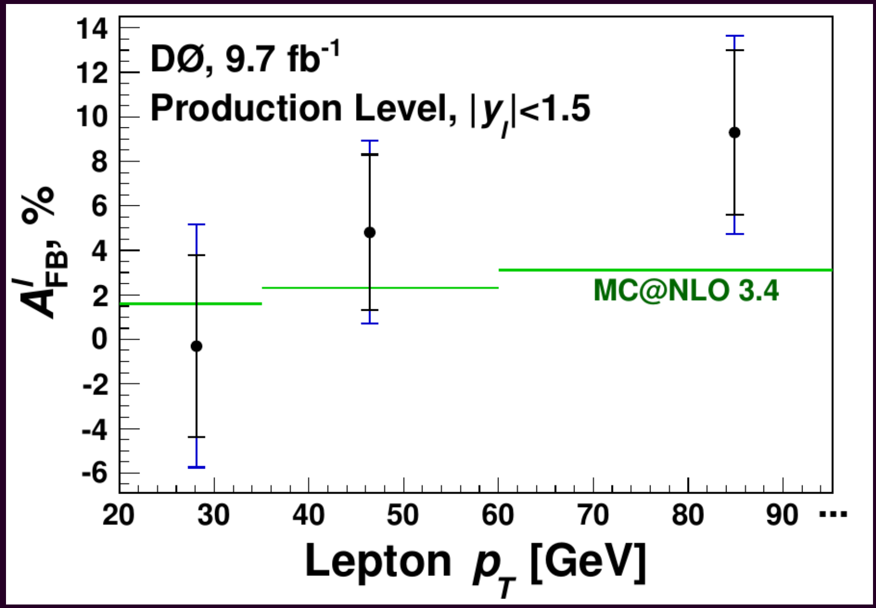
1. Measured within $|y_l| < 1.5$:

$$A_{\mathrm{FB}}^{l} = 0.042 \pm 0.020(\mathrm{stat.}) \pm 0.014(\mathrm{syst.})$$

2. Extrapolated value:

$$A_{\mathrm{FB}}^{l} = 0.047 \pm 0.023(\mathrm{stat.}) \pm 0.015(\mathrm{syst.})$$

First $A_{\mathrm{FB}}^{l}(p_T^l)$ measurement:

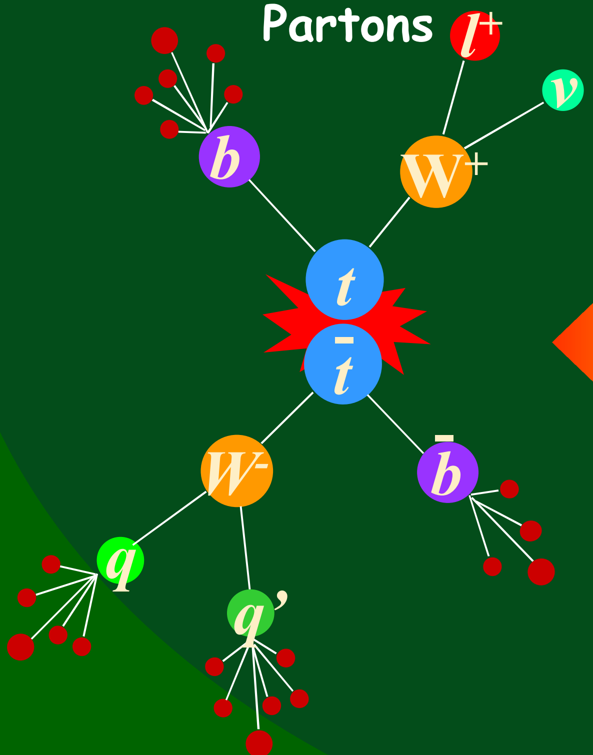


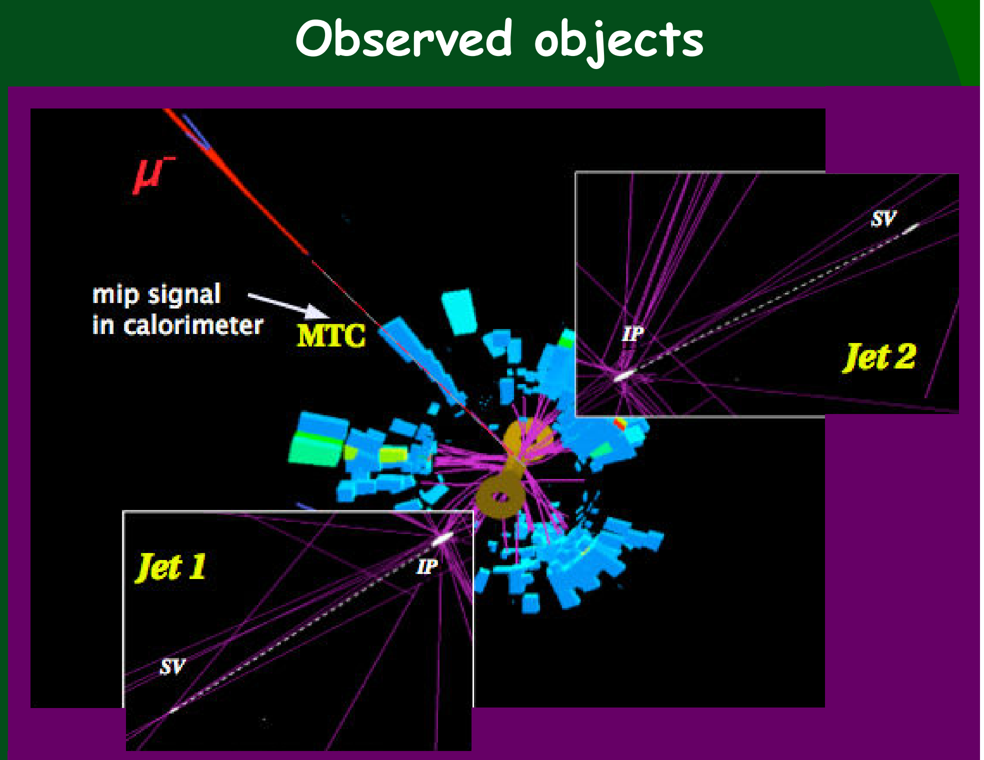
- Motivated by e.g., PRD 87 (2013) 034039
- Fit for W+jets A_{FB}^{l} per p_T^l bin
- Correct for p_T^l migrations

$t\bar{t}$ A_{FB} in l+jets

Just like in A_{FB}^{l}:
selection, sample composition, background modeling,…

But need to reconstruct the $t\bar{t}$ pair to find $\Delta y(t\bar{t})$ and $m(t\bar{t})$





Main challenge: which jet came from which quark?

l+jets

Reconstruction

New kinematic fit algorithm for events with ≥4 jets

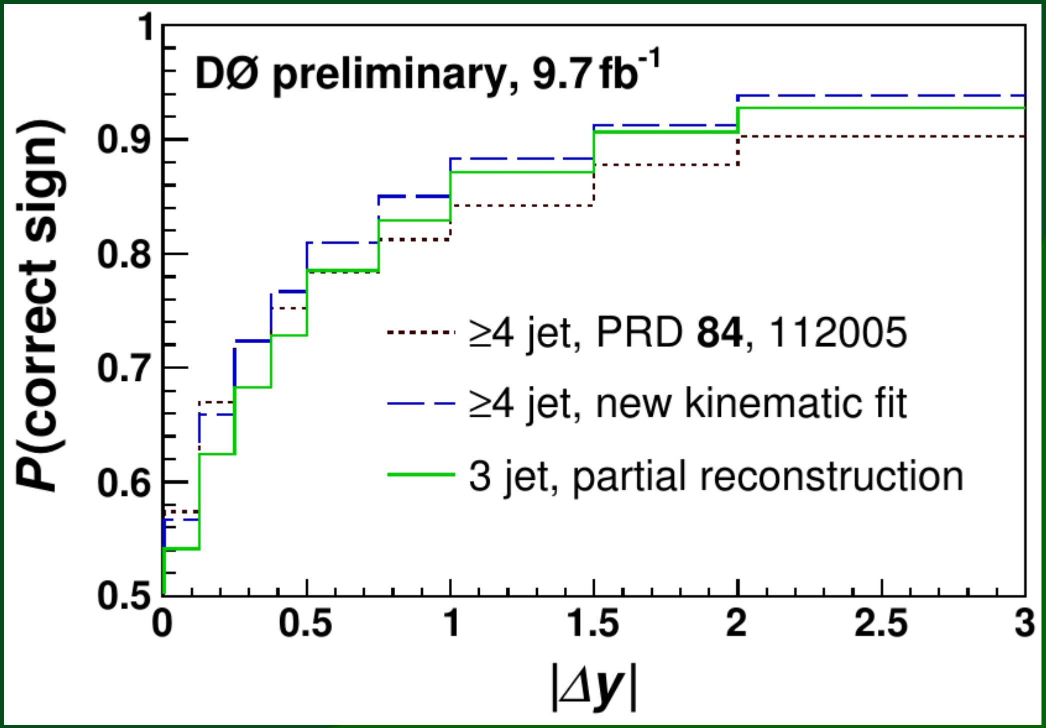
- allows extensive checks of data modeling
  - improved modeling of $p_T(t\bar{t})$
- uses analytical solution for neutrino $\vec{p}$ [NIMA **736** (2014) 169]

$m(t\bar{t})$ from multivariate regression combining 3 algorithms

- Simple algorithm robust to ISR in high $m(t\bar{t})$ events

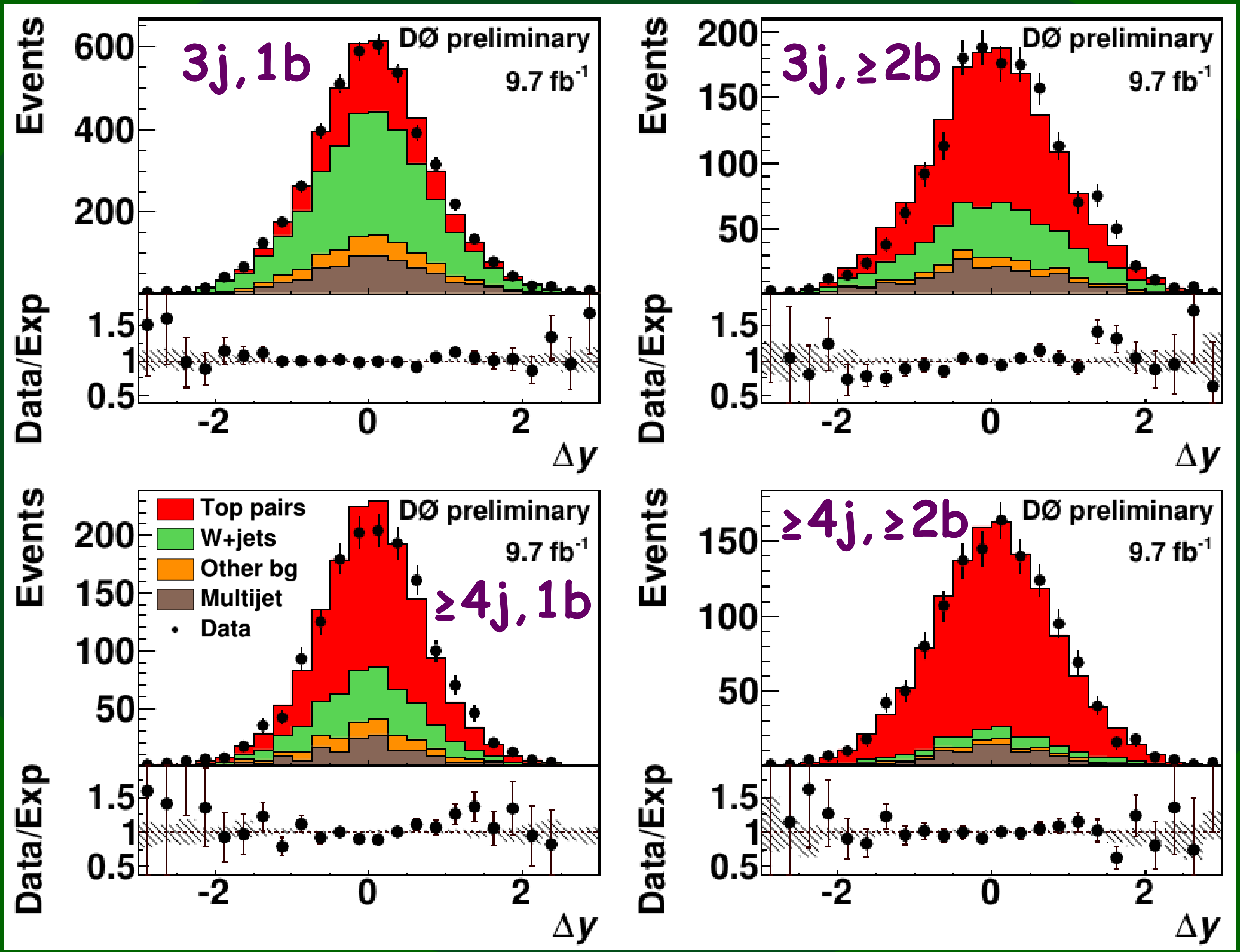
New partial reconstruction algo. for events with 3 jets

- Each quark-to-jet assignment evaluated using nine observables
- Some refinements for $m(t\bar{t})$



l+jets

Data distributions

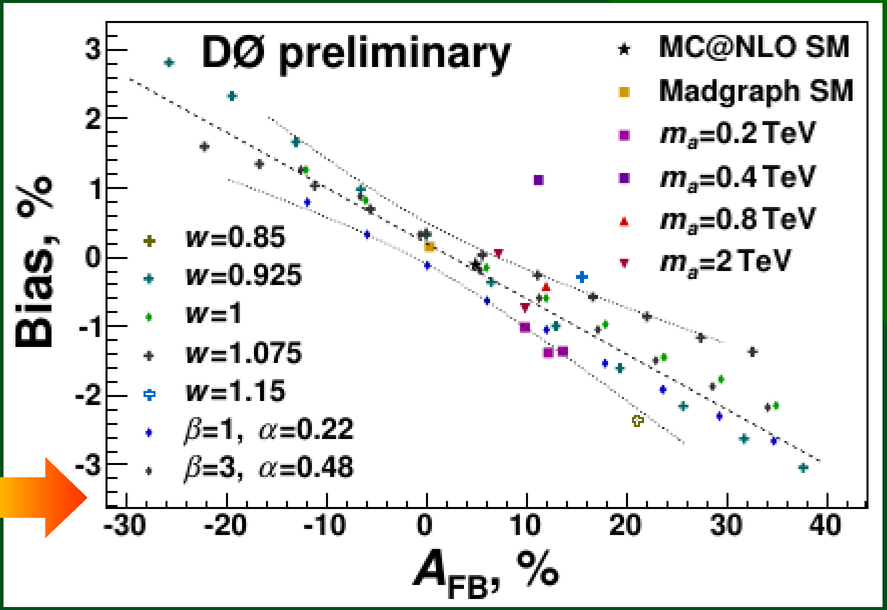


l+jets

Inclusive A_{FB}

Regularized unfolding

- 200 bins (4 channels) → 26 bins
- Account for different bkg. Levels
- Optimized from ensemble testing which includes systematic effects
- Results are calibrated
  - w. different prod.-level distributions



$$A_{FB} = 0.106 \pm 0.027(\text{stat.}) \pm 0.013(\text{syst.})$$

Our most precise measurement

Compatible with SM predictions and with CDF result [PRD **87** (2013) 092002] of $A_{FB} = 0.164 \pm 0.039(\text{stat.}) \pm 0.026(\text{syst.})$

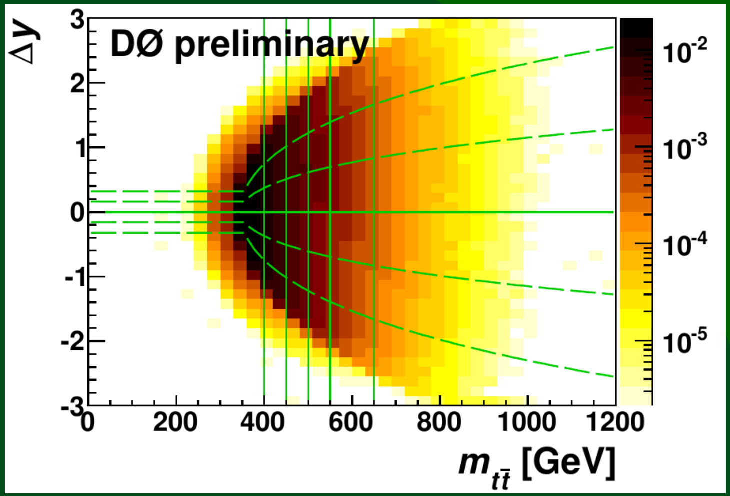
l+jets

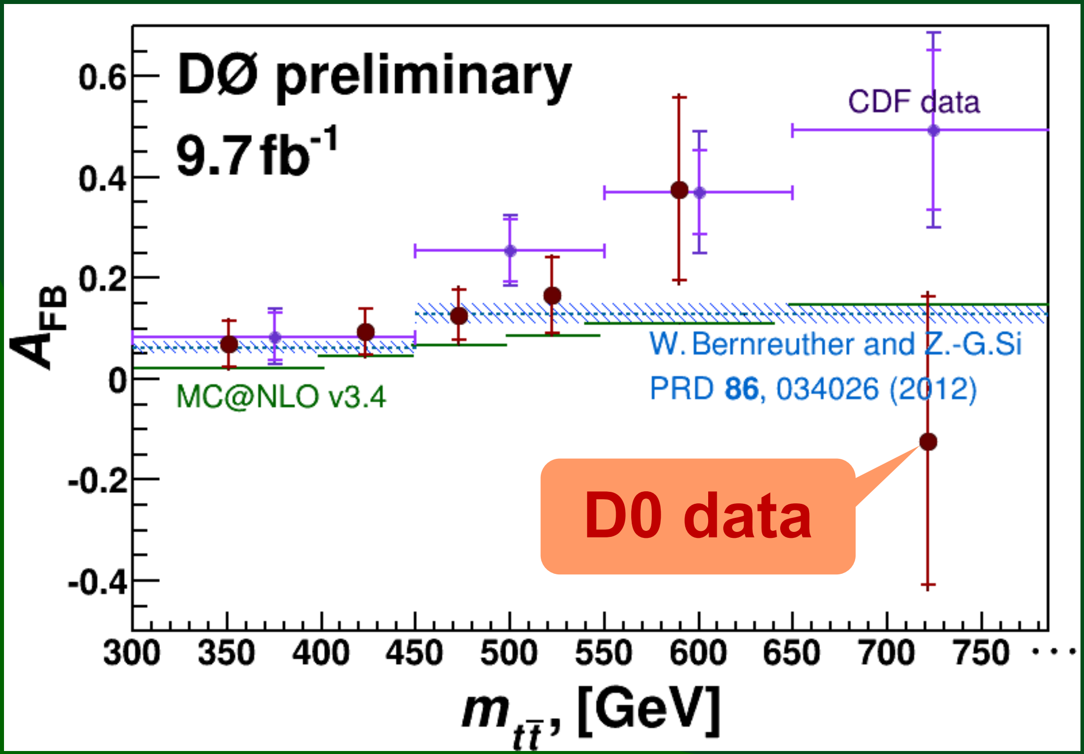
Differential A_{FB}

Unfolding similar to 1D case

Bins chosen to avoid kinematic edge

Full 2D regularization by curvature of event density.





Fitted slope:

$(3.9 \pm 4.4)10^{-4}\ \mathrm{GeV}^{-1}$

Compatible with SM and CDF result.

CDF result is 1.8σ away:
$(15.5 \pm 4.8)10^{-4}\ \mathrm{GeV}^{-1}$

Summary

The Tevatron experiments measured various forward-backward asymmetries in $t\bar{t}$ production

- $t\bar{t}$ A_{FB} of Δy
  - As a function of $m(t\bar{t})$ and $|\Delta y|$
- A_{FB}^{l} in dilepton and l+jets channels
- $A_{\mathrm{FB}}^{\Delta\eta}$
- Recently published $d\sigma/d\cos\theta$ from CDF

Not all results included in this talk

CDF results somewhat higher than standard model predictions

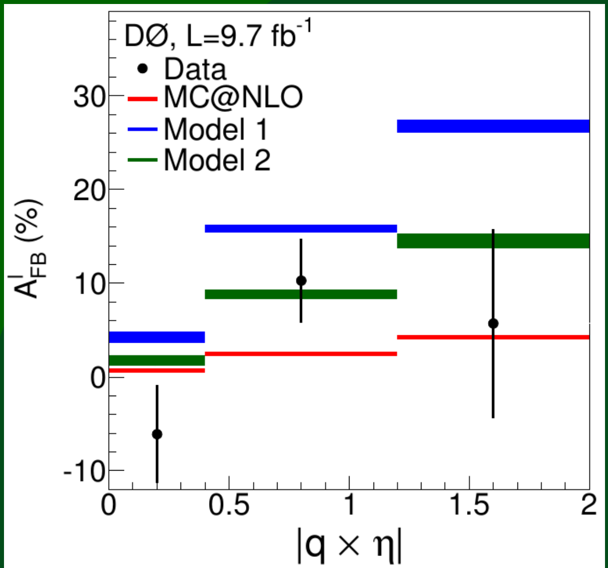
D0 results agree well with standard model prediction

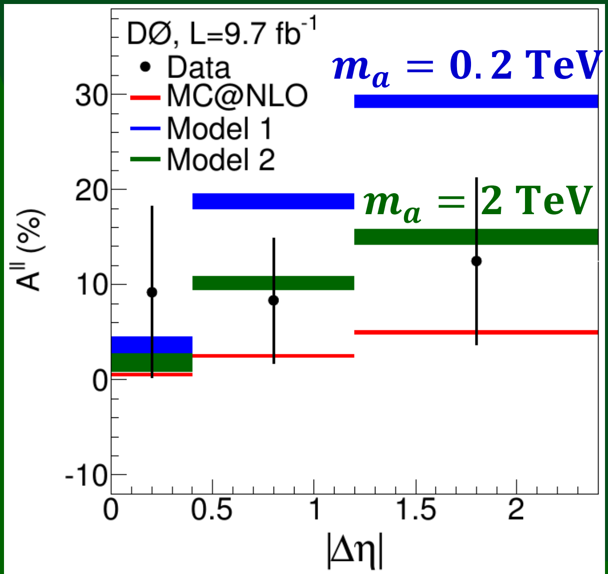
But the results from the two experiments are consistent

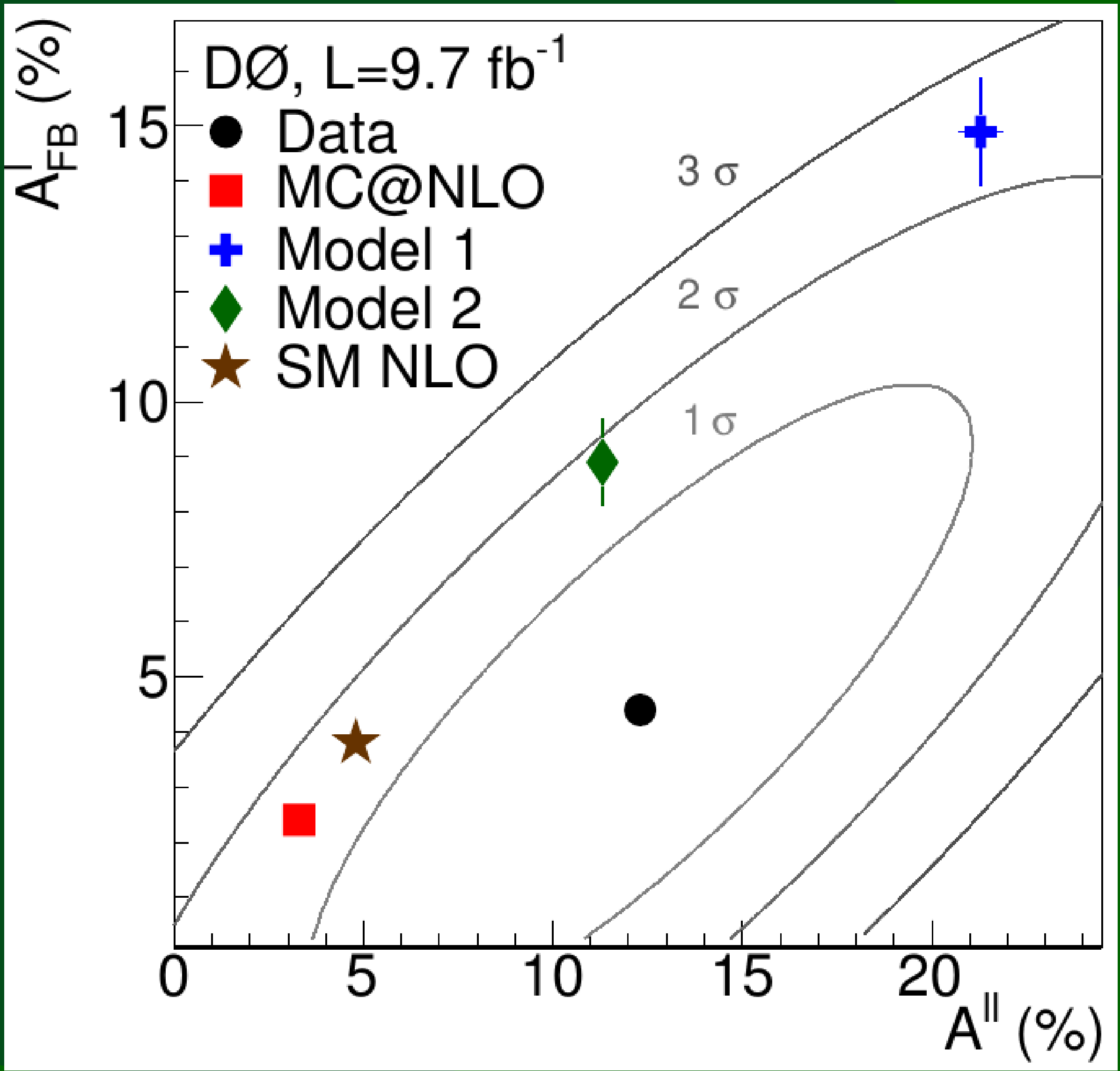
Started work on combining the measurements…

Back up slides

DØ A_{FB}^{l} and $A_{FB}^{\Delta\eta}$ in dileptons





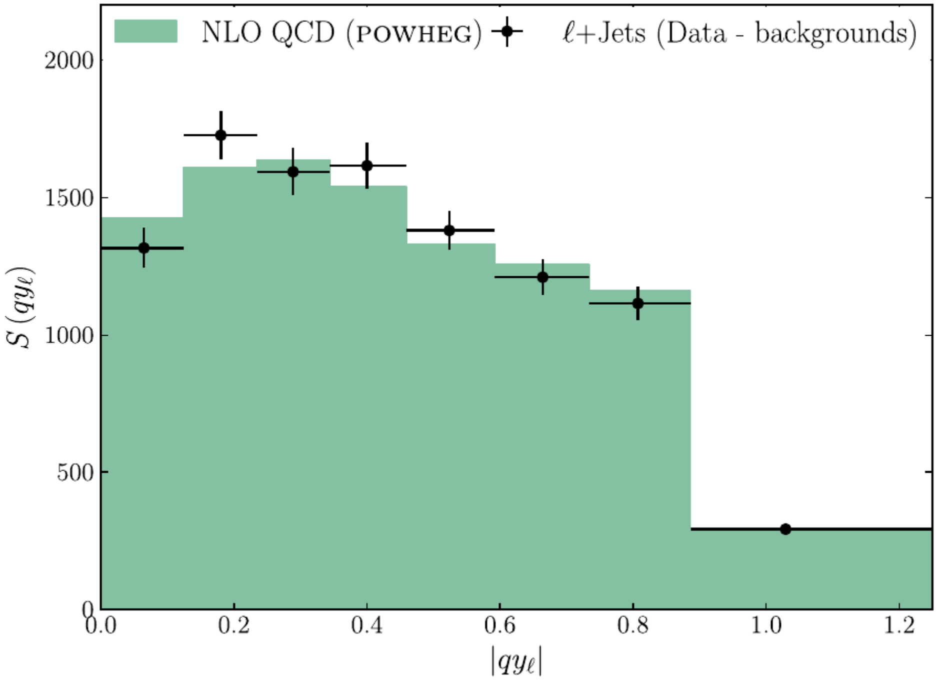


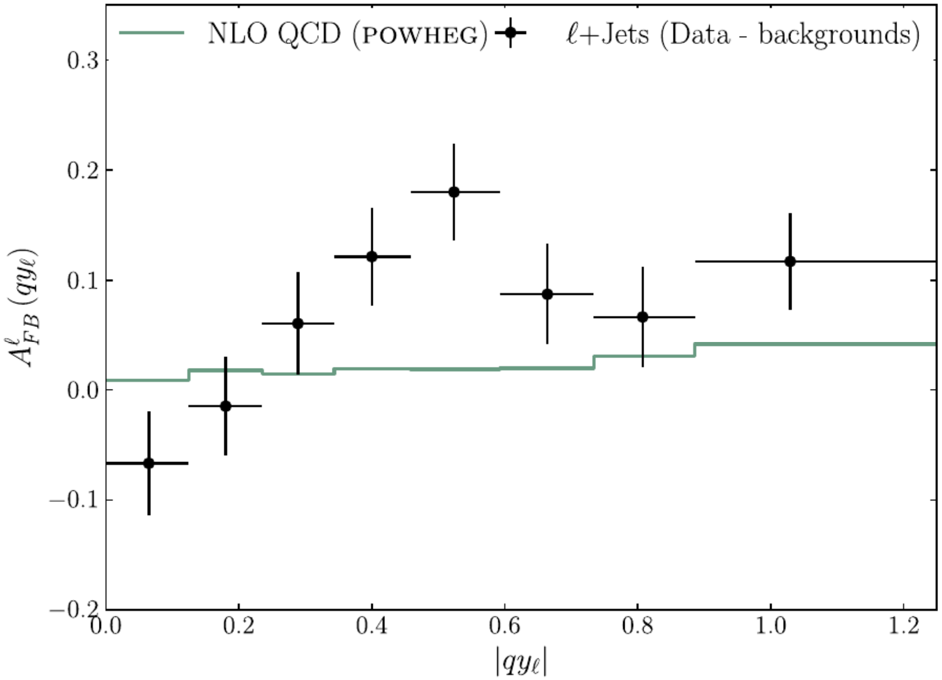
CDF Separating out A^{l}_{FB}

$$N(qy_l)$$

$$S(qy_l) = \frac{N(qy_l) + N(-qy_l)}{2}$$

$$A(qy_l) = \frac{N(qy_l) - N(-qy_l)}{N(qy_l) + N(-qy_l)}$$





Looks the same for different SM and BSM scenarios

The interesting part

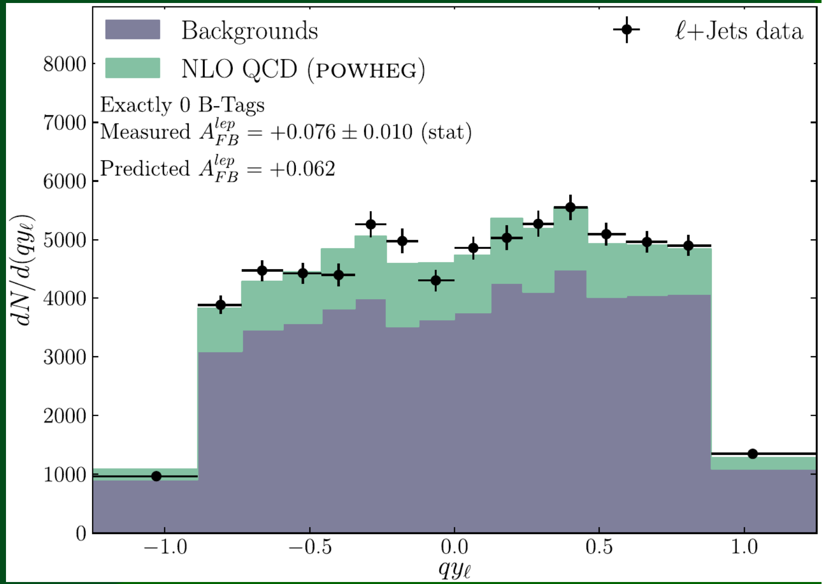
CDF l+jets, Cross checks

TABLE VI. Summary of asymmetries observed in subsamples selected by charge, lepton type, and jet multiplicity. Exclusive categories are grouped together by horizontal lines. Also reported is the inclusive result. Uncertainties include both statistical and systematic contributions.

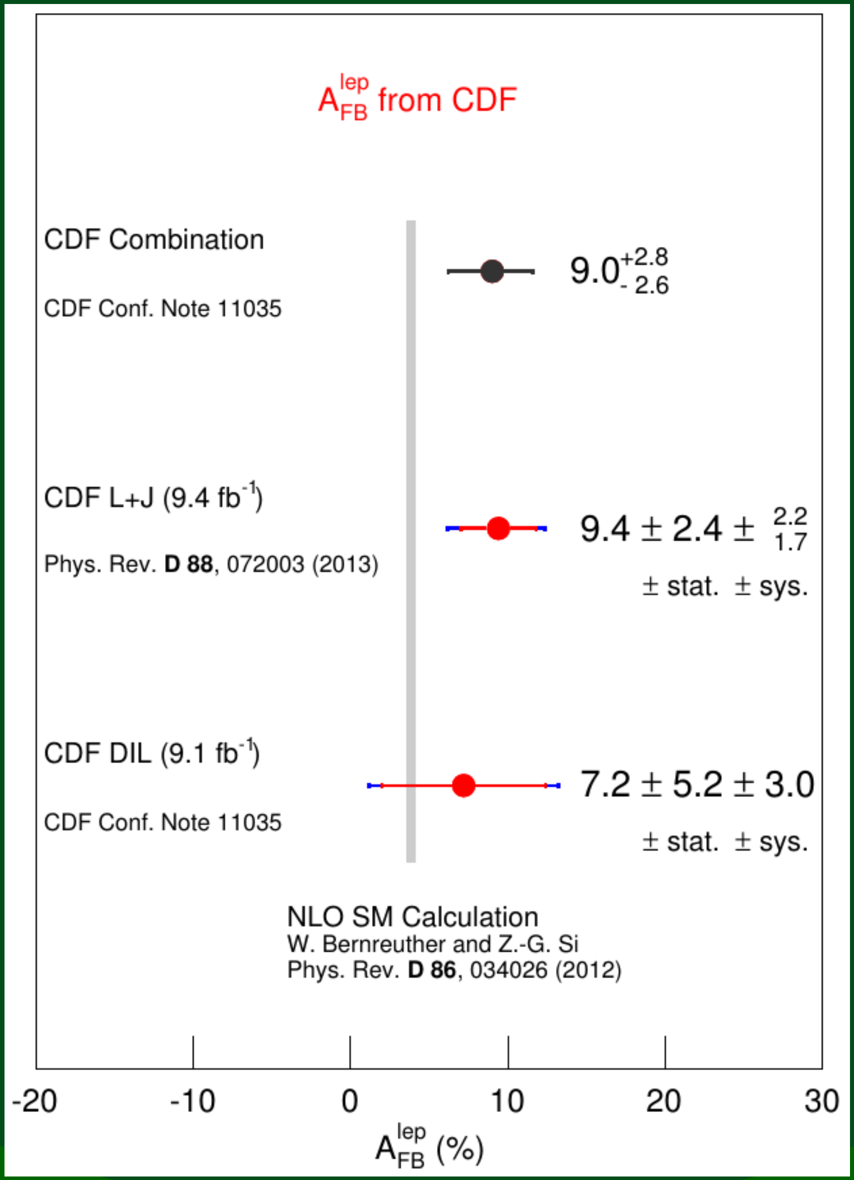
Sample	Event yield	Raw	Background-subtracted	Fully extrapolated
Electrons	1788	0.050 ± 0.024	0.050 ± 0.033	$0.062^{+0.052}_{-0.049}$
Muons	2076	0.081 ± 0.022	0.087 ± 0.029	$0.119^{+0.039}_{-0.037}$
Positive	1884	0.099 ± 0.023	0.110 ± 0.031	$0.125^{+0.043}_{-0.041}$
Negative	1980	0.036 ± 0.022	0.034 ± 0.031	$0.063^{+0.046}_{-0.042}$
$W + 4$	2682	0.064 ± 0.019	0.064 ± 0.024	$0.084^{+0.035}_{-0.032}$
$W + 3 + 1$	1182	0.072 ± 0.029	0.092 ± 0.049	$0.115^{+0.067}_{-0.065}$
Inclusive	3864	0.067 ± 0.016	0.070 ± 0.022	$0.094^{+0.032}_{-0.029}$

TABLE III. Comparison of the predicted and measured asymmetries in the zero-tag control sample. "Signal + backgrounds" is the predicted asymmetry when the A^{ℓ}_{FB} of the $t\bar{t}$ component is fixed to 0.070.

	Asymmetry
NLO SM	0.017
Backgrounds	0.074
NLO SM + backgrounds	0.062
Signal + backgrounds	0.073
Data	0.076 ± 0.010



CDF A_{FB}^{l} combination



DØ dilepton, syst

TABLE III: Systematic uncertainties for the corrected and the extrapolated asymmetries. All values are given in %.

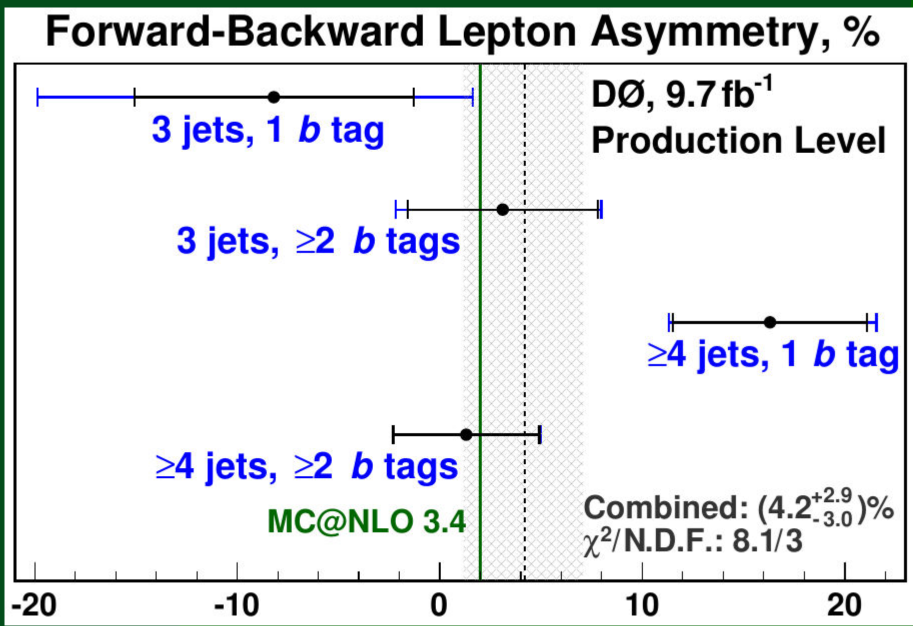
	Corrected		Extrapolated	
	$A^{\ell}_{\rm FB}$	$A^{\ell\ell}$	$A^{\ell}_{\rm FB}$	$A^{\ell\ell}$
Source				
Object ID	0.54	0.50	0.59	0.60
Background	0.66	0.74	0.72	0.88
Hadronization	0.52	0.62	0.62	0.92
MC statistics	0.19	0.23	0.23	0.37
Total	1.02	1.12	1.14	1.46

MC@NLO+Herwig *vs.* Alpgen+Pythia
→ Recoil modeling & Hadronization together

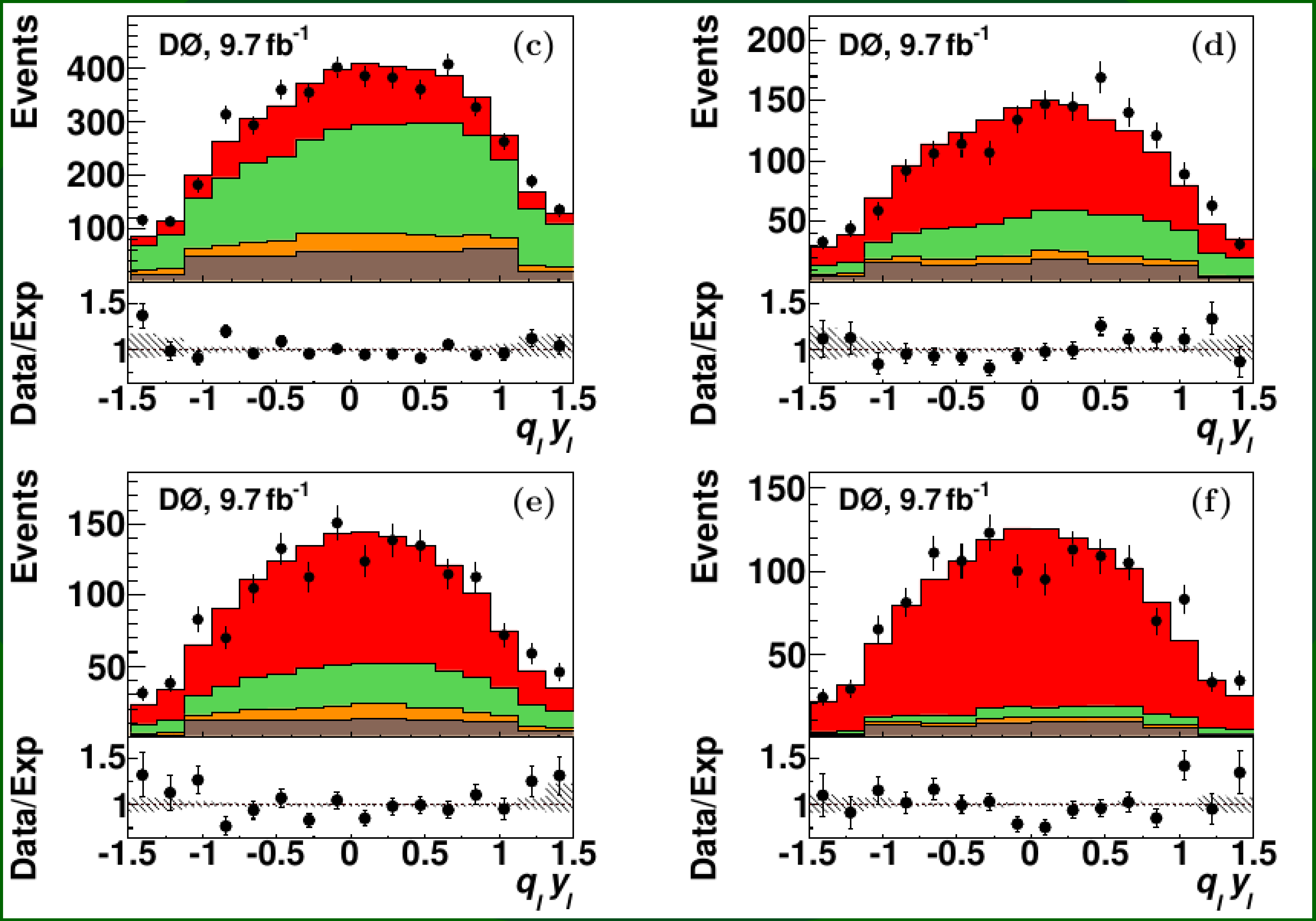
$$R = A^{\ell}_{\rm FB}/A^{\ell\ell} = 0.36 \pm 0.20$$

DØ A^{l}_{FB} l+jets, syst

	Absolute uncertainty, %		
	Reconstruction level		Prod. level
Source	Prediction	Measurement	Measurement
Jet reco	−0.1	–	–
JES/JER	+0.1	+0.1/−0.3	+0.2/−0.3
Signal modeling	–	−0.2	+0.6/−0.4
b tagging	±0.1	+0.5/−0.8	+0.8/−1.1
Bg subtraction	n/a	+0.1/−0.3	+0.1/−0.3
Bg modeling	n/a	+1.4/−1.5	+1.3/−1.5
PDFs	–	+0.3/−0.2	+0.1/−0.2
Total	±0.1	+1.5/−1.7	+1.7/−2.0



A_{FB}^{l} l+jets, signal channels



A^{l}_{FB} l+jets, 0 b tag channels

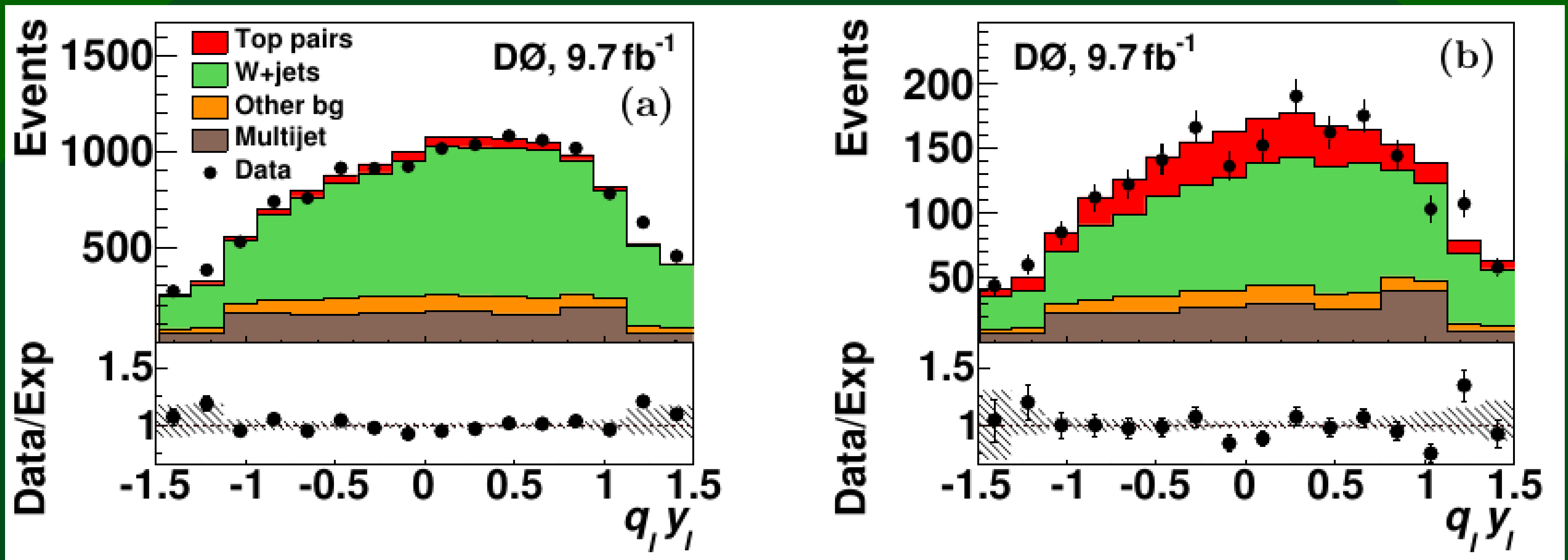
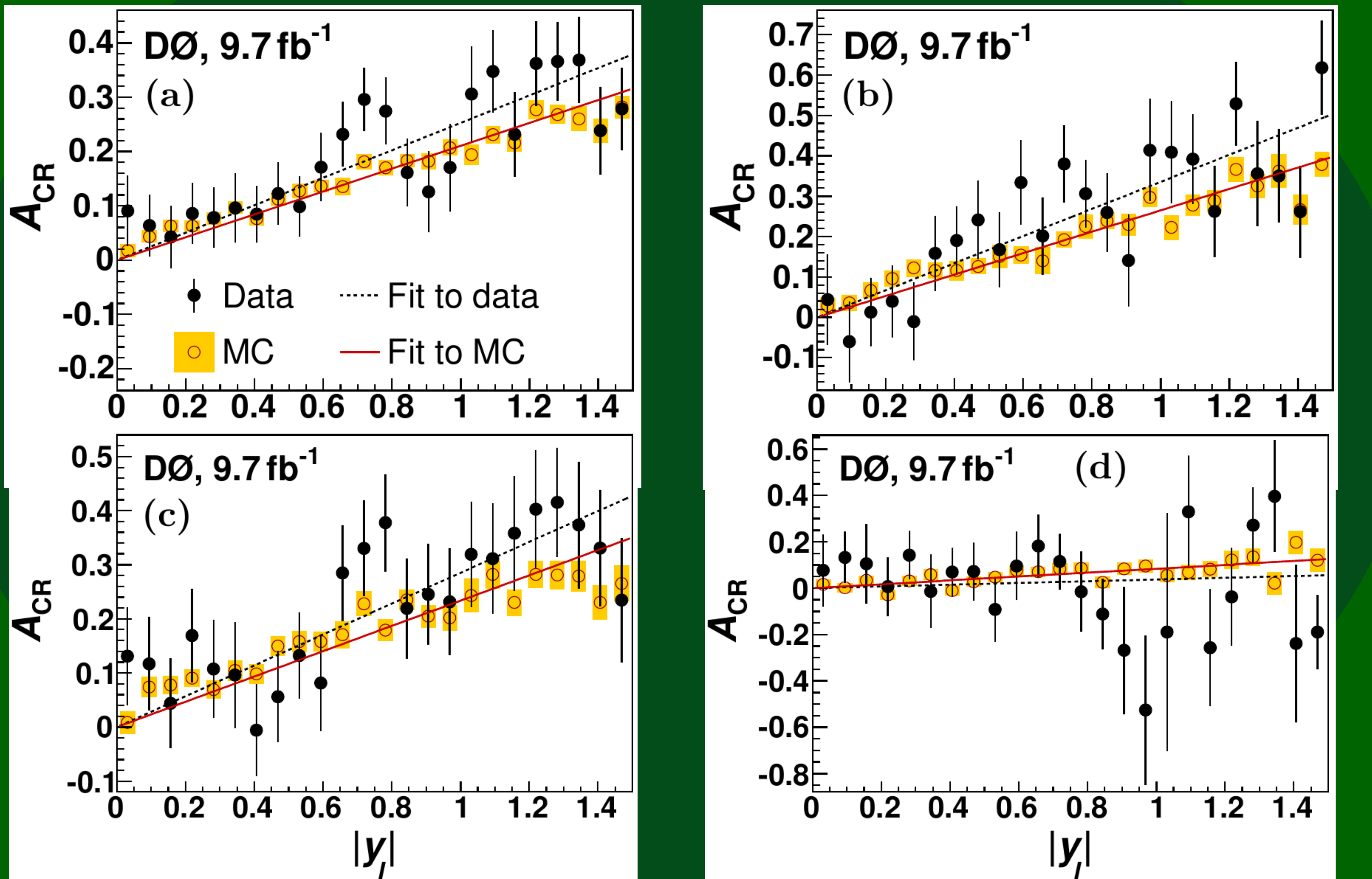


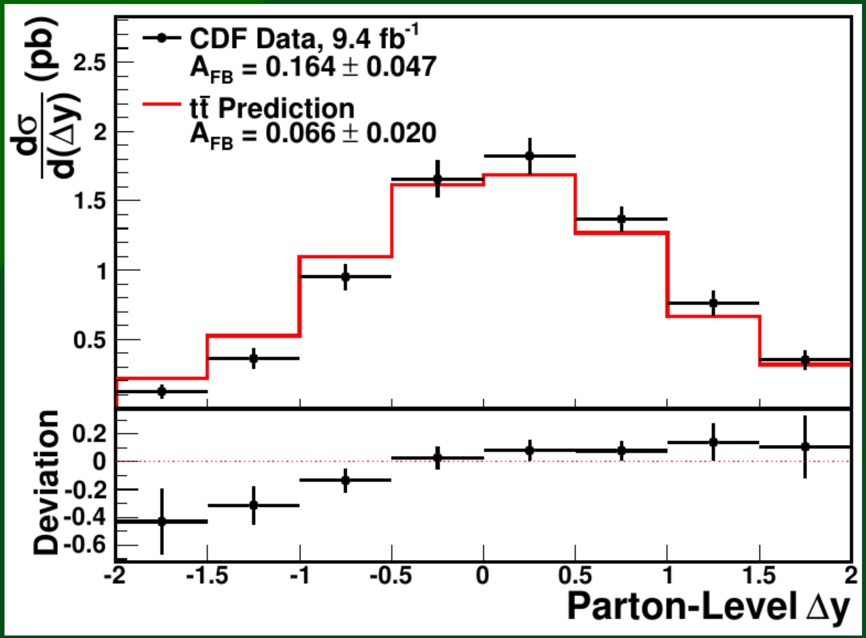
TABLE III: Parameters of the $q_l y_l$ reweighting of the W+jets background, effects on A_{CR}, and PDF uncertainties. The first row lists the parameter α of the $q_l y_l$ reweighting with its statistical uncertainty. The second row lists the effect of the reweighting on A_{CR}. The next two rows list the up and down uncertainties on A_{CR} due to PDFs.

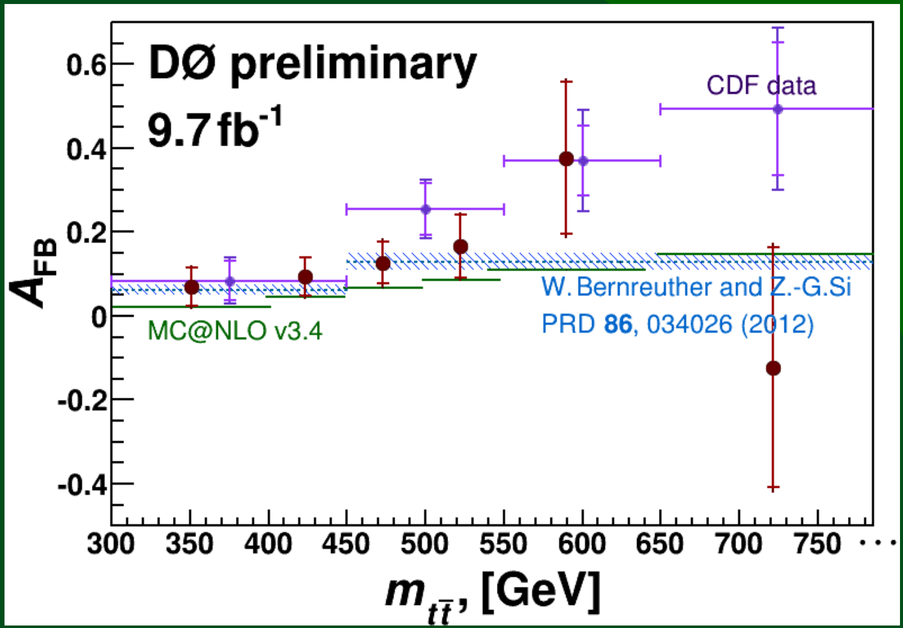
	p_T^l range, GeV			
Quantity	≥ 20	20–35	35–60	≥ 60
α, %	4.5 ± 1.8	7.9 ± 2.7	5.7 ± 2.4	-6.6 ± 4.3
ΔA_{CR}, %	2.7 ± 1.0	4.7 ± 1.6	3.3 ± 1.4	-3.9 ± 2.6
σ^{+}_{CR}, %	1.0	0.5	1.2	0.8
σ^{-}_{CR}, %	1.7	1.6	1.7	1.8

DØ A^{l}_{FB} W+jets, by p^{l}_{T}



Errors on $A_{\mathrm{FB}}(m_{t\bar{t}})$





Eff. sample size in 2D relative to the size in 1D

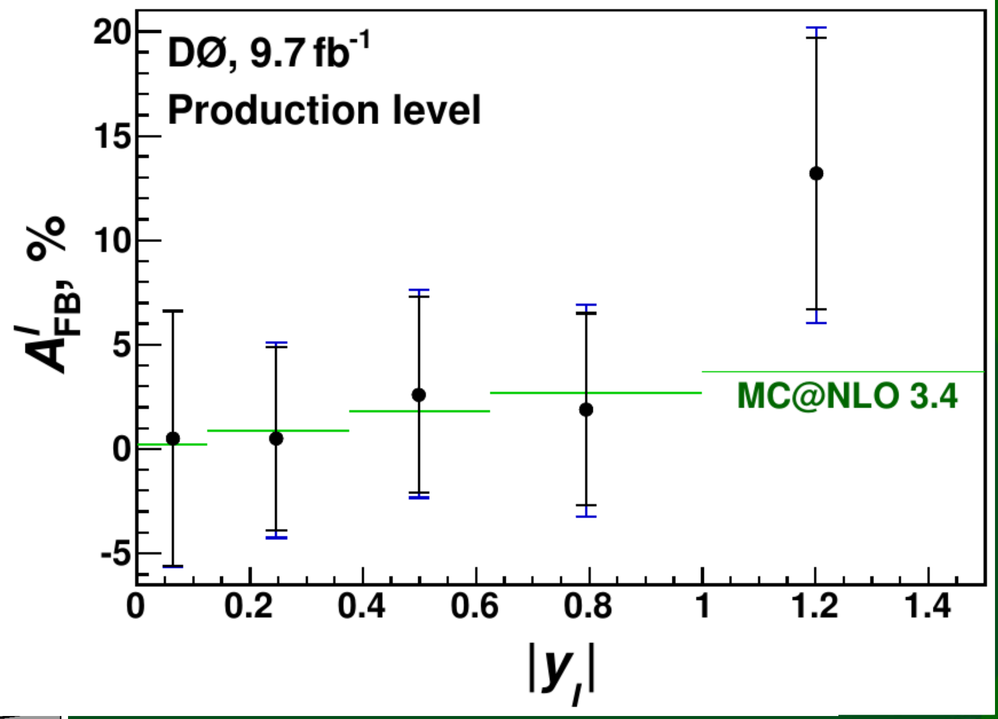
- D0 with 2D regularization: 1.2
- CDF with 1D regularization: 1.4

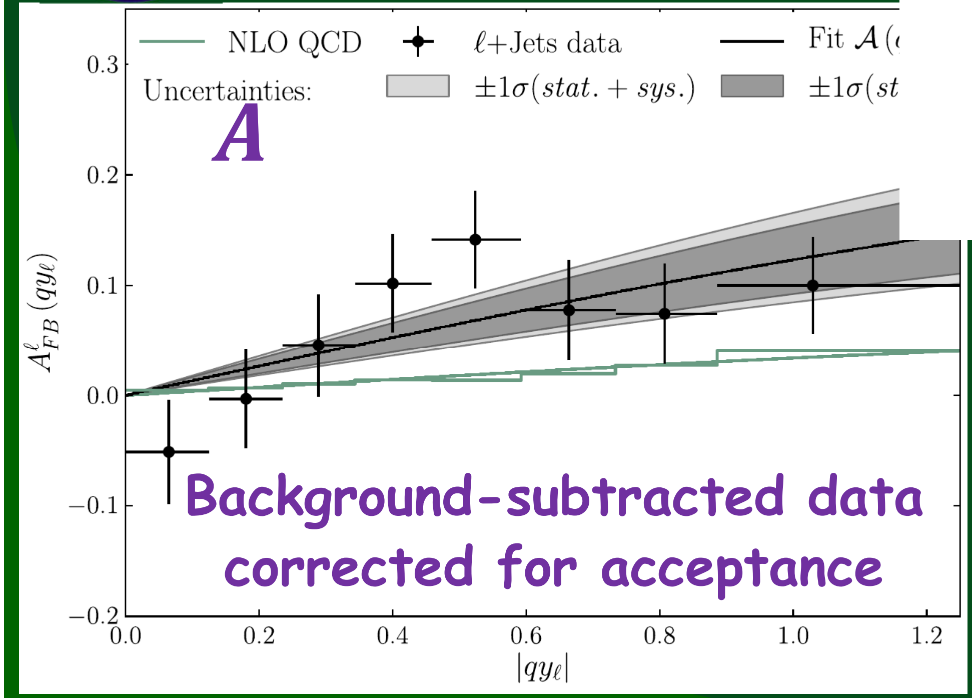
DØ Correlations on $A_{\mathrm{FB}}(m_{t\bar{t}})$

l+jets, $A_{\mathrm{FB}}(m_{t\bar{t}})$

	$m_{t\bar{t}}$ range (GeV)					
	< 400	400–450	450–500	500–550	550–650	> 650
< 400	+1.00	+0.89	+0.39	−0.19	−0.25	+0.12
400–450	+0.89	+1.00	+0.67	+0.10	−0.32	+0.12
450–500	+0.39	+0.67	+1.00	+0.68	−0.27	+0.05
500–550	−0.19	+0.10	+0.68	+1.00	+0.04	−0.12
550–650	−0.25	−0.32	−0.27	+0.04	+1.00	−0.41
> 650	+0.12	+0.12	+0.05	−0.12	−0.41	+1.00

$A^{l}_{\mathrm{FB}}(|y_l|)$

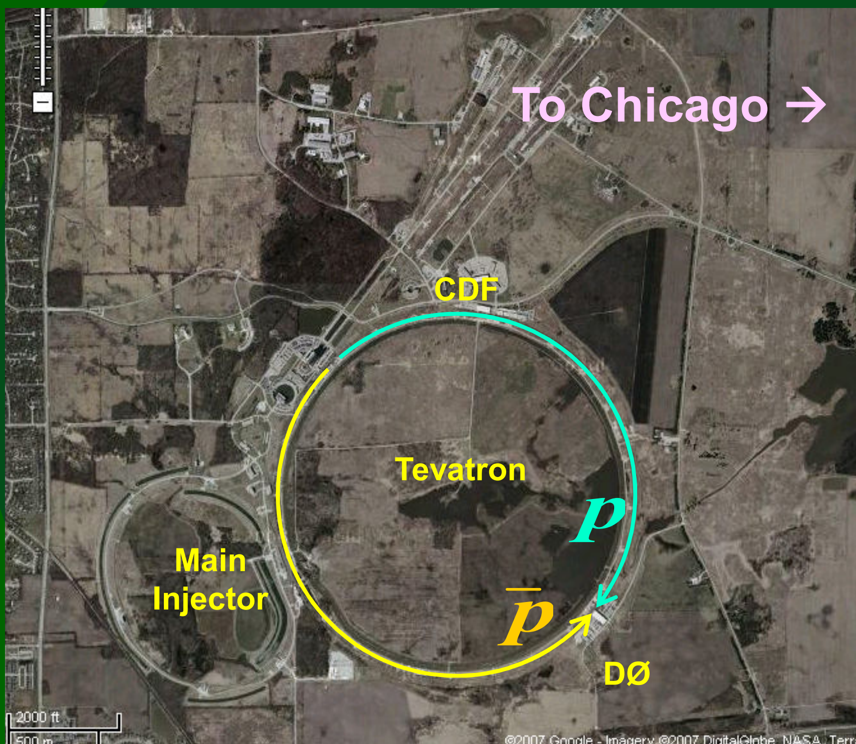




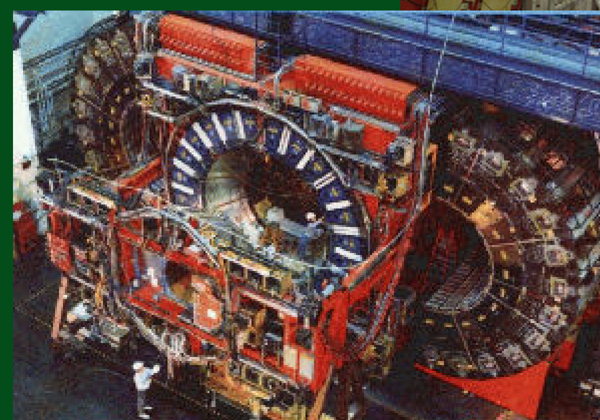
Experimental Apparatus

Fermilab Tevatron Collider

Run II 2002-2011



The detectors



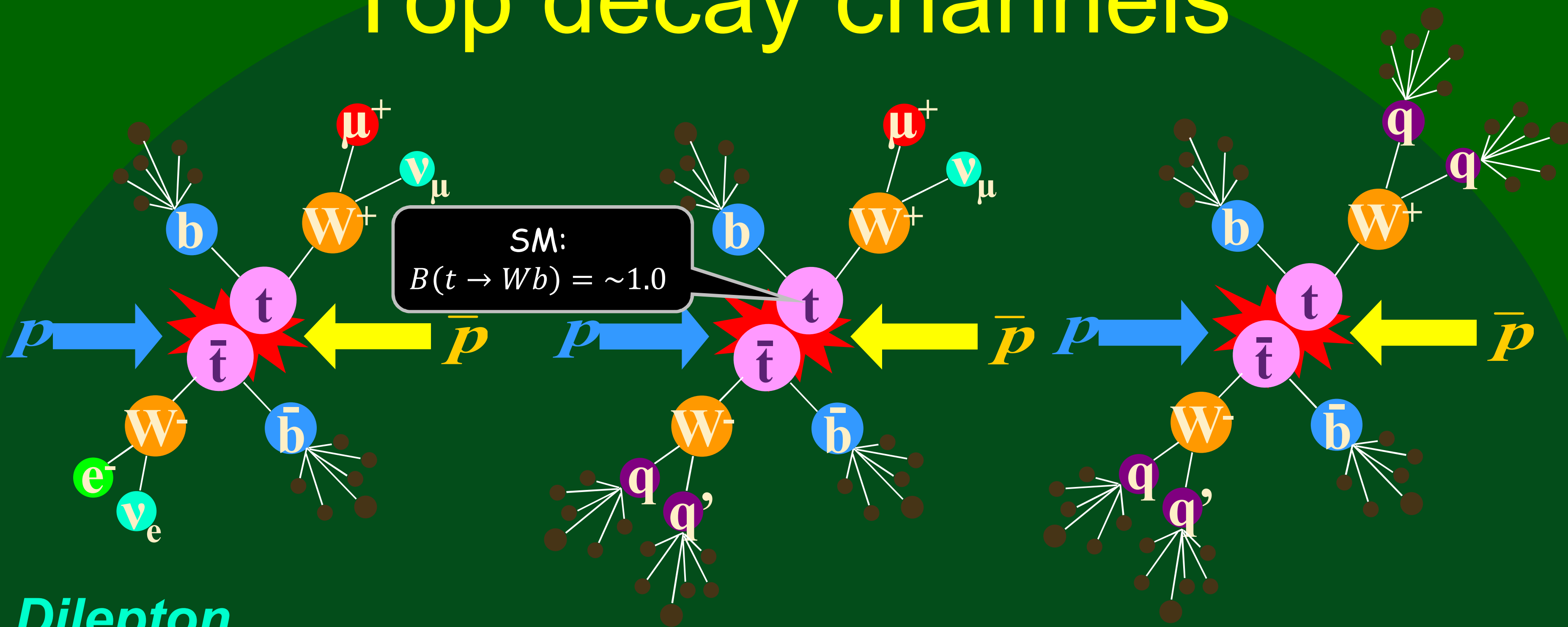
The collisions

- $p\bar{p}$ at $E_{c.m.} = 1.96\,\mathrm{TeV}$
- $\sim 12\mathrm{fb}^{-1}$ per experiment

General purpose detectors

Top physics relies on tracking, calorimetry and muon detectors.

Top decay channels



Dilepton

1. Isolated high p_T
   ee, $e\mu$, or $\mu\mu$
2. ≥2 jets
3. Large p_T imbalance
   - MET / $\not{E}_T$ when measured by calorimetry

Low branching fraction (~5%)

Lepton+jets

Isolated high p_T e or μ

- ≥4 jets
- p_T imbalance

The golden channel

All hadronic

- 2 *b*-tagged jets
- ≥6 jets

Huge background

A bit of history

- SM predictions: <4% (2006) → >8% (now)
- DØ: reco.-level 12±8%, 0.9 fb^{-1}, PRL100(2008)142002, 221 citations
- CDF: 24±14% 1.9 fb^{-1}, PRL100(2008)202001, 215 citations
- CDF: 15.8±7.2% 5.3 fb^{-1}, PRL83(2011)112003, 388 citations
  - For $m(t\bar{t}) > 450\text{GeV}$, 47.5±11.4% (MCFM prediction: 8.8%)

Good agreement with the standard model