Measurement of the angular asymmetries in the production of top quark pairs in the $p\bar{p}$ collisions

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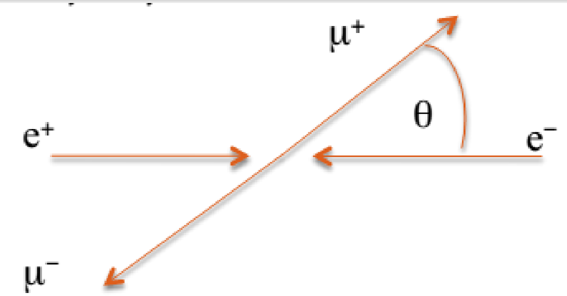
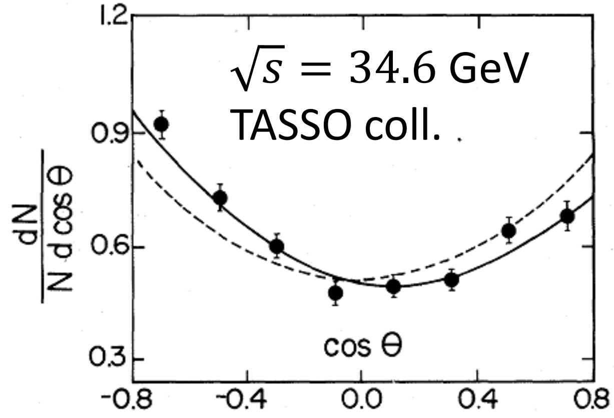
for the DØ collaboration

Asymmetry in $t\bar{t}$ production

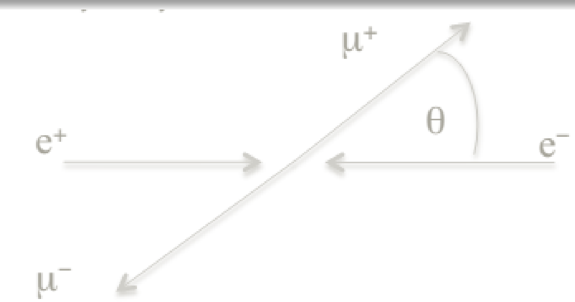
- first motivation - in early 80's asymmetry observed in $e^+e^- \to \mu^+\mu^-$ at only $\sqrt{s} = 34.6$ GeV - verification the validity of EW theory (Z resonance) (e.g. PRL 48 (1982) 1701)

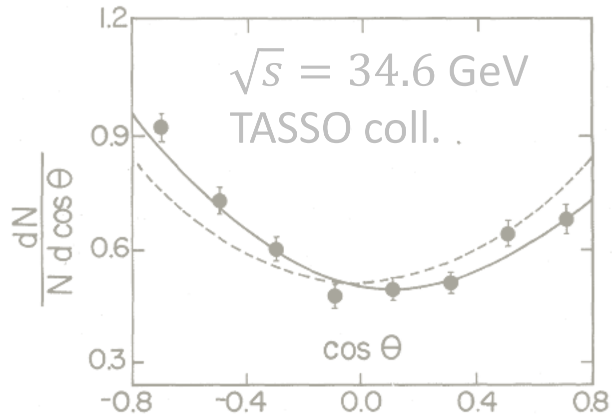




Asymmetry in $t\bar{t}$ production

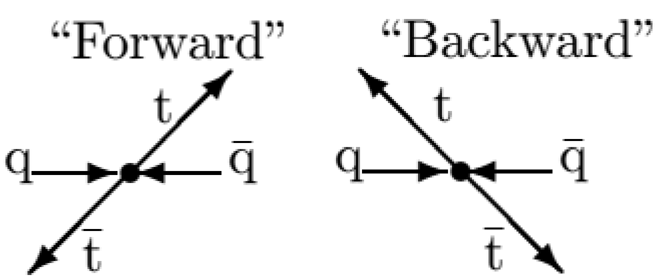
- first motivation - in early 80's asymmetry observed in $e^+e^- \to \mu^+\mu^-$ at only $\sqrt{s} = 34.6$ GeV - verification the validity of EW theory (*Z* resonance) (e.g. PRL 48 (1982) 1701)



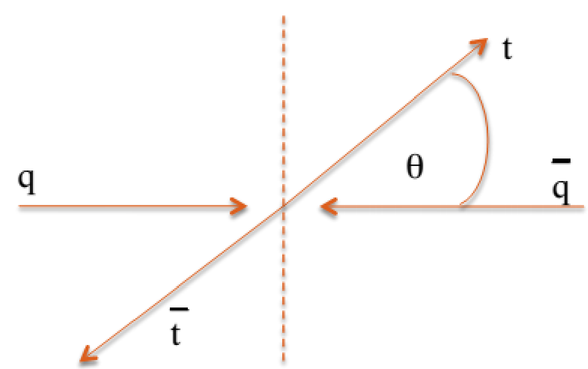


- similarly in $p\bar{p} \to t\bar{t}$ - small SM prediction, sensitive to new physics (e.g. axi-gluons)
- for angular variable *x* in some rest frame:

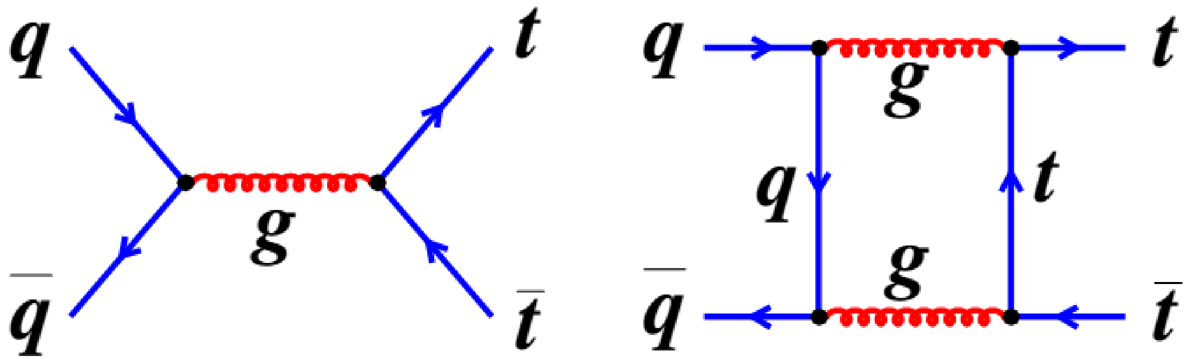
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B} \quad (N_F = N(x > 0), N_B = N(x < 0))$$



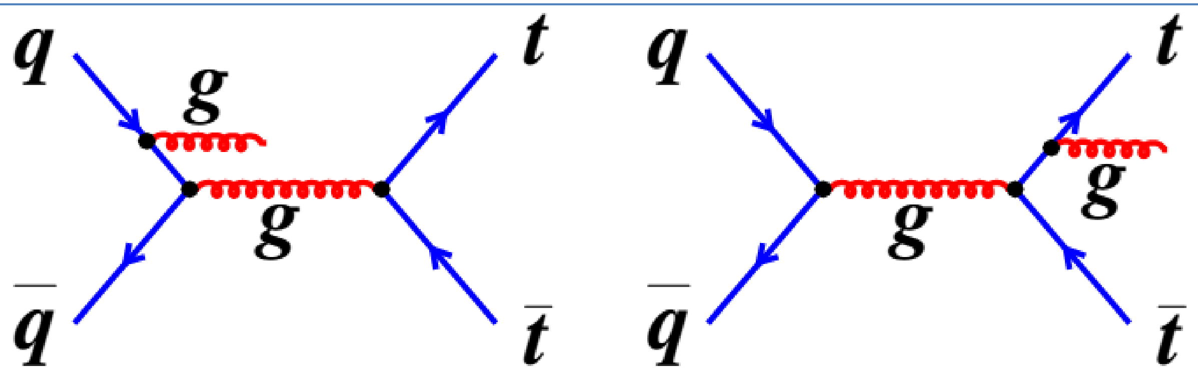
- at the Tevatron it is about incoming quarks (and their QCD charge)



Predictions in SM



- born ($\alpha_s{}^2$) and box ($\alpha_s{}^4$)
- positive asym.
- NLO inteferences



- ISR and FSR ($\alpha_s{}^3$)
- negative asym.
- final state with extra gluon -> large transverse momentum of $t\bar{t}$
- possible extra jets

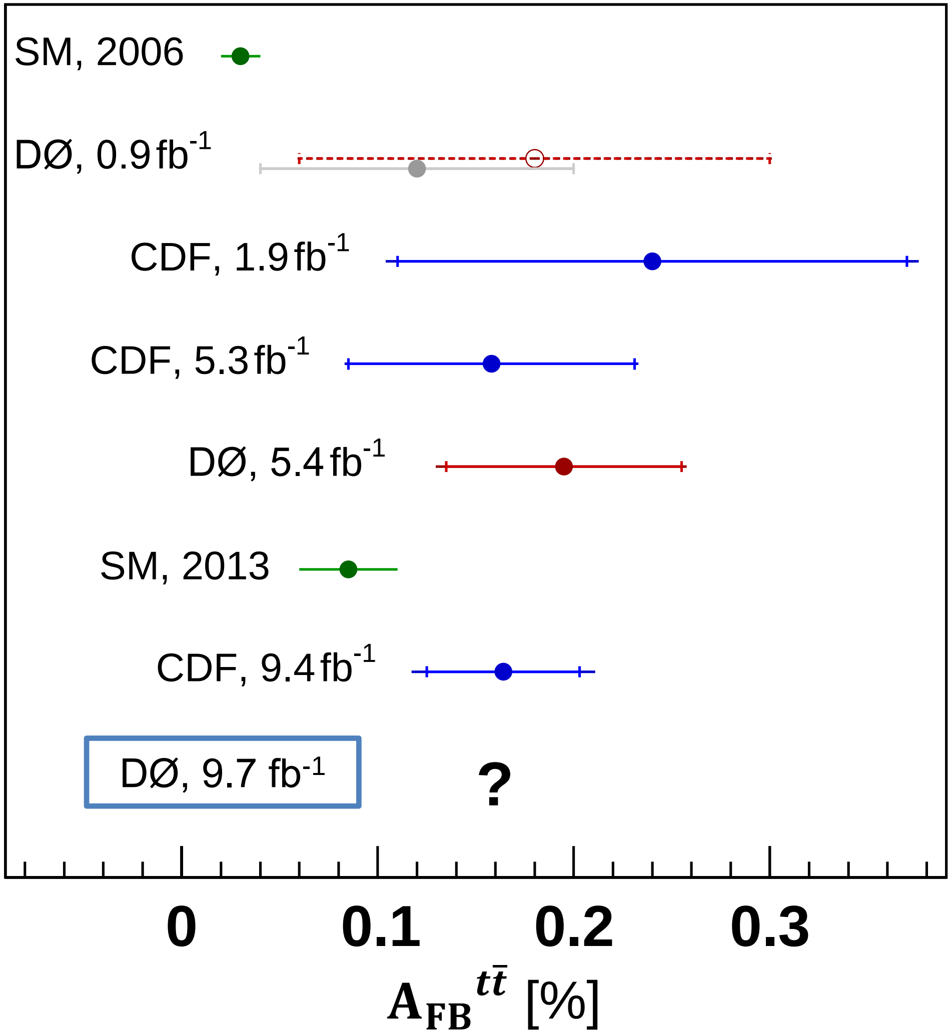
- forward and backward events differ in jet multiplicity, transverse momentum of $t\bar{t}$ system and thus in acceptance
- phase space dependency

Definitions of the asymmetries

- in the rest frame: $$A_{FB} = \frac{N(\cos\theta>0)-N(\cos\theta<0)}{N(\cos\theta>0)+N(\cos\theta<0)}$$
  - for $p\bar{p}$ $\cos\theta \to y$
- inclusive asymmetry based on Δy: $$A_{FB}{}^{t\bar{t}} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$$
  - $\Delta y = y_t - y_{\bar{t}}$, needs full reconstruction of the top pair decay, same in lab and $t\bar{t}$ rest frame
- asymmetry based on rapidity of the lepton (from top decay): $$A_{FB}{}^{l} = \frac{N(q_l y_l>0)-N(q_l y_l<0)}{N(q_l y_l>0)+N(q_l y_l<0)} = \frac{N(q_l\times\eta_l>0)-N(q_l\times\eta_l<0)}{N(q_l\times\eta_l>0)+N(q_l\times\eta_l<0)}$$
  - lepton angles well measured at DØ, no need for full reconstruction of decay
- dilepton asymmetry based on $\Delta\eta$: $$A^{ll} = \frac{N(\Delta\eta>0)-N(\Delta\eta<0)}{N(\Delta\eta>0)+N(\Delta\eta<0)}$$
  - $\Delta\eta = \eta(l^+) - \eta(l^-)$, correlated with $A_{FB}{}^{l}$ in dilepton

$A_{FB}^{t\bar{t}}$ history

$t\bar{t}$ forward-backward asymmetry



PRL 81(1998)49

PRL 100(2008)142002

PRL 101(2008)202001

PRD 83(2011)112003

PRD 84(2011)112005

PRD 86(2013)034026

PRD 87(2013)092002

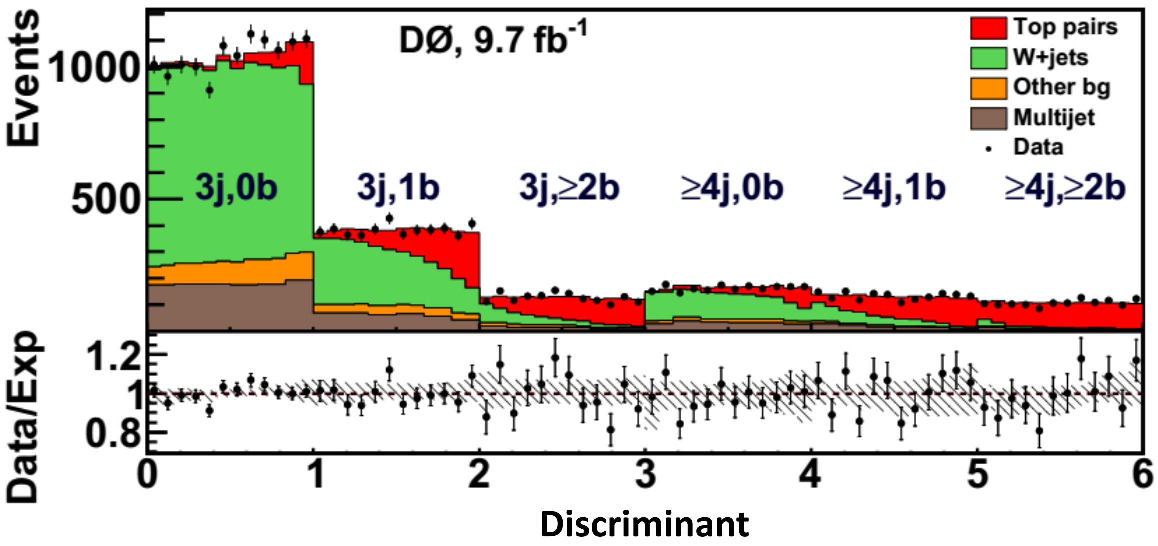
Selection

- full DØ dataset of 9.7 fb^{-1}
- *l*+jets:
  - one isolated lepton ($p_T > 20$ GeV, $|\eta| < 1.1$ for *e*, $|\eta| < 2.0$ for *μ*, *y* < 1.5)
  - 3 or more jets ($p_T > 20$ GeV, $|\eta| < 2.5$, leading jet $p_T > 40$ GeV)
  - at least one b-tagged jet (MVA)
  - significant missing transverse energy ($E_{T,miss} > 20$ GeV)
  - additional quality cuts
- dilepton:
  - two isolated leptons (*e* or *μ*) with opposite charge ($p_T > 15$ GeV, $|\eta| < 1.1$ or $1.5 - 2.5$ for *e*, $|\eta| < 2.0$ for *μ*)
  - high missing transverse energy
  - at least 2 jets and one tagged as *b*-jet (MVA) ($p_T > 20$ GeV, *eμ* - 1 or 2 jets)
  - all leptons $|\Delta\eta_d| < 2.4$, $|q \times \eta_d| < 2.0$
  - additional quality cuts
- improvements:
  - **lepton+3 jets (one lost jet), triggers, *b*-tagging, new kinematic fit algorithm, combination of selection channels, reduced stat. and systematic uncertainties (jet reconstruction, better selection cuts)**

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

- submitted to PRD: arXiv:1403.1294
- *l*+3 jets - one jet lost, partial reco double the statistics, but larger background in the 3 jets channel

	3j, ≥1 btag	≥4j, ≥1 btag
Signal	**2245**	**2222**
BG	**3841**	**705**
S/N	**0.6**	**3.2**



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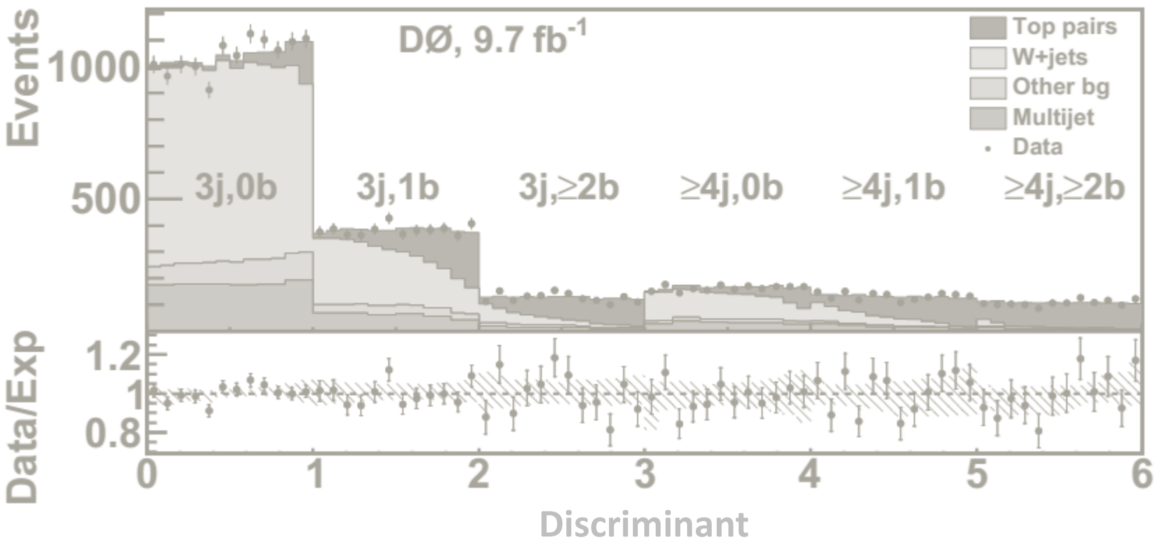
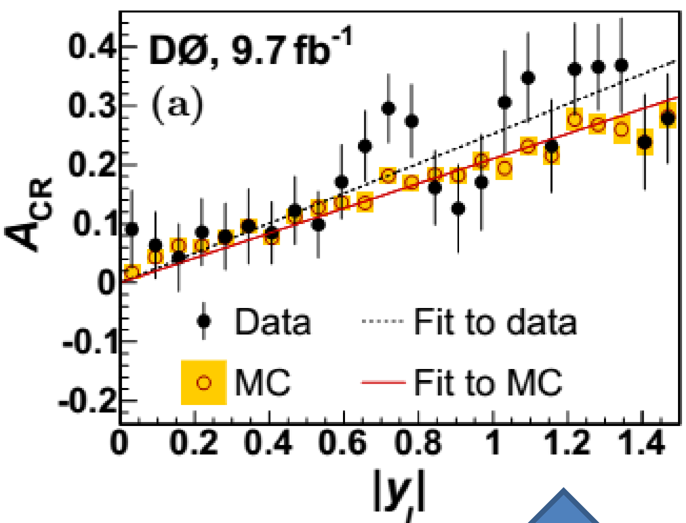
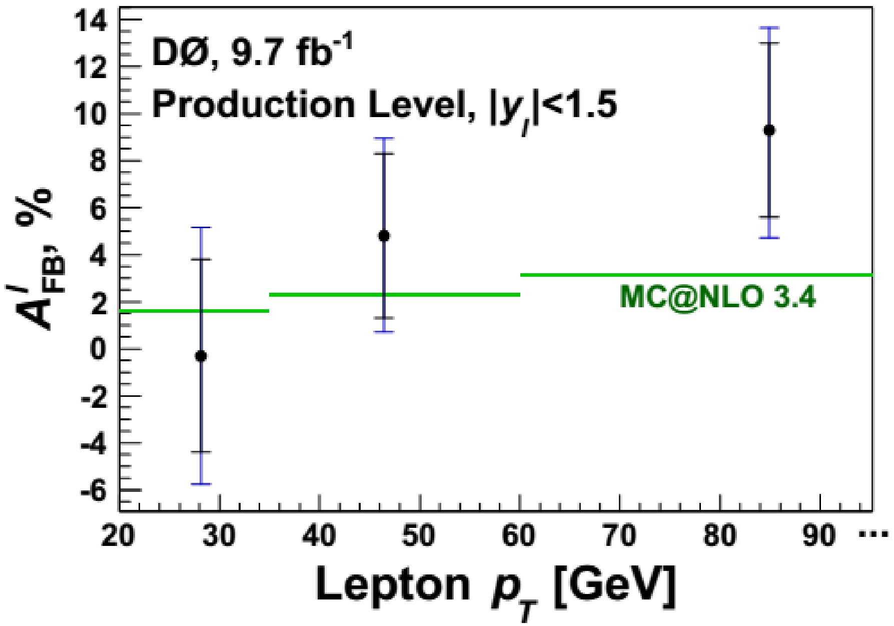


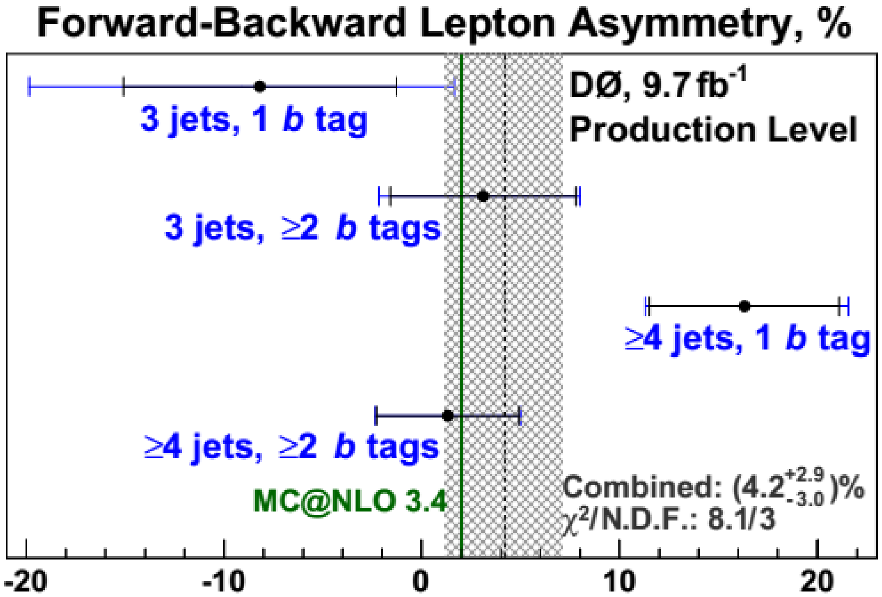


- need to calibrate for asymmetry in leptons from *W*+jets background - in *W*+jets control region: 3 jets 0 *b*-tag
  - this region is not used for measurement

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

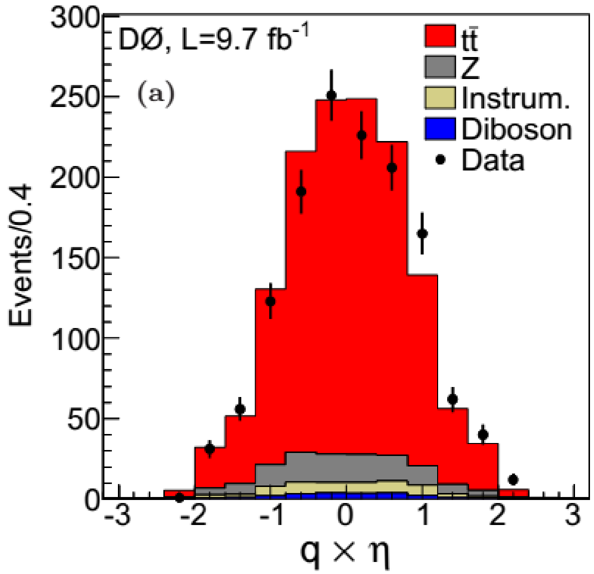
- submitted to PRD: arXiv:1403.1294
- first measurement of asymmetry vs. lepton p_T
- prediction MC@NLO + HERWIG A^l_{FB}=(2.0±0.1)%
- measured $A^l_{FB}=(4.2\pm2.3(\text{stat})\ \pm^{1.7}_{2.0}(\text{syst}))\%$
  at parton level, extrapolated to full phase space

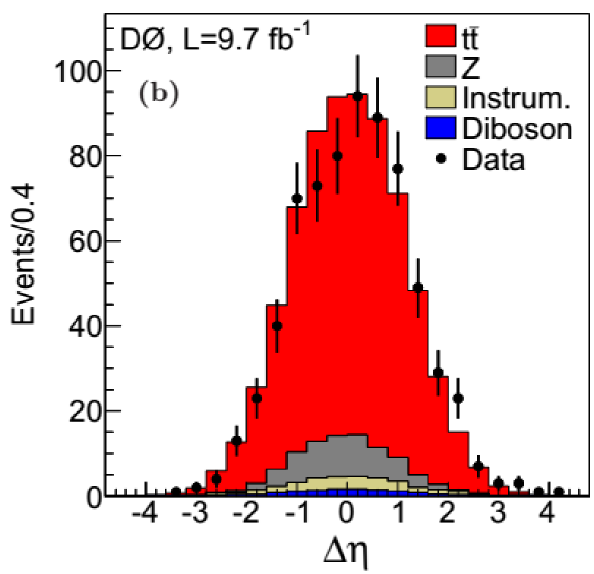




$A_{FB}{}^{l}$ in dilepton

- PRD 88(2013)112002
- raw asymmetry → (detector level)





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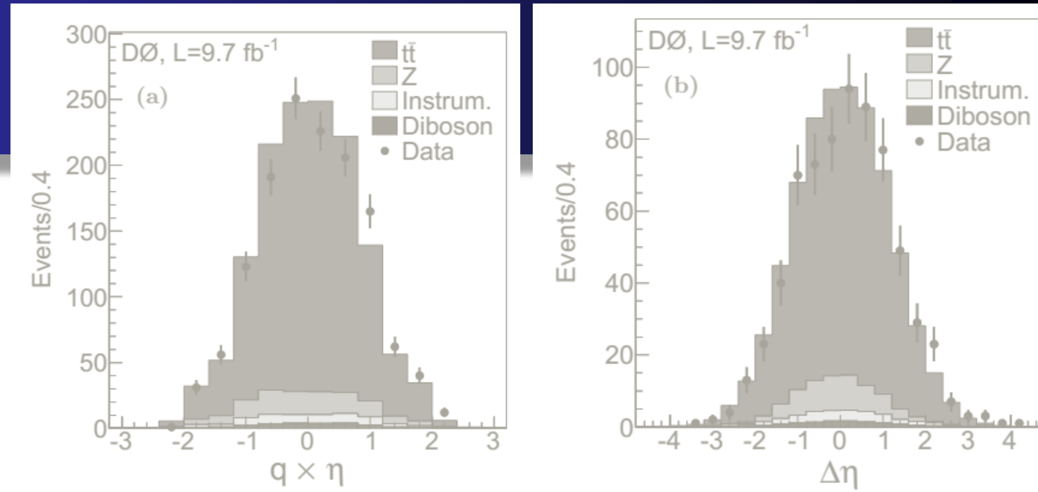
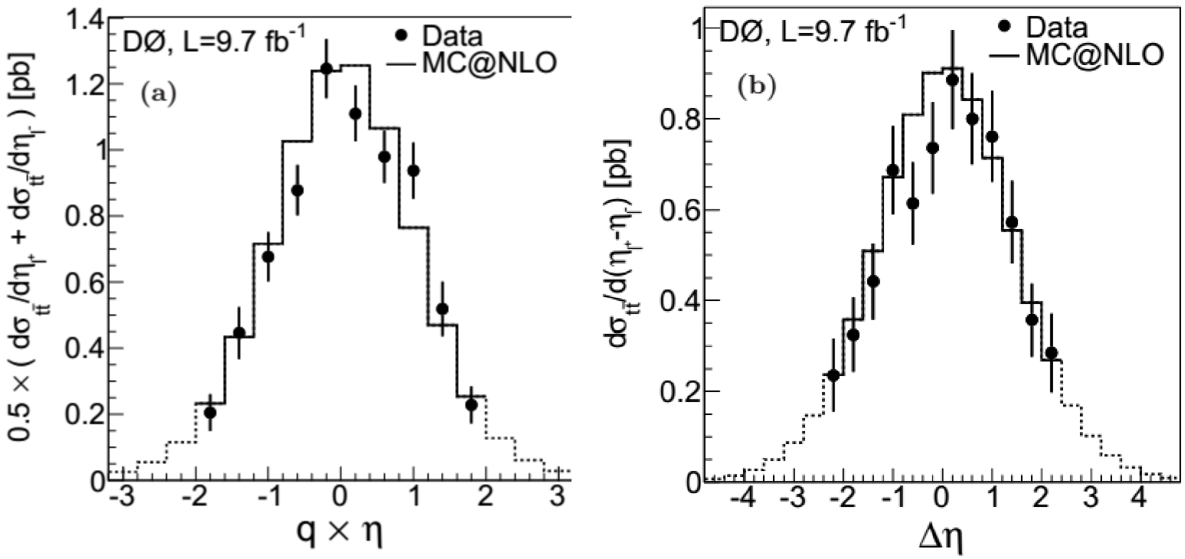


- correction + restriction → (parton level)
  - extrapolation



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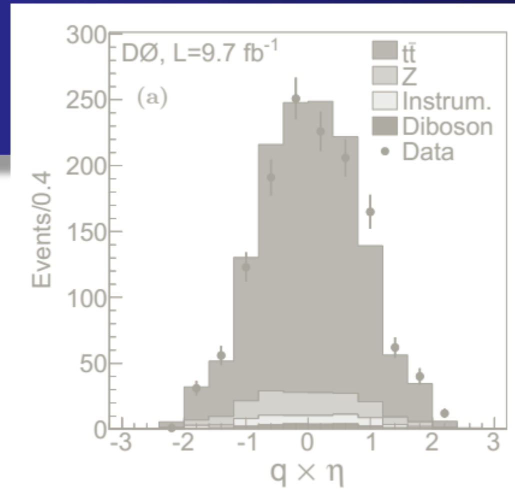
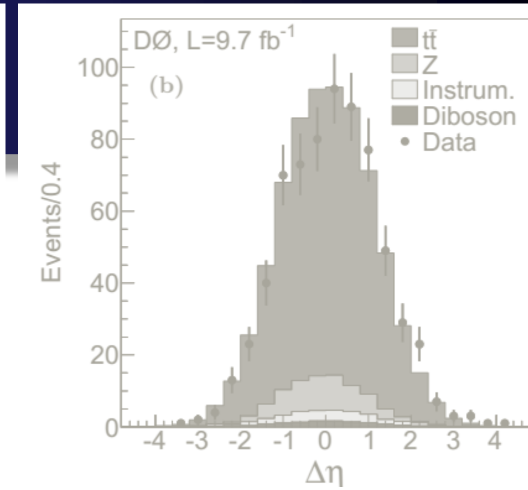
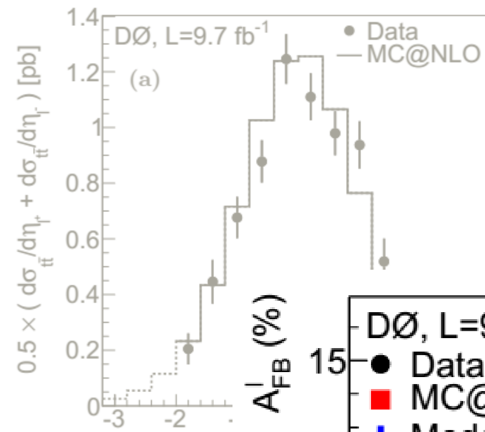
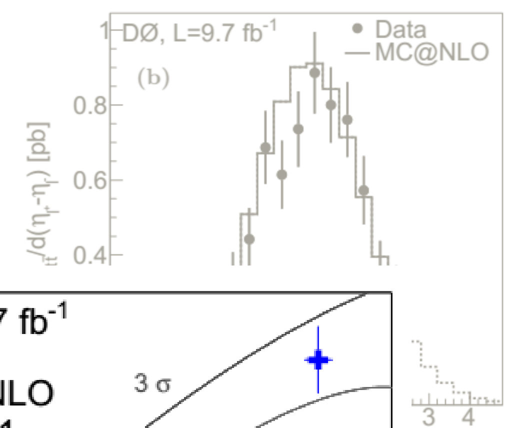




- correction + restriction → (production level)
  - extrapolation





- results ($ee + e\mu + \mu\mu$)

A^{l}_{FB}=(4.4±3.7(stat)±1.1(syst))%

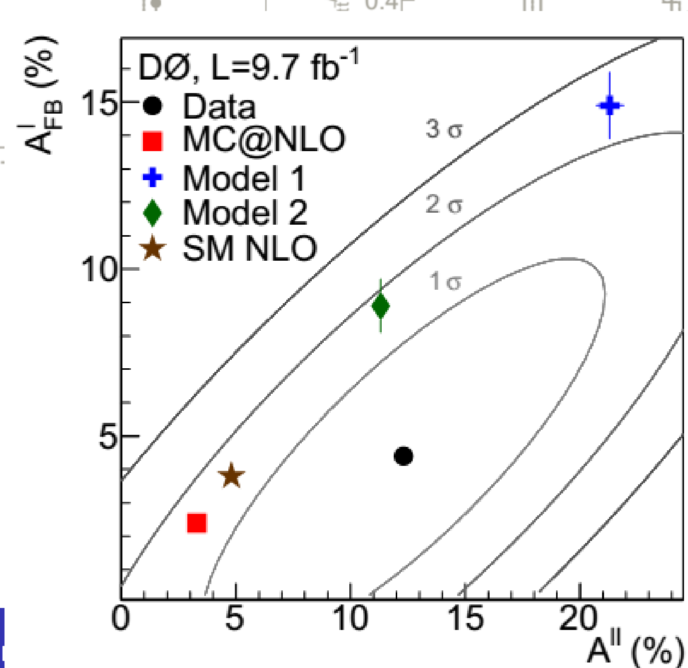
A^{ll}=(12.3±5.4(stat)±1.5(syst))%

SM pred. (PRD 86(2012)034026)

A^{l}_{FB}=(3.8±0.3)%

A^{ll}=(4.8±0.4)%

model1 - right handed axigluon 0.2 TeV
model2 - right handed axigluon 2 TeV



Summary of $A_{FB}{}^{l}$ results

- both *l*+jets and dilepton measured in $|y_l| < 1.5$ (parton level)
  - dilepton A^l_{FB}=(4.3±3.4(stat)±1.0(syst))%
  - *l*+jets A^l_{FB}=(4.2±2.3(stat) $\pm^{1.7}_{2.0}$(syst))%
  - combined by BLUE method A^l_{FB}=(4.2±2.4)%
- and extrapolated to cover the full phase space

  A^l_{FB}=(4.7±2.3(stat)±1.5(syst))%

  =(4.7±2.7)%

- to be compared to SM calculation (Bernreuter & Si PRD 86(2012)034026)

  A^l_{FB}=(3.8±0.3)% (NLO+EW)

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

- submitted to PRD arXiv:1405.0421
- similarly to $A_{FB}{}^{l}$ lepton + 3 jets included with developed algorithm for partial reconstruction
- the reconstructed Δy distribution is "unfolded" accounting for the difference in S/N in four channels (jets=3, ≥4; btags =1, ≥2)
- regularized unfolding is minimization of (package TUnfold)

Production level counts

$$\chi^2 = (r - Tu)^T V^{-1} (r - Tu) + \tau^2 (Lu)^T Lu$$

Reconstruction level counts

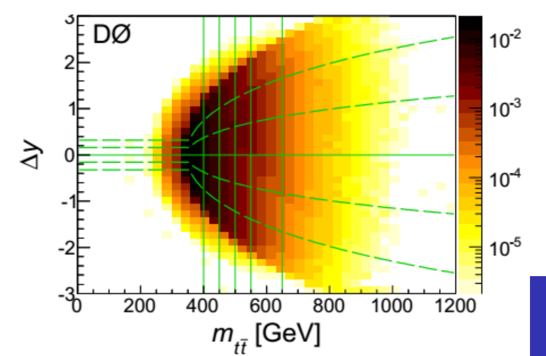
Covariance matrix for r

Matrix to calculate 2nd derivative

Migrations and acceptance matrix

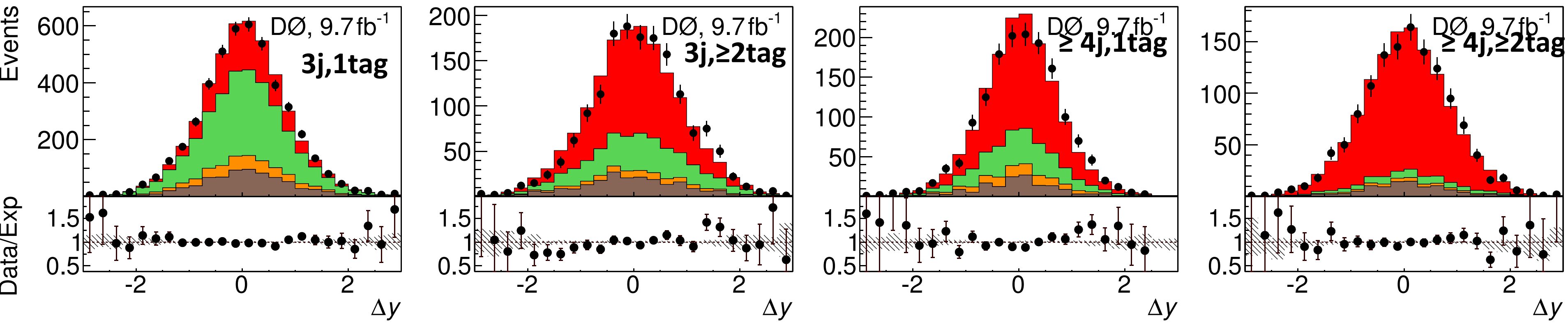
Regularization strength parameter

- Developed 2D unfolding for the differential measurement (A_{FB}vs. $M_{t\bar{t}}$)



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

- submitted to PRD arXiv:1405.0421
- reconstruction level results

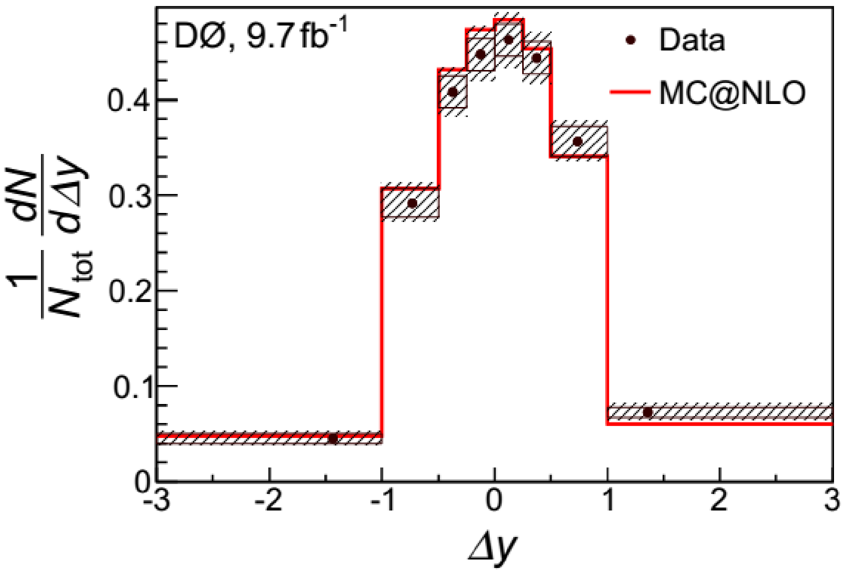


- unfolded to the parton level

A^{tt}_{FB}=(10.6±2.7(stat)±1.3(syst))%

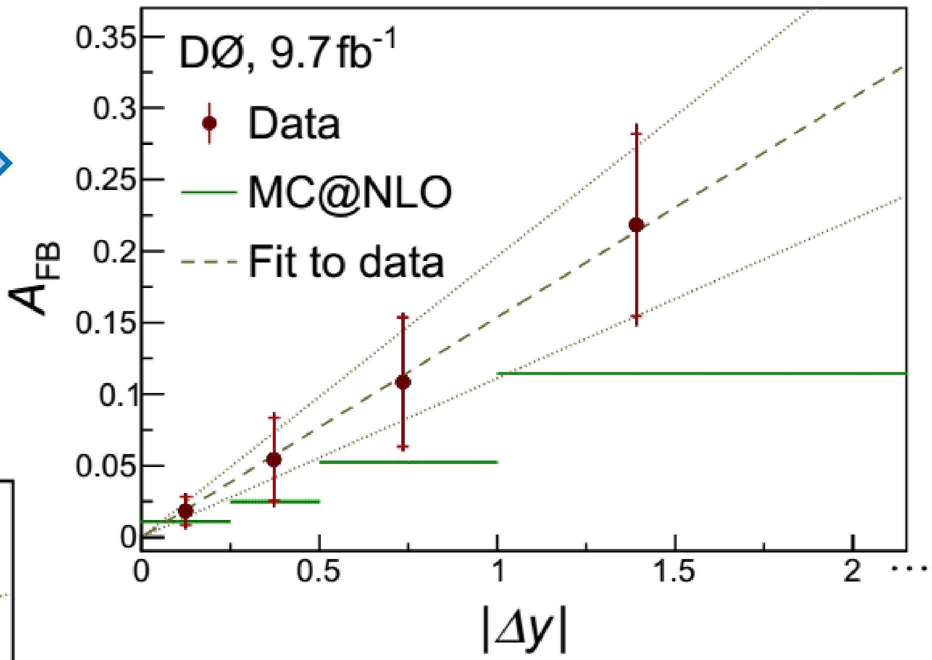
SM pred. (PRD 86(2012)034026)

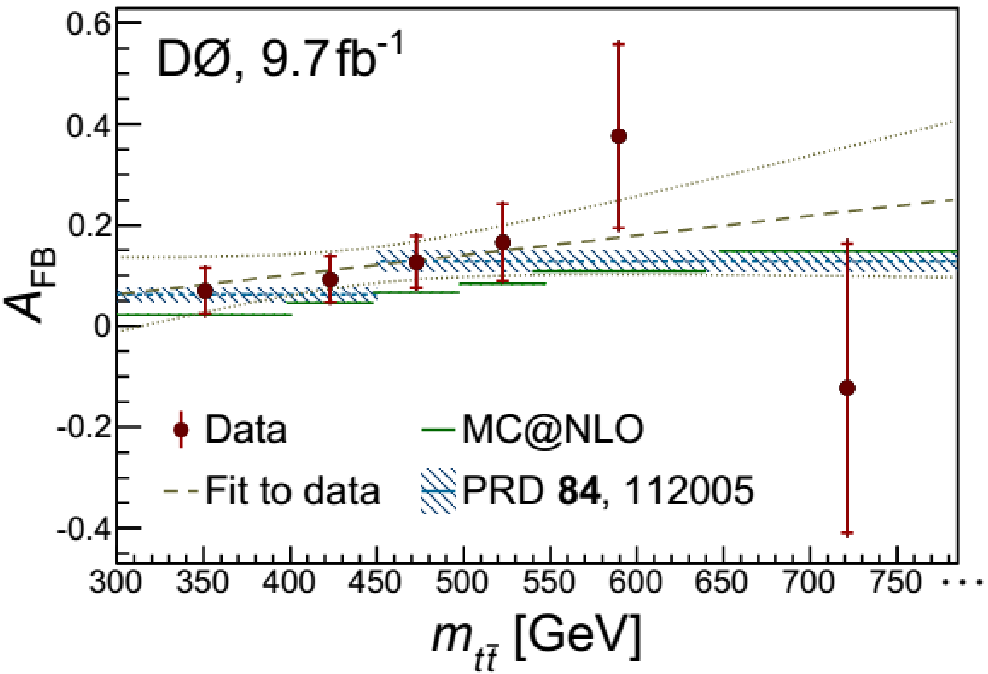
A^{tt}_{FB}=(8.8±0.9)%



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

- dependencies:
- on $|\Delta y|$ (slope 0.154 ± 0.043, MC@NLO predicts 0.080)

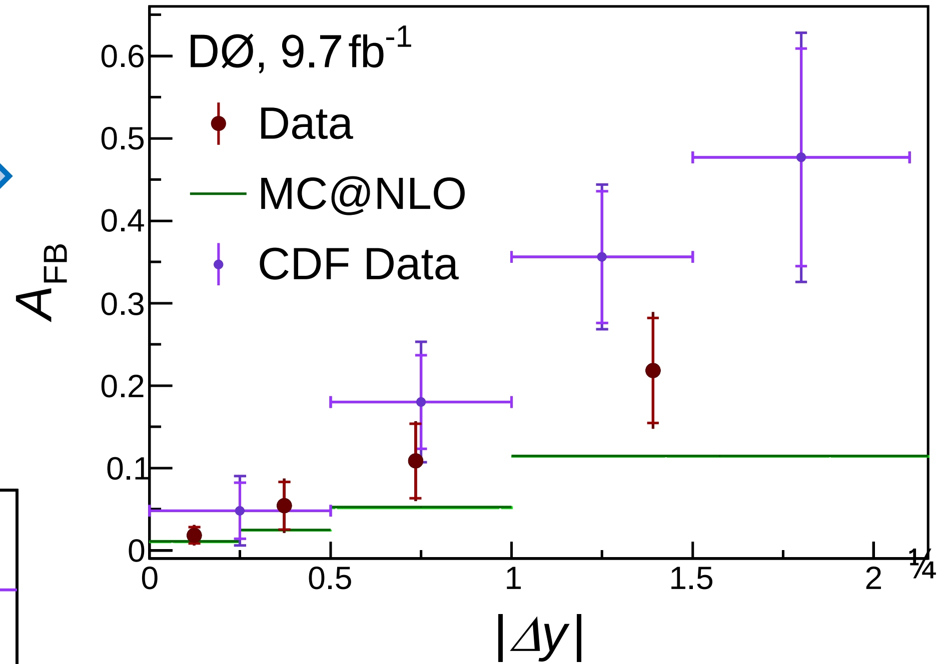




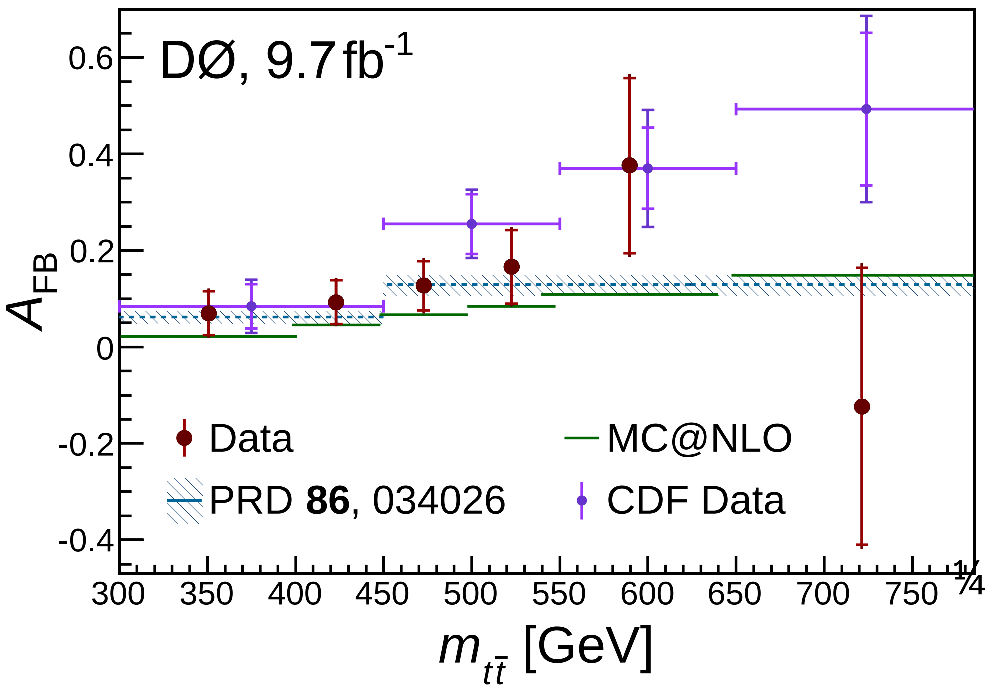
- on $M_{t\bar{t}}$ (slope $(3.9 \pm 4.4) \cdot 10^{-4}$, MC@NLO predicts $3.8 \cdot 10^{-4}$)
- submitted to PRD arXiv:1405.0421

$A_{FB}^{t\bar{t}}$ in *l*+jets with CDF

- dependencies:
- on $|\Delta y|$
  $\alpha(D\text{Ø}) = 0.154 \pm 0.043$
  $\alpha(CDF) = 0.253 \pm 0.062$



- on $M_{t\bar{t}}$
  $\alpha(D\text{Ø}) = (3.9 \pm 4.4) \cdot 10^{-4}$
  $\alpha(CDF) = (15.5 \pm 4.8) \cdot 10^{-4}$



Summary

- lepton asymmetry and p_T dependency (*l*+jets and dilepton comb.)

  $\boxed{A^{l}_{FB} = (4.7 \pm 2.7)\%}$

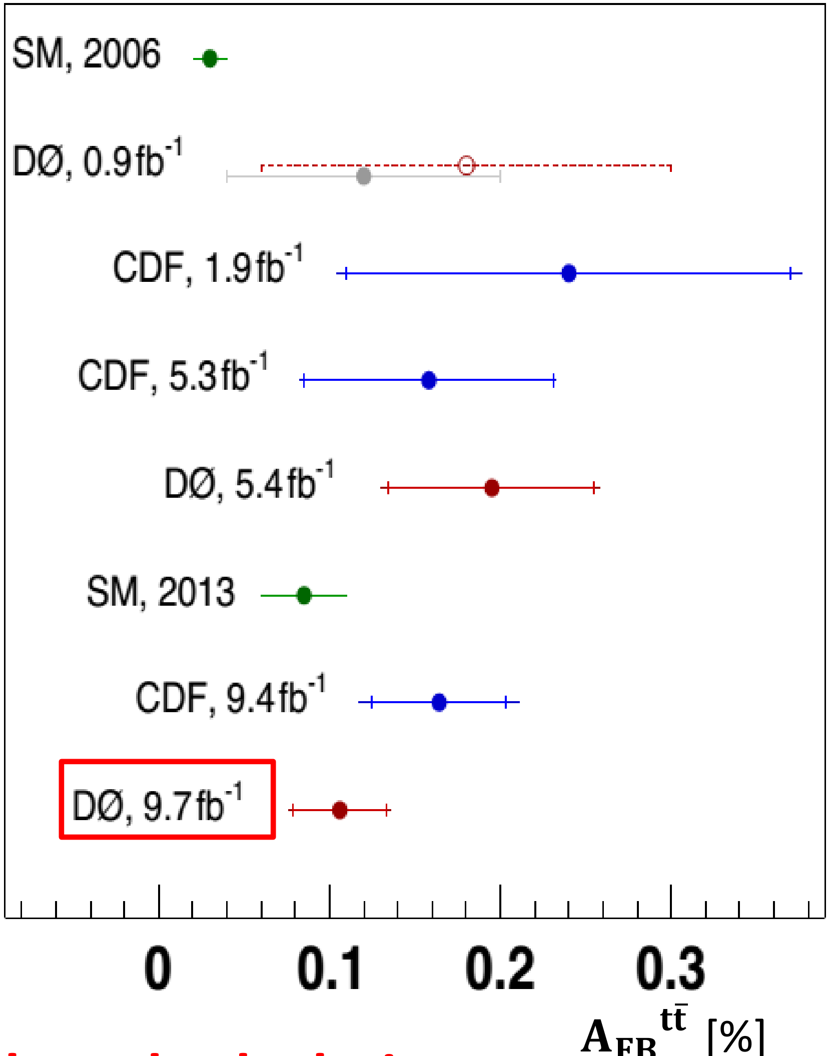
  SM NLO+EW $(3.8 \pm 0.3)\%$

- incl. Δy asymmetry and its dependency on $M_{t\bar{t}}$ (*l*+jets)

  $\boxed{A^{tt}_{FB} = (10.6 \pm 3.0)\%}$

  SM NLO+EW $(8.8 \pm 0.9)\%$

- results extrapolated, prediction PRD 86(2012)034026

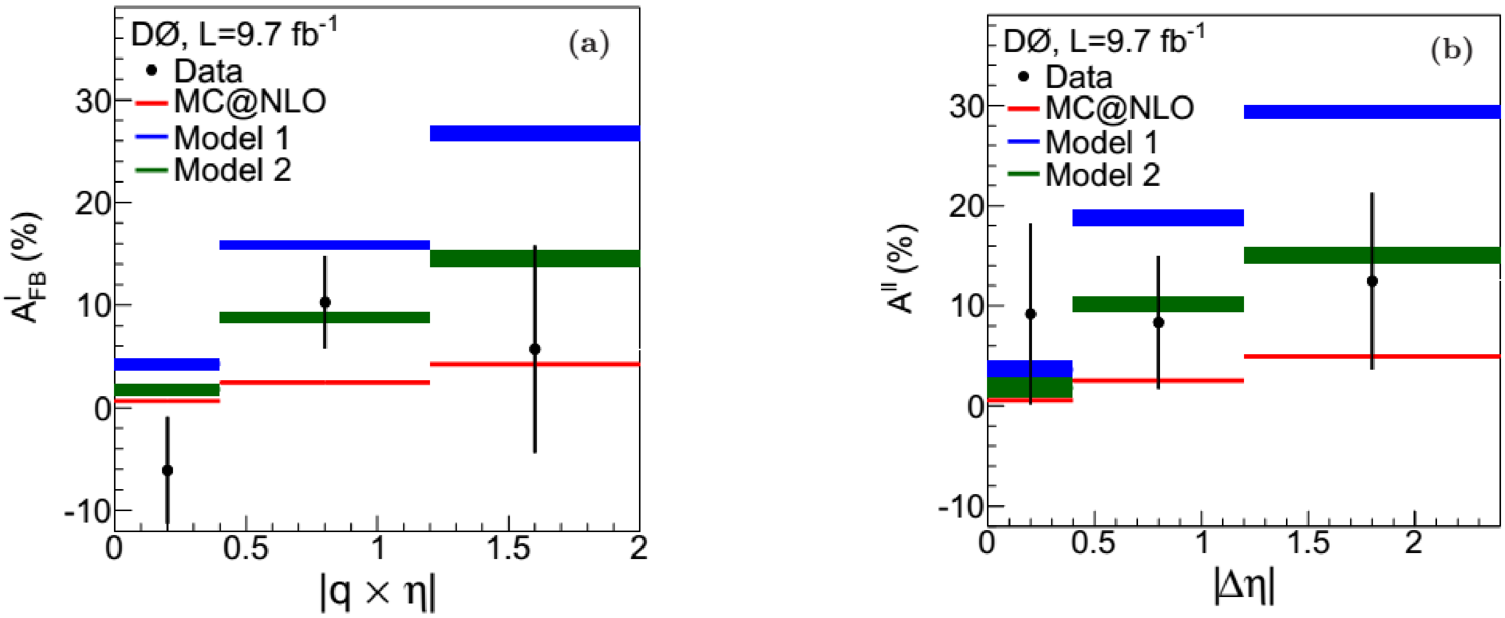


- **The results are consistent with SM-based calculations**

Backup slides

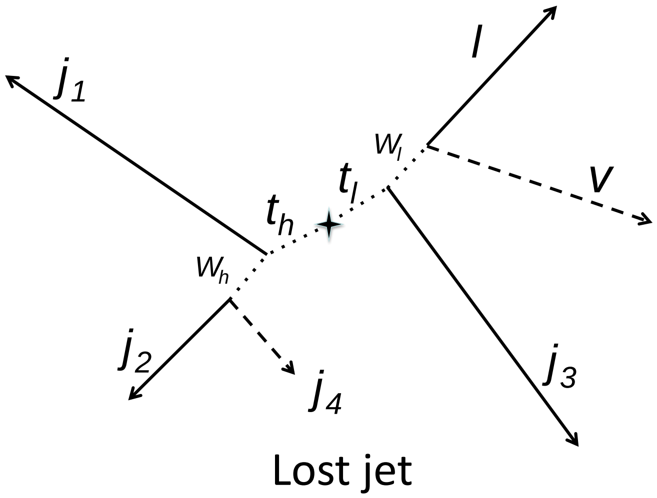
$A_{FB}{}^{l}$ in dilepton

- BSM models can generate a large A_{FB} from the presence of a color-octet vector particle (the so-called axigluon) with large mass m_G and chiral couplings. Generated two axigluon samples: Model 1 has a right-handed coupling to the SM quarks of $0.8g_s$ and no left-handed coupling. The axigluon mass is set to 0.2 TeV and the width to 50 GeV. Model 2 has a right-handed coupling to light SM quarks of $-1.5g_s$ a coupling of $6g_s$ to top quarkk, and no left-handed coupling, with the axigluon mass set to 2 TeV and width to 670 GeV.



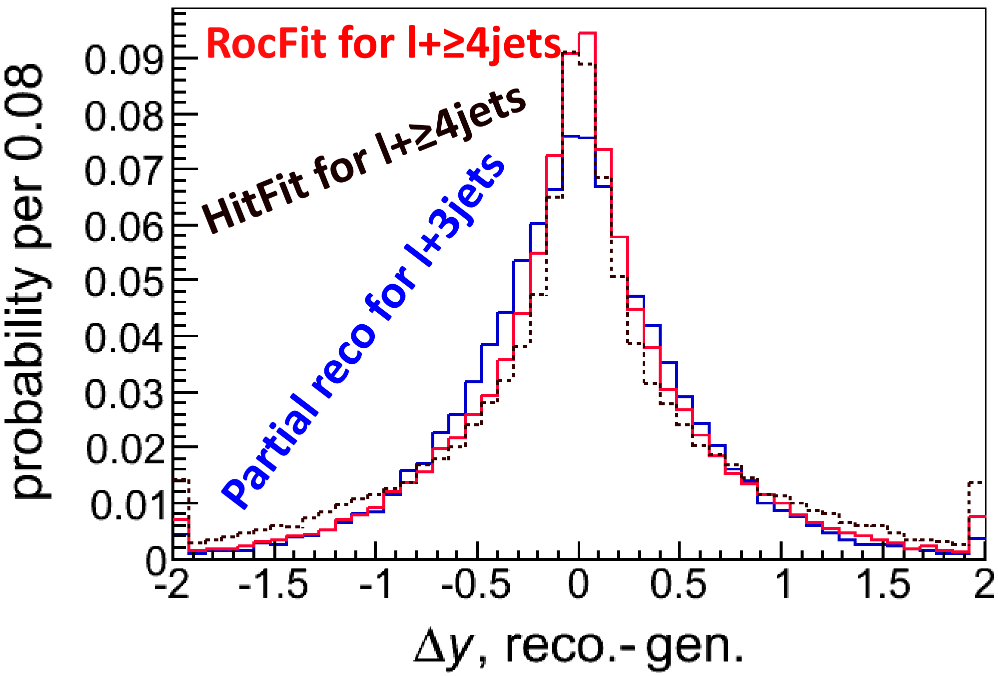
Partial reconstruction in l+3jet channel

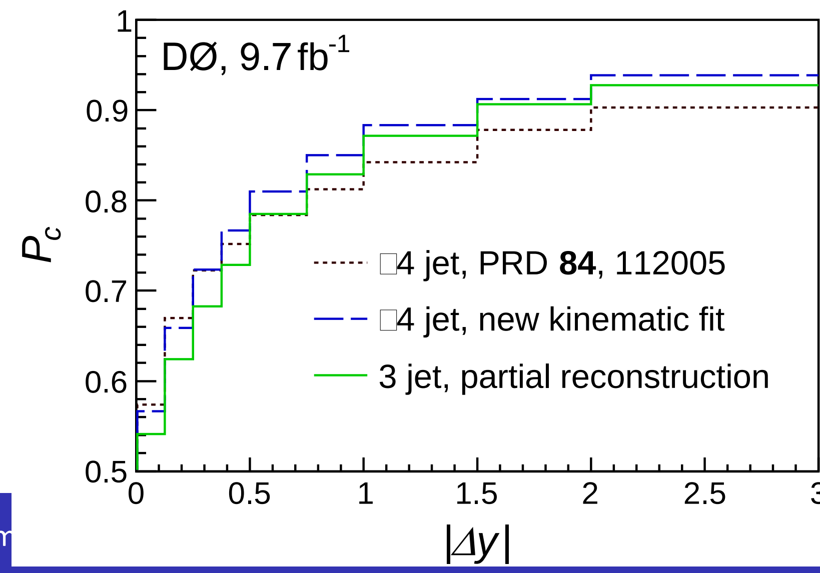
- arXiv:1310.3263v1 [hep-ex]
- Jet is lost mostly because it is too soft (74%), so its effect on ttbar kinematics is minimal. It is far more important to find the correct assignment of quarks to the existing jets.
- **Assumption:** lost jet is from the "hadronic" top decay (True in 80% of the cases)



Partial reconstruction performance

- P_C - probability to correctly reconstruct the sign of Δy
- P(HITFIT)=75.6% - l+≥4jets
- P(ROCFIT)=77.6% - l+≥4jets
- P(Partial)=74.5% - l+3jets
- **Why does partial reco perform so well?**
- In l+≥4jets the four leading jets match the ttbar decay products in 55% events, the rest – ISR/FSR
- In l+3jet events 98% of the events have all three jets matched to ttbar decay, even though some information is lost, no wrong information is added.

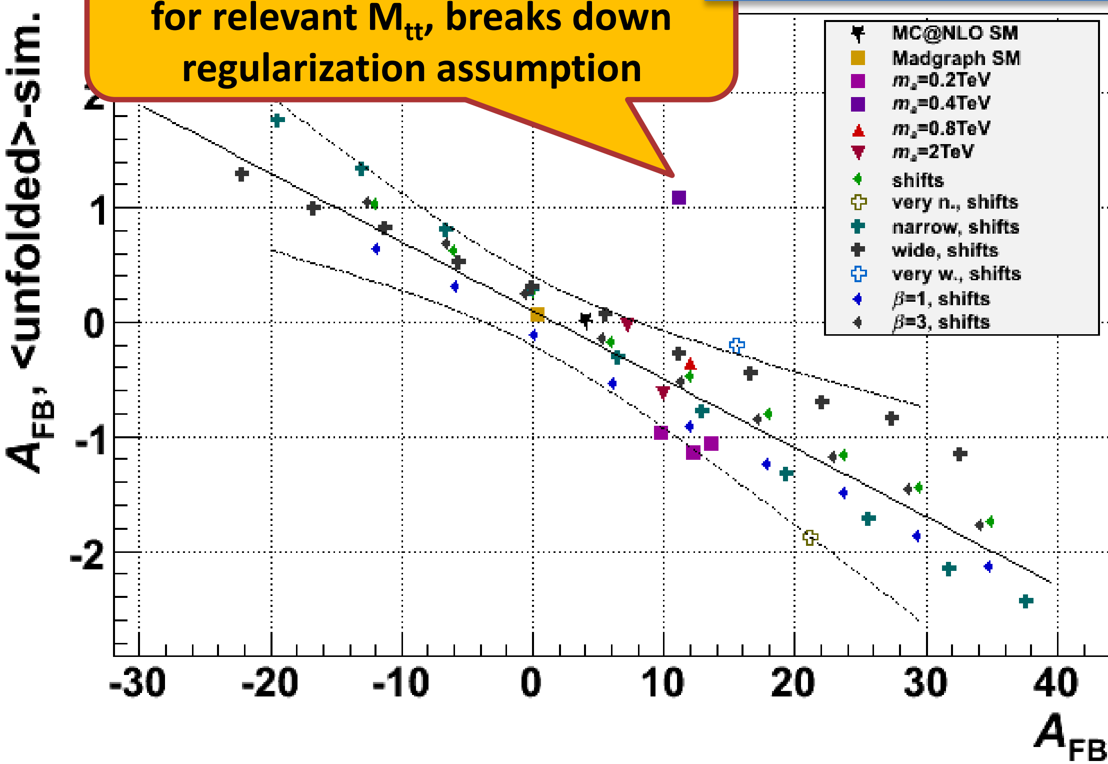


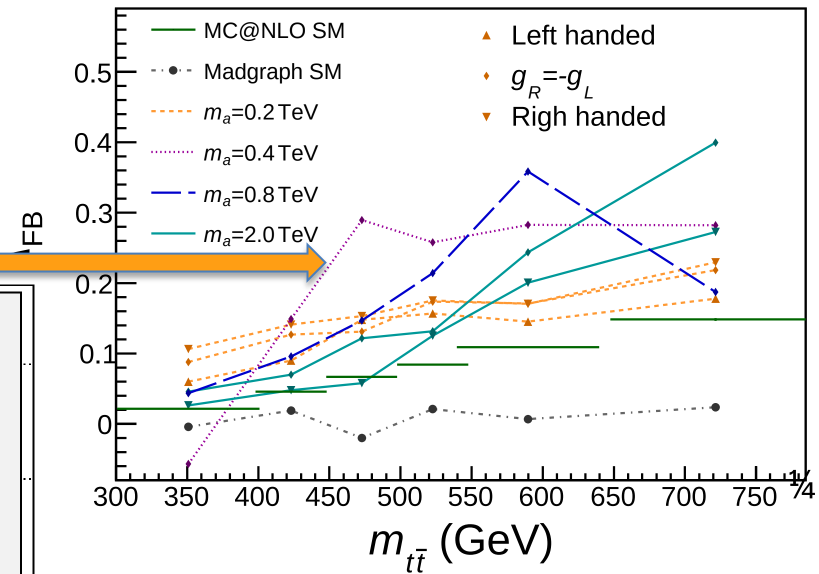


Calibration of the unfolding method

- Calibrated the method using ensembles of pseudodata based several toy MC and axigluon models

m_A=0.4 TeV – fast changing A_{FB} for relevant M_{tt}, breaks down regularization assumption





Systematic uncertainties

TABLE IV: Systematic uncertainties on A_{FB}, in absolute %. For the 2D measurement, the range of changes in A_{FB} over the six $m_{t\bar{t}}$ bins is given.

Source	Reco. level inclusive	Production level inclusive	Production level 2D
Background model	$+0.7/-0.8$	1.0	1.1–2.8
Signal model	< 0.1	0.5	0.8–5.2
Unfolding	N/A	0.5	0.9–1.9
PDFs and pileup	0.3	0.4	0.5–2.9
Detector model	$+0.1/-0.3$	0.3	0.4–3.3
Sample composition	< 0.1	< 0.1	< 0.1
Total	$+0.8/-0.9$	1.3	2.1–7.5

TABLE VII: Systematic uncertainties on A^{l}_{FB}. Uncertainties smaller than 0.1% are omitted.

	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	$+1.5/-1.7$	$+1.7/-2.0$

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

	Corrected		Extrapolated	
	A^{ℓ}_{FB}	$A^{\ell\ell}$	A^{ℓ}_{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

The uncertainties due to **unfolding** are dominated by the calibration uncertainties. The uncertainties associated with the choice of the regularization strength and statistical fluctuations in the MC samples used to find the migration matrix are also included.

Consistency in reco-level $A_{FB}^{t\bar{t}}$

- Better resolution has a more significant effect at the unfolding level because it minimizes migrations

Run period	3j, 1b	3j, 2b	4j, 1b	4j, 2b	Total	Comment
First 5.4 fb^{-1}			Combined		9.2±3.7%	PRD84(2011)112005
First 5.4 fb^{-1}			12.0±5.4	8.3±4.1	9.9±3.4%	9% improvement in uncertainty due to split channels, b-tagging
First 5.4 fb^{-1}	7.0±7.3	12.0±6.0	12.0±5.4	8.3±4.1	10.1±2.7	26% improvement - add 3j
Sec 4.3 fb^{-1}	2.4±9.1	9.1±6.0	9.2±6.4	2.9±5.0	6.0±3.1	
Total 9.7 fb^{-1}	5.4±6.0	10.7±4.2	11.0±4.4	5.9±3.3	7.9±2.1	29% improvement (exp 34%) due to *L*