# $t\bar{t}$ Asymmetries at Tevatron and LHC


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on behalf of the Tevatron and LHC experiments

# Outline

- Introduction and Definitions
- Asymmetries at Tevatron
- Asymmetries at LHC
- Conclusion & Outlook

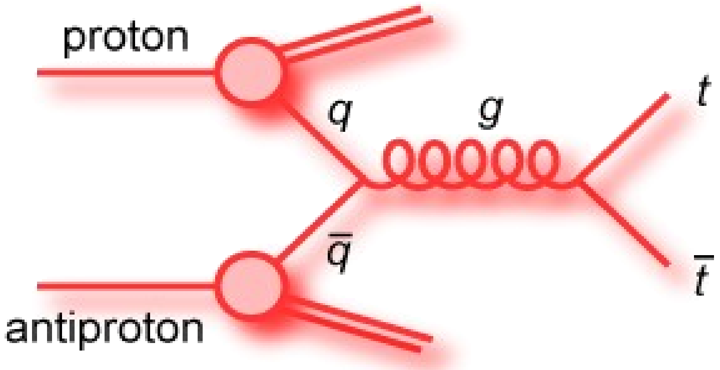
# Introduction and Definitions

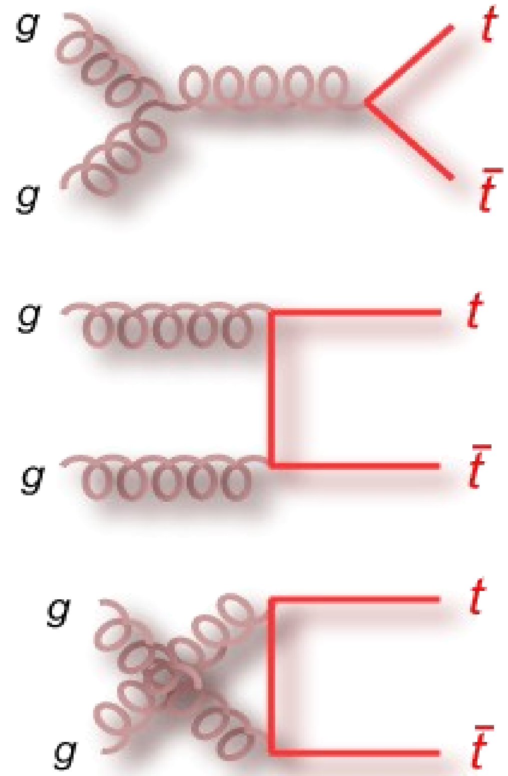
# $t\bar{t}$ Production at Tevatron and LHC

- $t\bar{t}$ production via strong interaction
- At Tevatron:

  85% + 15%

- At LHC:
  7 TeV: 20% + 80%




- Production cross section (@Tevatron):

  NNLO+NNLL: $\sigma = 7.24^{+0.23}_{-0.27}\,pb$ @ $m_t$=172.5GeV

  Baernreuther, Cakon, Mitov, PLB 710, 612 (2012)

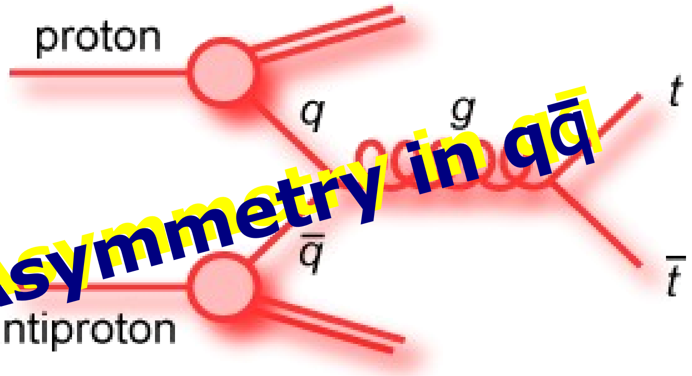
- 20 times higher @LHC (7TeV):

  $\sigma = 164.6^{+11.4}_{-15.7}\,pb$

# $t\bar{t}$ Production at Tevatron and LHC

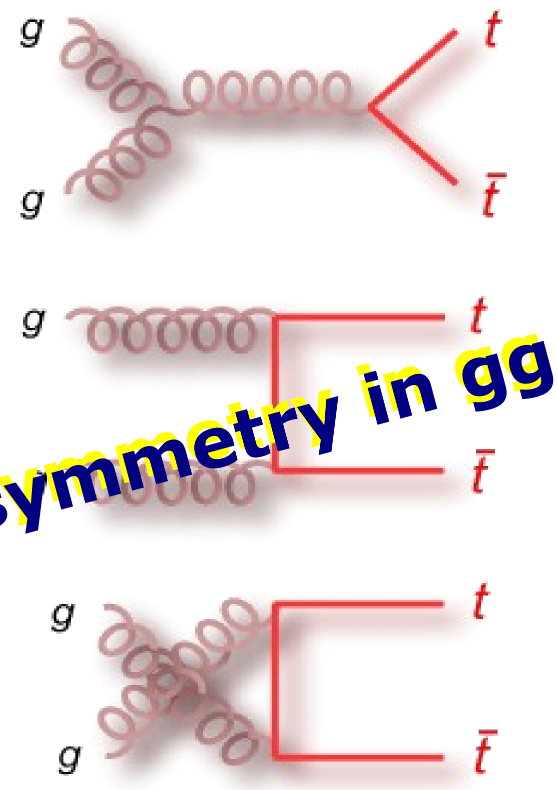
- $t\bar{t}$ production via strong interaction
- At Tevatron:

  85%




  + 15%

- At LHC:
  7 TeV: 20% + 80%

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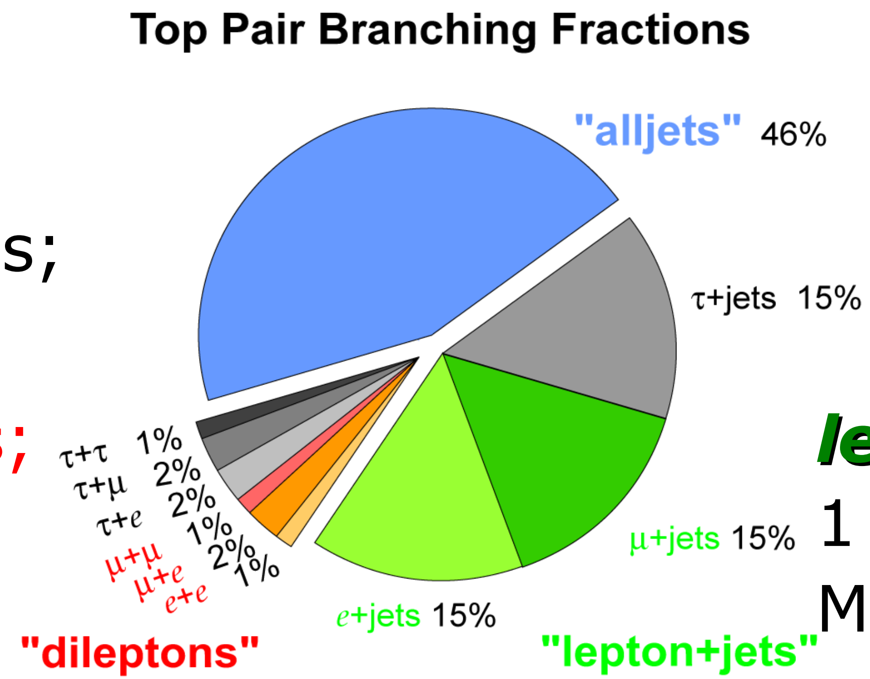
# Final States in $t\bar{t}$

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

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

**pure hadronic:**
≥6 jets (2 b-jets)

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




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

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Top Pair Branching Fractions

***dilepton:***
2 isolated leptons;
High missing $E_T$
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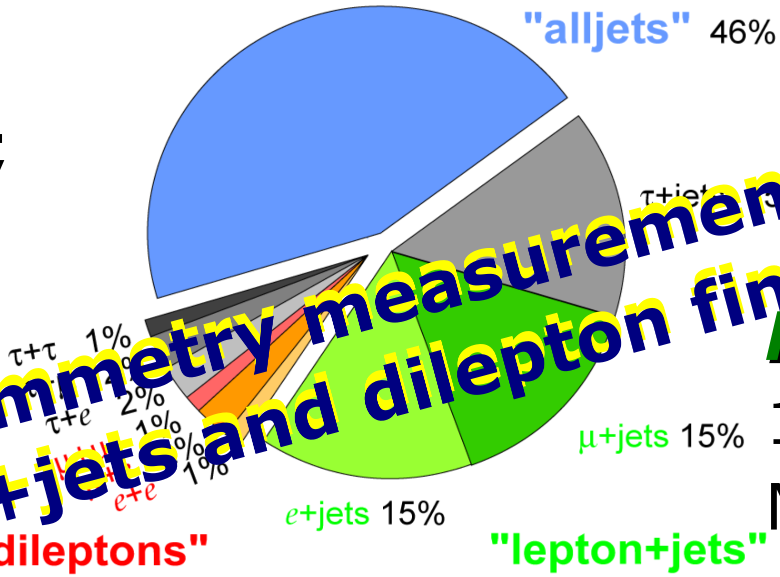
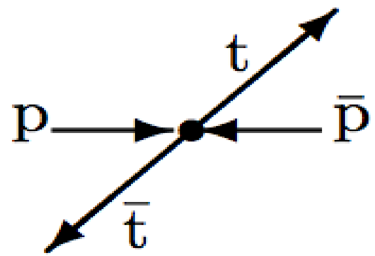



**Asymmetry measurements in lepton+jets and dilepton final states**

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

# Asymmetry Definitions

- Do top quarks follow preferentially the initial quark or antiquark direction?




- Several asymmetry definitions can be studied
  - $t\bar{t}$ Forward backward asymmetry

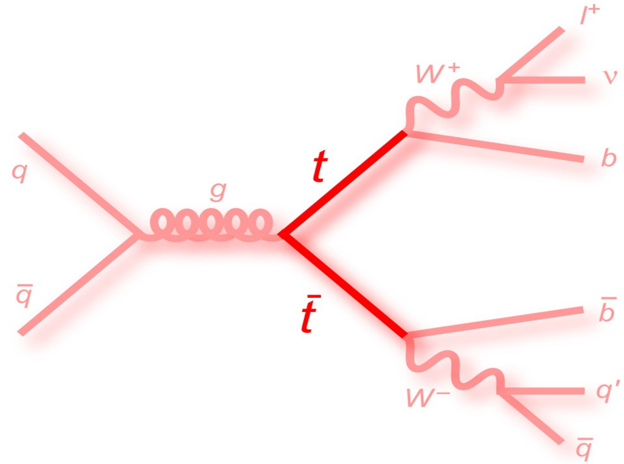
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right)$$

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

  - Lepton based asymmetry

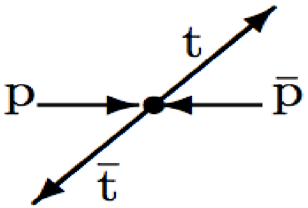
$$A_{FB}^{l} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

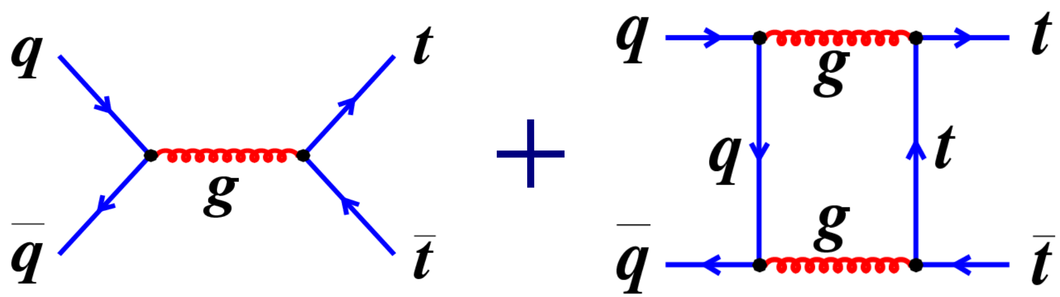



    - Complementary measurement to FB asymmetry

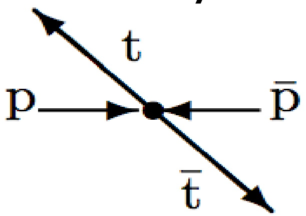
# Asymmetry Idea

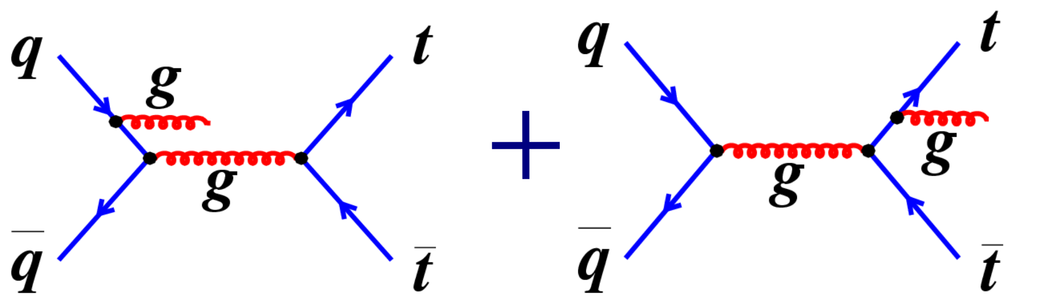
- LO: No charge asymmetry expected
- NLO QCD: Interference between $q\bar{q}$ diagrams
  - Asymmetry in QCD:Interference of C=1 and C=-1 amplitudes are odd under $t \leftrightarrow \bar{t}$ → cause asymmetry
- Tree level and box diagrams:
  - Positive asymmetry




- Initial and final state radiation:
  - Negative asymmetry



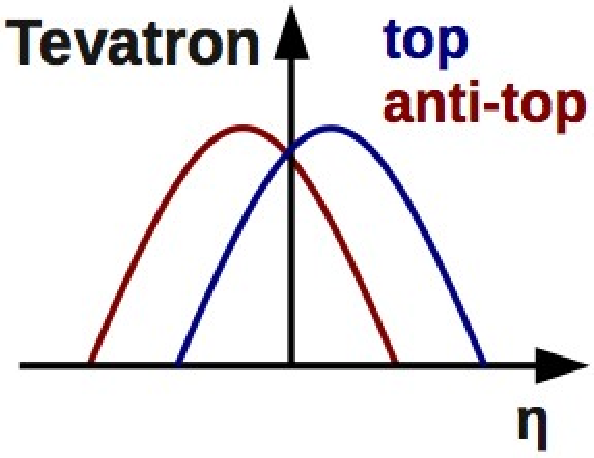



# Tevatron and LHC Difference

- Tevatron: $p\bar{p}$ is CP eigenstate → pp (LHC) is not
  → different way to measure the effect at Tevatron and LHC
- LHC: Quarks valence quarks, antiquark always from the sea
  → antitop less boosted and more central than top in case of asymmetry
- LHC: Measure charge asymmetry

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

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$



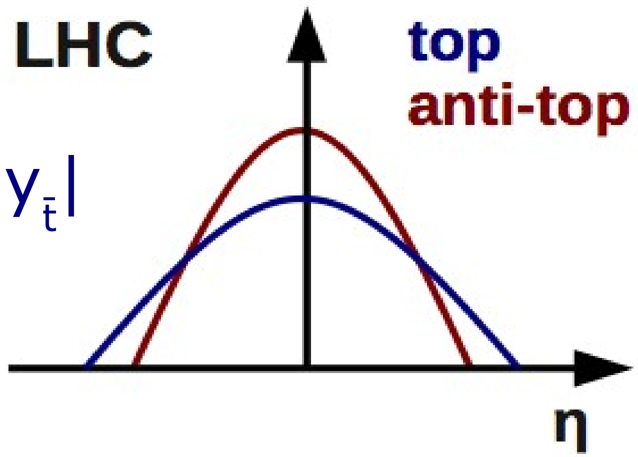

Tevatron

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

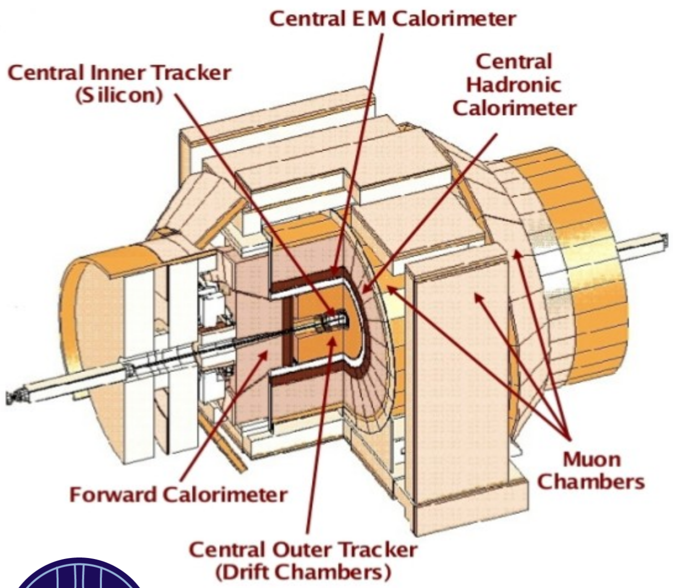
LHC

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

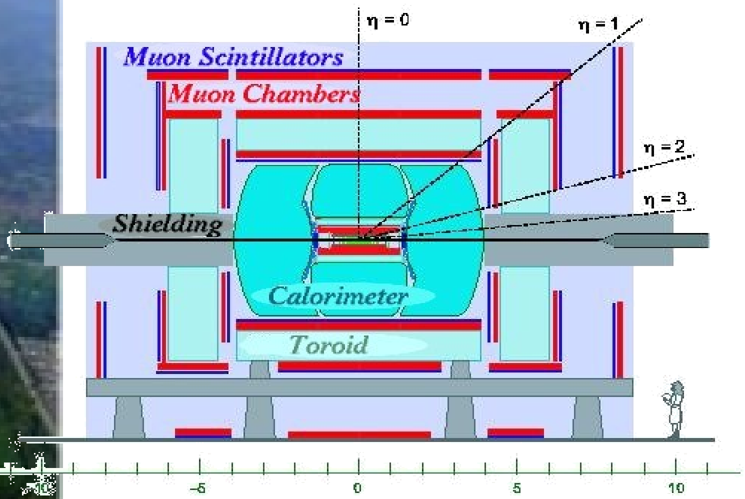
$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$



# Asymmetries at the Tevatron







# SM Predictions at the Tevatron

- Dominant contribution from $q\bar{q}$, but also from gq channels
- Higher order QCD contributions
  - NLO+NNLL by Ahrens et al.; arXiv:1106.6051
  - Approximative NNLO by Kidonakis
- Additionally: QED contributions enhance the asymmetry

Kuhn, Rodrigo, 2011; Hollik, Pagani 2010; Bernreuther, Si 2010

| Pecjak, Top2011 | $A_{FB}^{t\bar{t}}$ [%] | $A_{FB}^{p\bar{p}}$ [%] |
|---|---|---|
| NLO | $7.32^{+0.69+0.18}_{-0.59-0.19}$ | $4.81^{+0.45+0.13}_{-0.39-0.13}$ |
| NLO+NNLL [Ahrens et. al.'11] | $7.24^{+1.04+0.20}_{-0.67-0.27}$ | $4.88^{+0.20+0.17}_{-0.23-0.18}$ |
| $\mathrm{NNLO}_{\mathrm{approx}}$ [Kidonakis '11] | | $5.2^{+0.0}_{-0.6}$ |
| EW'/NLO' ($\mu = m_t$) [Bernreuther, Si '10] | 0.05 | 0.04 |
| EW/NLO ($\mu = m_t$) [Hollik, Pagani '10] | 0.22 | 0.22 |
| NLO(QCD+EW) [Bernreuther, Si, '12] | 8.8±0.6 | |

$b\bar{b} \rightarrow t\bar{t}$ included

Extra photonic corrections

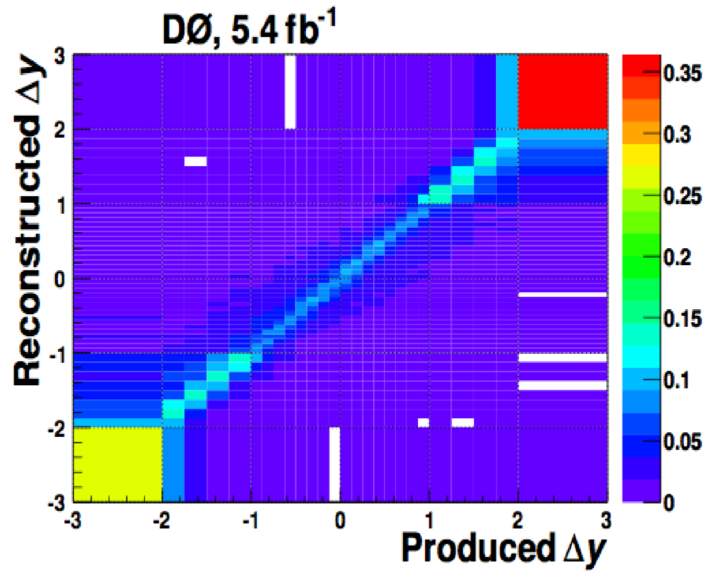
NLO PDFs in numerator, mixed QCD and EW corrections

# Analysis Strategy l+jets

- Select l+jets or dilepton events; get distributions of y, $\Delta$y
  - reconstruction of full $t\bar{t}$ event using kinematic fitter
- Subtract background from Data
  - DØ: Background fitted with likelihood discriminant
  - CDF: Background from MC prediction and orthogonal samples
  - But: due to acceptance and detector effects: results not comparable
- Unfolding: Correct for acceptance & resolution effects
- CDF: 4 bin matrix inversion in $\Delta$y

$$\vec{n}_{production} = A^{-1} S^{-1} \vec{n}_{reco}$$

  - A: (diagonal) acceptance matrix; S: migration matrix
- DØ: regularized unfolding



# Results l+jets

- Results after unfolding:

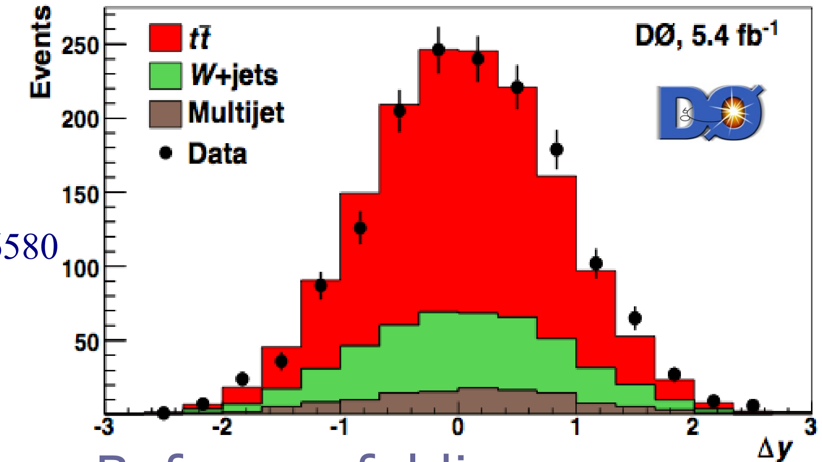
  CDF: $A_{FB}^{t\bar{t}}$= 16.2 ± 4.7%

  (NLO (QCD+EW) prediction: 6.6%)

  DØ: $A_{FB}^{t\bar{t}}$=19.6±6.5%

  W. Bernreuther, Z. G. Si, arXiv:1205.6580

  - Statistically limited
  - Several studied modeling issues studied




Before unfolding

- Lepton-based asymmetries:
  - Very good resolution → unfolding easy
  - DØ (l+jets): $A_{FB}^{l}$=14.2±3.8%

    (MC@NLO pred: 0.8±0.6%)

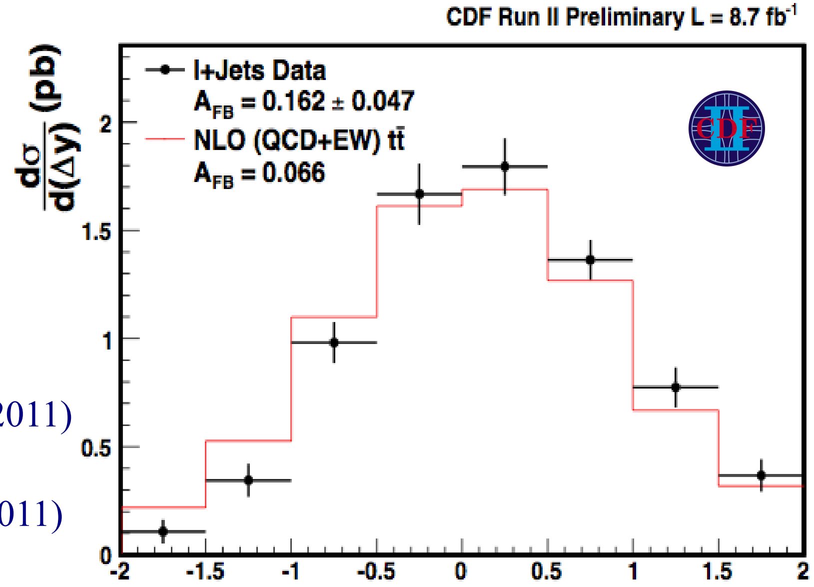
→ ~3 sigma away from prediction!

PRD 84, 112005 (2011)

PRD 83 112003 (2011)

  - CDF: $A_{FB}^{l}$=6.6±2.5%

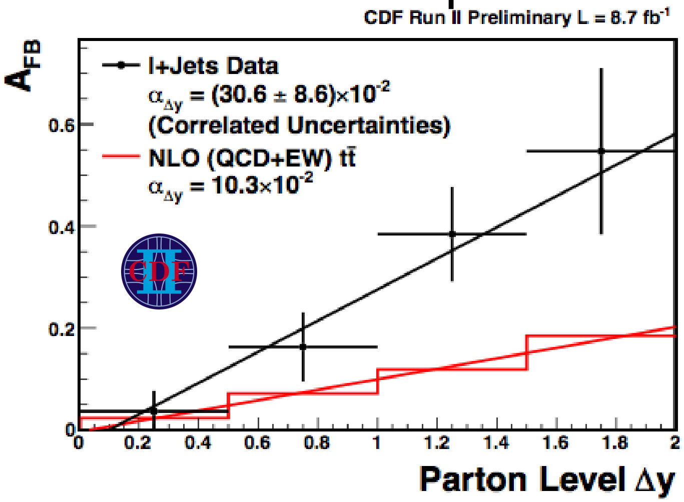
    (NLO (QCD+EW) prediction: 1.6%)

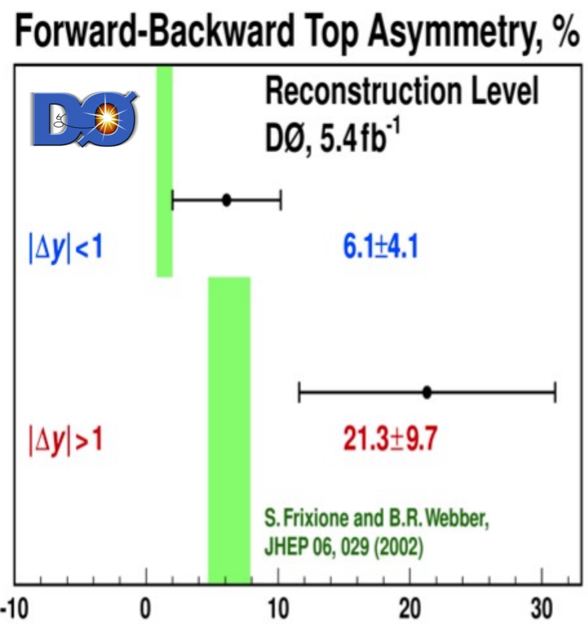


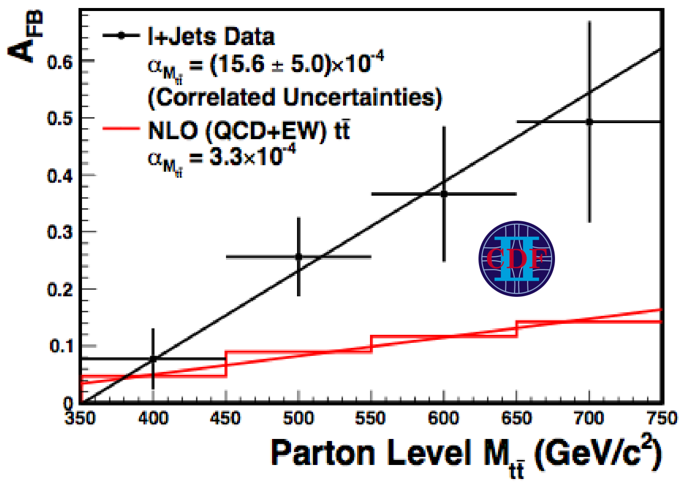

After unfolding

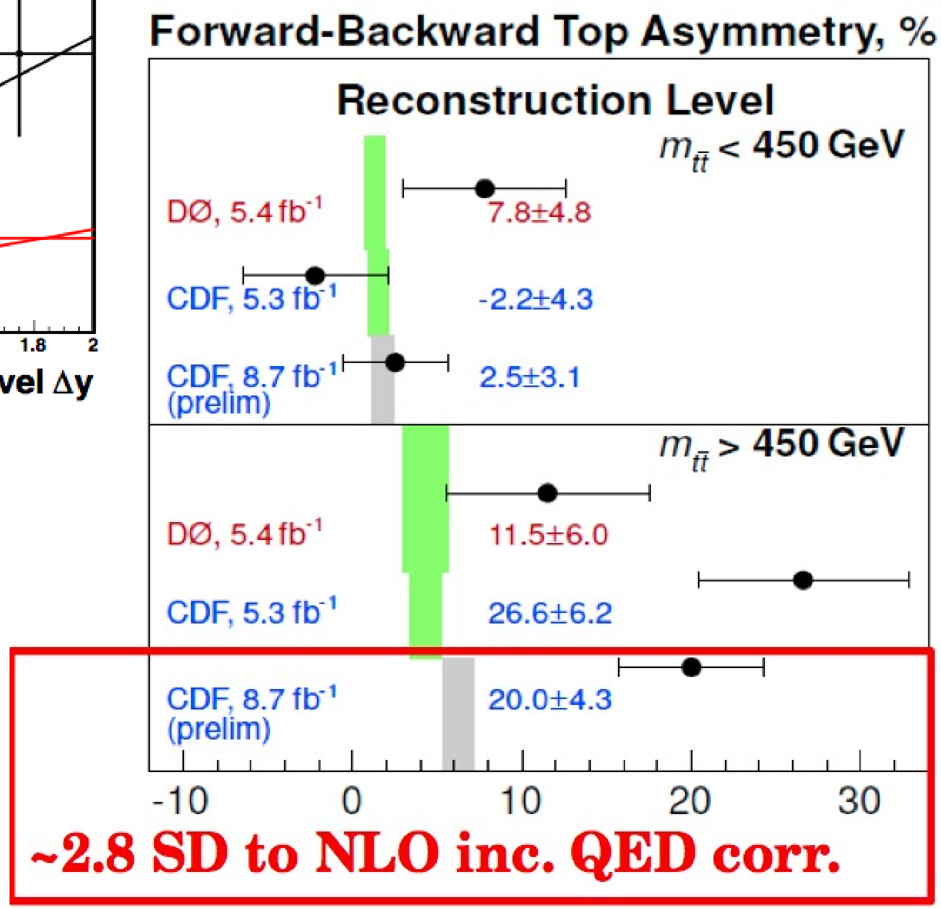
# Results l+jets

- Asymmetry depends on several variables ($m_{t\bar{t}}$, rapidity, etc.)
  - BSM could show a different mass dependence than in SM
- CDF & DØ: study $m_{t\bar{t}}$ & $\Delta y$ dependence



# Results dilepton

- Various asymmetries can be explored (additional to $A_{FB}^{l}$ and $A_{FB}^{t\bar{t}}$)

$$A_{FB}^{ll} = \frac{N(\Delta\eta>0) - N(\Delta\eta<0)}{N(\Delta\eta>0) + N(\Delta\eta<0)} \qquad A_{FB}^{CP} = \frac{N_{l^+}(\eta>0) - N_{l^-}(\eta<0)}{N_{l^+}(\eta>0) + N_{l^-}(\eta<0)}$$

  - No reconstruction of the full $t\bar{t}$ system required except for $A_{FB}^{t\bar{t}}$

| DØ | Unfolded (%) | Predicted NLO QCD+QED (%) |
|---|---|---|
| $A_{FB}^{l}$ | 5.8±5.3 | 4.7±0.1 |
| $A_{FB}^{ll}$ | 5.3±8.4 | 6.2±0.2 |
| $A_{FB}^{CP}$ | -1.8±5.3 | -0.3±0.1 |

**CDF**

$A_{FB}^{t\bar{t}}$=42±16%

(prediction 6±1%)

$A_{FB}^{l}$=14±5% (before correction)

- All statistically limited
- DØ combination l+jets and dilepton $A_{FB}^{l}$=11.8±3.2%

arXiv:1207.0364 [hep-ex]

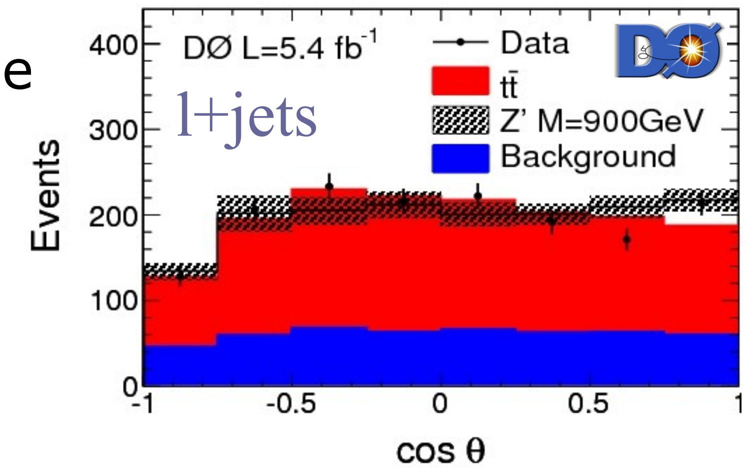
# Top Polarization

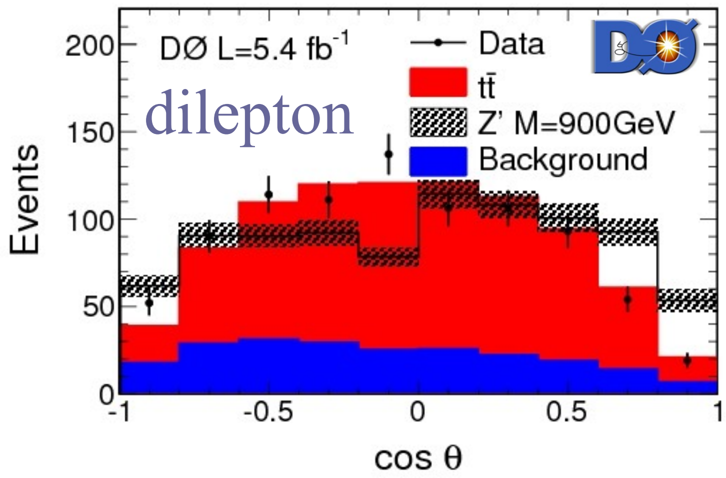
- Various BSM models predicting asymmetry>SM, predict also top polarization !=0

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,n}} = \frac{1}{2}\left(1 + \mathcal{P}_n \kappa_i \cos\theta_{i,n}\right)$$

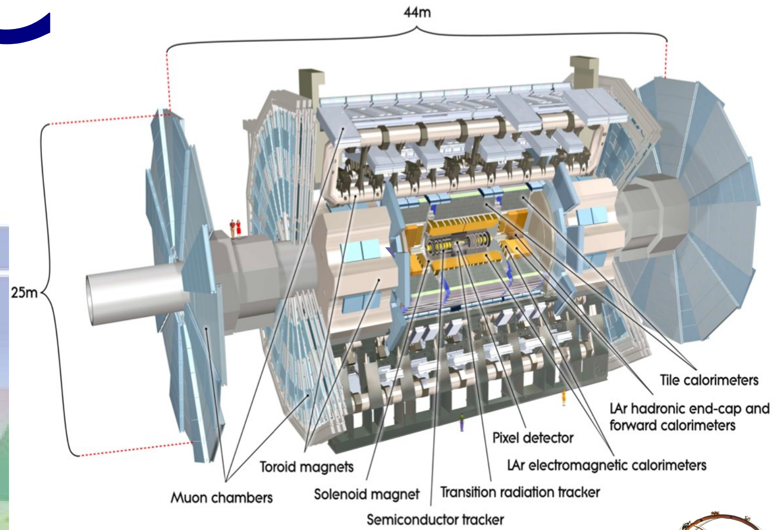
$P_n$: polarization; $\kappa_i$: spin analyzing power of decay product i;
$\theta_i$: direction of daughter wrt. chosen axis

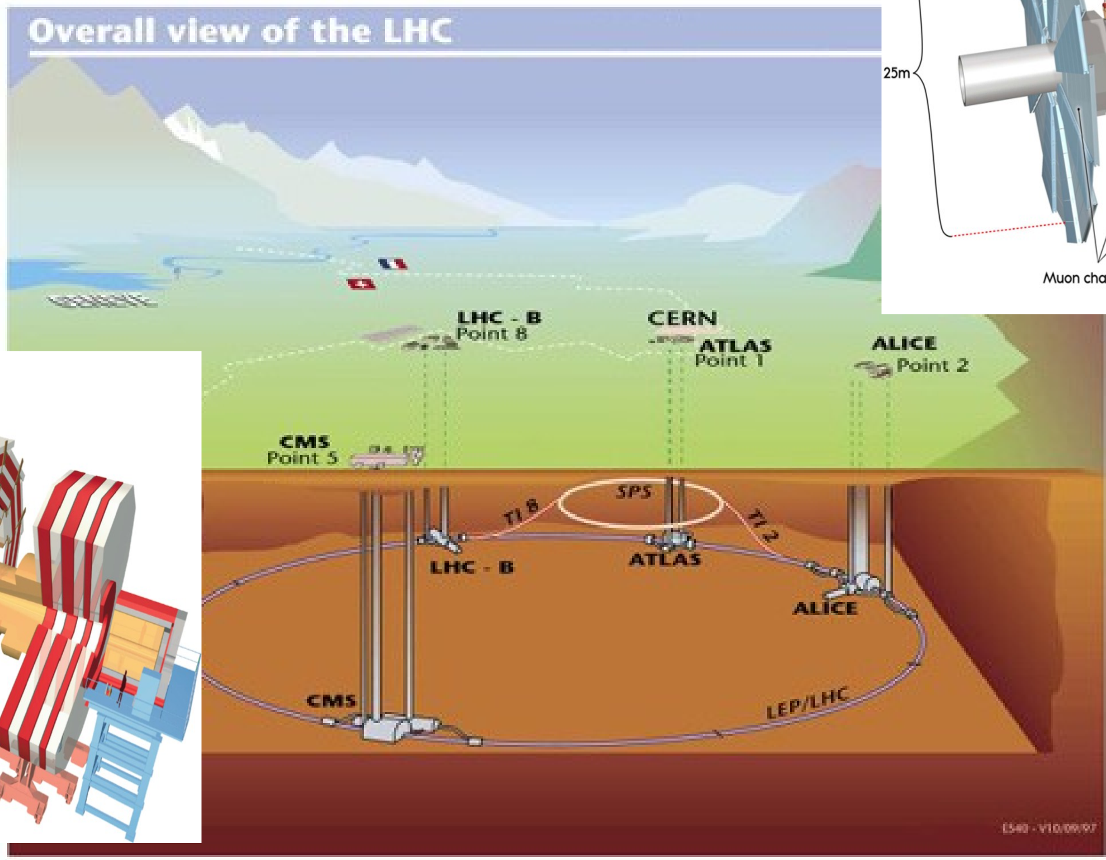
- First study done by DØ: good agreement with SM at reconstruction level
  - Reconstruction done with neutrino weighting
  - Plots are at Reco level

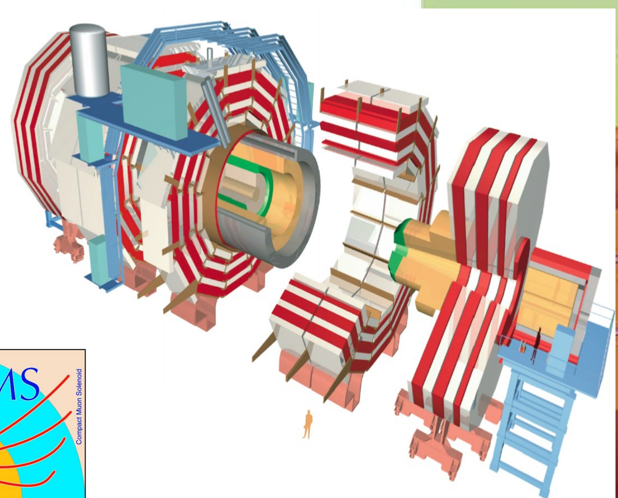


# Asymmetries at the LHC



# Asymmetry Measurements

- Measurements at ATLAS:
  - $A_C$ in l+jets final state ($1.04 fb^{-1}$): inclusive and $m_{t\bar{t}}$ dependent
  - $A_C$ and $A_C^{ll}$ in dilepton final state $4.7 fb^{-1}$
    - $A_C^{ll}$ does not require full $t\bar{t}$ event reconstruction
    - Sensitive to top polarization effect → additional information
- Measurements at CMS:
  - $A_C$ in l+jets final state ($4.7 fb^{-1}$)
    - Inclusive
    - Dependent on $m_{t\bar{t}}$, rapidity and $p_T^{t\bar{t}}$

$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

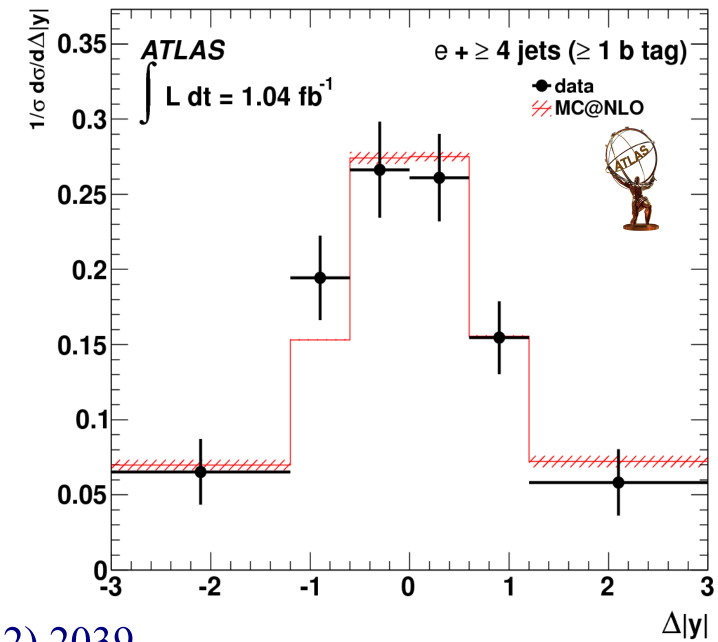
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

$$A_C^{ll} = \frac{N(\Delta|\eta|>0) - N(\Delta|\eta|<0)}{N(\Delta|\eta|>0) + N(\Delta|\eta|<0)}$$

$$\Delta|\eta| = |\eta_{l^1}| - |\eta_{l^2}|$$

# Results l+jets Inclusive

- Correction of detector and acceptance effects via unfolding
  - Atlas: iterative Bayesian unfolding
  - CMS: regularized unfolding
- Atlas: $A_C$=-0.019±0.028(stat)±0.024(syst)
  - Consistent with MC@NLO prediction of 0.006±0.002
- CMS: $A_C$=0.004±0.010 (stat)±0.012(syst)
- Systematic uncertainties comparable to statistical
  - Main systematics related to $t\bar{t}$ modeling, JES (Atlas), unfolding method (CMS)
- Good agreement with SM predictions

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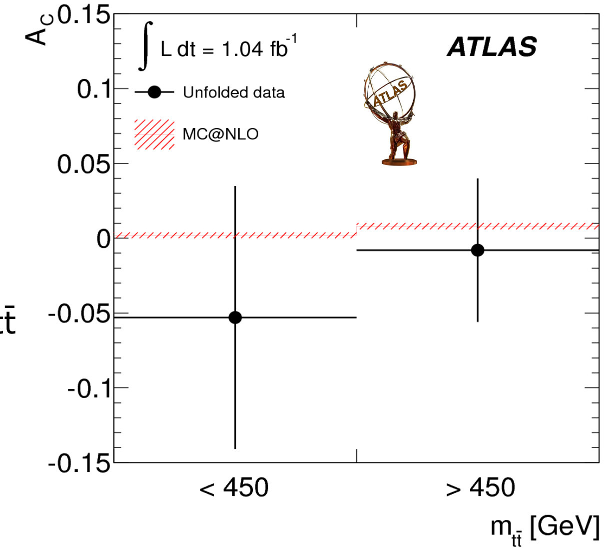
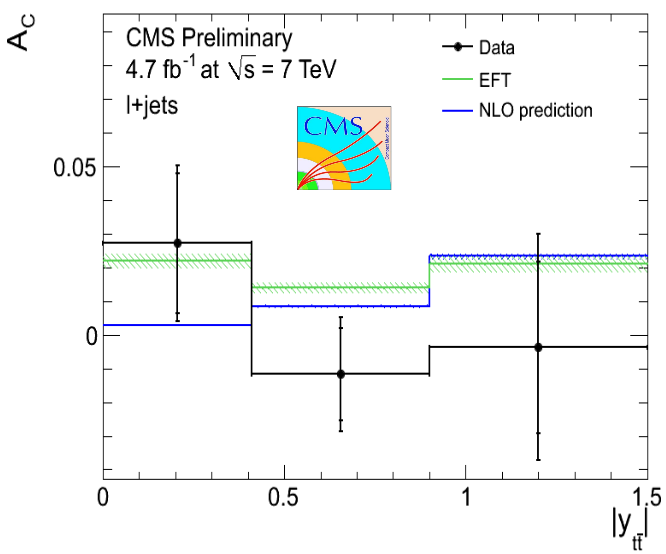
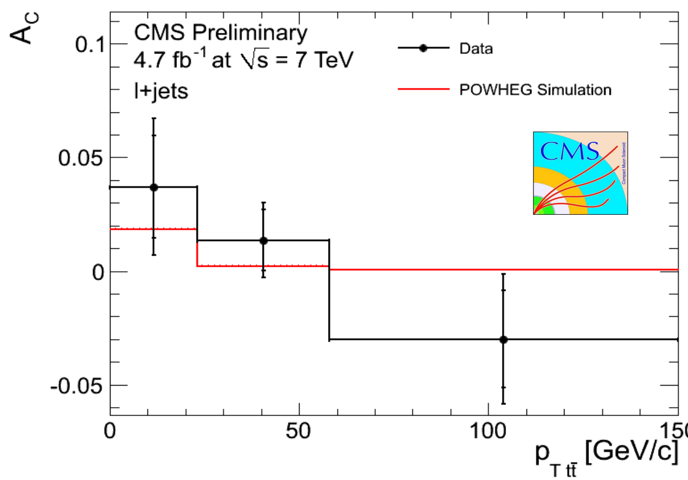
# Results l+jets Differential

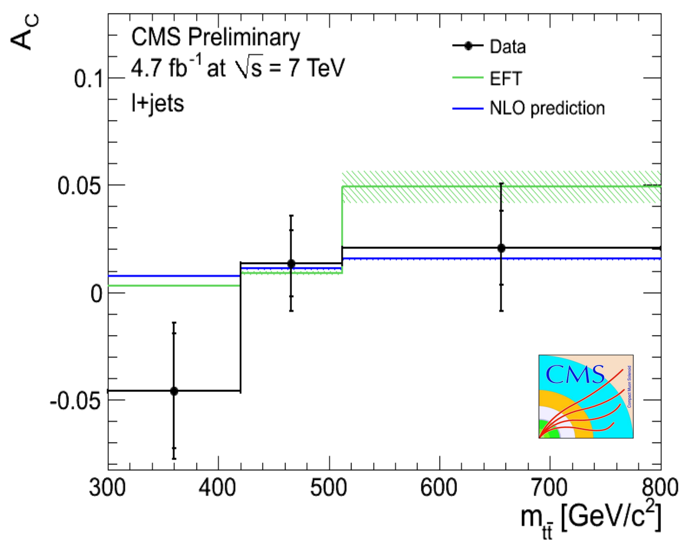
- Asymmetry depends on various variables
  - $p_T^{t\bar{t}}$ sensitive to ratio of negative and positive contributions to overall asymmetry
  - $m_{t\bar{t}}$ dependence as $q\bar{q}$ process enhanced for larger $m_{t\bar{t}}$
  - gg-fusion dominant in central rapidity region, $q\bar{q}$ process contributes more for forward rapidity region




EFT: using axial-vector coupling model of gluon to top

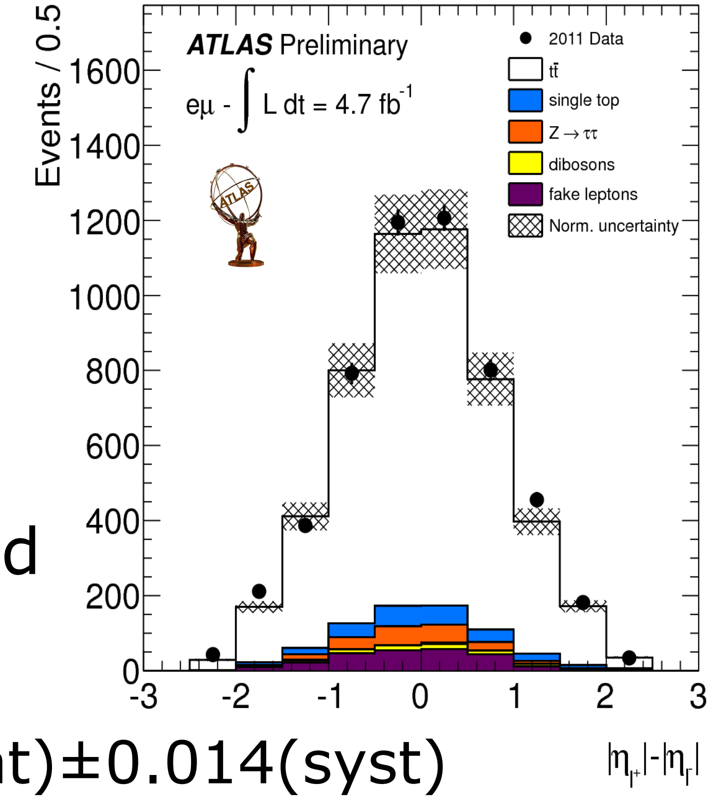


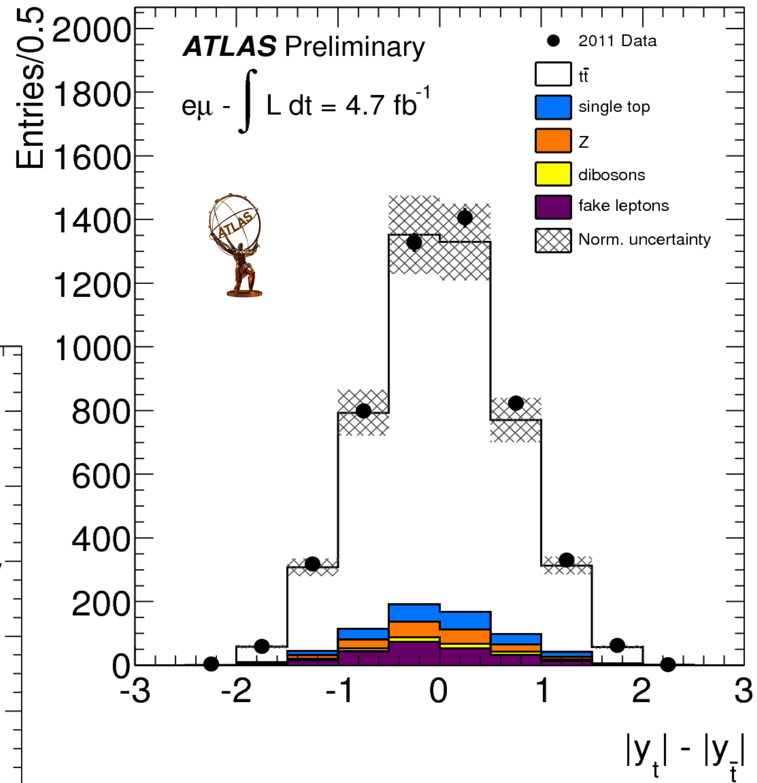

- No significant dependency can be seen

# Results dilepton

- Inclusive measurements:
  - $A_c^{ll}$=0.023±0.012(stat)±0.008(syst)
    - MC@NLO prediction: 0.004±0.001
  - $A_C$=0.057±0.024(stat)±0.015(syst)

$$A_C^{ll} = \frac{N(\Delta|\eta|>0) - N(\Delta|\eta|<0)}{N(\Delta|\eta|>0) + N(\Delta|\eta|<0)}$$



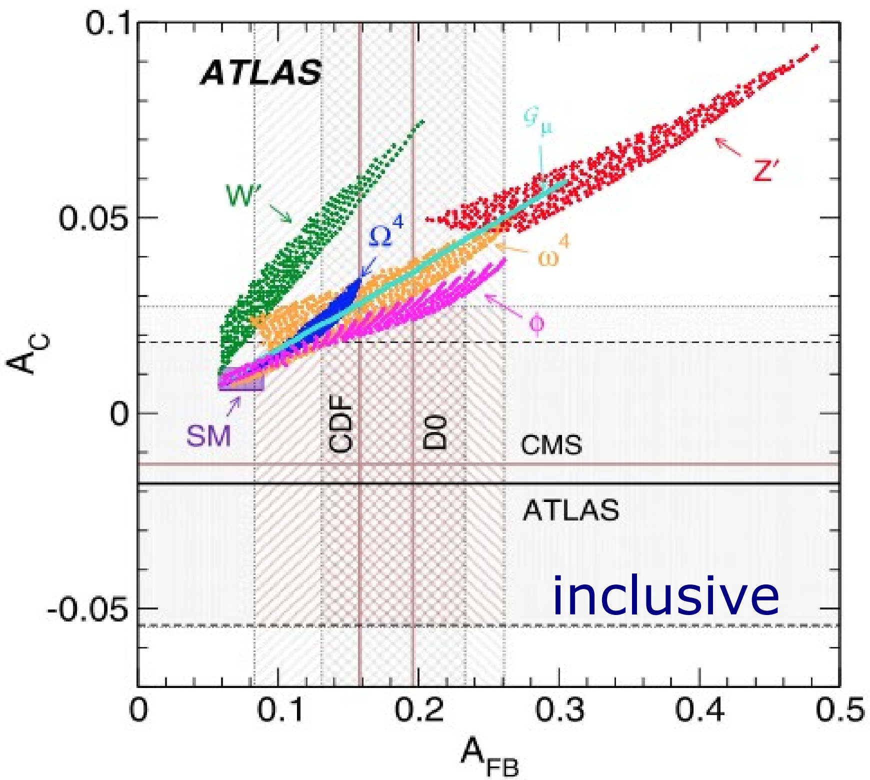



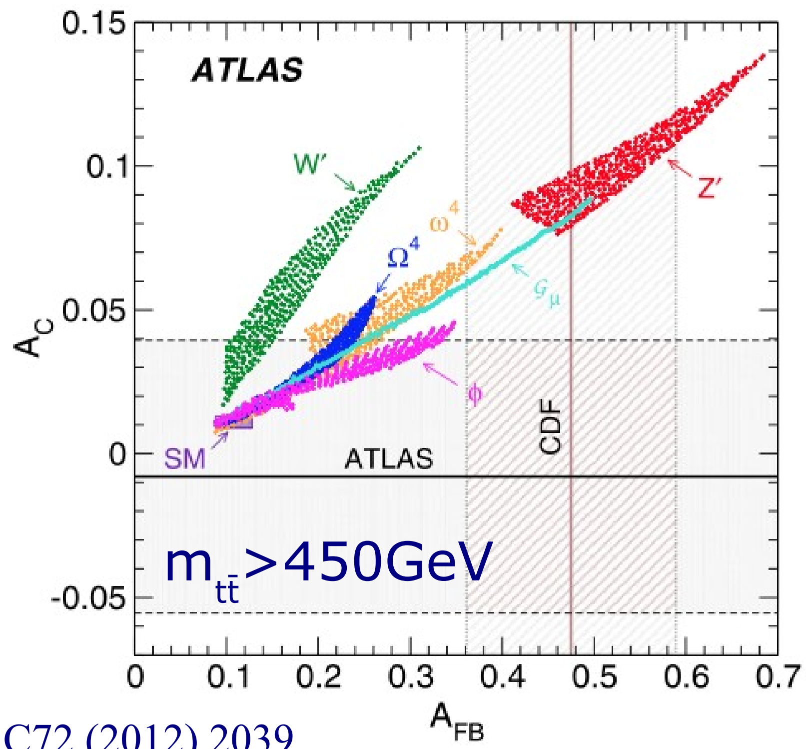

- Combination of Atlas $A_C$ results in l+jets and dilepton final state
  - $A_C$=0.029±0.018(stat)±0.014(syst)

See also poster by J. Cuth

# Tevatron and LHC – Model consideration

- LHC measurements disfavor several models
  - Z': outside the measurement
  - Other models: tension with CDF's mass dependence

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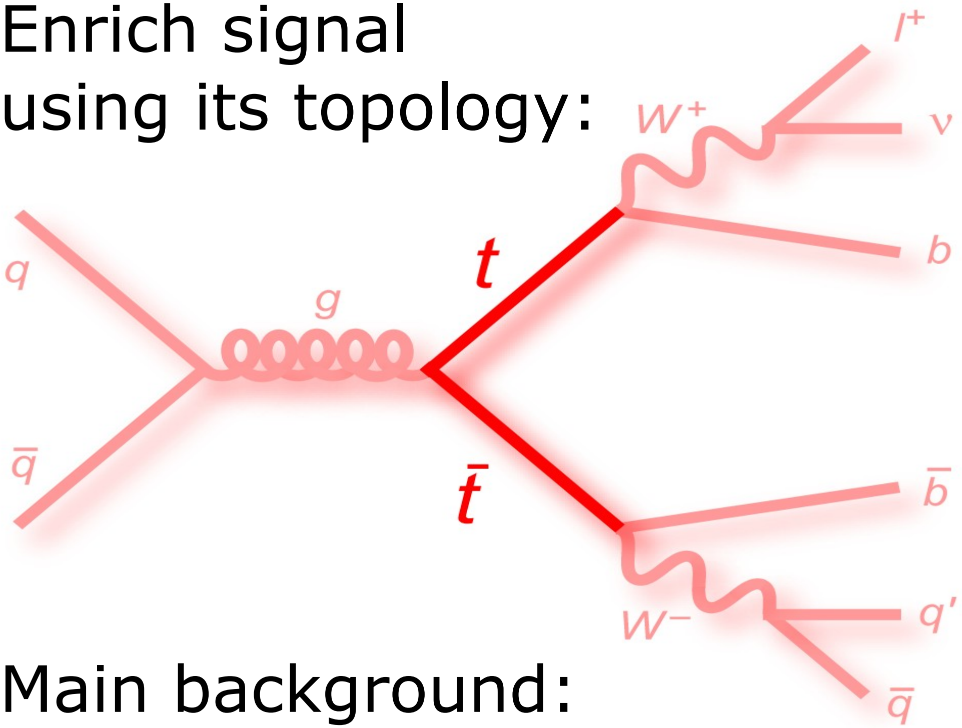
# Summary

- Asymmetry measurements larger than theory prediction at Tevatron
  → hint for new physics?
- No deviation from SM at LHC
  → several models can be excluded
  - More data available
    → soon sensitive to SM prediction
- Asymmetries at Tevatron statistically limited
- Additional measurements needed to distinguish models and ensure proper modeling
  → $p_T^{t\bar{t}}$, polarization, Asymmetries in $b\bar{b}$

# BACKUP

# Event Selection l+jets

- Enrich signal using its topology:




Exactly 1 isolated lepton (e or $\mu$) with high $p_T$

Missing $p_T$ for neutrino ($\not{E}_T$): >20GeV

≥4 jets with $p_T$>20GeV;

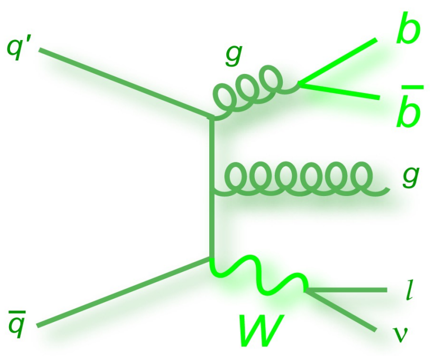
CDF: $|\eta|<2.0$; DØ: $|\eta|<2.5$

≥1 jet b-tagged

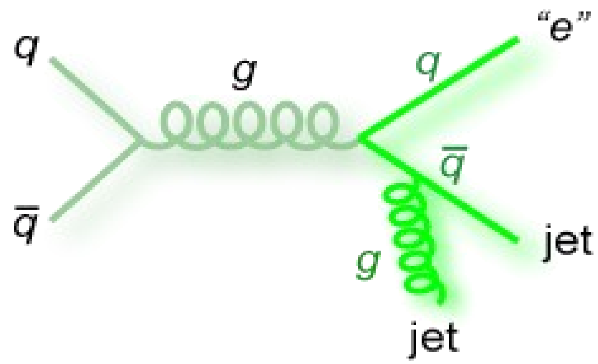
reconstruction of full $t\bar{t}$ event using kinematic fitter

- Main background:

W+jets

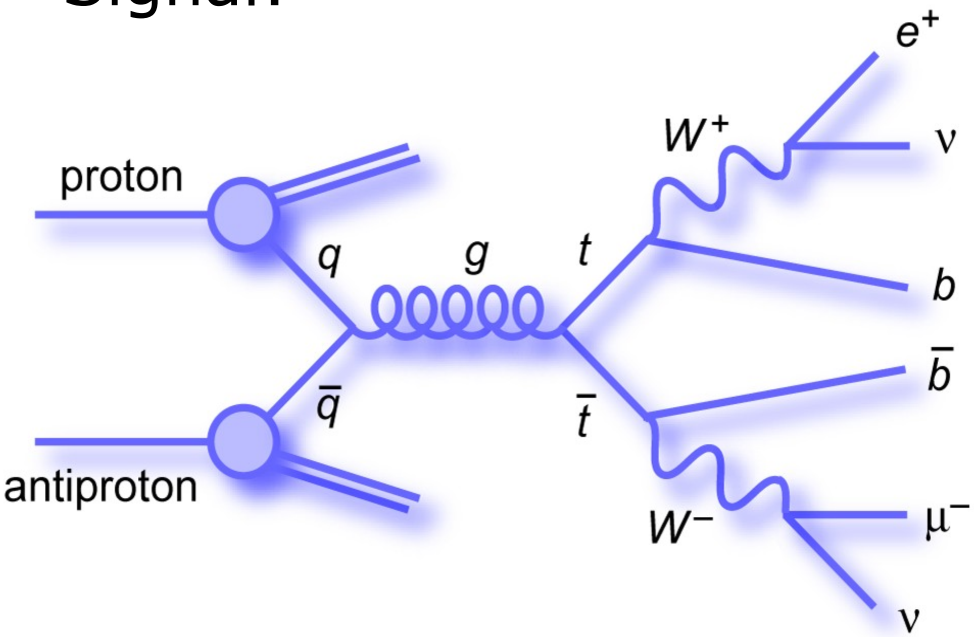



and QCD multijets



# Event Selection dilepton

- Signal:




2 leptons (e or $\mu$) with $p_T$>20GeV; opposite charges

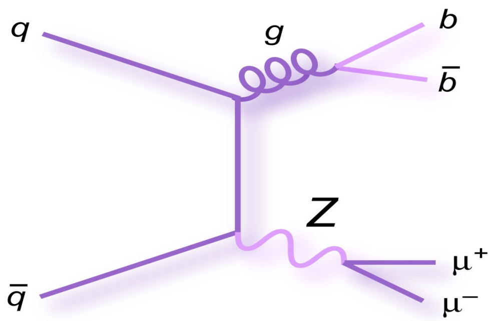
Large $\not{E}_T$ to account for the two neutrinos

≥2 jets

Large $H_T$ (scalar sum of lepton & jet $p_T$ & $\not{E}_T$)

- Main background:

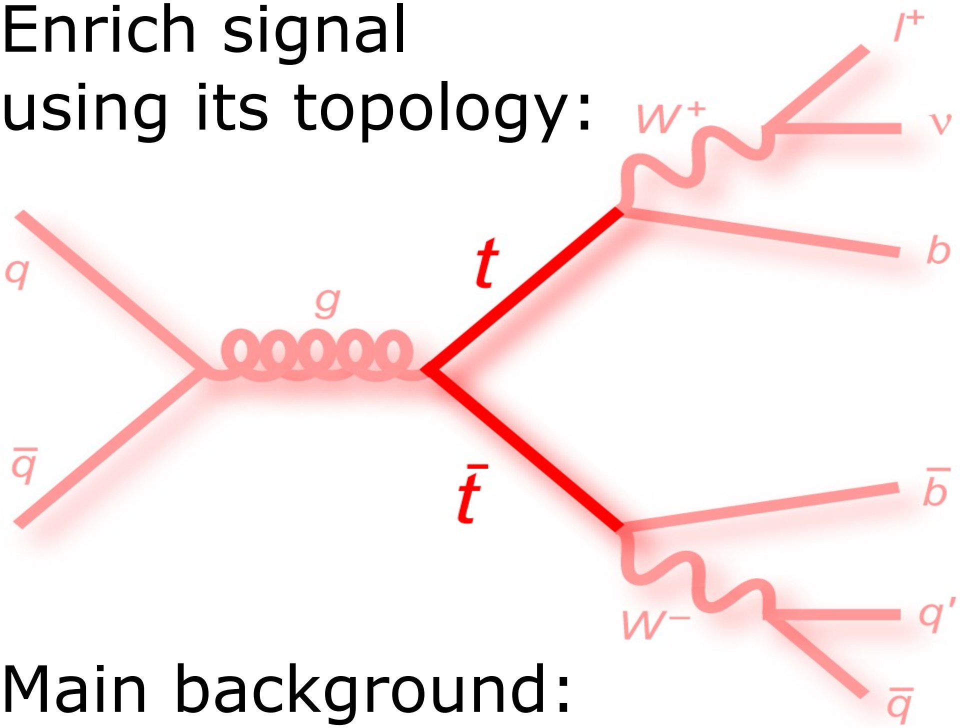
Z+jets




and fake lepton (QCD multijet)

# Tevatron: Event Selection l+jets

- Enrich signal using its topology:




1 lepton (e or ) with $p_T$>20GeV; | |<1.1 (DØ: | |<2.0)

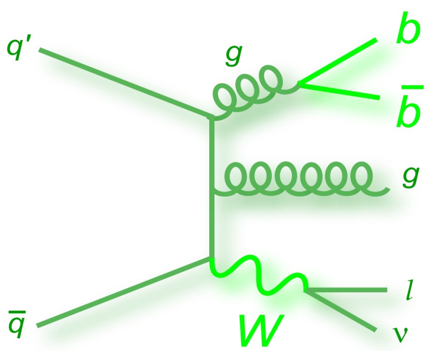
Missing $p_T$ for neutrino ($\not{E}_T$): >20GeV

≥4 jets with $p_T$>20GeV;
CDF: | |<2.0; DØ: | |<2.5

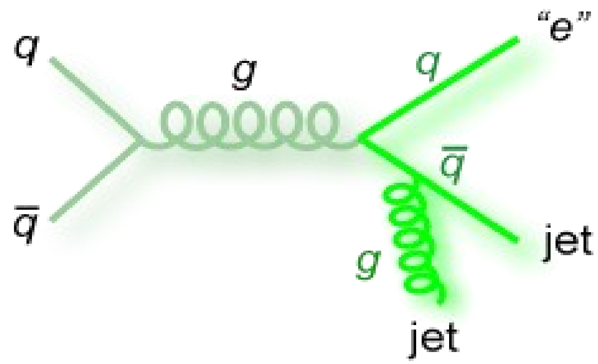
≥1 jet b-tagged

- Main background:

W+jets

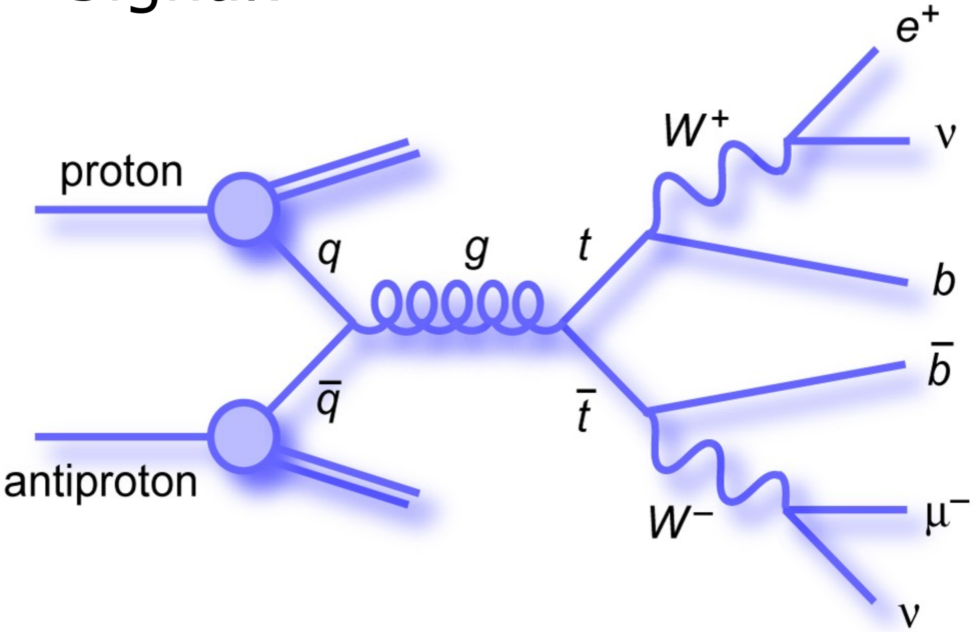



and QCD multijets



# Tevatron: Event Selection dilepton

- Signal:




2 leptons (e or ) with $p_T$>20GeV; | $_e$|<1.1 or 1.2<| $_e$|<2.8; | |<1.1

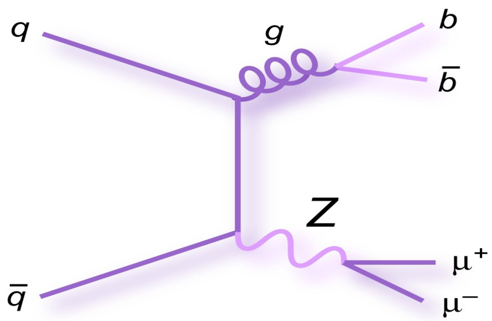
$\not{E}_T$>25 or 50GeV (depending on angle between $\not{E}_T$ direction and closest lepton or jet)

≥2 jets with $p_T$>15GeV and | |<2.5

$H_T$ (scalar sum of lepton & jet $p_T$ & $\not{E}_T$)>200GeV

- Main background:

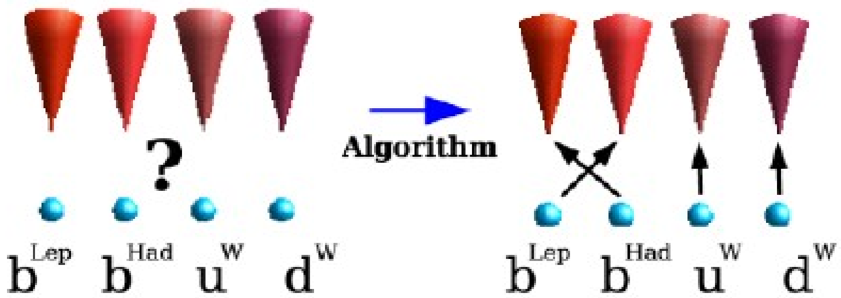
Z+jets

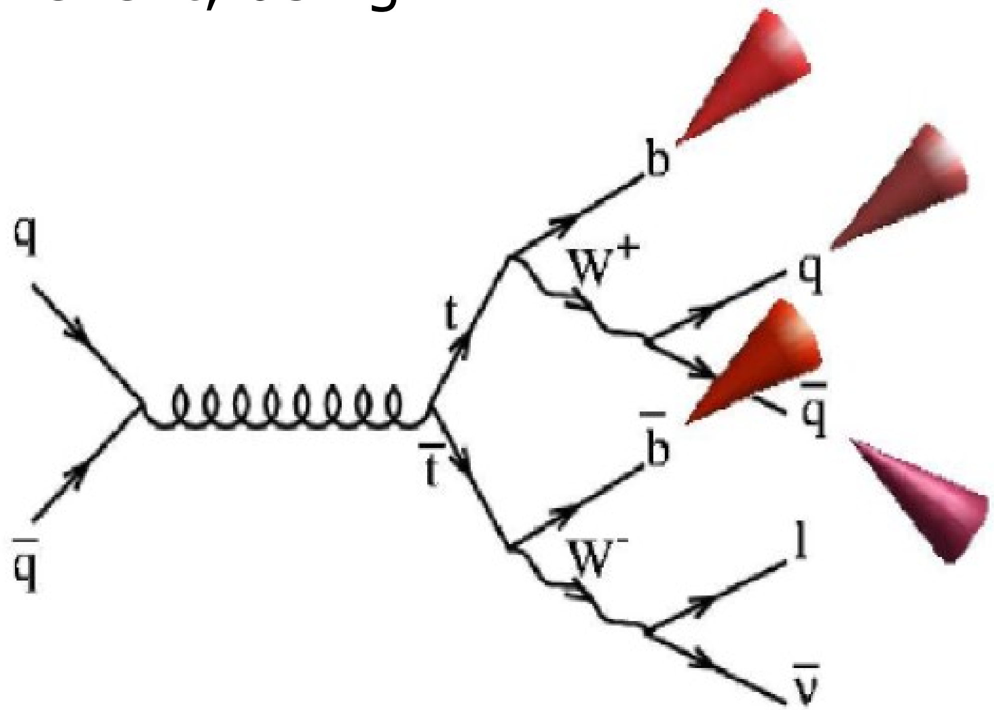



and QCD multijets

# $t\bar{t}$ Reconstruction

- L+jets: kinematic fit to reconstruct full event, using
  - Fixed top mass
  - Two jets have to have $m_{jj}=m_W$
  - B-jet identification
- Experimental resolutions taken into account

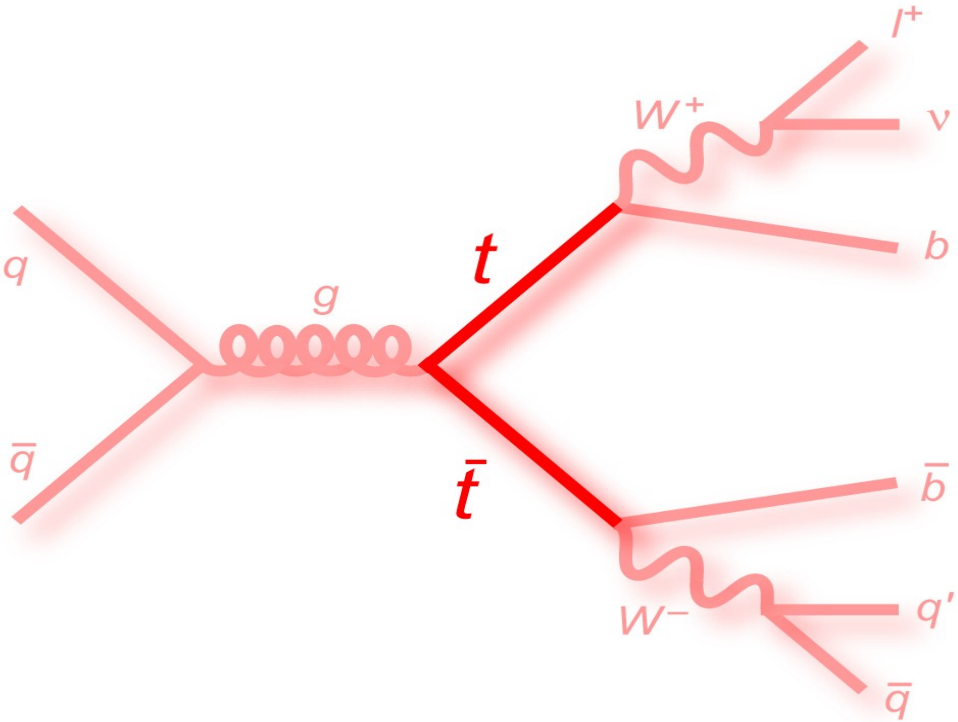



- Dilepton: also kinematic fitter, but more dof (2 neutrinos) → use a priori probability distributions as input, calculate probability

# LHC: Selection & Reconstruction

- Selection: $t\bar{t}$ l+jets selection




1 lepton (e or ) with $p_T$>30GeV (Atlas: 25GeV for e, 20GeV for ); | |<2.5

Missing $p_T$ for neutrino ($\not{E}_T$): no cut for CMS; Atlas: >35GeV

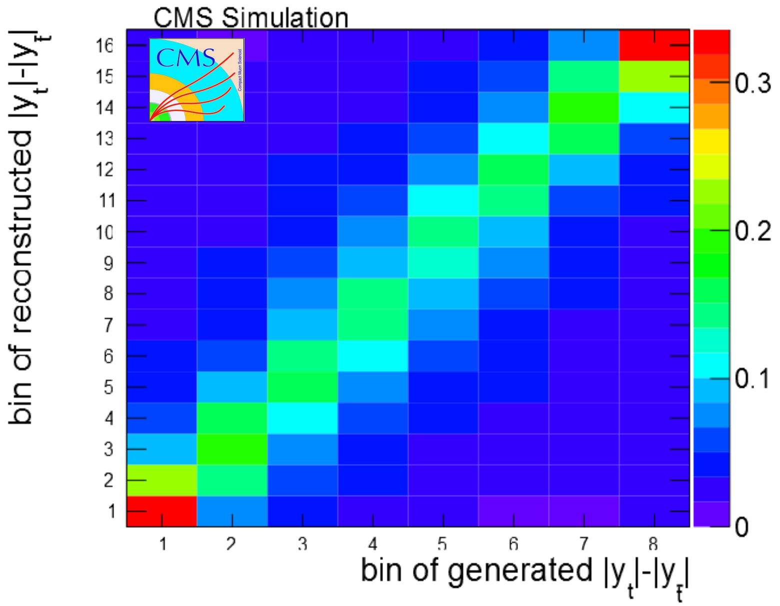
≥4 jets with $p_T$>30GeV (Atlas: >25GeV); CMS: | |<2.4; Atlas: | |<2.5

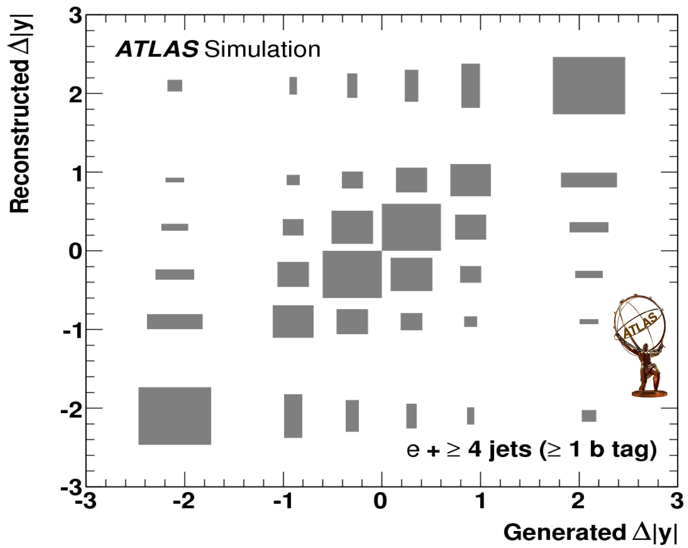
≥1 jet b-tagged

- Reconstruction of $t\bar{t}$ system:
  - Atlas: likelihood to assign the right combination
  - CMS: $^2$ test

# Selection and Unfolding

- Both use standard $t\bar{t}$ selection
  - multijet/fakes estimated with Matrix Method
  - Background modeling checked in orthogonal samples
  - Reconstruction in dilepton done using matrix element method
- Correction of detector and acceptance effects via unfolding
  - After subtracting background estimate from data
- CMS: regularized unfolding
- Atlas: iterative Bayesian unfolding



# Systematics Atlas l+jets

| Source of systematic uncertainty on $A_C$ | Electron channel | Muon channel |
|---|---|---|
| *Detector modelling* | | |
| Jet energy scale | 0.012 | 0.006 |
| Jet efficiency and resolution | 0.001 | 0.007 |
| Muon efficiency and resolution | $<0.001$ | 0.001 |
| Electron efficiency and resolution | 0.003 | 0.001 |
| b-Tag scale factors | 0.004 | 0.002 |
| Calorimeter readout | 0.001 | 0.004 |
| Charge mis-ID | $<0.001$ | $<0.001$ |
| b-Tag charge | 0.001 | 0.001 |
| *Signal and background modelling* | | |
| Parton shower/fragmentation | 0.010 | 0.010 |
| Top mass | 0.007 | 0.007 |
| $t\bar{t}$ modelling | 0.011 | 0.011 |
| ISR and FSR | 0.010 | 0.010 |
| PDF | $<0.001$ | $<0.001$ |
| $W+$jets normalisation and shape | 0.008 | 0.005 |
| $Z+$jets normalisation and shape | 0.005 | 0.001 |
| Multijet background | 0.011 | 0.001 |
| Single top | $<0.001$ | $<0.001$ |
| Diboson | $<0.001$ | $<0.001$ |
| MC statistics | 0.006 | 0.005 |
| Unfolding convergence | 0.005 | 0.007 |
| Unfolding bias | 0.004 | $<0.001$ |
| Luminosity | 0.001 | 0.001 |
| Total systematic uncertainty | 0.028 | 0.024 |

# Systematics CMS l+jets

| Systematic uncertainty | inclusive $A_C$ |
|---|---|
| JES | 0.002 |
| JER | 0.002 |
| Pileup | 0.001 |
| Generator | 0.001 |
| Migration matrix | 0.002 |
| Unfolding | 0.008 |
| W+jets | 0.004 |
| Multijet | 0.001 |
| Lepton ID/sel. efficiency | 0.006 |
| $Q^2$ scale | 0.002 |
| Hadronization | 0.001 |
| PDF | 0.002 |
| Total | 0.012 |

# Systematics Atlas dilepton

| | $ee$ | $e\mu$ | $\mu\mu$ |
|---|---|---|---|
| *Signal and background modeling* | | | |
| Signal generator | 0.011 | 0.003 | 0.002 |
| ISR and FSR | 0.004 | 0.004 | 0.006 |
| Parton shower/fragmentation | 0.001 | 0.004 | 0.003 |
| PDF | <0.001 | <0.001 | <0.001 |
| Z+jets | 0.005 | 0.004 | 0.001 |
| Diboson | <0.001 | <0.001 | <0.001 |
| Single top | <0.001 | <0.001 | <0.001 |
| Multijet background | 0.014 | 0.002 | <0.001 |
| *Detector modeling* | | | |
| Jet efficiency and resolution | 0.008 | 0.001 | 0.003 |
| Jet energy scale | 0.006 | 0.001 | 0.002 |
| Muon efficiency and resolution | <0.001 | 0.001 | 0.002 |
| Electron efficiency and resolution | 0.005 | 0.003 | <0.001 |
| Calibration | 0.019 | 0.002 | 0.004 |
| Luminosity | 0.002 | <0.001 | <0.001 |
| Total | 0.029 | 0.009 | 0.009 |

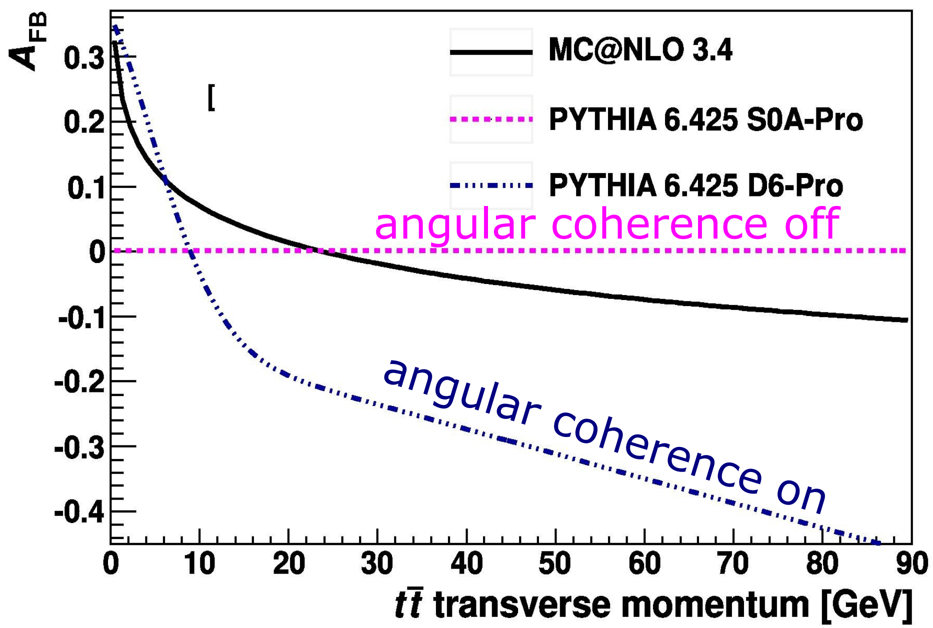
Table 4: List of all systematic uncertainties on the lepton-based asymmetry.

| | $ee$ | $e\mu$ | $\mu\mu$ |
|---|---|---|---|
| *Signal and background modeling* | | | |
| Signal generator | 0.014 | 0.009 | 0.002 |
| ISR and FSR | 0.008 | 0.002 | 0.018 |
| Parton shower/fragmentation | 0.001 | 0.001 | 0.001 |
| PDF | 0.001 | <0.001 | <0.001 |
| Z+jets | 0.001 | 0.006 | 0.002 |
| Diboson | <0.001 | <0.001 | <0.001 |
| Single top | <0.001 | <0.001 | <0.001 |
| Multijet background | 0.012 | 0.010 | 0.001 |
| *Detector modeling* | | | |
| Jet efficiency and resolution | 0.007 | 0.001 | 0.005 |
| Jet energy scale | 0.003 | 0.002 | 0.006 |
| Muon efficiency and resolution | 0.004 | 0.003 | 0.005 |
| Electron efficiency and resolution | 0.013 | 0.006 | 0.002 |
| Calibration | 0.004 | 0.001 | 0.002 |
| Luminosity | <0.001 | 0.001 | <0.001 |
| Total | 0.028 | 0.017 | 0.021 |

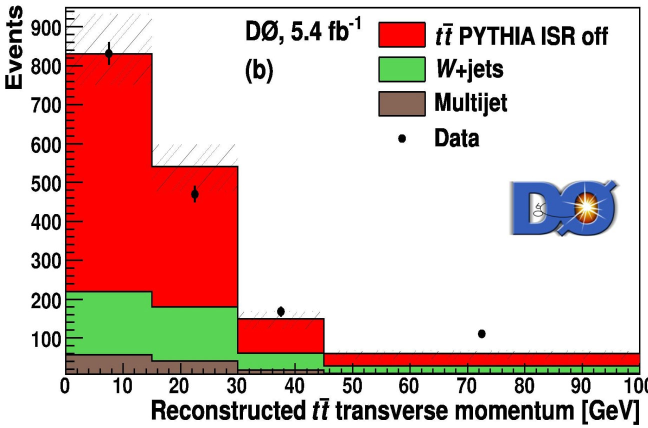
able 5: List of all systematic uncertainties on the $t\bar{t}$-based asymmetry.

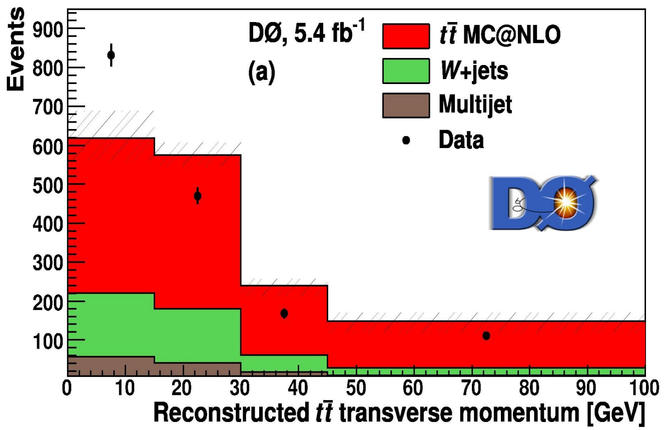
# Modeling Issues

- Sensitivity of asymmetry prediction to modeling studied at DØ
- Noted a dependence on $p_T^{t\bar{t}}$
  - e. g. when switching angular coherence between top and initial parton shower on/off
  - Effect included as systematic uncertainty for now (1.6%)




- Top pair $p_T$ difficult to model in data




→ better understanding needed (dedicated measurement)