Experimental Top Quark Physics Part III

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Part III: Asymmetry and Searches

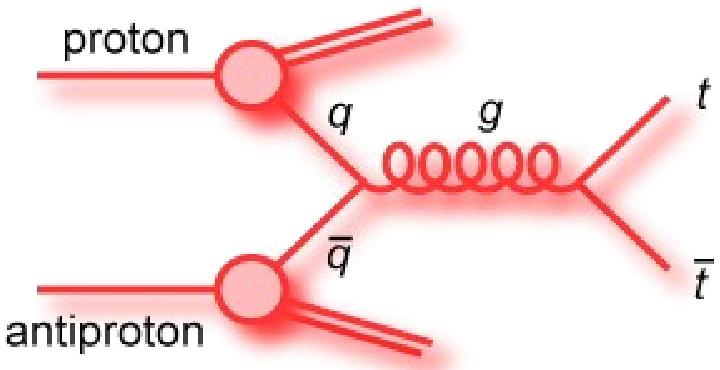
- $t\bar{t}$ Asymmetries
  - Tevatron
  - LHC
  - Related analyses
- Searches in the top sector
  - Overview
  - Search for dark matter

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

- $t\bar{t}$ production via strong interaction

- At Tevatron:

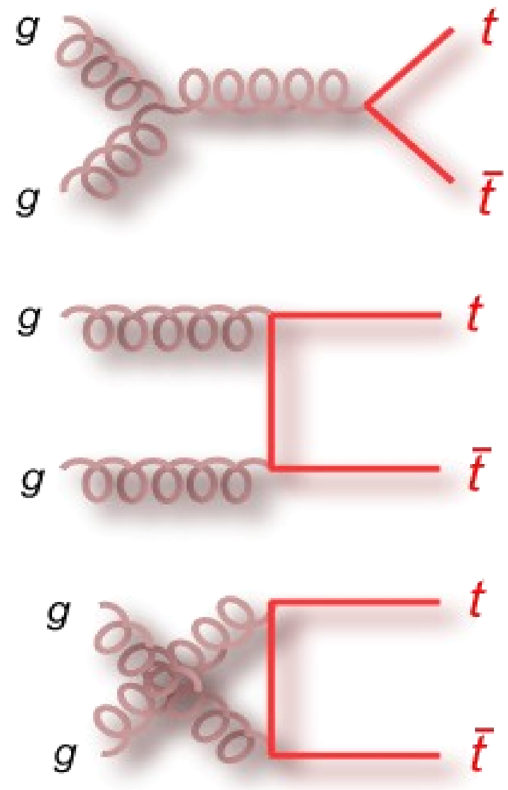
  85%



+ 15%

- At LHC:
  14 TeV: 10% + 90%

  7 TeV: 15% + 85%



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

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- At Tevatron:

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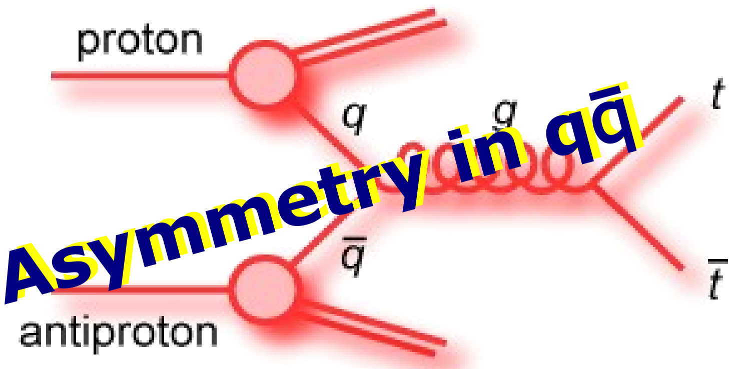
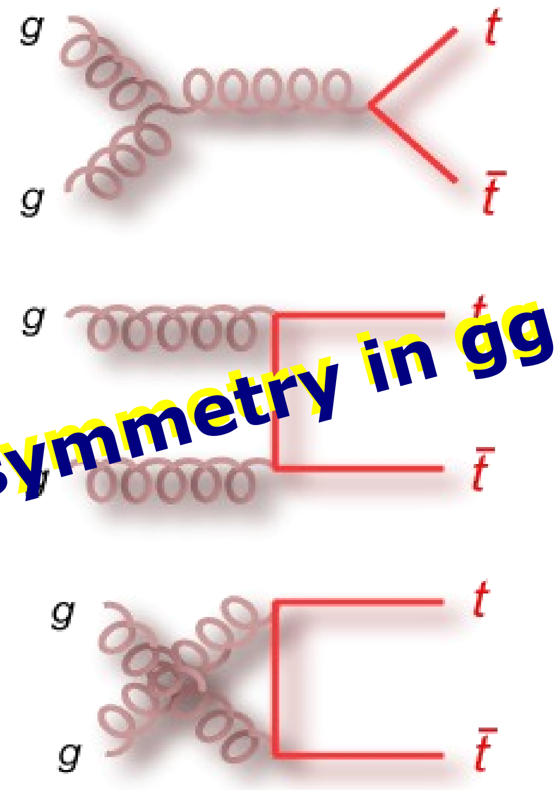


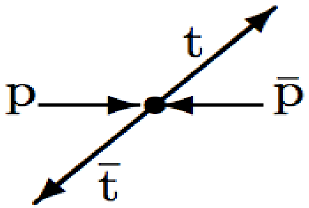
Asymmetry in $q\bar{q}$

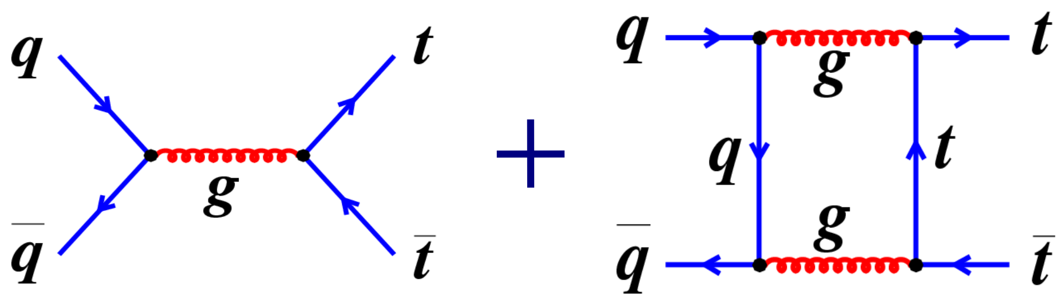


No asymmetry in gg

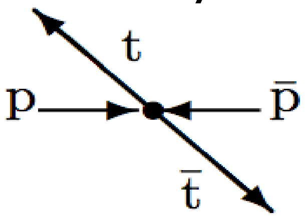
Asymmetry Idea

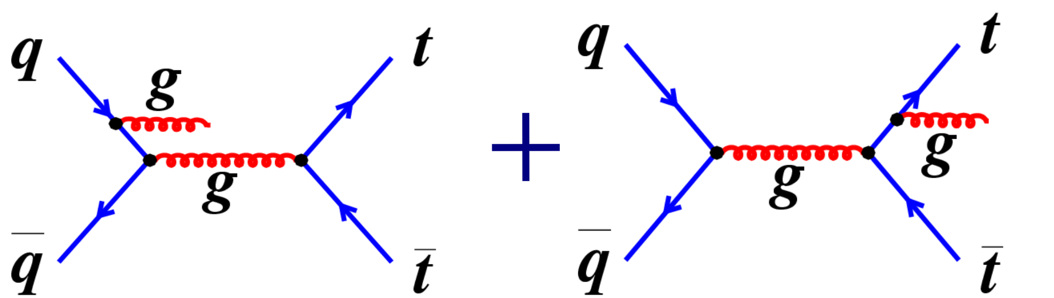
- LO: No charge asymmetry expected
- NLO QCD: Interference between $q\bar{q}$ diagrams
  - Asymmetry in QCD:Interference of C=1 and C=-1 amplitudes are odd under $t \leftrightarrow \bar{t}$ $\rightarrow$ cause asymmetry
- Tree level and box diagrams:
  - Positive asymmetry





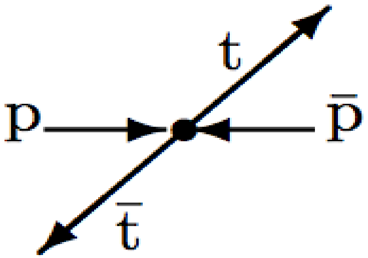
- Initial and final state radiation:
  - Negative asymmetry





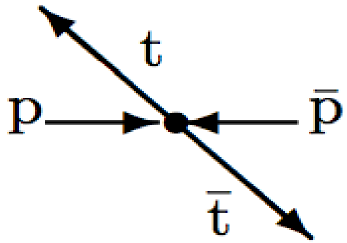
Asymmetry Definitions

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



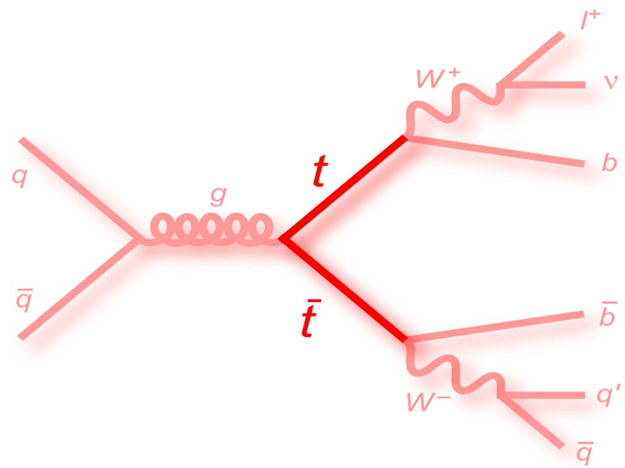
y>0

In $t\bar{t}$ rest frame:
check how often top is in direction of proton momentum
(at Tevatron)



y<0

$$y=\frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \quad \text{or} \quad \eta=-\ln\tan(\theta/2)$$



- Several asymmetry definitions can be studied

Asymmetry Definitions

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

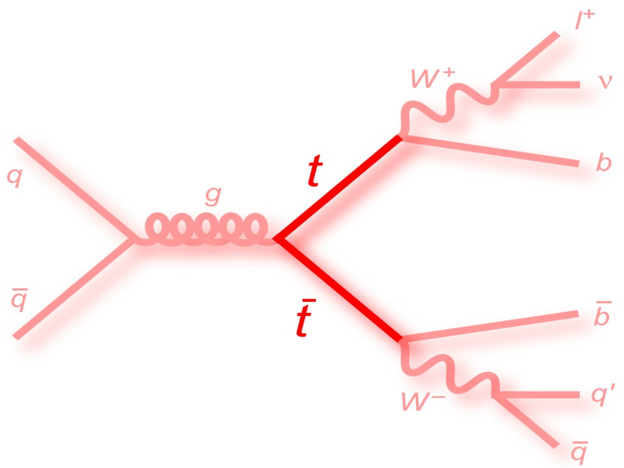
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

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

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

  - Lepton based asymmetry

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

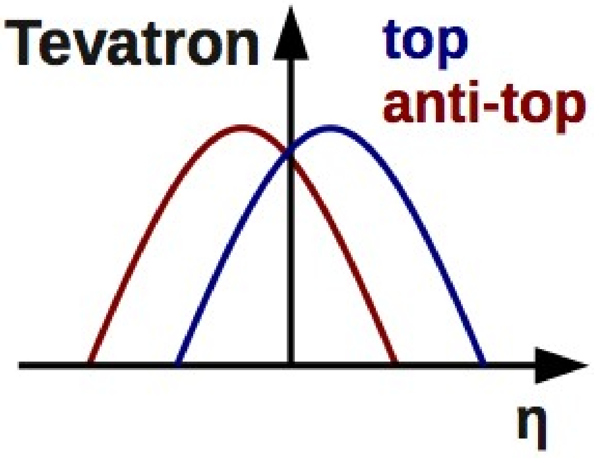


    - Sensitive to polarization of the top quark
    - Complementary information to forward-backward asymmetry

Tevatron and LHC Difference

- Tevatron: $p\bar{p}$ is CP eigenstate $\rightarrow$ pp (LHC) is not
  $\rightarrow$ different way to measure the effect at Tevatron and LHC

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



Tevatron

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

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

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

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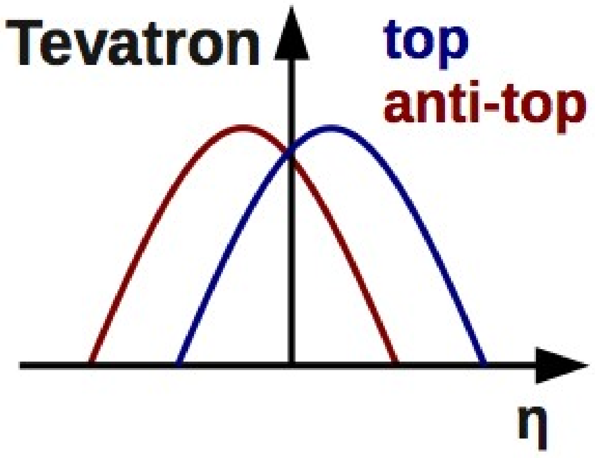

Tevatron LHC

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

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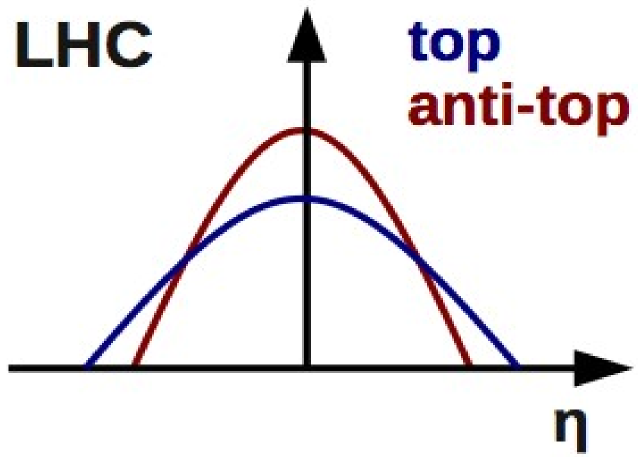
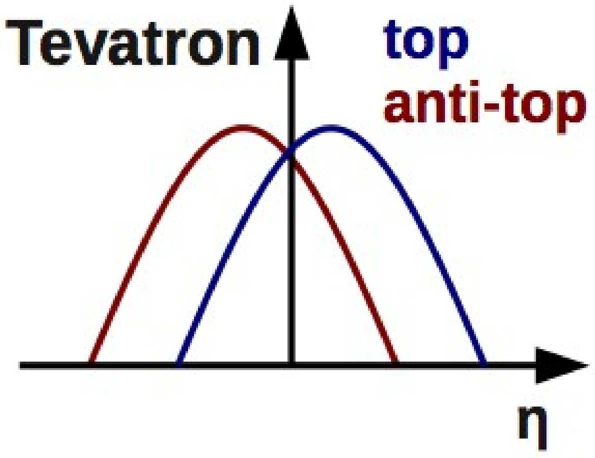


Tevatron and LHC Difference

- 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

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

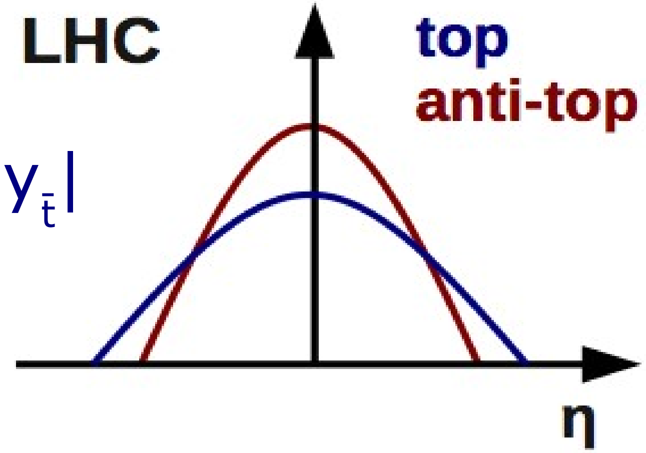
$$A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}$$



Tevatron: $y = y_t - y_{\bar{t}}$

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

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



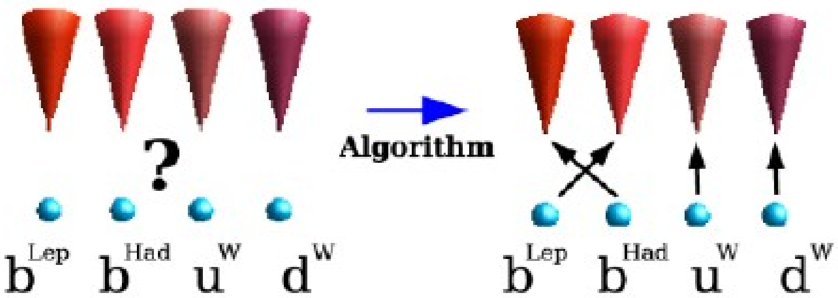
Asymmetry Analyses

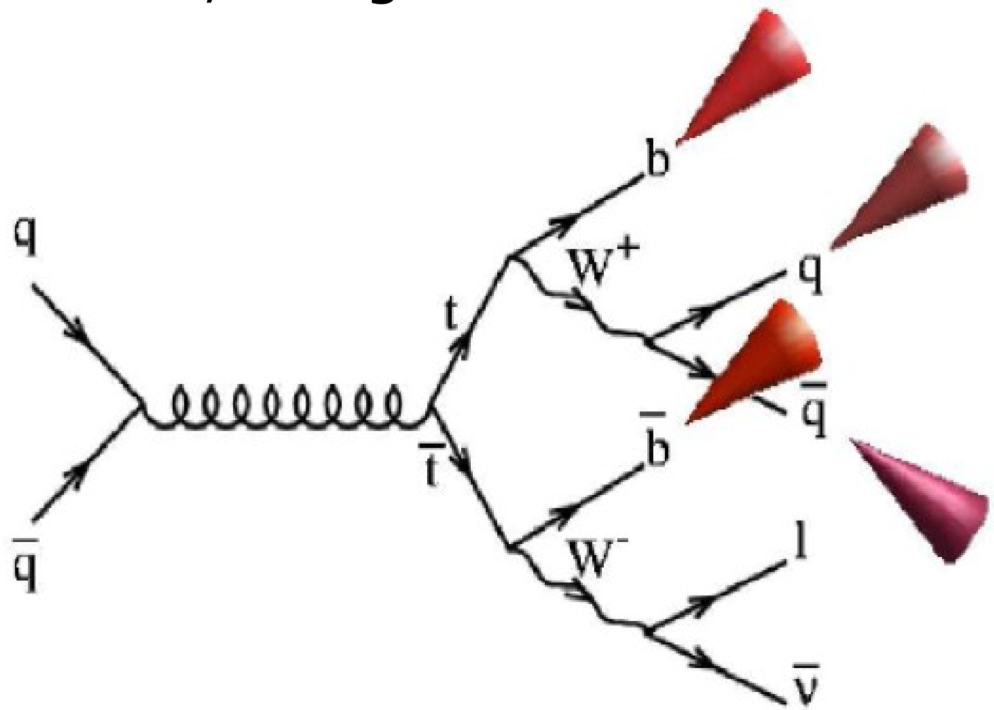
- Asymmetries measured at all 4 experiments
  - In l+jets and dilepton final states
- Deviation of asymmetry from SM prediction seen at DØ and CDF

  $\longrightarrow$ caused quite some interest
  - No deviation seen at the LHC for charge asymmetry
- Analysis strategy:
  - Reconstruct $t\bar{t}$ system (not necessary for leptonic asymmetry)
  - Extract raw asymmetry
  - Unfold
  - Additionally: check of modeling and dependencies

$t\bar{t}$ 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



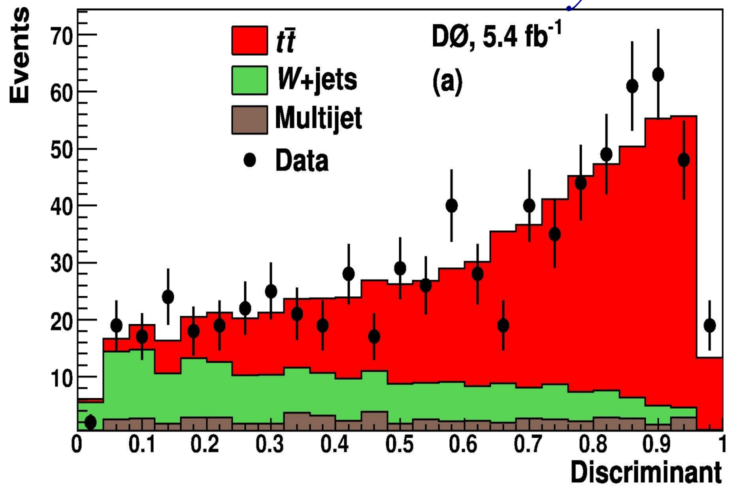


- Dilepton: also kinematic fitter, but more dof (2 neutrinos) → use a priori probability distributions as input, calculate probability (neutrino weighting)

Extract the raw Asymmetries

- Step 1: estimate background
  - DØ: Background fitted with likelihood discriminant
  - CDF: background estimate from MC

Discriminant with $\Delta y < 0$



Extract the raw Asymmetries

- Step 1: estimate background
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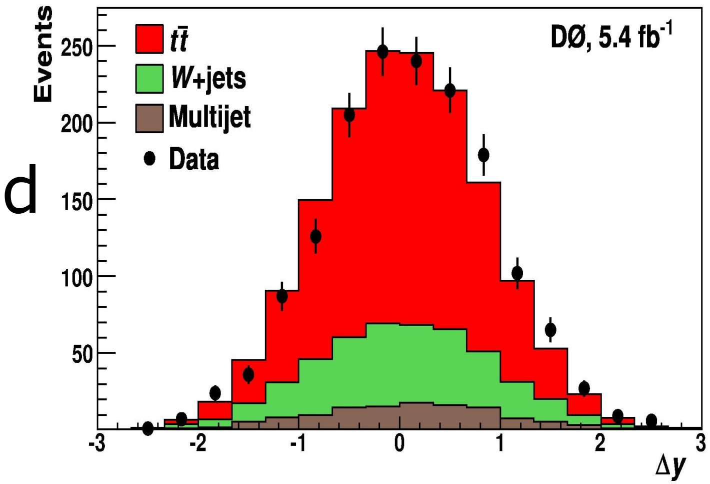
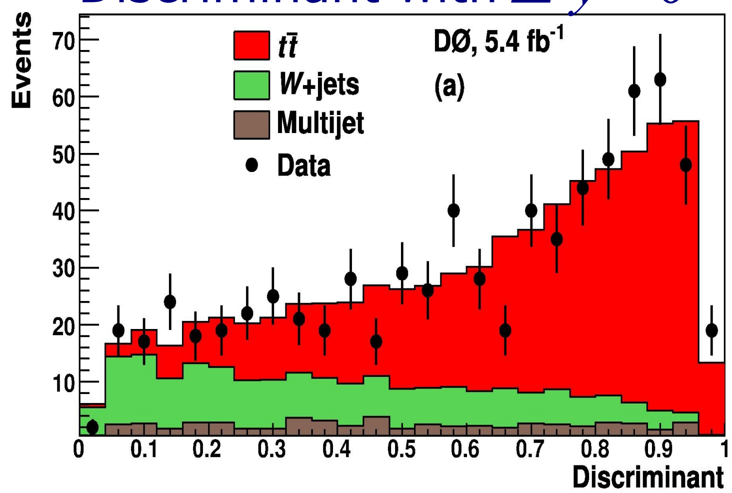
- Step 2: get Δy distribution and subtract background



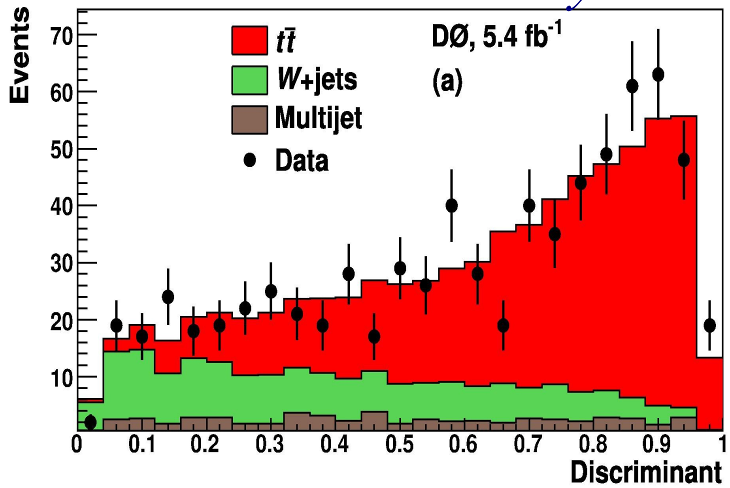
Discriminant with $\Delta y < 0$

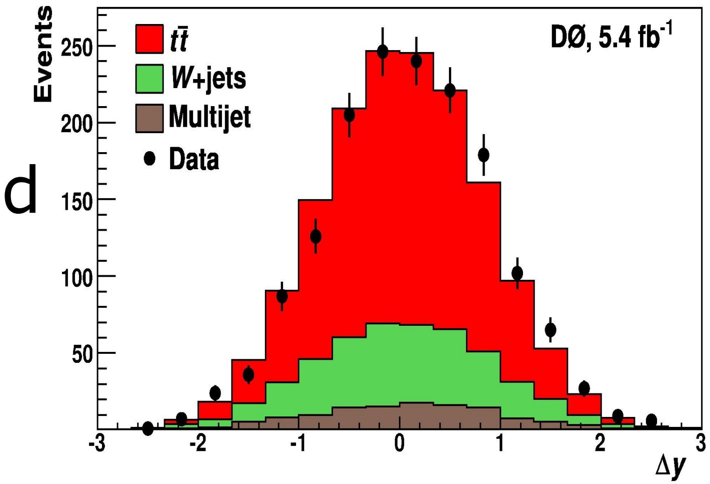


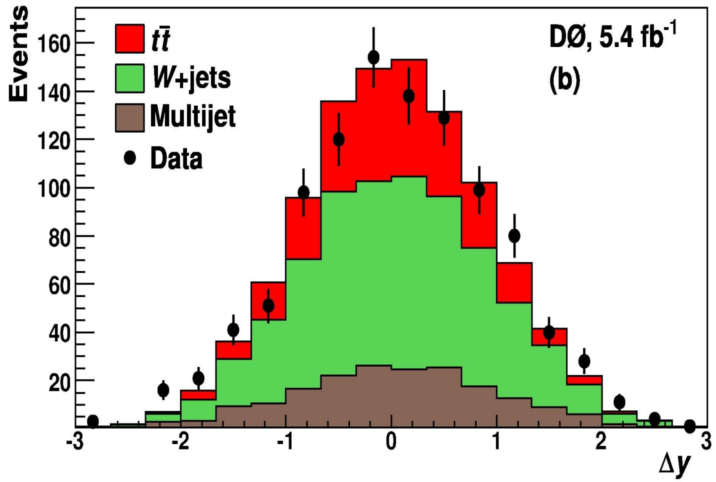
Extract the raw Asymmetries

- Step 1: estimate background
  - DØ: Background fitted with likelihood discriminant
  - CDF: background estimate from MC
- Step 2: get Δy distribution and subtract background
- Check modeling of background in background-dominated control samples

Discriminant with $\Delta y < 0$







Unfolding

- Detector and resolution effects
  - Smearing of true info
  - No direct comparison between results of different experiments and to theory predictions possible
- Unfolding: Correct for acceptance & resolution effects
  - Requires knowledge of the acceptance and detector resolution

Example from G. Cowan

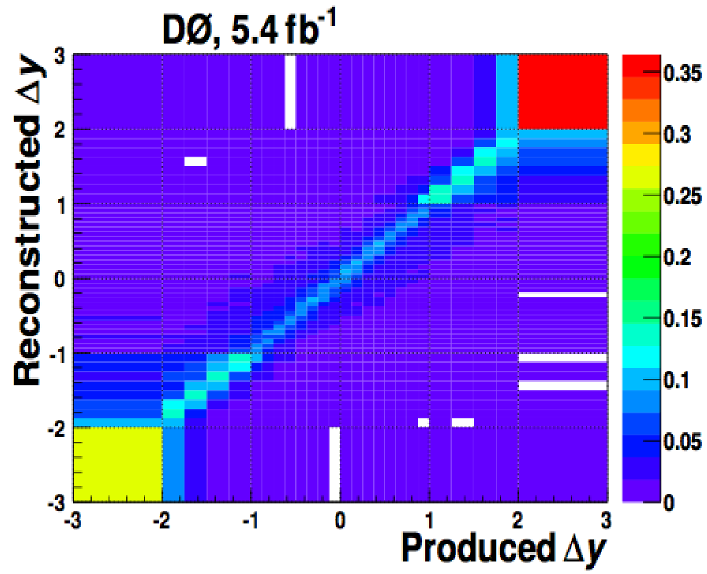
Unfolding

- Step 3: unfold the result to particle level
- CDF: 4 bin matrix inversion in y (edges: -3, -1, 0, 1, 3)

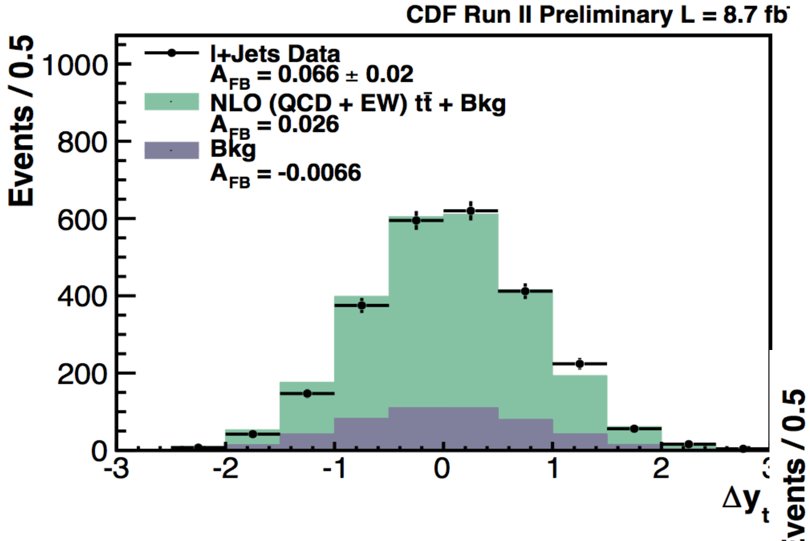
$$\vec{n}_{production} = A^{-1} S^{-1} \vec{n}_{reco}$$

  - A: (diagonal) acceptance matrix
  - S: migration matrix

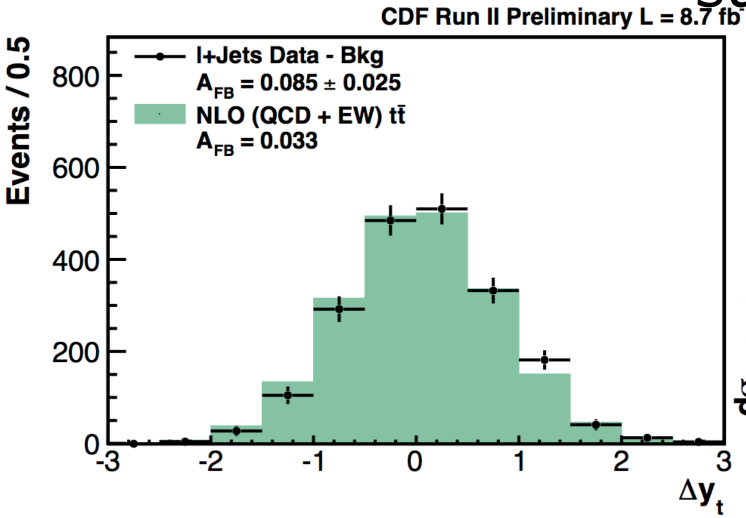
- DØ: regularized unfolding using TUnfold from ROOT
  - Regularization: "low pass filter" to filter out wild fluctuations
  - Better statistical strength than 4 bin matrix inversion



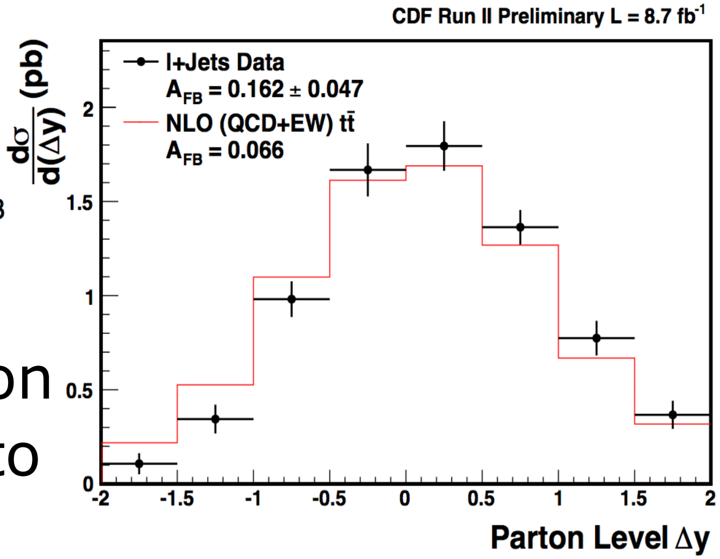
Post-Unfolding



1) Raw distribution before background subtraction



2) Raw distribution after background subtraction



3) Unfolded distribution (directly comparable to theory predictions)

Inclusive Asymmetries (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%

  - Statistically limited
- 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%)

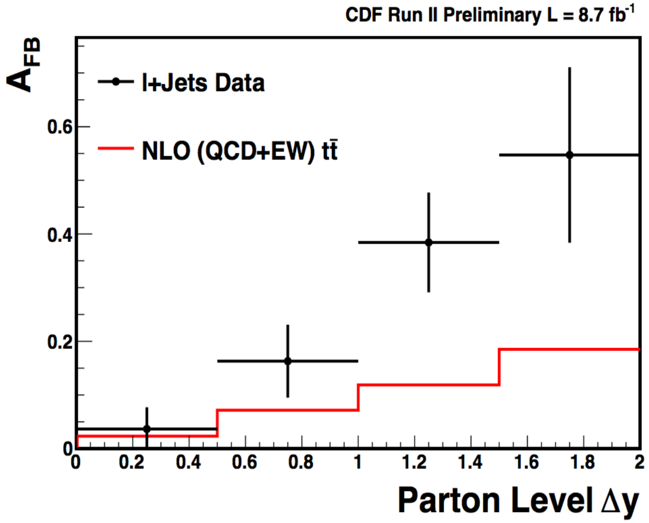
  → ~3 sigma away from prediction!
  - CDF: A_{FB}^{l}=6.6±2.5% (NLO (QCD+EW) prediction: 1.6%)

LHC results

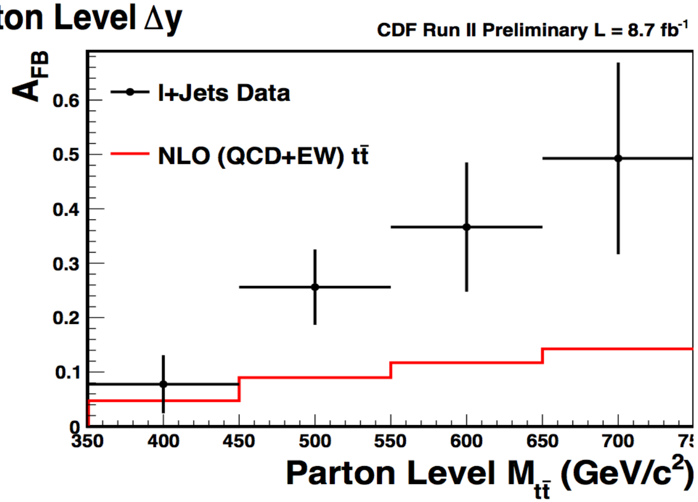
- Atlas: A_C=-0.019±0.028(stat) ±0.024(syst)
  - Consistent with MC@NLO prediction of 0.006±0.002
- CMS: A_C=0.004±0.010 (stat) ±0.012(syst)

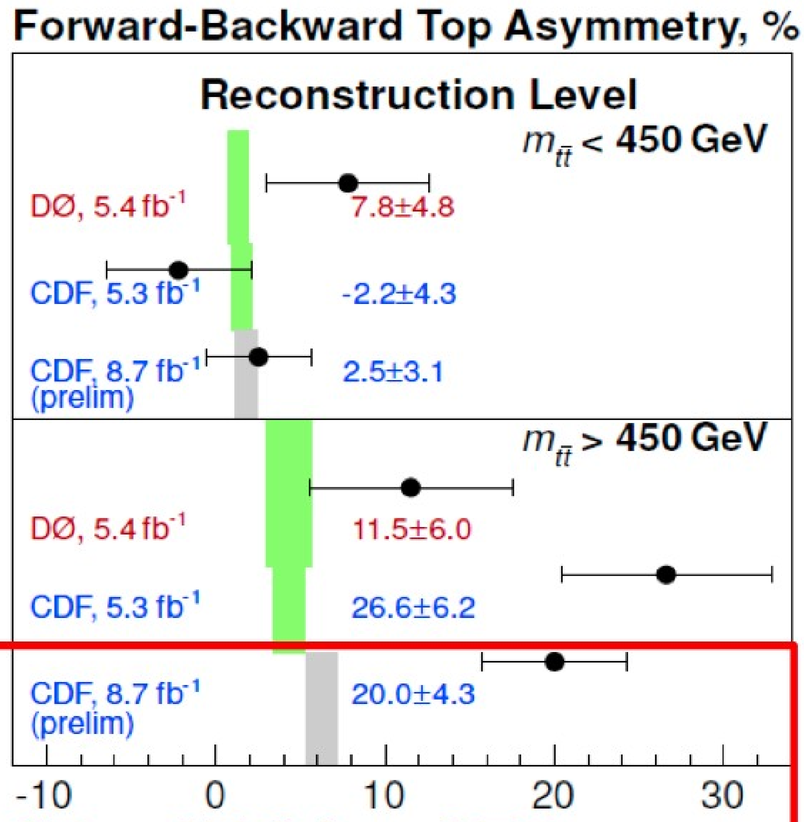
Dependencies

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



- No dependency seen at LHC

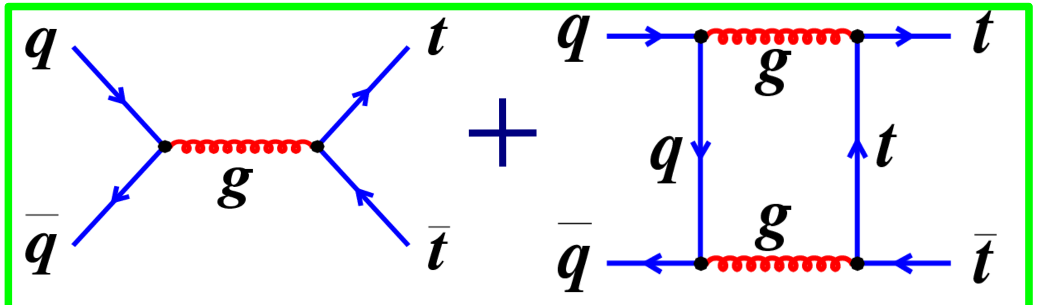




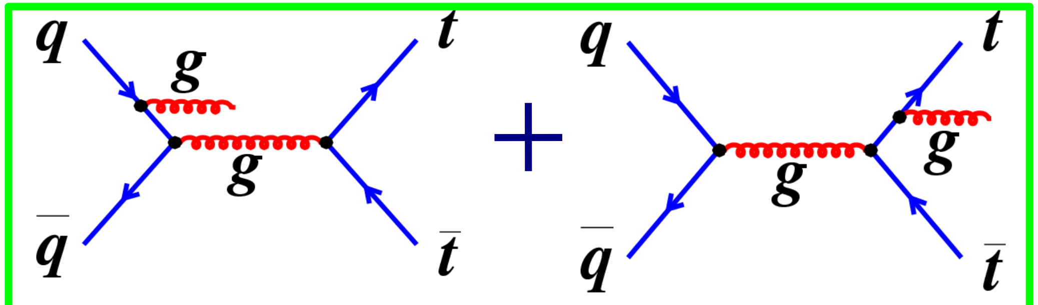
~2.8 SD to NLO inc. QED corr.

Modeling Issues

- Asymmetry measurement sensitive to several things
- Number of jets



Positive asymmetry

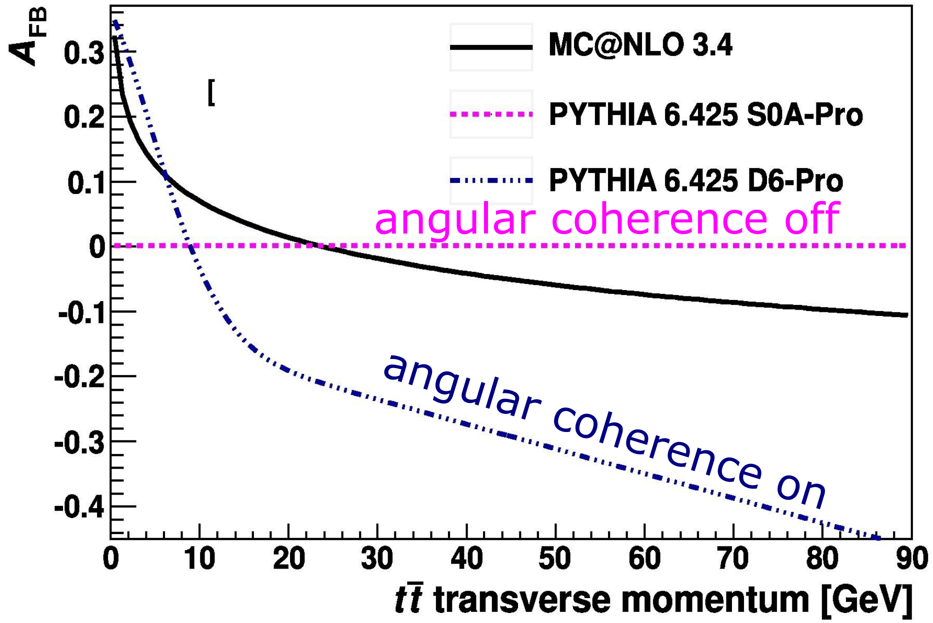


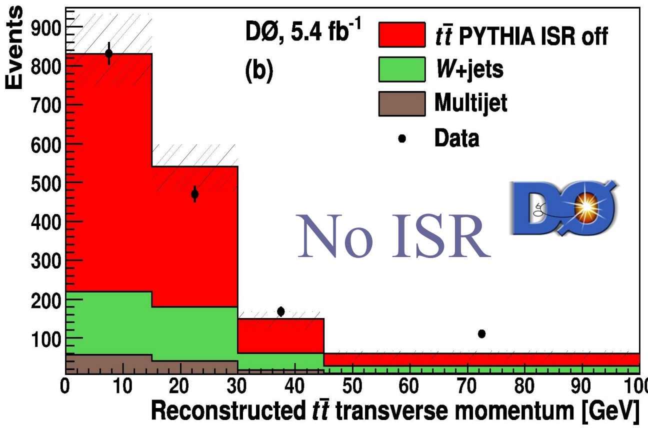
Negative asymmetry; additional jet!

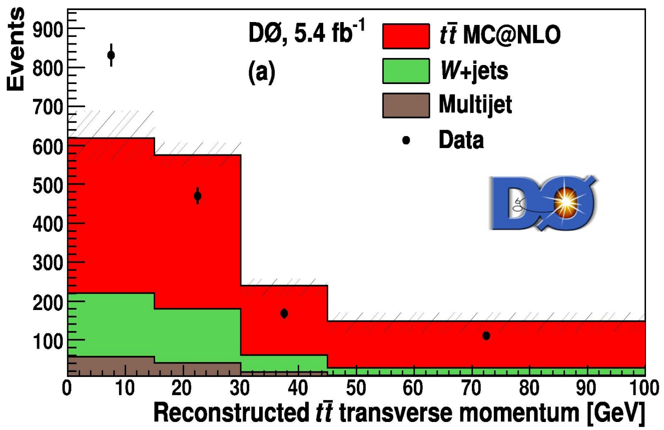
	$l+\geq4$ jets	$l+4$ jets	$l+\geq5$ jets
Raw $N_{\Delta y>0}$	849	717	132
Raw $N_{\Delta y<0}$	732	597	135
$A_{\rm FB}$(%)	9.2±3.7	12.2±4.3	-3.0±7.9
MC@NLO $A_{\rm FB}$ (%)	2.4±0.7	3.9±0.8	-2.9±1.1

Modeling Issues

- DØ: Noted a dependence on $p_T^{t\bar{t}}$
  - $p_T^{t\bar{t}}$: sensitive to additional radiation
- Switching angular coherence between top and initial parton shower on/off → different dependency
- Top pair p_T difficult to model in data







Discriminate New Physics Models

- What if the asymmetry is caused by physics beyond the SM?
  - Further measurements needed to distinguish the models
- Several ideas (by theorists) on further measurements
  - Enhance $q\bar{q}$ fraction at LHC with velocity cuts
  - Measure leptonic asymmetry (done already!)
    - Many models predict different behaviour of both
  - Measure asymmetry at threshold
    - Measure the relative contribution of $q_L\bar{q}_L$ and $q_R\bar{q}_R$ of $t\bar{t}$ production (at threshold)
      $\longrightarrow$ many models enhance one of these fractions
  - Top quark polarization

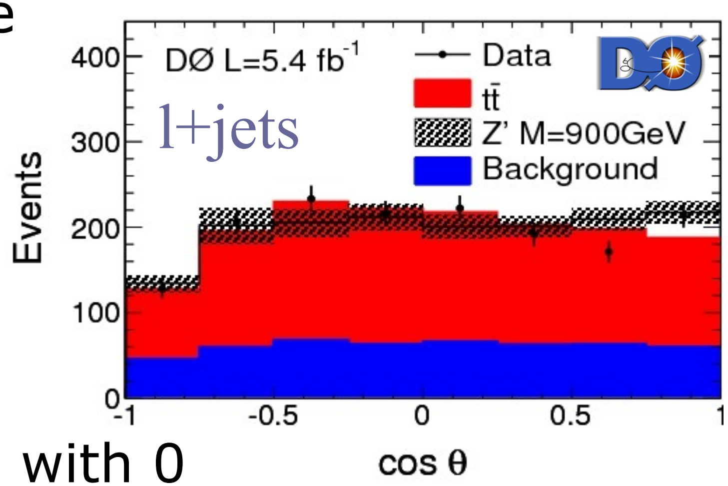
Top Polarization

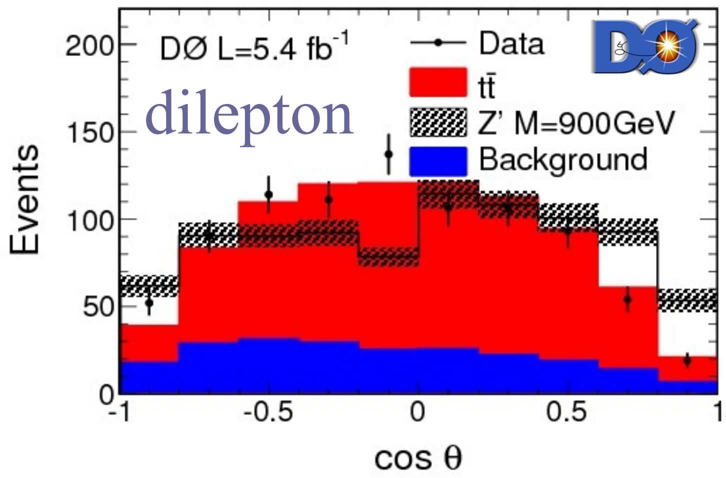
- Various BSM models predicting asymmetry>SM, predict also top polarization !=0

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

P_n: polarization; κ_i: spin analyzing power of decay product i; θ_i: direction of daughter wrt. chosen axis

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

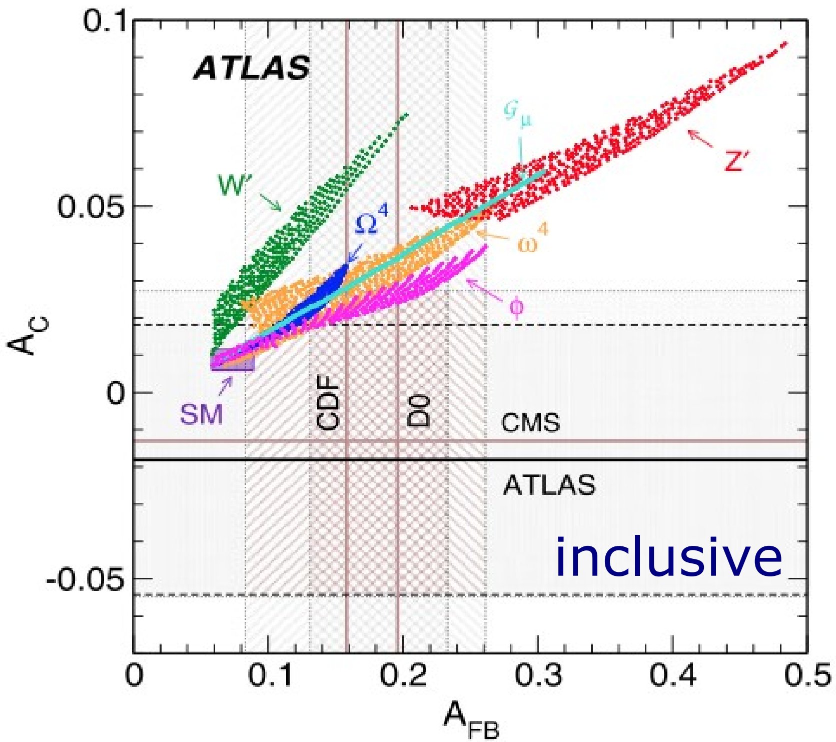


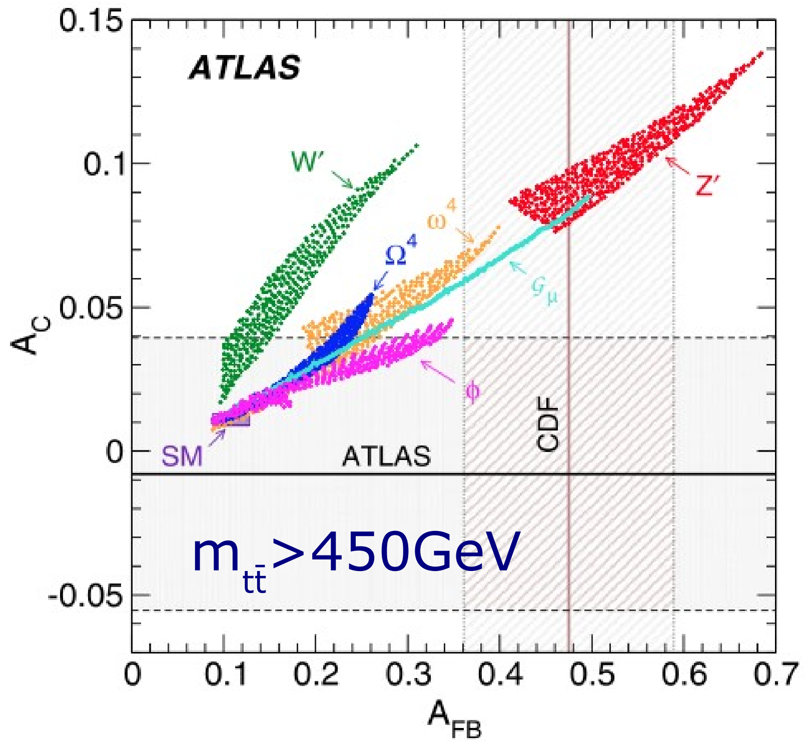


- CMS: measured polarization compatible with 0

Tevatron and LHC – Model consideration

- NP models can predict different asymmetry at Tevatron and LHC
- LHC measurements disfavor several models
  - Z': outside the measurement
  - Other models: tension with CDF's mass dependence





Summary Asymmetry

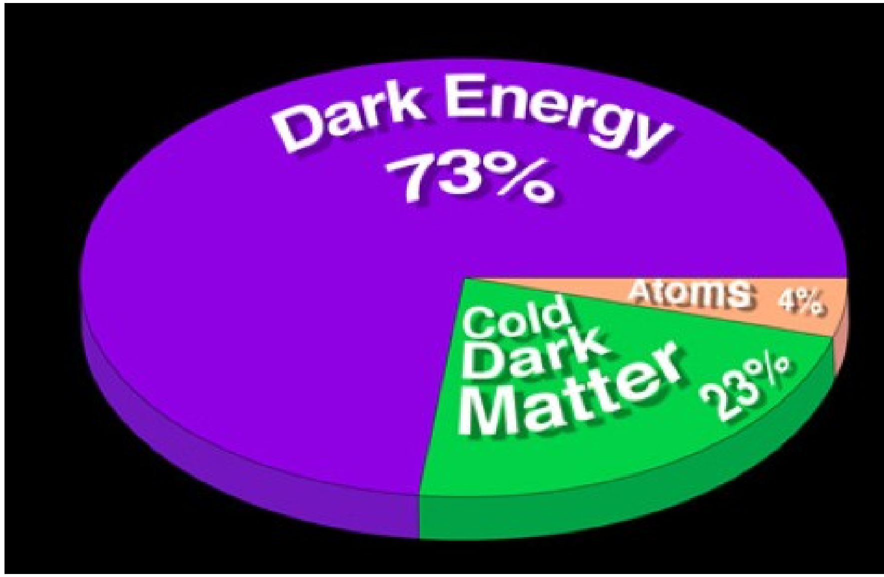
- Asymmetry: example for measurement deviating from SM
  - Excitement in experimental and theory community
- Deviation: Hint for new physics – or something else?
  - Missing parts in theory calculation?
  - Some modeling?
- Complementary measurements at Tevatron and LHC
  - No deviation seen at LHC
  - Exclusion of several models possible

Searches in the Top Sector

- Top quark heavy, large coupling to Higgs
  - Considered a special window to new physics
- A variety of direct searches have been performed in the top sector
  - t', Z', W', H^+, stop, FCNC, boosted top, $t\bar{t}H$,...
- A variety of methods is used
  - Classical "bump" searches (e. g. $t\bar{t}$ resonances)
  - Multivariate techniques ($t\bar{t}H$)
  - Checking for deviations from SM between different decay channels (H^+)

Example: Dark Matter Search at the LHC via $t\bar{t}+\not{E}_T$

- SM only describes ~4% of what the universe is made of
  - Most is dark energy and dark matter

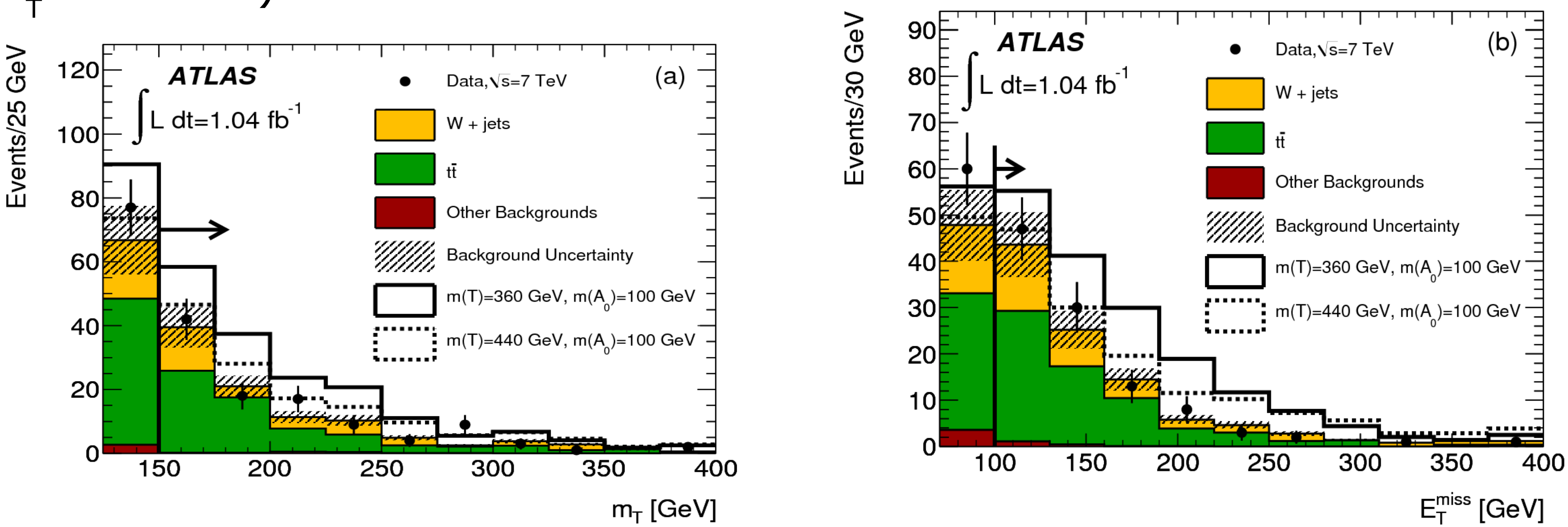


- Candidates for dark matter cold be some long lived particle, interacting weakly
  - Lightest SuSy particle (neutralino)

    $\rightarrow$ no interaction in the detector: large $\not{E}_T$
- Dark matter search example in the top sector: production of pair of exotic top partners T
  - T decaying into top and stable, neutral weakly interacting particle A_0
  - $pp \rightarrow T\bar{T} \rightarrow t\bar{t}A_0A_0$

Search in $t\bar{t}+\not{E}_T$

- Supersymmetric models: T is stop quark; A_0 the neutralino
  - Other model interpretation of this search possible
- Select events with $t\bar{t}$ l+jets final state
- Large $\not{E}_T$ (>100GeV) and large transverse mass of lepton and $\not{E}_T$ (m_T>150GeV)



Search in $t\bar{t}+\not{E}_T$

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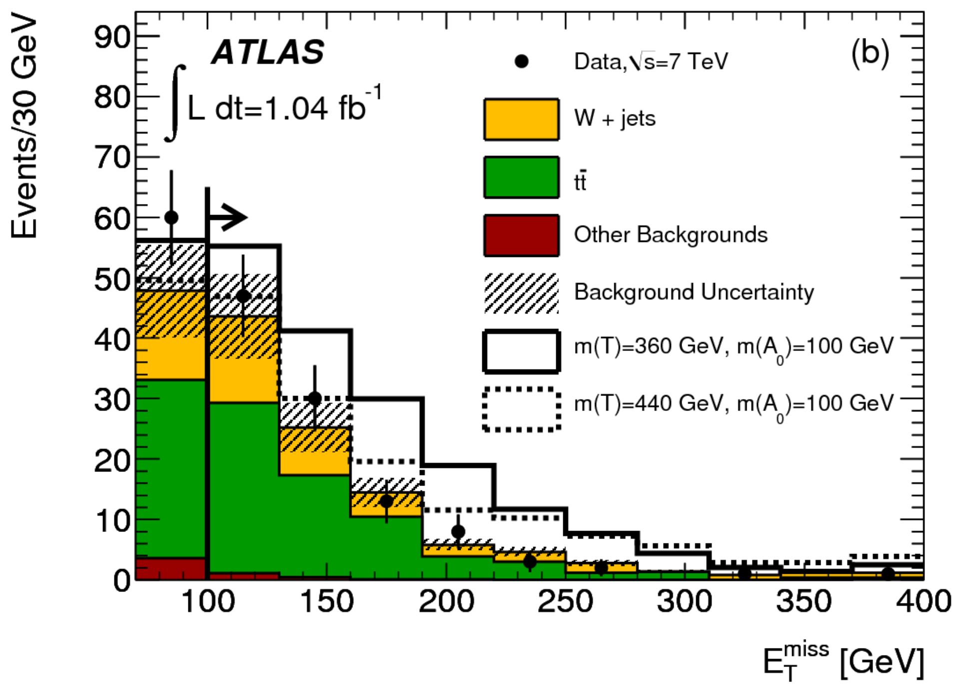
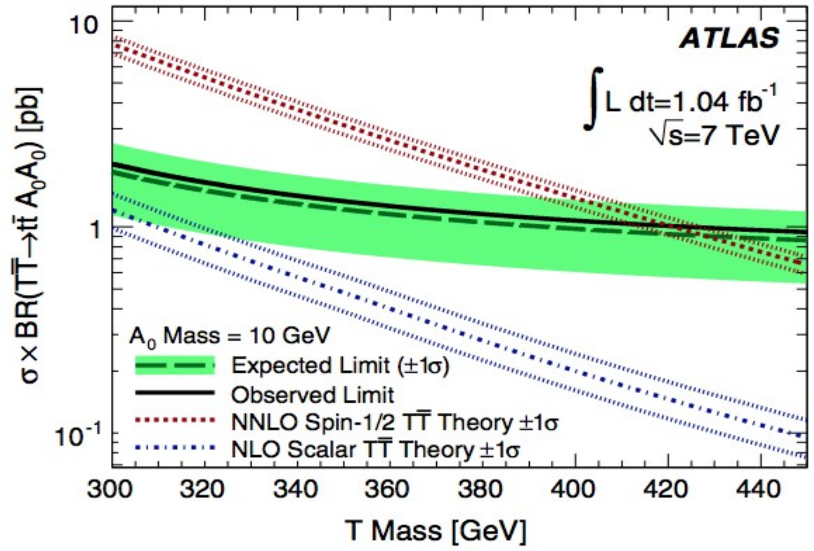
  - Other model interpretation of this search possible
- Select events with $t\bar{t}$ l+jets final state
- Large $\not{E}_T$ (>100GeV) and large transverse mass of lepton and $\not{E}_T$ (m_T>150GeV)
- Main background: SM $t\bar{t}$ events
  - e. g. if lepton misses acceptance of detector
- Check for various mass combinations of T and A_0
  - Grid of 300GeV≤m(T)≤450GeV and 10GeV≤m(A_0)≤150GeV

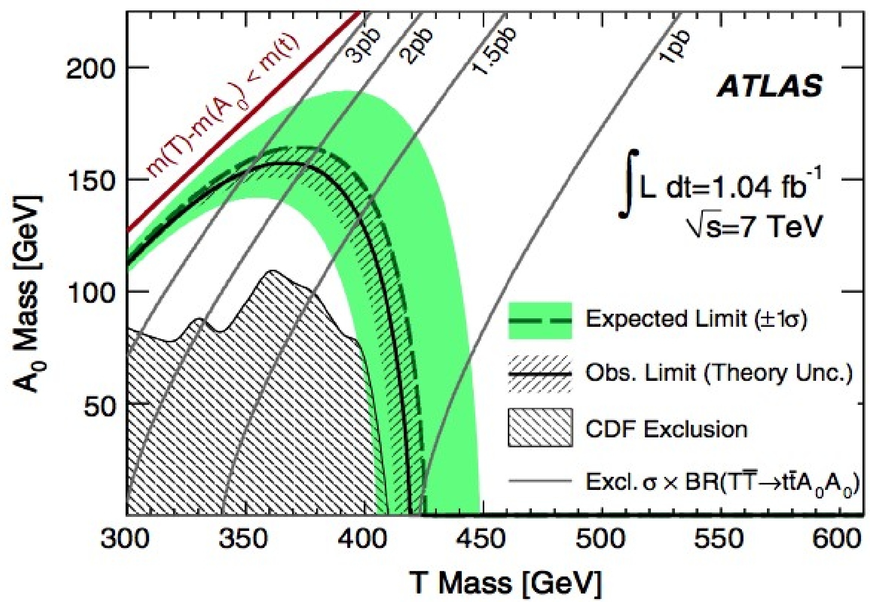


Limits

- No deviation from SM prediction can be seen → set exclusion limits
- Exclusion limits on cross section times Br($T\bar{T} \rightarrow t\bar{t}A_0A_0$)
  - 95% CL



- For spin-1/2 $T\bar{T}$ models: set limits on parameter space of T and A_0 mass



Summary

- Exciting times of top quark physics!
  - At all experiments
    (despite my biased selection purely based on where I have more direct insight)
- Even after Higgs discovery: still the heaviest known elementary particle
  - Special role in search for new physics
  - Top-Higgs Yukawa coupling important to measure
    (predicted to be ~1)
- LHC: top quark factory
  - Still a lot to explore 8-)

BACKUP

The Top Quark

- Heaviest known elementary particle:

$$m_t = 173.3 \pm 1.1 \text{GeV}$$

arXiv:1007.3178

- Standard Model:
  - Single or pair production
  - Electric charge +2/3 e
  - Short lifetime $0.5\text{x}10^{-24}$s
    - Bare quark - no hadronization
  - ~100% decay into Wb
  - Large coupling to SM Higgs boson