Forward-backward asymmetry in top-antitop production in proton-antiproton collisions

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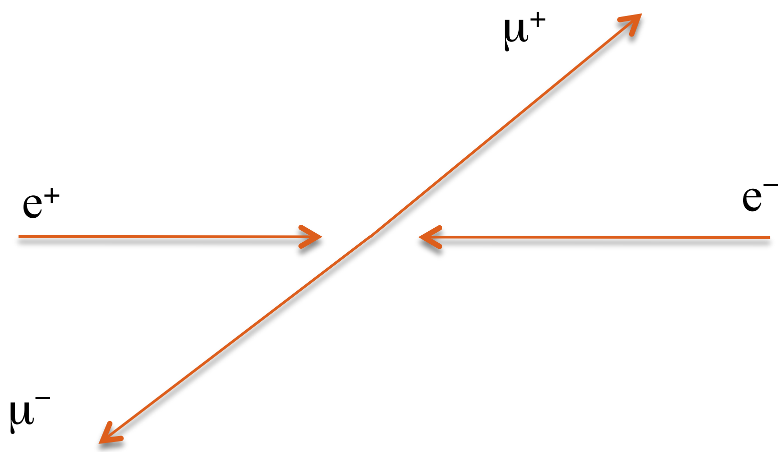
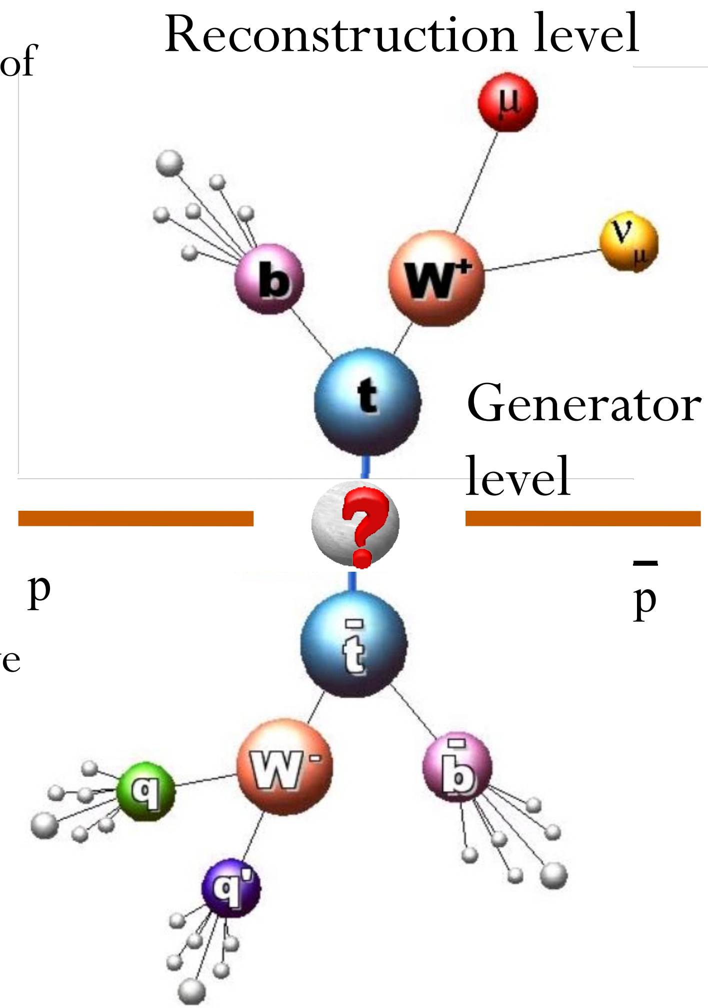
Asymmetry in top-antitop production

- In early 80s asymmetry observed in $e^+e^- \rightarrow \mu^+\mu^-$ at sqrt(s)=34.6 GeV<< M_Z was used to verify the validity of EW theory (Phys. Rev. Lett. 48, 1701–1704 (1982)



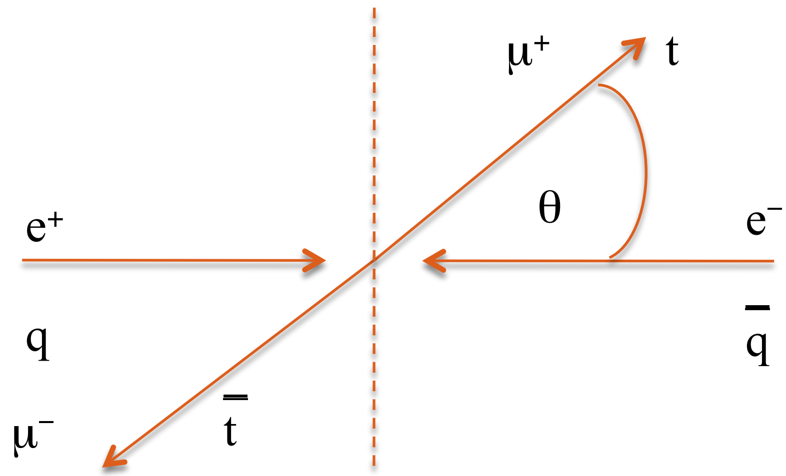


- Similarly, asymmetry in $p\bar{p} \rightarrow t\bar{t}$ production could give information about new physics
  - Mediator with axial coupling in s-channel
  - Abnormally enhanced t-channel production
- Complications:
  - Top is not observed directly, but reconstructed through its decay products
  - Proton and antiproton are not point-like objects, lab frame is different from rest frame

Definitions

- Asymmetry defined for ee→μμ

$$A = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$



- In proton-antiproton collisions θ→y
- *Δy* is invariant to boosts along *z*-axis

$$\Delta y = y_t - y_{\bar{t}} = q_l(y_{leptonic} - y_{hadronic})$$

- Asymmetry based on Δy is the same in lab and tt rest frame

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

- Asymmetry based on rapidity of lepton from top decay
  - Lepton angles are measured with a good precision

$$A_l = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

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History of measurements and predictions

D0, reconstruction level

- PRL 100, 142002(2008) $A(0.9\,fb^{-1}) = (12 \pm 8)\%$
- ICHEP2010 $A(4.3\,fb^{-1}) = (8 \pm 4)\%$

$$A(MC@NLO) = (0.8 \pm 1)\%$$

CDF, generator level

- PRL 101, 202001(2008) $A(1.9\,fb^{-1}) = (24 \pm 14)\%$
- Phys. Rev. D 83,112003 (2011) $A(5.3\,fb^{-1}) = (15.7 \pm 7.4)\%$

$$A(MC@NLO) = (5.0 \pm 0.1)\%$$

Reconstruction of top-antitop signal

Require :

$\rightarrow$1 lepton with $p_T > 20 GeV$

$\rightarrow \not{E}_T > 20 GeV$

$\rightarrow \geq 4$ jets with $p_T > 20 GeV$

$\rightarrow$leading jet with $p_T > 40 GeV$

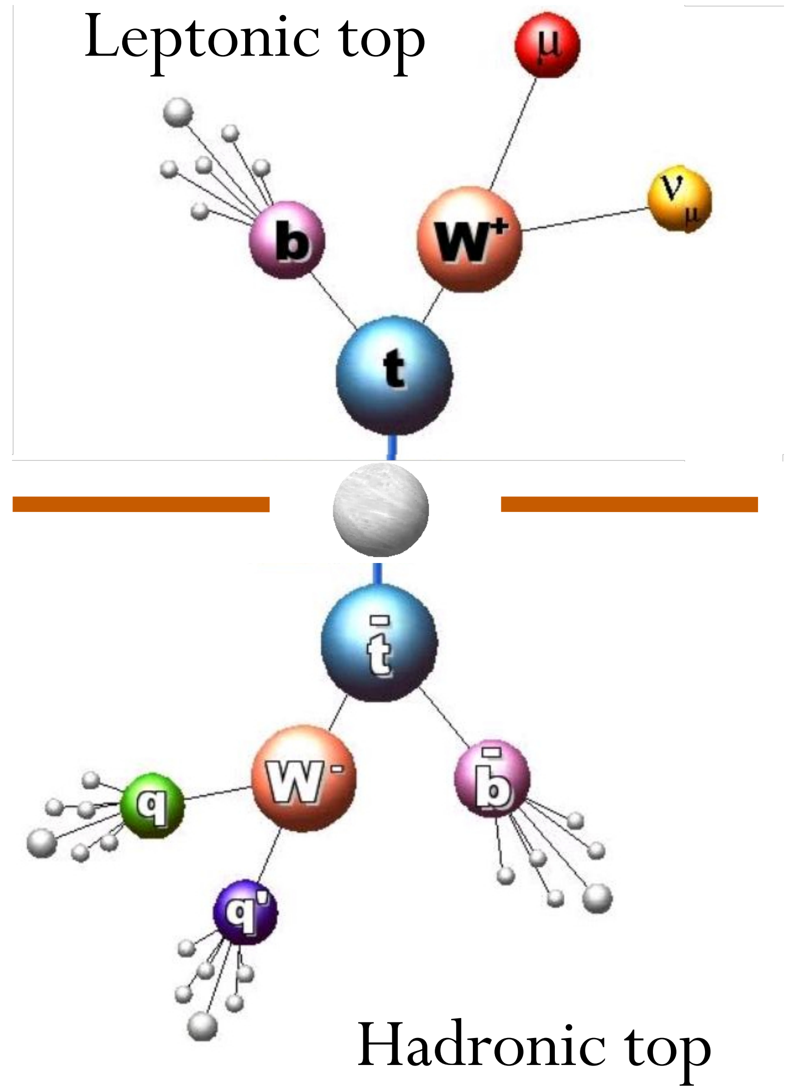
$\rightarrow \geq 1$ b - tag

$\rightarrow$In kinematic fit constrain

$-M_W = 80.4 GeV$

$-M_t = 172.5 GeV$

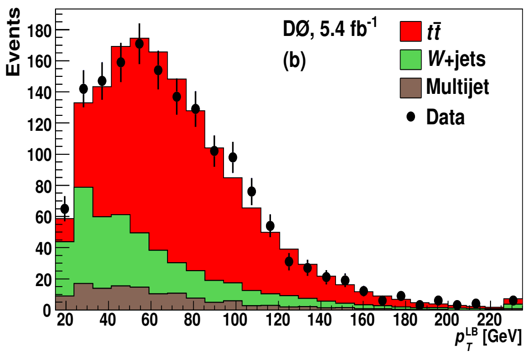
$\rightarrow$Charge of lepton determines which reconstructed quark is top



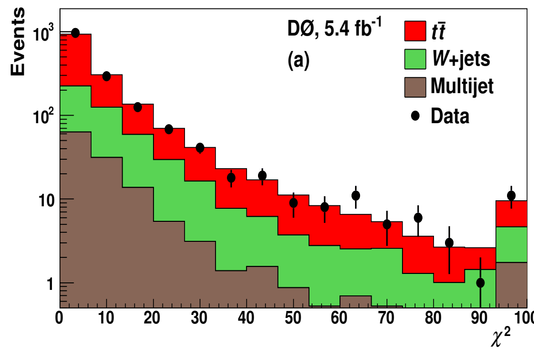
1581 events pass the selection requirements in 5.4 fb^{-1}

Asymmetry at reconstruction level

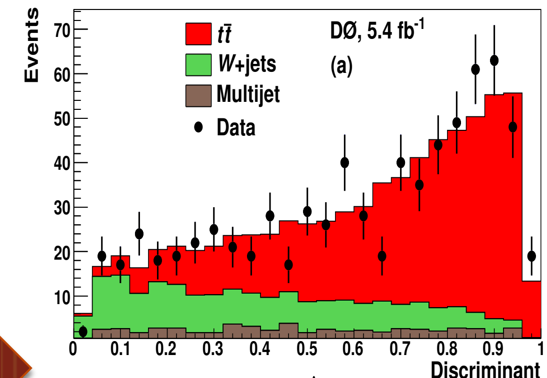
- Using kinematic variables of *l+jets* events construct a discriminant and fit events with $\Delta y>0$ and $\Delta y<0$ for top fraction



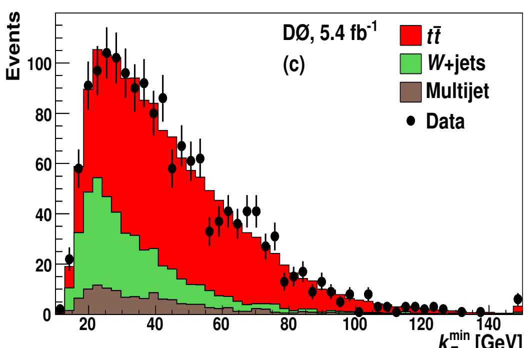
Leading b-jet p_T



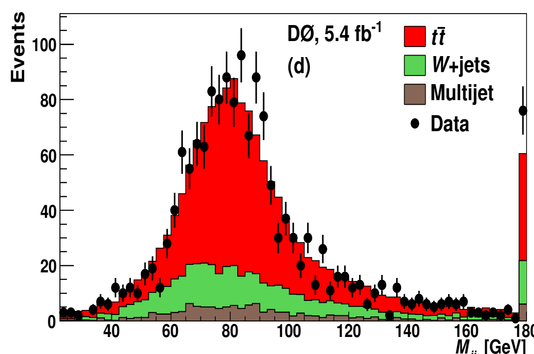
χ^2 of kinematic fit



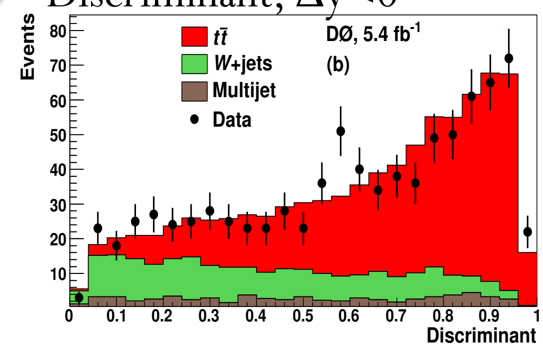
Discriminant, $\Delta y<0$



$k_T$min



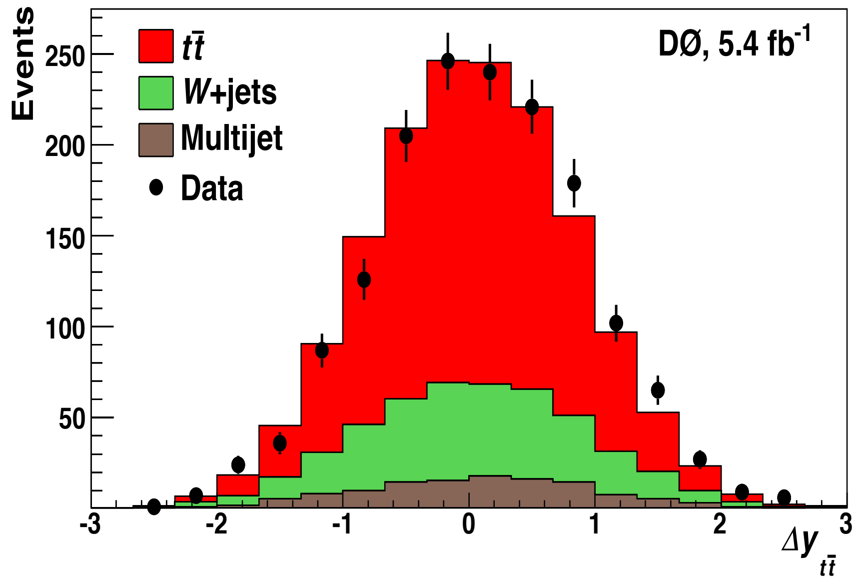
M_{jj}

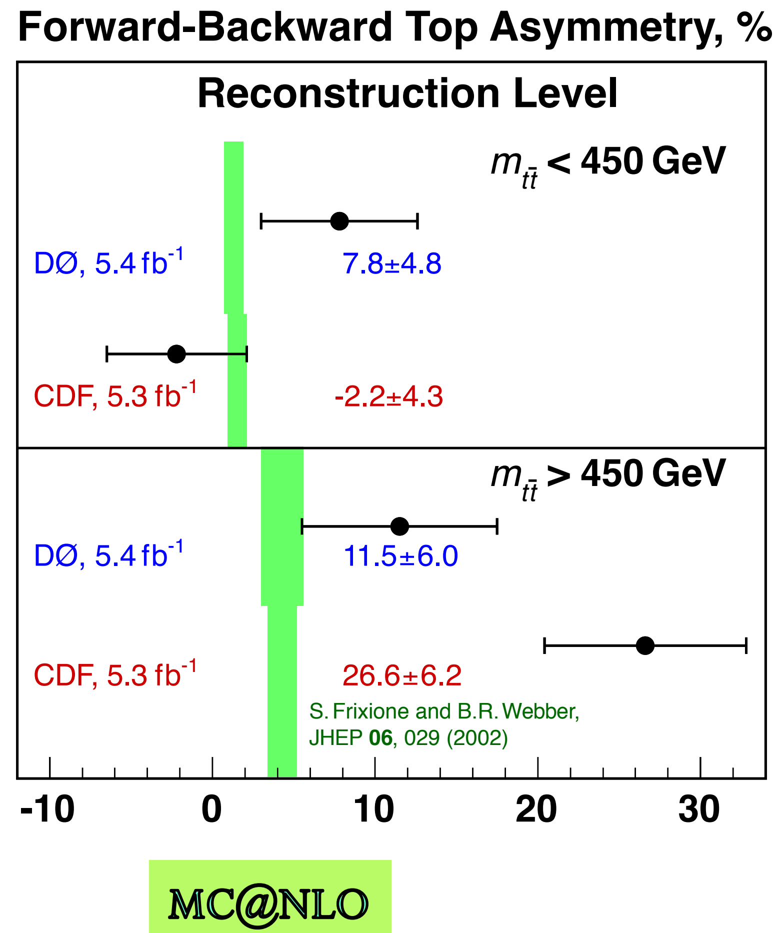


Discriminant, $\Delta y>0$

$$A = (9.2 \pm 3.6^{+0.8}_{-0.9})\% \Leftrightarrow A(MC@NLO) = (2.4 \pm 0.3^{+0.7}_{-0.5})\%$$

Asymmetry dependence on M_{tt}





$$A = (9.2 \pm 3.6^{+0.8}_{-0.9})\%$$

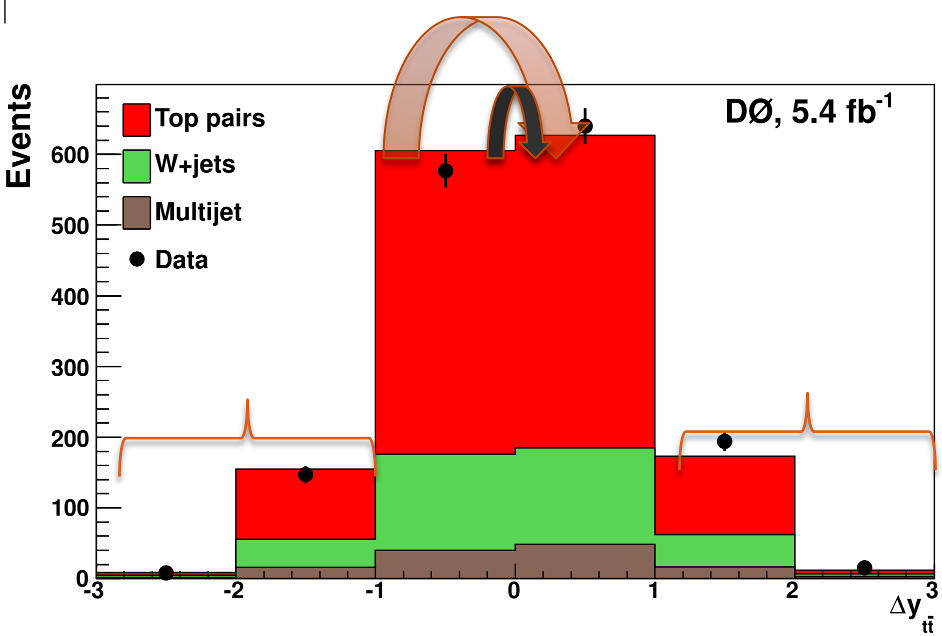
$$A(MC@NLO) = (2.4 \pm 0.3^{+0.7}_{-0.5})\%$$

Generated asymmetry

- "Unfolding" =correcting for acceptance (A) and detector resolution (S)
- **Method 1**: 4 bin Likelihood unfolding :

$$\vec{n}_{reco} = SA\vec{n}_{gen} \Rightarrow \vec{n}_{gen} = A^{-1}S^{-1}\vec{n}_{reco}$$

$$\Rightarrow A = (16.9 \pm 7.7^{+1.8}_{-2.6})\%$$



Problem with Method 1: migration of events near inner bin edge (Δy→0) is underestimated, while for the outer edge it is overestimated

Solution: *fine* bins closer to Δy=0

Problem: statistical fluctuations in data make the fine bin unfolding unstable

Solution: employ ***regularization***

Bonus: reduced statistical uncertainties

Method 2: fine bin unfolding with regularization

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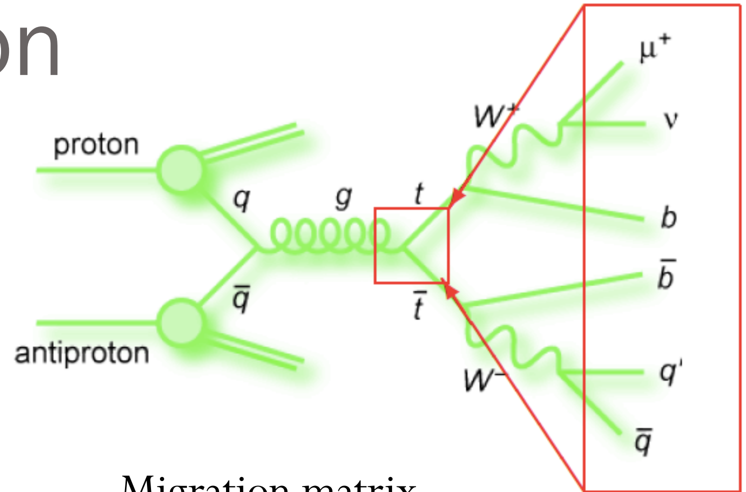
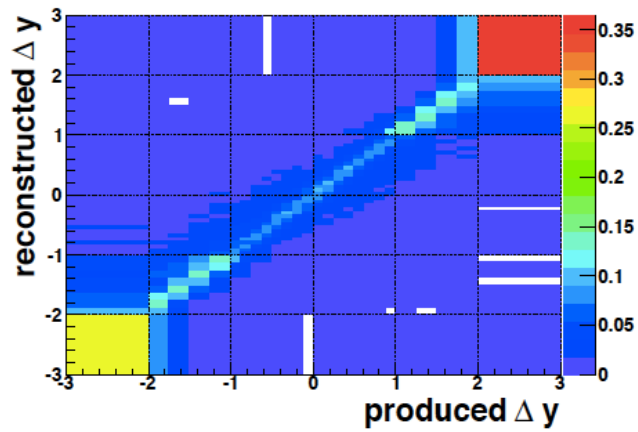


$$A_{reco} = (9.2 \pm 3.6^{+0.8}_{-0.9})\%$$

Migration matrix



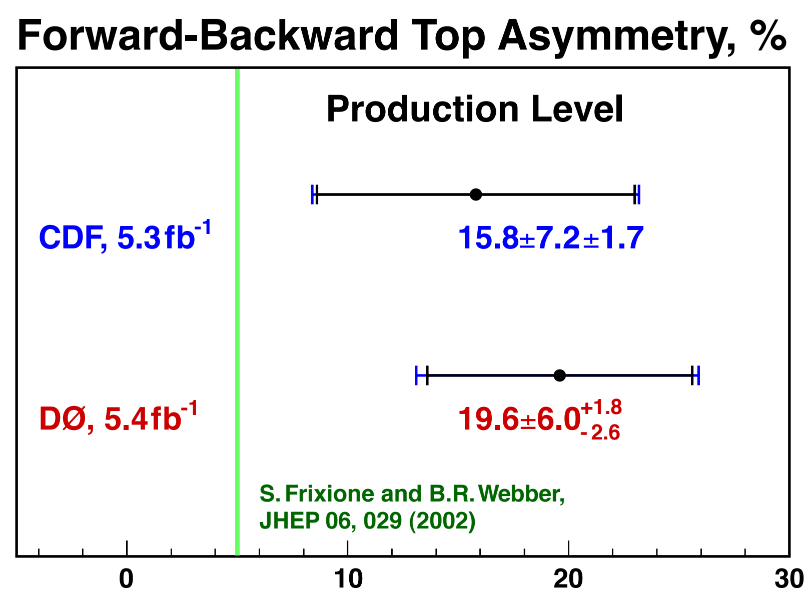
$$A_{gen} = (19.6 \pm 6.0^{+1.8}_{-2.6})\%$$

Results for asymmetry, in %

- Reconstruction level (experiments cannot be directly compared, only to Monte Carlo after reconstruction and selection)
  - D0 (5.4 fb^{-1}) $9.2 \pm 3.6^{+0.8}_{-0.9}$
  - MC@NLO (D0) $2.4 \pm 0.3^{+0.7}_{-0.5}$
  - CDF (5.3 fb^{-1}) 7.5 ± 3.7
  - MC@NLO (CDF) 2.4 ± 0.5
- Generator level

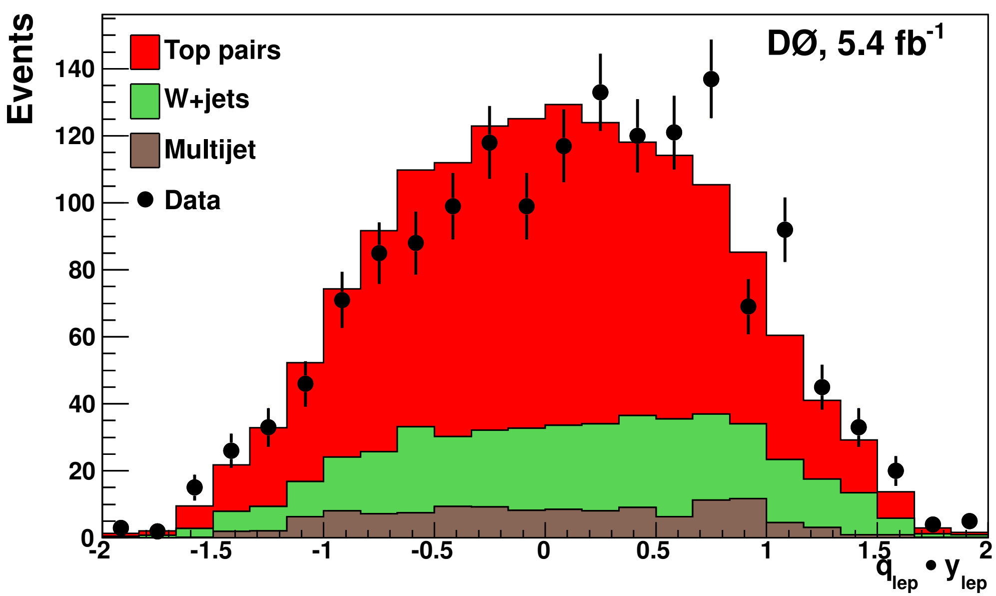
(experiments can be directly compared)

  - D0 $19.6 \pm 6.0^{+1.8}_{-2.6}$
  - CDF $15.8 \pm 7.2 \pm 1.7$
  - MC@NLO 5.0 ± 0.1



Lepton-based asymmetry, in %

- Since lepton direction is defined with a very good precision, lepton based asymmetry is simpler to extract
- Lepton from top decay carries information about underlying asymmetry at production
- Can be directly compared to theoretical predictions



Reconstruction level

$$A_l = 14.2 \pm 3.7 \pm 0.7$$

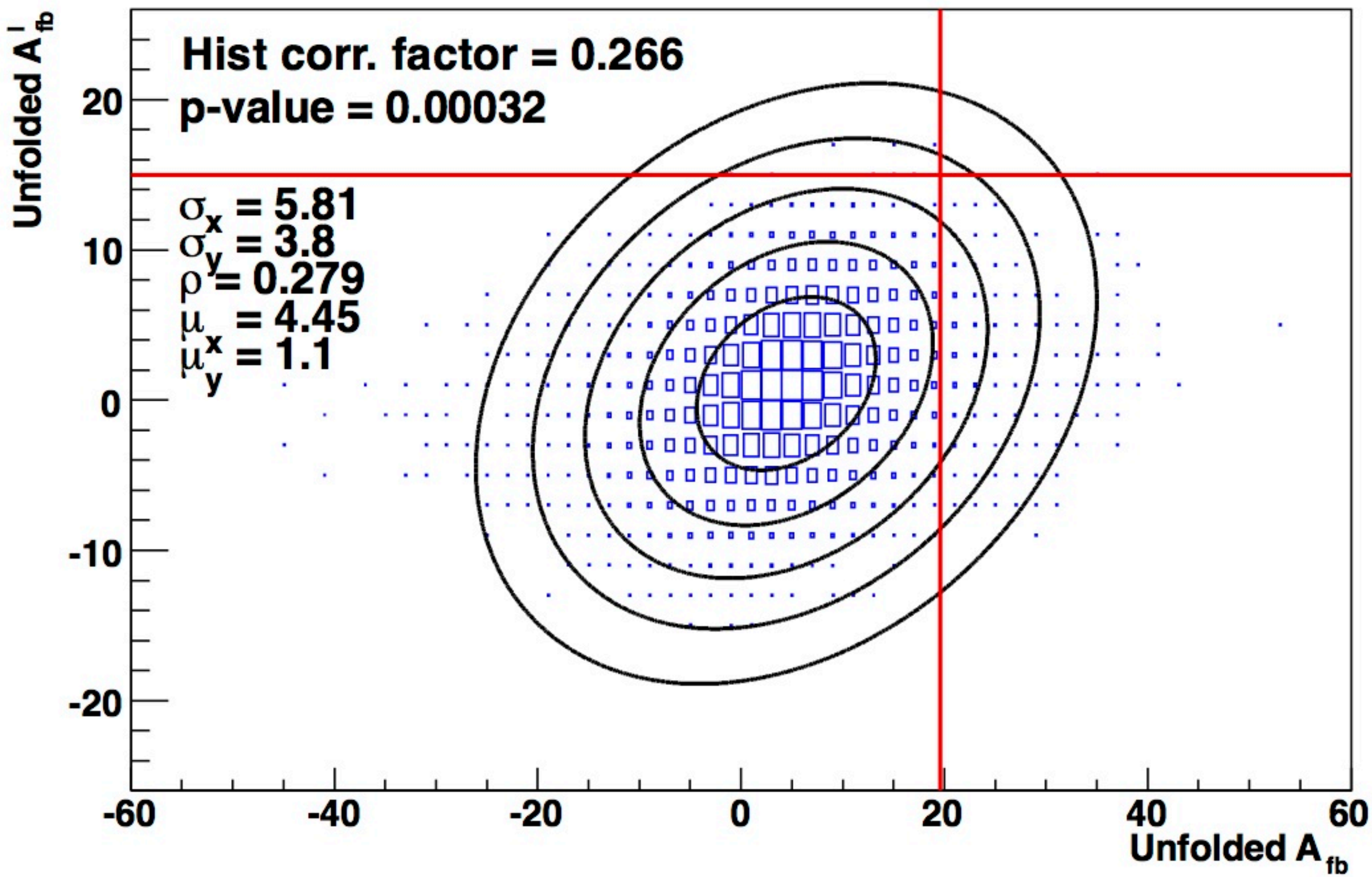
$$A_l(MC@NLO) = 0.8 \pm 0.3 \pm 0.5$$

Generated level

$$A_l = 15.2 \pm 3.8^{+1.0}_{-1.3}$$

$$A_l(MC@NLO) = 2.1 \pm 0.1$$

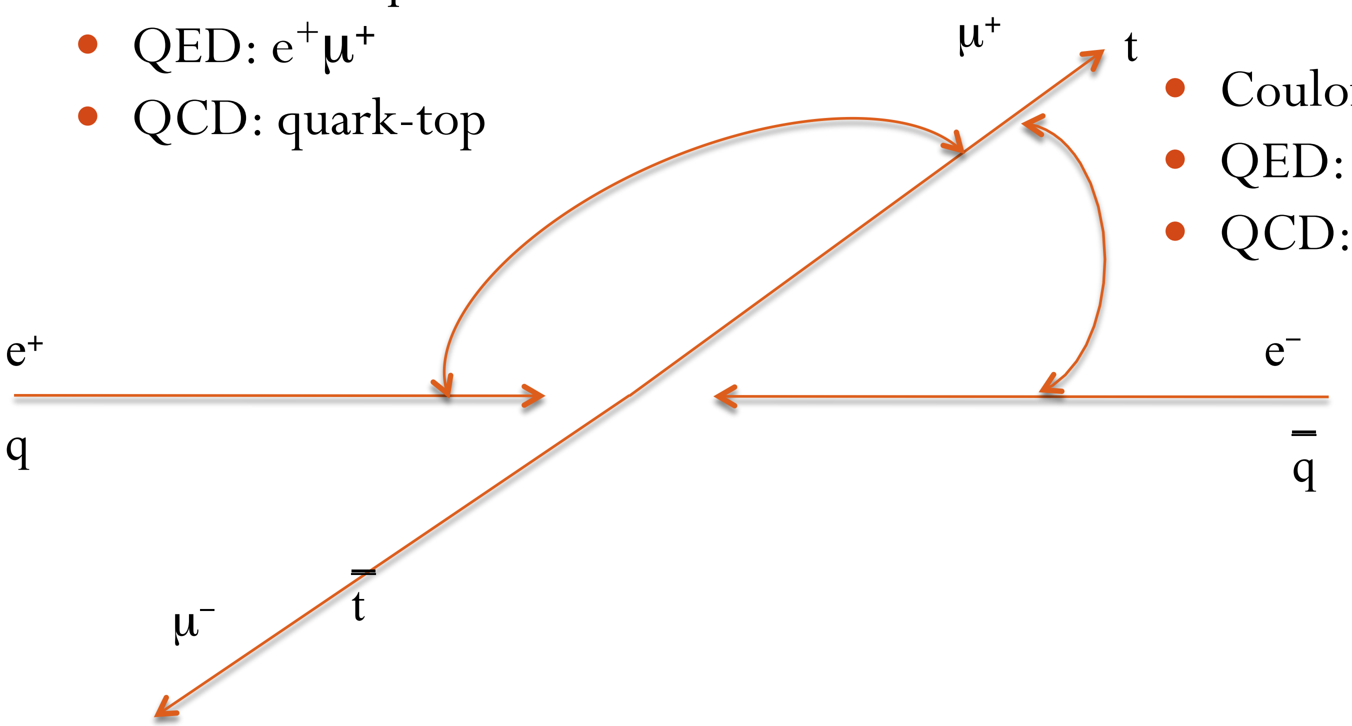
Unfolded A_{FB}^{lep} vs A_{FB}



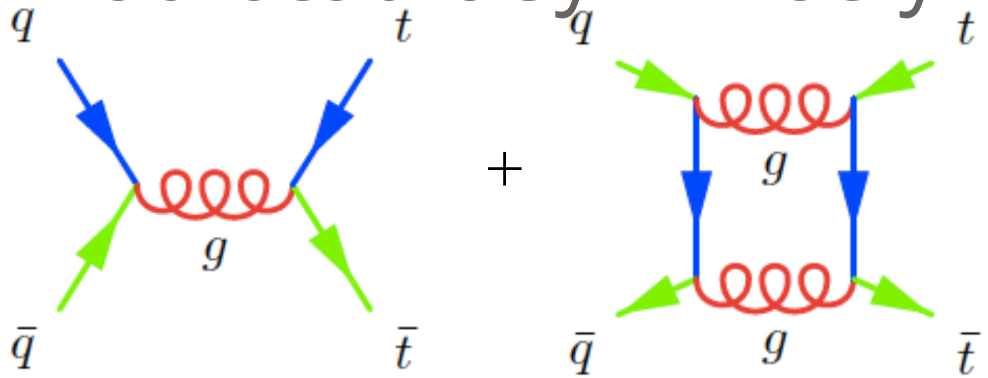
Interpretation of the Asymmetry

- Coulomb repulsion
- QED: $e^+\mu^+$
- QCD: quark-top

- Coulomb attraction
- QED: $e^-\mu^+$
- QCD: antiquark-top



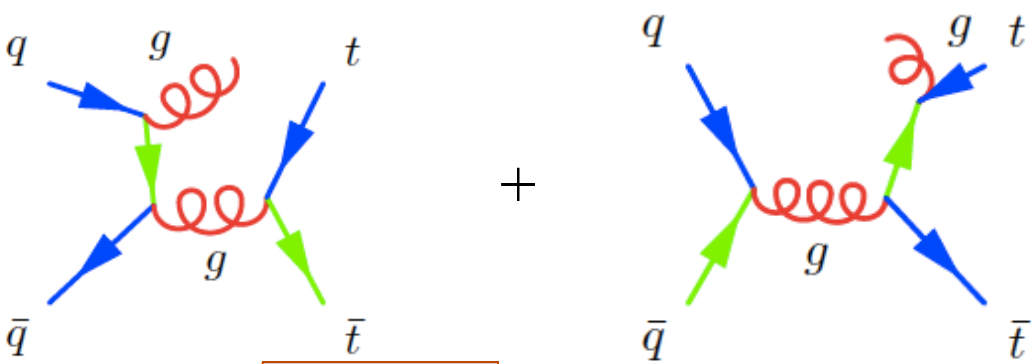
Predicted asymmetry in SM



$l + 4\ jets$

$data: 12.2 \pm 4.2\%$

$MC@NLO: 3.9 \pm 0.3\%$



$l + \geq 5\ jets$

$data: -3.0 \pm 7.8\%$

$MC@NLO: -2.9 \pm 0.7\%$

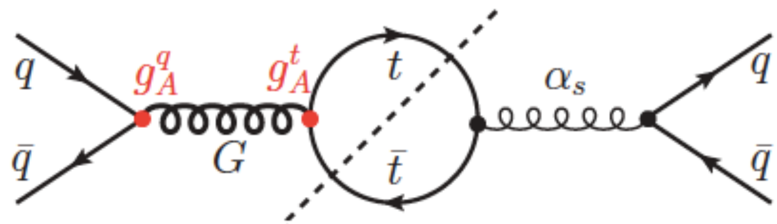
Born(α_s^2) and box(α_s^4)

- Coulomb-like repulsion of top and quark and attraction of antitop and quark in QCD
- Interference – α_s^3
- Positive asymmetry
- Final state with no extra partons → small transverse momentum of the tt system

ISR (α_s^3) and FSR(α_s^3)

- Interference – α_s^3
- Negative asymmetry
- Final state with extra gluons →large transverse momentum of the tt system
- Possible extra jets

S-channel: color-octet vectors (axigluons)



Axigluon contributions to $t\bar{t}$ production

$$\sigma_a^{\mathrm{INT}} \sim g_A^q\, g_A^t \frac{1}{M_{t\bar{t}}^2 - M_G^2}\,, \qquad \sigma_s^{\mathrm{NP}} \sim (g_A^q)^2 (g_A^t)^2 \frac{M_{t\bar{t}}^2}{(M_{t\bar{t}}^2 - M_G^2)^2}\,.$$

A positive charge asymmetry $\sigma_a^{\mathrm{NP}} > 0$ requires

- $M_G > M_{t\bar{t}}$: flavor non-universal axigluon couplings,
- $M_G < M_{t\bar{t}}$: flavor universal axigluon couplings.

Upper limit on $|g_A^q\, g_A^t|/M_G^2$: effect on total cross section $\sigma_{t\bar{t}} \sim \sigma_s^{\mathrm{NP}}$ and resonance in spectrum $d\sigma_{t\bar{t}}/dM_{t\bar{t}}$.

Experimental constraints on axigluons

- Indirect
  - D-mixing M_G>200GeV
  - EW precision (Zbb, Γ_Z, σ_{had}) M_G>500GeV
- Direct – dijet resonances

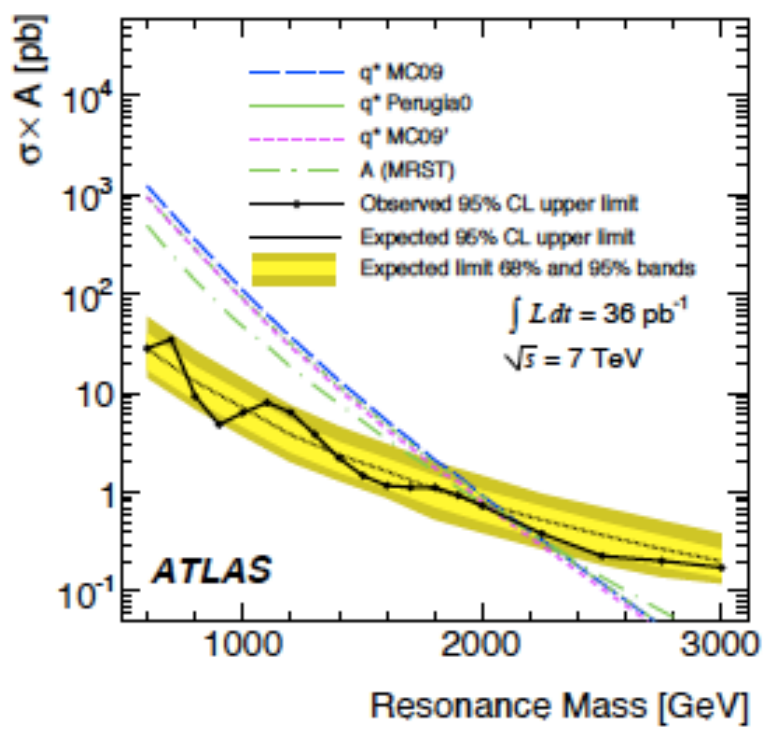
  LHC pp→G→2 jets

Atlas M_G>2TeV (**Γ/M<15%**)

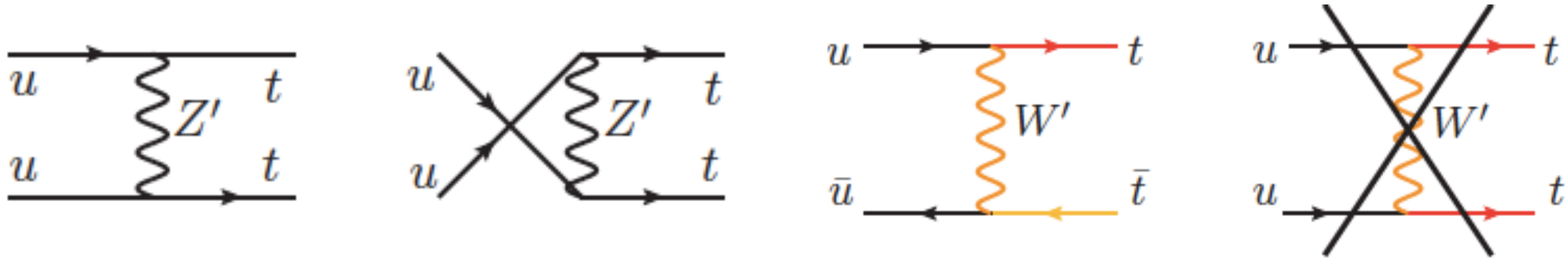
From angular distribution

M_G>1.7TeV

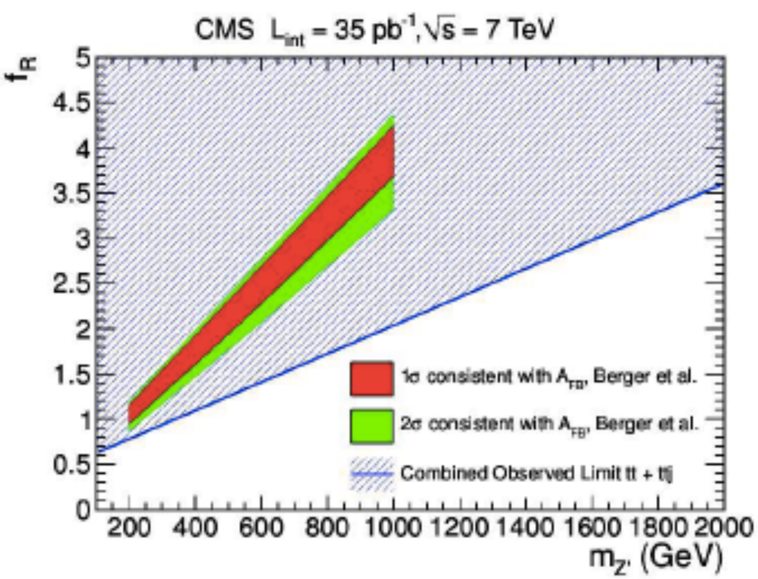
Caveat: limits are probably not applicable for low mass (<400GeV) and large width



t-channel: Z', W'



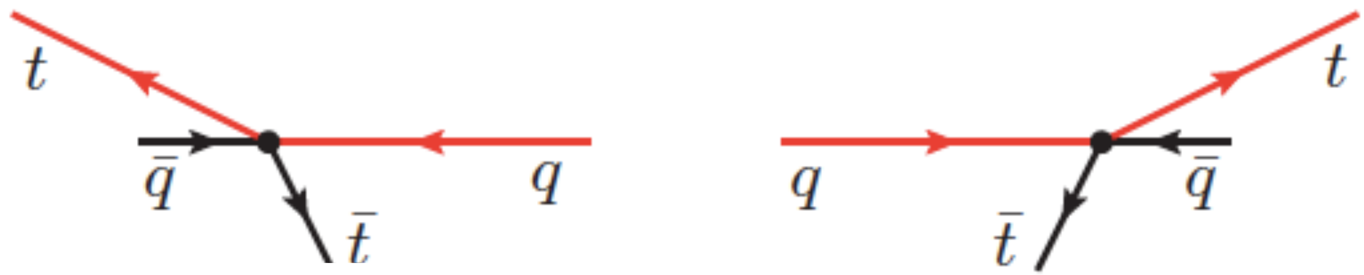
Direct constraint :
from like-sign tops at LHC

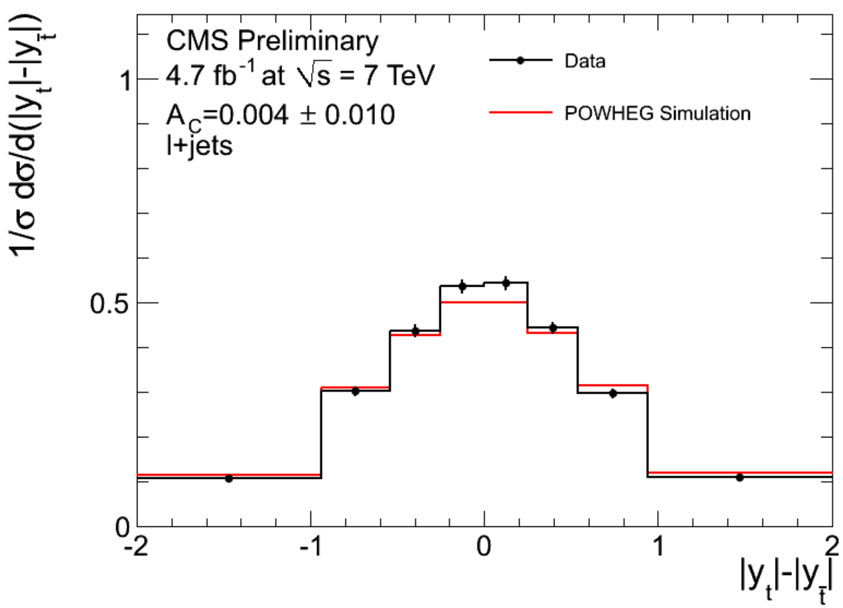


- Introduce $SU(2)_X$ that places $(u\ t)_R$ in the same doublet
- W' carries "top number" thus suppressing like-sign top production at LHC
- Predicted asymmetry due to W' ~30%
  - More forward than SM or s-channel production
  - As a result observed asymmetry reduced to 20%
- Least constrained by other experimental data, asymmetries in agreement with observed
- Test this hypothesis by using top polarization

How to compare to charge asymmetry at LHC

- 2 problems compared to Tevatron:
  - Large fraction of top pairs (~90%) are produced in gluon fusion
  - Direction of quark (vs antiquark) is determined from the boost with ~70% accuracy
  - Naively, **20% asymmetry at Tevatron** corresponds to **0.8% asymmetry at LHC**
    - But need relevant models to extrapolate predictions.





A (CMS, 4.7 fb^{-1})= 0.4 +- 1.0 (stat.) +- 1.2 (syst.)% = 0.4+-1.6%
***A*(Atlas, 0.7 fb^{-1})=−2.4±1.6 (stat) ±2.3 (syst)%=-2.4+-2.8%**

These results are completely consistent with the corresponding the asymmetry measured by Tevatron.

A word of caution about systematics on the prediction

- How well do we know the production mechanism of top pair in pp?
- gg vs qqbar fractions depend strongly on gluon pdf at high x

$$F^{q\bar{q}}(x) = 1 - F^{gg}(x)$$

- Since qqbar fraction is only ~10% of gg, 10% uncertainty on gg fraction corresponds to a factor of two uncertainty on F_{qq}
- Uncertainty on expected observed asymmetry is directly proportional to uncertainty on the qqbar fraction:

$$A_{observed} = \frac{N_F - N_B}{N_{total}} = \frac{N_F^{gg} + N_F^{qq} - N_B^{gg} - N_B^{qq}}{N_{total}} = A^{gg}F^{gg} + A^{qq}F^{qq} = A^{qq}F^{qq}$$

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Instead of conclusion: Personal remarks

- Results are consistent between Tevatron experiment and correspond to ~20% asymmetry at production level
  - More certainty with full dataset
- Simple cross check with lepton-based asymmetry also shows significant asymmetry
- LHC results are not at the precision to contradict the Tevatron data yet
  - But will be very soon
- Standard Model QCD calculation for asymmetry exists only at α_s^3 level, which is LO for asymmetry
  - α_s^4 prediction for asymmetry is expected soon
- Most BSM explanations are contradicted by other experimental results

It's a lovely mystery!

Systematics on A

TABLE VII. Systematic uncertainties on $A_{\rm FB}$.

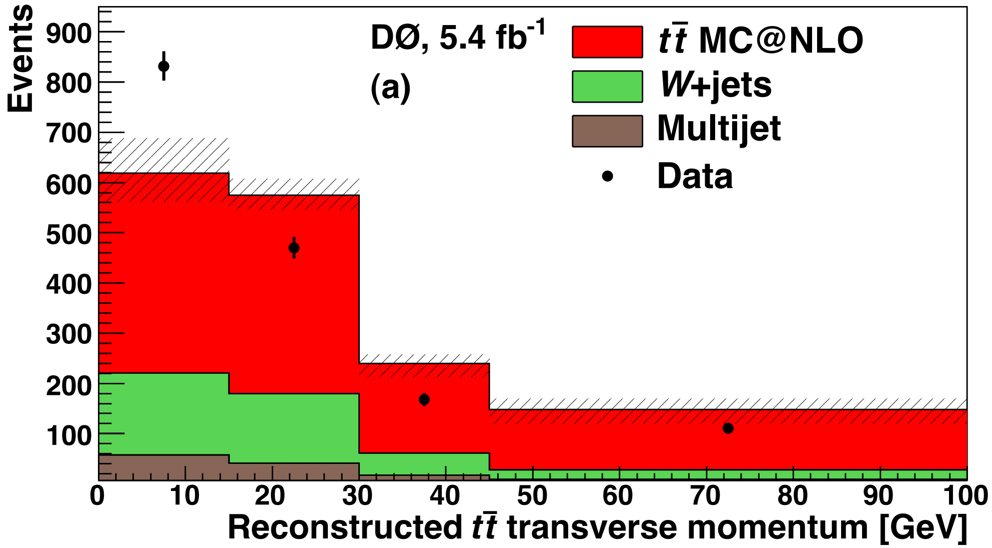
	Absolute uncertainty [a] (%)		
	Reconstruction level		Prod. level
Source	Prediction	Measurement	Measurement
Jet reco	±0.3	±0.5	±1.0
JES/JER	$+0.5$	-0.5	-1.3
Signal modeling	±0.3	±0.5	$+0.3/-1.6$
b-tagging	-	±0.1	±0.1
Charge ID	-	$+0.1$	$+0.2/-0.1$
Bg subtraction	-	±0.1	$+0.8/-0.7$
Unfolding Bias	-	-	$+1.1/-1.0$
Total	$+0.7/-0.5$	$+0.8/-0.9$	$+1.8/-2.6$

Systematics on A_l

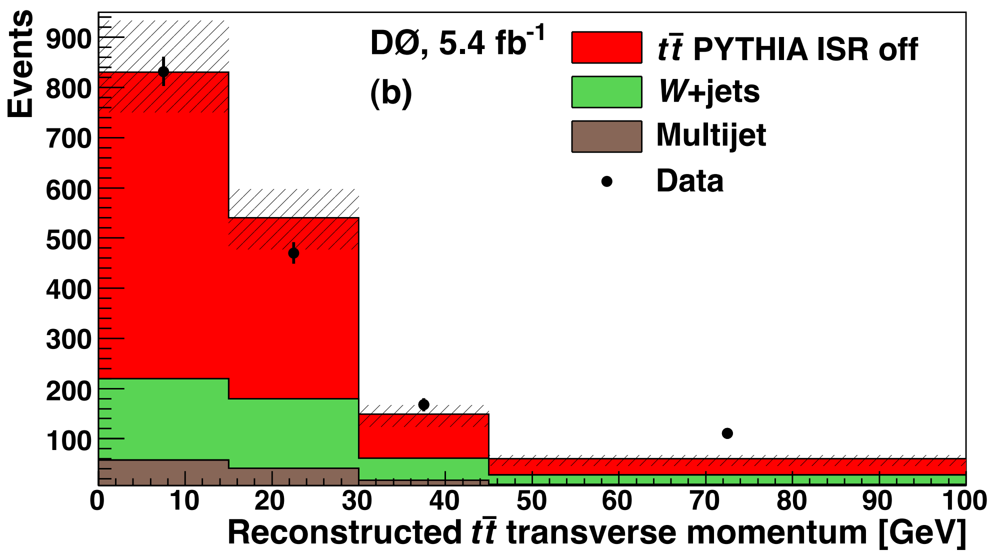
TABLE VIII. Systematic uncertainties on A^l_{FB}.

	Absolute uncertainty [a] (%)		
	Reconstruction level		Prod. level
Source	Prediction	Measurement	Measurement
Jet reco	± 0.3	± 0.1	± 0.8
JES/JER	$+0.1$	-0.4	$+0.1/-0.6$
Signal modeling	± 0.3	± 0.5	$+0.2/-0.6$
b-tagging	-	± 0.1	± 0.1
Charge ID	-	$+0.1$	$+0.2/-0.0$
Bg subtraction	-	± 0.3	± 0.6
Total	± 0.5	± 0.7	$+1.0/-1.3$

Modeling of gluon radiation

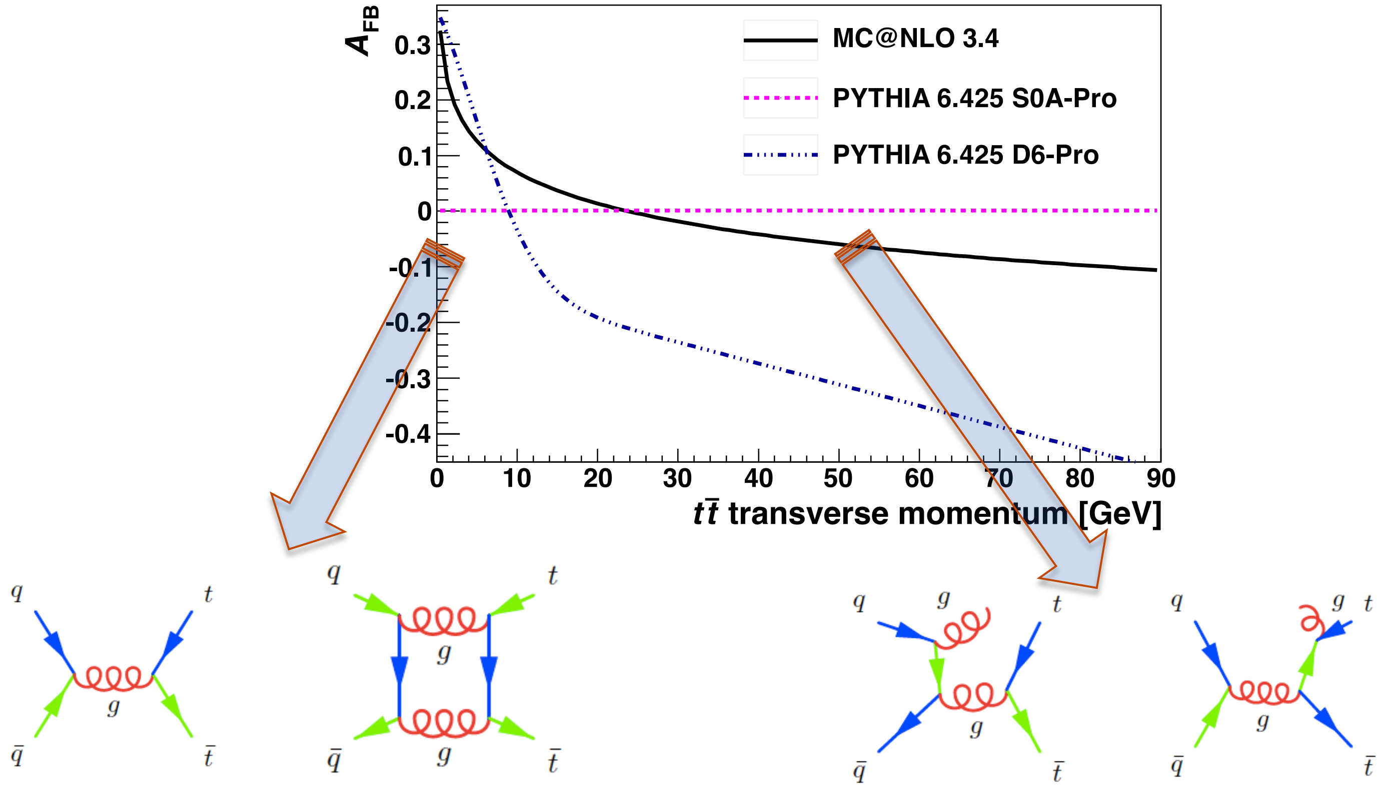


- p_T^{tt} spectrum suggests that gluon radiation might be mismodeled by MC@NLO+HERWIG
- lower radiation is preferred



- best agreement with PYTHIA ISR off
- This suggests a higher contribution from 2→2 processes, e.g. Born+box

Asymmetry and gluon radiation



- MC@NLO+HERWIG suggests strong dependence of asymmetry on p_T^{tt}
- Some PYTHIA tunes suggest even more dramatic dependence while other do not – the main parameter that affects this behavior is angular coherence of ISR
- Asymmetry dependence on p_T^{tt} is a source of systematic uncertainty on the ***measured*** value of asymmetry
- Higher weight of 2→2 processes (Born+box) would shift the ***predicted*** asymmetry toward more positive and higher values: **yet it is hard to make 20% from 5%**

Predicted asymmetries: axigluons

Heavy axigluon [Ferrario & Rodrigo, Phys.Rev.D80:051701,2009][Haisch & SW, arXiv:1106.0529]

Flavor non-universal couplings $g_A^q = -g_A^t = 1$, $M_G = 2\,\text{TeV}$, $\Gamma_G/M_G = 10\%$.

- Effects limited by dijet production (g_A^q).

$$(A_{\text{FB}}^t)^{>}_{\text{max}} = 20\%$$

Light axigluon [Tavares & Schmaltz, arXiv:1107.0978][see also Barcelo et al., arXiv:1106.4054]

Flavor universal couplings $g_A^q = g_A^t = 1/3$, $M_G = 400\,\text{GeV}$, $\Gamma_G/M_G \gtrsim 10\%$.

- Evade bounds from dijet production (g_A^q) and T parameter (g_A^t).
- Need large width Γ_G to suppress resonance in $M_{t\bar{t}}$ spectrum
  $\rightarrow$ additional matter in axigluon decay.

$$(A_{\text{FB}}^t)^{>}_{\text{NP}} \approx 30\%$$