Forward-backward asymmetry of the top quark-antiquark pairs at the Tevatron: a window for new physics ?

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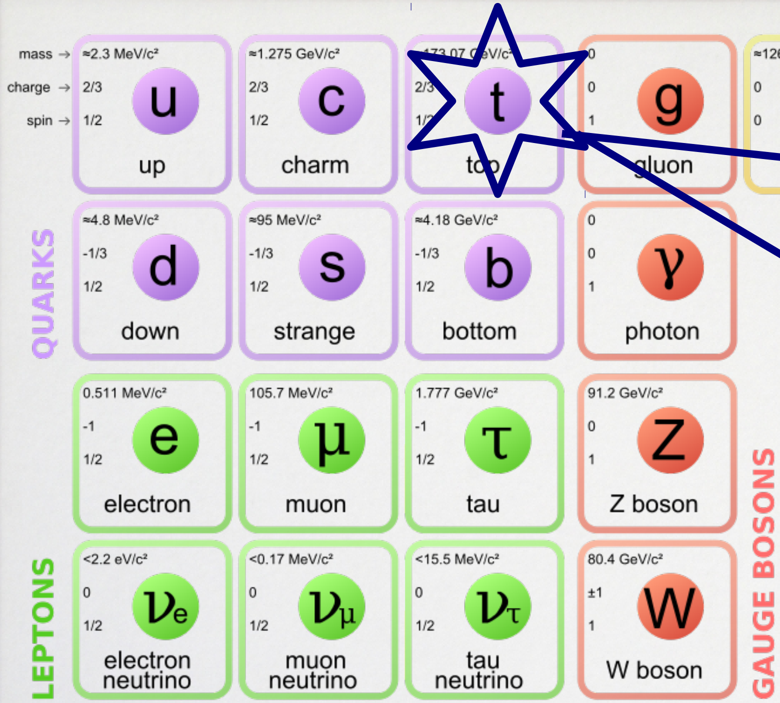
ANL lunch seminar
2014.02.11

The top quark ...



Discovery !

VOLUME 74, NUMBER 14 — PHYSICAL REVIEW LETTERS — 3 APRIL 1995

Observation of the Top Quark

S. Abachi,[12] B. Abbott,[33] M. Abolins,[23] B. S. Acharya,[40] I. Adam,[10] D. L. Adams,[34] M. Adams,[15] S. Ahn,[12] H. Aihara,[20]

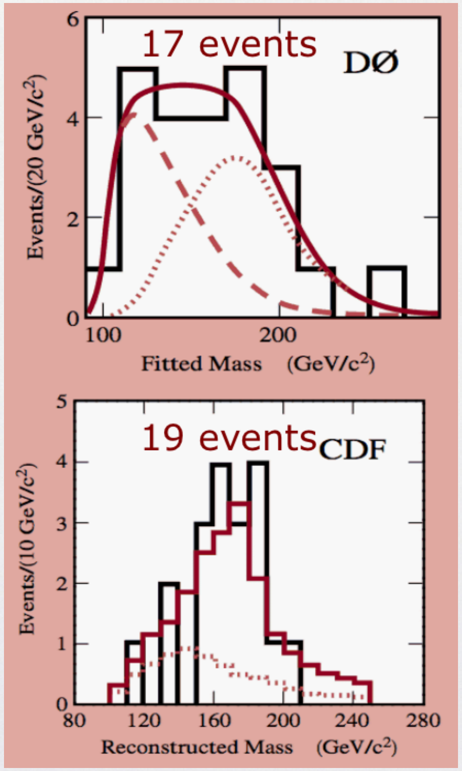
(D0 Collaboration)

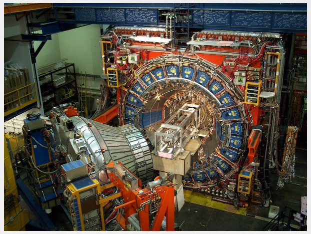
VOLUME 74, NUMBER 14 — PHYSICAL REVIEW LETTERS — 3 APRIL 1995

Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

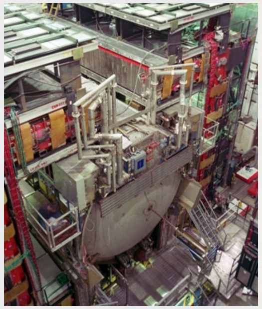
F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[24] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4]

(CDF Collaboration)





←CDF det.



Do det.→

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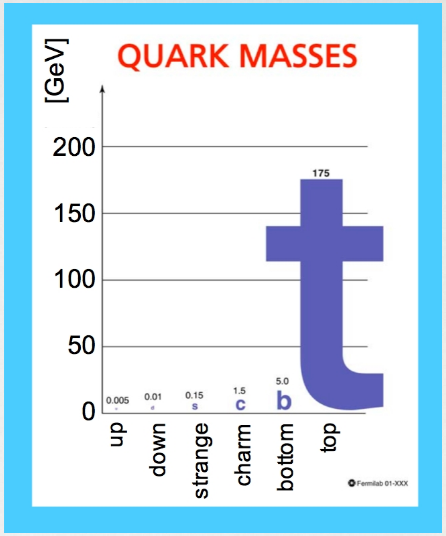
… a special quark !

- Heaviest known elementary particle ($M_{top} \sim M_{gold\ atom}$)

$$\mathcal{L}_{Yukawa} = -\lambda_{top}\bar{\psi}_{l,top}\phi\psi_{r,top}$$

$$\lambda_{top} \approx 1$$

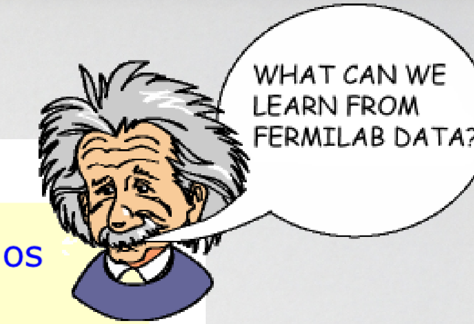


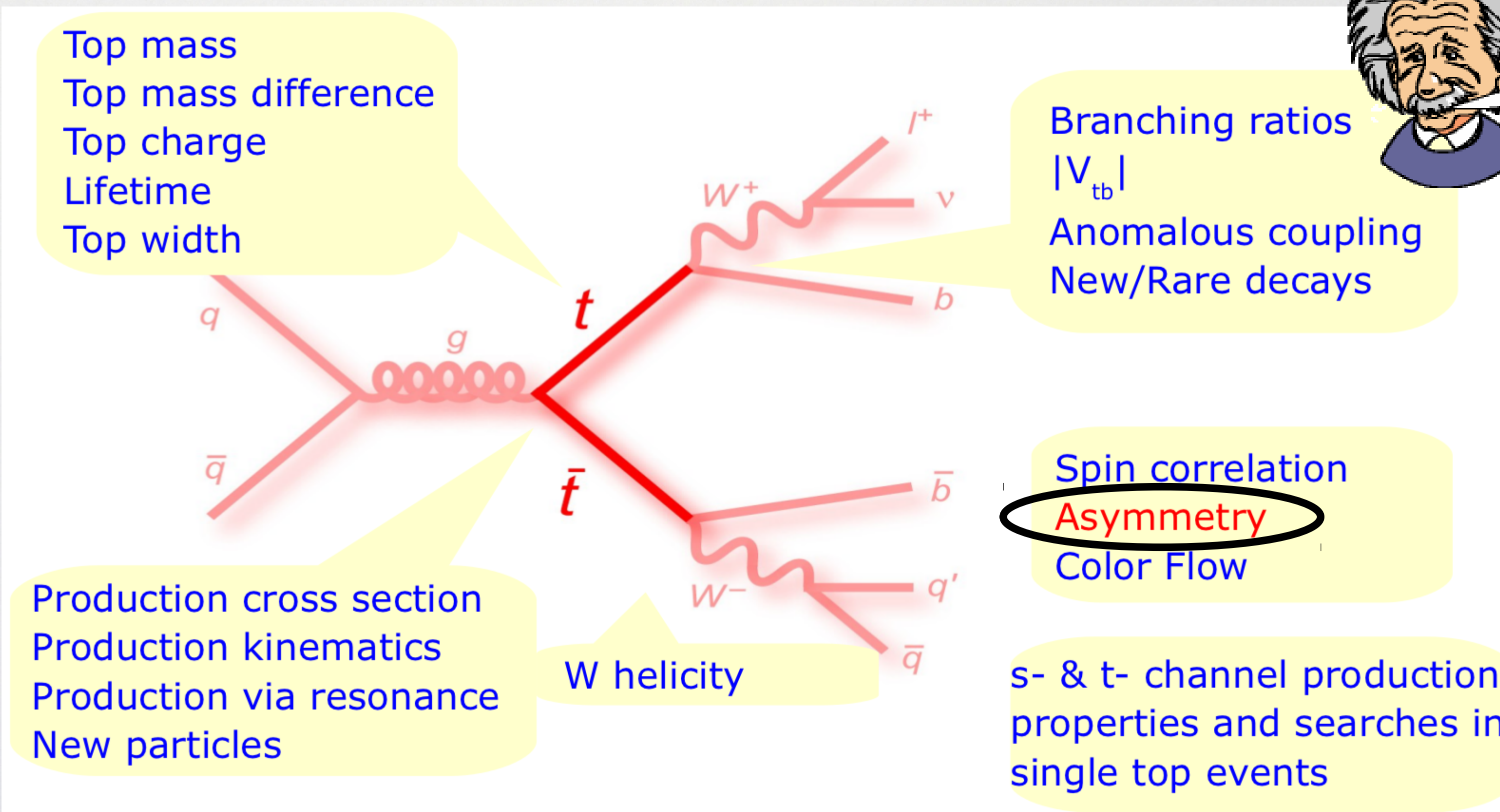
  - top life time ~ 10^{-25}s << hadronization time
  - M_{top} = 173.07 ± 0.89 GeV

- Strong coupling to Higgs boson : special role ?
- Decays before hadronizing : study of a bare quark.

Ideal sector to search for new physics !
→ study the top quark properties in details.

Top quark properties

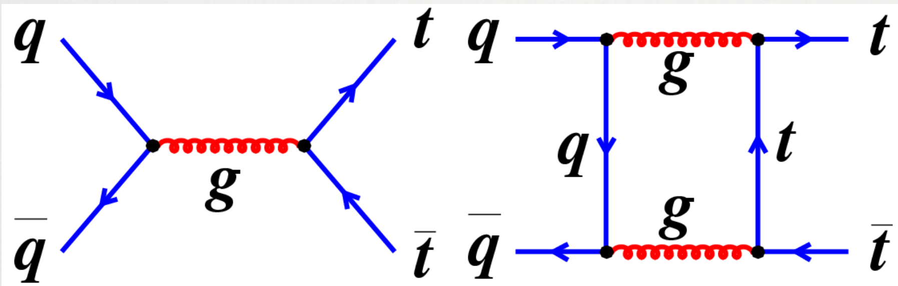


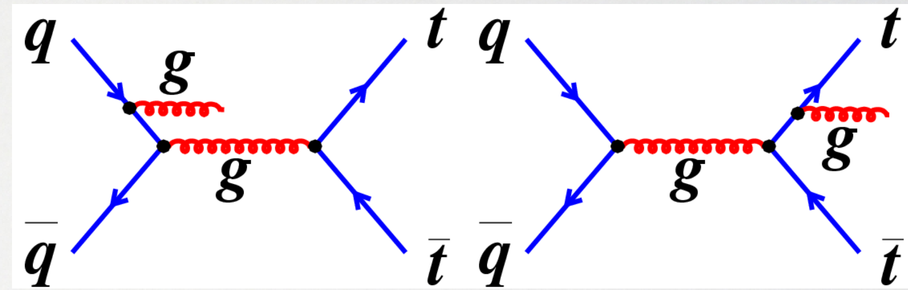


We are going to focus on the charge asymmetry of the top quark-antiquark pairs which have been studied both at the Tevatron (this talk) and at the LHC (few words in the conclusion).

Theory of the charge asymmetry

At NLO, QCD predicts a $t\bar{t}$ production asymmetry via $q\bar{q}$ annihilation. Due to the interferences :

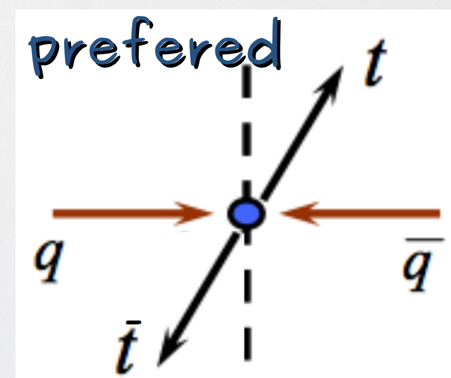




positive asymmetry > negative asymmetry

Kühn, Rodrigo Phys. Rev. Lett. 81, 49-52 (1998)

''the system is less perturbated if the outgoing positive electric charge field (colour field for tops) flows in the direction of the incoming positive electric charge field''



Non SM processes can modify the asymmetry (axigluon, Z' ...)

Standard Model predictions

$$A_C = \frac{\sigma_A}{\sigma_S}, \qquad \sigma_{S,A} = \int_0^1 \mathrm{d}\cos\theta \left(\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}\cos\theta} \pm \frac{\mathrm{d}\sigma_{\bar{t}t}}{\mathrm{d}\cos\theta} \right)$$

NLO QCD: only asymmetric term known so far

$$A_C^{\mathrm{QCD}} = \frac{\alpha_s^3 \sigma_A^{(1)} + \alpha_s^4 \sigma_A^{(2)} + \ldots}{\alpha_s^2 \sigma_S^{(0)} + \alpha_s^3 \sigma_S^{(1)} + \alpha_s^4 \sigma_S^{(2)} + \ldots}$$

Symmetric term (cross-section) known at NNLO QCD

[Mitov, Czakon & Fiedler PRL 110 252004 (2013)]

Also, EW corrections to take into account: + ~25% .

Holik & Pagani PRD 84, 093003 (2011)

Standard Model predictions

Will be our baseline for predictions.

- Bernreuther & Si PRD 86 034026 (2012)

consistent fixed-order perturbative expansion NLO/LO

- Holik & Pagani PRD 84, 093003 (2011)

same with different set of PDF

- Kühn & Rodrigo JHEP 1201, 063 (2012) :

same with LO PDF instead of NLO PDF

- Ahrens et al. PRD 84 074004 (2011)

NLO + NNLL

Consistent predictions

≠

- Campbell & Ellis arXiv:1204.1513 [hep-ph]

NLO/NLO computation

→ decrease by ~20%

\+ larger uncertainty

MC@NLO MCFM

- Event generator :

NLO/NLO computation

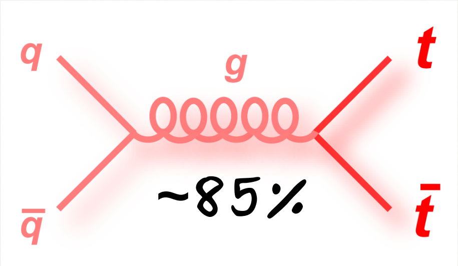
→ decease by ~30 %

Theoretical uncertainties: PDF, factorization & renormalization scales.

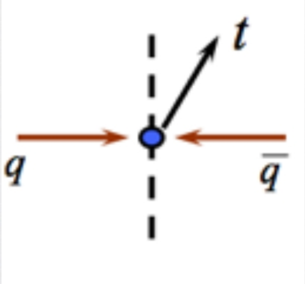
Also, uncertainty may be underestimated

Brodsky & Wu PRD 85 114040 (2012).

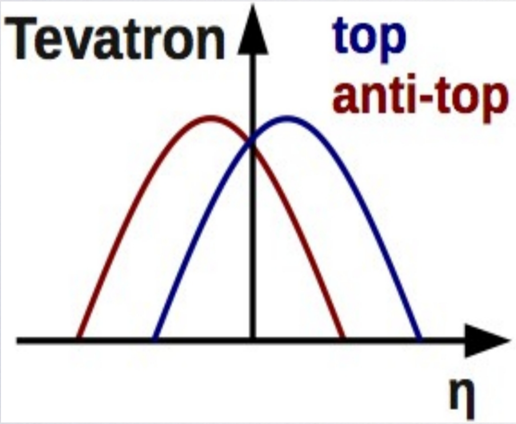
Charge asymmetry at the Tevatron

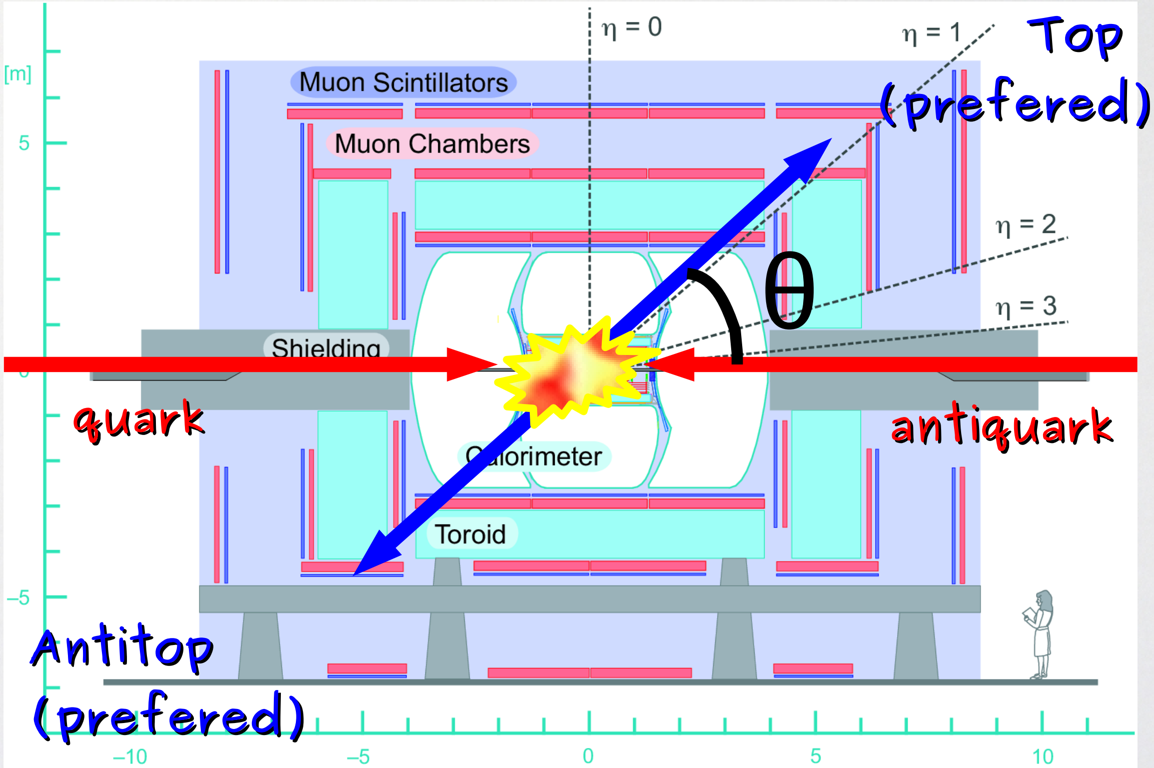


→ dominant production process at the Tevatron (there is **no asymmetry** in gluons fusion production)



CM ≈ LAB frame



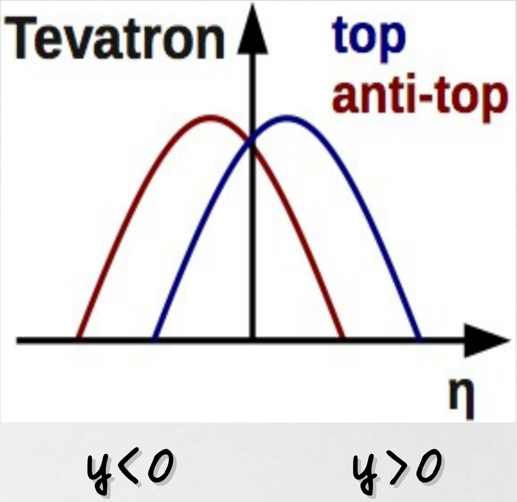


Forward–Backward
asymmetry

Observables : looking at the tops

* top-based asymmetry :

Do top quark preferentially follows the initial quark direction ?



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

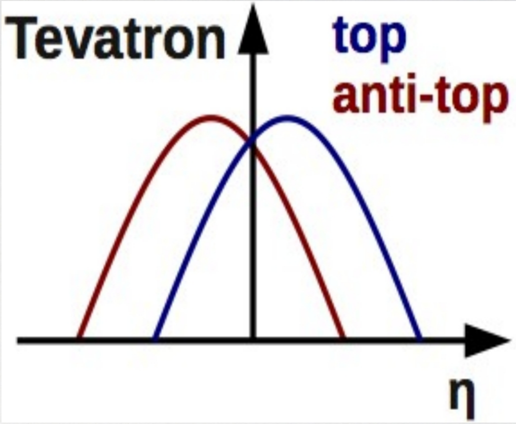
$$\Delta y = y_{top} - y_{antitop}$$

$$y = \frac{1}{2} ln \frac{E + p_z}{E - p_z}$$

Goes from 0 (p_z=0, transverse to the beam direction) to ∞ ($E=p_z$, along the beam direction).

* lepton-based asymmetry :

Looking at the leptons from the top quark decays



- ✗ no need to reconstruct the $t\bar{t}$ system & leptons are well measured
- ✗ influence from top polarization (if any)
- ✗ dilute asymmetry

Lepton's flight direction is correlated to the top's flight direction

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

$$\Delta\eta = \eta_{\ell+} - \eta_{\ell-}$$

$$A^{\ell}_{FB} = \frac{N(q\times\eta > 0) - N(q\times\eta < 0)}{N(q\times\eta > 0) + N(q\times\eta < 0)}$$

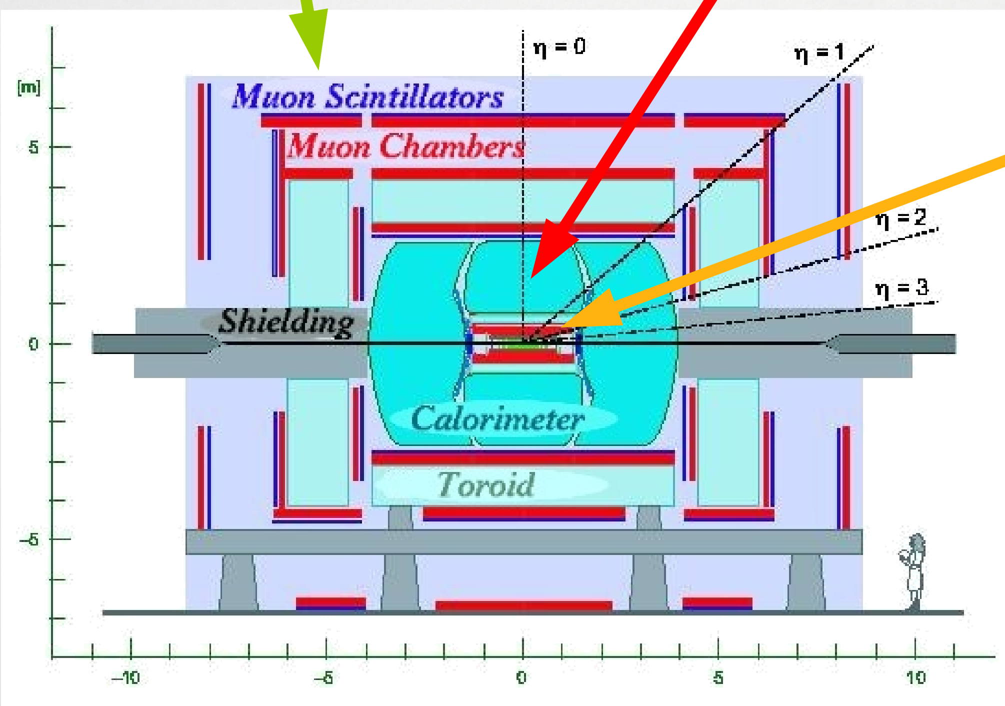
$$\eta = ln(tan\frac{\theta}{2})$$

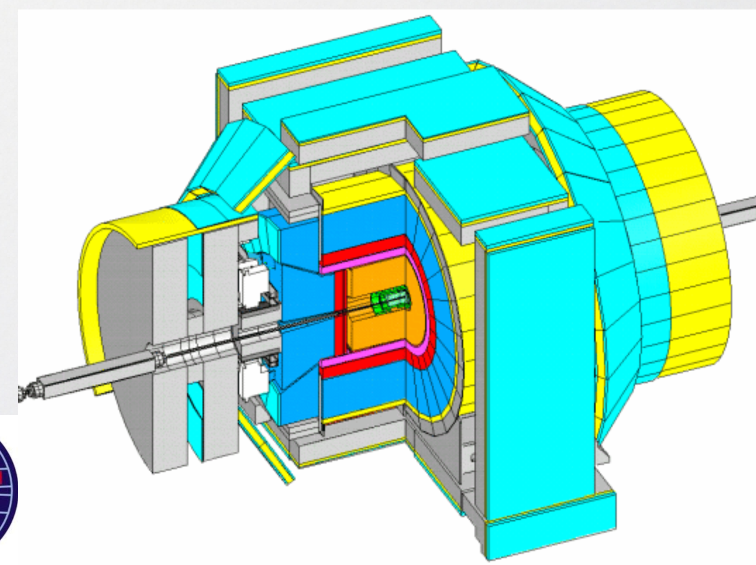
Experimental apparatus

Muon chamber : identification and momentum measurement of muons.

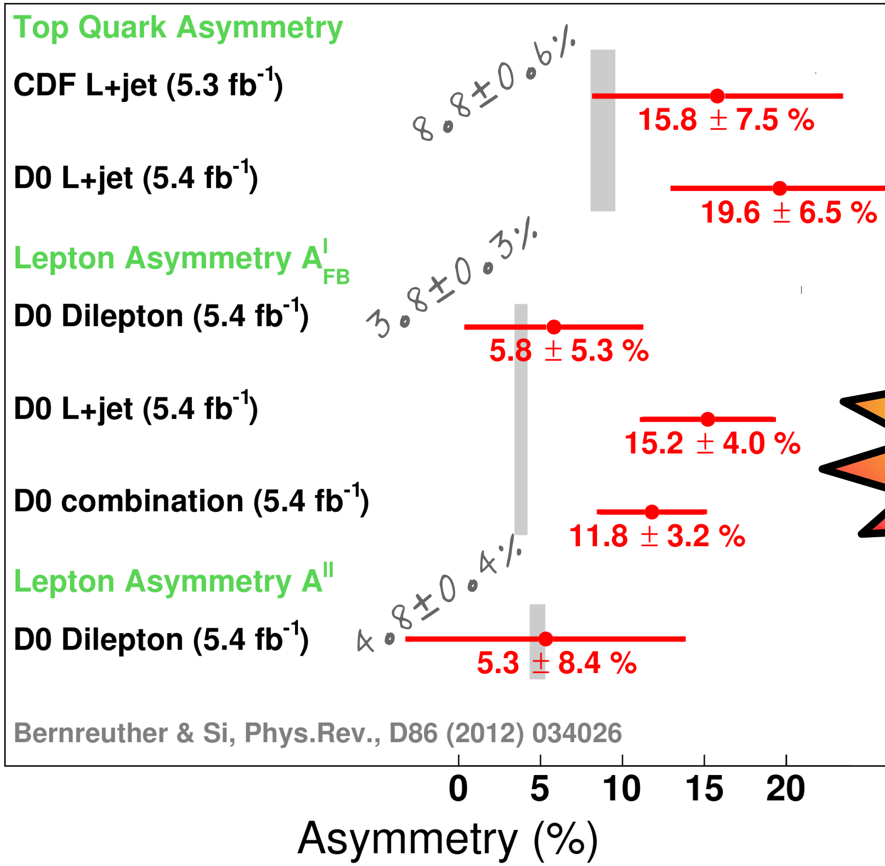
Calorimeter : identification and energy measurement for jets and electrons.

Tracker : detection and momentum measurement for charge particles.

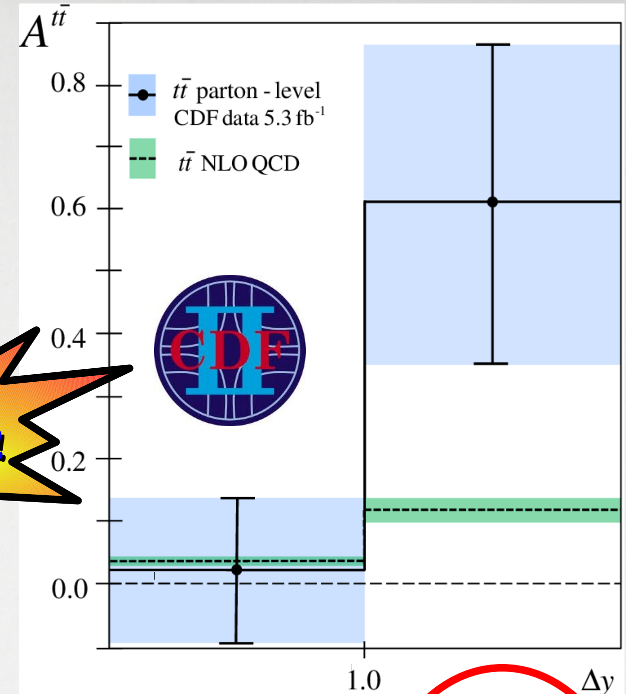


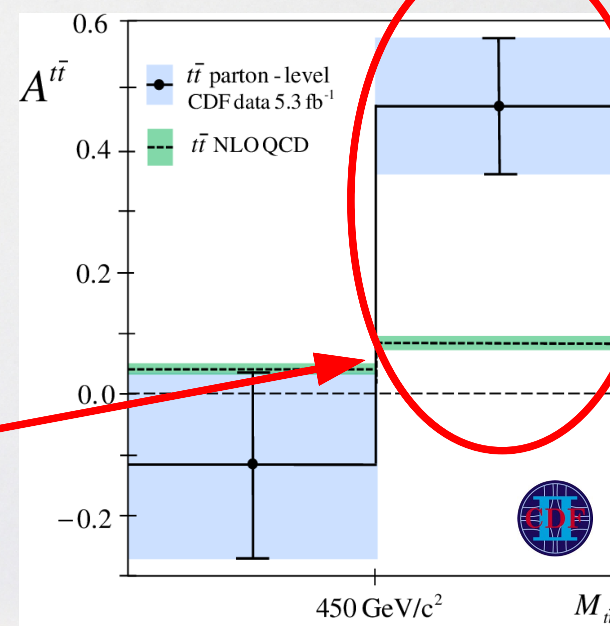


Previous measurements (2012)



Hot topic!



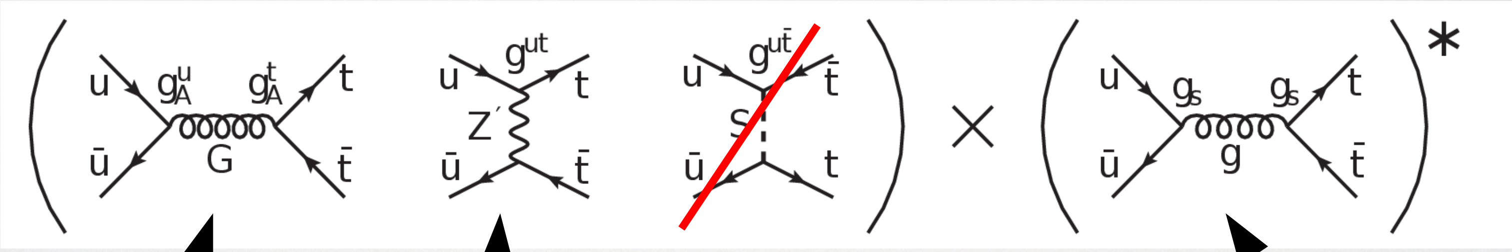


With half of the Tevatron statistics : deviations between measurements and predictions up to **3 SD** !!

Physics beyond the Standard Model ?

Some new physics models could explain the deviations observed at the Tevatron

tree level interferences with SM



''axigluon'' : massive color octet with axial-vector couplings to quark in the s-channel

Z' : vector boson with flavor changing couplings in the t-channel

SM model $t\bar{t}$ production

Let's focus on the axigluon model.

[Frampton, Glashow, PLB190 (1987) 157]

Axigluon model

Contribution to $t\bar{t}$ production from SM gluon / axigluon interference :

$$\sigma_a^{INT} \approx g_s^2 \frac{g_A^q g_A^t}{M_{t\bar{t}}^2 - M_G^2}$$

QCD coupling constant

mass of the $t\bar{t}$ pair

axigluon mass

Axial−vector coupling to light (q) and top (t) quarks

* We need :

$$\sigma_a^{INT} > 0$$

to observe a positive contribution to the asymmetry

$$M_G > M_{t\bar{t}} \;,\; g_A^q \cdot g_A^t < 0$$

[Frampton, Shu, Wang, PLB683 (2010) 294]

$$M_G \leq M_{t\bar{t}} \;,\; g_A^q \cdot g_A^t > 0$$

[Tavares, Schmaltz, PRD84 (2011) 054008]

Axigluon model

Contribution to the $t\bar{t}$ production from axigluon self-interf :

No contribution to the asymmetry but it constraints the model.

$$\sigma_s^{NP} \approx (g_A^q)^2 (g_A^t)^2 \frac{M_{t\bar{t}}^2}{(M_{t\bar{t}}^2 - M_G^2)^2}$$

→ σs(NP) contribution should be small to respect the agreement between the measured and predicted $t\bar{t}$ cross-section.

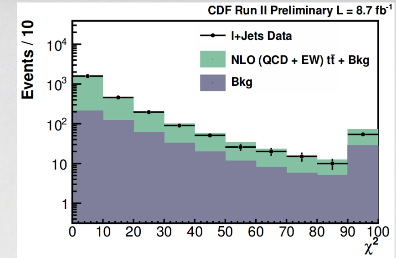
e.g. : if the axigluon mass is close to the $t\bar{t}$ resonance ($M_G \sim M_{ttbar}$) → couplings should be very small !

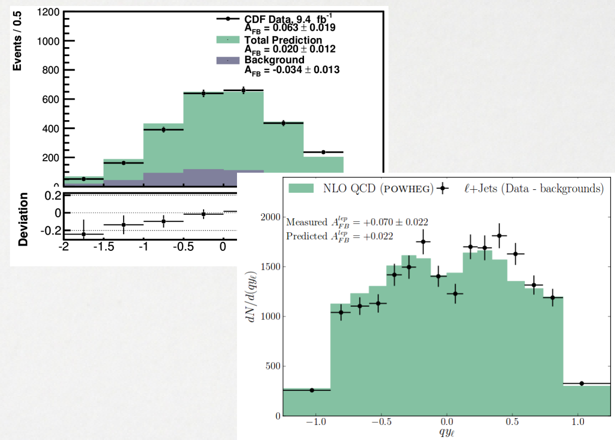
Also, the width of axigluon should be large not to be seen in the $t\bar{t}$ production spectrum.

Measurement procedure

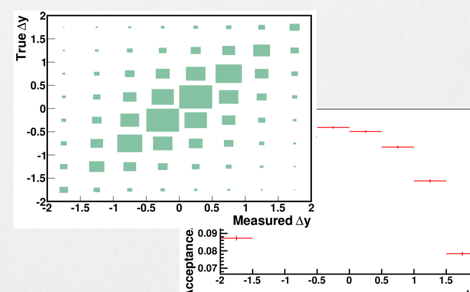
1. Event selection

2. Kinematic reconstruction

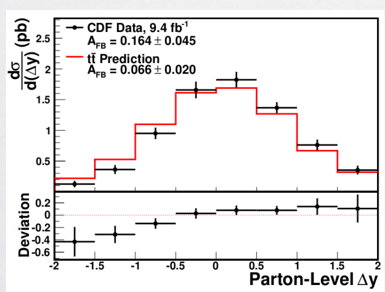




3. Measurement in data after background subtraction



4. Correct for reconstruction and acceptance effects & study systematic uncertainties



5. Unfolded results

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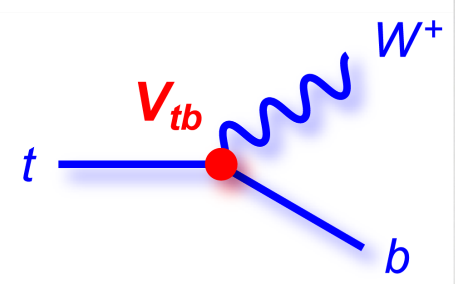
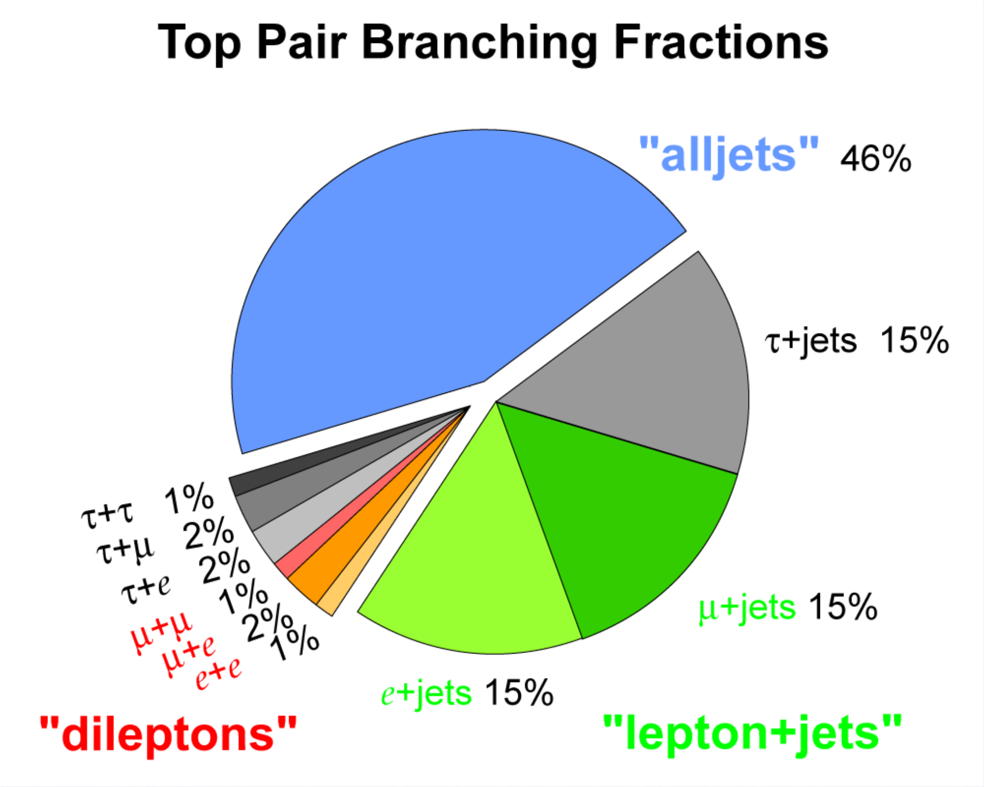
Top quark pair signatures

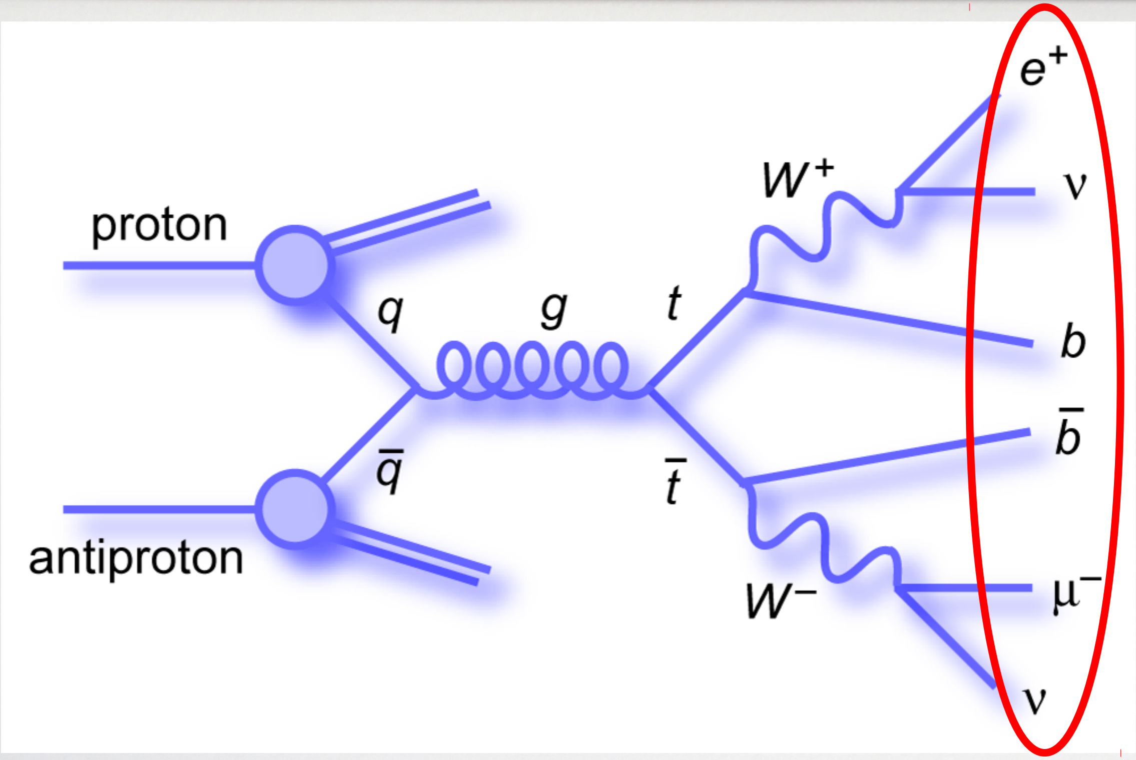
- Top quark decays ~100% in $t \rightarrow Wb$. Final states are defined according to the W boson decay modes.





- We are interested in the dilepton and l+jets channels.

Event selection: dilepton channel

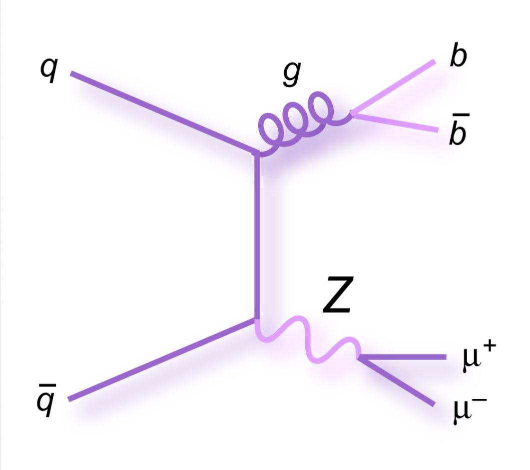


* 2 isolated leptons : electron (e) or muon (μ)
* High missing E_T from the 2 neutrinos
* 2 b-jets

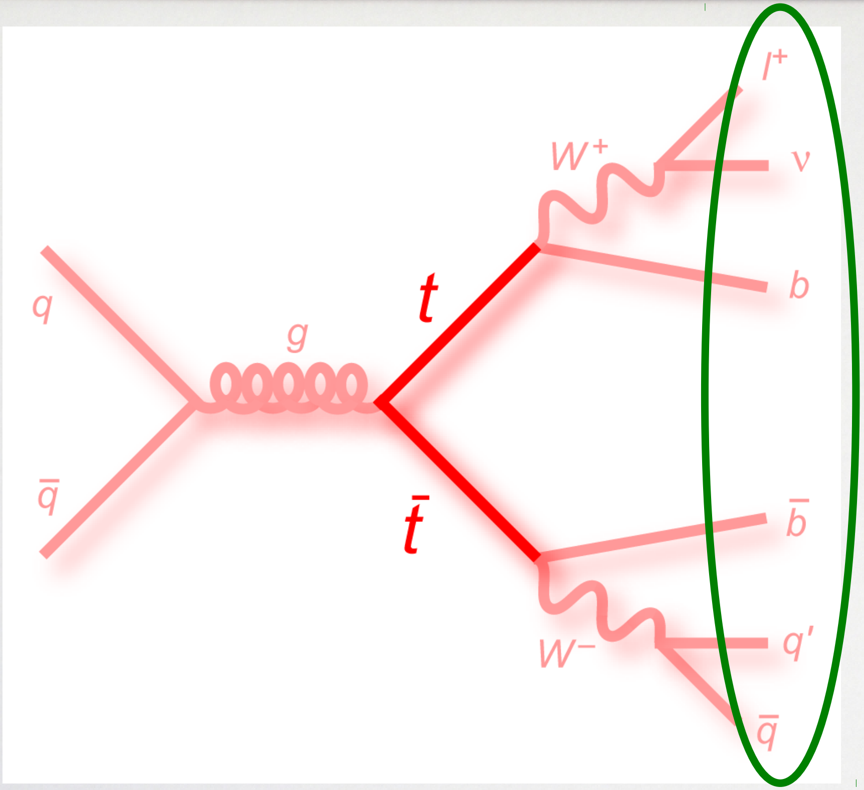
event selection according to this topology

Small rate

Small background :
* Drell-Yan (from MC) →
* Instrumental (from data) :
W+jets, multijets → fake leptons



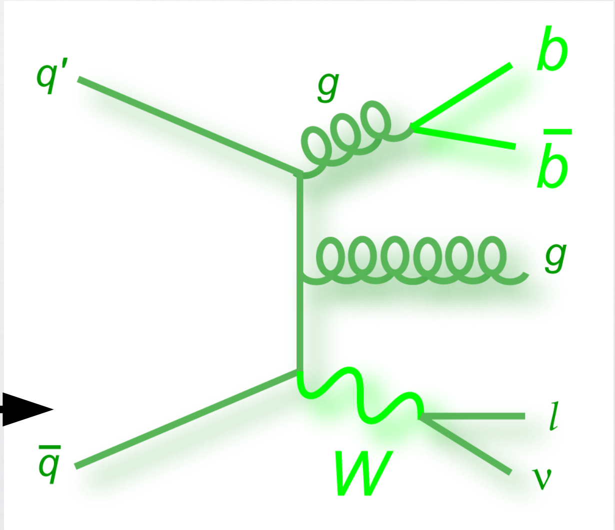
Event selection: l+jets channel



* 1 isolated lepton : electron (e) or muon (μ)
* High missing E_T from the neutrino
* >= 4 jets (2 b-jets)

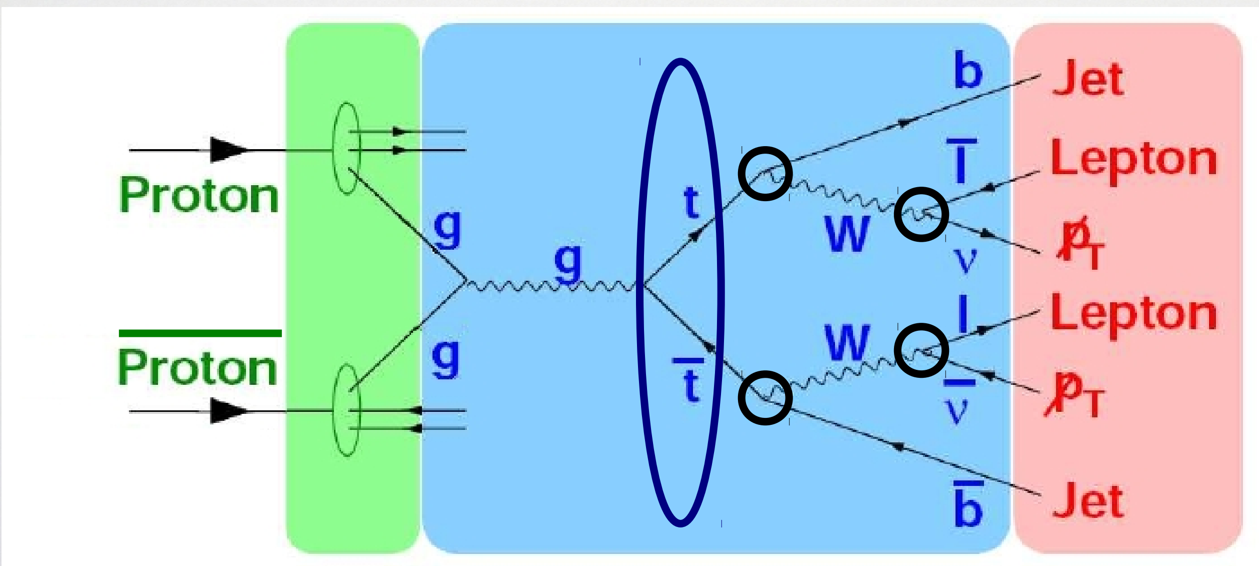
Good rate

Reasonable background :
* W+jets (from MC & Data)
* Multijet (data) → fake leptons



ttbar reconstruction

* top life time ~ 10^{-25}s → the top quark is not observed in the detectors … Need to reconstruct top's kinematic to compute the $t\bar{t}$-based charge asymmetry.



wanted

measured

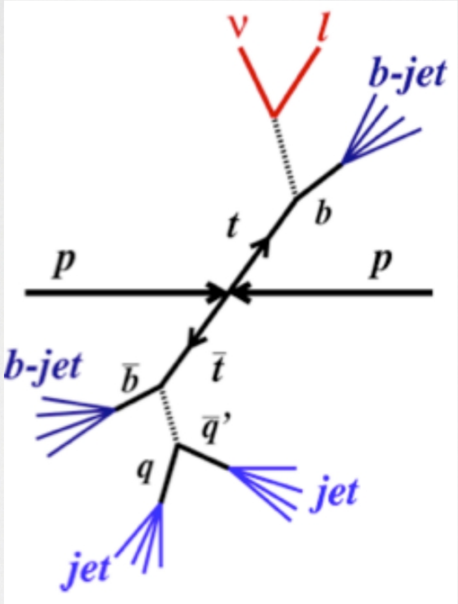
Energy-momentum conversation at each vertex (black dot)

System of equations

$$
\begin{aligned}
P_b + P_{W^+} &= P_t \\
P_{\bar{b}} + P_{W^-} &= P_{\bar{t}} \\
P_{l^+} + P_{\nu} &= P_{W^+} \\
P_{l^-} + P_{\bar{\nu}} &= P_{W^-} \\
P_{\nu_{1x}} + P_{\nu_{2x}} &= E_x^{miss} \\
P_{\nu_{1y}} + P_{\nu_{2y}} &= E_y^{miss}
\end{aligned}
$$

ttbar reconstruction

* N(unknowns) > N(knowns) → M_W and M_T fixed to their world average values within their uncertainties.



* Test different lepton–jet permutation, e.g.: $M_{jj}=M_W$.

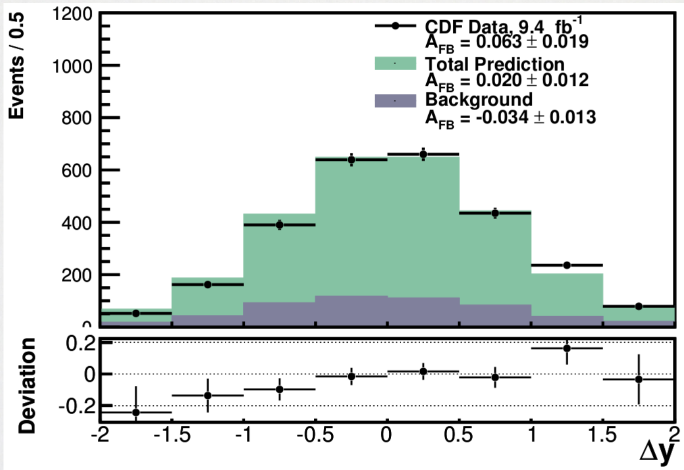
* Experimental resolution is taken into account.

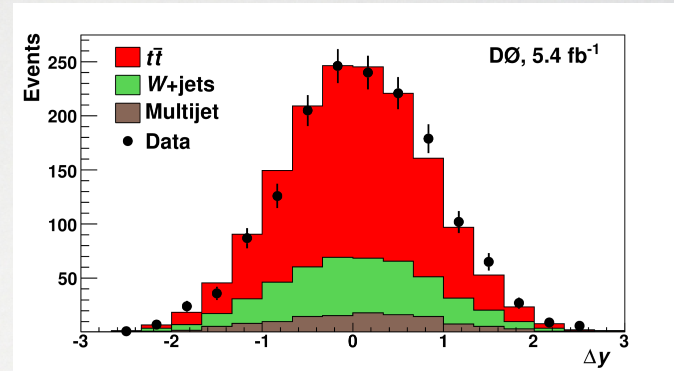
* l+jets : kinematic fit to reconstruct the full event

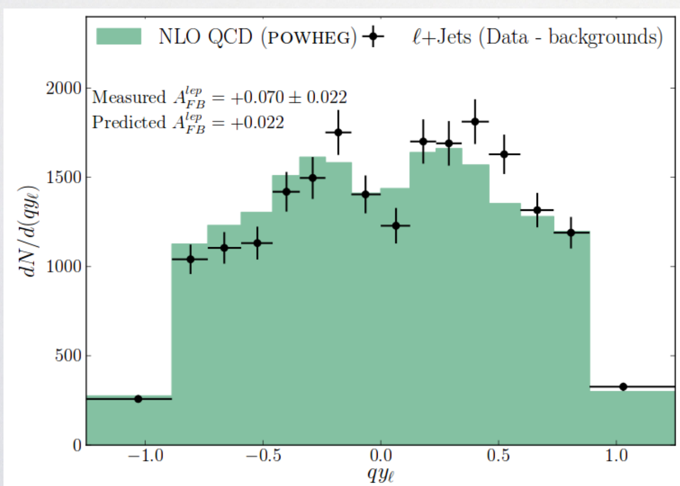
* dilepton : also a kinematic fit but the system is less constrained due to the 2 neutrinos → need additional assumptions (e.g. : $p_{T,ttbar}$ related to neutrino's p_T).

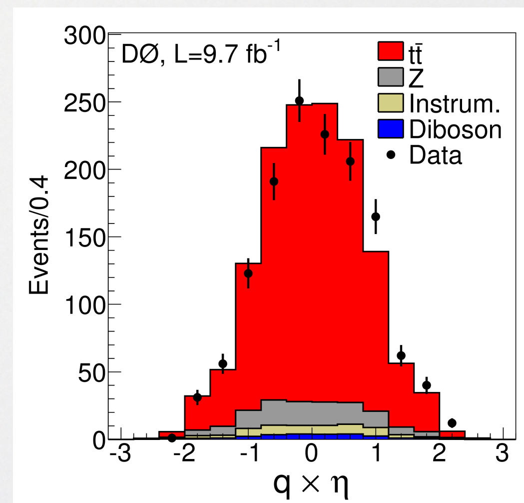
Raw (detector) asymmetry

Background subtracted data ...









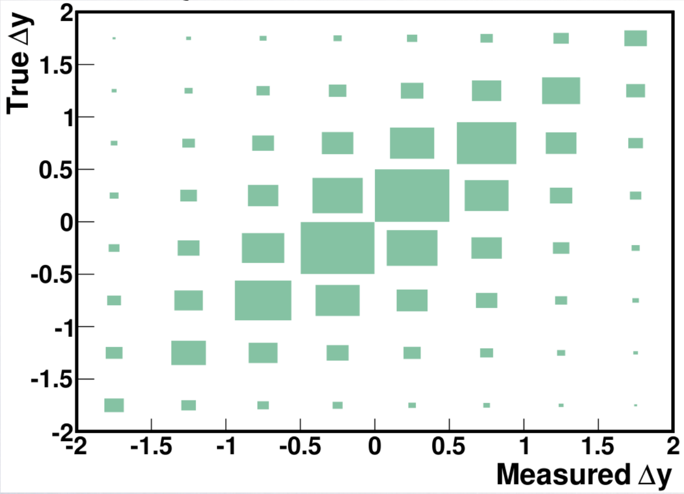
But can't compare due to different acceptance cuts and detector effects.

Unfolding

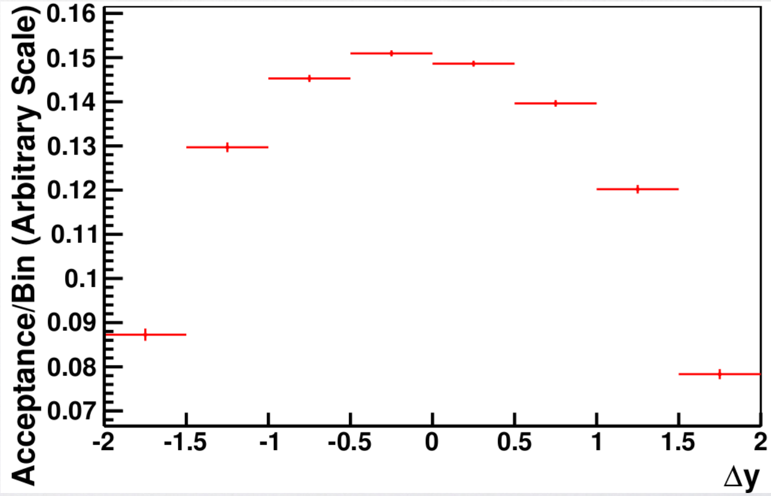
Correct for acceptance and detector effects back to the parton (production) level.

$$\vec{n}_{\text{meas}} \propto S.A.\vec{n}_{\text{parton}} \Rightarrow \vec{n}_{\text{parton}} = S^{-1}A^{-1}\vec{n}_{\text{meas}}$$

migration matrix

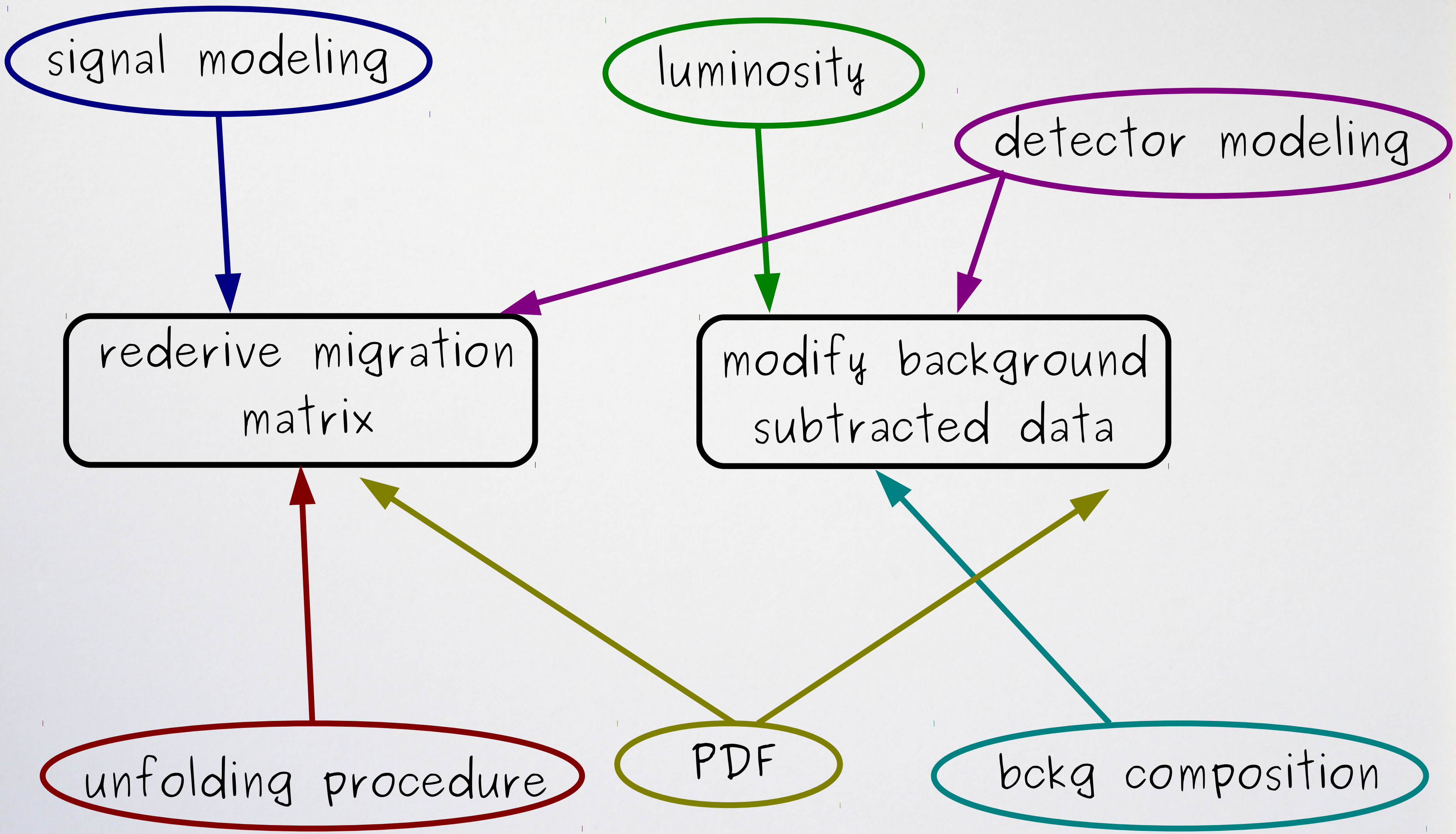


selection efficiency



Systematic uncertainties

The main systematic uncertainties and techniques to estimate them are:



Tevatron $t\bar{t}$ asymmetry measurements

D0 l+jets

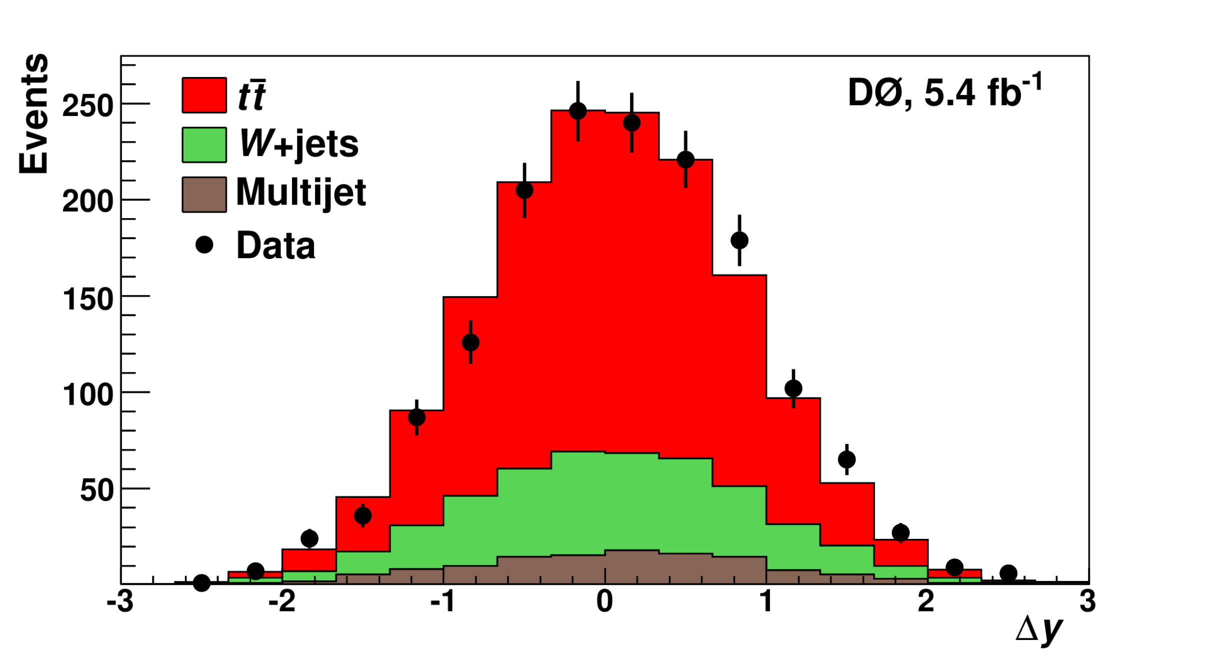
[Phys. Rev. D 84, 112005 (2011)]

TABLE IV. Δy-based asymmetries.

	A_{FB} (%) Reconstruction level	A_{FB} (%) Production level
Data	9.2 ± 3.7	19.6 ± 6.5
MC@NLO	2.4 ± 0.7	5.0 ± 0.1

TABLE III. Reconstruction-level A_{FB} by subsample.

Subsample	A_{FB} (%) Data	A_{FB} (%) MC@NLO
$m_{t\bar{t}} < 450$ GeV	7.8 ± 4.8	1.3 ± 0.6
$m_{t\bar{t}} > 450$ GeV	11.5 ± 6.0	4.3 ± 1.3
$\lvert\Delta y\rvert < 1.0$	6.1 ± 4.1	1.4 ± 0.6
$\lvert\Delta y\rvert > 1.0$	21.3 ± 9.7	6.3 ± 1.6



half-statistics

prediction : 8.8 ± 0.6 %

[Bernreuther & Si PRD 86 034026 (2012)]

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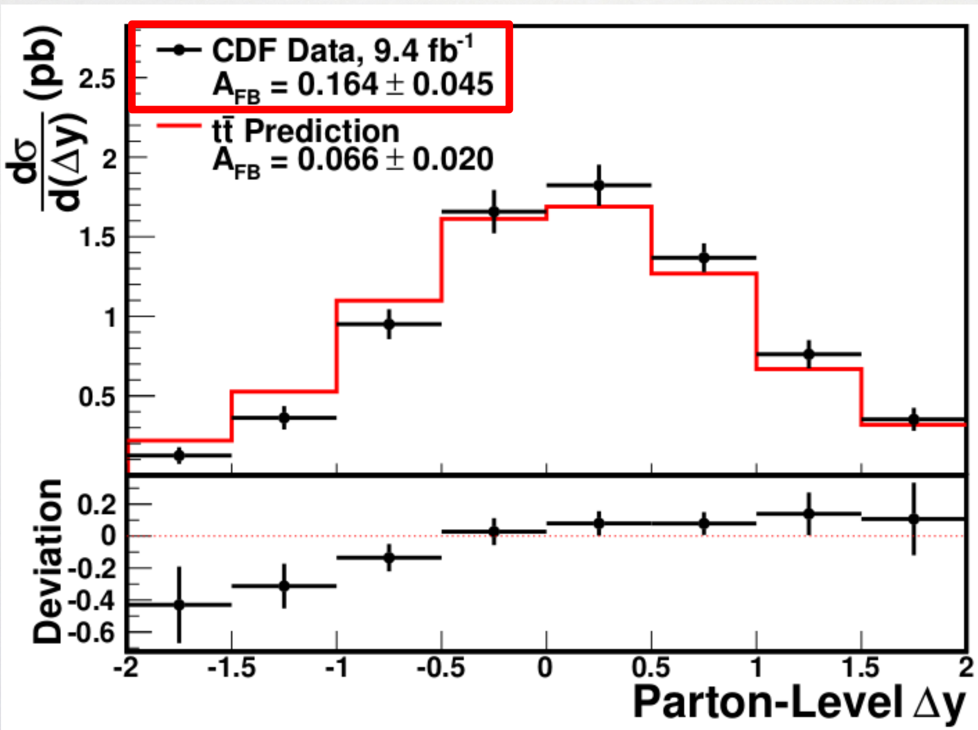
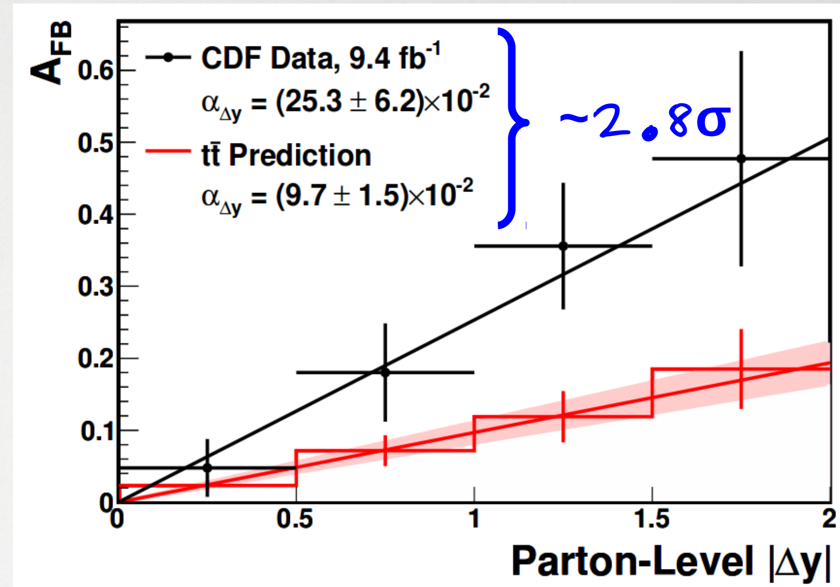
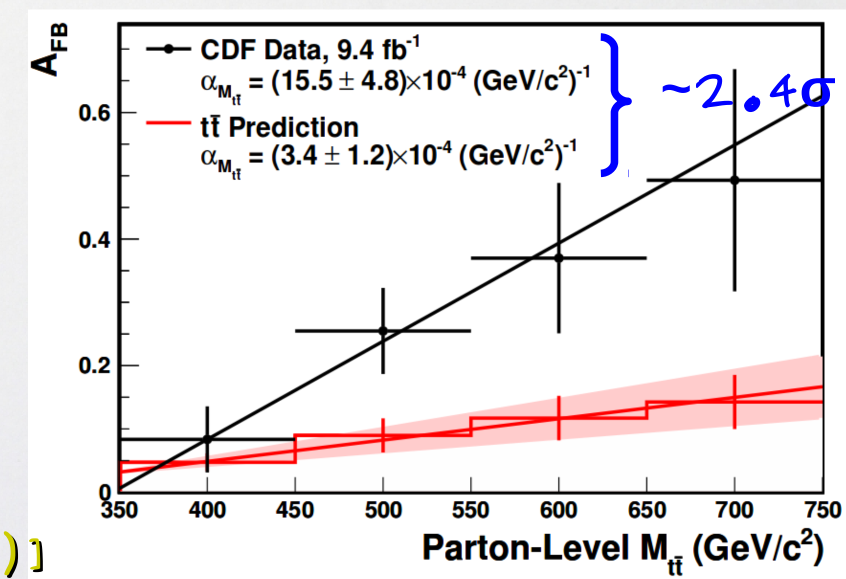
CDF l+jets

[Phys. Rev. D 87, 092002 (2013)]







full-statistics

prediction : 8.8 ± 0.6 %

[Bernreuther & Si PRD 86 034026 (2012)]

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Tevatron leptonic $t\bar{t}$ asymmetry measurements

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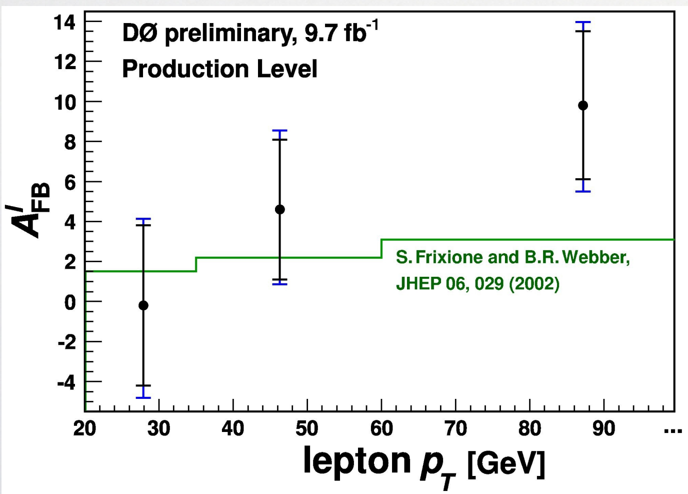
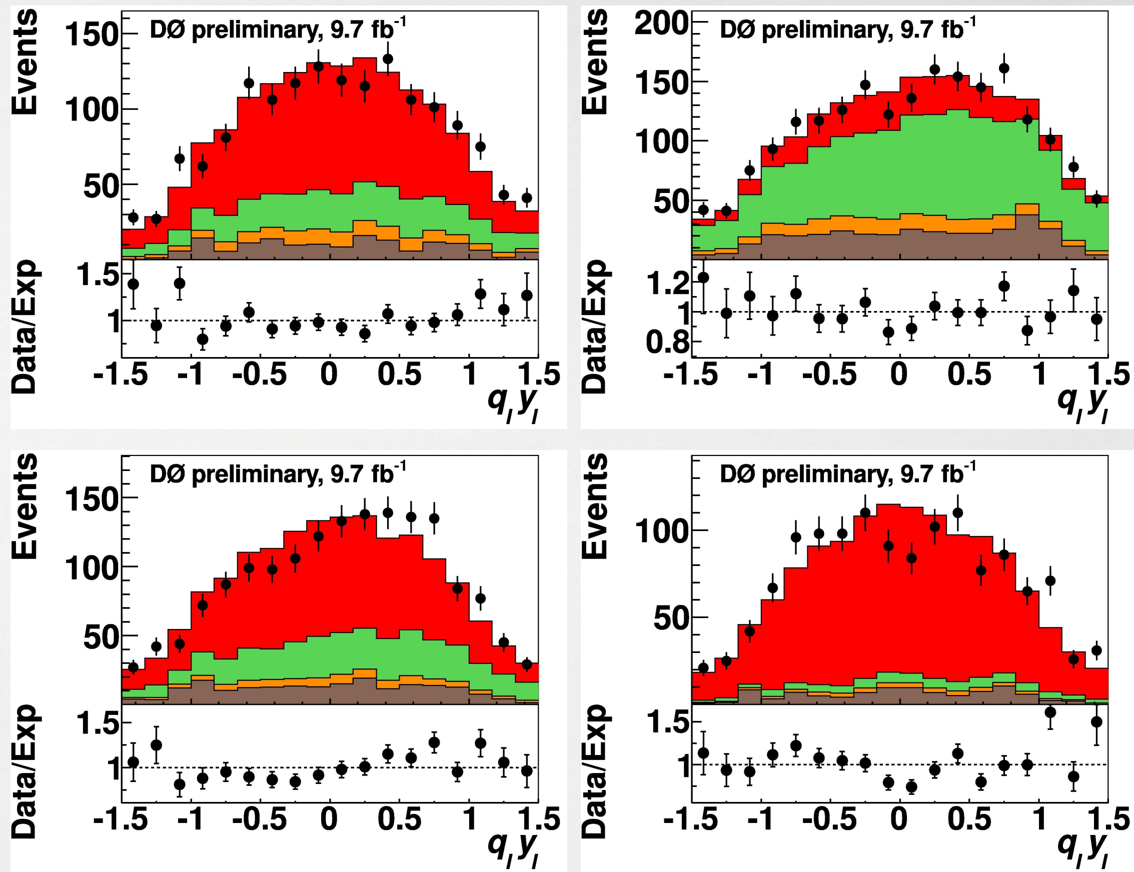
DØ l+jets

[DØ note 6381]

$|y_{lep}| < 1.5$

Quantity	Inclusive
Data	$4.7 \pm 2.3^{+1.1}_{-1.4}$
MC@NLO	2.3





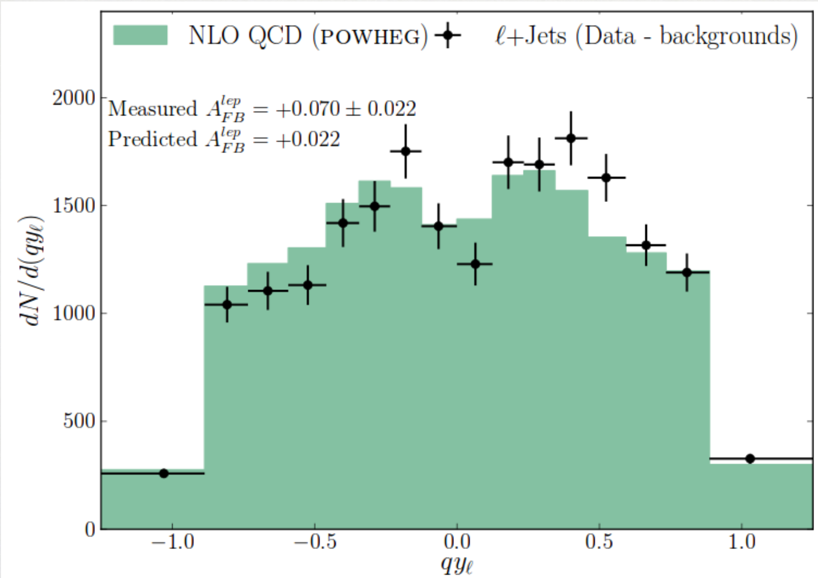
full-statistics

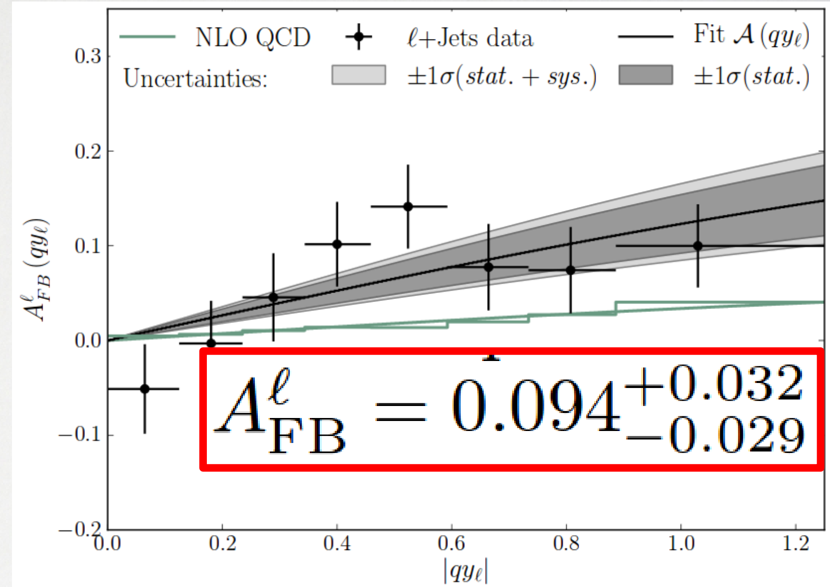
prediction : 3.8 ± 0.3 %

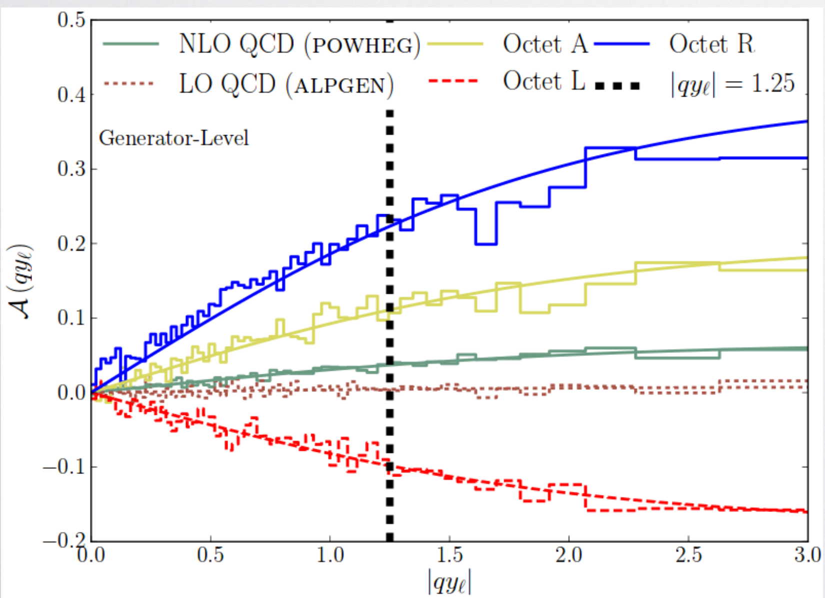
[Bernreuther & Si PRD 86 034026 (2012)]

ANL lunch seminar

CDF l+jets







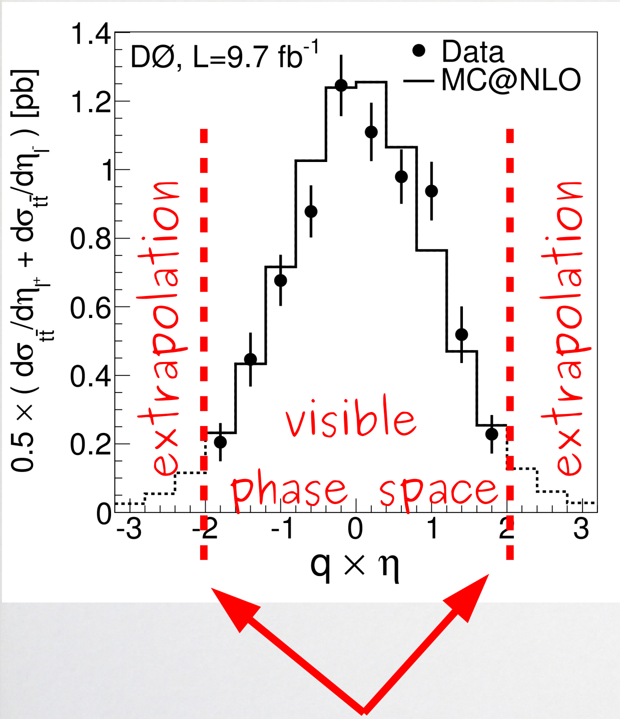
Results is extrapolated to the full phase space using a fitted function :

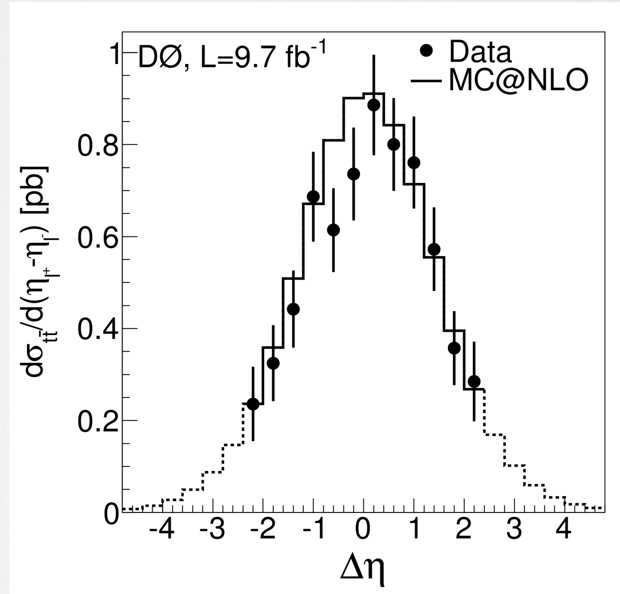
$$\mathcal{F}(qy_\ell) = a \tanh\left(\frac{qy_\ell}{2}\right)$$

prediction : 3.8 ± 0.3 %

[Phys. Rev. D 88, 072003 (2013)]

DØ dilepton



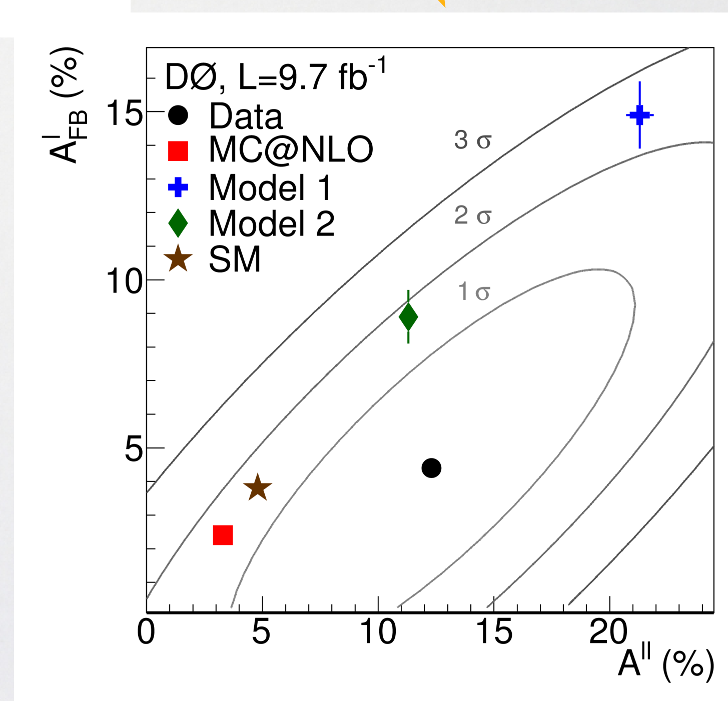


$$A^{extr}_{meas} = A^{corr}_{meas} \times f_{extr}$$

$$f_{extr} = \frac{A^{full\ acceptance}_{\mathrm{MC@NLO}\ t\bar{t}}}{A^{fiducial}_{\mathrm{MC@NLO}\ t\bar{t}}}$$

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

$$R_{SM} = 0.79 \pm 0.10$$

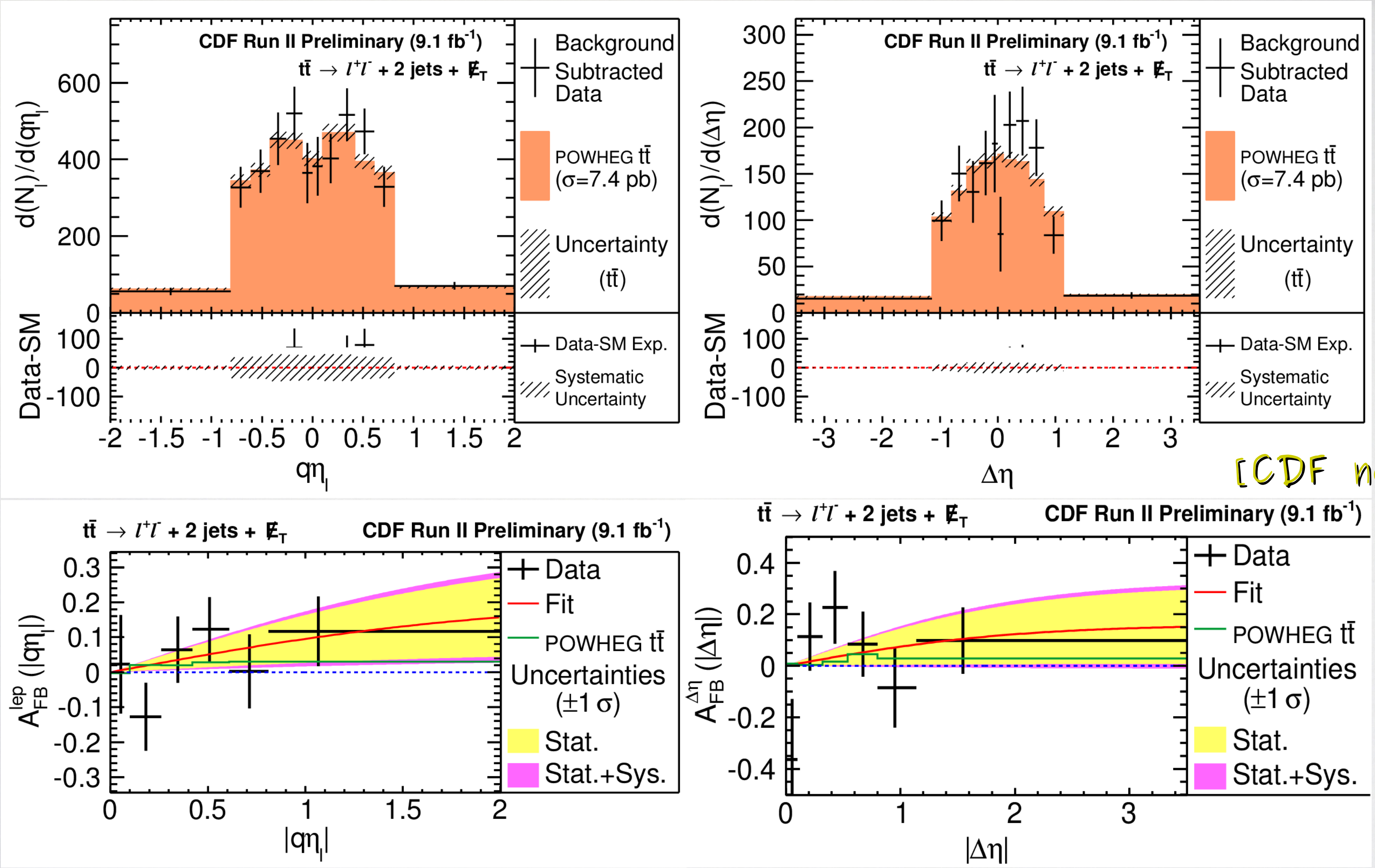


$$A^{\ell}_{\mathrm{FB}} = (4.4 \pm 3.7\ (\mathrm{stat}) \pm 1.1\ (\mathrm{syst}))\%$$

$$A^{\ell\ell} = (12.3 \pm 5.4\ (\mathrm{stat}) \pm 1.5\ (\mathrm{syst}))\%.$$

[Phys. Rev. D 88, 112002 (2013)]

CDF dilepton



[CDF note 11035]

$$A_{FB}^{lep} = 0.072 \pm 0.052(\text{stat.}) \pm 0.030(\text{sys.})$$

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

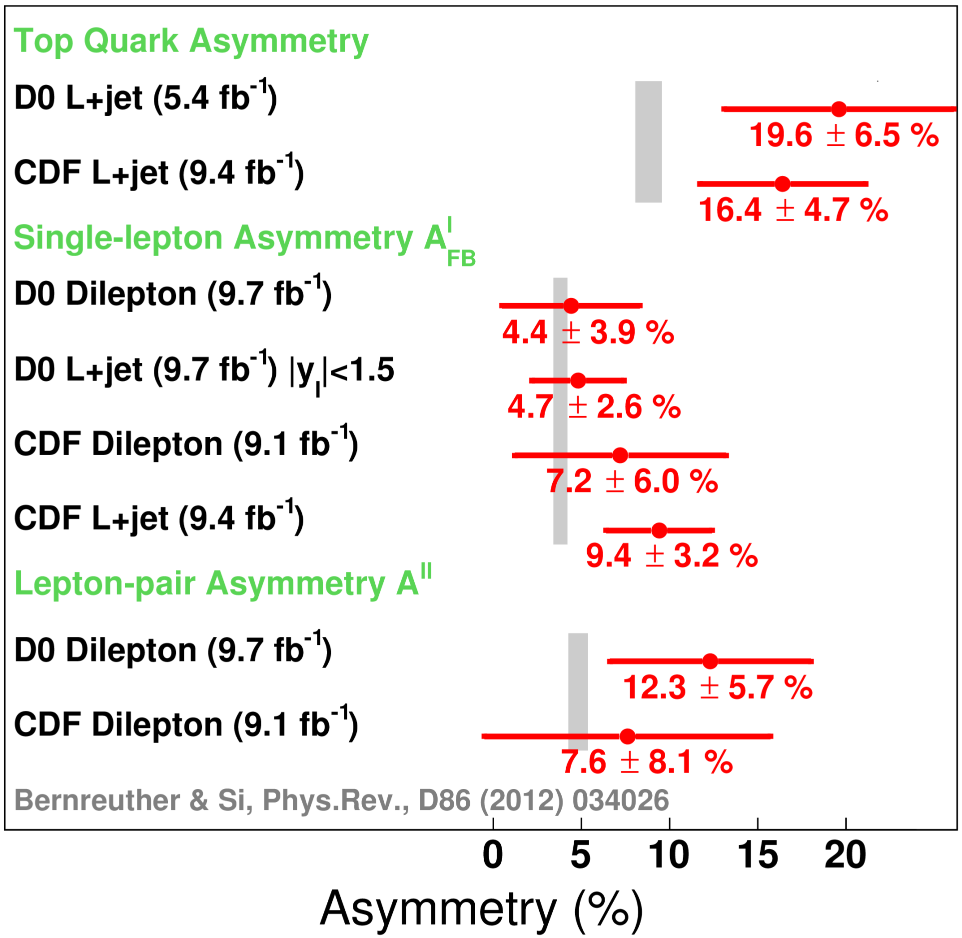
prediction : 0.038 ± 0.003 % and 0.048 ± 0.004 %

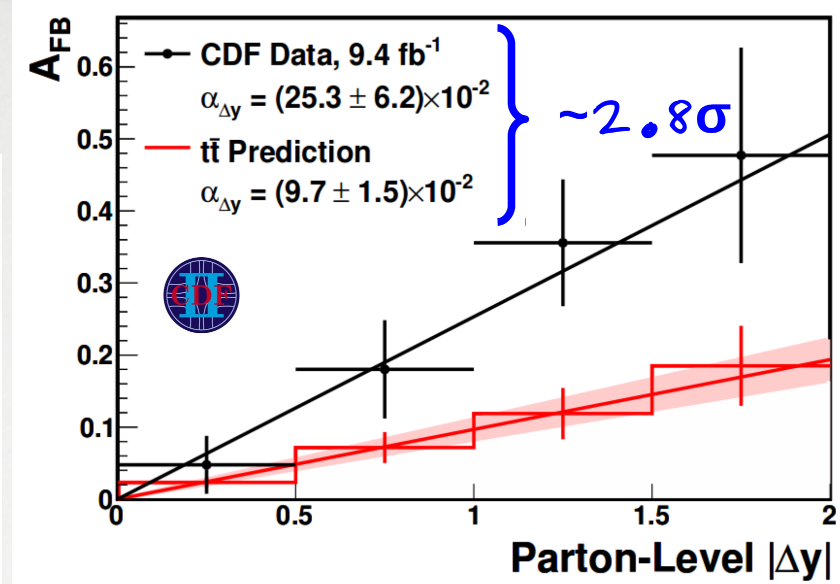
[Phys. Rev. D 88, 072003 (2013)]

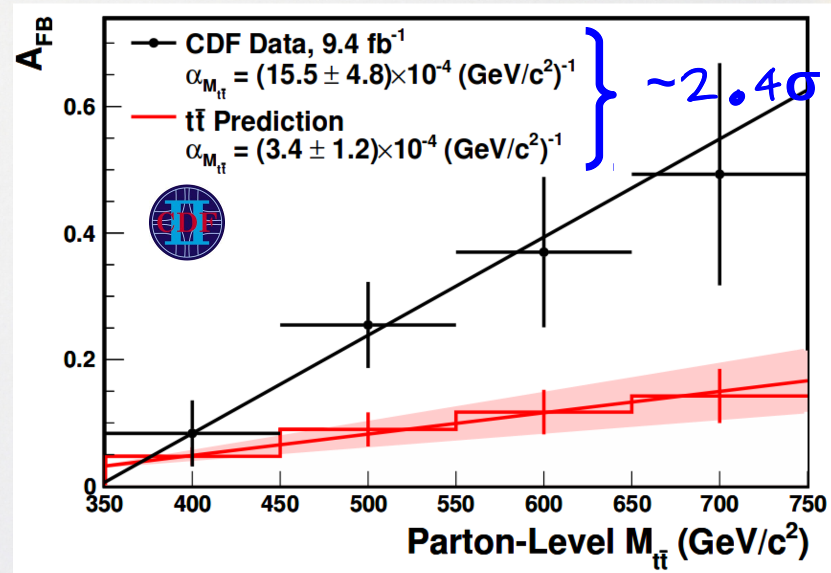
ANL lunch seminar

Tevatron measurements summary

Statistically limited ... ☹

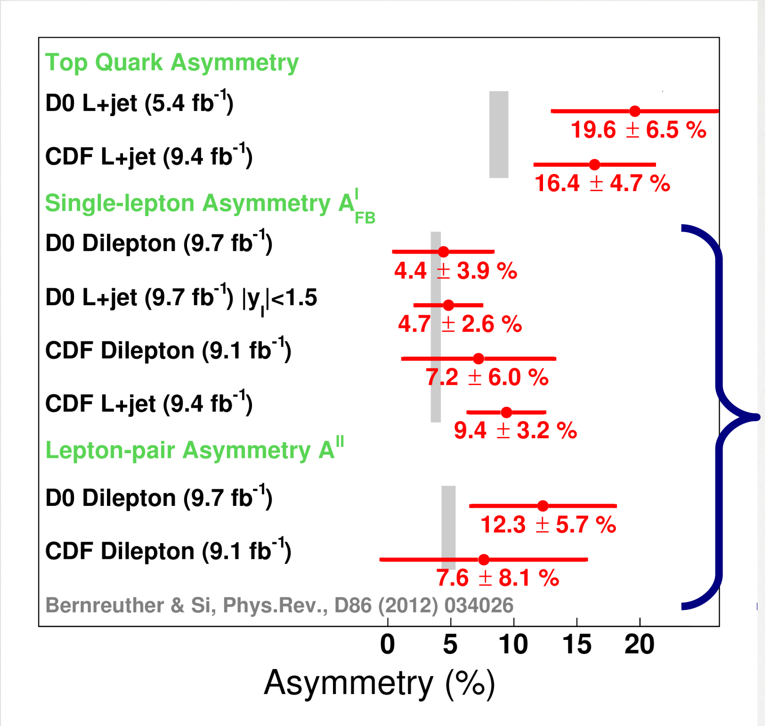






Time to **combine** → Tevatron **legacy** measurement !

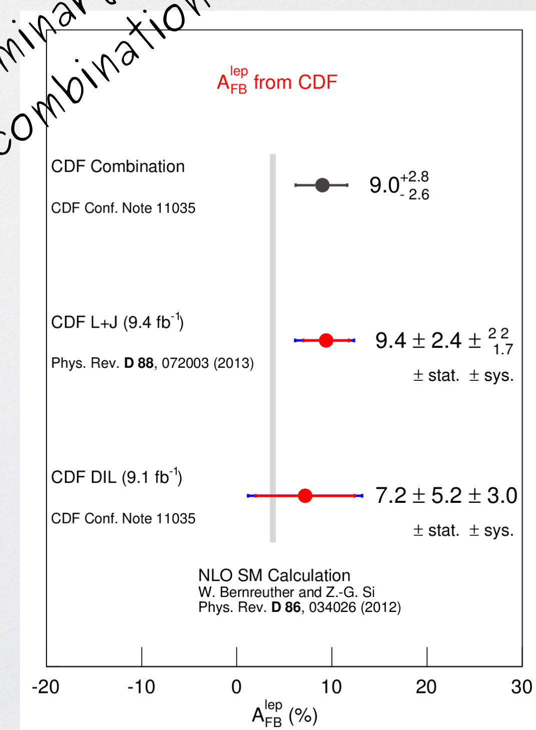
Tevatron asymmetry combination



→ New result to be released soon.

All the leptonic measurement with the full statistics are released.

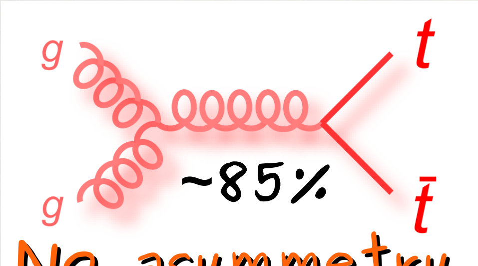
Preliminary CDF combination



CDF and D0 are working on the Tevatron combination. Expected uncertainty ~1.5 % for the single-lepton asymmetry.

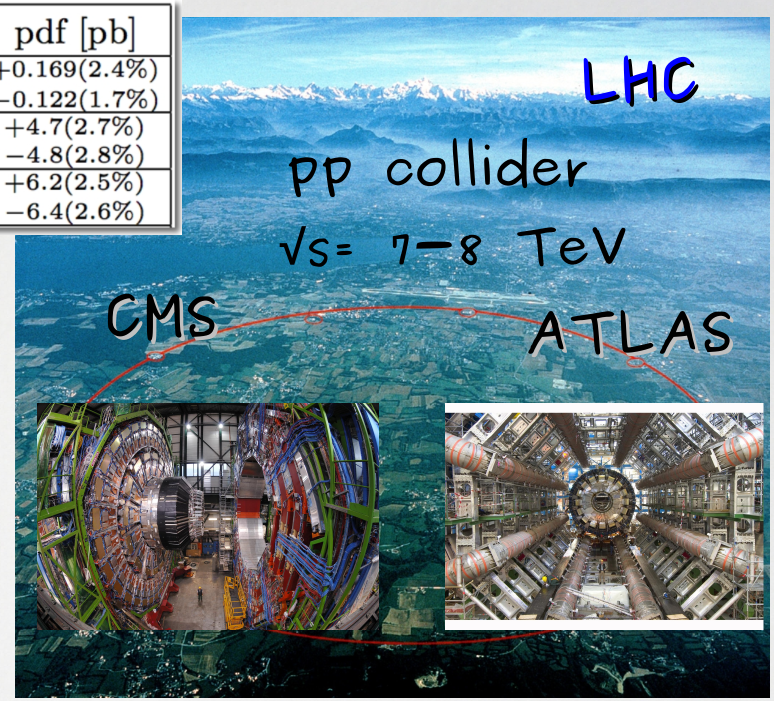
LHC measurements

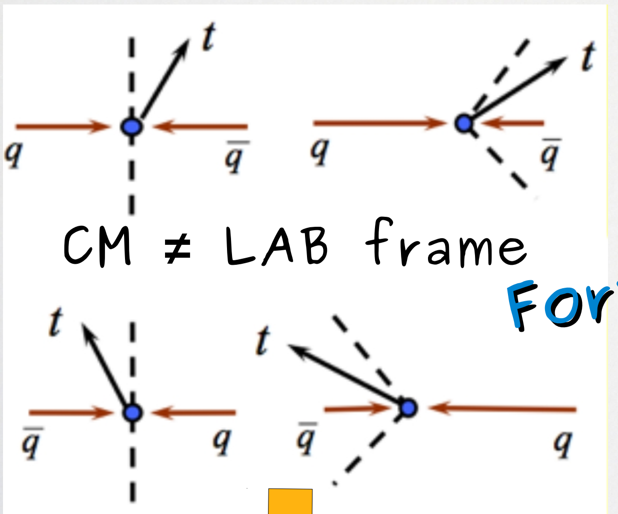
[Mitov, Czakon & Fiedler PRL 110 252004 (2013)]



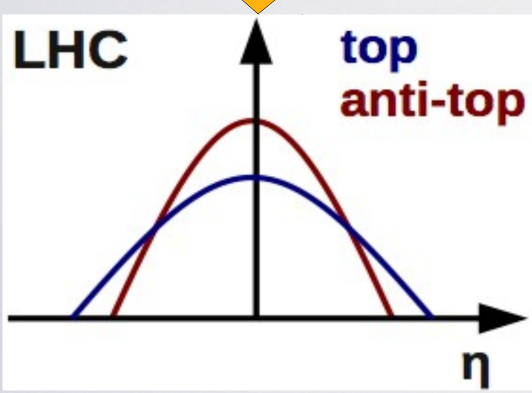
No asymmetry

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)



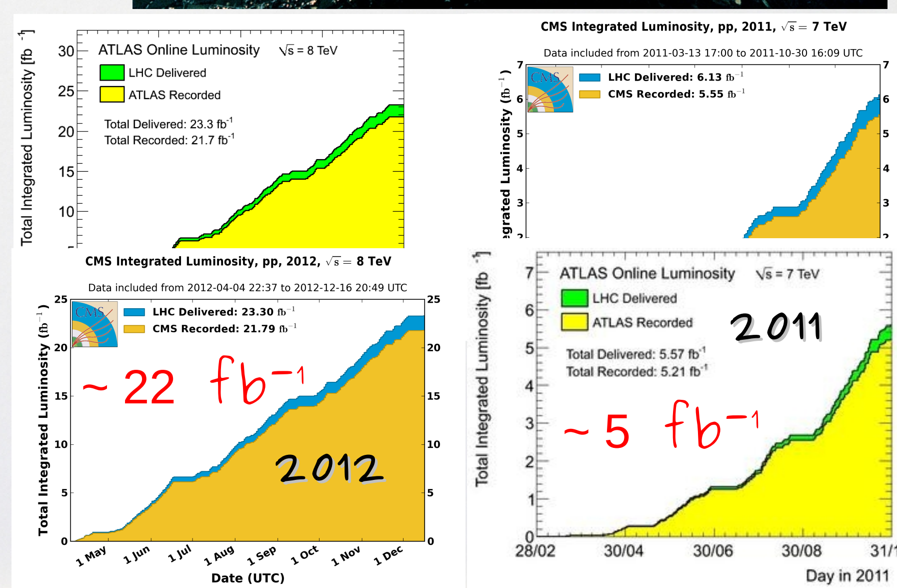


Forward-Central asymmetry



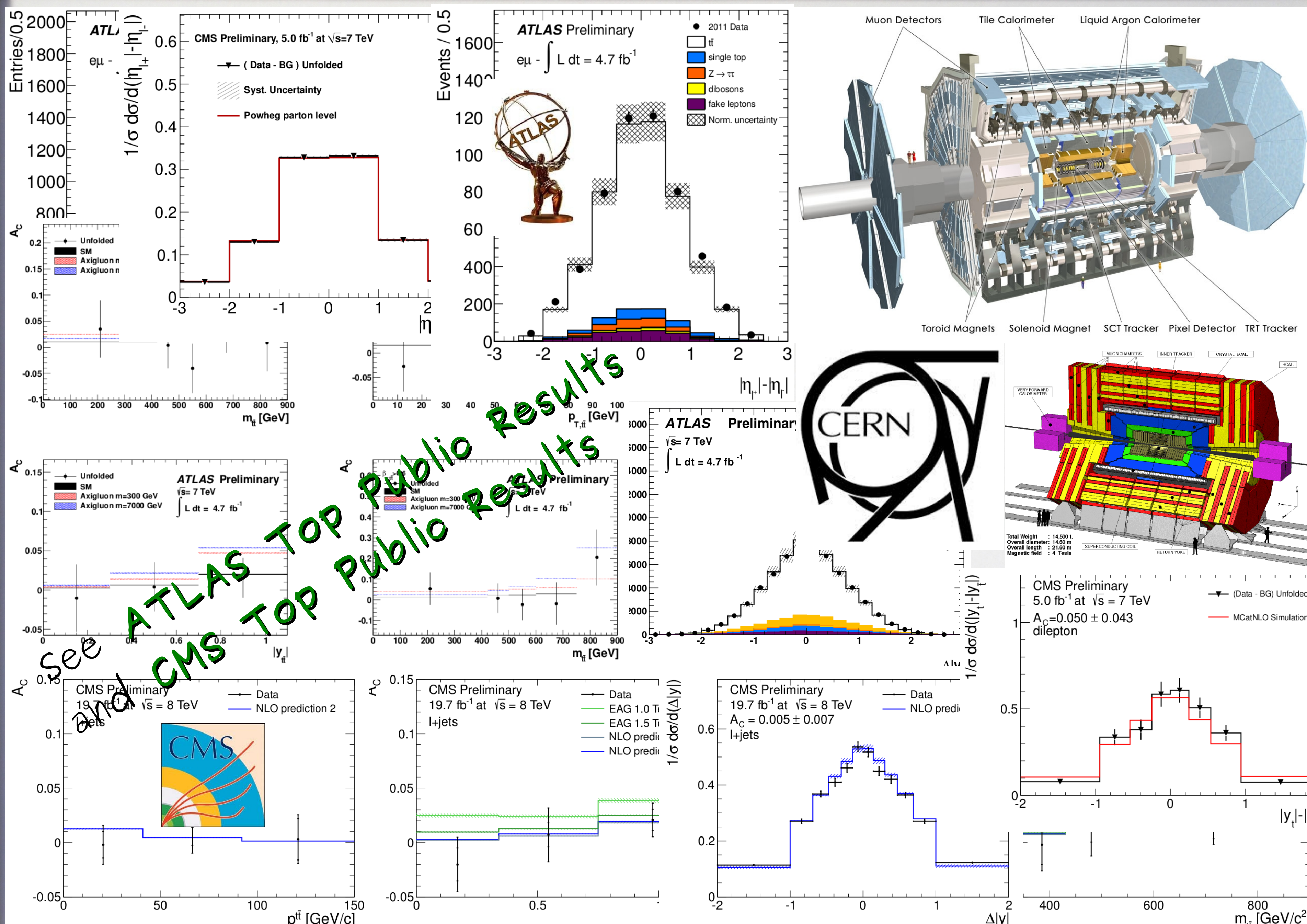
Smaller asymmetry at the LHC:

A_C 1.23±0.05%



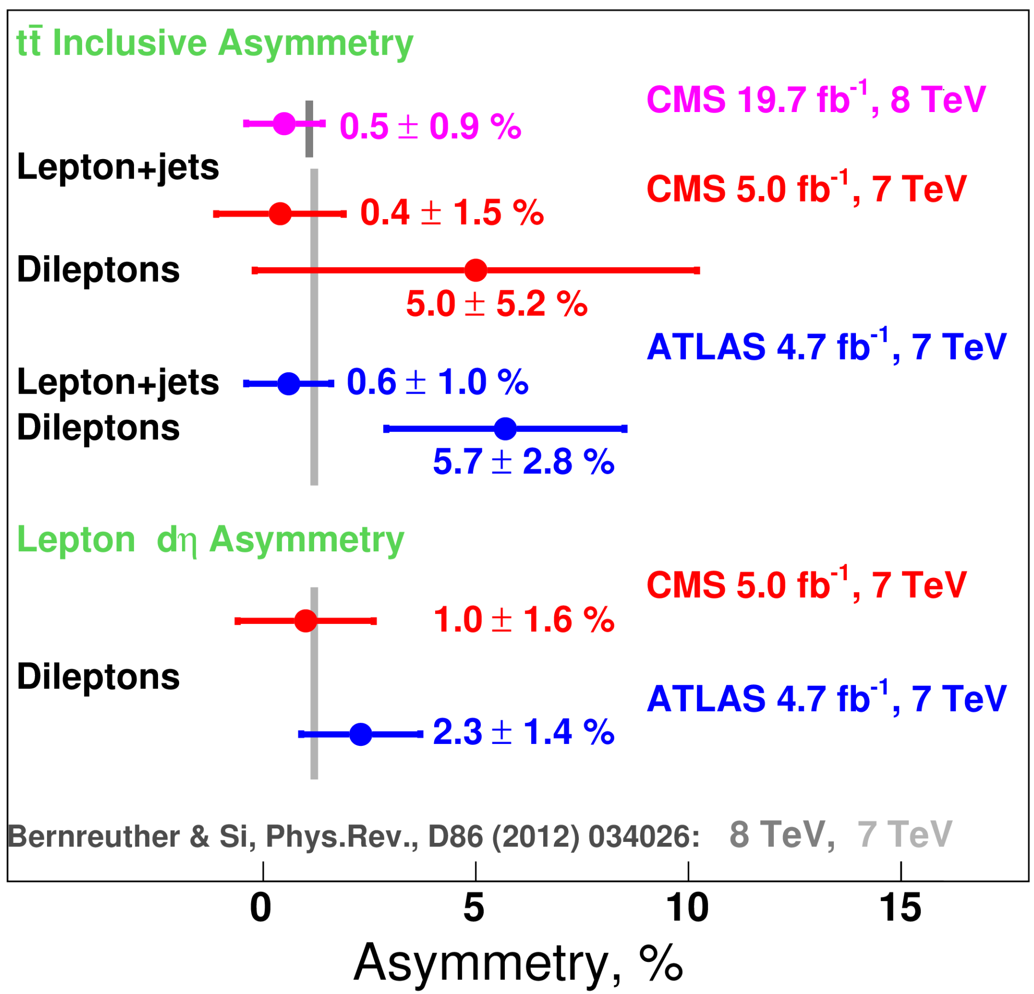
Lot of measurements ...

ANL lunch seminar



see ATLAS Top Public Results and CMS Top Public Results

LHC measurements summary

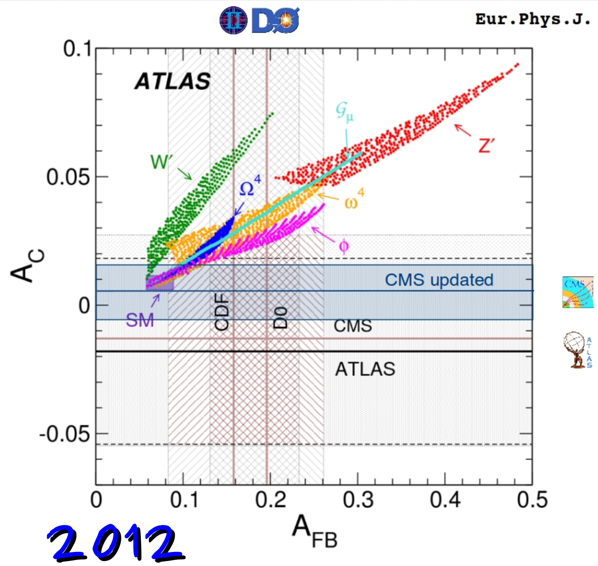


No deviations seen so far at the LHC.

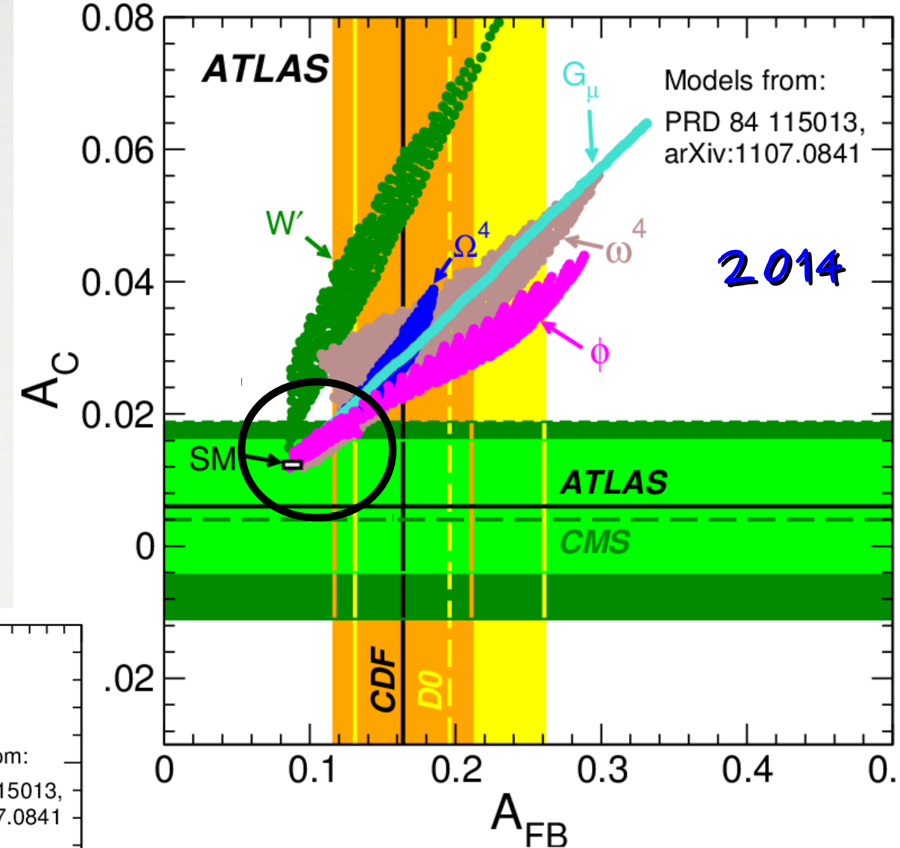
Results start to be limited by the systematic uncertainties. Need new phase space to increase the sensitivity.

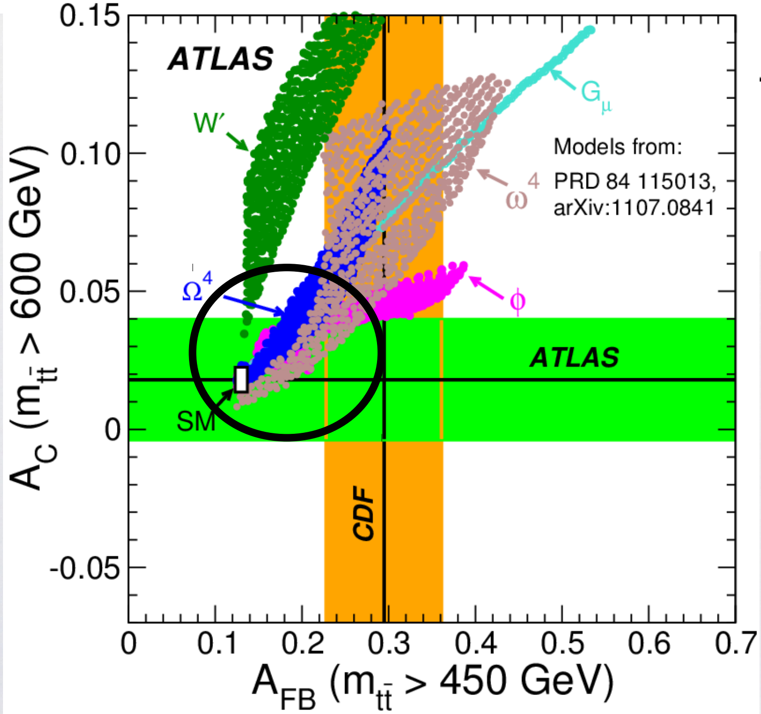
→ New physics implications ???

New physics scenarios



Eur.Phys.J. C72, 2039 (2012)





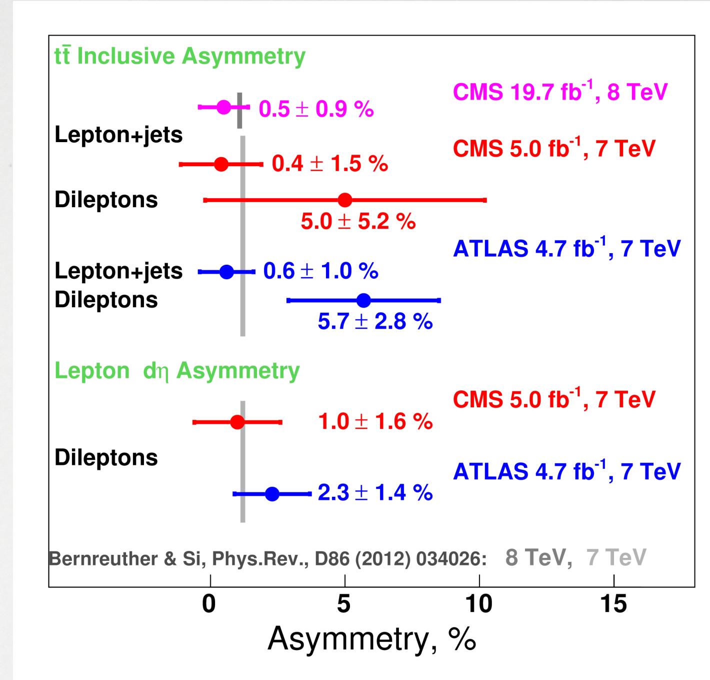
[CERN-PH-EP-2013-177]

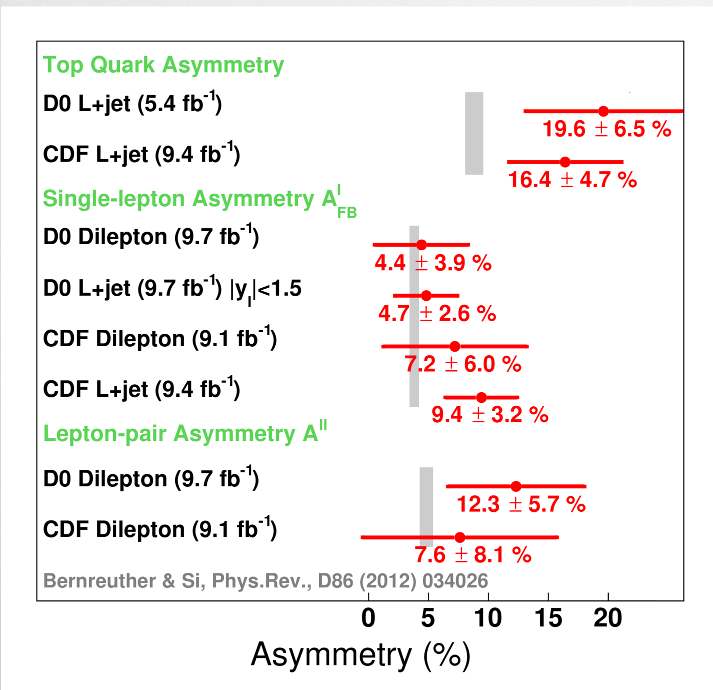
G_μ: axigluon

Conclusion & outlook

Top charge asymmetry → New physics ?

LHC : no deviations so far. Results start to be limited by the systematic uncertainties. Will need to look at special region of the phase space to increase the sensitivity.





Tevatron : 2 σ deviations (espacially at high invariant mass). Waiting for final D0 results. → need to combine CDF & D0 results to achieve the best possible sensitivity.

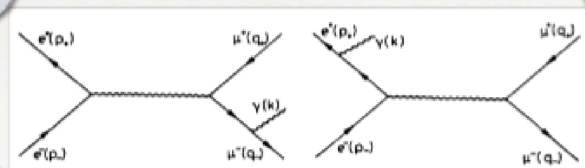
Also : wait for **NNLO** predictions !

MERCI

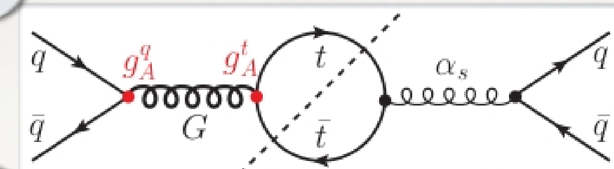
By the way: I'm on the post-doc market after June 2014 ...

Additional materials

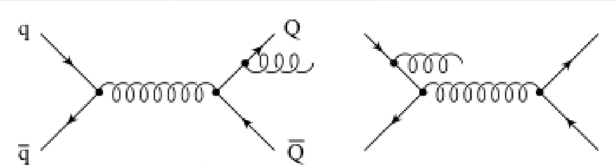
BRIEF HISTORY OF CHARGE ASYMMETRY



[Berends et al., Nucl.Phys. B63 (1973) 381]



[Antunano et al., PRD77 (2008) 014003]



[Kühn, Rodrigo, PRD59 (1999) 054017]

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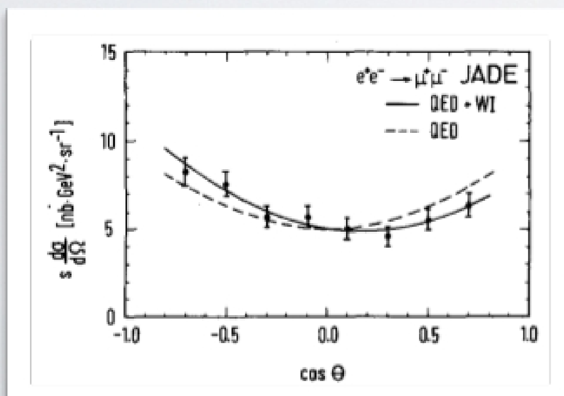
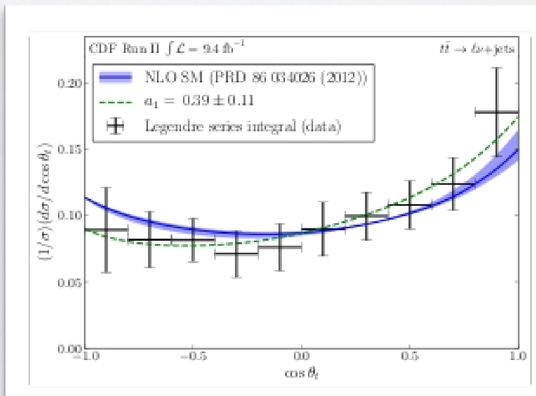
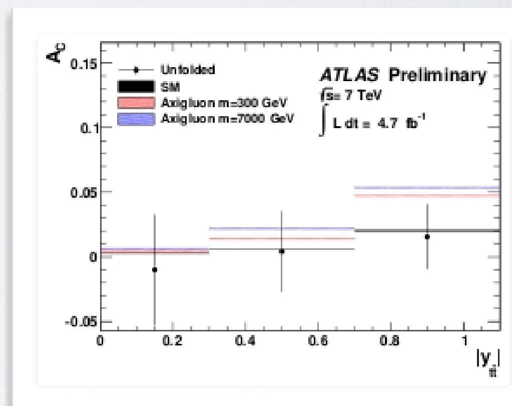
TOP2013, Germany



PETRA @ DESY



Tevatron @ Fermilab



LHC @ CERN

2

Axigluon constraints

* Dijet and top pair production.

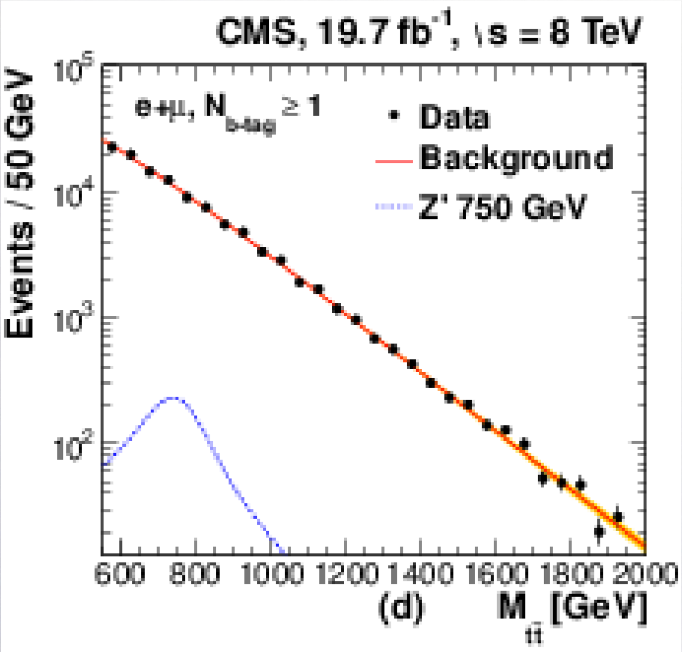
* LHC charge asymmetry.

* Electroweak precision observable.

[Bai et al., JHEP1103 (2011) 003]

[Haisch, Westhoff, JHEP1108 (2011) 088]

[Gresham, Shelton, Zurek, JHEP1303 (2013) 008]



CMS M(ttbar) measurement

AXIGLUON SURVIVORS

Heavy, flavor-sensitive:

$$M_G \approx 2\,\mathrm{TeV}$$
$$g_A^q = -g_A^t \sim 1.0\,g_s$$

Light, broad, flavor-universal:

$$200 \lesssim M_G \lesssim 450\,\mathrm{GeV}$$
$$g_A^q = g_A^t \sim 0.3\,g_s$$

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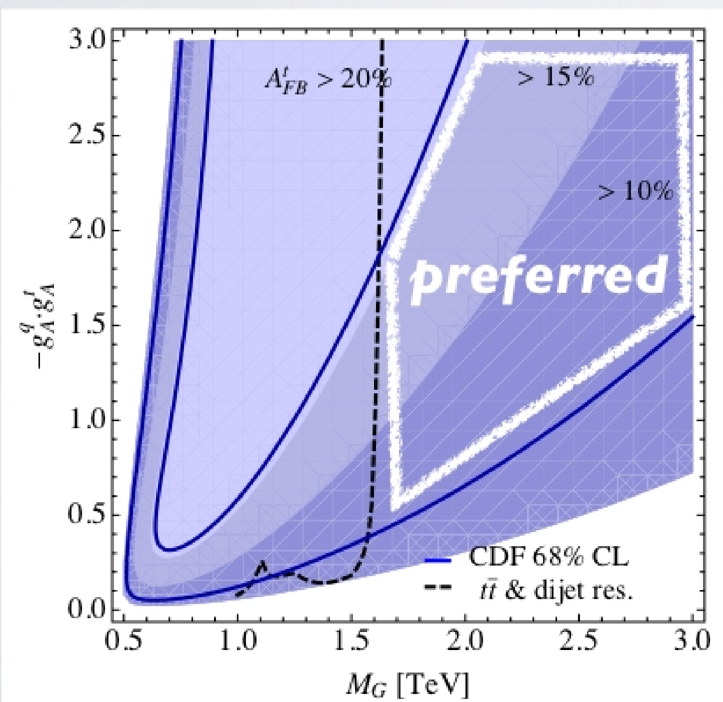
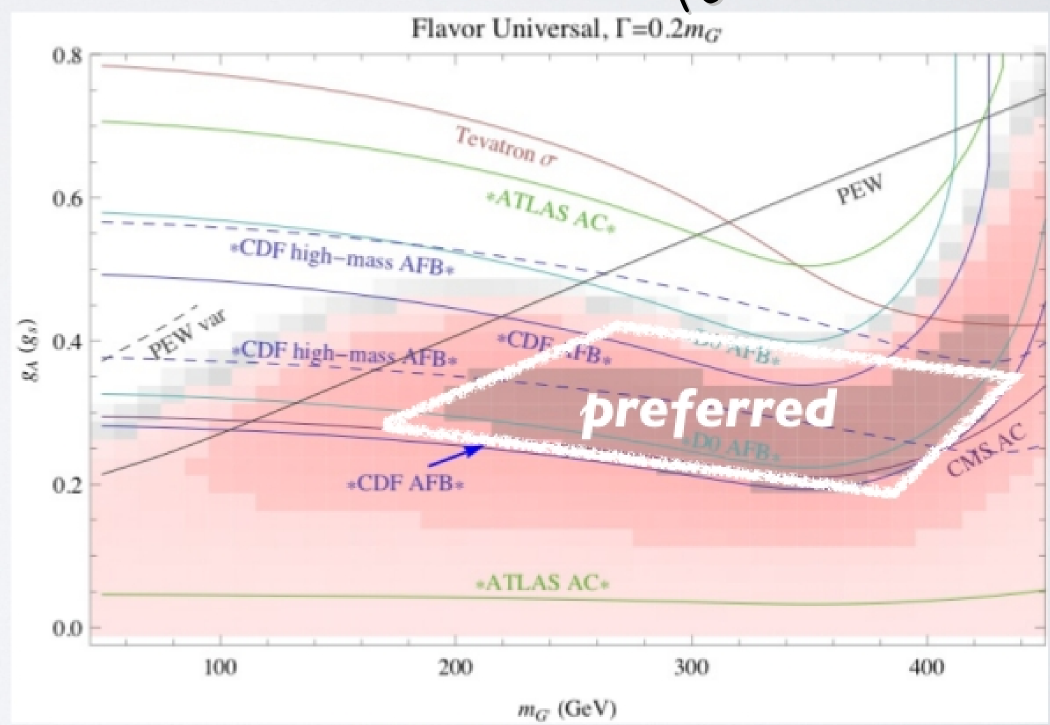
TOP2013, Germany



[Haisch, Westhoff, JHEP1108 (2011) 088 updated]



[Gresham, Shelton, Zurek, JHEP1303 (2013) 008]

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SM predictions

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]	$7.24^{+1.04+0.20}_{-0.67-0.27}$	$4.88^{+0.20+0.17}_{-0.23-0.18}$
$NNLO_{approx}$ [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

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

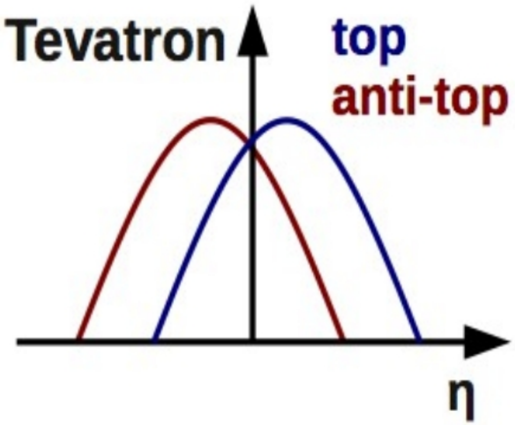
Extra photonic corrections

NLO(QCD+EW) [Bernreuther, Si, '12] 8.8±0.6

NLO PDFs in numerator, mixed QCD and EW corrections

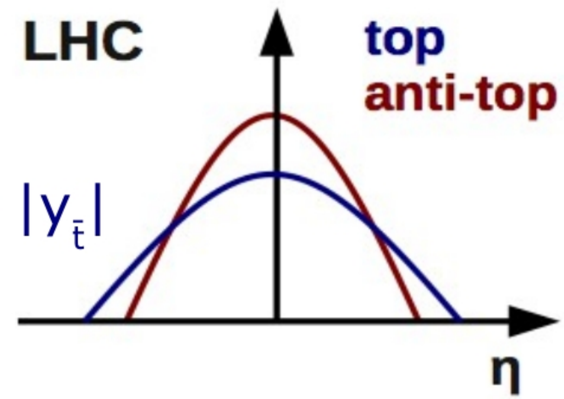
LHC measurements

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



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

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

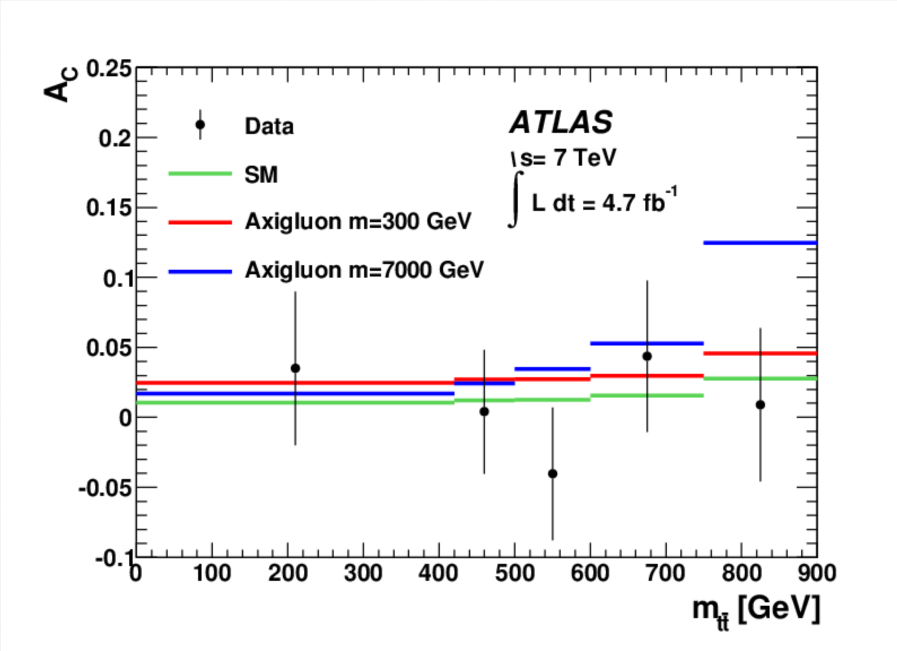


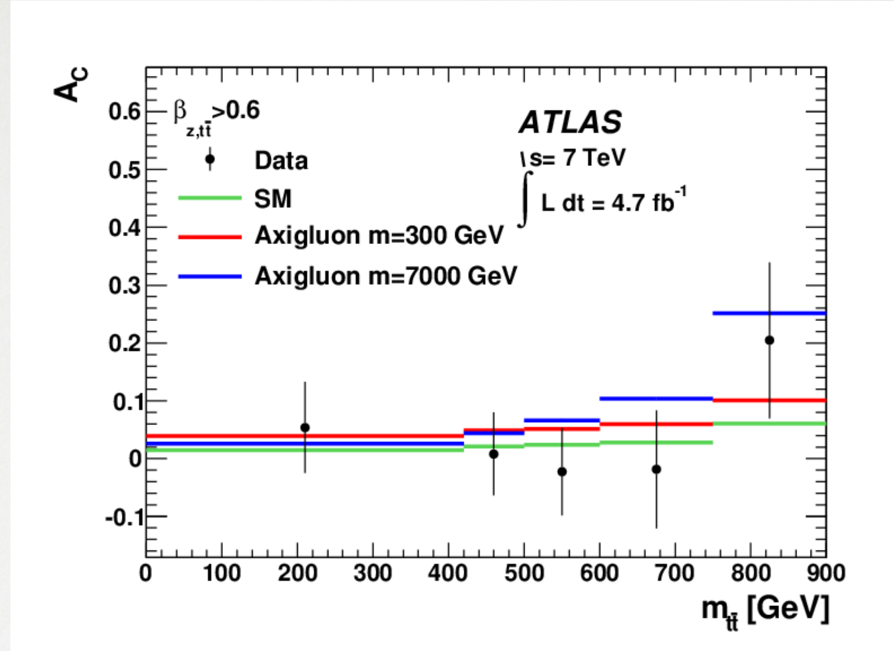
Special region of the phase space

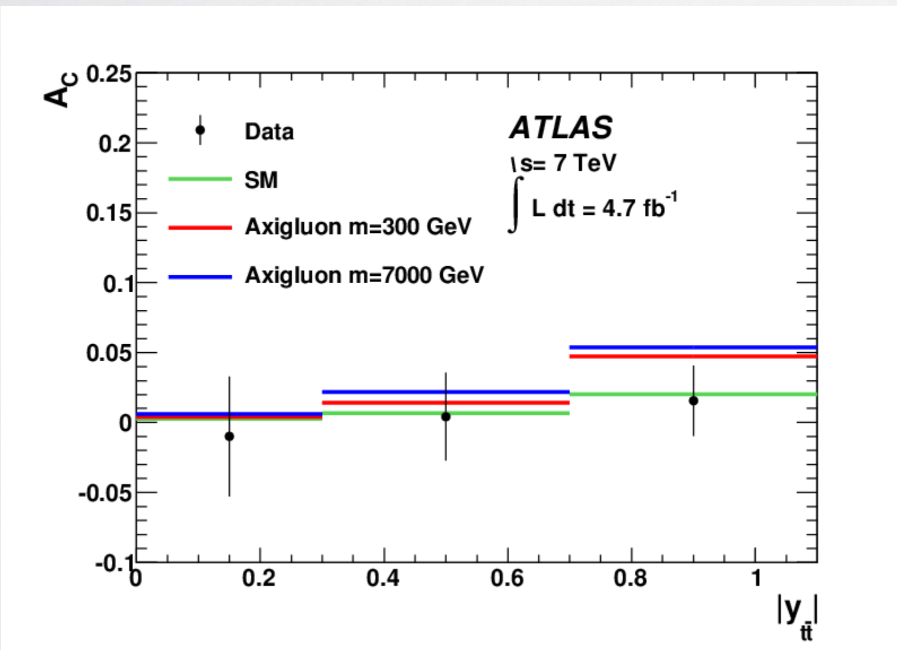
- A_C versus $p_{T,ttbar}$
- A_C versus m_{ttbar}
- A_C versus $\beta_{z,ttbar}$

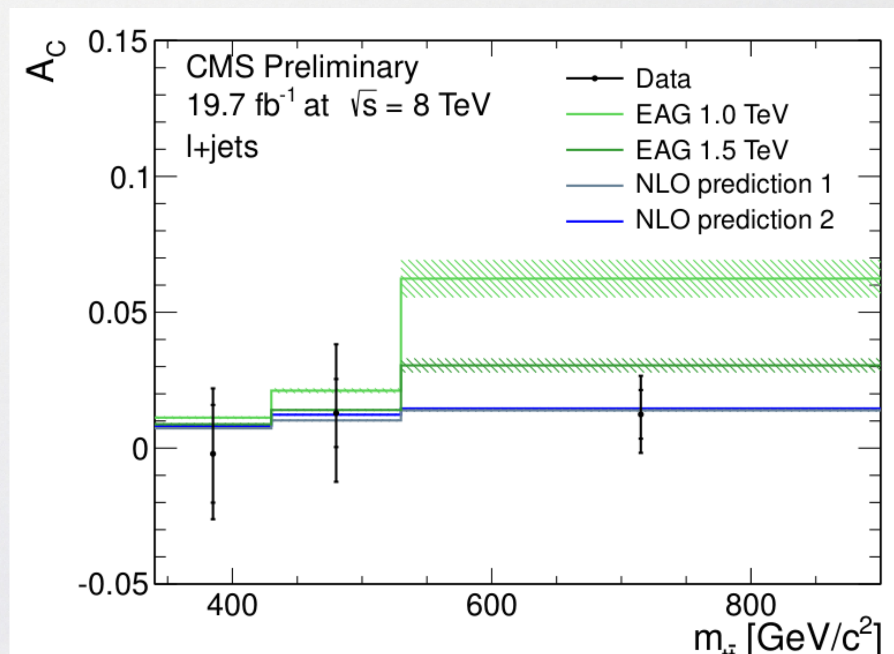
=> more sensitive to new physics models.

LHC measurements









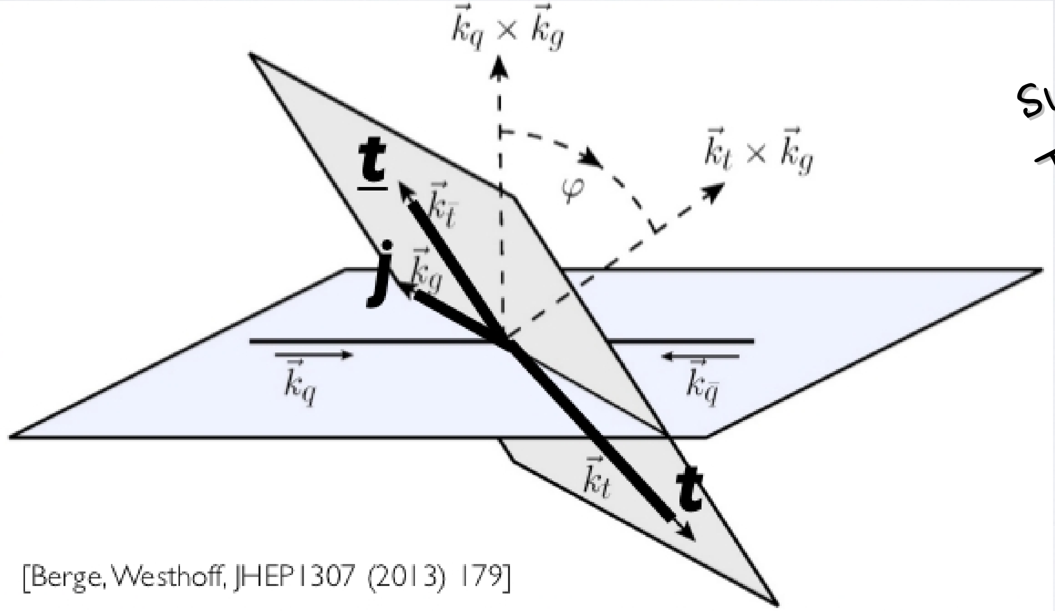
ANL lunch seminar

CHARGE ASYMMETRY WITH A JET HANDLE

Probe asymmetry at LO QCD by exploiting jet kinematics:

$$d\hat{\sigma}_A(q\bar{q} \to t\bar{t}j) = \left[d\hat{\sigma}(t\bar{t}) - d\hat{\sigma}(\bar{t}t)\right](\theta_j, E_j, \varphi, \Delta E), \quad \Delta E = E_t - E_{\bar{t}}$$

Susanne Westhoff
TOP2013, Germany



[Berge, Westhoff, JHEP1307 (2013) 179]

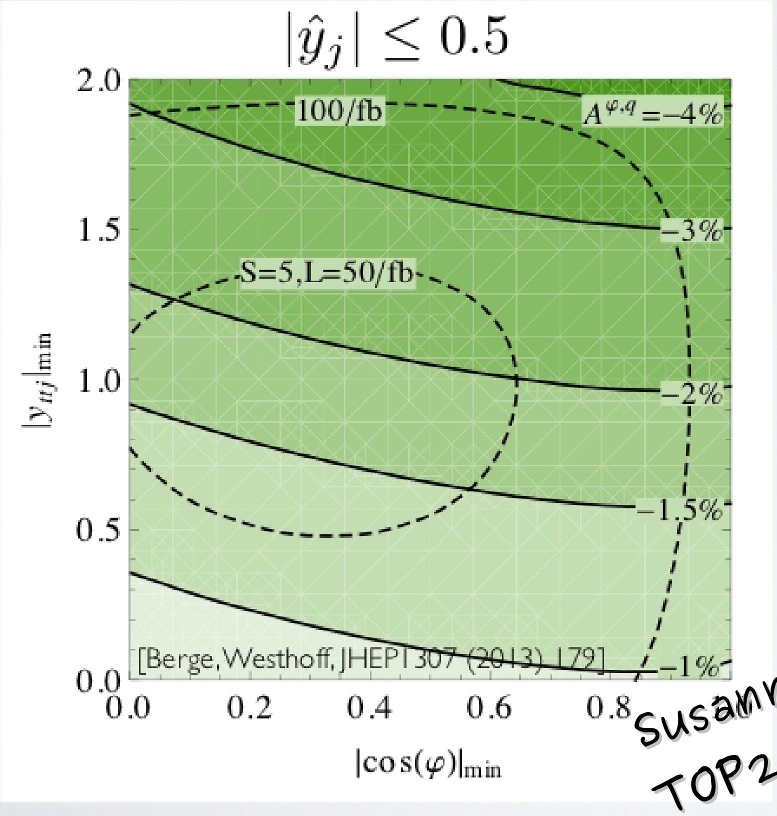
$q\bar{q}$ channel: incline asymmetry $\frac{d\hat{\sigma}_A^{\varphi}}{d\theta_j} = \frac{d\hat{\sigma}(\cos\varphi > 0)}{d\theta_j} - \frac{d\hat{\sigma}(\cos\varphi < 0)}{d\theta_j}$

qg channel: energy asymmetry $\frac{d\hat{\sigma}_A^{E}}{d\theta_j} = \frac{d\hat{\sigma}(\Delta E > 0)}{d\theta_j} - \frac{d\hat{\sigma}(\Delta E < 0)}{d\theta_j}$

NEW OBSERVABLES AT LHC @ 14 TEV

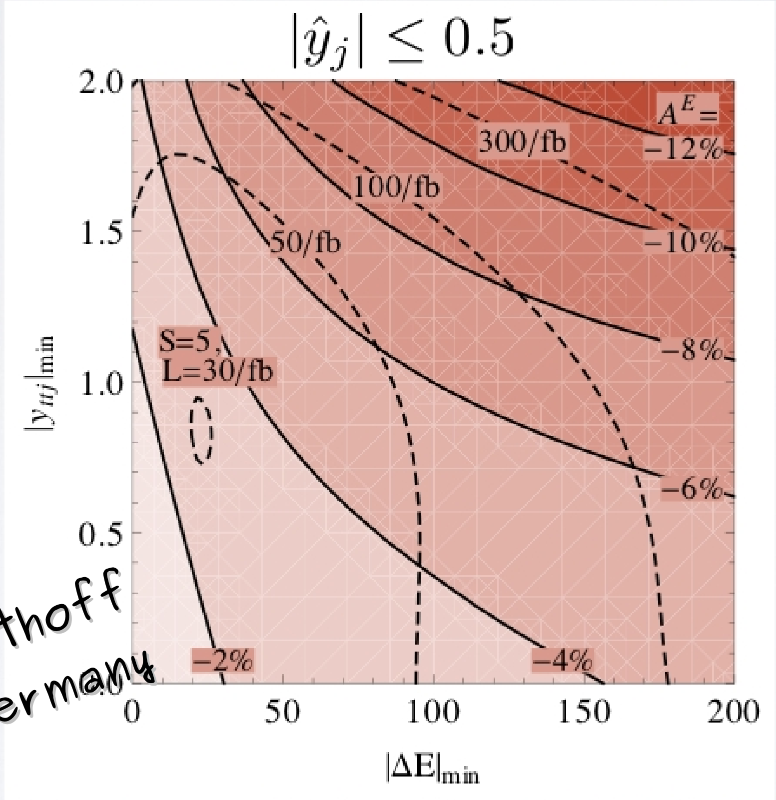
Incline asymmetry:

$$A^{\varphi,q} = \frac{\sigma_A^{\varphi}(y_{t\bar{t}j} > 0) - \sigma_A^{\varphi}(y_{t\bar{t}j} < 0)}{\sigma_S}$$



Energy asymmetry:

$$A^E = \frac{\sigma_A^E}{\sigma_S} = \frac{\sigma(\Delta E > 0) - \sigma(\Delta E < 0)}{\sigma(\Delta E > 0) + \sigma(\Delta E < 0)}$$



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TOP2013, Germany

Good discovery potential during first run at 14 TeV.

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ANL lunch seminar

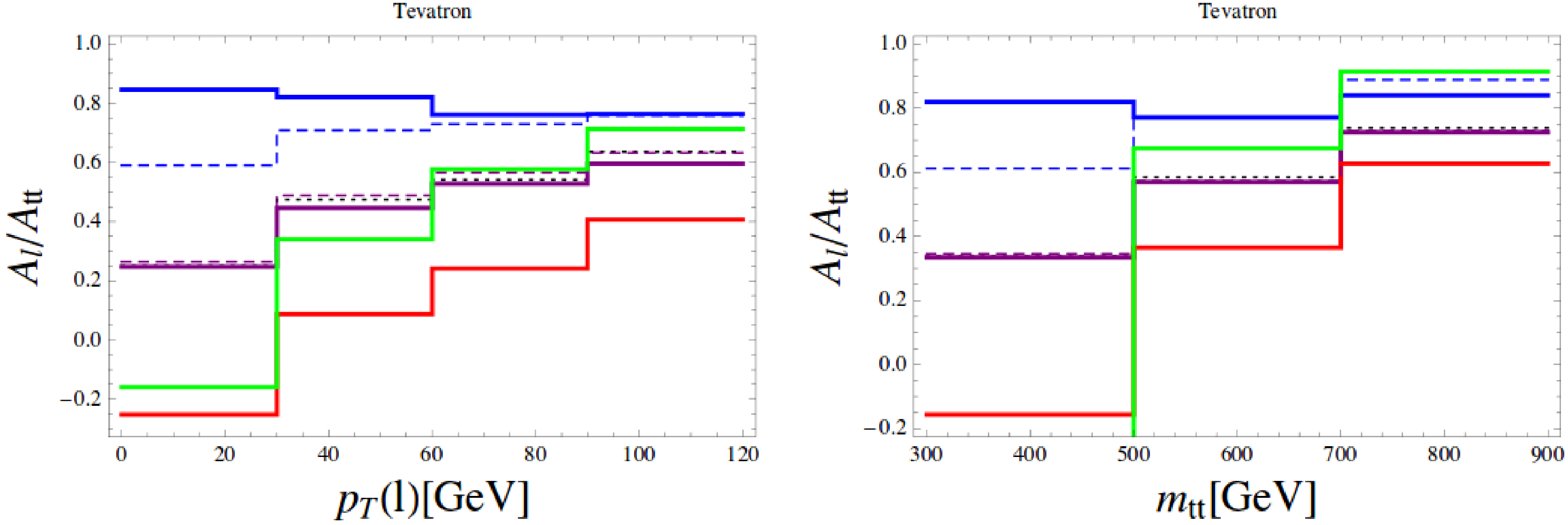


Figure 8: Distribution of the ratio $A_\ell/A_{t\bar{t}}$ at the Tevatron as a function of $p_{T,\ell}$ (left) and $m_{t\bar{t}}$ (right) for the SM (dotted black) and for the BSM benchmarks studied in this paper: Axi200R (solid blue), Axi200L (solid red), Axi200A (solid purple), Axi2000R (dashed blue), Axi2000A (dashed purple), and Zp220 (solid green).

[Falkowski et al. arXiv:1401.2443 [hep-ph]]

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

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

$$\Delta|y|^{tl} \equiv \begin{cases} |y_{l+}| - |y_{\bar{t}}|, & \text{for leptonic top decays} \\ |y_t| - |y_{l-}|, & \text{for leptonic anti-top decays} \end{cases}$$

Generated asymmetry

[Phys. Rev. D 87, 092002 (2013))]

TABLE I. Parton-level asymmetry predictions of POWHEG, MC@NLO, and MCFM after applying electroweak corrections.

	MC@NLO	POWHEG	MCFM
Inclusive	0.067 ± 0.020	0.066 ± 0.020	0.073 ± 0.022
$\lvert\Delta y\rvert < 1$	0.047 ± 0.014	0.043 ± 0.013	0.049 ± 0.015
$\lvert\Delta y\rvert > 1$	0.130 ± 0.039	0.139 ± 0.042	0.150 ± 0.045
$M_{t\bar{t}} < 450$ GeV$/c^2$	0.054 ± 0.016	0.047 ± 0.014	0.050 ± 0.015
$M_{t\bar{t}} > 450$ GeV$/c^2$	0.089 ± 0.027	0.100 ± 0.030	0.110 ± 0.033

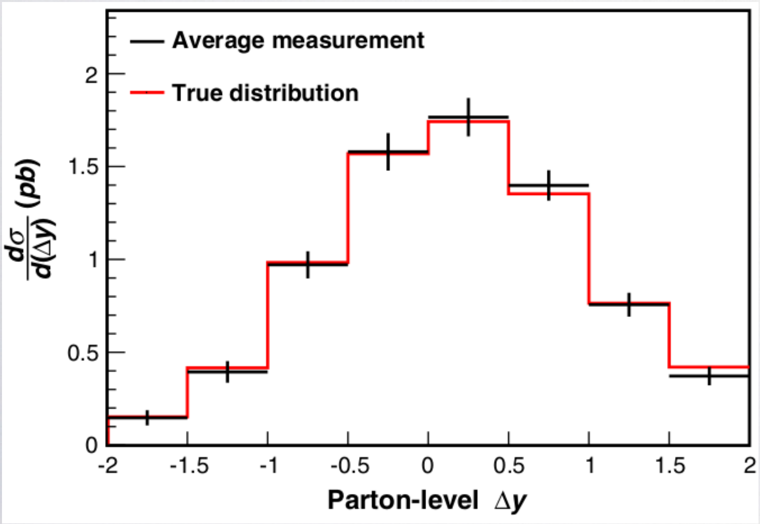
Unfolding & regularization

Correct for acceptance and detector effects back to the parton (production) level.

$$\vec{n}_{meas} \propto S.A.\vec{n}_{parton} \quad \Rightarrow \quad \vec{n}_{parton} = S^{-1} A^{-1} \vec{n}_{meas}$$

Add a regularization term to limit the statistical fluctuations:

$$\vec{n}_{parton} = S^{-1} \tau^{1/2} C A^{-1} \vec{n}_{meas}$$



prior condition due to an expecting behavior, e.g.: smooth distribution.

strength of the regularization

CDF l+jets ttbar asymmetry uncertainties

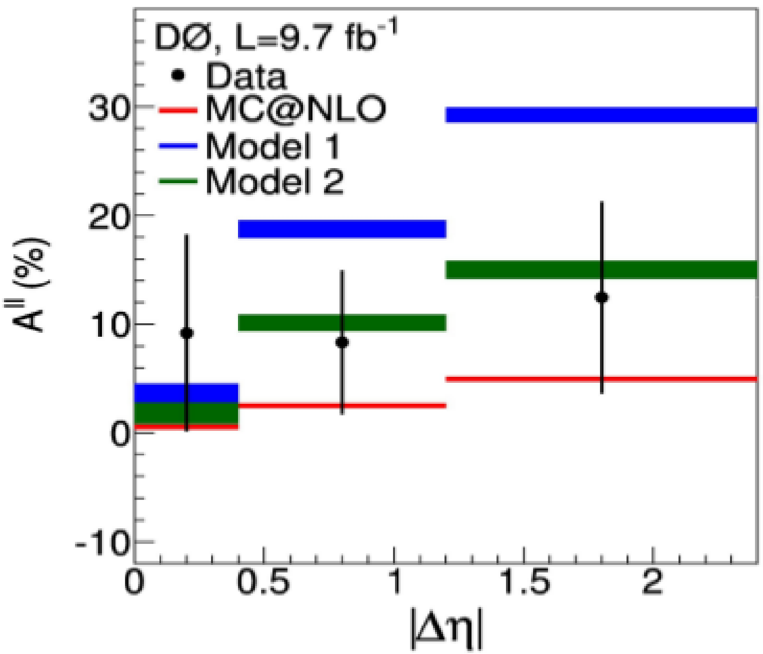
TABLE V. Systematic uncertainties on the parton-level A_{FB} measurement.

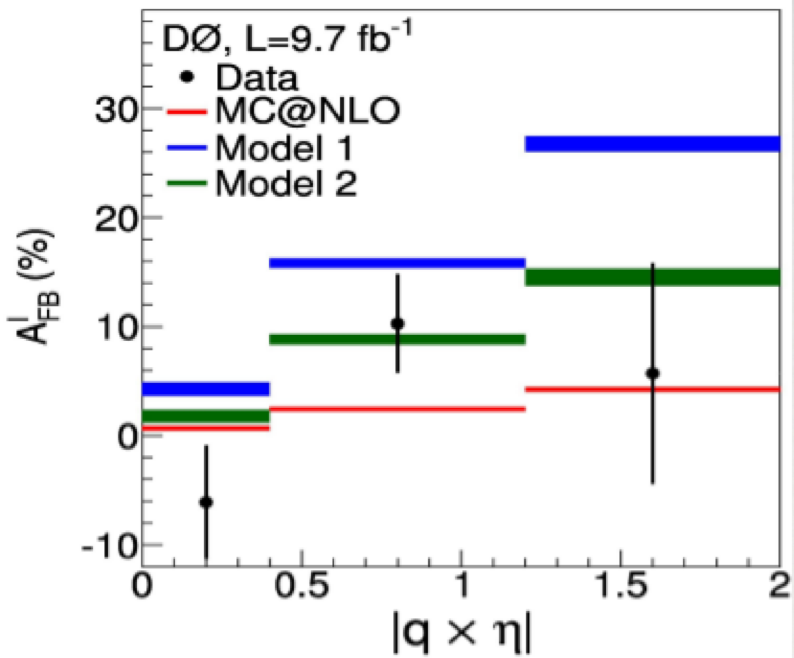
Source	Uncertainty
Background shape	0.018
Background normalization	0.013
Parton shower	0.010
Jet energy scale	0.007
Initial- and final-state radiation	0.005
Correction procedure	0.004
Color reconnection	0.001
Parton-distribution functions	0.001
Total systematic uncertainty	0.026
Statistical uncertainty	0.039
Total uncertainty	0.047

CDF l+jets lept asymmetry uncertainties

Source of Uncertainty	Value
Backgrounds	0.015
Recoil Modeling	+0.013 −0.000
Color Reconnection	0.0067
Parton Showering	0.0027
PDF	0.0025
JES	0.0022
IFSR	0.0018
Total Systematic	+0.021 −0.017
Data Statistics	0.024
Total Uncertainty	+0.032 −0.029

D0 dilepton asymmetry





	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

ATLAs l+jets ttbar asymmetry uncertainties

Source of systematic uncertainty	δA_C	
	Inclusive	$m_{t\bar{t}} > 600$ GeV
Lepton reconstruction/identification	< 0.001	0.001
Lepton energy scale and resolution	0.003	0.003
Jet energy scale and resolution	0.003	0.003
Missing transverse momentum and pile-up modelling	0.002	0.002
Multijet background normalisation	< 0.001	0.001
b-tagging/mis-tag efficiency	< 0.001	0.001
Signal modelling	< 0.001	< 0.001
Parton shower/hadronisation	< 0.001	< 0.001
Monte Carlo statistics	0.002	< 0.001
PDF	0.001	< 0.001
W+jets normalisation and shape	0.002	< 0.001
Statistical uncertainty	0.010	0.021

Table 3: List of systematic uncertainties for the inclusive asymmetry (central column) and the asymmetry with the $m_{t\bar{t}} > 600$ GeV requirement (right column). For variations resulting in asymmetric uncertainties, the average absolute deviation from the nominal value is reported. The values reported for each systematic uncertainty are the variation of the mean of posteriors computed considering 1σ variations.

CMS l+jets ttbar asymmetry uncertainties

Systematic uncertainty	shift in inclusive A_C	range of shifts in differential A_C
JES	0.001	0.001 – 0.005
JER	0.001	0.001 – 0.005
Pileup	0.001	0.000 – 0.003
b tagging	0.000	0.001 – 0.003
Lepton ID/sel. efficiency	0.002	0.001 – 0.003
Generator	0.003	0.001 – 0.015
Hadronization	0.000	0.000 – 0.016
p_T weighting	0.001	0.000 – 0.003
Q^2 scale	0.003	0.000 – 0.009
W+jets	0.002	0.001 – 0.007
Multijet	0.001	0.002 – 0.009
PDF	0.001	0.001 – 0.003
Unfolding	0.002	0.001 – 0.004
Total	0.006	0.007 – 0.022

CDF extrapolation

$$\mathcal{S}(qy_\ell) = \frac{N(qy_\ell) + N(-qy_\ell)}{2}$$

$$\mathcal{A}(qy_\ell) = \frac{N(qy_\ell) - N(-qy_\ell)}{N(qy_\ell) + N(-qy_\ell)},$$

→

$$\mathcal{F}(qy_\ell) = a \tanh\left(\frac{qy_\ell}{2}\right)$$

Asym (full phase space) $= \dfrac{\int_0^\infty dqy_\ell \left[\mathcal{A}(qy_\ell) \times \mathcal{S}(qy_\ell)\right]}{\int_0^\infty dqy_\ell \mathcal{S}(qy_\ell)}$

This is the sum of the asymmetry values in the different bins weighted by the fraction of events in these bins.