Forward-backward asymmetry in $p\bar{p} \to t\bar{t}$ events at the Tevatron

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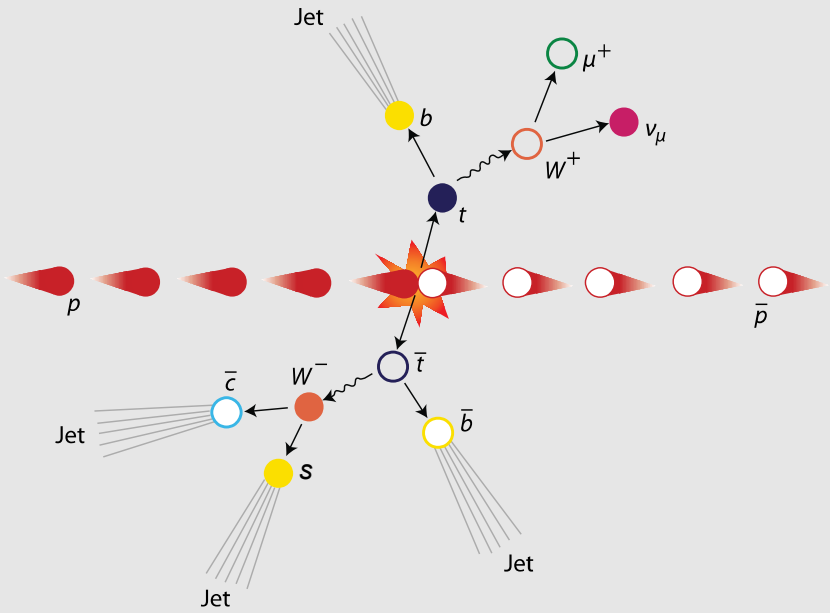
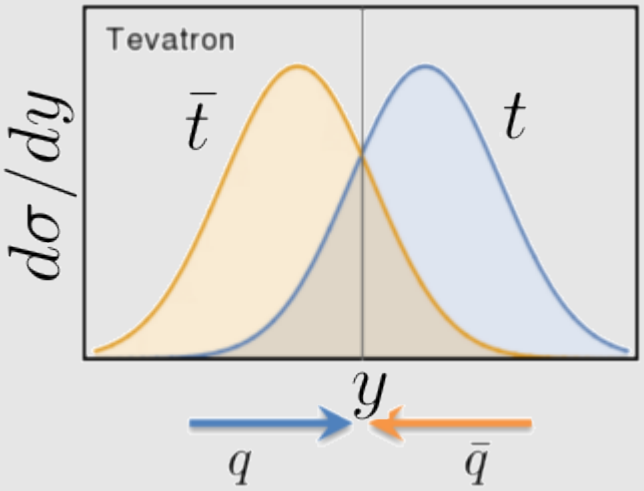
for
the CDF and DZero Collaborations

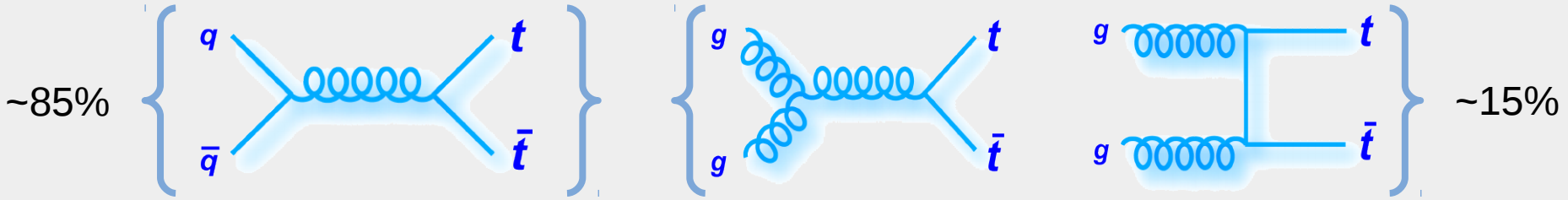
ICHEP 2018





Producing tops @ Tevatron

Run II data (2001-2011): $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV
- ~12 fb^{-1} delivered per experiment
- ~10 fb^{-1} for analysis
- Largest, highest energy $p\bar{p}$ data set



- At the Tevatron top mostly produced in pairs via $q\bar{q}$ annihilation
→ a unique data set for the top quark studies
- LHC: 80-90% gluon fusion

Cross-section (NNLO +NNLL QCD for m_t=172.5 GeV):

$$\sigma_{t\bar{t}} = 7.35^{+0.23}_{-0.27}\ \mathrm{pb}$$

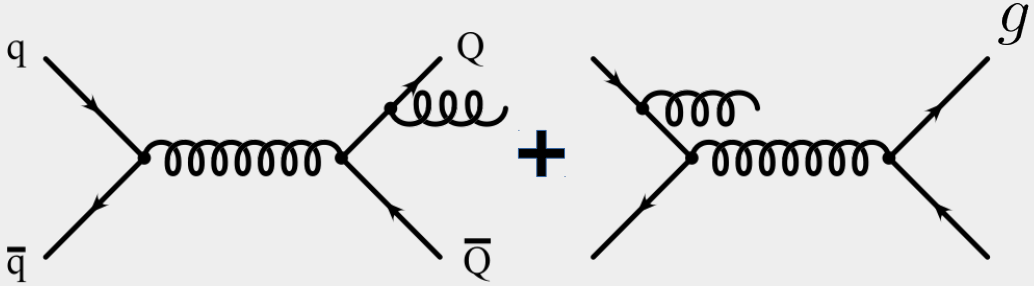
Czakon,Fiedler and Mitov, PRL **110** (2013) 252004
Czakon and Mitov, Comput. Phys. Commun. **185** (2014) 2930

$t\bar{t}$ production asymmetry

Differential distributions of heavy flavor produced in lowest order processes are symmetric for quark and antiquark final states

$$q + \bar{q} \rightarrow Q + \bar{Q}$$
$$g + g \rightarrow Q + \bar{Q}$$

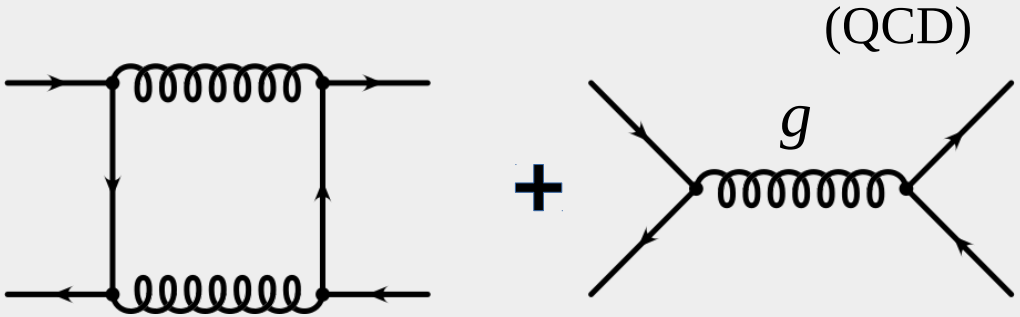
Negative asymmetry



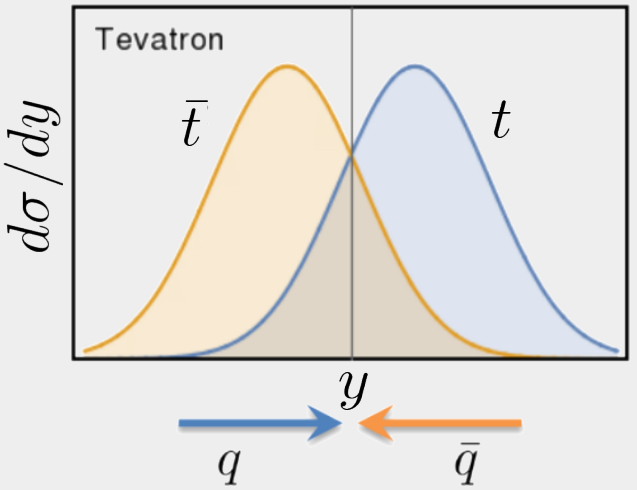
Interference with diagrams having real or virtual gluon emission have sizeable effect on Q, $\bar{Q}$ production

=> production charge asymmetry

Positive asymmetry



(EW)
or Z/γ*
non-neglegible



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Differential distributions of heavy flavor produced in lowest order processes are symmetric for quark and antiquark final states

$$q + \bar{q} \rightarrow Q + \bar{Q}$$
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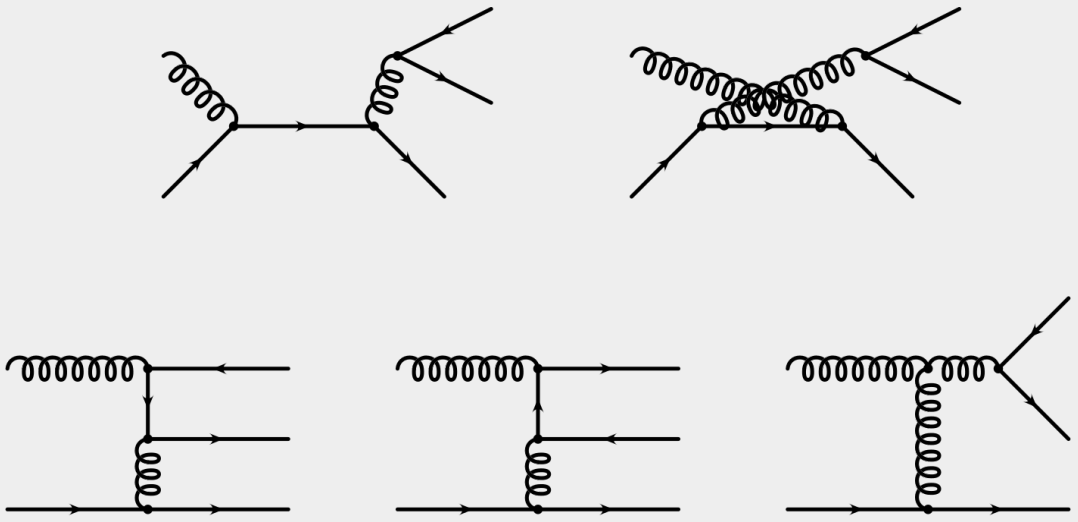
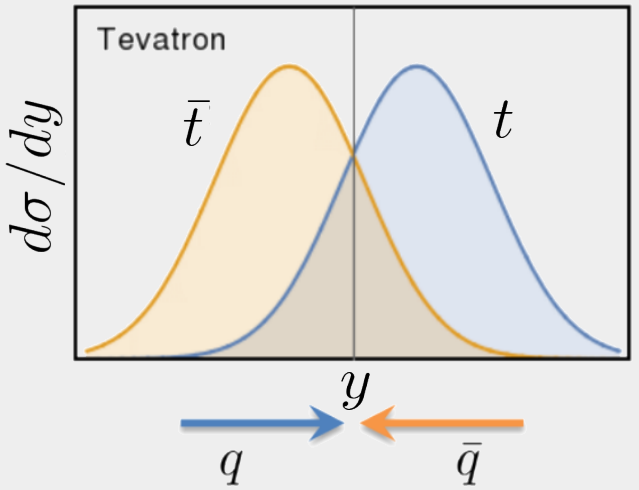
Additional contributions to asymmetry in production of heavy quarks through flavor excitation:

$$g + q \rightarrow Q + \bar{Q} + q$$





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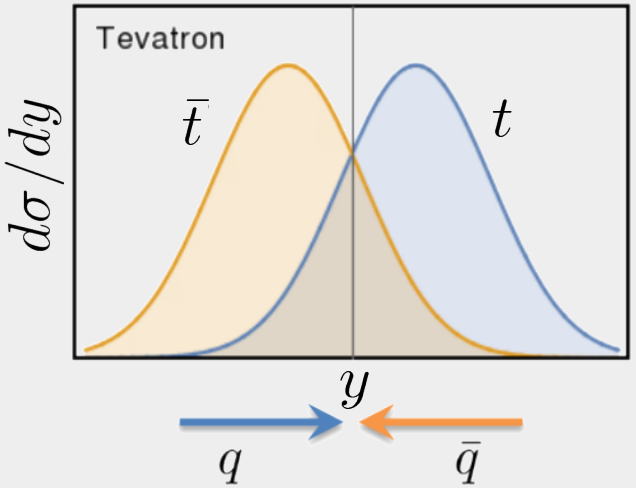
$t\bar{t}$ production asymmetry

forward-backward asymmetry in $p\bar{p}$ collisions $\Delta y = y_t - y_{\bar{t}}$



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

SM predicts asymmetry in $t\bar{t}$ production at NLO from events with $q\bar{q}$ (gq) initial states (gg is symmetric)

SM asymmetry is small, but measurable: ~9.5% (NNLO)

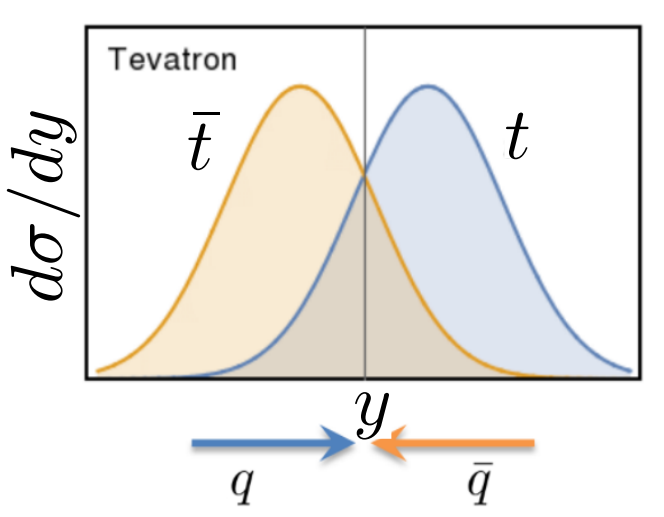
Czakon, Fiedler and Mitov, PRL **115**, 5, 052001 (2015)

- Sensitive test for new physics models
- Could be enhanced by NP processes eg W'/Z', axigluon

$t\bar{t}$ production asymmetry

forward-backward asymmetry in $p\bar{p}$ collisions

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



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

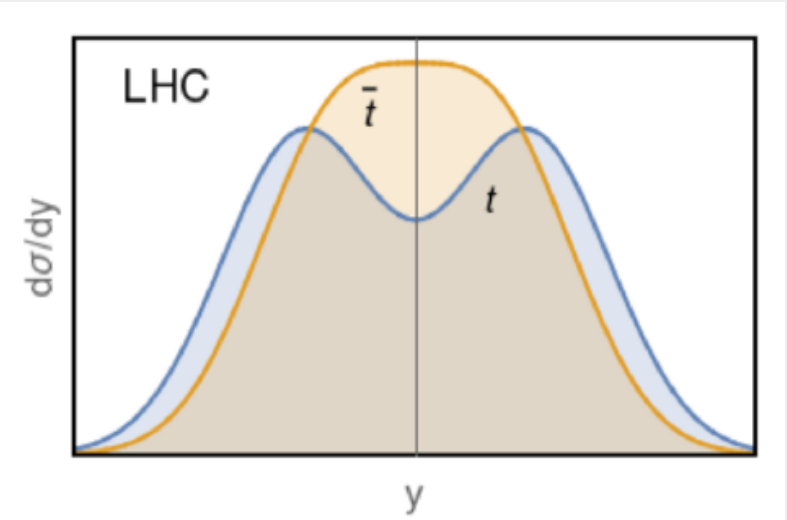
(charge asym. ~ 1%)

Comparison with pp collisions

Symmetric initial state

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

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



- Asymmetric PDF for antiquarks (sea) and quarks (mostly valence)
- Observable effect => broadening distribution of top quarks

Tevatron and LHC measurements complementary for testing new physics models

Tevatron A_{FB} history

Measurements:

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

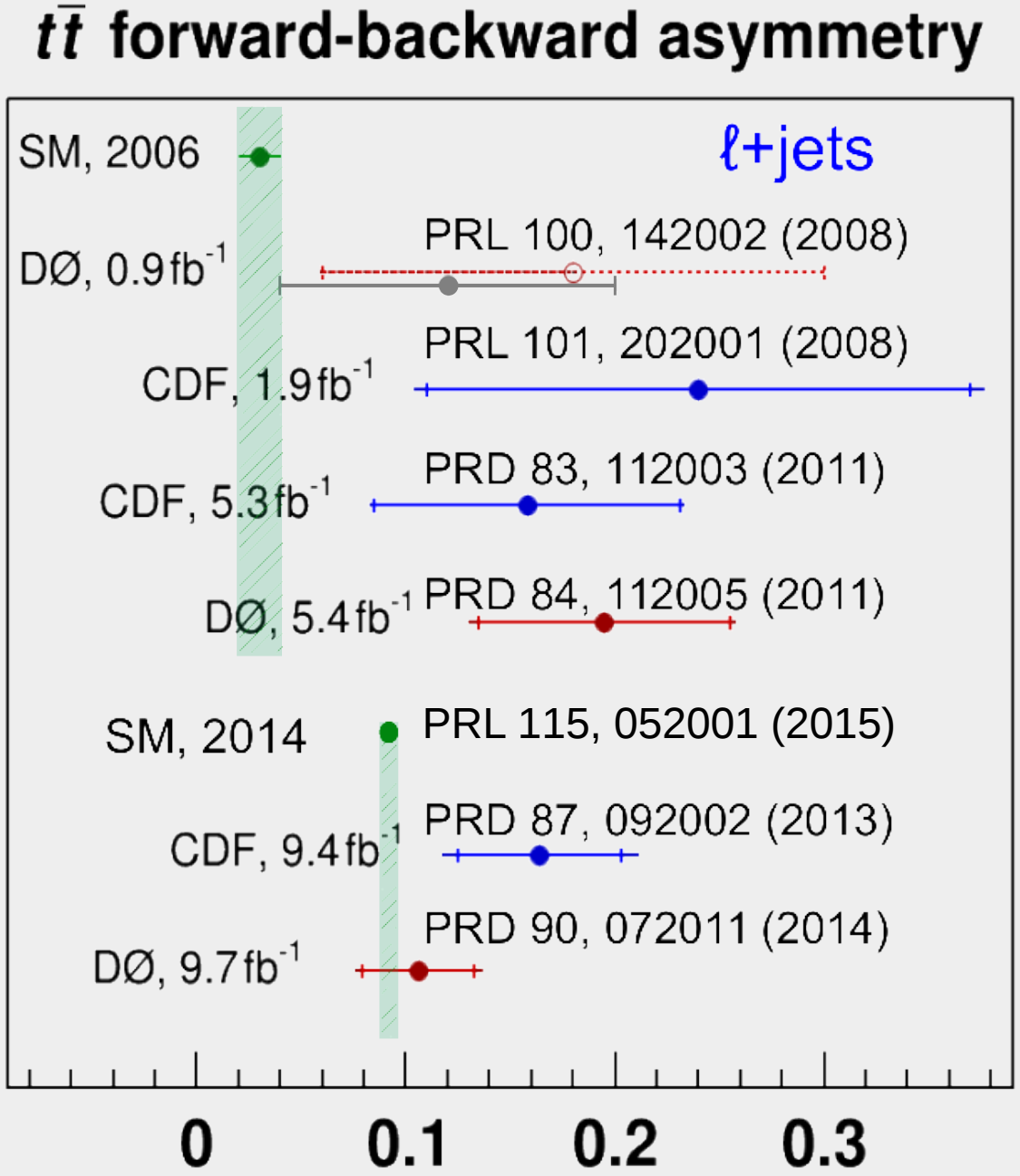
$$\Delta y = y_t - y_{\bar{t}}$$

Much interest in past years:

- ℓ+jets analyses showed departure from NLO SM expectations

More recent publications:

- NNLO QCD+ NLO EW calculation gives larger effect: ~9.5±0.5%
- More data, analyses improved:
  - Dilepton channels added 2015 – 2016
  - Latest experimental results are lower
  - More compatible with SM



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Understanding of asymmetry has evolved on multiple fronts:

- Improvements to theory calculations
- Data collection

latest

- **Combined Tevatron measurements and differential distributions**
  - All combinations calculated using BLUE method
  - Account for correlations in analysis methods and inputs

Phys. Rev. Lett. 120, 042001 (2018)

Inclusive asymmetries

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

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

$t\bar{t}$ asymmetry vs NNLO prediction: **1.3 SD**

$$A_{FB}^{\ell} = \frac{N_\ell(q \times \eta > 0) - N_\ell(q \times \eta < 0)}{N_\ell(q \times \eta > 0) + N_\ell(q \times \eta < 0)}$$

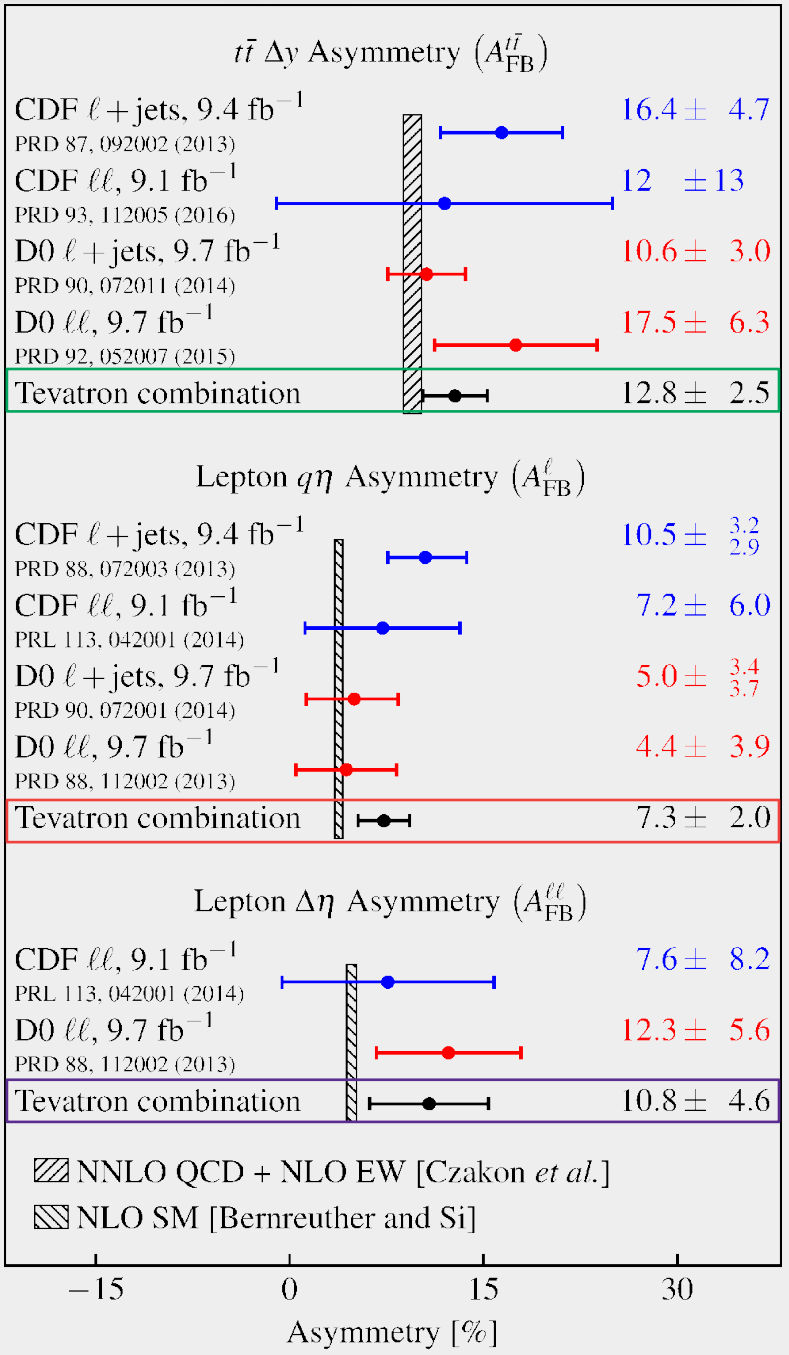
Lepton qη asymmetry vs NLO prediction: **1.6 SD**

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

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

Lepton Δη asymmetry vs NLO prediction: **1.3 SD**

Note: the three asymmetry measurements are correlated!



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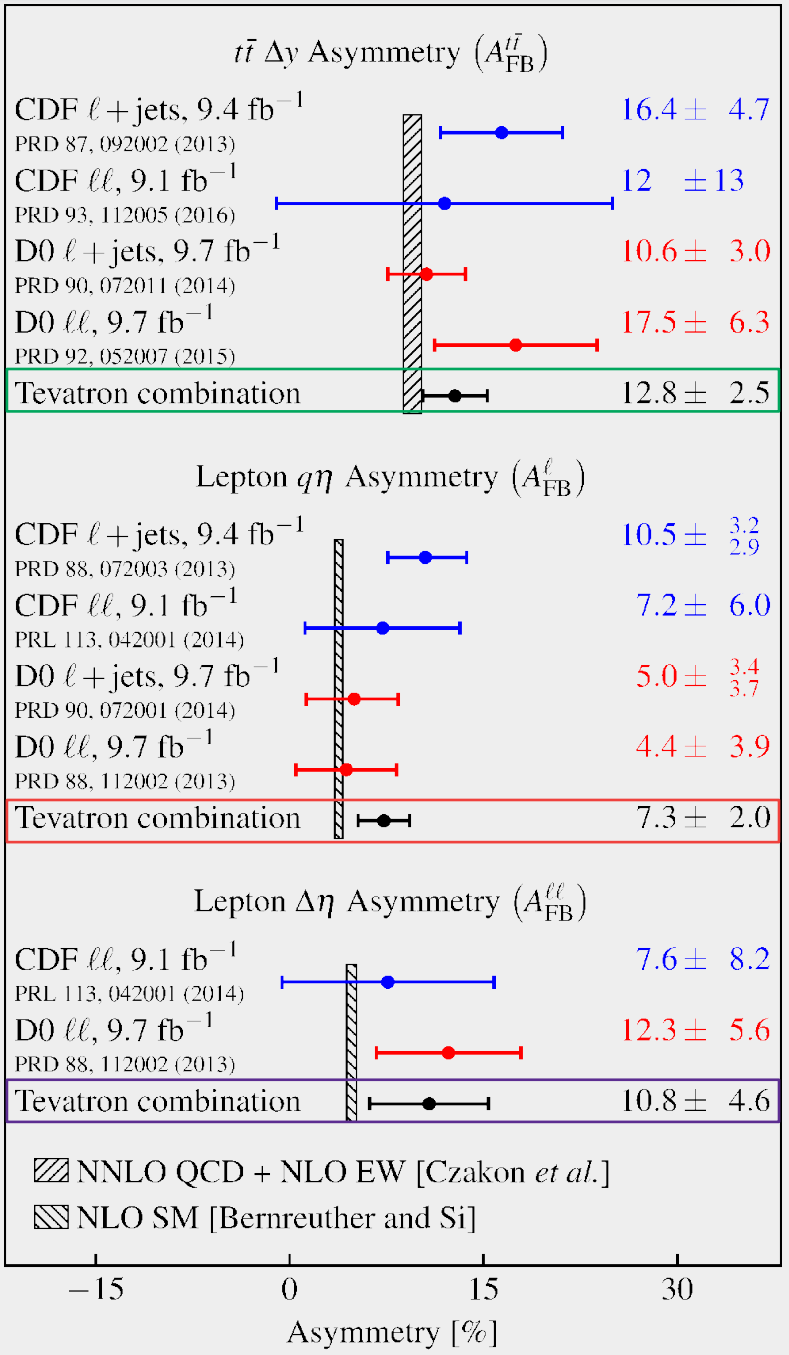
Lepton Δη asymmetry vs NLO prediction: **1.3 SD**

Results compatible with SM

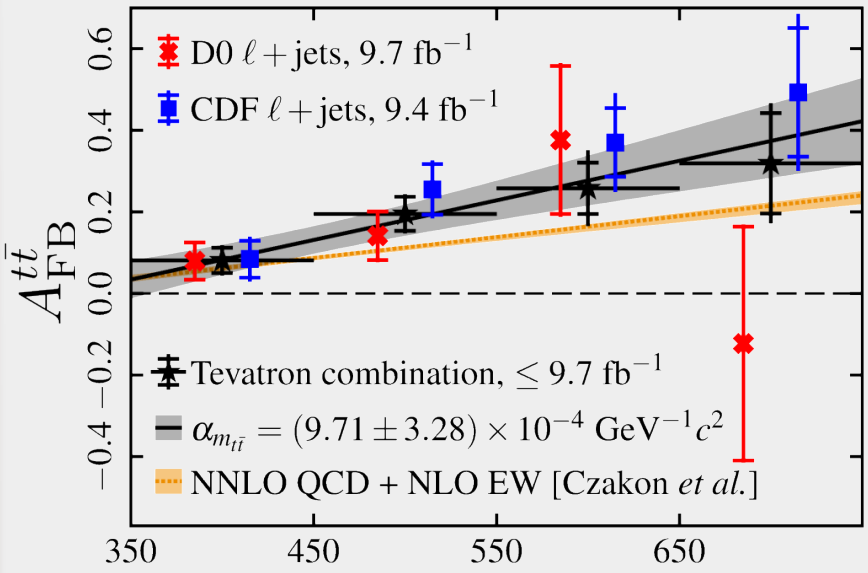


Phys. Rev. Lett. 120, 042001 (2018)

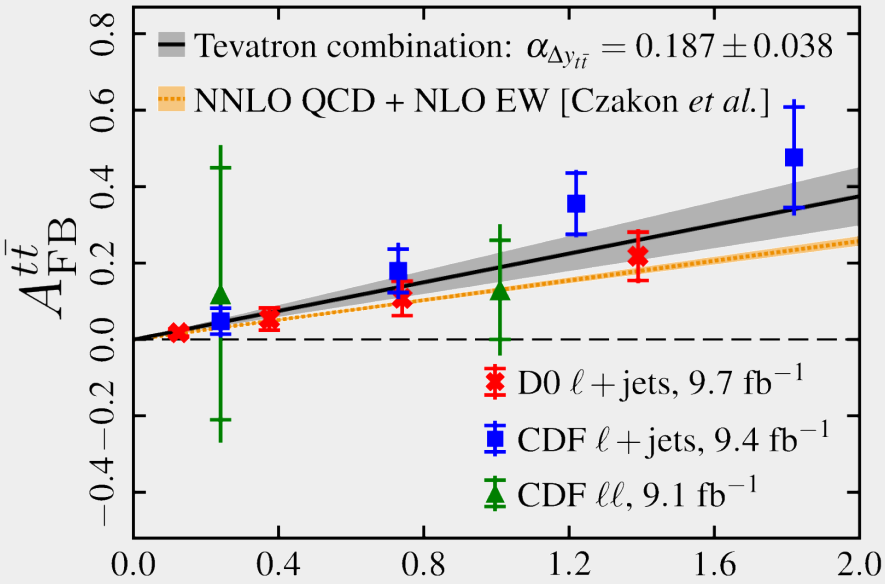
Differential measure of $A_{fb}^{t\bar{t}}$

Combined $A_{FB}^{t\bar{t}}$ as a function of $m_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$

- Include bin-to-bin correlations due to unfolding
- Compare to NNLO QCD + NLO EW calculation



Mass ($m_{t\bar{t}}$ [GeV]) dependence combination



$\Delta y_{t\bar{t}}$ dependence

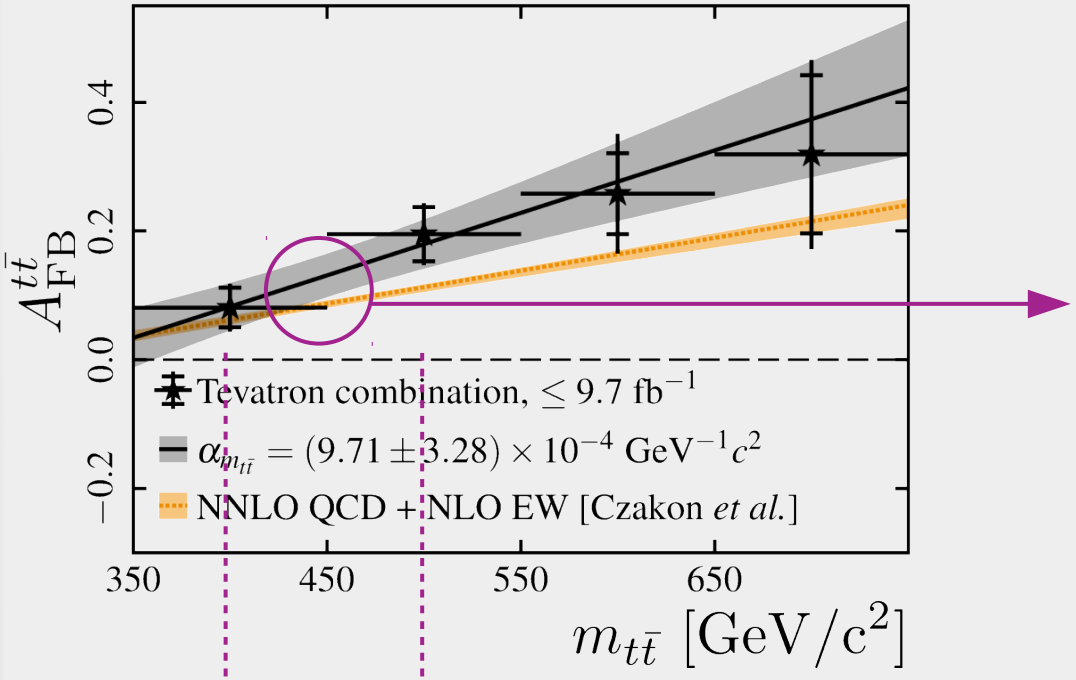
- Fit combination with $\beta+\alpha$ x ($m_{t\bar{t}}$-450 (GeV))
  - α=(9.71± 3.28)x10^{-4} /GeV,
  - β = 0.131 ± 0.034
- NNLO QCD + NLO EW prediction
  - $\alpha = (5.11^{+0.42}_{-0.64})\times 10^{-4}$ /GeV,
  - $\beta = 0.087^{+0.005}_{-0.006}$
- Agreement within 1.3 s.d.

- Fit individual measurements with a single slope parameter α
  - α=(0.187± 0.038)
- NNLO QCD + NLO EW prediction
  - $\alpha=(0.129^{+0.006}_{-0.012})$
- Agreement within 1.5 s.d.

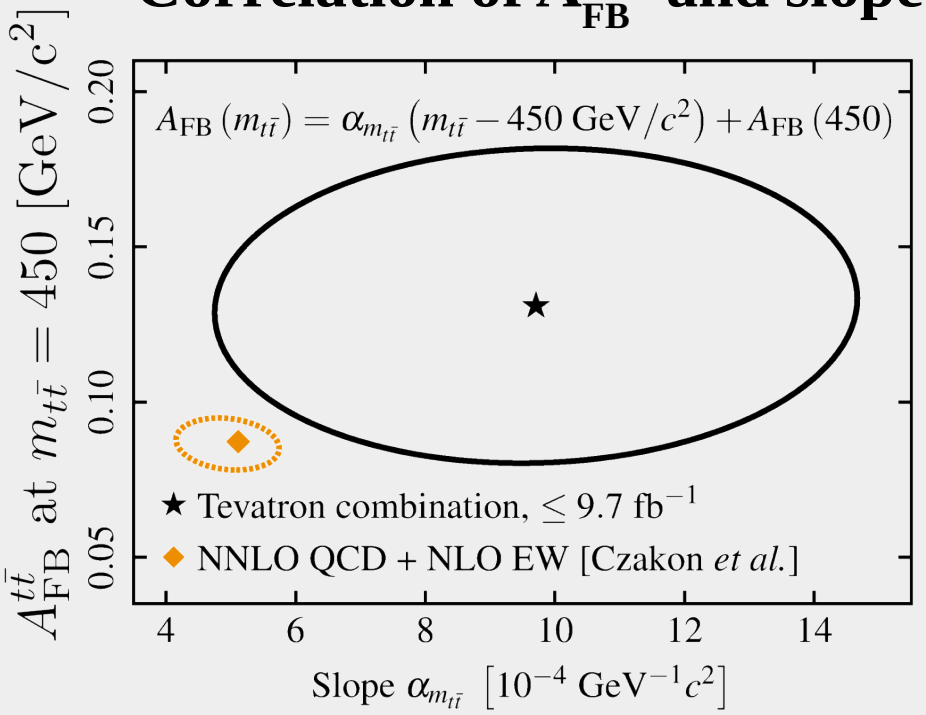
Phys. Rev. Lett. 120, 042001 (2018)

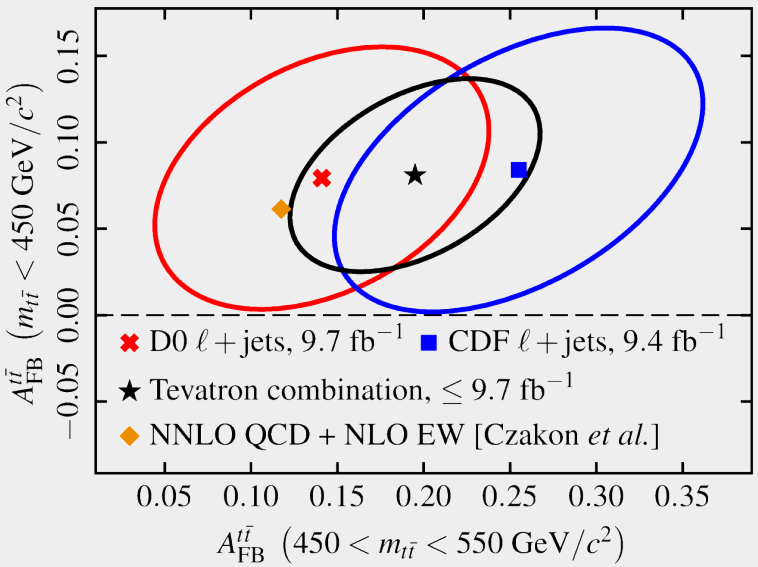
Differential measure of $A_{fb}^{t\bar{t}}$

Combined $A_{FB}^{t\bar{t}}$ vs $m_{t\bar{t}}$



Correlation of $A_{FB}^{t\bar{t}}$ and slope





Correlation of first and second bins in $m_{t\bar{t}}$

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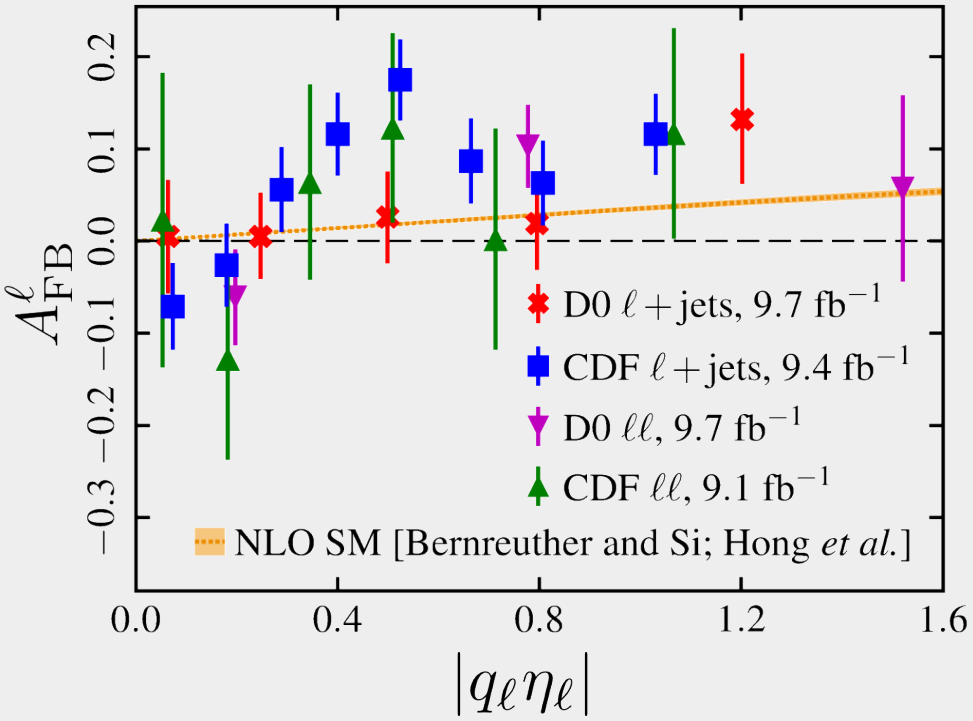
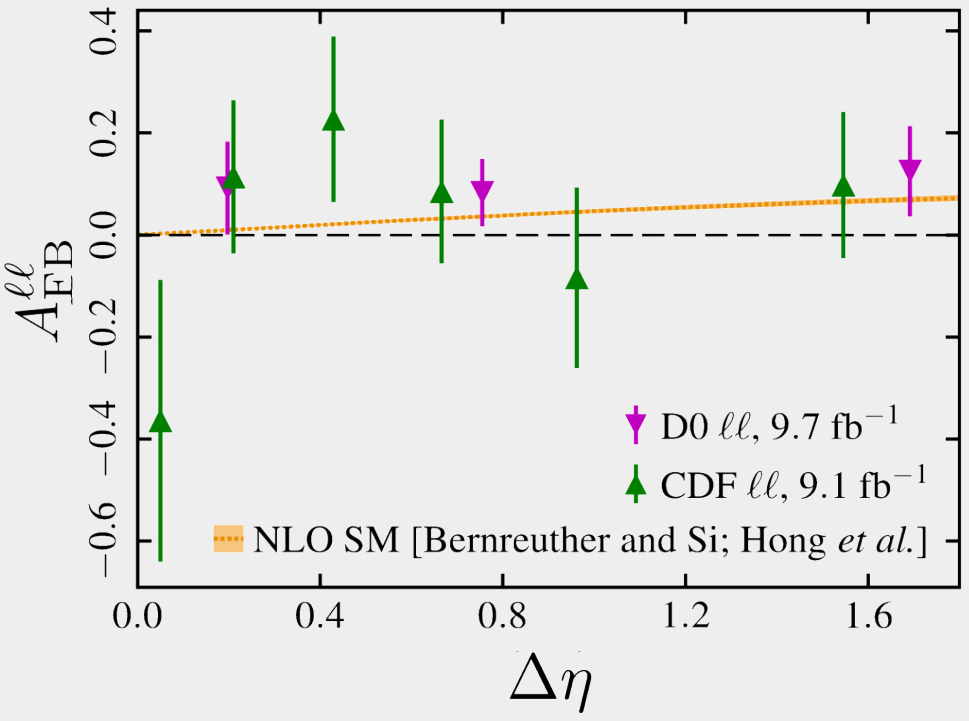
A_{FB}^{ℓ} and $A_{FB}^{\ell\ell}$

Comparison with NLO QCD+ NLO EW calculation

Lepton charge asymmetry



Lepton Δη asymmetry



Summary

Twenty (plus) years after discovery, Tevatron data still providing new insights into top quark physics

Precise measurements, complementary to LHC's pp initial state
(production asym., transverse polarization, s-chan single top, m_{top}, ...)

Final measurements of the top-quark production asymmetry at the Tevatron and more refined theory calculations are in better agreement than was observed in earlier studies (~1.5σ)

$A_{FB}^{t\bar{t}}$ in agreement with Standard Model

Additional slides

Top pair production signatures

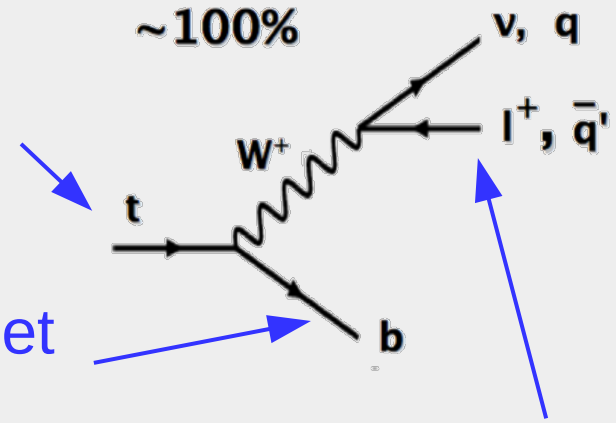
Well known decay signatures

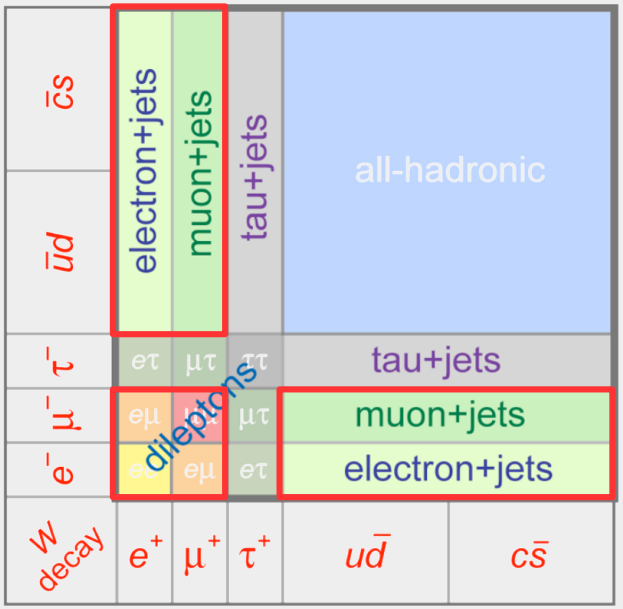
Effective event ID using:

high mass (kinematic selections)

heavy flavor jet tagging

top decay:





dilepton (e/μ) 6%

$\ell\ell$

e/μ+jets 34%

$\ell + \text{jets}$

isolated high p_T lepton(s)+ missing p_T or energetic jets

Typical event selections

Lepton + Jets

- Trigger: single lepton and lepton+jets
- Isolated electron or muon
  - p_T > 20 GeV
  - $|\eta(\mu)| < 2.0$, $|\eta(e)| < 1.1$
- At least 3 jets pT>20 GeV
- Missing transverse momentum > 20 GeV
- Additional selections:
  - Use of the b-jet identification
  - Event kinematic selections

Dileptons

- Trigger: dileptons
- Two isolated leptons (electrons and/or muons)
  - p_T > 15 GeV
  - $|\eta(\mu)| < 2.0$
  - $|\eta(e)| < 1.1$ and $1.5<|\eta(e)| <2.5$
- At least 2 jets pT>20 GeV
- Missing transverse momentum > 20 GeV
- Additional selections:
  - Use of the b-jet identification
  - Event kinematic selections

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Signal and Background

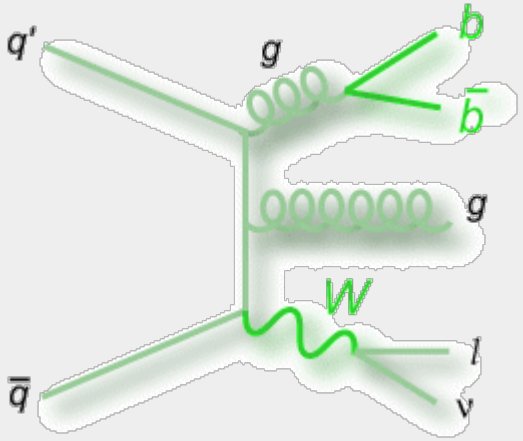
$t\bar{t}$ simulation: **ALPGEN** + **PYTHIA** (parton showering + hadronization)

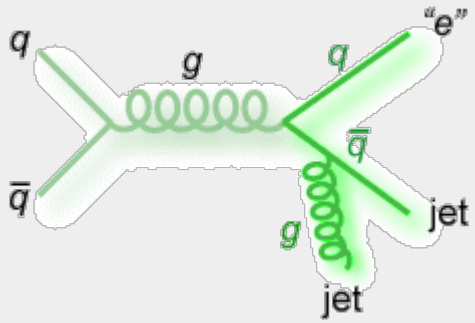
- Systematic uncertainty studies: **MC@NLO**+**HERWIG**, different **PYTHIA** versions
- Acceptance 10-20% (4 – 6 reconstructed objects in the final state)

Dominant backgrounds

Lepton + Jets

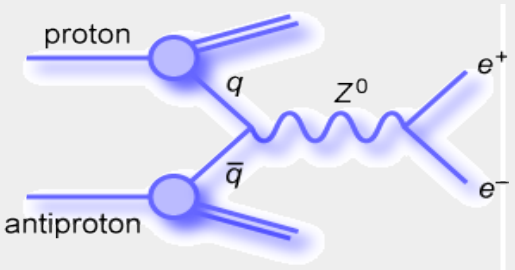
- W+jets (Wbbj, Wccj, Wjjj)
- Multijet events with misidentified leptons
- Dibosons (WW, WZ, ZZ) +jets





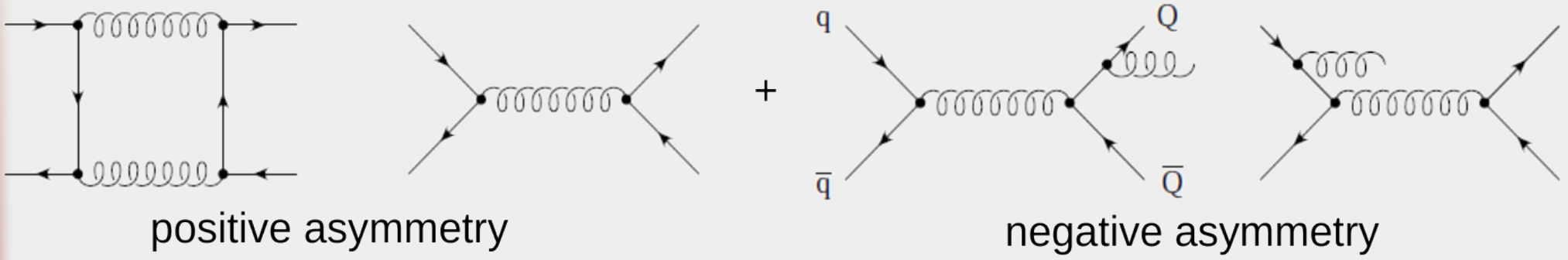
Dileptons

- Z → μμ, ee, ττ + jets (D-Y)
- Dibosons (WW, WZ, ZZ) + jets
- W+jets and multijet events with misidentified leptons



$t\bar{t}$ production asymmetry

top and tbar show a forward-backward asymmetry in $p\bar{p}$ collisions

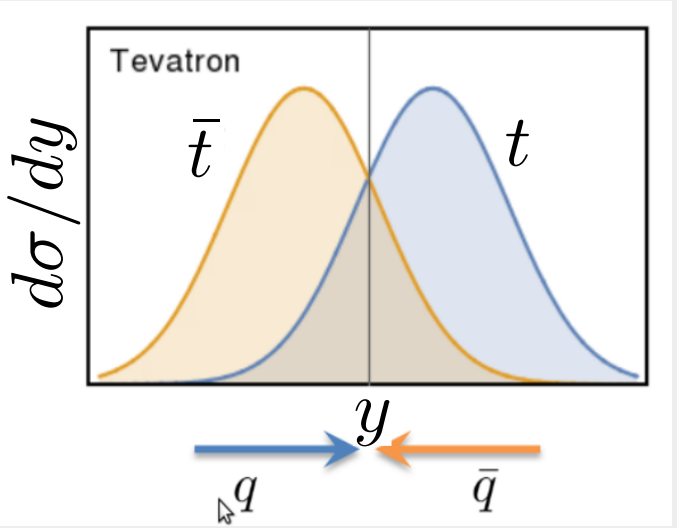


SM asymmetry is small, ~9.5% (NNLO)

Czakon, Fiedler and Mitov,
PRL **115**, 5, 052001 (2015)

=> sensitive to test new physics contributions

- NLO 2→2 (interference between Born and box diagrams), LO 2→3: expect (5—10)% asymmetry (higher order corrections are small)
- NLO 2→3 (ISR/FSR interference): has negative asymmetry and reduces expected asymmetry
  ⇒ strong dependence from phase space region
- gg initiated processes are symmetric

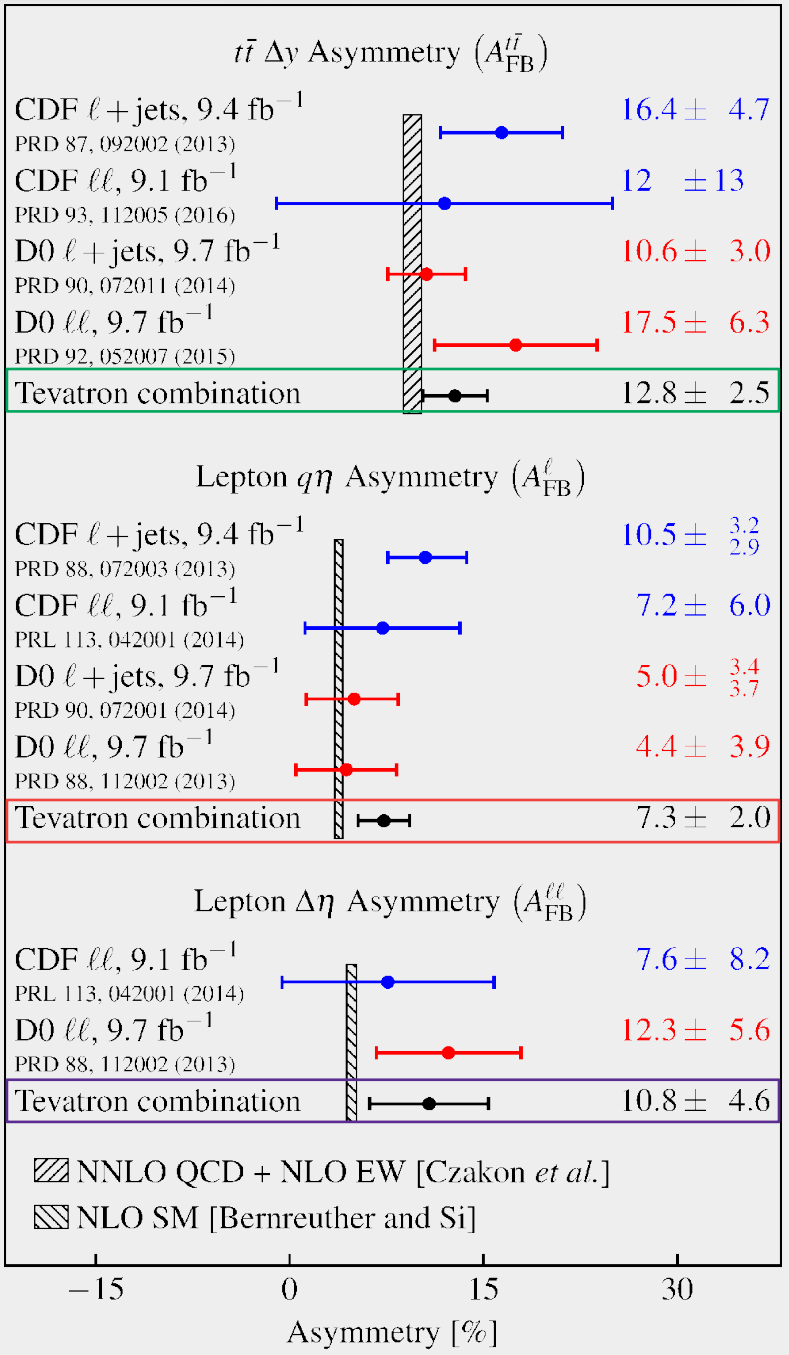


Phys. Rev. Lett. 120, 042001 (2018)

Inclusive asymmetries @ Tevatron

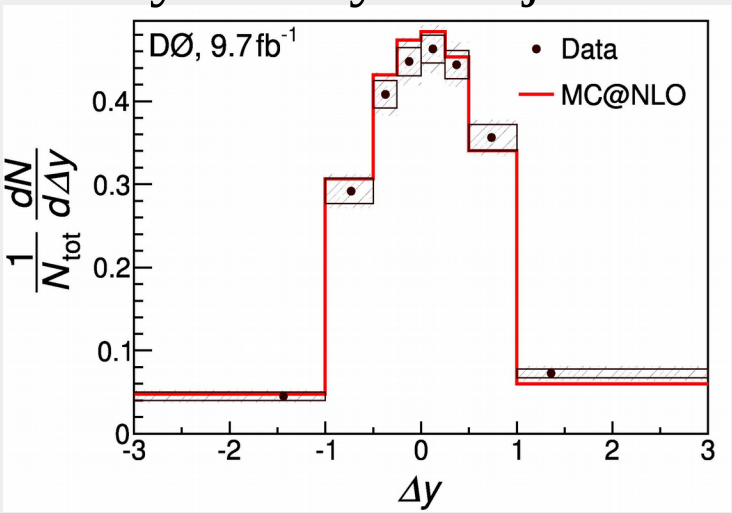
- Use BLUE to combine measurements
- Standardize and combine systematic uncertainties.
  - All results are limited by the statistical uncertainty
  - Main correlation between experiments from signal models ~ 10% total correlation
- Consistency:
  - $t\bar{t}$ asymmetry vs NNLO prediction: **1.3 SD**
  - Lepton qη asymmetry vs NLO prediction: **1.6 SD**
  - Lepton Δη asymmetry vs NLO prediction: **1.3 SD**

Note: the three asymmetry measurements are correlated!



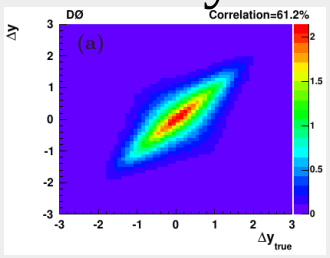
Examples of A_{FB} measures

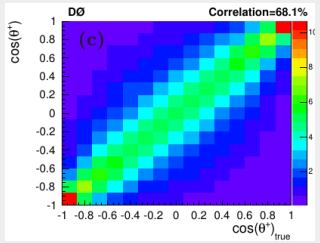
$t\bar{t}$ asymmetry in ℓ+jets channel

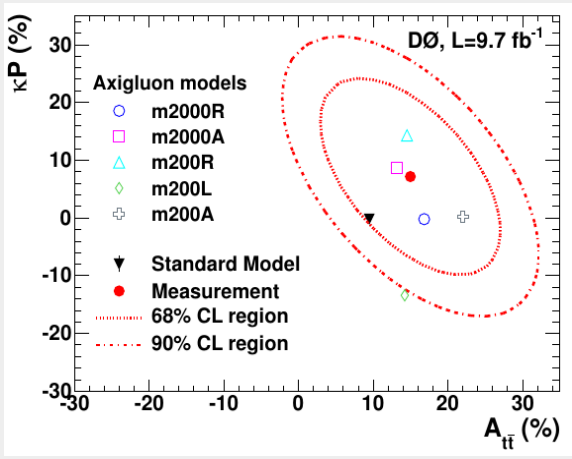


Phys. Rev. D 90, 072011 (2014)

$t\bar{t}$ asymmetry in $\ell\ell$ channel

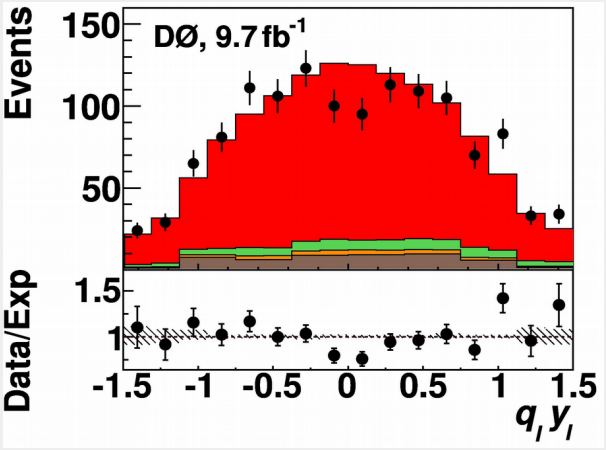






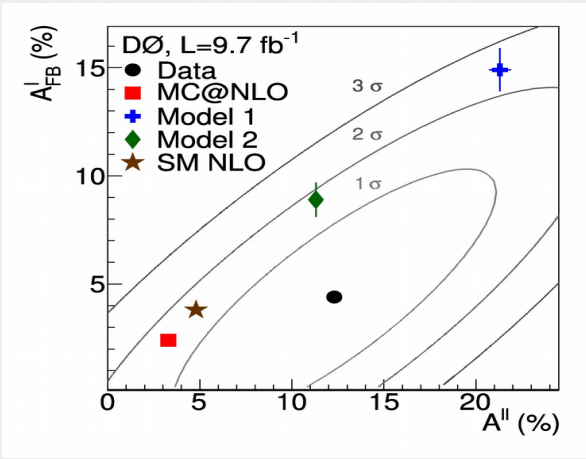
Phys. Rev. D 92, 052007 (2015)

Leptonic asymmetry in ℓ+jets chan.



Phys. Rev. D 90, 072001 (2014)

A^{ℓ}_{FB} vs $A^{\ell\ell}_{FB}$



Phys. Rev. D 88, 112002 (2013)