Top Quark Physics at the Tevatron

Sandra Leone

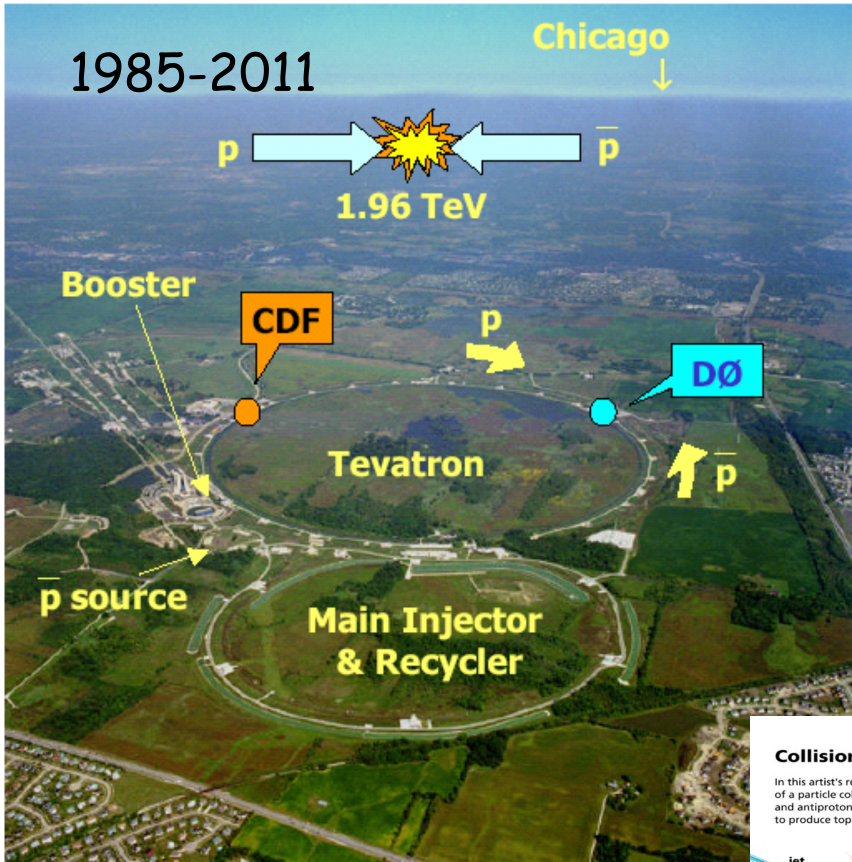
(INFN Pisa)

On behalf of the CDF and D0 Collaborations

Rencontres de Physique de la Vallée d'Aoste

La Thuile March 1st, 2018

The Fermilab Tevatron



Run II: $\sqrt{s}$ = 1.96 TeV, 10 fb^{-1} on tape
Tevatron stopped operating on September 2011 after a 26 years career

The birthplace of the top quark, observed in 1995 by CDF and D0

Announcement of top quark discovery:
March 2nd, 1995 ⇒ Top is fully grown up

news release
fermi national accelerator laboratory
Operated by Universities Research Association, Inc. for the U.S. Department of Energy

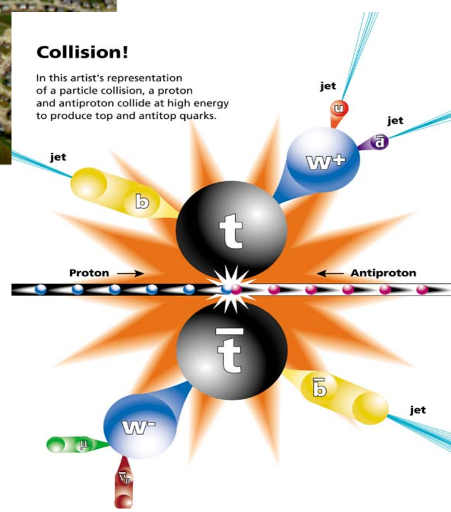
Public Information Office, P.O. Box 500, Batavia, IL 60510 • Telephone: 708-840-3351 • Facsimile: 708-840-8780

NEWS MEDIA CONTACTS:
Judy Jackson, 708/840-4112 (Fermilab)
Gary Pitchford, 708/252-2013 (DOE)
Jeff Sherwood, 202/586-5806 (DOE)

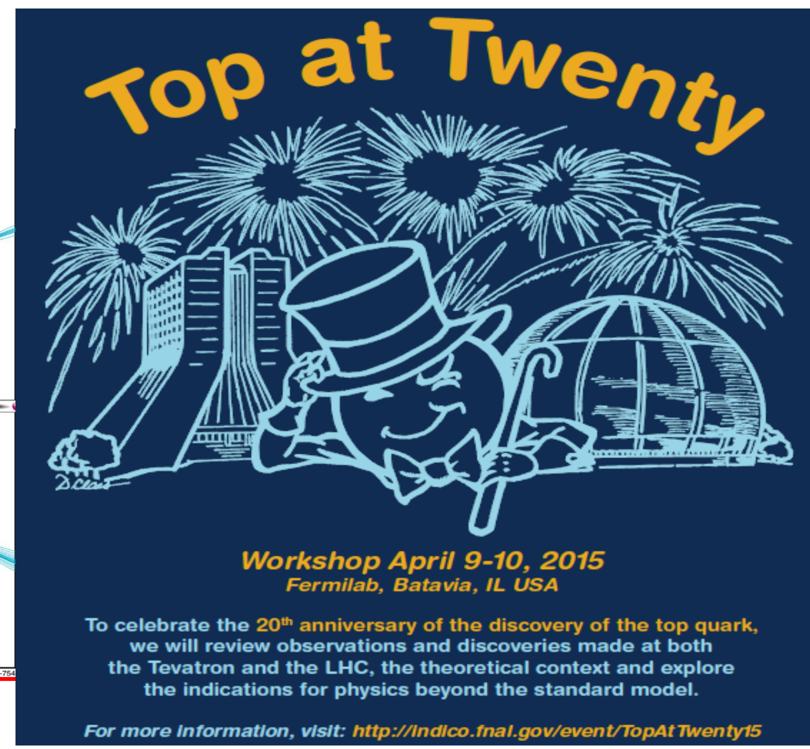
95-2
March 1, 1995

PHYSICISTS DISCOVER TOP QUARK

Batavia, IL—Physicists at the Department of Energy's Fermi National Accelerator Laboratory



PRL 74 2626, PRL 74 2632 (1995)



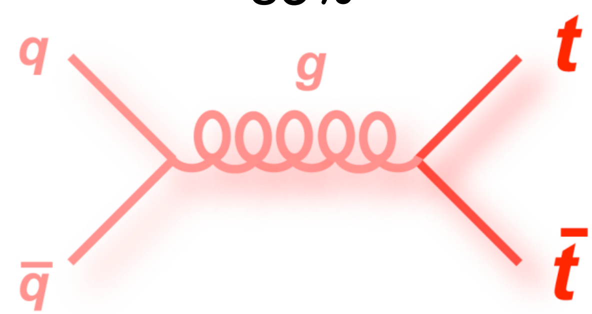
Top Quark Production at Tevatron

- QCD pair production

$\sigma_{SM} = 7.35^{+0.28}_{\;0.33}$ pb

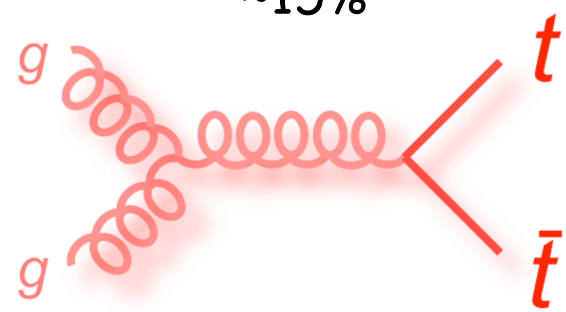
(for m_{Top}= 172.5 GeV)
(PRL 110, 252004 (2013))

~85%



Dominant process at Tevatron

~15%



Dominant process at LHC (~90%)

Tevatron is the right place to study the $q\bar{q}$ annihilation in $t\bar{t}$ production

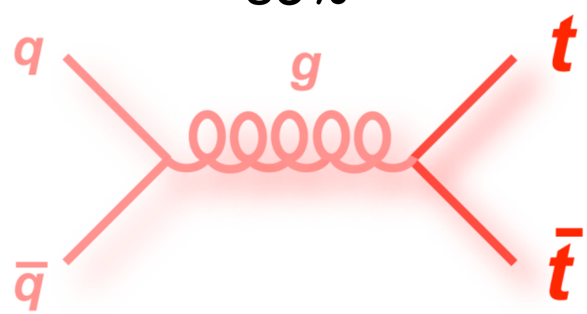
Top Quark Production at Tevatron

- QCD pair production

$\sigma_{SM} = 7.35^{+0.28}_{0.33}$ pb

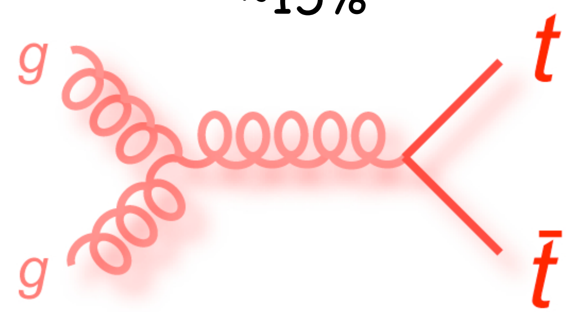
(for m_{Top}= 172.5 GeV)
(PRL 110, 252004 (2013))

~85%



Dominant process at Tevatron

~15%



Dominant process at LHC (~90%)

Tevatron is the right place to study the $q\bar{q}$ annihilation in $t\bar{t}$ production

---

Small cross section!

⇒ Observation in ~ 67 pb^{-1} ⇒ ~ 500 ttbar pairs produced per experiment

⇒ In 10 fb^{-1} ⇒ ~ 73500 ttbar pairs produced

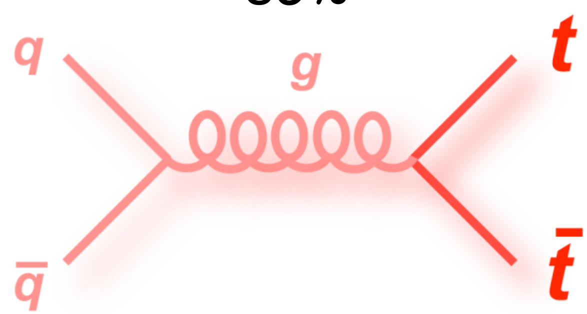
Top Quark Production at Tevatron

- <u>QCD pair production</u>

$\sigma_{SM} = 7.35^{+0.28}_{\ 0.33}$ pb

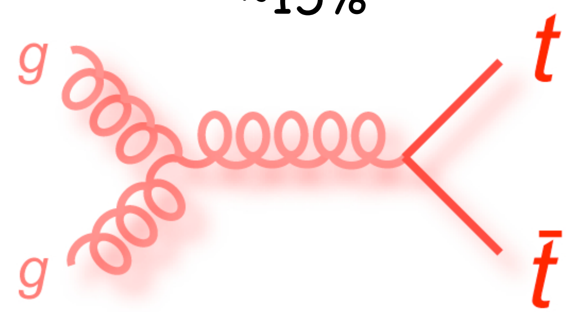
(for m_{Top}= 172.5 GeV)
(PRL 110, 252004 (2013))

~85%



Dominant process at Tevatron

~15%



Dominant process at LHC (~90%)

Tevatron is the right place to study the $q\bar{q}$ annihilation in $t\bar{t}$ production

- <u>EWK single-top production</u>
- <u>first observed at Tevatron in 2009</u>
- (PRL 103 092001, PRL 103 092002 (2009))

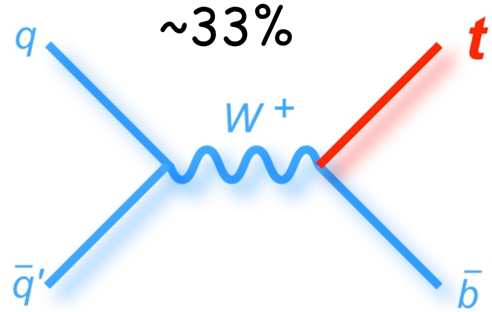
➢ s-channel: σ_{SM} = 1.04 ± 0.06 pb
➢ t-channel: σ_{SM} = 2.1 ± 0.1 pb

(for m_{Top}= 173 GeV)

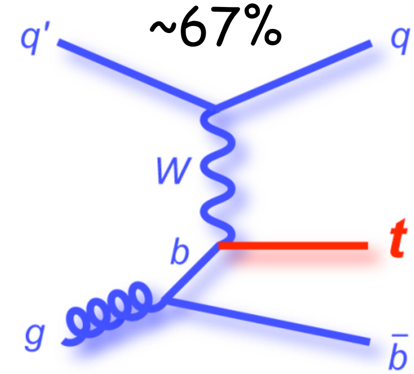
PRD 83, 091503 (2011),PRD 81, 054028 (2010)
PRD 82, 054018 (2010) arxiv:1210.7813.

Dominant modes at Tevatron:

s-channel
~33%

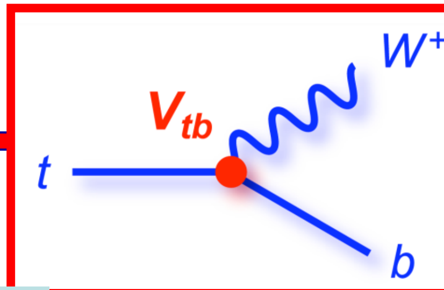


t-channel
~67%



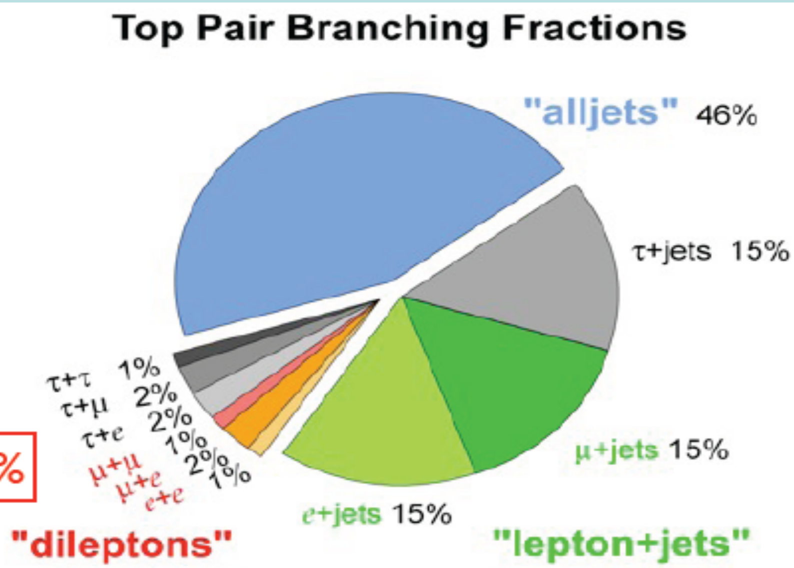
- Single top associated production Wt: σ ~ 0.2 pb, too small at the Tevatron

Top Quark Decay



SM predicts BR($t \rightarrow Wb$) ≈ 100%

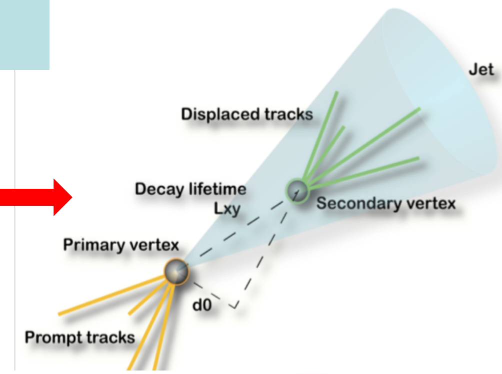
Event topology determined by the W decay mode



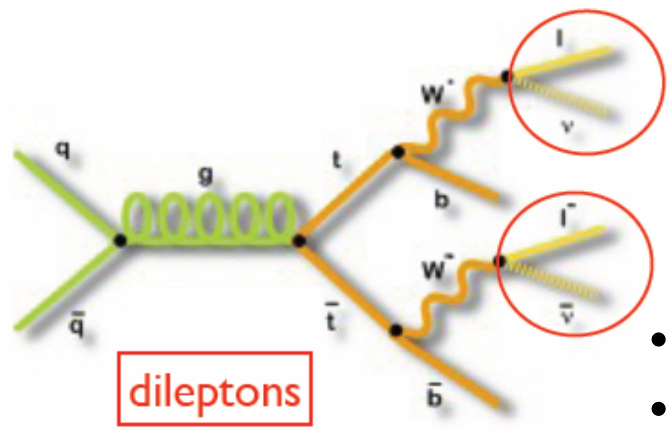
~4.5%

~30%

b quarks are always present



lepton+jets



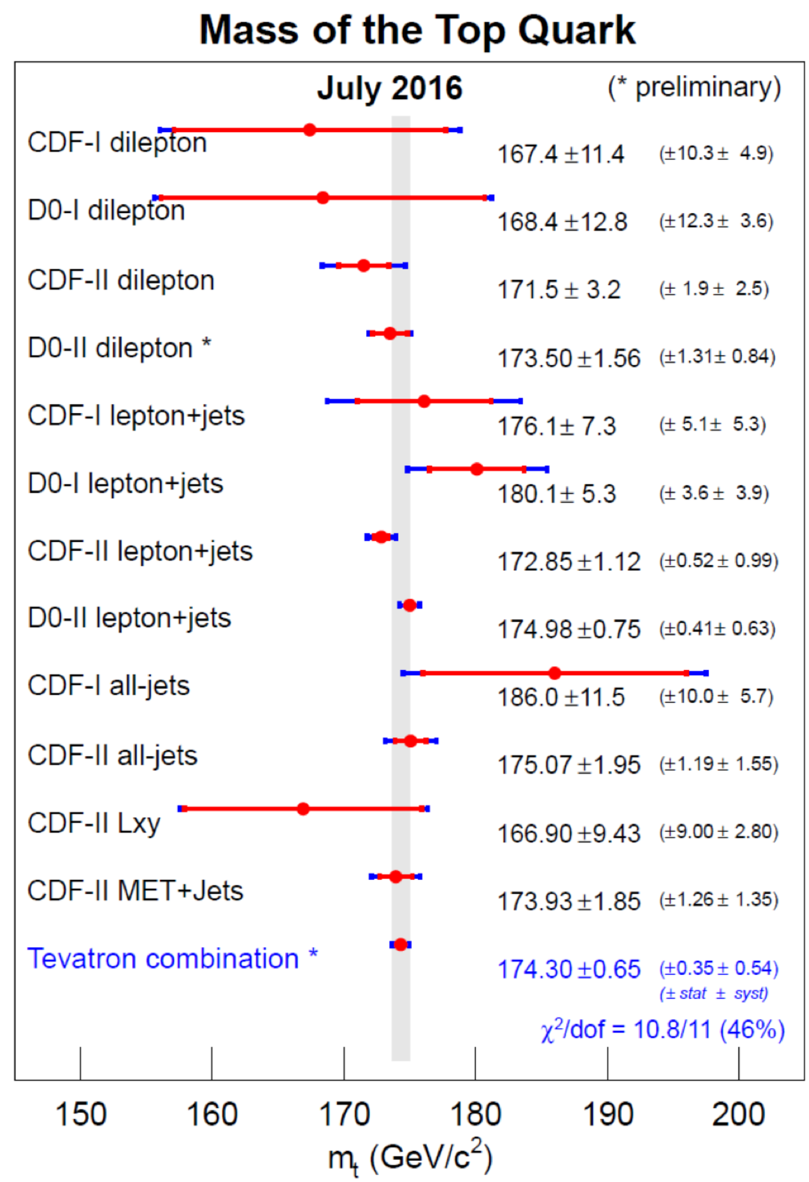
dileptons

- Small rate
- Small background

- Golden channel:
- Good rate
- Manageable background

Top mass: what do we measure?

- More than 20 years ago, CDF & D0 assembled all the pieces needed to discover the top
  - ⇒ The standard strategy to study the top quark remains the same today
- Top quark mass standard measurement:
  - ⇒ based on comparison of kinematic observables with MC generated at different top masses
  - ⇒ determination of the best-fit value of the MC top-quark mass parameter
- On going theoretical work:
  - ⇒ to translate the MC top-quark mass into a mass in a well defined renormalization scheme
- <u>Experimental way to address the question of the top-quark mass definition:</u>
  - ⇒ Use alternative methods to determine the top-quark mass
    - ✓ With less inputs from MC
    - ✓ With different sensitivity to systematics
    - ✓ Using theory computation with well defined mass (i.e. from cross section, single top events, ttbar+jets etc.)



arXiv:1608.01881

D0 pole mass from inclusive cross section

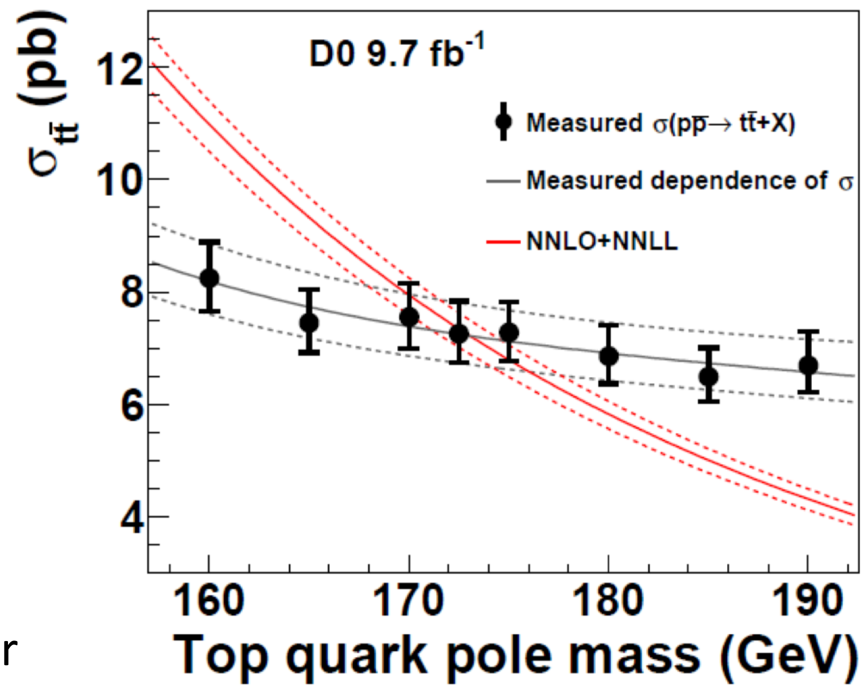
- Compare the experimental $t\bar{t}$ cross section measurement with the theory computation
- From inclusive cross-section measurement in lepton+jets and dilepton channels:

$$\sigma_{tt} = 7.26 \pm 0.13 (\text{stat.})\ ^{+0.57}_{-0.50}\ (\text{syst.})\ \text{pb}$$

  - Input top quark mass varied, MVA discriminant studied for each point
  - dependence parametrized with a fourth-order polynomial function
  - compared to NNLO+NNLL prediction
  - extracting the most probable mass + uncertainty with normalized joint-likelihood function:

$$m_{top} = 172.8 \pm 1.1\ (\text{theo.})\ ^{+3.3}_{-3.1}\ (\text{exp.})\ \text{GeV}$$

dominated by experimental uncertainties



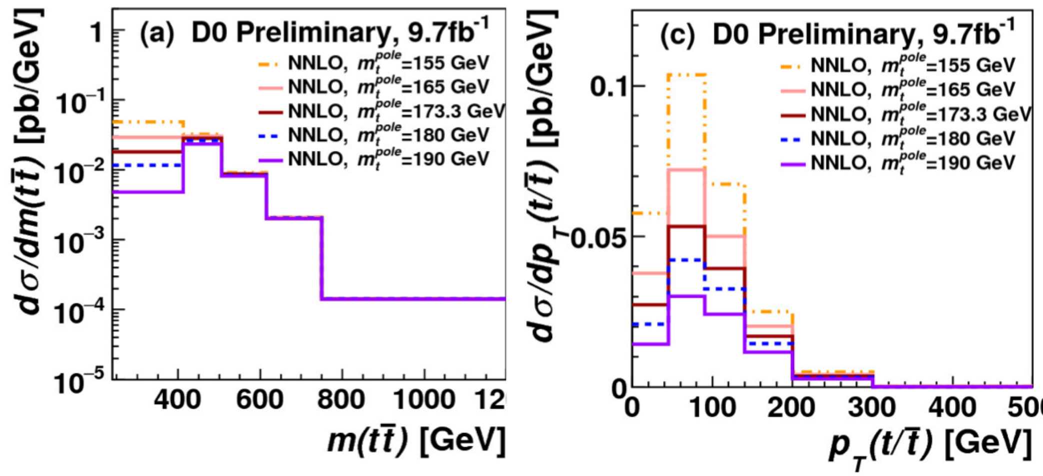
PRD 94, 092004 (2016)

- Advantage: extract the top-quark mass in a well defined renormalization scheme
- Drawback: less precise than direct measurements

1.9% relative uncertainty

D0 pole mass from diff. cross section

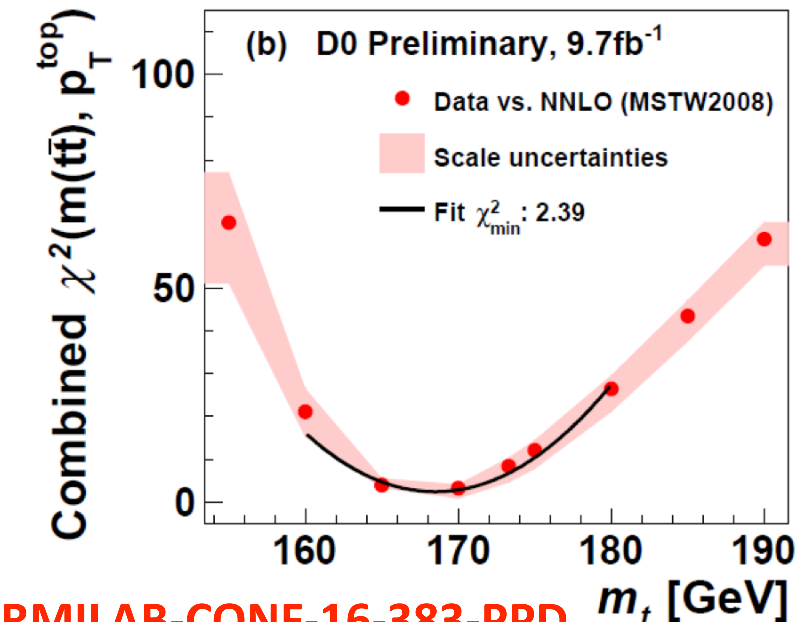
- Using the differential tt̄ cross section:
  - ✓ additional information coming from the shape of the distributions
  - ✓ possible since NNLO differential predictions are now available (JHEP 1605, 034 (2016))



- $p_T{}^{top}$ and m_{tt} sensitive to pole mass
- Unfolded differential distributions from D0 paper PRD 90 092006 (2014)
- compared to NNLO QCD calc. , four different PDF sets
- χ^2 fit to both distributions
  - p_T vs. m_{tt}

$$m_{top}=169.1\pm 2.5 \text{ (total) GeV}$$

- better uncertainty than inclusive (1.5%)
  - ✓ even with only lepton+jets
  - ✓ Theory input not using NNLL

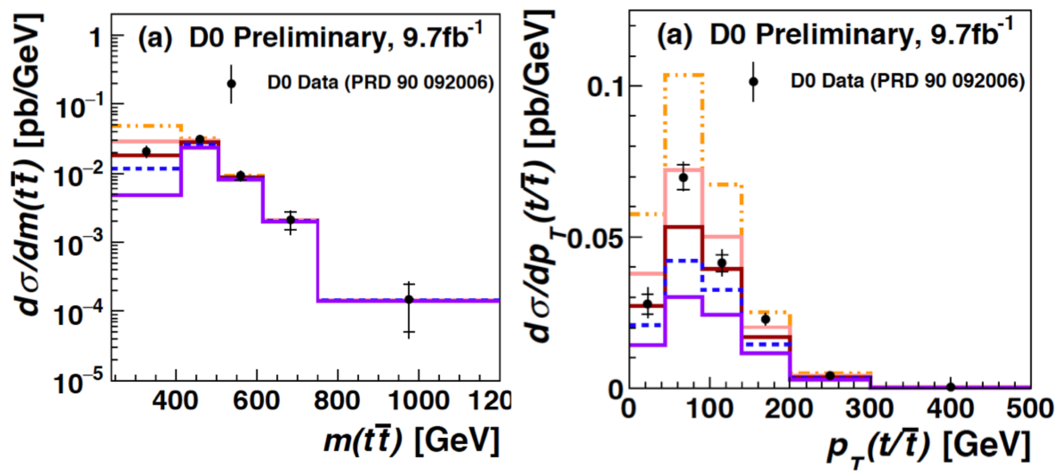


FERMILAB-CONF-16-383-PPD

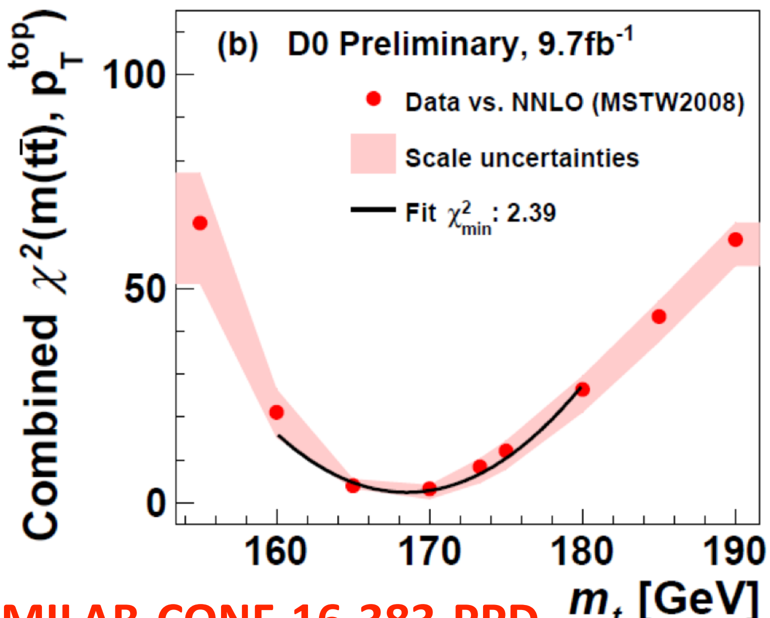
D0 Note 6473-CONF

D0 pole mass from diff. cross section

- Using the differential $t\bar{t}$ cross section:
  - ✓ additional information coming from the shape of the distributions
  - ✓ possible since NNLO differential predictions are now available (JHEP 1605, 034 (2016))



- $p_T^{\ top}$ and m_{tt} sensitive to pole mass
- Unfolded differential distributions from D0 paper PRD 90 092006 (2014)
- compared to NNLO QCD calc. , four different PDF sets
- χ^2 fit to both distributions
  - p_T vs. m_{tt}



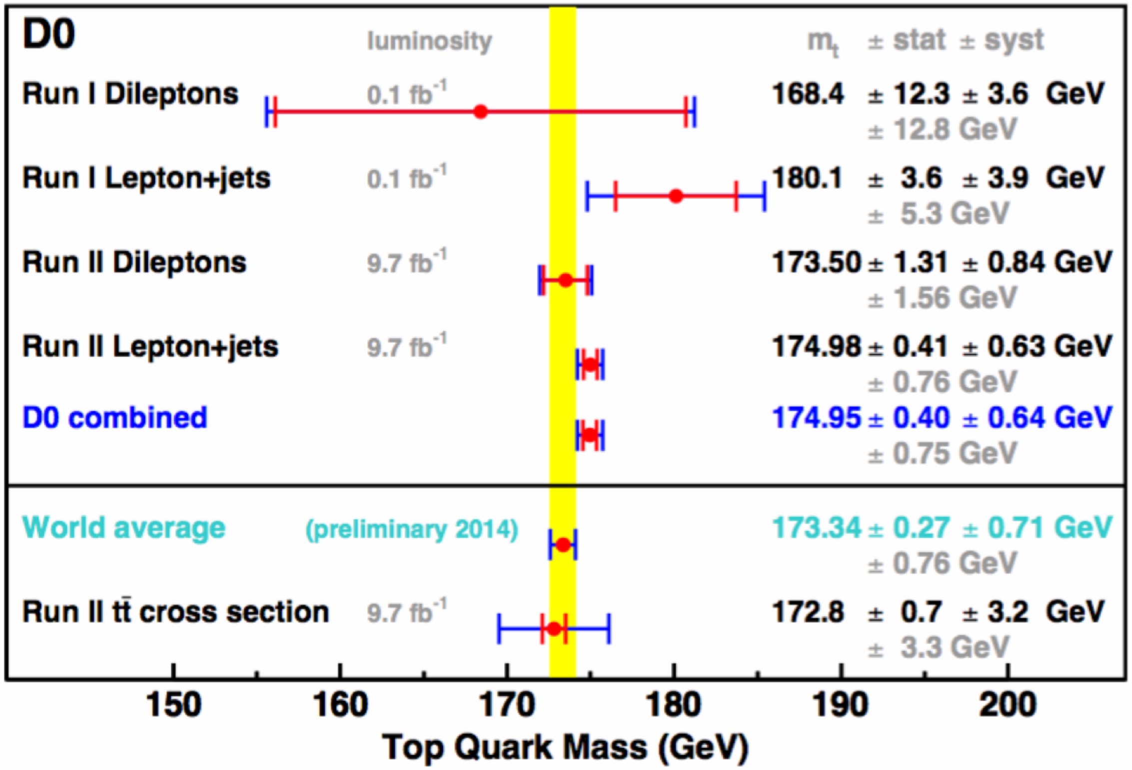
$$m_{top} = 169.1 \pm 2.5 \text{ (total) GeV}$$

- better uncertainty than inclusive (1.5%)
  - ✓ even with only lepton+jets
  - ✓ Theory input not using NNLL

FERMILAB-CONF-16-383-PPD

D0 Note 6473-CONF

D0 legacy top mass combination



- All data analyzed
- Combined with BLUE

χ^2/ndof = 2.5/3, prob = 47 %: good consistency between the measurements

	D0 combined values (GeV)
top quark mass	174.95
In situ light-jet calibration	0.41
Response to b, q, and g jets	0.16
Model for b jets	0.09
Light-jet response	0.21
Out-of-cone correction	< 0.01
Offset	< 0.01
Jet modeling	0.07
Multiple interaction model	0.06
b tag modeling	0.10
Lepton modeling	0.01
Signal modeling	0.35
Background from theory	0.06
Background based on data	0.09
Calibration method	0.07
Systematic uncertainty	0.64
Statistical uncertainty	0.40
Total uncertainty	0.75

D0 top quark mass combination:

m_{top}=**174.95 ±0.40** (stat.) **±0.64** (syst.) GeV

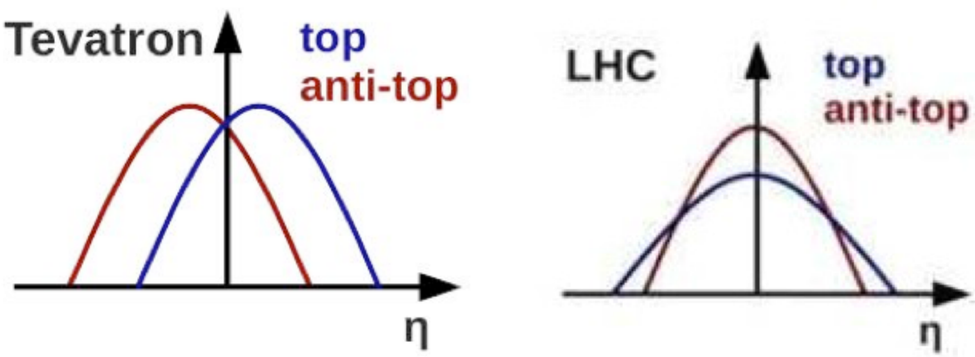
0.43% relative uncertainty

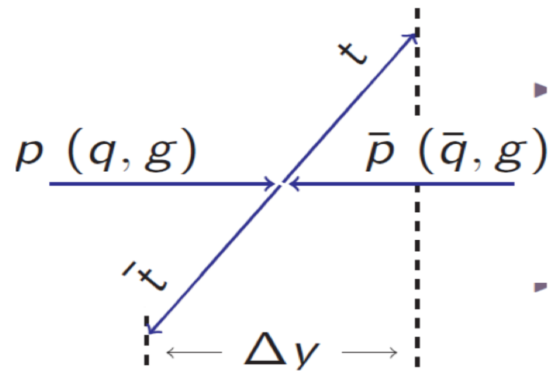
PRD 95, 112004 (2017)

Forward backward asymmetry (A_{FB})

QCD +EW theory predicts positive asymmetry from qqbar→ttbar annihilation: top quark tends to go in the same direction as incoming proton at Tevatron

- NNLO+NNLL predicts ~9.5%(arXiv:1411.3007) while gg remains symmetric
- New physics can modify this asymmetry (Z´,axigluons,..)
- Experimentally, asymmetries based on fully reconstructed top quarks using the rapidity difference (Δy) of t→lνb and antitop t→jjb, or using one or two leptons from top decay





- In terms of frame-independent rapidity difference (Δy) between top and antitop:

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

- In terms of rapidity of lepton(s) from top decay:

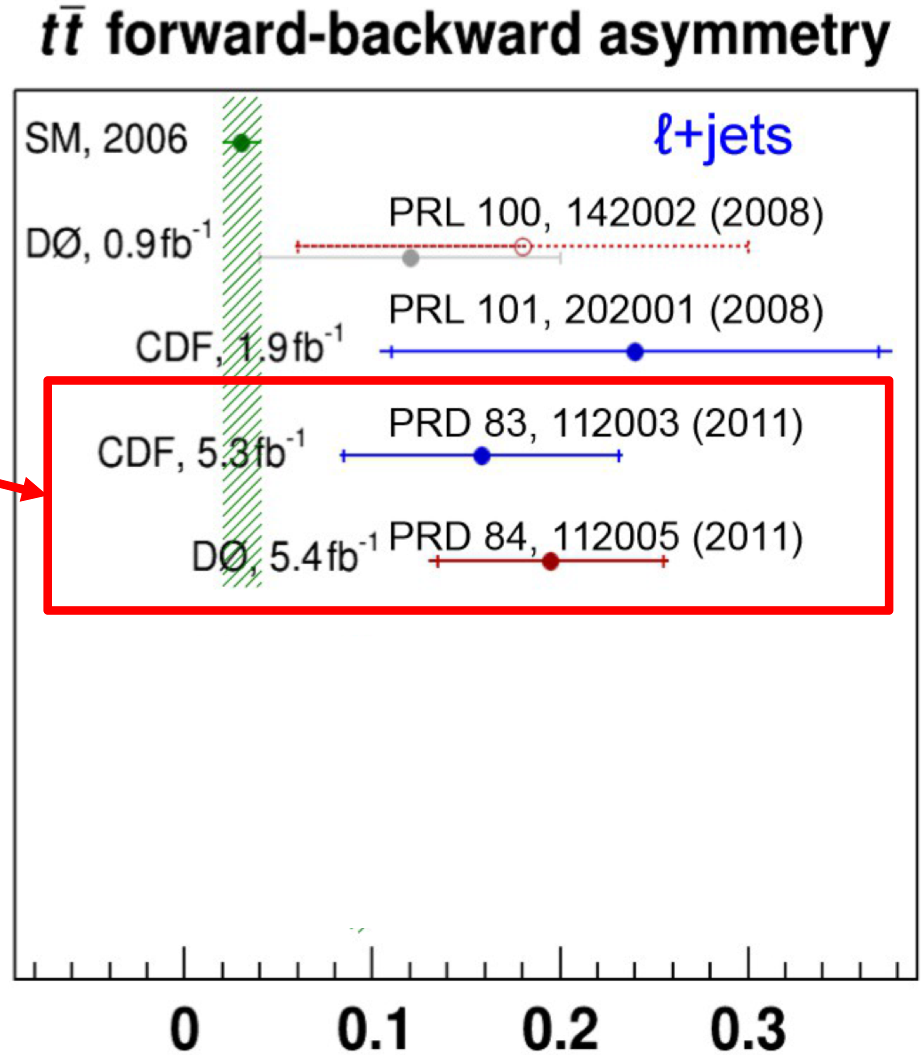
$$A_l = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

A_{FB} : a bit of history

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

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

- Lots of excitement in the past years!
  - → First Tevatron l+jets analysis showed small deviations from SM

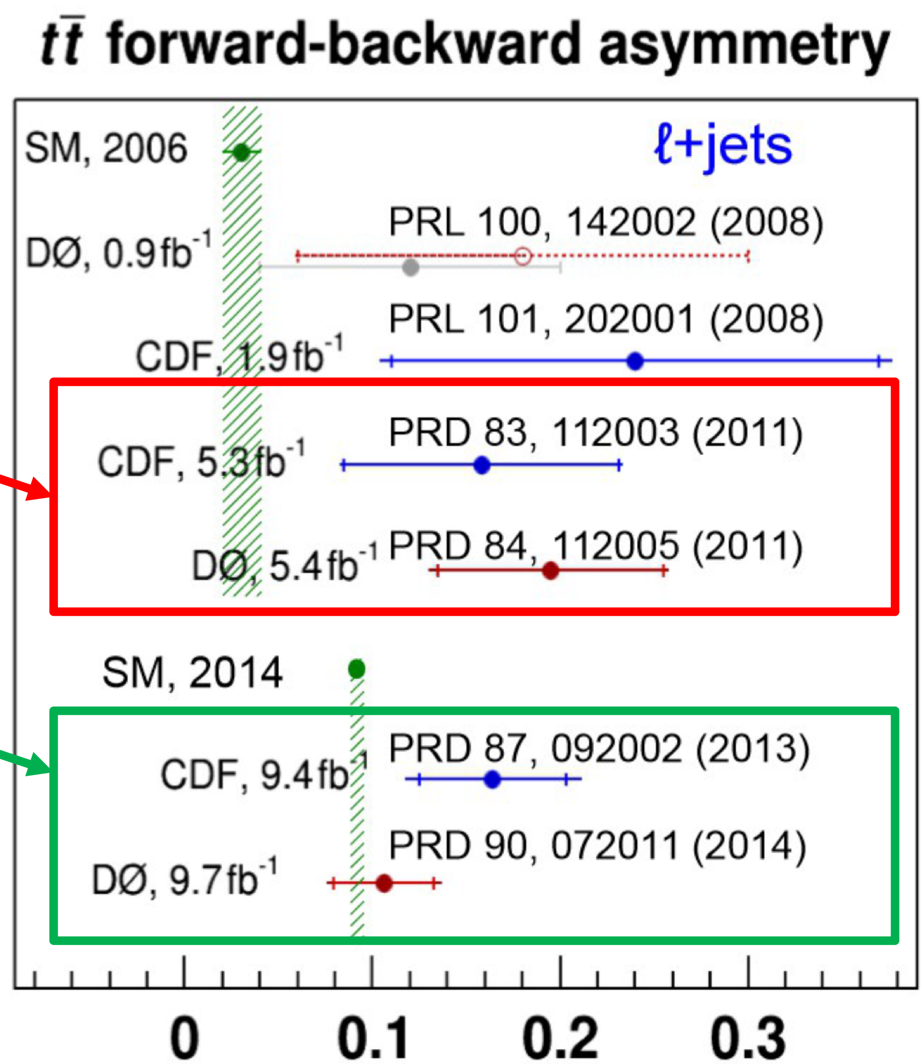


A_{FB} : a bit of history

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

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

- Lots of excitement in the past years!
  - → First Tevatron l+jets analysis showed small deviations from SM
- More recent results show a lower value
  - → More data and more refined analysis

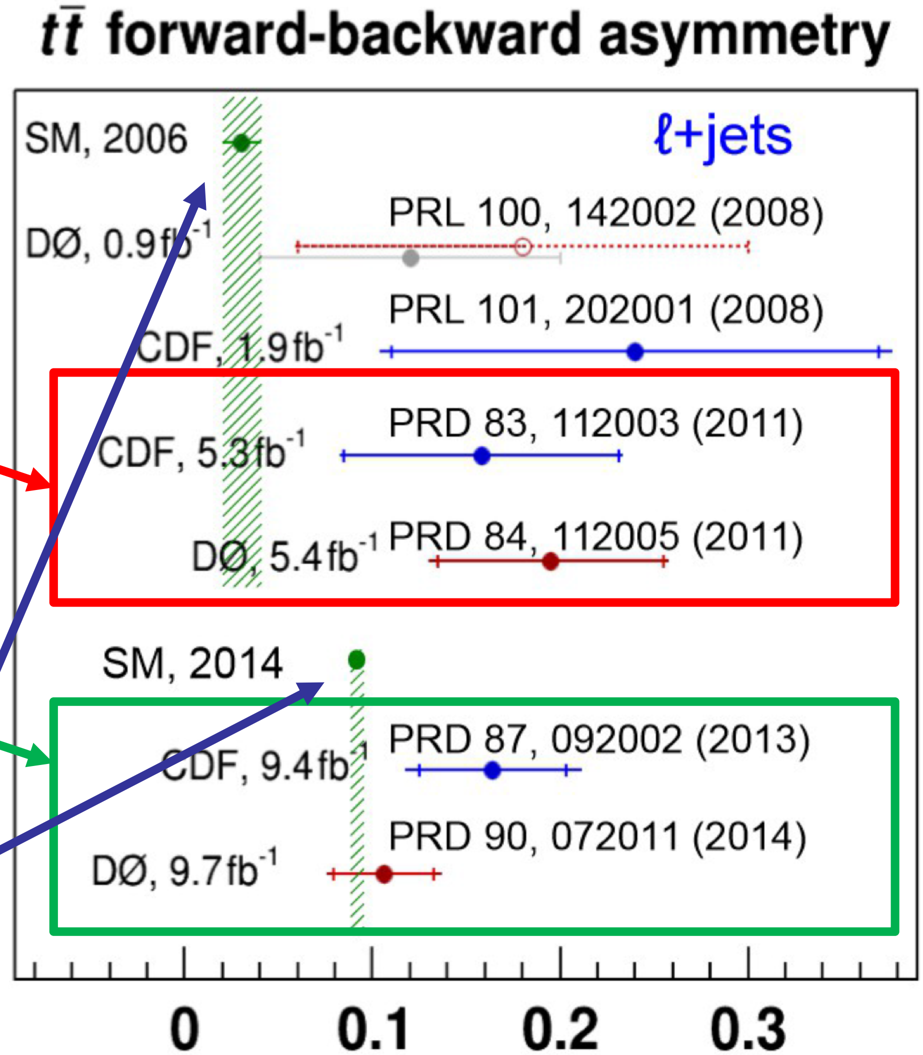


A_{FB} : a bit of history

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

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

- Lots of excitement in the past years!
  → First Tevatron l+jets analysis showed small deviations from SM
- More recent results show a lower value
  → More data and more refined analysis
- NNLO QCD + NLO EW expectations estimated to be higher



A^{tt}_{FB} Tevatron Combination

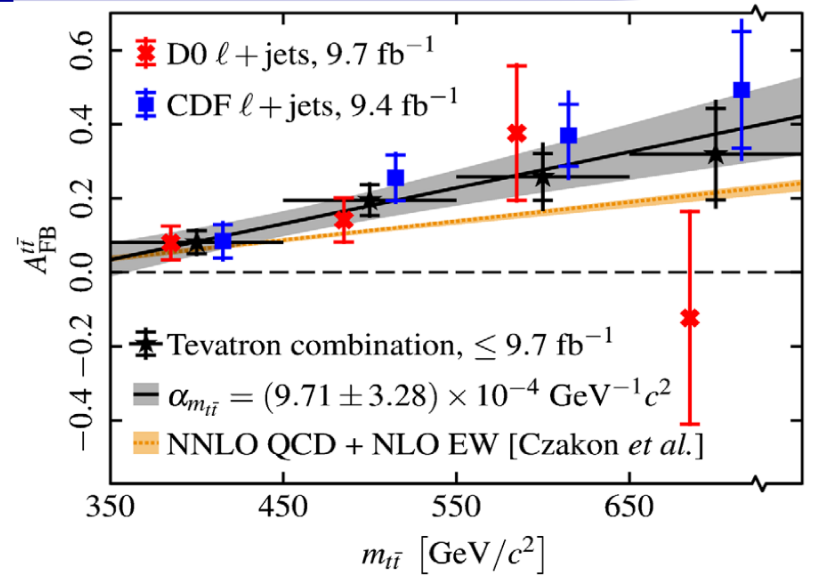
- Final Tevatron result
- CDF and D0 results combined using BLUE
- All correlations taken into account

Combined measurement:

A^{tt}_{FB} = 0.128 ± 0.025

Prediction: A^{tt}_{FB} = 0.095 ± 0.007

- **Agreement within: 1.3σ**



Mass dependence

- Tevatron combination:

$\alpha = (9.71 \pm 3.28)\times10^{-4}$/GeV, $\beta = 0.131 \pm 0.034$

- NNLO QCD + NLO EW prediction:

$\alpha = (5.11^{+0.42}_{-0.64})\times10^{-4}$/GeV, $\beta = 0.087^{+0.005}_{-0.006}$

- **Agreement within 1.3σ**

$|\Delta y_{tt}|$ dependence

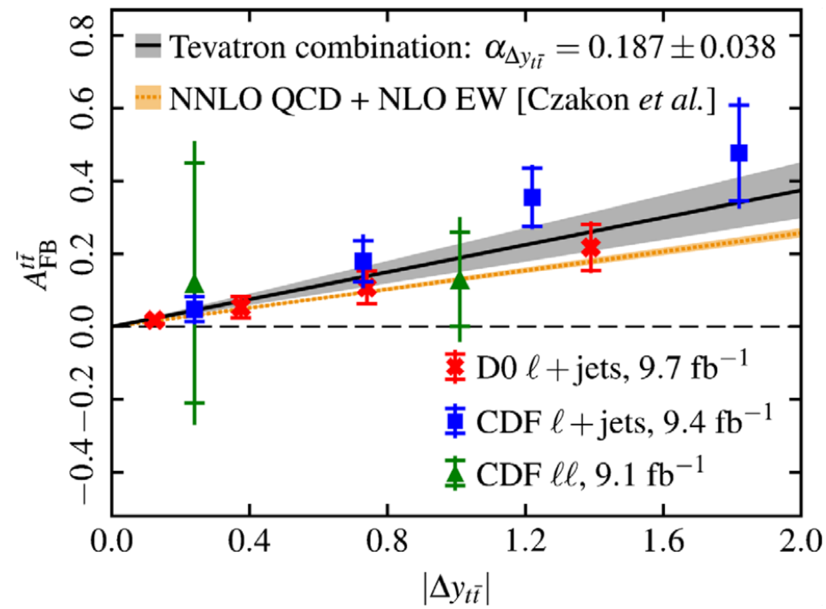
- Tevatron combination:

$\alpha = 0.187 \pm 0.038$

- NNLO QCD + NLO EW prediction:

$\alpha = 0.129^{+0.006}_{-0.012}$

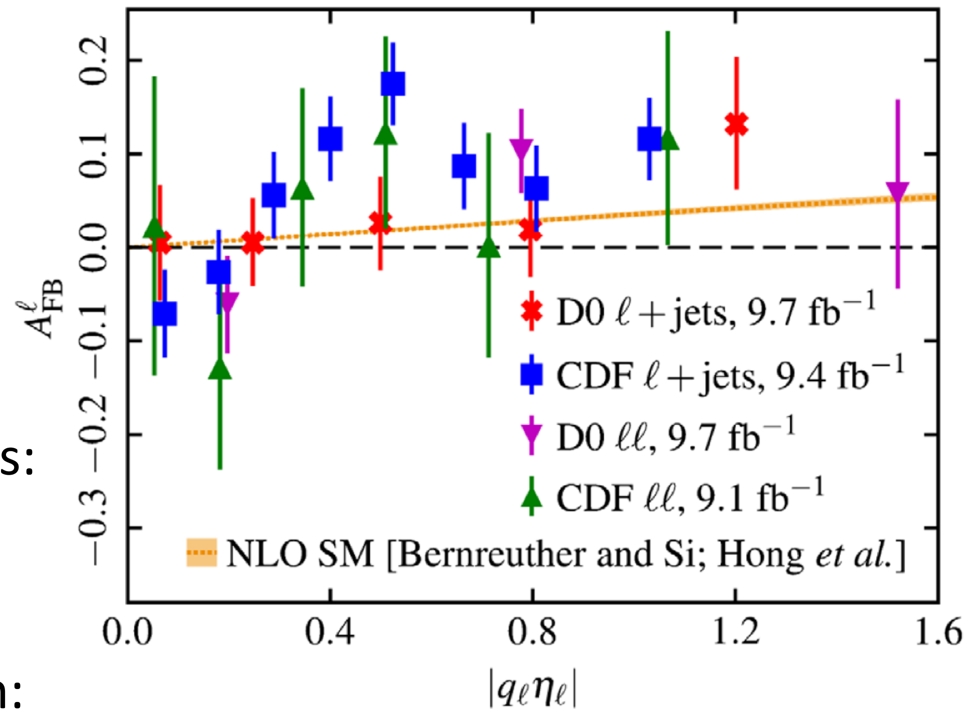
- **Agreement at the level of 1.5σ**



NEW! PRL 120, 042001 (2018)

Single lepton A^l_{FB} Tevatron Combination

$$A^{\ell}_{\mathrm{FB}} = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}$$



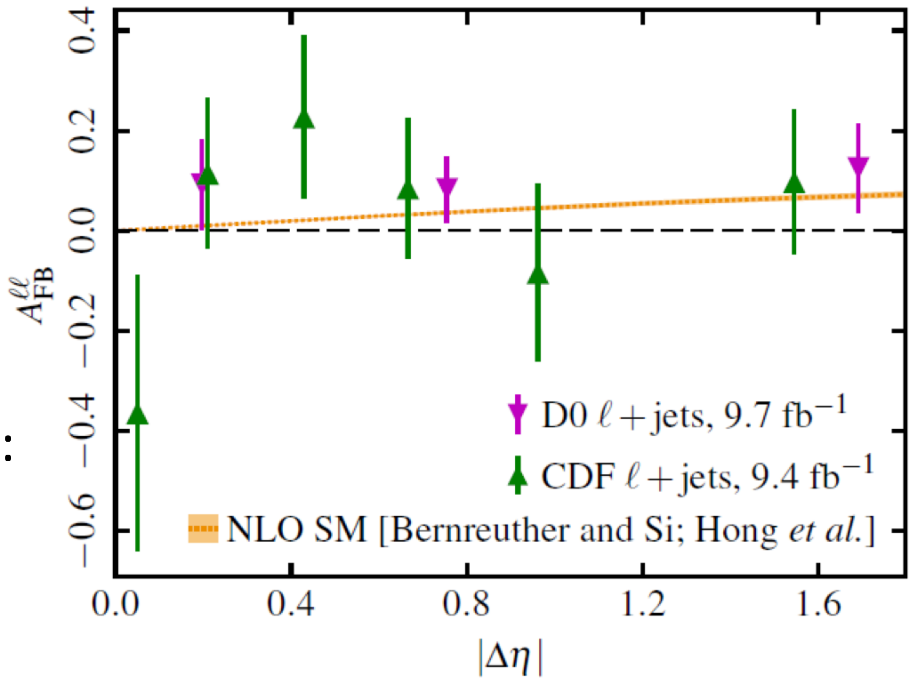
- Combination of inclusive measurements:
  A^l_{FB} = 0.073 ± 0.020
- NLO QCD + NLO EW inclusive prediction:
  A^l_{FB} = 0.038 ± 0.003
- Agreement within 1.6σ
- No combination of differential measurements

NEW! PRL 120, 042001 (2018)

Dilepton A^{ll}_{FB} Tevatron Combination

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

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



- Combination of inclusive measurements:
  A^{ll}_{FB} = 0.108 ± 0.046

- NLO QCD + NLO EW prediction:
  A^{ll}_{FB} = 0.048 ± 0.004

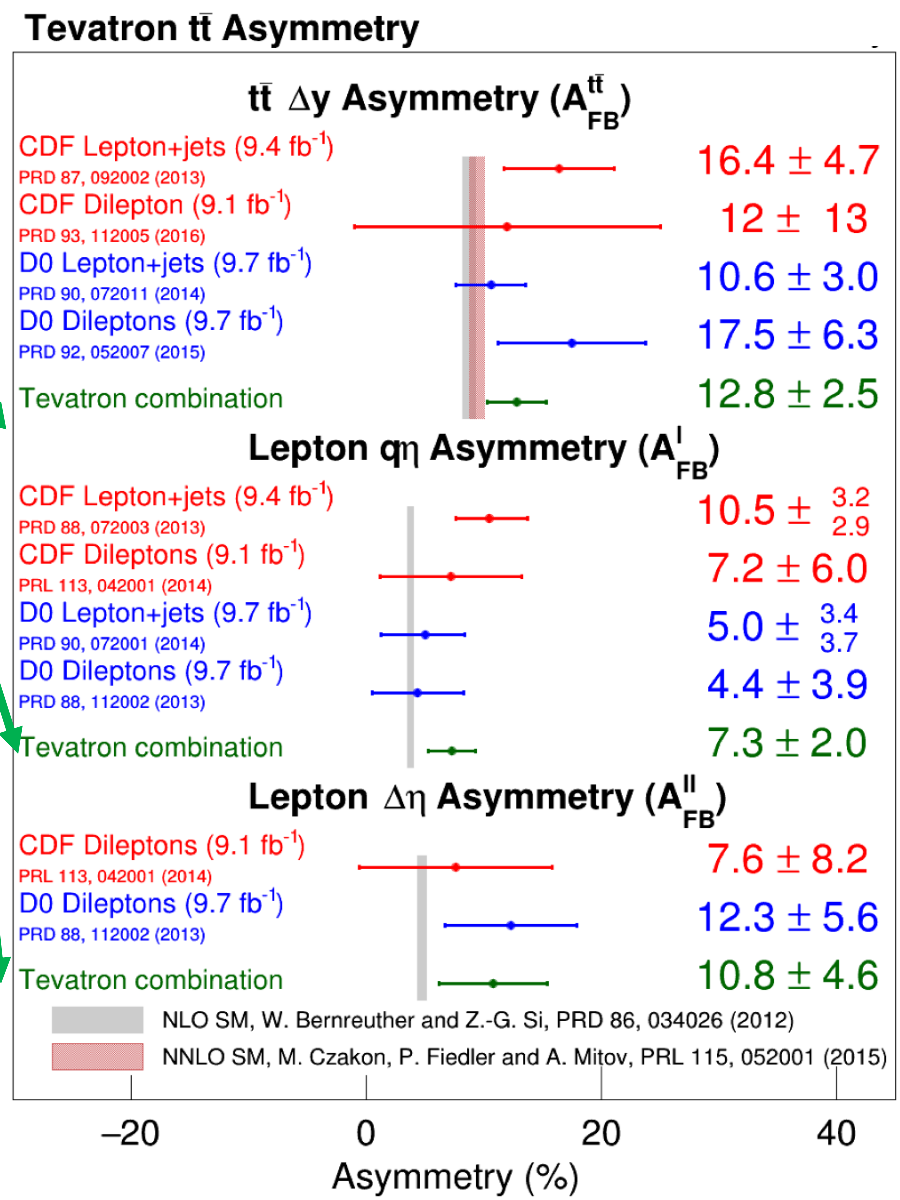
- Consistency within 1.3σ

- No combination of differential measurements

NEW! PRL 120, 042001 (2018)

Tevatron Combination

- The measurements and their combinations are consistent with each other and with the SM predictions



NEW! PRL 120, 042001 (2018)

Top polarization in lepton + jets channel

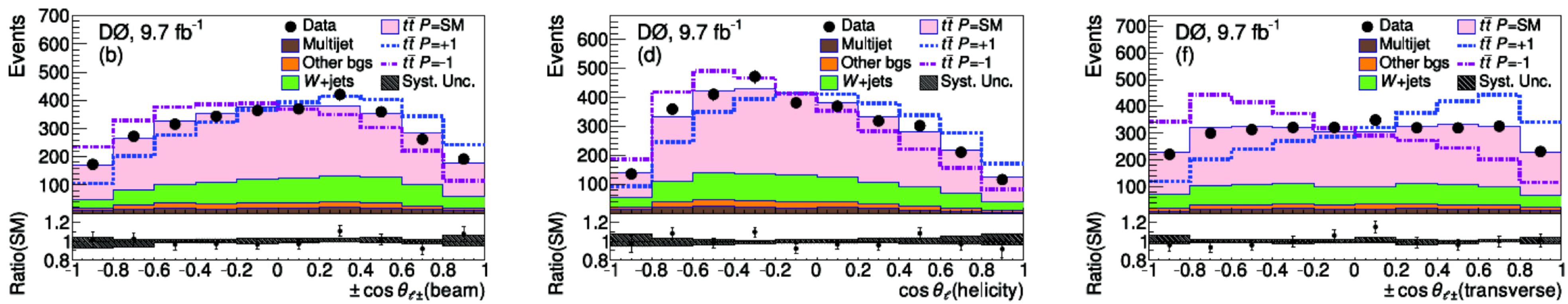
- SM: top quark is produced almost unpolarized in ttbar pair production
- Top polarization can be measured through angular distributions of decay products:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,\hat{n}}} = \frac{1}{2}(1 + P_{\hat{n}}\kappa_i \cos\theta_{i,\hat{n}})$$

P_n – polarization
k_i – spin-analyzing power (~1 for leptons)

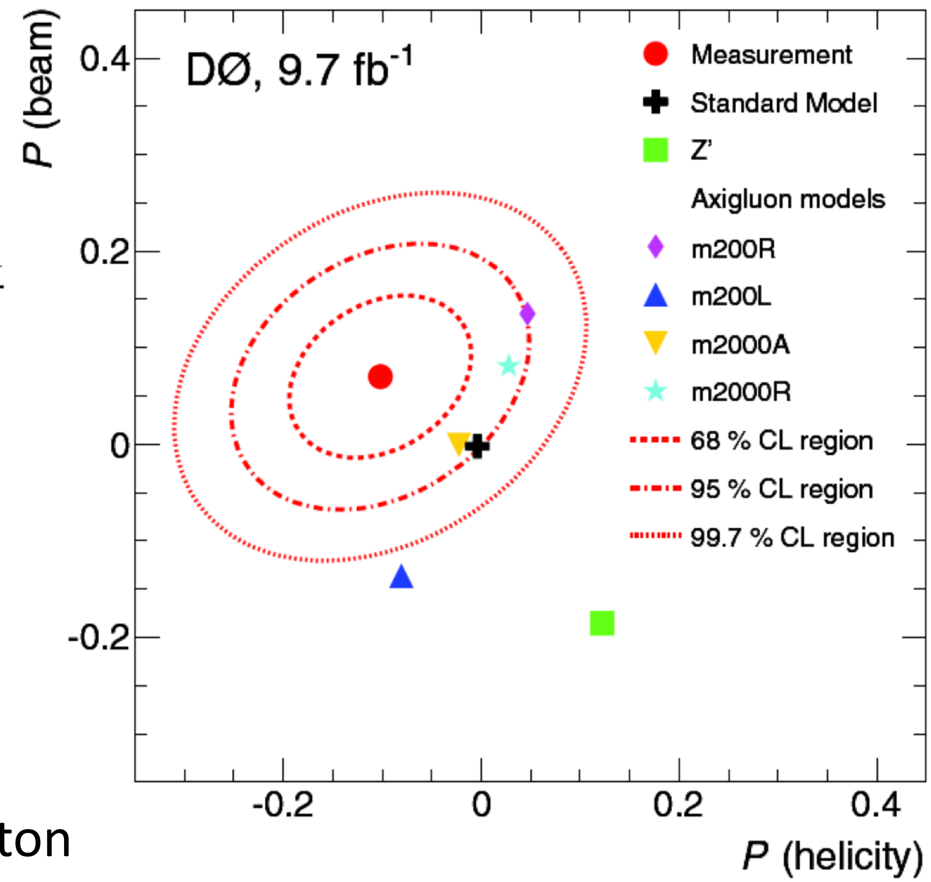
θ angle between decay product (in parent top rest frame) and quantization axis (in tt rest frame)

- 3 quantization axes used: beam, helicity, transverse axis
- Sample composition determined using kinematic discriminant based on likelihood ratio of various variables
- Template fit to cos θ distributions with top polarizations P = ± 1 for lepton + >=4 jet events



Top polarization in lepton + jets channel

Axis	Measured polarization	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Beam—D0 comb.	$+0.081 \pm 0.048$	-0.002
Helicity	-0.102 ± 0.061	-0.004
Transverse	$+0.040 \pm 0.035$	$+0.011$



PRD 95, 011101(R) (2017)

- Performed also combination with D0 dilepton channel
- Results consistent with theory at the level of 1-2σ

Top polarization in dilepton channel

NEW!

- Top dilepton final state channels ee, $e\mu$, $\mu\mu$
- The methods of estimating the signal and backgrounds follow AFB measurement analysis
- Examine ($cos\ \theta+$, $cos\ \theta-$) 2D distribution:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}(1 + \alpha_+ P_+ \cos\theta_+ + \alpha_- P_- \cos\theta_- - C\ \cos\theta_+ \cos\theta_-)$$

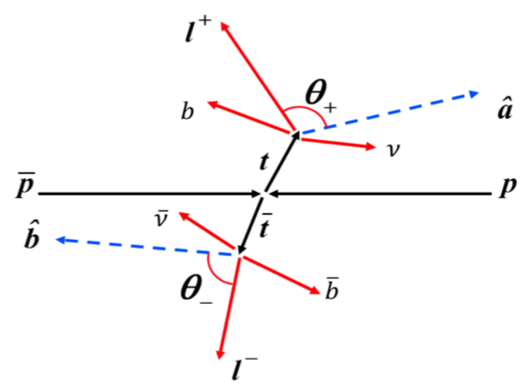
$\boldsymbol{\alpha_\pm}$: the lepton spin-analyzing power ($\approx$ **1** @NLO)
$\boldsymbol{P_\pm}$: the degree of polarization of the top quark
$\boldsymbol{C}$: the $\boldsymbol{t\bar{t}}$ spin correlation coefficient

- weight signal templates using double differential angular distribution formula

We consider two special cases:

1. CP Conserved(CPC) : $\alpha P^{CPC} = \alpha_+ P_+ = \ \alpha_- P_-$
2. CP Maximally Violated(CPV) : $\alpha P^{CPV} = \alpha_+ P_+ = -\alpha_- P_-$

In SM αP=0 at tree level and negligible in higher order



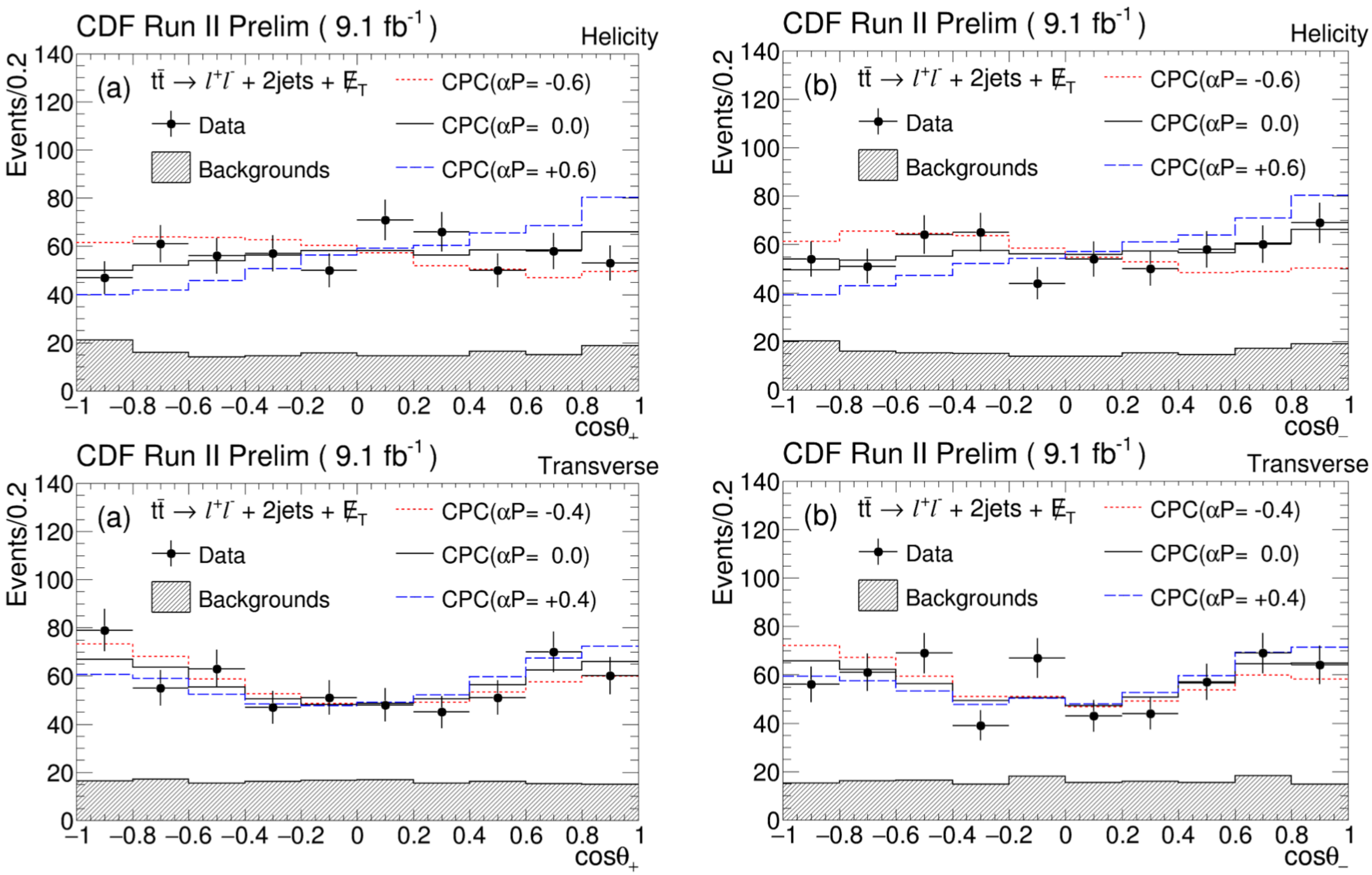
$\hat{a}$: The quantization axis of top quark
$\hat{b}$: The quantization axis of anti-top quark

- Consider two spin quantization bases and the two assumption of top quark production mechanism: (helicity basis, transverse basis) x (CPC, CPV)

Top polarization in dilepton channel

NEW!

1 dimensional comparison of data and signal + backgrounds

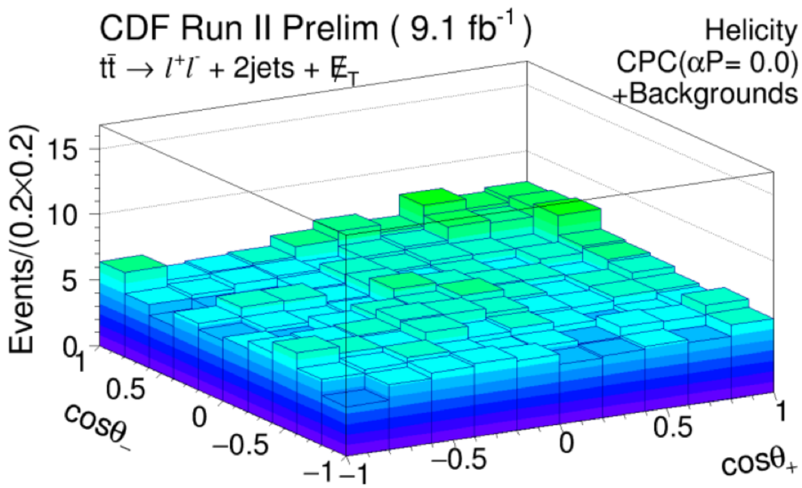


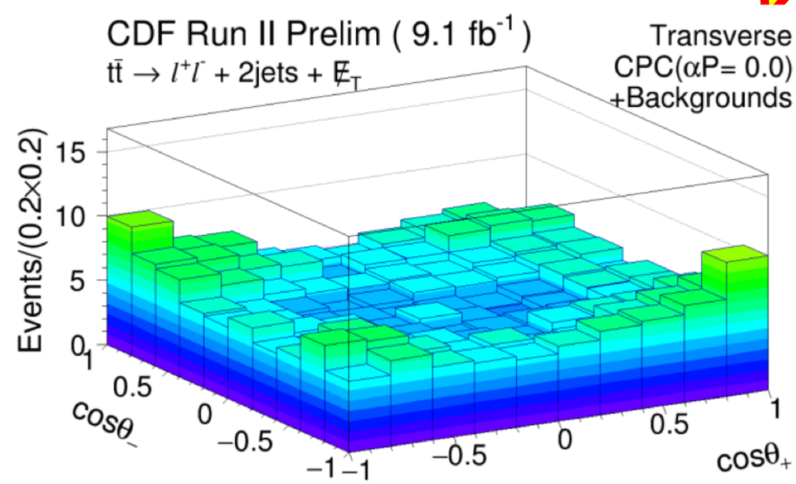
As an example, two extreme αP allowed in the physical region are shown for CPC in helicity and transverse frame.

Top polarization in dilepton channel

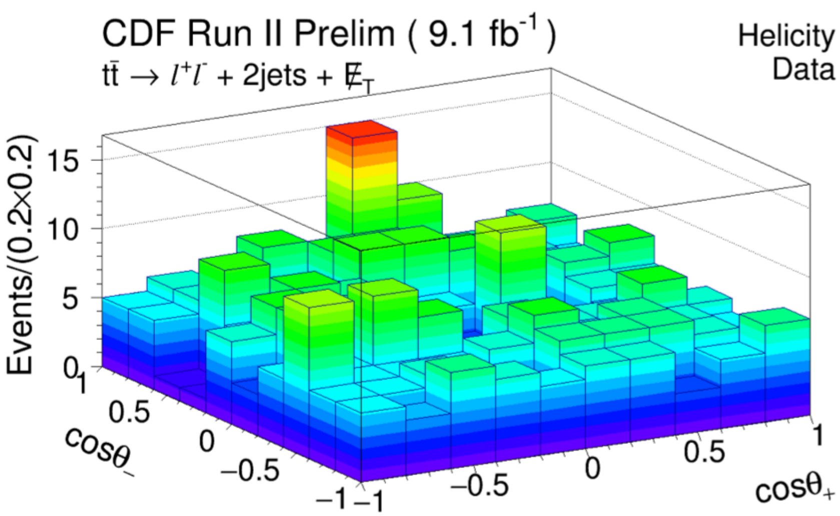
NEW!

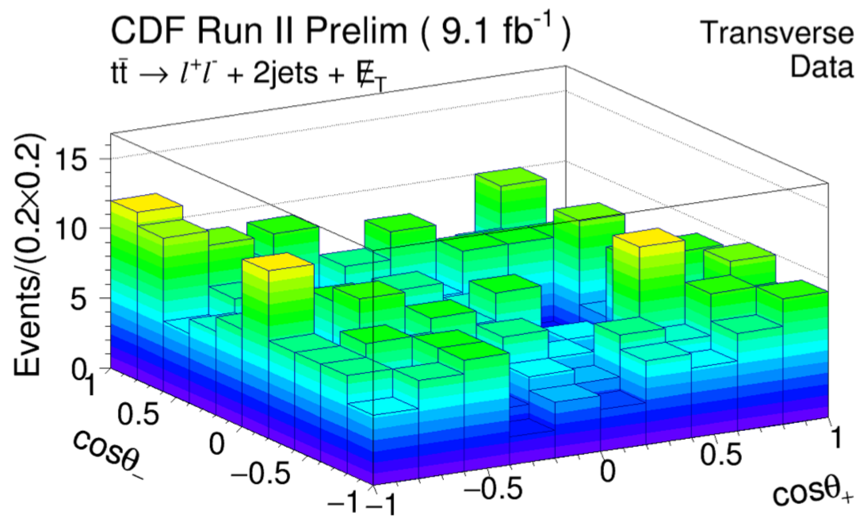
Example of signal +backgrounds 2-dim templates in Helicity and Transverse base





Data distributions





Top polarization in dilepton channel

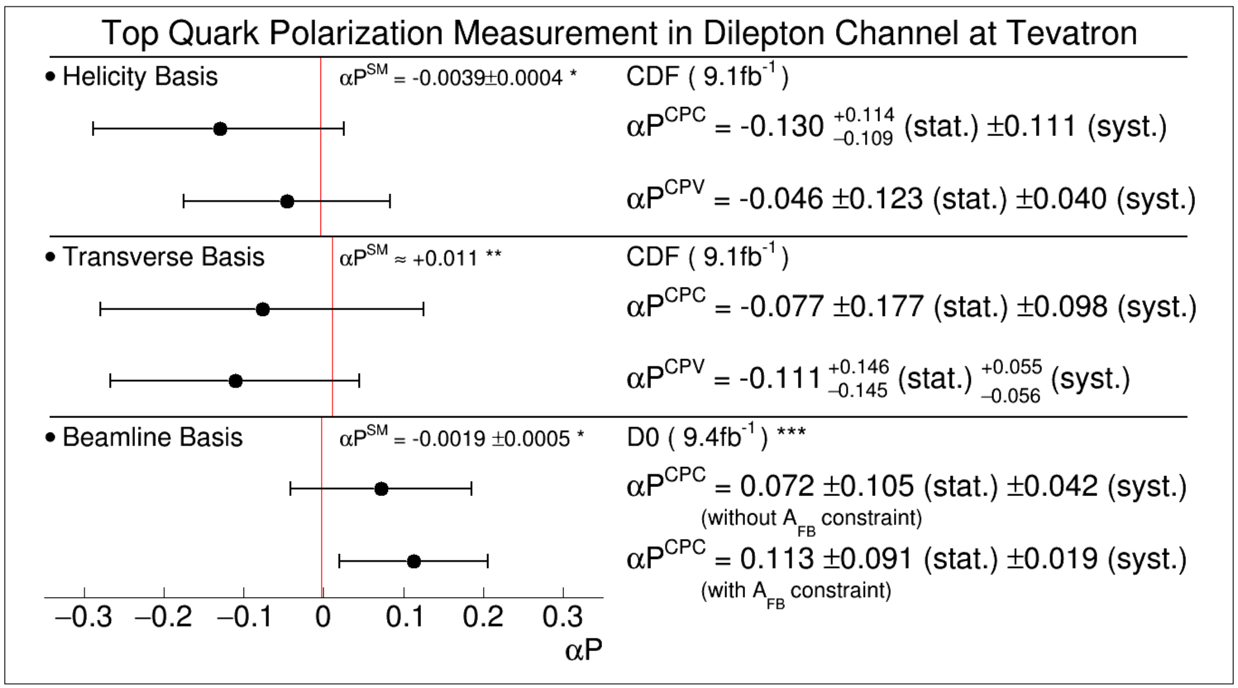
NEW!

- Likelihood fit with 2 dimensional distribution

$$\alpha P^{\rm CPC}_{\rm helicity} = -0.130\ ^{+0.114}_{-0.109}\ ({\rm stat.})\ \pm 0.111\ ({\rm syst.})$$
$$\alpha P^{\rm CPV}_{\rm helicity} = -0.046\ \pm 0.123\ ({\rm stat.})\ \pm 0.040\ ({\rm syst.})$$
$$\alpha P^{\rm CPC}_{\rm transverse} = -0.077\ \pm 0.177\ ({\rm stat.})\ \pm 0.098\ ({\rm syst.})$$
$$\alpha P^{\rm CPV}_{\rm transverse} = -0.111\ ^{+0.146}_{-0.145}\ ({\rm stat.})\ ^{+0.055}_{-0.056}\ ({\rm syst.})$$

The measured polarizations are consistent with the SM predictions

CDF Run II Prelim



* PRD 78, 017503 (2008) ** JHEP. 08 (2013) 072. *** PRD 92, 052007 (2015)

Conclusion

- Several years after the end of RunII the Tevatron continues providing valuable top physics results
- Many top quark areas of study (i.e. cross sections, single top s-channel, spin correlations, A_{FB}) are complementary to LHC measurements
- CDF & D0 are in the process of making the last Tevatron legacy measurements:
  - ⇒ **The final Tevatron A_{FB} combination just published**
  - ⇒ **D0 published the top quark pole mass meas. from cross sections**
  - ⇒ **CDF approved last week a new top polarization measurement in the dilepton channel**
- All measurements are in agreement with SM prediction

Conclusion

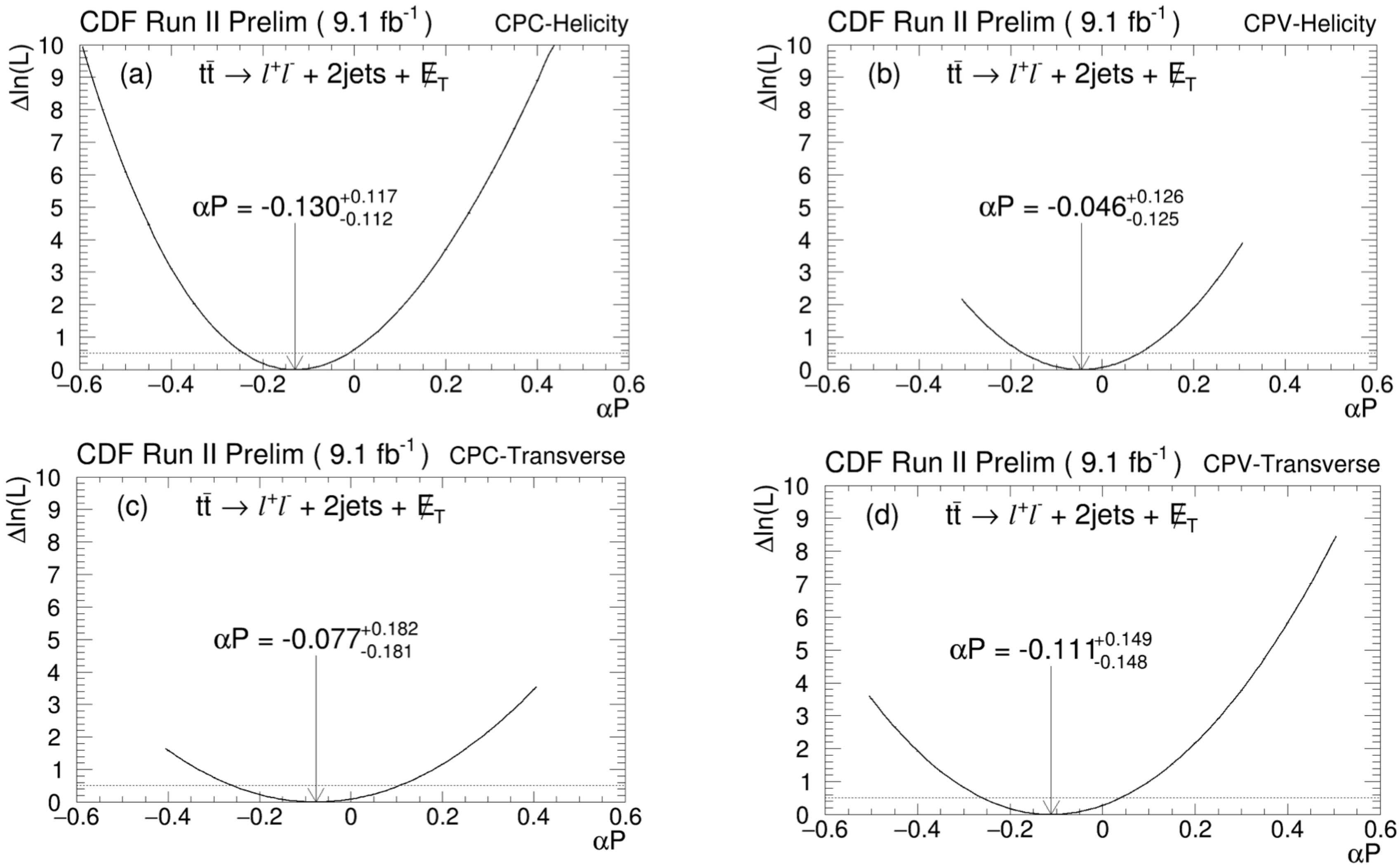
- Several years after the end of RunII the Tevatron continues providing valuable top physics results
- Many top quark areas of study (i.e. cross sections, single top s-channel, spin correlations, A_{FB}) are complementary to LHC measurements
- CDF & D0 are in the proce... the last Tevatron legacy measurements
  - ⇒ The final Tev...
  - ⇒ D0 measured the t... sections

Thank you!

- For more details:
- http://www-cdf.fnal.gov/physics/new/top/top.html
- http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/
- http://tevewwg.fnal.gov

Backup

Top polarization in dilepton channel



We build a binned likelihood function with Gaussian constraints on the numbers of the signal and backgrounds.

minimize ($-log\mathcal{L}$) to find the best fit αP.

Top polarization in dilepton channel

Systematic uncertainties are evaluated using pseudoexperiments with varied αP values

CDF Run II Prelim (9.1 fb^{-1})

Sources	Helicity CPC	Helicity CPV	Transverse CPC	Transverse CPV
	(-0.130)	(-0.046)	(-0.077)	(-0.111)
PDF	$^{+0.015}_{-0.016}$	$^{+0.002}_{-0.004}$	$^{+0.006}_{-0.003}$	$^{+0.002}_{-0.008}$
ISR/FSR	± 0.018	± 0.015	± 0.030	± 0.012
JES	± 0.045	± 0.003	± 0.005	± 0.005
Renormalization Scale	± 0.013	± 0.007	± 0.020	± 0.031
Top Quark Mass	± 0.050	± 0.006	± 0.047	± 0.014
MC Generator	± 0.076	± 0.014	± 0.049	± 0.016
Color Reconnection	± 0.009	± 0.013	± 0.011	± 0.022
Parton Showering	± 0.014	± 0.012	± 0.045	± 0.012
Background Shape	$^{+0.029}_{-0.028}$	± 0.028	$^{+0.039}_{-0.040}$	± 0.028
Total Syst.	± 0.111	± 0.040	± 0.098	$^{+0.055}_{-0.056}$
Stat.	$^{+0.114}_{-0.109}$	± 0.123	± 0.177	$^{+0.146}_{-0.145}$
Total Uncertainty	$^{+0.159}_{-0.155}$	± 0.129	± 0.203	± 0.156