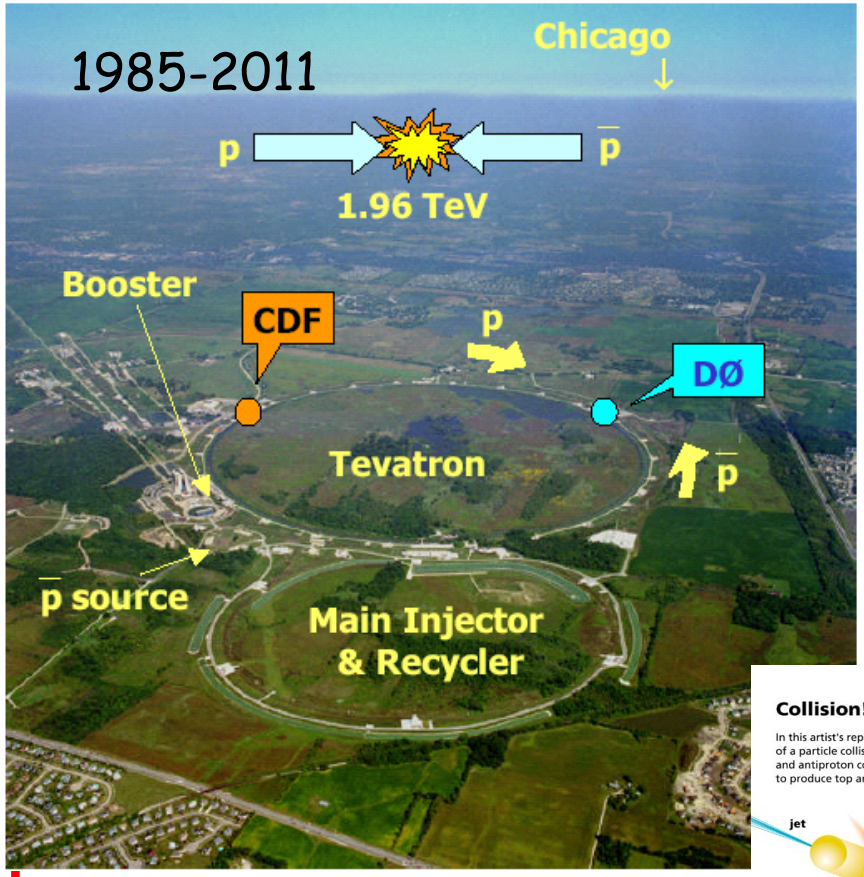

# Top Quark Physics at the Tevatron

Sandra Leone
(INFN Pisa)

On behalf of the CDF and D0 Collaborations

Bologna, June 7, 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

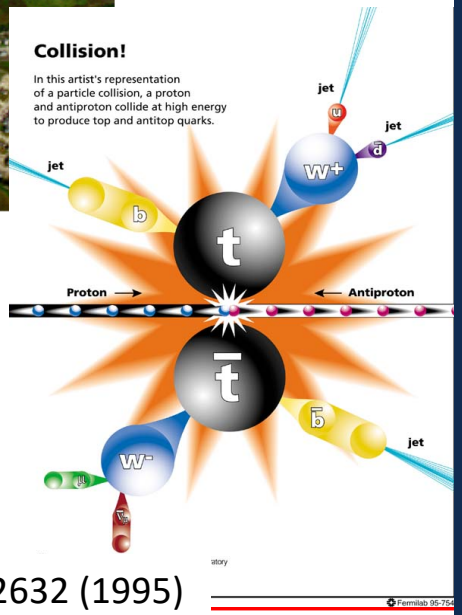
Public Information Office, P.O. Box 500, Batavia, IL 60510 • Telephone: 708-840-3351 • Facsimile: 708-840-8780

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

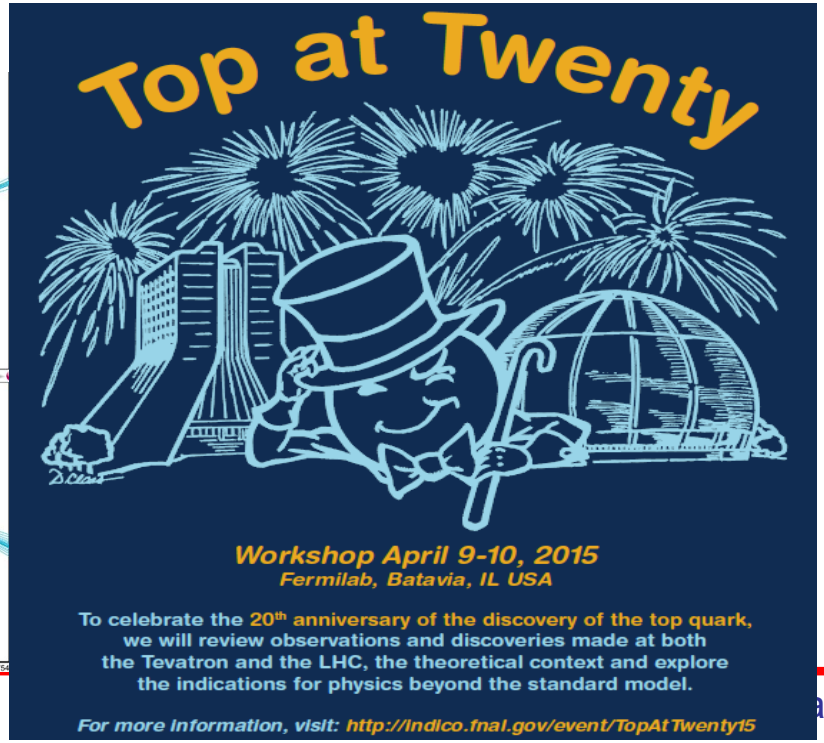
95-2
March 1, 1995

PHYSICISTS DISCOVER TOP QUARK

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




PRL 74 2626, PRL 74 2632 (1995)



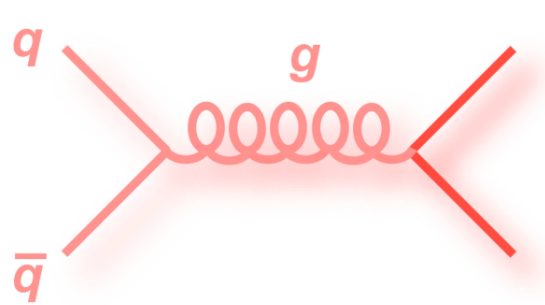
# Top Quark Production at Tevatron

- QCD pair production

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

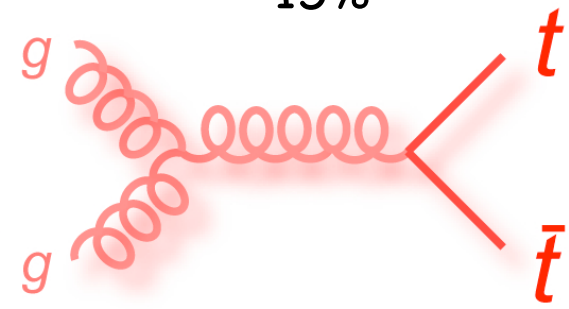
(for $m_{Top}$= 172.5 GeV)
(PRL 110, 252004 (2013))

~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

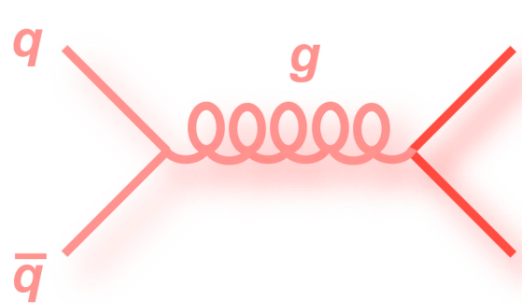
# Top Quark Production at Tevatron

- QCD pair production

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

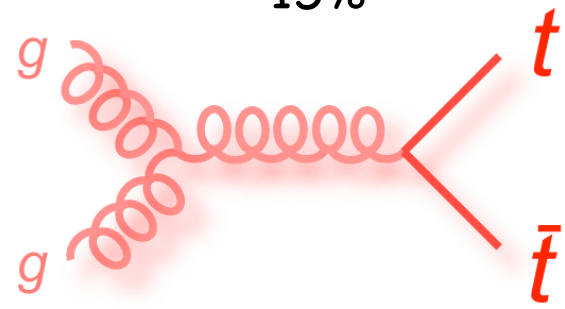
(for $m_{Top}$= 172.5 GeV)
(PRL 110, 252004 (2013))

~85%




Dominant process at Tevatron

~15%



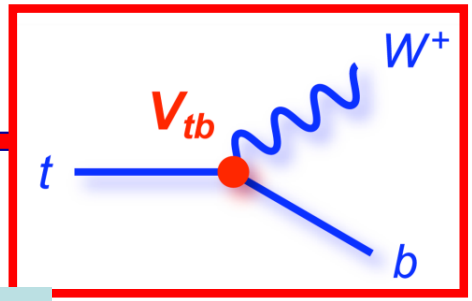

Dominant process at LHC (~90%)

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

Small cross section!
$\Rightarrow$ Observation in ~ 67 $pb^{-1}$ $\Rightarrow$ ~ 500 ttbar pairs produced per experiment

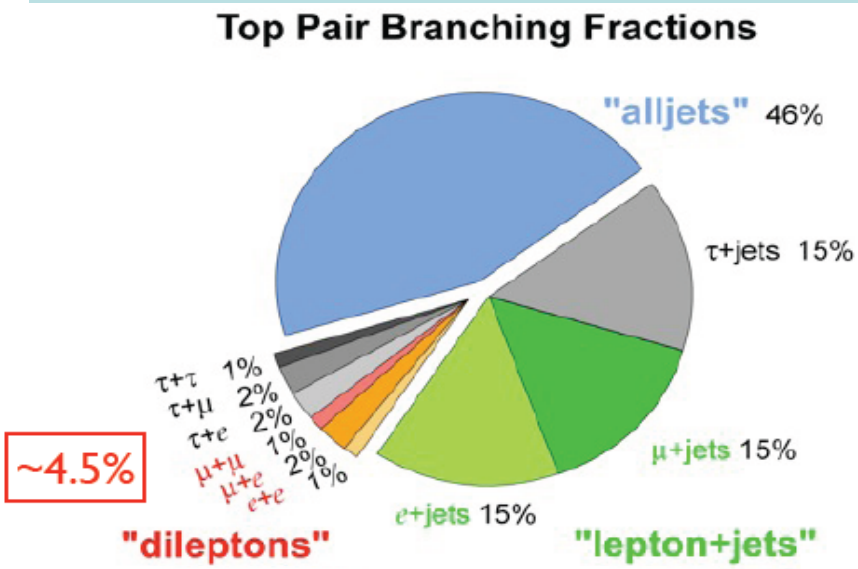
$\Rightarrow$ In 10 $fb^{-1}$ $\Rightarrow$ ~ 73500 ttbar pairs produced

# Top Quark Decay

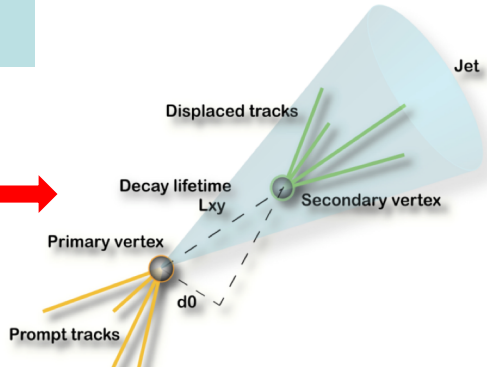



SM predicts BR( $t \rightarrow Wb$) ≈ 100%

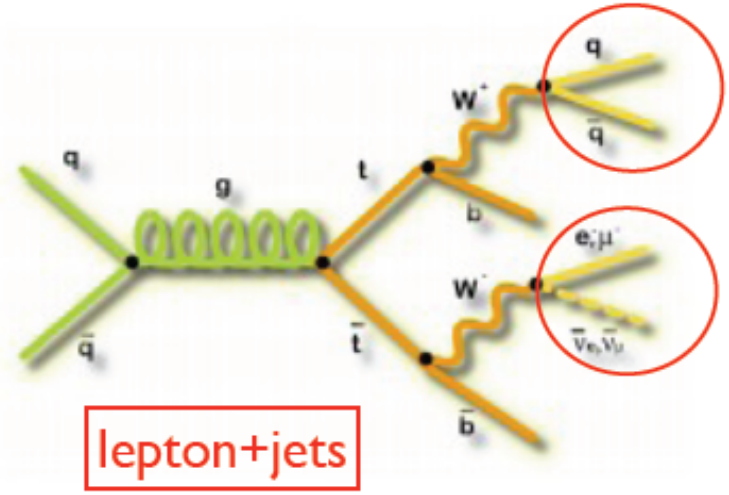
Event topology determined by the W decay mode

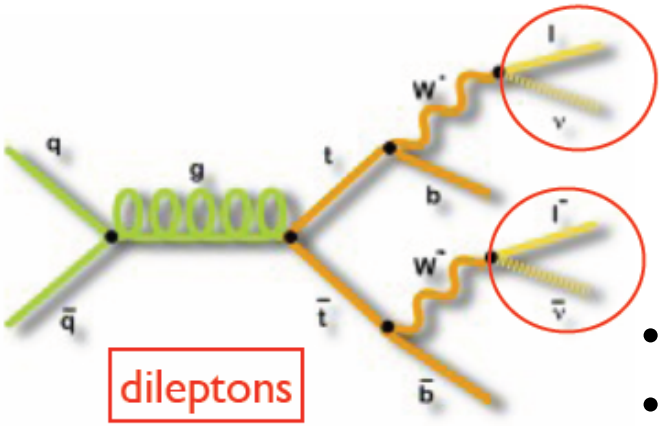



b quarks are always present




~30%



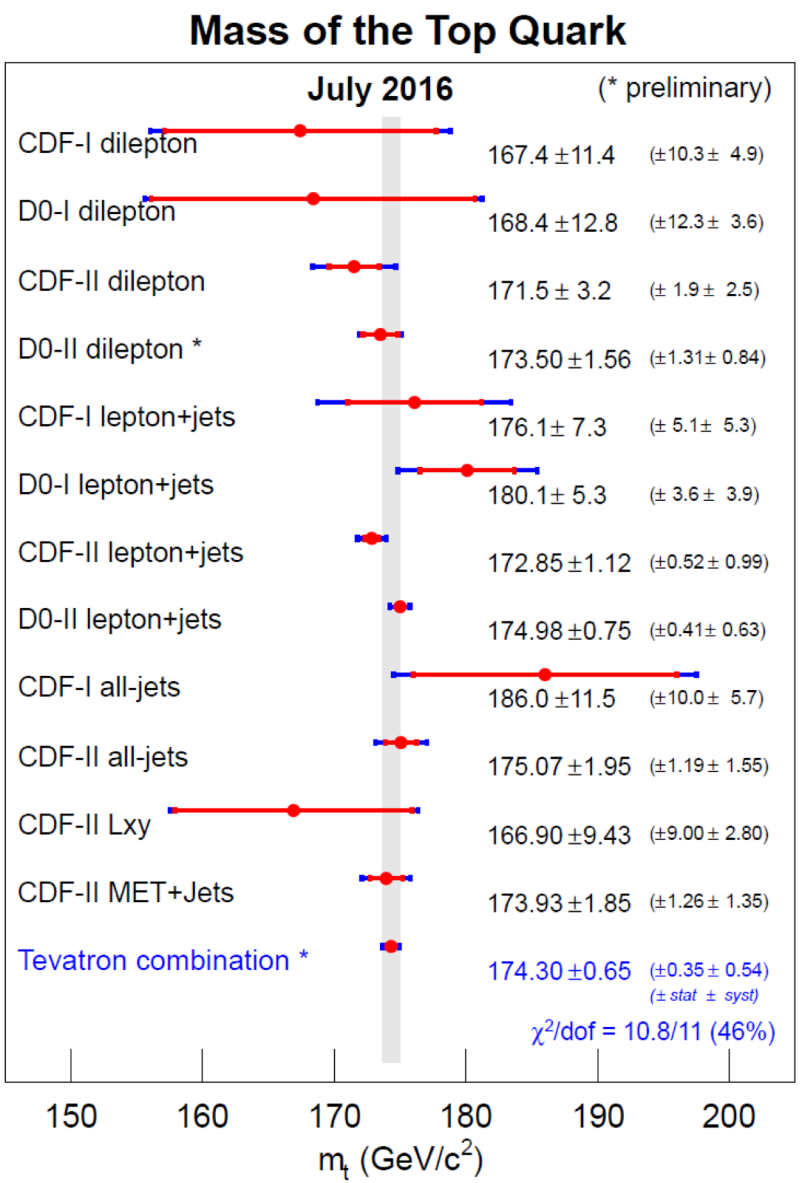




- Small rate
- Small background

- 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 top quarks 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

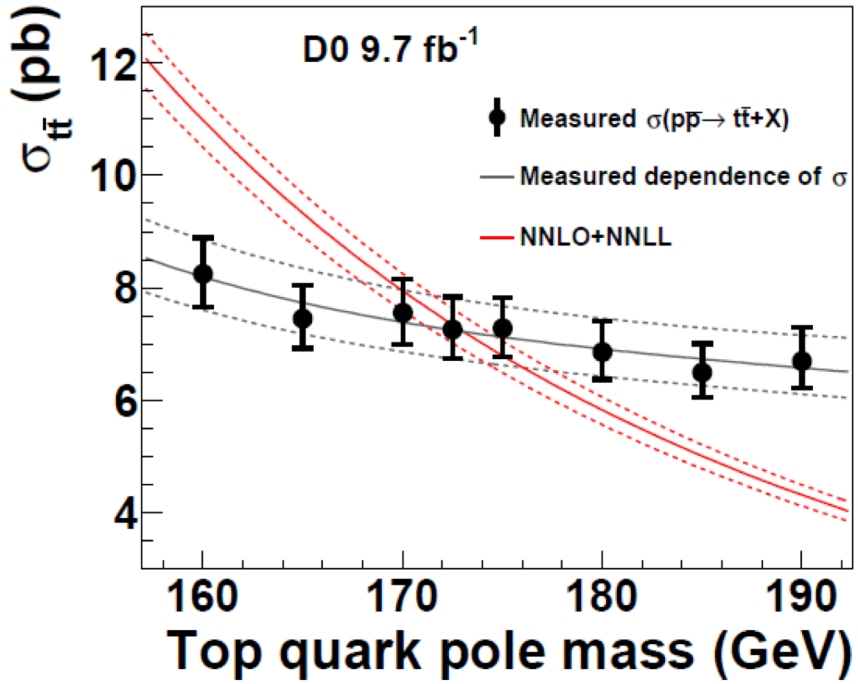
- From inclusive cross-section measurement in lepton+jets and dilepton channels:

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

  - dependence from mass parametrized with a fourth-order polynomial function
  - compared to NNLO+NNLL prediction
  - extracting the most probable mass + uncertainty with normalized joint-likelihood function:

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

dominated by experimental uncertainties



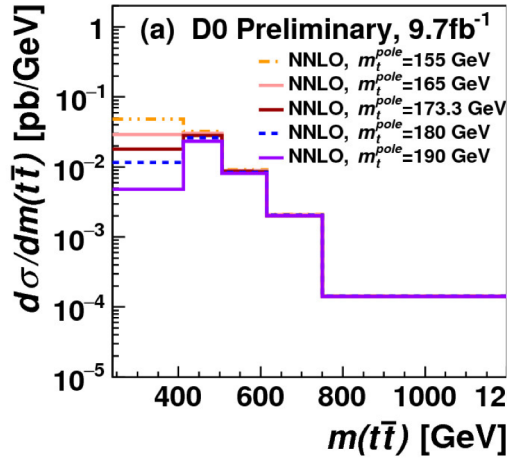

PRD 94, 092004 (2016)

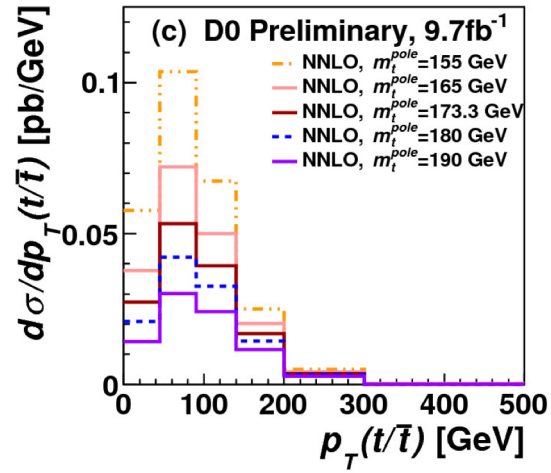
- Advantage: extract the top-quark mass in a well defined renormalization scheme
- Drawback: less precise than direct measurements

**1.9%** relative uncertainty

# D0 pole mass from diff. cross section

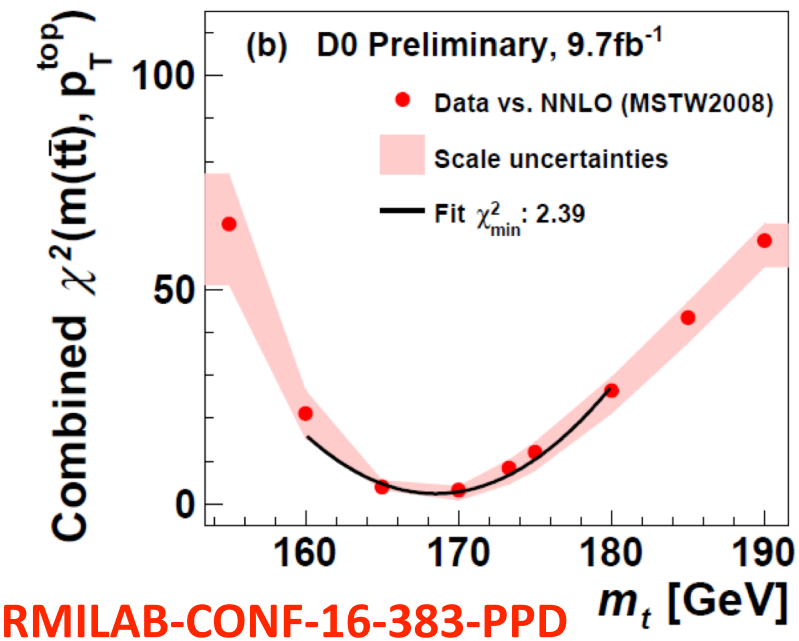
- Using the differential $t\bar{t}$ cross section:
  - ✓ additional information coming from the shape of the distributions
  - ✓ possible since NNLO differential predictions are now available (JHEP 1605, 034 (2016))




- $p_T{}^{top}$ 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
- $\chi^2$ fit to both distributions
  - $p_T$ vs. $m_{tt}$

$$m_{top}=169.1\pm2.5\ (\text{total})\ \text{GeV}$$



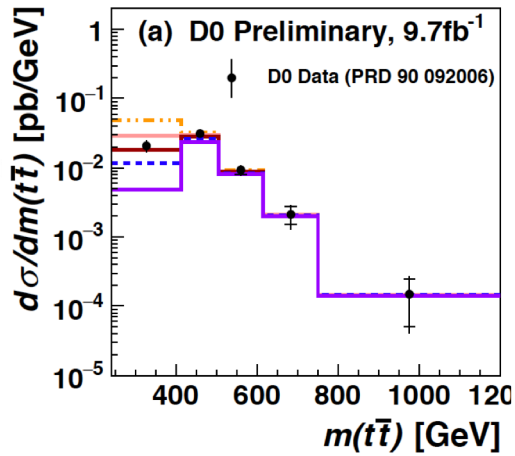

- better uncertainty than inclusive (1.5%)
  - ✓ even using only lepton+jets
  - ✓ Theory input not using NNLL

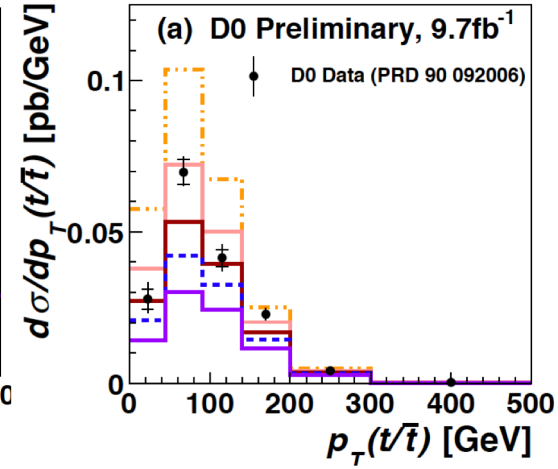
**FERMILAB-CONF-16-383-PPD**

**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))

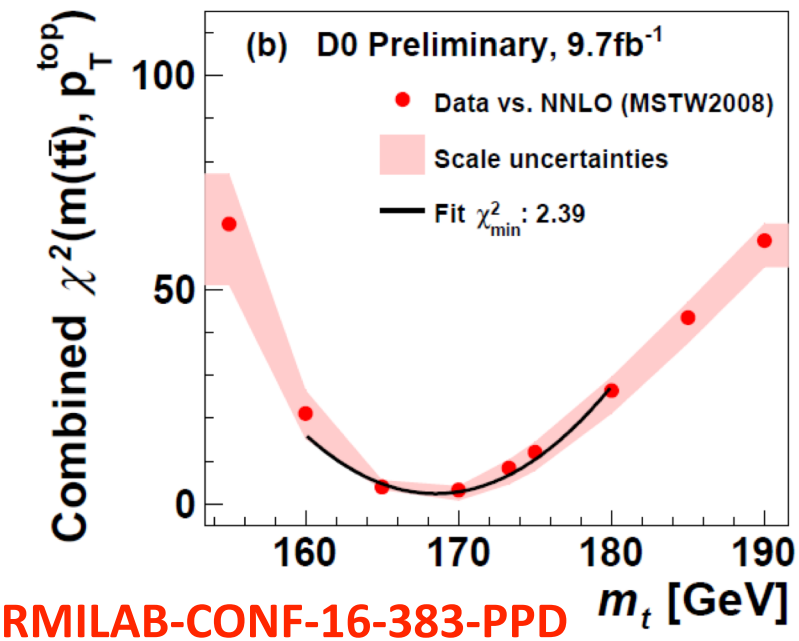



- $p_T{}^{top}$ and $m_{tt}$ sensitive to pole mass
- Unfolded differential distributions from D0 paper PRD 90 092006 (2014)
- compared to NNLO QCD calc. , four different PDF sets
- $\chi^2$ fit to both distributions
  - $p_T$ vs. $m_{tt}$

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

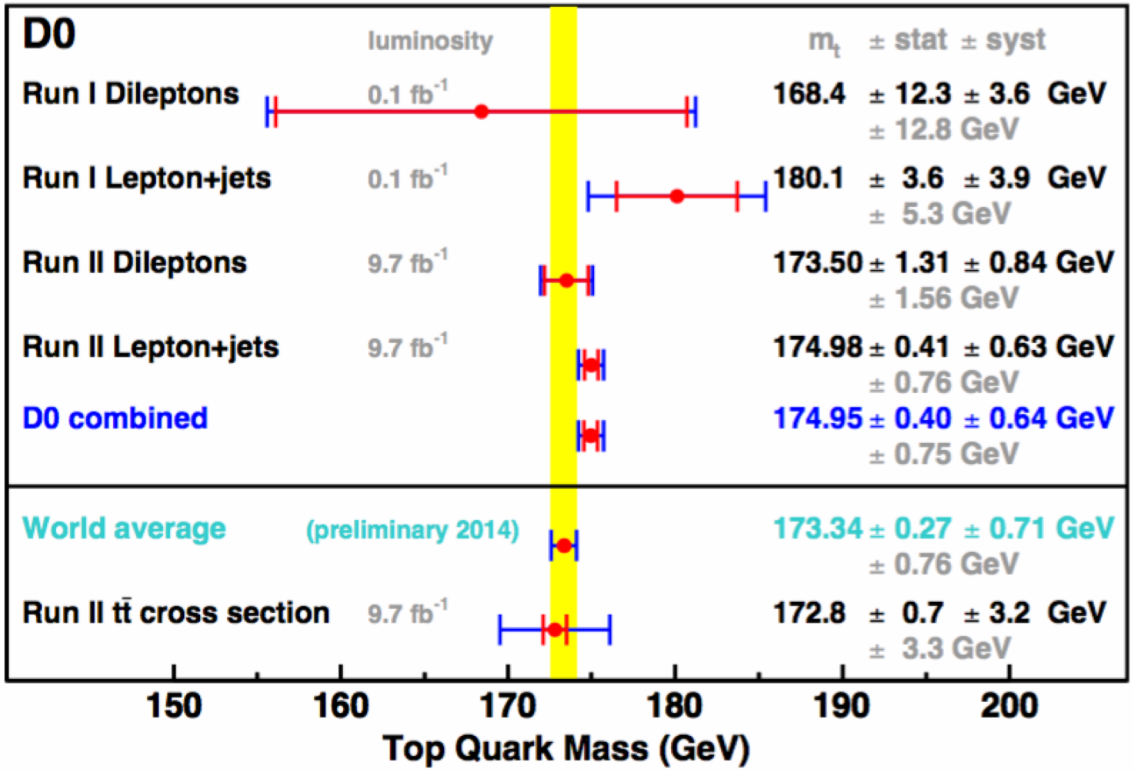
- better uncertainty than inclusive (1.5%)
  - ✓ even using only lepton+jets
  - ✓ Theory input not using NNLL




**FERMILAB-CONF-16-383-PPD**

**D0 Note 6473-CONF**

# D0 legacy top mass combination




- All data analyzed
- Combined with BLUE

$\chi^2$/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 |

**PRD 95, 112004 (2017)**

D0 top quark mass combination:

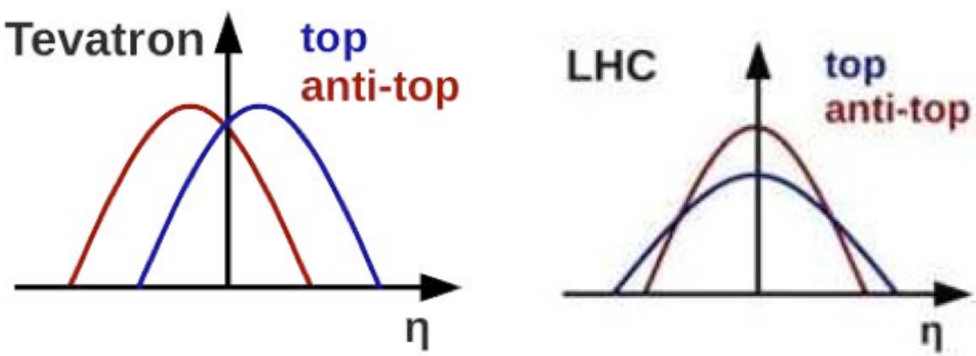
$m_{top}$=**174.95** ±**0.40** (stat.) ±**0.64** (syst.) GeV

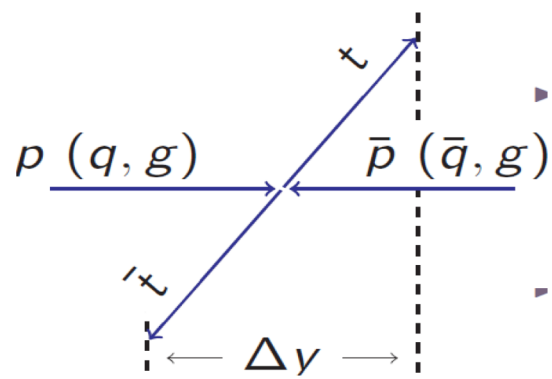
**0.43%** relative uncertainty

# 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→lvb 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:

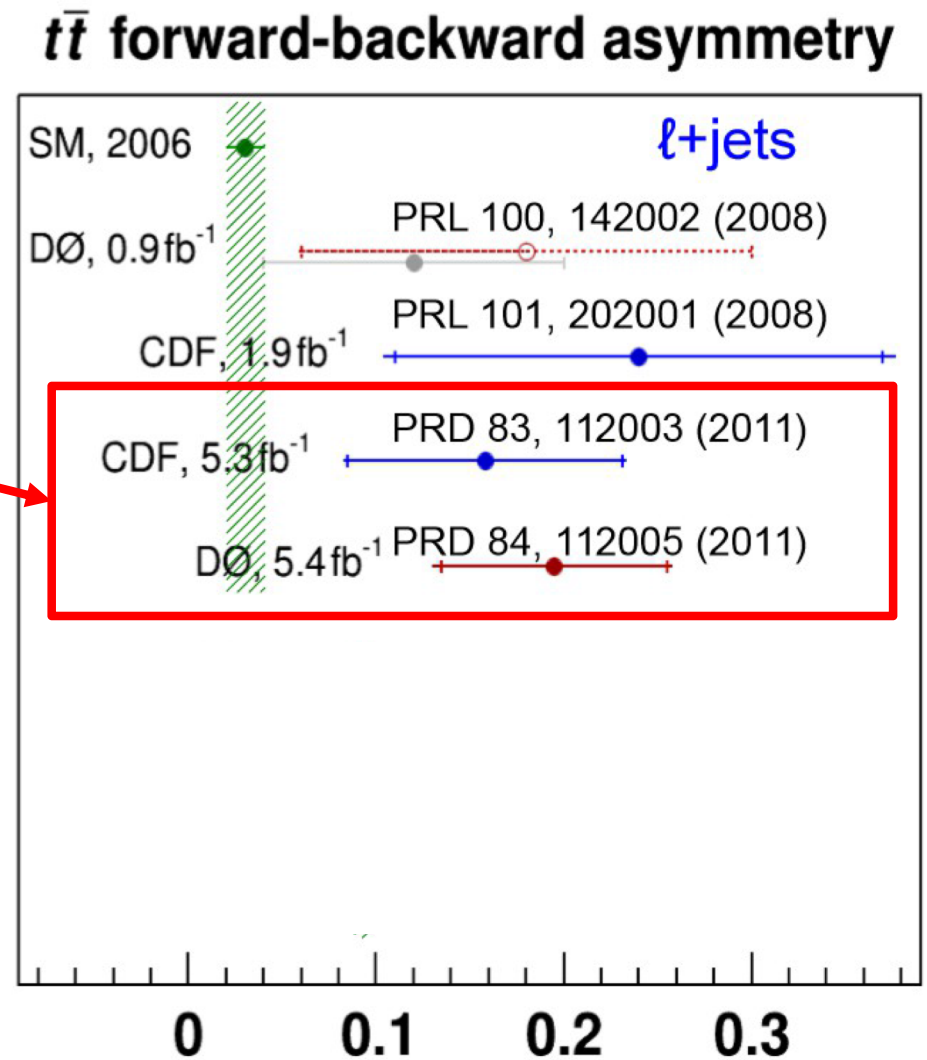
$$A_l = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

# $A_{FB}$ : a bit of history

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

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

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

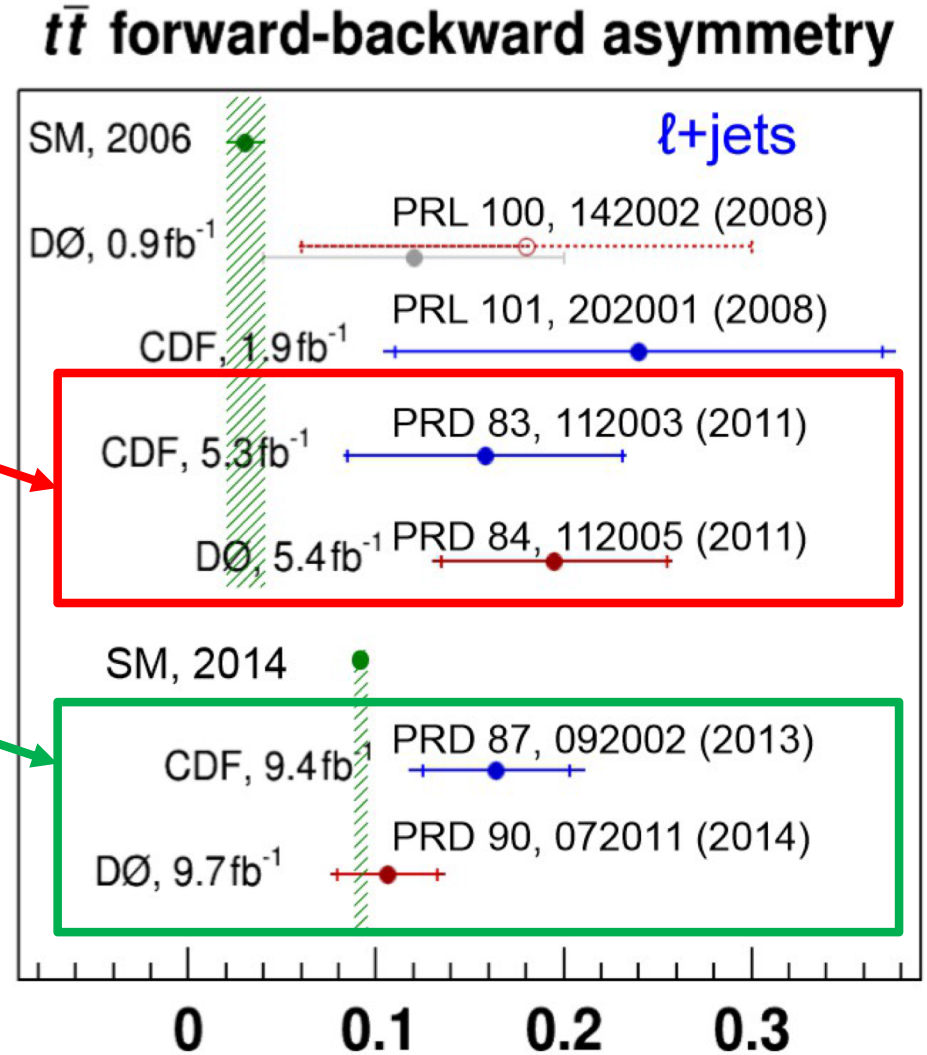


# $A_{FB}$ : a bit of history

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

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

- 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

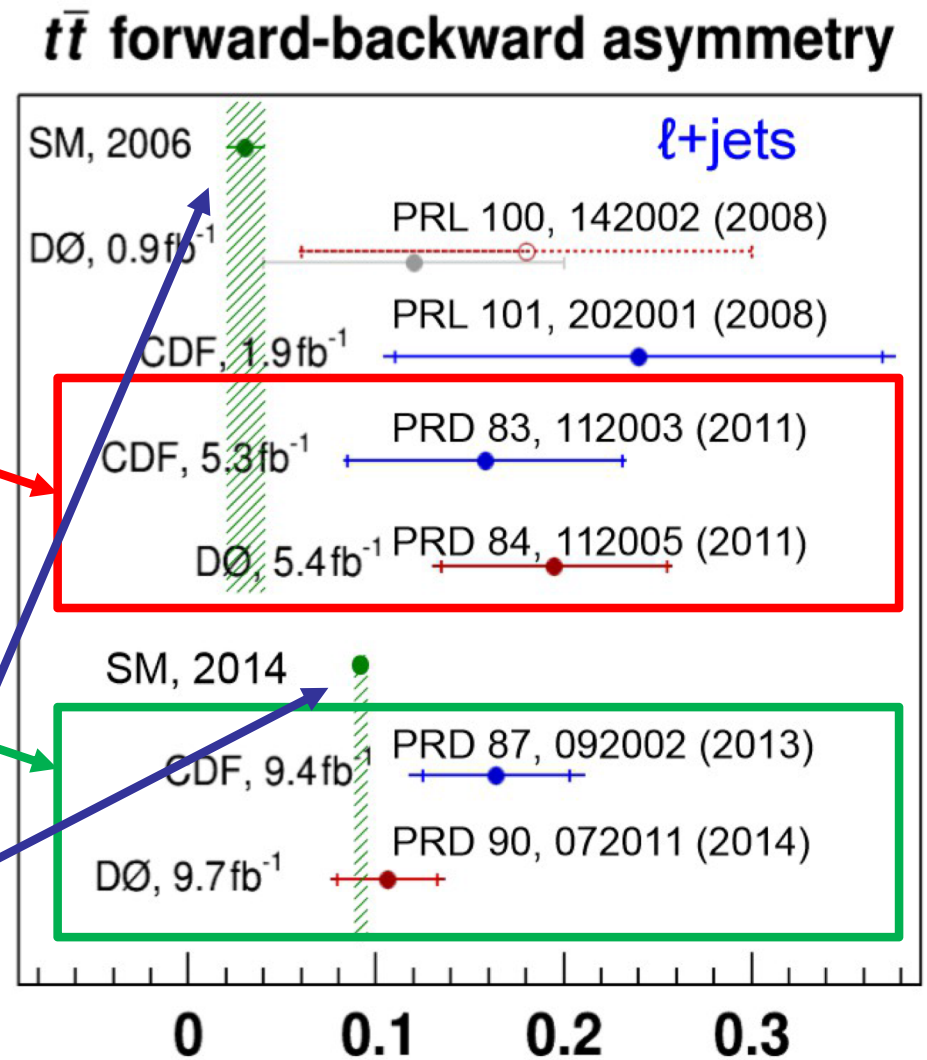


# $A_{FB}$ : a bit of history

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

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

- 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

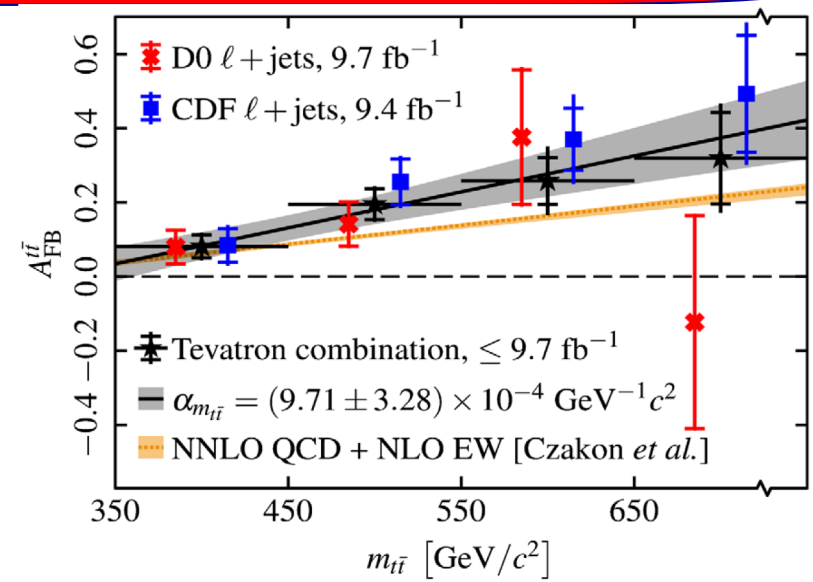
- Final Tevatron result
- CDF and D0 results combined using BLUE
- All correlations taken into account

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:

α = (9.71 ± 3.28)x10$^{-4}$/GeV, β = 0.131 ± 0.034

- NNLO QCD + NLO EW prediction:

α = (5.11 $^{+0.42}_{-0.64}$)x10$^{-4}$/GeV, β = 0.087 $^{+0.005}_{-0.006}$

- **Agreement within 1.3σ**

**$|\Delta y_{tt}|$ dependence**

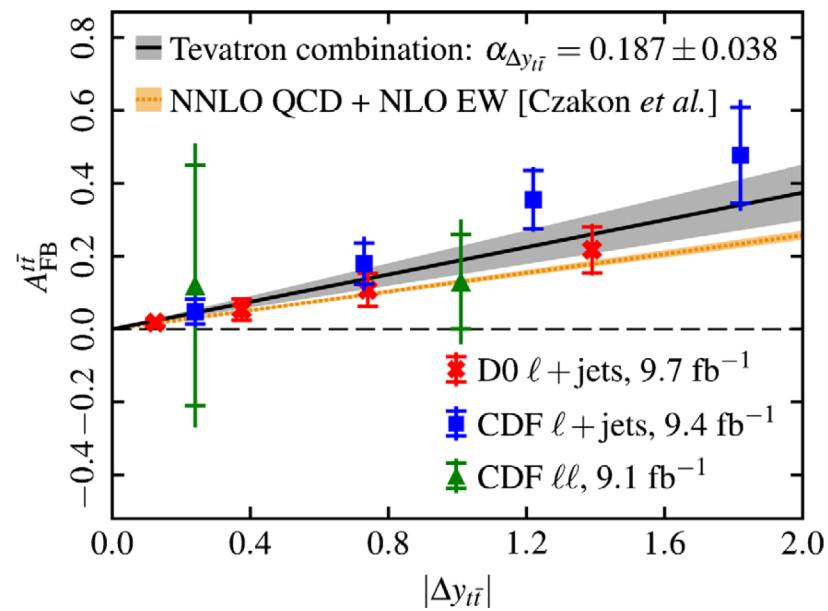
- Tevatron combination:

α = 0.187 ± 0.038

- NNLO QCD + NLO EW prediction:

α = 0.129 $^{+0.006}_{-0.012}$

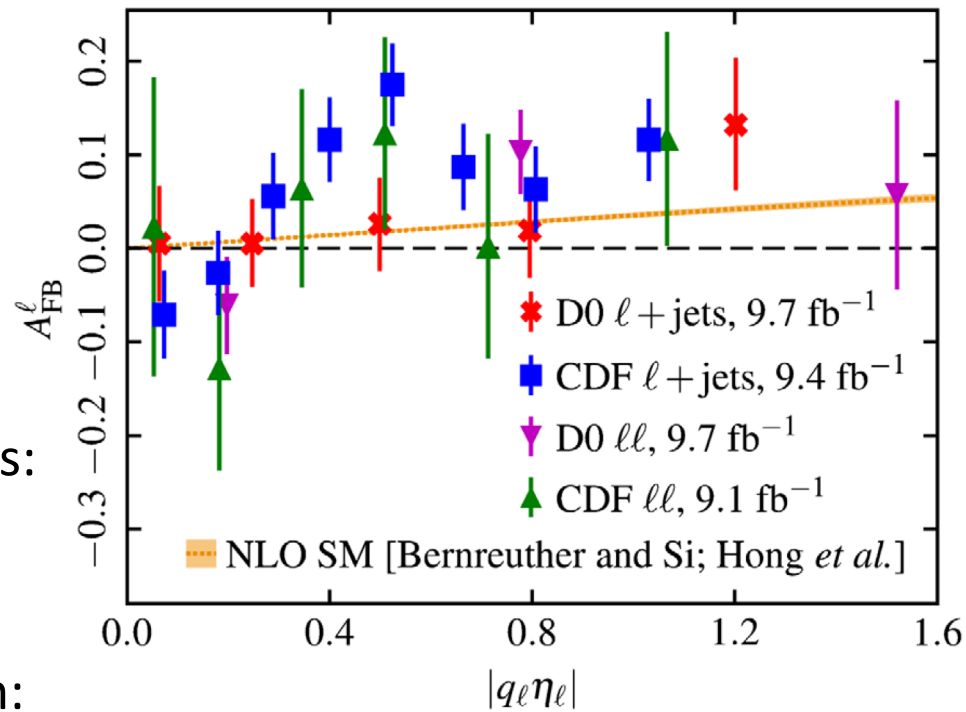
- **Agreement at the level of 1.5σ**




**NEW! PRL 120, 042001 (2018)**

# Single lepton $A^l_{FB}$ Tevatron Combination

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



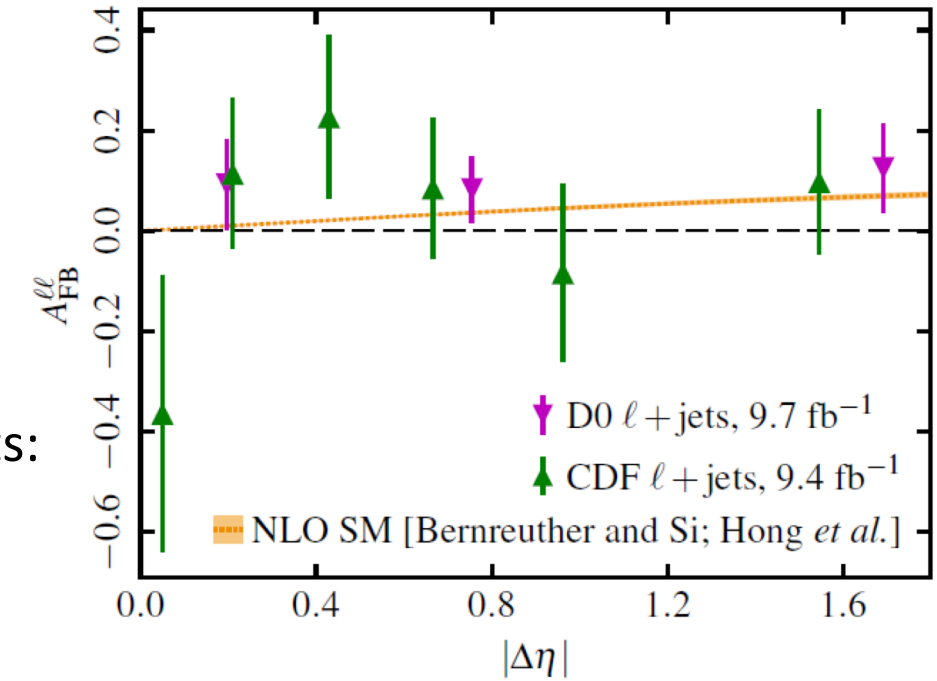

- Combination of inclusive measurements:
  **$A^l_{FB}$ = 0.073 ± 0.020**
- NLO QCD + NLO EW inclusive prediction:
  **$A^l_{FB}$ = 0.038 ± 0.003**
- Agreement within 1.6σ
- No combination of differential measurements

**NEW! PRL 120, 042001 (2018)**

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

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

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

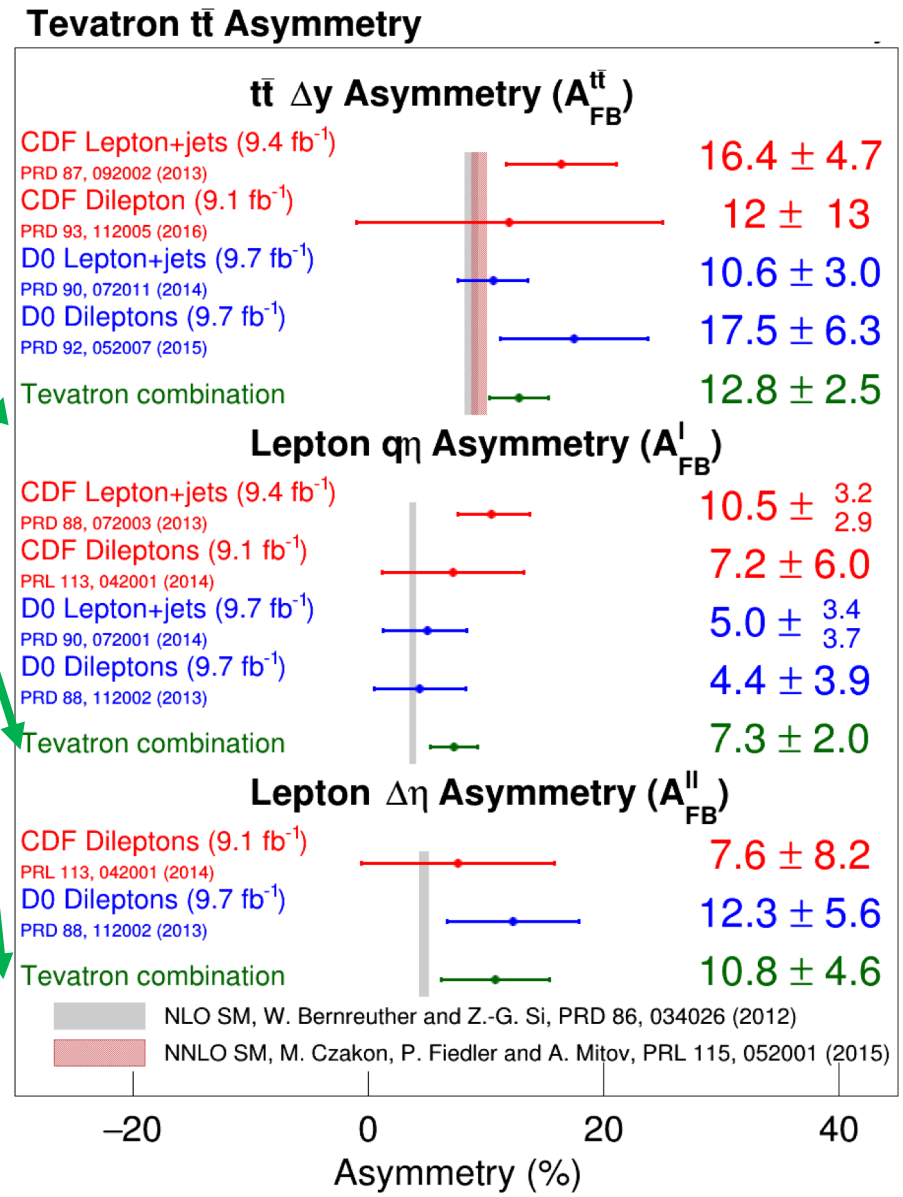



- Combination of inclusive measurements:
  **$A^{ll}_{FB}$ = 0.108 ± 0.046**
- NLO QCD + NLO EW prediction:
  **$A^{ll}_{FB}$ = 0.048 ± 0.004**
- Consistency within 1.3σ
- No combination of differential measurements

**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

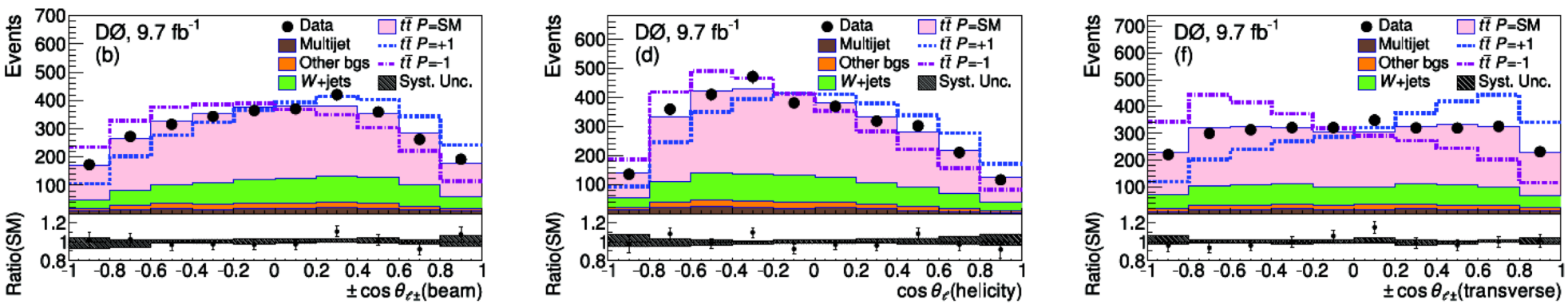
- SM: top quark is produced almost unpolarized in ttbar pair production
- Top polarization can be measured through angular distributions of decay products:

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

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

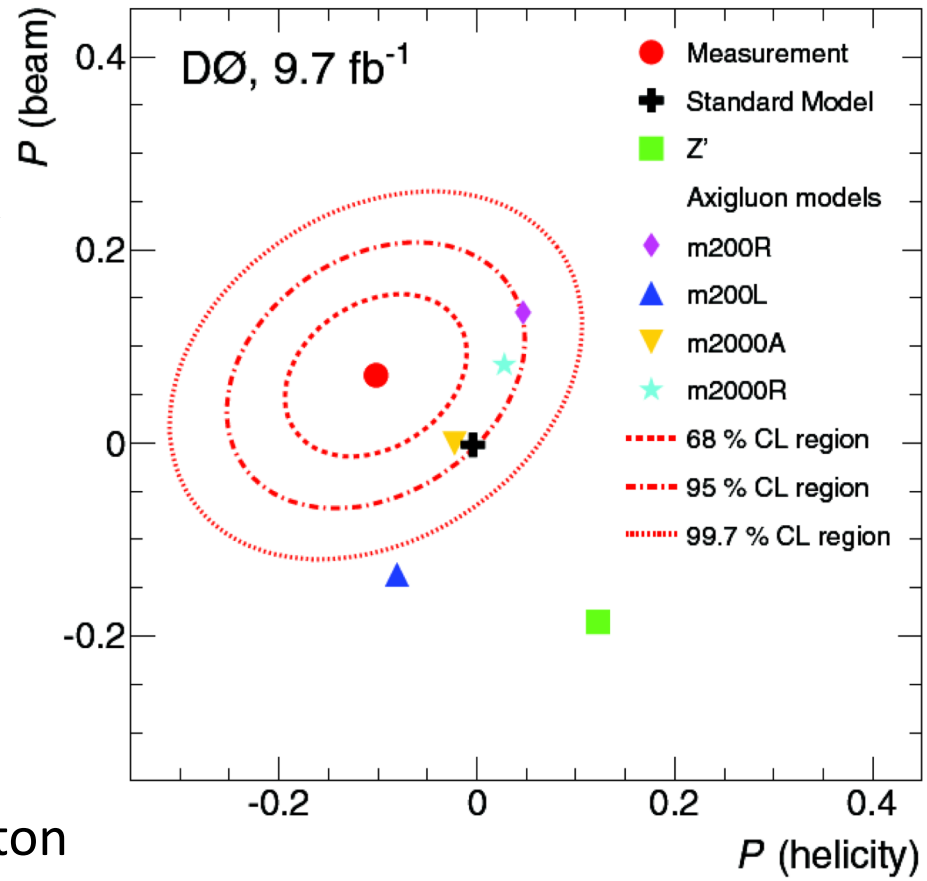
$\theta$ angle between decay product (in parent top rest frame) and quantization axis (in tt rest frame)

- 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 $\theta$ 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 | $-0.102 \pm 0.061$ | $-0.004$ |
| 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 $A_{FB}$ measurement analysis
- Examine ($cos\ \theta$+ , $cos\ \theta$- ) 2D distribution:

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

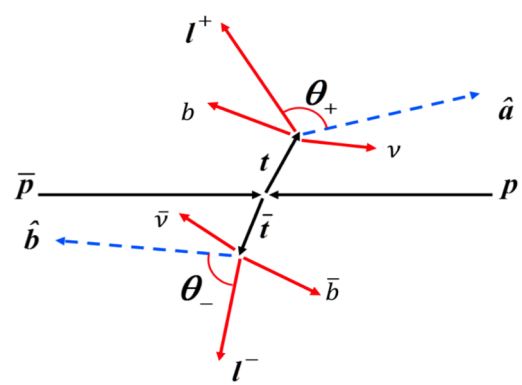
$\boldsymbol{\alpha_\pm}$ : the lepton spin-analyzing power ($\approx$ **1** @NLO)
$\boldsymbol{P_\pm}$ : the degree of polarization of the top quark
$\boldsymbol{C}$ : the $\boldsymbol{t\bar{t}}$ spin correlation coefficient

- 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 $\alpha$P=0 at tree level and negligible in higher order



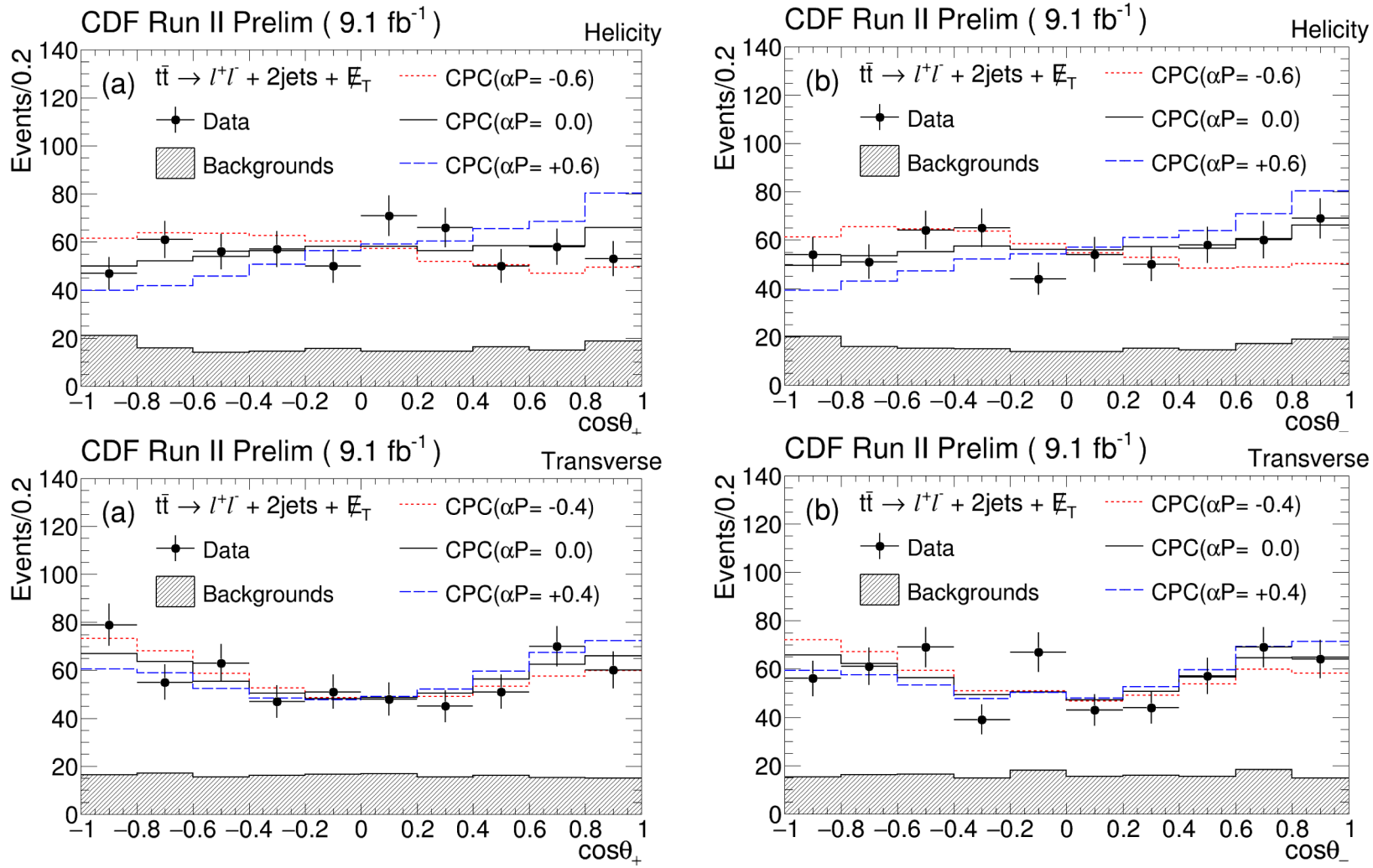

$\hat{a}$ : The quantization axis of top quark
$\hat{b}$ : The quantization axis of anti-top quark

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

# Top polarization in dilepton channel

NEW!

One dimensional comparison of data and signal + backgrounds

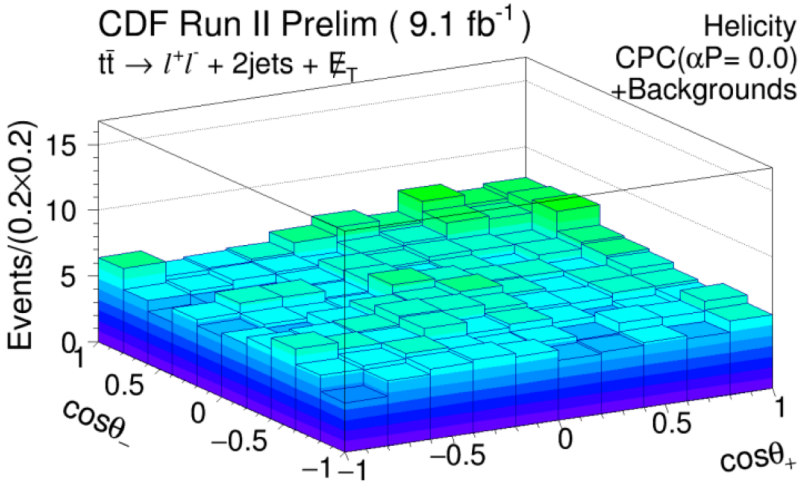


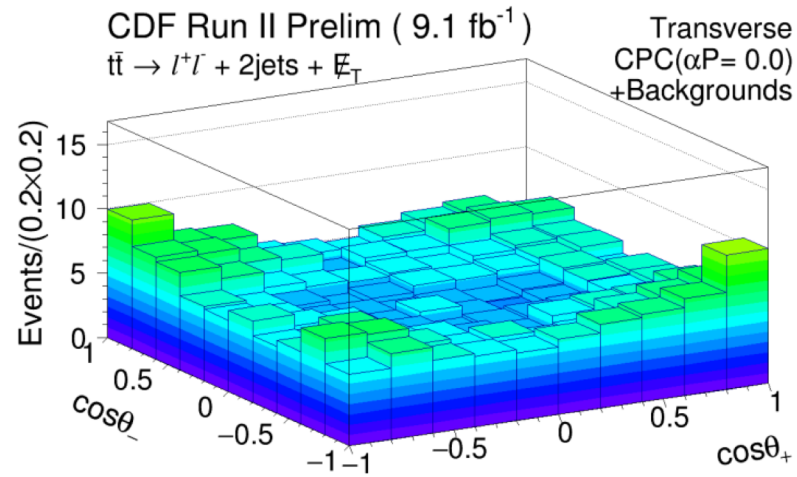

As an example, two extreme αP allowed in the physical region are shown for CPC in helicity and transverse frame.

# Top polarization in dilepton channel

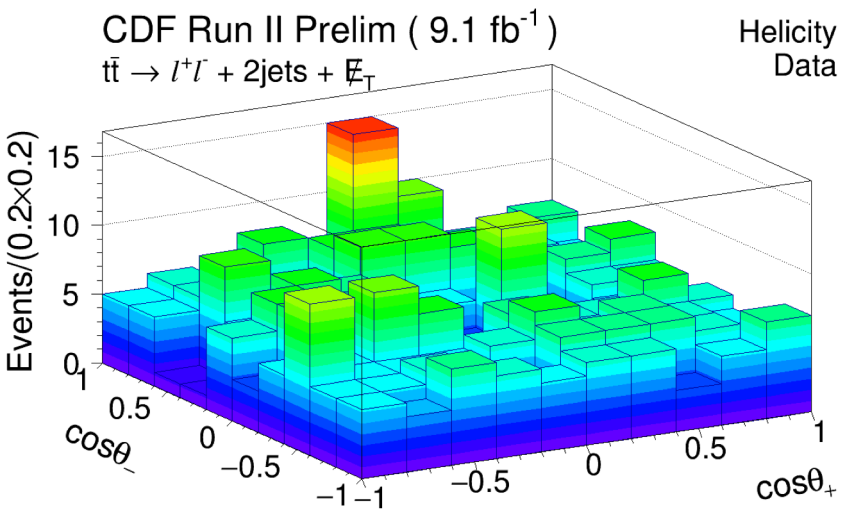
NEW!

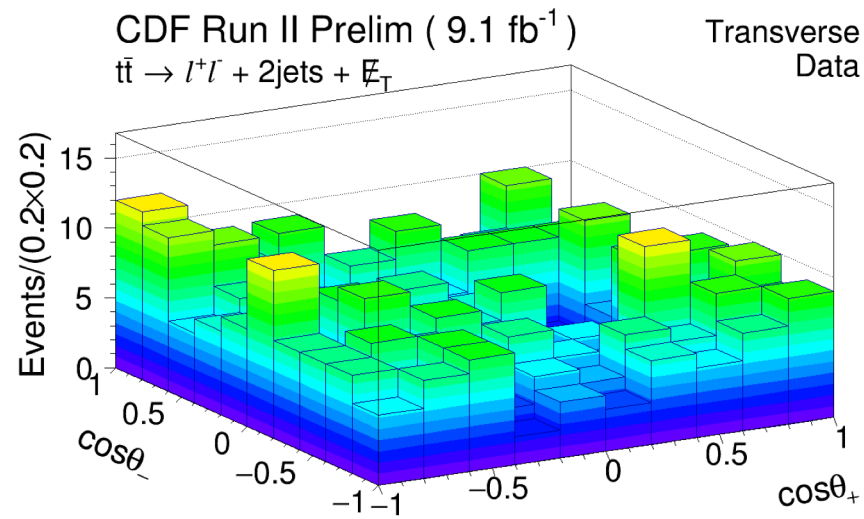
Example of signal +backgrounds 2-dim templates in Helicity and Transverse base




## Data distributions



# Top polarization in dilepton channel

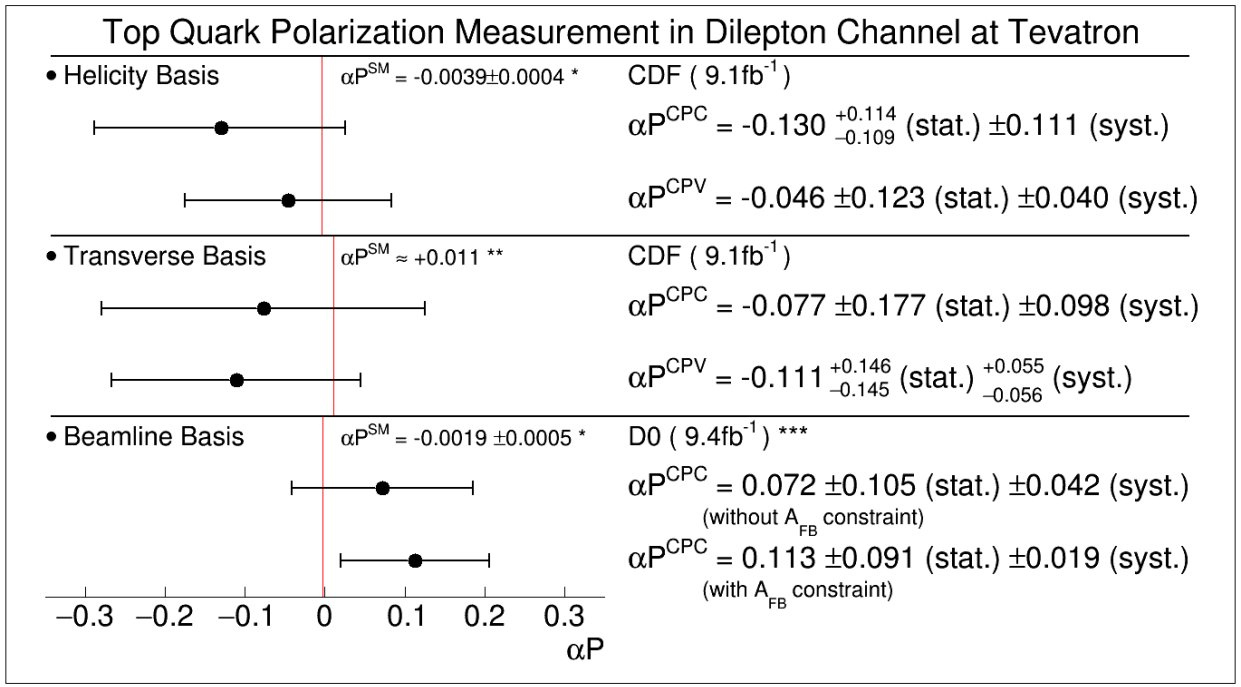
NEW!

- Likelihood fit results using 2 dimensional distributions:

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

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 recently presented 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 process of finishing the last Tevatron legacy measurements
  - ⇒ **The final Tev**
  - ⇒ **D0 measured the to 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