Latest Top/EWK results at Tevatron

Precise theory for precise experiments
(2016/09/25-2016/10/10)
Guy Nhon, ICISE, Vietnam
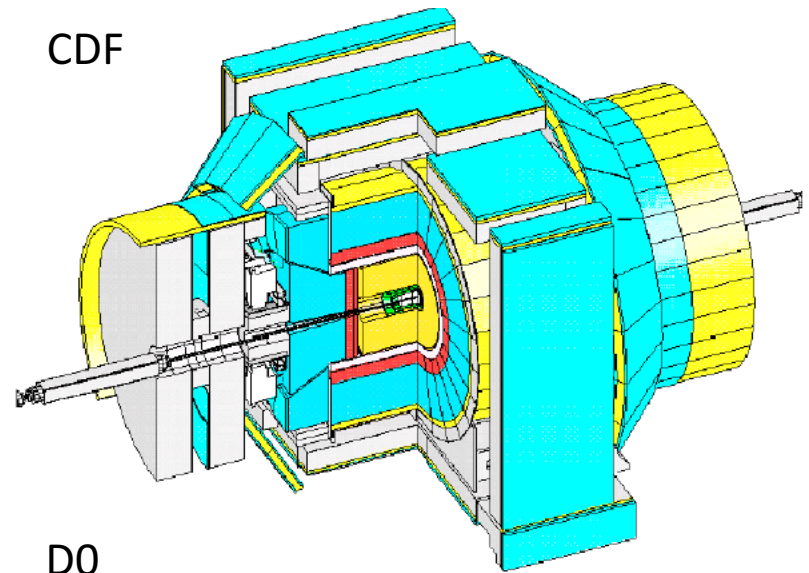
Youngdo Oh
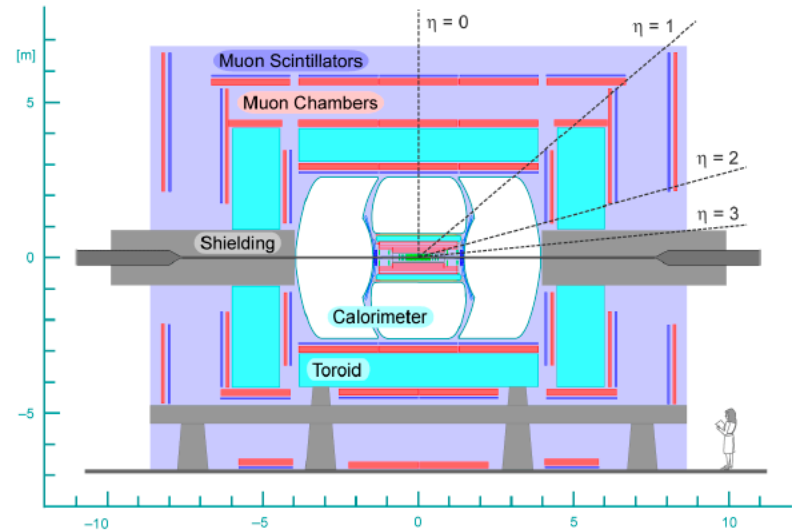**Kyungpook National University**

Tevatron

- Proton-antiproton collider , $\sqrt{s} = 1.96$ TeV
- Peak luminosities ~ $3 - 4 \times 10^{32}$ cm^{-2}s^{-1}
- Top quark discovery at 1995
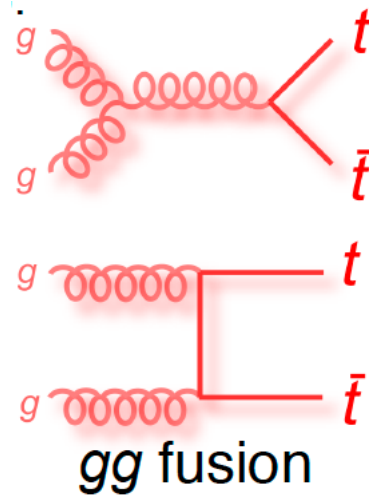- Shutdown in September 2011
- ~10fb^{-1}/experiments recorded

CDF

D0

60 km east

Top quark

- Top the the heaviest fundamental particle : Mtop ~ 173.34 GeV

- Liftetime ~ 5 x 10^{-25}s << Λ_{QCD} ➔ We can observe bare quark properties.

- Top pair production

Tevatron vs. LHC

$q\bar{q}$: 85% vs ~10%
gg: 15% vs. ~90%

gg fusion
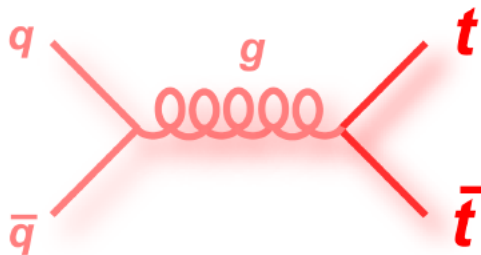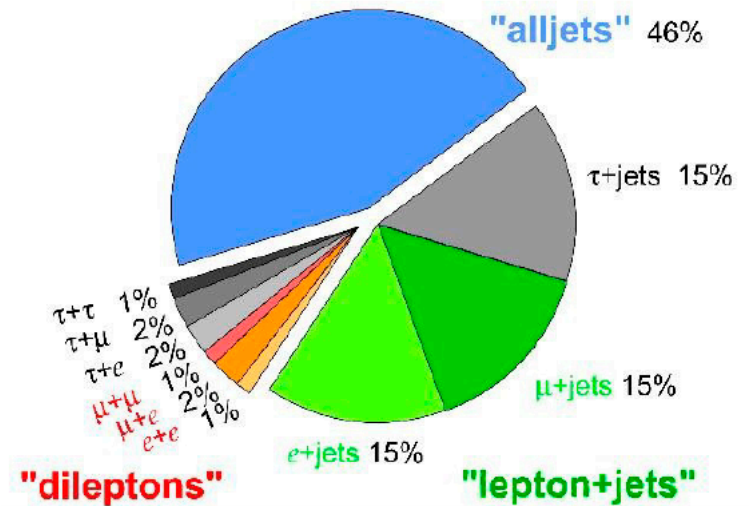
- Top pair decay channels
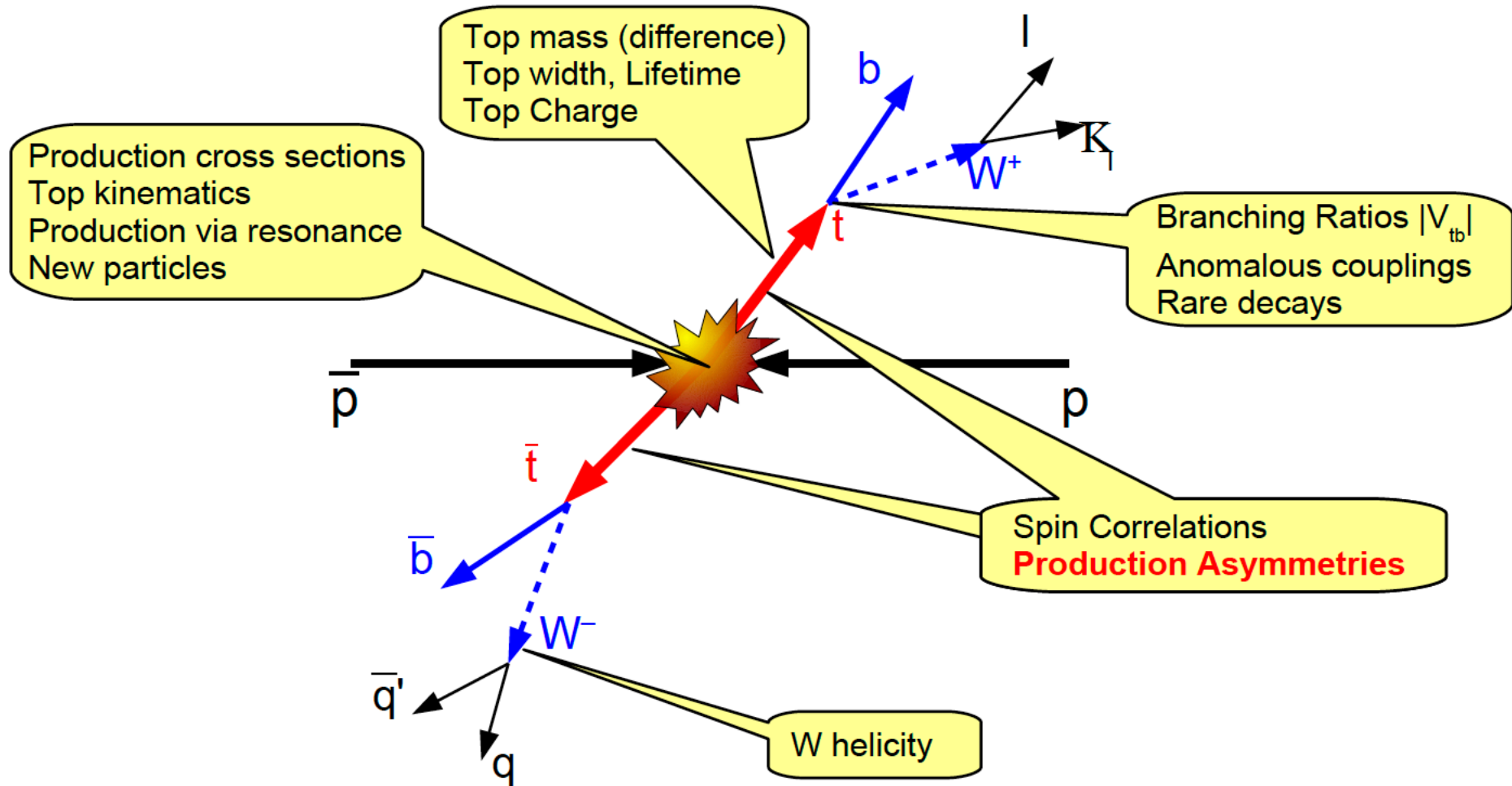
Top Mass – Tevatron combination

$$m_{\rm t} = 174.30 \pm 0.35\,({\rm stat}) \pm 0.54\,({\rm syst})\ {\rm GeV}/c^2.$$

|	Tevatron combined values (GeV/c^2)
$M_{\rm t}$	174.30
In situ light-jet calibration (iJES)	0.31
Response to $b/q/g$ jets (aJES)	0.11
Model for b-jets (bJES)	0.10
Out-of-cone correction (cJES)	0.03
Light-jet response (1) (rJES)	0.05
Light-jet response (2) (dJES)	0.14
Lepton modeling (LepPt)	0.01
Signal modeling (Signal)	0.36
Jet modeling (DetMod)	0.05
b-tag modeling (b-tag)	0.07
Background from theory (BGMC)	0.04
Background based on data (BGData)	0.07
Calibration method (Method)	0.07
Offset (UN/MI)	0.00
Multiple interactions model (MHI)	0.06
Systematic uncertainty (syst)	0.54
Statistical uncertainty (stat)	0.35
Total uncertainty	0.65

Mass of the Top Quark

July 2016 (* preliminary)

CDF-I dilepton	167.4 ±11.4	(±10.3 ± 4.9)
D0-I dilepton	168.4 ±12.8	(±12.3 ± 3.6)
CDF-II dilepton	171.5 ± 3.2	(± 1.9 ± 2.5)
D0-II dilepton *	173.50 ±1.56	(±1.31 ± 0.84)
CDF-I lepton+jets	176.1± 7.3	(± 5.1 ± 5.3)
D0-I lepton+jets	180.1± 5.3	(± 3.6 ± 3.9)
CDF-II lepton+jets	172.85 ±1.12	(±0.52 ± 0.99)
D0-II lepton+jets	174.98 ±0.75	(±0.41 ± 0.63)
CDF-I all-jets	186.0 ±11.5	(±10.0 ± 5.7)
CDF-II all-jets	175.07 ±1.95	(±1.19 ± 1.55)
CDF-II Lxy	166.90 ±9.43	(±9.00 ± 2.80)
CDF-II MET+Jets	173.93 ±1.85	(±1.26 ± 1.35)
Tevatron combination *	174.30 ±0.65	(±0.35 ± 0.54) (± stat ± syst)

χ^2/dof = 10.8/11 (46%)

$m_{\rm t}$ (GeV/c^2)

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Combination of measurements of $\sigma_{t\bar{t}}$ in the dilepton, ℓ + jets, and all-jets final states, using data collected by the CDF and D0 collaborations, $p\bar{p}$ collision at $\sqrt{s} = 1.96\,\text{TeV}$

PRD 89, 072001 (2014)*



archiv.1605.06168, sub. to PRD
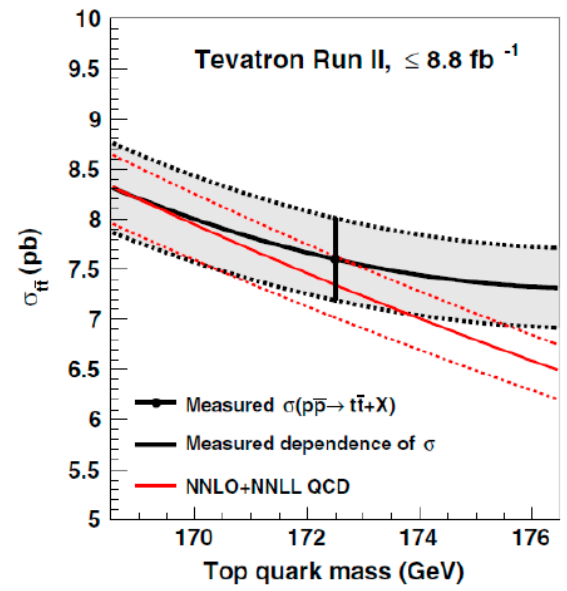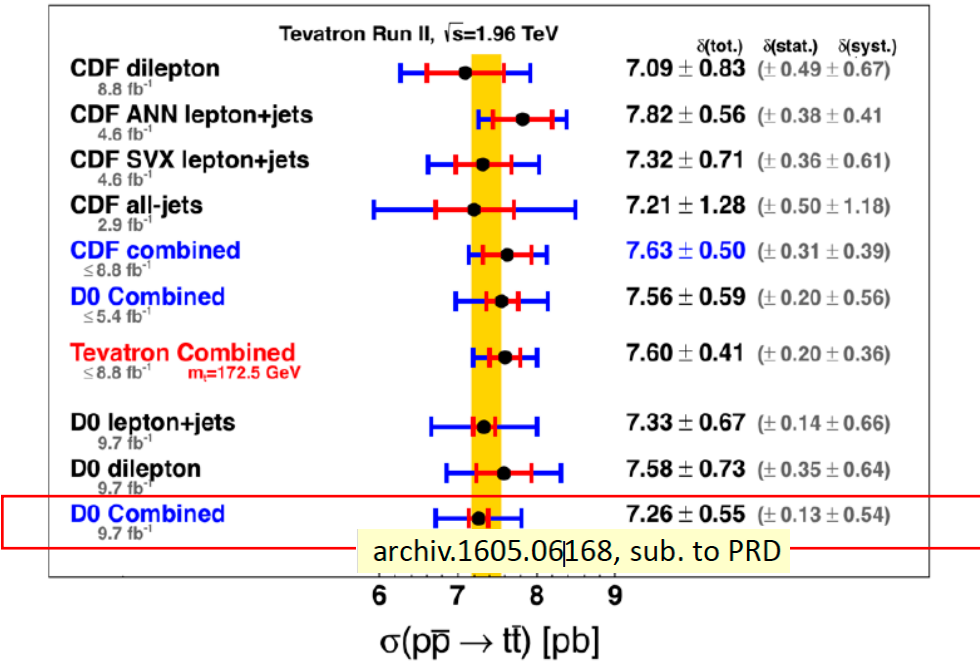
Combined Cross section: $\sigma_{t\bar{t}} = 7.60 \pm 0.41\ \text{pb}$ 5.4% rel. uncertainty

✓ The latest D0 result not included in Tevatron combination
✓ The CDF full statistics result is in preparation!

New combination is expected !

Asymmetries of top production

- Asymmetry source :
    - No asymmetry in LO
    - Interference at NLO ==> higher orders with $q\bar{q}$ and qg
    - gg fusion is symmetric

Positive asymmetry   Negative asymmetry
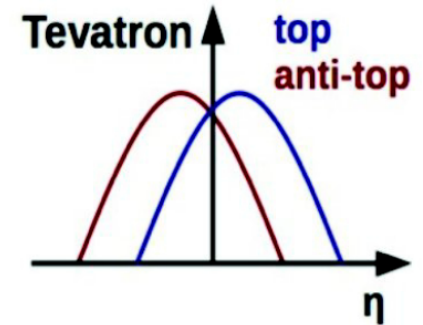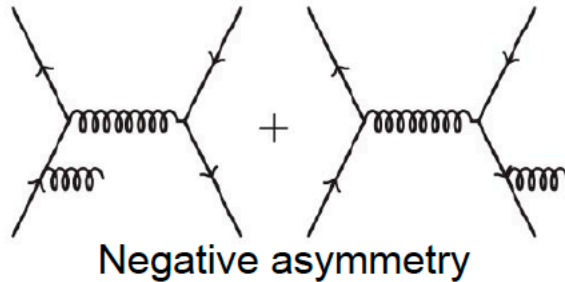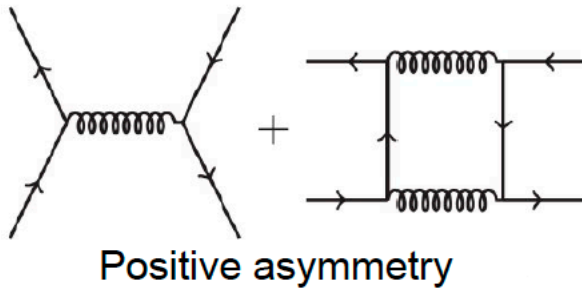
- Asymmetry measurements are based on fully reconstructed top quarks or lepton(s) from top decay

- CDF and D0 measured FB asymmetry in $t\bar{t}$ using Δy (= $y_t - y_{\bar{t}}$) and $m_{t\bar{t}}$ using l+jets and ll channel.
- $A_{FB}^{t\bar{t}}$ depends on Δy and $m_{t\bar{t}}$ linearly.
- $A_{FB}^{t\bar{t}}$ = 9.5 ± 0.7 % (NNLO SM)

Uncertainty	CDF ℓ+jets	CDF dilepton	D0 ℓ+jets	D0 dilepton
Statistical	0.039	0.11	0.027	0.056
Background	0.022	0.04	0.010	0.007
Signal	0.011	0.05	0.005	0.026
Detector	0.007	0.02	0.003	0.001
Method	0.004	0.02	0.005	0.014
PDF	0.001	0.01	0.004	0.003

Tevatron Preliminary

Analysis	$A_{FB}^{t\bar{t}}$	Uncertainty			Weight
		Stat.	Syst.	Total	
CDF ℓ+ jets	0.164	0.039	0.026	0.047	0.25
CDF dilepton	0.12	0.11	0.07	0.13	0.01
D0 ℓ+ jets	0.106	0.027	0.013	0.030	0.64
D0 dilepton	0.175	0.056	0.031	0.063	0.11
Combination	0.128	0.021	0.014	0.025	

(a)

- CDF lepton+jets, 9.4 fb^{-1}
- CDF dilepton, 9.1 fb^{-1}
- D0 lepton+jets, 9.7 fb^{-1}
- NNLO SM, Czakon, et al. JHEP 05(2016)034

(b)
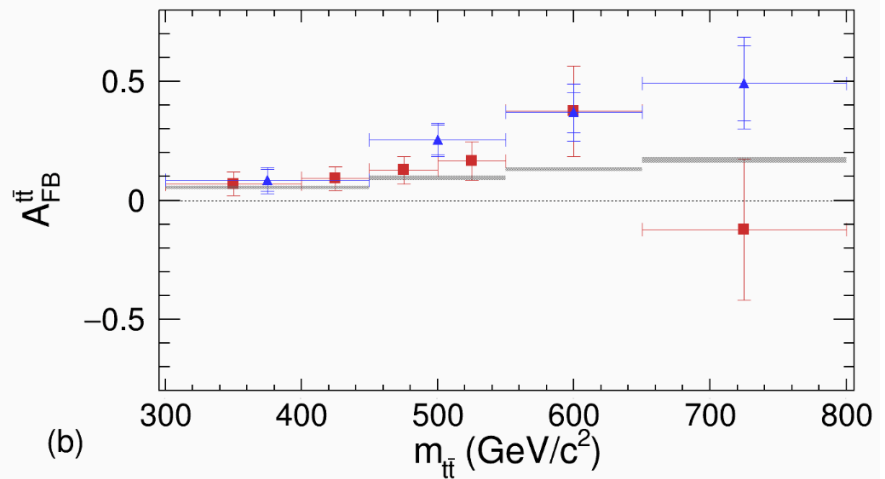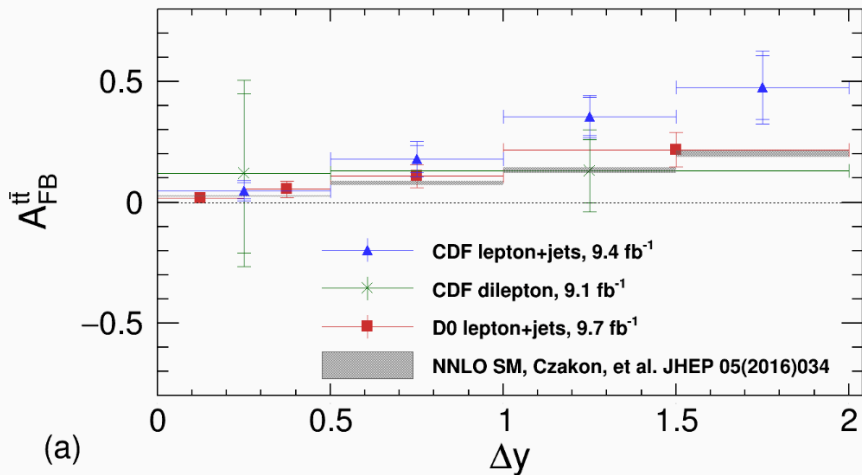
Asymmetries - A_{FB}^{l}

- Lepton asymmetry depends on top pair production asymmetry.
- CDF and D0 measured FB asymmetry of lepton from top decay using l+jets and ll channel.
- A_{FB}^{l} = 3.8 ± 0.5 % (NLO SM)

Uncertainty	CDF $\ell+$ jets	CDF dilepton	D0 $\ell+$ jets	D0 dilepton
Statistical	0.024	0.052	0.027	0.037
Background	0.015	0.029	+0.016 −0.018	0.008
Signal	0.0074	negligible	0.008	0.005
Detector	0.0022	0.004	+0.008 −0.011	0.005
Method	+0.013 −0.000	0.006	0.008	0.004
PDF	0.0025	negligible	0.002	

CDF
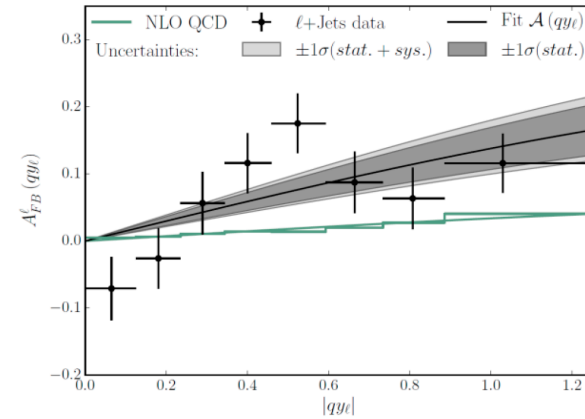
Analysis	A_{FB}^{ℓ}	Uncertainty			Weight
		Stat.	Syst.	Total	
CDF $\ell+$ jets	0.105	0.024	+0.022 −0.017	+0.032 −0.029	0.40
CDF dilepton	0.072	0.052	0.030	0.060	0.11
D0 $\ell+$ jets	0.050	0.027	+0.020 −0.024	+0.034 −0.037	0.27
D0 dilepton	0.044	0.037	0.011	0.039	0.23
Combination	0.073	0.016	0.012	0.020	

Tevatron Preliminary
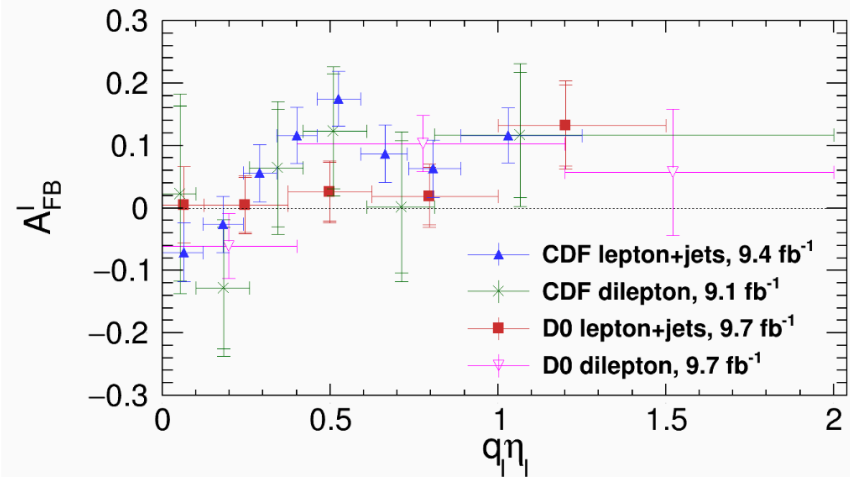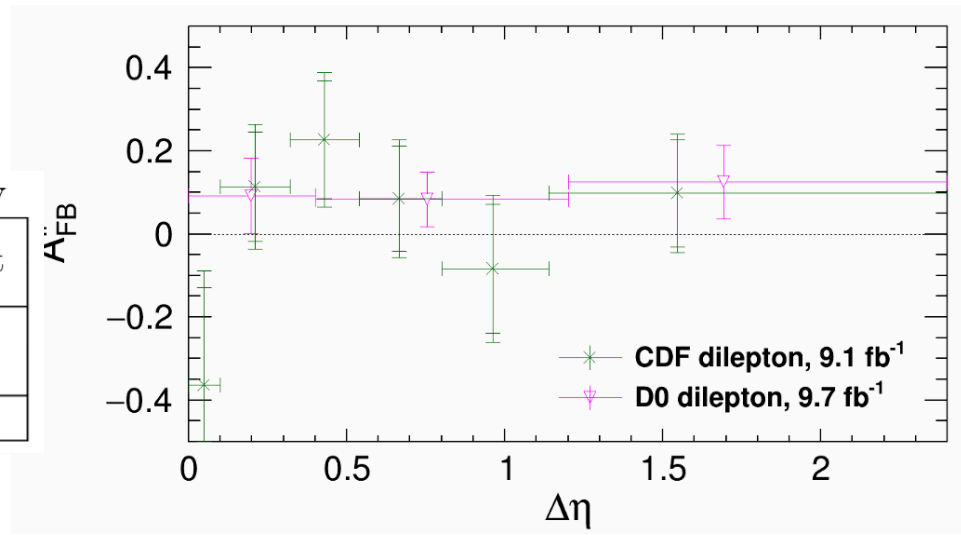
- Lepton asymmetry depends on top pair production asymmetry.
- CDF and D0 measured FB asymmetry of lepton from top decay using l+jets and ll channel.
- A_{FB}^{ll} = 4.8 ± 0.4 % (NLO SM)
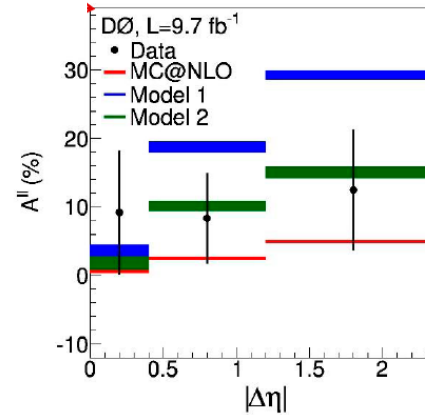
Uncertainty	CDF dilepton	D0 dilepton
Statistical	0.072	0.054
Background	0.037	0.009
Signal	negligible	0.009
Detector	0.003	0.006
Method	0.013	0.004
PDF	negligible	

Analysis	$A_{FB}^{\ell\ell}$	Uncertainty			Weight
		Stat.	Syst.	Total	
CDF dilepton	0.076	0.072	0.037	0.082	0.32
D0 dilepton	0.123	0.054	0.015	0.056	0.68
Combination	0.108	0.043	0.016	0.046	

Tevatron Preliminary

Tevatron A_{FB} - Combination

- All symmetries ($A_{FB}^{t\bar{t}}$ and leptonic A_{FB}) measured by CDF and D0 were combined and compared with SM predictions.

  → Well agreement with SM

$A_{FB}^{t\bar{t}}$ = 12.8 ± 2.5 % (CDF + D0)
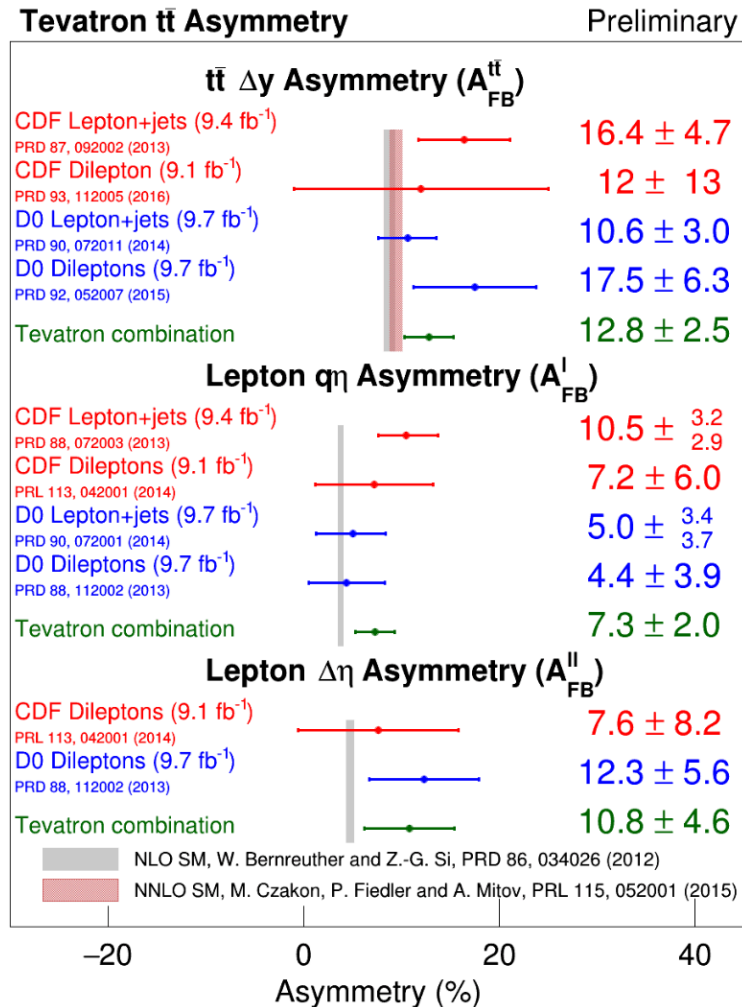$\phantom{A_{FB}^{t\bar{t}}}$ = 9.5 ± 0.7 % (NNLO SM)

A_{FB}^{l} = 7.3 ± 2.0 % (CDF + D0)
$\phantom{A_{FB}^{l}}$ = 3.8 ± 0.5 % (NLO SM)

A_{FB}^{ll} = 10.8 ± 4.6 % (CDF + D0)
$\phantom{A_{FB}^{ll}}$ = 4.8 ± 0.4 % (NLO SM)

NEW!

Top quark polarization – D0

Top polarization measured along 3 quantization axes: beam, helicity and transverse.
- ✓ Measurement in ℓ +jets - final state contains a lepton + ≥3 jets
- ✓ Measured polarization: using distributions of leptons along the mentioned 3 axes.

Cos of lepton/*d-quark* angle vs axis **n**

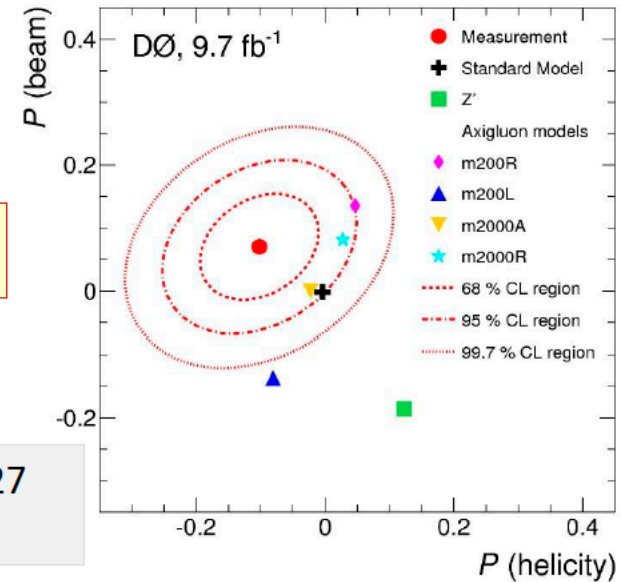$$\frac{1}{\Gamma}\frac{d\Gamma}{dc_{\theta 1}dc_{\theta 2}} = \frac{1}{4}\left(1 + \kappa_1 P_{\vec{\nu}} c_{\theta 1} + \rho\kappa_2 P_{\vec{n}} c_{\theta 2} - \kappa_1\kappa_2 C\, c_{\theta 1}c_{\theta 2}\right)$$

Spin correlation → from SM

Polarization *wrt* **n**

NEW!

arXiv:1607.07627
subm. to PRL

	3 jets		≥ 4 jets	
Source	e+jets	μ+jets	e+jets	μ+jets
W +jets	1741 ± 26	1567 ± 15	339 ± 3	295 ± 3
Multijet	494 ± 7	128 ± 3	147 ± 4	49 ± 2
Other Bkg	446 ± 5	378 ± 2	87 ± 1	73 ± 1
$t\bar{t}$ signal	1200 ± 25	817 ± 20	1137 ± 24	904 ± 23
Sum	3881 ± 37	2890 ± 25	1710 ± 25	1321 ± 23
Data	3872	2901	1719	1352

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	$+0.040 \pm 0.034$	$+0.011$

2D visualization of longitudinal top polarizations in ℓ+jets ch. along beam and helicity axes compared with SM and BSM

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Top quark lifetime, $\tau_t \approx 5 \cdot 10^{-25} s$ << spin-decorrelation time, $\tau_{\text{spin}} \approx 3 \cdot 10^{-21} s$

$\Rightarrow$ QCD: unpolarized t and $\bar{t}$ quarks, but the spins of t and $\bar{t}$ are correlated.

Spin correlation observable:

$\sigma(..) \equiv$ cross section referred to spin state of q and $\bar{q}$ relative to quantization axes

$$O = \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)}$$

✓ Matrix element technique applied to dilepton ($\ell\ell$) and ℓ+jets final state

NEW!

✓ Tevatron vs LHC spin correlations: $q\bar{q}$ annihil. vs like-helicity **gg** fusion (complement.)

✓ Spin correlation discriminant event-by-event:

$$R(x) = \frac{P_{t\bar{t}}(x, \text{SM})}{P_{t\bar{t}}(x, \text{SM}) + P_{t\bar{t}}(x, \text{null})}$$

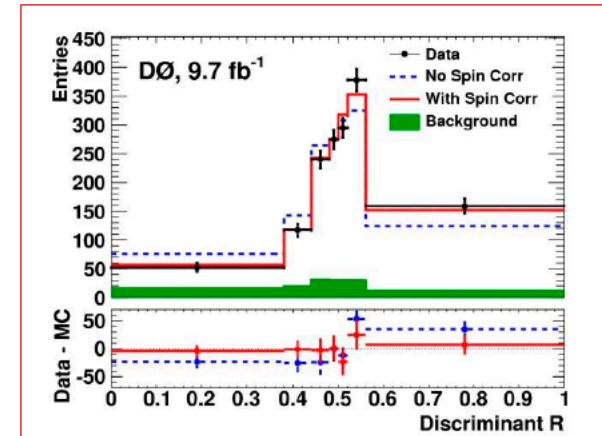Probability for SM/null (uncorrelated) hypotesis

PLB 757, 199 (2016)

✓ Off-diagonal spin basis (max. correlations for $p\bar{p}$)

$O_{\text{off}} = 0.89 \pm 0.16(\text{stat}) \pm 0.15(\text{syst})$ SM: $O_{\text{off}} = 0.80^{+0.01}_{-0.02}$

Significance from zero: 4.2 σ

Assuming absence of non-SM → fraction of gg fusion:

$f_{gg} = 0.08 \pm 0.16(\text{stat+syst})$ SM (NLO): $f_{gg} = 0.135$
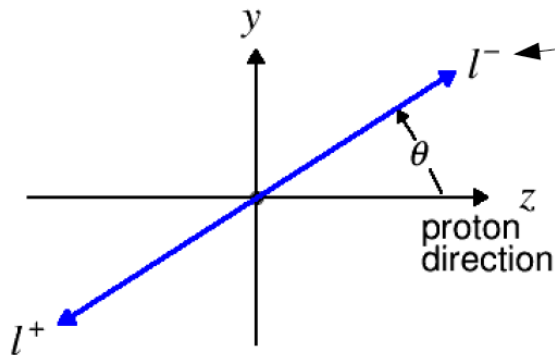
Effective leptonic electroweak mixing angles

- Drell-Yan process at the Tevatron
  - lepton polar anlgle distribution at center of mass frame is asymmetric
  - Parity violation of Z decays.
  - Born level angular distribution ~ $1+\cos^2\vartheta+A_4\cos\vartheta$

Collins-Soper Center of Mass Frame

- Forward (f): $\cos\vartheta \geq 0$
- Backward (b): $\cos\vartheta < 0$

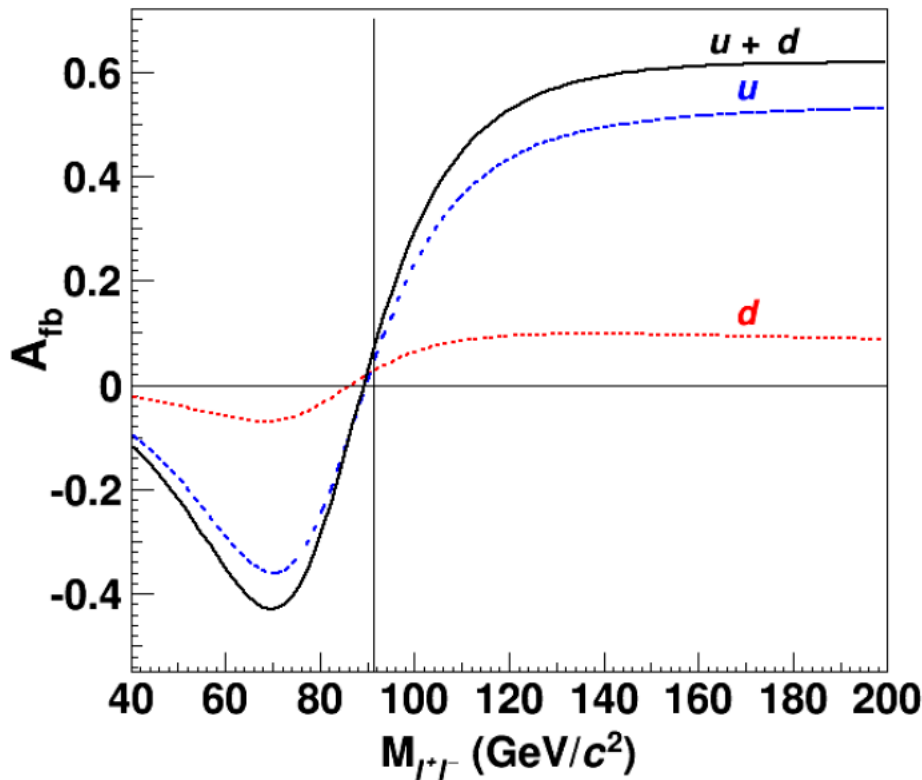- Forward-backward cross section symmetry is a probe to the electroweak mixing angle

$$A_{fb} = \frac{\sigma_f - \sigma_b}{\sigma_f + \sigma_b} = \frac{3}{8}A_4$$

$$A_{\mathrm{fb}}(M) = \frac{\sigma^+(M) - \sigma^-(M)}{\sigma^+(M) + \sigma^-(M)} = \frac{3}{8} A_4(M)$$

$A_{\mathrm{fb}}^{(u)}$: u-quark contribution

$A_{\mathrm{fb}}^{(d)}$: d-quark contribution

$$A_{\mathrm{fb}}^{(u)} + A_{\mathrm{fb}}^{(d)} = A_{\mathrm{fb}}^{(u+d)}$$

- Measure asymmetry in mass bins
  $A_{\mathrm{fb}} = (N_f - N_b)/(N_f + N_b)$
- Fit A_{fb} to templates with
  varying values of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
  to get best-fit value
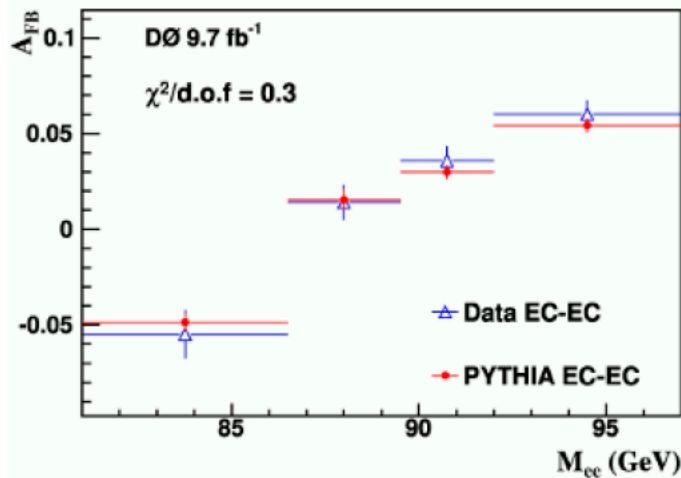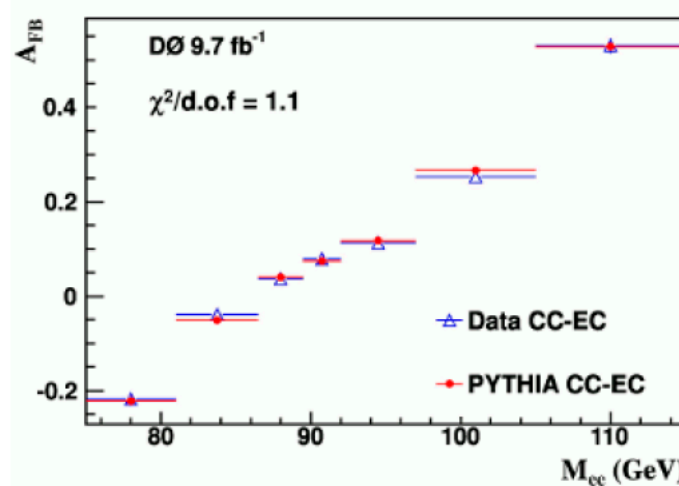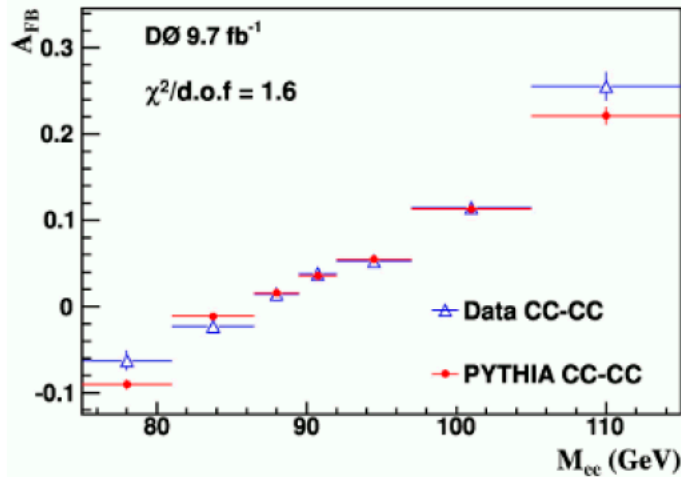- Experimental effects applied to
  templates or corrected in A_{fb}

Expectation:
- Z-Z interference term:
  sensitive to $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
  best precision near M_Z
    – most events at the pole
    – minimal γ-Z interference
- γ-Z interference term:
  zero at Z pole [~ $1-(M_Z/M)^2$]
  dominates away from pole
  sensitive to PDFs

Extraction of $sin^2\theta_{eff}^{lept}$: D0

Only electron channel

Input
- Afb and template (Pythia) with varying $sin^2\theta_{eff}^{lept}$
- Fit Afb to templates for best $sin^2\theta_{eff}^{lept}$

Result $\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23139 \ \pm 0.00043$ (stat.)
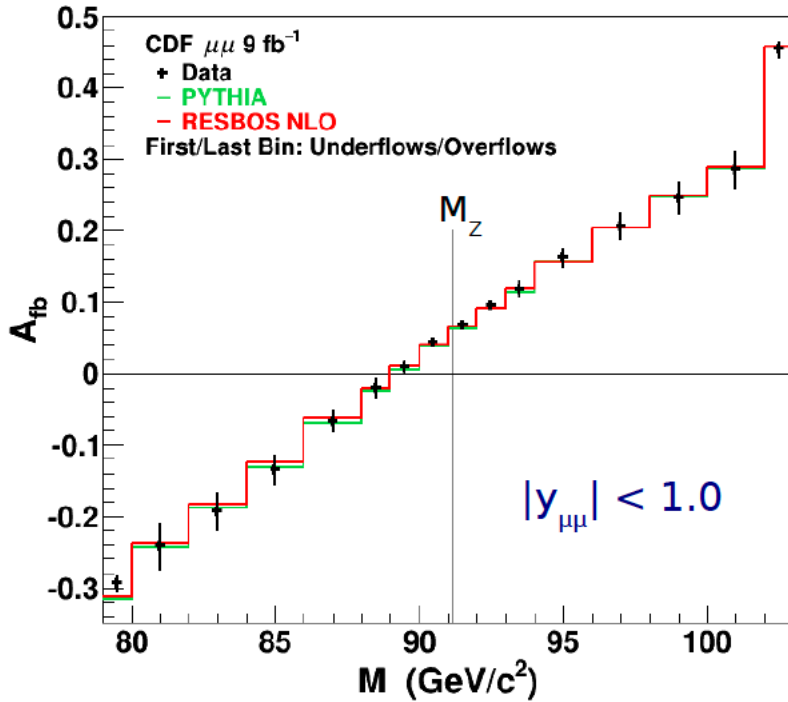
± 0.00008 (syst.)

± 0.00017 (PDF).

Extraction of $sin^2\theta_{eff}^{lept}$: CDF
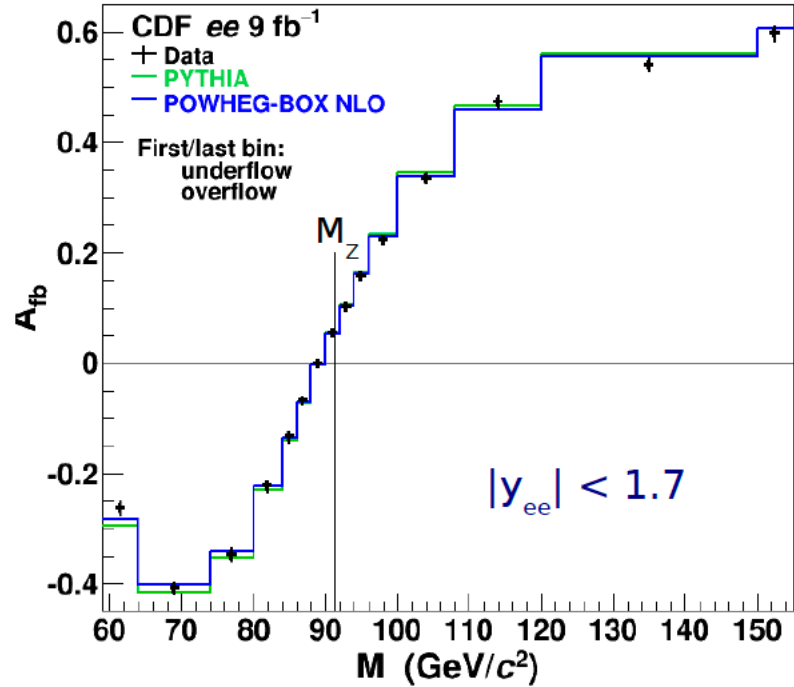
Muon channel

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.2315 \pm 0.0009 \ (\text{stat.})$$
$$\pm 0.0002 \ (\text{syst.})$$
$$\pm 0.0004 \ (\text{PDF}).$$

Electron channel

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23248 \pm 0.00049 \ (\text{stat.})$$
$$\pm 0.00004 \ (\text{syst.})$$
$$\pm 0.00019 \ (\text{PDF})$$

muon + electron

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23221 \pm 0.00043 \ (\text{stat.})$$
$$\pm 0.00007 \ (\text{syst.})$$
$$\pm 0.00016 \ (\text{PDF})$$

Combination of $sin^2\theta_{eff}^{lept}$: CDF + D0

Input observable values
- Standardized D0 value : 0.23137 ± 0.00043 (stat) ± 0.00019 (syst)
- CDF ee⊕µµ value : 0.23221 ± 0.00043 (stat) ± 0.00018 (syst)

Input uncertainty categories
- Statistics: CDF: 0.00043, D0: 0.00043
- PDF: CDF: 0.00016, D0: 0.00017 (100% correlated)
- Other systematics: CDF: 0.00007, D0: 0.00008 (uncorrelated)

Results of BLUE method

- $sin^2\theta_{eff}^{lept} = 0.23179 \pm 0.00030$ (stat)
  ± 0.00017 (syst)

- χ^2 of combination: 1.8 (18% probability)
- Uncertainties
  - Statistics: 0.00030
  - PDF: 0.00017
  - Other systematics: 0.00005
  - Standardization: 0.00003

Inference of W mass

$$\sin^2\theta_{eff}^{lept} = Re[\kappa_l(M_Z^2,\sin^2\theta_w)]\sin^2\theta_w$$
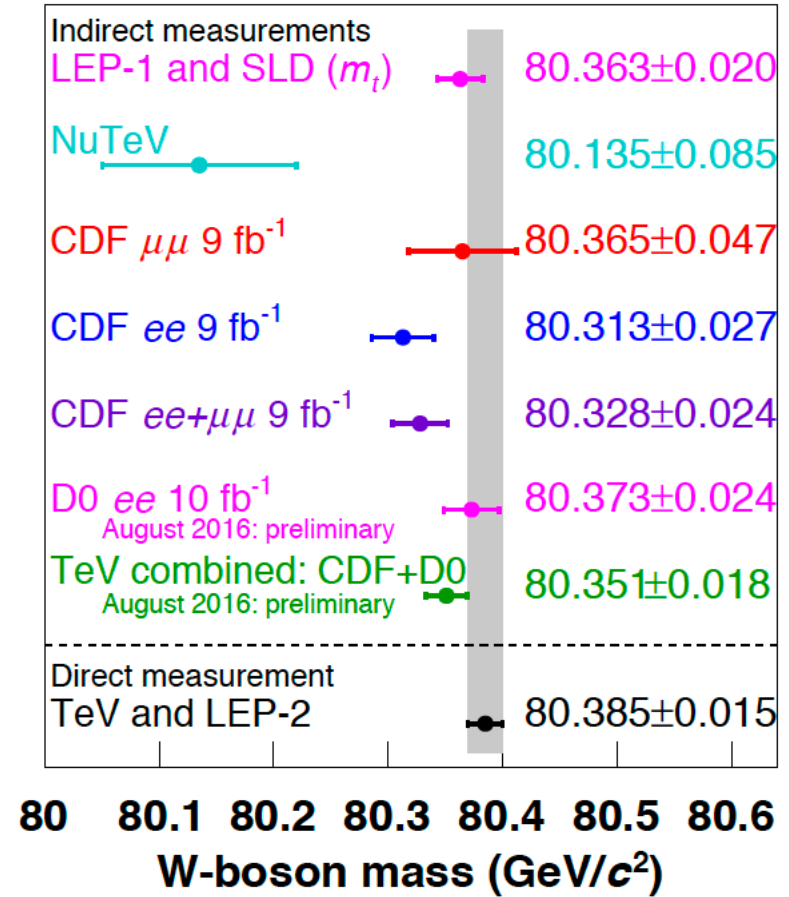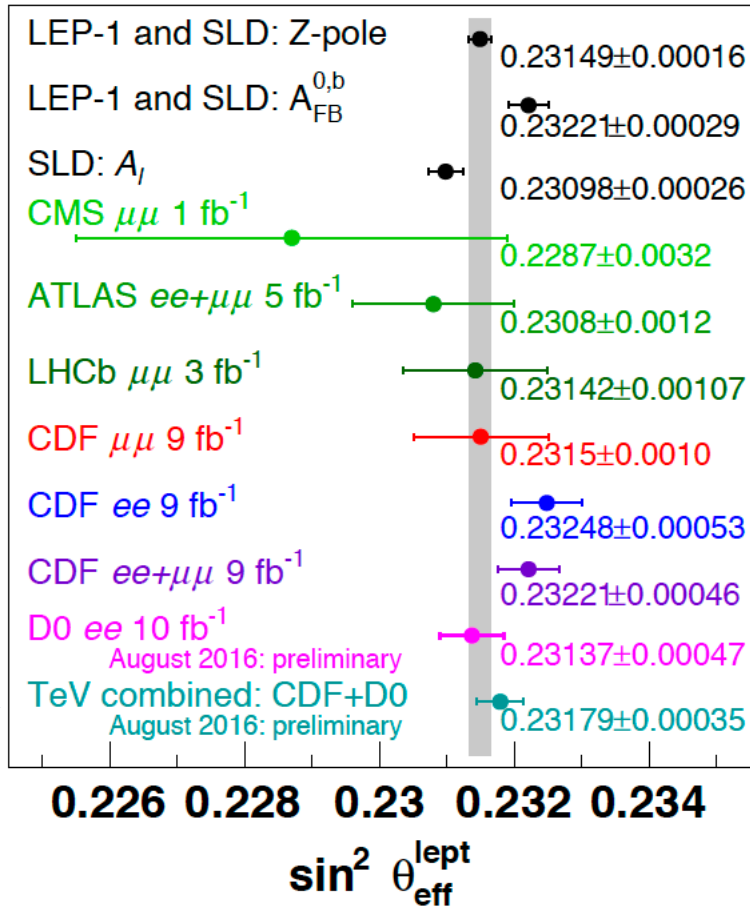$$\hookrightarrow \approx 1.037$$

$\sin^2\theta_w$ and M_w equivalent in SM on-shell renormalization scheme (ZFITTER)
- $\sin^2\theta_w \equiv 1 - M_w^2/M_Z^2$ all orders definition
- M_Z well measured by LEP-1 and SLD: 91.1875 ± 0.0021 GeV/c^2

Inferences

	$\sin^2\theta_w$	M_w
– CDF only:	$0.22400\pm0.00041\pm0.00019$	$80.328\pm0.021\pm0.010$ GeV/c^2
– D0 only:	$0.22313\pm0.00041\pm0.00020$	$80.373\pm0.021\pm0.010$ GeV/c^2
– Combination:	$0.22356\pm0.00029\pm0.00019$	$80.351\pm0.015\pm0.010$ GeV/c^2
	(stat) (syst)	(stat) (syst)

Summary

- CDF and D0 provided remarkable results on top quark properties

  - Top mass
  - Top antitop pair production cross section
  - Asymmetries in top antitop production
  - Top spin correlation and polarization

- $sin^2\theta_{eff}^{lept}$ are extracted from Drell-Yan lepton pair asymmetry
  - CDF used electron and muon channel , D0 used electron channel
  - Both of CDF and D0 are combined
  - Indirectly, W mass is extracted.

- Results from CDF and D0 are still coming and some of them are under combining ...
  - www-cdf.fnal.gov , www-d0.fnal.gov