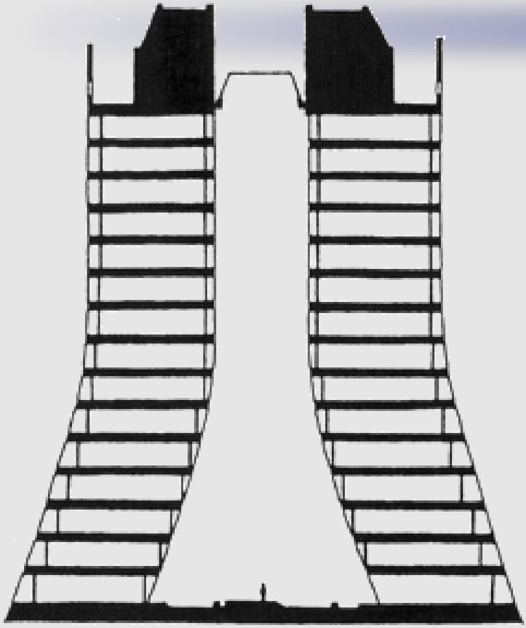
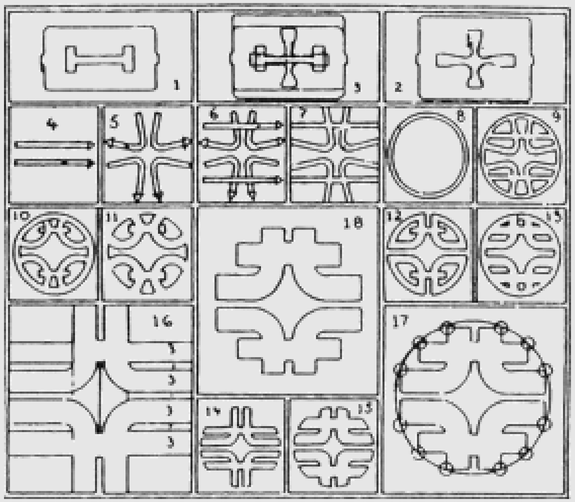
Electroweak measurements at the Tevatron





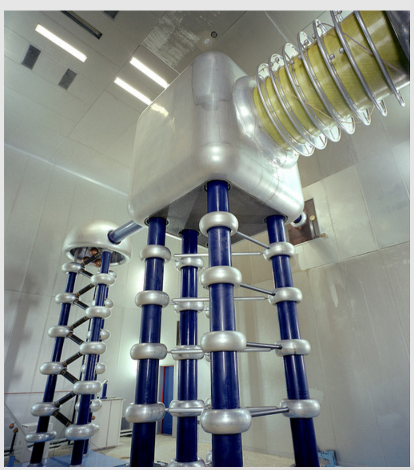
Higgs Hunting 2016

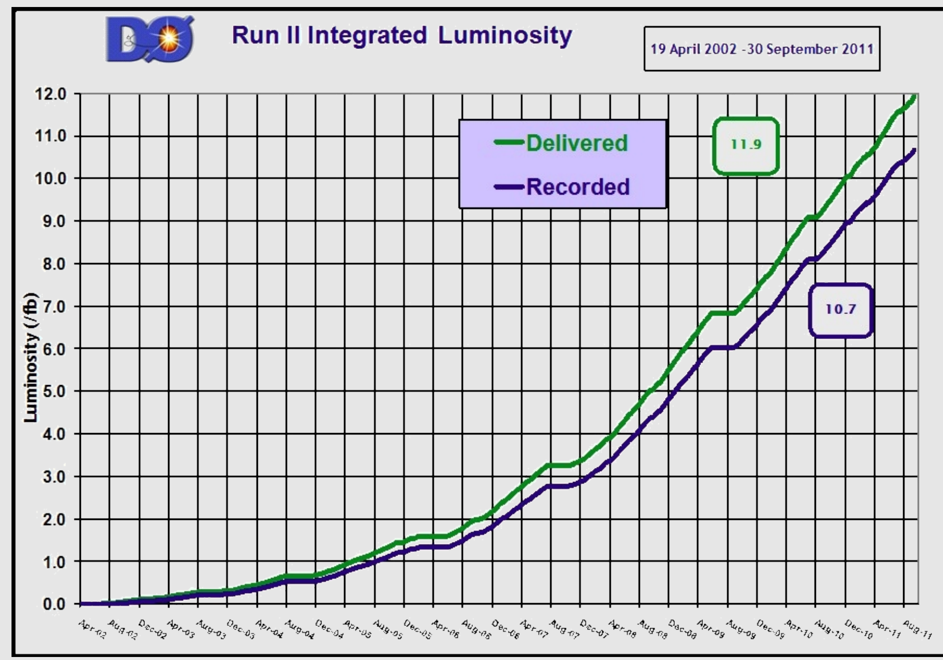
Bob Hirosky
for the CDF and D0 Collaborations

Tevatron Data

CDF and D0 continue a rich physics program analyzing ~10fb^{-1} of recorded data from ~2001-2011

- World's highest energy p-$\bar{p}$ data set (2 TeV C.O.M.)
- Unique physics studies
- Complementary/competitive results in LHC era



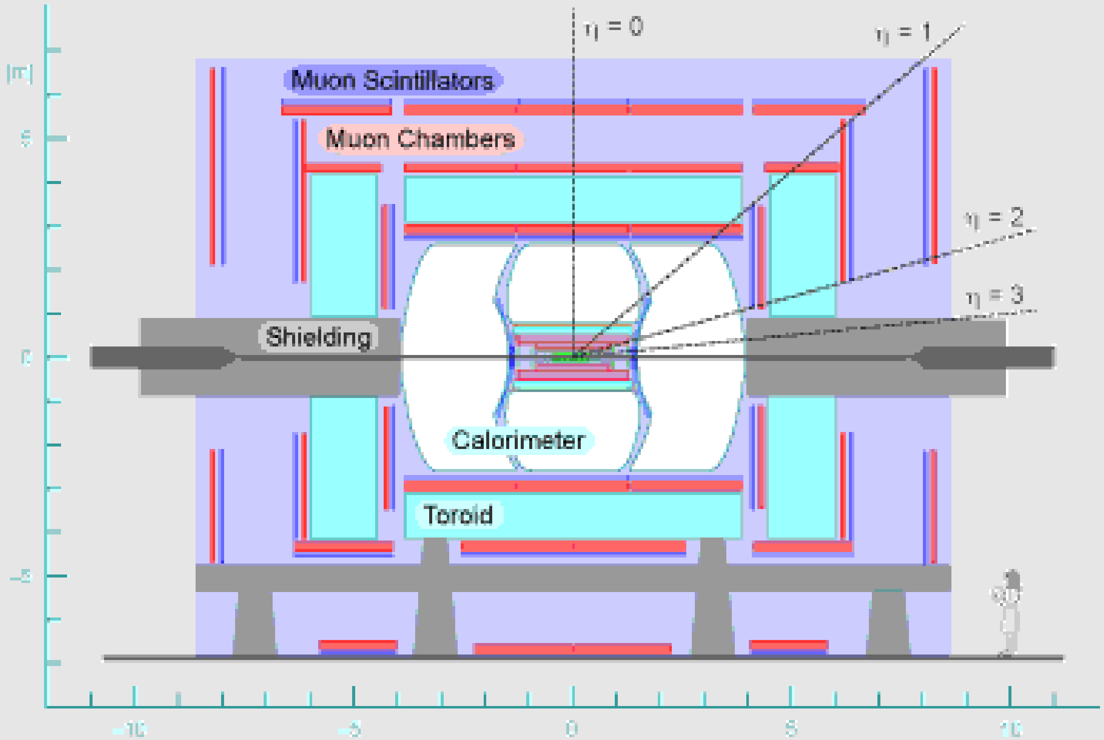


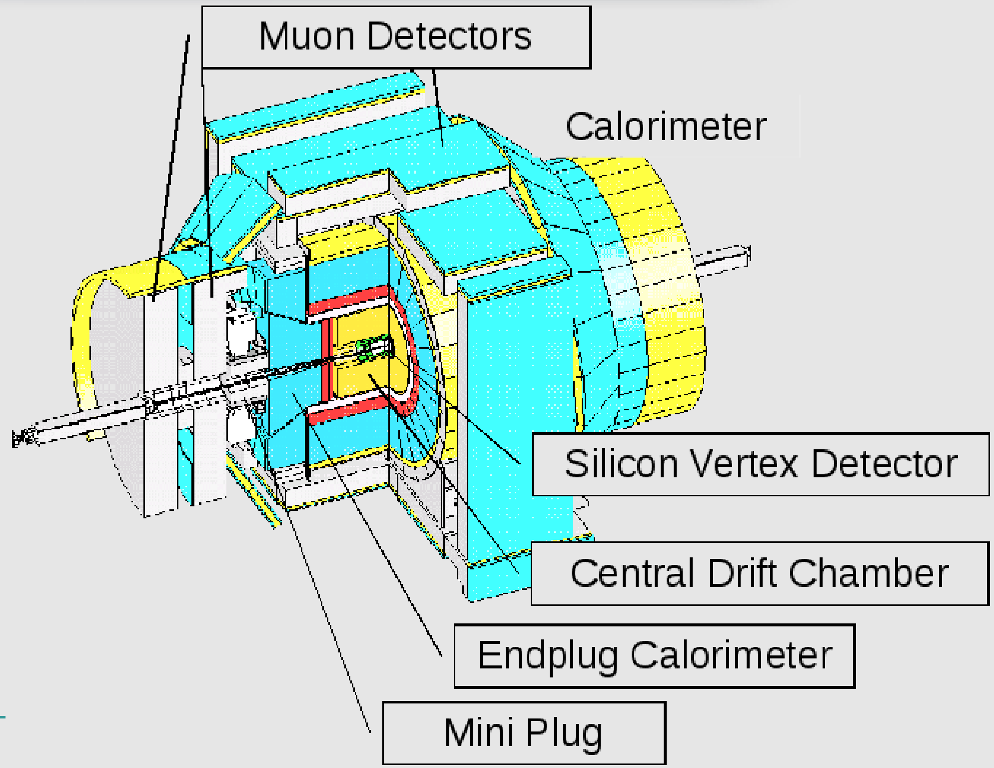
Pre-Summary

- Diboson plus heavy flavor measurements
  $WW \to l\nu + cs$, $WZ \to l\nu + cc/bb$
- Top quark properties measurements
  production, asymmetries, polarization, spin correlation
- Direct and indirect measures of the top quark mass
  newest measurements, latest Tevatron combination, pole mass
- $\sin^2\theta_W$ and indirect measure of m_W
  from asymmetry in leptonic Z boson decays

The CDF and DO Detectors

Multipurpose, large acceptance, well understood





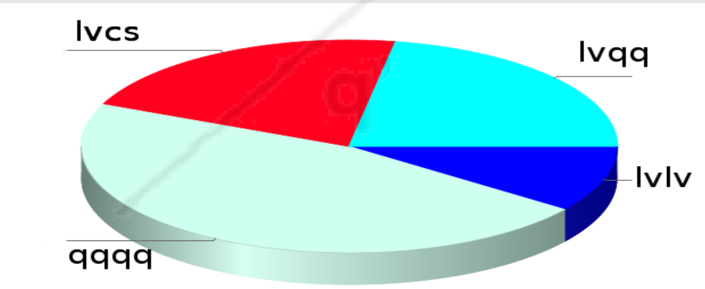
- Emphasizes calorimeter depth/hermeticity, muon coverage
- Some trade off in tracking volume

- Emphasizes greater tracking volume/performance
- Some trade offs in calorimeter depth and muon coverage

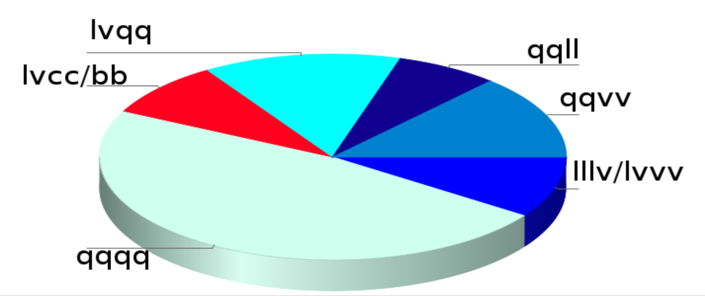
Diboson Search in lν + heavy-flavor jets

- Theoretically well known process => probe of SM couplings => significant excess may imply new physics
- Benchmark of experimental sensitivity to rare processes, in a variety of final states
- Background to associated Higgs production with W bosons: WH $\rightarrow$ lν + bb and WZ $\rightarrow$ lν + bb share same final state

WW final state BRs



WZ final state BRs



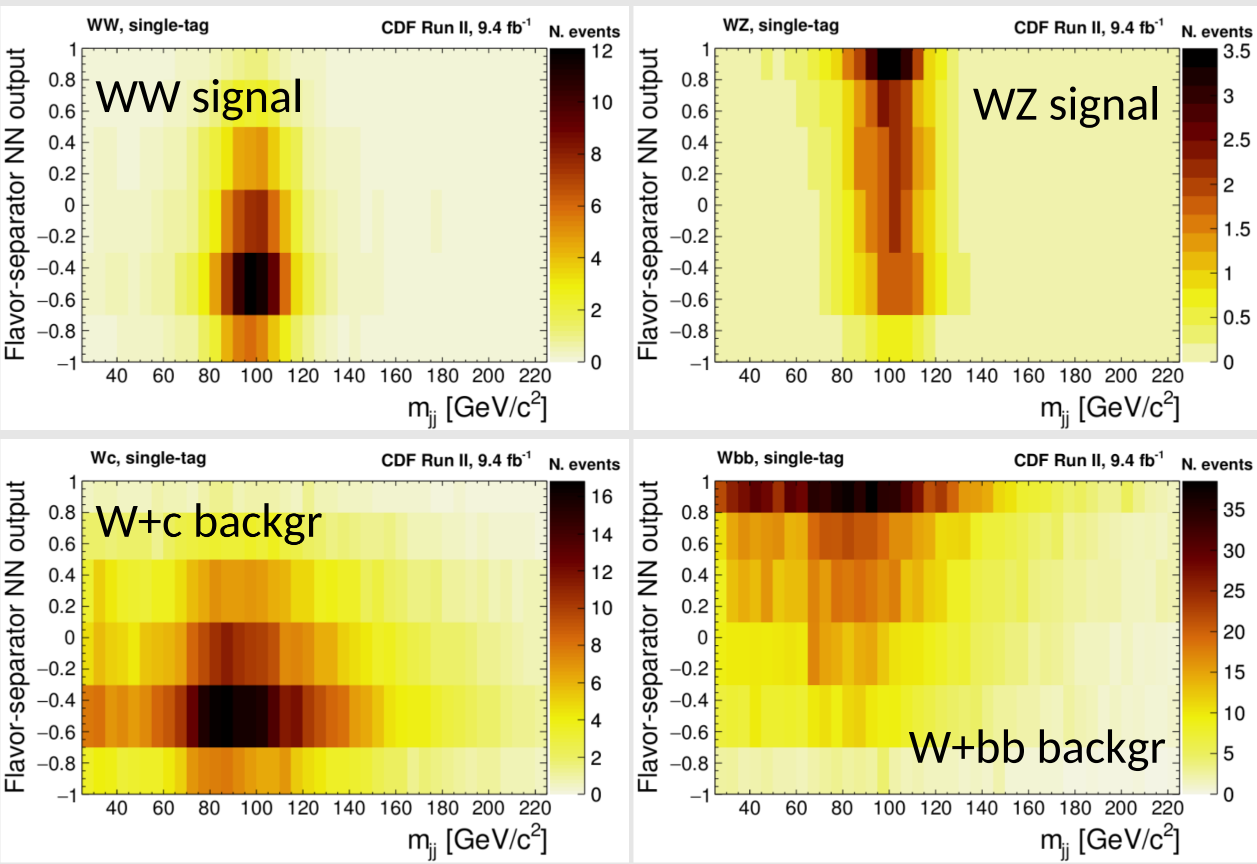
Leptonic final states (small BR):
$\Rightarrow$ Clean signature, low background, good precision
Semi-leptonic fnl states (experimentally challenging):
$\Rightarrow$ Large non-resonant background, V+jets, QCD
$\Rightarrow$ Poor di-jet mass resolution: no W,Z separation

No precise measurement of WZ in semi-leptonic final state => determine from combined WW and WZ heavy-flavor (HF) decays

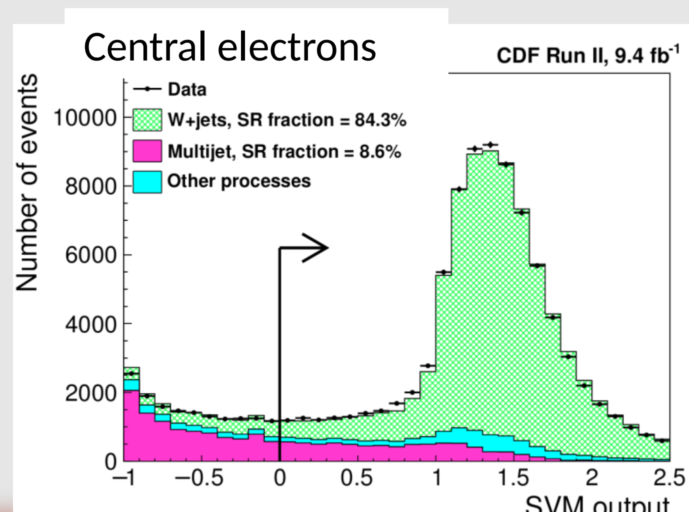
Diboson Search in $l\nu$ + heavy-flavor jets

- Secondary-vertex jet tagging to enrich sample in HF and reduce W+jets background
- Search peak region over large non-resonant background ⇒ use m_{jj} as discriminant

WW → lν+cs versus WZ → lν +cc/bb ⇒ 1-tag vs 2-tag and Flavor-separator NN

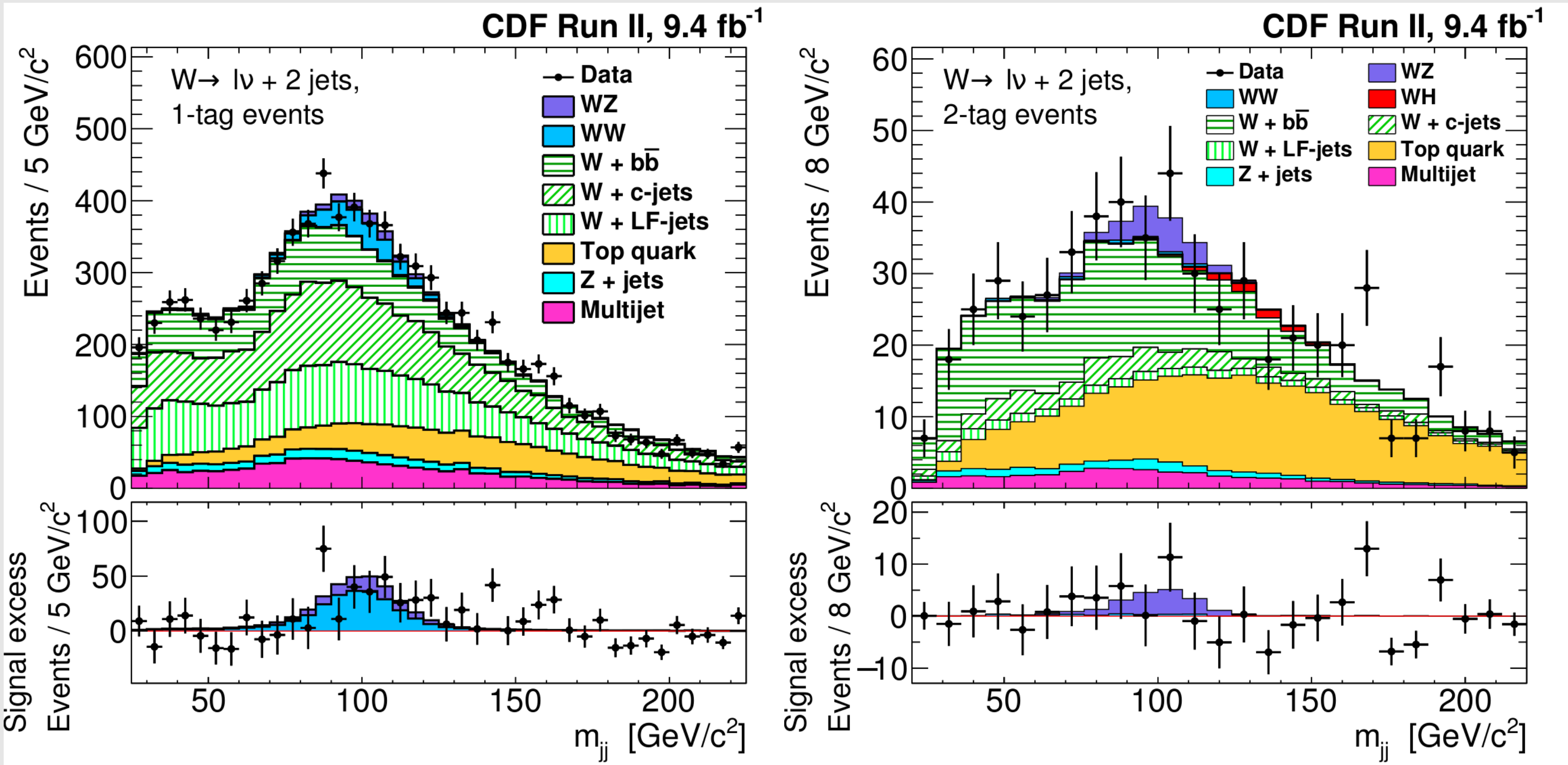


- Data is superposition of signal, multi-jet, W+jets
- SVM MVA used for MJ rejection, and for templates of normalization fit



Diboson Search in lν + heavy-flavor jets

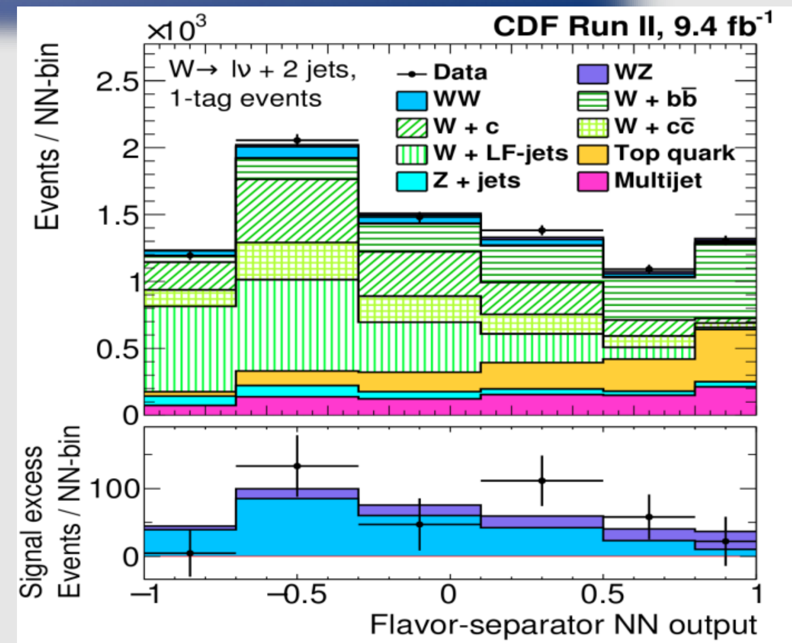
Di-jet Invariant Mass Distributions
Following calibration of W+HF yields

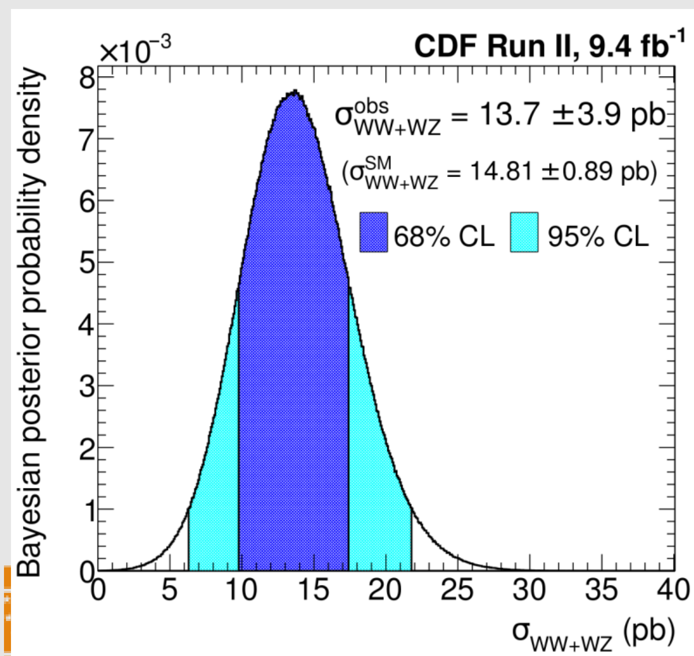


Single HF tag events Double HF tag events

Diboson Search in lν + heavy-flavor jets

- Apply flavor-separator NN to obtain b-quark versus c-quark separation
- 2-dimensional m_{jj} vs flavor-separator NN for single-tag events
- Different signal and background composition across NN values





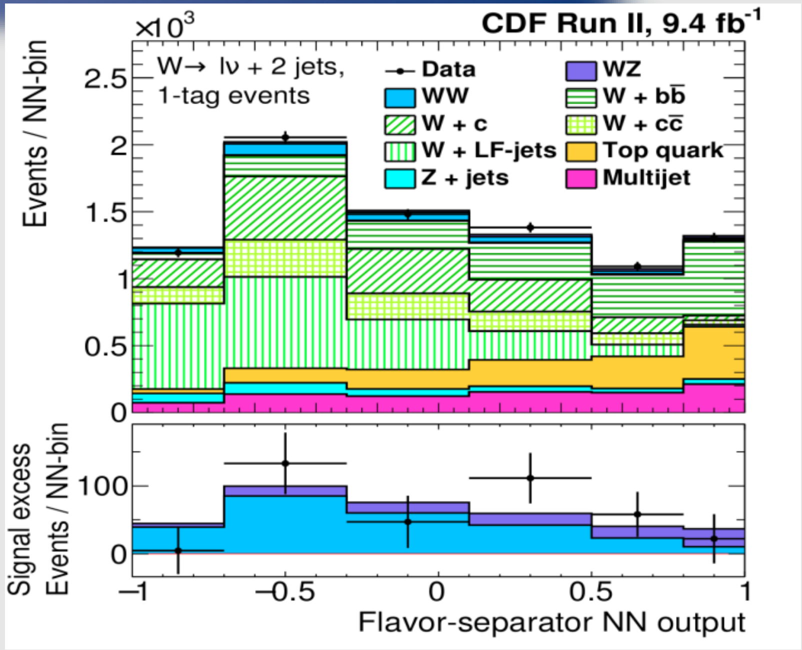
Build likelihood function with S&B yield and shape predictions

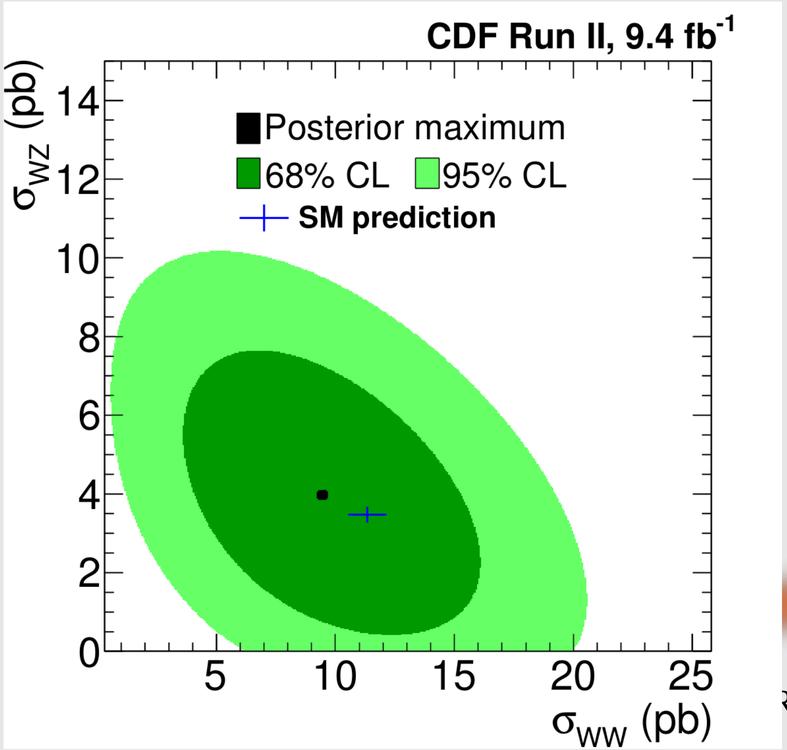
Cross Sec. extraction using Bayesian analysis

$$\sigma^{obs}_{WW+WZ} = 13.7 \pm 2.4(\mathrm{stat}) \pm 2.9(\mathrm{syst}) = 13.7 \pm 3.9\ \mathrm{pb}$$

Diboson Search in $l\nu$ + heavy-flavor jets

- Apply flavor-separator NN to obtain b-quark versus c-quark separation
- 2-dimensional m_{jj} vs flavor-separator NN for single-tag events
- Different signal and background composition across NN values





WW vs WZ simultaneous signal extraction
⇒ using 2D posterior distribution

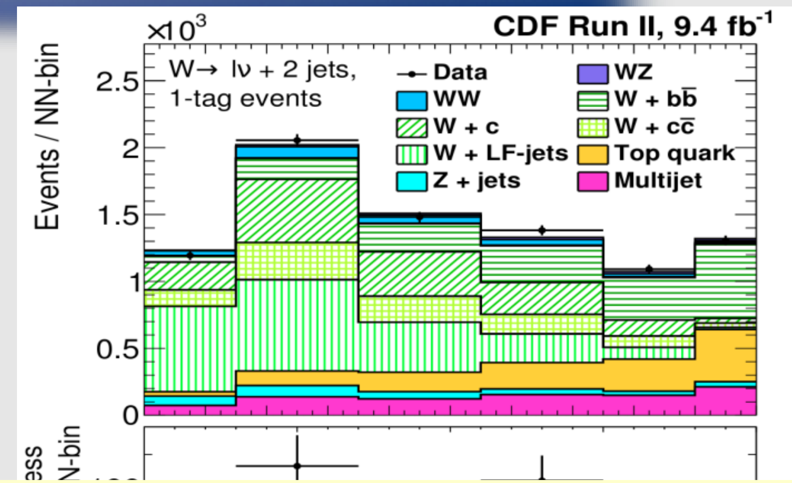
$$\sigma^{obs}_{WW} = 9.4^{+3.0}_{-3.0}(\text{stat})^{+2.9}_{-2.9}(\text{syst}) = 9.4 \pm 4.2\ \text{pb}$$

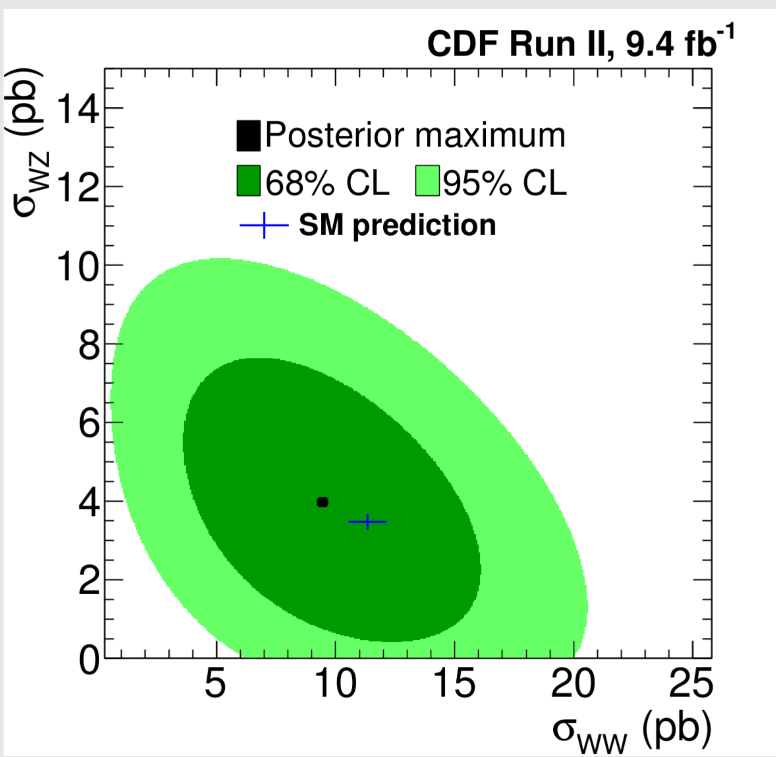
$$\sigma^{obs}_{WZ} = 3.7^{+2.0}_{-1.8}(\text{stat})^{+1.4}_{-1.2}(\text{syst}) = 3.7^{+2.5}_{-2.2}\ \text{pb}$$

Phys.Rev. D94 (2016) 032008

Diboson Search in $l\nu$ + heavy-flavor jets

- Apply flavor-separator NN to obtain b-quark versus c-quark separation
- 2-dimensional m_{jj} vs flavor-separator NN for single-tag events
- Different signal and background composition across NN va





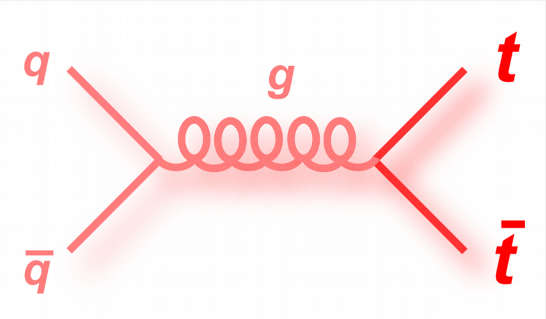
- **Total diboson cross section measured with a precision of about 30%, comparable with other experiment measurements in semi-leptonic final-states**
- **Separate WW and WZ cross sections measured with a precision of 45% and 60% respectively**
- **Most precise measure of WZ in this final state**

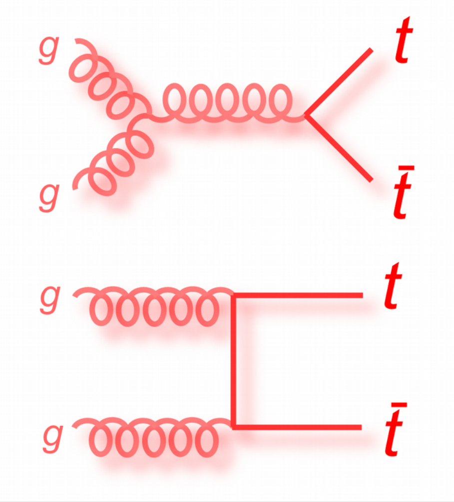
Top quark production

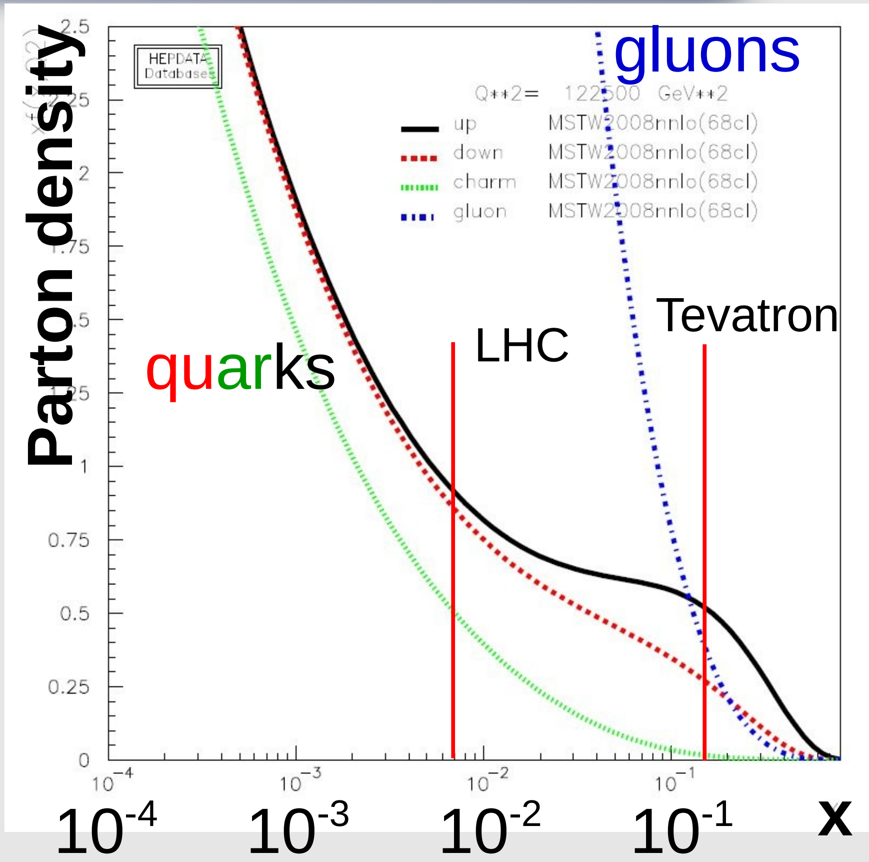
<u>Strong interaction:</u> Top pairs

Tevatron vs. LHC (13 TeV):

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







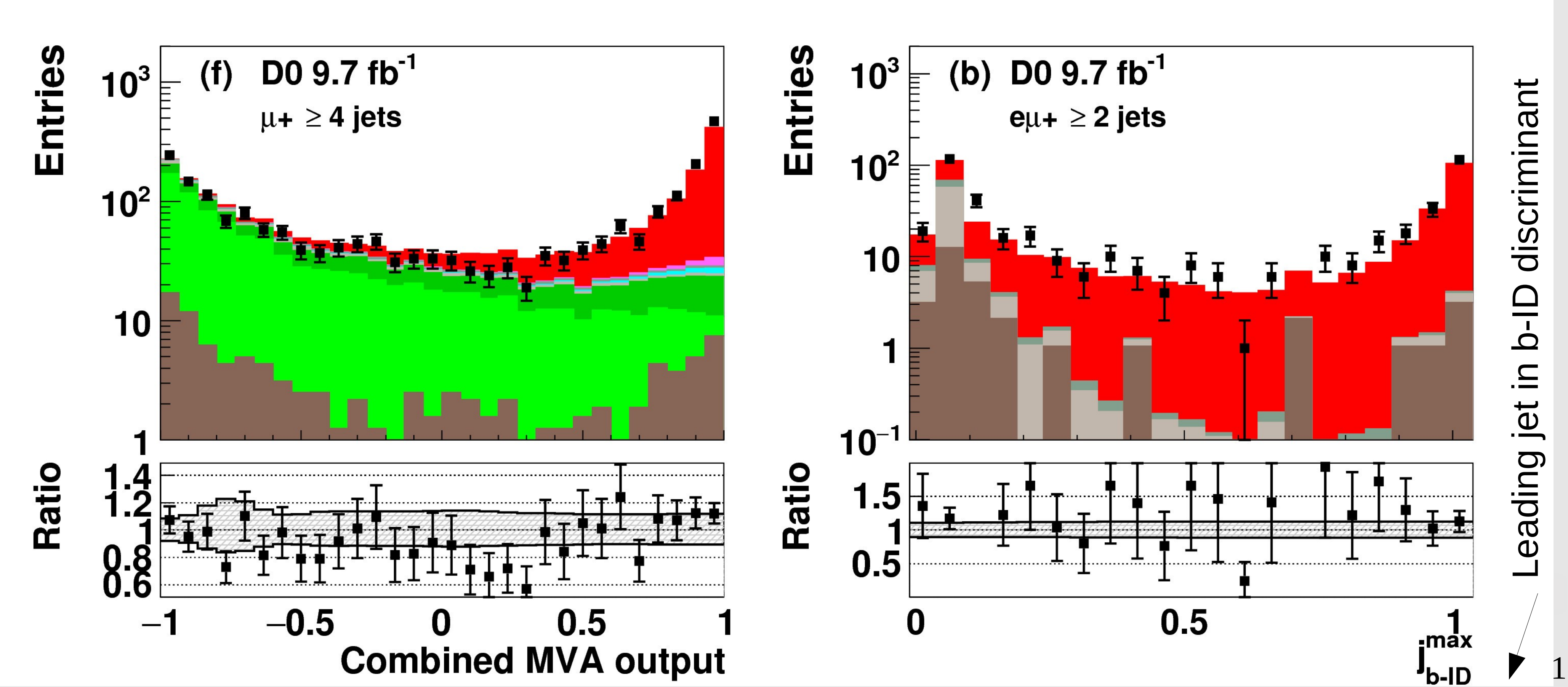
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$

LHC 13 TeV $\sigma = 832^{+40}_{-46}$ pb

$t\bar{t}$bar inclusive cross section

Employ MVA methods optimized to extract m(top) using topological and kinematic distributions, MVA discriminant sensitive to HF decays

Apply profile log-LH fits, extract XS for dilepton, l+jets and combination



arxiv:1605.06168, subm. to PRD

$t\bar{t}$bar inclusive cross section

Combination of dilepton & l+jets:

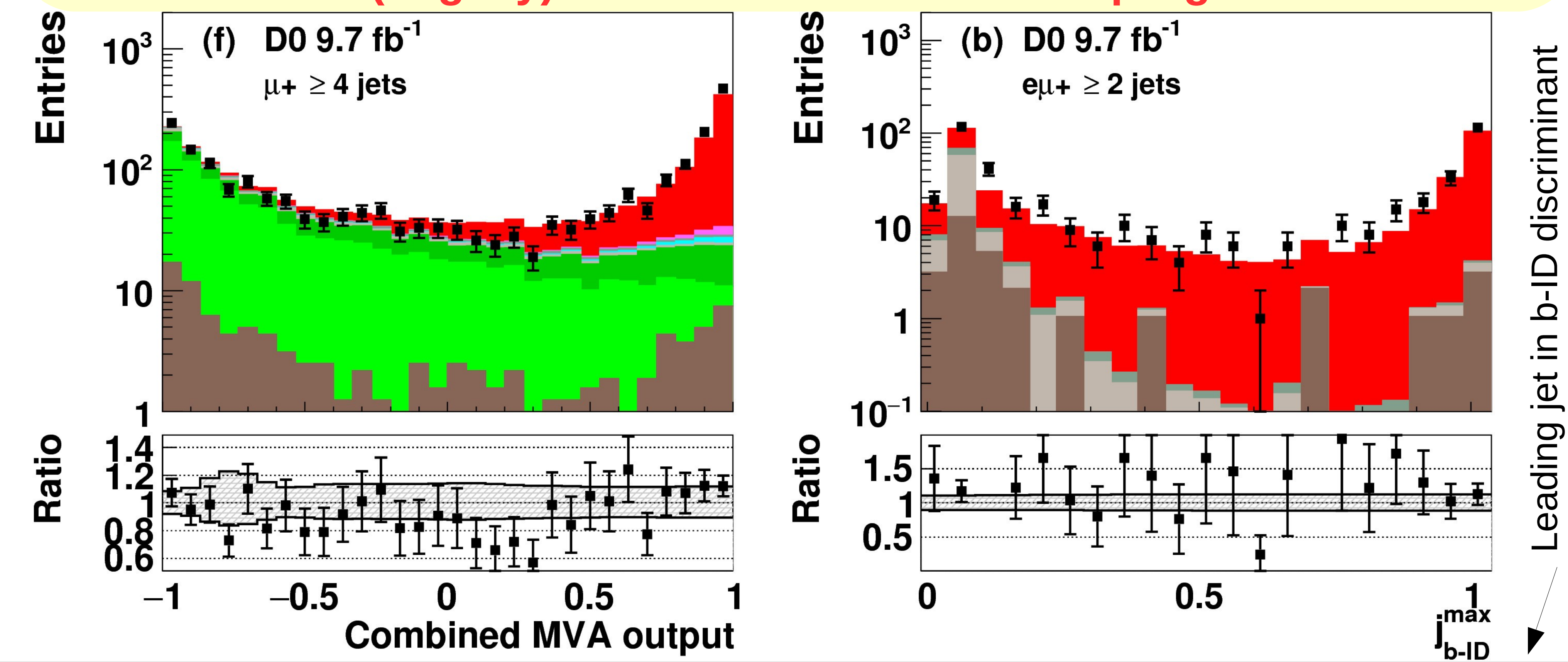
Subm. to PRD

σ = 7.26 ± 0.13 (stat.) ± 0.57/0.50 (syst.) pb

$\delta\sigma/\sigma$ = 7.6%

Theory (NNLO+NNLL, top++):
7.16 pb ± 3.5%

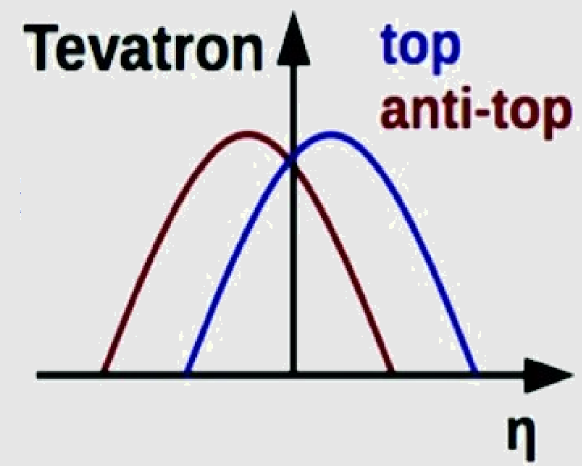
Final (Legacy) Tevatron Combination in progress



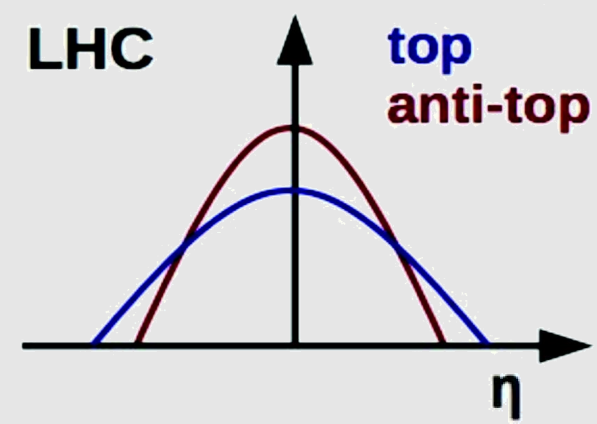
$t\bar{t}$ asymmetry measurements

Interference effects at NLO QCD in $q\bar{q}$ initial states:

- Forward-backward asymmetry at Tevatron
- No valence anti-quarks at LHC → t more central



SM predictions at NLO (QCD+EWK)
Tevatron: A_{FB} ~ 10 % vs. LHC: A_C ~ 1 %
NNLO+NNLL



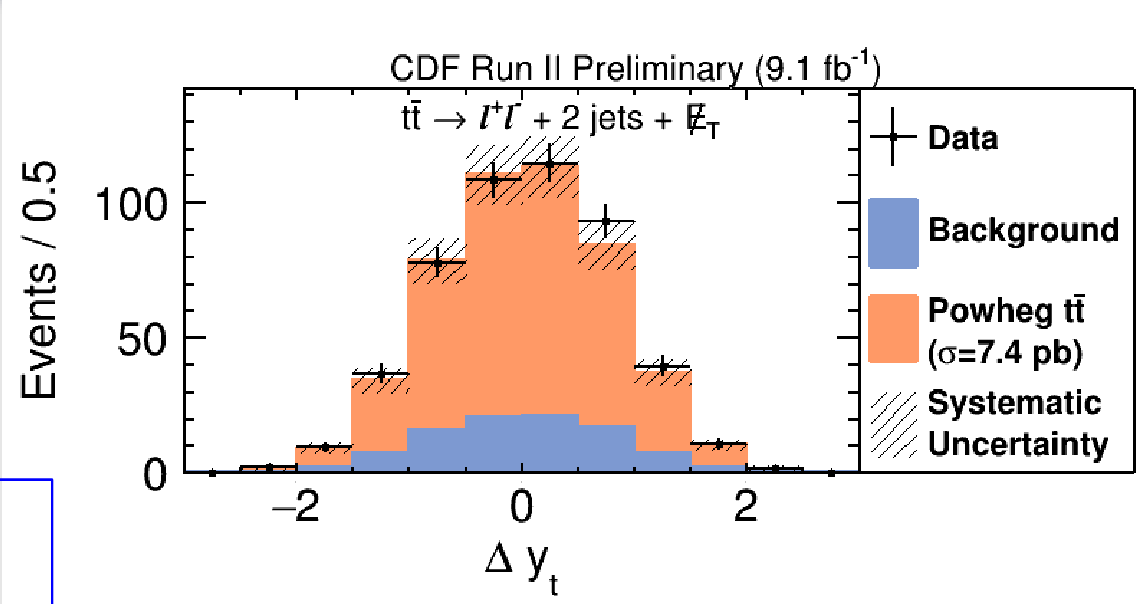
Experimentally: Asymmetries based on decay leptons or fully reconstructed top quarks

Large ensemble of Tevatron studies to date, will briefly summarize most recent measurements

Δy_t A_{FB} in dilepton events

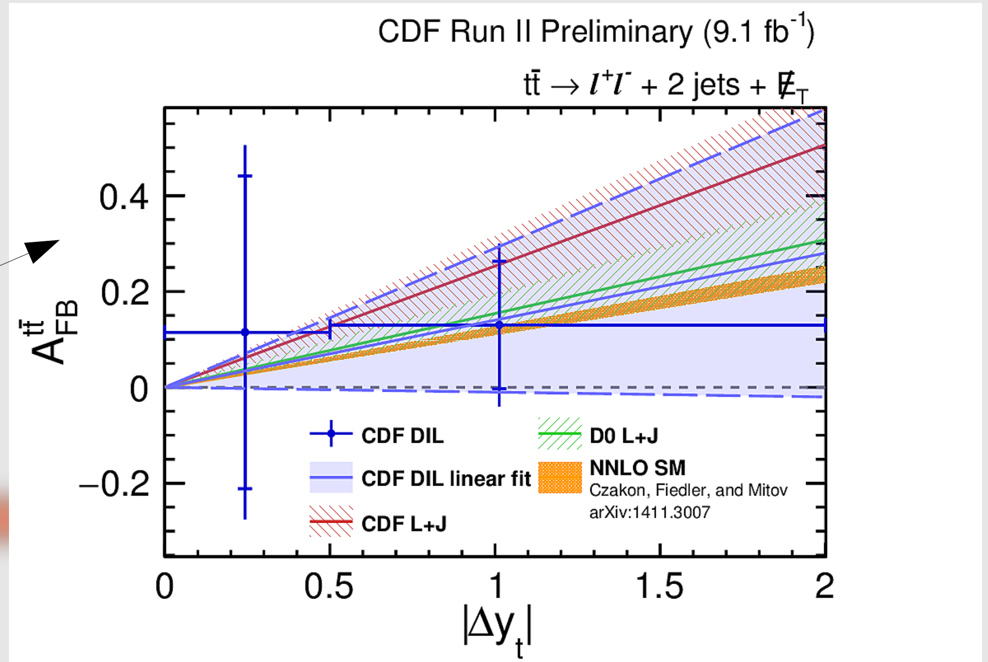
Likelihood-based kinematic reconstruction

- Probability density dist for each solution
- Inclusive and differential measures



Integrated:
A_{FB} = 12 ± 11 (stat.) ± 7 (syst.) %
A_{FB} = 12 ± 13 (tot.) %
A_{FB} ℓℓ & ℓ+jets: 0.164 ± 0.047
Agreement with the SM w/in ~1.5σ

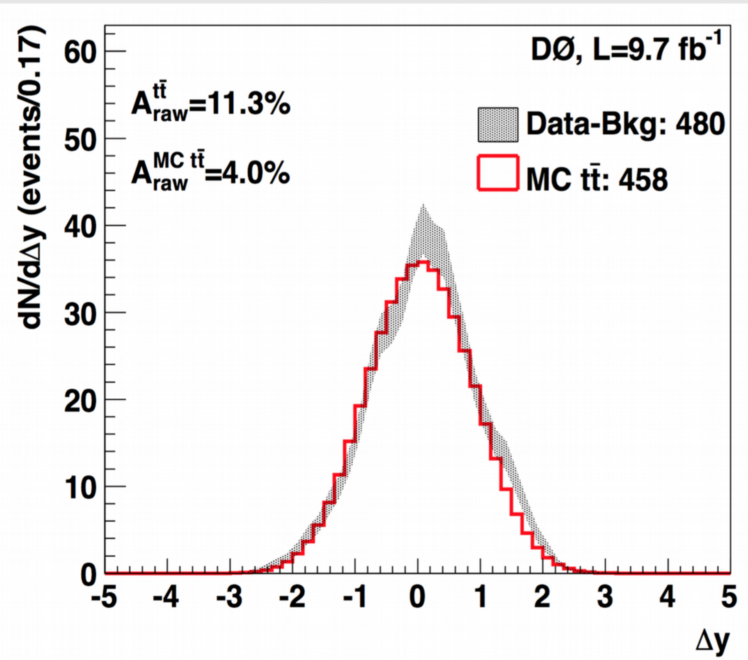
Differential (combination):
Slope in |Δy| agrees with theory and D0 result in l+jets
Agreement with the SM w/in ~2.0σ



Δy_t A_{FB} and polarization in dilepton events

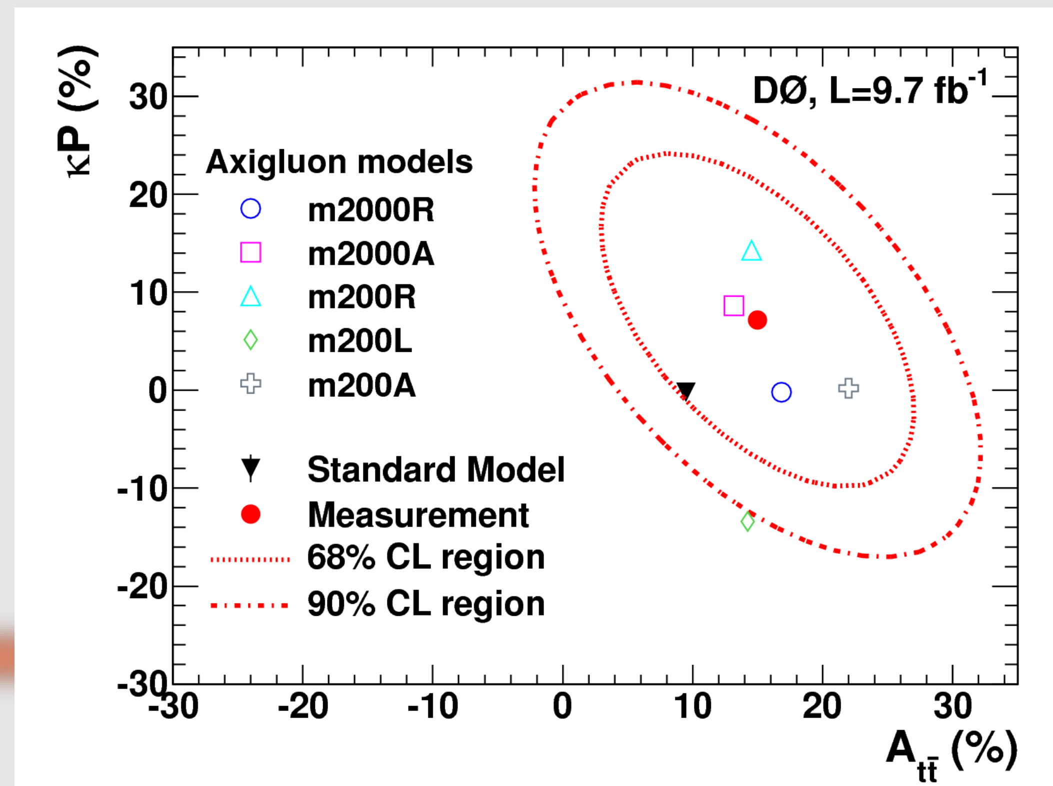
Phys. Rev D 92, 052007 (2015)

Matrix-Element based analysis, per event for correct Δy assignment



Simultaneous 2D measurement:

(Polarization measured in beam basis)



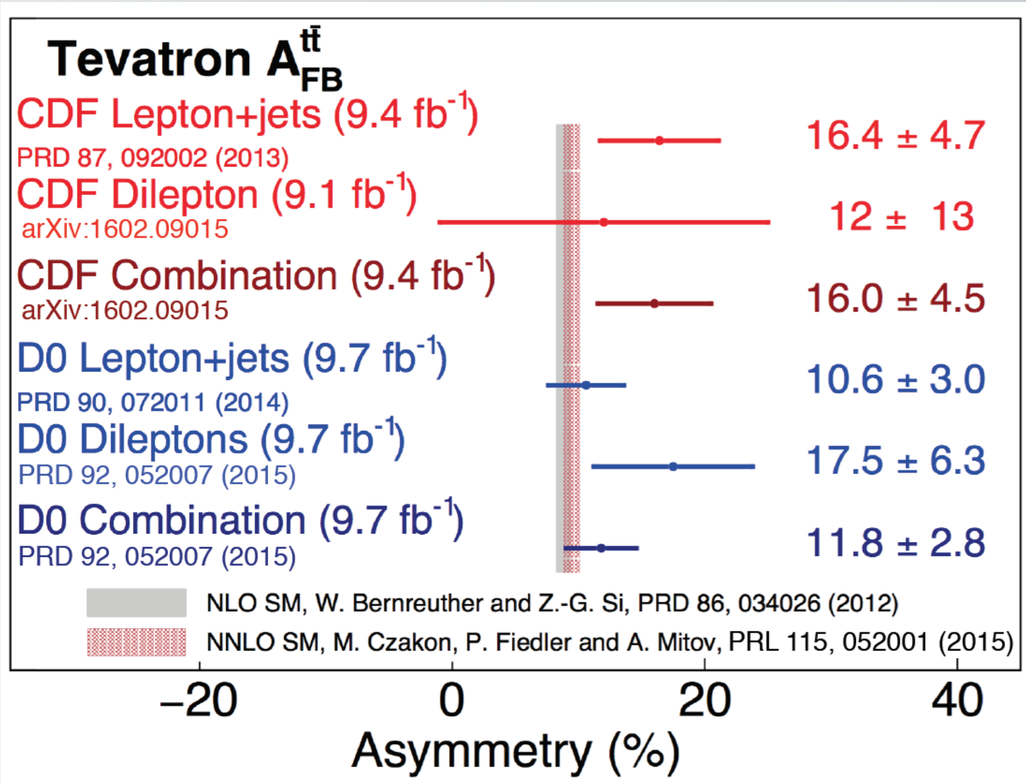
A_{FB} = 15.0 ± 8.0 (tot.) %

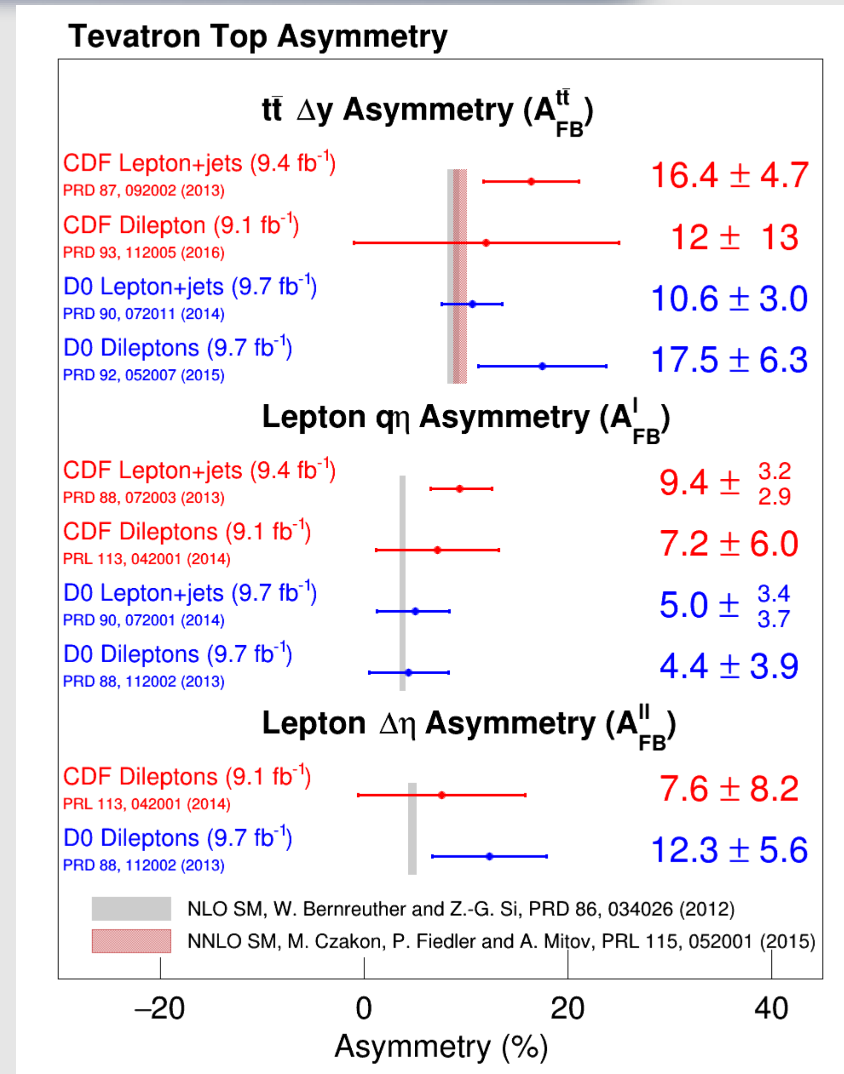
κP = 7.2 ± 11.3 (tot.) %

Constrain *P* to SM value:
(SM polarization essentially 0)

A_{FB} = 17.5 ± 6.4 (tot.) %

$t\bar{t}$ asymmetries at Tevatron



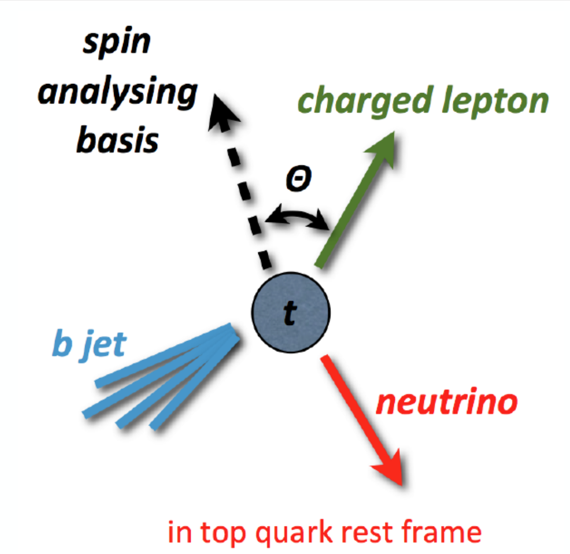


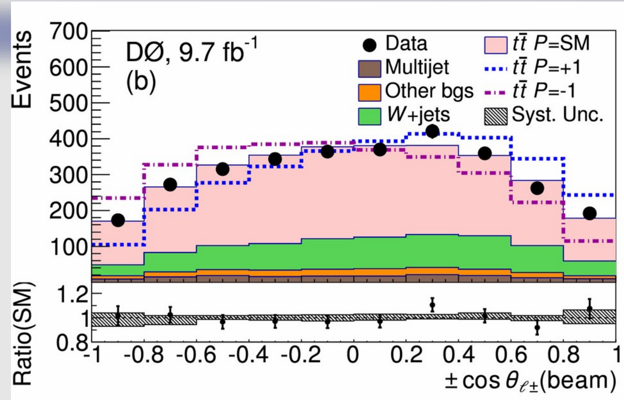
- Overall agreement with SM
- **Legacy Tevatron combination is underway**

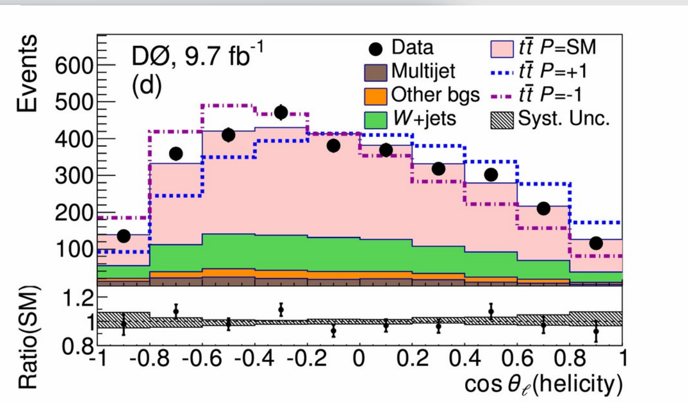
ℓ+jets channel

Subm. to PRL [arXiv:1607.07627]

Measure of top quark polarization





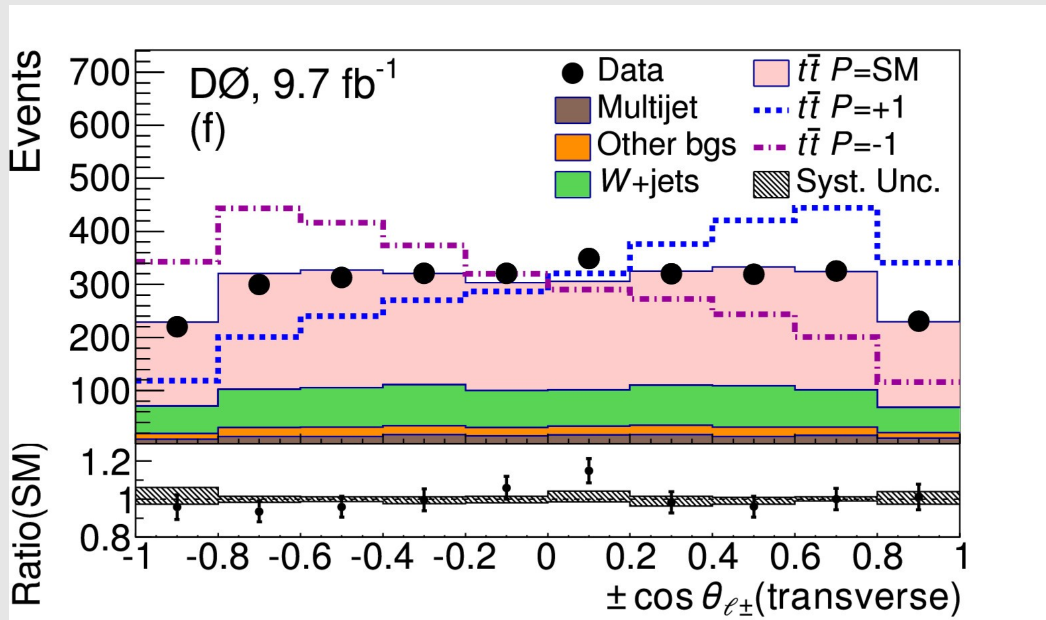


Measured wrt 3 quant. Axes:
- beam
- Helicity: wrt parent top
- Transverse to tt̄ production plane

1st measurement of the transverse polarization ===>

SM expectation is 0

(SM almost 0 for helicity and beam as well)



Axis	Measured polarization $P_{\hat{n}}$	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Helicity	-0.102 ± 0.060	-0.004
Transverse	$+0.040 \pm 0.034$	$+0.011$

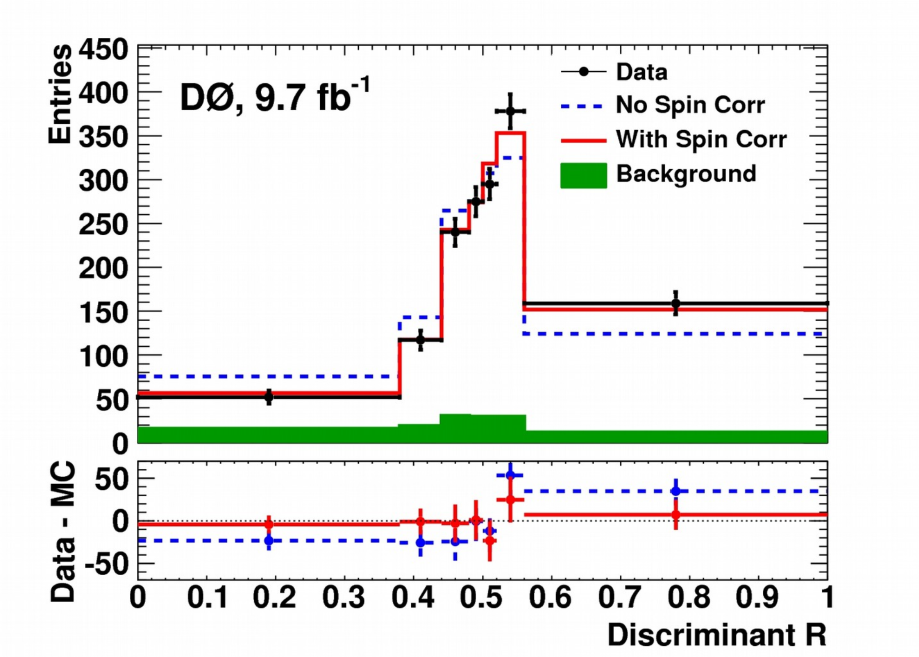
dilepton & l+jets combination:

$P_{Beam} = 0.081 \pm 0.048$

All in agreement with the SM

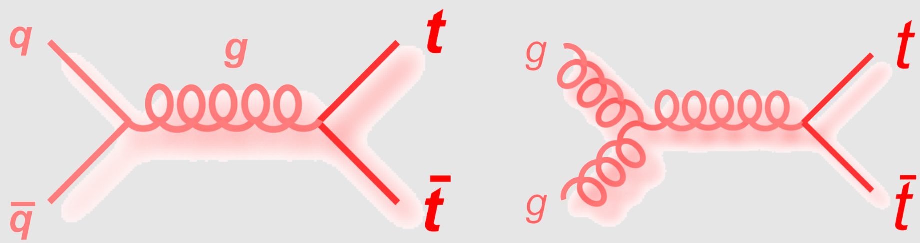
Phys. Lett. B 757, 199 (2016)

Top quark spin correlations



Different quantity at Tevatron and LHC:

- Production at threshold and well above
- $p\bar{p}$ versus pp collisions



Complementary to the LHC results

Initial states, effects of light top quark partners on SM spin correlation expectation

$$R = \frac{P_{\rm sgn}(H=c)}{P_{\rm sgn}(H=u) + P_{\rm sgn}(H=c)}$$

- Matrix element technique ($\ell\ell$ & ℓ+jets), spin correlation discriminant
- Optimized off-diagonal basis

O_{off} = 0.89 ± 0.22 (tot.)

$O_{off,\ MC@NLO}$ = 0.766

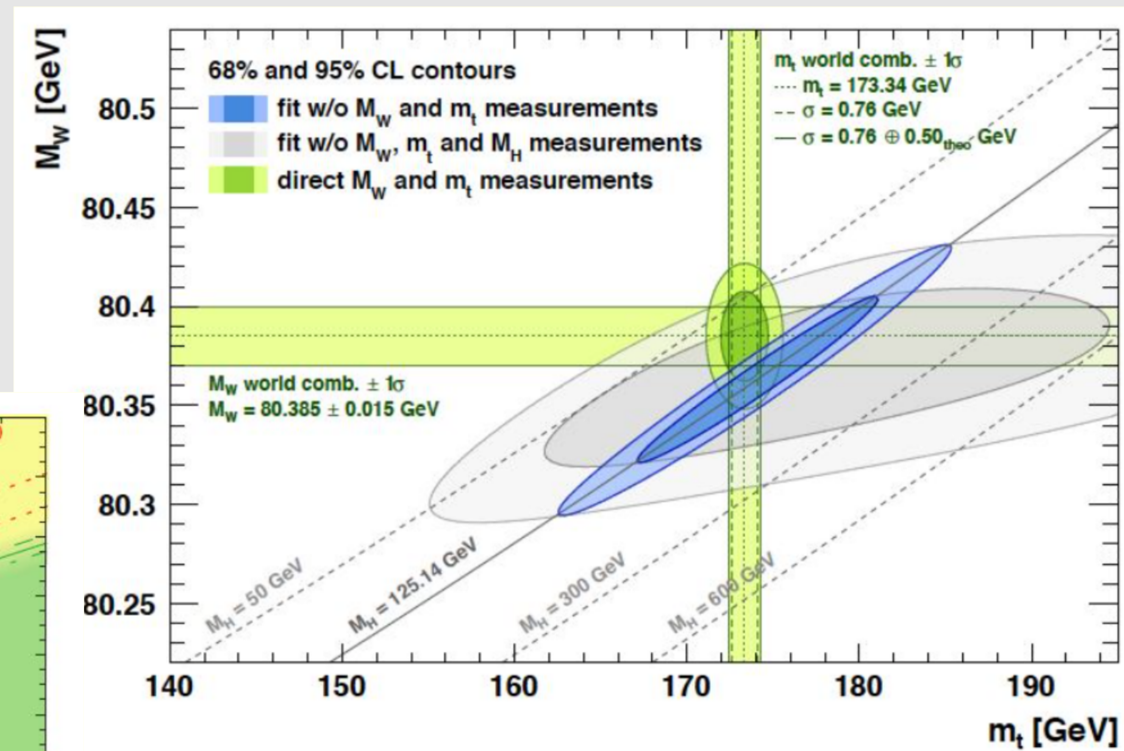
Evidence for spin correlation: 4.2 s.d. (observed)

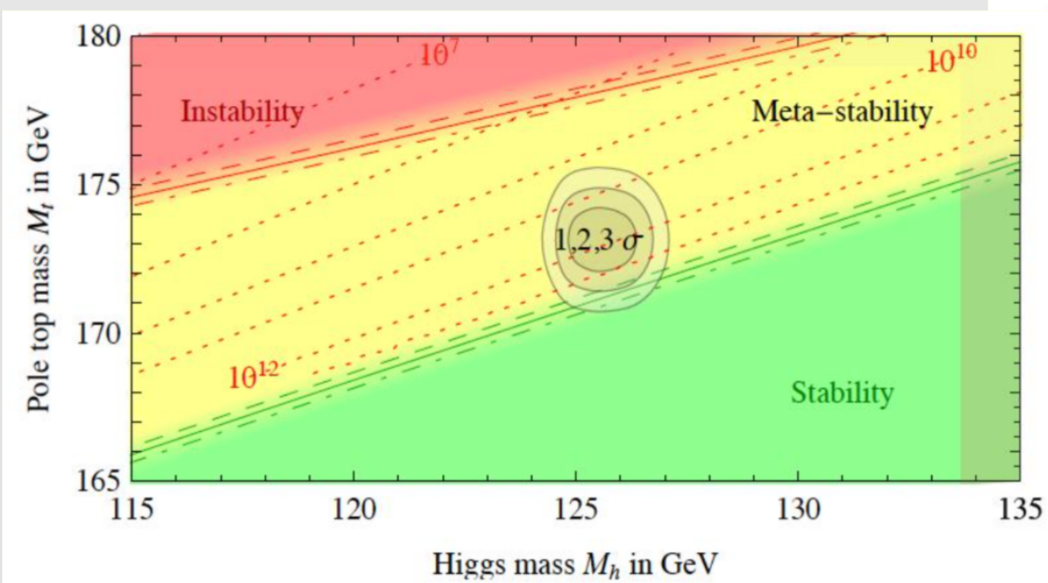
F_{gg} = 0.08 ± 0.16 (SM inference)

Top/W mass

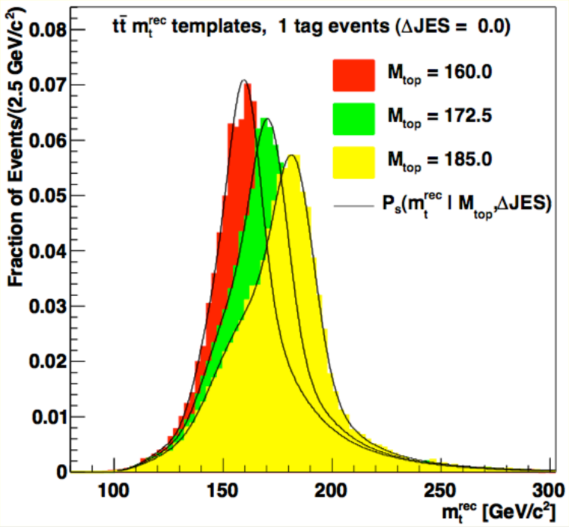
- m_t,m_W,m_H important parameters for vacuum stability
- t quark is the heaviest elementary particle: importance in loop corrections
- or sensitivity to new corrections/couplings

With precise knowledge of all m_t , m_W , m_H : strong consistency test of the SM





Top/W mass measurement

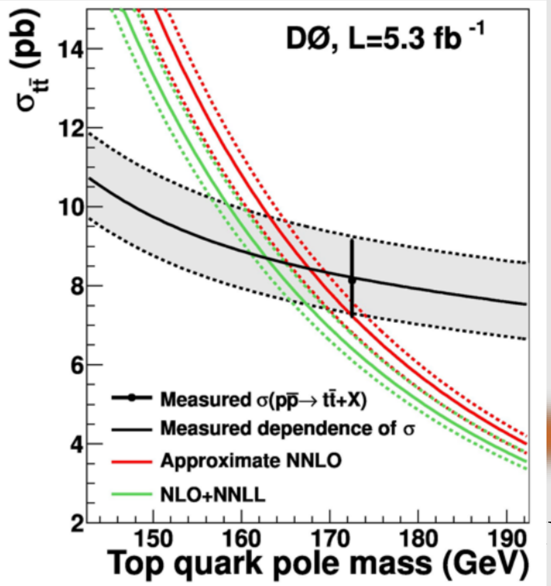


Direct measurements

- template method:
  - compare an observable in data with MC generated with different masses
  - application to m_W requires exceptional tuning to accurately model data
- matrix element method
  - build an event probability based on the LO $t\bar{t}$ matrix element using the full kinematics of the event

need to calibrate method to correct for any potential biases, eg
• EM scale vs electrons from Z deacy
• for top with at least one W decaying hadronically, can calibrate JES constraining M_{jj} to M_W

PLB 703, 422 (2011)



Indirect measurements

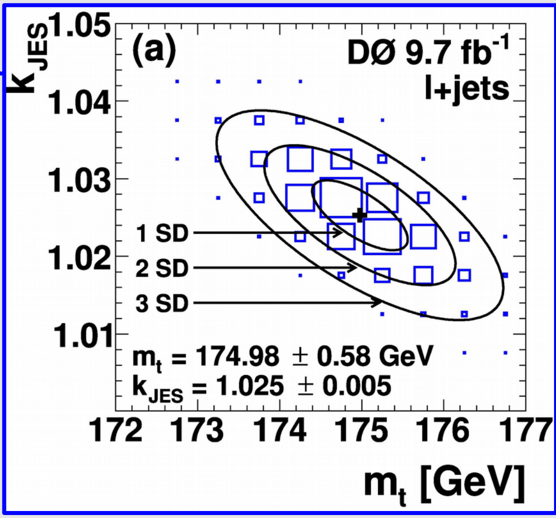
- May involve less input from MC or different sensitivity to systematics
- For m_t extraction of a mass in a better defined renormalization scheme

Most recent
direct m_t measures from Tevatron

ℓ+jets matrix element top mass

m_t = 174.98 ± 0.58(stat ± 0.49(syst) GeV +JES)

$\Delta m_t / m_t$ = 0.43%



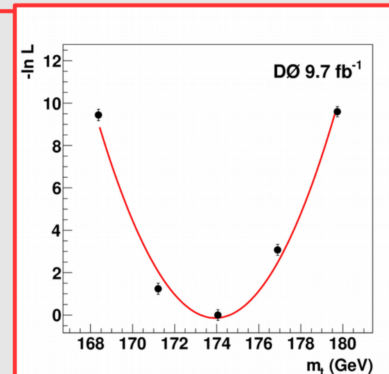
PRL 113, 032002 (2014),
PRD 91, 112003 (2015)

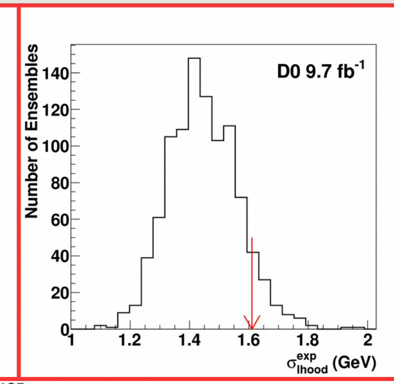
Phys. Lett. B 752 18 (2016)

dilepton matrix element top mass

m_t = 173.93 ± 1.61(stat) ± 0.88(syst)GeV

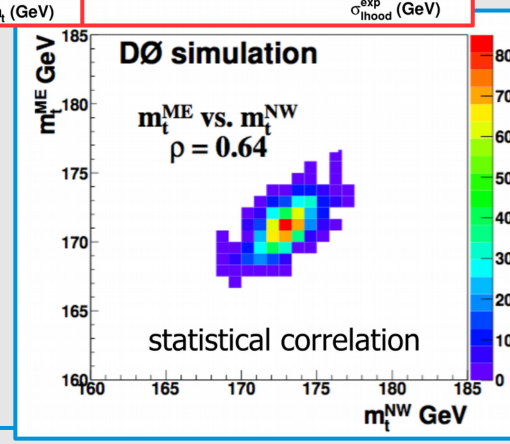
$\Delta m_t / m_t$ = 1.05%





Phys. Rev. D 94, 032004 (2016)

$$\omega = \frac{1}{N}\sum_{i=1}^{N}\prod_{j=x,y}\exp\left(-\frac{(\not{E}_{T_{j,i}}^{\rm calc} - \not{E}_{T_j}^{\rm obs})^2}{2\sigma^2_{\not{E}^u_{T\,j}}}\right)$$



dilepton neutrino weighting mass

m_t = 173.32 ± 1.36(stat) ± 0.85(syst)GeV

$\Delta m_t / m_t$ = 0.93%

D0 note 6484

dilepton combination (new)

m_t = 173.50 ± 1.31(stat) ± 0.84(syst)GeV

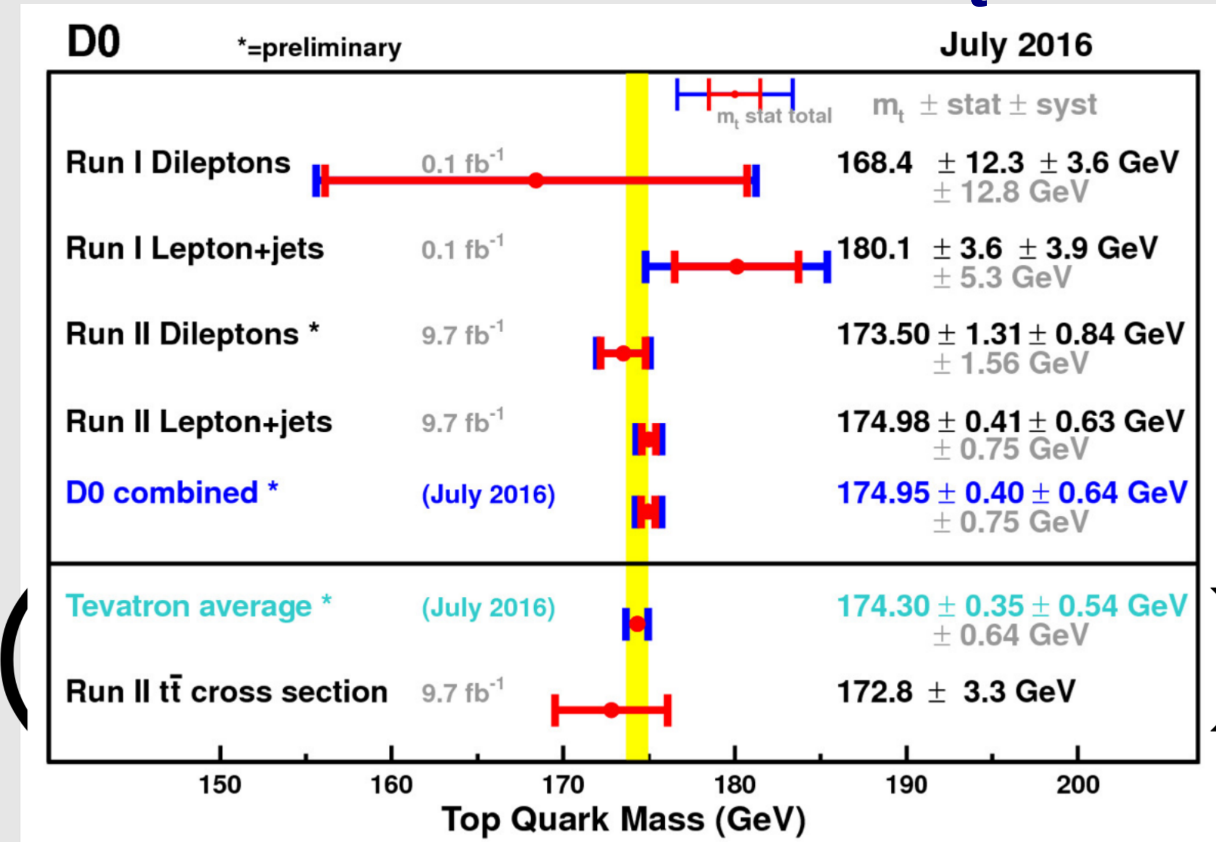
$\Delta m_t / m_t$ = 0.81%

BLUE method

update from previous 2011 result

D0 note 6484

New D0 m_t combination



	Run I		Run II	
	$\ell+$jets	$\ell\ell'$	$\ell+$jets	$\ell\ell'$
In situ light-jet calibration (iJES)			×	×
Response to $b/q/g$ jets (aJES)	o	o	×	×
Model for b jets (bJES)	×	×	×	×
Out-of-cone correction (cJES)	×	×	×	×
Light-jet response (dJES)	o	o	×	×
Lepton modeling (LepPt)	o	o	×	×
Signal modeling (Signal)	×	×	×	×
Jet modeling(DetMod)	×	×	×	×
b-tag modeling (b-tag)	o	o	×	×
Background from theory (BGMC)	×	o	×	o
Background based on data (BGData)				
Calibration method (Method)				
Offset (UN/MI)	×	×		
Multiple interactions model (MHI)	o	o	×	×
Statistical				

o,x: 100% correlated
o not correlated with x

D0 combination (preliminary)
m_t = 174.95 ± 0.40 (stat) ± 0.64 (syst) GeV
$\Delta m_t / m_t$ = 0.43%

χ^2 /ndof = 2.5/3, prob = 47 %

	D0 Run I		D0 Run II	
	$\ell+$jets	$\ell\ell'$	$\ell+$jets	$\ell\ell'$
Pull	0.98	−0.51	0.63	−1.06
Weight	0.00	−0.00	0.96	0.03

update from previous 2014 result

arXiv:1608.01881

New Tevatron m_t combination

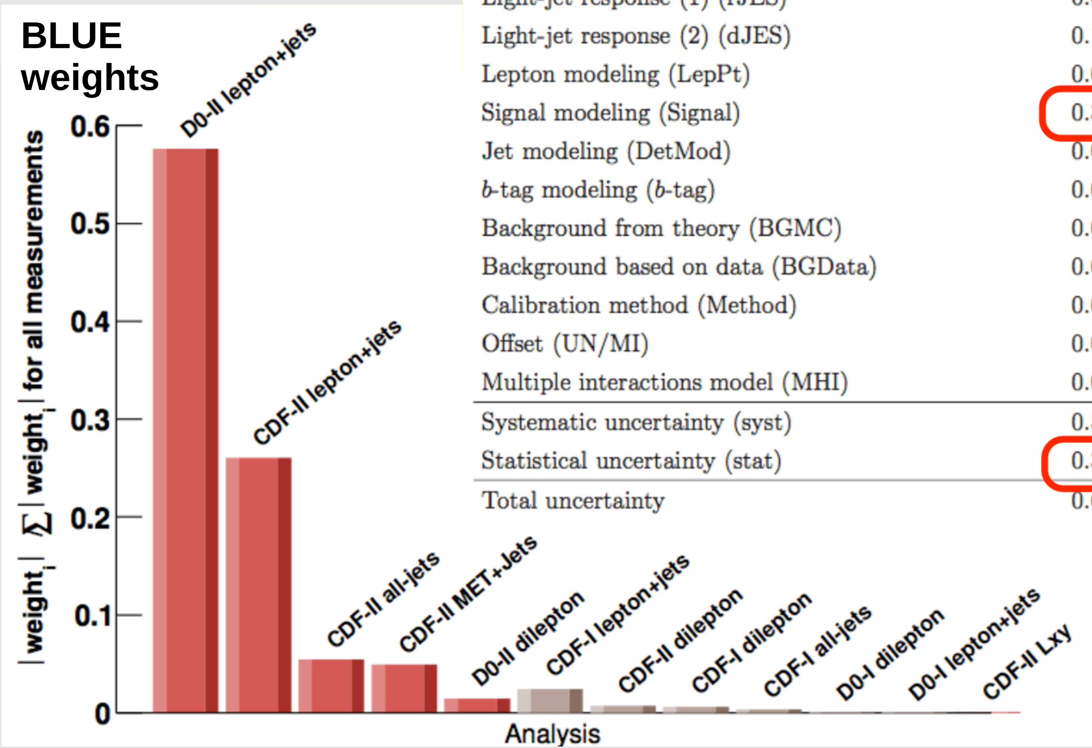
- new D0 dilepton measurement
- published CDF all-jets measurement

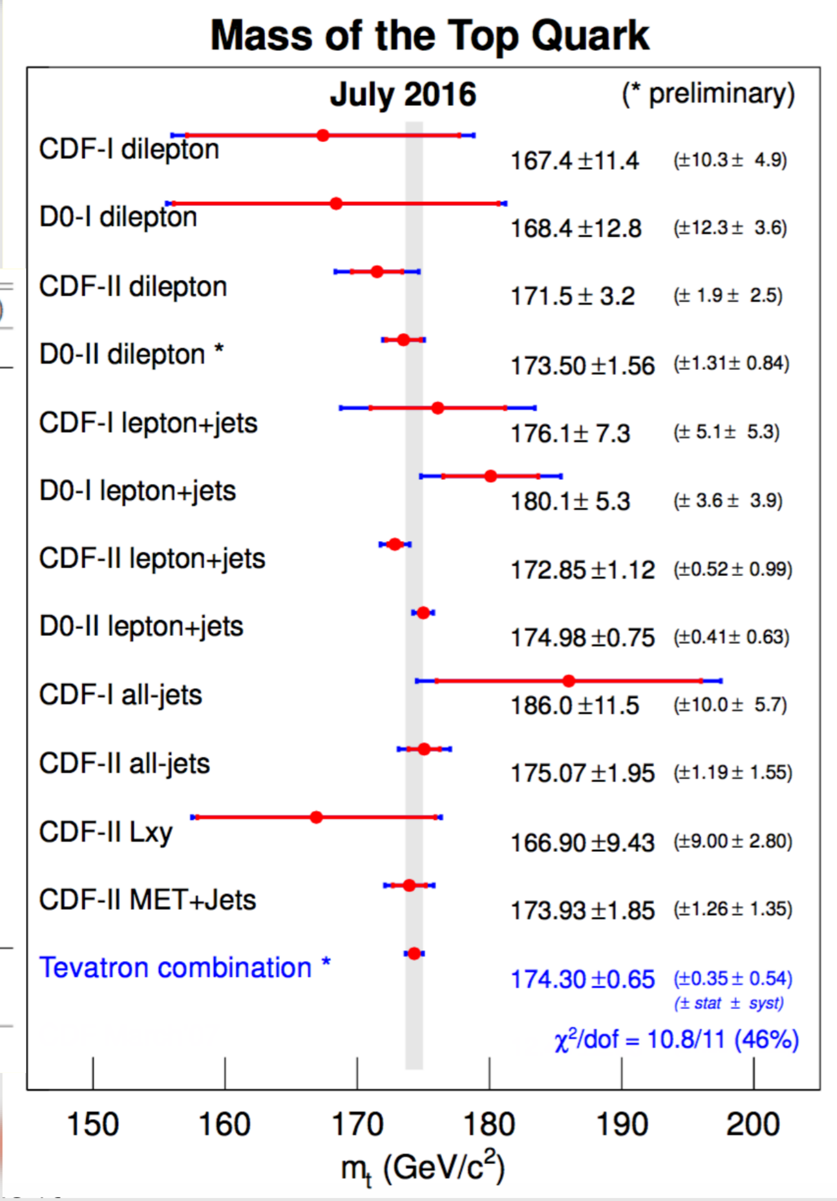
m_t = 174.30 ± 0.35 (stat) ± 0.54 (syst) GeV

$\Delta m_t / m_t$ = 0.37%

χ^2/dof = 10.8/11, prob = 46%

	Tevatron combined values (GeV/c^2)
M_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





top quark mass from $t\bar{t}$ cross section

- compare the experimental tt cross section measurement with the theory computation (depend differently on the top quark mass)
- cross section vs m_t parametrized with (third order polynomial)/m_t^4
  - theoretical cross section computed at NNLO with top++
  - experimental $\ell\ell$ & ℓ+jets with 9.7 fb^{-1}

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

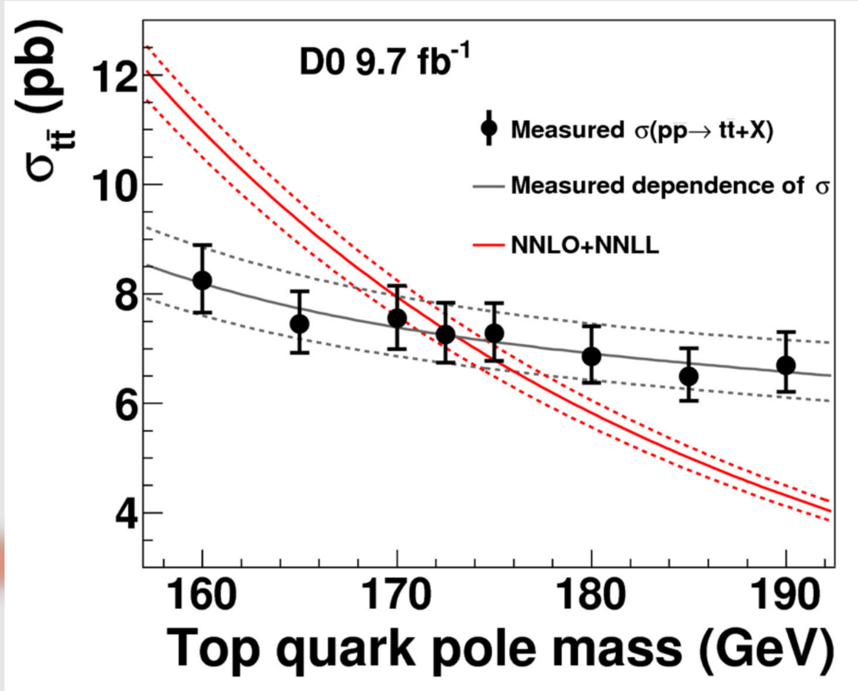
Advantage/Drawback
- extract the top quark mass in a well defined renormalization scheme (pole mass in theory computation)
- less precise than direct measurements

$$L(m_t) = \int f_{\text{exp}}(\sigma|m_t)\ [f_{\text{scale}}(\sigma|m_t) \otimes f_{\text{PDF}}(\sigma|m_t)]\ d\sigma.$$

gaussian — flat — gaussian

$$m_t = 172.8 \pm 1.1\,(\text{theo.})\ ^{+3.3}_{-3.1}\,(\text{exp.})\ \text{GeV}$$
$$m_t = 172.8^{+3.4}_{-3.2}\,(\text{tot.})\ \text{GeV}$$

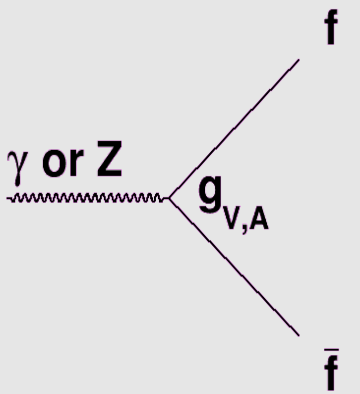
$\Delta m_t/m_t = 1.9\%$



Born level qq → $\gamma^*/Z \rightarrow \ell^+\ell^-$ asymmetry

SM vector (V) and axial (A) current couplings of fermions

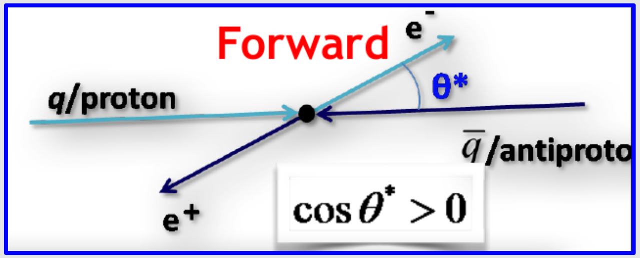
- Z : $g_V = T_3\ (1\text{-}4|Q|\sin^2\theta_W)$ $g_A = T_3$; $\sin^2\theta_W = 1-(M_W/M_Z)^2$
- γ : $g_V = Q$ $g_A = 0$



(σ_f - σ_b) lepton asymmetry arises from two V-A interference terms

- $\gamma_{VV} \otimes Z_{AA}$: $Q^{(\ell)}\ Q^{(q)}\ T_3^{(q)}\ T_3^{(\ell)}$ ← independent of $\sin^2\theta_W$
- $Z_{VV} \otimes Z_{AA}$: $T_3^{(l)}\ (1\text{-}4|Q^{(\ell)}|\sin^2\theta_W)\ T_3^{(q)}\ (1\text{-}4|Q^{(q)}|\sin^2\theta_W)\ T_3^{(q)}\ T_3^{(\ell)}$

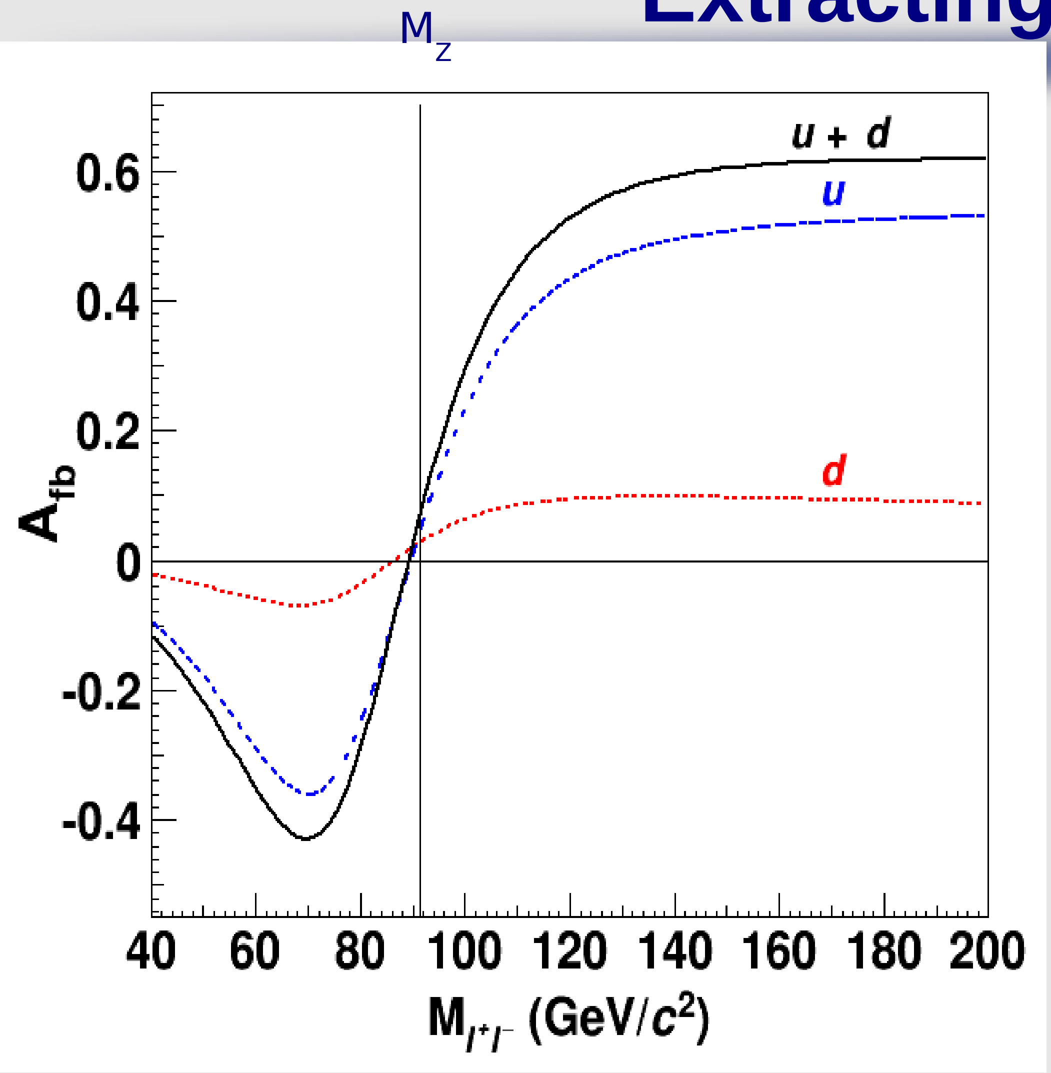
 [↳ 0.1] [↳ 0.4, 0.7]



Electroweak radiative corrections

- Turn $\sin^2\theta_W$ into fermion-type dependent effective mixing angles $\sin^2\theta_{eff}$
  - leptonic, u-type quark, d-type quark
- A_{fb} most sensitive to effective leptonic mixing angle @M_Z : $\sin^2\theta_{eff}^{lept}$

Extracting $\sin^2\theta_{eff}^{lept}$



Measure asymmetry in mass bins

$A_{fb} = (N_f - N_b)/(N_f + N_b)$

Fit A_{fb} to templates with

varying values of $\sin^2\theta_{eff}^{lept}$

to get best-fit value

Experimental effects applied to templates or corrected in A_{fb} data

Expectation:

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

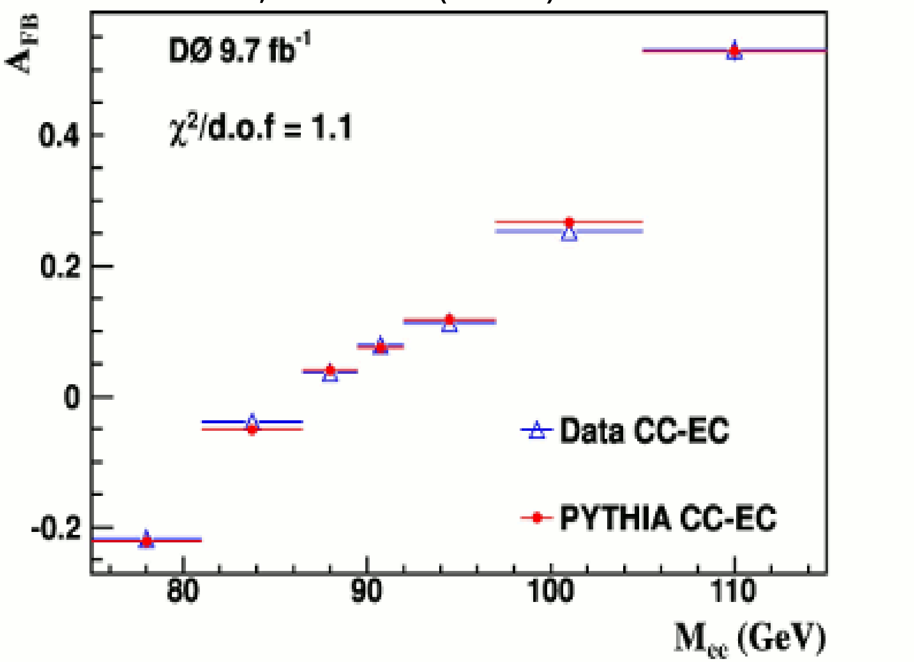
$A_{fb}^{(u)}$: u-quark contribution

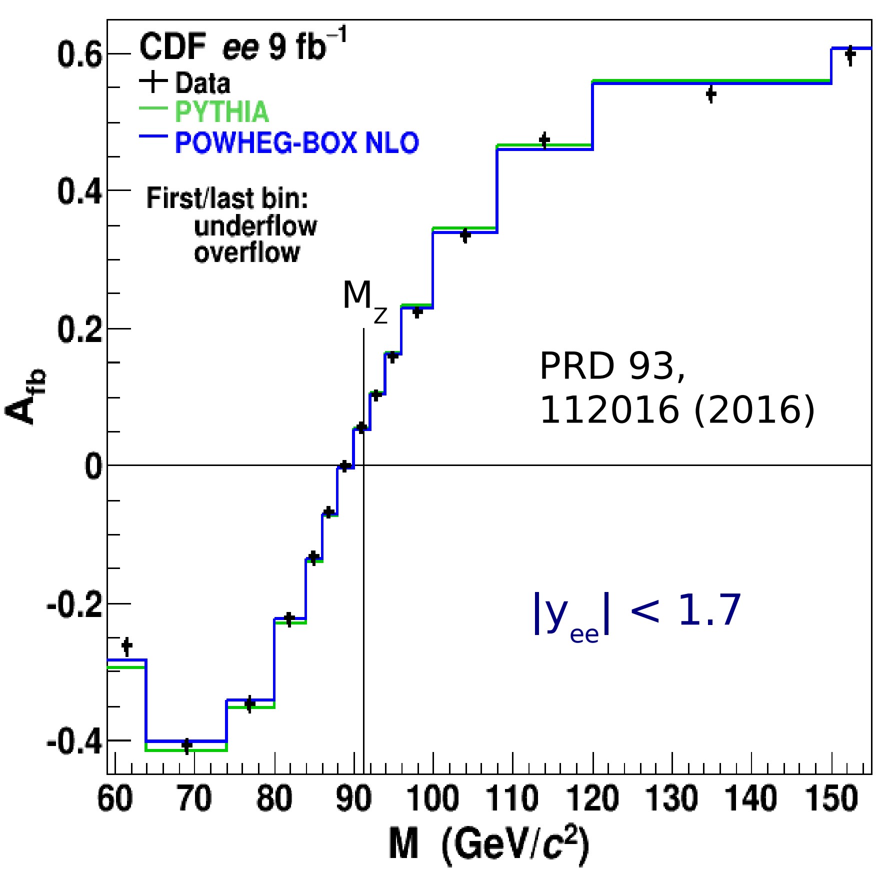
$A_{fb}^{(d)}$: d-quark contribution

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

A_{FB} measurements at D0 & CDF ee channel

PRL 115, 041801 (2015)





Inputs:

- A_{fb} measurement (three regions used)
- templates (PYTHIA)
  include detector simulation,
  varying values of $\sin^2\theta_W$,
  adjusted for EW radiative corrections

Fit A_{fb} to templates for best-fit $\sin^2\theta_{eff}^{lept}$

Muon analysis: in progress

Measurements corrected, templates are pure calculations and for the specified kinematic range

RESBOS and POWHEG-BOX best-fit templates include EWK radiative corrections

Summary of $\sin^2\theta_{eff}^{lept}$ extraction

Asymmetries in data separately fit to templates then best-fit values combined

Template calculation

- PYTHIA 6.23 with NNPDF v2.3(NLO) PDFs
- Higher order QCD effect corrections applied to generated events
- Detector simulation included

Adjustment for electroweak radiative corrections

- Fit value biased: $\sin^2\theta_{eff}^{lept}$ and quark $\sin^2\theta_{eff}$'s differ in value
- Bias correction +0.00008 estimated by ZGrad+ResBos applied to result

Final result

$\sin^2\theta_{eff}^{lept}$ = 0.23147 ± 0.00047 (total)

↕ ↕

statistics:	**0.00043**
PDF:	**0.00017**
other systematics:	**0.00008**

Asymmetry measurements corrected for direct fits to calculations [EPJ C 76, 321 (2010)]

- Measurement: angular-weighted event sums method
- Simulation: matrix unfolding of detector and QED FSR smearing; residual bias correction of a few percent

Simulation (unfolding)

- PYTHIA 6.2(CTEQ5L) ⊕ PHOTOS 2.0(QED FSR) ⊕ CDF detector simulation
- Higher order QCD effect corrections applied to generated events

Templates

- POWHEG-BOX(NLO) ⊕ NNPDF v3.0(NNLO) PDFs ⊕ PYTHIA 6.4 parton showers
- ZFITTER 6.43 electroweak radiative corrections incorporated fermion-type dependent effective mixing angles $\sin^2\theta_{eff}$

$\sin^2\theta_{eff}^{lept}$ values from template fits

- μμ analysis: 0.23141±0.00086 (stat) ← refit - same template framework as ee
- ee analysis: 0.23248±0.00049 (stat) fit χ^2's simply combined into a joint χ^2

Best-fit value of joint χ^2: 0.23221±0.00046 (total)

↕ ↕

statistics:	**0.00043**
PDF:	**0.00016**
other systematics:	**0.00006**

Result standardization for the combination

Common PDF and EW correction baselines for consistency

NNPDF v3.0

- Includes LHC data, improved implementation for PDFs and ensembles

ZFITTER SM electroweak radiative corrections

- Used by LEP-1 and SLD for standard-model analysis at Z pole

Standardization paths for CDF and D0

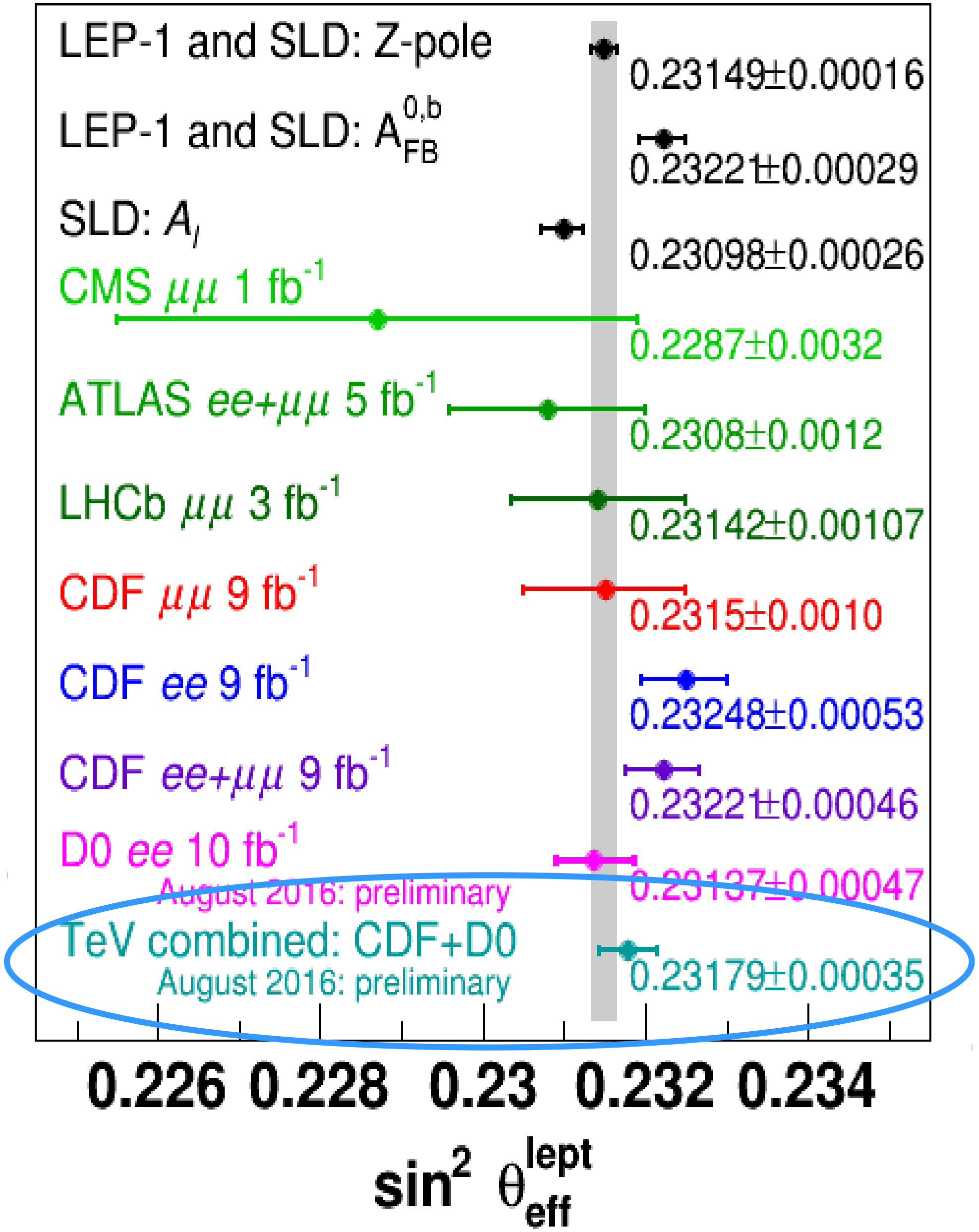
CDF: Already at baseline

D0 : Standardization corrections to $\sin^2\theta_{eff}^{lept}$ value ($\Delta\sin^2\theta_{eff}^{lept} = -0.00010 \pm 0.00005$)

- Δ(PDF): NNPDF v2.3 → v3.0 offset = **-0.00024±0.00004**
  - Difference of v3.0 pseudodata $\sin^2\theta_{eff}^{lept}$ and v2.3 template fit value
    - Afb pseudodata: v3.0 default PDF with reference value of $\sin^2\theta_{eff}^{lept}$
    - Templates : v2.3 default PDF with varying values of $\sin^2\theta_{eff}^{lept}$
- Δ(RadCor): ZGrad+ResBos → ZFITTER offset = **+0.00014±0.00004**
  - Difference of $\sin_2\theta_{eff}^{lept}$ results with and without ZFITTER corrections

↳ analog of PYTHIA templates

BLUE combination of $\sin^2\theta_{eff}^{lept}$ results



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)
- Standardization: D0 0.00005 (only applies to D0)

Results of BLUE method

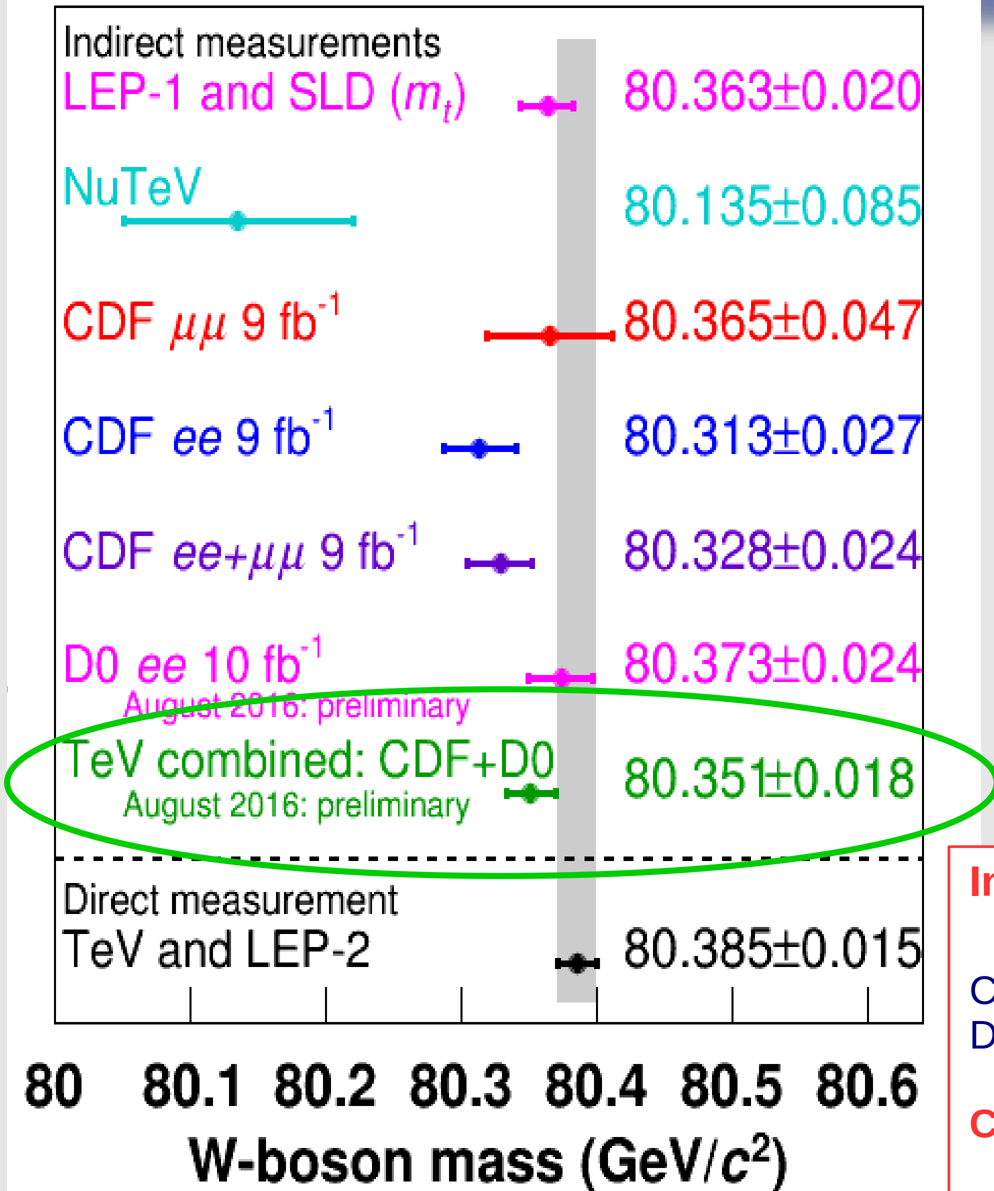
$\sin^2\theta_{eff}^{lept}$ = 0.23179 ± 0.00030 (stat) ± 0.00017 (syst)

χ2 of combination: 1.8 (18% probability)

Uncertainties

Statistics:	0.00030
PDF:	0.00017
Other systematics:	0.00005
Standardization:	0.00003

Inference of W-boson mass



$\sin^2\theta_W$ 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: 91.1875±0.0021 GeV

Standard model help from ZFITTER is needed

- $\sin^2\theta_{eff}^{lept} = \mathrm{Re}[\kappa_l(M_Z^2, \sin^2\theta_W)]\sin^2\theta_W$
  ↳ ≈1.037
- Form factors depend on standard-model input parameters
  - Most sentitive to top-quark mass 173.2±0.9 GeV
  - Form factor uncertainty to $\sin^2\theta_W$: 0.00008
  - Higgs mass value: 125 GeV

Inferences

	$\sin^2\theta_W$	M_W
CDF only:	0.22400±0.00041±0.00019	80328±21±10 MeV
D0 only:	0.22313±0.00041±0.00020	80373±21±10 MeV

Combination:

	$\sin^2\theta_W$	M_W
	0.22356±0.00029±0.00019	**80351±15±10 MeV**
	(stat) (syst)	(stat) (syst)

Post-Summary

Many new results in top/EW measurements from the Tevatron

- Diboson plus heavy flavor measurements
  - Improving precision in $WZ \rightarrow l\nu + cc/bb$
- Top quark properties measurements
  - Unique/complimentary results
- Direct and indirect measures of the top quark mass
  - High precision, novel experimental techniques
- $\sin^2\theta_W$ and indirect measure of m_W
  - World class precision

Next steps

Many new results in top/EW measurements from the Tevatron

- Diboson plus heavy flavor measurements
  - Improving precision in $WZ \rightarrow l\nu + cc/bb$
- Top quark properties measurements (Legacy combinations)
  - Unique/complimentary results
- Direct and indirect measures of the top quark mass (Legacy combinations)
  - High precision, novel experimental techniques
- $\sin^2\theta_W$ and indirect measure of m_W (D0 muon channel + Legacy combinations)
  - World class precision
- Direct measures of m_W not forgotten ...

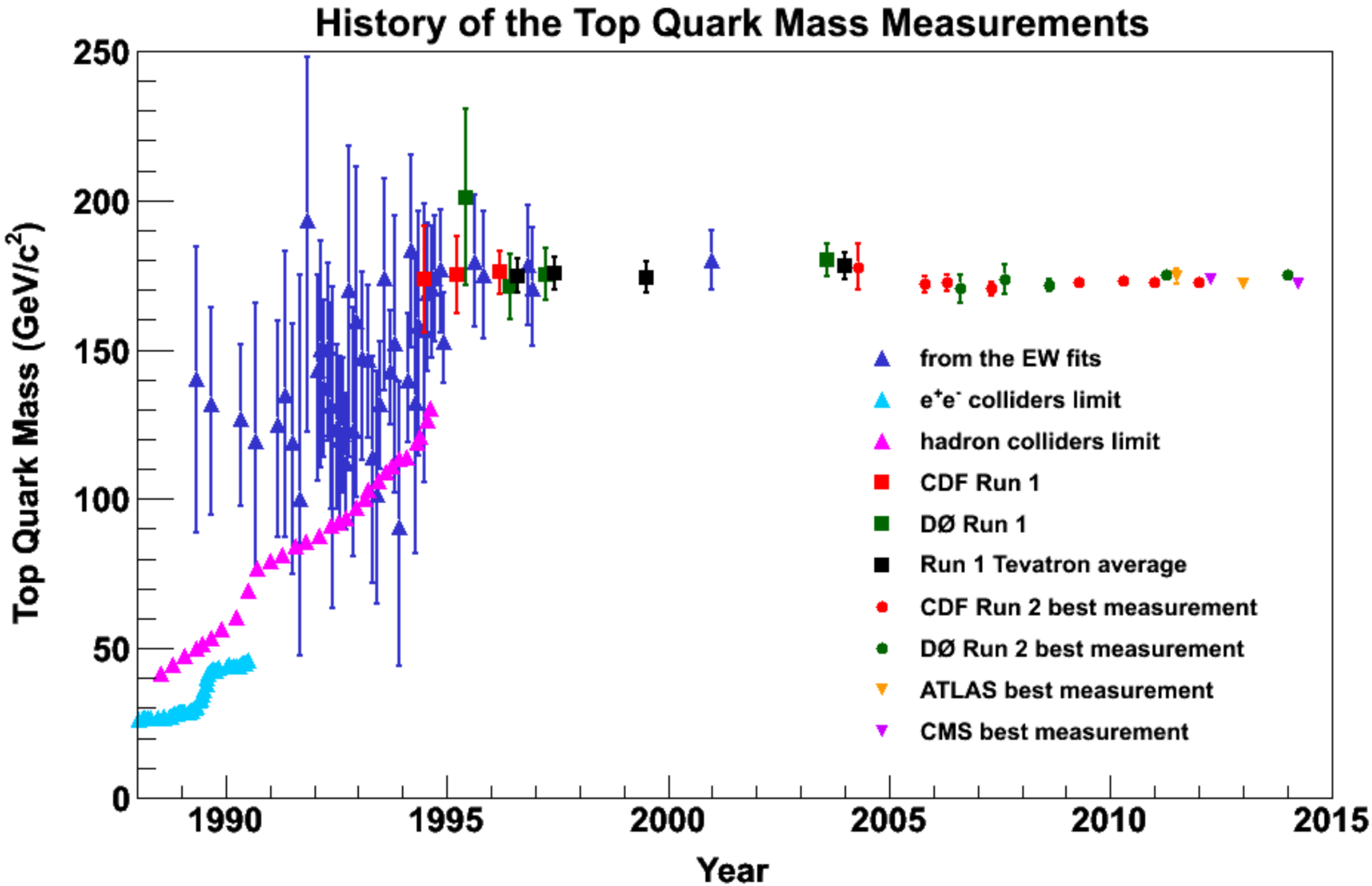
Next steps

Many new results in top/EW measurements from the Tevatron

- Diboson plus heavy flavor measurements
  - Improving precision in *WZ→ lν + cc/bb*
- Top qu ... s)
  - Uniqu
  - nations)
- Direct a
  - High p

- $\sin^2\theta_W$ and indirect measure of m_W (D0 muon channel + Legacy combinations)
  - World class precision
- Direct measures of m_W not forgotten ...

Innovation is not over!

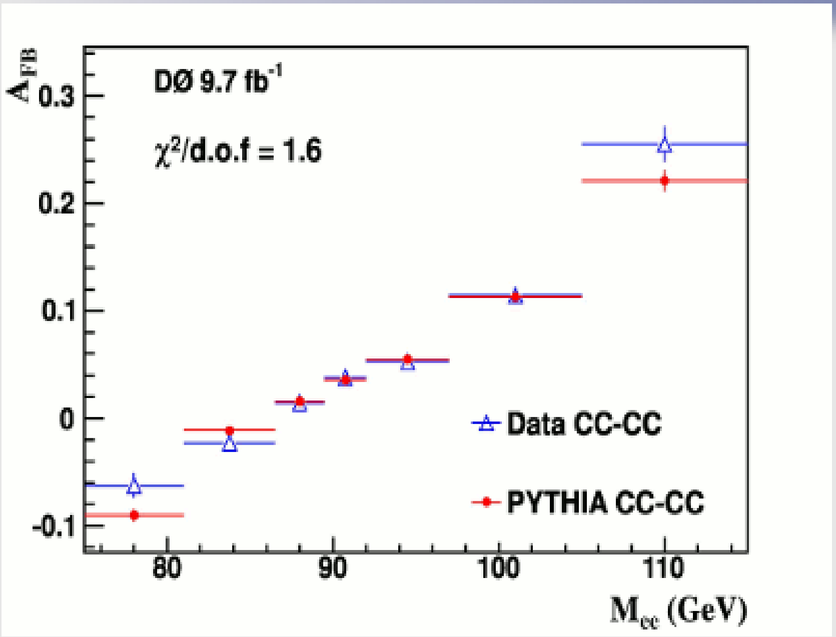


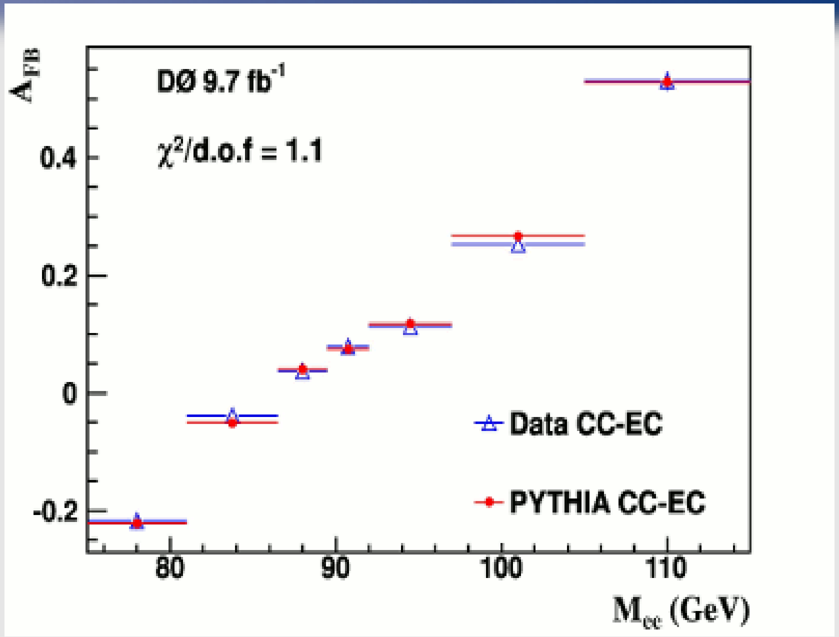
Many of these analysis techniques have been pioneered at Tevatron

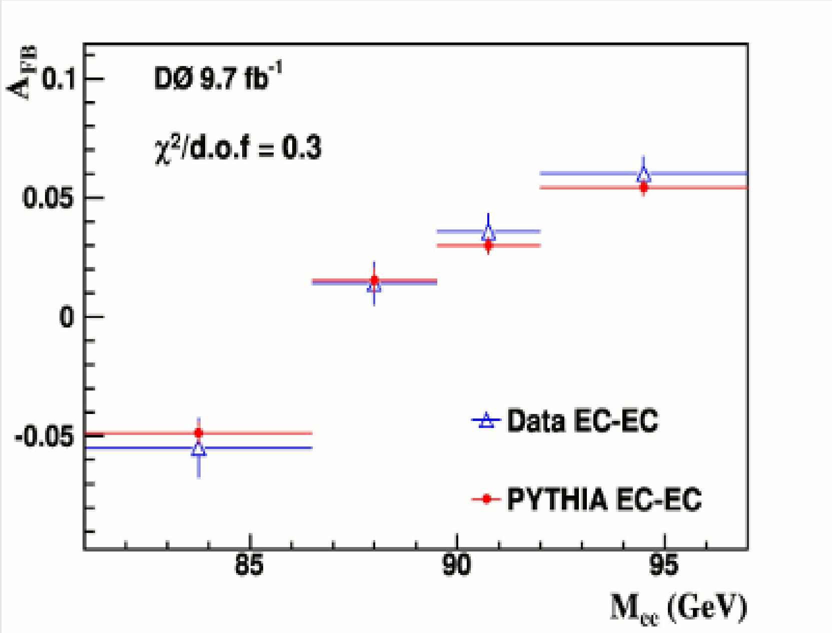
Effective leptonic weak mixing angle from Drell-Yan events

PRL 115, 041801 (2015)

A_{FB} measurements at D0 in ee channel







Inputs:
- A_{fb} measurement
- templates (PYTHIA)
  include detector simulation,
  varying values of $\sin^2\theta_{eff}^{lept}$

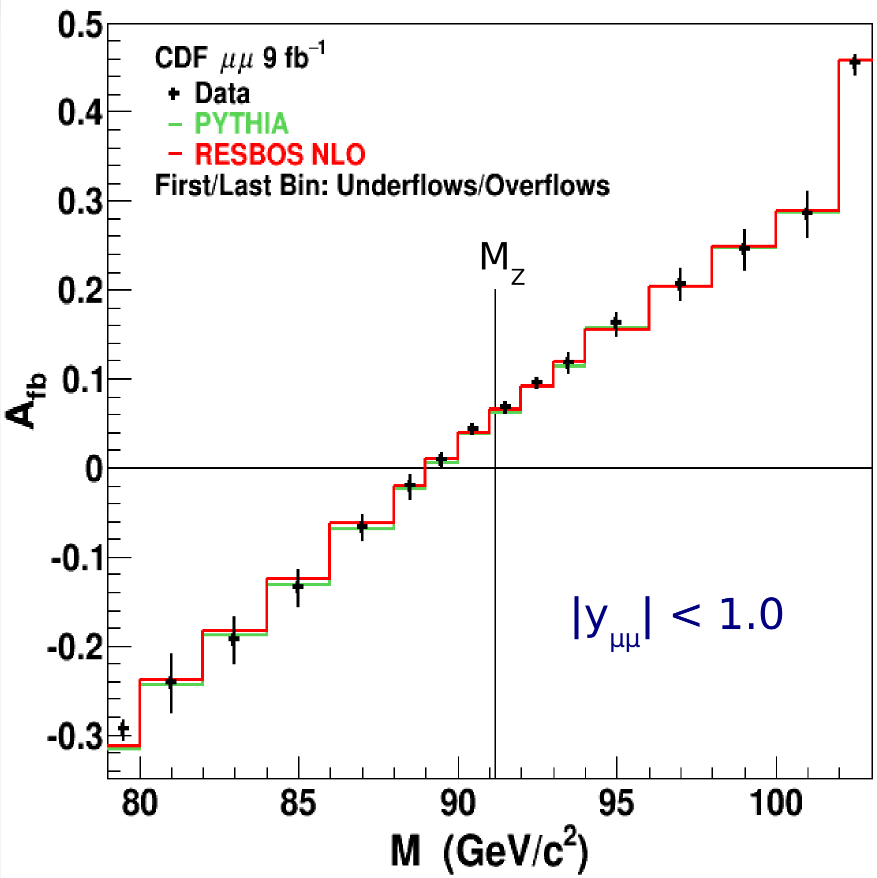
Fit A_{fb} to templates for best-fit $\sin^2\theta_{eff}^{lept}$

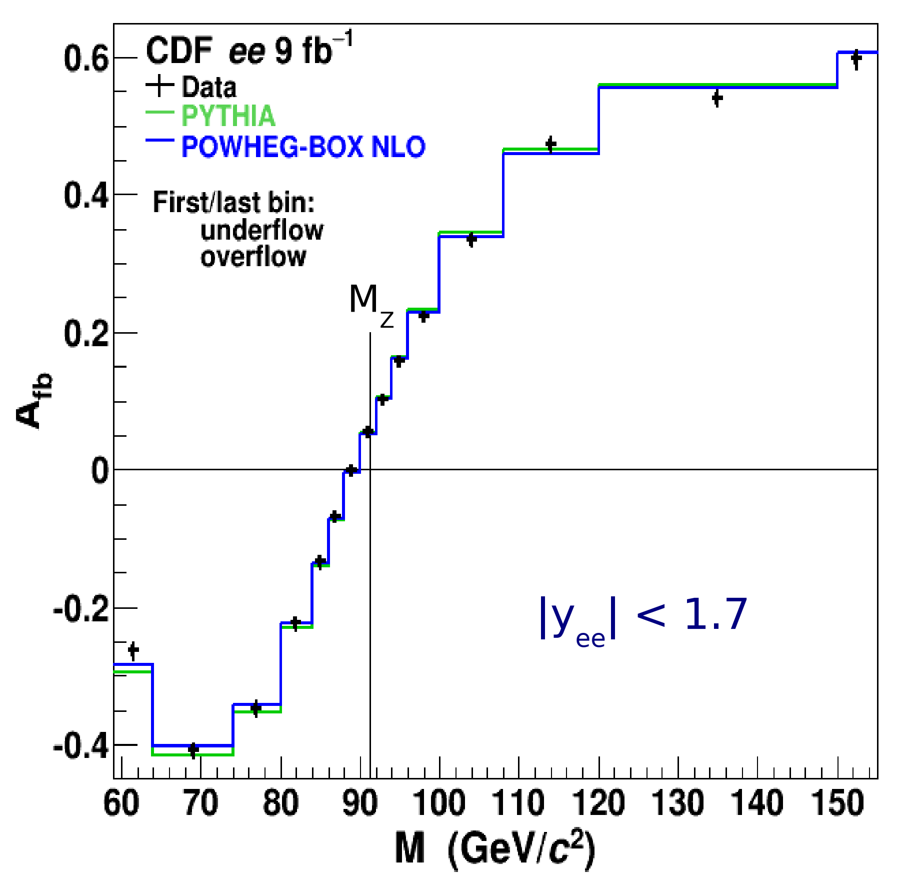
Muon analysis: in progress

A_{fb} measurements

PRD 89, 072005 (2014)

PRD 93, 112016 (2016)





Measurements corrected, templates are pure calculations
and for the specified kinematic range

RESBOS and POWHEG-BOX best-fit templates include EWK radiative corrections

Radiative correction treatments

D0 mixing angle results: improved

- PYTHIA template: single mixing angle and running α_{em}
- ZGrad+ResBos adjustment: improves accounting for differences of fermion-dependent effective mixing angles @ M_Z

CDF ZFITTER based results: improved even more

- Complex-valued form-factors ρ and κ for Born Z-couplings

$$g_v^f(\text{Born}) \rightarrow \sqrt{\rho_f}\, T_3^f(1 - 4|Q_f|\kappa_f \sin^2\theta_W)$$

$$g_A^f(\text{Born}) \rightarrow \sqrt{\rho_f}\, T_3^f$$

ρ_f / κ_f: functions of fermion type, M_{ll}^2, $\sin^2\theta_W$

1-4% corrections

- Photon-propagator form factor (real part aka running α_{em})