Top and electroweak measurements at the Tevatron

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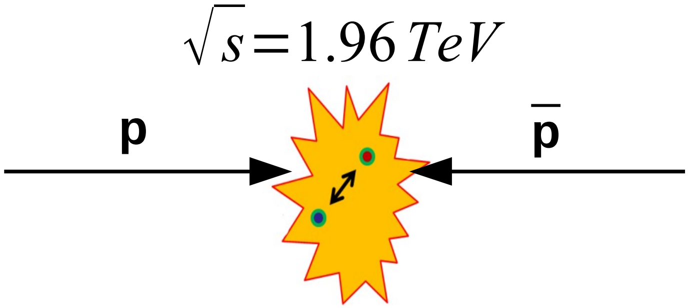
On behalf of CDF and D0 collaborations

La Thuile 2016, March 6-12

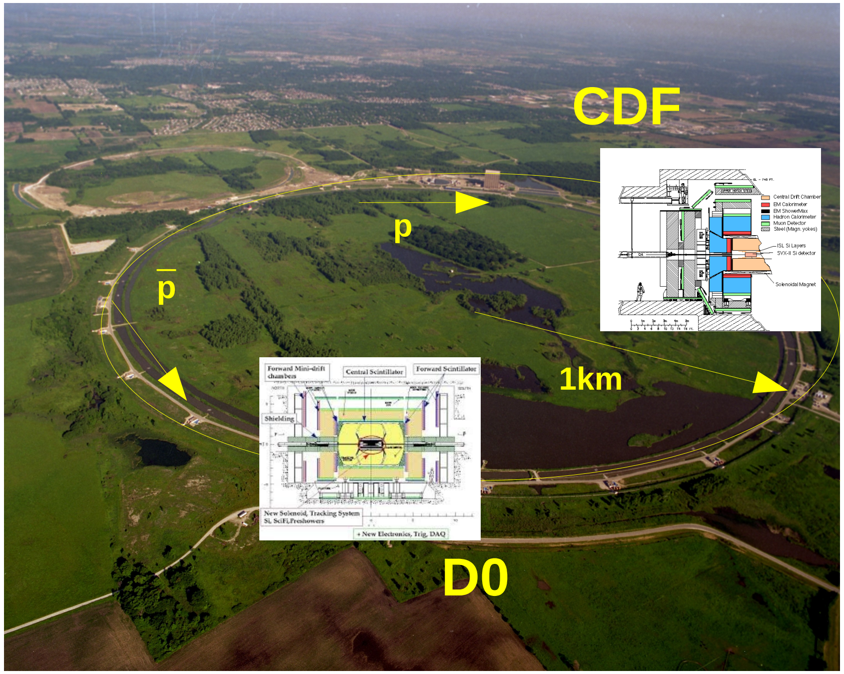
Outline

→ Top quark measurements
  → top quark mass
    - Tevatron & World combinations
    - recent D0 measurement
    - pole mass from x-sec

→ Electroweak measurements
  → WW/WZ production
  → weak mixing angle
  → W boson mass (indirect)



Tevatron



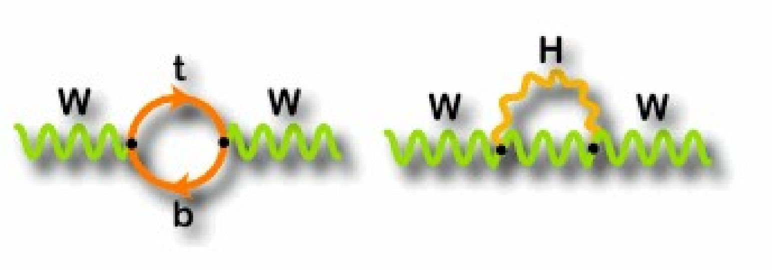
Top quark production at Tevatron (see K.Bloom's talk)

Top quark mass

Why to measure it?

→ Its Yukawa coupling is ~1 => may play a special role in EW symmetry breaking

→ linked to *W* and *H* boson masses through radiative corrections
=> precise measurement provides a test of EW sector of the SM



→ linked to *H* boson mass and stability of SM vacuum (and of Universe)
=> precise measurement provides information on whether our universe resides in a stable or metastable region

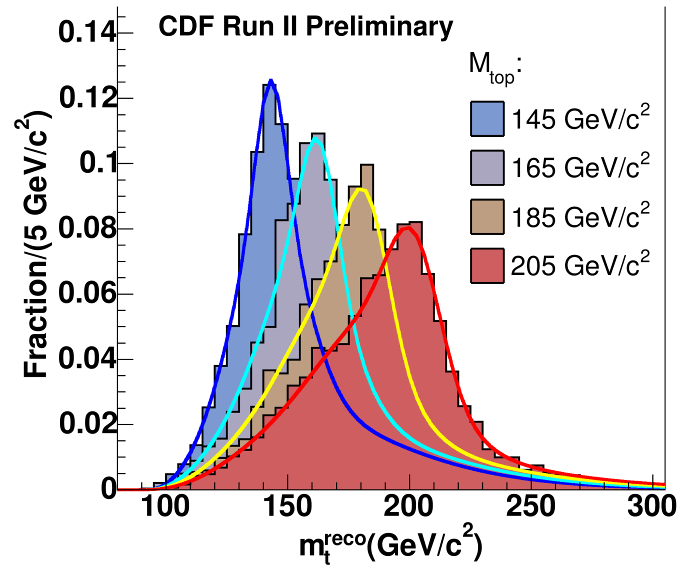
→ short lifetime => precise study of pure QCD and EW effects.

Top quark mass

How do we measure it? → Several methods to choose:

Template method:

- → use **variable sensitive to top mass** (e.g. m_t^{reco} from decay products)
- → constrain JES (by another variable)
- → likelihood fit to various templates
- → fast, but worse stat. Uncertainties



Matrix element method:

- → evaluate **event-by-event probability** based on the full event kinematics
- → signal probability:

$$P_{t\bar{t}} = \frac{1}{\sigma_{t\bar{t}}(m_t)} \sum_{j-p} \int \sum_{flavors} dq_1 \, dq_2 \underbrace{\frac{d\sigma(p\bar{p} \rightarrow t\bar{t} \rightarrow y)}{dy}}_{\text{Matrix element}} \cdot \underbrace{f(q_1) f(q_2)}_{\text{PDFs}} \cdot \underbrace{W(x;y)}_{\text{resolution}} \cdot dy$$

- → mass extracted from global likelihood

Top mass – world combination

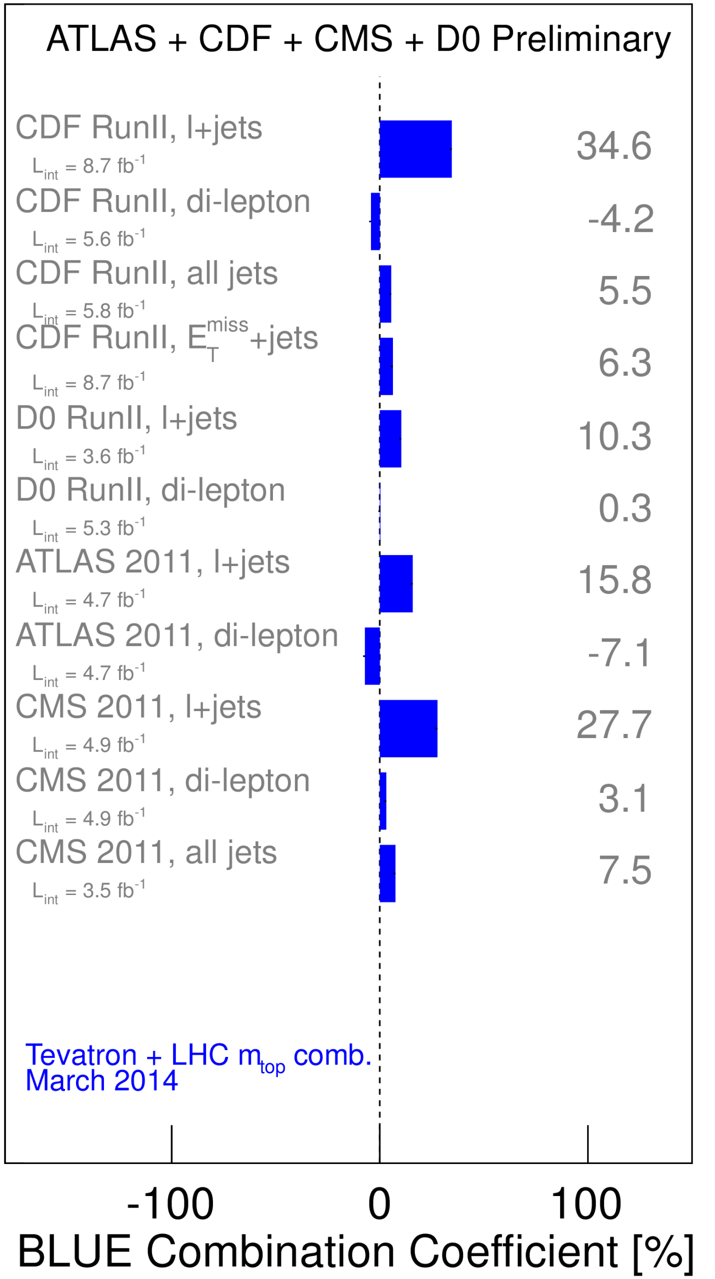
- Using analytic BLUE method
  - determines the weights, which are used in a linear combination of the inputs
  - minimize total uncertainty

$$M_t = 173.34 \pm 0.76\ GeV$$

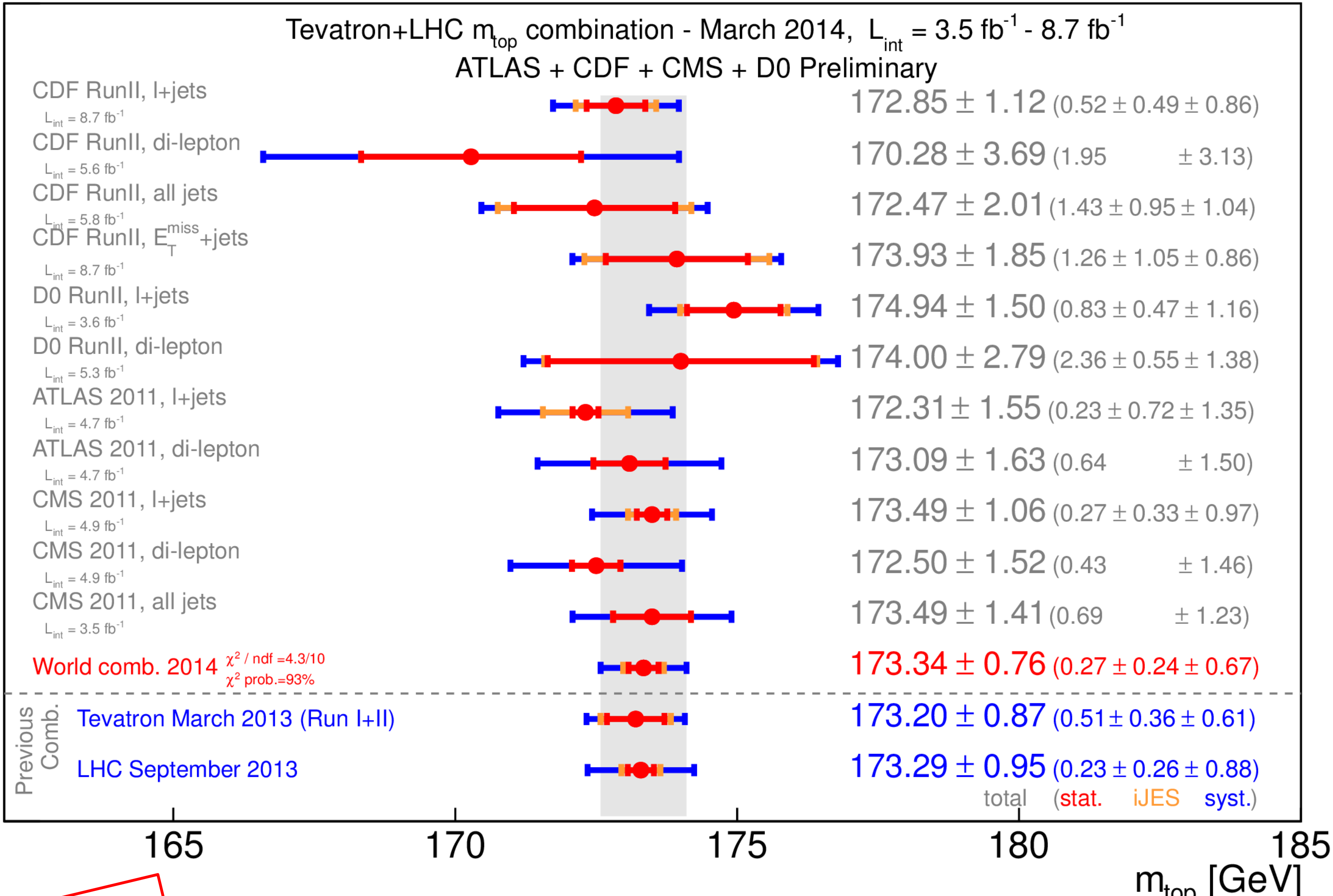
$$\delta m_t / m_t = 0.44\%$$

$$\chi^2 = 4.3/10\ NDF\ \ (93\%)$$

arXiv:1403.4427 [hep-ex]



Top mass – world combination



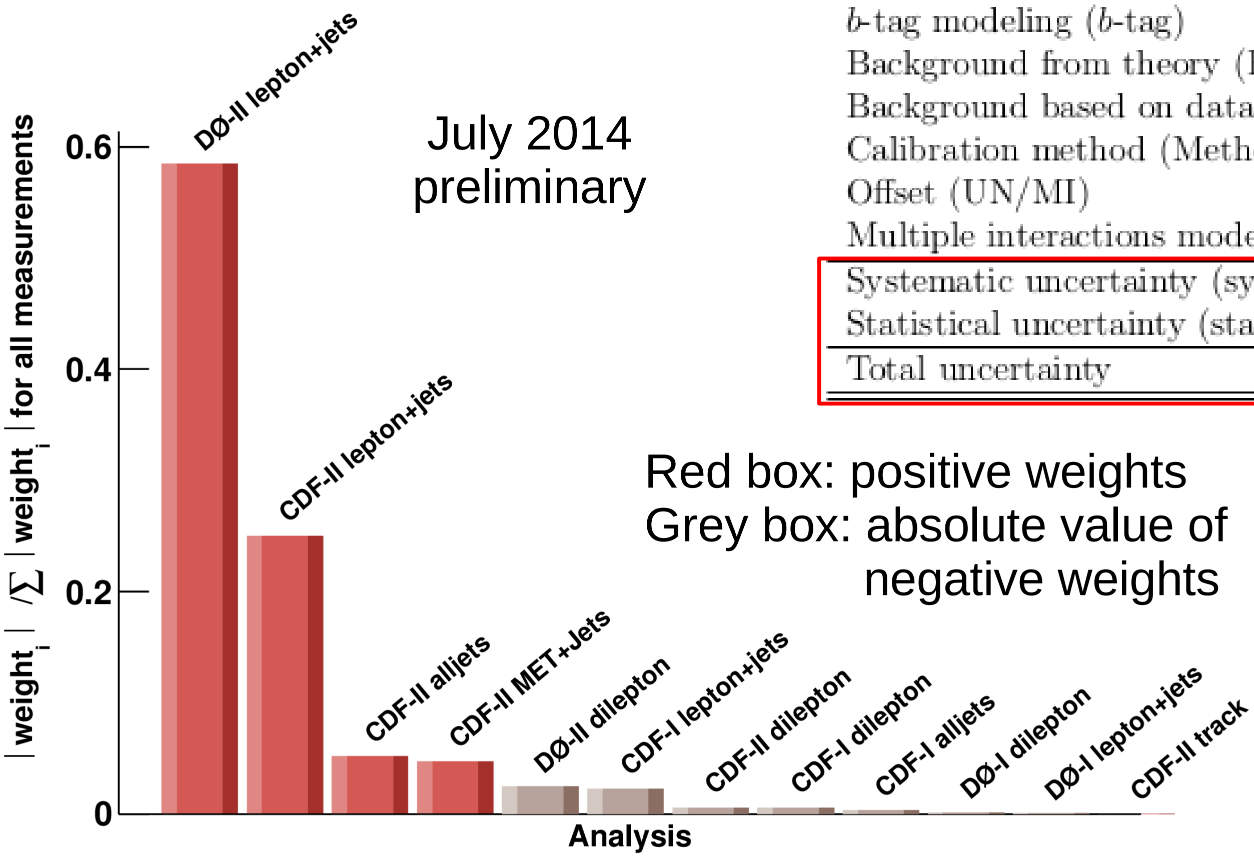
after combination

arXiv:1403.4427 [hep-ex]

Top mass – Tevatron combination

- BLUE method used
- Includes Run I results
- 3 measurements updated after world combination:
  D0 l+jets,
  CDF dilepton & all-jets

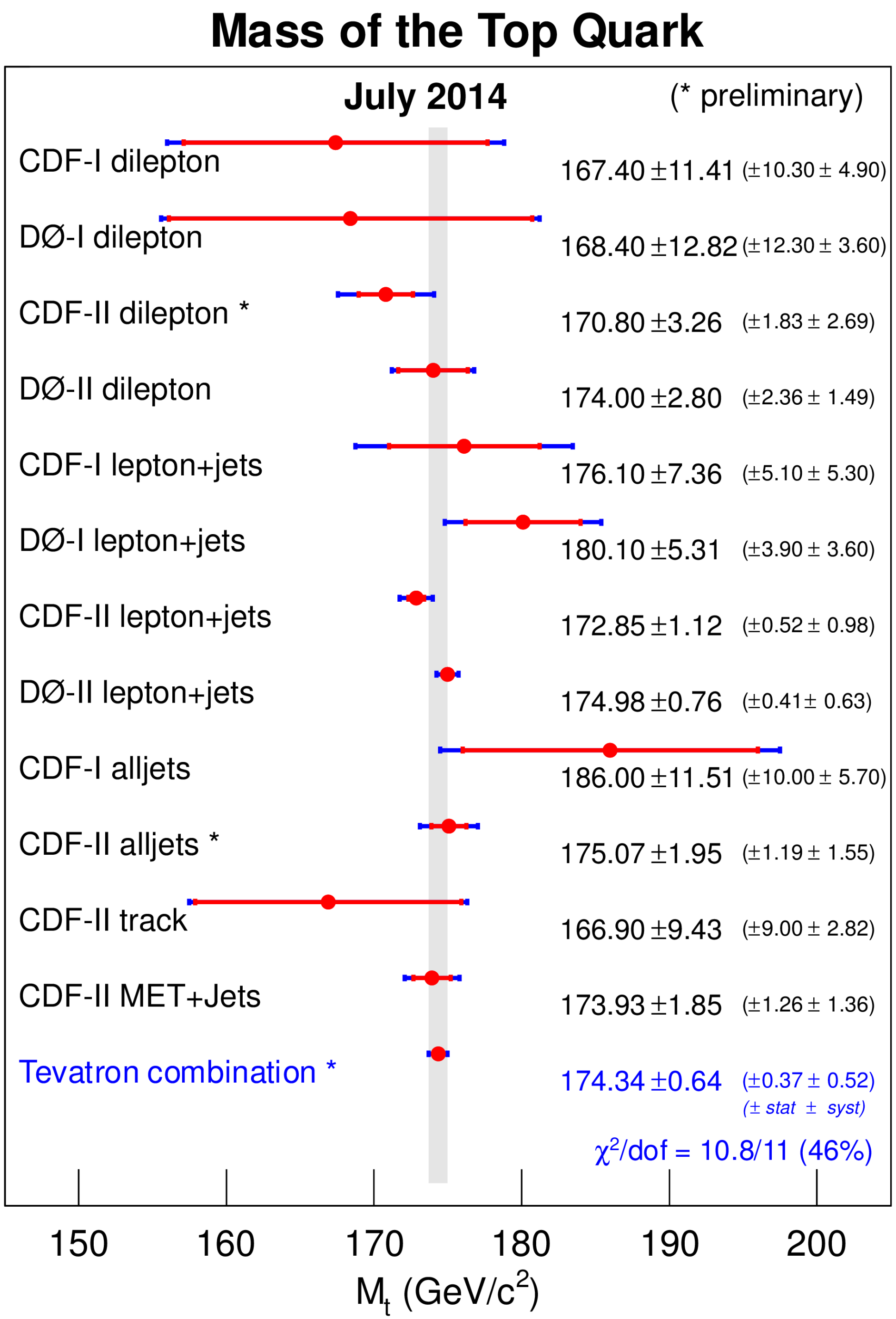
	Tevatron combined values (GeV/c^2)
M_t	174.34
In situ light-jet calibration (iJES)	0.31
Response to $b/q/g$ jets (aJES)	0.10
Model for b jets (bJES)	0.10
Out-of-cone correction (cJES)	0.02
Light-jet response (1) (rJES)	0.05
Light-jet response (2) (dJES)	0.13
Lepton modeling (LepPt)	0.07
Signal modeling (Signal)	0.34
Jet modeling (DetMod)	0.03
b-tag modeling (b-tag)	0.07
Background from theory (BGMC)	0.04
Background based on data (BGData)	0.08
Calibration method (Method)	0.07
Offset (UN/MI)	0.00
Multiple interactions model (MHI)	0.06
Systematic uncertainty (syst)	0.52
Statistical uncertainty (stat)	0.37
Total uncertainty	0.64



Red box: positive weights
Grey box: absolute value of negative weights

arXiv: 1407.2682 [hep-ex]

Top mass – Tevatron combination



$$M_t = 174.34 \pm 0.64\ GeV$$

$$\delta m_t / m_t = 0.37\%$$

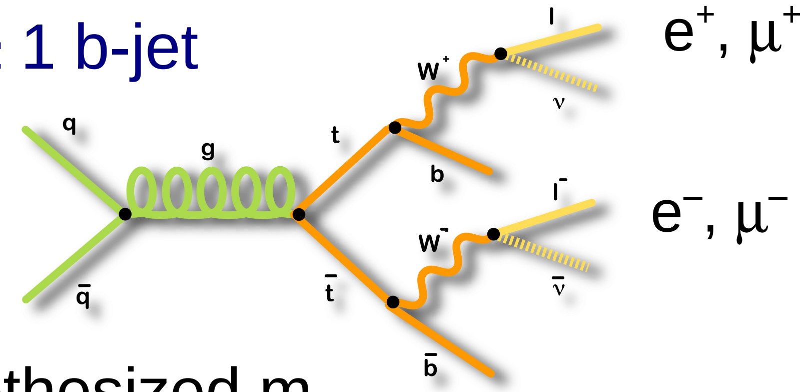
$$\chi^2 = 10.8/11\ NDF\ \ (46\%)$$

arXiv:1407.2682 [hep-ex]

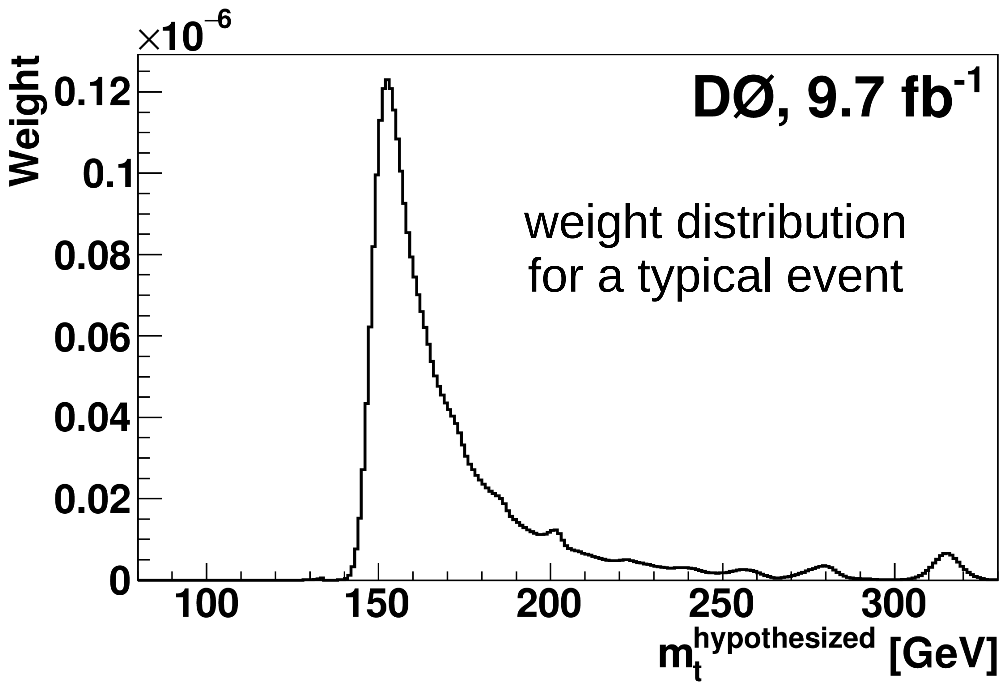
★ UPDATED after combination

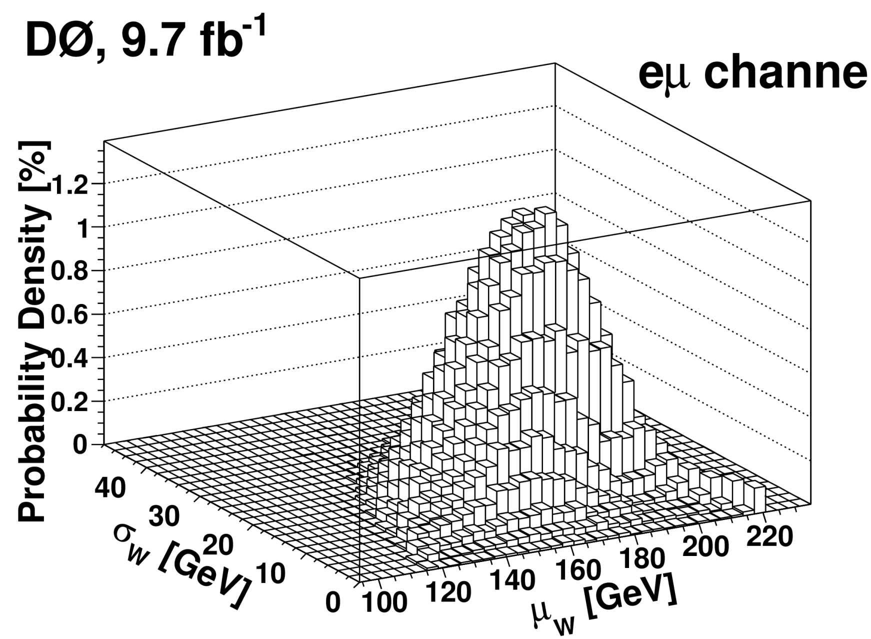
Top quark mass in dileptons

→ Select events with 2 leptons, ≥ 2 jets, ≥ 1 b-jet
→ MET cut in ee, μμ events
→ H_T cut in eμ events



→ "**neutrino weighting**" for various hypothesized m_t
→ scan neutrino rapidities, compute weight w by comparing neutrino momenta with measured MET
→ extract mean and σ from the distribution $w(m_t)$

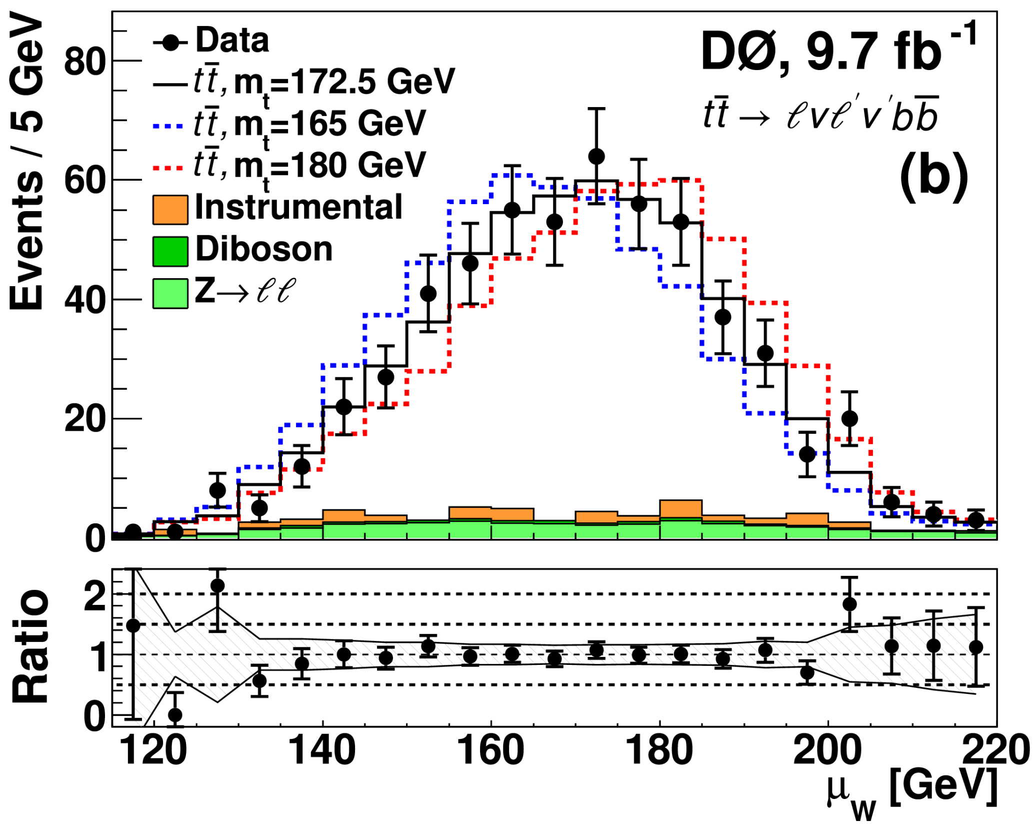




Top quark mass in dileptons

→ Parameters of the reconstruction optimized to minimize the expected statistical uncertainty

→ Maximum likelihood fit to the templates



Phys. Lett. B 752, 18 (2016)

→ **most precise dilepton meas. at the Tevatron!**

→ main systs: JES and higher order effects

$$m_t = 173.32 \pm 1.36(stat) \pm 0.85(syst)\ GeV$$

$$\delta m_t / m_t = 0.93\%$$

Top quark pole mass

→ Results presented so far measures **mass** (**m_t^{MC}**) used as input in MC generator ≠ **m_t^{pole}** (but must be close ~1 GeV)

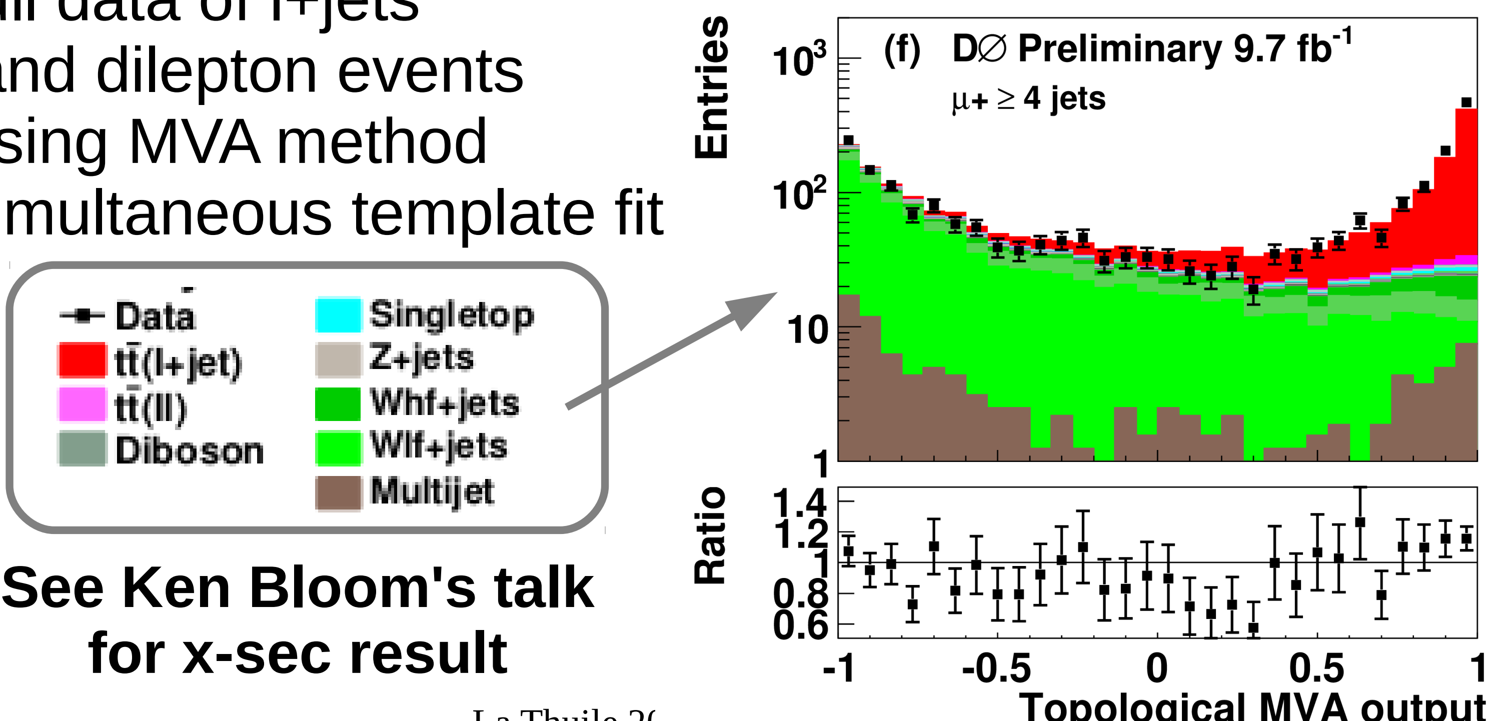
→ can not be used directly for precise NLO / NNLO theoretical predictions

→ **m_t^{pole}** can be extracted from inclusive cross-section meas.

→ full data of l+jets and dilepton events

→ using MVA method

→ simultaneous template fit

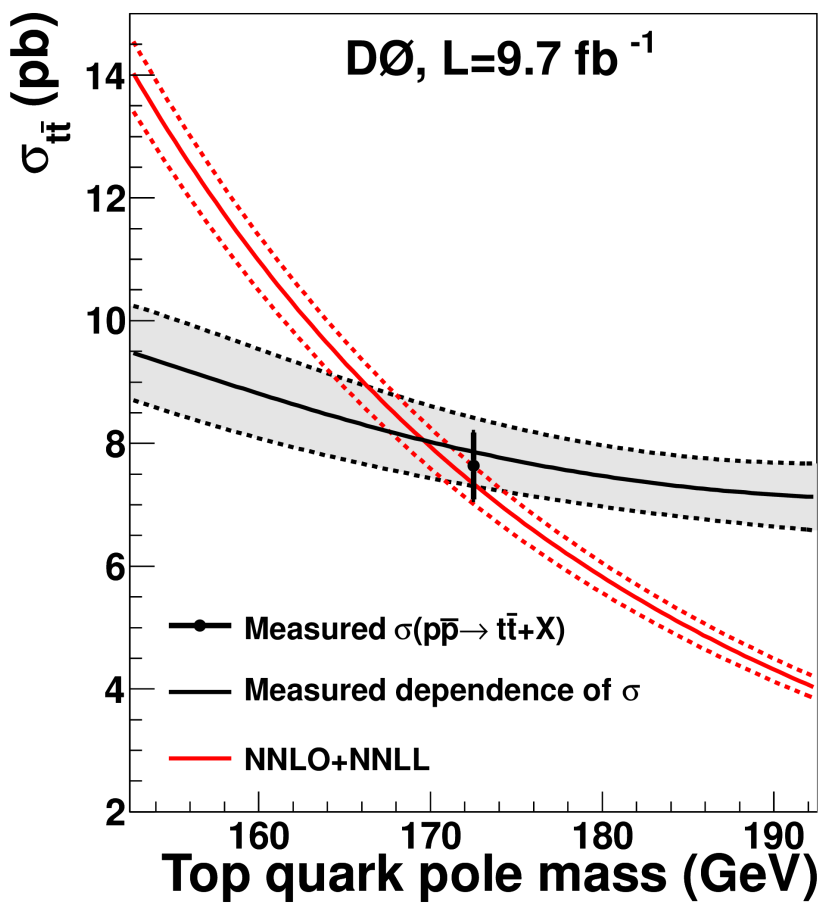


See Ken Bloom's talk for x-sec result

Top quark pole mass

→ m_t^{pole} extraction:

- → measure cross section in different mass points
- → parametrize distribution with cubic fit
- → use normalized joint likelihood function



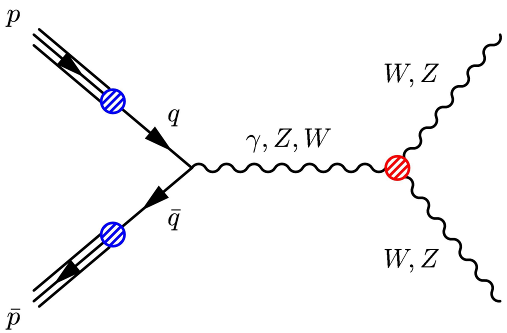
$$m_t = 169.5^{+3.3}_{-3.4}\ GeV$$

$$\delta m_t / m_t = 1.9\%$$

D0 Note 6453-CONF

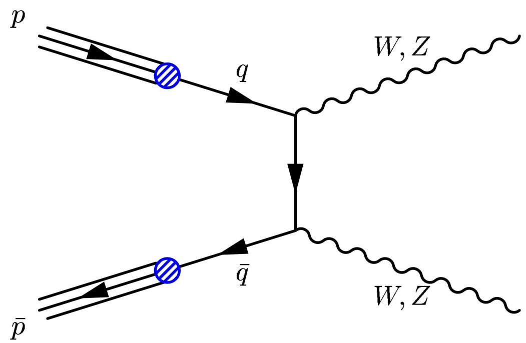
→ **most precise** top pole mass measurement **at Tevatron!**

Electroweak measurements



→ WW and WZ production

→ directly **probes** triple Gauge **coupling terms of the SM**



→ CDF uses full data to select events:
1 lepton, MET, 2 high E_T jets, ≥ 1 HF-tag

$W \rightarrow l\nu$ and e.g. $W^+ \rightarrow c\bar{s}$ (or $Z \rightarrow b\bar{b}, c\bar{c}$)

→ HF-tag – presence of secondary vertex

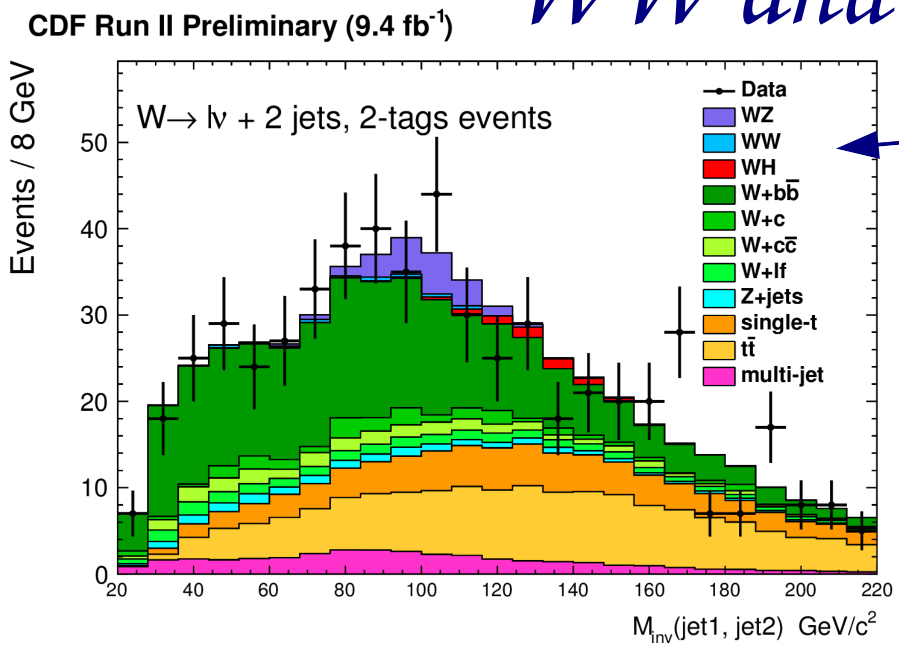
→ Divide sample by # of tags

→ using NN flavour separator (b or c) + dijet inv. mass M_{jj}
to distinguish WW and WZ production

→ 2D distribution is used to signal-background discrimination in events with 1-tag (in 2-tag events only M_{jj} is used)

WW and WZ production

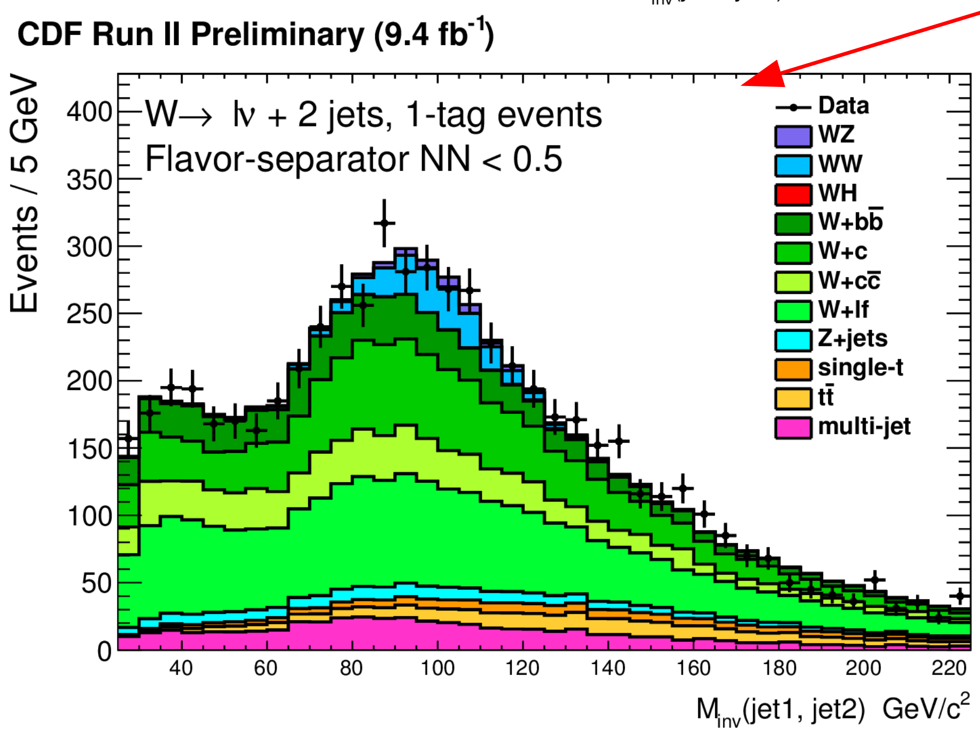
2-tag sample

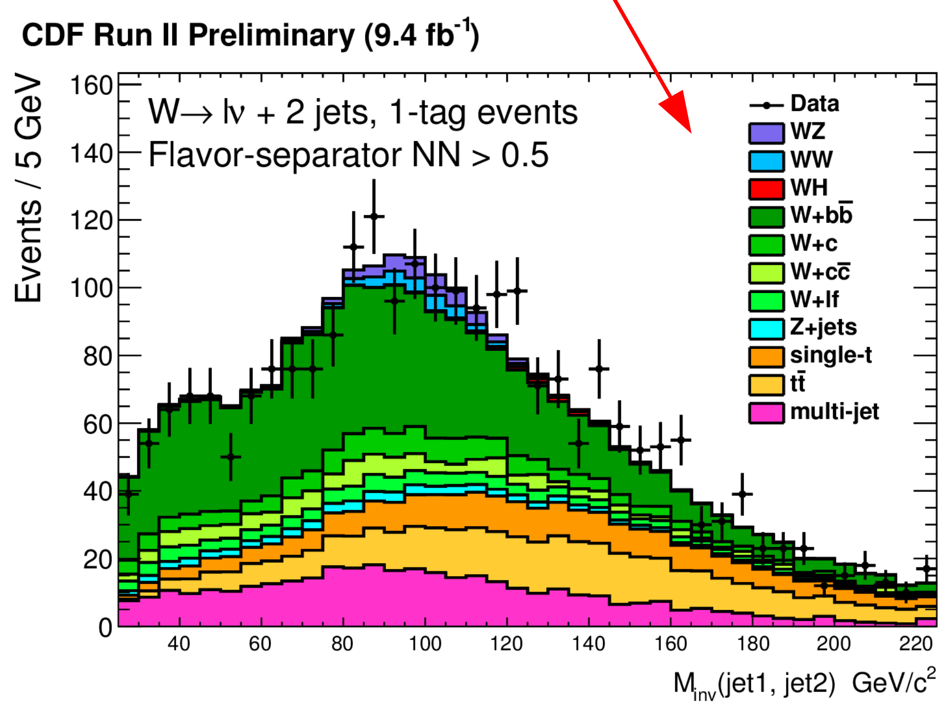


NN flavour separator
1 ~ b-tag
~ –0.5 ~ c-tag
–1 ~ ligt flavour

CDF note 11157

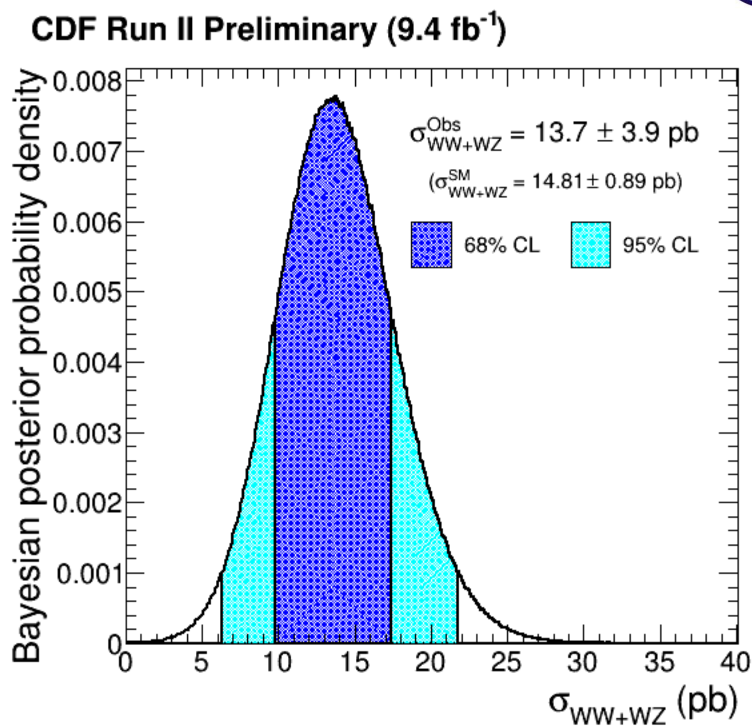
1-tag sample





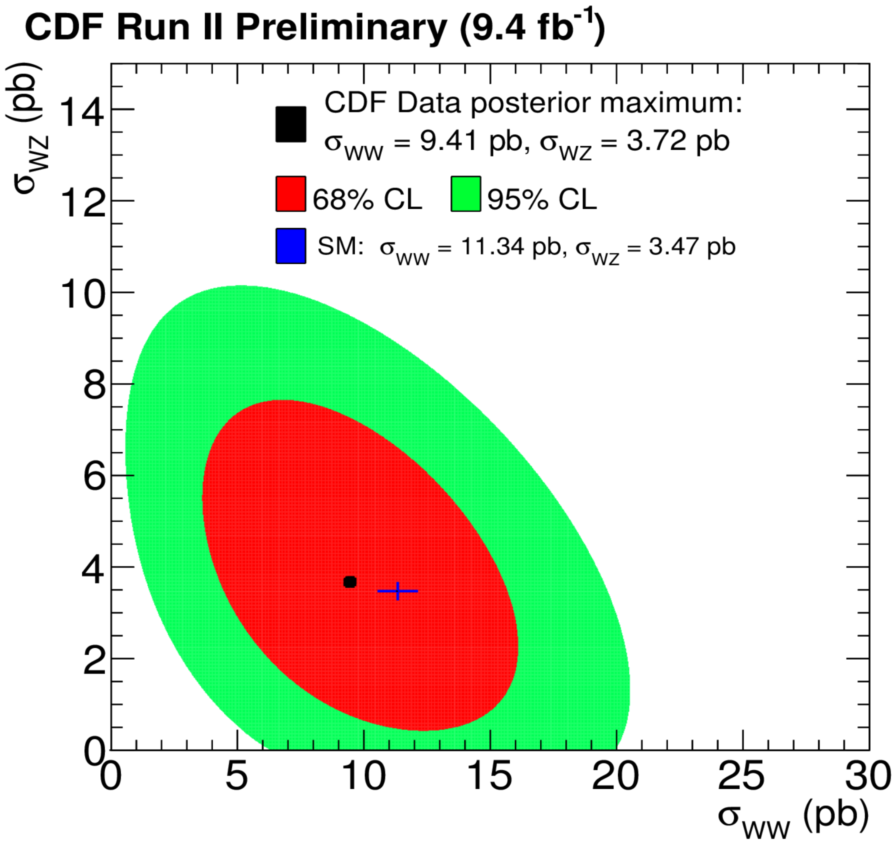
WW and WZ production

→ **Bayesian statistical analysis** used to extract the results
→ systematics – nuisance parameters
→ significance extracted by PEs



$$\sigma^{Obs}_{WW+WZ} = (13.7 \pm 3.9)\ pb$$
significance: $3.69\,\sigma$

CDF note 11157



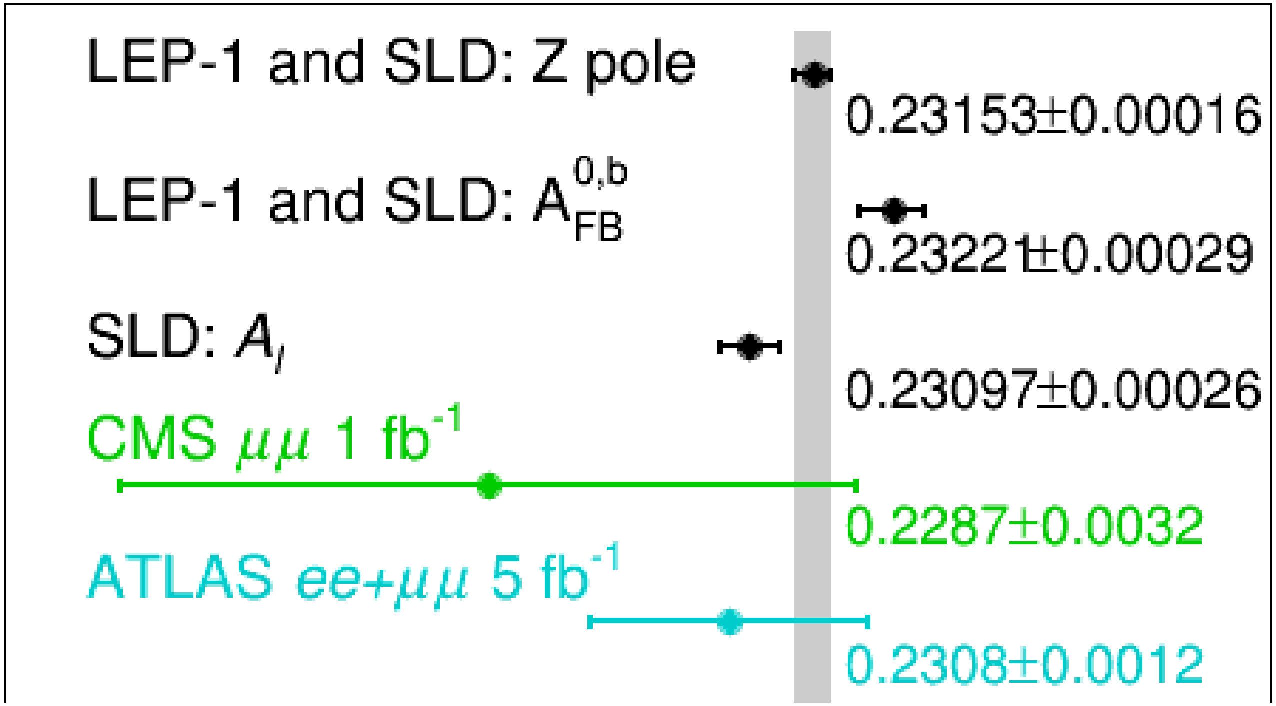
$$\sigma^{Obs}_{WW} = (9.4 \pm 4.2)\ pb \quad \text{signif.: } 2.87\,\sigma$$
$$\sigma^{Obs}_{WZ} = (3.7^{+2.5}_{-2.2})\ pb \quad \text{signif.: } 2.12\,\sigma$$

Consistent with SM!

and D0 measurement
(PRL118 181803, (2012))

Electroweak measurements

→ *electroweak mixing angle – why to measure it?*

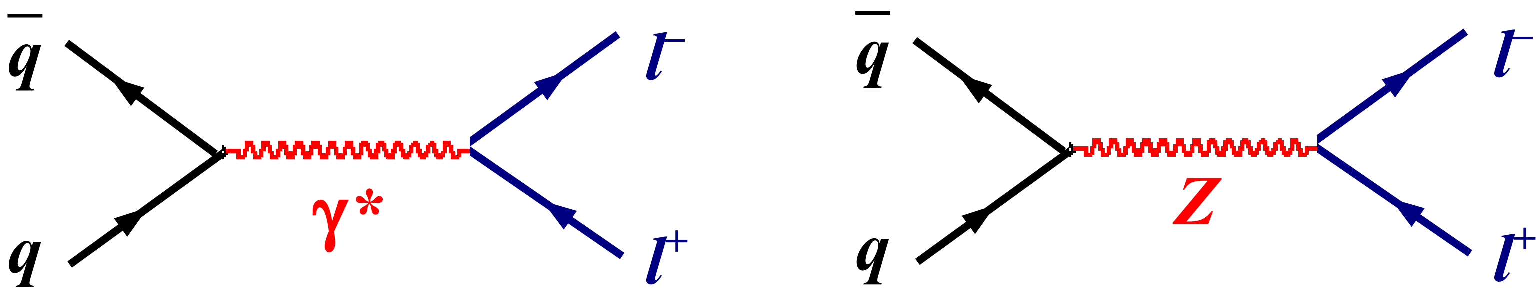


→ Discrepancy between LEP and SLD measurements **~3.2 σ**

→ LHC Run I measurements – big uncertainties

Electroweak measurements

→ electroweak mixing angle – from Drell-Yan lepton pairs



Coupling to fermion: $g_V^f = Q_f$, $g_A^f = 0$ $\qquad$ $g_V^f = I_3 - 2Q_f \sin^2\theta_W$, $g_A^f = I_3$

→ the couplings affects lepton angular distribution => **production A_{FB}**

→ two sources:

→ $\gamma - Z$ interference (no dependence on $\sin^2\theta_W$)

→ Z self-interference – product of g_V^f from lepton and quark vertices

\- → related to $\sin^2\theta_W$

→ I_3, $\sin^2\theta_W$ **couplings** strength **altered by weak radiation corrections**

→ multiplicative factor of a few %

→ effective $\sin^2\theta_W$ at lepton vertex → $\sin^2\theta_{eff}^{lept}$

Electroweak measuremets

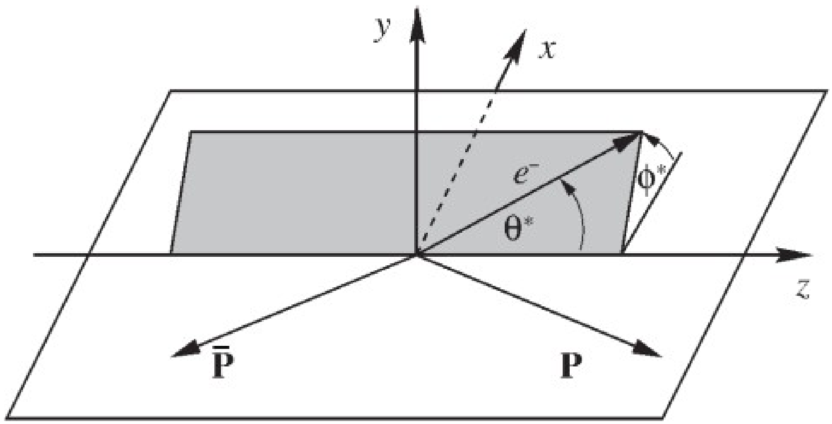
→ *forward-backward asymmetry*

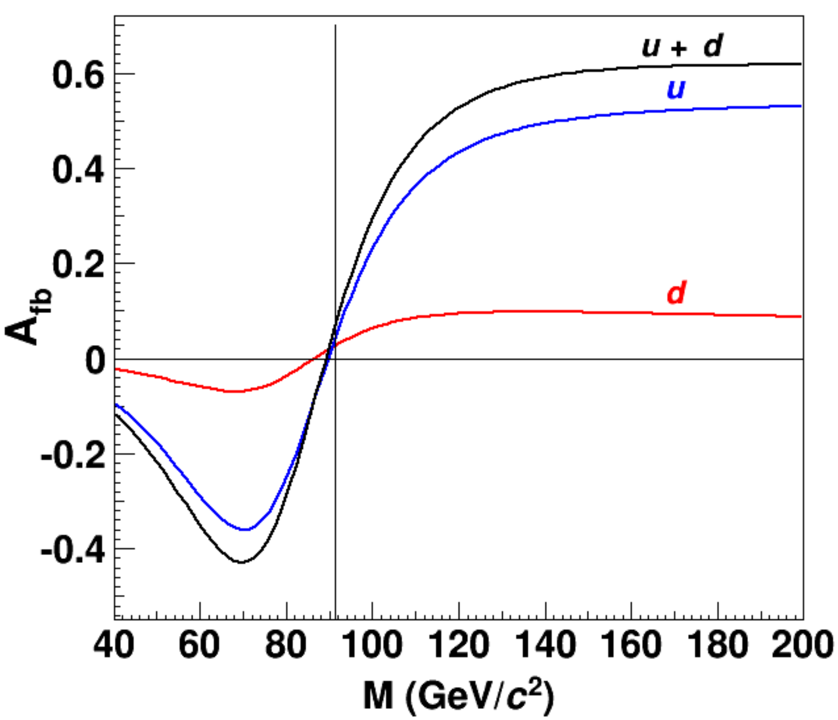
→ lepton angular distribution is measured in the **Collins-Soper rest frame** of the boson.

→ $\boldsymbol{\theta^*}$ = polar angle of the l^- – relative to the direction of incoming quark

$$A_{FB} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$\sigma^+ = \sigma(\cos\theta^* > 0)$$
$$\sigma^- = \sigma(\cos\theta^* < 0)$$





Typical behavior of A_{FB}

M – lepton pair invariant mass

u+d – total asymmetry

Intercepts at $M=M_Z$

→ related to $\sin^2\theta_W$

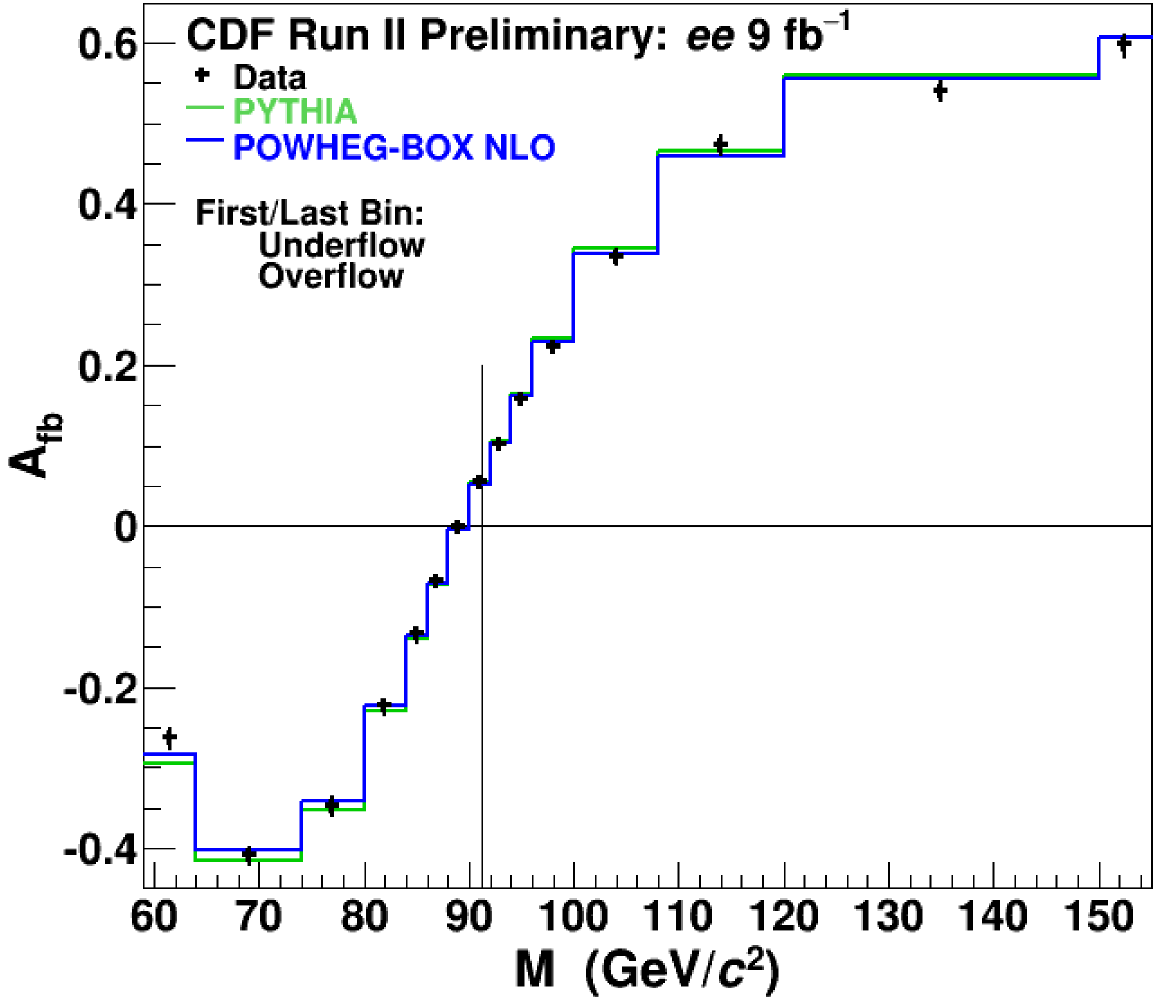
Electroweak mixing angle

→ measurement using $Z \rightarrow e^{+}e^{-}$ data – full Run II sample

→ measure A_{FB} in 15 bins of lepton pair invariant mass M

→ Perform full corrections to data and simulation

  → resolution unfolding, acceptance, detector non-uniformity

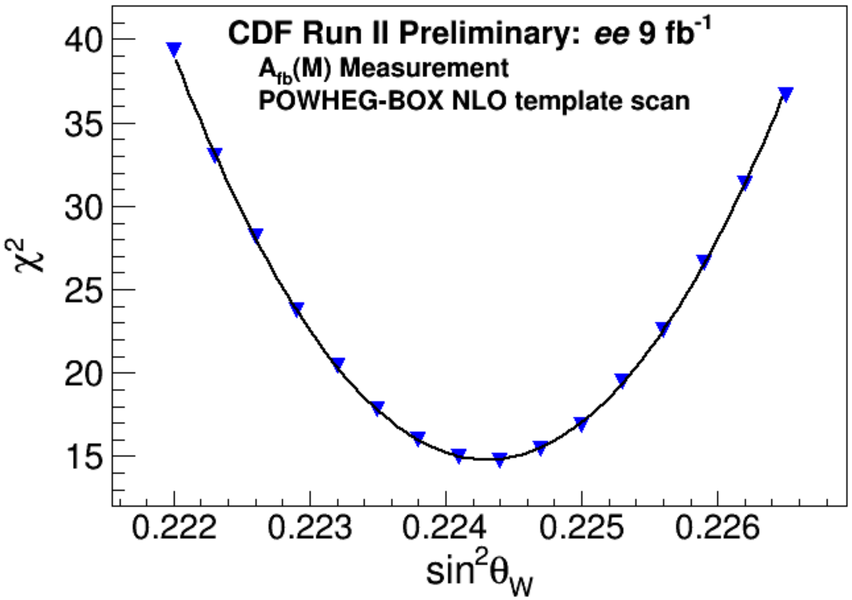


Electroweak mixing angle

→ *extracting of $\sin^2\theta_W$*

→ Produce Monte Carlo A_{FB} (M, $\sin^2\theta_W$) templates calculated using different values of $\sin^2\theta_W$

→ Extract $\sin^2\theta^{lept}_{eff}$ and $\sin^2\theta_W$ by evaluating χ^2 for templates



Systematics:

Source	$\sin^2\theta^{\text{lept}}_{\text{eff}}$	$\sin^2\theta_W$
Energy scale	±0.00002	±0.00002
Backgrounds	±0.00003	±0.00003
QCD scales	±0.00002	±0.00002
NNPDF-3.0 PDF	±0.00016	±0.00015
QCD EBA	±0.00007	±0.00007

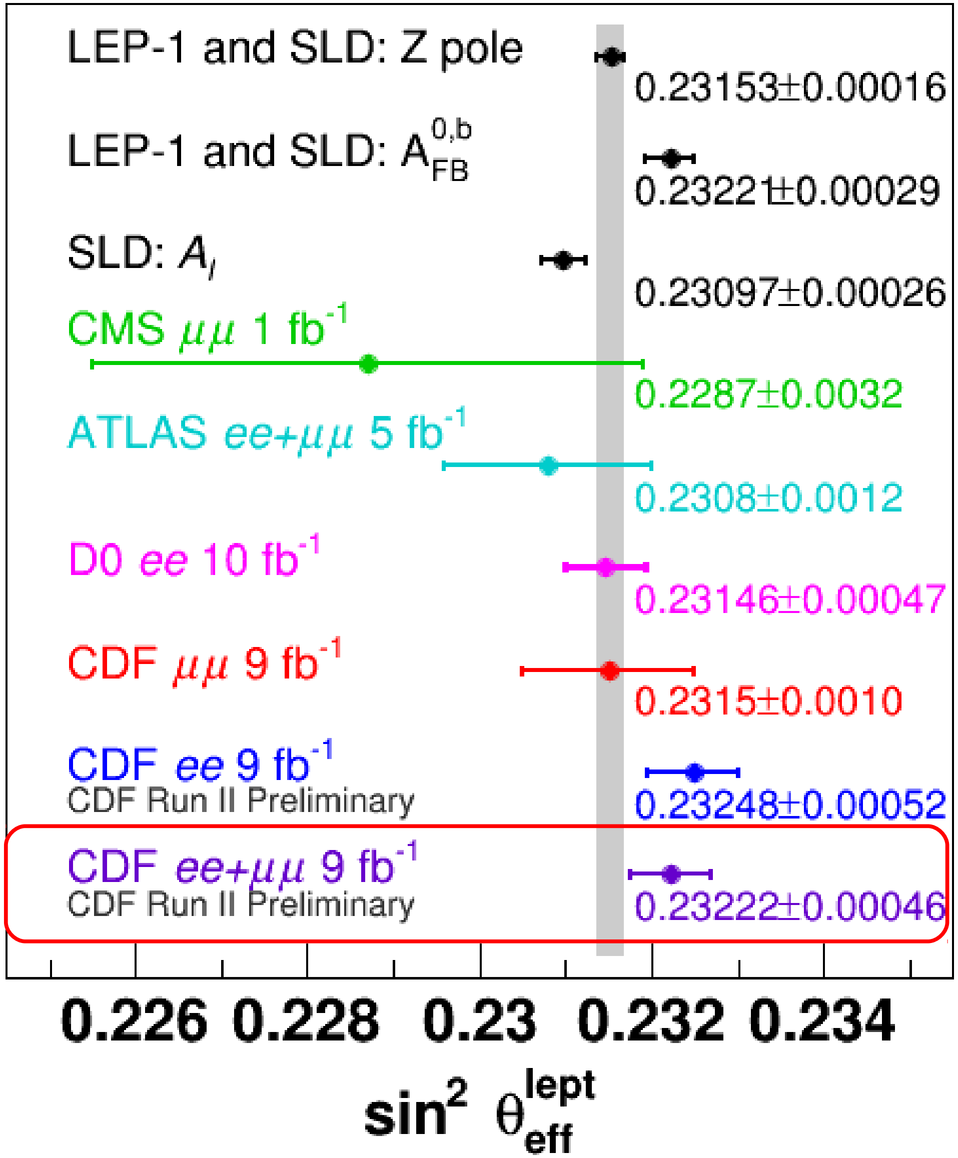
CDF note 11178

$$\sin^2\theta^{lept}_{eff} = 0.23222 \pm 0.00042(stat) \pm 0.00018(syst)$$
$$\sin^2\theta_W = 0.22401 \pm 0.00041(stat) \pm 0.00017(syst)$$

Electroweak mixing angle

Combination of CDF ($Z \to ee$) and CDF ($Z \to \mu\mu$)

→ both measurements are jointly used in fits:



$$\sin^2\theta_{eff}^{lept} = 0.23222 \pm 0.00046$$
$$\sin^2\theta_W = 0.22428 \pm 0.00050$$

CDF note 11178

Most precise from hadron colliders!

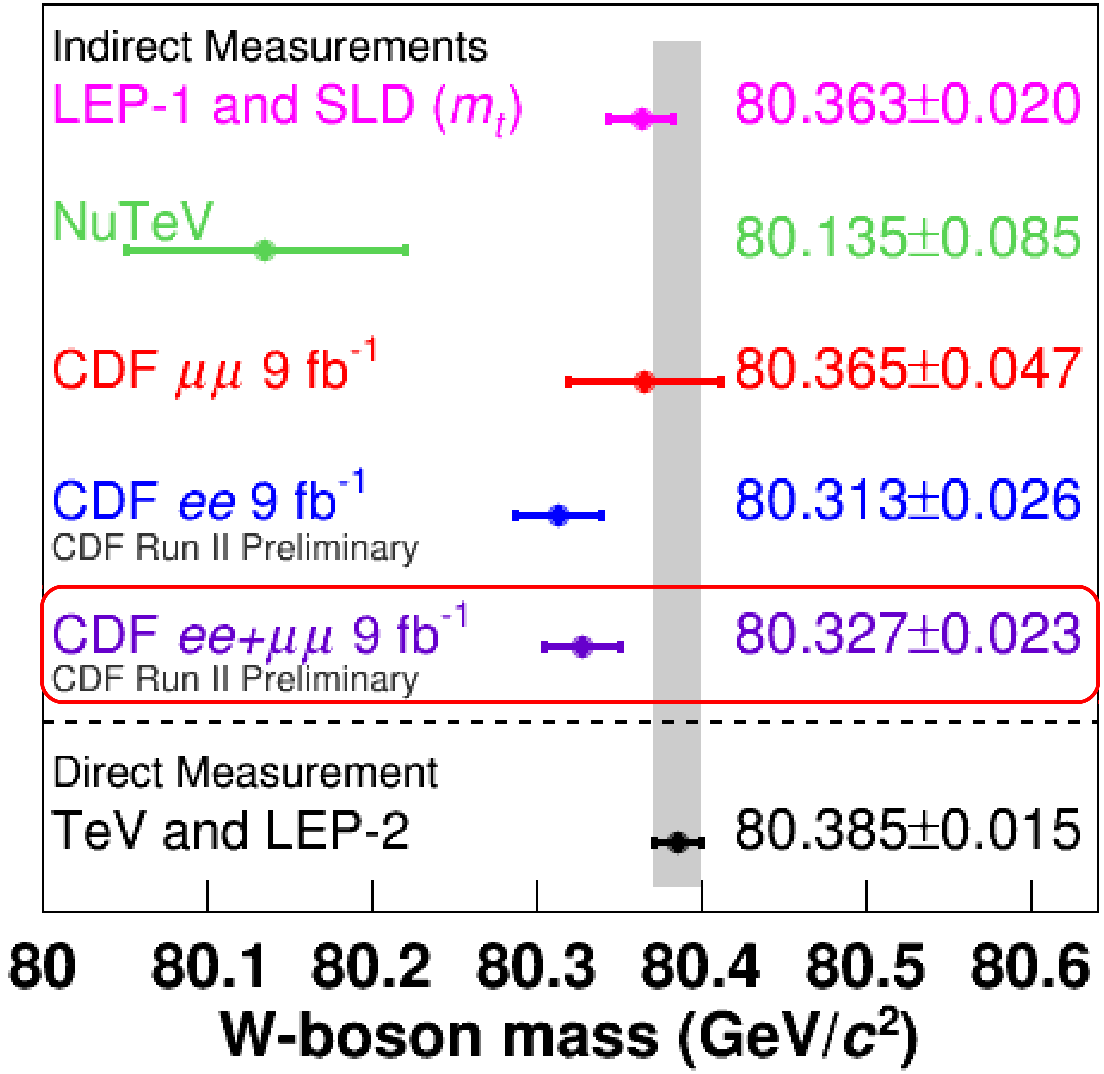
S. Ferry's talk - LHCb result:

$$\sin^2\theta_{eff}^{lept} = 0.2314 \pm 0.0011$$

Indirect measurement of W mass

→ using the measurement of weak mixing angle

CDF note 11178



In all orders of perturbation theory:

$$\sin^2\theta_W = 1 - M_W^2 / M_Z^2$$

on-shell particle masses

Conclusions

→ Tevatron finalizes **measurements with full data se**t

→ Many **top mass** measurements **updated since World combination**
  → **increased precision** of Tevatron combination
    → more optimized analysis
    → improvements in treatment of systematics

→ **New WW+WZ production** measurement in semileptonic channel

→ Updated **weak mixing angle** measurement
    → **more precise than LHC** measurements!

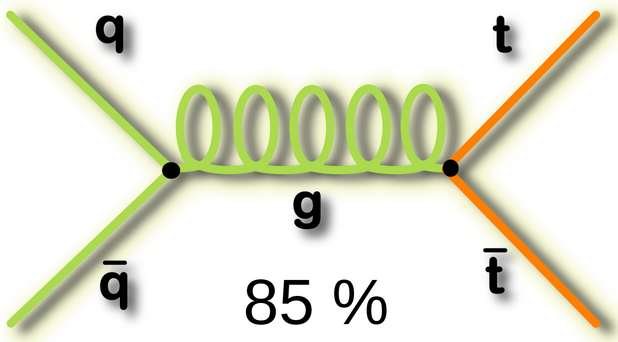
→ Still many ongoing measurements. Stay tuned!

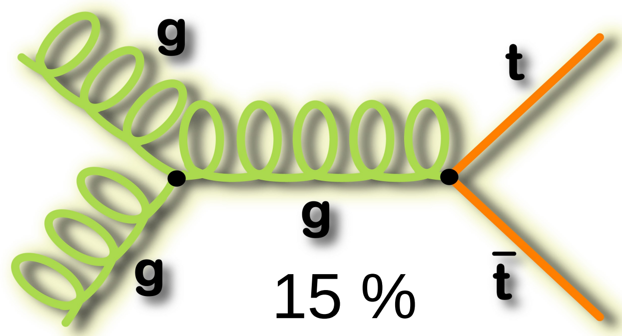
Thank you for your attention!

Back up slides

Top quark production

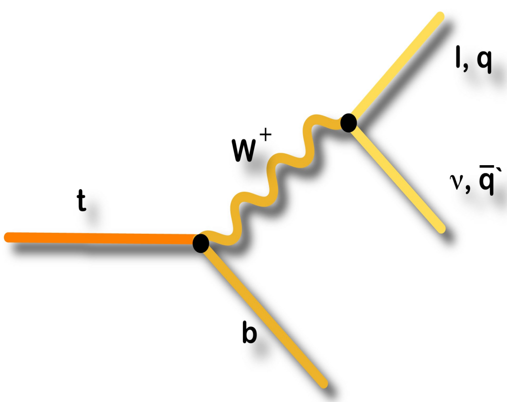
- At Tevatron, top quark is mainly produced in $t\bar{t}$ pairs:

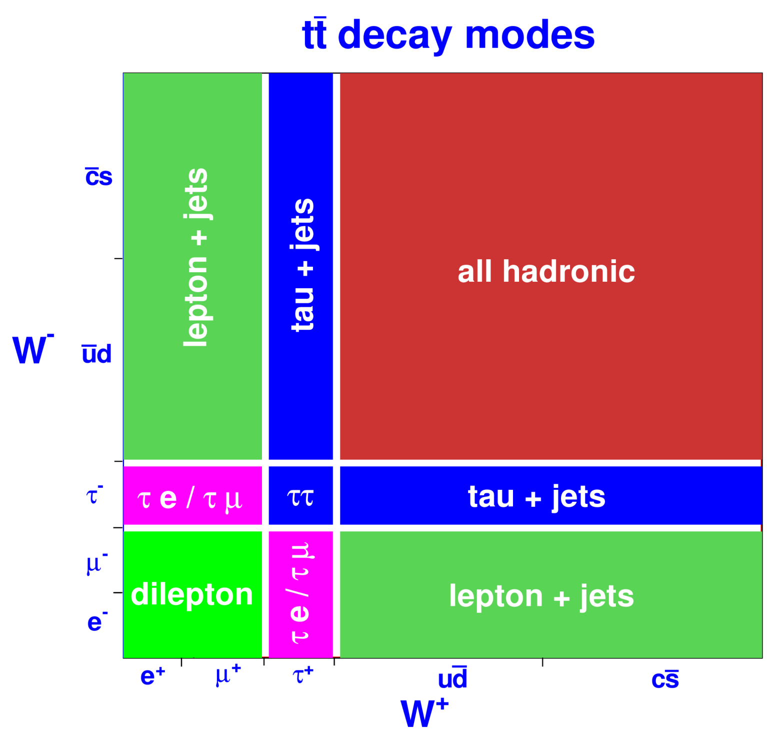




According to SM:

$$\Gamma(t \rightarrow Wb) \sim 100\,\%$$





Channels:

→ lepton+Jets ~ 30%

→ dilepton ~ 5%

→ all hadronic ~ 44%

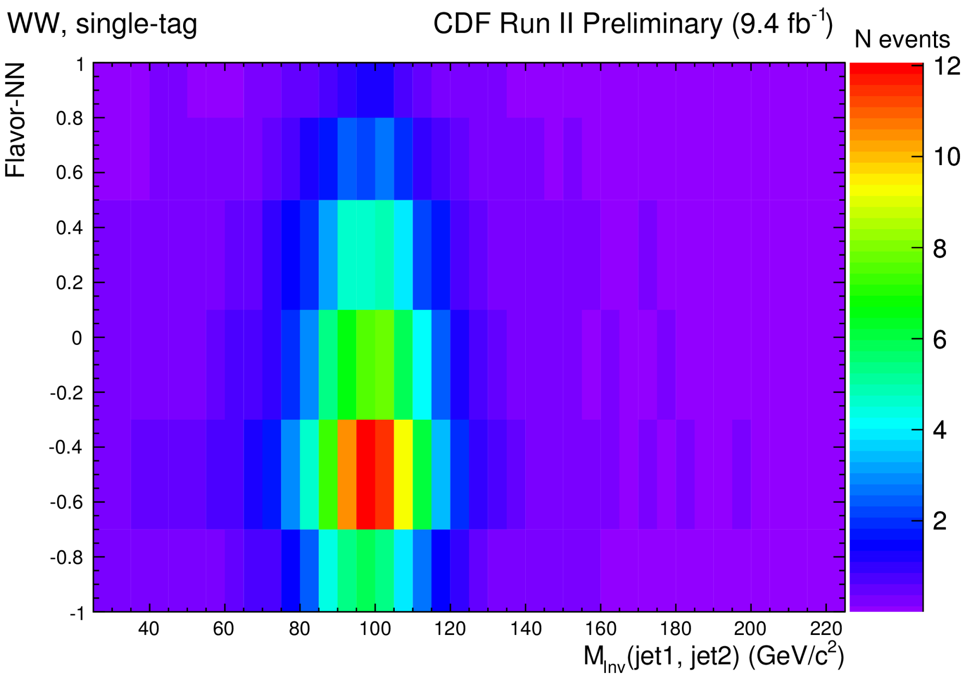
lepton = ***e*** or $\boldsymbol{\mu}$

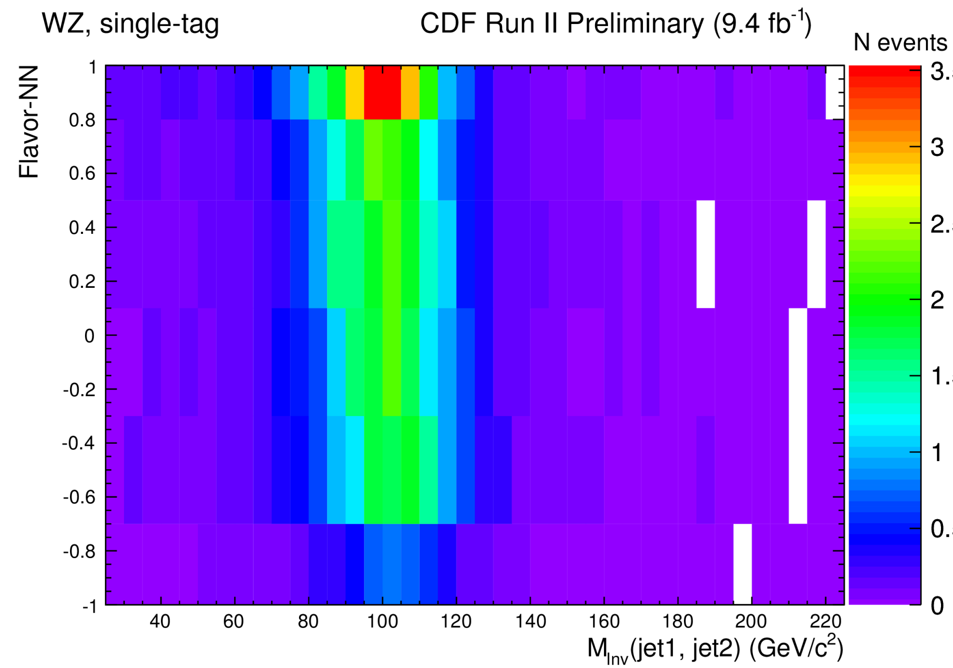
Top quark mass in dileptons

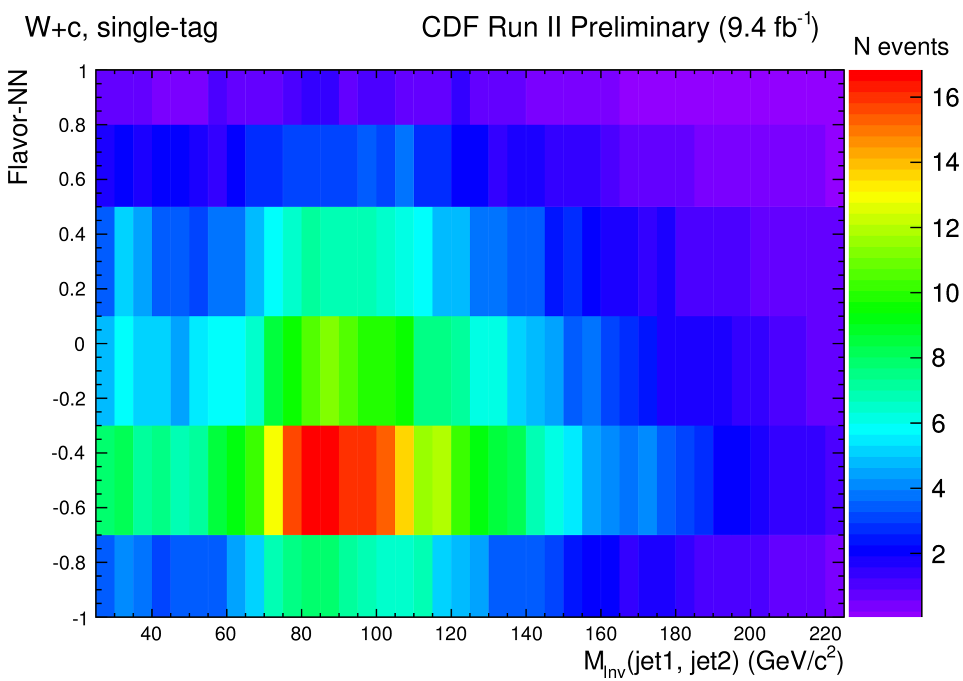
Source	σ_{m_t} [GeV]
Jet energy calibration	
Absolute scale	∓ 0.47
Flavor dependence	∓ 0.27
Residual scale	$^{+0.36}_{-0.35}$
b quark fragmentation	$+0.10$
Object reconstruction	
Trigger	-0.06
Electron p_T resolution	± 0.01
Muon p_T resolution	∓ 0.03
Electron energy scale	± 0.01
Muon p_T scale	± 0.01
Jet resolution	∓ 0.12
Jet identification	$+0.03$
b tagging	∓ 0.19
Signal modeling	
Higher-order effects	-0.33
ISR/FSR	± 0.15
$p_T(t\bar{t})$	-0.07
Hadronization	-0.11
Color reconnection	-0.22
Multiple $p\bar{p}$ interactions	-0.06
PDF uncertainty	± 0.08
Background modeling	
Signal fraction	± 0.01
Heavy-flavor scale factor	± 0.04
Method	
Template statistics	± 0.18
Calibration	± 0.07
Total systematic uncertainty	± 0.85

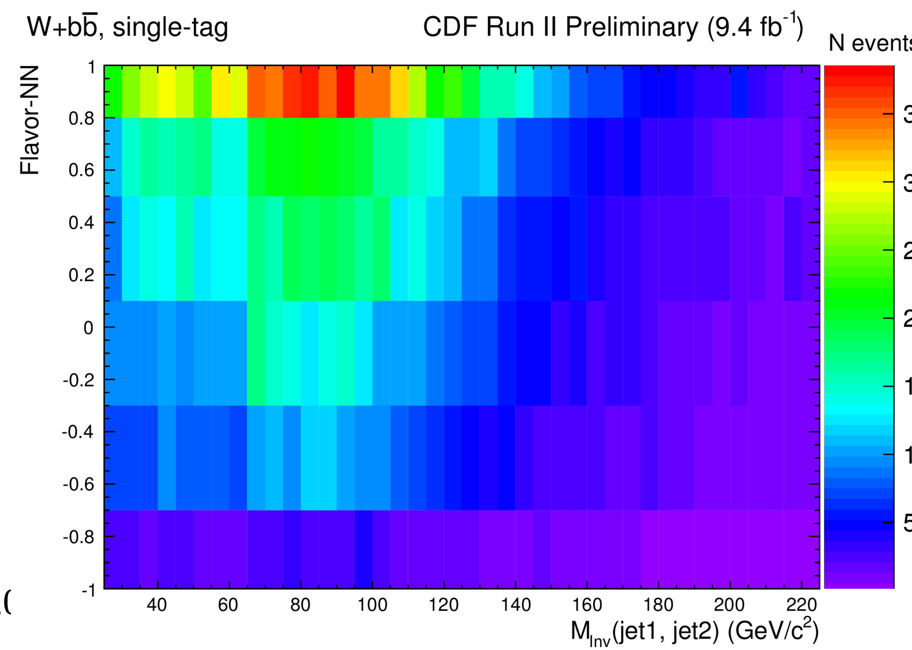
Systematic uncertainties

Electroweak measurements

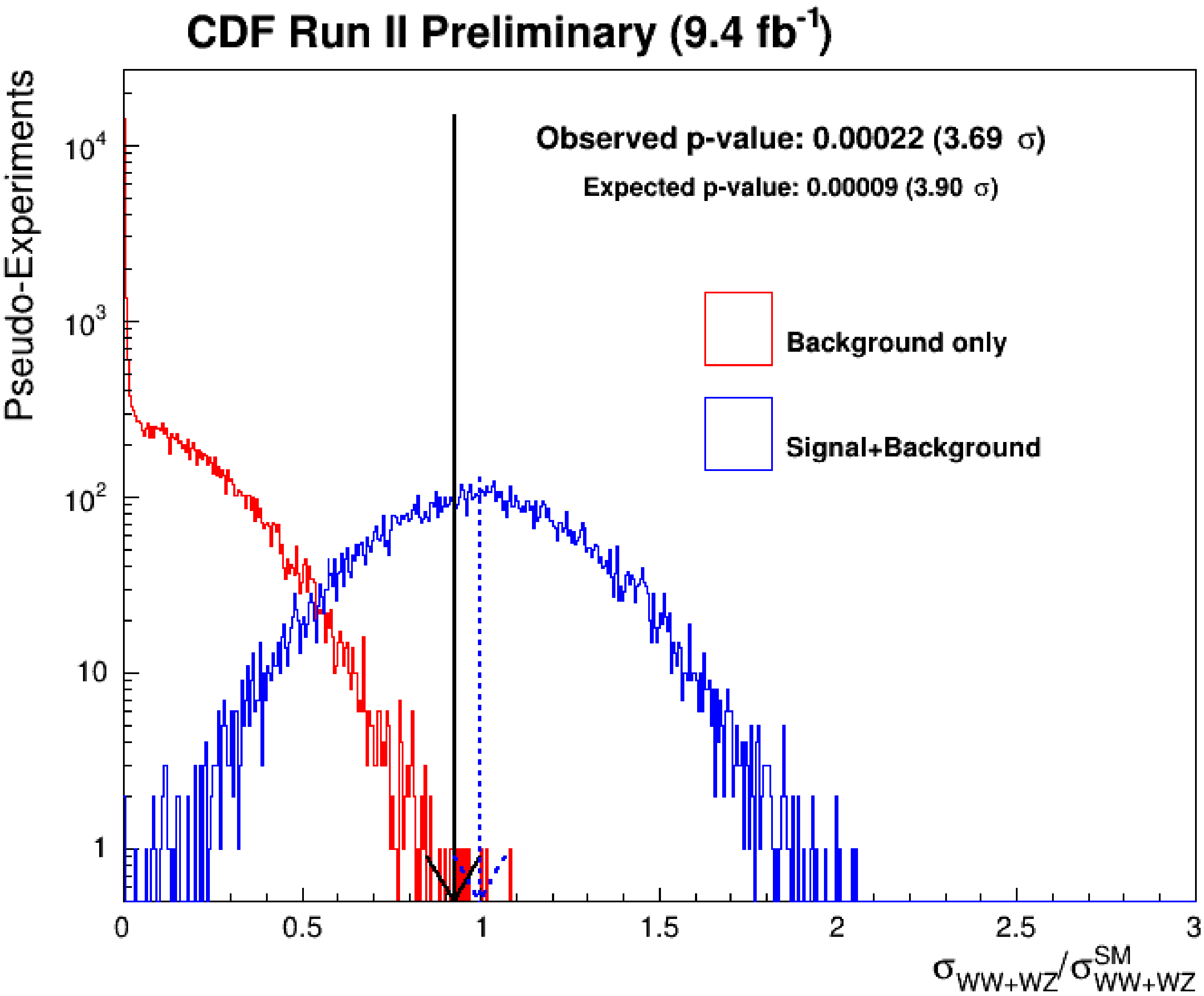








WW and WZ production



WW and WZ production