Measurements of W boson and top quark mass at the Tevatron

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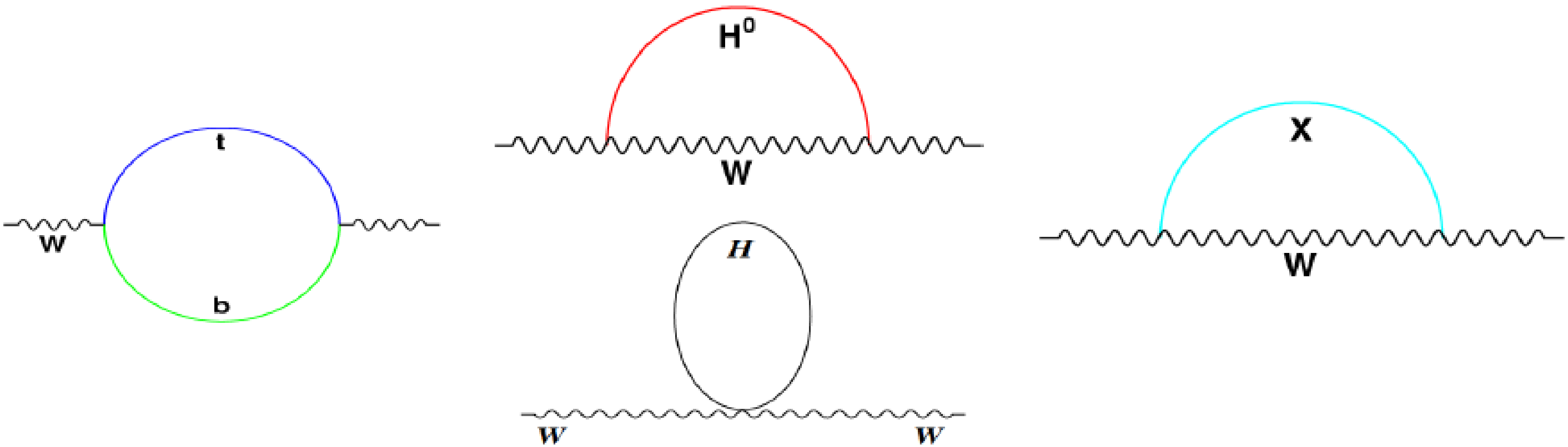
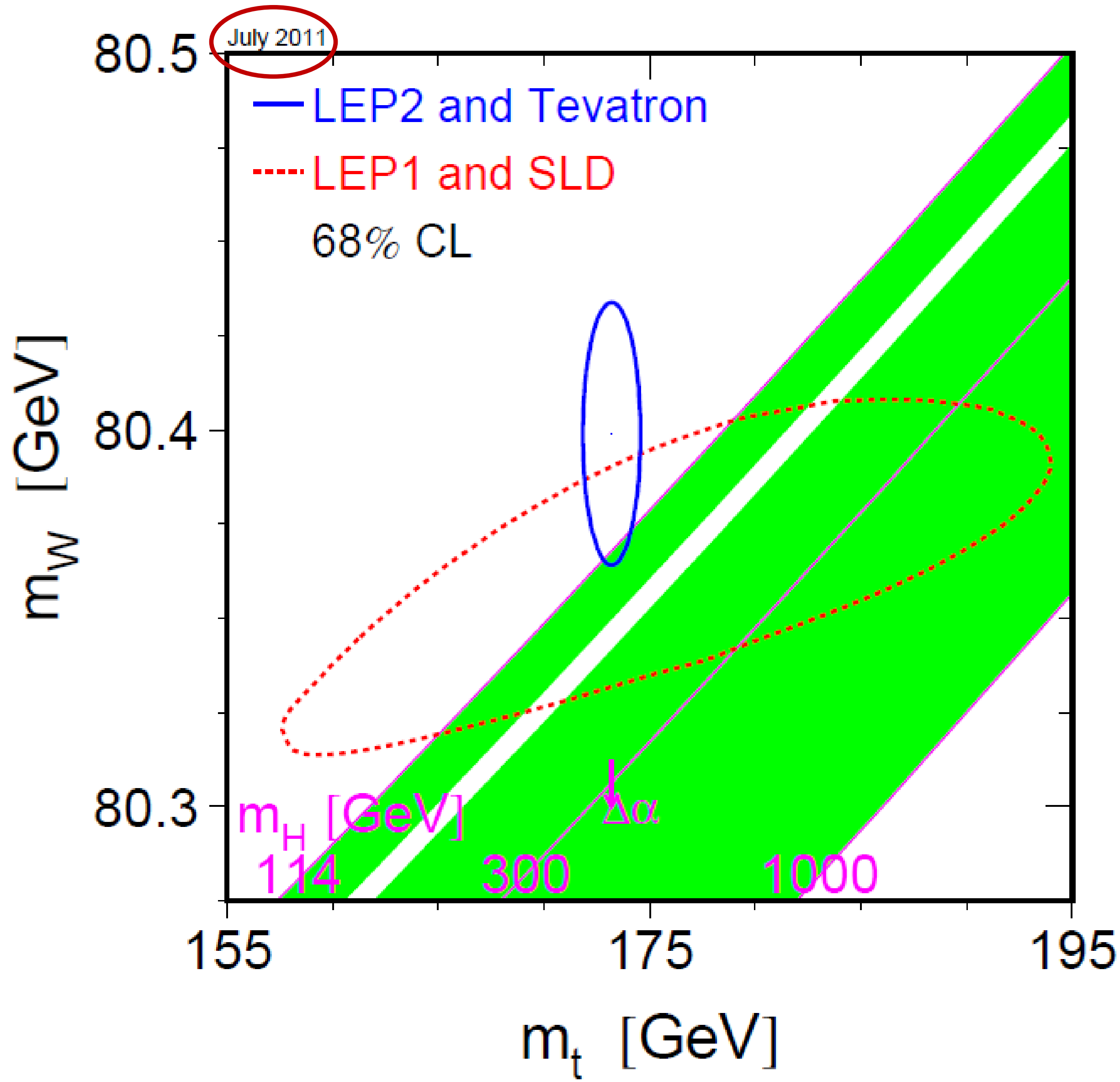
Motivation of *W* and top mass measurements

- Masses are not predicted and should be measured!!
- Radiative corrections of W boson due to heavy quark (top) and Higgs loops (and some new physics particle)



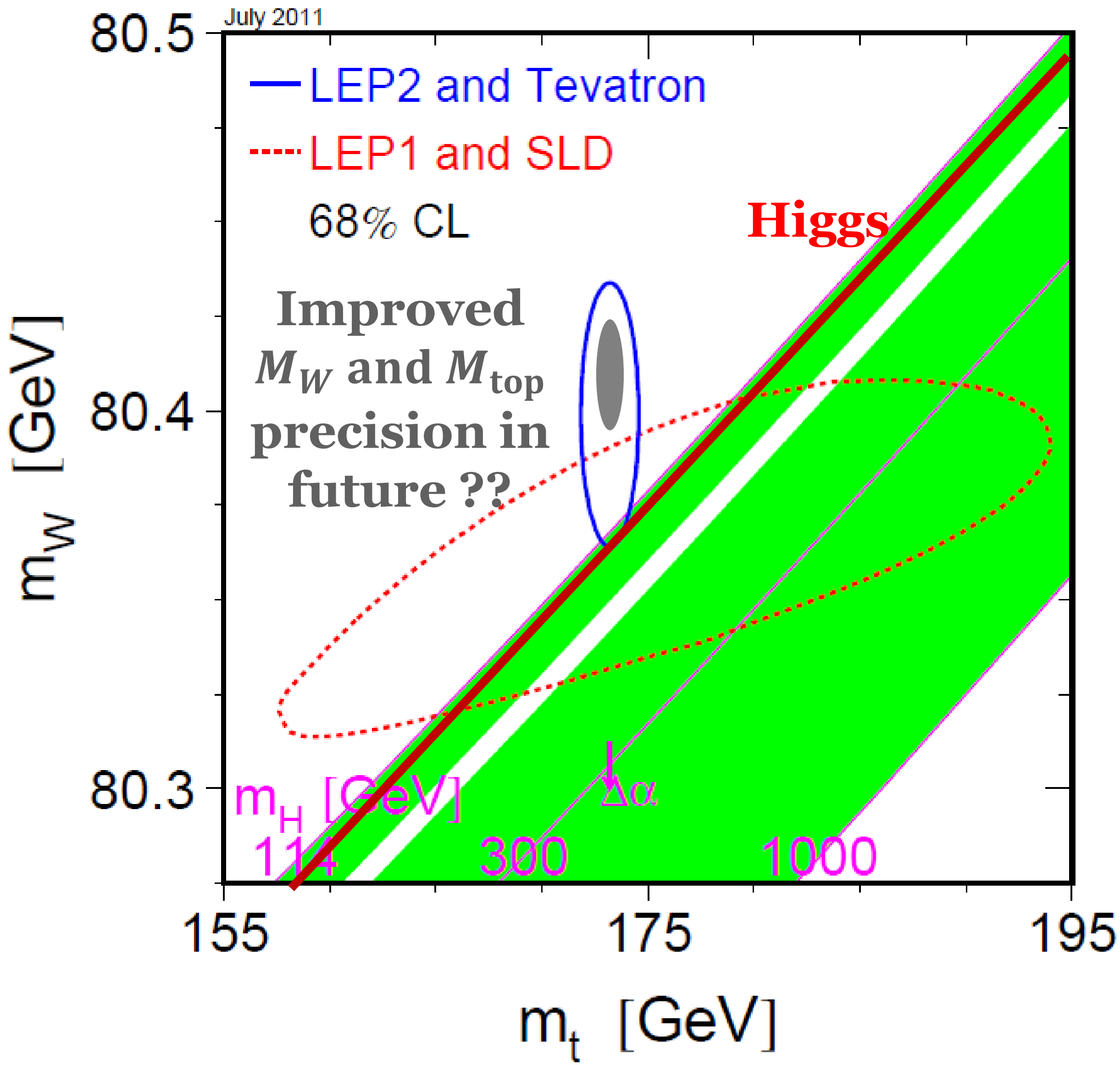
- Indirect determination of Higgs boson mass
- Comparison with direct observation can be important test of SM

Motivation



July 2011
80.5
80.4
80.3
LEP2 and Tevatron
LEP1 and SLD
68% CL
m_W [GeV]
m_H [GeV]
114
300
1000
Δα
155
175
195
m_t [GeV]

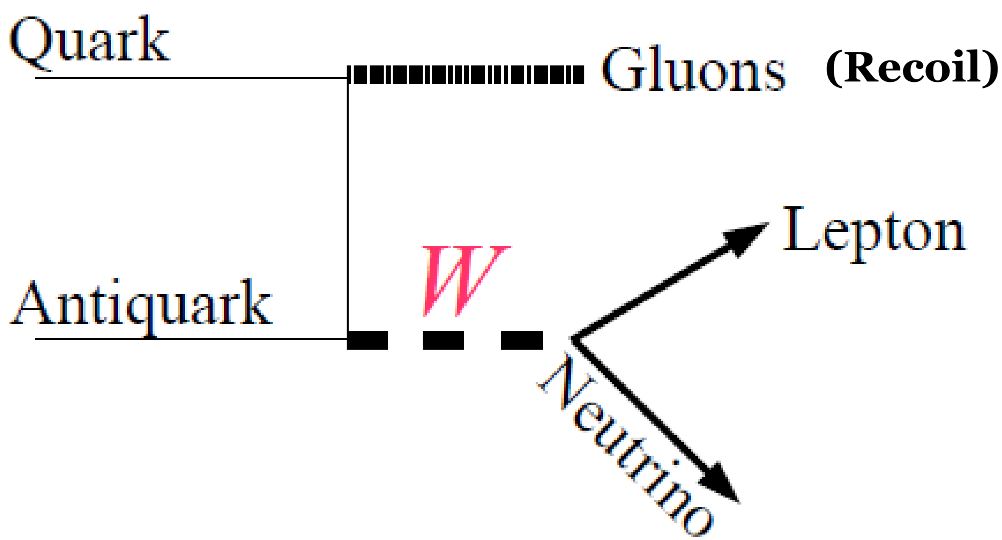
Motivation

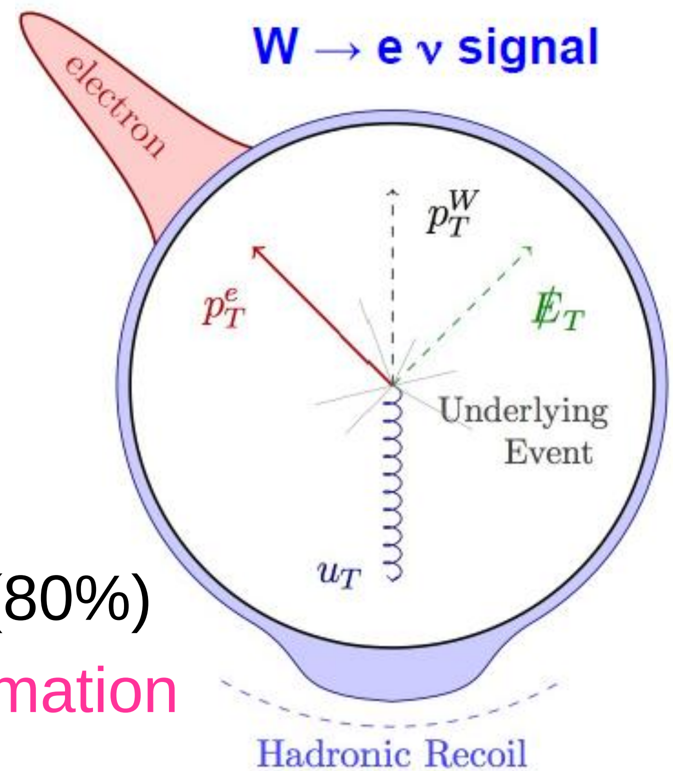


Precision test of SM

W boson mass (M_W) measurements

W boson production at the Tevatron



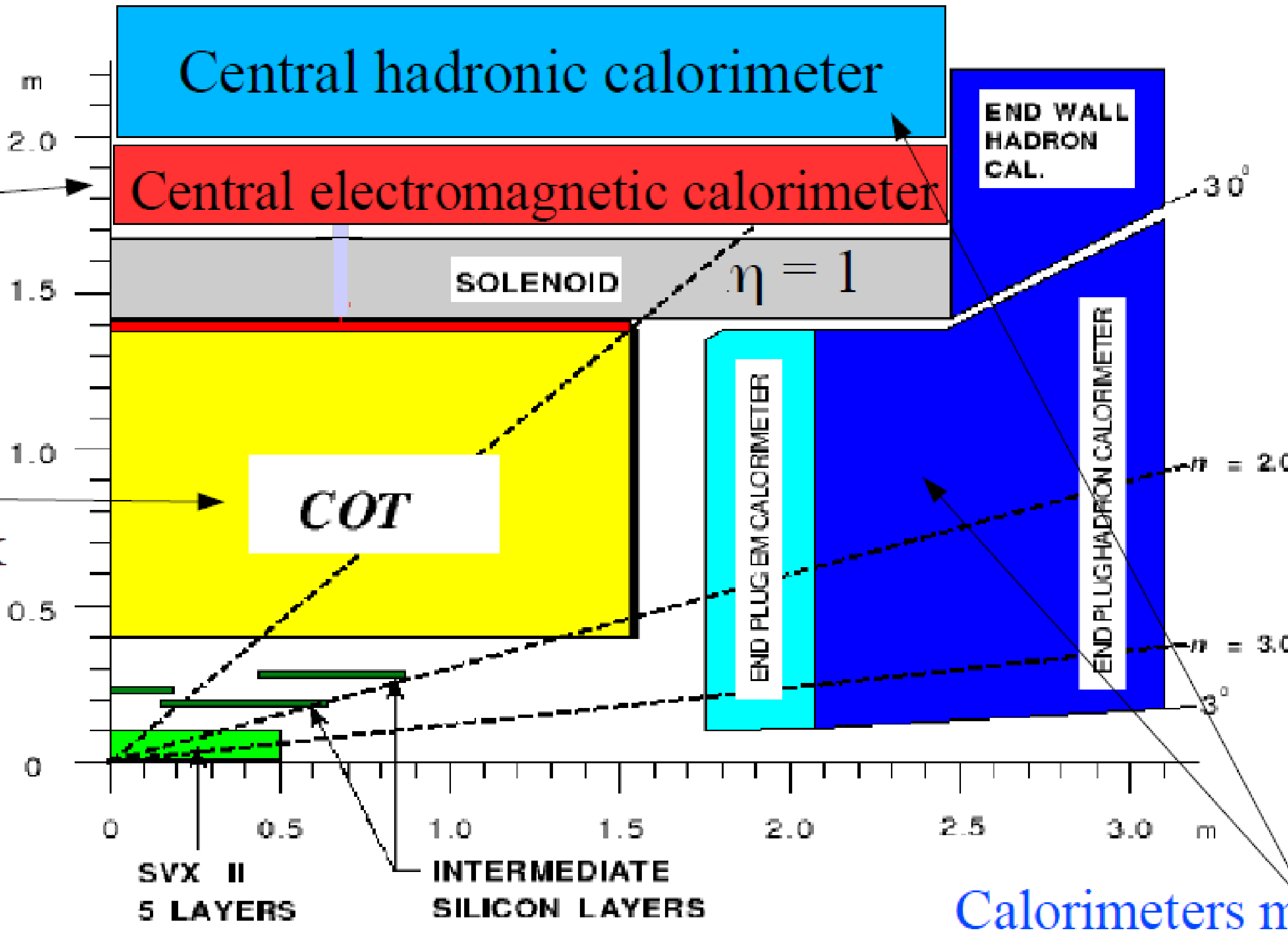


- Quark-antiquark annihilation dominant (80%)
- Lepton p_T carries most of W mass information
  - Should be measured very precisely (0.01%)
- Initial state QCD radiation is order of 10 GeV, soft hadronic recoil in calorimeter
  - 0.5-1% precision

CDF detector

EM calorimeter provides precise electron energy measurement

Drift chamber provides precise lepton track momentum measurement

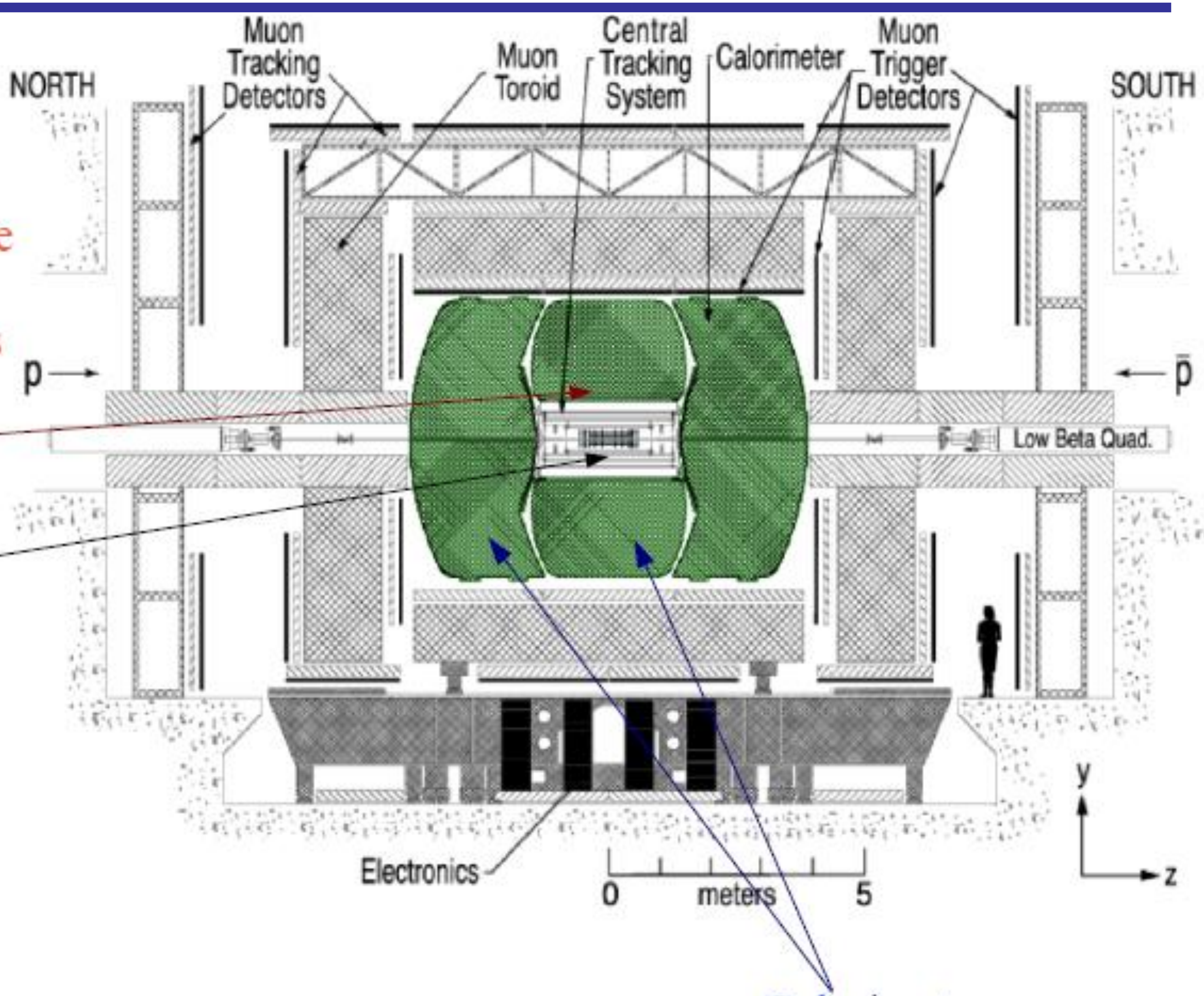


Calorimeters measure hadronic recoil particles

D0 detector

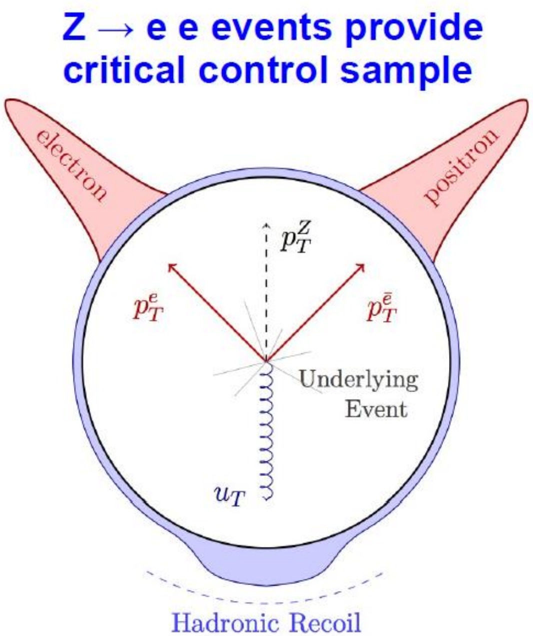
Highly-segmented, stable Uranium+liquid Argon EM calorimeter provides precise electron energy measurement

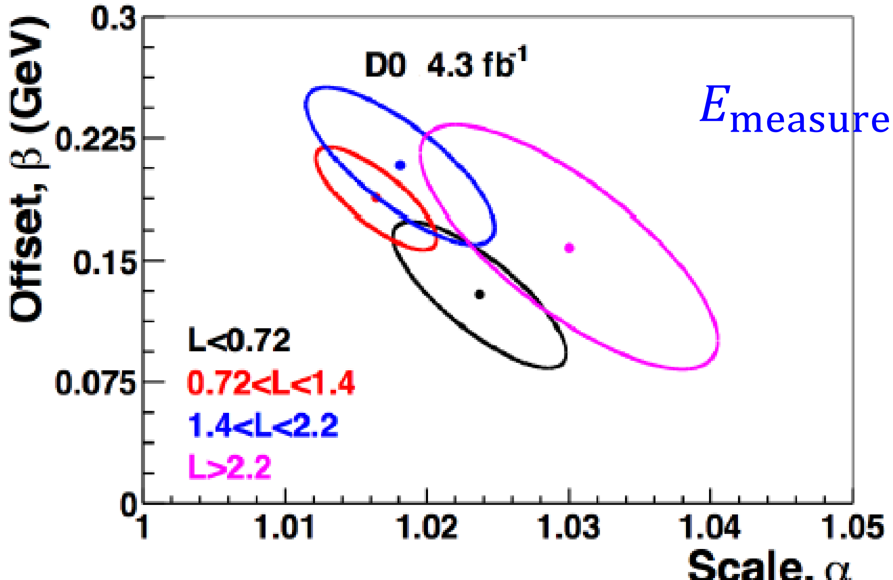
Silicon and Scintillating fiber trackers provides precise lepton track position measurement



Calorimeters measure hadronic recoil particles

Electron energy scale at D0





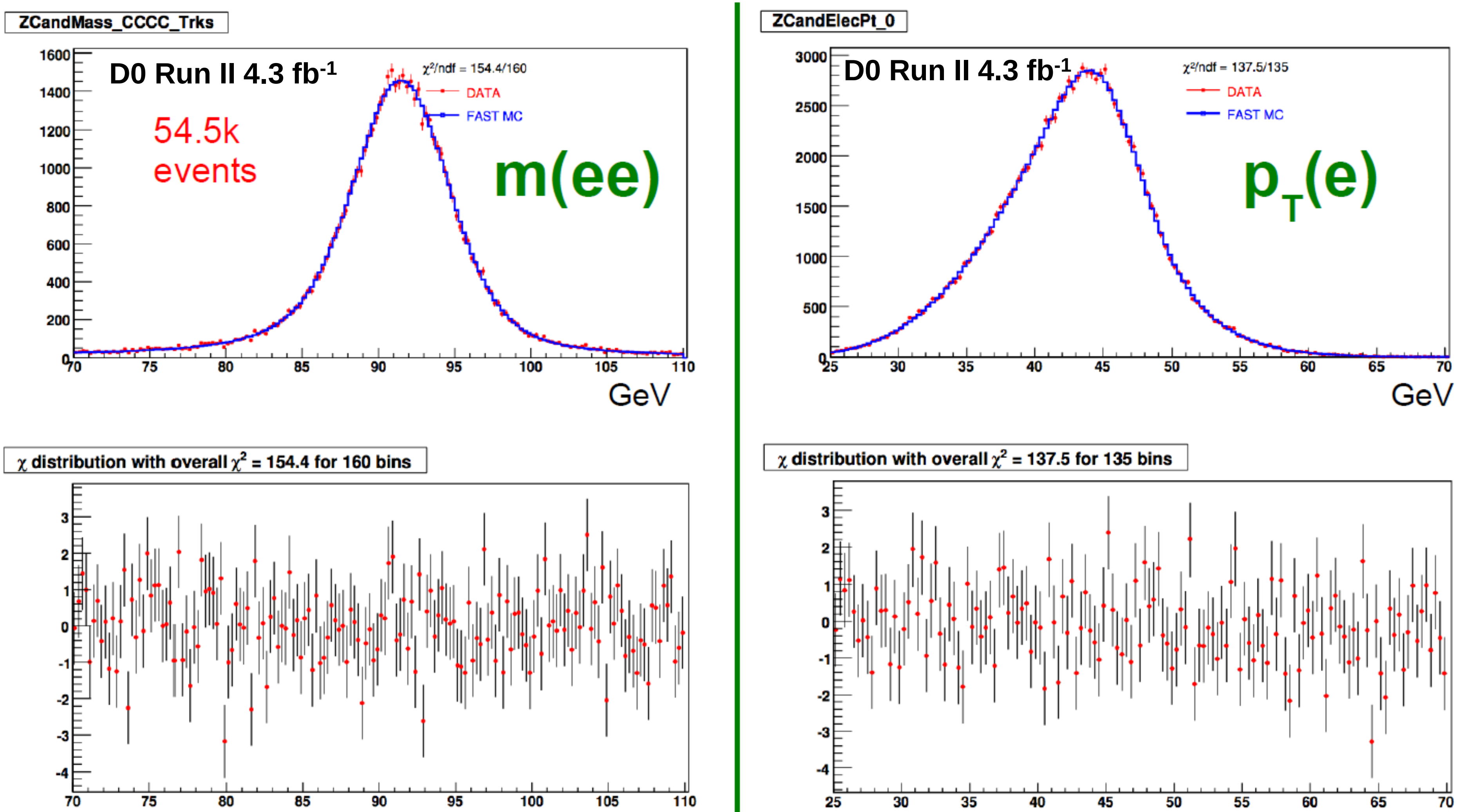
- Correct for low-energy non-linearity
  - Energy loss due to upstream dead material
  - Modeling of underlying event energy flow
  - Electronics noise and pileup

- Straight-line model for calorimeter
  - Using $Z \rightarrow ee$ with known Z mass from LEP
  - $\Rightarrow$ Measure M_W/M_Z

$$E_{\text{measured}} = \text{scale} \cdot (E_{true} - 43\text{ GeV}) + \text{offset} + 43\text{ GeV}$$

- Calibration procedure checked with closure test performed with GEANT pseudo-data

$Z \to ee$ data at D0



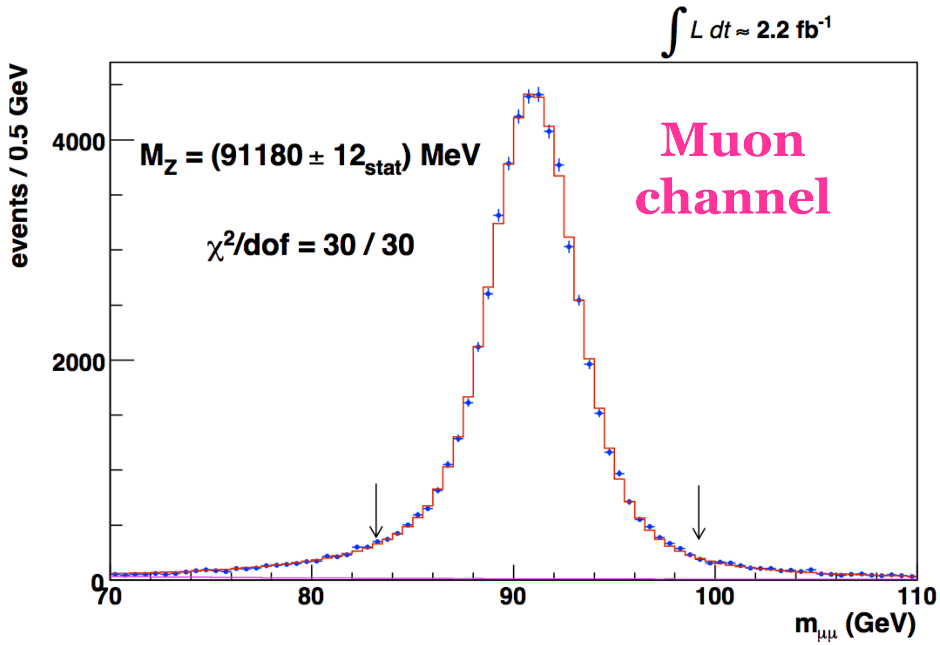
m(Z) = 91.193 ± 0.017 (stat) GeV

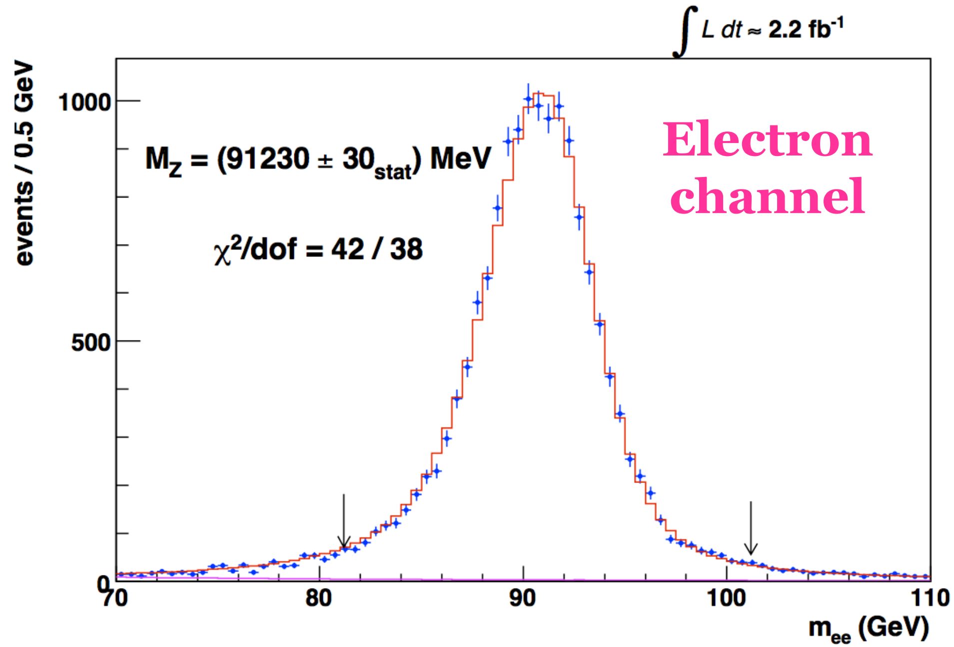
- Good agreement between data and parameterized Monte Carlo

CDF electron and Muon measurement

- A complete detector simulation of all quantities measured in the data
  - Tracker Calibration
    - Alignment of the drift chamber tracker using cosmic rays
    - Track momentum scale and non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass fits
    - Confirmed using $Z \rightarrow \mu\mu$ mass fit
  - Electromagnetic Calorimeter Calibration
    - Fit the E/p spectrum which transfer drift chamber momentum scale
    - Confirmed using $Z \rightarrow ee$ mass fit
  - Hadronic recoil modelling
    - Use p_T balance in $Z \rightarrow ll$

$Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ Mass Cross-check at CDF



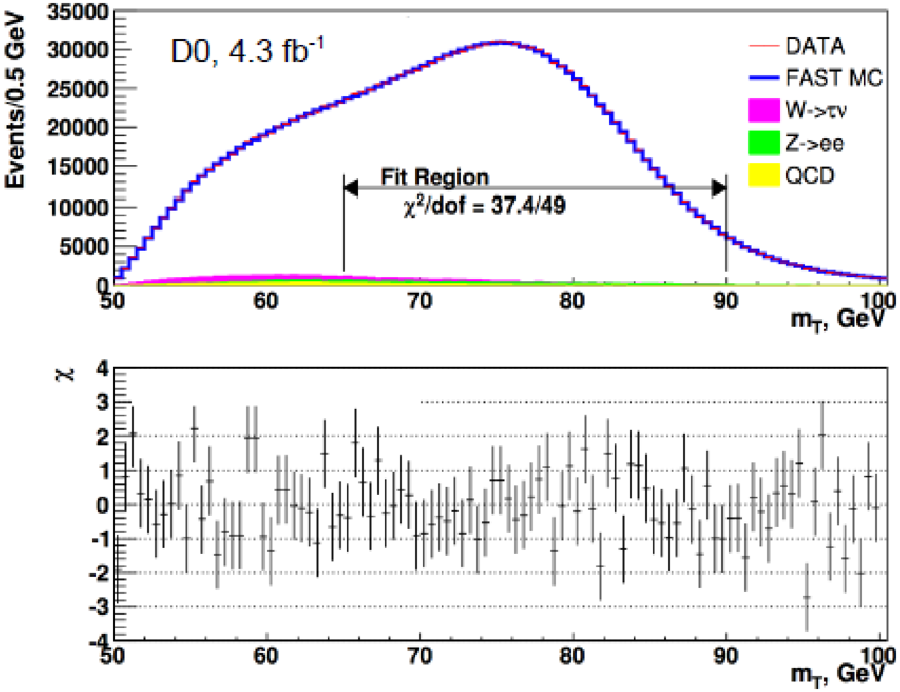


- With modeling of track momentum and calorimeter energy, we perform the Z mass fit for the confirmation
- Results are consistent with PDG value

$$M_Z = 91188 \pm 2 \text{ MeV}$$

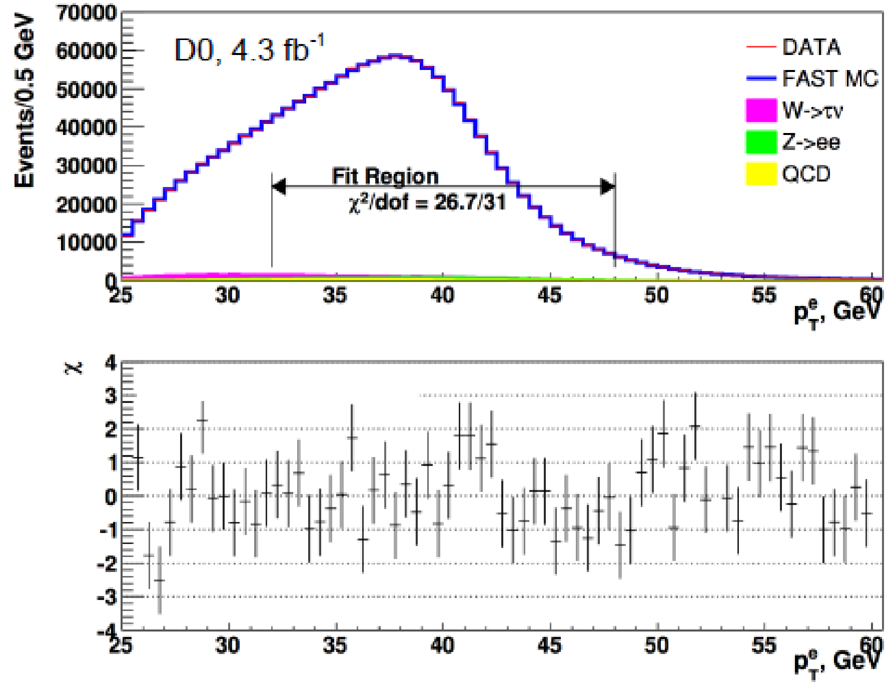
W mass fits at D0 (4.3 fb^{-1})

m_T



- Fit result
- $M_W = 80371 \pm 13$ MeV (stat)

$p_T(e)$



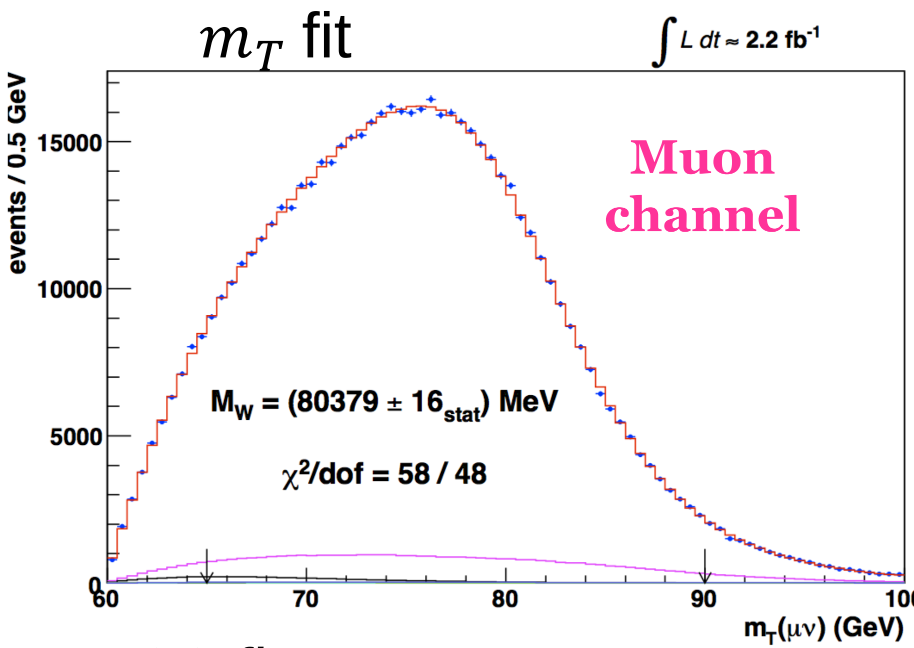
- Fit result
- $M_W = 80343 \pm 14$ MeV (stat)

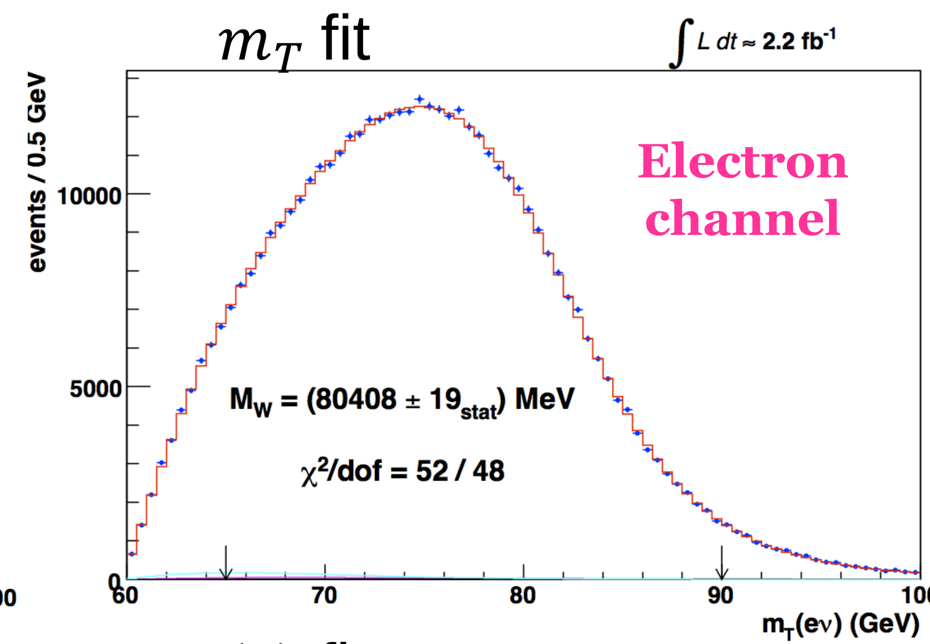
Combined result

Phys. Rev. Lett. 108, 151804 (2012)

$$M_W = 80367 \pm 13\ (\text{stat.}) \pm 22\ (\text{syst})\ \text{MeV}/c^2$$

W mass fits at CDF (2.2 fb^{-1})





$p_T(\mu)$ fit :

$M_W = 80348 \pm 18\ \mathrm{MeV(stat.)}$

$E_T(e)$ fit :

$M_W = 80393 \pm 21\ \mathrm{MeV(stat.)}$

Neutrino transverse momentum fits are performed in both experiments for the cross-check

Combined result **Phys. Rev. Lett. 108, 151803 (2012)**

$$M_W = 80387 \pm 12\ (\mathrm{stat.}) \pm 15\ (\mathrm{syst})\ \mathrm{MeV/c^2}$$

Uncertainties

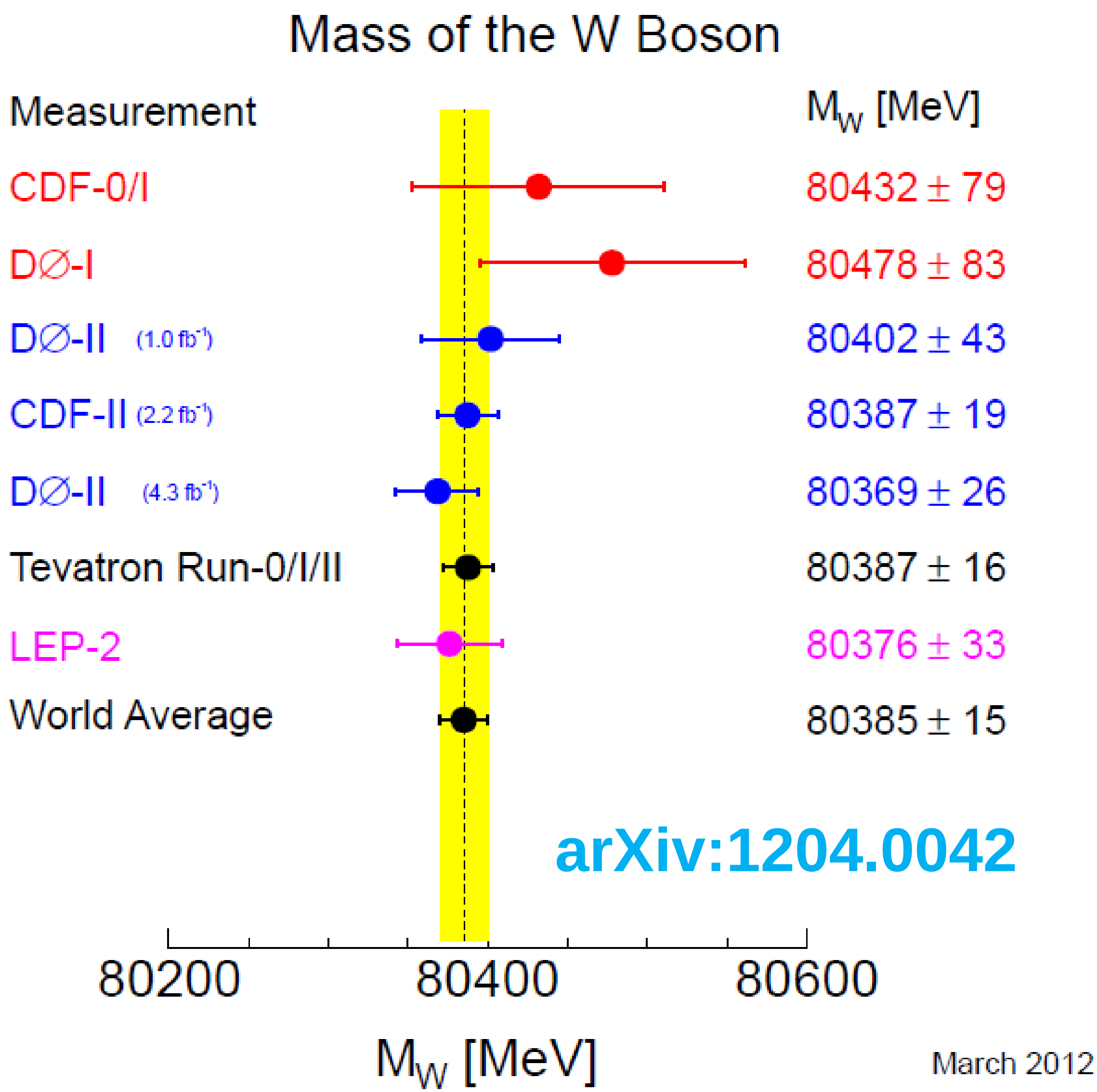
Uncertainty	D0	CDF
Lepton energy scale/resolution/modelling	17	7
Hadronic recoil energy scale and modeling	5	6
Backgrounds	2	3
Parton distributions (PDFs)	11	10
QED radiation	7	4
$p_T(W)$ model	2	5
Total Systematic Uncertainty	22	15
W-boson statistics	13	12
Total Uncertainty	26 MeV	19 MeV

Largely Stat. in origin – reduced with large sample

Largely Theory in origin – need some works to reduce

PDF may be a single dominant uncertainty in the full data set measurement

Combination of W boson mass measurements



Scope for full data-set measurements

- 2-5 bigger data samples are available in both experiments
- Most of the systematic uncertainties can be scaled down with data statistics
  - PDF is not the case unfortunately
- PDF uncertainty would be a crucial source for the precision
- New electroweak measurements at Tevatron and LHC can further constrain PDFs
  - W boson charge asymmetry
  - Z boson rapidity distribution
  - $W \rightarrow l\nu$ lepton rapidity distribution
  - W+charm production
  - …
- ΔM_W below 15 MeV in each experiment and below 10 MeV from Tevatron may be possible

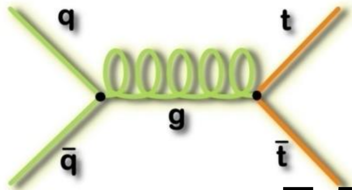
Top quark mass (M_{top}) measurements

Top quark production and decay at Tevatron

Production

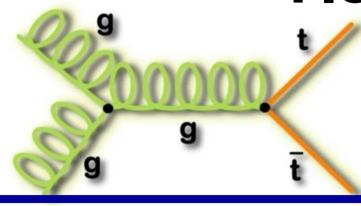
Pair production

~85%

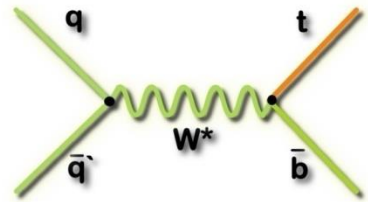


~7.5 pb

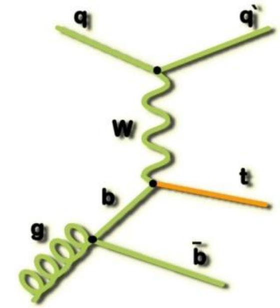
~15%



Single top production



s channel~1 pb

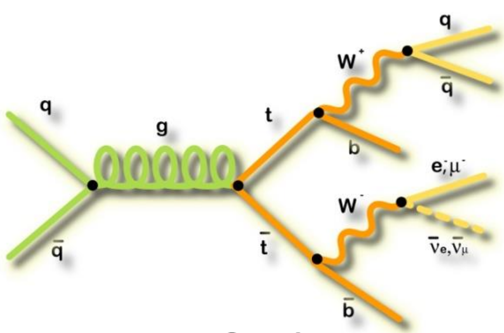


t channel~2 pb

Decay

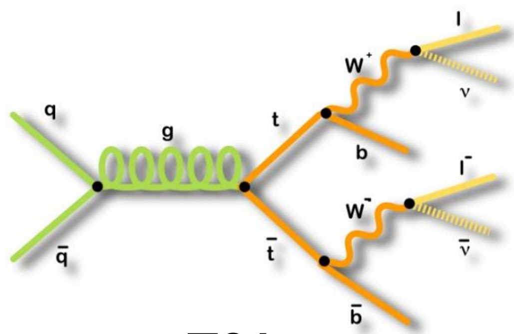
$t \to bW$ ~100%

Lepton+Jets



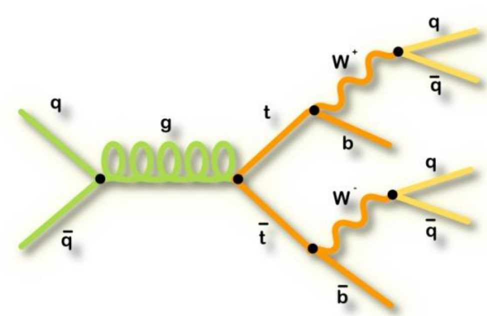
34%

Dilepton



7%

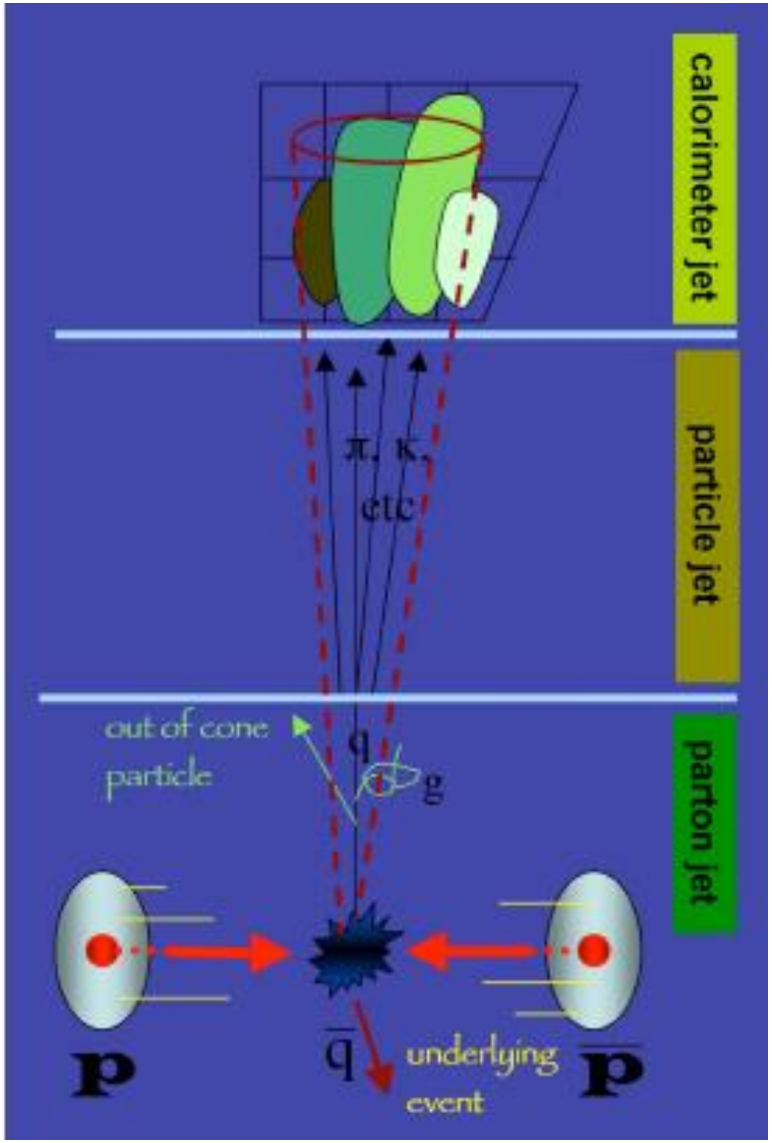
All Jets

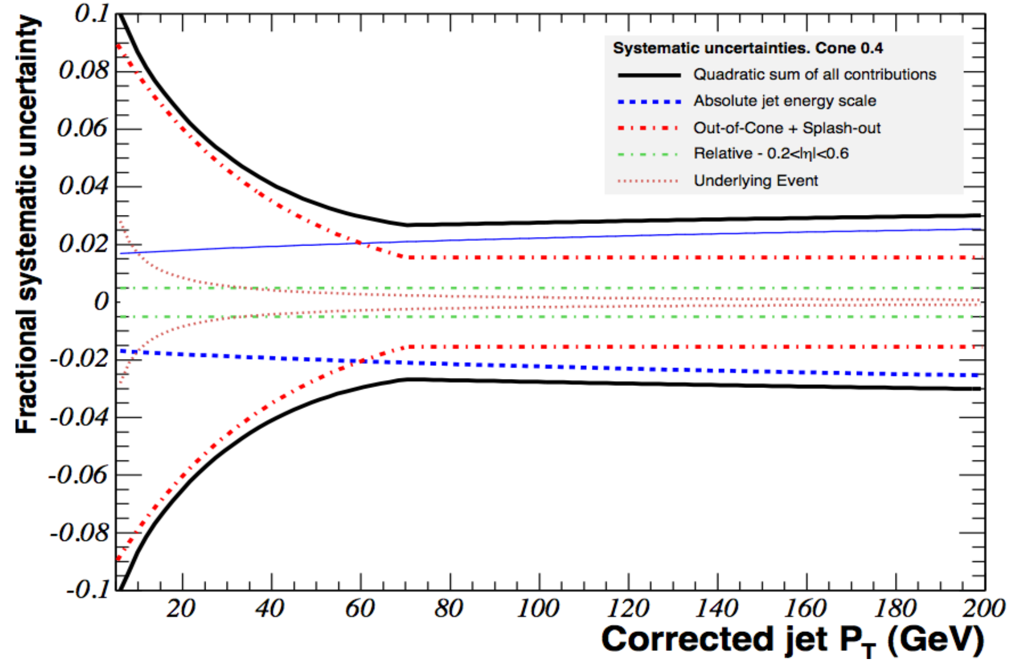


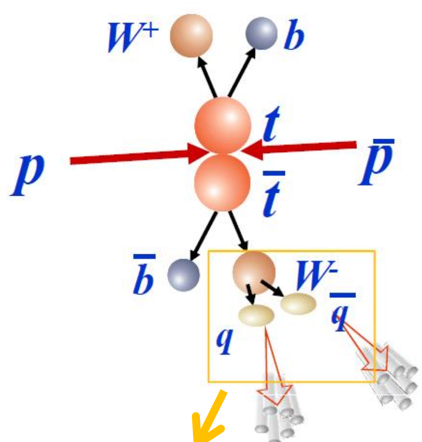
44%

Hadronic tau : 15%

Jet energy scale (JES)







Measured JES uncertainty

Lepton+jets : 1.0 GeV/c^2

Dilepton : 2.9 GeV/c^2

(CDF 5.6 fb^{-1}, template method)

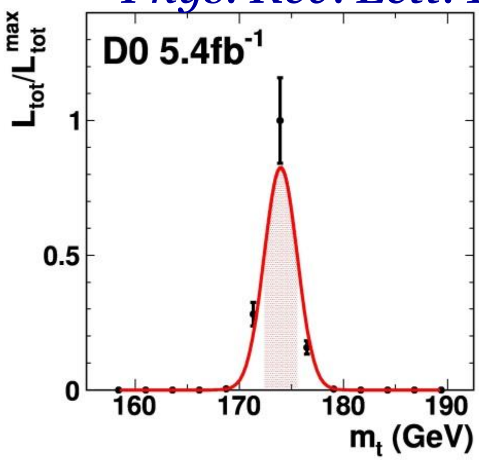
In situ JES calibration

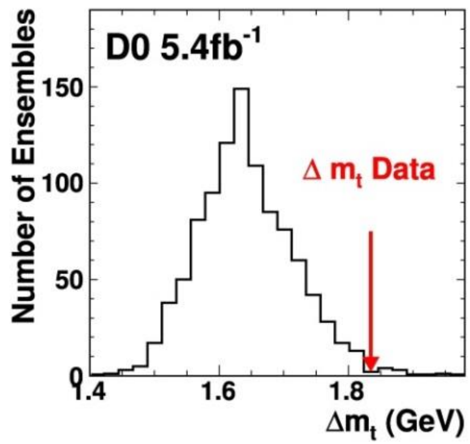
D0 dilepton channel

- Matrix element method

Phys. Rev. Lett. 107, 082004 (2011)

5.4 fb^{-1}





174.0 ± 1.8 (stat.) ± 2.4 (syst.) GeV/c^2

Dilepton

Source	Uncertainty (GeV)
Jet energy calibration	
Overall scale	0.9
Flavor dependence	0.5
Residual scale	0.3
Signal modeling	
ISR/FSR	0.4
Color reconnection	0.5
Higher order effects	0.6
b quark fragmentation	0.1
PDF uncertainty	0.5
Object reconstruction	
Muon p_T resolution	0.2
Electron energy scale	0.2
Muon p_T scale	0.2
Jet resolution	0.3
Jet identification	0.3
Method	
Calibration	0.1
Template statistics	0.5
Signal fraction	0.2
Total systematic uncertainty	1.5

- Template method + JES calibration derived from lepton+jets

174.0 ± 2.4 (stat.) ± 1.4 (syst.) GeV/c^2

Phys. Rev. D 86, 051103 (2012)

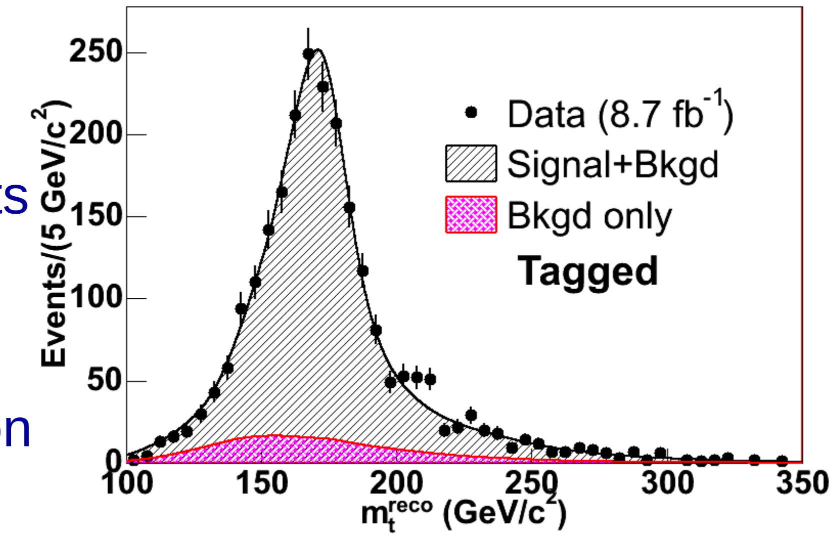
- Combine two results

$M_{top} = 173.9 \pm 1.9$ (stat.) ± 1.6 (syst) GeV/c^2

CDF lepton+jets with full data set

Lepton+Jets

8.7 fb^{-1}



- 8.7 fb^{-1} data – 3989 candidate events
  - Five categories based on b-tagging and jets requirement
- Improvement
  - Employ neural network jet energy correction
  - Include 0-tag and loose 1-tag sample
  - Obtain approximately 25% additional gain in statistical precision
- Template method
  - Three variables : two of mass terms and one hadronic W mass (*in situ* JES calibration) from kinematic fitter
- Most precise single measurement at the Tevatron

$$M_{top} = 172.85 \pm 0.71(\text{stat.}) \pm 0.85(\text{syst.}) = 172.85 \pm 1.11 \text{ GeV}/c^2$$

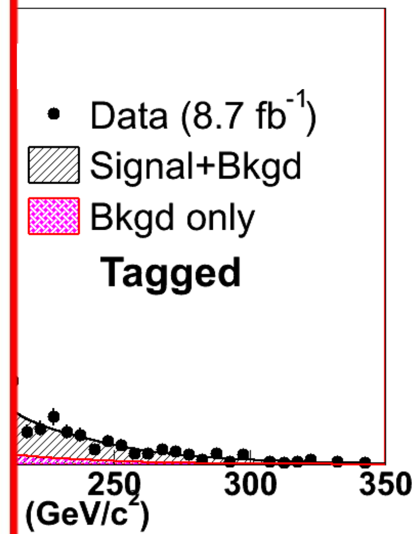
Phys. Rev. Lett. 109, 152003 (2012)

CDF lepton+jets with full data set

Lepto

- 8.7 fb
  - Fiv
    req
- Impro
  - Em
  - Incl
  - Obt ... on
- Temp
  - Thr ... ss (*in situ* JES
    cali
- Most

Source	Systematic uncertainty
Residual jet energy scale	0.52
Signal modeling	0.56
Higher-order corrections	0.09
b jet energy scale	0.18
b tagging efficiency	0.03
Initial and final state radiation	0.06
Parton distribution functions	0.08
Gluon fusion fraction	0.03
Lepton energy scale	0.03
Background shape	0.20
Multiple hadron interaction	0.07
Color reconnection	0.21
MC statistics	0.05
Total systematic uncertainty	0.85



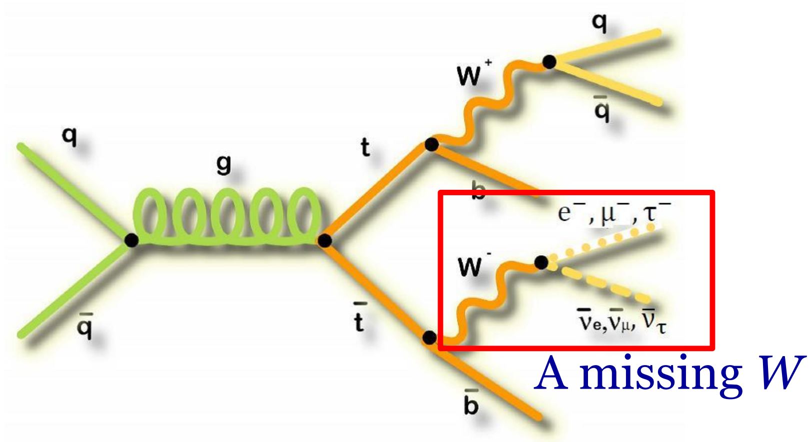
M_{top}=172.85 ±0.71(stat.) ±0.85(syst.)=172.85 ±1.11 GeV/c^2

Phys. Rev. Lett. 109, 152003 (2012)

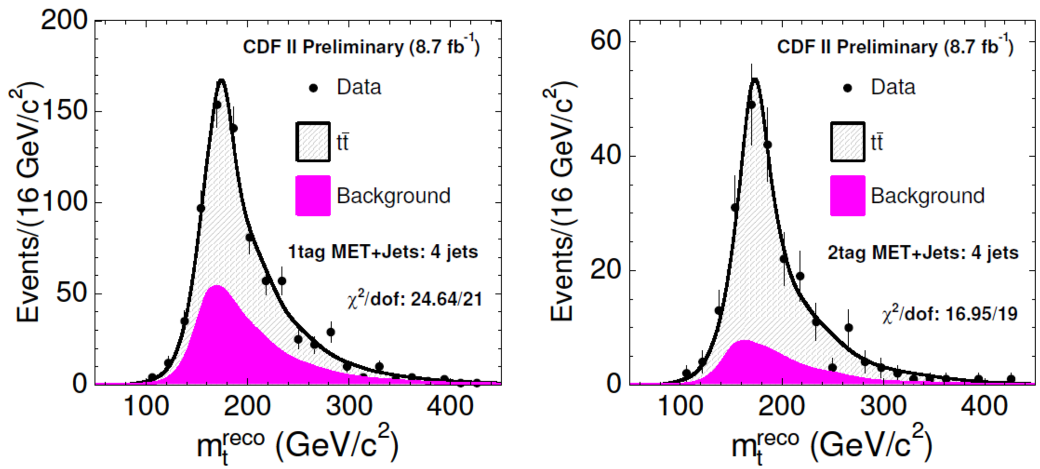
No lepton, Missing energy, jets with full data set

MET+Jets

8.7 fb^{-1}



- Full Event Reconstruction
  - Use kinematic fitter
  - Only single *W* is missing
    - Overconstrained system
- Template method
  - Two reconstructed top masses and dijet (*W*) mass
  - *In situ* JES calibration

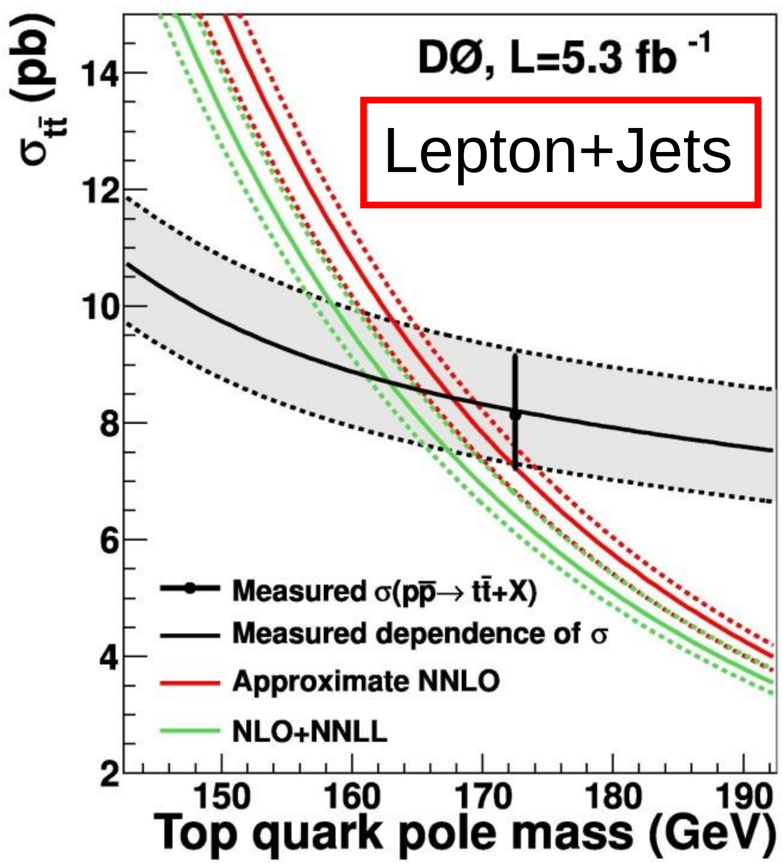


arXiv:1305.3339

M_{top} = 173.93 ± 1.64 (stat.+JES) ± 0.87 (syst.) GeV/c^2
= 173.93 ± 1.85 GeV/c^2

What mass? Pole, $\overline{\rm MS}$, or … ?

- Measured $M_{\rm top}$ corresponds to the mass implemented in the simulation ($M_{\rm MC}$)   ($M_{\rm MC} \approx M_{\rm pole}$??)
- Extract mass from cross section measurements



Pole Mass

Theoretical prediction	$m_t^{\rm pole}$ (GeV)	$\Delta m_t^{\rm pole}$ (GeV)
MC mass assumption	$m_t^{\rm MC} = m_t^{\rm pole}$	$m_t^{\rm MC} = m_t^{\overline{\rm MS}}$
NLO [12]	$164.8^{+5.7}_{-5.4}$	-3.0
NLO+NLL [13]	$166.5^{+5.5}_{-4.8}$	-2.7
NLO+NNLL [14]	$163.0^{+5.1}_{-4.6}$	-3.3
Approximate NNLO [15]	$167.5^{+5.2}_{-4.7}$	-2.7
Approximate NNLO [16]	$166.7^{+5.2}_{-4.5}$	-2.8

$\overline{\rm MS}$ Mass

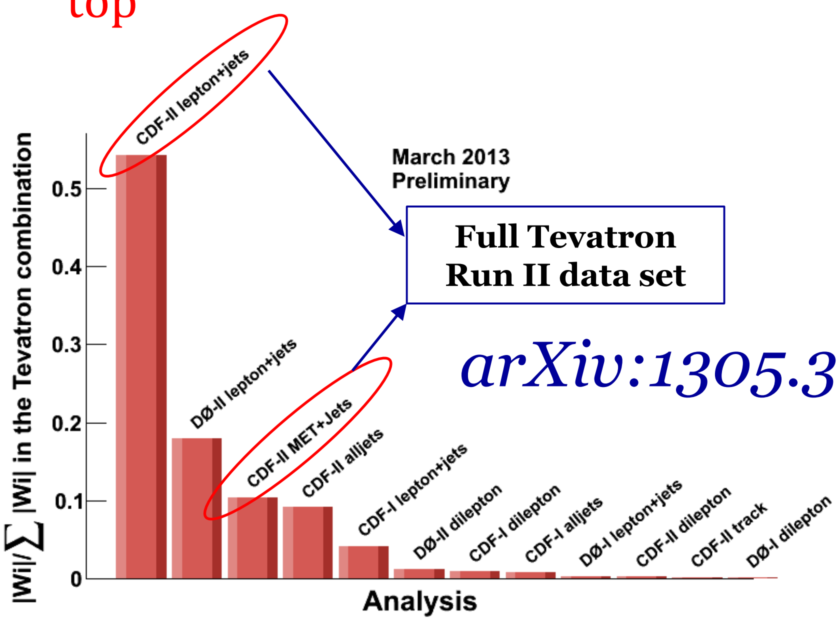
Theoretical prediction	$m_t^{\overline{\rm MS}}$ (GeV)	$\Delta m_t^{\overline{\rm MS}}$ (GeV)
MC mass assumption	$m_t^{\rm MC} = m_t^{\rm pole}$	$m_t^{\rm MC} = m_t^{\overline{\rm MS}}$
NLO+NNLL [14]	$154.5^{+5.0}_{-4.3}$	-2.9
Approximate NNLO [15]	$160.0^{+4.8}_{-4.3}$	-2.6

Phys. Lett. B 703, 422 (2011)

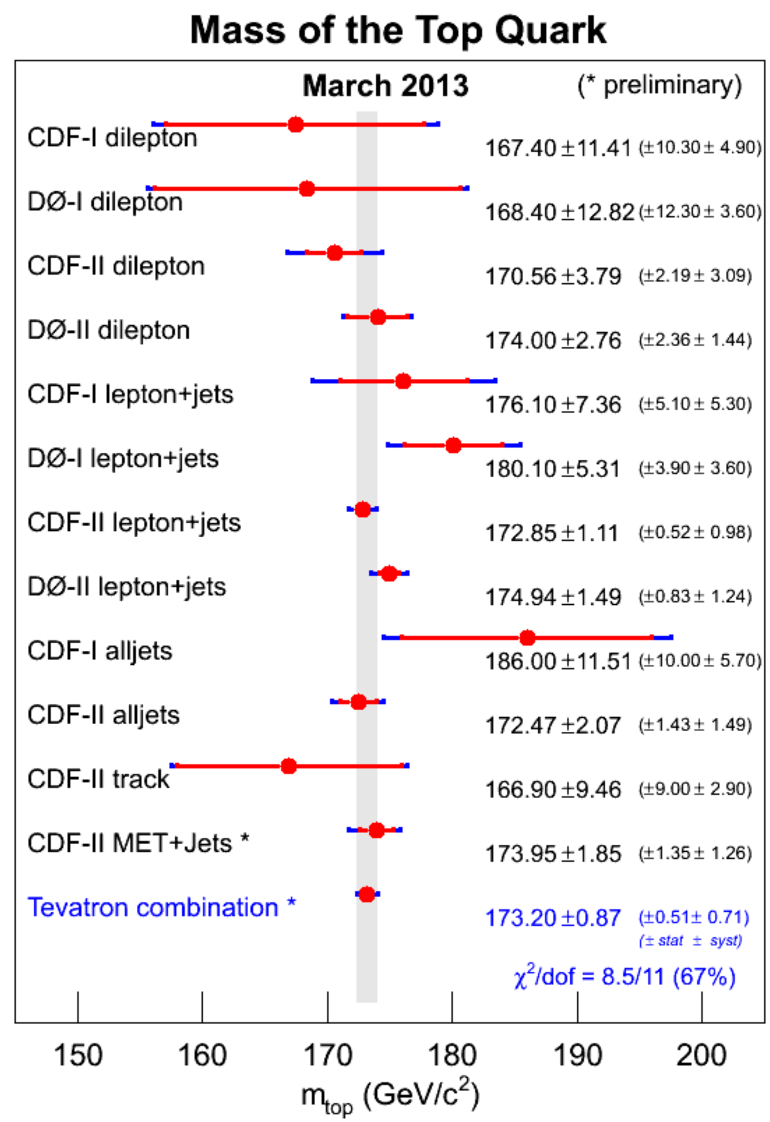
Combination of top mass measurements at Tevatron

- A joint CDF and D0 working group performs the combination of top quark measurements
  - ❖ Using Best Linear Unbiased Estimator (BLUE)

M_{top} = 173.20 ± 0.87GeV/c^2



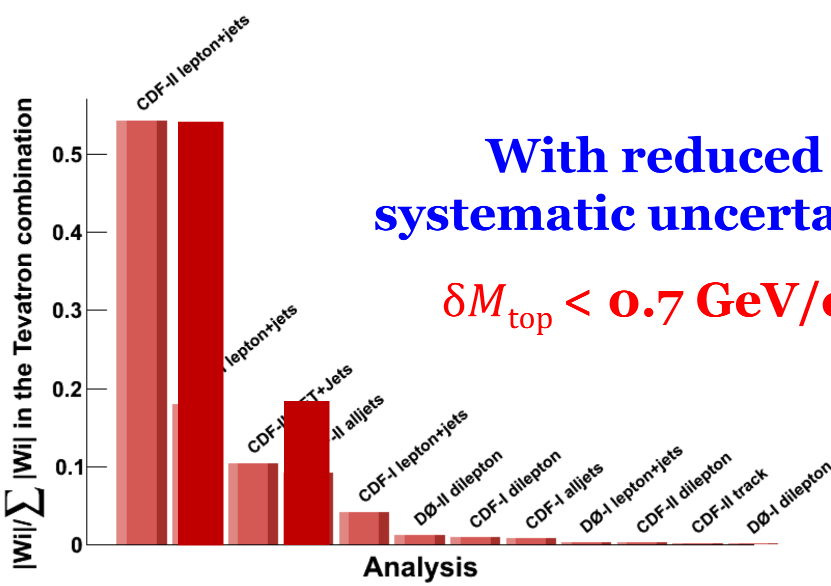
arXiv:1305.3939



Outlook of final words from Tevatron

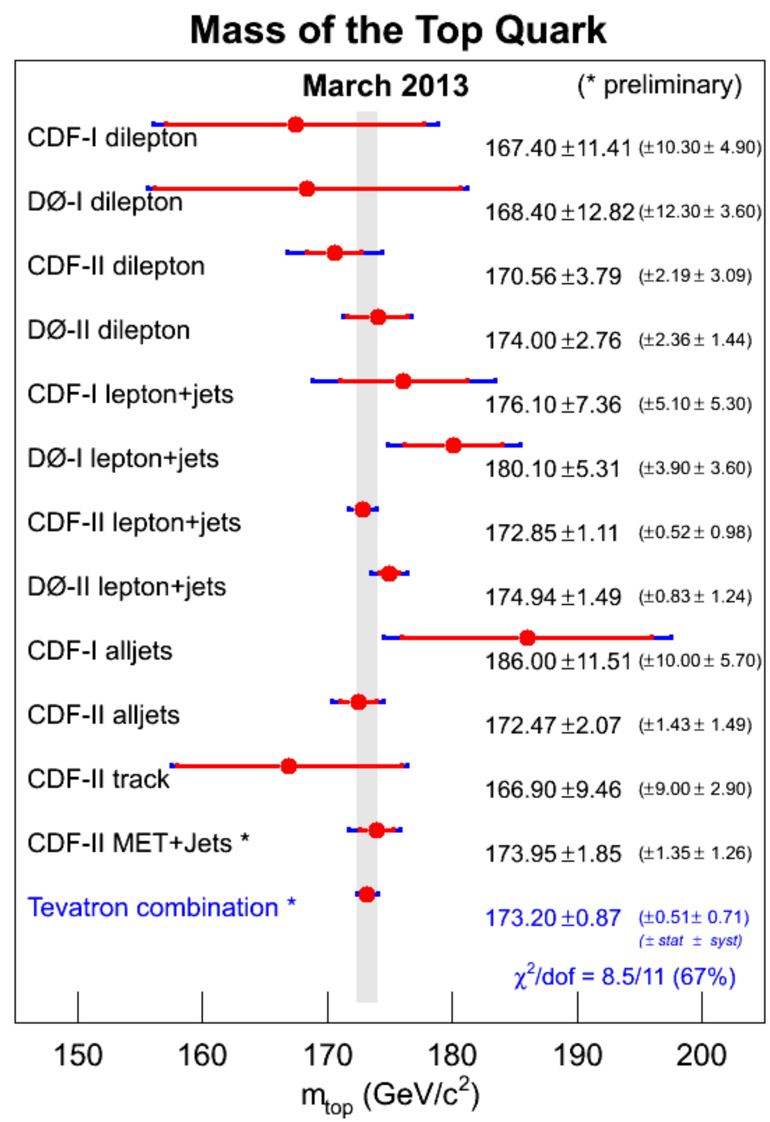
- A joint CDF and D0 working group performs the combination of top quark measurements
  - ❖ Using Best Linear Unbiased Estimator (BLUE)

δM_{top} < 0.8 GeV/c^2

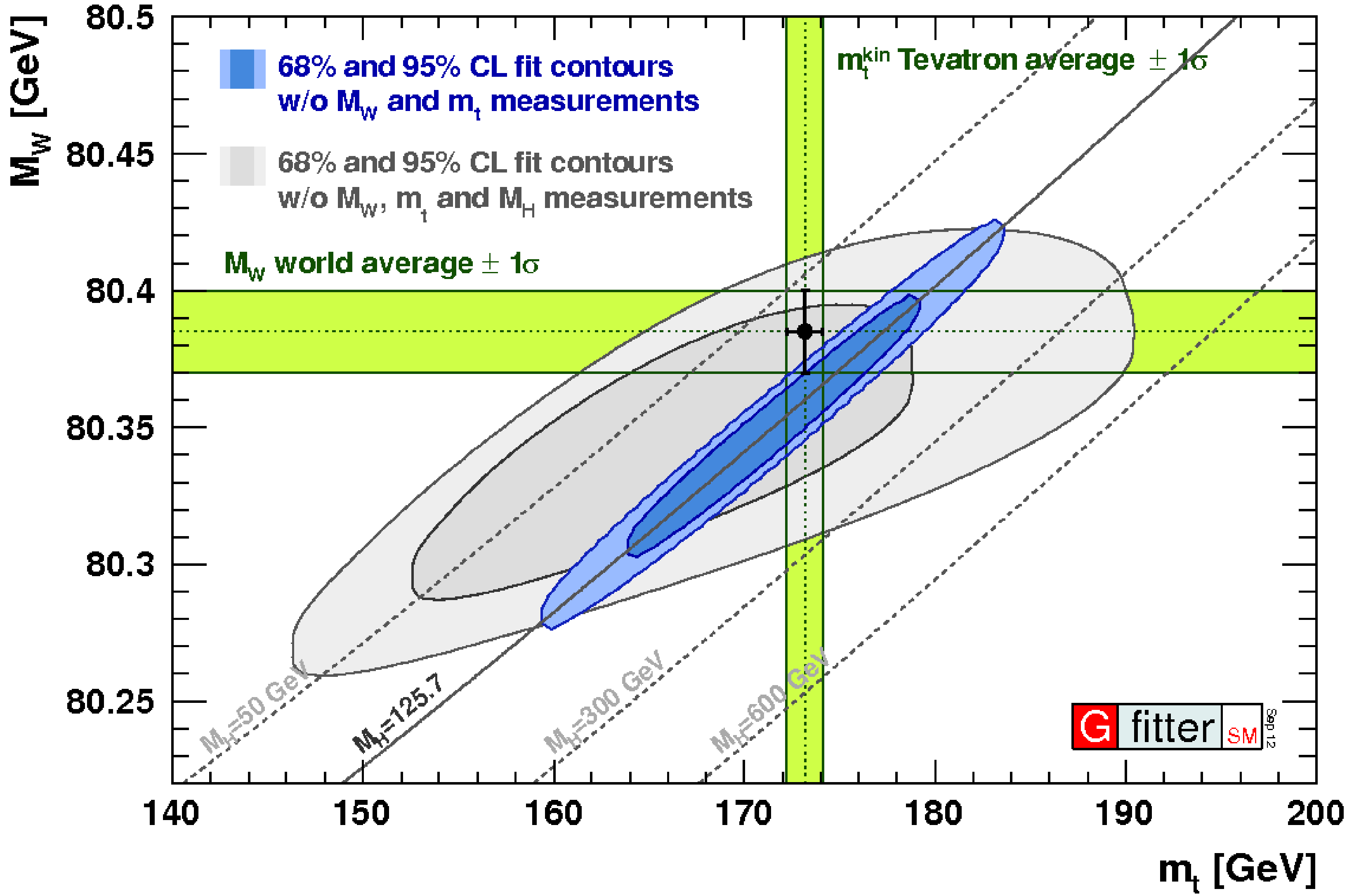


With reduced systematic uncertainty

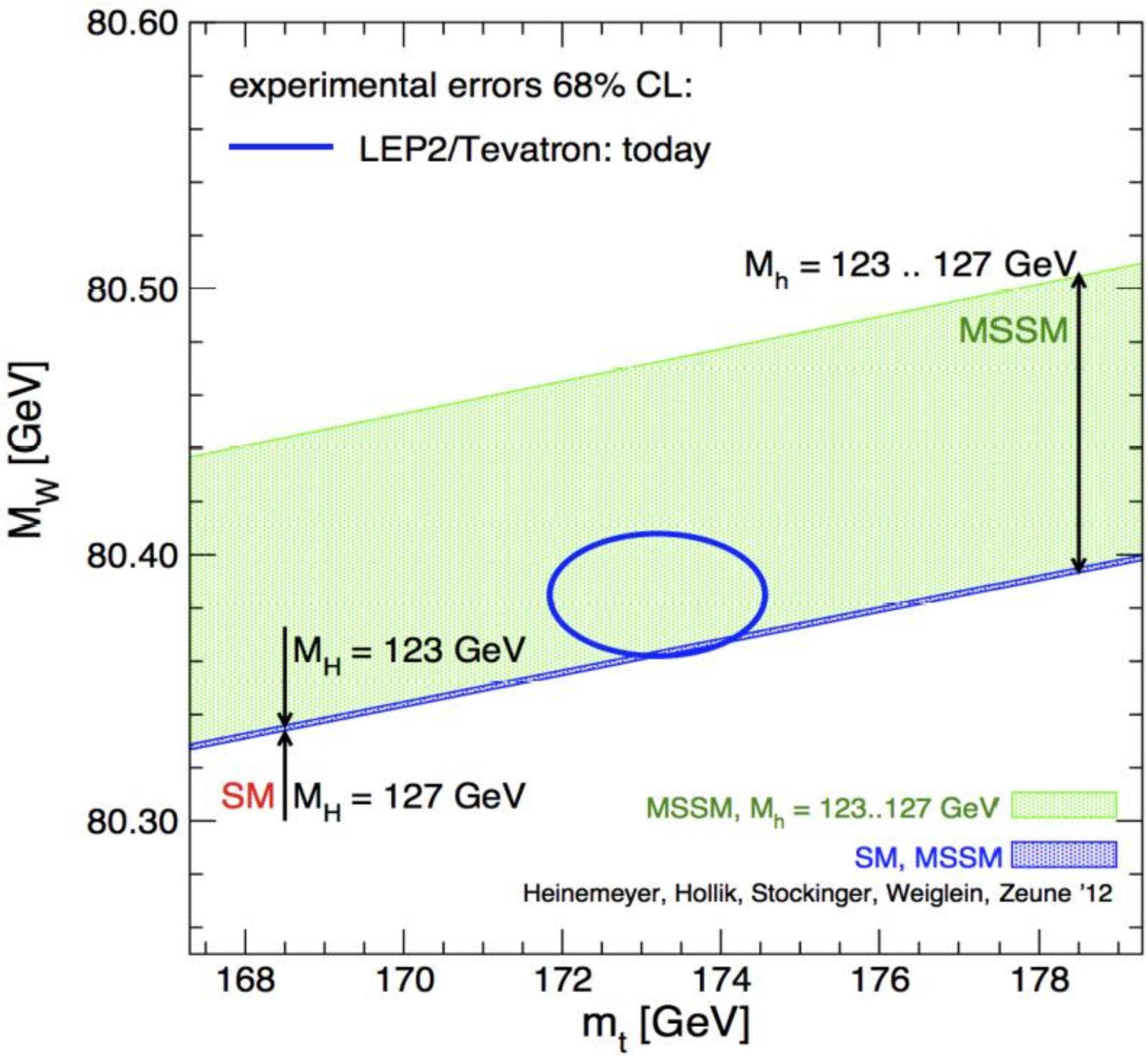
δM_{top} < 0.7 GeV/c²



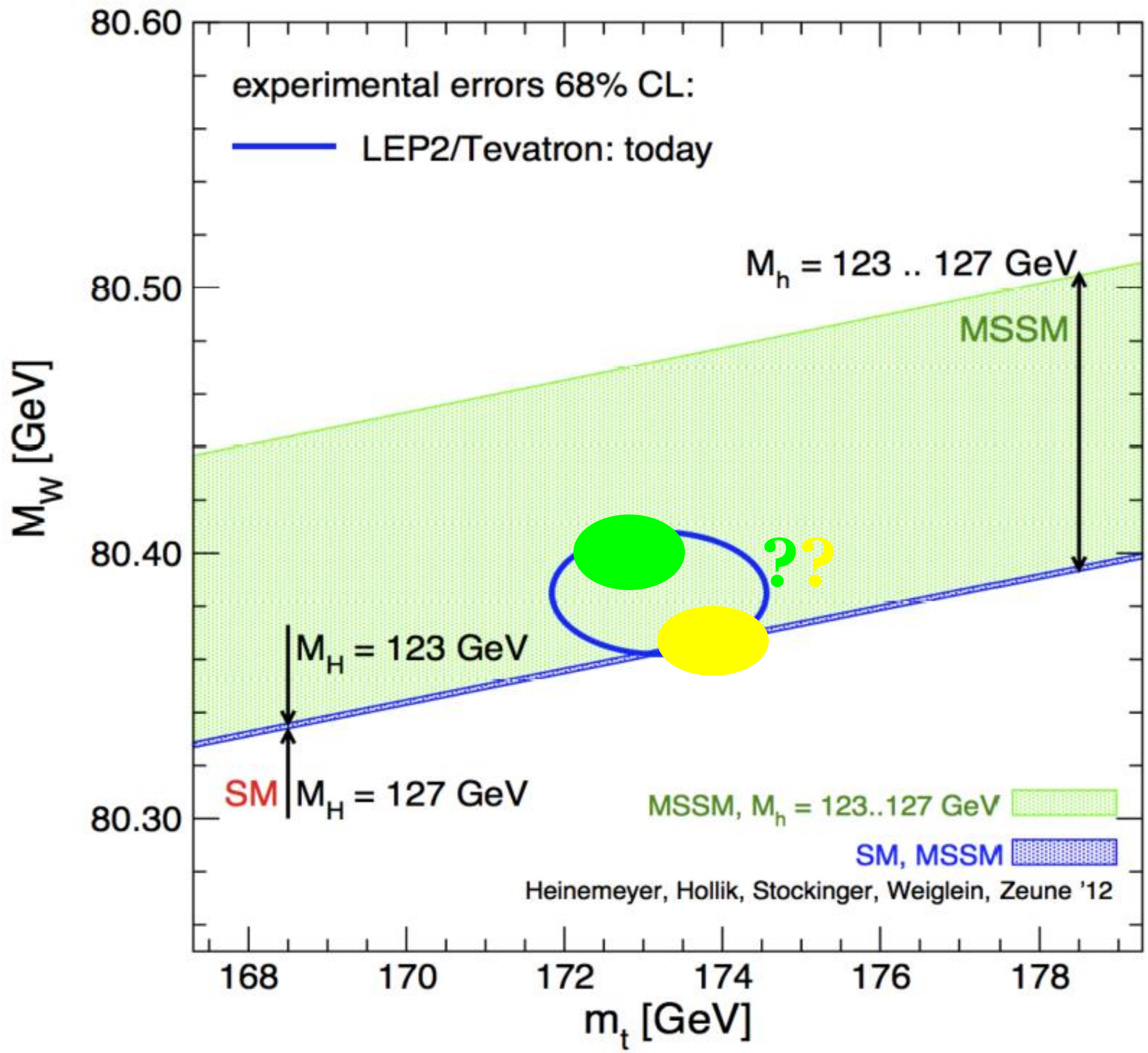
Test of Electroweak Quantum Loops



Current M_W and M_{top}



Future with half uncertainty?



Summary

- M_W and M_{top} are very interesting parameters to measure with increasing precision and have been measured precisely at Tevatron
- Tevatron combinations are

$$M_W = 80387 \pm 16\ \text{MeV}/c^2$$

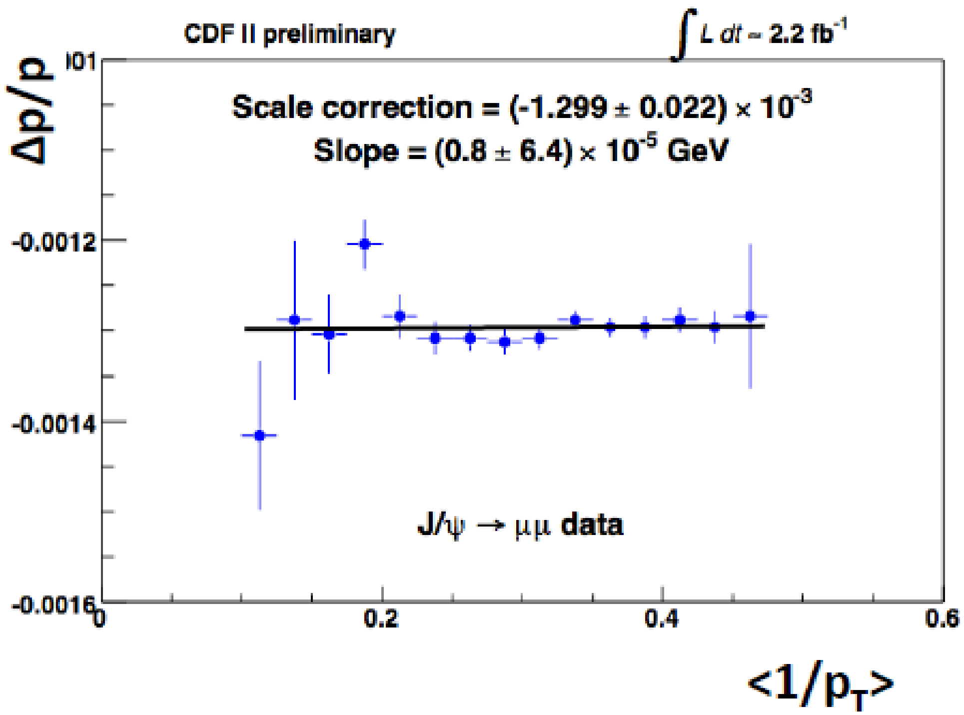
  - World average of $M_W = 80385 \pm 15\ \text{MeV}/c^2$

$$M_{\text{top}} = 173.20\ \pm 0.87\ \text{GeV}/\text{c}^2$$

- New global electroweak fit $M_{\text{H}} = 94^{+29}_{-24}\ \text{GeV}/c^2$ is consistent with direct measured $M_{\text{H}} \sim 125\ \text{GeV}/\text{c}^2$ within 1 standard deviation
- **Precision *W* boson and top quark mass measurements are still on going at the Tevatron**

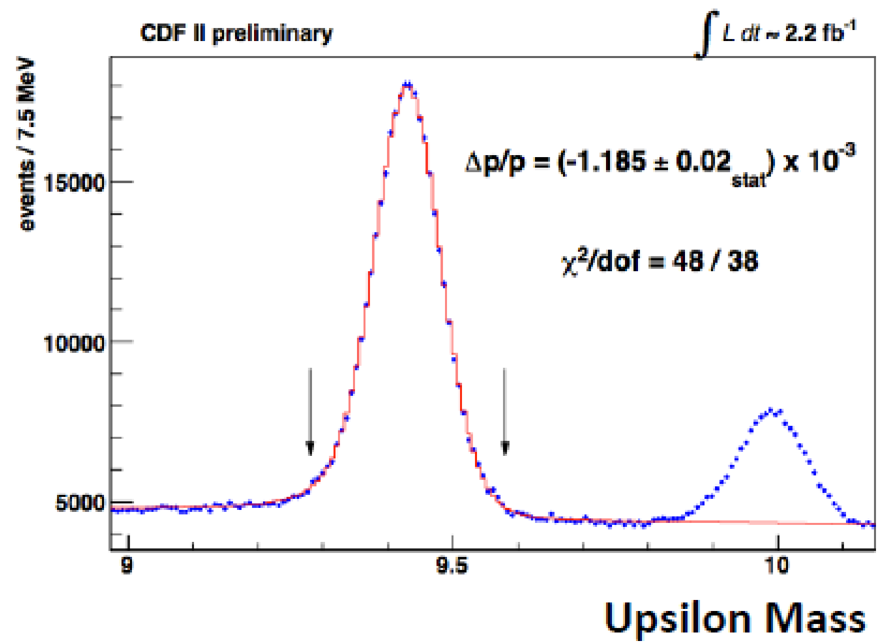
Backup

CDF lepton momentum scale



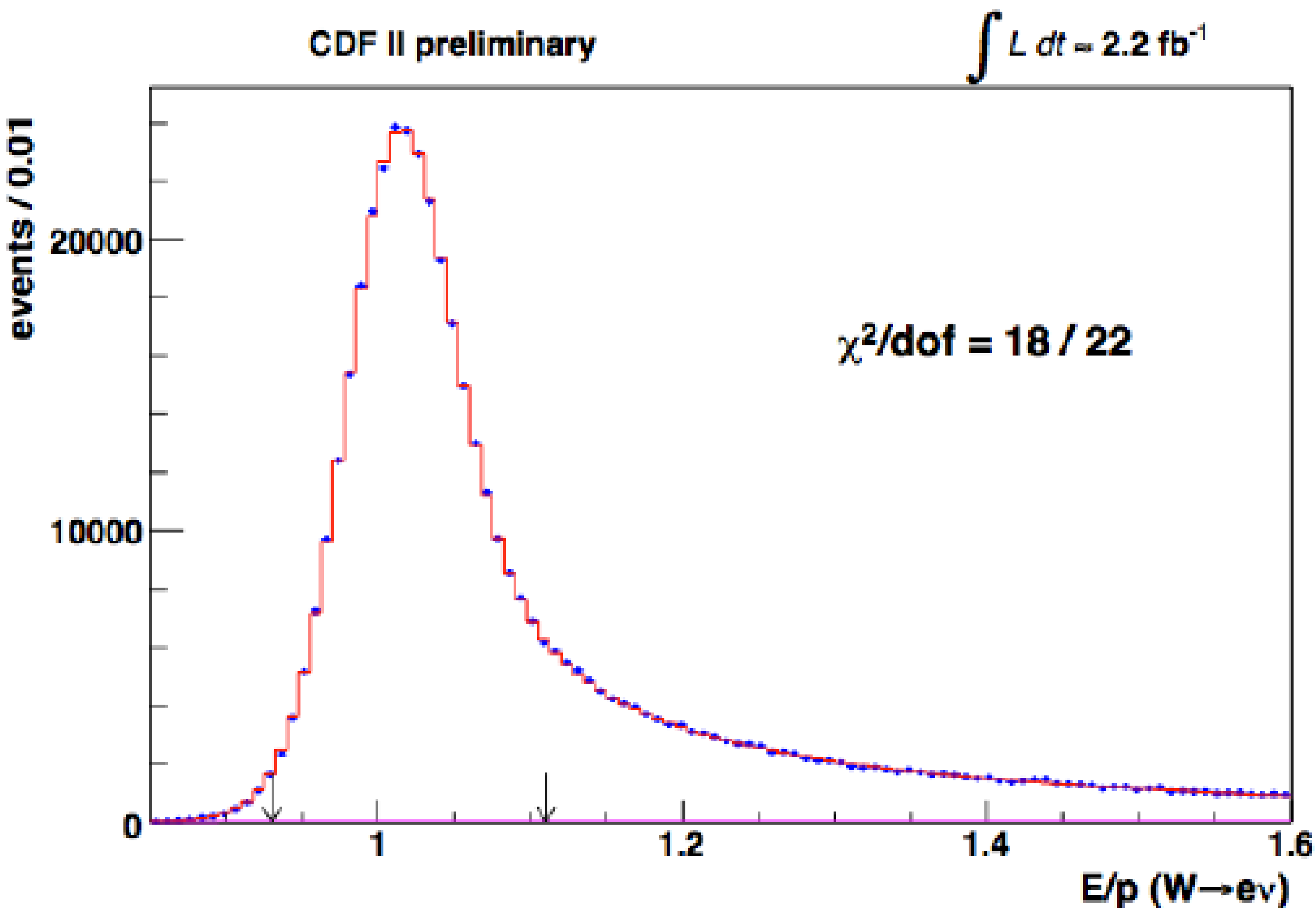
CDF MUONS

ΔM_W = 7 MeV



With this p-scale measured Z→μμ mass is: 7 ± 12 MeV below PDG

CDF E/p modeling

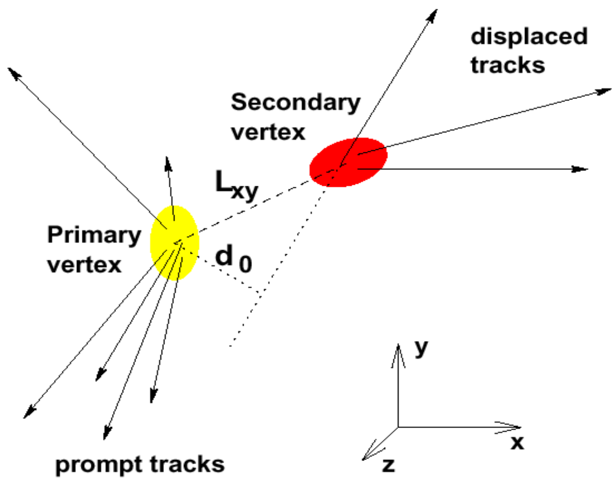


Systematic Uncertainties on m_T fit (MeV)

Source	CDF $m_T(\mu,\nu)$	CDF $m_T(e,\nu)$	DØ $m_T(e,\nu)$
Experimental – Statistical power of the calibration sample.			
Lepton Energy Scale	7	10	16
Lepton Energy Resolution	1	4	2
Lepton Energy Non-Linearity			4
Lepton Energy Loss			4
Recoil Energy Scale	5	5	
Recoil Energy Resolution	7	7	
Lepton Removal	2	3	
Recoil Model			5
Efficiency Model			1
Background	3	4	2
W production and decay model – Not statistically driven.			
PDF	10	10	11
QED	4	4	7
Boson p_T	3	3	2

B-tagging

- Top quark is almost always decay to a *b* quark and W boson



- B hadron can be identified by long displacement of secondary vertex
- B tagging reduce the number of jet-to-parton assignment
- B-tagging improve signal to background ratio
  - Usual B-tagging efficiency~40% with 0.5% fake

Sample **(CDF example)**	Di-lepton (e,μ)	Lepton+jets (e,μ)	All Hadronic NN selection
0-b-tags S/B	1:1	1:4	1:20
1-b-tags S/B	4:1	4:1	1:5
2-b-tags S/B	20:1	20:1	1:1
Events in 1 fb^{-1} ($\geq$ 1 b-tag)	25	180	150 (2 b-tags)

Measurement technique (Matrix element technique)

- Try to extract as much information as possible from every event using theoretical prediction for $t\bar{t}$ production and decay
- Integrate over unknown parton energies given a measured jet energy
- For each event, we calculate probability to be $t\bar{t}$ with certain mass M_{top}

Transfer function between parton and detector response

$$P(\vec{x}; M_{top}, JES) \propto \int ME \times TF \times PDF$$

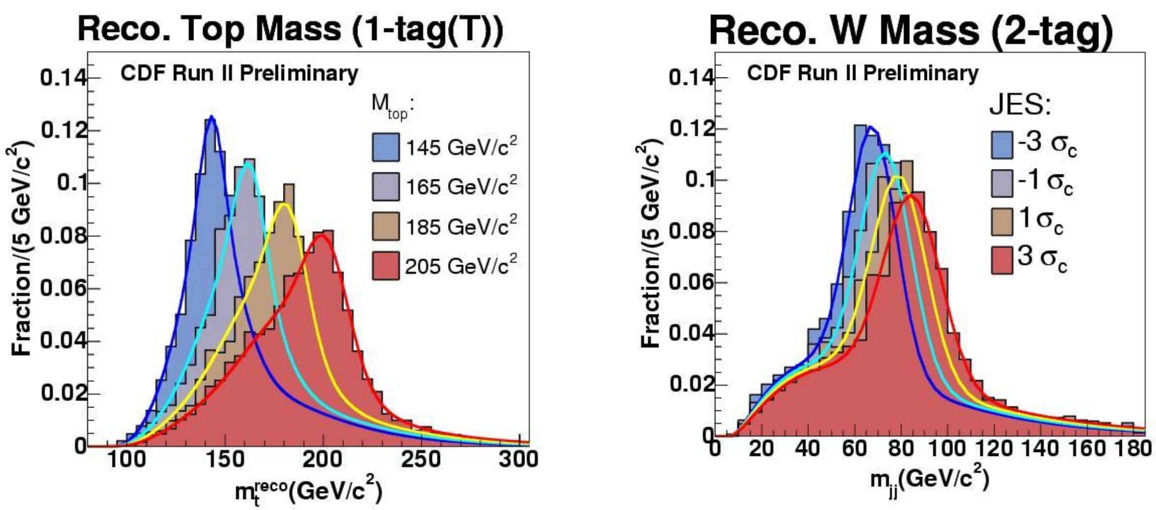
$t\bar{t}$ Matrix element

Parton distribution function

- Background probability is also calculated using background matrix element
- Perform the maximum likelihood fit to extract M_{top}

Measurement technique (template method)

- Identify variables $\vec{x}$ sensitive to M_{top} (or JES)
- Using MC, generate signal distribution of $\vec{x}$ as a function of M_{top} (or JES)
- Parametrize templates in terms of probability density function then assign the probability for certain mass and JES

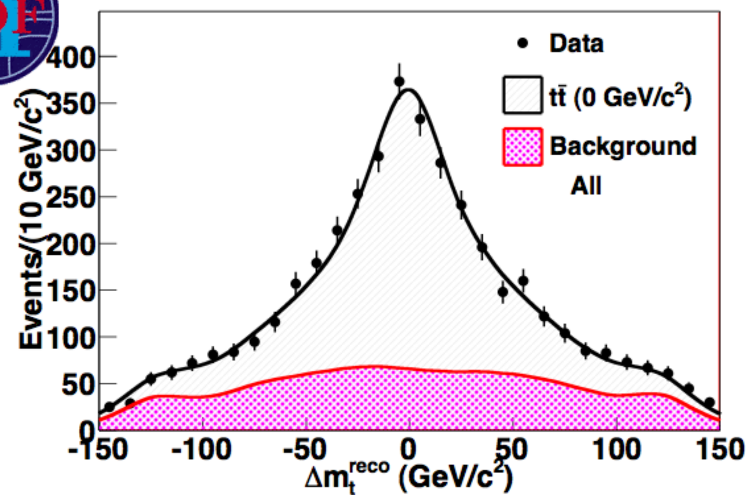


$$P(\vec{x}; M_{top}, \Delta JES)$$

- Construct likelihood based on probabilities

t and $\bar{t}$ mass difference

- If CPT is conserved, ΔM_{top} should be zero (SM)
- We test this assumption by measuring ΔM_{top}
- We use similar technique with mass measurements



ME technique but allow different mass of top and anti-top

3.6 fb^{-1} Lepton+Jets

$\Delta M_{top} = +0.8 \pm 1.9$ GeV/c^2

Phys. Rev. D 84, 052005 (2011)

8.7 fb^{-1} Lepton+Jets

Kinematic reconstruction and template fit

$\Delta M_{top} = -1.95 \pm 1.26$ GeV/c^2

Phys. Rev. D 87, 052013 (2013)