New results on top-quark mass, including new methods, from the Tevatron

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on behalf of the CDF and D0 collaborations

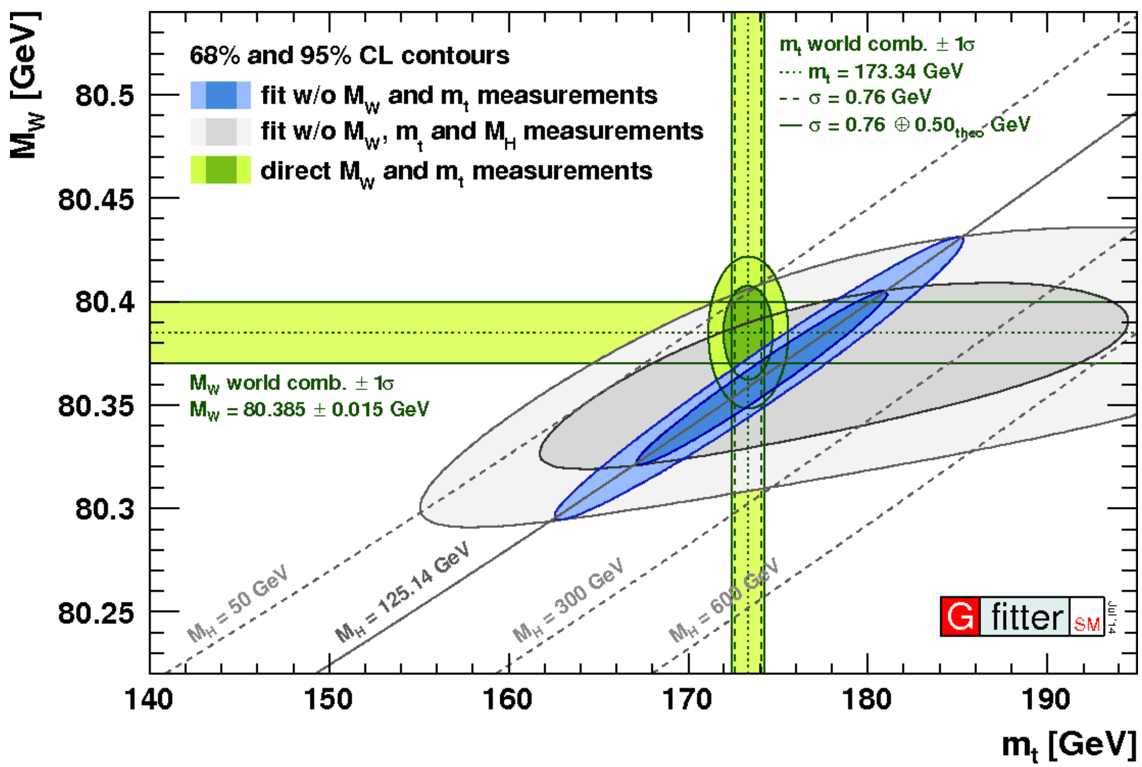
Outline

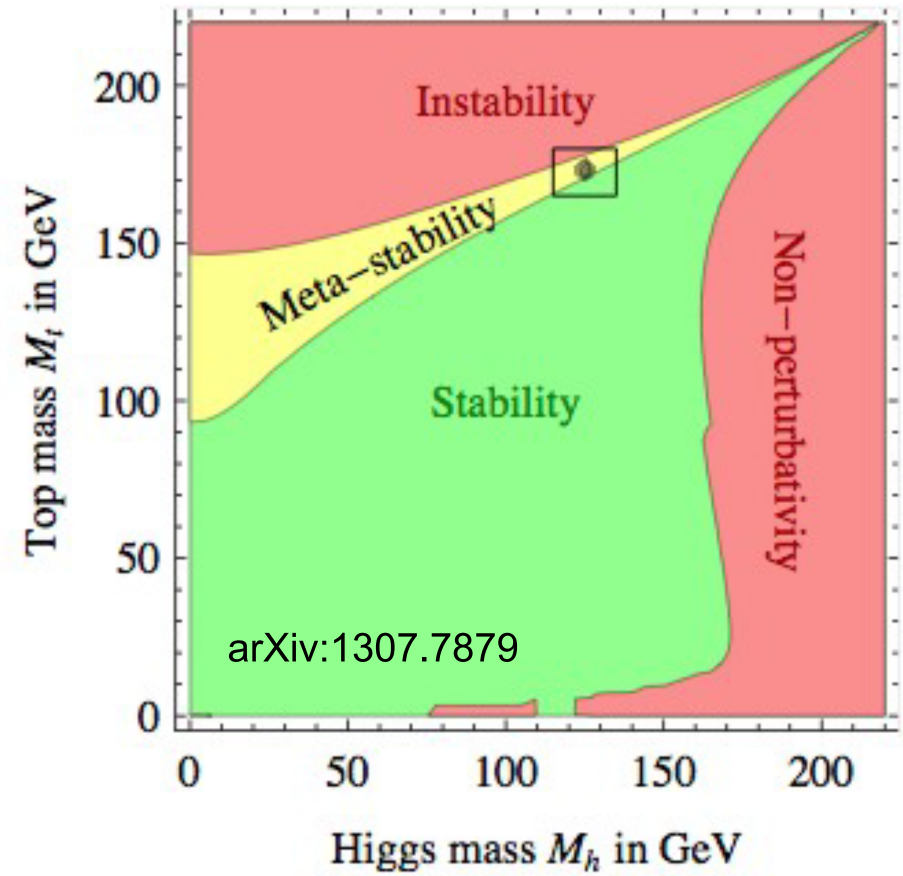
- Introduction
- Matrix element method in lepton+jets (D0)
- All-hadronic top mass measurement (CDF)
- MET+jets (CDF)
- Tevatron top mass combination
- Dilepton channel
  - D0
  - CDF
- Pole mass from cross-section (D0)
  - Inclusive and differential
- Conclusions

- Cover most recent and sensitive results in this talk
- All results presented use the full Run II dataset 9-10 fb^{-1}

Purpose of top quark mass measurement

- Self-consistency of the standard model
- Stability of the universe





- Develop detailed understanding
  - Of detector
  - Of theoretical top quark modeling

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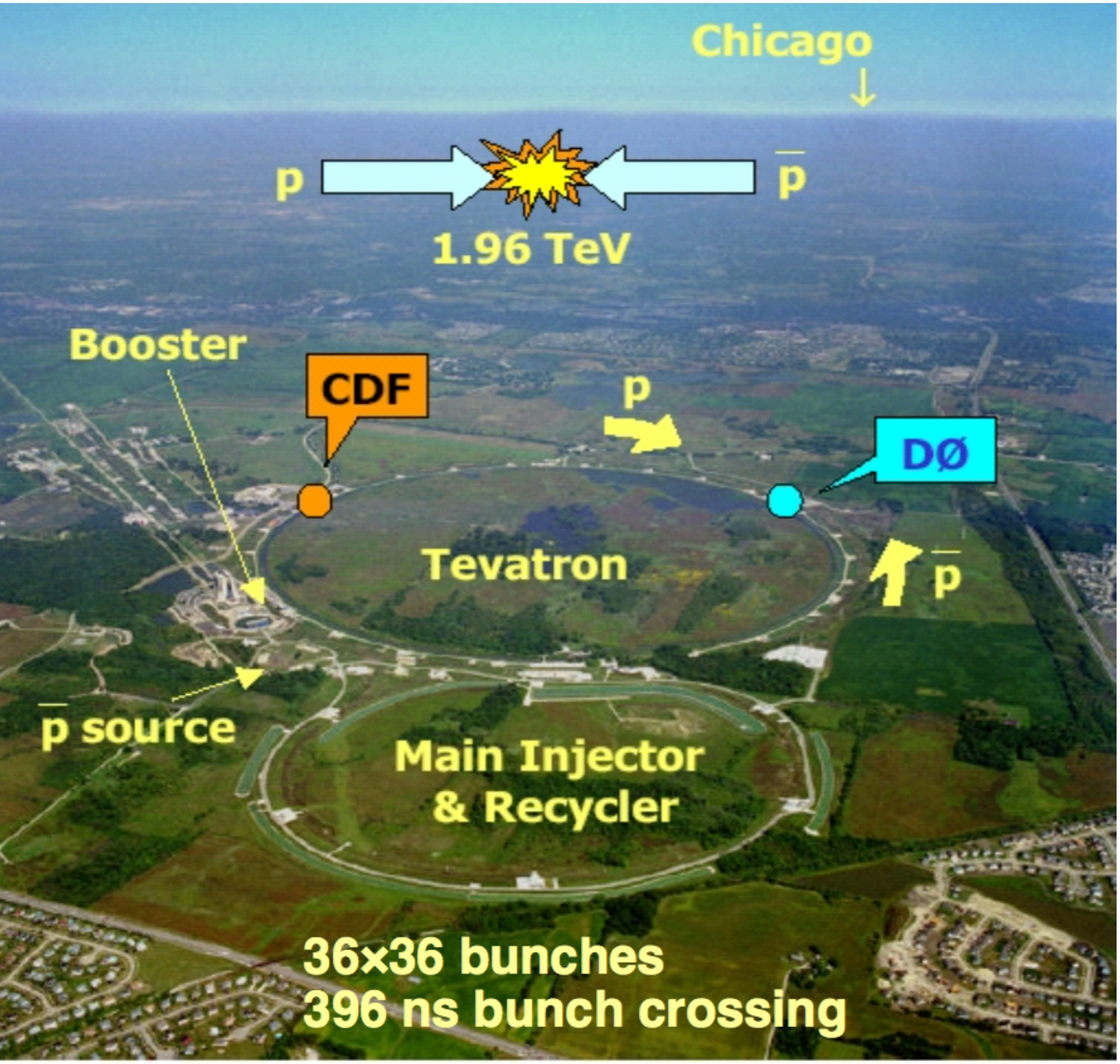
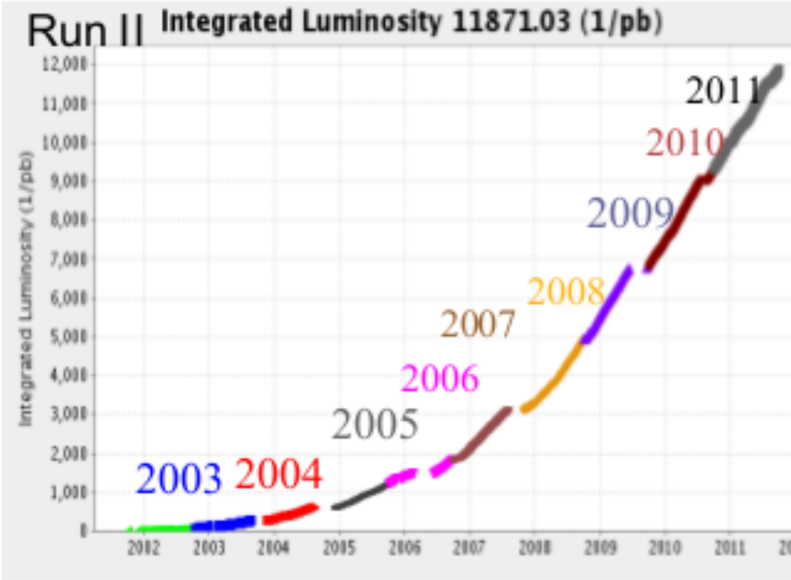
Tevatron, CDF and D0



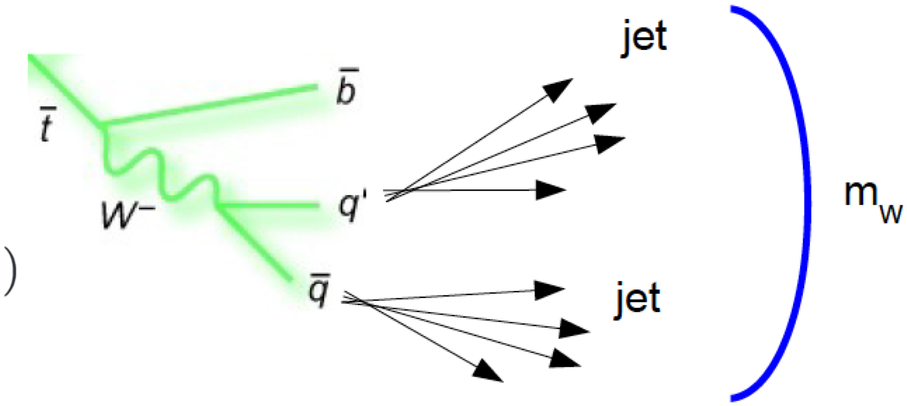
- 1.96 TeV
- 10 fb^{-1} of proton-antiproton collision data



lepton+jets: Matrix Element Method

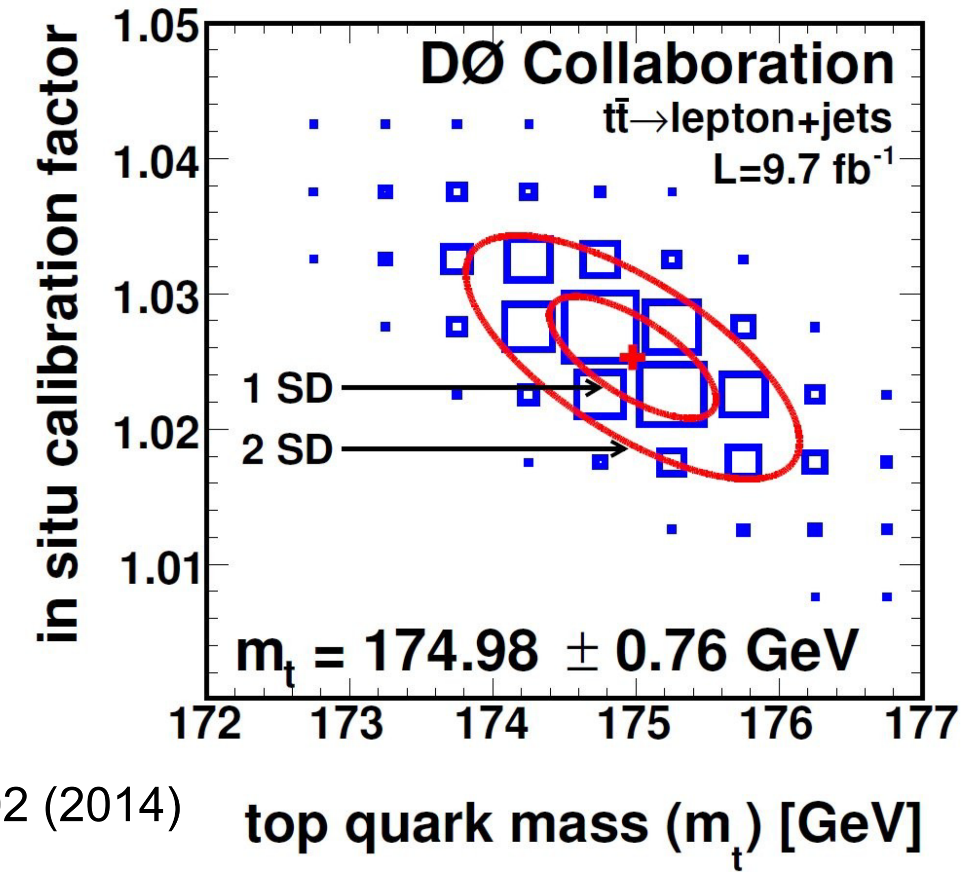
- Use full event kinematic information by applying matrix element method

$$P_{\text{sig}} = \frac{1}{\sigma_{\text{obs}}^{t\bar{t}}(m_t, k_{\text{JES}})} \int \sum \mathrm{d}\sigma(\vec{y}, m_t)\mathrm{d}\vec{q}_1\mathrm{d}\vec{q}_2 f(\vec{q}_1) f(\vec{q}_2) \times W(\vec{x}, \vec{y}; k_{\text{JES}})$$



  - Define likelihood from matrix elements (dσ), PDF (*f*), transfer functions (W) (parton<-> jets)
  - Integrate over unmeasured quantities
  - CPU demanding

- 2D measurement of jet energy calibration factor and top quark mass



Phys. Rev. Lett. 113, 032002 (2014)
PRD 91, 112003 (2015)

lepton+jets: Matrix Element Method

- Largest systematic uncertainties:

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections	+0.15
Hadronization and UE	+0.26
Detector modeling:	
Residual jet energy scale	±0.21
Flavor-dependent response to jets	±0.16

- Precise top quark mass measurement:

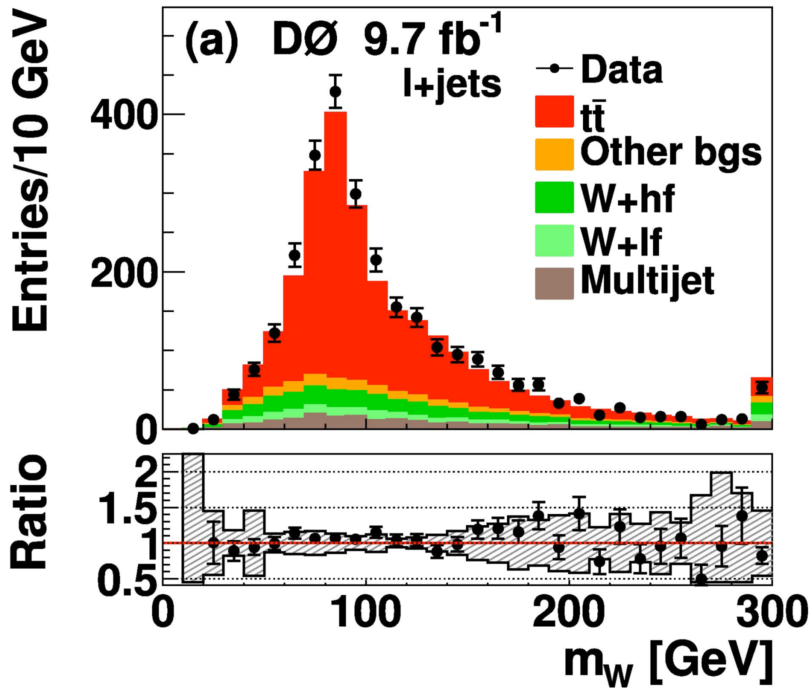
m_t = 174.98 ± 0.58 (stat.) ± 0.49 (syst) GeV

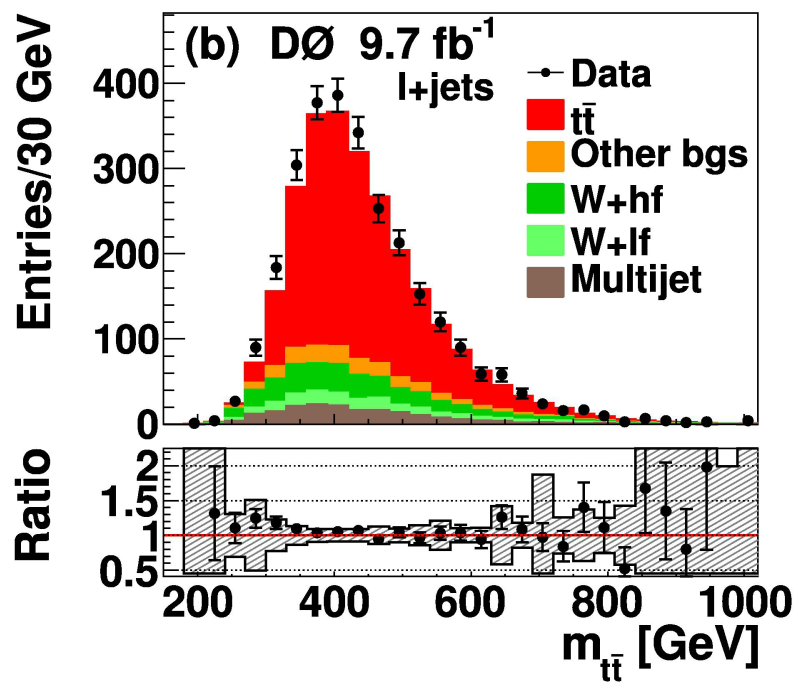
m_t = 174.98 ± 0.76 (total) GeV

0.43% relative uncertainty

Phys. Rev. Lett. 113, 032002 (2014)

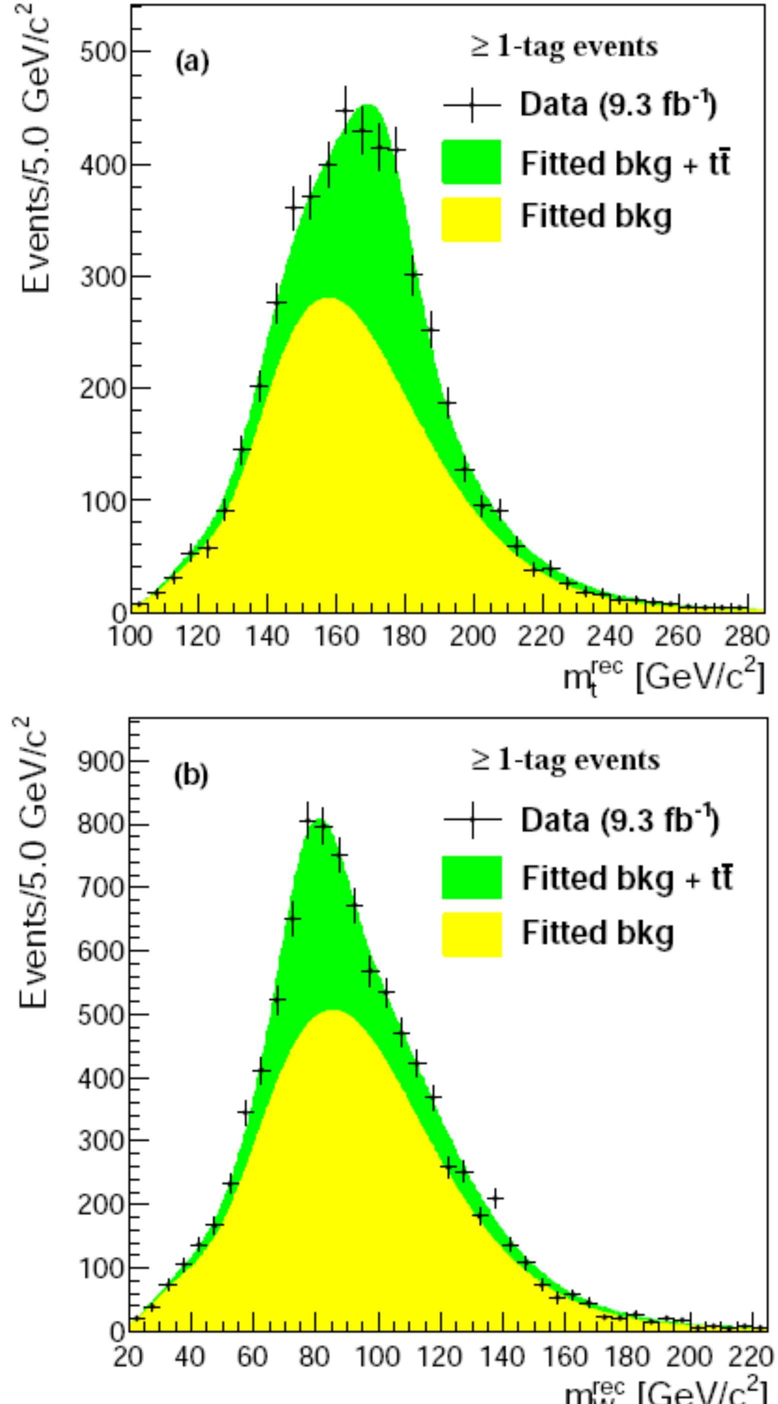
- Details and checks in PRD: PRD 91, 112003 (2015)





All-jet measurement

- Event selection
  - 6 – 8 jets
    - p_T > 15 GeV, $|\eta| \le 2.0$
  - 1-3 b-tags
  - MET significance cut + NN discrimination
- Background modeling:
  - Pretag sample times b-tagging rate
  - Use correction factors for multiple b-quarks per events from background dominated samples (inverse NN cut)
  - All possible combinations are taken into account
- Top quark mass from template fit to m_{top}^{rec} and m_W^{rec} in data



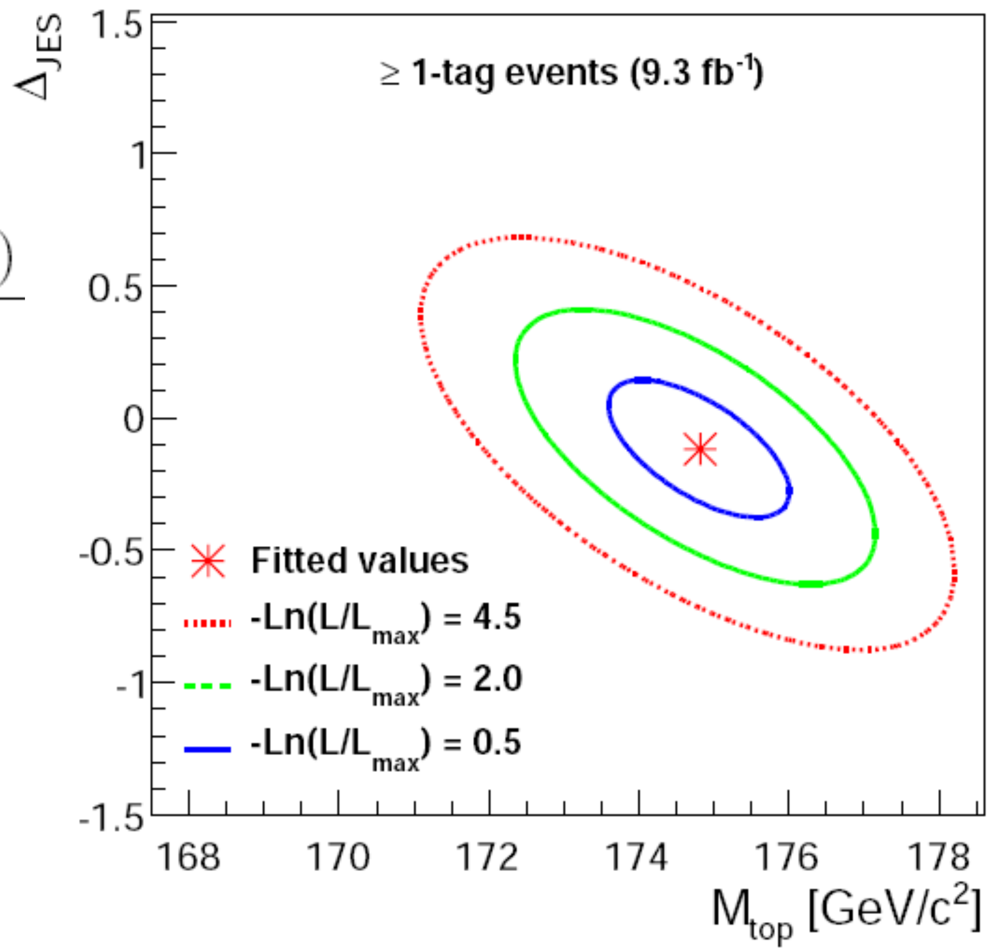
Phys.Rev. D90 (2014) 9, 091101

All-jet measurement

- 2D measurement of jet energy calibration factor and top quark mass

- Largest systematic uncertainties:

Source	$\sigma_{M_{\text{top}}}$ (GeV/c^2)
Generator (hadronization)	0.29
Parton distribution functions	$^{+0.18}_{-0.36}$
Color reconnection	0.32
Δ_{JES} fit	0.97
Other free parameters of the fit	0.41
Templates sample size	0.34
Residual JES	0.57



$$M_{\text{top}} = 175.07 \pm 1.19\,(\text{stat})\;{}^{+1.55}_{-1.58}\,(\text{syst})\;\text{GeV}/c^2$$

1.1% relative uncertainty

Phys.Rev. D90 (2014) 9, 091101

MET+jets

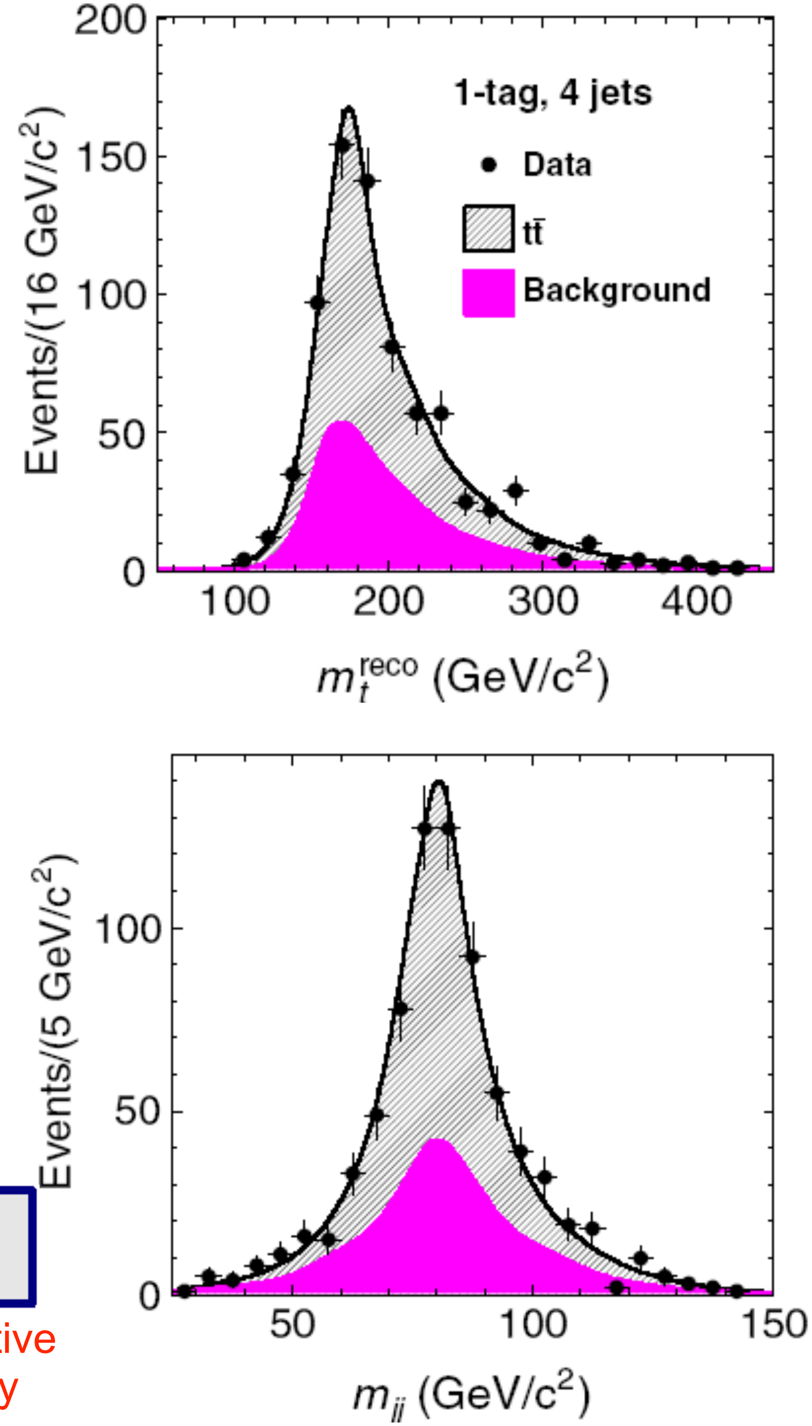
- Event selection similar to lepton+jets
- Except: No identified leptons
  - MET significance > 3 $GeV^{1/2}$
  - 4-6 jets
  - topological cuts + NN discriminant cut
  - Use b-tagging to classify events
- Top reconstruction procedure similar to lepton+jets
- Largest systematic uncertainties:

Source	Uncertainty (GeV/c^2)
Residual jet-energy scale	0.44
MC generator	0.36
Color reconnection	0.28
gg fraction	0.27
Radiation	0.28

M_{top} = 173.93 ± 1.64 (stat+JES) ± 0.87 (syst) GeV

1.1% relative uncertainty

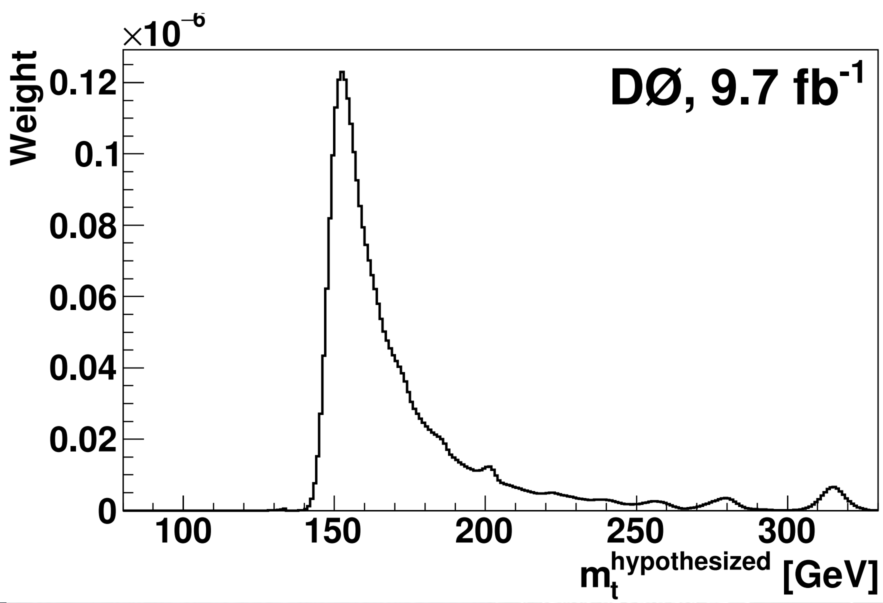
PRD (R) 88 011101 (2013)



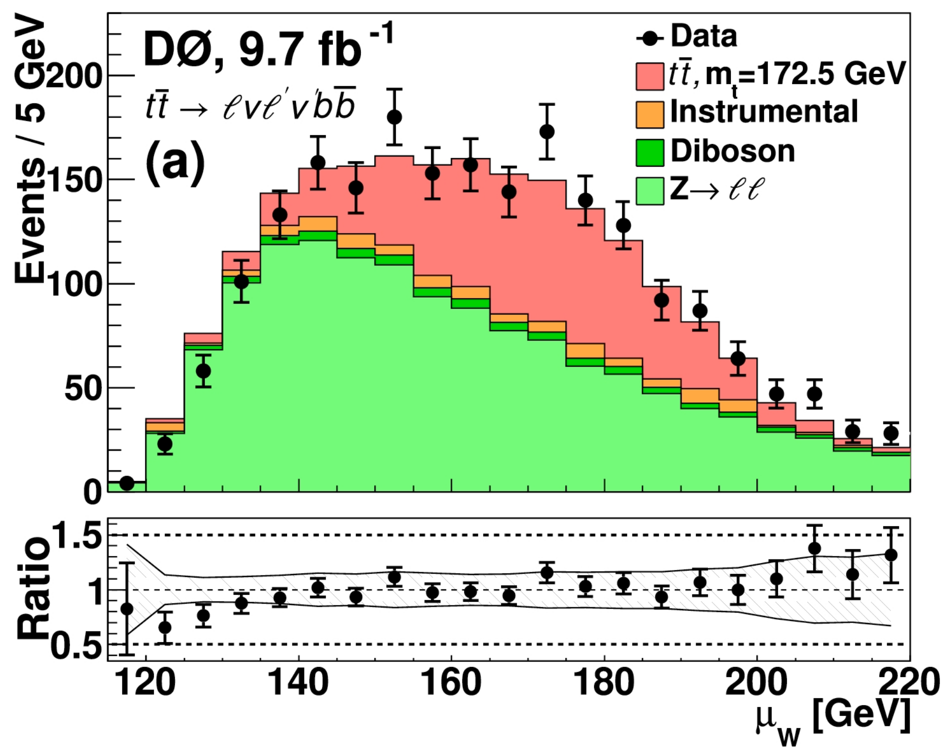
Dilepton neutrino weighting

- 2 leptons, p_T > 15 GeV
- 2 jets, 1 b-jet
- Backgrounds from Z+jets, Dibosons, instrumental
- For each event, scan $m_t^{hypothesized}$ to calculate a weight w for each possibility for the momenta of the two neutrinos:

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



- First two moments of w distribution give top mass sensitivity (μ_w, σ_w)
- Comprehensive optimization of method parameters



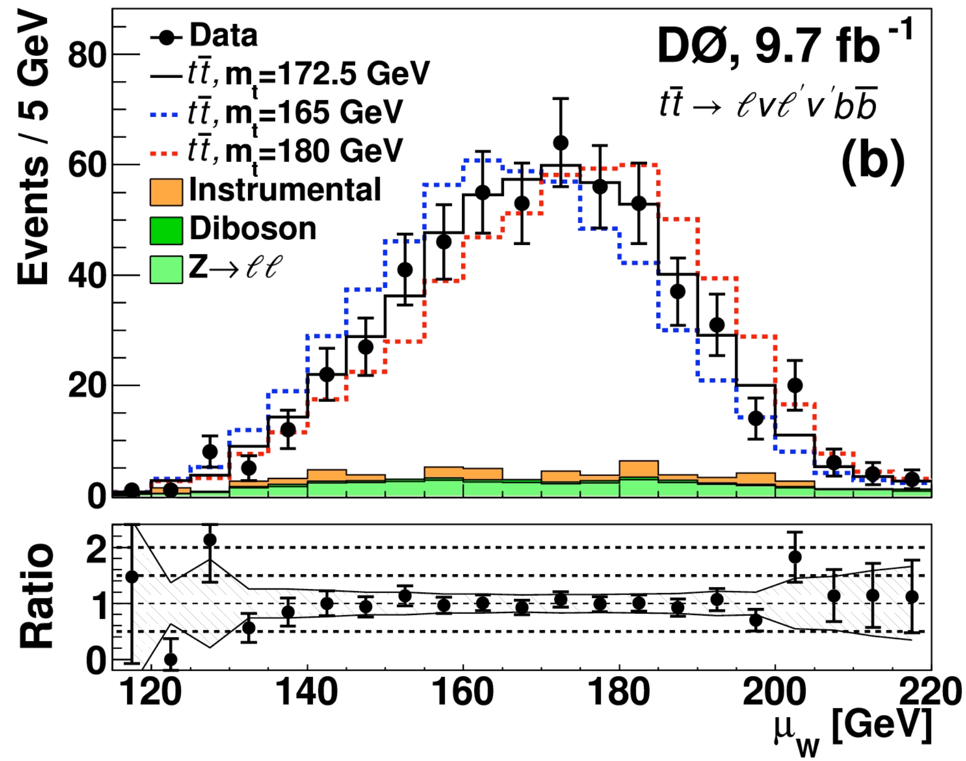
PLB 757, 199 (2016)

Neutrino weighting measurement

- Apply jet energy calibration from lepton+jets measurement

- Largest systematic uncertainties:

Source	σ_{m_t} [GeV]
Jet energy calibration	
Absolute scale	∓ 0.47
Flavor dependence	∓ 0.27
Residual scale	$^{+0.36}_{-0.35}$
Signal modeling	
Higher-order effects	-0.33
Color reconnection	-0.22



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

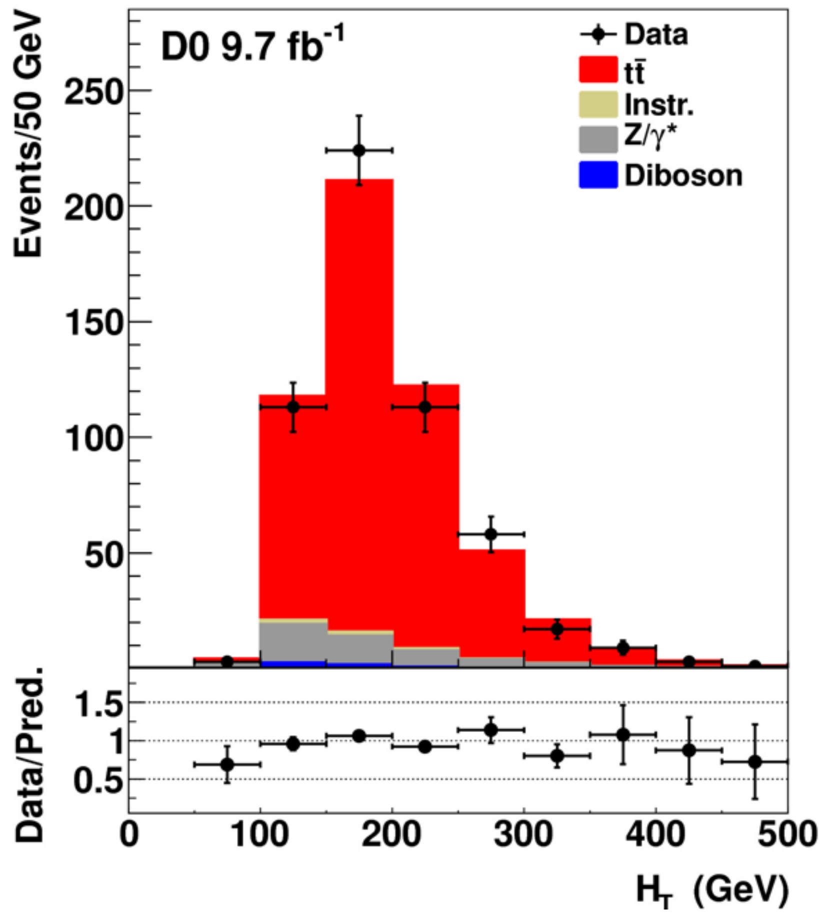
0.9% relative uncertainty

arXiv:1508.03322

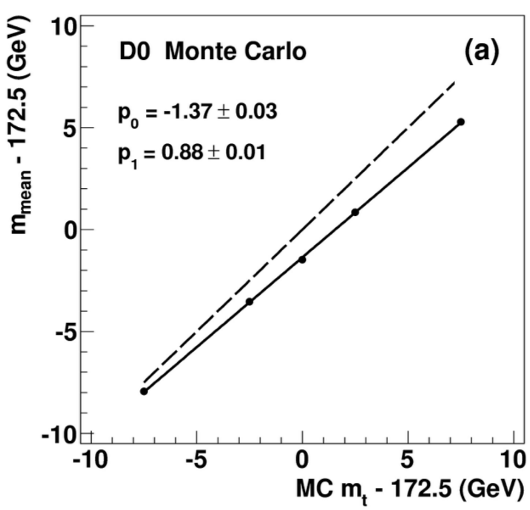
- Most precise Tevatron dilepton measurement

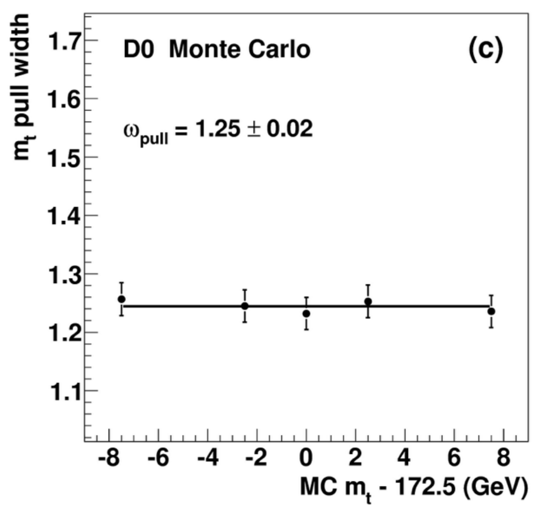
Dilepton matrix element

- 2 leptons, p_T > 15 GeV
- 2 jets, 1 b-jet
  - p_T > 20 GeV
- Backgrounds from Z+jets, Dibosons, instrumental
- Same matrix element calculation as in lepton+jets
  - But MET ambiguity
  - Requires additional integration



Calibration for top mass and statistical uncertainty





PRD 94, 032004 (2016)

Dilepton matrix element result

- JES constraint from lepton+jets measurement

Dominant systematic uncertainties

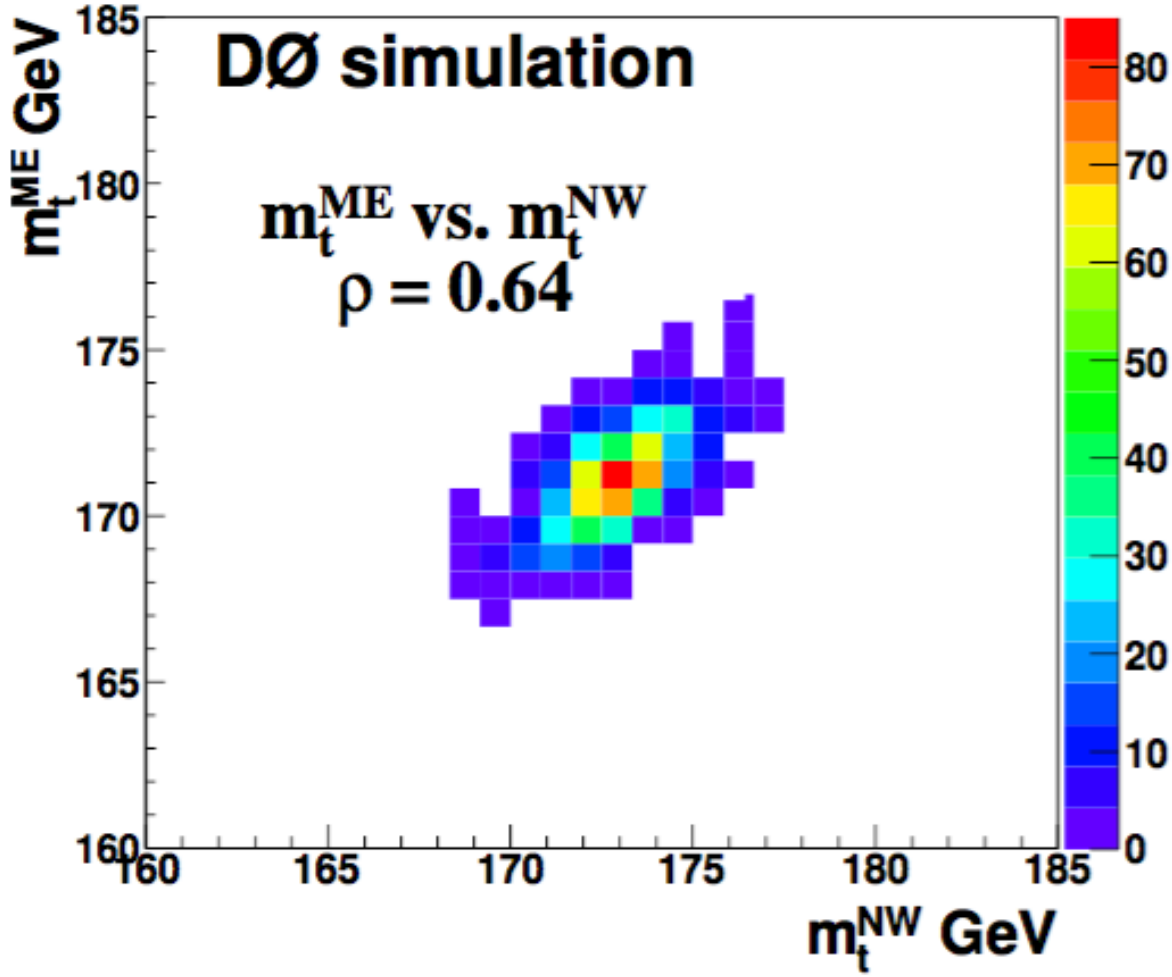
Source	Uncertainty (GeV)
Signal and background modeling:	
Higher order corrections	$+0.16$
ISR/FSR	± 0.16
Hadronization and UE	$+0.31$
Detector modeling:	
Residual jet energy scale	-0.20
Uncertainty on k_{JES} factor	∓ 0.46
Flavor dependent jet response	∓ 0.30
Total systematic uncertainty	± 0.88
Total statistical uncertainty	± 1.61
Total uncertainty	± 1.84

$$m_t = 173.93 \pm 1.61 \text{ (stat)} \pm 0.88 \text{ (syst) GeV}$$

PRD 94, 032004 (2016)

Dilepton combination

- Combination of 2 results:
  - Neutrino weighting
  - Matrix element
- Different selection cuts
- Same sources of systematic uncertainty
- Correlation from pseudo-experiments



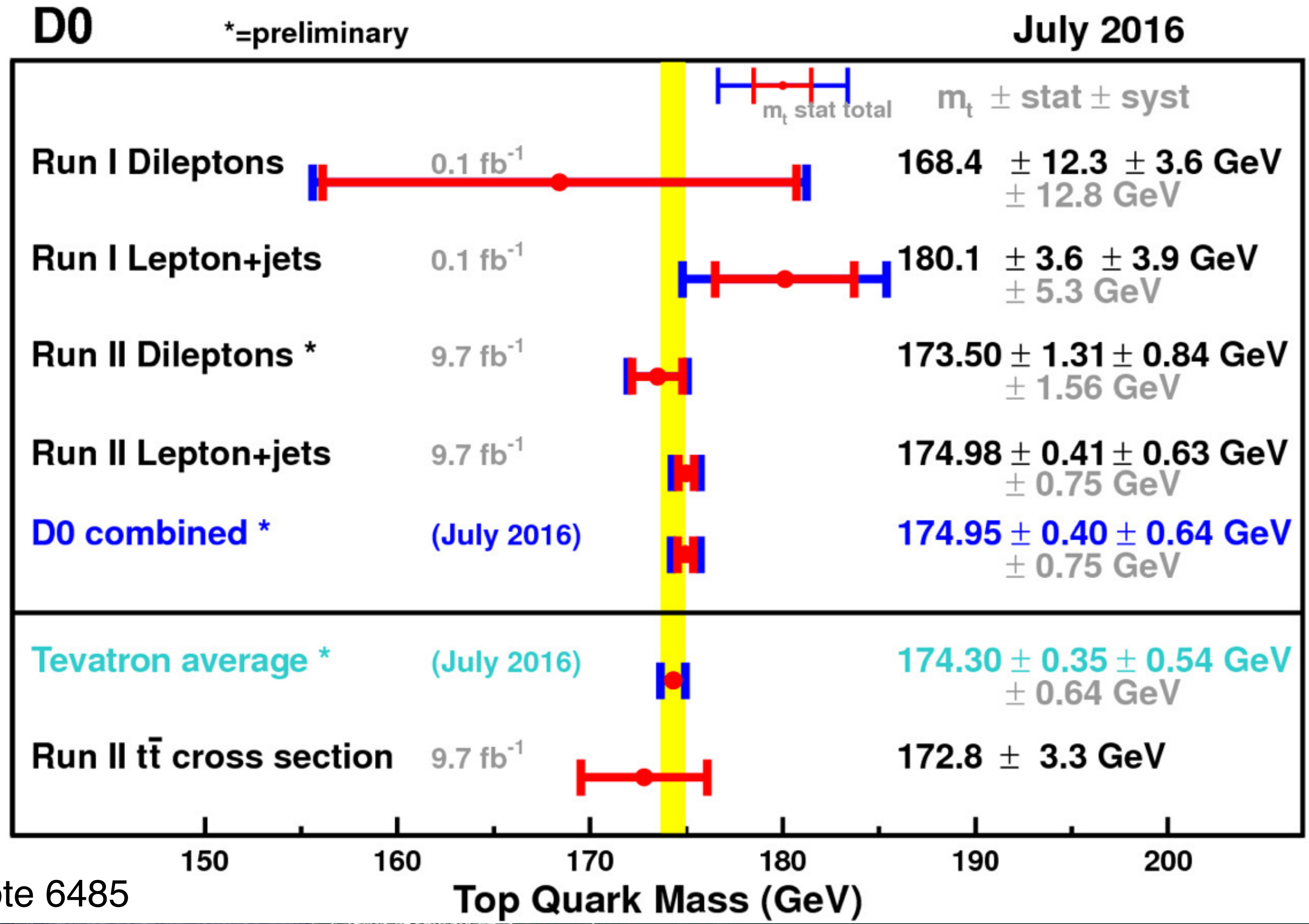
$$m_t = 173.50 \pm 1.31(\text{stat}) \pm 0.84(\text{syst})\ \text{GeV}$$

0.9% relative uncertainty

D0 note 6484

New D0 combination

- Update since 2011
  - New lepton+jets measurements
  - New dilepton measurements



0.4% relative uncertainty

D0 Note 6485

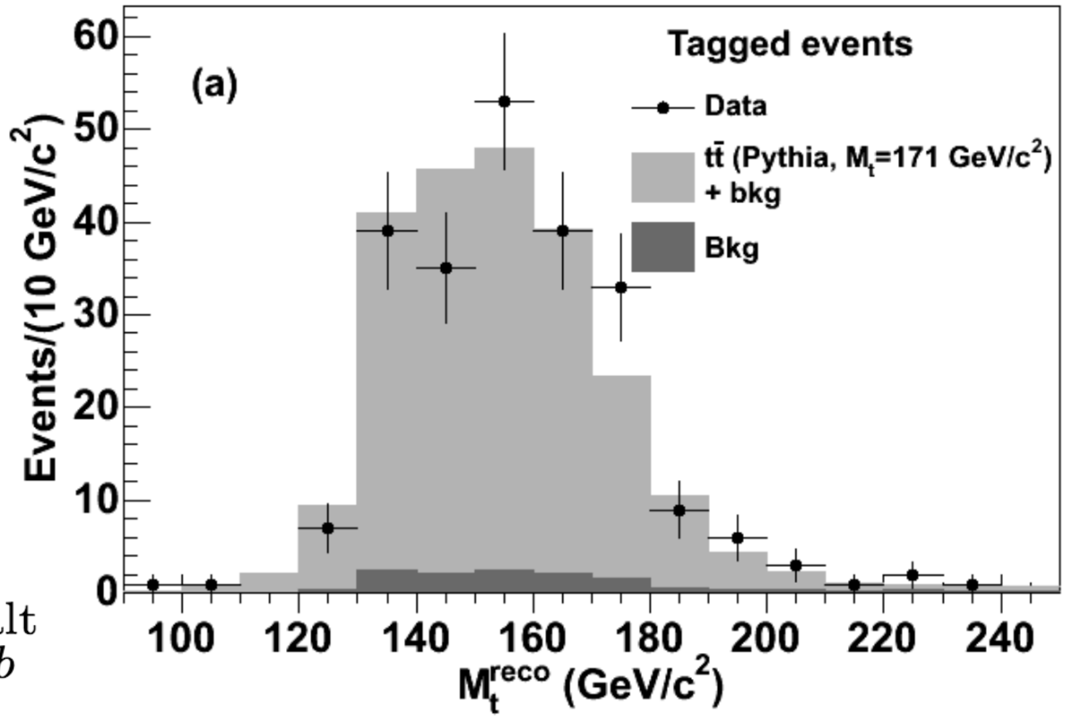
Dilepton measurement

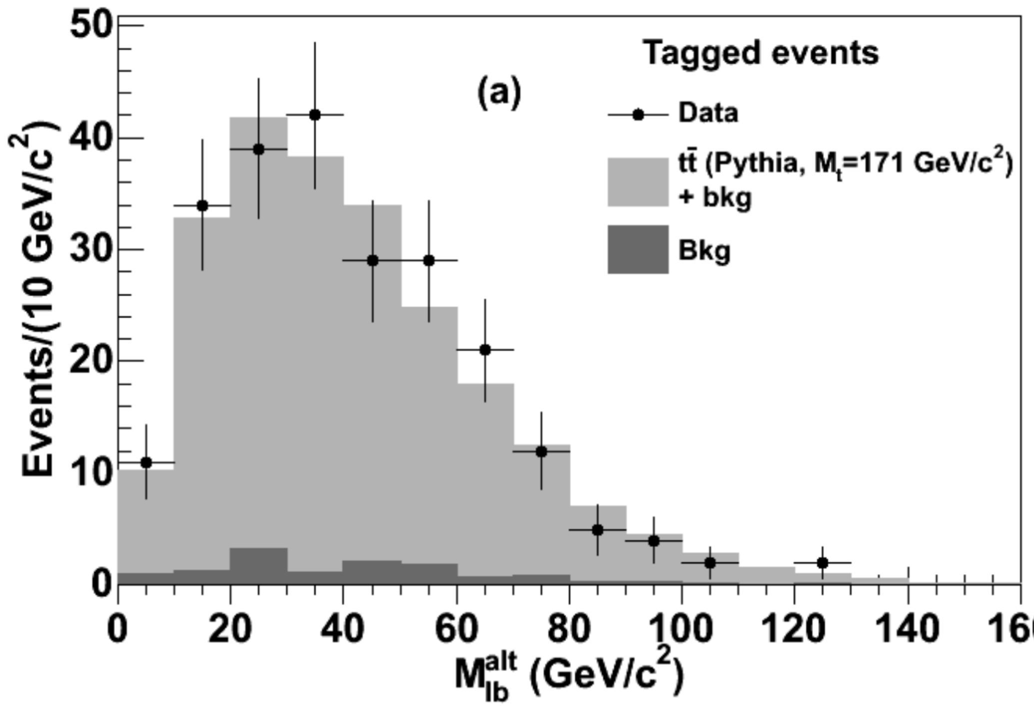
- Event selection
  - 2 leptons p_T > 20 GeV
  - MET > 25 GeV
  - H_T > 200 GeV
  - Z veto and topological cuts
- Reconstruct effective top quark mass

$$M^{\text{hyb}} = w \cdot M_t^{\text{reco}} + (1-w) \cdot M_{\ell b}^{\text{alt}}$$

  - w is optimized (=0.6)
  - M^{reco} is mass from neutrino weighting
  - M^{alt} is alternative, less JES dependence

$$M_{\ell b}^{\text{alt}} = c^2 \sqrt{\frac{\langle \ell_1, b_1 \rangle \cdot \langle \ell_2, b_2 \rangle}{E_{b_1} \cdot E_{b_2}}}$$



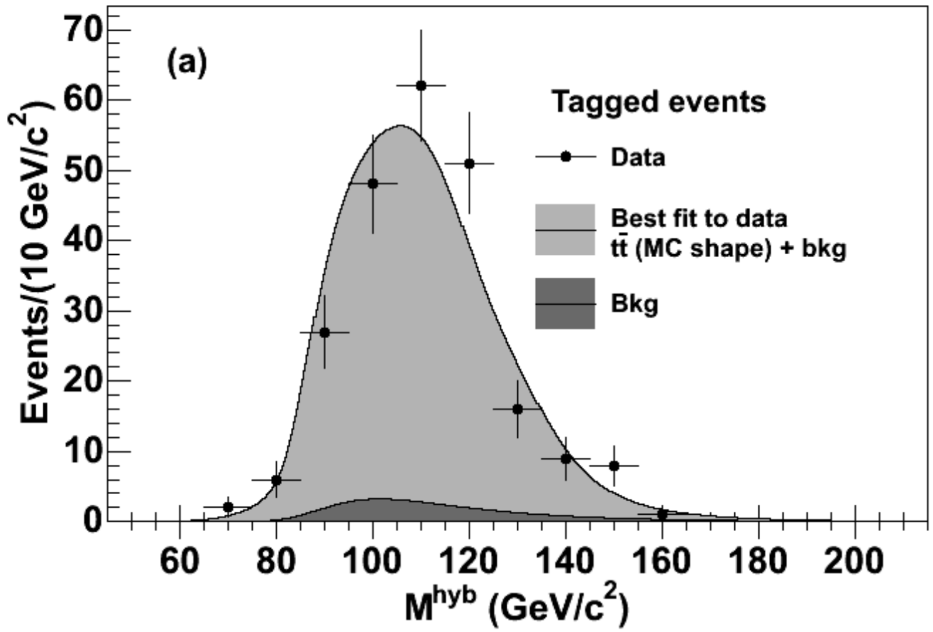


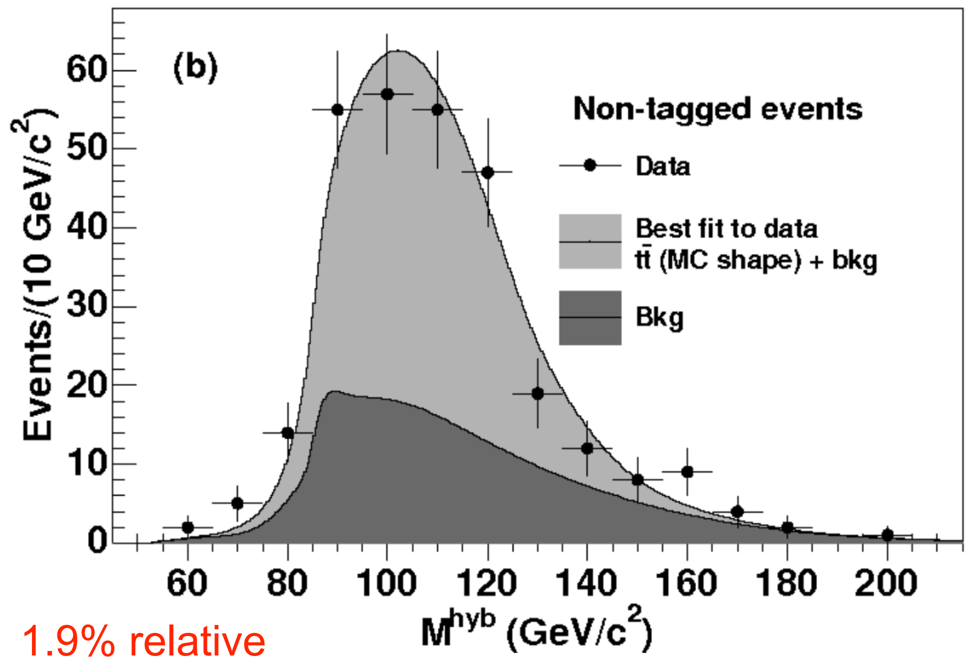
PRD 92 032003 (2015)

Dilepton measurement

- Largest systematic uncertainties:

Systematic uncertainties (GeV/c^2)	
Jet-energy scale	2.2
NLO effects	0.7
Monte Carlo generators	0.5





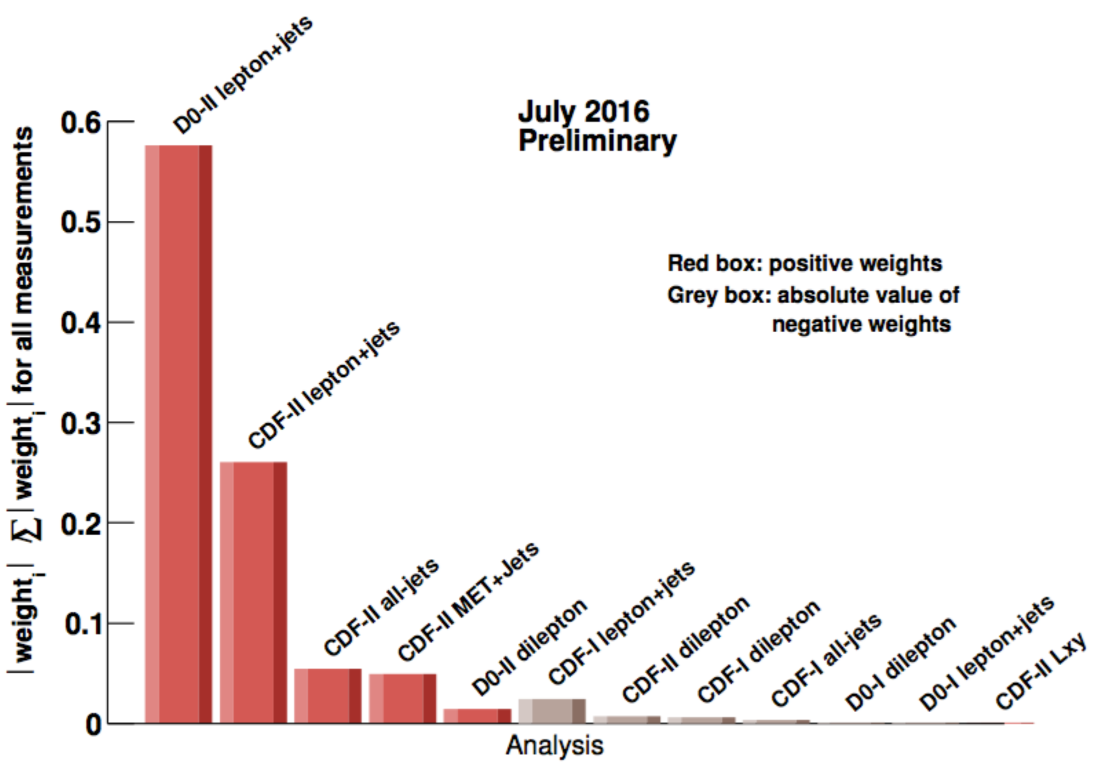
M_{top} = 171.5 ± 1.9 (stat) ± 2.5 (syst) GeV/c^2

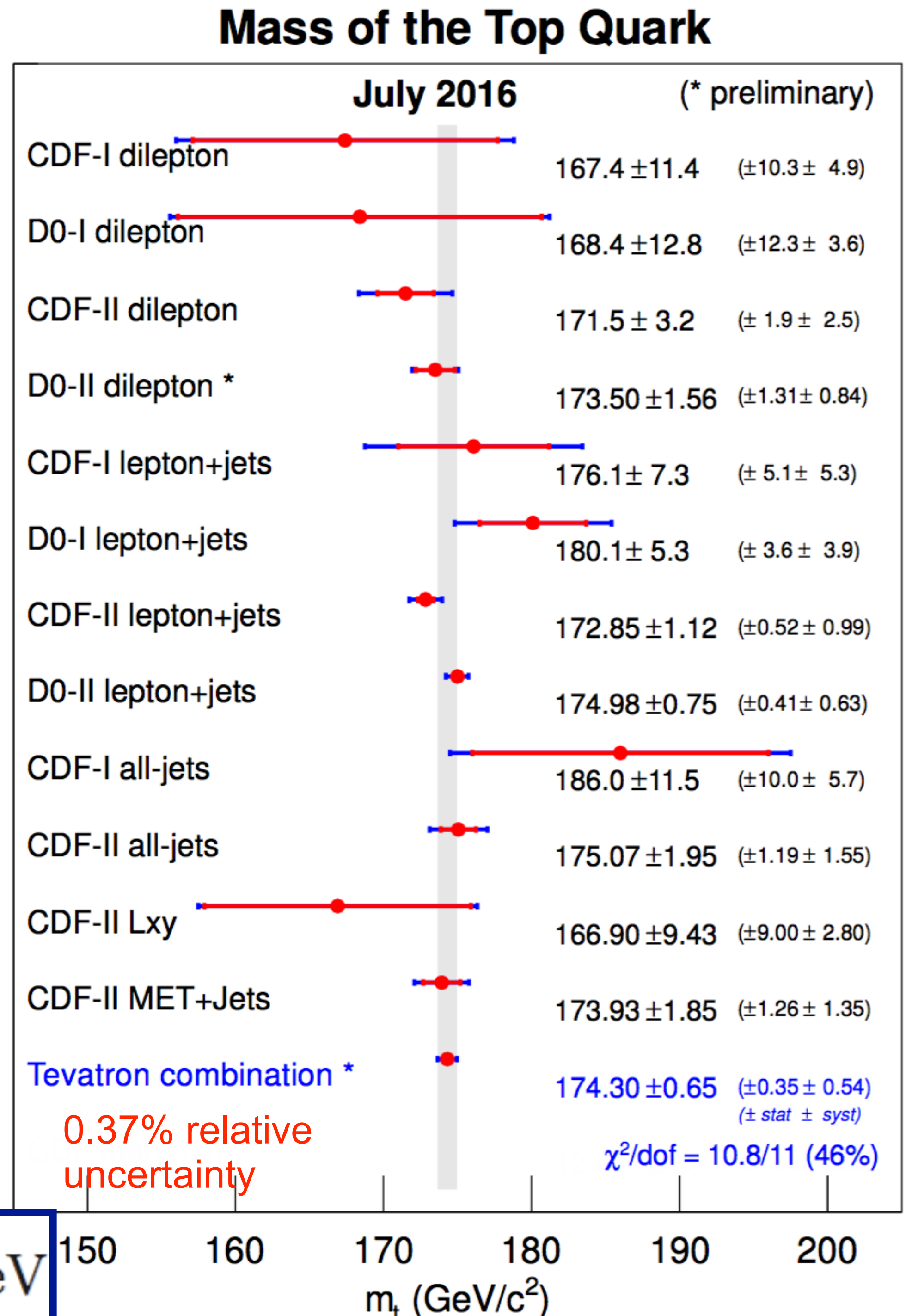
1.9% relative uncertainty

PRD 92 032003 (2015)

Tevatron top quark mass combination

- First new combination since 2014
  - Central value decreases by 40 MeV
  - Total uncertainty unchanged: 650 MeV





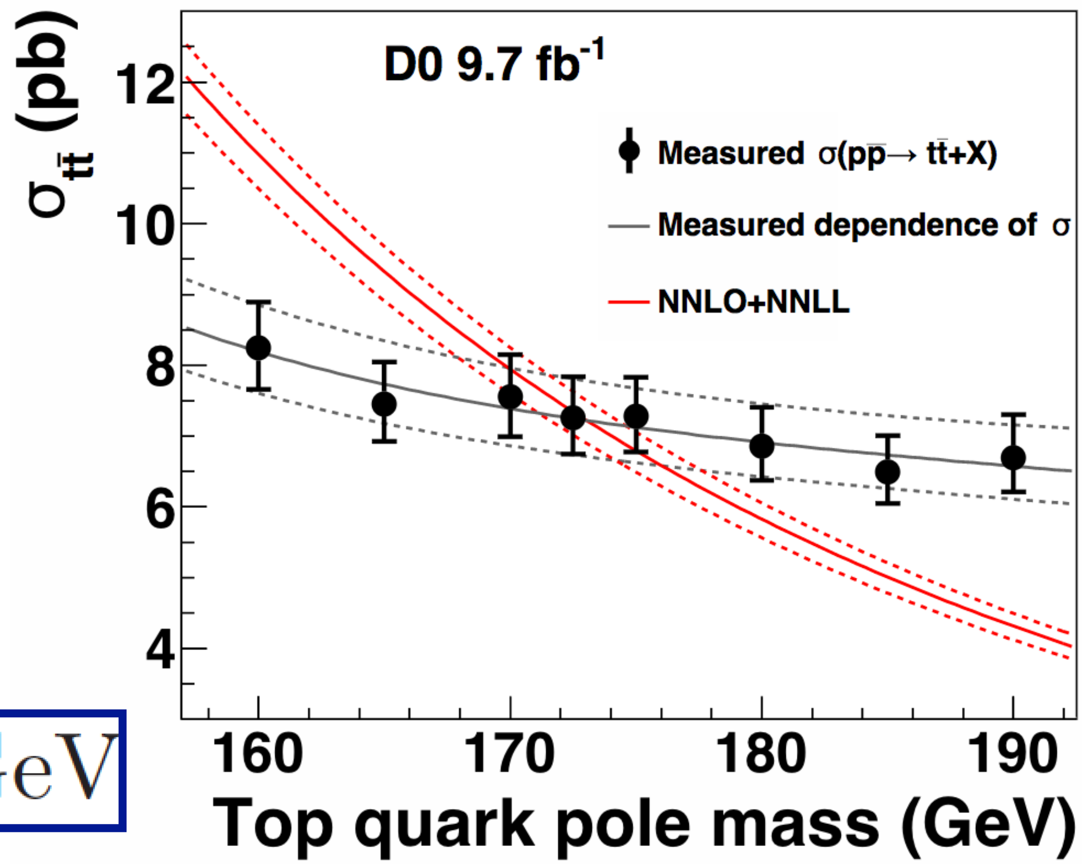
$$m_t = 174.30 \pm 0.35\,(\text{stat}) \pm 0.54\,(\text{syst})\ \text{GeV}$$

Pole mass from inclusive cross-section

- Cross-section measurement in lepton+jets and dileptons

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

- Repeat measurement with varying input top quark mass
  - Changing acceptance, kinematics
- Compared to NNLO+NNLL prediction
  - Avoids theoretical interpretation issues
  - MC mass vs pole mass



arXiv:1605.06168

- Result for pole mass:

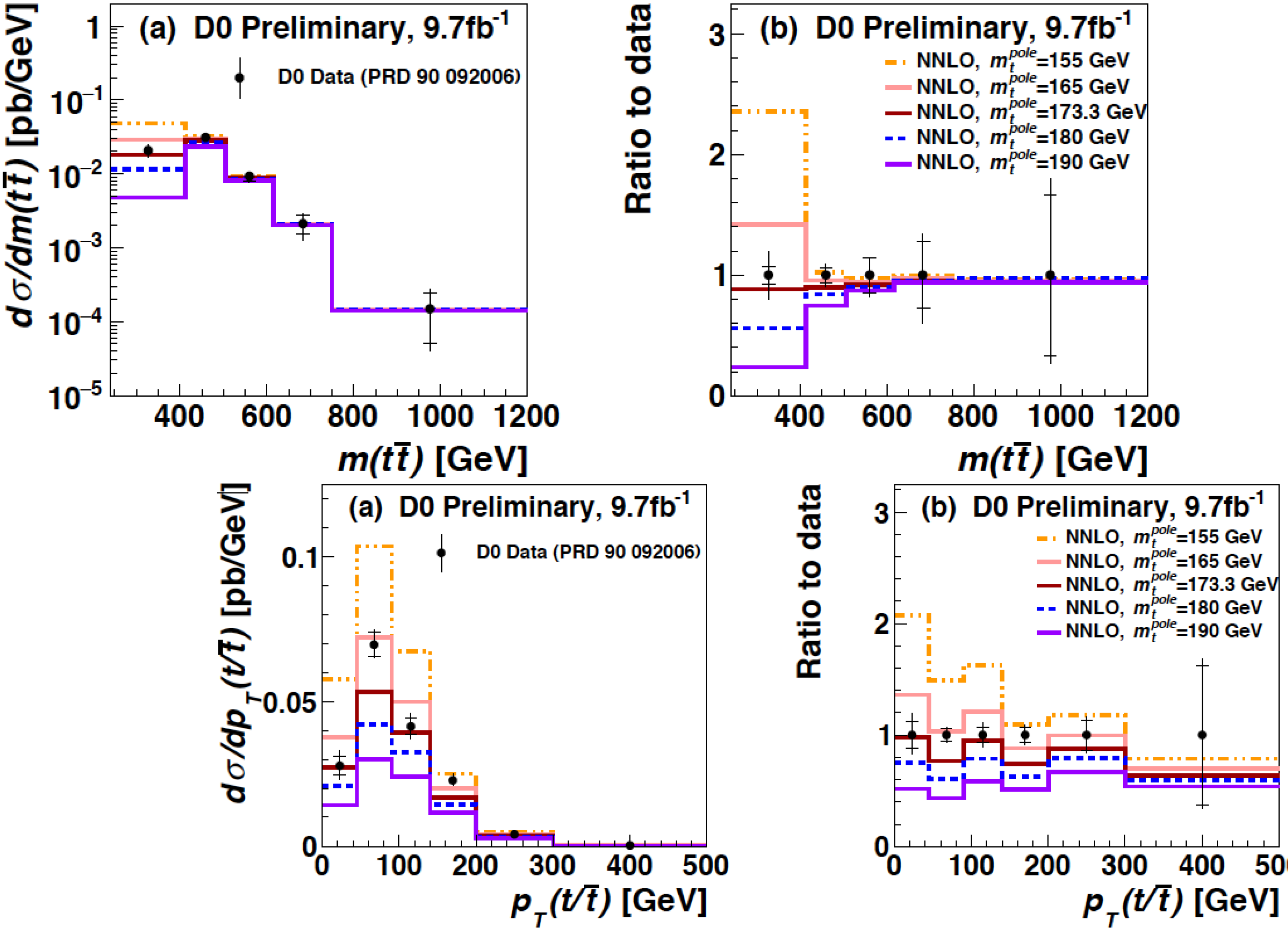
$$m_t = 172.8^{+3.4}_{-3.2}\,(\text{tot.})\ \text{GeV}$$

2.0% relative uncertainty

Pole mass from differential cross-section

- Top quark momentum distribution is sensitive to pole mass
- Invariant mass of top-antitop system is sensitive to pole mass
- Theoretically well-defined mass measurement
- Improvement upon extraction from total cross-section by using differential distributions
- Lepton+jets decay mode
- Compare differential distributions to NNLO QCD calculation
  - M. Czakon, D. Fiedler, D. Heymes and A. Mitov are paper authors
  - NLO and NNLO, 4 different PDF sets
- Compare to unfolded differential distributions
  - PRD 90 092006 (2014)
  - Reduced luminosity uncertainty

Differential distributions

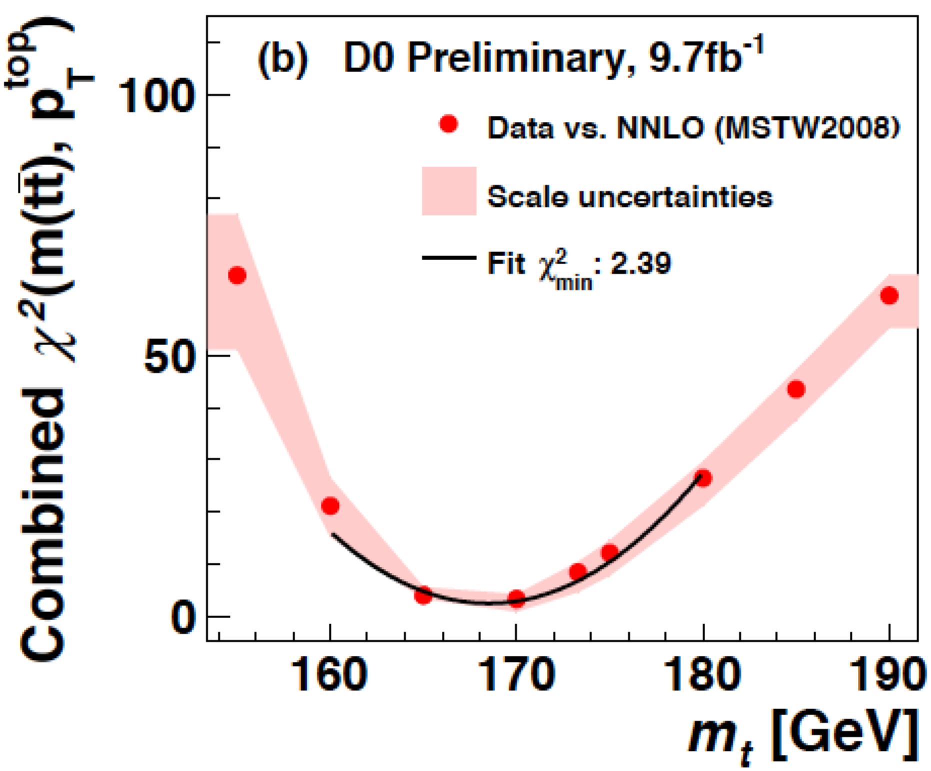


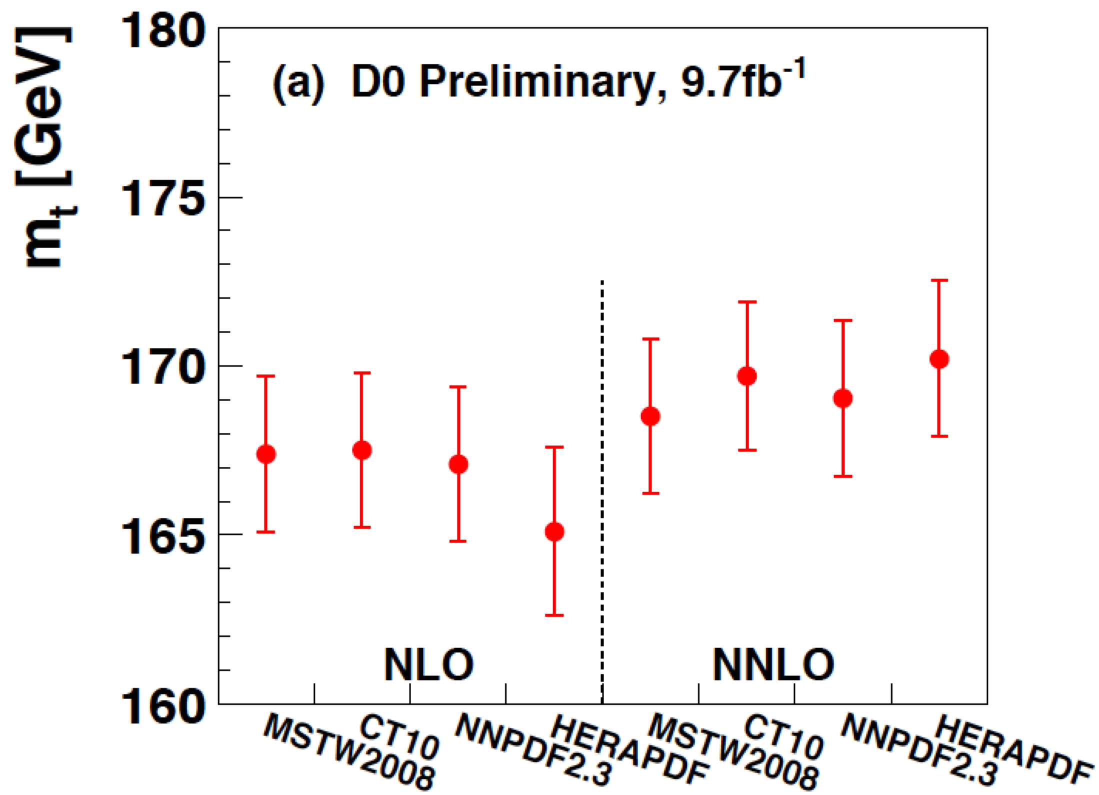
Result

- Chi-squared fit to both distributions: p_T vs m_{tt}
  - Use full 2d correlation matrix
  - Correlation factor 0.12
- Experimental uncertainty 2 GeV, theo uncertainty 1 GeV
- Fit result: 169.1 ± 2.5 GeV

1.5% relative uncertainty

  - smaller than pole mass from inclusive cross-section due to no NNLL corrections and larger lepton+jets cross-section





Conclusions

- Final Tevatron top quark mass results are now being published
  - Based on 10 fb^{-1}
- All top quark decay modes are covered
  - Highest precision in lepton+jets
  - Tevatron combination has uncertainty of 650 MeV
- Measurements of both MC mass and of pole mass
- Tevatron top quark mass measurements are still competitive with LHC measurements
  - Well-understood datasets, well-modeled detectors
  - Sophisticated analysis techniques
  - Work ongoing to understand difference D0-CMS in lepton+jets

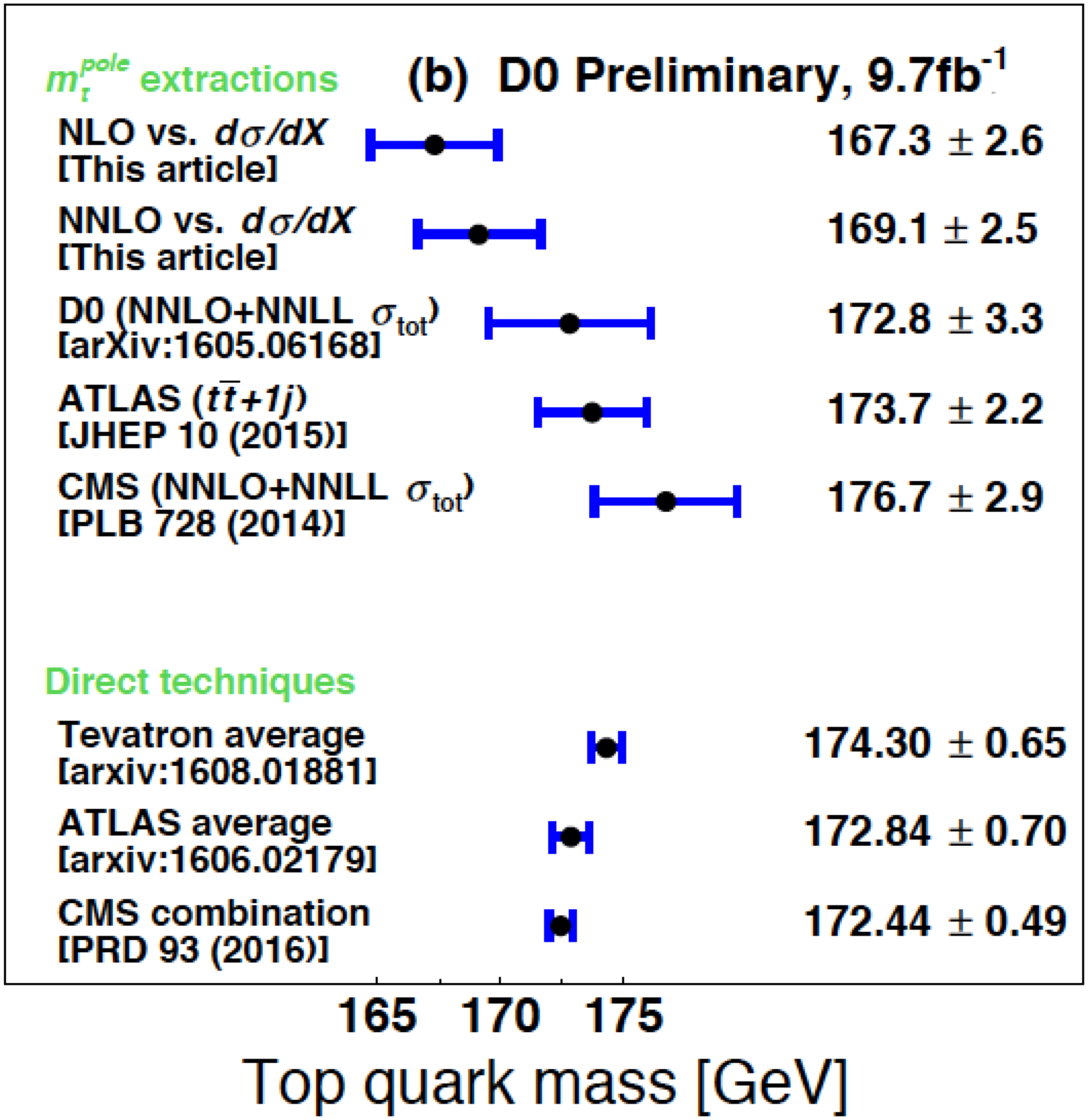
Backup slides

Tevatron combination uncertainties

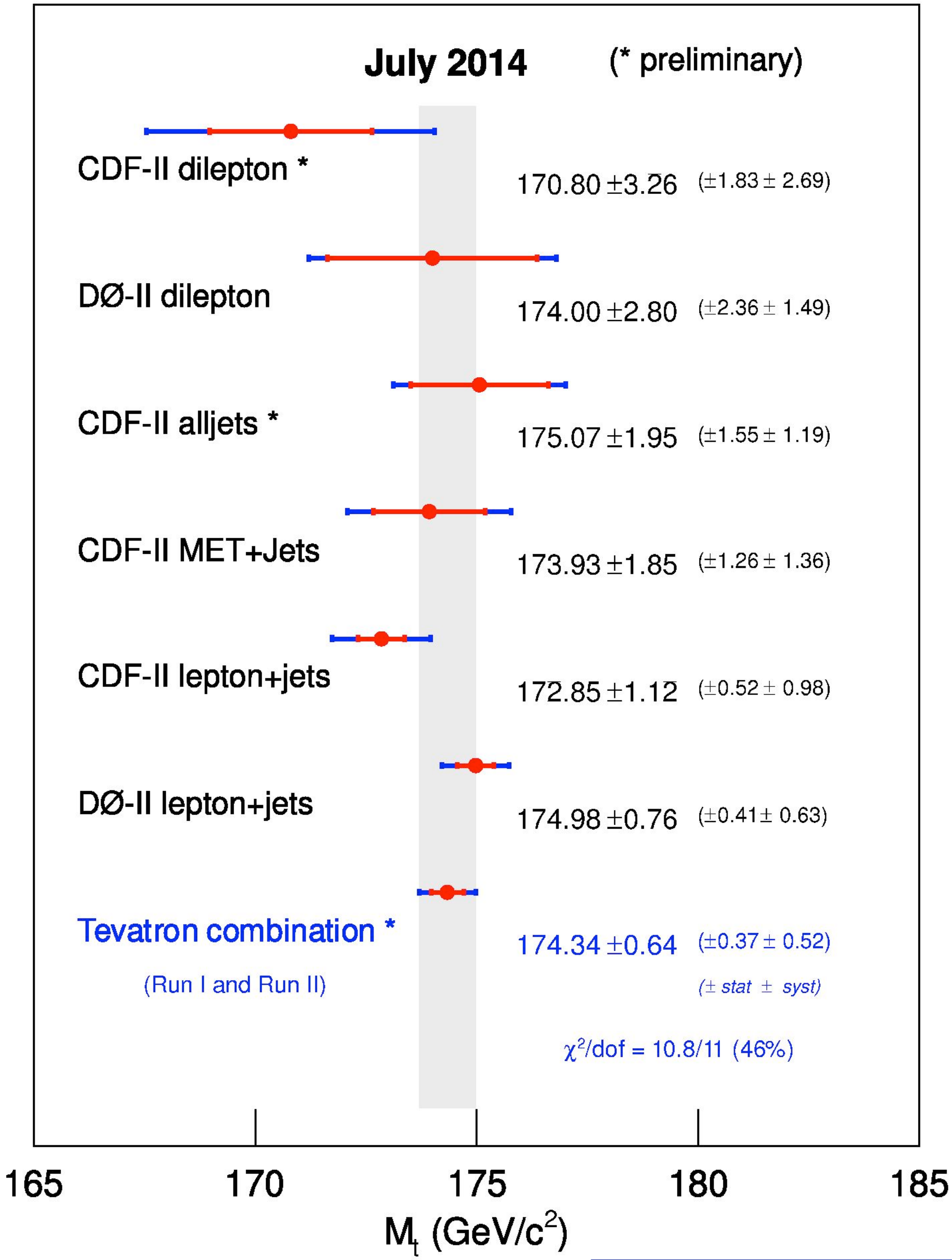
- 650 MeV uncertainty
- 0.37%
- χ^2 = 10.8/11
- prob = 46%

	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

Mass measurement summary



Tevatron mass combination 2014



Systematic uncertainties (GeV/c^2)

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

0.37% relative uncertainty

$$M_t = 174.34 \pm 0.37\,(\mathrm{stat}) \pm 0.52\,(\mathrm{syst})\ \mathrm{GeV}/c^2$$

arXiv:1407.2682