Top Quark Mass Measurements at D0

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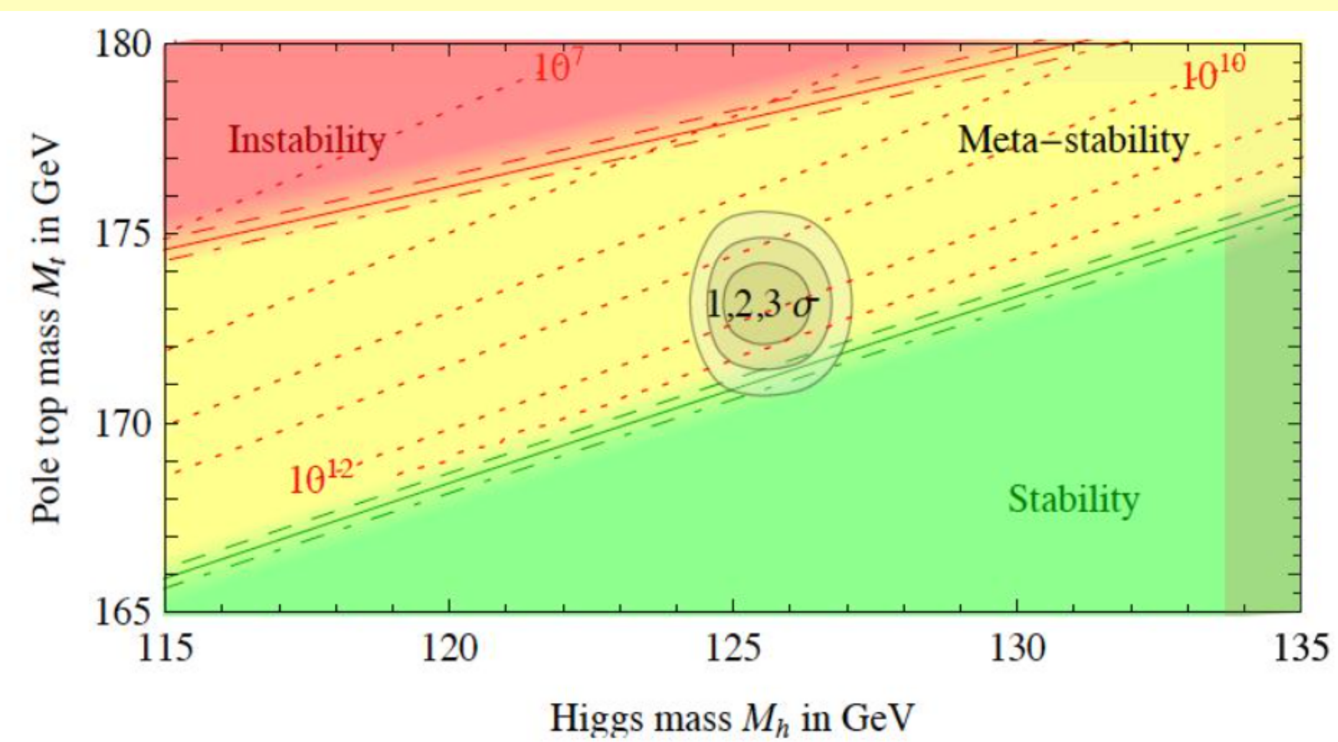
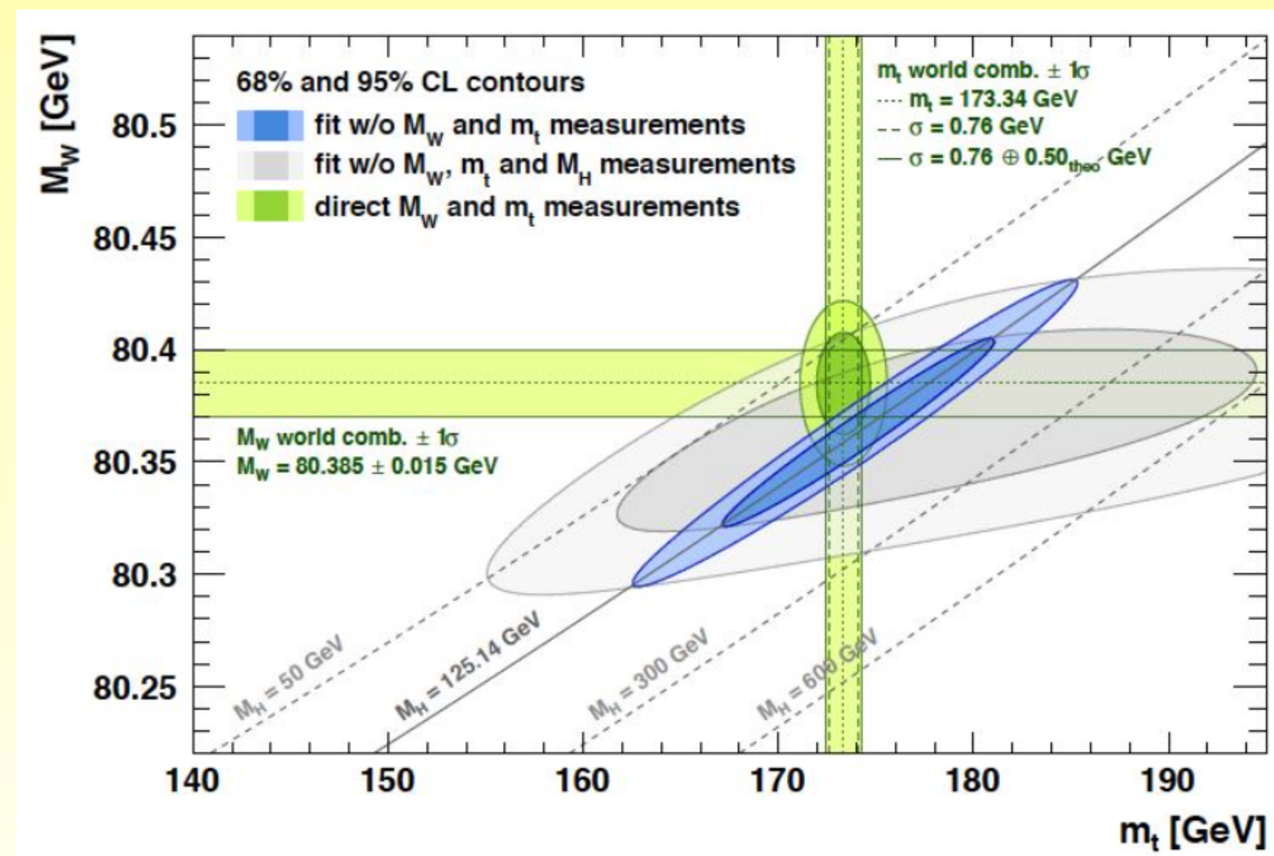
On behalf of the D0 collaboration

ICHEP 2016, Chicago, 6 August 2016

Why do we care about the top quark mass ?

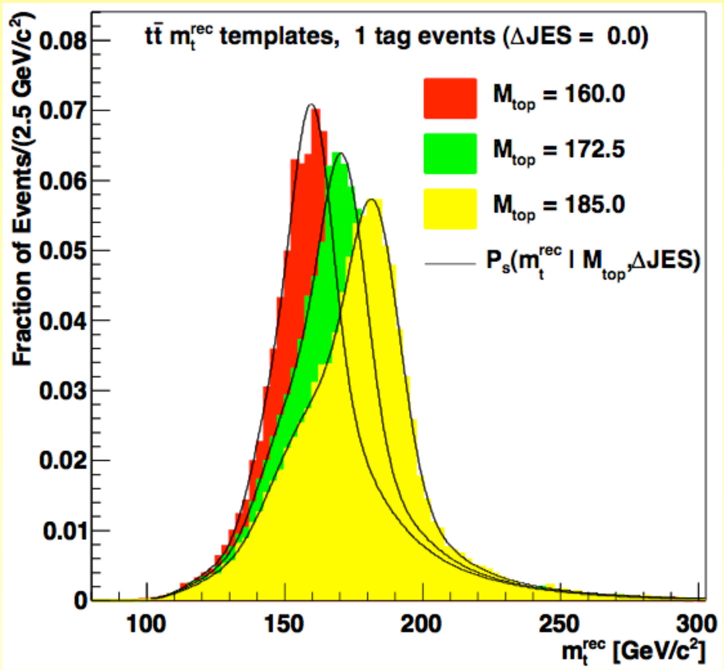
- The top quark is the heaviest elementary particle:
  - important parameter for vacuum stability
  - consistency of the SM (m_t, m_W, m_H)
  - importance in loop corrections





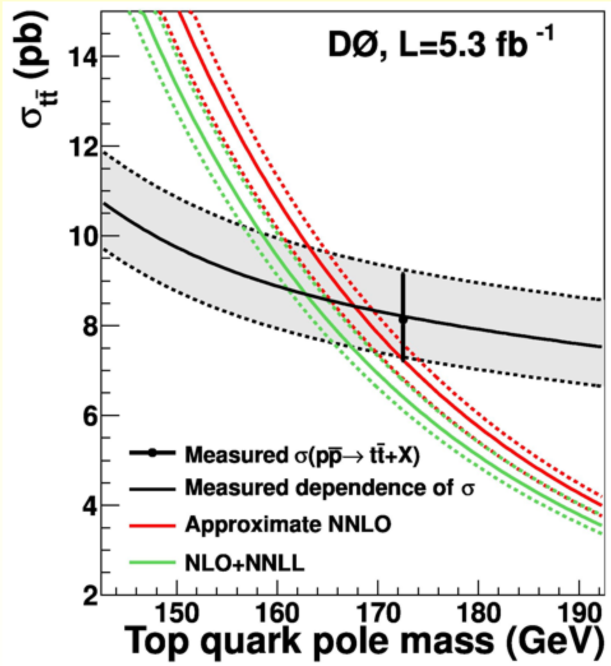
How to measure the top-quark mass ?

- direct measurements
  - template method:
    compare an observable in data with MC generated with different masses
  - matrix element method
    build an event probability based on the LO $t\bar{t}$ matrix element using the full kinematics of the event



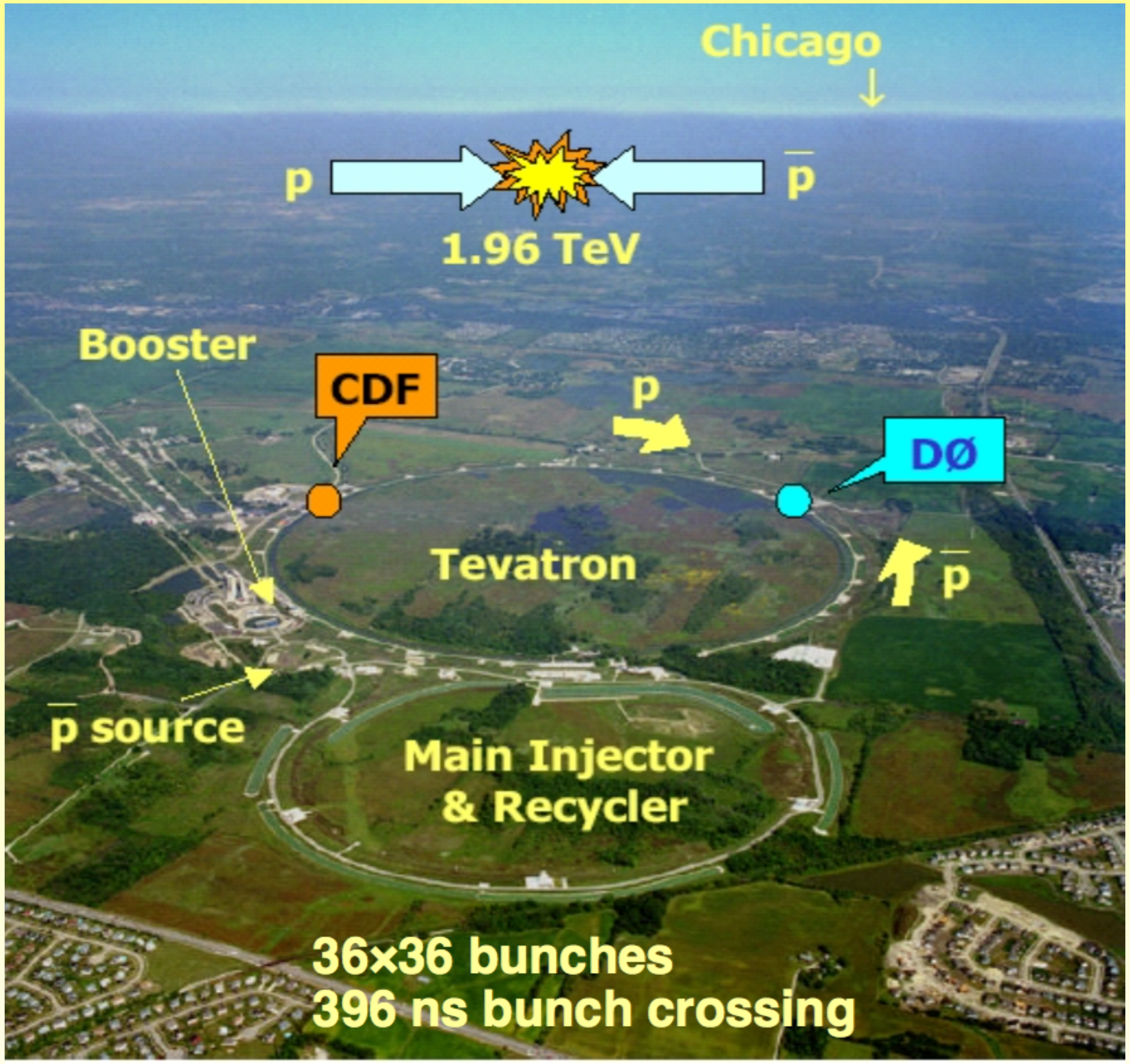
- need to calibrate the method to correct for any potential biases
- for channel with at least one W decaying hadronically, can calibrate the jet energy scale (JES) constraining M_{jj} to M_W

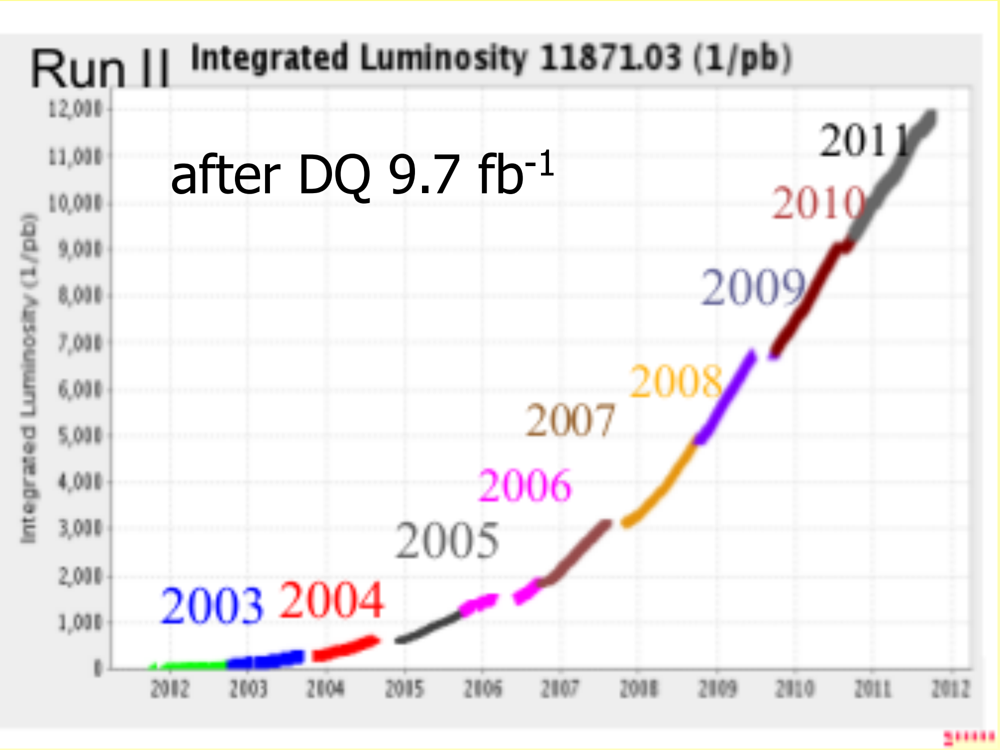
PLB 703, 422 (2011)

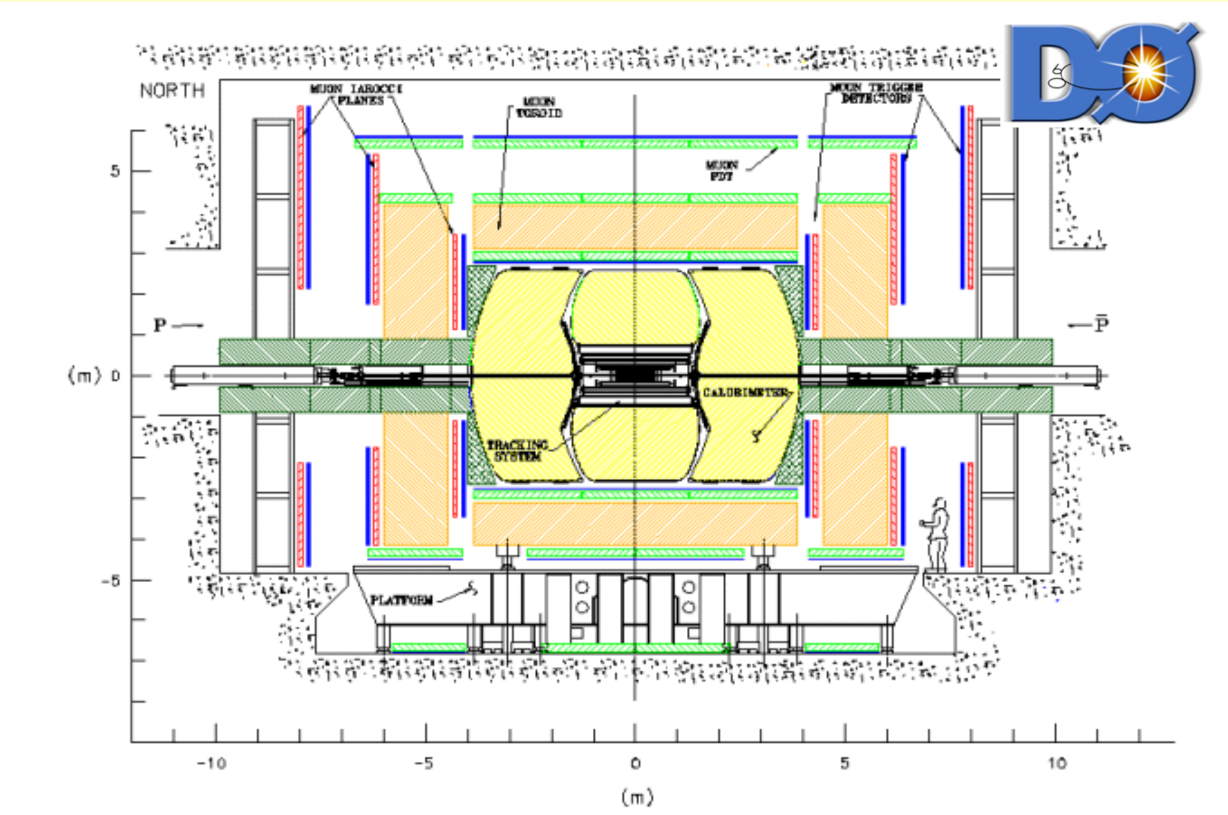


- indirect measurements
  - less input from MC or different sensitivity to systematics but currently less precise than the direct ones
  - extraction of a mass in a better defined renormalisation scheme
    in this talk: top quark mass from the $t\bar{t}$ cross section

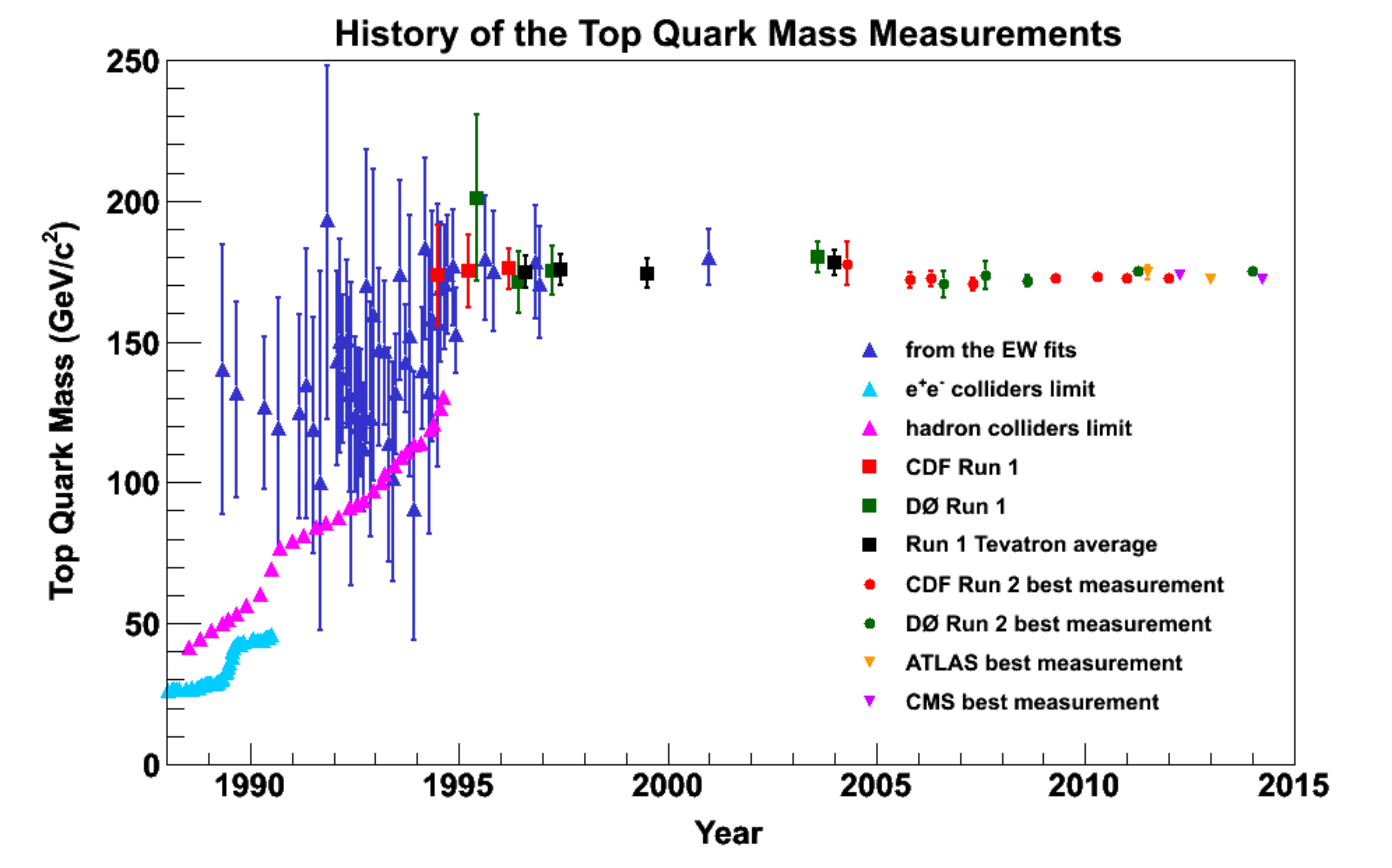
The Tevatron and the D0 experiment







Top quark mass measurements



Many of these analysis techniques have been pioneered at Tevatron

l+jets matrix element top mass measurement

- The matrix element method in the lepton+jets channel:
  - maximize the probability for a set of events as a function of the top mass and overall jet energy scale factor

$$P_{\mathrm{evt}} = A(\vec{x})[f P_{\mathrm{sig}}(\vec{x}; m_t, k_{\mathrm{JES}}) + (1-f) P_{\mathrm{bkg}}(\vec{x}; k_{\mathrm{JES}})]$$

acceptance efficiency

signal fraction

signal probability

background probability

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

observed cross section

differential cross section

from the LO qq̄ → tt̄ matrix element

PDF

transfer functions

from reco x to gen y

Contribution	e+jets			μ+jets		
$t\bar{t}$	918.1	±	3.6	824.9	±	3.5
Other backgrounds	97.8	±	0.5	79.2	±	0.9
W+hf	126.0	±	2.1	162.2	±	2.8
W+lf	77.9	±	2.1	101.0	±	2.9
Multijet	144.4	±	24.2	48.2	±	16.1
Expected	1364.1	±	24.7	1215.5	±	17.0
Observed		**1502**			**1286**	

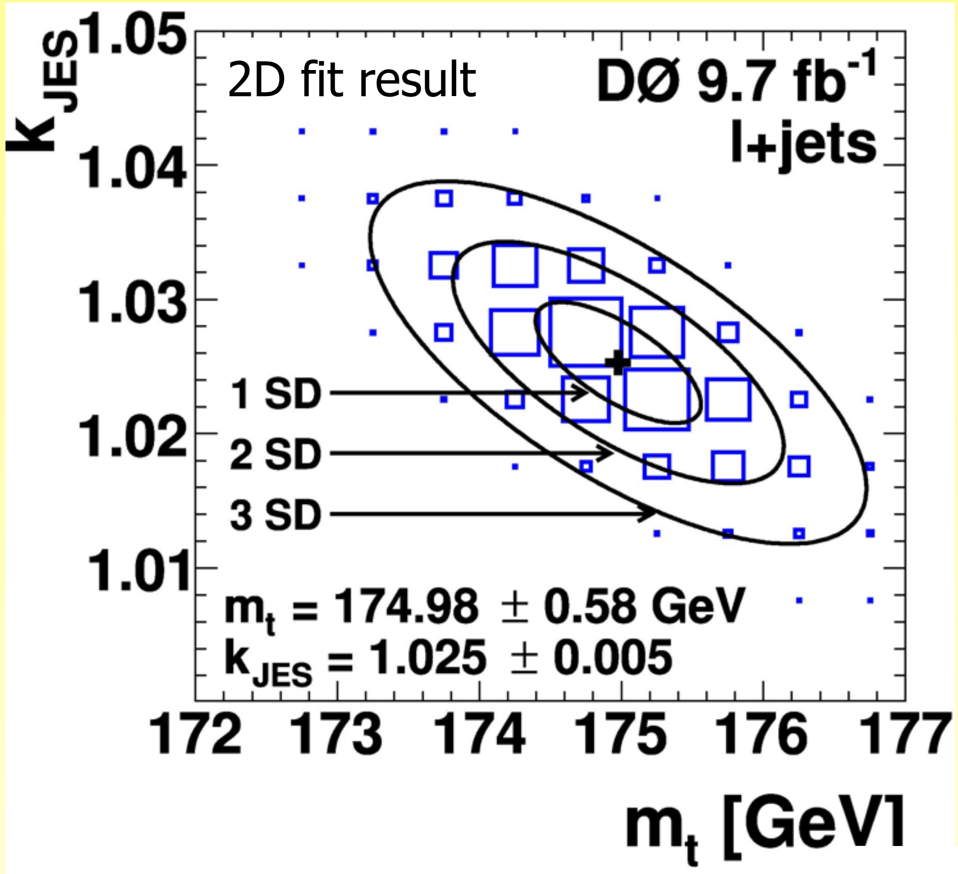
l+jets matrix element top mass result

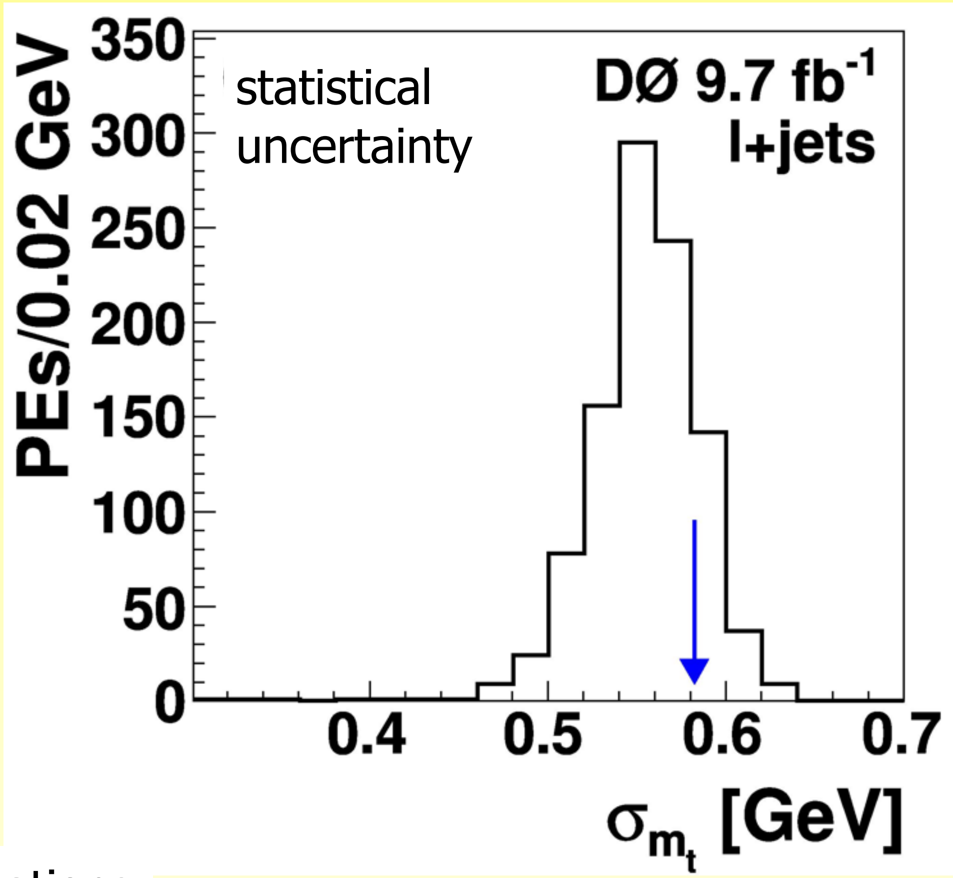
PRL 113, 032002 (2014), PRD 91, 112003 (2015)

$$m_t = 174.98 \pm 0.58\,(\text{stat} + \text{JES}) \pm 0.49\,(\text{syst})\ \text{GeV}$$

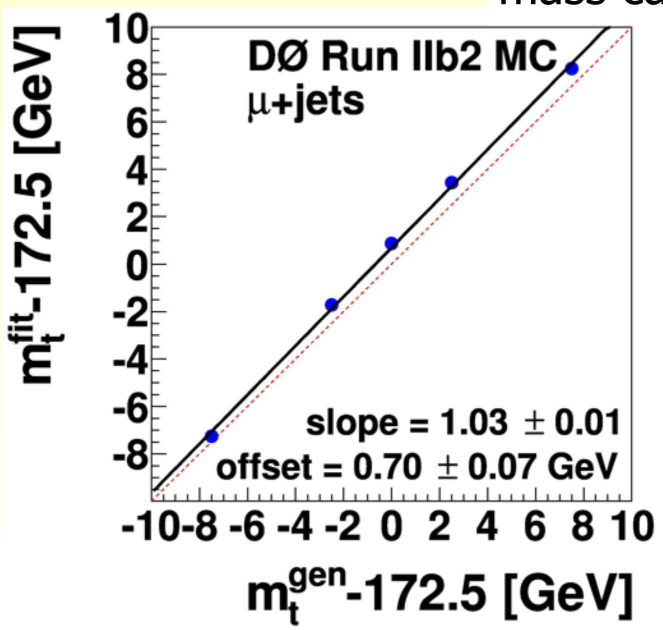
$$k_{\text{JES}} = 1.025 \pm 0.005$$

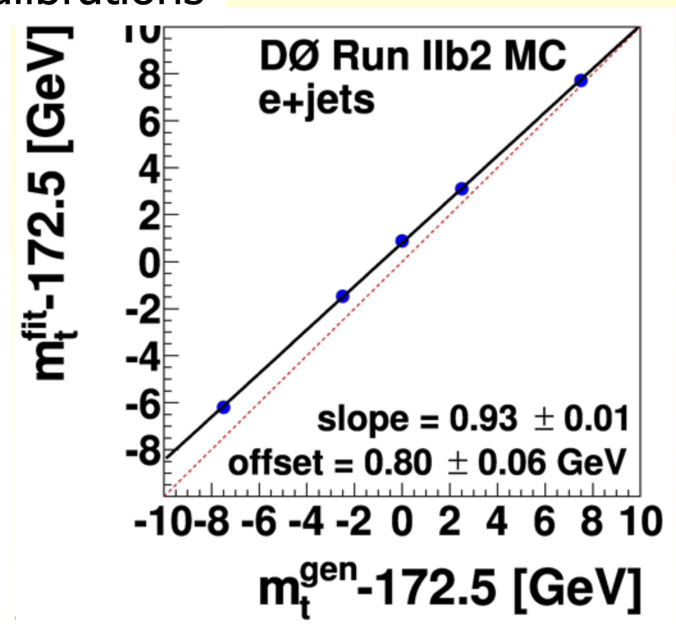
$\Delta m_t/m_t = 0.43\%$





mass calibrations

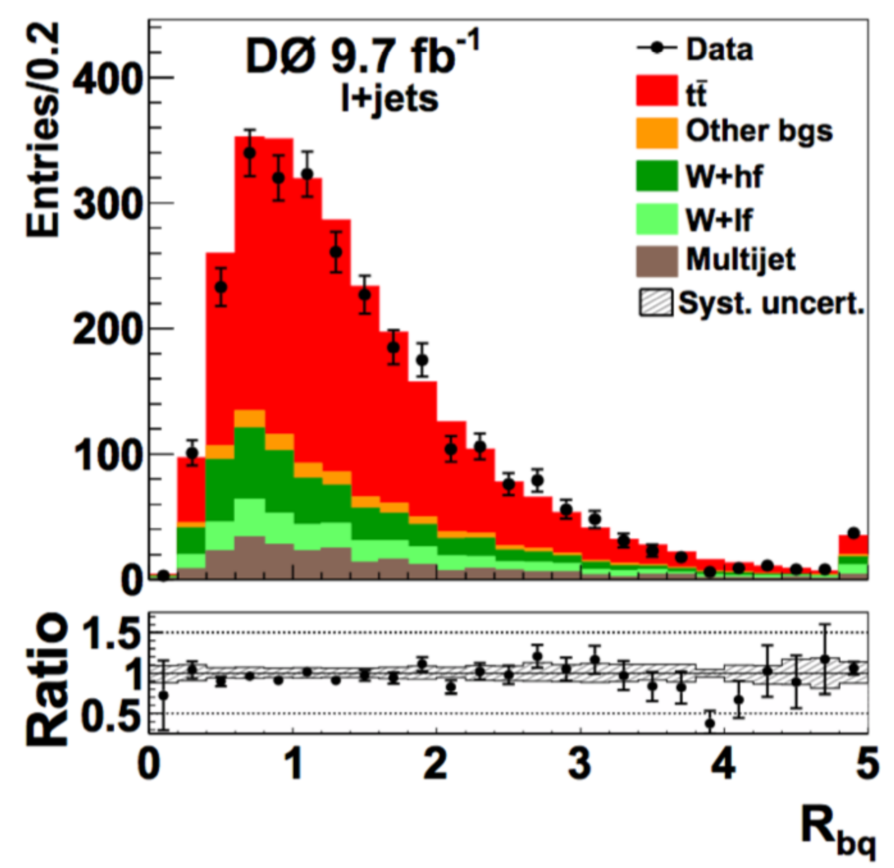




l+jets matrix element systematics

- check of the JES flavor response

$$R_{bq} = (p_T^{b_1} + p_T^{b_2})/(p_T^{j_1} + p_T^{j_2})$$



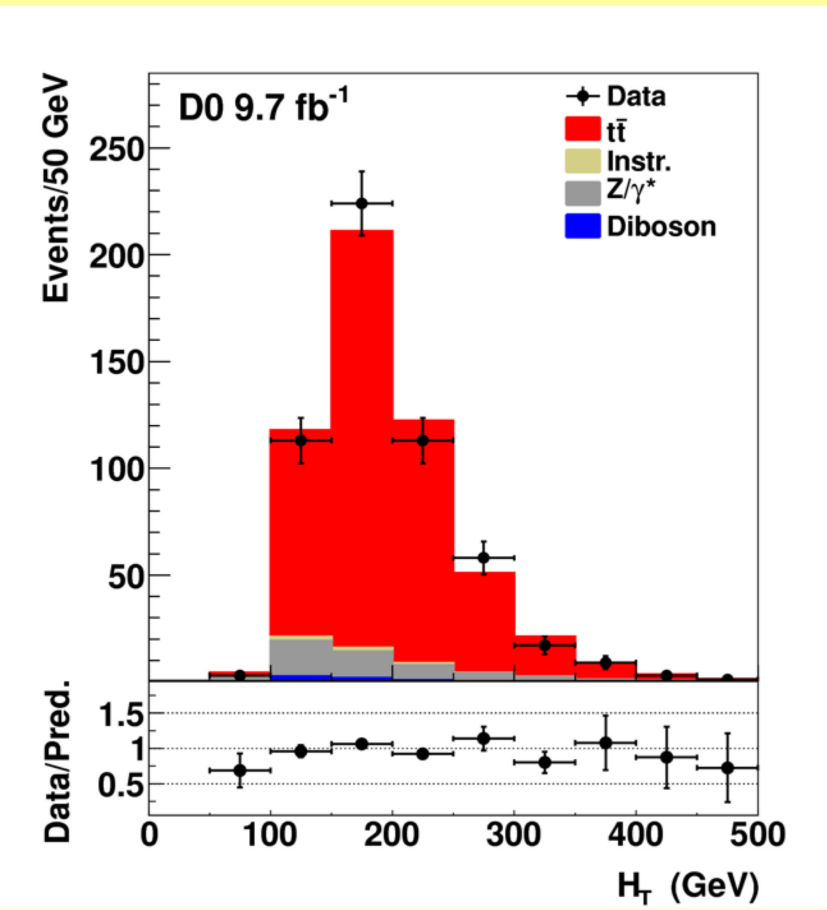
$$k_{\mathrm{bJES}} = 1.008 \pm 0.0195\,(\mathrm{stat})\,^{+0.037}_{-0.031}\,(\mathrm{syst})$$

consistent with unity

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections	$+0.15$
Initial/final state radiation	± 0.09
Hadronization and UE	$\boxed{+0.26}$
Color reconnection	$+0.10$
Multiple $p\bar{p}$ interactions	-0.06
Heavy flavor scale factor	± 0.06
b-jet modeling	$+0.09$
PDF uncertainty	± 0.11
Detector modeling:	
Residual jet energy scale	$\boxed{\pm 0.21}$
Flavor-dependent response to jets	± 0.16
b tagging	± 0.10
Trigger	± 0.01
Lepton momentum scale	± 0.01
Jet energy resolution	± 0.07
Jet ID efficiency	-0.01
Method:	
Modeling of multijet events	$+0.04$
Signal fraction	± 0.08
MC calibration	± 0.07
Total systematic uncertainty	± 0.49
Total statistical uncertainty	$\boxed{\pm 0.58}$
Total uncertainty	± 0.76

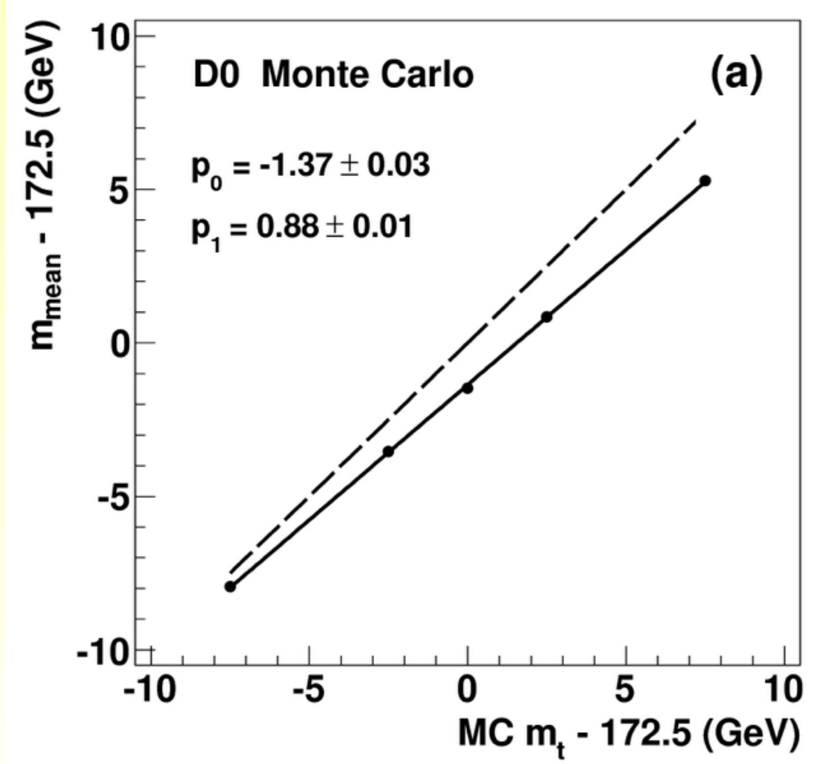
dilepton matrix element top mass measurement

- Dilepton matrix element method
  - same formula as for l+jets but no possible JES in-situ constraints
  - more integration because of the unconstraint kinematics

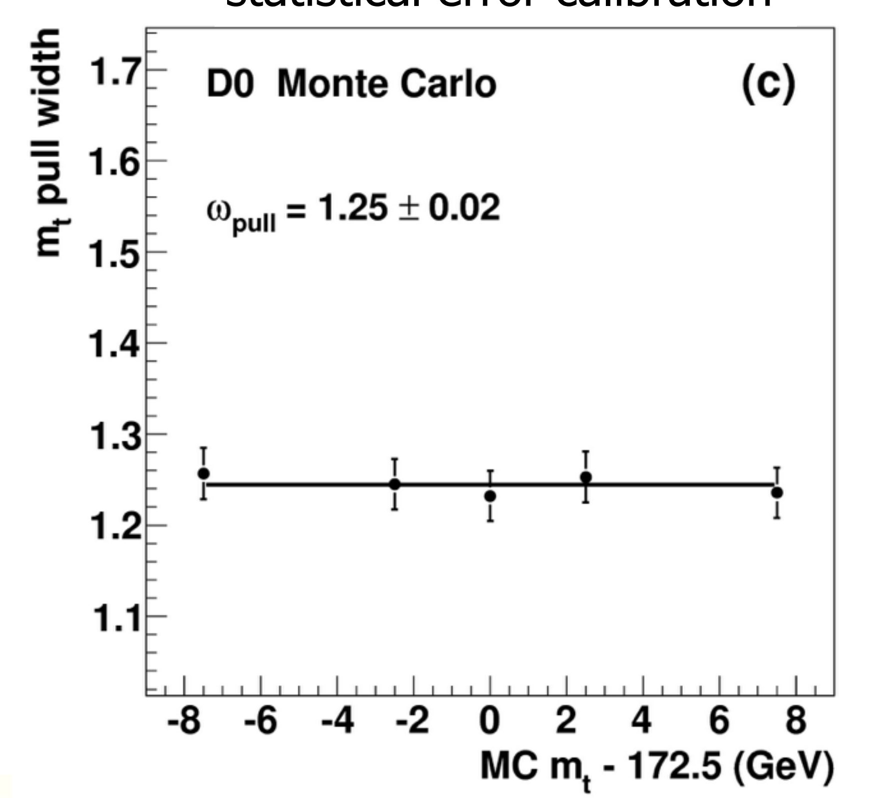


	Z/γ^* + jets	Diboson	Instr.	$t\bar{t}$	Total	Data
$e\mu$	$13.0^{+1.7}_{-1.6}$	$3.7^{+0.8}_{-0.8}$	$16.4^{+4.0}_{-4.0}$	$260.6^{+22.5}_{-16.3}$	$293.8^{+23.5}_{-17.7}$	346
ee	$13.8^{+2.1}_{-1.9}$	$1.9^{+0.4}_{-0.4}$	$1.8^{+0.2}_{-0.2}$	$88.0^{+9.1}_{-8.2}$	$105.5^{+10.3}_{-9.5}$	104
$\mu\mu$	$10.6^{+1.3}_{-1.4}$	$1.7^{+0.4}_{-0.4}$	$0^{+0.05}_{-0.05}$	$76.0^{+6.2}_{-4.1}$	$88.3^{+6.7}_{-4.7}$	92
$\ell\ell$	$37.4^{+5.1}_{-4.9}$	$7.3^{+1.6}_{-1.6}$	$18.2^{+4.0}_{-4.0}$	$424.6^{+37.8}_{-28.6}$	$487.6^{+40.5}_{-31.9}$	545

mass calibration



statistical error calibration



dilepton matrix element top mass result

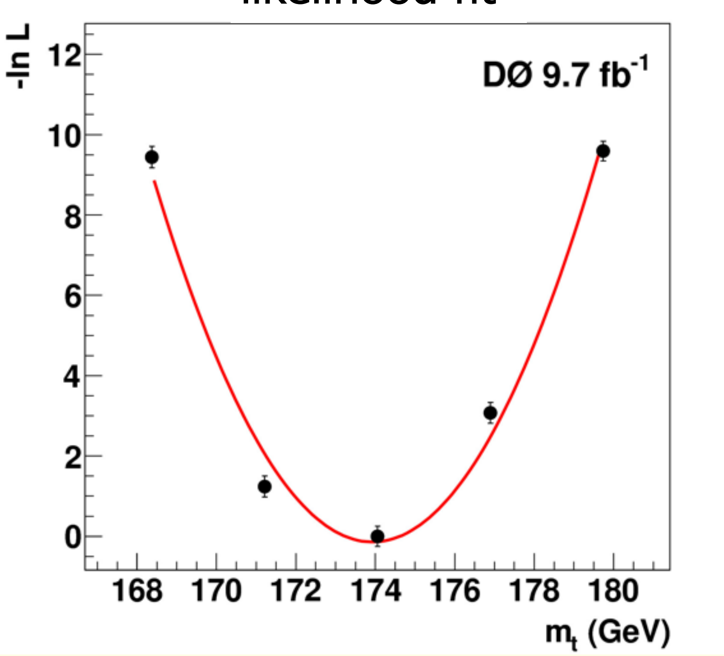
arXiv:1606.02814, accepted to PRD

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

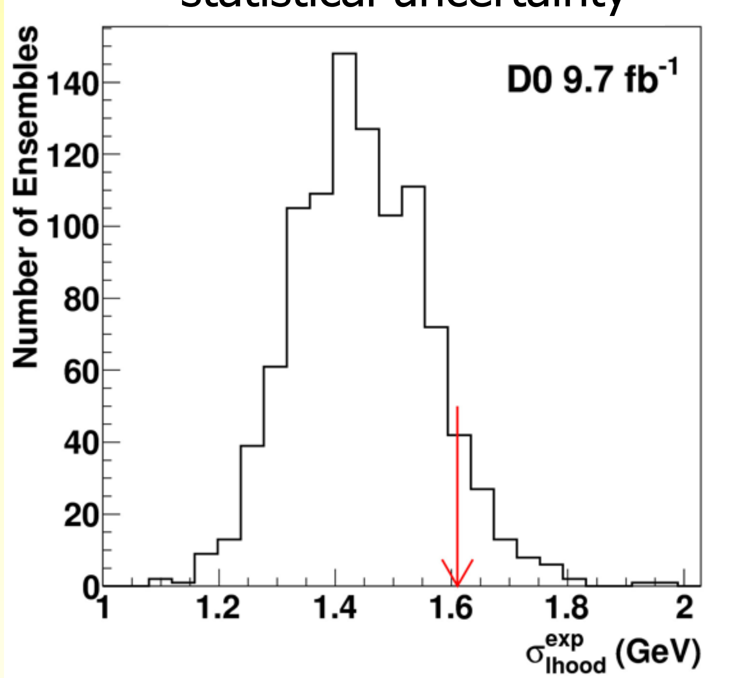
$\Delta m_t/m_t = 1.05\%$

use overall JES scale factor obtained in the lepton+jets analysis

likelihood fit



statistical uncertainty

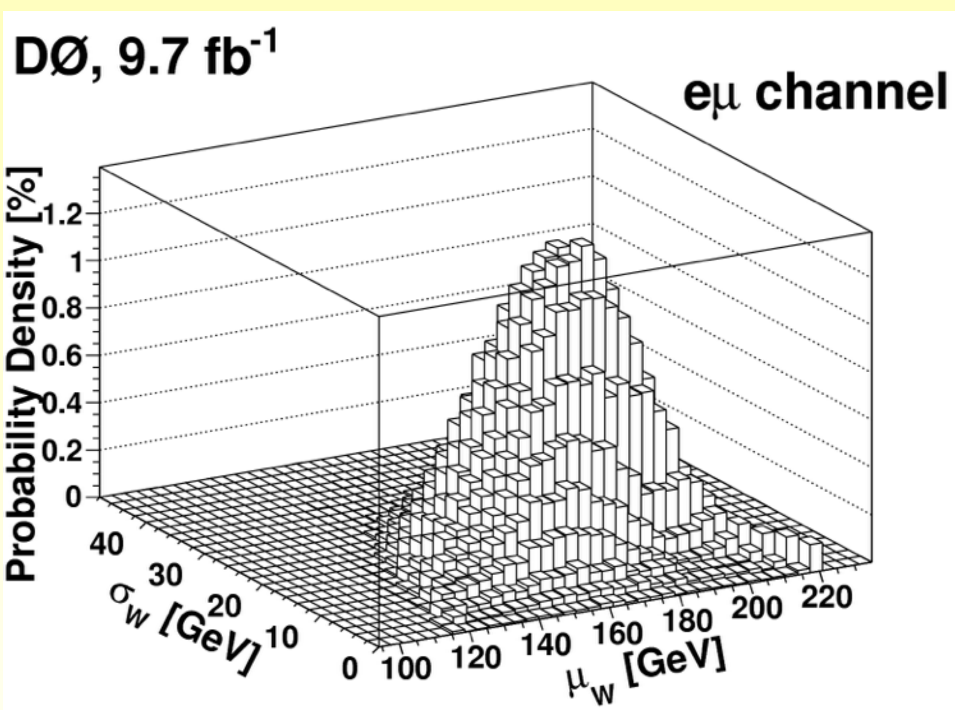


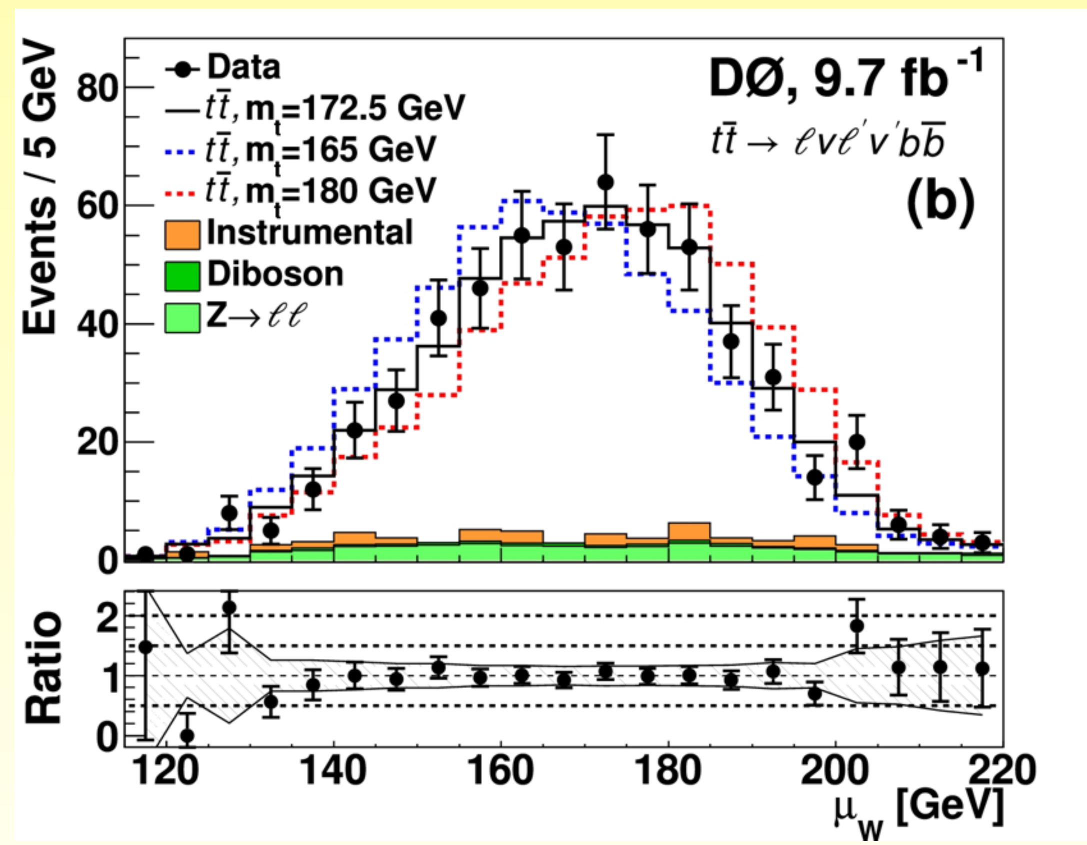
Source	Uncertainty (GeV)
Signal and background modeling:	
Higher order corrections	$+0.16$
ISR/FSR	± 0.16
Hadronization and UE	$+0.31$
Color Reconnection	$+0.15$
b-jet modelling	$+0.21$
PDF uncertainty	± 0.20
Heavy flavor	∓ 0.06
$p_T(t\bar{t})$	$+0.03$
Multiple $p\bar{p}$ interactions	-0.10
Detector modeling:	
Residual jet energy scale	-0.20
Uncertainty on k_{JES} factor	∓ 0.46
Flavor dependent jet response	∓ 0.30
Jet energy resolution	∓ 0.15
Electron momentum scale	∓ 0.10
Electron resolution	∓ 0.16
Muon resolution	∓ 0.10
b-tagging efficiency	∓ 0.28
Trigger	± 0.06
Jet ID	$+0.08$
Method:	
MC calibration	± 0.03
Instrumental background	± 0.07
MC background	± 0.06
Total systematic uncertainty	± 0.88
Total statistical uncertainty	± 1.61
Total uncertainty	± 1.84

dilepton neutrino weighting top mass measurement

- Dilepton neutrino weighting method
  - sample the neutrino rapidities for given value of m_t
  - measure the agreement of the calculated and observed missing E_T components with a weight distribution for each event: $\omega(m_t)$
  - use the 2 first moments of the distribution $(\mu_\omega, \sigma_\omega)$ in a 2D template fit

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





dilepton neutrino weighting top mass result

Phys. Lett. B 752 18 (2016)

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

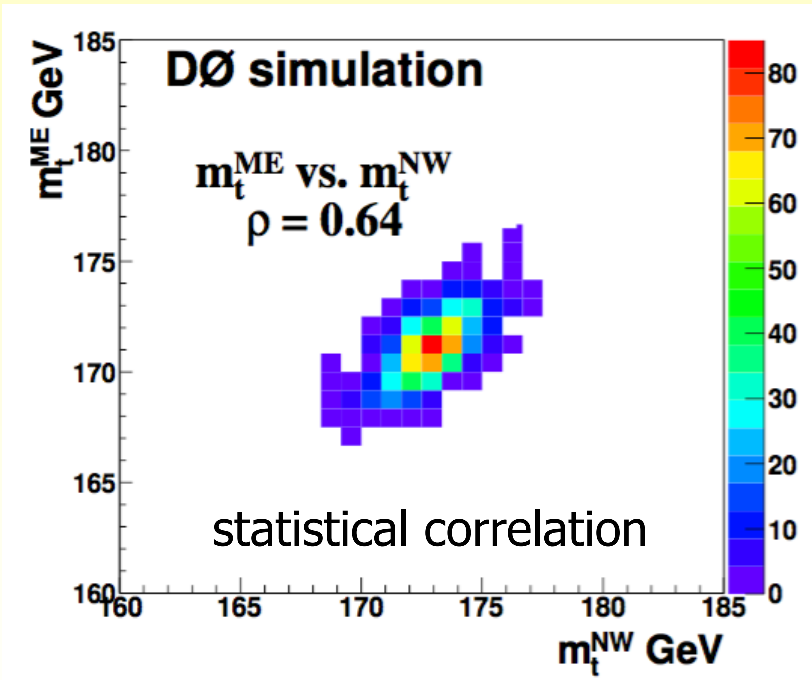
$\Delta m_t/m_t = 0.93\%$

use overall JES scale factor obtained in the lepton+jets analysis

- Combination of the 2 dilepton results
  - BLUE combination of the matrix element and neutrino weighting results

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

D0 note 6484



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

new D0 top mass combination

D0 Note 6485

- update since previous 2011 result
  - new lepton+jets and dilepton measurements

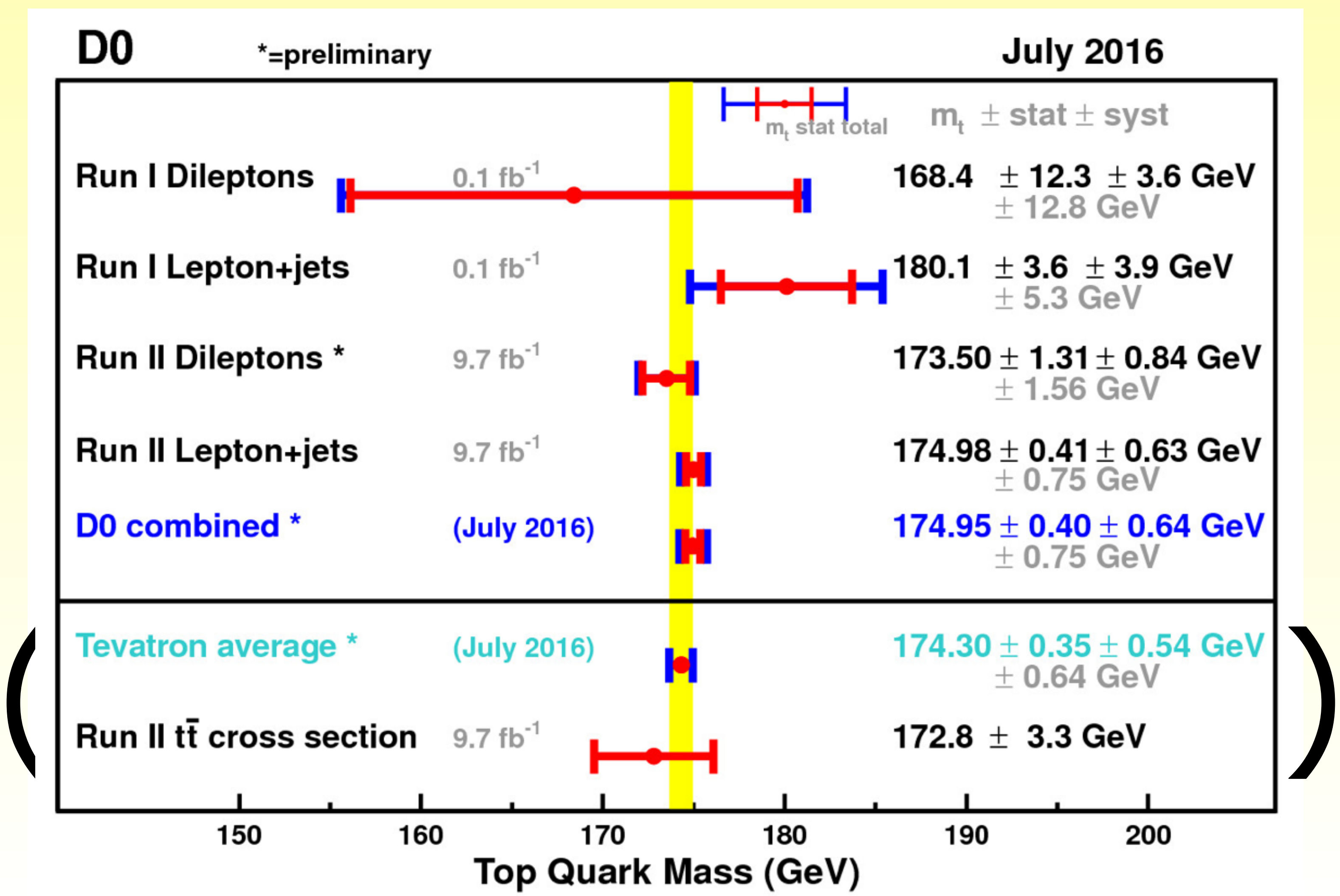
$$174.95 \pm 0.40\,(\text{stat}) \pm 0.64\,(\text{syst})\ \text{GeV}$$

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

	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



new Tevatron top mass combination

arXiv:1608.01881, D0 Note 6486, CDF Note 11204

- update since previous 2014 result
  - new D0 dilepton measurement
  - published CDF all-jets measurement

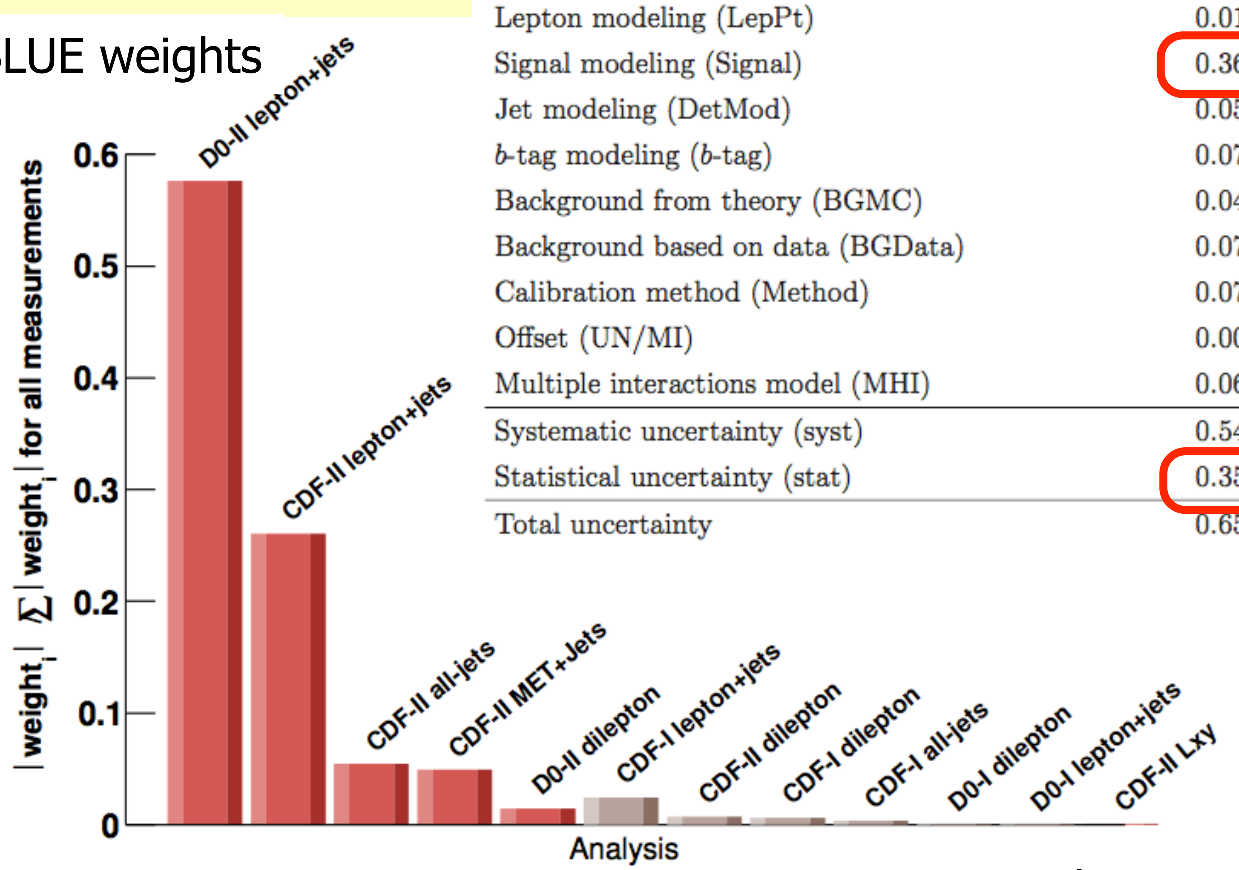
$$m_t = 174.30 \pm 0.35\,(\text{stat}) \pm 0.54\,(\text{syst})\ \text{GeV}$$

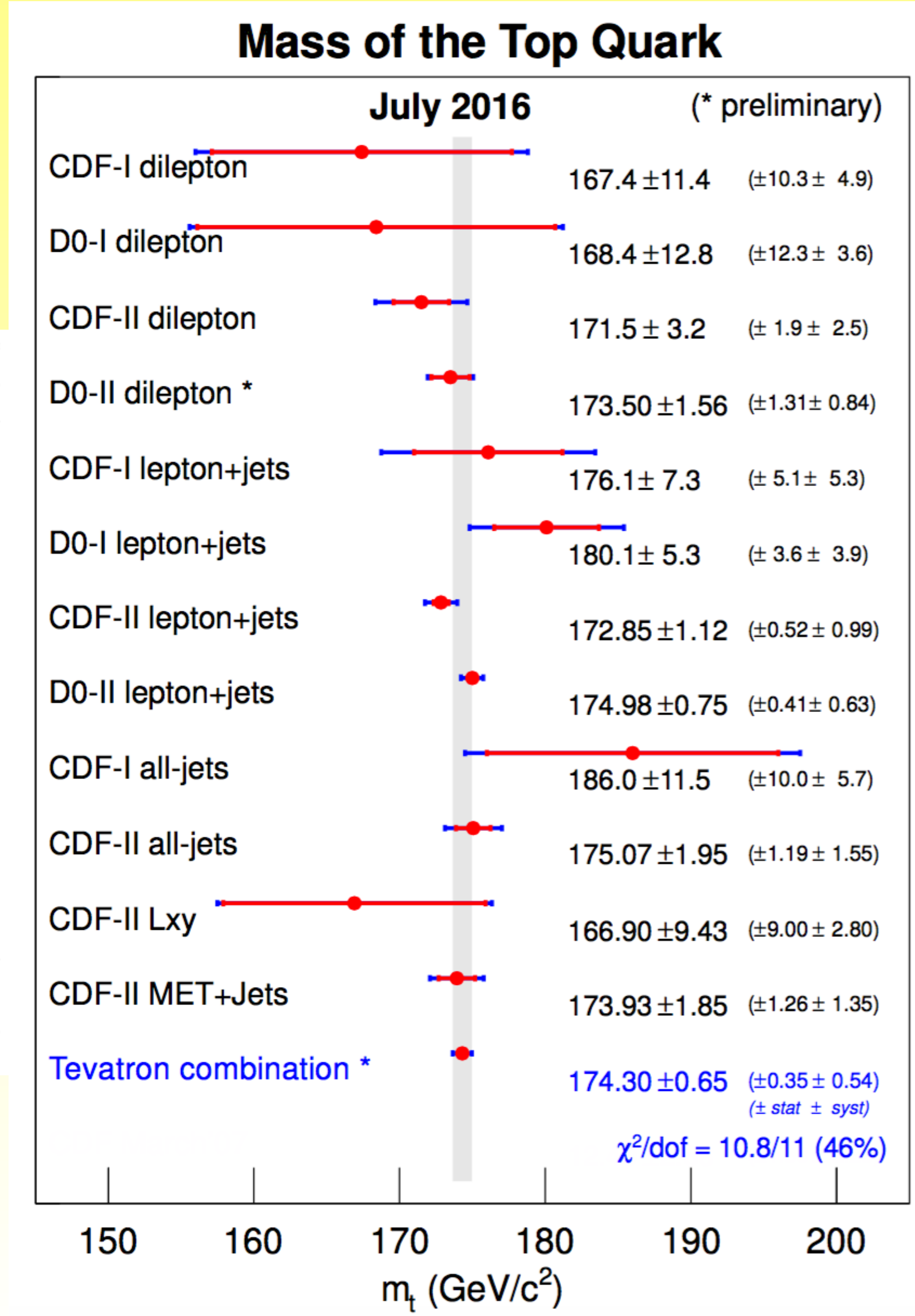
$\Delta m_t/m_t = 0.37\%$

$\chi^2 = 10.8/11$, 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

BLUE weights





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

arXiv:1605.06168, submitted to PRD

- **Method**
  - compare the experimental $t\bar{t}$ 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 ljets+dilepton with 9.7 fb^{-1}

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

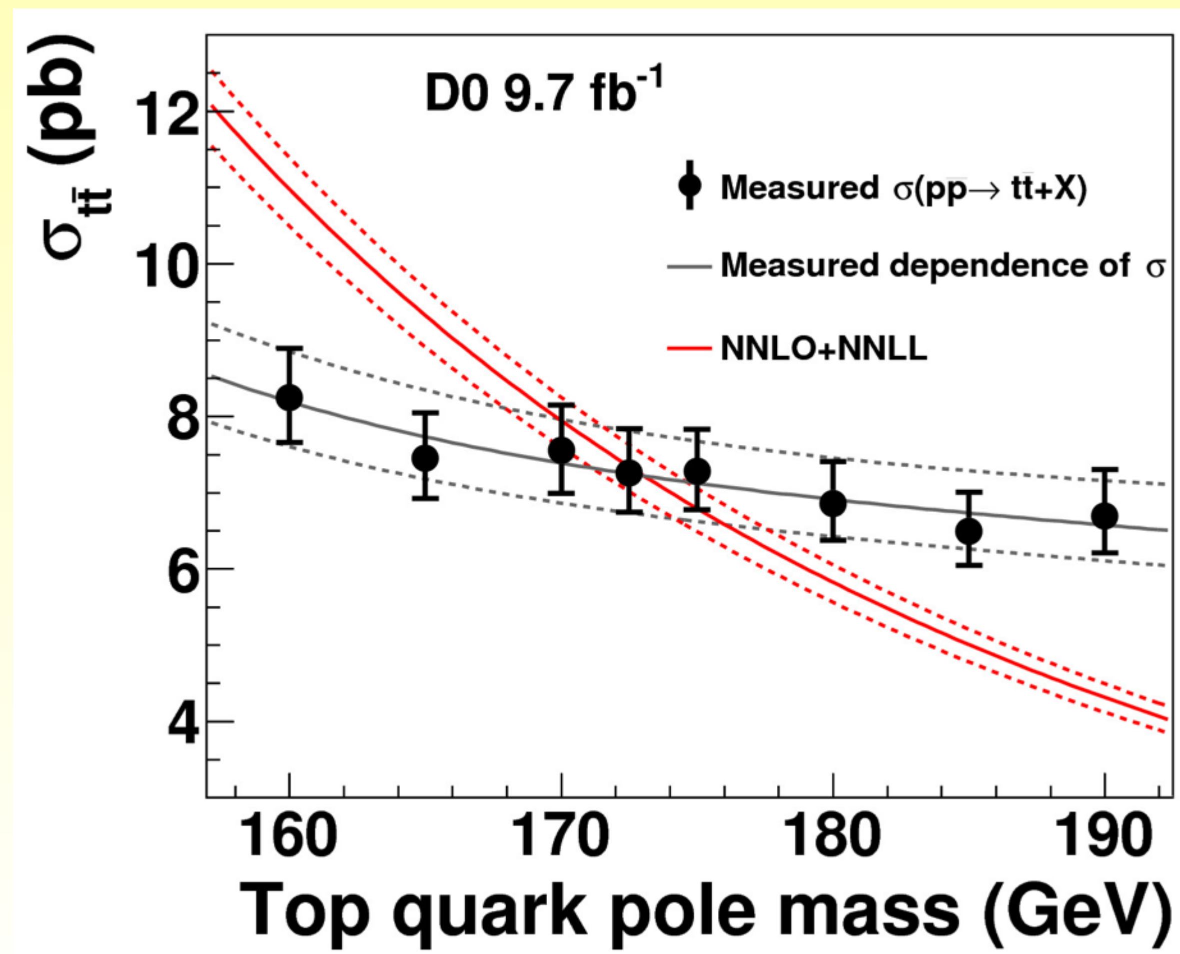
see talk from Andreas Jung on Thursday August 4th

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

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

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

$\Delta m_t/m_t = 1.9\%$



Conclusion

- D0 recently published dilepton top quark mass measurements with the full dataset
  - matrix element result: $173.93 \pm 1.61\ (\mathrm{stat}) \pm 0.88\ (\mathrm{syst})\ \mathrm{GeV}$ $\Delta m_t/m_t = 1.05\%$
  - neutrino weighting result: $173.32 \pm 1.36(\mathrm{stat}) \pm 0.85(\mathrm{syst})\ \mathrm{GeV}$ $\Delta m_t/m_t = 0.93\%$

- update combinations of direct top quark mass measurements:
  - new D0 combination: $174.95 \pm 0.40\ (\mathrm{stat}) \pm 0.64\ (\mathrm{syst})\ \mathrm{GeV}$ $\Delta m_t/m_t = 0.43\%$
  - new Tevatron combination: $174.30 \pm 0.35\ (\mathrm{stat}) \pm 0.54\ (\mathrm{syst})\ \mathrm{GeV}$ $\Delta m_t/m_t = 0.37\%$

- D0 measurement from the $t\bar{t}$ cross section: $172.8^{+3.4}_{-3.2}\ (\mathrm{tot.})\ \mathrm{GeV}$ $\Delta m_t/m_t = 1.9\%$

Sept 30, 2011