Top quark mass measurements at the Tevatron

- (Introduction)
- Top Quark Mass measurements
- Conclusions & Outlook

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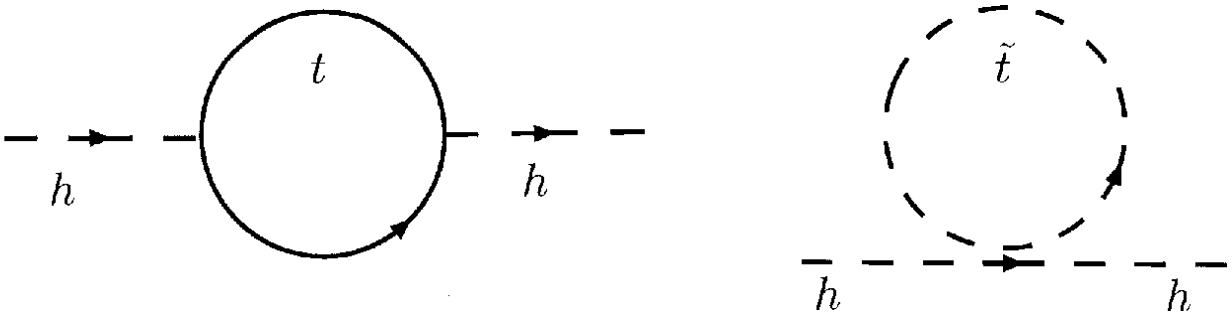
April 10th, 2015

Top @ Twenty workshop, Fermilab

Introduction

- Top is the heaviest fundamental particle discovered so far
  → m_t = **174.34 ± 0.76 GeV** arxiv:1407.2682
- Lifetime: $\tau \approx 5\times10^{-25}$ s << Γ_{QCD}
  → **Observe bare quark properties**
- Large Yukawa coupling to Higgs boson
  → $\lambda_t \sim 1$
  special role in electroweak symmetry breaking ?

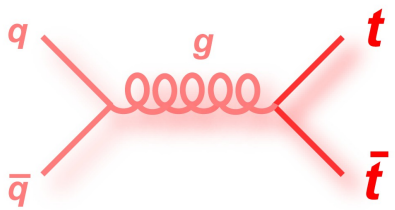
- If we could calculate the Higgs mass:
  → Large corrections to the Higgs mass from top quark "loops"
  (Hierarchy problem)



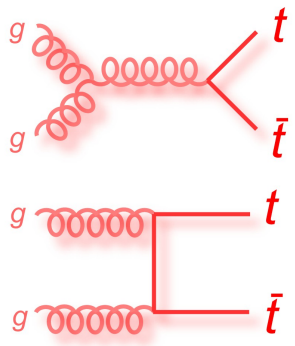
Top quarks as window to new physics

Production

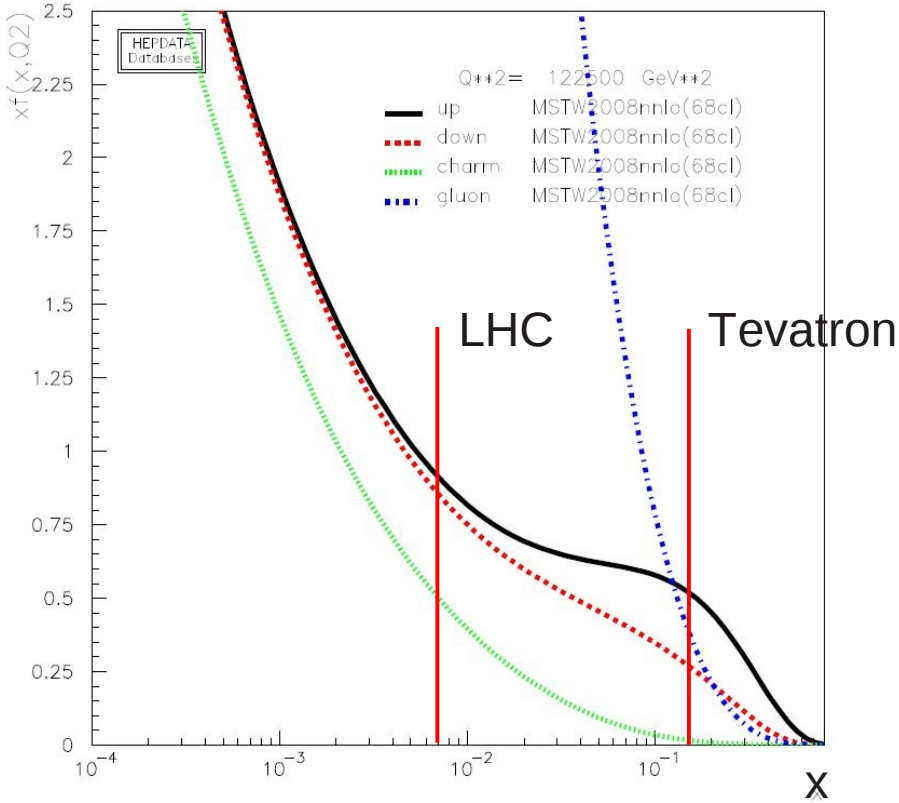
- Strong interaction:



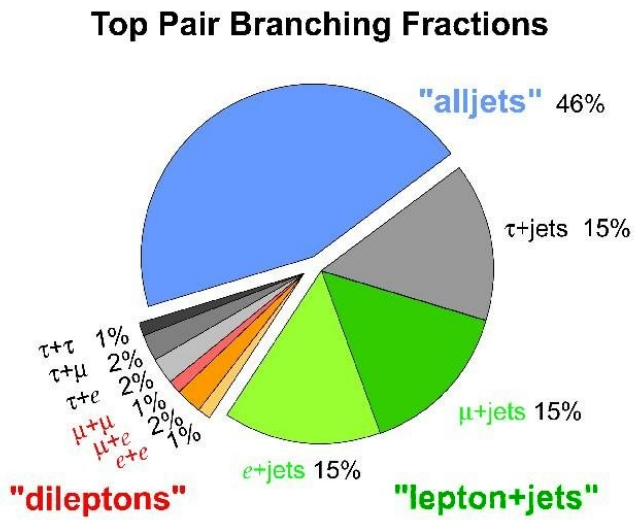
$q\bar{q}$ annihilation



gg fusion



- Different decay channels:



Tevatron vs. LHC:

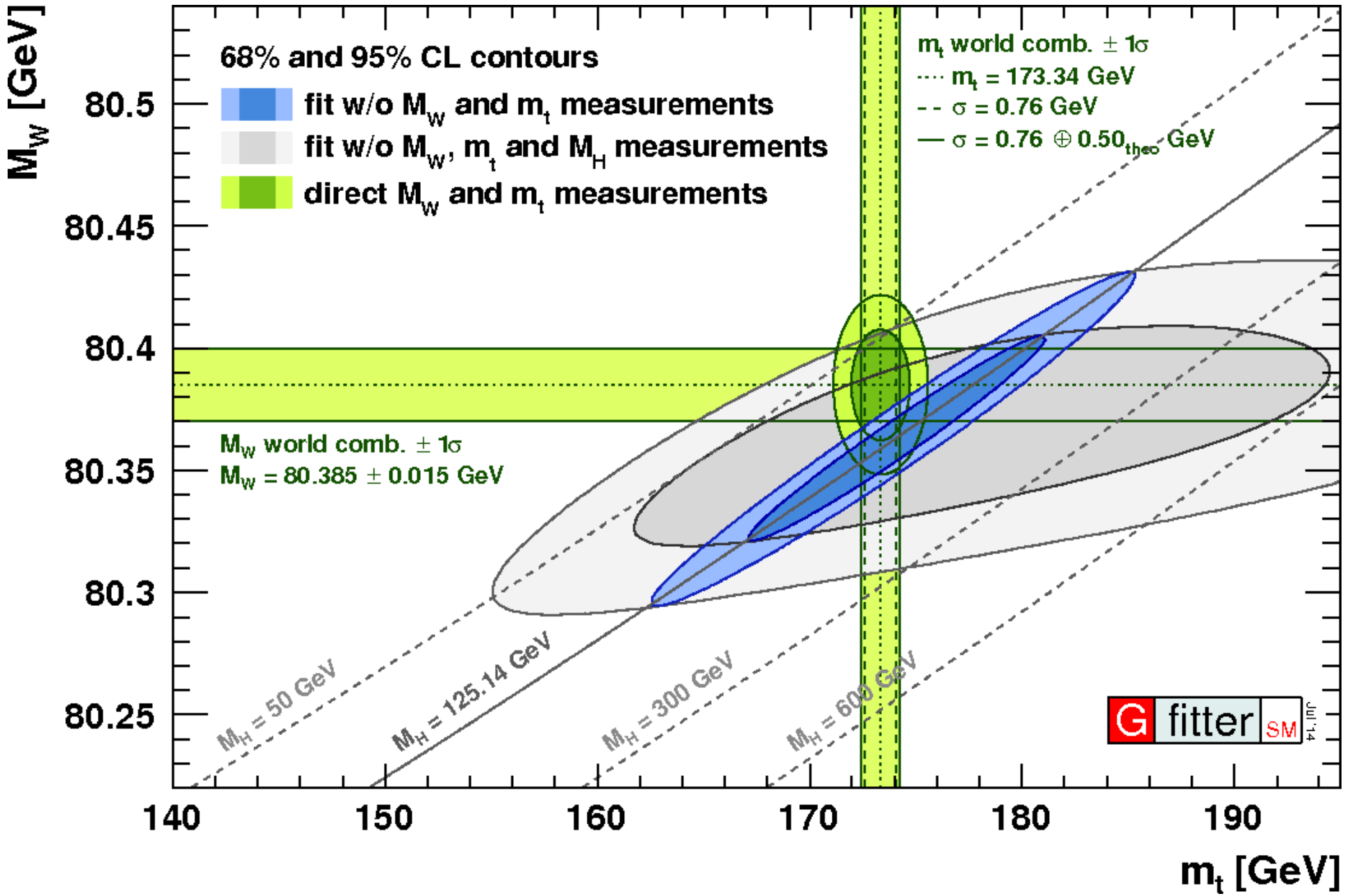
$q\bar{q}$: ~85% ~15/13% (~10%, 14 TeV)

gg: ~15% ~85/87% (~90%, 14 TeV)

(1.96 TeV 7/8 TeV)

- Worlds largest $p\bar{p}$ data set for a long time
- Complementary to LHC due to different IS

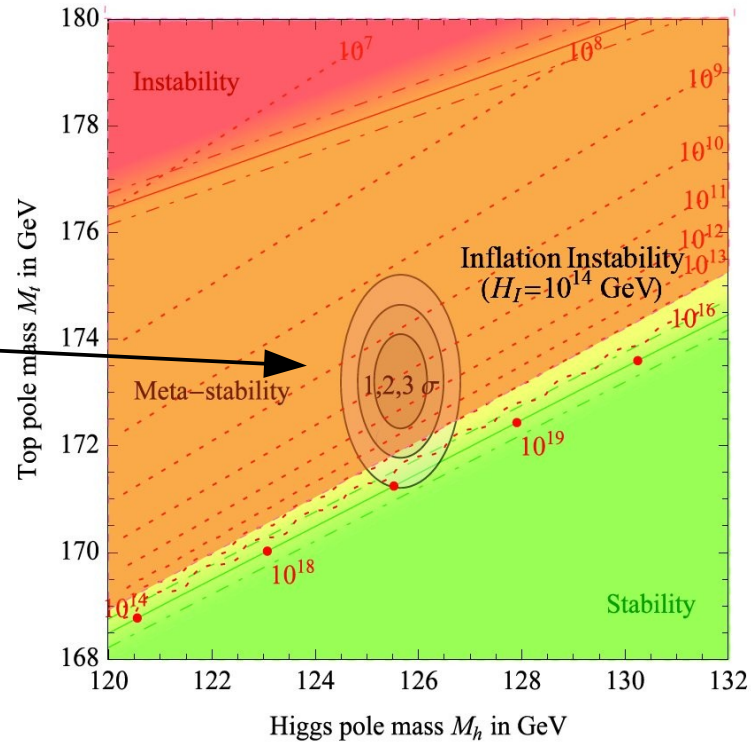
SM self-consistency

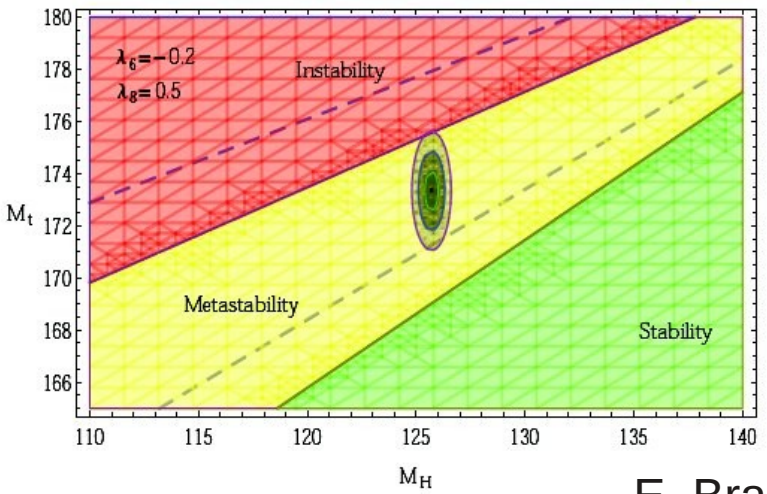


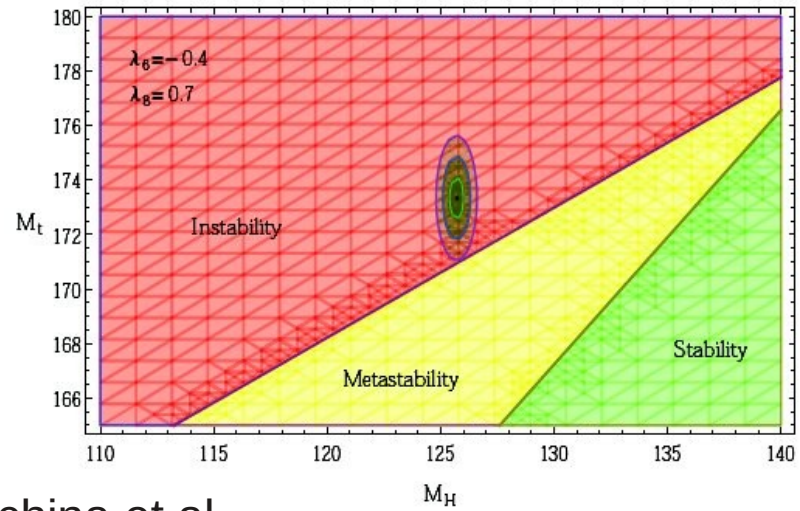
Fate of the universe

- With the Higgs discovery the SM can be extrapolated to Planck scale energies
- "Test" the stability of the electroweak vacuum, under assumption of no new physics:
  → meta-stable, life time > $O(10^{80})\ t_{universe}$

→ but new physics can change that dramatically







E. Branchina et al.

Measurement methods

- **Matrix Element method** (leading order) calculates event probability densities from dσ/dX

$$P(x, m_t) = \frac{1}{\sigma(m_t)} \int \sum \underbrace{d\sigma(y, m_t)}_{\text{LO ME}}\, dq_1 dq_2\, \underbrace{f(q_1) f(q_2)}_{\text{PDFs}}\, \underbrace{W(y, x, k_{\mathrm{JES}})}_{\text{Transfer function}}$$

- **Ideogram method** event likelihood based on Breit-Wigner (signal) convoluted with detector resolutions

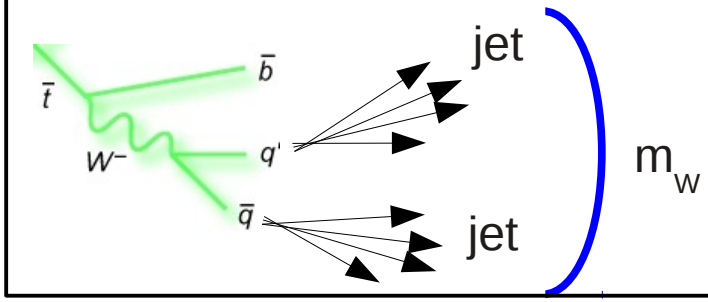
$$\mathcal{L}\left(\text{sample}|m_{\mathrm{t}}, \mathrm{JSF}\right) = \prod_{\text{events}} \left(\sum_{i=1}^{n} P_{\mathrm{gof}}(i) \left(\sum_j f_j P_j(m_{\mathrm{t},i}^{\mathrm{fit}}|m_{\mathrm{t}}, \mathrm{JSF}) \times P_j(m_{\mathrm{W},i}^{\mathrm{reco}}|m_{\mathrm{t}}, \mathrm{JSF}) \right) \right)^{w_{\mathrm{event}}}$$

- **Template method** compares histograms in data to simulations (including detector resolutions)

- Depend on MC → We measure "MC mass"

- **Alternative methods** ("End-point", J/ψ , "σ")

W boson fully reconstructed:
→ In-situ calibration, Constrain reconstructed m_W to m_W

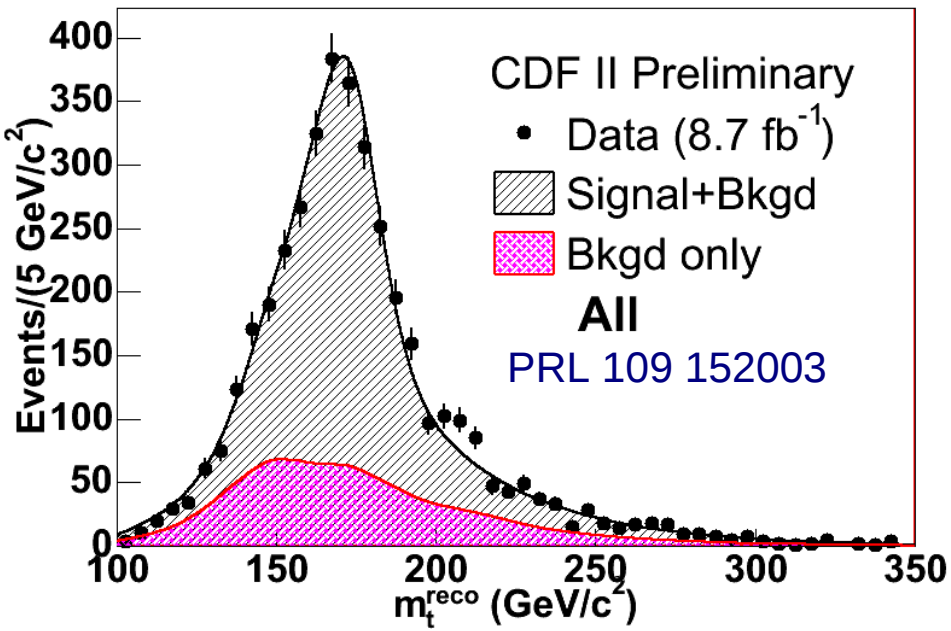


CDF template method

- Reconstruct lepton+jets event kinematics by minimizing:

$$\mathcal{L}_k = \exp\left(-\frac{(n_b - n_b^0)^2}{2\sigma_{n_b}^2}\right) \times \prod_{i=1}^{N} \frac{n_s P_{sig}(m_t^{\rm reco}, m_{\rm jj}, m_t^{\rm reco(2)}; M_{top}, \Delta_{JES}) + n_b P_{bg}(m_t^{\rm reco}, m_{\rm jj}, m_t^{\rm reco(2)}; \Delta_{JES})}{n_s + n_b}$$

- 3D template fit of m_{jj}^{reco}, m_t^{reco1}, m_t^{reco2}
- <u>Largest uncertainties:</u> Generator & JES



CDF II Preliminary 8.7 fb^{-1}

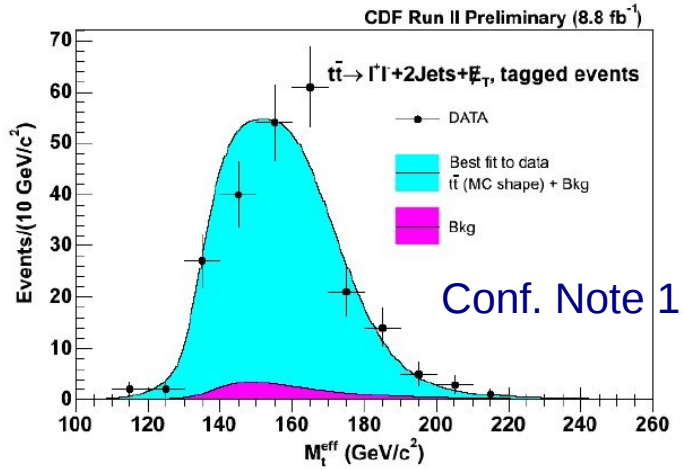
Systematic	GeV/c^2
Residual JES	0.52
Generator	0.56
Next Leading Order	0.09
PDFs	0.08
b jet energy	0.10
b tagging efficiency	0.03
Background shape	0.20
gg fraction	0.03
Radiation	0.06
MC statistics	0.05
Lepton energy	0.03
MHI	0.07
Color Reconnection	0.21
Total systematic	0.84

→ m_t = 172.85 ± 0.71 (stat+JES) ± 0.84 (syst) GeV $\delta m_t/m_t$ = 0.63%

CDF template method

- Dilepton decay channel using Hybrid method to reduce JES uncertainty
  - $m_t^{eff} = w\, m_t^{reco} + (1-w)\, m_t^{alt}$, with:
    - → m_t^{reco} sensitive to true m_t
    - → m_t^{alt} less sensitive to m_t

      but does not use jet energies

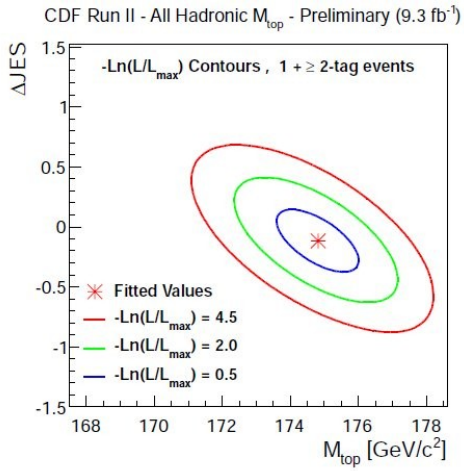


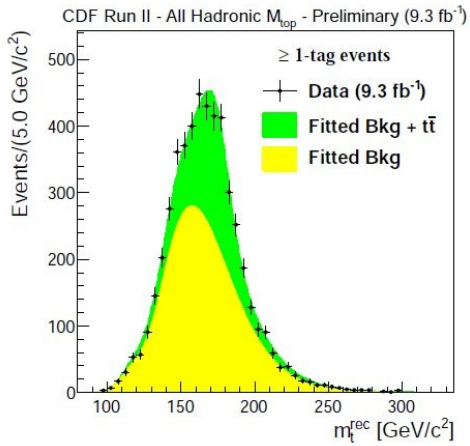
Conf. Note 11072

→ $m_t = 170.80 \pm 1.83$ (stat. + JES) ± 2.69 (syst.) GeV $\delta m_t/m_t = 1.9$ %

- All-hadronic decay channel:
  - Data driven bg model
  - S/B ~ 1 for ≥ 2 *b*-tags
  - For each event reconstruct *W* mass and *t* mass by minimizing χ^2
  - Hadronic *W decay* for in-situ JES cal.

PRD 90 091101





→ $m_t = 175.07 \pm 1.19$ (stat. + JES) ± 1.56 (syst.) GeV $\delta m_t/m_t = 1.1$ %

CDF combination

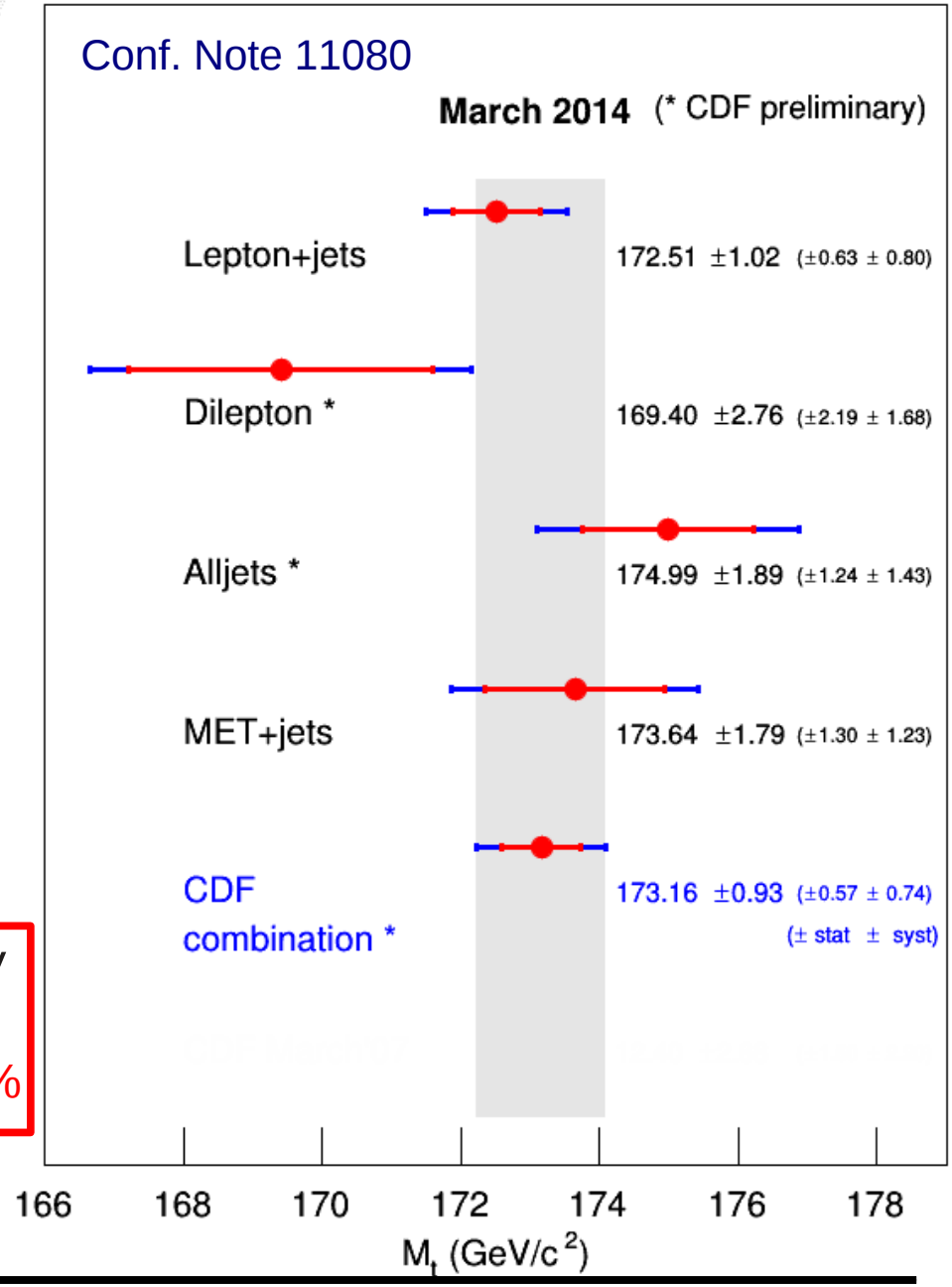
- Combination using BLUE
- Careful study of correlations, all taken into account
- Per channel correlations:

CDF Preliminary

Final State	M_t [GeV/c^2]	Correlations			
		$M_t^{\ell+\text{jets}}$	$M_t^{\ell\ell}$	M_t^{alljets}	M_t^{MET}
$M_t^{\ell+\text{jets}}$	172.51 ± 1.02	1.00			
$M_t^{\ell\ell}$	169.40 ± 2.76	0.40	1.00		
M_t^{alljets}	174.99 ± 1.90	0.25	0.26	1.00	
M_t^{MET}	173.64 ± 1.79	0.25	0.20	0.13	1.00

→ m_t = 173.16 ± 0.57 (stat.) ± 0.74 (syst) GeV

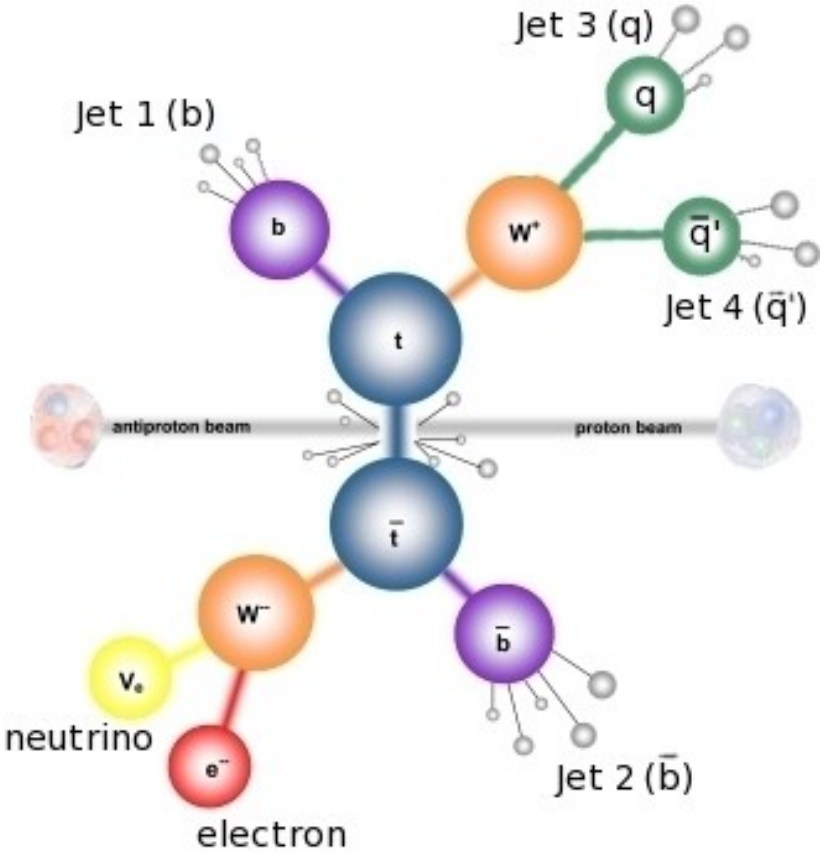
m_t = 173.16 ± 0.93 (total) GeV $\delta m_t/m_t$ = 0.54%



D0 matrix element

- "Matrix Element" method calculates event probability densities *P* from differential cross sections and detector resolutions:

$$P(x, m_t) = \frac{1}{\sigma(m_t)} \int \sum \underbrace{d\sigma(y, m_t)}_{\text{Differential cross sections}} \, dq_1 dq_2 \, \underbrace{f(q_1) f(q_2)}_{\text{"Structure" of colliding particles}} \, \underbrace{W(y, x, k_{\mathrm{JES}})}_{\text{Detector resolutions}}$$



- Top quark decays lead to complex final states in detector
- 10 dimensional phase space integration **and** summing over all possible jet – parton assignments
- Disadvantage: **high computational demands**

D0 matrix element

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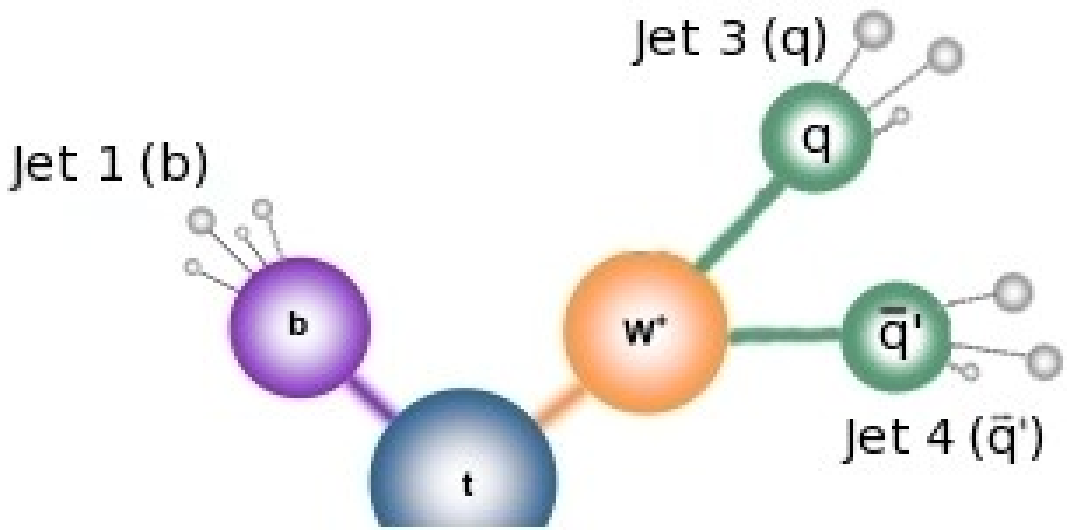
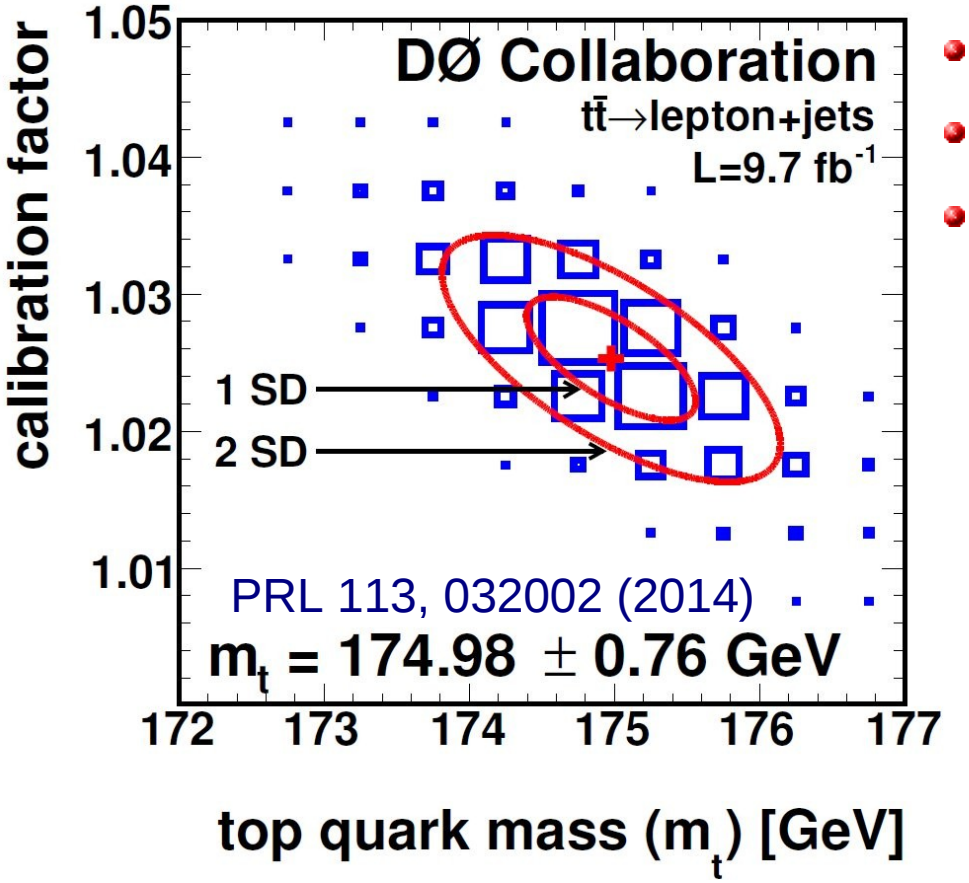
- Most precise method available – makes best use of the event info
- "Cross-calibrate" results by using the *W* boson decay:



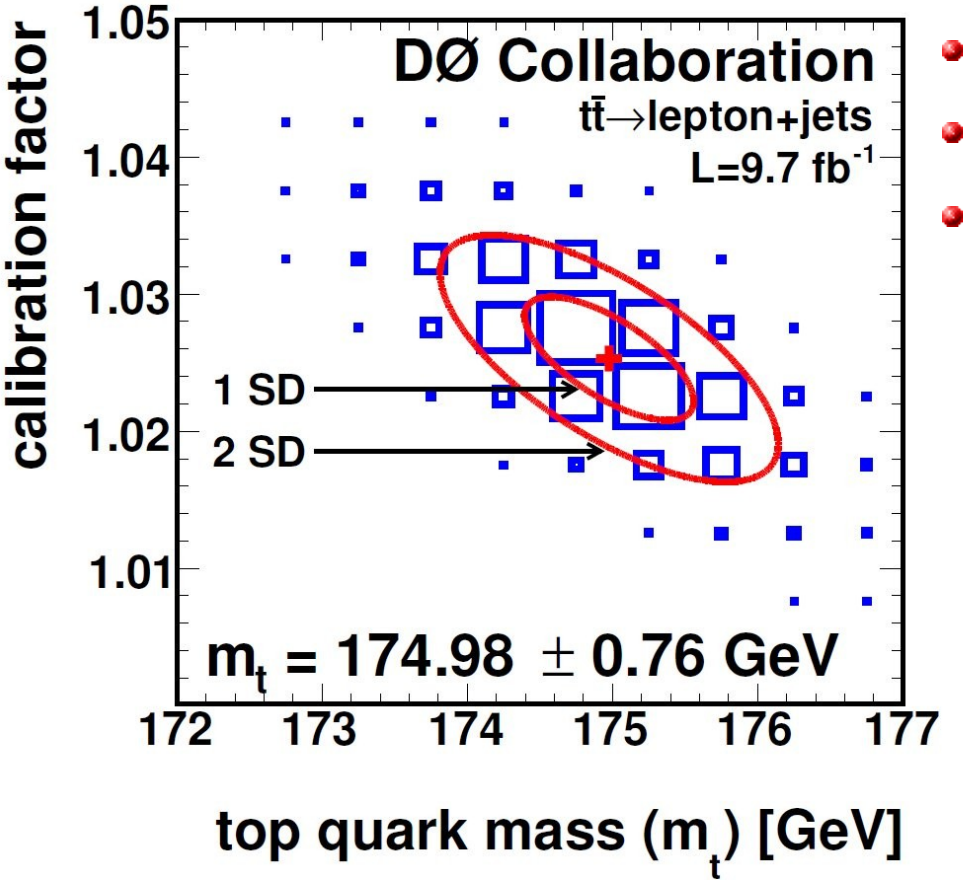
- Constrain jets of hadronic W decay to known W mass
- World average from Particle Data Group: 80.398 GeV

D0 matrix element



- lepton+jets, exactly 4 jets & ≥ 1 *b*-tag
- 2D measurement of k_{JES} and m_t
- **Factorize systematic uncertainties**, avoid double-counting:
  - → statistical unc. of systematical unc. is **0.01 – 0.05 GeV**
  - → higher order corrections: ± 0.25 GeV (3.6/fb), now ± 0.15 GeV

D0 matrix element



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

m_t = 174.98 ± 0.76 (total) GeV 0.43% relative uncertainty

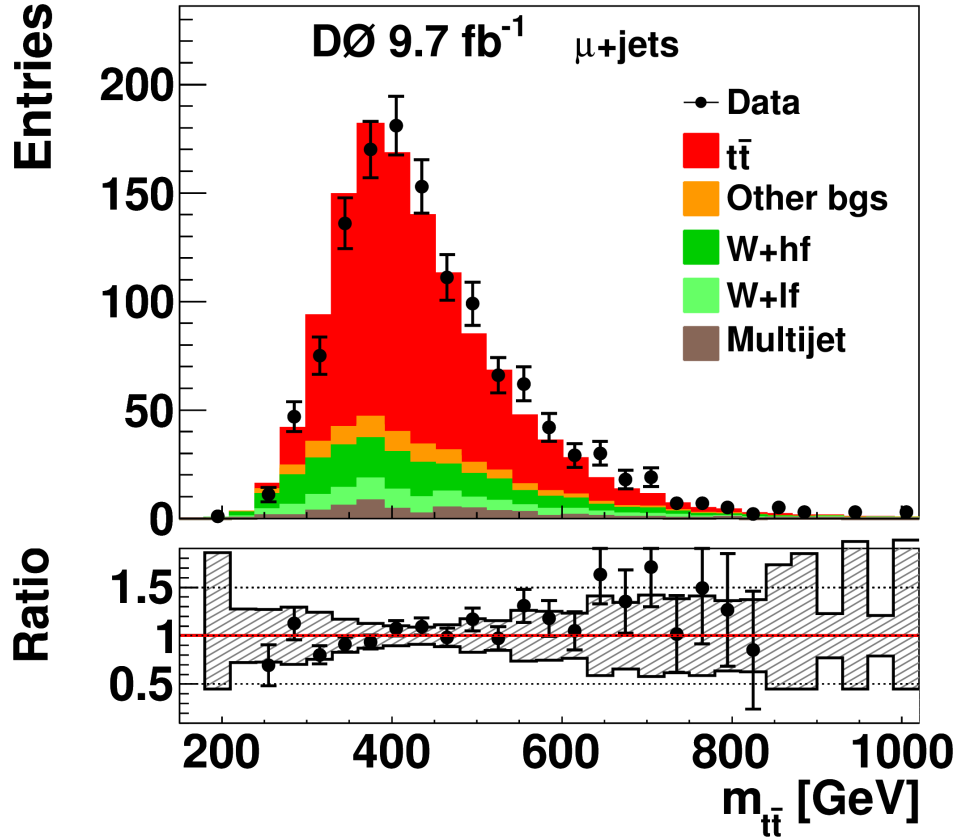
Single most precise measurement!

PRL 113, 032002 (2014)

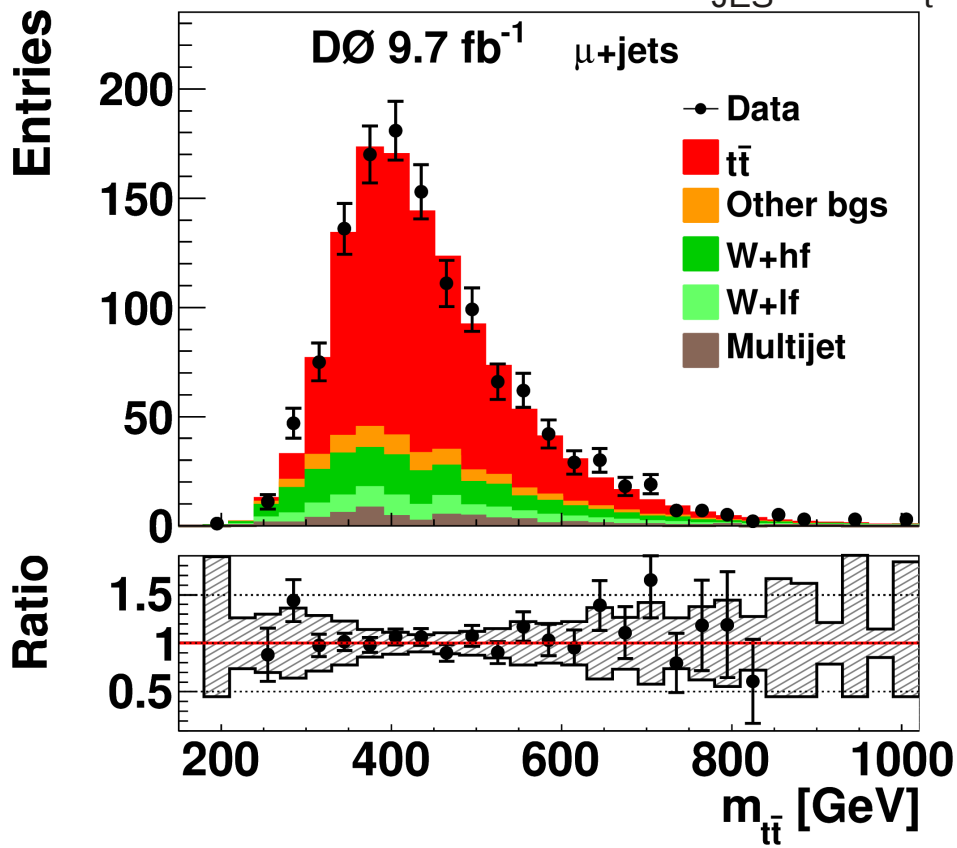
For comparison CMS:
m_t = 172.02 ± 0.77 GeV

D0 matrix element

Before applying corrections:

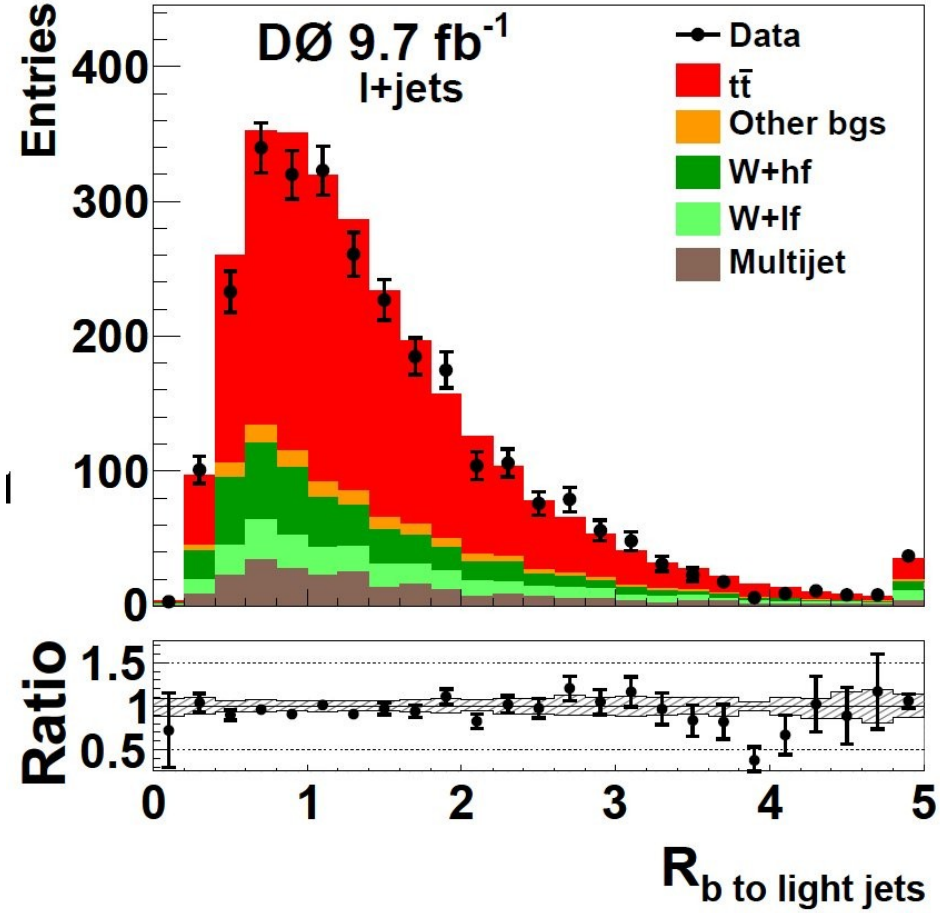


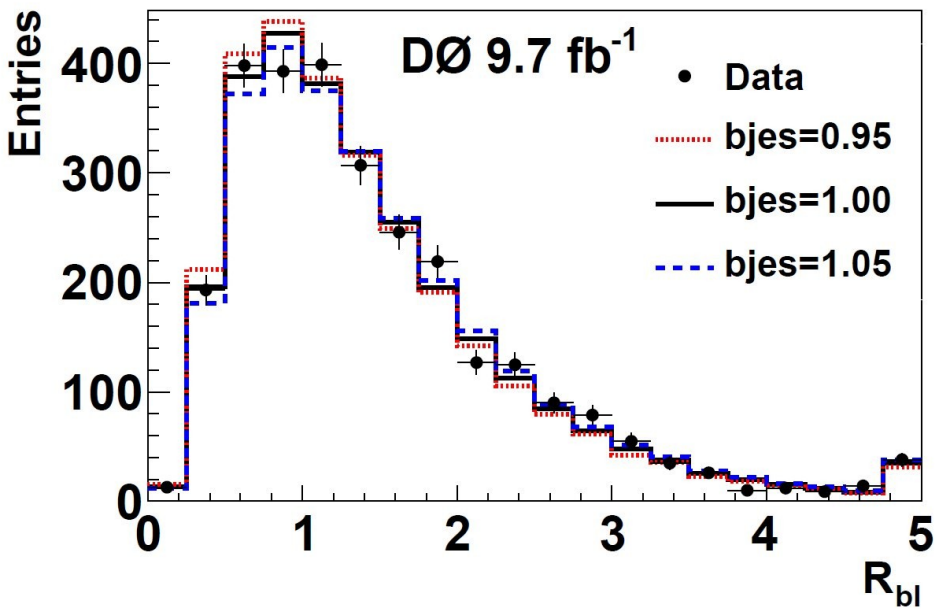
After applying corrections: k_{JES}, σ, m_t



- Apply results of the measurement to "MC" and verify that data is well described within uncertainties – it is !

D0 matrix element





≥ 2 btag

$$R_{bl} = \frac{p_T^{bjet1} + p_T^{bjet2}}{p_T^{ljet1} + p_T^{ljet2}}$$

== 1 btag

$$R_{bl} = \frac{p_T^{bjet1}}{(p_T^{ljet1} + p_T^{ljet2})/2}$$

- Measure ratio of p_T of *b*- to light jets → sensitive to *b*-JES ('ATLAS method')
- Template fit including dominant systematic uncertainties

→ $R_{bl} = 1.008 \pm 0.0195\ (\text{stat.}) \pm^{0.037}_{0.031}\ (\text{syst.})$

Subm. to PRD
arXiv:1501.07912

- Important cross-check of *b*-JES; after all corrections applied ~ 1.

Systematic uncertainties

- Highly precise measurements, dominant systematic uncertainties:

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	+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	±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	±0.58
Total uncertainty	±0.76

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

- "Standard" measurements depend on MC → We measure MC mass
  - Addressed by signal model uncertainty

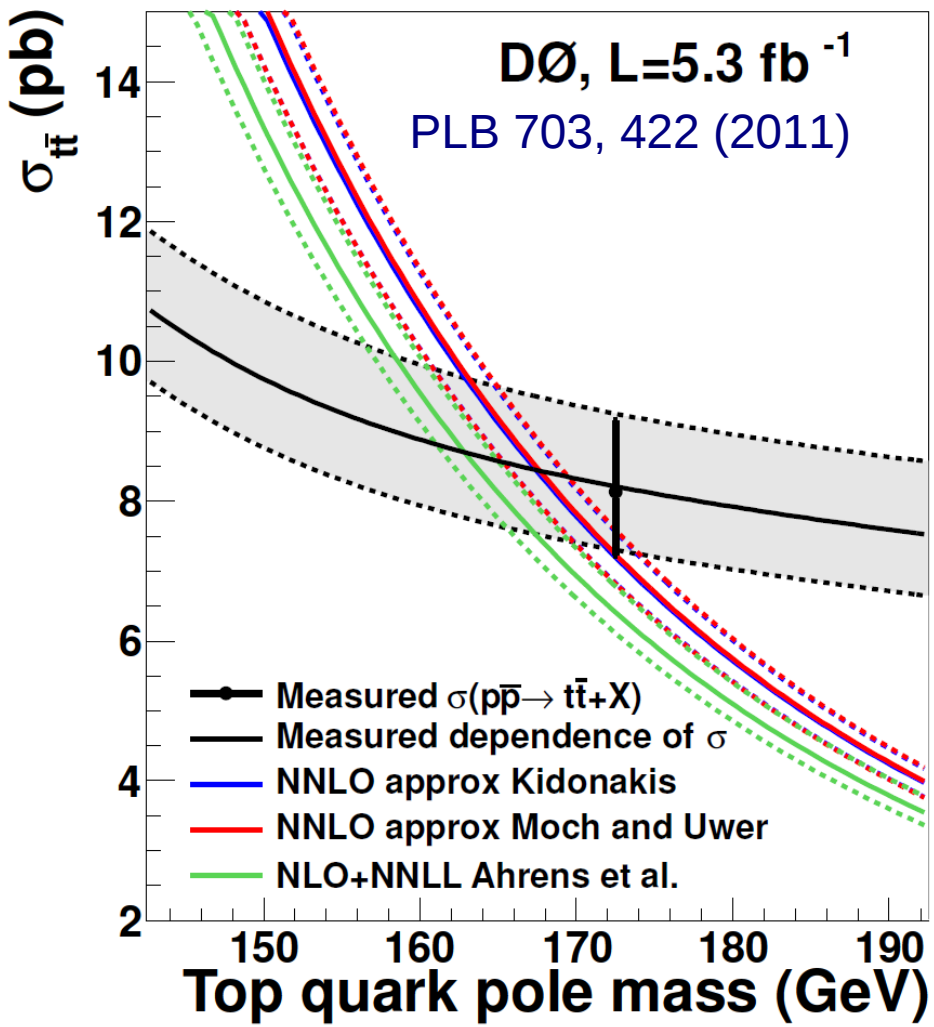
- "Translation" uncertainty from measured "MC mass" to pole mass
  - Additional theoretical uncertainty of about 0.5 – 1 GeV
  - → Use alternative methods, e.g. extract mass from cross sections

Alternative methods

- Mass is convention dependent:

Depends on the renormalization scheme

- Direct mass measurement is close to the pole mass
- Derive m_t^{pole} from intersection of measured $\sigma_{t\bar{t}}$ and theoretical predictions:

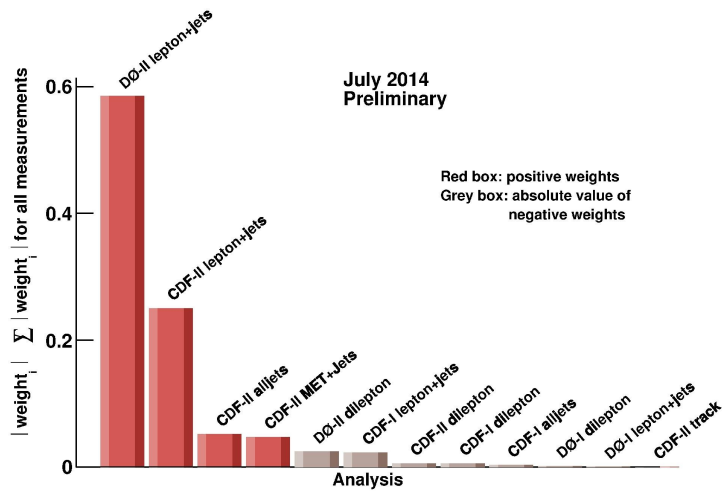


Theoretical prediction	m_t^{pole} (GeV)	Δm_t^{pole} (GeV)
MC mass assumption	$m_t^{MC} = m_t^{pole}$	$m_t^{MC} = m_t^{\overline{MS}}$
NLO [11]	$164.8^{+5.7}_{-5.4}$	-3.0
NLO+NLL [12]	$166.5^{+5.5}_{-4.8}$	-2.7
NLO+NNLL [13]	$163.0^{+5.1}_{-4.6}$	-3.3
Approximate NNLO [14]	$167.5^{+5.2}_{-4.7}$	-2.7
Approximate NNLO [15]	$166.7^{+5.2}_{-4.5}$	-2.8

→ $m_t = 167.5 + 5.4 - 4.7$ GeV

Tevatron combination

- Combined using BLUE
- Careful study of correlations, all taken into account
- Individual weights of measurements:

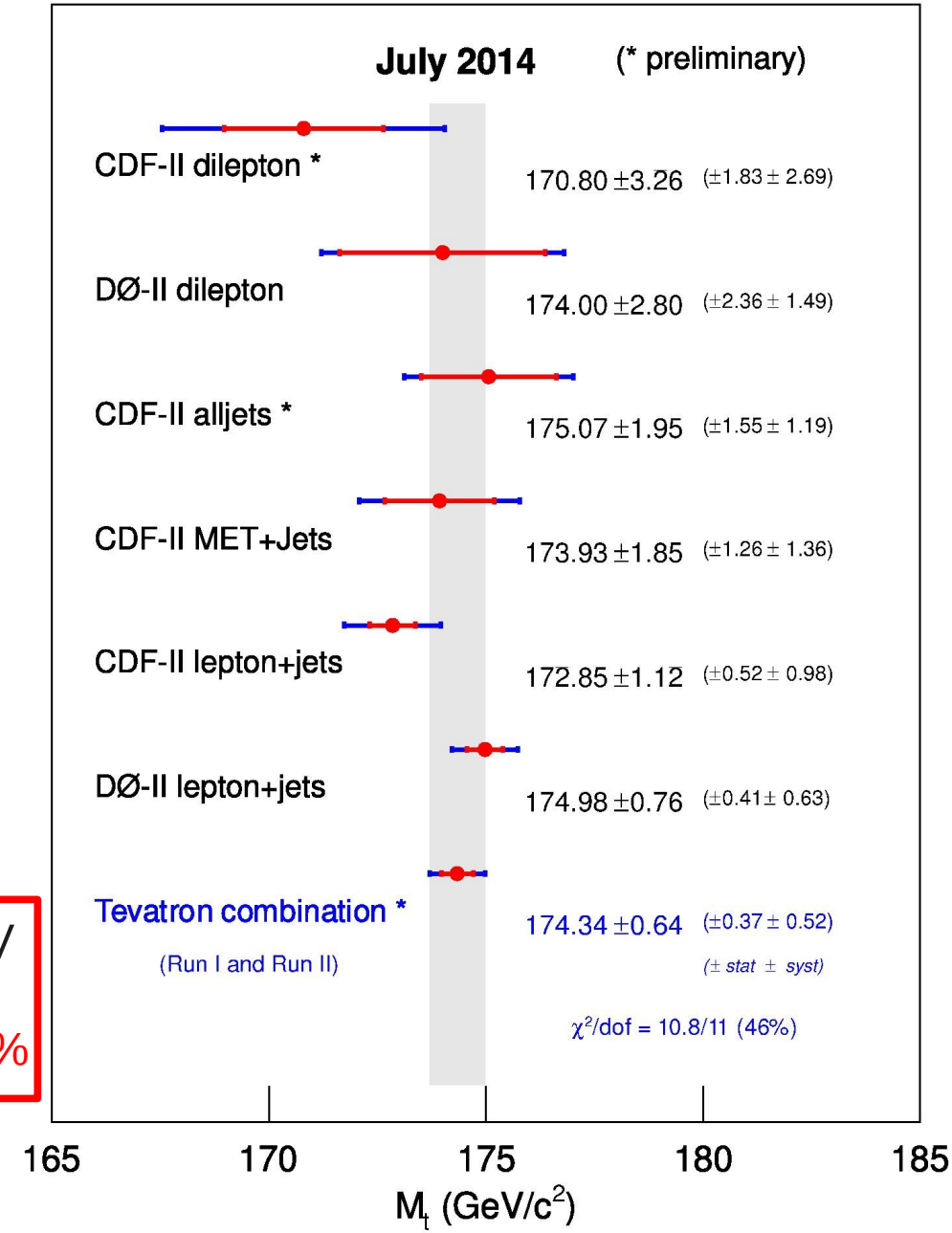


arxiv:1407.2682

m_t = 174.34 ± 0.37 (stat.) ± 0.52 (syst) GeV

m_t = 174.34 ± 0.64 (total) GeV $\delta m_t/m_t$ = 0.37%

For comparison CMS combination: m_t = 172.38 ± 0.68 GeV

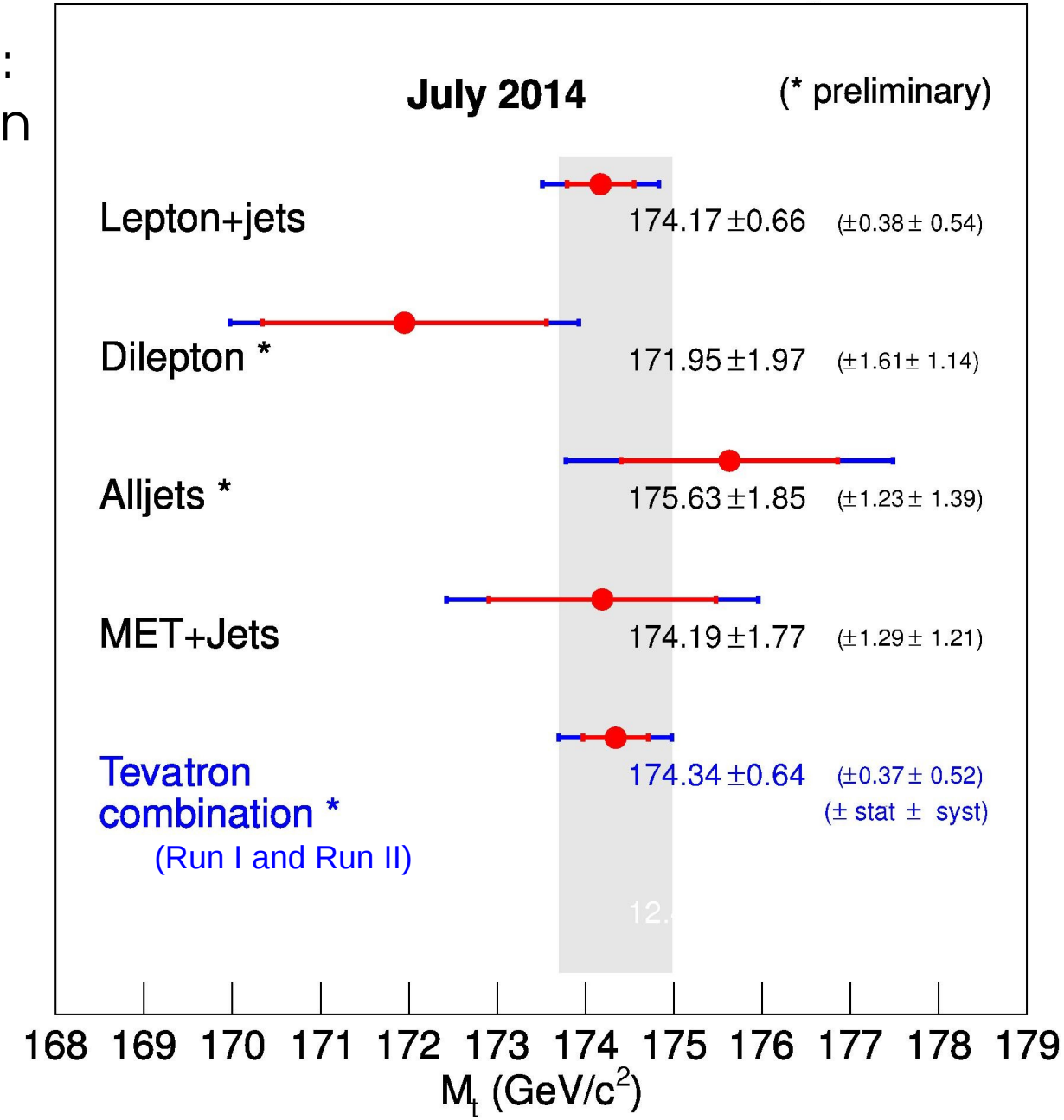


Tevatron combination

Combination of decay channels:

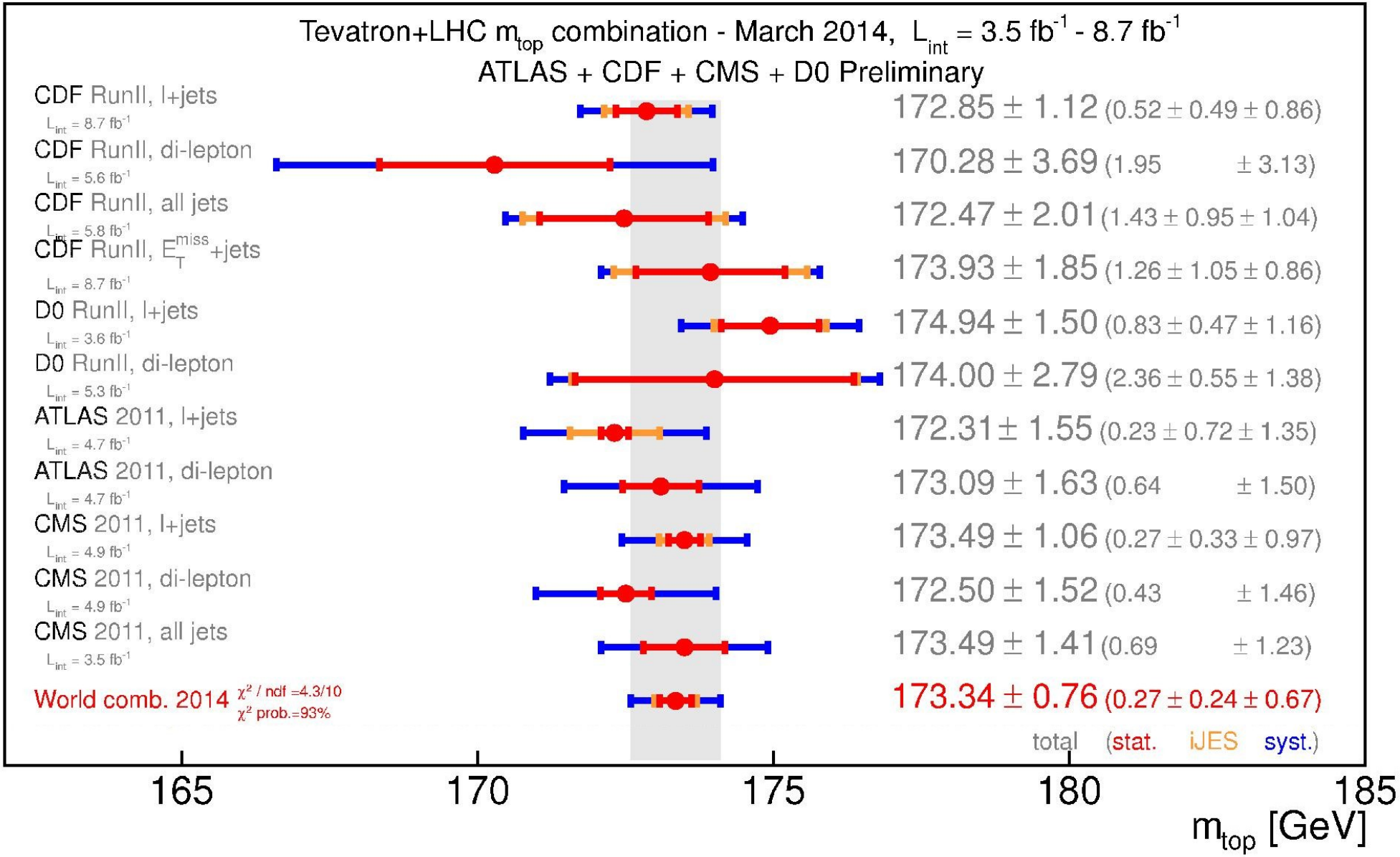
- Combination driven by precision of D0 l+jets results
- Very good agreement seen
- χ^2 of combination:

χ^2/dof = 10.8/11 (46 %)



World combination

- World combination (ATLAS + CDF + CMS + D0): arXiv:1403.4427

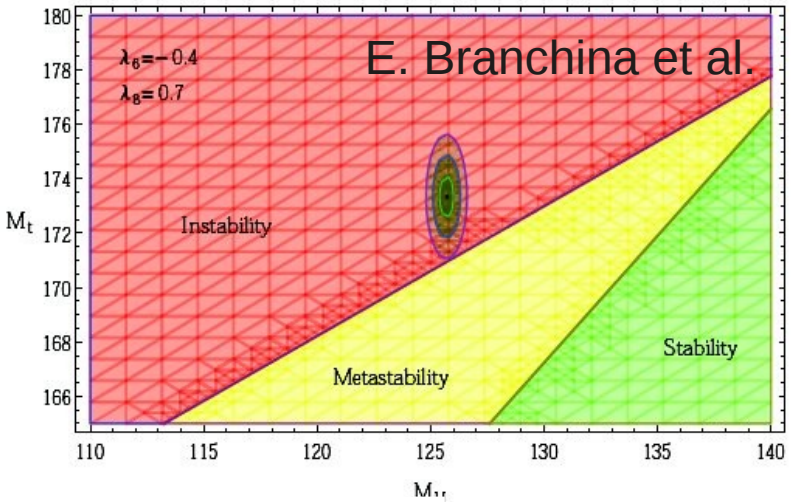


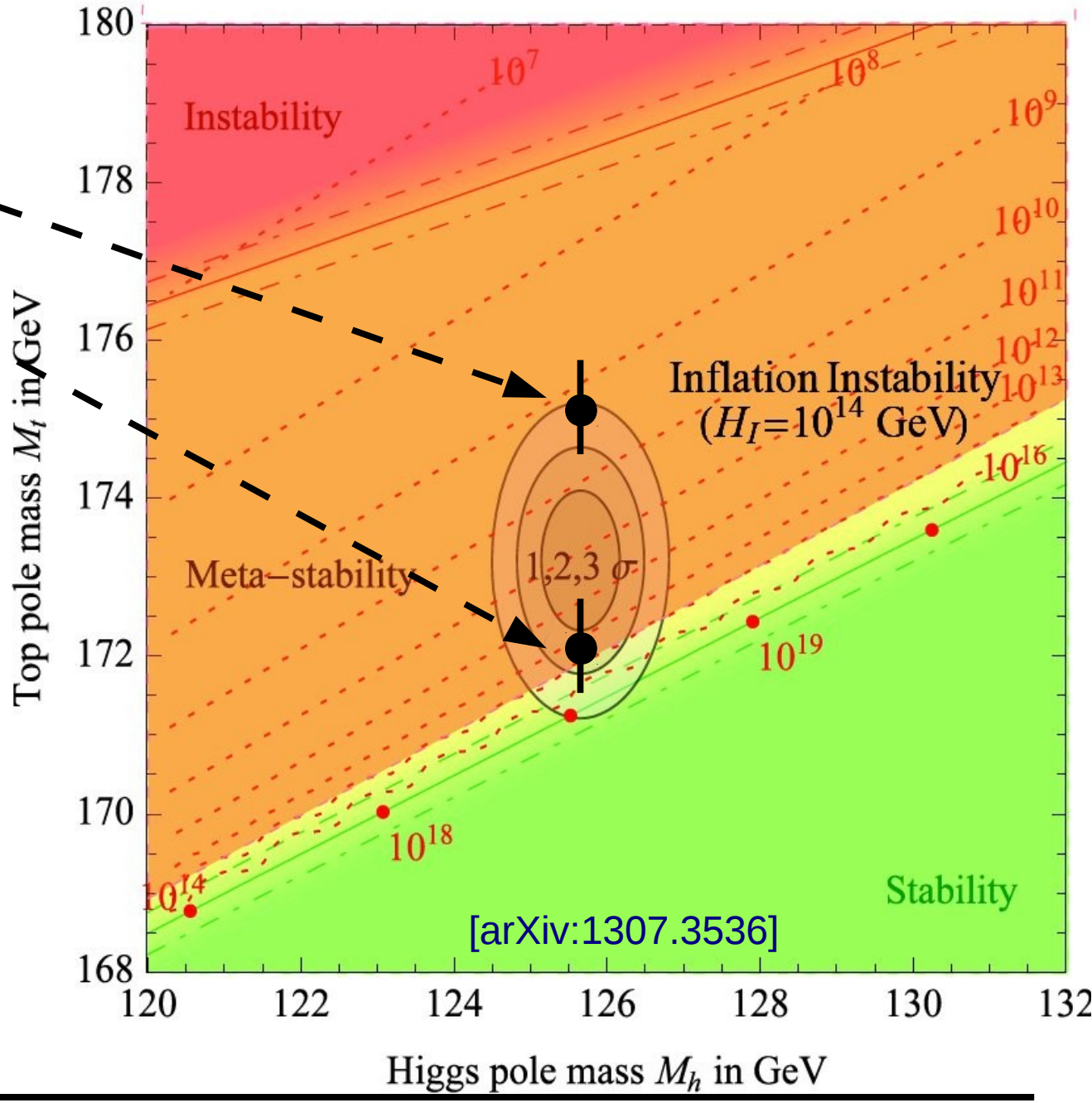
Fate of the universe

- Contour is world average
- Add latest measurements:
  D0 m_t = 174.98 ± 0.76 GeV

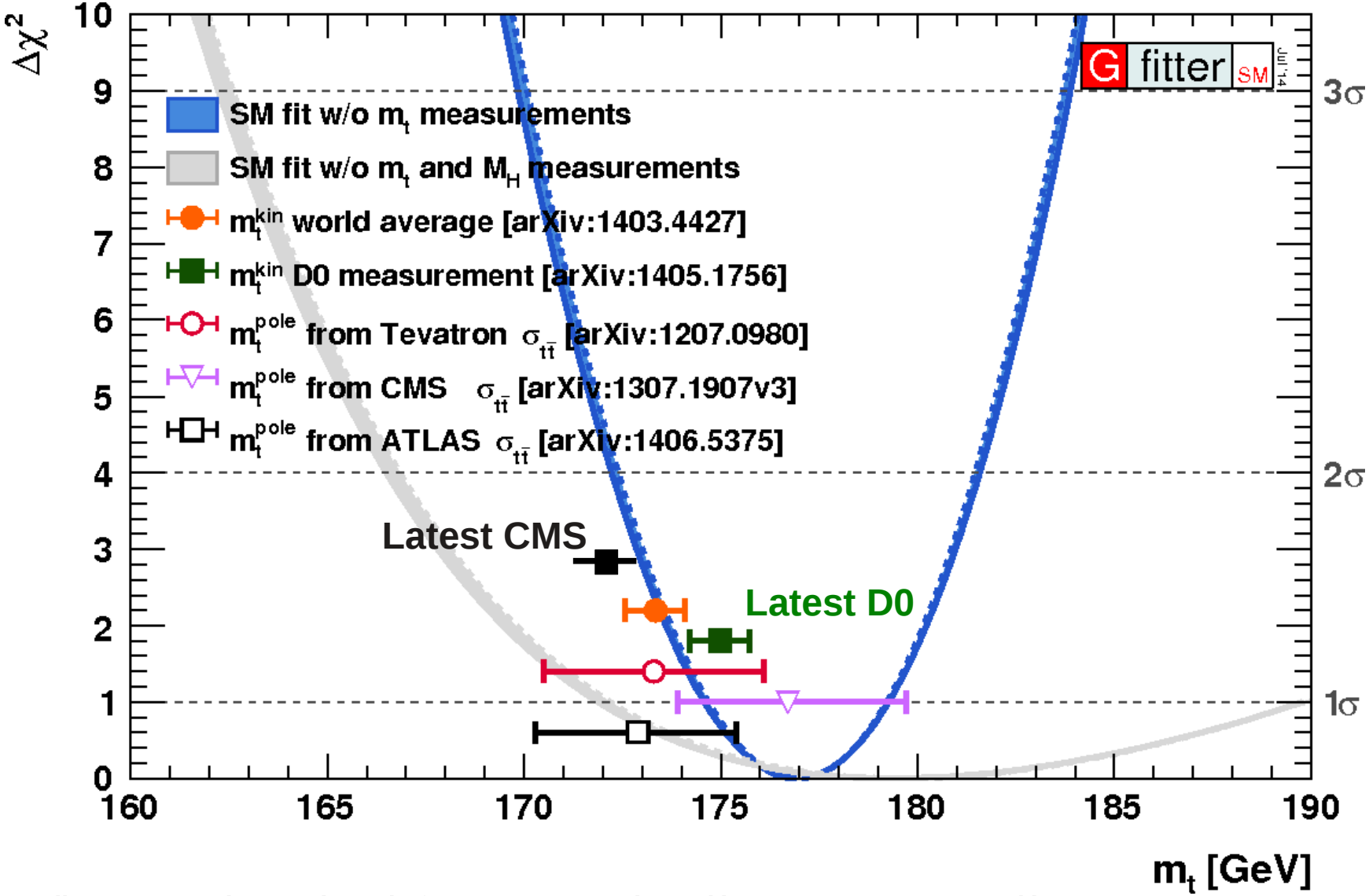
  CMS m_t = 172.02 ± 0.77 GeV
- But: extrapolation, mass definition
  → additional uncertainties not included here

- <u>Benchmark new physics:</u>





Standard model fit



→ "pole" extracted from production cross sections

→ "kin" direct measurements, e.g. matrix element method

Conclusion & Outlook

- Many results in various channels, only some shown
- Expect new results by D0 very soon
- Precision measurements of the top quark mass part of the legacy of the Tevatron
- Most precise latest combination:

m_t = 174.34 ± 0.37 (stat.) ± 0.52 (syst) GeV

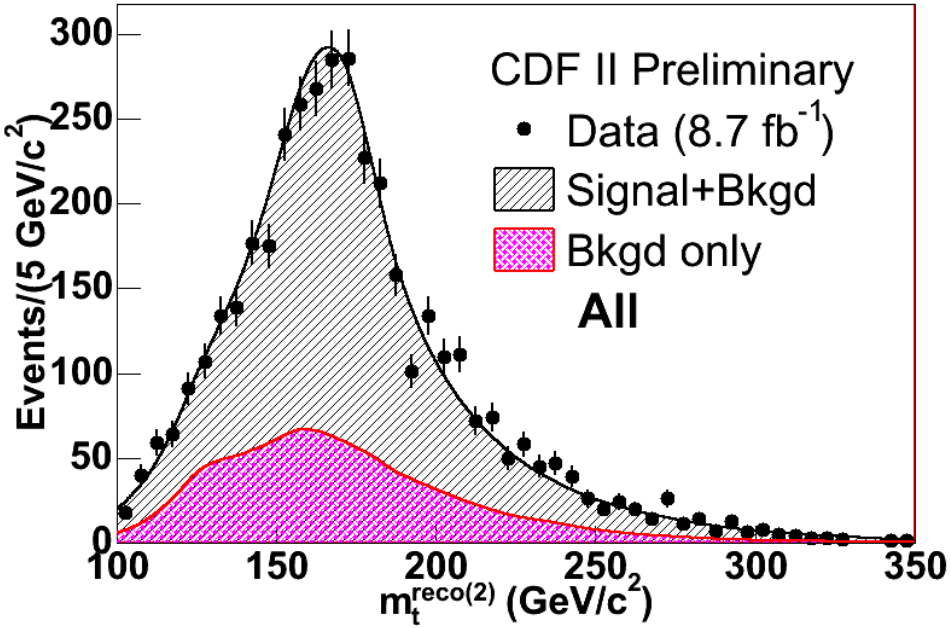
m_t = 174.34 ± 0.64 (total) GeV $\delta m_t/m_t = 0.37\%$

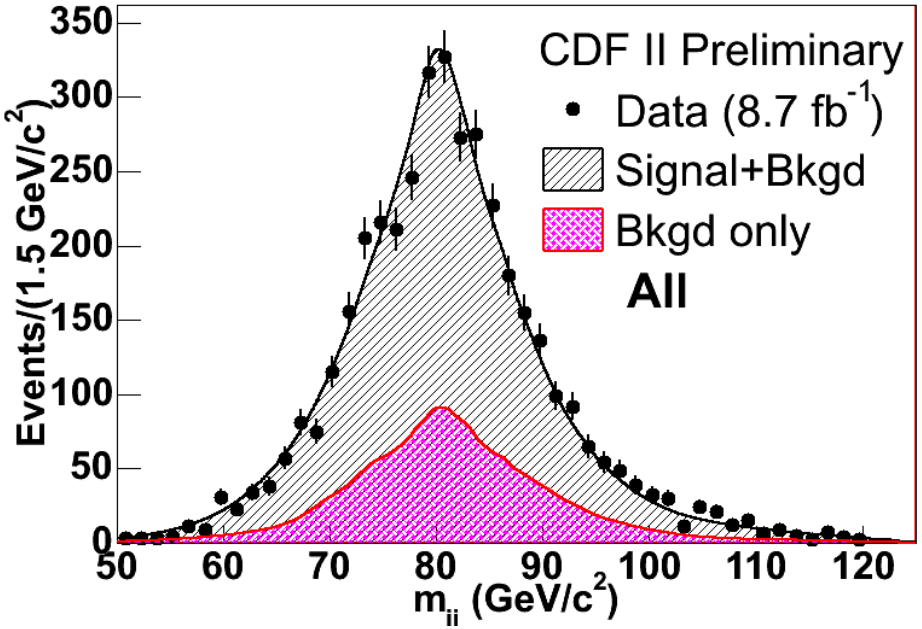
D0 web pages

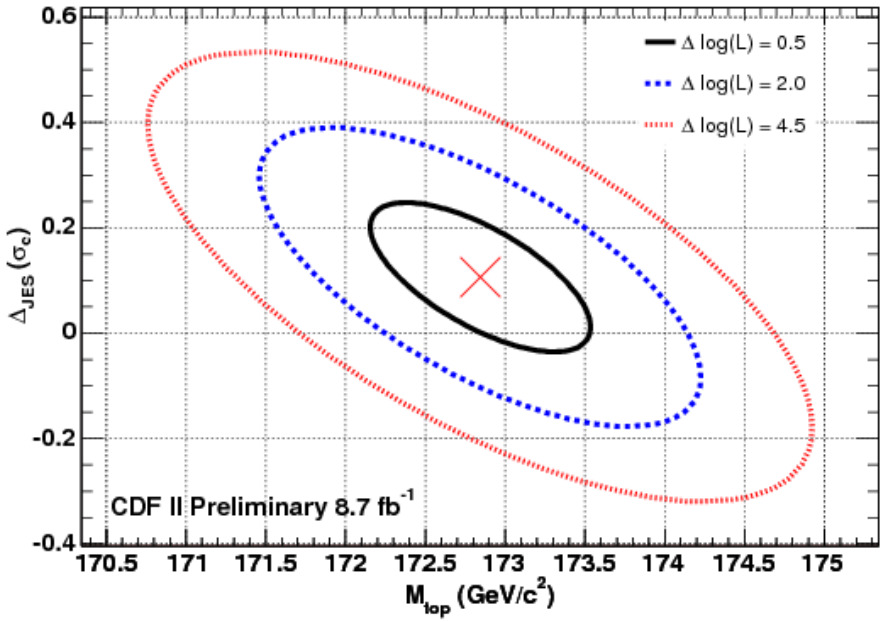
CDF web pages

Backup

CDF template methods

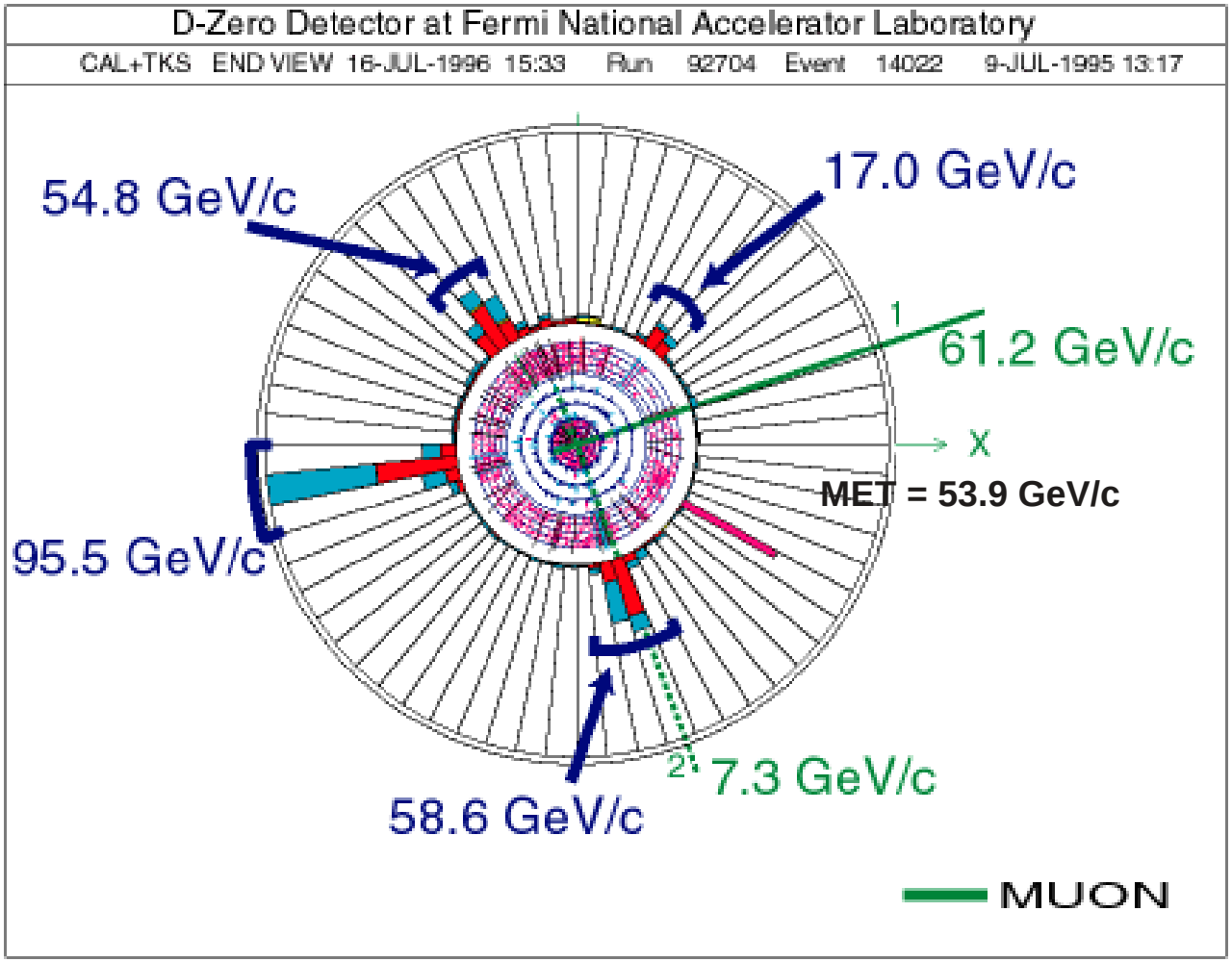






CDF combination

- Distinct signature: **lepton** and at least 4 jets



- Identify events based on "single leptons" with high transverse momentum – worked/works at Tevatron/LHC

CDF combination

Updates compared to last publication/measurement:

- More data 3.6/fb → 9.7/fb (full Run II)
- Improved object IDs (e, μ, b)
- Faster method:
  - Random number generation
  - Modify treatment of kJES
    → Verified that method gets same result as with "old" method, but factor of **~ 100 faster**
  - Allowed **dramatic increase** in MC statistics

Higher-order effects	±0.25
ISR/FSR	±0.26
Hadronization and UE	±0.58
Color reconnection	±0.28
Multiple $p\bar{p}$ interactions	±0.07
Modeling of background	±0.16
W+jets heavy-flavor scale factor	±0.07
Modeling of b jets	±0.09
Choice of PDF	±0.24
Residual jet energy scale	±0.21
Data-MC jet response difference	±0.28
b-tagging efficiency	±0.08
Trigger efficiency	±0.01
Lepton momentum scale	±0.17
Jet energy resolution	±0.32
Jet ID efficiency	±0.26

Phys. Rev. D 84, 032004 (2011)

→ Typical statistical uncertainty:
~0.25 GeV → ~ 0.01 – 0.05 GeV

D0 matrix element

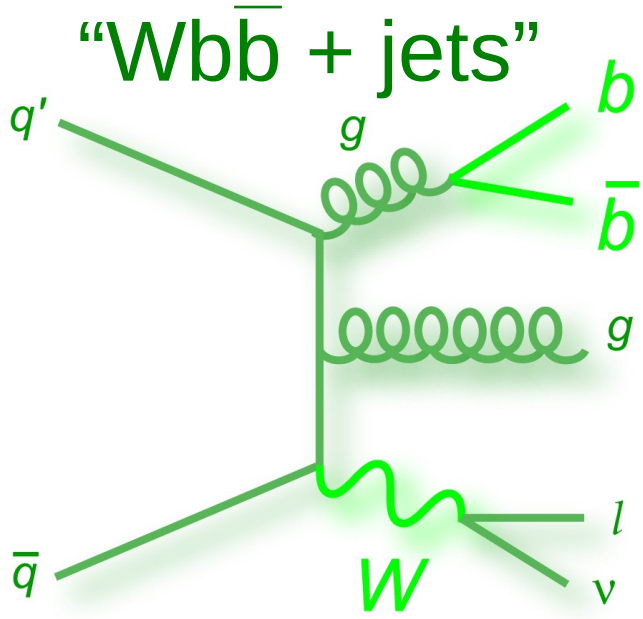
Dominated by:

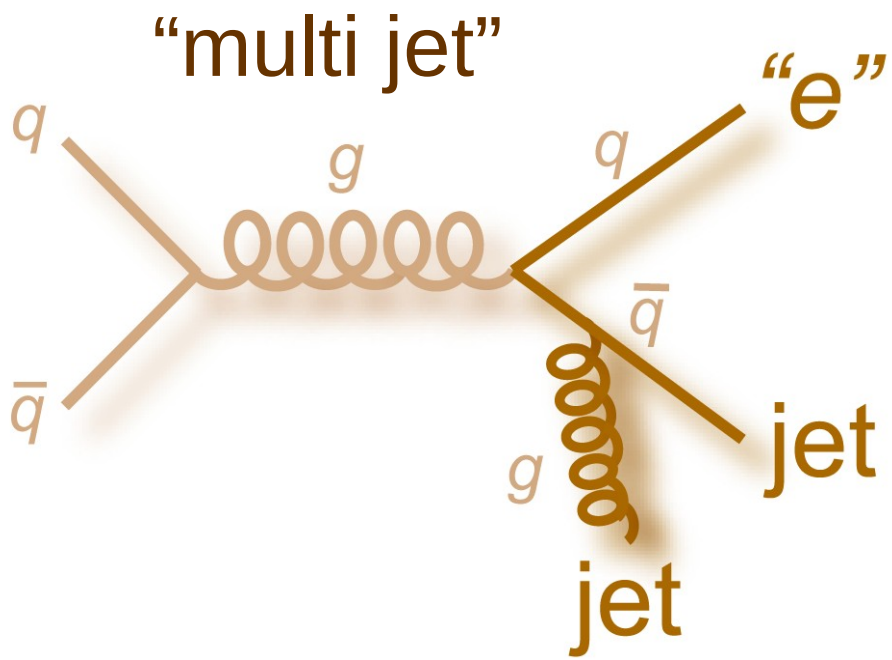
- Uncertainties related to the signal model
- Uncertainities related to the Jet energy scale

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	+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	±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

Sample composition

- Background from other physics processes and instrumental sources, e.g.

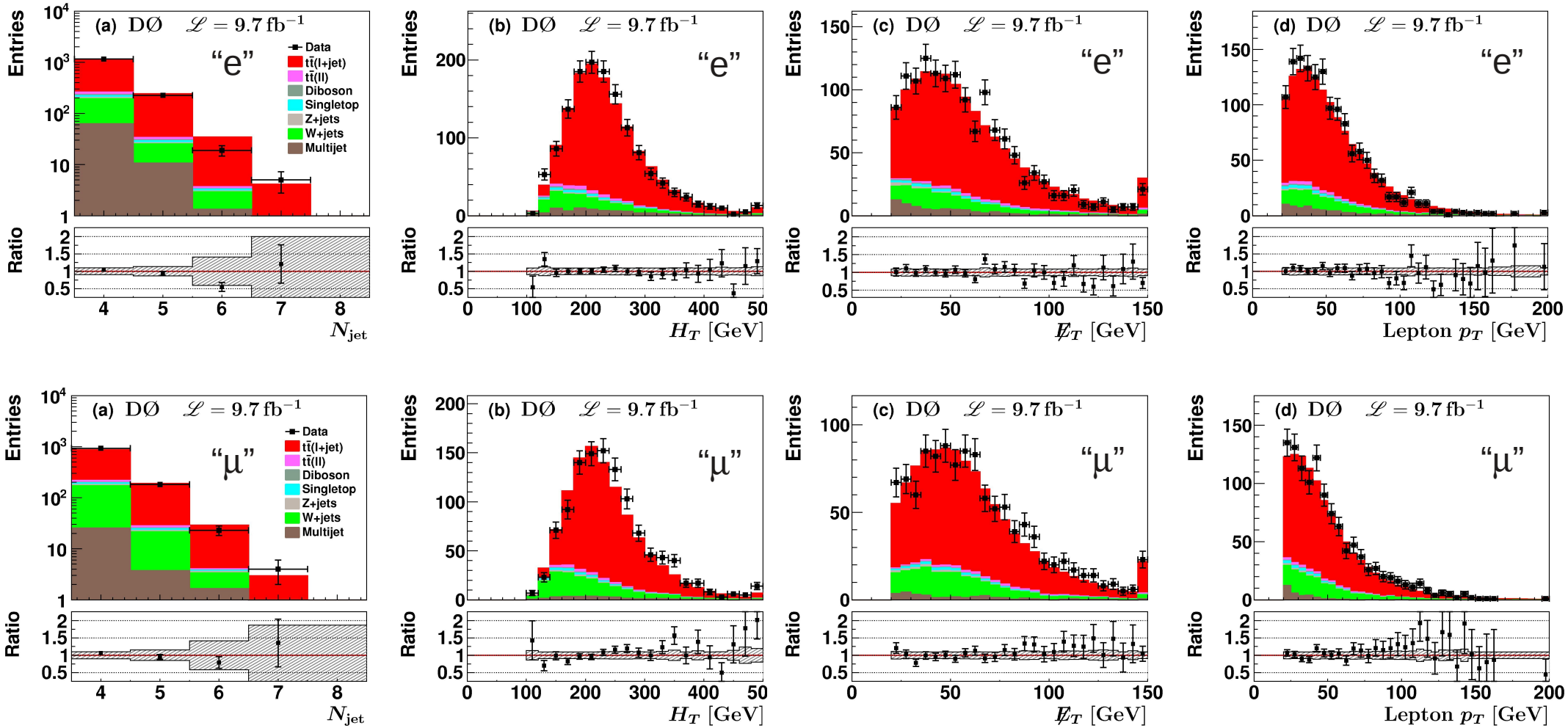




- Multi jet and W+heavy flavor (Whf) contribution derived from data
- <u>Samples for signal and backgrounds:</u>
  - $t\bar{t}$: Alpgen+Pythia, alternative also: Alpgen+Herwig, MC@NLO+Herwig
  - W/Z+jets & W/Zhf+jets: Alpgen+Pythia
  - Diboson: Pythia
  - Single top: CompHep

D0 control plots

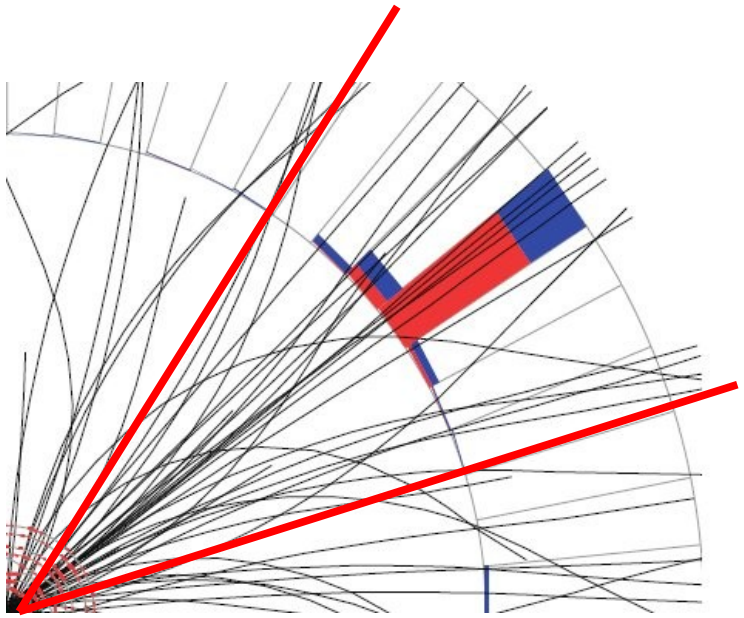
- Now check the signal region to measure differential cross sections: *e* or μ + ≥ 4 jets



(assuming the measured $t\bar{t}$ cross section)

Jet energy scale

- Its not just a "jet" from a quark...in reality much more complex:
  - Initial state & final state radiation, underlying events, multiple parton interaction, the parton shower
  - Need a correction to take these effects into account



- JES corrects reconstructed energy back to particle level (D0 case)
  - To be exact: D0 JES only valid for Pythia Tune A

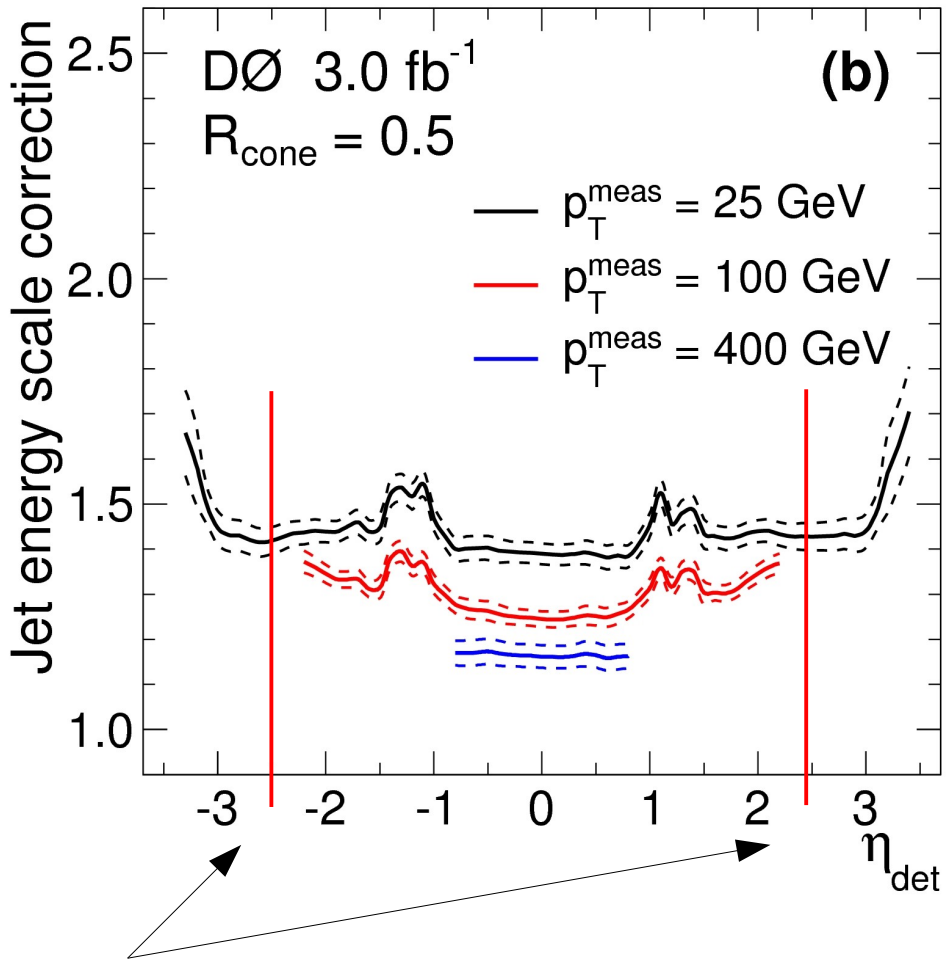
$$E^{\mathrm{ptcl}} = \frac{E^{\mathrm{meas}} - E_{\mathrm{O}}}{R \cdot S}$$

E_O – offset correction
R – response correction
S – Showering corrections, In/Out of cone

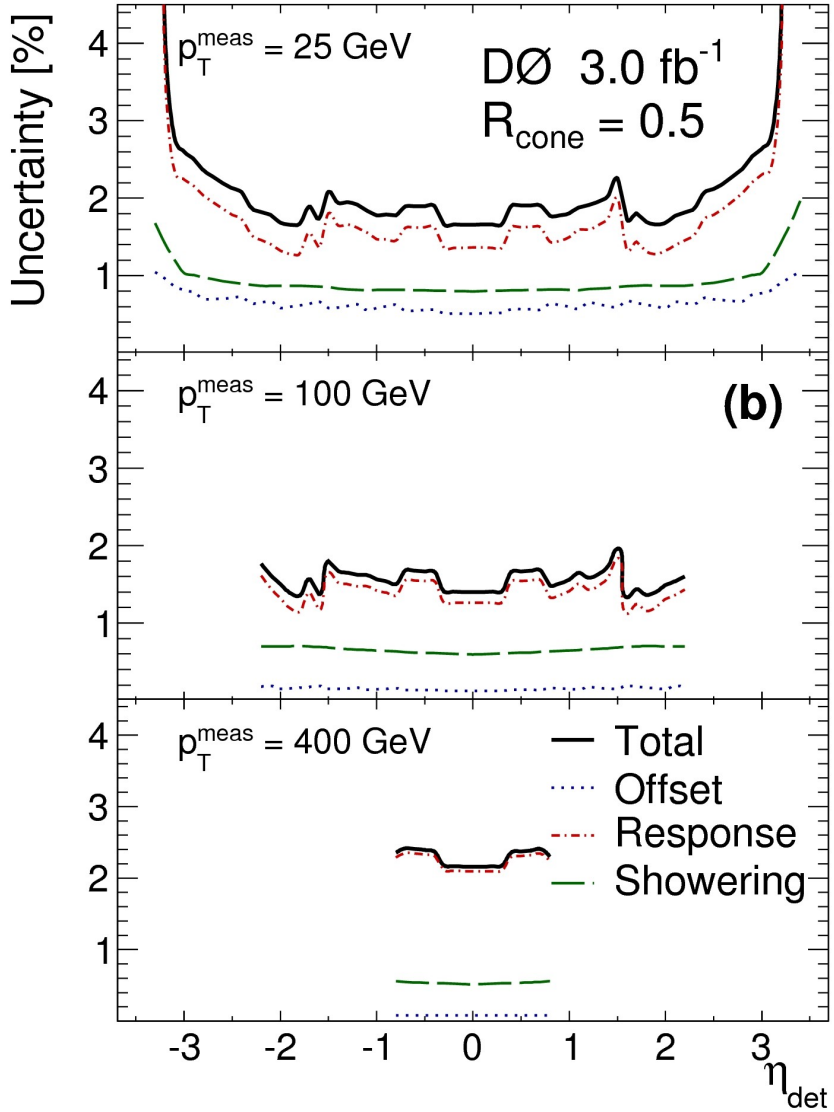
Jet energy scale

- Latest JES calibration applied
- Correction depends on jet energy, uncertainties of 1-2%

Accepted by NIM



Jet cuts required in top quark measurements



Single particle response

- JES does not distinguish quark and gluon jets
- Employ γ+jets events to calibrate response in MC to data
- Derive a correction factor F_{corr} for MC:

$$F_{\mathrm{corr}} = \frac{1}{\langle F \rangle_{\gamma+\mathrm{jet}}} \cdot \frac{\sum_i E_i \cdot R_i^{\mathrm{data}}}{\sum_i E_i \cdot R_i^{\mathrm{MC}}}$$

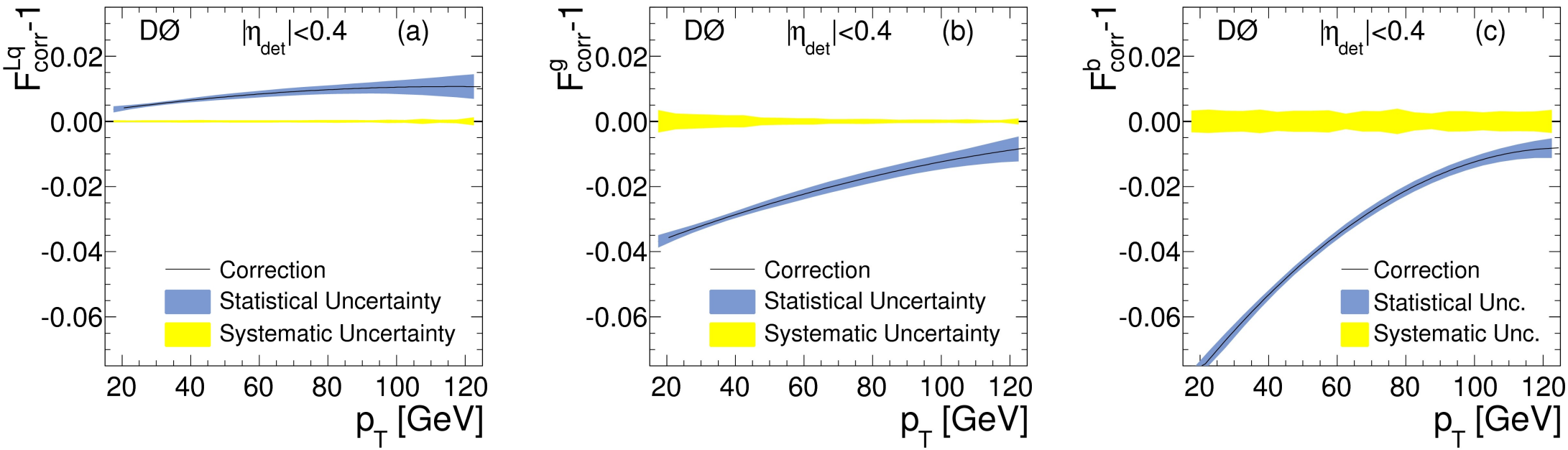
- Response in calorimeter for data or MC for particle *i* inside particle jet
- Matching with $dR < 0.25$

- Preserves standard JES calibration
- <u>Calibration by using:</u>
  - Reconstructed jet p_T with offset correction: p_T^{corr}
  - p_T of EM cluster with tight photon ID: p_T^{γ}
  - Calibrate ratio $p_T^{corr} / p_T^{\gamma}$

Assuming the single particle composition as in MC

Single particle response

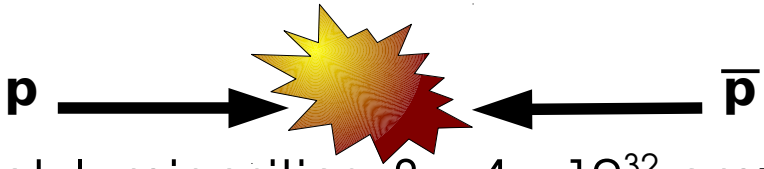
- Improves MC description of jets and reduces sample-dependency
- Resulting F_{corr} for different jet flavors and their uncertainties



- Small correction to light quarks (*u,d,s,c*), several % for *g* and *b* quarks
- Without that correction, the measurement (see 1\fb result) suffers an uncertainty for the b/light response ratio of 0.83 GeV, by far dominant source Phys. Rev. Lett. 101, 182001 (2008)

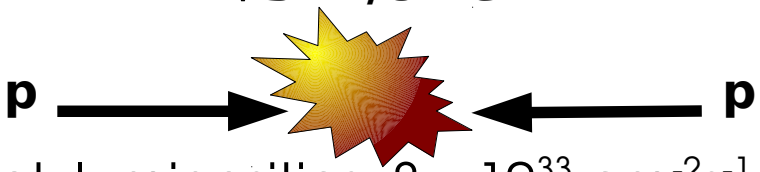
Accelerator

√s=1.96 TeV

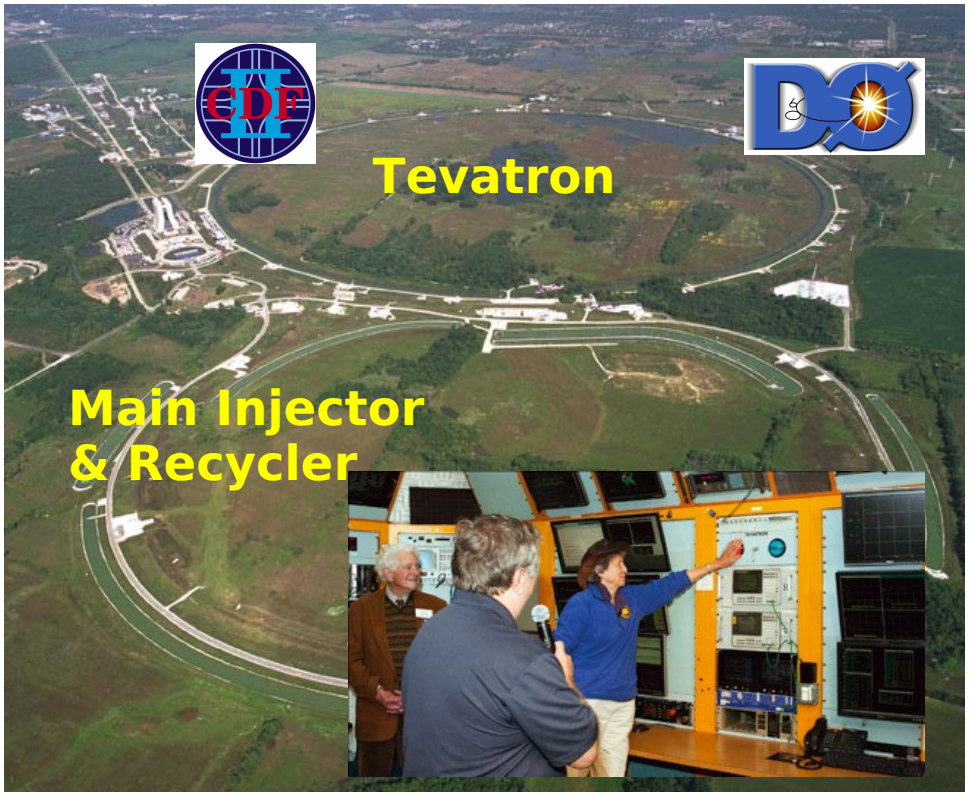


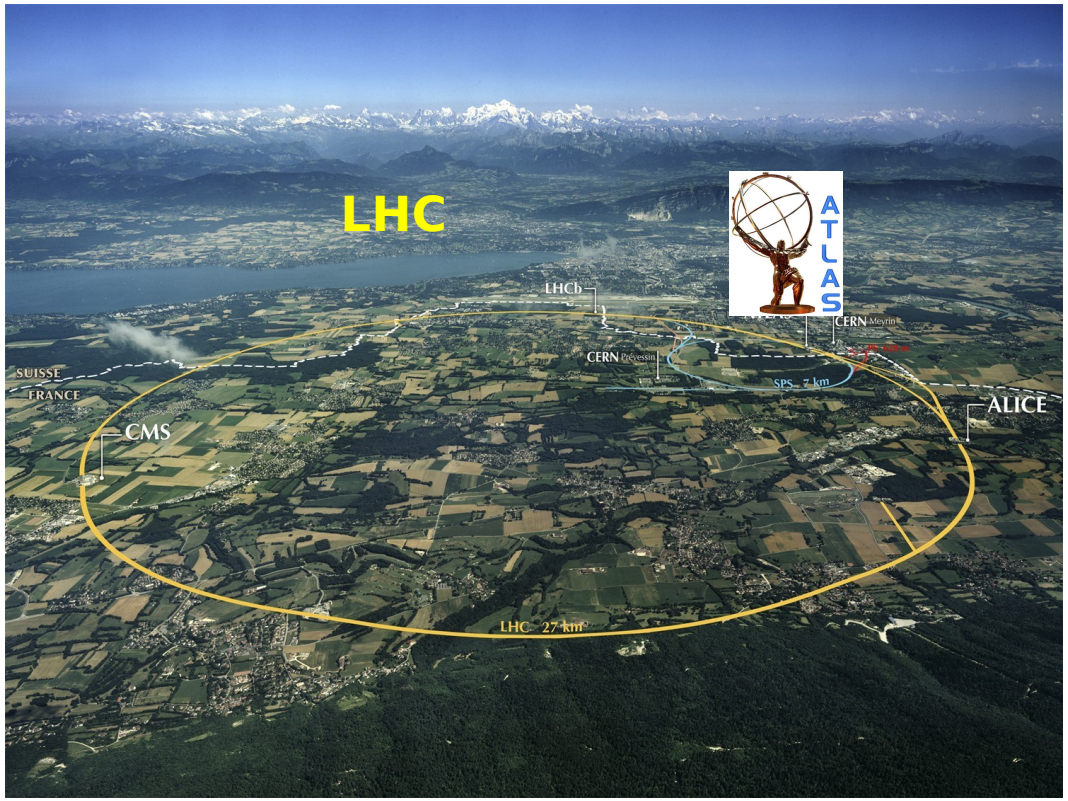
- Peak luminosities: 3 – 4 x 10^{32} $cm^{-2}s^{-1}$
- ~10 fb^{-1} per experiment recorded
- Tevatron shutdown September 2011

√s=7/8 TeV



- Peak luminosities: 8 x 10^{33} $cm^{-2}s^{-1}$
- ~5 / 20 fb^{-1} per experiment recorded
- LHC consolidation/upgrades till 2015



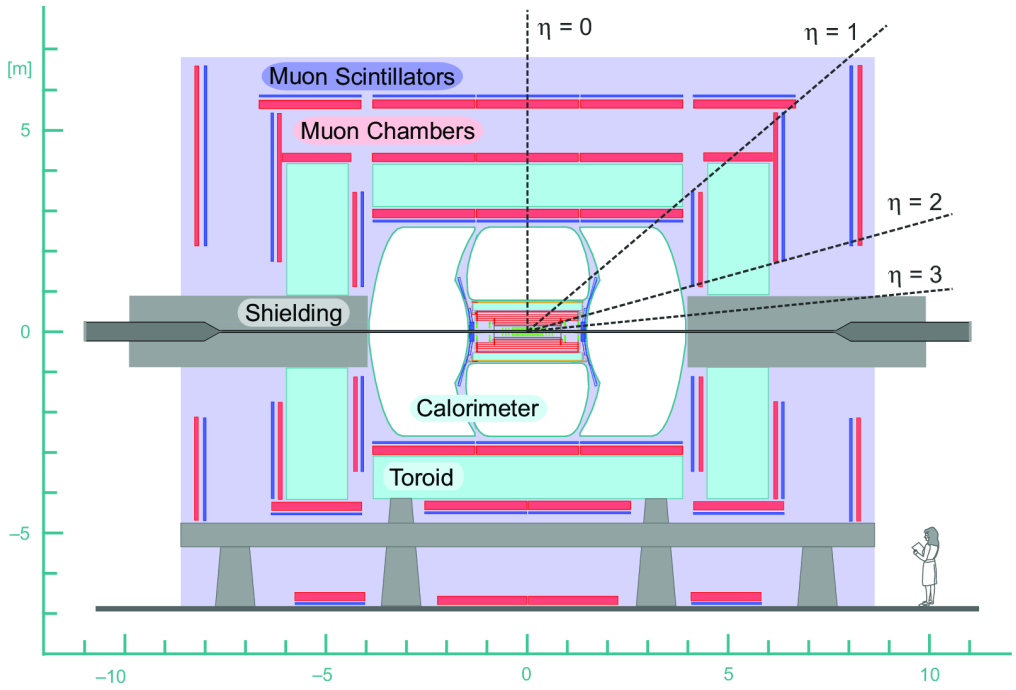


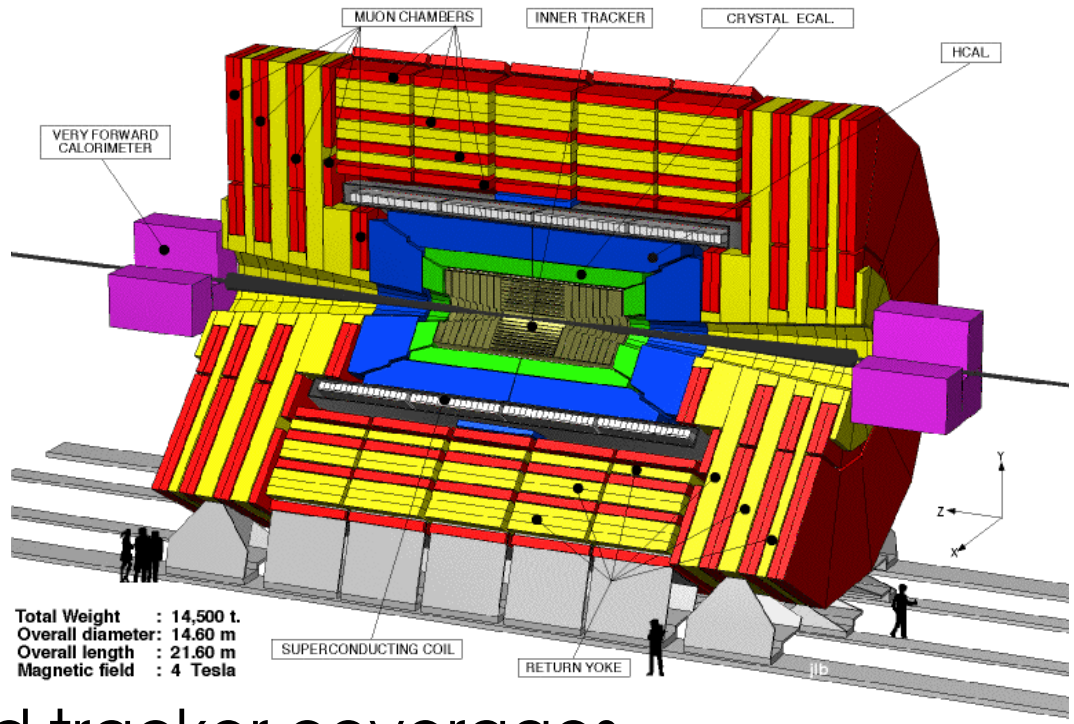
Big thanks to the Accelerator Divisions!

Experiments

General purpose 4π detectors:

- **Tracker**: Detection and momentum measurement for charged particles
- **Calorimeters**: Identification and energy measurement of jets and electrons
- **Muon system**: Identification and momentum measurement of muons





- Tevatron: Similar calorimeter and tracker coverages
- LHC: Increased coverage compared to Tevatron