Measurement of the Top Quark Mass at DØ

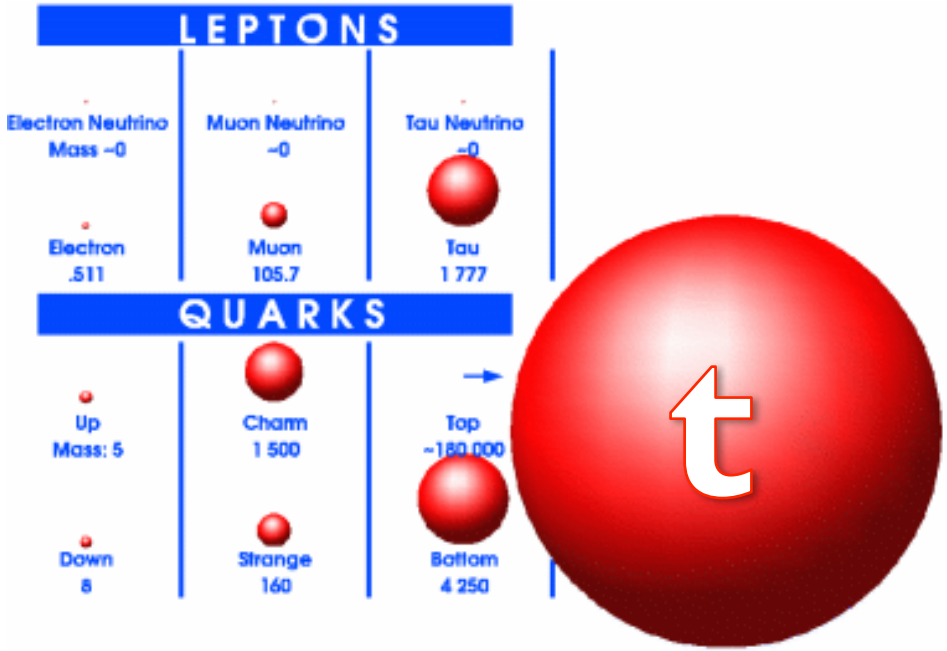
Zhenyu Ye/Fermilab

Fermilab W&C Seminar, 2011/9/29

The
DØ
Collaboration

Top Quark in the Standard Model

- Weak isospin partner of b quark, spin=1/2, charge=+2/3.
- Heaviest (~175 GeV) fundamental particle discovered so far.
- Yukawa coupling 0.996±0.006. A special role in EWSB ?
- Lifetime (~10^{-24}s) <<$1/\Lambda_{QCD}$, decays before hadronization.



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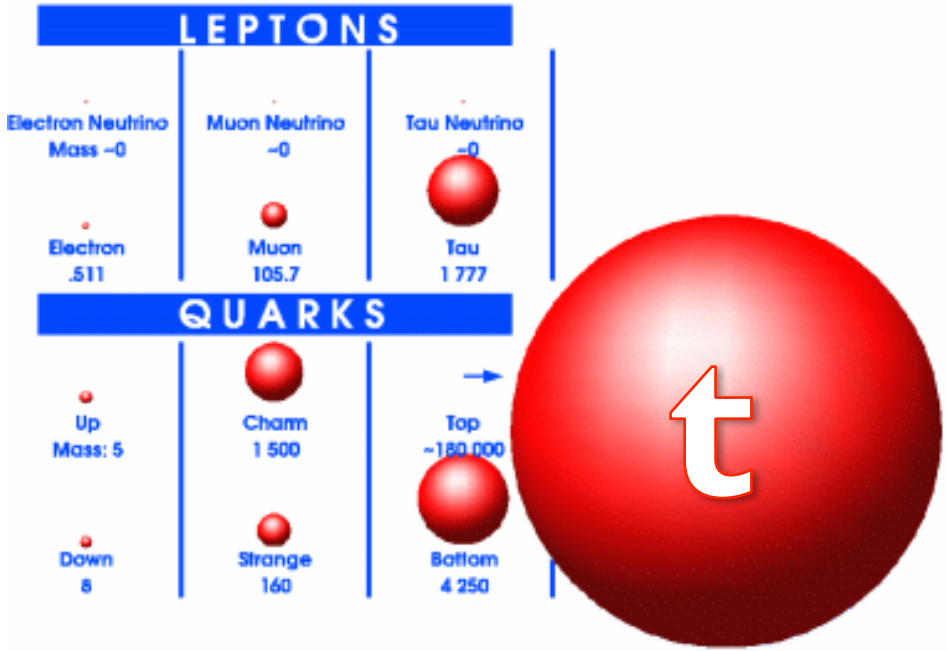
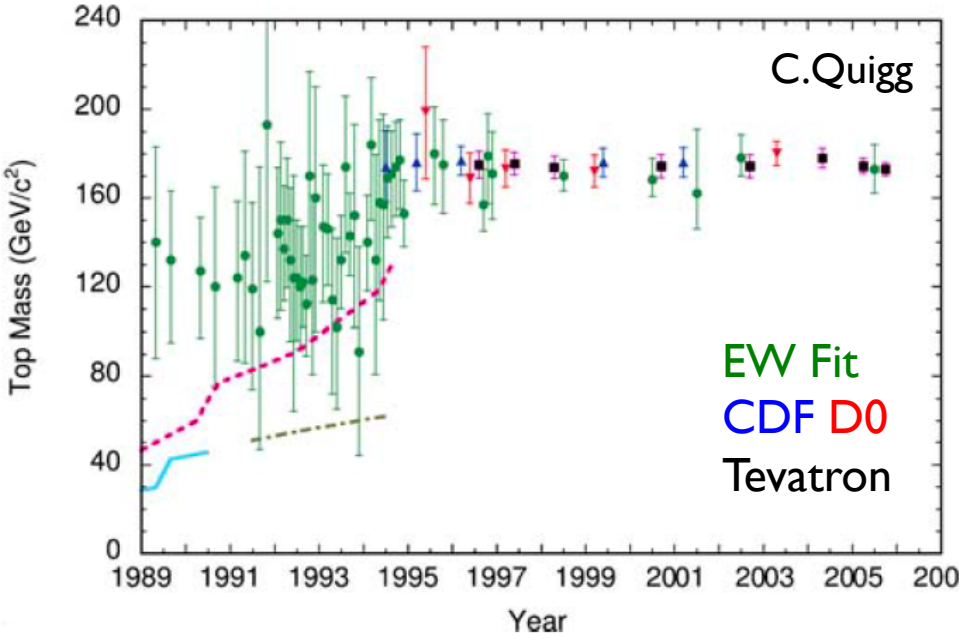


Is the top quark "standard"?

A Bit History on Top Quark

- 1976: discovery of the bottom quark at Fermilab suggested the existence of the top quark
- 1984: PETRA m_t>23.3 GeV
- 1988: UA1 m_t>44 GeV
- 1990: TRISTAN m_t>30.2 GeV
  - SLC m_t>40.7 GeV
  - LEP m_t>45.8 GeV
  - UA1 m_t>60 GeV
  - UA2 m_t>69 GeV
- 1992: CDF m_t>91 GeV
- 1994: DØ m_t>128 GeV
- 1994: evidence of top quark from CDF

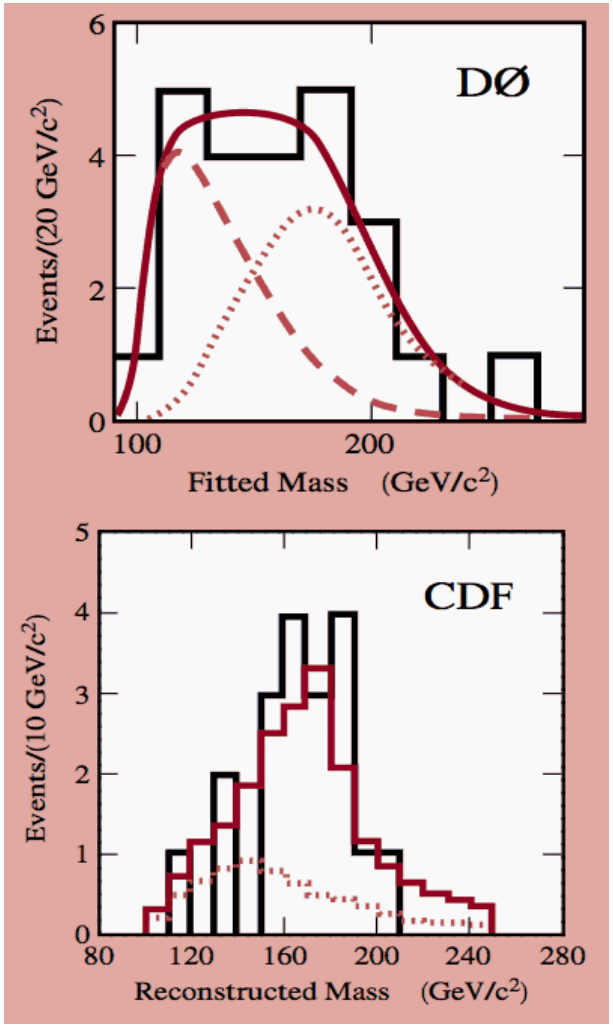


A Bit History on Top Quark

1995 Feb --- discovery of top quark reported by CDF & DØ in Tevatron Run I (1992-1996).

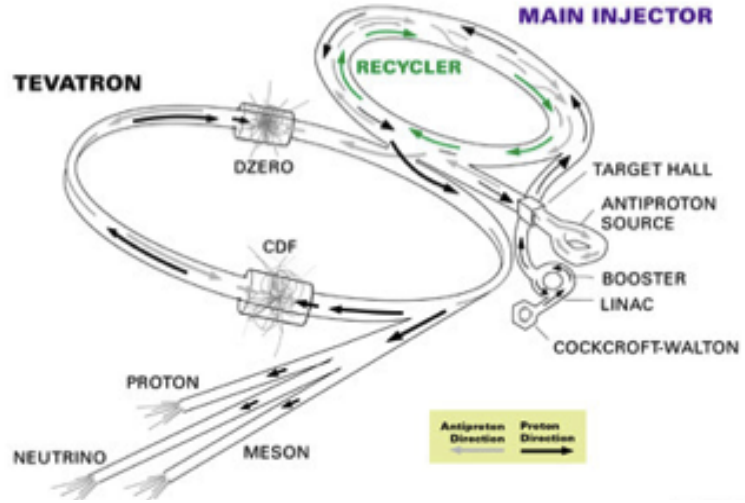
- CDF(67 pb^{-1}) :
  m_t=176±13 GeV, σ =$6.8^{+3.6}_{-2.4}$ pb,
  observed 19 events, expected 6.9 bkg,
  bkg-only hypothesis rejected at 4.8 σ

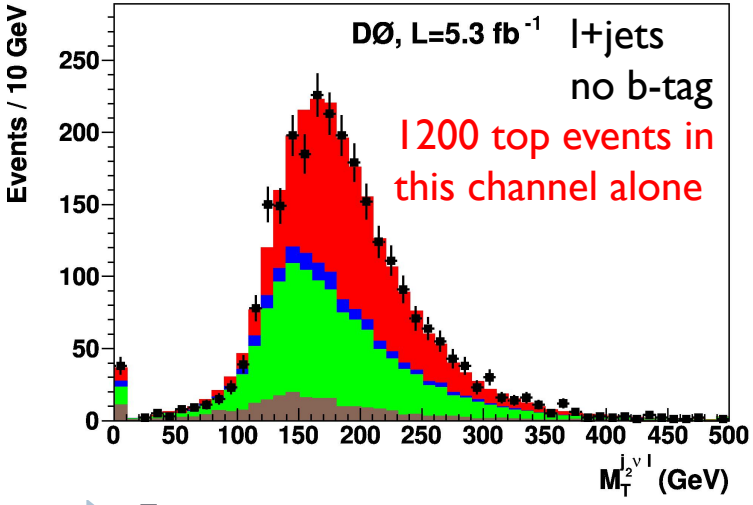
- D0 (50 pb^{-1}):
  m_t=199±30 GeV, σ =6.4±2.2 pb,
  observed 17 events, expected 3.8 bkg,
  bkg-only hypothesis rejected at 4.6 σ

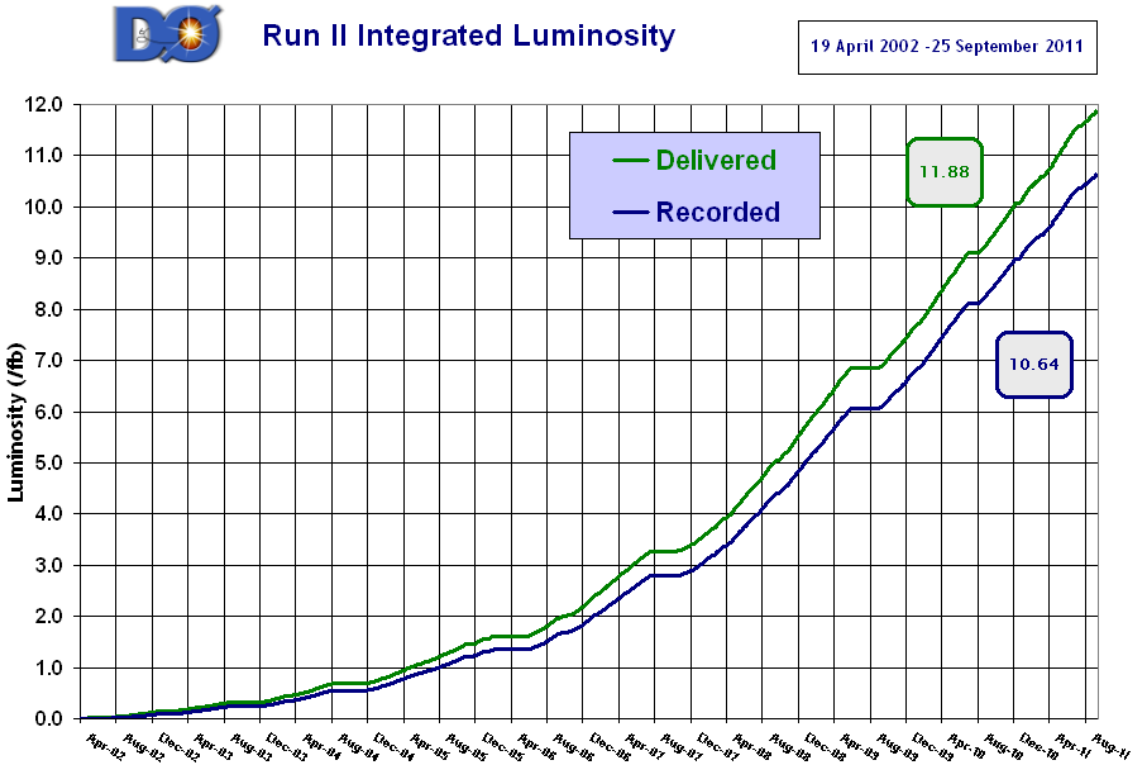


Where Are We Now?

Tevatron Run II 2001-2011

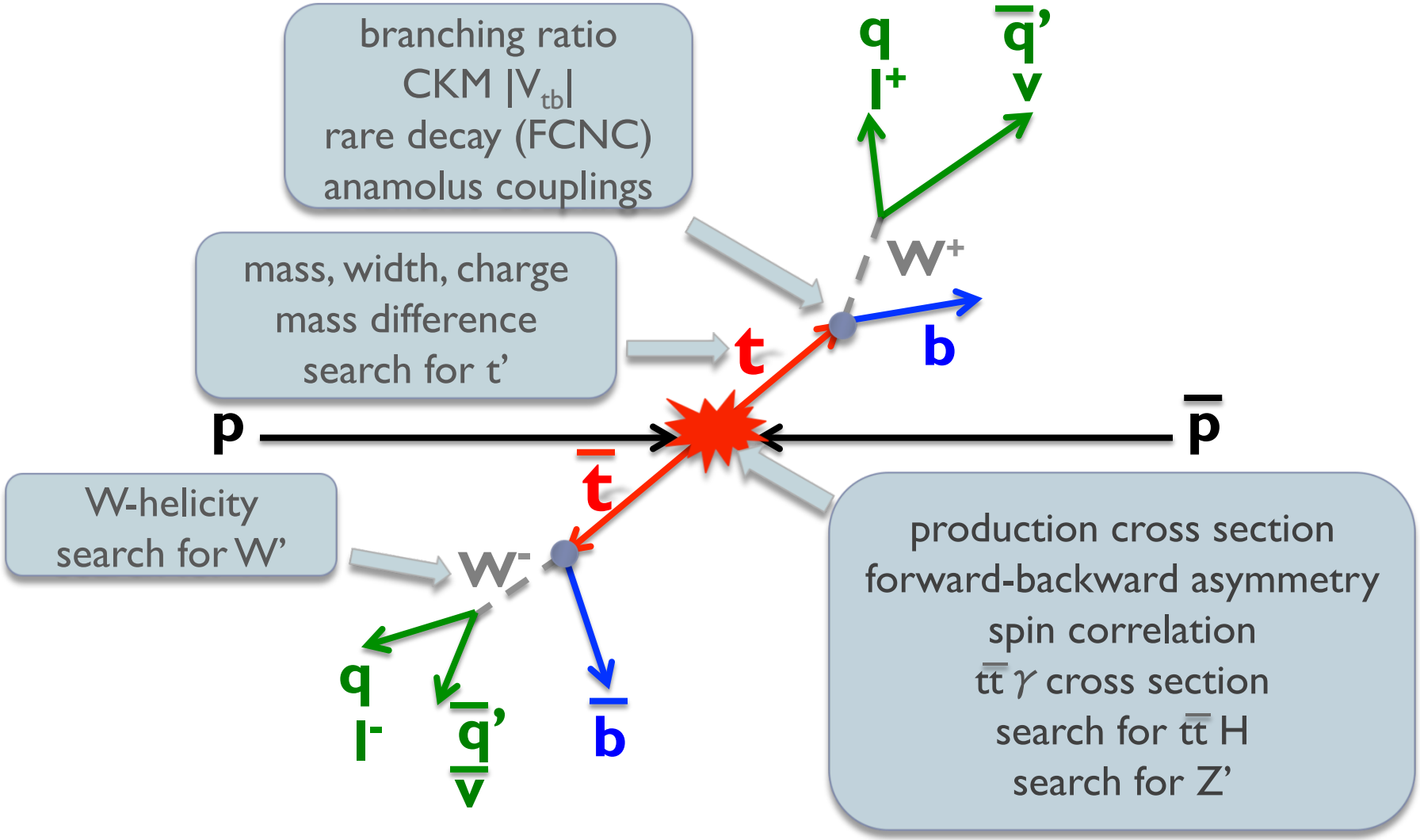




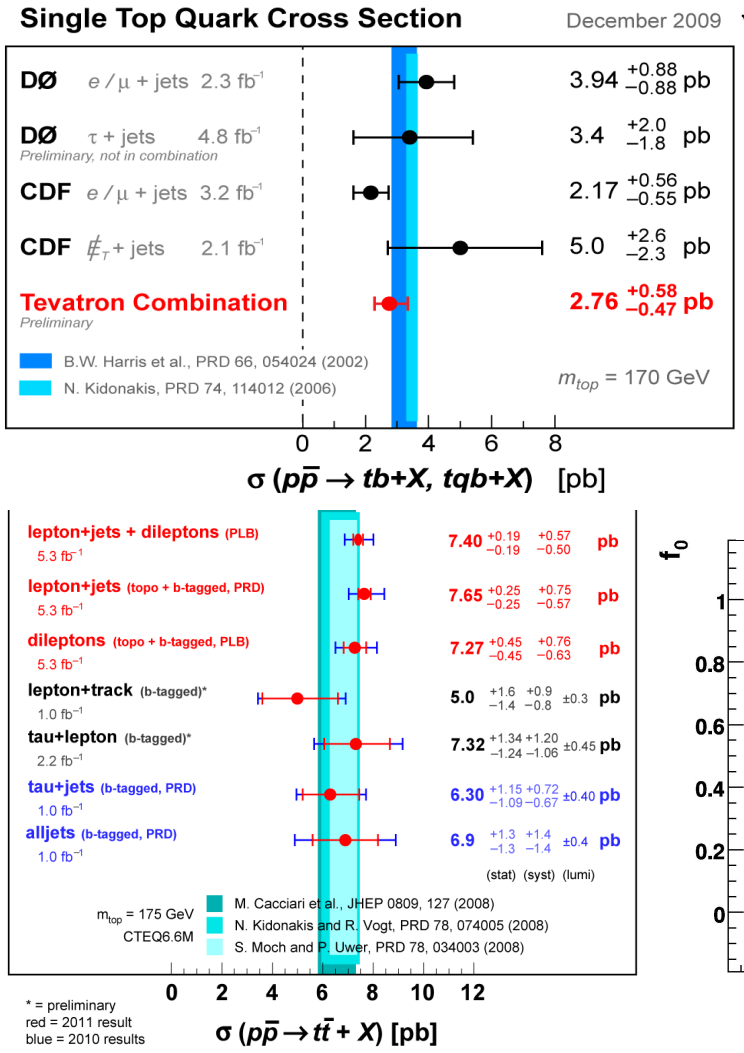


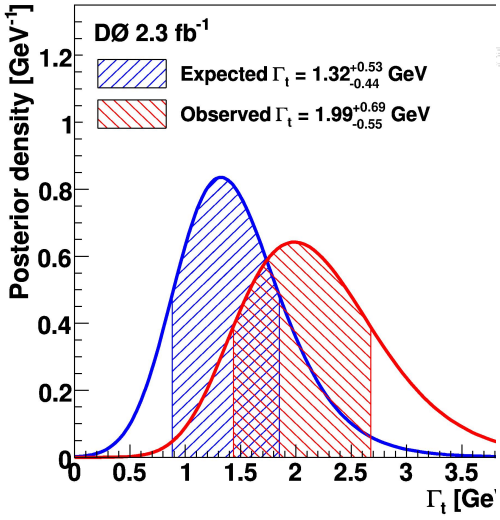
Many thanks to Accelerator Division!

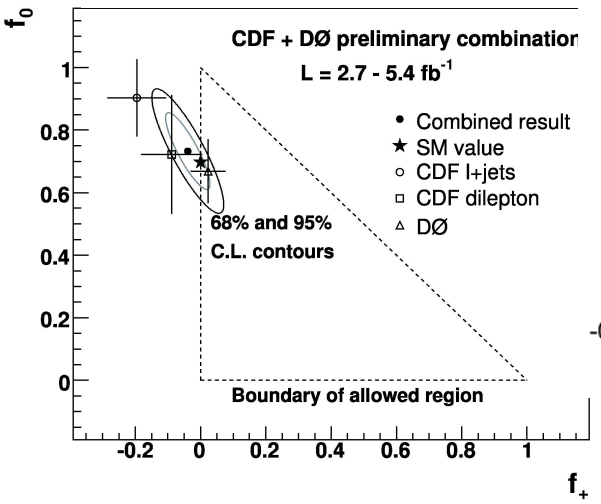
Top Quark Physics

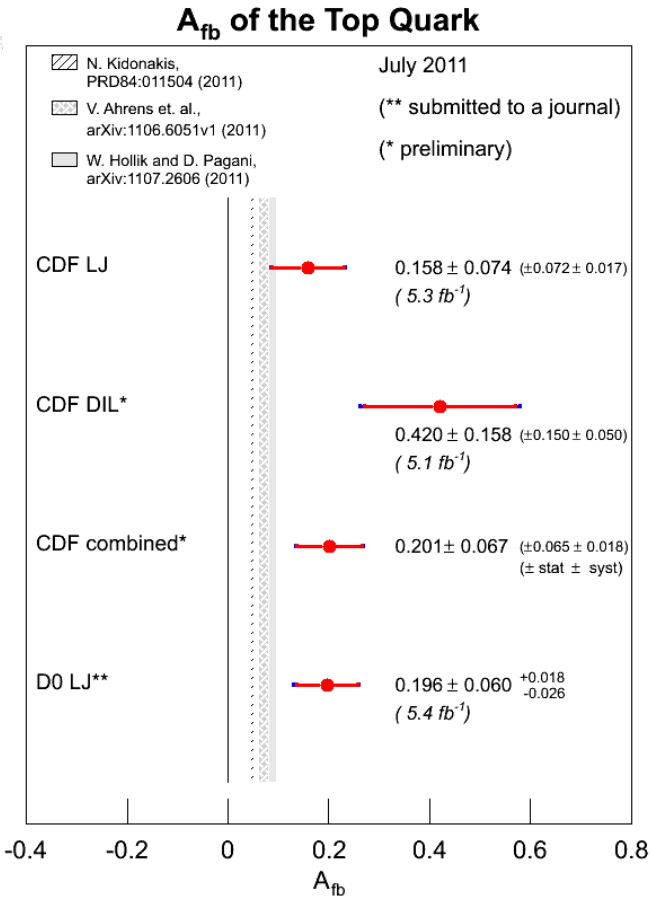


Top Quark Physics









Outline

- Introduction
- Precision measurement of the top-quark mass
  - lepton+jets channel
  - dilepton channel
- Top-antitop quark mass difference
- Summary and outlook

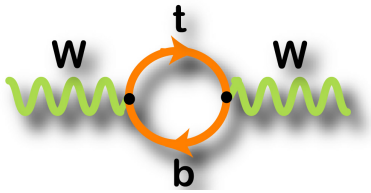
Top-Quark Mass

- Top mass is a free parameter in the SM.
- Top and Higgs masses enter in the radiative correction to the W mass. Knowing top and W masses constrains Higgs mass.

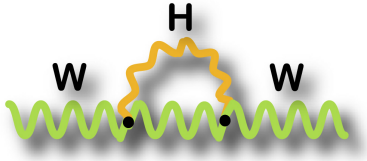
$$M_W^2 = \frac{\pi\alpha/\sqrt{2}G_F}{\sin^2\theta_W \quad (1-\Delta r)}$$

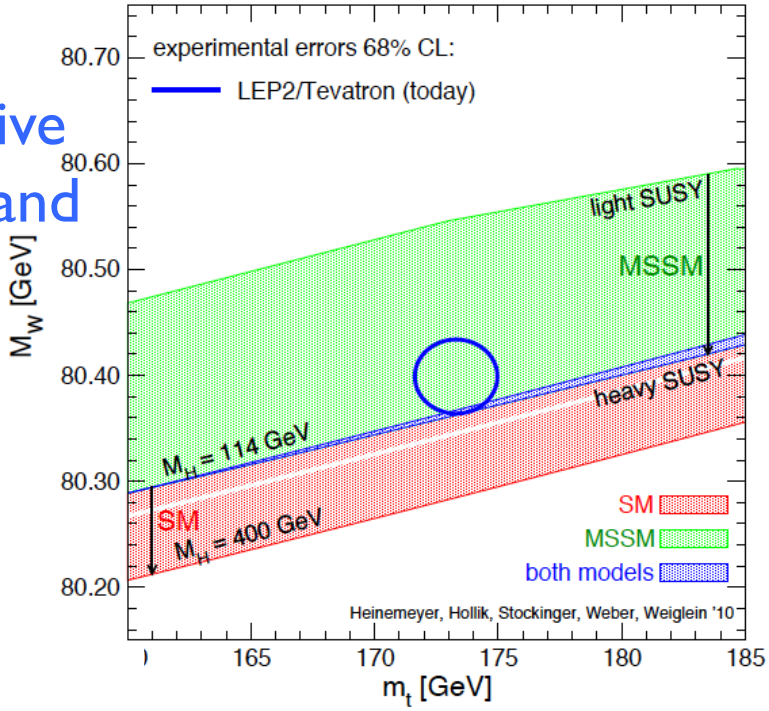
radiative correction

$$(\Delta r)_{top} \approx -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\frac{1}{\tan^2\theta_W}$$



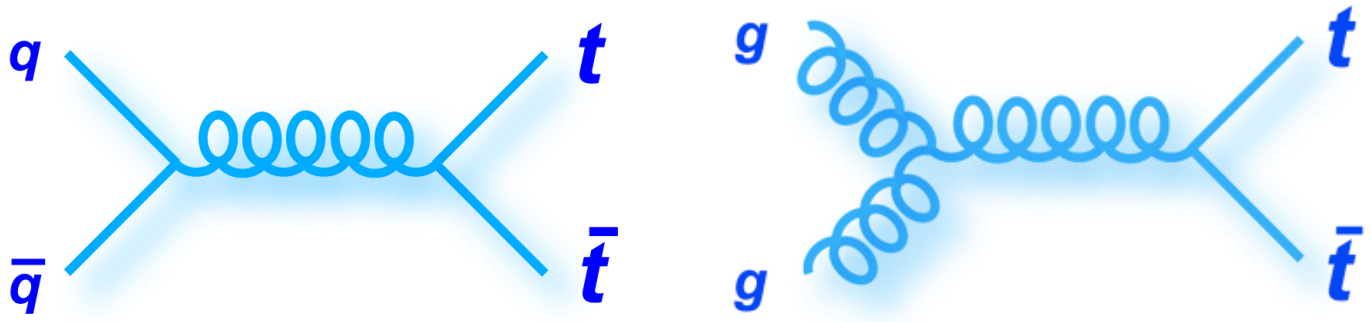
$$(\Delta r)_{Higgs} \approx \frac{3G_F M_W^2}{24\sqrt{2}\pi^2}\left(\ln\frac{m_H^2}{M_Z^2} - \frac{5}{6}\right)$$



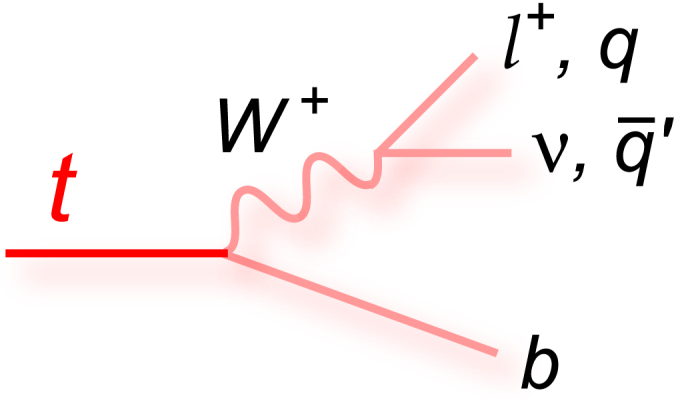


- New physics might affect the top-quark mass measurement differently in different top quark final states.

Top-Quark Production and Decay

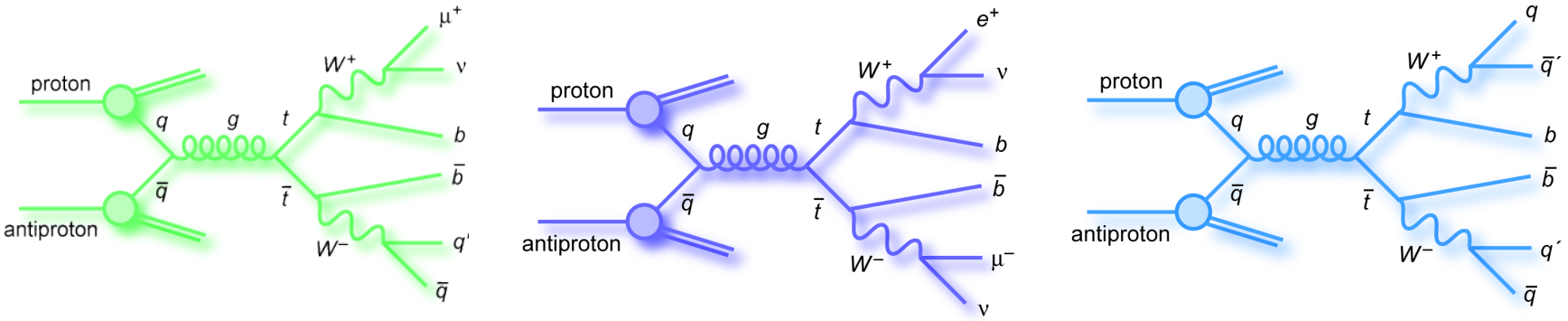


Tevatron RunII: σ (m_t=173 GeV) ~7.5 pb, 85% qqbar annihilation, 15% gg fusion



Standard Model: Γ_t~1.4 GeV, BR(t➔W⁺b)~100%

Top-Quark Production and Decay



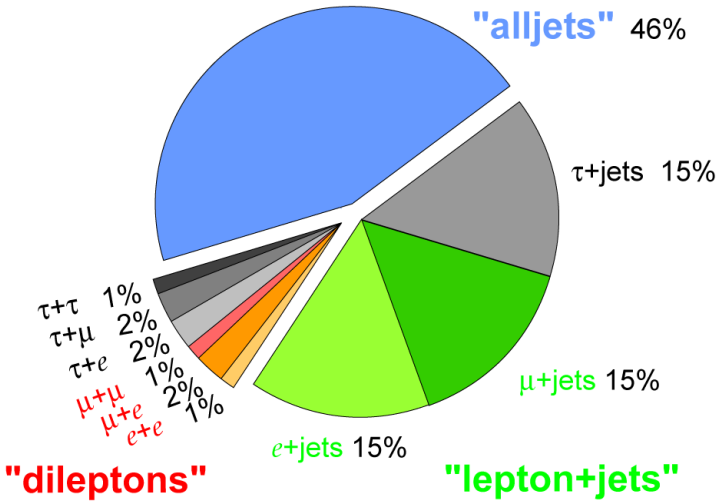
lepton+jets: $t\bar{t} \rightarrow lvqq'b\bar{b}$

dilepton: $t\bar{t} \rightarrow ll'vv'b\bar{b}$

all hadronic: $t\bar{t} \rightarrow qq'q''q'''b\bar{b}$

(lepton refers to electron and muon.)

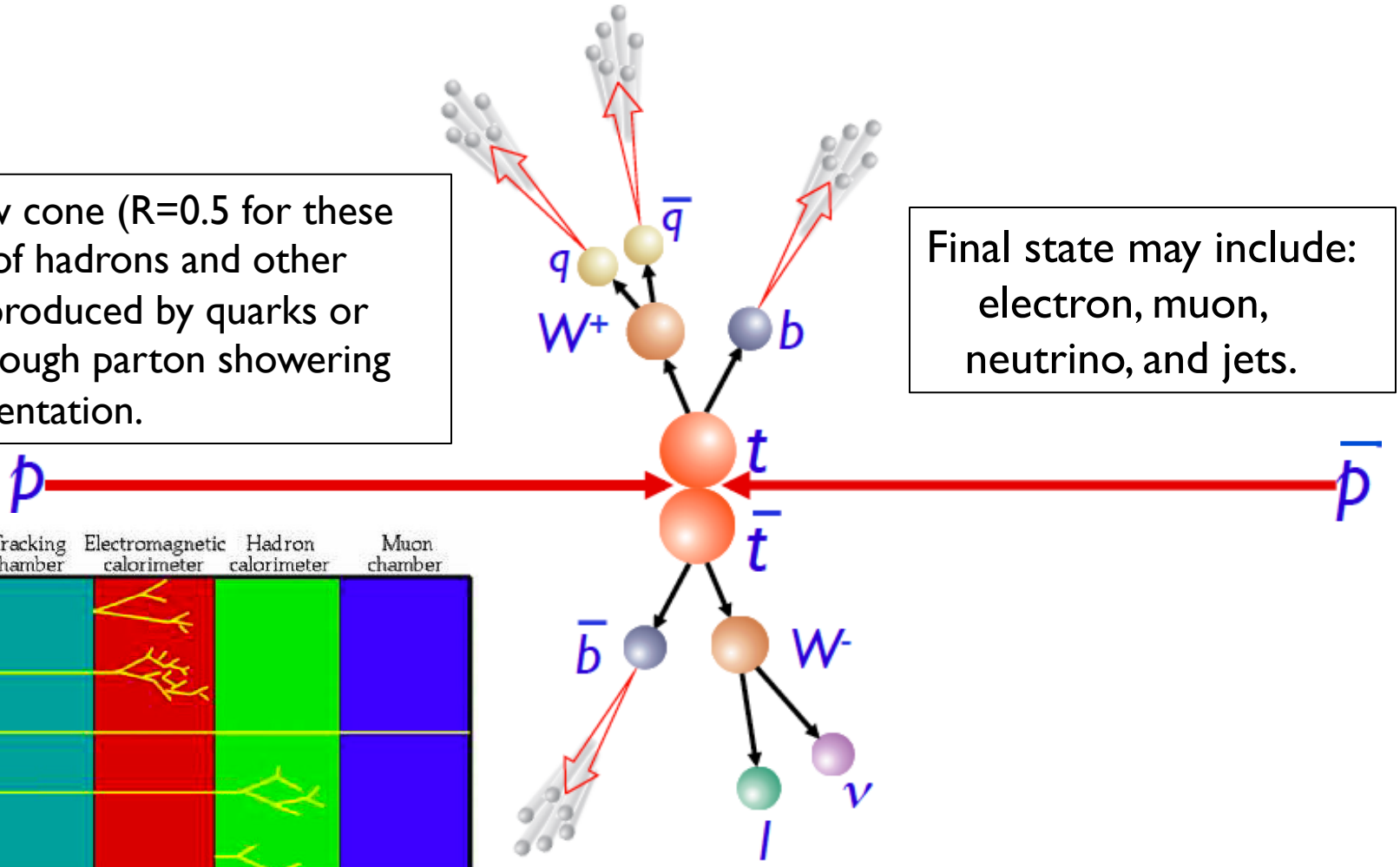
Top Pair Branching Fractions



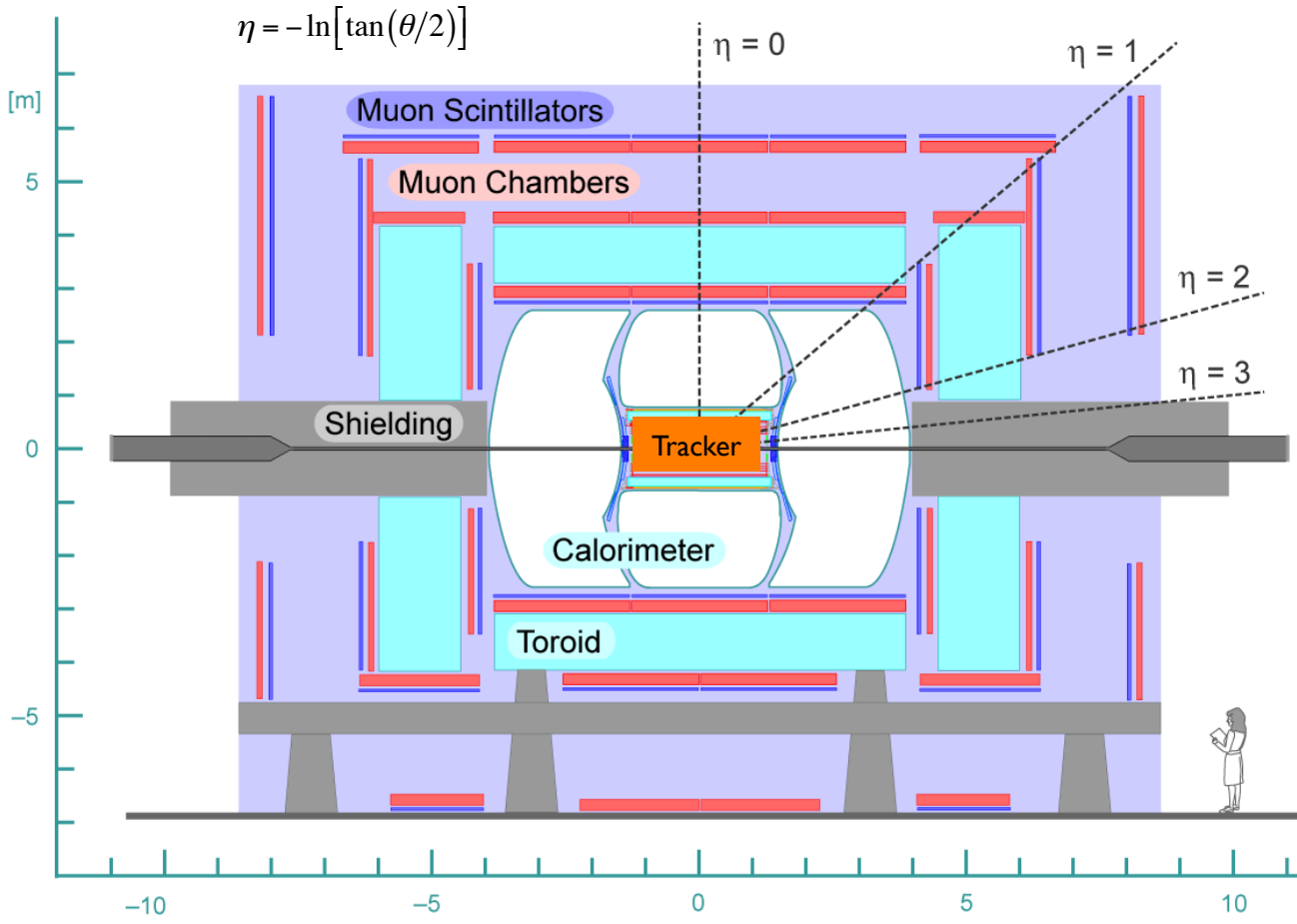
Top-Quark Final States

jet: narrow cone (R=0.5 for these analyses) of hadrons and other particles produced by quarks or gluons through parton showering and fragmentation.

Final state may include: electron, muon, neutrino, and jets.



DØ Detector



Tracker (2T Solenoid):
- silicon microstrip tracker
- scintillator fibre tracker

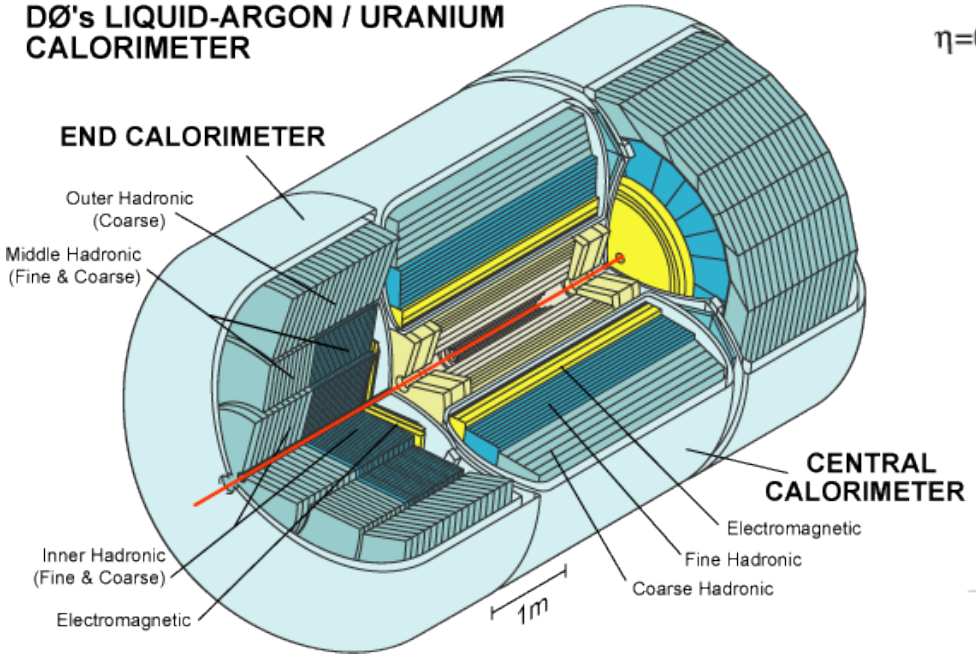
Calorimeter:
- liquid Ar+Uranium

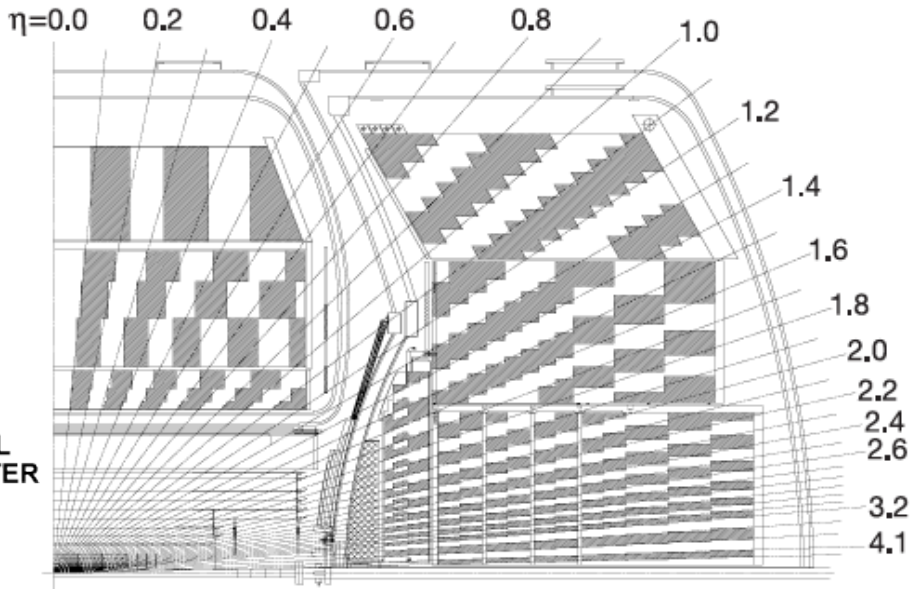
Muon system (1.8T Toroid):
- drift tubes
- scintilation counters

More details can be found in W&C seminar "Measurement of W boson mass at DØ" by Jan Stark on 2009/3/20

Fermilab

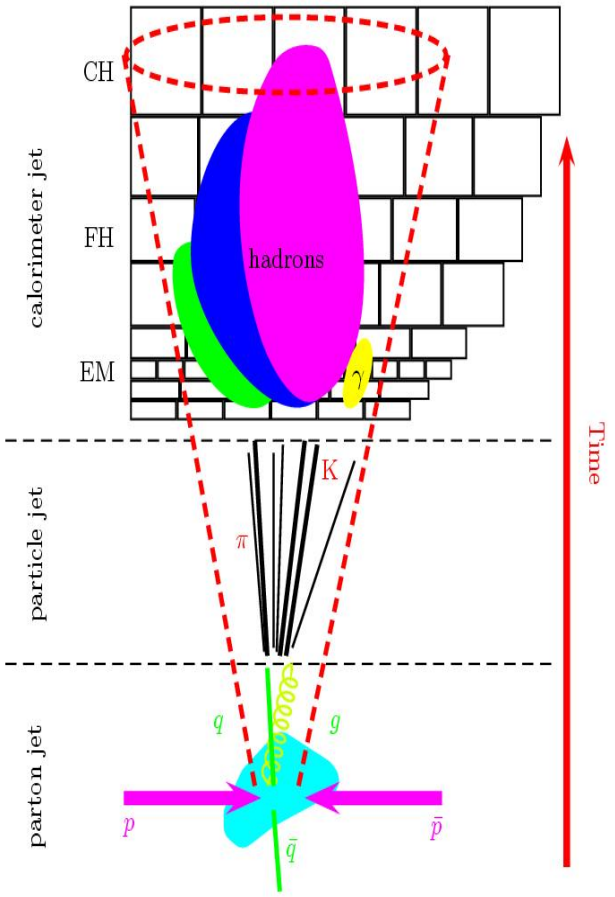
DØ Calorimeter





Electronics Calibration	Inter-Φ Calibration	Inter-η Calibration
Injecting known signal into pre-amplifiers and equalize readout response.	Based on the fact that interactions should be symmetric in Φ.	Using $Z \rightarrow e^+e^-$ for EM layers (absoluate scale) and dijet events for hadronic layers.

Jet Energy Scale (I)

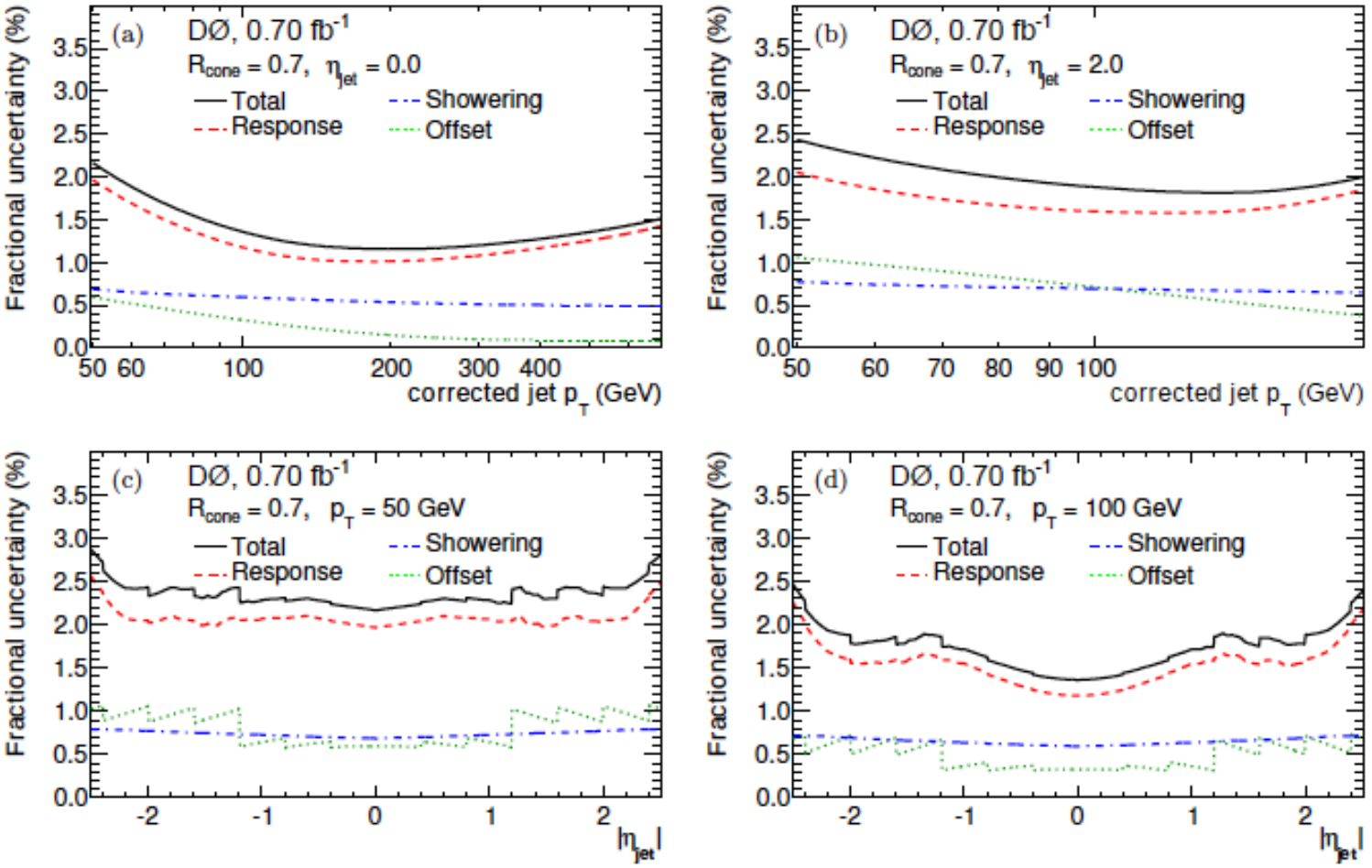


- Jet energy scale is determined from photon+jet and dijet events at D0.
  - absolute scale set by the photon energy which is well measured by the EM calorimeter.
  - relative scale determined from transverse momentum balance.
- The energy of each reconstructed calorimeter jet is corrected from the raw energy to the energy of the corresponding particle jet:

$$E_{ptcl} = \frac{E_{raw} - E_O}{R_{jet} \cdot S_{jet}}$$

  - E_O: contribution for pile-up, noise and MPI
  - R_{jet}: calorimeter energy response to particle jet
  - S_{jet}: energy leaking into/out of the jet cone

Jet Energy Scale (II)



- Typical jet energy scale uncertainty is about 2-3%. More on this later.

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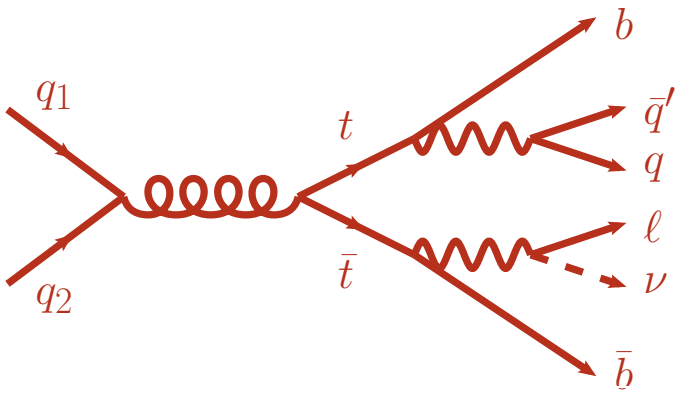
Lepton+Jets Channel

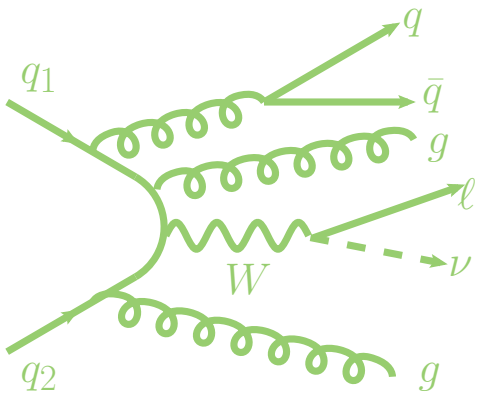
- One e/ μ , four jets (two of them are b-quark jets), missing transverse momentum $\not{p}_T$ due to the ν ;
- Reasonable branching ratio: ~30%
- Modest background level: W+jets, multijet

Golden channel for the top-quark mass measurement!

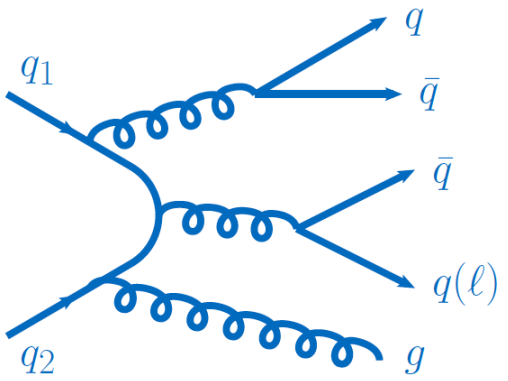
ttbar



W+jets



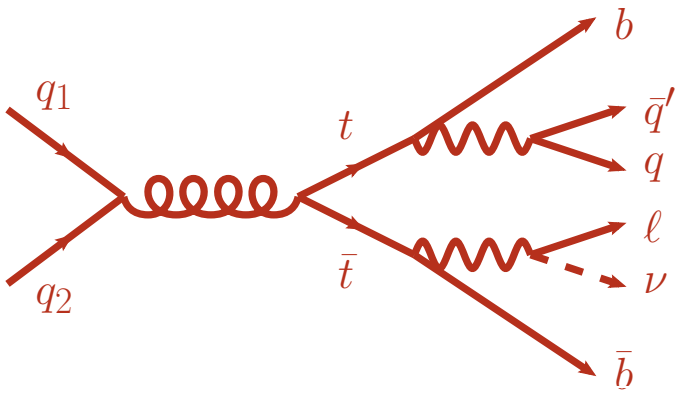
multijet



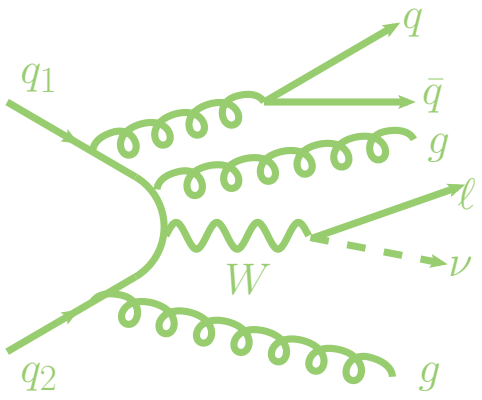
Event Selection (I)

- Event pre-selection cuts (minimizing bias on the measured top-quark mass):
  - single lepton or lepton+jets trigger;
  - exactly one isolated lepton with p_T>20 GeV;
  - exactly four jets with p_T>20GeV, leading one> 40GeV, and $|\eta|$<2.5;
  - missing transverse momentum $\not{p}_T$>20 (25) GeV for e (μ)+jets.

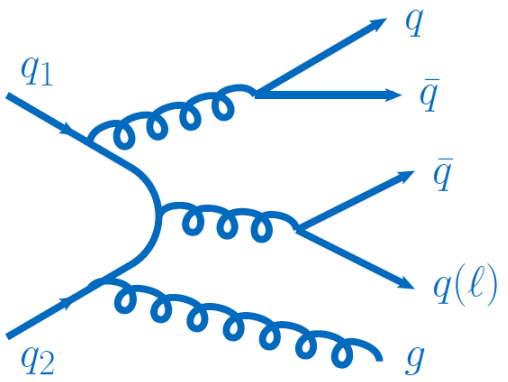
ttbar (MC)



W+jets (MC)



multijet (data)



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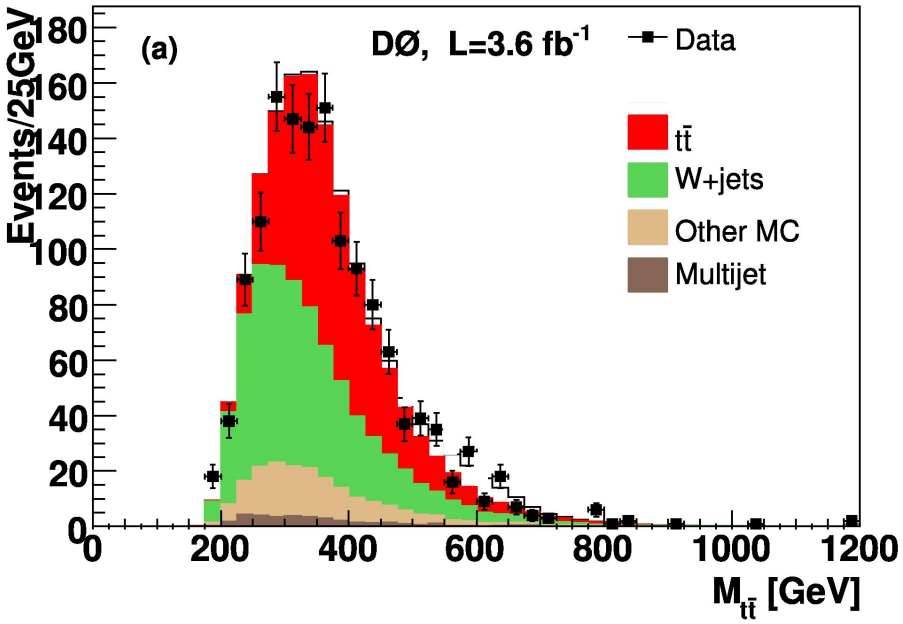
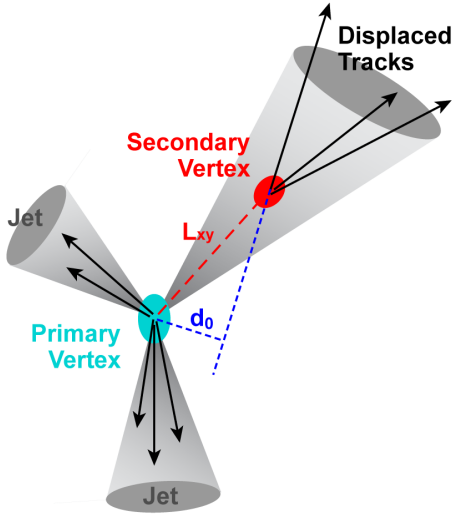
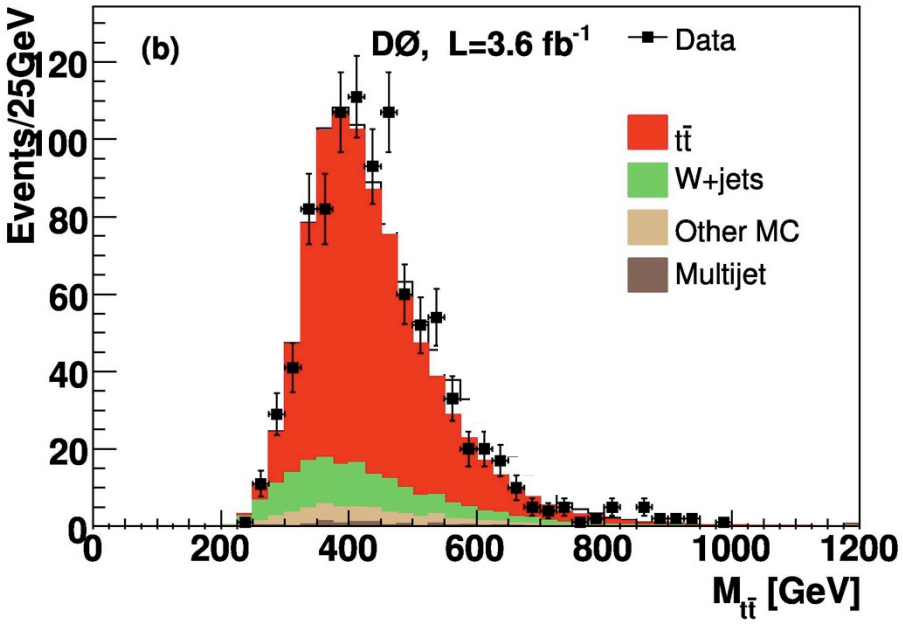
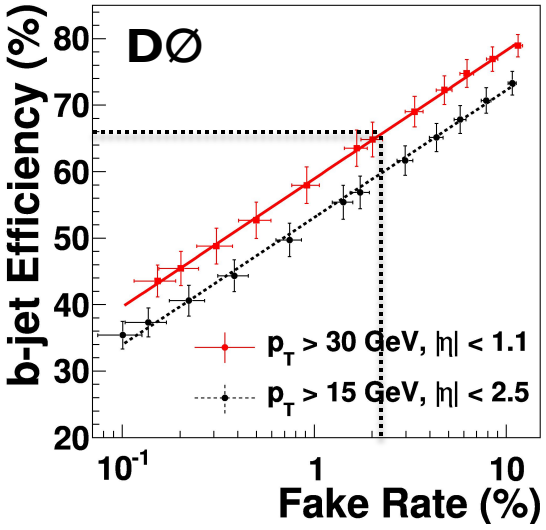


Event Selection (III)

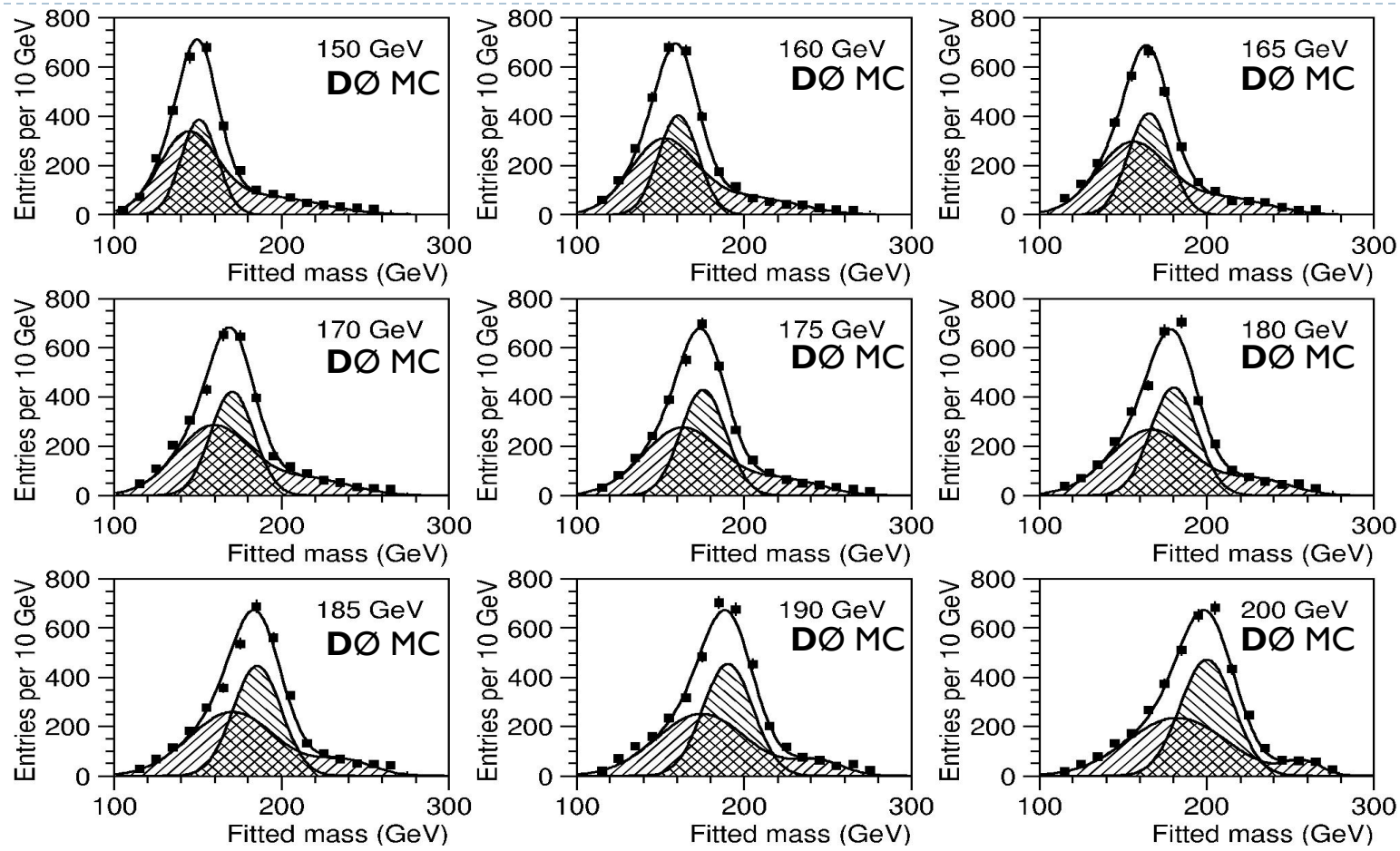
- Additional event selection cut:
  - By requiring at least one jet tagged as a b-quark jet, the signal purity can be increased from ~35% to ~70%, while losing only 1/4 of signal events.







How to Measure m_t - Template Method



Build MC templates for a quantity that is sensitive to m_t ;
Compare data to MC templates to extract m_t from data.

Matrix Element Method (I)

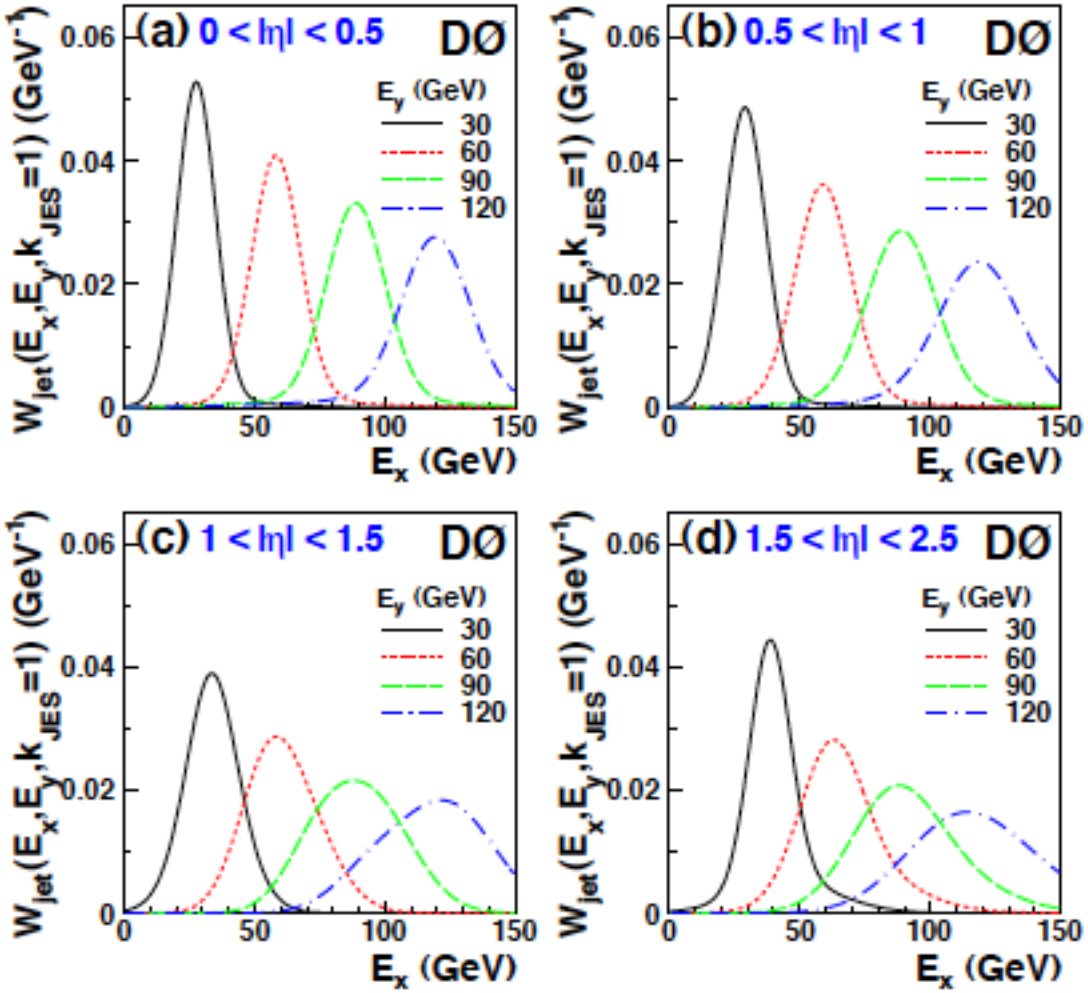
- Matrix element method is based on the calculation of event probability densities estimated from differential cross section and detector resolutions.

$$P_{sig}(x;m_t)=\frac{1}{\sigma_{obs}(m_t)}\times\int dq_1\,dq_2 f(q_1)f(q_2)\frac{(2\pi)^4\left|M(y,m_t)\right|^2}{4\sqrt{(q_1\cdot q_2-m_1m_2}}d\Phi_6 W(y;x)$$

Parton densities | LO matrix element | Transfer functions

- Transfer functions encode detector resolutions and provide mappings from the parton kinematic y to the measured one x.
  - Dirac δ function for lepton and jet angular resolution;
  - Gaussian functions for lepton energy resolution;
  - Double Gaussian functions for jet energy resolution (see next slides).

Jet Energy Transfer Function (I)



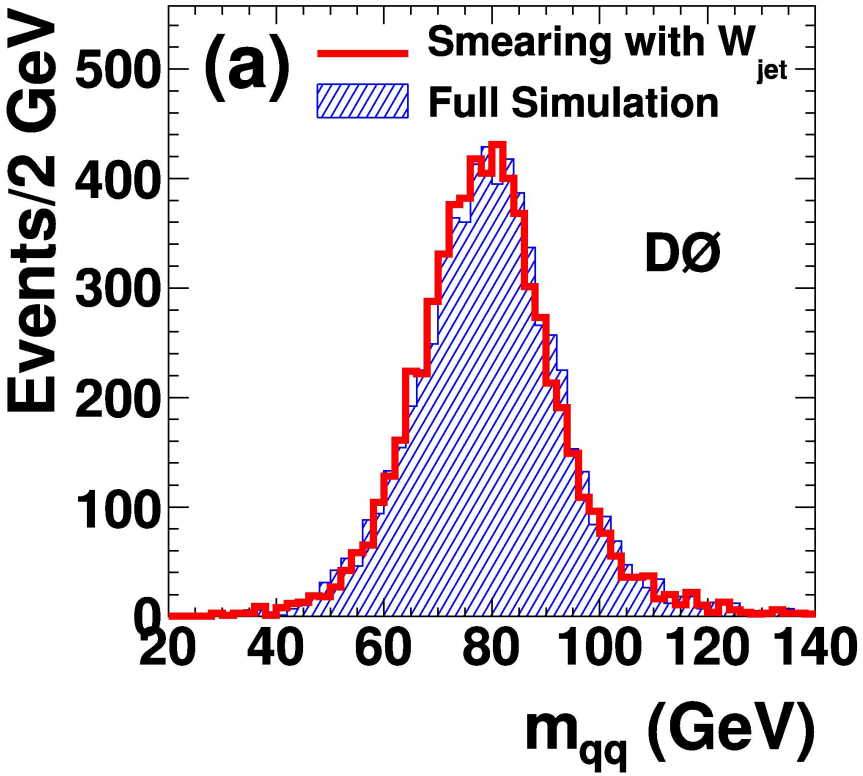
Jet TFs determined with MC and parametrized as

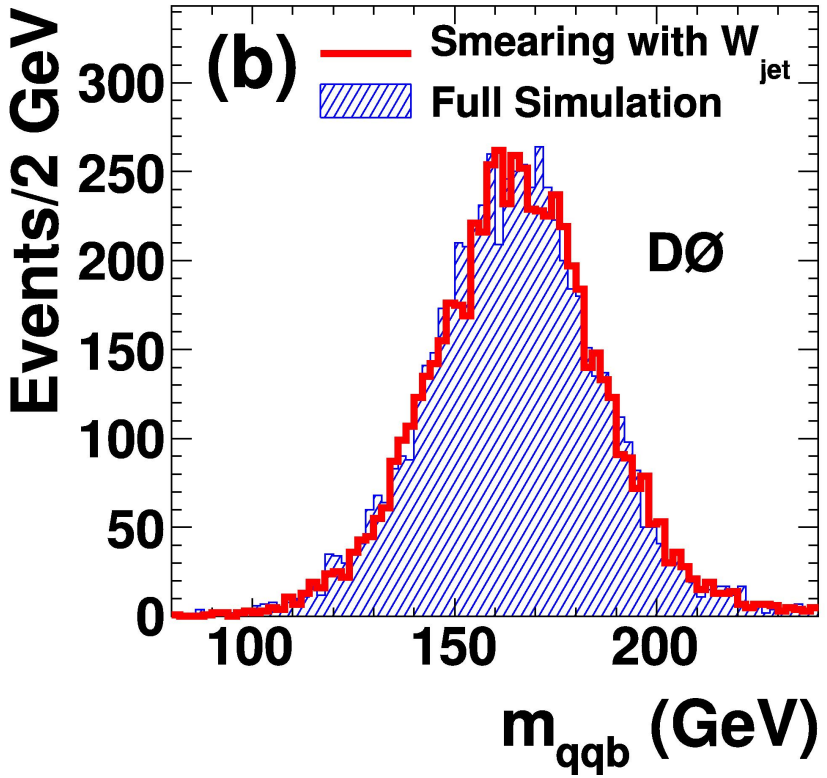
$$W_{jet}(E_x;E_y)=\frac{1}{\sqrt{2\pi}\left(p_2+p_3p_5\right)}$$

$$\times\left[\exp\left(-\frac{\left[\left(E_x-E_y\right)-p_1\right]^2}{2p_2^2}\right)\right.$$

$$\left.+p_3\exp\left(-\frac{\left[\left(E_x-E_y\right)-p_4\right]^2}{2p_5^2}\right)\right]$$

Jet Energy Transfer Function (II)





Verify that TFs describe well the detector resolutions.

Matrix Element Method (II)

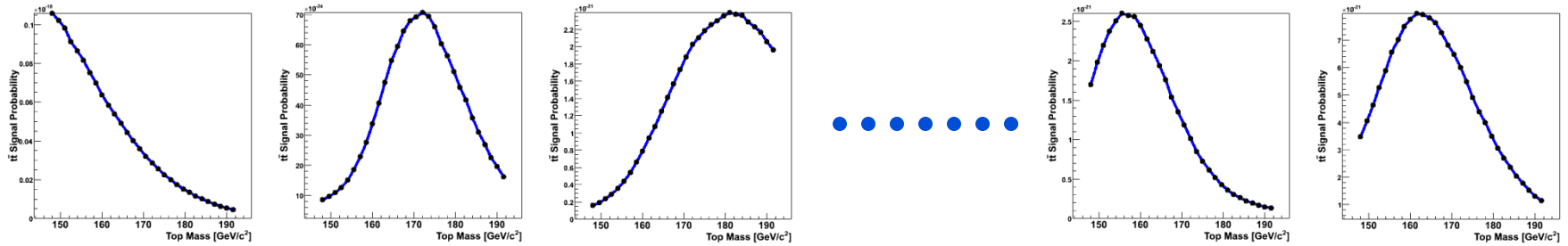
- Similarly we write down the probability for background. And the probability to observe an event can be written as:

$$P_{evt}\left(x;m_t,f\right)=f\cdot P_{sig}(x;m_t)+\left(1-f\right)\cdot P_{bkg}(x)$$

where f is the fraction of the signal events.

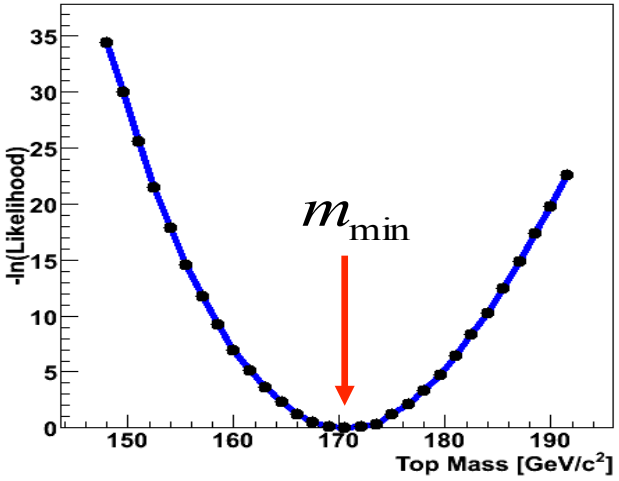
- ME methods use the full event kinematic information and allow signal-like events contribute more to the result, thus usually yield better results in terms of precision than template methods.

Matrix Element Method (III)



From these we build the likelihood function

$$L(x_1 \ldots x_n; m_{top}) = \prod_{i=1}^{n} P(x_i; m_{top})$$

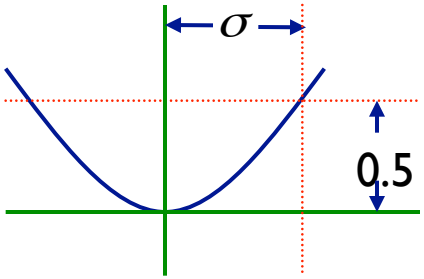


The best estimate of the top mass is then determined by minimizing:

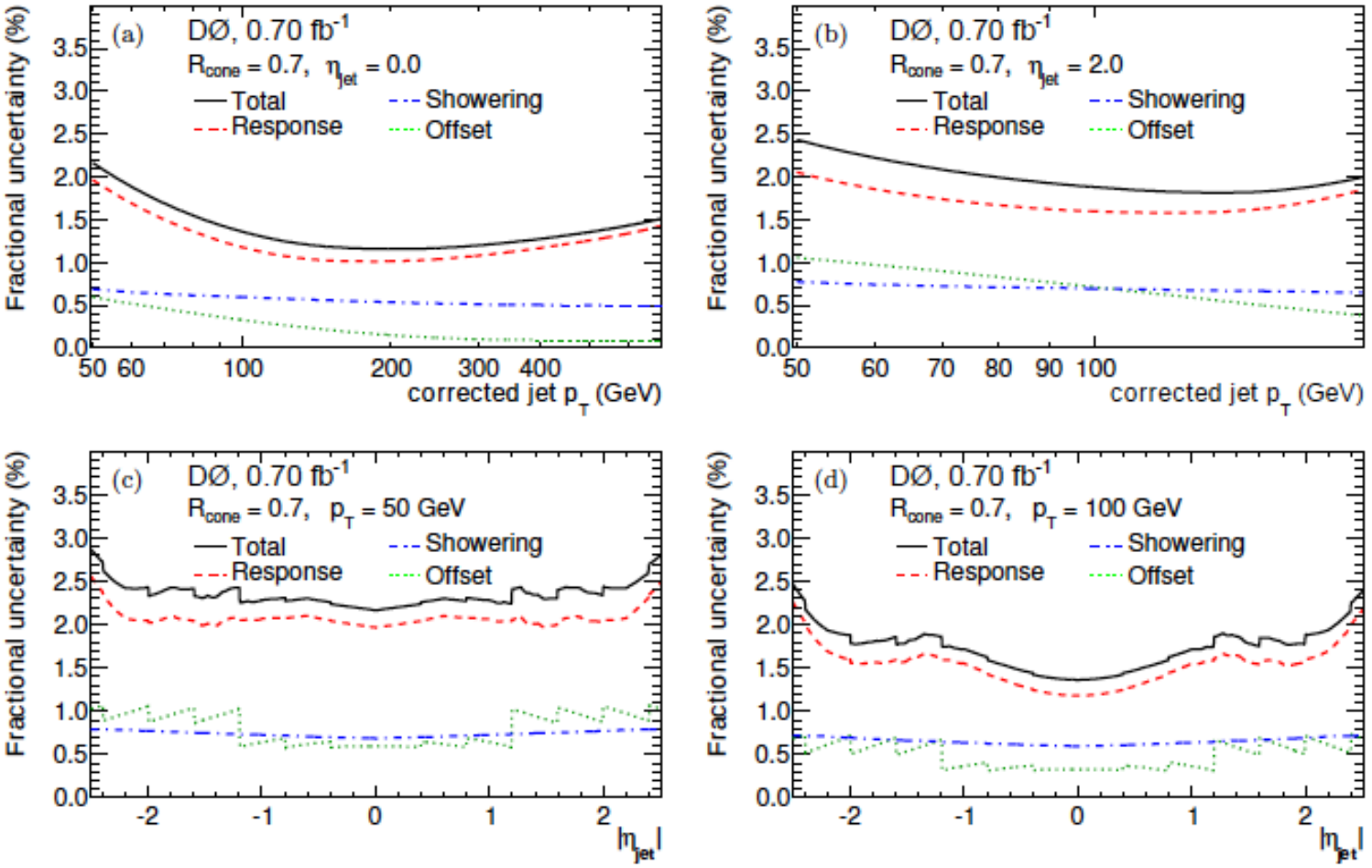
$$-\ln L\ (x_1 \ldots x_n; m_{top})$$

And the statistical error can be estimated from:

$$\ln[L\ (m_{\min})] - \ln[L\ (m_{\min} \pm \sigma)] = 0.5$$



Jet Energy Scale (II)



- Typical jet energy scale uncertainty is about 2-3%, which can lead to an uncertainty in top-quark mass of as large as 2 GeV.

In-situ JES Calibration

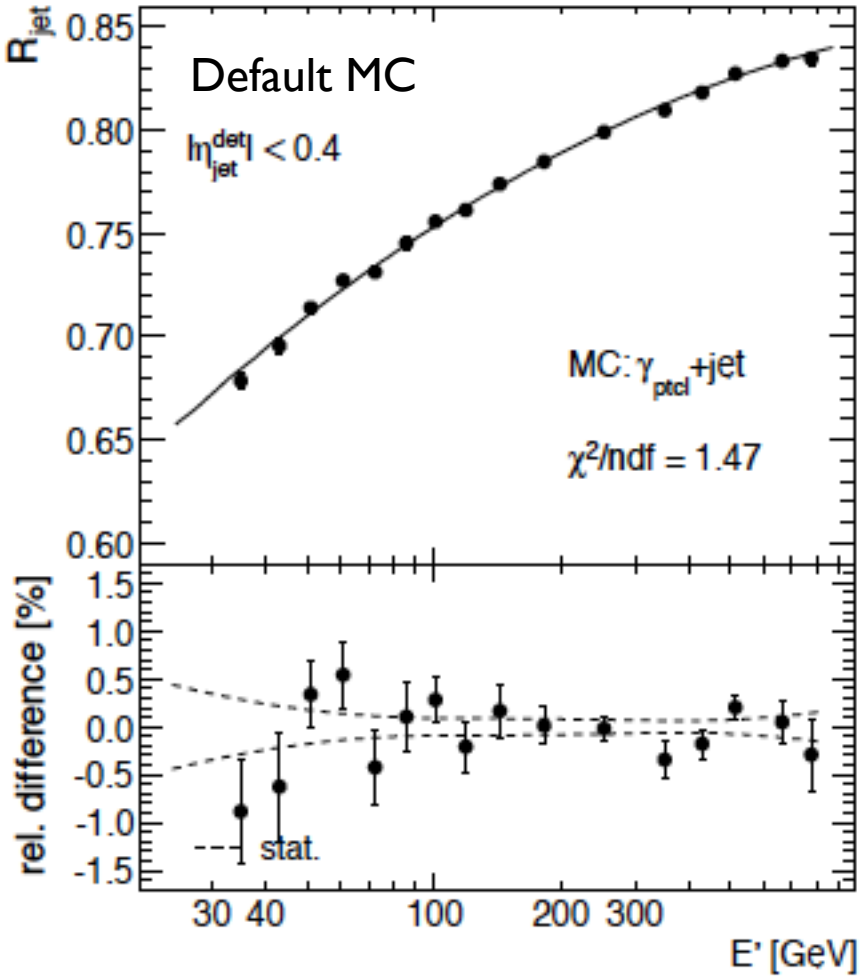
It is possible to calibrate the jet energy scale in-situ by using the two jets from the hadronic decayed W and the well-known W mass, and obtain a better knowledge on jet energy scale and thus on top quark mass.

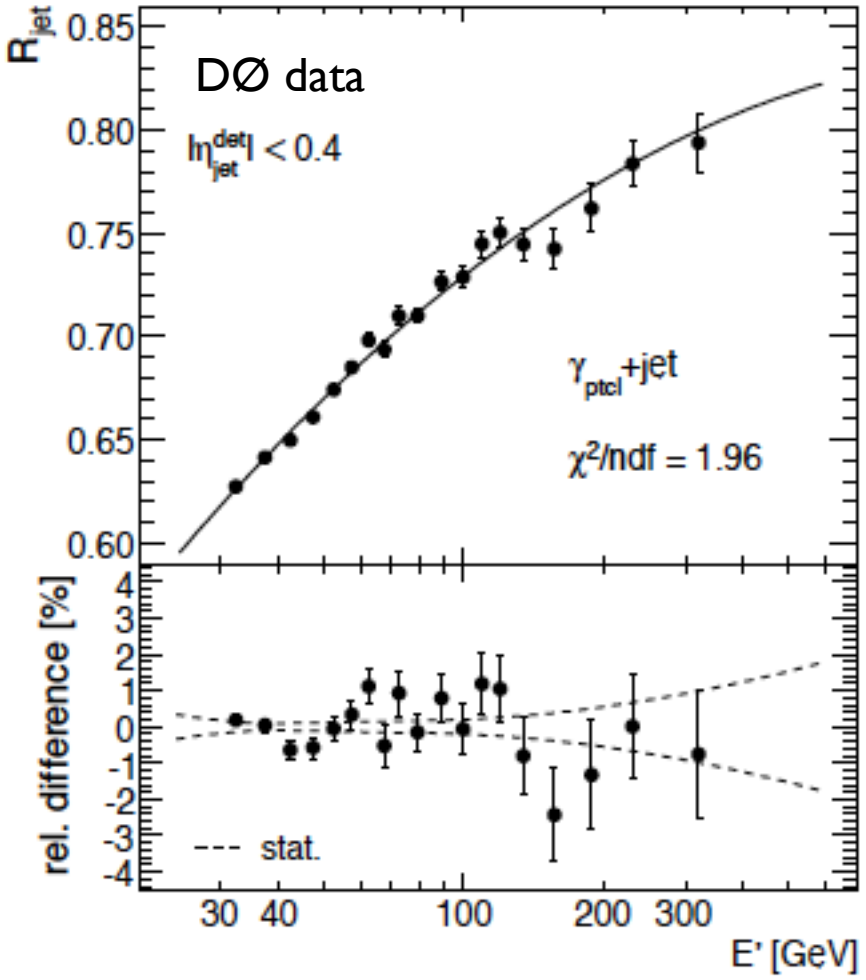
$$P_{sig}(x;m_{top}) = \frac{1}{\sigma_{obs}(m_{top})} \times \int dq_1\, dq_2 f(q_1) f(q_2) \frac{(2\pi)^4 \left|M(y,m_{top})\right|^2}{4\sqrt{(q_1 \cdot q_2 - m_1 m_2}} d\Phi_6 W(y;x)$$

$$P_{sig}(x;m_{top},k_{JES}) = \frac{1}{\sigma_{obs}(m_{top})} \times \int dq_1\, dq_2 f(q_1) f(q_2) \frac{(2\pi)^4 \left|M(y,m_{top})\right|^2}{4\sqrt{(q_1 \cdot q_2 - m_1 m_2}} d\Phi_6 W(y;x,k_{JES})$$

k_{JES} is a global multiplicative factor for jet energy scale. Uncertainty on k_{JES} can be much smaller than 2%, leading to an much reduced uncertainty in the measured top-quark mass.

Correction for MC-Data Difference (I)





Correction for MC-Data Difference (II)

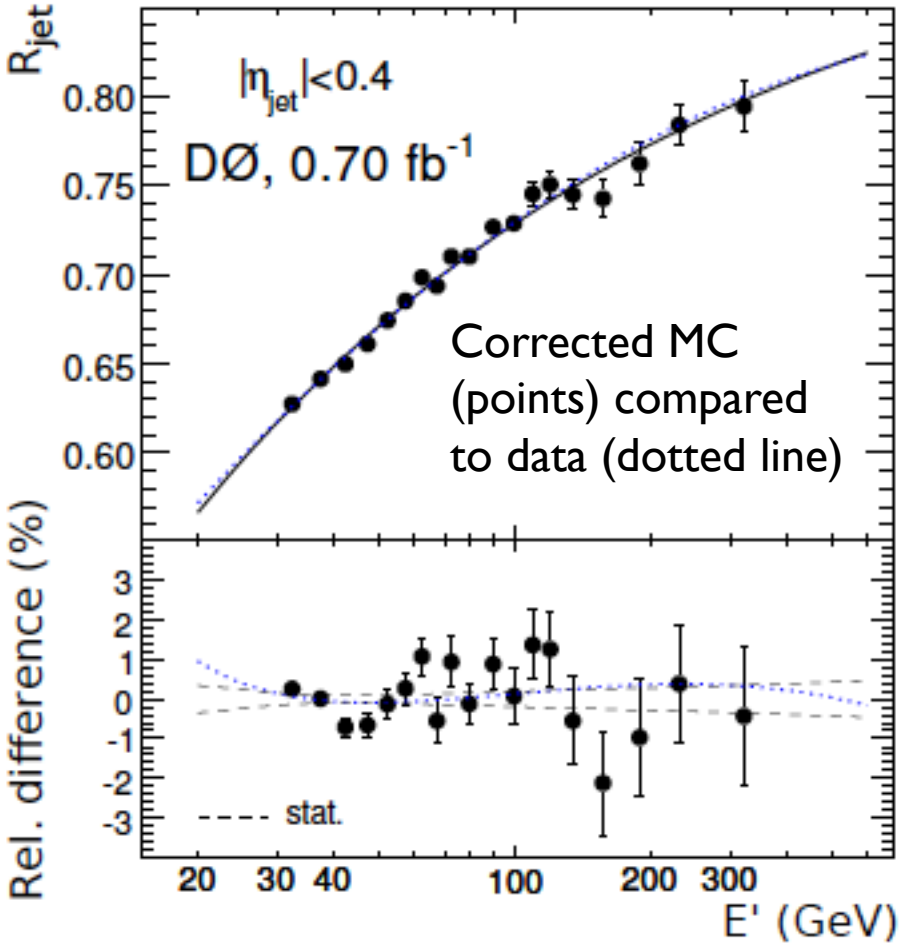
Need MC to well represent the data: use the particle jet matched to a reco-level jet in MC to estimate a MC-to-data correction factor

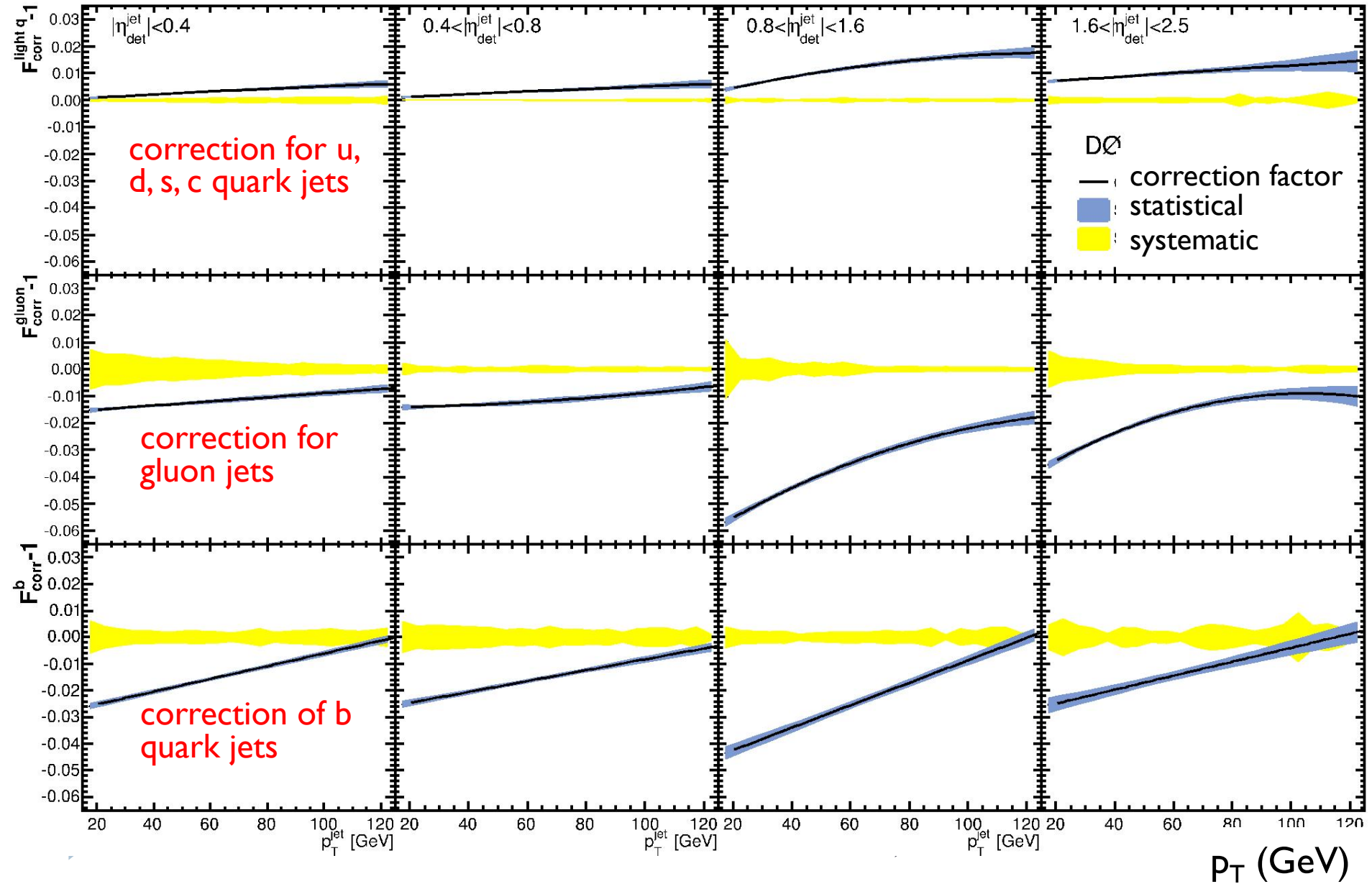
$$F^{corr} = \frac{\sum_i E_i^{true}(particle) \cdot R_i^{data}}{\sum_i E_i^{true}(particle) \cdot R_i^{MC}}$$

where i sums over all the particles in the partic jet, R is the single particle response in data and MC (depend on particle type, energy and η).

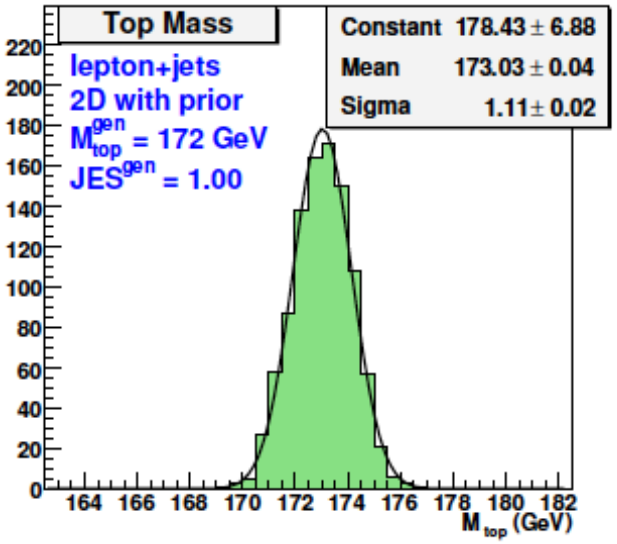
Then we apply the above correction factor to the reco jet to correct for the MC-data difference

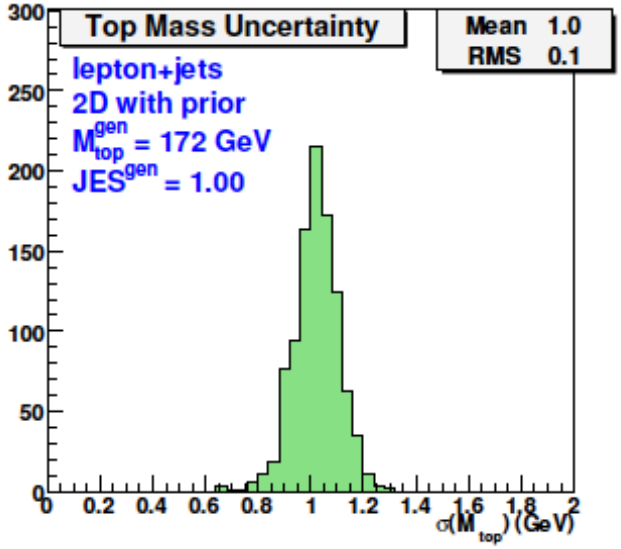
$$E_{jet}^{corr} = F^{corr} \cdot (E_{jet}^{raw} - E_O)$$

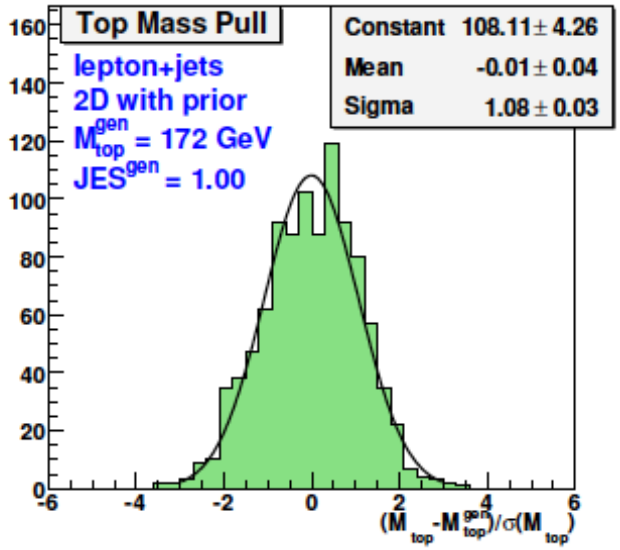



$|\eta^{jet}_{det}|<0.4$
$0.4<|\eta^{jet}_{det}|<0.8$
$0.8<|\eta^{jet}_{det}|<1.6$
$1.6<|\eta^{jet}_{det}|<2.5$
$F^{light\ q}_{corr}-1$
$F^{gluon}_{corr}-1$
$F^{b}_{corr}-1$
correction for u, d, s, c quark jets
correction for gluon jets
correction of b quark jets
DØ
correction factor
statistical
systematic
p^{jet}_T [GeV]
p_T (GeV)

Calibration of the Method (I)



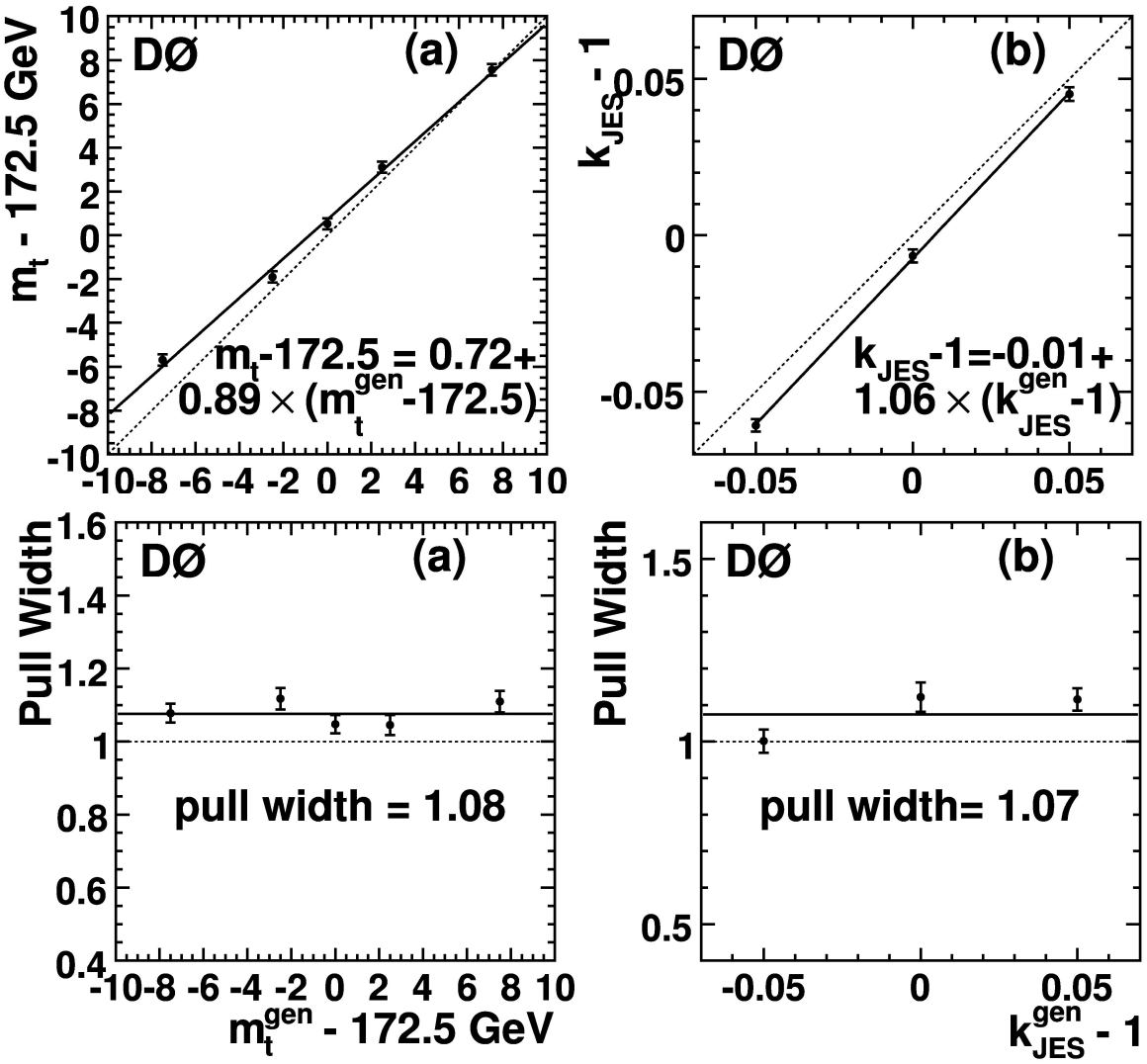




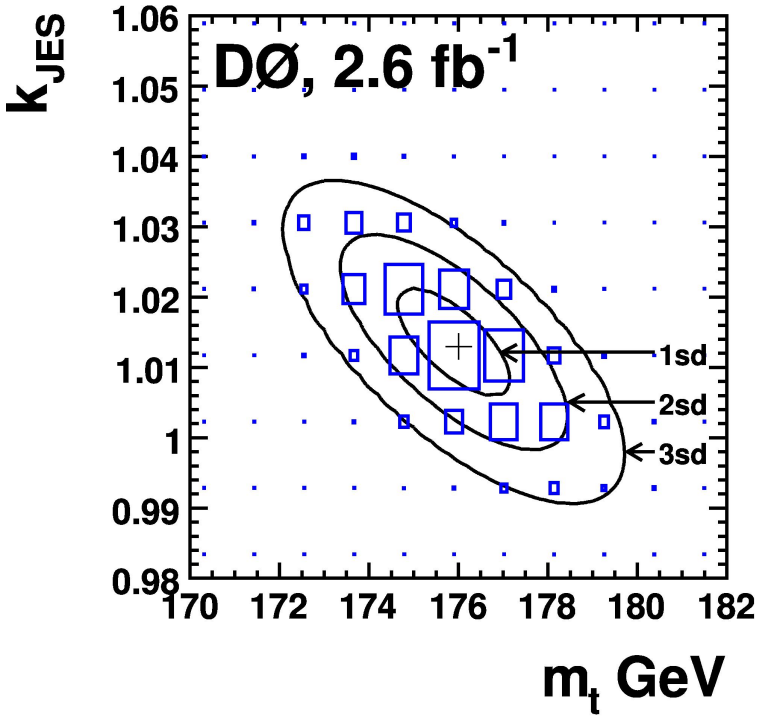
- In order to estimate and correct for biases on the measured top-quark mass and uncertainty, we perform MC pseudo-experiments. Each pseudo-experiment consists of MC events randomly drawn from signal and background MC samples according to the signal fraction measured in data.

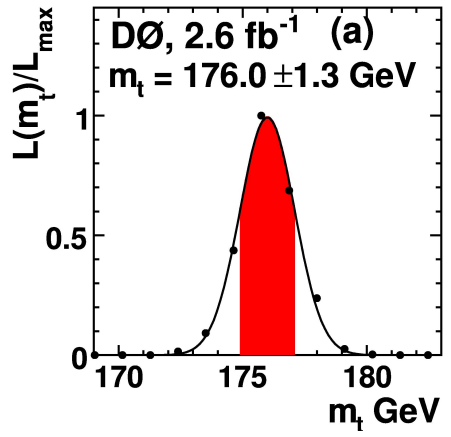
Calibration of the Method (II)

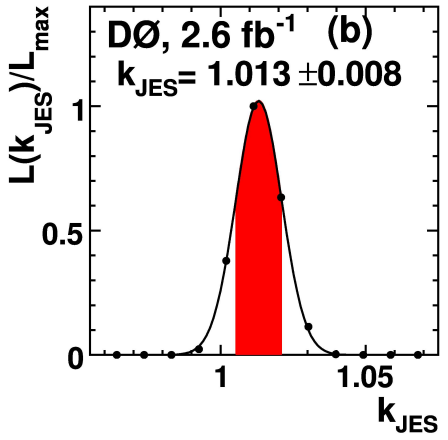
We perform MC pseudo-experiments to estimate biases on the measured masses and uncertainty.

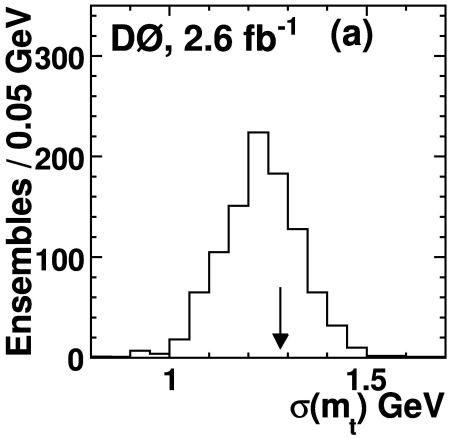


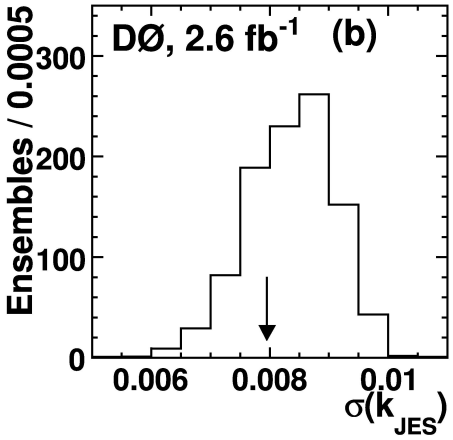
Lepton+Jets Result (I)











$$m_t(2.6\ \mathrm{fb}^{-1}) = 176.0 \pm 1.0(\mathrm{stat}) \pm 0.8(\mathrm{JES}) \pm 1.0(\mathrm{syst})\ \mathrm{GeV}$$

Lepton+Jets Result (II)

PRD 84, 032004 (2011)

Combine the new 2.6fb^{-1} RunIIb result

$$m_t(2.6\ \mathrm{fb}^{-1}) = 176.0 \pm 1.0(\mathrm{stat}) \pm 0.8(\mathrm{JES}) \pm 1.0(\mathrm{syst})\ \mathrm{GeV}$$

with the updated 1.0fb^{-1} RunIIa result using the BLUE method

$$m_t(1.0\ \mathrm{fb}^{-1}) = 172.4 \pm 1.4(\mathrm{stat}) \pm 1.1(\mathrm{JES}) \pm 1.0(\mathrm{syst})\ \mathrm{GeV}$$

we obtain a result corresponding to 3.6 fb^{-1} of data:

$$m_t(3.6\ \mathrm{fb}^{-1}) = 174.9 \pm 0.8(\mathrm{stat}) \pm 0.8(\mathrm{JES}) \pm 1.0(\mathrm{syst})\ \mathrm{GeV}$$

$$= 174.9 \pm 1.5\ (\mathrm{GeV})$$

relative uncertainty 0.9%

Systematic Uncertainties (I)

Source	Uncertainty (GeV)
Modeling of production:	
Modeling of signal:	
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
Modeling of detector:	
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
Method:	
Multijet contamination	±0.14
Signal fraction	±0.10
MC calibration	±0.20
Total	±1.02

Physics modeling: 0.80 GeV

Detector modeling: 0.57 GeV

Method: 0.26 GeV

Total systematic: 1.02 GeV

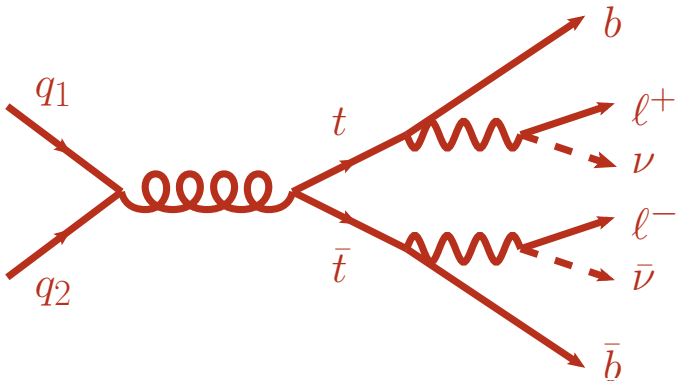
Outline

- Introduction
- Precision measurements of the top-quark mass
  - lepton+jets channel
  - dilepton channel
- Top-antitop quark mass difference
- Summary and outlook

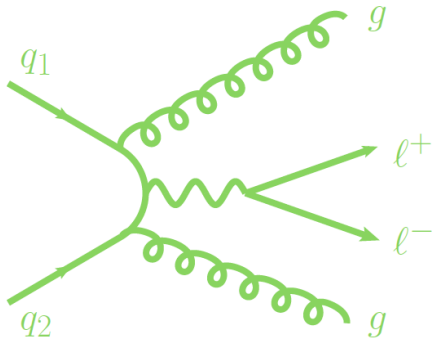
Dilepton Channel

- Two oppositely charged leptons, two b-quark jets, missing transverse momentum $\not{p}_T$ due to the two ν's
- Small branching ratio: ~5%
- Small background: Z/ γ^* + jets
- No hadronically decaying W ➔ can't do in-situ JES

ttbar (MC)

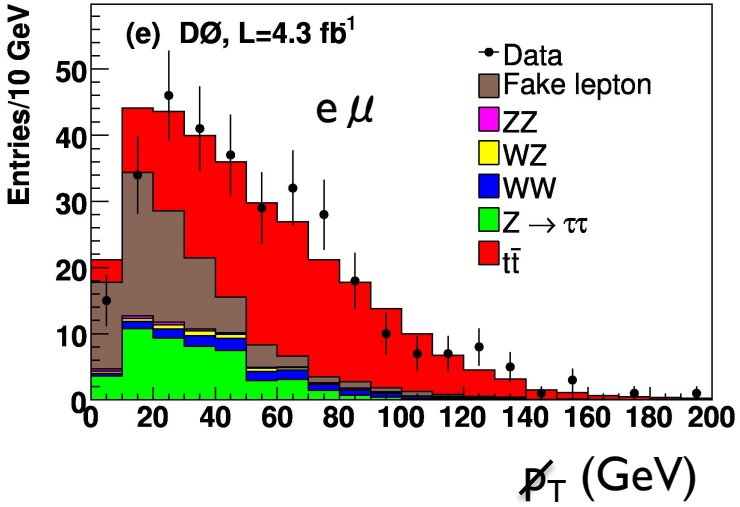


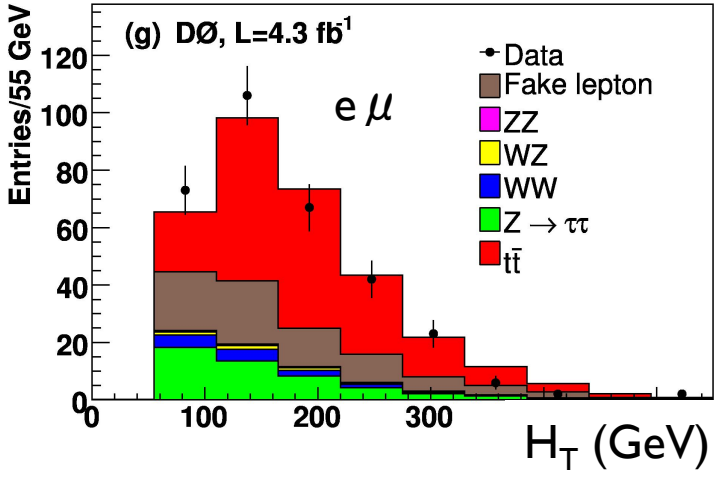
Z+jets (MC)



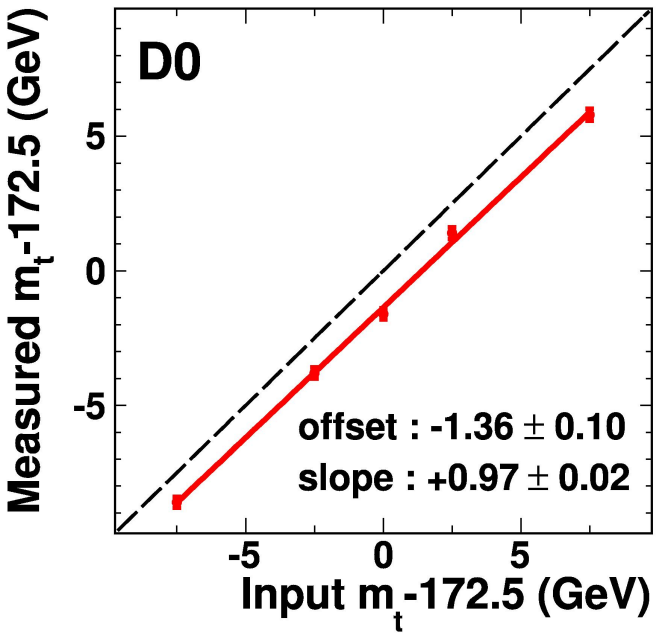
Event Selection

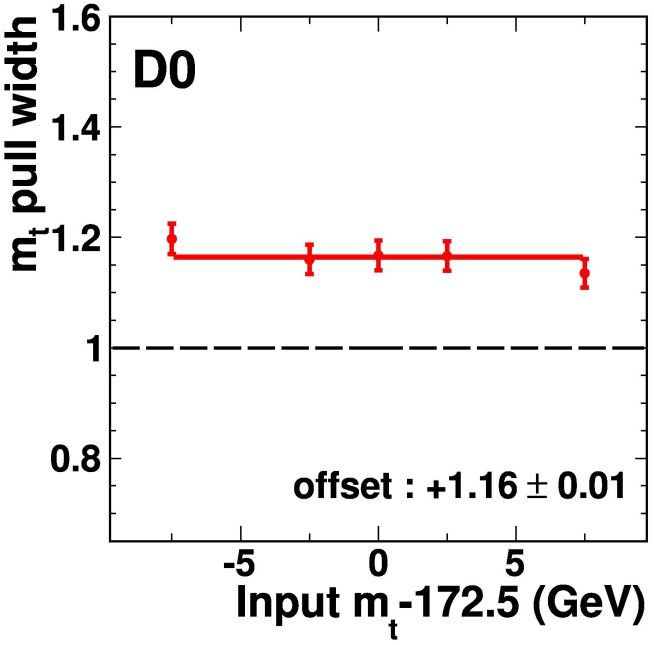
- Event selection cuts (minimizing bias on the measured top-quark mass):
  - single lepton triggers for ee or $\mu\ \mu$, lepton and l+jets triggers for e μ;
  - two oppositely charged, isolated leptons with p_T>15 GeV, and $|\eta|$<1.1 or 1.5<$|\eta|$<2.5 for e ($|\eta|$<2 for μ);
  - at least two jets with p_T>20 GeV, and $|\eta|$<2.5;
  - large $\not{p}_T$ significance(=$\not{p}_T/\sigma(\not{p}_T)$) for ee and $\mu\ \mu$; $\not{p}_T$>40 GeV for $\mu\ \mu$; H_T (=scale sum of all object p_T) >115 GeV for e μ.





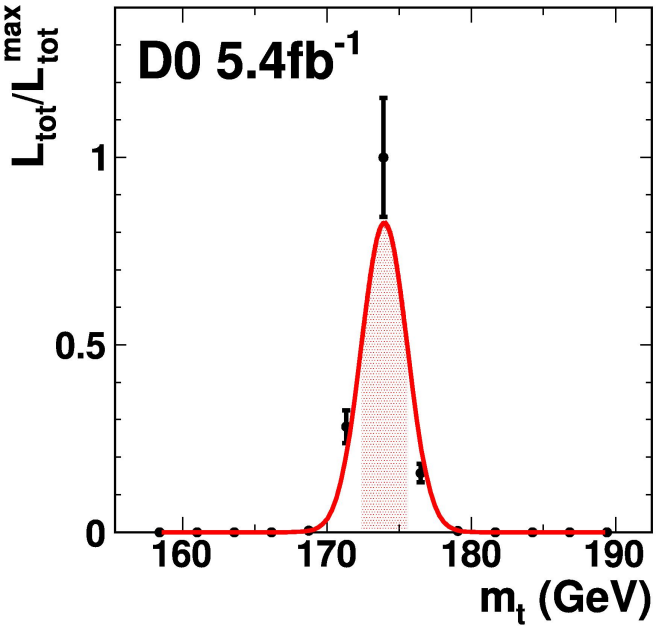
Calibration of the Method





We perform MC pseudo-experiments to estimate biases on the measured top-quark mass and uncertainty.

Dilepton Channel Result



$m_t = 174.0 \pm 1.8(\text{stat}) \pm 2.4(\text{syst})$ GeV

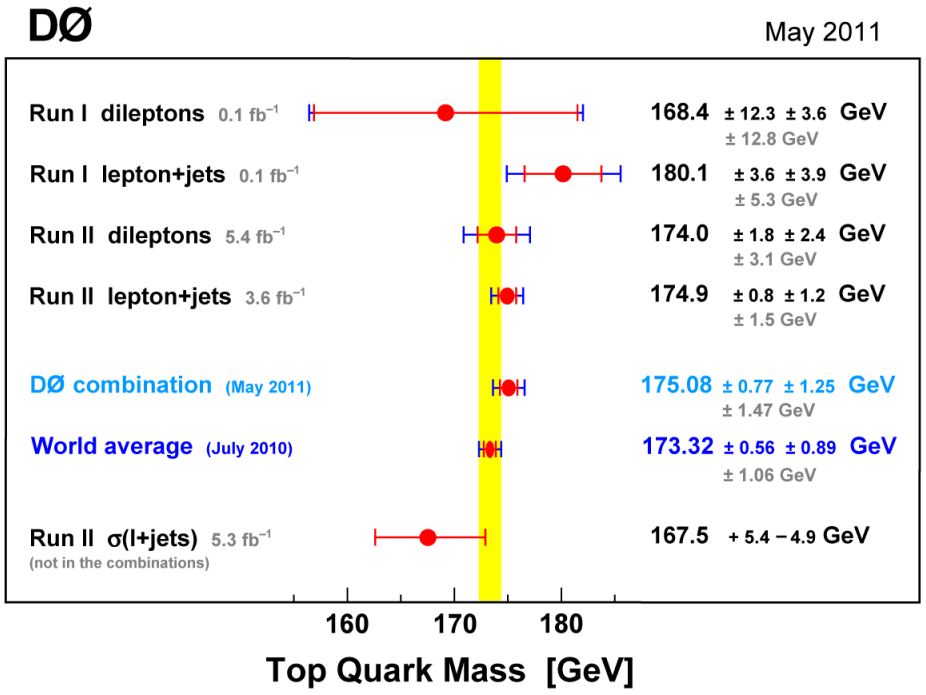
relative uncertainty 1.7%

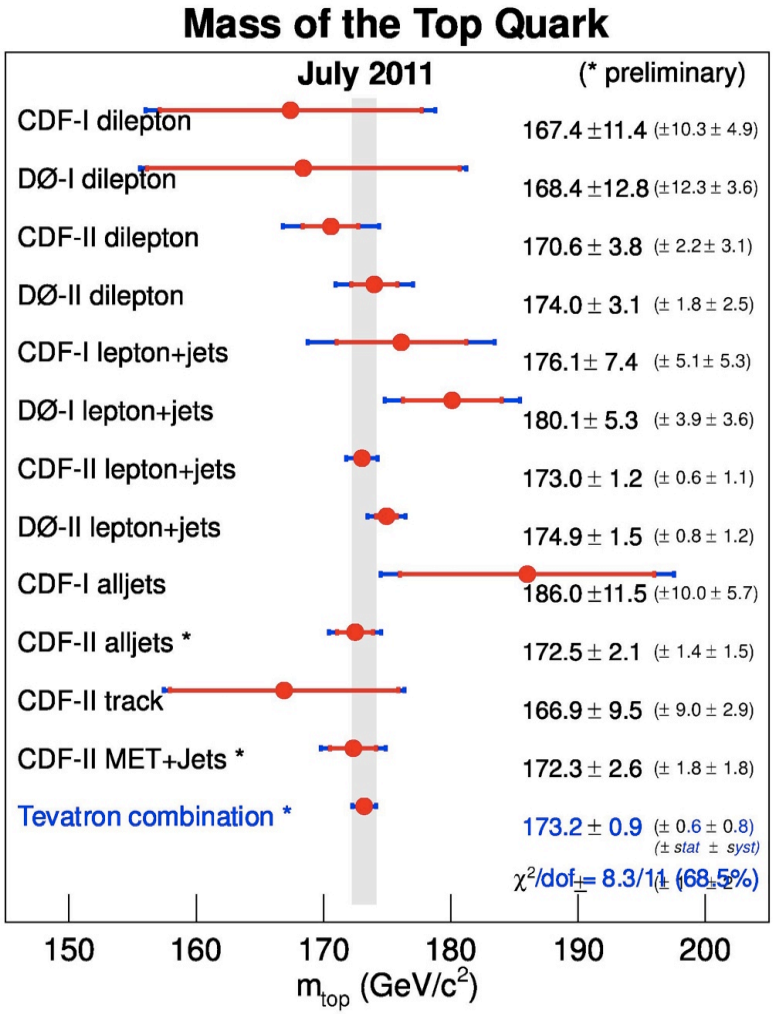
World's most precise measurement in this channel!

PRL 107, 082004 (2011)

Source	Uncertainty (GeV)
Detector modeling:	
b/light jet response	± 1.6
JES	± 1.5
Jet resolution	± 0.3
Muon resolution	± 0.2
Electron p_T scale	± 0.4
Muon p_T scale	± 0.2
ISR/FSR	± 0.2
Signal modeling:	
Higher order and hadronization	± 0.7
Color reconnection	± 0.1
b-quark modeling	± 0.4
PDF uncertainty	± 0.1
Method:	
MC calibration	± 0.1
Signal fraction	± 0.5
Total	± 2.4

Top-Quark Mass Combination





- Results are consistent across all channels and between two experiments.
- The precision reaches 0.6%, dominated by the systematic uncertainty.
- Achieved with great efforts from both experimentalists and theorists.

Outline

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  - dilepton channel
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Top-Antitop Quark Mass Difference

- Because of the very short life time, the top (and antitop) quark decays before hadronizing.
- This allows direct measurements of top and antitop masses and to examine the CPT invariance theorem.

- The first result from DØ (1 fb^{-1}) in 2009:

$$\Delta m_t = 3.8 \pm 3.4(stat) \pm 1.2(syst)\ GeV$$

PRL 103, 132001 (2009)

- The first result from CDF (5.6 fb^{-1}) in 2010:

$$\Delta m_t = -3.3 \pm 1.4(stat) \pm 1.0(syst)\ GeV$$

PRL 106, 152001 (2011)

2 σ effect ?!

Data Analysis

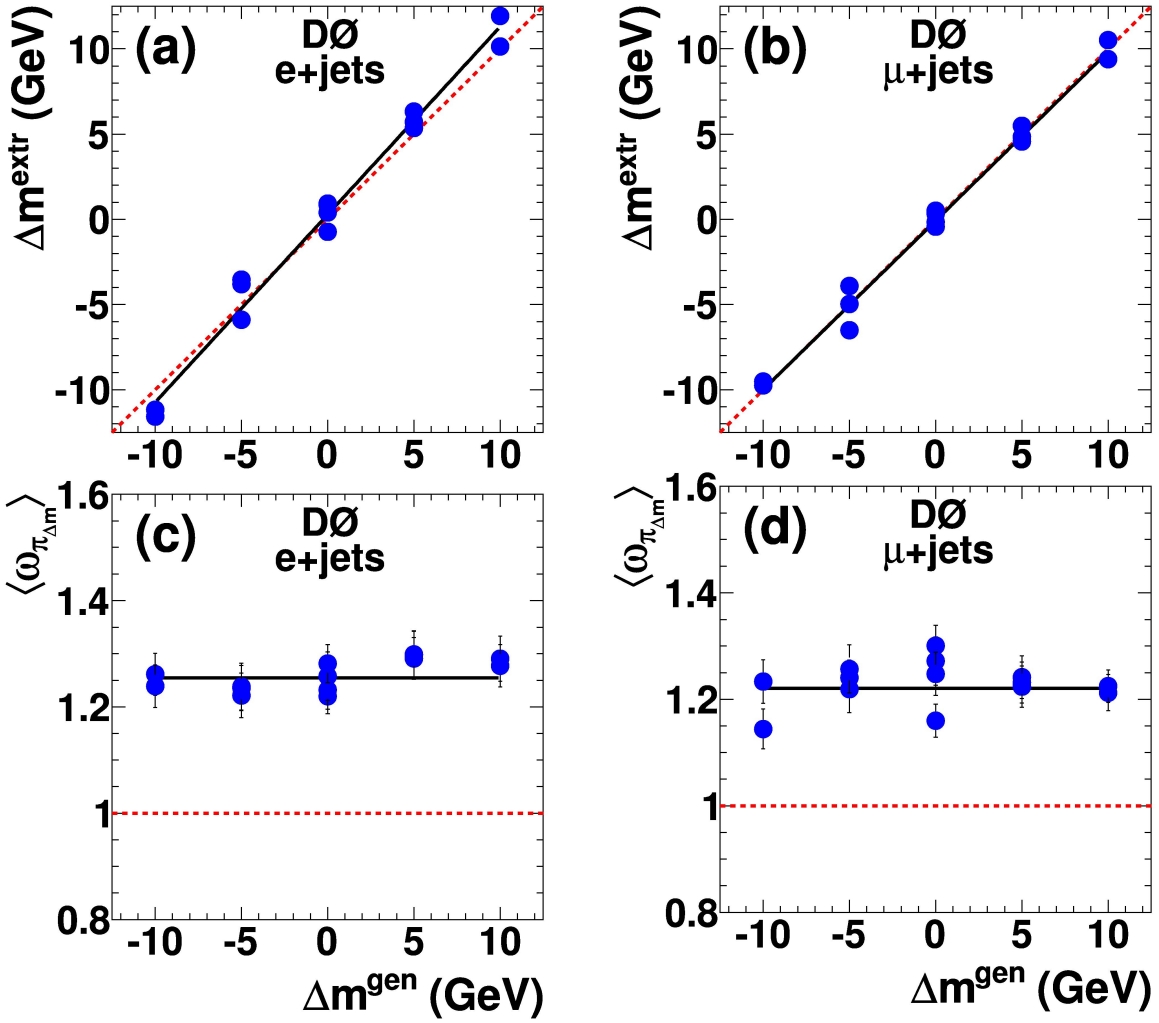
- Same data and event selection as the top-quark mass measurement in the lepton+jets channel.
- Using a matrix element method:

$$P_{sig}(x;M_t,M_{\bar{t}}) = \frac{1}{\sigma_{obs}(M_t,M_{\bar{t}})} \times \int dq_1\, dq_2 f(q_1) f(q_2) \frac{(2\pi)^4 \left|M(y,M_t,M_{\bar{t}})\right|^2}{4\sqrt{(q_1 \cdot q_2 - m_1 m_2}} d\Phi_6 W(y;x)$$

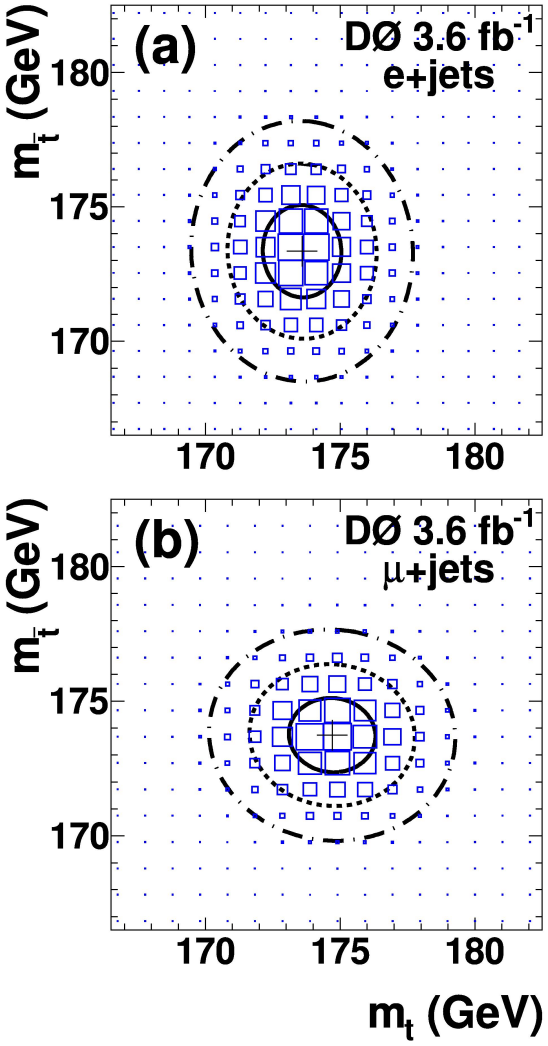
  independently measured the masses of the top and antitop quarks, also extracted the average top-antitop mass as a cross-check.
- We used the lepton charge to tell whether the leptonic decayed W was from top or antitop, and measured the top and antitop quark masses in both the leptonic as well as (mainly) hadronic channels.
- Took into account all possible differences in the detector response between particles and antiparticles (lepton charge ID, jet energy scale difference between b and bbar or c and cbar quark jet, …).

Calibration of the Method

We perform MC pseudo-experiments to estimate biases on the measured mass difference and uncertainty.



Top-Antitop Quark Mass Difference



PRD 84, 052005 (2011)

Source	Uncertainty on Δm (GeV)
Modeling of detector:	
Jet energy scale	0.15
Remaining jet energy scale	0.05
Response to b and light quarks	0.09
Response to b and $\bar{b}$ quarks	0.23
Response to c and $\bar{c}$ quarks	0.11
Jet identification efficiency	0.03
Jet energy resolution	0.30
Determination of lepton charge	0.01
ME method:	
Signal fraction	0.04
Background from multijet events	0.04
Calibration of the ME method	0.18
Total	0.47

$$\Delta m_t = 0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})\ \text{GeV}$$

Summary and Outlook

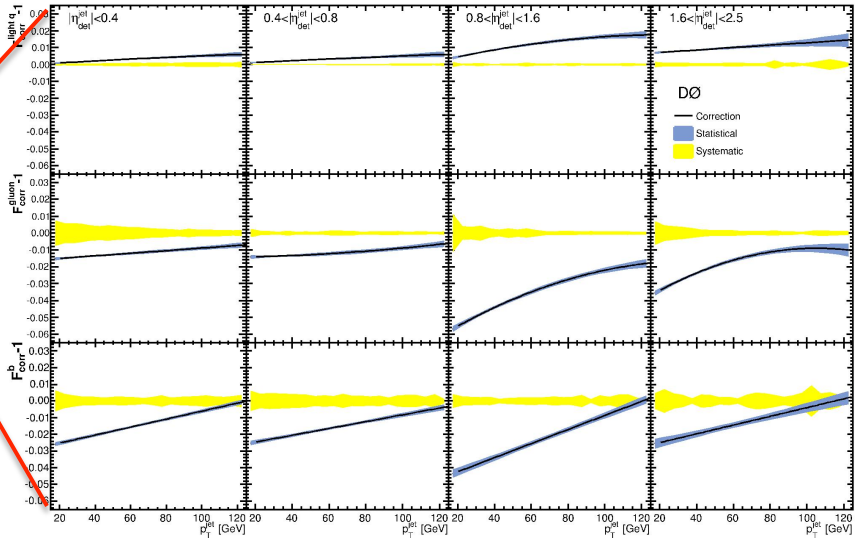
- The precision of the top-quark mass measurement has reached 0.6%, and is dominated by systematic uncertainty.
- With 1-2 times more data on tape, we expect that statistical and JES-related uncertainties will be significantly reduced.
- We are also working hard to improve our understandings of systematic effects in order to further improve the precision of the measurement:
  - detectror modeling
  - ISR/FSR
  - parton showering
  - color reconnection
  - …

Systematic Uncertainties (II)

Source	Uncertainty (GeV)
Modeling of production:	
Modeling of signal:	
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
Modeling of detector:	
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
Method:	
Multijet contamination	±0.14
Signal fraction	±0.10
MC calibration	±0.20
Total	±1.02

was about 1 GeV

Physics modeling: 0.80 GeV



Total systematic: 1.02 GeV

Systematic Uncertainties (II)

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Modeling of production:	
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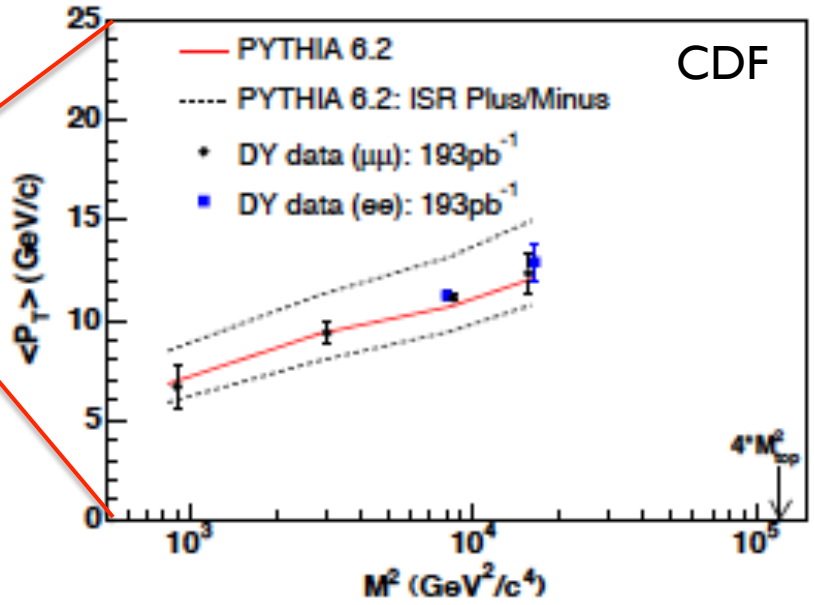


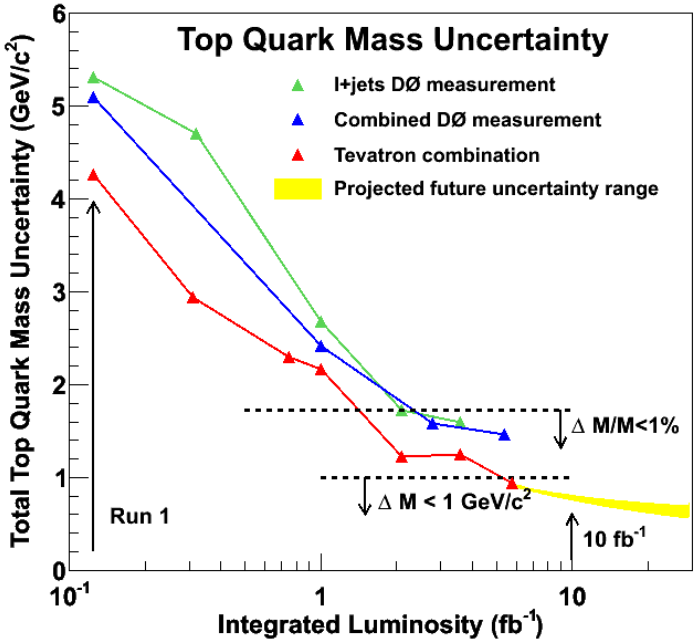
Detector modeling: 0.57 GeV

Method: 0.26 GeV

Total systematic: 1.02 GeV

Summary and Outlook

- The precision of the top-quark mass measurement has reached 0.6%, and is dominated by systematic uncertainty.
- With ~2 times more data on tape to be analyzed, we expect that both the statistical and JES-related uncertainties will be significantly reduced.
- We are also working hard to improve our understandings of systematic effects in order to further improve the precision of the measurement.
- Can the final Tevatron result reach a precision that is close to 0.4%?



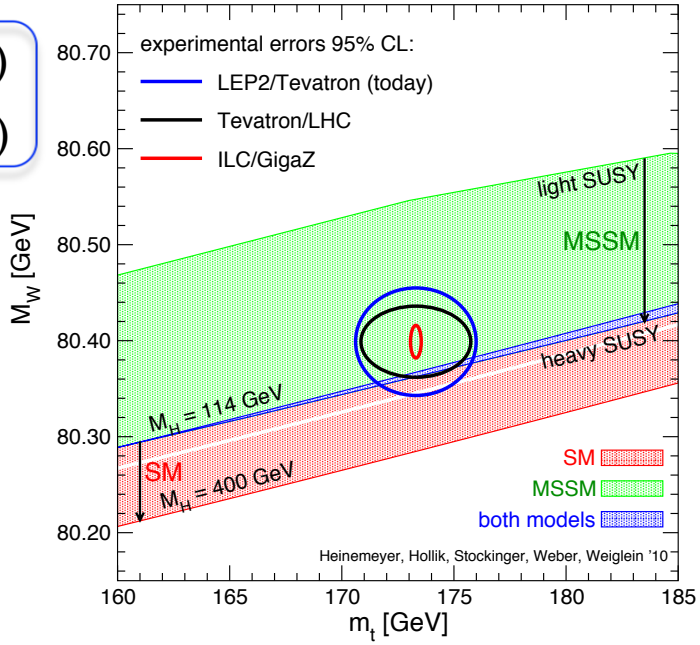
Summary and Outlook

- LHC experiments have enter the game of the top-mass measurement, currently with a much worse precision than the Tevatron. As there will be a huge size of top-quark sample, the statistical uncertainty will become negligible, and it will take a lot of efforts to understand all the systematic effects.

m_t(ATLAS)=175.9±0.9(stat)±2.7(syst) GeV (0.7 fb^{-1})

m_t(CMS)=173.4±1.9(stat)±2.7(syst) GeV (36 pb^{-1})

- The top-quark mass measurement at the LHC may eventually be able to reach and become better than the Tevatron result, but it will take a new energetic lepton collider to push dramatically the precision.

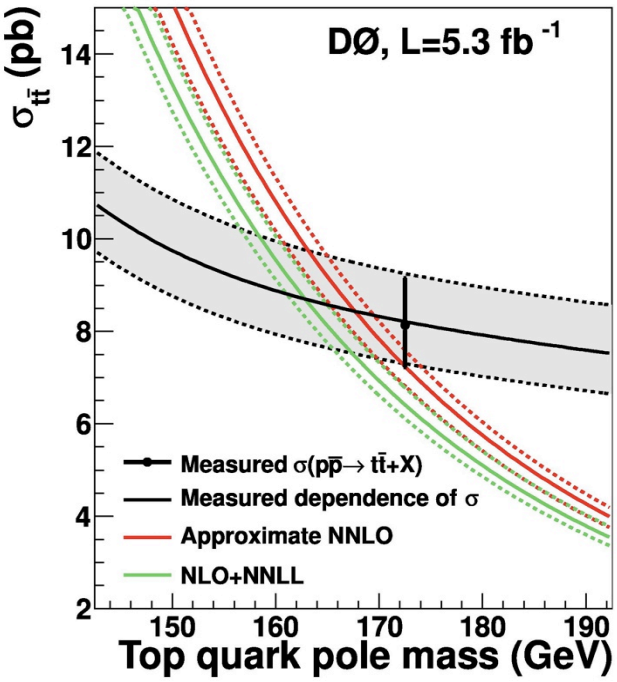


Top Quark Mass From Cross Section

- Top quark carries color, thus its pole mass m_t^{pole} can only be defined with ambiguity ~ $\Lambda_{QCD.}$
- Its definition in field theory depend on renormalization scheme, often used is $\overline{\mathrm{MS}}$ scheme.
- Direct measurements use LO or NLO matrix element MC generators with parton showering to extract the result. It is believed that the mass from such direct measurements is close to the top quark pole mass but there is no precise answer yet. Theorists are working on this issue.

Top Quark Mass From Cross Section

PLB **703**, 422 (2011)



Theoretical prediction	$m_t^{\rm pole}$ (GeV)	
MC mass assumption	$m_t^{\rm MC} = m_t^{\rm pole}$	$\Delta(m_t^{\rm MC} = m_t^{\overline{\rm MS}})$
NLO [9]	$164.8^{+5.7}_{-5.4}$	-2.8
NLO+NLL [10]	$166.5^{+5.5}_{-4.8}$	-2.6
NLO+NNLL [11]	$163.0^{+5.1}_{-4.6}$	-3.3
Approximate NNLO [12]	$167.5^{+5.2}_{-4.7}$	-2.6
Approximate NNLO [13]	$166.7^{+5.2}_{-4.5}$	-2.6

- MC is used to estimate the acceptance for the cross section measurement. Therefore the measured cross section only weakly depends on the value of the top quark mass in MC.
- A constraint on the top quark pole mass is obtained by combining the experimental and theoretical inputs.
- The result is insensitive to the interpretation of the top quark mass in MC.

Top Quark Discovery

Announcement of top quark discovery in public seminar at Fermilab on March 2nd, 1995