Measurements of the Top Quark Mass at DØ

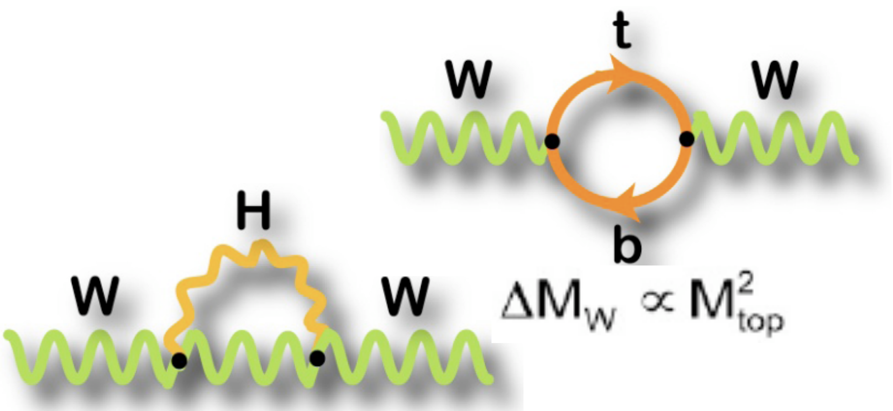
Oleg Brandt for the DØ collaboration
II. Physikalisches Institut, Georg-August-Universität Göttingen

Why is m_{top} so interesting?

- The top is special:
  - Heaviest particle of the SM
  - Yukawa coupling is ~1
  - $\Gamma_{top} << \Lambda_{QCD}$
    - → top is the only "bare" quark!

Why is m_{top} so interesting?

- **The top is special:**
  - **Heaviest particle of the SM**
  - **Yukawa coupling is ~1**
  - **$\Gamma_{top} << \Lambda_{QCD}$**
    - **→ top is the only "bare" quark!**
  - **Use m_{top} to infer m_{Higgs} via radiative corrections:**



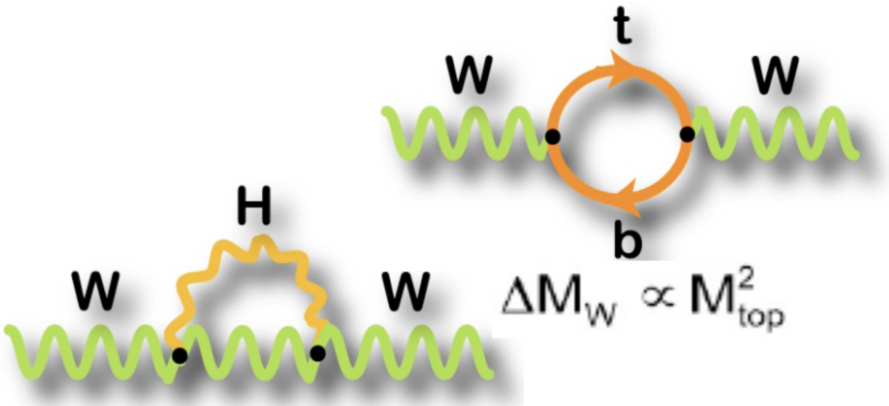
$\Delta M_W \propto M_{top}^2$

$\Delta M_W \propto \ln M_H$

- **Even with the Higgs found, need EW fits to check whether it is the fundamental scalar, as predicted!**

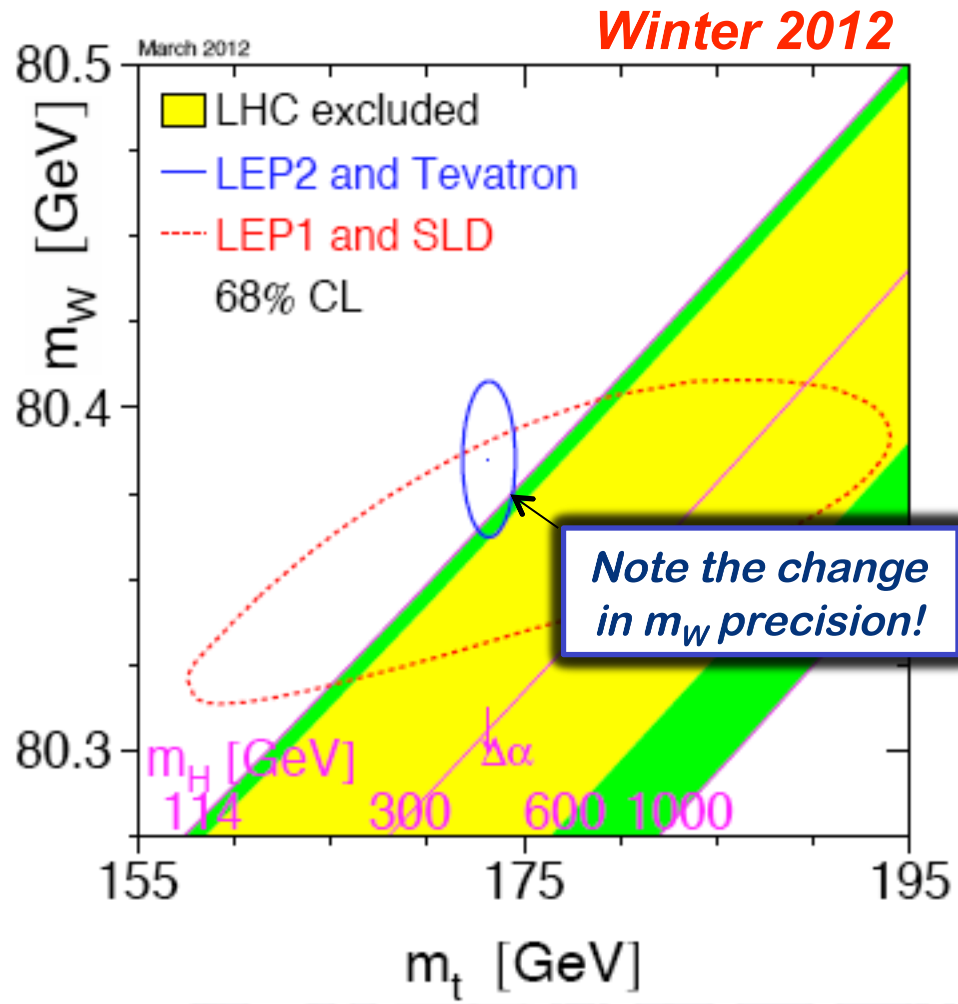
Why is m_{top} so interesting?

- **The top is special:**
  - **Heaviest particle of the SM**
  - **Yukawa coupling is ~1**
  - **$\Gamma_{top} << \Lambda_{QCD}$**
    - **→ top is the only "bare" quark!**
  - **Use m_{top} to infer m_{Higgs} via radiative corrections:**



$\Delta M_W \propto M_{top}^2$

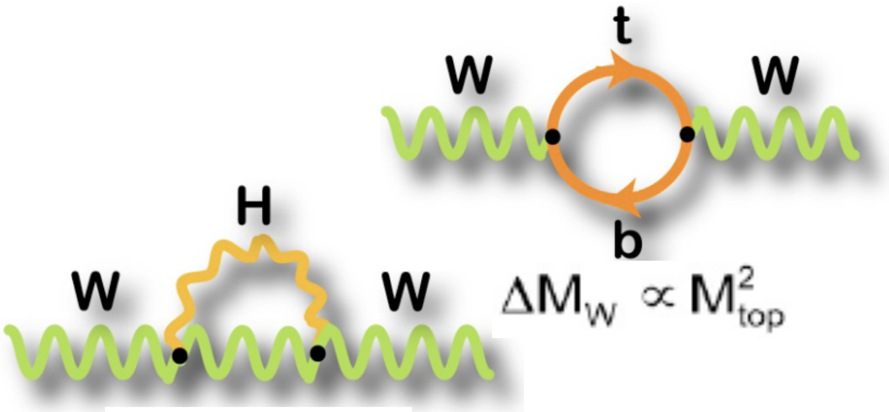
$\Delta M_W \propto \ln M_H$



- **Even with the Higgs found, need EW fits to check whether it is the fundamental scalar, as predicted!**

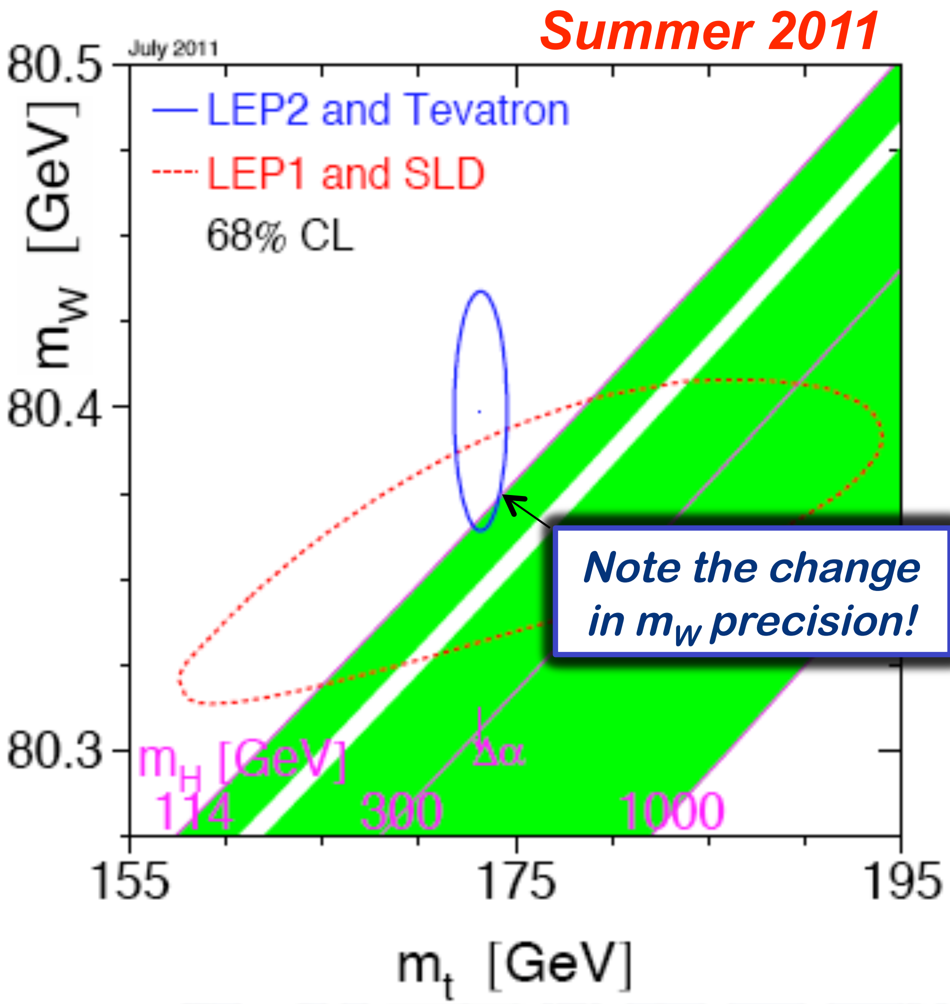
Why is m_{top} so interesting?

- **The top is special:**
  - **Heaviest particle of the SM**
  - **Yukawa coupling is ~1**
  - $\Gamma_{top} << \Lambda_{QCD}$
    - **→ top is the only "bare" quark!**
  - **Use m_{top} to infer m_{Higgs} via radiative corrections:**



$\Delta M_W \propto M_{top}^2$

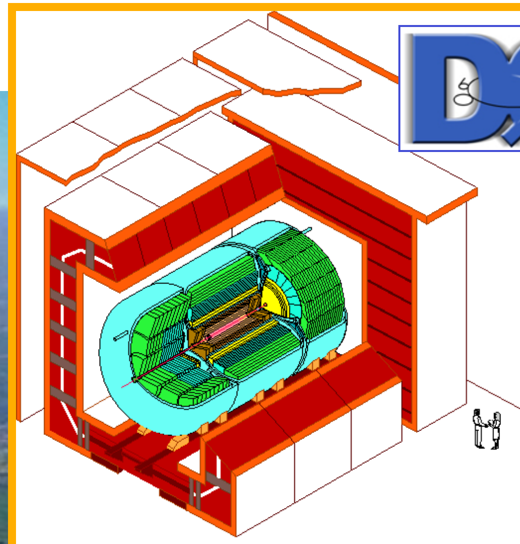
$\Delta M_W \propto \ln M_H$

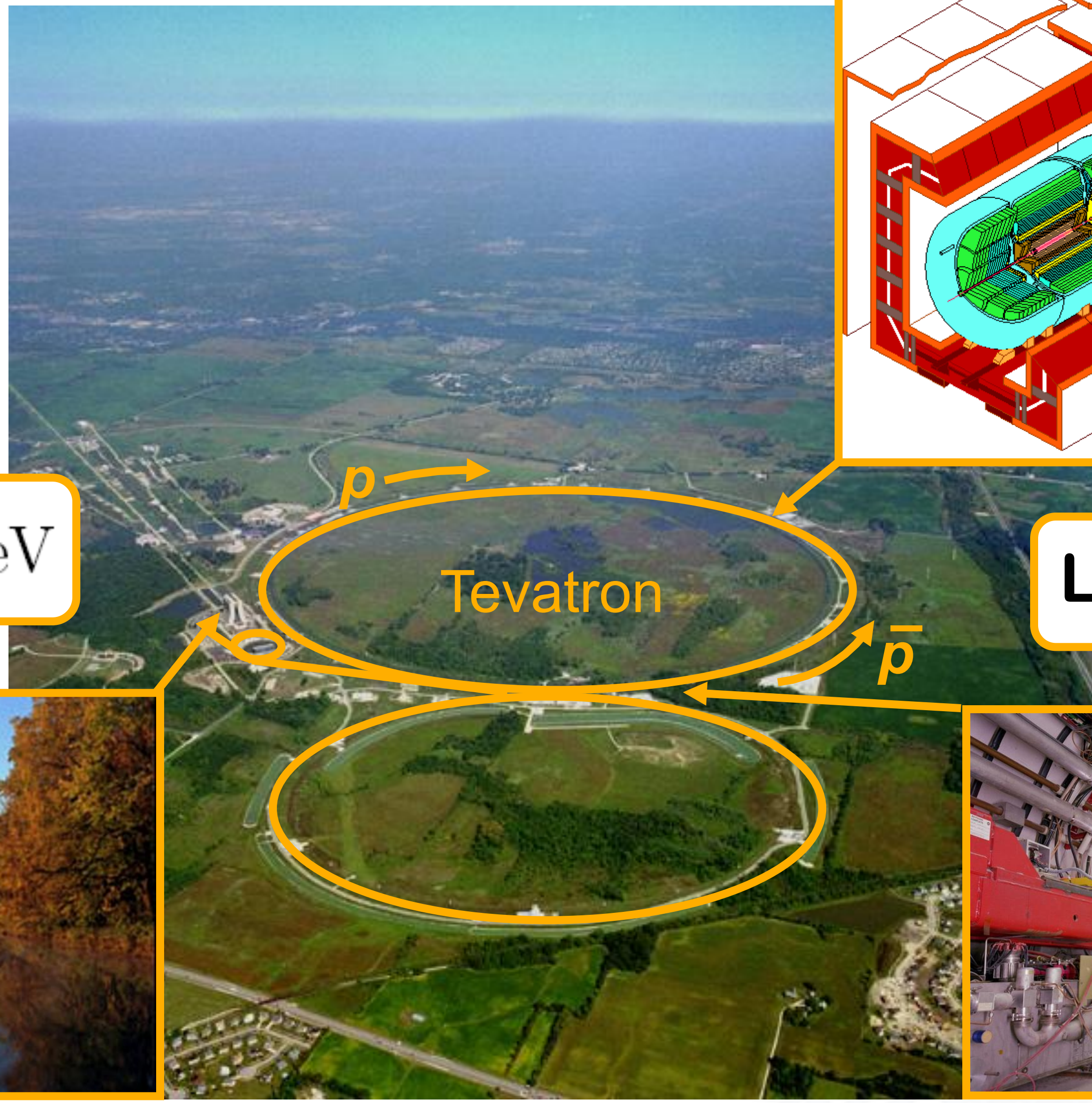


- **Even with the Higgs found, need EW fits to check whether it is the fundamental scalar, as predicted!**

More about the top birth place…

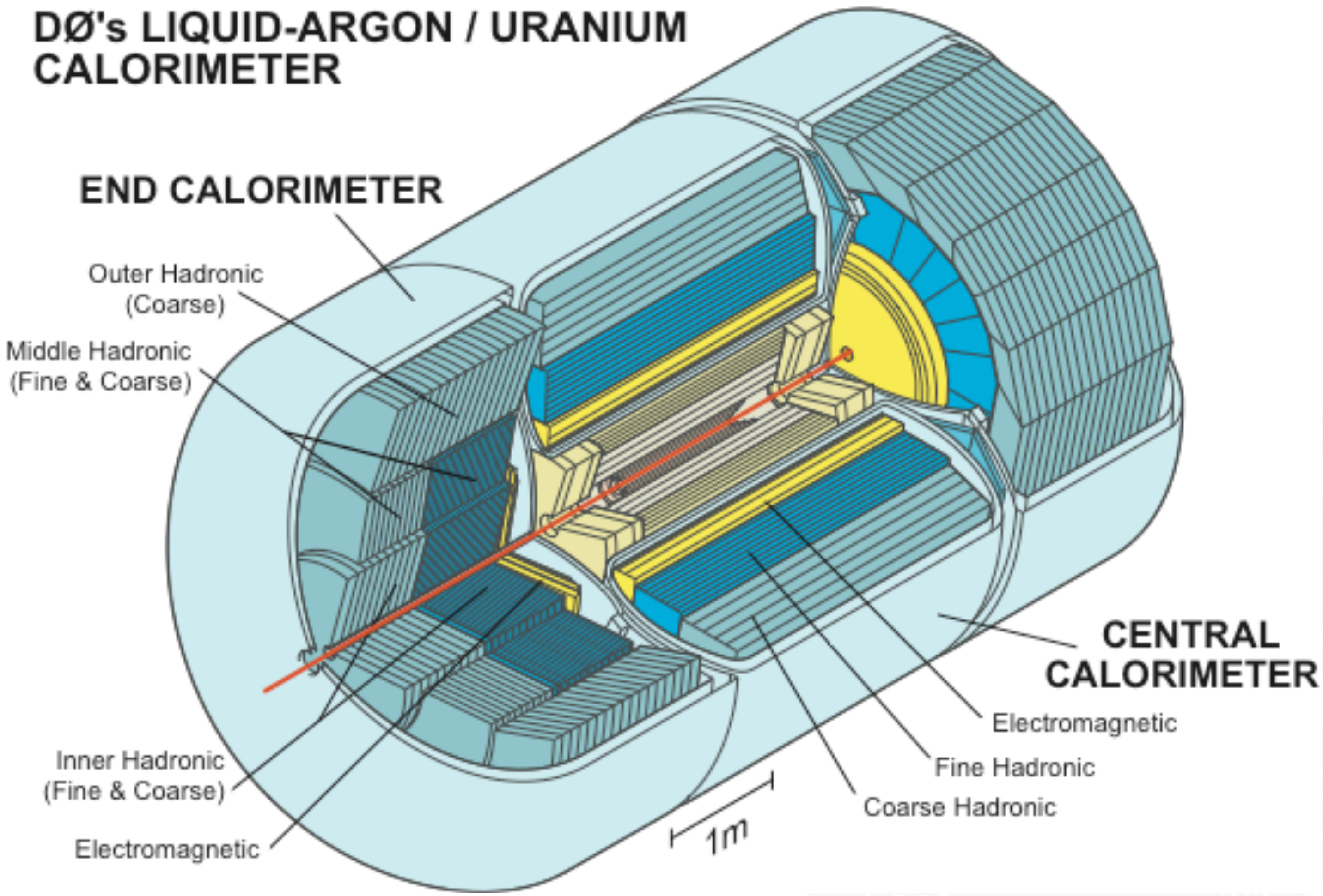
$\sqrt{s} = 1.96\,\text{TeV}$





L ~ 10.7 fb^{-1}

The DØ Calorimeter



EM calorimeter	**22%/√E + 4%**
Hadronic calorimeter	**68%/√E + 5%**

m_{top} in lepton+jets channel

- **Matrix Element method (3.6 fb^{-1})**
  - **Calculate probability on an event-by-event basis:**

$$P_{\text{evt}}(x, m_{\text{top}}) \propto f P_{\text{sig}}(x, m_{\text{top}}) + (1-f) P_{\text{bgr}}(x)$$

*Phys. Rev. D **84**, 032004 (2011)*

- **Matrix Element method (3.6 fb^{-1})**
  - Calculate probability on an event-by-event basis:

$$P_{\text{evt}}(x, m_{\text{top}}) \propto f P_{\text{sig}}(x, m_{\text{top}}) + (1-f) P_{\text{bgr}}(x)$$

  - The clue:

$$P_{\text{sig}}(x, m_{\text{top}}) \equiv \frac{1}{\sigma_{t\bar{t}}(m_{\text{top}})} \int W(x,y) \mathrm{d}\sigma_{t\bar{t}}(y, m_{\text{top}})$$

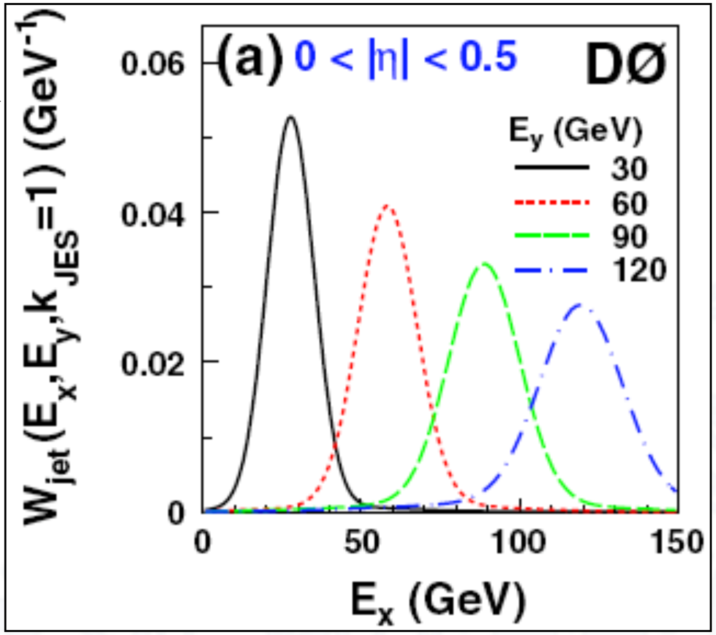
$$\propto |\mathcal{M}_{t\bar{t}}|^2(y, m_{\text{top}})$$

    - For each event, we calculate $P_{\text{sig}}(x, m_{\text{top}})$ based on its consistency to come from $t\bar{t}$ production, depending on m_{top}
  - → Maximal use of stat. information on event-by-event basis!
    - *(Disadvantage: high computational demand)*

*Phys. Rev. D **84**, 032004 (2011)*

Transfer functions

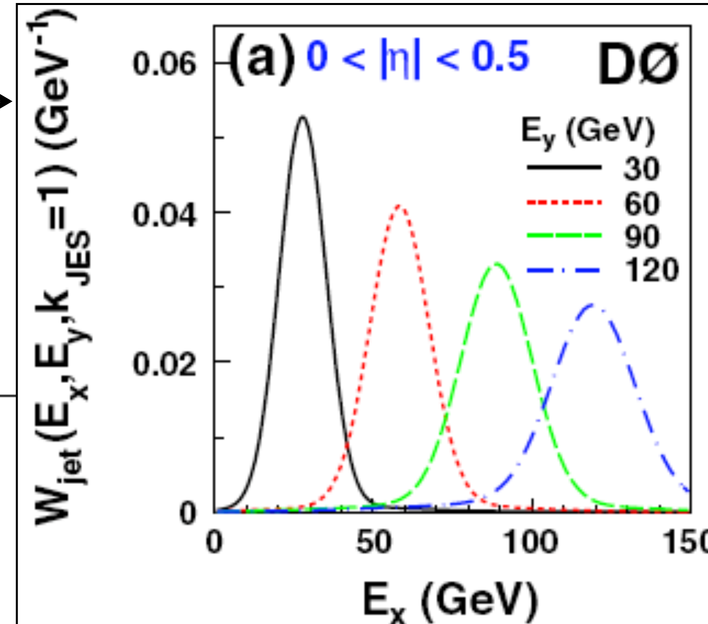
- The Transfer Functions $W(x, y; JES)$ to map parton-level quantities y to reconstruction-level ones x.
  - Treat separately:
    - Light quark jets
    - b-tagged jets w/ soft muon tag
    - All other b-jets
  - x 4 $|\eta|$ regions for each

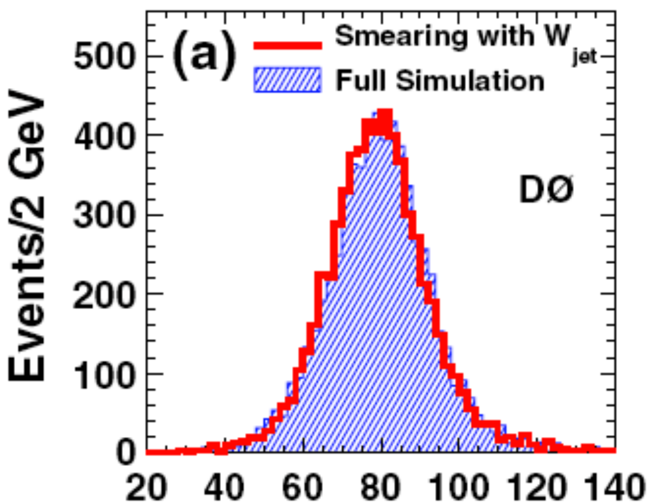


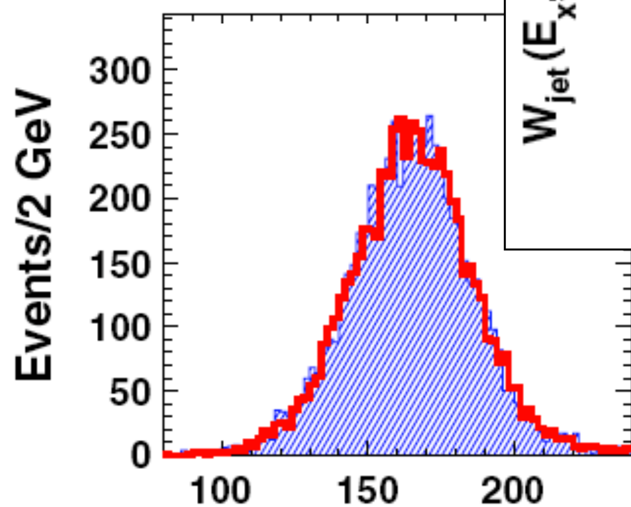
Phys. Rev. D ***84***, *032004 (2011)*

Transfer functions

- The **Transfer Functions** $W(x, y; JES)$ to map **parton-level quantities** y to **reconstruction-level ones** x.
  - Treat separately:
    - Light quark jets →
    - b-tagged jets w/ soft muon tag
    - All other b-jets
  - x 4 $|\eta|$ regions for each







hadronic W decays → m_{qq} (GeV)

hadronic top decays → m_{qqb} (GeV)

Phys. Rev. D ***84****, 032004 (2011)*

m_{top} in lepton+jets channel

- **Matrix Element method (3.6 fb^{-1})**
  - Define the signal probability for 4-jet events as:

$$P_{\rm sig} = \frac{1}{\sigma_{\rm obs}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int \sum_{\rm flavors,\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1)f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\rm JES})$$

Permutation weight, b-tag based

LO Matrix Element, ~ m_{top}
[from Phys. Lett. B 411, 173 (1997)]

Transfer Function
~ k_{JES}

Phys. Rev. D ***84***, *032004 (2011)*

m_{top} in lepton+jets channel

- **Matrix Element method (3.6 fb^{-1})**
  - Define the signal probability for 4-jet events as:

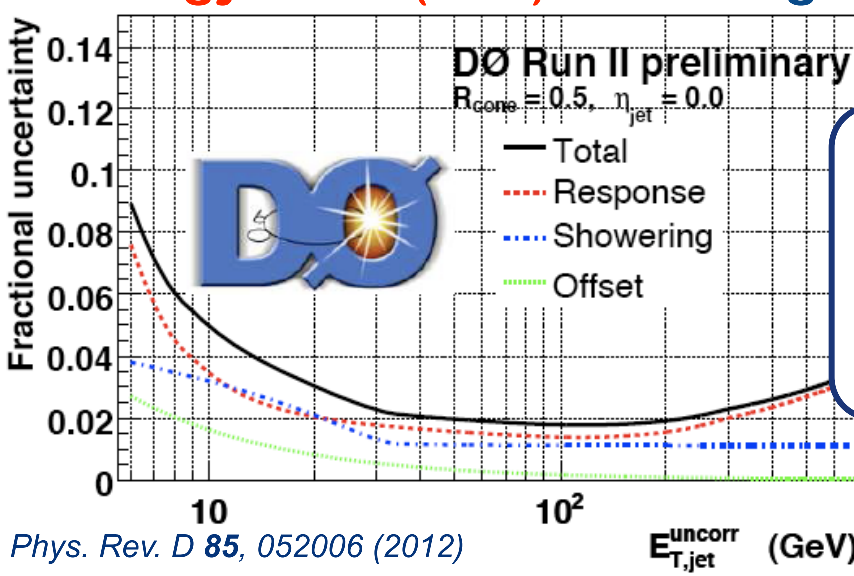
$$P_{\rm sig} = \frac{1}{\sigma_{\rm obs}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int \sum_{\rm flavors,\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1)f'(q_2)}{\sqrt{(\eta_{\alpha\beta}q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x,y;k_{\rm JES})$$

Permutation weight, b-tag based

LO Matrix Element, ~ m_{top}
[from Phys. Lett. B 411, 173 (1997)]

Transfer Function ~ k_{JES}

  - Jet energy scale (JES) is the largest systematic uncertainty



Phys. Rev. D **85**, 052006 (2012)

δ(JES) ≈ 2%
for $\eta \approx 0$, $p_T > 20$ GeV
→
$\delta^{\rm direct}_{\rm JES}(m_{\rm top})$ ≈2-3%

Phys. Rev. D **84**, 032004 (2011)

m_{top} in lepton+jets channel

- **Matrix Element method (3.6 fb^{-1})**
  - Define the signal probability for 4-jet events as:

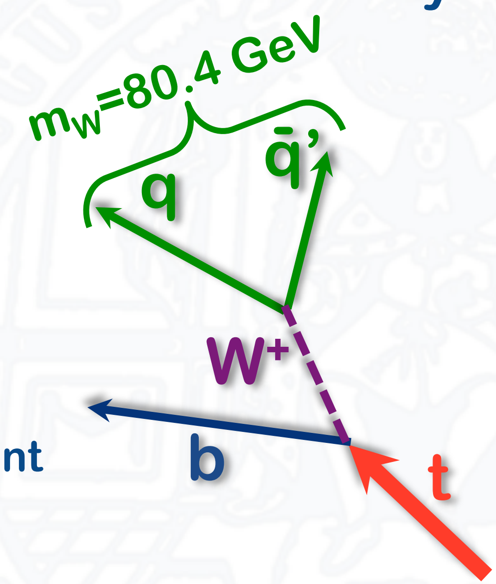
$$P_{\rm sig} = \frac{1}{\sigma^{t\bar{t}}_{\rm obs}} \sum_{i=1}^{24} w_i \int \sum_{\rm flavors,\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1)f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\rm JES})$$

Permutation weight, b-tag based

LO Matrix Element, ~ m_{top}
[from Phys. Lett. B 411, 173 (1997)]

Transfer Function
~ k_{JES}

  - Jet energy scale (JES) is the largest systematic uncertainty
    - Determine the JES in situ:
      - Constrain the mass of the dijet system from hadronic W decay to m_W=80.4 GeV
    - → $\delta^{\rm in\ situ}_{\rm JES}(m_{\rm top}) \approx$ 0.5%! and $\propto \frac{1}{\sqrt{N}}$!
  - Background probability similar (no m_{top} dependence)
    - use ME for W+4 jets from VECBOS, event-by-event



Phys. Rev. D **84**, 032004 (2011)

Single particle response correction

- Derive a **correction** for particle jets matched to reconstructed jets in MC:

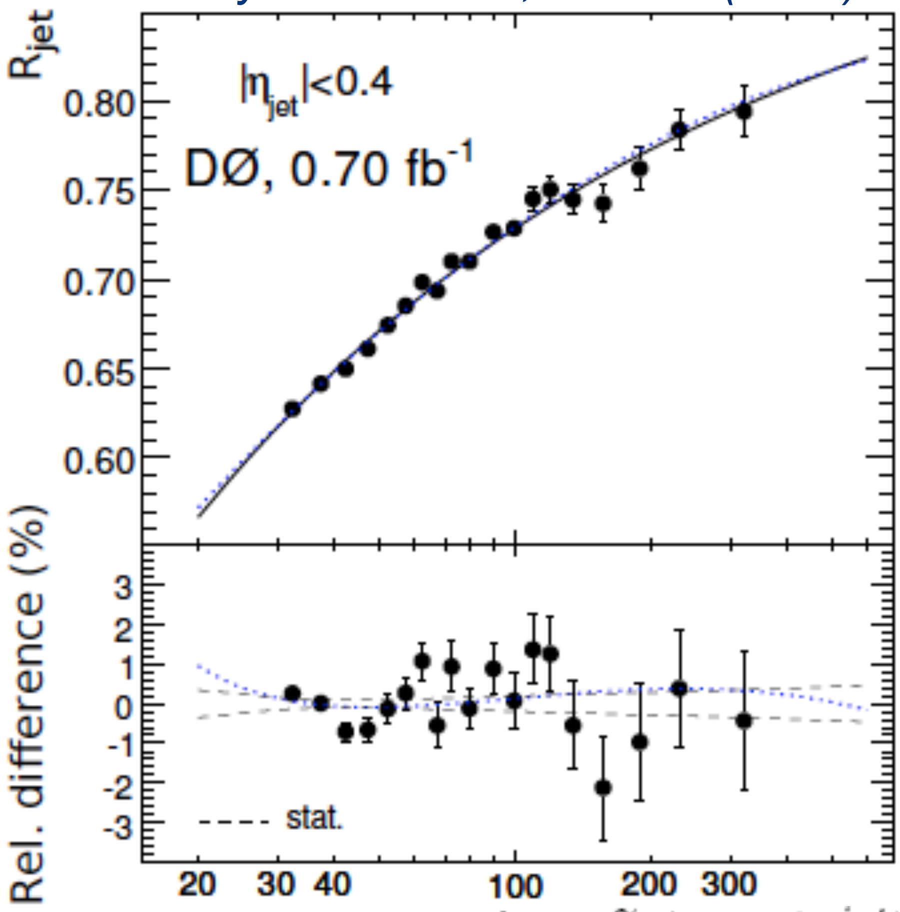
$$\mathcal{D} = \frac{\sum E_i \cdot R_i^{\mathrm{Data}}}{\sum E_i \cdot R_i^{\mathrm{MC}}}$$

  - Sum runs over all particles
  - R_i → single particle response
  - $R_i = R_i(\text{particle type}, E, \eta)$
- Derive **flavour-dependent** correction for the MC:

$$F^{\beta}_{\mathrm{corr}} = \mathcal{D}^{\beta} / \langle \mathcal{D}^{\gamma+\mathrm{jet}} \rangle$$

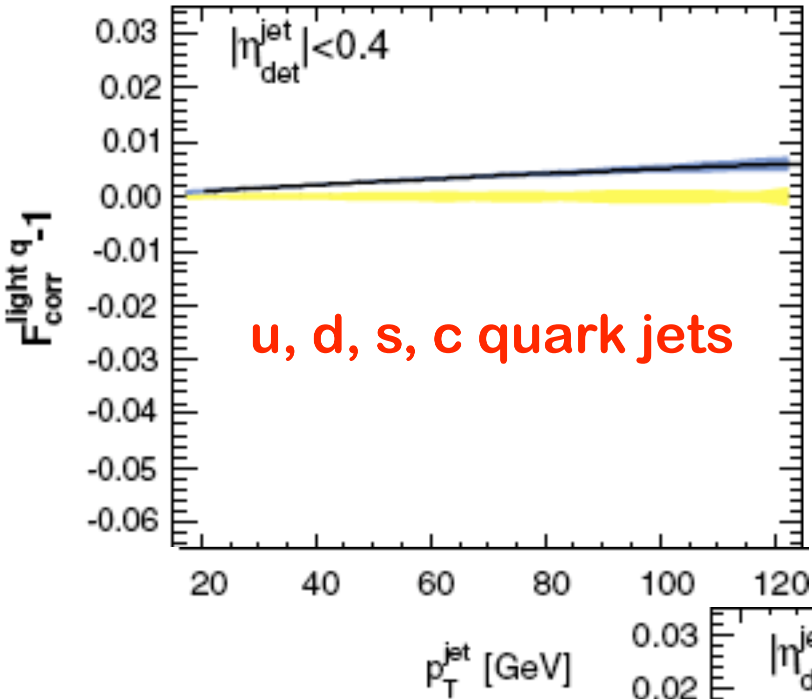
  - Where $\beta (= \text{light quark, gluon or } b \text{ quark})$
- → **preserves default JES!**

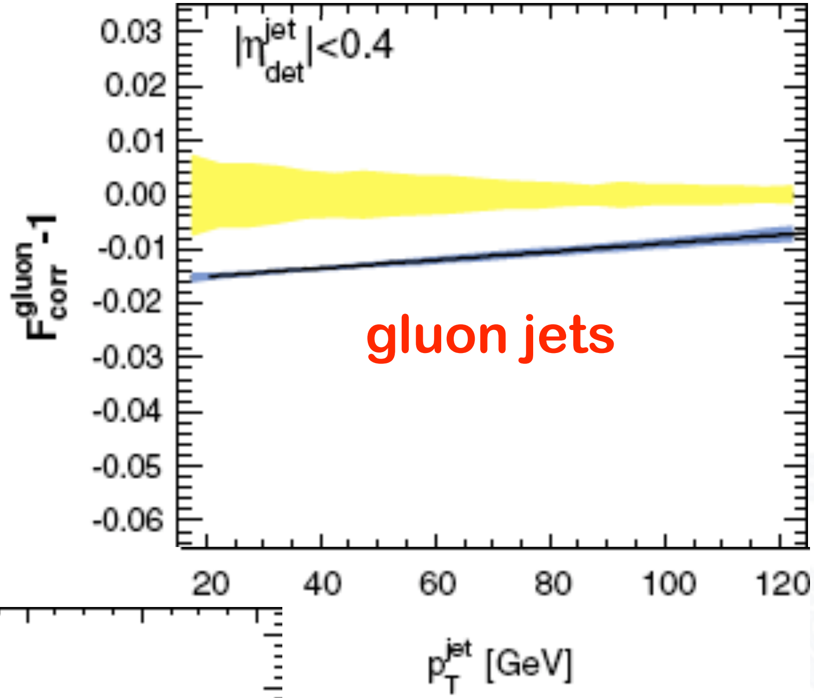
Phys. Rev. D ***85**, 052006 (2012)*

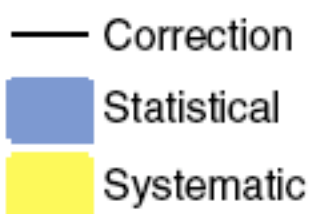


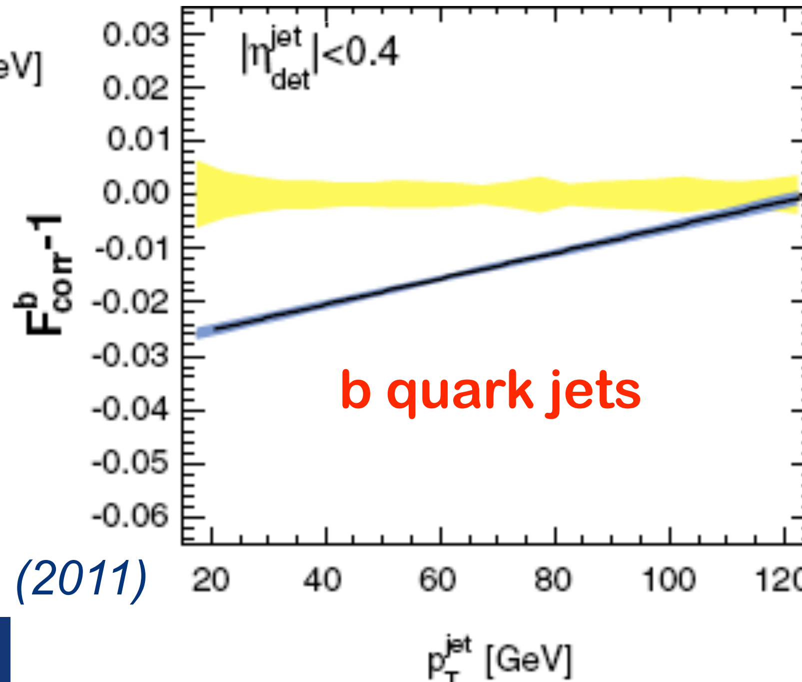
$E' = p_T^{\gamma} / cosh(\eta^{jet})$

Single particle response correction





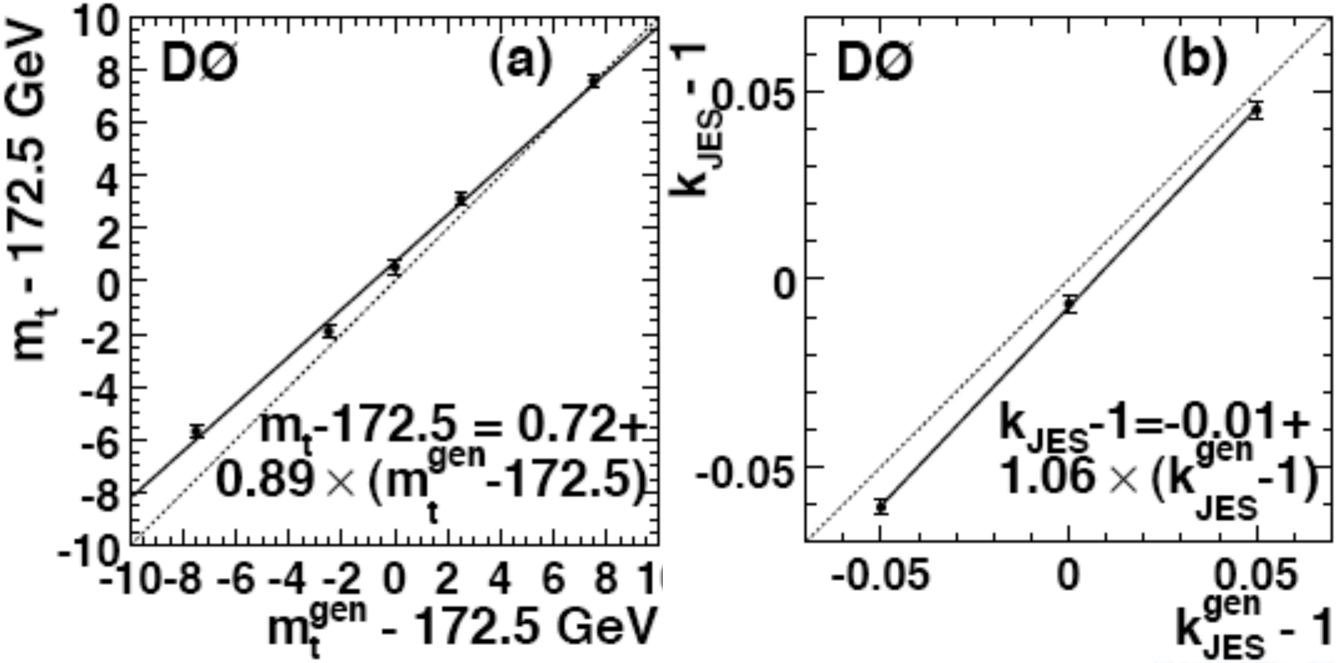




*Phys. Rev. D **84**, 032004 (2011)*

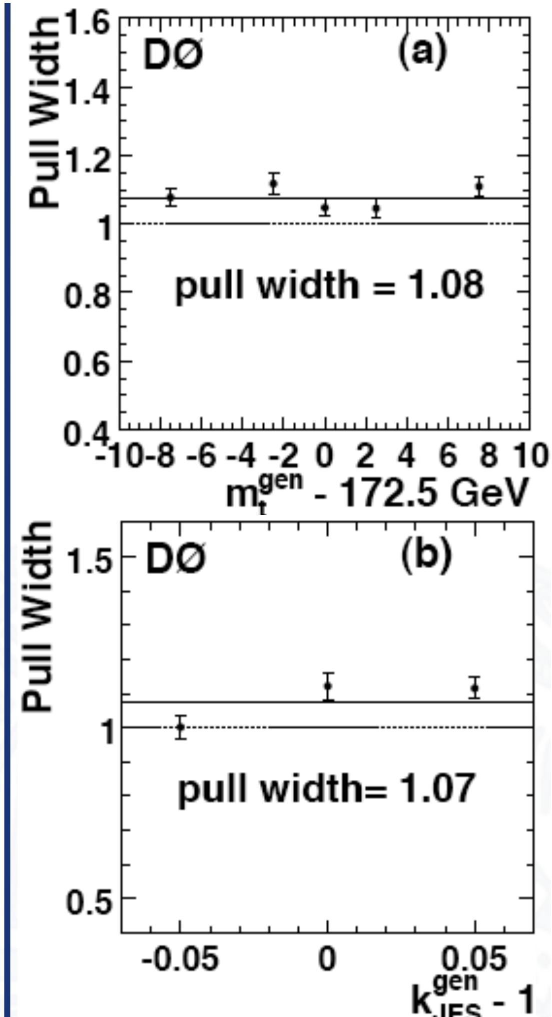
Method calibration

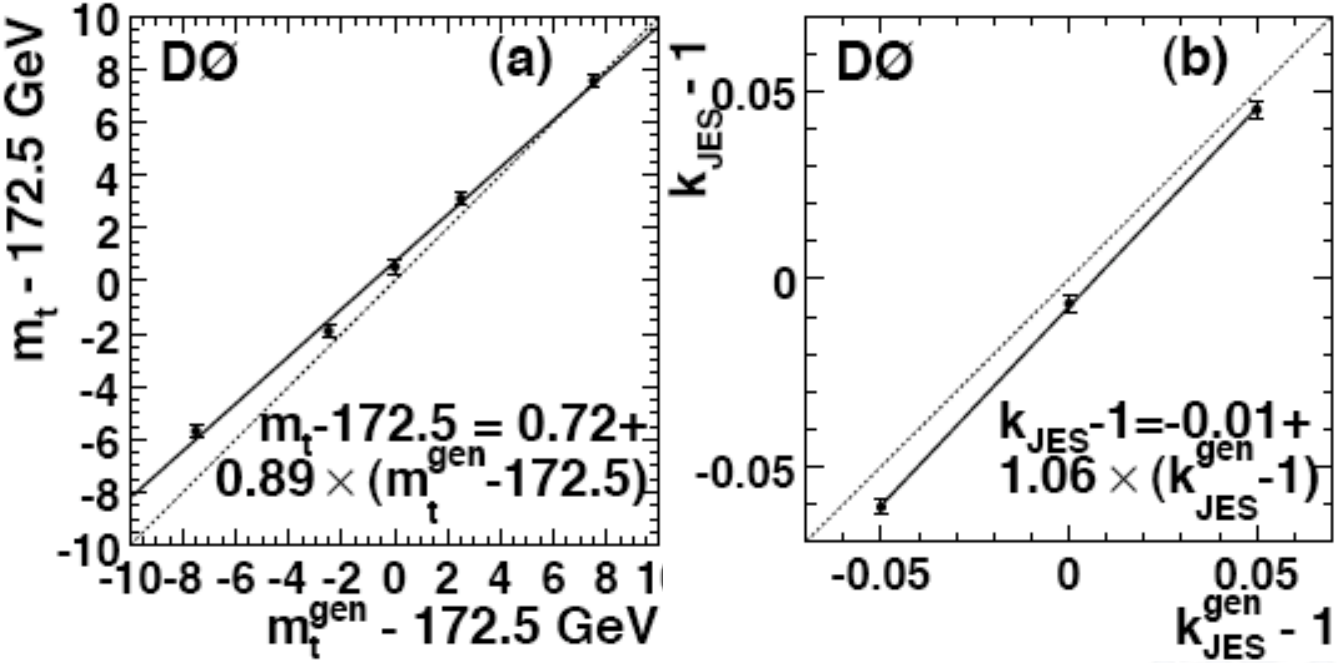
- **Behold! We need to calibrate the method:**
  - is the extracted central value unbiased?



Method calibration

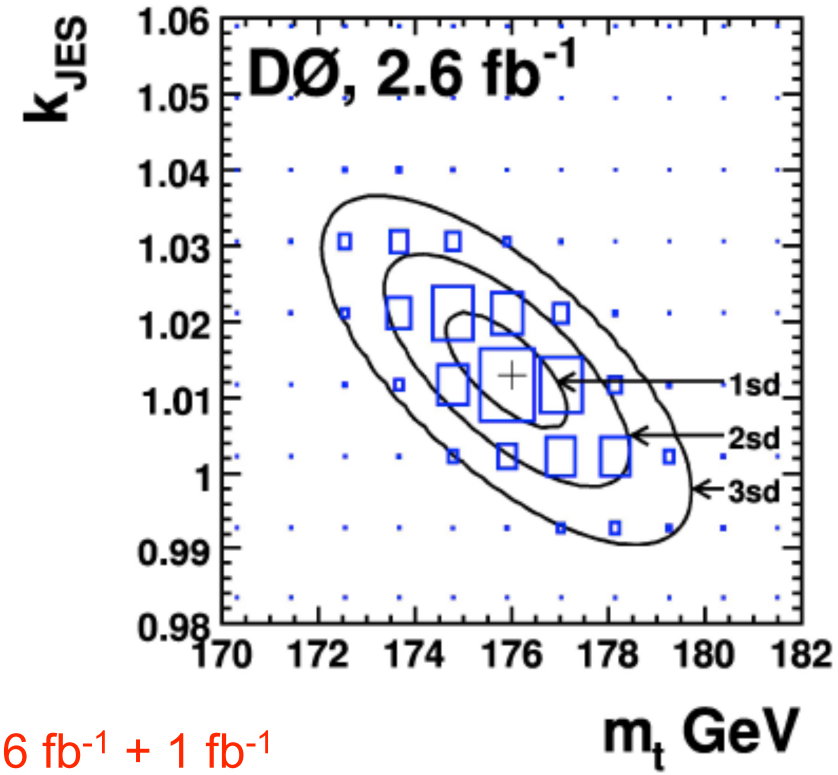
- **Behold! We need to calibrate the method:**
  - is the extracted **central value unbiased?**
  - is the **statistical uncertainty over/ underestimated?**





pull:
$$(m_t - \langle m_t \rangle)/\sigma(m_t)$$

m_{top} in lepton+jets channel



Combine 2.6 fb^{-1} + 1 fb^{-1}

$$m_t(3.6\ fb^{-1}) = 174.9 \pm 0.8(stat) \pm 0.8(JES) \pm 1.0(syst)\ GeV$$
$$= 174.9 \pm 1.5\ (GeV)$$

Relative uncertainty: 0.9%!

*Phys. Rev. D **84**, 032004 (2011)*

- **Main systematic uncertainties:**
  - **Signal modeling: Hadronisation + UE (0.6 GeV), colour reconnection (0.3 GeV)**
  - **Detector modeling: jet energy resolution (0.3 GeV), particle response (0.3 GeV)**

m_{top} in the ll channel (ME method)

- Apply the ME method to the dilepton channel ($5.4\ fb^{-1}$)
  - Additional challenge: the tt system is kinematically 1x underconstrained if m_{top} is a free parameter!
    - → assume prior for $p_T(tt)$ from MC simulation
    - → integrate over neutrino momenta (with Jacobian)
  - Use LO ME like l+jets analysis
  - Dominant background: Z+2jets processes
    - → calculate $P_{bkg} = P_{Z+2jets}$ using VECBOS
  - No in-situ calibration of the JES possible
    - Large syst. uncertainty from JES calibration
    - Similarly large syst. uncertainty from b-quark JES
    - → will improve for full dataset

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

m_{top} in the *ll* channel (ME method)

- Apply the ME method to the dilepton channel (5.4 fb^{-1})
  - Additional challenge: the tt system is kinematically 1x underconstrained if m_{top} is a free parameter!
    - → assume prior for p_T(tt) from MC simulation
    - → integrate over neutrino momenta (with Jacobian)
  - Use LO ME like l+jets analysis
  - Dominant background: Z+2jets processes
    - → calculate $P_{bkg} = P_{Z+2jets}$ using VECBOS
  - No in-situ calibration of the JES possible
    - Large syst. uncertainty from JES calibration
    - Similarly large syst. uncertainty from b-quark JES
    - → will improve for full dataset
  - Final result:

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

Relative uncertainty: 1.8%!

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

m_{top} in the ll channel (vWT method)

- **Neutrino weighting method (5.4 fb^{-1}):**
  - dilepton events are kinematically underconstrained
    - Postulate distributions in pseudorapidity of neutrinos from MC
    - Calculate weight distribution vs. m_{top}
    - Use 1st and 2nd moment of this distribution to form templates
  - Apply in-situ JES calibration from l+jets channel:

$$1.013 \pm 0.008(\mathrm{stat})$$

    - Caveat:
      k_{JES} can be final state-dependent, so we derive a dedicated response correction and estimate the corresponding systematic uncertainty (we'll do this for all future m_{top} measurements in ll)

arXiv:1201.5172 [hep-ex] (2011)

m_{top} in the ll channel (vWT method)

- **Neutrino weighting method (5.4 fb^{-1}):**
  - dilepton events are kinematically underconstrained
    - Postulate distributions in pseudorapidity of neutrinos from MC
    - Calculate weight distribution vs. m_{top}
    - Use 1st and 2nd moment of this distribution to form templates
  - Apply in-situ JES calibration from l+jets channel:

$$1.013 \pm 0.008(\text{stat})$$

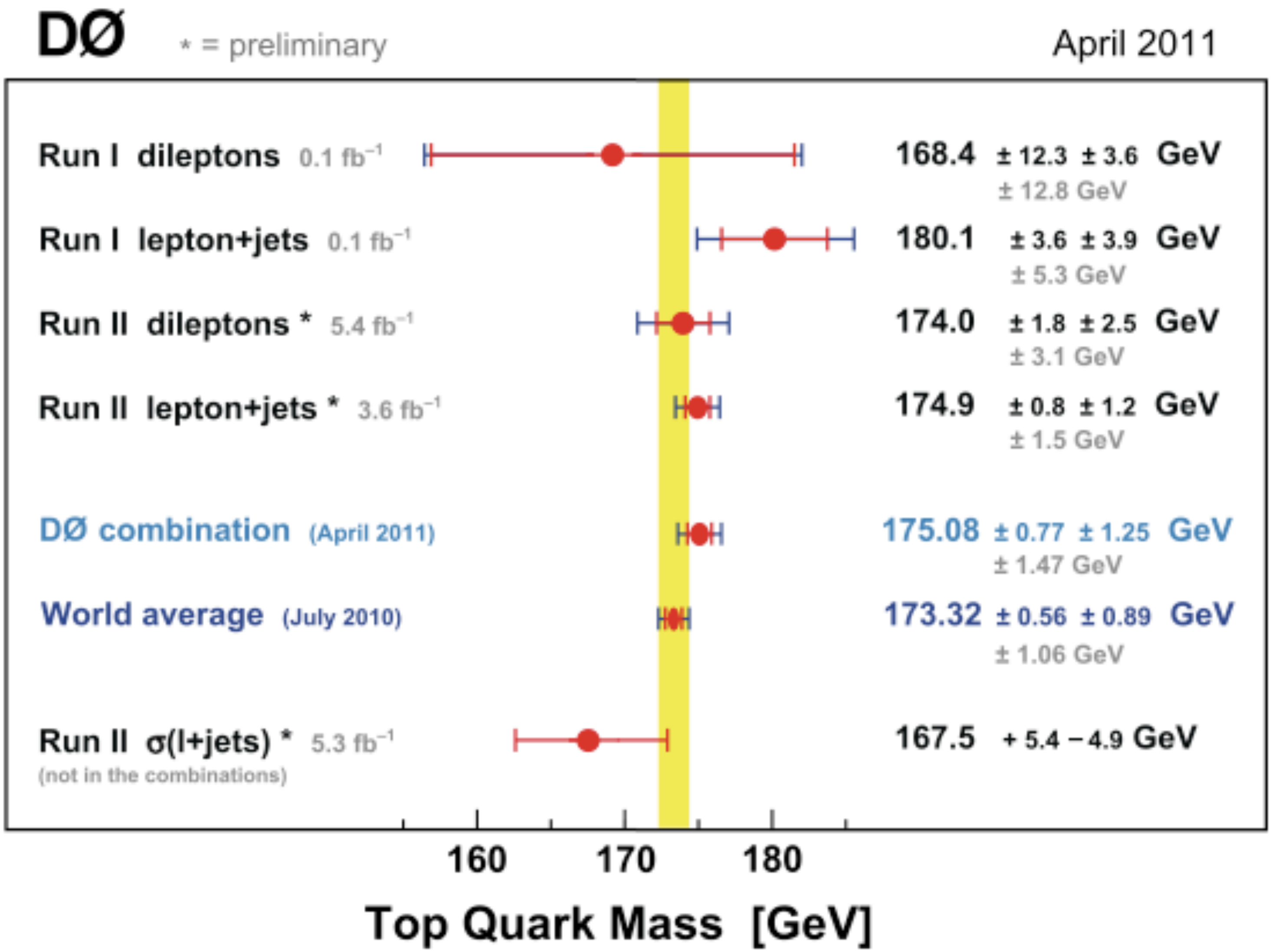
    - Caveat:
      k_{JES} can be final state-dependent, so we derive a dedicated response correction and estimate the corresponding systematic uncertainty (we'll do this for all future m_{top} measurements in ll)
  - Final result:

$$m_t = 174.0 \pm 2.4(\text{stat}) \pm 1.4(\text{syst}) \text{ GeV}$$

Relative uncertainty: 1.6%
Best Tevatron dilepton result!

arXiv:1201.5172 [hep-ex] (2011)

DØ m_{top} combination



DØ Note 6189

DØ m_{top} combination

	Run II	
	ℓ + jets	$\ell\ell$
Luminosity	3.6 fb^{-1}	5.4 fb^{-1}
m_{top}	174.94 GeV	173.97 GeV
iJES	0.53	0.00
aJES	0.00	1.57
bJES	0.07	0.40
cJES	0.00	0.00
dJES	0.63	1.50
rJES	0.00	0.00
Det. Modeling	0.36	0.33
Lepton pt	0.18	0.49
Signal Modeling	0.72	0.74
Bkg from MC	0.18	0.00
Bkg from Data	0.23	0.47
Method	0.16	0.10
CR	0.28	0.10
MHI	0.05	0.00
UN/MI	0.00	0.00
syst. uncertainty	1.24	2.45
stat. uncertainty	0.83	1.83
total	1.50	3.06

In-situ JES calibration from hadronic W's
~ 1/√N

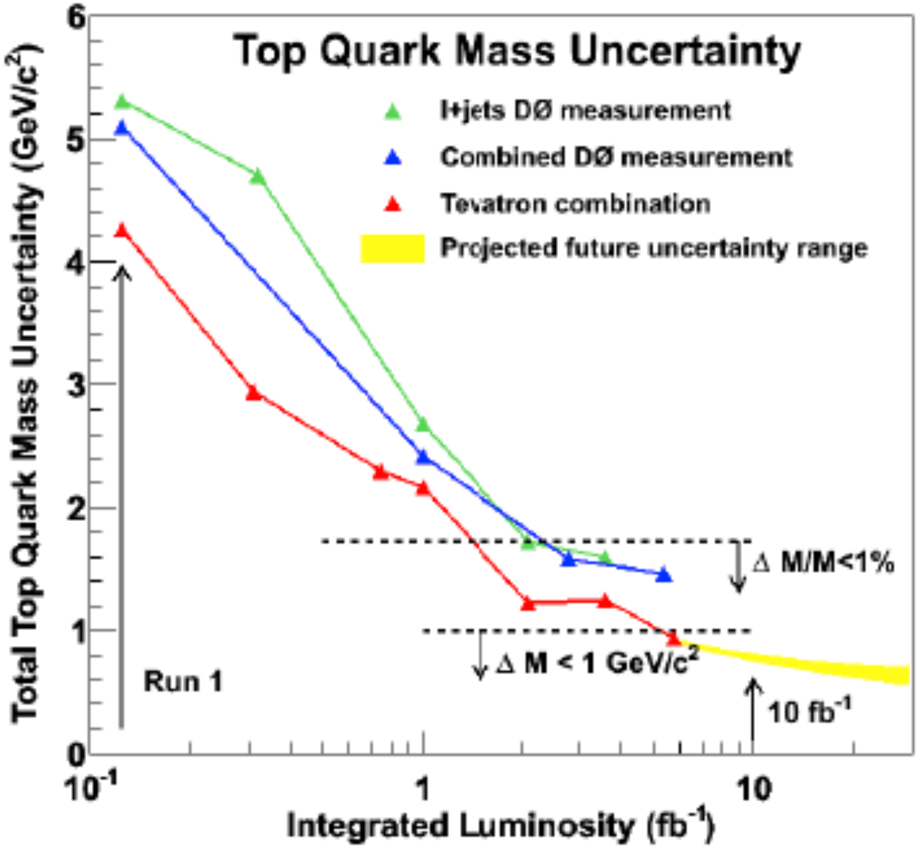
Limited size of calibration samples for the JES measurement (residual JES) + single particle response systematic:
~ 1/√N

Signal modeling uncertainties (NLO corrections, hadronisation+UE, ISR / FSR, PDF uncertainty):
~ √brain effort

DØ Note 6189

DØ m_{top} combination

	Run II	
	ℓ + jets	$\ell\ell$
Luminosity	3.6 fb^{-1}	5.4 fb^{-1}
m_{top}	174.94 GeV	173.97 GeV
iJES	0.53	0.00
aJES	0.00	1.57
bJES	0.07	0.40
cJES	0.00	0.00
dJES	0.63	1.50
rJES	0.00	0.00
Det. Modeling	0.36	0.33
Lepton pt	0.18	0.49
Signal Modeling	0.72	0.74
Bkg from MC	0.18	0.00
Bkg from Data	0.23	0.47
Method	0.16	0.10
CR	0.28	0.10
MHI	0.05	0.00
UN/MI	0.00	0.00
syst. uncertainty	1.24	2.45
stat. uncertainty	0.83	1.83
total	1.50	3.06



Relative uncertainty: 0.8%
Expect this limit to be improved…

DØ Note 6189

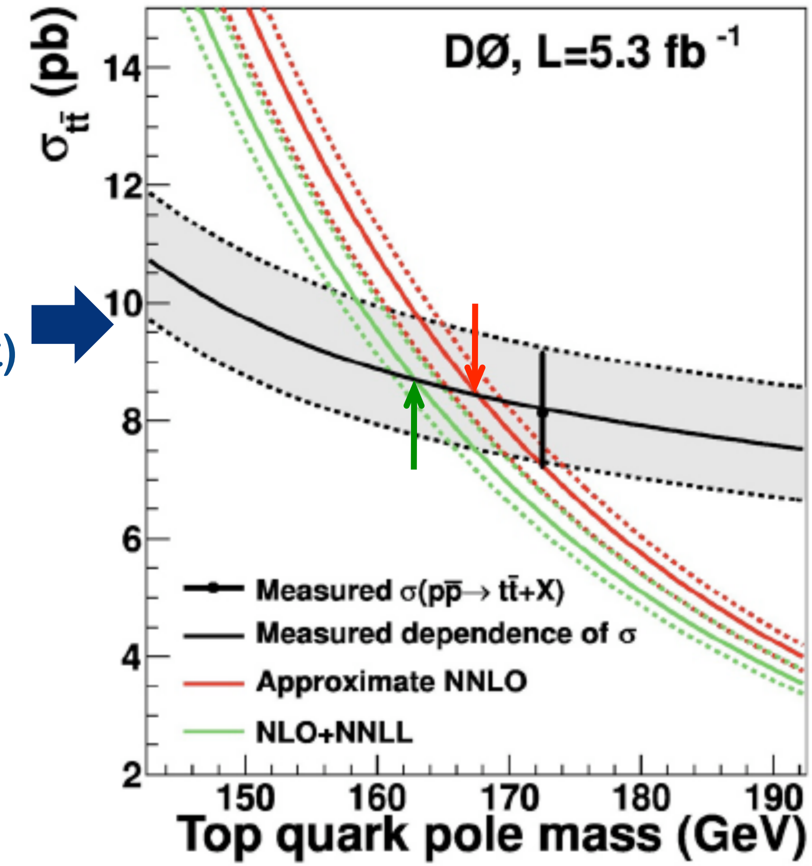
Mass from cross section

- Different mass definitions in fixed order calculations:
  - $m_t^{\text{pole}}, \; m_t^{\overline{\text{MS}}}, \; m_t^{\text{min subtraction}}, \; \ldots$
  - What we typically measure in kinematic fits is m_t^{MC}
    - Theory interpretation difficult
    - Arguably, m_t^{MC} closer to m_t^{pole}

*Phys. Lett. B **703** 422 (2011)*

Mass from cross section

- Different mass definitions in fixed order calculations:
  - $m_t^{\text{pole}},\ m_t^{\overline{\text{MS}}},\ m_t^{\text{min subtraction}},\ \ldots$
  - What we typically measure in kinematic fits is m_t^{MC}
    - Theory interpretation difficult
    - Arguably, m_t^{MC} closer to m_t^{pole}
  - Can measure $m_t^{\overline{\text{MS}}}$ or m_t^{pole} from comparison with $\sigma_{t\bar{t}}^{\overline{\text{MS}}}$ or $\sigma_{t\bar{t}}^{\text{pole}}$!
    - Account for the weak dependence of $\sigma_{t\bar{t}}$ on m_t^{MC} (acceptance effect)



Phys. Lett. B ***703*** *422 (2011)*

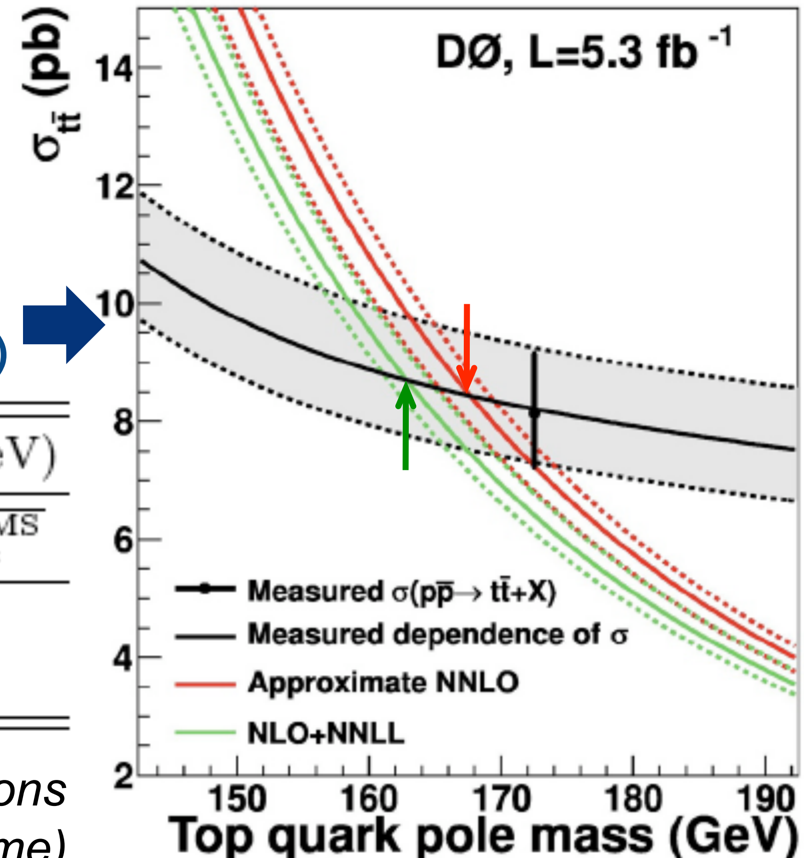
Mass from cross section

- **Different mass definitions in fixed order calculations:**
  - $m_t^{\text{pole}}, \; m_t^{\overline{\text{MS}}}, \; m_t^{\text{min subtraction}}, \; \ldots$
  - What we typically measure in kinematic fits is m_t^{MC}
    - Theory interpretation difficult
    - Arguably, m_t^{MC} closer to m_t^{pole}
  - Can measure $m_t^{\overline{\text{MS}}}$ or m_t^{pole} from comparison with $\sigma_{t\bar{t}}^{\overline{\text{MS}}}$ or $\sigma_{t\bar{t}}^{\text{pole}}$!
    - Account for the weak dependence of $\sigma_{t\bar{t}}$ on m_t^{MC} (acceptance effect)

Theoretical prediction	m_t^{pole} (GeV)	Δm_t^{pole} (GeV)
MC mass assumption	$m_t^{\text{MC}} = m_t^{\text{pole}}$	$m_t^{\text{MC}} = m_t^{\overline{\text{MS}}}$
NLO+NNLL [14]	$163.0^{+5.1}_{-4.6}$	-3.3
Approximate NNLO [15]	$167.5^{+5.2}_{-4.7}$	-2.7

[14] V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak, and L. L. Yang, J. High Energy Phys. **1009**, 097 (2010); V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak, and L. L. Yang, Nucl. Phys. Proc. Suppl. **205–206**, 48 (2010).
[15] S. Moch and P. Uwer, Phys. Rev. D **78**, 034003 (2008); U. Langenfeld, S. Moch, and P. Uwer, Phys. Rev. D **80**, 054009 (2009).

+ other calculations (also $\overline{\text{MS}}$ scheme)



*Phys. Lett. B **703** 422 (2011)*

Top-antitop mass difference meas't

- CPT is essential for a locally Lorentz-invariant QFT
  - $m_{particle}$!= $m_{antiparticle}$ → CPT violated!
    - Top is the only quark where this test is possible: $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s

Phys. Rev. D ***84***, 052005 (2011)

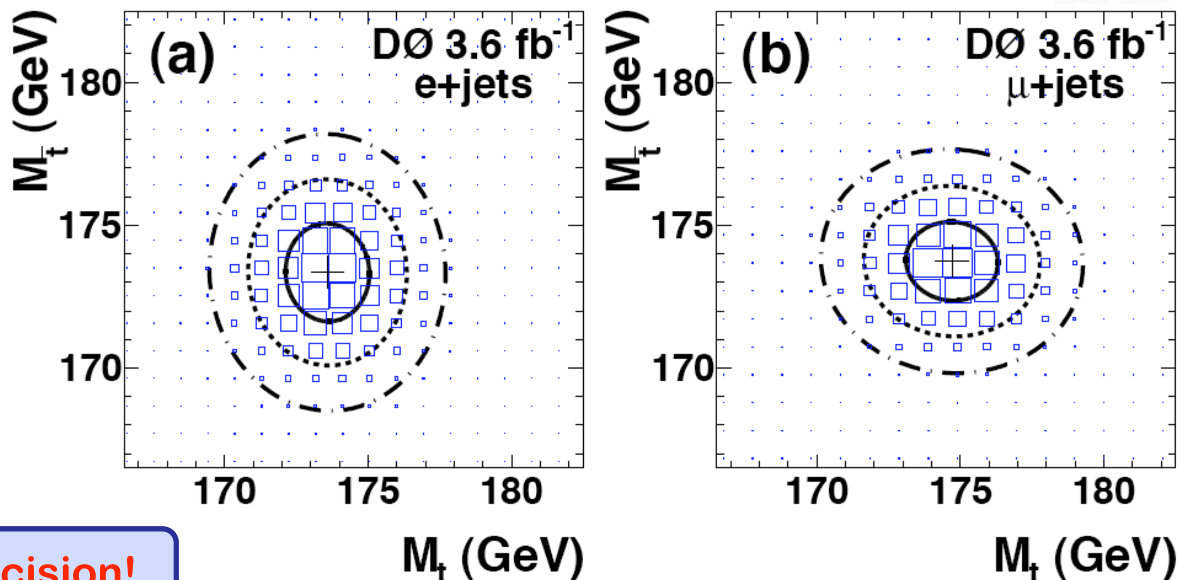
Top-antitop mass difference meas't

- CPT is essential for a locally Lorentz-invariant QFT
  - $m_{particle}$!= $m_{antiparticle}$ → CPT violated!
    - Top is the only quark where this test is possible: $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s
  - Use the most statistically sensitive method at hand (ME):
    - $P(m_{top},k_{JES}) \rightarrow P(m_t,m_{tbar})$
    - Use lepton charge to tag t and $\bar{t}$
  - Direct and indepentent measurement of m_t and $m_{\bar{t}}$!

Phys. Rev. D ***84***, *052005 (2011)*

Top-antitop mass difference

- CPT is essential for a locally Lorentz-invariant QFT
  - $m_{particle}$!= $m_{antiparticle}$ → CPT violated!
    - Top is the only quark where this test is possible: $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s
  - Use the most statistically sensitive method at hand (ME):
    - $P(m_{top}, k_{JES}) \rightarrow P(m_t, m_{tbar})$
    - Use lepton charge to tag t and $\bar{t}$
  - Direct and indepentent measurement of m_t and $m_{\bar{t}}$!



<1% relative precision!

$$\Delta m \equiv m_t - m_{\bar{t}} = 0.8 \pm 1.8\ \text{(stat)} \pm 0.5\ \text{(syst)}\ \text{GeV}$$

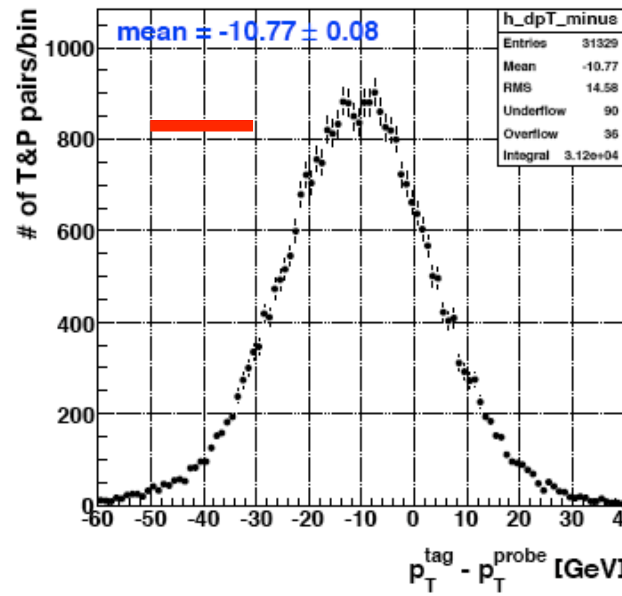
Phys. Rev. D **84**, *052005 (2011)*

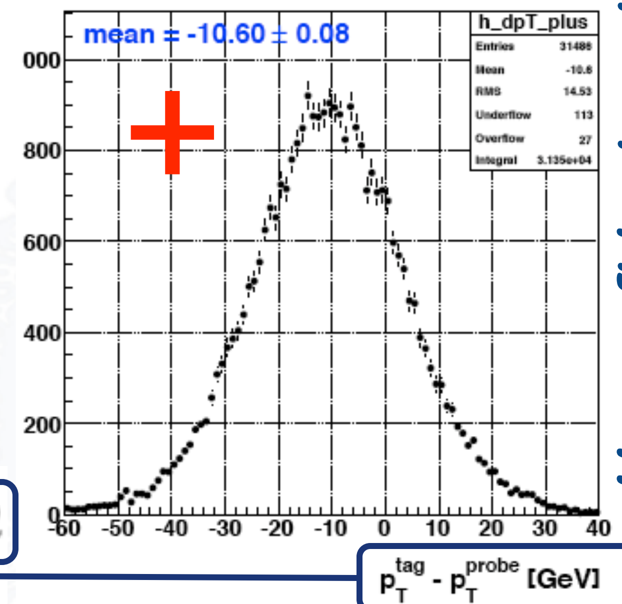
Top-antitop mass difference

- **Lots of work went into evaluating the sytematic uncertainties for this precision measurement:**

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

fractional response difference
$$f_{\Delta\mathscr{R}} \equiv \frac{\Delta\mathscr{R}}{\langle {}^1/_2 \cdot (p_T^{\text{tag}} + p_T^{\text{probe}})\rangle} = 0.0042$$





Use soft leptons to tag b and bbar jets

Phys. Rev. D ***84***, *052005 (2011)*

Summary and outlook

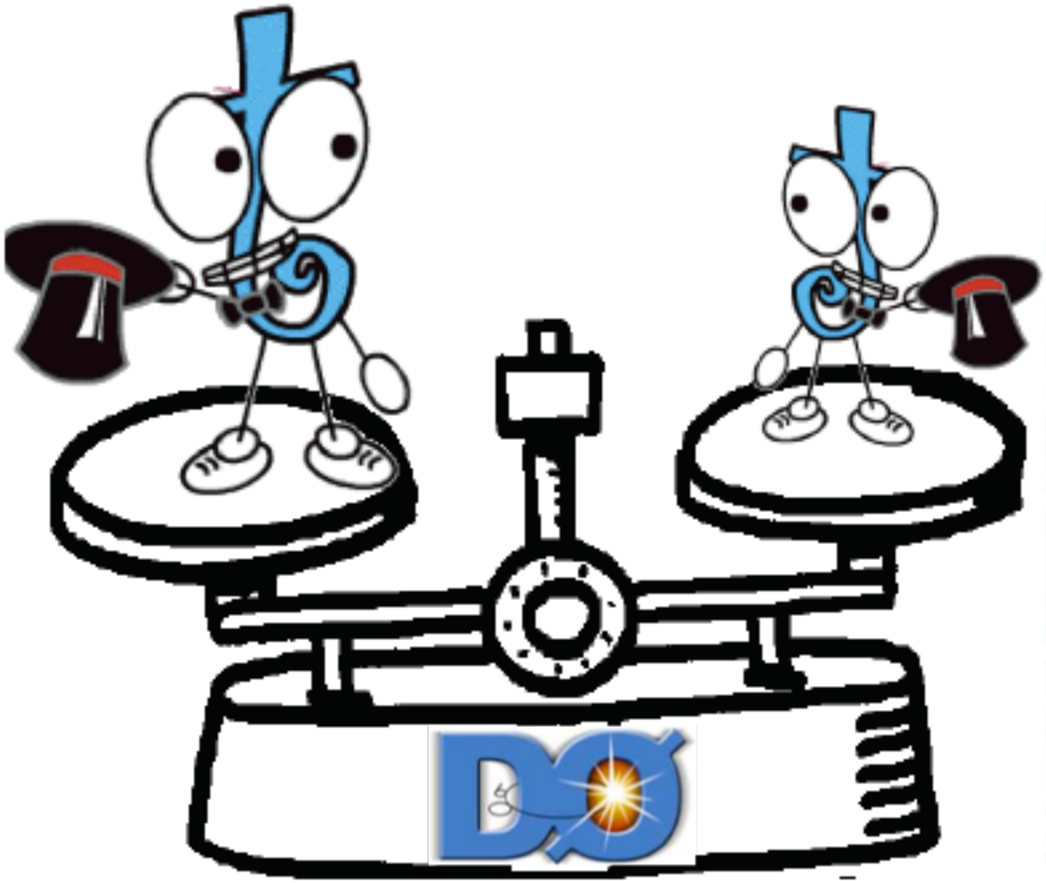
- Top quark mass measurement is a Tevatron legacy:
  - Many systematic uncertainties generically smaller at the Tevatron compared to the LHC:
    - tt signal modeling: ISR, kinematics of production
    - Run conditions: more uniform + substantially less pile-up
  - → we need to capitalise on this
  - The Tevatron will provide a substantial contribution to the world average m_{top} until ILC (uncertatinty now: 0.54%)

Summary and outlook

- **Top quark mass measurement is a Tevatron legacy:**
  - Many systematic uncertainties generically smaller at the Tevatron compared to the LHC:
    - tt signal modeling: ISR, kinematics of production
    - Run conditions: more uniform + substantially less pile-up
  - → we need to capitalise on this
  - The Tevatron will provide a substantial contribution to the world average m_{top} until ILC (uncertatinty now: 0.54%)
- **We are expecting many more exciting results from the Tevatron and the LHC in the coming years:**
  - CDF: http://www-cdf.fnal.gov/physics/new/top/top.html
  - DØ: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html
- **15 years after the top quark discovery, the era of precision measurements in the top sector has begun!**


GAME OVER
... FOR THE TEVATRON (2011)

We are looking ahead to more exciting measurements from the Tevatron!



m_{top} in lepton+jets channel

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

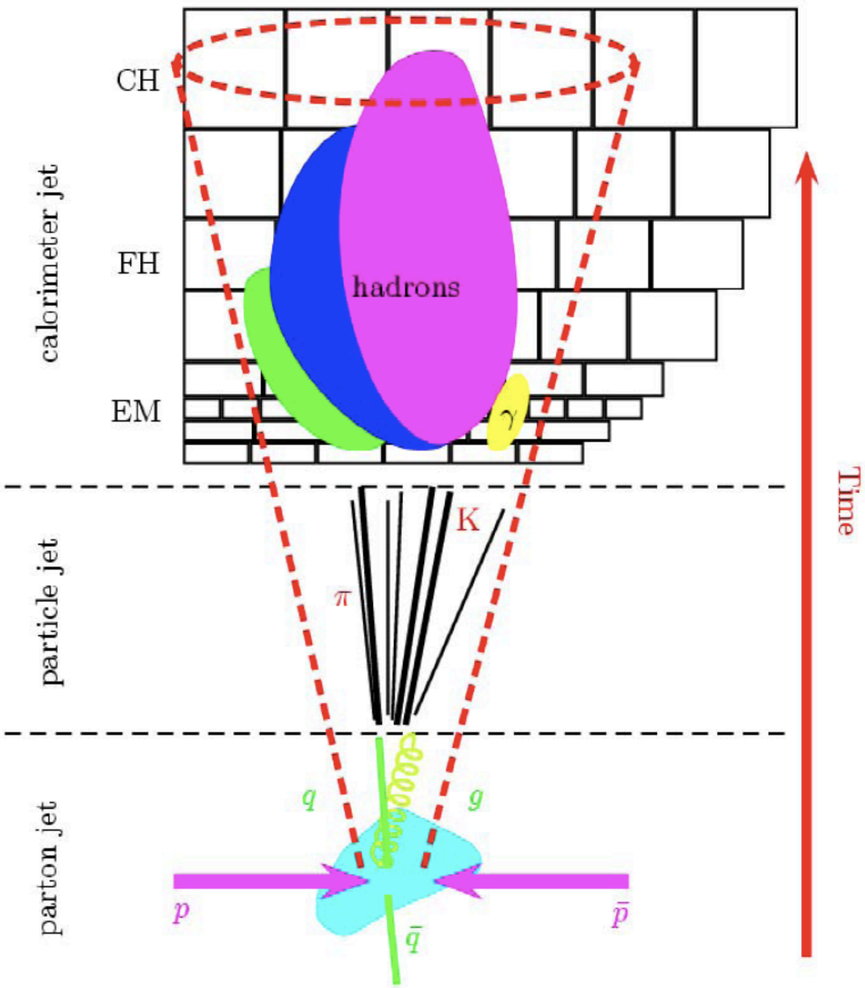
Modeling of signal: **0.8 GeV**

Modeling of detector: **0.6 GeV**

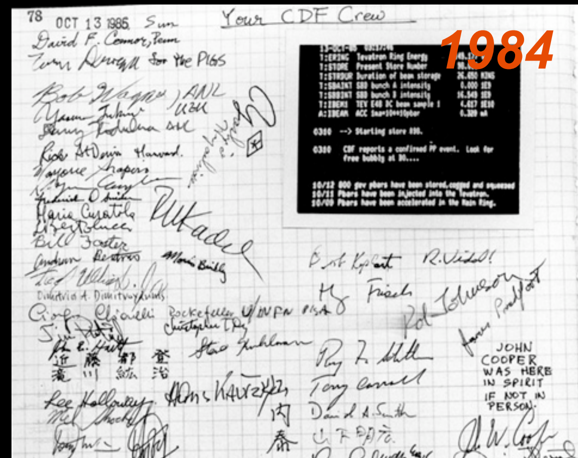
Method: **0.3 GeV**

Experimental Challenges

- We are interested in parton-level quantities for our top measurements
  - Map the energies of reco-level jets particle jets (D0) / partons (CDF)
  - This is referred to as a Energy Scale (JES) corr'n
  - With the current size of samples:
    - s(JES)/JES ~ 1.5% (D0)
    - s(JES)/JES ~ 2.5% (CDF)
- And many more:
  - Lepton ID, p_T scale




1983


1984
Your CDF Crew
JOHN COOPER WAS HERE IN SPIRIT IF NOT IN PERSON

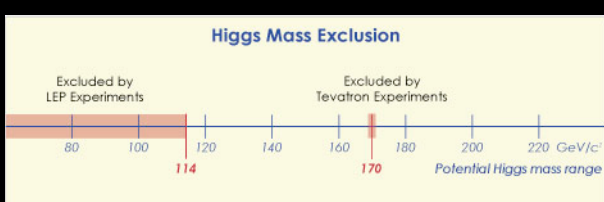

1985

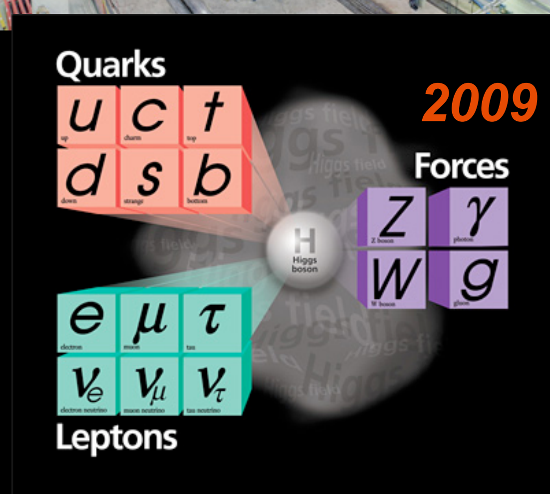

1991

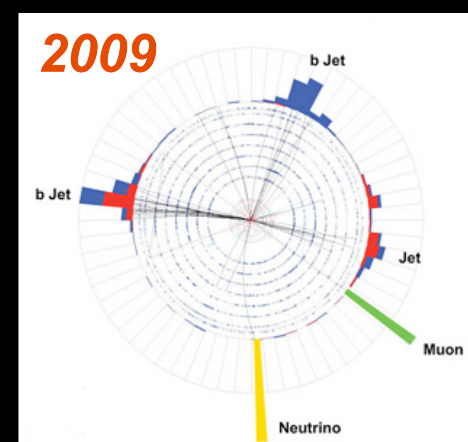

1992


1995
Cultura e Spettacoli
Dove vai, cacciatore di quark?
Batavia is center of universe
Alles Quark, oder was?
I predatori del quark perduto
For physicists, last piece of a puzzle
Nation
Truth by Consensus
RICERCA ITALIANA

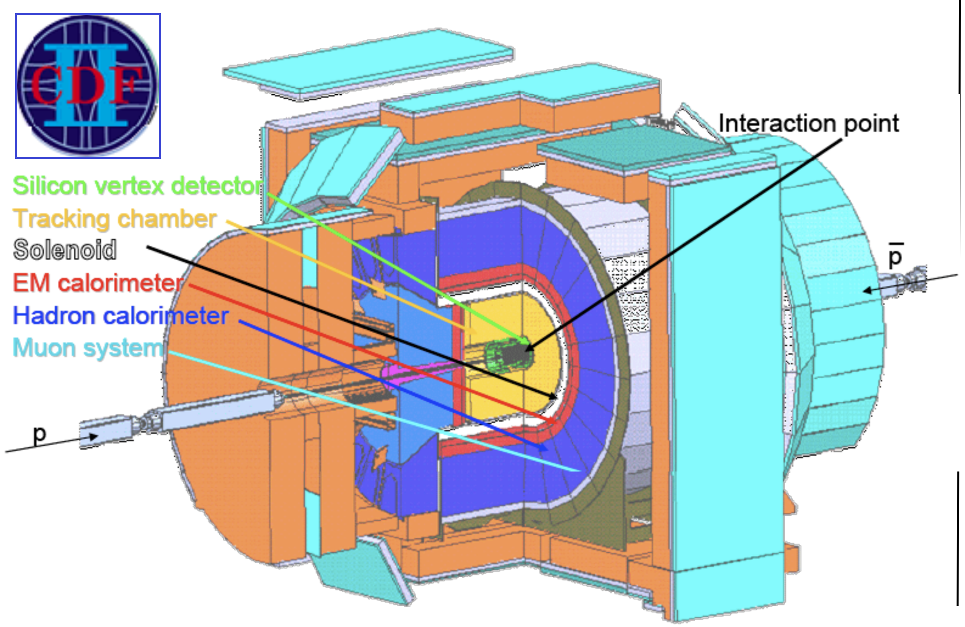
2008

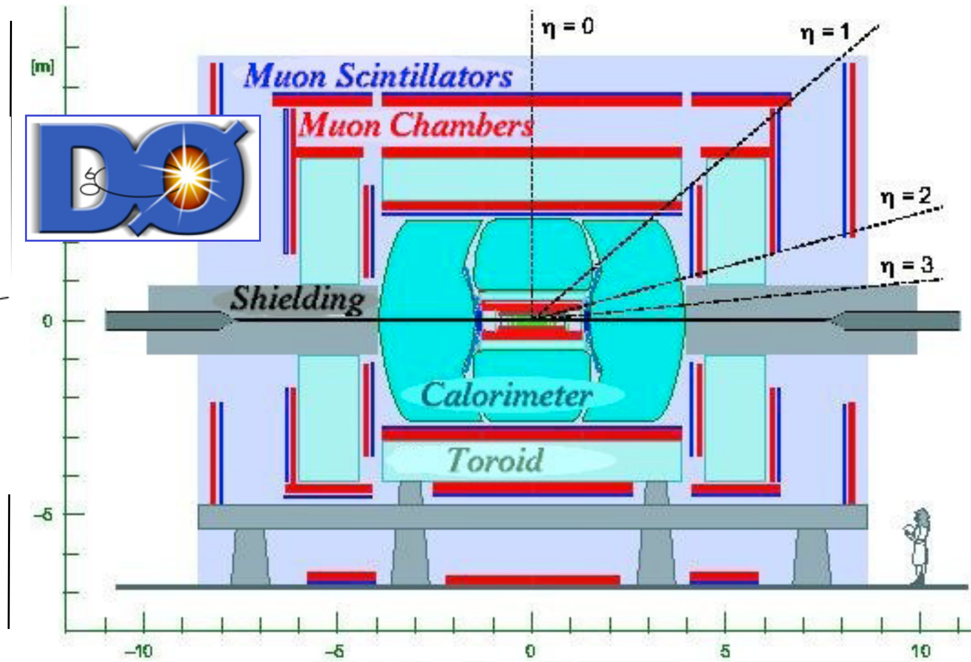

Higgs Mass Exclusion
Excluded by LEP Experiments
Excluded by Tevatron Experiments
80
100
120
140
160
180
200
220 GeV/c²
114
170
Potential Higgs mass range


2009
Quarks
u
c
t
d
s
b
Forces
Z
γ
W
g
H
Higgs boson
e
μ
τ
νe
νμ
ντ
Leptons


2009
b Jet
b Jet
Jet
Muon
Neutrino

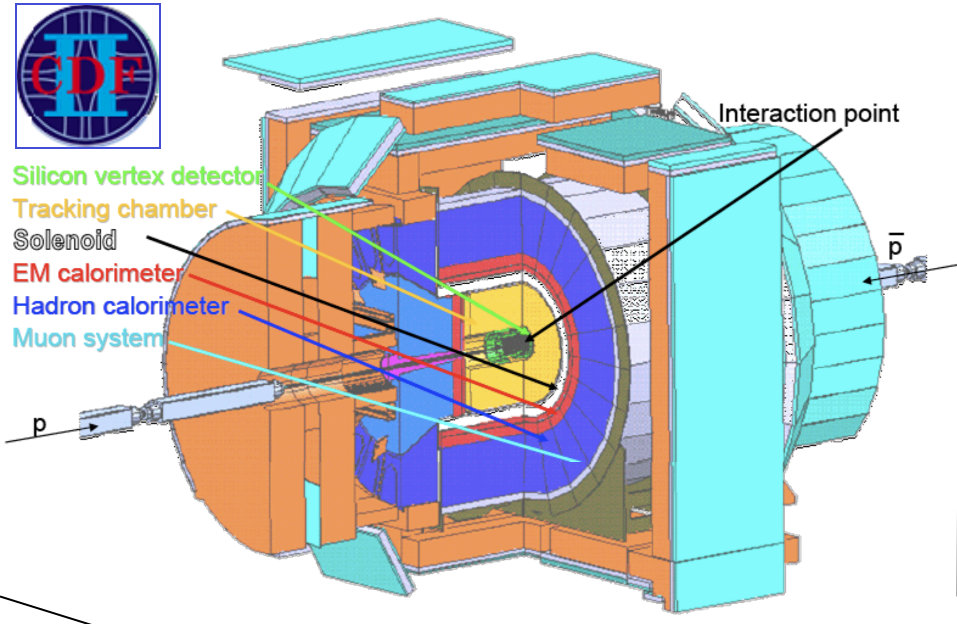
The CDF and D0 detectors

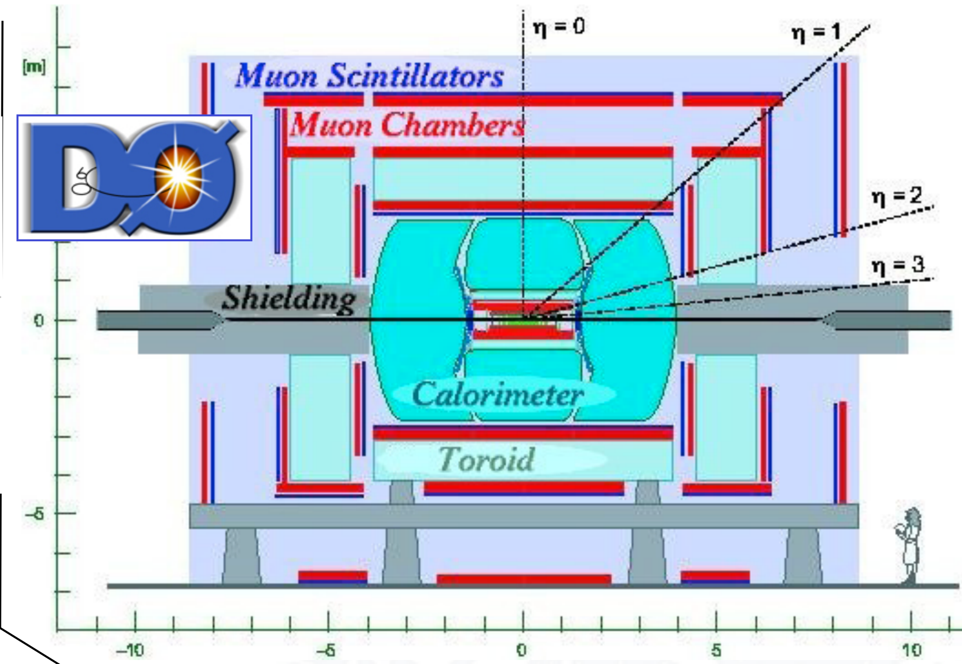




	CDF	DØ
EM calorimeter	14%/√E + 1%	22%/√E + 4%
Hadronic calorimeter	70%/√E + 5%	68%/√E + 5%

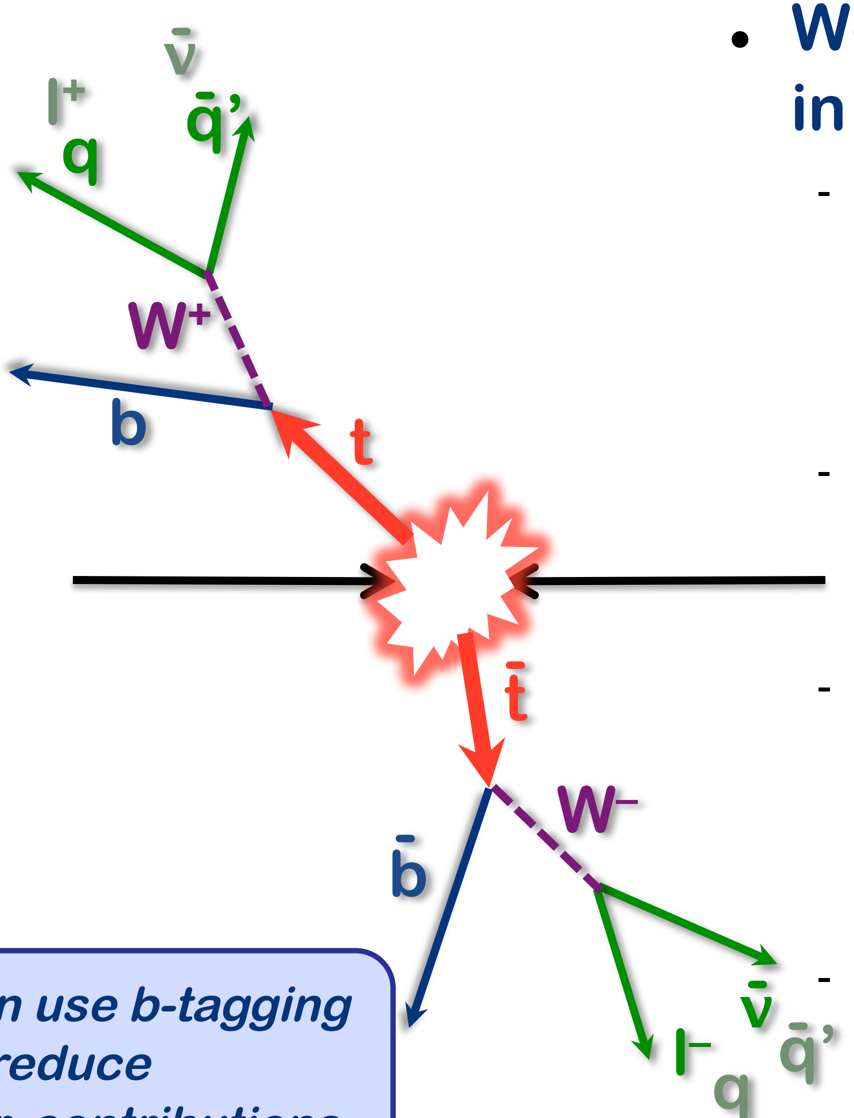
The CDF and D0 detectors





Tracking	Silicon	$\|\eta\| < 2-2.5$		Silicon	$\|\eta\| < 3$	
	Drift cell	$\|\eta\| < 1.1$		Fiber	$\|\eta\| < 1.7$	
Calorimetry	Scintillators	$\|\eta\| < 3.6$		LAr/DU	$\|\eta\| < 4$	
Muon chambers	Drift Scintillators	$\|\eta\| < 1.5$		Drift Scintillators	$\|\eta\| < 2.0$	

The tt event sample



Can use b-tagging to reduce bgr. contributions

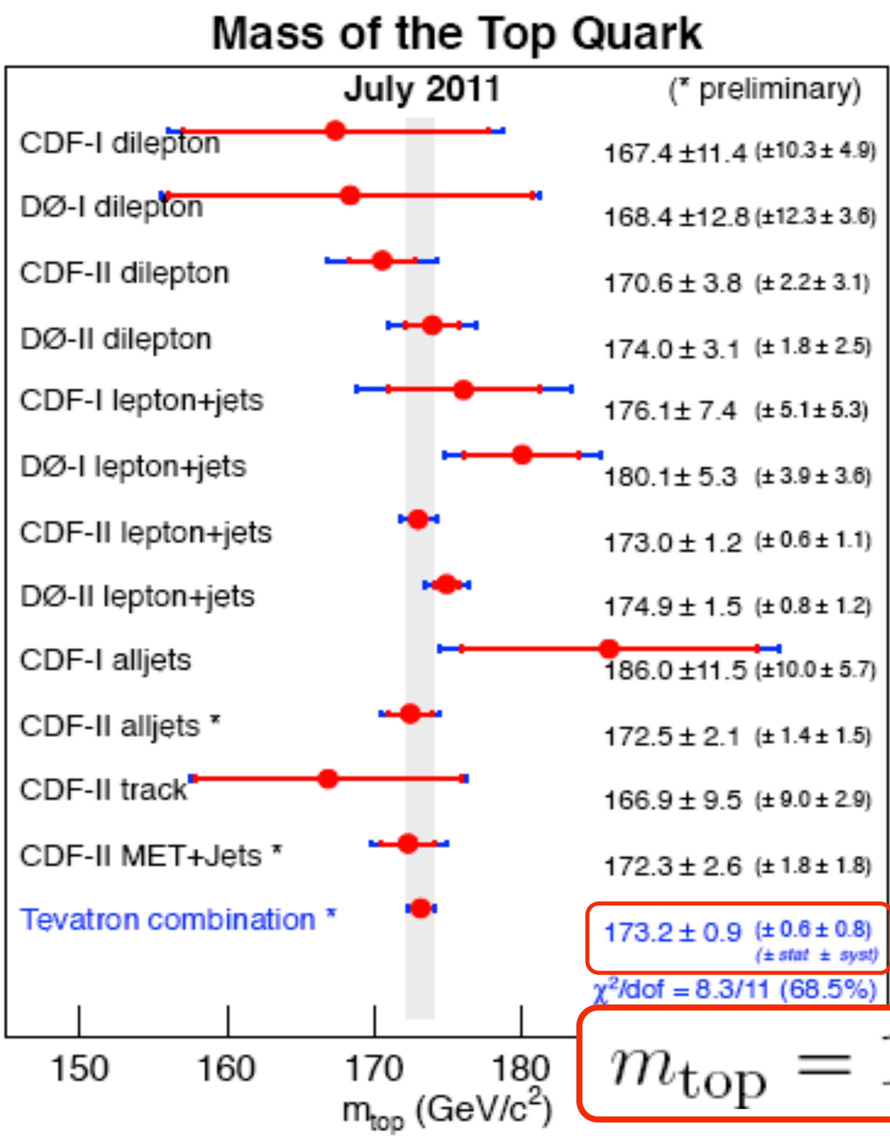
- **We measure the top mass in tt events:**
  - **Dilepton channel**: low back-grounds, but underconstrained kinematics for m_{top} measurement and low rate
  - **l+jets channel**: good compromise between kinematic reconstruction, high rate, and backgrounds
  - **All-hadronic channel**: highest branching ratio, very high backgrounds from QCD multijet production
  - **Other orthogonal channels**:
    - MET + jets
    - …

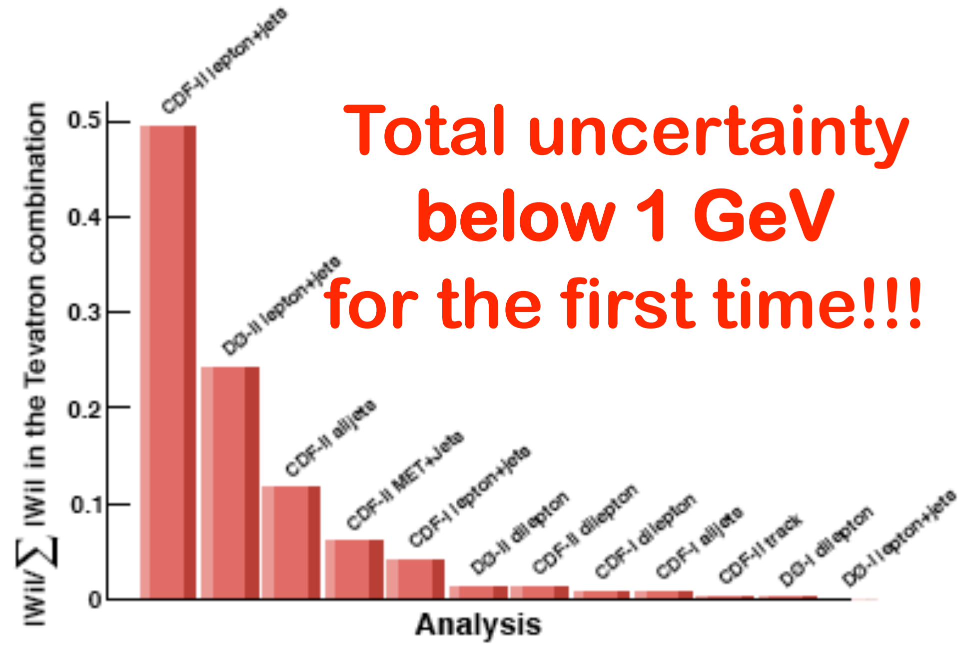
Overview of top properties

Property	Measurement	SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
	D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
	D0: 2.90 ± 0.59 pb		5.4
σ_{tb} (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
	D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
Charge asymmetry	CDF: 0.158 ± 0.074	0.06	5.3
	D0: 0.196 ± 0.065		5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
	D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: 0.18 ± 0.08 pb	0.17 ± 0.03 pb	6.0
$\lvert V_{tb}\rvert$	CDF: $\lvert V_{tb}\rvert = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$	1	3.2
	D0: $\lvert V_{tb}\rvert = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$	CDF: > 0.61 @ 95% CL	1	0.2
	D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
	D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL	2/3	5.6
	D0: 4/3 excluded @ 92% CL		0.37
Γ_t	CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
	D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3

Table by F. Deliot Autum 2011

Tevatron Combination





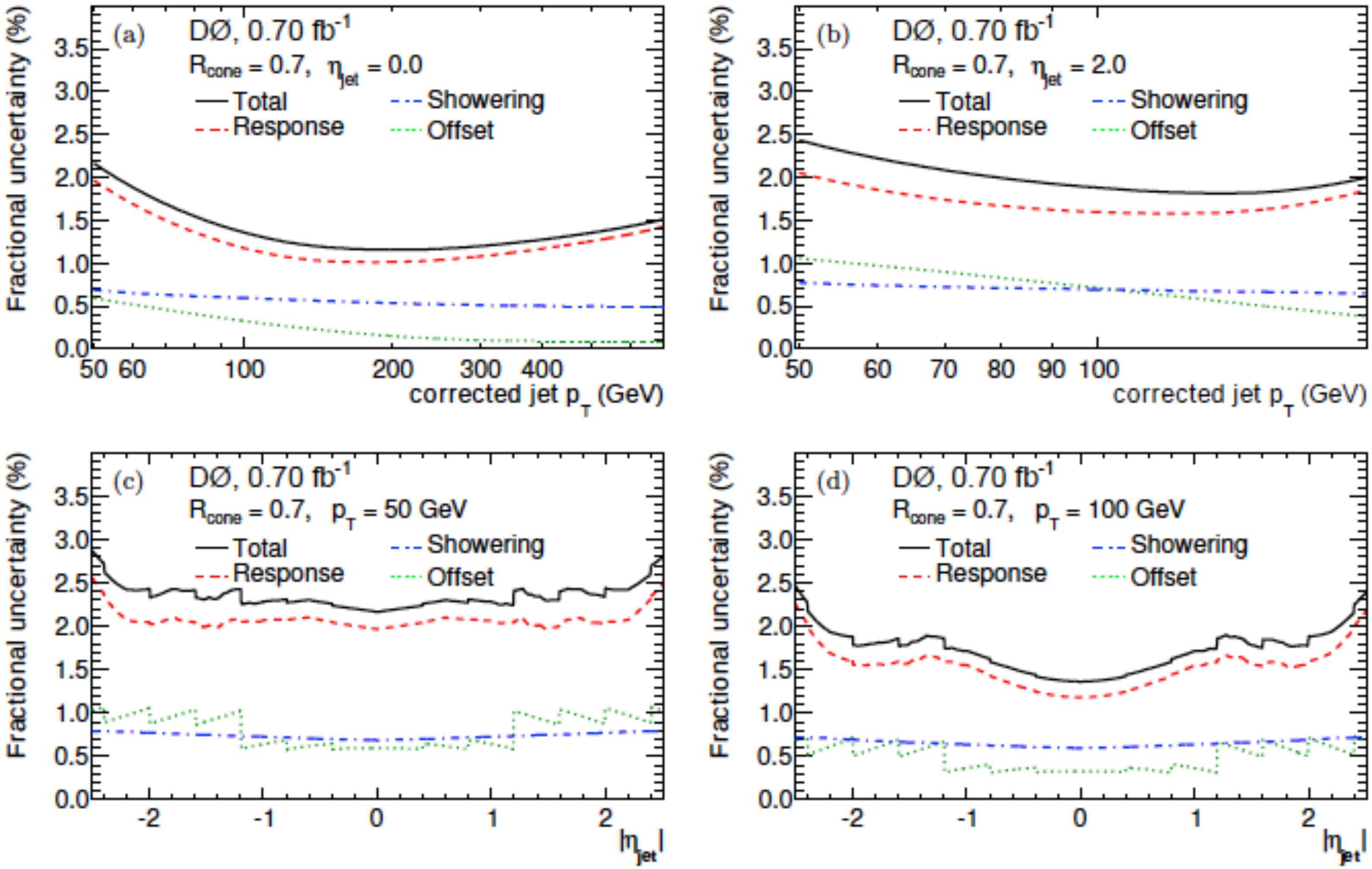
Total uncertainty below 1 GeV for the first time!!!

$$m_{\text{top}} = 173.2 \pm 0.6\,(\text{stat}) \pm 0.8\,(\text{syst})$$

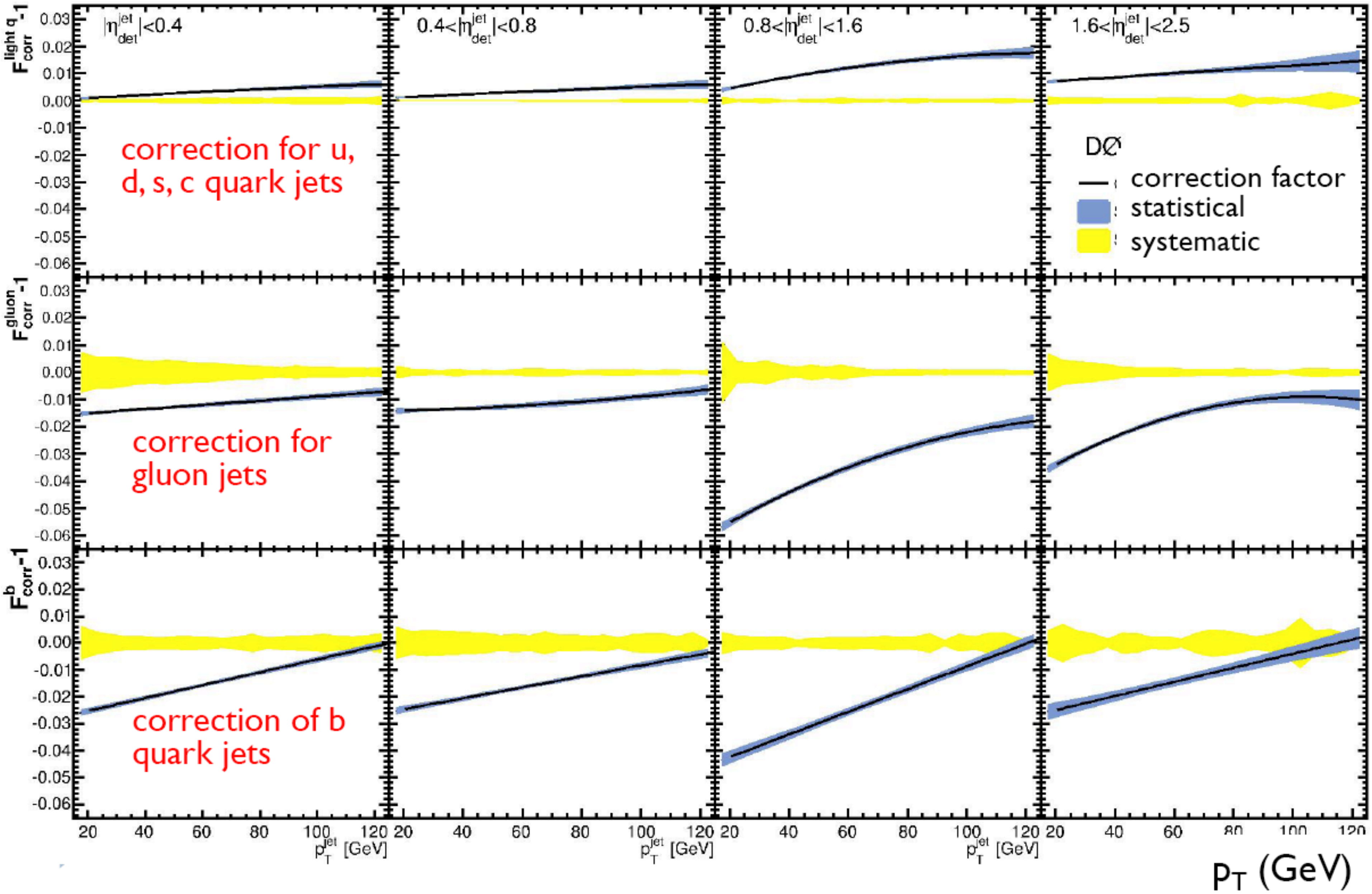
arXiv:1107.5255 [hep-ex]

Jet energy scale (JES)

- Typical JES uncertainty 2-3 %
  - → can lead to an uncertainty on m_{top} as large as 2 GeV!



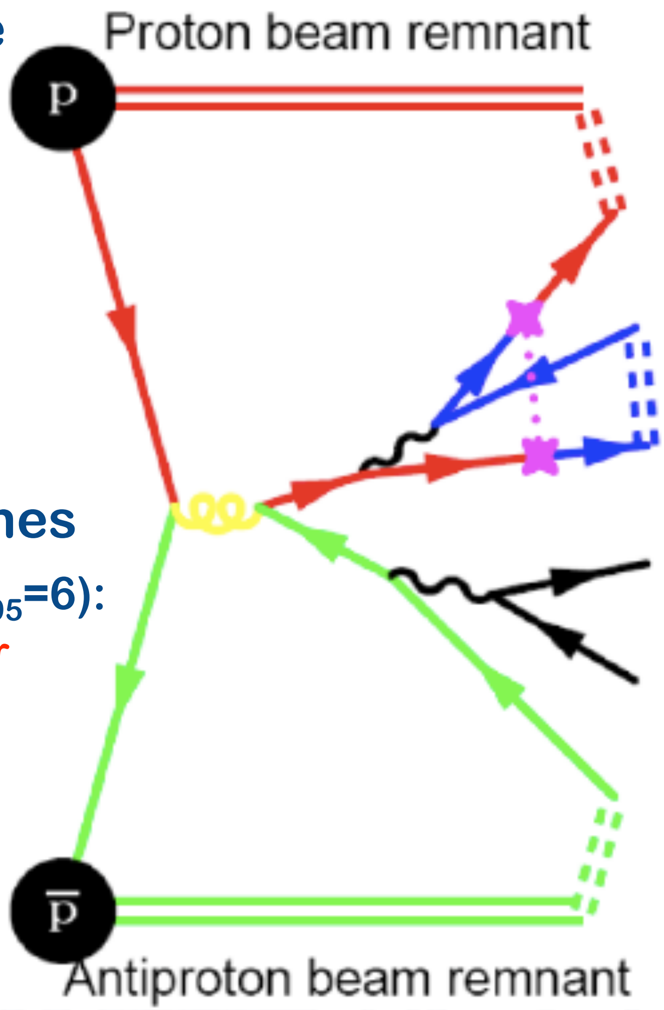
Single particle response correction



Parton shower uncertainties

- **Hadronisation and underlying event:**
  - Uncertainty for the current l+jets analysis: 0.58 GeV
    - We evaluated this uncertainty by comparing
      - alpgen+herwig vs.
      - alpgen+pythia events
  - This is the dominant systematic uncertainty
  - It contains:
    - Statistical component
    - JES component
    - The actual effects from hadronisation & UE
  - → working out strategies to remove the former two
- **Q^2 vs p_T^2 ordered shower:**
  - Currently not included in systematic uncertainties
    - Will cross-check:
      - Pythia with D0 Tune A
      - Pythia with Perugia 2011C (same CTEQ6L1 pdf)

- **Colour reconnection (CR)**
  - could be an important systematic uncertainty
  - cf. [arXiv:0807.3248] by Skands+Wicke
  - Hadronisation regions of jets from W and b decay can overlap:
    - Possible effect on m_{top} due to colour reconnection
  - Very few experimental handles to constrain CR effects…
  - Currently compare Apro vs ACRpro tunes
    - This was pythia authors' first shot ($MSTP_{95}$=6):
      - $P_{\mathrm{keep}} = (1 - \zeta P_{78})^{n_{\mathrm{int}}}$: probability for a string piece to survive the annealing
        - n_{int} : # of p-pbar interactions in event
        - $\zeta = 1$ (for ACRpro)
        - P_{78} = 0.09 (for ACRpro)
  - → Looking at more realistic models

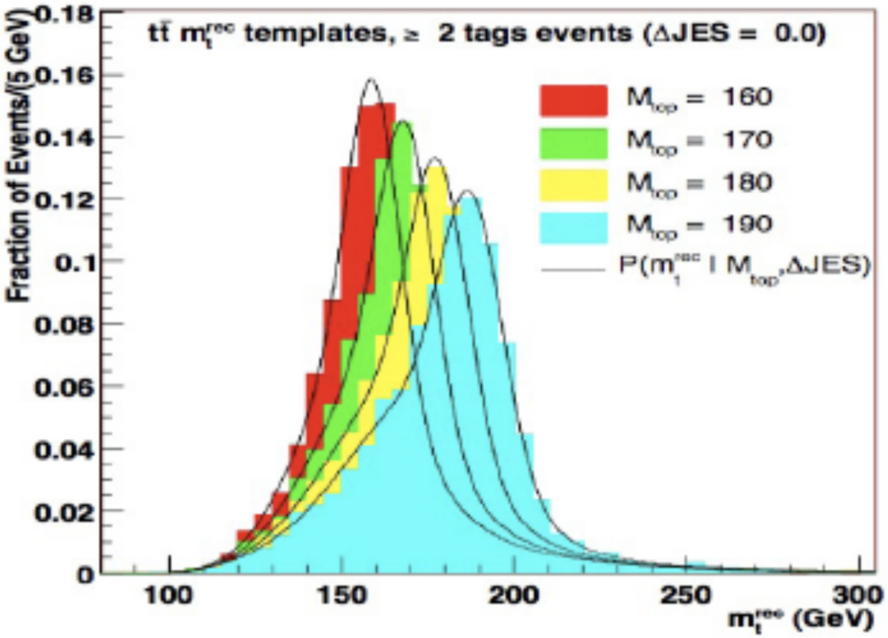


Higher order effects + ISR/FSR

- **Higher order corrections:**
  - 0.10 +/- 0.25 GeV in the current l+jets analysis. Compare:
    - mc@nlo (+ herwig)
    - alpgen + herwig
- **Initial/final state radiation (ISR/FSR):**
  - 0.26 +/- 0.19 GeV in the current l+jets analysis.
  - Use pythia stand-alone with variations to:
    - α_S in the parton shower (ISR/FSR)
    - Λ_{QCD} in the parton shower (ISR/FSR)
    - Derived from the p_T spectrum of Z→ll events
      - This is possible for ISR (and of course FSR) only at the Tevatron: both are dominated by quark lines (LHC: ISR dominated by gluon lines!)
  - Look at other more realistic possibilities (alpgen-based) using the novel phi* variable in Z→ll events

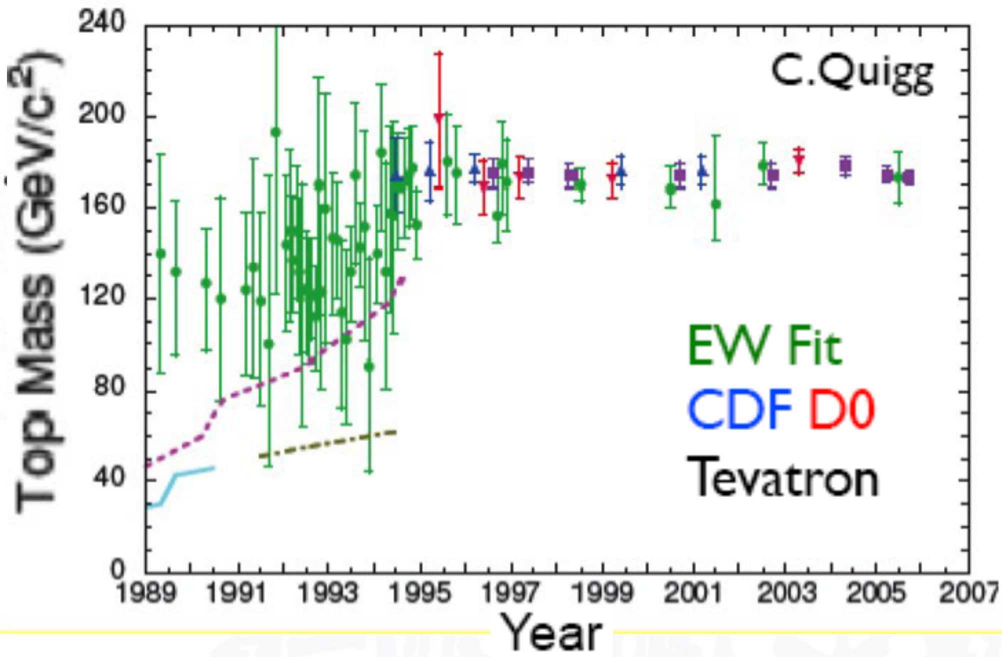
Top mass measurements: methods

- The measurements shown today are based on:
  - Template method
  - Matrix Element method
- Template method:
  - Pick a set of variables x sensitive to $m_{\rm top}$, e.g. $x = m_{\rm top}^{\rm reco}$
  - Create "templates" = distributions in x using MC:
  - Maximise the likelihood of their consistence with the data
  - → Advantages:
    - few assumptions
    - fairly straight forward
    - combination of channels easy



A bit of history

- 1976: discovery of the Ypsilon at Fermilab
  - indicates the existence of the top quark
  - from here on, the race for the top has begun!
- 1984: PETRA m_{top}>23.3 GeV
- 1988: UA1 m_{top}>44 GeV
- 1990:
  - TRISTAN m_{top}>30.2 GeV
  - SLC m_{top}>40.7 GeV
  - LEP m_{top}>45.8 GeV
  - UA1 m_{top}>60 GeV
  - UA2 m_{top}>69 GeV
- 1992: CDF m_{top}>91 GeV
- 1994: DØ m_{top}>128 GeV
- 1994: evidence of top quark from CDF



Top-antitop mass difference meas't

- CPT invariance is a necessary prerequisite for a locally Lorentz-invariant QFT
  - An established CPT invariance would be the end of not only the SM itself, but its theoretical footing!
- If $M_{particle}$!= $M_{antiparticle}$ → CPT violated!
  - We have never tested this on a bare quark (status 2yrs ago)
- The top quark is the only known quark where this test is possible:
  - Hadronisation time scale >> $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s

Top-antitop mass difference meas’t

- CPT invariance is a necessary prerequisite for a locally Lorentz-invariant QFT
  - An established CPT invariance would be the end of not only the SM itself, but its theoretical footing!
- If $M_{particle}$!= $M_{antiparticle}$ → CPT violated!
  - We have never tested this on a bare quark (status 2yrs ago)
- The top quark is the only known quark where this test is possible:
  - Hadronisation time scale >> $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s
- First result (D0, 1 fb^{-1}):

PRL 103, 132001 (2009)

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

- First result from CDF (5.4 fb^{-1}):

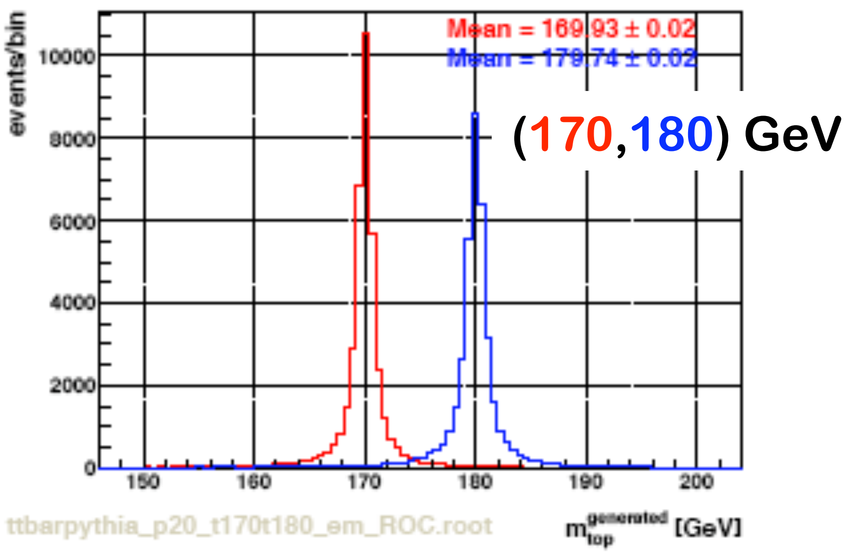
PRL 106, 152001 (2011)

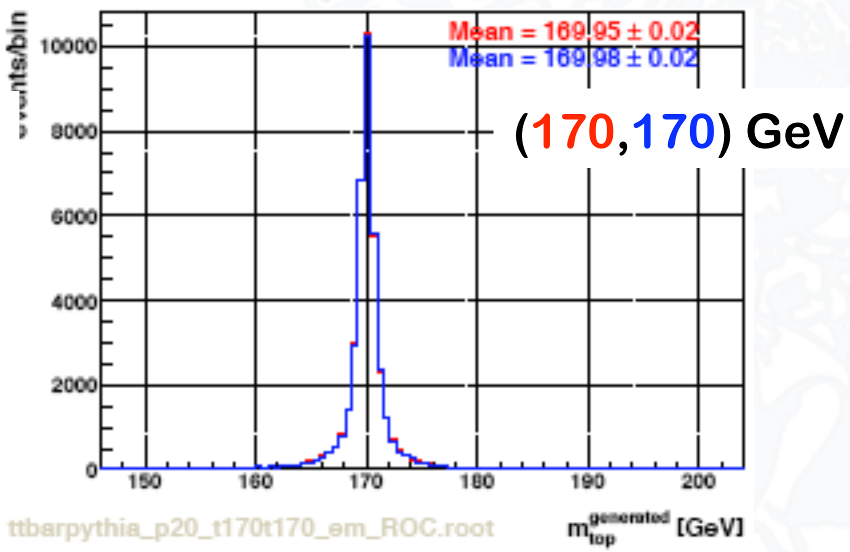
$$\Delta m_t = -3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})\ \text{GeV}$$

  - → 2 SD effect?

Top-antitop mass difference (D0)

- In standard pythia, it is impossible to generate tt events with M_t != M_{tbar}, modify pythia (6.413):
  - Allow for separate setting of M_t, M_{tbar}
  - Adjust description of all M_t, M_{tbar} related kinematic quantities:
    - e.g. resonance widths $\Gamma_t, \Gamma_{\bar{t}}$
  - Use standard CTEQ6L1 PDFs at scale:
    - $Q^2 = (p_T^{\text{scat}})^2 + \frac{1}{2}\{P_1^2 + P_2^2 + M_t^2 + M_{\bar{t}}^2\}$



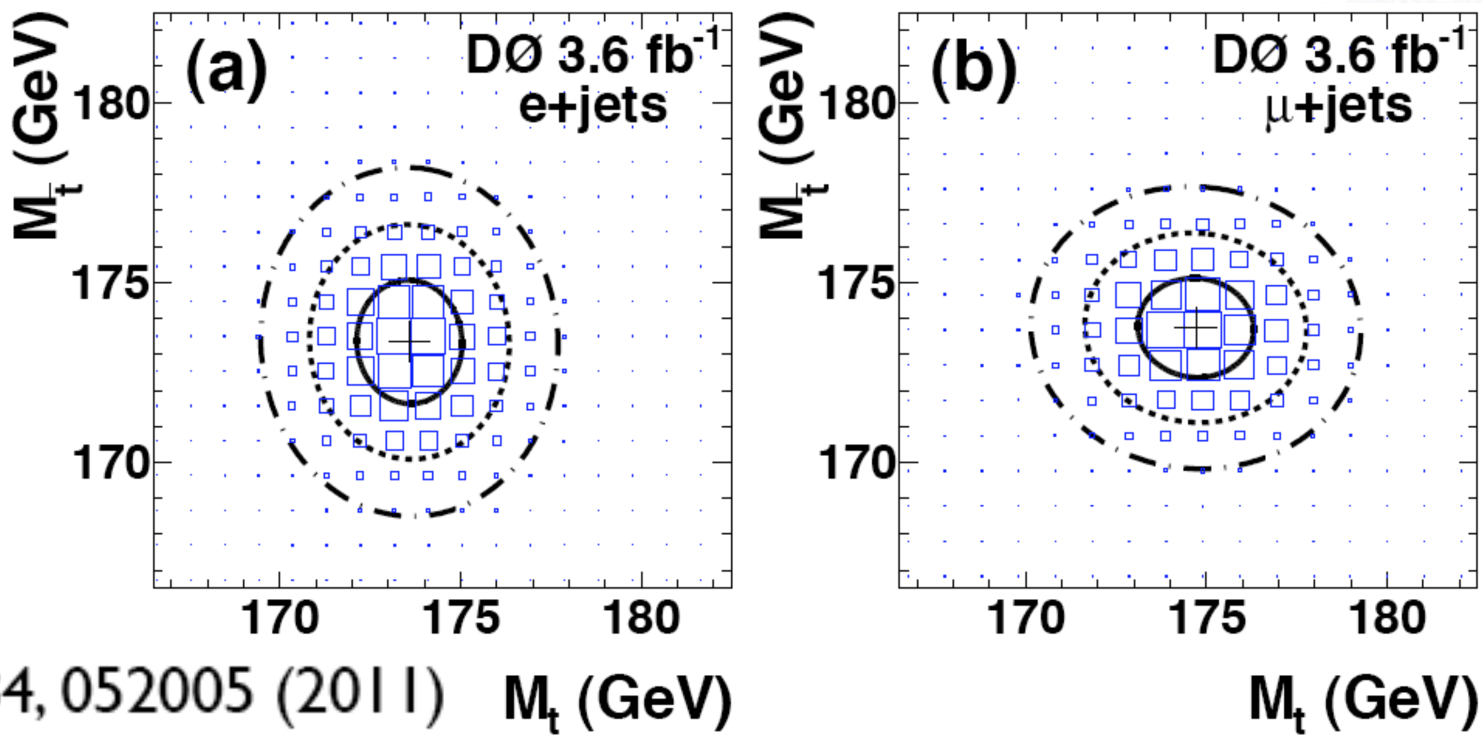


Top-antitop mass difference (D0)

- **Use the most statistically sensitive technique – ME**
  - $P(m_{top},k_{JES}) \rightarrow P(m_t,m_{tbar})$
    - Direct and indepentent measurement of m_t and m_{tbar}!
  - Use lepton charge to tag t and tbar:

Relative precision: 1%

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



PRD 84, 052005 (2011)

m_{top} in the *ll* channel (ME method)

- **Apply the ME method to the dilepton channel**
  - Additional challenge: the tt system is kinematically 1x underconstrained if m_{top} is a free parameter!
    - → assume prior for $p_T(tt)$ from MC simulation
    - → integrate over neutrino momenta (with Jacobian)
  - The ME used here is:

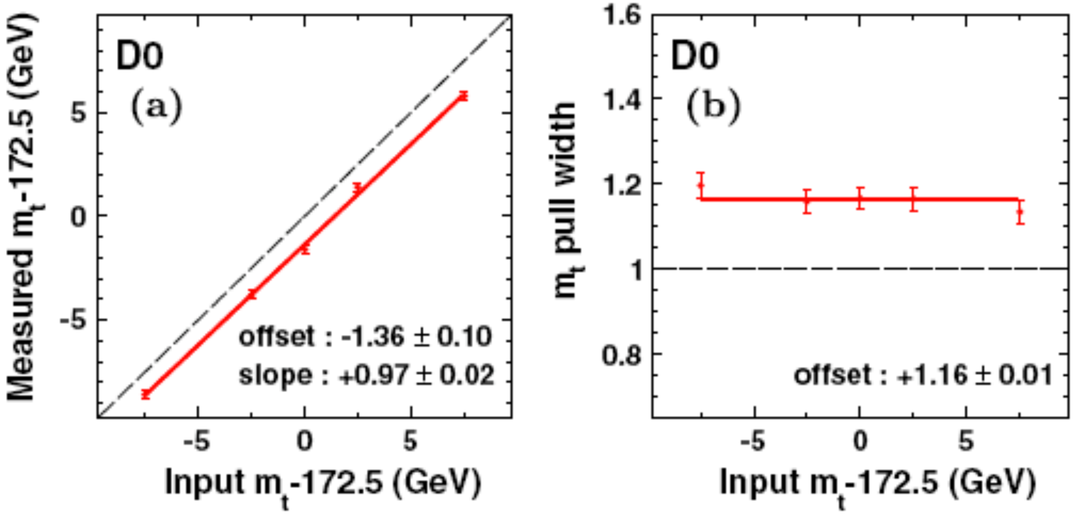
$$P_{t\bar{t}}(x; m_t) = \frac{1}{\sigma_{\text{obs}}(m_t)} \cdot \sum_{i=1}^{8} \int dq_1 dq_2 f_{\text{PDF}}(q_1) f_{\text{PDF}}(q_2) \frac{(2\pi)^4 |M(y; m_t)|^2}{q_1 q_2 s} d\Phi_6 W(x, y) W(p_T^{t\bar{t}})$$

  - Dominant background: Z+2jets processes
    - → calculate $P_{bkg} = P_{Z+2jets}$ using VECBOS
  - No in-situ calibration of the JES possible
    - Large systematic uncertainty from JES calibration
    - Similarly large systematic uncertainty from b-quark JES

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

m_{top} in the ll channel (ME method)

- **Method calibration:**

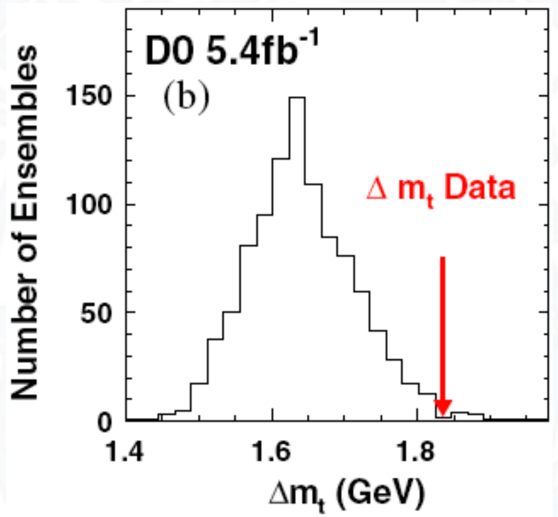


- **Final result:**

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

Relative uncertainty: 1.8%!

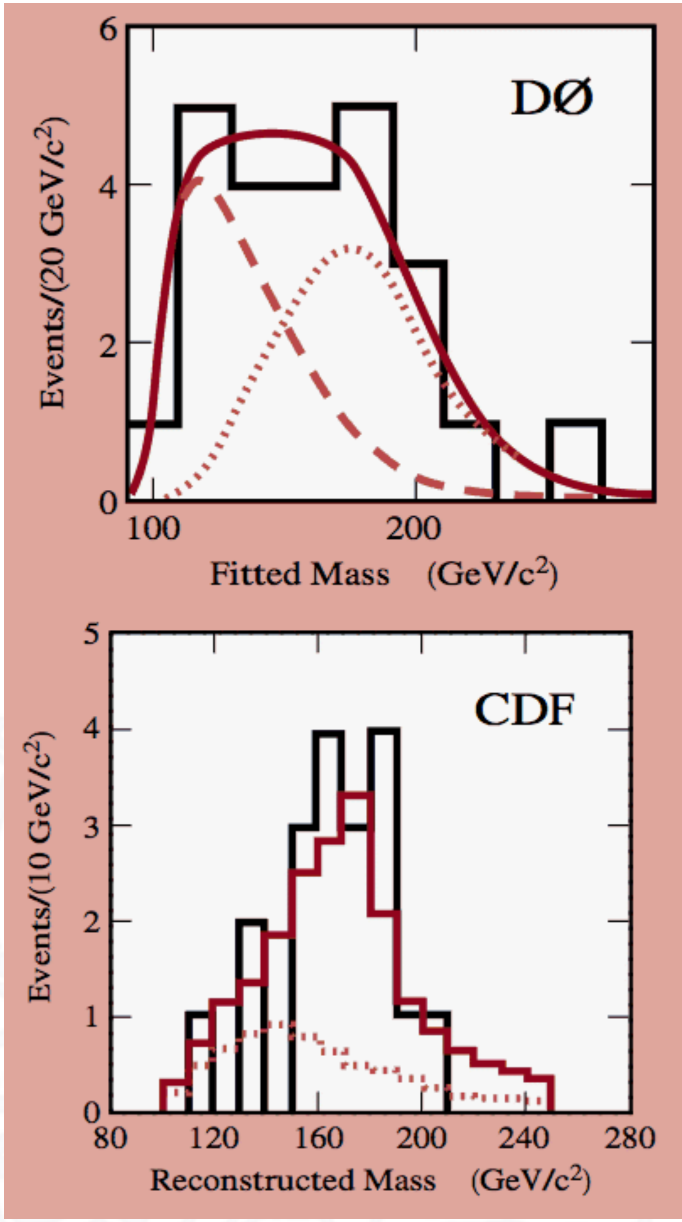
Phys. Rev. Lett. ***107****, 082004 (2011)*



The birth (1995)

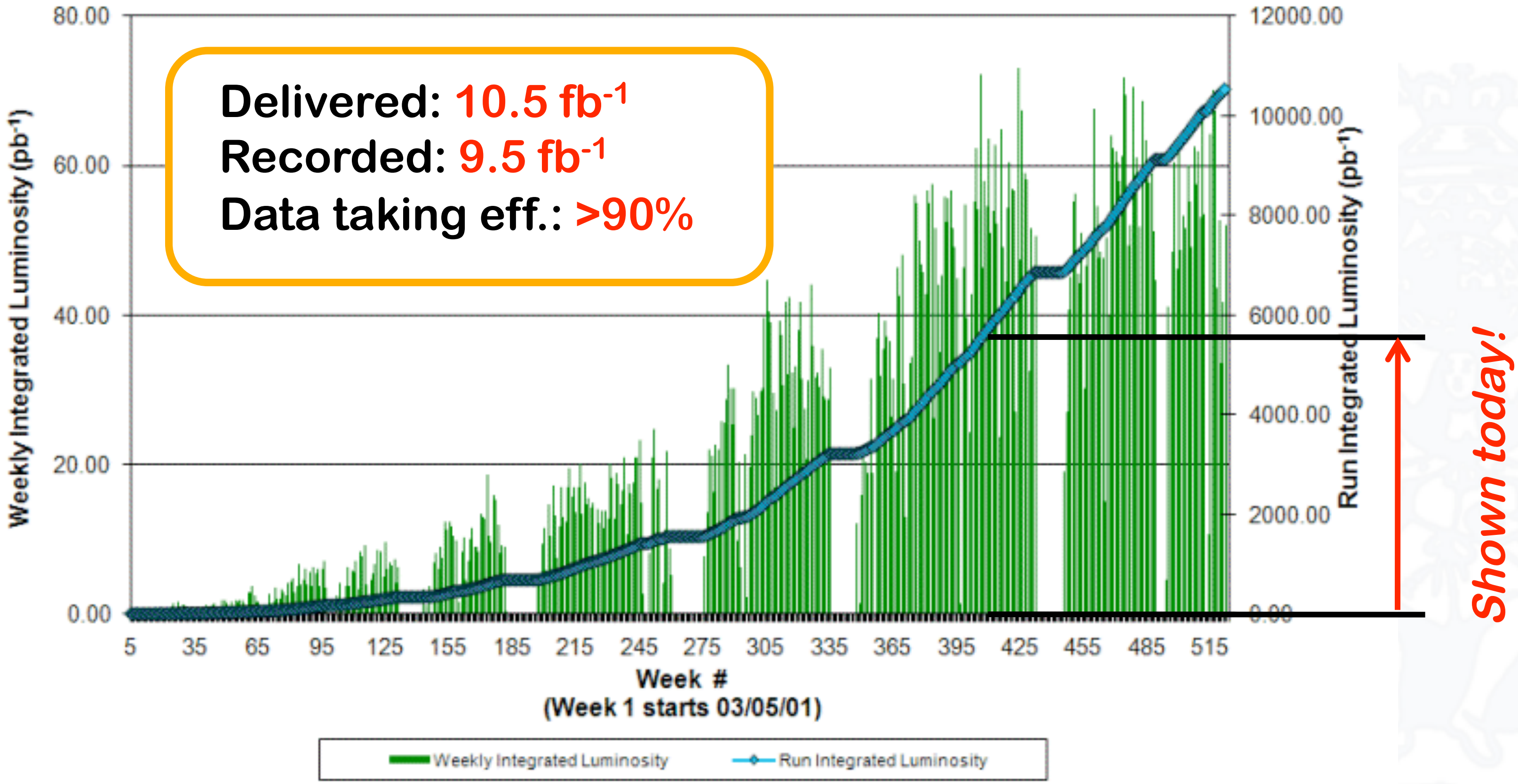
- D0 (50 pb^{-1}, 4.6σ):
  - σ=6.4±2.2 pb
  - m_{top}=199±30 GeV

- CDF (67 pb^{-1}, 4.8σ):
  - $\sigma=6.8^{+3.6}_{-2.4}$ pb
  - m_{top}=176±13 GeV



Analyzed dataset

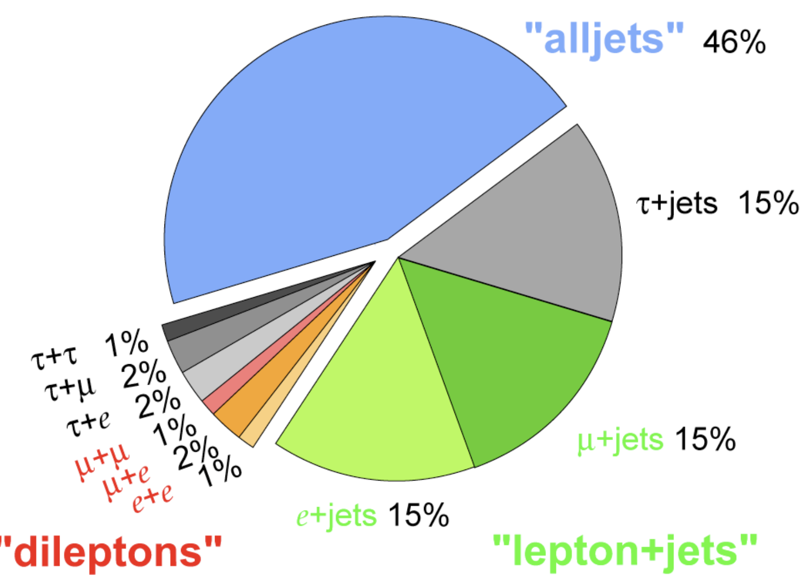
- Tevatron has shown a great performance in FY 2010!
- We keep enlarging our calibration samples
  - Better handles on experimental uncertainties:
    - e.g. Jet Energy Scale (JES), Jet Energy Resolution, etc.

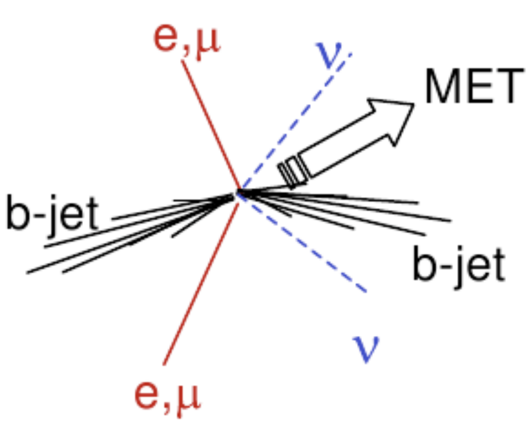


… and Decay

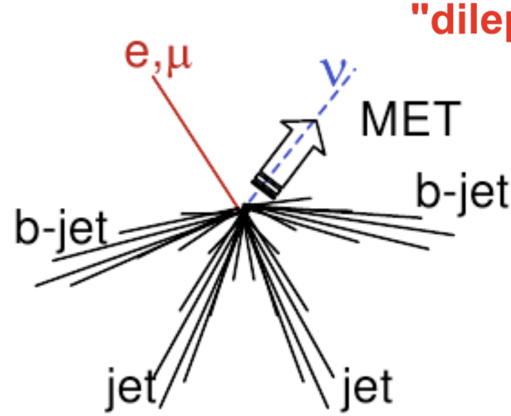
- **In the SM:**
  - $|V_{tb}|$ = 0.9990-0.9992 @ 95% C.L. assuming 3 CKM generations
- **Characterise tt final states by top decays!**

Top Pair Branching Fractions

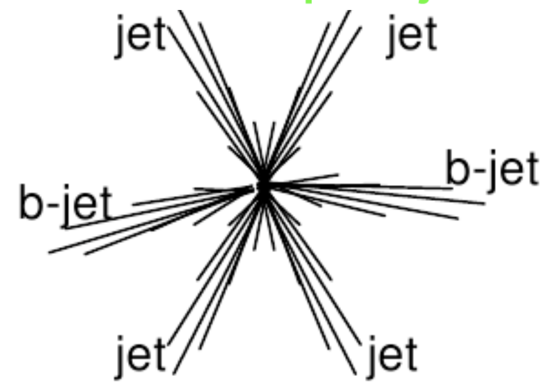




Dilepton
(BR~5%, low bckg)



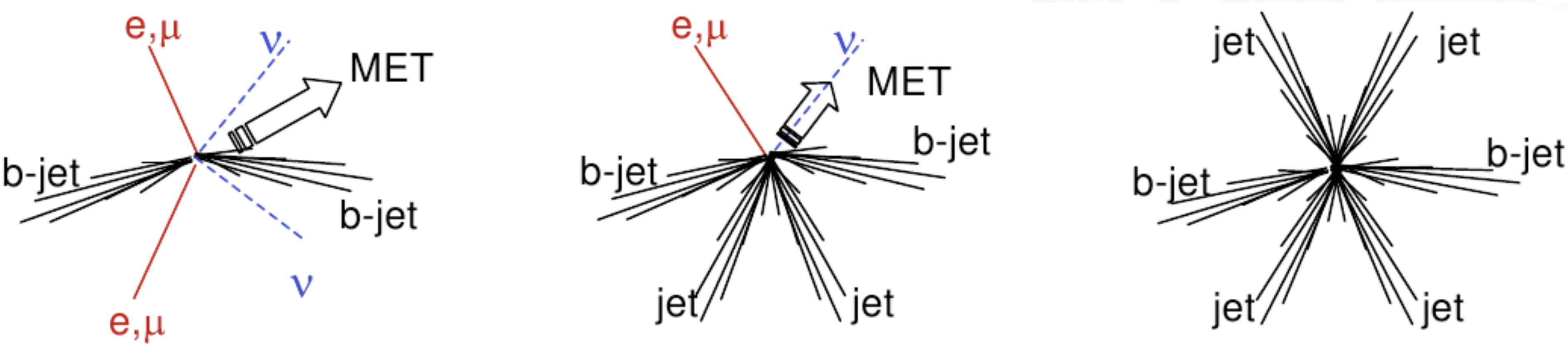
Lepton+jets
(BR~30%, moderate bckg)



All-hadronic
(BR~46%, huge bckg)

Typical ttbar preselection

Dilepton	Lepton+jets	All-hadronic
2 high-p_T leptons	1 high-p_T lepton (>20 GeV)	No leptons
Missing E_T	Missing E_T (>40 GeV)	No missing E_T
2 jets	4 jets (> 20GeV)	6 jets
≥ 0 b-tags	≥ 1 b-tag	≥ 1 b-tag
S/B:		



Dilepton (BR~5%, low bckg)

Lepton+jets (BR~30%, moderate bckg)

All-hadronic (BR~46%, huge bckg)

The DØ Detector