KIRCHHOFF-INSTITUT FÜR PHYSIK
HGSFP
Bundesministerium für Bildung und Forschung

Precision measurement of the mass of the top quark in l+jets final states using 9.7 fb^{-1} of DØ data

Oleg Brandt (U Heidelberg)
on behalf of the DØ collaboration

Today's Menu

- Motivation
- Selection
- The matrix element technique
- Calibration of method
- Result in data
- Data/MC comparisons
- Systematic uncertainties
  - Systematic uncertainties
    - Systematic uncertainties
      - Systematic uncertainties
        - Systematic uncertainties
- Conclusion
- 2014 Tevatron combination
- Anything to be learned?

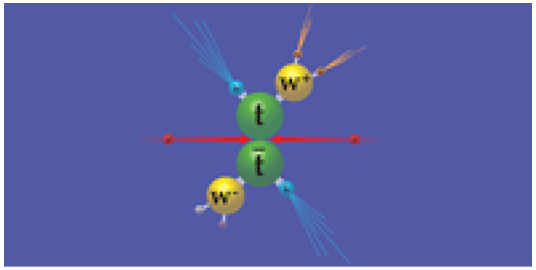
PRL **113,** 032002 (2014)

Precision Measurement of the Top Quark Mass in *Lepton + Jets* Final States

(D0 Collaboration)

Physics spotlight

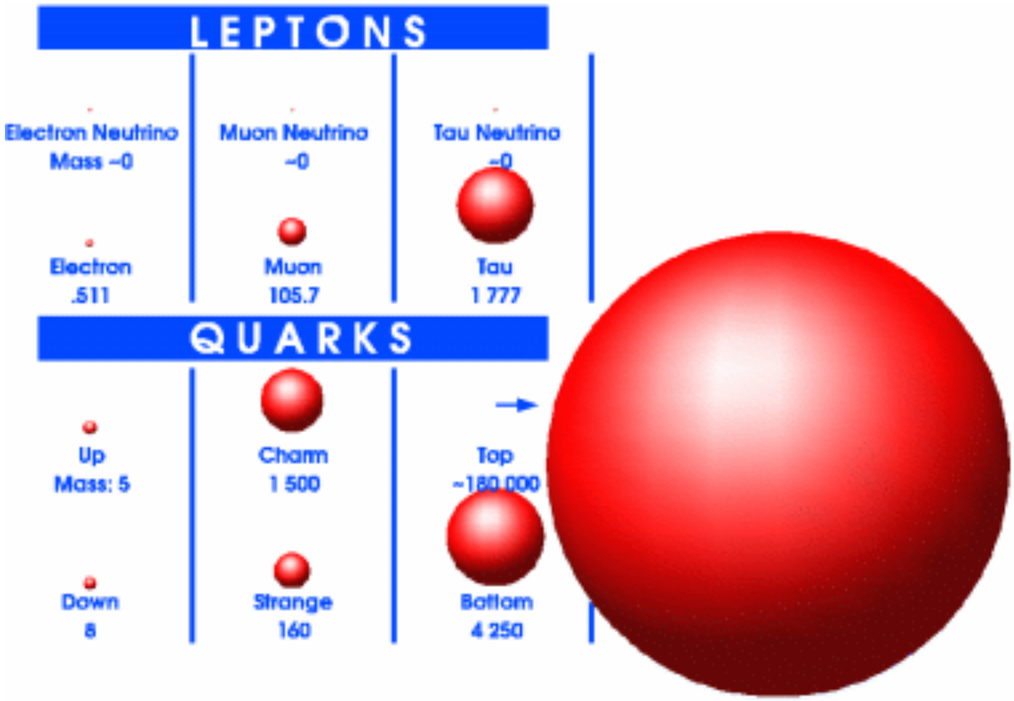
Synopsis:
Top Quark Mass Gets an Update



24 Feb. 1995

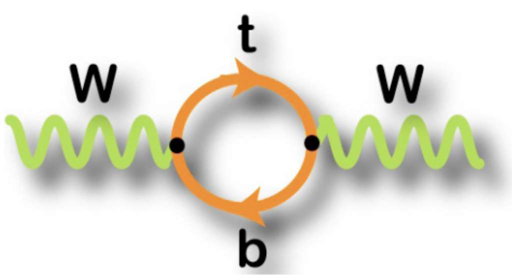
Motivation

- The **top quark is special**:
  - It is the heaviest quark of the SM!
    - Why is it so heavy?
    - Does it play a special role in EWSB?

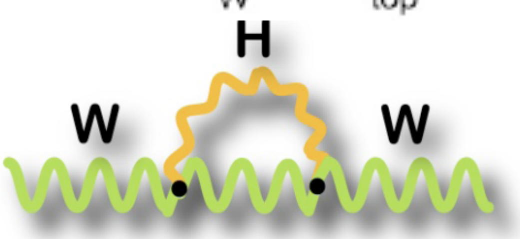


Motivation

- The **top quark is special:**
  - It is the heaviest quark of the SM!
    - Why is it so heavy?
    - Does it play a special role in EWSB?
  - M_W related to m_t & M_{Higgs}:



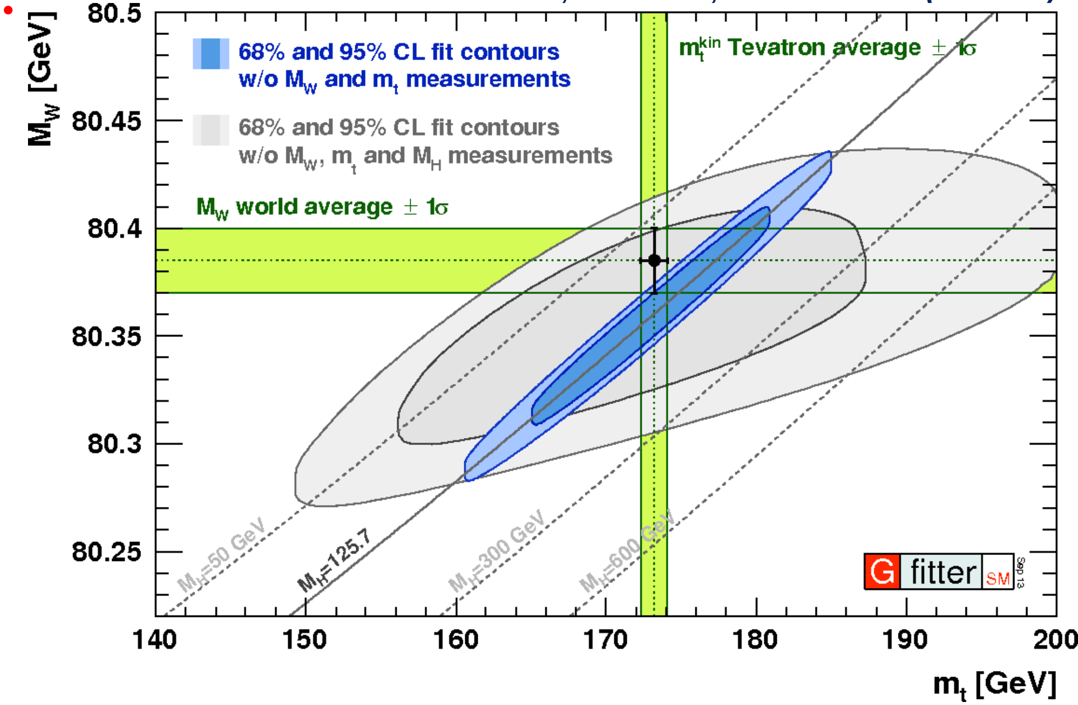
$$\Delta M_W \propto M_{top}^2$$



$$\Delta M_W \propto \ln M_H$$

Overconstrain M_W, m_t, and M_{Higgs}
→ Consistency check of the SM!

GFitter Coll., EPJC, ***72*** *2005 (2012)*

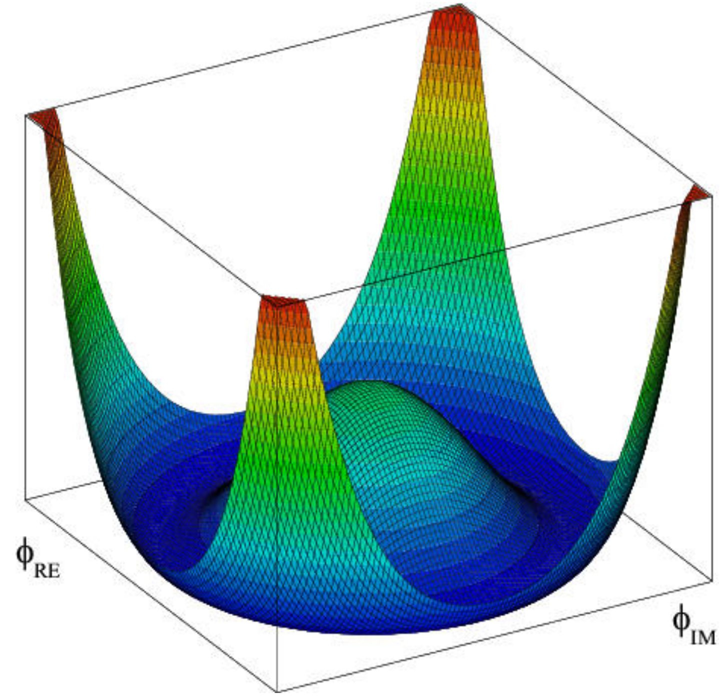


Motivation

- If this is not enough, the **top quark mass** is a **fundamental parameter of the SM**
- The **fate of our Universe depends on m_t**!
  - Consider the Higgs Lagrangian:

$$\mathcal{L}_H = \left| \left(\partial_\mu - igW^a_\mu \tau^a - i\frac{g'}{2}B_\mu \right) \phi \right|^2 + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2,$$

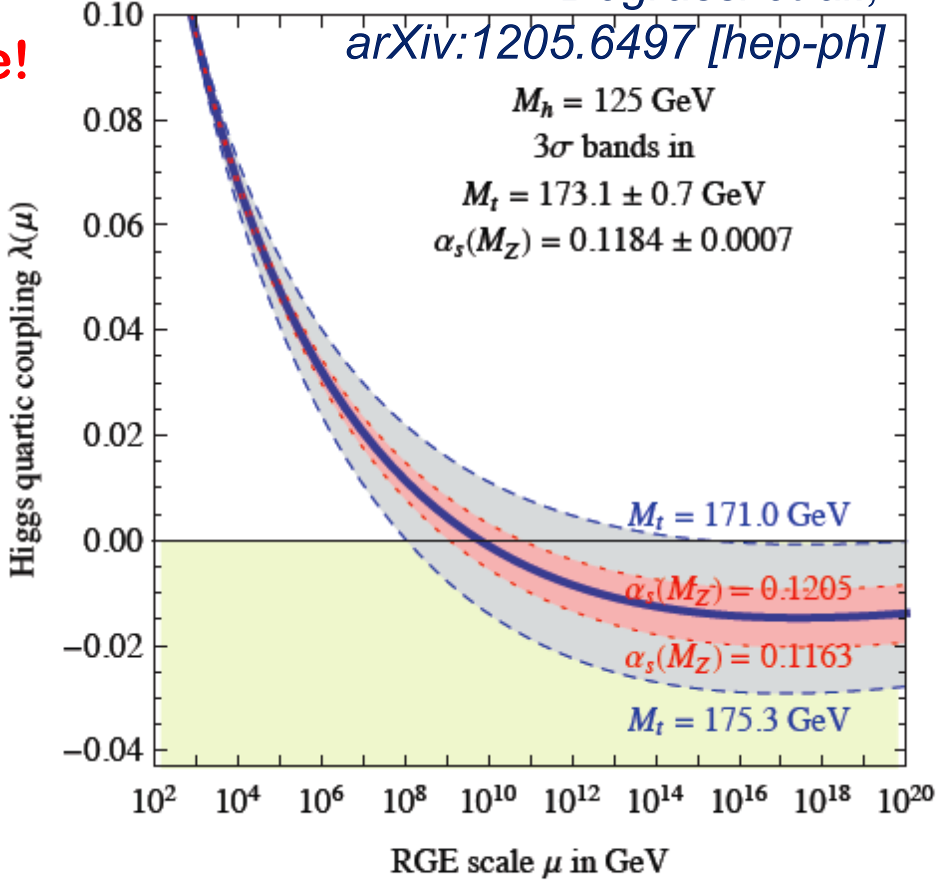
  - The quartic Higgs self-coupling term $\lambda(\phi^\dagger\phi)^2$ is responsible for the mexican-hat shape of the potential
  - This works only if λ is positive…



Motivation

- λ receives **radiative corrections** from all particles of the SM, **mostly from the top quark**!
  - We can evolve these corrections using running group equation to Planck scale:
    - **λ should remain positive!**

Degrassi et al., arXiv:1205.6497 [hep-ph]



With the current world's best values for m_t and m_{Higgs}:
→ **Our Universe is only metastable!**

The calculation includes NNLO effects, RG equation at NNNLO

Will the top quark save our Universe?

Stay tuned!

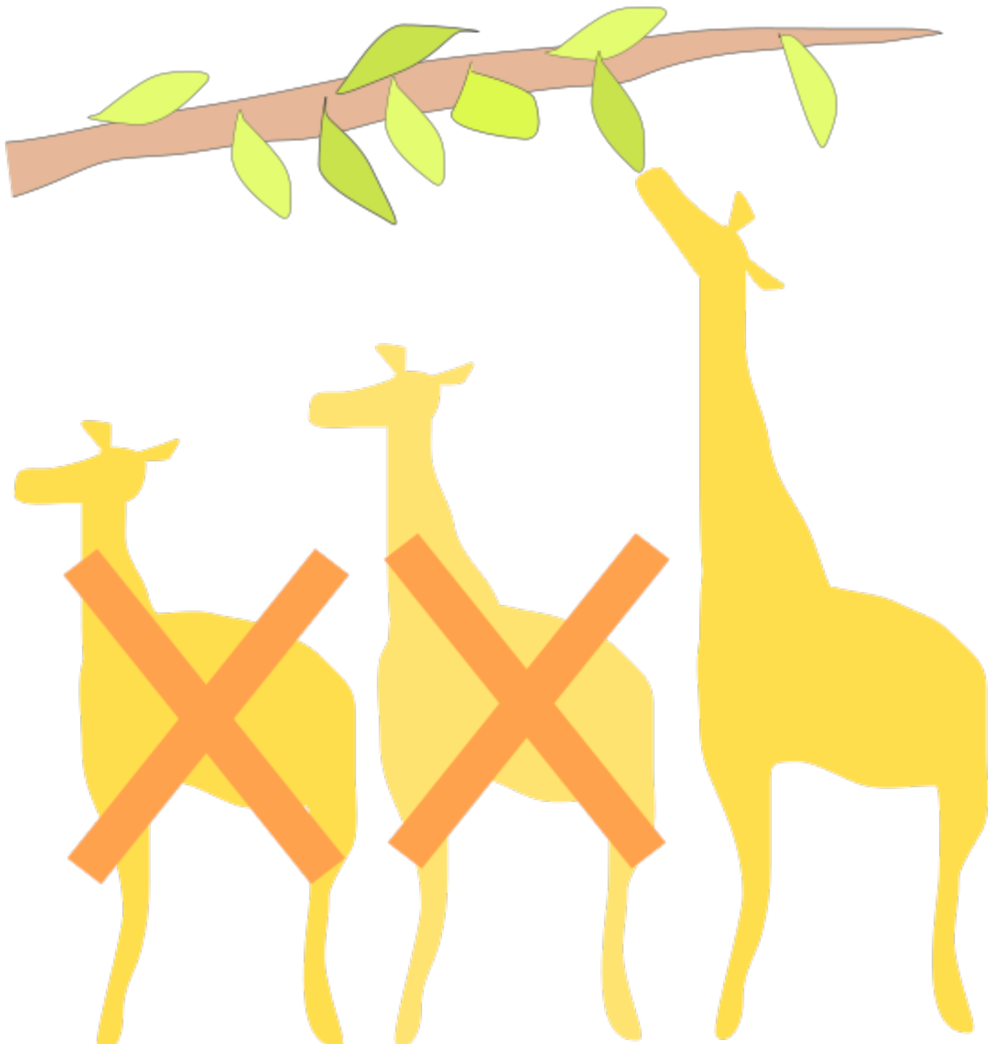
We'll know more in 10^{12} years…

Will the top quark save our Universe?

Stay tuned!

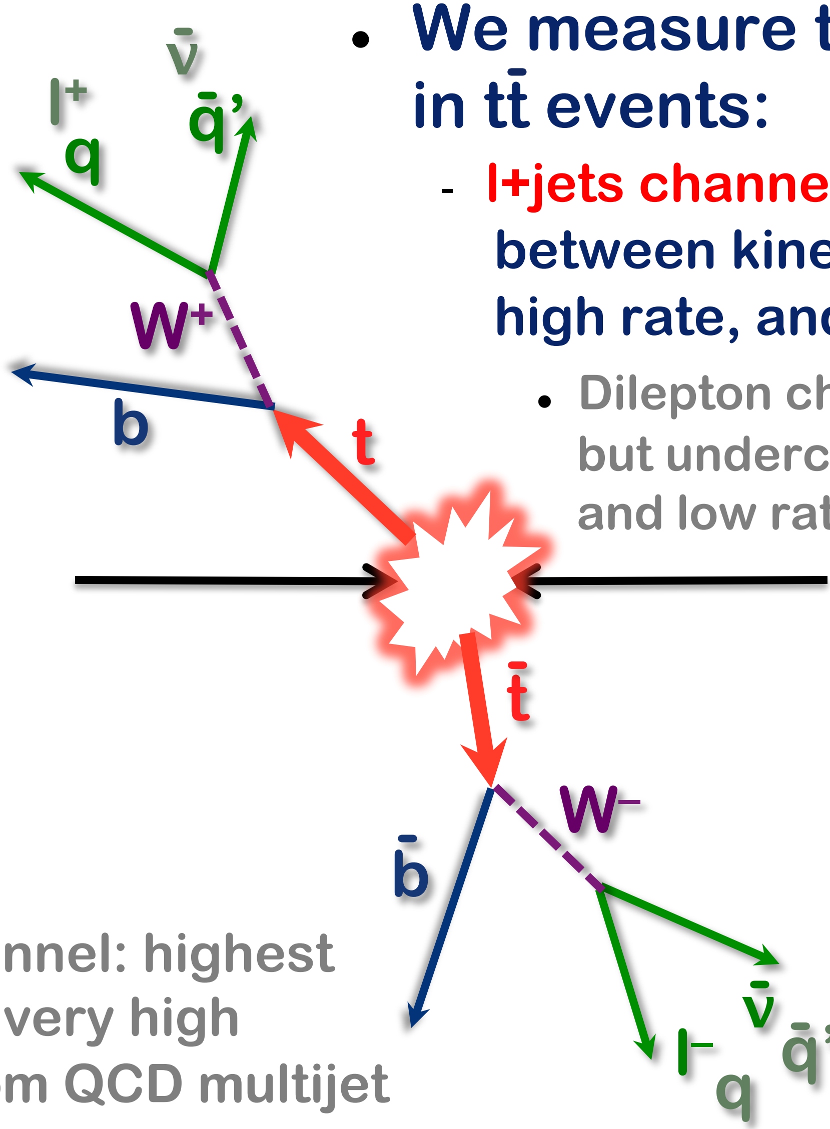
We will measure m_t, M_{Higgs}, and α_s with higher precision!

Selection



Selection

- We measure the top mass in $t\bar{t}$ events:
  - l+jets channel: good compromise between kinematic reconstruction, high rate, and backgrounds
    - Dilepton channel: low backgrounds, but underconstrained kinematics and low rate
  - All-hadronic channel: highest branching ratio, very high backgrounds from QCD multijet production



Selection overview

- Use full 9.7 fb^{-1} of integrated luminosity & require:
  - Exactly one tight isolated electron or muon with:
    - $p_T > 20$ GeV, $|\eta_{muon}| < 2$, $|\eta_{electron}| < 1.1$
  - Exactly four jets with cone parameter R=0.5 and:
    - $p_T > 20$ GeV, leading jet $p_T > 40$ GeV
  - Reject multijet events with
    - $\not{p}_T > 20$ GeV
    - Topological cuts
  - One or more b-tagged jet ($\varepsilon_b \approx 65\%$, $\varepsilon_{light} \approx 10\%$) to further reject backgrounds

Selection overview

- We split our data sample into four epochs:
    - Run IIa (1.1 fb^{-1})
    - Run IIb1 (1.2 fb^{-1})
    - Run IIb2 (3.0 fb^{-1})
    - Run IIb3 (4.4 fb^{-1})
  - This is done to accurately take into account the detector response variations due to factors like:
    - Time dependence due to instantaneous luminosity
      - E.g. track reconstruction efficiency, b-tagging
    - Varying detector configuration
      - E.g. addition of Layer 0 to the silicon tracker after Run IIa
- We use dedicated MC simulations to model the detector response in each of those epochs

Simulations used

- Simulations are done with:
  - $t\bar{t}$ signal: alpgen+pythia (0,1,2 light partons)
  - W+jets: alpgen+pythia (0,1,...,5 light partons)
  - W+cc, W+bb: alpgen+pythia (0,1,2,3 light partons)
  - Multijet events: from data
    - Use "matrix method" to predict its yield [1]
    - Use events with inverted lepton isolation requirements to model the shape

[1] *DØ Coll., submitted to PRD, arXiv:1401.5785 [hep-ex].*

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- To make sure we are on the same page:
  - We measure the so-called MC mass:
    - In our case m_t as implemented in alpgen
  - Close, but not necessarily identical to the pole mass

[1] *DØ Coll., submitted to PRD, arXiv:1401.5785 [hep-ex].*

Selection overview

- **Sample composition** assuming $\sigma_{t\bar{t}} = 7.24$ pb [1]:

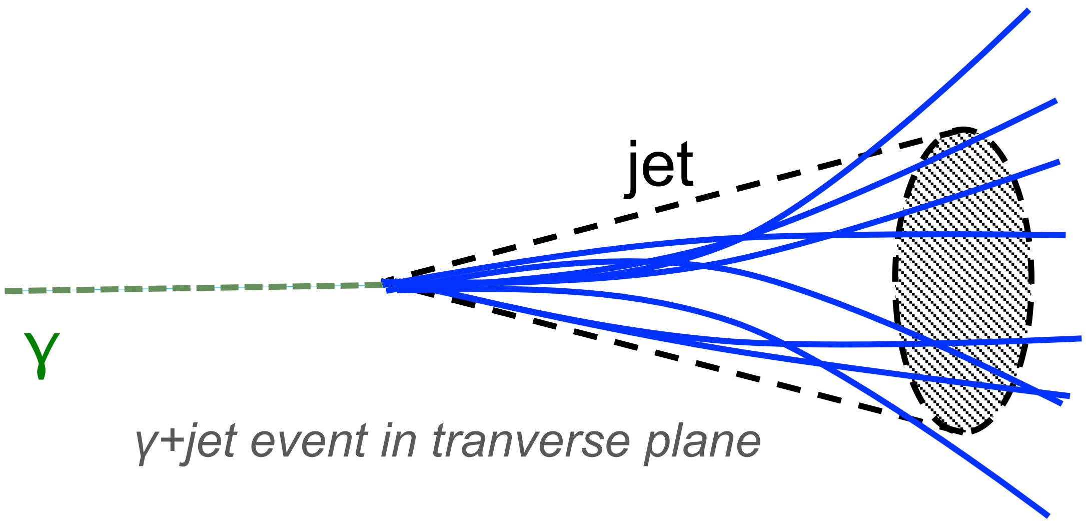
Contribution	$e+$jets			$\mu+$jets		
Data	1502.00	±	38.76	1286.00	±	35.86
$t\bar{t}$	918.11	±	3.63	824.88	±	3.48
$W+$jets	77.85	±	2.13	101.03	±	2.93
$W+$HF	125.98	±	2.12	162.21	±	2.81
Multijet	144.41	±	24.19	48.17	±	16.11
Other backgrounds	97.75	±	0.51	79.24	±	0.94
Expected	1364.10	±	24.65	1215.53	±	17.00

- We expect a signal fraction (f) of
  - 67% (e+jets)
  - 68% (μ+jets)
- *(will show data/simulations comparison plots later in the talk)*

[1] Czakon et al, *PRL* ***109****, 132001 (2012).*

Jet energy scale (JES) calibration

- We **calibrate jet energies** at detector level to **particle level** (in data and MC)
- Calibration procedure in a nutshell:
  - Calibrate EM energy scale with $Z \rightarrow e^+e^-$
  - Correct energy scale for electrons to that of photons
  - Use **γ+jet events to calibrate major components of JES**
    - Expect momentum balance in transverse plane



γ+jet event in tranverse plane

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

  - Use γ+jet and dijet events to extend calibration in pT,η

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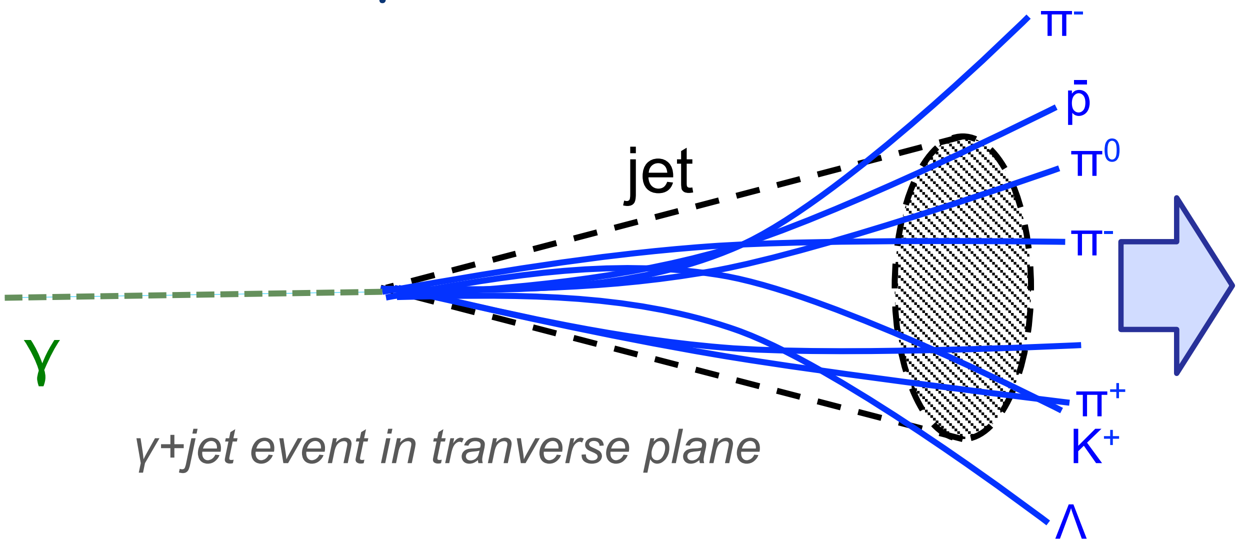

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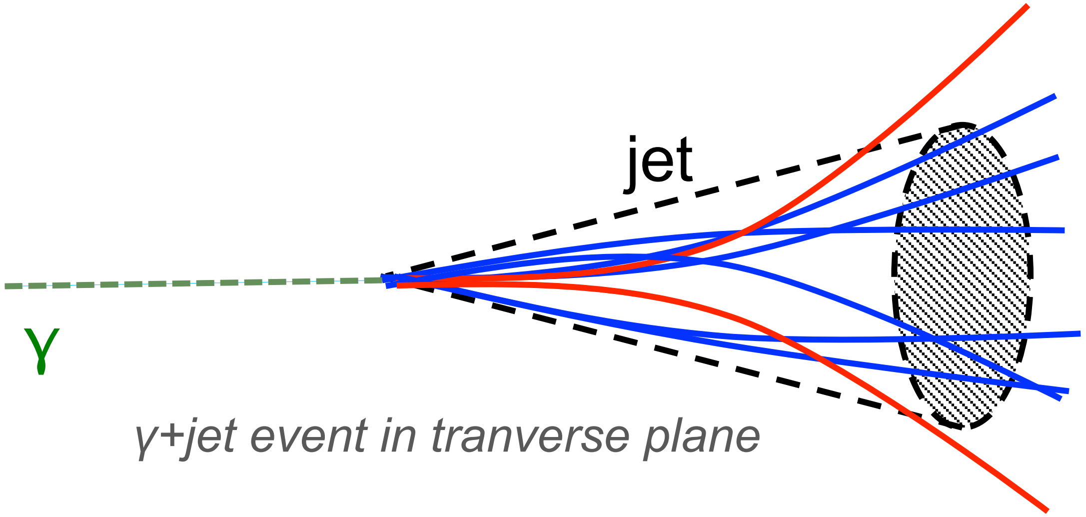

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$$E^{\mathrm{ptcl}} = \frac{E^{\mathrm{meas}} - E_{\mathrm{O}}}{R \cdot S}$$

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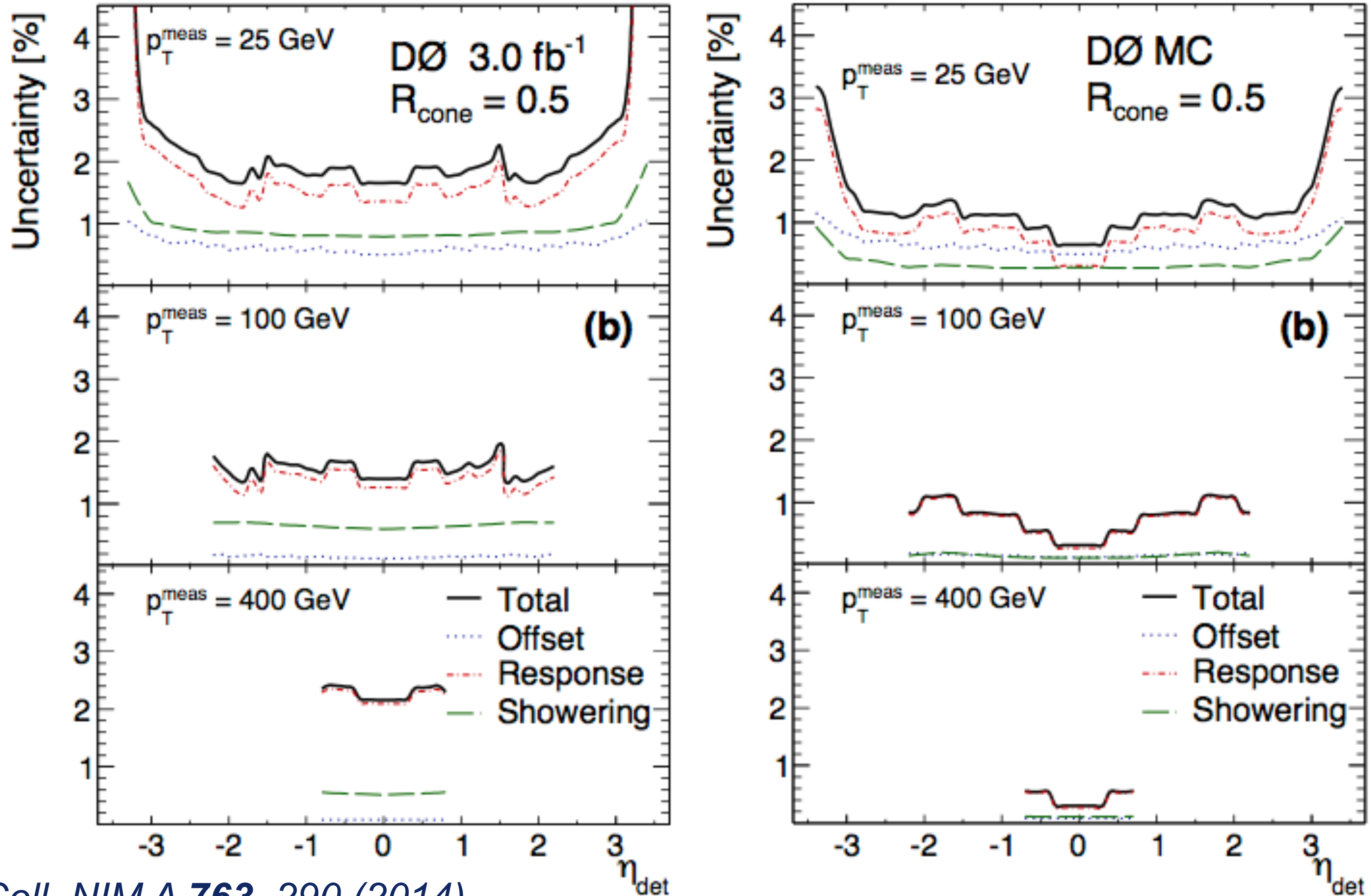
Refined jet energy scale calibration

- We use the new jet energy scale (JES) calibration:



*DØ Coll, NIM A **763**, 290 (2014)*

Figures are representative of all Run II

Refined jet energy scale calibration

- Apply dedicated corrections for:
  - u, d, c, s quark jets
  - b quark jets
  - gluon jets
- The correction is given by:

preserves default JES per constructionem

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

- Derive single particle responses R_i in data/MC for:
  - γ, $e^\pm$, $\mu^\pm$, $\pi^\pm$, $K^\pm$, K_0^S, K_0^L, $p^\pm$, n and Λ
    - Use γ+jet sample → quark-dominated
    - Use dijet sample → gluon-dominated

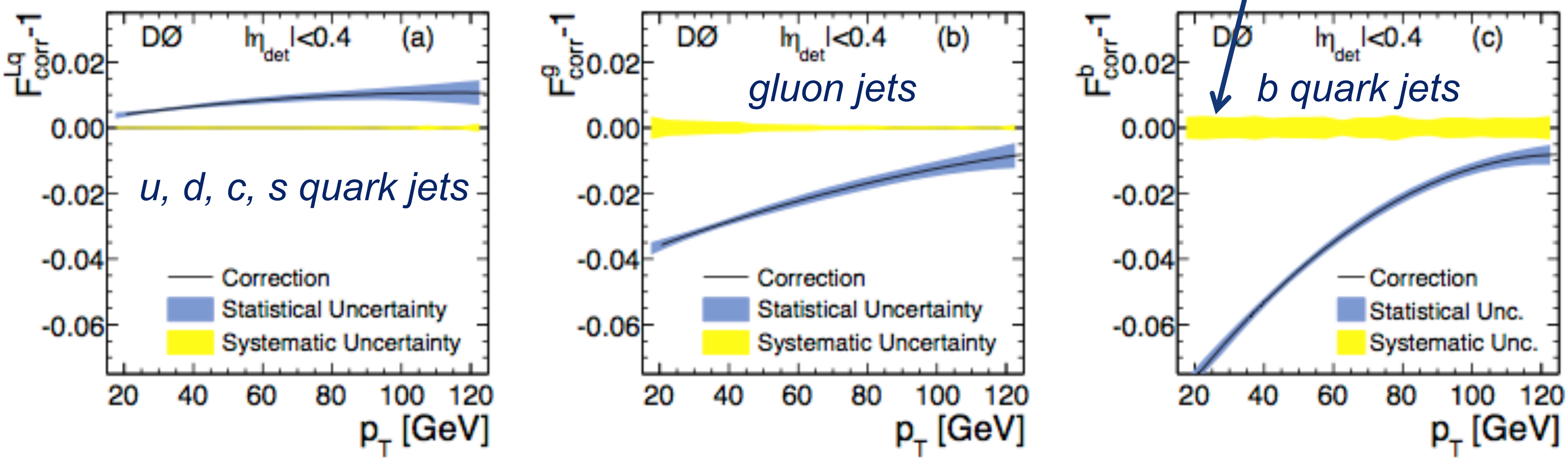
    Simultaneous fit
  - Take flavour composition of the samples from MC [1]

*DØ Coll, NIM A **763**, 290 (2014)*

[1] ***X-check:*** *uncertainty from this assumption covered by systematic uncertainty assigned*

- The final flavour-dependent correction:

[1]



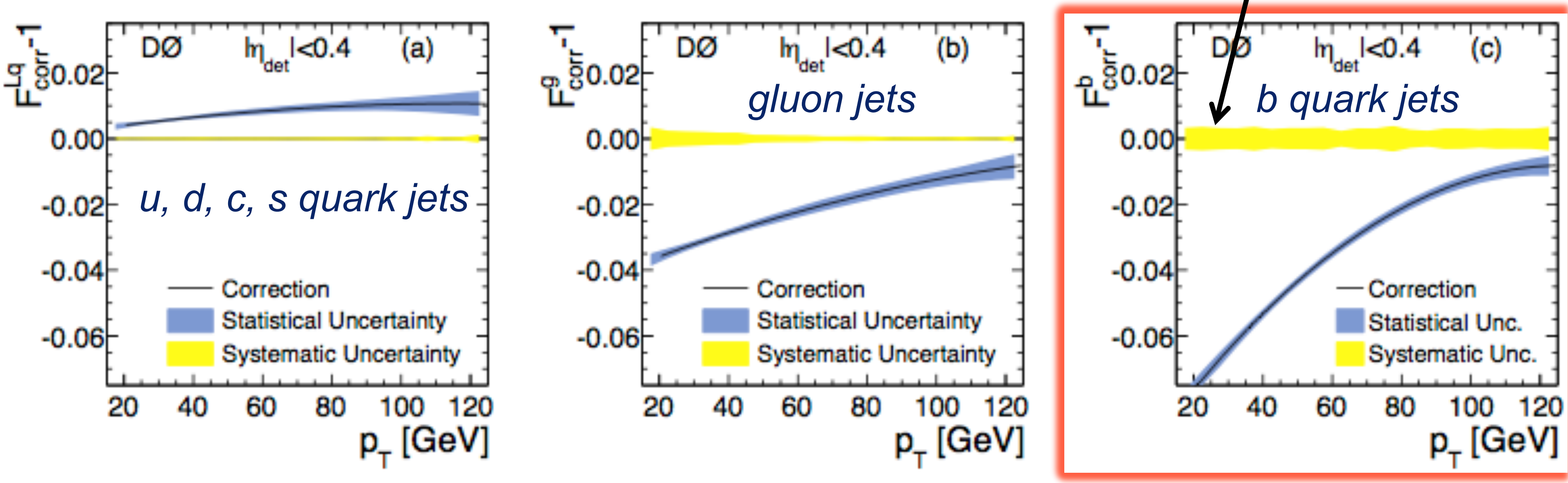
*DØ Coll, NIM A **763**, 290 (2014)*

[1] *Dominant source of systematic uncertainty: single particle response shapes in MC*

Refined jet energy scale calibration

- The final **flavour-dependent correction**:

[1]



- The correction accounts for the difference in **JES for b quark jets and light quark jets**:
  - Substantial reduction of one of the dominant systematic uncertainties!

*DØ Coll, NIM A **763**, 290 (2014)*

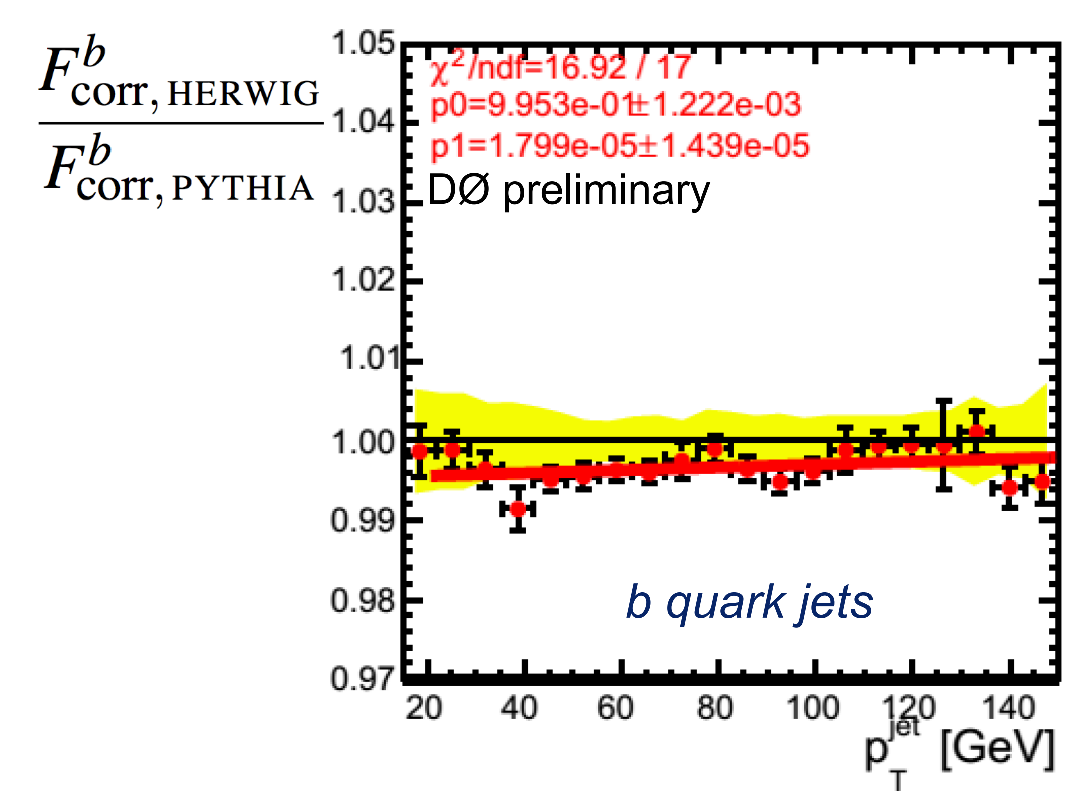
[1] *Dominant source of systematic uncertainty: single particle response shapes in MC*

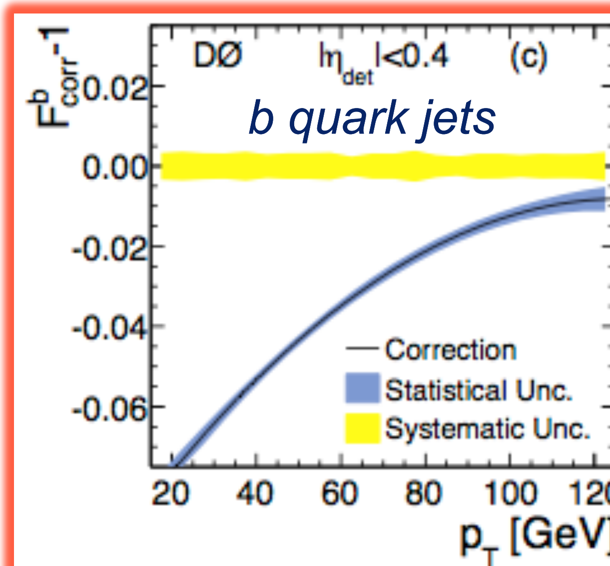
Refined jet energy scale calibration

- The final **flavour-dependent correction**:

Cross-check #3:

Study impact of shower composition:





Excursion of double-ratio from unity covered by systematic uncertainties

Double-ratio plot preliminary (some weights for efficiencies from ID, trigger etc. missing)

The matrix element technique

The matrix element technique

- **Matrix Element (ME) technique:**
  - Calculate the event probability on an event-by-event basis:

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

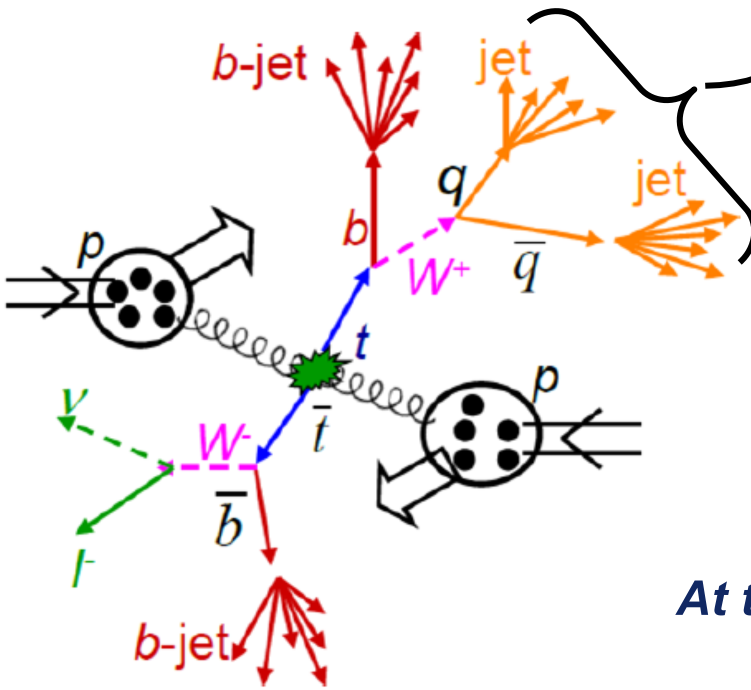
$$P_{\mathrm{sig}}(m_{\mathrm{top}}) \propto \int \ldots \underline{\mathrm{d}\sigma_{t\bar{t}}(m_{\mathrm{top}})}$$

$$\mathrm{d}\sigma_{t\bar{t}} \propto |\mathcal{M}_{t\bar{t}}|^2(m_{\mathrm{top}})$$

  - **Advantages:**
    - Use 4-vectors with maximal kinematic and topological information → maximal statistical power
  - **Disadvantages:**
    - High computational demand + theory assumptions

The matrix element technique

- perform an **in-situ calibration of the JES:**
  - Constrain energies of the two jets from W to be consistent with M_W
  - This allows a **simultaneous** extraction of m_t and the **overall JES factor** k_{JES}**!**



$M_W \sim k_{JES}$

At tree level, we have 4 partons evolving into 4 jets:
→ 24 jet-parton assignments

The ME technique in our measurement

DØ matrix element technique in l+jets final states

b tagging-based weight to identify relevant jet-parton assignments

Integration over phase space (10 dim)

$$P_{\rm sig} = \frac{1}{\sigma_{\rm obs}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int \overbrace{d\rho\, dm_1^2\, dM_1^2\, dm_2^2\, dM_2^2\, d\rho_\ell\, dq_1^x\, dq_1^y\, dq_2^x\, dq_2^y}$$

$$\sum_{\rm flavors,\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1)f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\rm JES})$$

LO matrix element
PRD 53, 4886 (1996)
PLB 411, 173 (1997)

Phase space factor

Transfer functions (TFs) to map parton level quantities y to reco level quantities x

*DØ Coll., PRD **84**, 032004 (2011)*

The ME technique in our measurement

DØ matrix element technique in l+jets final states

Normalisation by observed cross section using the same LO ME

Sum over all 24 possible jet-parton assignments

$$P_{\rm sig} = \frac{1}{\sigma_{\rm obs}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int d\rho\, dm_1^2\, dM_1^2\, dm_2^2\, dM_2^2\, d\rho_\ell\, dq_1^x\, dq_1^y\, dq_2^x\, dq_2^y$$

$$\sum_{\text{flavors},\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1) f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\rm JES})$$

Sum over incoming parton flavours and all neutrino p_z solutions

PDFs for Björken-x and PD for transverse momenta of incoming partons

*DØ Coll., PRD **84**, 032004 (2011)*

The ME techique: improvements

- We **numerically calculate a 10 dimensional integral** using MC integration techniques
  - Identical to the 3.6 fb^{-1} result [1] except:
    - Use **low-discrepancy sequences for the MC integration**
      - Deterministic sequence of points in our 10-dim parameter space providing optimal convergence
    - **Factorise the JES factor k_{JES} from the ME calculation**
      - Include it via the transfer function
  - **Reduction of calculation time by o(100)!**

[1] *DØ Coll., PRD **84**, 032004 (2011)*

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    - **Factorise the JES factor k_{JES} from the ME calculation**
      - Include it via the transfer function
  - **Reduction of calculation time by o(100)**
- Increase the size of calibration samples!
  - Typical **statistical uncertainty** from size of MC samples:
    - **≈ 0.25 GeV → 0.01–0.05 GeV**

Uncertainty (GeV)
±0.25
±0.26
±0.58
±0.28
±0.07
±0.16
±0.07
±0.09
±0.24
±0.21
±0.28

Excerpt from the table of systematic uncertainties of the 3.6 fb^{-1} analysis [1]

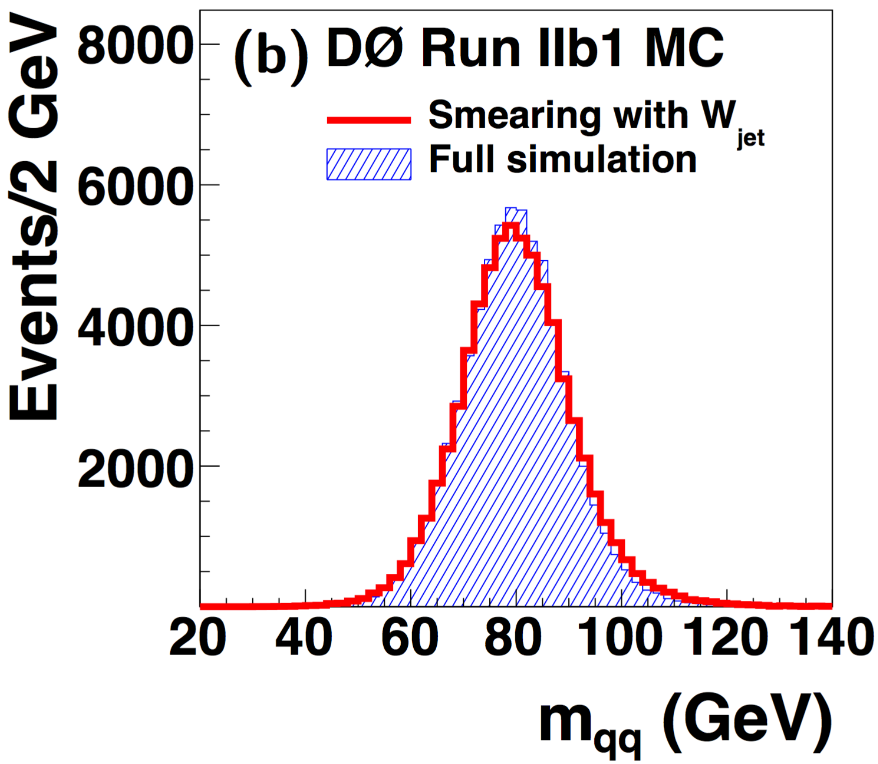
[1] *DØ Coll., PRD* ***84****, 032004 (2011)*

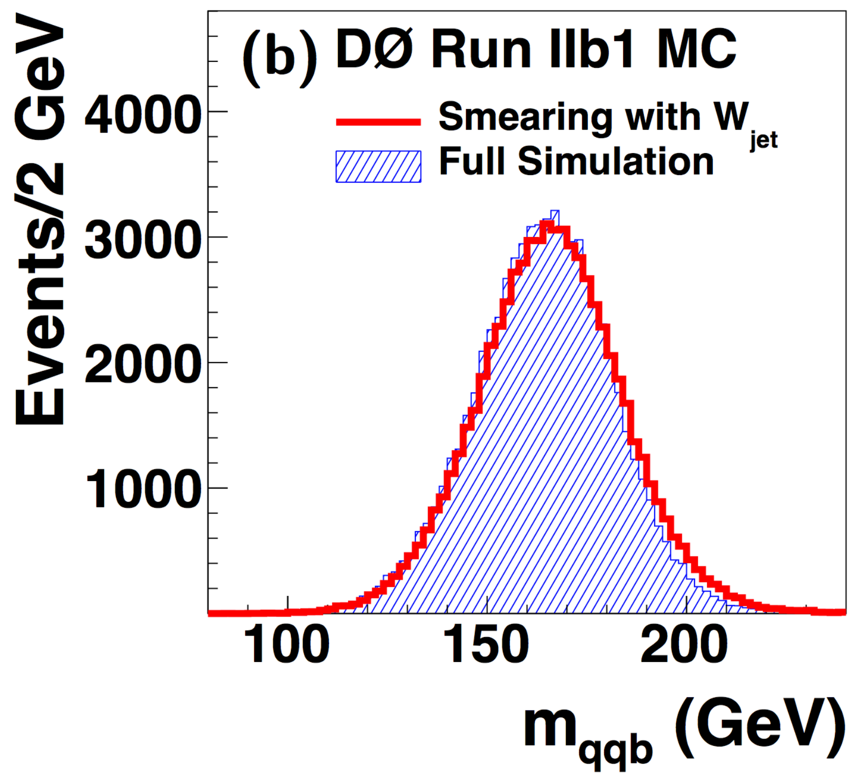
Transfer functions

- The Transfer Functions $W(x, y; k_{\mathrm{JES}})$ relate parton-level quantities to detector-level ones
- Parametrise the detector response:
  - For jets, we use the sum of two Gaussians:
- Parametrise jet energies:
  - treat separately: light quark jets, b-tagged jets with soft muon tag, all other b-jets
  - x 4 $|\eta|$ regions for each
- Direction of jets and leptons in η x ϕ well-measured:
  - → use δ-functions as transfer function!

Transfer function validation

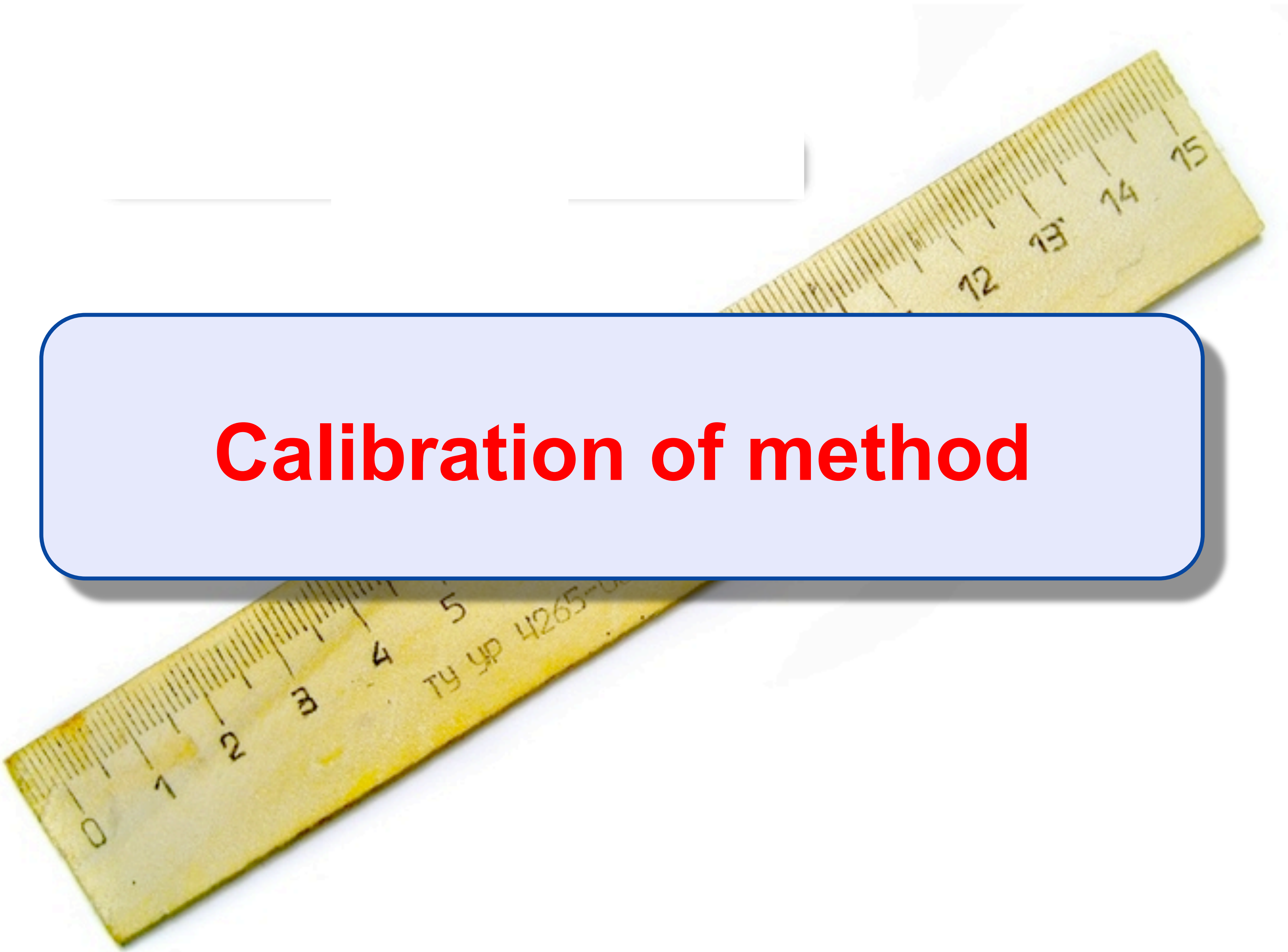
- Compare parton momenta smeared with transfer functions to jet momenta in full simulation in:
  - Invariant mass of dijet system matched to W boson
  - Invariant mass of trijet system matched to top quark





- Very good description of detector response!

Representative MC simulations → cf. backup for all



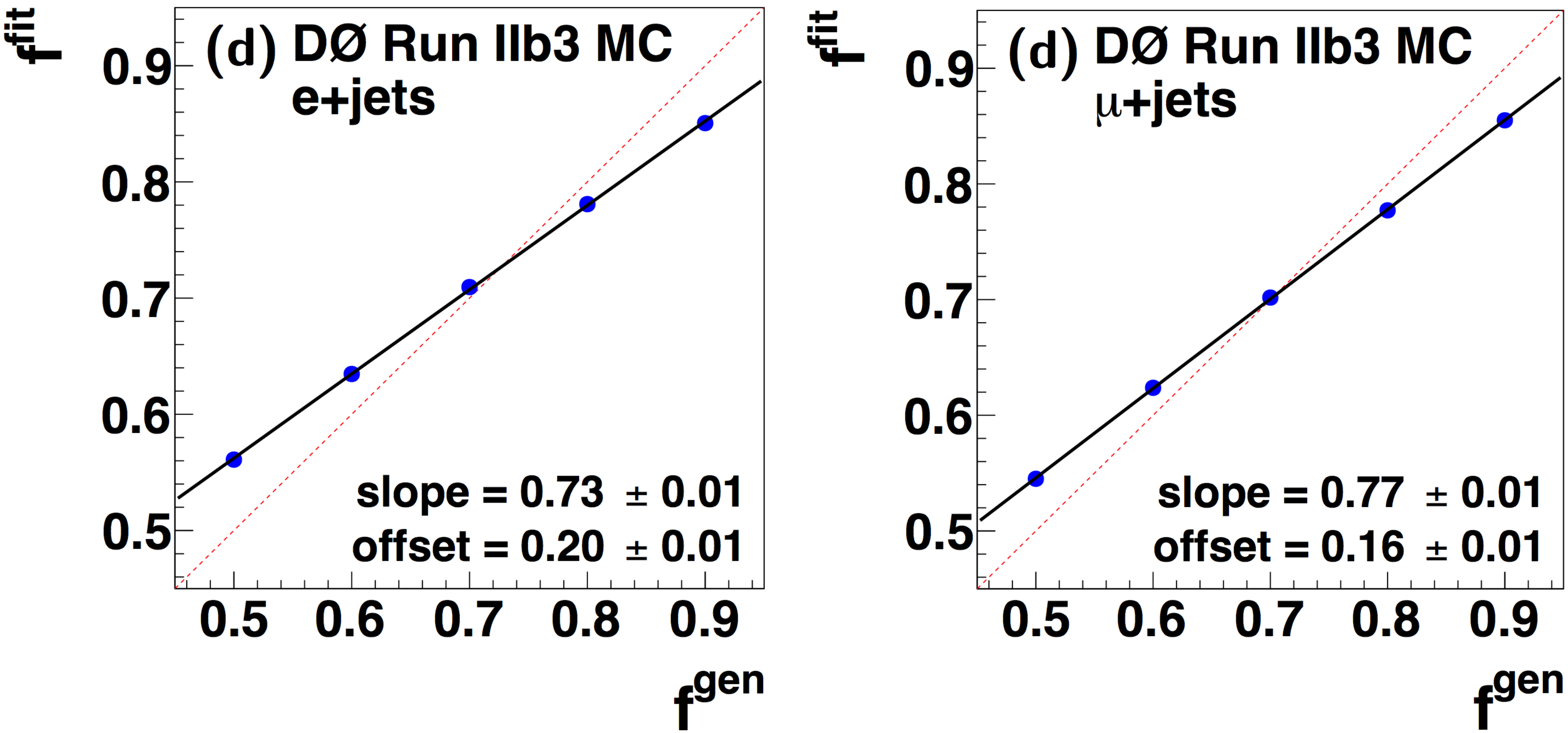
Calibration of method

Calibration of method response

- **Calibrate** the method with **pseudo-experiments (PE)**
  - Keep in mind we use P_{evt} obtained from **first principles** with a LO ME and parametrised detector response
    - → calibration imperative
    - (in template methods this is merely a consistency check)
  - Dedicated calibration for **each epoch & channel**
    - → total of 4 x 2 = 8 calibrations
  - Each PE consists of N_{data}
  - PEs include:
    - **W+jets background** (dominant, adjusted according to f)
    - **MJ background** (11% and 4% for e and mu+jets)
    - (Other backgrounds contribute a total of ~ 5%)
  - Construct PEs according to signal fraction (f) measured from data
  - 1000 PEs performed at each calibration point

Extracting signal fraction from data

- We extract the signal fraction from data
  - Integrate $L(f,m_t,k_{JES})$ over m_t and k_{JES} → maximise in f
  - Calibrate method response in f:



(Perfect method response to f is achieved at parton level with events generated according to the LO matrix element for the 2→2 process)

Representative MC simulations, see backup for all

Extracting signal fraction from data

- We measure (after calibration):

Epoch	Final state	Signal fraction	$\sigma_{t\bar{t}}$ (pb)
Run IIa	e+jets	0.72	8.9
	μ+jets	0.65	7.8
Run IIb1	e+jets	0.77	7.6
	μ+jets	0.66	6.8
Run IIb2	e+jets	0.68	7.8
	μ+jets	0.66	7.5
Run IIb3	e+jets	0.56	7.6
	μ+jets	0.75	8.0
Run II	**e+jets**	**0.63**	**7.8**
	μ+jets	**0.70**	**7.6**

- Values in good agreement with $\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}$ pb [1]

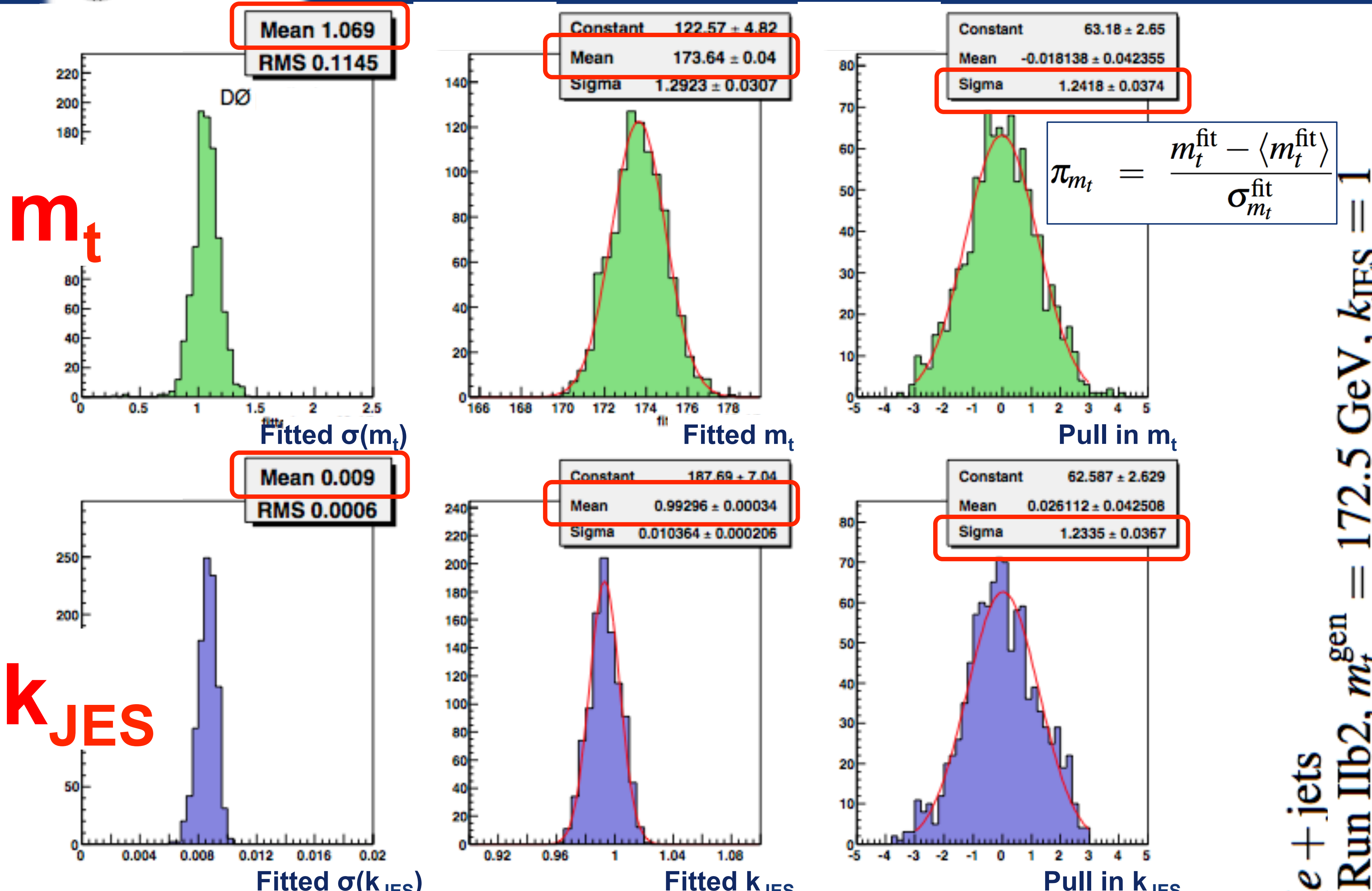
Typical statistical+calibration uncertainty on signal fraction: 1%, on σ_{tt}: about 0.1 pb

*[1] DØ Collaboration, Phys. Rev. D **84**, 012008 (2011).*

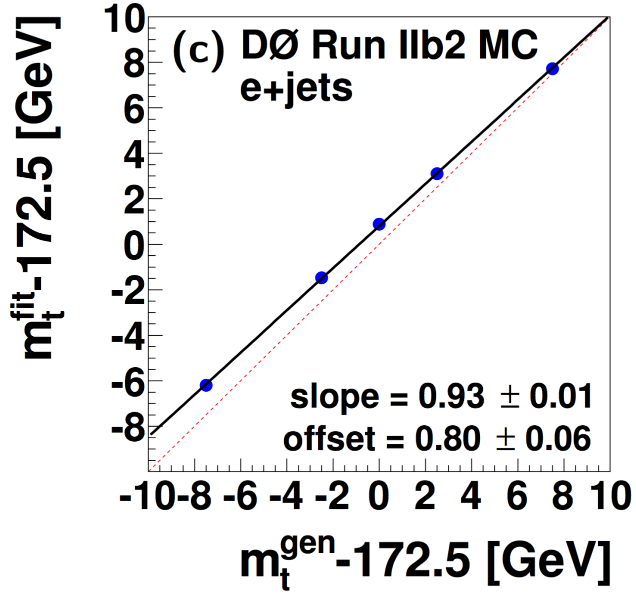
Calibration of method response in m_t, k_{JES}

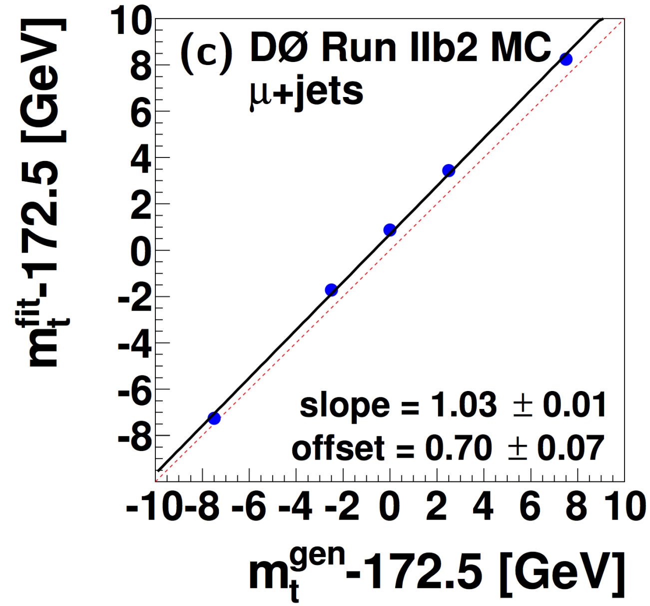
- For calibration of **method response in m_t and k_{JES}**:
  - Construct PEs according to the signal fractions measured for given epoch+channel
  - Vary N_{sig} in PEs according to binomial statistics
  - 1000 PEs performed at each calibration point
- Calibrate m_t with samples at
  - m_t = 165,170,172.5,175,180 GeV
  - k_{JES} = 1
- Calibrate k_{JES} with samples at
  - k_{JES} = 0.95, 1, 1.05
  - m_t = 172.5 GeV
  - k_{JES} variation is done for background as well

Calibration of method response in m_t, k_{JES}

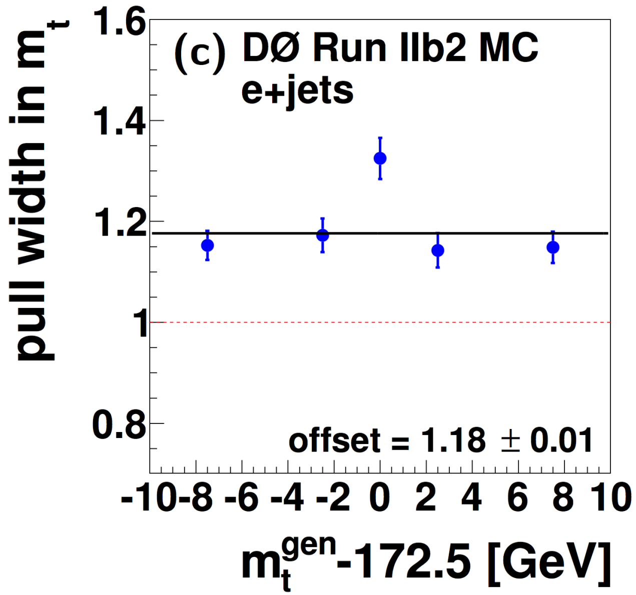


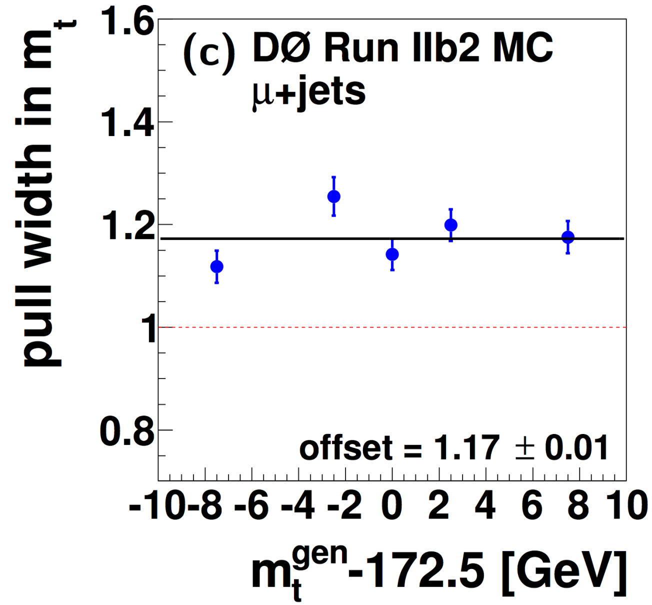
Calibration of method response in m_t





Calibrate m_t & $\sigma(m_t)$

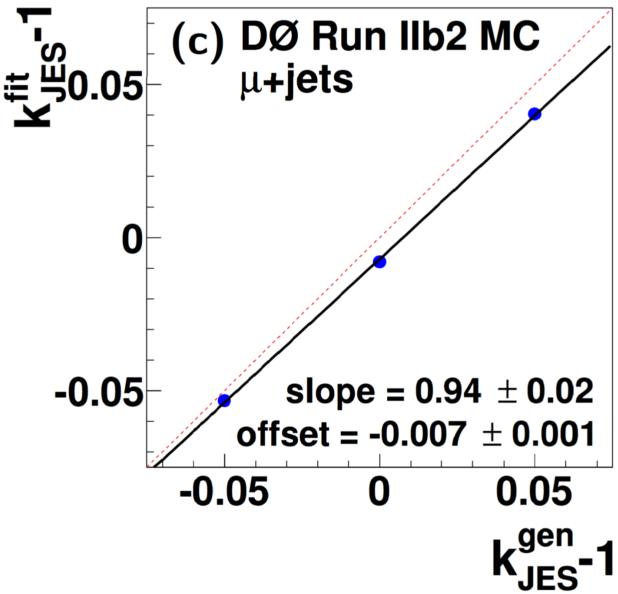


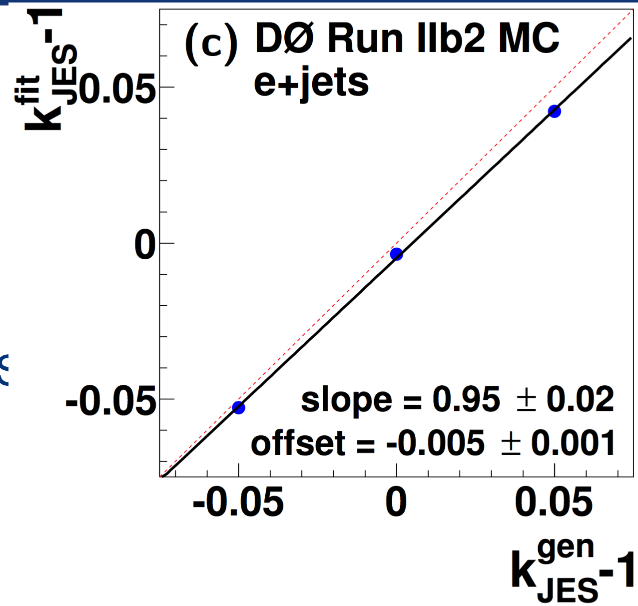


Calibrate $\sigma(m_t)$

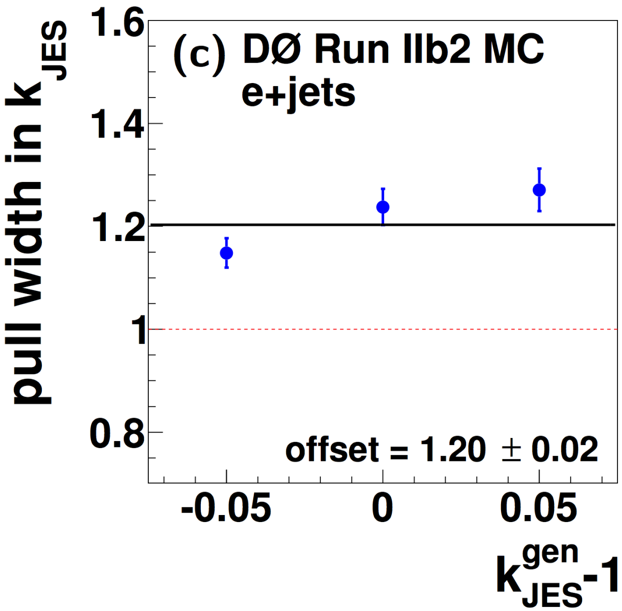
Representative MC simulations for Run IIb2 data
→ cf. backup for others

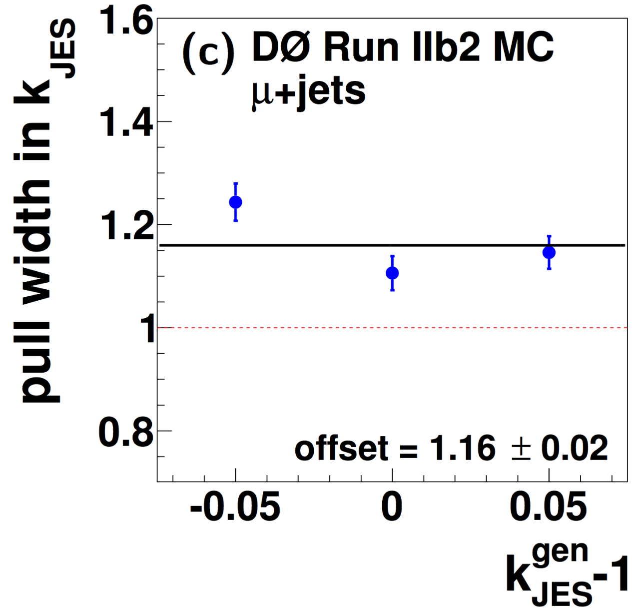
Calibration of method response in k_{JES}





Calibrate k_{JES} & $\sigma(k_{JES})$





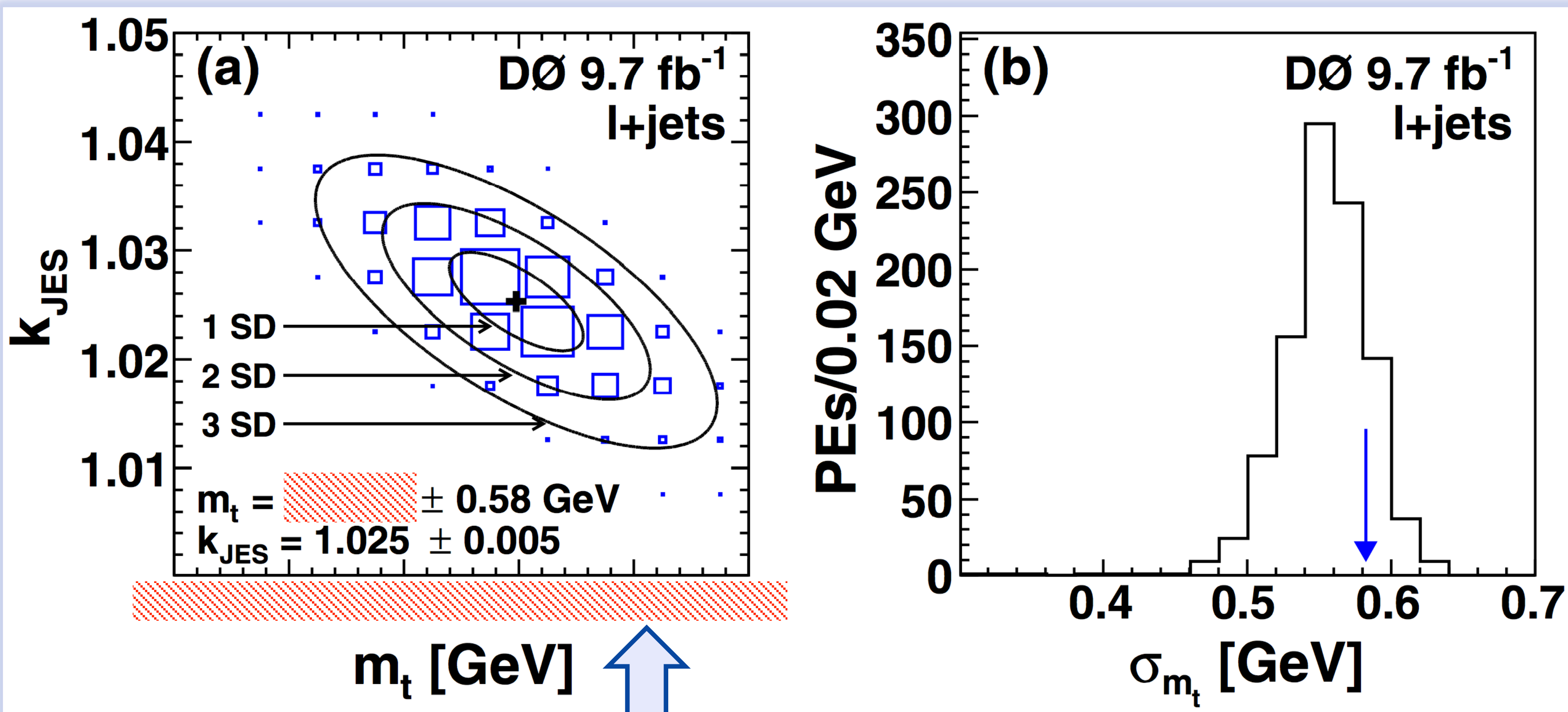
Calibrate $\sigma(k_{JES})$

Representative MC simulations for Run IIb2 data

→ cf. backup for others

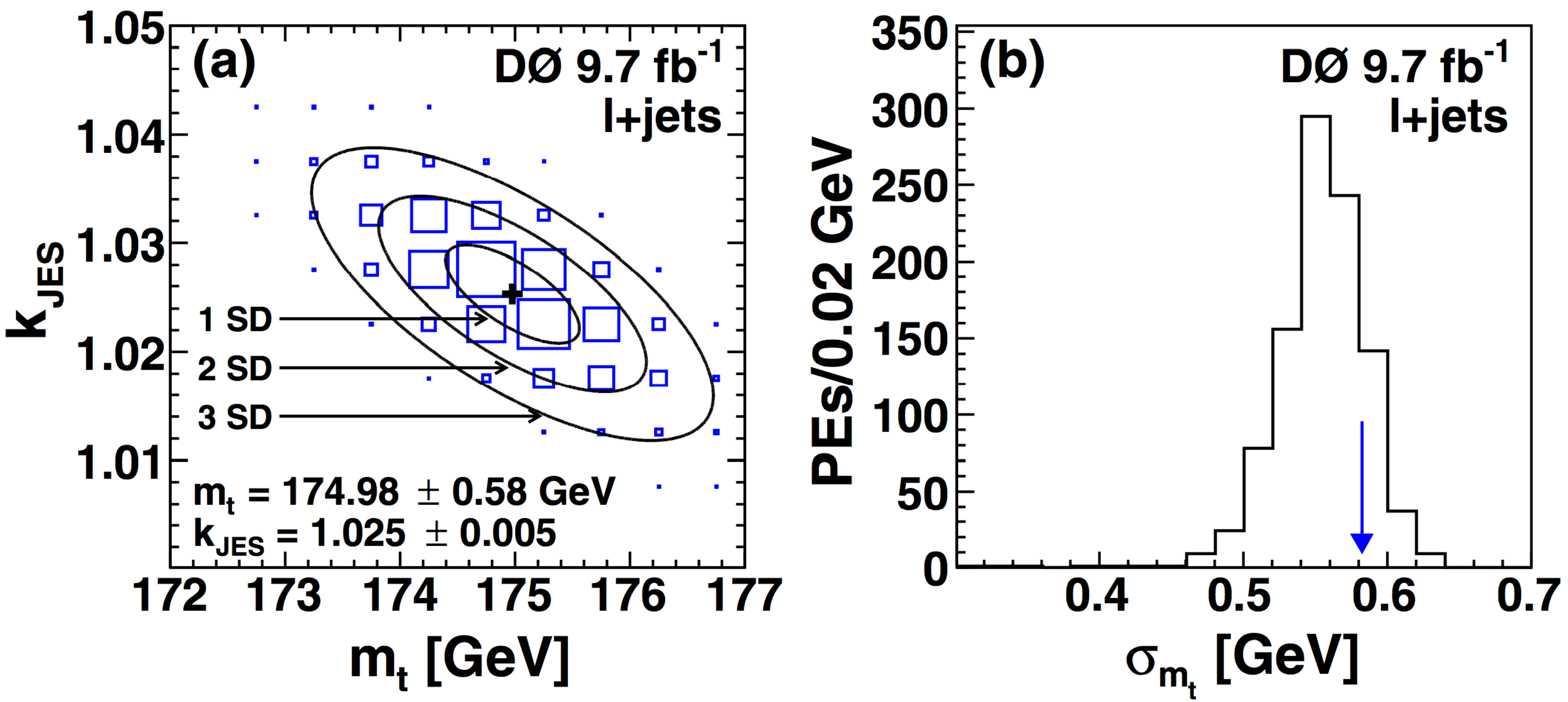
Result

Result



Data analysis was performed blinded in m_t by adding an offset drawn from [-2 GeV, 2 GeV] around 172.3 GeV (World average) according to a uniform prior

Result



Data analysis was unblinded in last stages of review

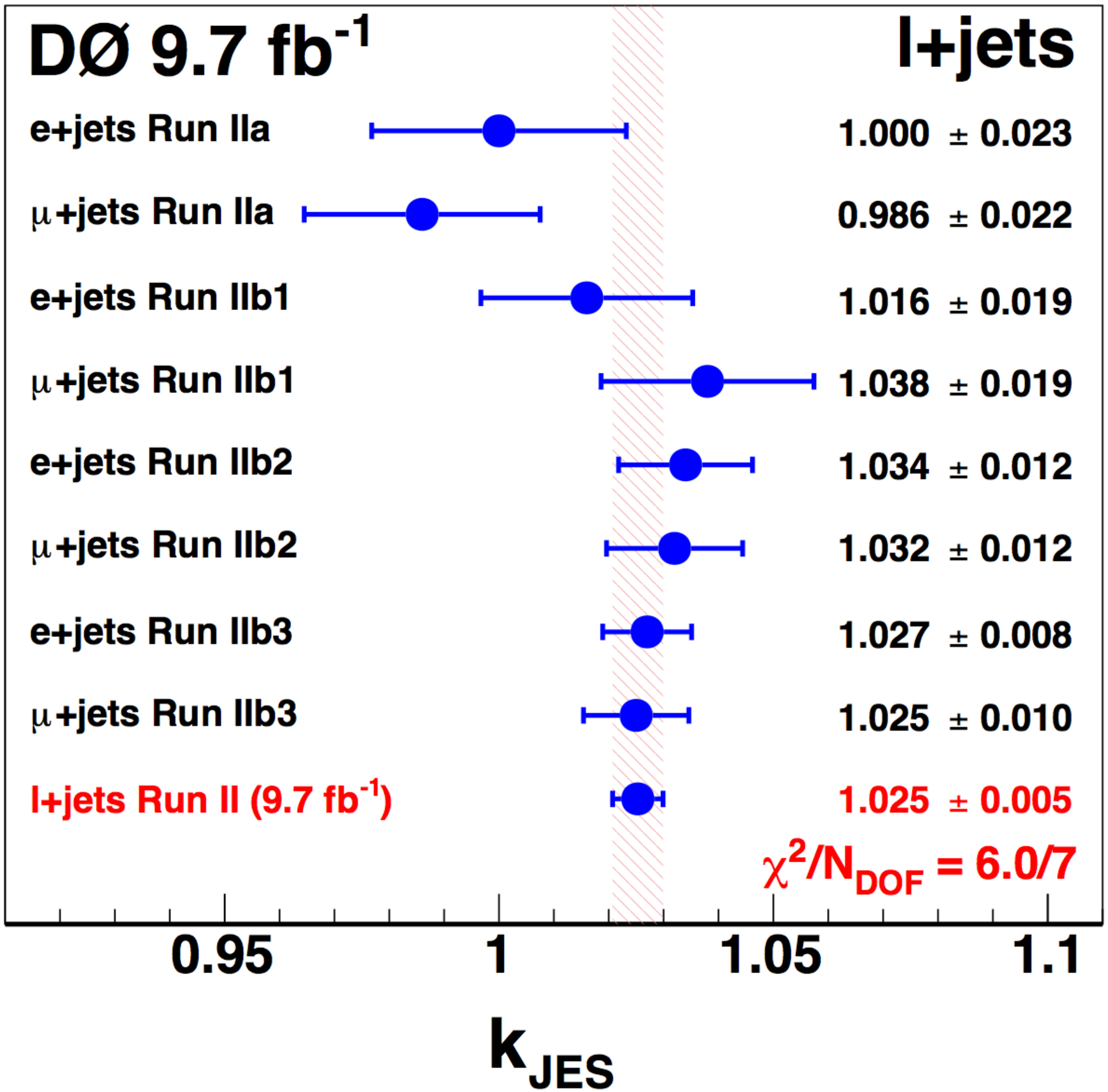
Final result in l+jets final states using the full Run II dataset of 9.7 fb^{-1} (statistical uncertainty only)

$$m_t = 174.98 \pm 0.41\,(\text{stat}) \pm 0.41\,(\text{JES})\ \text{GeV}.$$

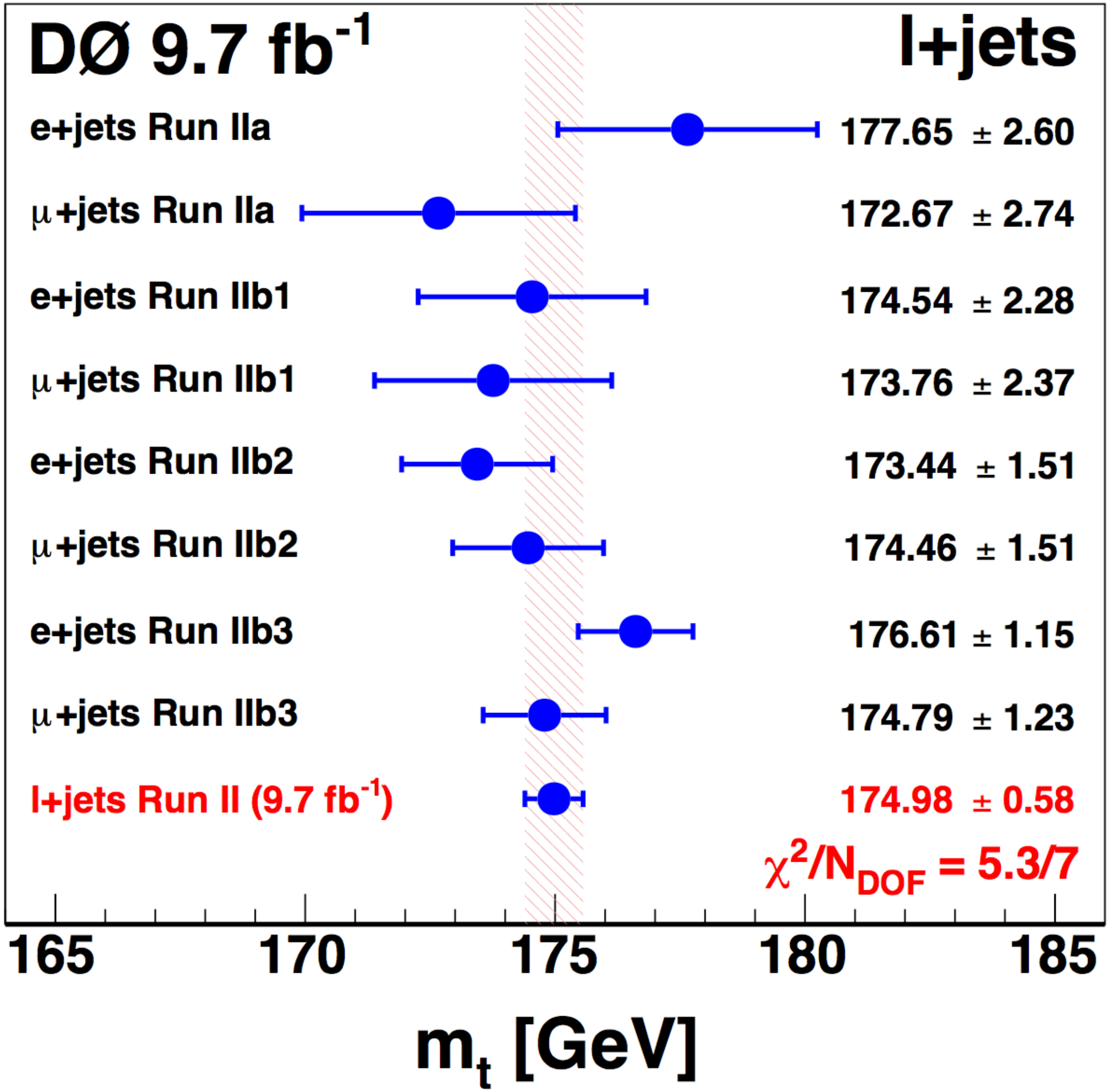
Summary per final state

$$\begin{aligned}
\ell+\text{jets, final} &: & m_t &= 174.98 \pm 0.58\ (\text{stat+JES})\ \text{GeV}, \\
& & k_{\text{JES}} &= 1.025 \pm 0.005\ (\text{stat}); \\
e+\text{jets, final} &: & m_t &= 175.55 \pm 0.81\ (\text{stat+JES})\ \text{GeV}; \\
& & k_{\text{JES}} &= 1.026 \pm 0.006\ (\text{stat}); \\
\mu+\text{jets, final} &: & m_t &= 174.36 \pm 0.84\ (\text{stat+JES})\ \text{GeV}. \\
& & k_{\text{JES}} &= 1.025 \pm 0.007\ (\text{stat});
\end{aligned}$$

Results per data taking epoch & channel



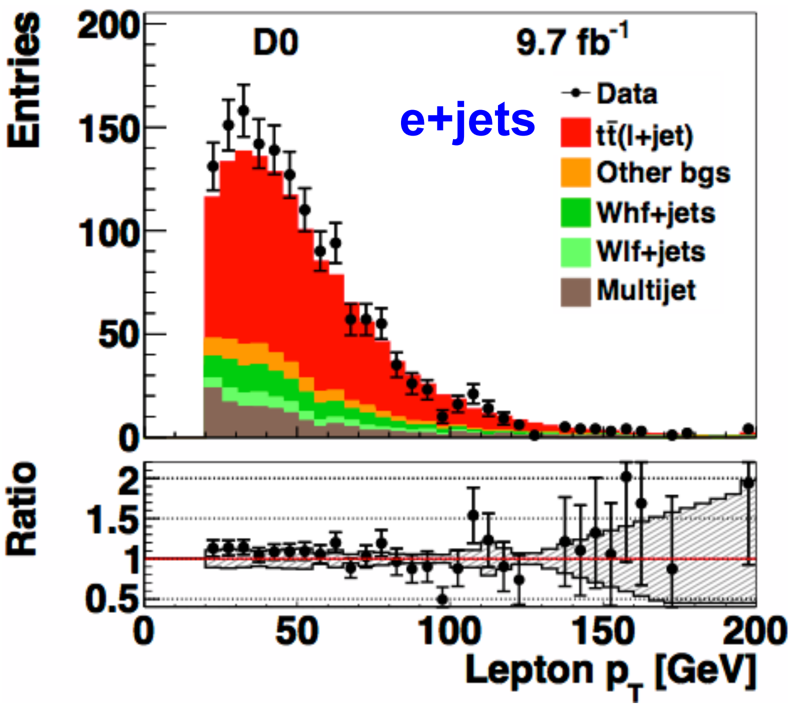
Results per data taking epoch & channel

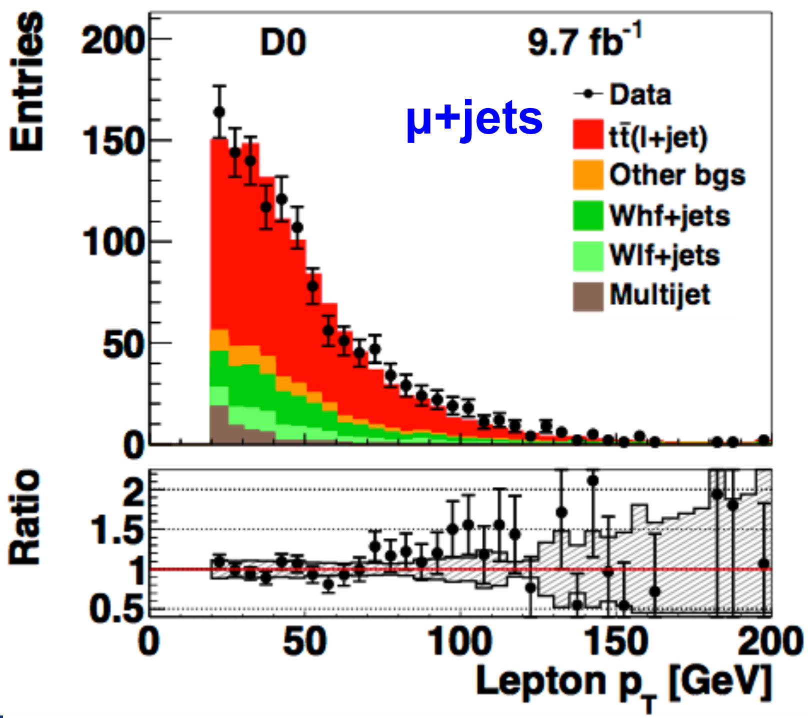


Data/MC comparisons for best fit m_t, k_{JES}, and f

Data/MC comparisons

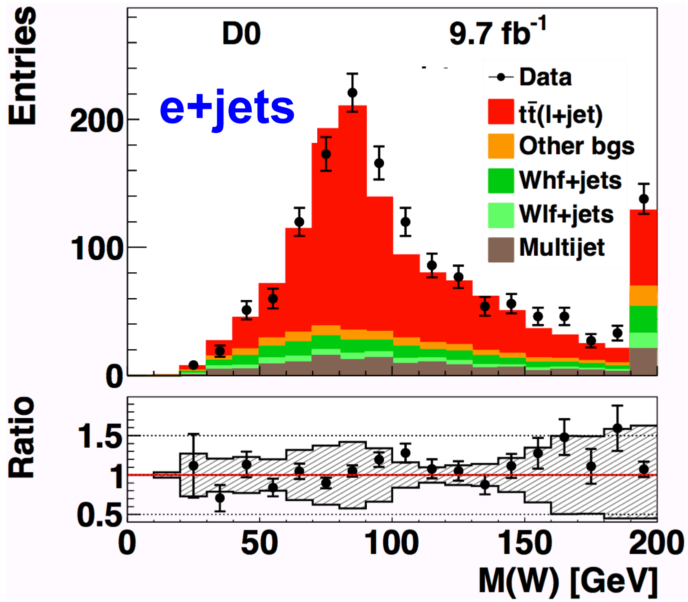
- In the following, showing "post-fit" data/MC comparison plots
  - Use cross sections fitted with the ME technique:
    - 7.8 pb for e+jets
    - 7.6 pb for μ+jets
  - Use $t\bar{t}$ simulations with m_t = 175 GeV, k_{JES}=1.025

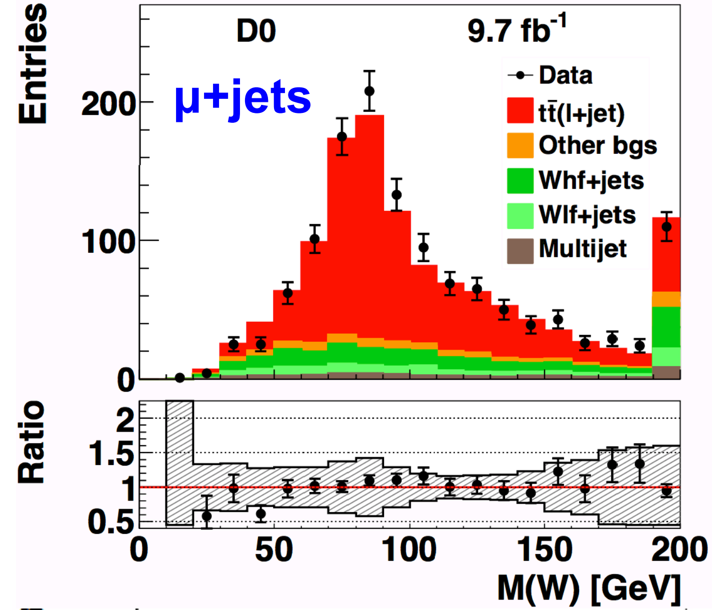


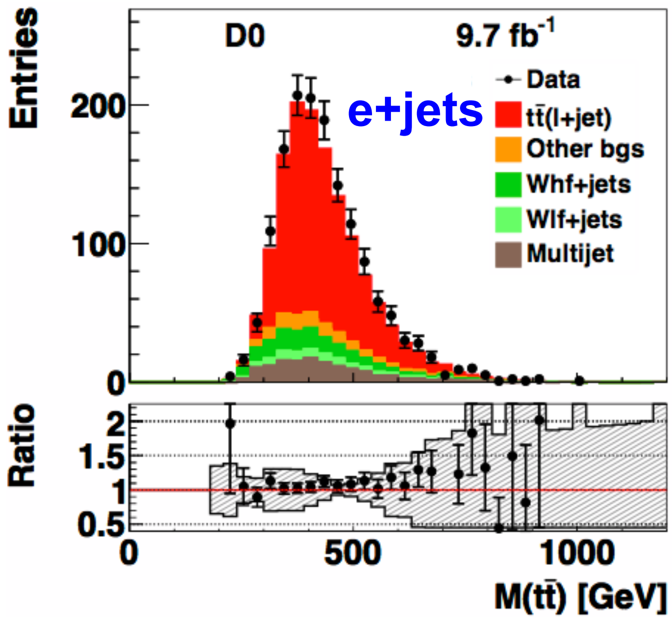


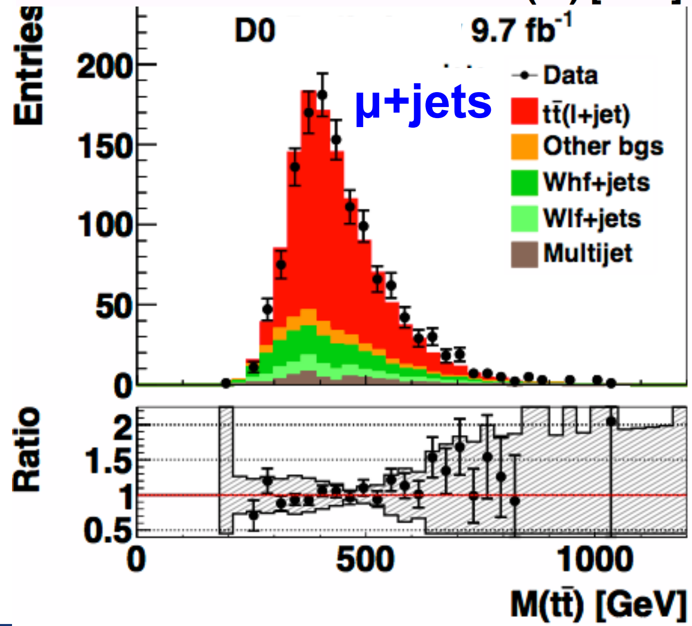
More data/MC comparisons in backup

Data/MC comparisons









More data/MC comparisons in backup

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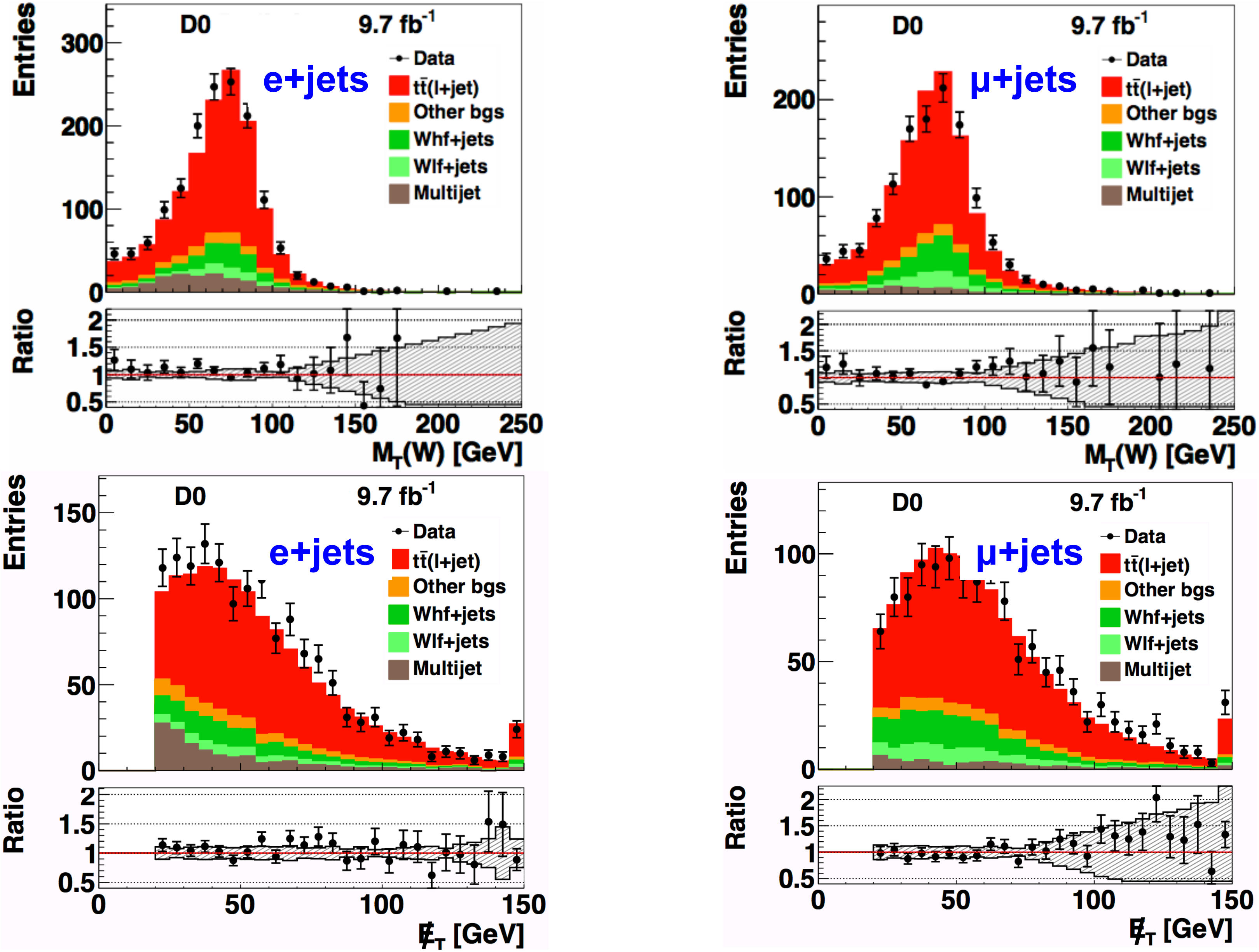
Data/MC comparisons



More data/MC comparisons in backup

Systematic uncertainties

Systematic uncertainties

- **Procedures:**
  - Construct pseudo-experiments identically to the default calibration:
    - including dominant W+jets background
    - Method related uncertainties also include next-to-dominant MJ background
  - For four signal modeling uncertainties:
    - Compare different models for m_t=172.5 GeV, k_{JES}=1
    - Stat. uncert. $\mathcal{O}$(0.05 GeV)
  - For all other uncertainties, re-derive calibration
    - Stat. uncert. $\mathcal{O}$(0.01 GeV)
- Discuss **refinements** in the following:
  1. Uncertainty due to limited size of MC samples
  2. New calibration of the detector
  3. Refined treatment of signal modeling uncertainties

Refinement from increased MC samples

This measurement

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections*	0.15
Initial/final state radiation*	0.09
Hadronization & 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
Data-MC jet response difference	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	[illegible]
Total statistical uncertainty	[illegible]
Total uncertainty	[illegible]

*Result using 3.6 fb^{-1}: DØ Coll., PRD **84**, 032004 (2011)*

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

Note: for a given source of uncertainty, we cite:
max{ statistical uncertainty, |face value of systematic| }

Refinement from new calibrations

This measurement

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections*	0.15
Initial/final state radiation*	0.09
Hadronization & 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
Data-MC jet response difference	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	[illegible]
Total statistical uncertainty	[illegible]
Total uncertainty	[illegible]

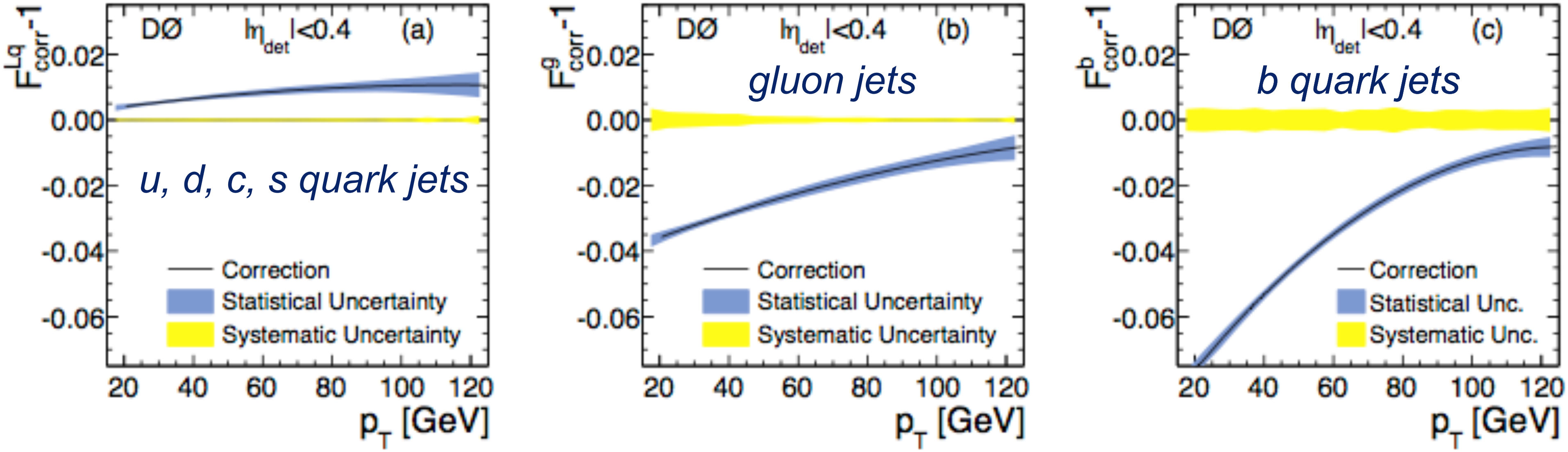
*Result using 3.6 fb^{-1}: DØ Coll., PRD **84**, 032004 (2011)*

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

Also here we profit from the increased size of calibration samples

Flavor dependent response

- **Use new JES calibration including flavour-dependent response correction as integral part [1]:**



- **→ Uncertainty from flavor-dependent response:**
  - **0.16 GeV** (was 0.28 GeV)
- **This uncertainty accounts for JES difference between light quark jets and b quark jets**

[1] *in the previous measurement (DØ Coll., PRD **84**, 032004 (2011)), the flavour-dependent response correction was used as an a posteriori correction.*

Refinement from $t\bar{t}$ signal modeling

This measurement

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections*	0.15
Initial/final state radiation*	0.09
Hadronization & UE*	0.26
Color reconnection*	0.10
Multiple $p\bar{p}$ interactions	0.06
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b-jet modeling	0.09
PDF uncertainty	0.11
Detector modeling:	
Residual jet energy scale	0.21
Data-MC jet response difference	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	
Total statistical uncertainty	
Total uncertainty	

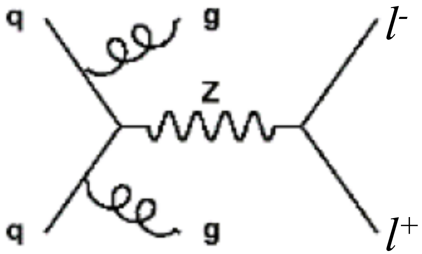
*Result using 3.6 fb^{-1}: DØ Coll., PRD **84**, 032004 (2011)*

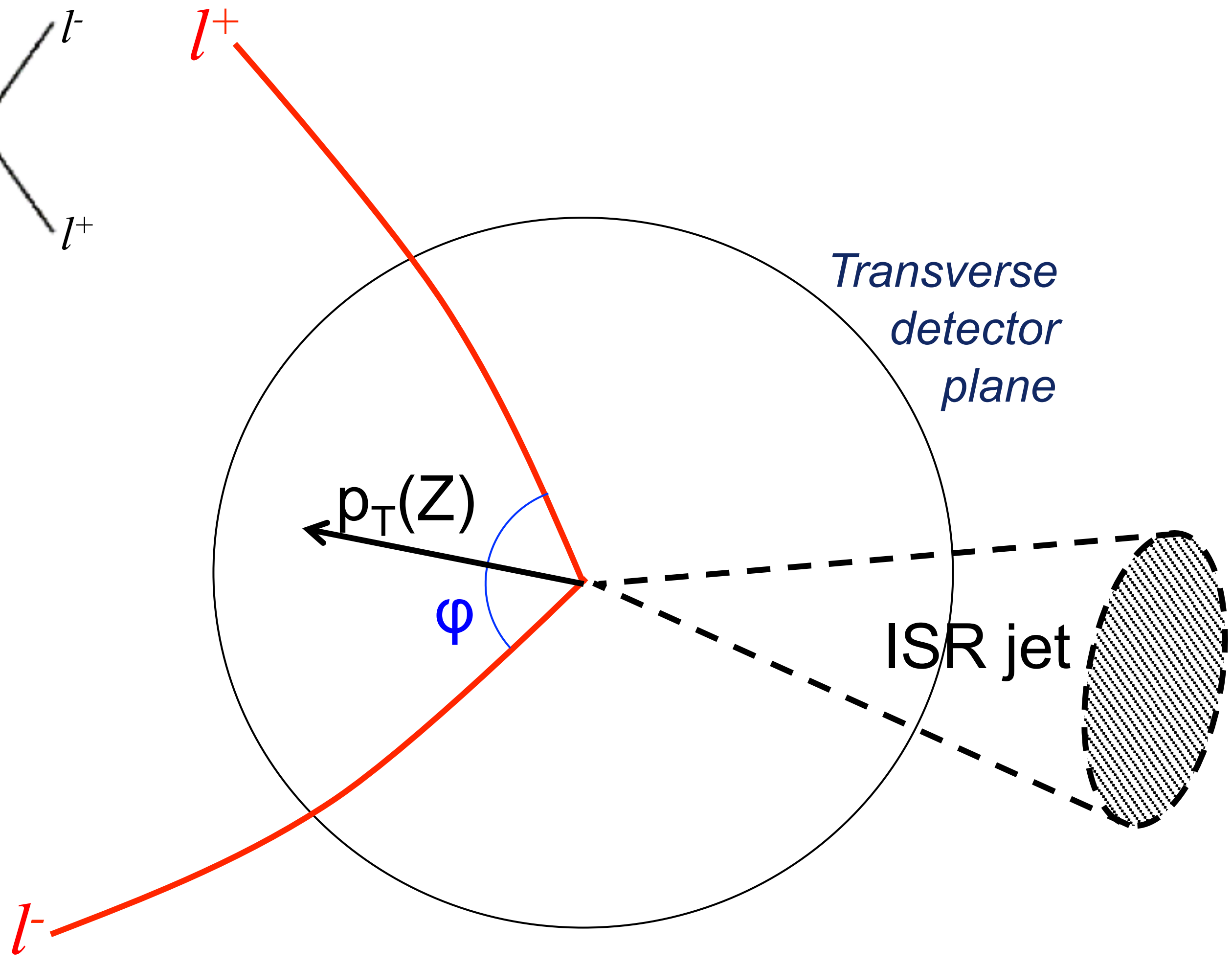
Source	Uncertainty (GeV)
Modeling of production:	
Modeling of signal:	
Higher-order effects	±0.25
ISR/FSR	±0.26
Hadronization and UE	±0.58
Color reconnection	±0.28
Multiple $p\bar{p}$ interactions	±0.07
Modeling of background	±0.16
W+jets heavy-flavor scale factor	±0.07
Modeling of b jets	±0.09
Choice 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

Also here we profit from the increased size of calibration samples

Initial/final state radiation

- Constrain ISR/FSR by studying Drell-Yan events
  - Measurement of $p_T(Z)$ using φ* variable [1]

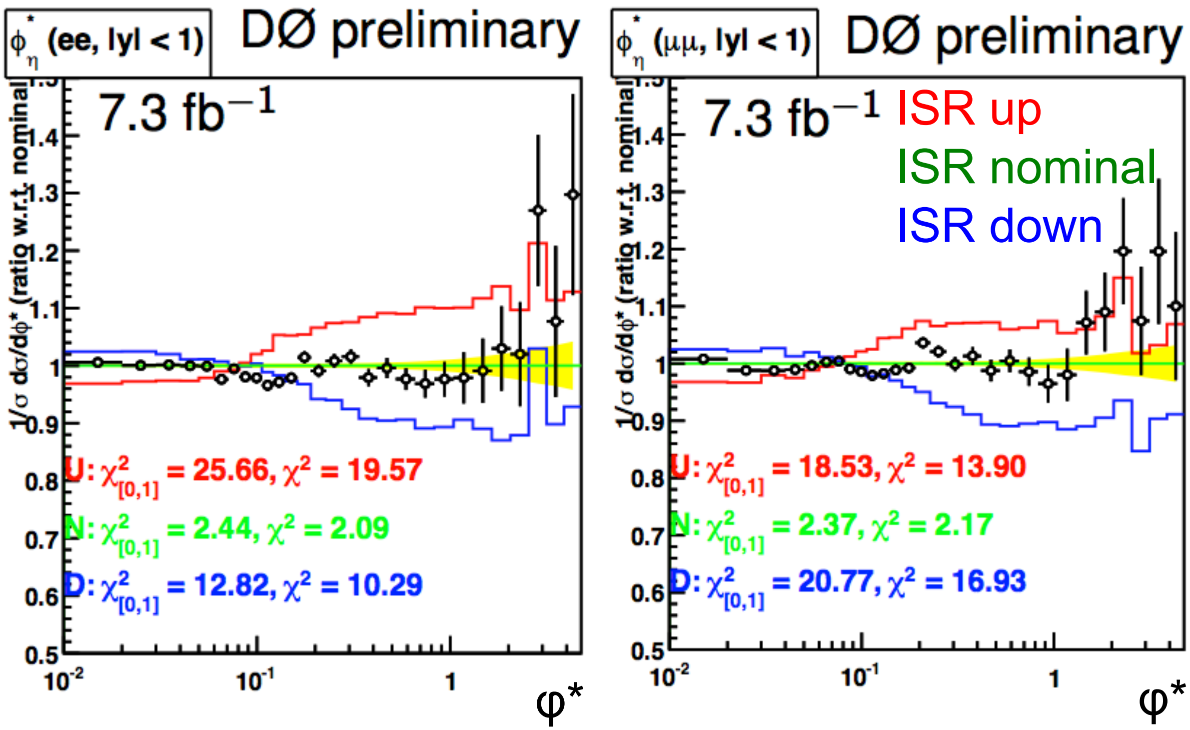




[1] DØ Coll., PRL **106**, 122001 (2011)

Initial/final state radiation

- Constrain **ISR/FSR by studying Drell-Yan** events
  - Measurement of $p_T(Z)$ using φ^* variable [1]
- Vary ISR/FSR via **CKKW renormalization scale in alpgen** (`ktfac`), as suggested in [2]
  - `ktfac` variations by **±1.5** cover excursions of MC from data



Also tune in other kinematic regions:
- 1<|y|<2
- |y|>2

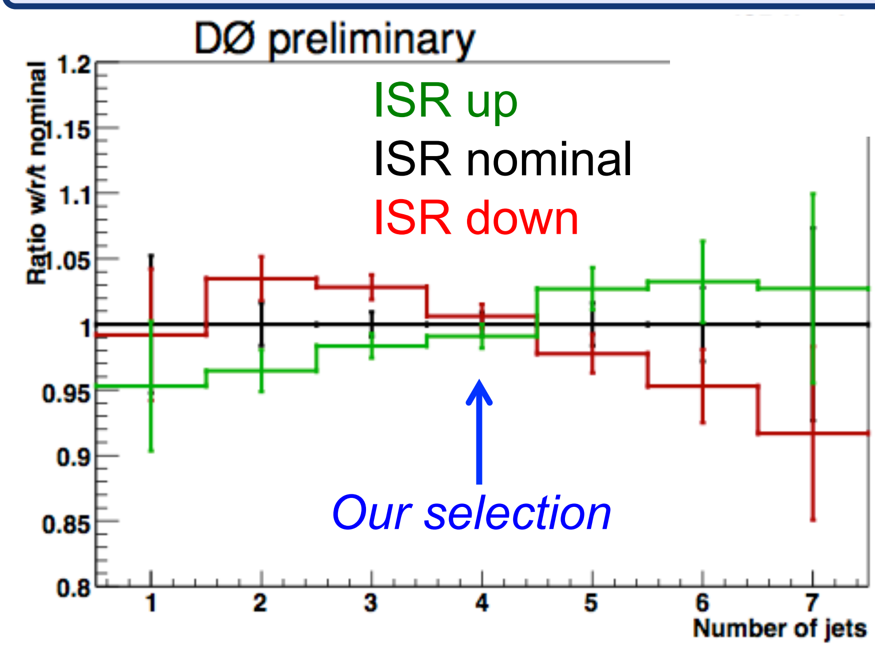
(cf. backup)

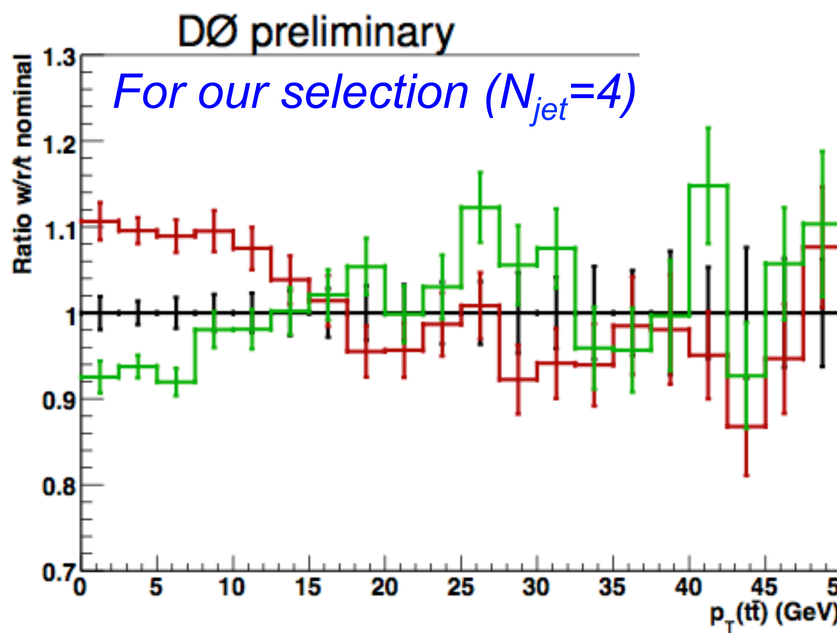
[1] DØ Coll., PRL **106**, 122001 (2011)
[2] M. Mangano, P. Skands et al, EPJ **C72** 2078 (2012)

Initial/final state radiation

- Constrain **ISR/FSR by studying Drell-Yan** events
  - Measurement of $p_T(Z)$ using φ^* variable [1]
- Vary ISR/FSR via **CKKW renormalization scale in alpgen** (`ktfac`), as suggested in [2]
  - `ktfac` variations by **±1.5** cover excursions of MC from data

The effect of ISR/FSR variations in top-antitop events

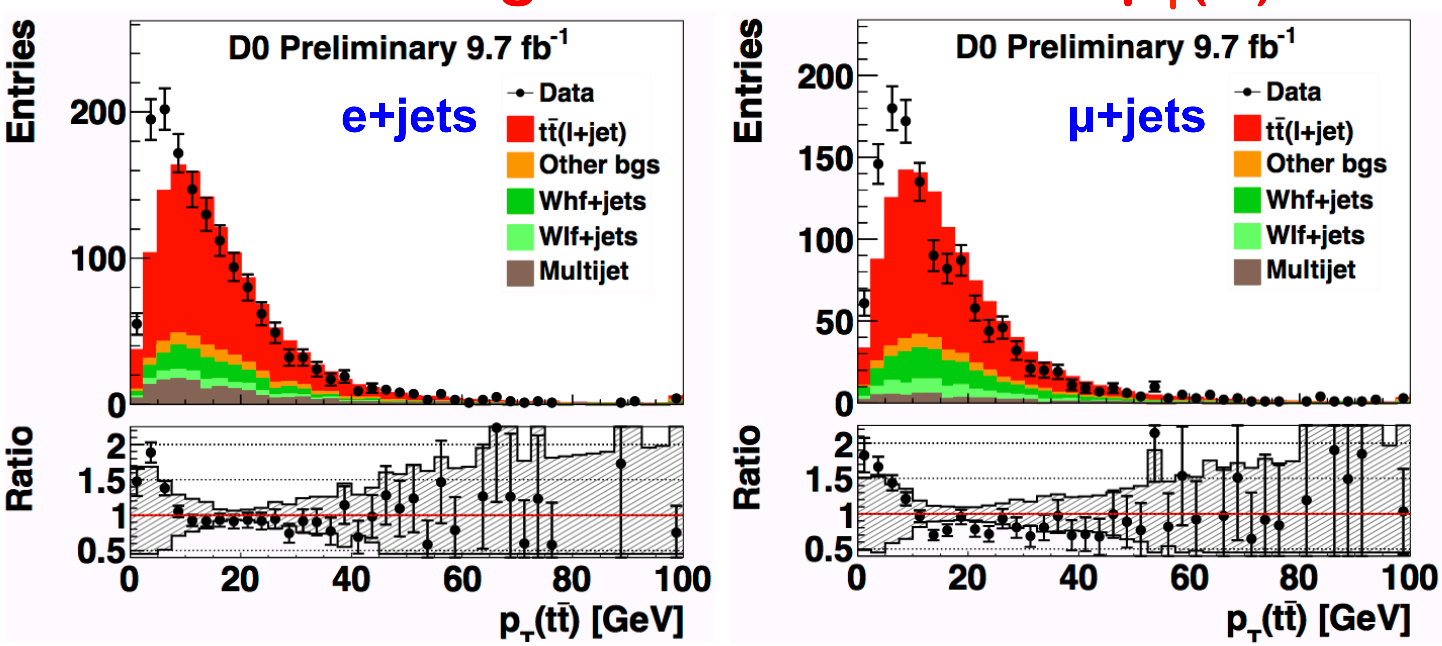




[1] DØ Coll., PRL **106**, 122001 (2011)
[2] M. Mangano, P. Skands et al, EPJ **C72** 2078 (2012)

Initial/final state radiation

- Constrain **ISR/FSR by studying Drell-Yan events**
    - Measurement of $p_T(Z)$ using φ^* variable [1]
  - Vary ISR/FSR via **CKKW renormalization scale in alpgen** (`ktfac`), as suggested in [2]
    - `ktfac` variations by **±1.5** cover excursions of MC from data
- In addition: **reweight $t\bar{t}$ simulations in $p_T(t\bar{t})$ to data**



  - Effect may be related to ISR/FSR mismodelling

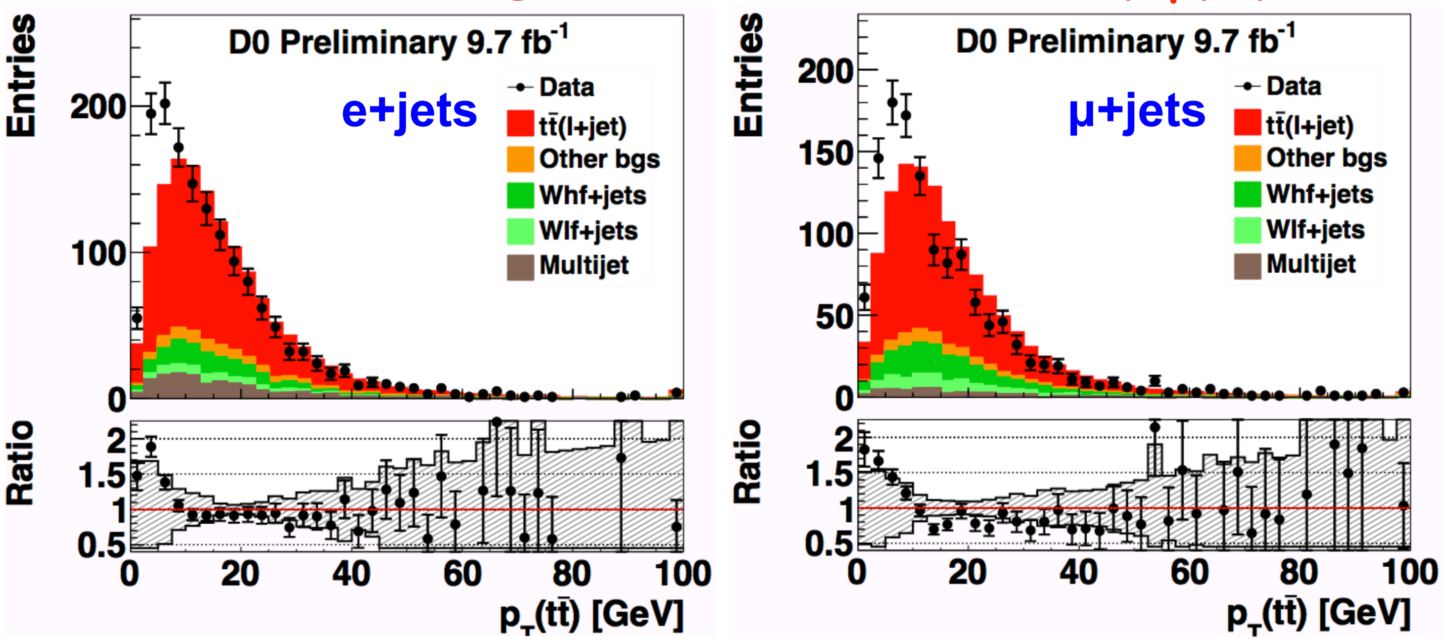
[1] DØ Coll., PRL **106**, 122001 (2011)
[2] M. Mangano, P. Skands et al, EPJ **C72** 2078 (2012)

Initial/final state radiation (0.09 GeV)

- Constrain ISR/FSR by studying Drell-Yan events
  - Measurement of $p_T(Z)$ using φ* variable [1]
- Vary ISR/FSR via CKKW renormalization scale in alpgen (ktfac), as suggested in [2]
  - ktfac variations by ±1.5 cover excursions of MC

0.06 GeV

- In addition: reweight $t\bar{t}$ simulations in $p_T(t\bar{t})$ to data



- Effect may be related to ISR/FSR mismodelling

0.07 GeV

Refinement from $t\bar{t}$ signal modeling

This measurement

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections*	0.15
Initial/final state radiation*	0.09
Hadronization & 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
Data-MC jet response difference	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	
Total statistical uncertainty	
Total uncertainty	

Source	Uncertainty (GeV)
Modeling of production:	
Modeling of signal:	
Higher-order effects	±0.25
ISR/FSR	±0.26
Hadronization and UE	±0.58
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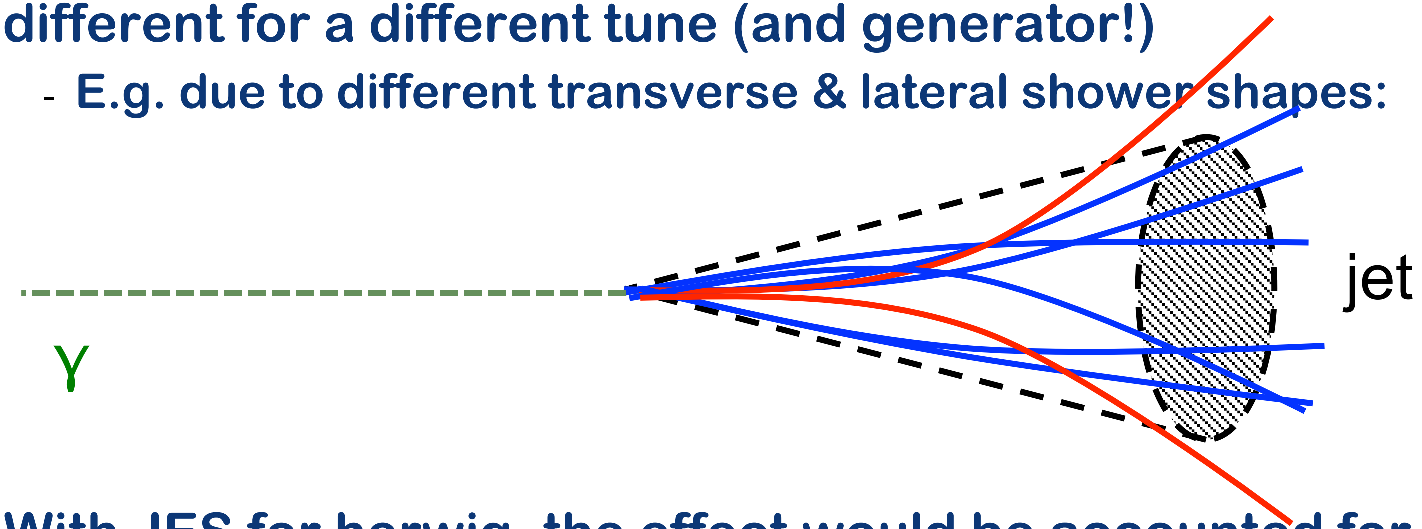
Signal fraction	±0.10
MC calibration	±0.20
Total	±1.02

*Result using 3.6 fb^{-1}: DØ Coll., PRD **84**, 032004 (2011)*

Also here we profit from the increased size of calibration samples

Hadronization and underlying event

- Compare alpgen+herwig vs alpgen+pythia (default)
- Combination of two effects:
  1. The actual effect we are interested in
  2. Component from different JES (differential in p_T,η)
     - Strictly, our JES is valid only for pythia with D0 Tune A
     - One can argue from first principles that JES will be different for a different tune (and generator!)
       - E.g. due to different transverse & lateral shower shapes:



     - With JES for herwig, the effect would be accounted for
       - Factorize uncertainties to avoid double-counting:
         - We have an uncertainty for dependence of JES on p_T,η…

Hadronization and underlying event

- Factor out the component from different JES
  - Evaluate using the momenta of particle level jets matched to detector level jets with $\Delta R=0.25=R_{cone}/2$
  - Apply default selection at detector level
    - → minimize bias from acceptance etc.
- We also factor out the effect of different $p_T(t\bar{t})$ in:
    - Default (alpgen+pythia)
    - Alternative model (alpgen+herwig)
  - Achieved by reweighting default simulation in $p_T(t\bar{t})$ to match the alternative model
  - This effect is already taken into account in ISR/FSR uncertainty
- → Hadronization and underlying event uncertainty:
  - 0.26 GeV (was: 0.58 GeV)

Refinement from $t\bar{t}$ signal modeling

This measurement

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections*	0.15
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Total statistical uncertainty	
Total uncertainty	

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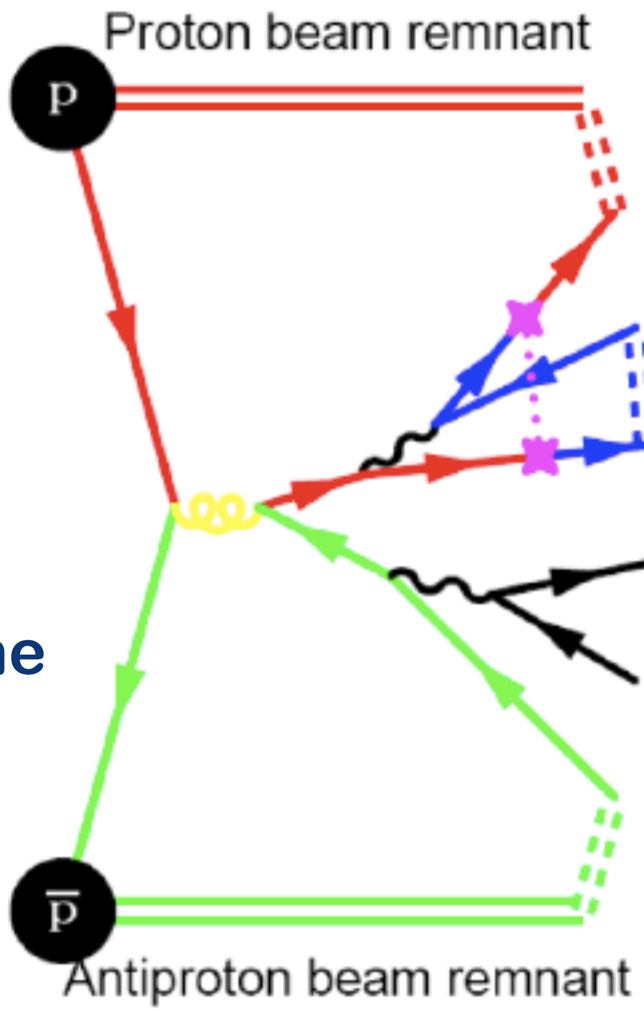
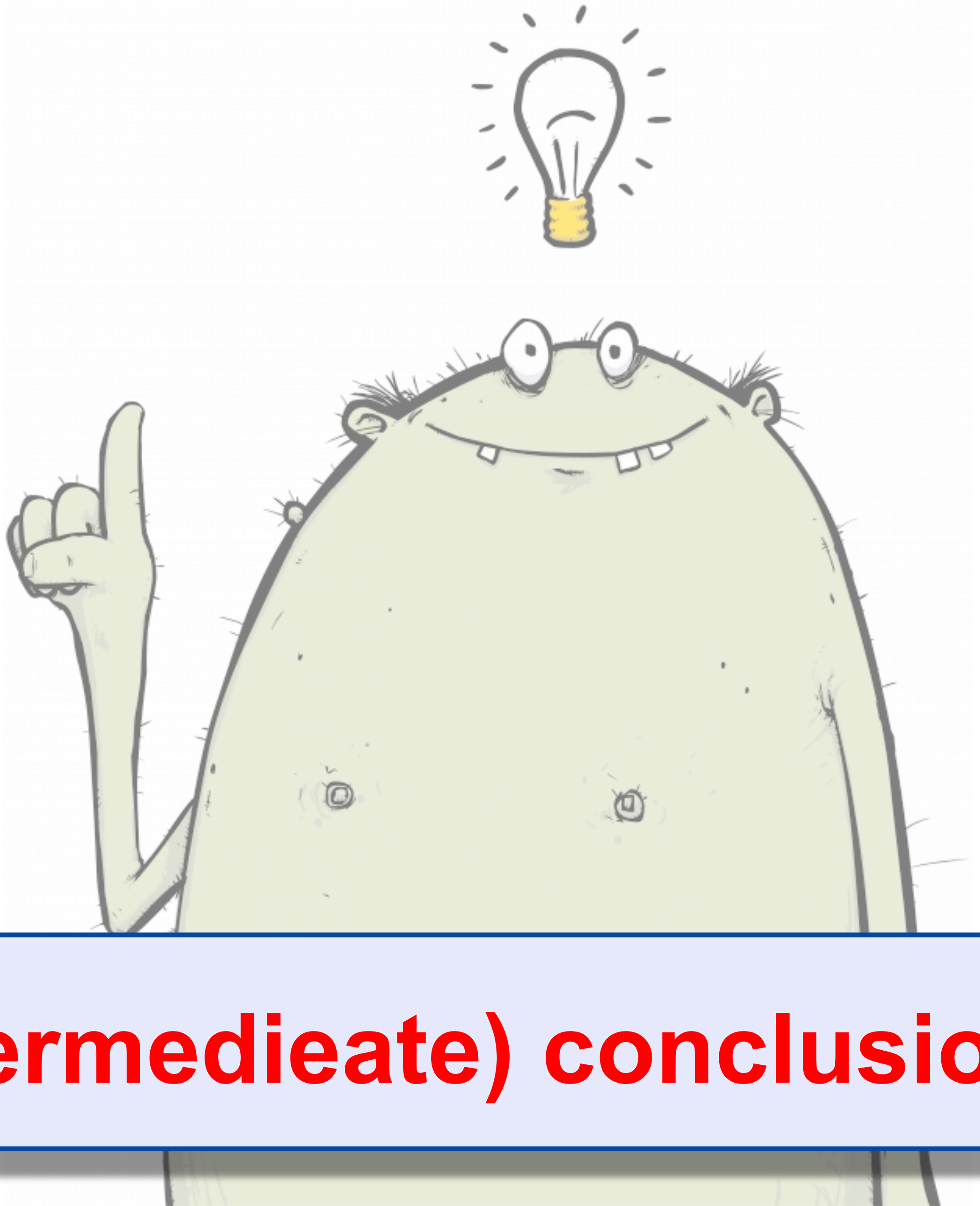
Method:	
Multijet contamination	±0.14
Signal fraction	±0.10
MC calibration	±0.20
Total	±1.02

Also here we profit from the increased size of calibration samples

Color reconnection

- Use new color reconnection model:
  - Parametrises colour string survival probability in terms of the rapidity difference of beginning and end of color string
  - Old crude model:
    - ad-hoc breaking up of color connections with some probability
- Compare pythia with Perugia 2011 vs Perugia 2011NOCR tunes
- Use identical hard ME events for the comparison
- → Uncertainty from color reconnection:
  - 0.10 GeV (was: 0.28 GeV)





(Intermedieate) conclusions

Conclusions

Results of three years of hard work and countless studies…

This measurement

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections*	0.15
Initial/final state radiation*	0.09
Hadronization & UE*	0.26
Color reconnection*	0.10
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Heavy flavor scale factor	0.06
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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	
Total uncertainty	

1.02 GeV

0.49 GeV

*Result using 3.6 fb^{-1}: DØ Coll., PRD **84**, 032004 (2011)*

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

Conclusions

- Lots of work went into **refining** the evaluation of **systematic uncertainties** for this measurement:
  - 1) **Acceleration of the ME technique** by $\mathcal{O}(100)$:
    - Eliminate the statistical component from systematics
  - 2) For "free": the great work done by the **JES group**!!!
  - 3) **Refine the evaluation of uncertainties**
    - include new, modern models + factorise sources

Conclusions

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  - 3) **Refine the evaluation of uncertainties**
    - include new, modern models + factorise sources

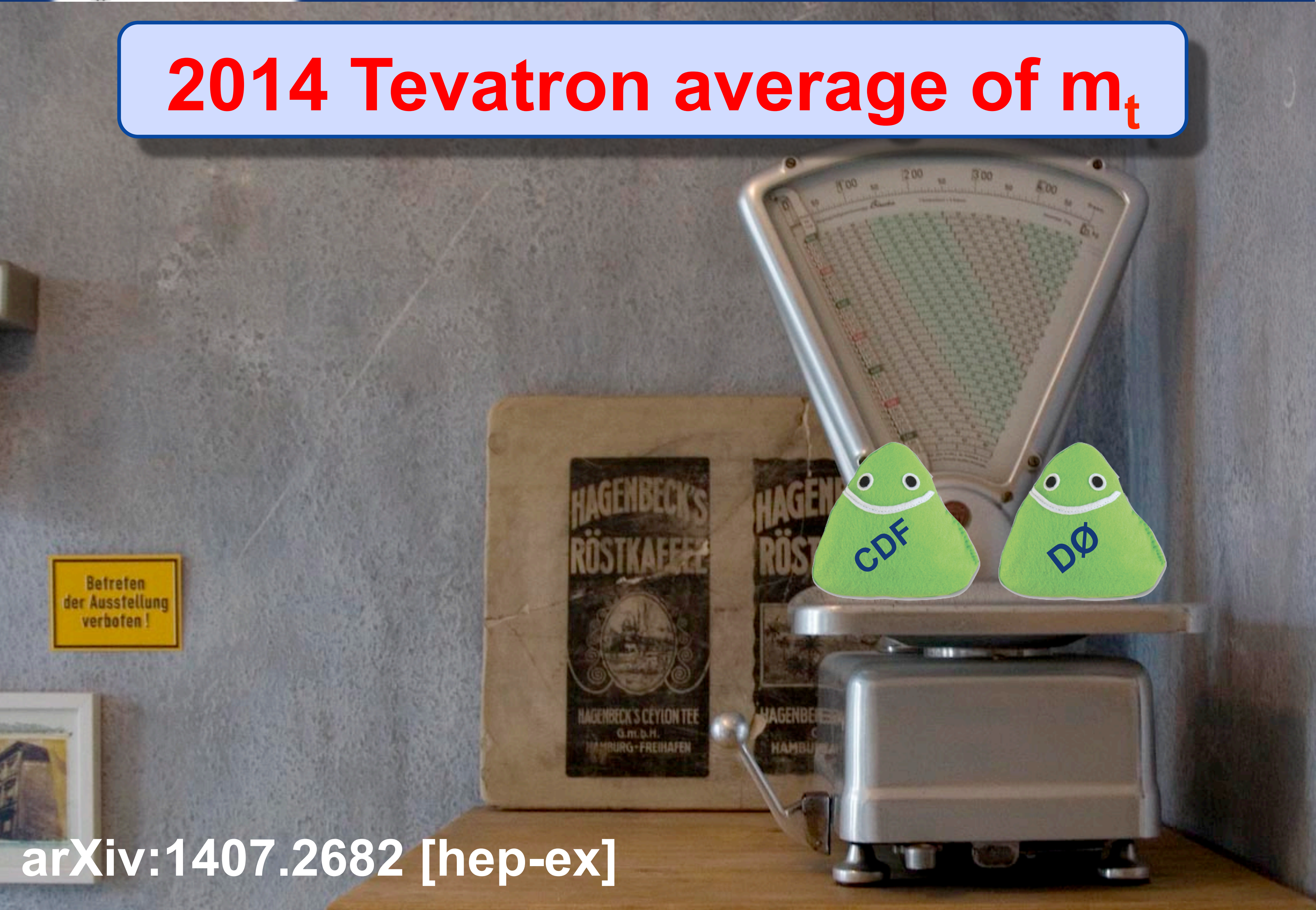
$$m_t = 174.98 \pm 0.76 \text{ GeV} \quad \mathbf{0.43\%}$$

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

0.44% - Most precise @ LHC: $172.04 \pm 0.19\ (\text{stat.+JSF}) \pm 0.75\ (\text{syst.})$ GeV.

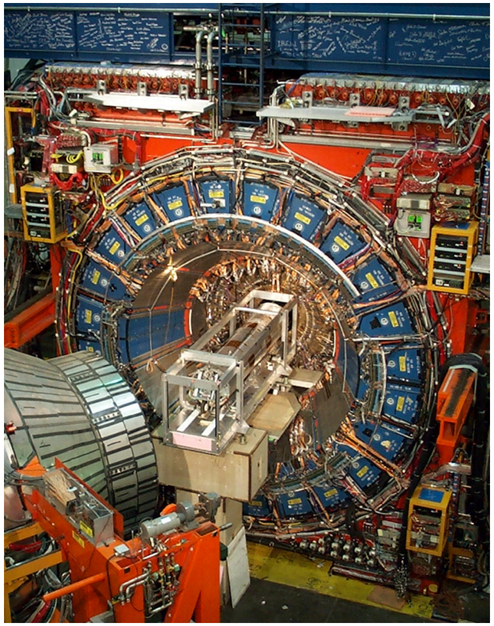
0.64% - 2nd most precise @ Tevatron: $172.9 \pm 0.5\ (\text{stat}) \pm 1.0\ (\text{syst})$ GeV

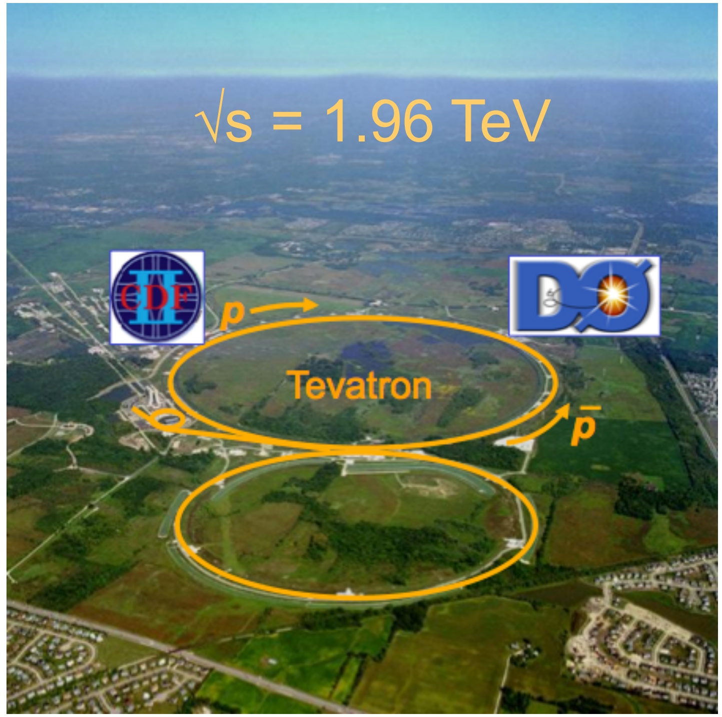
2014 Tevatron average of m_t



arXiv:1407.2682 [hep-ex]

Tevatron average: input measurements





- **Run I:**
  - **PRD 63, 032003 (2001)** [CDF l+jets, 0.1 fb^{-1}]
  - Nature 429, 638 (2004) [DØ l+jets, 0.1 fb^{-1}]
  - PRL 82, 271 (1999) [CDF dilep., 0.1 fb^{-1}]
  - PRL 80, 2063 (1998) [DØ dilep., 0.1 fb^{-1}]
  - PRL 79, 1992 (1997) [CDF all-jets, 0.1 fb^{-1}]
- **Run II:**
  - PRL 109, 152003 (2012) [CDF l+jets, 8.7 fb^{-1}]
  - PRL 113, 032002 (2014) [DØ l+jets, 9.7 fb^{-1}]
  - CDF-Conf 11072 (2014) [CDF dilep., 9.1 fb^{-1}]
  - PRD 86, 051103 (2012) [DØ dilepton 5.4 fb^{-1}]
  - CDF-Conf 11084 (2014) [CDF all-jets, 9.3 fb^{-1}]
  - PRD 88, 011101 (2013) [CDF E_T+jets, 8.7 fb^{-1}]
  - PRD 81 032002 (2009) [CDF L_{xy}, 1.9 fb^{-1}]

arXiv:1407.2682 [hep-ex]

Tevatron average: inputs

	Run I published					Run II published					Run II prel.	
	CDF			DØ		CDF			DØ		CDF	
	ℓ+jets	$\ell\ell$	all-jets	ℓ+jets	$\ell\ell$	ℓ+jets	Lxy	MEt	ℓ+jets	$\ell\ell$	$\ell\ell$	all-jets
$\int \mathcal{L}\, dt$	0.1	0.1	0.1	0.1	0.1	8.7	1.9	8.7	9.7	5.4	9.1	9.3
Result	176.1	167.4	186.0	180.1	168.4	172.85	166.90	173.93	174.98	174.00	170.80	175.07
In situ light-jet calibration (iJES)	n/a	n/a	n/a	n/a	n/a	0.49	n/a	1.05	0.41	0.55	n/a	0.97
Response to $b/q/g$ jets (aJES)	n/a	n/a	n/a	0.0	0.0	0.09	0.00	0.10	0.16	0.40	0.18	0.02
Model for b jets (bJES)	0.6	0.8	0.6	0.7	0.7	0.16	0.00	0.17	0.09	0.20	0.28	0.20
Out-of-cone correction (cJES)	2.7	2.6	3.0	2.0	2.0	0.21	0.36	0.18	n/a	n/a	1.65	0.37
Light-jet response (1) (rJES)	3.4	2.7	4.0	n/a	n/a	0.48	0.24	0.40	n/a	n/a	1.72	0.42
Light-jet response (2) (dJES)	0.7	0.6	0.3	2.5	1.1	0.07	0.06	0.04	0.21	0.56	0.46	0.09
Lepton modeling (LepPt)	n/e	n/e	n/e	n/e	n/e	0.03	0.00	n/a	0.01	0.35	0.36	n/a
Signal modeling (Signal)	2.6	2.9	2.0	1.1	1.8	0.61	0.90	0.63	0.35	0.86	0.96	0.53
Jet modeling (DetMod)	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.07	0.50	0.00	0.00
b-tag modeling (b-tag)	0.4	0.0	0.0	0.0	0.0	0.03	0.00	0.03	0.10	0.00	0.05	0.04
Background from theory (BGMC)	1.3	0.3	0.0	1.0	1.1	0.12	0.80	0.00	0.06	0.00	0.30	0.00
Background based on data (BGData)	0.0	0.0	1.7	0.0	0.0	0.16	0.20	0.15	0.09	0.20	0.33	0.15
Calibration method (Method)	0.0	0.7	0.6	0.6	1.1	0.05	2.50	0.21	0.07	0.51	0.19	0.87
Offset (UN/MI)	n/a	n/a	n/a	1.3	1.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Multiple interactions model (MHI)	n/e	n/e	n/e	n/e	n/e	0.07	0.00	0.18	0.06	0.00	0.30	0.22
Systematic uncertainty (syst)	5.3	4.9	5.7	3.9	3.6	0.98	2.82	1.36	0.63	1.49	2.69	1.55
Statistical uncertainty (stat)	5.1	10.3	10.0	3.6	12.3	0.52	9.00	1.26	0.41	2.36	1.83	1.19
Total uncertainty	7.3	11.4	11.5	5.3	12.8	1.12	9.43	1.85	0.76	2.80	3.26	1.95

arXiv:1407.2682 [hep-ex]

Combination methodology

- The combination is performed using BLUE:
  - BLUE: Best Linear Unbiased Estimate
    - Obtain best unbiased estimate via linear combination of input measurements by minimising the total uncertainty on the combined result
  - Assume uncertainties are Gaussian
  - Use categories of uncertainties that are uncorrelated
  - For a given category of uncertainty:
    - take into account correlations between individual measurements

arXiv:1407.2682 [hep-ex]

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This is the tricky bit, discuss in the following + detailed cross-checks

arXiv:1407.2682 [hep-ex]

Categorisation of uncertainties

- **Jet energy scale (JES):**
  - iJES → statistical component (cf. next page)
  - aJES → response variations versus jet flavour
  - bJES → modelling of b quark jets
  - cJES → out-of-cone correction
  - dJES → response variations versus η and p_T
  - rJES → absolute response calibration (CDF)
- **Theory and signal modelling:**
  - Signal MC generator + associated PDF, hadronisation model, underlying event + colour reconnection
- **Detector modelling**
  - Detector resolution effects, reconstruction efficiencies, b-quark jet identification (b-tagging), …

arXiv:1407.2682 [hep-ex]

Correlations between uncertainties

Category	ρ_{all}	ρ_{CDF}	$\rho_{DØ}$	$\rho_{RunXCDF}$	$\rho_{RunXDØ}$	$\rho_{channel}$	$\rho_{chnlData}$
Stat	0	0	0	0	0	0	0
iJES	0	0	0	0	1	0	0
aJES	0	0	0	1	1	0	0
bJES	1	1	1	1	1	1	1
cJES	1	1	1	1	1	1	1
rJES	0	1	1	1	1	0	0
dJES	0	0	0	1	1	0	0
LepPt	0	0	0	1	1	0	0
Signal	1	1	1	1	1	1	1
DetMod	0	1	1	1	1	0	0
B-tag	0	0	0	1	1	0	0
BGMC	0	0	0	0	0	1	0
BGData	0	0	0	0	0	0	1
Method	0	0	0	0	0	0	0
Offset	0	1	1	1	1	0	0
MHI (pile-up)	0	0	0	1	1	0	0

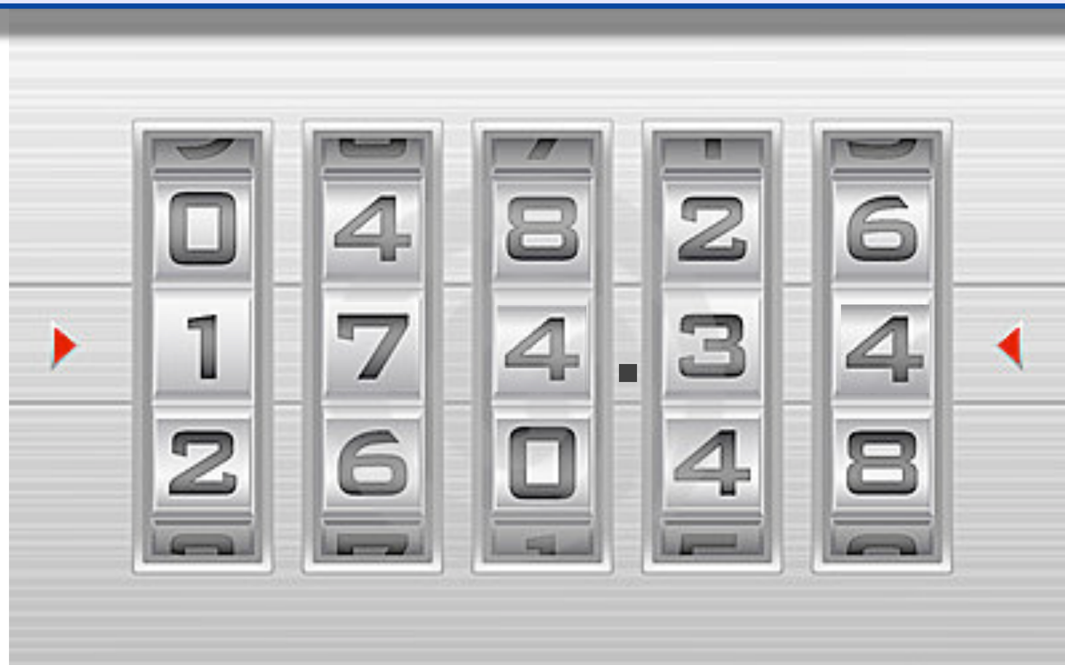
$\rho_{CDF(DØ)}$ → ρ within an experiment

$\rho_{channel}$ → ρ within a channel

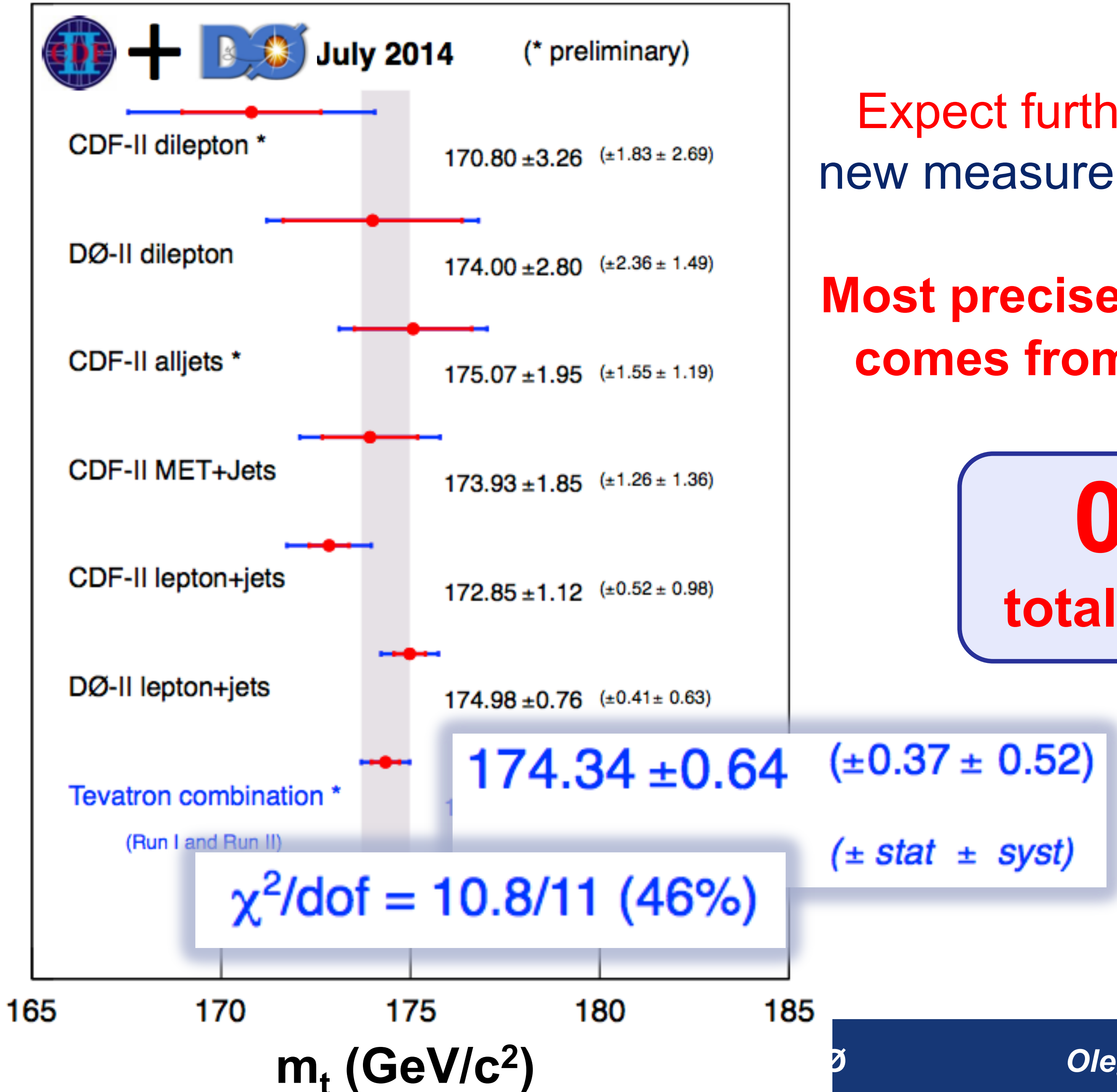
$\rho_{RunXCDF(DØ)}$ → ρ within an experiment and within an epoch

$\rho_{chnlData}$ → ρ within a channel, within an experiment, within an epoch

Combined result



Tevatron combination



Expect further improvements as new measurements enter the game

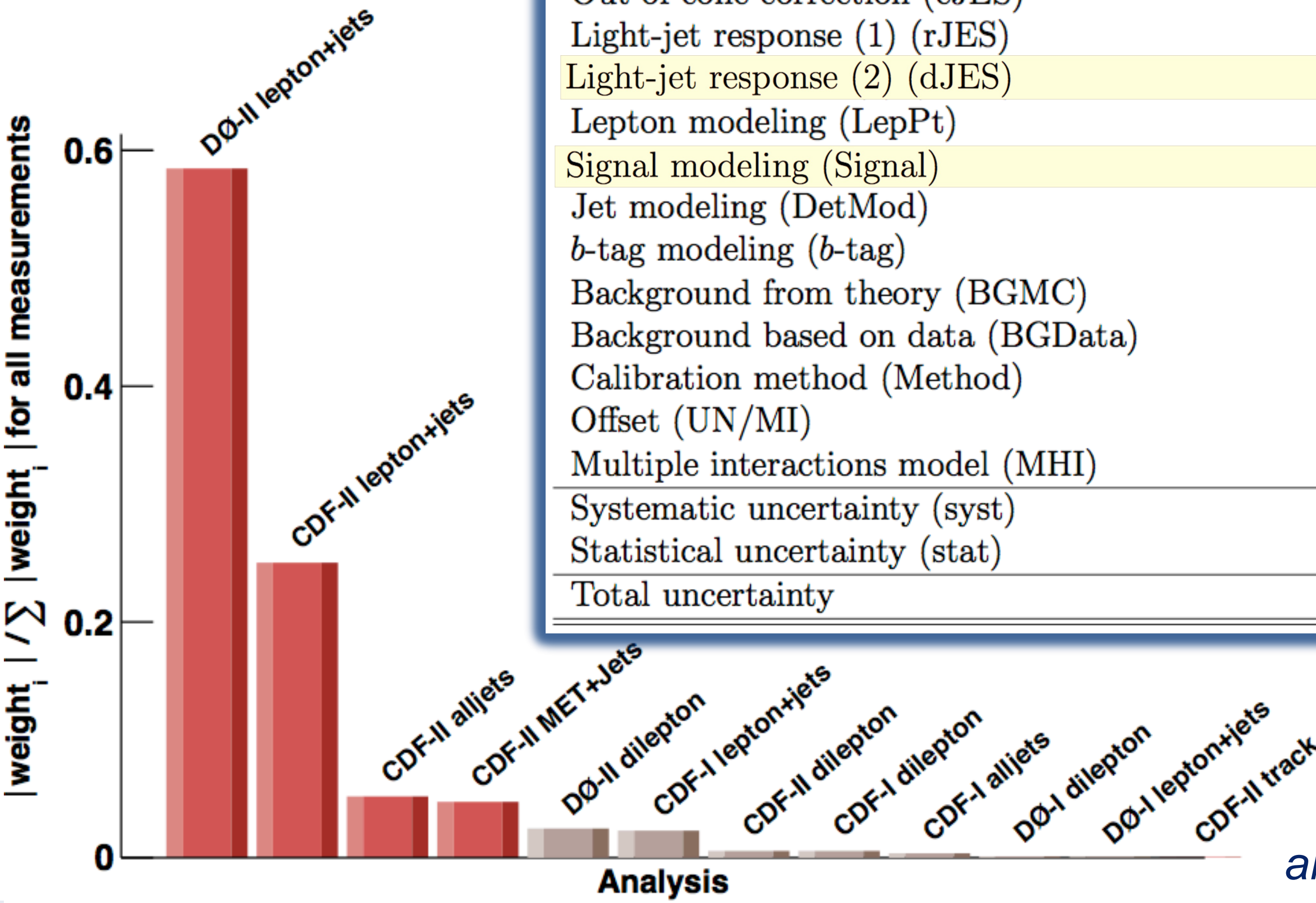
Most precise determination of m_t comes from the Tevatron (yet)

0.37%
total uncertainty

arXiv:1407.2682 [hep-ex]

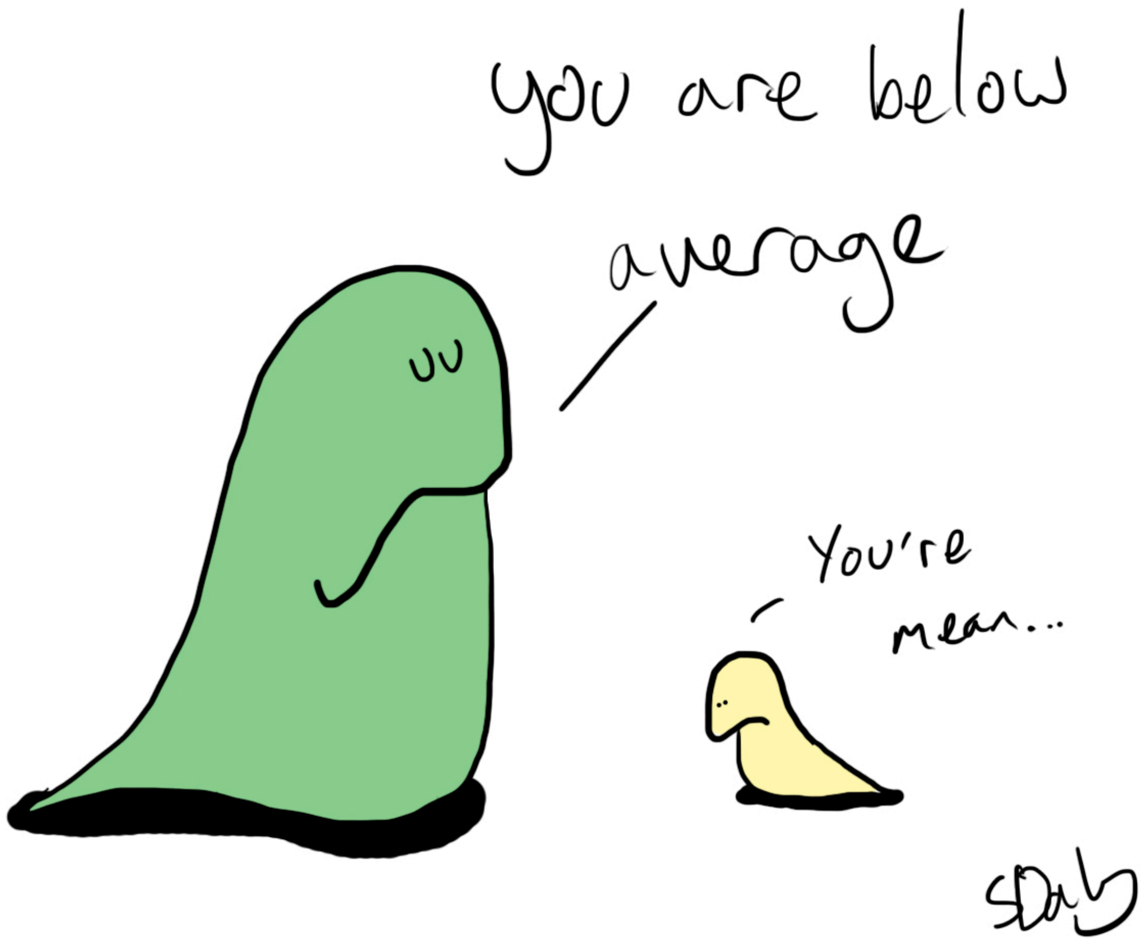
Tevatron combination

	Tevatron combined values (GeV/c^2)
M_t	174.34
In situ light-jet calibration (iJES)	0.31
Response to $b/q/g$ jets (aJES)	0.10
Model for b jets (bJES)	0.10
Out-of-cone correction (cJES)	0.02
Light-jet response (1) (rJES)	0.05
Light-jet response (2) (dJES)	0.13
Lepton modeling (LepPt)	0.07
Signal modeling (Signal)	0.34
Jet modeling (DetMod)	0.03
b-tag modeling (b-tag)	0.07
Background from theory (BGMC)	0.04
Background based on data (BGData)	0.08
Calibration method (Method)	0.07
Offset (UN/MI)	0.00
Multiple interactions model (MHI)	0.06
Systematic uncertainty (syst)	0.52
Statistical uncertainty (stat)	0.37
Total uncertainty	0.64

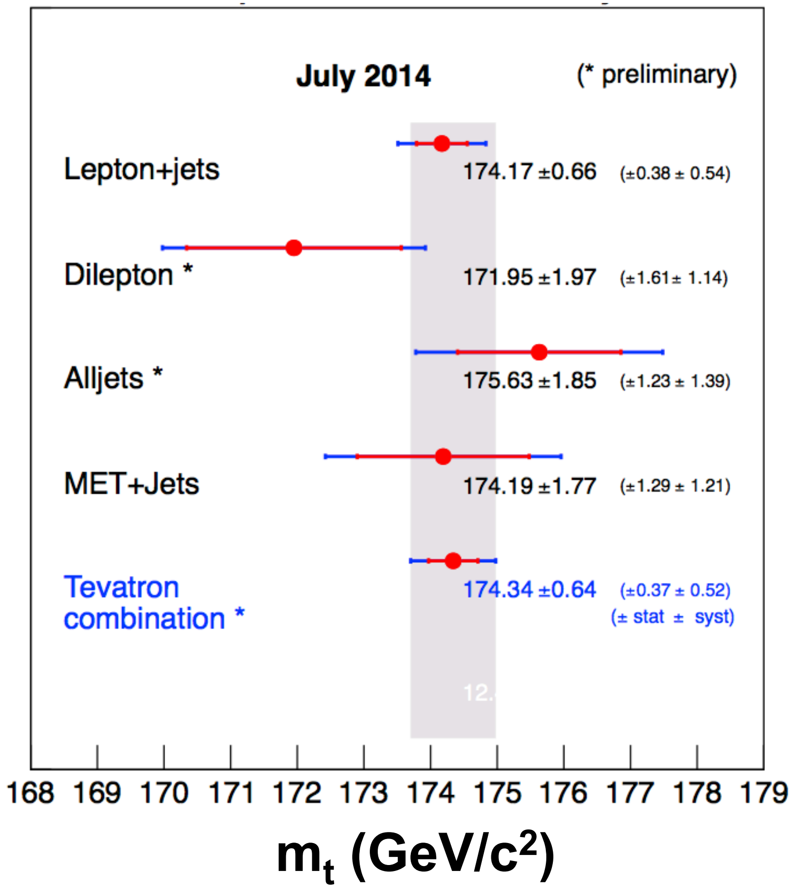


arXiv:1407.2682 [hep-ex]

Cross-checks



Tevatron average: cross checks



Parameter	Value (GeV/c^2)	Correlations $M_t^{all-jets}$	$M_t^{\ell+jets}$	$M_t^{\ell\ell}$	M_t^{MEt}
$M_t^{all-jets}$	175.63 ± 1.85	1.00			
$M_t^{\ell+jets}$	174.17 ± 0.66	0.21	1.00		
$M_t^{\ell\ell}$	171.95 ± 1.97	0.21	0.41	1.00	
M_t^{MEt}	174.19 ± 1.77	0.11	0.23	0.18	1.00

Probability of the χ^2-statistic of pair-wise differences:
22%, 42%, 99%, 13%, 35%, 55%

	Run I published					Run II published					Run II prel.	
	CDF			DØ		CDF			DØ		CDF	
	ℓ+jets	$\ell\ell$	all-jets	ℓ+jets	$\ell\ell$	ℓ+jets	L_{XY}	MEt	ℓ+jets	$\ell\ell$	$\ell\ell$	all-jets
Pull	0.24	−0.61	+1.01	+1.09	−0.46	−1.64	−0.791	−0.24	+1.60	−0.13	−1.11	0.39
Weight [%]	−2.6	−0.7	−0.4	−0.1	−0.14	+28.8	+0.1	+5.5	+67.2	−2.9	−0.66	+6.0

arXiv:1407.2682 [hep-ex]

Anything to be learned?

Anything to be learned?

Disclaimer:

This is just my personal view what could be useful in the context of m_t measurements in the next decade

This refers to "conventional" measurements of m_t (but may also apply to e.g. m_t extraction from σ_{tt})

- **1) It is crucial to understand the origin of systematic uncertainties:**
  - **Factorise effects into different categories, if applicable**
  - **The total uncertainty is a quadratic sum of all effects**
    - **Double-counting counts!**

Anything to be learned?

- 2) Finite statistics of MC samples results in a sizable statistical component of systematic uncertainties
  - Increase size of MC samples
    - Typical statistical component @ LHC: 0.1 GeV
    - The bottle neck can be:
      - Generation and simulation of MC events
      - Their analysis with advanced method like the ME technique
- 3) Ironically, the dominant limitation in precision comes from the soft part of the tt event
  - We need to better understand and constrain the hadronisation model
  - OR we fit the b-quark JES in-situ `a la ATLAS
    - No free lunch: increased statistical uncertainty
      - Not an issue with Run II data (hopefully!)
      - Clearly an issue with MC samples

Anything to be learned?

- 4) We need to improve our understanding of the **signal modeling part (hard+soft)**
  - **Include new generators** as they become available, e.g.:
    - Sherpa, aMC@NLO, herwig++, pythia8, etc
  - **Reject models** which are in tension with datasets used for tuning of generators or parton shower simulation
    - E.g. fHerwig?
- 5) We are eagerly awaiting MC generators which can **simulate the full tt decay at NLO**
  - Then the finite width of t propagator is accounted for
    - → **well-defined concept of m_t!**

Anything to be learned?

- 6) The ME technique may be less sensitive to systematic uncertainties
  - Evaluates the impact of an uncertainty in context of a concrete model for tt production described by the ME
  - Canonical example:
    - Reduced sensitivity of LO ME to tt events with initial/final state radiation due to lower P_{sig}
- 7) Measure m_t in various regions of phase space
  - Check for biases
    - Reject models
  - Evaluate systematic uncertainties from data


GAME OVER
BONUS MATERIAL

Comparison with previous measurements

- Current World average:

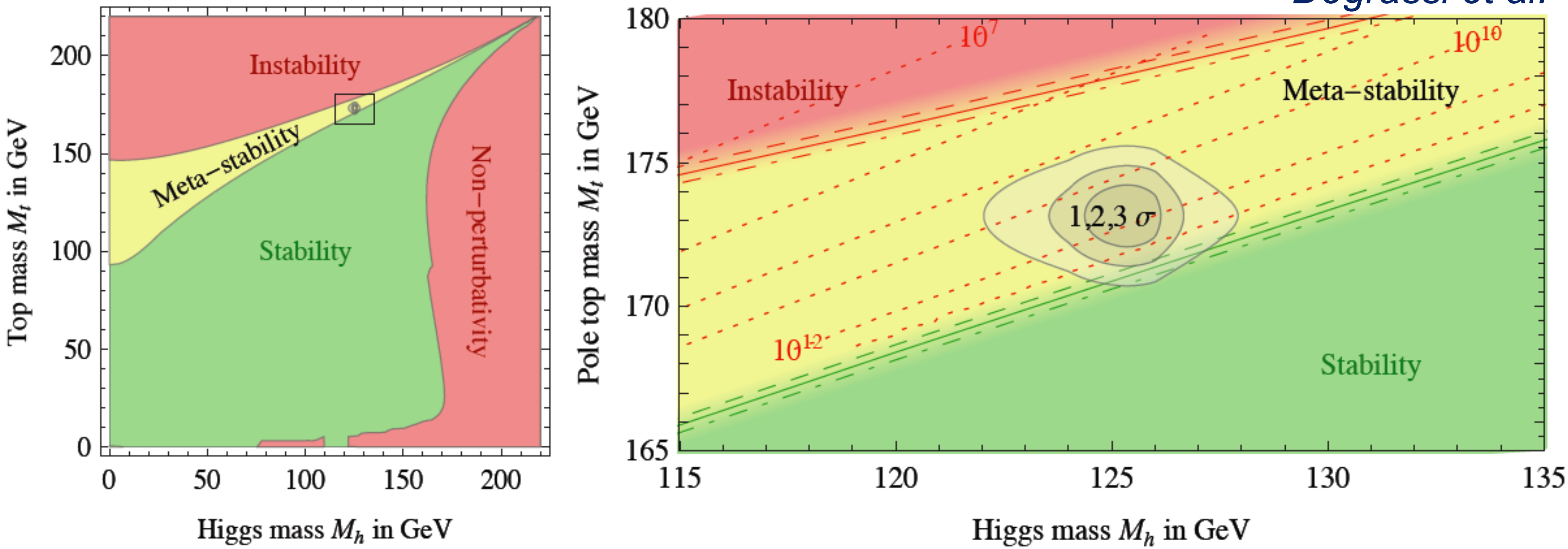
$$m_t = 173.34 \pm 0.76\,\mathrm{GeV}$$

arXiv:1403.4427 [hep-ex]

- Assuming no statistical correlation between this result and the combination
  - Taking full uncertainty for the Tevatron average
  - Taking statistical uncertainty only for this measurement
  - Consistency at 1.71 SD level (p-value of 3.1%)

- **The phase diagram of the Universe:**

Degrassi et al.



Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	±1.4 GeV
α_s	experimental uncertainty in α_s	±0.5 GeV
Experiment	Total combined in quadrature	±1.5 GeV
λ	scale variation in λ	±0.7 GeV
y_t	$\mathcal{O}(\Lambda_{QCD})$ correction to M_t	±0.6 GeV
y_t	QCD threshold at 4 loops	±0.3 GeV
RGE	EW at 3 loops + QCD at 4 loops	±0.2 GeV
Theory	Total combined in quadrature	±1.0 GeV

Flavor-dependent correction

- Apply dedicated corrections for:
  - u, d, c, s quark jets
  - b quark jets
  - gluon jets
- The correction is given by:

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

  - F_{corr} preserves default JES by construction
- Derive single particle responses R_i in data/MC for:
  - γ, $e^\pm$, $\mu^\pm$, $\pi^\pm$, $K^\pm$, K_0^S, K_0^L, $p^\pm$, n and Λ
  - (Keep in mind that DØ corrects jet energies to particle level in data and in MC)

DØ Coll, Section 14 in arXiv:1312.6873 [hep-ex], submitted to NIM

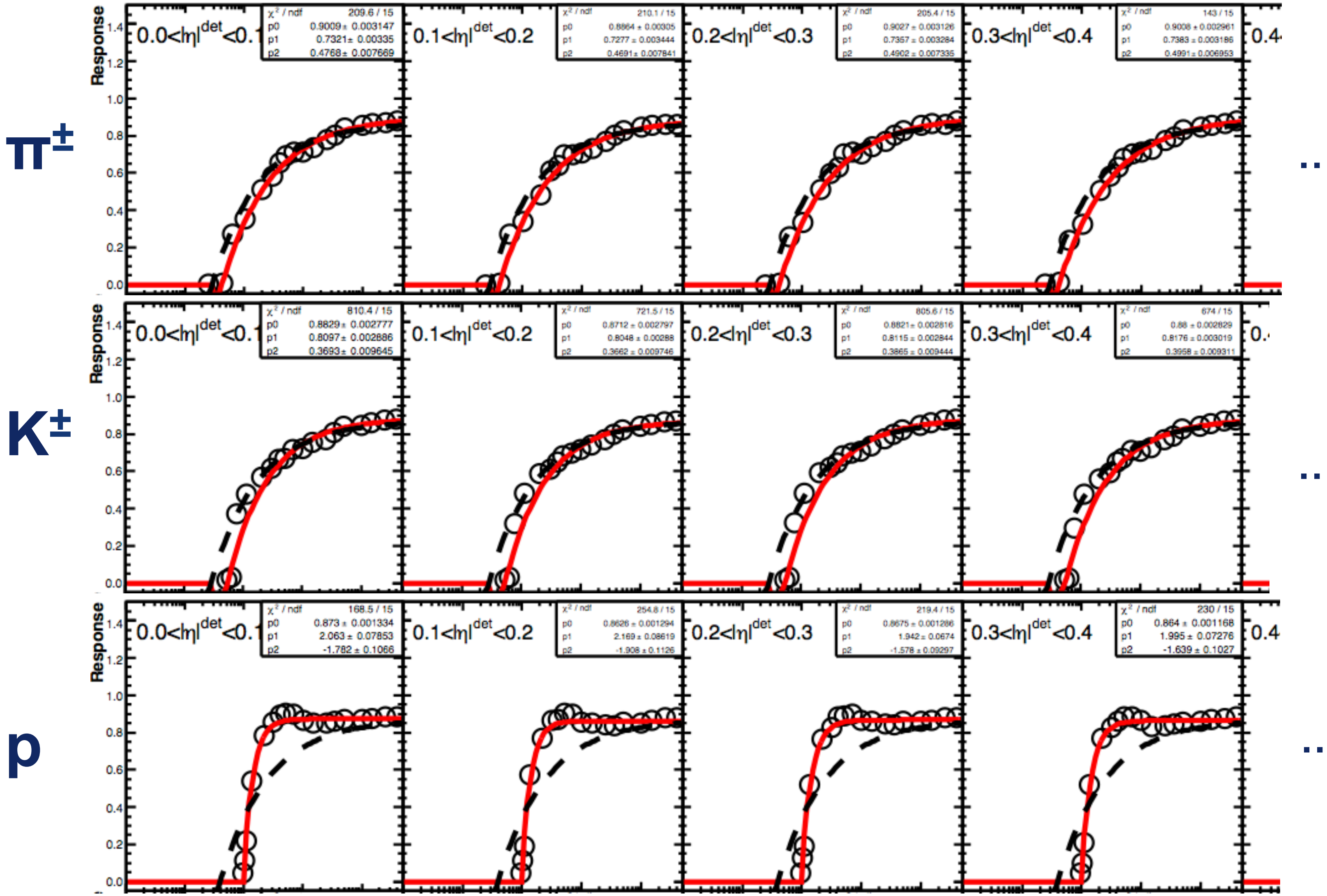
Flavor-dependent correction

- **Derive single particle responses R_i in MC:**
  - **Use single particle MC samples for each of**
    - $\gamma,\ e^{\pm},\ \mu^{\pm},\ \pi^{\pm},\ K^{\pm},\ K_0^S,\ K_0^L,\ p^{\pm},\ n$ and Λ
  - **Using:**
    - **Zero energy noise suppression off for default**
    - **(Noise suppression on → systematic uncertainty)**
  - **Fit with appropriate function:**
    - **e, μ, γ (not shown):**
      - **Calibrated separately and have one function each**
    - **For all hadrons:**
      - **Response function is (but different fit parameters!):**
      - $R_h^{MC} \;=\; p_h^0 \cdot \left[1 - p_h^1 \cdot (E/0.75)^{p_h^2 - 1}\right]$ if $p_T > m_h$; 0 if $p_T < m_h$;

DØ Coll, Section 14 in arXiv:1312.6873 [hep-ex], submitted to NIM

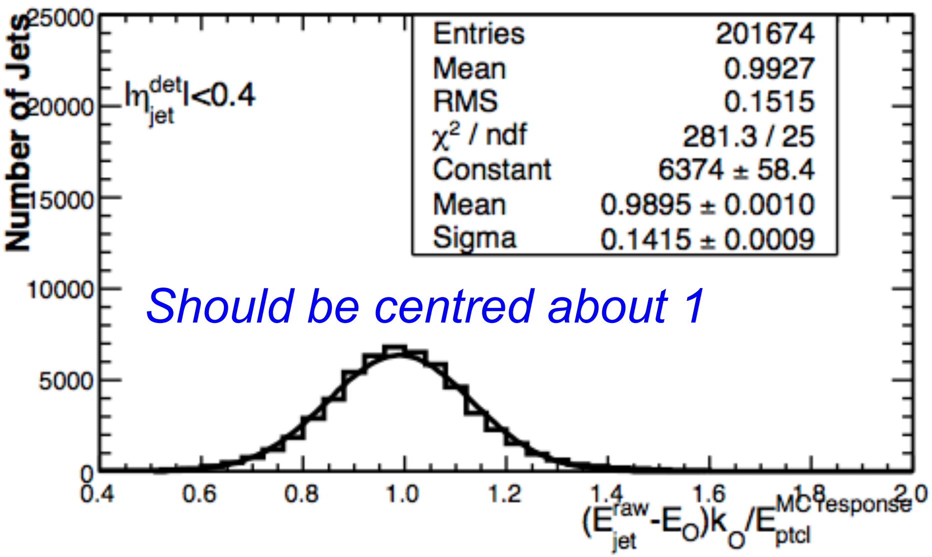
Flavor-dependent correction

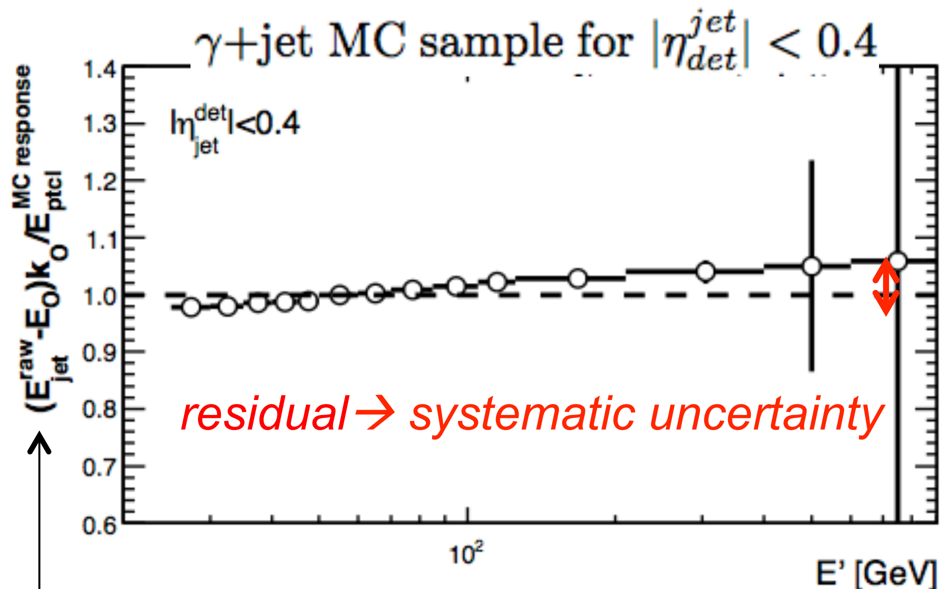
- Few example fits of MC response for three particles:



Flavor-dependent correction

- **Closure test: check that $\sum_i E_i \cdot R_i^{MC}$ describes the raw offset-corrected energy $(E_{jet}^{raw} - E_O) \cdot k_O$ correctly**
  - **Example:**





E' is given by $p_T^\gamma \cdot cosh(\eta^{jet})$

$$y = (E_{jet}^{raw} - E_O) \cdot k_O / \sum_i E_i \cdot R_i^{MC}$$

E_{jet}^{raw} is the raw jet energy

E_O is the offset correction for noise and pile-up (in- and out-of-time)

k_O is the correction for noise suppression bias & only needed to perform closure test

Flavor-dependent correction

DØ Coll, Sec. 14 arXiv:1312.6873 [hep-ex], subm. to NIM

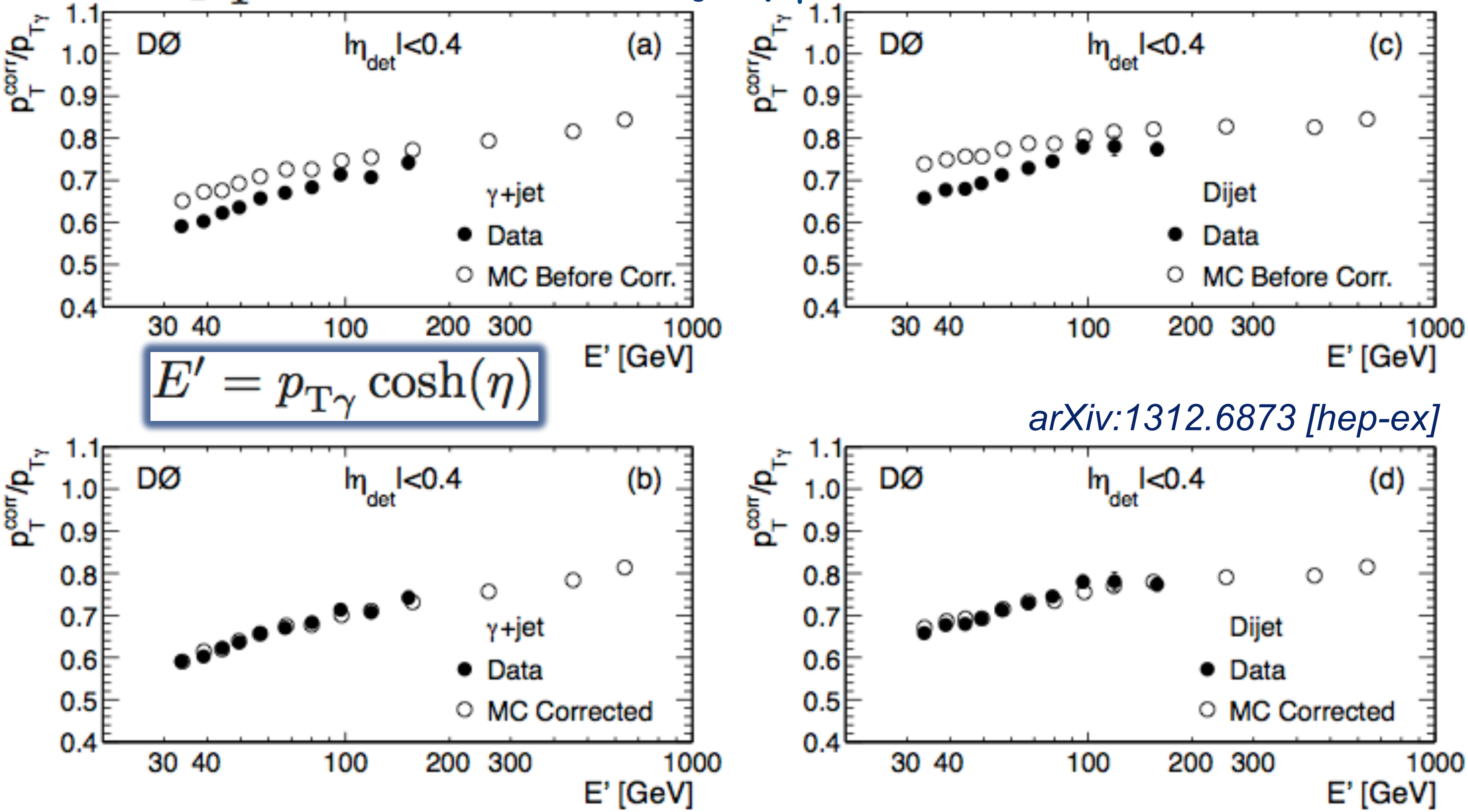
- Deriving single particle responses in data:
  - For e, μ, γ:
    - Assume perfect modelling of detector response by MC
      - Systematic uncertainty estimated on this assumption
  - For hadrons $\pi^{\pm}$, $K^{\pm}$, K_0^S, K_0^L, $p^{\pm}$, n and Λ:
    - Basic shapes in *E*,*η* (i.e. per-hadron fit parameters) from MC
    - Fit unique (not per-bin or hadron) parameters *A, B, C*:

$$R_h^{data} = C \cdot p_h^0 \cdot \left[1 - A \cdot p_h^1 \cdot (E/0.75)^{p_h^2 + B - 1}\right] \text{ if } p_T > m_h;\ 0 \text{ if } p_T < m_h$$

      - Identical to R_h^{MC} for $A = C = 1$ and $B = 0$
    - Find an optimal set of *A, B, C* to tune MC jet responses such that the ratios $p_{T,\ corr}^{jet}/p_T^{\gamma}$ are consistent in data and MC
      - Use the particle composition of the jet from MC as a function of the jet energy and η
      - Measure $p_{T,\ corr}^{jet}/p_T^{\gamma}$ in data and MC samples enriched with isolated photons ("γ+jet") and inverted photon isolation ("dijet")
      - Here, $p_{T,\ corr}^{jet}$ is reconstructed jet p_T with offset correction

Flavor-dependent correction

- **Closure test of the flavour-dependent response:**
  - p_T^{corr} is reconstructed jet p_T with offset correction

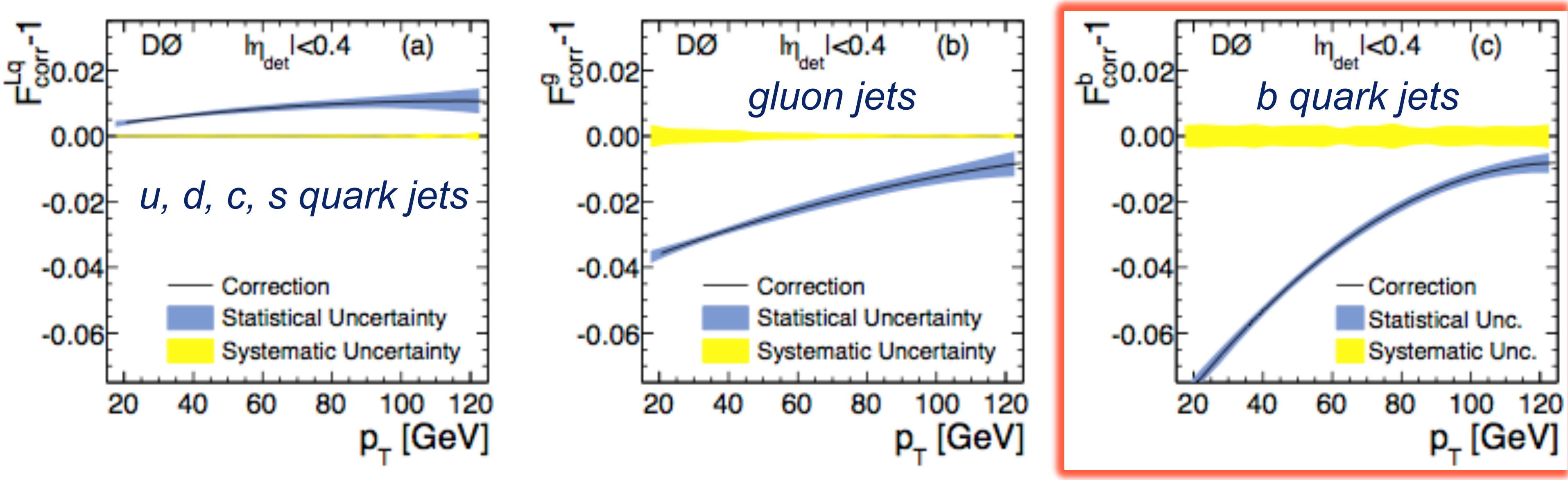


$$E' = p_{T\gamma} \cosh(\eta)$$

arXiv:1312.6873 [hep-ex]

Flavor-dependent correction

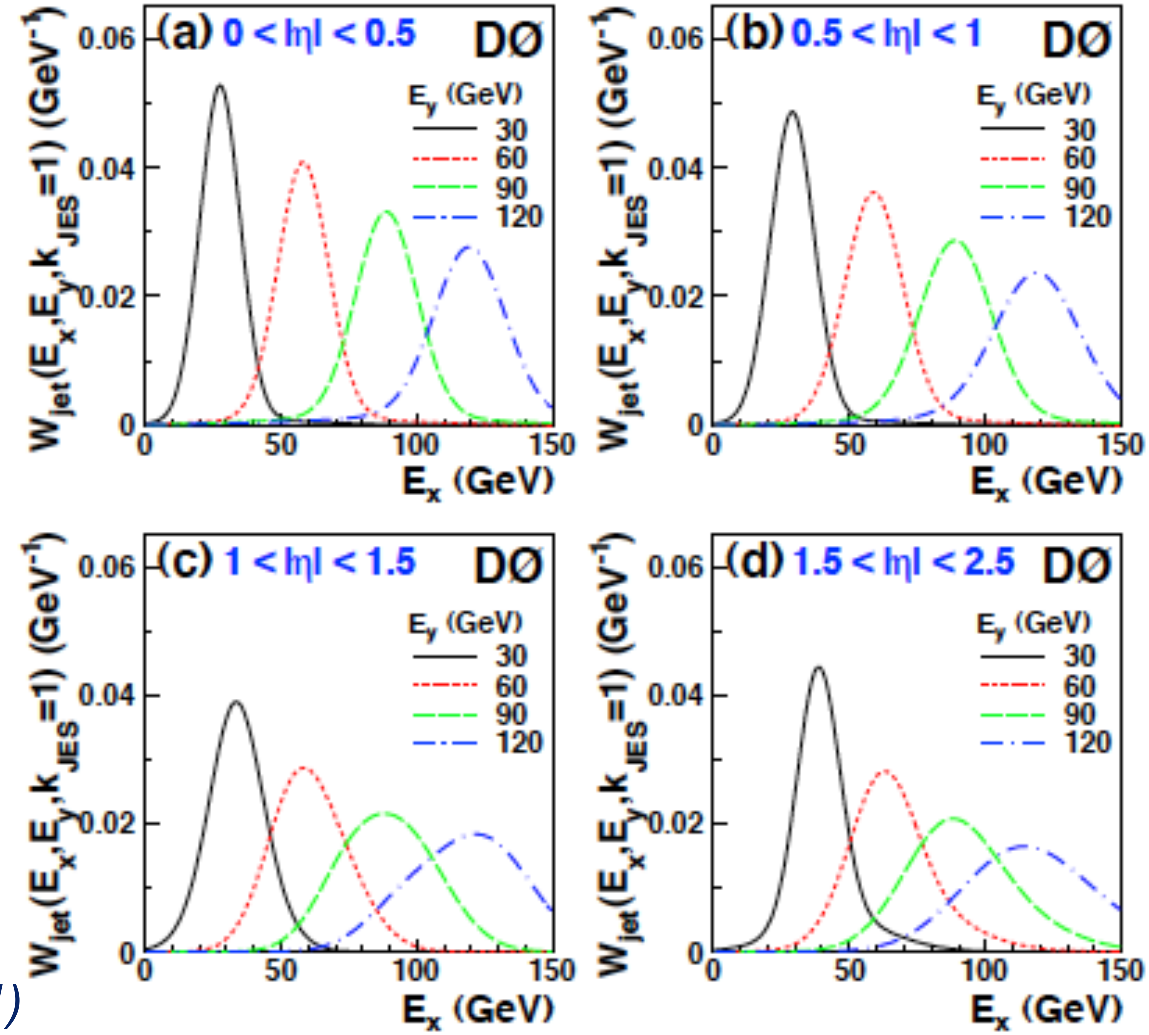
- The final **flavour-dependent correction**:



- The correction accounts for the difference in **JES for b quark jets and light quark jets**:
  - Substantial reduction of one of the dominant systematic uncertainties!

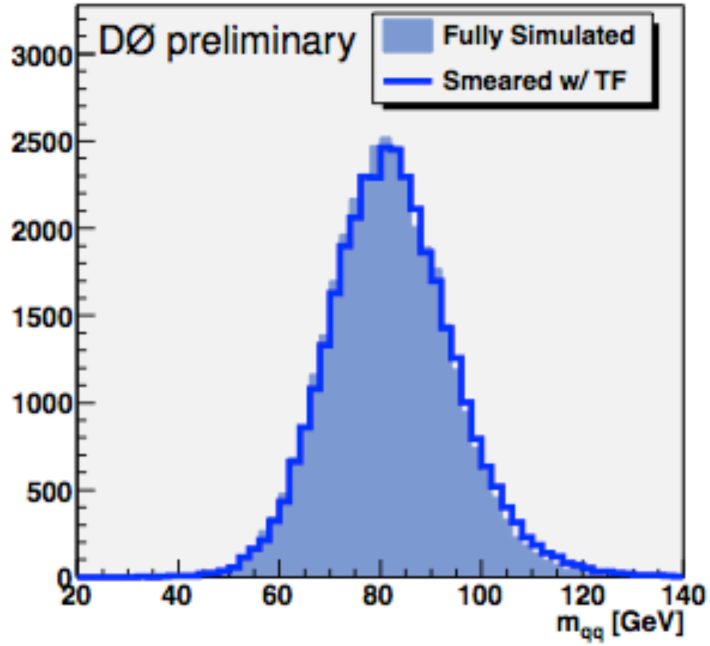
DØ Coll, Section 14 in arXiv:1312.6873 [hep-ex], submitted to NIM

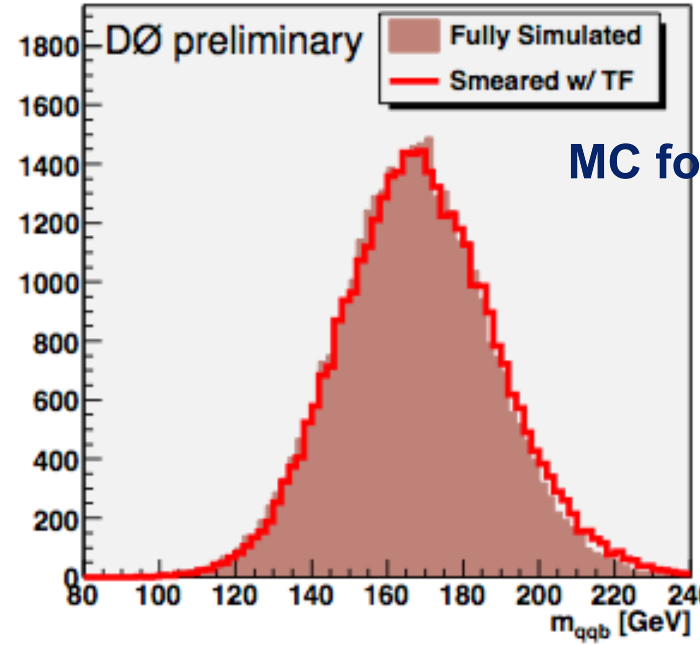
- The **Transfer Functions** $W(x, y; JES)$ relate parton-level quantities to reconstruction-level ones
- Some typical examples for light quark jets from [1]



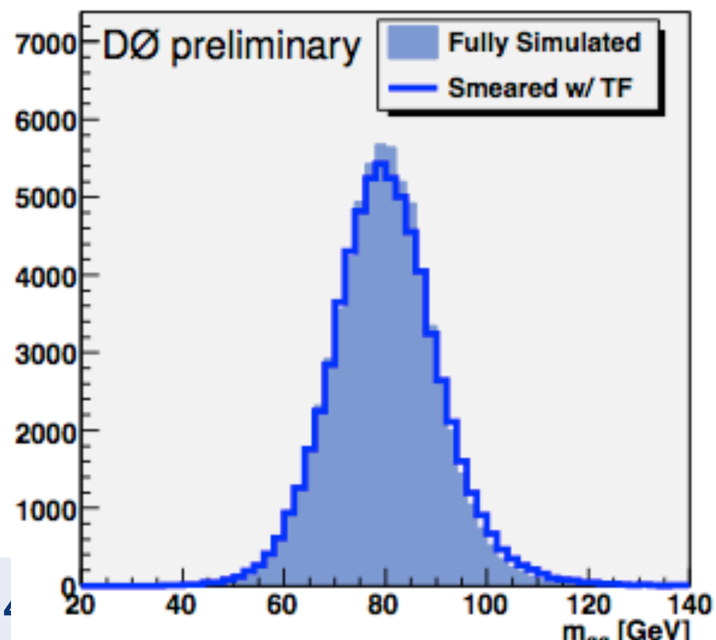
[1] *DØ Coll, PRD **84**, 032004 (2011)*

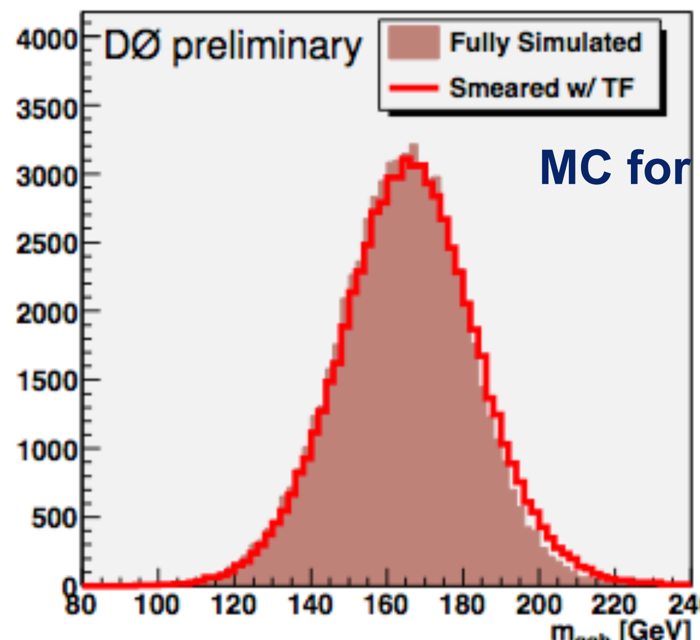
Transfer function validation





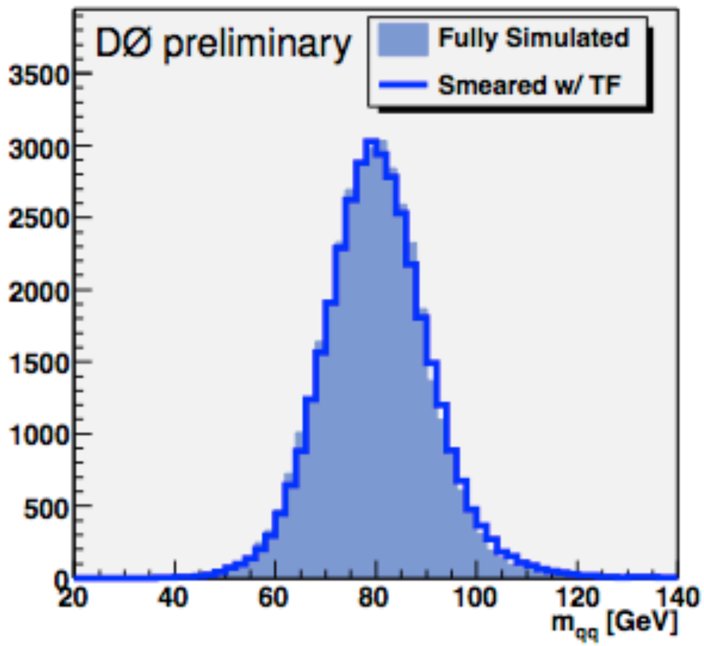
MC for Run IIa ($1.1\ fb^{-1}$)

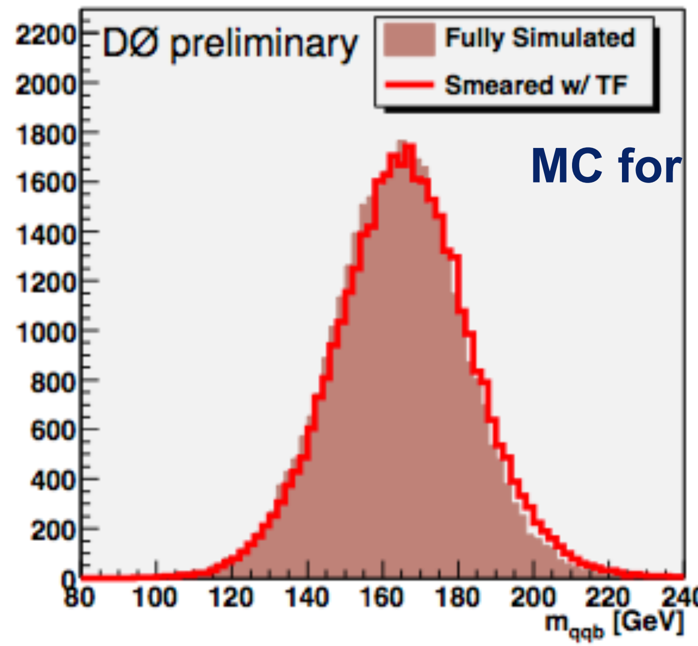




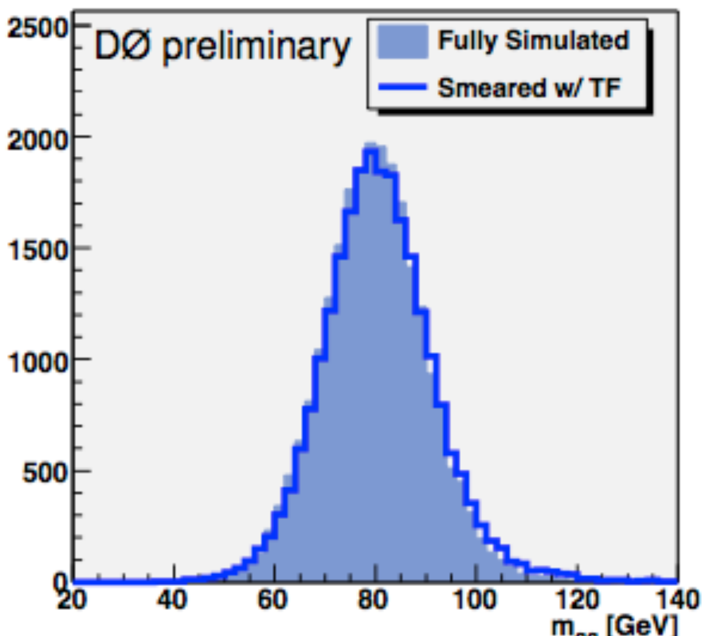
MC for Run IIb1 ($1.3\ fb^{-1}$)

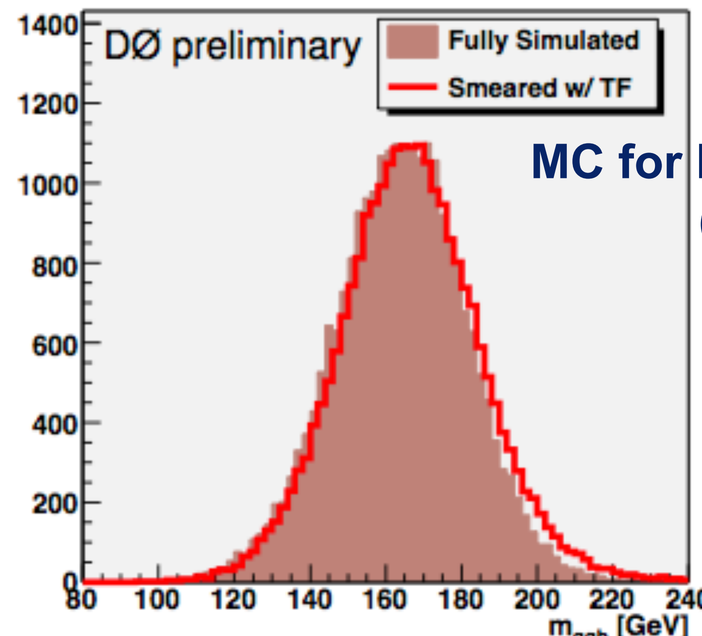
Transfer function validation





MC for Run IIb2 ($3.0\ fb^{-1}$)

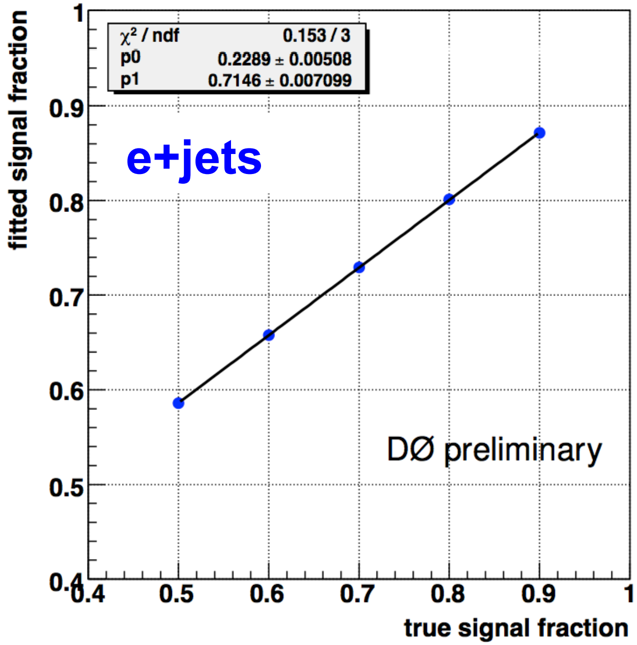


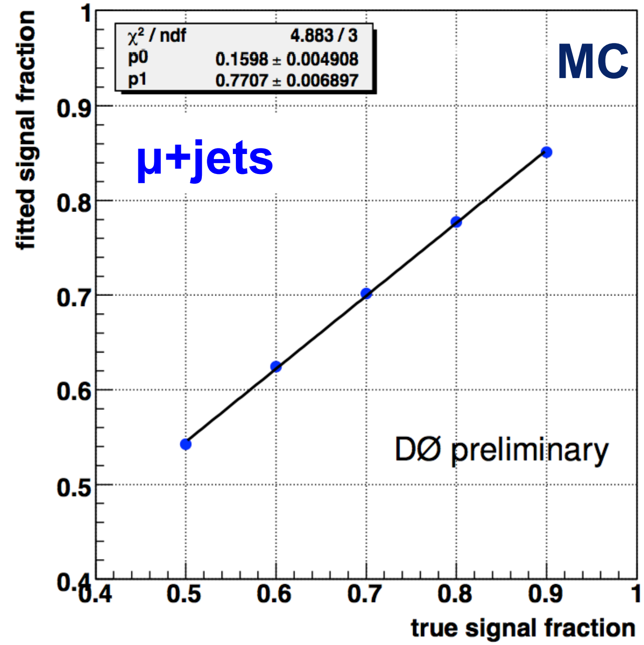


MC for Run IIb3 ($4.4\ fb^{-1}$)

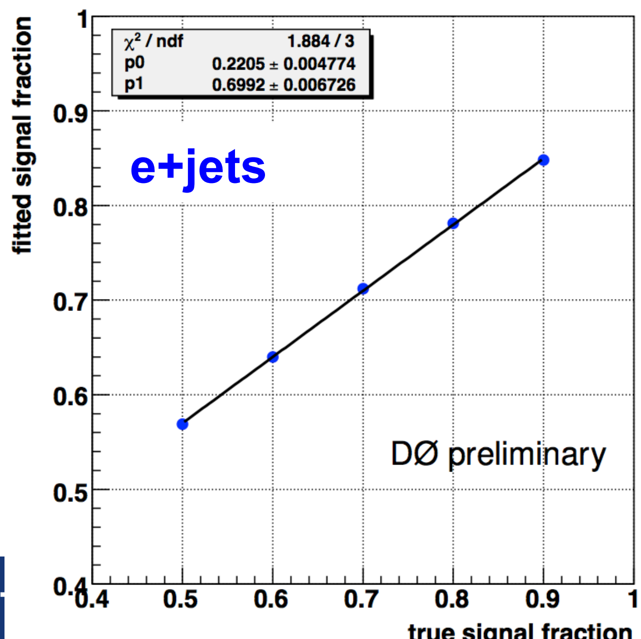
Method response in f

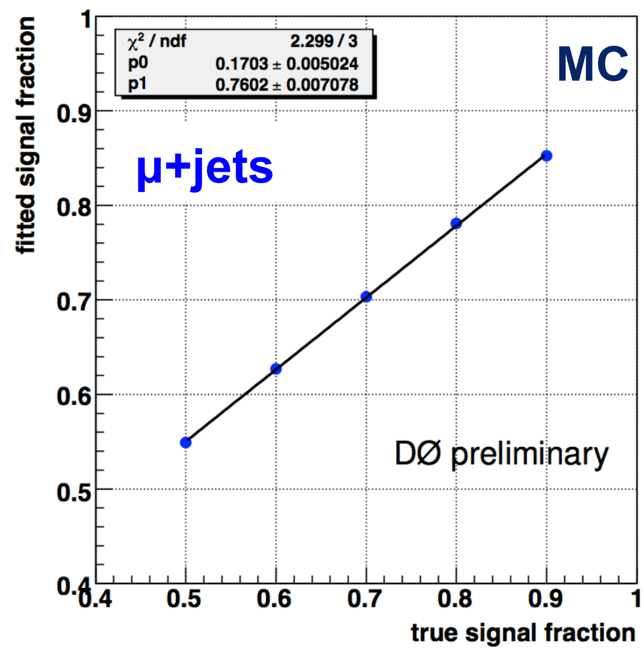
MC for Run IIa (1.1 fb^{-1})



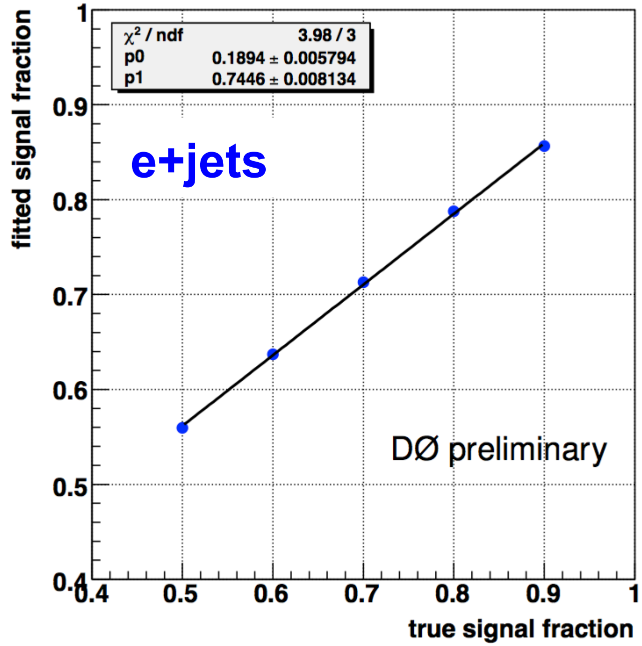


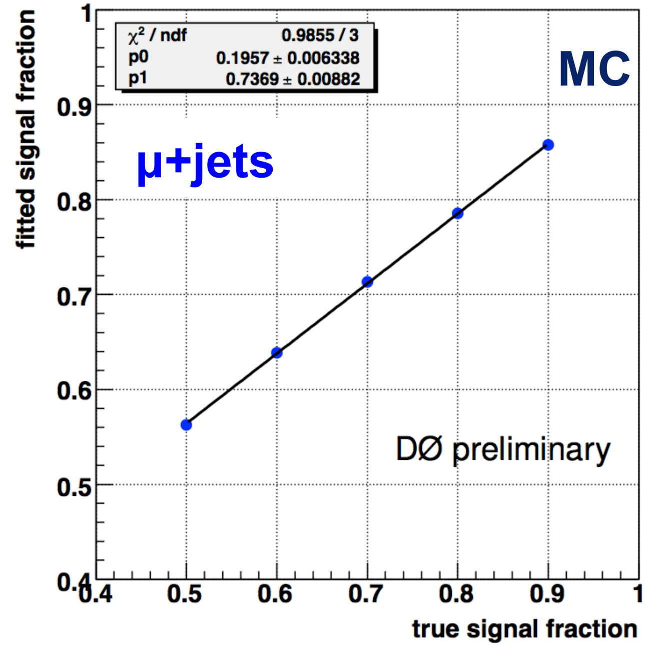
MC for Run IIb1 (1.3 fb^{-1})



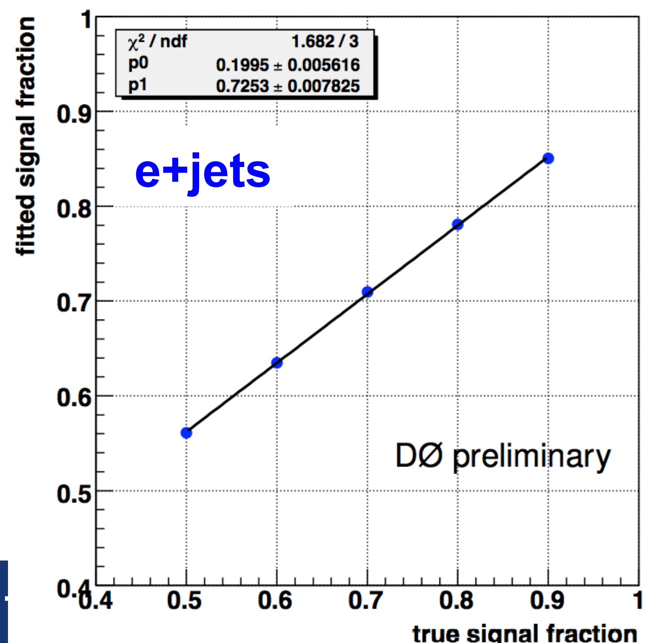


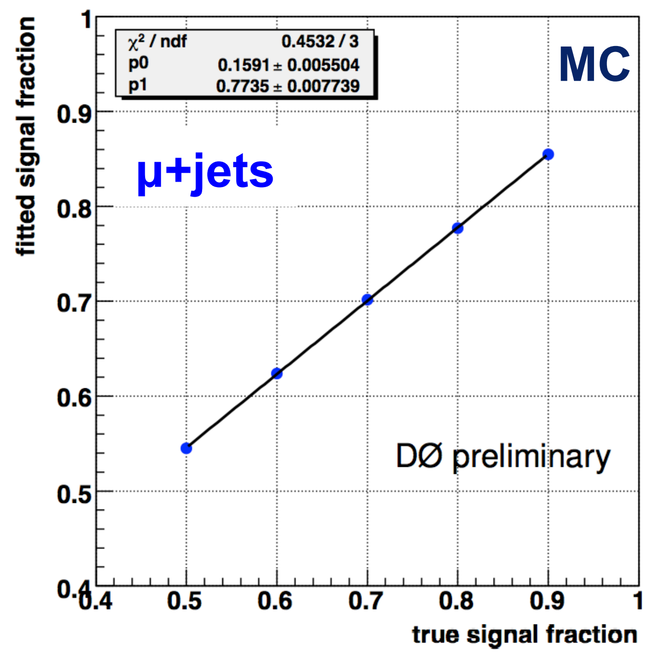
Method response in f





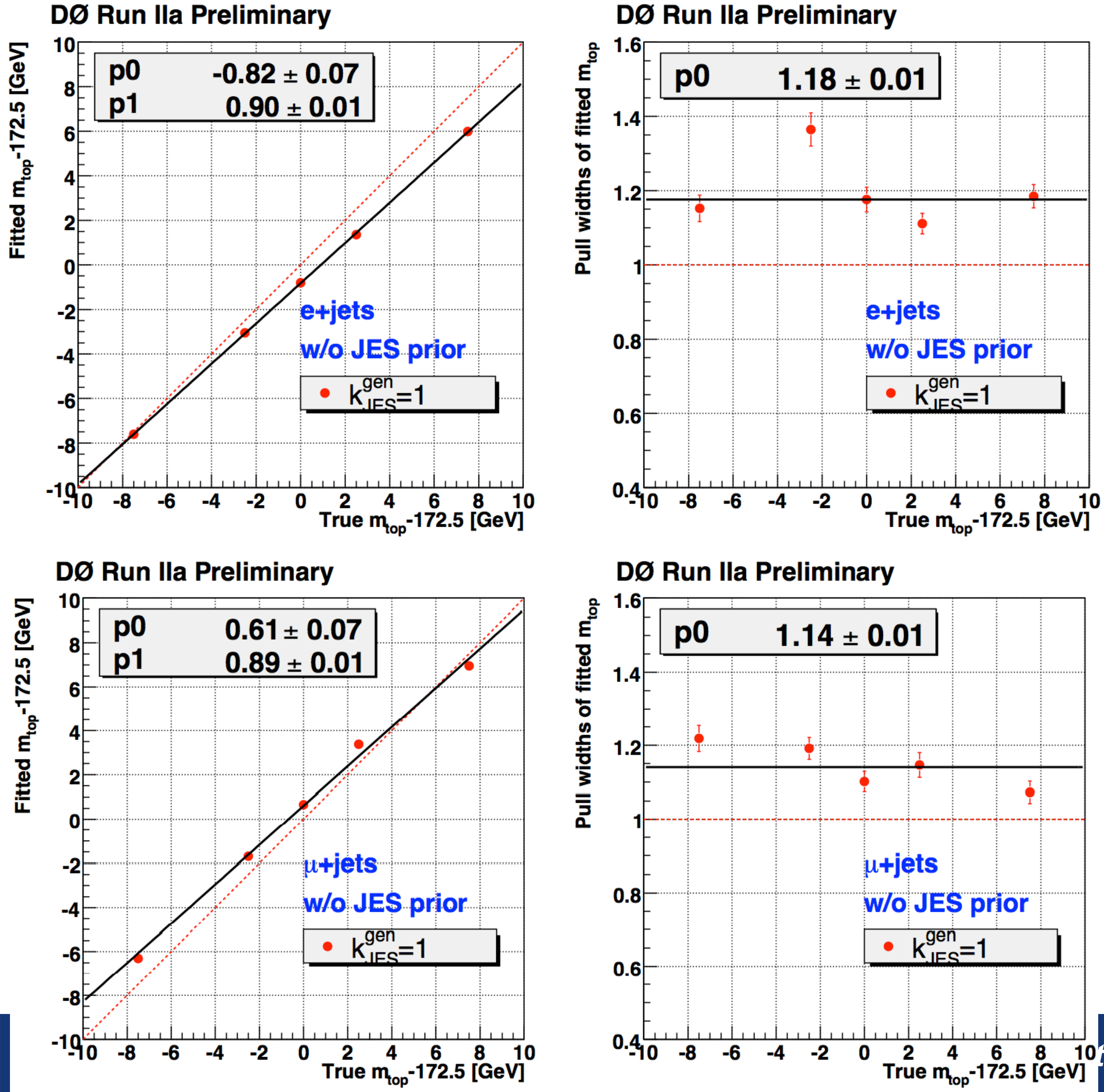
MC for Run IIb2 (3.0 fb^{-1})



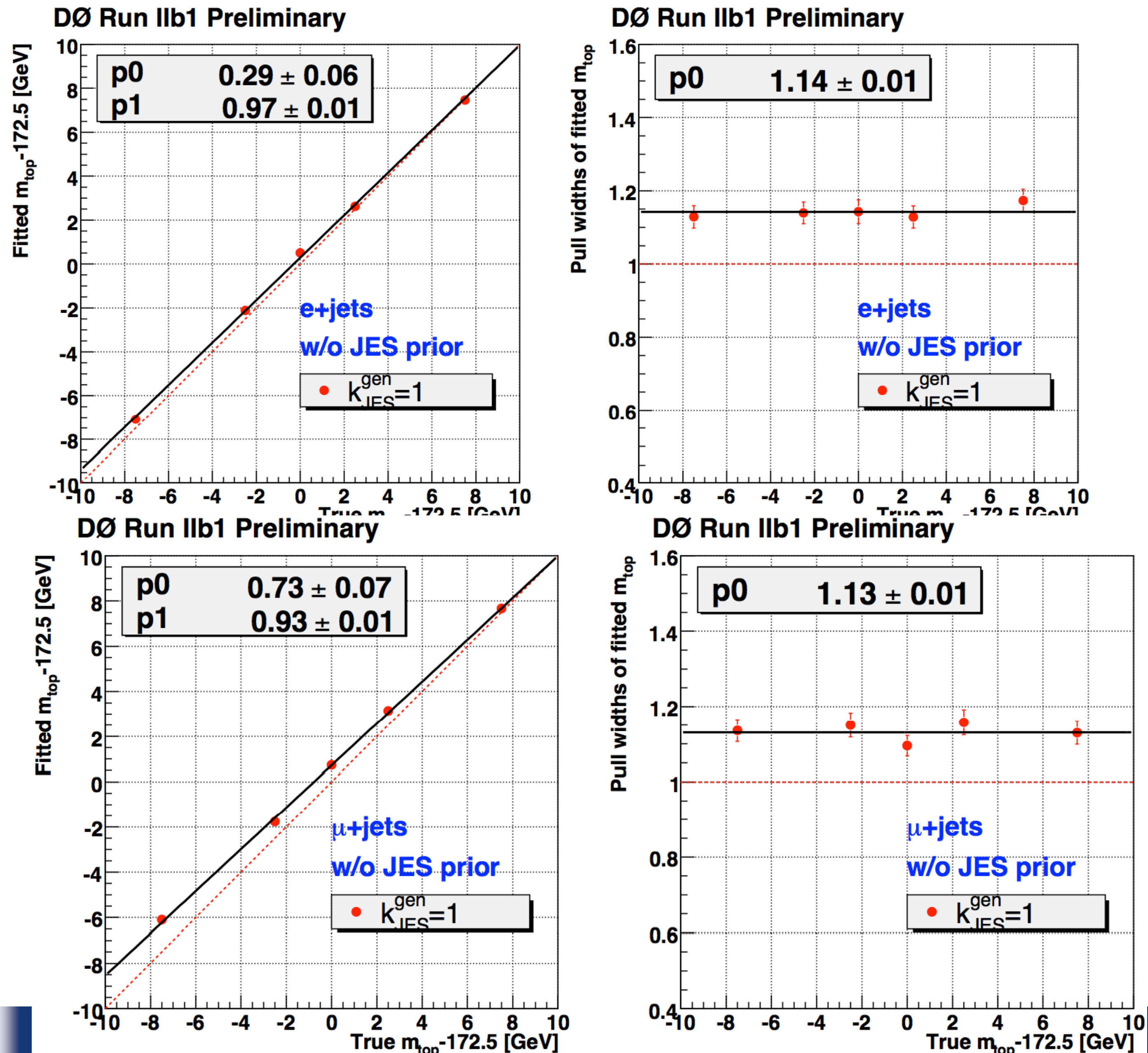


MC for Run IIb3 (4.4 fb^{-1})

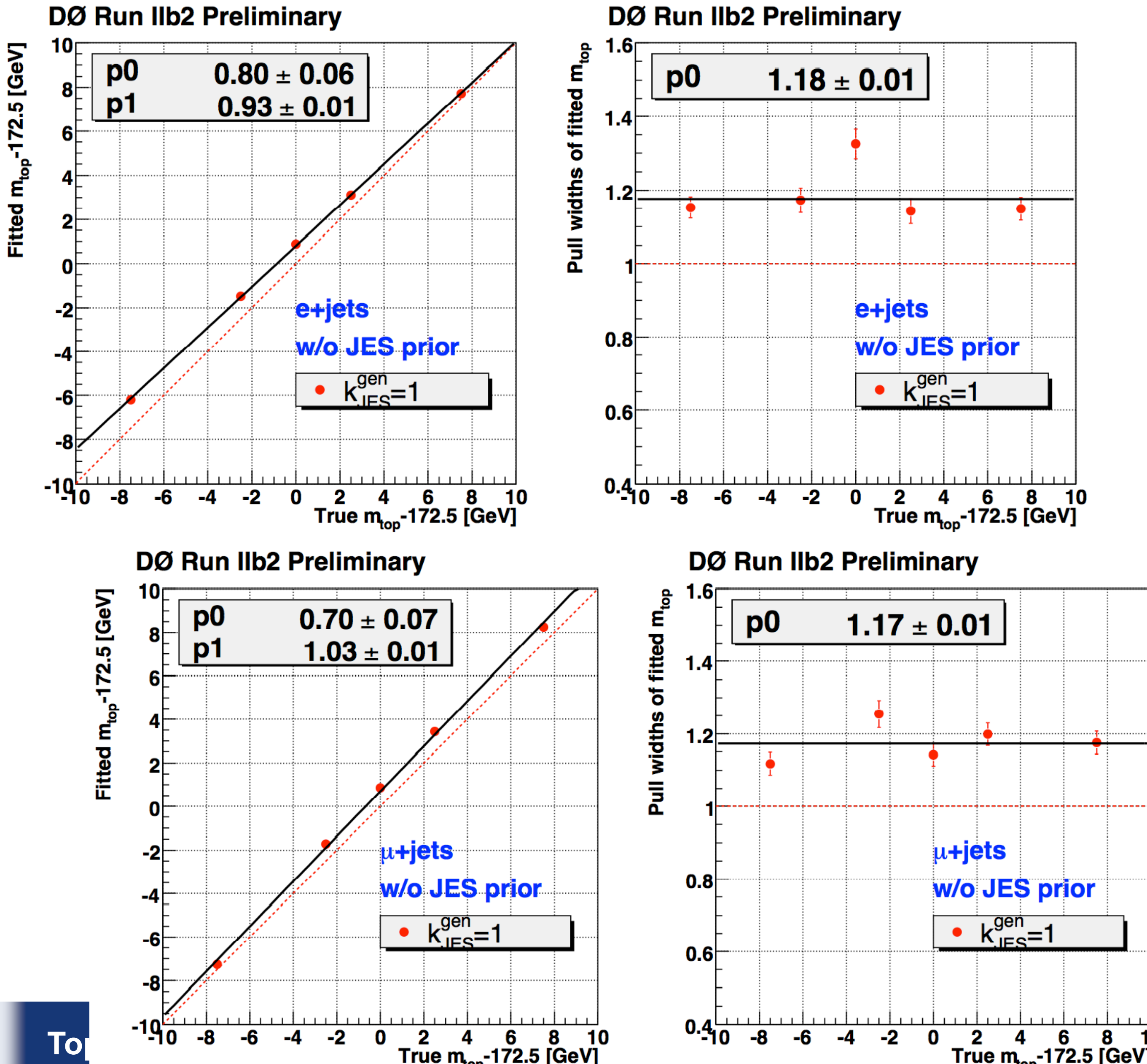
Method response in m_t



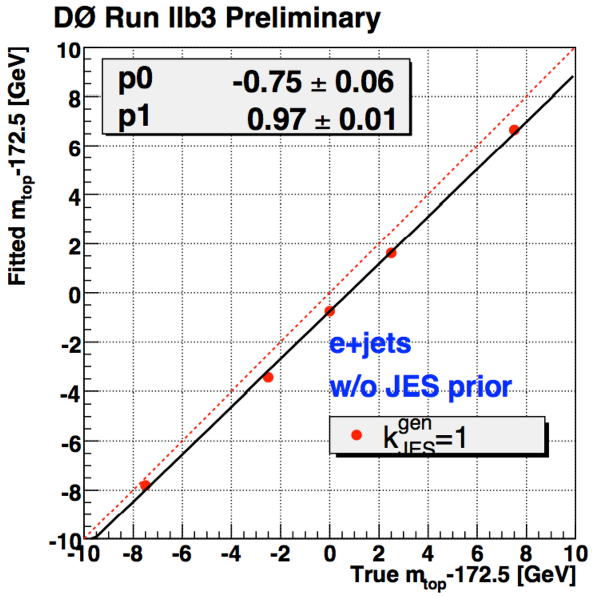
Method response in m_t

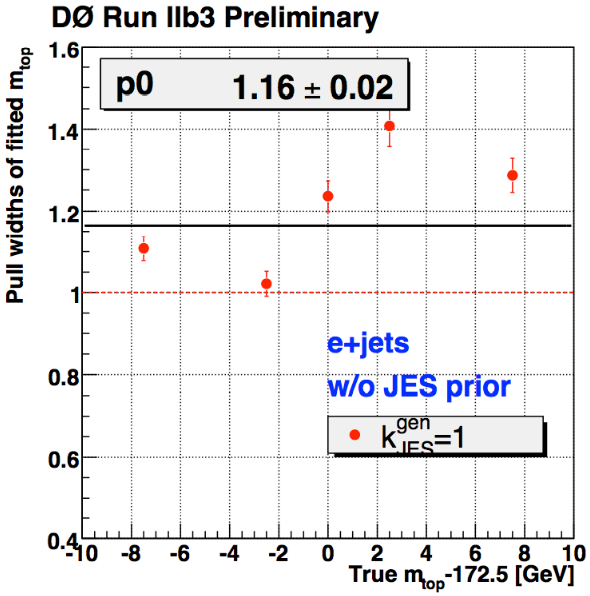


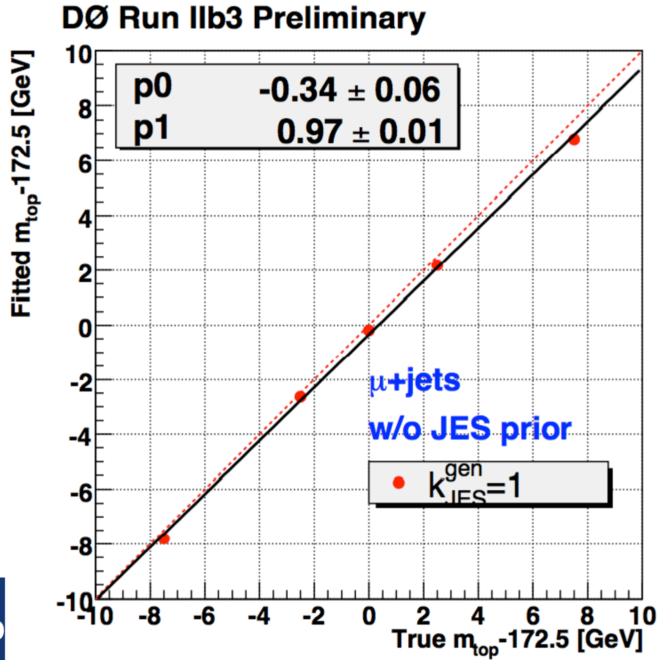
Method response in m_t

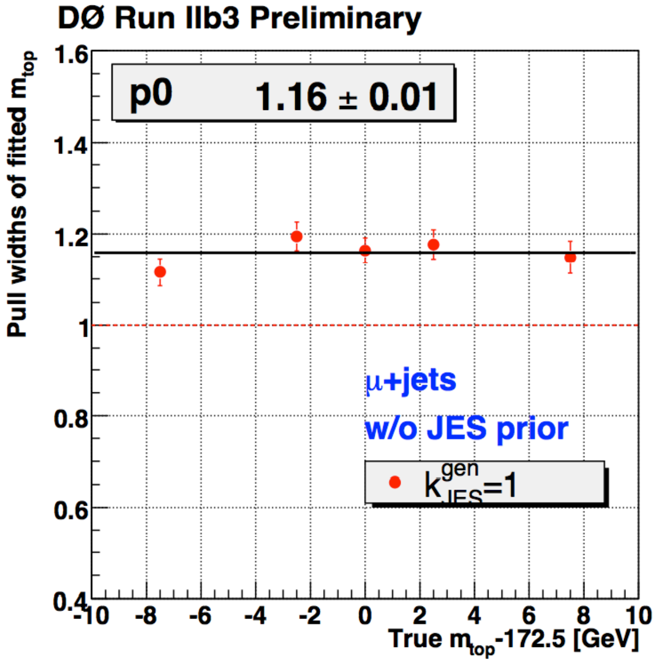


Method response in m_t

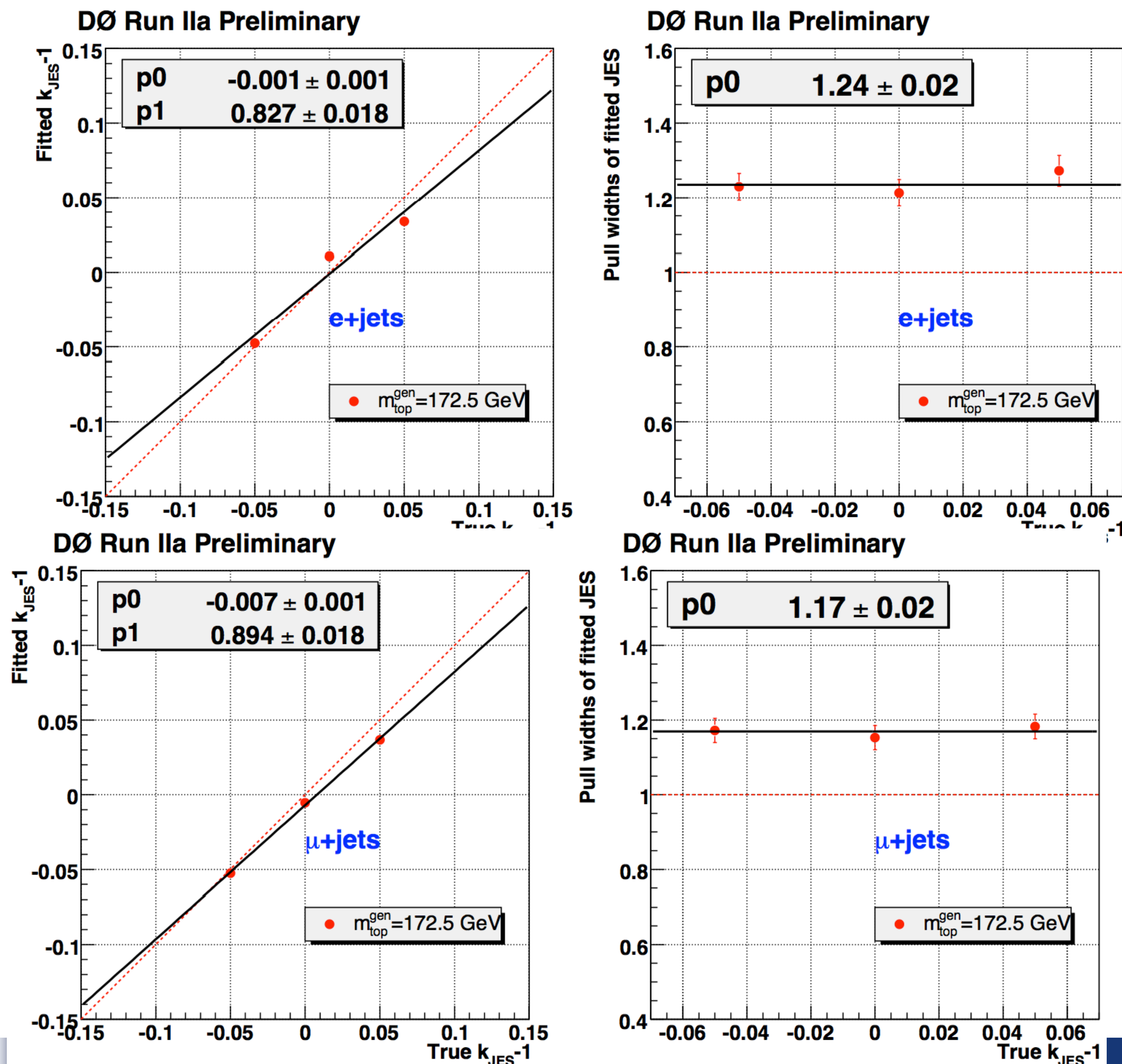




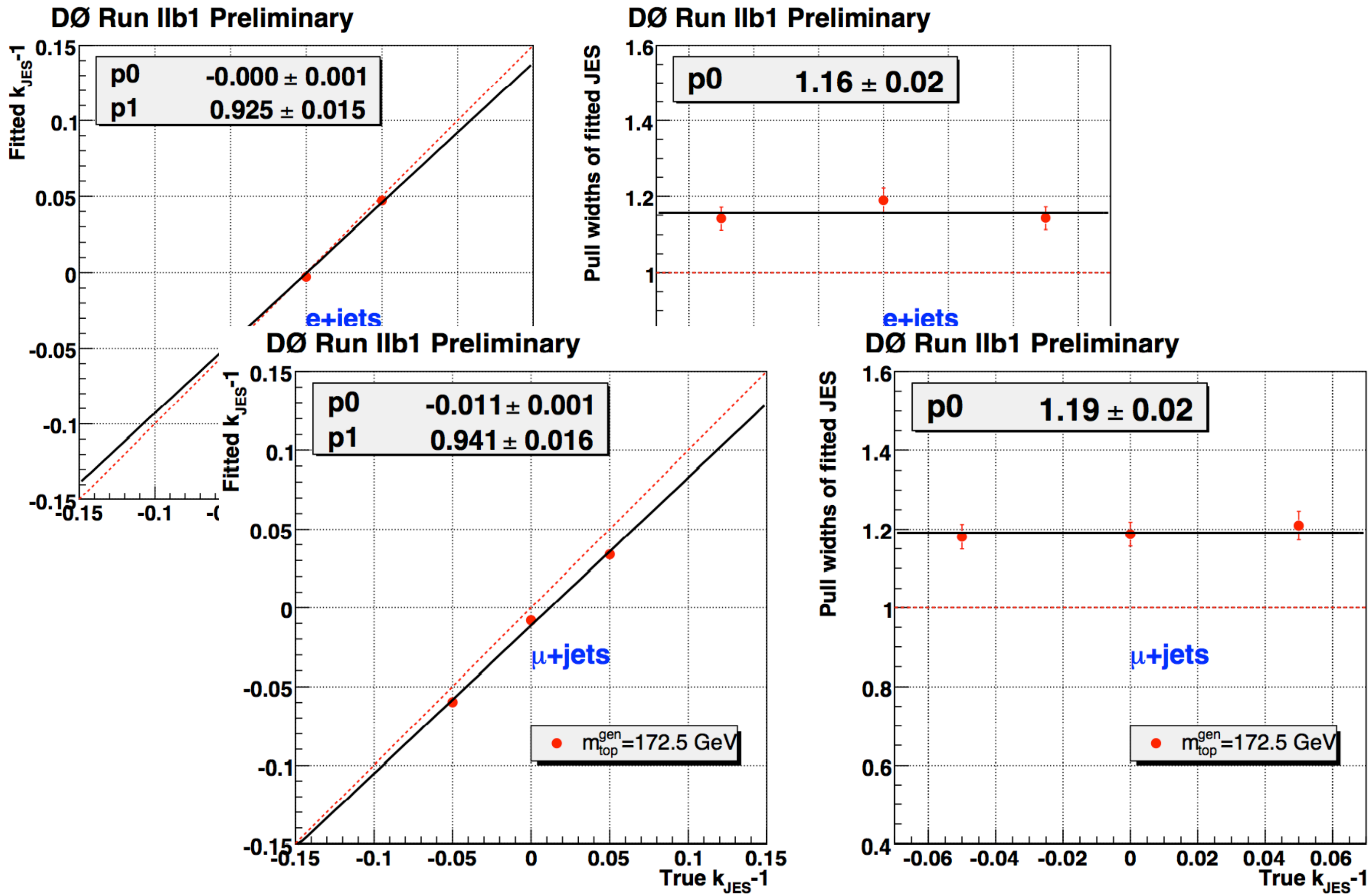




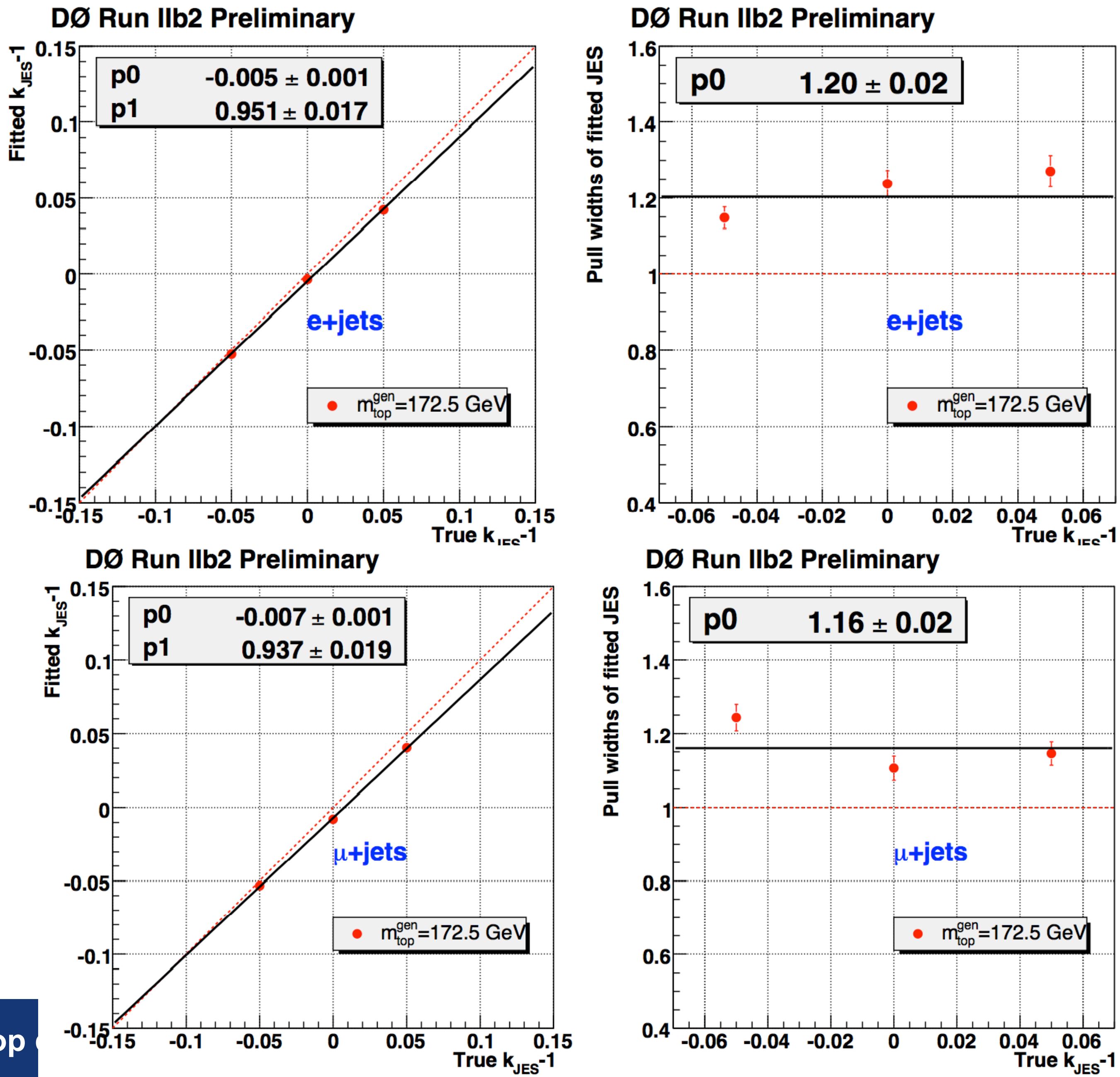
Method response in k_{JES}



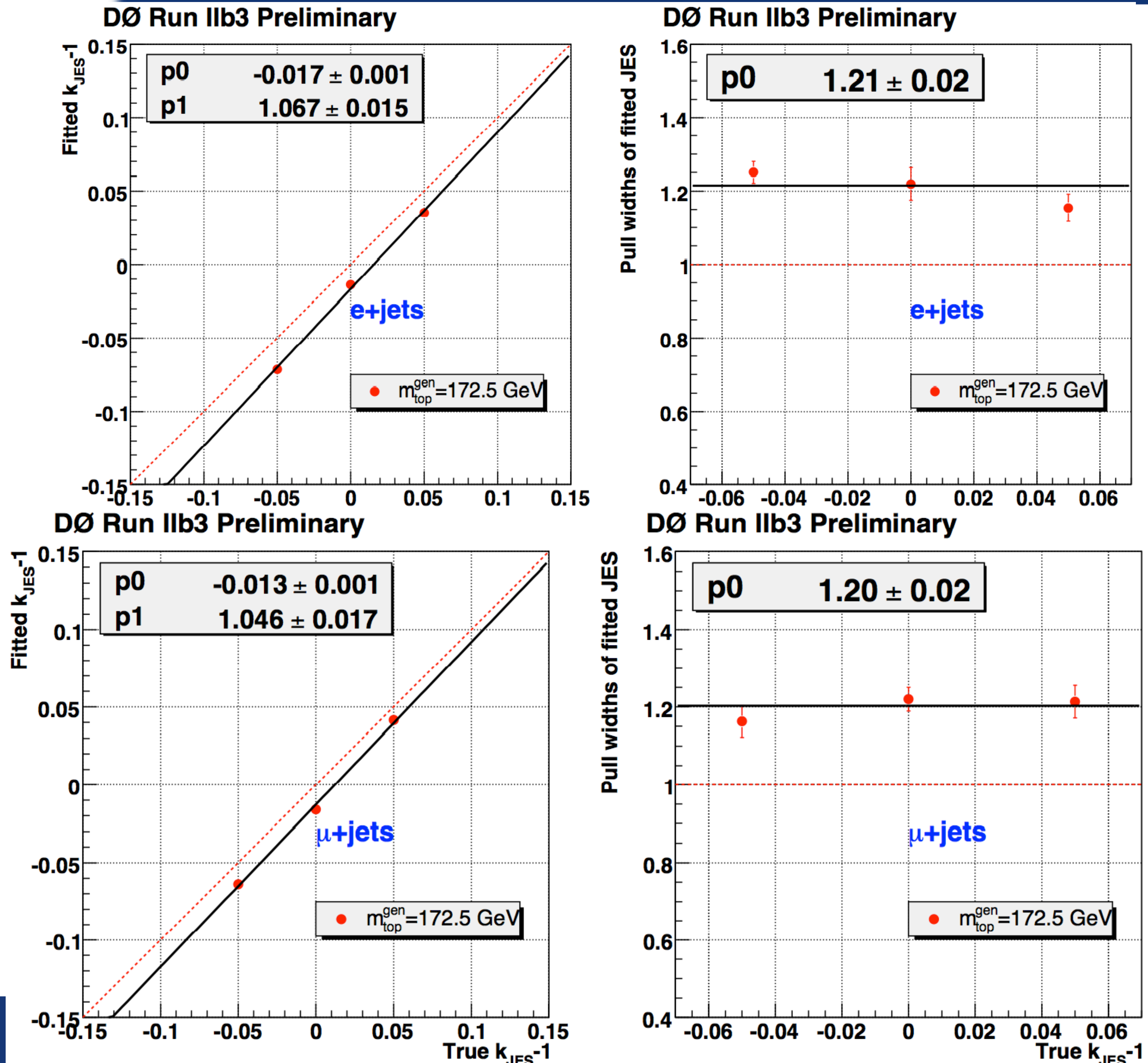
Method response in k_{JES}



Method response in k_{JES}



Method response in k_{JES}



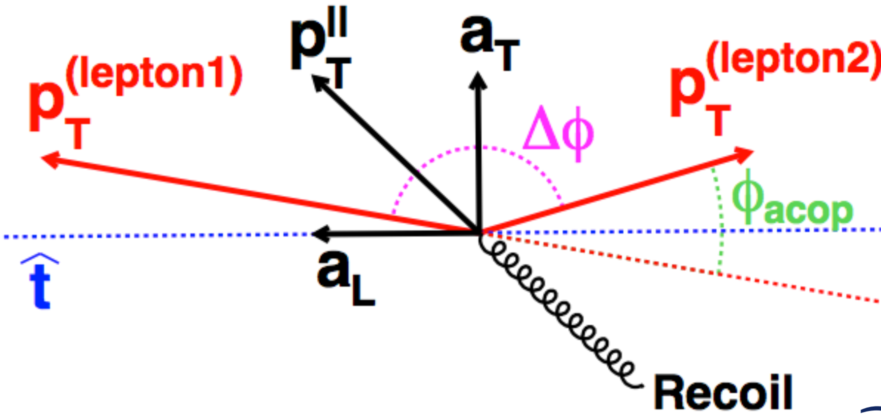
Residual JES

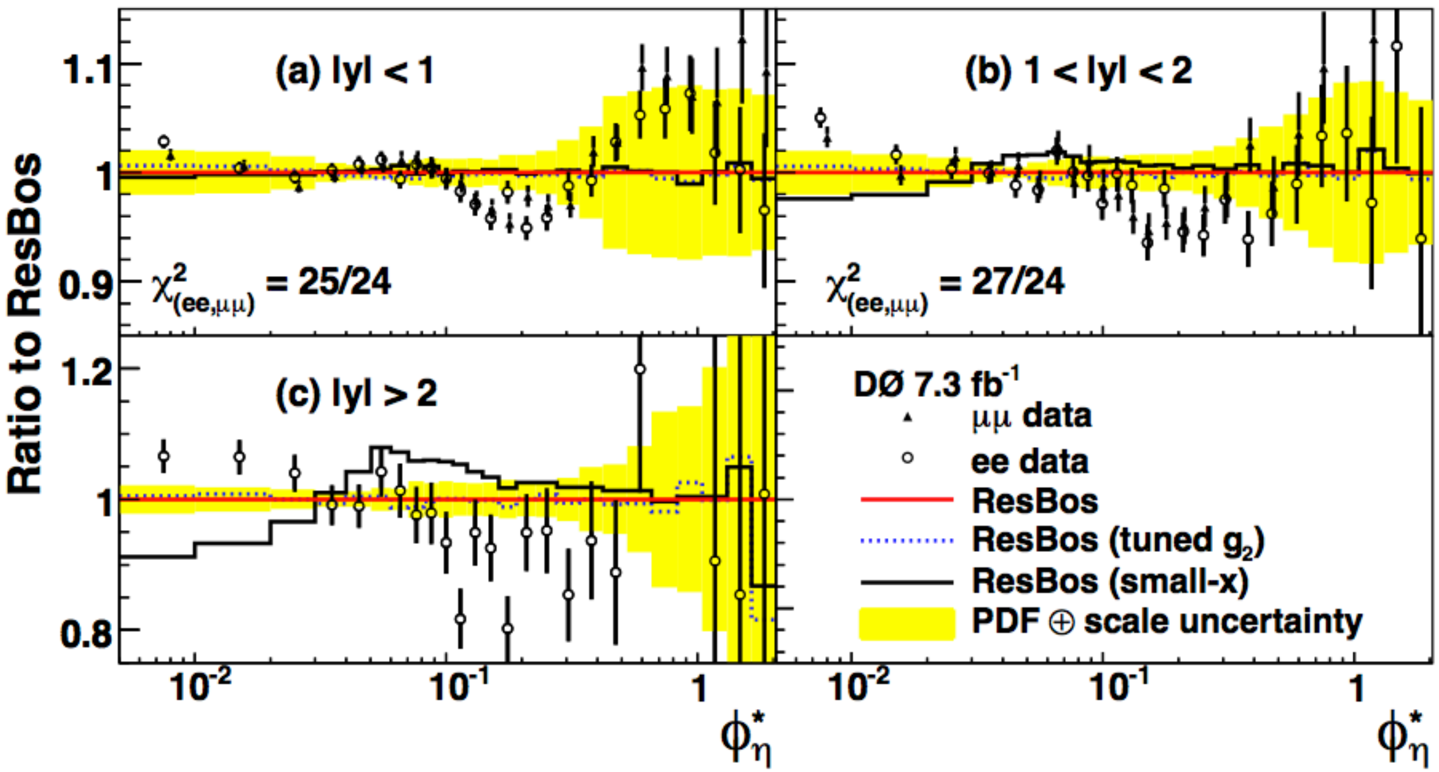
- Even though we perform an in-situ calibration of JES, this is only an overall calibration
  - k_{JES} cannot account for any effects differential in (p_T,η)
  - Study various parametrisations:
    - *0.13 GeV* Vary jet energies according to upper error corridor on the JES, differentially in (p_T,η) using a parametrisation
    - *0.08 GeV* Same for lower error corridor using a parametrisation
    - *0.20 GeV* Vary jet energies according to upper error on JES jet-by-jet, i.e. w/o parametrisation
    - *0.21 GeV* Assuming a linear increase in JES which is 0 for E=0 and increases such as to touch the upper error corridor
  - In reality, only one parametrisation is correct
    - → take envelope
- → Uncertainty from residual JES variations in (pT,η):
  - 0.21 GeV (was: 0.21 GeV)

φ* measurement

- Based on 7.3 fb^{-1} of data
- Observable:

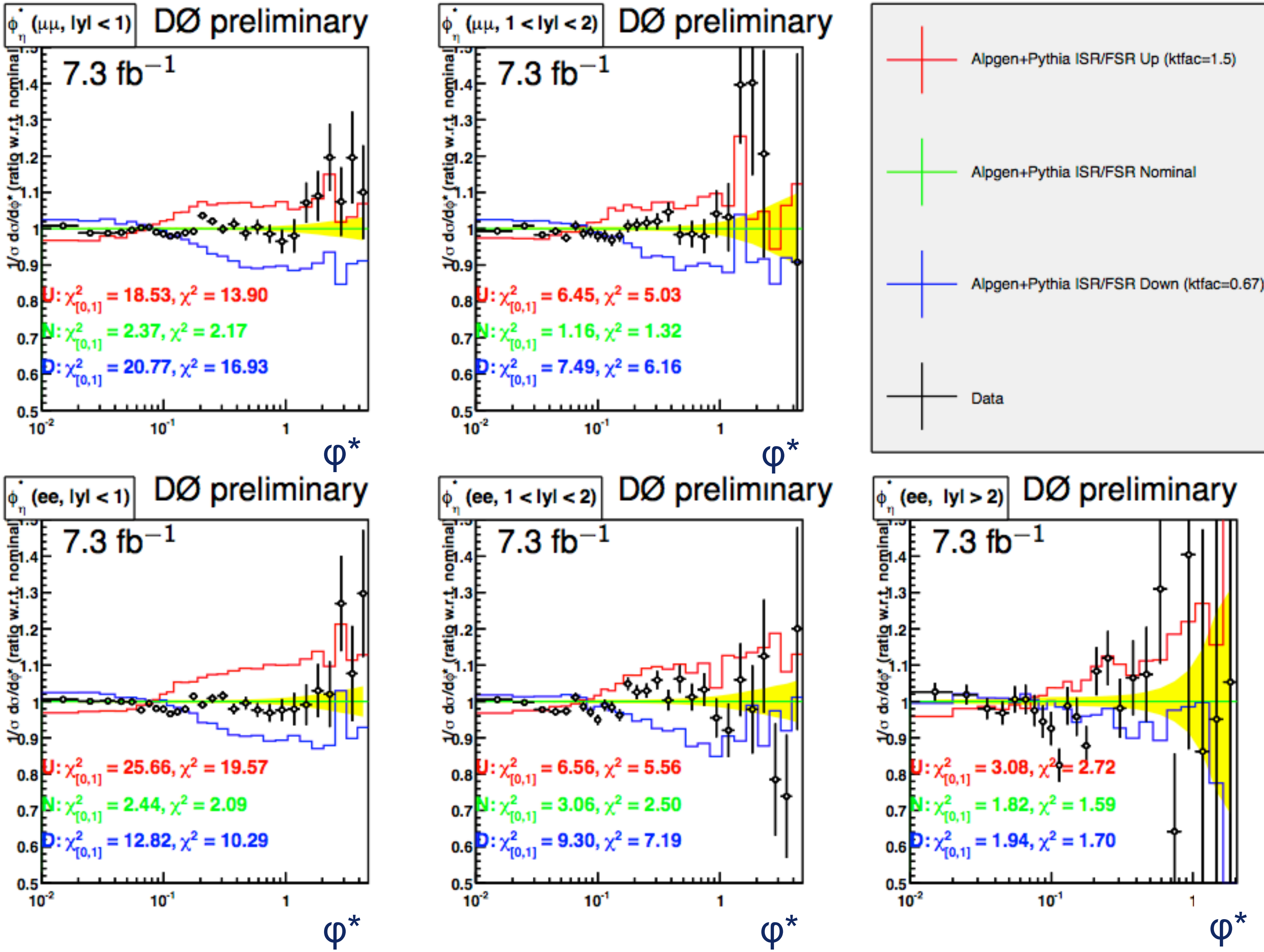
$$\phi^*_\eta = \tan(\phi_{acop}/2)\sin(\theta^*_\eta)$$





[1] DØ Coll., PRL **106**, 122001 (2011)

ISR/FSR



Unfolded spectra from: *DØ Coll., PRL **106**, 122001 (2011)*

Calibration formulae

- For reference:

$$m_t^{'} = \frac{(m_t - 172.5\ \text{GeV}) - p_0^{m_t}}{p_1^{m_t}} + 172.5\ \text{GeV}$$

$$k_{\text{JES}}^{'} = \frac{(k_{\text{JES}} - 1) - p_0^{k_{\text{JES}}}}{p_1^{k_{\text{JES}}}} + 1\,.$$

$$\sigma^{'}(m_t^{'}) = \sigma(m_t^{'}) \times w_{\text{pull}}(m_t)\,,$$

$$\sigma^{'}(k_{\text{JES}}^{'}) = \sigma(k_{\text{JES}}^{'}) \times w_{\text{pull}}(k_{\text{JES}})$$

$$pull = \frac{\langle x \rangle - \bar{x}}{\sigma}$$

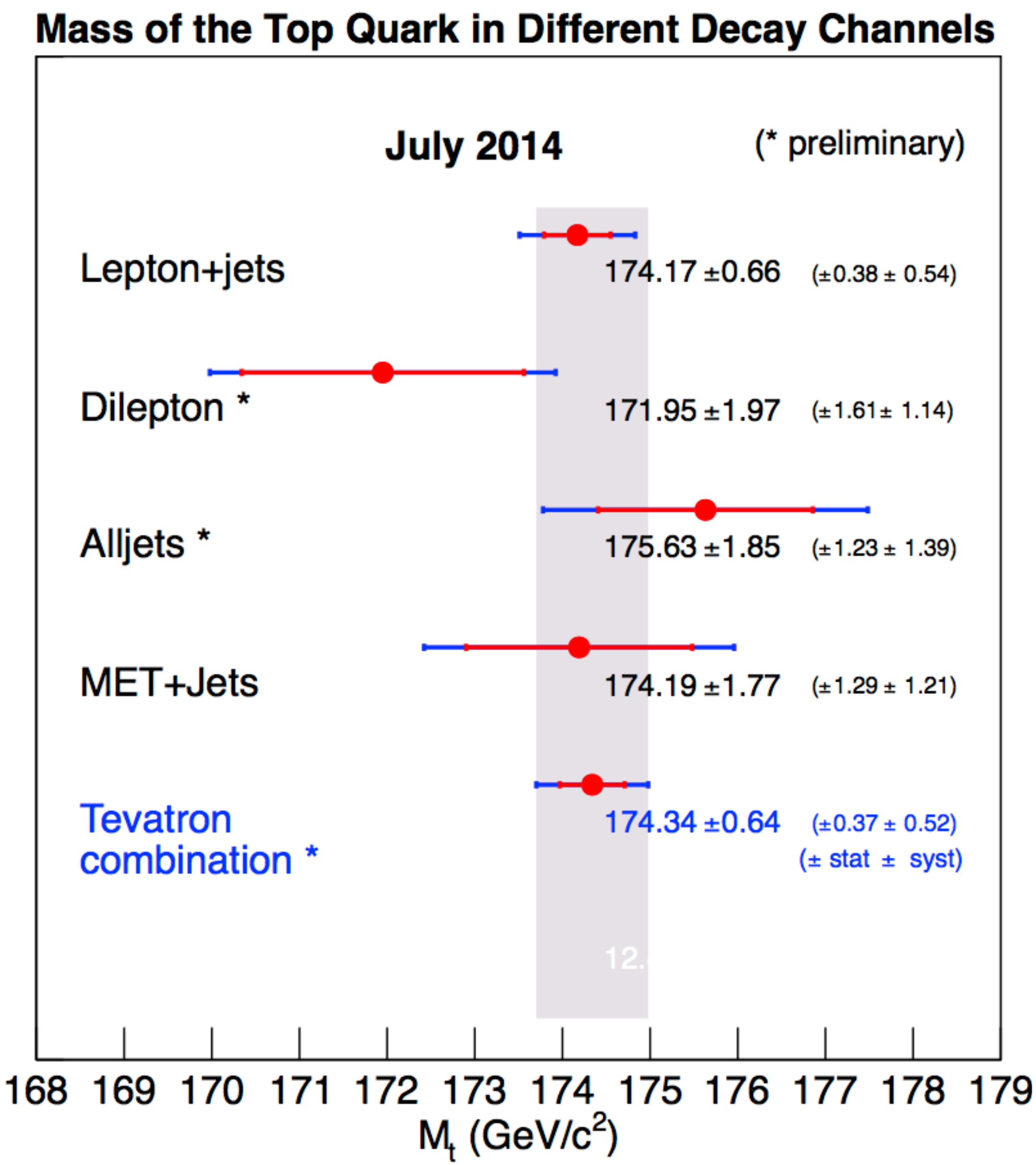
Top quark mass: Tevatron combination

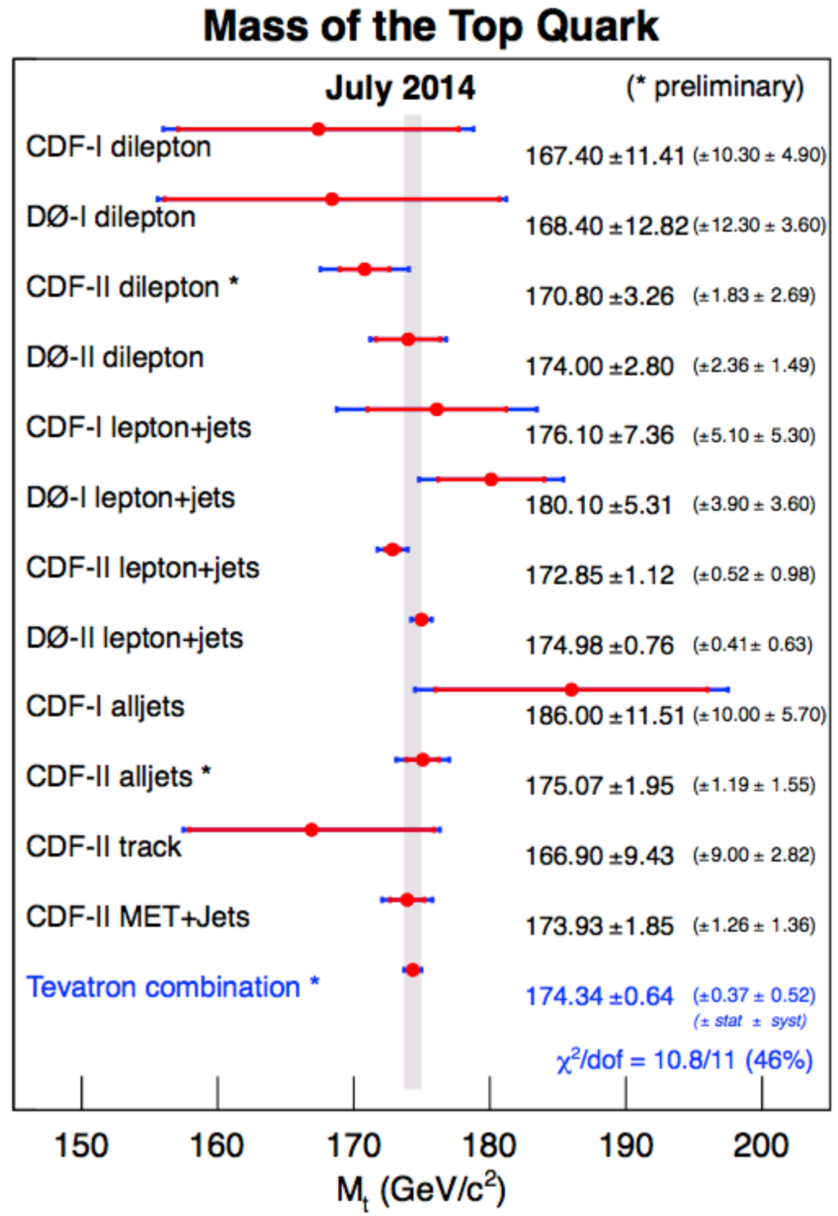
	Run I published					Run II published					Run II prel.	
	CDF			DØ		CDF			DØ		CDF	
	ℓ+jets	$\ell\ell$	all-jets	ℓ+jets	$\ell\ell$	ℓ+jets	L_{XY}	MEt	ℓ+jets	$\ell\ell$	$\ell\ell$	all-jets
CDF-I ℓ+jets	1.00	0.29	0.32	0.26	0.11	0.49	0.07	0.26	0.19	0.12	0.54	0.27
CDF-I $\ell\ell$	0.29	1.00	0.19	0.15	0.08	0.29	0.04	0.16	0.12	0.08	0.32	0.17
CDF-I all-jets	0.32	0.19	1.00	0.14	0.07	0.30	0.04	0.16	0.08	0.06	0.37	0.18
DØ-I ℓ+jets	0.26	0.15	0.14	1.00	0.16	0.22	0.05	0.12	0.13	0.07	0.26	0.14
DØ-I $\ell\ell$	0.11	0.08	0.07	0.16	1.00	0.11	0.02	0.07	0.07	0.05	0.13	0.07
CDF-II ℓ+jets	0.49	0.29	0.30	0.22	0.11	1.00	0.08	0.32	0.28	0.18	0.52	0.30
CDF-II L_{XY}	0.07	0.04	0.04	0.05	0.02	0.08	1.00	0.04	0.05	0.03	0.06	0.04
CDF-II MEt	0.26	0.16	0.16	0.12	0.07	0.32	0.04	1.00	0.17	0.11	0.29	0.18
DØ-II ℓ+jets	0.19	0.12	0.08	0.13	0.07	0.28	0.05	0.17	1.00	0.36	0.15	0.14
DØ-II $\ell\ell$	0.12	0.08	0.06	0.07	0.05	0.18	0.03	0.11	0.36	1.00	0.10	0.09
CDF-II $\ell\ell$	0.54	0.32	0.37	0.26	0.13	0.52	0.06	0.29	0.15	0.10	1.00	0.32
CDF-II all-jets	0.27	0.17	0.18	0.14	0.07	0.30	0.04	0.18	0.14	0.09	0.32	1.00

	Run I published					Run II published					Run II prel.	
	CDF			DØ		CDF			DØ		CDF	
	ℓ+jets	$\ell\ell$	all-jets	ℓ+jets	$\ell\ell$	ℓ+jets	L_{XY}	MEt	ℓ+jets	$\ell\ell$	$\ell\ell$	all-jets
Pull	0.24	−0.61	+1.01	+1.09	−0.46	−1.64	−0.791	−0.24	+1.60	−0.13	−1.11	0.39
Weight [%]	−2.6	−0.7	−0.4	−0.1	−0.14	+28.8	+0.1	+5.5	+67.2	−2.9	−0.66	+6.0

Parameter	Value (GeV/c^2)	Correlations			
		$M_t^{\text{all-jets}}$	$M_t^{\ell+\text{jets}}$	$M_t^{\ell\ell}$	M_t^{MEt}
$M_t^{\text{all-jets}}$	175.63 ± 1.85	1.00			
$M_t^{\ell+\text{jets}}$	174.17 ± 0.66	0.21	1.00		
$M_t^{\ell\ell}$	171.95 ± 1.97	0.21	0.41	1.00	
M_t^{MEt}	174.19 ± 1.77	0.11	0.23	0.18	1.00

Top quark mass: Tevatron combination





Correlations btw. uncertainties world combo

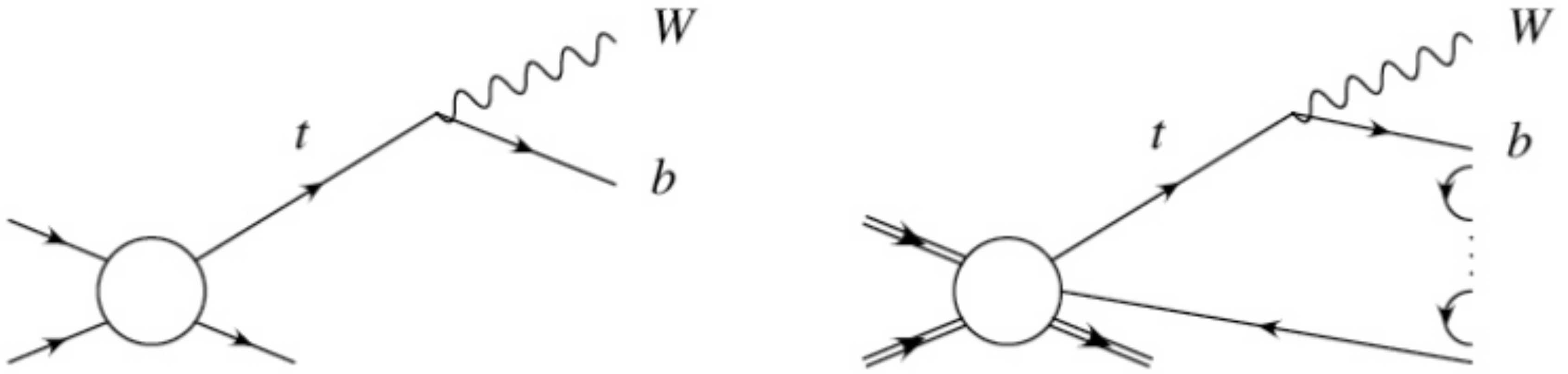
- Input: correlations between uncertainty categories:

	ρ_{EXP}				ρ_{LHC}	ρ_{TEV}	ρ_{COL}	
	ρ_{CDF}	ρ_{D0}	ρ_{ATL}	ρ_{CMS}			$\rho_{ATL-TEV}$	$\rho_{CMS-TEV}$
Stat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
iJES	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
stdJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
flavourJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
bJES	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.5
MC	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Rad	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
CR	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PDF	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
DetMod	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
b-tag	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
LepPt	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
BGMC†	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
BGData	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Meth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MHI	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0

  - ρ_{CDF}, ρ_{D0}, ρ_{ATL} ρ_{CMS} : correlations within an experiment
  - ρ_{LHC}, ρ_{TEV} : correlations within the collider (LHC/Tevatron)
  - $\rho_{ATL-TEV}$, $\rho_{CMS-TEV}$: correlations between ATLAS or CMS and Tevatron

Which m_{top} do we measure?

- *(I only want to refresh our memory here)*
- The top **mass** is **not an observable** per se and has to be inferred from its effect on kinematic observables
- The mass **cannot be well-defined at LO**
- The **pole mass** corresponds to our physical intuition of a stable particle
  - m_{top} is the "pole" in the top quark propagator
    - Although this is not fully correct (hadronisation effects)
  - The pole mass can never be determined with **precision** better than Λ_{QCD}:

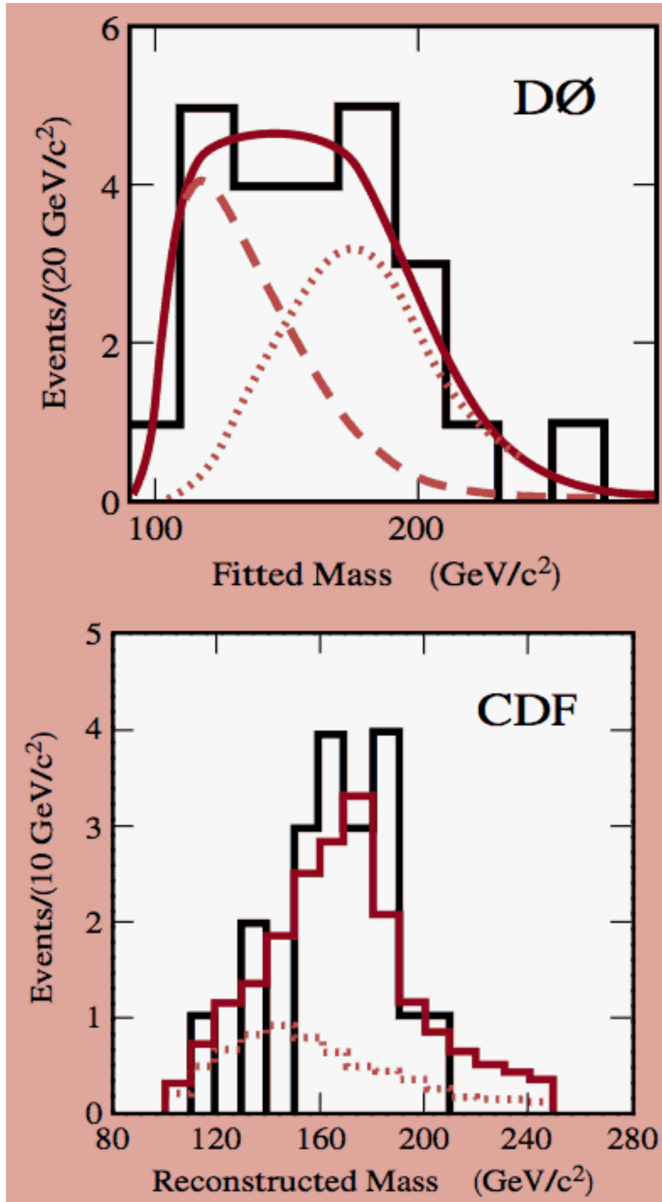


Which m_{top} do we measure?

- Other popular mass definition schemes:
  - e.g. modified minimal subtraction scheme ($\overline{MS}$), also referred to as running mass $m_{top}(\mu_r)$
    - The μ_r dependence can be used to absorb logarithmic corrections through resummation (in specific cases)
      - better behaviour of perturbative predictions
  - The $\overline{MS}$ mass can be translated into the pole mass at any fixed order of perturbation theory
- What we typically measure at hadron colliders, is:
  - Neither the $\overline{MS}$ mass, nor the pole mass → m^{MC}
  - "Close" to the pole mass
    - "Close" not quantified yet
- True also for NLO generators like e.g. powheg
  - finite width effects of top propagator are not simulated, but generated via reweighting

The birth weight

- 24 Feb. 1995:
  - Simultaneous PRL submission by CDF and DØ
- CDF (67 pb^{-1}) :
  - $\sigma = 6.8^{+3.6}_{-2.4}$ pb,
  - observed 19 events, expected 6.9 bkg
    - bkg-only hypothesis rejected at 4.8σ
  - m_{top}=176±13 GeV
- D0 (50 pb^{-1}):
  - σ=6.4±2.2 pb,
  - observed 17 events, expected 3.8 bkg
    - → bkg-only hypothesis rejected at 4.6σ
  - m_{top}=199±30 GeV



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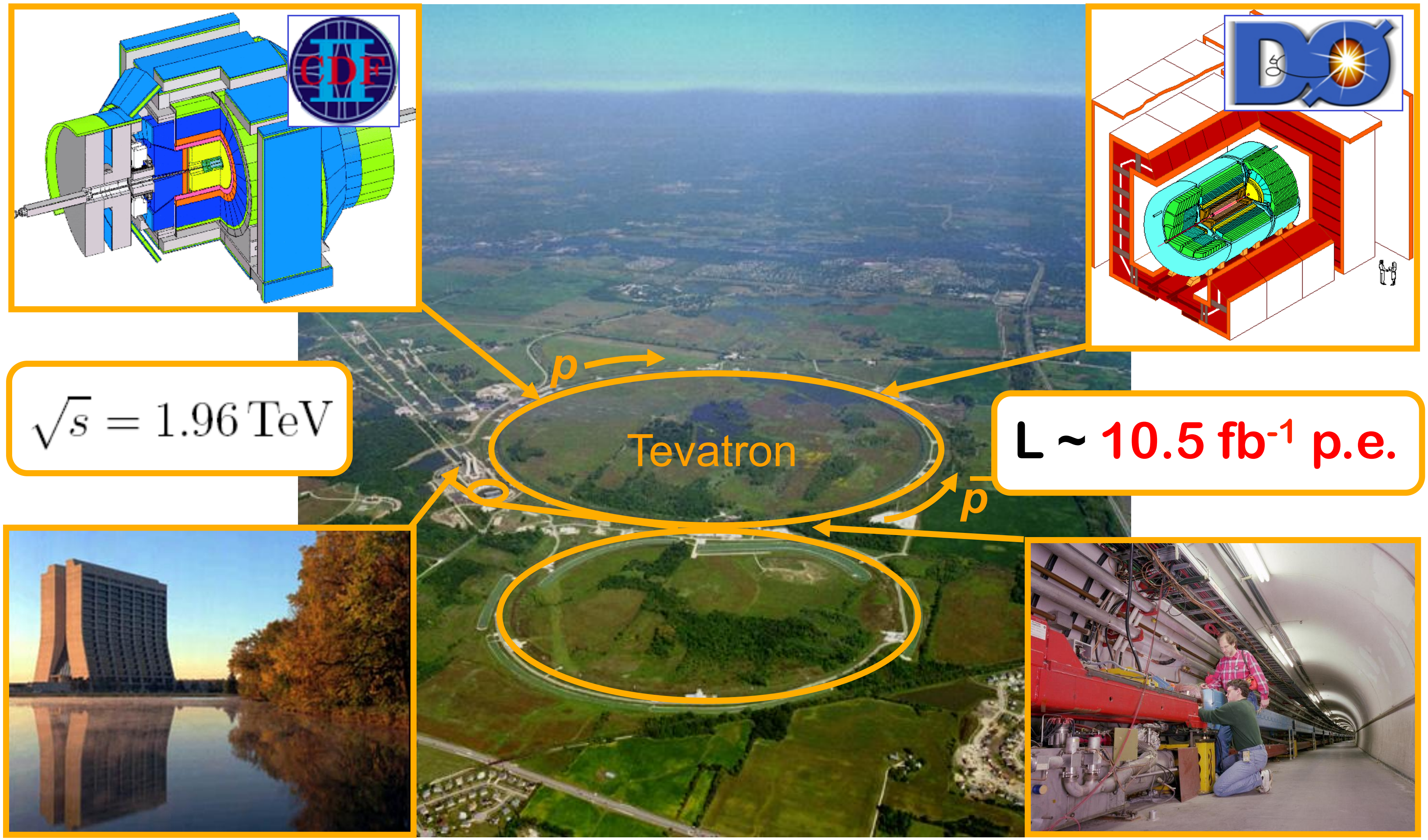
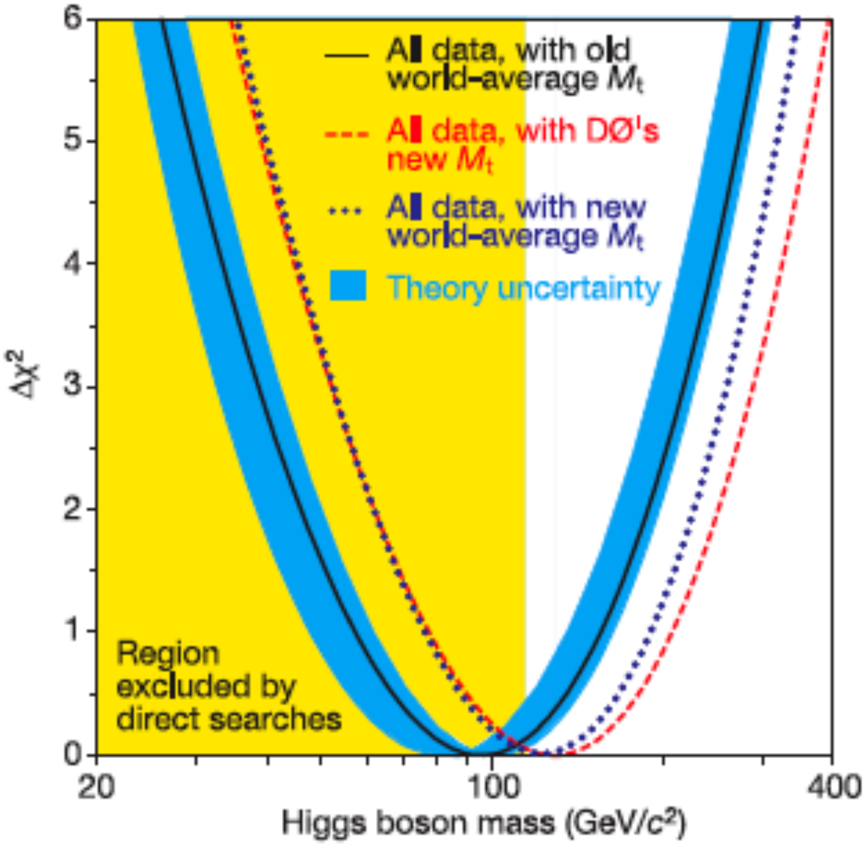
More about the birth place…



First implementation of MEM in HEP

- The first (published) measurement in HEP using the MEM:



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Explorer satellite.

A precision measurement of the mass of the top quark

DØ Collaboration*

*A list of authors and their affiliations appear at the end of the paper

The standard model of particle physics contains parameters—such as particle masses—whose origins are still unknown and which cannot be predicted, but whose values are constrained through their interactions. In particular, the masses of the top quark (M_t) and W boson (M_W)[1] constrain the mass of the long-hypothesized, but thus far not observed, Higgs boson. A precise measurement of M_t can therefore indicate where to look for the Higgs, and indeed whether the hypothesis of a standard model Higgs is consistent with experimental data. As top quarks are produced in pairs and decay in only about 10^{-24} s into various final states, reconstructing their masses from their decay products is very challenging. Here we report a technique that extracts more information from each top-quark event and yields a greatly improved precision (of $\pm$ 5.3 GeV/c^2) when compared to previous measurements[2]. When our new result is combined with our published measurement in a complementary decay mode[3] and with the only other measurements available[2], the new world average for M_t becomes[4] 178.0 $\pm$ 4.3 GeV/c^2. As a

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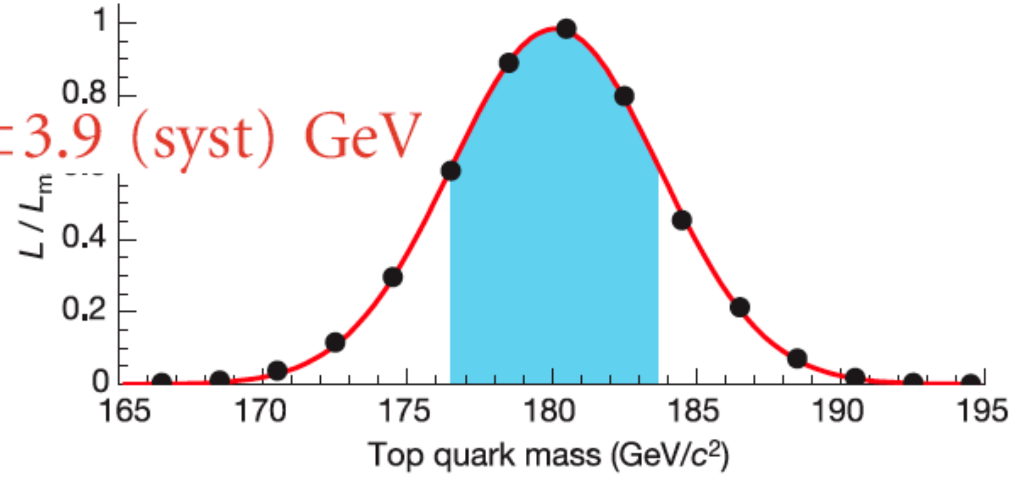
letters to nature

:he experimen-   top quark in our previous publication, and correspond to an

First implementation of MEM in HEP



- The **final result:**
  - $M_t = 180.1 \pm 3.6\ (\text{stat})\ \pm 3.9\ (\text{syst})\ \text{GeV}$
    - Using 125 pb^{-1} of p-pbar collisions @ 1.8 TeV, 71 events
- **Previous** result:
  - $M_t = 173.3 \pm 5.6\ (\text{stat})\ \pm 5.5\ (\text{syst})\ \text{GeV}$
    - same dataset, 91 candidates
- **Much higher statistical sensitivity:**
  - Corresponding to **2.4x more data** with old method!
  - Systematic uncertainties are also smaller
- *Already this analysis*
  - *Was using jet-parton transfer functions*
  - *Looked at 12 possible jet-parton assignments (4 jets)*
  - *Used numerical integration in 5 variables*