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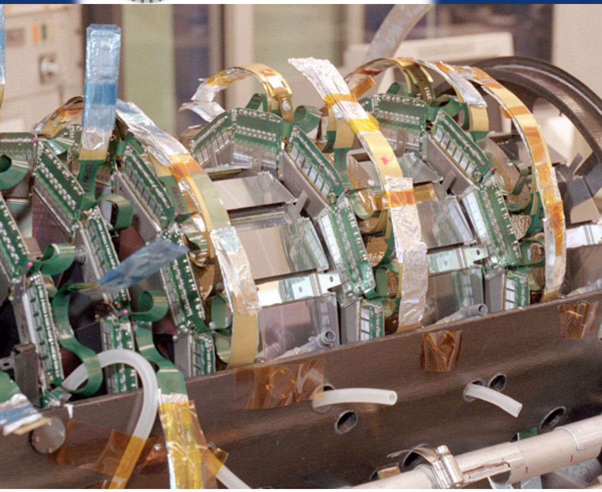
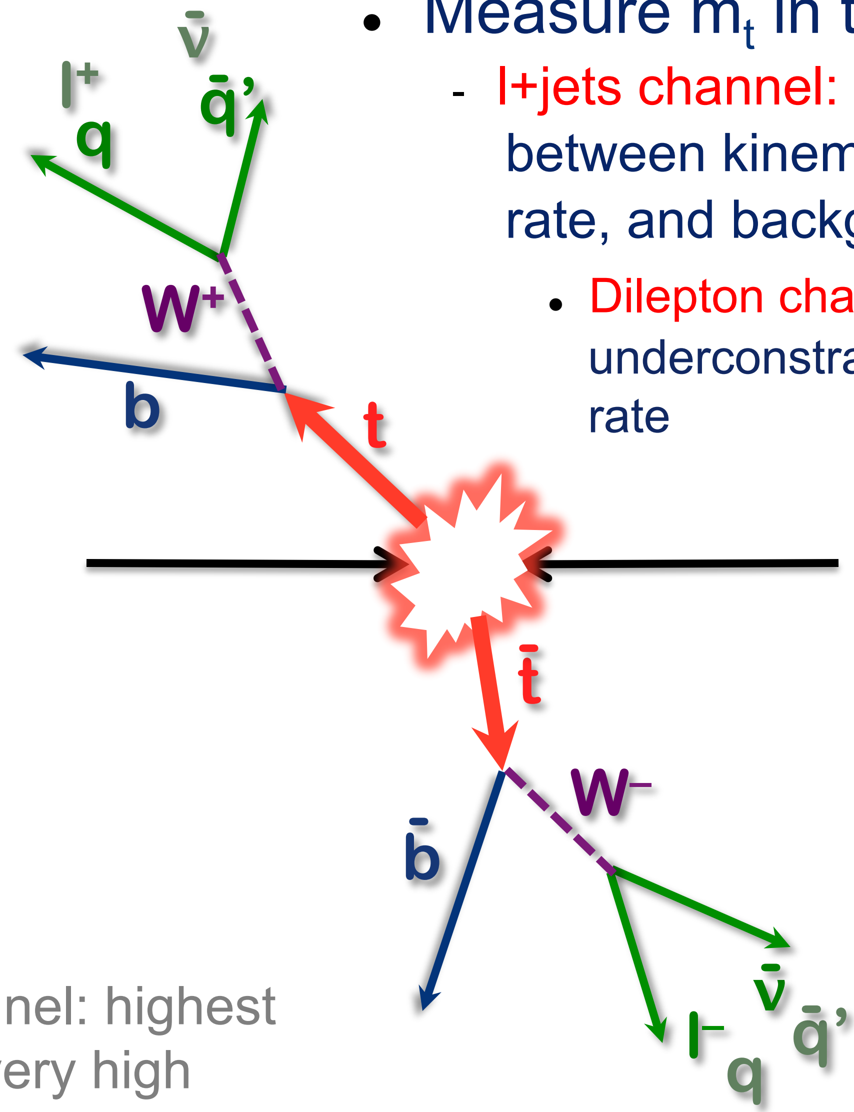



# Direct measurement of the top quark mass in $p\bar{p}$ collisions at DØ

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

# Characterisation by final state

- Measure $m_t$ in tt events [1]:
  - l+jets channel: good compromise between kinematic reconstruction, high rate, and backgrounds
    - Dilepton channel: low backgrounds, but underconstrained kinematics and low rate



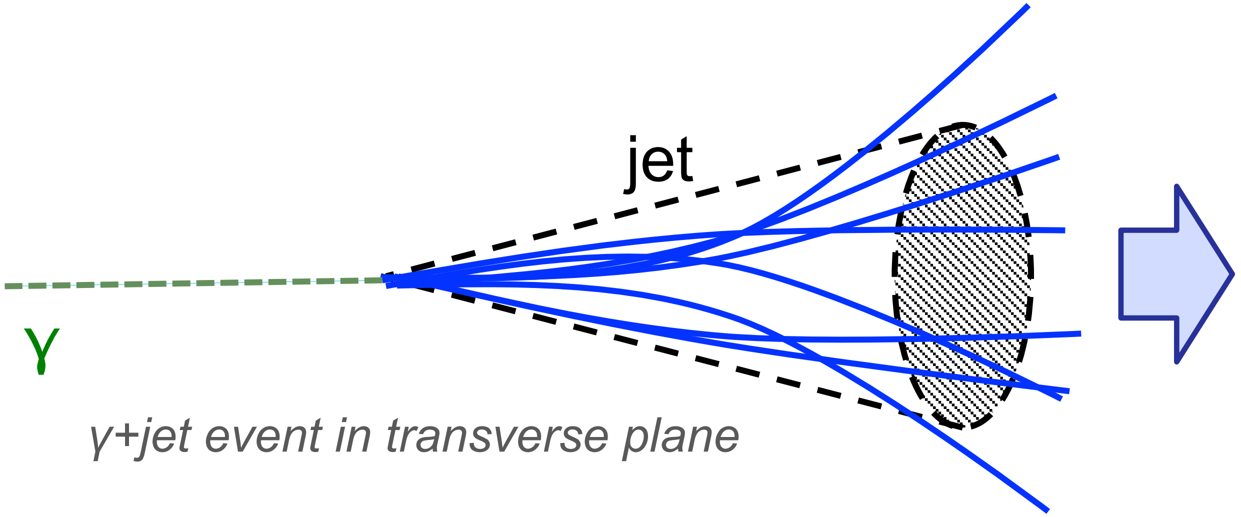

- All-hadronic channel: highest branching ratio, very high backgrounds from QCD multijet events

*[1] "bar" notation implicit*

# Jet energy scale (JES) calibration

*NIM A 763, 442 (2014)*

- 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 transverse plane*

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

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

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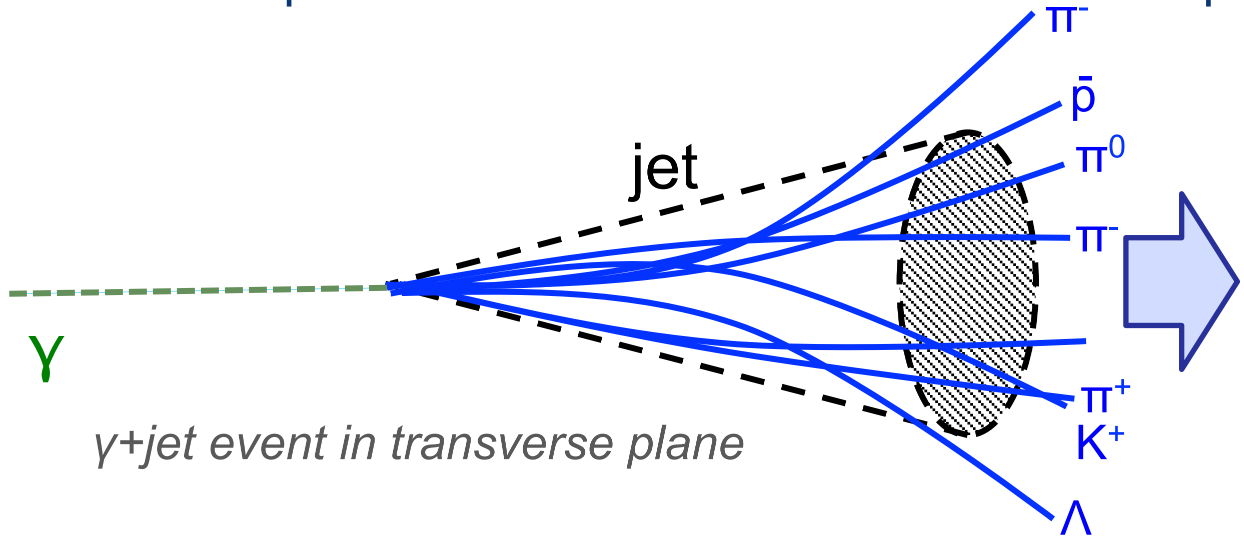


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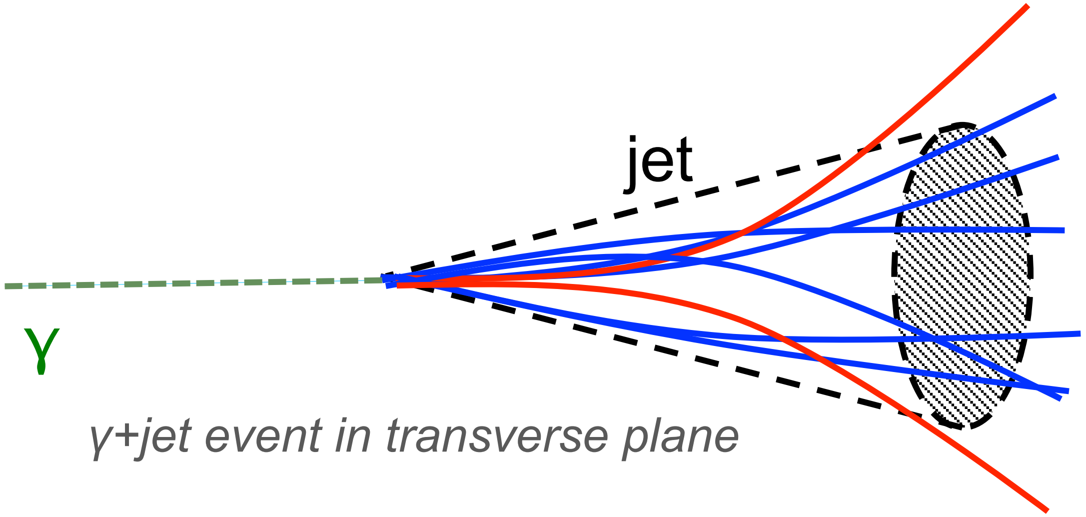



*γ+jet event in transverse plane*

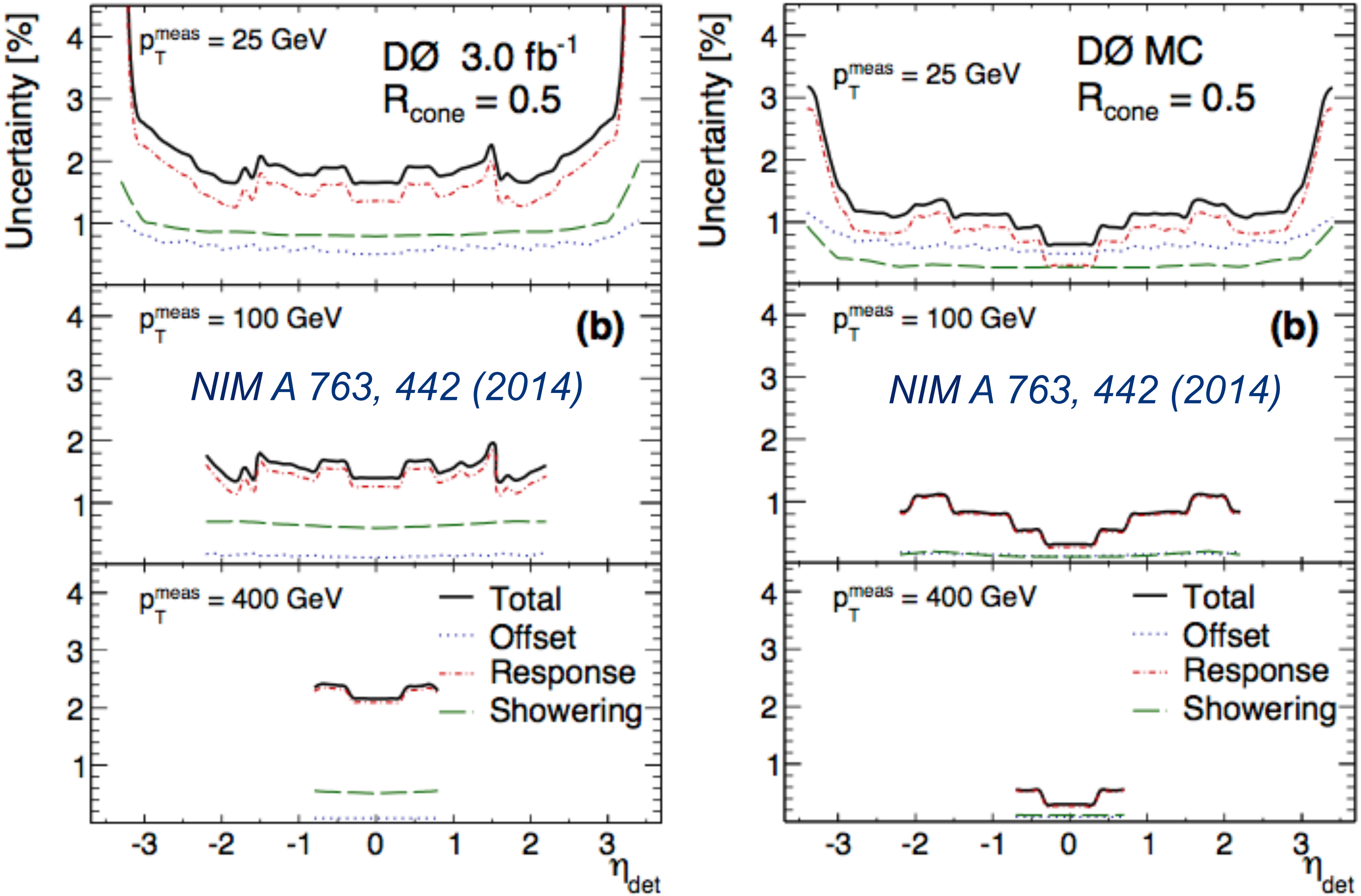
$$E^{\text{ptcl}} = \frac{E^{\text{meas}} - E_{\text{O}}}{R \cdot S}$$

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

*NIM A 763, 442 (2014)*

# Refined jet energy scale calibration

- Use final Run II jet energy scale (JES) calibration:



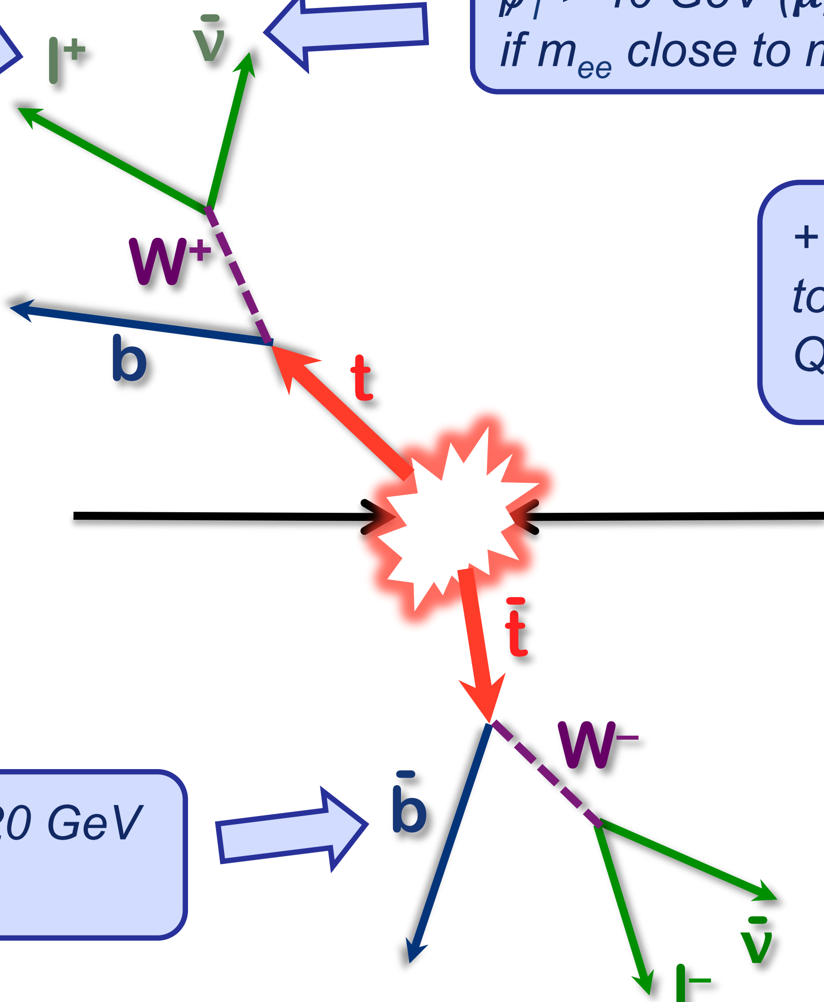

*Figures are representative of all Run II*

# $m_t$ in the dilepton channel (9.7 fb$^{-1}$)

*$p_T$ > 15 GeV,*
*$|\eta_\mu|$ < 2 or*
*$|\eta_e|$ < 2.5*

*$\not{p}_T$ > 40 GeV (**$\mu\mu$**, ee only if $m_{ee}$ close to $m_Z$)*

*+ Topological selections to reduce Z+jets and QCD multijet (MJ) events*




*≥2 jets with $p_T$ > 20 GeV*
*≥1 b-tag*

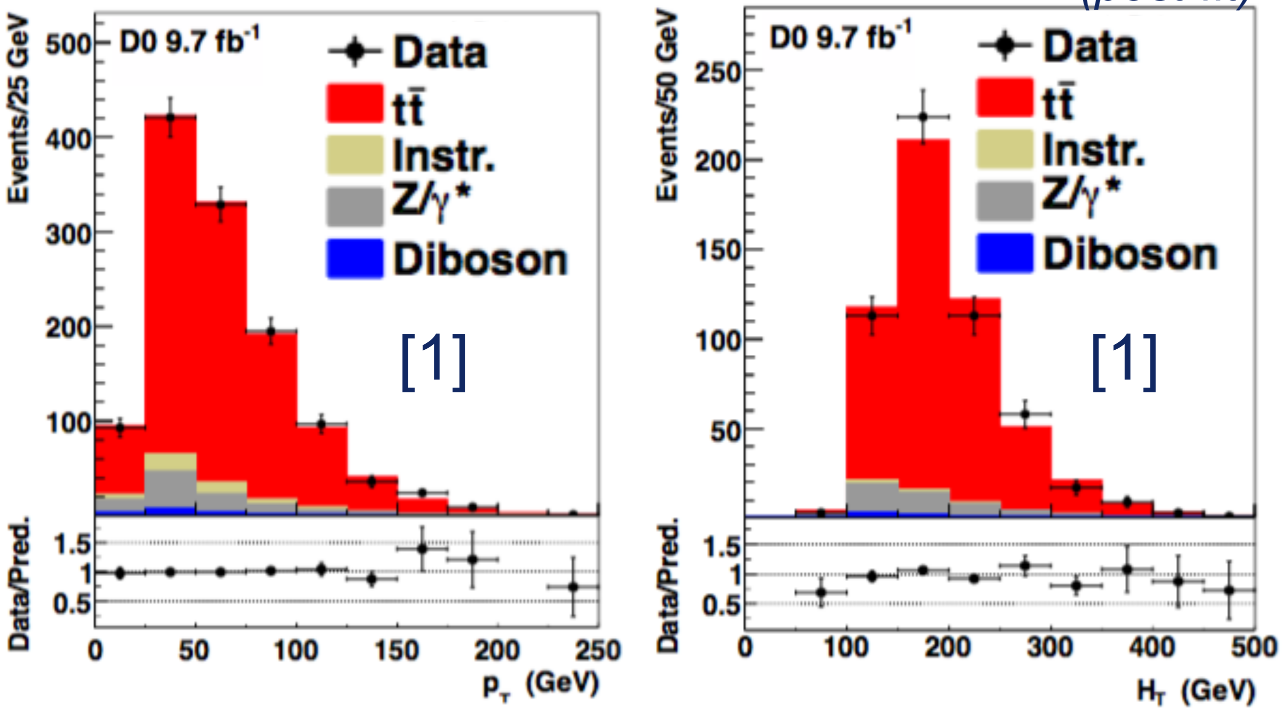
*PRD **94**, 032004 (2016)*
*PLB **752**, 18 (2016)*

# $m_t$ in the dilepton channel (9.7 $fb^{-1}$)

- **Challenge:**
  - tt system kinematically 1x underconstrained if $m_t$ free!
    - → ME method (5.3 $fb^{-1}$) [1]:
    - → Neutrino weighting method, νWT (5.4 $fb^{-1}$) [2]:

- **Data/MC agreement:**

*(post-fit)*





*[1] PRD **94**, 032004 (2016)*
*[2] PLB **752**, 18 (2016)*

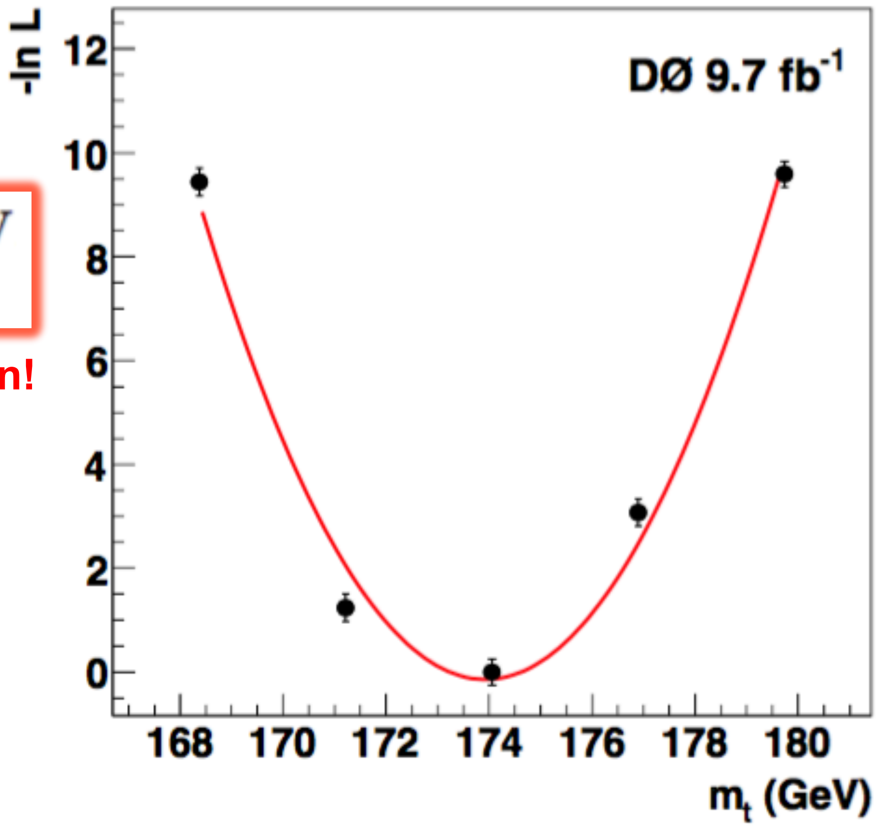
# $m_t$ in the dilepton channel ($9.7\ fb^{-1}$)

*Note: analysis was performed blinded in $m_t$*

- **Matrix element method, ME ($9.7\ fb^{-1}$) [1]:**
  - Postulate $y_\nu$ from MC, solve kinematics
  - Apply in-situ JES calibration from l+jets [2]
  - ME method similar to l+jets
- **Result:**

$$m_t = 173.93 \pm 1.61\ (\text{stat}) \pm 0.88\ (\text{syst})\ \text{GeV}$$
$$= 173.93 \pm 1.84\ \text{GeV}$$

**1.1% precision!**



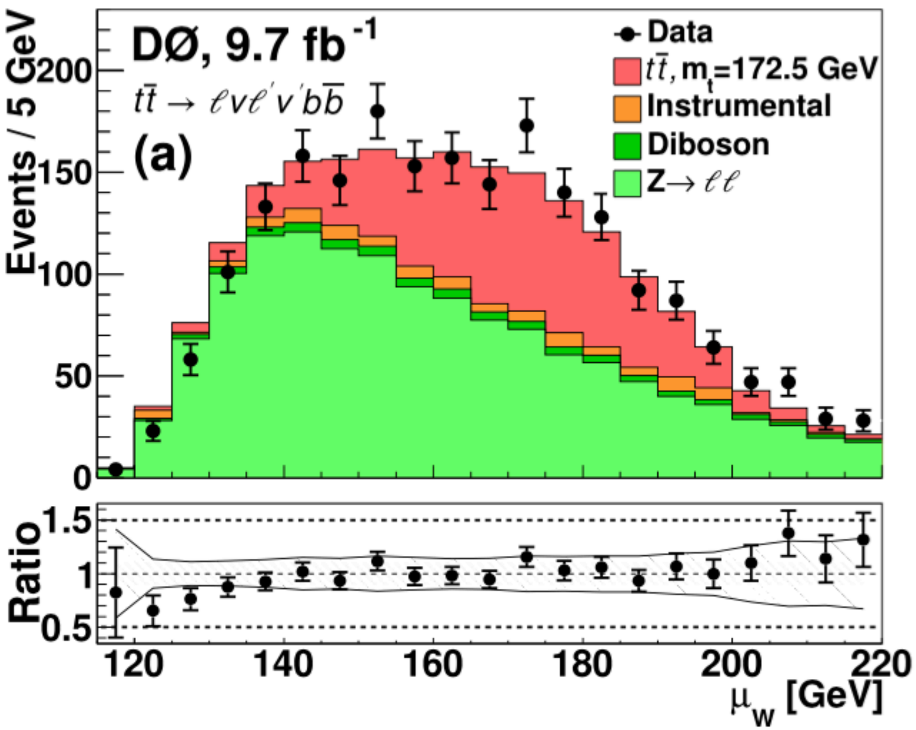

- **Systematics:**
  - JES: absolute (0.46 GeV)
  - JES: flavour-dependence (0.30 GeV)
  - B-tagging (0.28 GeV)
  - Hadronisation and UE (0.32 GeV)


*[1] PRD **94**, 032004 (2016)*
*[2] PRL **113**, 032002 (2014), PRD **91**, 112003 (2015)*

# $m_t$ in the dilepton channel (9.7 fb$^{-1}$)

- **Neutrino weighting method, vWT (9.7 fb$^{-1}$) [1]:**
  - assume $p_T(tt)$ from MC & integrate over $p_{\nu 1}$, $p_{\nu 2}$
  - Apply in-situ JES calibration from l+jets [2]
  - Template method to extract $m_t$:

*Note: analysis was performed blinded in $m_t$*




- **Result:**

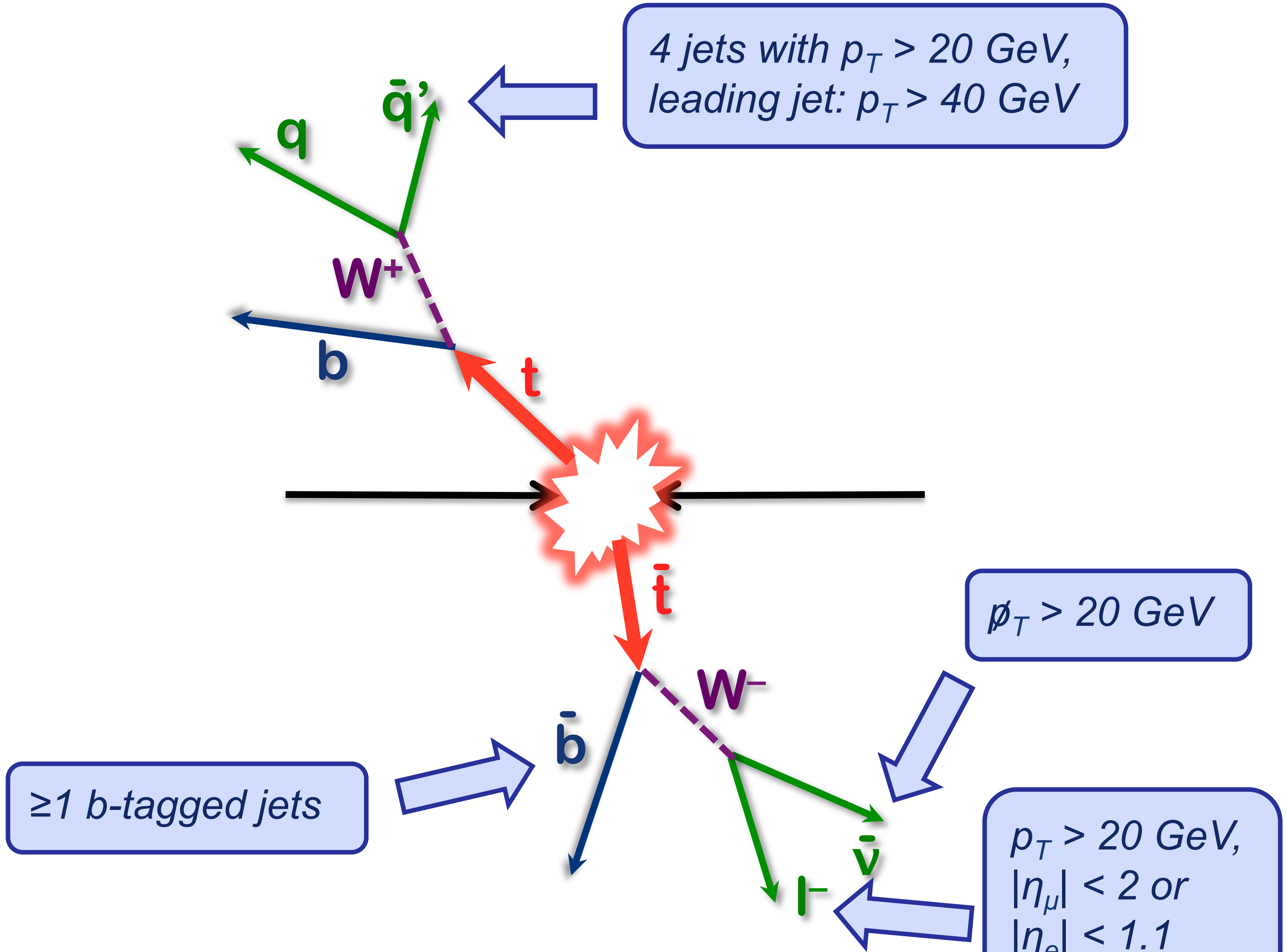
$$m_t = 173.32 \pm 1.36(\text{stat}) \pm 0.85(\text{syst})\ \text{GeV}$$
$$= 173.32 \pm 1.60\ \text{GeV}.$$

Most precise Tevatron dilepton result:
**0.9% precision!**

- **Systematics:**
  - JES: absolute (0.47 GeV)
  - JES: residual (0.27 GeV)
  - JES: flavour-depend. (0.36 GeV)
  - Higher order effects (0.33 GeV)

*[1] PLB **752**, 18 (2016)* *[2] PRL **113**, 032002 (2014), PRD **91**, 112003 (2015)*

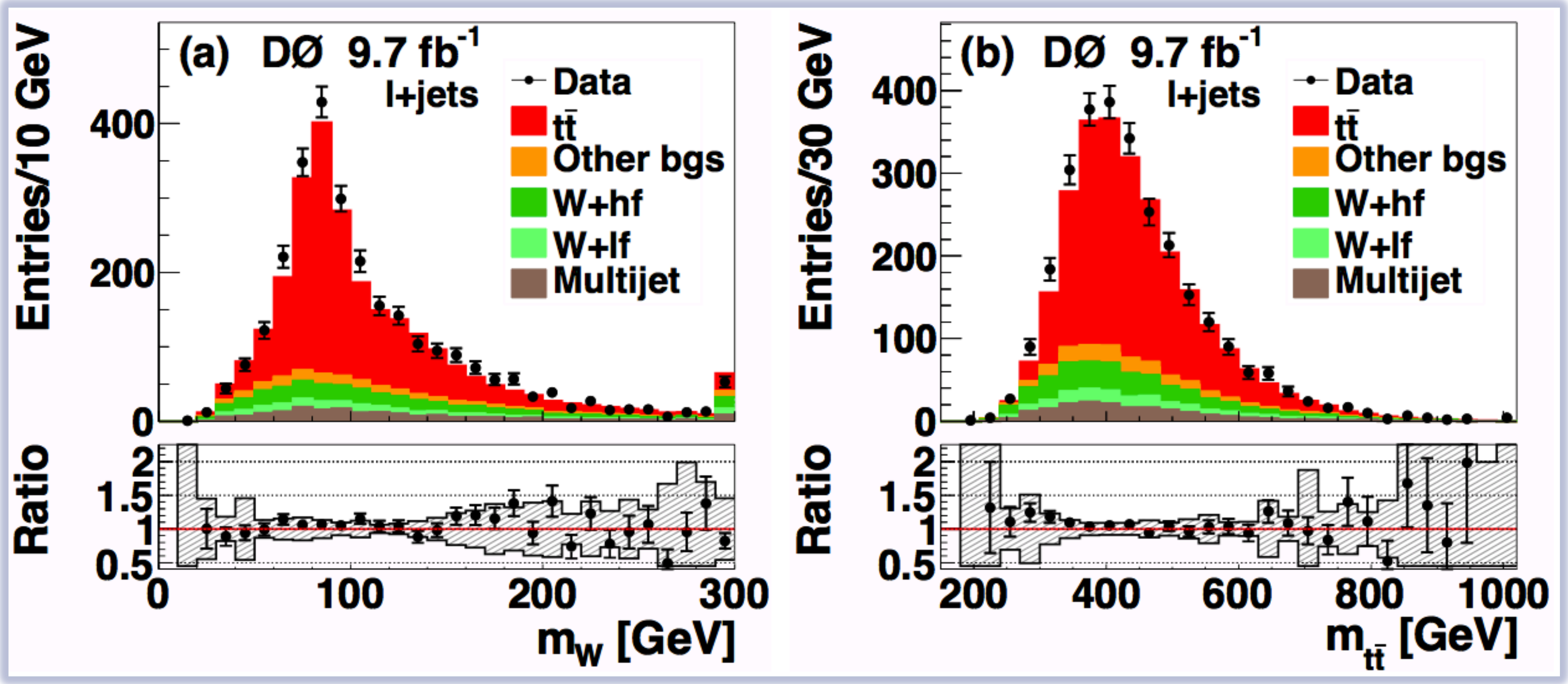
# $m_t$ in the l+jets channel (9.7 fb$^{-1}$)




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

# $m_t$ in the l+jets channel (9.7 fb$^{-1}$)

- **Postfit [1] Data/MC comparison:**




*[1] Measured $\sigma_{tt}$, $m_t$ and overall jet energy scale factor used*

*[2] PRL **113**, 032002 (2014), PRD **91**, 112003 (2015)*

- **Matrix Element (ME) technique [1]:**
  - Calculate the event probability on an event-by-event basis:

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

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

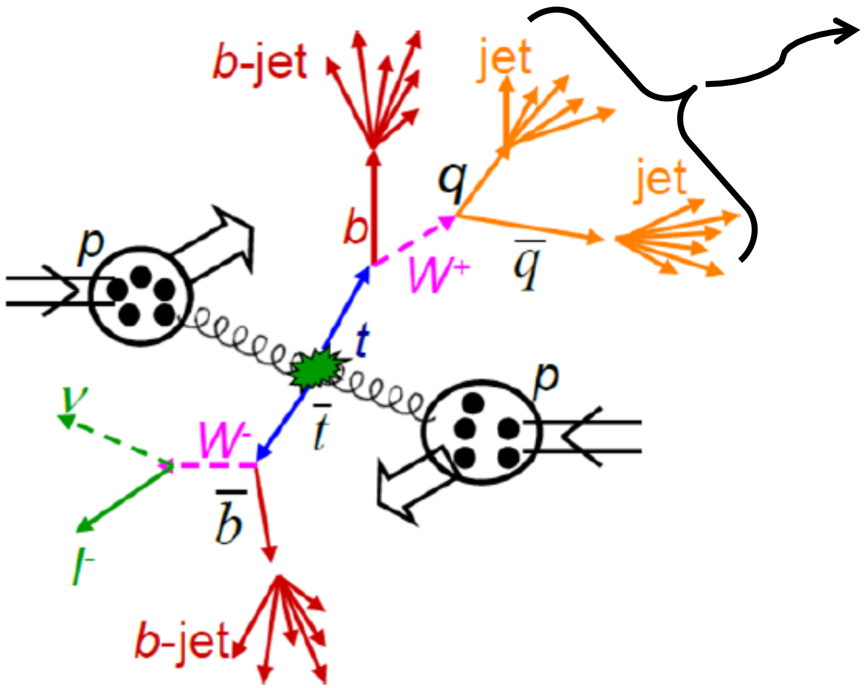
$${\rm d}\sigma_{t\bar{t}} \propto |\mathcal{M}_{t\bar{t}}|^2(m_{\rm top})$$

  - **Advantage:**
    - Use 4-vectors with maximal kinematic and topological information → maximal statistical sensitivity
  - **Disadvantage:**
    - High computational demand

*[1] ME method used: OB, G. Gutierrez, M.H.L.S. Wang, Z. Ye, NIM A* ***775****, 27 (2015)*

# $m_t$ in the l+jets channel (9.7 $fb^{-1}$)

- **In situ JES calibration:**
  - Two-jet system from W→qq' be consistent with $M_W$
  - Likelihood as function of ($m_t$,$k_{JES}$)




***$M_W$ ~ $k_{JES}$***

overall jet-energy scale-factor

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

# $m_t$ in the l+jets channel (9.7 fb$^{-1}$)

## Result of three years of hard work and countless studies…

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

| 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* | 0.49 |
| *Total statistical uncertainty* | 0.58 |
| *Total uncertainty* | 0.76 |

**1.02 GeV**

**0.49 GeV**

Result using 3.6 fb$^{-1}$: 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 |

# $m_t$ in the l+jets channel (9.7 fb$^{-1}$)

- **Calculate a 10 dimensional integral [1]**
  - Identical to the 3.6 fb$^{-1}$ [2] result except:
    - Low-discrepancy sequences for 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
      - Included via transfer function
  - Reduction of calculation time by o(100)
    - → Enlarge calibration samples!
  - Reduce statistical component from MC stats:

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

*From systematics table of the 3.6 fb$^{-1}$ analysis [2]*

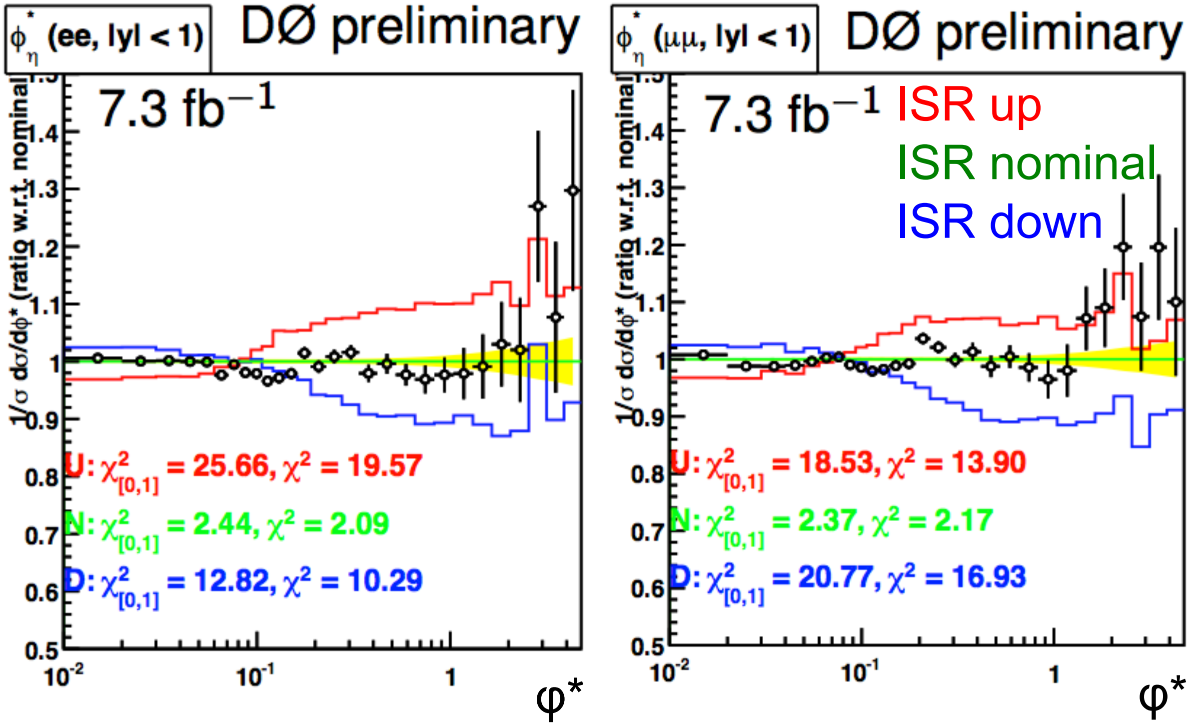
**≈0.25 GeV → ≈0.01–0.05 GeV!**

*[1] ME method used: OB, G. Gutierrez, M.H.L.S. Wang, Z. Ye, NIM A **775**, 27 (2015)*

*[2] DØ Coll. PRD **85** 032004 (2011)*

# $m_t$ in the l+jets channel (9.7 fb$^{-1}$)

- **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



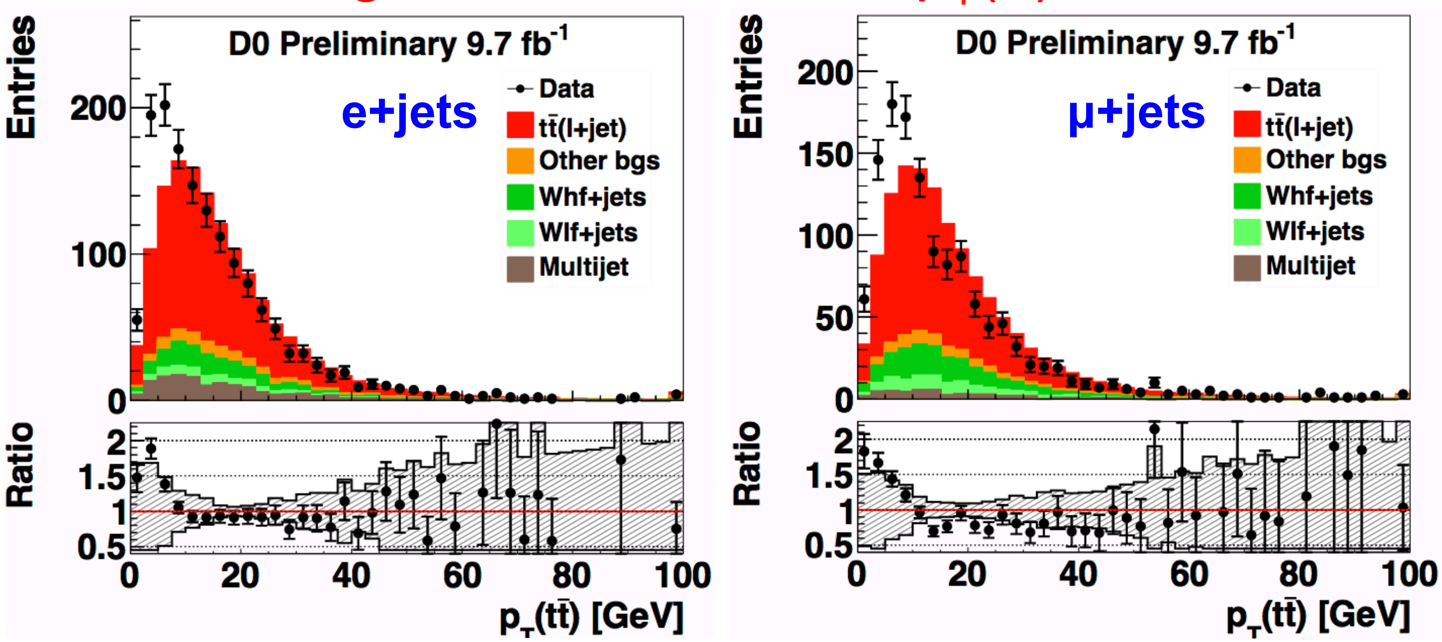

**Also tune in other kinematic regions:**
- **1<|y|<2**
- **|y|>2**

**(cf. backup)**


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

# $m_t$ in the l+jets channel (9.7 fb$^{-1}$)

- **Constrain ISR/FSR by studying Drell-Yan events**
  - Measurement of $p_T(Z)$ using $\varphi^*$ 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
- In addition: reweight tt simulations in $p_T$(tt) to data




- Effect may be related to ISR/FSR mismodelling

***0.06 GeV***

***Total: 0.09 GeV***
***(was: 0.26 GeV)***

***0.07 GeV***

# $m_t$ in the l+jets channel (9.7 fb$^{-1}$)

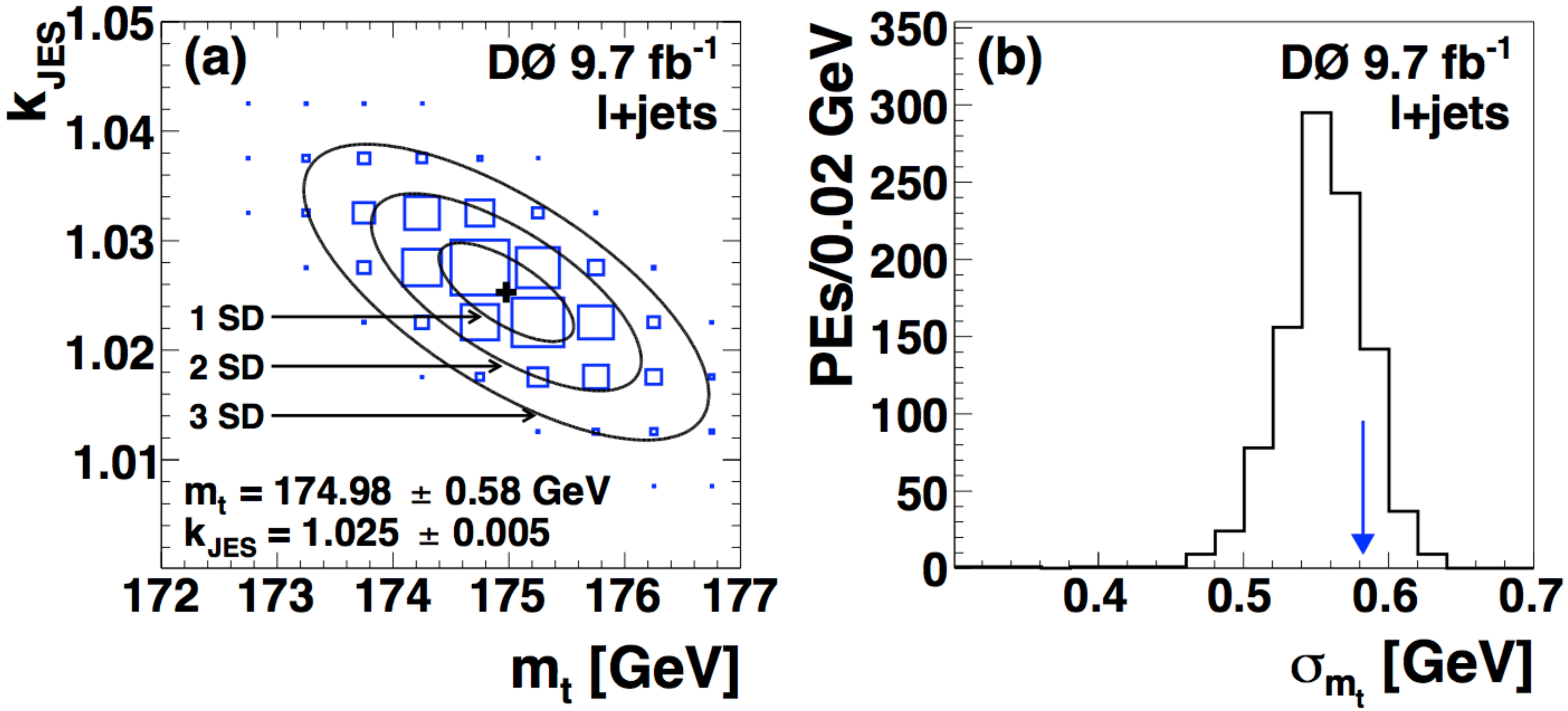
*Note: analysis was performed blinded in $m_t$*

- **Result:**

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

$$\Delta m_t / m_t = 0.43\%!$$

*Most precise Tevatron result*

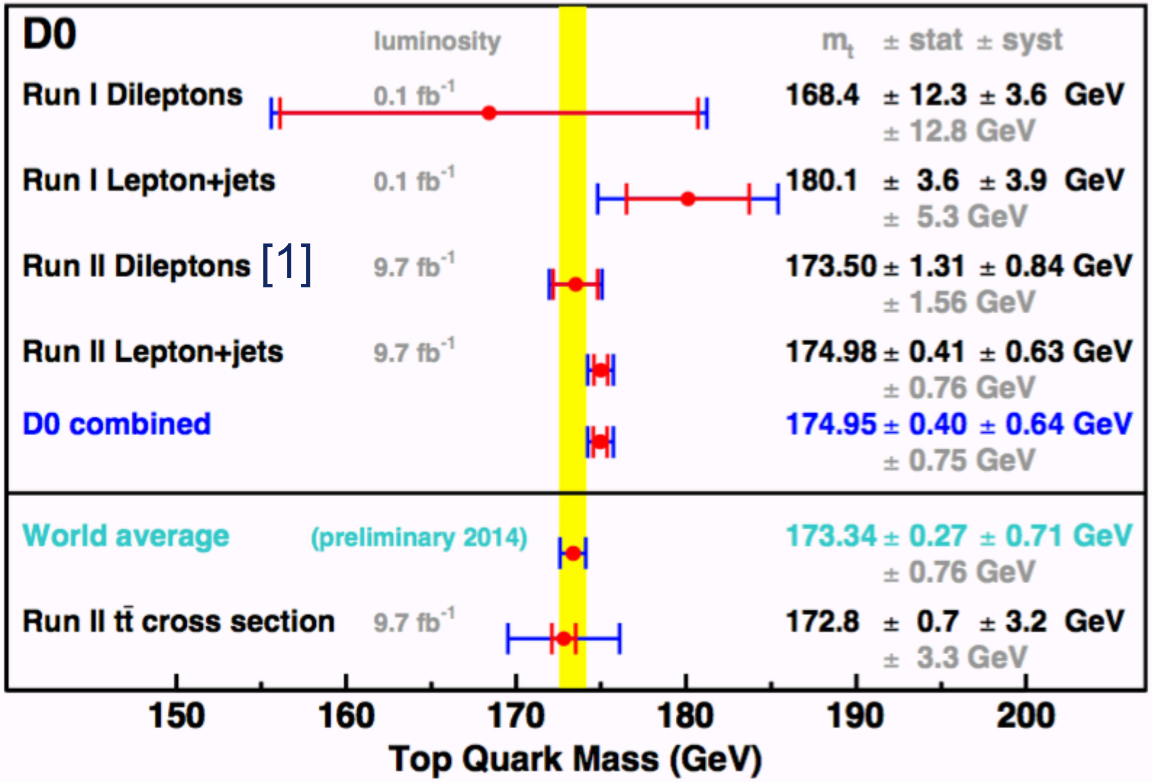



*PRL **113**, 032002 (2014), PRD **91**, 112003 (2015)*

# DØ legacy $m_t$ combination

- **Result:**

*PRD **95**, 112004 (2017)*




*p-value = 47%*

*PRD **95**, 112004 (2017)*

| | D0 combined value |
|---|---|
| top quark mass | 174.95 |
| In situ light-jet calibration | **0.41** |
| Response to $b$, $q$, and $g$ jets | 0.16 |
| Model for $b$ jets | 0.09 |
| Light-jet response | **0.21** |
| Out-of-cone correction | < 0.01 |
| Offset | < 0.01 |
| Jet modeling | 0.07 |
| Multiple interaction model | 0.06 |
| $b$ tag modeling | 0.10 |
| Lepton modeling | 0.01 |
| Signal modeling | **0.35** |
| Background from theory | 0.06 |
| Background based on data | 0.09 |
| Calibration method | 0.07 |
| Systematic uncertainty | 0.64 |
| Statistical uncertainty | 0.40 |
| Total uncertainty | 0.75 |

*[1] Run II Dilepton: combination of ME (p9) and vWt (p10) results*

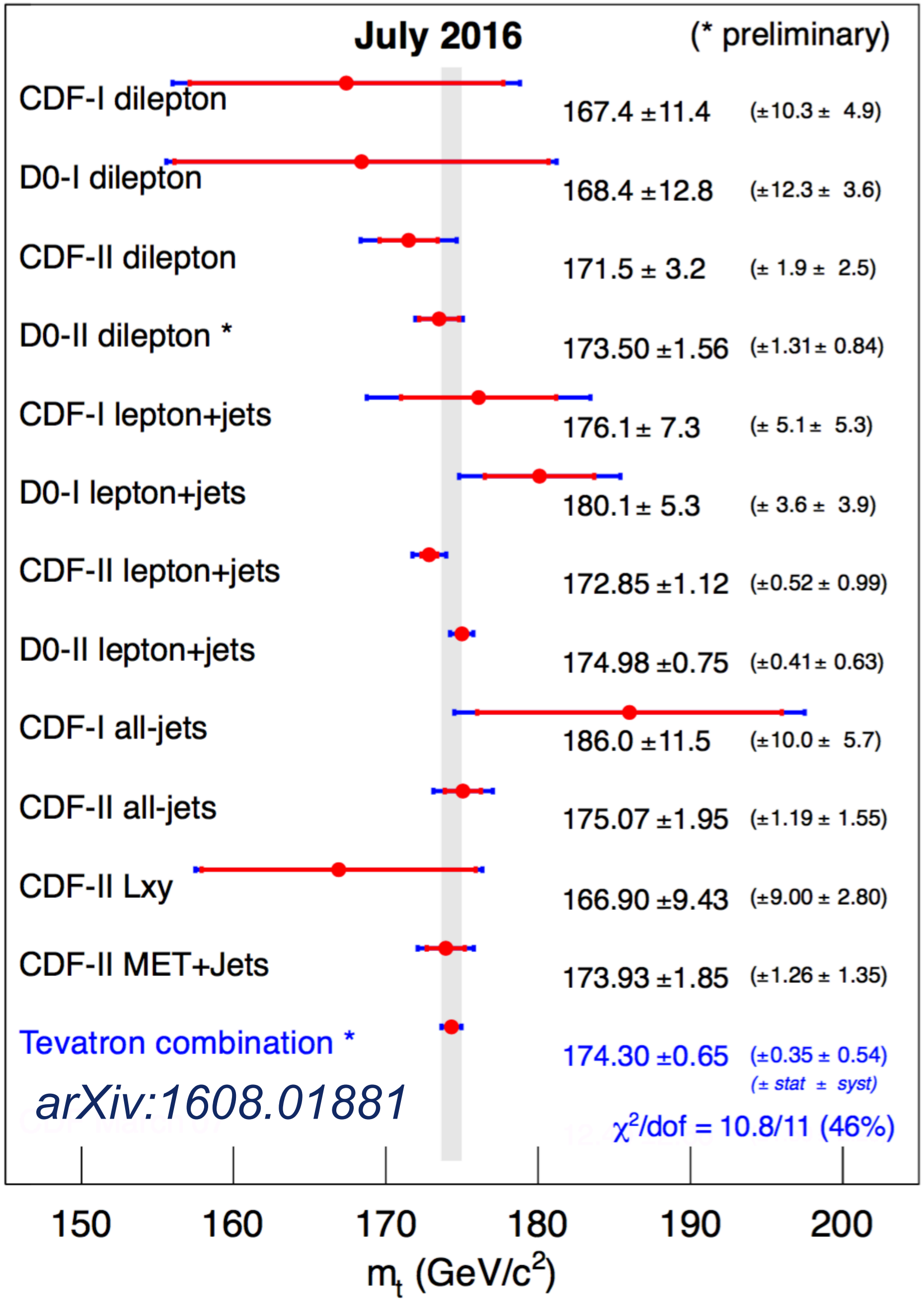
# Tevatron combination

- **Result:**

*arXiv:1608.01881*

| | Tevatron combined values (GeV/$c^2$) |
|---|---|
| $M_t$ | 174.30 |
| In situ light-jet calibration (iJES) | 0.31 |
| Response to $b/q/g$ jets (aJES) | 0.11 |
| Model for $b$-jets (bJES) | 0.10 |
| Out-of-cone correction (cJES) | 0.03 |
| Light-jet response (1) (rJES) | 0.05 |
| Light-jet response (2) (dJES) | 0.14 |
| Lepton modeling (LepPt) | 0.01 |
| Signal modeling (Signal) | 0.36 |
| Jet modeling (DetMod) | 0.05 |
| $b$-tag modeling ($b$-tag) | 0.07 |
| Background from theory (BGMC) | 0.04 |
| Background based on data (BGData) | 0.07 |
| Calibration method (Method) | 0.07 |
| Offset (UN/MI) | 0.00 |
| Multiple interactions model (MHI) | 0.06 |
| Systematic uncertainty (syst) | 0.54 |
| Statistical uncertainty (stat) | 0.35 |
| Total uncertainty | 0.65 |

***References to individual analyses*** *from the Tevatron $m_t$ combination paper*



# Conclusions/Outlook

- **DØ legacy measurements finalised**
  - Lots of work went into:
    - Final, improved calibration of the detector
      - Jet energy scale, flavour-dependent jet energy scale
    - Refining the evaluation of systematic uncertainties
      - Especially treatment of uncertainties from signal modelling
  - Dilepton ME: $m_t = 173.93 \pm 1.81$ GeV, $\Delta m_t/m_t = 1.1\%$
  - Dilepton vWt: $m_t = 173.32 \pm 1.60$ GeV, $\Delta m_t/m_t = 0.9\%$
    - Most precise Tevatron dilepton result
  - l+jets: $m_t = 174.98 \pm 0.76$ GeV, $\Delta m_t/m_t = 0.43\%$
    - Most precise Tevatron result
  - Combination: $m_t = 174.95 \pm 0.75$ GeV, $\Delta m_t/m_t = 0.43\%$
- **Tevatron legacy:**
  - Combination: $m_t = 174.30 \pm 0.65$ GeV, $\Delta m_t/m_t = 0.37\%$
- **World combination?**


GAME OVER
... FOR THE TEVATRON (2011)

# Comparison with previous measurements

- Current World average:

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

*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%)

---

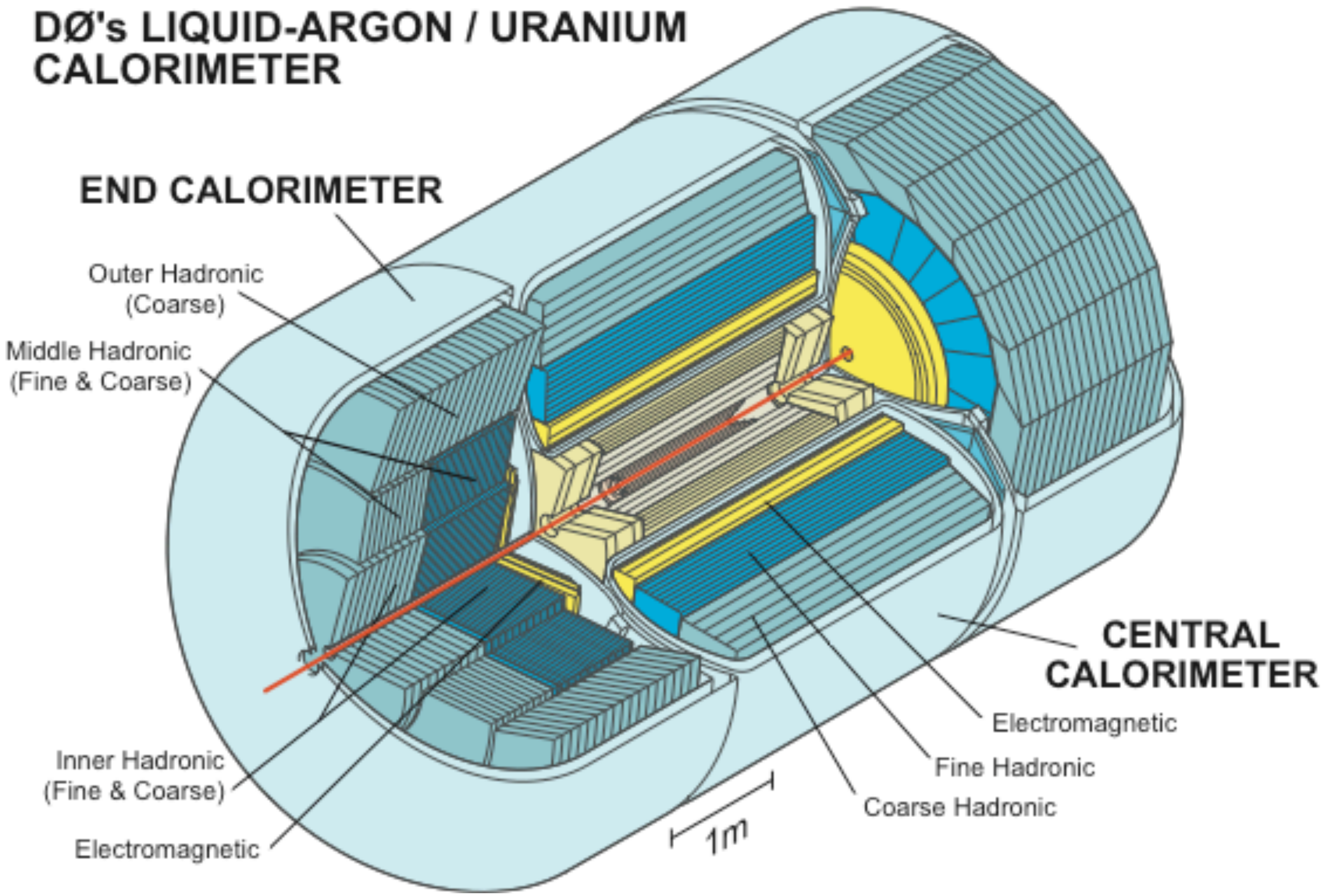
- Current Tevatron average:

$$m_t = 173.2 \pm 0.87\,\text{GeV}$$

*arXiv:1305.3929 [hep-ex]*

- Making the same assumptions:
  - Consistency at 1.70 SD level (p-value of 3.3%)

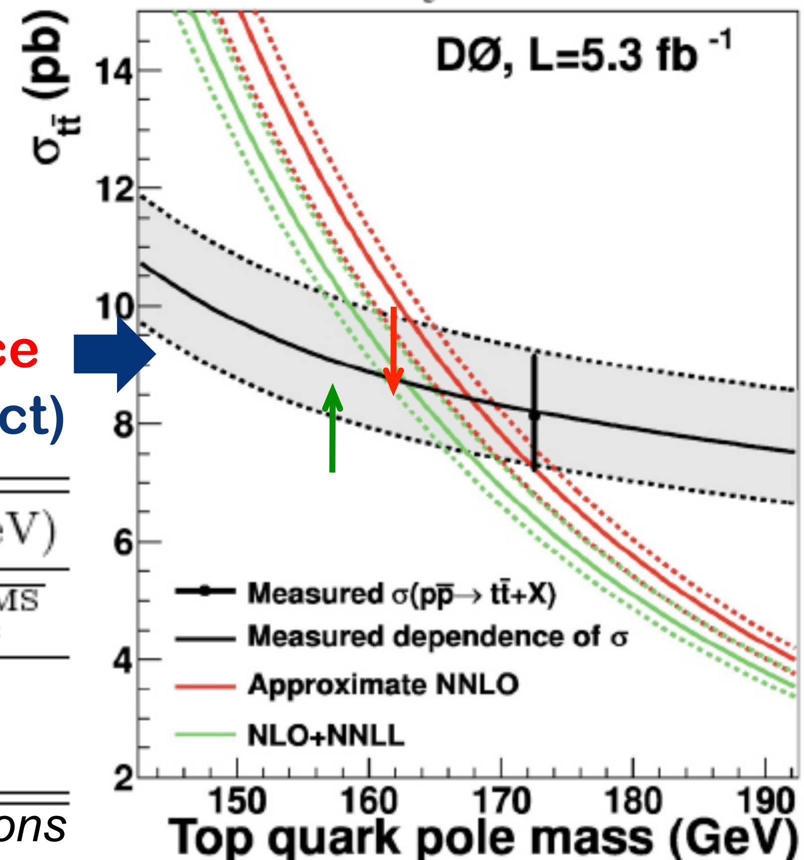
# The DØ Calorimeter




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

# $m_{top}$ from cross section (5.3 fb$^{-1}$)

- 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 $m_t^{\text{MC}}$
    - Theory interpretation difficult
    - Arguably, $m_t^{\text{MC}}$ closer to $m_t^{\text{pole}}$
  - Can measure $m_t^{\overline{\text{MS}}}$ or $m_t^{\text{pole}}$ 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 $m_t^{\text{MC}}$ (acceptance effect)




| Theoretical prediction | $m_t^{\text{pole}}$ (GeV) | $\Delta m_t^{\text{pole}}$ (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] | $167.5^{+5.2}_{-4.7}$ | $-2.7$ |

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

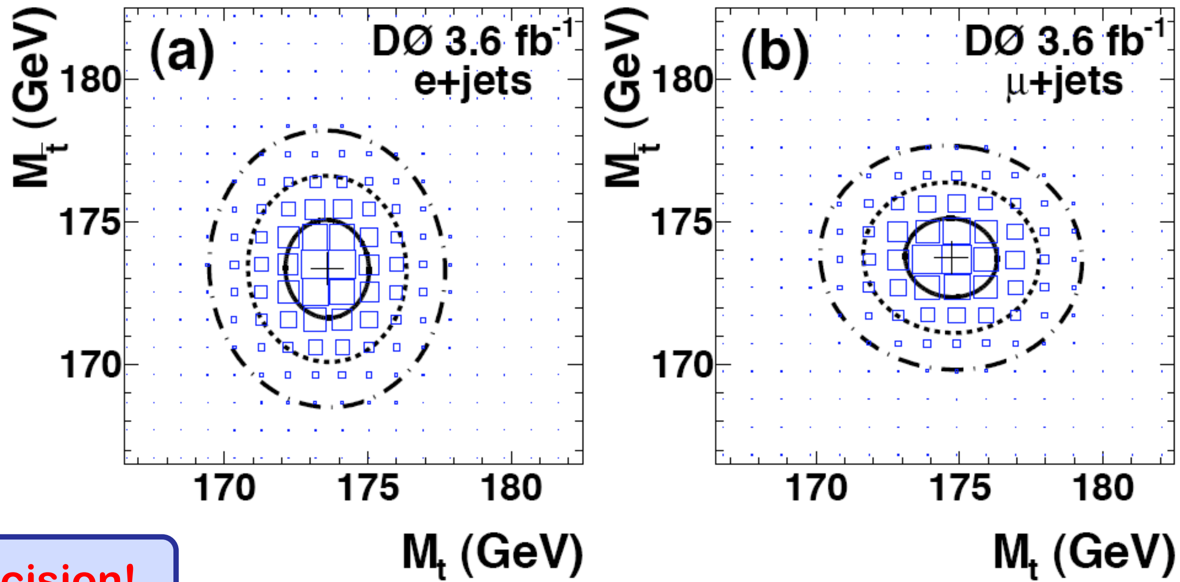
*Phys. Lett. B **703** 422 (2011)*


[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).

# Top-antitop mass difference (3.6 $fb^{-1}$)

- **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 directly
  - Use the most statistically sensitive method at hand (ME):
    - $P(m_{top},k_{JES})$ → $P(m_t,m_{tbar})$ & 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)

<1% relative precision!

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

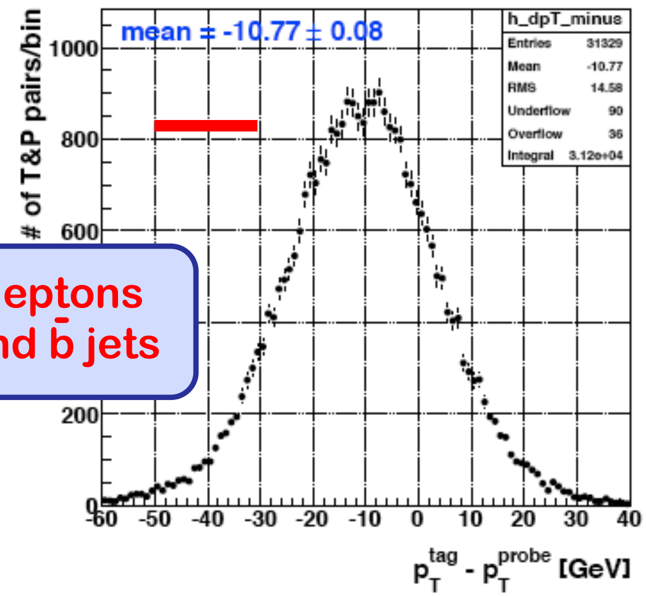
# Top-antitop mass difference (3.6 fb$^{-1}$)

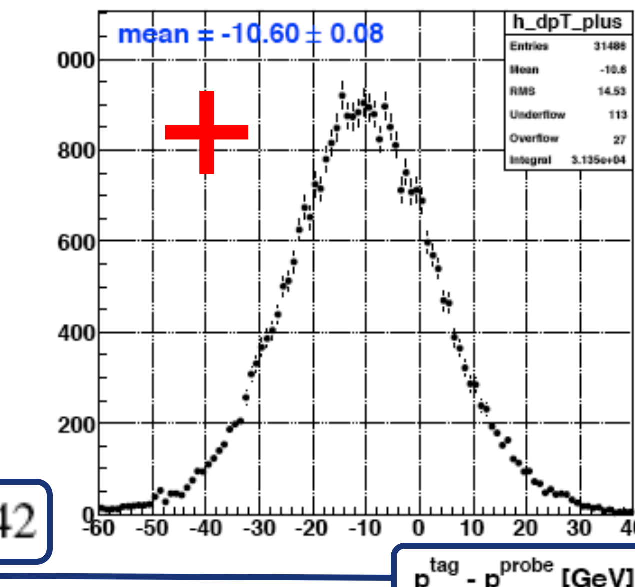
- Lots of work went into evaluating sytematic uncertainties for this precision measurement:

| Source | Uncertainty on $\Delta m$ (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 |

Use soft leptons to tag b and $\bar{b}$ jets

fractional response difference $f_{\Delta\mathscr{R}} \equiv \dfrac{\Delta\mathscr{R}}{\langle 1/2 \cdot (p_T^{tag} + p_T^{probe})\rangle} = 0.0042$

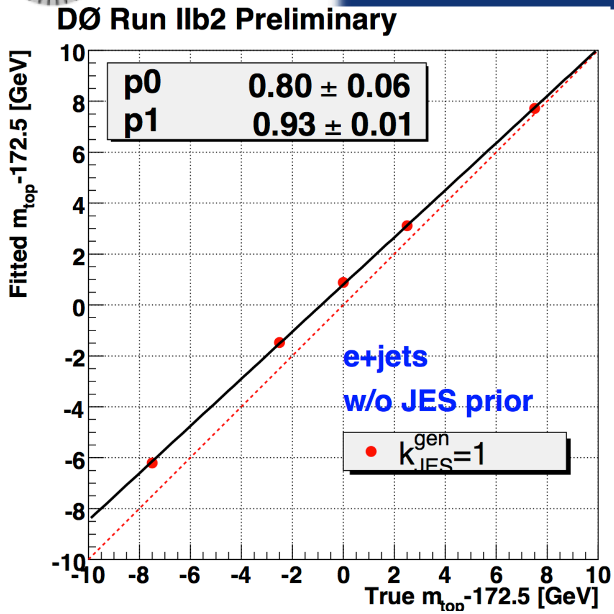


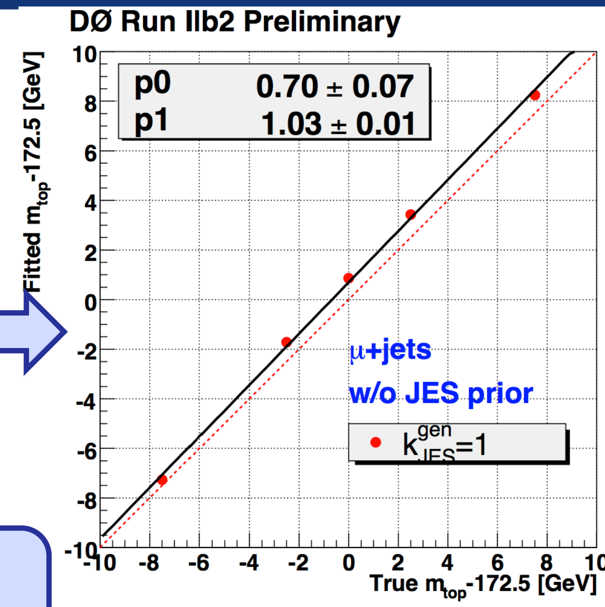

*Phys. Rev. D* ***84***, *052005 (2011)*

# $m_{top}$ in the l+jets channel (9.7 $fb^{-1}$)

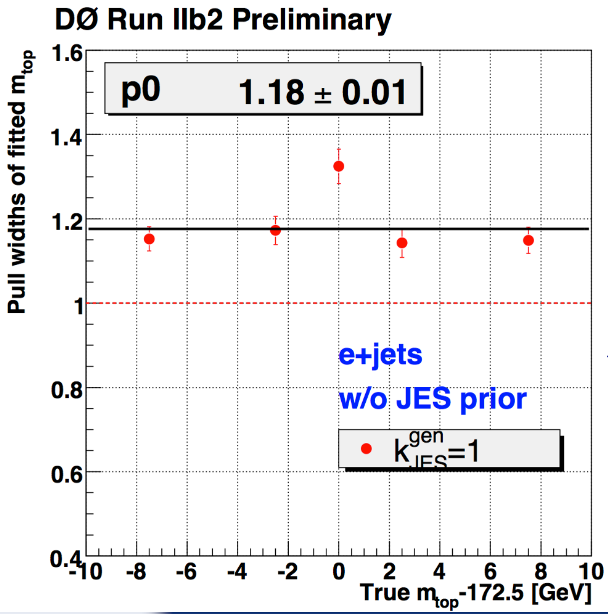
*DØ Coll., arXiv:1405.1756 [hep-ex], accepted by PRL*



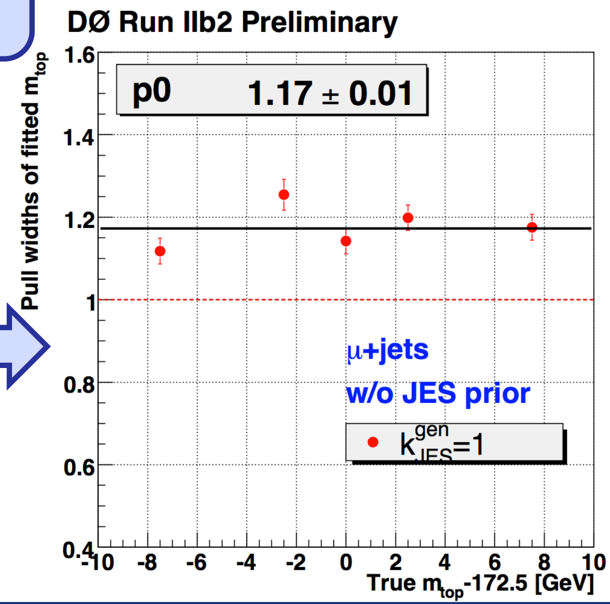

Calibrate $m_t$ & $\sigma(m_t)$




*Similar procedure for $k_{JES}$ (not shown)*




Calibrate $\sigma(m_t)$




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

# $m_{top}$ in the l+jets channel (9.7 $fb^{-1}$)

- Keep in mind that, for a given uncertainty, we cite:
  - max{ statistical uncertainty, |face value of systematic| }

*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* | |

*statistical component: 0.01 GeV*

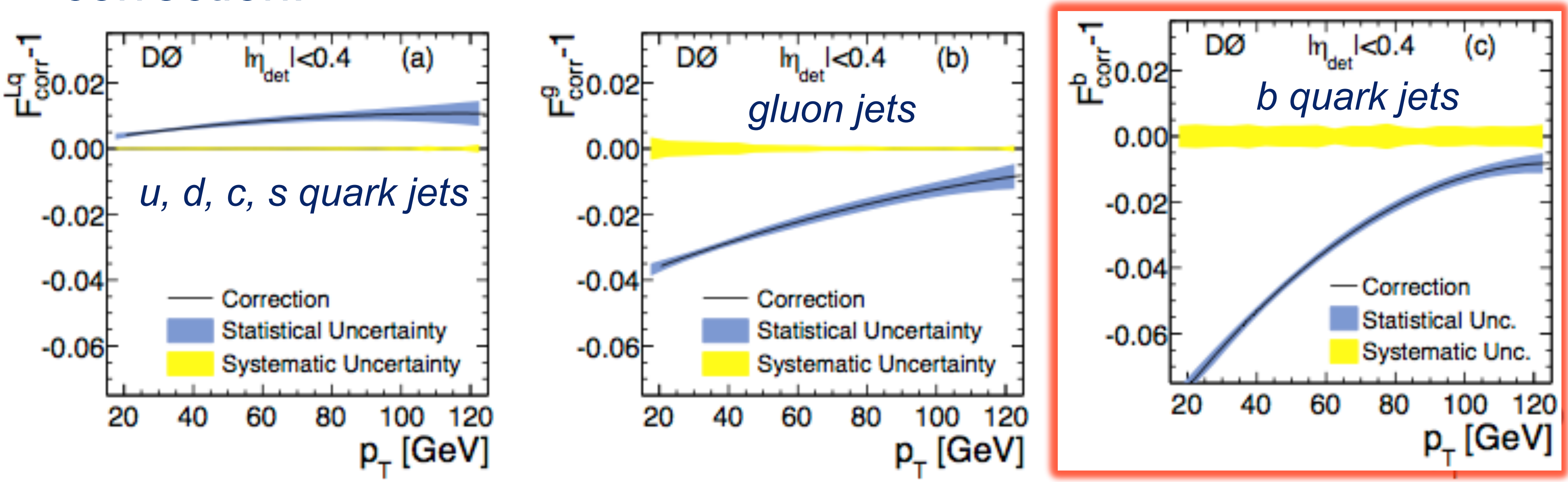
*Result using 3.6 $fb^{-1}$: DØ Coll., PRD **84**, 032004 (2011)*

| 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 |

*stat. component: ≈1/4 GeV*

# $m_{top}$ in the l+jets channel (9.7 $fb^{-1}$)

- Use new JES calibration including flavour-dependent response correction:

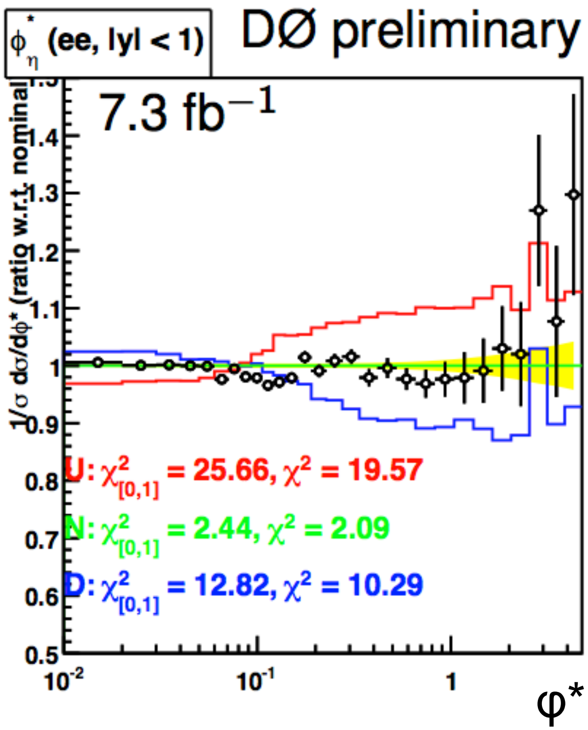


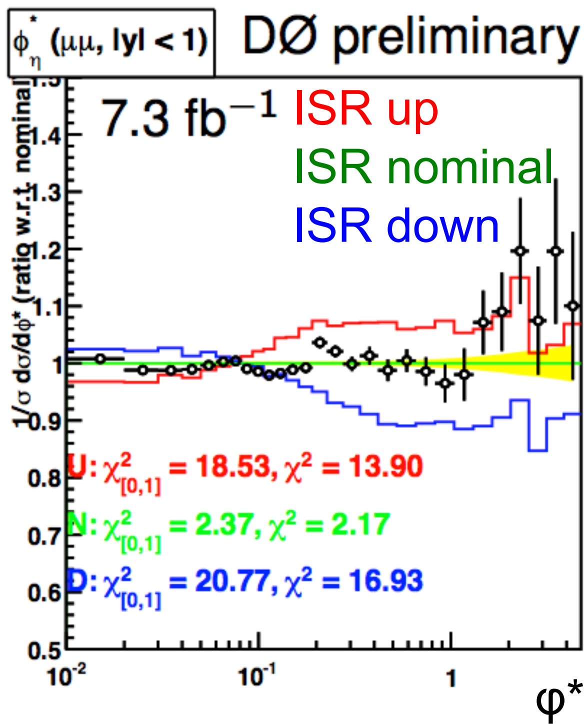

  - → Uncertainty from flavor-dependent response:
    - 0.16 GeV (was 0.28 GeV)
  - This uncertainty accounts for JES difference between light quark jets and b quark jets

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

# $m_{top}$ in the l+jets channel ($9.7\ fb^{-1}$)

- 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



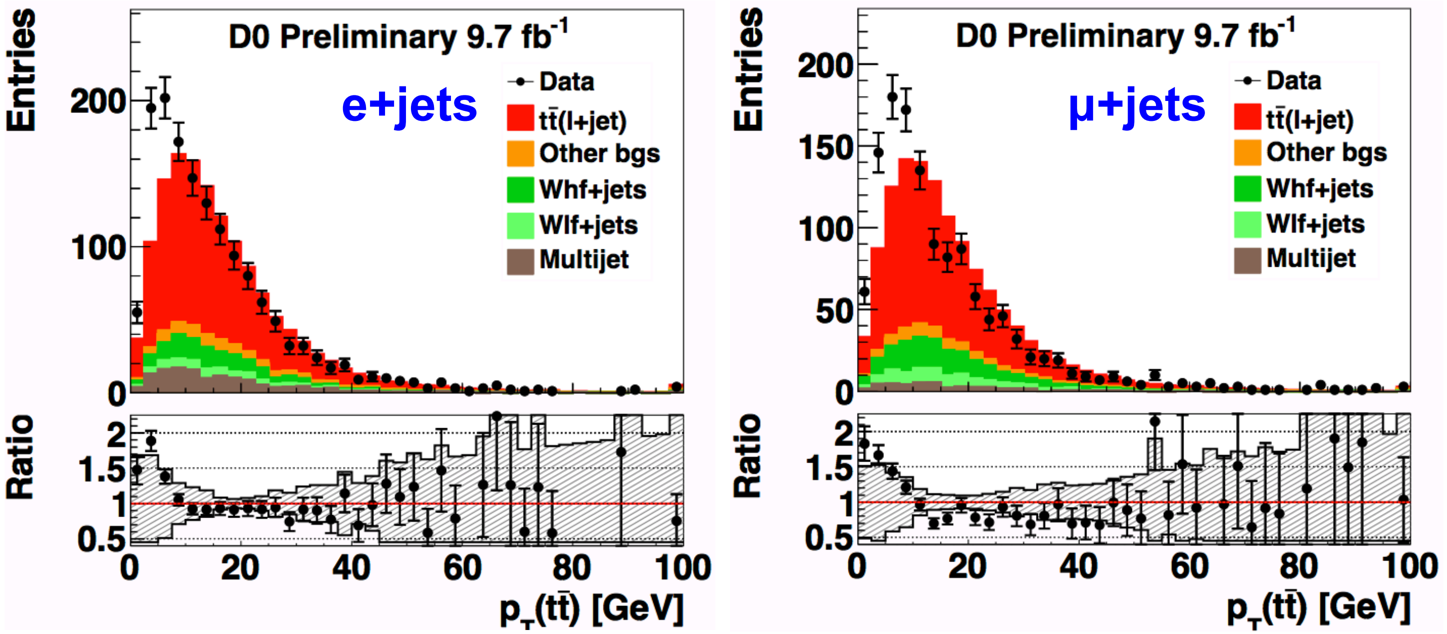

**Also tune in other kinematic regions:**
- **1<|y|<2**
- **|y|>2**

**(cf. backup)**


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

# $m_{top}$ in the l+jets channel (9.7 fb$^{-1}$)

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




  - Effect may be related to ISR/FSR mismodelling

0.06 GeV

Total: 0.09 GeV
(was: 0.26 GeV)

0.07 GeV

# $m_{top}$ in the l+jets channel (9.7 $fb^{-1}$)

- 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
  - Apply default selection at detector level
    - → minimize bias from acceptance etc.
- We also factor out the effect of different $p_T$(tt) in:
    - Default (alpgen+pythia)
    - Alternative model (alpgen+herwig)
  - Achieved by reweighting default simulation in $p_T$(tt) 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)

# Selection overview

- Sample composition assuming $\sigma_{t\bar{t}} = 7.24$ pb

| 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 obtain a signal fraction (f) of
  - 61% (e+jets)
  - 64% (μ+jets)

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

# 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:

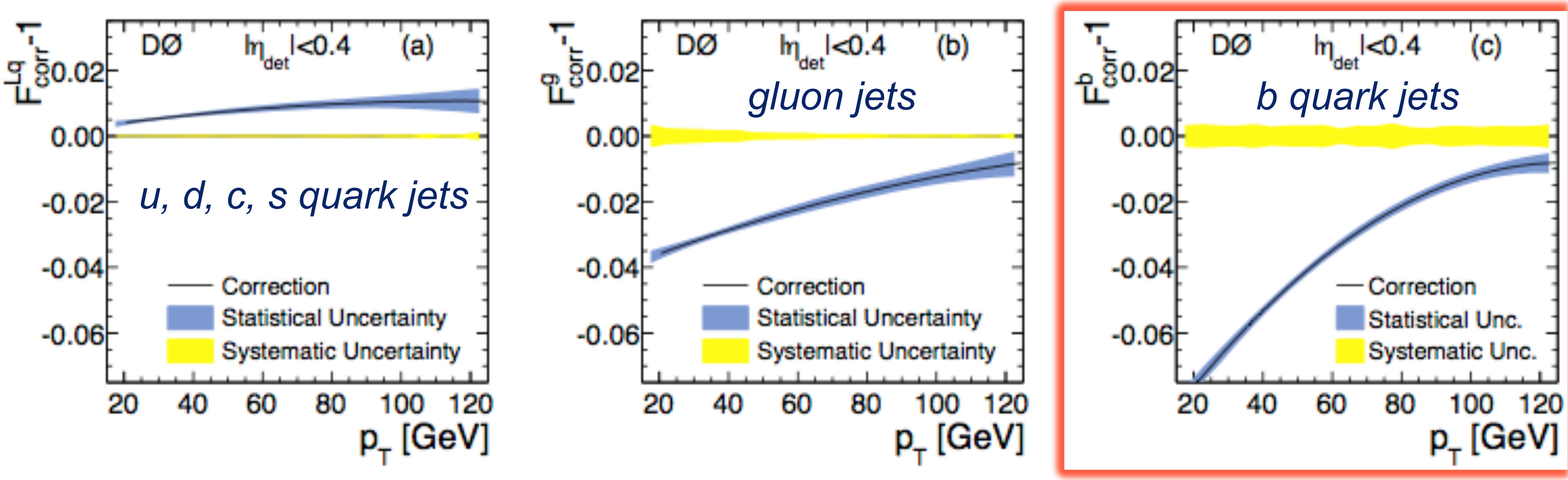
$$F_{\mathrm{corr}} = \frac{1}{\langle F \rangle_{\gamma+\mathrm{jet}}} \cdot \frac{\sum_i E_i \cdot R_i^{\mathrm{data}}}{\sum_i E_i \cdot R_i^{\mathrm{MC}}}$$

  - $F_{\mathrm{corr}}$ preserves default JES by construction
- Derive single particle responses $R_i$ for:
  - $\gamma$, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $K^0_{\mathrm{S}}$, $K^0_{\mathrm{L}}$, $p^{\pm}$, $n$, $\Lambda$, $\Sigma$, and $\Xi$
  - (Keep in mind that DØ corrects jet energies to particle level in data and in MC)

*DØ Coll, arXiv:1312.6873 [hep-ex], submitted to NIM*

# Refined jet energy scale calibration

- The final flavour-dependent correction:

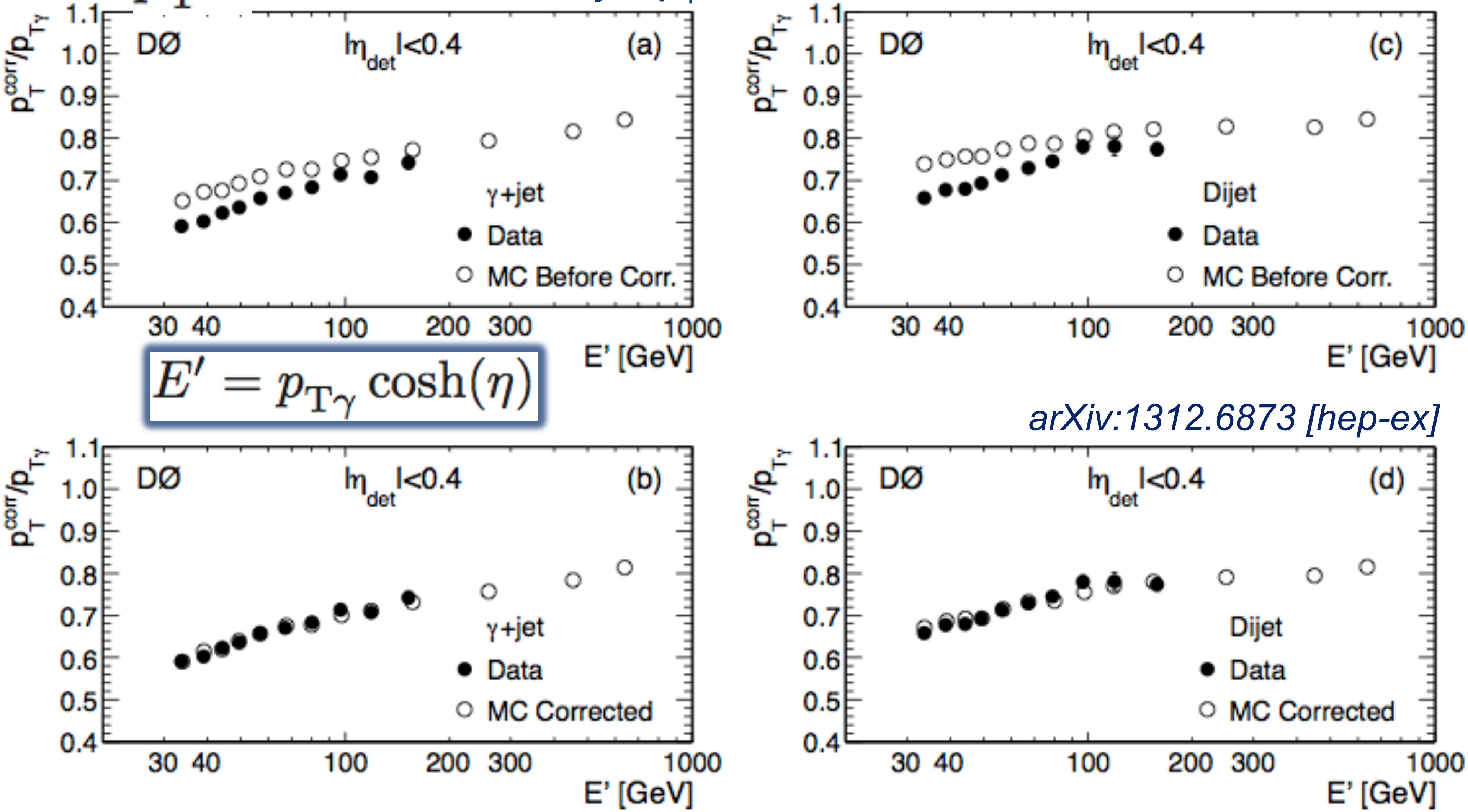



- The correction accounts for the difference in JES for b quark jets and light quark jets:
  - Substantial reduction of one of the dominant systematic uncertainties!

*arXiv:1312.6873 [hep-ex]*

# Refined jet energy scale calibration

- 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]*

# 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)

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

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

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

*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

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

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

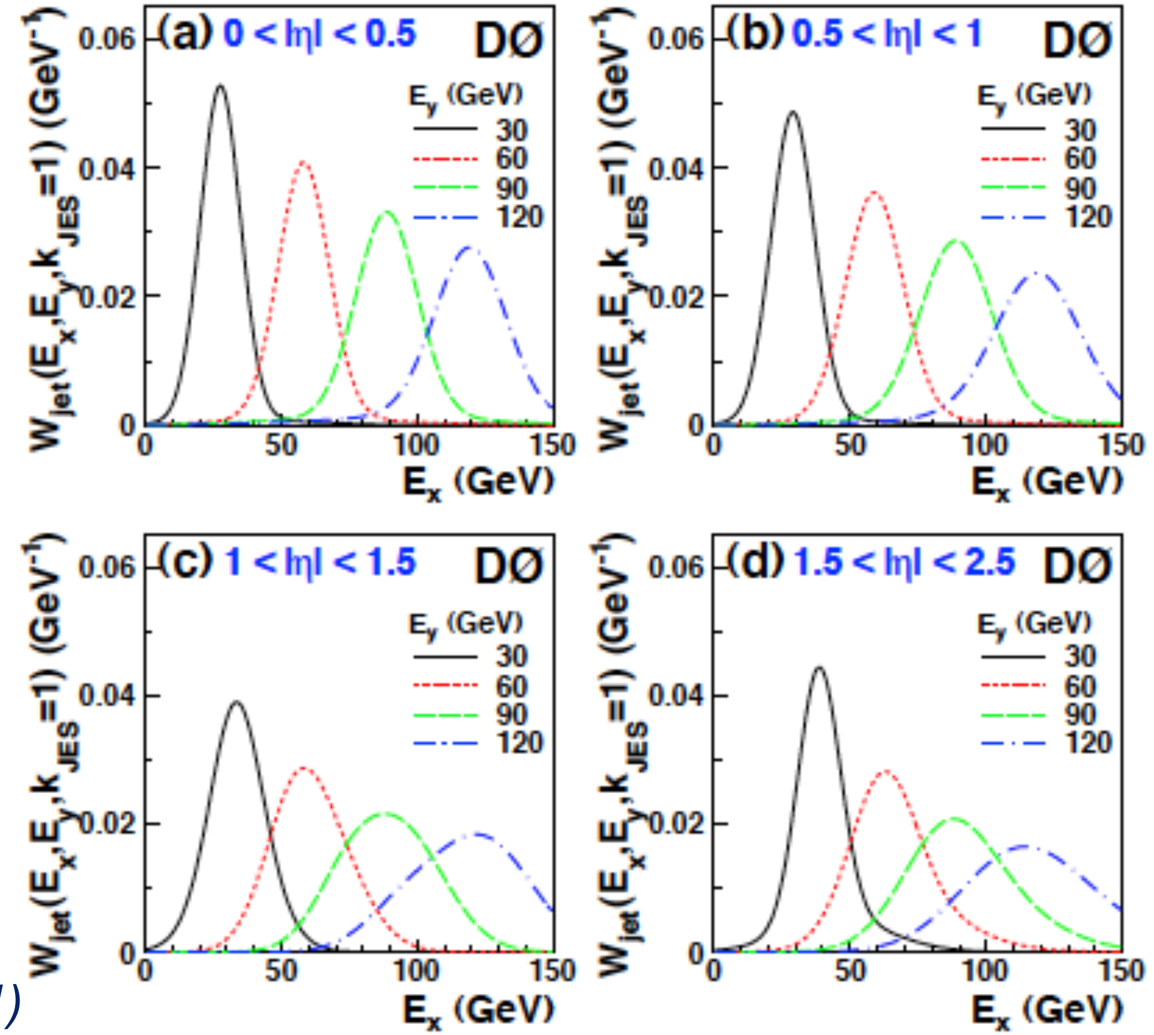
Sum over incoming parton flavours and all neutrino $p_z$ solutions

PDFs for Björken-x and transverse momenta of incoming partons

*PRD **84**, 032004 (2011)*

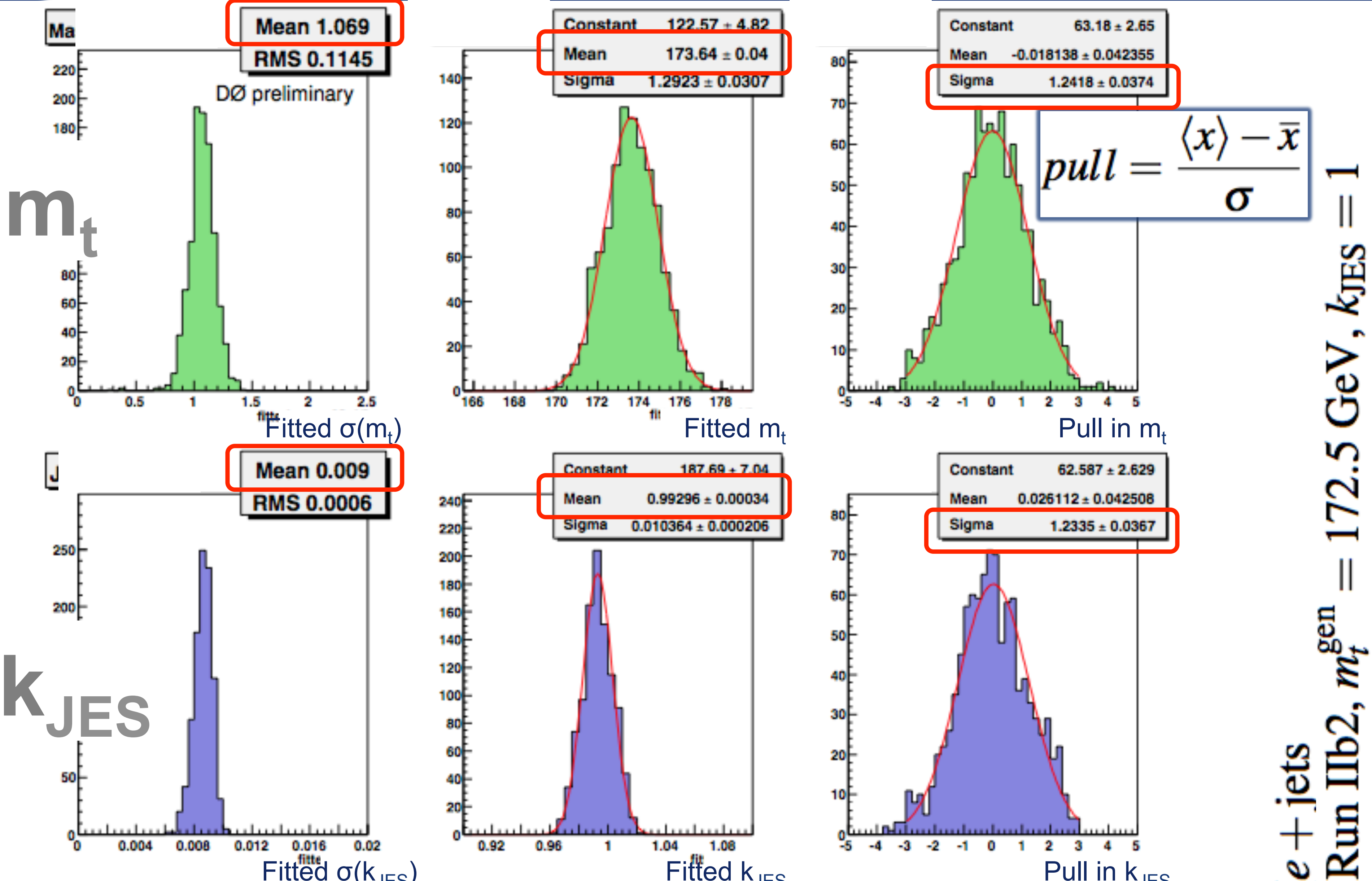
# Top mass with the MEM @ DØ

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

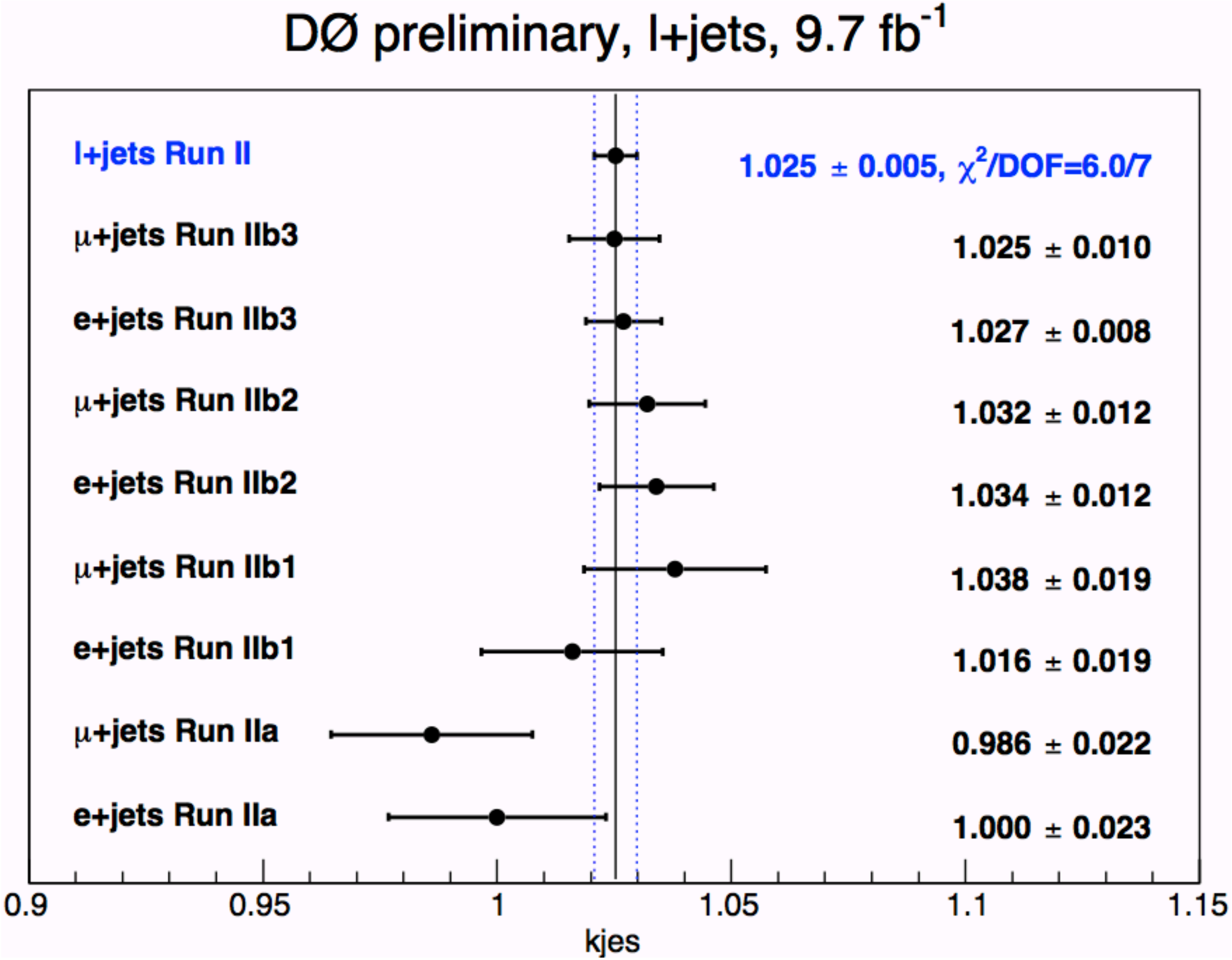



[1] *DØ Coll, PRD **84**, 032004 (2011)*

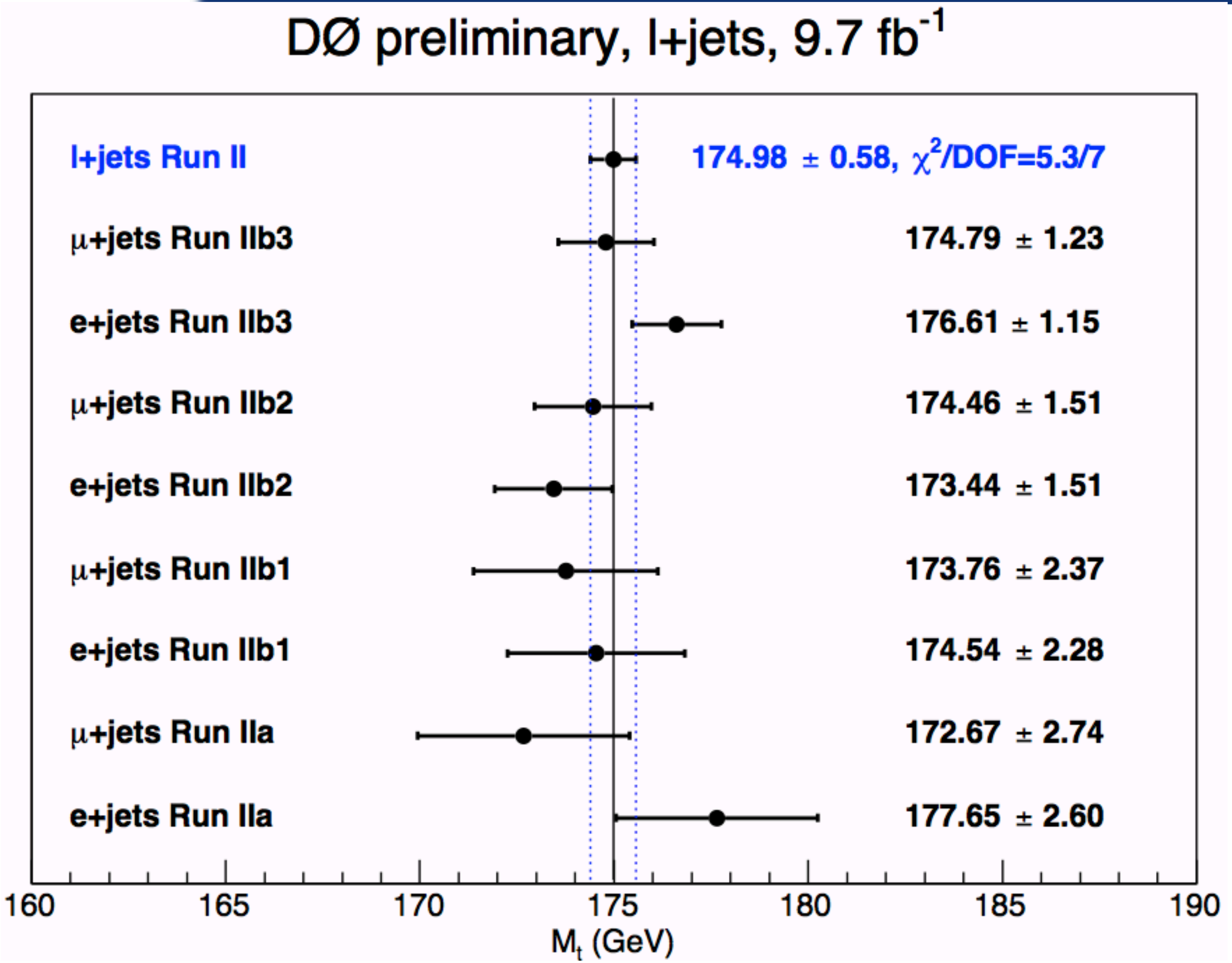
# Calibration of method response in $m_t$, $k_{JES}$



# Results per data taking epoch & channel



# Results per data taking epoch & channel



# Extracting signal fraction from data

- We measure (after calibration):

| Epoch | Channel | Signal fraction | $\sigma_{t\bar{t}}$ (pb) |
|---|---|---|---|
| Run IIa | $e$+jets | 0.72 | 8.9 |
| | $\mu$+jets | 0.65 | 7.8 |
| Run IIb1 | $e$+jets | 0.77 | 7.6 |
| | $\mu$+jets | 0.66 | 6.8 |
| Run IIb2 | $e$+jets | 0.68 | 7.8 |
| | $\mu$+jets | 0.66 | 7.5 |
| Run II3+4 | $e$+jets | 0.56 | 7.6 |
| | $\mu$+jets | 0.75 | 8.0 |
| Run II | $e$+jets | 0.63 | 7.8 |
| | $\mu$+jets | 0.70 | 7.6 |

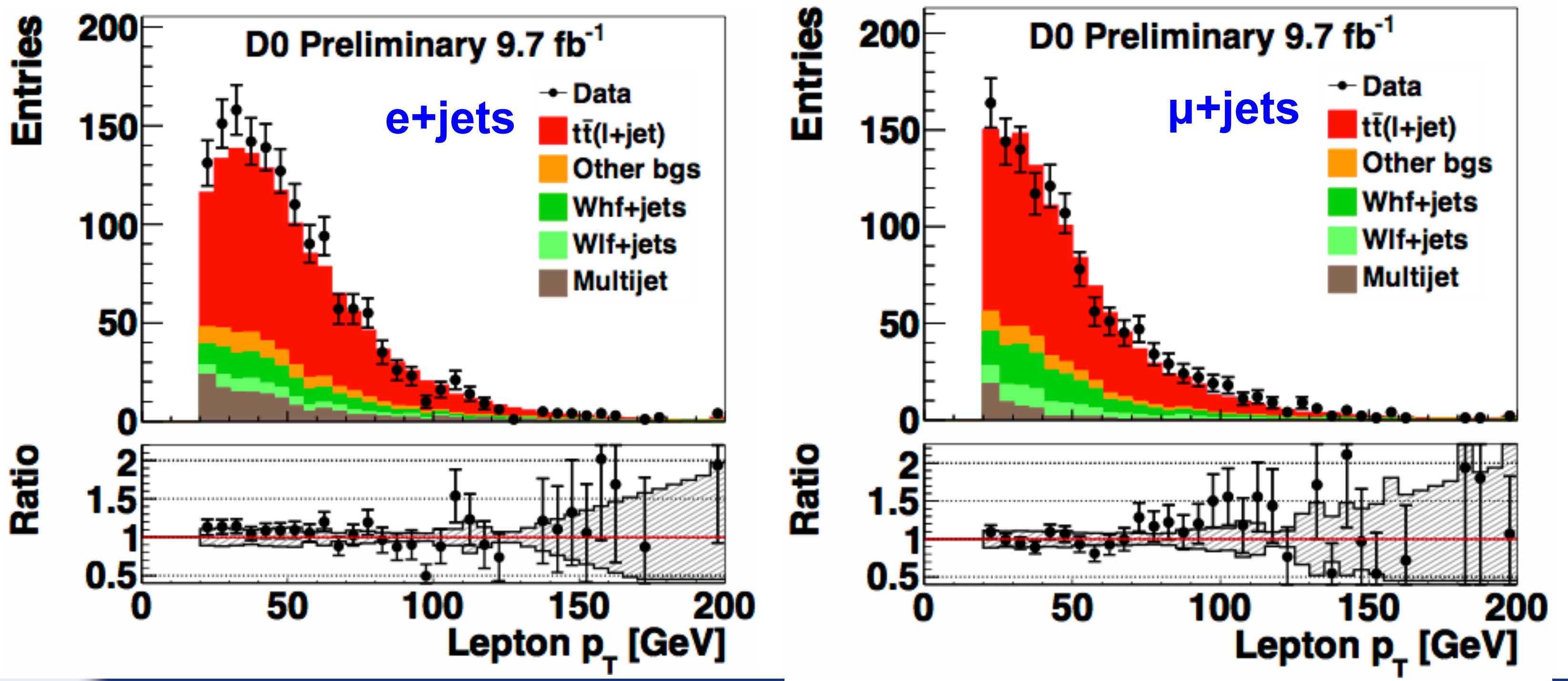
- Values in good agreement with $\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}$ pb

*Typical statistical+calibration uncertainty on signal fraction: 1%, on $\sigma_{tt}$: about 0.1 pb*

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

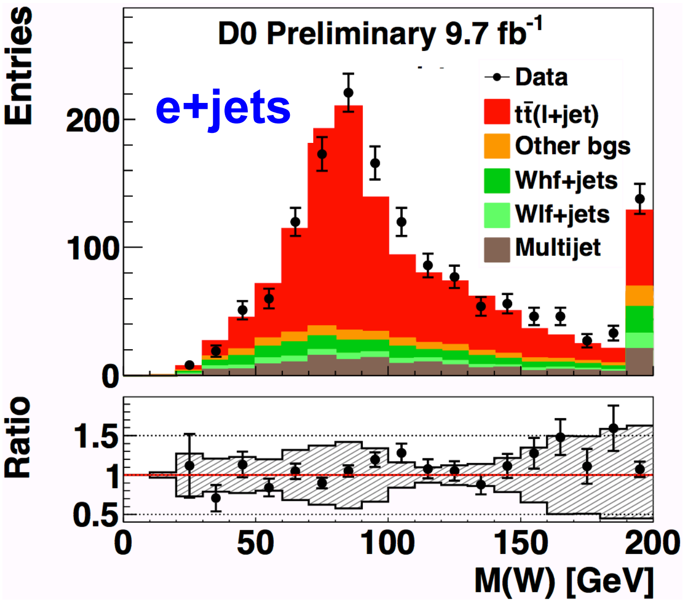
# Data/MC comparisons

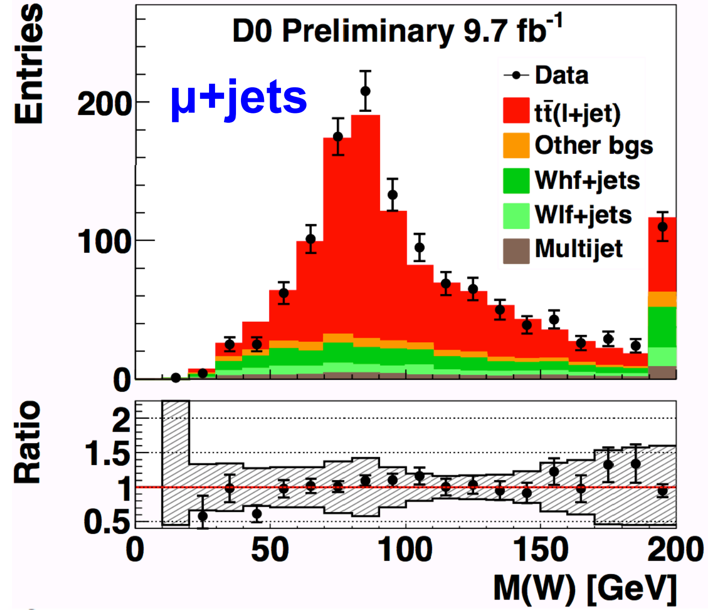
- In the following, showing "post-fit" data/MC comparison plots
  - Use cross sections fitted with the ME technique:
    - 7.8 pb for e+jets
    - 7.6 pb for μ+jets
  - Use $t\bar{t}$ simulations with $m_t$ = 175 GeV

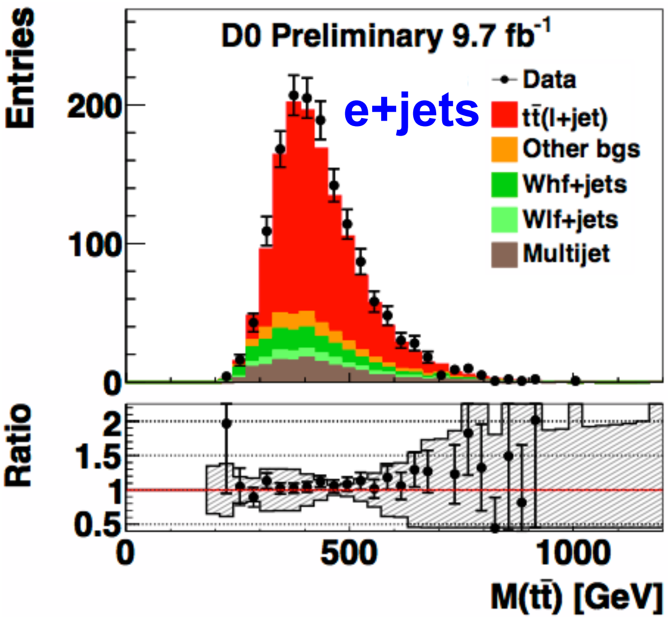


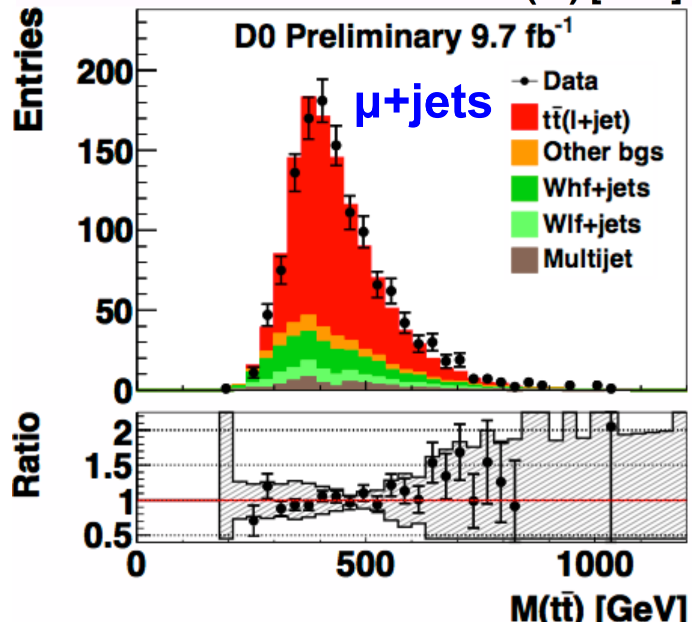

*More data/MC comparisons in backup*

# Data/MC comparisons (post-fit)



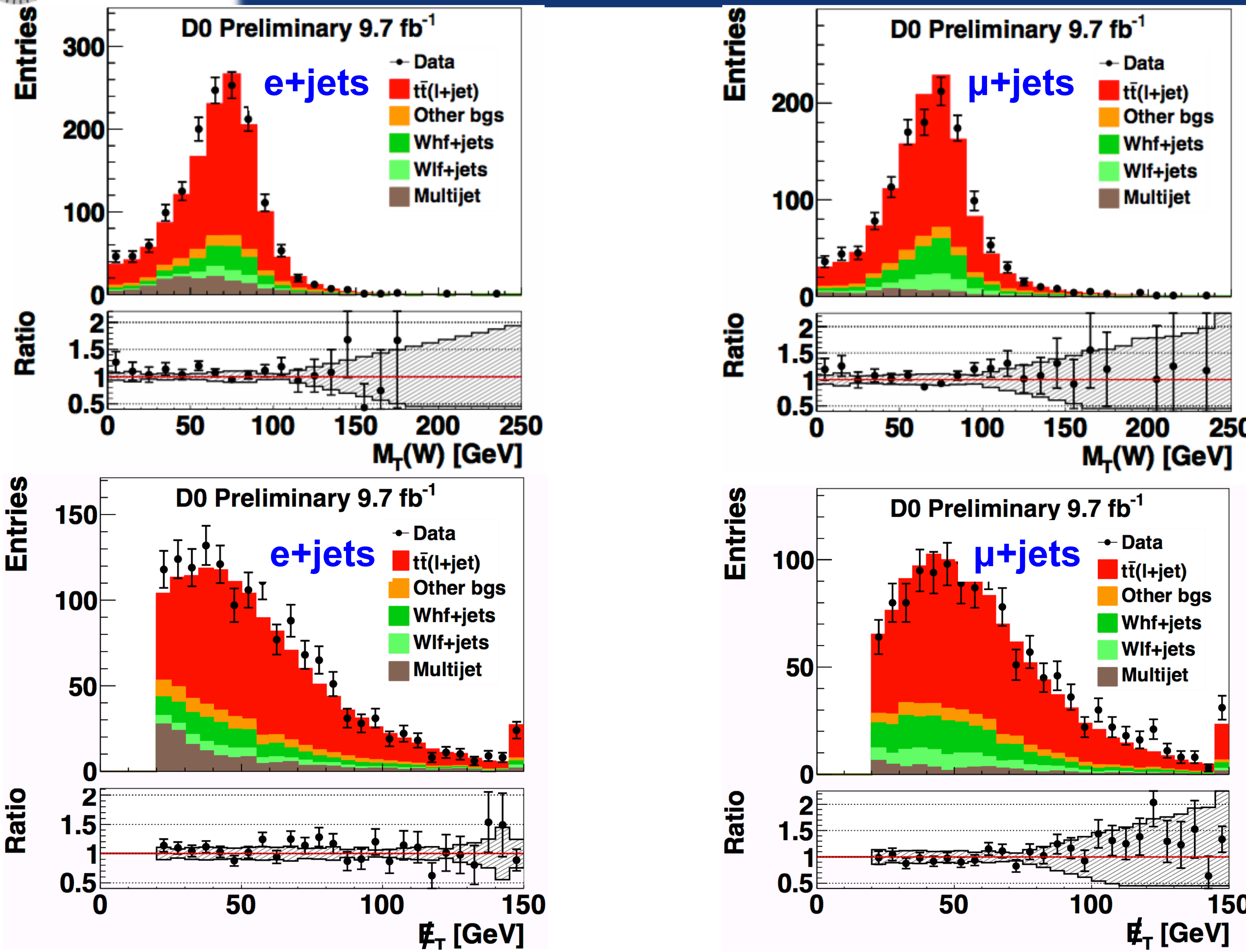




*More data/MC comparisons in backup*

# Data/MC comparisons

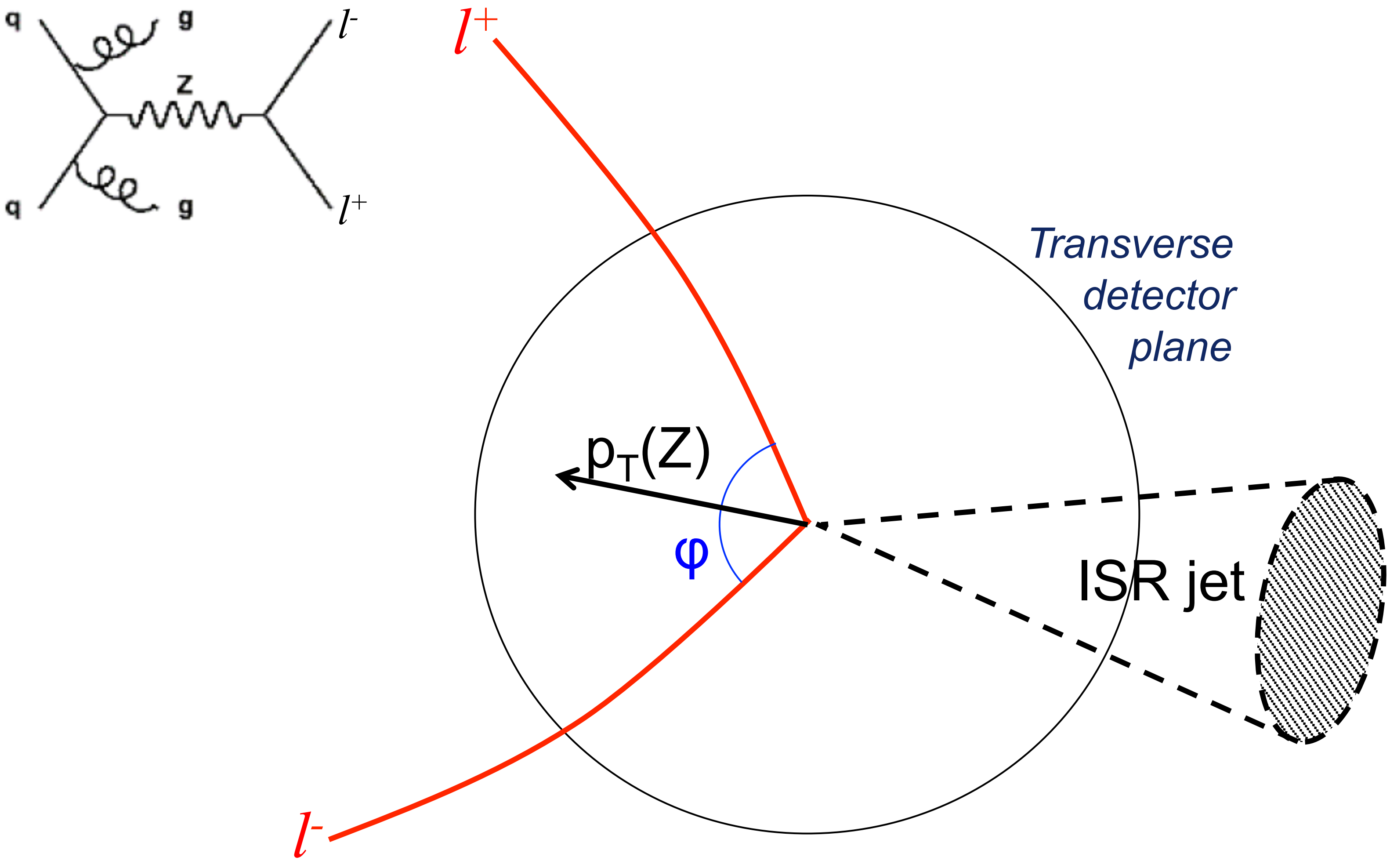



*More data/MC comparisons in backup*

# Systematic uncertainties

# Initial/final state radiation

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

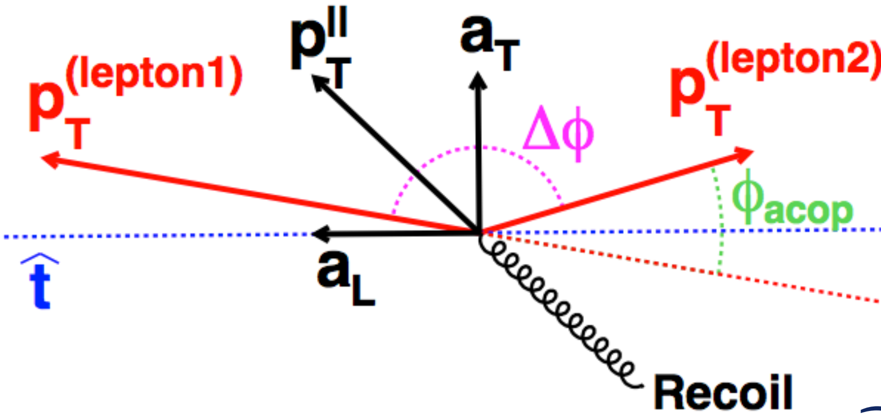


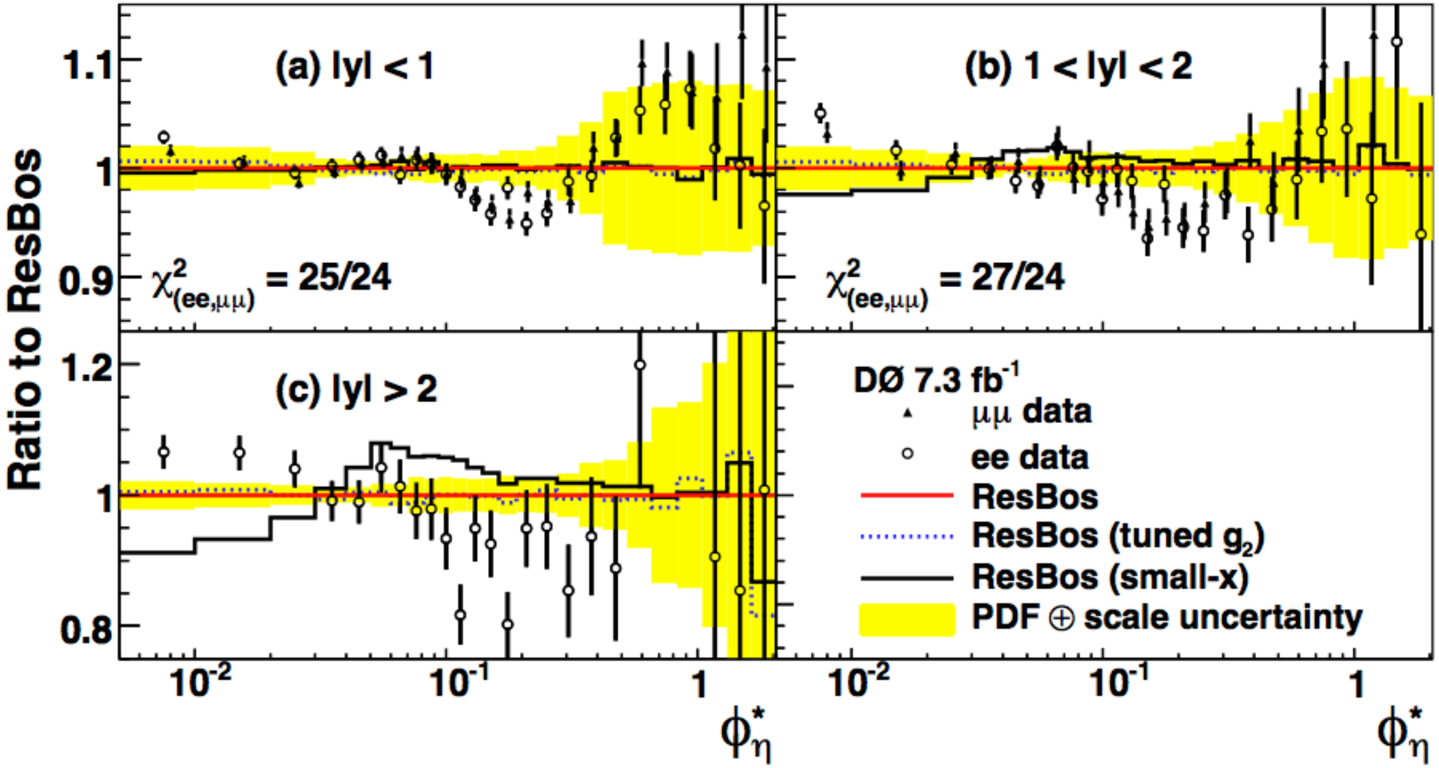

[1] DØ Coll., PRL **106**, 122001 (2011)

# φ* measurement

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

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

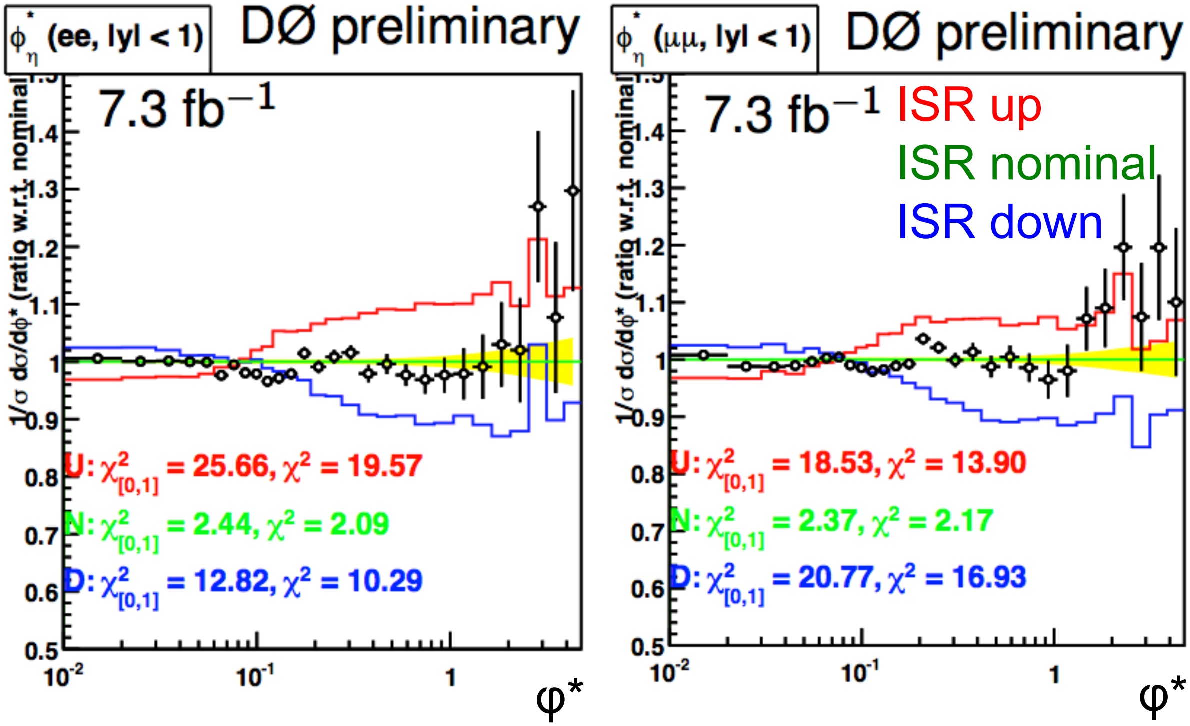



[1] DØ Coll., PRL **106**, 122001 (2011)

# 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

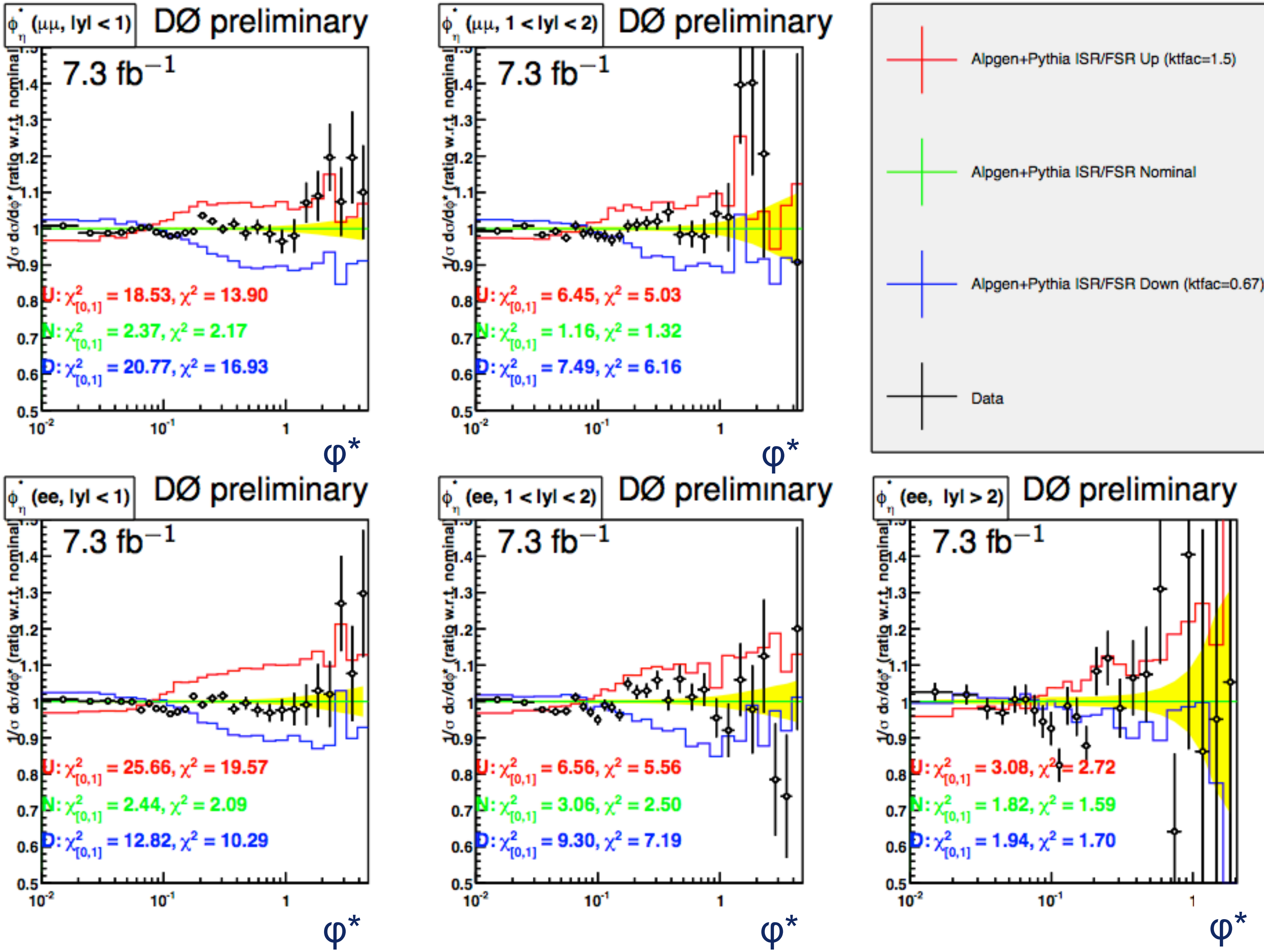



**Also tune in other kinematic regions:**
- **1<|y|<2**
- **|y|>2**

**(cf. backup)**


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

# ISR/FSR

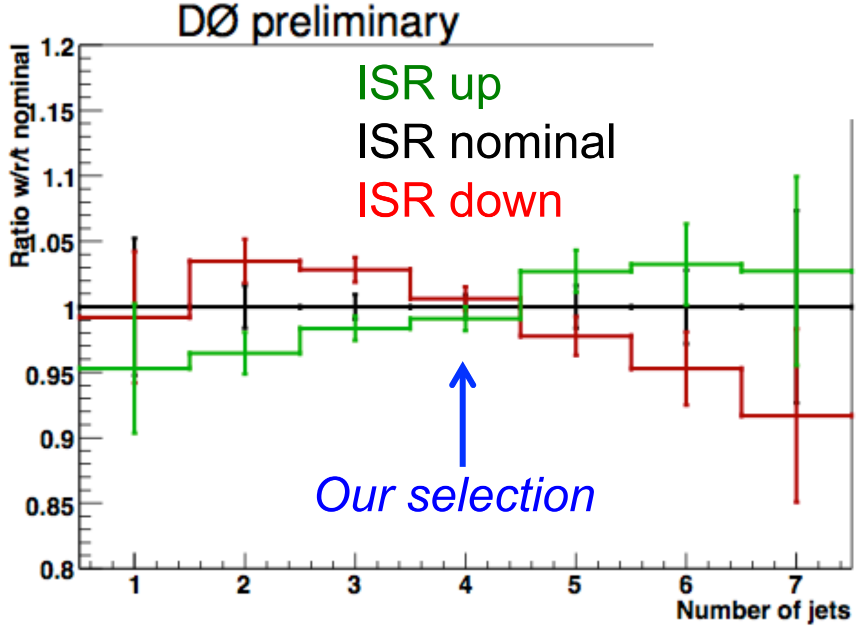


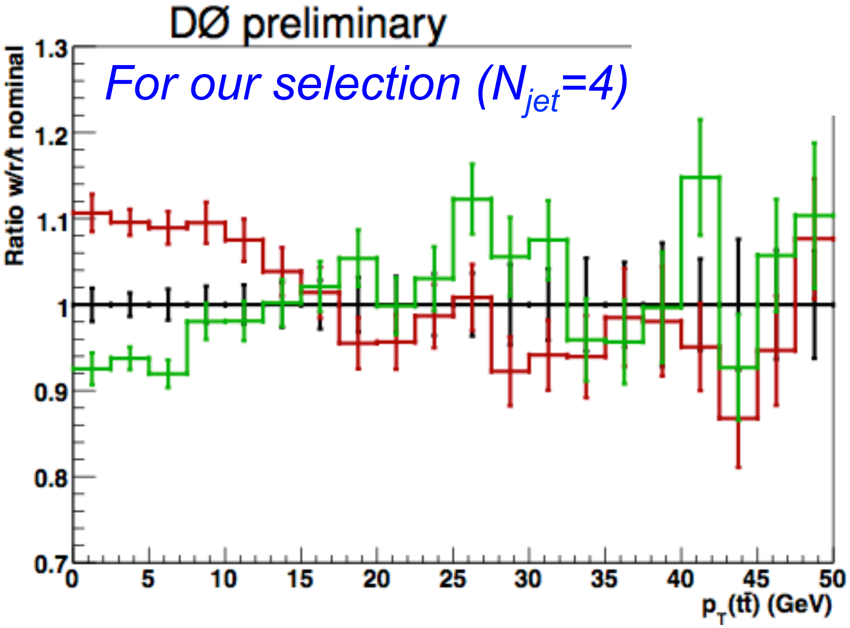

Unfolded spectra from: *DØ Coll., PRL **106**, 122001 (2011)*

# 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

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

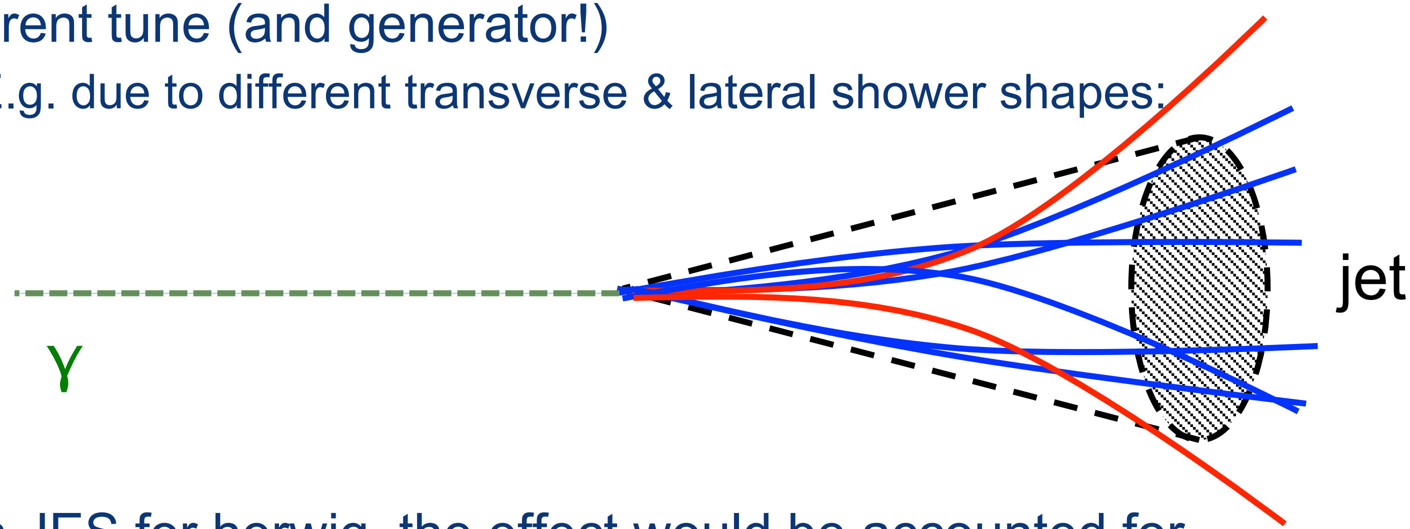



[1] DØ Coll., PRL **106**, 122001 (2011)
[2] M. Mangano, P. Skands et al, EPJ **C72** 2078 (2012)

# 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:



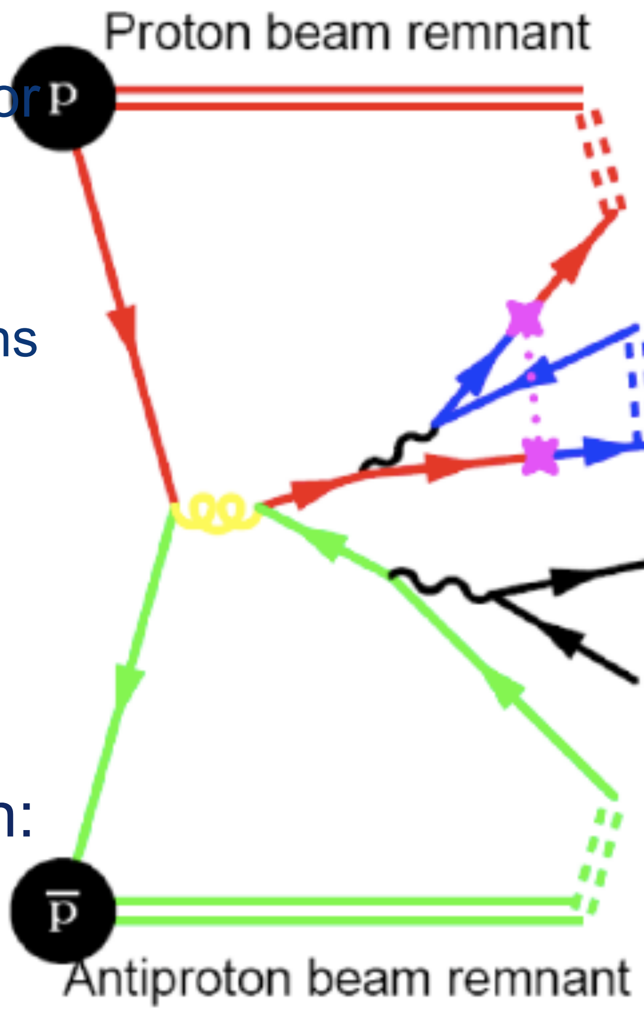

     - With JES for herwig, the effect would be accounted for
       - Factorize uncertainties to avoid double-counting:
         - We have an uncertainty for dependence of JES on $p_T$,η…

# 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 ΔR=0.25
  - 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)

# 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)



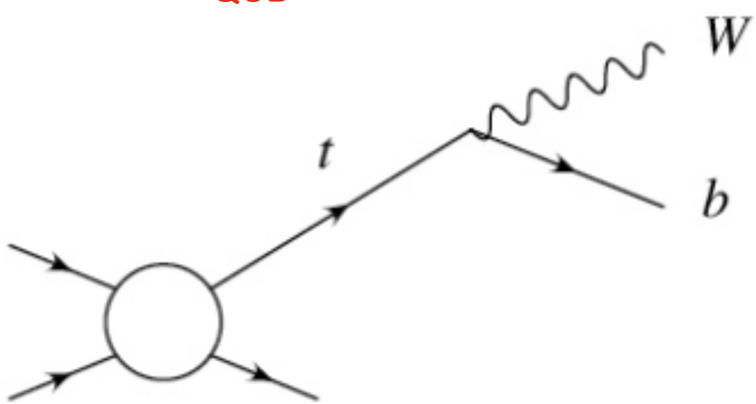
# Residual JES

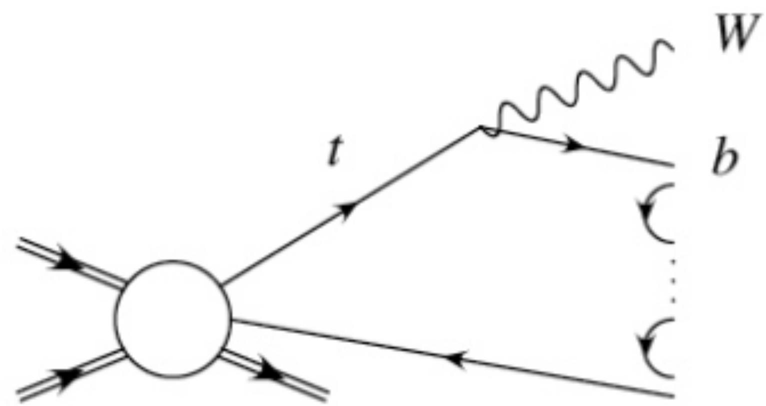
- Even though we perform an in-situ calibration of JES, this is only an overall calibration
  - $k_{JES}$ cannot account for any effects differential in ($p_T$,η)
  - Study various parametrisations:
    - *0.13 GeV* Vary jet energies according to upper error corridor on the JES, differentially in ($p_T$,η) 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)

# 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 $\Lambda_{QCD}$:



# 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 $\mu_r$ 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