Experimental techniques in top studies

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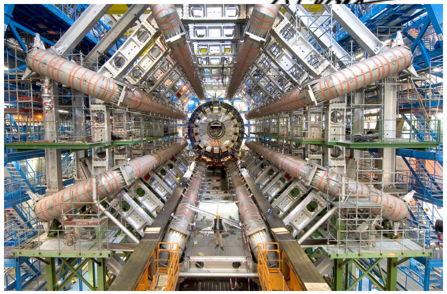
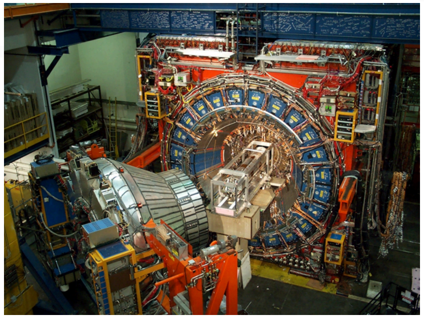
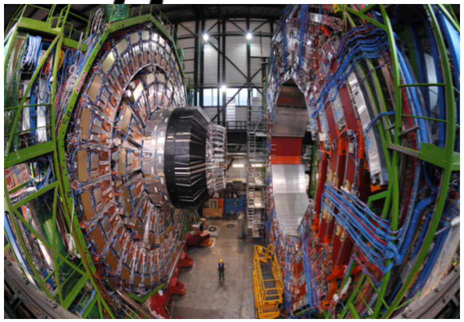
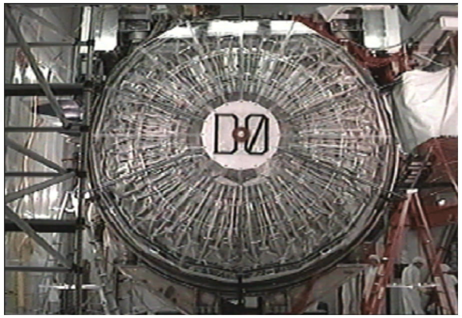
for ATLAS, CDF, CMS, & DØ



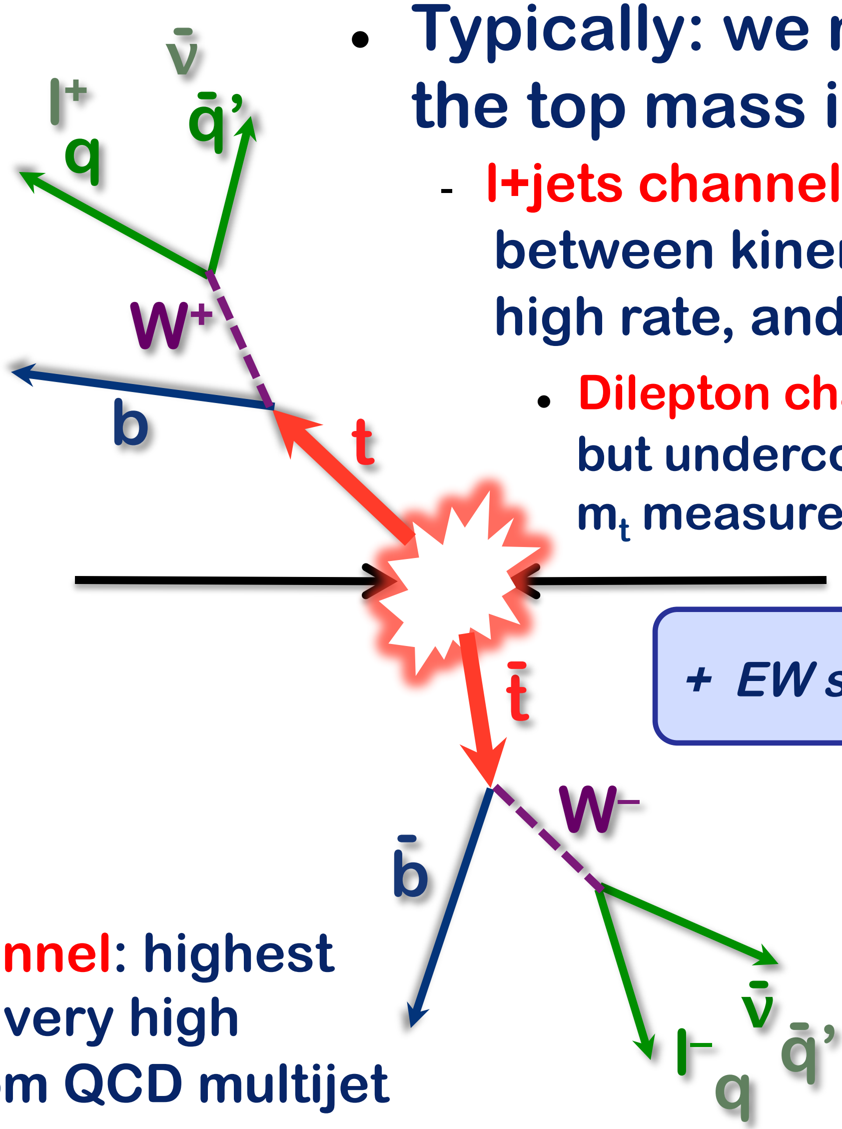






Definition of decay channels

- Typically: we measure the top mass in tT events:
  - **l+jets channel**: good compromise between kinematic reconstruction, high rate, and backgrounds
    - **Dilepton channel**: low backgrounds, but underconstrained kinematics for m_t measurement and low rate



+ EW single top production

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

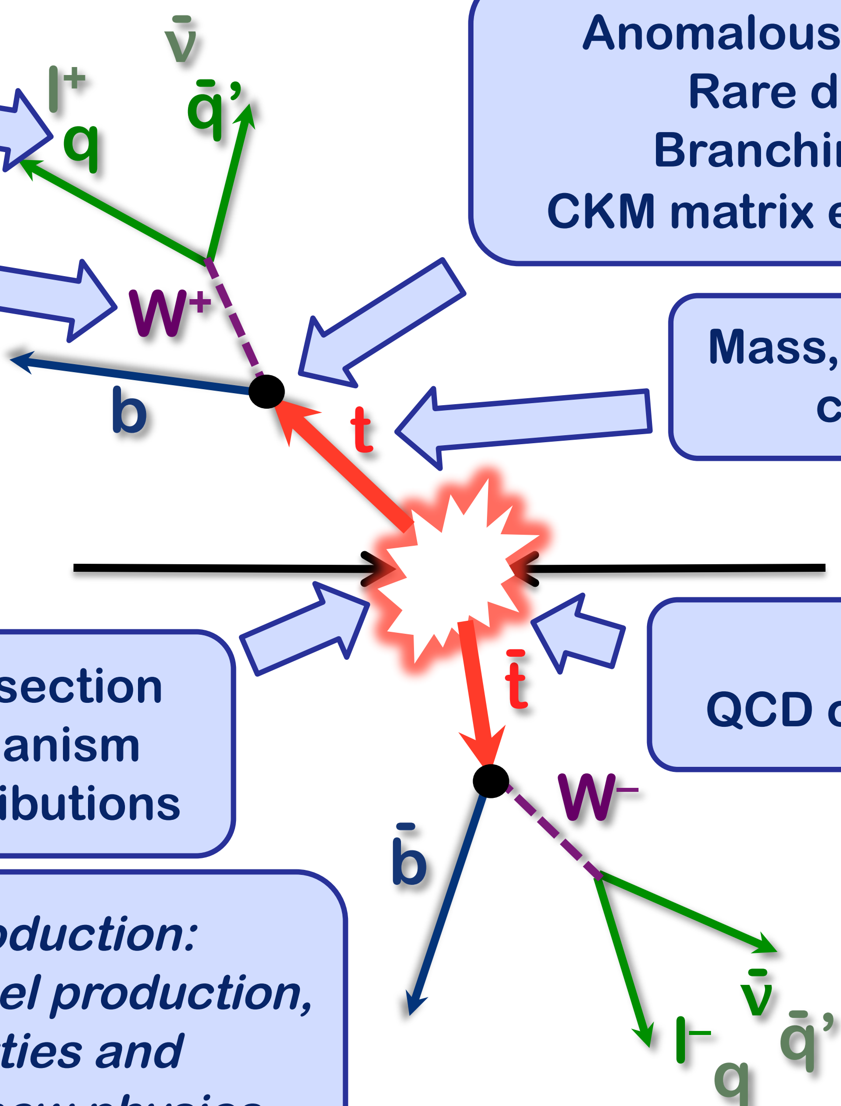
A wealth of top properties

Colour flow

W helicity

Anomalous couplings
Rare decays
Branching ratio
CKM matrix element $|V_{tb}|$

Mass, mass difference
charge, width



Spin correlation
QCD charge asymmetry A_{FB}

Production cross section
Production mechanism
New physics contributions

+ EW single top production:
- s- and t-channel production,
- kinem. properties and
- searches for new physics

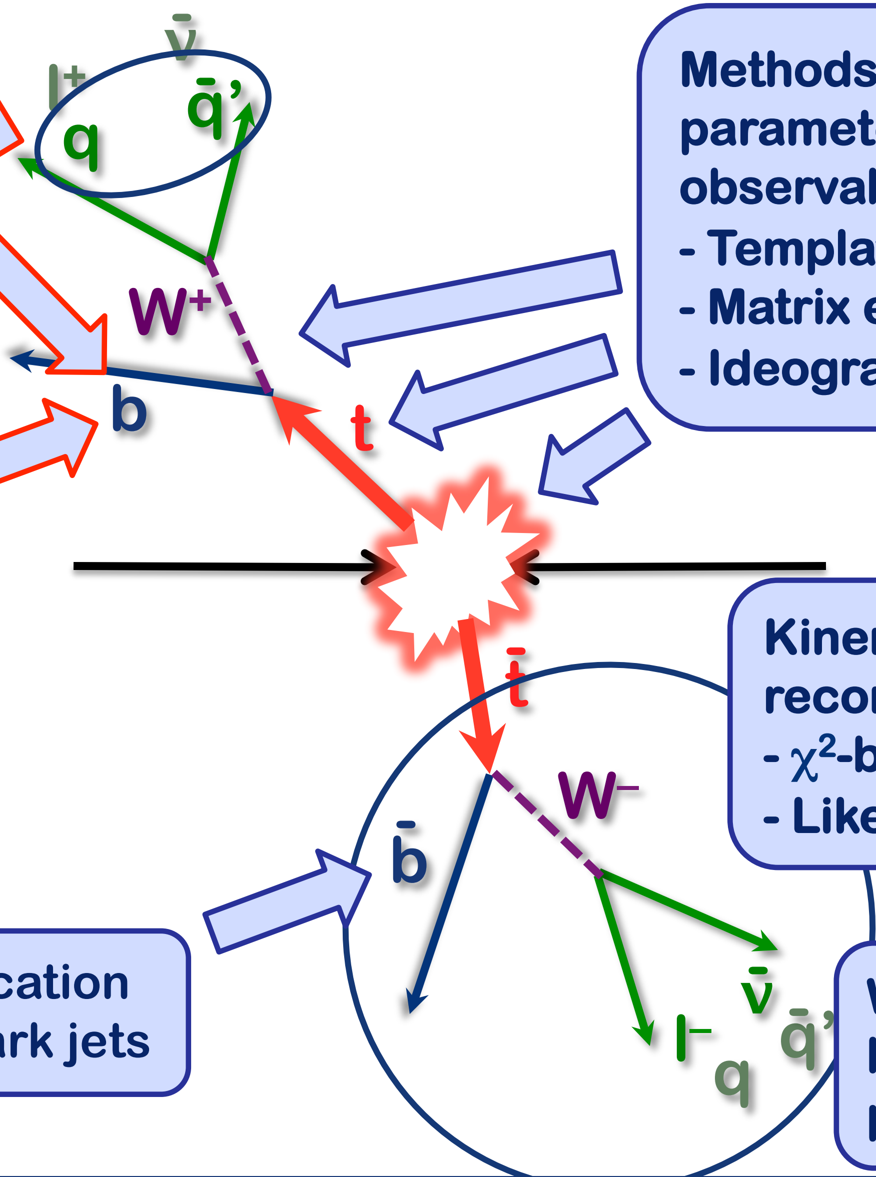
This talk is not about these measurements, but the experimental techniques behind them

Key ingredients to top measurements

Calibration of the jet energy scale (JES)

Calibration of b quark JES

Methods to extract SM parameters (e.g. m_t) or observables (e.g. A_{FB}):
- Template method
- Matrix element method
- Ideogram method



Kinematic fits to reconstruct tT system:
- χ^2-based
- Likelihood-based

Identification of b quark jets

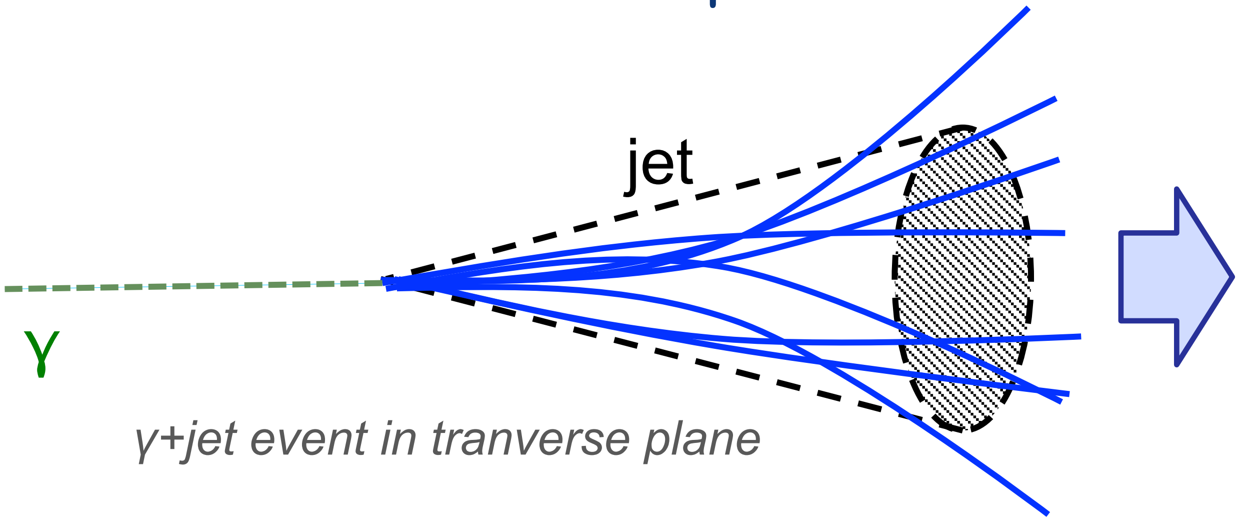
Will not talk about boosted top taggers pseudo-top definition

Jet reconstruction (for top physics)

- **ATLAS:**
  - anti-k_t jets with radius parameter R=0.4, input:
    - topological calorimeter clusters at EM scale or at local cluster-weighted scale (e/h compensation)
- **CDF:**
  - Cone algorithm with R=0.4, input:
    - Projective calorimeter towers
- **CMS:**
  - anti-k_t jets with R=0.5, input:
    - Particle flow candidates (e/h compensation, measurements from tracker if better resolution)
- **D0:**
  - Iterative mid-point seeded cone algorithm, R=0.5, input
    - Projective calorimeter towers grouped into protojets

Jet energy scale (JES) calibration

- Generic procedure to **calibrate jet energies** in a nutshell:
  - Calibrate **EM energy scale with SM candles**, i.e. $Z \rightarrow e^+e^-$
    - Central (well instrumented) region for absolute calibration
    - Correct energy scale for electrons to that of photons
    - Use **γ+jet events to calibrate major components of JES**
      - Basic idea: expect momentum balance in transverse plane



γ+jet event in tranverse plane

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

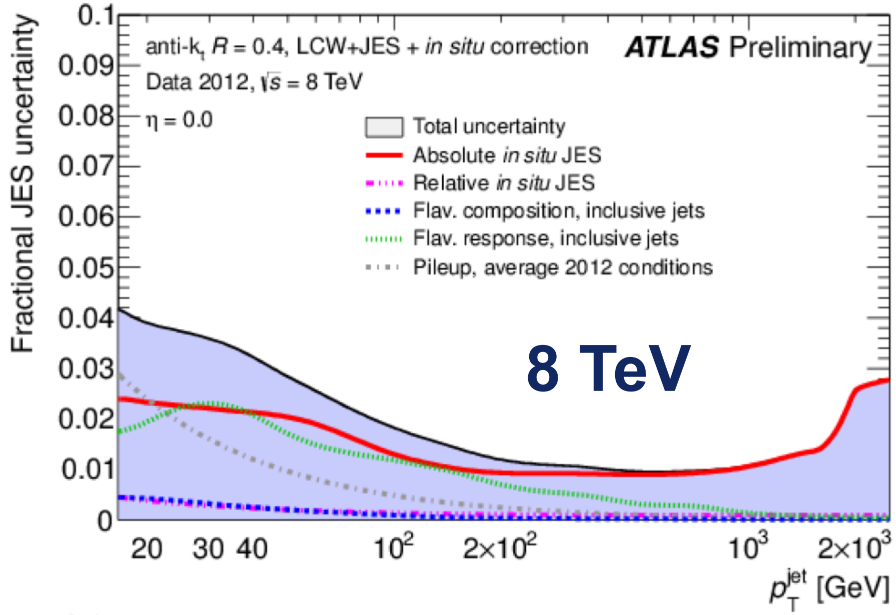
    - **Alternatively use Z+jet** events to calibrate JES
  - Use **γ+jet, Z+jet, and dijets** to extend calibration in p_T,η

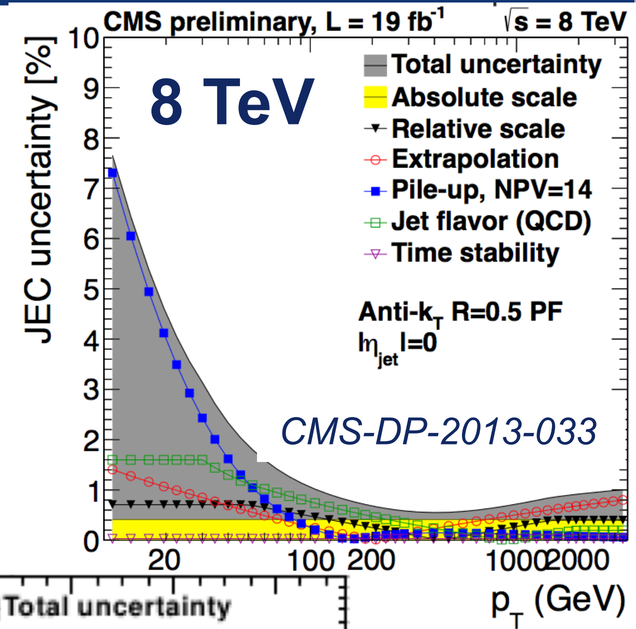
JES uncertainties

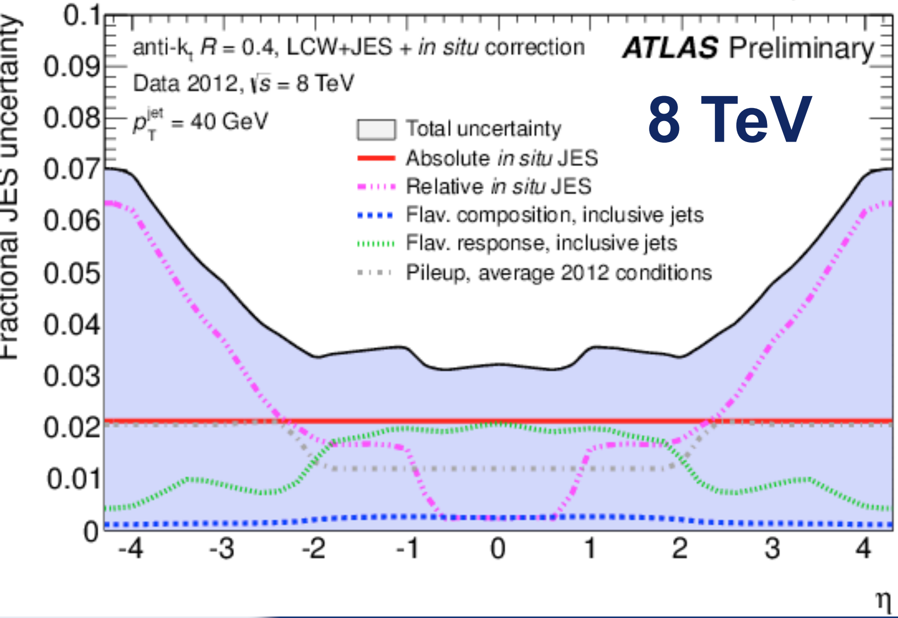
- For many measurements, the **JES uncertainty is dominant** or next-to-dominant
  → need to understand well experimentally
  - Pronounced **dependence of JES on η**:
    - Better instrumentation for **central** η, $\Delta_{JES} \approx 1.5\%$
    - More material & pile up for forward η, $\Delta_{JES} \approx 3\%$-5%
  - Pronounced **dependence on p_T**
    - (Relatively) larger impact from noise and pile up for small p_T, $\Delta_{JES} \approx 5\%$
    - Statistics and extrapolation issues for p_T > 400 GeV (1000 GeV) for Tevatron (LHC), $\Delta_{JES} \approx 3\%$
    - **Best resolution for:**
      - **50 GeV < pT < 400 GeV (Tevatron) , $\Delta_{JES} \approx 1.5\%$**
      - **100 GeV < p_T < 1000 GeV (LHC), $\Delta_{JES} \approx 1.5\%$**

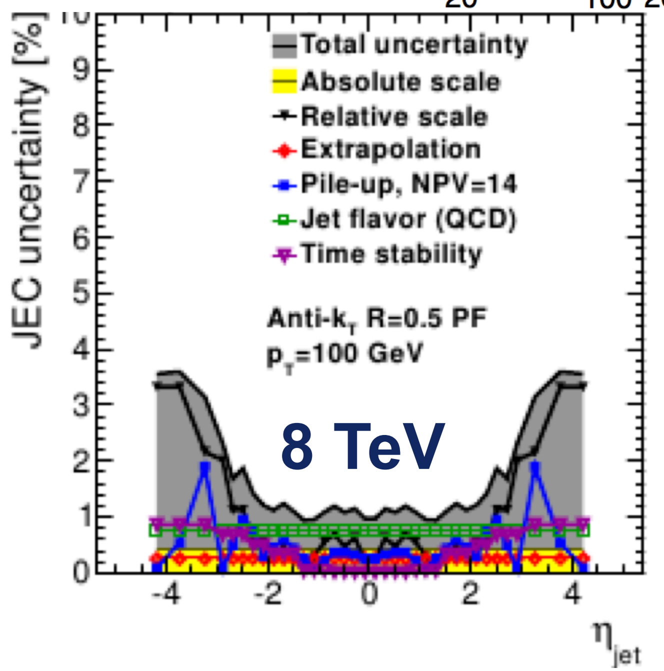
To get an idea: Δm_t is almost directly proportional to Δ_{JES}, $\Delta\sigma_{tT} \approx$ 2-3% from Δ_{JES}

JES uncertainties

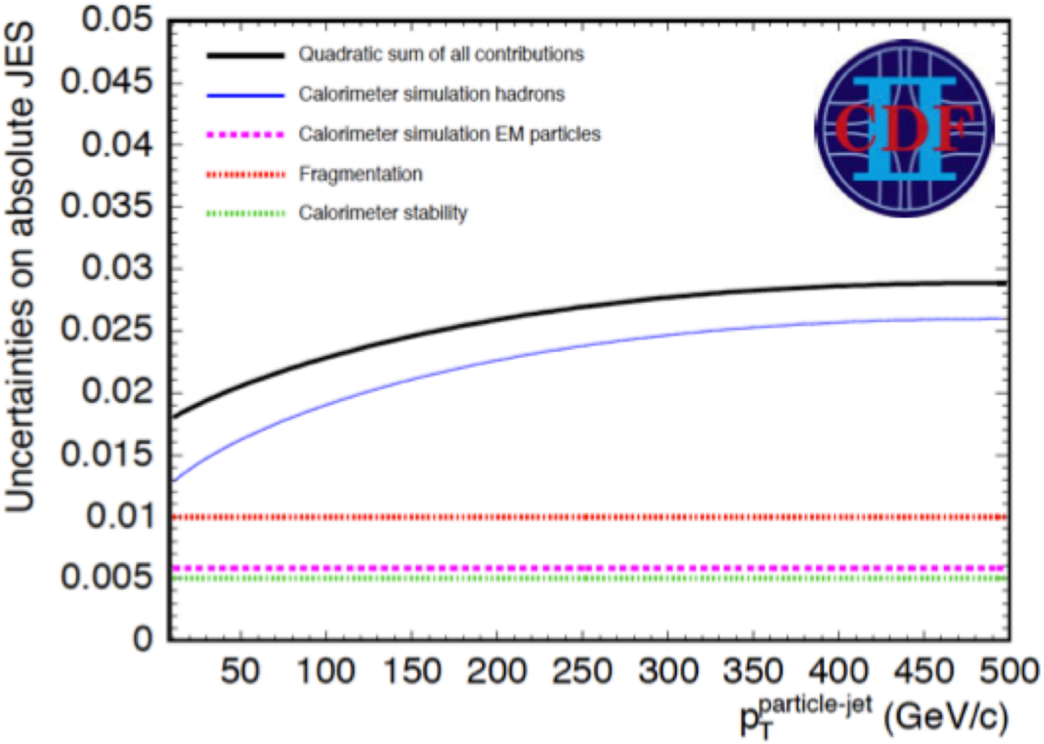


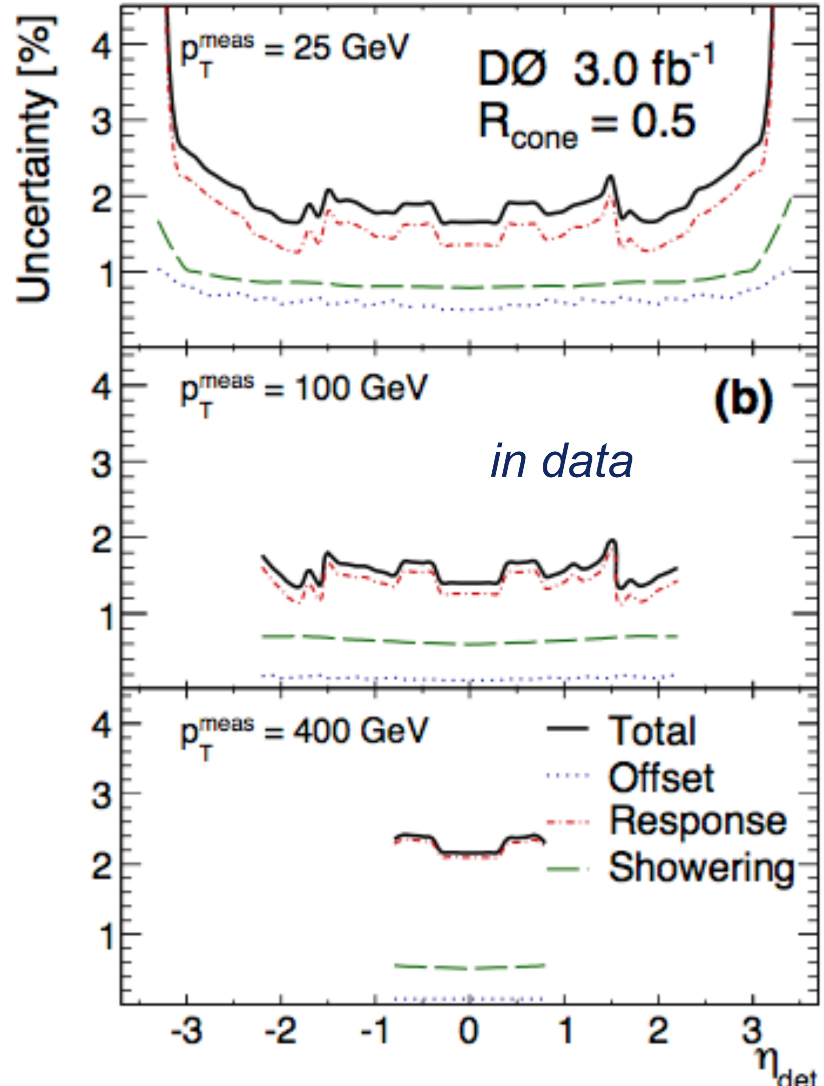






JES uncertainties





in data

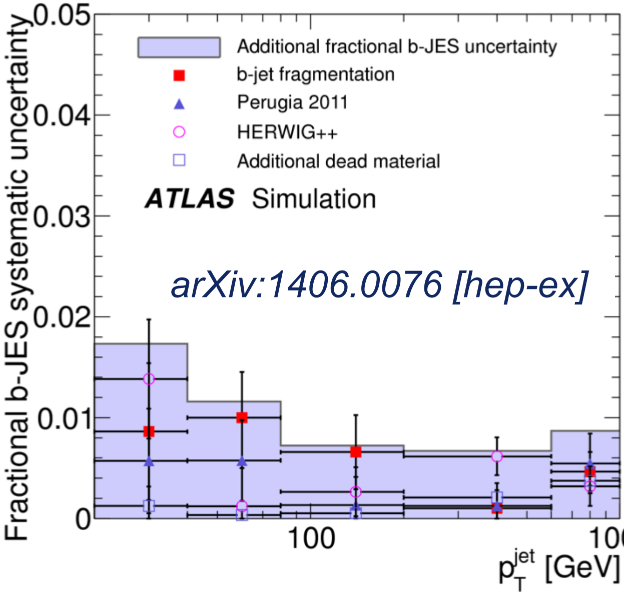
*DØ, NIM A **763**, 290 (2014)*

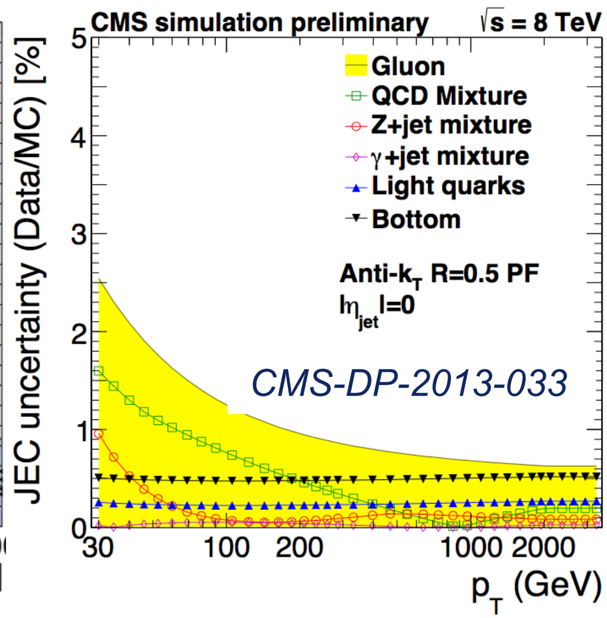
Flavour-dependence of JES calibration

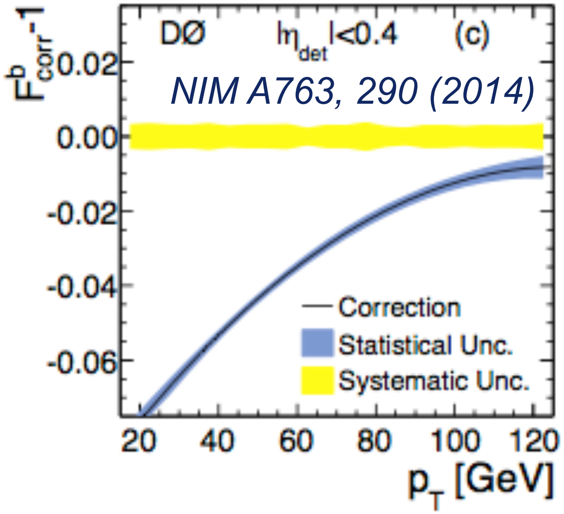
- JES calibration is determined in samples dominated by:
  - gluon jets (LHC)
  - quark jets at low p_T, gluon jets at high p_T (Tevatron)
- JES differences between the flavours expected due to:
  - Size in (η,φ): g > b > q jets
  - Mass: b > q > g jets
  - Particle composition of the jet
  - Specifically for b quark jets:
    - Decay tables of b quark jets
    - b quark fragmentation
- Difference between quark-gluon jets not so important at Tevatron since initial state 85% dominated by qQ
- Difference between b and q jets important both at LHC and Tevatron

Flavour-dependence of JES calibration

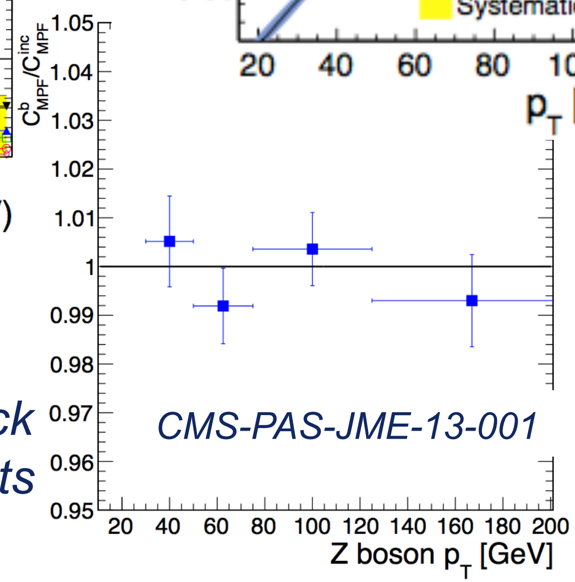
- **Typically, estimate the uncertainty on the difference between b quark JES and standard JES by comparing fragmentation and parton shower models**







Cross-check using Z+b events



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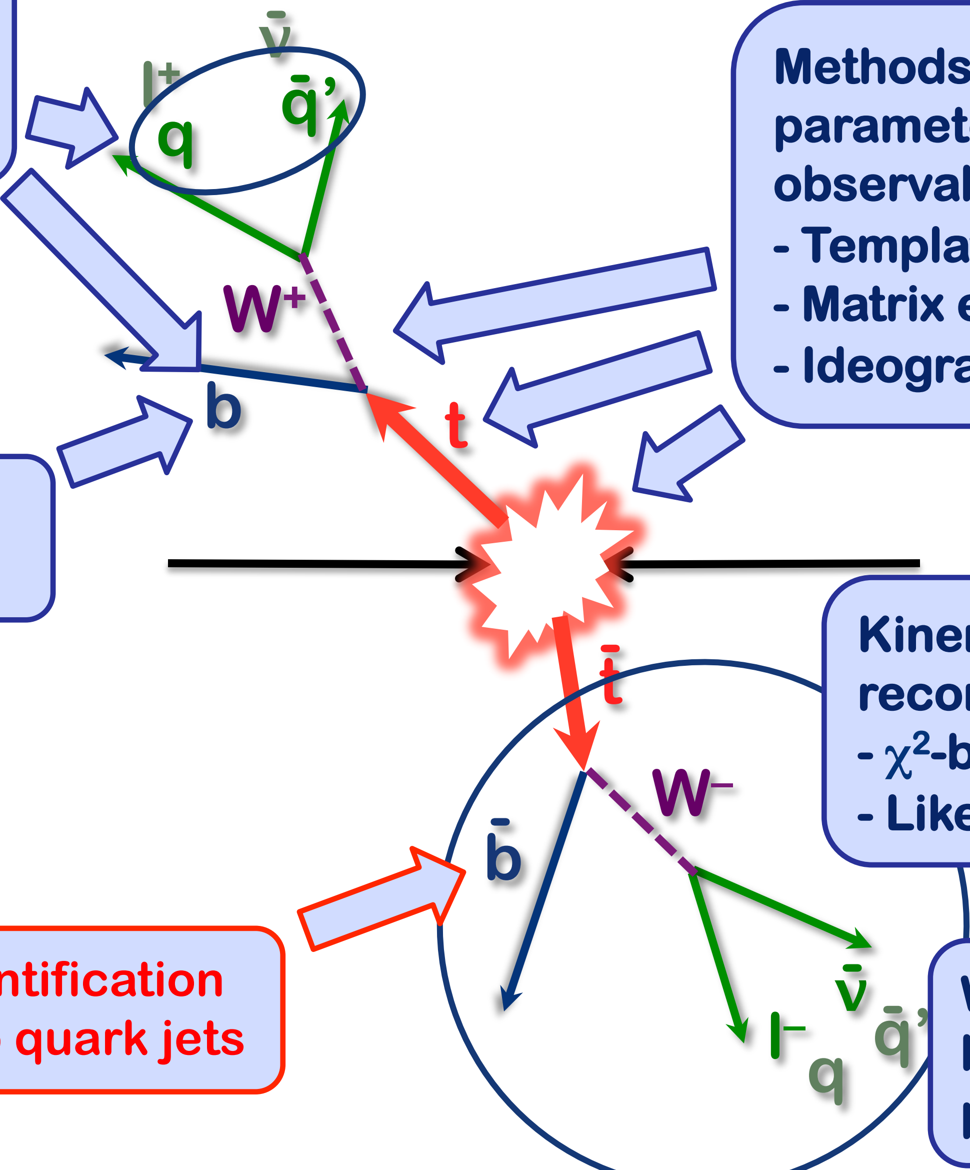


Methods to extract SM parameters (e.g. m_t) or observables (e.g. A_{FB}):
- Template method
- Matrix element method
- Ideogram method

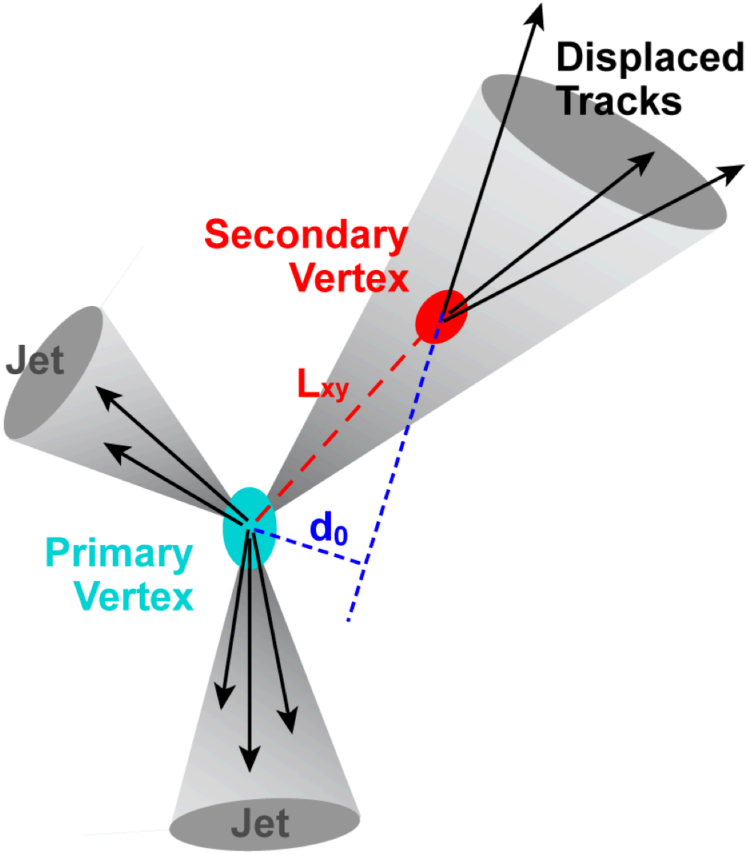
Kinematic fits to reconstruct $t\bar{t}$ system:
- χ^2-based
- Likelihood-based

Identification of b quark jets

Will not talk about boosted top taggers pseudo-top definition

b–tagging in top analyses

- Expect 2 b quark jets in each tT event, at least one in single top at Born level
  - → Use them to separate signal from background
- Identify b quark jets through dedicated algorithms (all experiments), which combine information from:
  - Existence of a displaced secondary vertex
  - Impact parameters of tracks associated with the secondary vertex
  - Mass of the secondary vertex
  - Etc.



b–tagging in top analyses

- Typical operation points chosen in top analyses:

	ATLAS	CDF	CMS	DØ
$\varepsilon_{\text{b quark}}$	70%	60%	≈ 70%	65%
$\varepsilon_{\text{light quark}}$	≈ 1%	≈ 3%	1%	≈ 3%

- Uncertainties dependent on p_T and η (similar mechanism as for JES)
  - Can have a pronounced impact on shape-sensitive analyses like e.g. measurement of $\sigma_{\text{single top}}$

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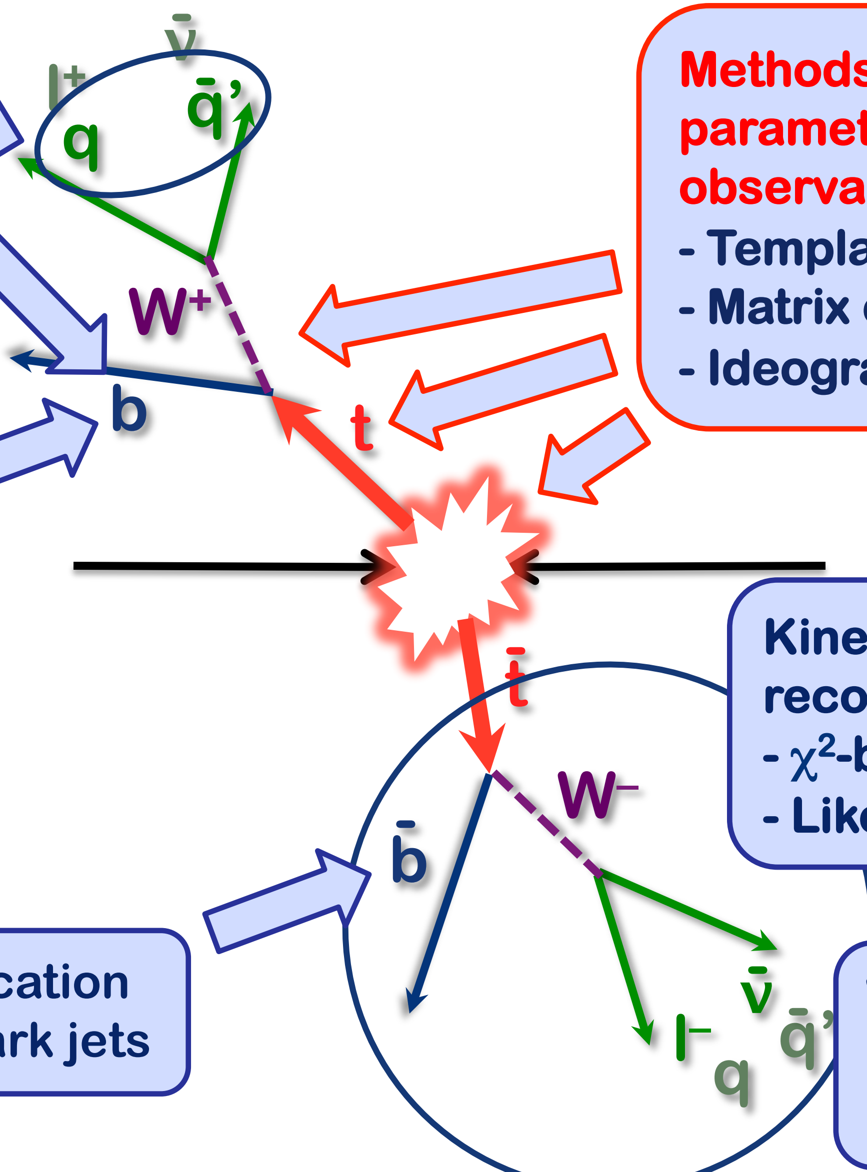

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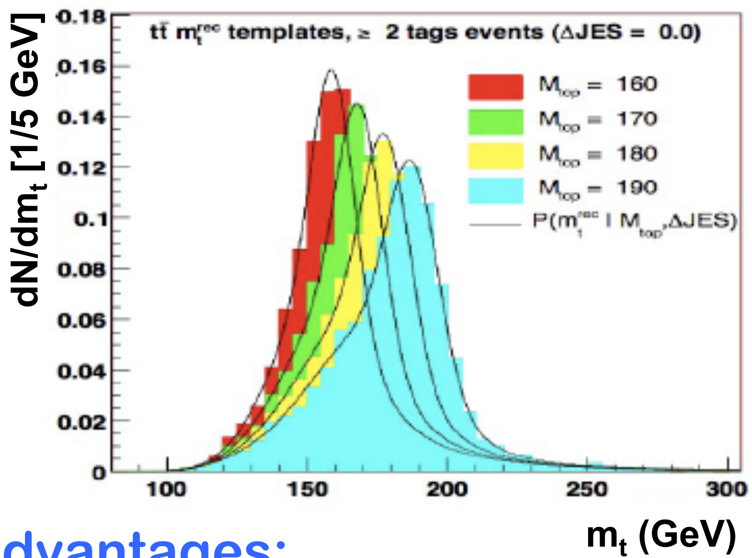
Measurement techniques using m_t example

Template method:

- Exploit dependence of m_t on kinematic observables
  - Form templates using MC
  - Maximise consistency of templates with data given m_t



- Advantages:
  - Robust and straight-forward
- Drawback:
  - Sub-optimal sensitivity

Matrix element method:

- Directly calculate the event probability as:

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

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

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

- Advantages:
  - Use full 4-vectors → maximal use of statistical information
  - Theory assumptions
- Drawback:
  - Computationally intensive
  - Theory assumptions

Ideogram method

- In-between the two

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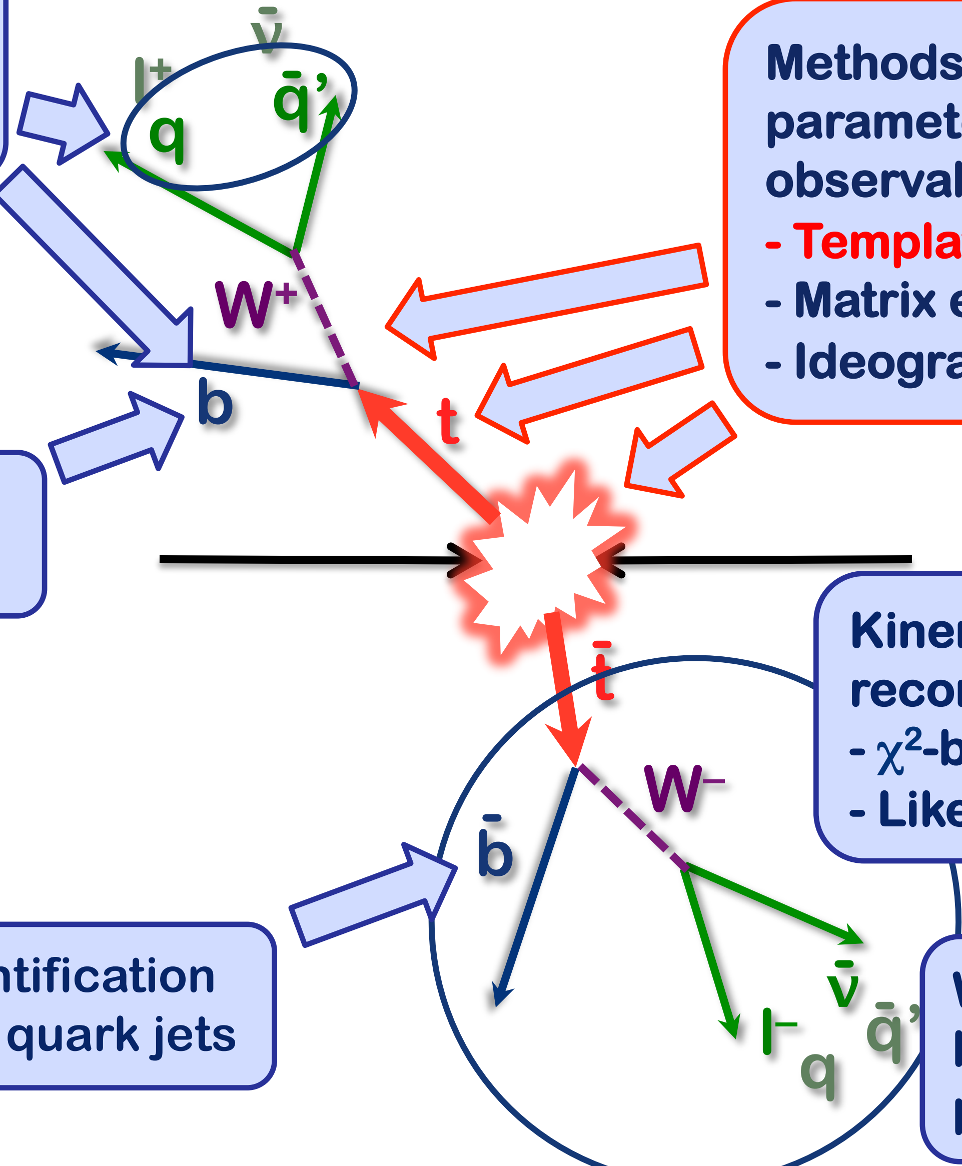

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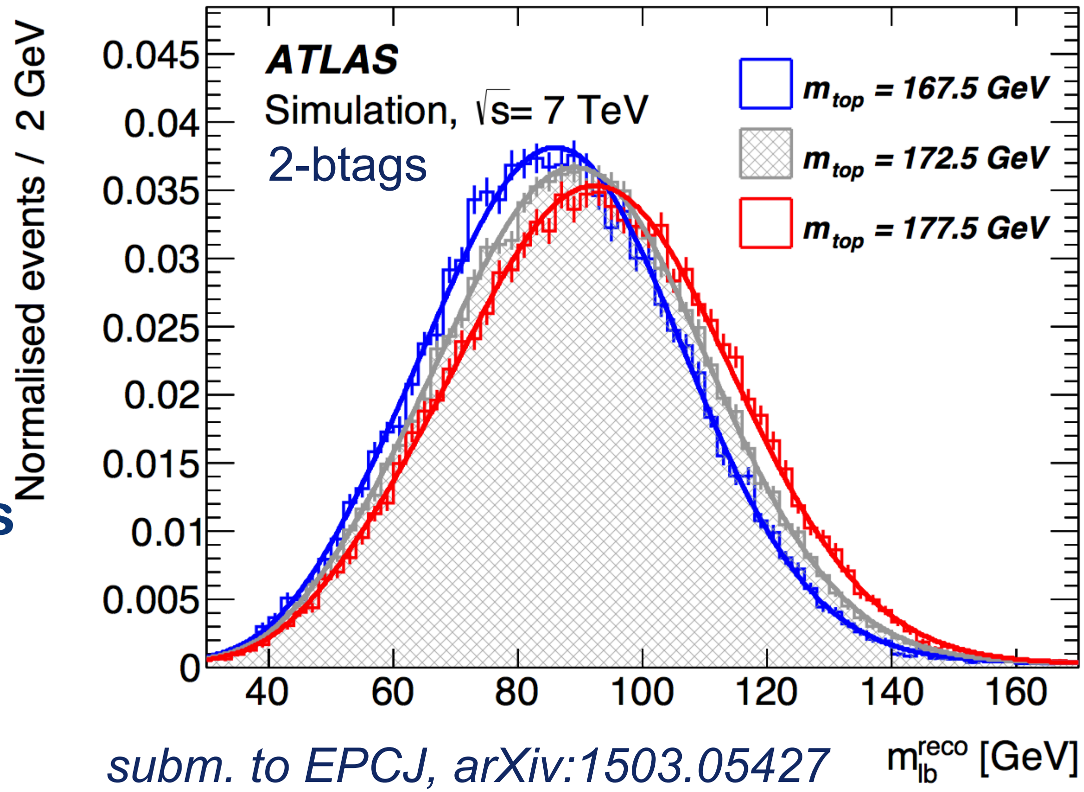
Template method using example of m_t

- Example: m_t by ATLAS in $\ell\ell$ channel using 4.6 fb^{-1}
- Apply template method using the observable $m_{\ell b}$:
  - Average invariant mass of the charged lepton and b quark system in the event
  - → reduced sensitivity to systematic uncertainties
- Signal templates:
  - Use simulated tT and single top events
  - Parametrised
    - (Gaussian + Landau)
- Background templates:
  - Sum of all backgrounds
  - Parametrised
    - (Landau)



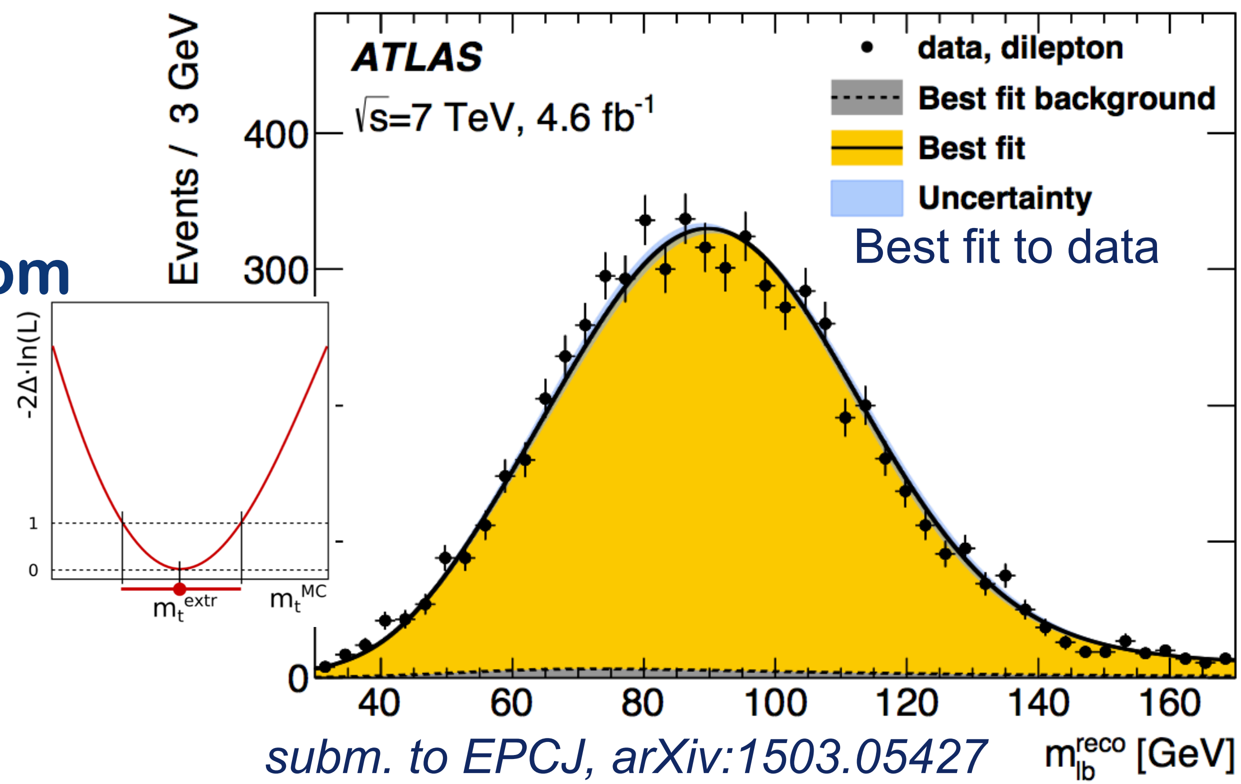
subm. to EPCJ, arXiv:1503.05427

Template method using example of m_t

- Define signal and background **templates in each analysis region** (1 and 2 b-tags)
- Extract m_t through maximising

$$\mathcal{L}^{\text{dilep}}_{\text{shape}}(m_{\text{top}}, f_{\text{bkg}}) = \prod_{i=1}^{N} \left[(1 - f_{\text{bkg}}) \cdot P^{\text{sig}}_{\text{top}}(m^{\text{reco},i}_{\ell b} \,|\, m_{\text{top}}) + f_{\text{bkg}} \cdot P^{\text{bkg}}_{\text{top}}(m^{\text{reco},i}_{\ell b}) \right]$$

- Result:
  - $m_t = 173.79$ GeV
- Obtain statistical uncertainty Δm_t from $\ln L(m_t \pm \Delta m_t) = \ln L(m_t^{best}) - ½$
  - $\Delta m_t = 0.54$ GeV



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Template method using example of m_t

- Several **sources of systematic uncertainty** can affect the analysis
- Typical for template methods:
  - "Method" category: choice of parametrisation or binning
    - Modify method within reasonable limits, check alternative $m_t \rightarrow \Delta m_t$
- Other uncertainties typically estimated using **alternative simulations when constructing pseudo-experiments (PE)**
  - PEs reflect our expectation about the data sample
    - E.g. in terms of signal/background ratio + binomial fluctuations

	Uncertainty	$\Delta m_t \pm$ stat
	Method	0.09 ± 0.07
signal modelling	Signal MC	0.26 ± 0.16
	Hadronisation	0.53 ± 0.09
	ISR/FSR	0.47 ± 0.05
	Underlying event	0.05 ± 0.05
	Colour reconnection	0.14 ± 0.05
	PDF	0.11 ± 0.00
backgr.	*W/Z*+jets norm	0.01 ± 0.00
	W/Z+jets shape	0.00 ± 0.00
	NP/fake-lepton norm.	0.04 ± 0.00
	NP/fake-lepton shape	0.01 ± 0.00
Detector resonse	Jet energy scale	0.75 ± 0.08
	b-jet energy scale	0.68 ± 0.02
	Jet resolution	0.19 ± 0.04
	Jet efficiency	0.07 ± 0.00
	Jet vertex fraction	0.00 ± 0.00
	b-tagging	0.07 ± 0.00
	$E_{\mathrm{T}}^{\mathrm{miss}}$	0.04 ± 0.03
	Leptons	0.13 ± 0.00
	Pile-up	0.01 ± 0.00

subm. to EPCJ, arXiv:1503.05427

Template method using example of m_t

- For each source, determine m_t with alternative model
  - This number comes with a statistical component, e.g. from limited size of MC samples
    - Very small if determined by reweighting identical MC events
    - If not possible, can reduce it by e.g. using identical hard ME events while changing hadronisation
    - Ideally, should be always smaller than face value of the effect
- Total uncertainty:
  - Combine all Δm_t in quadrature.
    - Here: 1.30 GeV

	Uncertainty	Δm_t ± stat
	Method	0.09 ± 0.07
signal modelling	Signal MC	0.26 ± 0.16
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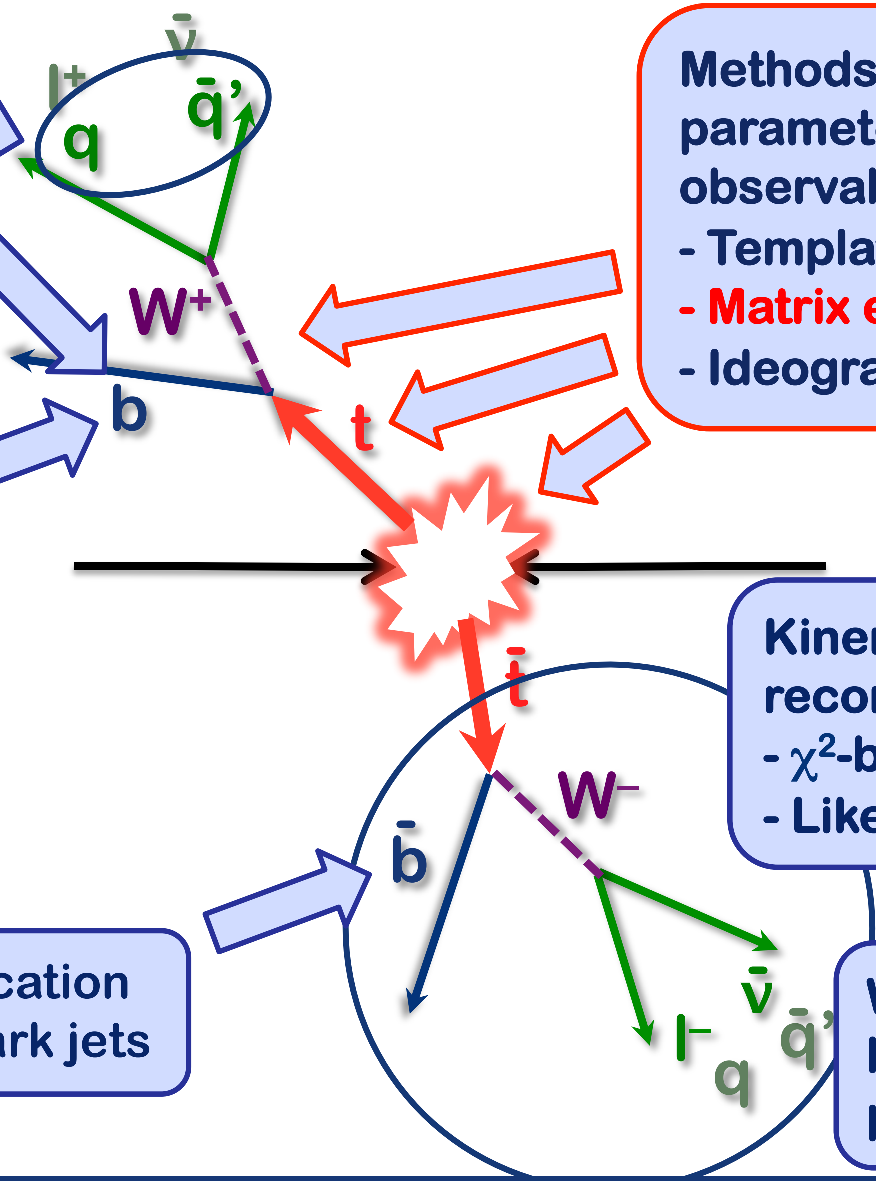
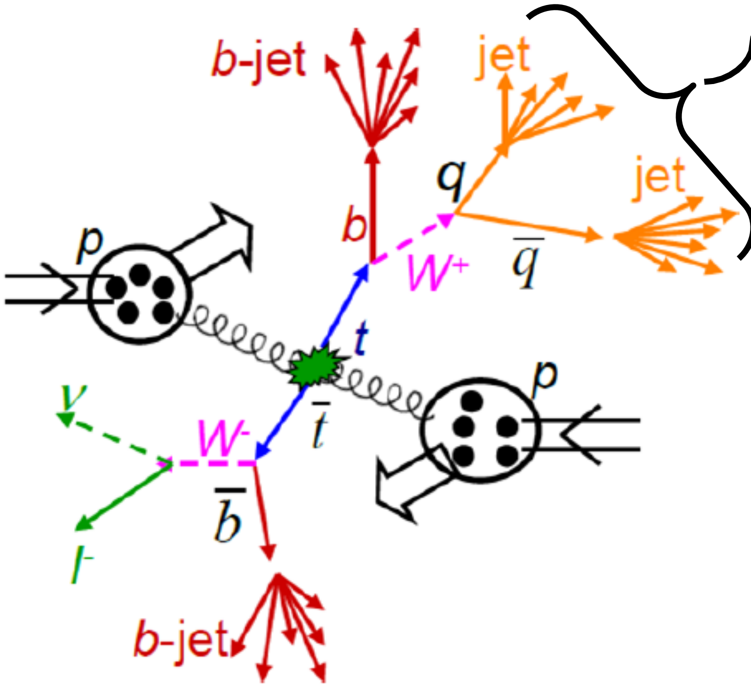
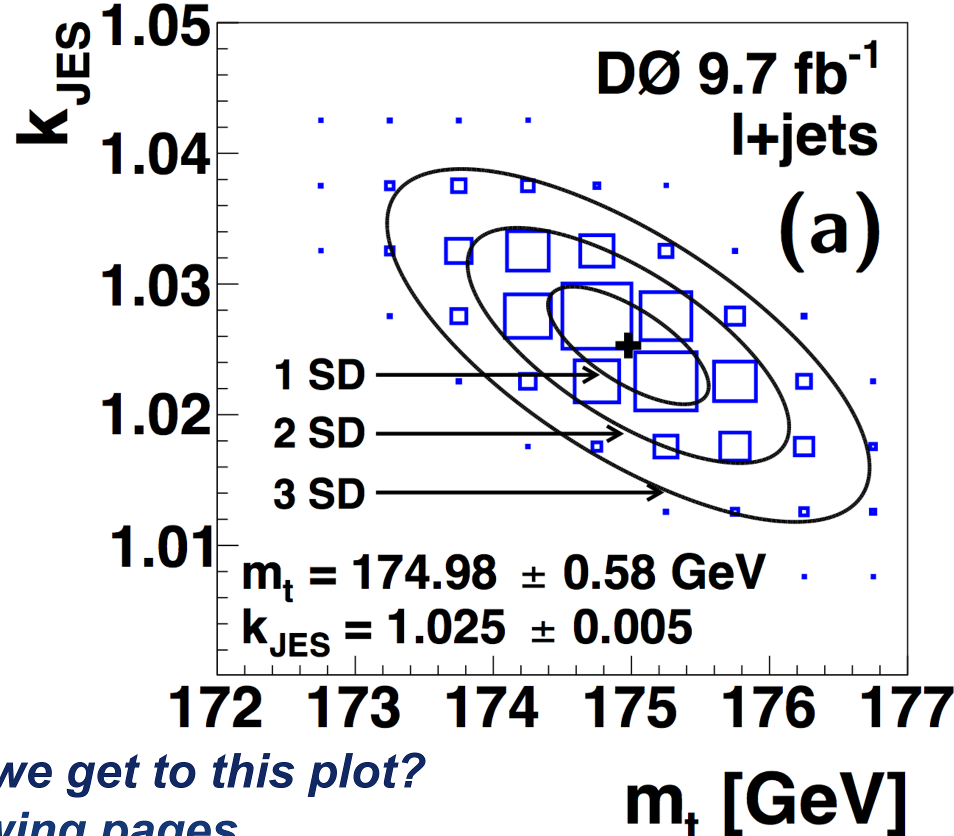


Matrix element method with m_t as example

- perform an in-situ calibration of the JES:
  - Constrain energies of the two jets from W to be consistent with M_W (not only specific to ME method)
  - This allows a simultaneous extraction of m_t and the overall JES factor k_{JES}!

$M_W \sim k_{JES}$





How do we get to this plot?
→ Following pages

Matrix element method example from DØ in l+jets

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

Integration over phase space (10 dim)

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

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

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, PRL **113** 032002 (2014)*

Matrix element method with m_t as example

Matrix element method example from DØ in l+jets

Normalisation by observed cross section using the same LO ME

Sum over all 24 possible jet-parton assignments

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

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

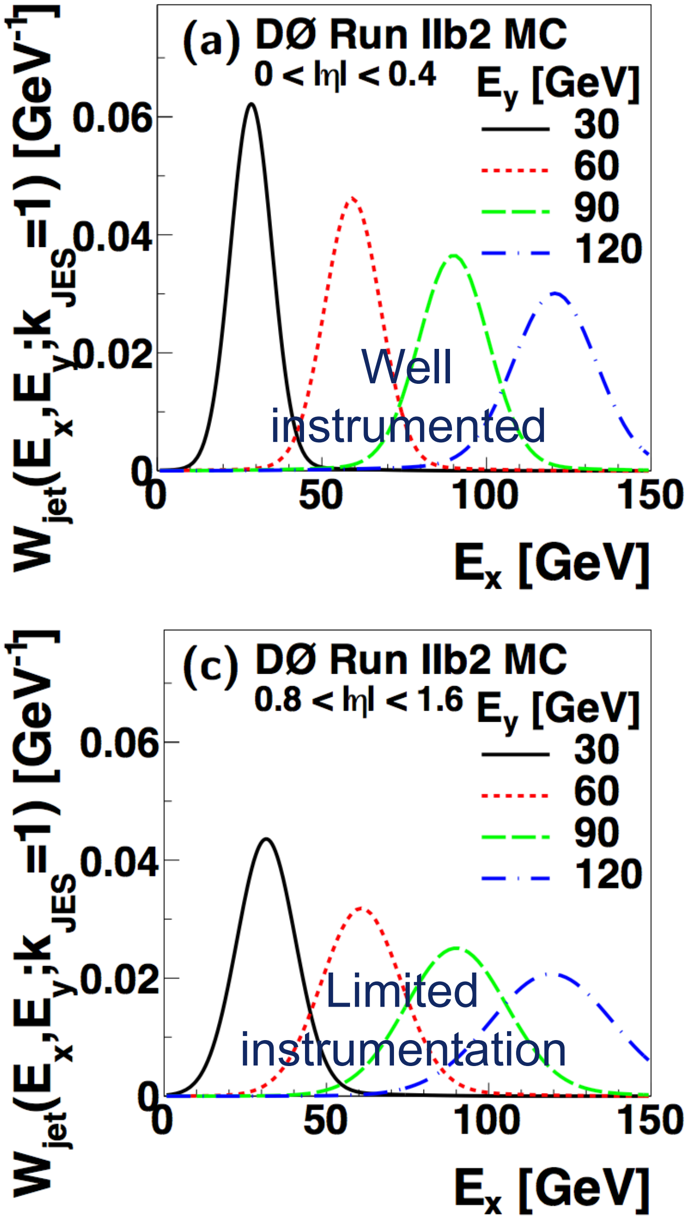
Sum over incoming parton flavours and all neutrino p_z solutions

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

*DØ, PRL **113** 032002 (2014)*

Matrix element method with m_t as example

- The **Transfer Functions** $W(x, y; k_{JES})$ relate parton-level quantities to detector-level ones
- **Parametrise the detector response**:
  - Typically, two Gaussians are used:
    - One for the core of the distribution
    - One for the tails
- **Direction** of jets and leptons in (η,ϕ) **well-measured:**
  - → typically use δ-functions as transfer function



Matrix element method with m_t as example

- The computational challenge of the ME method comes from numerical calculation of an *N*-dimensional integral using the MC method (DØ: *N*=10)
  - Reduce calculation time by orders of magnitude using importance sampling (e.g. in m_t or m_W)
  - Recent further improvements [1]:
    - Use 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
      - Include it via the transfer function
    - Reduction of calculation time by o(100)

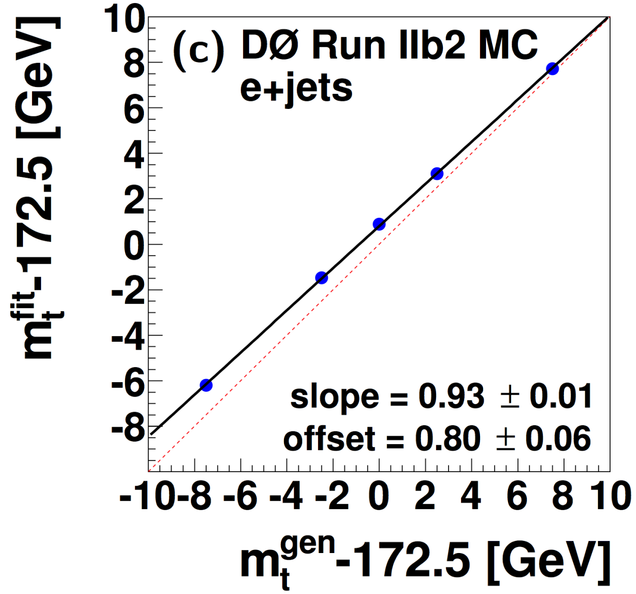
Computation time for a typical tT event only 80 sec now.
→ Can employ at LHC!

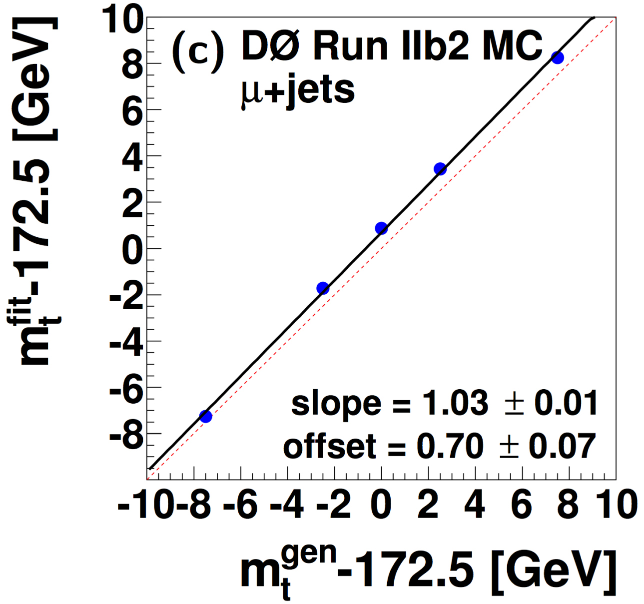
*[1] OB, G. Gutierrez, MHLS. Wang, Z. Ye, NIM A **775** 27 (2015)*

Matrix element method with m_t as example

- 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)

Matrix element method with m_t as example

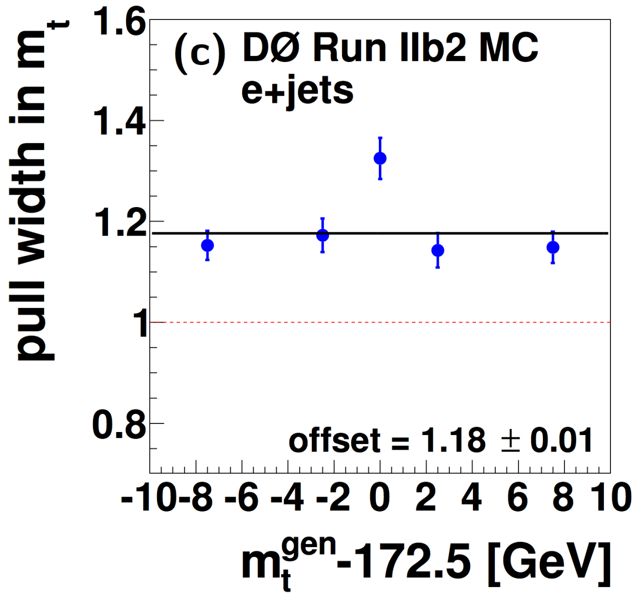


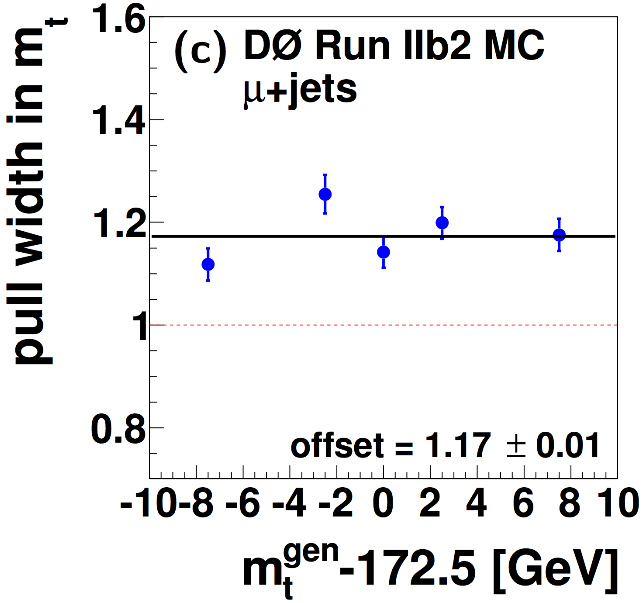


Calibrate
m_t & $\sigma(m_t)$

+ *similar calibrations for k_{JES}*

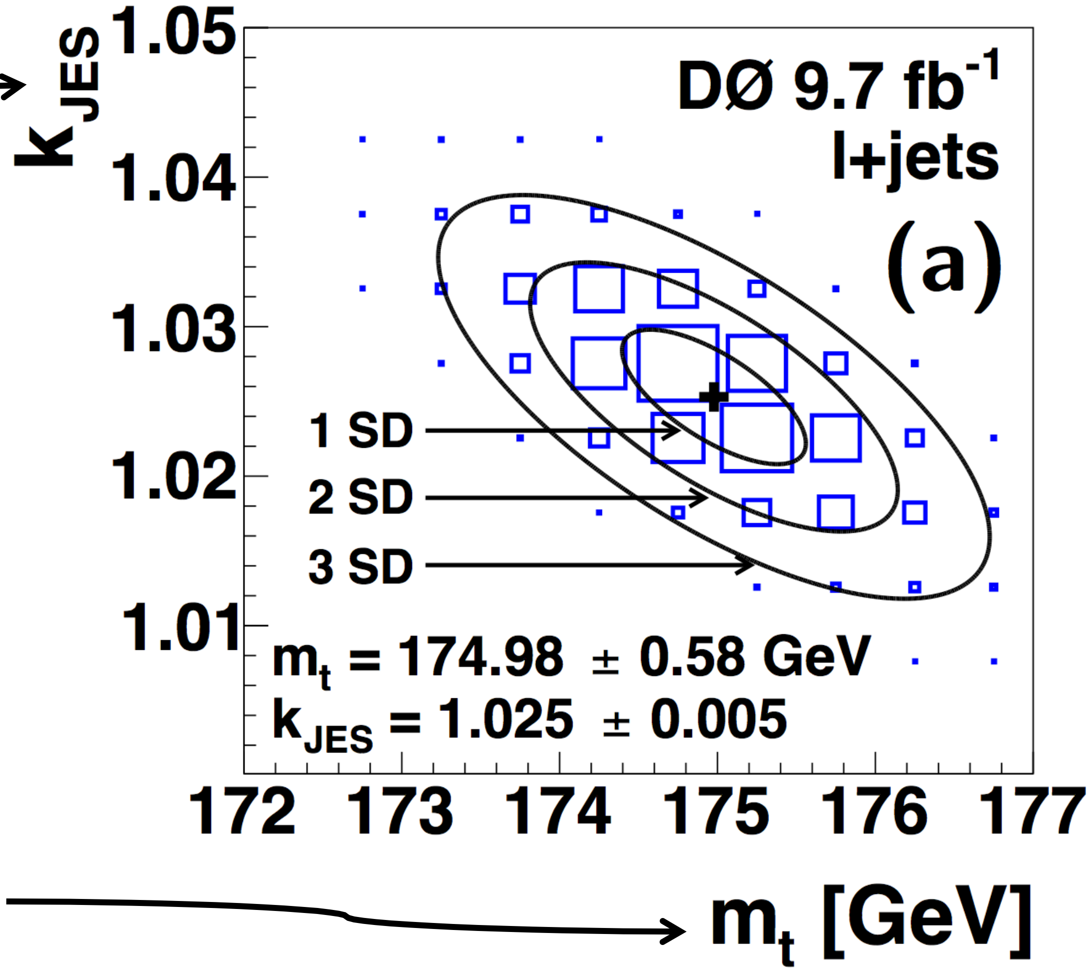
Calibrate
$\sigma(m_t)$





Matrix element method with m_t as example

Likelihood over all events in data

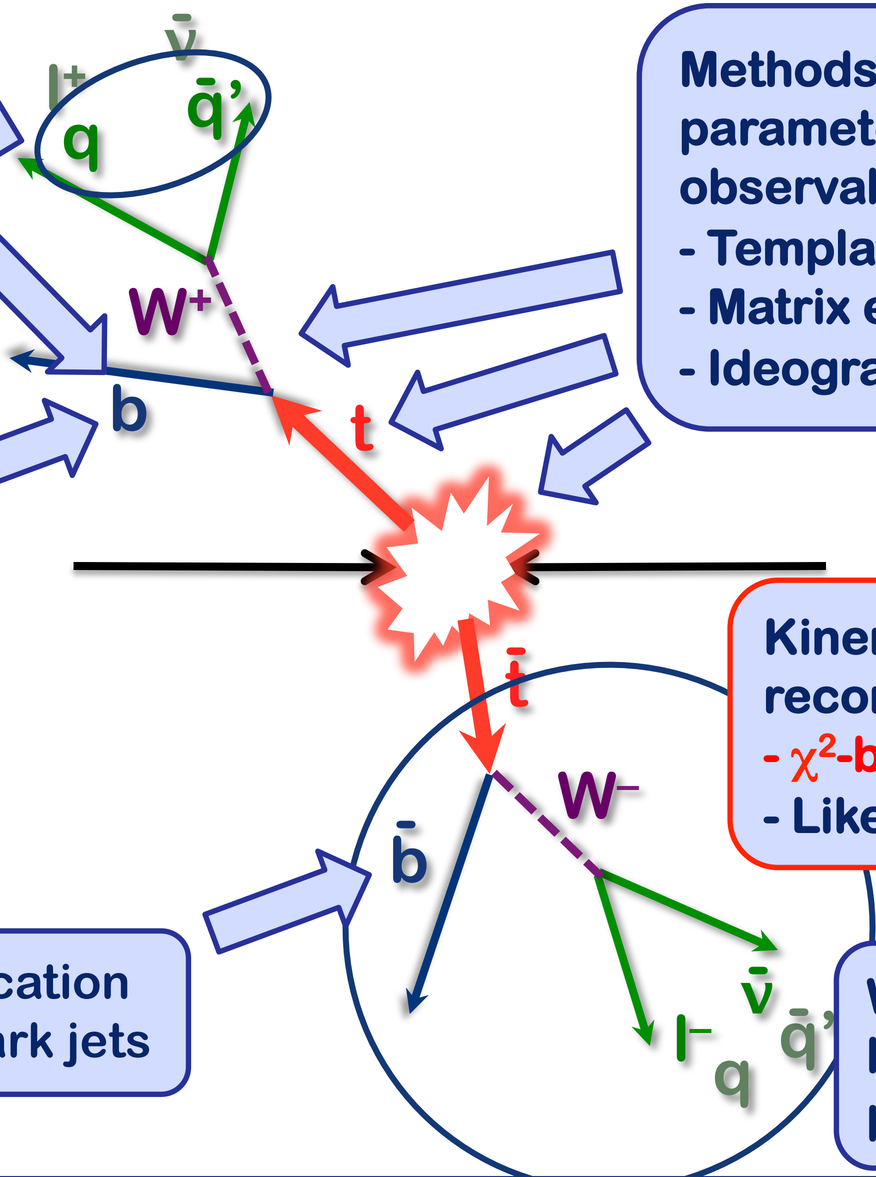


Apply calibrations for response and pull

Key ingredients to top measurements

Calibration of the jet energy scale (JES)

Methods to extract SM parameters (e.g. m_t) or observables (e.g. A_{FB}):
- Template method
- Matrix element method
- Ideogram method



Calibration of b quark JES

Kinematic fits to reconstruct tt system:
- χ^2-based
- Likelihood-based

Identification of b quark jets

Will not talk about boosted top taggers pseudo-top definition

Kinematic χ^2-based fit using m_t as example

- Challenge:
  - Reconstruct $t\bar{T}$ system, e.g. for measuring A_{FB}, A_C, Δm_t, m_t
    - Several assignments between partons and jets possible in the LO picture
    - Additional jets from ISR/FSR further complicate the picture
  - Perform kinematic fit of the event using χ^2-minimisation
- Measurement of m_t by CDF in ℓ+jets as an example
  - Reduce combinatorics:
    - consider only 4 jets leading in p_T and assignments consistent with b-tagging
      - 2 b-tags: 2 jet-parton assignments
      - 1 b-tag: 6 assignments
      - 0 b-tags: 12 assignments

*CDF, PRL **109**, 152003 (2012)*

Kinematic χ^2-based fit using m_t as example

- **For each jet-parton assignment, calculate:**

$$\chi^2 = \Sigma_{i=\ell,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \Sigma_{j=x,y} \frac{(U_j^{fit} - U_j^{meas})^2}{\sigma_j^2}$$

$$+ \underbrace{\frac{(M_{jj} - M_W)^2}{\Gamma_W^2}}_{\textit{JES constraint}} + \underbrace{\frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2}}_{\textit{MET constraint}} + \underbrace{\frac{(M_{bjj} - m_t^{\mathrm{reco}})^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - m_t^{\mathrm{reco}})^2}{\Gamma_t^2}}_{m_{top}\ \textit{extraction}}$$

  - **The name χ^2-based fit comes from the resolution terms**
- **Apply template method in observables:**
  - $\mathrm{m}_t^{\mathrm{reco}}$: **best jet-parton assignment**
  - $m_t^{\mathrm{reco}(2)}$: **second-best assignment**
  - m_{jj} : **dijet invariant mass**

$\left.\begin{matrix} m_t^{\mathrm{reco}} \\ m_t^{\mathrm{reco}(2)} \end{matrix}\right\}$ *m_t extraction*

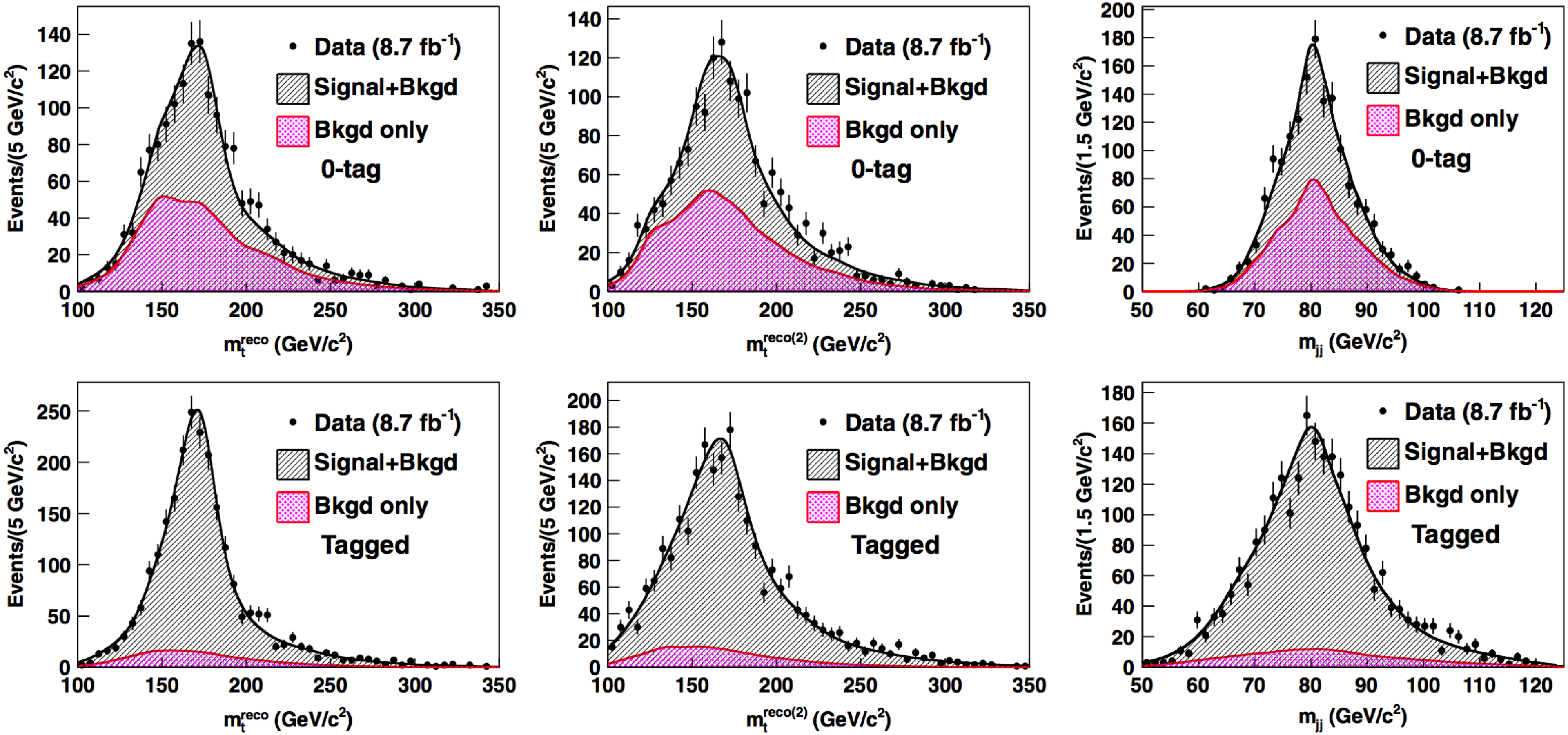
$\left.m_{\mathrm{jj}}\right\}$ *k_{JES} extraction*

- **Reject events with too high χ^2 to improve resolution**

CDF, PRL ***109****, 152003 (2012)*

Kinematic χ^2-based fit using m_t as example

- Best fit of templates to data, as seen before:



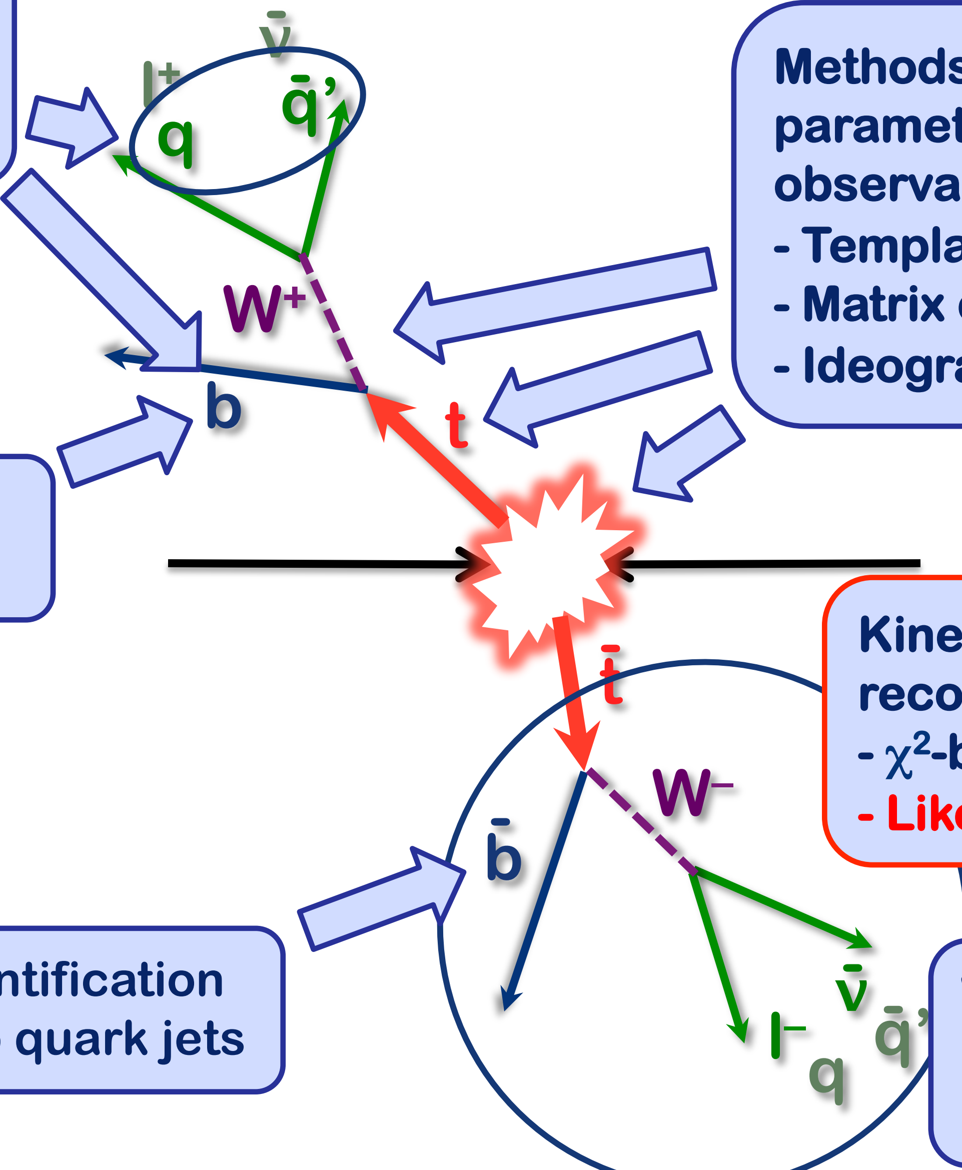
*CDF, PRL **109**, 152003 (2012)*

Key ingredients to top measurements

Calibration of the jet energy scale (JES)

Calibration of b quark JES

Identification of b quark jets



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Kinematic fits to reconstruct tt system:
- χ^2-based
- Likelihood-based

Will not talk about boosted top taggers pseudo-top definition

KIRCHHOFF-INSTITUT FÜR PHYSIK

Kinematic likelihood fit using m_t as example

- Drawback of the χ^2-based method:
  - Only consider χ^2-like resolution terms
    - No account for non-Gaussian resolution terms
- Alternative: maximise kinematic likelihood
  - Consider experimental resolutions through transfer functions (TF) like the ME method
- Example: ATLAS m_t measurement in ℓ+jets [1]
  - Update of the measurement exists [2], but does not include all the tables/plots I want to show

    → use [1] throughout for consistency

[1] *ATLAS, CONF-2013-046*
[2] *ATLAS, subm. to EPJC, arXiv:1503.05427*

Kinematic likelihood fit using m_t as example

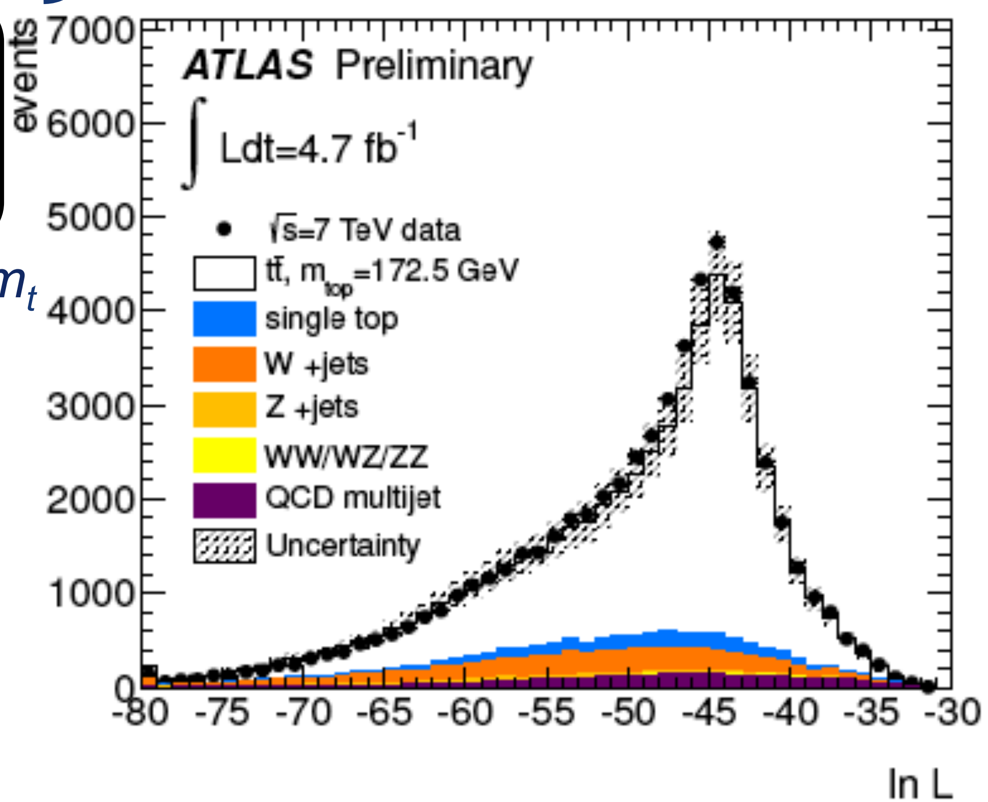
- **Likelihood:**

$$
\begin{aligned}
L \;=\; & \mathcal{T}\left(E_{\mathrm{jet}_1}|\hat{E}_{b_{\mathrm{had}}}\right)\cdot\mathcal{T}\left(E_{\mathrm{jet}_2}|\hat{E}_{b_\ell}\right)\cdot\mathcal{T}\left(E_{\mathrm{jet}_3}|\hat{E}_{q_1}\right)\cdot \\
& \mathcal{T}\left(E_{\mathrm{jet}_4}|\hat{E}_{q_2}\right)\cdot\mathcal{T}\left(E_x^{\mathrm{miss}}|\hat{p}_{x,\nu}\right)\cdot\mathcal{T}\left(E_y^{\mathrm{miss}}|\hat{p}_{y,\nu}\right)\cdot \\
& \left\{\begin{array}{ll} \mathcal{T}\left(E_e|\hat{E}_e\right) & \mathrm{e+jets} \\ \mathcal{T}\left(p_{\mathrm{T},\mu}|\hat{p}_{\mathrm{T},\mu}\right) & \mu\mathrm{+jets} \end{array}\right\}\cdot \\
& \mathcal{B}\left[m(q_1\,q_2)|m_W,\Gamma_W\right]\cdot\mathcal{B}\left[m(\ell\,\nu)|m_W,\Gamma_W\right]\cdot \\
& \mathcal{B}\left[m(q_1\,q_2\,b_{\mathrm{had}})|m_{\mathrm{top}}^{\mathrm{reco}},\Gamma_{\mathrm{top}}\right]\cdot \\
& \mathcal{B}\left[m(\ell\,\nu\,b_\ell)|m_{\mathrm{top}}^{\mathrm{reco}},\Gamma_{\mathrm{top}}\right]\cdot W_{\mathrm{btag}}\,.
\end{aligned}
$$

Detector resolutions parametrised through TFs

Breit-Wigner constraints for m_W and m_t

Correct jet-parton assignments:
70%: single b-tag
80%: two b-tags



ATLAS, CONF-2013-046

Kinematic likelihood fit using m_t as example

ATLAS-CONF-2013-046

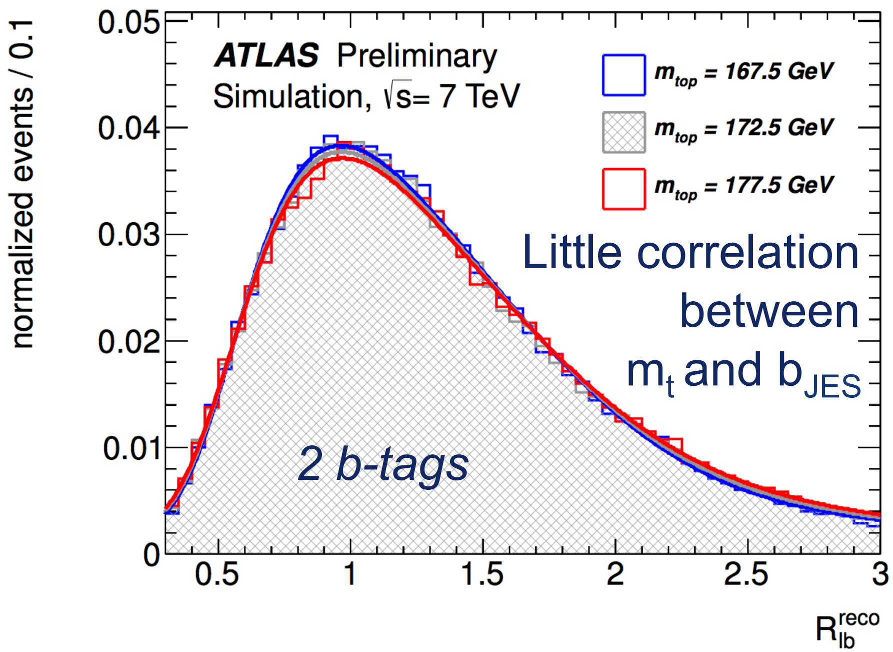
- In situ calibration of the JES for b-quark jets (b_{JES})
  - Introduce R_{lb} variable to provide sensitivity to b_{JES}:

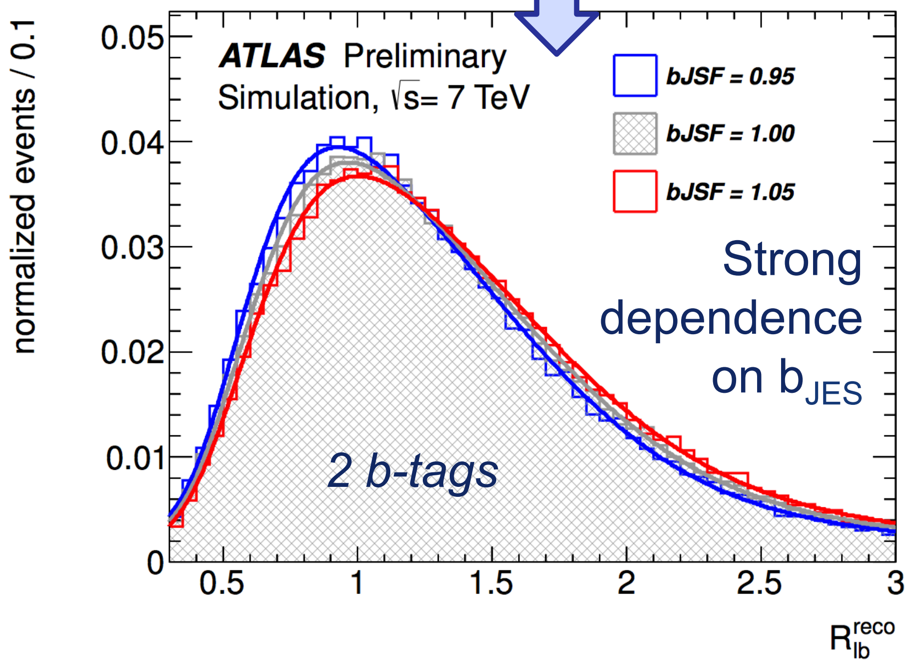
$$R_{\mathrm{lb}}^{\mathrm{reco,2b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{had}}} + p_{\mathrm{T}}^{b_{\mathrm{lep}}}}{p_{\mathrm{T}}^{W_{\mathrm{jet}_1}} + p_{\mathrm{T}}^{W_{\mathrm{jet}_2}}}$$

single b-tag

$$R_{\mathrm{lb}}^{\mathrm{reco,1b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{tag}}}}{(p_{\mathrm{T}}^{W_{\mathrm{jet}_1}} + p_{\mathrm{T}}^{W_{\mathrm{jet}_2}})/2}$$

two b-tags





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two b-tags

ATLAS-CONF-2013-046

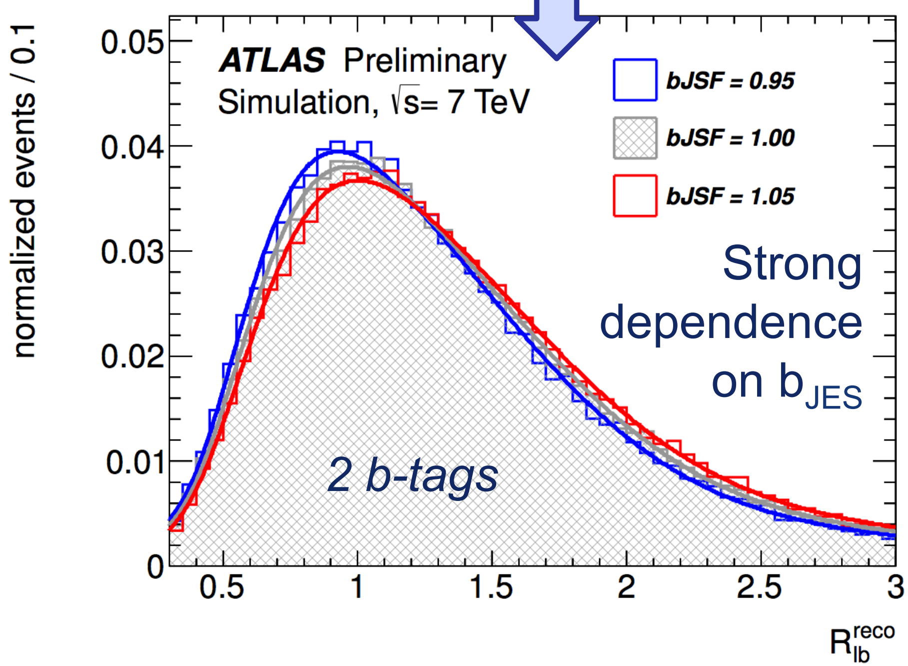
b_{JES} is simultaneously extracted with m_t and k_{JES} i.e., calibrated in situ:

→ Reduced systematic uncertainty

→ Increased statistical uncertainty:

$$\left.\begin{array}{l} \pm 0.23\ (m_t) \\ \pm 0.27\ (k_{JES}) \\ \pm 0.67\ (b_{JES})\ \text{GeV} \end{array}\right\} \pm 0.76\ \text{GeV}$$

(m_t and k_{JES} fit only: ±0.35 GeV)



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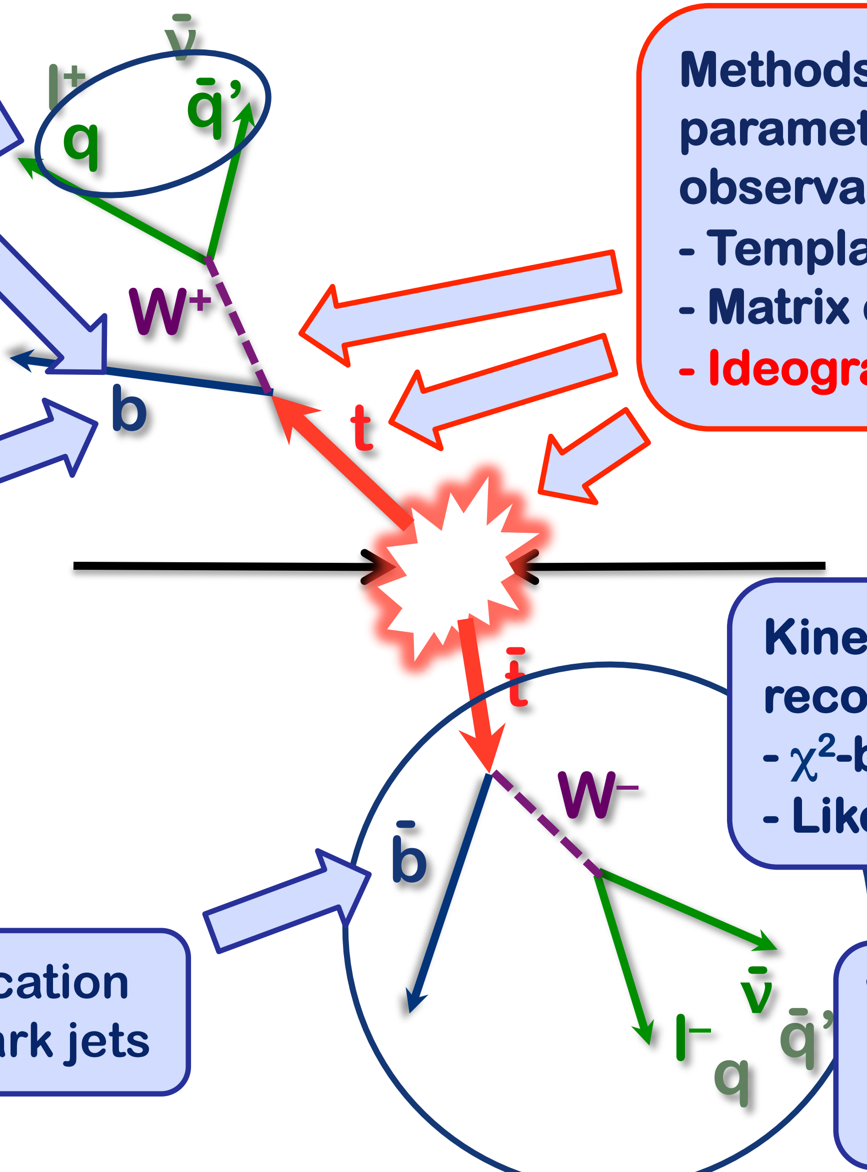


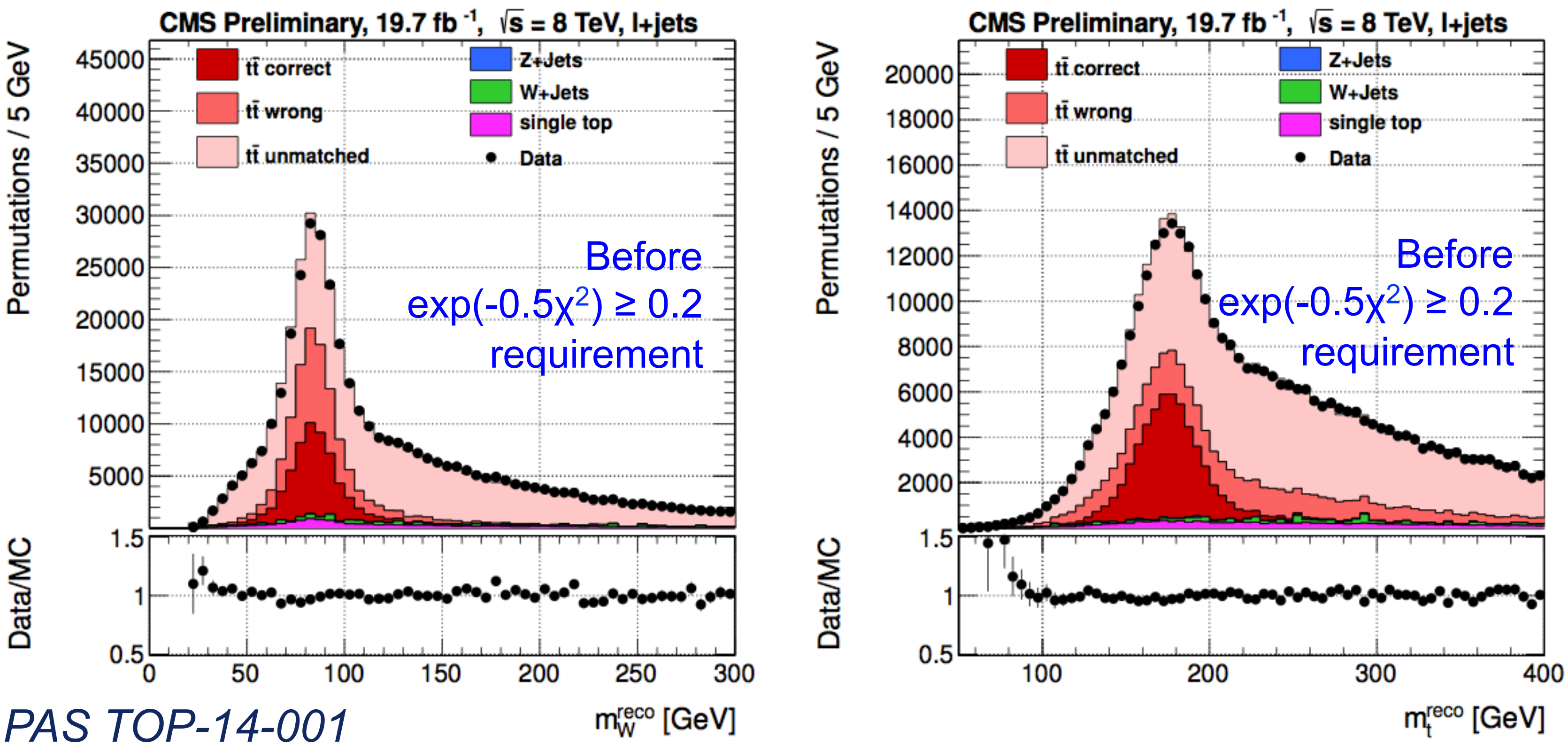
Ideogram method with m_t as example

- The ideogram method is conceptually in-between the ME method and the template method:
  - Calculates per-event probability like ME method
  - Defines PDs from distributions in MC like template method
  - Uses many approaches applied in template methods, like the χ^2-kinematic fit

CMS PAS TOP-14-001

Ideogram method with m_t as example

- Example: CMS m_t analysis in l+jets using 19.5 fb^{-1}
  - Require ≥4 jets with 2 b-tags to reduce combinatorics
  - Apply χ^2 **kinematic fit** for each jet-parton assignment
    - Consider all assignments with $\exp(-\chi^2/2) > 0.2$
      - **weighted by $\exp(-\chi^2/2)$**



CMS PAS TOP-14-001

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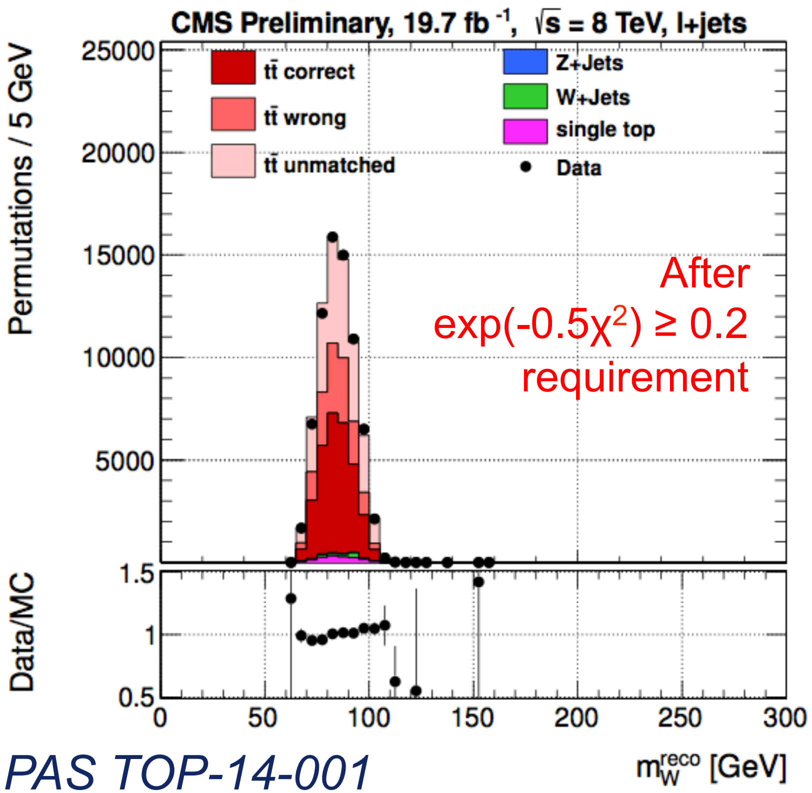
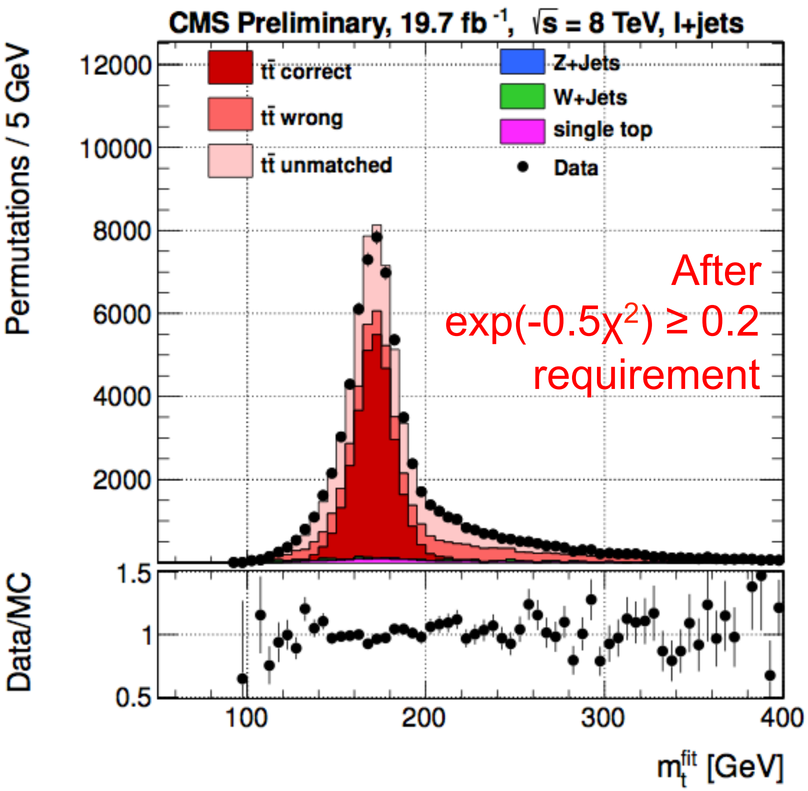




CMS PAS TOP-14-001

Ideogram method with m_t as example

CMS PAS TOP-14-001

- **Construct L from event probabilities:**

$$\mathcal{L}\left(\text{sample}|m_{\text{t}},\text{JSF}\right) = \prod_{\text{events}} \left(\sum_{i=1}^{n} P_{\text{gof}}(i) \left(\sum_{j} f_j \underbrace{P_j(m_{\text{t},i}^{\text{fit}}|m_{\text{t}},\text{JSF})}_{\text{PD in } m_t^{fit}} \times \underbrace{P_j(m_{\text{W},i}^{\text{reco}}|m_{\text{t}},\text{JSF})}_{\text{PD in } m_W^{reco}} \right) \right)^{w_{\text{event}}}$$

JSF=k_{JES}

j runs over correct, incorrect, unmatched jet-parton assignments

$$P_{\text{gof}} = \exp\left(-\tfrac{1}{2}\chi^2\right)$$

$$w_{\text{event}} = c \sum_{i=1}^{n} P_{\text{gof}}(i)$$

- **Extract final result by maximising L**
- **Dispel the myth:**
  - It is often claimed that the ideogram method is **by construction statistically more sensitive** than the template method
  - This generic statement does not hold:
    - ATLAS template @ 7 TeV: ± 0.34 GeV (stat m_t+k_{JES}) [1]
    - CMS ideogram @ 7 TeV: ± 0.43 GeV (stat m_t+k_{JES}) [2]

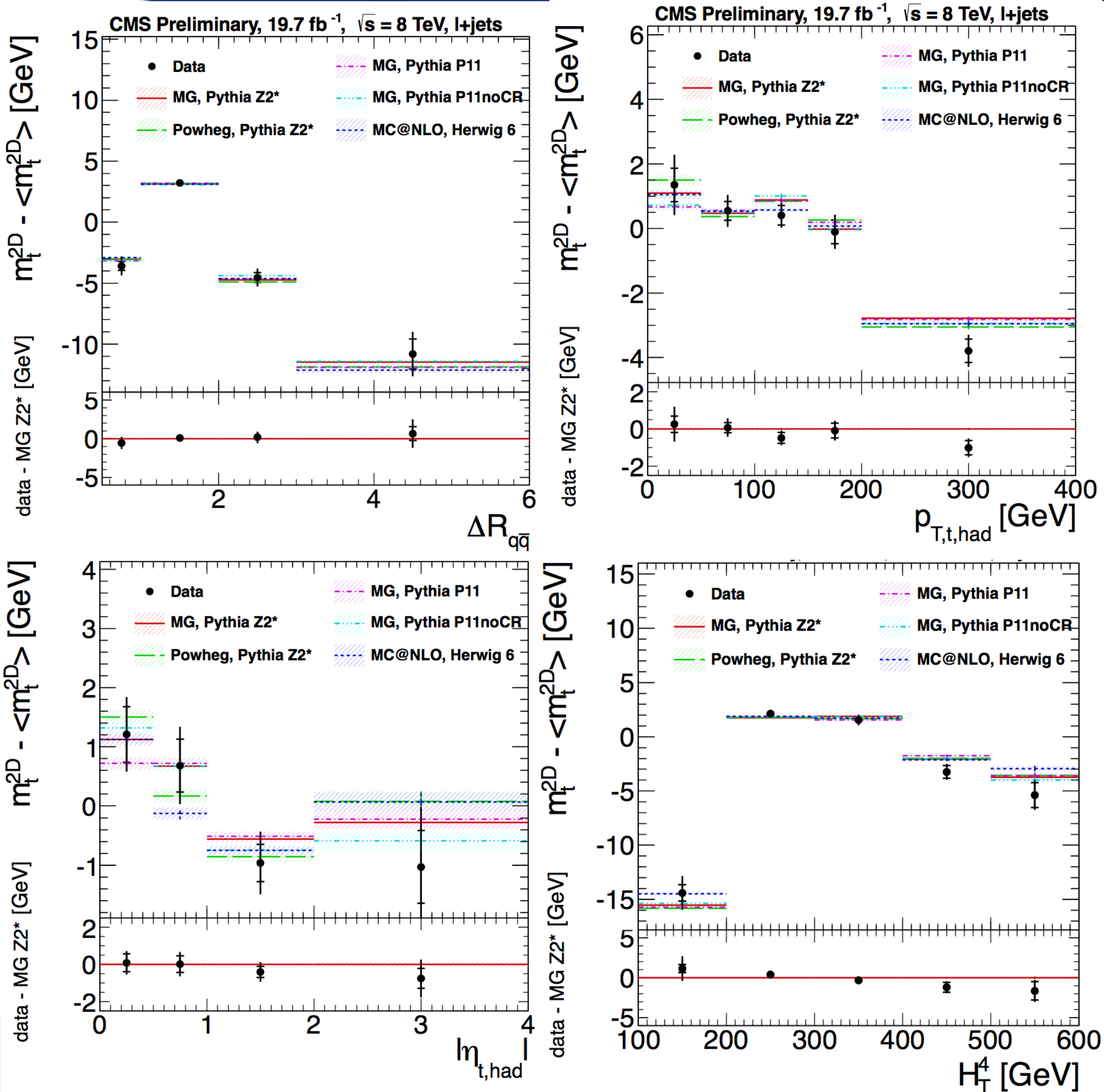
[1] CONF-2013-046
[2] JHEP 1212, 105 (2012)

Ideogram method with m_t as example

- Dependence of m_t on phase space used for the measurement studied → see next pages
  - This exciting study is definitely going in the right direction!
    - (not ideogramm-specific)
  - I see this as an Ansatz to study (and possibly evaluate) systematic uncertainties at the LHC
    - Similar (independent) studies at DØ indicate that the statistics is not sufficient at the Tevatron to reject any models

CMS PAS TOP-14-001

Ideogram method with m_t as example



Anything to be learned?

Disclaimer:

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

- **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
    - The bottle neck can be:
      - Generation and simulation of MC events
      - Their analysis with an advanced method

- 3) Ironically, the dominant limitation in precision often comes from the soft part of the event
  - We need to better understand and constrain the hadronisation model
    - (for m_t measurements can fit the b-quark JES in-situ)
      - 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 (cf. talk by S. Weinzierl)**

Anything to be learned?

- 6) The ME technique appears to be less sensitive to systematic uncertainties
  - Evaluates the impact of an uncertainty in context of a concrete model for top and background production described by the respective MEs
  - Canonical example:
    - Reduced sensitivity of LO ME to tT events with initial/final state radiation due to lower P_{tT}

- 7) Measure an observable or SM parameter in various regions of phase space
  - Check for biases
    - Reject models
  - Evaluate systematic uncertainties from data

Tevatron legacy to the LHC era?

leg·a·cy [leg-*uh*-see] Show IPA ***noun, plural -cies.***

1. *Law* . a gift of property, especially personal property, as money, by will; a bequest.
2. anything handed down from the past, as from an ancestor or predecessor: *the legacy of ancient Rome.*
3. an applicant to or student at a school that was attended by his or her parent.

- Besides the discovery of the top quark, the main legacy of the Tevatron are the experimental techniques:
  - First silicon trackers for b-tagging at a hadron collider
  - First time encounter with pile up in JES calibration
  - The matrix element technique (DØ in 2001)
  - Multivariate methods and their validation in the challenging hadron collider environment:
    - Single top observation (2009, CDF+DØ)
  - Methods to constrain multijet, V+jets background
  - Precision measurements above all (m_W, m_t)

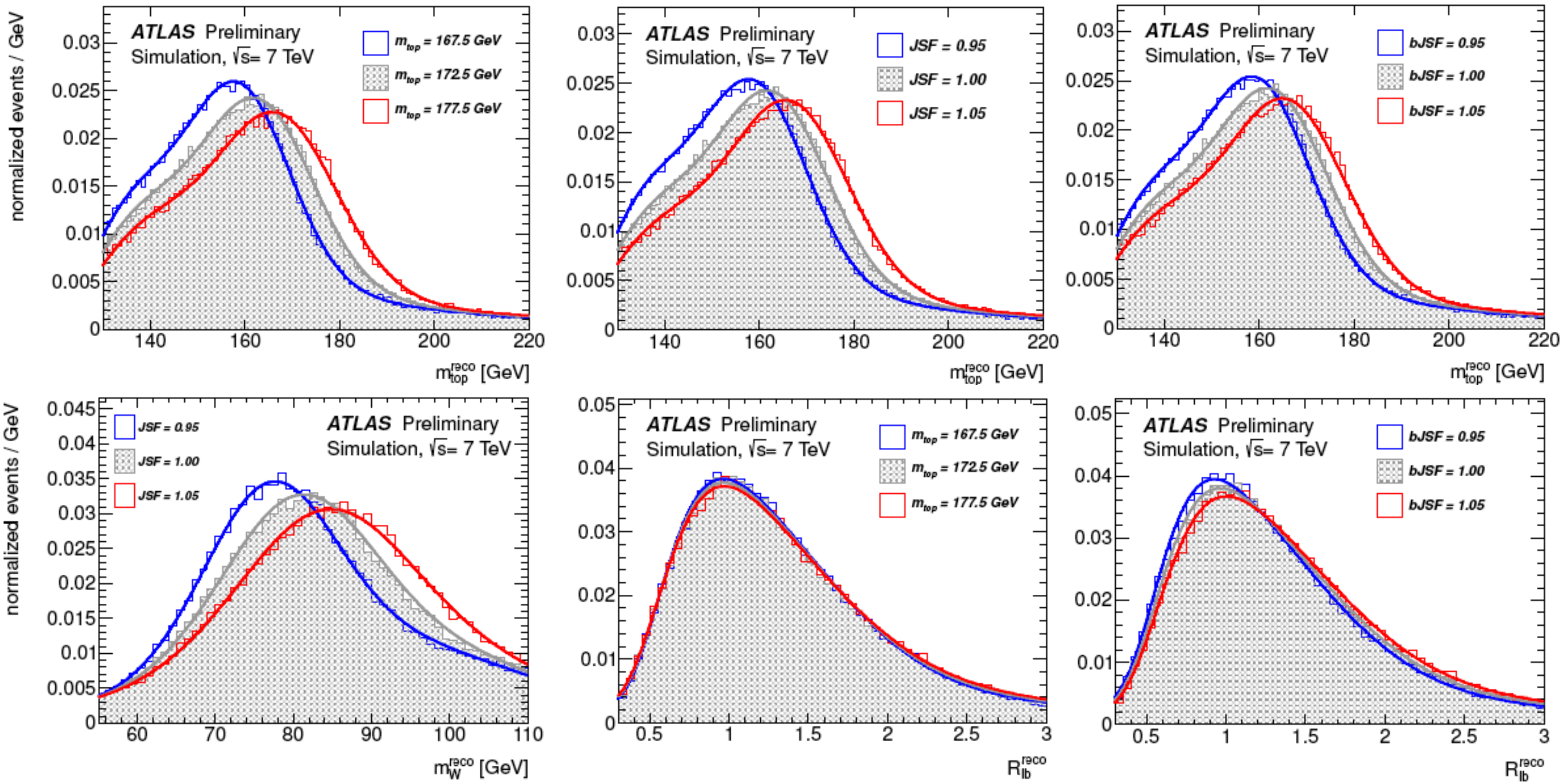
Summary and outlook

- Rich top programme at the Tevatron and the LHC!
  - Some measurements are complementary between the Tevatron and the LHC:
    - Cross section, spin correlations, strong colour charge asymmetry
  - Some measurements are a legacy of the Tevatron
    - E.g., top mass
- Cannot wait for more exciting results from the Tevatron and the LHC in the coming years!
  - CDF: http://www-cdf.fnal.gov/physics/new/top/top.html
  - DØ: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html
  - Atlas: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
- XX years after the discovery of the top quark:
  - The era of precision measurements in the top sector has begun!


GAME OVER
BONUS MATERIAL

3D Template method @ ATLAS

- Form templates on 5 x 5 x 5 grid in m_{top} x JSF x bJSF:



ATLAS-CONF-2013-046

Templates shown are for two b-tag events

3D Template method @ ATLAS

ATLAS-CONF-2013-046

	2D analysis		3D analysis		
	m_{top} [GeV]	JSF	m_{top} [GeV]	JSF	bJSF
Measured value	172.80	1.014	172.31	1.014	1.006
Data statistics	0.23	0.003	0.23	0.003	0.008
Jet energy scale factor (stat. comp.)	0.27	n/a	0.27	n/a	n/a
bJet energy scale factor (stat. comp.)	n/a	n/a	0.67	n/a	n/a
Method calibration	0.13	0.002	0.13	0.002	0.003
Signal MC generator	0.36	0.005	0.19	0.005	0.002
Hadronisation	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Underlying event	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Colour reconnection	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ISR and FSR (signal only)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Proton PDF	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
single top normalisation	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
W+jets background	0.02	0.000	0.03	0.000	0.000
QCD multijet background	0.04	0.000	0.10	0.000	0.001
Jet energy scale	0.60	0.005	0.79	0.004	0.007
b-jet energy scale	0.92	0.000	0.08	0.000	0.002
Jet energy resolution	0.22	0.006	0.22	0.006	0.000
Jet reconstruction efficiency	0.03	0.000	0.05	0.000	0.000
b-tagging efficiency and mistag rate	0.17	0.001	0.81	0.001	0.011
Lepton energy scale	0.03	0.000	0.04	0.000	0.000
Missing transverse momentum	0.01	0.000	0.03	0.000	0.000
Pile-up	0.03	0.000	0.03	0.000	0.001
Total systematic uncertainty	2.02	0.021	1.35	0.021	0.020
Total uncertainty	2.05	0.021	1.55	0.021	0.022

Note that the syst. uncertainty from bJES is now much reduced, as it is mostly absorbed in the bJSF!
→ at the cost of reduced stat. sensitivity

2D analysis is identical to 3D except for fixing R_{lb} to its default

3D Template method @ ATLAS

ATLAS-CONF-2013-046

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Method calibration	0.13	0.002	0.13	0.002	0.003
Signal MC generator	0.36	0.005	0.19	0.005	0.002
Hadronisation	1.30	0.008	0.27	0.008	0.013
Underlying event	0.02	0.001	0.12	0.001	0.002
Colour reconnection	0.03	0.001	0.32	0.001	0.004
ISR and FSR (signal only)	0.96	0.017	0.45	0.017	0.006
Proton PDF	0.09	0.000	0.17	0.000	0.001
single top normalisation	0.00	0.000	0.00	0.000	0.000
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Lepton energy scale	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Missing transverse momentum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Pile-up	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total systematic uncertainty	2.02	0.021	1.35	0.021	0.020
Total uncertainty	2.05	0.021	1.55	0.021	0.022

Also other effects which affect the modeling of jets like hadronisation (pythia vs herwig) and ISR/FSR are partially absorbed in bJSF through R_{lb} sensitivity!

2D analysis is identical to 3D except for fixing R_{lb} to its default

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QCD multijet background	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Jet energy scale	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
b-jet energy scale	0.92	0.000	0.08	0.000	0.002
Jet energy resolution	0.22	0.006	0.22	0.006	0.000
Jet reconstruction efficiency	0.03	0.000	0.05	0.000	0.000
b-tagging efficiency and mistag rate	0.17	0.001	0.81	0.001	0.011
Lepton energy scale	0.03	0.000	0.04	0.000	0.000
Missing transverse momentum	0.01	0.000	0.03	0.000	0.000
Pile-up	0.03	0.000	0.03	0.000	0.001
Total systematic uncertainty	2.02	0.021	1.35	0.021	0.020
Total uncertainty	2.05	0.021	1.55	0.021	0.022

No, there is no free lunch.

But the bottom line matters.

2D analysis is identical to 3D except for fixing R_{lb} to its default

Kinematic likelihood fit using m_t as example

b_{JES} is now calibrated in situ:

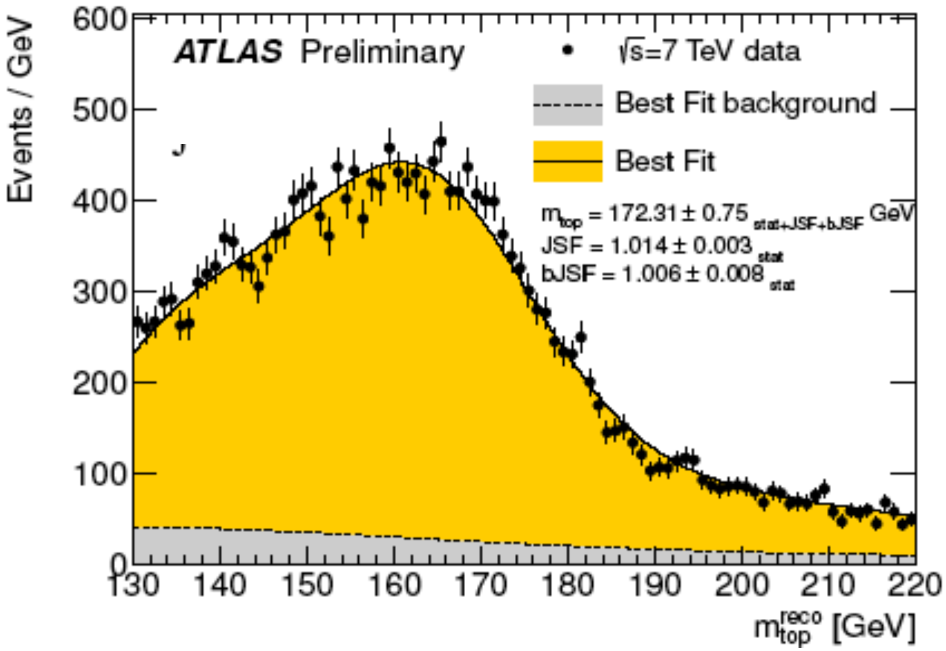
→ Reduced systematic uncertainty

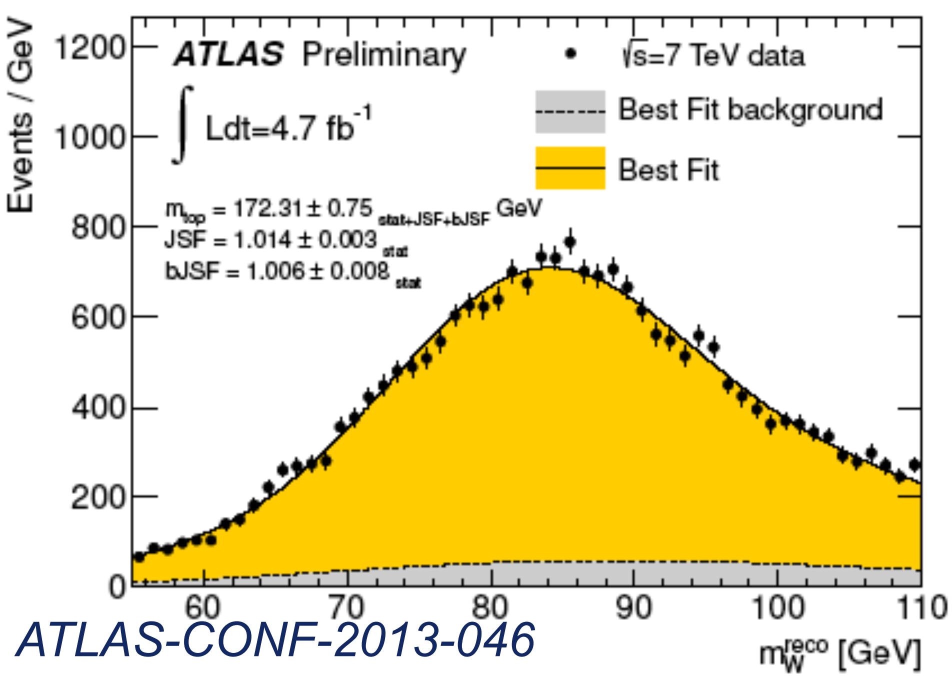
→ Increased statistical uncertainty:

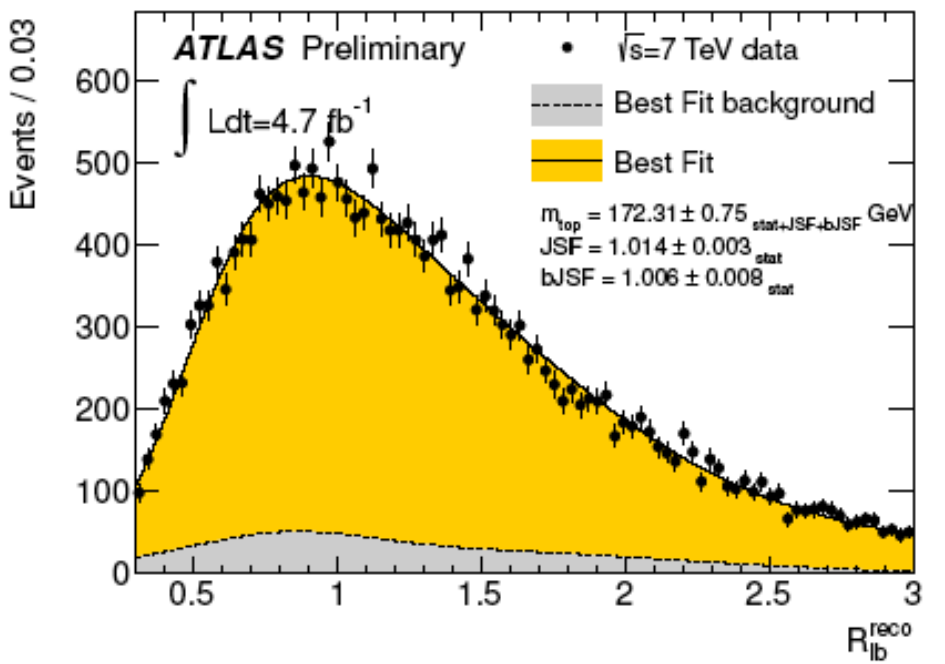
±0.23 (m_t) ±0.27 (k_{JES}) ±0.67 (b_{JES}) GeV

= ±0.76 GeV

(w/o bJES fit only: ±0.35 GeV)

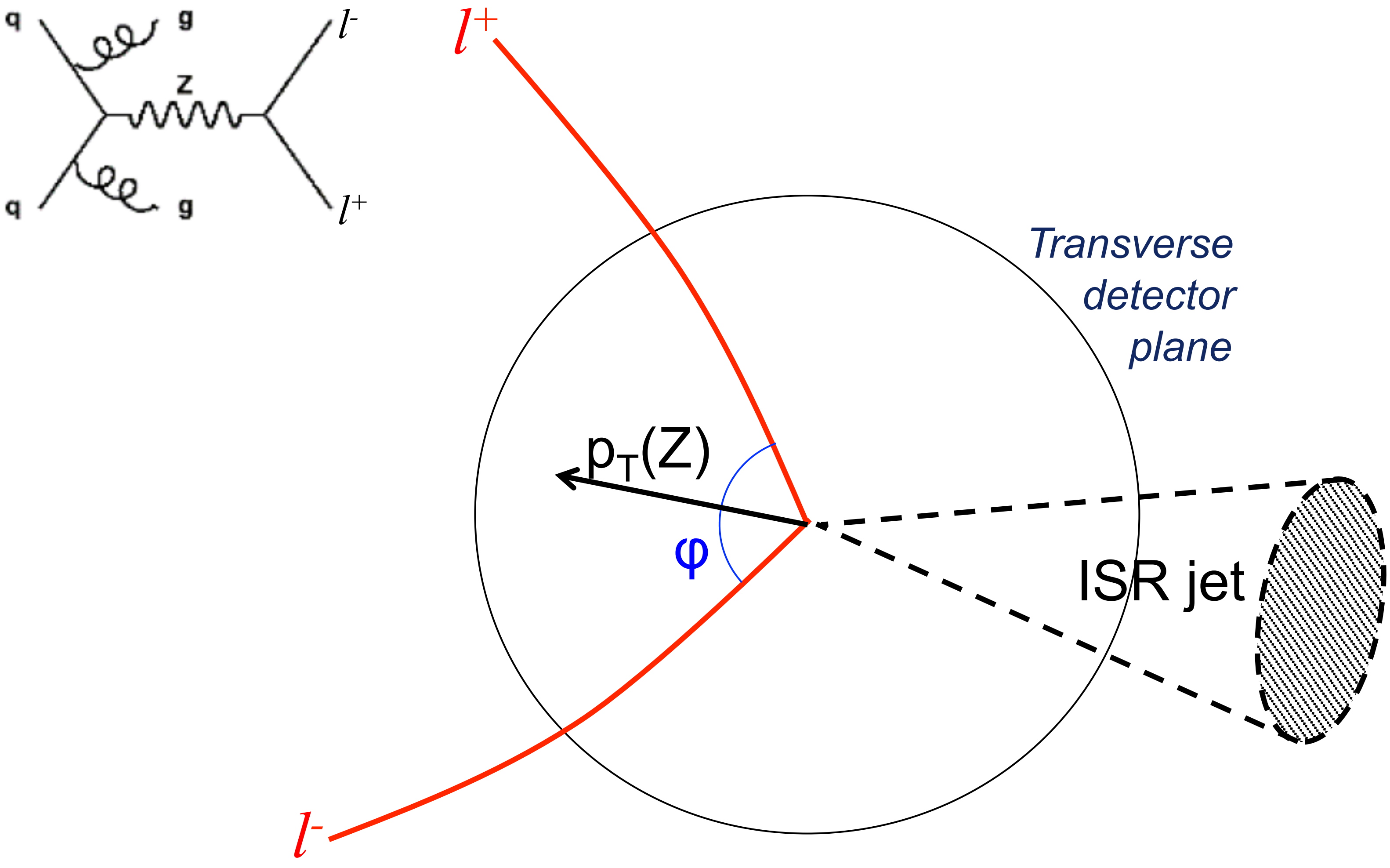






ATLAS-CONF-2013-046

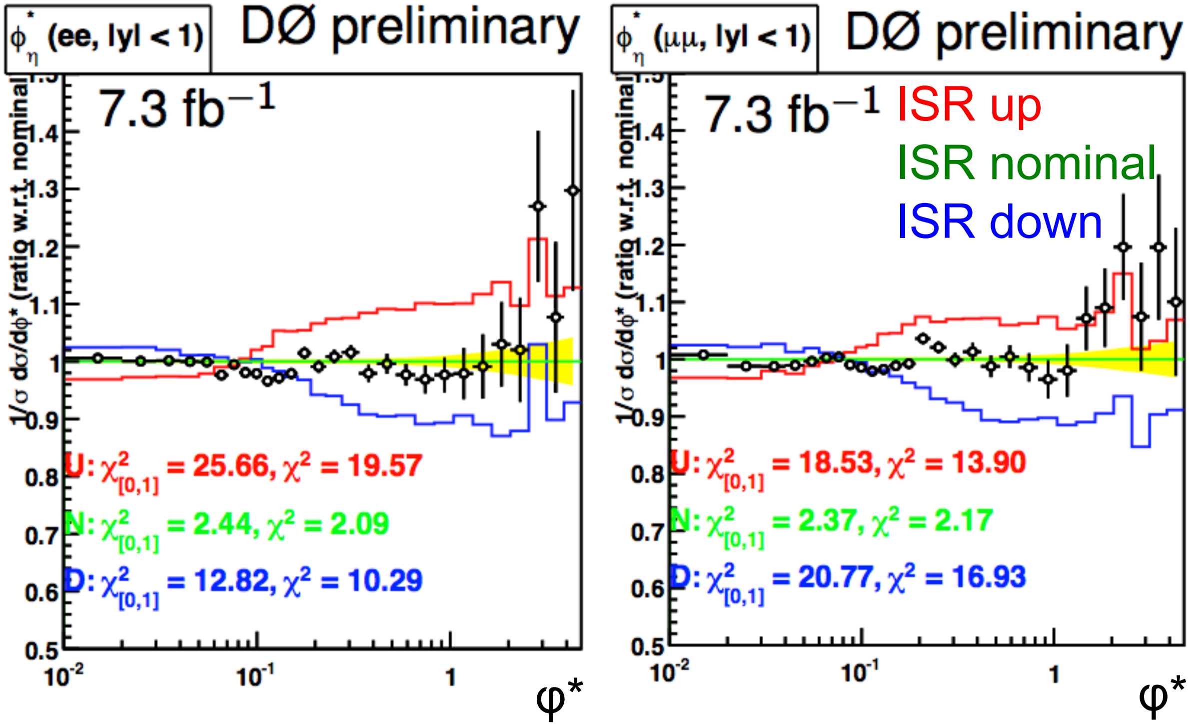
- Constrain ISR/FSR by studying Drell-Yan events
  - Measurement of $p_T(Z)$ using φ* variable [1]



[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:
- $1<|y|<2$
- $|y|>2$

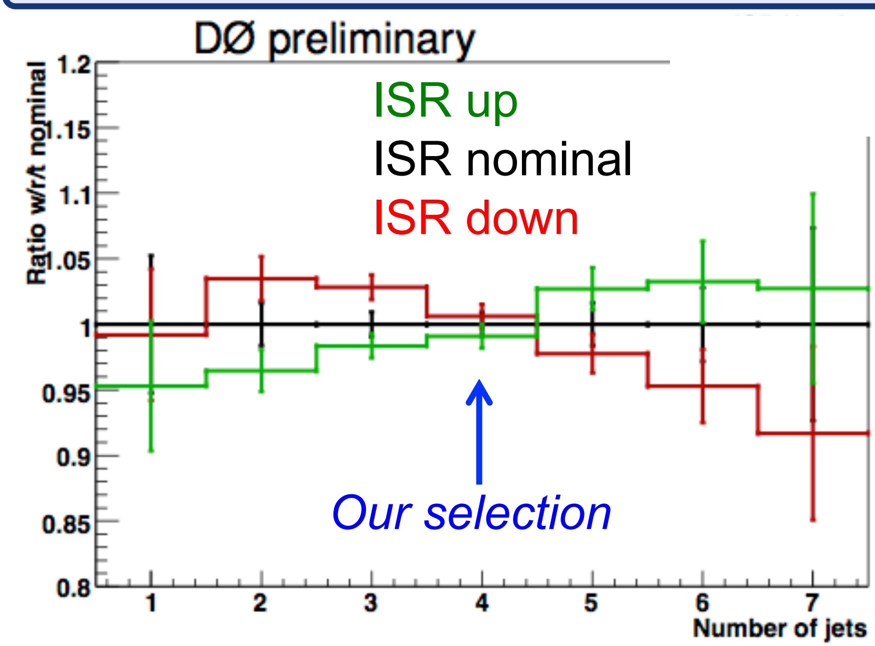
(cf. backup)

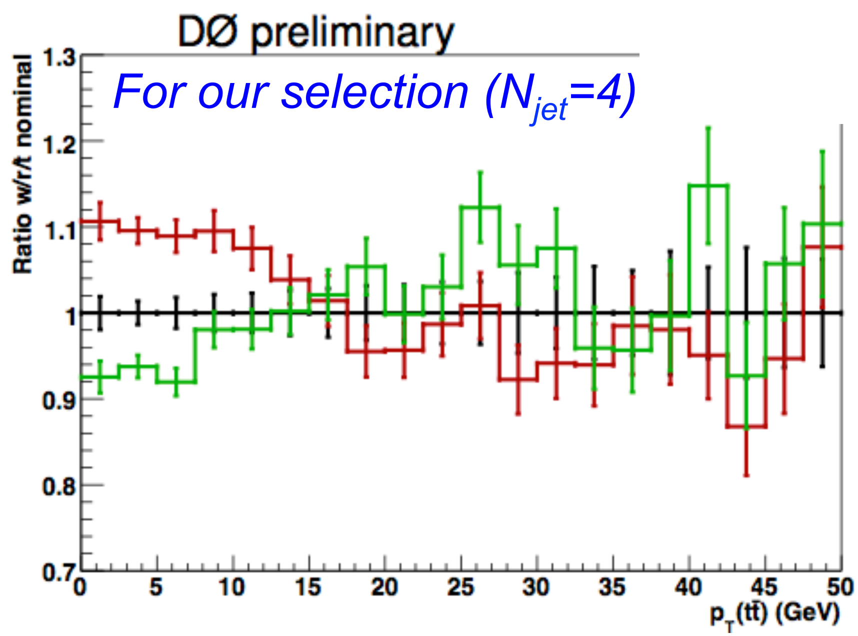
[1] DØ Coll., PRL **106**, 122001 (2011)
[2] M. Mangano, P. Skands et al, EPJ **C72** 2078 (2012)

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

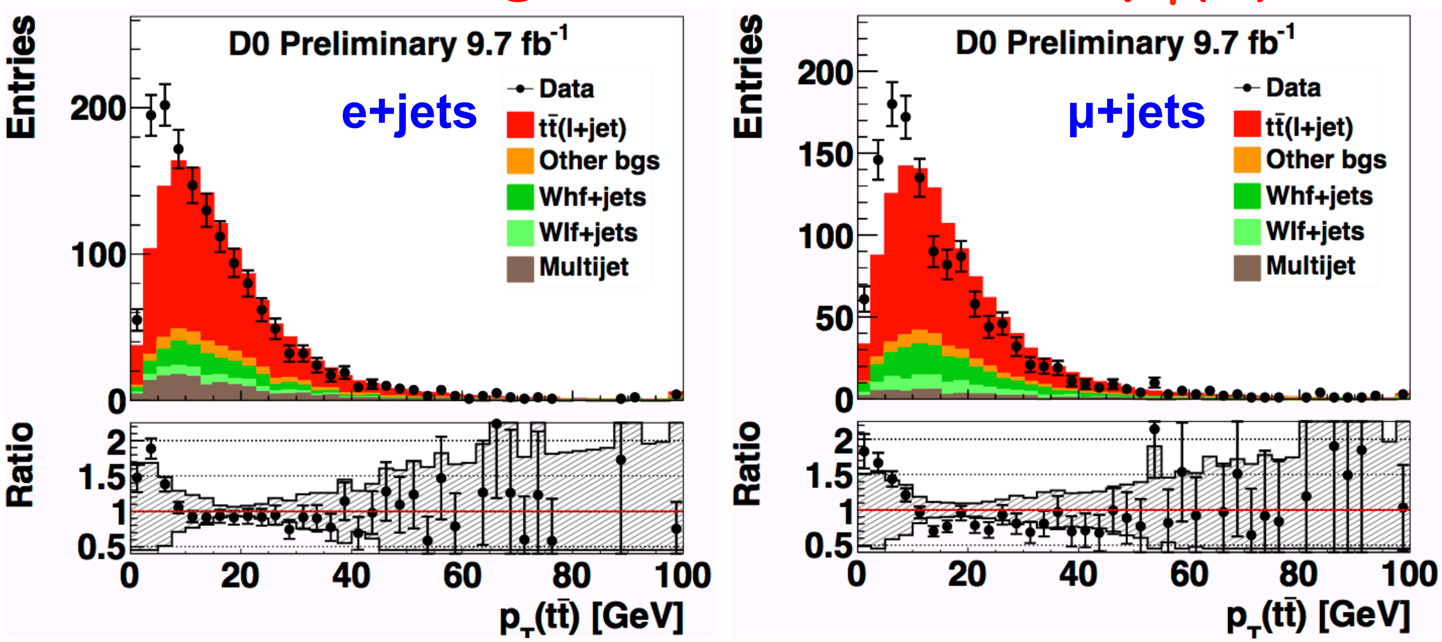




[1] DØ Coll., PRL **106**, 122001 (2011)
[2] M. Mangano, P. Skands et al, EPJ **C72** 2078 (2012)

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

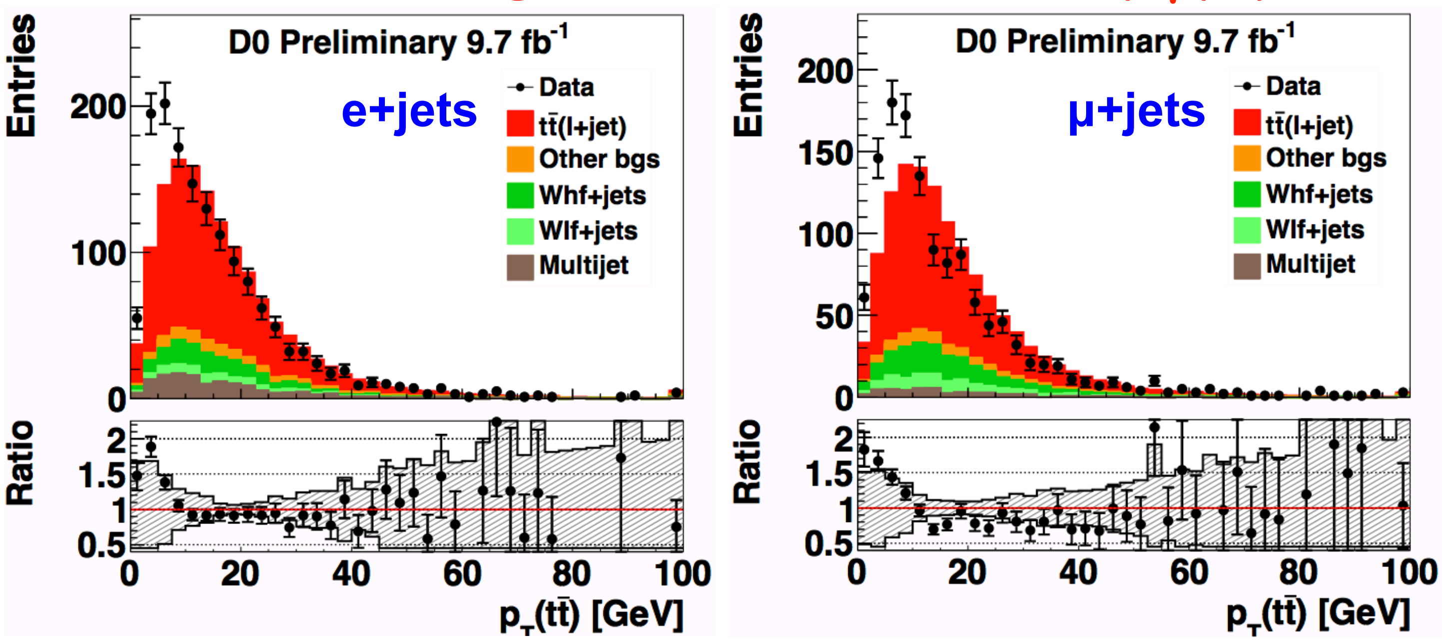
[1] DØ Coll., PRL **106**, 122001 (2011)
[2] M. Mangano, P. Skands et al, EPJ **C72** 2078 (2012)

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

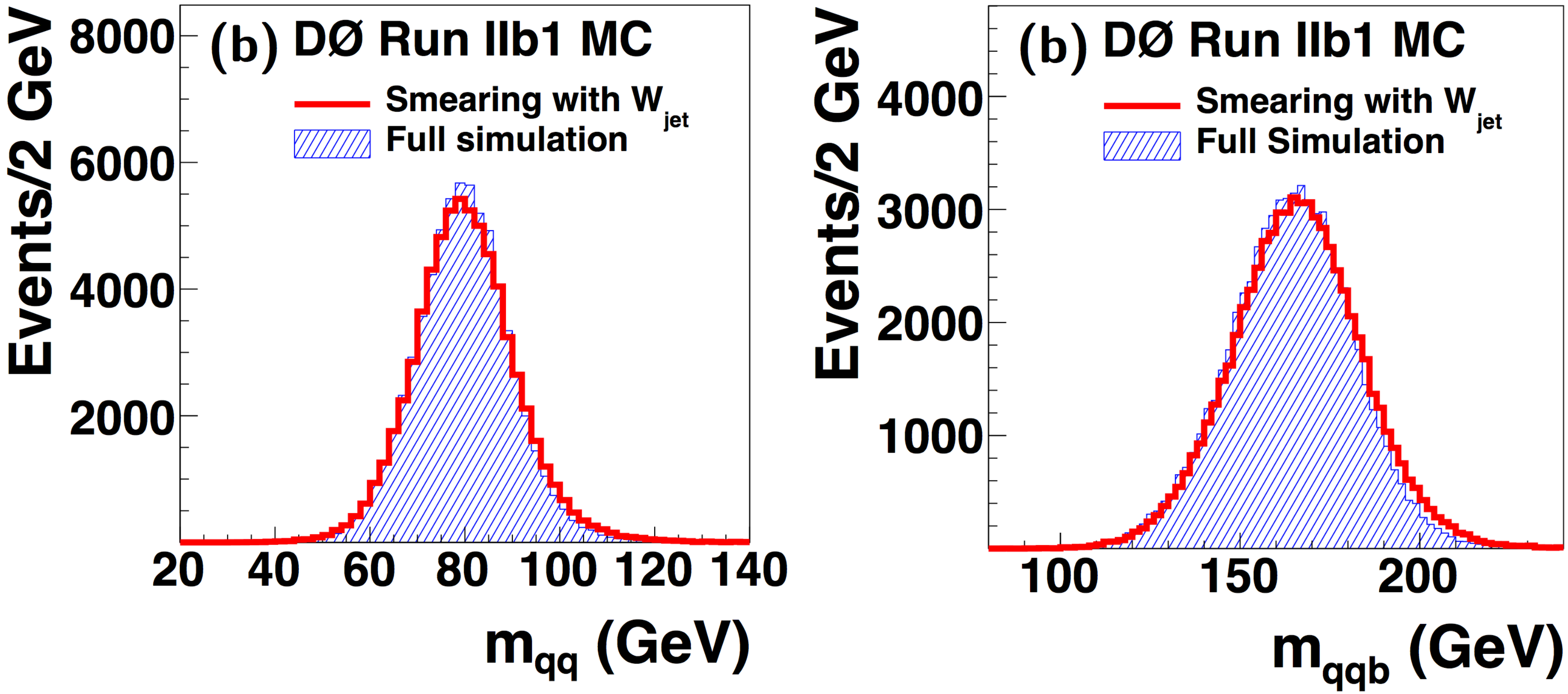


  - Effect may be related to ISR/FSR mismodelling

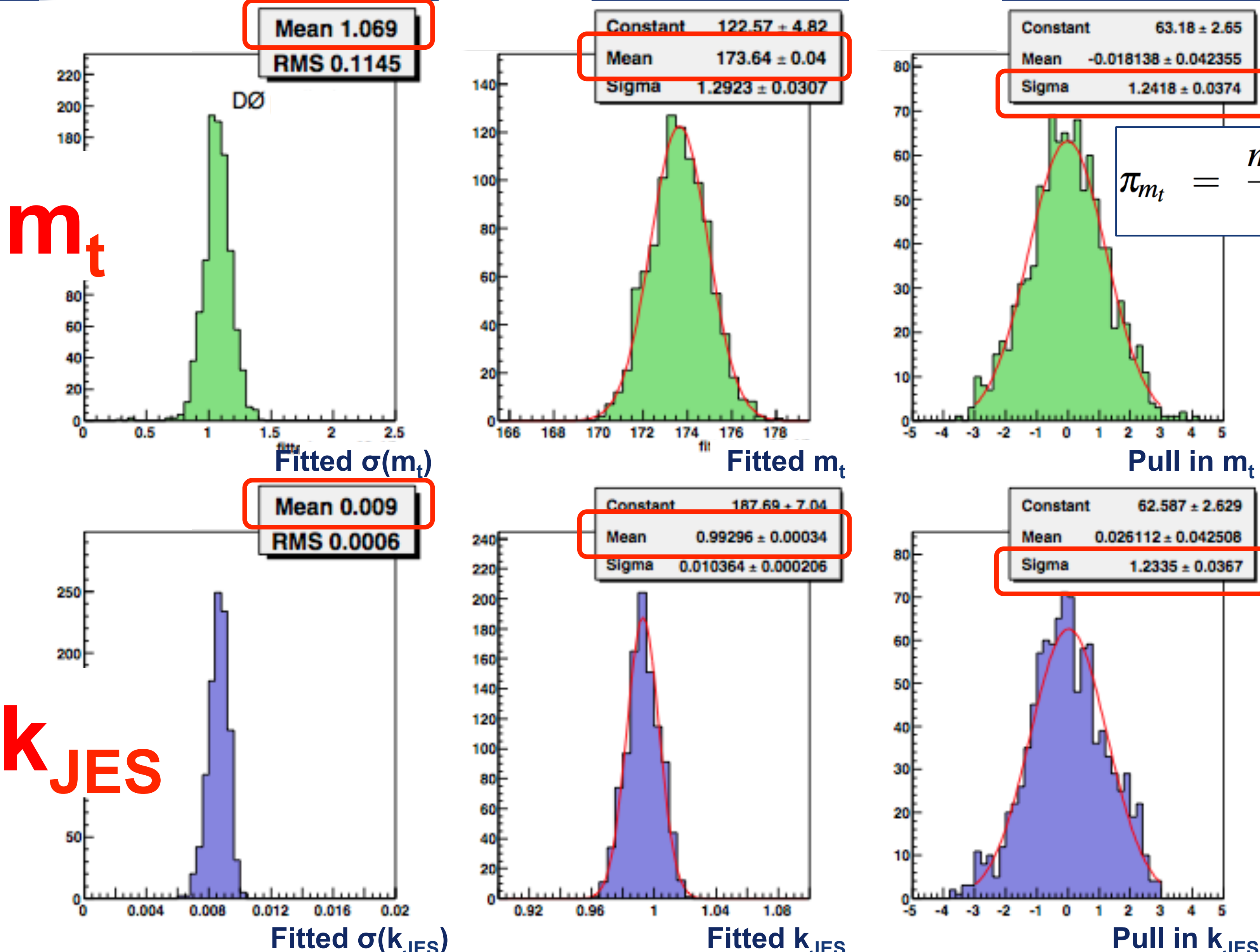
0.07 GeV

Matrix element method with m_t as example

- 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



Matrix element method with m_t as example

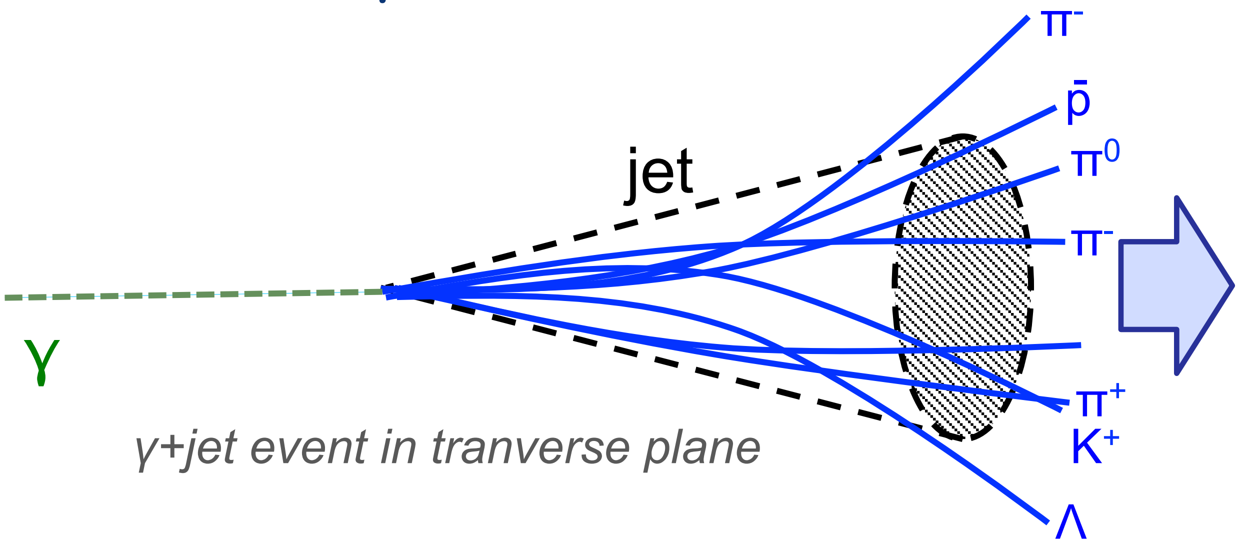


$$\pi_{m_t} = \frac{m_t^{\mathrm{fit}} - \langle m_t^{\mathrm{fit}} \rangle}{\sigma_{m_t}^{\mathrm{fit}}}$$

$e+$jets
Run IIb2, $m_t^{\mathrm{gen}} = 172.5$ GeV, $k_{\mathrm{JES}} = 1$

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

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

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

Jet energy scale (JES) calibration

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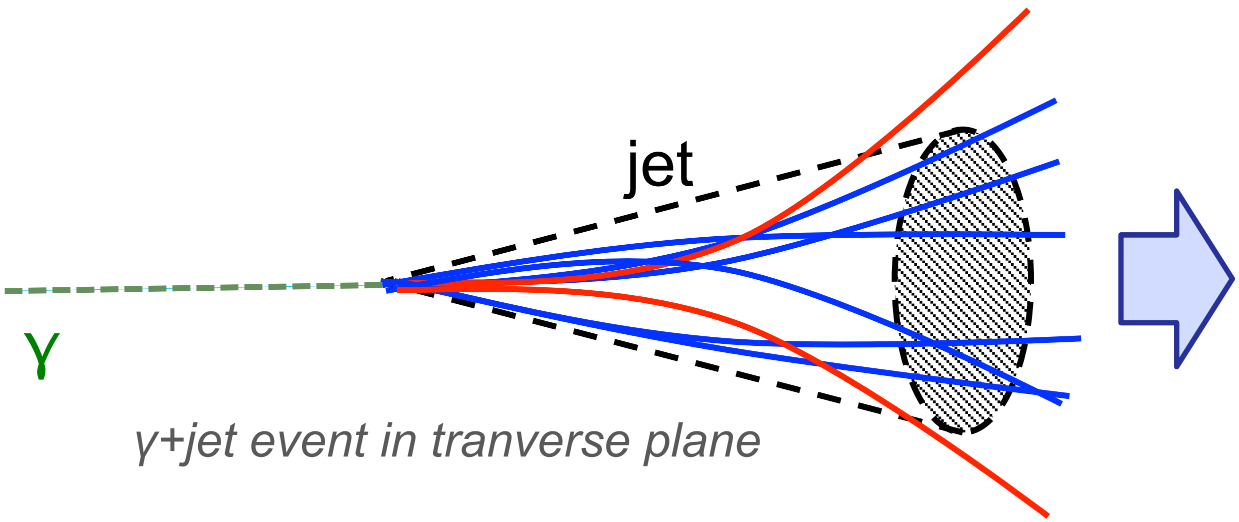


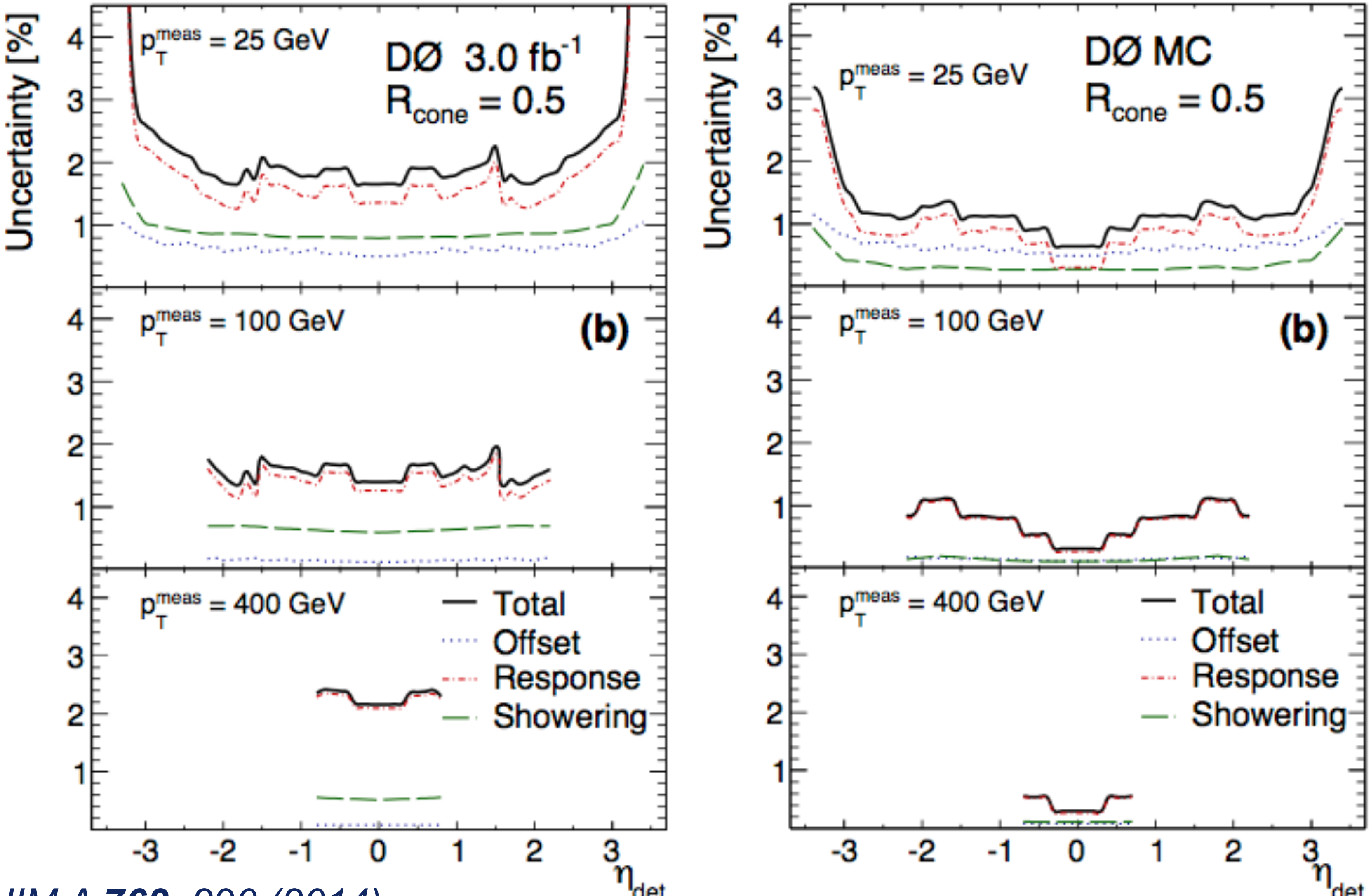
γ+jet event in tranverse plane

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

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

Refined jet energy scale calibration

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



*DØ, 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

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

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

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

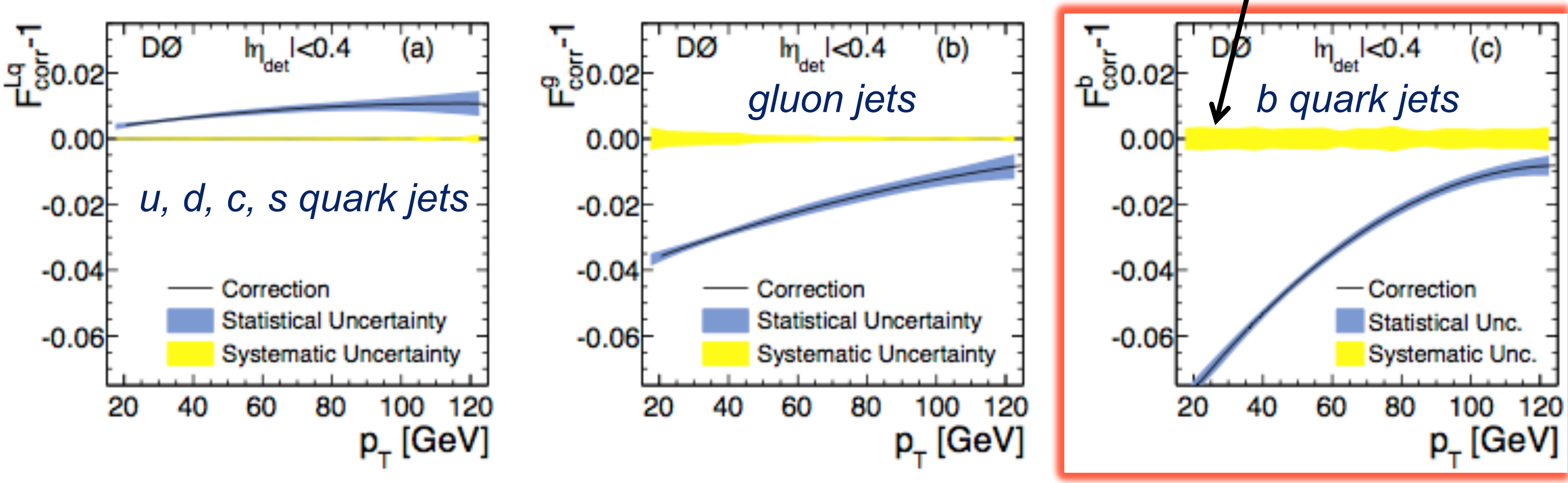
DØ Coll, NIM A ***763****, 290 (2014)*

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

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*

Flavor-dependent correction

- Derive single particle responses R_i in MC:
  - Use single particle MC samples for each of
    - γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, 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

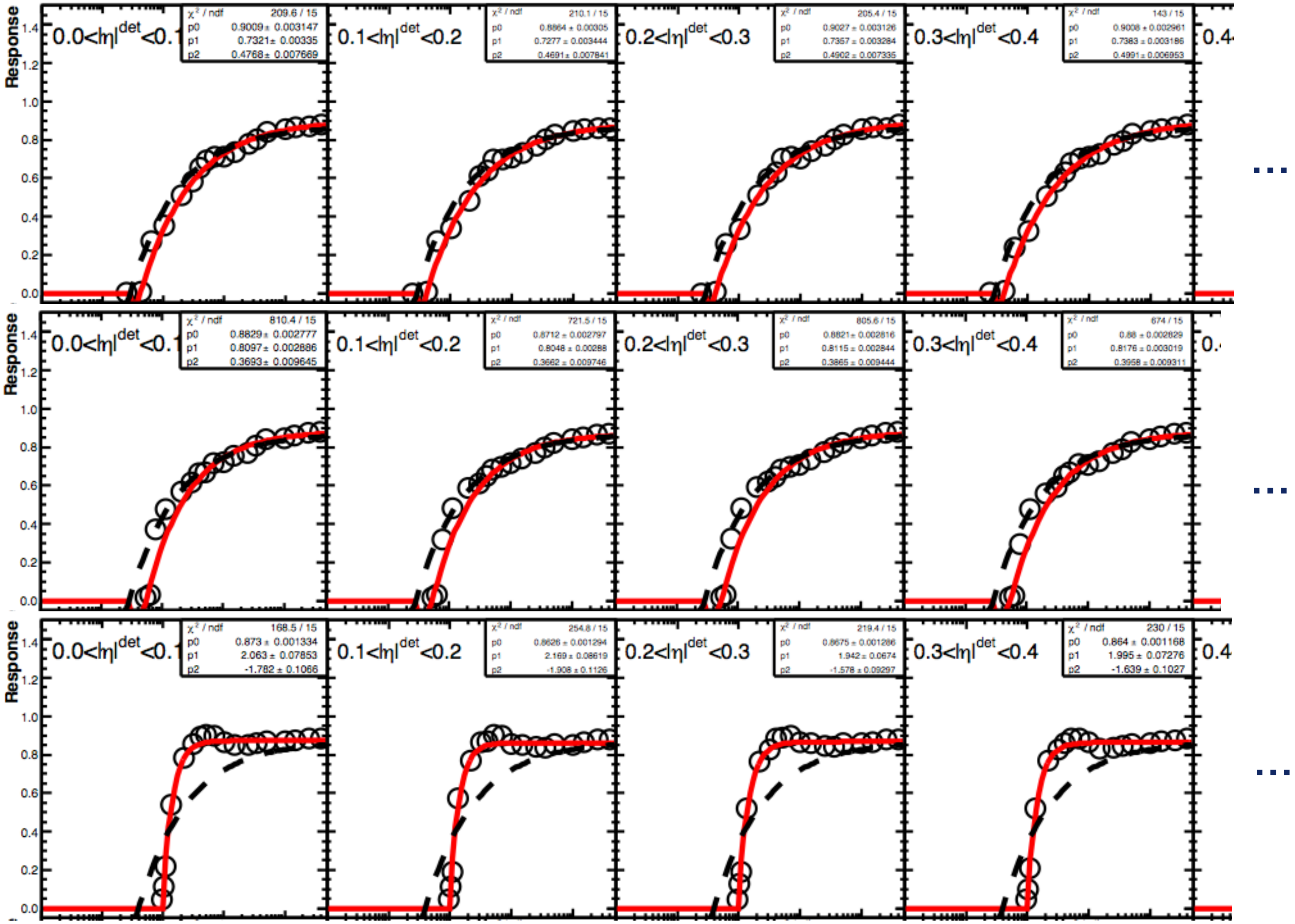
Flavor-dependent correction

- Few example fits of MC response for three particles:

$\pi^{\pm}$

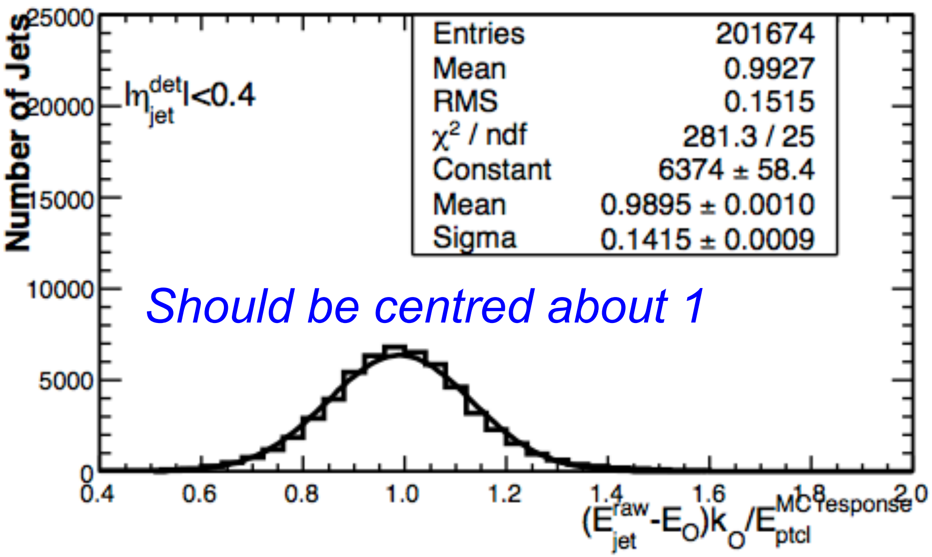
$K^{\pm}$

p

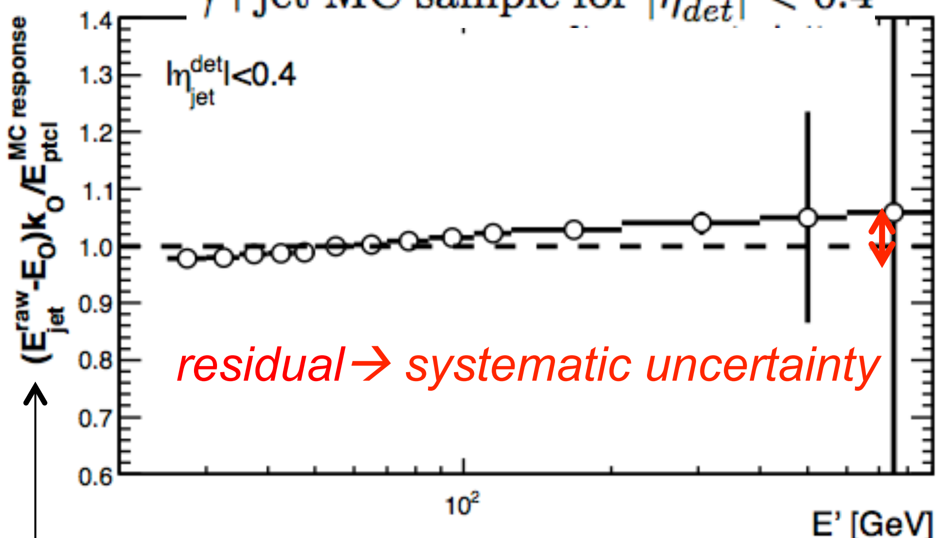


Flavor-dependent correction

- 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:



γ+jet MC sample for $|\eta_{det}^{jet}| < 0.4$



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

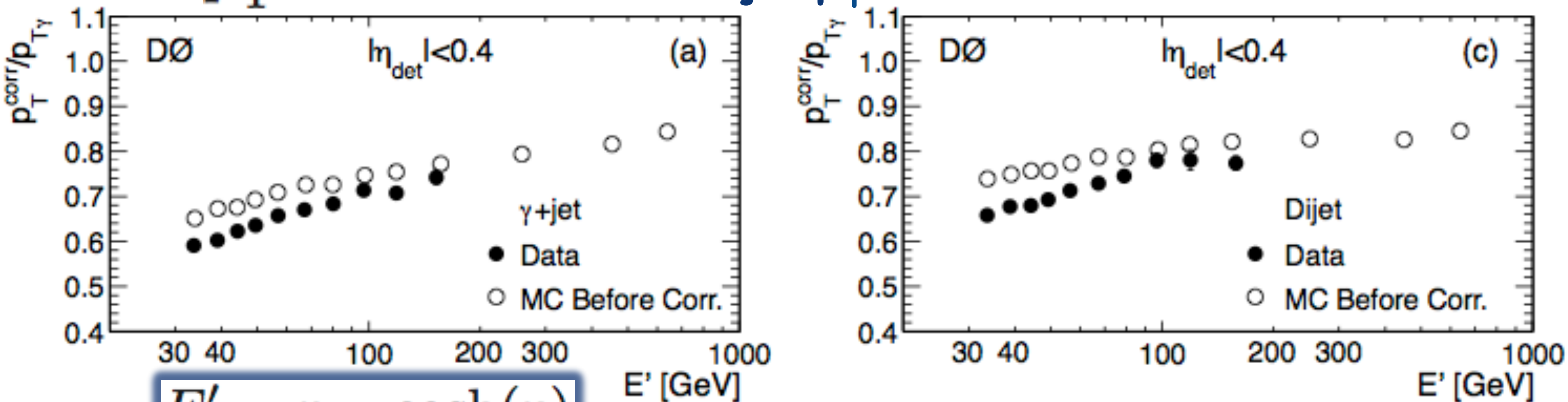
- Deriving single particle responses in data:
  - For e, μ, γ:
    - Assume perfect modelling of detector response by MC
      - Systematic uncertainty estimated on this assumption
  - For hadrons $\pi^{\pm}$, $K^{\pm}$, K_0^S, K_0^L, $p^{\pm}$, n and Λ:
    - Basic shapes in *E*,*η* (i.e. per-hadron 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

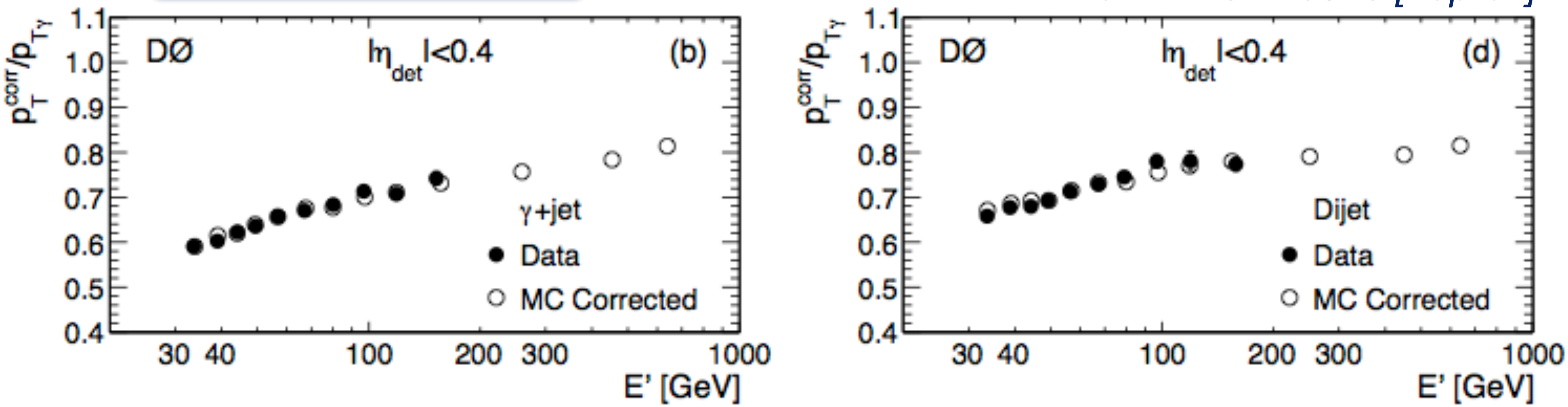
Flavor-dependent correction

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



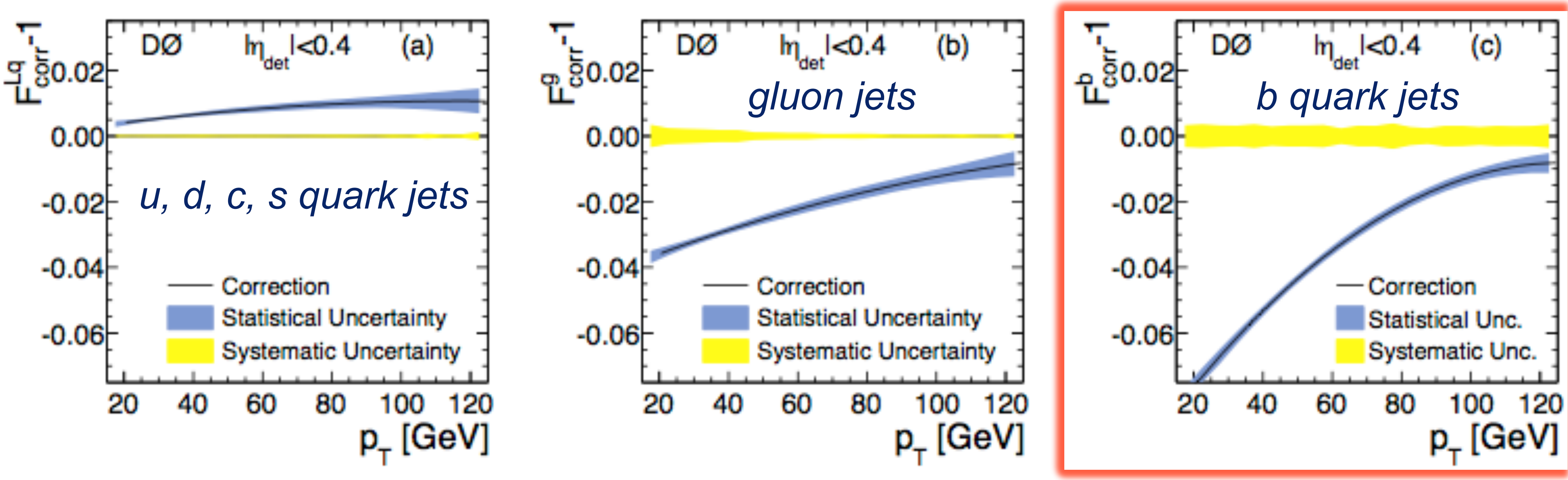
$$E' = p_{T\gamma} \cosh(\eta)$$

arXiv:1312.6873 [hep-ex]



Flavor-dependent correction

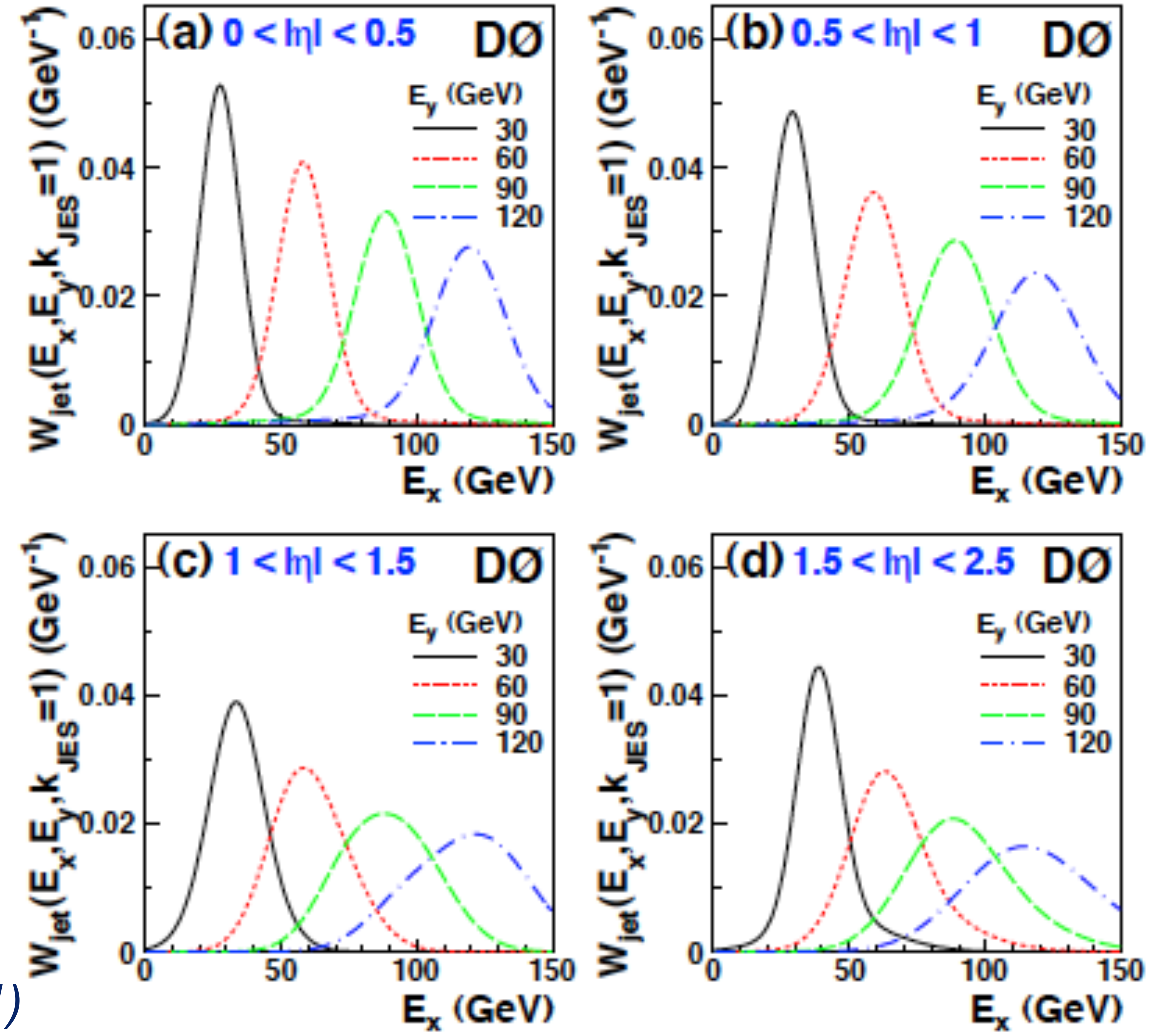
- The final flavour-dependent correction:



- 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

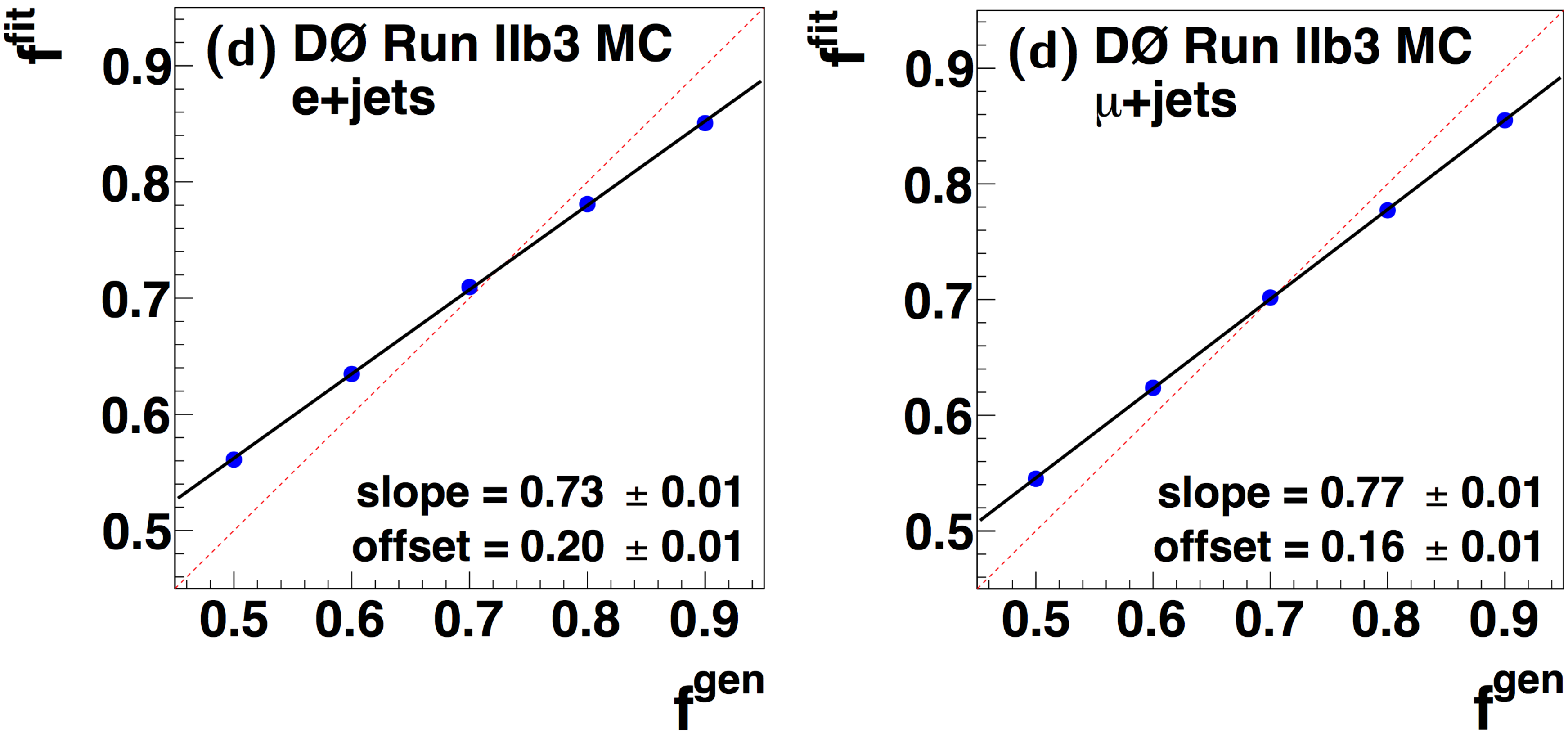
- The Transfer Functions $W(x, y; JES)$ relate parton-level quantities to reconstruction-level ones
- Some typical examples for light quark jets from [1]



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

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):

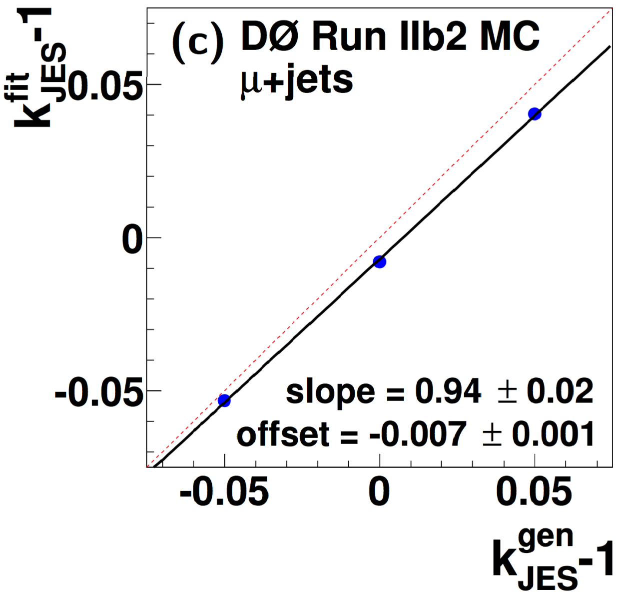
Epoch	Final state	Signal fraction	$\sigma_{t\bar{t}}$ (pb)
Run IIa	e+jets	0.72	8.9
	μ+jets	0.65	7.8
Run IIb1	e+jets	0.77	7.6
	μ+jets	0.66	6.8
Run IIb2	e+jets	0.68	7.8
	μ+jets	0.66	7.5
Run IIb3	e+jets	0.56	7.6
	μ+jets	0.75	8.0
Run II	**e+jets**	**0.63**	**7.8**
	μ+jets	**0.70**	**7.6**

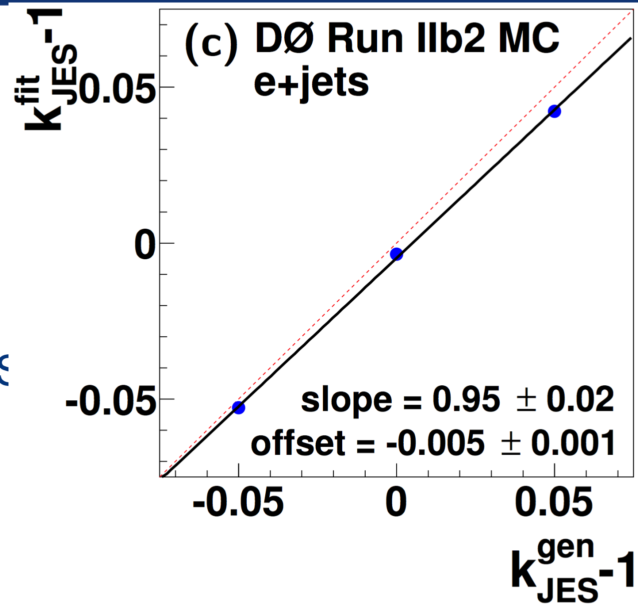
- Values in good agreement with $\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}$ pb [1]

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

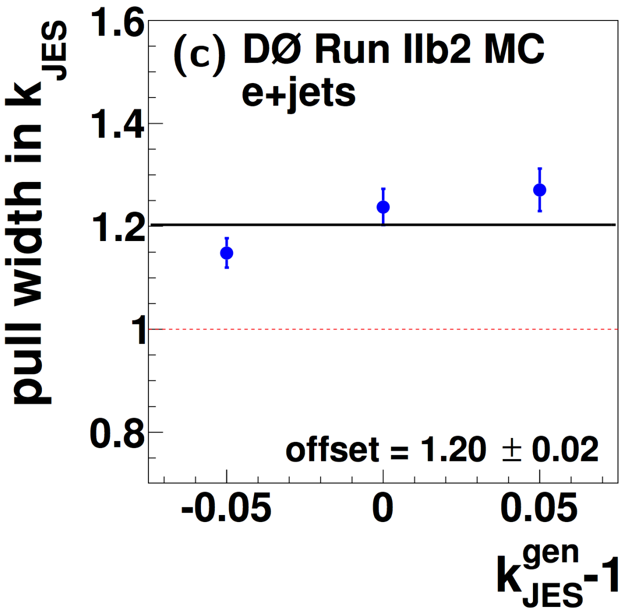
*[1] DØ Collaboration, Phys. Rev. D **84**, 012008 (2011).*

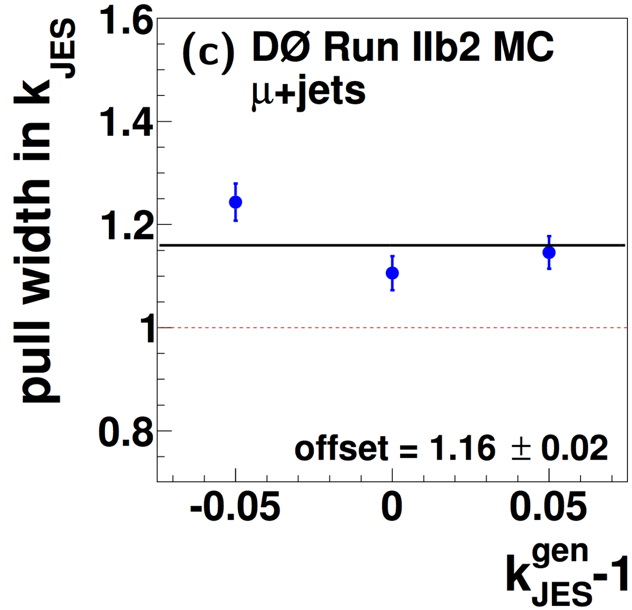
Calibration of method response in k_{JES}





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





Calibrate $\sigma(k_{JES})$

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

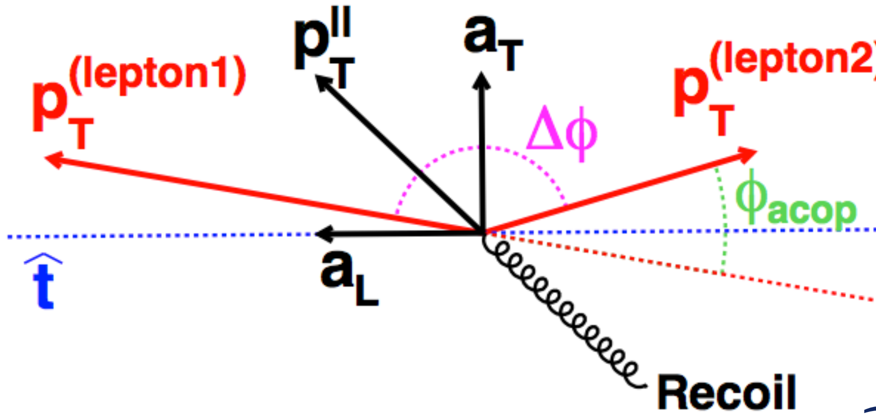
Residual JES

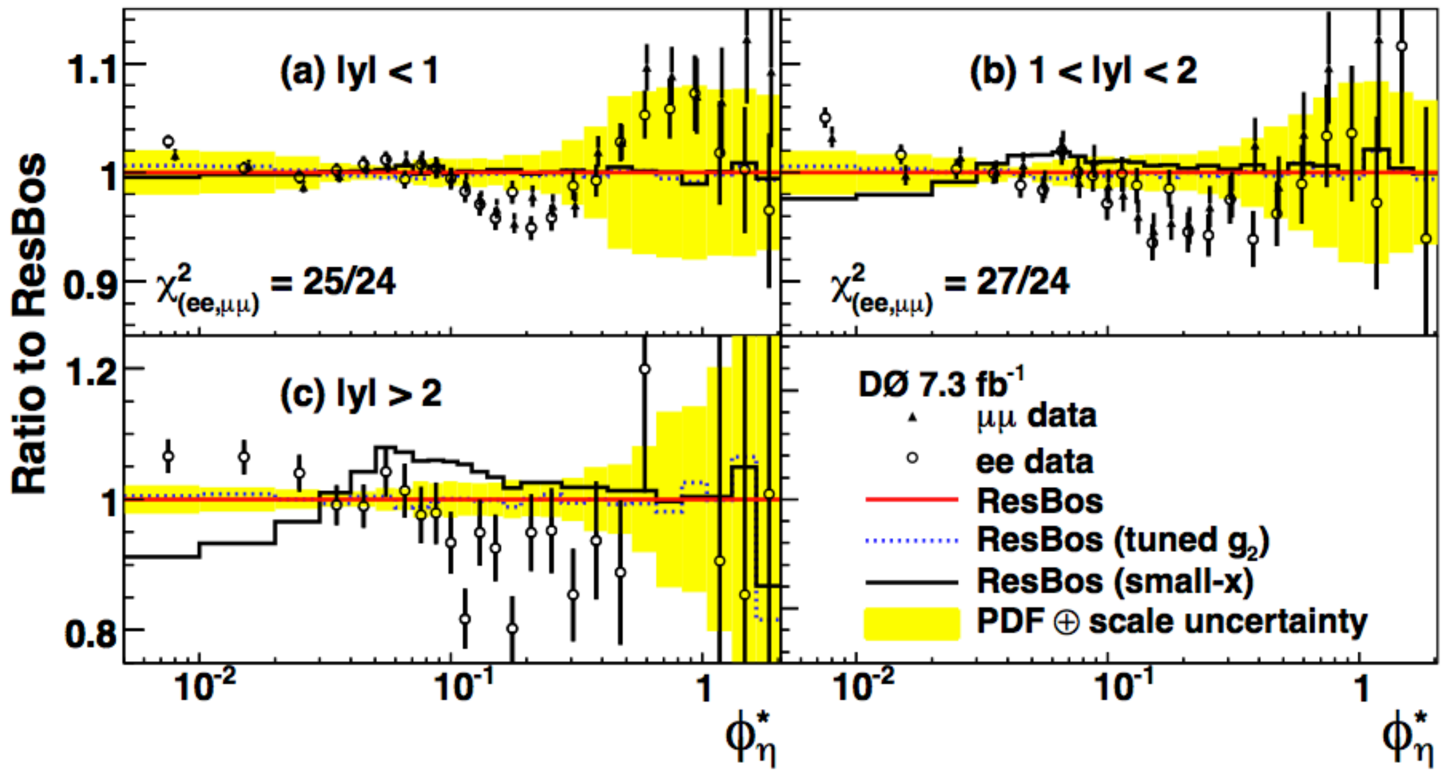
- Even though we perform an in-situ calibration of JES, this is only an overall calibration
  - k_{JES} cannot account for any effects differential in (p_T,η)
  - Study various parametrisations:
    - *0.13 GeV* Vary jet energies according to upper error corridor on the JES, differentially in (p_T,η)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

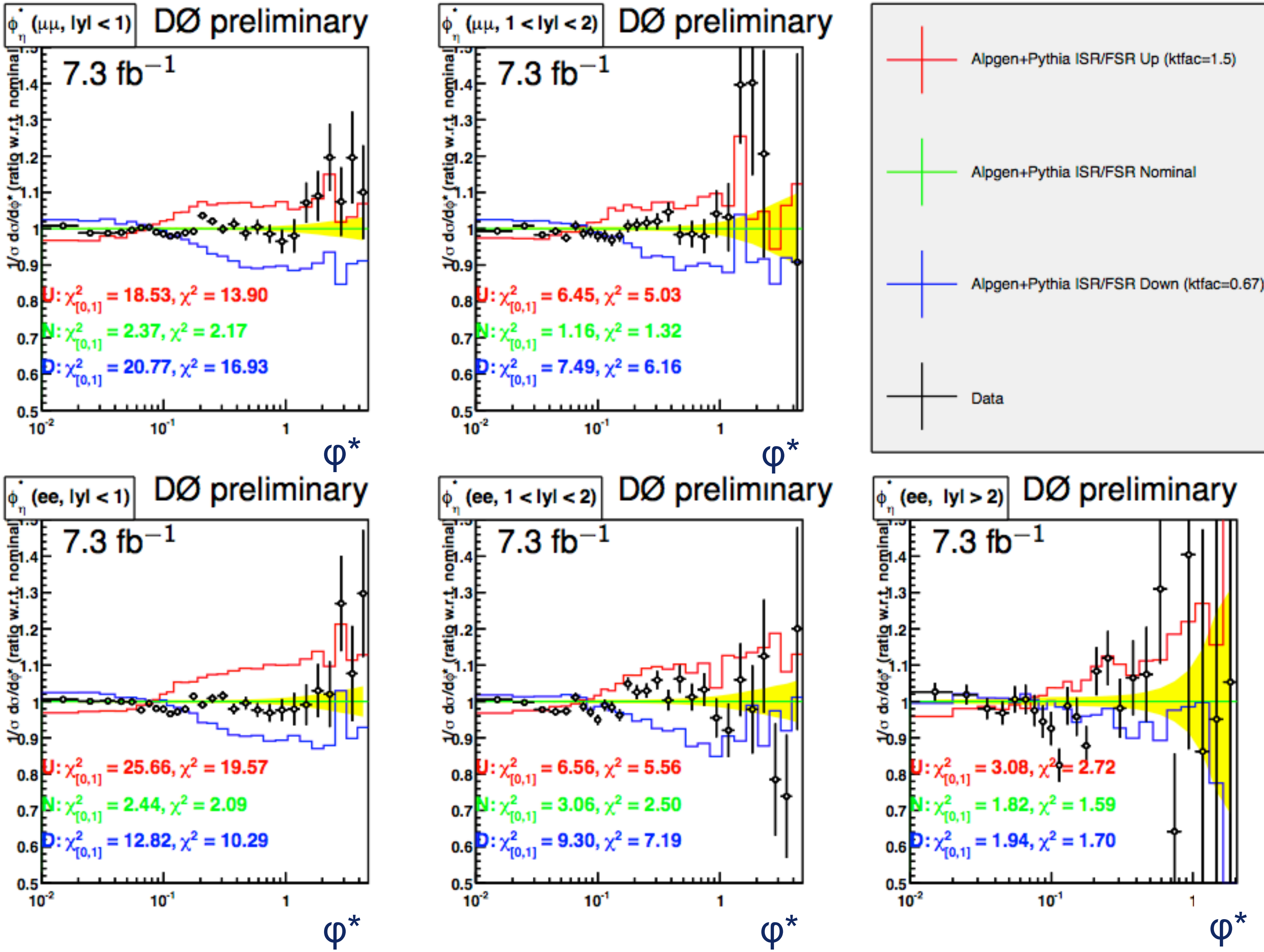
$$\phi^*_\eta = \tan\left(\phi_{\rm acop}/2\right)\sin(\theta^*_\eta)$$





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

ISR/FSR



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

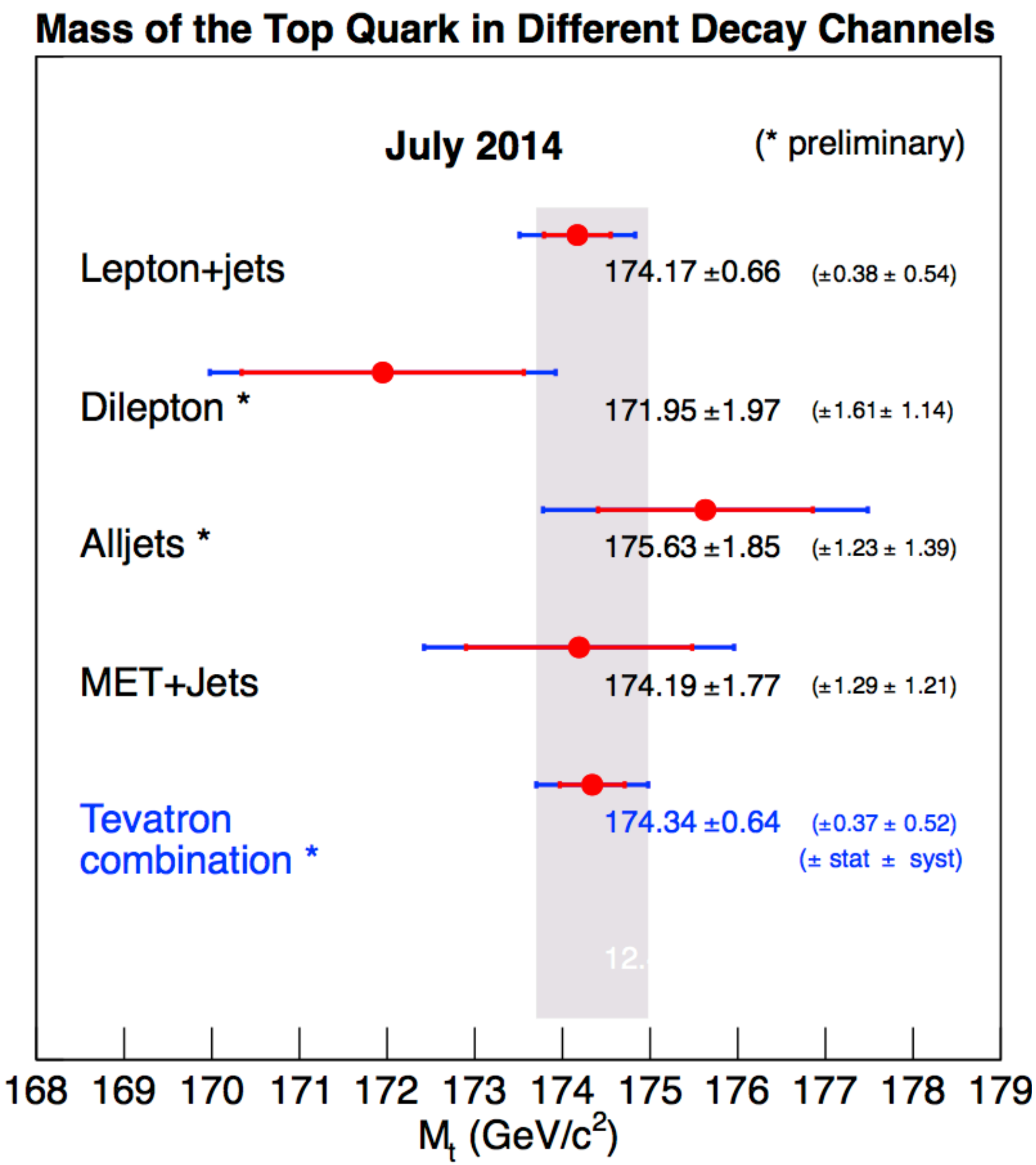
Top quark mass: Tevatron combination

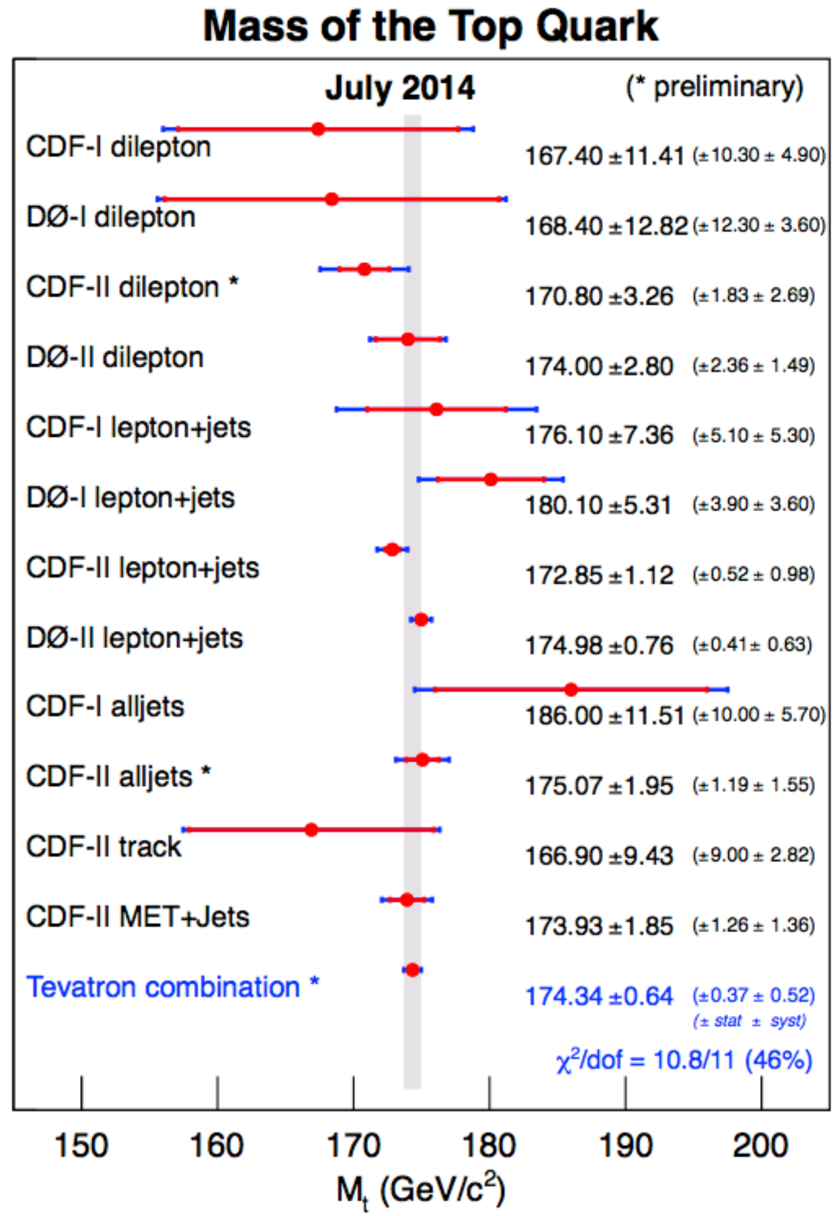
	Run I published					Run II published					Run II prel.	
	CDF			DØ		CDF			DØ		CDF	
	ℓ+jets	$\ell\ell$	all-jets	ℓ+jets	$\ell\ell$	ℓ+jets	L_{XY}	MEt	ℓ+jets	$\ell\ell$	$\ell\ell$	all-jets
CDF-I ℓ+jets	1.00	0.29	0.32	0.26	0.11	0.49	0.07	0.26	0.19	0.12	0.54	0.27
CDF-I $\ell\ell$	0.29	1.00	0.19	0.15	0.08	0.29	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			
		$M_t^{\mathrm{all-jets}}$	$M_t^{\ell+\mathrm{jets}}$	$M_t^{\ell\ell}$	M_t^{MEt}
$M_t^{\mathrm{all-jets}}$	175.63 ± 1.85	1.00			
$M_t^{\ell+\mathrm{jets}}$	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

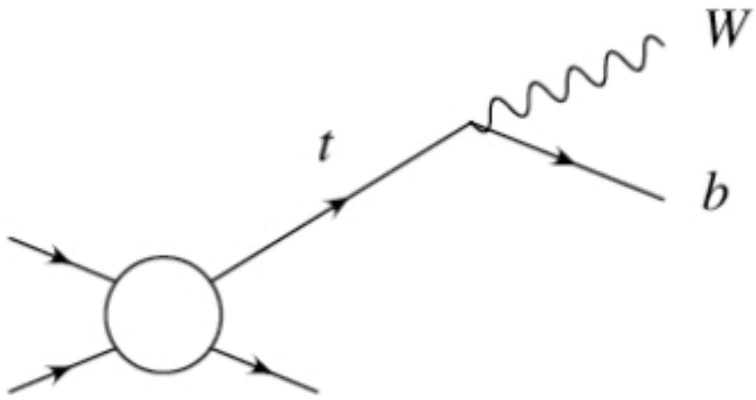
- **Input: correlations between uncertainty categories:**

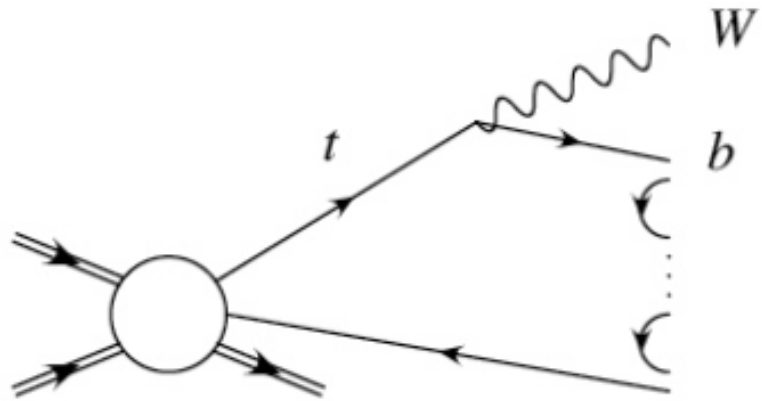
	ρ_{EXP}				ρ_{LHC}	ρ_{TEV}	ρ_{COL}	
	ρ_{CDF}	ρ_{D0}	ρ_{ATL}	ρ_{CMS}			$\rho_{ATL-TEV}$	$\rho_{CMS-TEV}$
Stat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
iJES	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
stdJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
flavourJES	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0
bJES	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.5
MC	1.0	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}:



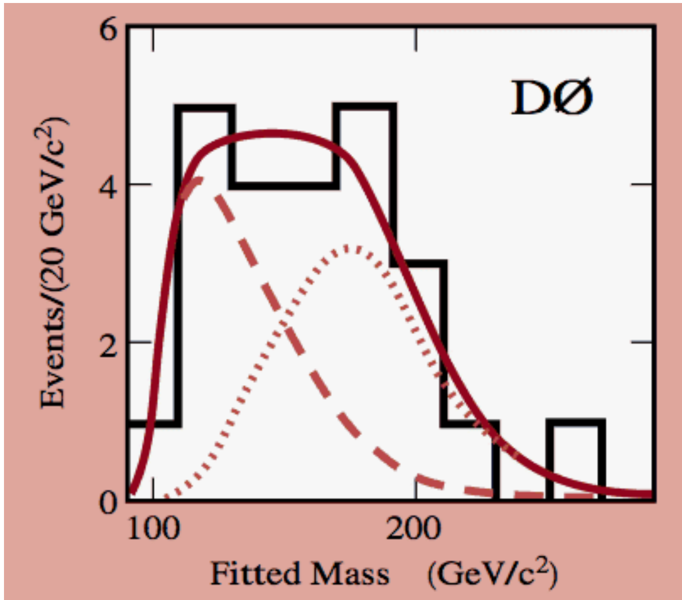


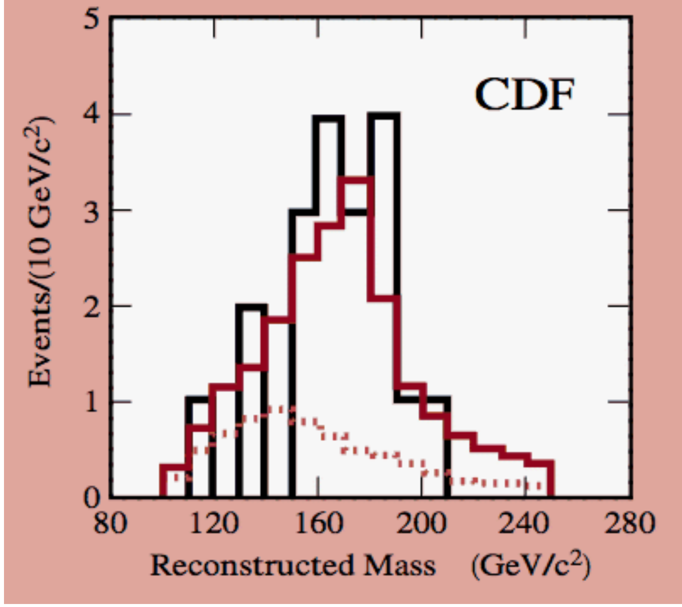
Which m_{top} do we measure?

- 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

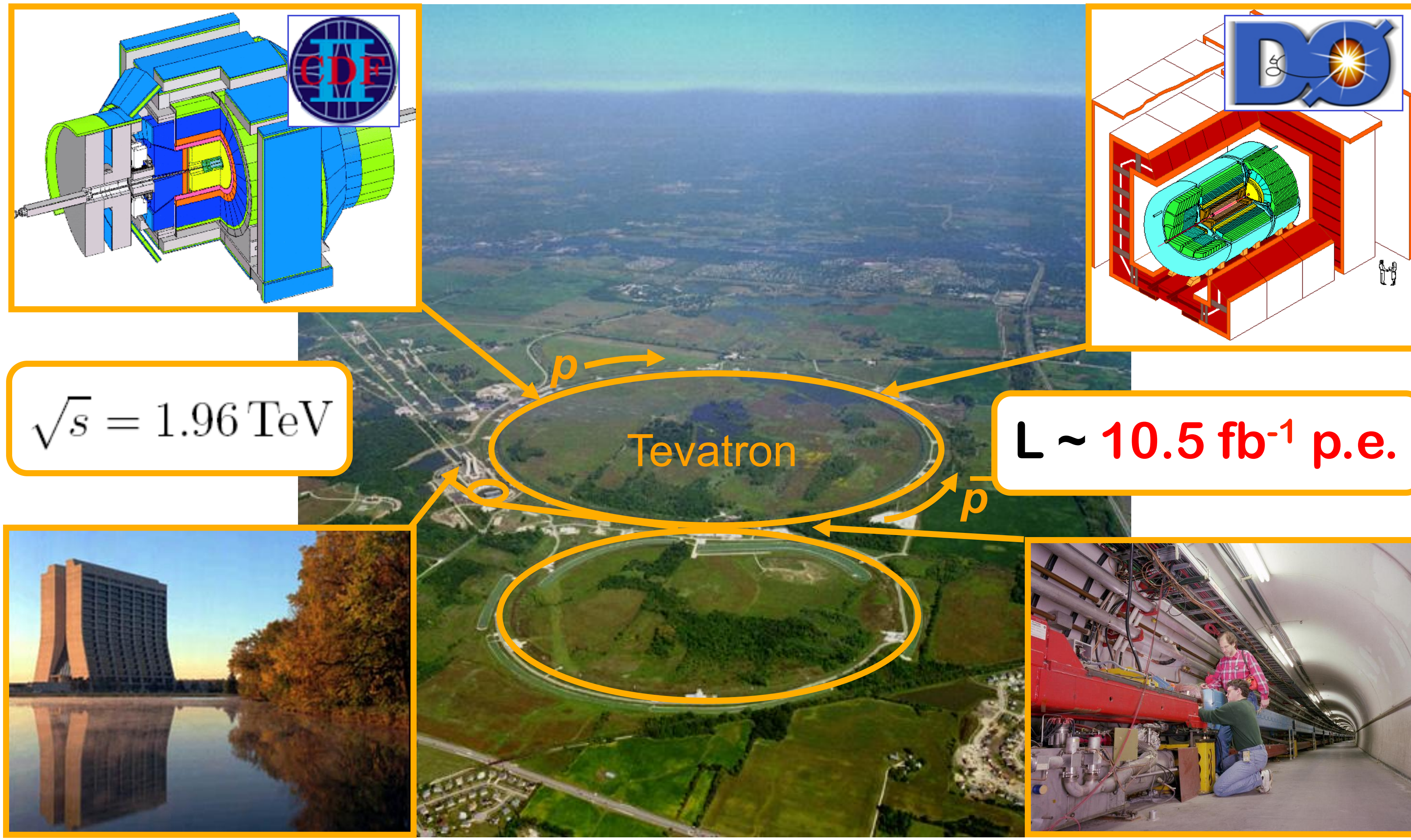
The birth weight

- **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





More about the birth place…

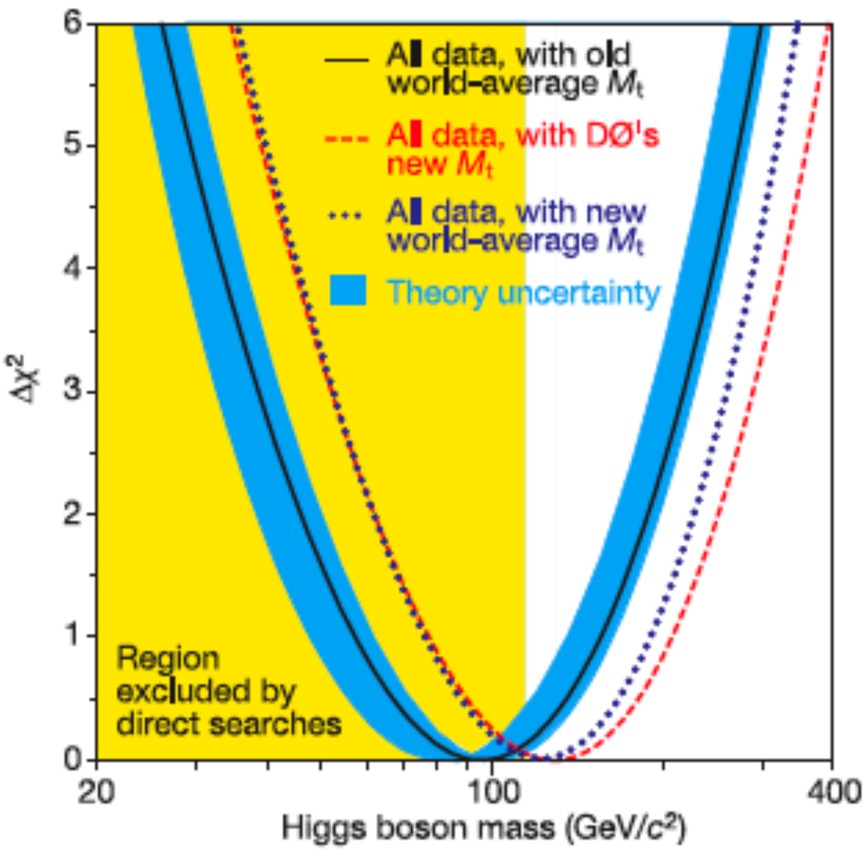


$\sqrt{s} = 1.96\,\mathrm{TeV}$

L ~ 10.5 fb^{-1} p.e.

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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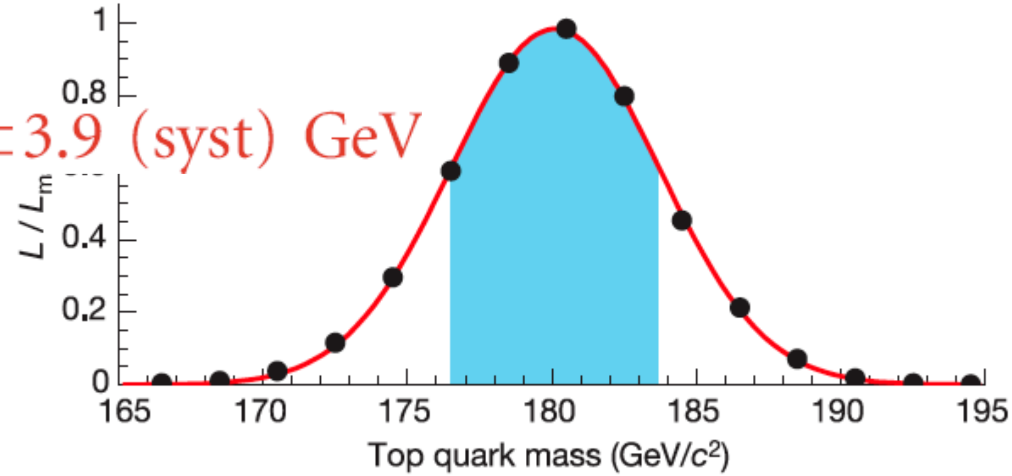
letters to nature

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

First implementation of MEM in HEP

- The **final result:**
  - $M_t = 180.1 \pm 3.6 \text{ (stat) } \pm 3.9 \text{ (syst) GeV}$
    - Using 125 pb^{-1} of p-pbar collisions @ 1.8 TeV, 71 events



- **Previous result:**
  - $M_t = 173.3 \pm 5.6 \text{ (stat) } \pm 5.5 \text{ (syst) GeV}$
    - 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*