Jets, Missing E_T, and Pileup Systematic Uncertainties

M.C. Vetterli

Simon Fraser University and TRIUMF

TOP 2013

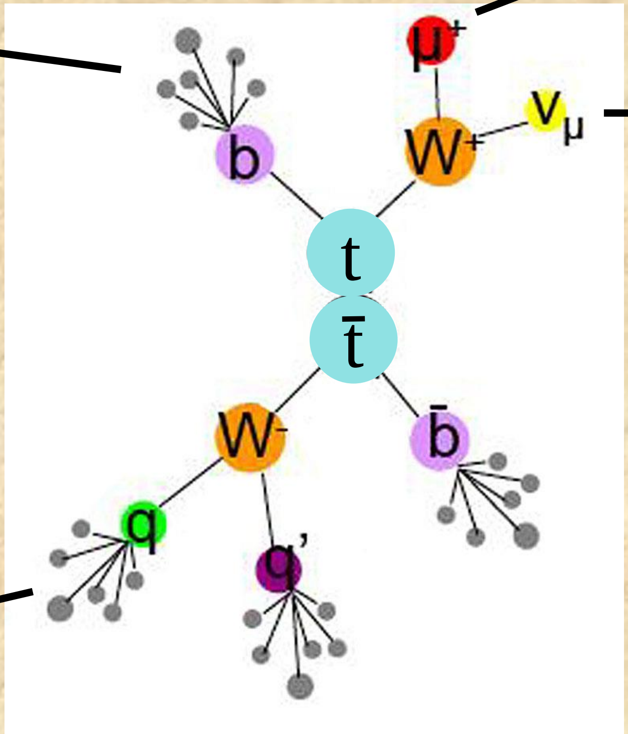
September 15th, 2013

On behalf of the ATLAS, CDF, CMS, DØ Collaborations

Context-1

Charged leptons

b-jets



Missing E_T

Light-quark jets

You need to understand the whole detector to do top-quark physics:

Jets & EtMiss

TRIUMF

Simon Fraser

Context-2

CDF combined channel X-section

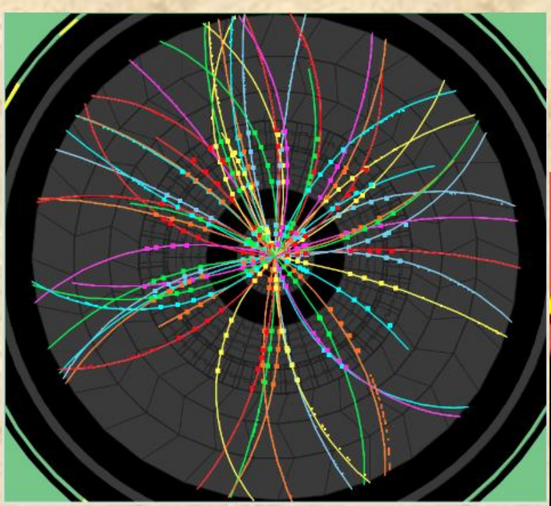
(CDF note 10926)

	DIL	LJ-ANN	LJ-SVX	HAD	CDF combined
Central value of $\sigma_{\bar{t}t}$	7.47	7.82	7.32	7.21	7.71
Uncertainties					
Statistical	0.50	0.38	0.36	0.50	0.31
Detector modeling	0.41	0.11	0.34	0.41	0.17
Signal modeling	0.24	0.23	0.23	0.44	0.22
Jet modeling	0.25	0.23	0.29	0.71	0.21
Method	0.00	0.01	0.01	0.08	0.01
Background from theory	0.02	0.13	0.29	0.00	0.10
Background based on data	0.10	0.07	0.11	0.59	0.07
Z boson theoretical normalization	0.00	0.16	0.15	0.00	0.13
Inelastic $p\bar{p}$ cross section	0.31	0.00	0.00	0.30	0.05
Luminosity detector	0.30	0.02	0.02	0.29	0.06
Total systematics	0.70	0.41	0.61	1.18	0.40

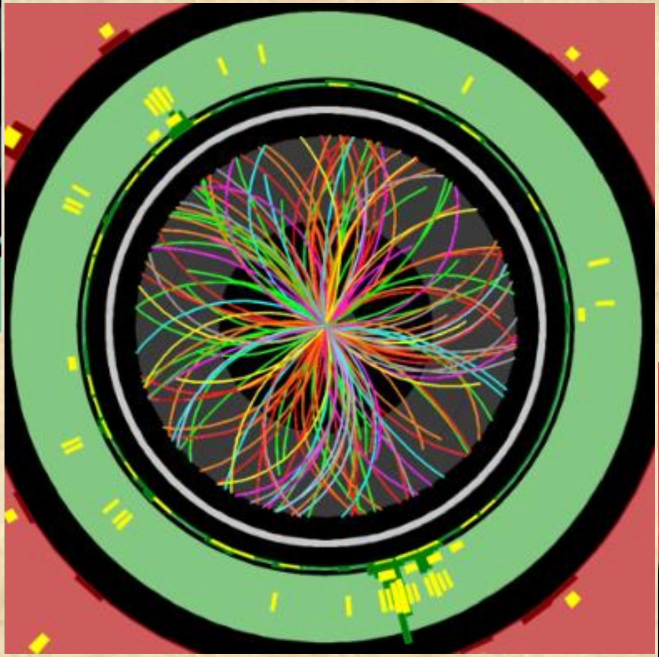
TABLE 2: CDF measurements of $\sigma_{\bar{t}t}$ and their combination, with breakdown shown for uncertainties (in pb).

Largest uncertainty

Context-3

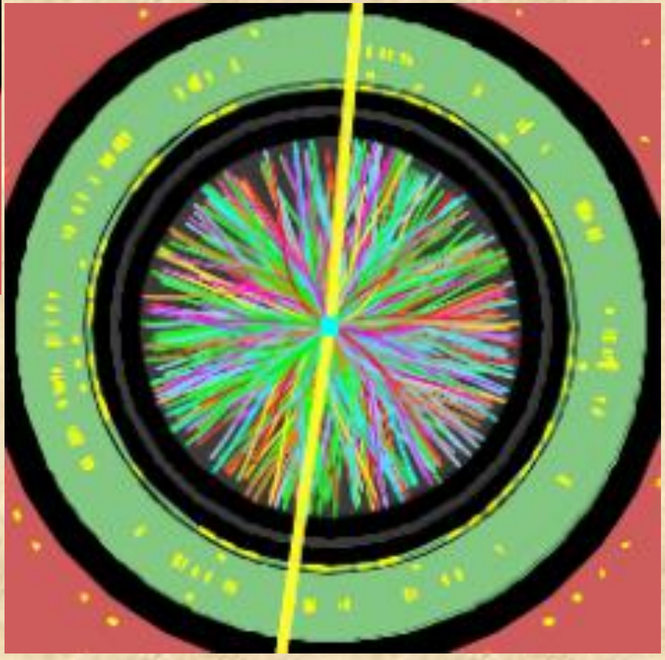


2 vertices



7 vertices

20 vertices



Things are getting messy!

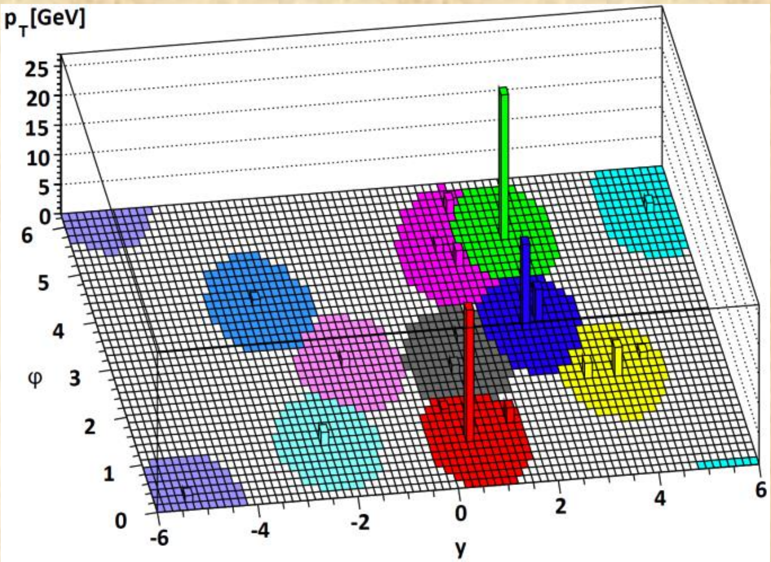
Jet Reconstruction

- *The anti-k_t algorithm with R=0.4 (0.5) is used for top physics at ATLAS (CMS) [several other values of R also used]*

$$d_{ij} = min(k_{ti}^{-2}, k_{tj}^{-2})\frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{-2}$$

$$\Delta_{ij}^2 = (\eta_i^2 - \eta_j^2) + (\phi_i^2 - \phi_j^2)$$

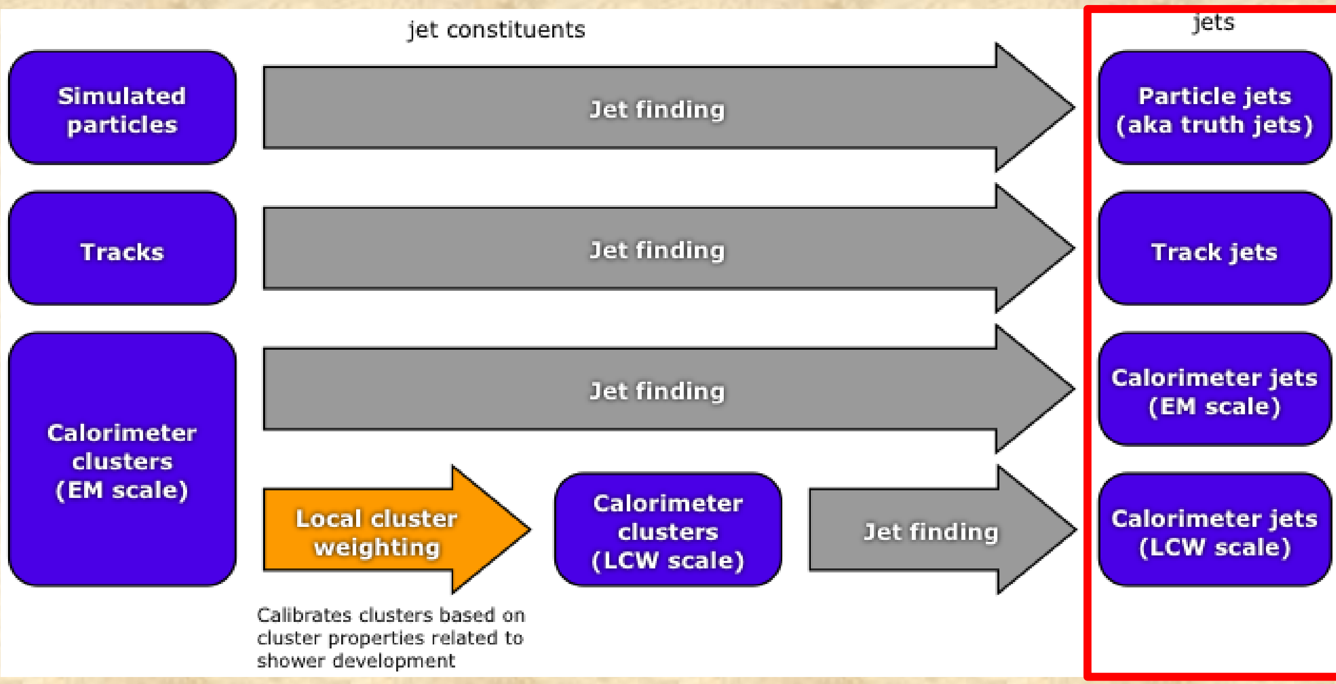


➔ *produces cone-like jets that are infrared and co-linear safe.*

- *Various objects are used as input (see following)*
- *CDF and D0 use an iterative cone algorithm (k_t as well)*

TRIUMF
Simon Fraser

Jet Reco Strategy - 1



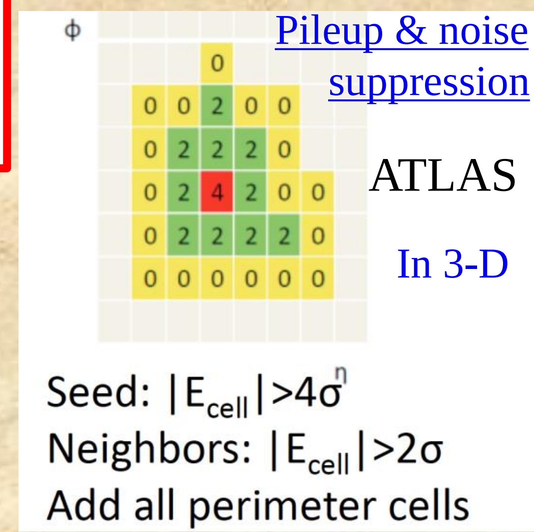
e.g. energy density,
shower depth

CDF: calo towers
D0: noise-suppressed towers
ATLAS: topo calo clusters

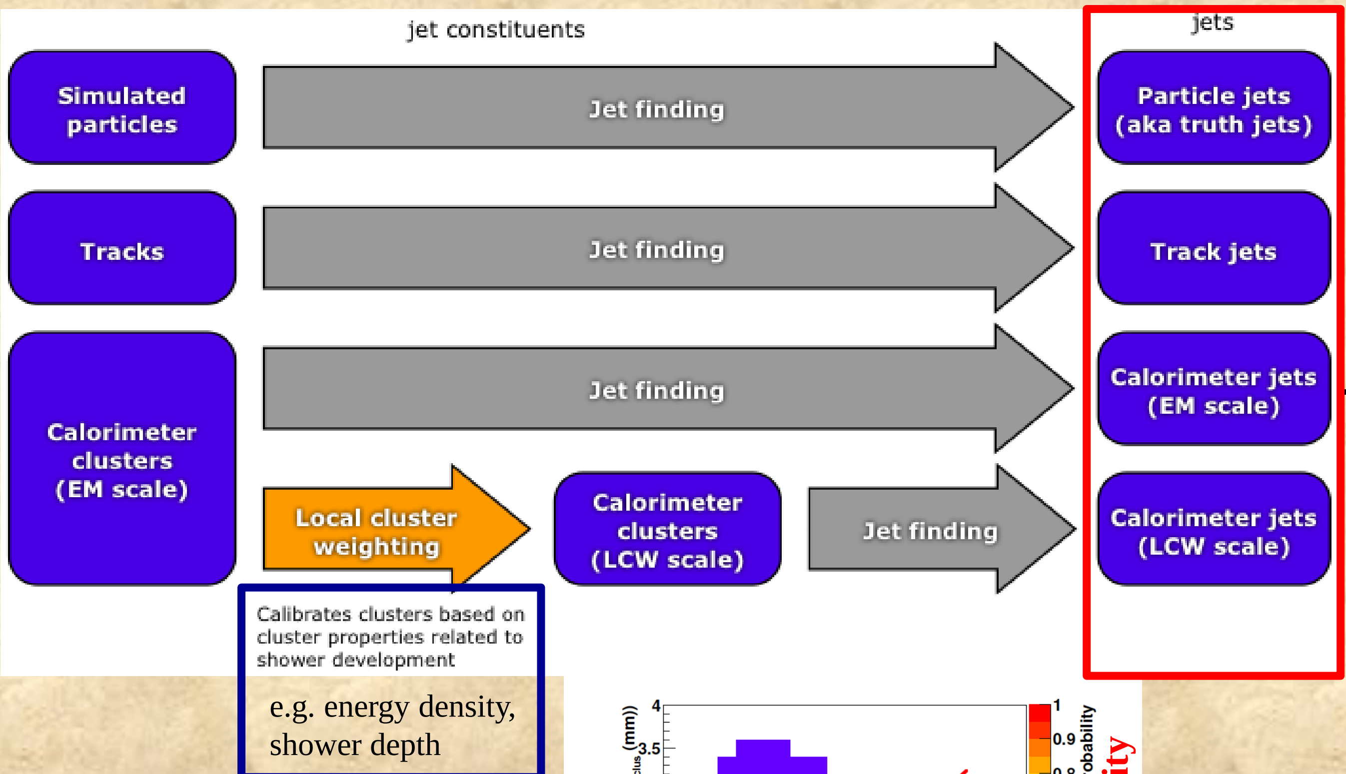
Pileup & noise suppression

ATLAS

In 3-D

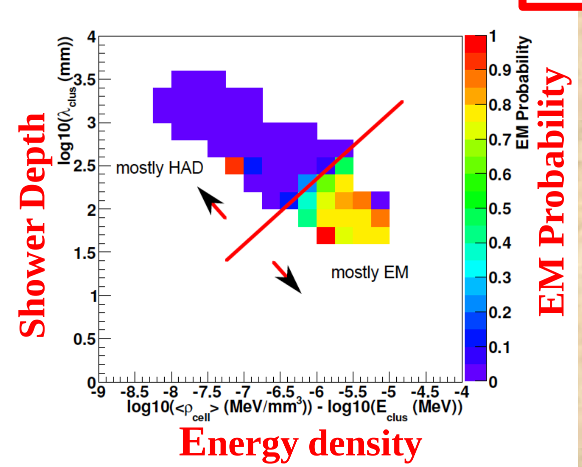


Jet Reco Strategy - 1

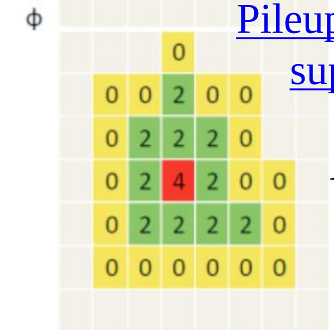


CDF: calo towers
D0: noise-suppressed towers
ATLAS: topo calo clusters

ATLAS
Important for resolution



Pileup & noise suppression



ATLAS

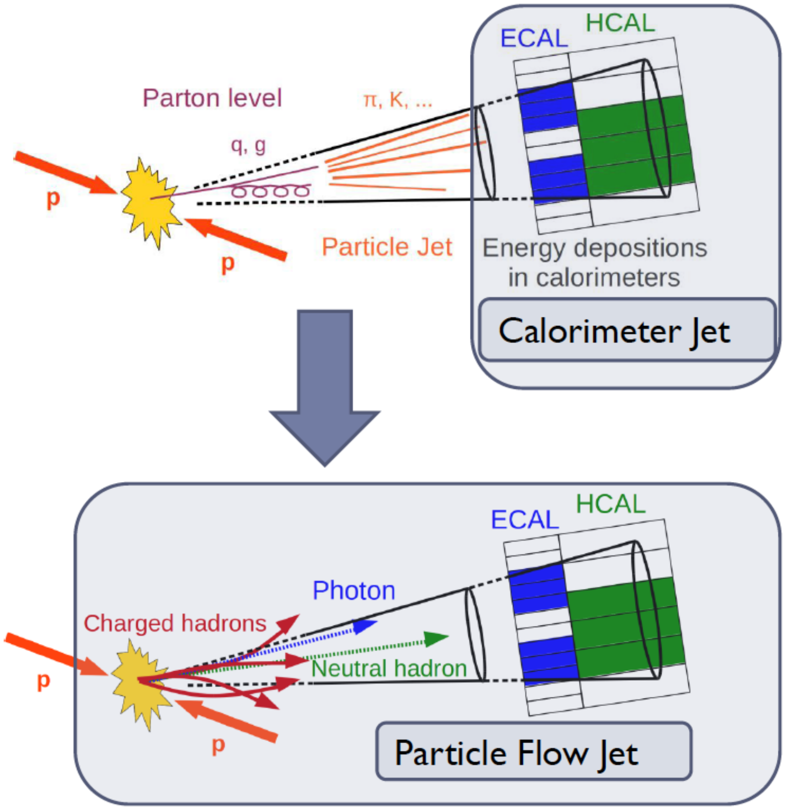
In 3-D

Seed: $|E_{cell}|>4\sigma$
Neighbors: $|E_{cell}|>2\sigma$
Add all perimeter cells

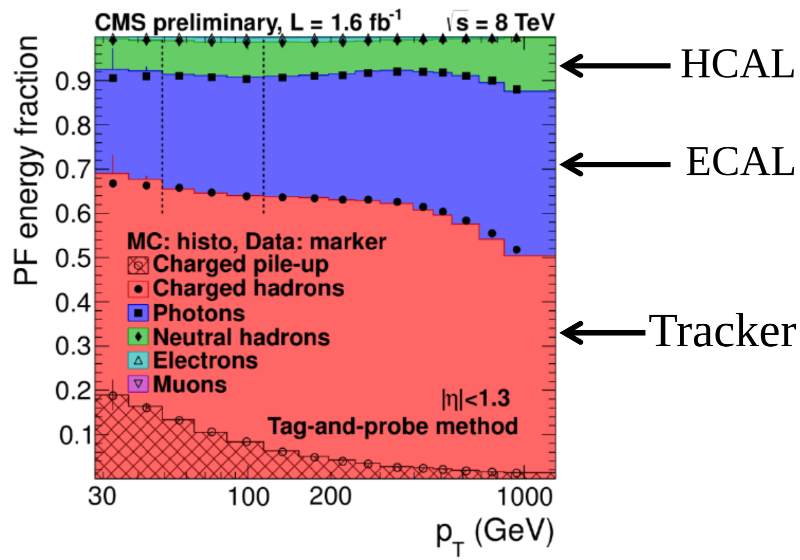
TRIUMF
Simon Fraser

Jet Reco Strategy - 2

Particle Flow (PF) approach

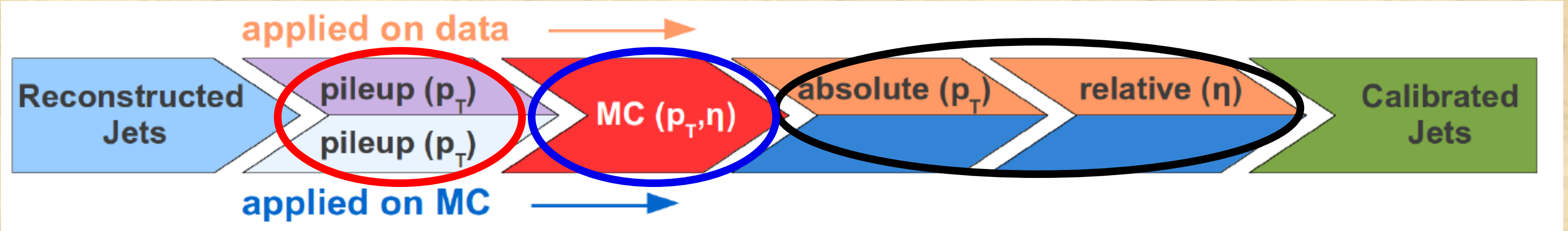


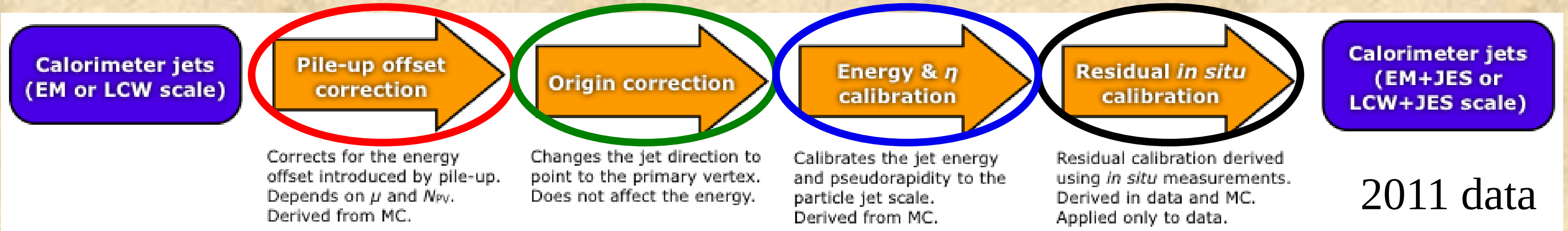
- Tries to reconstruct individual particles to form jets using all subdetector information
- Commissioned successfully on data
- Used in most CMS analyses



Simon Fraser

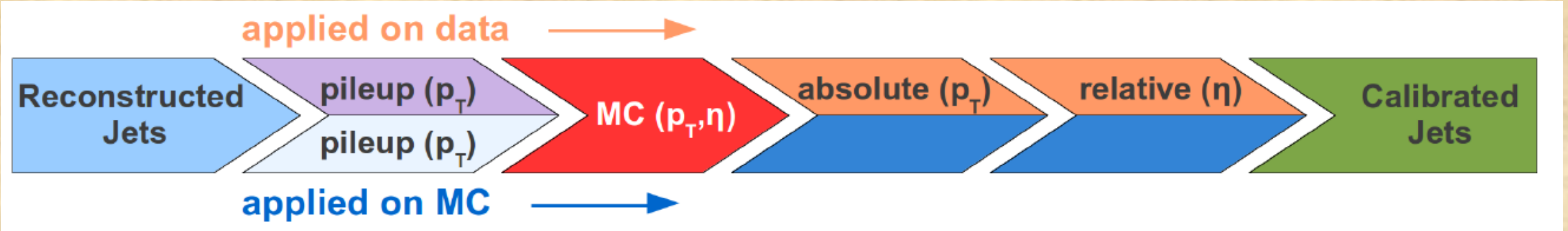
Jet Calibration Strategies

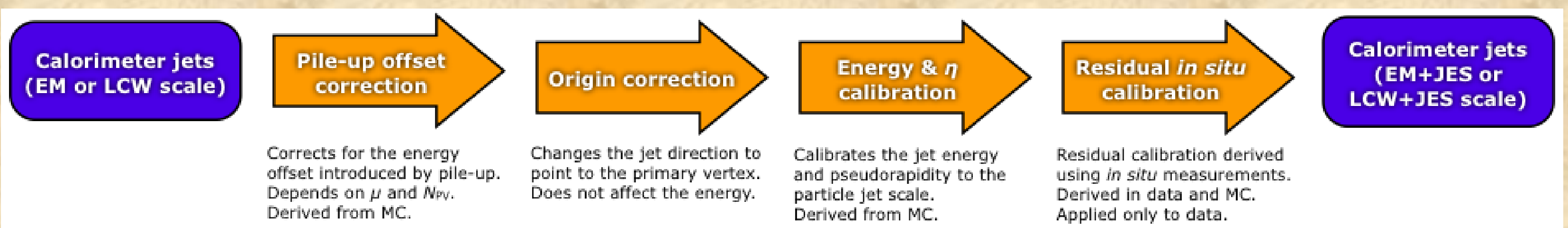




1) Correct for pileup
2) Correct for vertex position (ATLAS; not needed for PF jets)
3) Apply Monte-Carlo calibration factors
4) Apply residual calibration from in-situ measurements

Jet Calibration Strategies





$$p_T^{parton} = (p_T^{jet} \times C_\eta - C_{MI}) \times C_{Abs} - C_{UE} + C_{OOC} = p_T^{particle} - C_{UE} + C_{OOC}$$

C_η: η uniformity ; C_{MI}: pileup ; C_{abs}: calo response (MC-based)

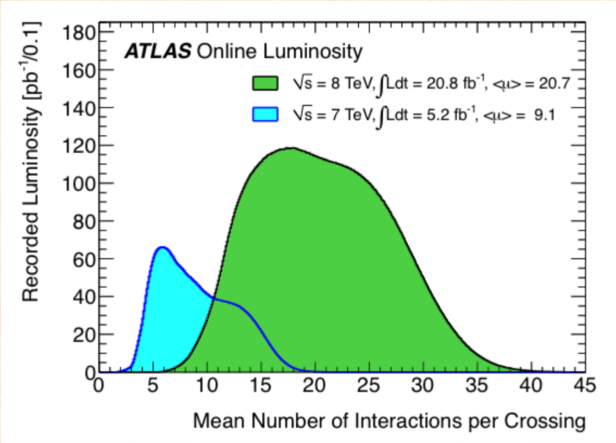
$$E_{\rm jet}^{\rm ptcl} = \frac{E_{\rm jet}^{\rm meas} - E_{\rm O}}{R_{\rm jet} S_{\rm jet}}$$

E_O: offset (pileup, noise); S_{jet}: showering correction

R_{jet}: Calorimeter response; from data (MPF)

Simon Fraser

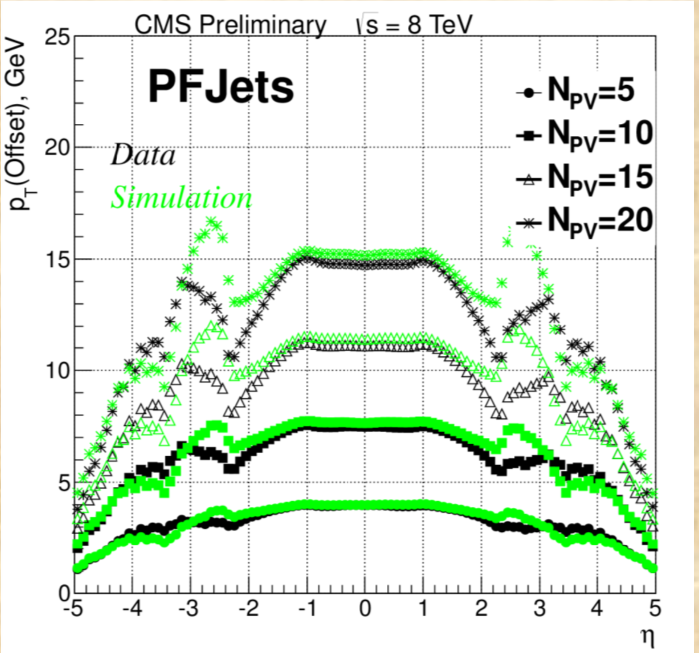
Pileup Corrections

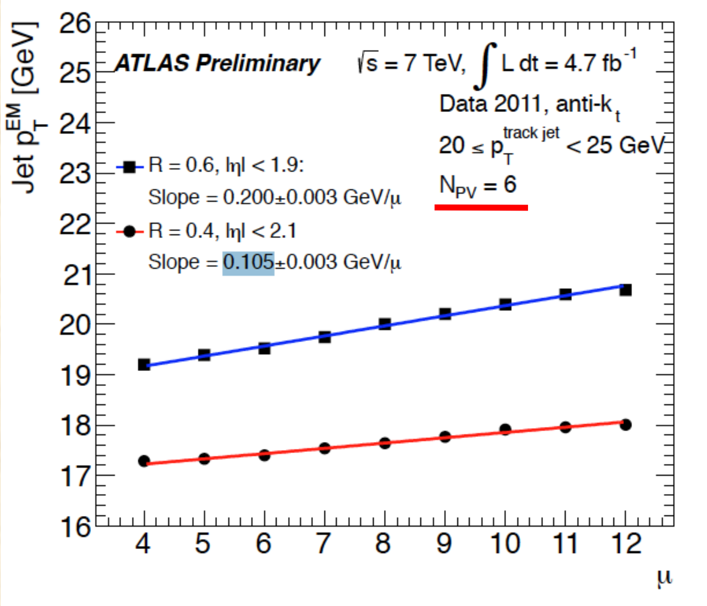


$$\mathcal{O}(N_{PV}, \mu, \eta_{det}) = \alpha(\eta_{det}) \cdot \left(N_{PV} - N_{PV}^{ref}\right) + \beta(\eta_{det}) \cdot \left(\mu - \mu^{ref}\right)$$

N_{PV} = # primary vertices (in-time pileup)

μ = ave. # of interactions/bunch crossing (out-of-time pileup)





TRIUMF

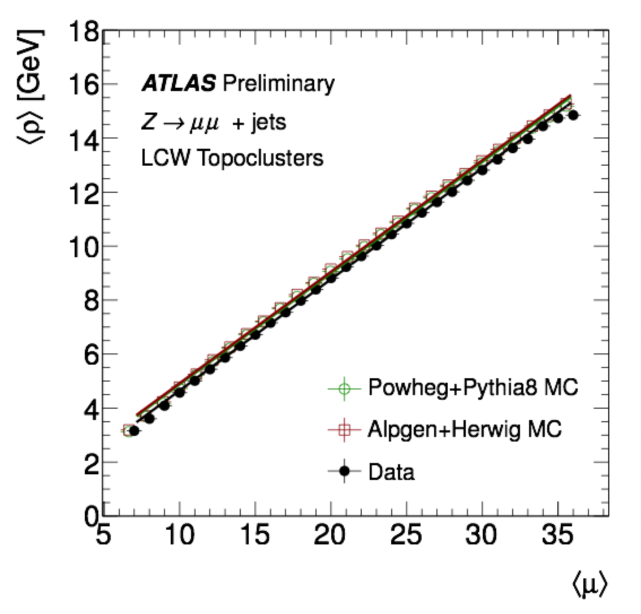
Simon Fraser

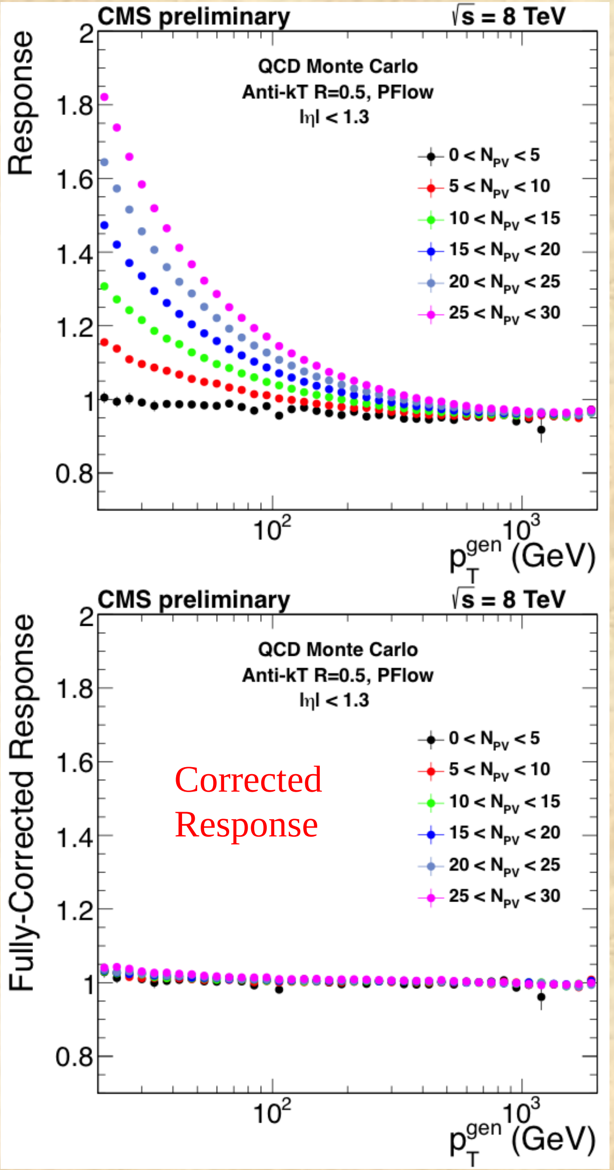
Pileup Corrections

And/or use a jet-area-based correction:

$$C_{\text{area}}(p_T^{\text{raw}}, A_j, \rho) = 1 - \frac{(\rho - \langle \rho_{\text{UE}} \rangle) \cdot A_j}{p_T^{\text{raw}}}$$

ρ = ave. E density ; A_j = jet area





TRIUMF
Simon Fraser

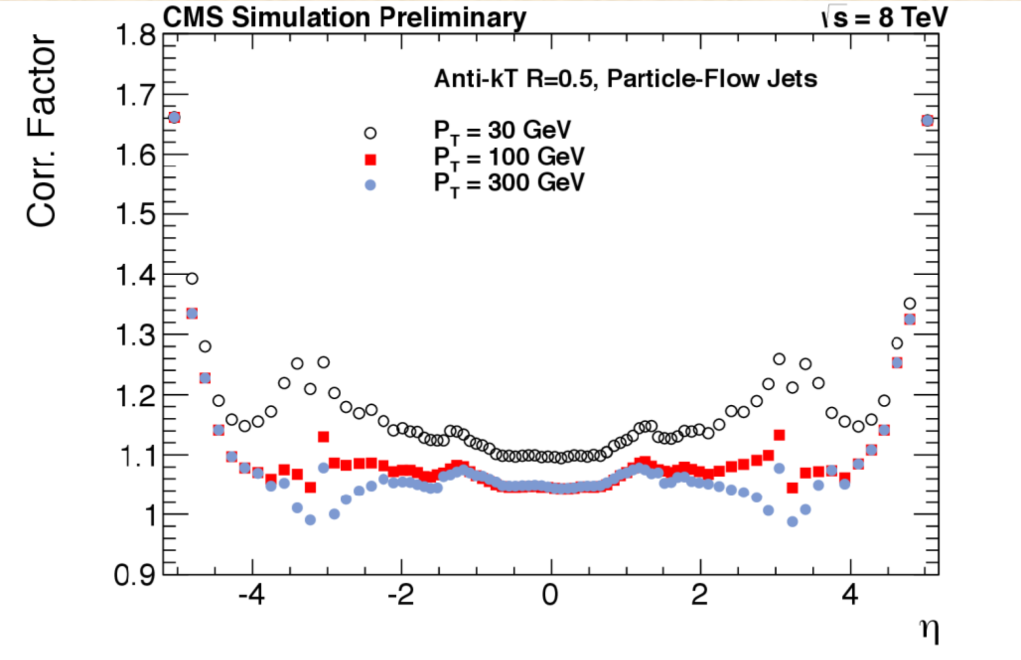
Response Corrections (p_t, η)

- Correct measured energy back to particle scale

- Based on Monte Carlo simulation:

  $\text{Corr} = p_T^{part}/p_T^{meas}$

- Monte Carlo simulation is validated by test-beam and single-hadron response data



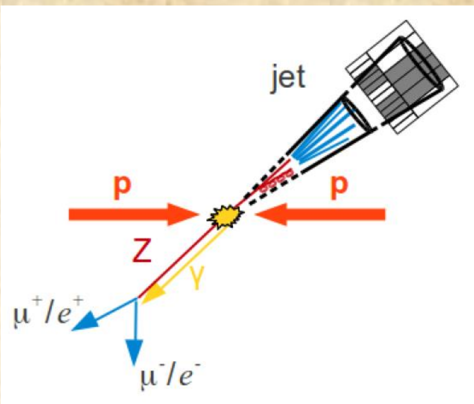
CMS: Apply to particle-flow jets

ATLAS: Apply to jets at EM-scale (EM+JES) & jets at local hadronic calibration scale (LCW+JES)

in-situ Calibration

The Monte Carlo is not perfect. Correct calibration using in-situ techniques:

Balance jet transverse momentum against that of a well-measured object (Z, γ)

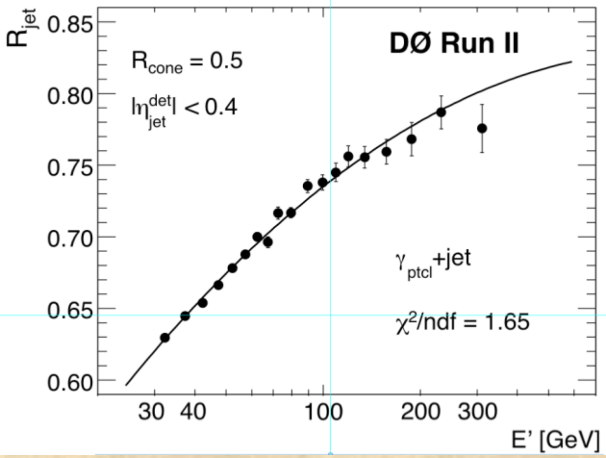


<u>Two techniques</u>:

+ *pt-balance:* balance the jet (but need OOC corrections)
+ *Missing Projection Fraction (MPF):* balance the whole hadronic recoil (no intrinsic EtMiss)

$$R_{balance} = \frac{p_T^{jet}}{p_T^{\gamma/Z}} \text{ and } R_{MPF} = 1 + \frac{\vec{E}_T^{miss} \cdot \vec{p}_T^{\gamma/Z}}{\left(p_T^{\gamma/Z}\right)^2}$$

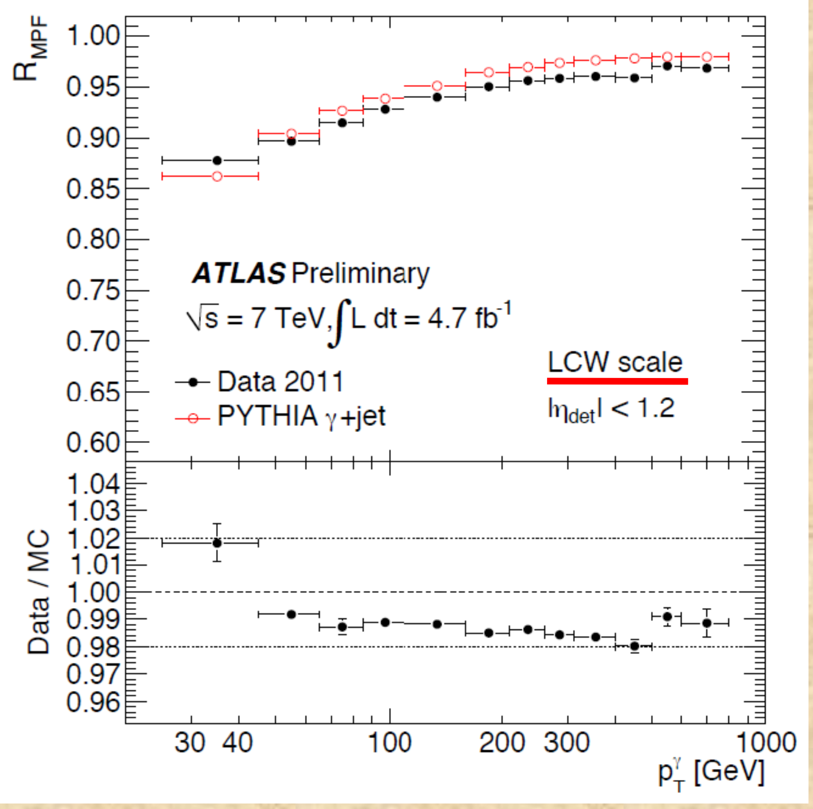
MPF method does not depend on the jet algorithm to 1st order.
It is also much less sensitive to (ISR, FSR, UE).
However, it does not test how well the MC models the out-of-cone correction.

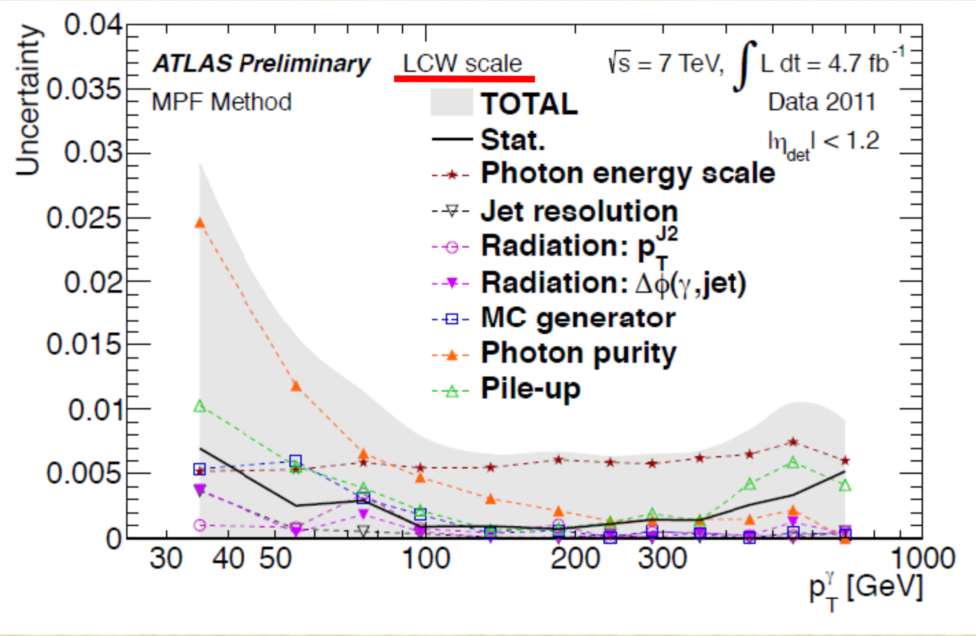


TRIUMF

Simon Fraser

in-situ Calibration – γ+jet





The MC-based calibration is off by 1-2% at ATLAS in 2011

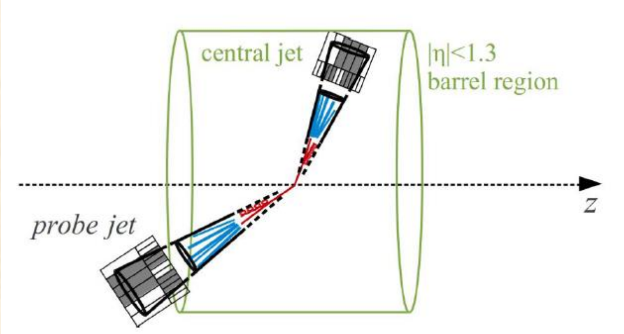
The γ+jet uncertainty is dominated by photon purity at low pt, and the photon energy scale at high pt

TRIUMF

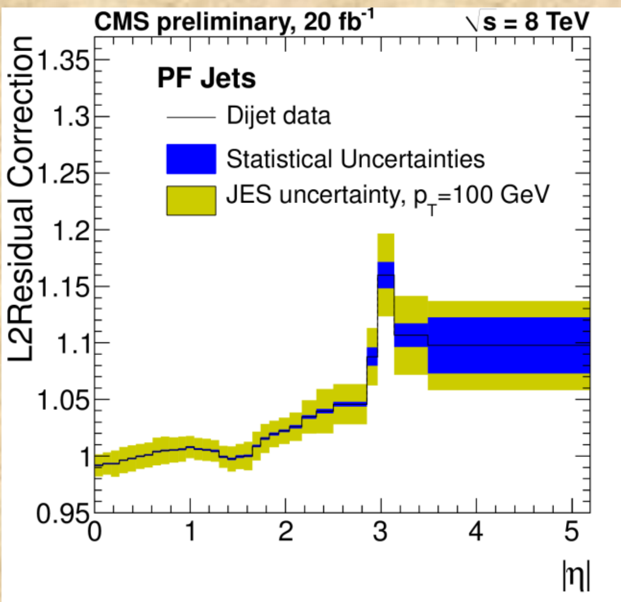
Simon Fraser

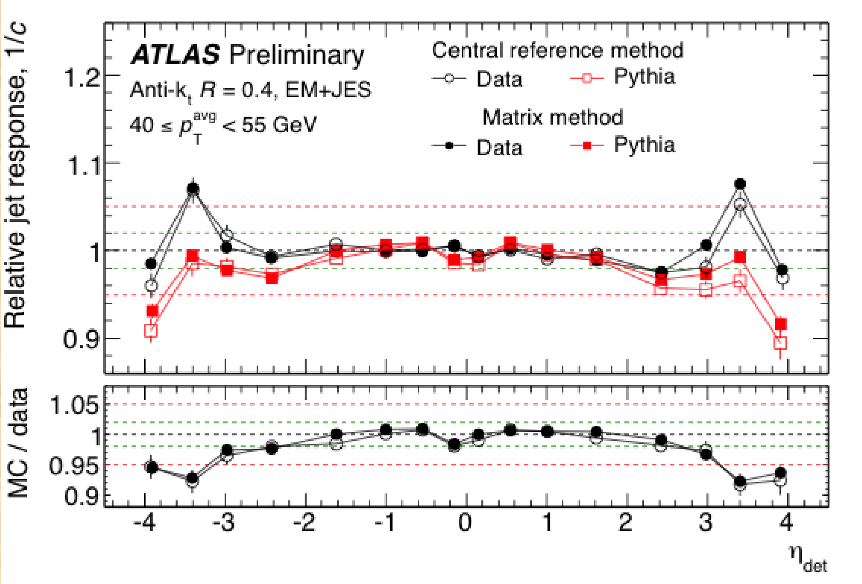
η-dependence

ATLAS: η-intercalibration
CMS: 'relative' correction
in-situ calibration using dijet events



- Use jets in the central region that have been calibrated by Z+jet and/or γ+jet as a reference

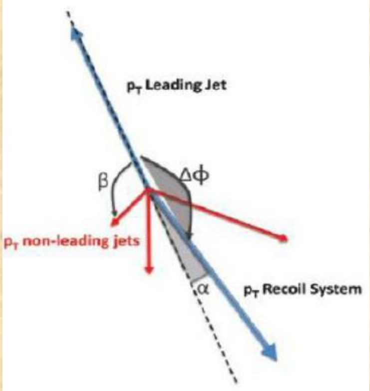




Simon Fraser

Calibration at high-pt; multijet events

Use calibrated jets at low pt to propagate the JES to larger pt.
You can bootstrap your way up to high pt.



Direct balance is used:

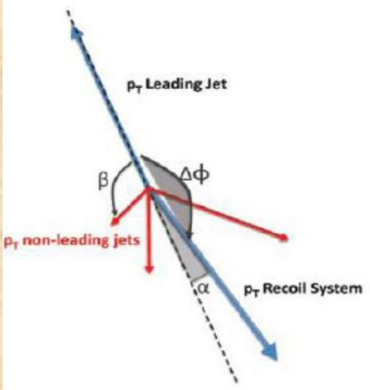
$$\text{MJB} = \frac{|\vec{p}_T^{\,\text{Leading}}|}{|\vec{p}_T^{\,\text{Recoil}}|}$$

MJB in data is compared to MJB in Monte Carlo.

Simon Fraser

Calibration at high-pt; multijet events

Use calibrated jets at low pt to propagate the JES to larger pt.
You can bootstrap your way up to high pt.



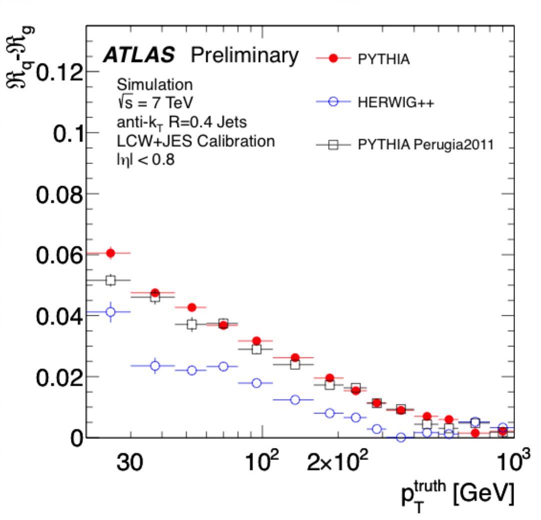
Direct balance is used:

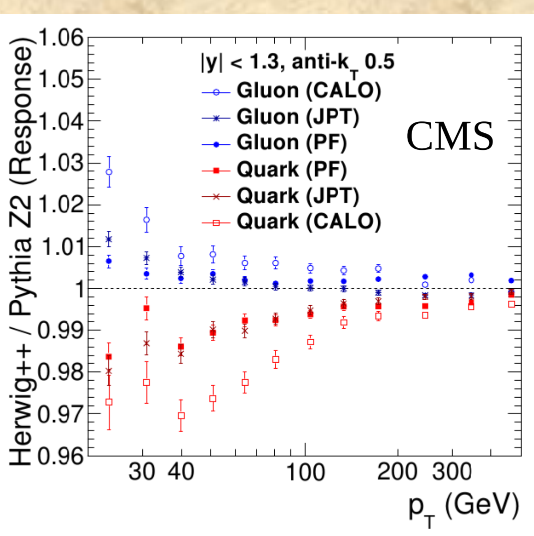
$$\text{MJB} = \frac{|\vec{p}_T^{\,\text{Leading}}|}{|\vec{p}_T^{\,\text{Recoil}}|}$$

MJB in data is compared to MJB in Monte Carlo.

Flavour Dependence of JES

- In-situ calibrations use Z/γ+jet events
  ➔ dominated by quark-induced jets
- Dijet events on the other hand are dominated by gluon-induced jet (more/softer particles)
- Uncertainties are determined by varying MC (e.g. PYTHIA vs HERWIG)



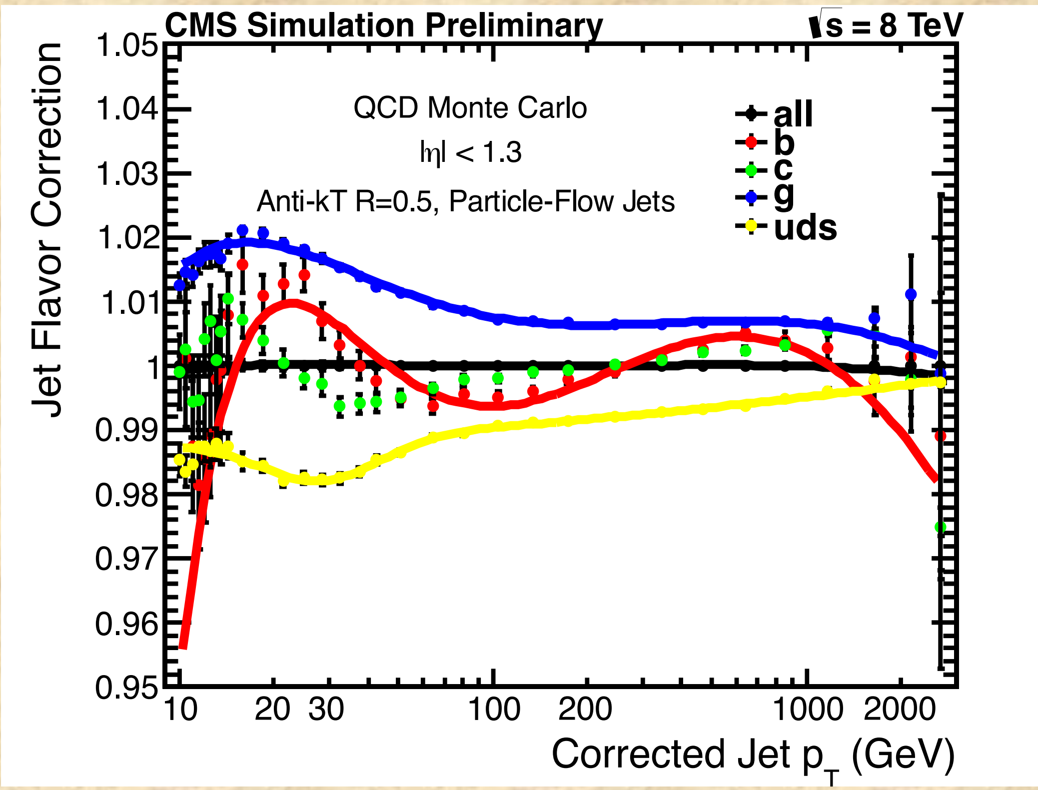


TRIUMF
Simon Fraser

Heavy Flavour jets

- b-jets can contain muons & neutrinos ➔ yet another response
- Study the differences in Monte Carlo

No specific bJES uncertainty needed

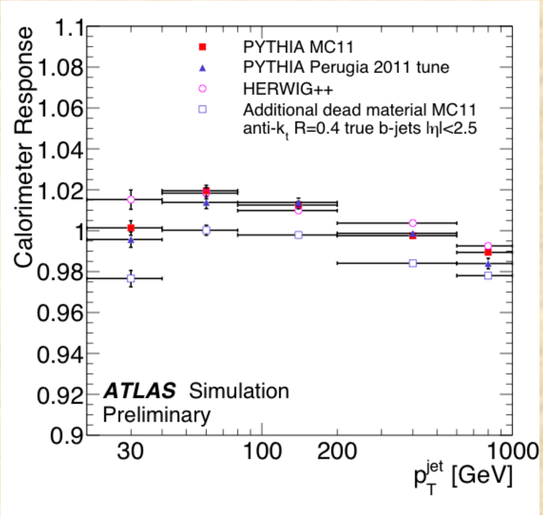


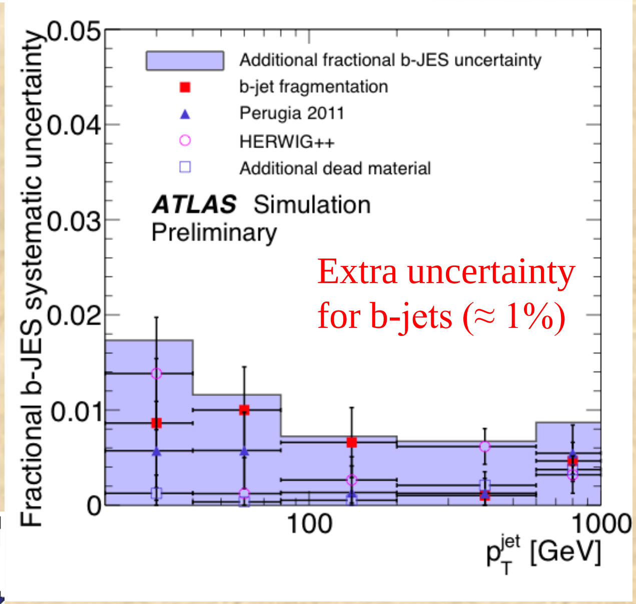
TRIUMF

Simon Fraser

Heavy Flavour jets

- Vary the MC models to get the bJES uncertainty

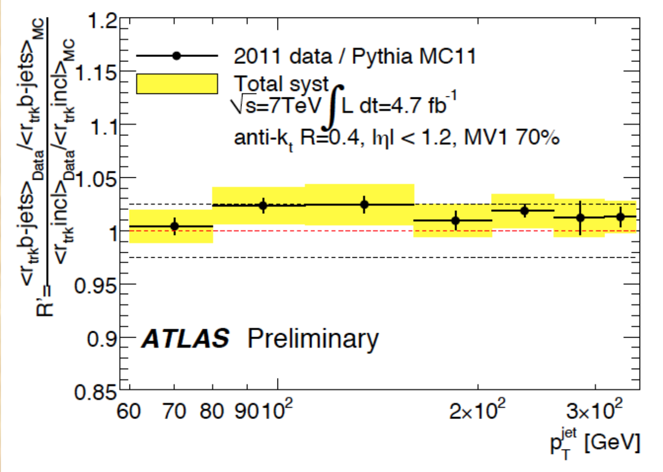




- Use b-tagged jets in ttbar events
  to validate the Monte Carlo study:
  - compare track jets to calo jets
  - take the double-ratio data/MC
  - compare b-jets & light jets

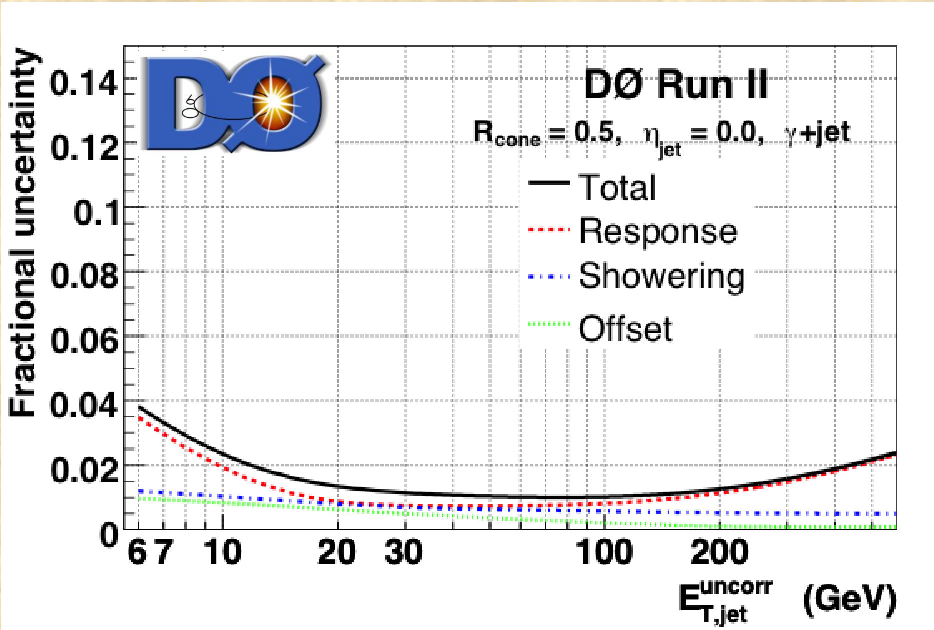
$$r_{\rm trk} = \frac{\sum \vec{p}_{\rm T}^{\,\rm track}}{p_{\rm T}^{\rm jet}}$$

$$R_{r_{\rm trk}} \equiv \frac{\langle r_{\rm trk}\rangle_{\rm Data}}{\langle r_{\rm trk}\rangle_{\rm MC}} \qquad R' \equiv \frac{R_{r_{\rm trk},b\text{-jet}}}{R_{r_{\rm trk},\rm inclusive}}$$

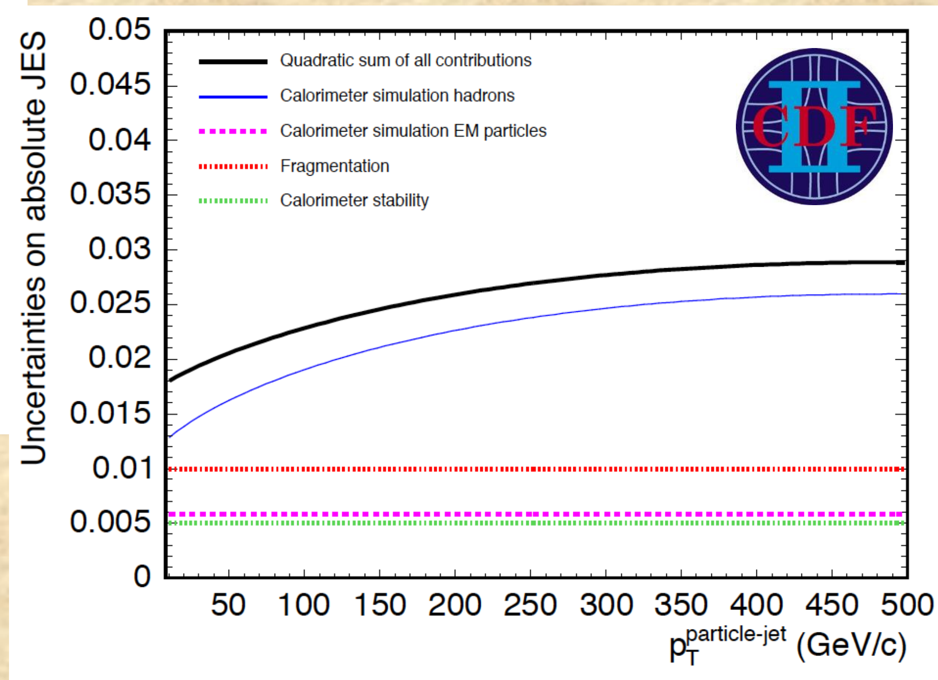


Simon Fraser

Uncertainties on JES - Tevatron



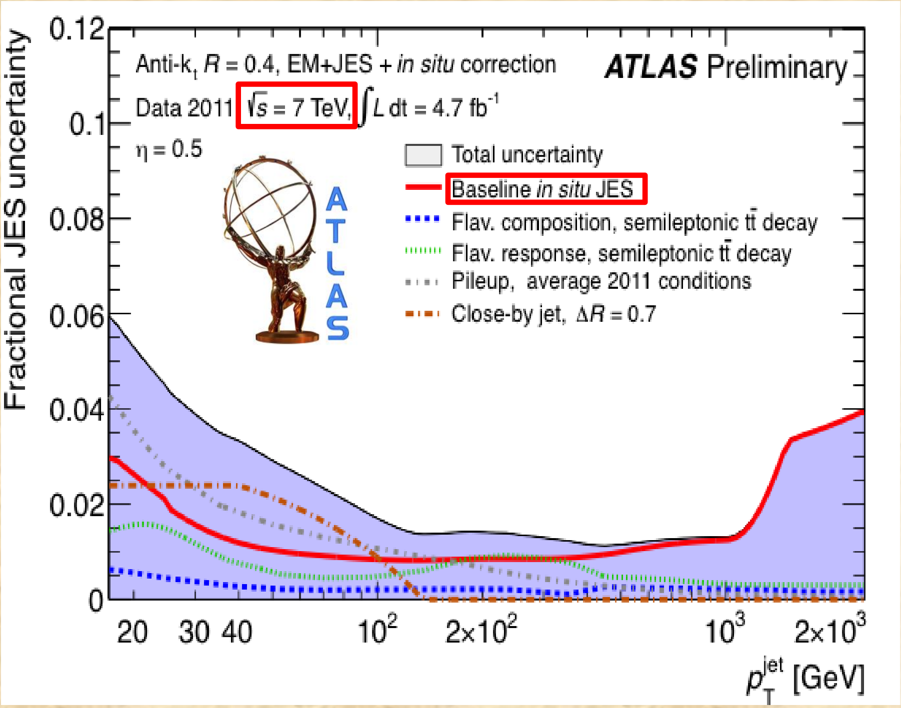
DØ: < 2% ; ≈ 1% (20-200 GeV)

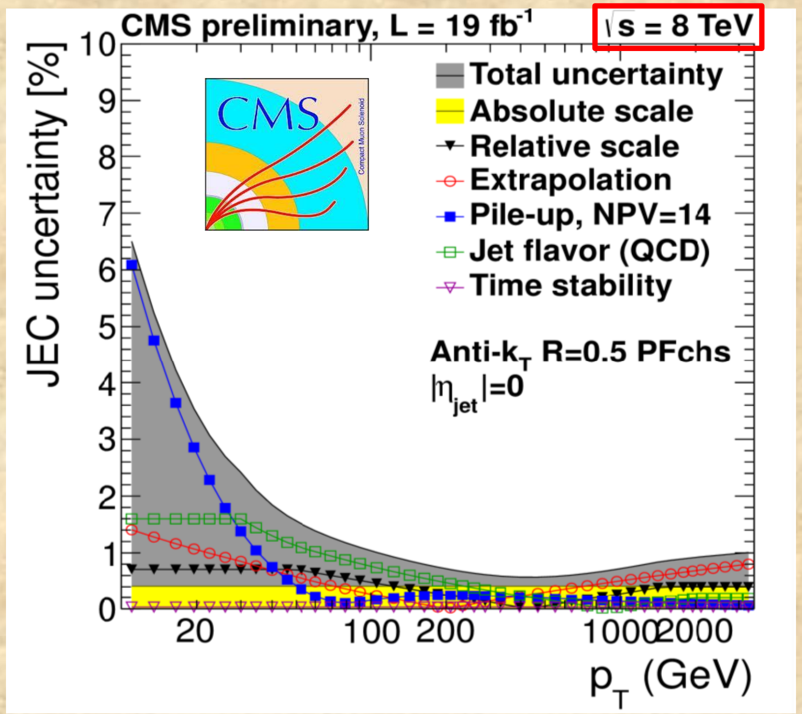


CDF: ≈ 2.5% ; < 2% at low pt

TRIUMF
Simon Fraser

Uncertainties on JES - LHC



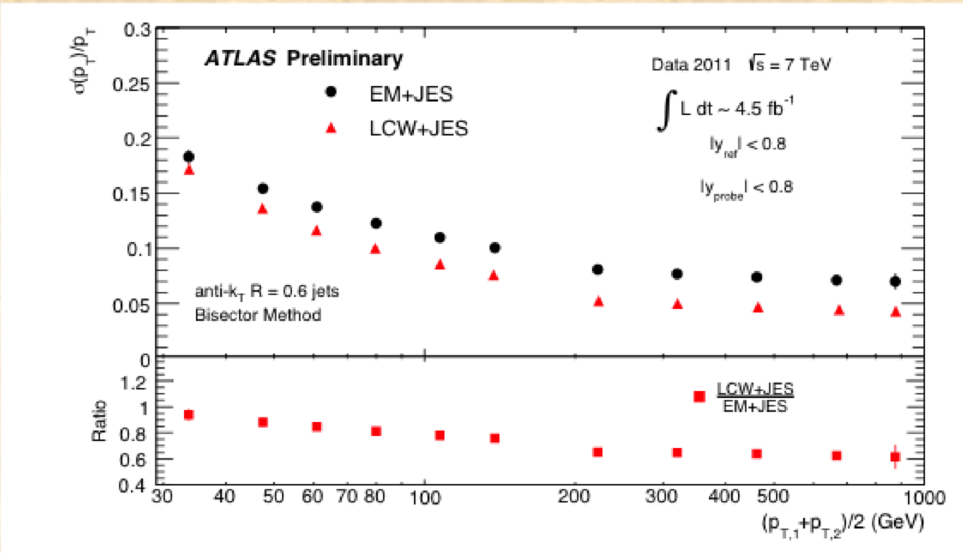


Pileup dominates at low pt and is worse at 8 TeV

TRIUMF

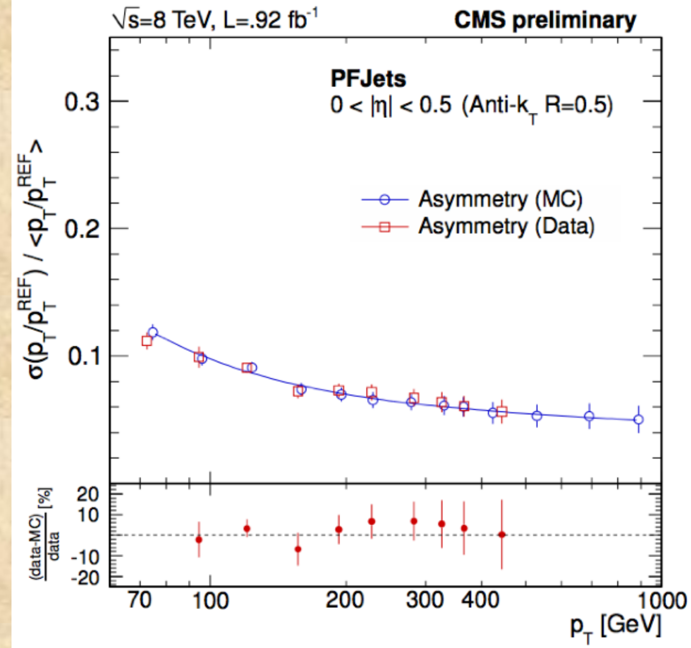
Simon Fraser

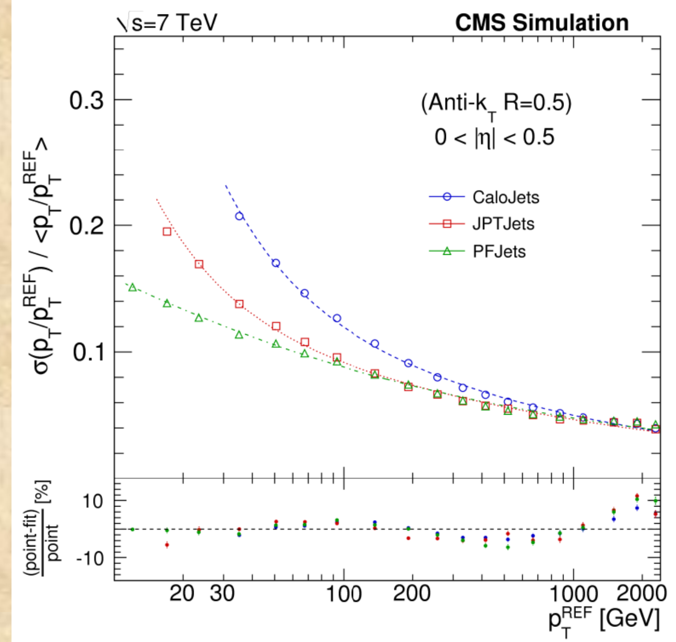
Jet Resolution



Measured using dijet events

PF and LCW improve jet resolution significantly, PF by using the better resolution of the tracker and the ECAL, LCW by providing "software compensation" for the calorimeter





TRIUMF

Simon Fraser

EtMiss reconstruction

Missing transverse momentum (E_T^{Miss}, $\not{E}_T$) can indicate the presence of neutrinos or other (new?) non-interacting particles.
It is calculated as the negative of the vectorial sum of all of the objects in the events

CMS: Three kinds of $\not{E}_T$:
1) PF $\not{E}_T$: calculated from particle flow objects ←
2) Calo $\not{E}_T$: calculated from calorimeter clusters (noise threshold)
3) TC $\not{E}_T$: Calo $\not{E}_T$ corrected for tracks $[-p_T(\pi) + p_T(\text{track})]$

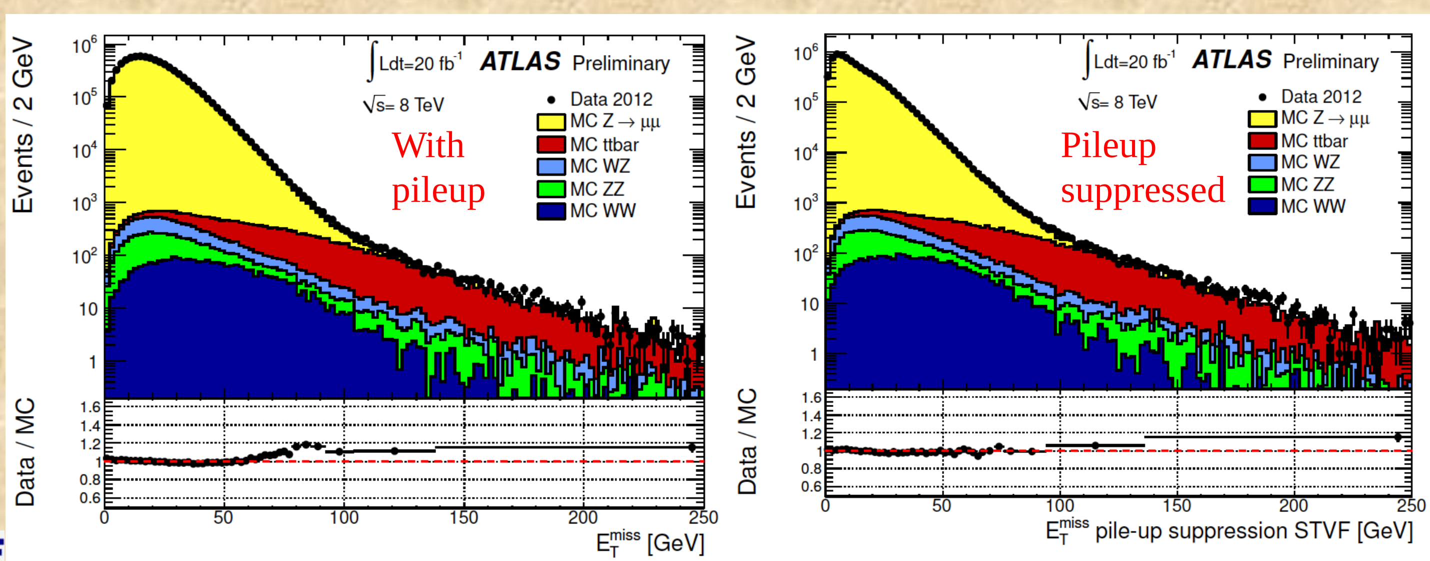
ATLAS: Many variants of E^{Miss}: calo-based or MET_RefFinal (uses reconstructed objects)

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,SoftTerm}} + E_{x(y)}^{\text{miss},\mu}$$

The "soft" term corresponds to clustered energy in the calorimeter, but that is not part of a jet.

EtMiss - Pileup

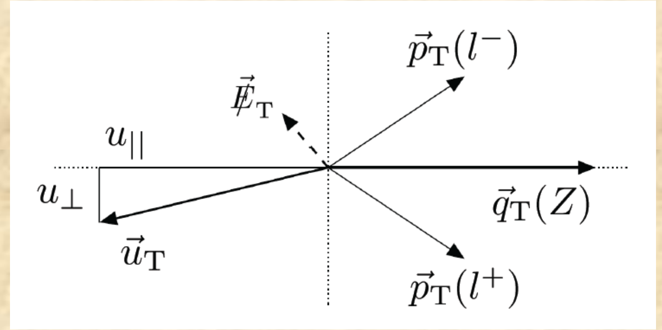
- The jet and soft terms are the most affected by pileup:
  - large-area objects that are dominated by hadronic energy deposits
- Corrections can be made in various ways:
  - as a function of N_{PV} and μ
  - as a function of object area
  - using MVA algorithms (CMS-2012)
- As a general rule, pileup corrections improve the E^{Miss} resolution, but worsen the scale (by over-correcting the soft terms)

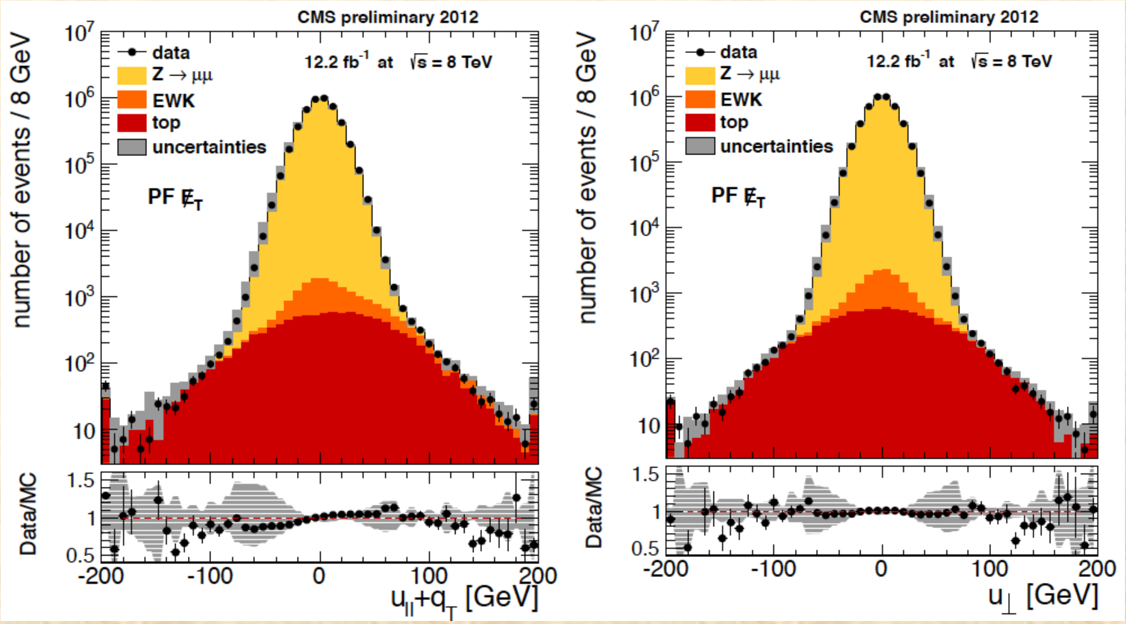


$Z \rightarrow \mu\mu$
no real E_T^{Miss}
(except in bkgnd processes)

Projections in Z+jets Events

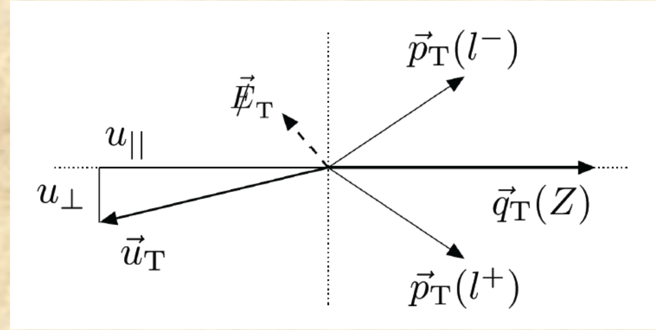
- $\vec{u}_T$ is the transverse momentum of the recoil
- $u_{||}$ should balance the transverse momentum of the Z
- $u_{\perp}$ is a measure of the underlying event (≈0)

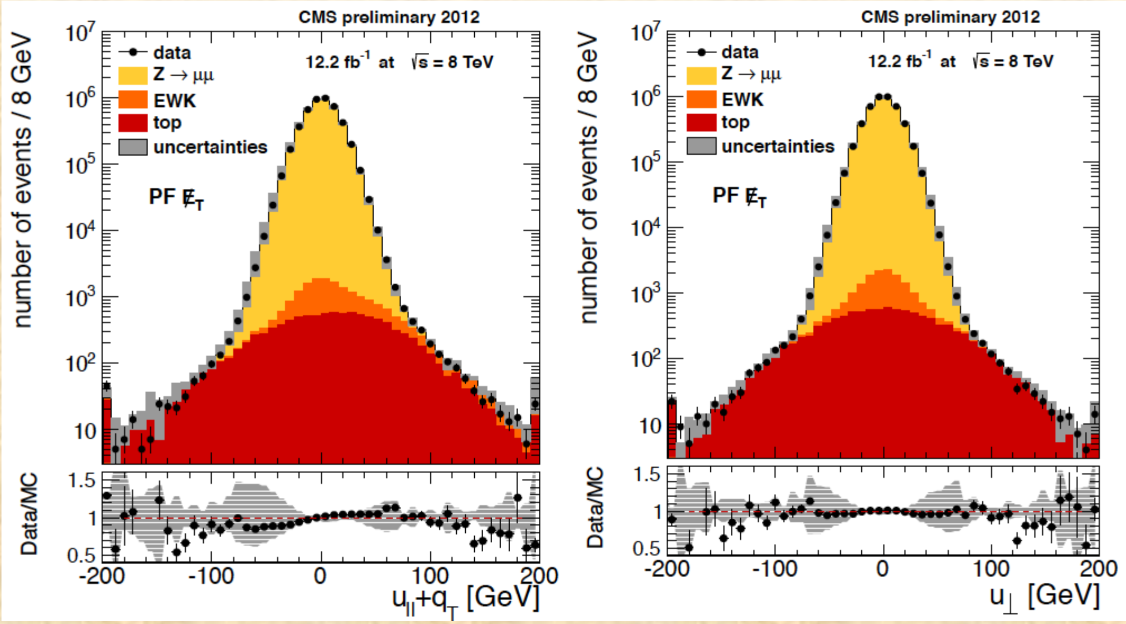




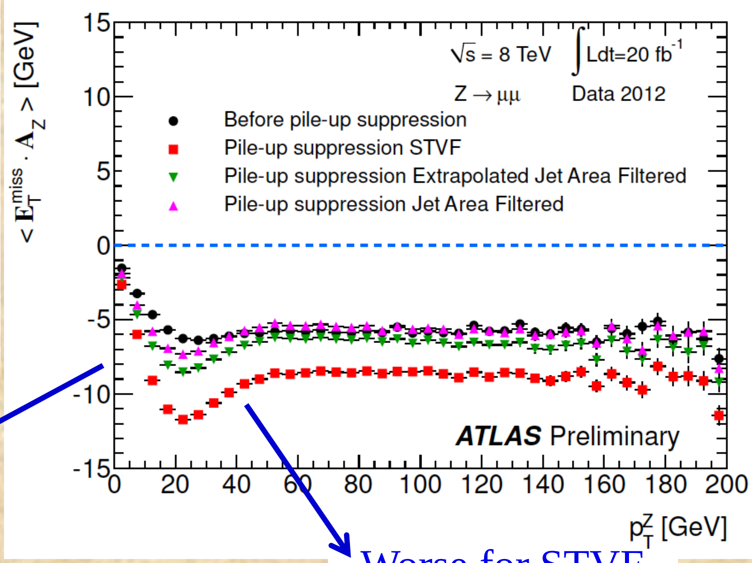
Projections in Z+jets Events

- $\vec{u}_T$ is the transverse momentum of the recoil
- $u_{||}$ should balance the transverse momentum of the Z
- $u_\perp$ is a measure of the underlying event (≈0)





E_T^{Miss} projected into the direction of the Z



Underestimate of the hadronic recoil

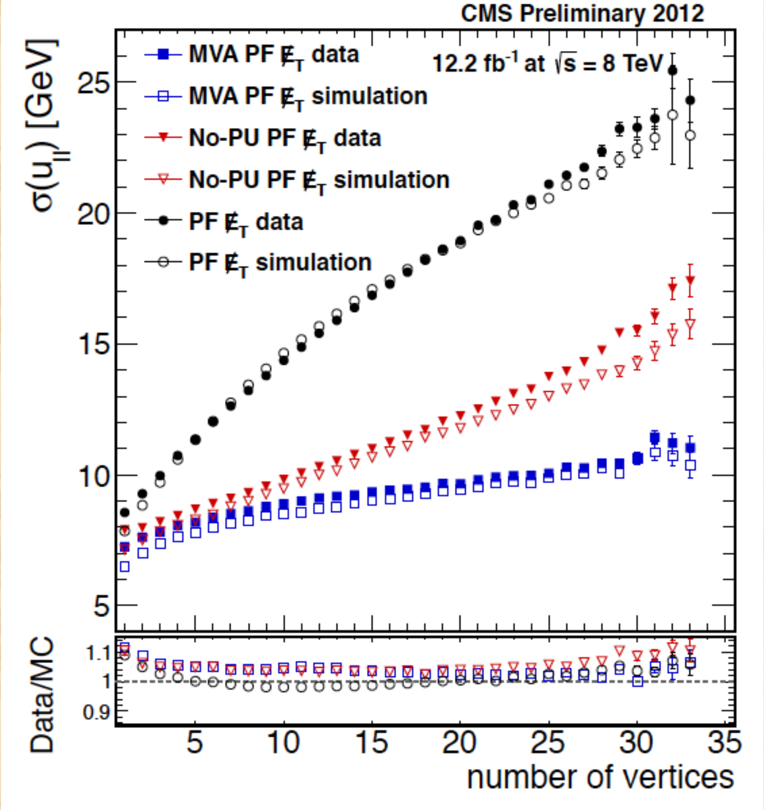
Worse for STVF
(Are soft clusters from the hard PV?)

TRIUMF

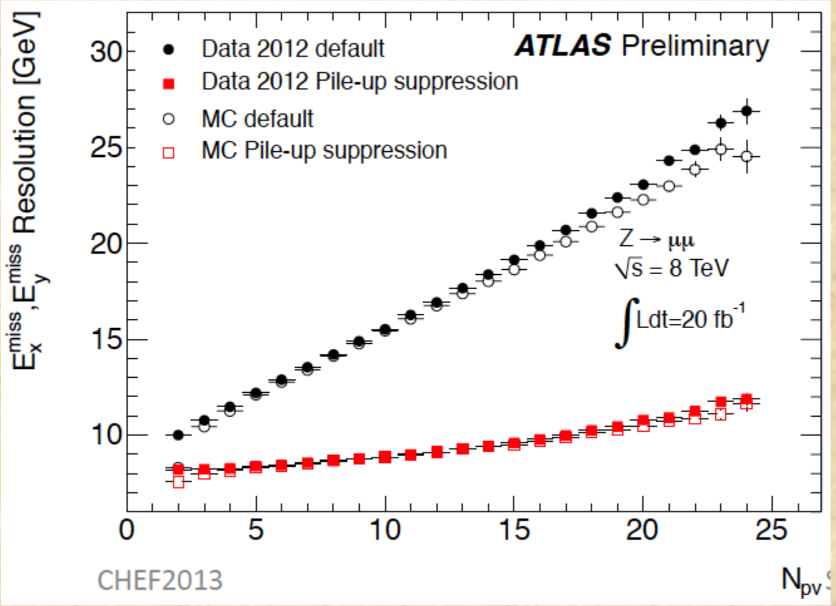
Simon Fraser

EtMiss resolution

Particle Flow jets with two different pileup suppression techniques.



Pileup suppression improves EtMiss resolution for both experiments



Simon Fraser

Summary

- *Jets and EtMiss are crucial to most (all?) physics analyses; top in particular*
- *Pileup is a significant effect at the LHC*
- *Several approaches have been developed for jet reconstruction & calibration*
- *Residual corrections from in-situ techniques*
- *All four experiments have JES uncertainties at the 1-2% level (absolute calibration)*
- *Missing E_T requires an understanding of the whole detector; well modeled*
- *Work continues to improve the situation even further*

What I didn't cover: - Large-R jets; boosted topologies
- ATLAS & CMS combined uncertainties (correlations)

Acknowledgements / Further Info

More information:

- ATLAS:

http://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissPublicResults?redirectedfrom=AtlasPublic.JetEtMissPublicCollisionResults&redirectedfrom=Atlas.JetEtMissPublicCollisionResults

- CMS: http://cms.web.cern.ch/org/cms-papers-and-results under "Jet and Missing Energy"
- CDF: http://arxiv.org/abs/hep-ex/0510047
- D0: http://www-d0.fnal.gov/phys_id/jes/public_RunIIa/

- Thanks to the colleagues at all four experiments who contributed material and suggestions!!

Backup Slides

Combining CMS & ATLAS Results - Correlations

A working group has been formed. See (Kirschenmann, Doglioni, Malaescu):
https://indico.cern.ch/getFile.py/access?contribId=7&sessionId=1&resId=0&materialId=slides&confId=245769

The following areas were identified for further study of correlations between the experiments:

1) in-situ Z+jets: *radiation suppression, out-of-cone bias, extrapolation to $\Delta\varphi=\pi$*

2) in-situ γ+jets: *same, but add photon purity*

3) Flavour response: *JES variation with jet composition*

4) bJES: *JES variation with jet composition*

5) High-pt: *Homogenize the treatment of high-pt uncertainties*

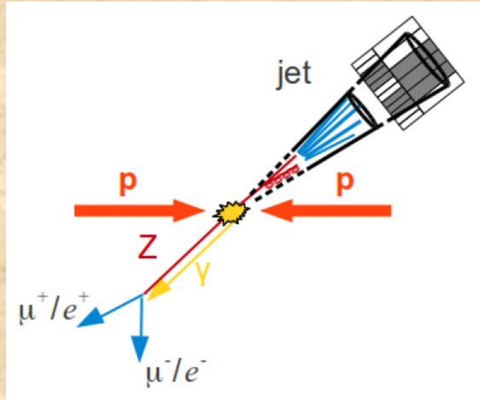
TRIUMF

Simon Fraser

in-situ Calibration-1

The Monte Carlo is not perfect. Validate calibration using in-situ techniques:

Balance jet transverse momentum against that of a well-measured object (Z, γ)

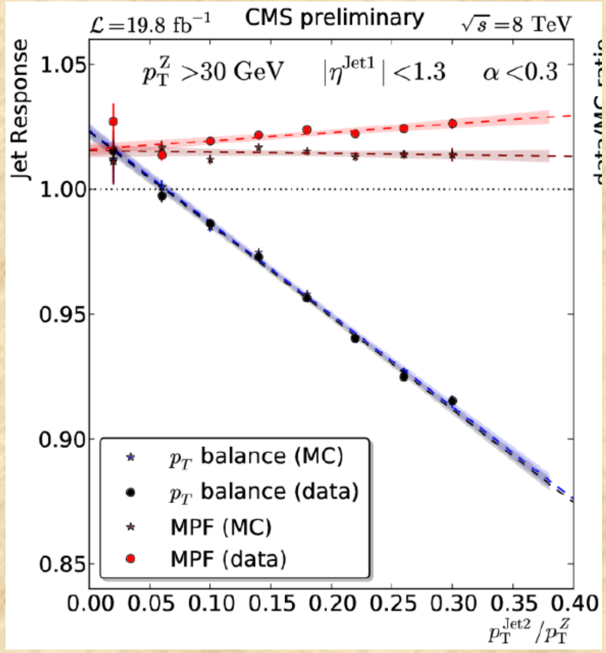


Two techniques:

+ *pt-balance:* balance the jet (but need OOC corrections)
+ *Missing Projection Fraction (MPF):*
  balance the whole hadronic recoil (no intrinsic EtMiss)

$$R_{balance} = \frac{p_T^{jet}}{p_T^{\gamma/Z}} \text{ and } R_{MPF} = 1 + \frac{\vec{E}_T^{miss} \cdot \vec{p}_T^{\gamma/Z}}{(p_T^{\gamma/Z})^2}$$

MPF method does not depend on the jet algorithm to 1st order.
It is also much less sensitive to (ISR, FSR, UE).
However, it does not test how well the MC models the out-of-cone correction.



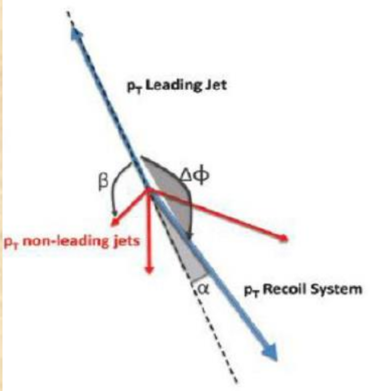
Z+jet good at low pt, where γ+jet has low purity
γ+jet good at mid-pt where Z+jet runs out of events

TRIUMF

Simon Fraser

Calibration at high-pt; multijet events

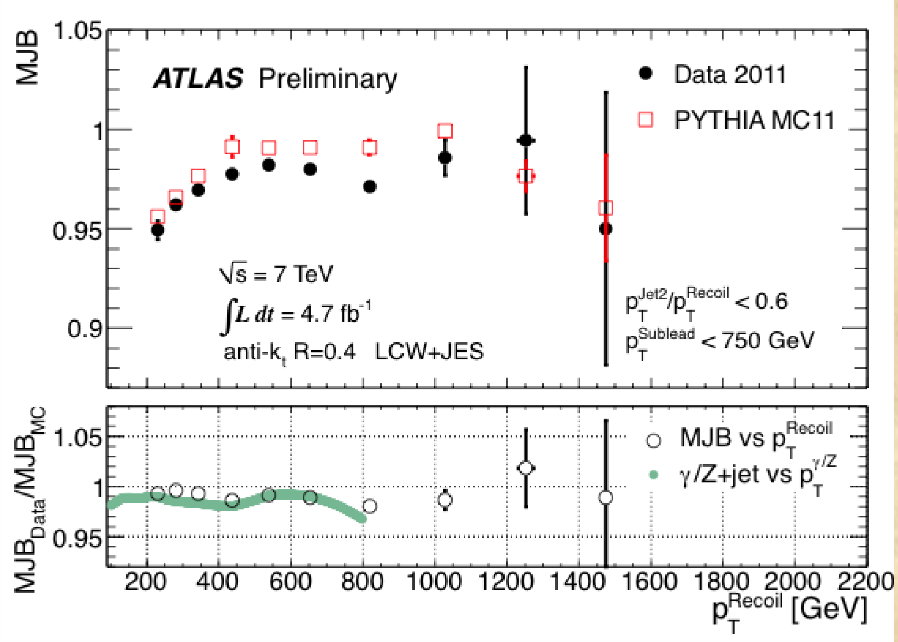
Use calibrated jets at low pt to propagate the JES to larger pt.
You can bootstrap your way up to high pt.



Direct balance is used:

$$\mathrm{MJB} = \frac{|\vec{p}_T^{\,\mathrm{Leading}}|}{|\vec{p}_T^{\,\mathrm{Recoil}}|}$$

MJB in data is compared to MJB in Monte Carlo.

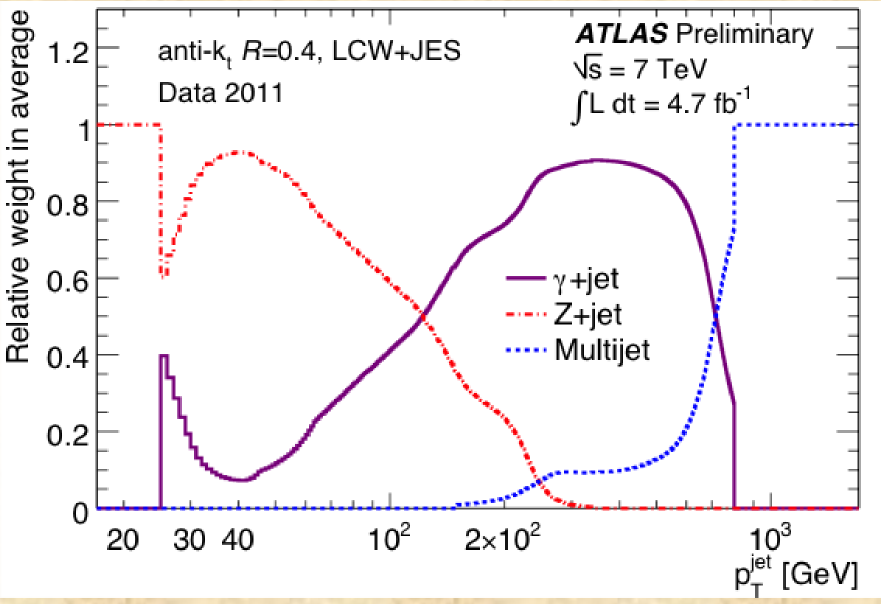


TRIUMF

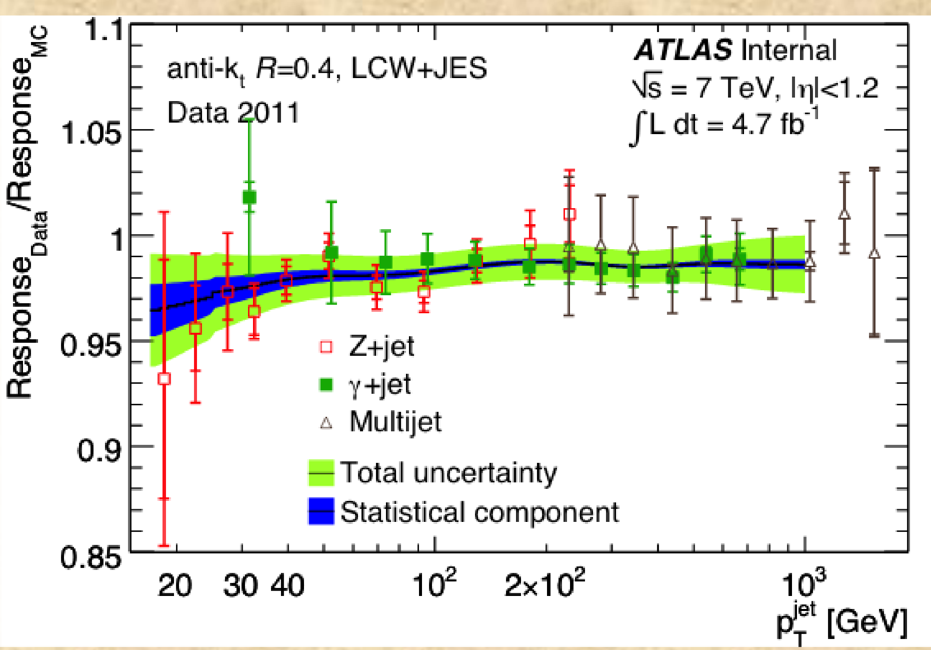
Simon Fraser

Combination of in-situ techniques

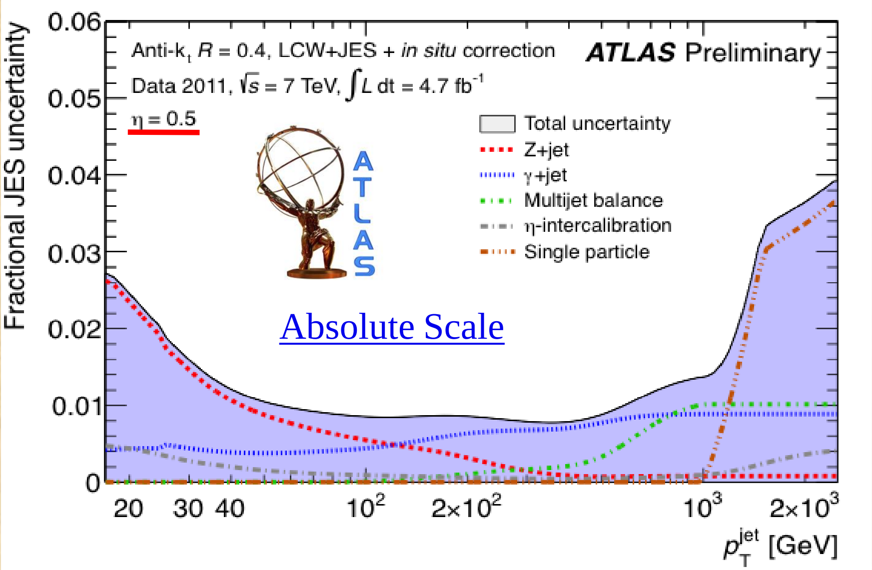
- Do a statistical combination of the in-situ methods as a function of p_T
- Use a weighted average for the final result
- A different method dominates in different regions of p_T

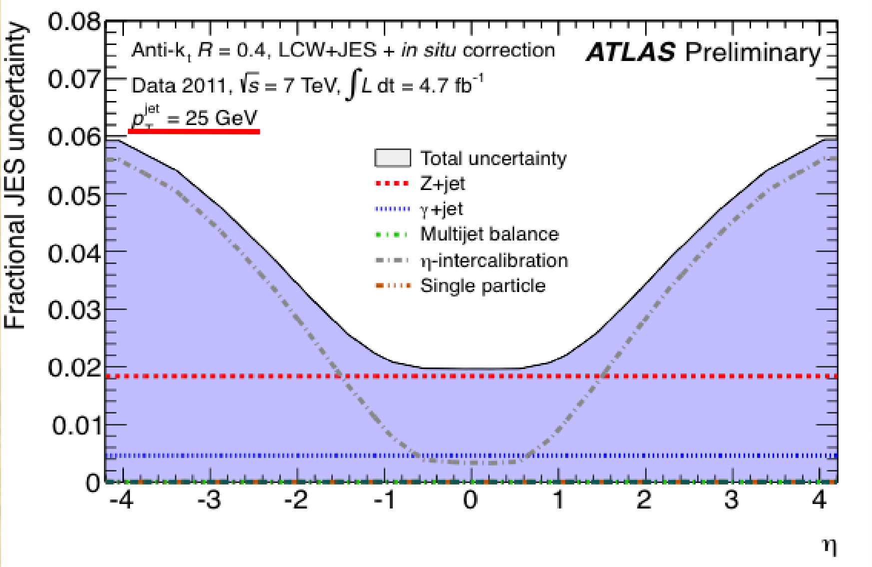


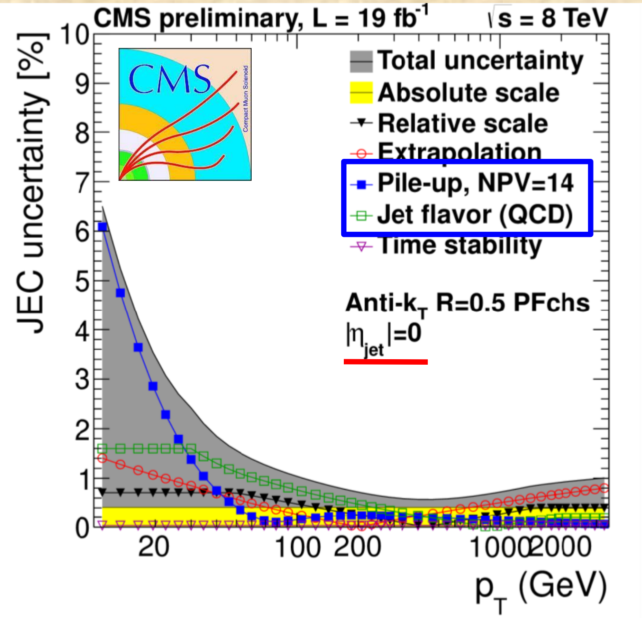
Absolute Energy Scale

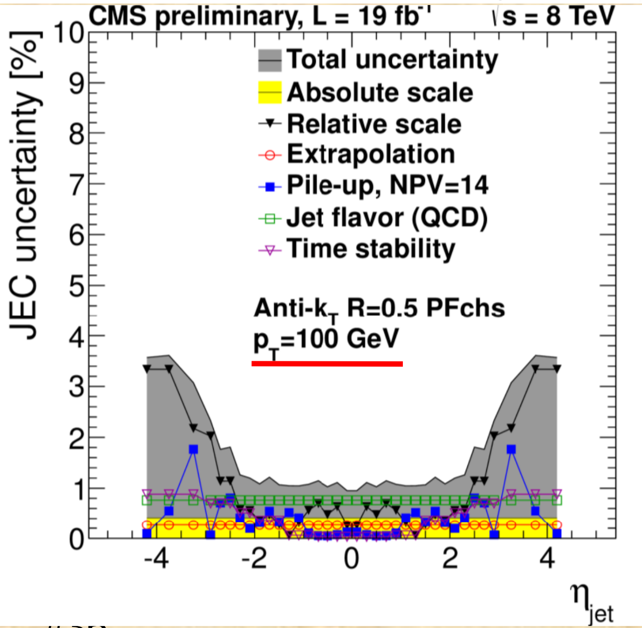


Uncertainties on JES - LHC









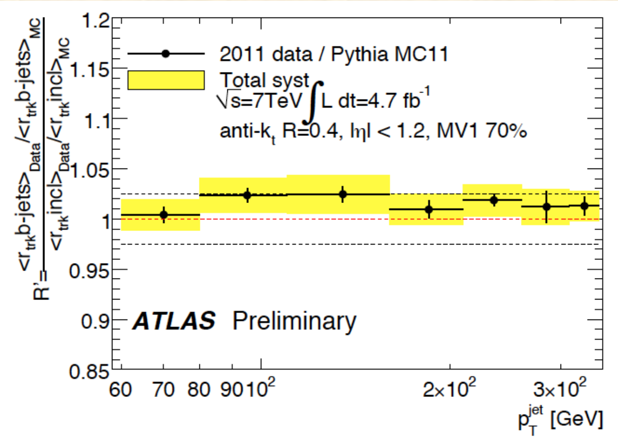
TRIUMF

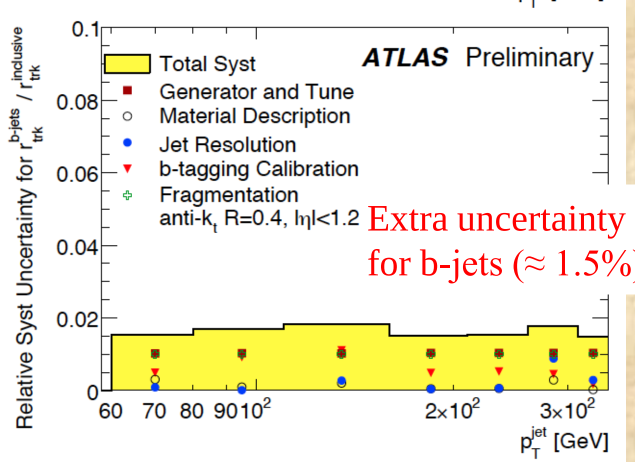
Simon Fraser

Heavy Flavour jets

- b-jets can contain muons & neutrinos ➔ yet another response
- Use b-tagged jets in ttbar events to test the Monte Carlo:
  - compare track jets to calo jets
  - take the double-ratio data/MC
  - compare b-jets & light jets

$$r_{\mathrm{trk}} = \frac{\sum \vec{p}_{\mathrm{T}}^{\,\mathrm{track}}}{p_{\mathrm{T}}^{\mathrm{jet}}} \qquad R_{r_{\mathrm{trk}}} \equiv \frac{\langle r_{\mathrm{trk}} \rangle_{\mathrm{Data}}}{\langle r_{\mathrm{trk}} \rangle_{\mathrm{MC}}} \qquad R' \equiv \frac{R_{r_{\mathrm{trk}},b\text{-jet}}}{R_{r_{\mathrm{trk}},\mathrm{inclusive}}}$$





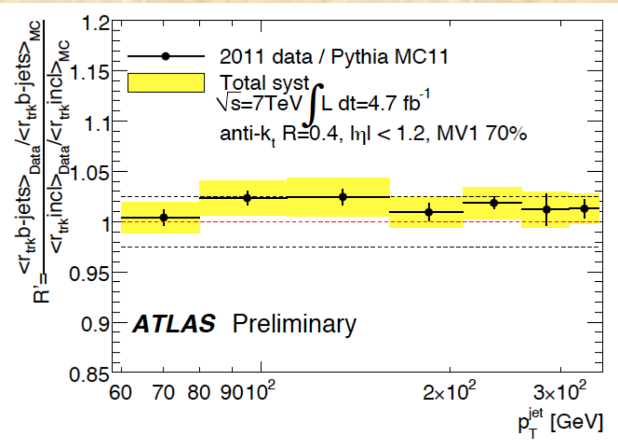
Extra uncertainty for b-jets (≈ 1.5%)

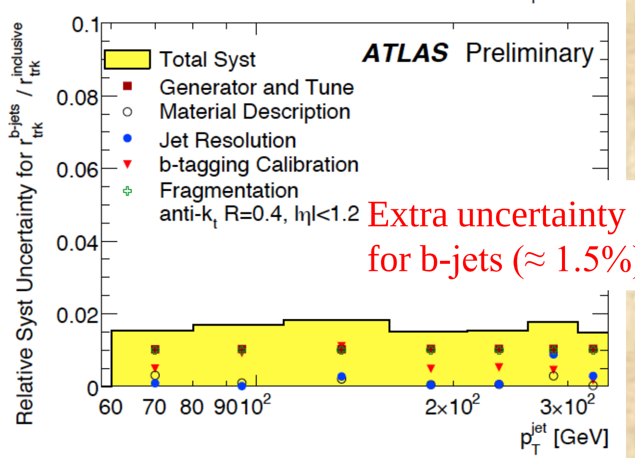
Heavy Flavour jets

- b-jets can contain muons & neutrinos ➔ yet another response
- Use b-tagged jets in ttbar events to test the Monte Carlo:
  - compare track jets to calo jets
  - take the double-ratio data/MC
  - compare b-jets & light jets

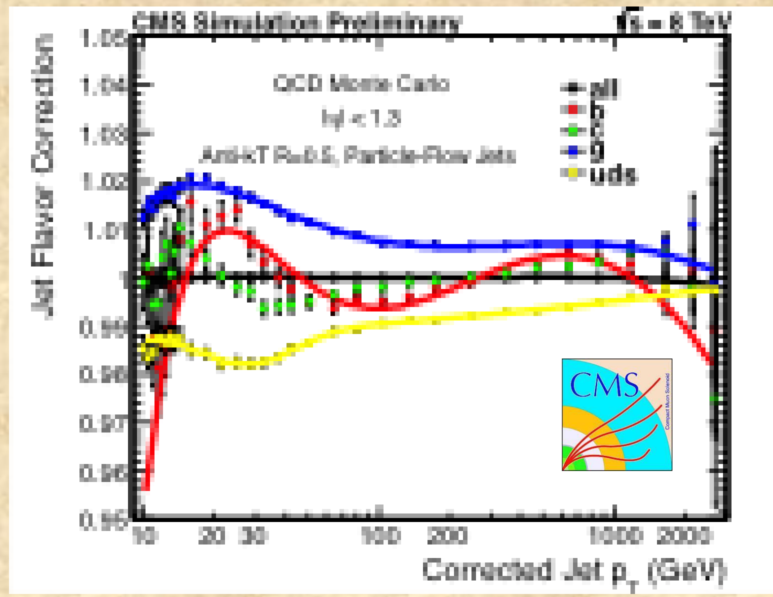
$$r_{\mathrm{trk}} = \frac{\sum \vec{p}_{\mathrm{T}}^{\,\mathrm{track}}}{p_{\mathrm{T}}^{\mathrm{jet}}} \qquad R_{r_{\mathrm{trk}}} \equiv \frac{\langle r_{\mathrm{trk}} \rangle \mathrm{Data}}{\langle r_{\mathrm{trk}} \rangle \mathrm{MC}} \qquad R' \equiv \frac{R_{r_{\mathrm{trk}},b\text{-jet}}}{R_{r_{\mathrm{trk}},\mathrm{inclusive}}}$$

Validate the Monte Carlo





Extra uncertainty for b-jets (≈ 1.5%)



No specific bJES uncertainty needed

Simon Fraser