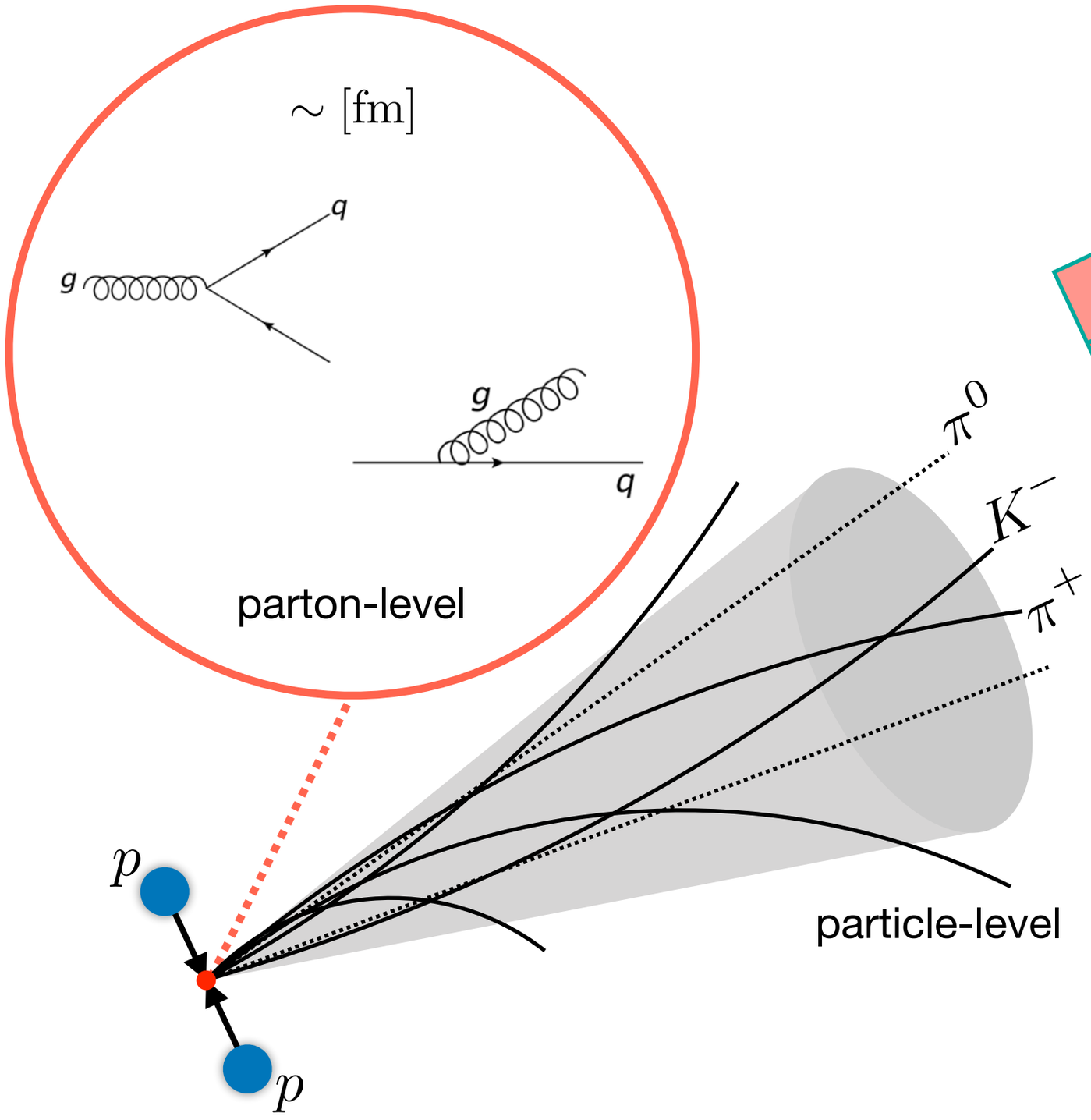
Measuring jet energy with the ATLAS detector

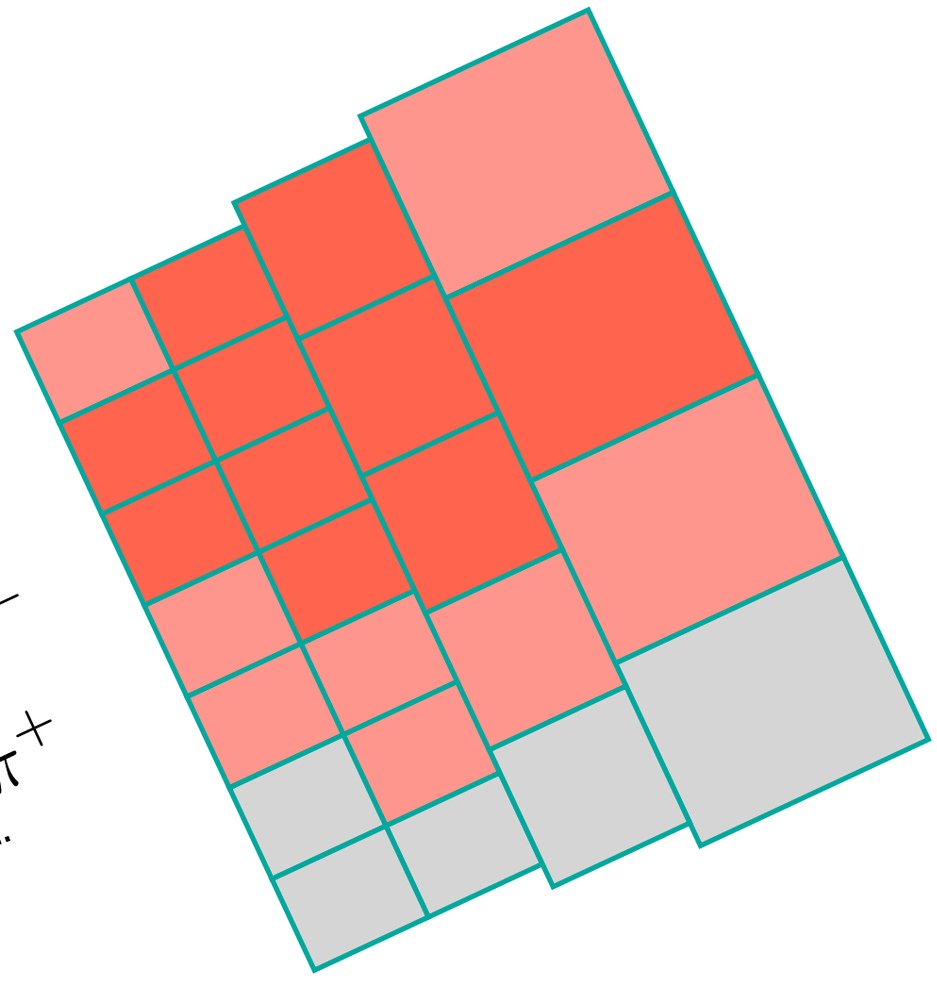
Tae Hyoun Park

February 17th, 2018
Winter Nuclear and Particle Physics Conference

Jets: what are they?

Jets are **collimated sprays of hadronic particles** produced in proton-proton collisions at the Large Hadron Collider.

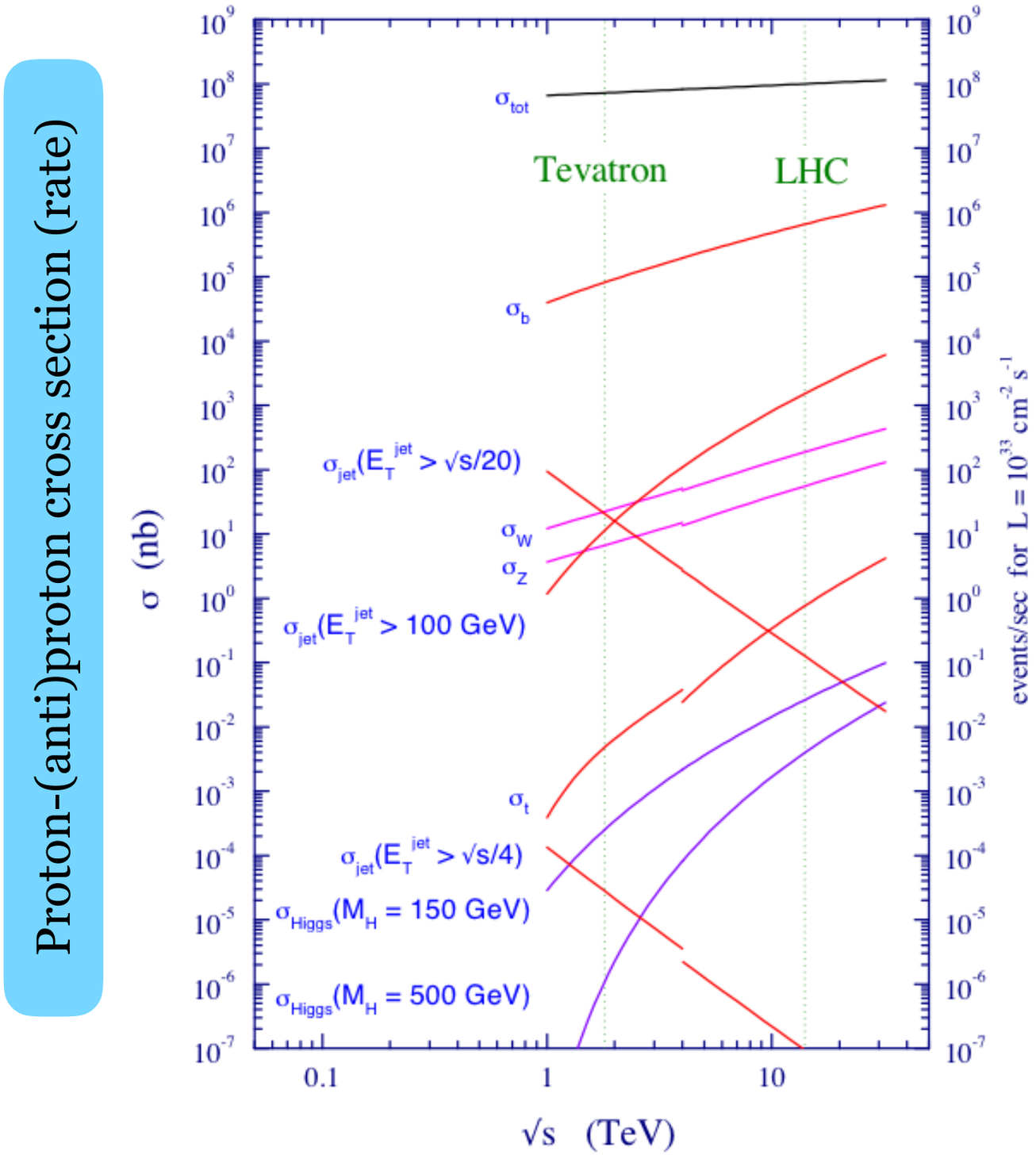




calorimeter energy
$\Rightarrow$ reconstructed jet
$\sim$ [m]

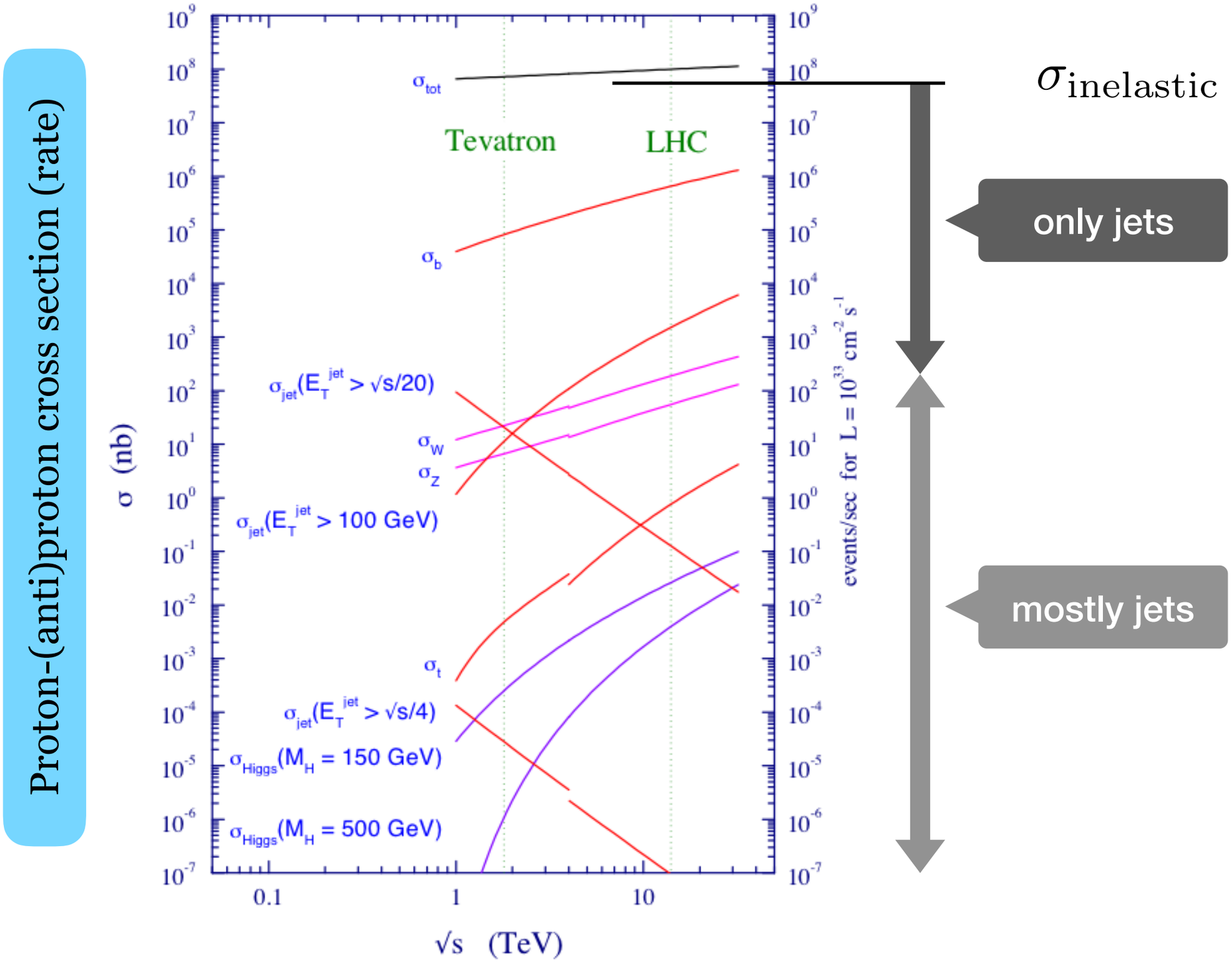
Jets: why are they important?

Jets are **(by far) the most dominant final state objects** produced in the proton-proton collisions at the Large Hadron Collider.



Jets: why are they important?

Jets are **(by far) the most dominant final state objects** produced in the proton-proton collisions at the Large Hadron Collider.

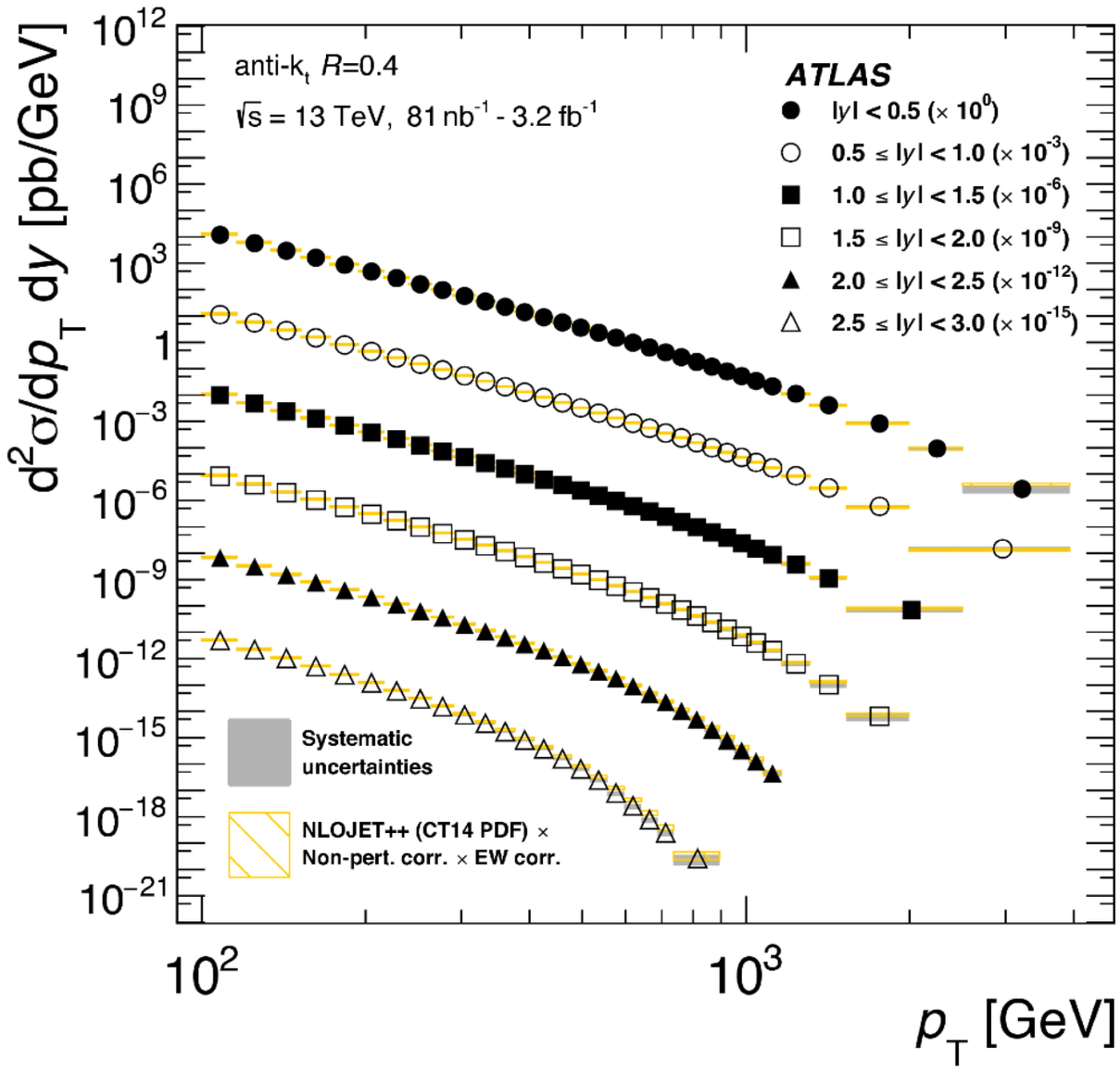


Jets: why are they important?

Jets are **key ingredients to study physics** (test the Standard Model, search for new phenomena, etc.) in the proton-proton collisions at the Large Hadron Collider.

CERN-EP-2017-157

Cross section of inclusive jet production



Jet transverse momentum

Jets: why are they important?

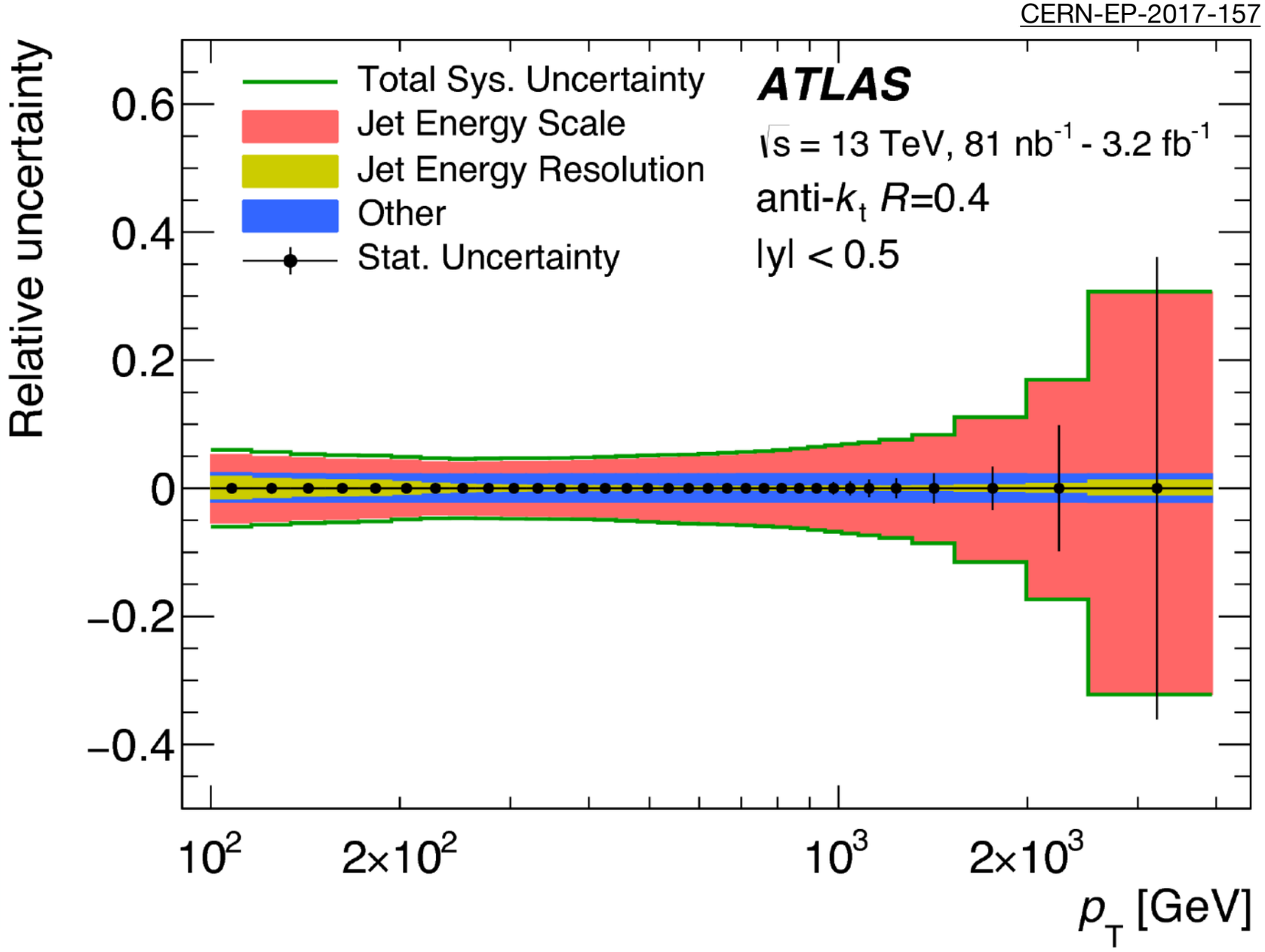
Jet energy calibration (scale) & resolution are the **important systematics** in many of these physics analyses.

Cross section of inclusive jet production

$\pm\Delta$

Relative uncertainty in cross section

CERN-EP-2017-157

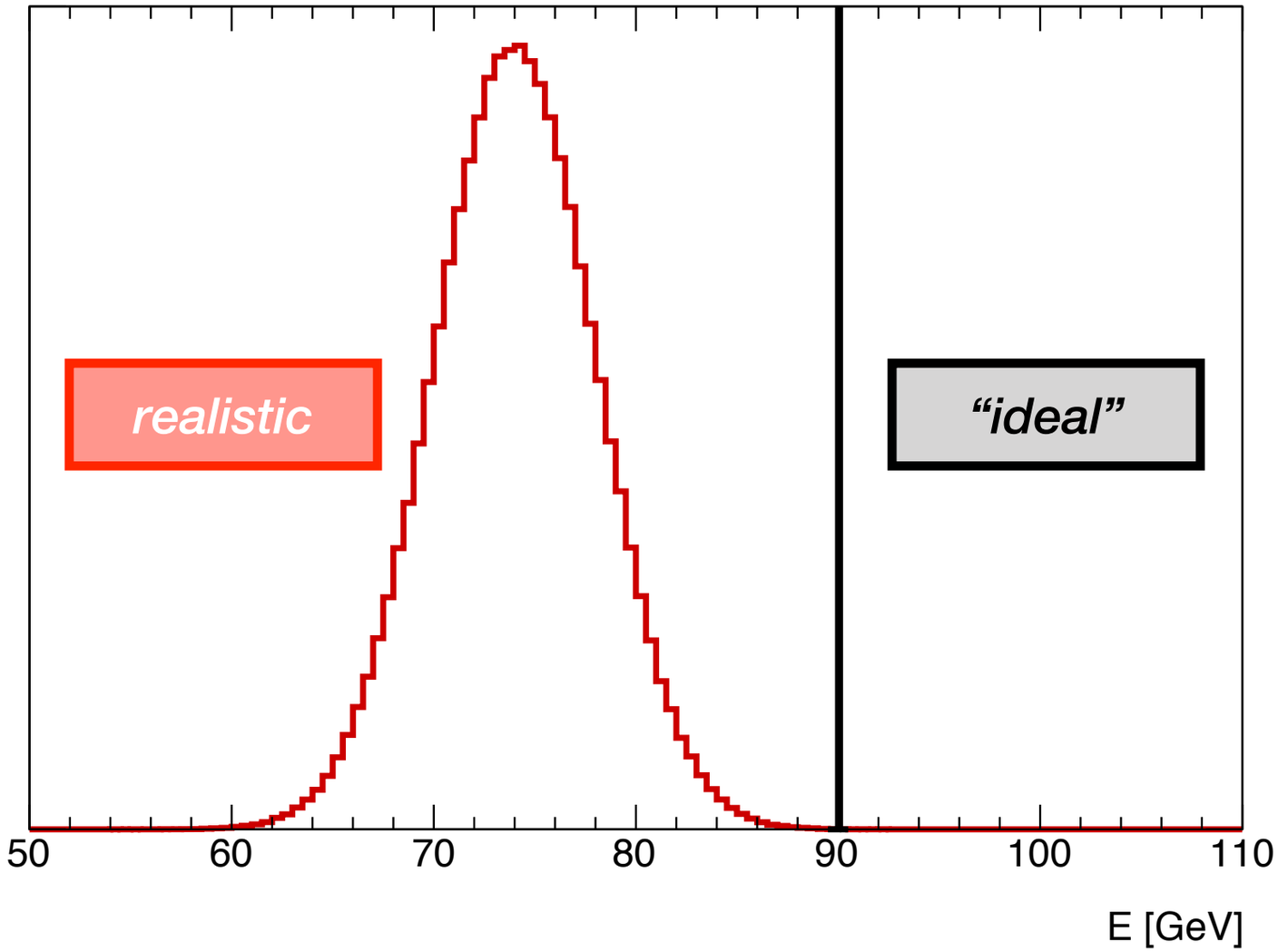


Jet transverse momentum

Energy measurement: example

Calorimeter

$$\pi^+ \longleftarrow$$
$$E = 90\,\mathrm{GeV}$$



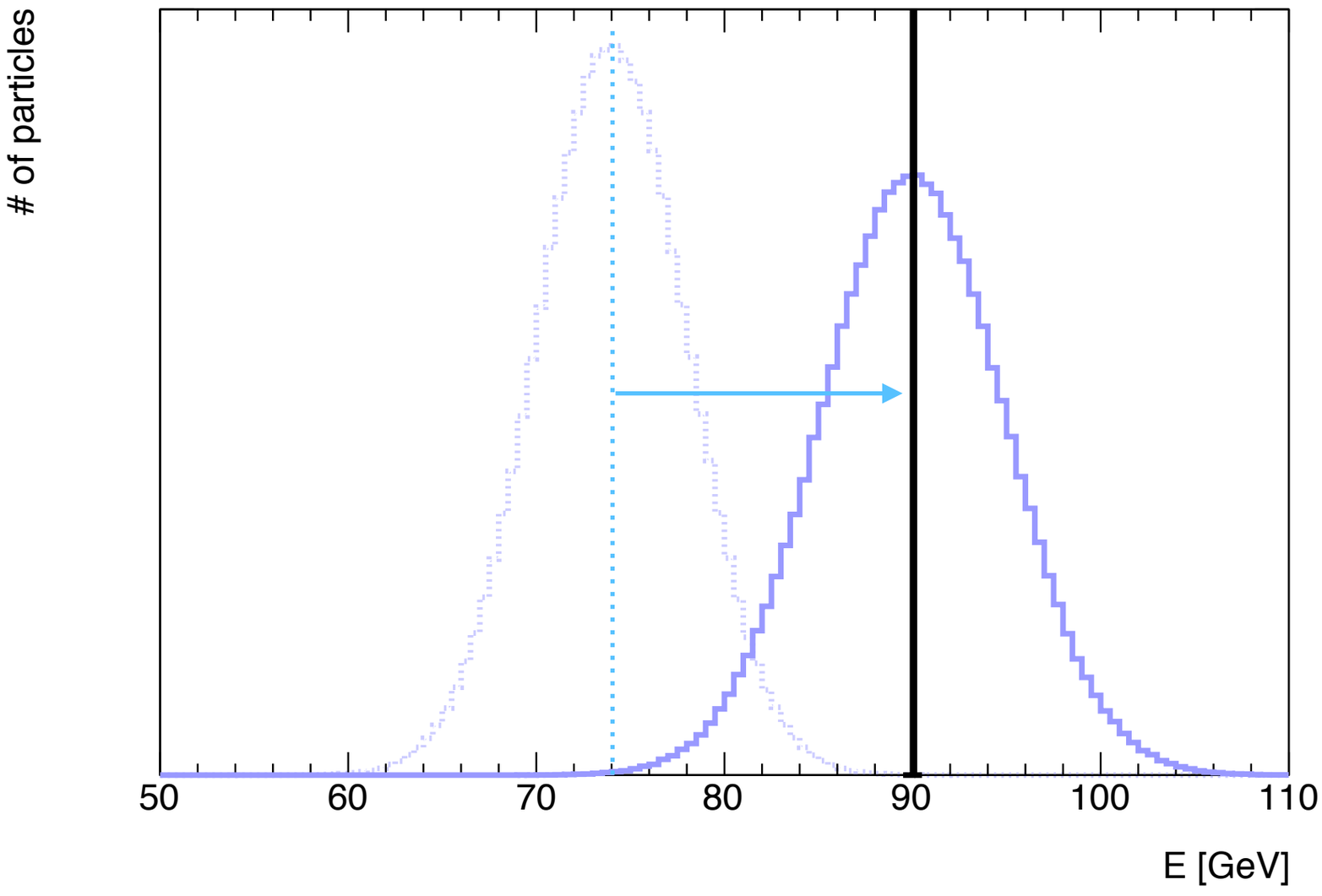
Consider injecting a beam of pions with precise energy into a calorimeter

The ATLAS calorimeters are non-compensating: hadrons are measured on average with less energy compared to electrons and photons

Energy measurement: example

Calorimeter

$$\pi^+ \longleftarrow E = 90\,\mathrm{GeV}$$



Consider injecting a beam of pions with precise energy into a calorimeter

The ATLAS calorimeters are non-compensating: hadrons are measured on average with less energy compared to electrons and photons

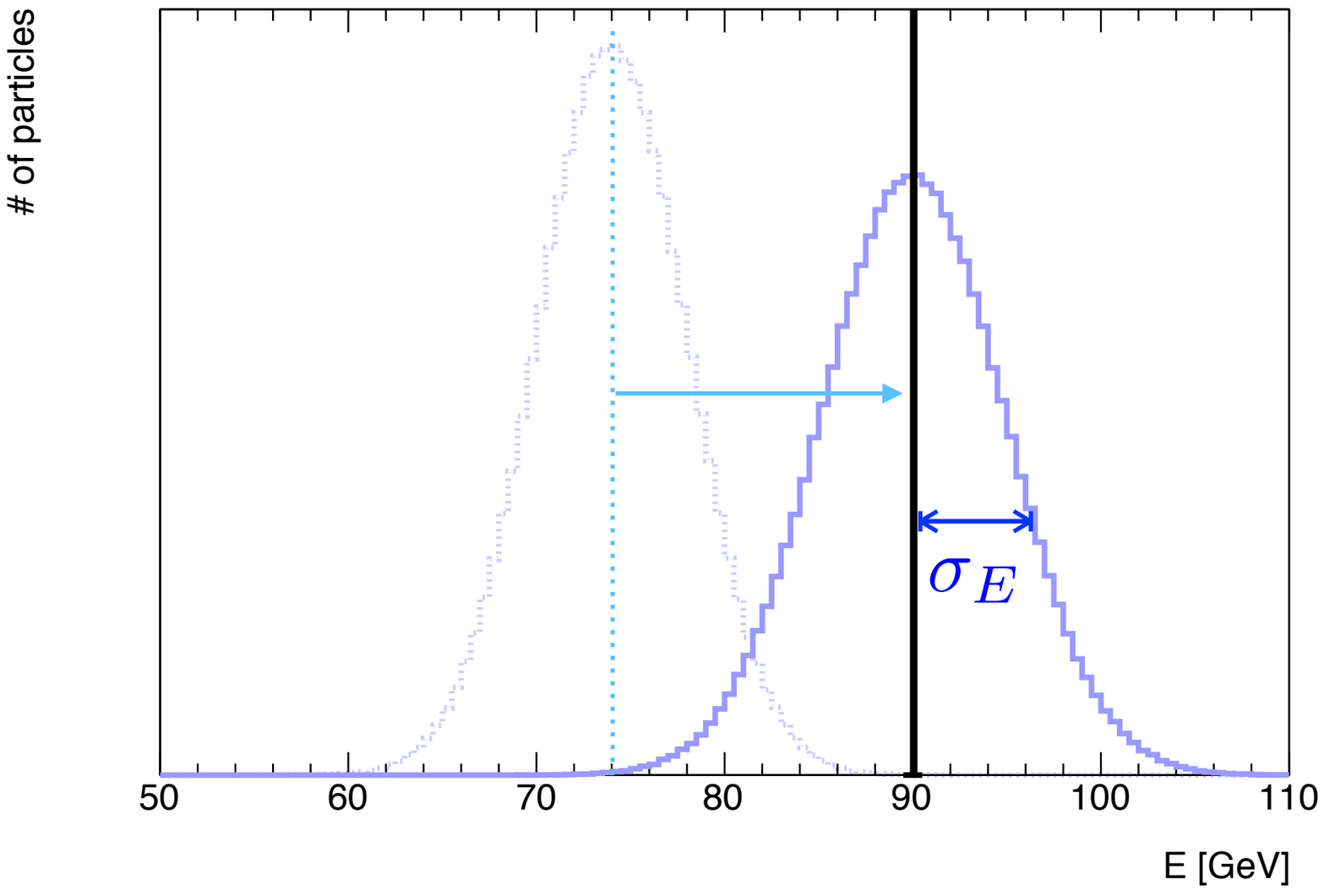
1. Calibration: scale measurement to true value (on average)

Energy measurement: example

Calorimeter

$$\pi^+ \longleftarrow$$

$$E = 90\,\mathrm{GeV}$$



Consider injecting a beam of pions with precise energy into a calorimeter

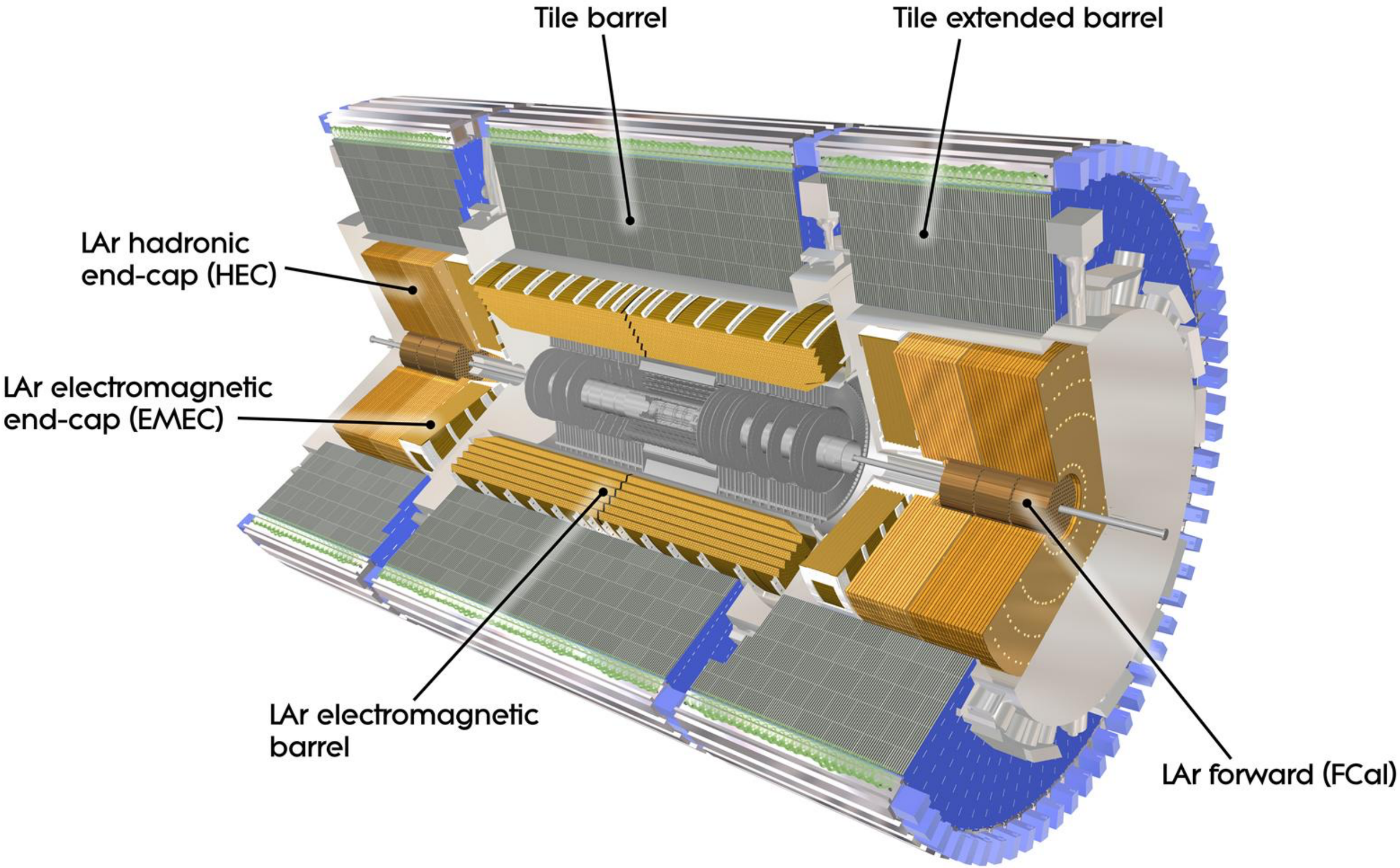
The ATLAS calorimeters are non-compensating: hadrons are measured on average with less energy compared to electrons and photons

1. Calibration: scale measurement to true value (on average)

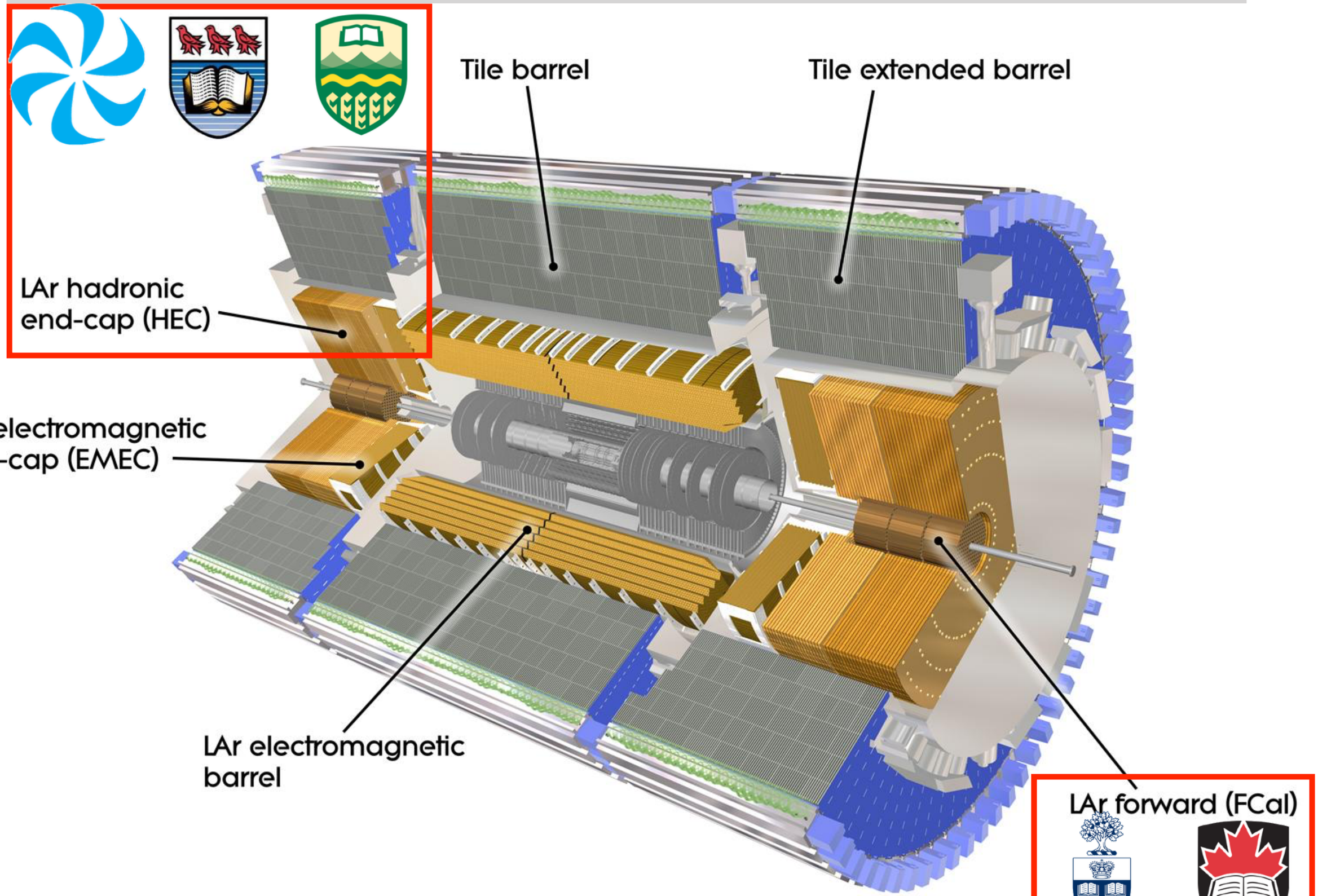
2. Resolution: the standard deviation (approx. gaussian)

$$\frac{\sigma_E}{E} = ?$$

ATLAS calorimeters

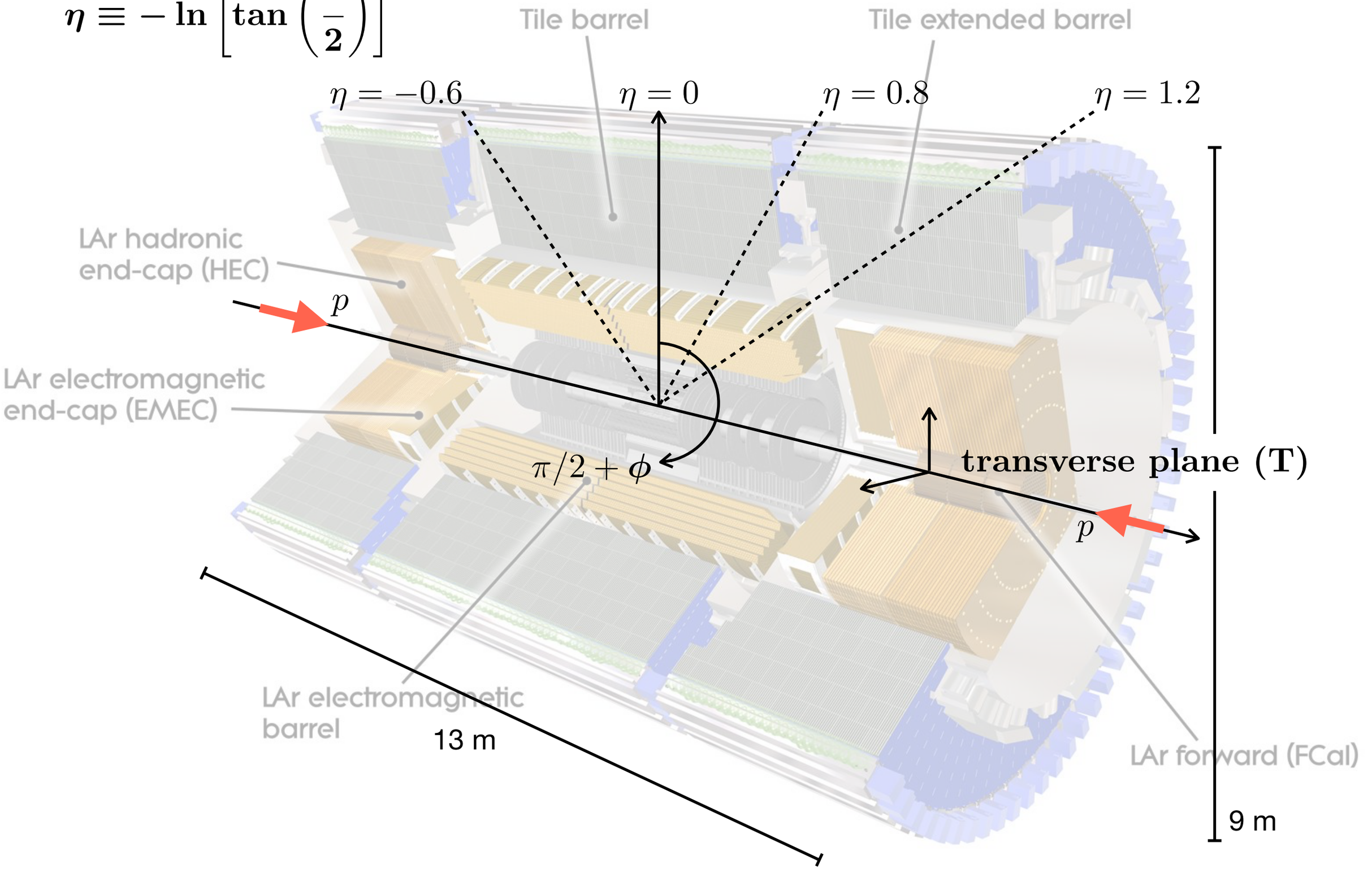


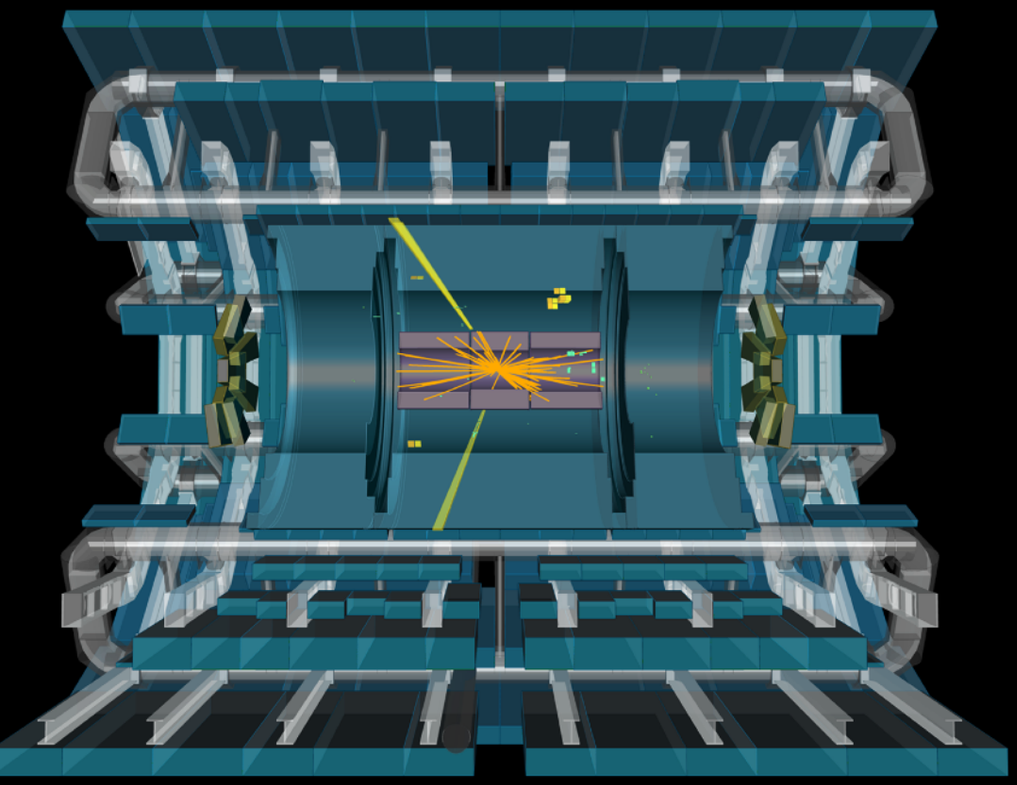
ATLAS calorimeters

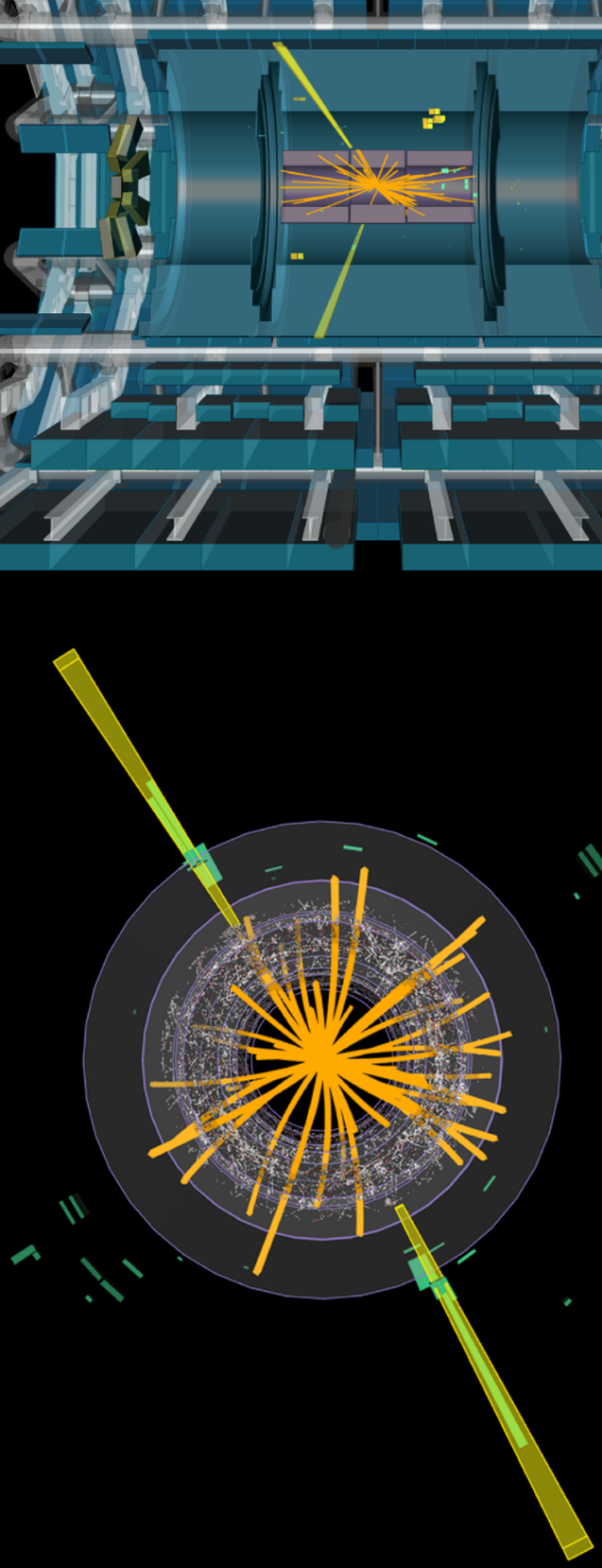


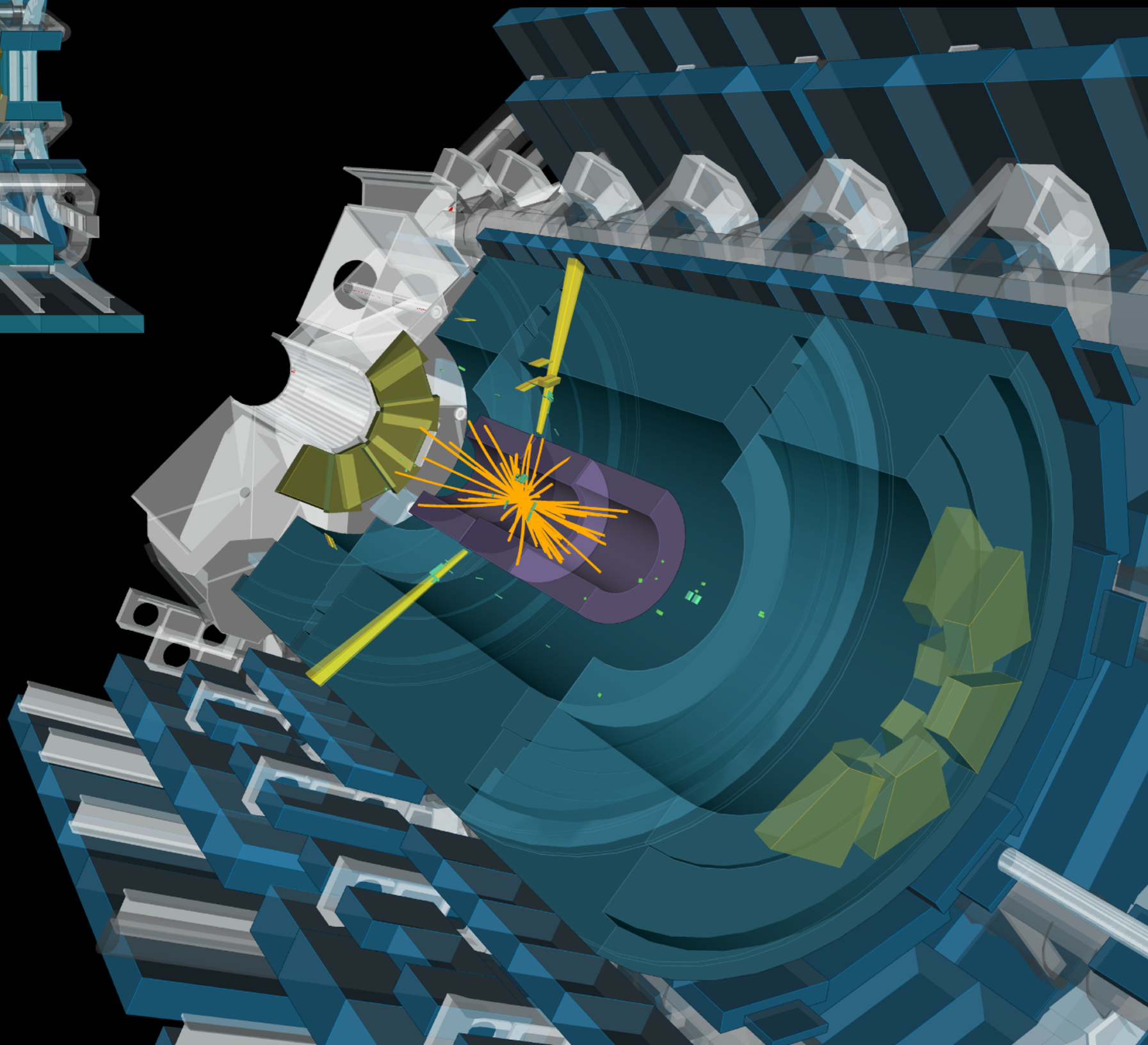
ATLAS calorimeters

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



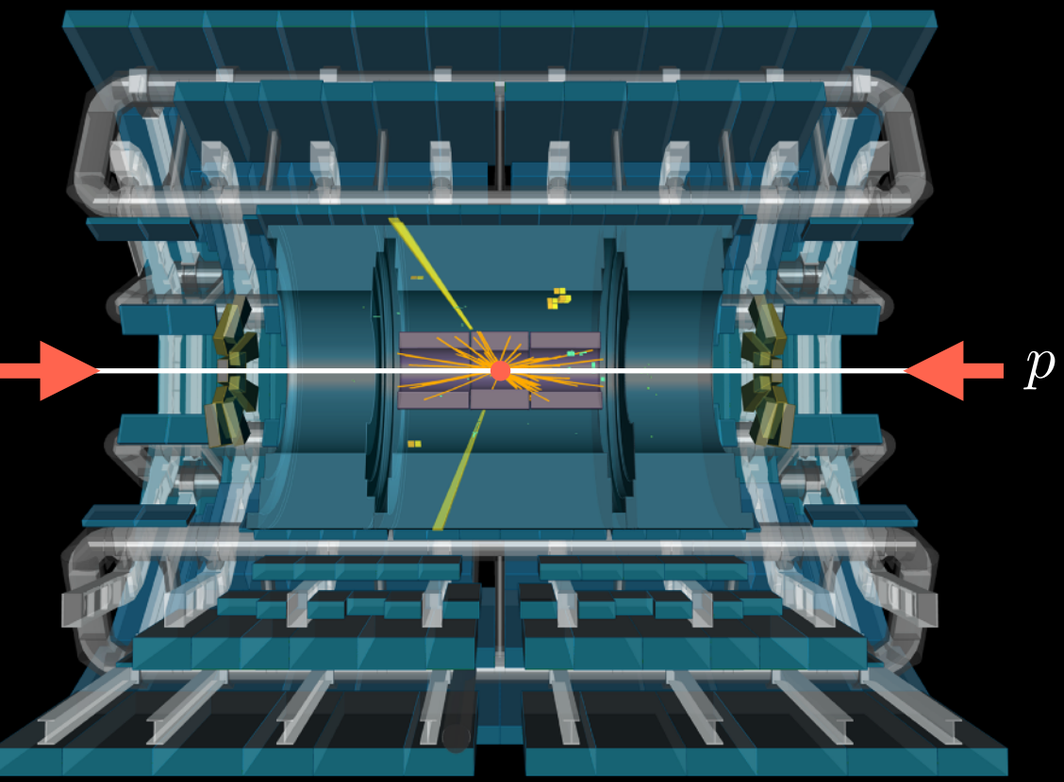


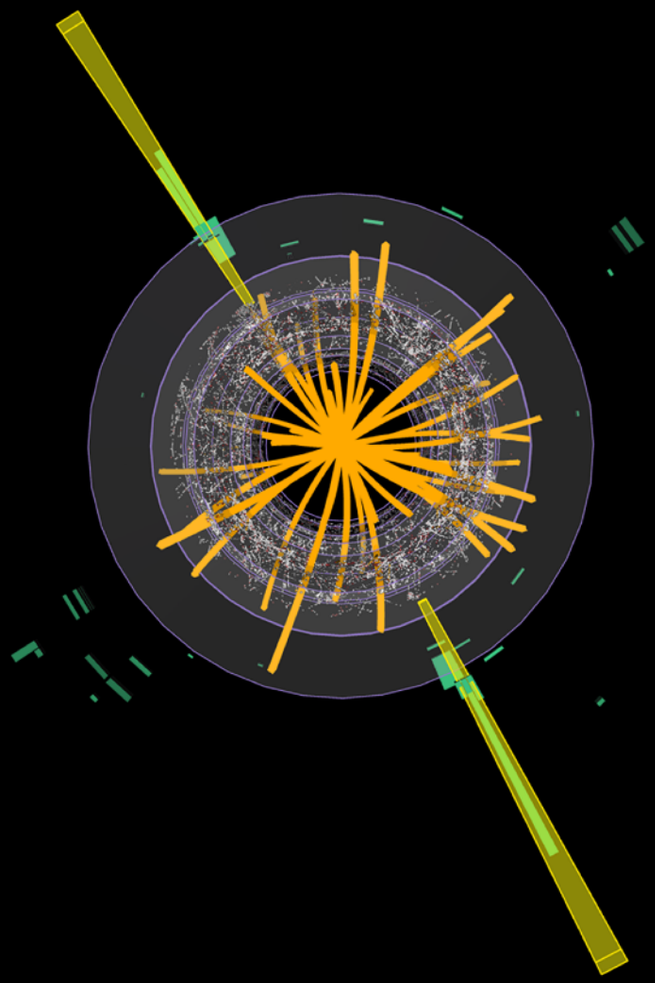


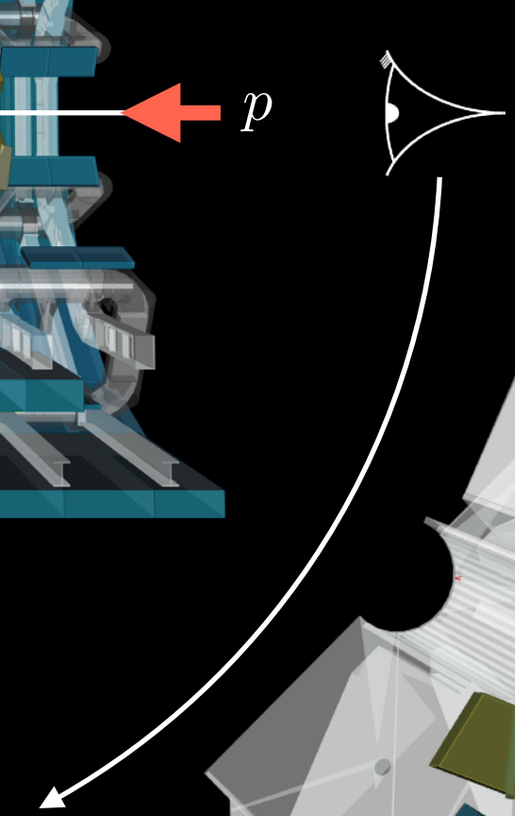


Run: 191426
Event: 86694500
2011-10-22 17:30:29 CEST

ATLAS EXPERIMENT
http://atlas.ch







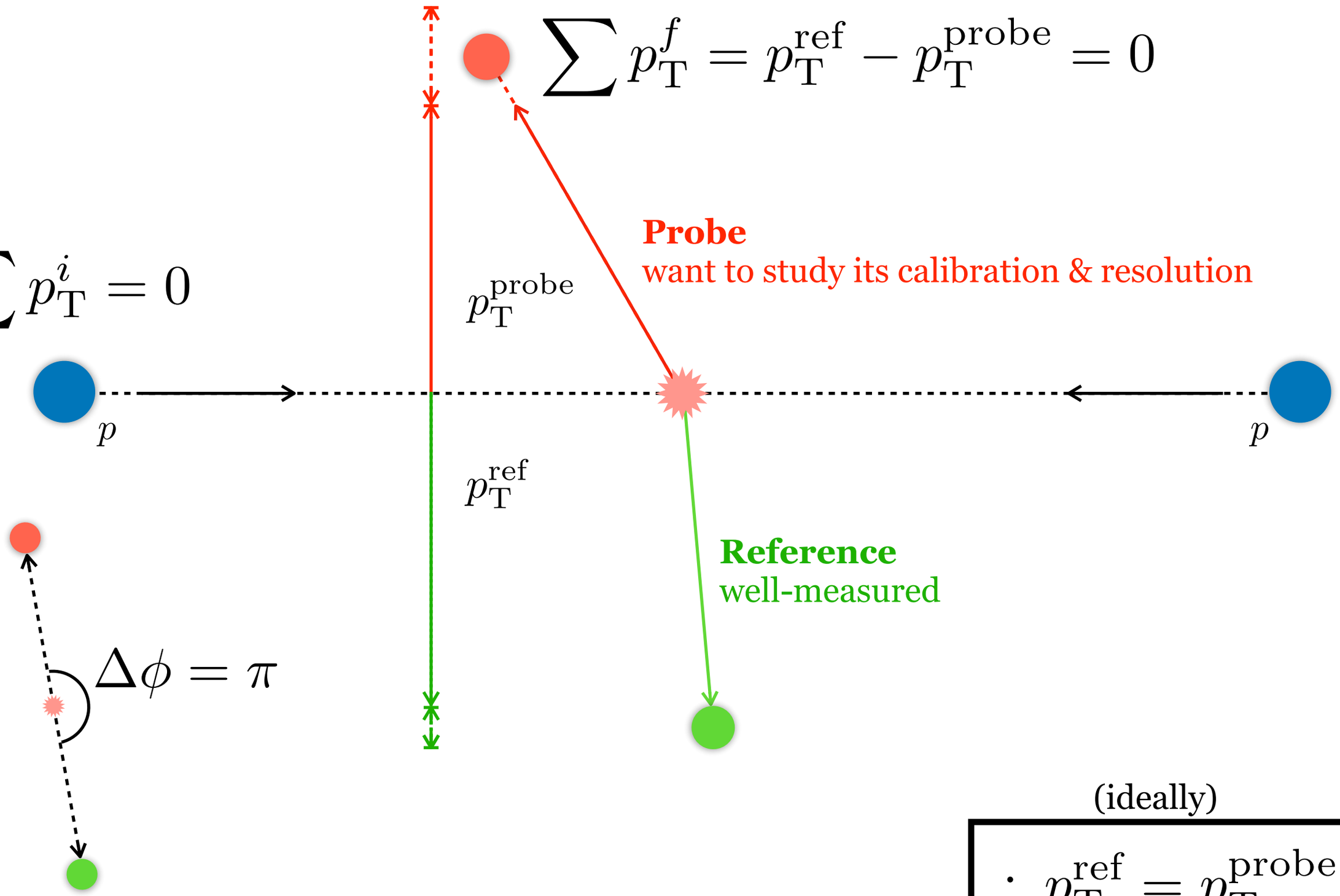
Run: 191426
Event: 86694500
2011-10-22 17:30:29 CEST

ATLAS EXPERIMENT
http://atlas.ch

Conservation of momentum

$$\sum p_{\mathrm{T}}^{f} = p_{\mathrm{T}}^{\mathrm{ref}} - p_{\mathrm{T}}^{\mathrm{probe}} = 0$$

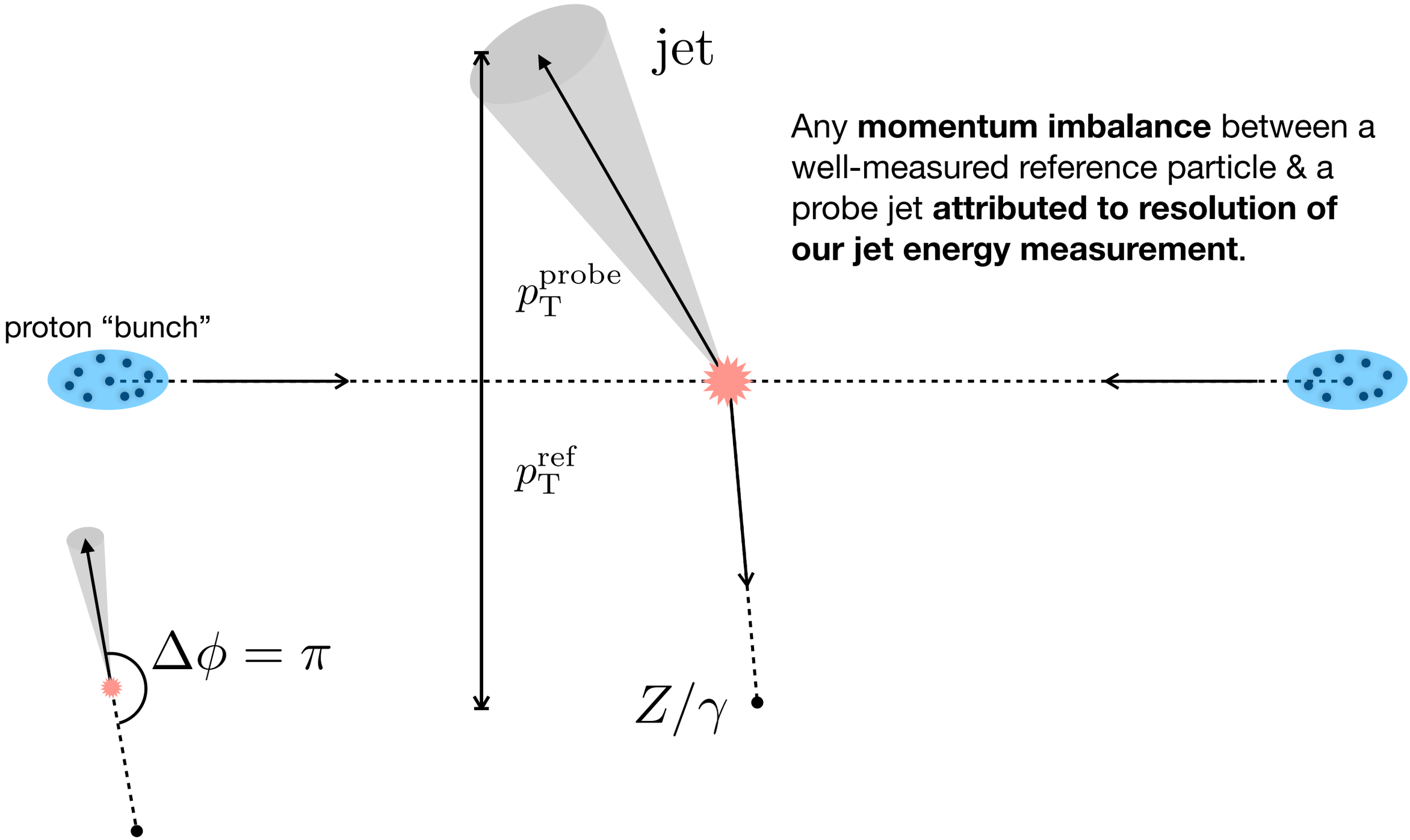
$$\sum p_{\mathrm{T}}^{i} = 0$$



(ideally)

$$\therefore p_{\mathrm{T}}^{\mathrm{ref}} = p_{\mathrm{T}}^{\mathrm{probe}}$$

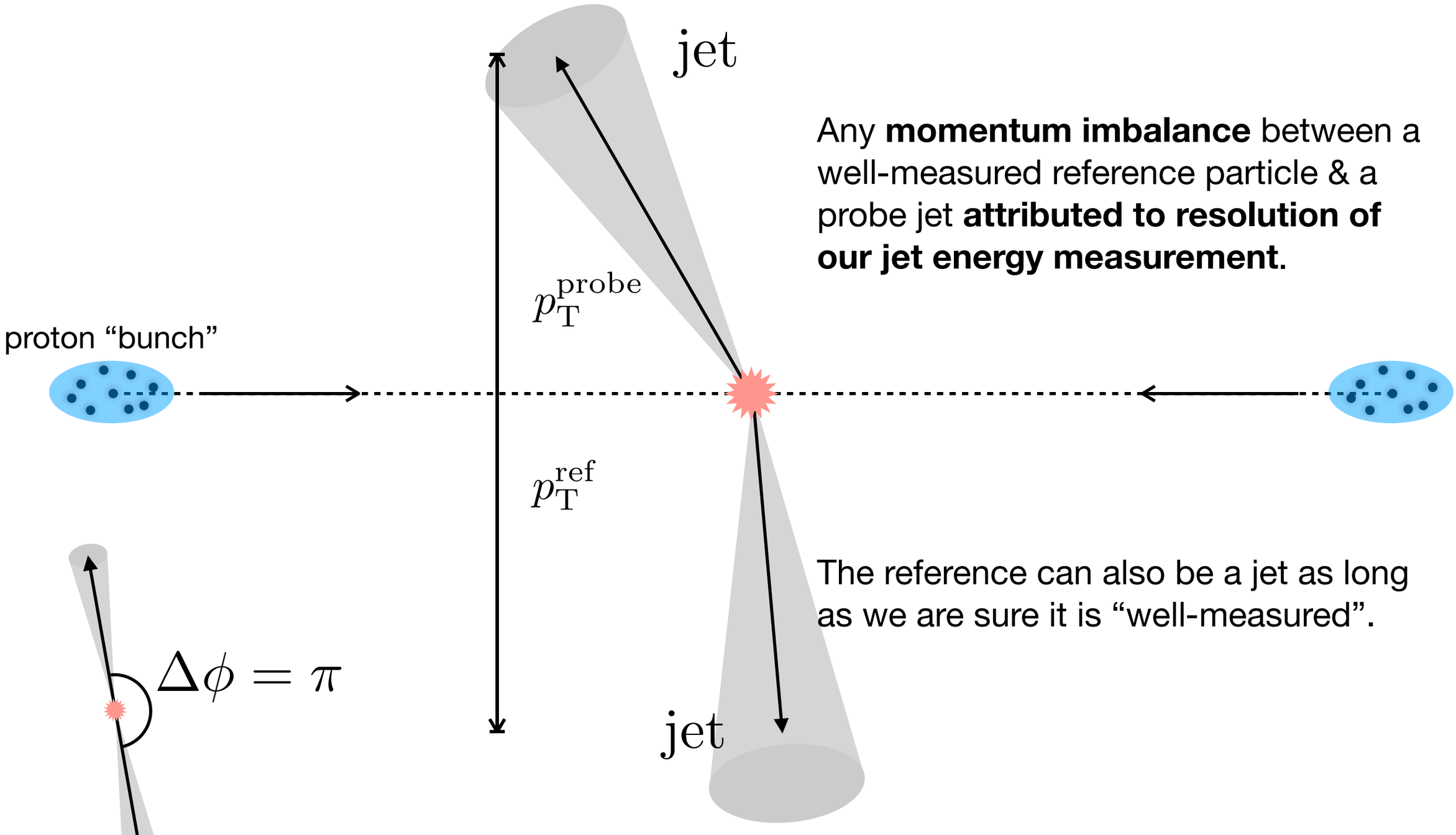
Conservation of momentum



Any **momentum imbalance** between a well-measured reference particle & a probe jet **attributed to resolution of our jet energy measurement.**

V+jet event

Conservation of momentum

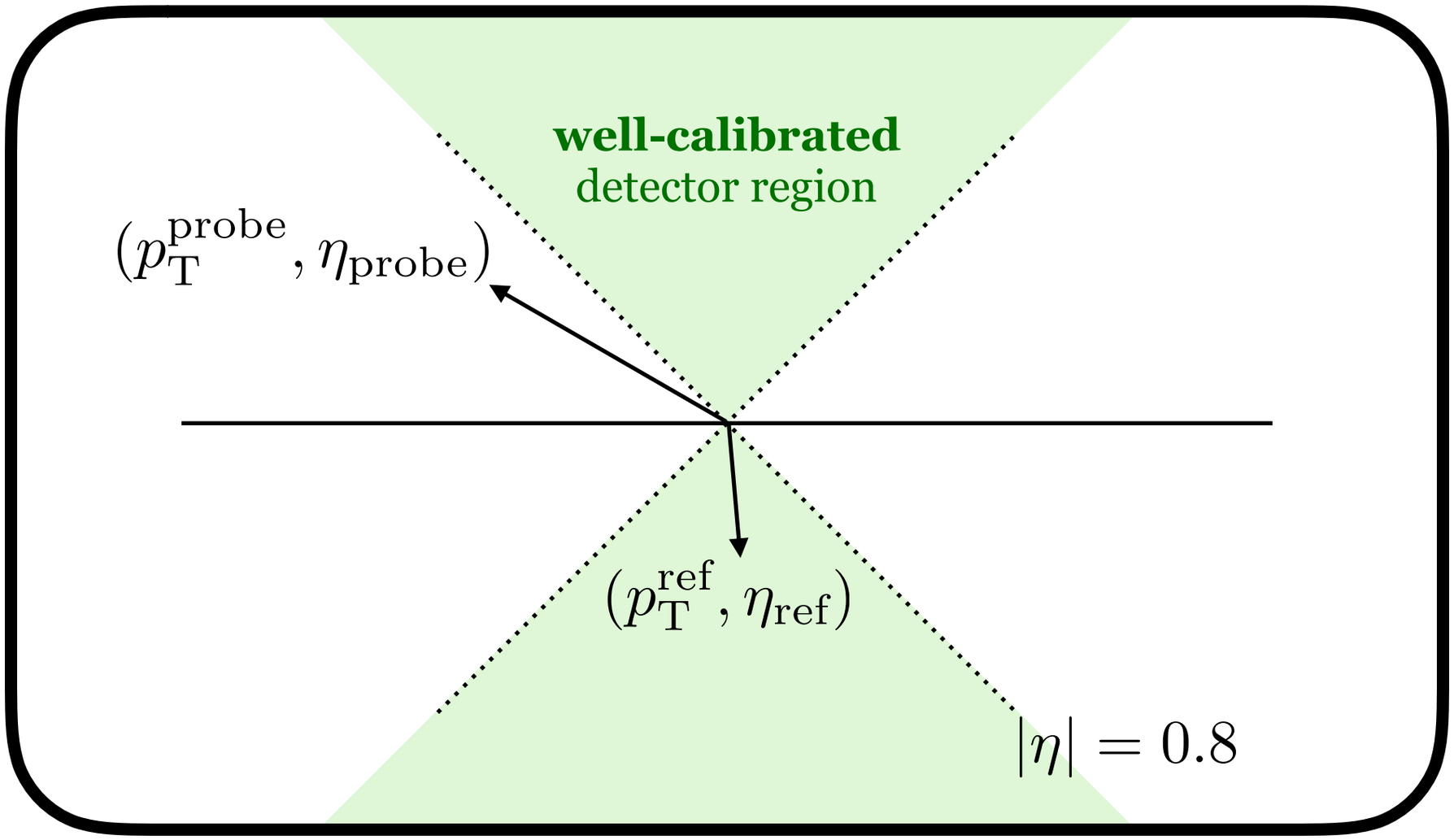


Any **momentum imbalance** between a well-measured reference particle & a probe jet **attributed to resolution of our jet energy measurement.**

The reference can also be a jet as long as we are sure it is “well-measured”.

dijet event

In-situ measurement

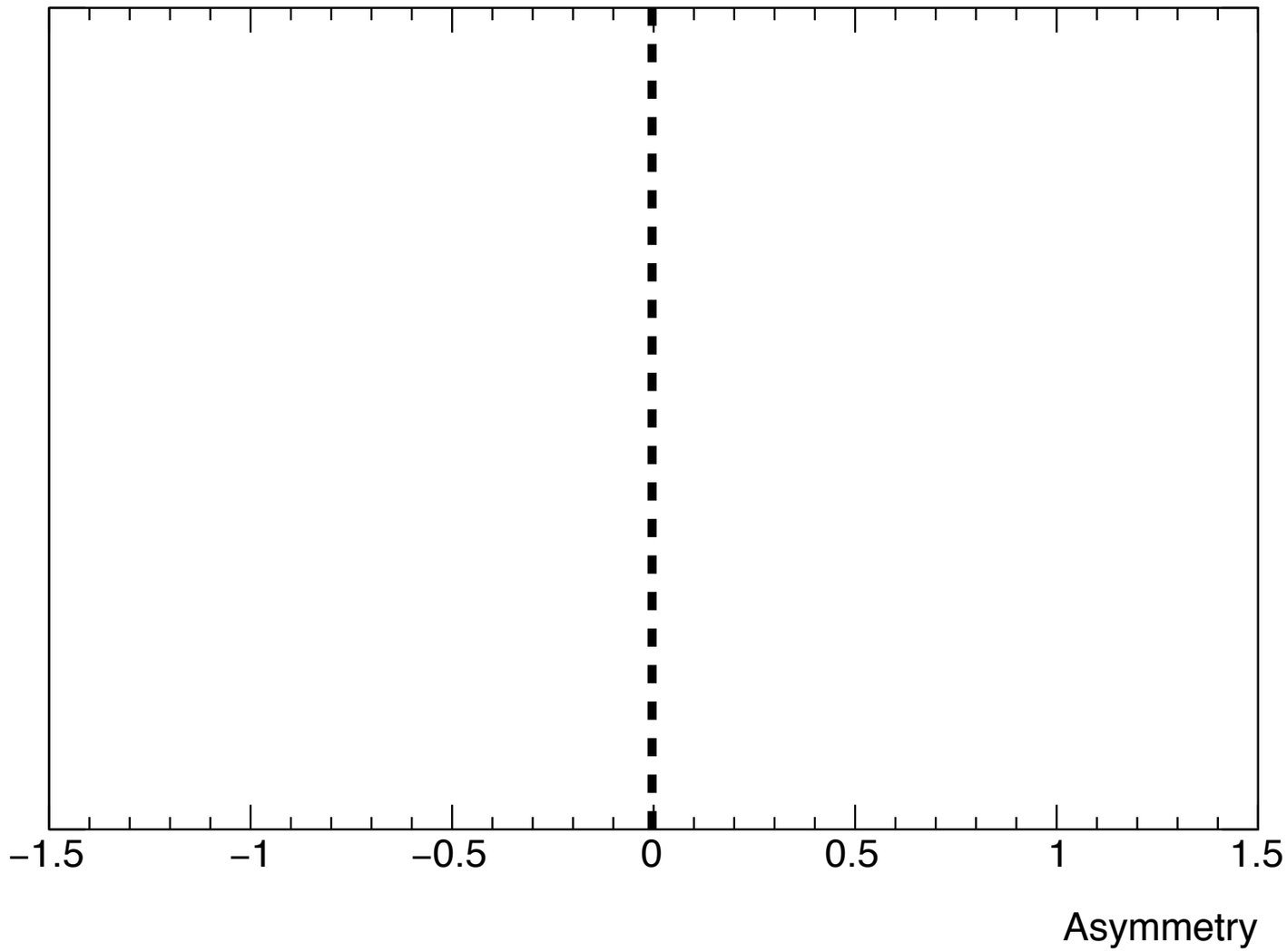


Define the **asymmetry** of the dijet system: $\mathcal{A} \equiv \dfrac{p_{\mathrm{T}}^{\mathrm{probe}} - p_{\mathrm{T}}^{\mathrm{ref}}}{p_{\mathrm{T}}^{\mathrm{avg}}}$

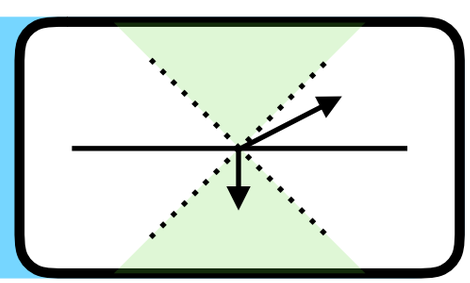
Study this quantity in **jet transverse momenta & detector region**: $\left(p_{\mathrm{T}}^{\mathrm{avg}}, \eta_{\mathrm{probe}}\right)$

Jet energy resolution

Perfect balance (calibration + resolution) will always give **zero asymmetry**.

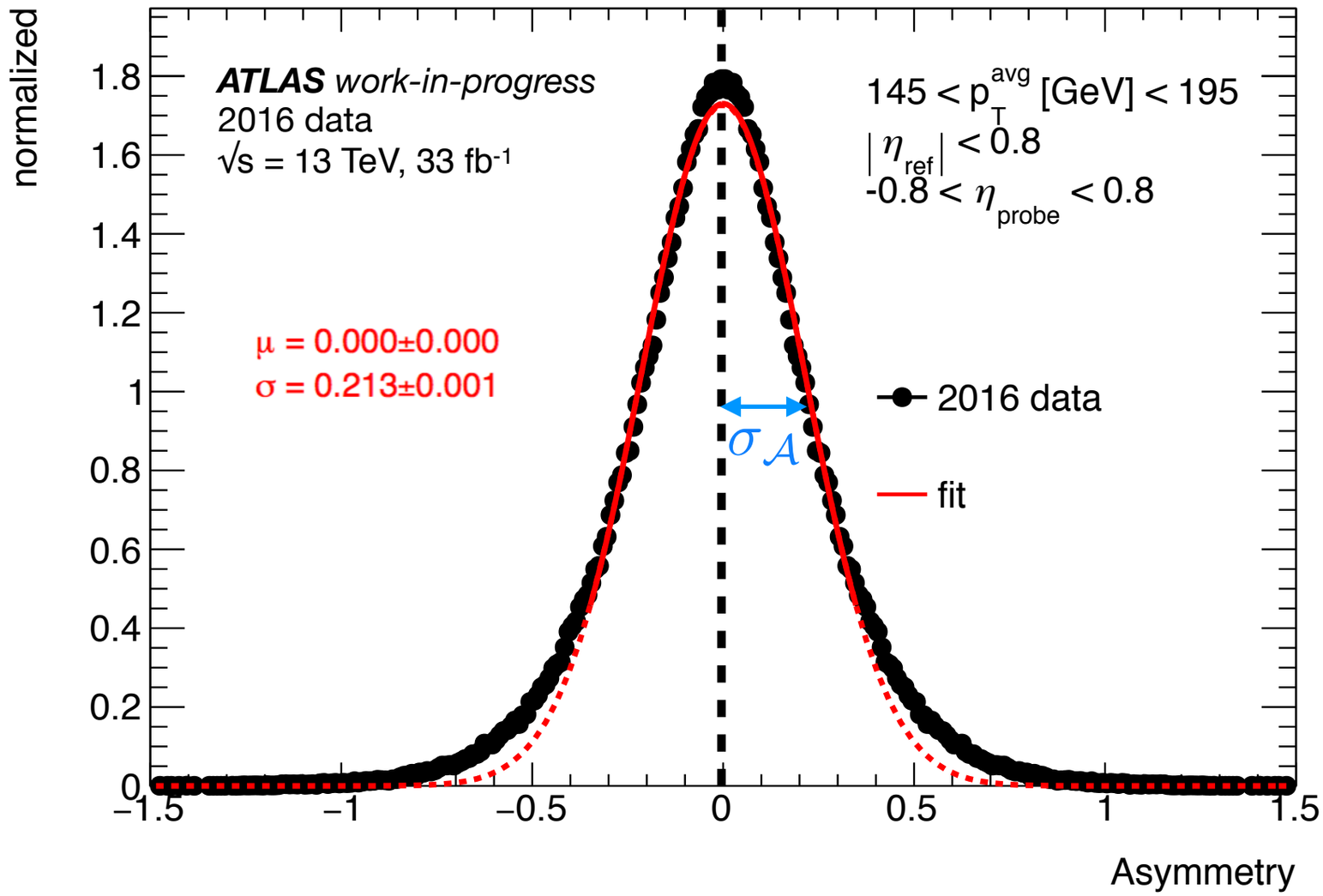


$$\sigma_{\mathcal{A}} = \left\langle \frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T}}} \right\rangle_{\mathrm{ref}} \oplus \left\langle \frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T}}} \right\rangle_{\mathrm{probe}}$$

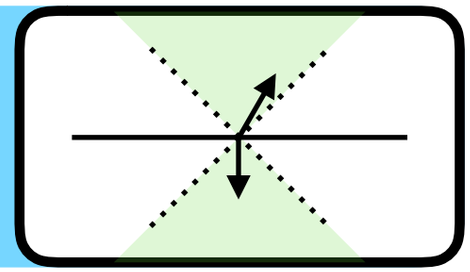


Jet energy resolution

Perfect balance (calibration + resolution) will always give zero asymmetry.
We observe a **width** around zero **due to energy resolution**.



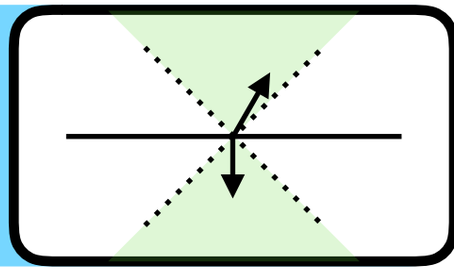
$$\left\langle \frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T}}} \right\rangle = \frac{\sigma_{\mathcal{A}}}{\sqrt{2}} \quad (|\eta_{\mathrm{probe}}| < 0.8)$$



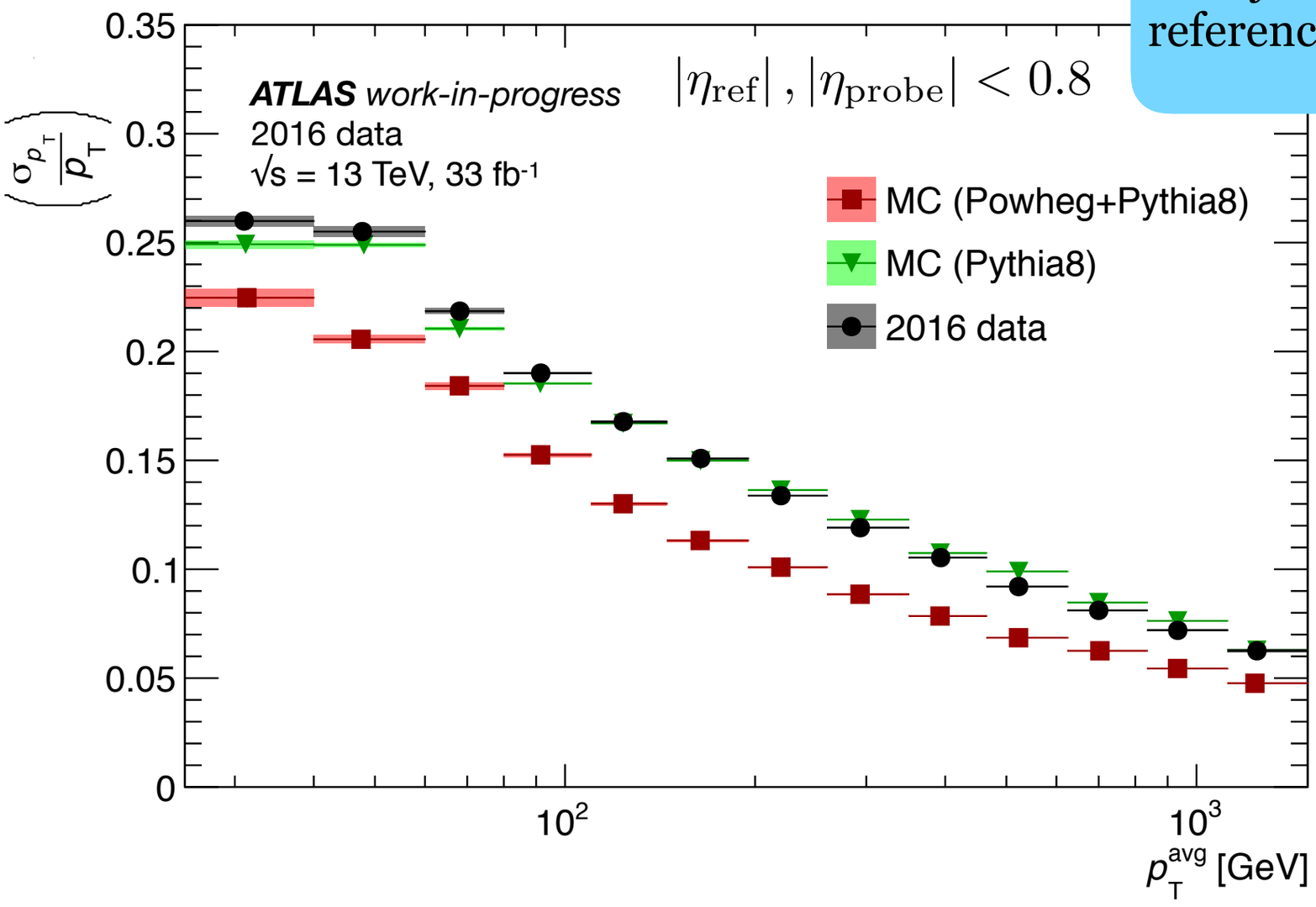
Jet energy resolution

First results of my work on **jet energy resolution** in **data collected in 2016**.
Monte Carlo simulations also studied for comparison.

both jets in reference region



relative jet energy resolution



$$* \quad \frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T}}} \approx \frac{\sigma_E}{E}$$

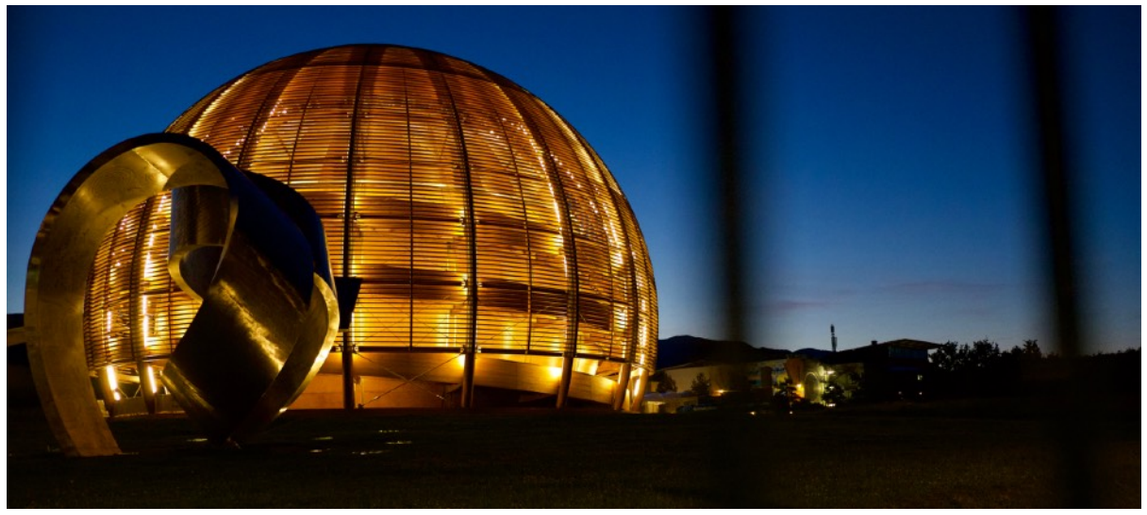
jet transverse momentum

Summary

- Detailed understanding of ATLAS detector's jet energy measurement is crucial for the experiment's physics analyses.

- Work is ongoing to determine the jet energy resolution in-situ using 2015-2017 data.

Thank you



Carleton UNIVERSITY

ATLAS EXPERIMENT

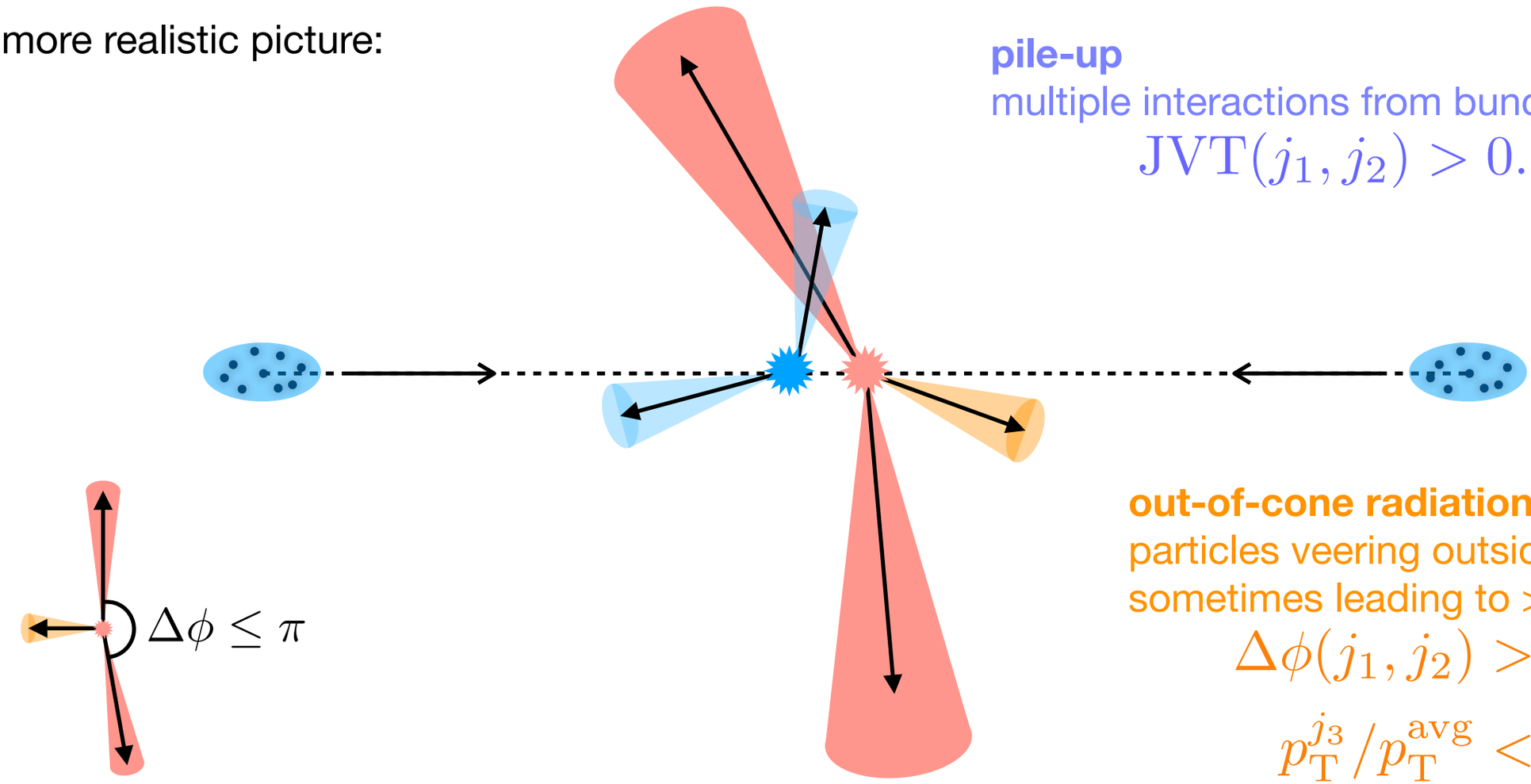
CERN

Backup

“Dijet” event?

Strictly speaking, a **dijet event** in data is a one which **exhibits dijet topology:** this is not necessarily a true dijet event!

more realistic picture:



$\Delta\phi \leq \pi$

pile-up
multiple interactions from bunch crossing

$$\mathrm{JVT}(j_1, j_2) > 0.59$$

out-of-cone radiation
particles veering outside jet cone
sometimes leading to >2 jets

$$\Delta\phi(j_1, j_2) > 2.5$$

$$p_{\mathrm{T}}^{j_3} / p_{\mathrm{T}}^{\mathrm{avg}} < 0.4$$

dijet event
what we want to study

consequence: these selections introduce systematics that must be carefully studied.

Why the slope?

Resolution of a sampling calorimeter typically take the form

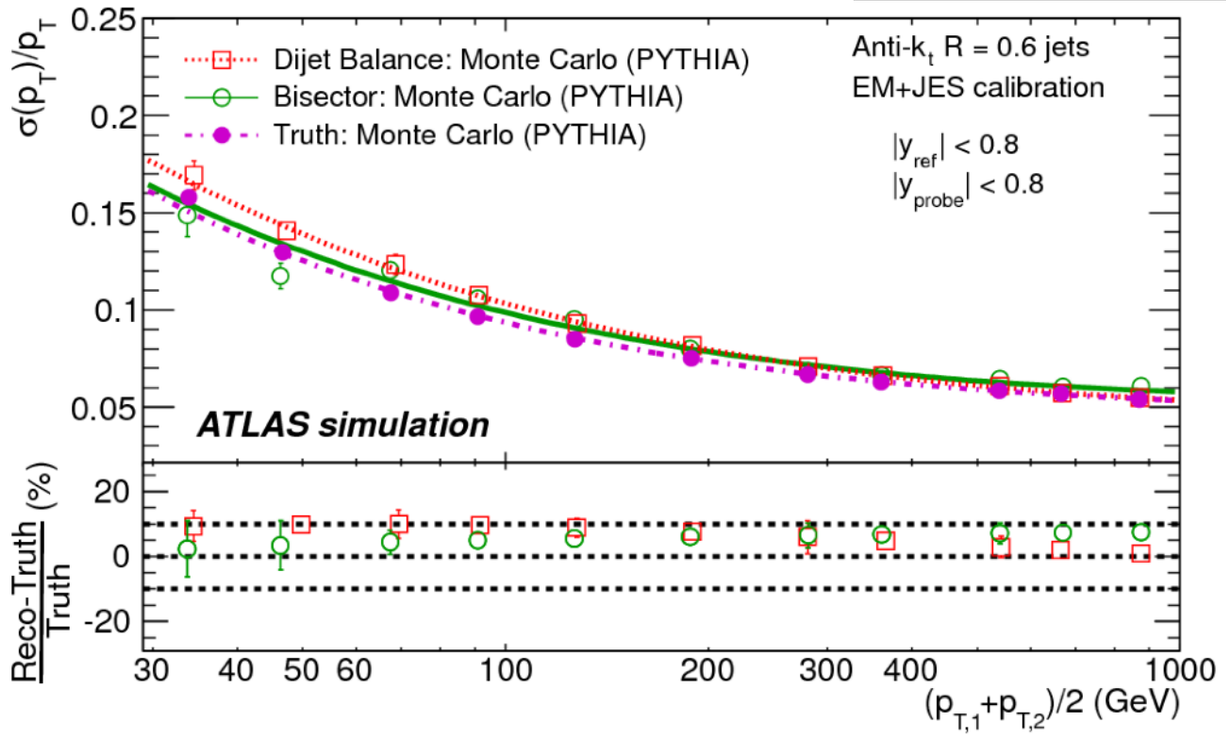
$$\frac{\sigma}{E} = \frac{N}{E} \oplus \frac{S}{\sqrt{E}} \oplus C$$

Noise : processes independent of jet energy
- electronic noise
- pileup

Constant : calorimeter design & parameters
- calorimeter dimensions
- dead material

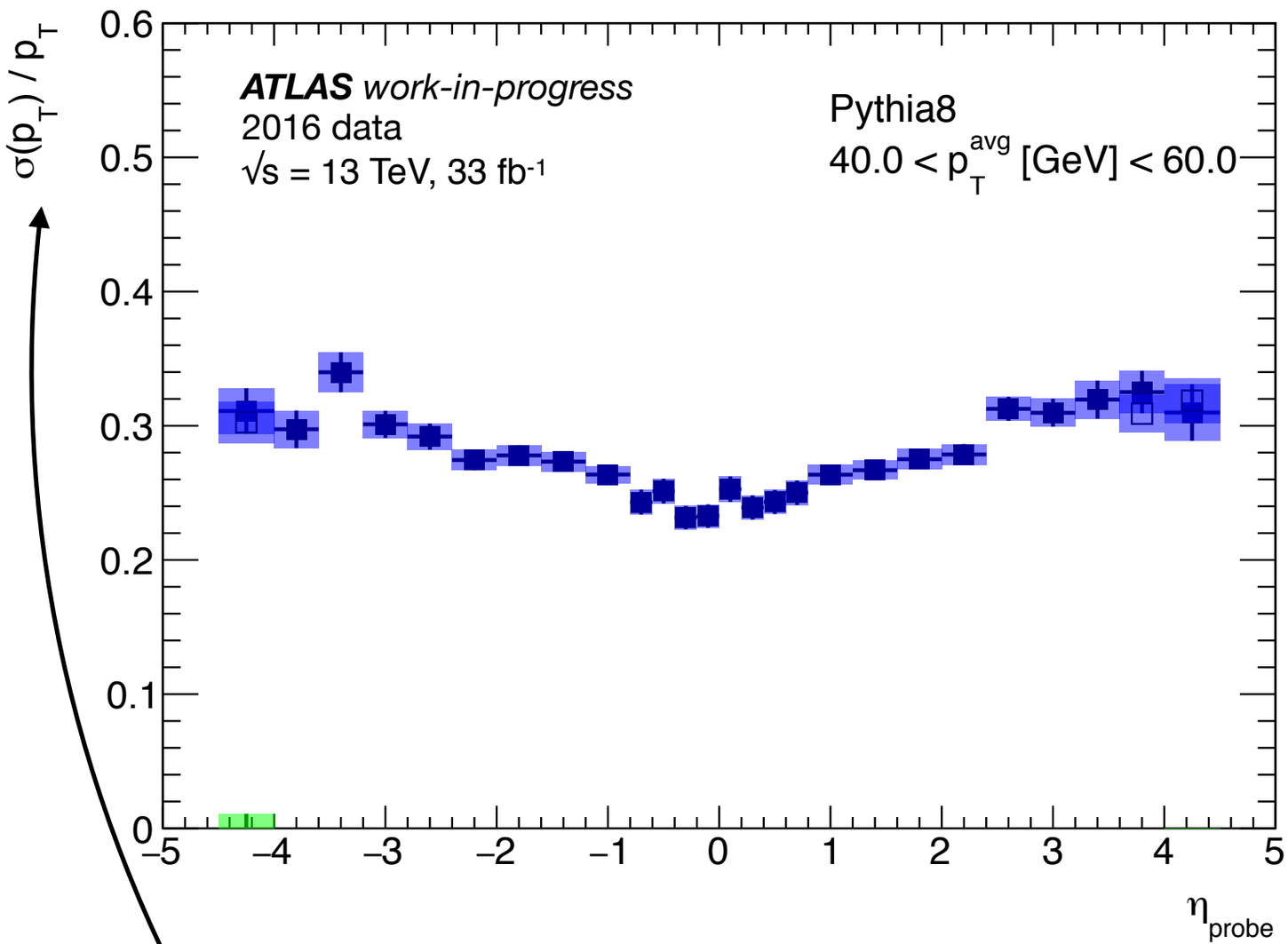
Stochastic : statistical fluctuations
- shower
- sampling
- signal

CERN-PH-EP-2012-191



Probing other detector regions?

Dijet event asymmetry will exhibit resolution effects from both reference (well-calibrated) & probe (want to study resolution) detector regions.



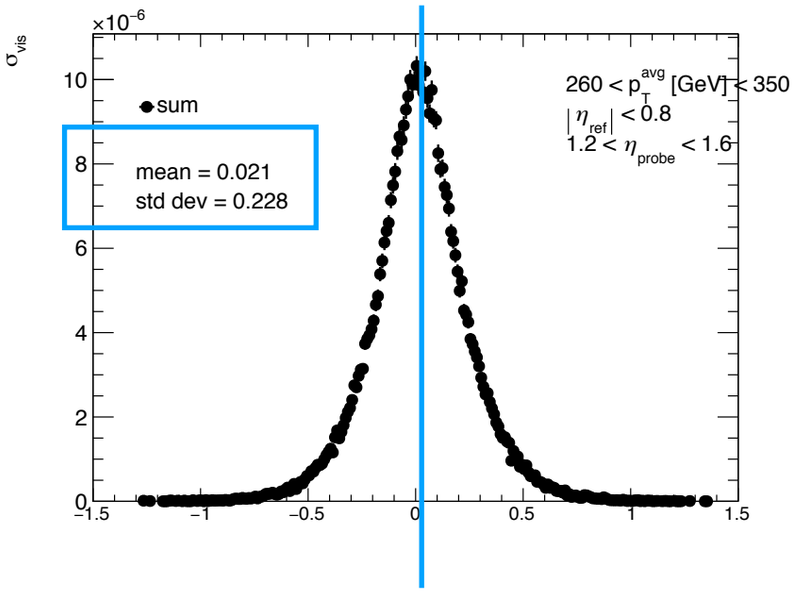
$$\left\langle \frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T}}} \right\rangle_{\mathrm{probe}} = \sigma_{\mathcal{A}} \ominus \left\langle \frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T}}} \right\rangle_{\mathrm{ref}}$$

already determined (pg. 20) then put in here

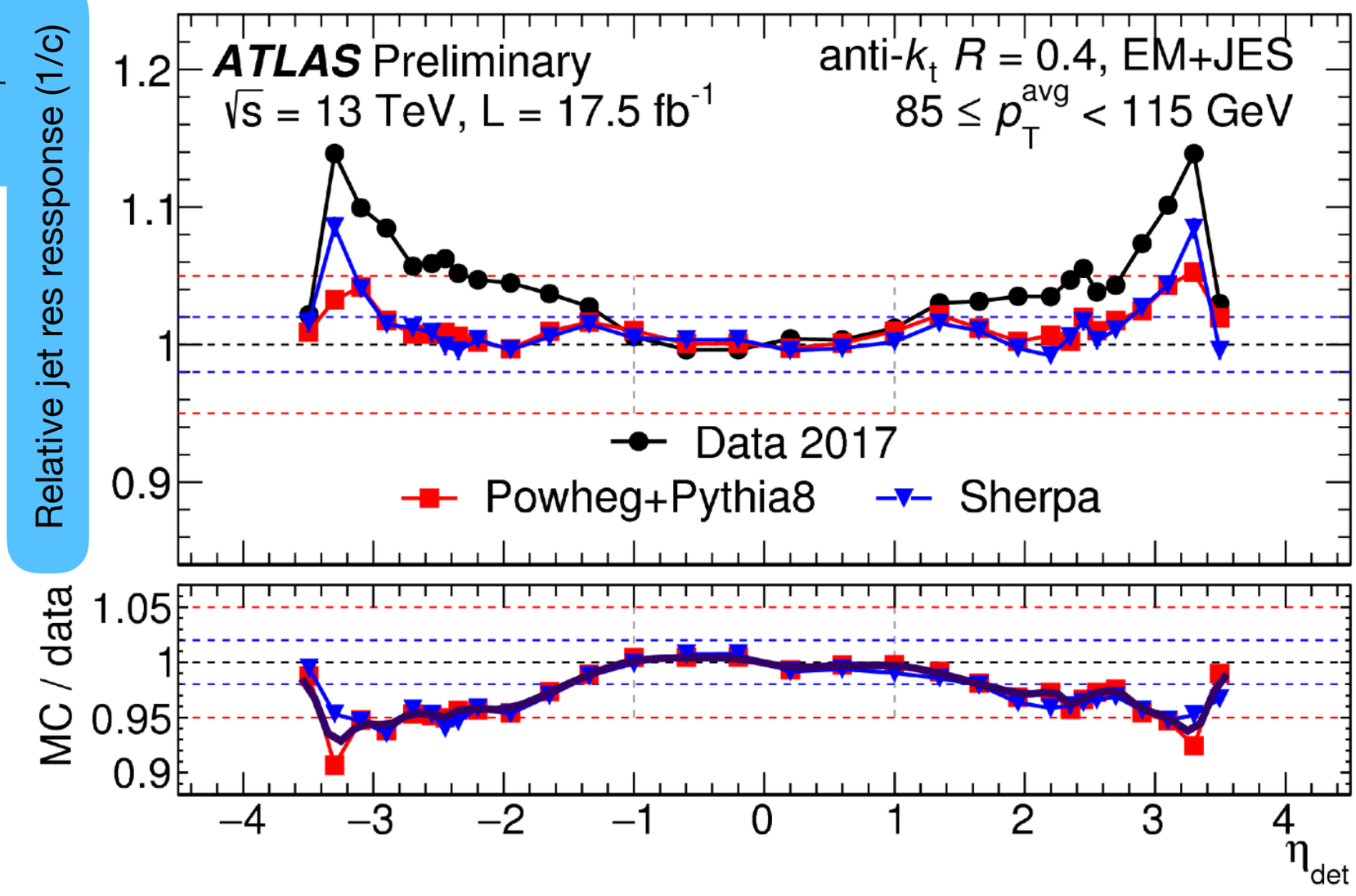
What about calibration?

Perfect balance (calibration + resolution) will always give zero asymmetry.
Measurements **requiring calibration** will be **centered away from zero**.

$$\left\langle \frac{p_{\mathrm{T}}^{\mathrm{probe}}}{p_{\mathrm{T}}^{\mathrm{ref}}} \right\rangle = \frac{2 - \langle \mathcal{A} \rangle}{2 + \langle \mathcal{A} \rangle}$$



JETM-2017-008



$$\left(\frac{\sigma_{p_\mathrm{T}}}{p_\mathrm{T}}\right) \overset{?}{\approx} \left(\frac{\sigma_E}{E}\right)$$

$$p_\mathrm{T} = \frac{E \ominus m}{\cosh\eta}, \quad m \equiv f(E, \{\eta_\mathrm{cell}, \phi_\mathrm{cell}\})$$ * topo-cluster input jets

$$\Rightarrow \left(\frac{\sigma_{p_\mathrm{T}}}{p_\mathrm{T}}\right)^2 \approx \left(\frac{\sigma_E}{E}\right)^2 + \left(\frac{\sigma_\eta}{\eta}\right)^2 + \left(\frac{\sigma_\phi}{\phi}\right)^2, \quad \frac{\sigma_\eta}{\eta}, \frac{\sigma_\phi}{\phi} \ll \frac{\sigma_E}{E}$$

$$\therefore \frac{\sigma_{p_\mathrm{T}}}{p_\mathrm{T}} \approx \frac{\sigma_E}{E}$$

angular resolution negligible relative to that of energy for jets measured in ATLAS