Jet Calibration in ATLAS

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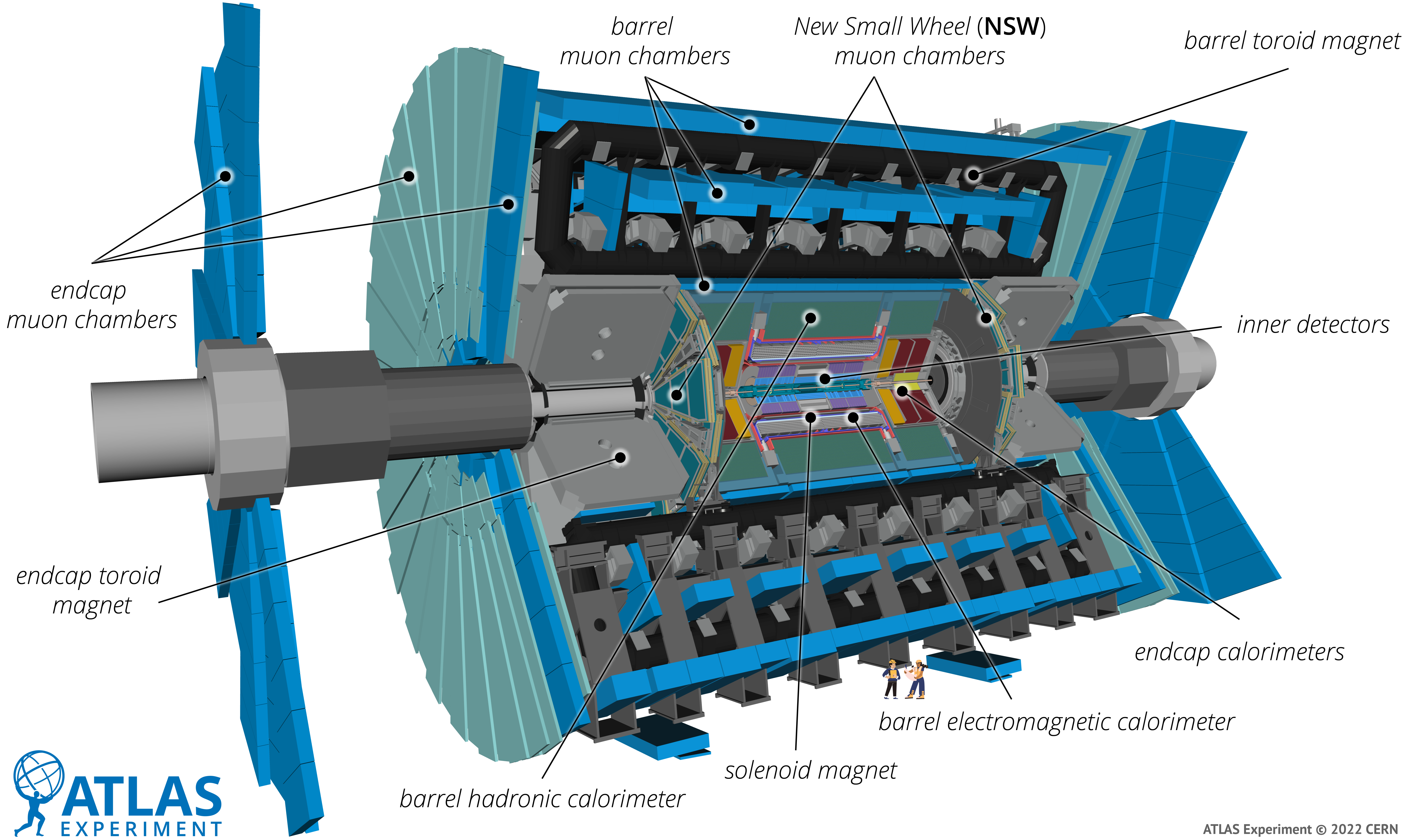
23/10/2023

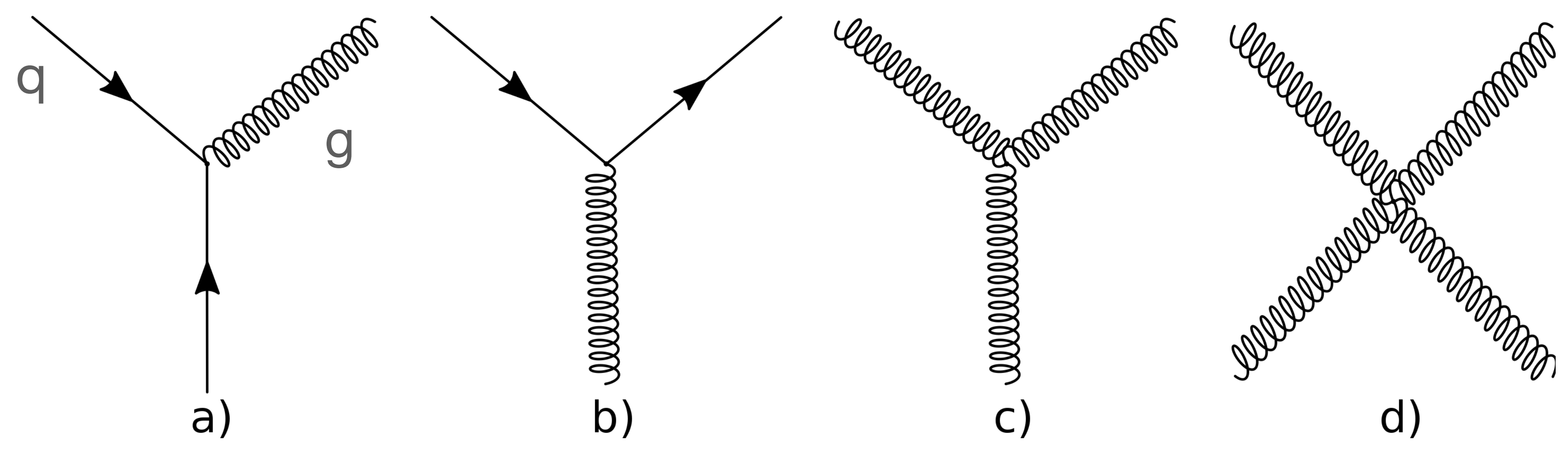
The ATLAS Detector



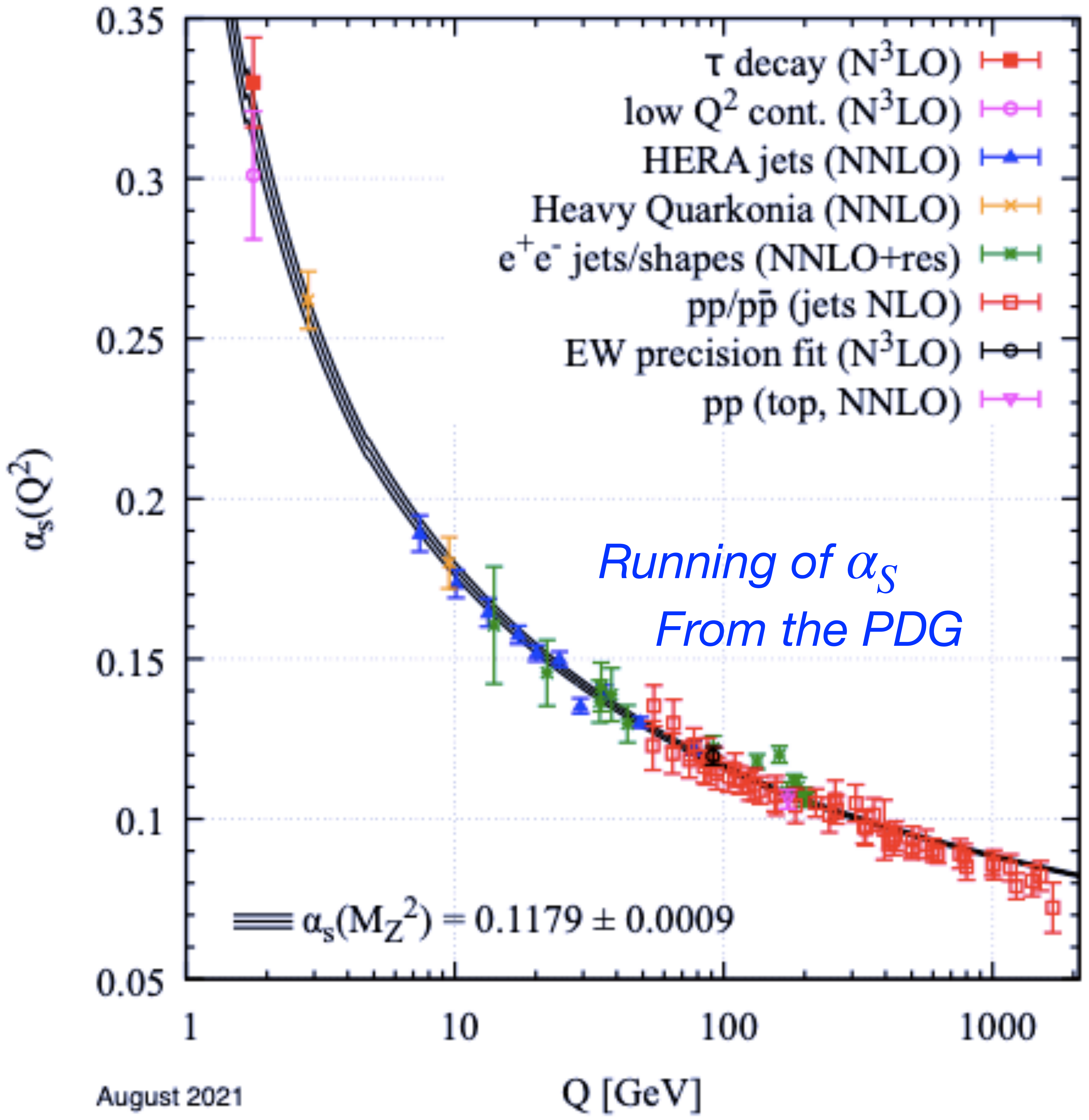
Strong interaction

- Carried by the gluon, parametrised by the strong coupling constant α_S

- Quarks and gluons carry colour charge
  $\rightarrow$ self-interaction



The fundamental couplings of the strong interaction

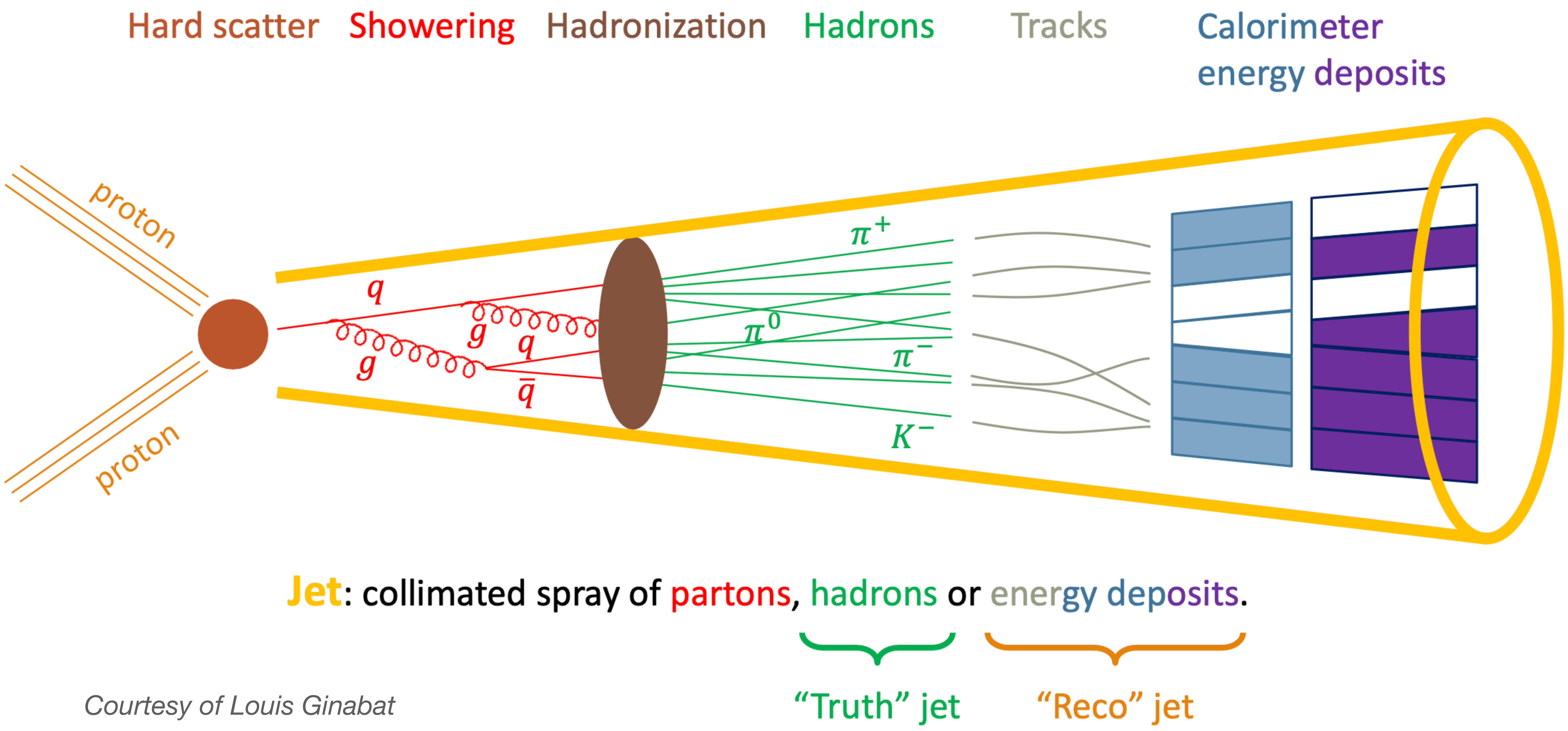


- They form bound colourless states (hadrons)

- Due to colour confinement, quarks and gluons shower and hadronise immediately into collimated bunches of particles $\rightarrow$ Jets

Jets

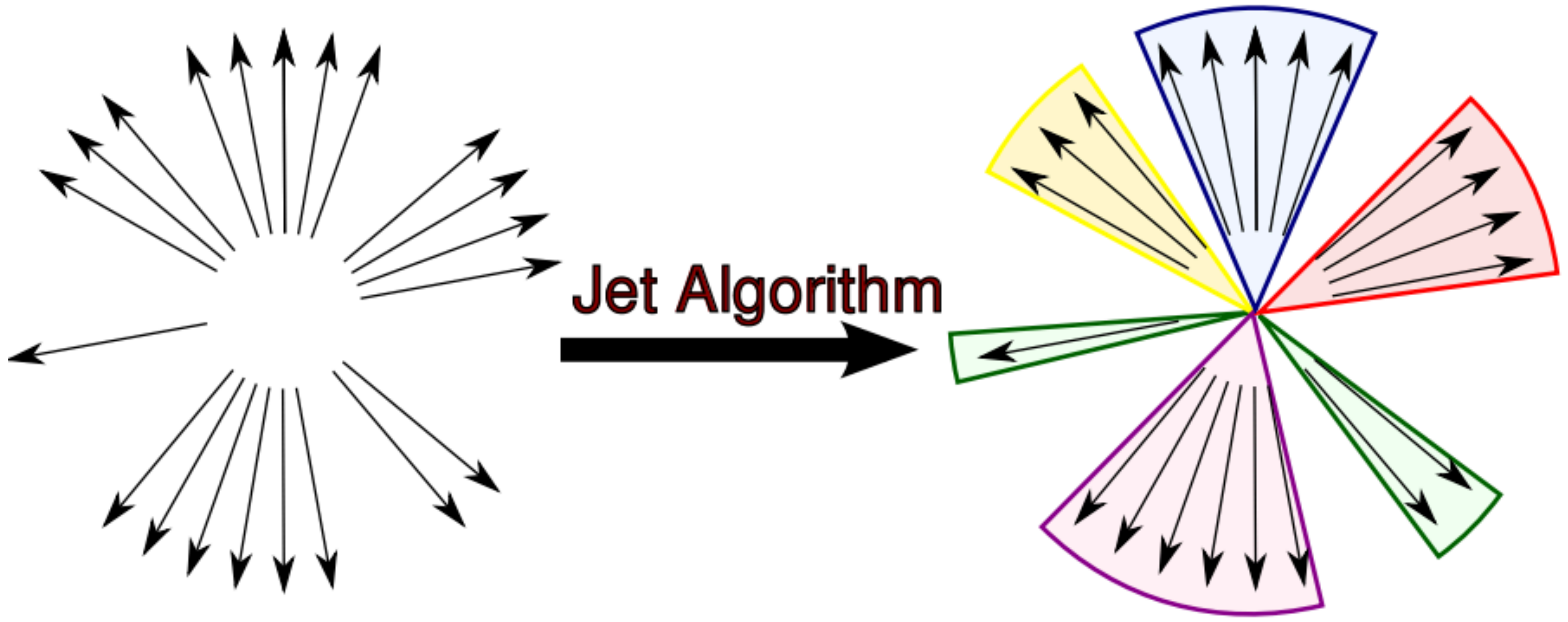
- Jets represent the shower produced by the hadronisation of a quark or gluon



Courtesy of Louis Ginabat

- Dominant production at the LHC
- Used either as signal or background in most analyses

Jet reconstruction

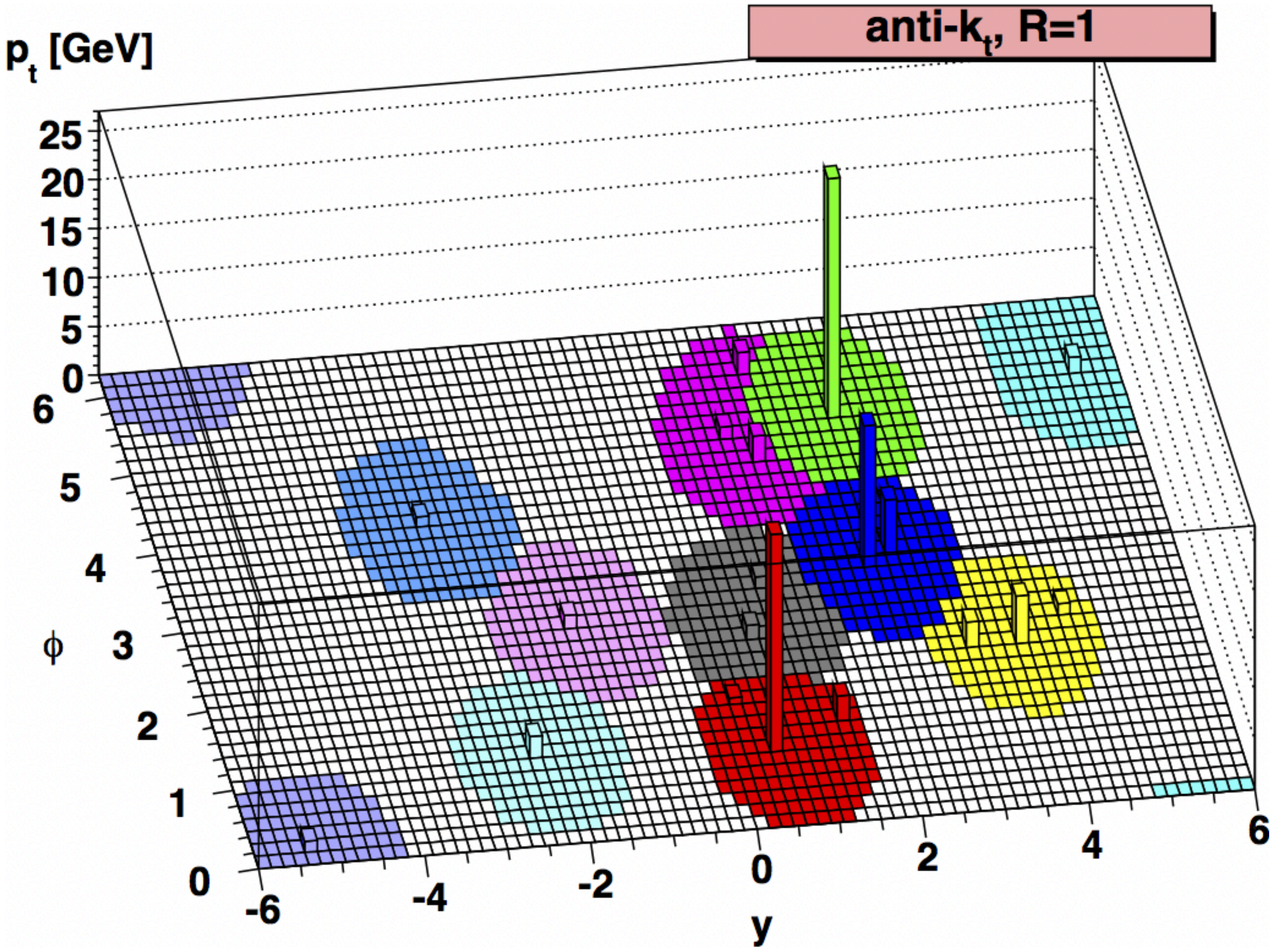


- Goal: Construct jets from the input 4-vectors
  - calorimeter hits and tracks (data)
  - simulated particles (mc truth)
  - simulated calorimeter hits and tracks (mc reco)

- Anti-k_T algorithm: sequential jet clustering algorithm of near-by entities, with

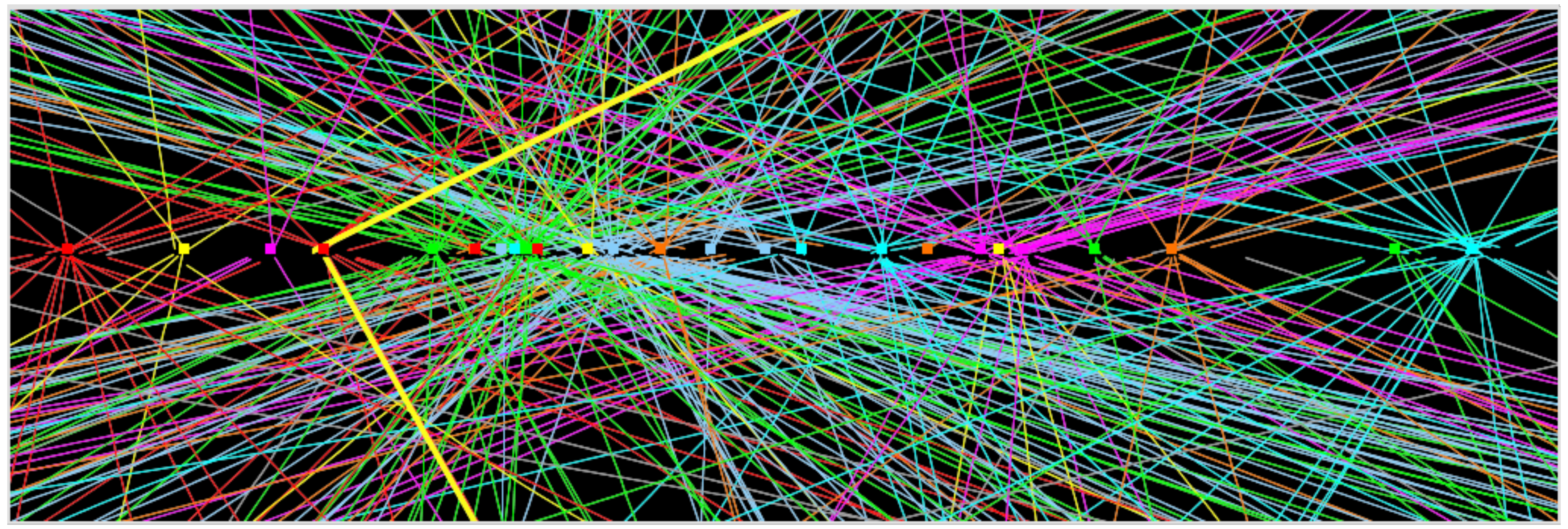
$$d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\frac{\Delta_{ij}}{R^2}$$

  and deduce the 4-vector of the associated jet



Jet calibration

Goal



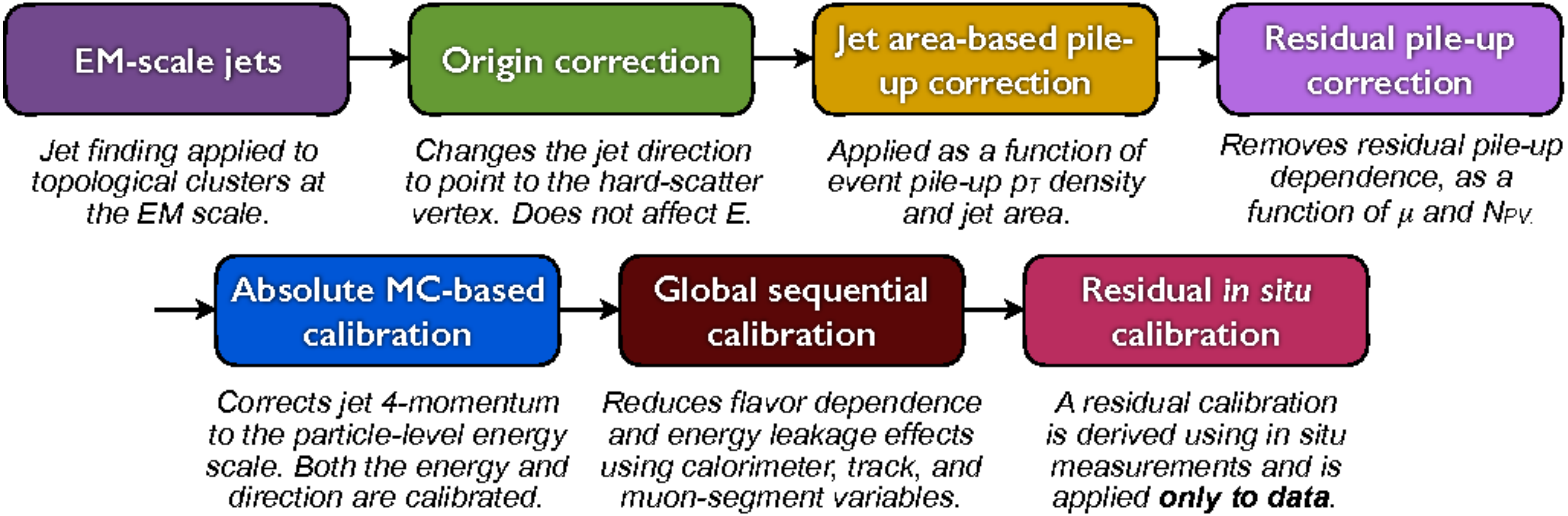
- To have the reconstructed 4-vector of the jet matching that of the true 4-vector corresponding jet (in data and mc)

- Correct energy and direction of the jet for:
  - Energy lost in the upstream material
  - Energy lost in dead material
  - Non-compensating nature of ATLAS detector
  - Bending of the particles in the magnetic field
  - Busy data taking environment resulting from the multiple proton-proton interaction (pile-up)

- Derive correction factors to be applied to reconstructed jets in mc and data

Jet calibration

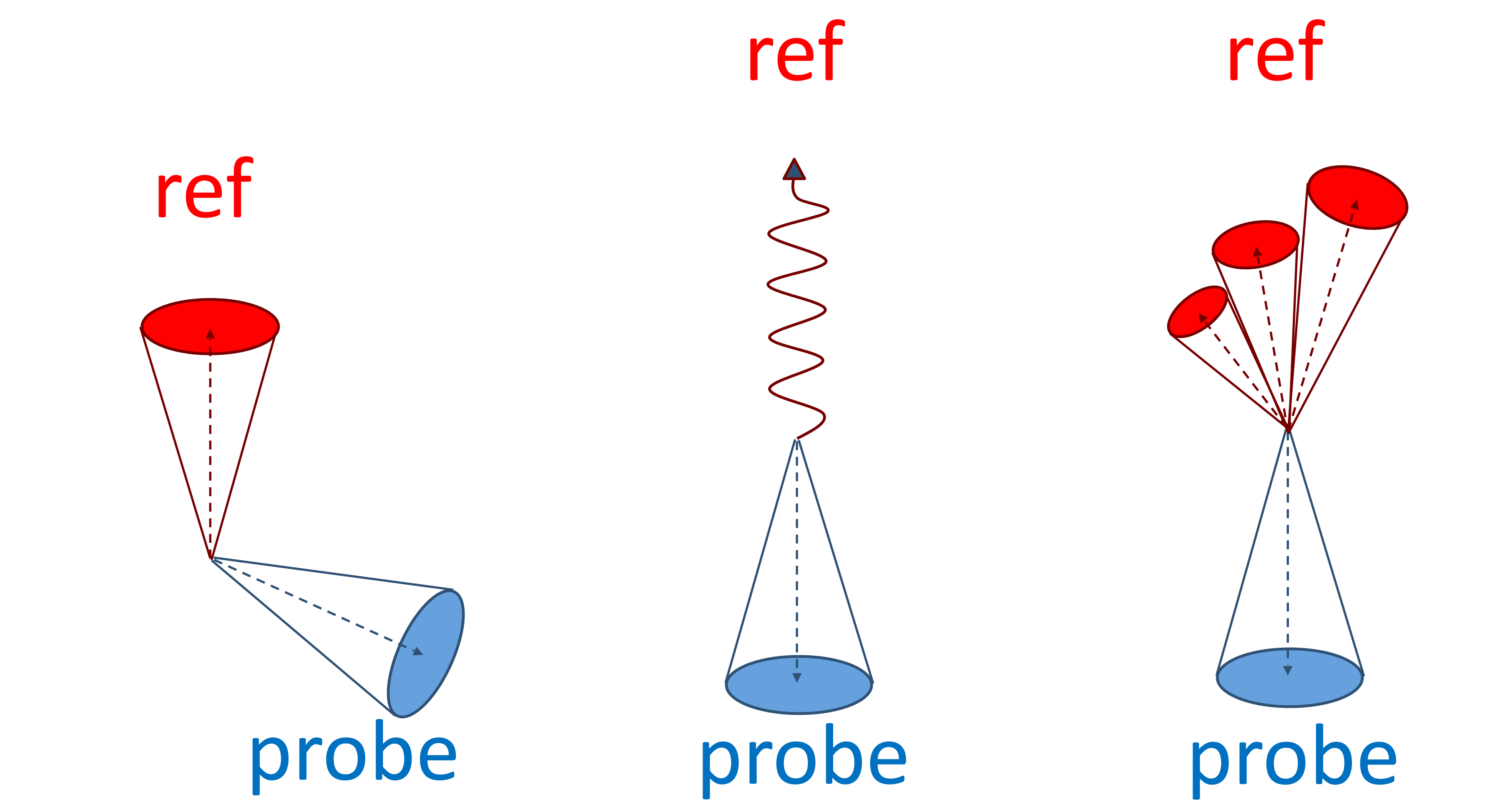
Principle



Residual in situ Calibration

GOAL: Correct the residual differences between data and Monte Carlo, with in situ measurement

Principle : Use of the p_T balance between a jet *(probe)* and a reference object *(ref)*



Dijet balance (η-intercalibration)

Z+jet balance, γ+jet balance

Multijet Balance

Correction factors derived in bins of p_T and η:

$$\mathscr{C} = \frac{c_{MC}}{c_{data}} = \frac{\mathscr{R}_{data}}{\mathscr{R}_{MC}} = \left[\frac{(p_T^{probe})_{reco}}{p_T^{ref}}\right]_{data} \Bigg/ \left[\frac{(p_T^{probe})_{reco}}{p_T^{ref}}\right]_{MC}$$

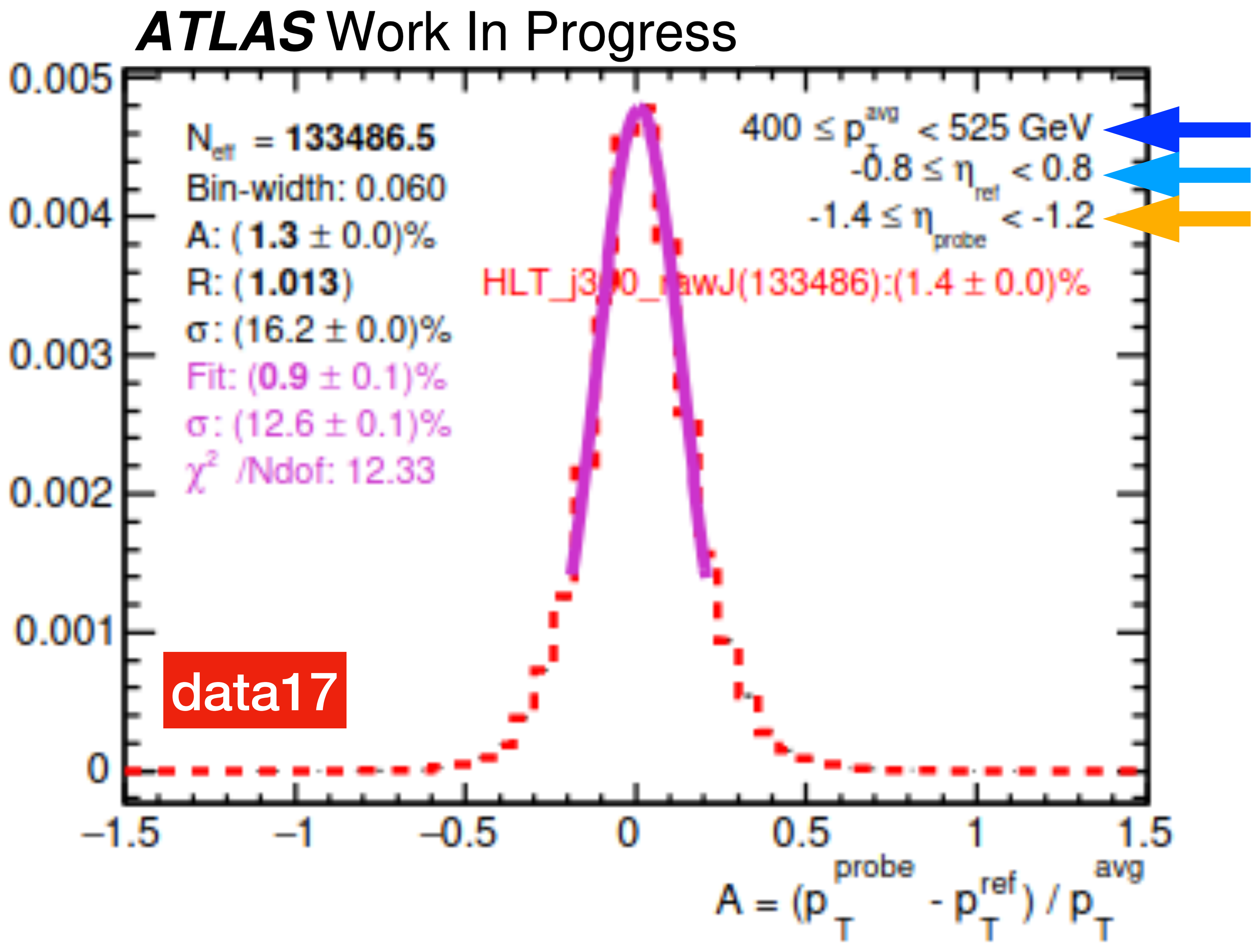
Intercalibration factors

Correction factors (to be applied to data)

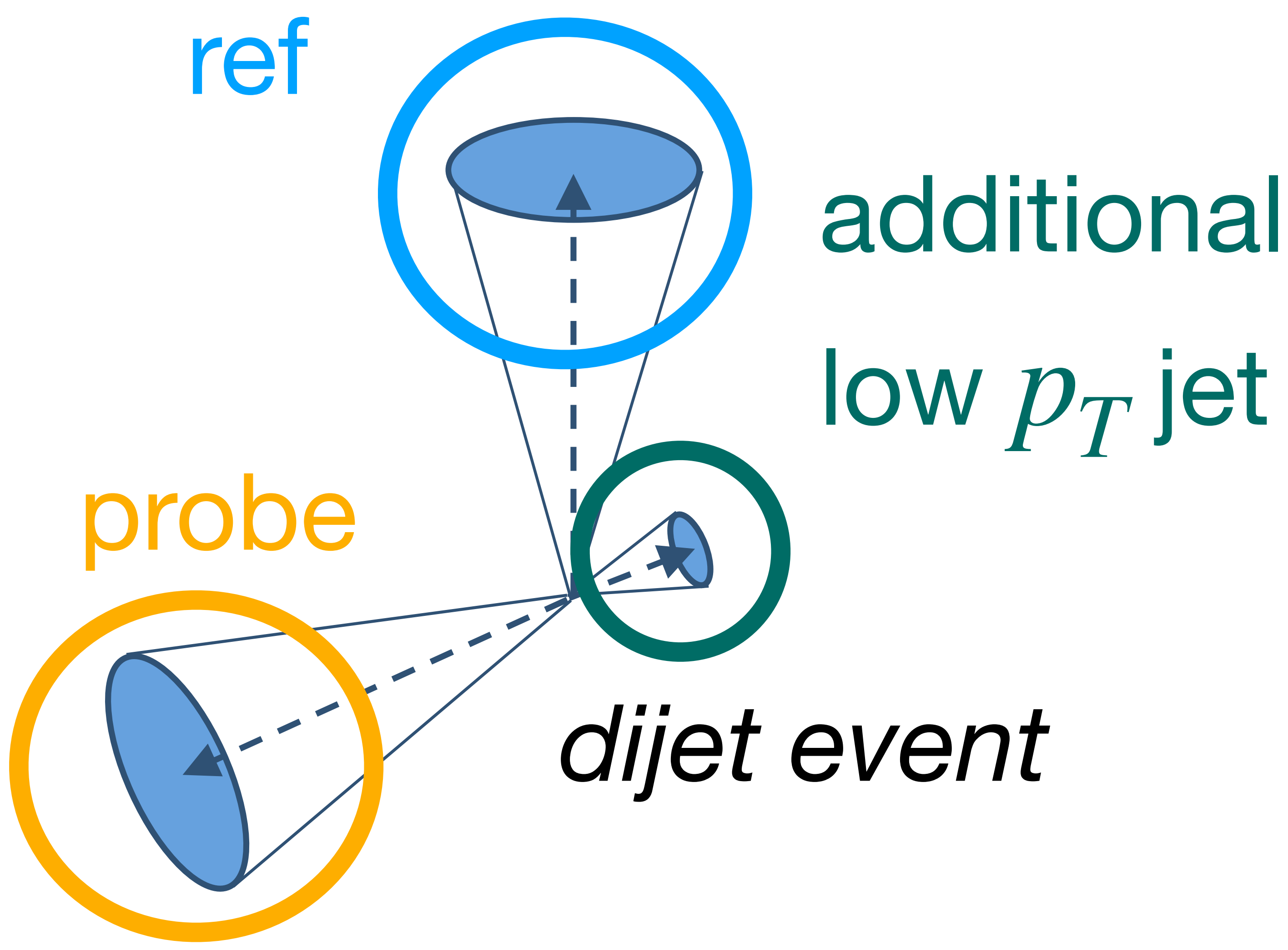
η-intercalibration $\rightarrow$ homogeneity in η

η-intercalibration

Using **di-jet events**



Exemple of an asymmetry distribution. The central value of a gaussian fit is extracted



Dijet Selection for R=0.4:

$\Delta\phi > 2.5$

$p_T^3 / p_T^{avg} < 0.25$

$JVT < 0.25$

Asymmetry in p_T :

$$\mathscr{A} = \frac{p_T^{probe} - p_T^{ref}}{p_T^{average}}$$

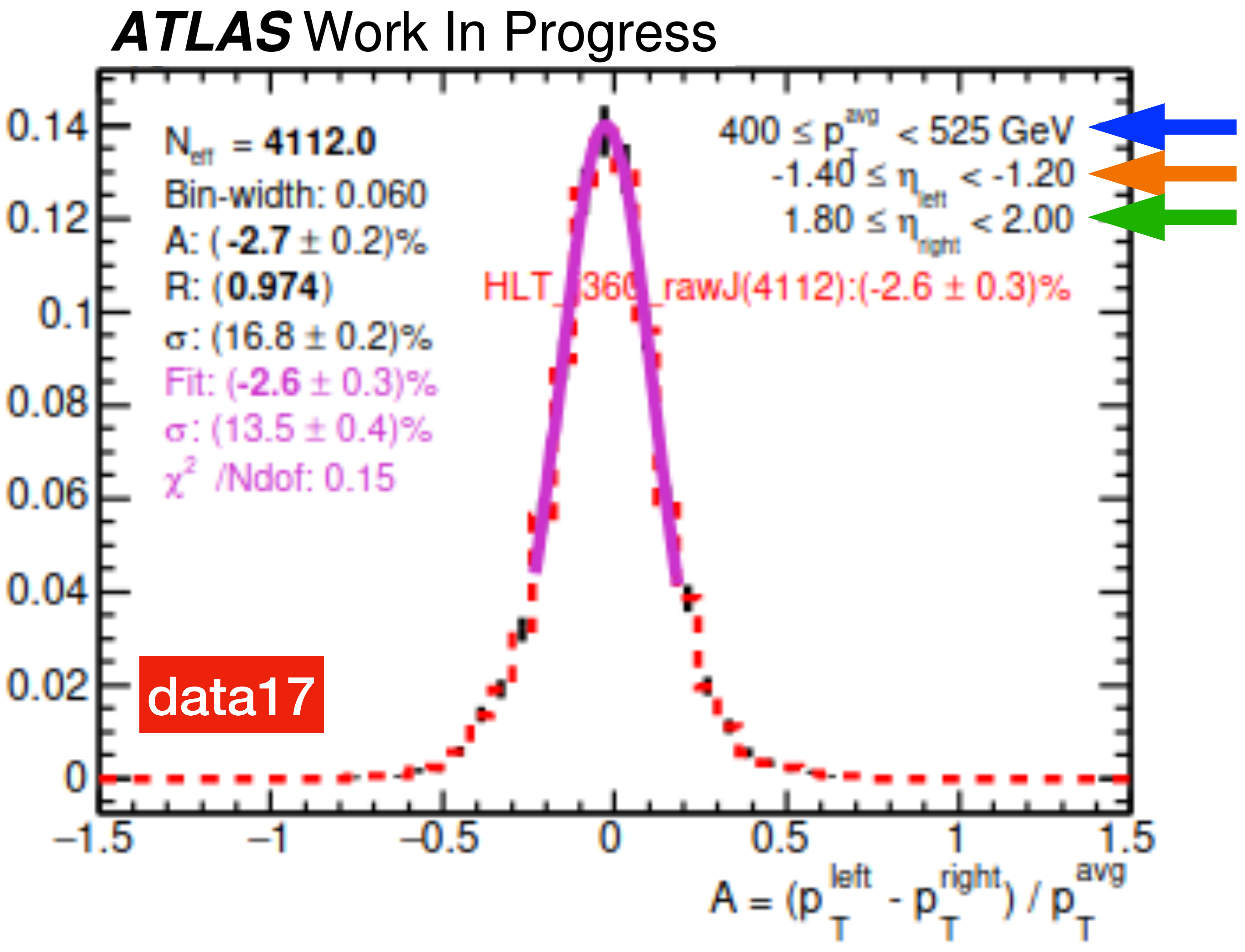
Standard Method:

- probe = jet to calibrate
  ref = jet in the reference region (central region)
- Asymmetry evaluated in bins of p_T^{avg}, η_{ref} and η_{probe}
- $\frac{1}{c} = \langle \mathscr{R} \rangle = \frac{2 + \langle \mathscr{A} \rangle}{2 - \langle \mathscr{A} \rangle}$ intercalibration factors

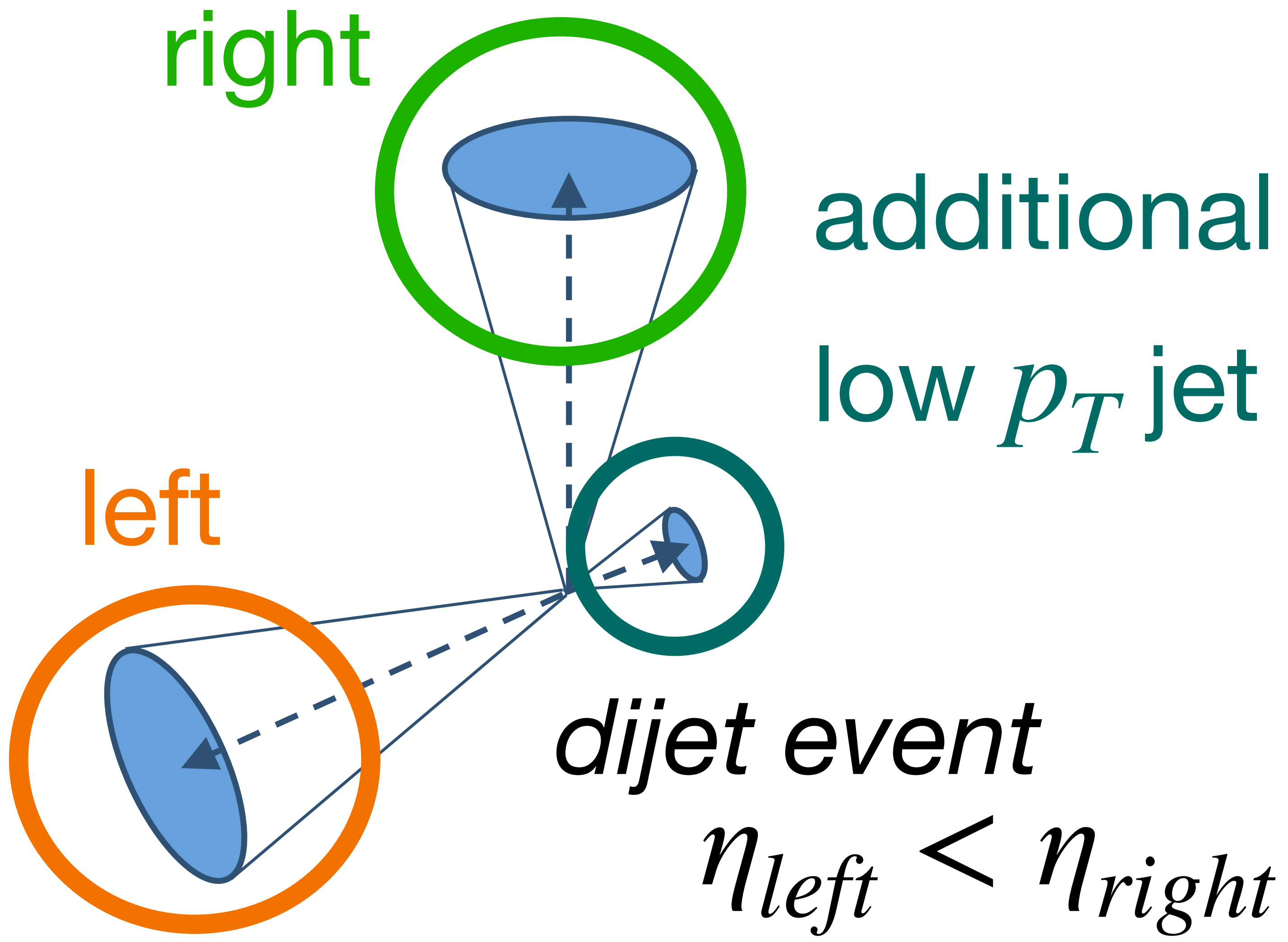
Problem : low statistics

η-intercalibration

→ **Matrix Method**



Exemple of an asymmetry distribution. The central value of a gaussian fit is extracted



Dijet Selection for R=0.4:

$\Delta\phi > 2.5$

$p_T^3/p_T^{avg} < 0.25$

$JVT < 0.25$

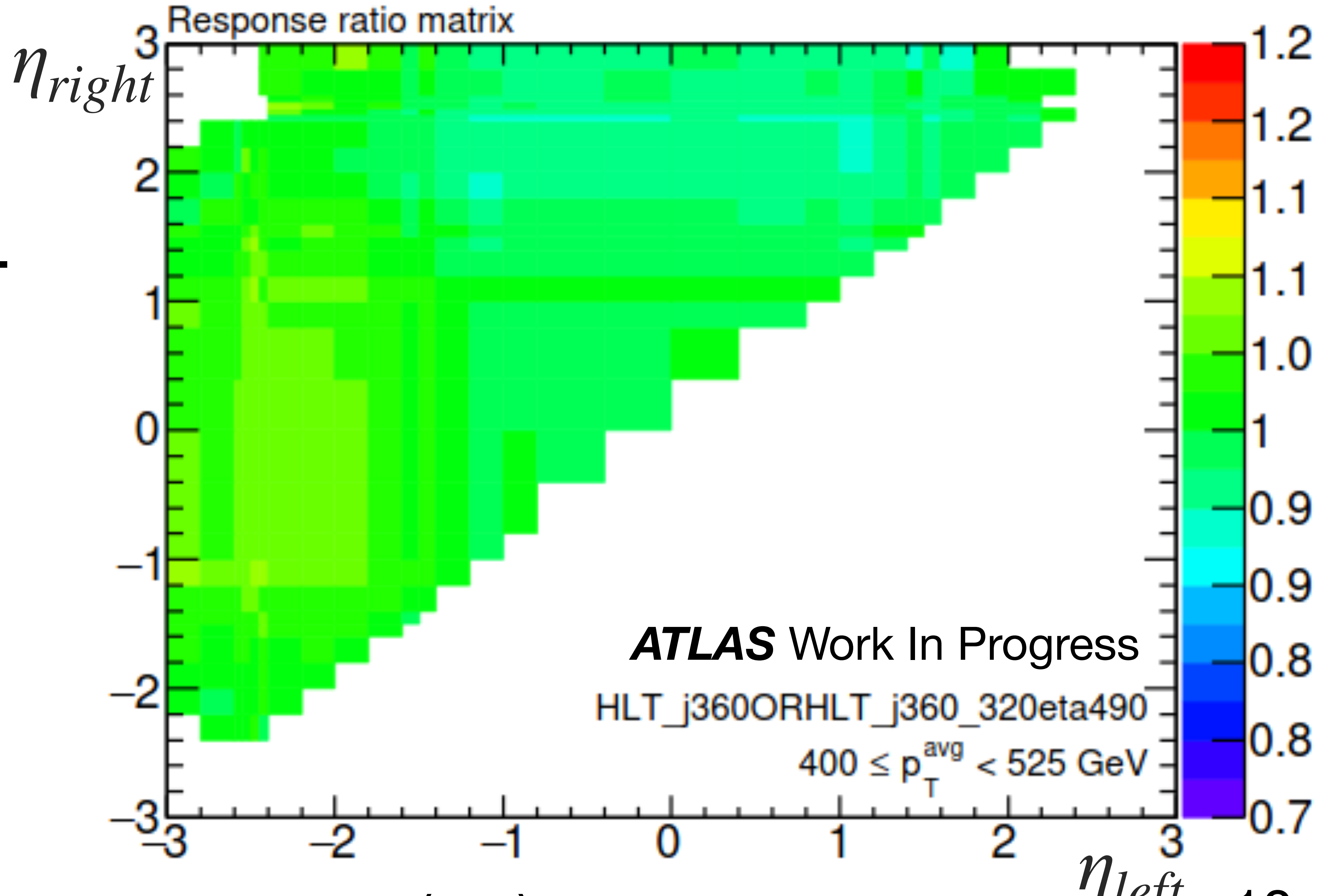
Asymmetry in p_T :

$$\mathscr{A} = \frac{p_T^{left} - p_T^{right}}{p_T^{average}}$$

- Asymmetry evaluated in bins of p_T^{avg}, η_{left} et η_{right}

- $$\langle \mathscr{R} \rangle = \frac{2 + \langle \mathscr{A} \rangle}{2 - \langle \mathscr{A} \rangle}$$

- $\langle \mathscr{R} \rangle$ distribution for each p_T^{avg} bin



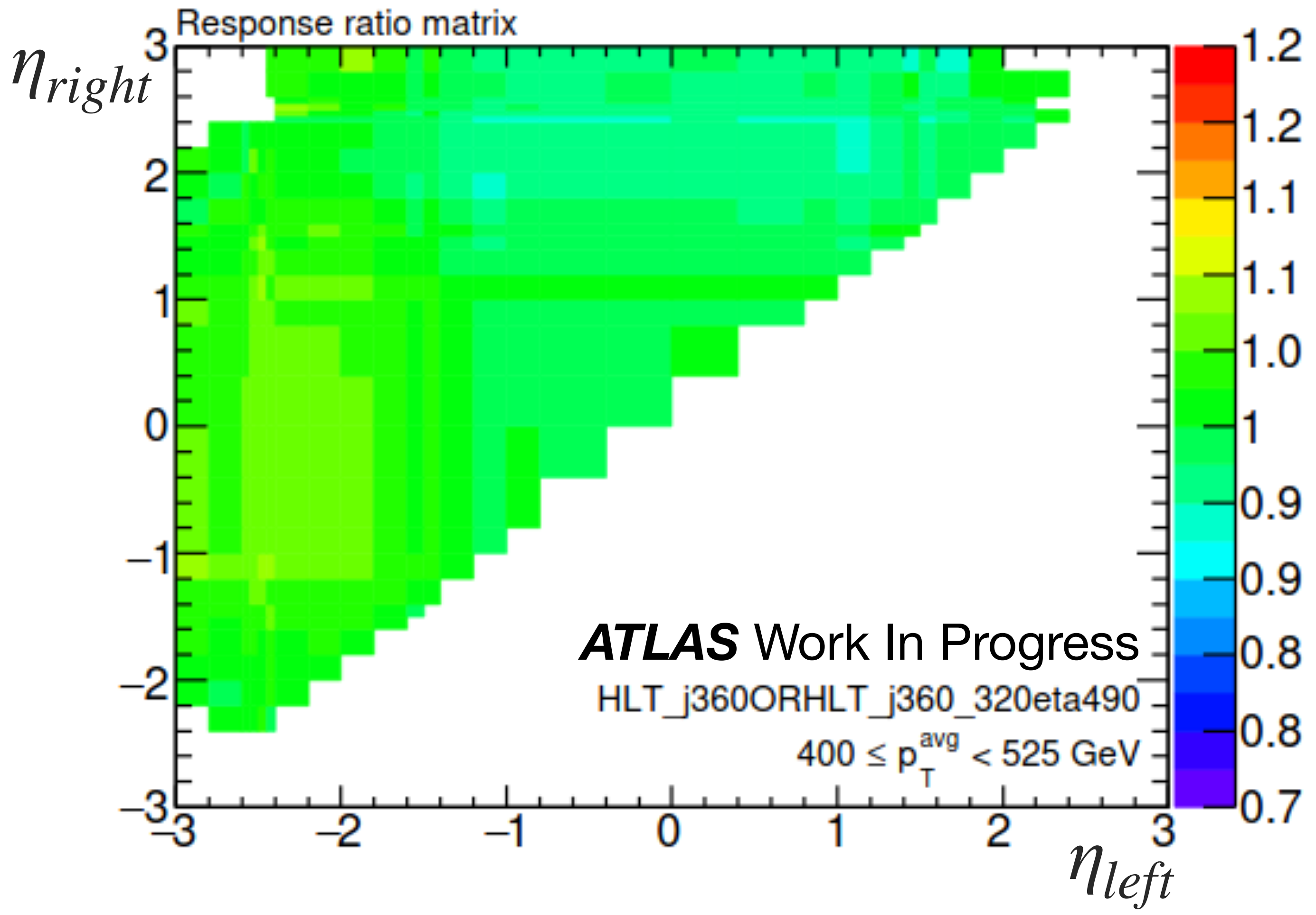
$\langle \mathscr{R} \rangle$ distribution

$$S(c_1,\ldots,c_N) = \sum_{j=1}^{N}\sum_{i=1}^{j-1}\left(\frac{1}{\Delta\langle\mathscr{R}_{ij}\rangle}\left(c_i\langle\mathscr{R}_{ij}\rangle - c_j\right)\right)^2 + X(c_1,\ldots,c_N)$$

η-intercalibration

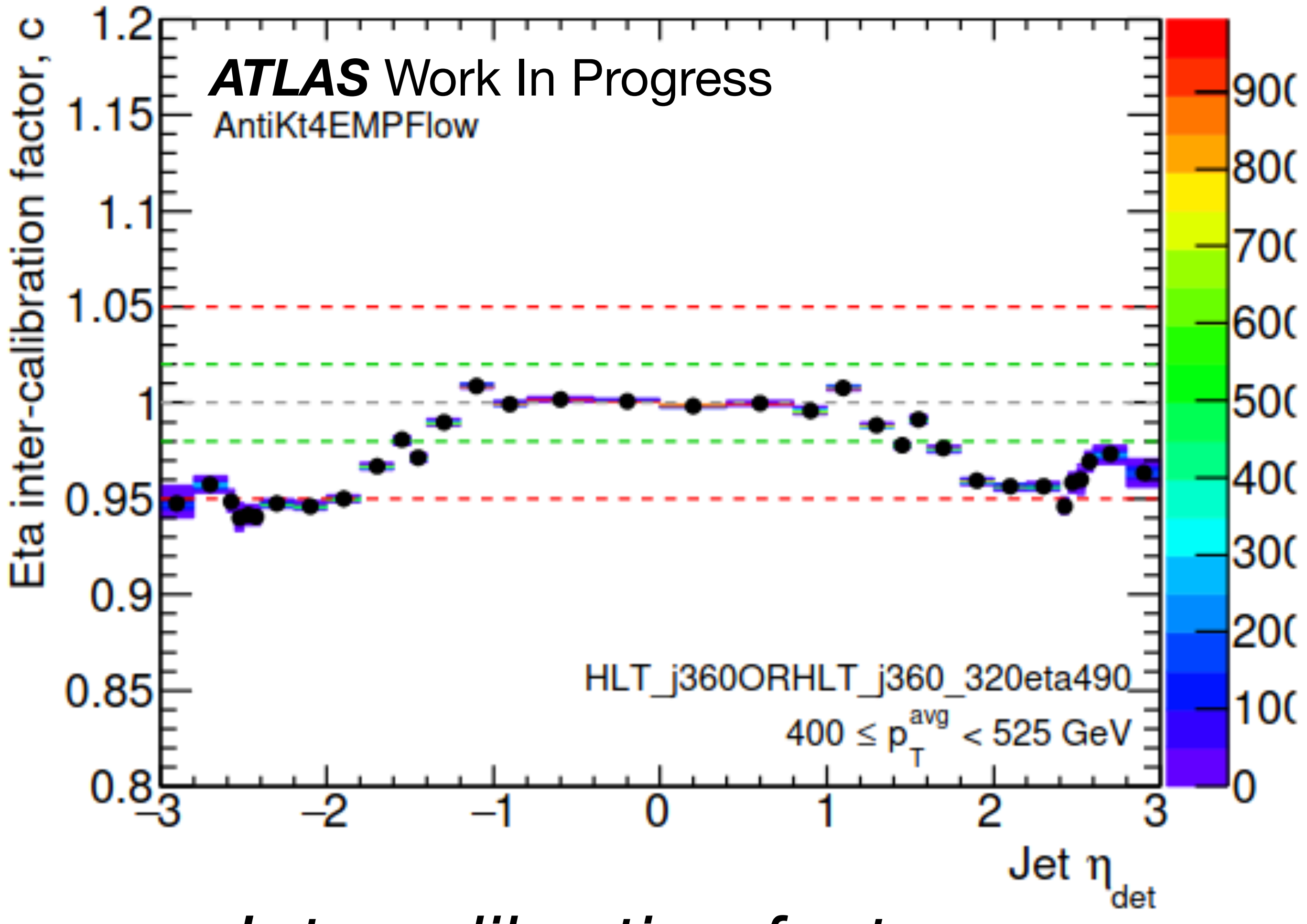
- In each bin of p_T^{avg} → **Over-constrained system** :

  N intercalibration factors to determined $< \sim \dfrac{N^2 - N}{2}$ *constraints*
- χ^2 **minimisation process**
- The correction factors are the **ratio of the inter-calibration factors** (mc/data)



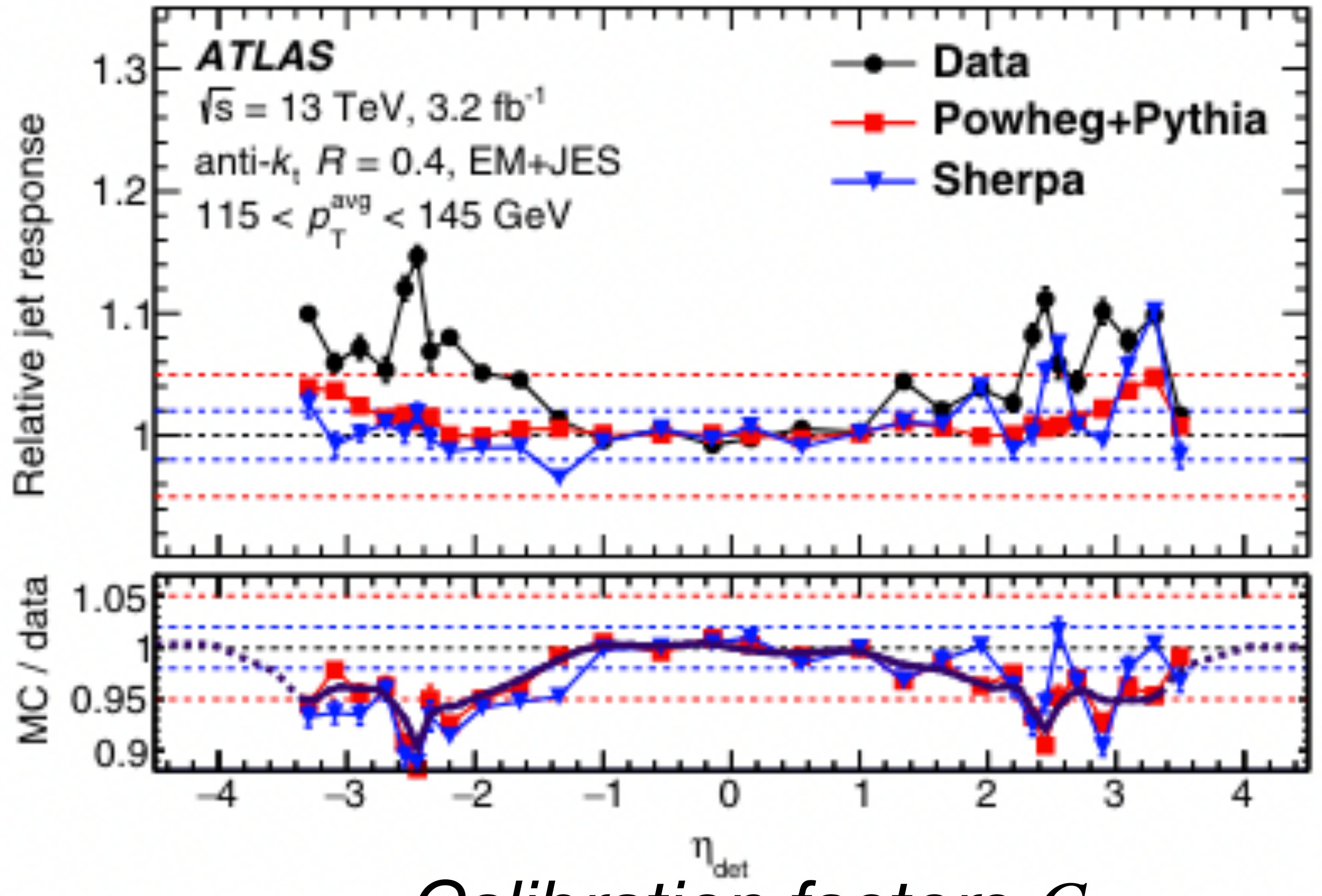
$\langle\mathscr{R}\rangle$ *distribution*

Minimisation →



Intercalibration factor c

Ratio+ smoothing →



Calibration factors C

From 1703.09665

data17

Global χ^2/NDF

- The intercalibration factors are determined by a χ^2 **minimisation process**:

$$S(c_1, \ldots, c_N) = \sum_{j=1}^{N} \sum_{i=1}^{j-1} \left(\frac{1}{\Delta \langle \mathcal{R}_{ij} \rangle} \left(c_i \langle \mathcal{R}_{ij} \rangle - c_j \right) \right)^2 + X(c_1, \ldots, c_N)$$

- A **global χ^2/NDF** can be calculated for each p_T bin:

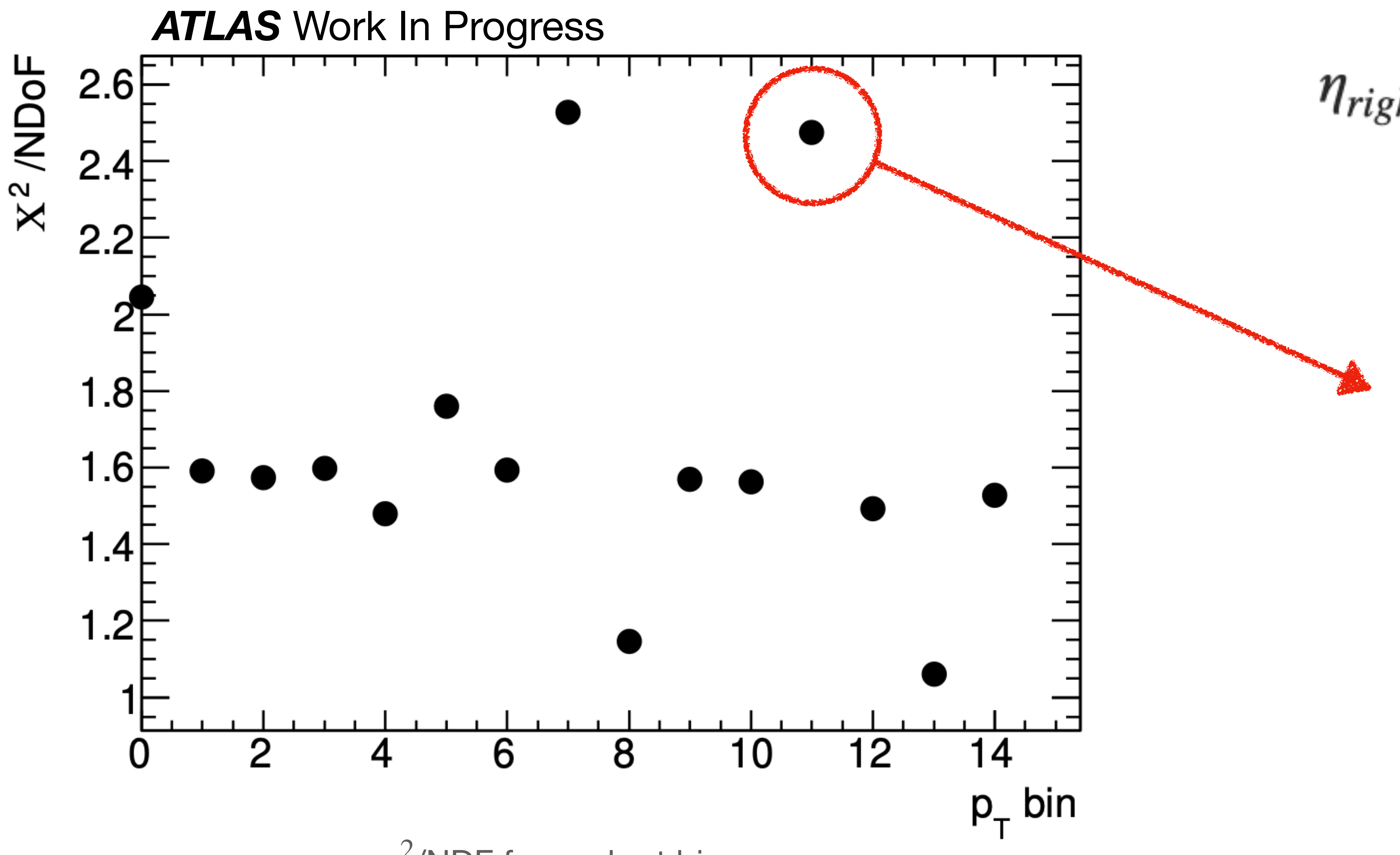
$$\chi^2 = \sum_{j=1}^{N} \sum_{i=1}^{j-1} \left(\frac{1}{\Delta \langle \mathcal{R}_{ij} \rangle} \left(c_i \langle \mathcal{R}_{ij} \rangle - c_j \right) \right)^2$$

$$NDF = \underbrace{\frac{N_{\eta bins}^2 - N_{\eta bins}}{2} - N_{dropped}}_{\text{\# of constraints}} \underbrace{- N_{\eta bins}}_{\text{\# of intercalibration factors}}$$

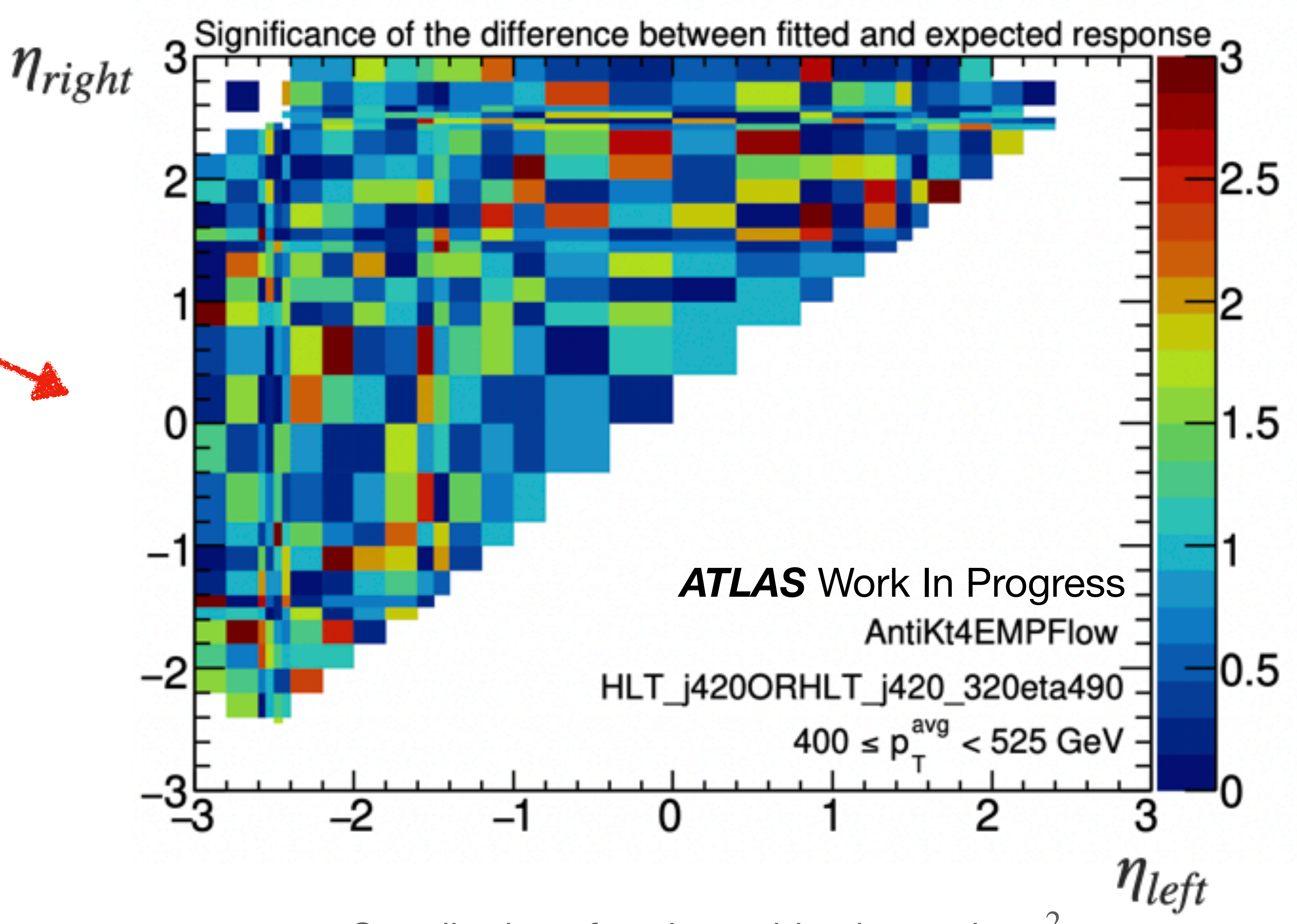
The global χ^2/NDF provides information on the compatibility between the constraints

Global χ^2/NDF

- The global χ^2/NDF study allows to target the highly contributing bins for studies



χ^2/NDF for each pt bin

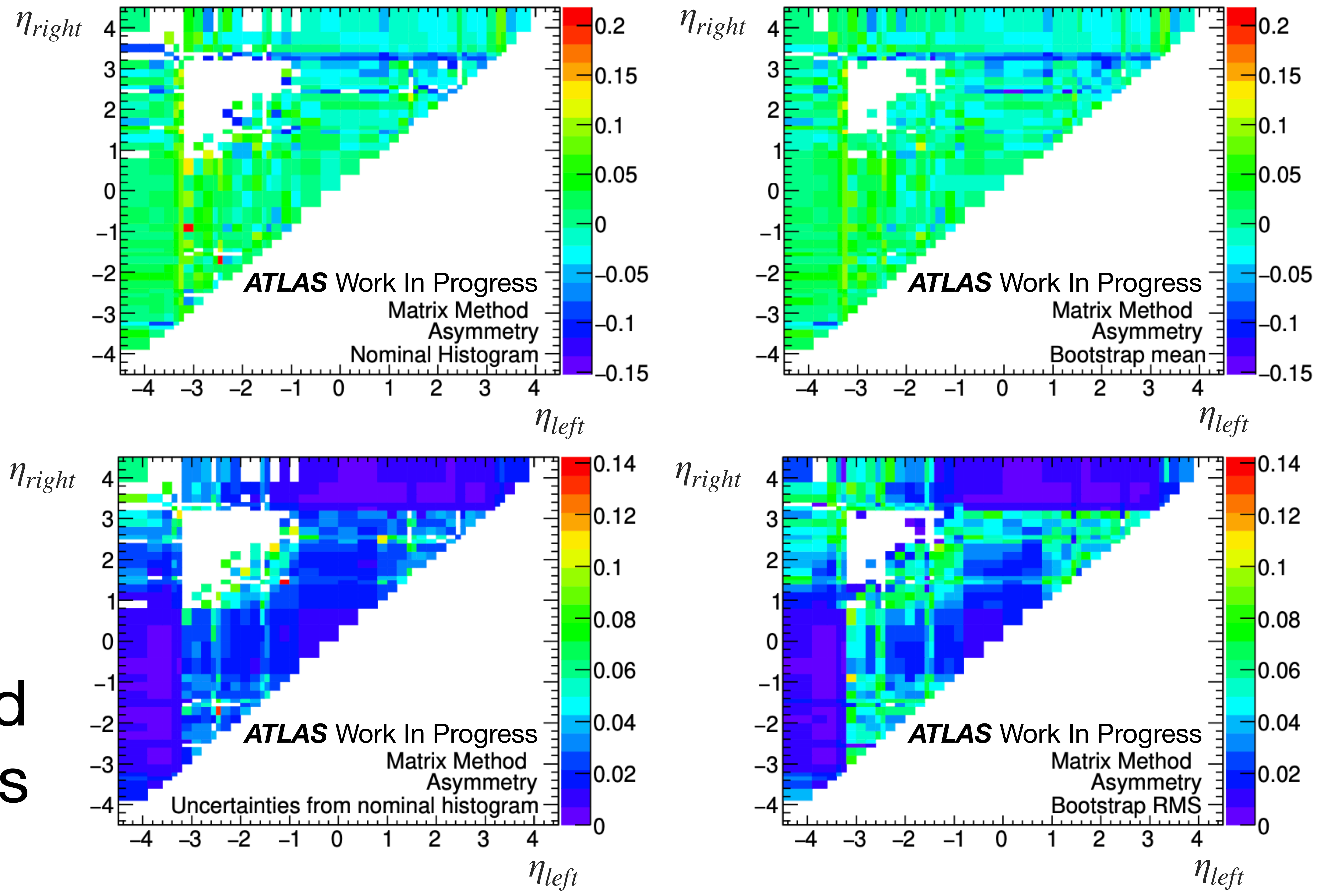


Contribution of each combination to the χ^2

Bootstrap Method

- Evaluate the **statistical uncertainty** of a measurement
- Using a set of **replicas of the nominal dataset**, derived by introducing **Poisson perturbations**
- Analysing each replica, the same way as the nominal dataset
- Extract the statistical uncertainty and **correlations** from the measurements
- The fluctuations that generate the bootstrap replicas are **deterministic**

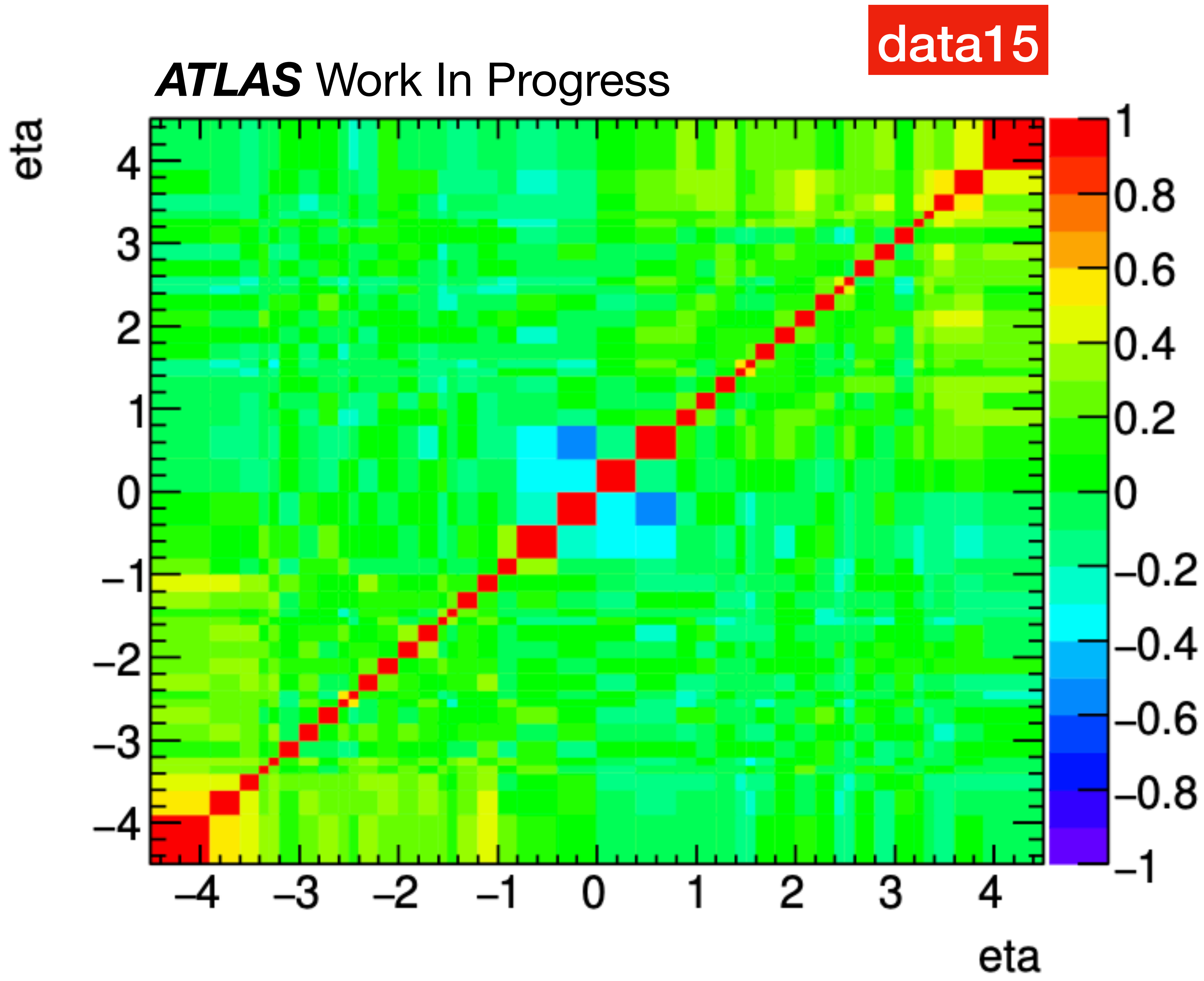
data15



$85 < p_T < 115$, working with 100 replicas

Bootstrap Method

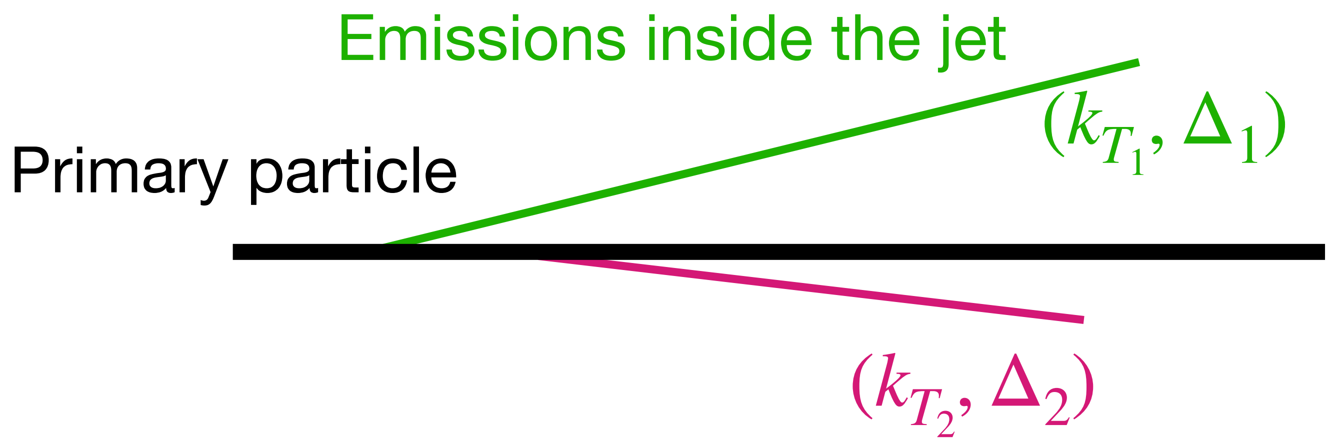
- Correlation Matrix, determined here for the first time
- Very important for quantitative data/theory comparisons e.g. for jet cross-sections
- (Anti-)correlations: in the MM, an asymmetry bin constrains two intercalibration factors
  → currently not taken into account in the computation of the uncertainties
- Could improve the calibration, **useful for many studies involving jets**

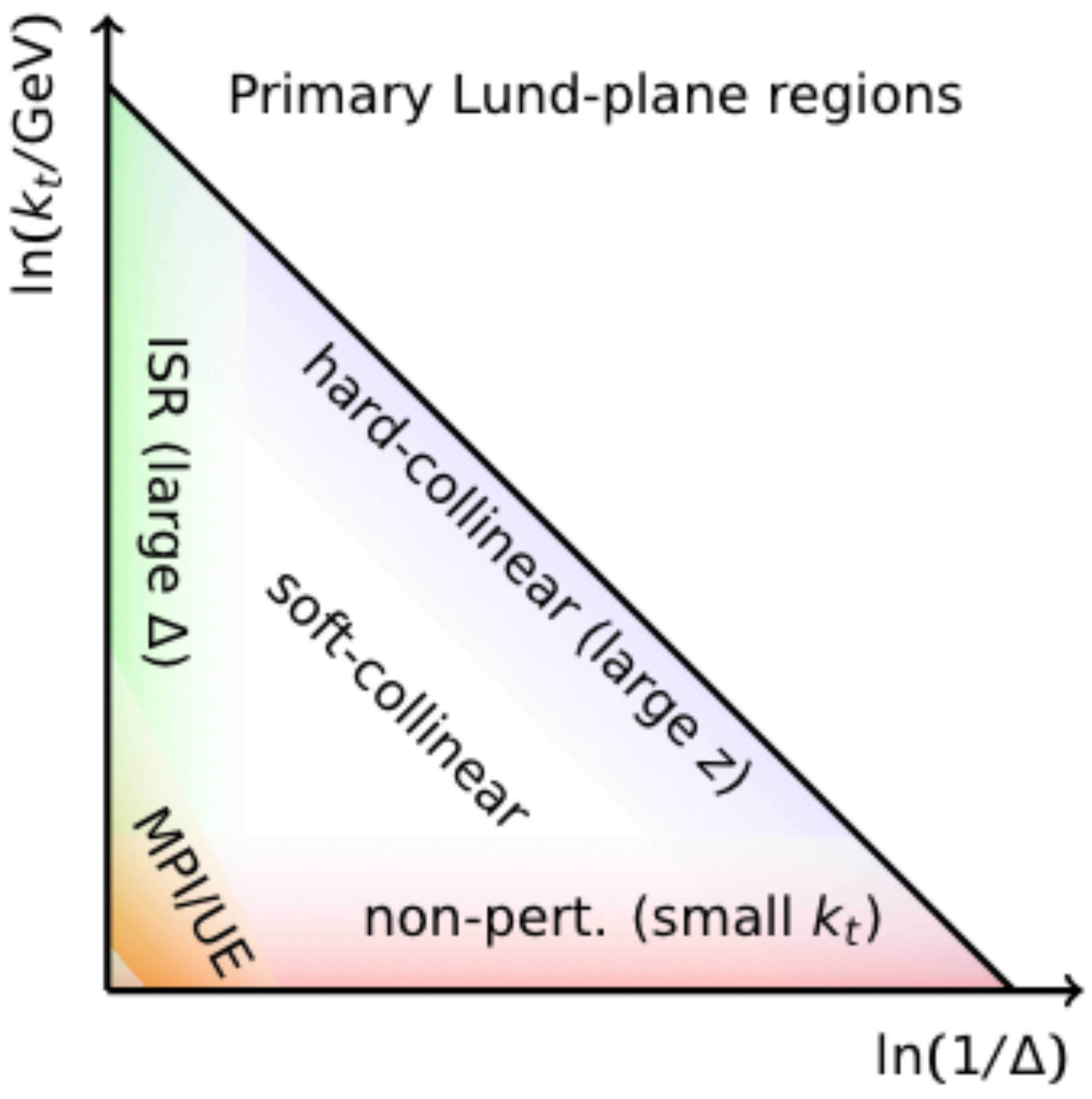


For $85 < p_T < 115$, 100 replicas

What's next

Jet substructure and α_S





From 1807.04758
Factorisation of QCD effects

- Usually: Jet production cross section
- **Lund Jet Plane**: a modern way to explore the jet substructure, sensitive to α_S
- Re-clustering the jet, entering the "emission" coordinates in a $(\ln(k_T), \ln(1/\Delta))$ plane
- Broad range of scale covered to **test the running of α_S**,
  + Normalisation sensitive to α_S

GOAL : Evaluation of α_S and test of its running as a function of the energy scale with Run-2 data

What's next

FCC-ee

FUTURE CIRCULAR COLLIDER

- FCC-ee : 91km of circumference, ~2040, e^+e^- collisions at 4 center of mass energies between 90 and 365 GeV. Very high statistics, very clean environment.
  $\rightarrow$ **Contraints on the detectors** : minimising the systematics to take advantage of the high statistic
- **Prospective studies of the Lund Jet Plane in a FCC-ee environment** with mc simulations

GOAL : Optimise the detector design (energy resolution, granularity, etc) for the Lund jet plane study, to improve the determination of α_S

Thank you for your attention!