Jets at LEP

Pao-ti Chang[2], **Yi Chen[1]**, Yang-Ting Chien[5], Yen-Jie Lee[1], Marcello Maggi[4], Chris McGinn[3], Dennis Perepelitsa[3]

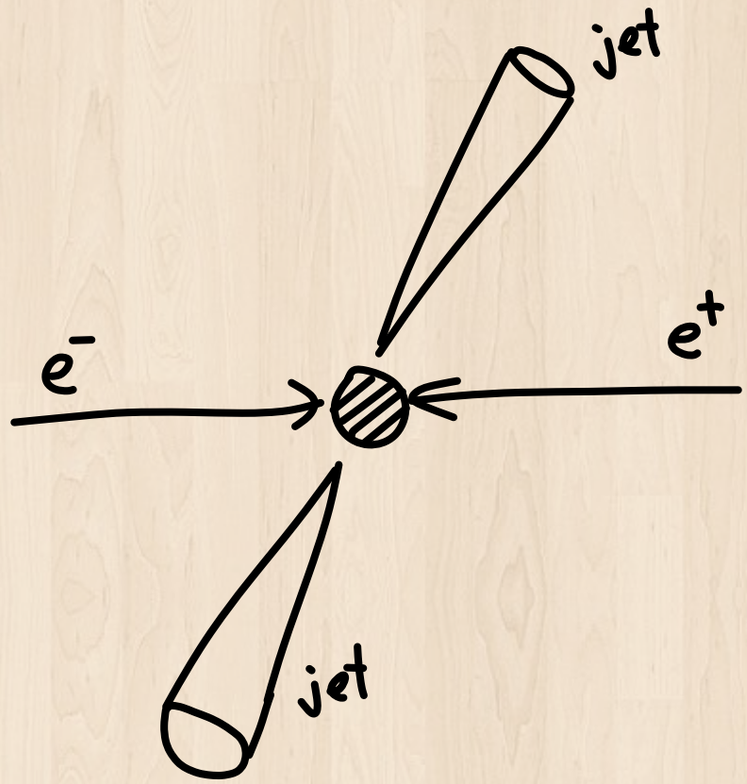
Sep 28, 2021. Jets for 3D Imaging at the EIC

[1] Massachusetts Institute of Technology
[2] National Taiwan University
[3] University of Colorado Boulder
[4] Universita degli Studi di Bari
[5] Georgia State University

The MITHIG's work is supported by DOE-NP

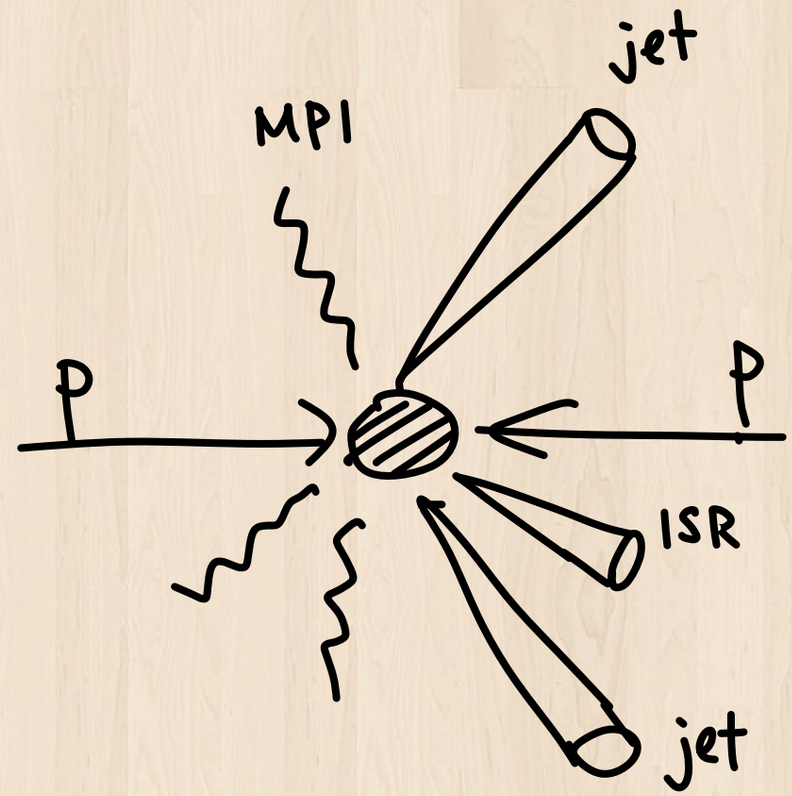
Modern jets with LEP

e^+e^-: clean



Better control of
event kinematics

Cleanest test of
pQCD and models

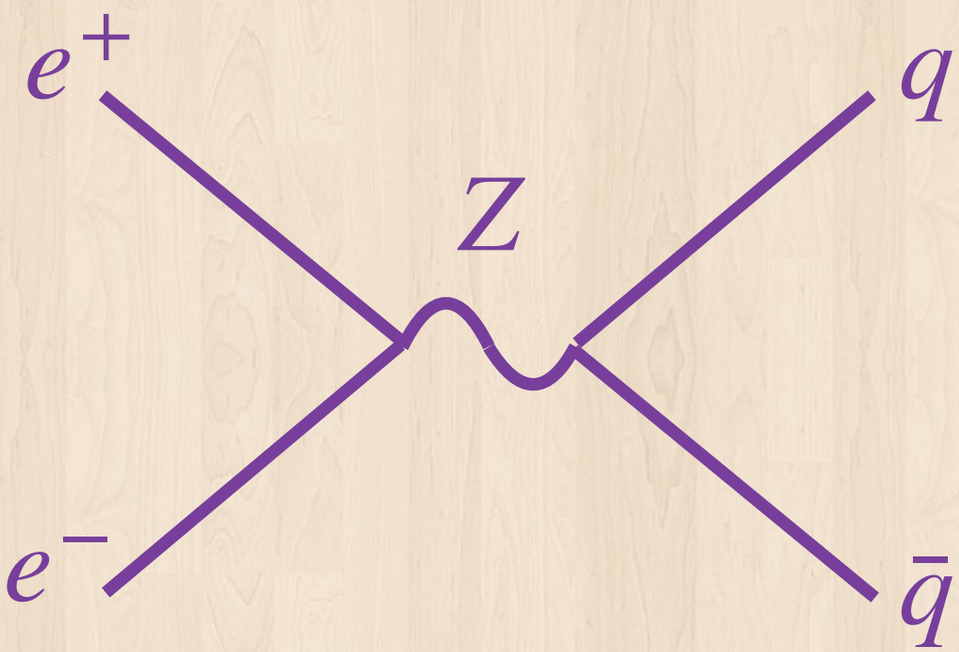


PDF convolution
No longitudinal control
More ISR
MPI

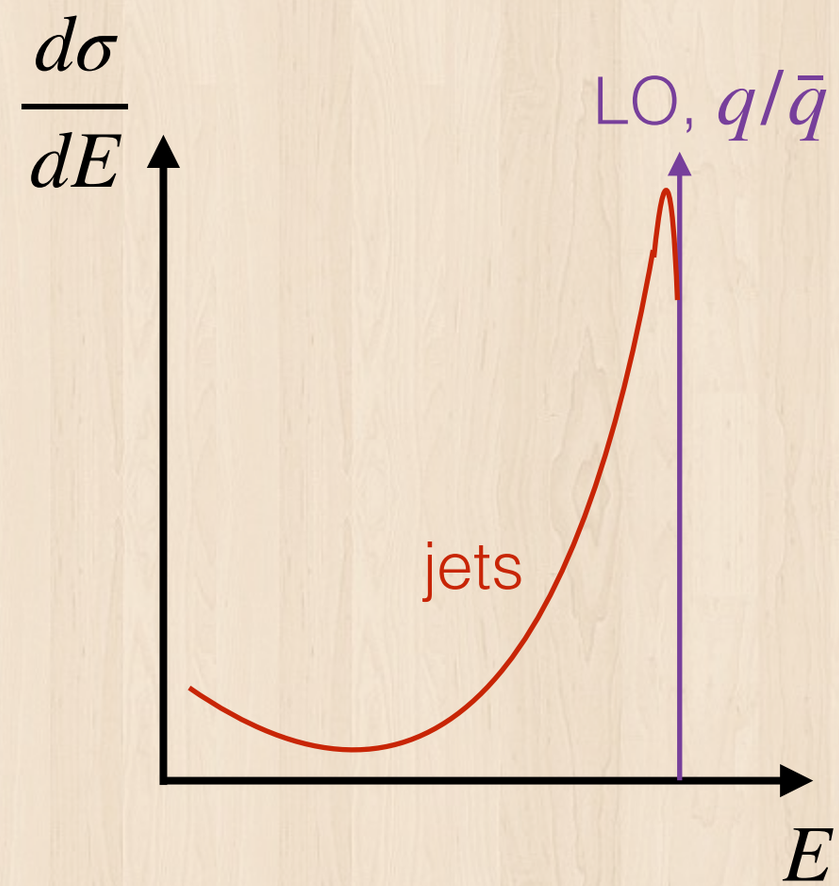
Complements well measurements from EIC

Peaked structure

91.2 GeV collisions



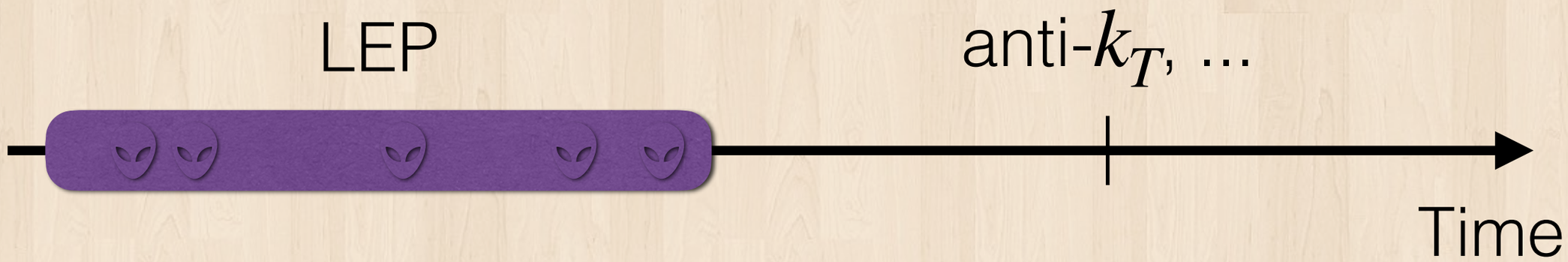
Dominant jet diagram



Peaked structure is useful for studying jets

Out-of-cone energy => “energy loss”

LEP jet measurements



Most jet measurements are done with
previous generation of jet algorithms
=> Not ideal for LHC/RHIC/EIC comparisons

Excellent opportunity for re-analysis with new algorithms

Today: a recent re-analysis of archived ALEPH data

List of measurements

anti-"k_T" jet, R = 0.4

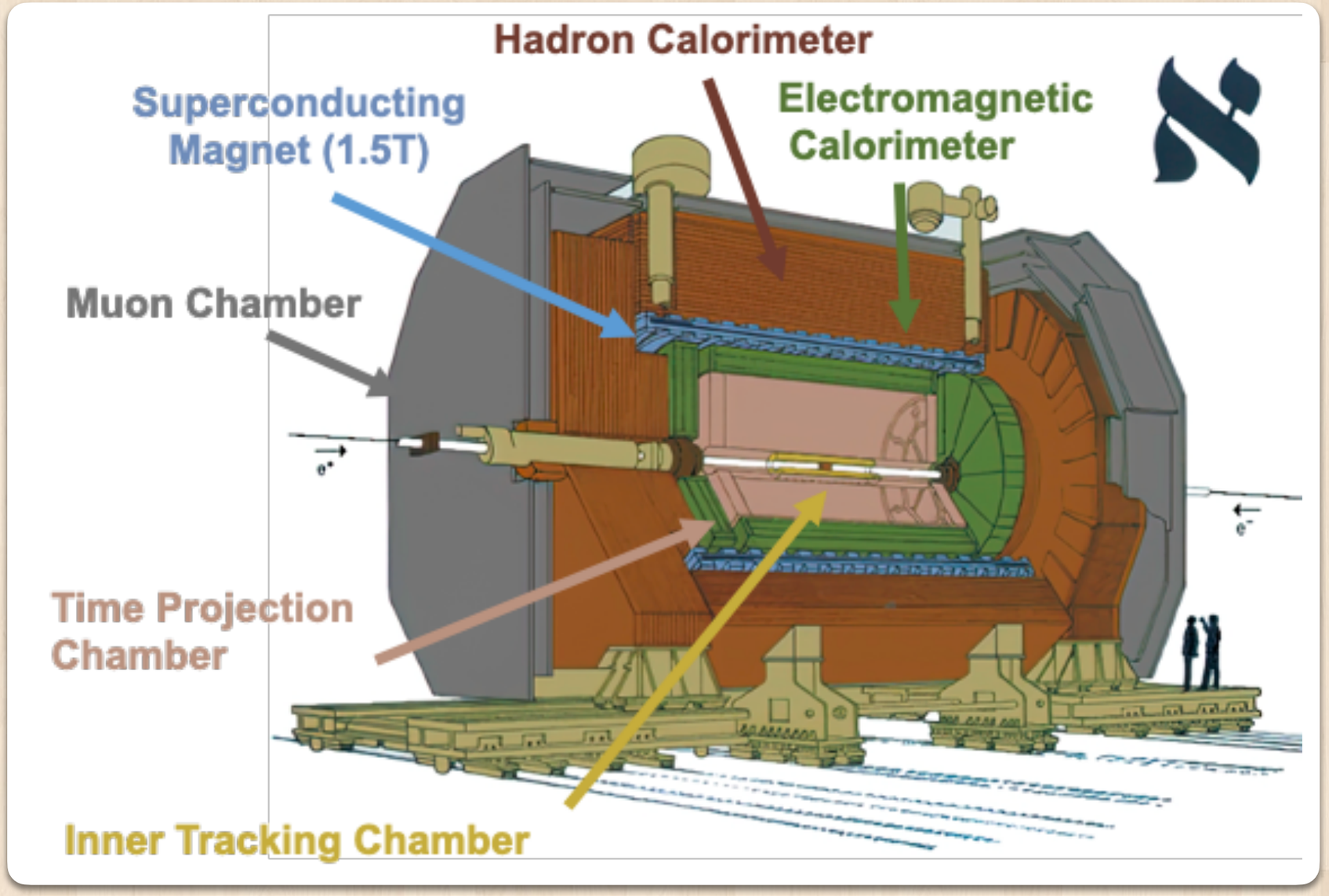
$0.2\pi < \theta_{\text{jet}} < 0.8\pi$ ← acceptance (avoid beam pipe)

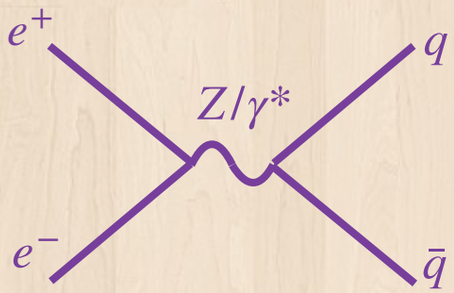
Inclusive jets	Leading dijets
Energy spectra	Energy spectra
Full jet mass	Sum energy spectra
Groomed jet mass	
Momentum sharing	
Groomed jet size	

Soft drop grooming

More details later!

ALEPH detector





LEP1 e^+e^- data taken at 91.2 GeV from 1992-1995

About 2.5M recorded hadronic events with ALEPH

Jets and calibration

Jet clustering

1994 archived data & simulation analyzed

Energy-flow objects (combining tracker, calorimeter and muon chambers) are used as input

In order to compare with LHC/RHIC

anti-"k_T" jet, R = 0.4

Hadron-hadron collider

$$d_{ij} = \min\left(p_{T,i}^{-2}, p_{T,j}^{-2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{T,i}^{-2}$$

e^+e^- distance measure

$$d_{ij} = \min\left(E_i^{-2}, E_j^{-2}\right)\frac{1-\cos\theta_{ij}}{1-\cos R}$$

$$d_{iB} = E_i^{-2}$$

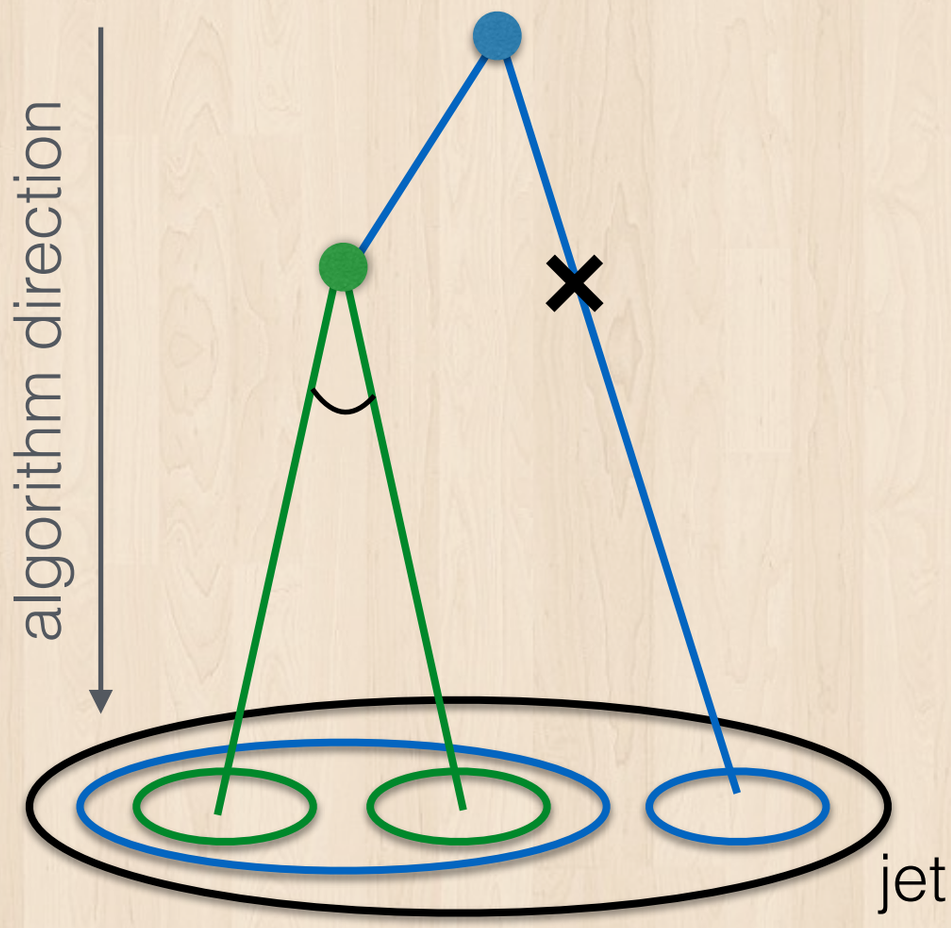
θ_{ij} = real opening angle

JHEP 0804 (2008) 063

EPJC 72 (2012) 1896

Jet grooming

Soft drop/mMDT grooming



$(z_{\text{cut}}, \beta) = (0.1, 0.0)$

Recluster jet constituents with C/A algorithm

Sequentially open up jet until condition is met

$$z \equiv \frac{\min(E_1, E_2)}{E_1 + E_2} > z_{\text{cut}} \left(\frac{\theta_{12}}{R}\right)^{\beta}$$

E instead of p_T $\qquad$ θ_{12} = real angle

r_g = opening angle

z_g = momentum sharing

M_g = invariant mass

JHEP 1405 (2014) 146

PRL 100 (2008) 242001

Jet calibration

"MC calibration" "Residual"

Jet energy scale in data = Jet energy scale in simulation × $\frac{\text{Jet energy scale in data}}{\text{Jet energy scale in simulation}}$

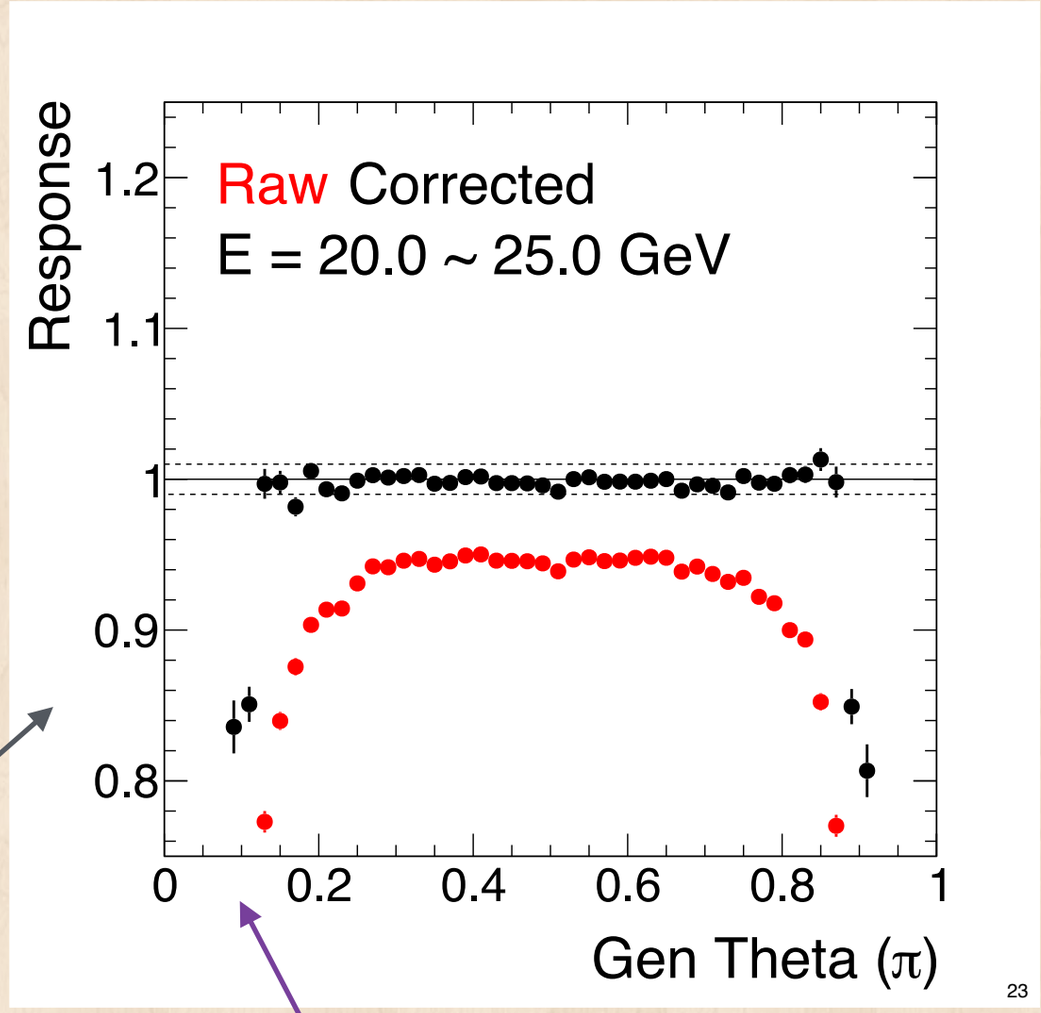
Inclusive Selection

Strategy: first go 99% of the way there with simulation
Then data and MC difference in restricted phase spaces

Simulated energy scale

Correct detector jet energy in bins of jet direction (θ_{jet})

Good closure with
$E > 10$ GeV
$0.2\pi < \theta_{\text{jet}} < 0.8\pi$



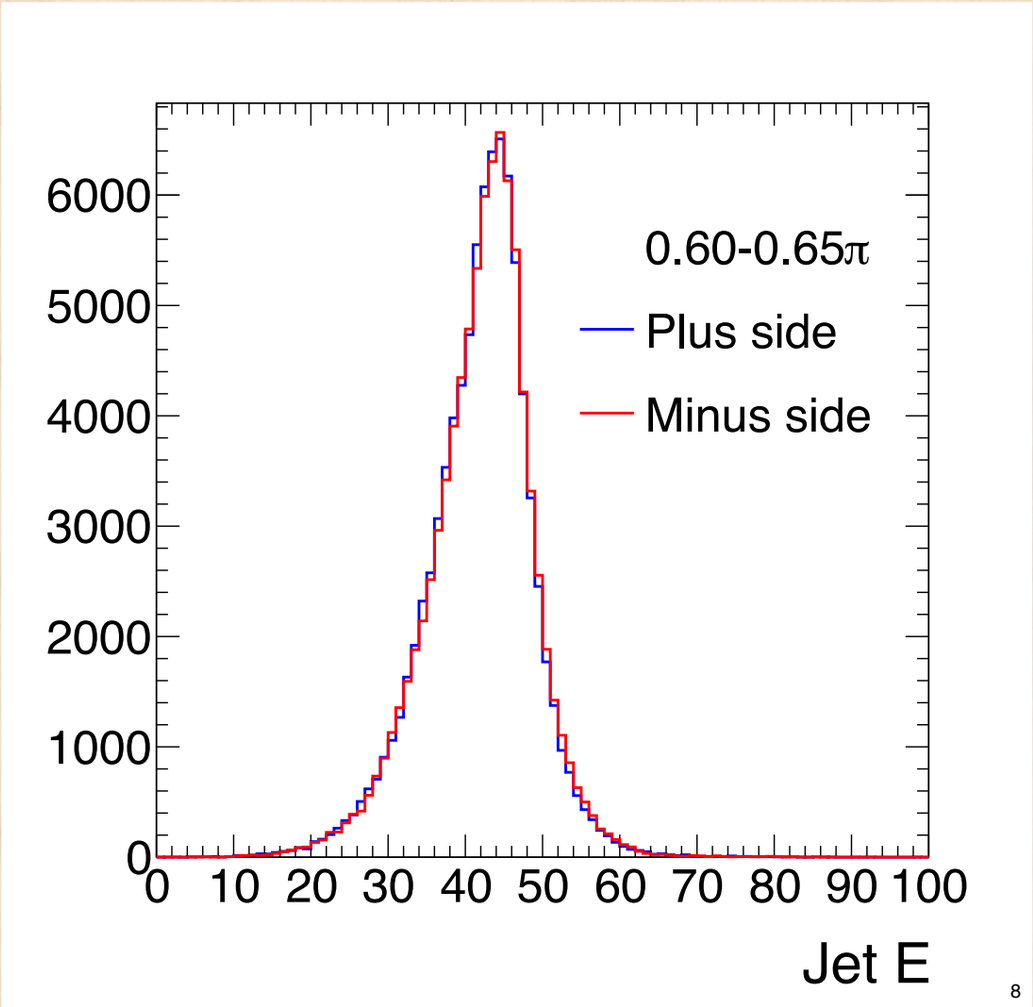
Example raw and corrected response (= reconstructed/generated)

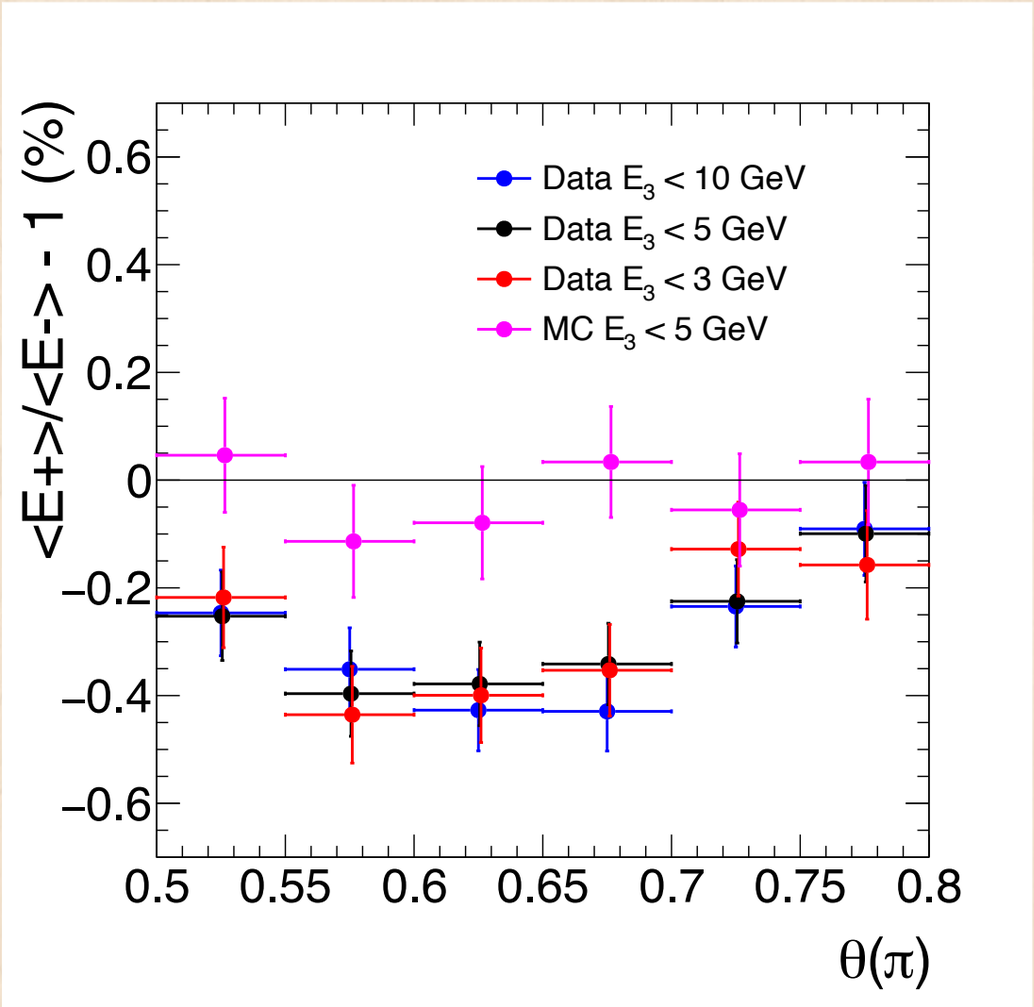
Energy leaking out around beam direction

arXiv 2108.04877

Residual calibration: step 1

Fiducial dijet, two sides of the detector



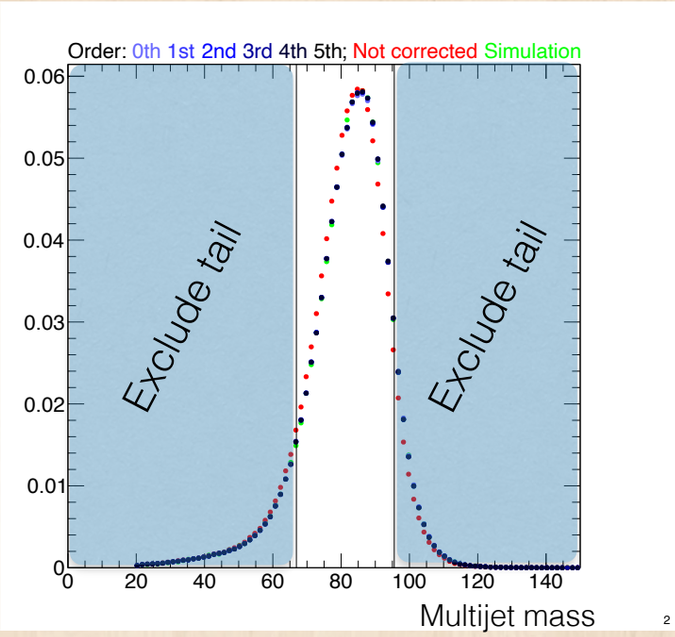


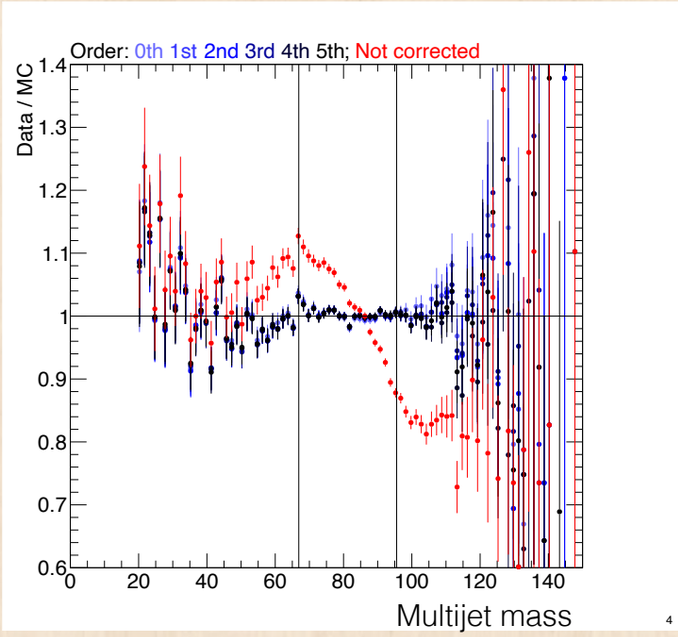
Look at data only, and calibrate out the difference between e^-- and e^+-going sides

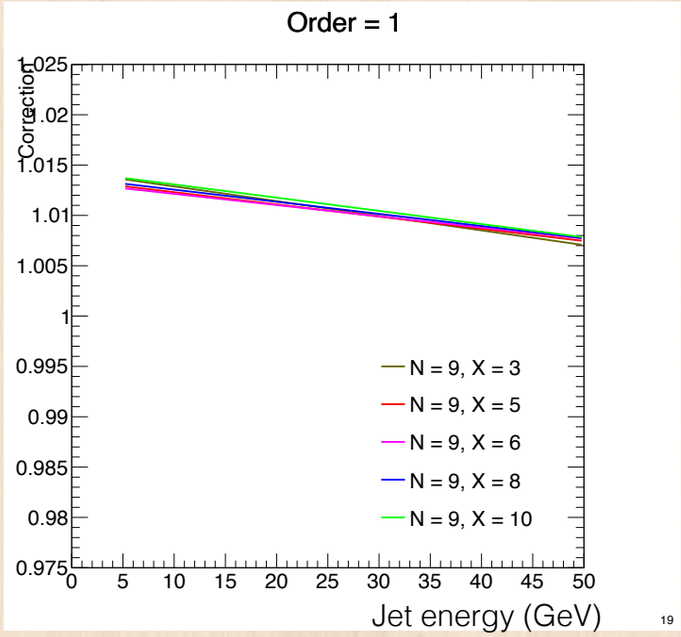
arXiv 2108.04877

Residual calibration: step 2

Fiducial multijet invariant mass







Take up to leading N jet above X GeV

Vary N and X for systematics

Fit jet energy correction function parameters

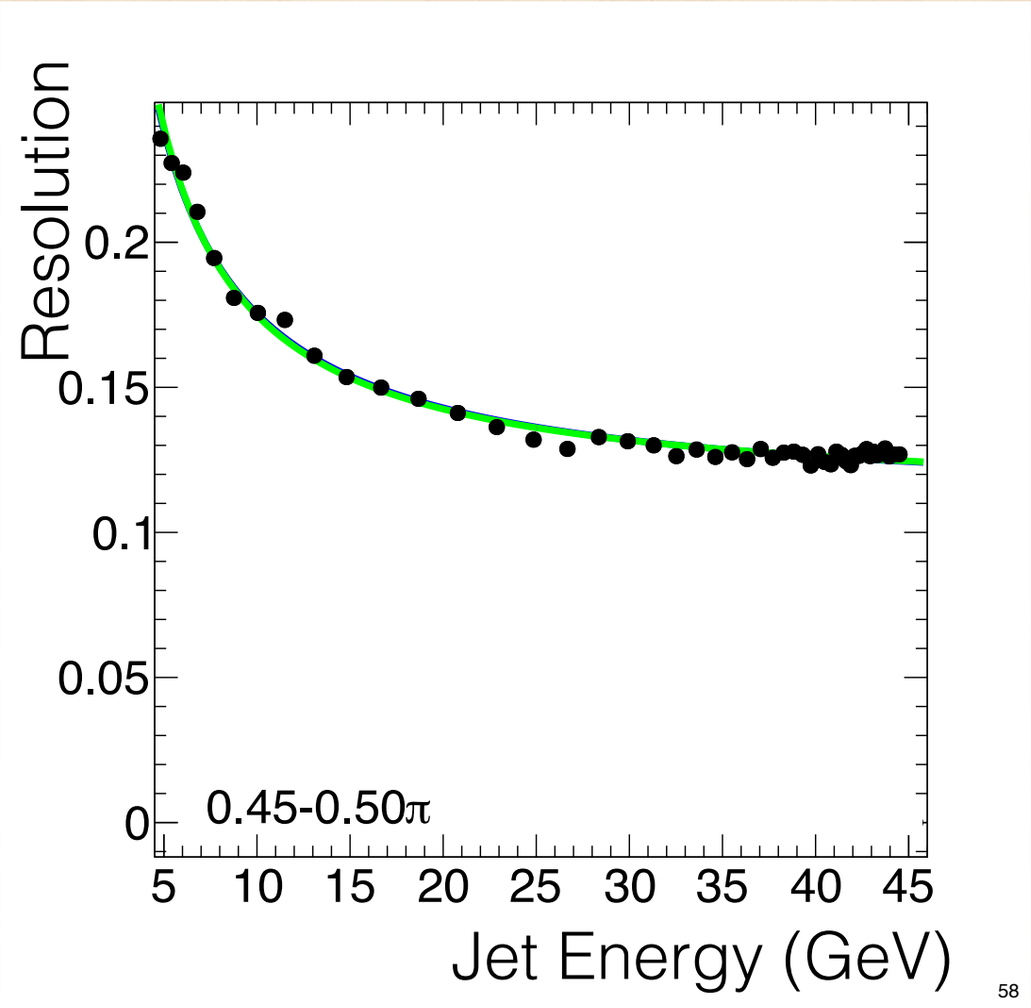
Minimize “quantile difference” (~KS) between data and MC curves

Nominal: linear correction as a function of energy

arXiv 2108.04877

Jet resolution

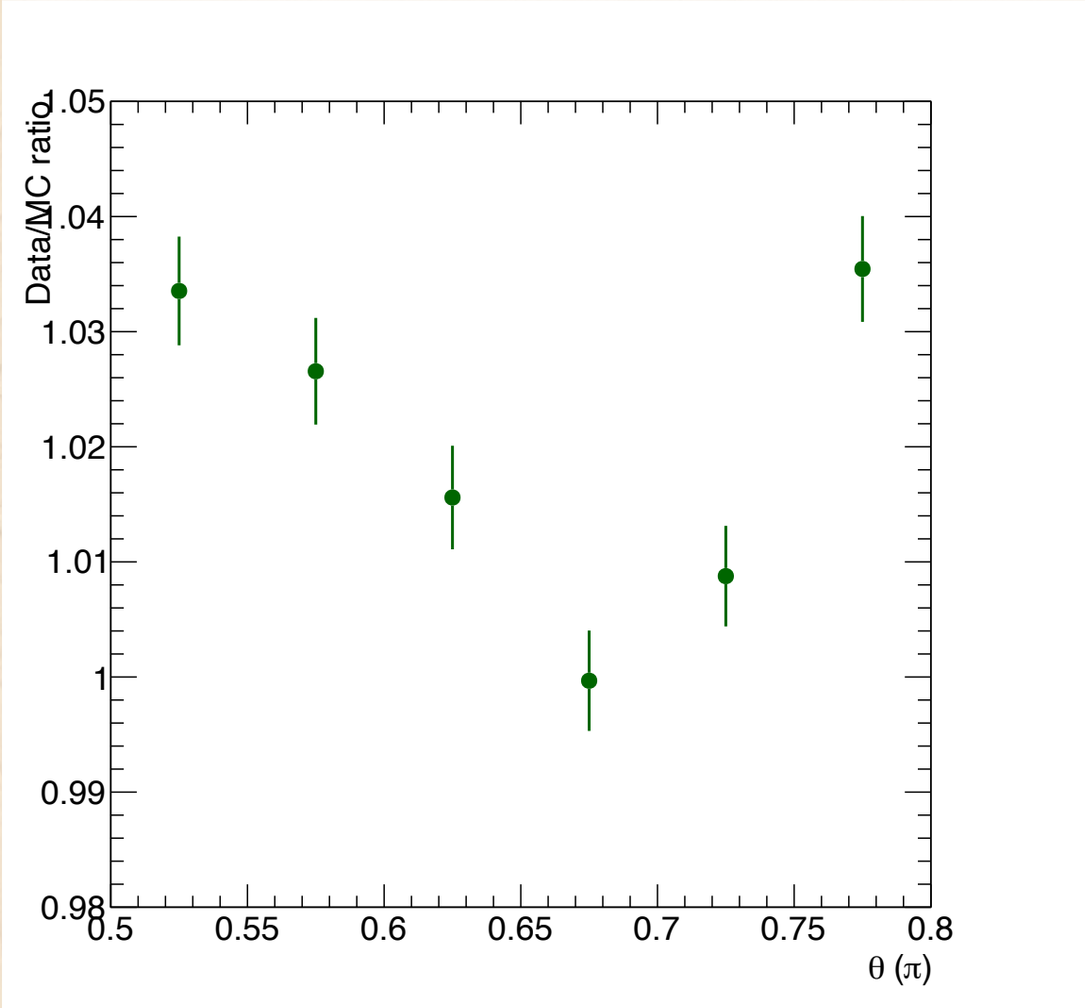
Jet resolution in simulation



Energy resolution: 10-25%

(Angular resolution: 0.01-0.05)

Fiducial dijet —
vary 3rd-leading jet as systematics

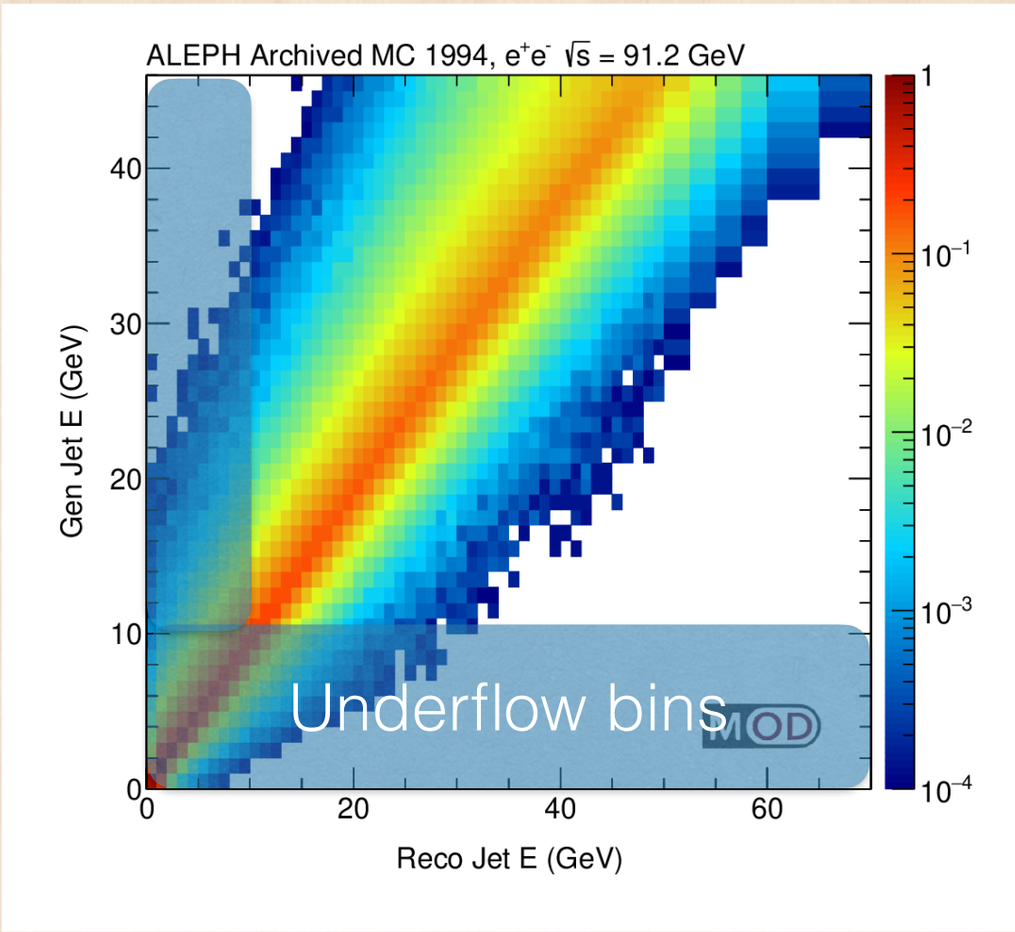


0-5% difference in energy resolution between data and MC

arXiv 2108.04877

Analysis

Unfolding



Example: inclusive jet energy

Unfolding performed using the **BayesUnfold** method implemented in **RooUnfold** package

SVD unfold as systematic check

Flat prior as nominal

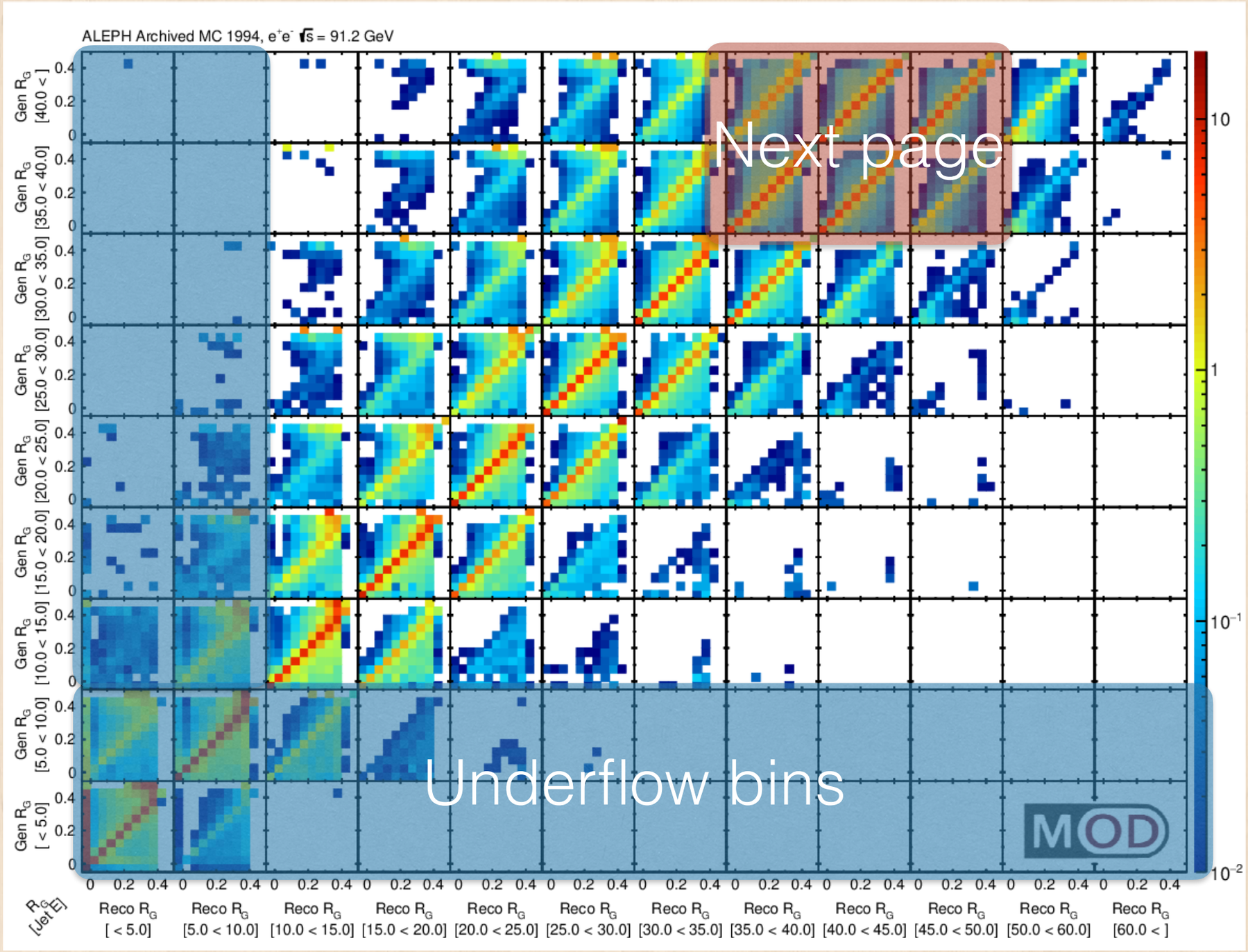
MC prior as systematic check

2D unfold for mass & groomed quantities

Due to energy migration

arXiv 2108.04877

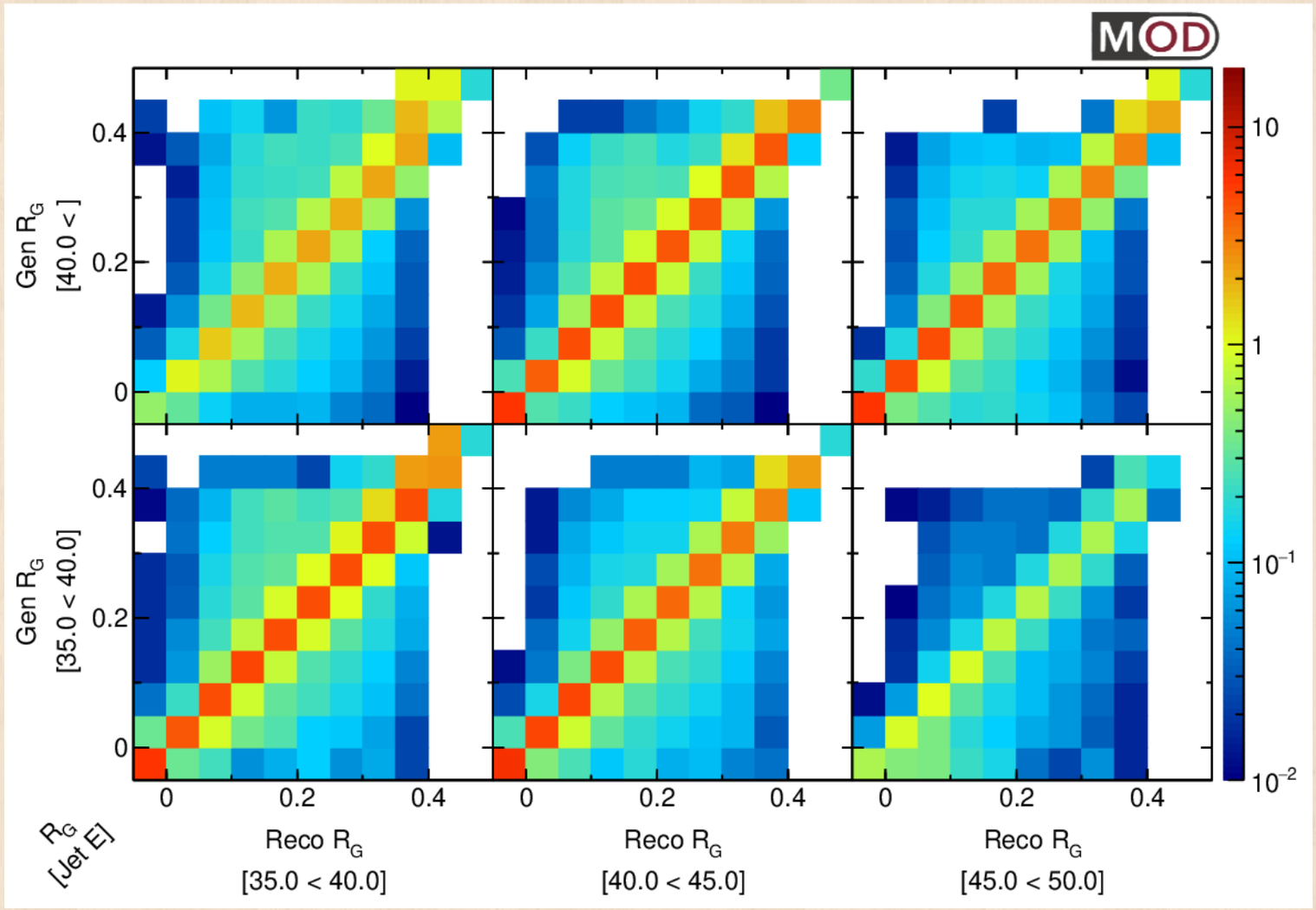
2D smearing matrix



arXiv 2108.04877

2D smearing matrix

Partial smearing matrix



Each block: different jet E

Generally well-behaved

Percent-level off-diagonal

Example: jet R_G

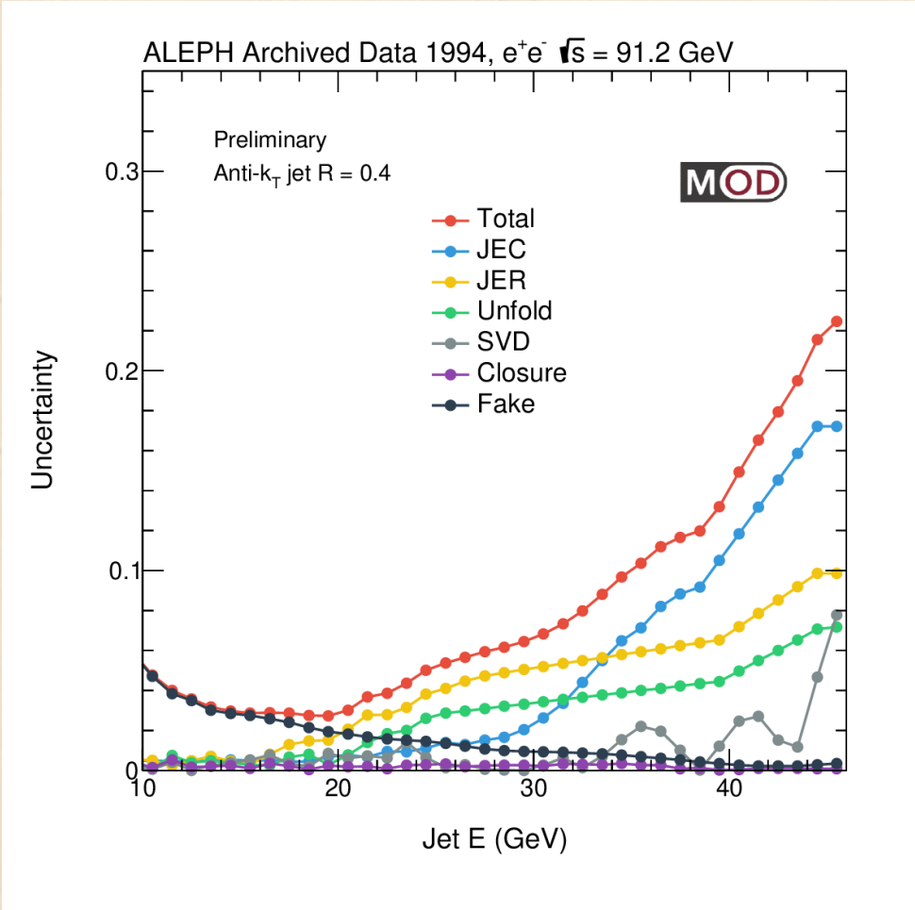
arXiv 2108.04877

Systematic uncertainties

- Jet-related
  scale: vary up/down
  resolution: vary jet smearing between 0-5%

- Unfolding
  prior: flat vs MC prior
  regularization parameter ± 1
  SVD: different unfold method

- Fake (combinatorial jet)
  generator jet matching studies

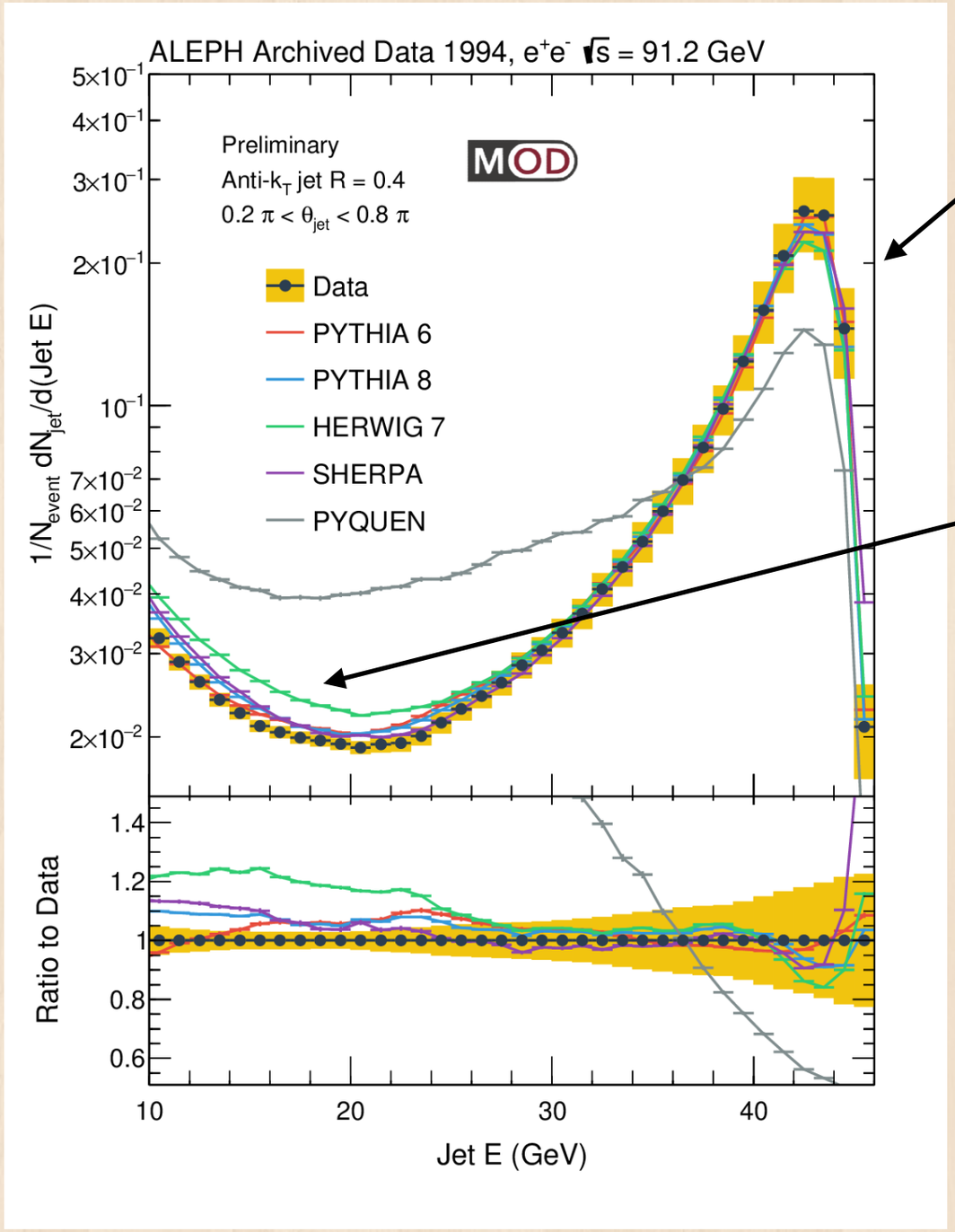


Example: inclusive energy

arXiv 2108.04877

Result

Jet energy



Clear peaked structure

Most energy captured by the jets

Simulation tend to over-predict lower energy jets

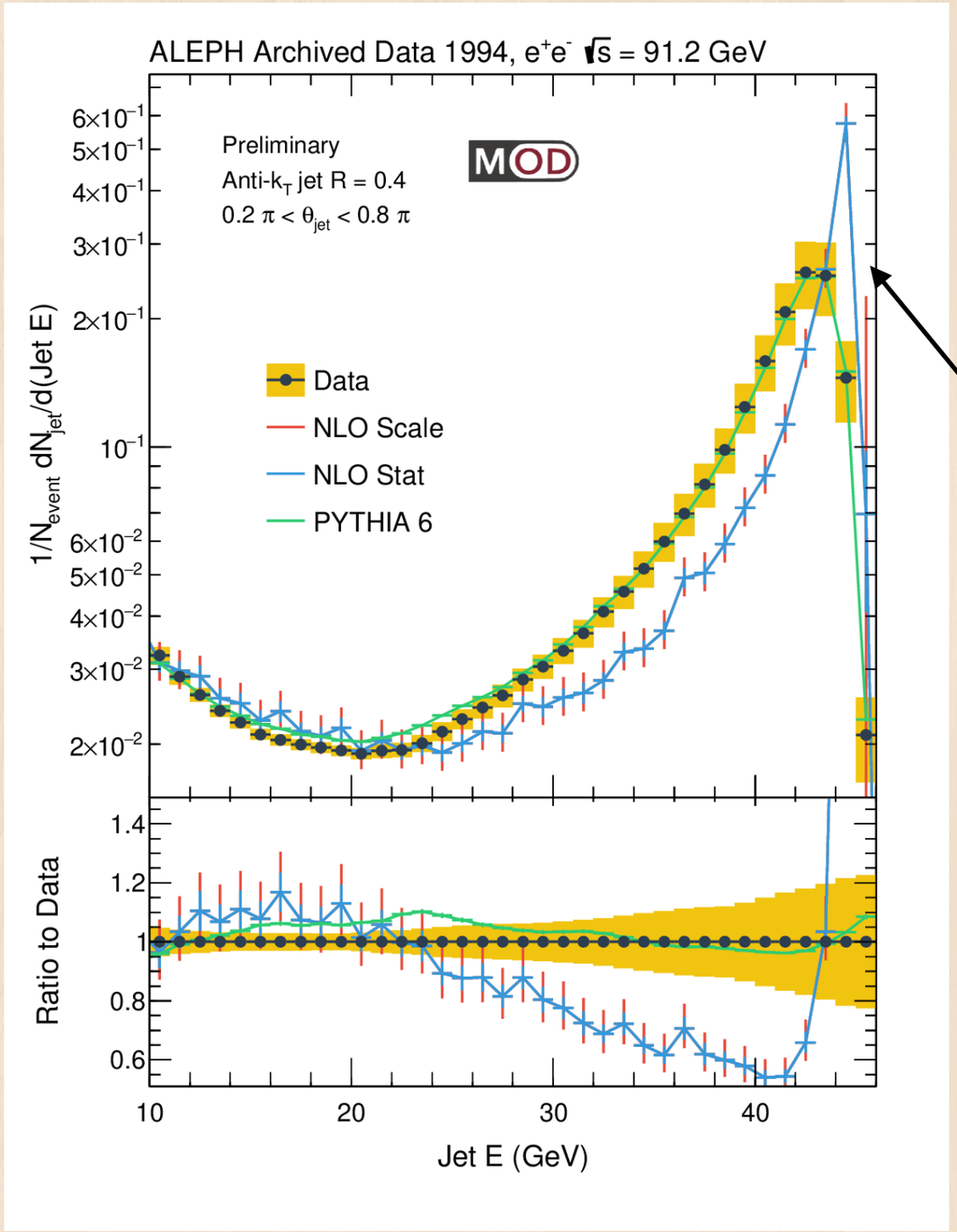
(**PYQUEN** = generator with jet quenching effects)

~minimum bias 5.02 TeV PbPb

(Simulation normalized to same area as data)

arXiv 2108.04877

Jet energy



LO parton level
= delta function at 45 GeV
not too interesting to plot

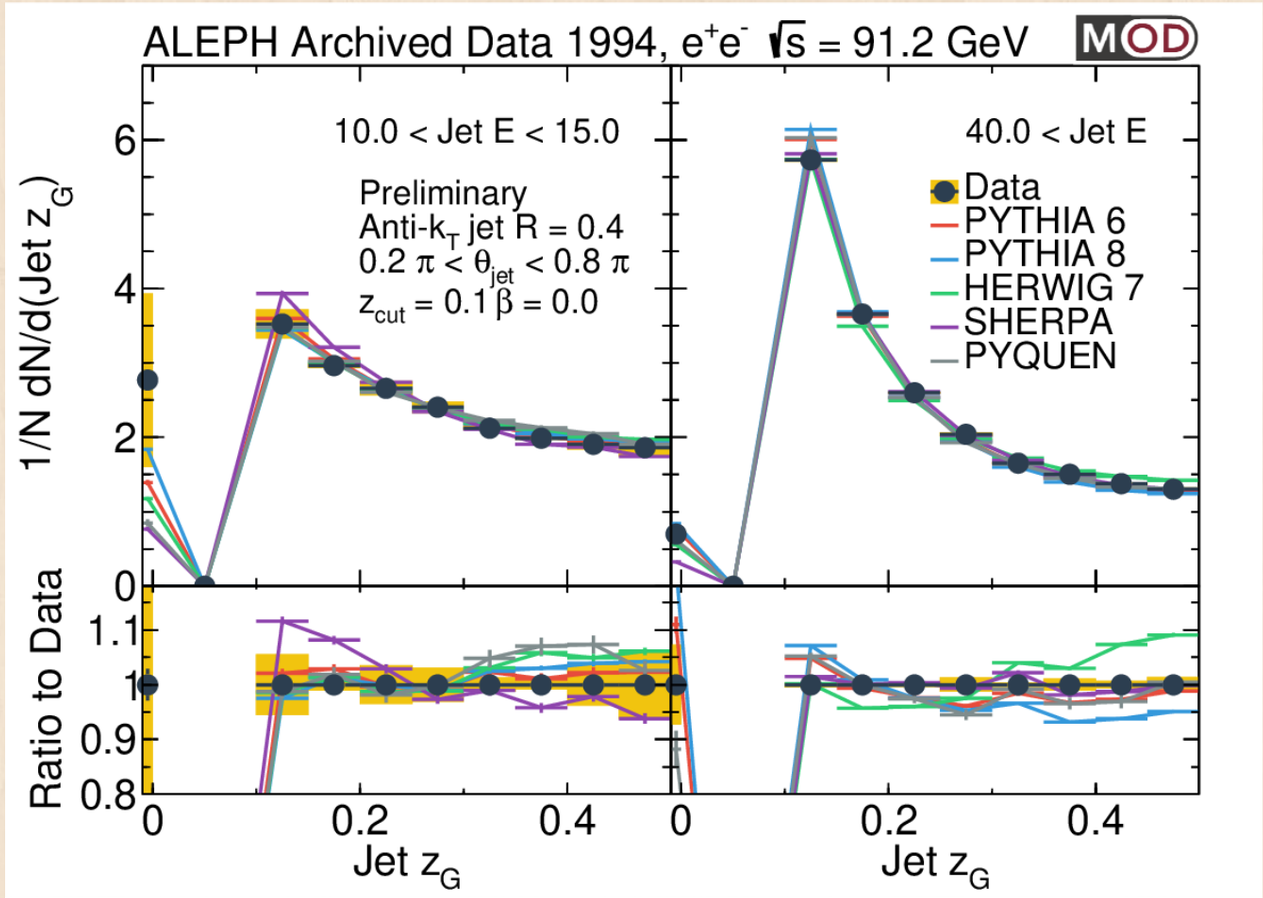
NLO parton level sharper than measured data

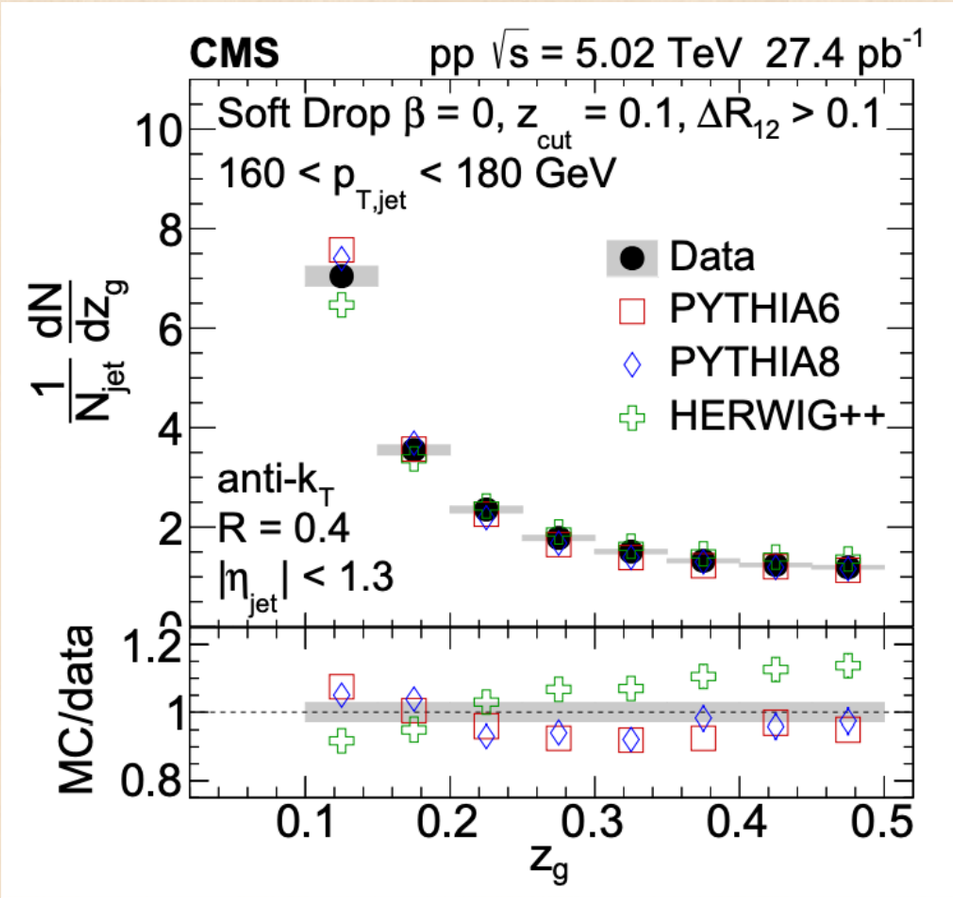
Calculation provided by João Pires (LIP)

(Data is the same as previous page)

Private communication with João Pires

Groomed z_G





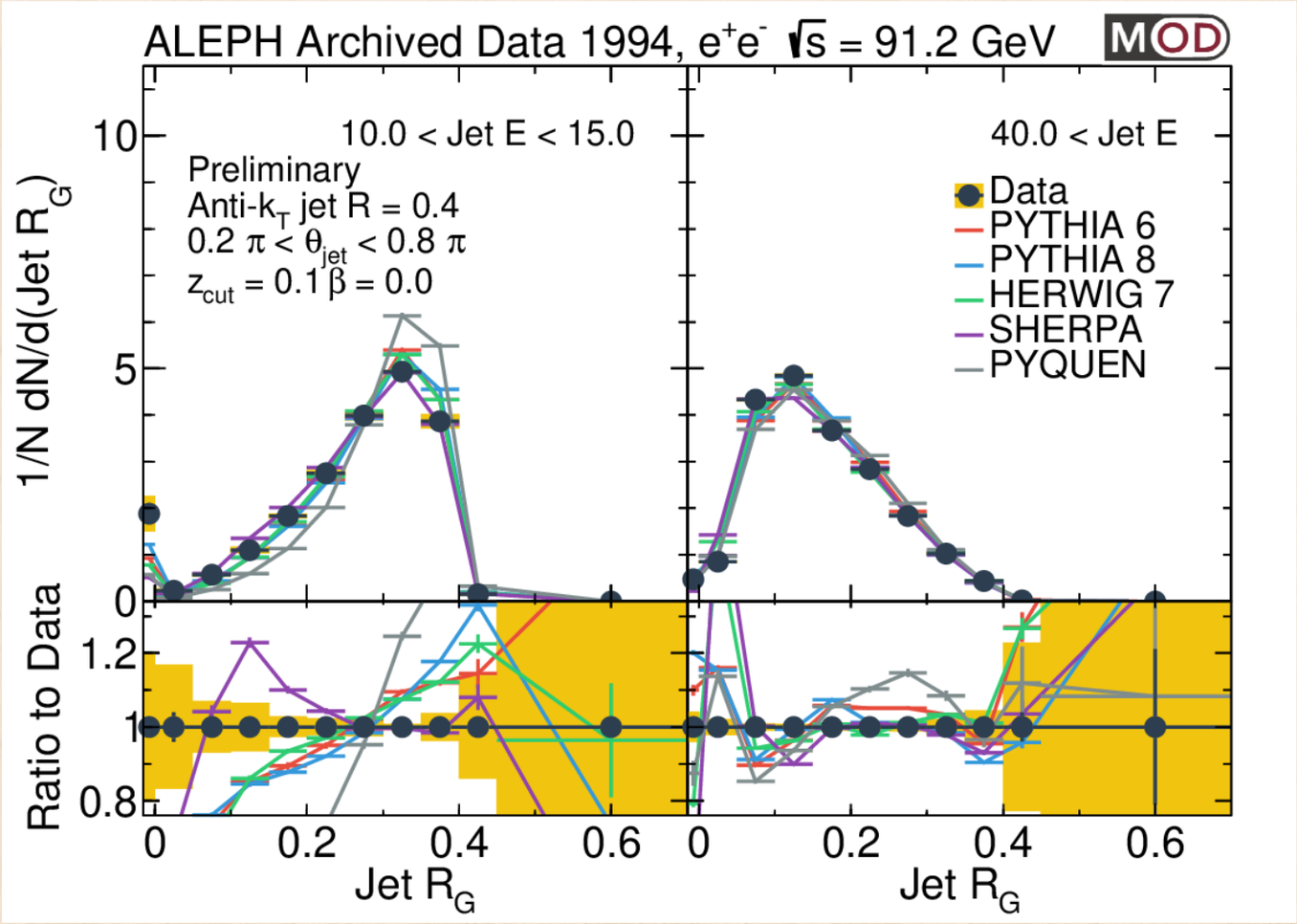
Very distinct behavior between low and high energy

At high energy similar to LHC results

Comparison to **PYTHIA** and **HERWIG** also similar

arXiv 2108.04877

Groomed R_G



Much higher R_G for low energy jets => soft radiation & combinatorial

High energy jets more similar to LHC/RHIC

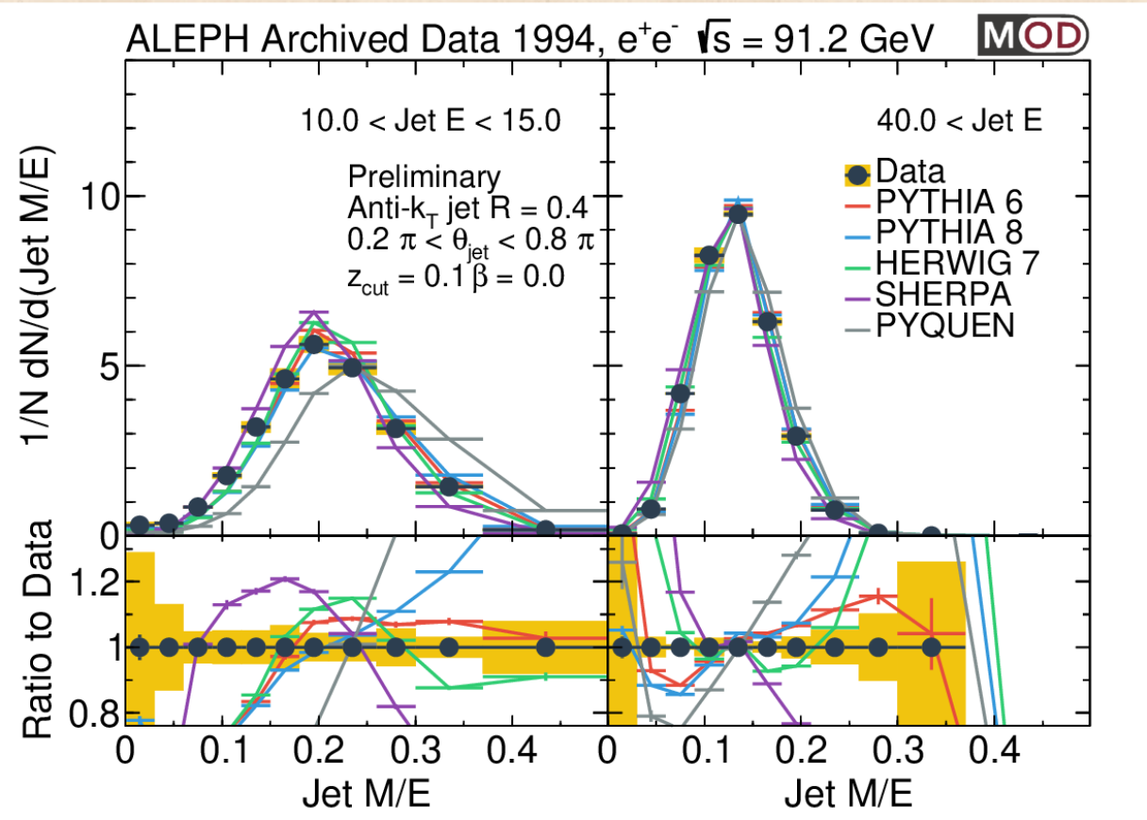
Very distinct behavior between low and high energy

Worse data/generator agreement at low energy

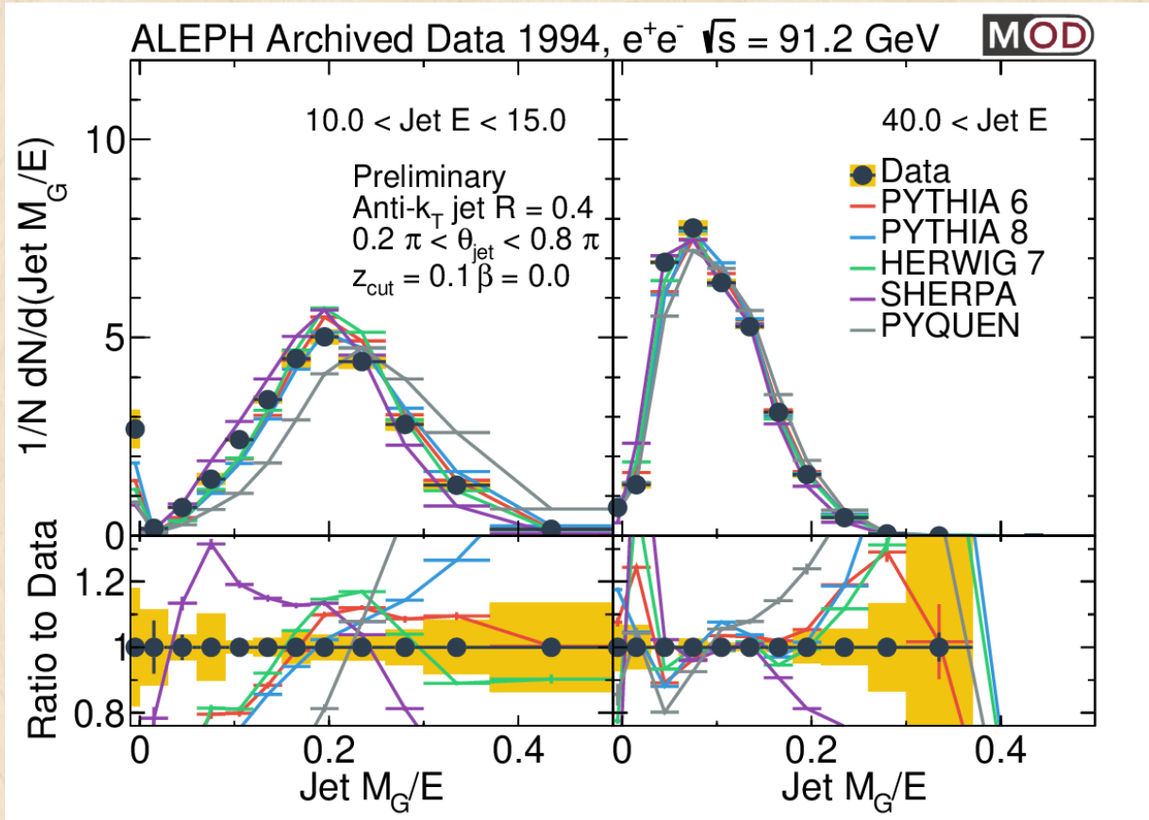
arXiv 2108.04877

Jet mass

Full jet



Groomed jet



High correlation between R_G and mass => similar trends

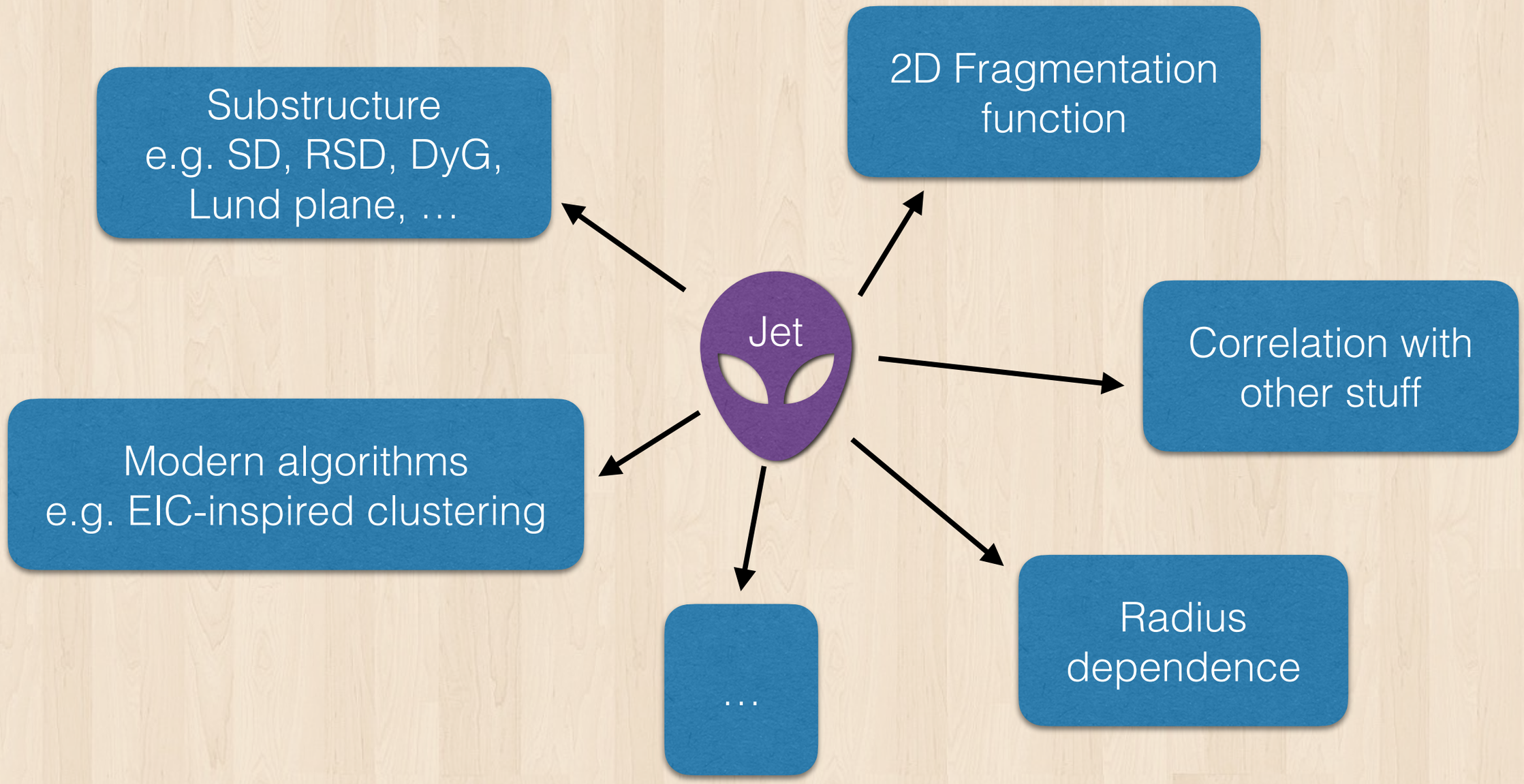
Difference between two masses sensitive to soft radiation => future studies

SHERPA lower mass; none of the generators agree with data fully

arXiv 2108.04877

Summary and outlook

Many possibilities

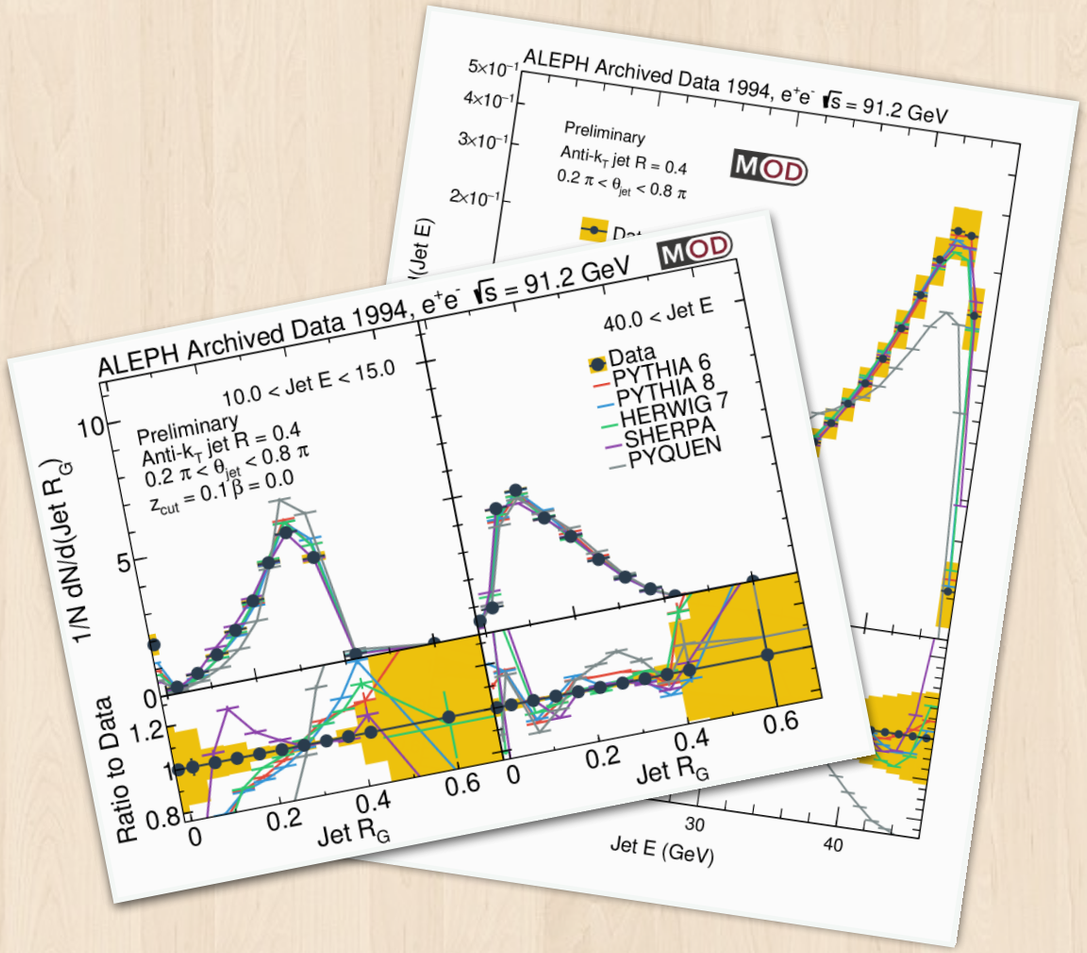


Testing ground for new algorithm developments

Provide reference measurements

Summary

- Measurement of anti-"k_T" jet spectra using 91.2 GeV archived ALEPH e^+e^- data — energy & substructure
  - Publication coming soon!
  - Decent jet performances
  - Generators do a decent job overall, some discrepancies remain
  - Many potential future measurements being explored



Thank you!

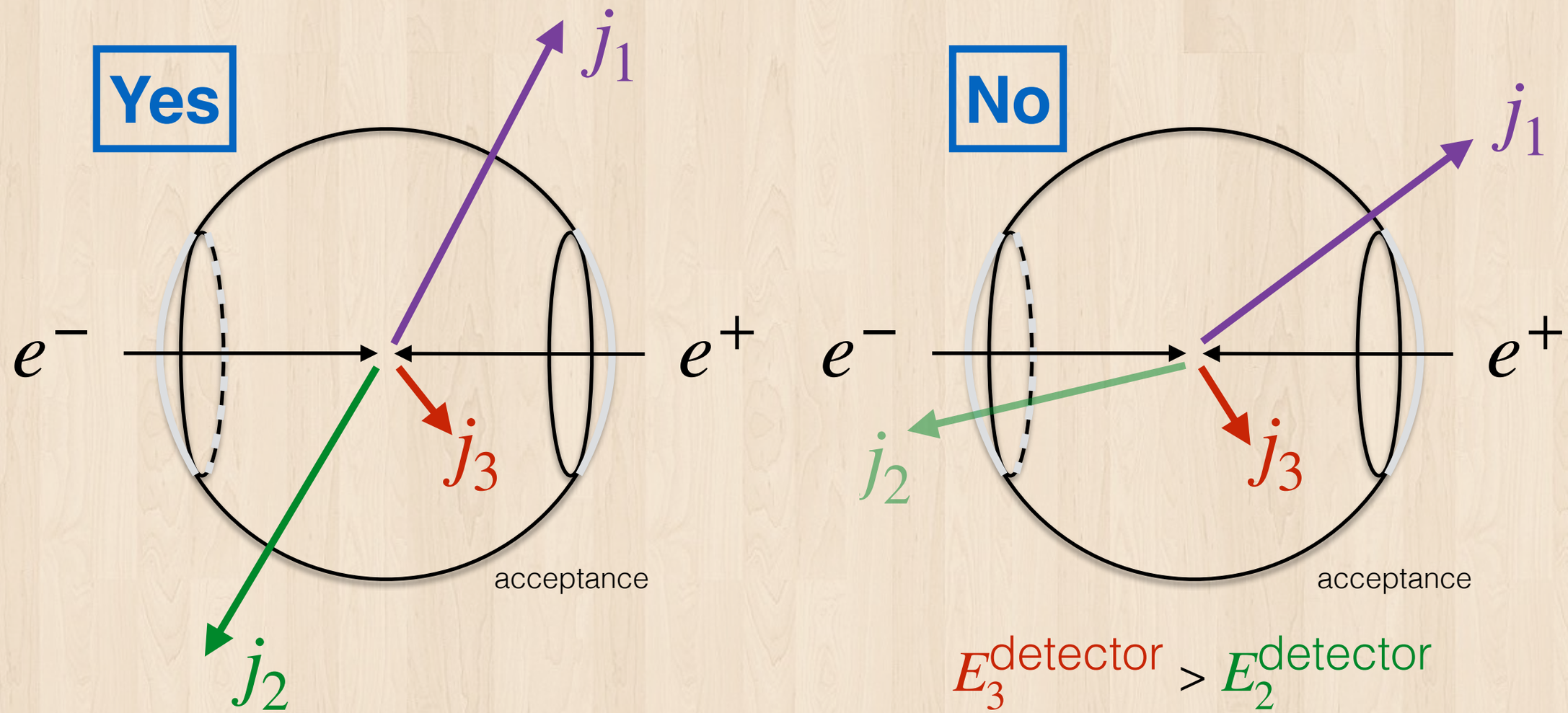
- We would like to thank Roberto Tenchini and Guenther Dissertori from the ALEPH collaboration for the useful comments and suggestions on the use of ALEPH archived data

- We would like to thank Felix Ringer, Jesse Thaler, Andrew Larkoski, Liliana Apolinário, Ben Nachman, Camelia Mironov, Jing Wang for the useful discussions on the analysis

Backup Slides Ahead

Selecting leading jets

Global leading dijet



We want to measure <u>global</u> leading dijet

But: out-of-acceptance jets appear lower in energy

Leading dijet selection

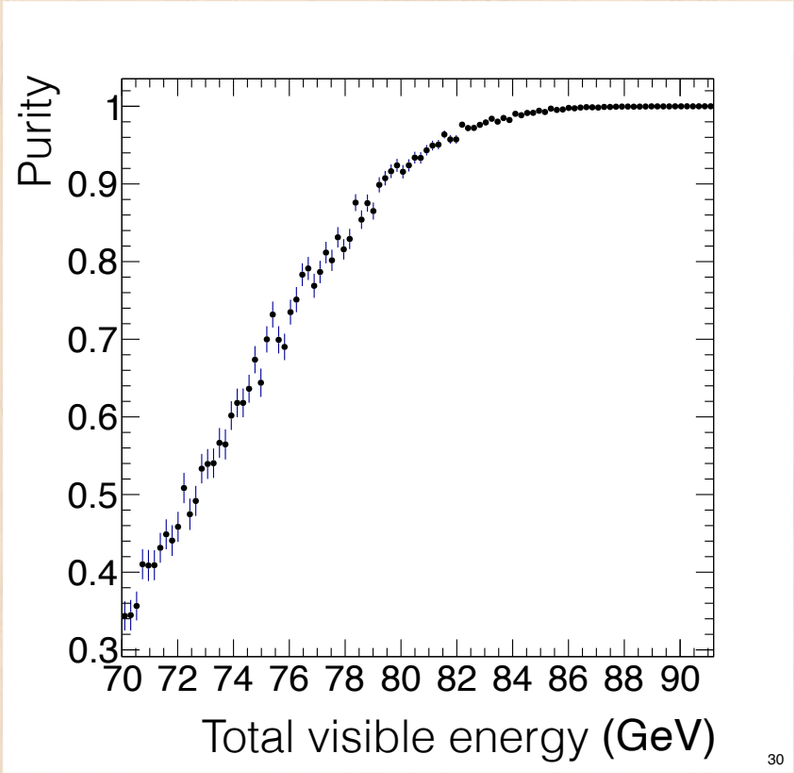
Solution: require minimal total visible energy

Total visible energy = total energy of…
{Particles inside acceptance} ∪
{Particles close to a jet with 5 GeV in acceptance}

Nominal working point: 99%

ie., >99% of events have global leading dijet within acceptance

Apply correction on measured spectra



Leading dijet correction

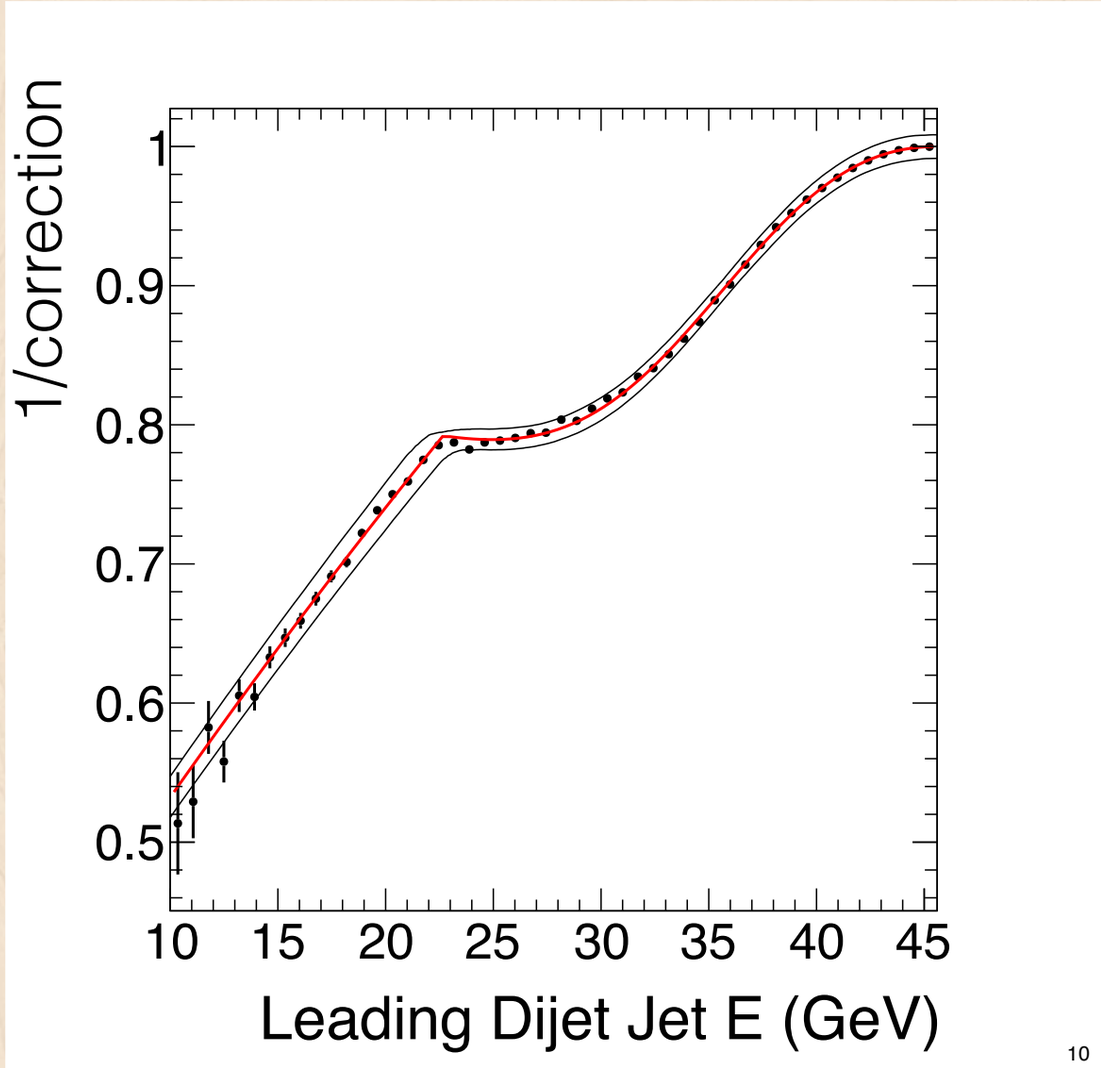
Data with visible energy selection

Unfolding (built with visible energy selection)

Truth level with visible energy selection

Truth level without visible energy selection

Correction



Correction derived from simulation