First measurement of anti-k_T jet spectra and jet substructure using the archived ALEPH e^+e^- data at 91.2 GeV

Yi Chen (MIT)

International Conference on High Energy Physics, Jul 7, 2022

In collaboration with Y.-J. Lee,
A. Badea, A. Baty, P. Chang,
Y.-T. Chien, G.M. Innocenti, M. Maggi,
C. McGinn, D. V. Perepelitsa, M. Peters,
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The MITHIG's work is supported by DOE-NP

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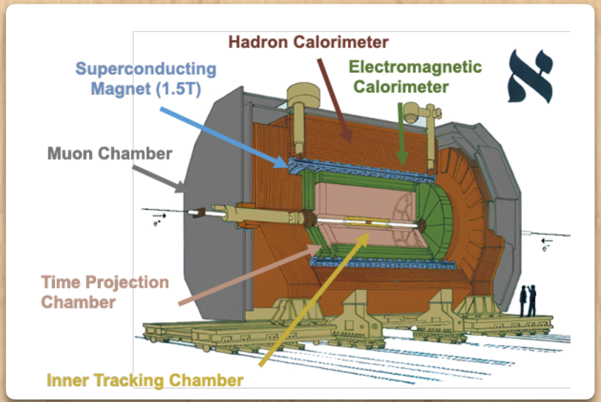
anti-“k_T” jet in e^+e^- with ALEPH

energy and substructure

$\sqrt{s} = 91.2$ GeV

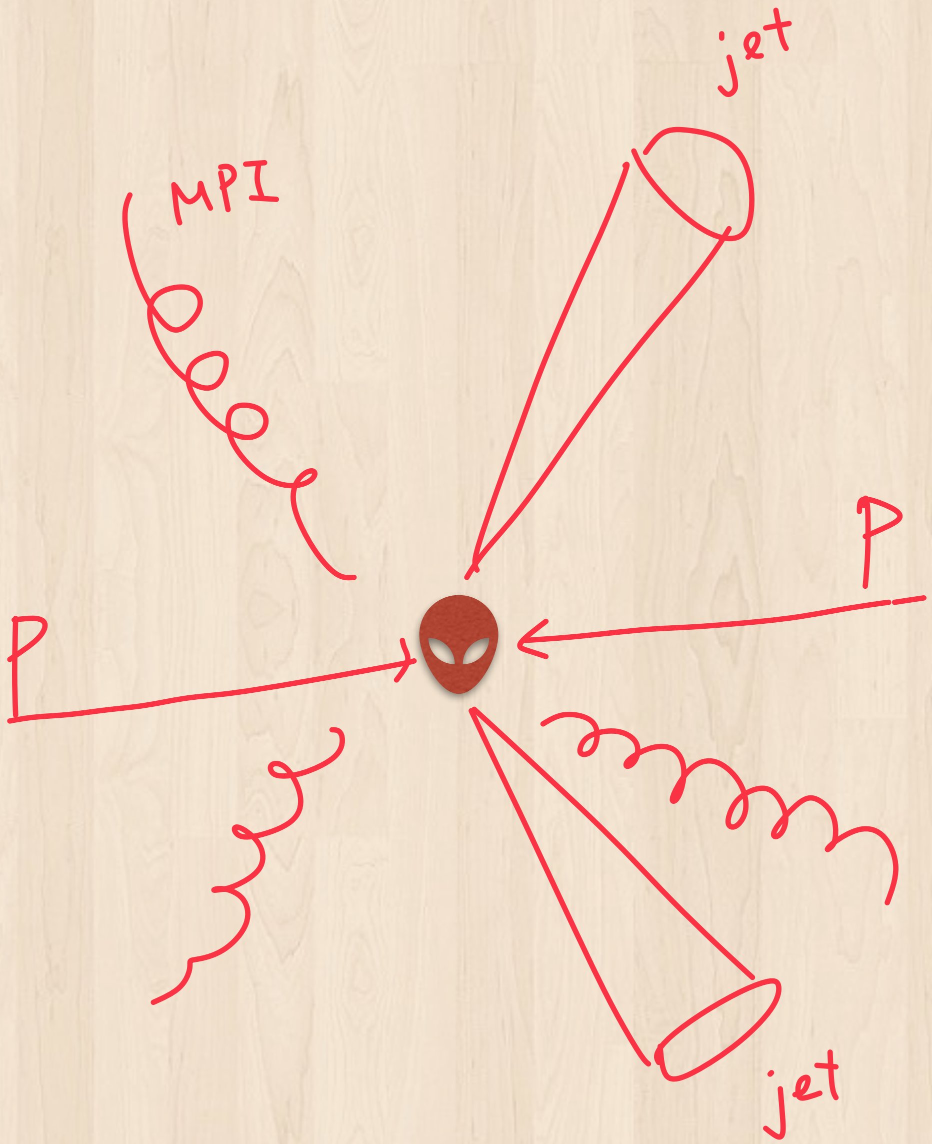


ALEPH, LEP

Presented by Yi  with friends

Why jet in LEP e^+e^-?

It's clean

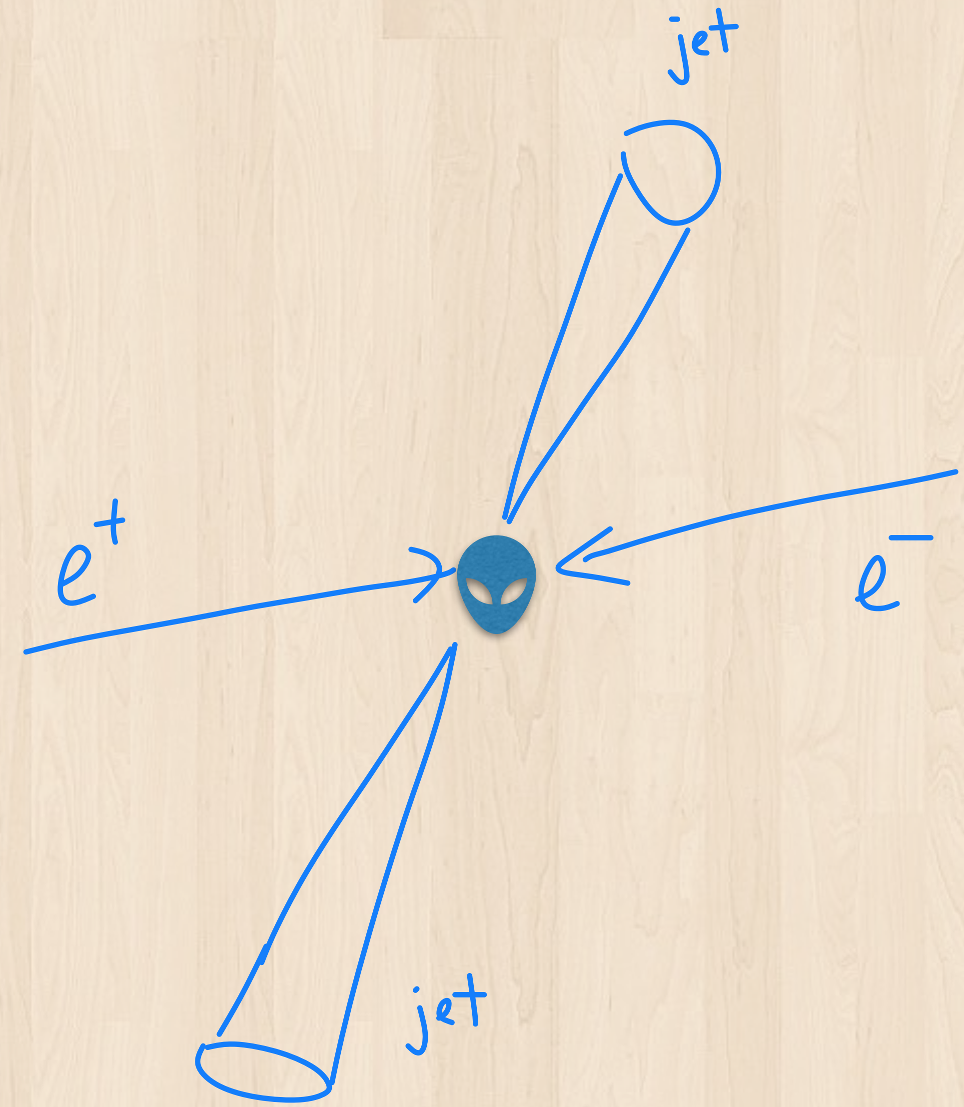


~~PDF~~

~~MPI~~

~~Beam remnant~~

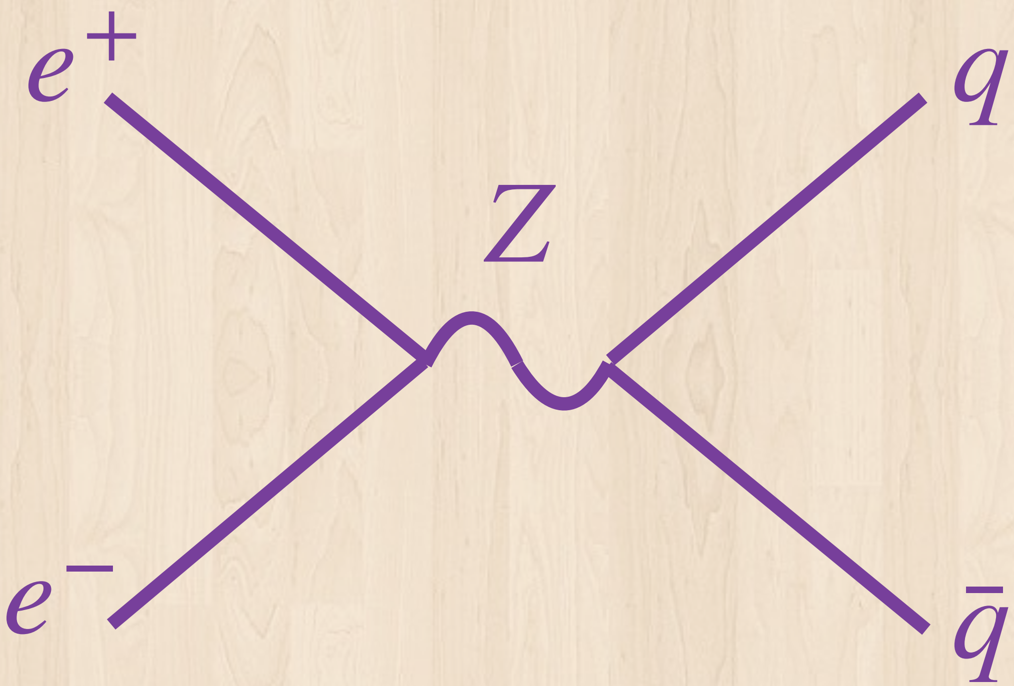
...



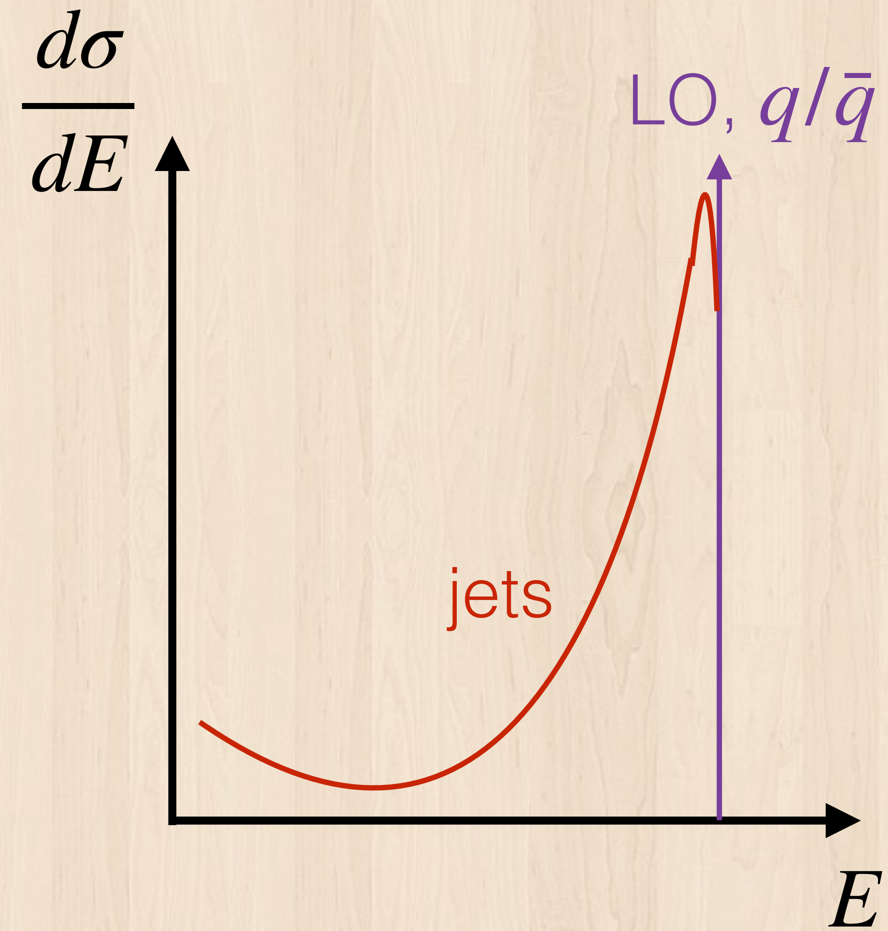
Cleanest test of QCD

It’s peaked and quark dominated

91.2 GeV collisions



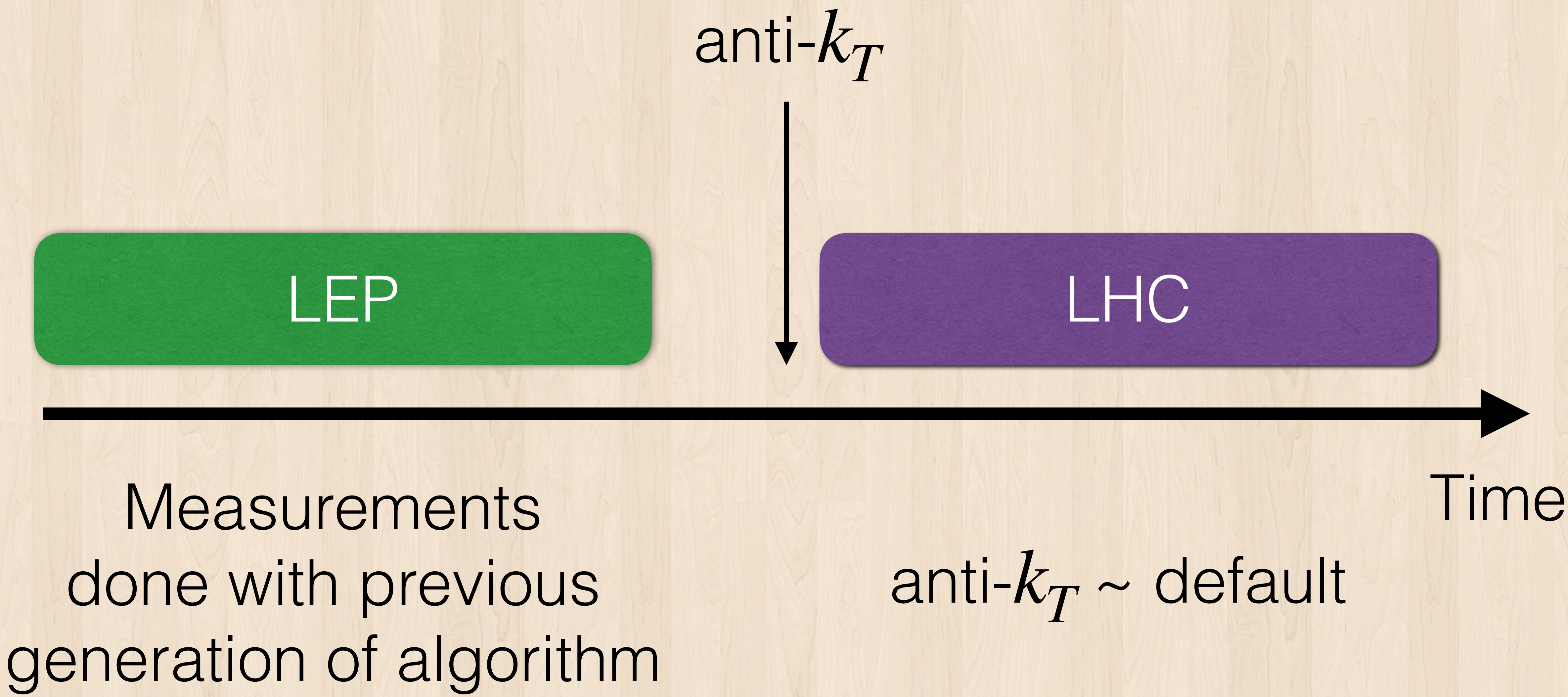
Dominant jet diagram



Peaked structure is useful for studying jets

Out-of-cone energy → “energy loss”

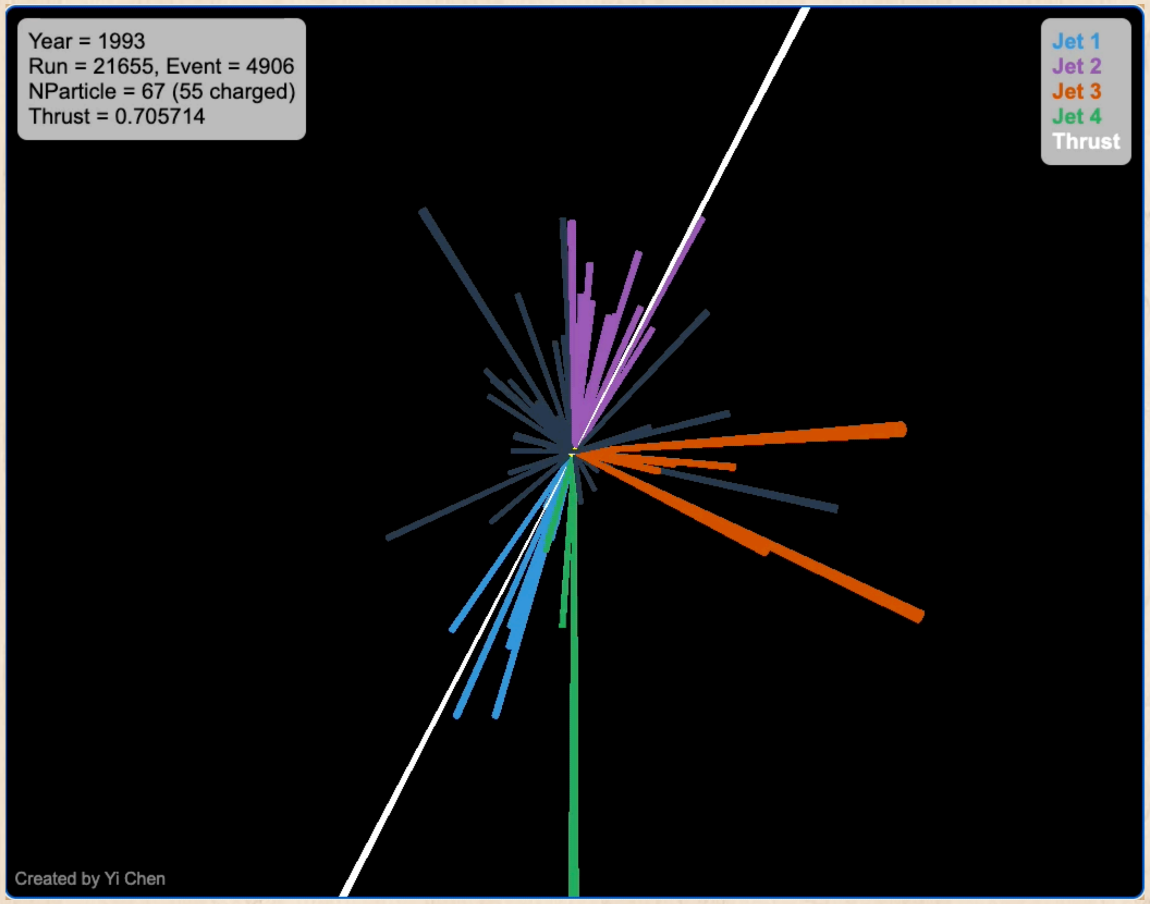
It predates anti-k_T



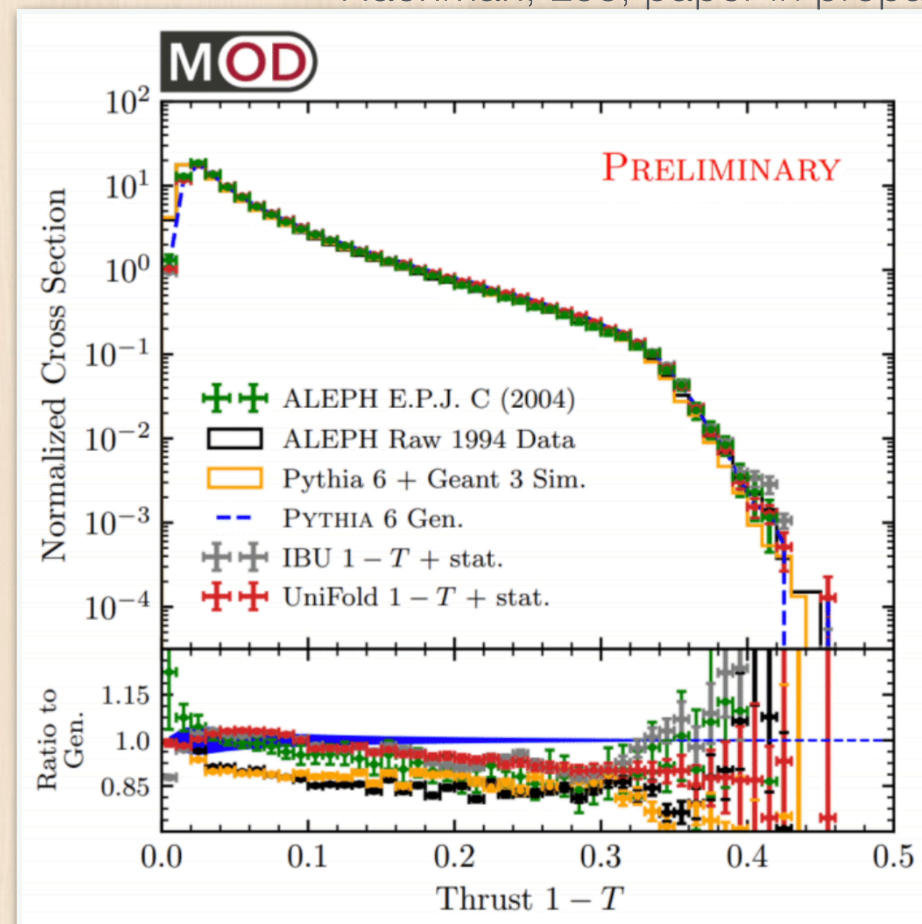
Excellent opportunity for re-analysis

High quality archived data

Badea, Komiske, Metodiev, Thaler, Nachman, Lee, paper in preparation



(link to animation)



Published results can be reproduced

Big thanks to ALEPH collaboration and MIT open data

ALEPH: EPJC 35 (2004) 456

Anti-"k_T" Jets

Jets are well calibrated

Energy flow object

Jet clustering

MC-based calibration

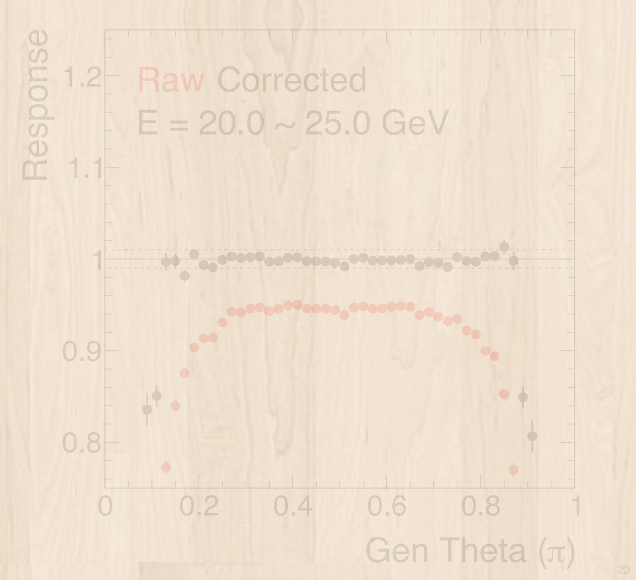
Data/MC residual calibration

Data/MC resolution

Cluster with e^+e^- version of anti-k_T

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

Two-steps:
+/- side difference
Multi jet mass



Up to 5% difference (relative)

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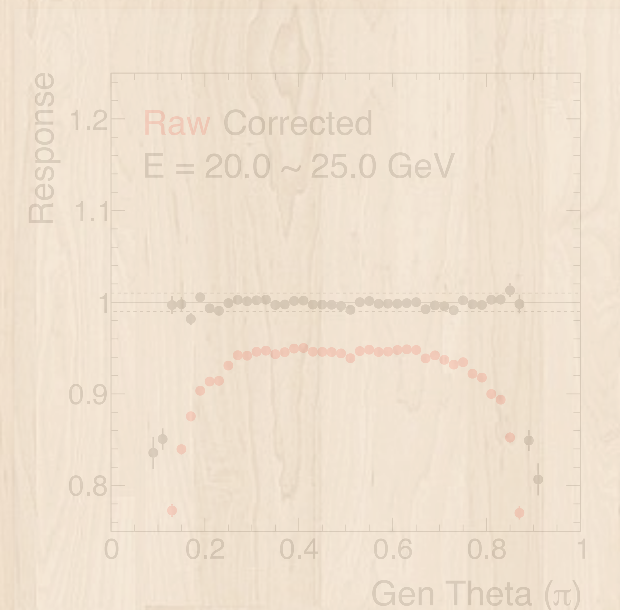

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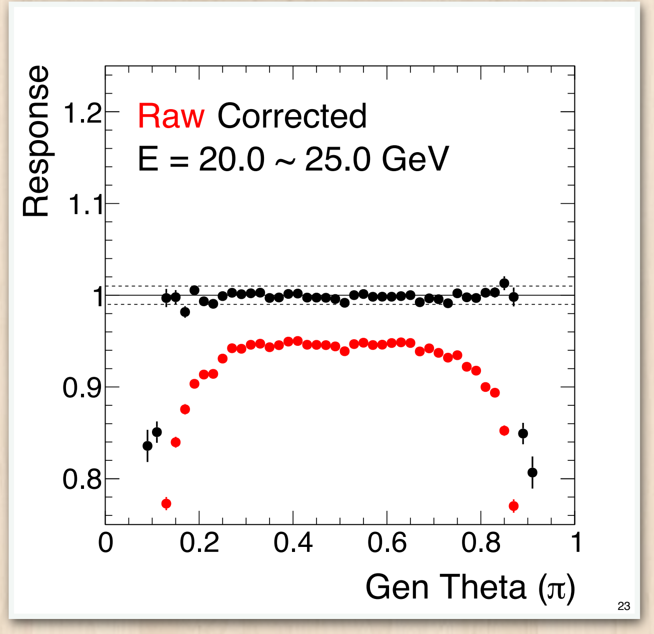

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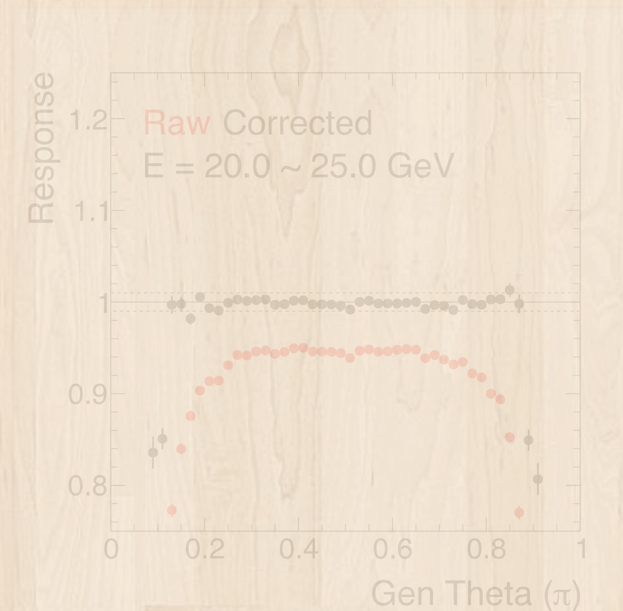

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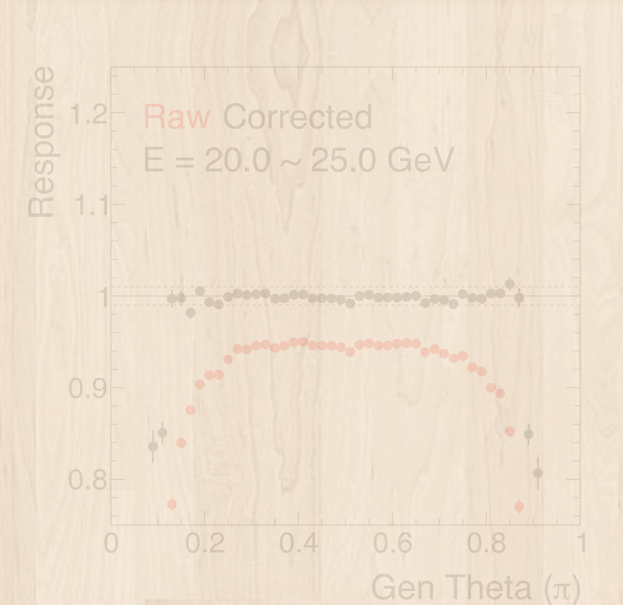
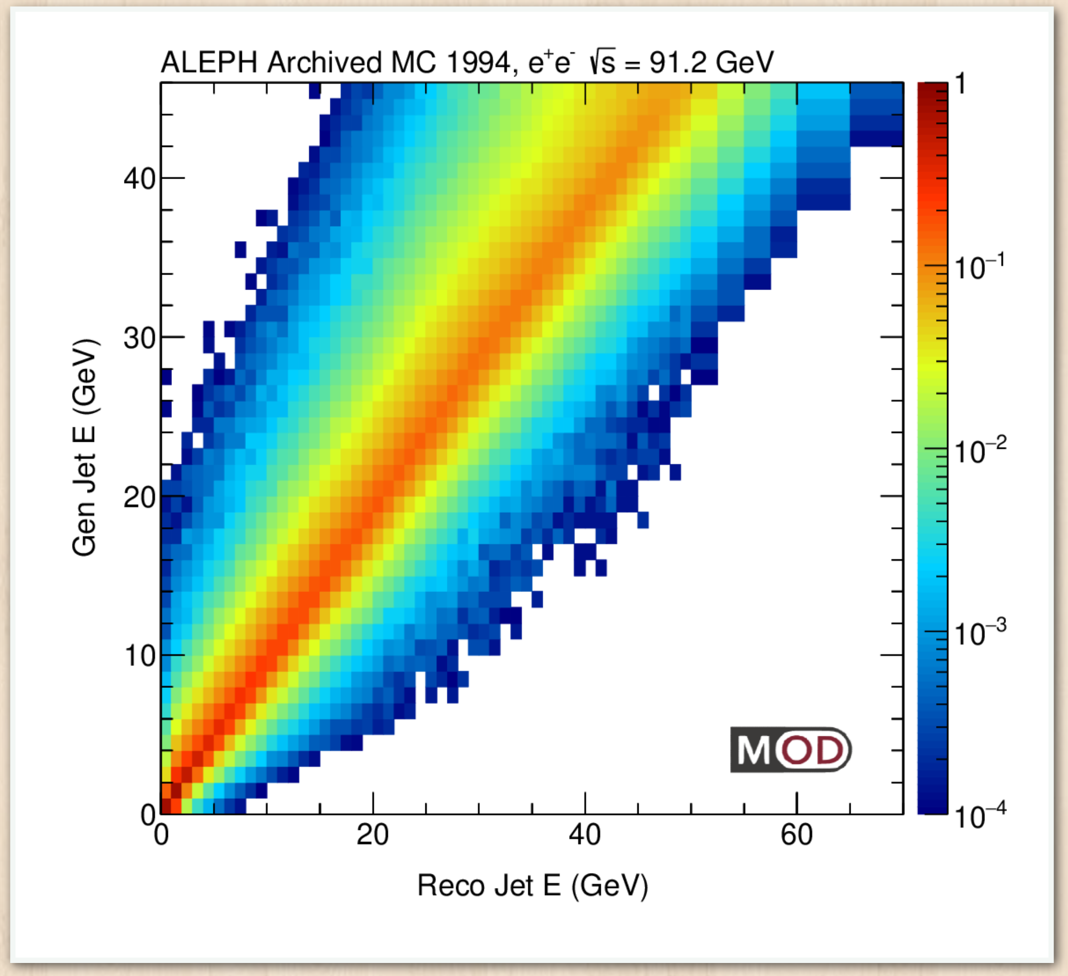
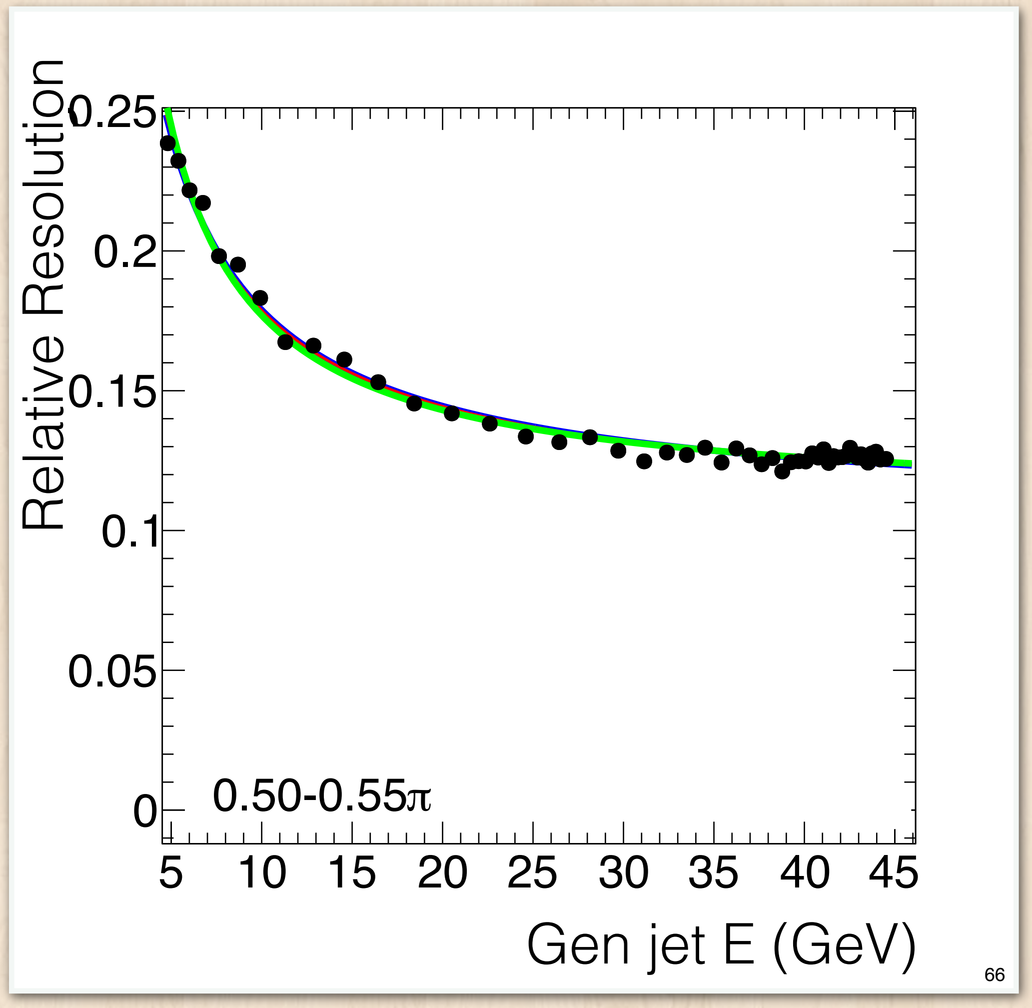


Up to 5% difference (relative)

Performance



Good correlation
No weird structure



Decent resolution
10-20% in the
range we measure

List of measurements (so far)

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	Energy sum
Groomed jet angle	
Energy sharing	
Groomed jet mass	

Soft drop grooming

Inclusive jet spectrum

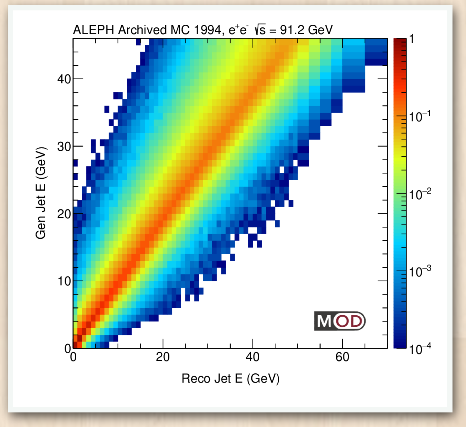
Analysis overview

Raw spectrum

Corrected spectrum

Unfolded spectrum

Jet calibration



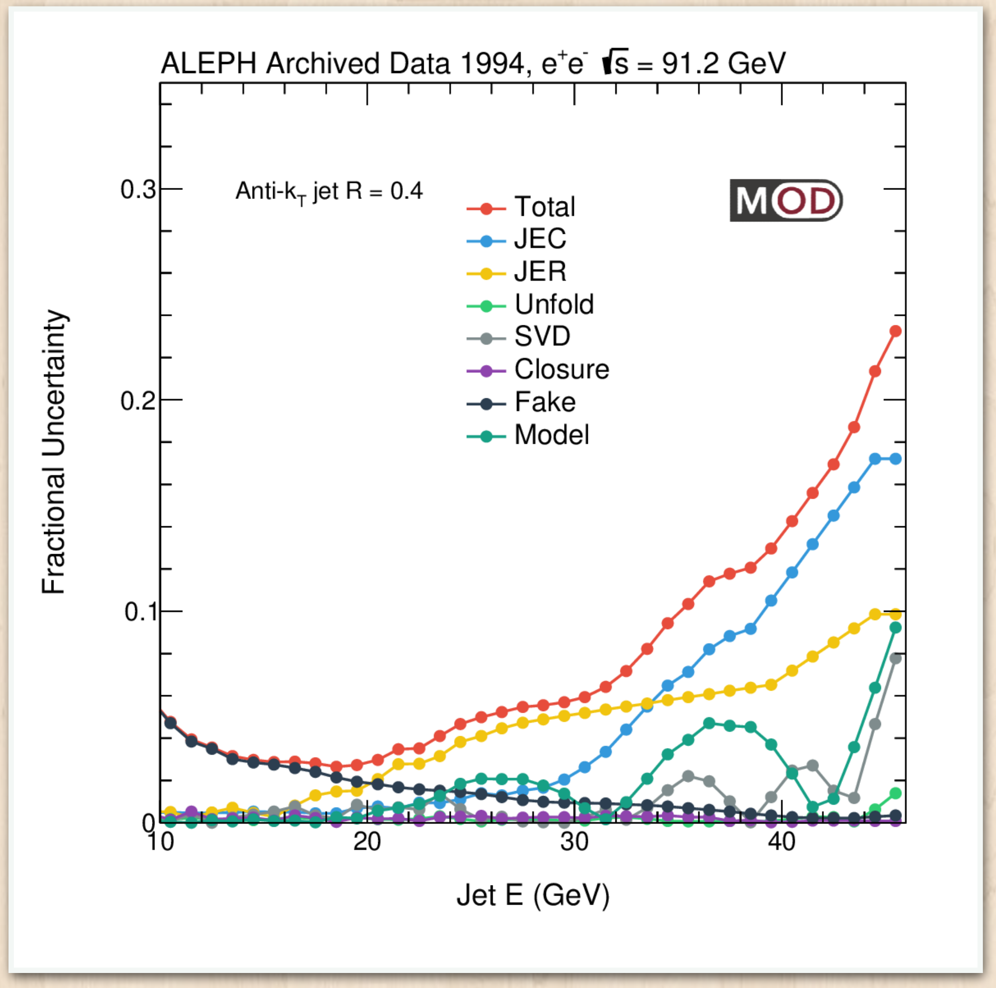
Systematic uncertainties

- Jet-related
  scale: change energy scale
  resolution: vary jet smearing

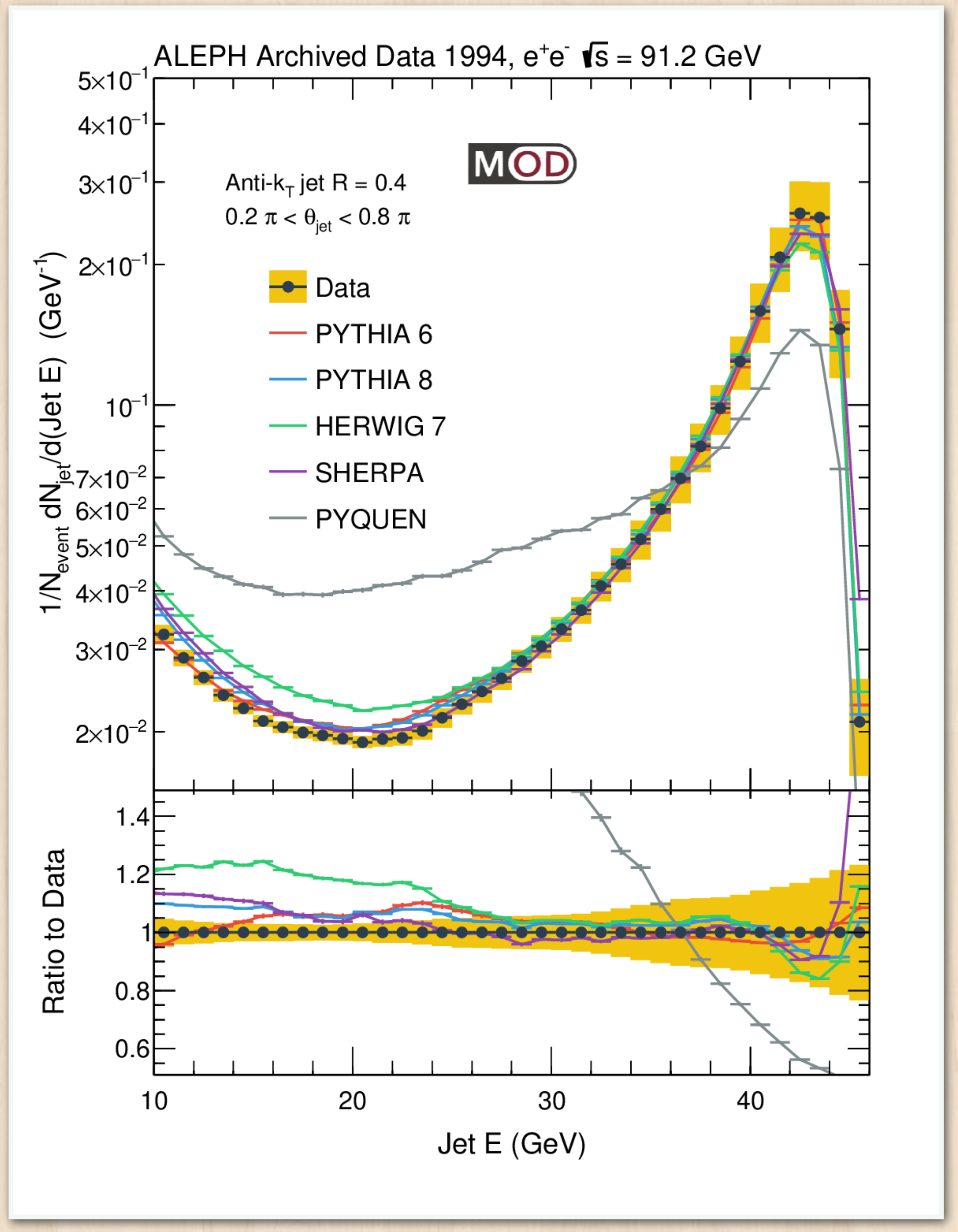
- Unfolding
  Prior & regularization
  Different unfold method

- Fake (combinatorial jet)
  generator jet matching studies

- Modeling



Energy spectrum



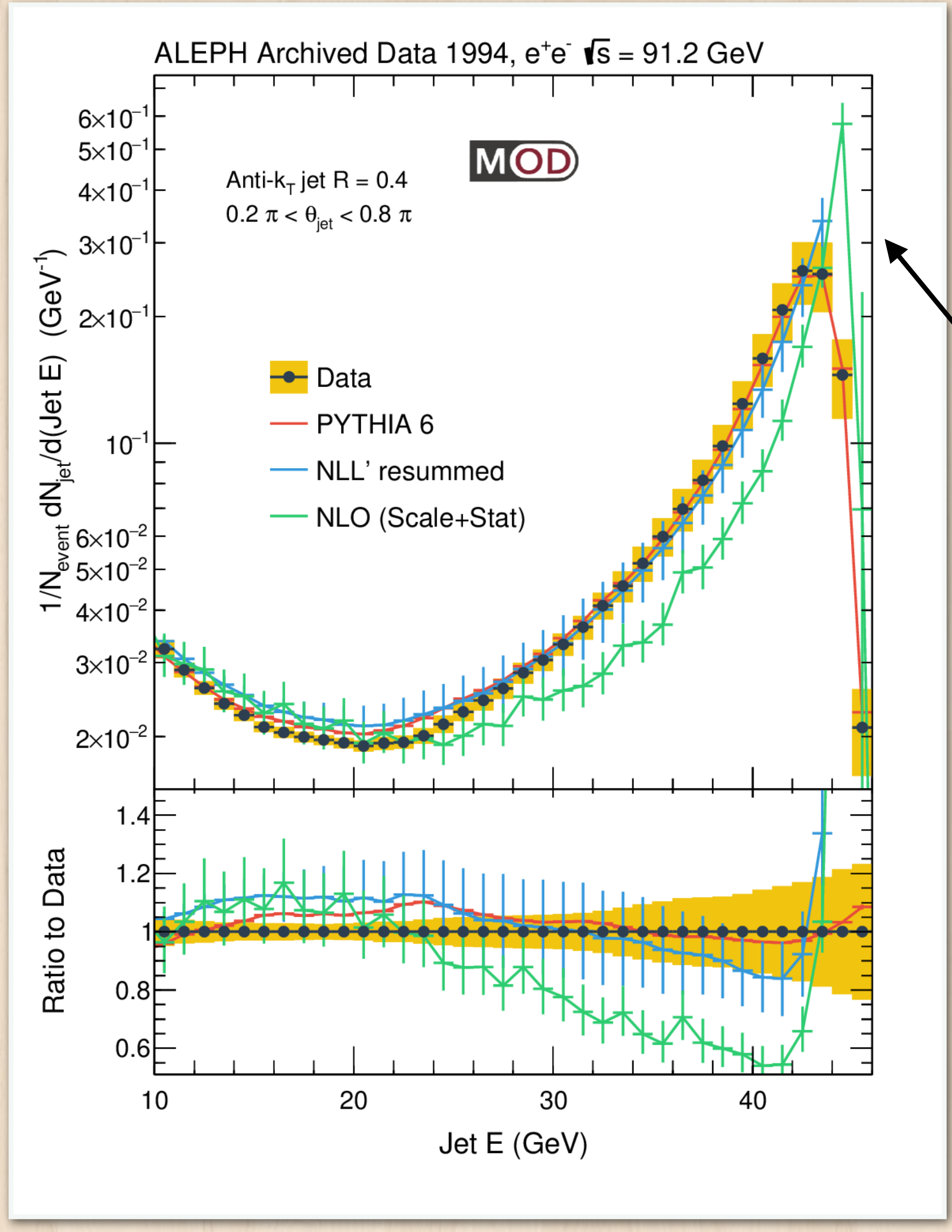
Comparison to MC and theory calculations (not shown in this plot)

Most generators can describe the peak region

Up to 10-20% disagreement at low E

→ out-of-cone energy, wide angle emission, …

Energy spectrum



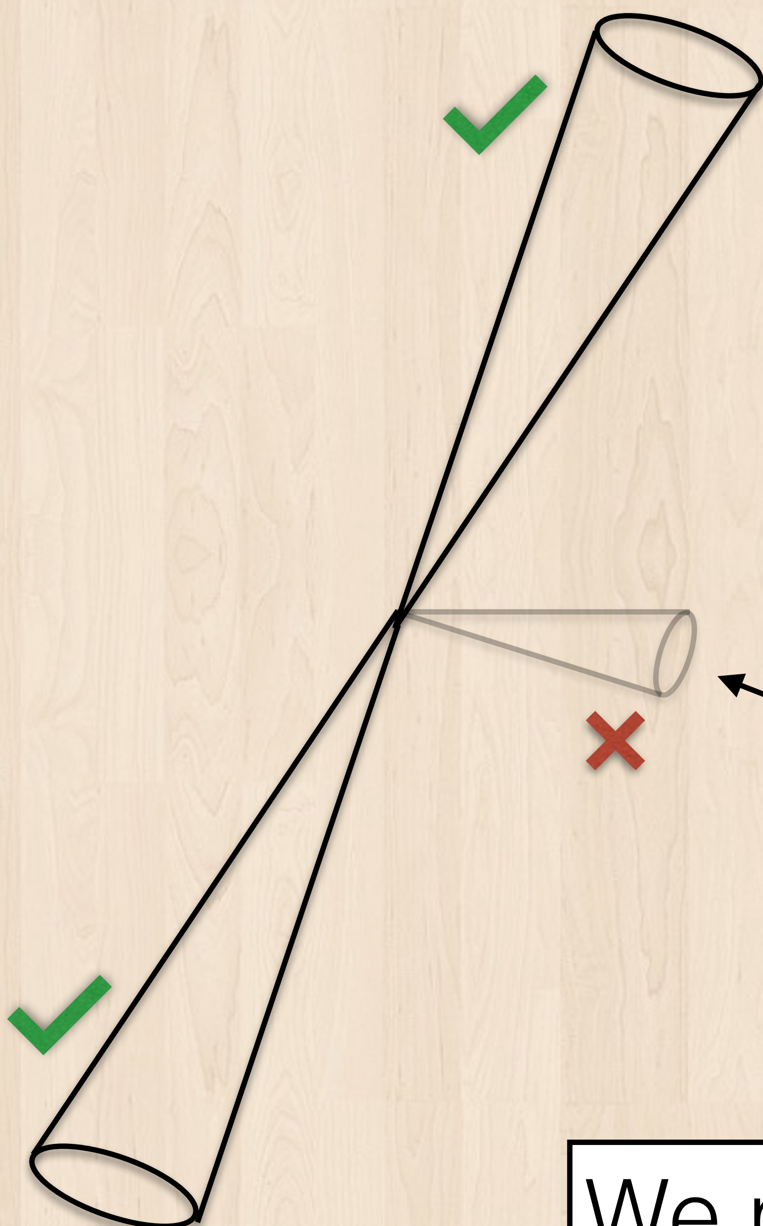
LO parton level
= delta function at 45 GeV
not too interesting to plot

NLO parton level sharper than measured data

NLL' resummed generally describe data

Leading dijet

Leading dijet

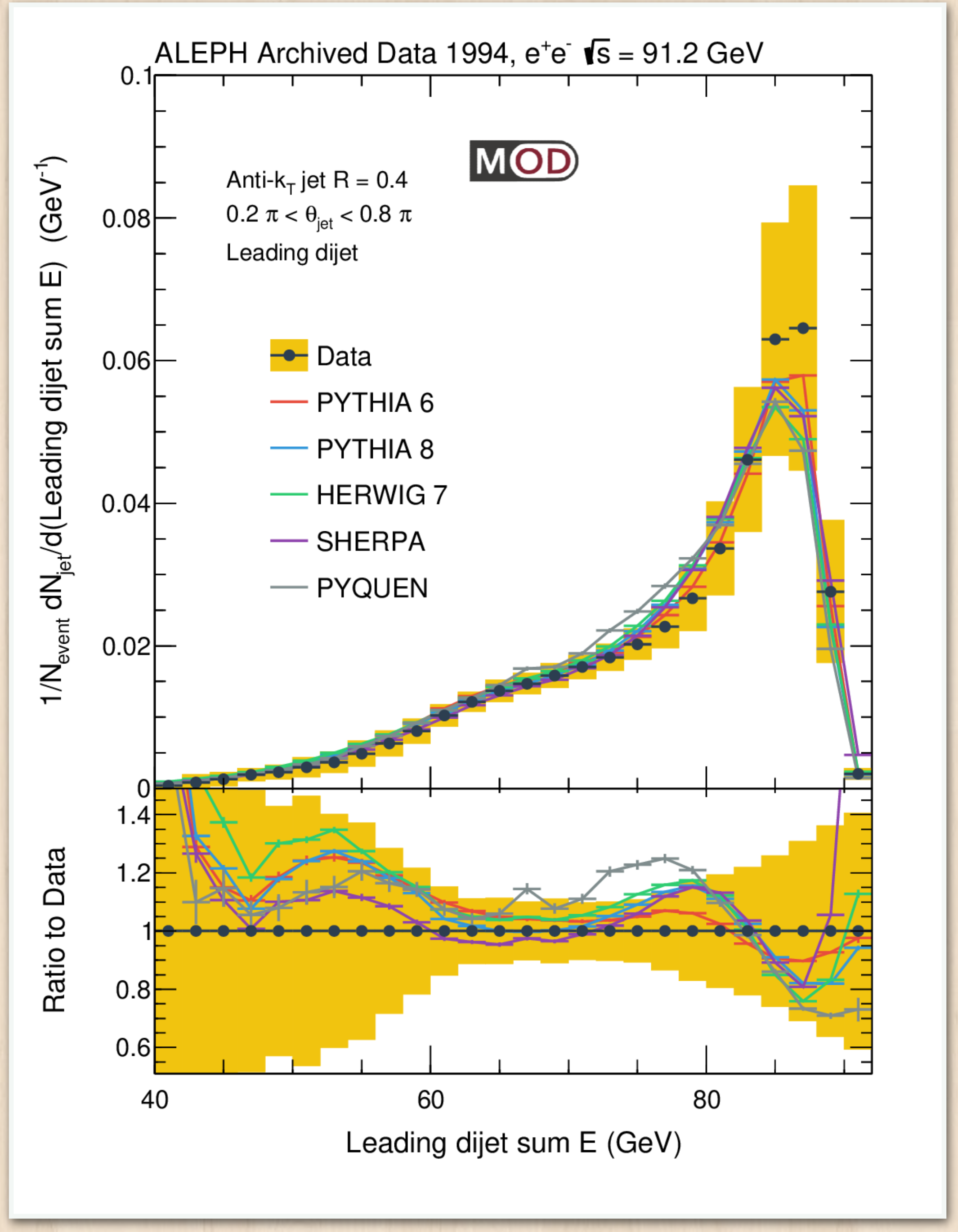


Better quantify the in-cone energy by limiting to only the leading dijet

Ignore the mini-jets

We measure the "global" leading dijet

Energy sum



Total in-cone energy in the leading two jets

Most generators can describe data within (large-ish) uncertainty

Dominated by modeling uncertainty

(Leading di-jet energy: not shown)

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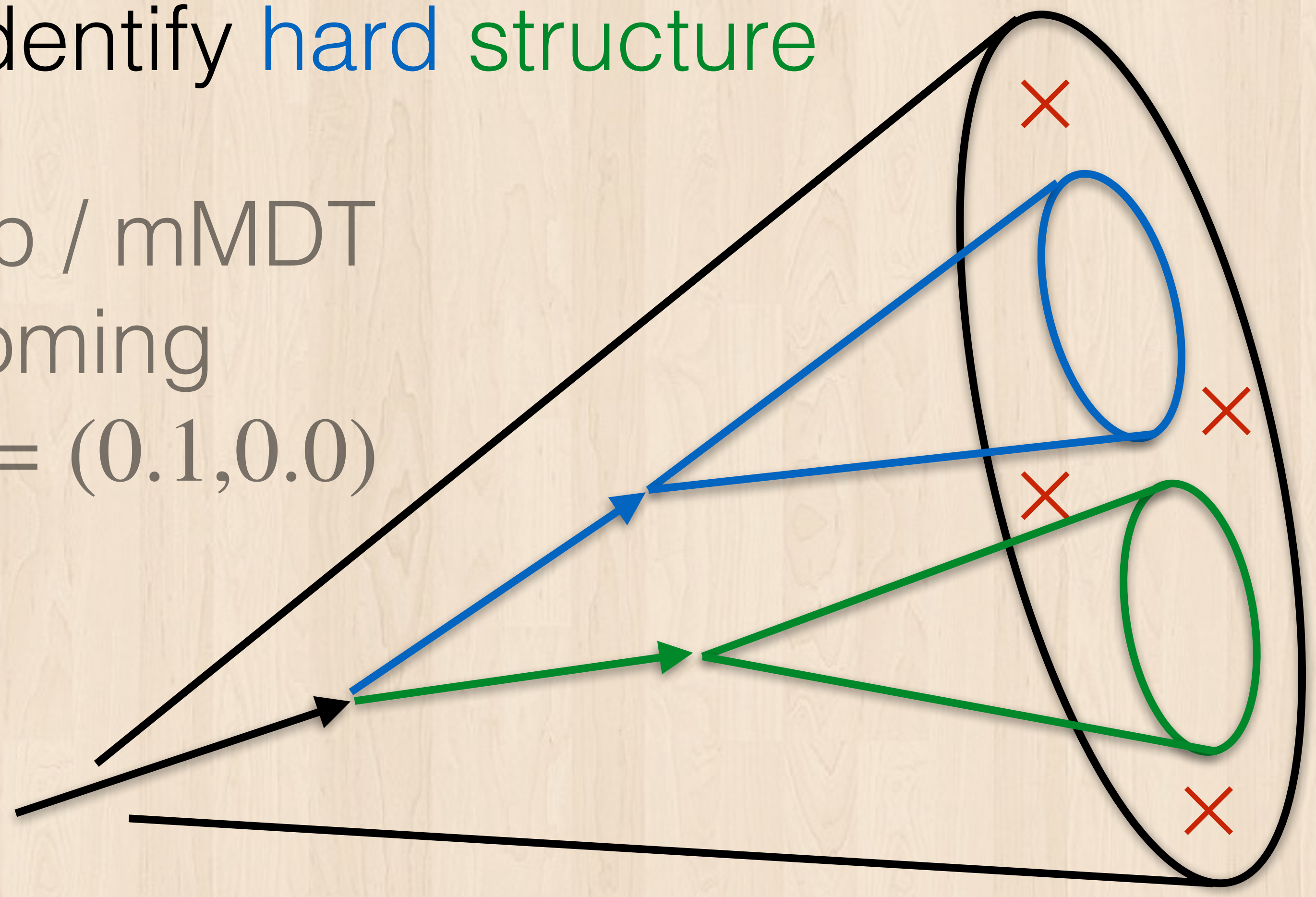
Inclusive jet structure & substructures

Jet substructure

Identify hard structure



Clean up
wide-angle
soft energy

Soft drop / mMDT
grooming
$(z_{\rm cut}, \beta) = (0.1, 0.0)$

Adapt to use energy and
opening angle for e^+e^-

Not shown due to time

R_g = opening angle
z_g = energy sharing
M_g = invariant mass

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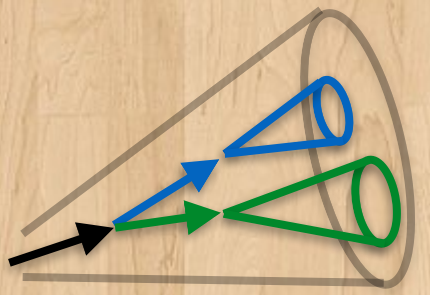
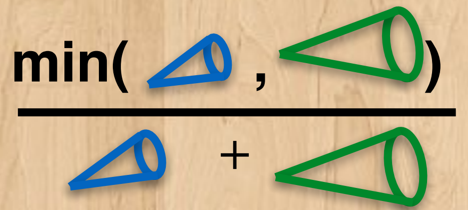
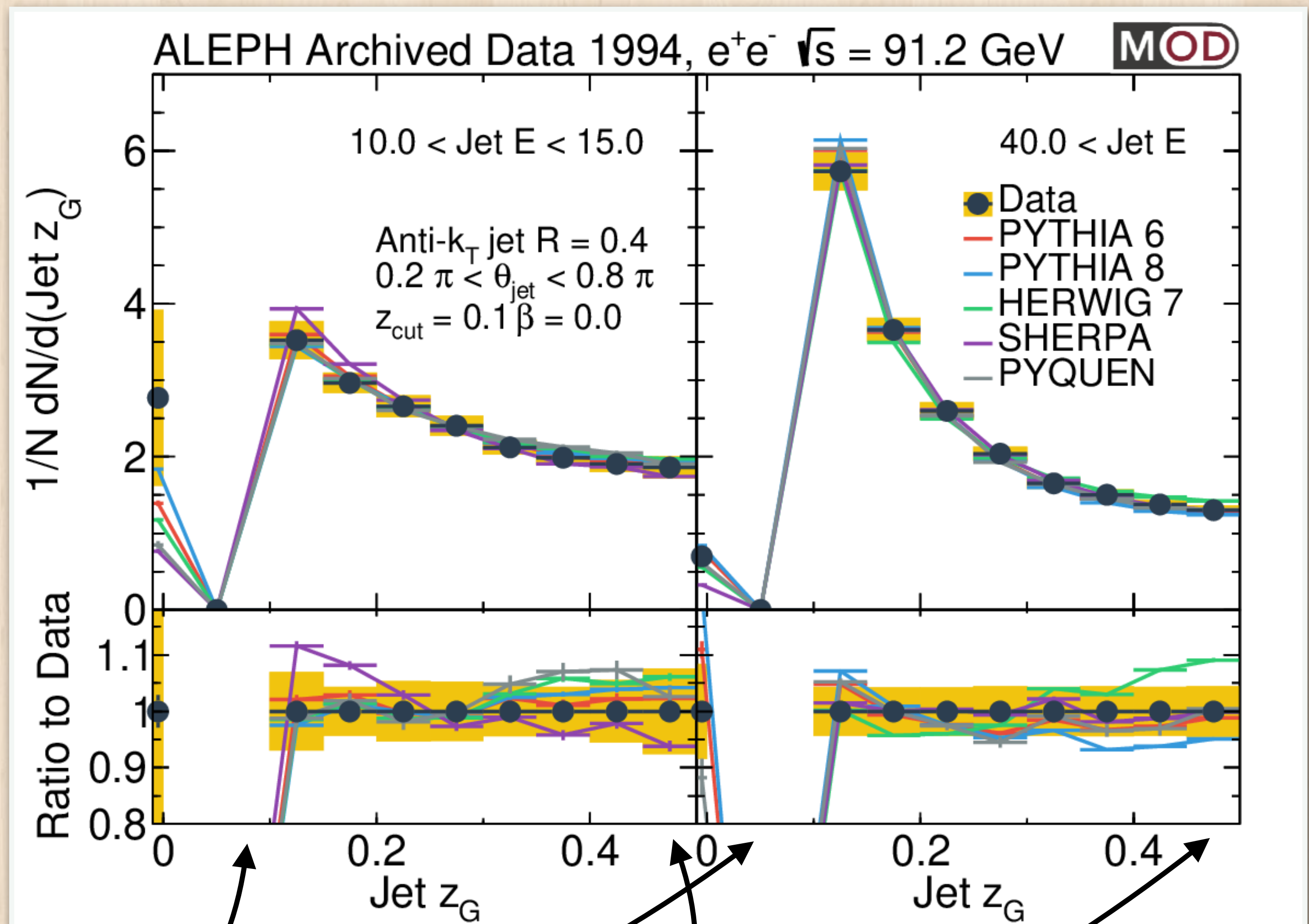
PRL 100 (2008) 242001

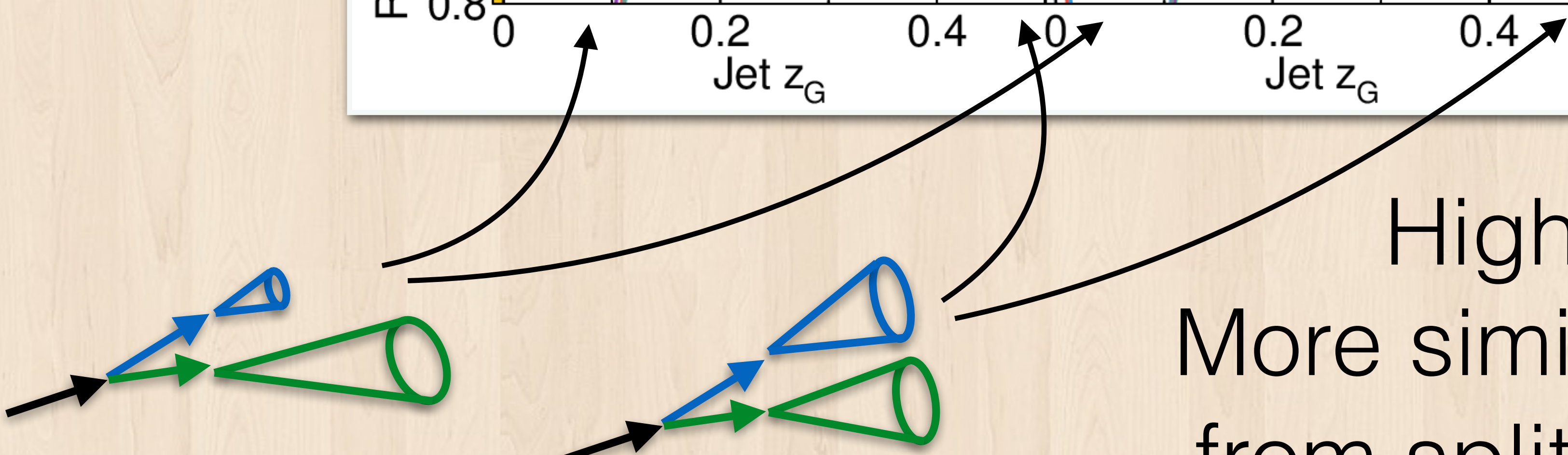


Energy sharing z_G

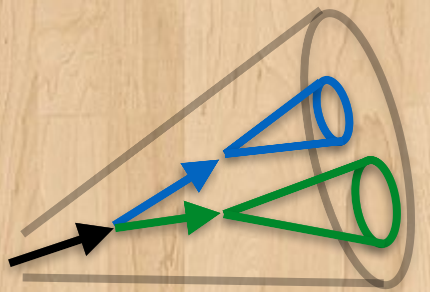


Measurement binned in energy (most not shown)

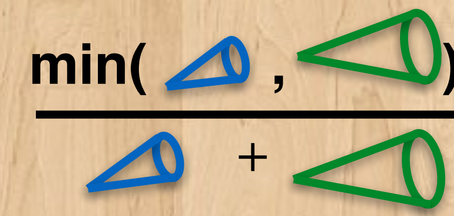


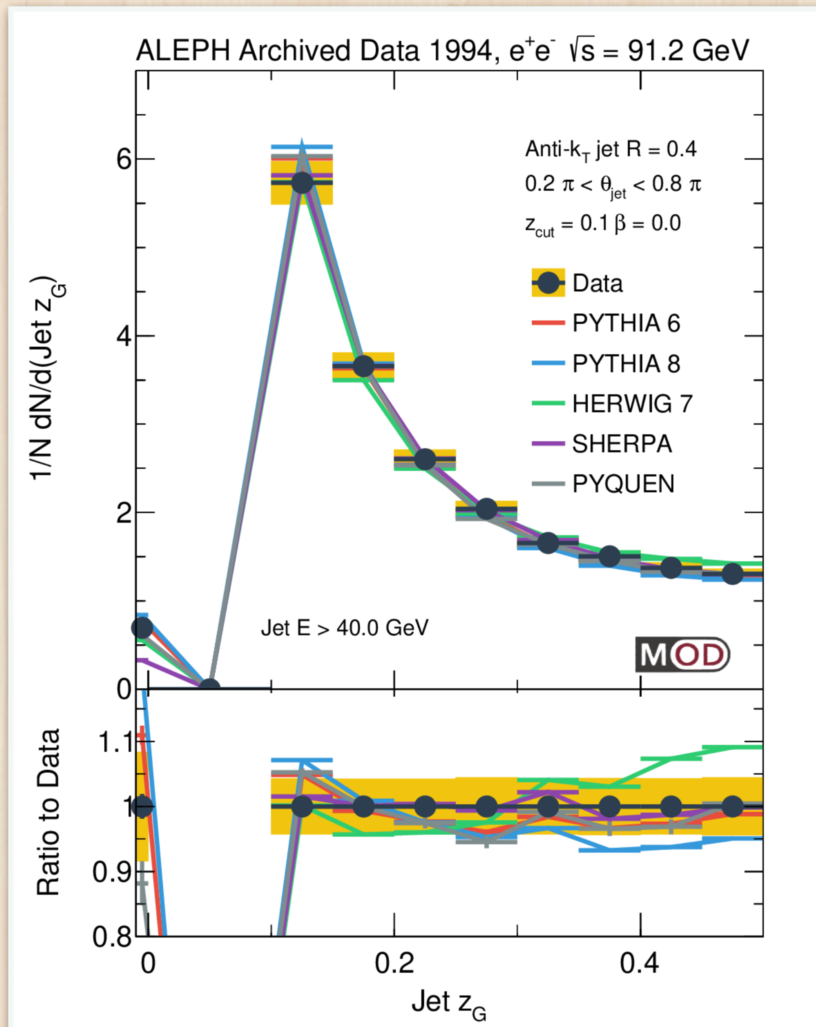


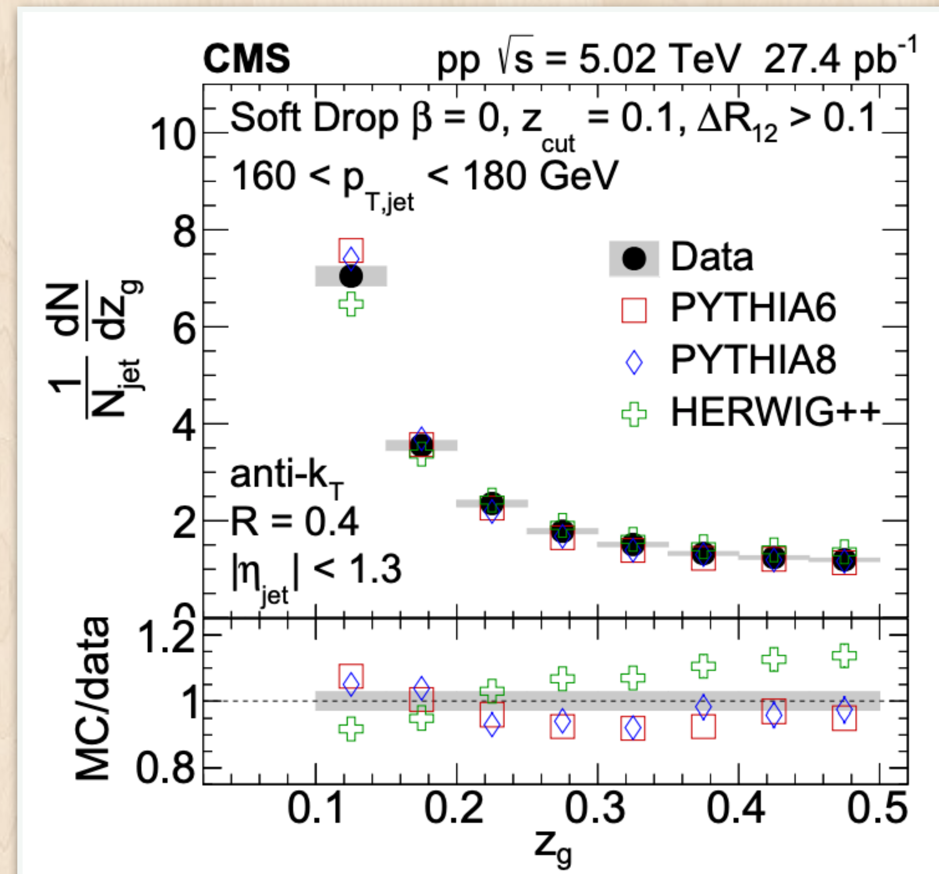
High energy
More similar to the $1/z$
from splitting function



Energy sharing z_G





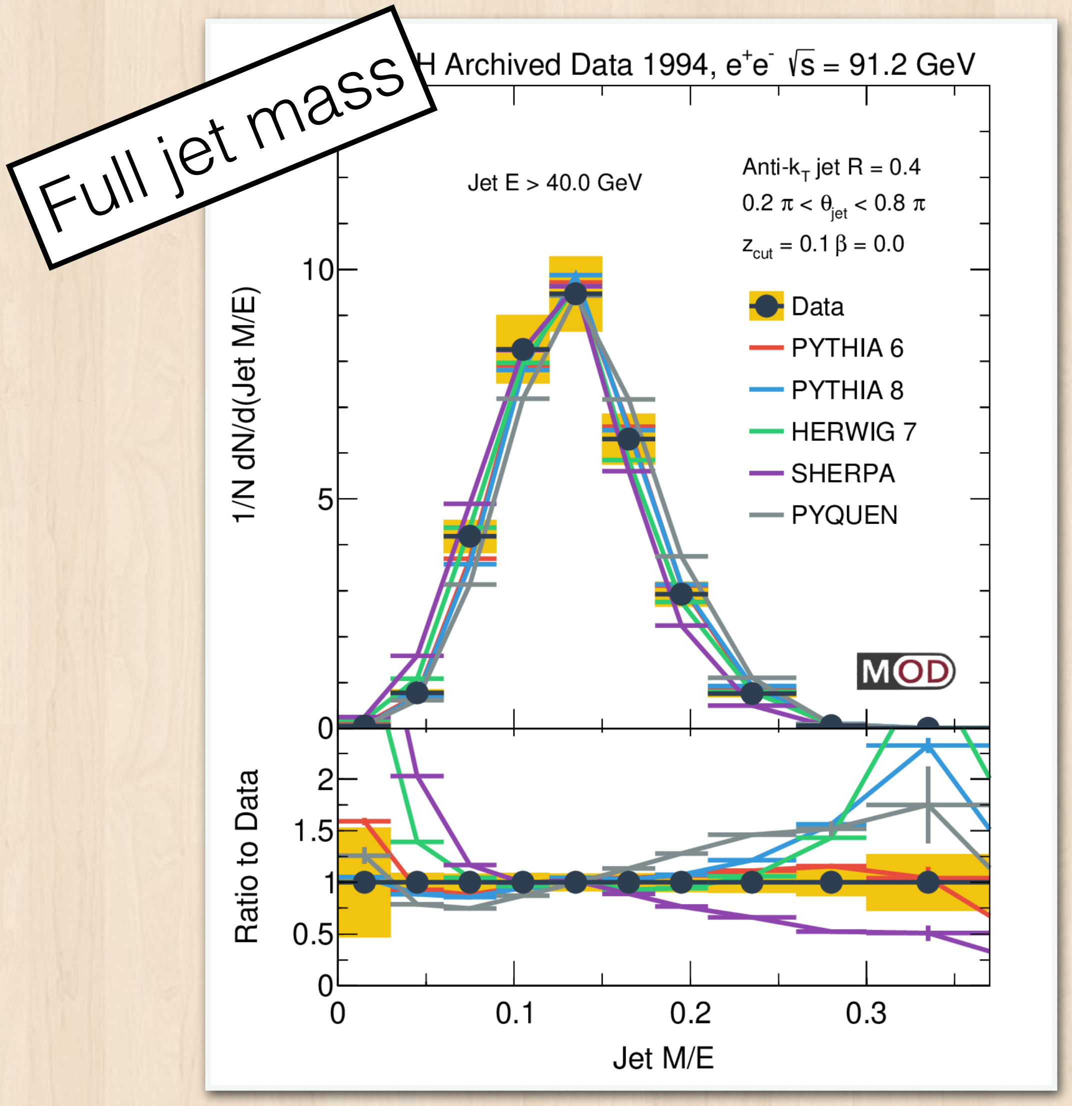


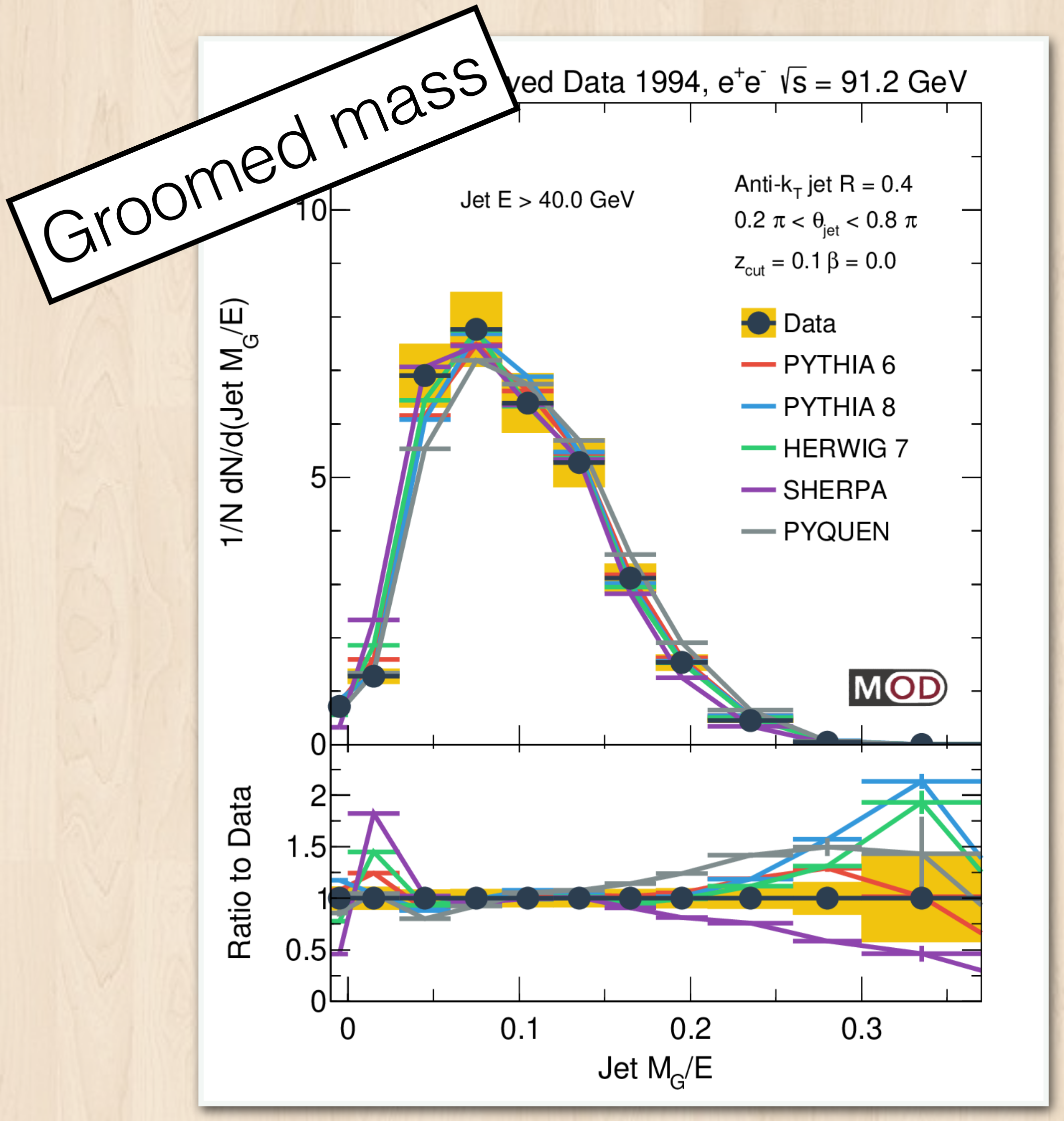
At high energy similar to LHC results

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

$\boxed{\text{Disagreement in LHC can be improved by } e^+e^- \text{ input}}$

Jet mass





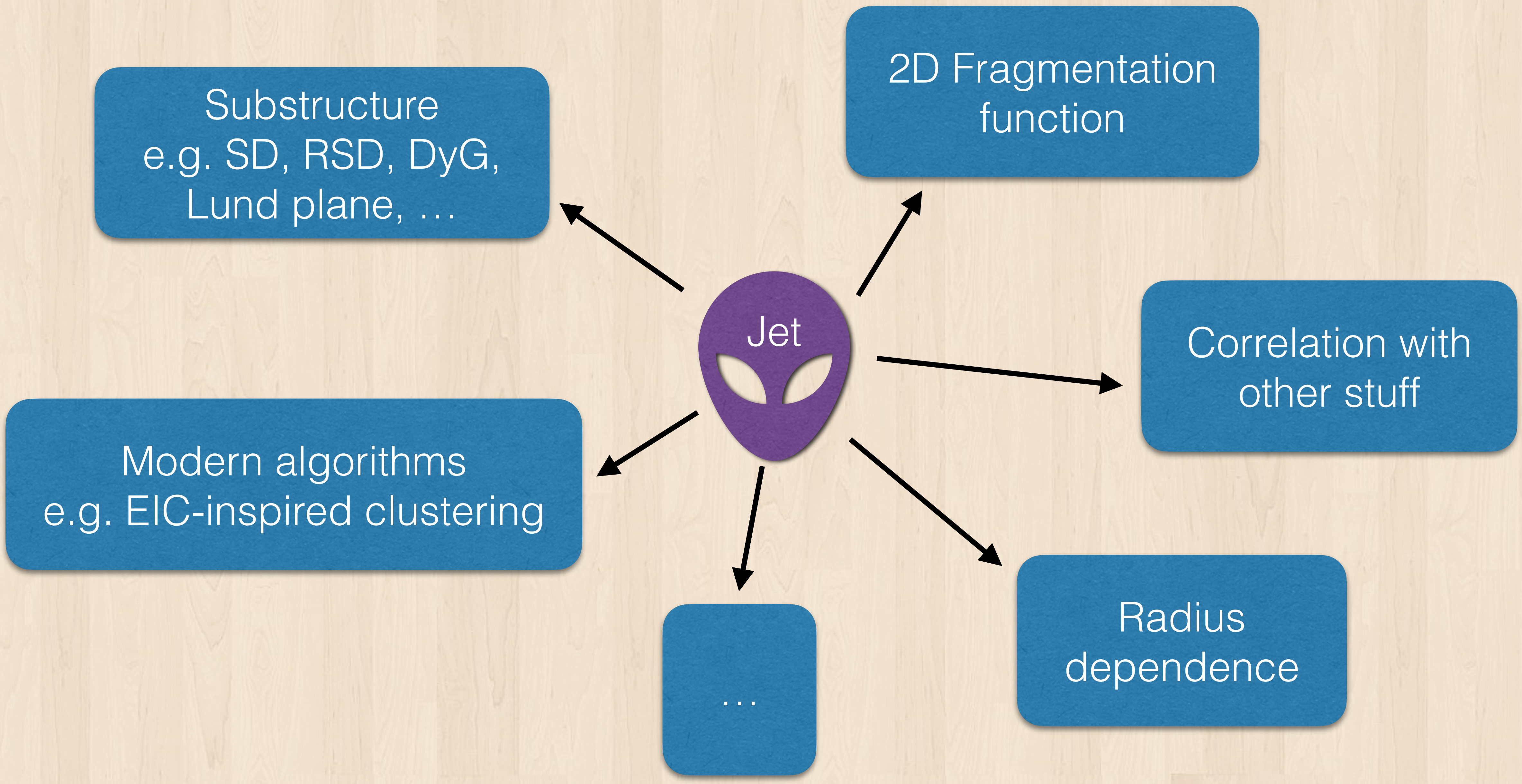
General shape vs tail

Explicit $(M - M_G)/E$

Interesting to compare to higher order generators

Looking into the future

Many future possibilities



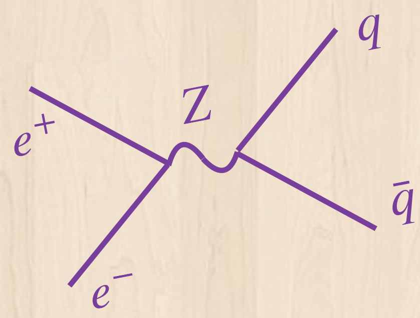
Testing ground for new algorithm developments

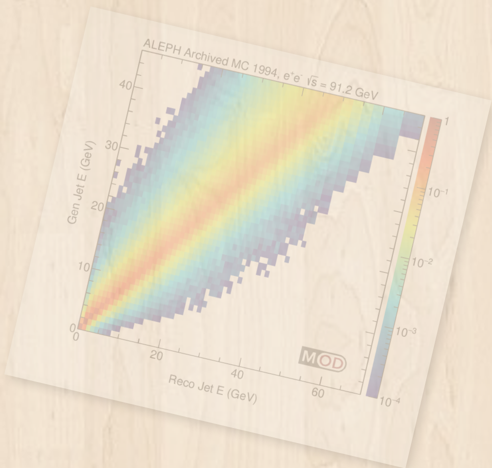
Provide reference measurements

Concluding remarks

Jets in LEP e^+e^- data

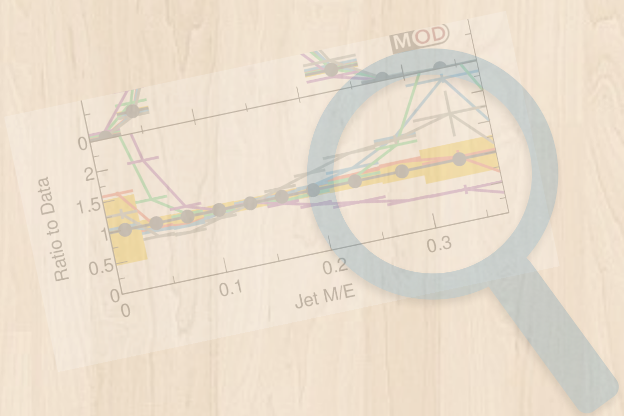
e^+e^- is the cleanest system to test QCD





Calibrated and measured jet spectra and substructure using the ALEPH archived data

Input for MC generators
+ reference result



Numerous future possibilities

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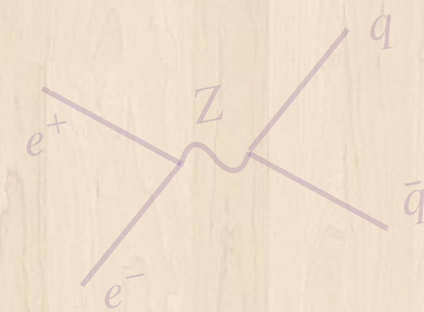

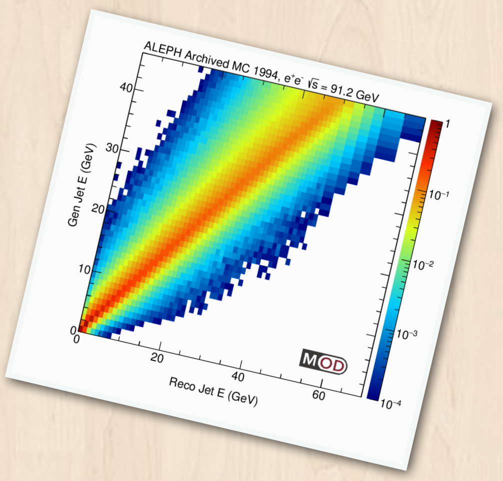

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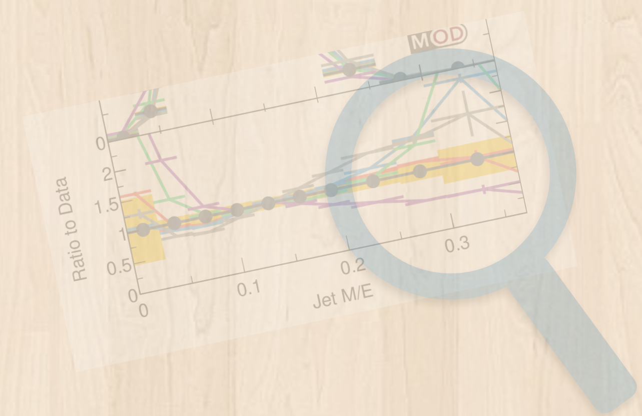

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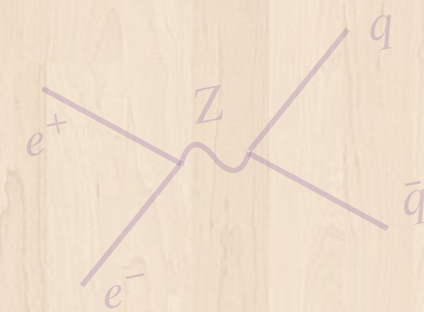

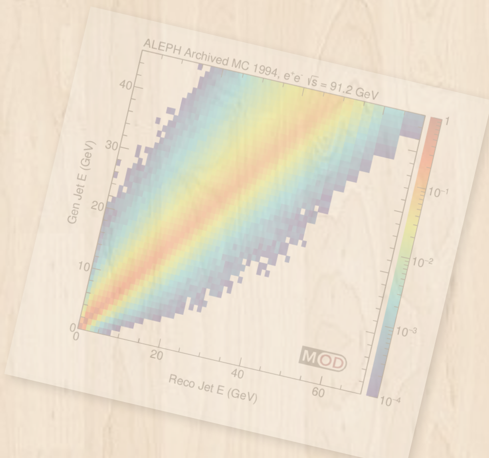

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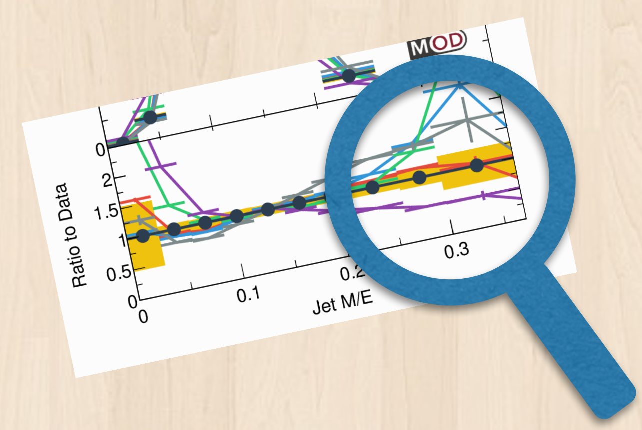

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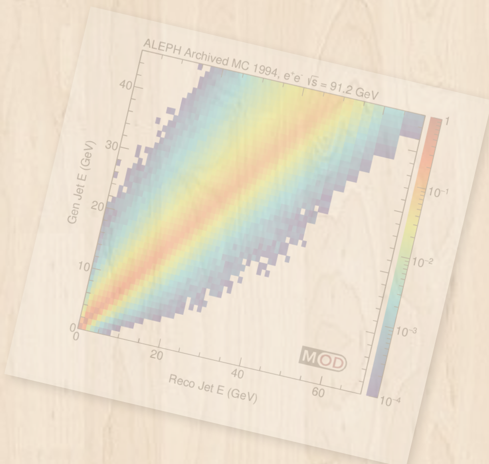

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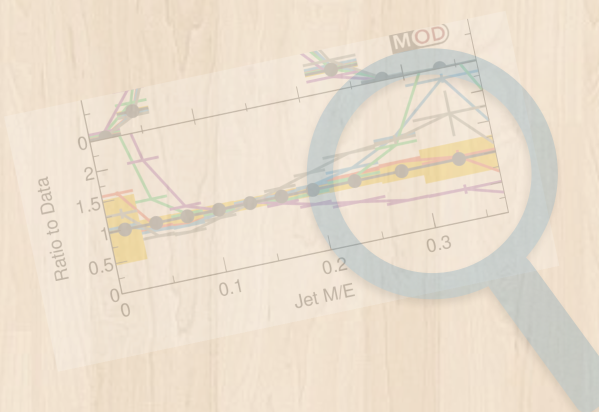

Numerous future possibilities

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

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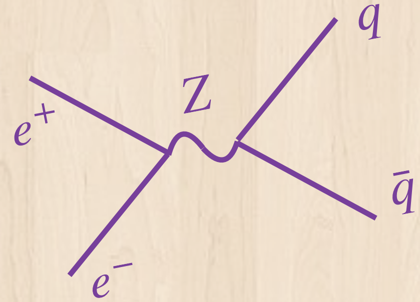

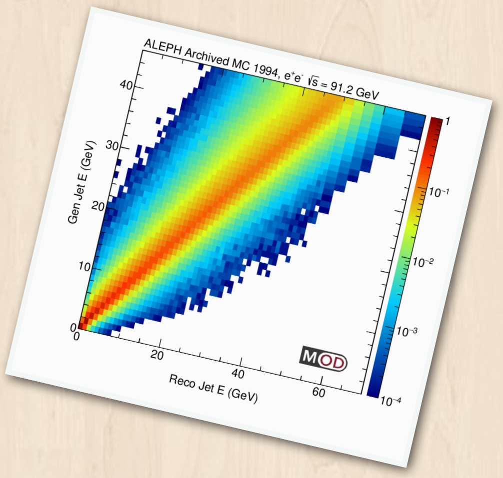

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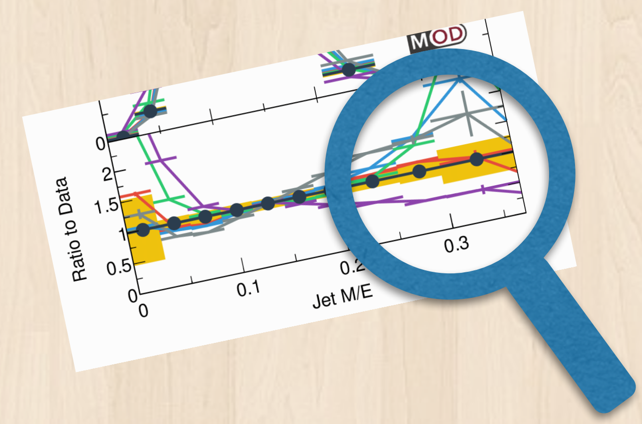
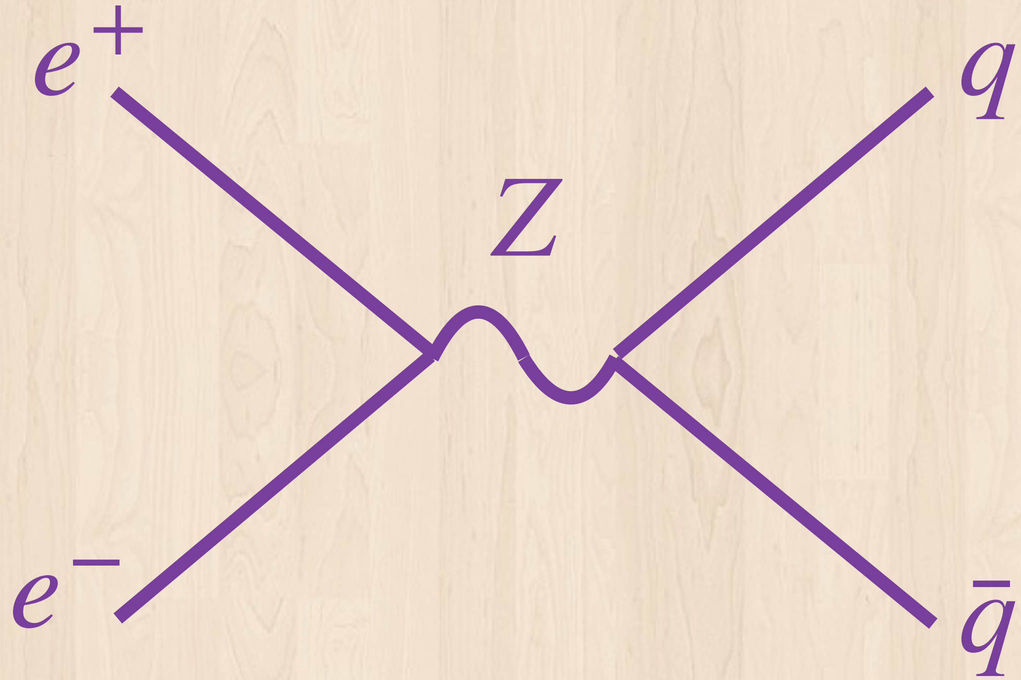


Numerous future possibilities

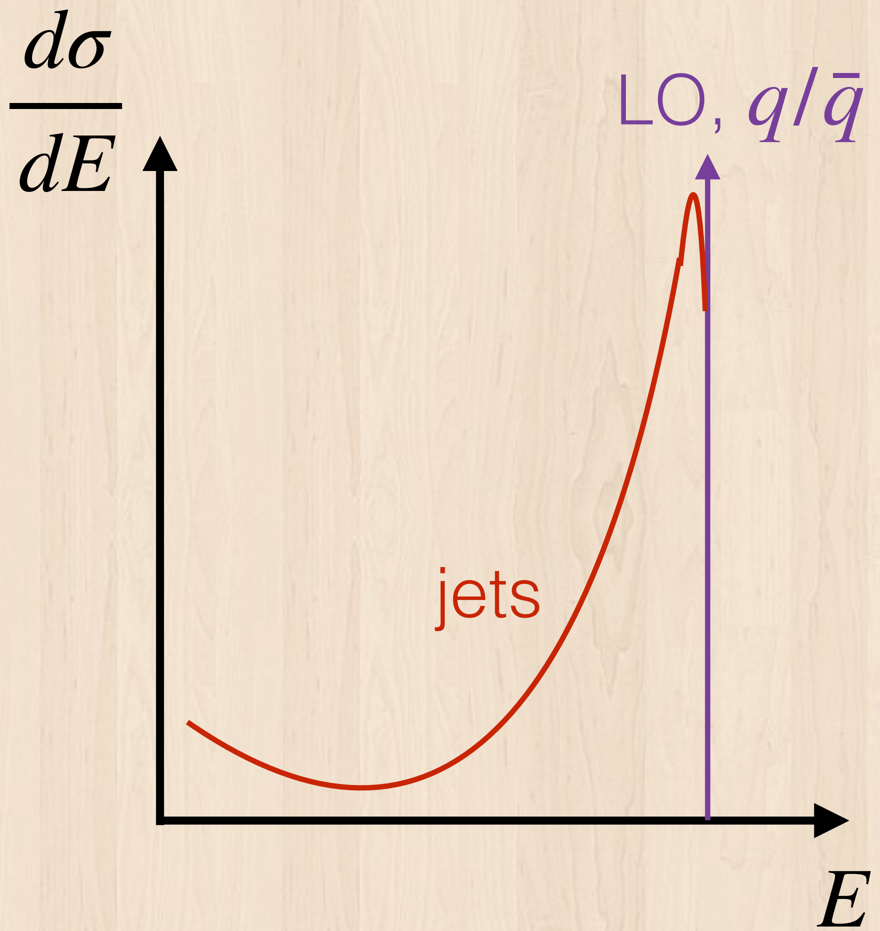
Backup Slides Ahead

Peaked structure

91.2 GeV collisions



Dominant jet diagram

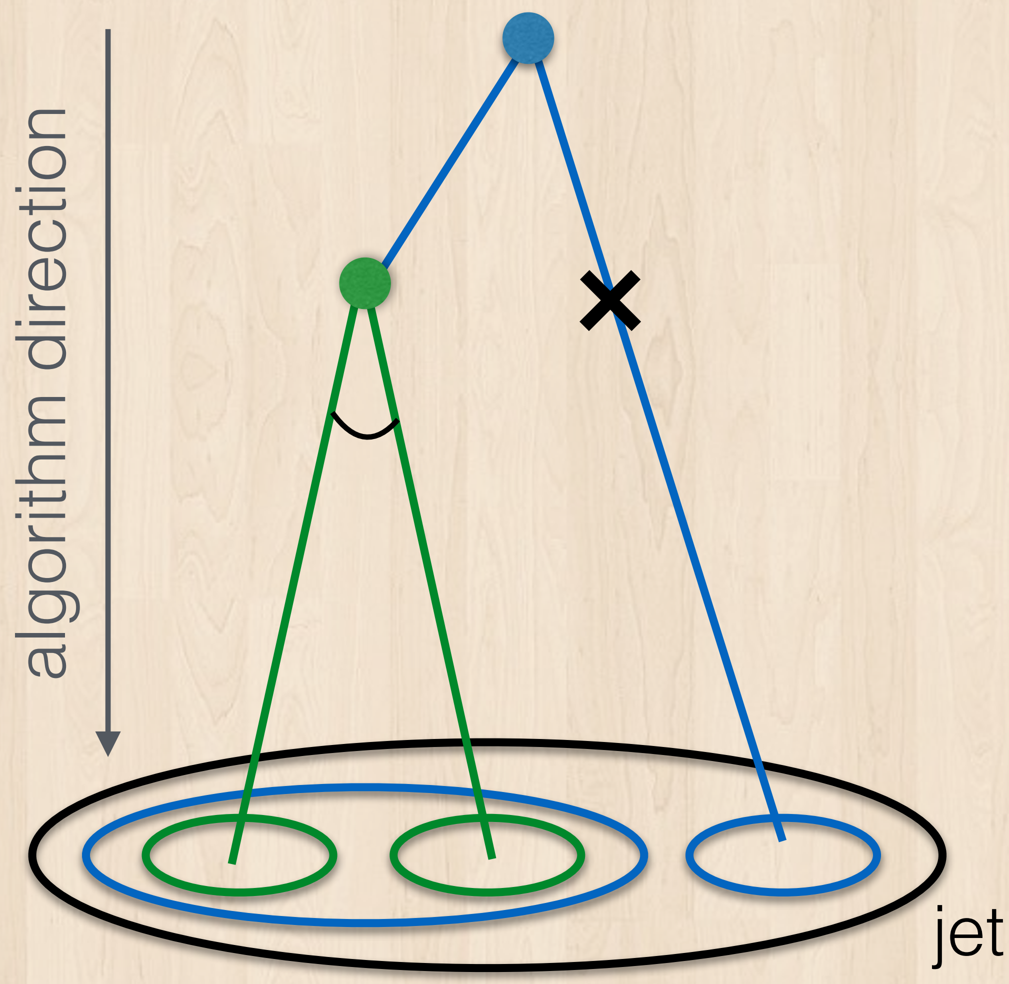


Peaked structure is useful for studying jets

Out-of-cone energy => "energy loss"

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

θ_{12} = real angle

r_g = opening angle

z_g = momentum sharing

M_g = invariant mass

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PRL 100 (2008) 242001

Jet calibration

"MC calibration" "Residual"

Jet energy scale in data = Jet energy scale in simulation × (Jet energy scale in data / Jet energy scale in simulation)

Inclusive

Selection

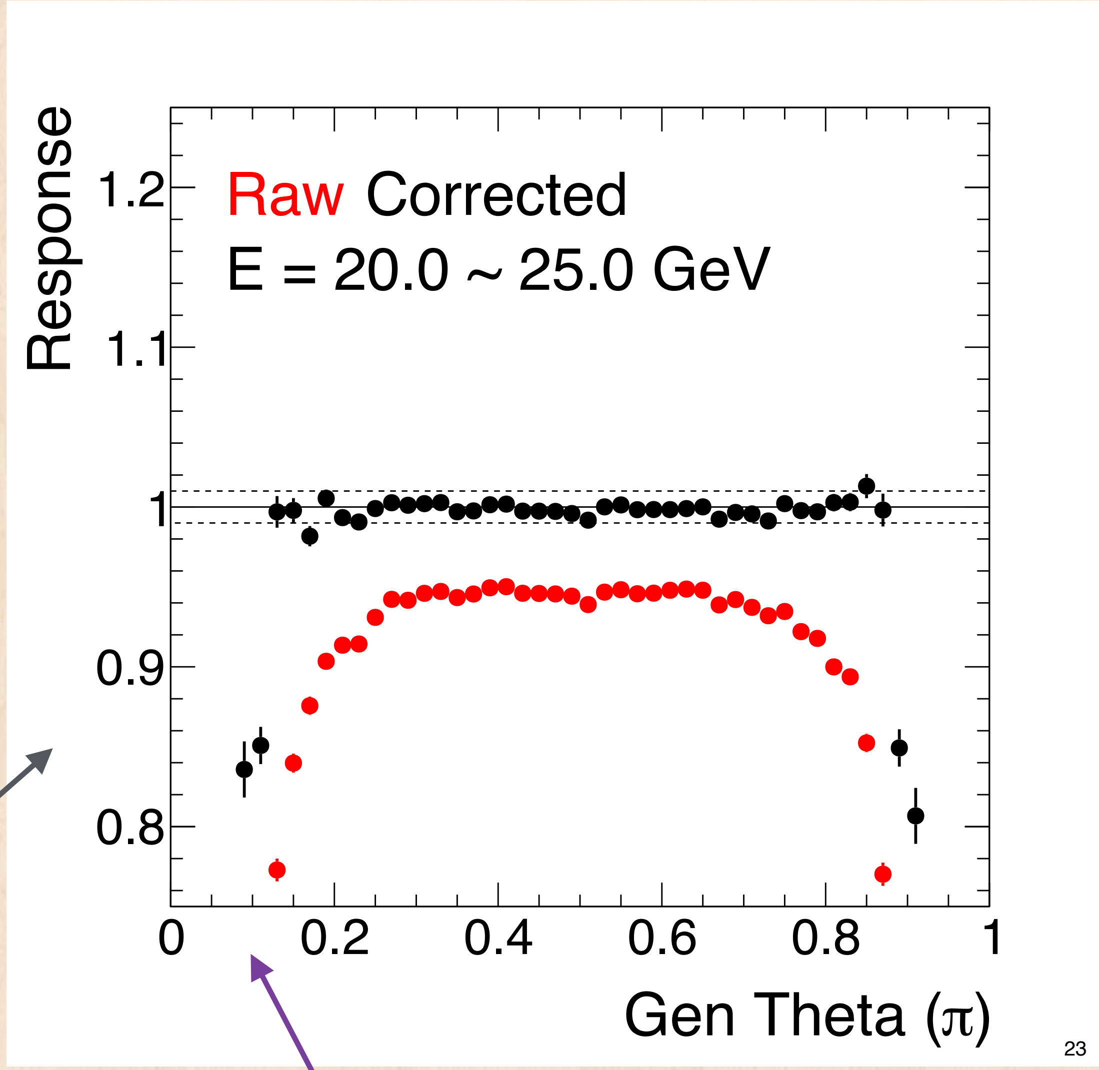
O(1%)

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
$0.2\pi < \theta_{\text{jet}} < 0.8\pi$



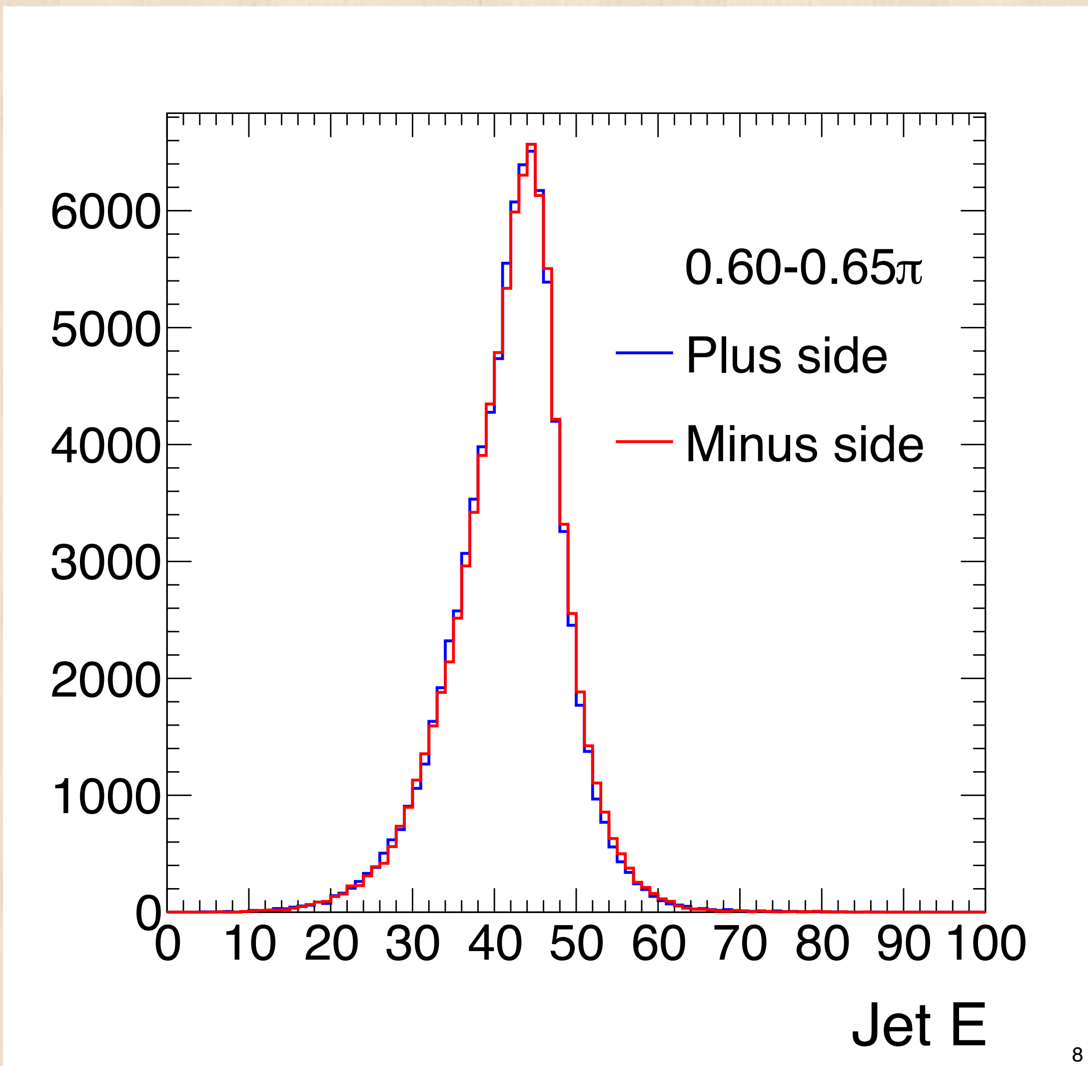
Example raw and corrected response (= reconstructed/generated)

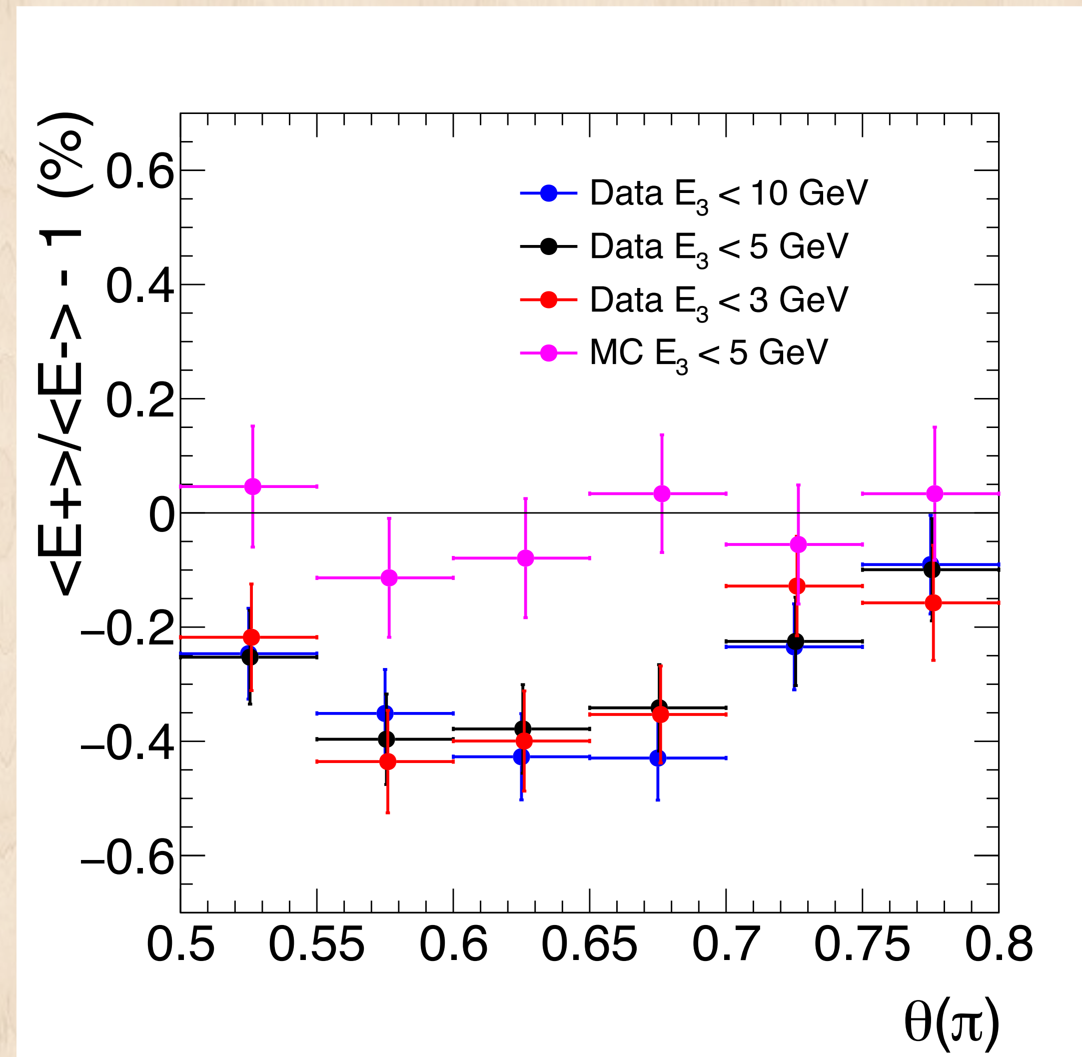
Energy leaking out around beam direction

arXiv 2108.04877

Residual calibration: step 1

Fiducial dijet, two sides of the detector



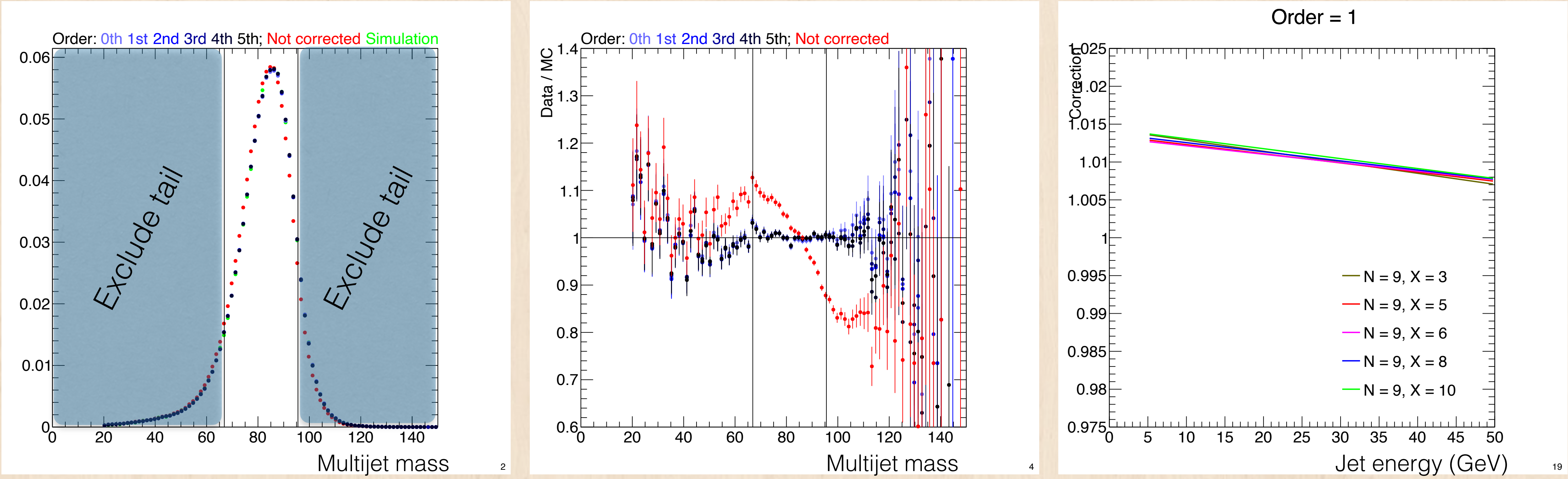


Look at data only, and calibrate out the difference between e^-- and e^+-going sides

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

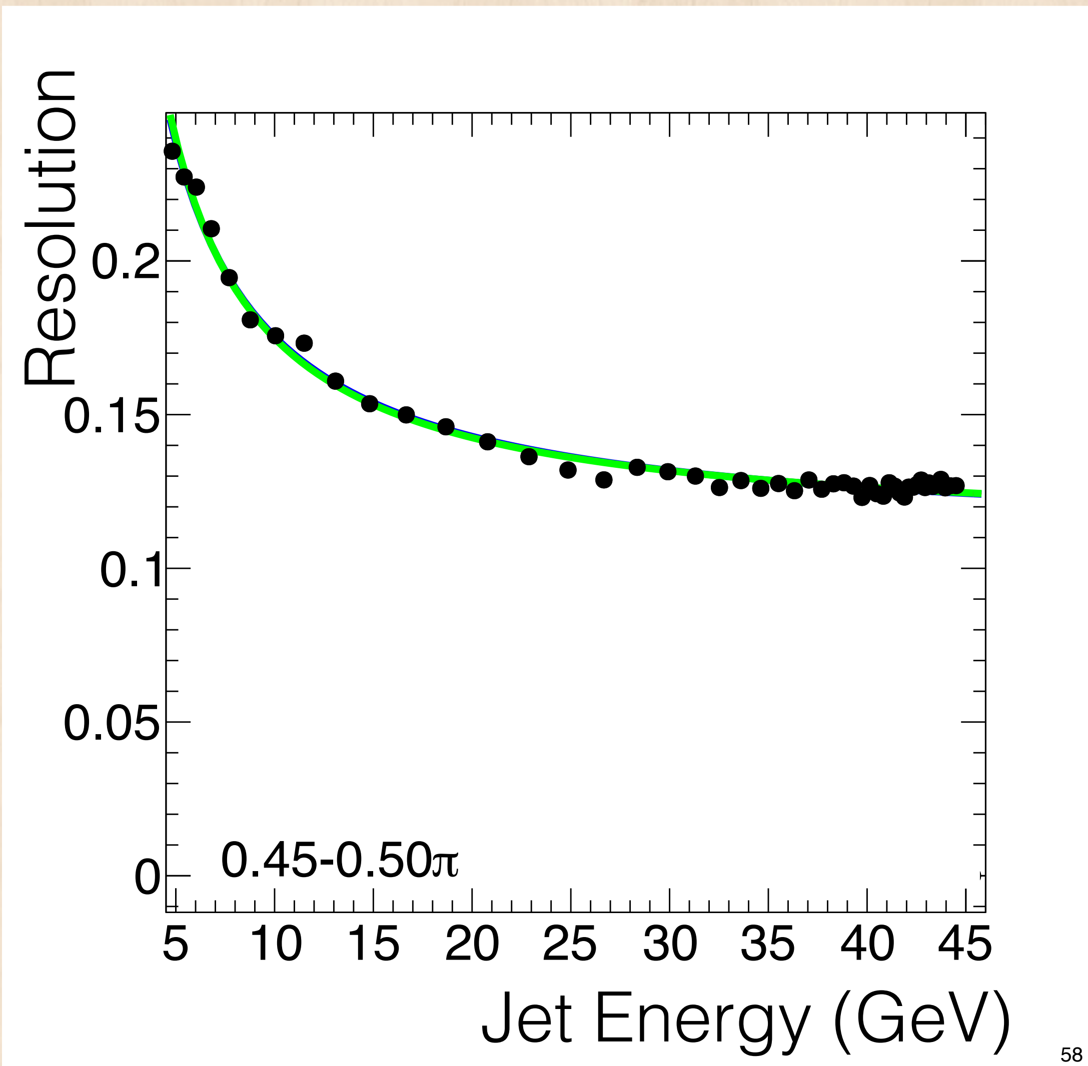
Minimize “quantile difference” (~KS) between data and MC curves

Nominal: linear correction as a function of energy

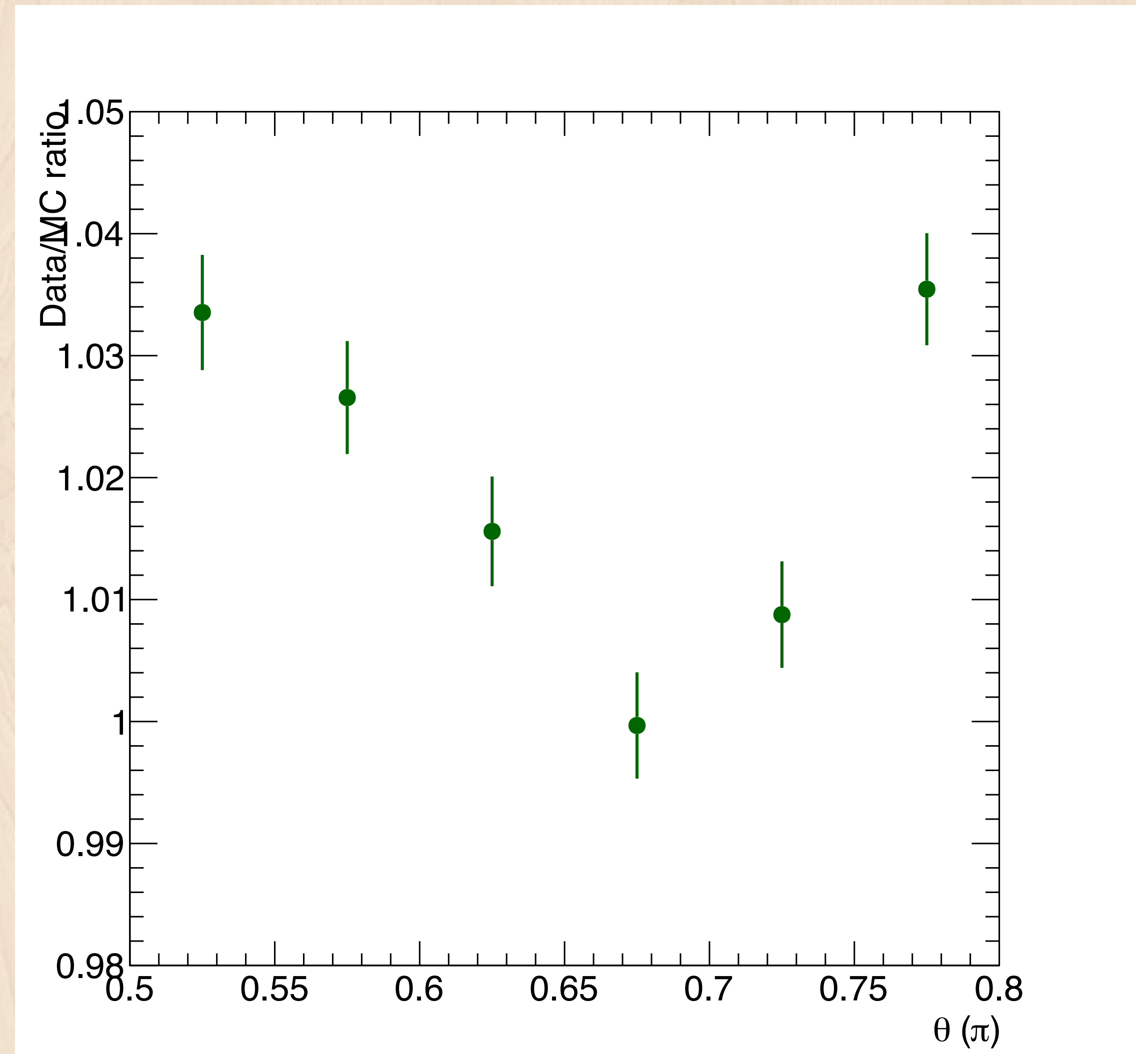
arXiv 2108.04877

Jet resolution

Jet resolution in simulation



Data resolution / MC resolution



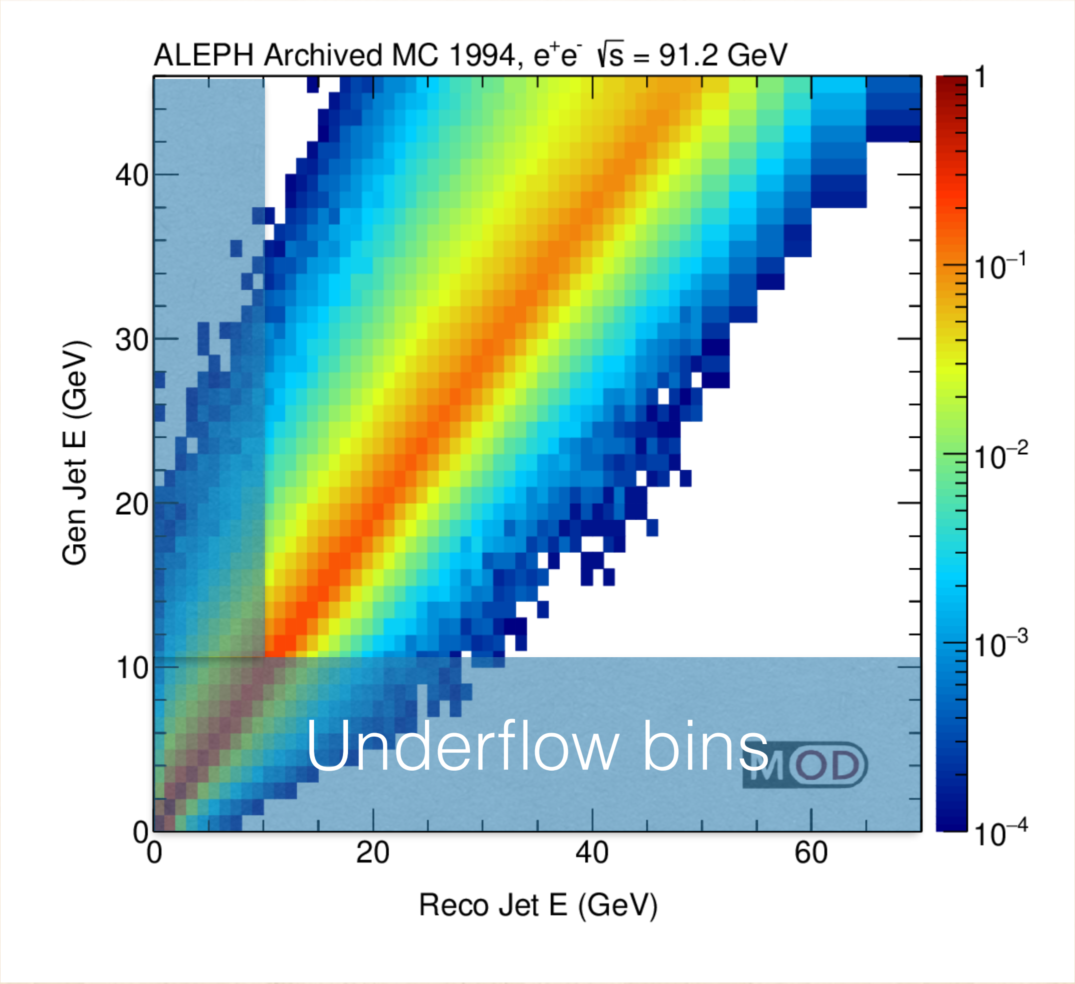
Energy resolution: 10-25%

(Angular resolution: 0.01-0.05)

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

arXiv 2108.04877

Unfolding



Example: inclusive jet energy

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

SVD unfold as systematic check

Flat prior as nominal

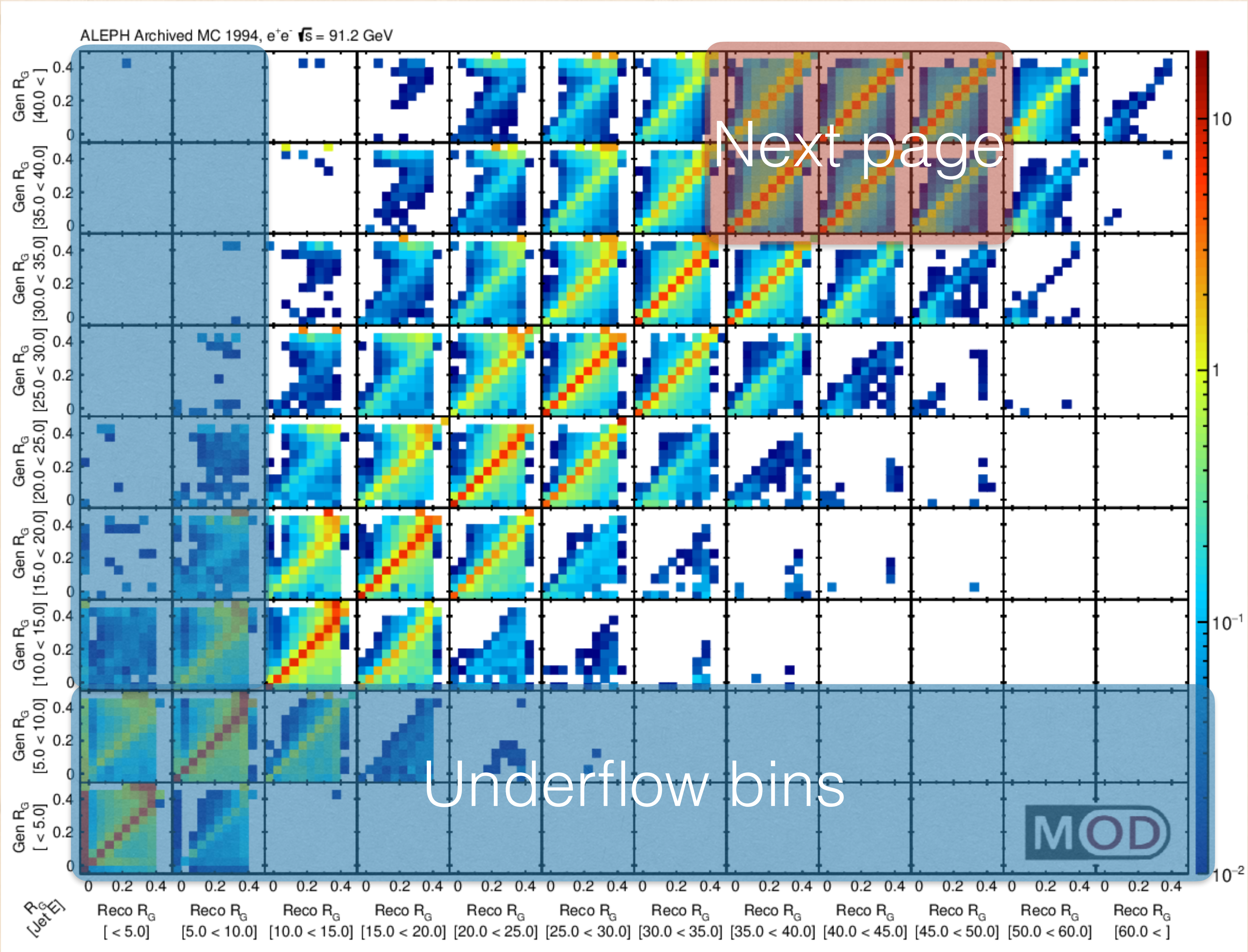
MC prior as systematic check

2D unfold for mass & groomed quantities

Due to energy migration

arXiv 2108.04877

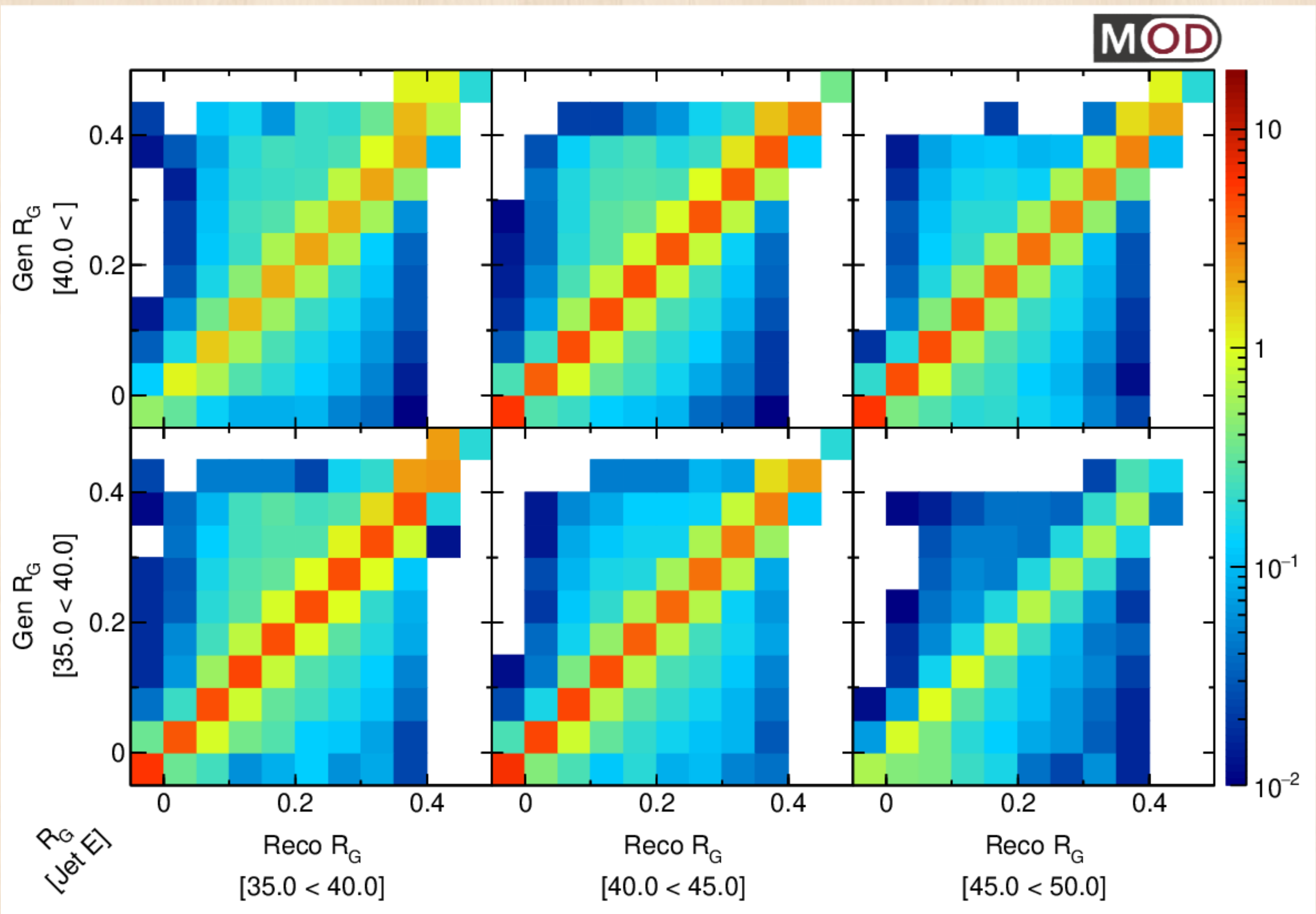
2D smearing matrix



arXiv 2108.04877

2D smearing matrix

Partial smearing matrix



Each block: different jet E

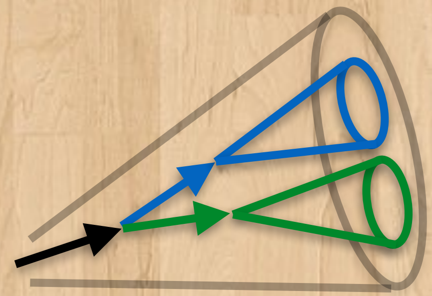
Generally well-behaved

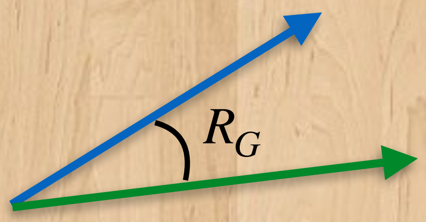
Percent-level off-diagonal

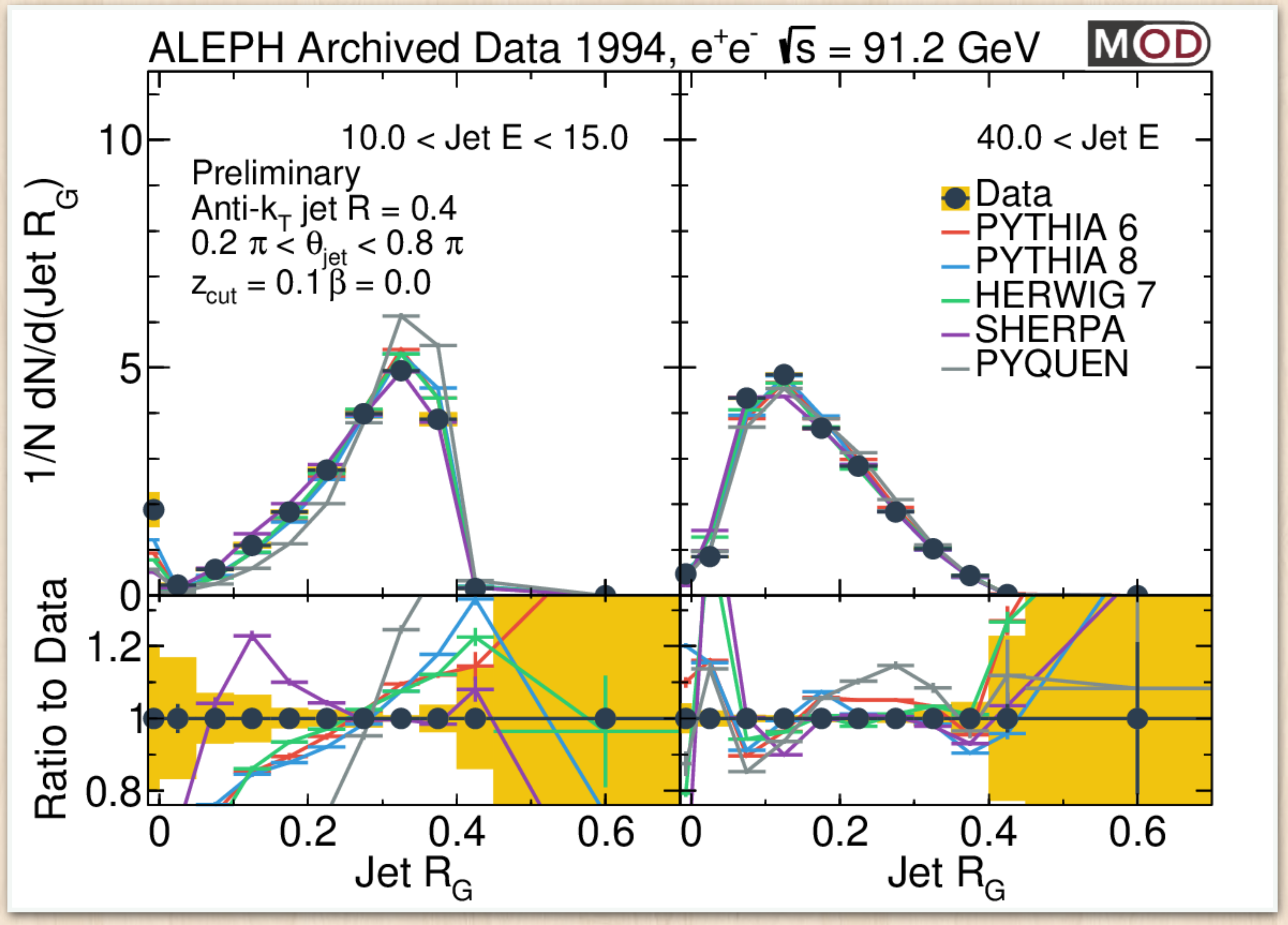
Example: jet R_G

arXiv 2108.04877

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

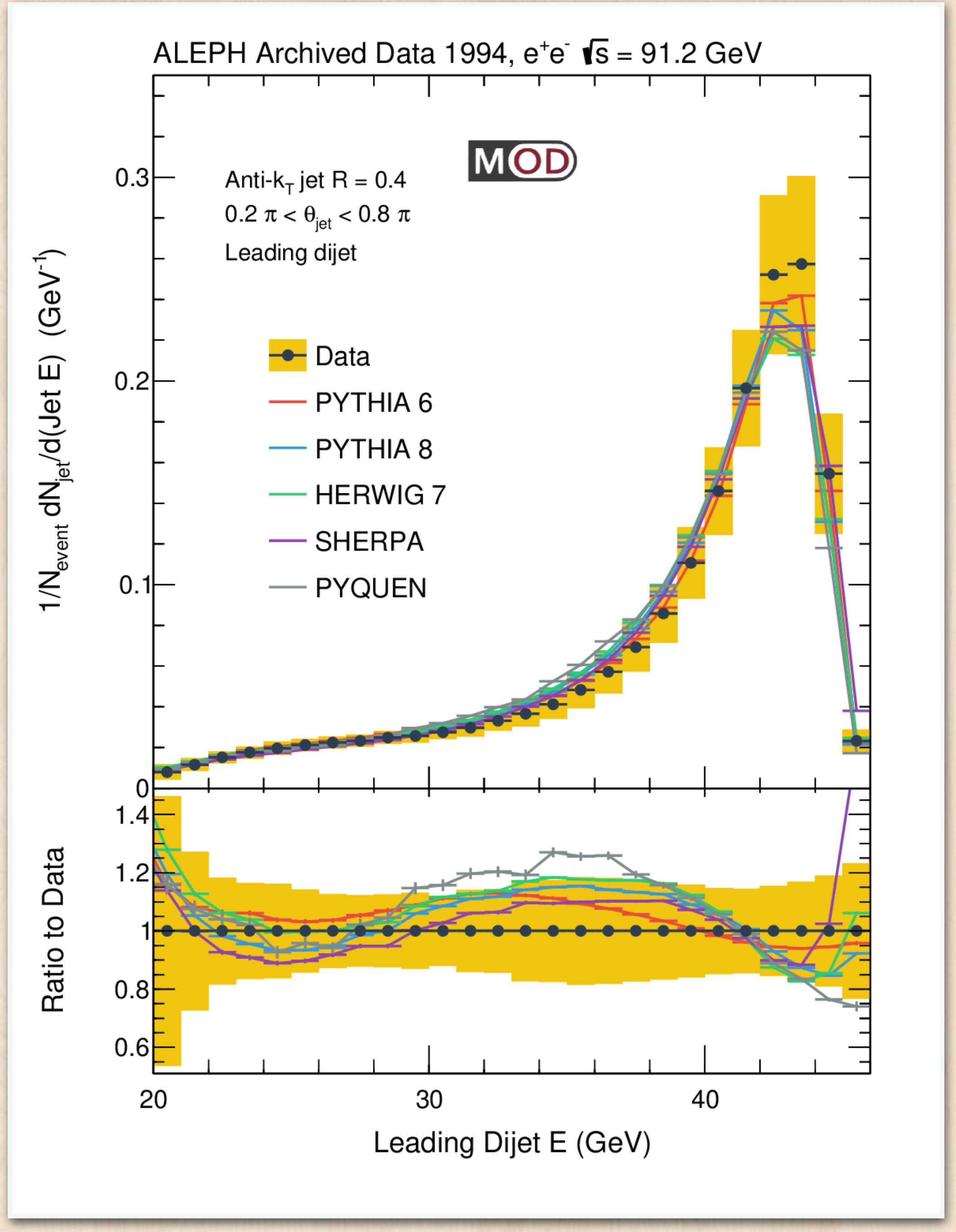
Worse data/generator agreement at low energy

Leading dijet energy

Focus on the peak part of the spectrum

Most generators can describe data within (large-ish) uncertainty

Uncertainty dominated by modeling uncertainty



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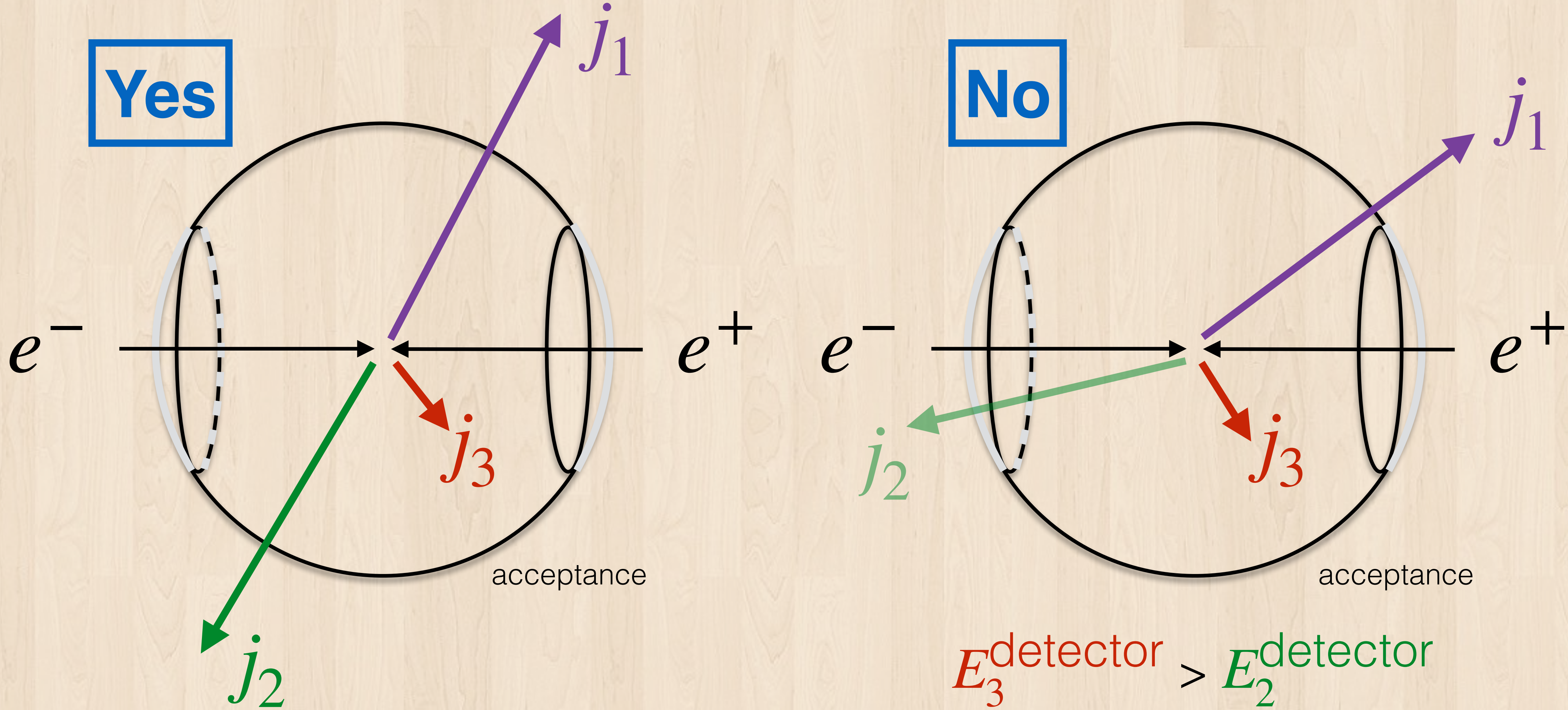
Global leading dijet



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

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

Leading dijet selection

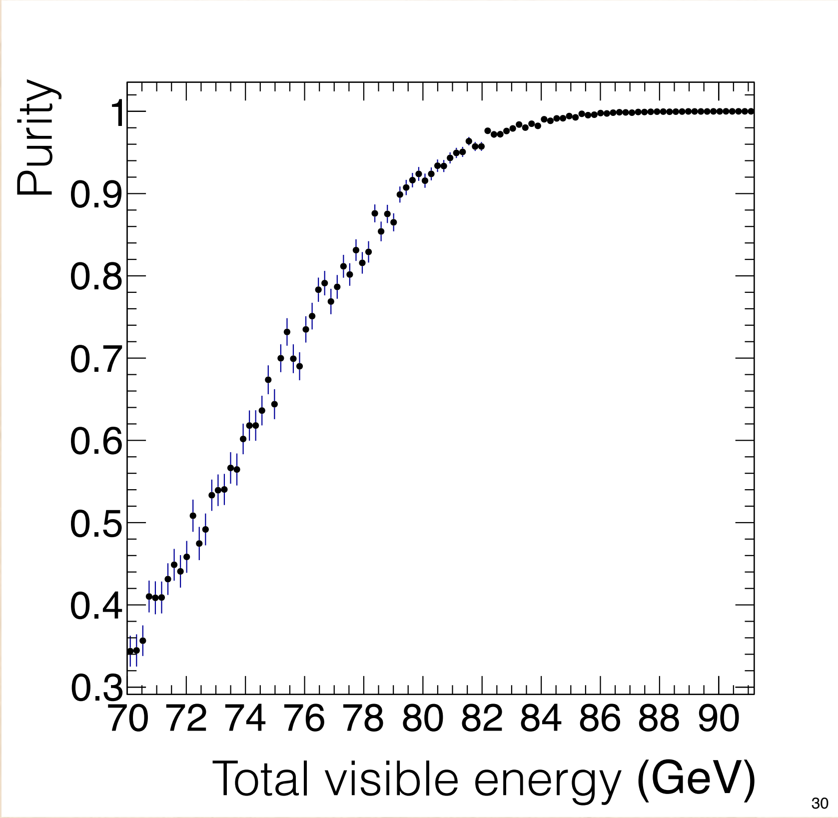
Solution: require minimal total visible energy

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

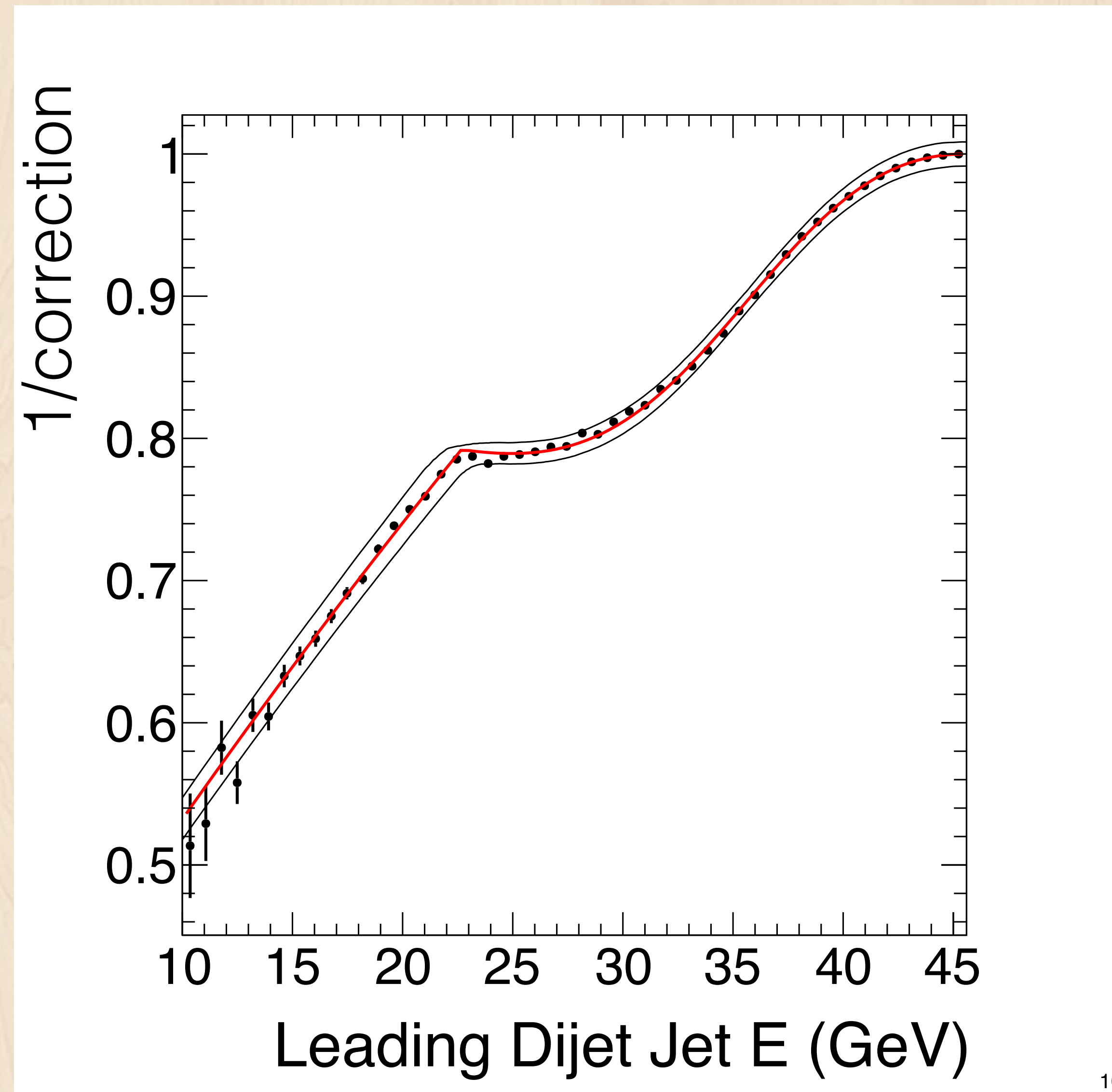
Data with visible energy selection

Unfolding (built with visible energy selection)

Truth level with visible energy selection

Truth level without visible energy selection

Correction



Correction derived from simulation