# Jets and calibration with the archived ALEPH $e^+e^-$ data


Luke Lu

Vanderbilt University

In collaboration with Anthony Badea (UChicago), Austin Baty (UIC), Benjamin Nachman (LBNL), Chris McGinn (MIT), Gian Michelle Innocenti (MIT), Hannah Bossi (MIT), Jingyu Zhang (Vanderbilt), Marcello Maggi (INFN), Michael Peters (MIT), Shuangyi Zhou (Vanderbilt), Tzu-An Sheng (MIT), Yen-Jie Lee (MIT), Yi Chen (Vanderbilt), Yu-Chen Chen (MIT)


## Motivation & ALEPH Data

**Motivation:**

- Jets are precision probes for QCD
- $e^+ e^-$ collision gives a good source of quark jets
- $e^+ e^-$ provides a clean reference
- $e^+ e^-$ does not have hadronic initial state
- These measurements provide a baseline for studying more complex environments such as pp and Pb–Pb collisions

**LEP and ALEPH archived data:**

- LEP shares the 26.7 km tunnel now used by the LHC
- Four primary experiments: ALEPH, DELPHI, L3, OPAL
- ALEPH collaboration archived their data for future use, extending the lifetime
- The Anti-$k_T$ [2] algorithm postdates the LEP shutdown
- The data format is converted to the MIT open data format

## Reanalysis effort

**Many data reanalysis projects:**

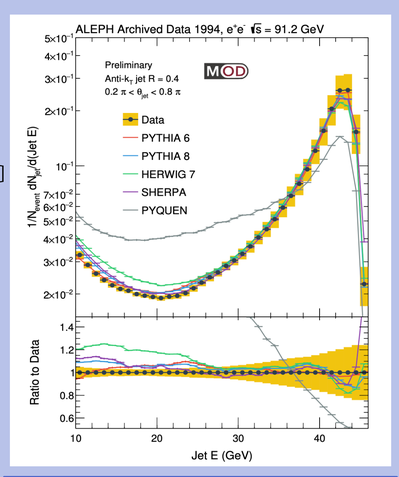
- 2–particle correlations
- Thrust measurement [5]
- Full–event energy–energy correlation (EEC) [3]

**First round of Jet measurements:**

- Inclusive jet spectrum
- Leading dijet spectrum
- Selected jet substructures: $z_g$, $r_g$, $\frac{M_g}{E}$, $\frac{M}{E}$

**Ongoing analyses include:**

- In–jet azimuthal particle distribution
- Jet spectrum with varying R
- Track energy spectrum and moments
- ...



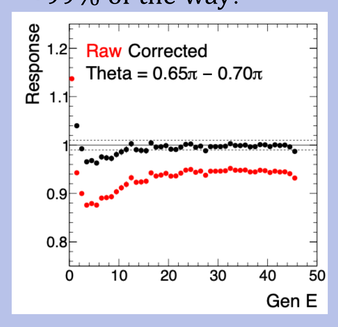

Inclusive jet energy spectrum from ALEPH 1994 data compared to various MC generators

## Jet Calibration [1]

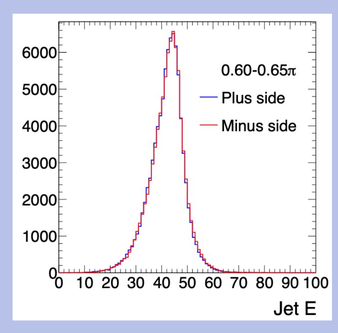
This work also done with different R's (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, 1.2)

MC-based Calibration → +/- Residual → Absolute Scale

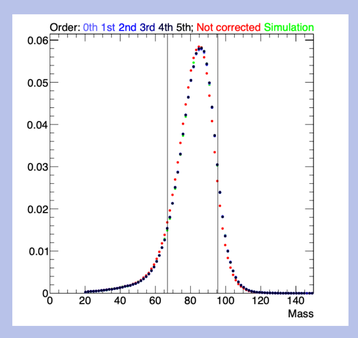
Apply simulation–derived jet response to correct reconstructed jet energies ~99% of the way.




Calibrate two halves of the detector against each other. Size of correction ≤ 0.5%.




Use multijet invariant mass to align data and MC. Size of correction ≤ 1%.




## Jet Resolution [1]

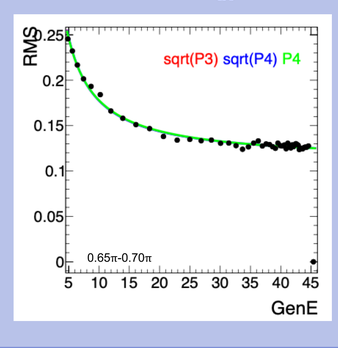
MC-based Parametrization → Data-Driven Resolution

Calibration aligns the mean jet energy

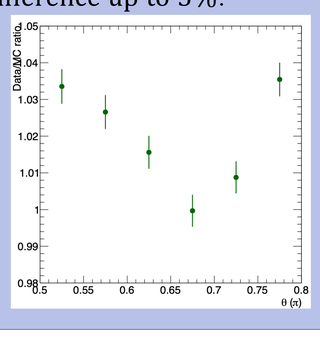
Resolution accounts for the width of the response

Both are essential for reconstructing true jet kinematics

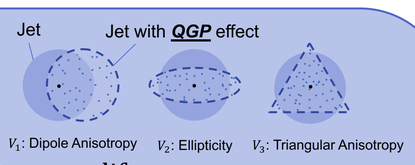
Jet energy resolution estimated from simulation as a function of energy and θ.



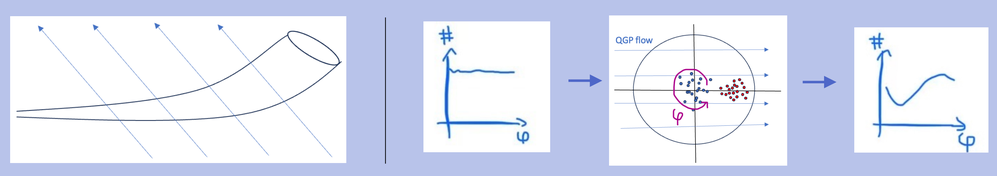

Measure data–simulation difference in resolution using dijet balance in data; observed a difference up to 5%.




## In-jet azimuthal particle distribution




Heavy–ion collision creates ***QGP***; ***QGP*** behaves like a fluid; ***QGP*** can modify how particles are distributed inside a jet.




To quantify the effect, we study the ϕ distribution,
We are looking at **three Fourier components: $V_1$, $V_2$ and $V_3$.**

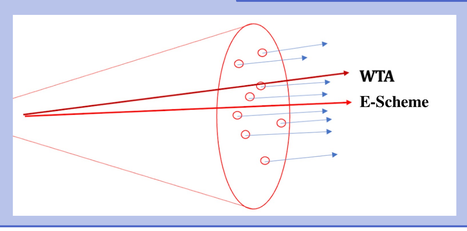
E- scheme is sensitive to soft particles
WTA is robust against soft particles

We study the baseline jet behavior without QGP effects using archived $e^+e^-$data from ALEPH.

We compare two jet axes:

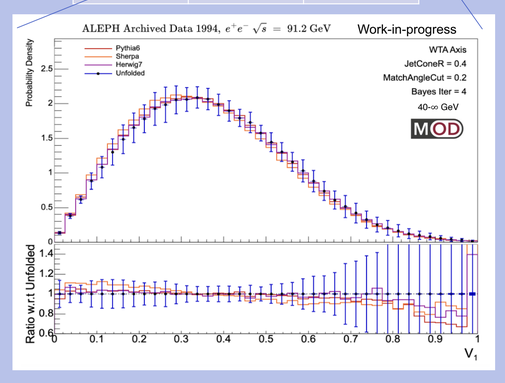
☆ E–scheme (Vectorial sum of momentum)

☆ WTA (follows leading energy in slice)




## Work-in-progress results

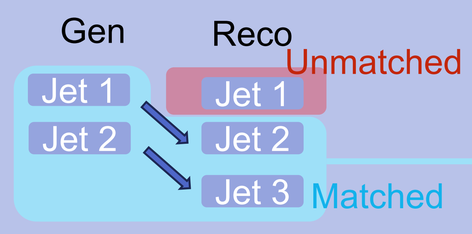
| | E-sheme | WTA |
|---|---|---|
| V1 | … | ○ |
| V2 | … | … |
| V3 | … | … |

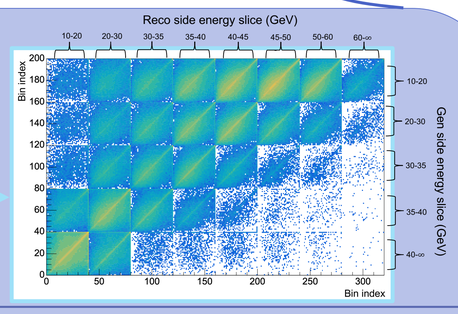



## Analysis Details

### Jet Matching

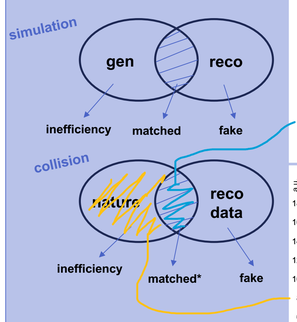
Global one–to–one assignment of reconstructed (Reco) and generated (Gen) jets using the Hungarian algorithm, minimizing angular distances (Δθ < 0.2 rad).
This allows precise jet–by–jet comparison for further analysis.

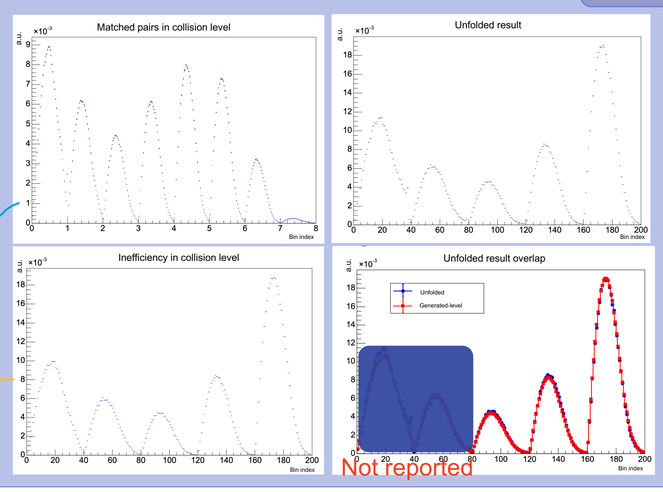



### Unfolded

Original distribution → Fake subtraction → 2D Unfolding [4] → Inefficiency correction → Final Result



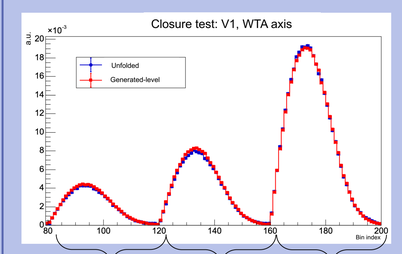




Not reported

### Closure test

Using detector–level simulation and running through analysis chain to reproduce generated–level quantities to validate the analysis.

We only report the three highest energy slices

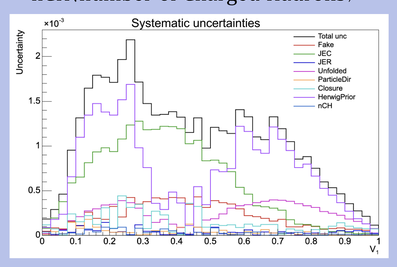



30—35GeV 35—40GeV 40—∞GeV

### Systematics

We consider these systematic variations:

- Fake (matching criterion)
- JEC (energy scale shift)
- JER (resolution smearing)
- Iter (unfolding stability)
- ParticleDir (directional bias)
- Closure (MC closure residual)
- HerwigPrior (prior dependence)
- nCH(number of Charged Hadrons)




## Summary & Next step

☆ Anti–$k_T$ [2] jets are calibrated to 1% precision in archived ALEPH data.

☆ The data is perfect for precision QCD studies with a lot of untapped potential.

☆ Many analyses are ongoing.

☆ We show one example of new ideas that can be investigated on in–jet particle distribution.

☆ Our results will provide a reference for current and future collider studies, including heavy–ion collisions involving QGP.


We would like to thank Roberto Tenchini and Guenther Dissertori (ALEPH Collaboration) for their valuable comments and suggestions.

We thank the ALEPH Collaboration for preserving and providing open access to data.



[1] Y. Chen et al., "Jet energy spectrum and substructure in e⁺e⁻ collisions at 91.2 GeV (ALEPH)," JHEP 06 (2022) 008, arXiv:2111.09914. [2] M. Cacciari, G. P. Salam & G. Soyez, "The anti-kt jet clustering algorithm," JHEP 04 (2008) 063, arXiv:0802.1189. [3] CMS Collaboration, "Observation of nuclear modification of EEC inside jets in heavy-ion collisions," Phys. Lett. B 866 (2025) 139556, arXiv:2503.19993. [4] G. D'Agostini, "Improved iterative Bayesian unfolding," arXiv:1010.0632 (2010). [5] Anthony Badea et al., "Analysis note: measurement of thrust in e⁺e⁻ collisions at √s = 91 GeV with archived ALEPH data," arXiv:2507.14349 [hep-ex] (2025).



**The Vanderbilt HENP group's work is supported by the US DOE-NP.**



**Email: kuan.lu@vanderbilt.edu**