High-precision measurement of full event EEC in 91 GeV e^+e^- collisions with archived ALEPH data

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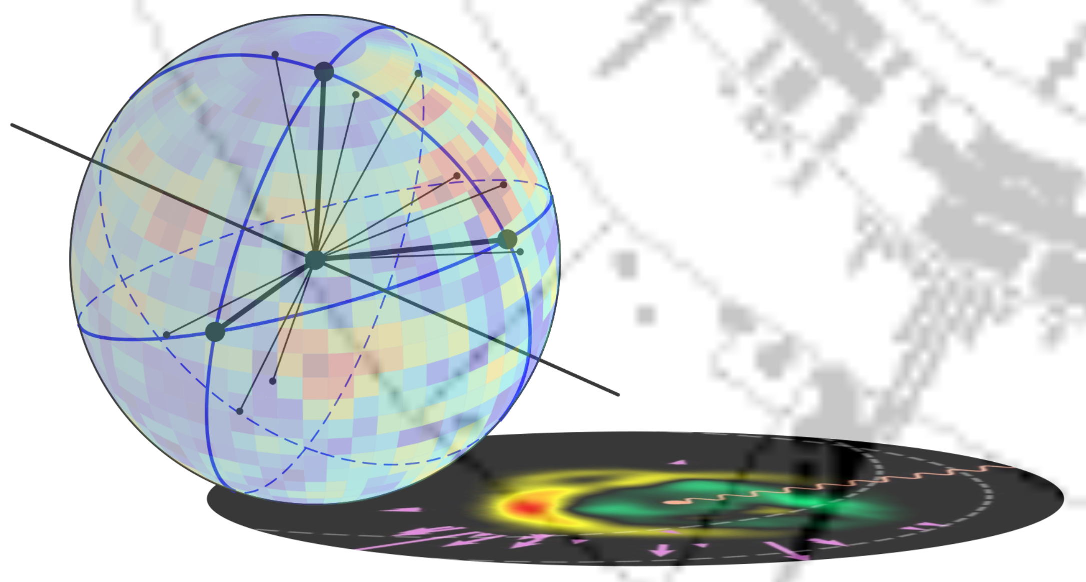

EEC Workshop, May 2025
CCNU, Wuhan, China

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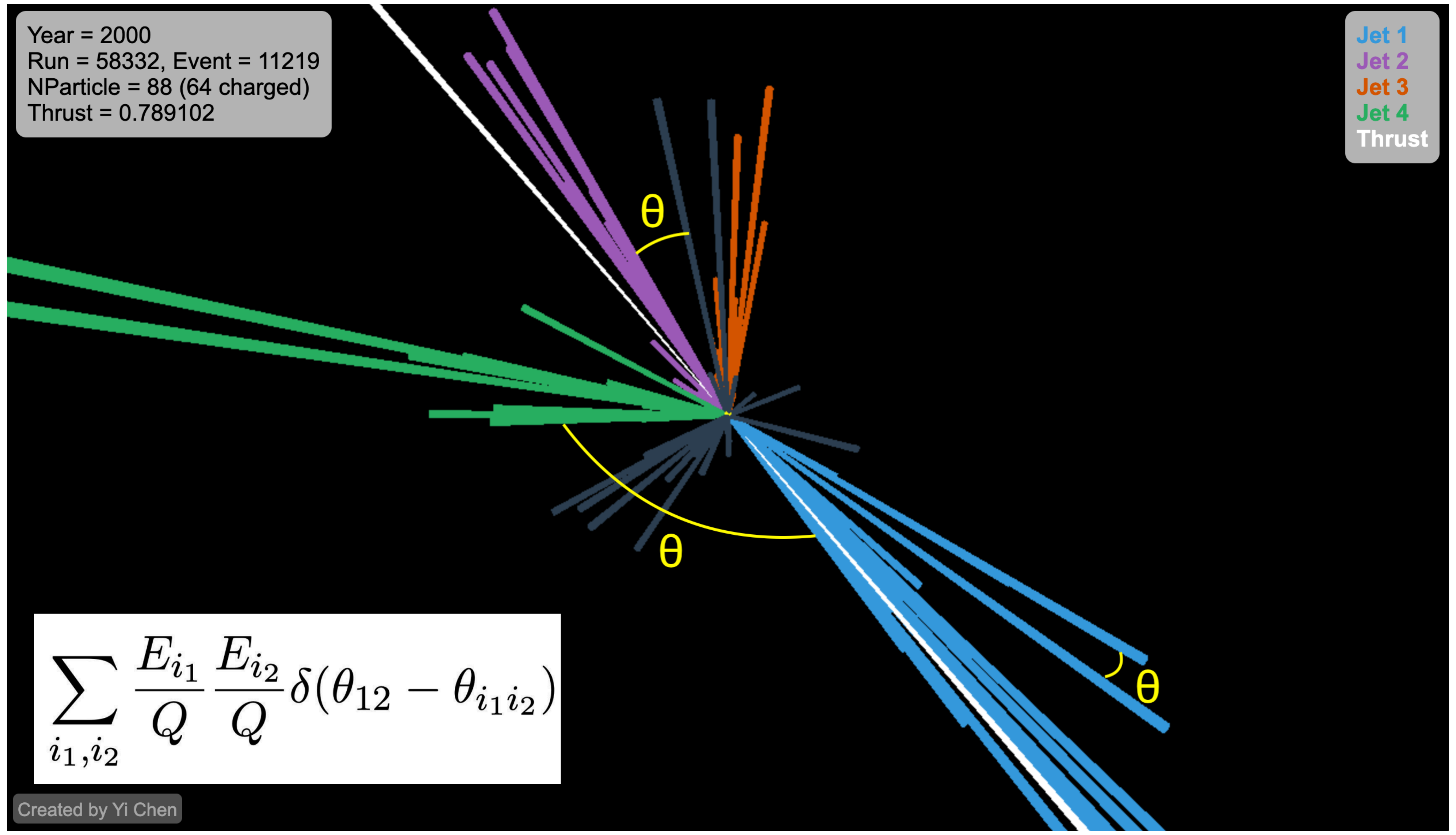
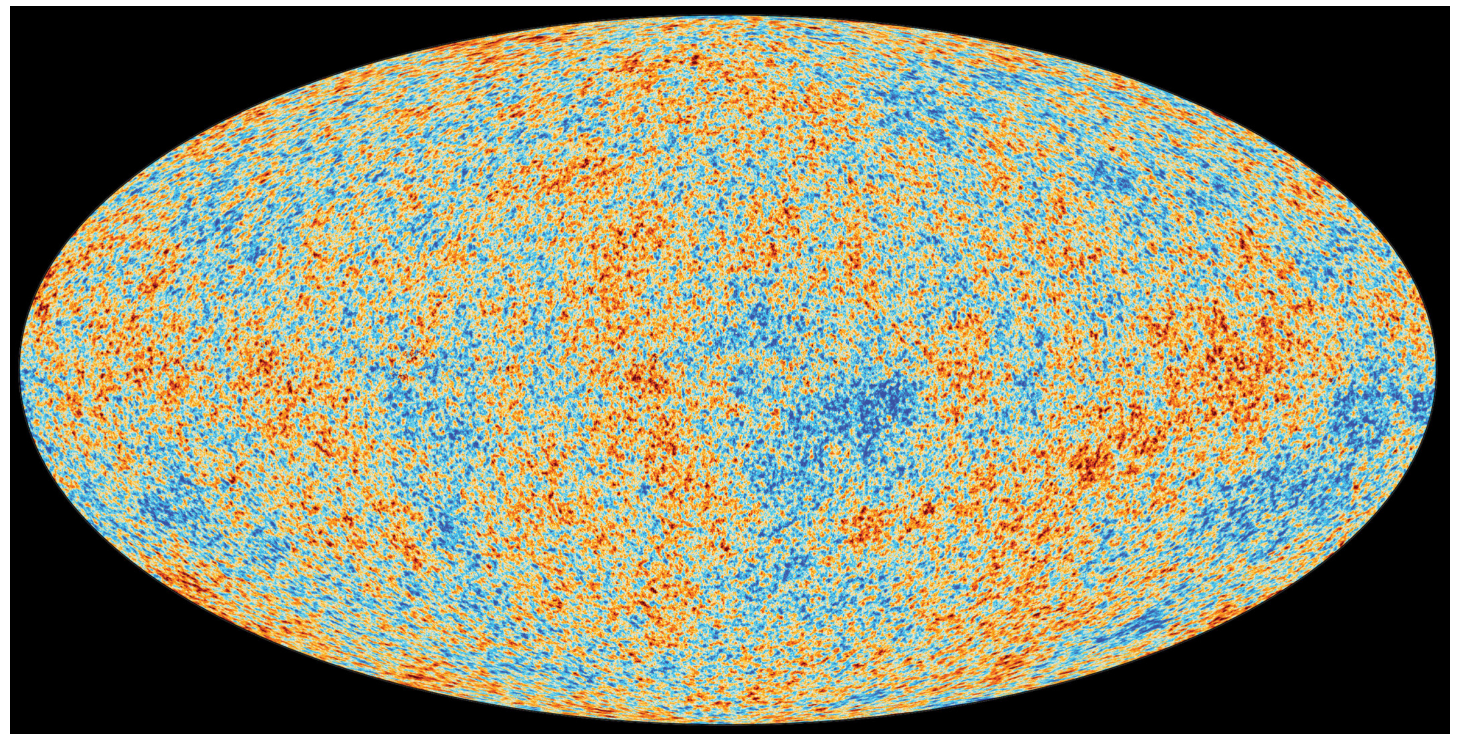
Outline

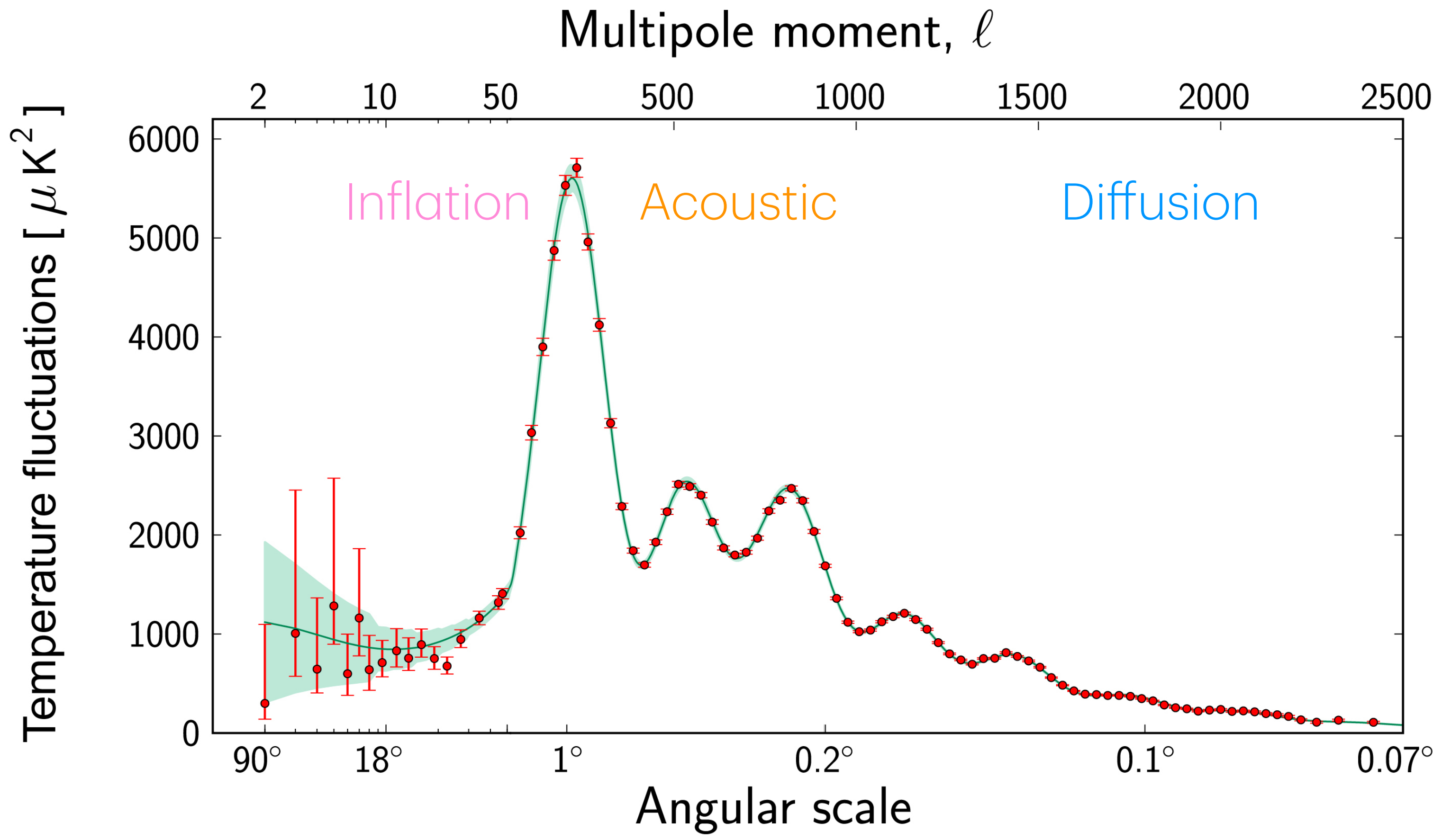
- Introduction
- The archived ALEPH dataset
- High precision measurement of EEC at 91 GeV with archived ALEPH data
- Discussions and future perspectives



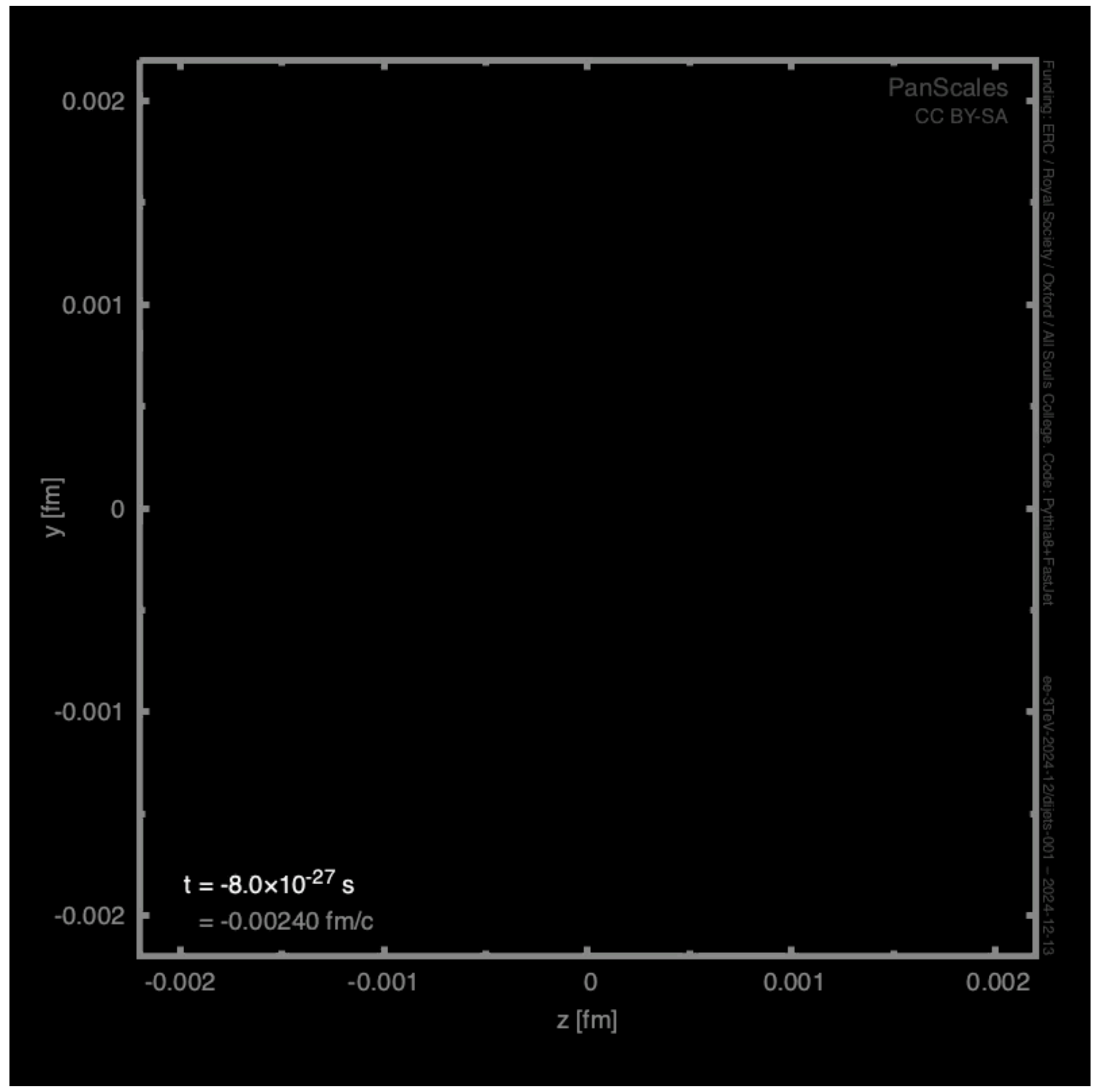
Full Range EEC

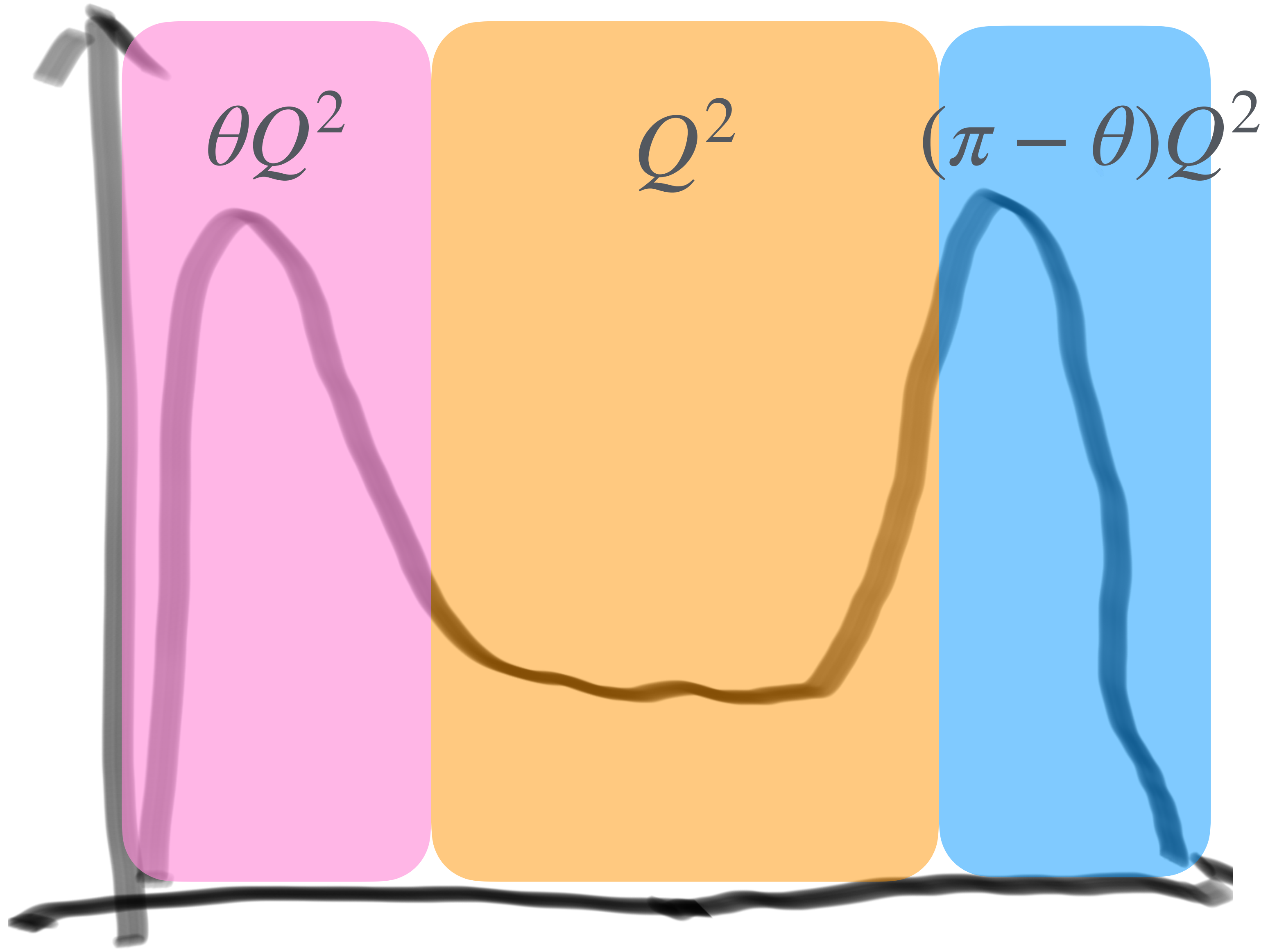
- Correlation of energy flux in full space
  - No complication from the definition of jet
- Angular scale imprints space-time QCD evolution in collider physics
  - Small angle: parton shower and hadronization in a "jet"
  - Wide angle radiation, "multi-jet" events
  - Back-to-back region: di-jet process modified by soft radiation



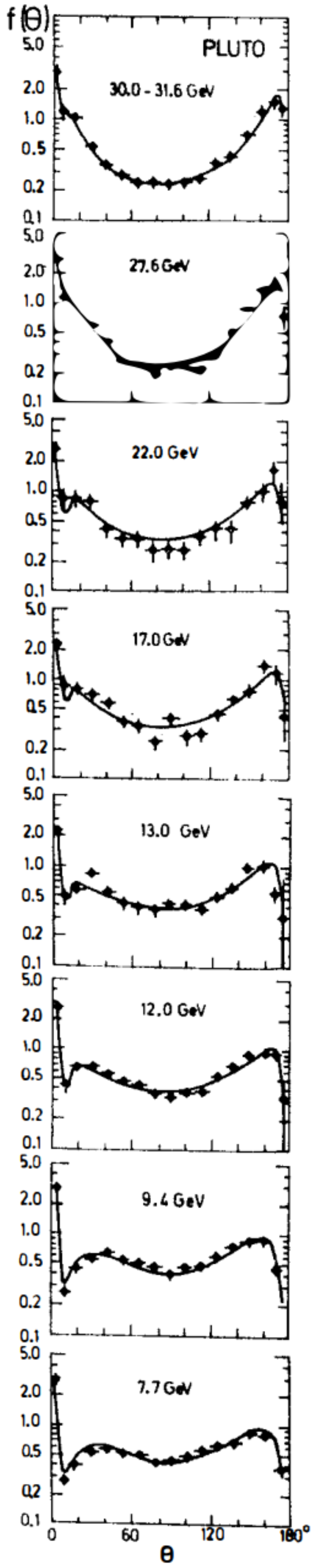


PanScales

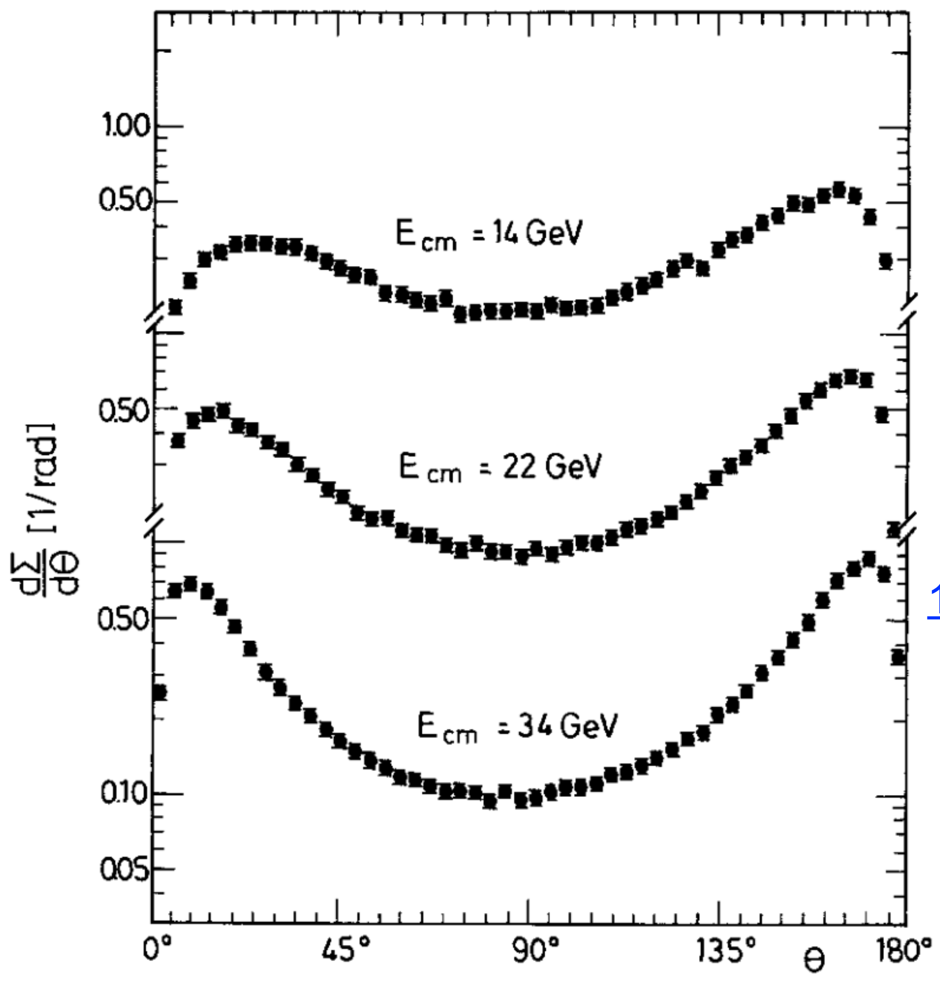




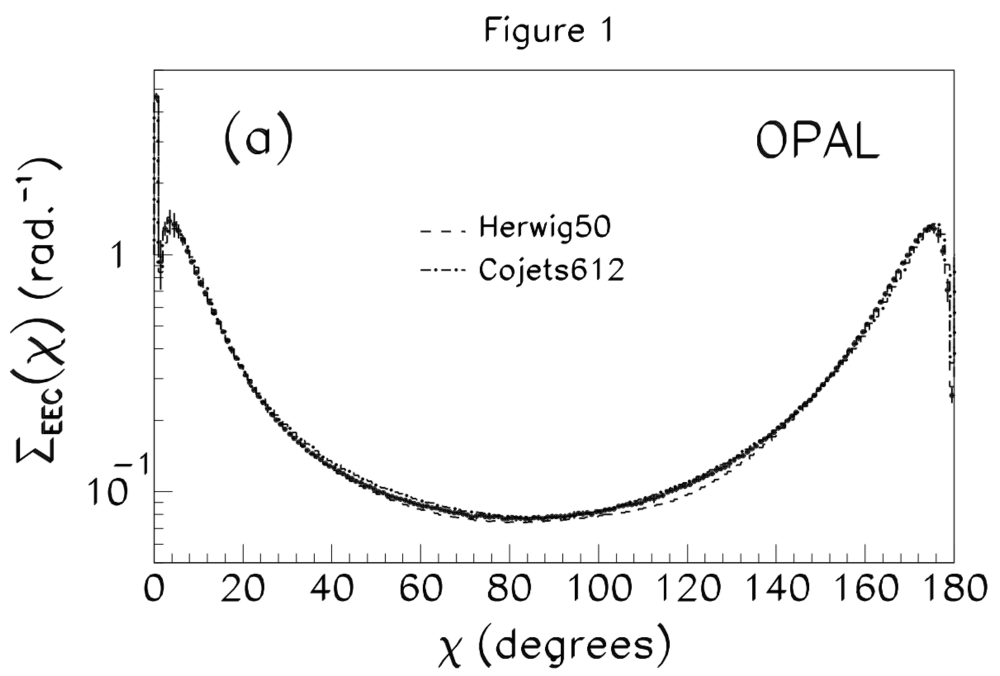
Previous Results



10.1016/0370-2693(81)91128-X



10.1007/BF01547922



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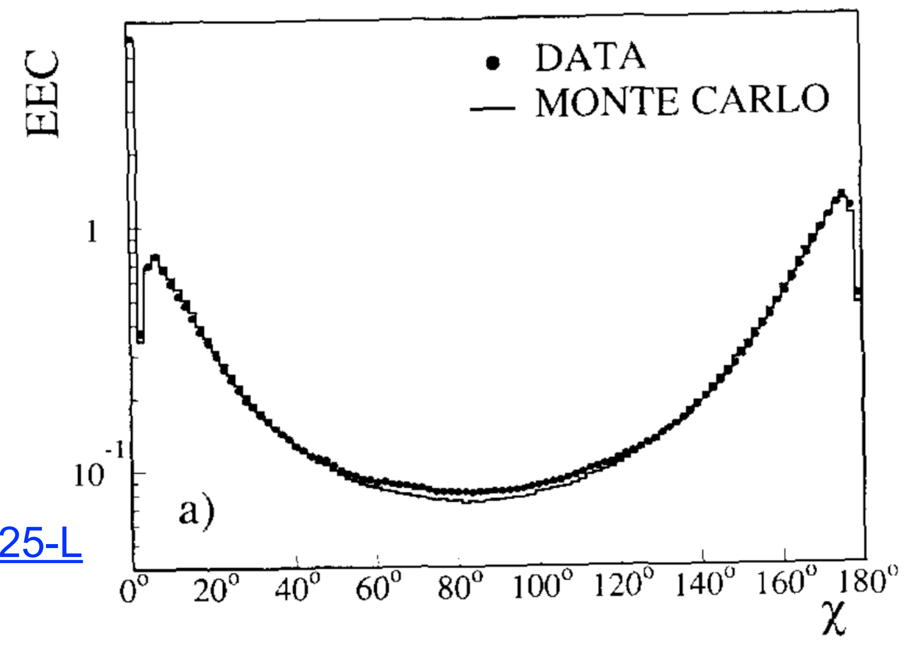
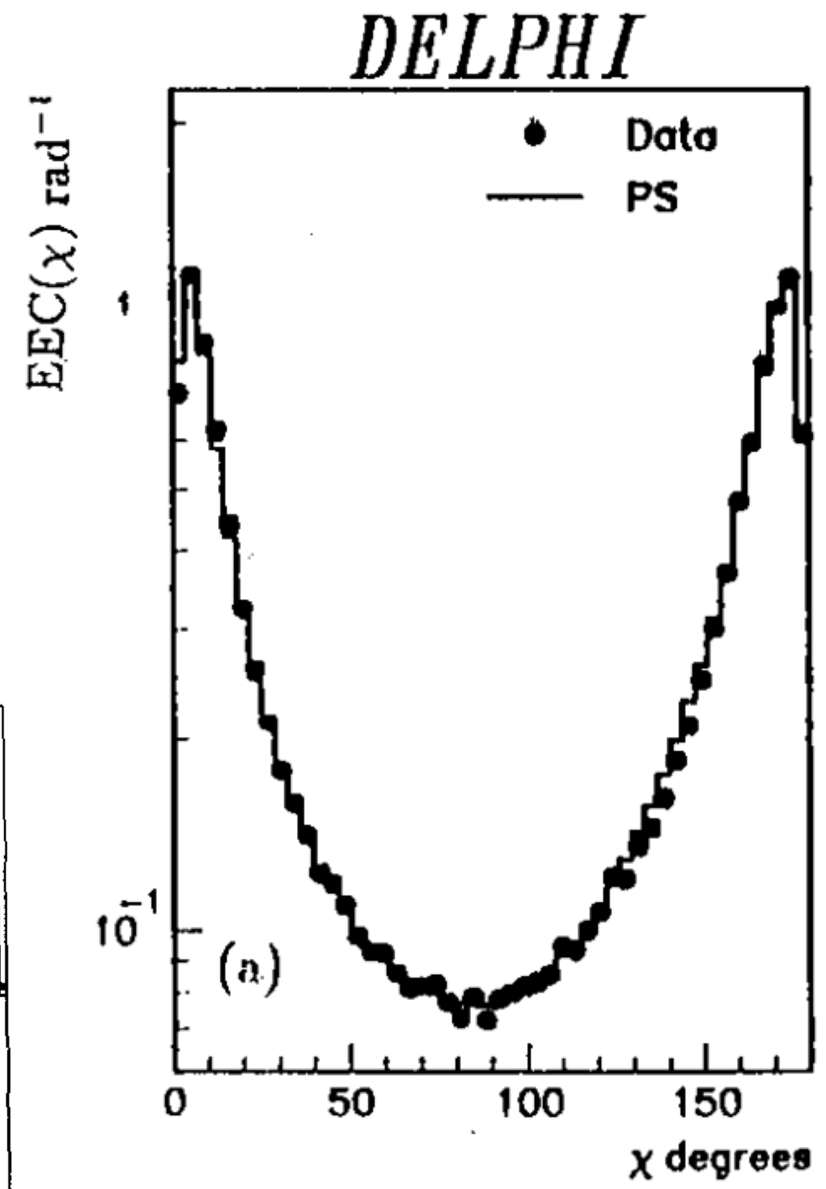
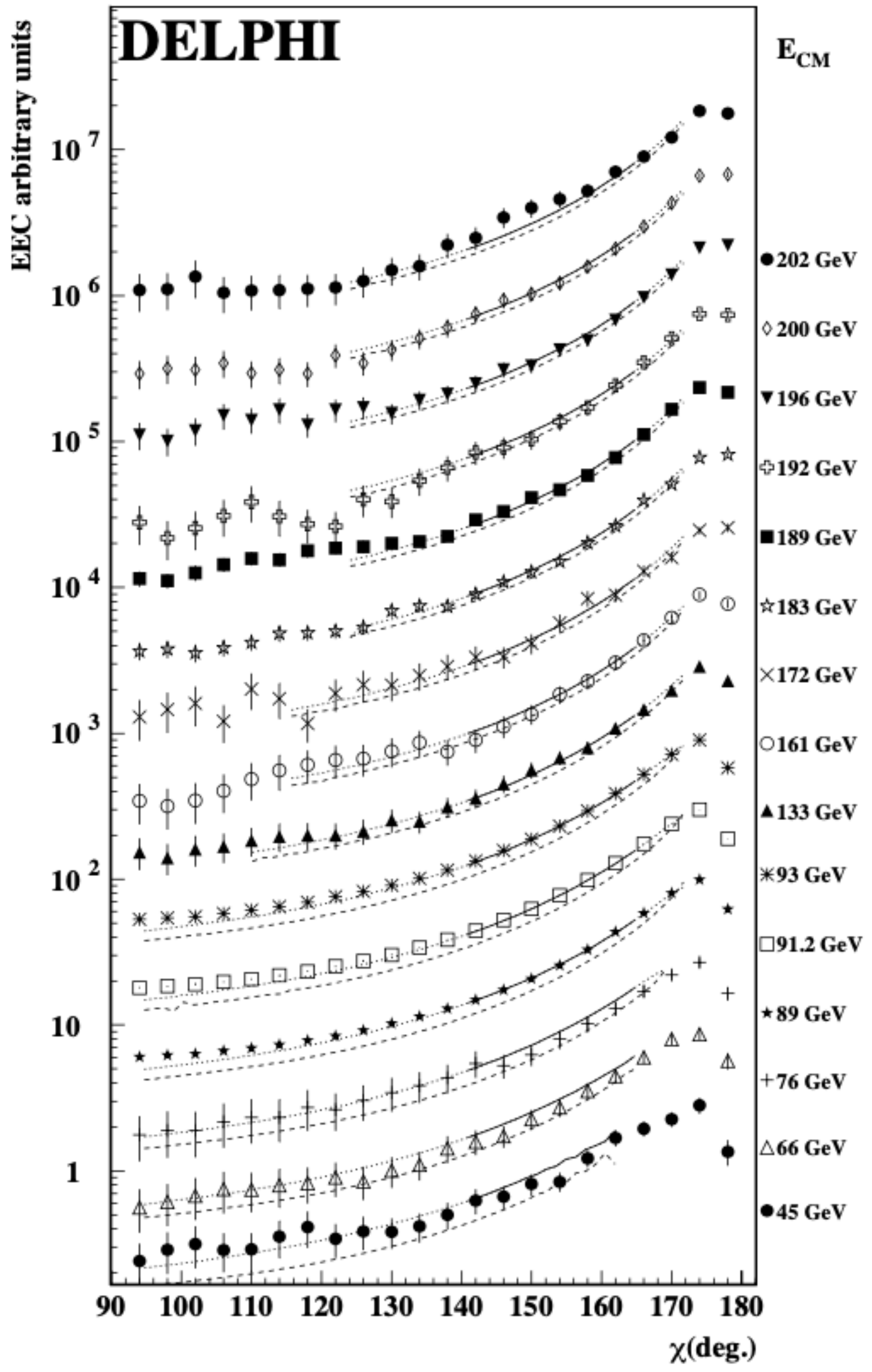


10.1016/0370-2693(91)91925-L



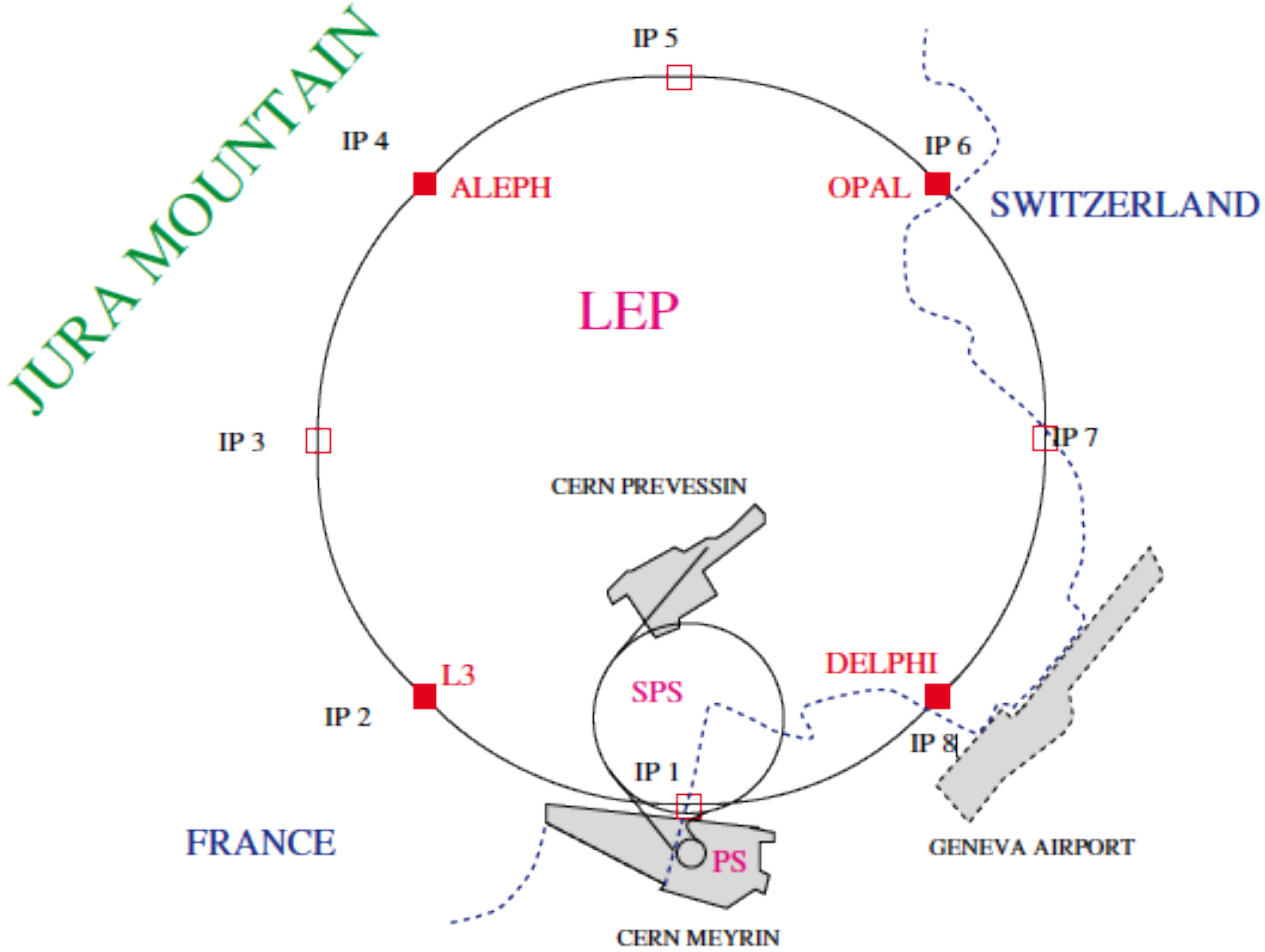
10.1016/0370-2693(90)91097-U

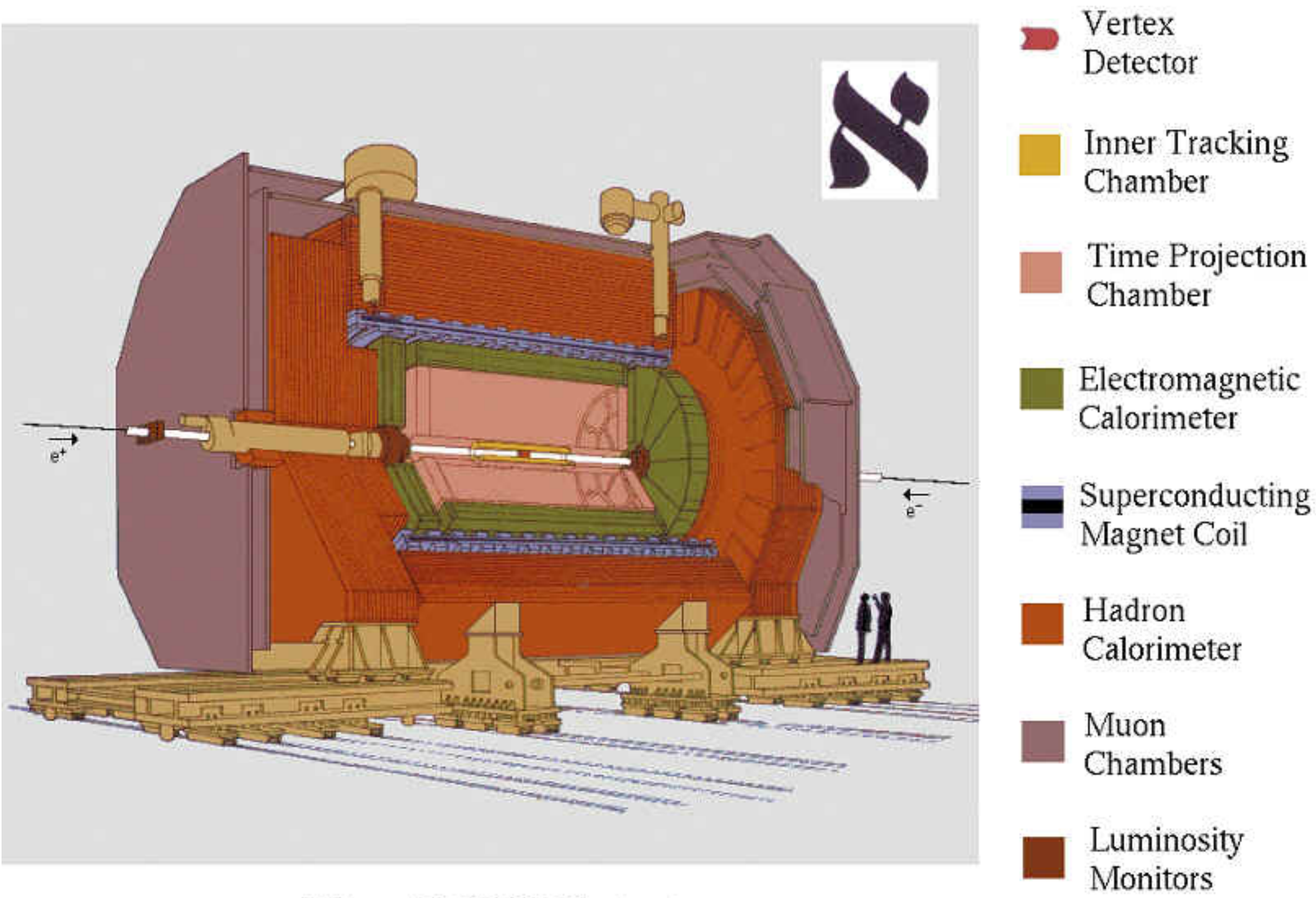
10.48550/arXiv.hep-ex/0307048



- Full range EEC is proposed in ~1970 to test QCD in e+e- collisions
  - Has been studied by many experiments in the 80's and 90's: PLUTO, JADE, OPAL, L3, DELPHI…
- Resolution not enough to reveal the full picture of QCD
  - **Calls for a high resolution and high precision measurement to test the latest theory development**

LEP and the ALEPH Experiment

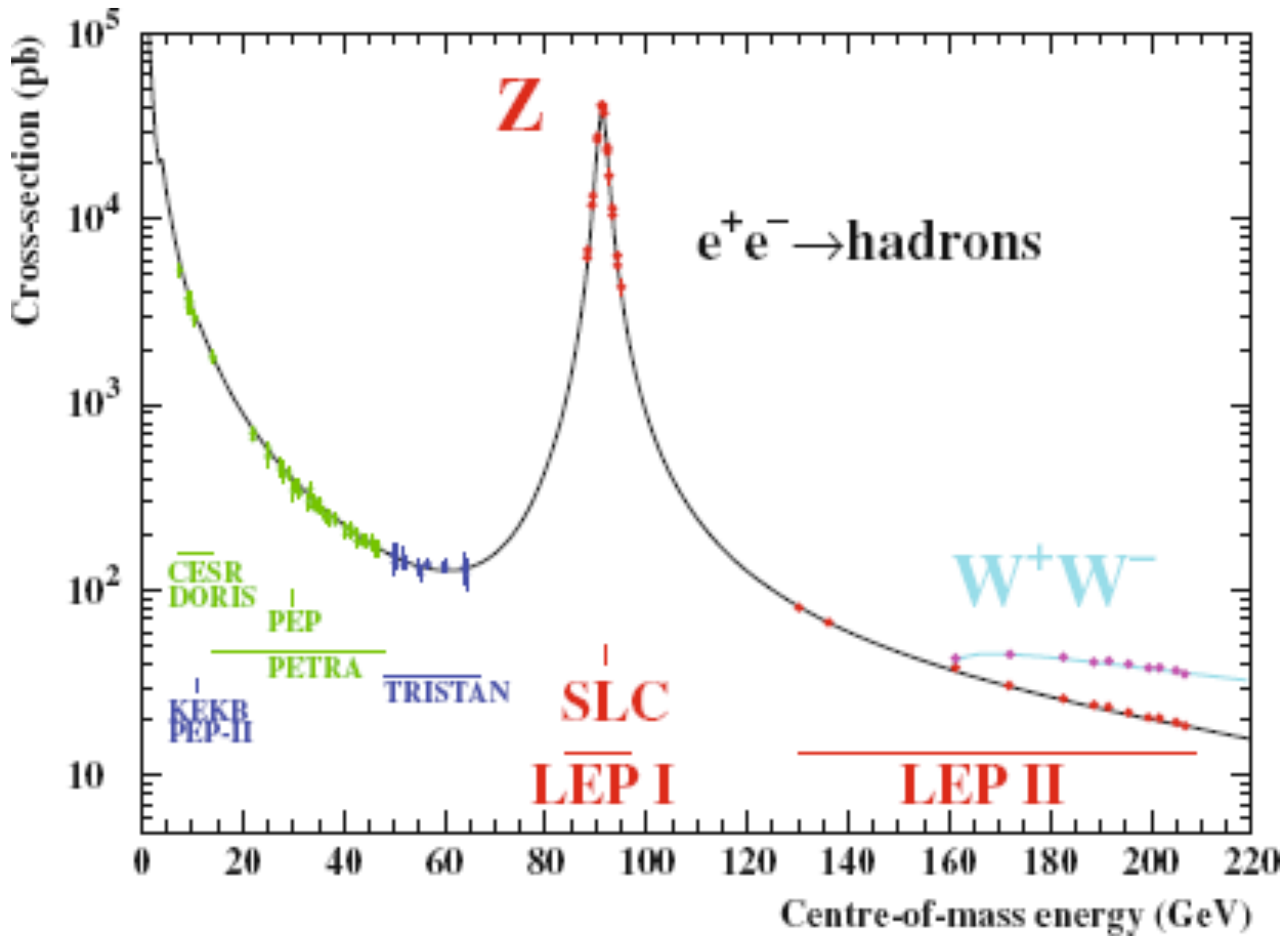


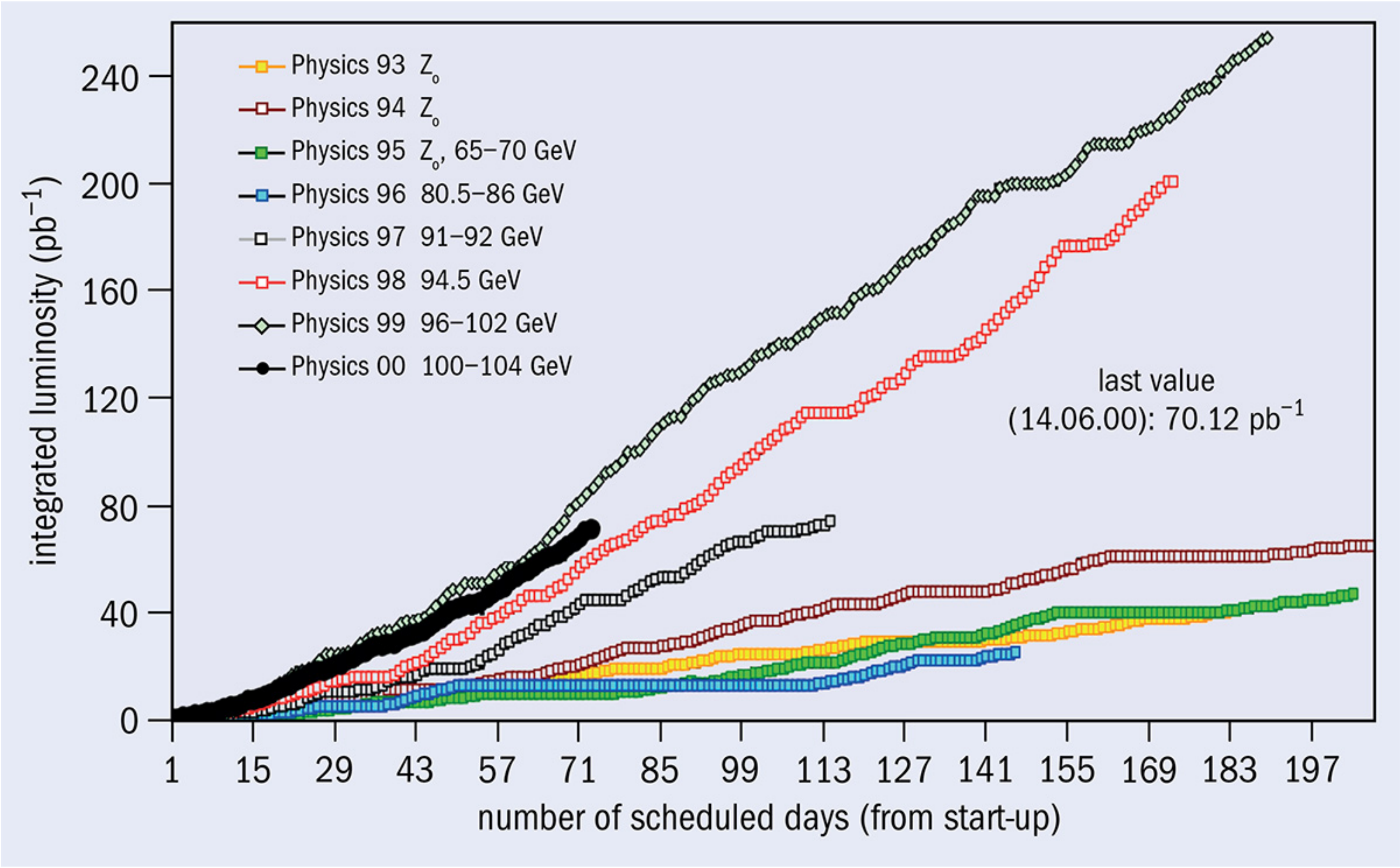


The ALEPH Detector

LEP and the ALEPH Experiment

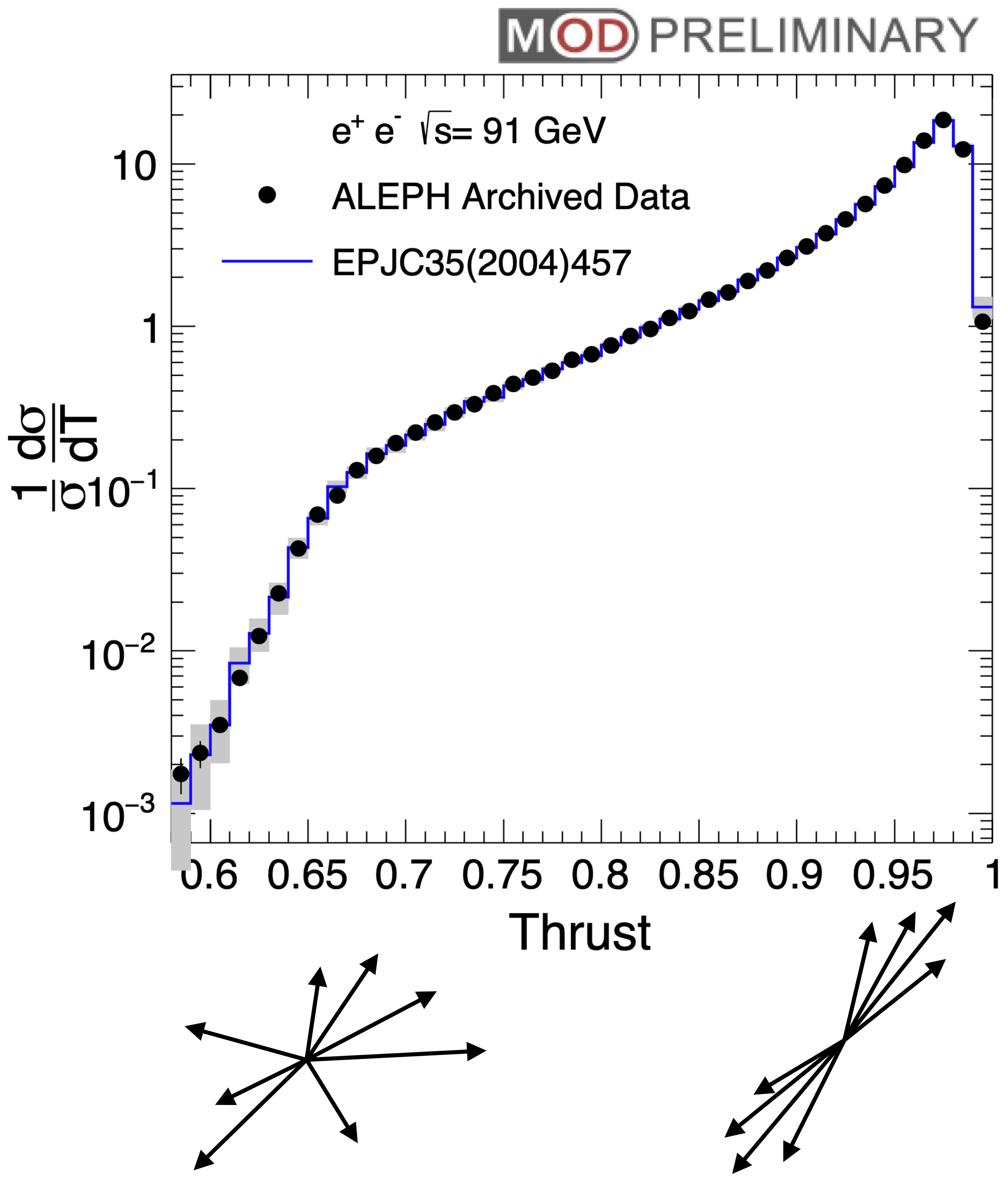
- Precision QCD laboratory and reference for pp and PbPb measurements
- Colorless initial-state
  - QED initial-state radiation
- Structureless beam
  - Negligible pile-up
- Point-like collision particle
  - **No underlying events and PDF effect**
  - **Fixed hard scale**





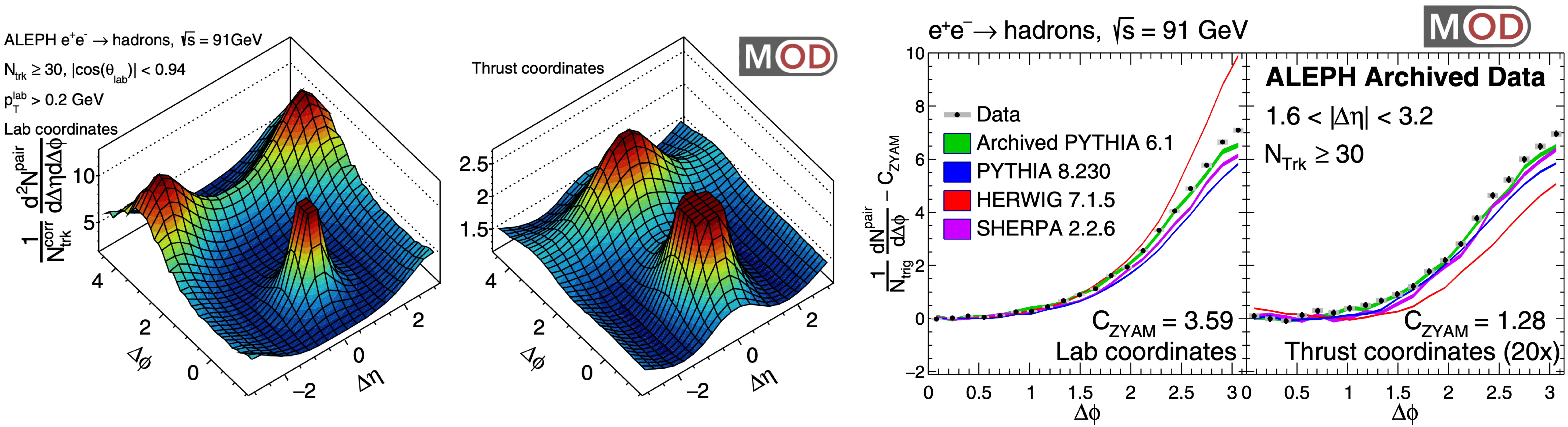
The Archived ALEPH Dataset

- February 2017: **Yen-Jie Lee** connected to **Gigi Rolandi** and later to spokesperson **Roberto Tenchini** about the use of archived data
- **Marcello Maggi** help extract the energy flow information and archived data and simulation
- Mid-2017: all samples converted to the MIT open-data format
- Started working on validation of the converted sample
- **Guenther Dissertori** provided analysis code from the QCD paper
- March 2018: successfully reproduced published thrust distribution



*On-going: generative ML to unfold and extract the strong coupling constant

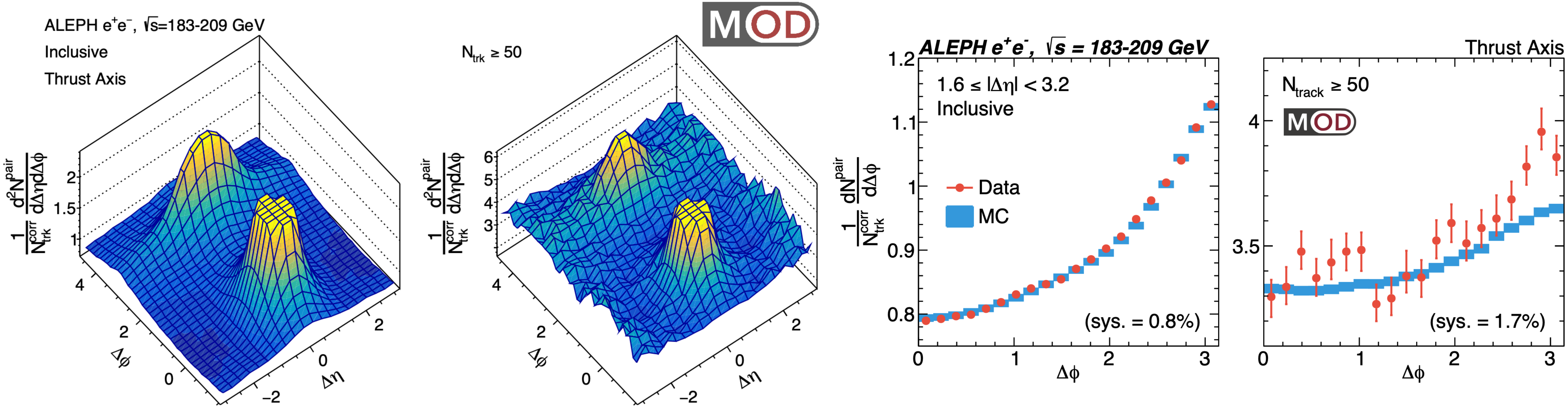
The Archived ALEPH Dataset: 2 Particle Correlation



[10.1103/PhysRevLett.123.212002](https://doi.org/10.1103/PhysRevLett.123.212002)

- First measurement of two-particle correlation function for e^+e^- collisions at 91 GeV
- No significant **ridge-like signal**

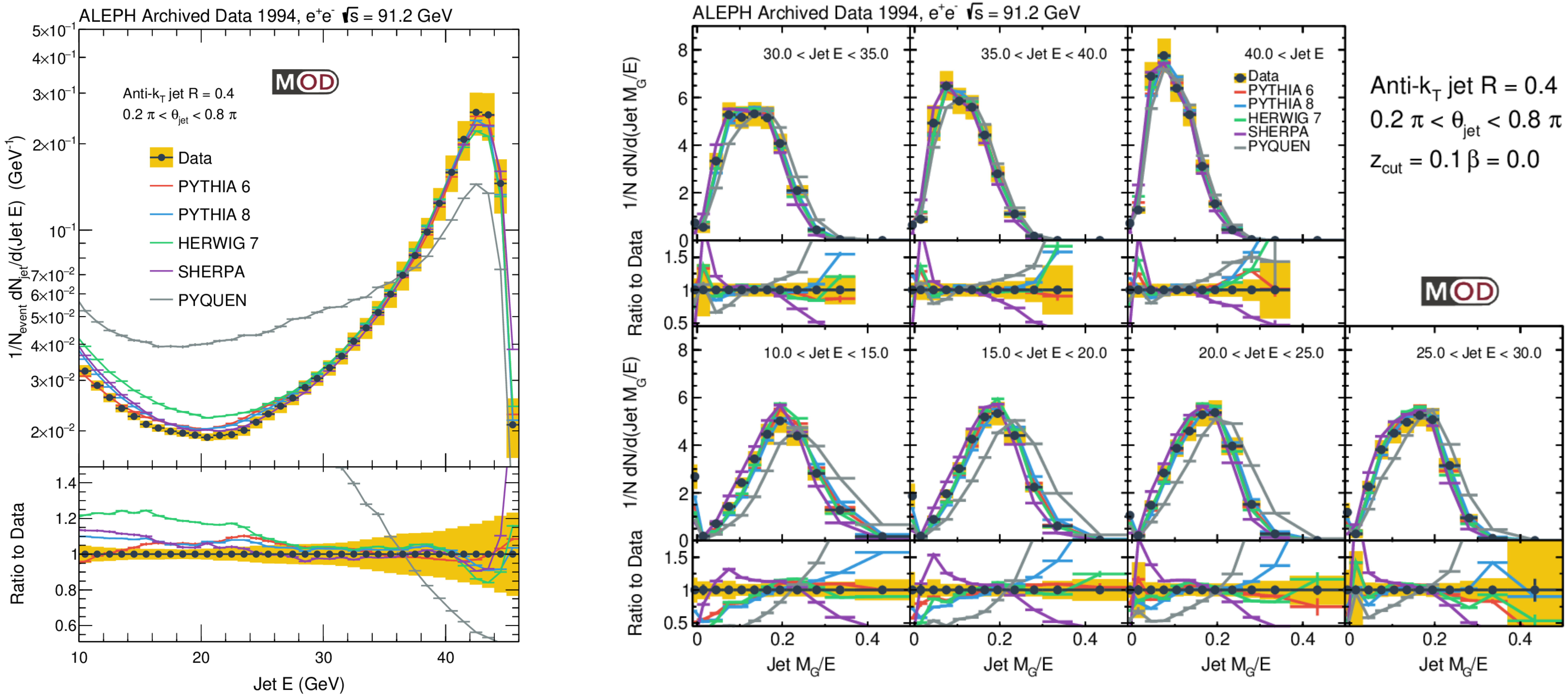
The Archived ALEPH Dataset: 2 Particle Correlation



10.1016/j.physletb.2024.138957

- First measurement of two-particle correlation for e^+e^- collisions up to 209 GeV
- LEP2 with thrust axis interesting structure in **high multiplicity events**

The Archived ALEPH Dataset: Jet and substructure

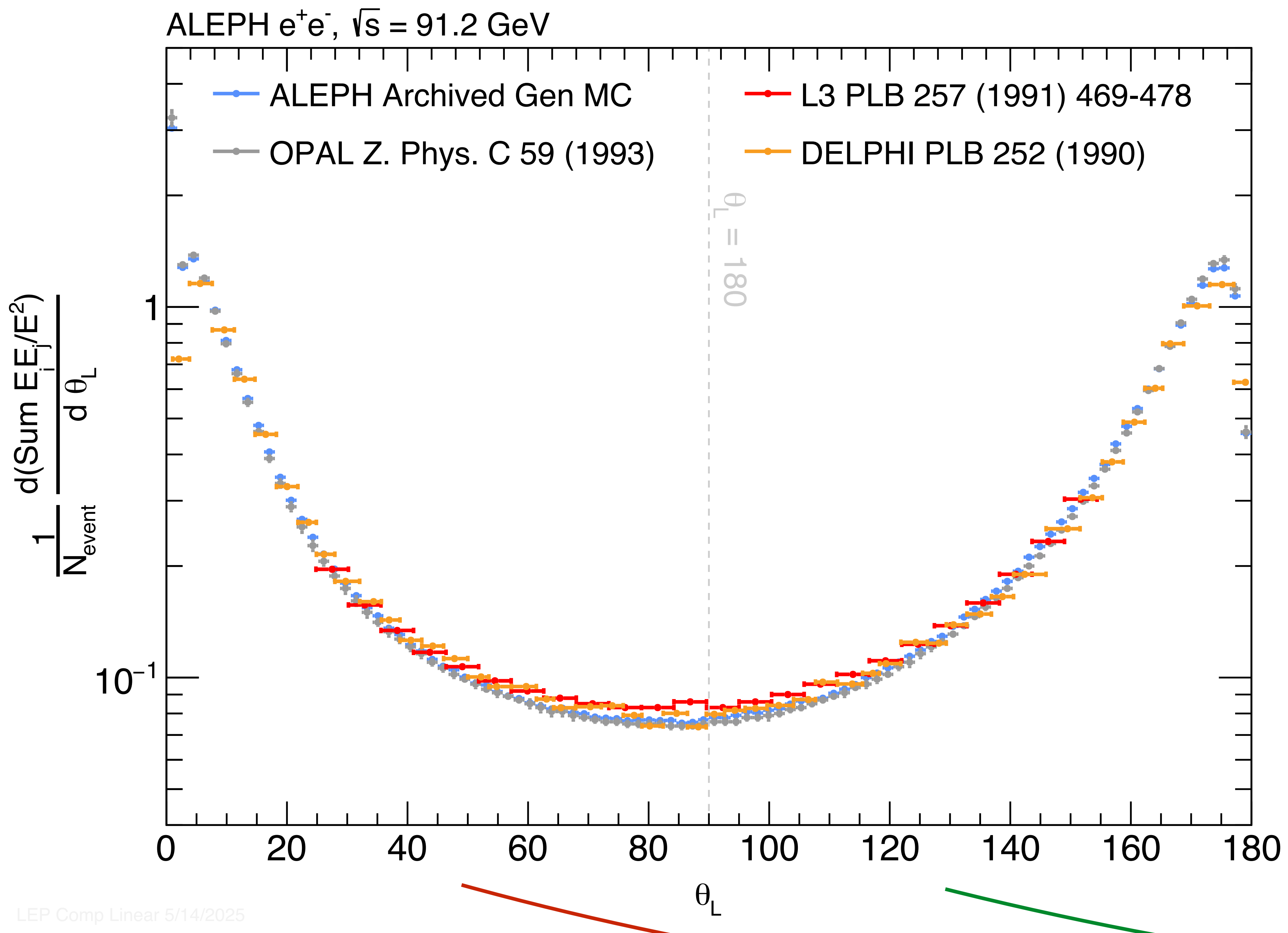


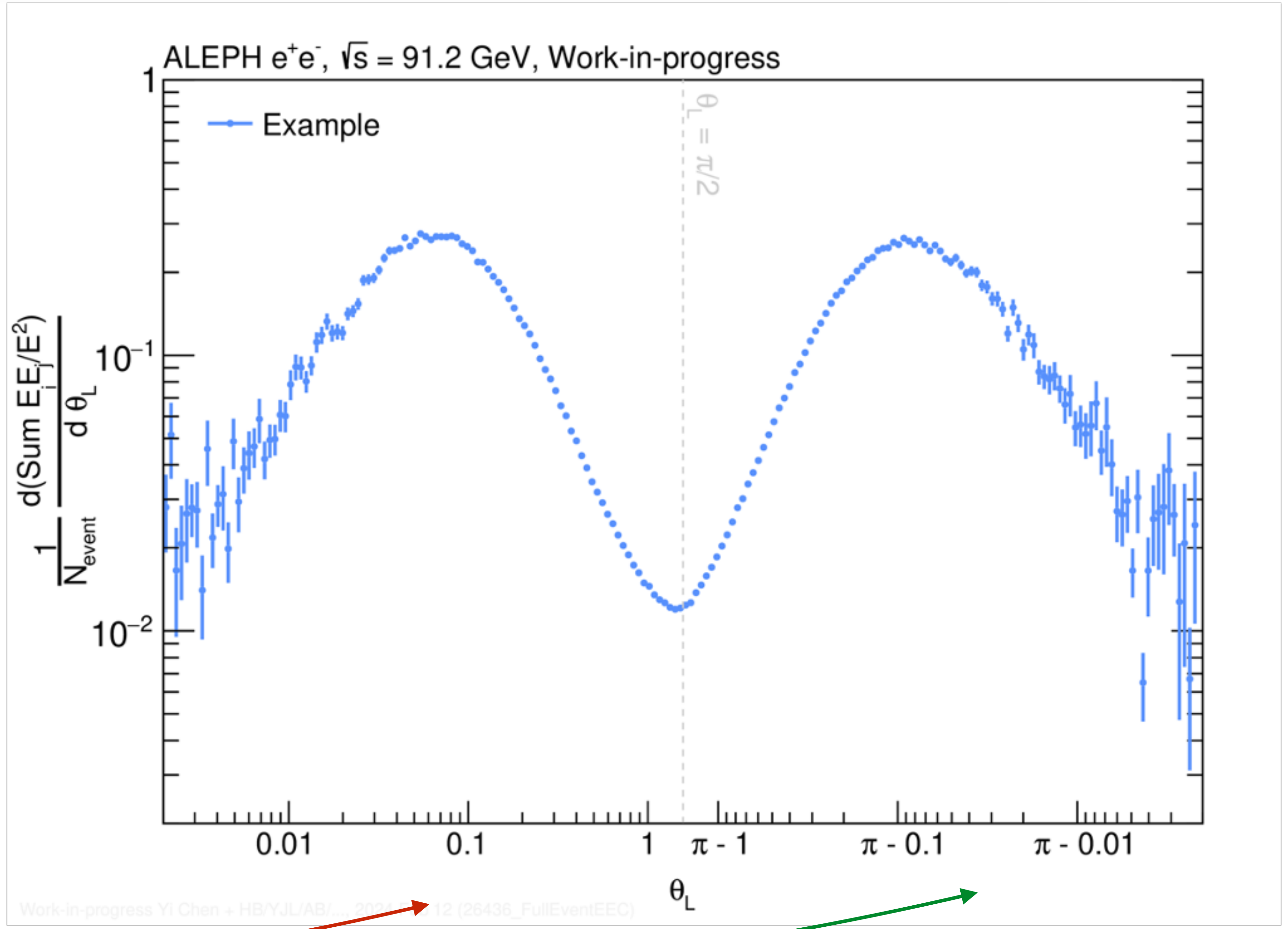
10.1007/JHEP06(2022)008

- First measurement **anti-k$_T$** jet spectrum and substructure in hadronic Z decays in e^+e^- collisions

Analysis Strategy

High resolution double-log style plot to present physics at small scale
Parametrization in θ and z = (1-cosθ)/2





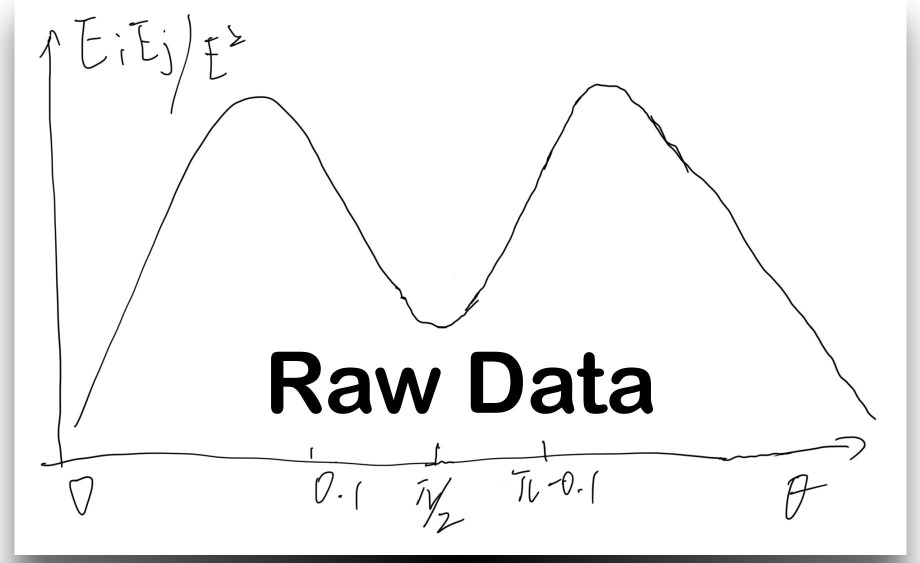
Log scale

Flipped log scale

Analysis Strategy

- Use only **charged tracks**
  - Much better momentum and position resolution than neutral
- **Detector response (fake, efficiency, and bin migration)** corrected using 2d D'Agostini unfolding
  - EEC weight and **θ (z)**
- **Acceptance and phase space (track and event selection)** corrections also applied

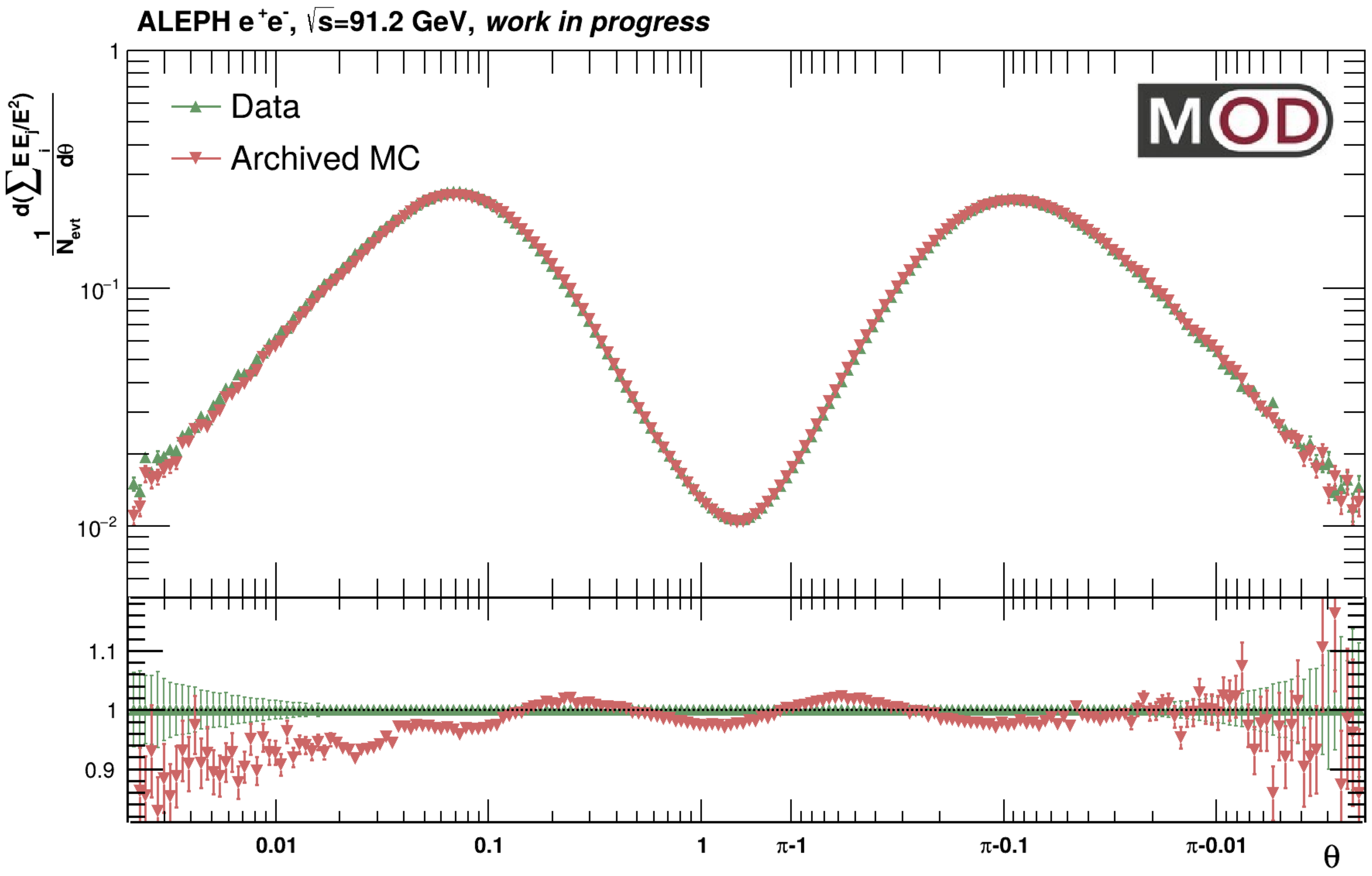
Event selection	
Acceptance	$7\pi/36 \leq \theta_{\text{sphericity}} \leq 29\pi/36$
Hadronic events	at least five good tracks
	total reconstructed charged-particle energy ≥ 15 GeV
Non-calibration runs	$E_{\text{vis}} < 200$ GeV
Charged particles	
Acceptance	$\lvert\cos\theta\rvert < 0.94$
High quality tracks	$p_{\text{T}} \geq 0.2$ GeV
	at least 4 TPC hits
Impact parameter	$d_0 < 2$ cm, $z_0 < 10$ cm

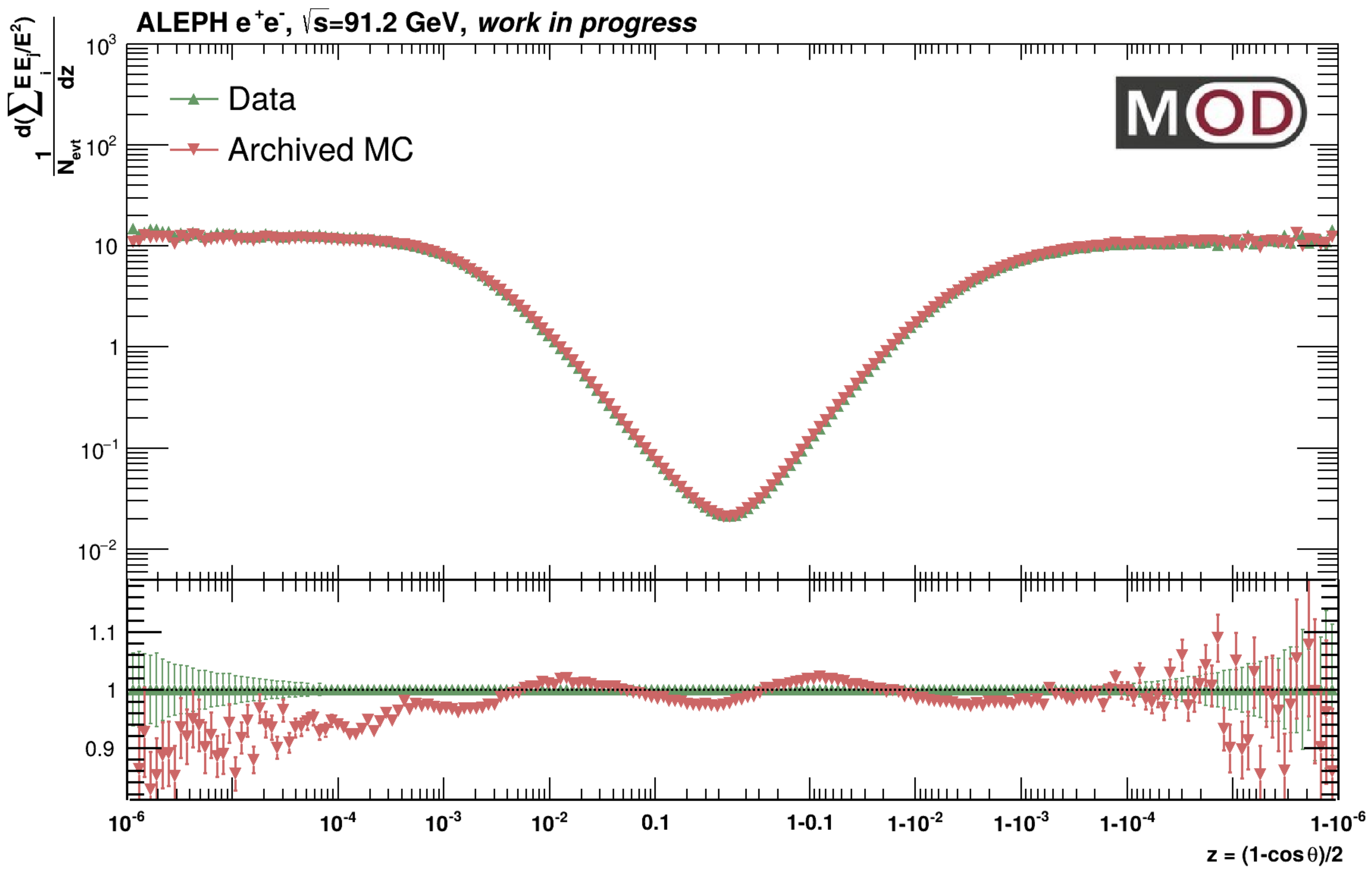


→ **Fake Removal** → **Migration Matrix Inversion** → **Track efficiency correction** → **Track and event selection correction**

Data vs MC Comparisons

To begin with: we have good data vs MC comparison at detector-level with archived ALEPH MC





Unfolding

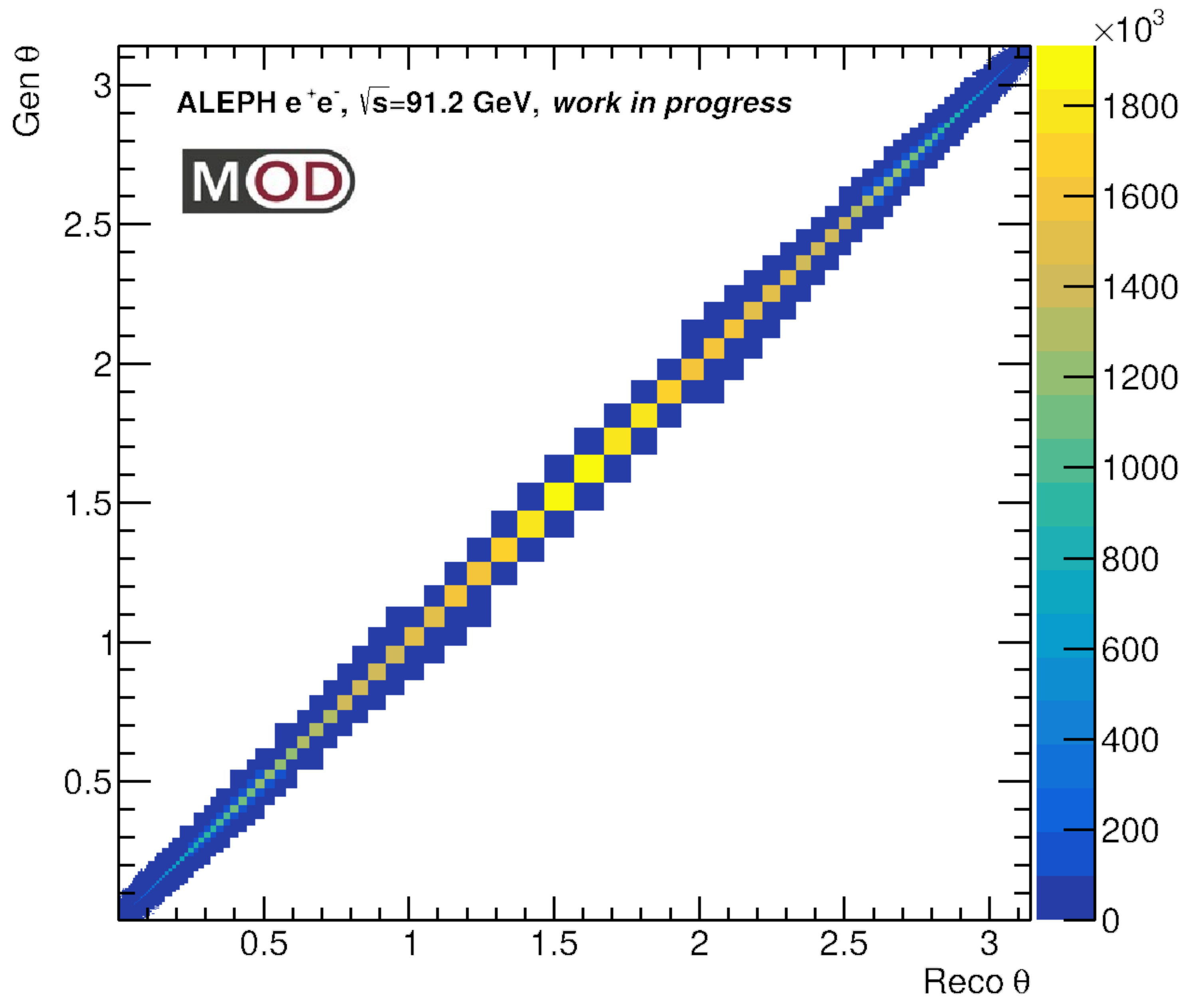
$y_{det.} = \epsilon \cdot U \cdot y_{gen.} + b$

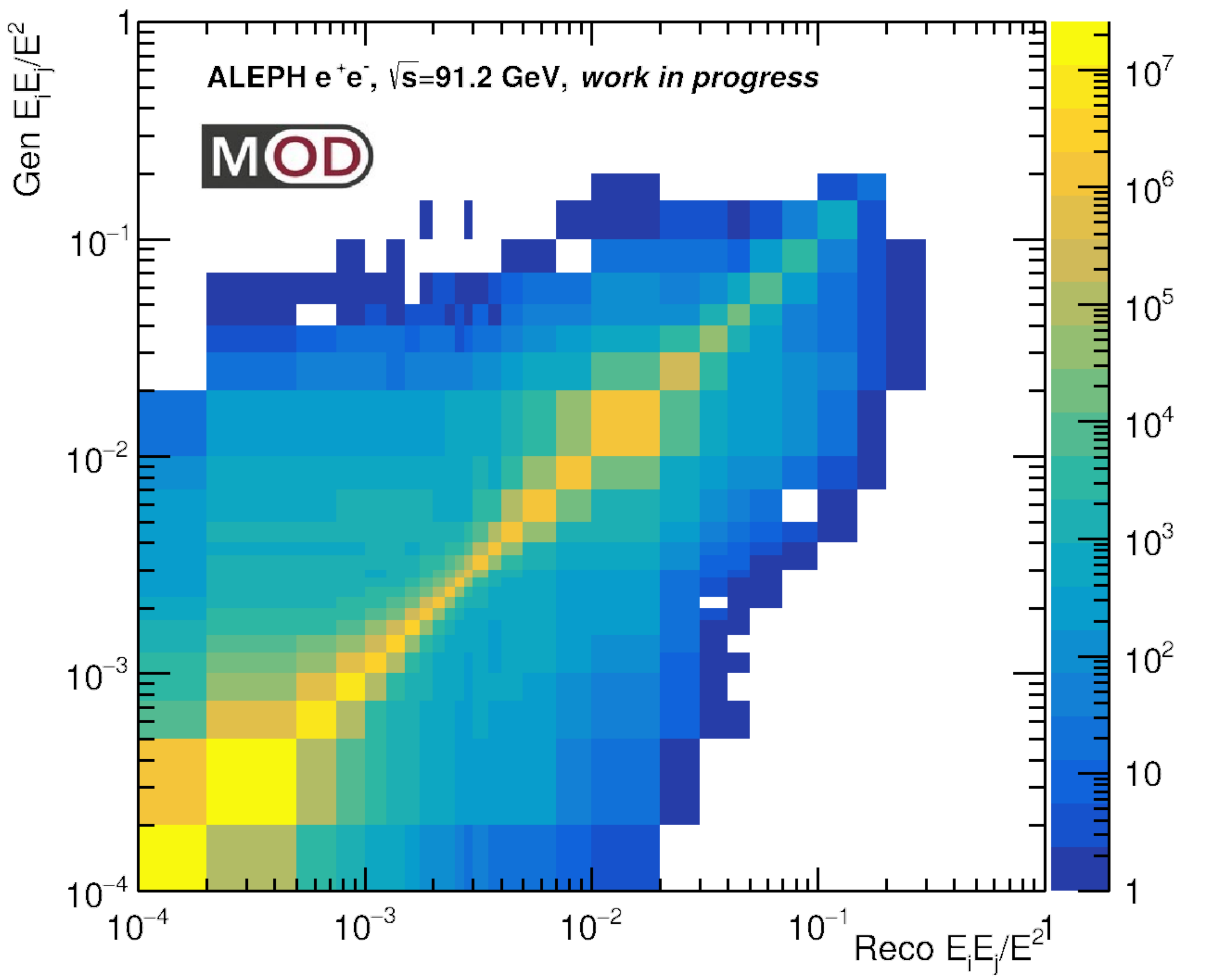
- ε → efficiency
- U → migration matrix
- b → fake
- **EEC weight** and **θ (z)**
- Estimated with MC samples with detailed detector simulation

$y_{gen.} = \epsilon^{-1} \cdot U^{-1} \cdot (y_{det.} - b)$

- Matrix inversion for matrices with singularities need regularization
  - D'Agostini iterative method with early stopping

(200 x 28) x (200 x 28) migration matrix



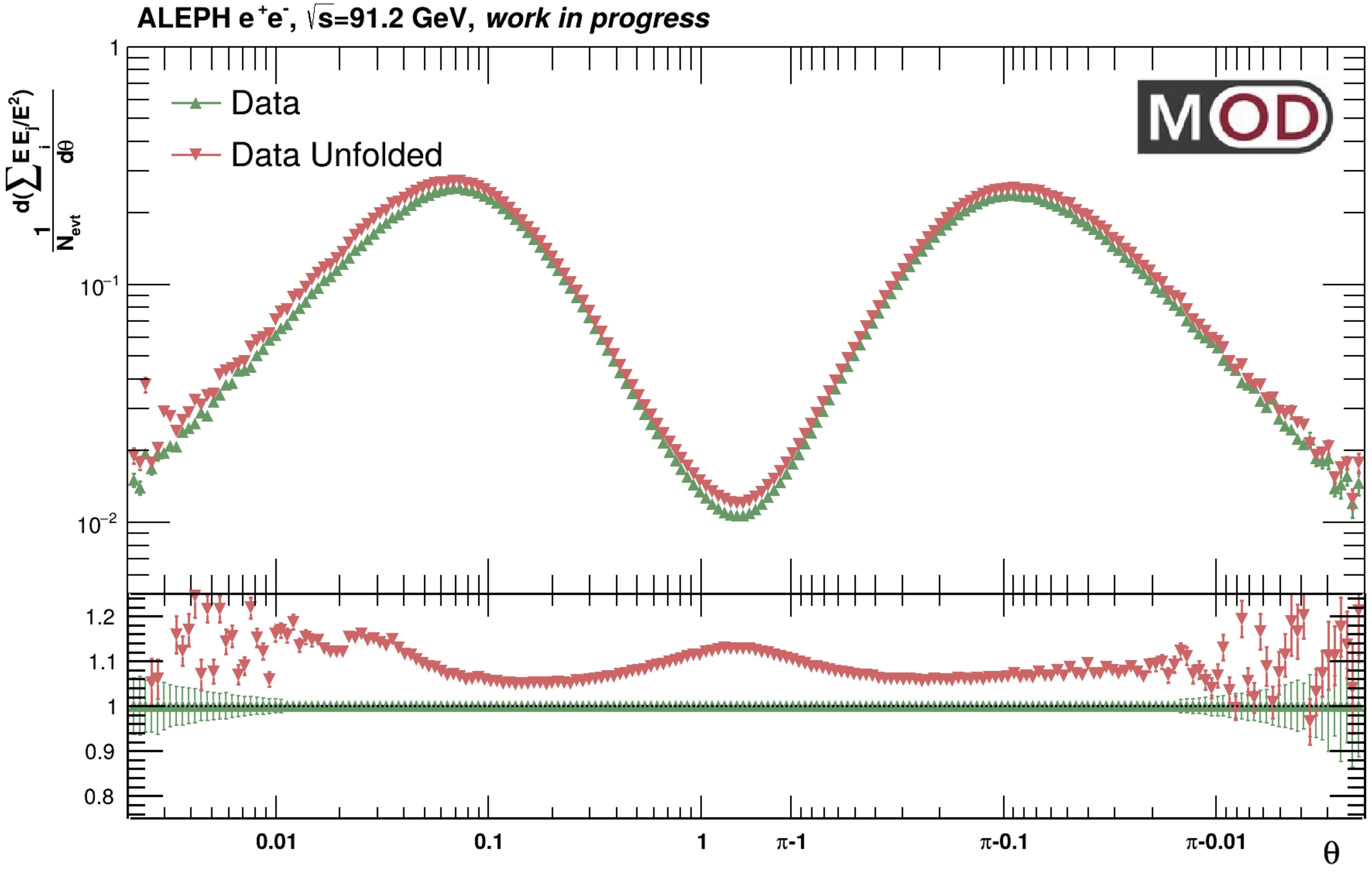


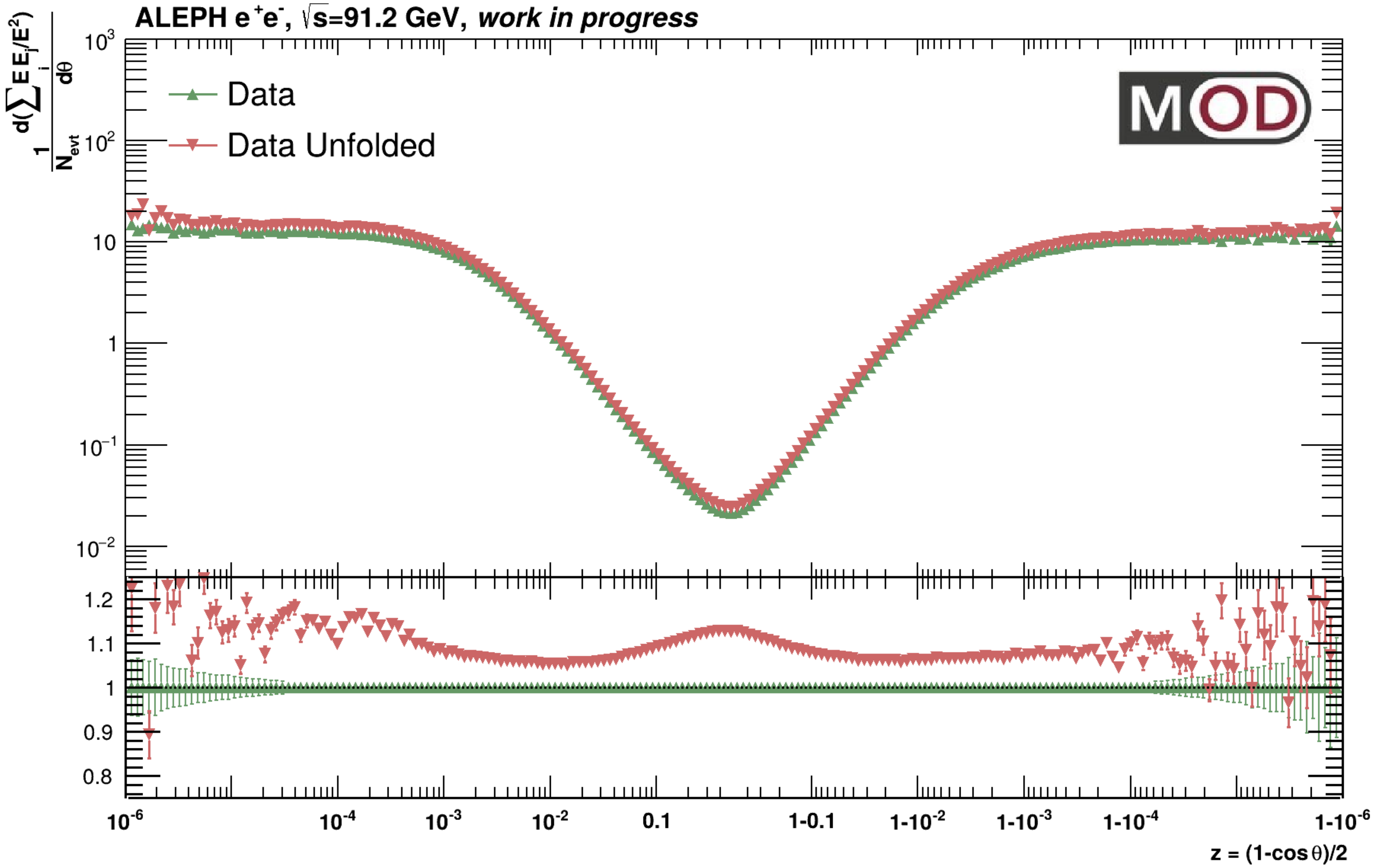
Small migration effect thanks to the fact that we are only using tracks

Unfolding

- Main effect from degraded **tracking reconstruction** for low p_T (**soft/forward**) and **merging** tracks

Size of Correction



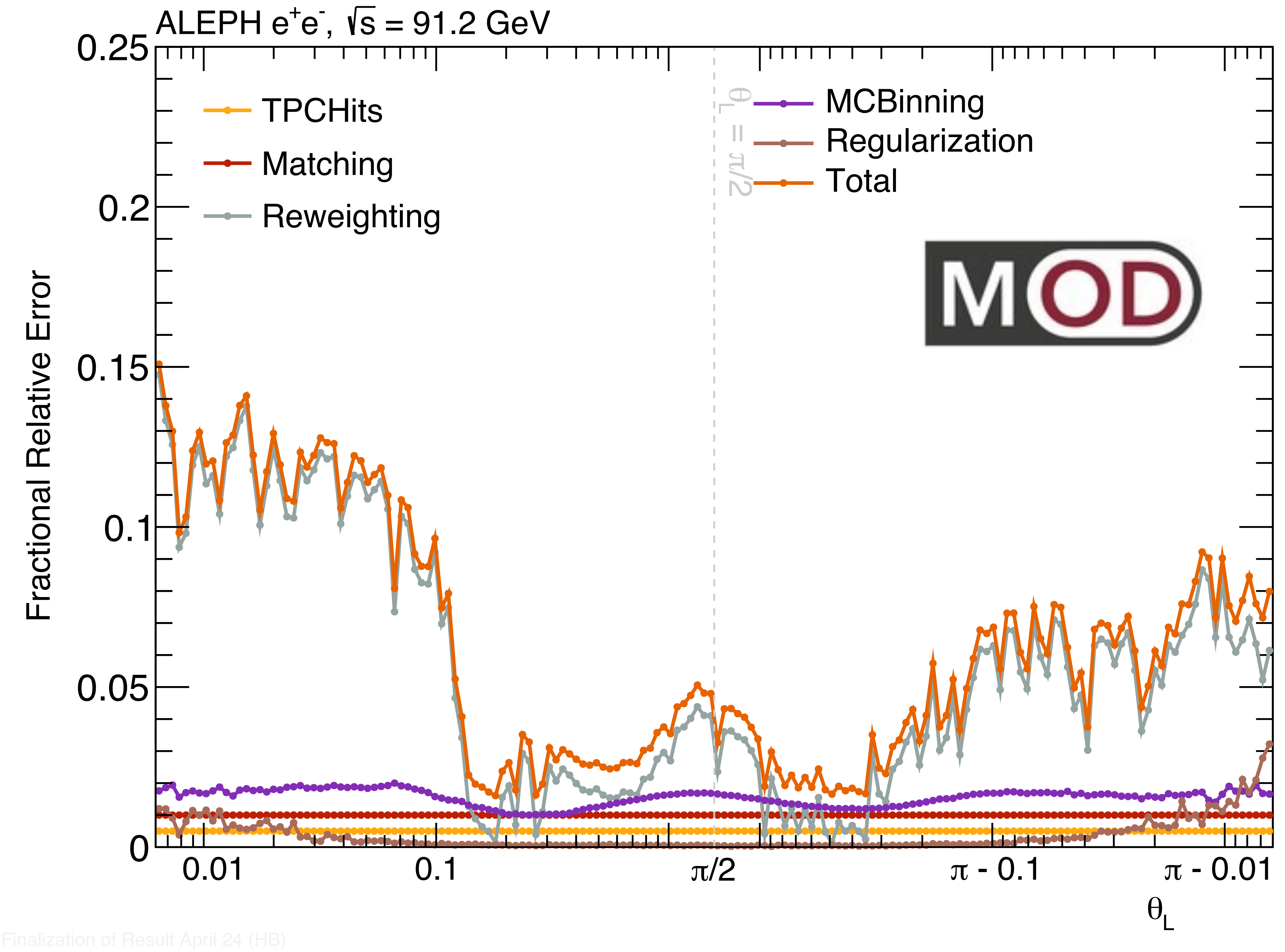


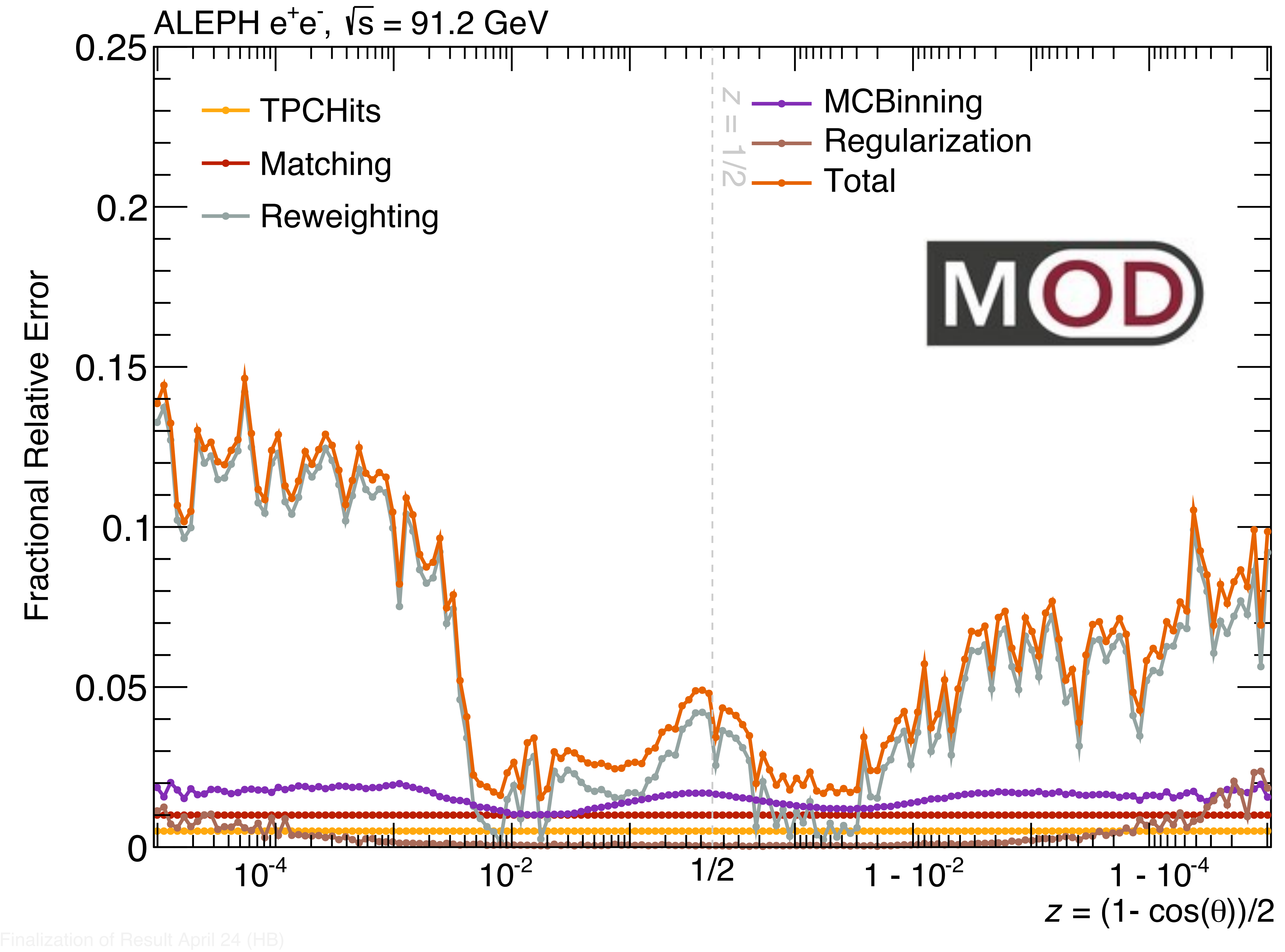
- 10%-20% correction depending on the angle mainly from degraded tracking efficiency for low p_T (**soft/forward**) and **merging** tracks
- Very small angle affected by numerical precision

Size of Correction

- Correct back to full phase space
- Effect dominated by **low p_T (Soft/forward)** tracks that is beyond the acceptance of the detector

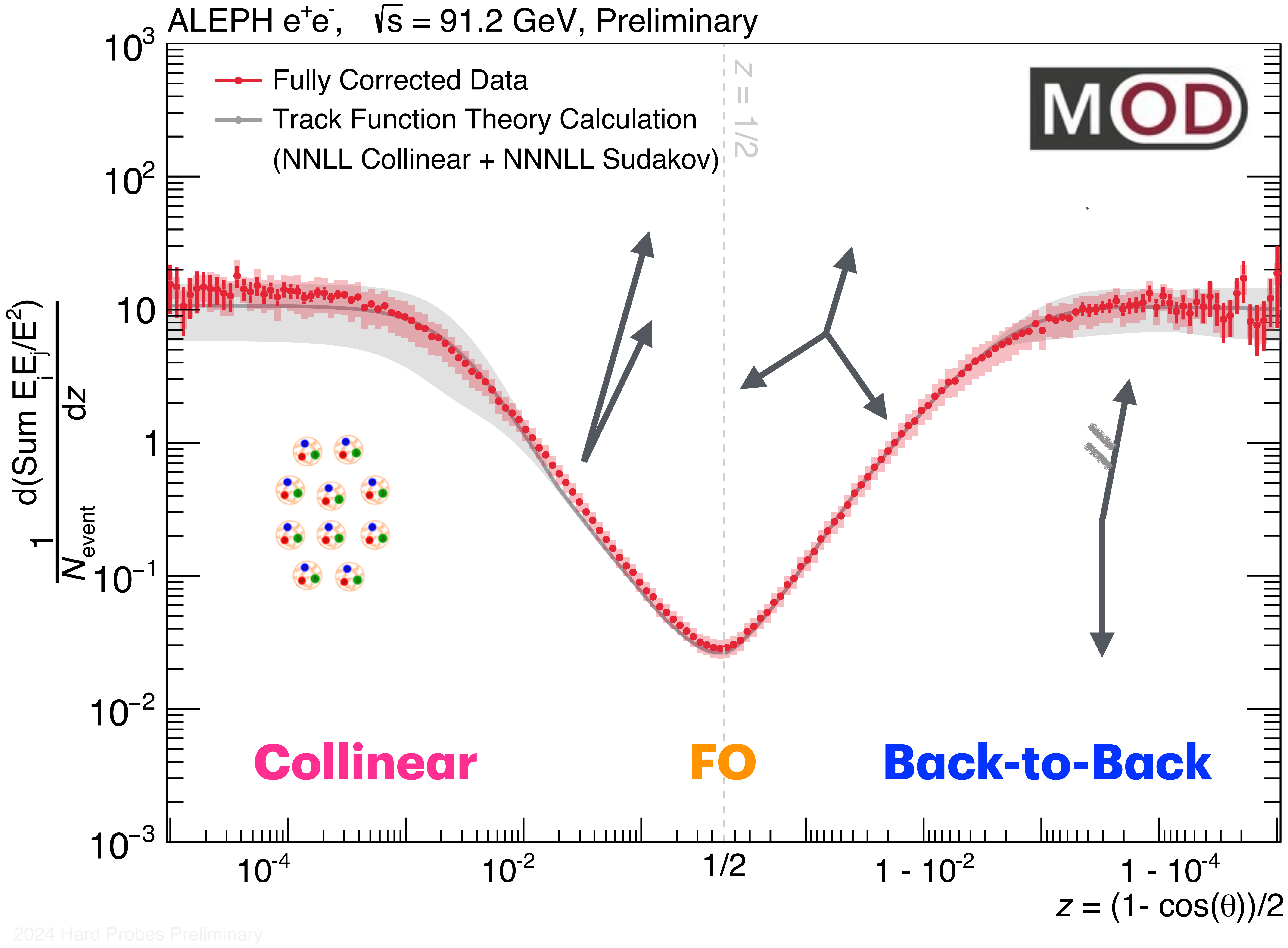
Systematic Uncertainties





- Main source of systematic uncertainty comes from the **model dependence** of the unfolding procedure
  - Estimated by **reweighting** the archived MC to match data and re-do the unfolding

Comparison with Analytical Prediction



Theory input: Max Jaarsma, Yibei Li, Ian Moult, and Huaxing Zhu

More info on slides from Yibei and Max

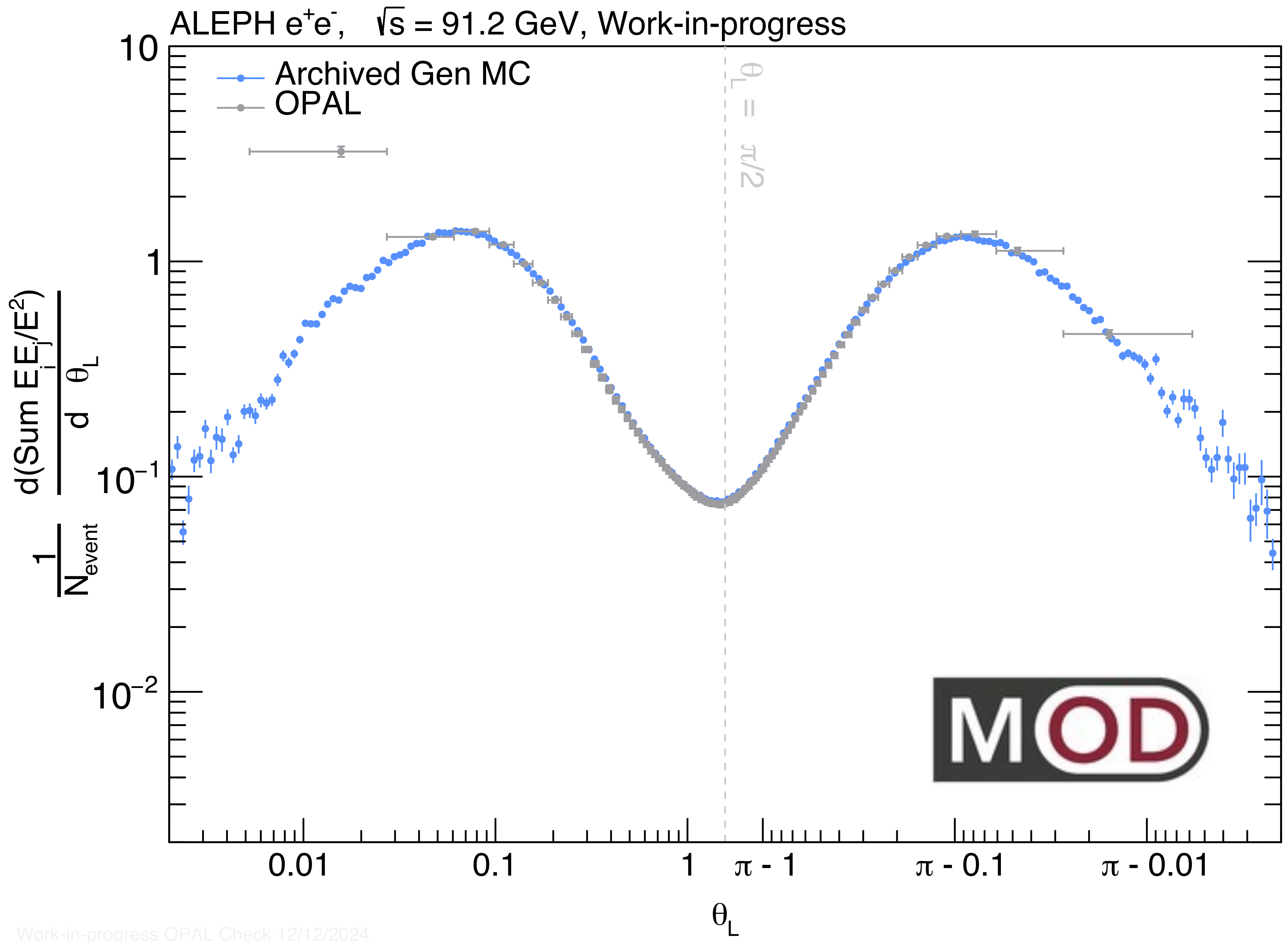
FO:
- **NNLO pQCD**

Collinear:
- **NNLL resummation**

Back-to-back:
- **NNNLL resummation**
- **Colins-Soper kernel from lattice QCD**
- **NP Ω parameter extracted from thrust**

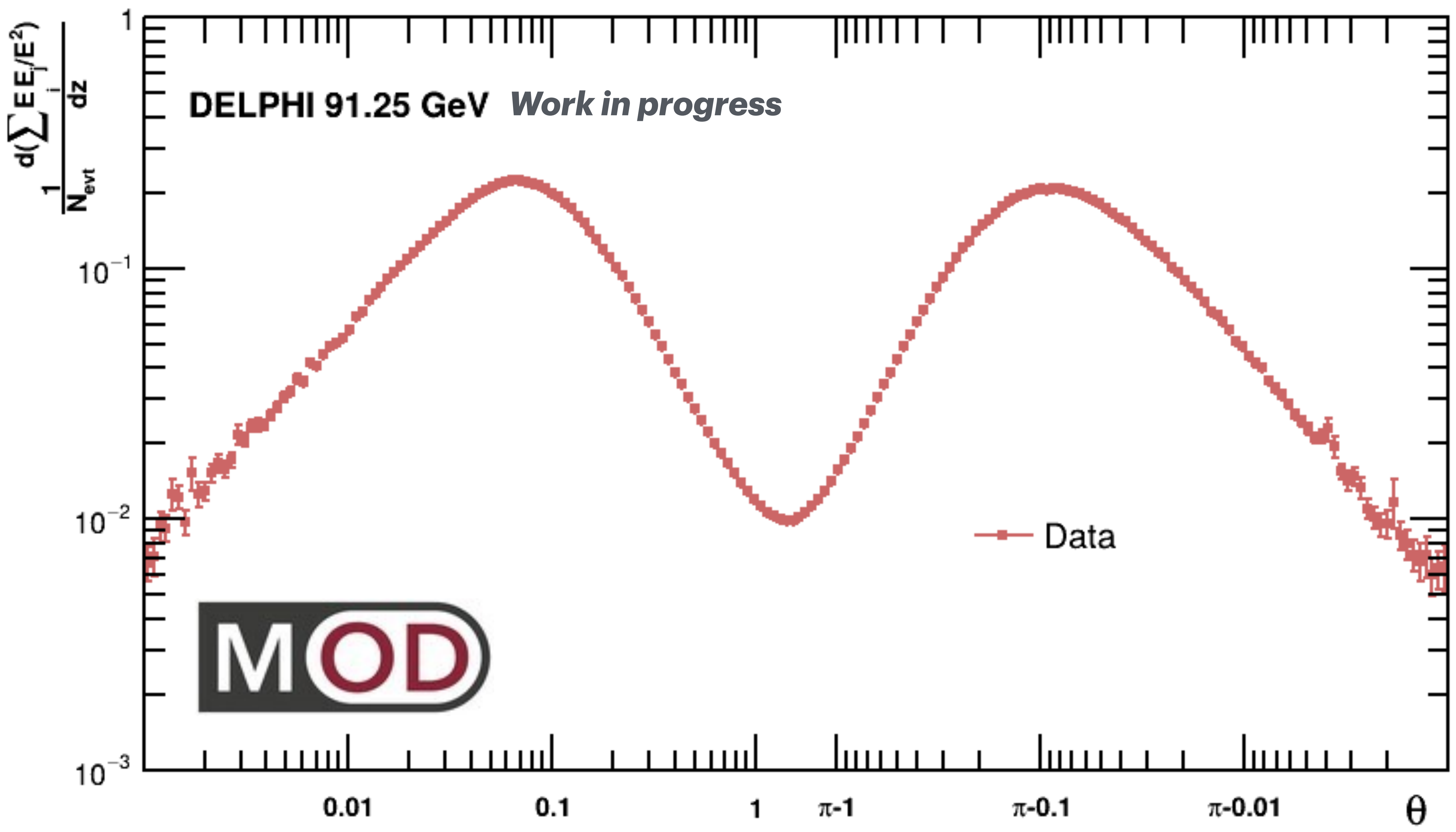
Conclusion

- High **resolution** and high **precision** measurement of EEC performed with archived ALEPH data at 91 GeV
- Measured distribution compared to analytic predictions to test QCD
- Paper publication including the unfolded data



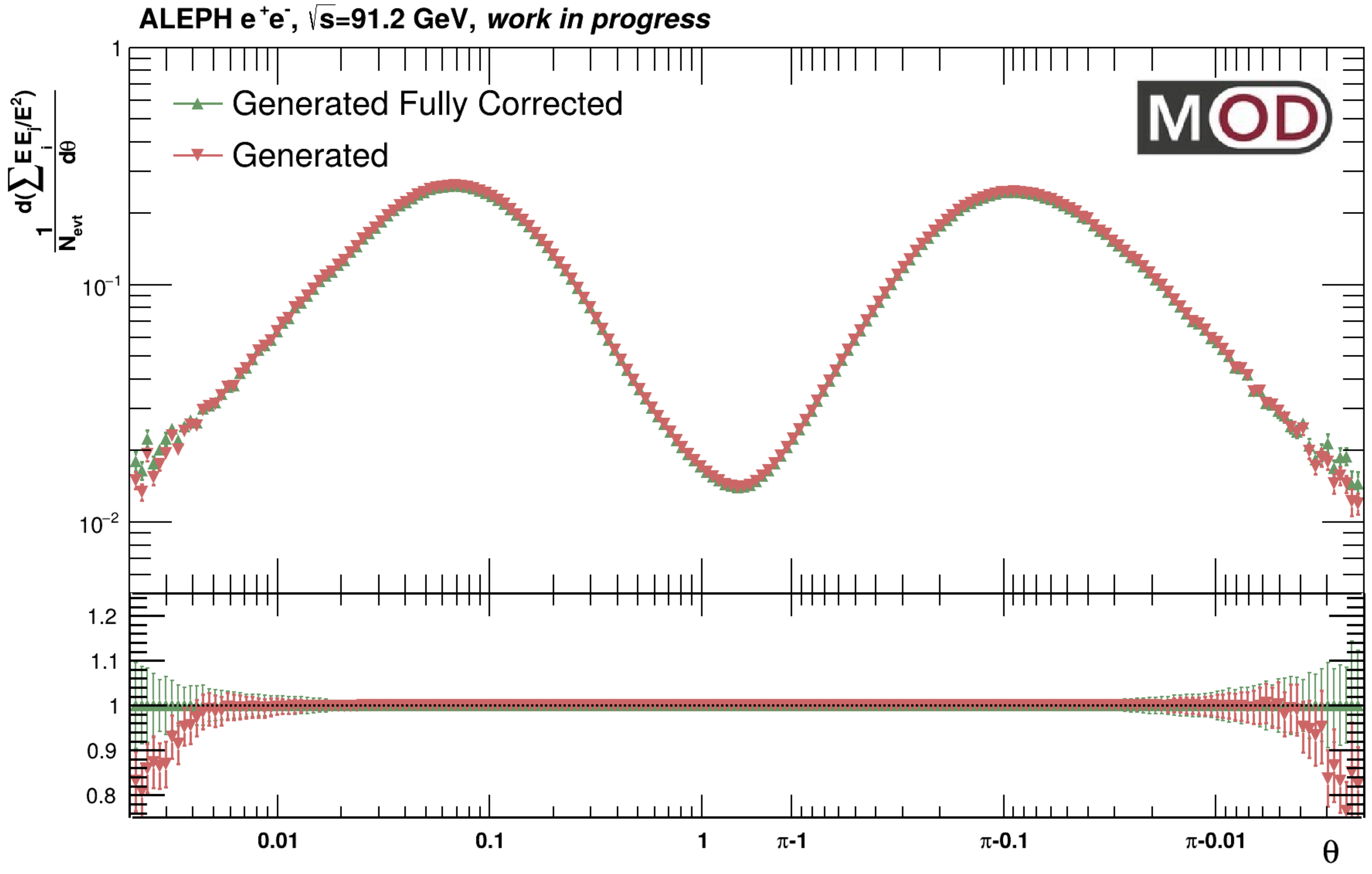
Further Perspectives

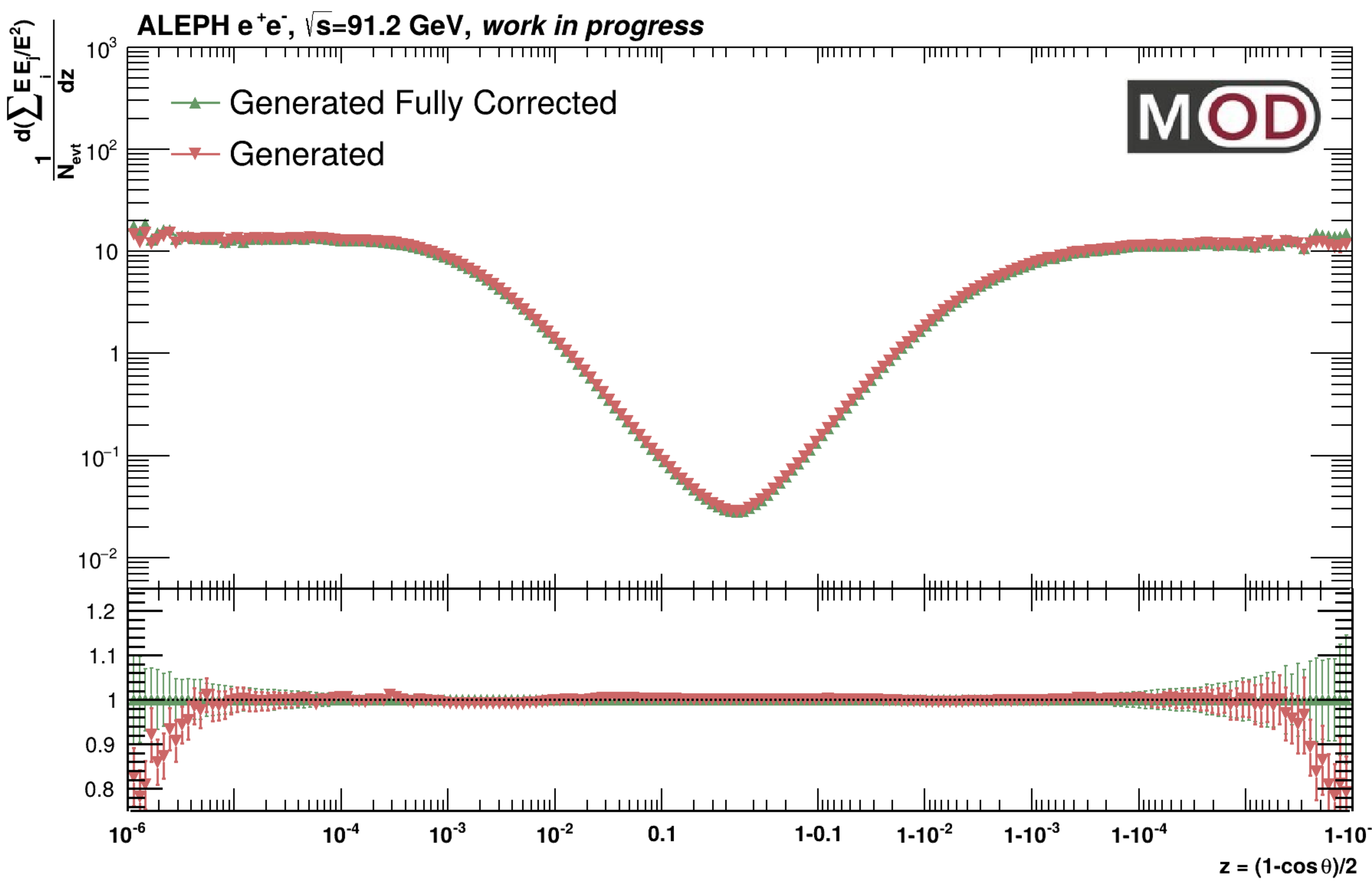
- EEC: **charge dependence, azimuthal dependence, energy dependence**, etc.
- E3C: **gluon spin correlation, α_s**
- DELPHI published their entire dataset, simulation, software for open access (August 2024)
  - Analysis of **2 particle correlation** on-going
  - Possible for b-tagging?



Backup

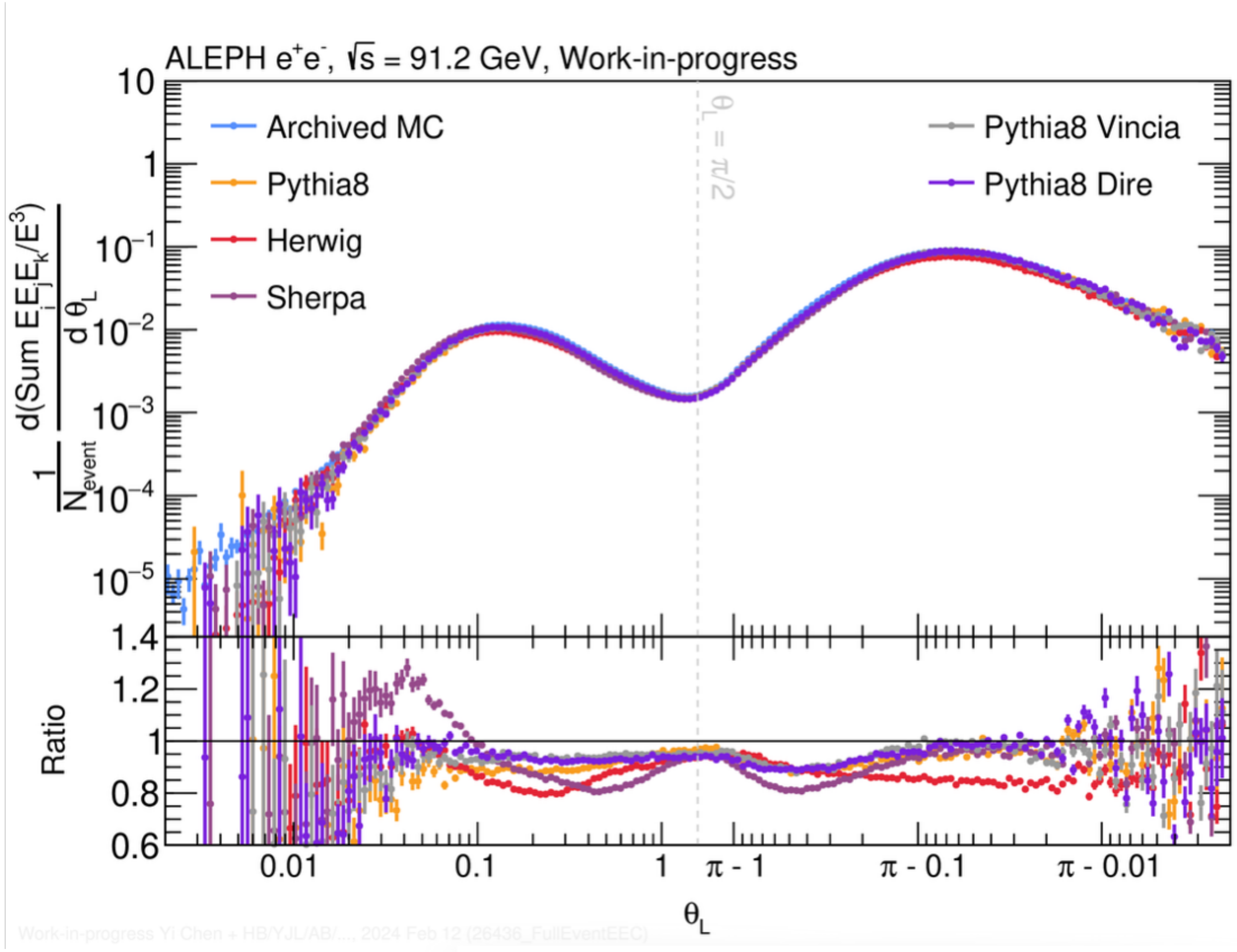
Closure

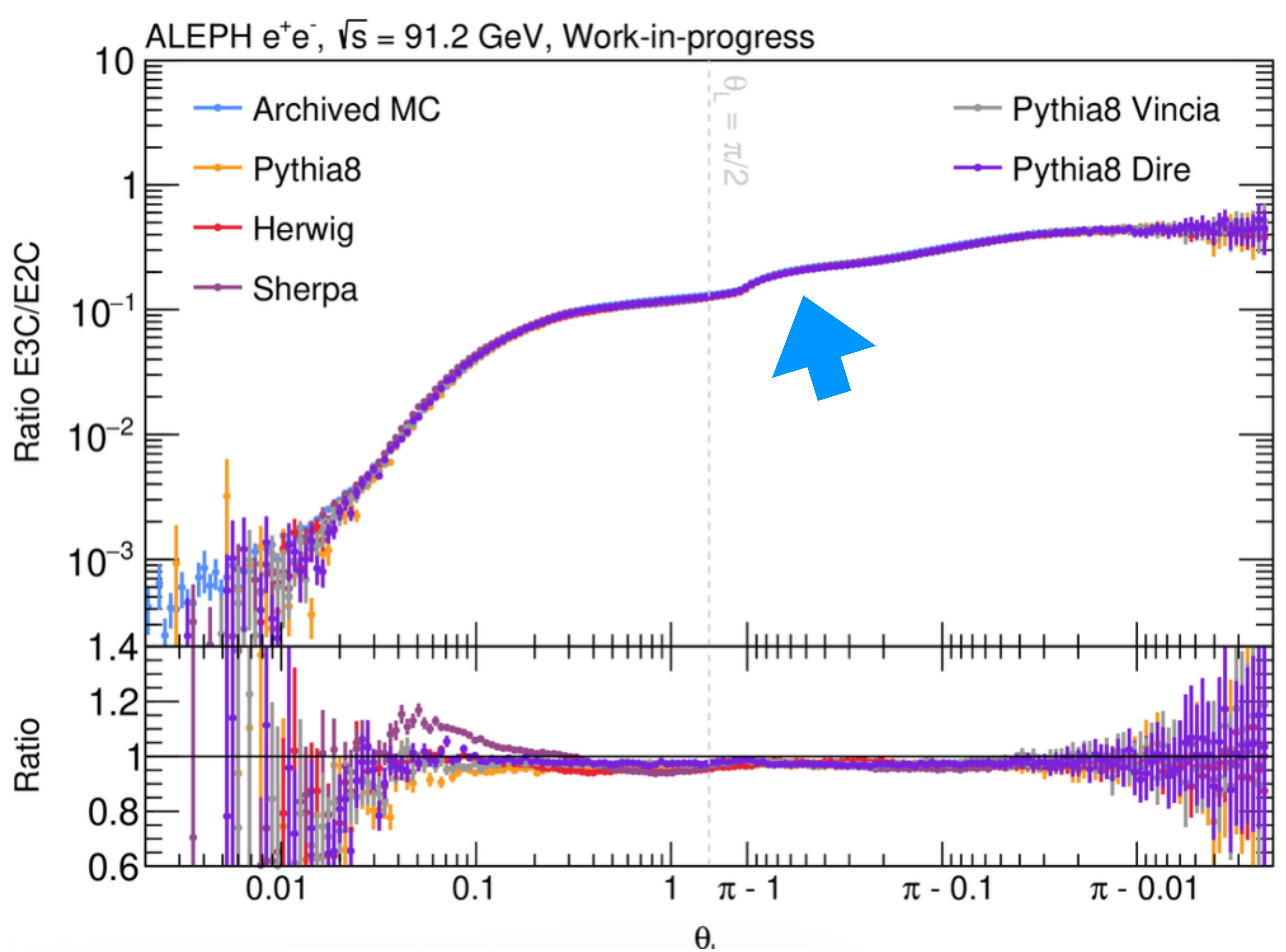




Measurement in very small angle limited by numerical precision

E3C





Non-trivial E3C shape and E3C/E2C ratio reveals the **3-jet** structure