From short to long-distance QCD with archived ALEPH e^+e^- at LEP

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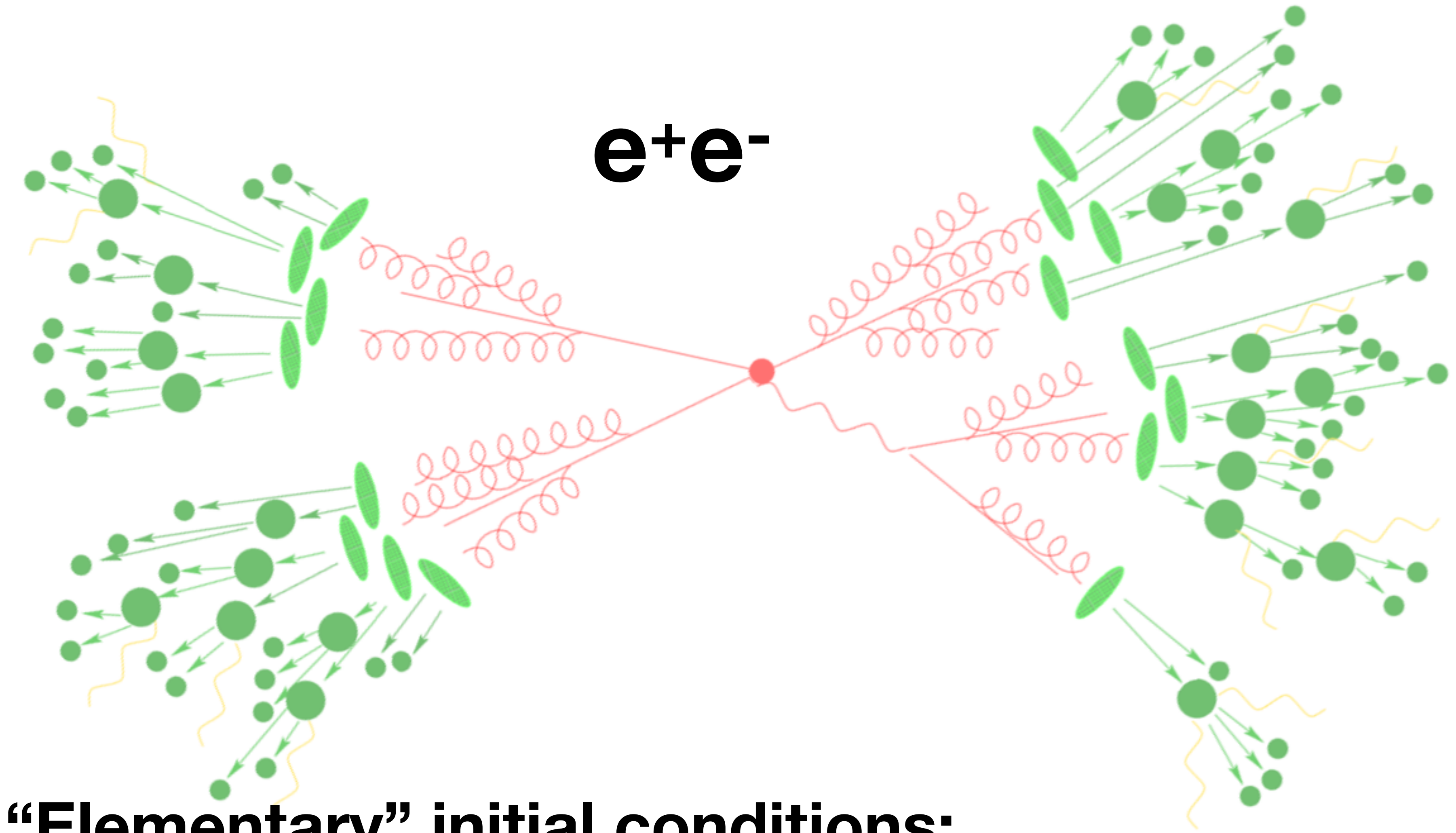
In collaboration with Yen-Jie Lee (MIT), Yu-Chen Chen (MIT) ,Yi Chen (Vanderbilt U.), Anthony Badea (U. Chicago), Austin Baty (UIC) , Marcello Maggi (INFN Bari), Christopher McGinn (MIT), Michael Peters (MIT) , Tzu-An Sheng (MIT), Jesse Thaler (MIT)

e^+e^- collisions as a QCD laboratory

→ **e^+e^- optimal conditions for "in-vacuum" QCD measurements**



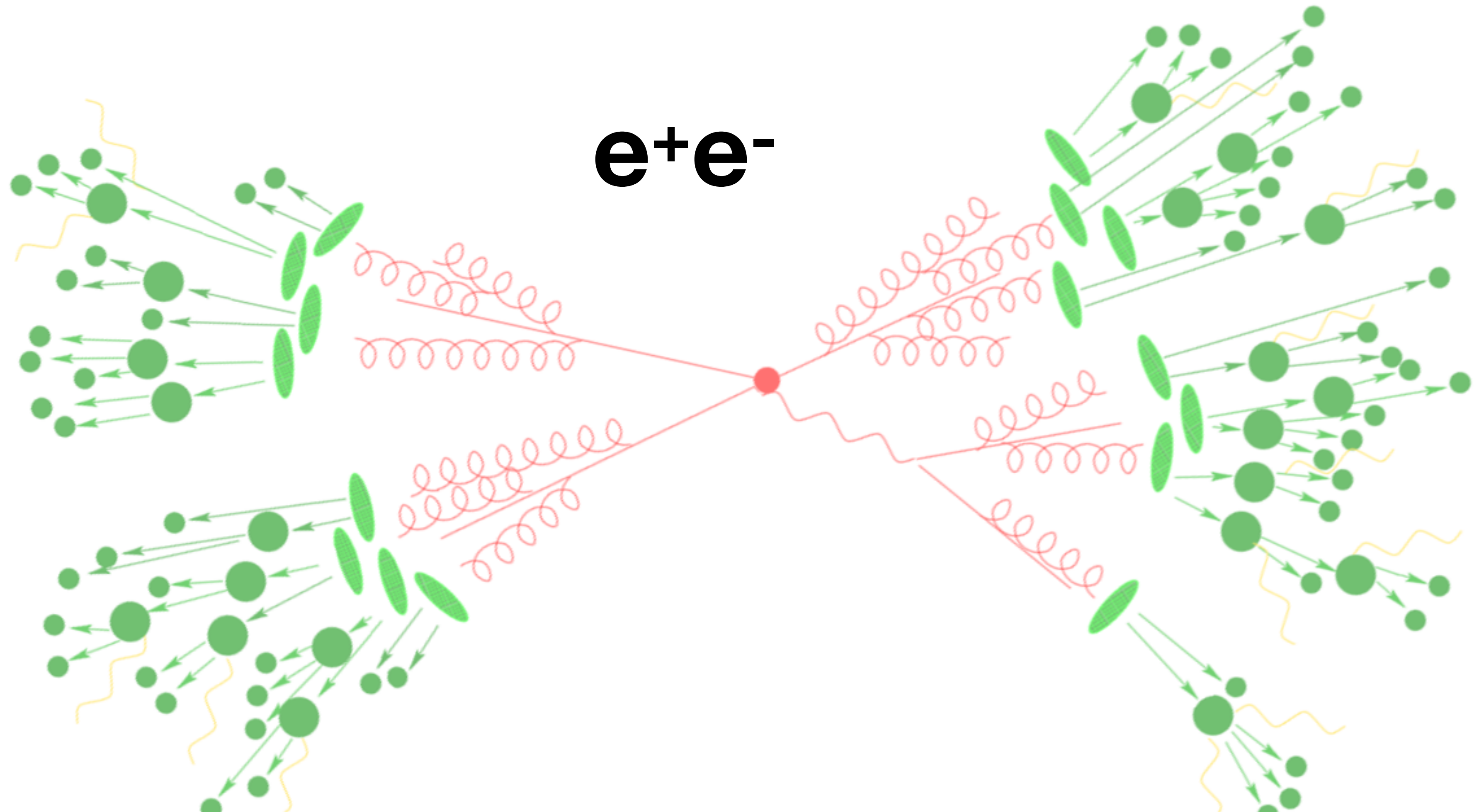
"Elementary" initial conditions:
- e^+e^- as point-like colorless colliding systems
- no gluonic initial state radiation
- no dependence on PDFs

Limited background sources:
- negligible contamination from soft QCD underlying
- no pileup

"In-vacuum" final state evolution

e^+e^- as an "elementary" reference for hadronic collisions

→ **e^+e^- optimal conditions for "in-vacuum" QCD measurements**



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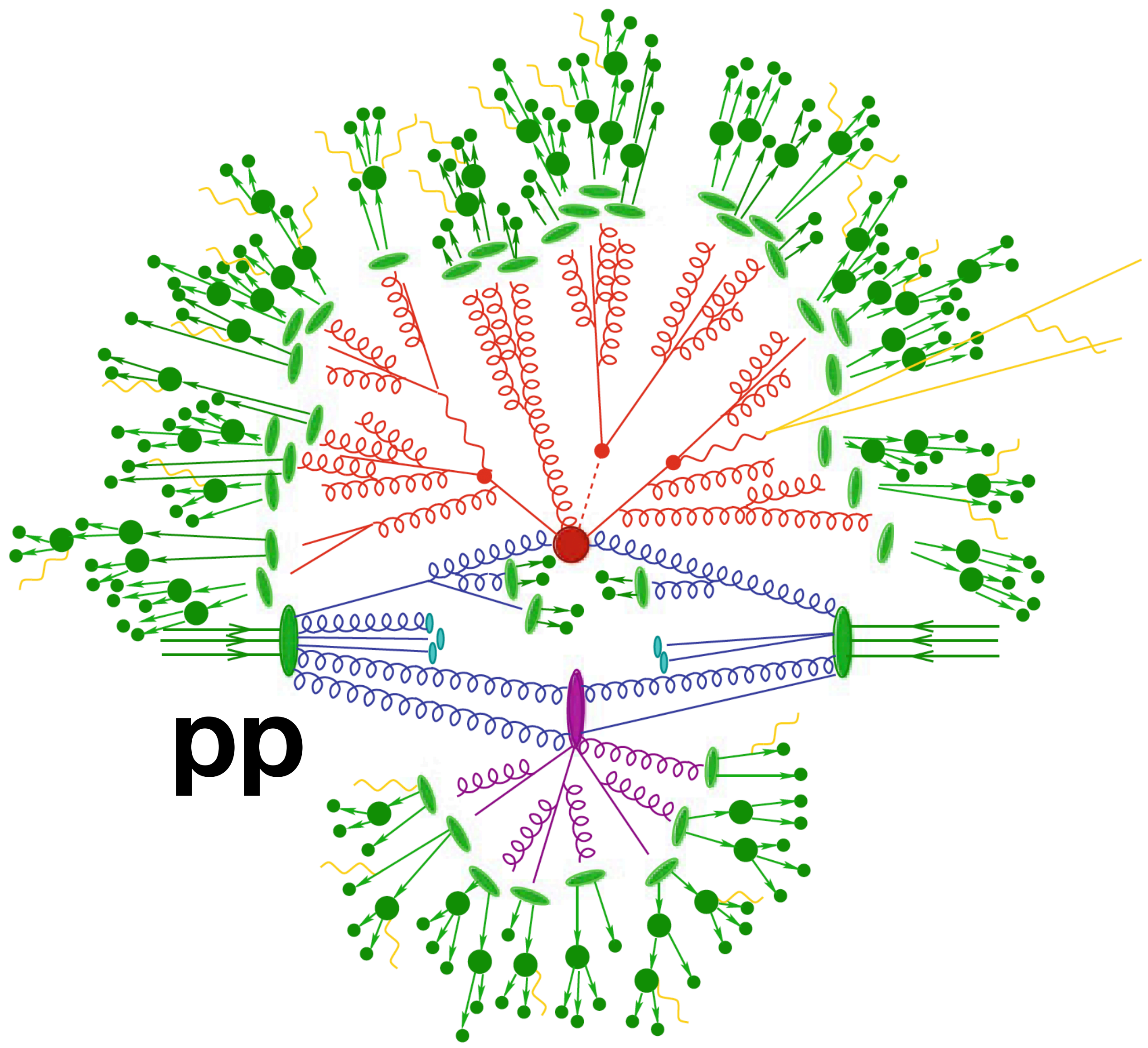
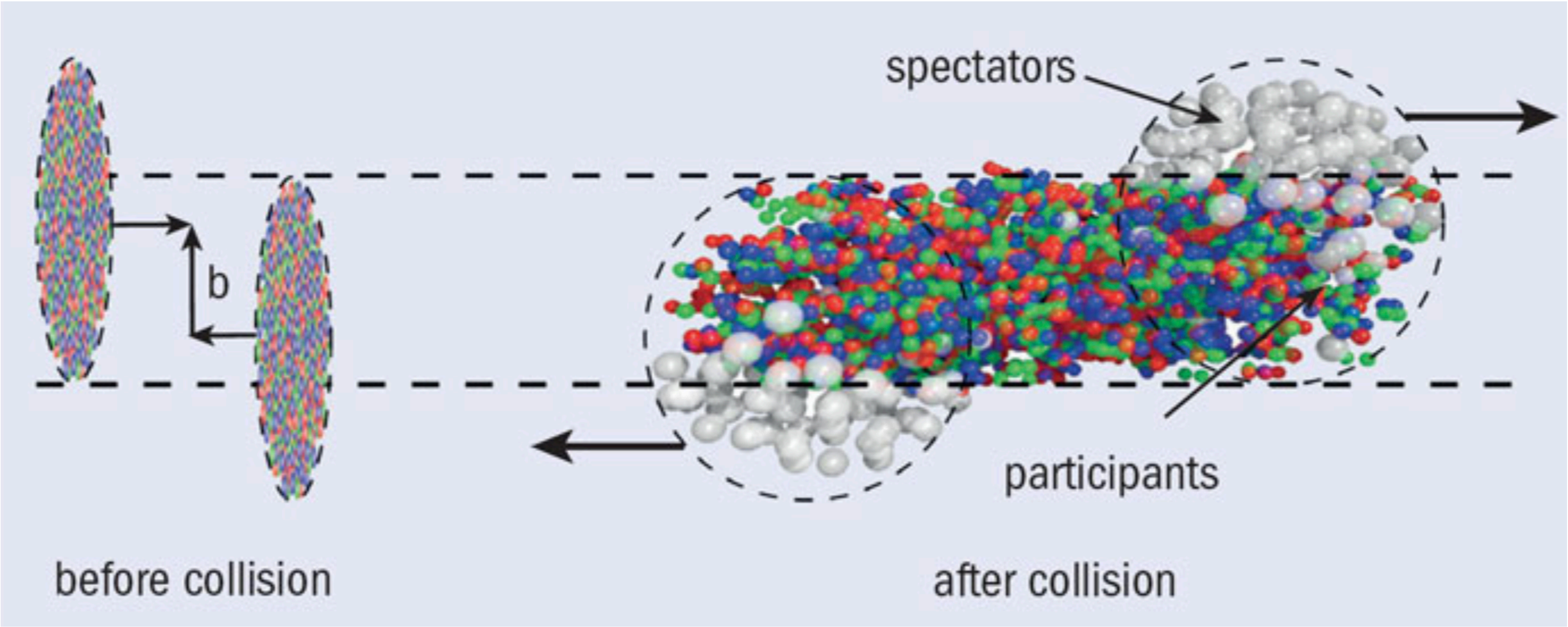
"In-vacuum" final state evolution

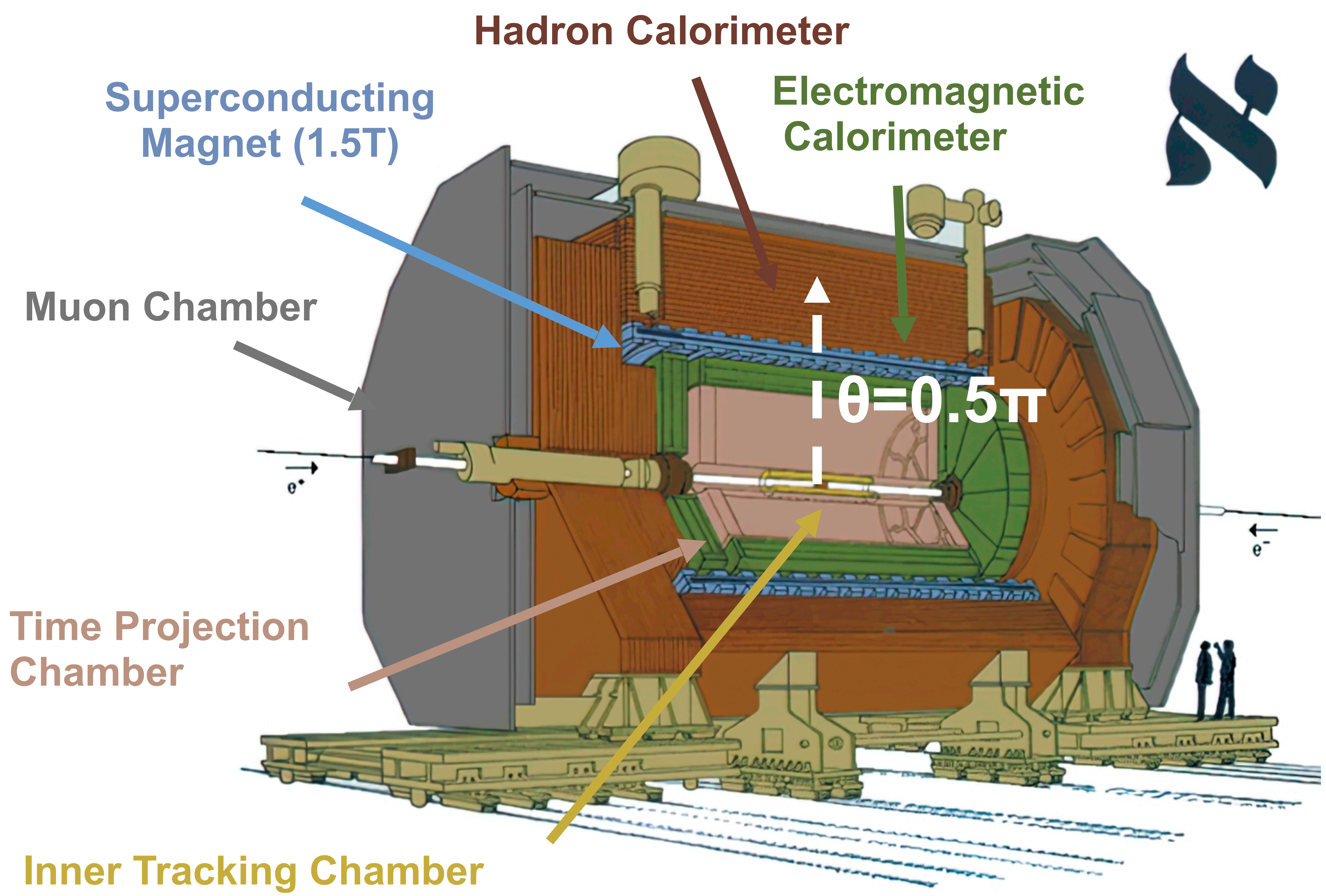


Best "in-vacuum" reference for pp, p-nucleus (pA) , and nucleus-nucleus (AA)
- strong color fields
- large underlying event background
- dependence on PDFs and nPDFs
- initial-state anisotropy
- final-state interactions
- …

nucleus-nucleus



Revisiting QCD phenomenology with ALEPH e+e- open data



ALEPH Collaboration, CERN-EP-90-25

ALEPH data

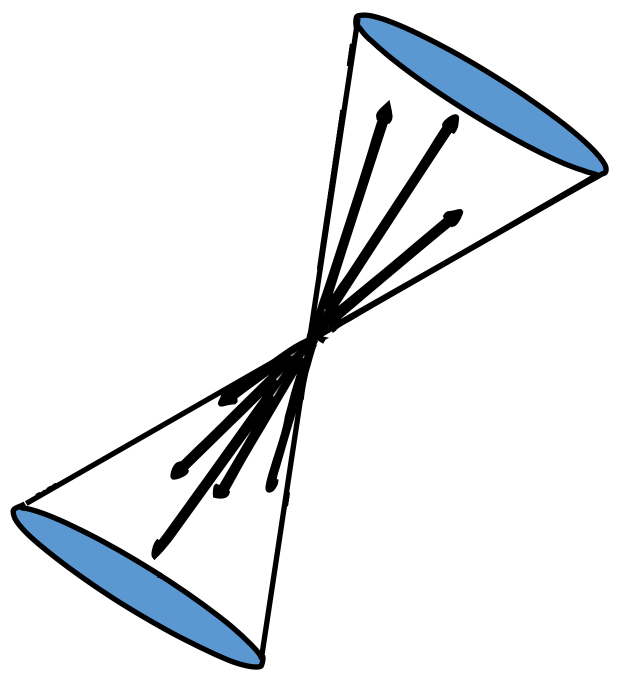
- Re-analyzed an MIT Open Data format
- Fully-simulated ALEPH archived Pythia6 MC *(for corrections and the comparison baseline)*

- LEP1 e^+e^- data at Z pole (91 GeV) taken between 1992-1995
- **LEP2 e^+e^- data above Z pole up 209 GeV**

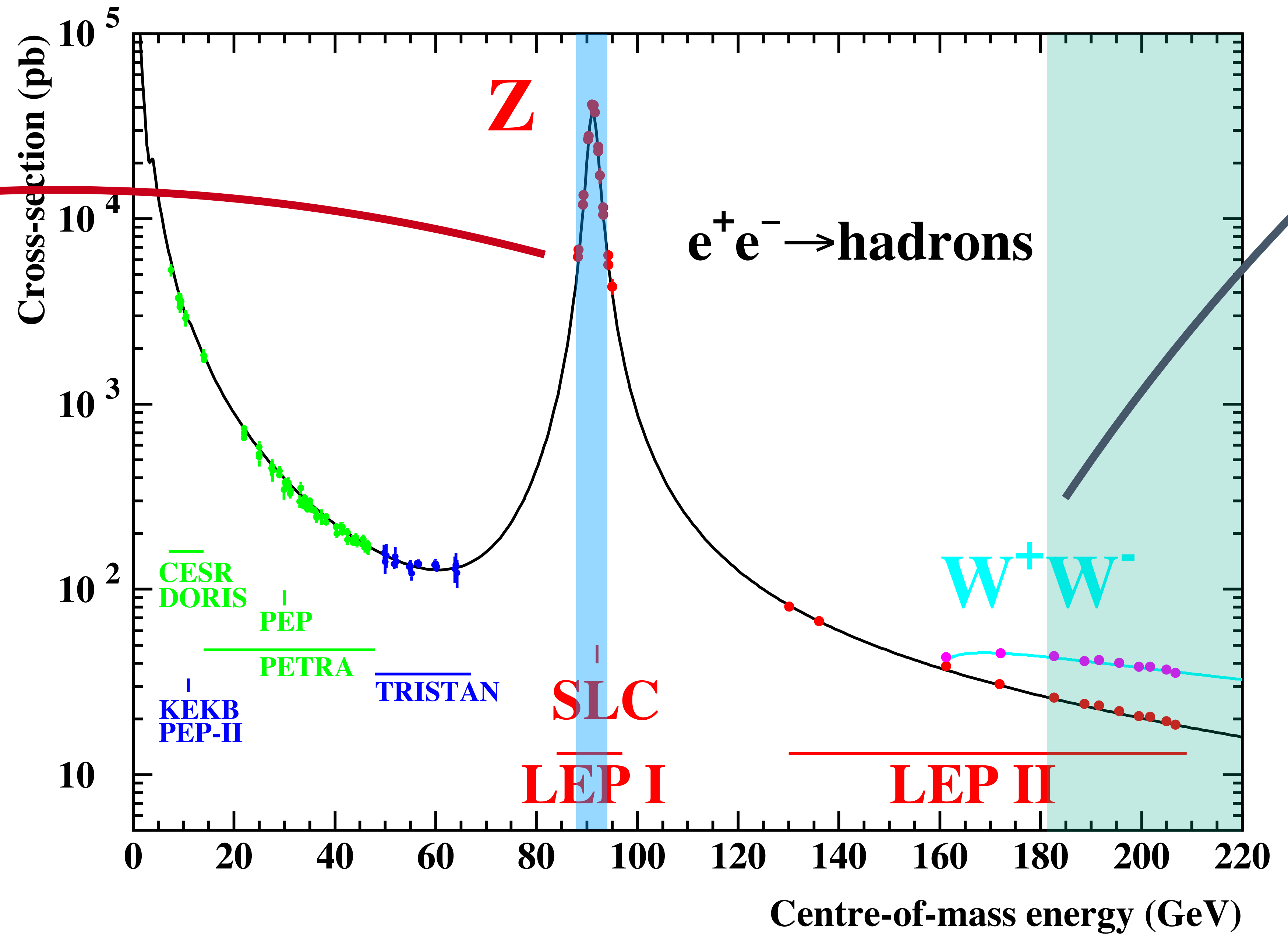
***Acknowledgement**: we would like to thank Roberto Tenchini and Guenther Dissertori from the ALEPH collaboration for the useful comments and suggestions on the use of ALEPH data*

LEP1 (1992–1995) & LEP2 (1996–2000) datasets

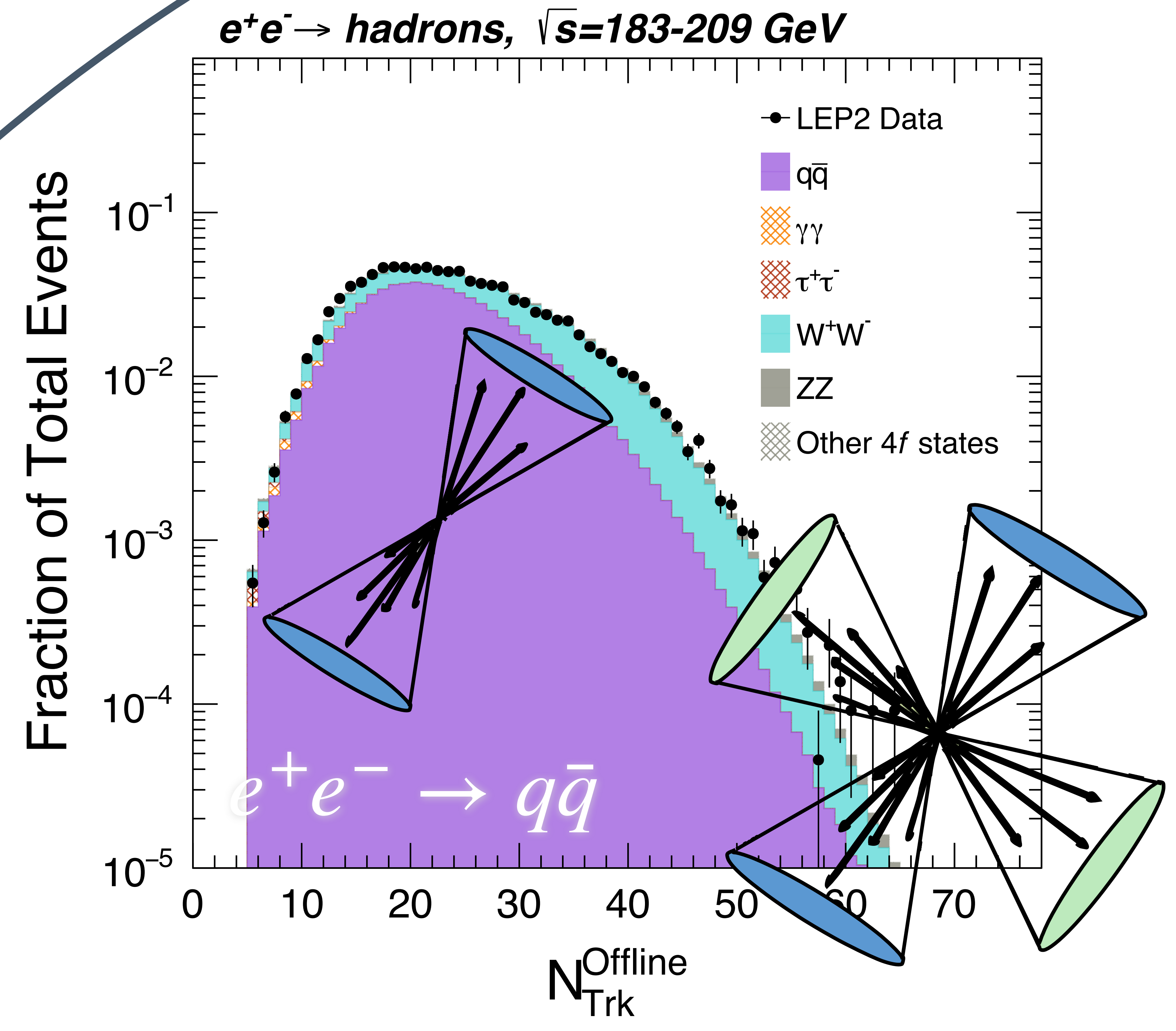
LEP 1 at Z pole (91 GeV):
hadronic data dominated by
$e^+e^- \to q\bar{q}$ events



$e^+e^- \to q\bar{q}$

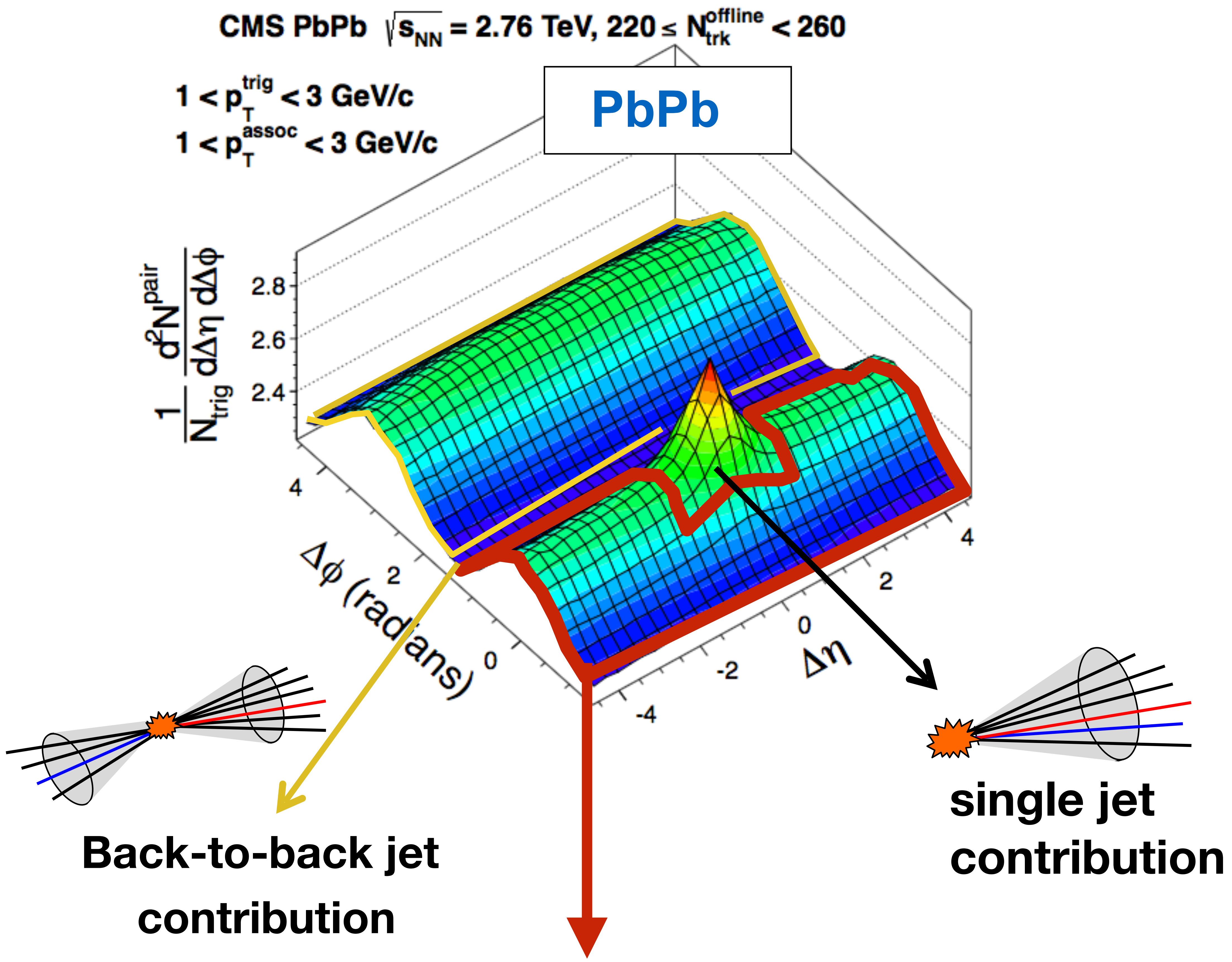


LEP 2 data above the WW threshold (183-209 GeV):



hadronic data at high-multiplicity
dominated by $e^+e^- \to W^+W^- \to 4f$

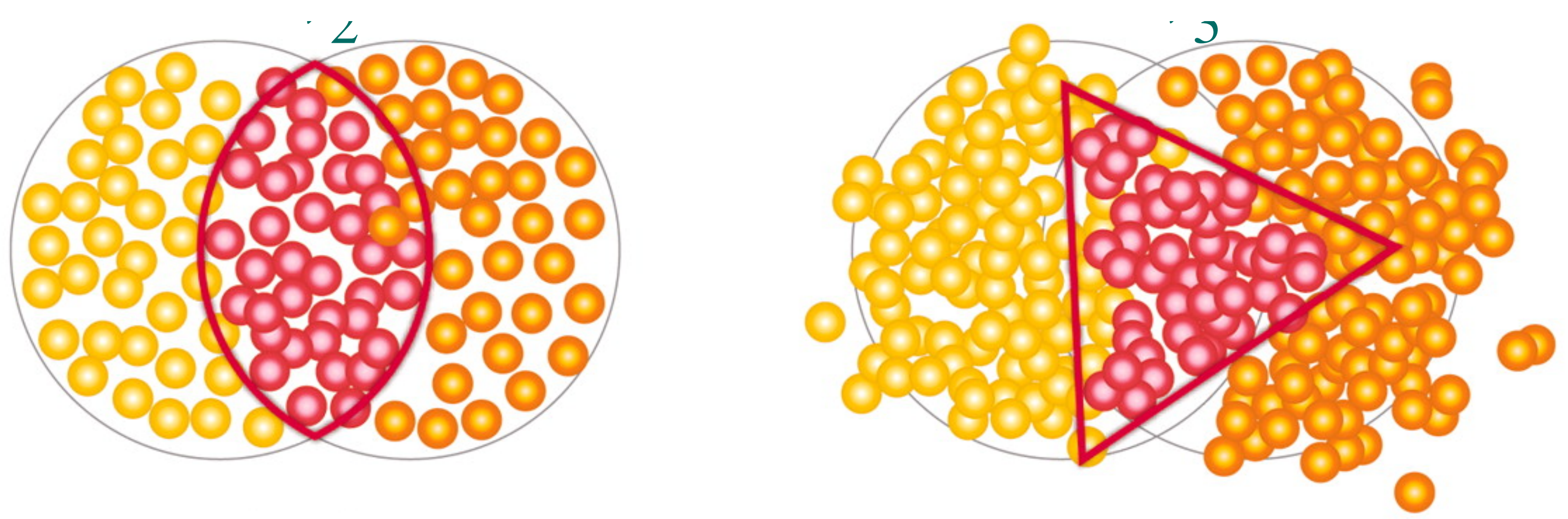
Ridge in AA: signature for a strongly-interacting medium



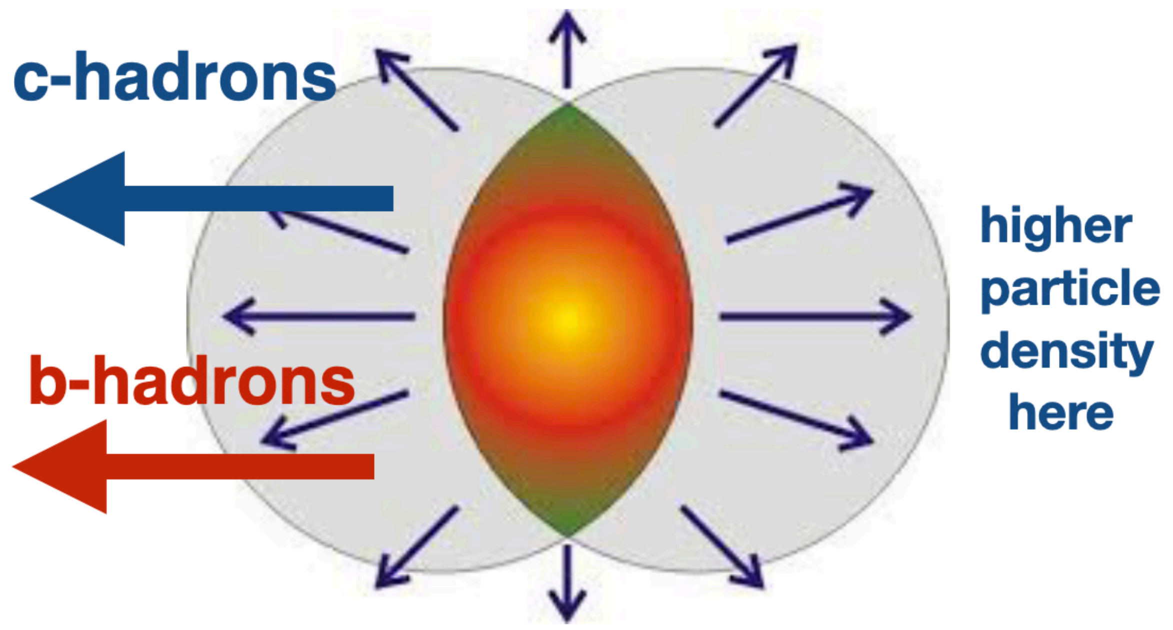
Near-side long-range (large Δη) correlation ("ridge"):
→ collective effect in a **strongly-interacting "liquid" medium**

"Ridge" interpretation for nucleus-nucleus collisions

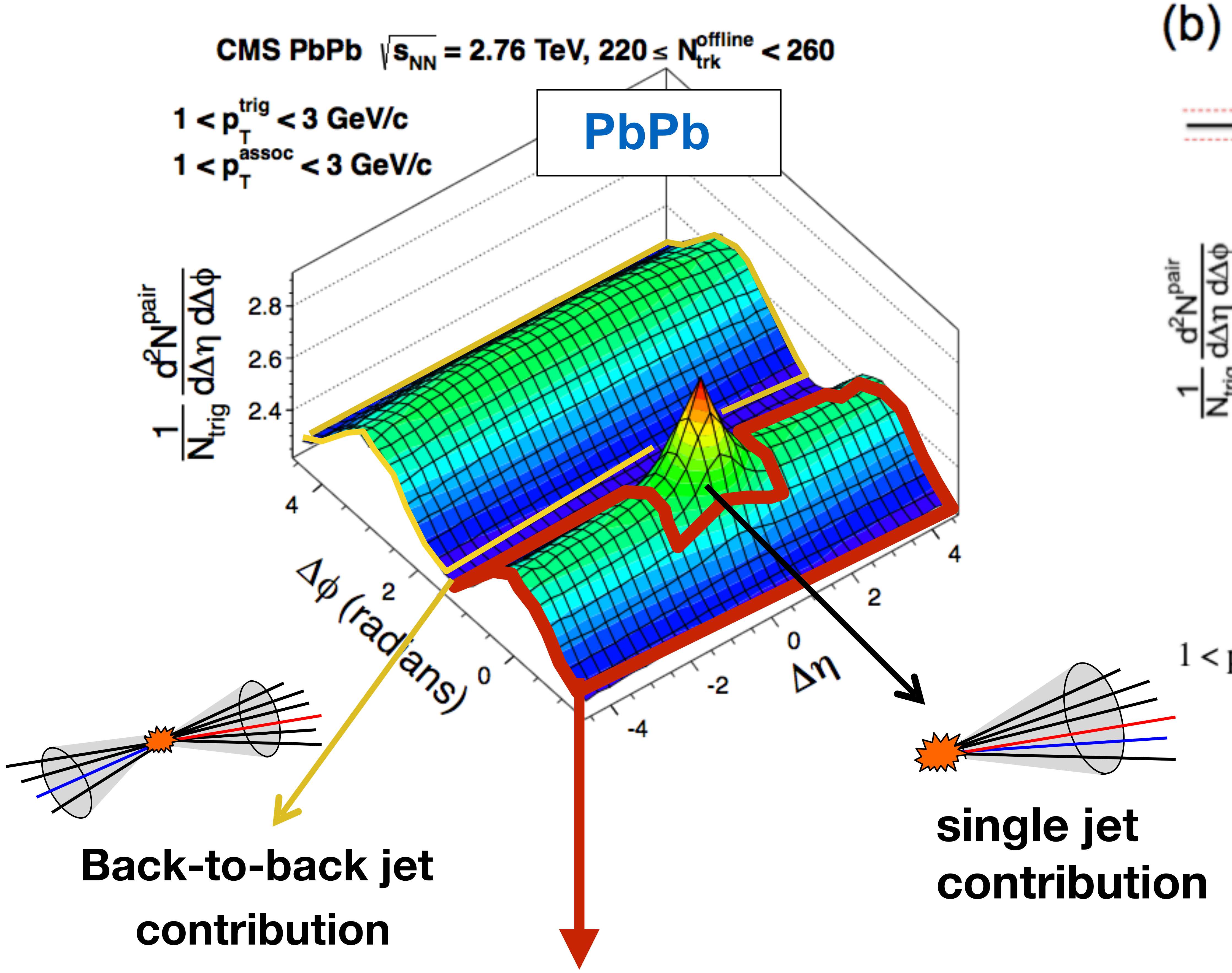
Initial-state anisotropy in non-central PbPb collisions

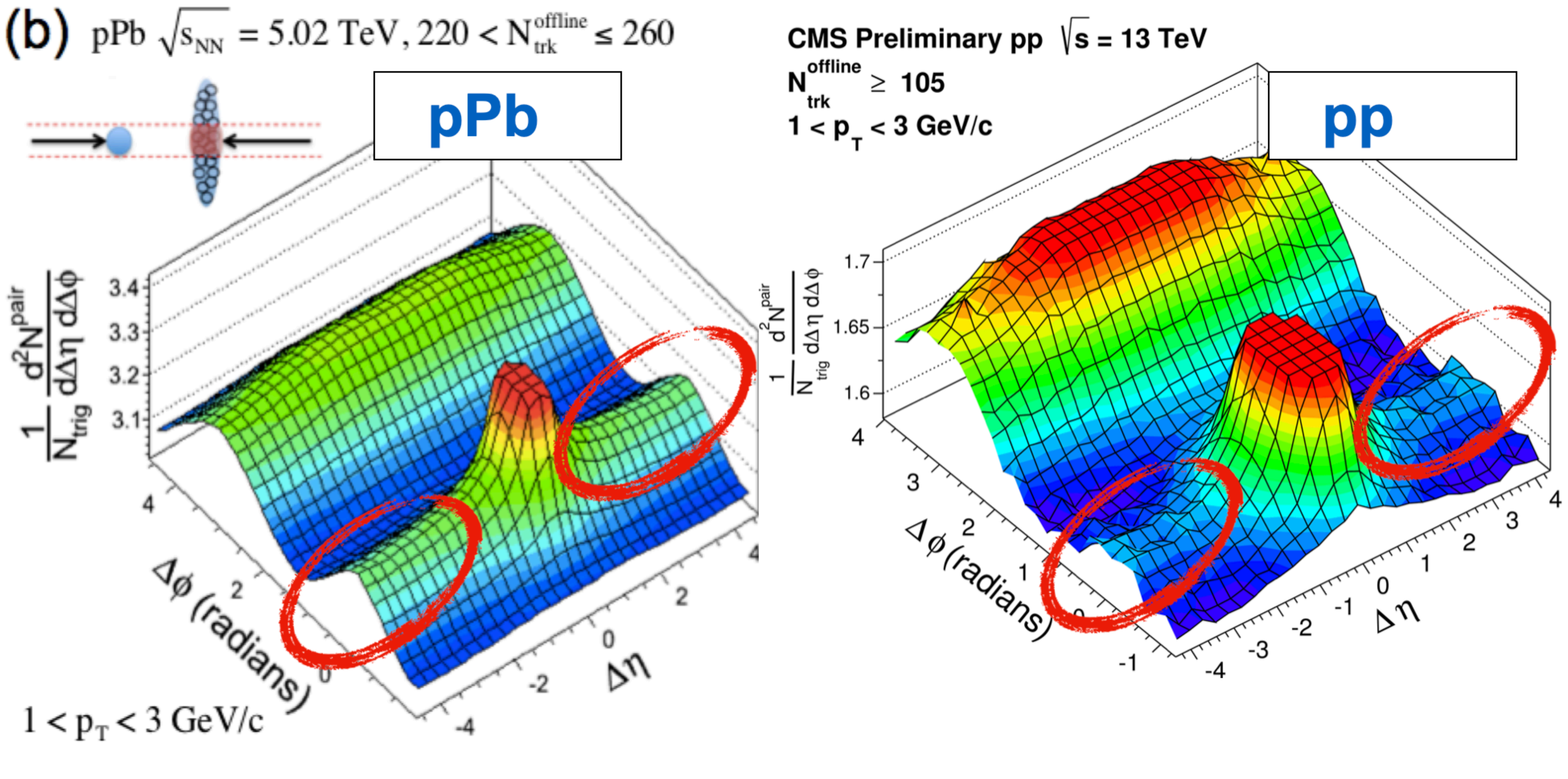


converted into hadron correlations by the medium



Emergence of the ridge in small collisions systems (pp, pA)





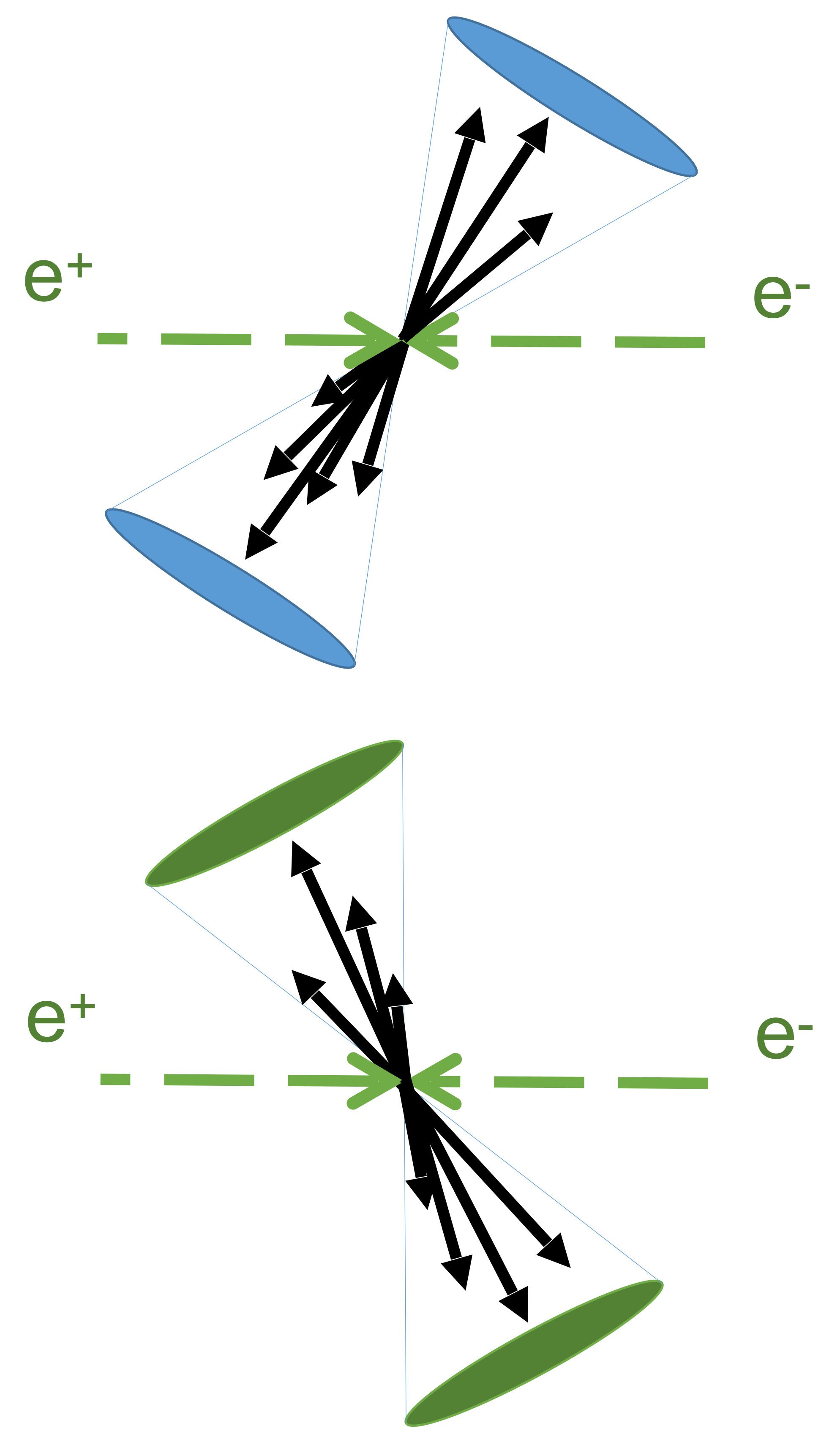
What is the nature/origin of the long-range correlation in "small systems"?

- Initial state effect (e.g., Color-Glass Condensate)
- Color-reconnection mechanisms? MPI?
- Final state effect due to mini-QGP?

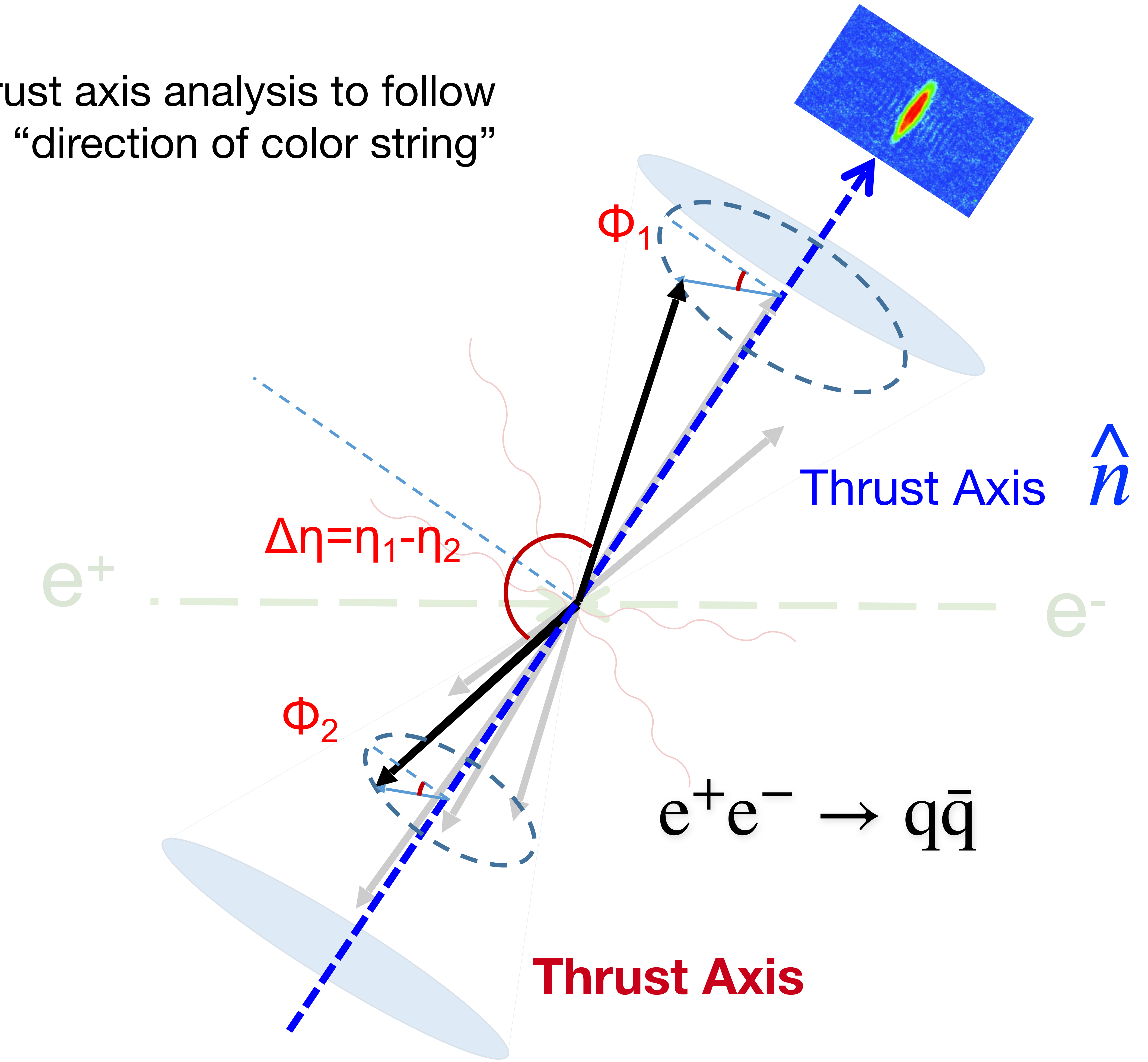
Can we obtain some insights from the "simplest" collision system?
→ Lets look at e^+e^- data!

Two-particle correlation in e^+e^-: reference axis?

Random orientation of the system

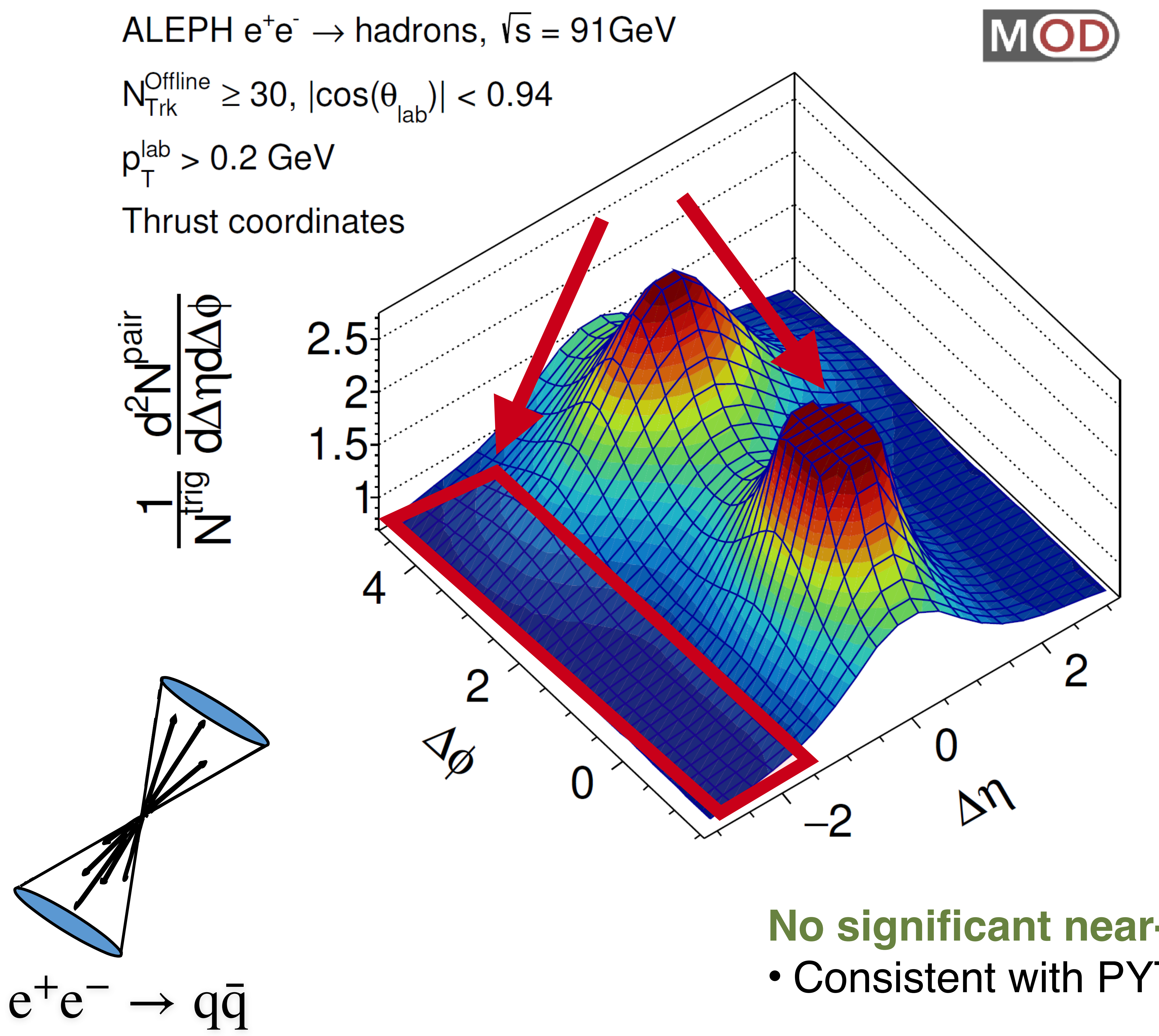


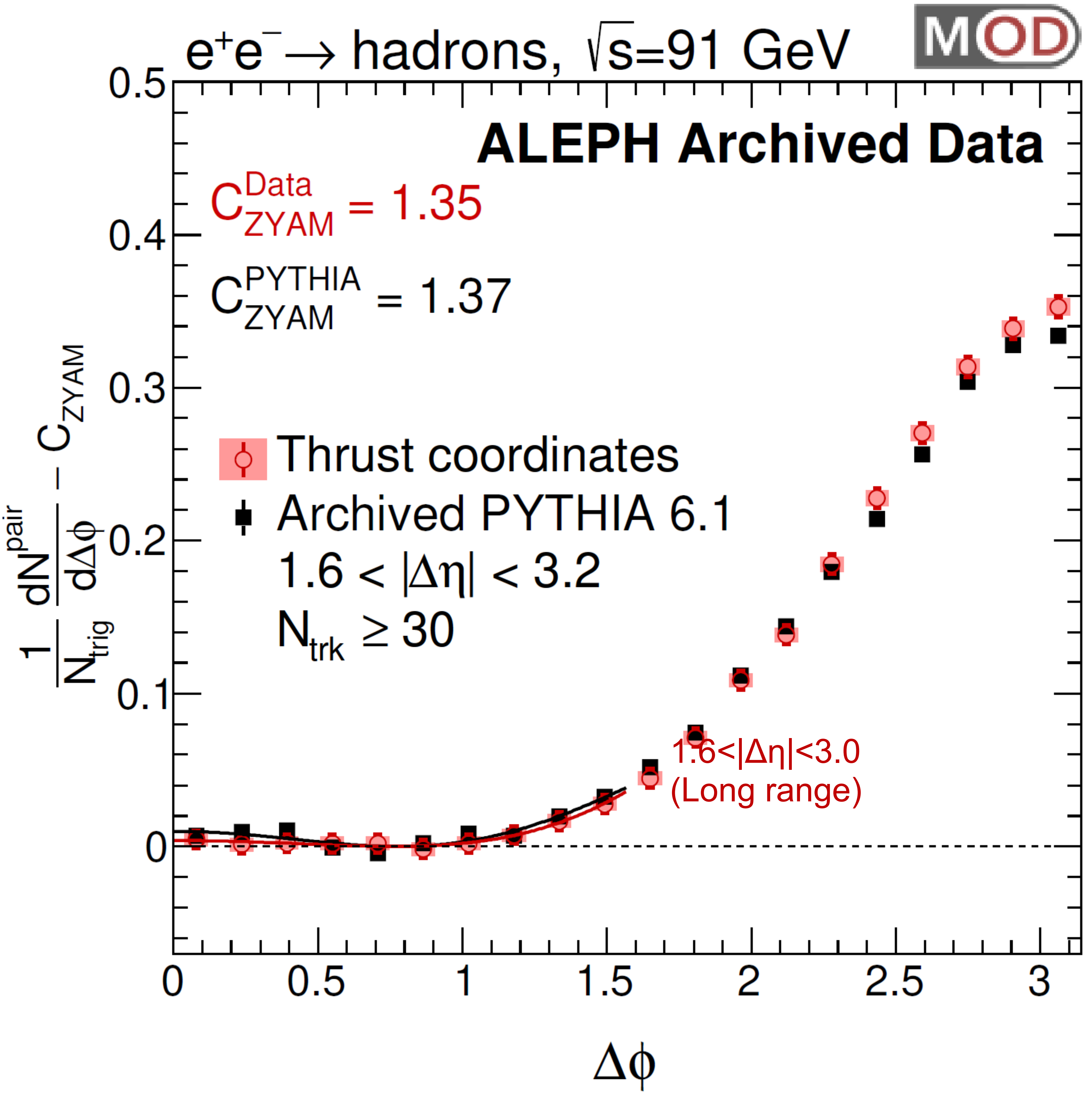
Thrust axis analysis to follow the "direction of color string"



- **Thrust reference axis**: sensitive to medium expanding perpendicular to the **outgoing final-state axis**
- In the thrust-axis reference frame article production distribution (dN/dη) is analogous to pp, AA collisions

Two-particle correlation with ALEPH LEP1 data





No significant near-side ridge at LEP1 energies and multiplicities

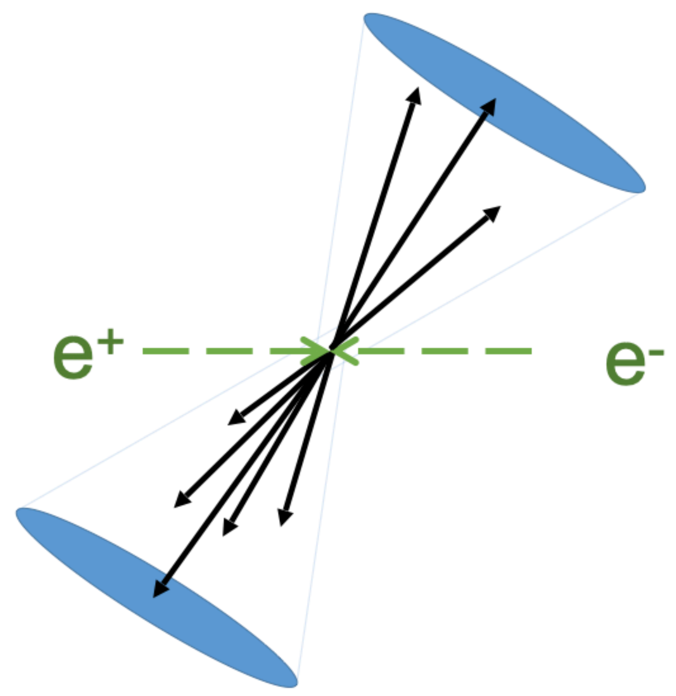
- Consistent with PYTHIA6 without additional final-state effects

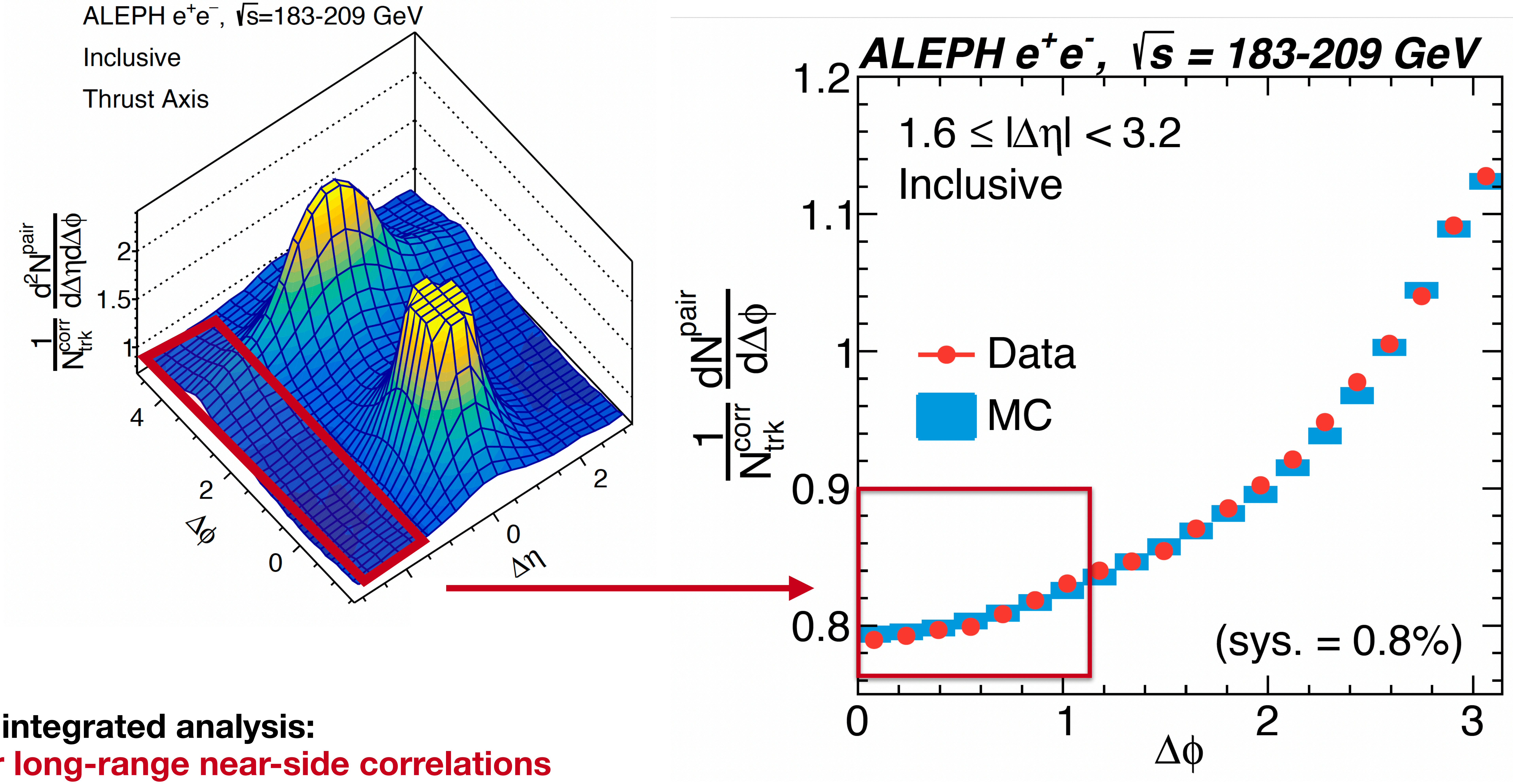
What will happen at higher energies and higher multiplicities → LEP2 data

A. Badea, Y.J. Lee et al. Phys. Rev. Lett. 123, 212002 (2019)

Two-particle correlation in LEP2: multiplicity-integrated result

→ hadronic data dominated by $e^+e^- \rightarrow q\bar{q}$ events also at LEP2 energies





In the multiplicity-integrated analysis:

→ **no evidence for long-range near-side correlations**

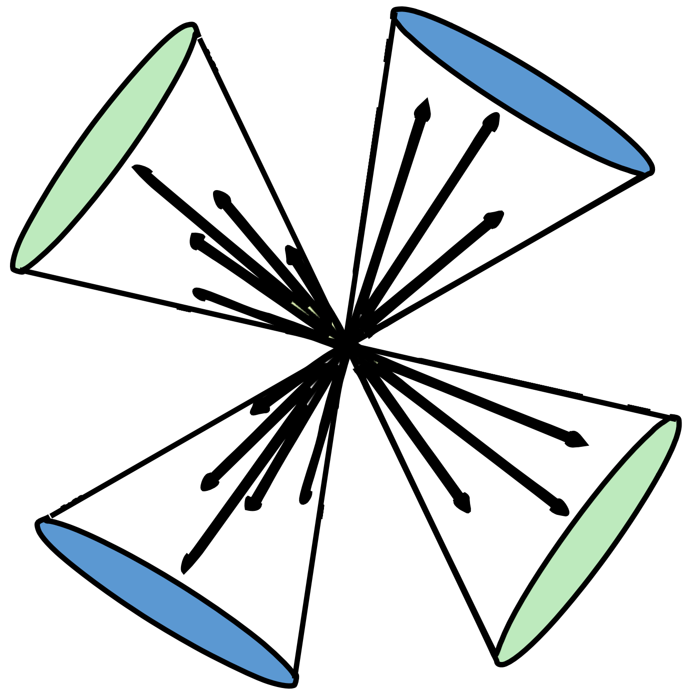
→ trend well described by MC calculations

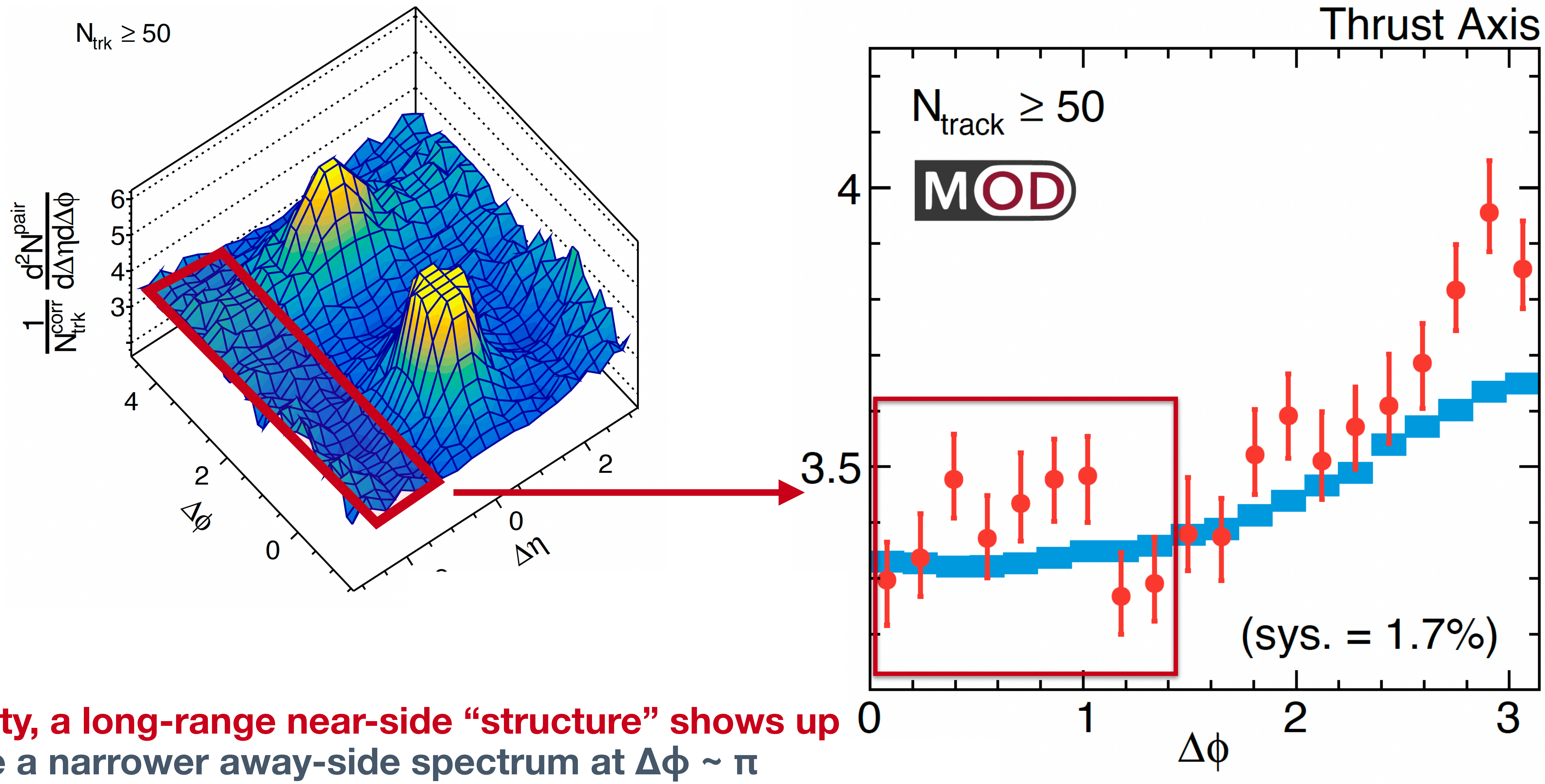
A. Badea, Y.J. Lee et al. Phys. Rev. Lett. 123, 212002 (2019)

Y.-C. Chen et al., arXiv.2312.05084

Two-particle correlation in LEP2: $N_{ch} > 50$

→ hadronic data dominated by $e^+e^- \rightarrow W^+W^- \rightarrow 4f$ events also at LEP2 energies



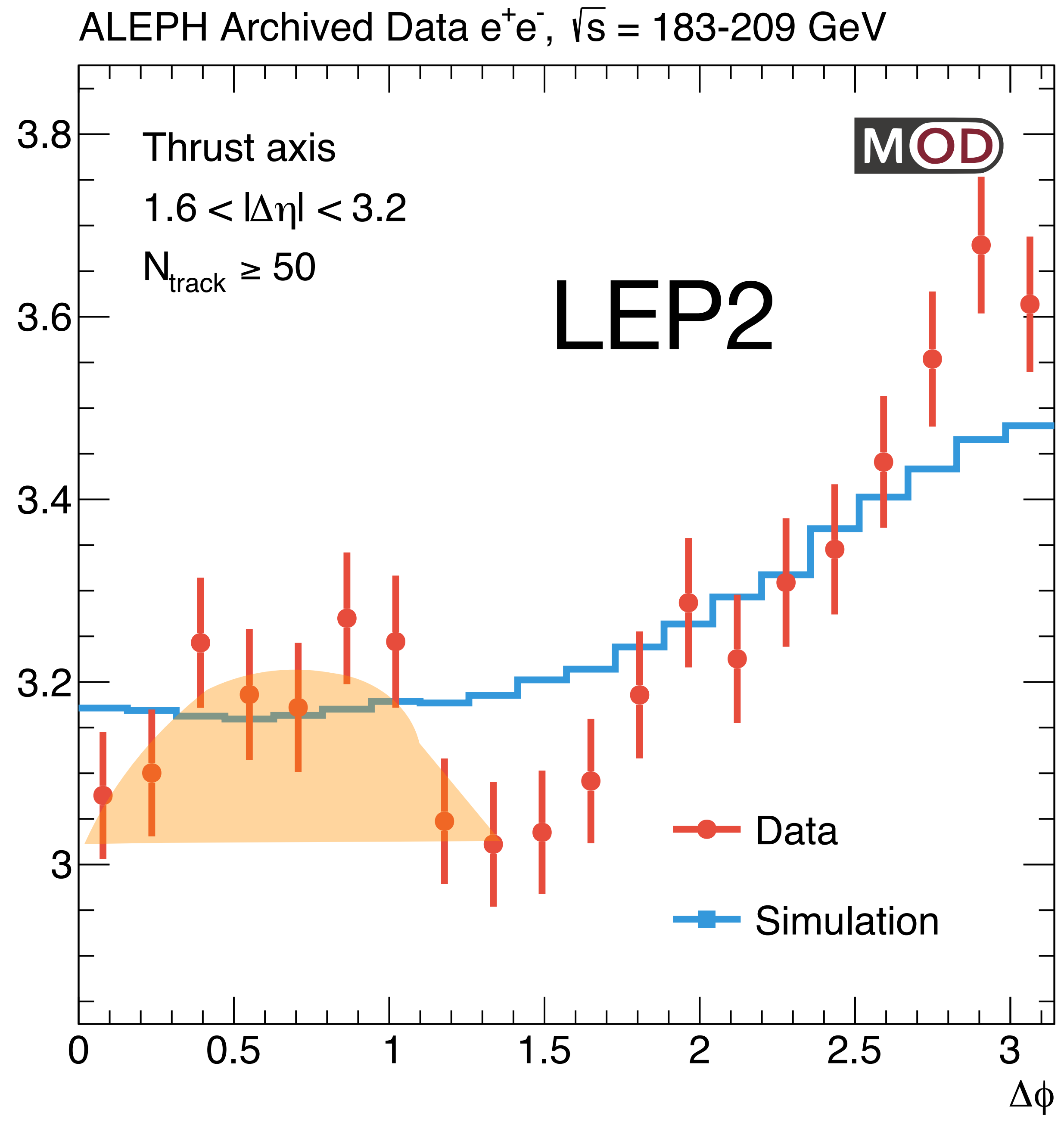


- **At high multiplicity, a long-range near-side "structure" shows up**
- **Data also feature a narrower away-side spectrum at Δϕ ~ π**

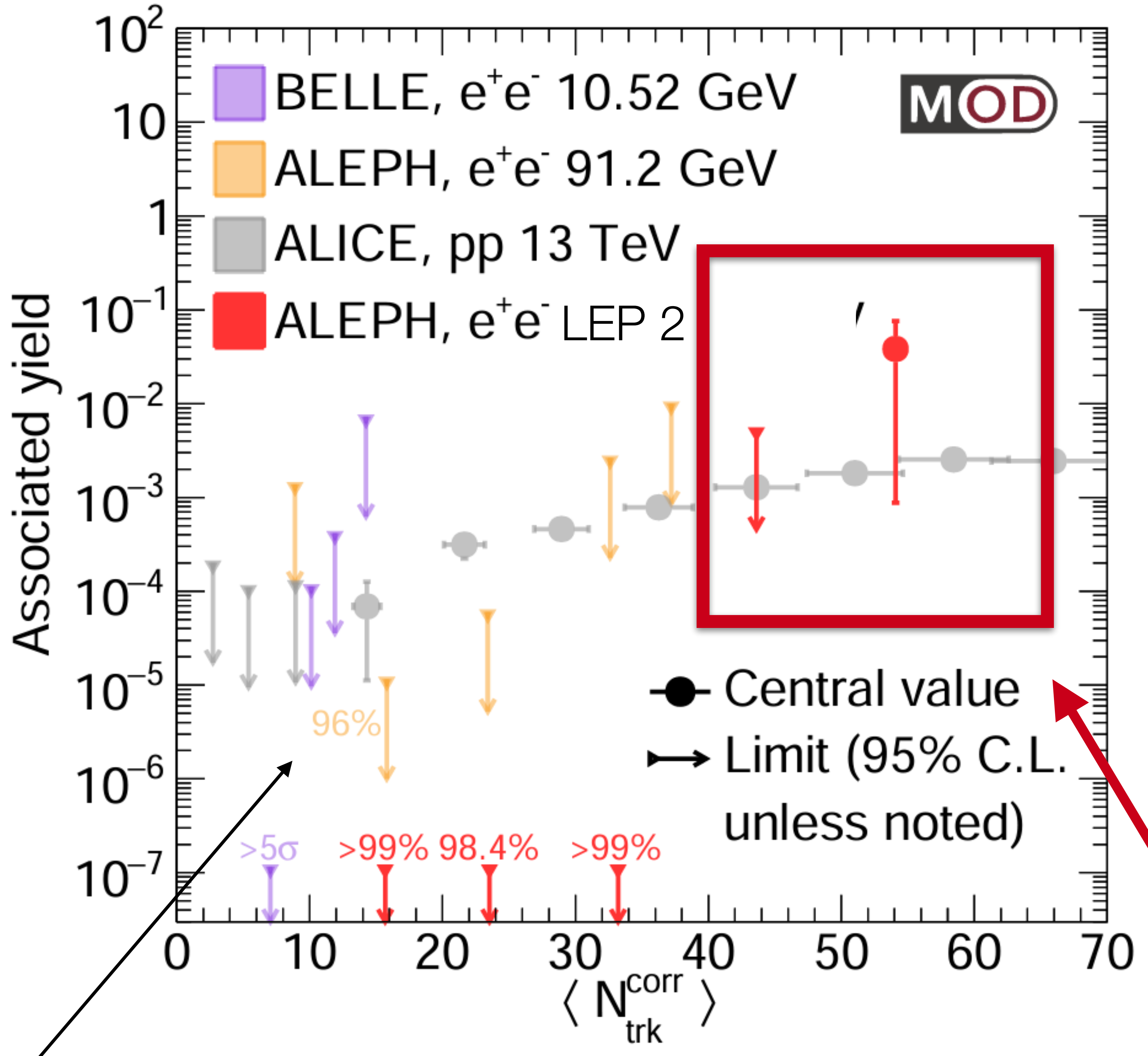
→ qualitatively the same type of signal that we have measured in pp, pPb, PbPb

Y.-C. Chen et al., arXiv.2312.05084

Associated yield vs N_{ch} to quantify the ridge magnitude



Associate yield:
integral of the near-side long-range structure

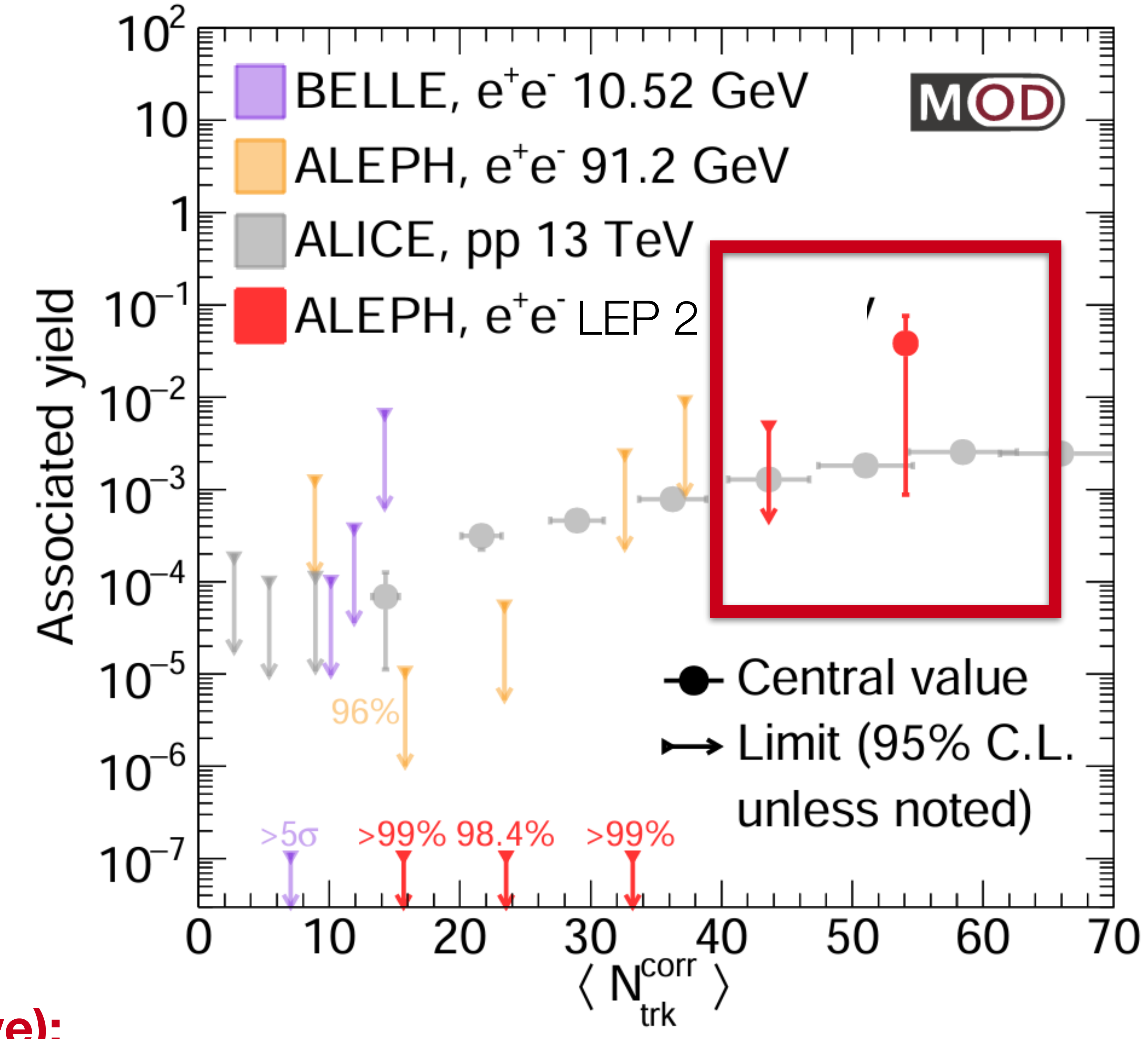


At low multiplicity (<40), **Belle**, **LEP1** and **LEP2** show less associated yields than **ALICE** proton-proton results

At high multiplicity, LEP2 data shows a non-zero yield
(very large uncertainties)

Y-.C. Chen et al., arXiv.2312.05084

Associated yield vs N_{ch} to quantify the ridge magnitude



Possible interpretations (not yet conclusive):

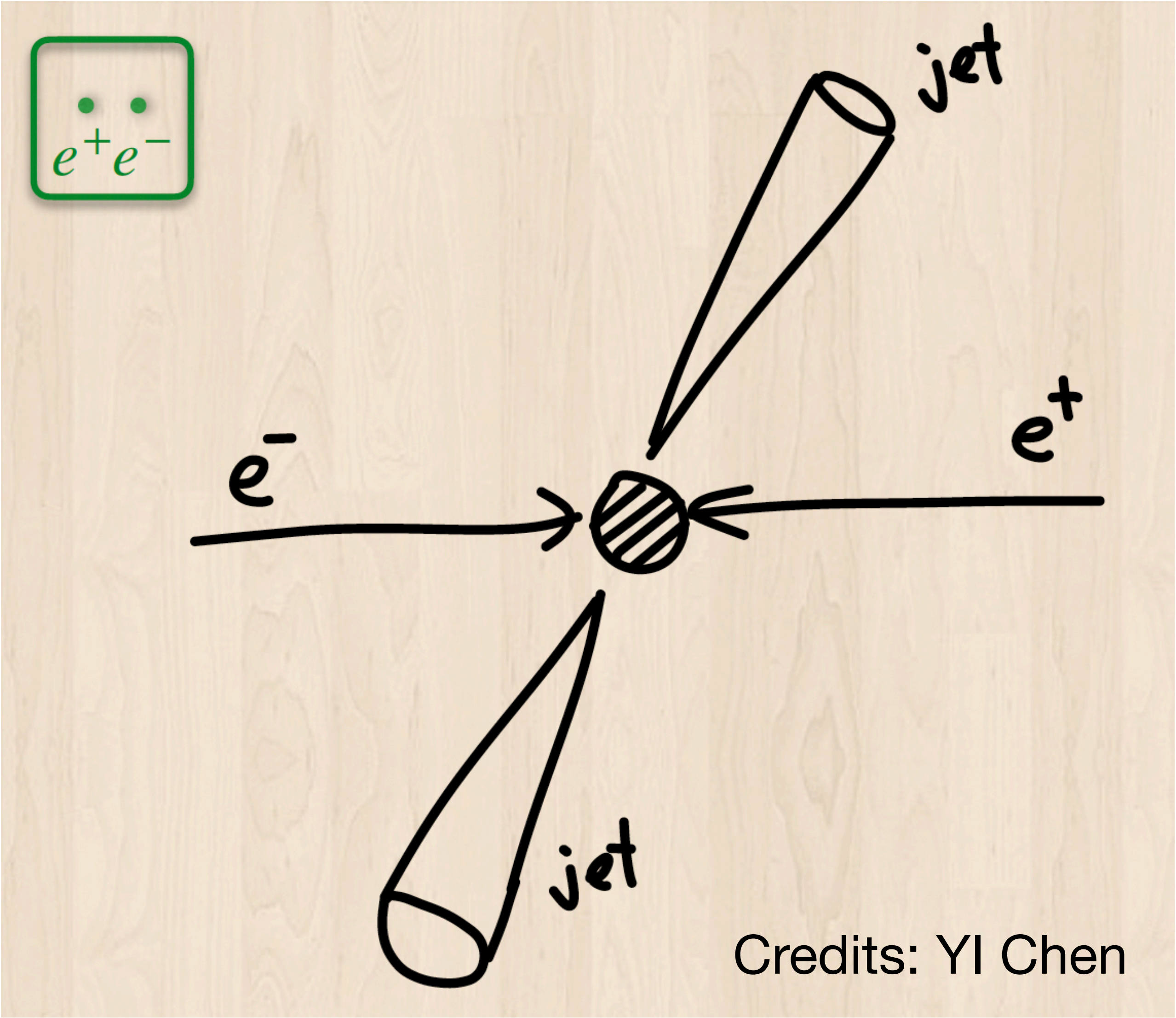
- ridge formed without initial-state anisotropies due to the presence of more complex color string configurations?
- non-negligible final-state interactions in e^+e^-?

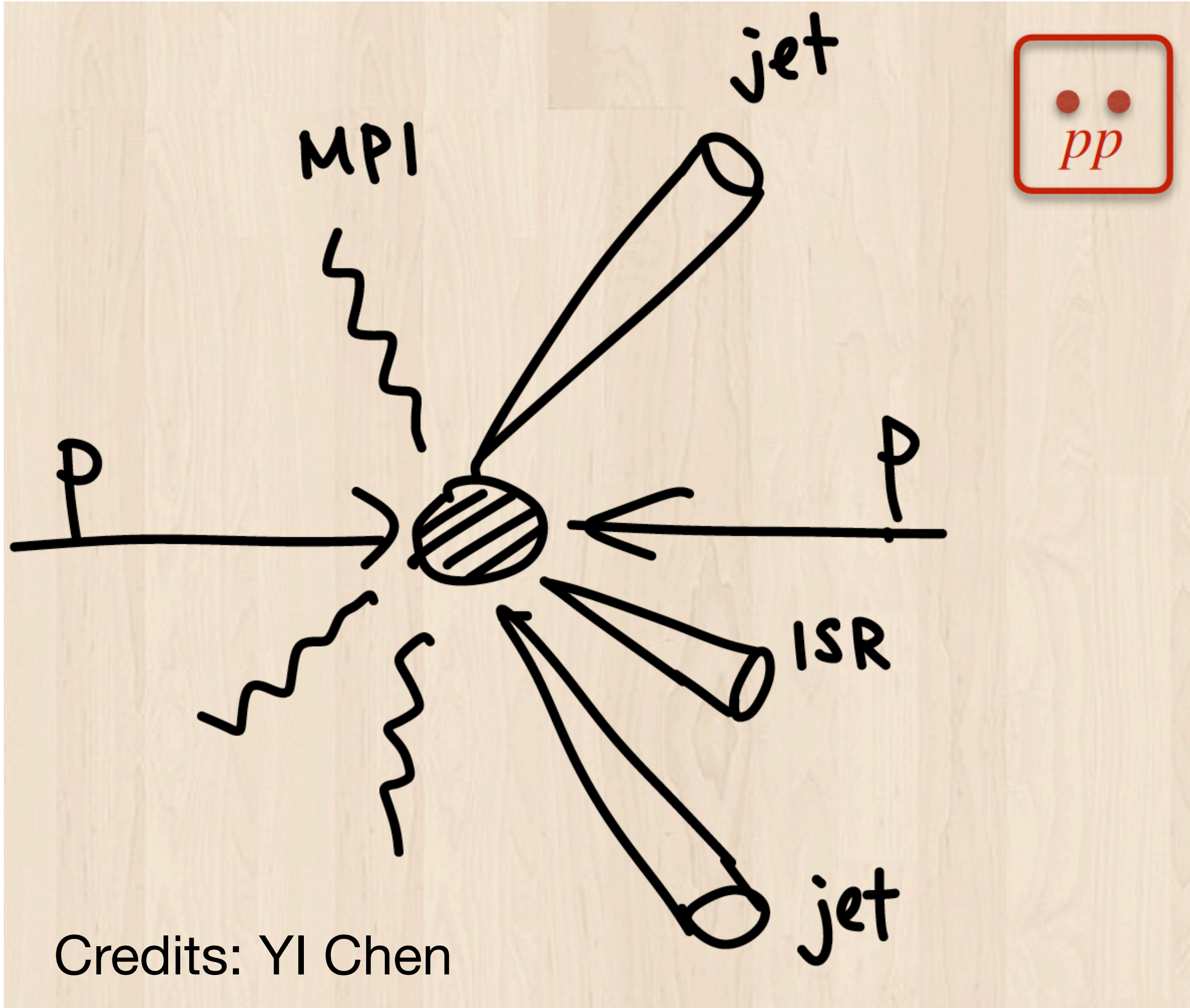
→ **push for more accurate measurements (e.g. in UPCs or eA collisions at the EIC) and further theory development!**

Y-.C. Chen et al., arXiv.2312.05084

More jet measurements in e^+e^- collisions?

→ significant progress has been made on jet definitions and jet clustering algorithms since LEP time!



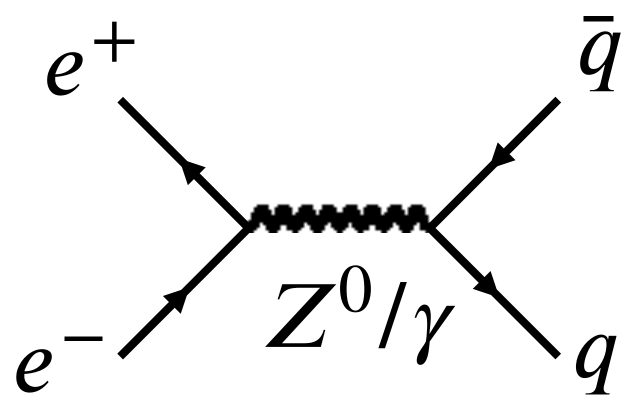


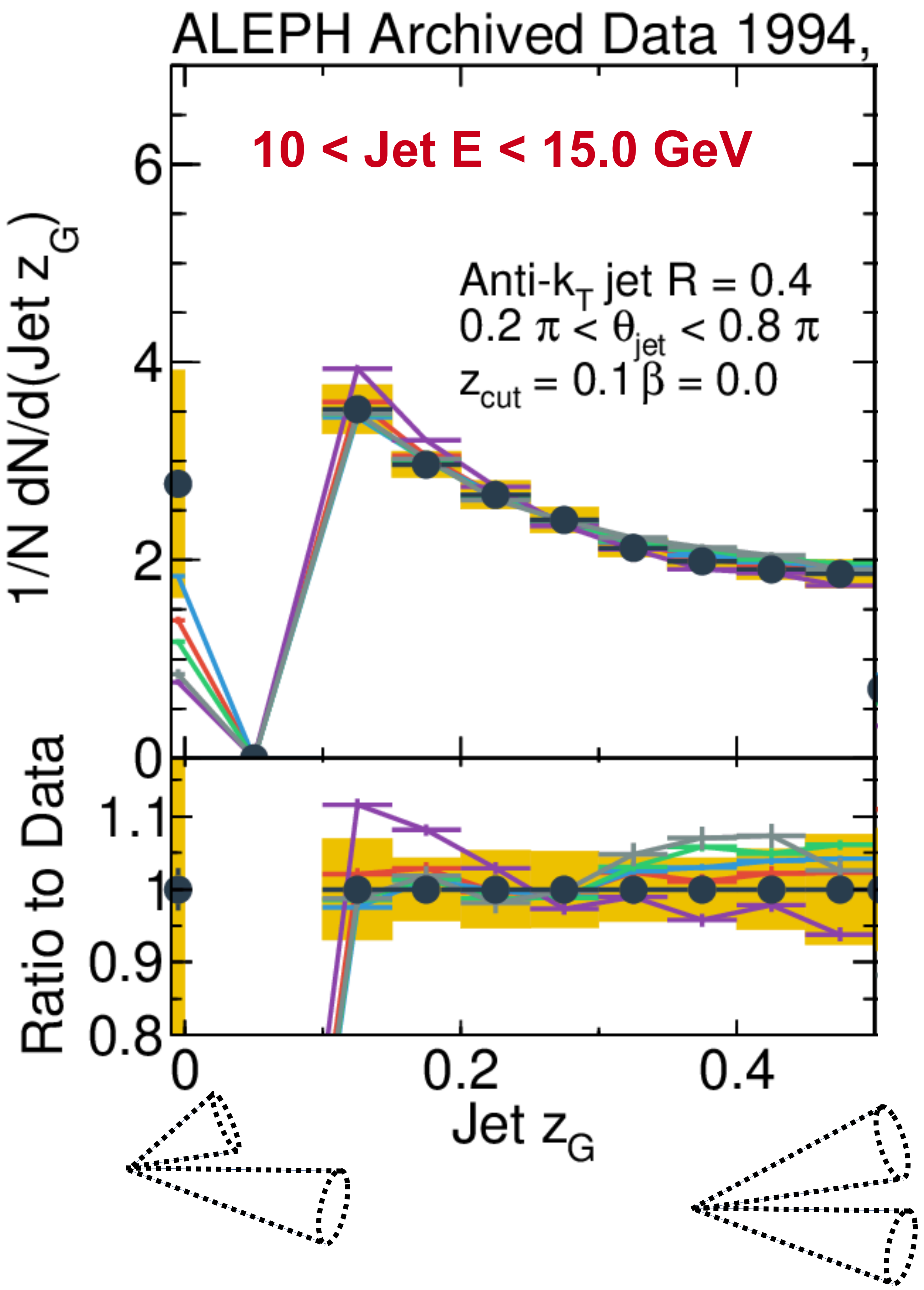
Physics interest for measuring modern observables in e^+e^- data :
→ validate the predictions of modern generators in the ultra-clear e^+e^- environment
→ "cure" some of the discrepancies observed at the LHC in the simple in e^+e- environment
→ opportunity to design new techniques that profit from the favorable theoretical/experimental conditions of e^+e^-

Highlight: energy sharing z_G in e^+e^- from LEP 1

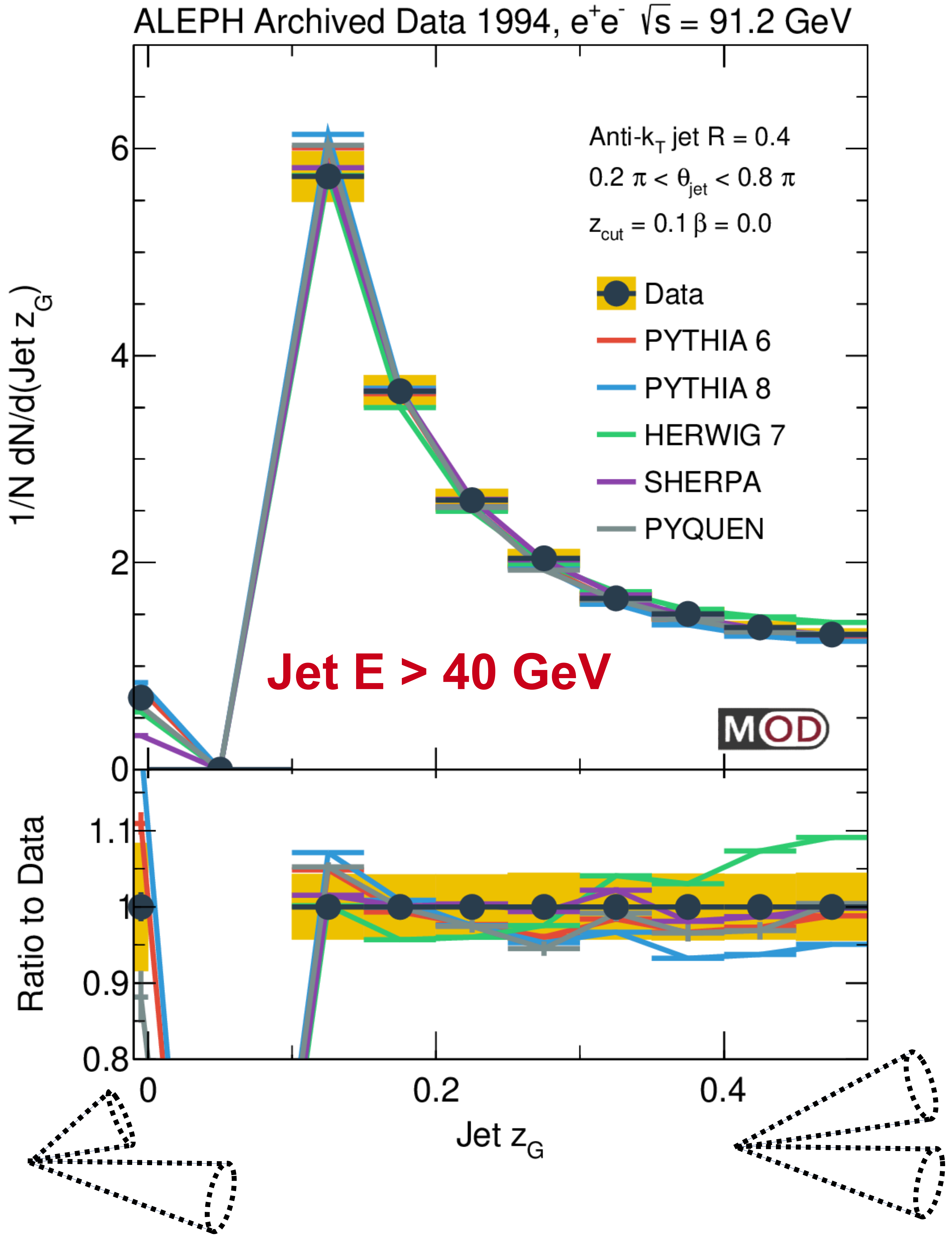
MITHIG-MOD-21-001
arXiv:2111.09914
JHEP 06 (2022) 008

LEP 1 dataset:
- About 1.3 M events
- dominated by quark jets





At low E: good agreement with MCs



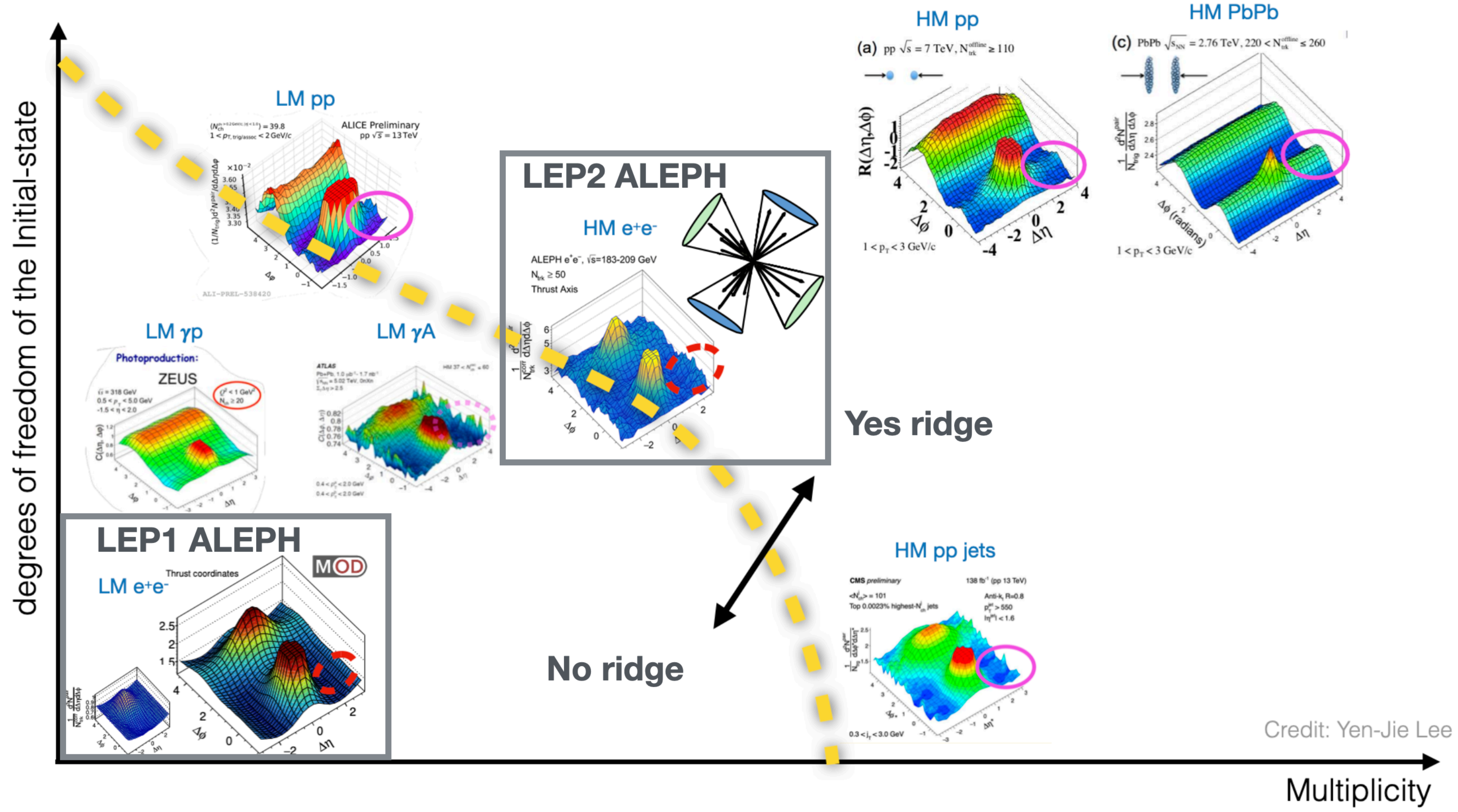
$$z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

At high E: evidence for some MC-data discrepancies
→ **qualitatively similar to the discrepancies observed in data-MC comparisons for pp**

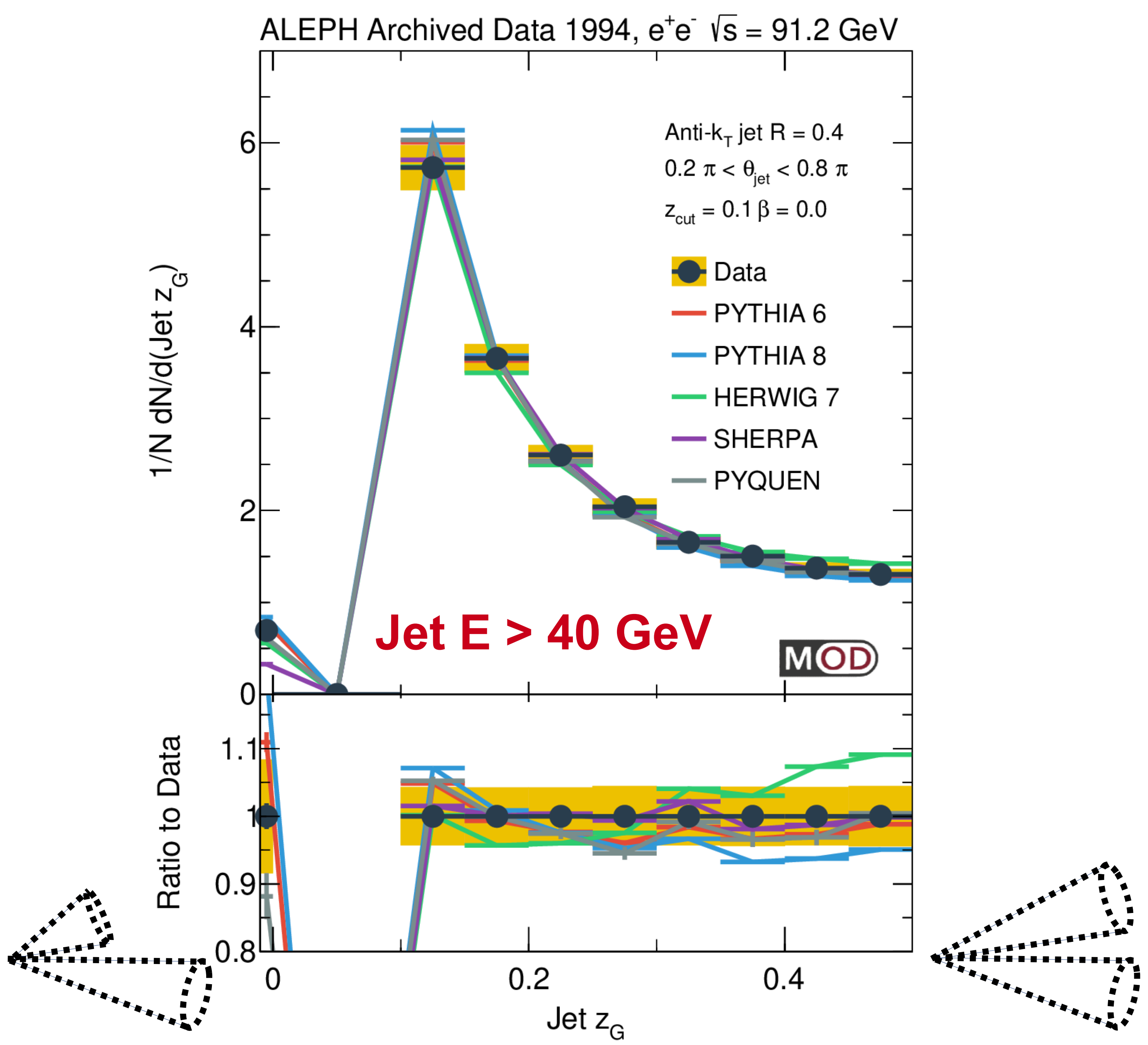
Conclusions and outlook

Unique features of e+e- collisions (point-like initial state, low background, in-vacuum final state..)
→ have motivated new studies in the perturbative and non-perturbative regime

New insights into collective phenomena in "small" systems



In-vacuum benchmark for detailed characterization of the parton shower evolution



Work is ongoing to extend this effort to new observables and phenomena
→ can we see indications of hadronization changes vs multiplicity?
→ can we map the transition between short and long-distance QCD with energy-energy correlators?
→ **Building the tools for future measurements in UPC at the LHC, the EIC and the FCC**

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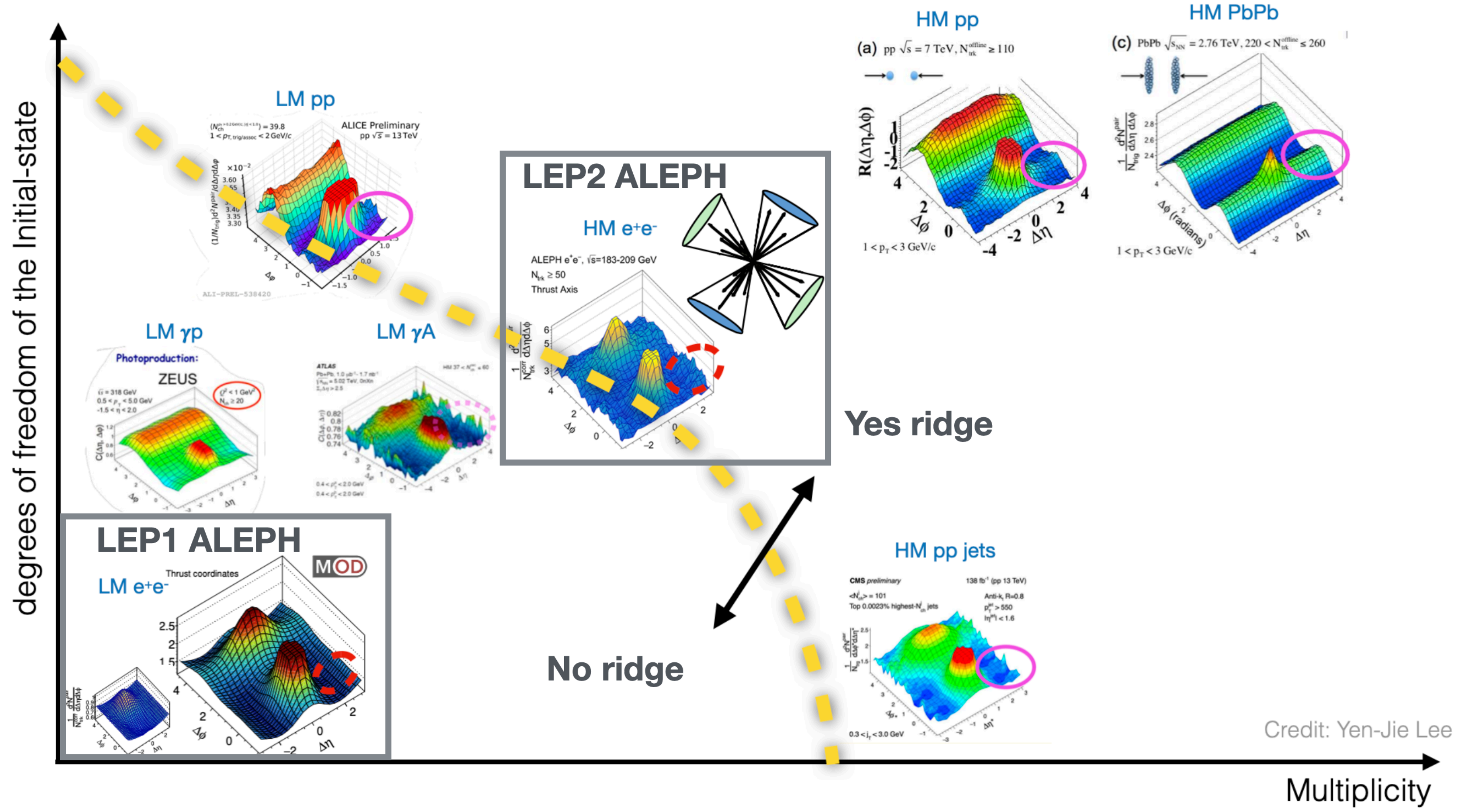

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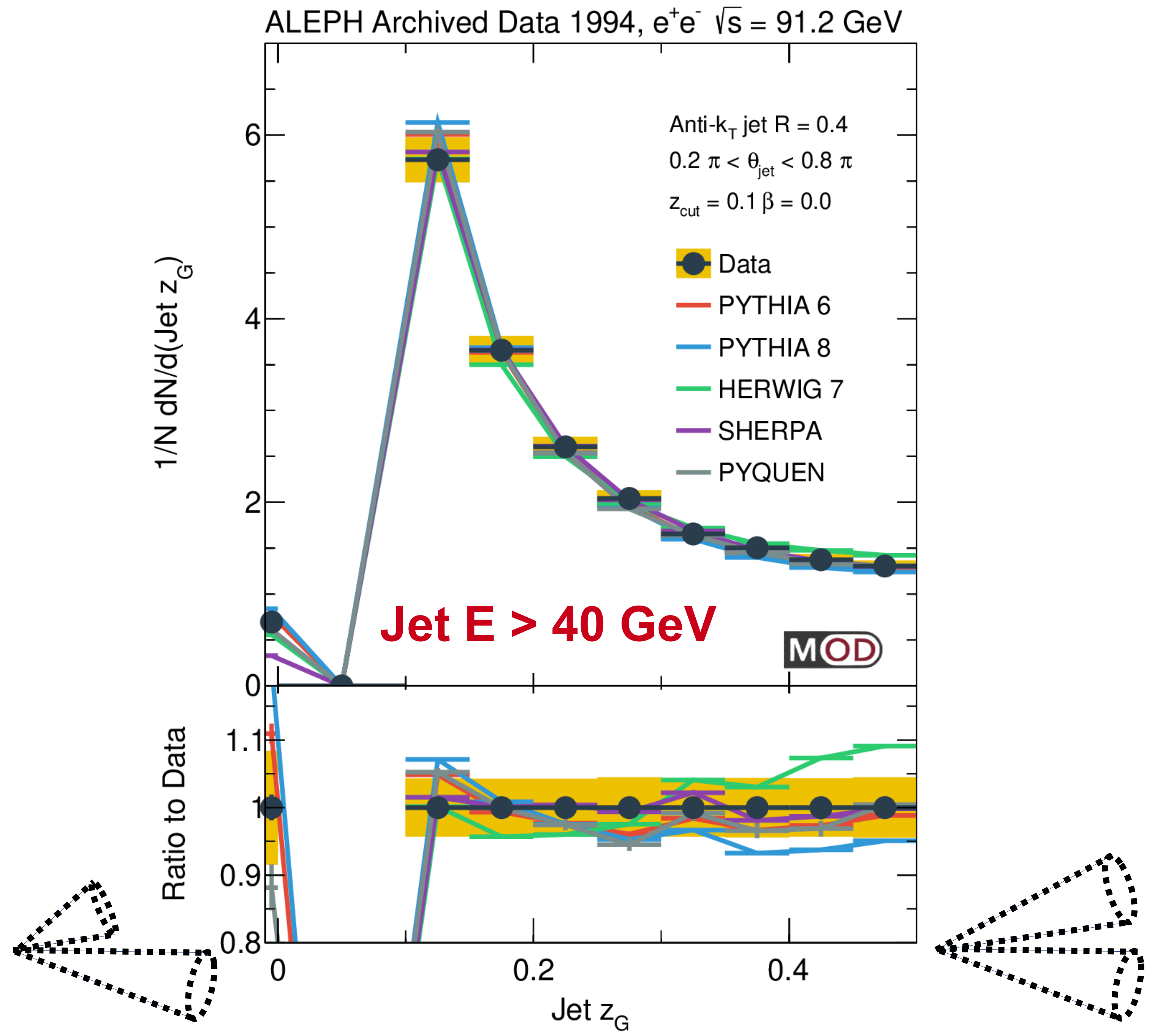

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Thank you for your attention!

BACKUP SLIDES

Highlight: e+e- LEP1 data and modern event generators

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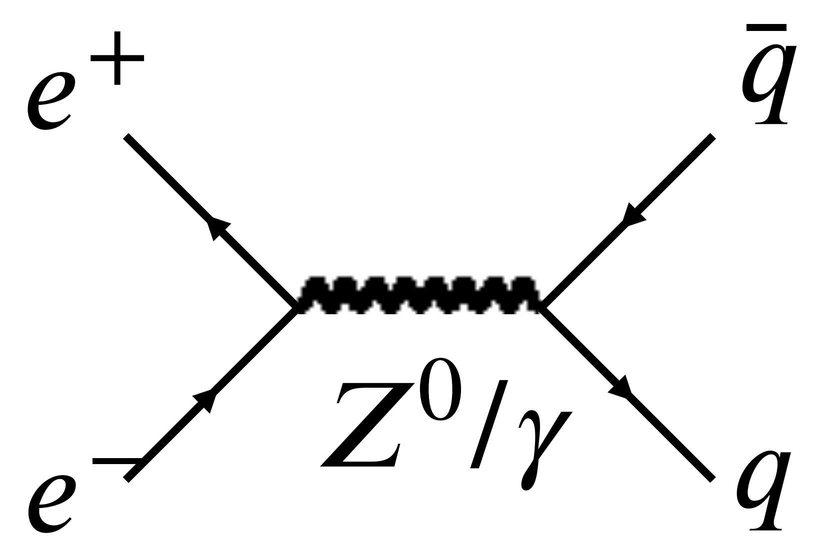
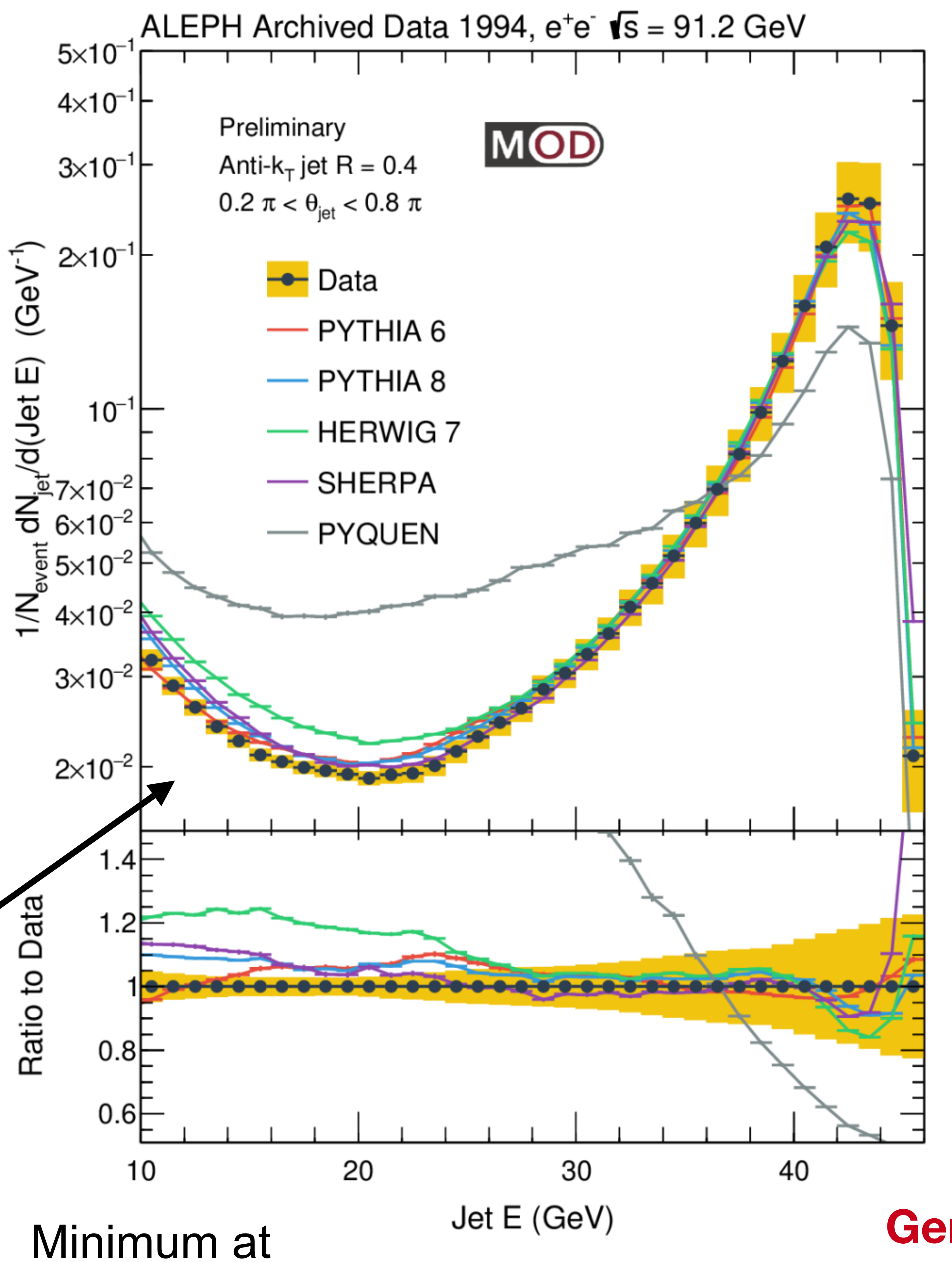


LEP 1 dataset:
- About 1.3 M events
- dominated by quark jets

At low E: increase due to a large number of jets from soft emissions or combinatorial

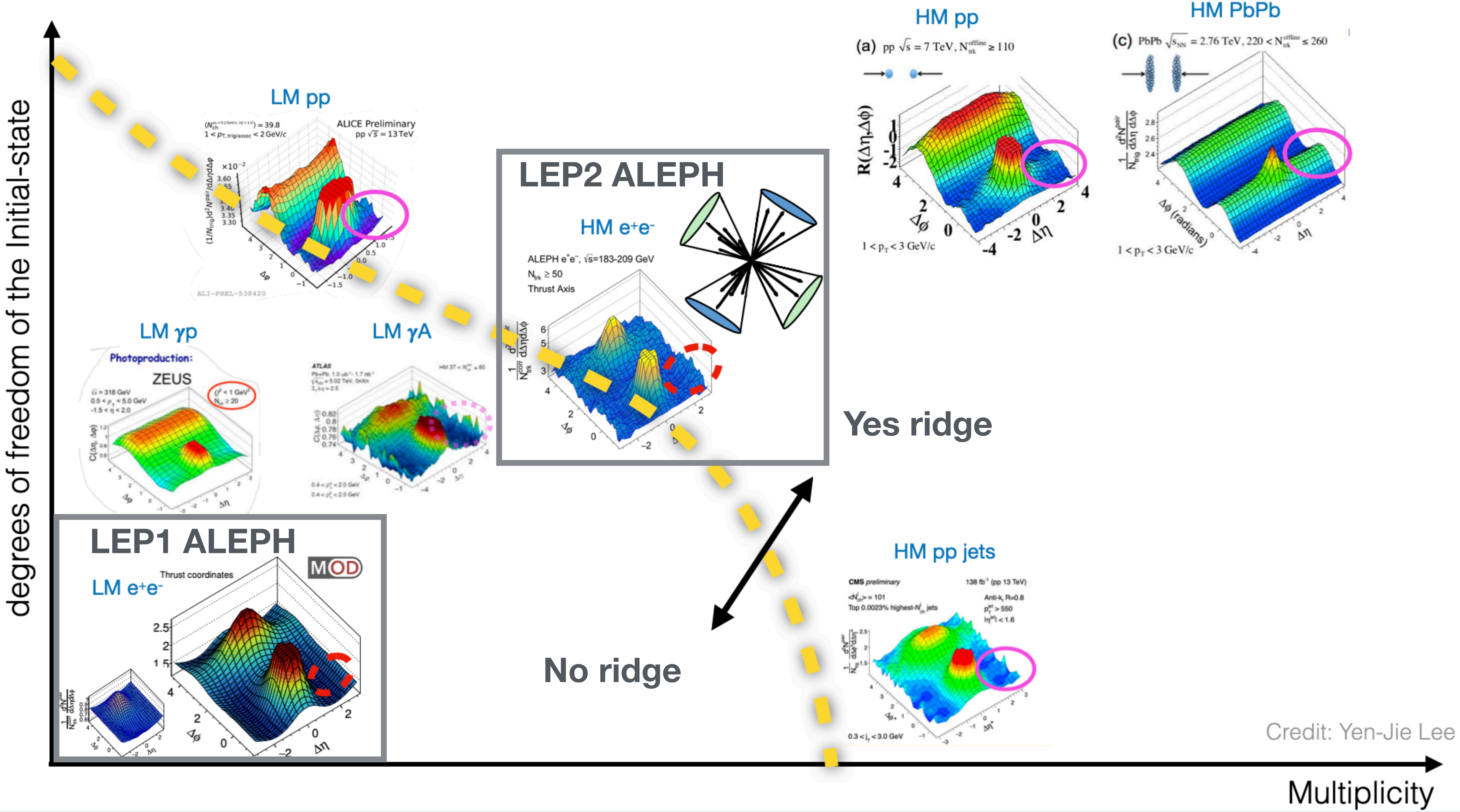


Minimum at around 20 GeV

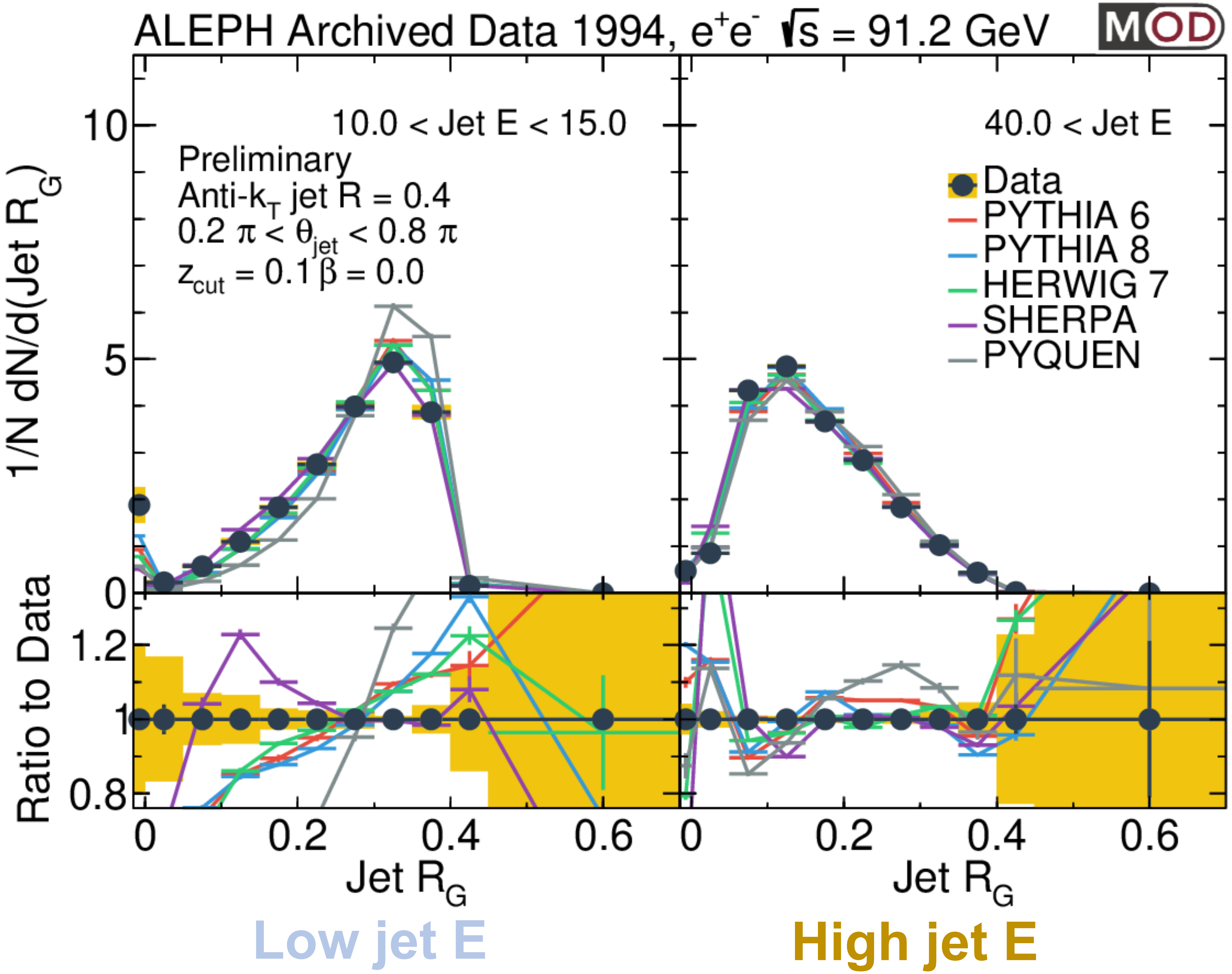
Jet energy: closest observable to the jet spectra analyses in pp collisions

The shape of the peak around 43 GeV ($Z \rightarrow q\bar{q}$) well described by by the anti-k_T algorithm with R=0.4

Generators capture the general features of the distributions but overpredict the spectra at low jet E


degrees of freedom of the Initial-state
Multiplicity
LM pp
ALICE Preliminary
LM γp
Photoproduction:
ZEUS
LM γA
LEP2 ALEPH
HM e+e-
ALEPH e+e-, √s=183-209 GeV
N_trk ≥ 50
Thrust Axis
HM pp
HM PbPb
Yes ridge
No ridge
LEP1 ALEPH
LM e+e-
Thrust coordinates
MOD
HM pp jets
CMS preliminary
Credit: Yen-Jie Lee

Groomed Jet Radius R_G vs. Event Generators



- **High jet E** (mainly quark jets):
  - Peak at smaller R_G value
  - Generators give a better description of the data
- **Low jet E** (mainly from soft emissions and combinatorial):
  - Peak at larger R_G value as one would expect
  - SHERPA gives a better description of the data
  - PYTHIA 6, PYTHIA 8, HERWIG, and PYQUEN overpredict the R_G

MITHIG-MOD-21-001
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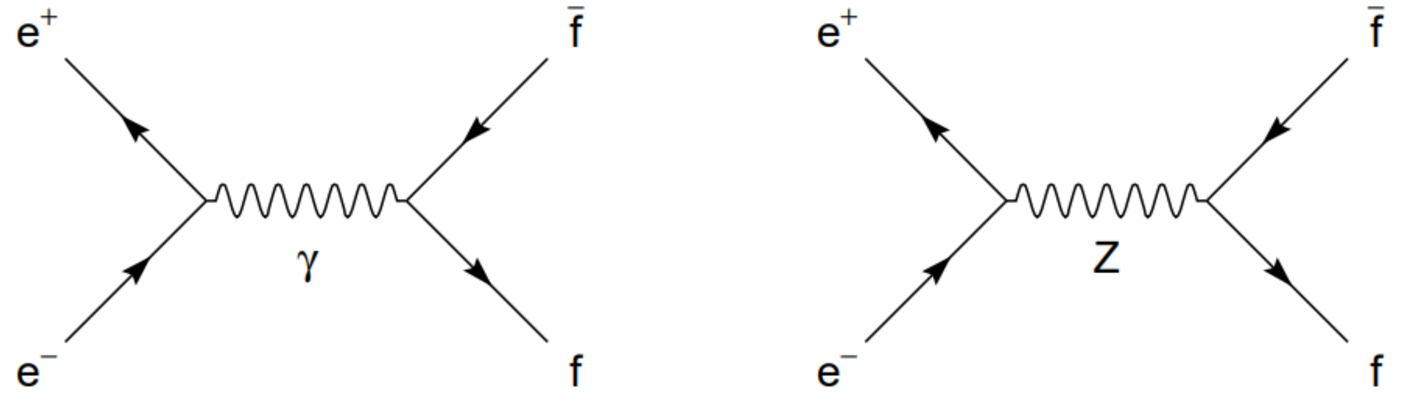
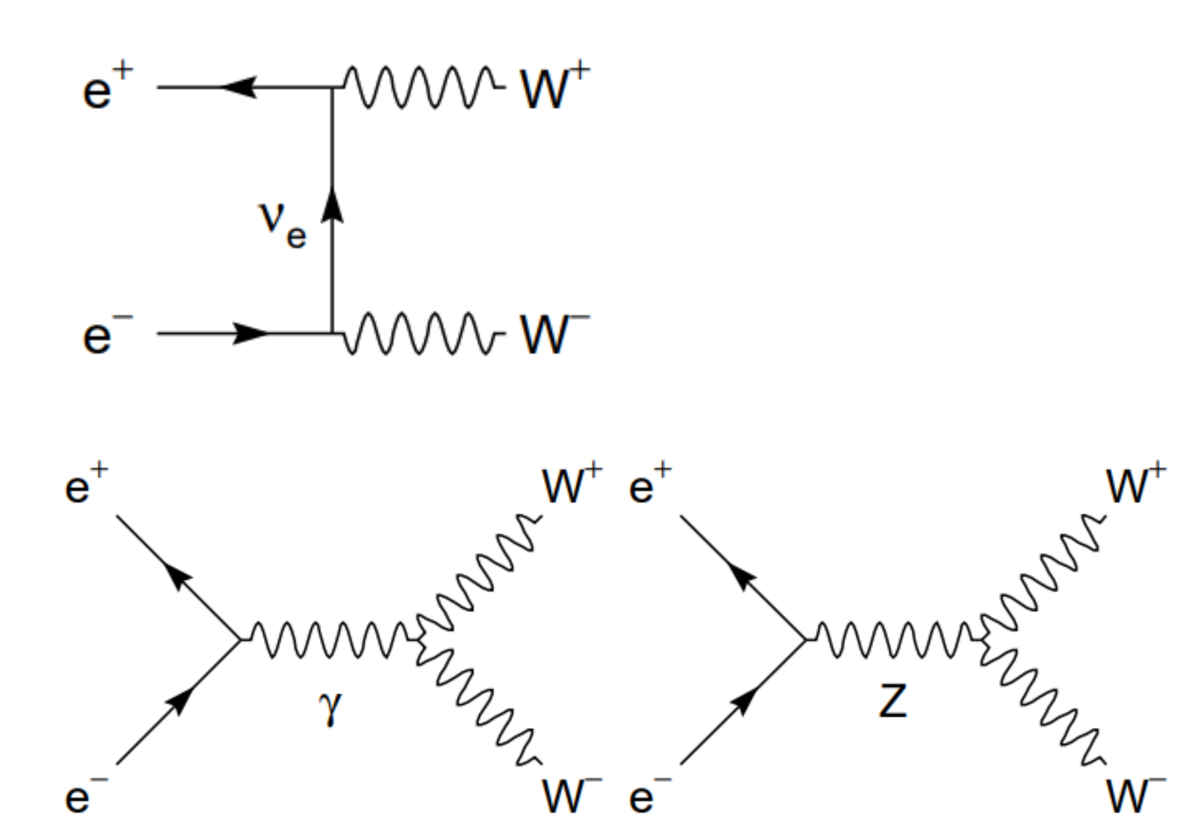
Charged Particle Multiplicity Distributions in LEP2 Data

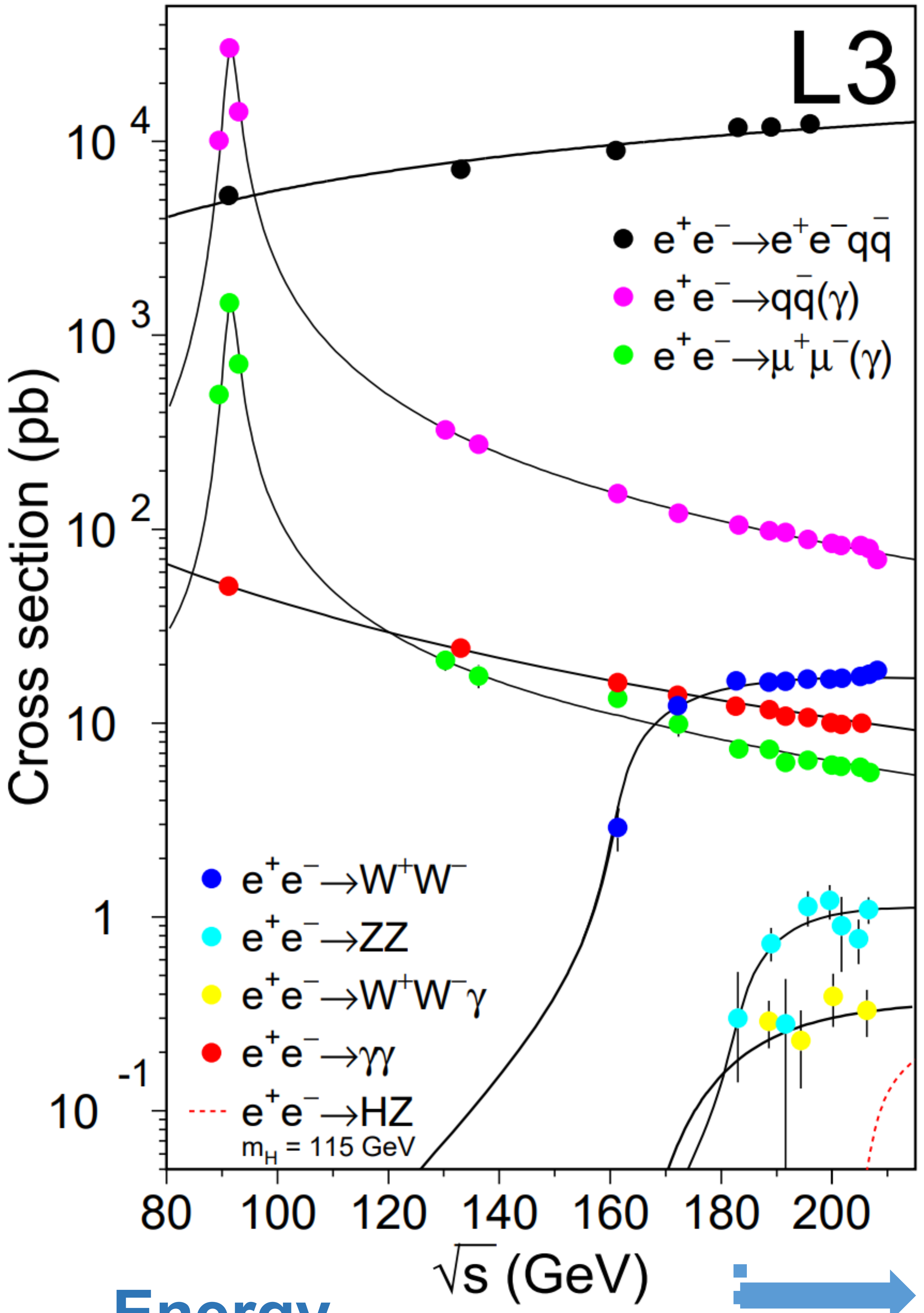
● $e^+e^- \to q\bar{q}(\gamma)$



● $e^+e^- \to W^+W^-$



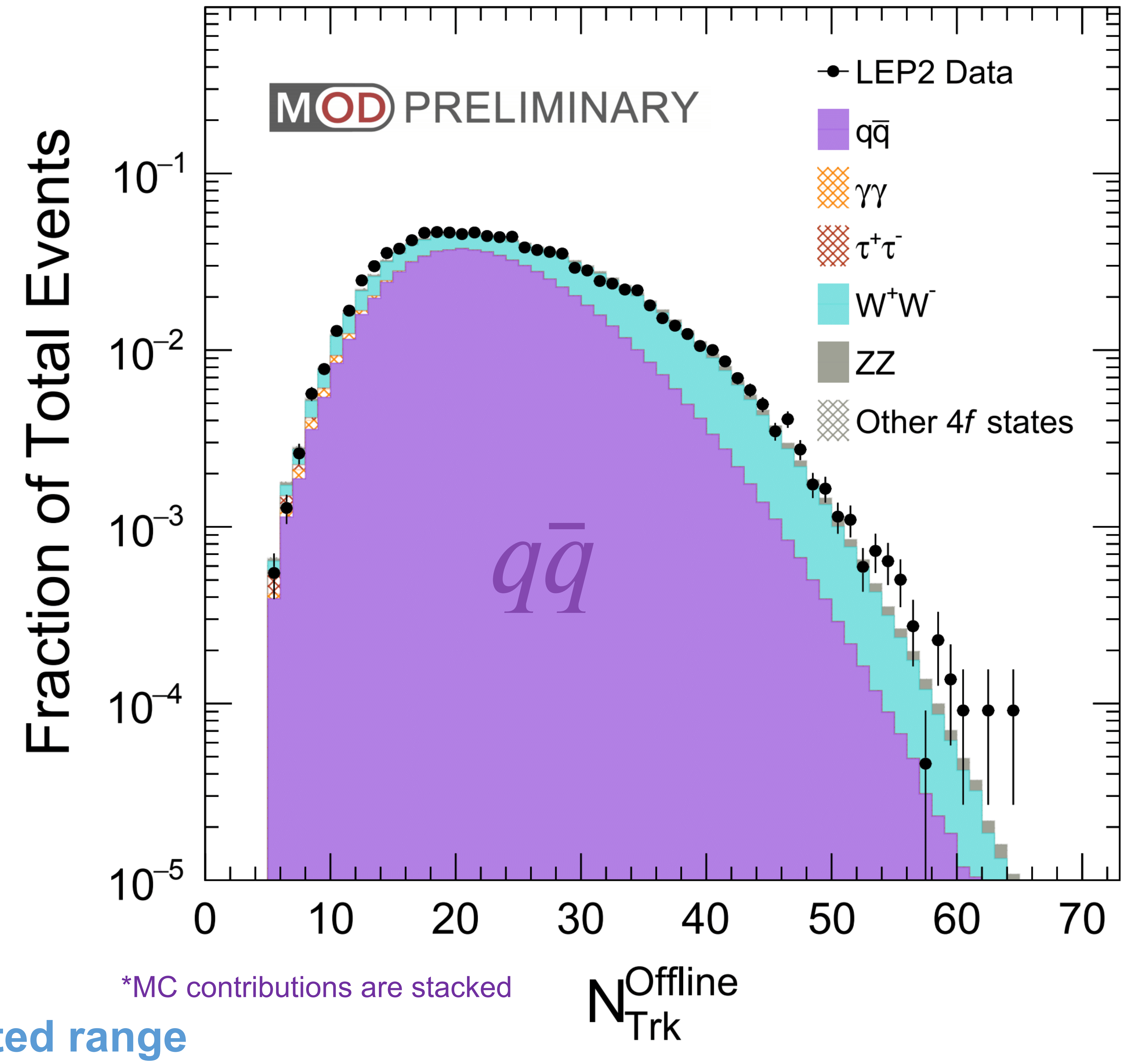
Phys. Rept. 532 (2013) 119-244



Energy

EPJC 63 611 (2009)

Reported range

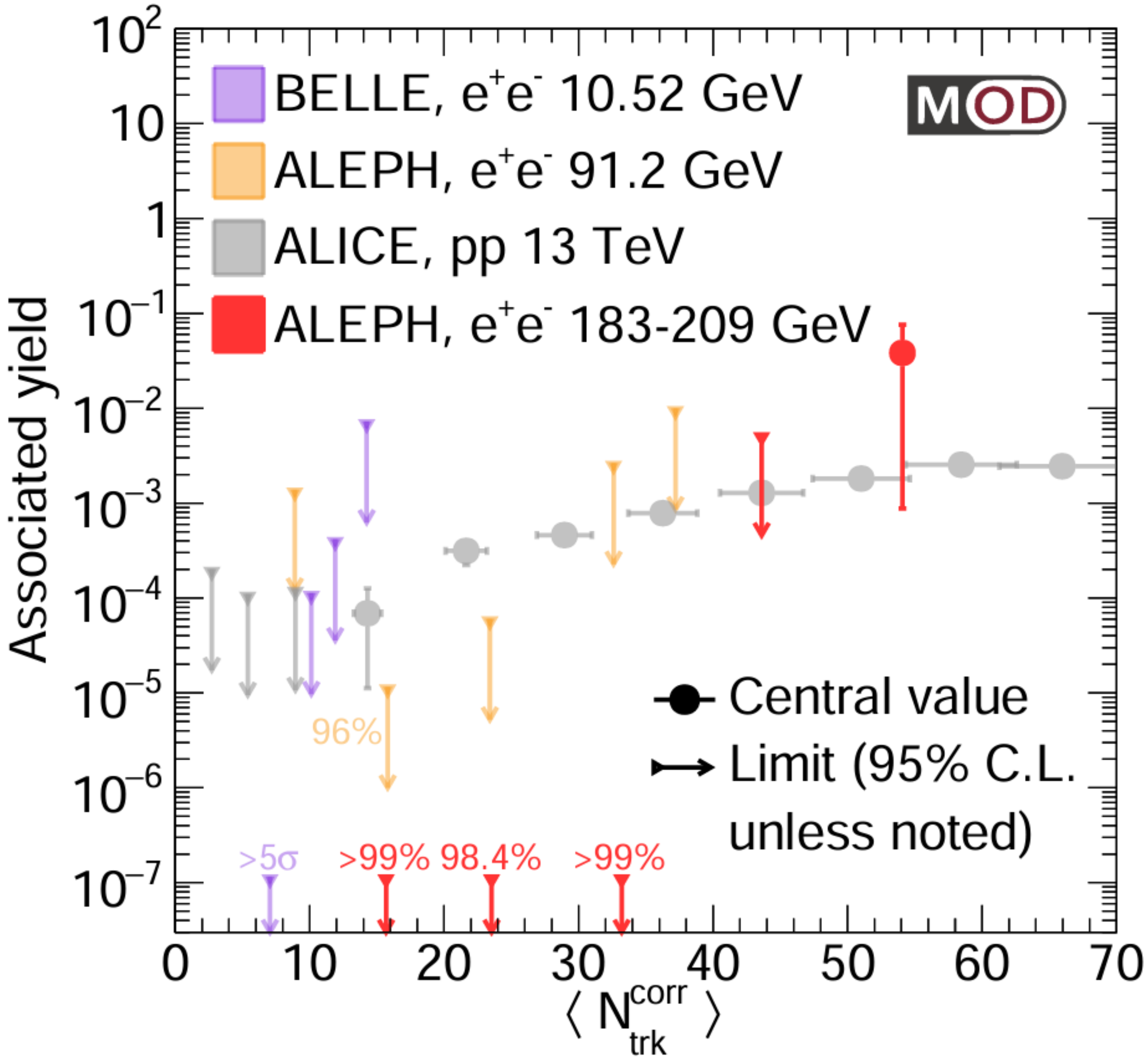


- **LEP2 energies** give access to also different physics processes
- At high multiplicity, W^+W^- contribution becomes significant

The Highest Multiplicity Events in Archived LEP2 Data

Associated Yield as a Function of Multiplicity

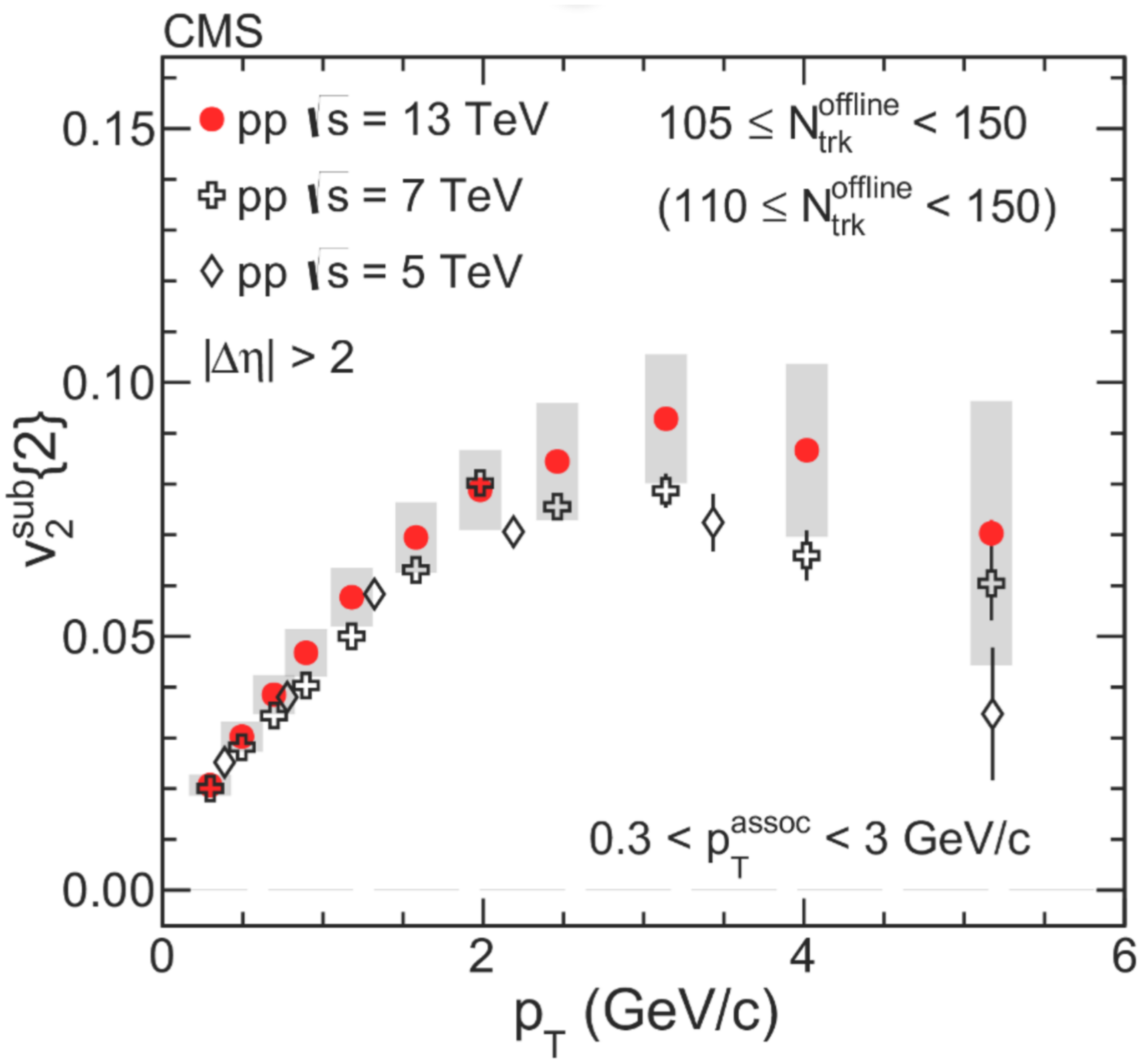
- Very tight upper limit set with Belle, LEP1 and LEP2 data set at low multiplicity (<40), lower than ALICE pp results
- Indication of an increasing trend at high multiplicity in LEP2 data
- Non-zero central value reported at the highest multiplicity bin with large statistical uncertainty

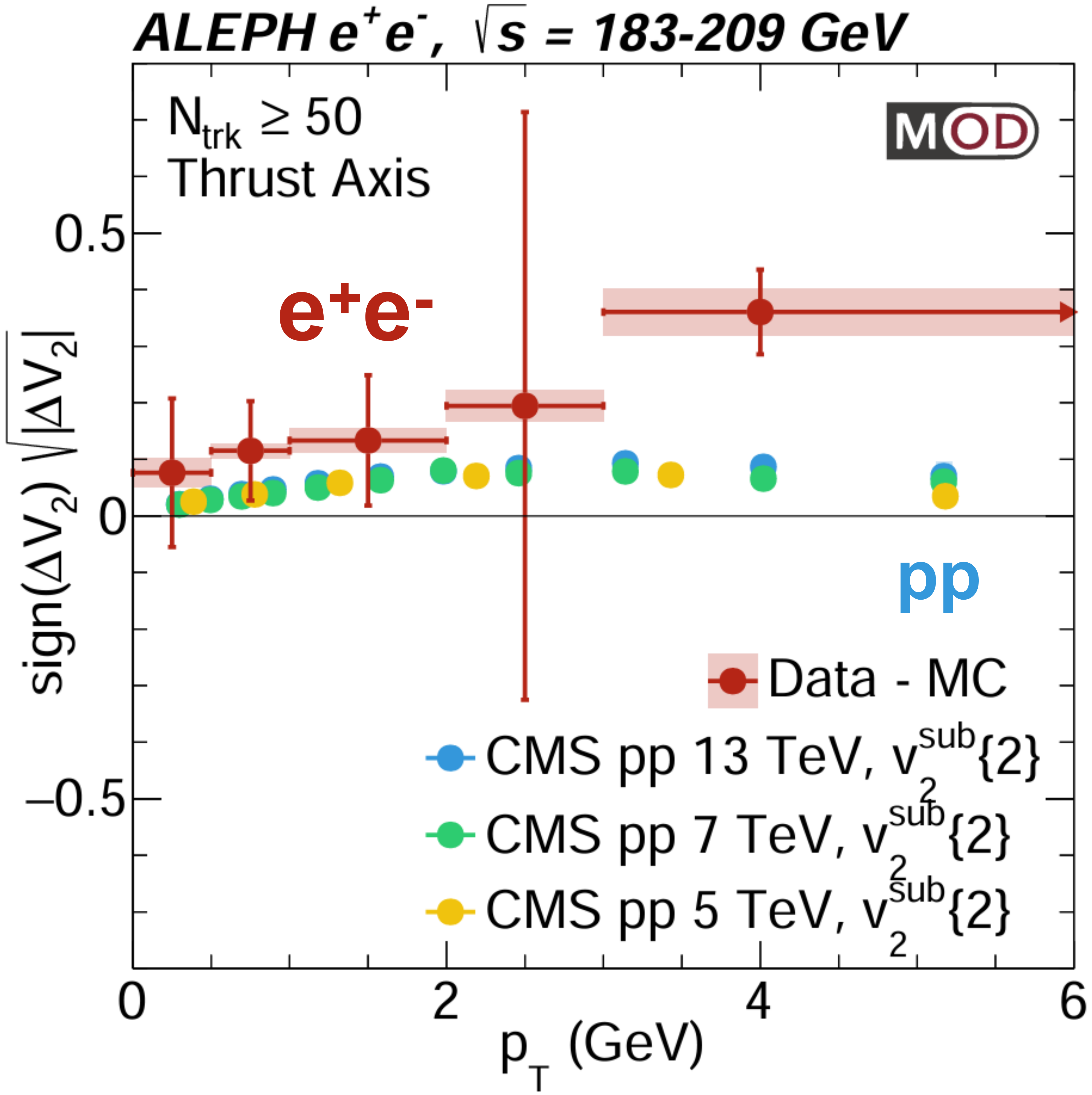


arXiv:2312.05084

Analysis note: MITHIG-MOD-NOTE-23-011 (arXiv:2309.09874)

Δv_2 in e^+e^- compared to v_2^{sub} in pp Collisions

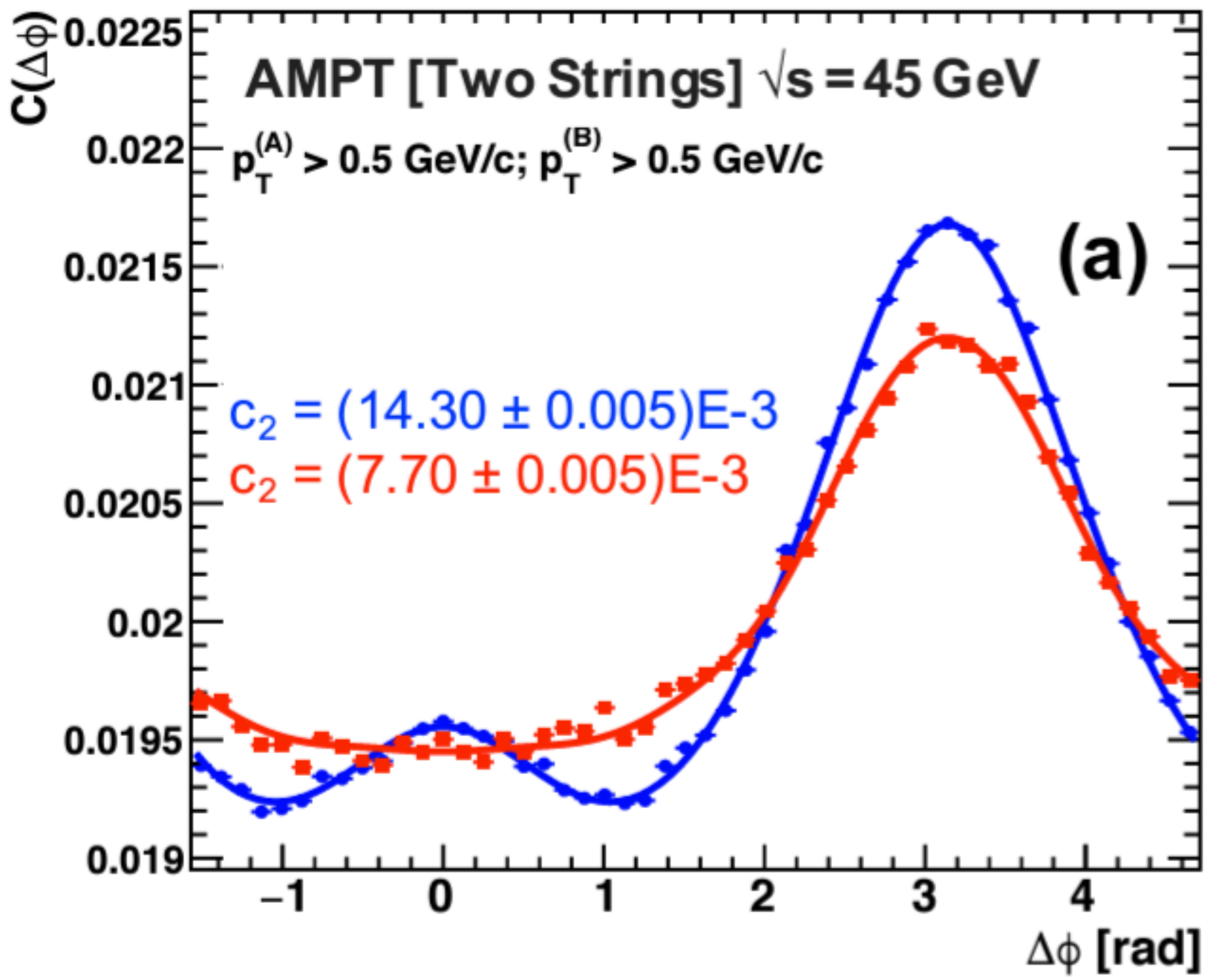


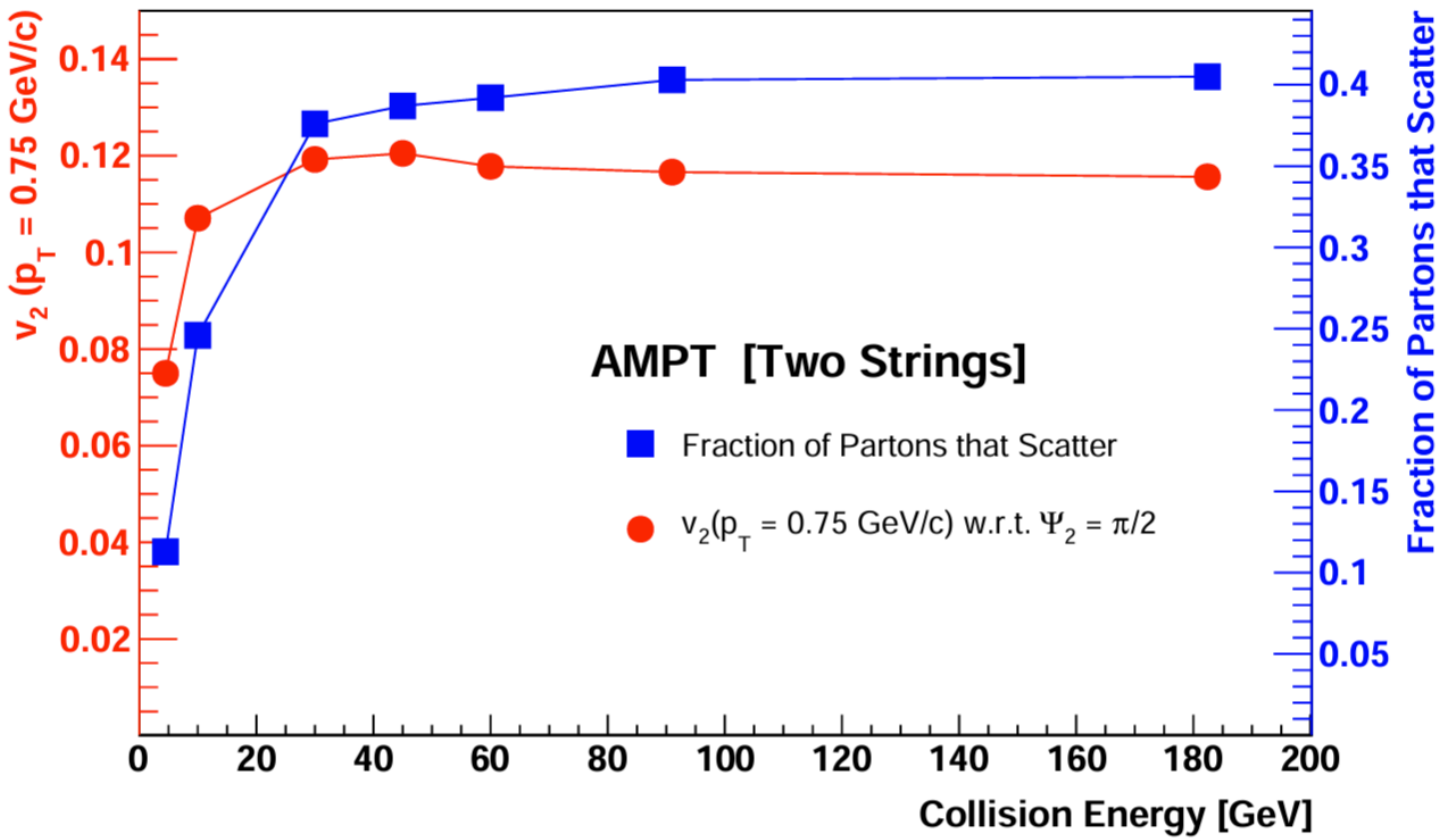


- MC based "Non-flow subtraction": $\Delta v_2 = v_2^{Data} - v_2^{MC}$
- Similar increasing trend in e^+e^- and pp data as a function of p_T

arXiv:2312.05084

Two-String Configuration Study with AMPT





PRC 97 (2018) 2, 024909

Hadronic Event Selection

- **Track Selection:**
  - Particle Flow Candidate 0, 1, 2
  - Number of TPC hits for a charged tracks >= 4
  - |d0| < 2 cm
  - |z0|< 10 cm
  - |cosθ|<0.94
  - p_T> 0.2 GeV (transverse momentum with respect to beam axis)
  - N_{TPC} >=4
  - x^2/ndf < 1000.

- **Neutral Hadron Selection:**
  - Particle Flow Candidate 4, 5 (ECAL / HCAL object)
  - E> 0.4 GeV
  - |cosθ|<0.98

- **Event Selection:**
  - Number of good charged particles >= 5 (including charged hadrons and leptons)
  - Number of good ch+neu. Particles >= 13
  - $E_{charged}$ > 15 GeV
  - $|\cos(\theta_{sphericity})|<0.82$

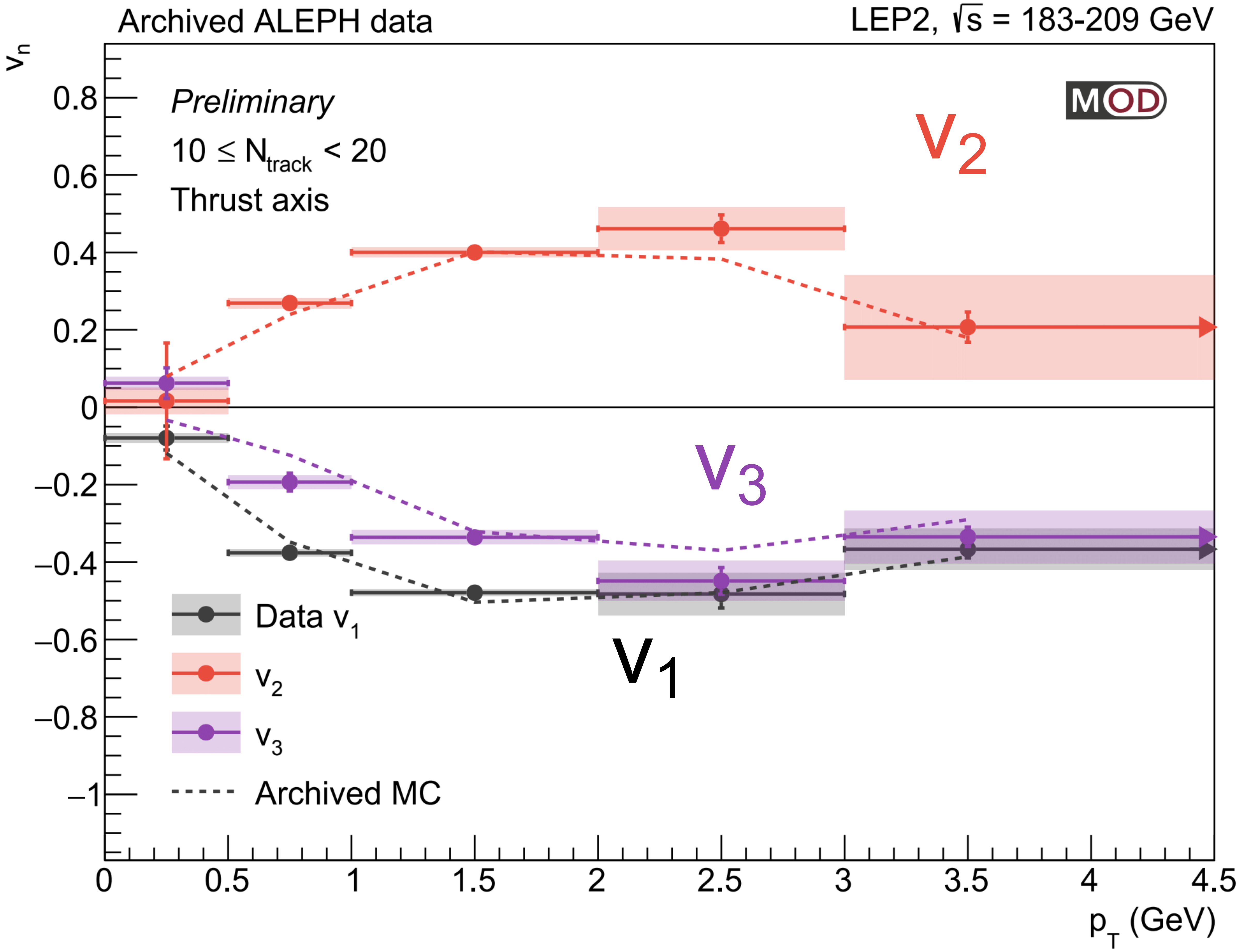
- **Jet reconstruction (anti k_T with R=0.4)**

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

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

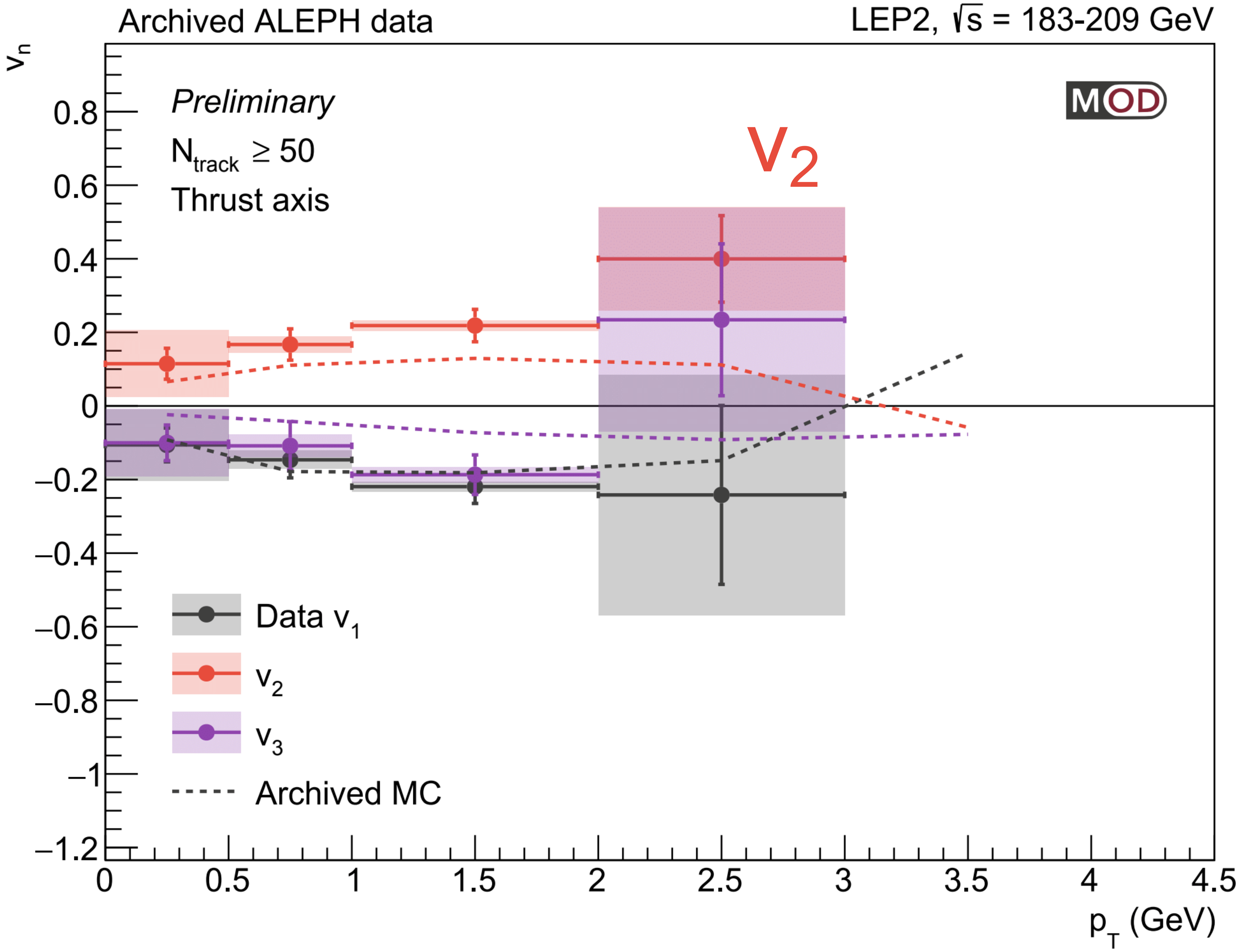
Extracted v_n vs. Charged Particle p_T

Low multiplicity 10 ≤N_{track} < 20



Good agreement between data and MC

High multiplicity N_{track}≥50



Larger v_2 and v_3 magnitudes than MC

Extracted v_n vs. Charged Particle p_T

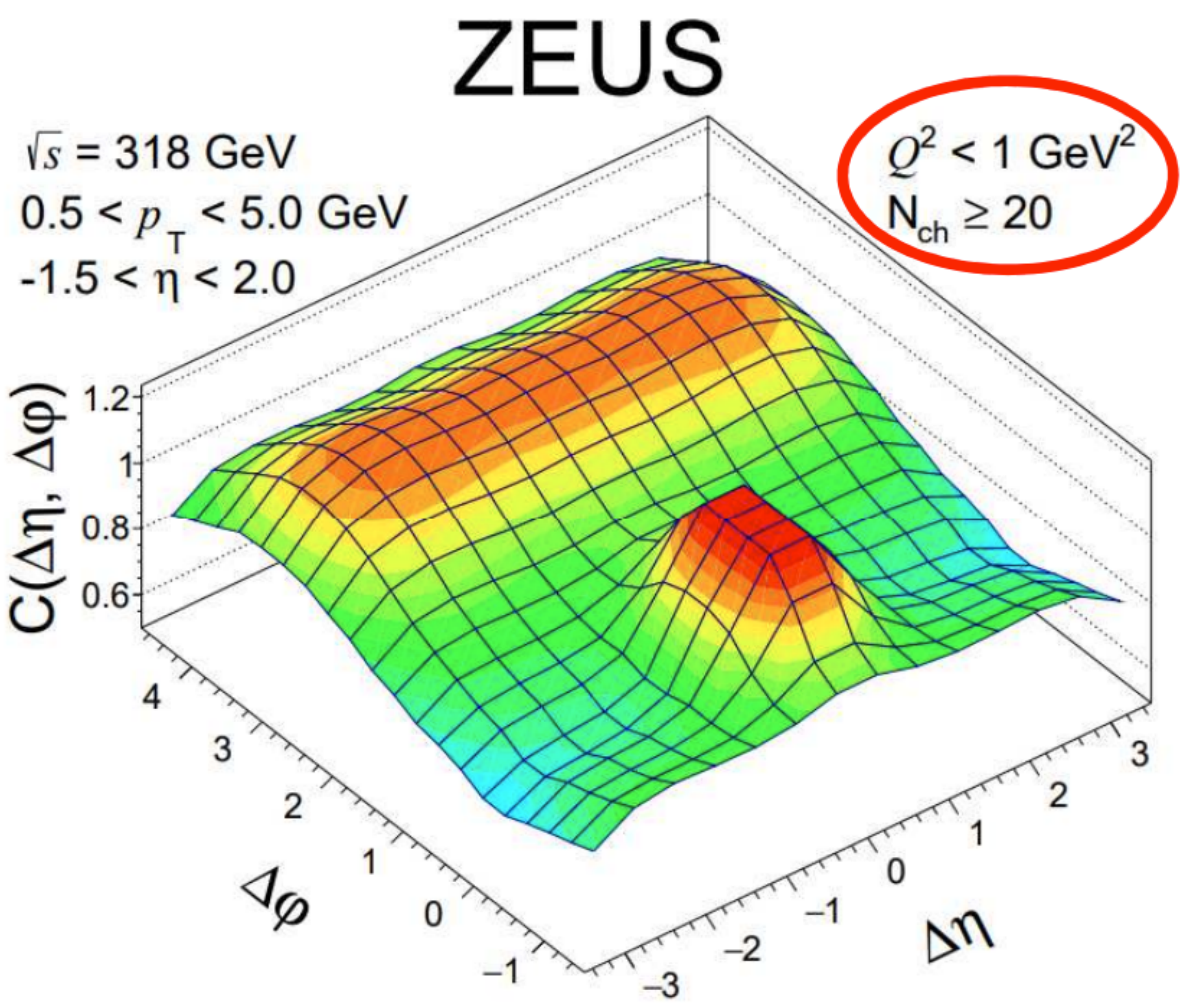
Photoproduction

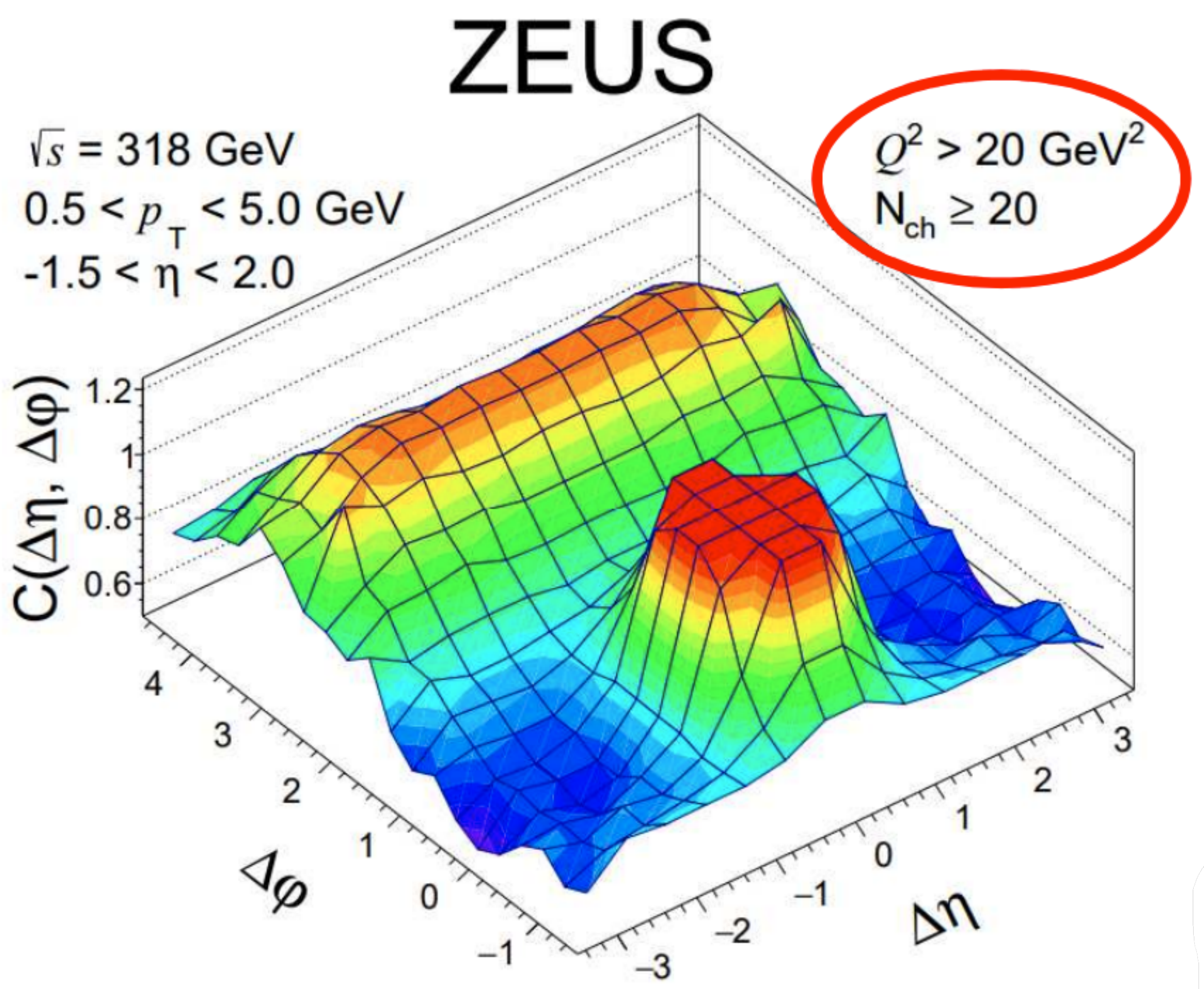
$1/\Lambda_{QCD} \sim 1$ fm

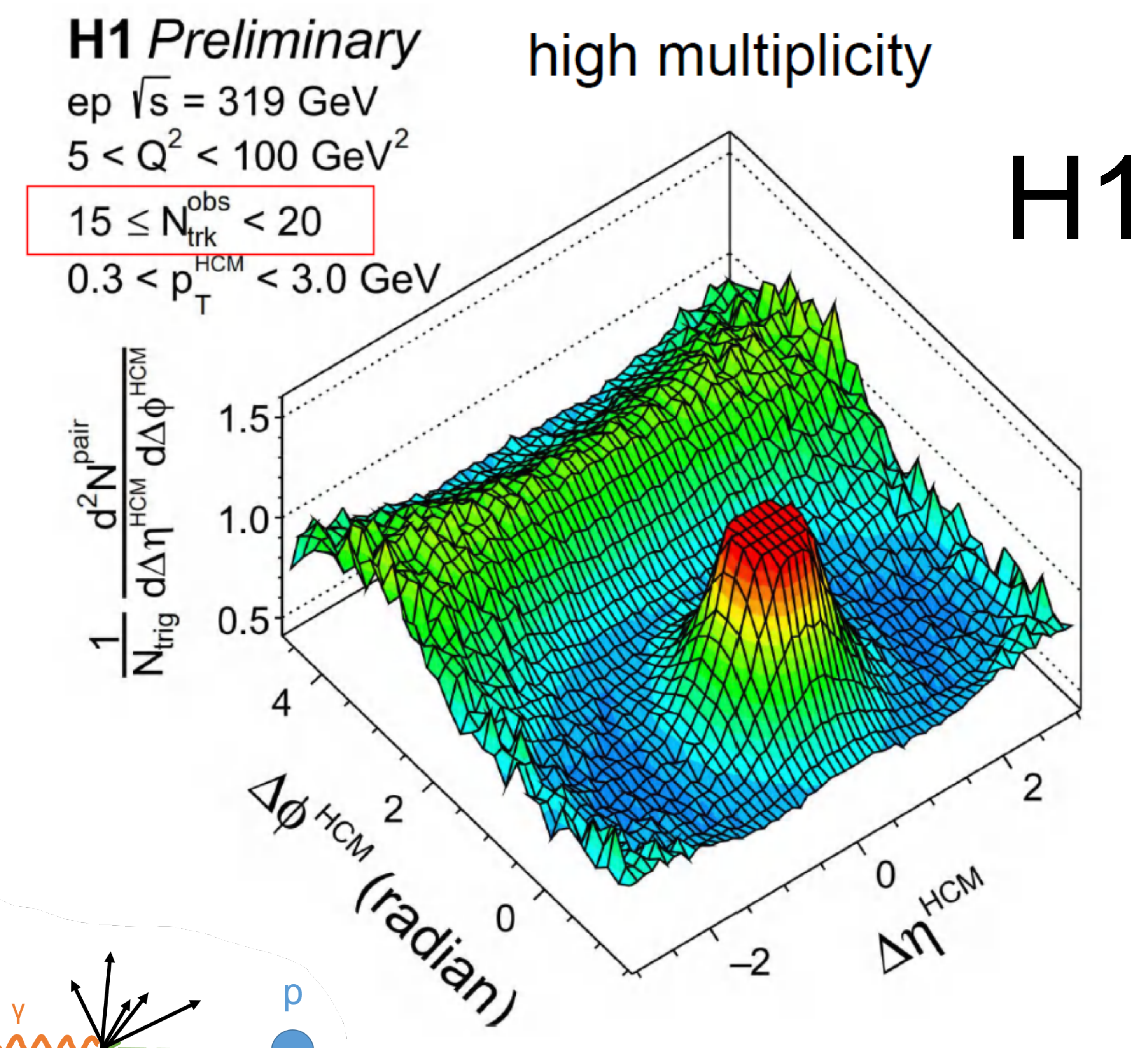
DIS

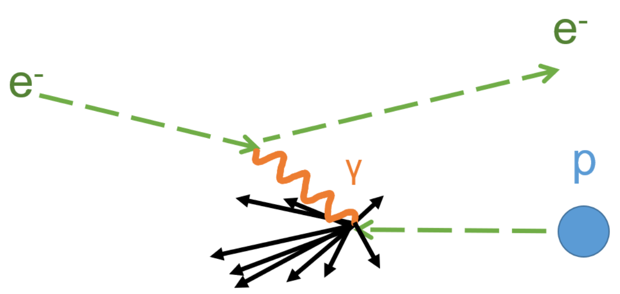
$1/Q < 0.2$ fm

DIS

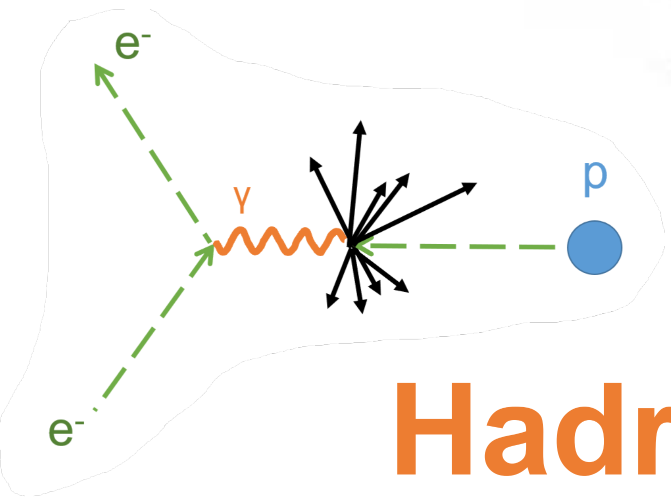








Lab Frame



Hadronic CM Frame

- ZEUS search in lab frame: No significant ridge-like signal in both photoproduction and DIS data with $N_{ch} > 20$

ZEUS DIS JHEP 04 (2020) 070
ZEUS Photoproduction JHEP 12 (2021) 102

- No significant ridge-like signal in H1 search in Hadronic CM Frame (Up to $N_{ch} = 20$)

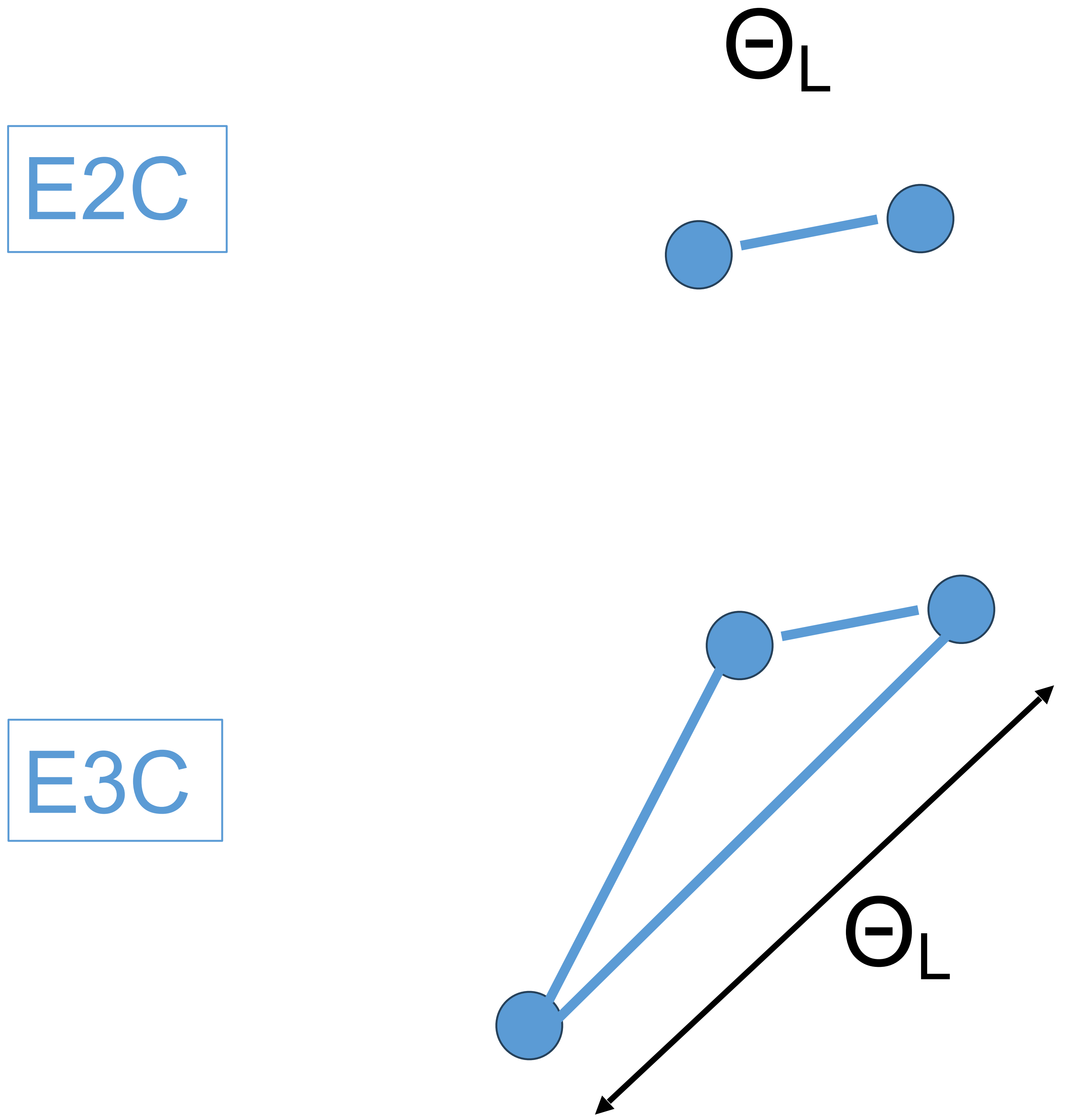
Definition of EEC in e+e-

- No Jet reconstruction, Full event

$$\frac{1}{N_{event}} \frac{d(\sum E_i E_j / E^2)}{d\theta_L}$$

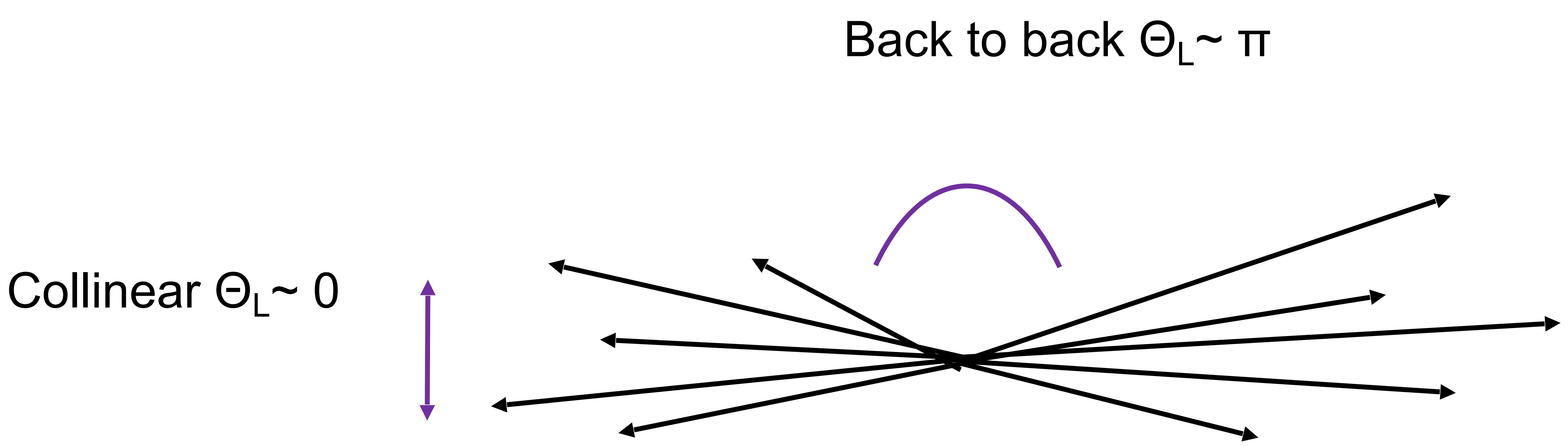
  - Sum over pairs of charged particles in the event
  - Normalize by total energy E in the event (**91.2 GeV by definition in LEP1**)
  - **Θ_L is the opening angle (in rad.)** as opposed to the R_L or x_L which is eta-phi
  - Average over all events considered

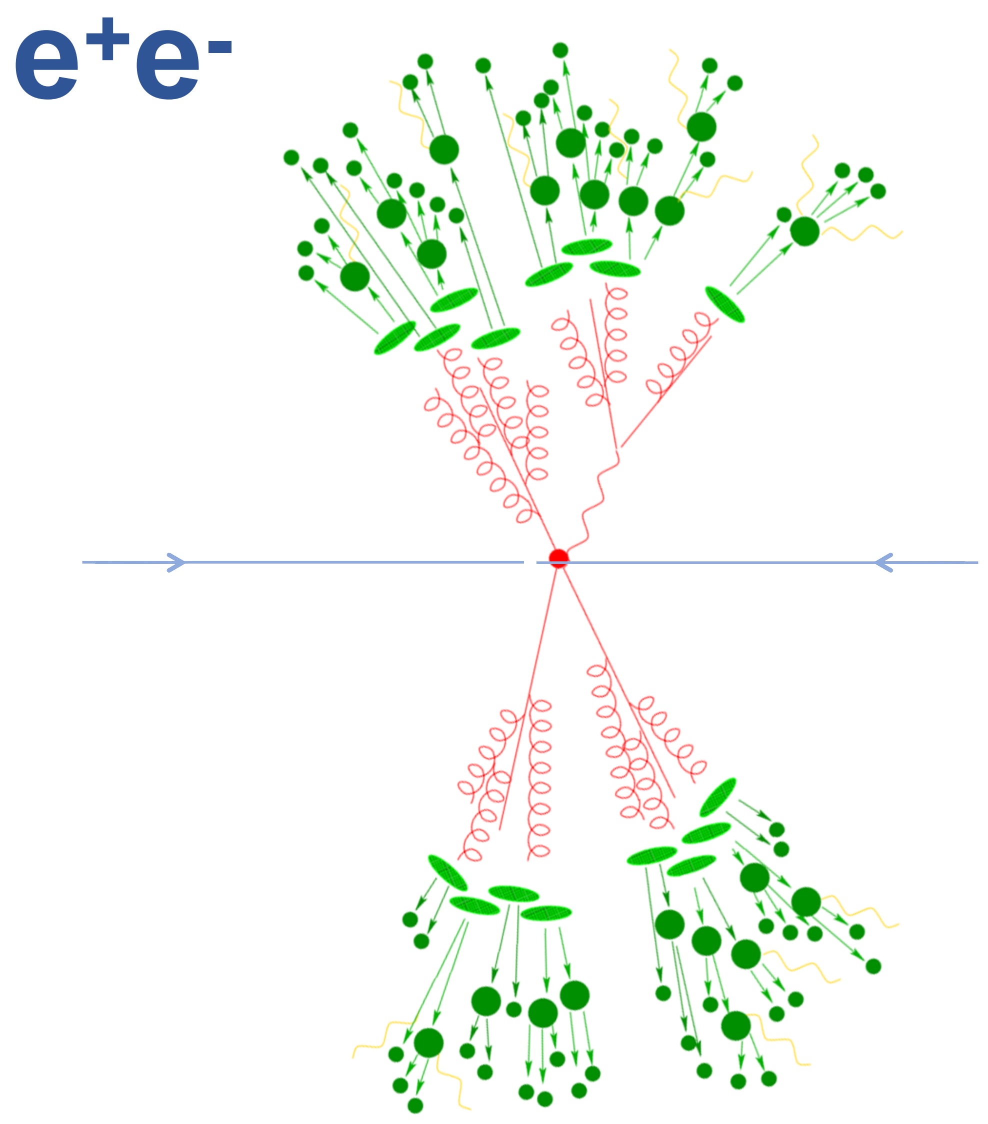
- Similar for 3-particle or higher correlators
  - For N-particle correlators, **Θ_L is defined as the largest angle of the pairs**



EEC in e^+e^-: Extending to back-to-back region

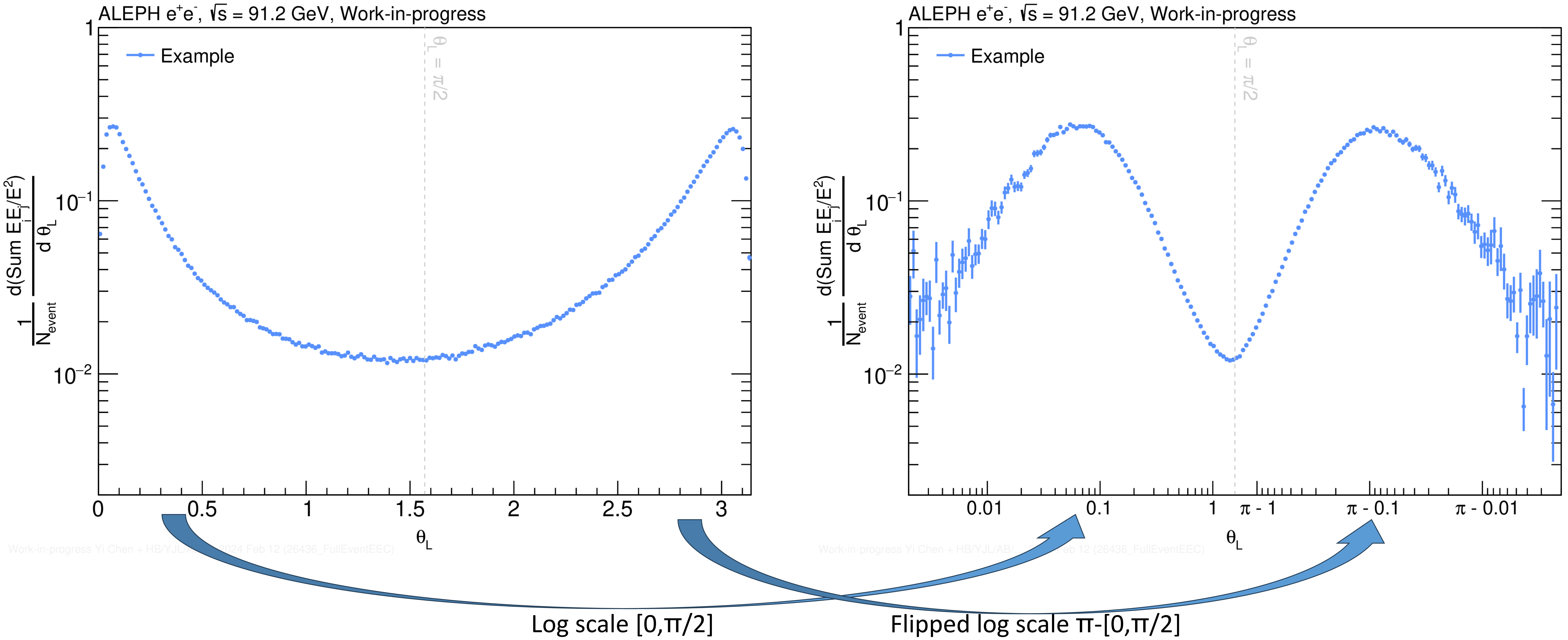
- **Back-to-back (Sudakov Limit)**
  - At $\Theta \sim \pi$
  - Study correlations of the full set of particles, not just those within jets
- **This variable cannot be explored with jet-substructure techniques**
  - Presents a unique opportunity in e^+e^-!
- Important ingredient into theory calculations to control non-perturbative effect
- Similar to the collinear limit, this can also be used to study confinement transition and strong coupling constant





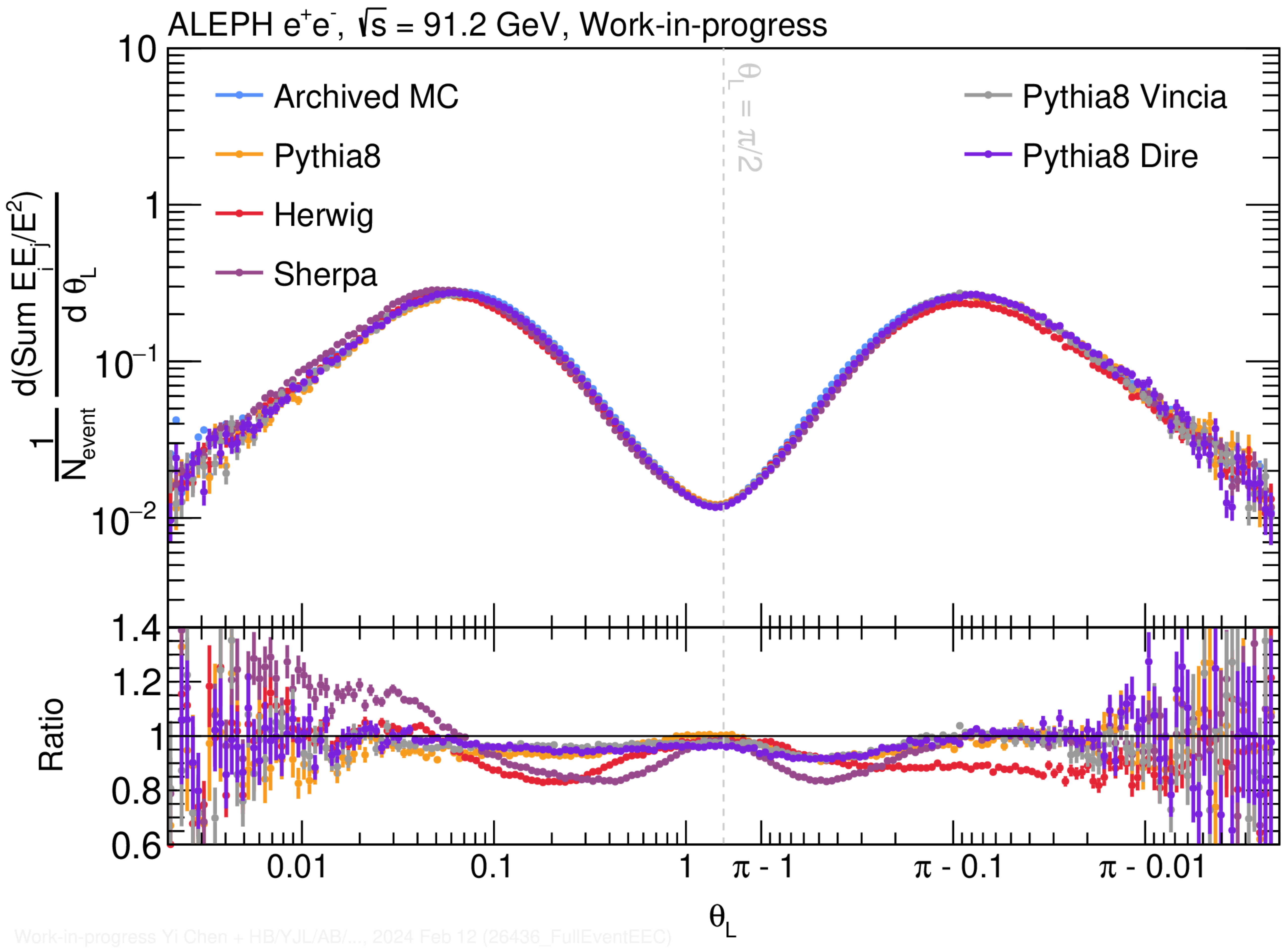
Two-particle EEC (E2C) from archived MC

- Presented in double-log-x scale to focus on the tail region



E2C from MC Generators

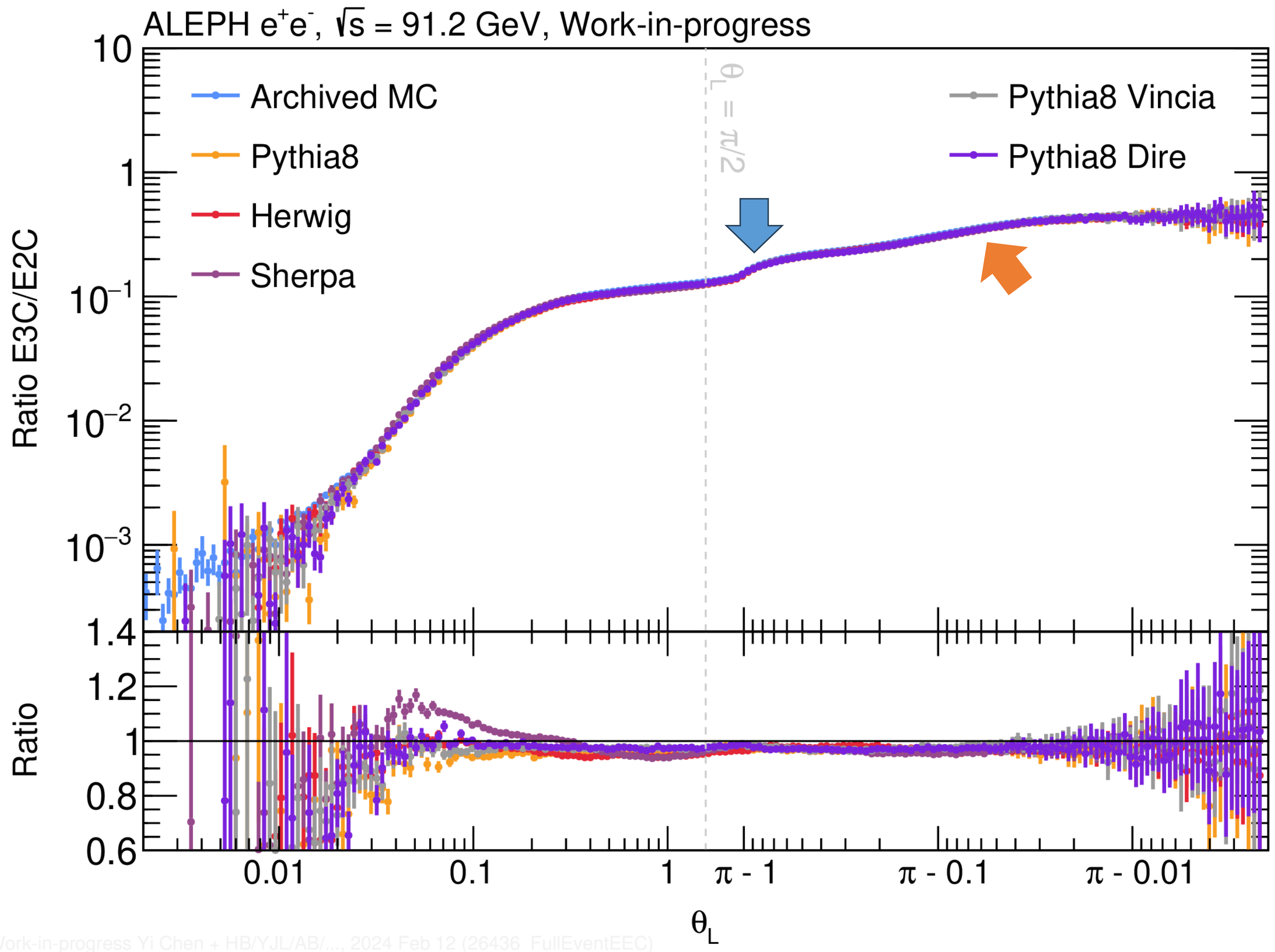
- **Dominant structures**
  - Dijet back to back
  - Left peak is what people are familiar with
  - No reason to be symmetric a priori
- Left peak (collinear)
  - Parton shower region
    - Different shower, different slope
  - Hadronization region
    - MCs roughly parallel to each other
  - Peak location
    - Correspond to 45 GeV scale
    - Different MC are a bit different
- Right peak (back-to-back)
  - Also, a peak and transition between Sudakov limit and parton shower

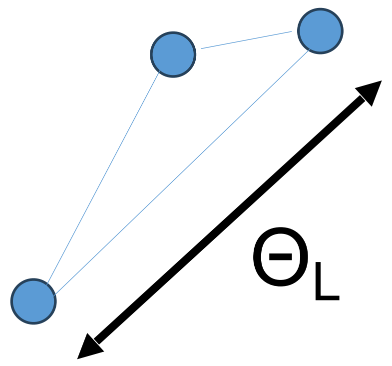


3-particle EEC (E3C) from MC in e+e-

- Observe non-trivial slope in the hadronization region
  - Away-side ($\Theta_L > \pi/2$) region: roughly flat
  - A small structure around $2\pi/3$:
    - Reject **3-jet** event removes this particular structure
  - Further increase beyond $2\pi/3$: **di-jet**

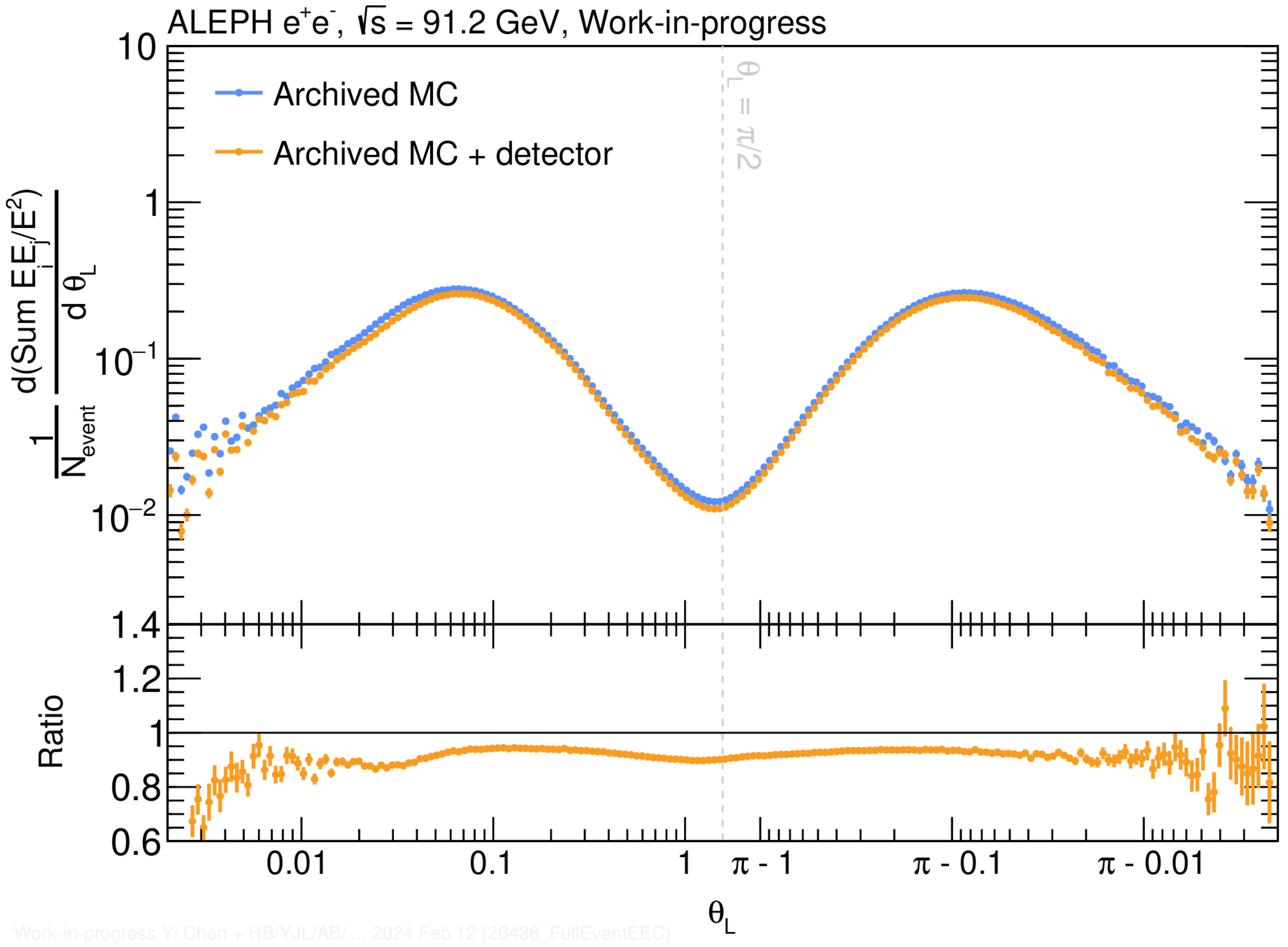
- MCs agree with each other within 5-10%
  - Except for the small angle region of SHERPA



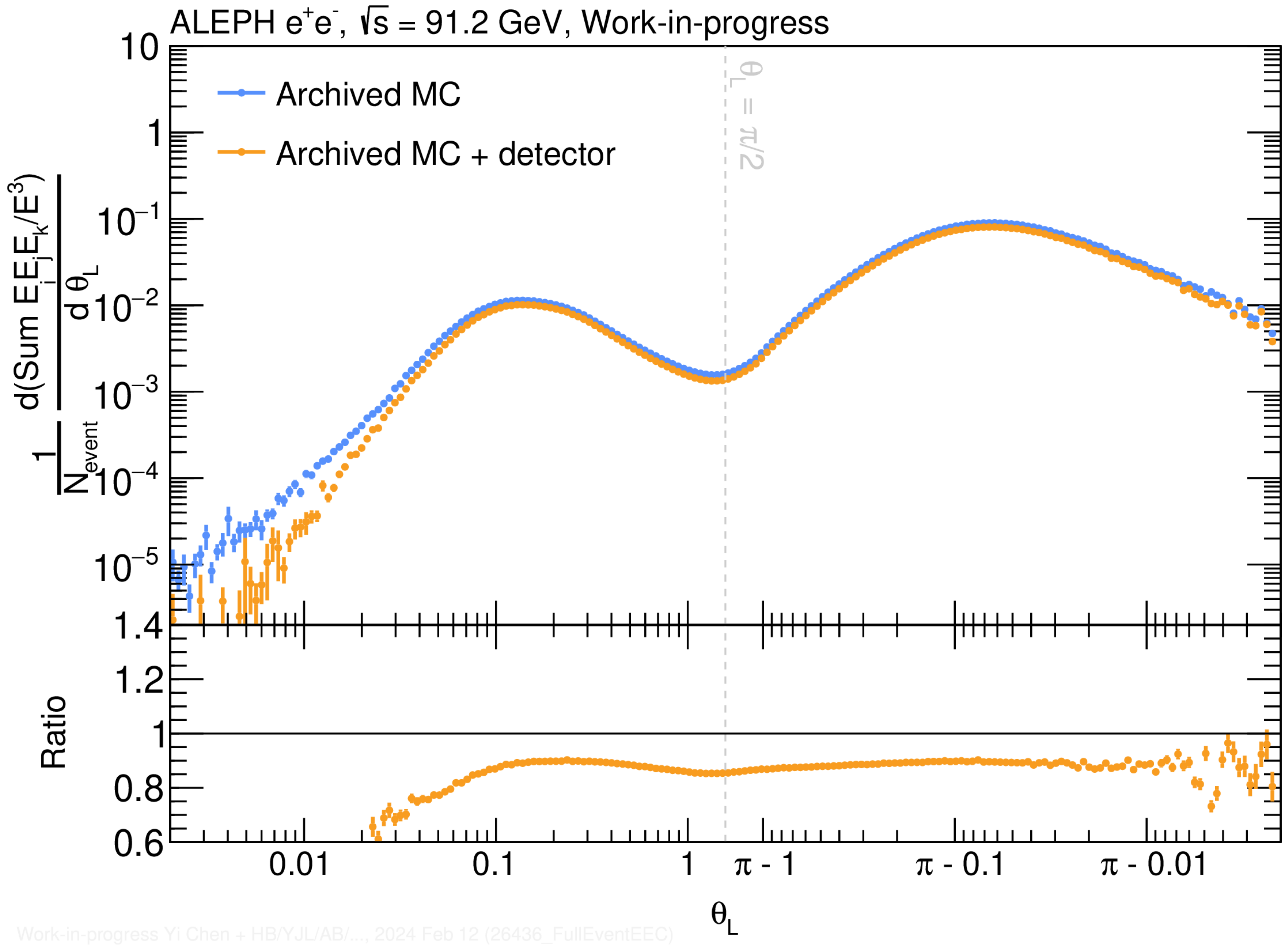


Detector Effects based on Archived ALEPH MC

- Will we be able to measure the correlators? **Yes!**
- Generator- and detector-level results are similar over a large phase space



E2C



E3C