Measurement of Two-Particle Correlations and Flow Coefficients in High Multiplicity e^+e^- Collisions Using Archived ALEPH Data at 91-209 GeV

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in collaboration with Austin Baty, Anthony Badea, Chris McGinn, Jesse Thaler, Gian Michelle Innocenti, and Tzu-An Sheng

ISMD 2023, Gyöngyös, Hungary, Aug. 24th

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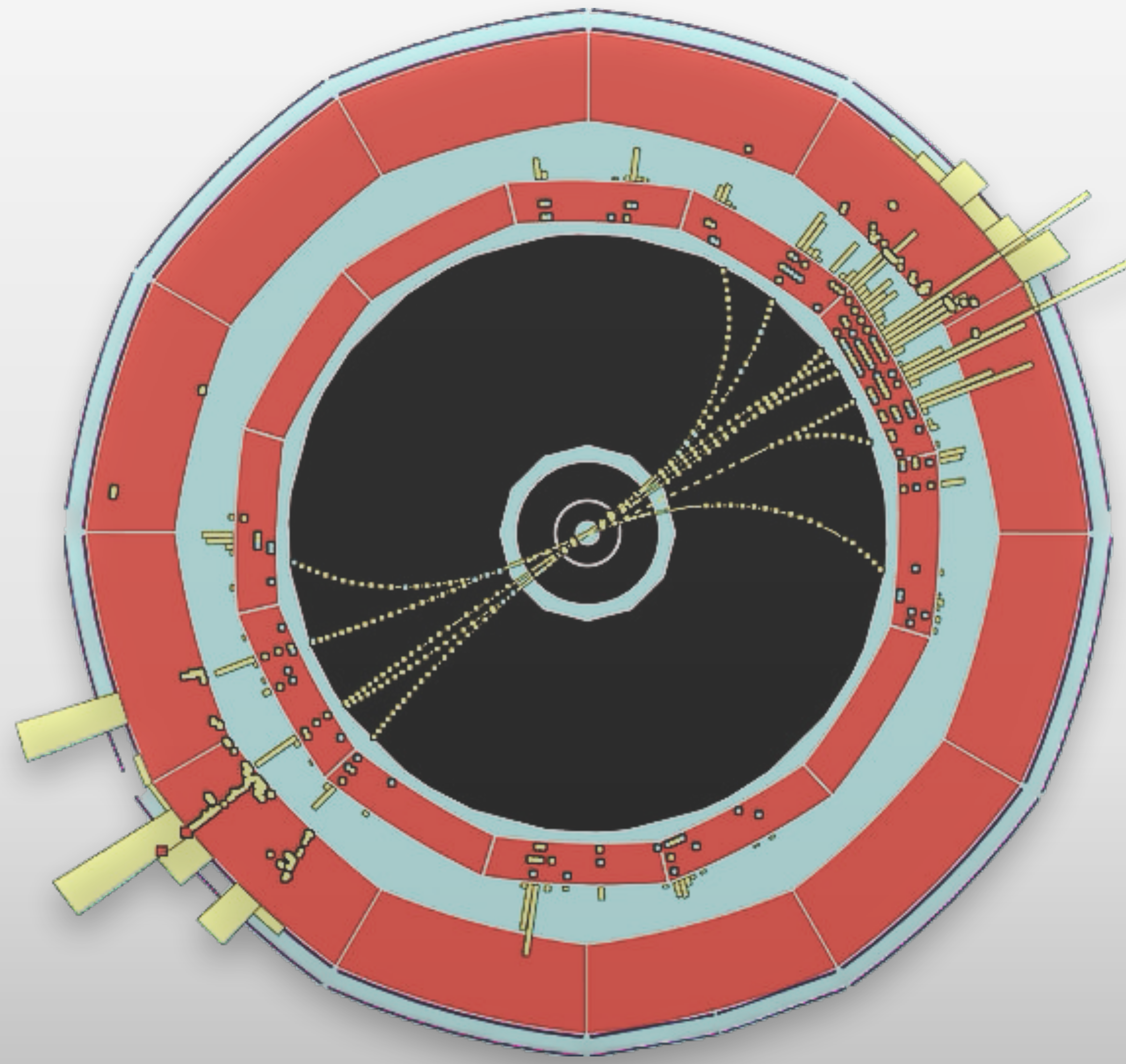
Advantages of e^+e^- collisions to study QCD

Structureless e^+/e^-

- No uncertainties from beam PDF
- No MPI, no pileup



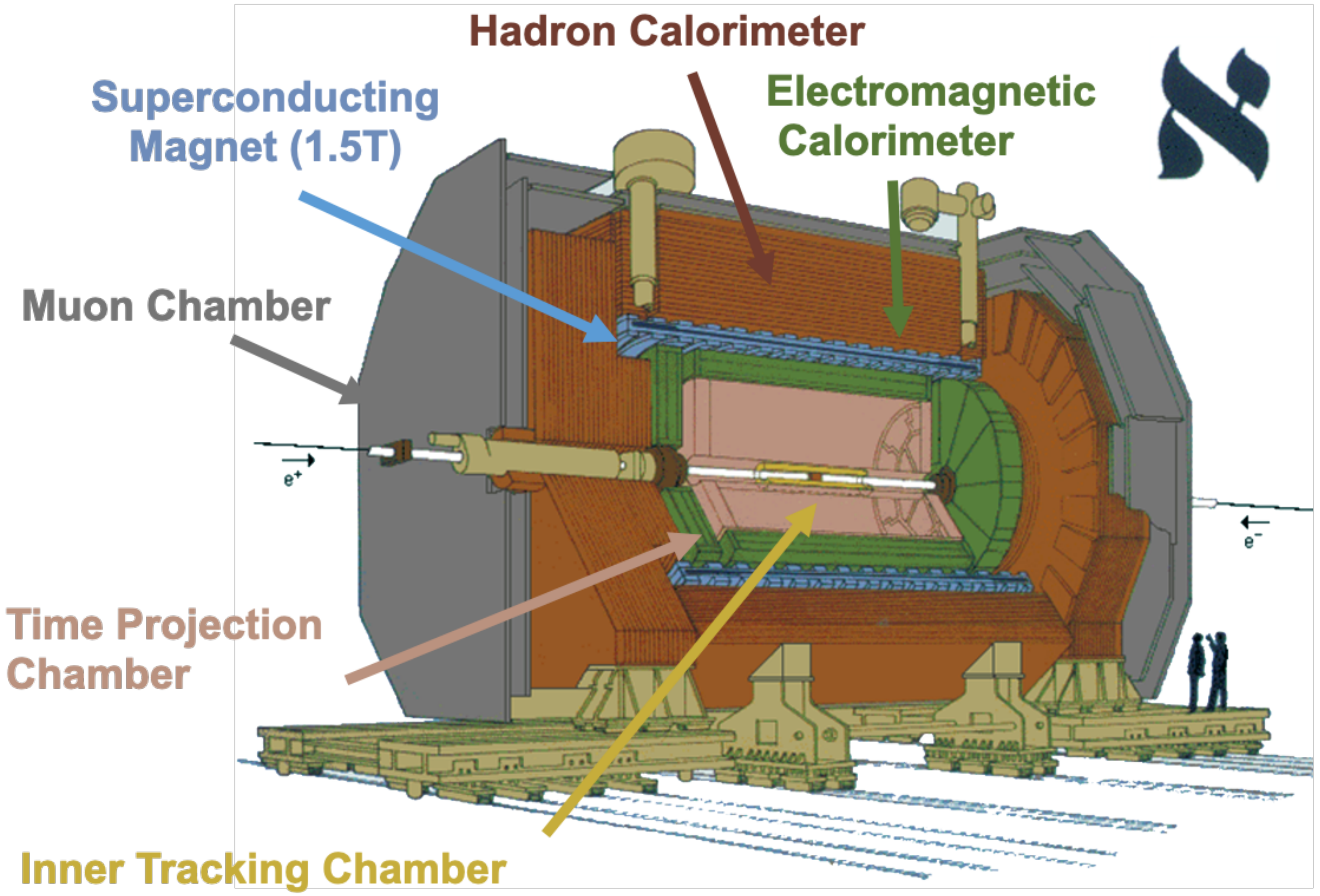
Negligible beam remnant

Controllable initial-state QED radiations

Color-neutral e^+/e^-

- No gluonic initial state radiations
- No initial state correlation effects (such as CGC)

The ALEPH detector and sample



- Re-analyze with MIT Open Data format
- ALEPH archived Pythia6 MC:
  for corrections and the comparison baseline

LEP1

Z-resonance dataset

- $\sqrt{s} = 91.2$ GeV
- Dominant by $e^+e^- \to \gamma^*/Z \to f\bar{f}$
- Suppressed bkg. at the Z-pole

LEP2

High-energy dataset

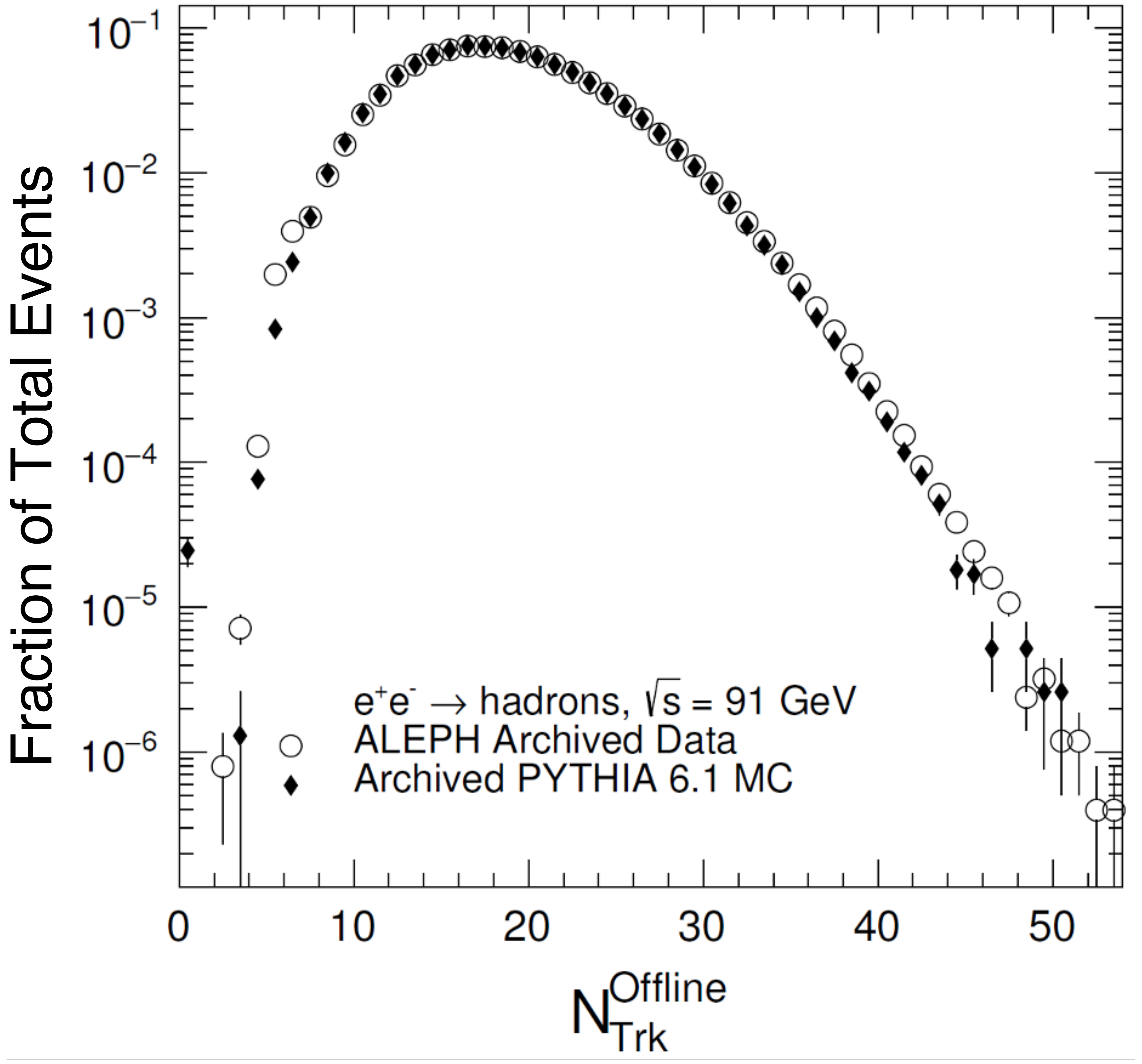
- $\sqrt{s} = 130\text{-}209$ GeV
- Above W^+W^- threshold $(160\ \text{GeV})$, more possible channels
- Radiative-return-to-$Z \Rightarrow$ effective COM energy $\sqrt{s'}$

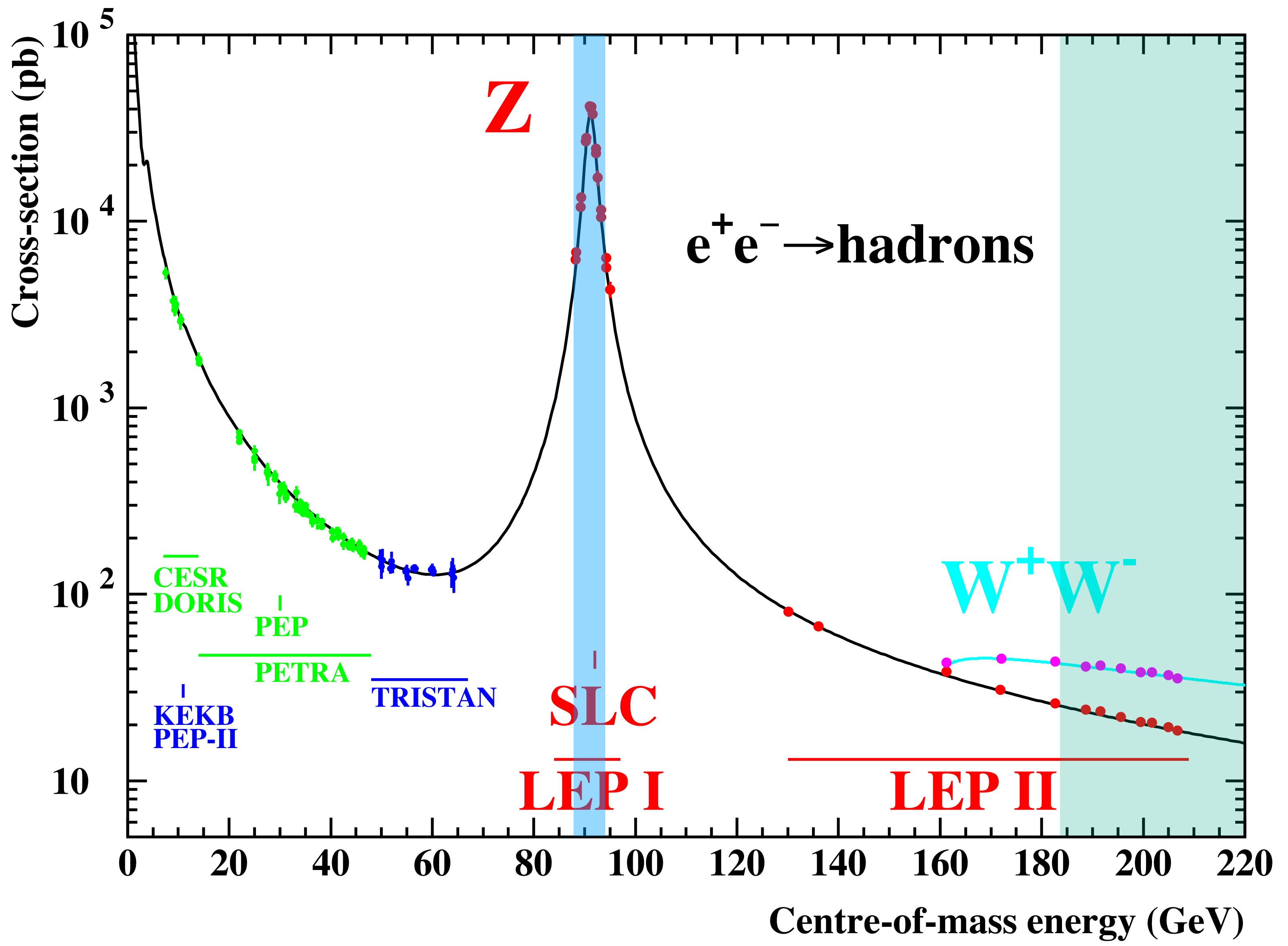
* There are also Z-resonance events in LEP2 sample

Charged multiplicity distributions

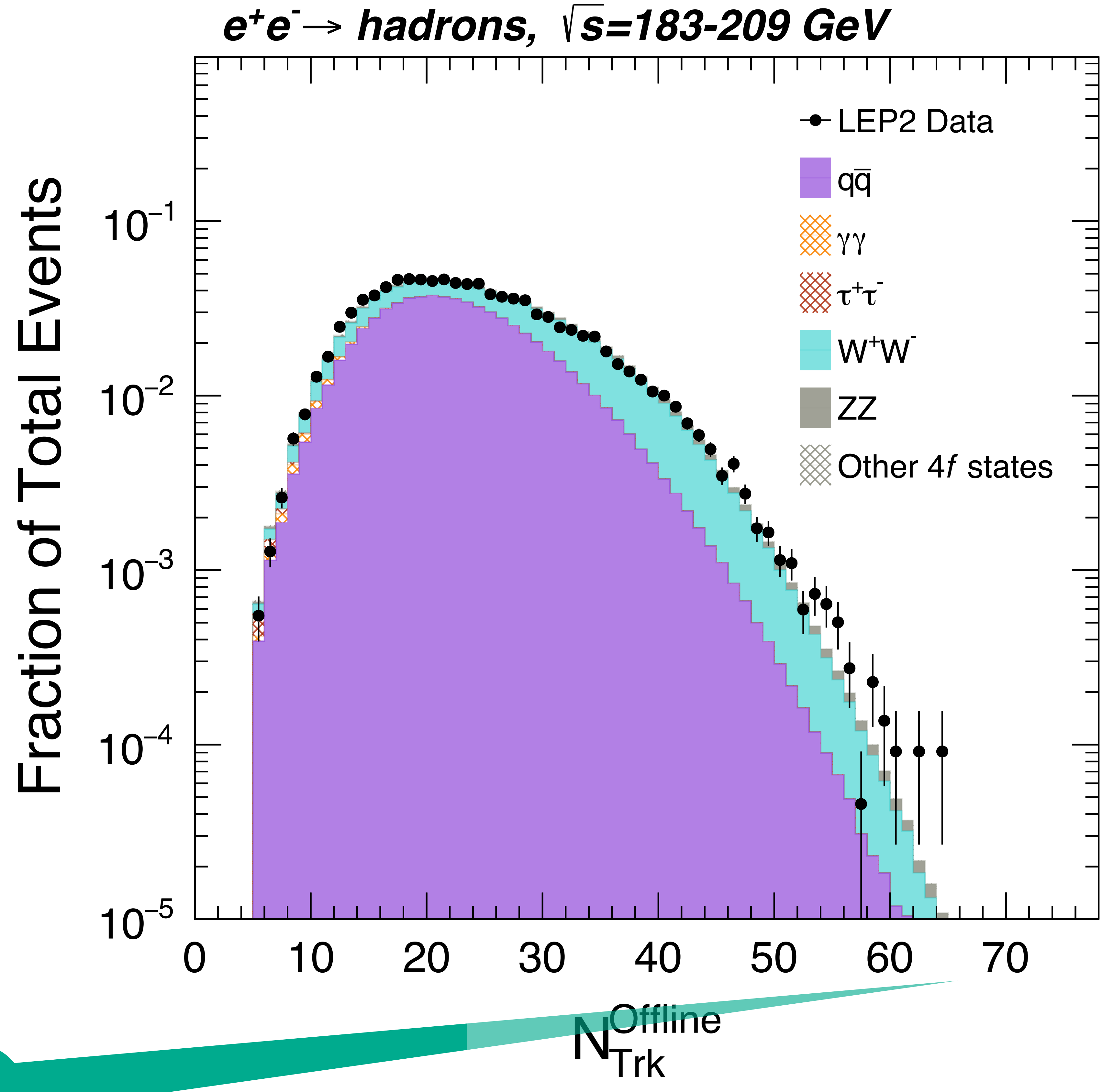
Z-resonance dataset

Clean!





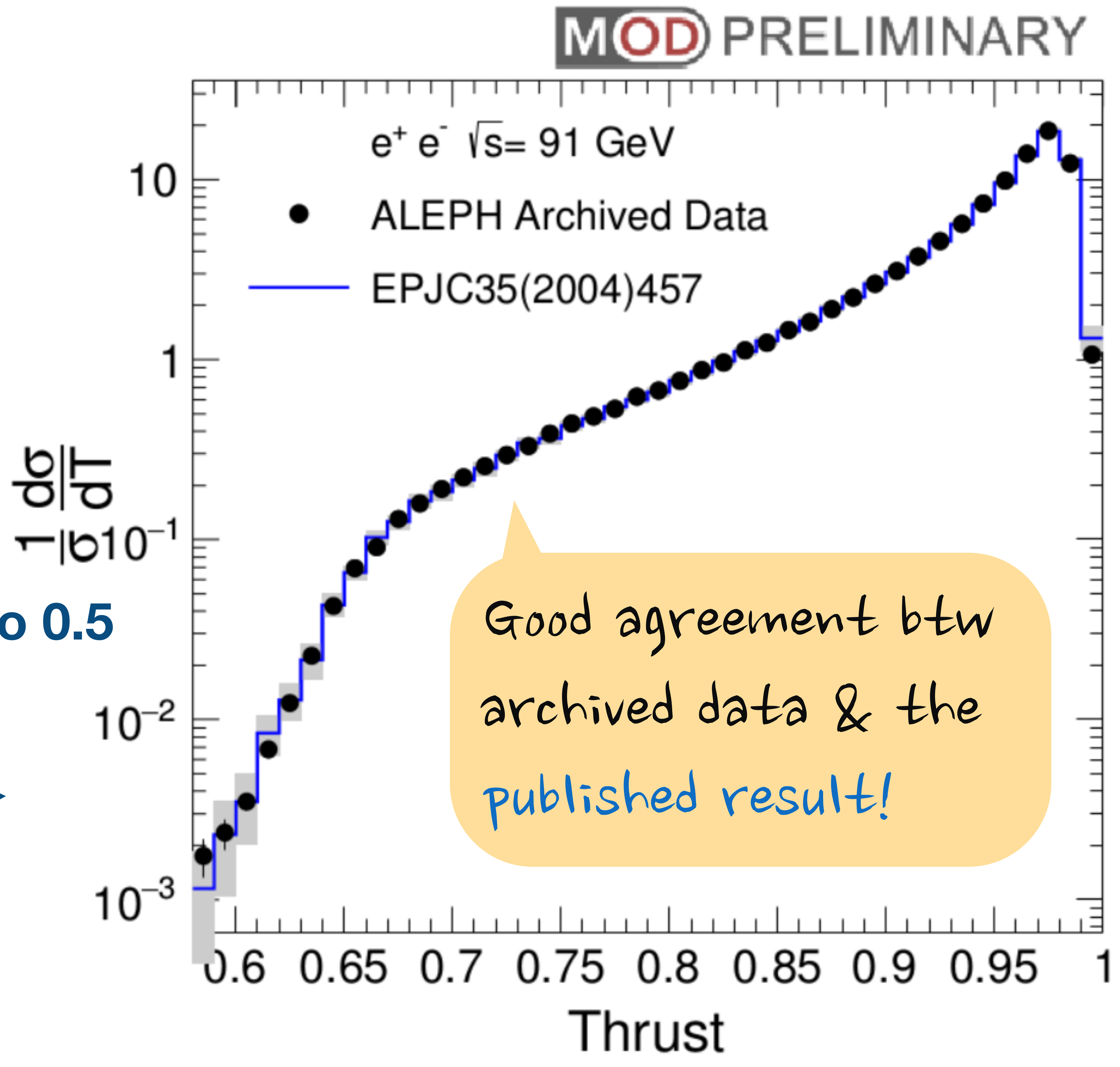
High-energy dataset



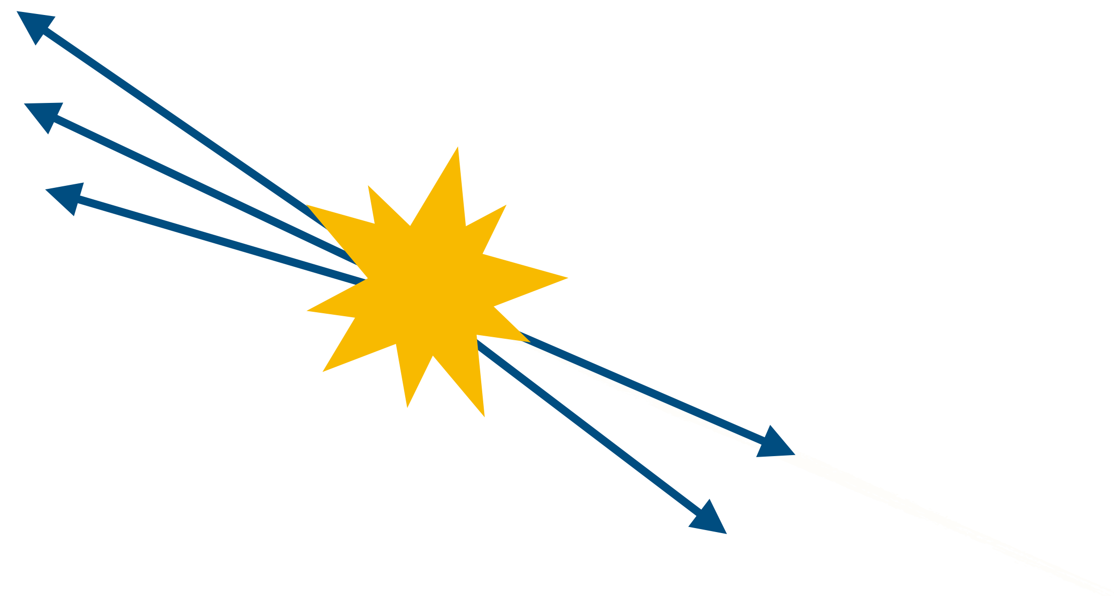
Higher multiplicity reach

* $N_{Trk}^{Offline}$: number of charged particles after selections

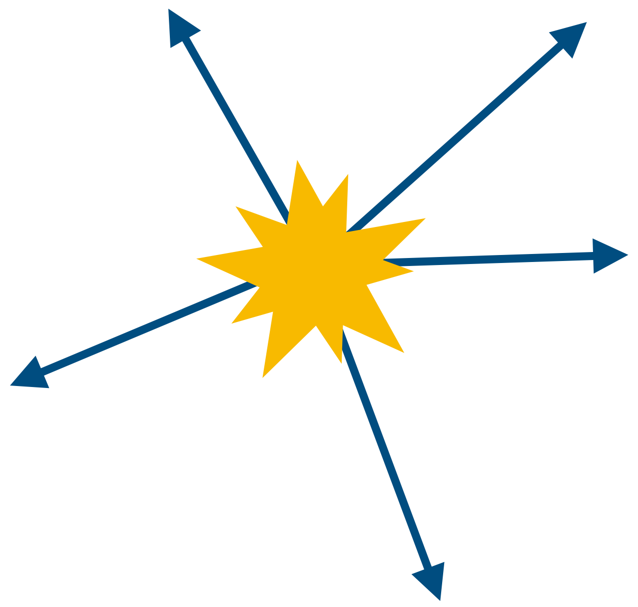
LEP1 Unfolded thrust distribution — Good quality data



Pencil-like: *T* closes to 1



Spherical: *T* closes to 0.5

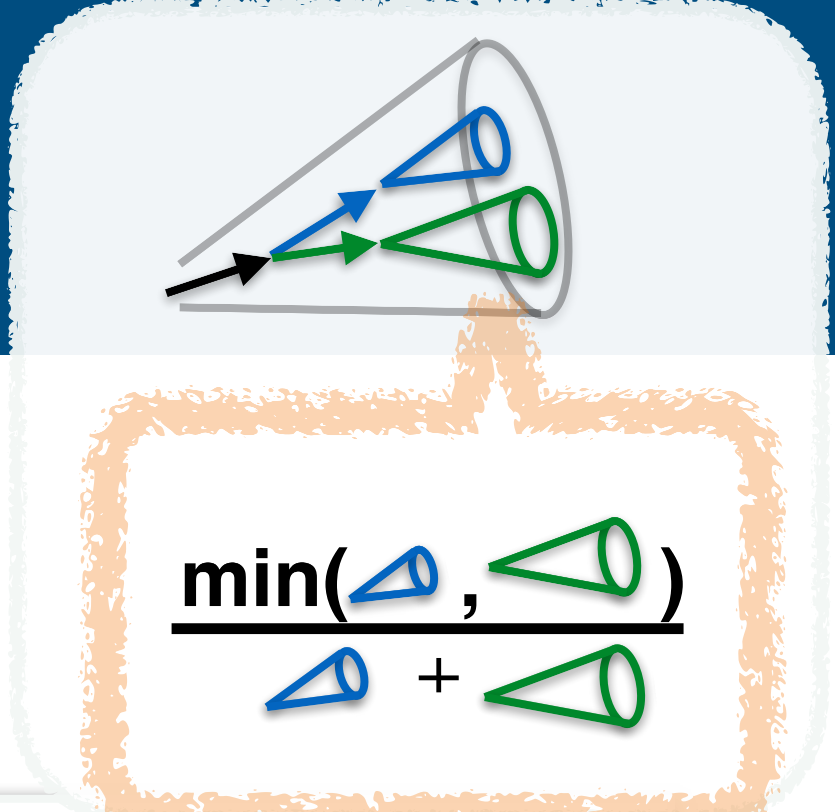


Thrust (T)

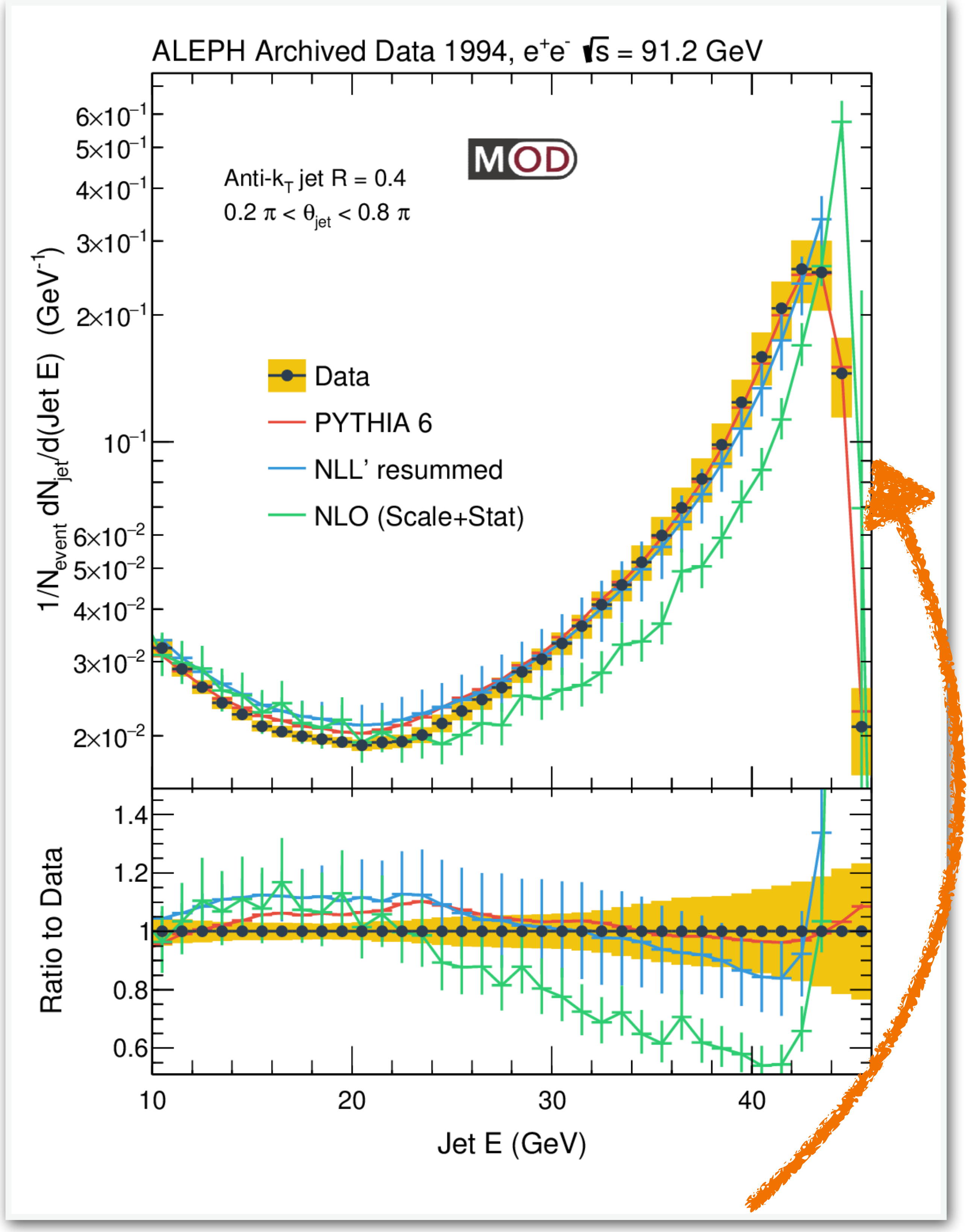
$$T = \max_{\hat{n}} \frac{\sum_i \left| \vec{p_i} \cdot \hat{n} \right|}{\sum_i \left| \vec{p_i} \right|}$$

LEP1

Further comparisons with MC — Anti-k_T jet measurements

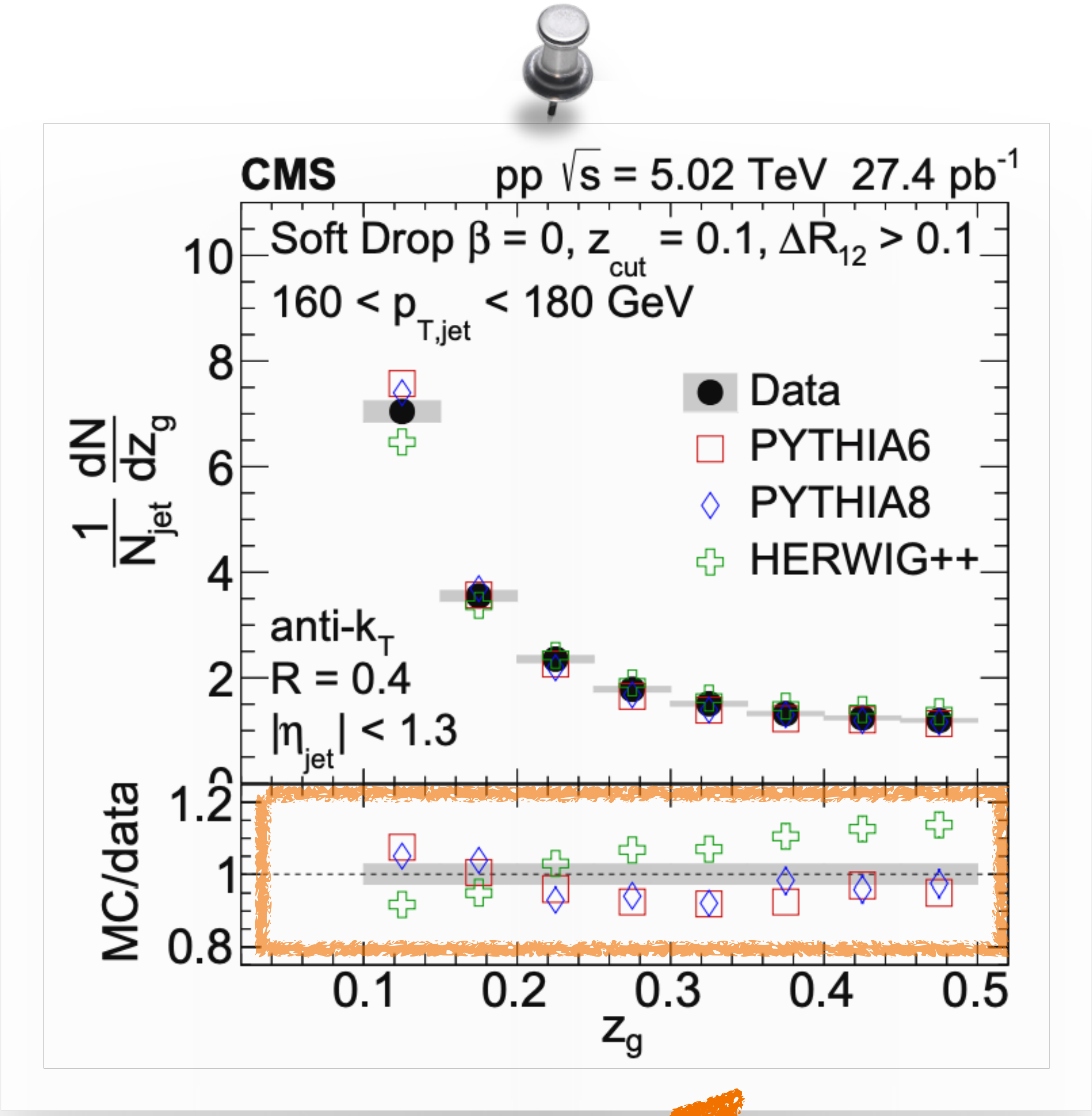


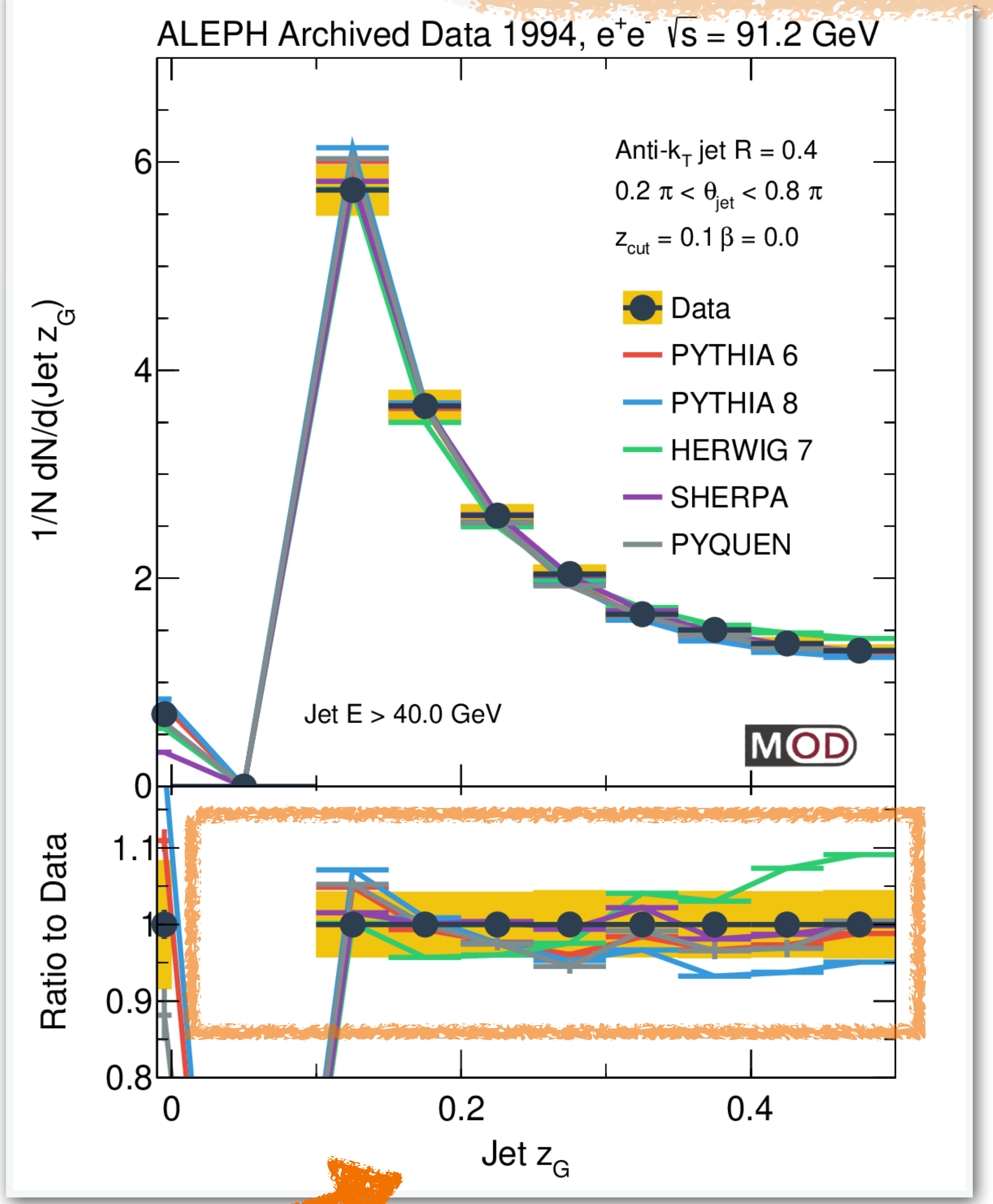
Jet energy spectrum



Rising edge sensitive to jet function

Jet substructure — energy sharing z_G





Similar trend btw e^+e^- & pp

Room for improvement already in e^+e^-!

ALEPH jet
[JHEP 06 (2022) 008]

Cleanest tests for heavy-ion phenomenology & QCD

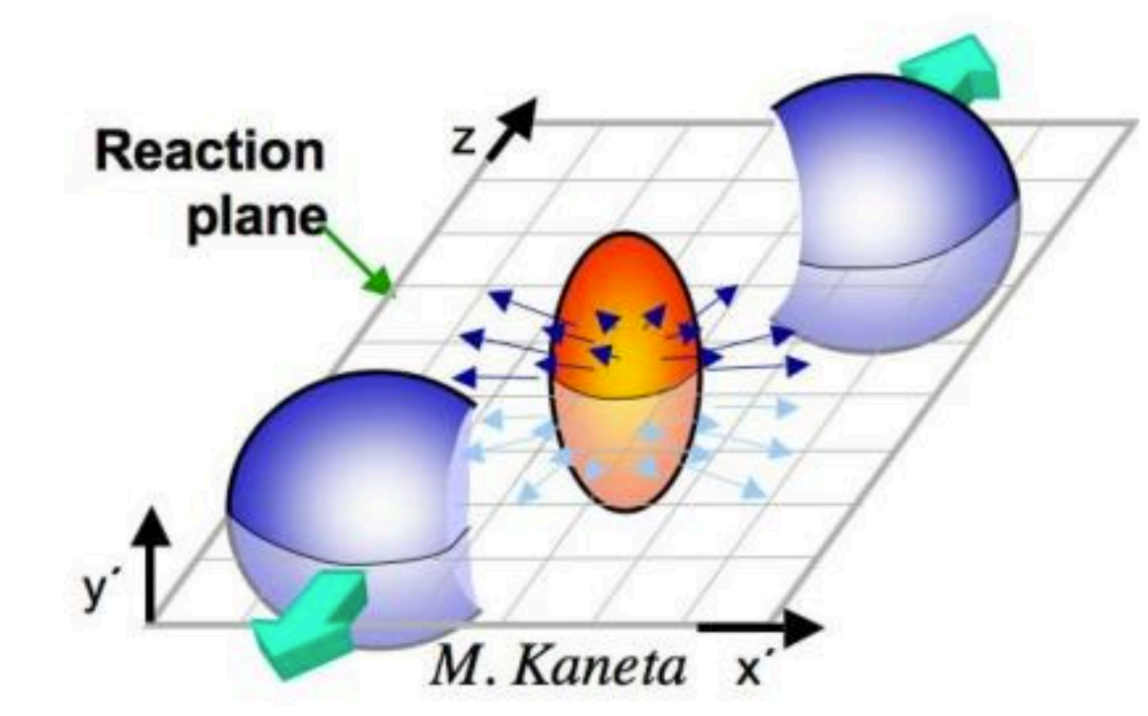
Two-particle correlations (2PC)

- Soft probe to study Quark-Gluon Plasma (QGP) in HI collisions
- **Spatial anisotropy** can happen as:

  Initial density fluctuation

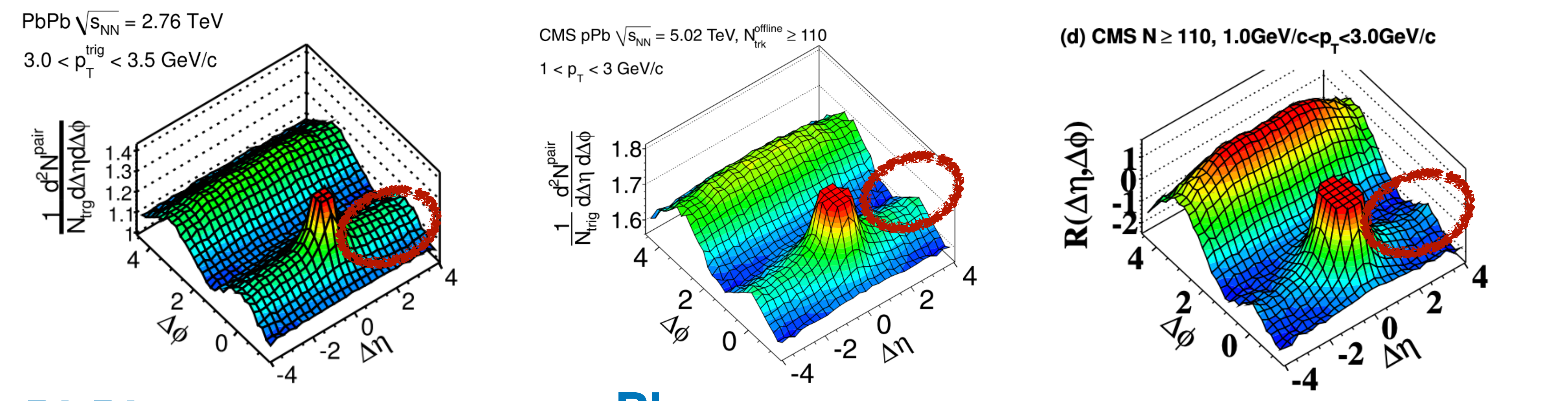
  +

  Hydrodynamical expansion of perfect-fluid-like QGP



Spatial anisotropy

- **Ridge-like signals** (spatial anisotropy) appears in not only AA, but also pA & pp!

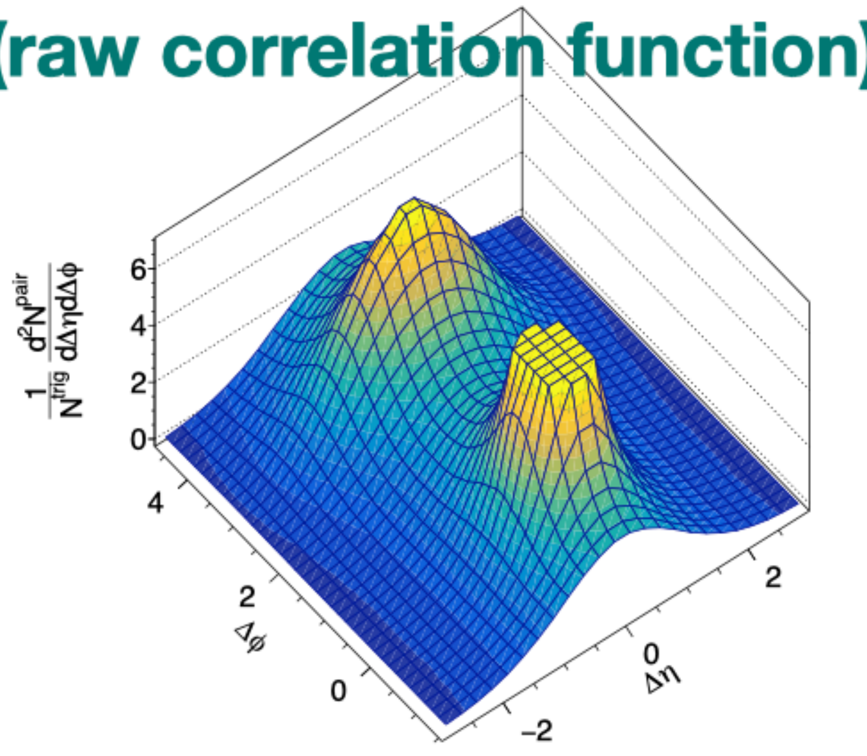


PbPb [Eur. Phys. J., C72] **pPb** [Phys. Lett. B718 (2013) 795-814] **pp** [JHEP 1009 (2010) 091]

- e^+e^- collisions is clean!
  - Onsets of azimuthal anisotropic correlations?
  - Useful test with the absence of initial state correlations effect

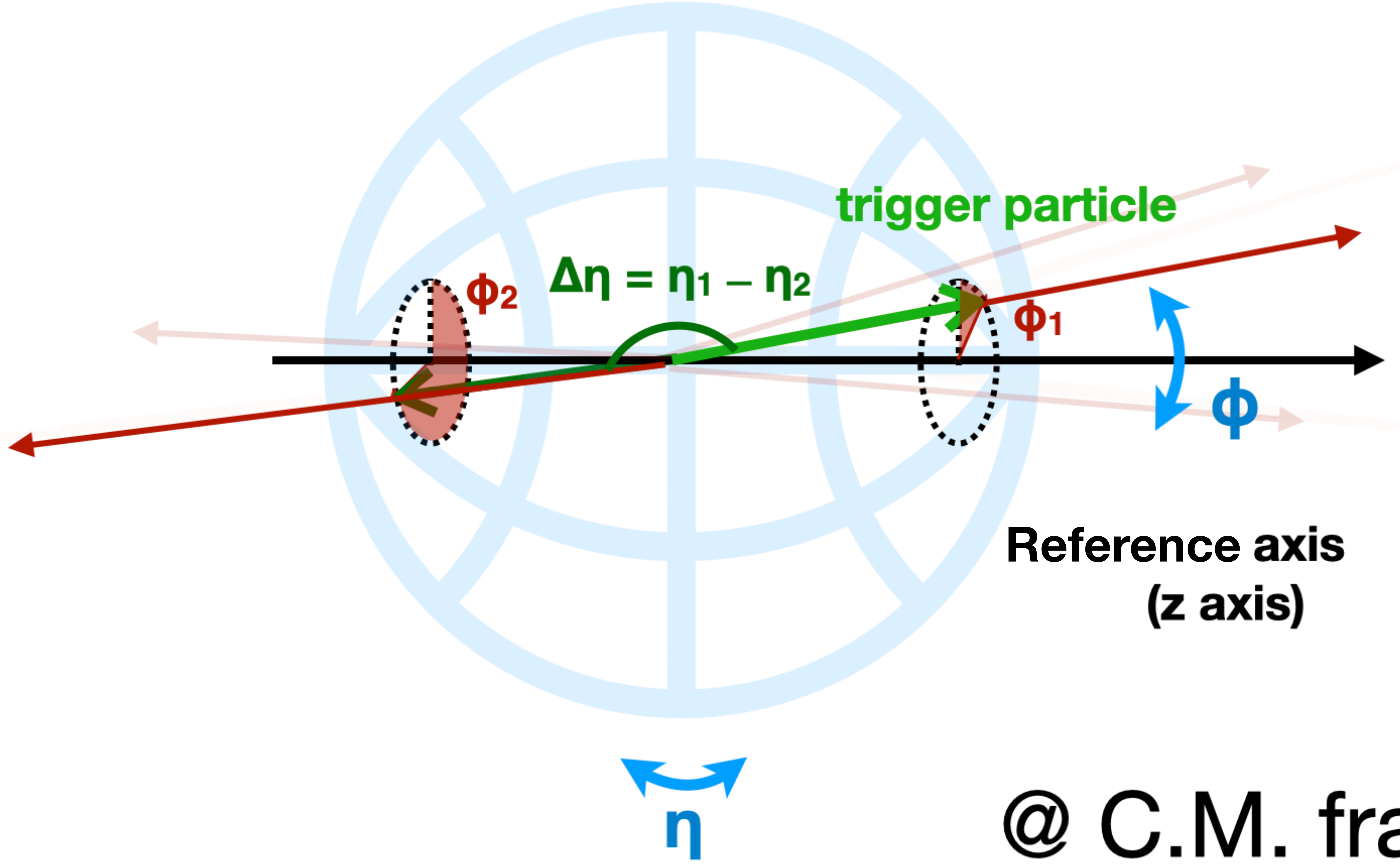
Analysis method: 2PC observable construction

Signal
(raw correlation function)



$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trk}^{corr}} \frac{d^2N^{same}}{d\Delta\eta d\Delta\phi}$$

Track pairs' angular difference in
η (pseudorapidity), ϕ (azimuthal angle)



$\eta = -\ln\tan(\theta/2)$

@ C.M. frame

Analysis method: 2PC observable construction

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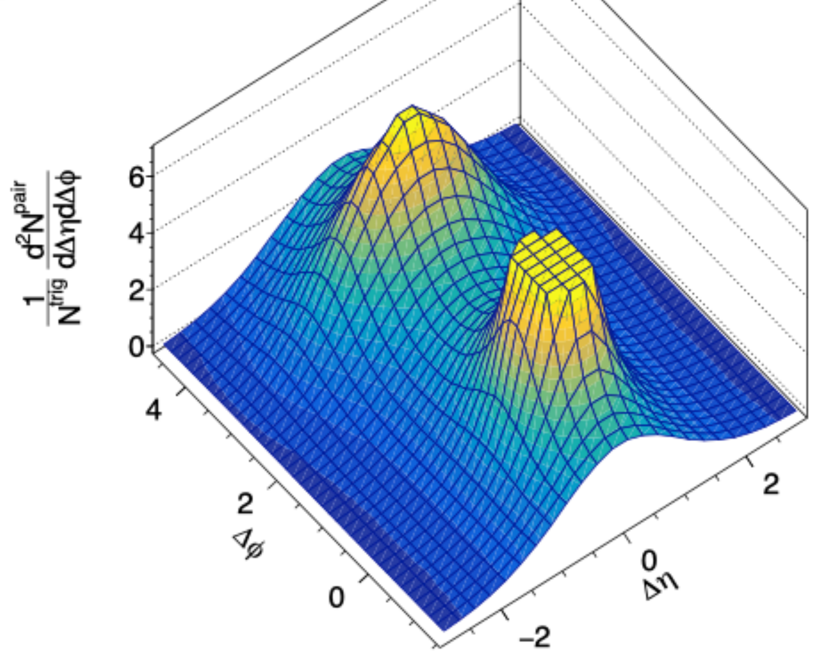
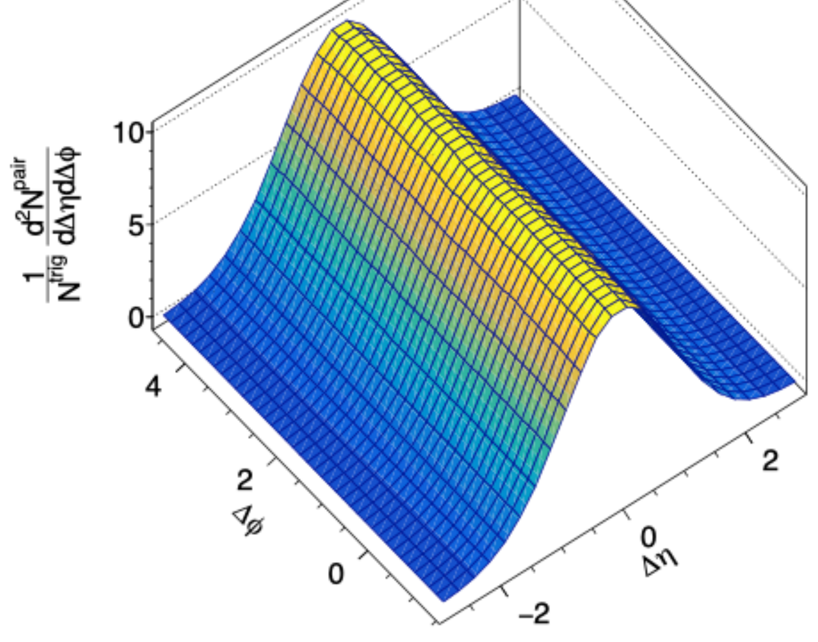
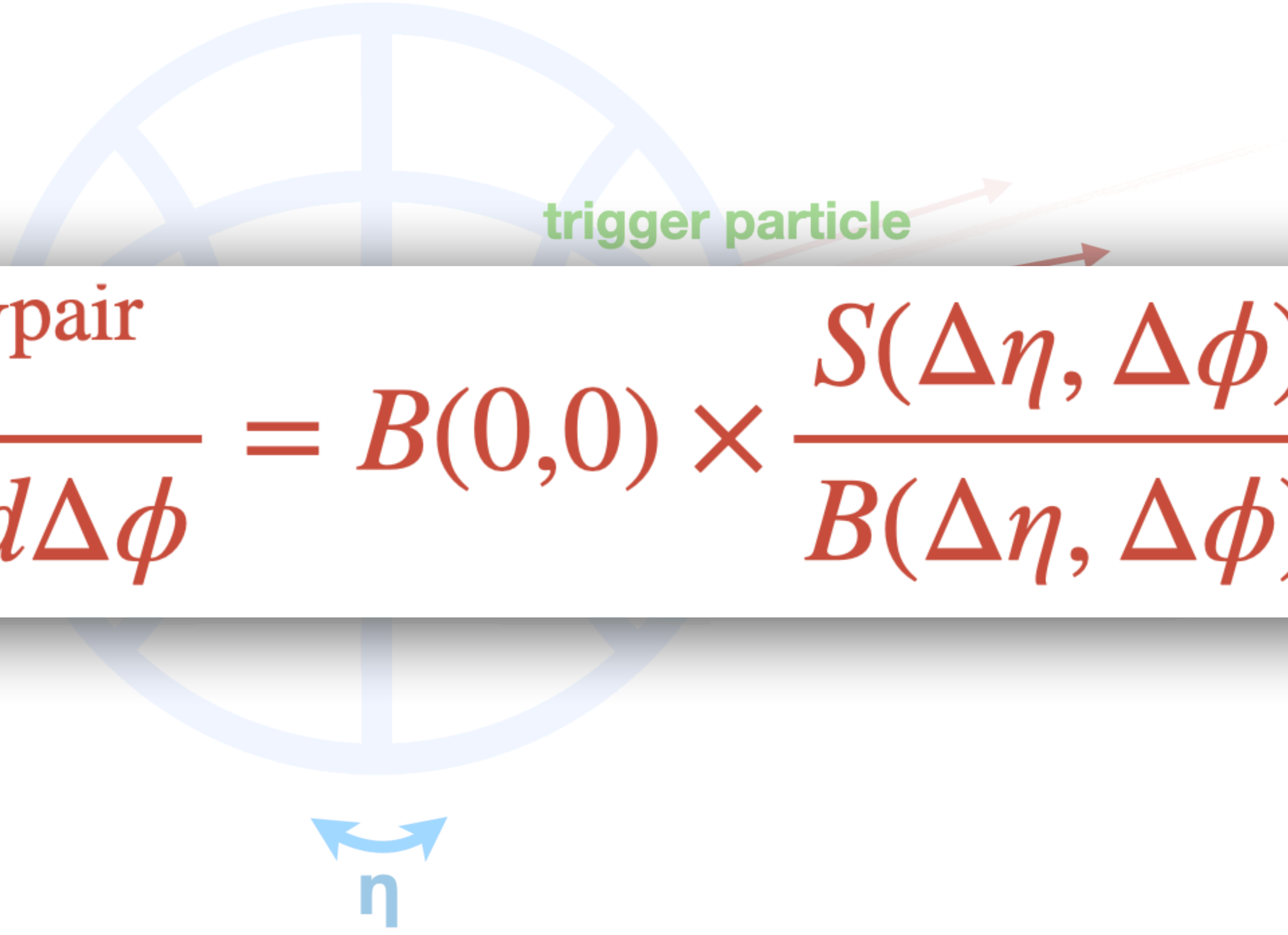
(raw correlation function)



Background
(accounting for baseline of random pairing)

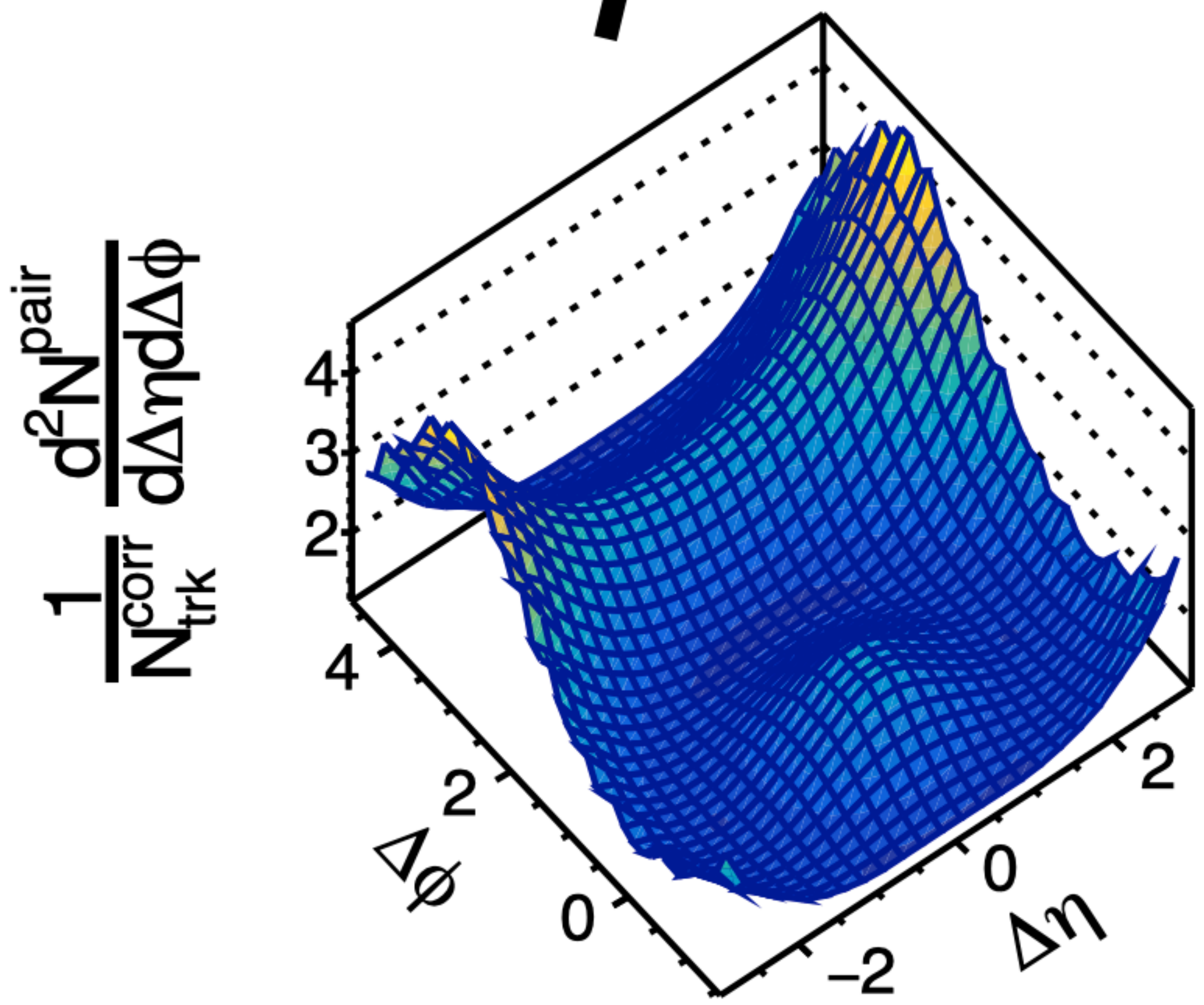


Track pairs' angular difference in
η (pseudorapidity), ϕ (azimuthal angle)



$$\frac{1}{N_{trk}^{corr}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

⇒

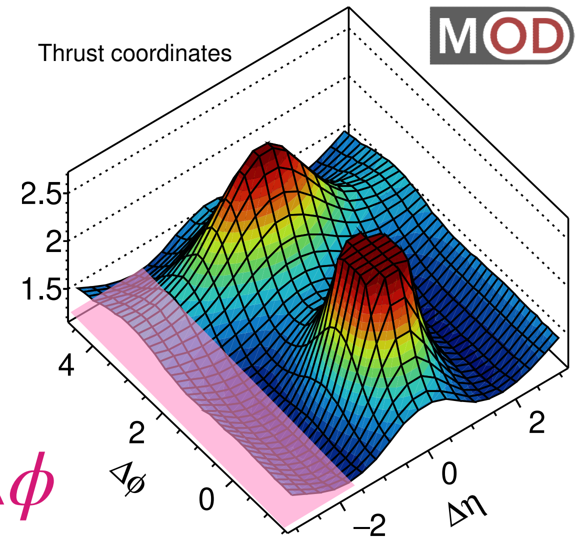


Two-particle correlation function
(per-trigger-particle associated yield)

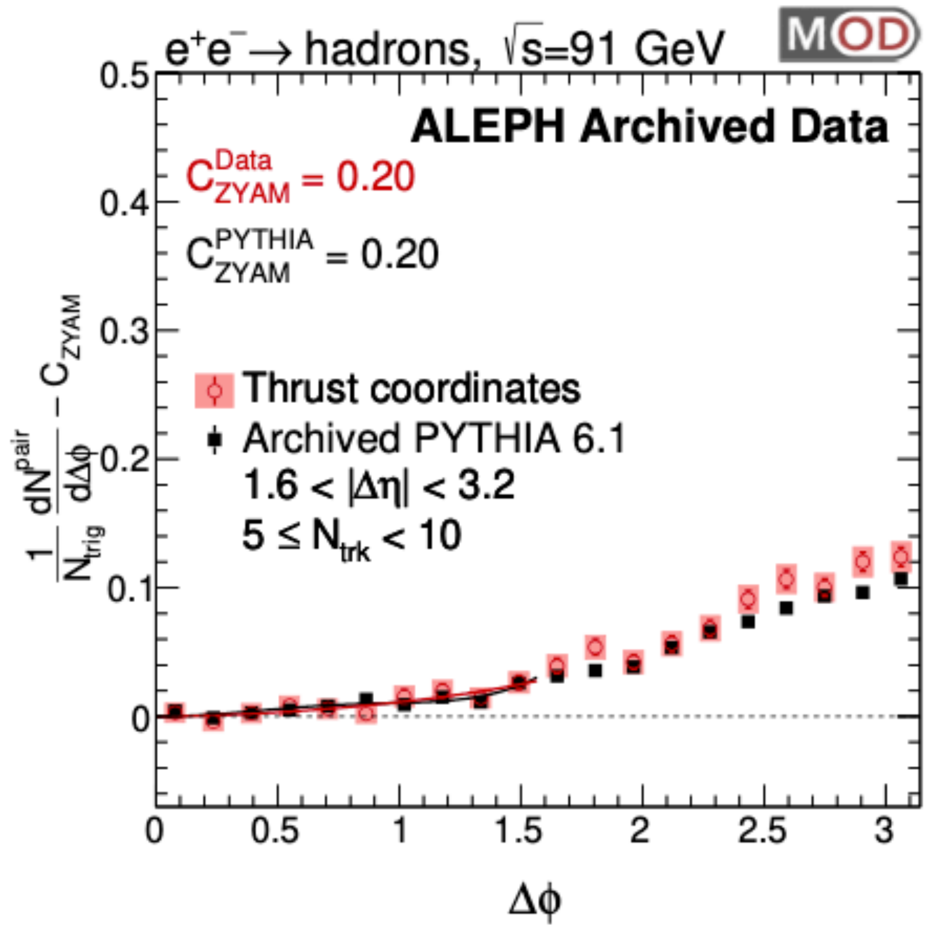
Long-range $(1.6 \leq |\Delta\eta| \leq 3.2)$ correlations

Data
PYTHIA6 MC

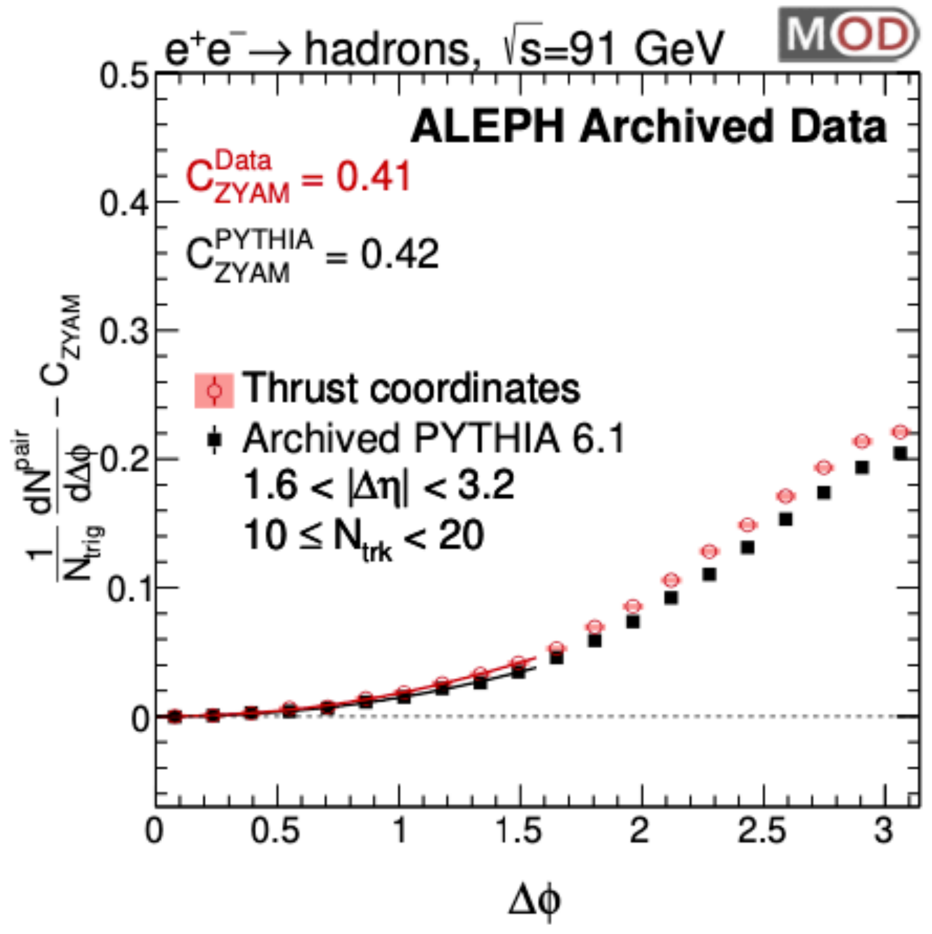
correlations projected in $\Delta\phi$



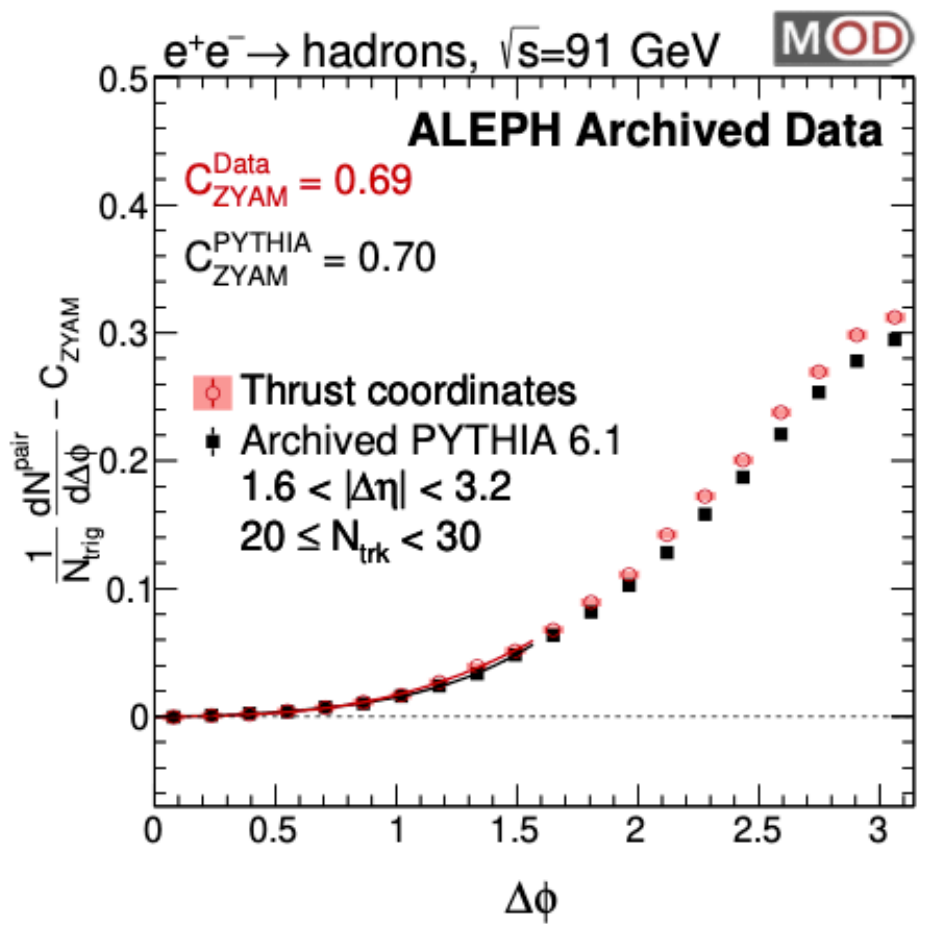
$5 \leq N_{trk} < 10$



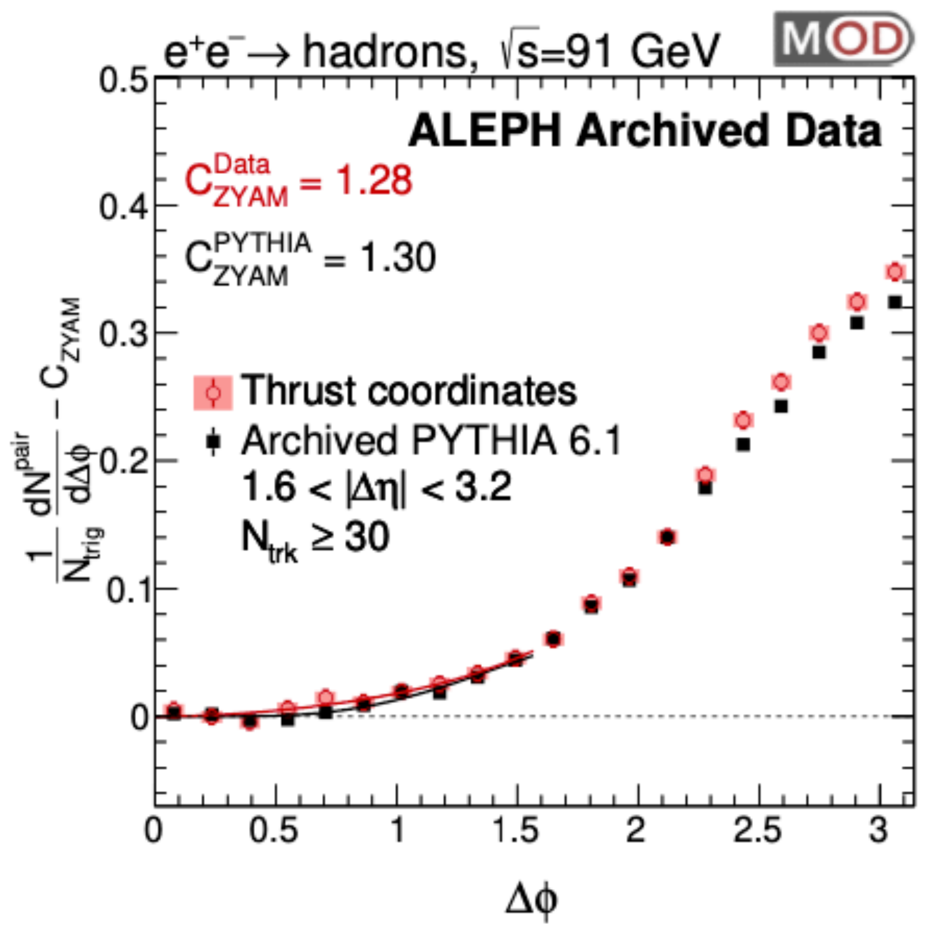
$10 \leq N_{trk} < 20$



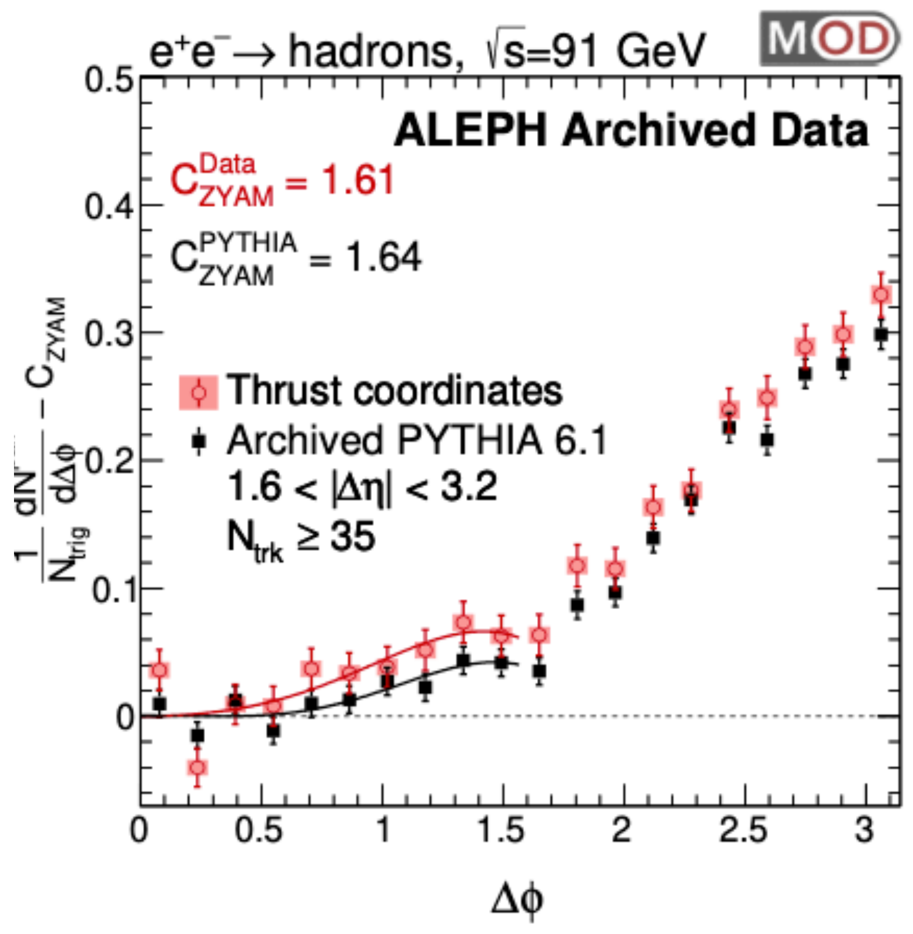
$20 \leq N_{trk} < 30$



$N_{trk} \geq 30$



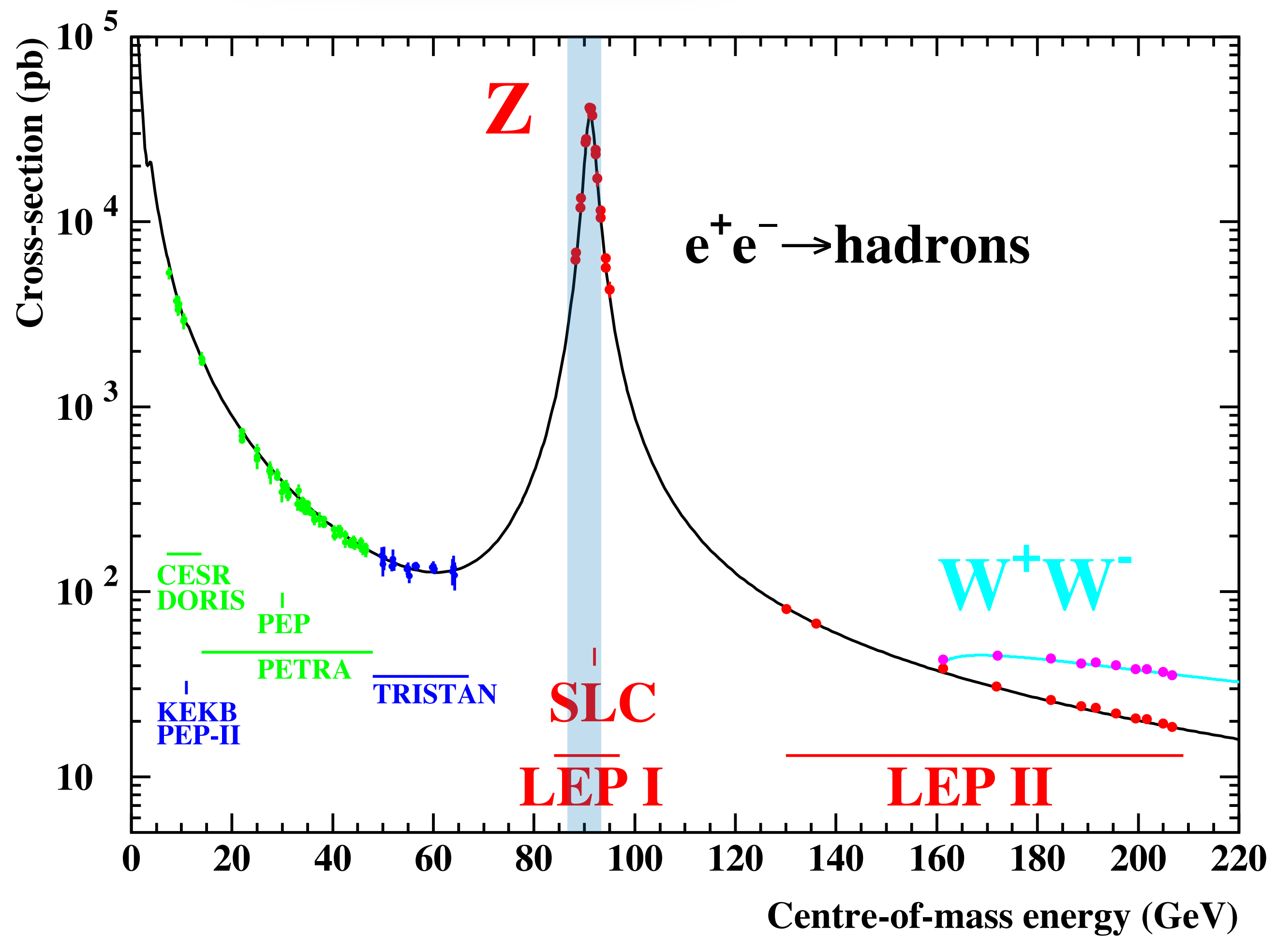
$N_{trk} \geq 35$

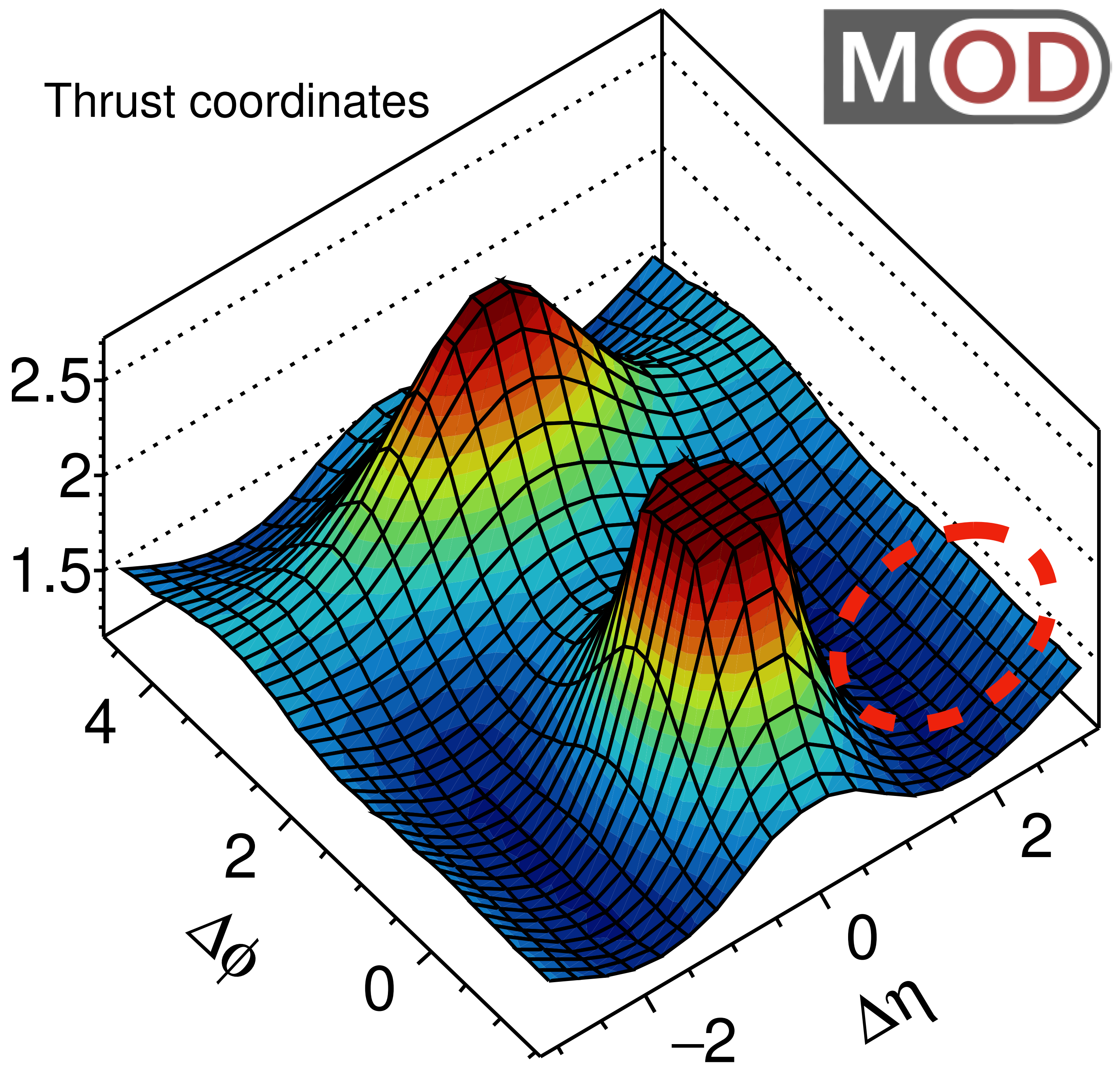


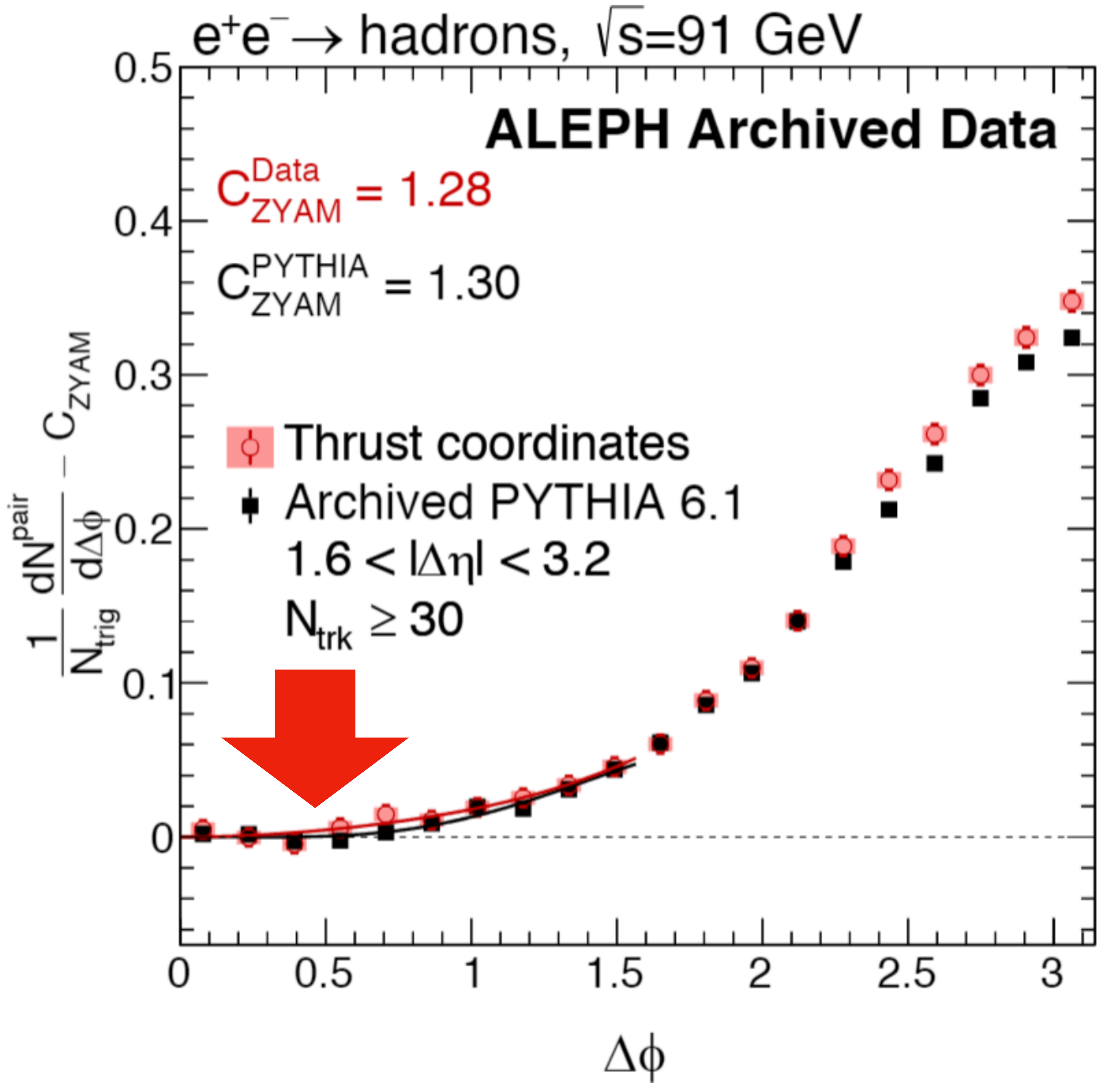
Good data/MC agreement!

LEP1 e^+e^- 2PC
[Phys. Rev. Lett. 123, 212002 (2019)]

LEP1 Results with high-multiplicity events





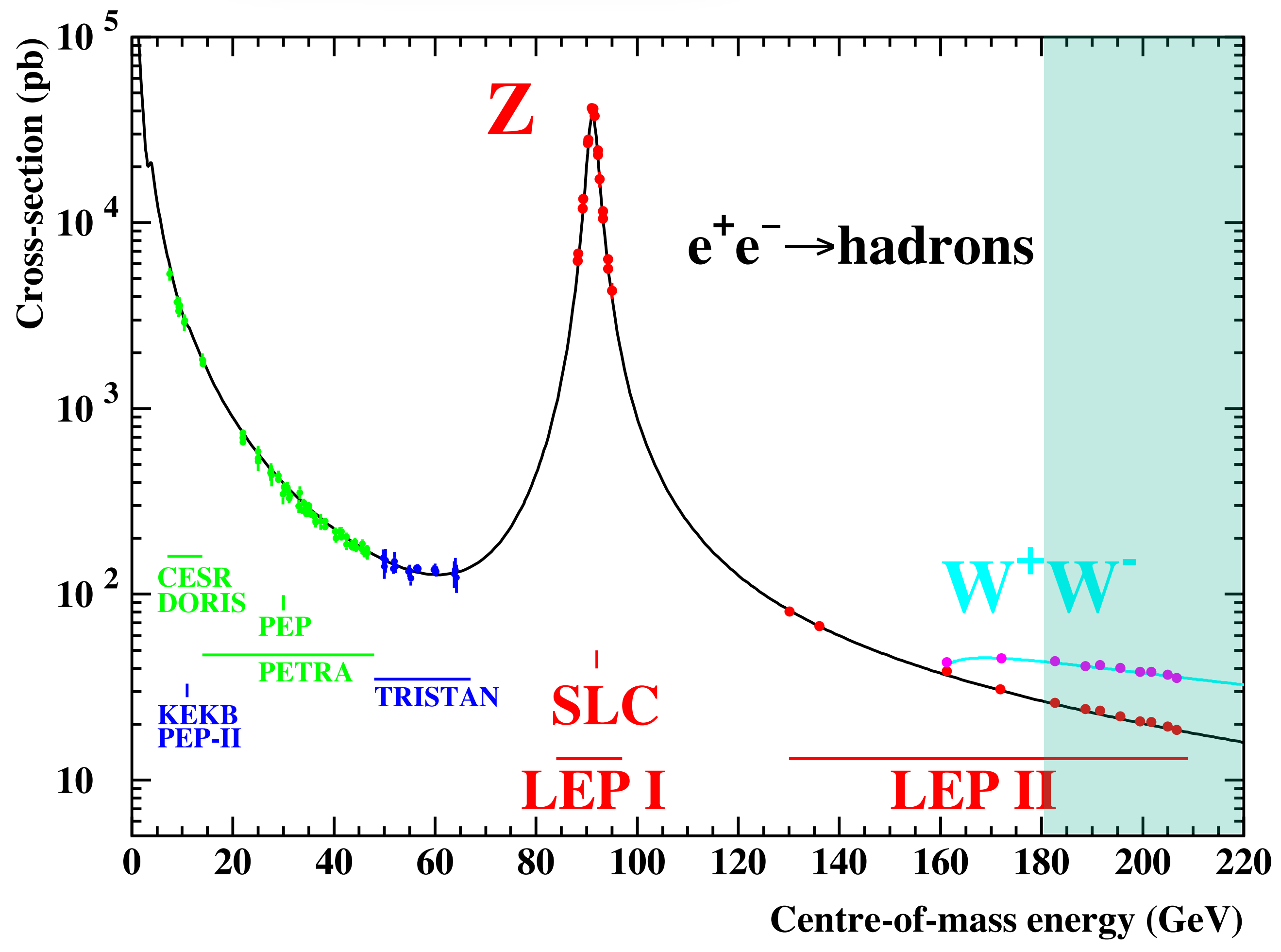


No significant ridge-like signal enhancement!

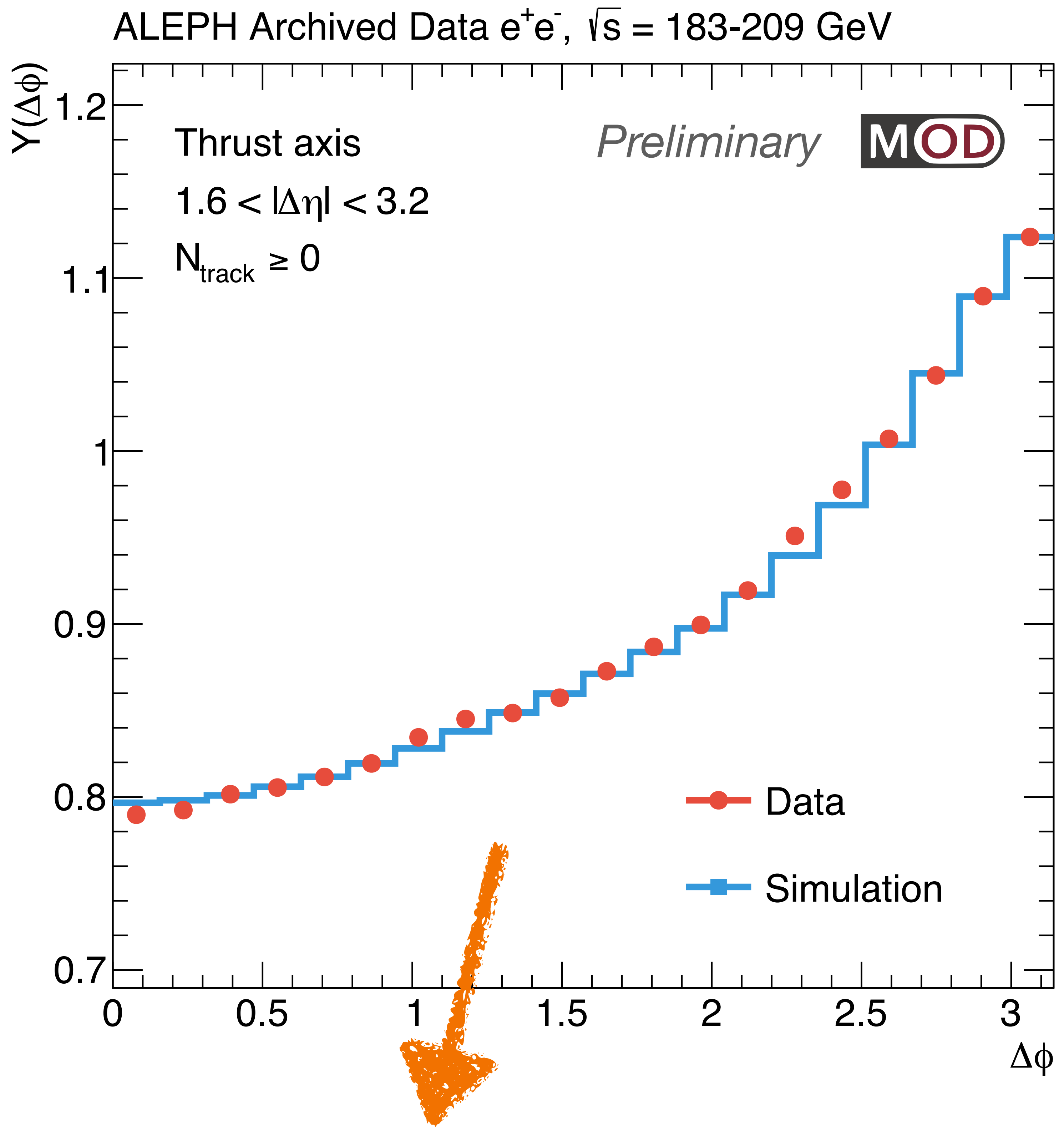
LEP1 e^+e^- 2PC

[Phys. Rev. Lett. 123, 212002 (2019)]

LEP2 High collision energy



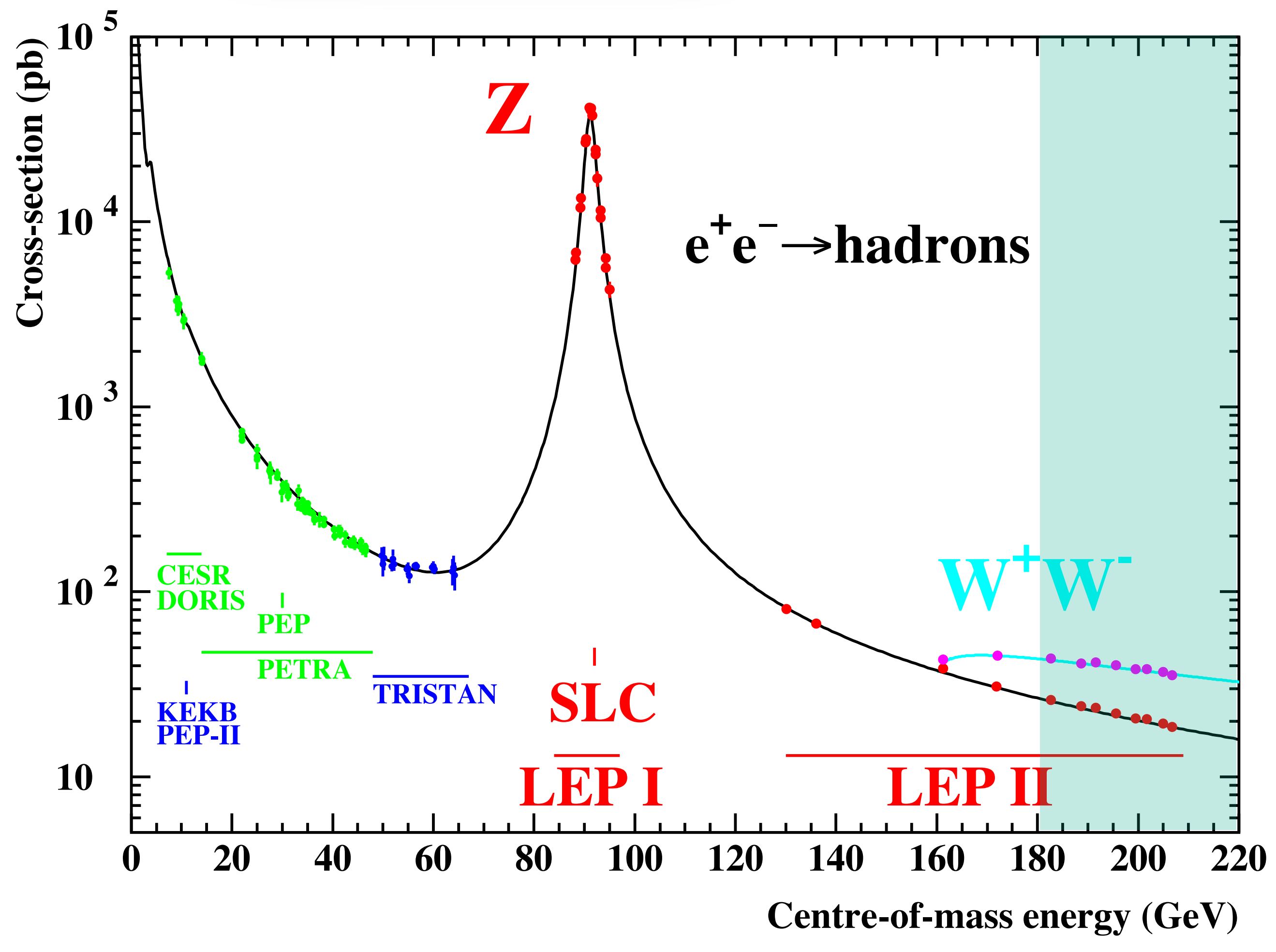
Inclusive in multiplicity

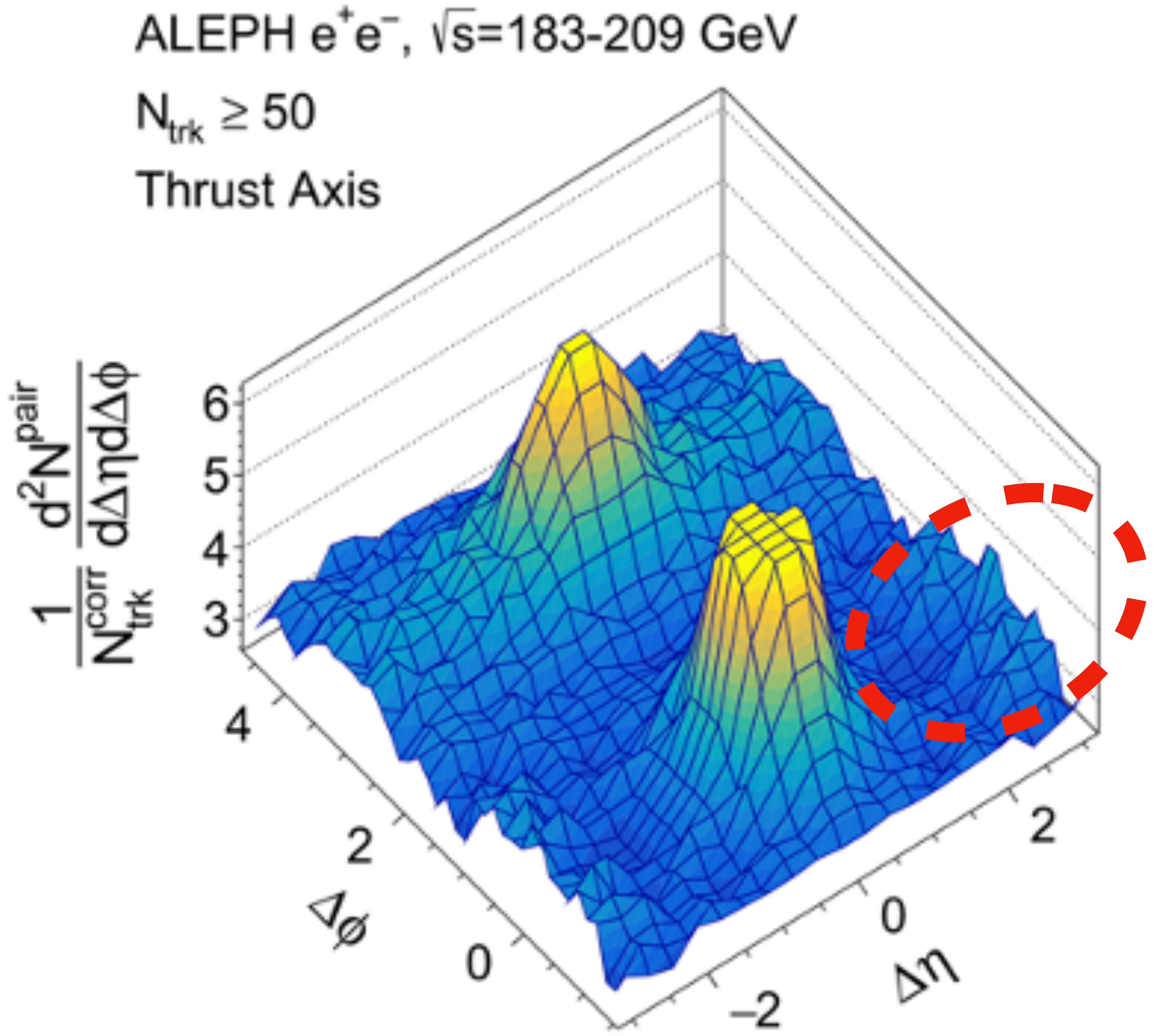


Fair data/MC agreement

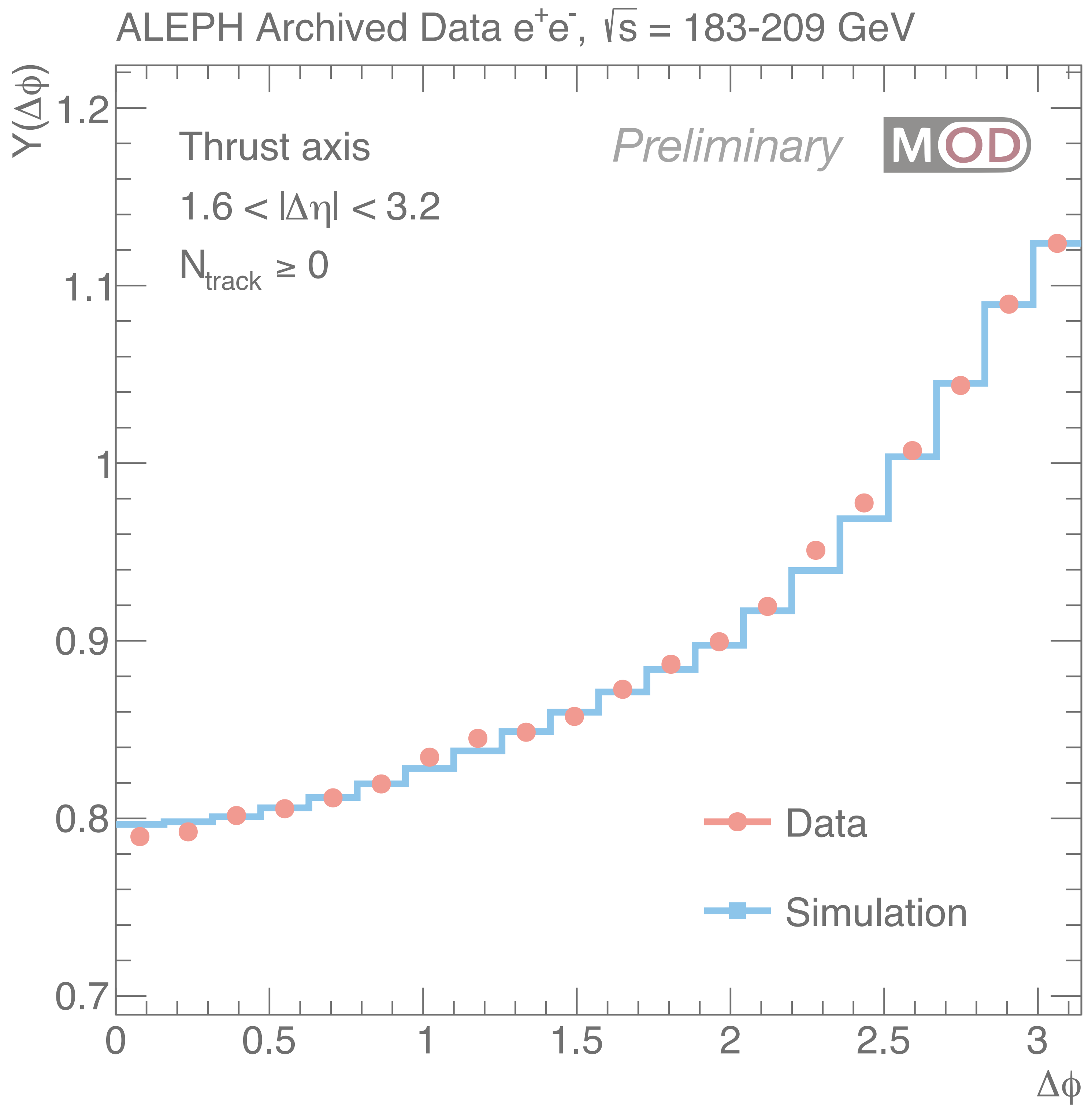
Preliminary!

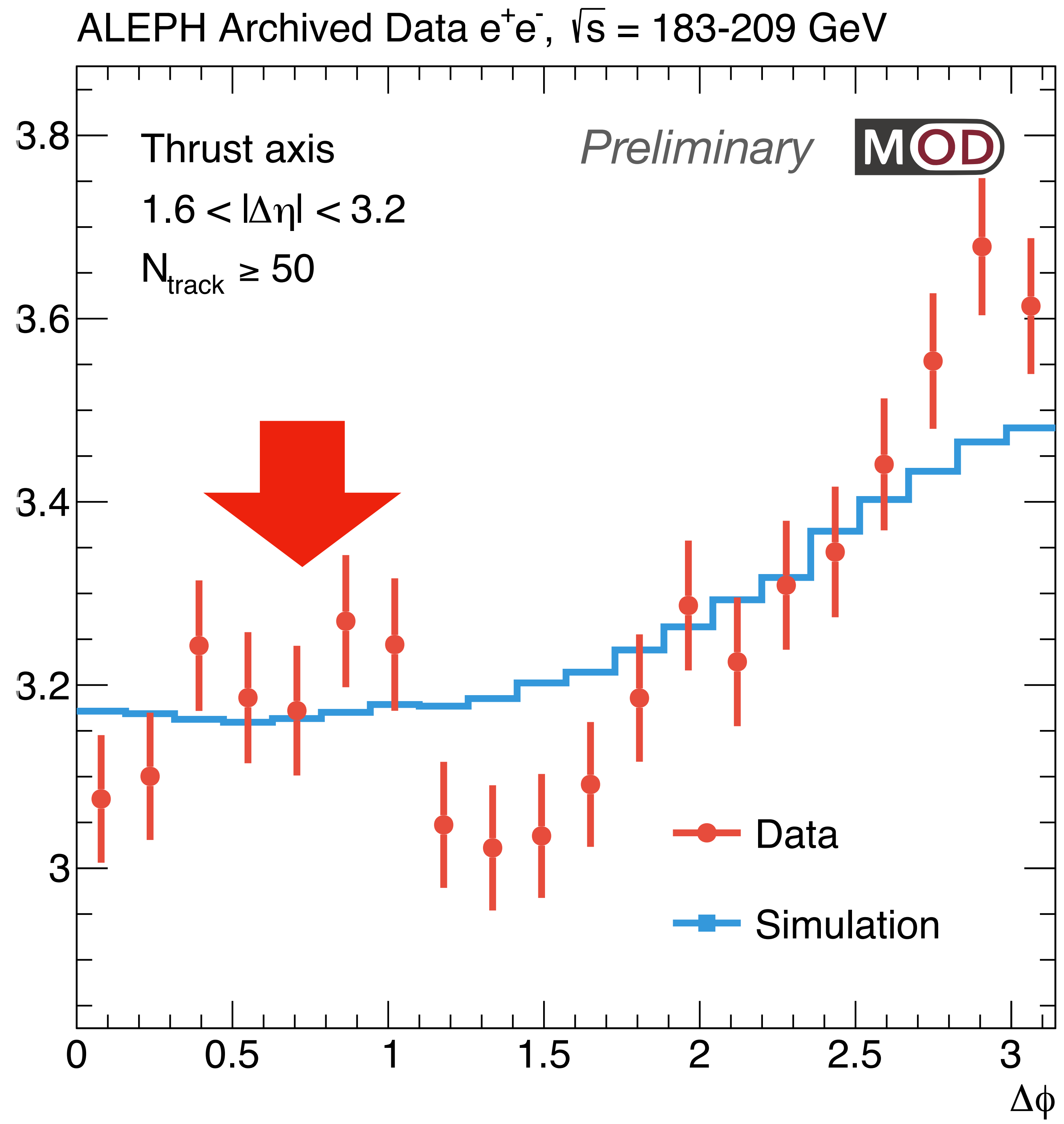
LEP2 High collision energy & high multiplicity





Inclusive **High multiplicity ($N_{Trk} \geq 50$)**





Interesting structures in high-multiplicity events

Preliminary!

LEP2

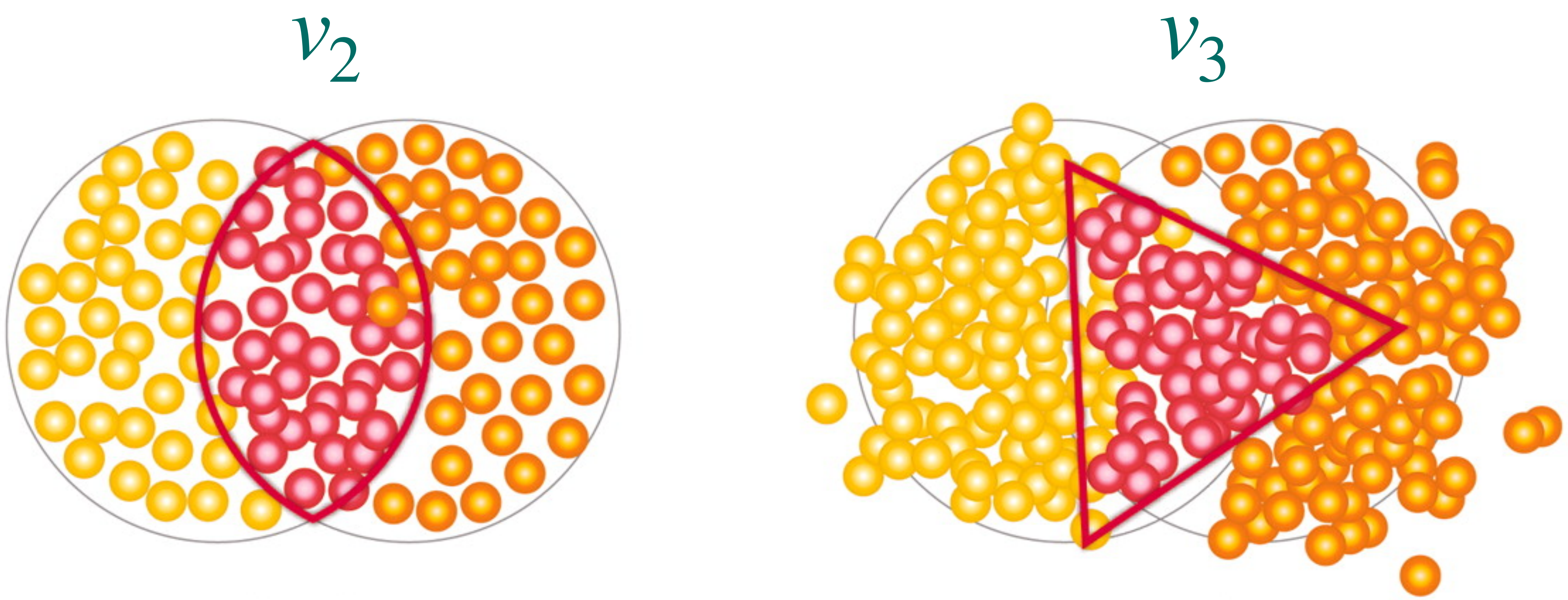
Flow coefficients — quantification of anisotropy

- To quantify the excess, Fourier fit on the 1-dim. correlation:

$$Y(\Delta\phi) = \frac{1}{N_{\rm trig}} \frac{dN^{\rm pairs}}{d\Delta\phi} = \frac{N^{\rm assoc}}{2\pi}\left(1 + \sum_{n=1}^{n_{\max}} 2V_{n\Delta}\cos(n\Delta\phi)\right)$$

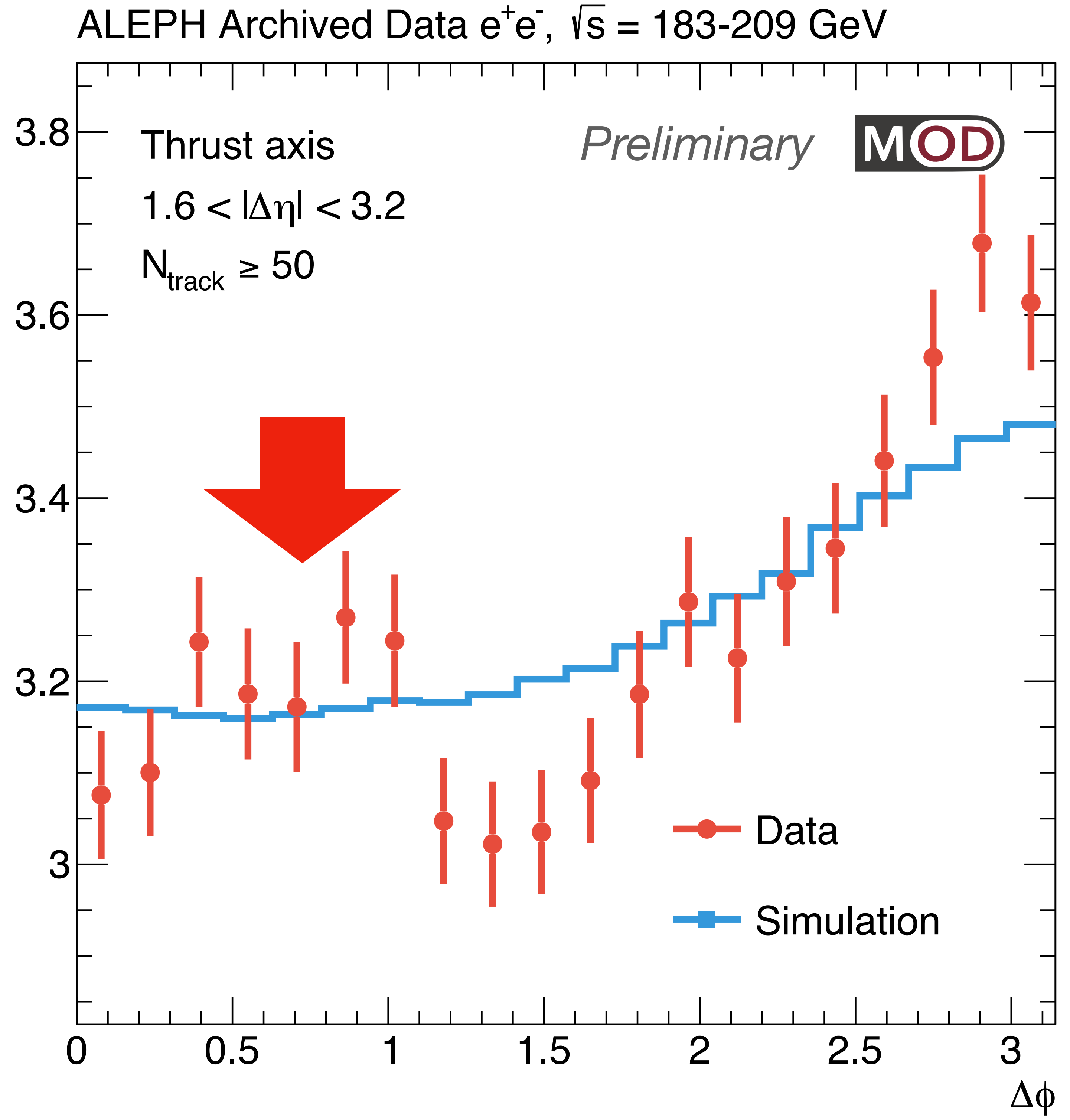
- The **flow coefficients** v_n correspond to different mode expansions:

$$v_n\{2,\ 1.6 < |\Delta\eta| < 3.2\} = \mathrm{sign}(V_{n\Delta})\sqrt{V_{n\Delta}}$$



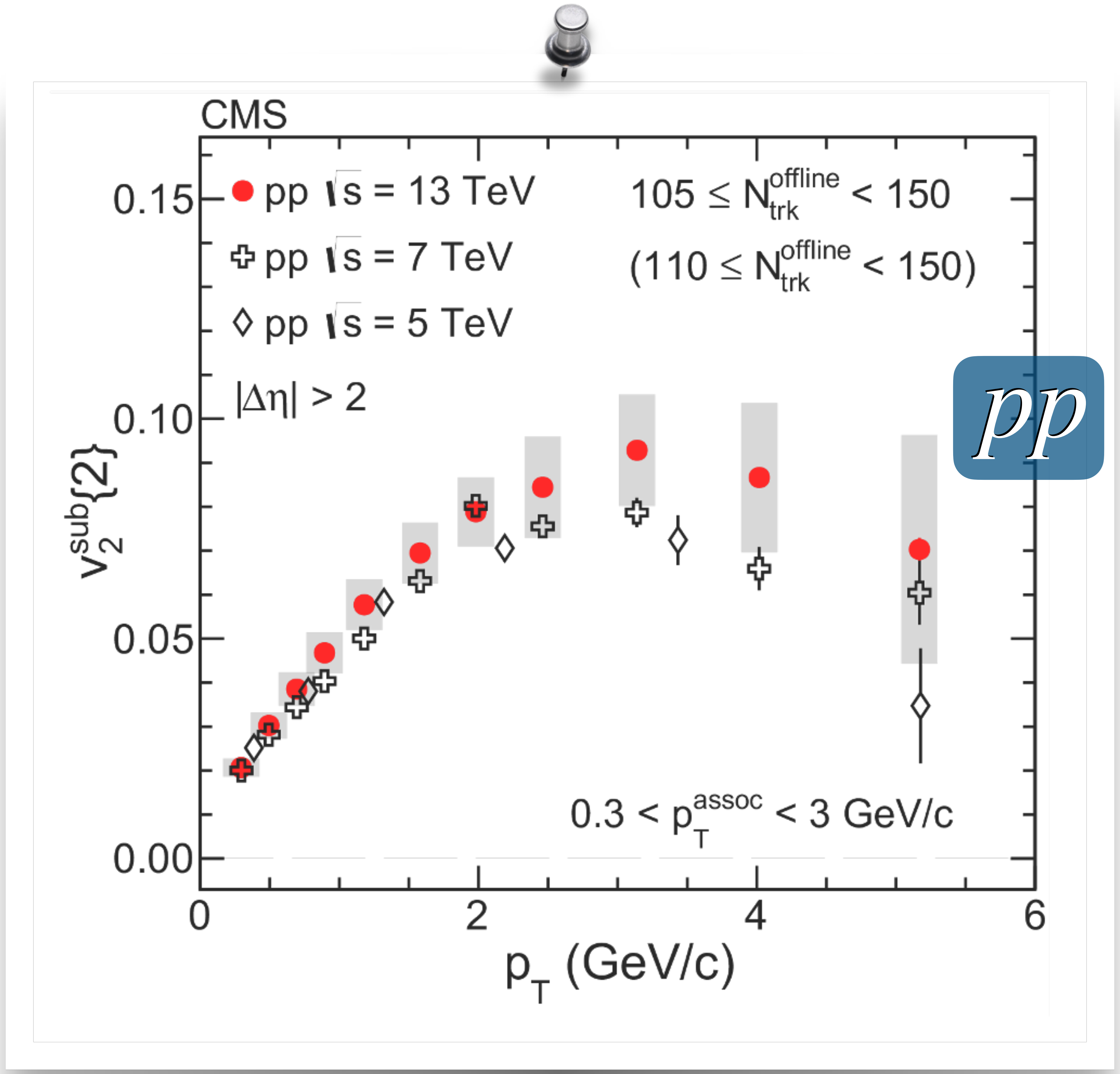
Elliptic flow

Triangular flow



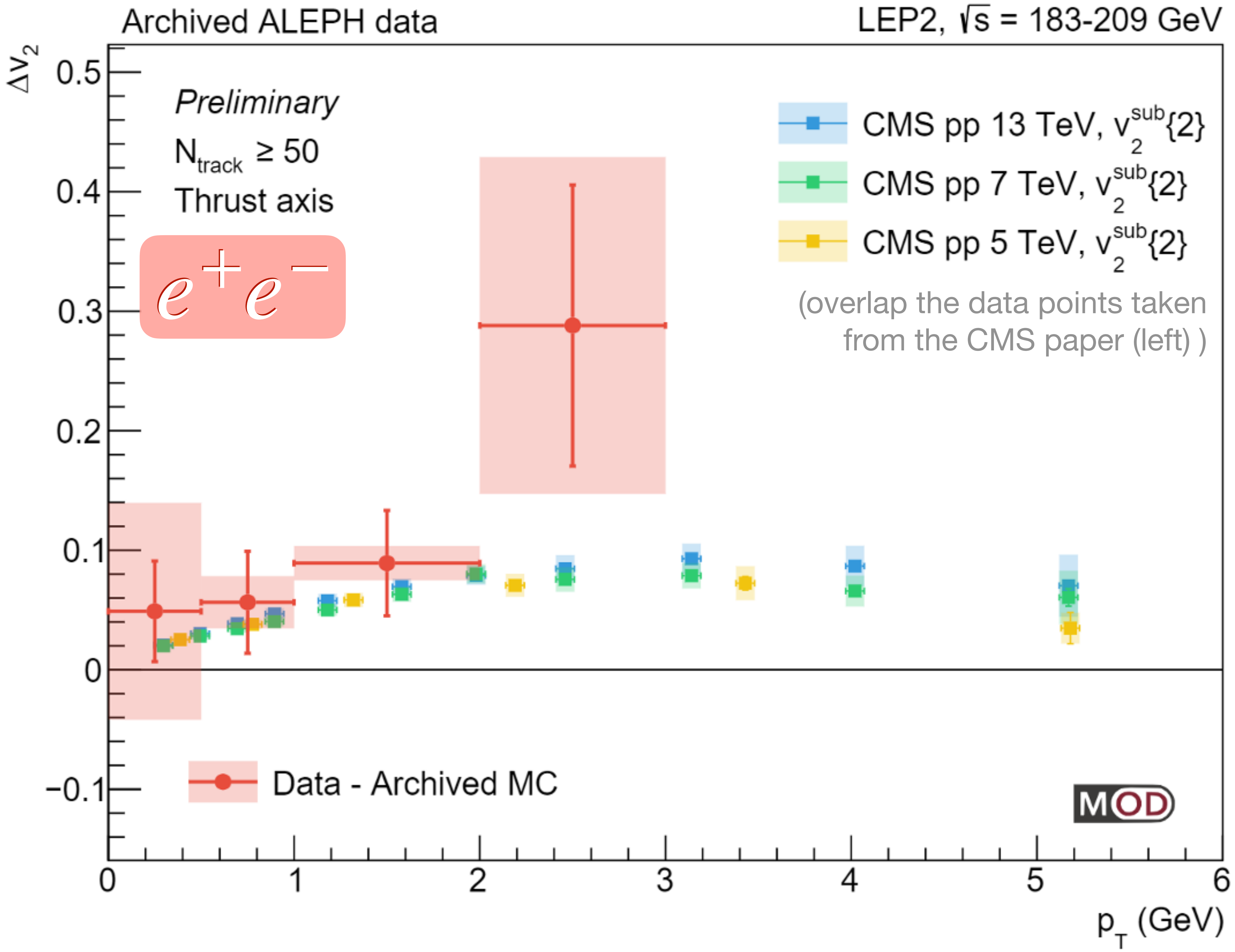
LEP2

Flow coefficients (v_2)



CMS pp [PLB 765 (2017) 193]

$v_{2,\,\mathrm{data}} - v_{2,\,\mathrm{MC}}$



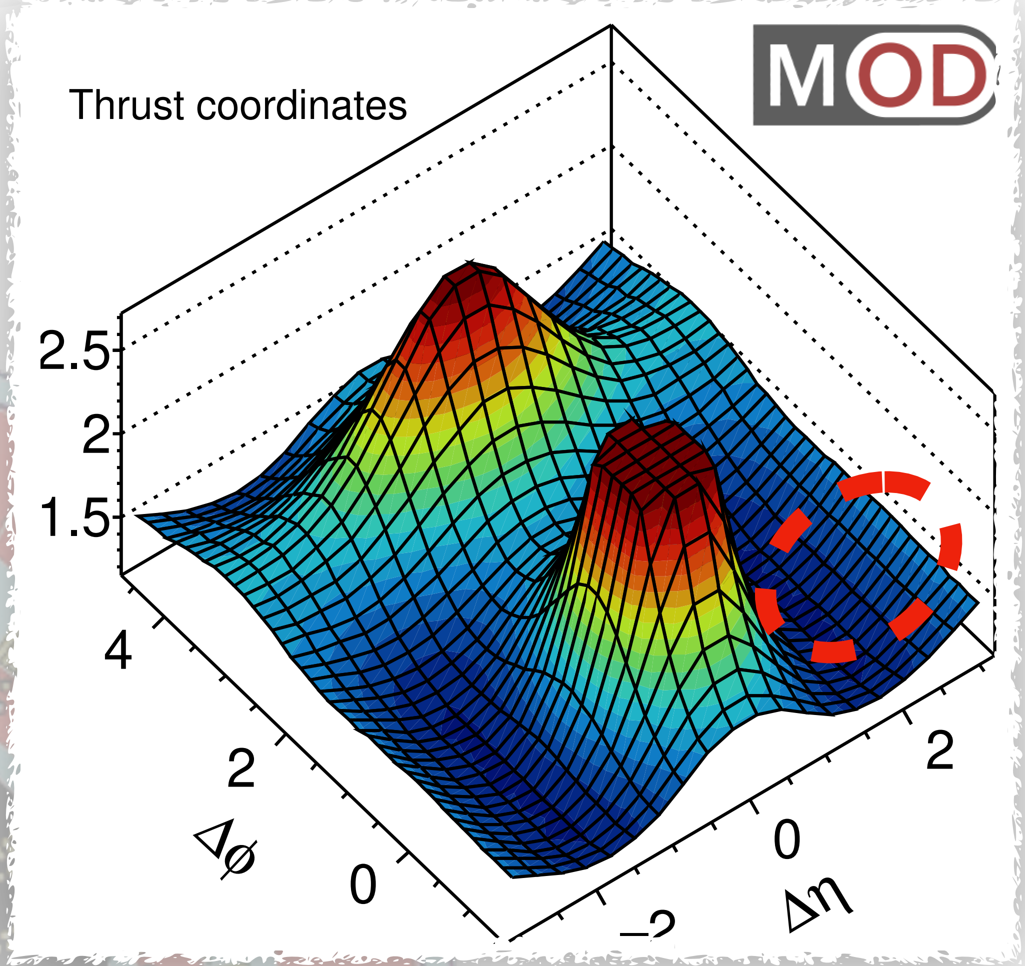
Similar trend btw e^+e^- & pp

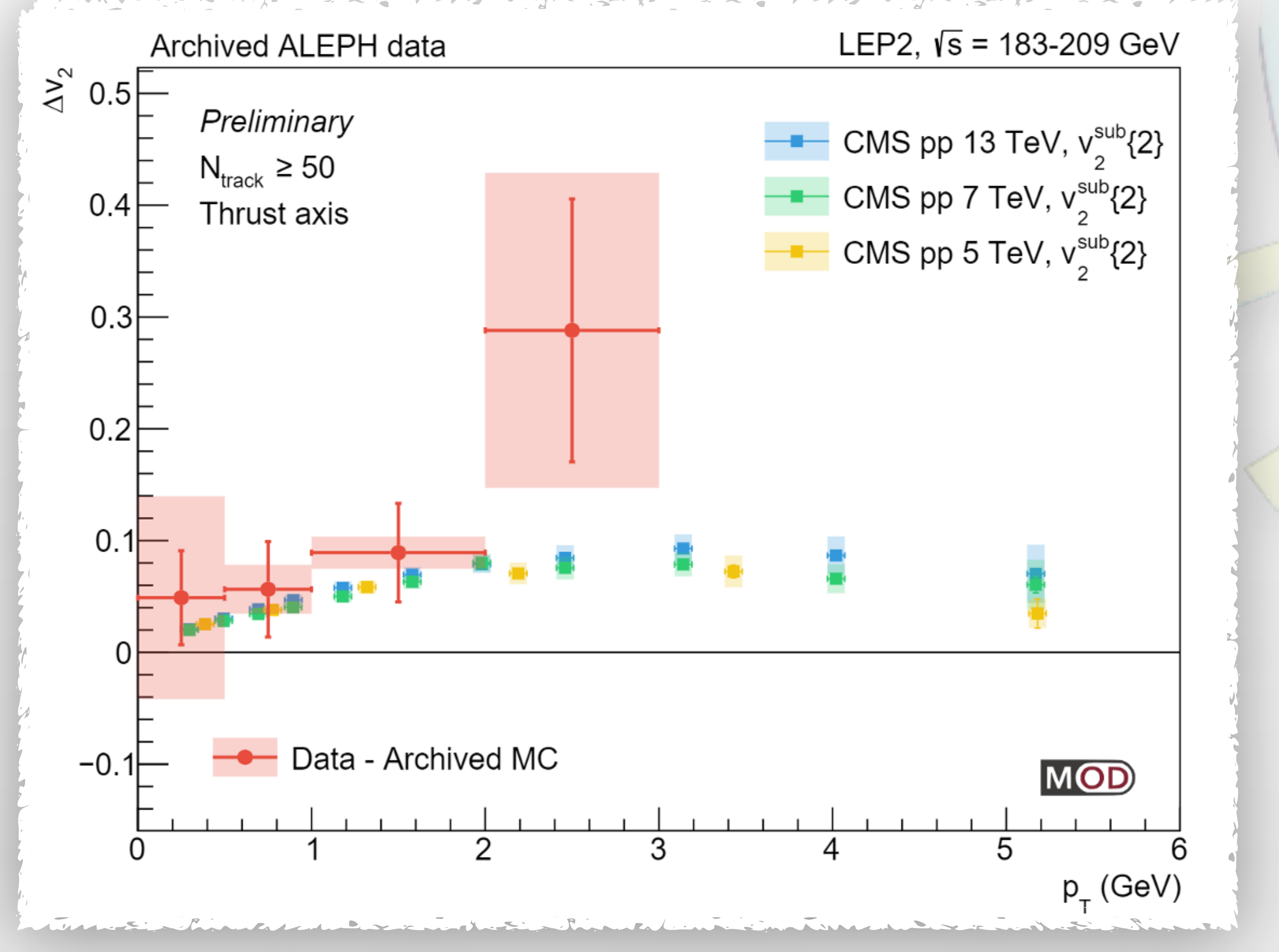
Preliminary!

Summary

Z-resonance dataset

- First 2PC analysis done in e^+e^- collision data
- No hint of the azimuthal anisotropic correlations
- Good agreements btw data & Pythia6 MC





High-energy dataset (@ $\sqrt{s}$ > 180 GeV)

- Potential long-range near-side enhancement appears only on data but not MC
- Flow coefficient v_2 demonstrates a correspondence with LHC pp data
- On-going. Stay tuned!

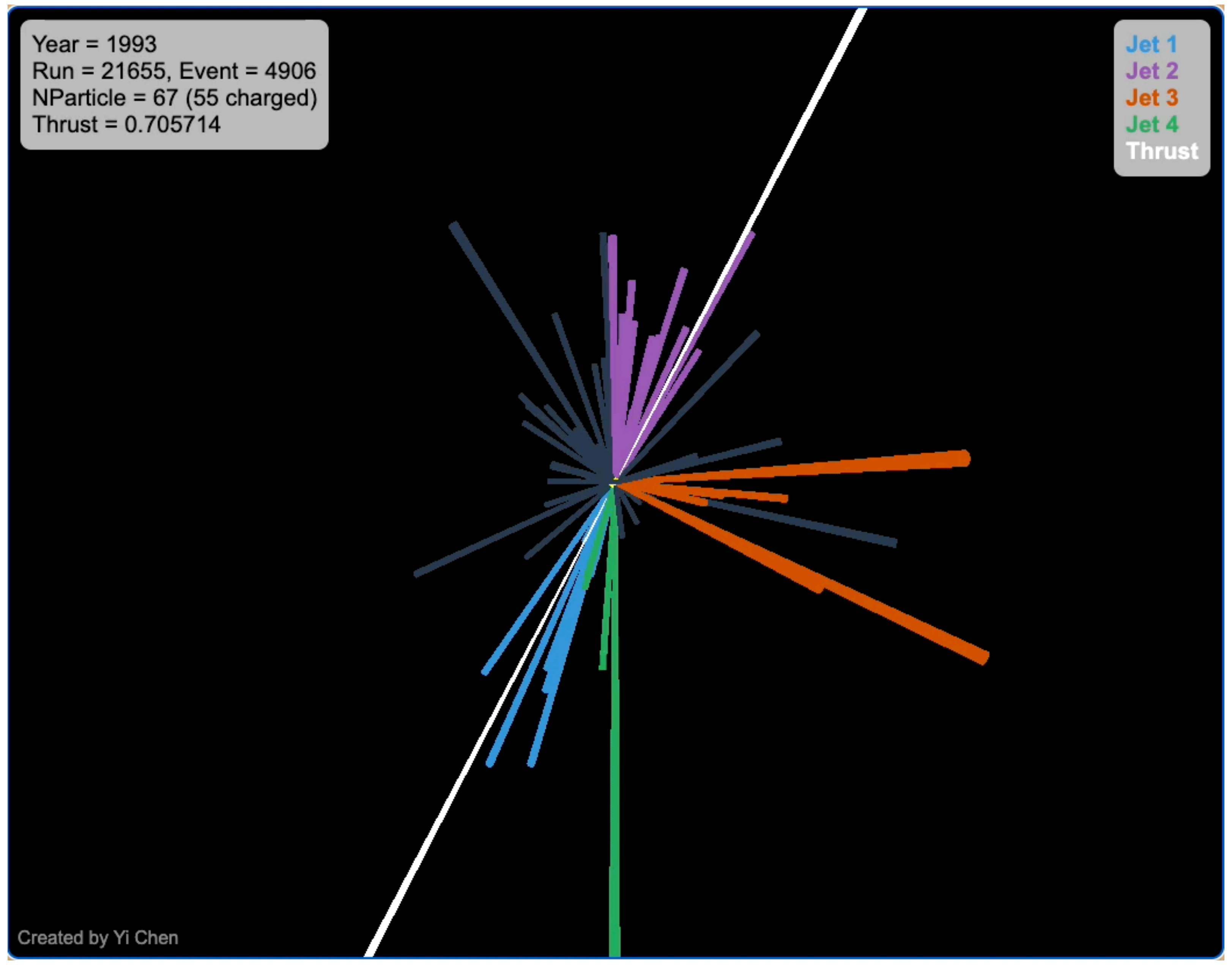
Thank you very much!

Backup

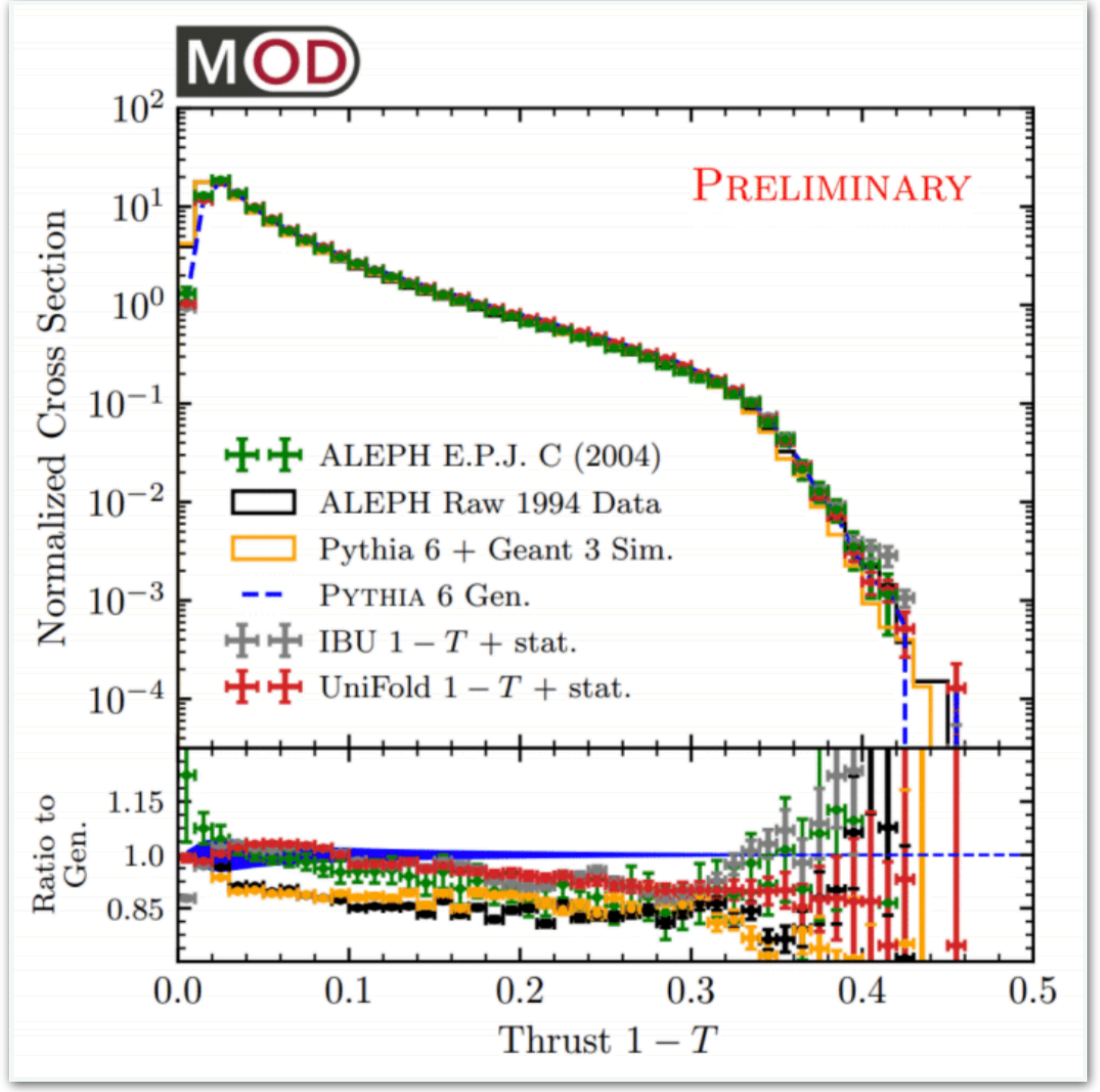
High quality archived data

(slides from BOOST 2022 by Yi Chen)

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



(to animation)



ALEPH: EPJC 35 (2004) 456

Published results can be reproduced

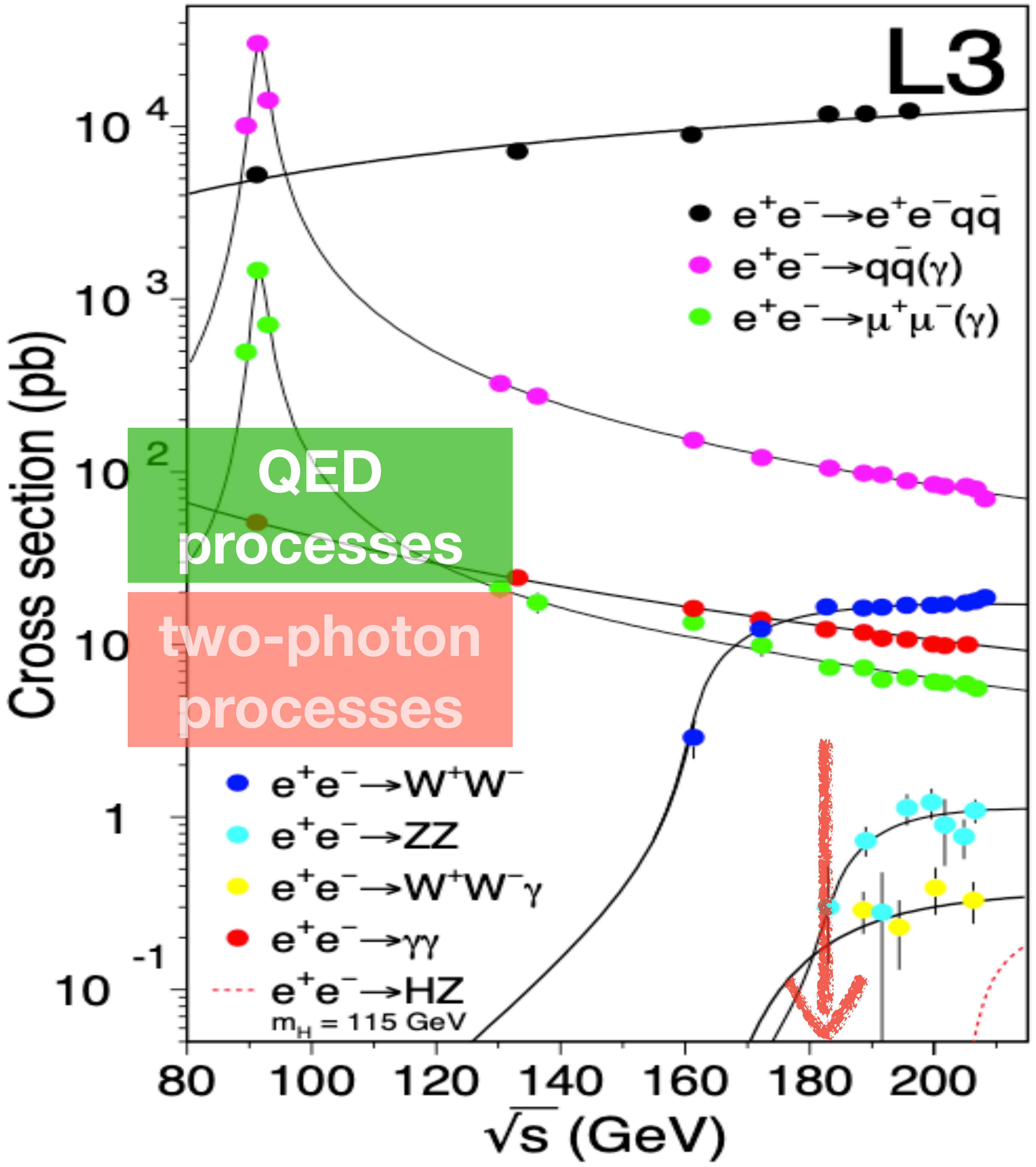
Big thanks to ALEPH collaboration and MIT open data

LEP 2 data & MC processes

Year *v.s.* √s *v.s.* int. L

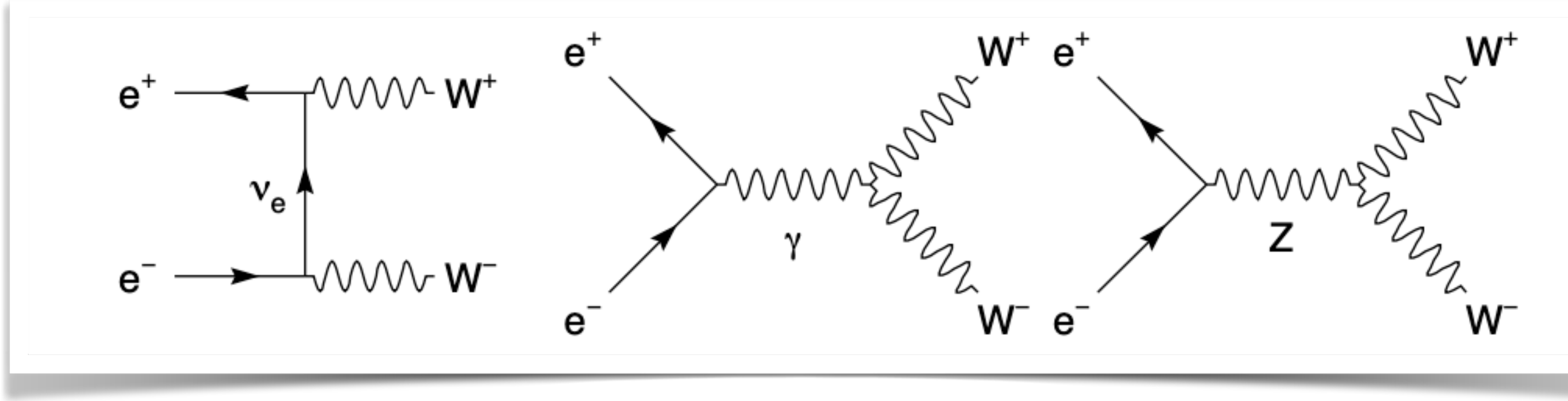
Year	Mean energy $\sqrt{s}$ [GeV]	Luminosity [pb^{-1}]
1995, 1997	130.3	6
	136.3	6
	140.2	1
1996	161.3	12
	172.1	12
1997	182.7	60
1998	188.6	180
1999	191.6	30
	195.5	90
	199.5	90
	201.8	40
2000	204.8	80
	206.5	130
	208.0	8
Total	130 – 209	745

√s *v.s.* X-section



Hadronic $q\bar{q}$ production

Four fermion processes

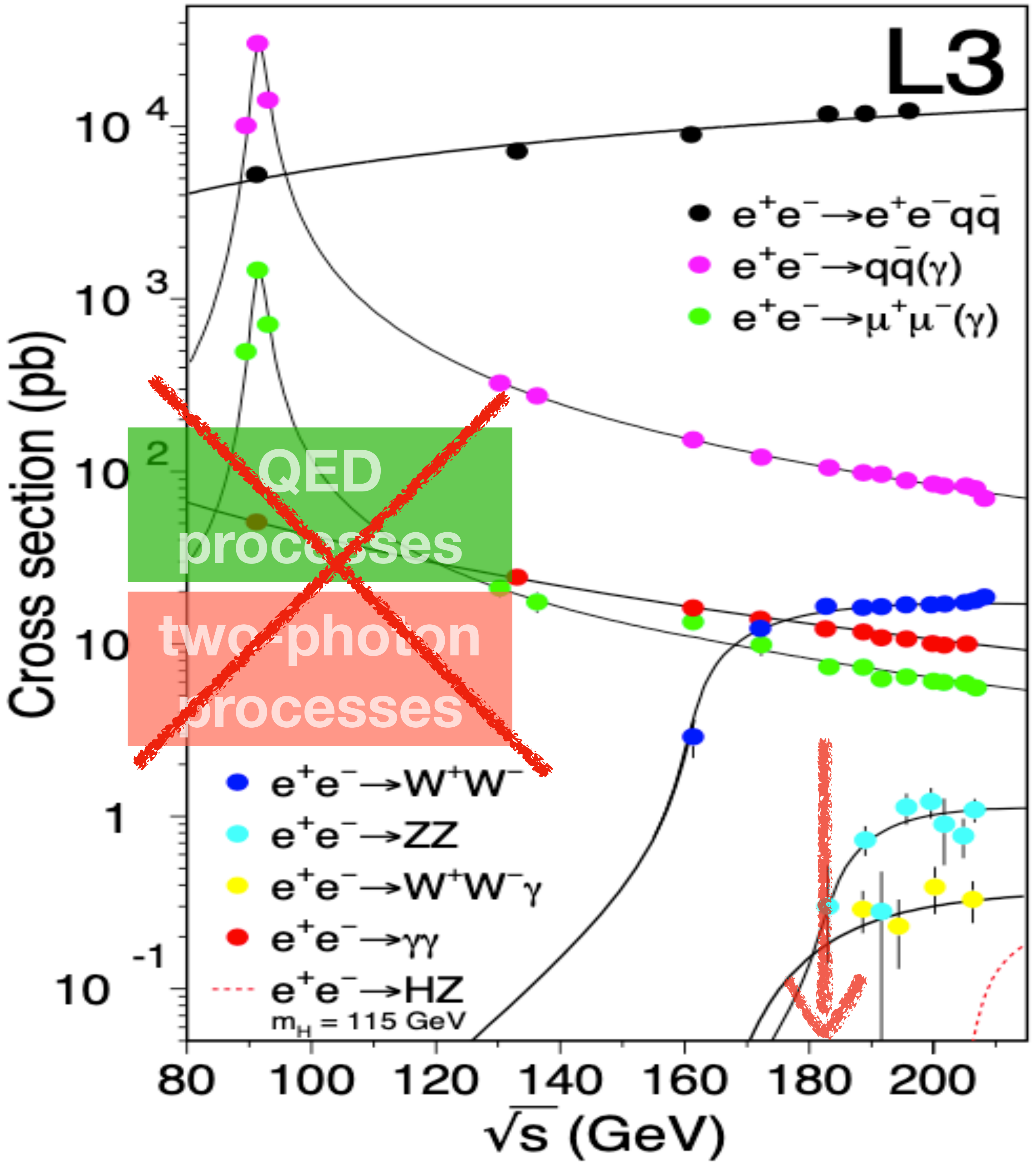


Diverse decay channels above $\sqrt{s}$ = 180 GeV

LEP 2 event selections

Acceptance
Polar angle of sphericity axis: $7\pi/36 < \theta_{\text{lab}} < 29\pi/36$

Hadronic event selection
≥ 5 tracks
$E_{\text{chgd.}} \geq 15\ \text{GeV}$



Hadronic $q\bar{q}$ production

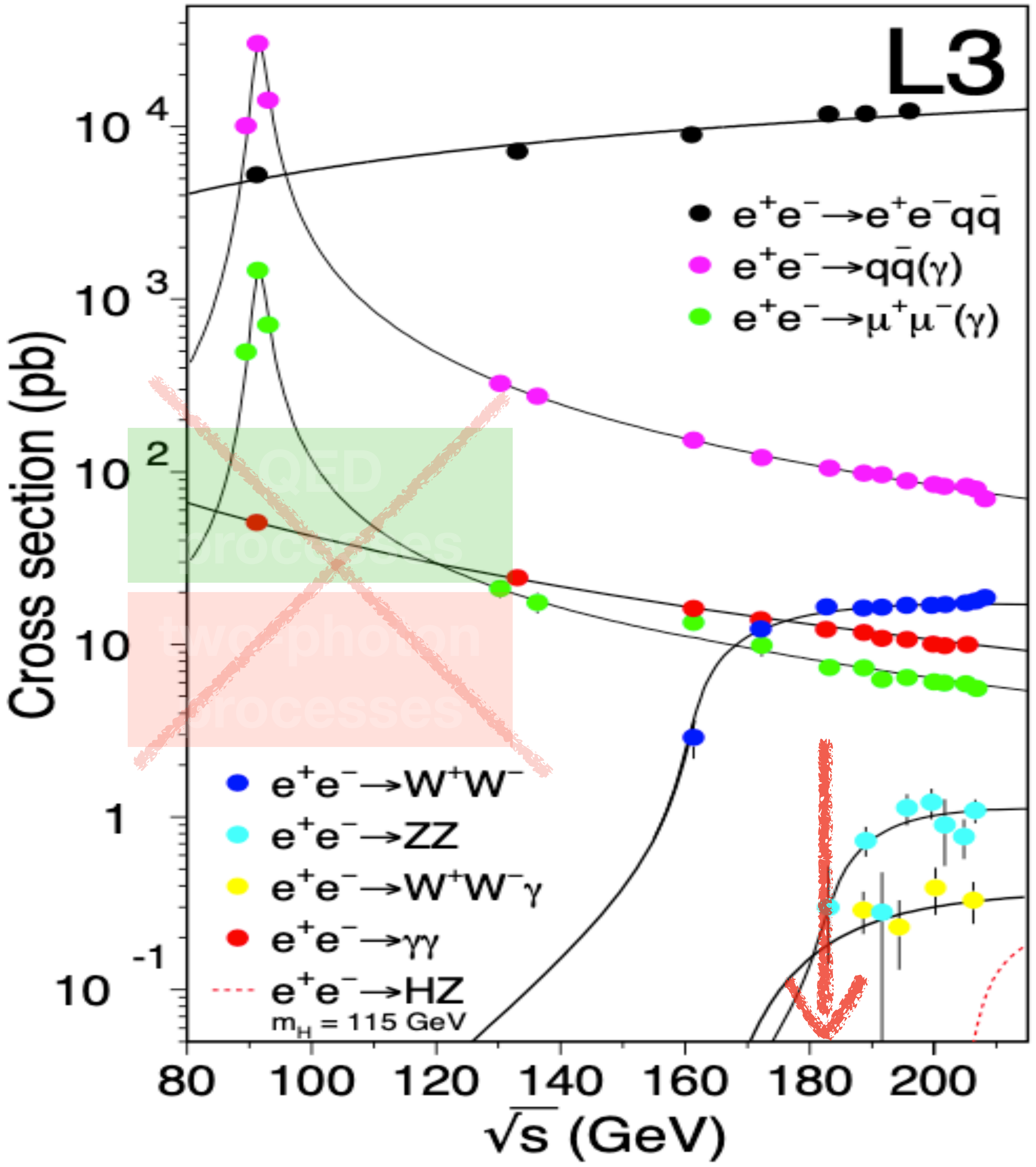
Four fermion processes

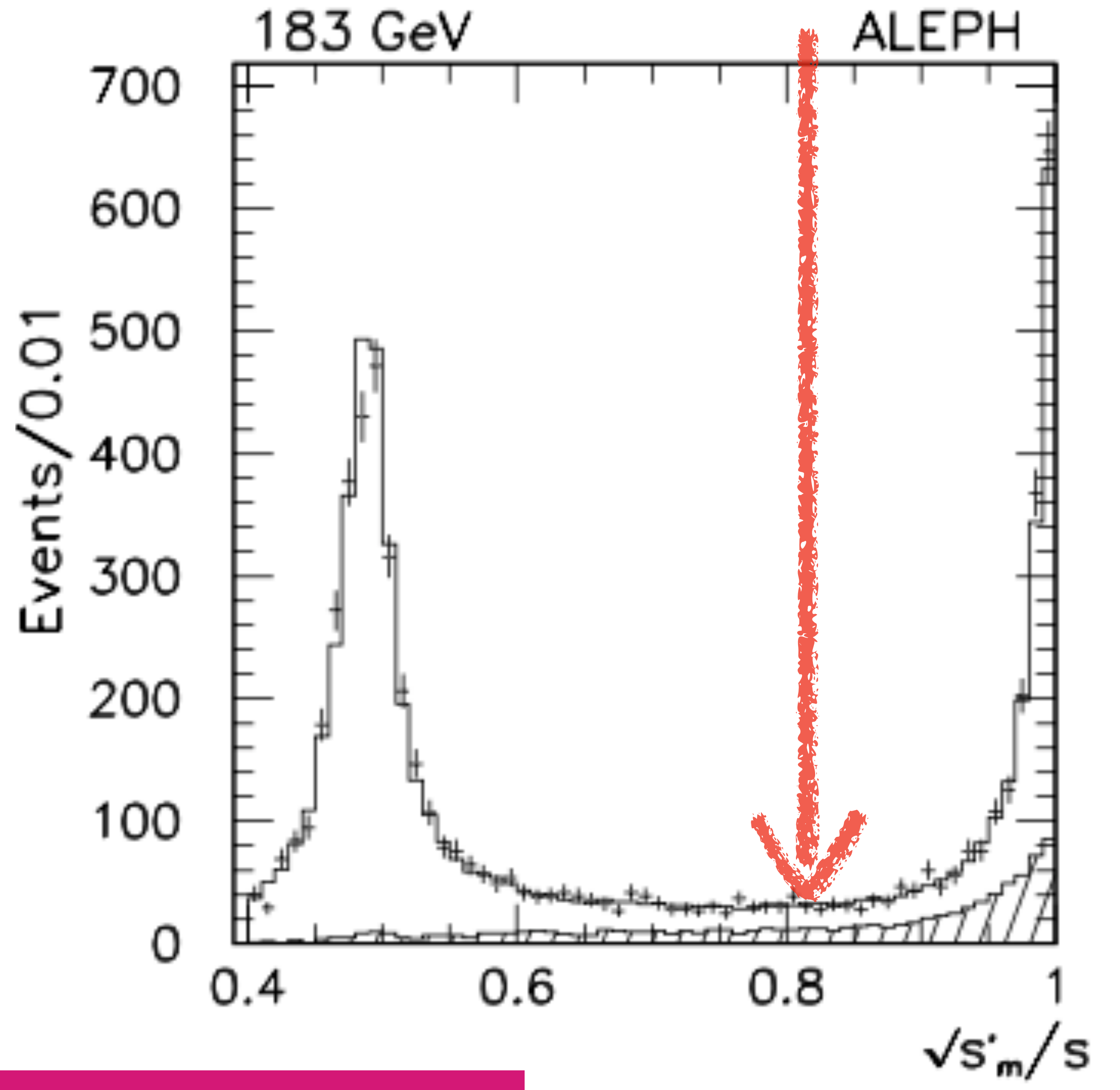
LEP 2 event selections

Acceptance
Polar angle of sphericity axis: $7\pi/36 < \theta_{\text{lab}} < 29\pi/36$

Hadronic event selection
$\geq$ 5 tracks
$E_{\text{chgd.}} \geq 15$ GeV

Radiative return to the Z
$\sqrt{s} \sim 90$ GeV





Hadronic $q\bar{q}$ production

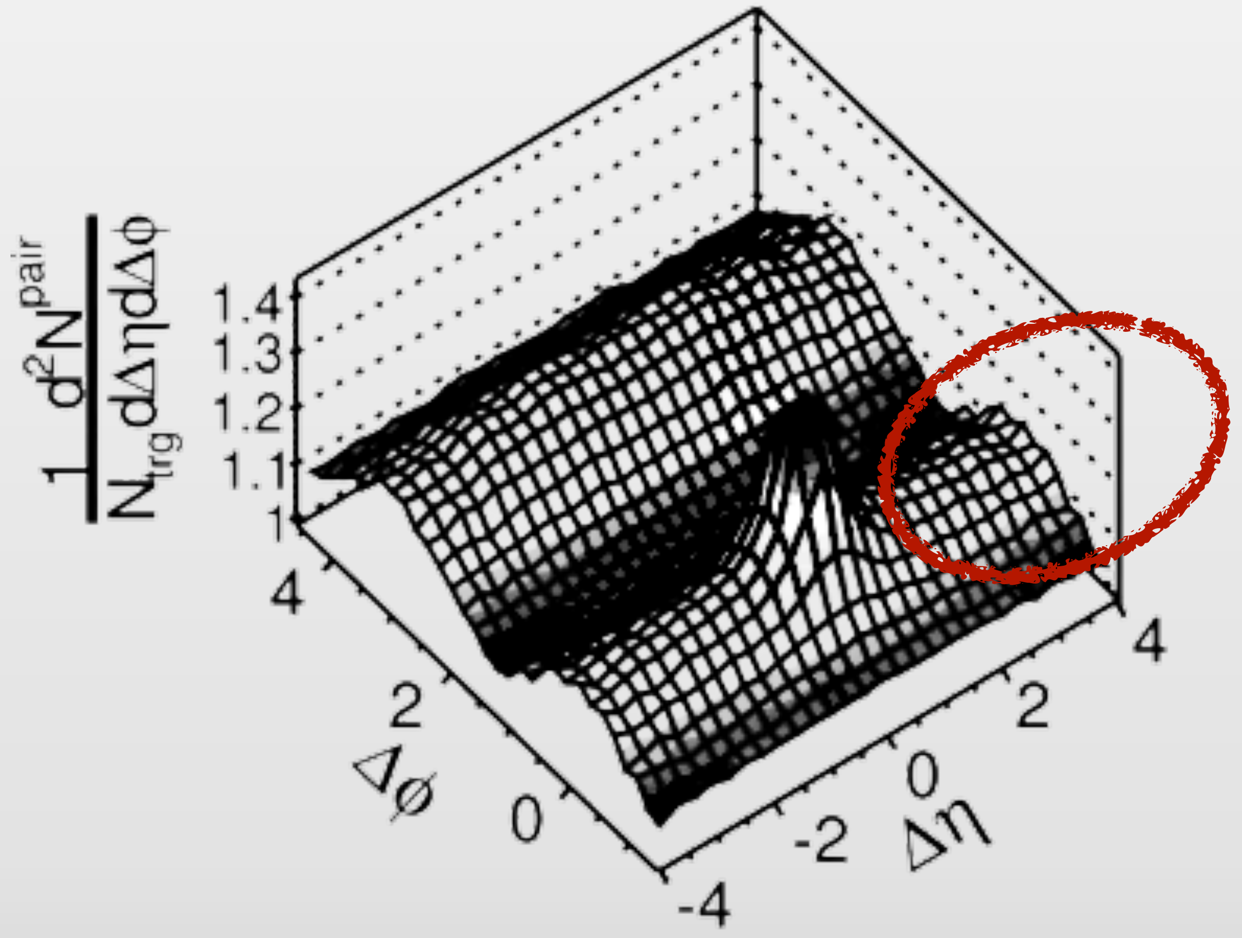
Ref: hep-ex/9904011

Four fermion processes

ISR cut

Required on the visible mass and the reconstructed center-of-mass energy

Two-particle correlations



Selection

Selection

Two-particle correlations

Residual MC correction

- **Track Selection:**
  - Particle flow candidate 0, 1, 2 (charged hadron / $e^{\pm}$ / $\mu^{\pm}$)
  - Number of TPC hits for a charged tracks (N_{TPC}) >= 4, χ^2/ndf < 1000
  - |d0| < 2 cm
  - |z0|< 10 cm
  - |cosθ|<0.94
  - p_T> 0.2 GeV (transverse momentum with respect to beam axis)

- **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
  - $|\cos(\theta_{sphericity})|<0.82$

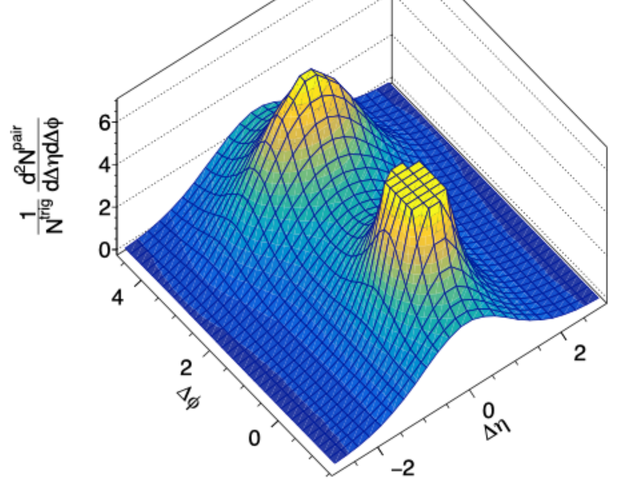
Analysis methods

Selection

Two-particle correlations

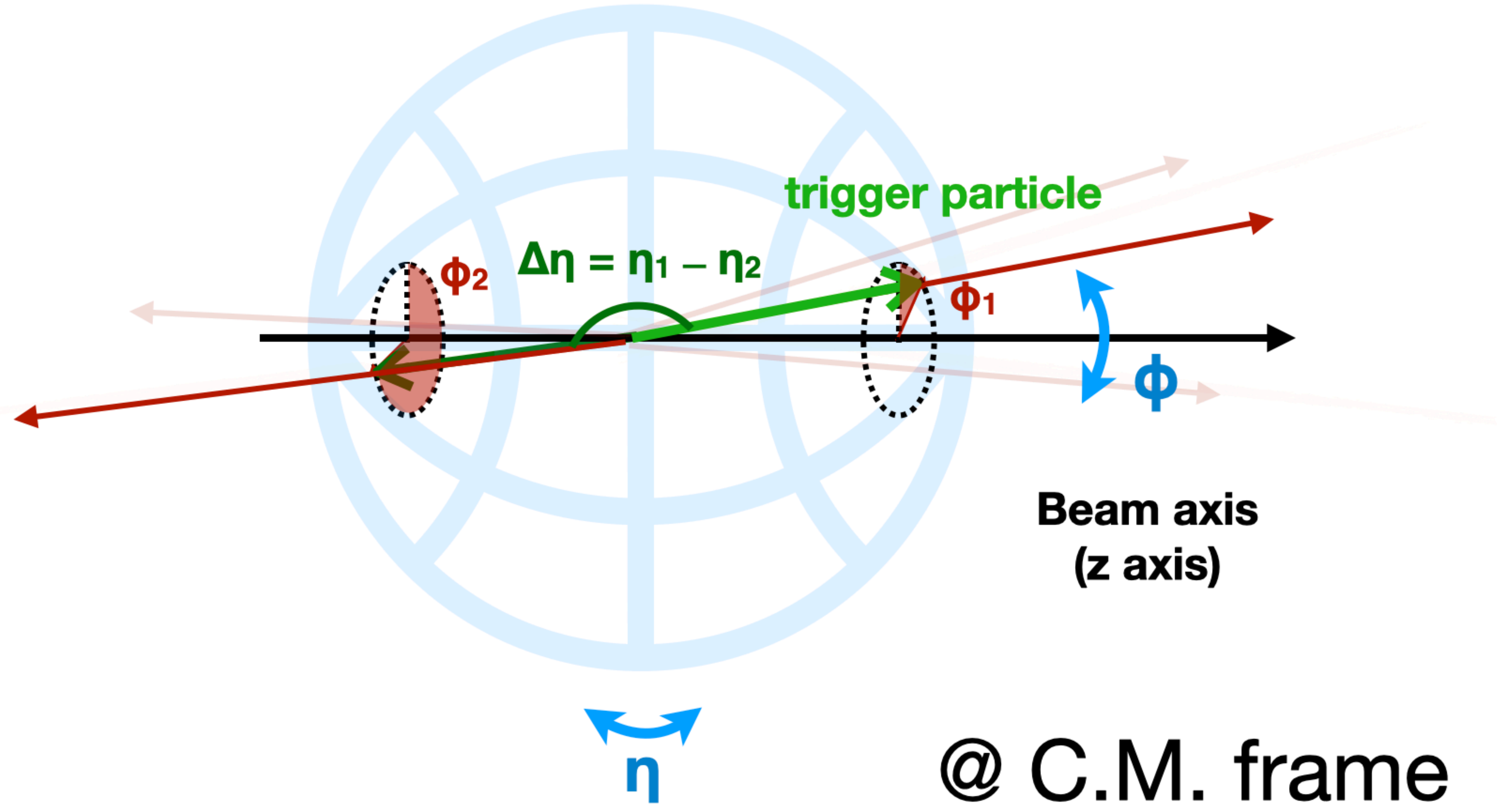
Residual MC correction

Signal
(raw correlation function)



$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trk}^{corr}} \frac{d^2 N^{same}}{d\Delta\eta d\Delta\phi}$$

Track pairs' angular difference in
η (pseudorapidity), ϕ (azimuthal angle)



@ C.M. frame

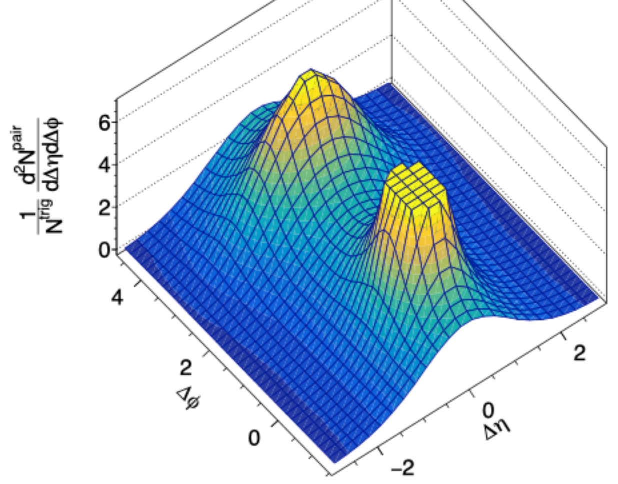
Analysis methods

Selection

Two-particle correlations

Residual MC correction

Signal
(raw correlation function)



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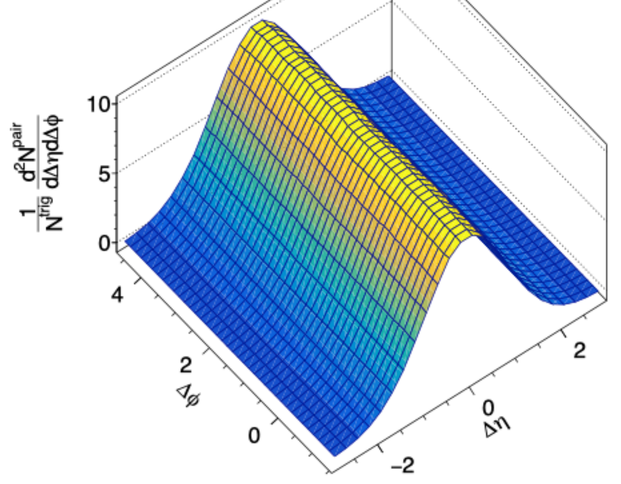
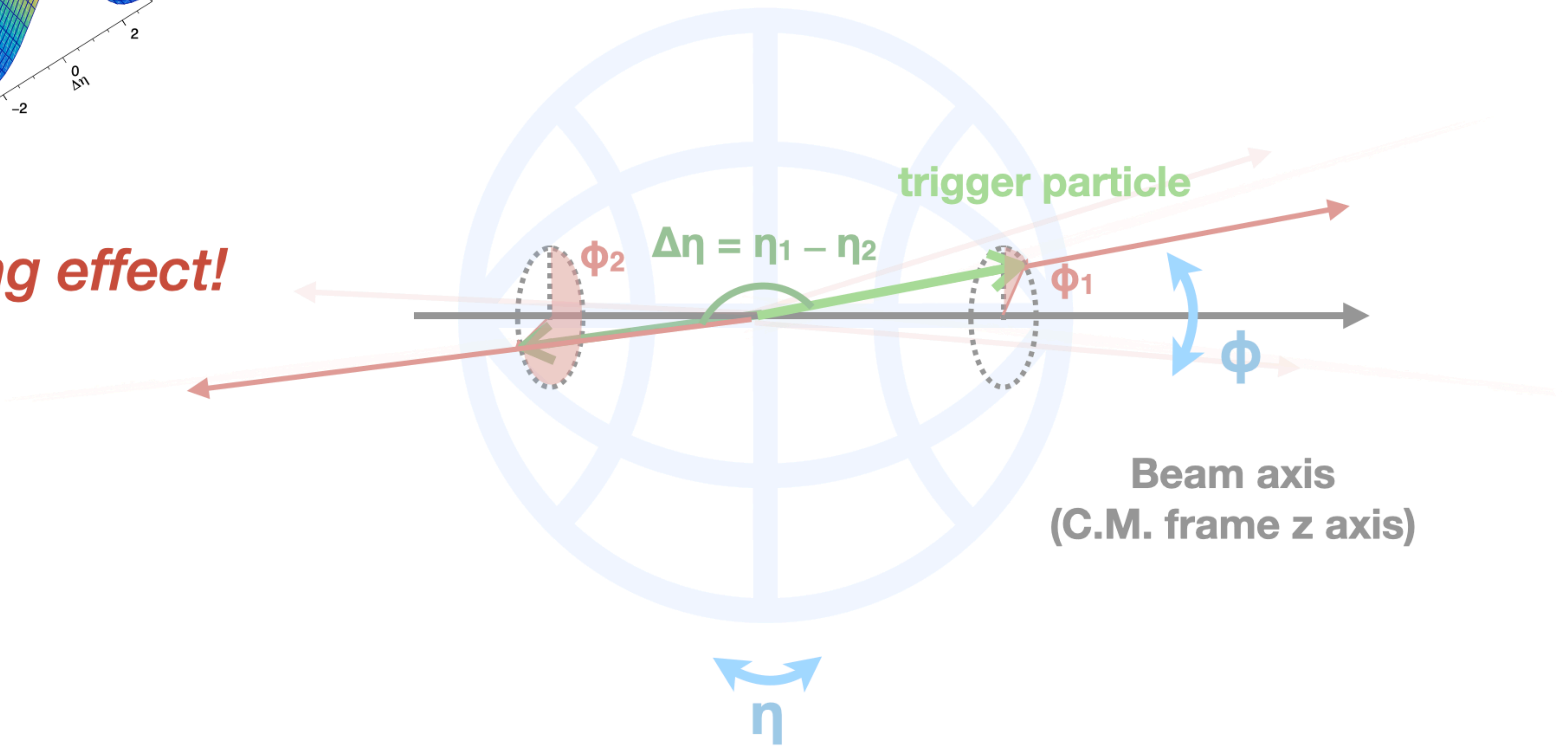
Background
(accounting for baseline of random pairing)



Track pairs' angular difference in
η (pseudorapidity), ϕ (azimuthal angle)



Factoring out the random pairing effect!

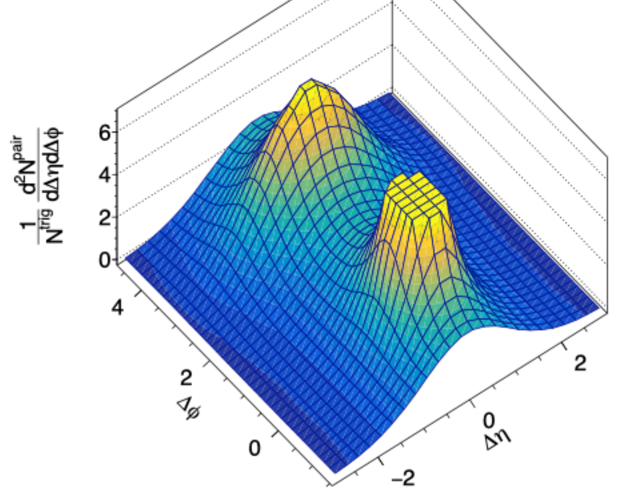
Analysis methods

Selection

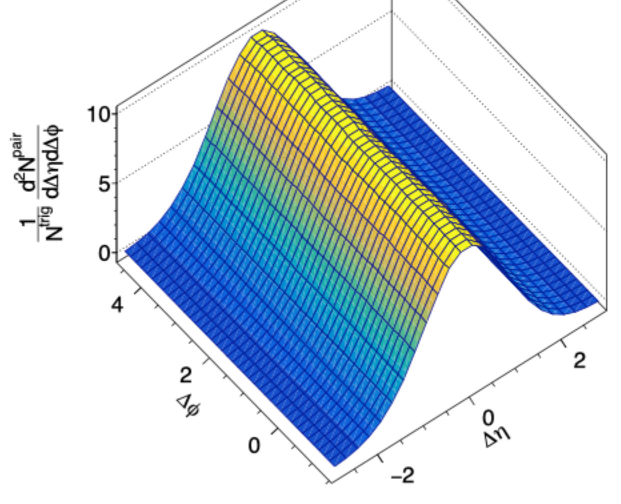
Two-particle correlations

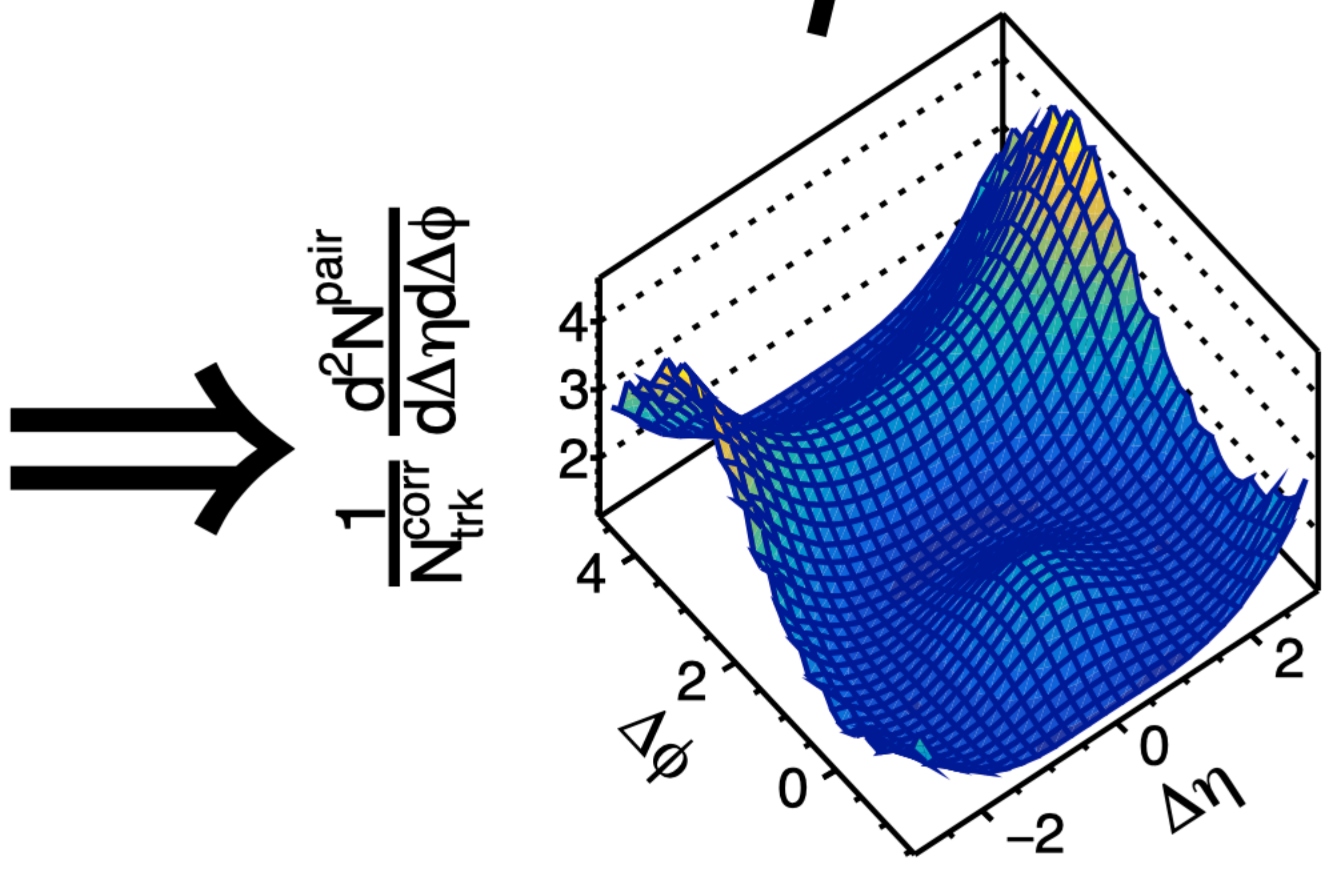
Residual MC correction

Signal
(raw correlation function)

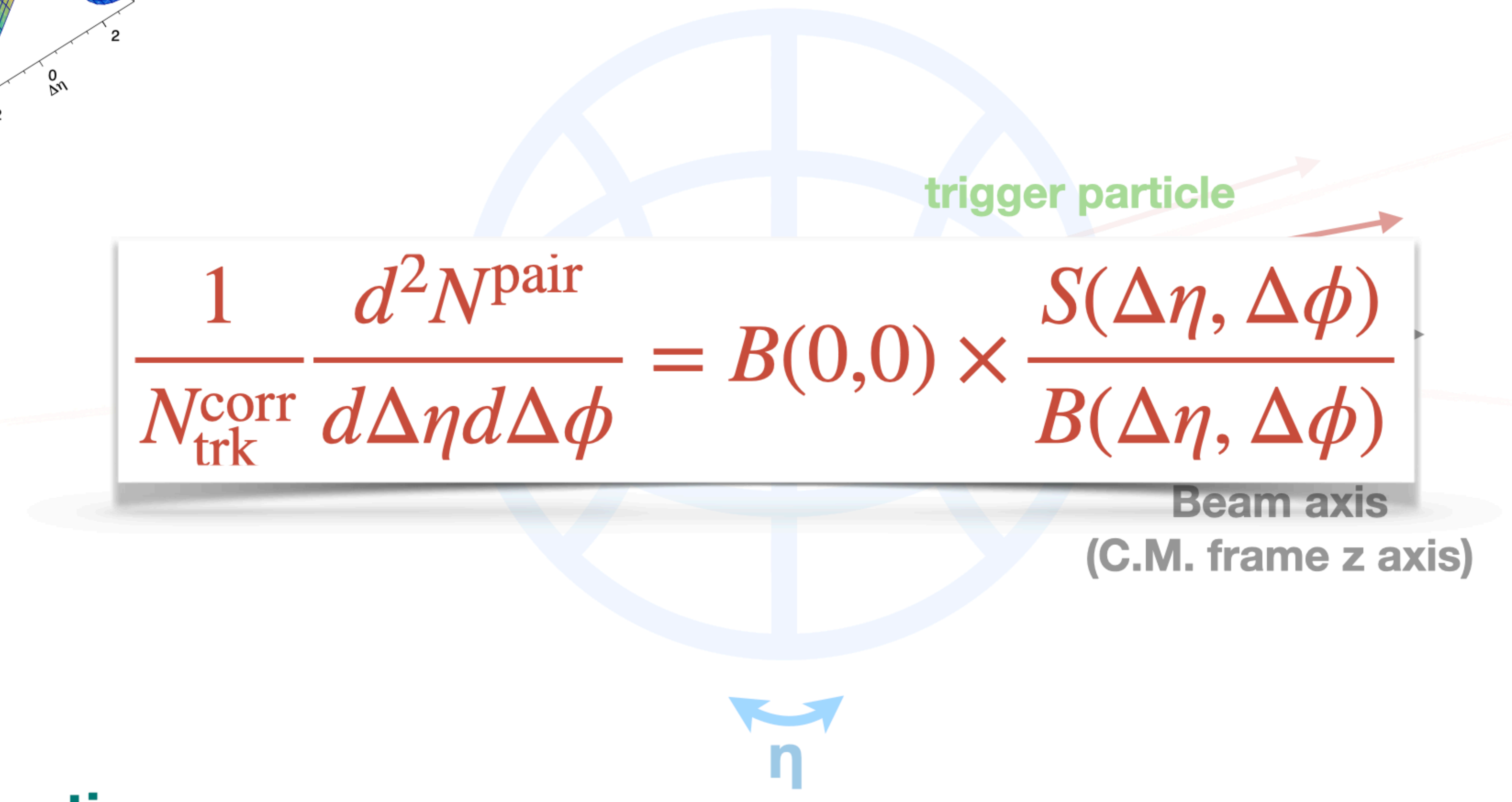


Background
(accounting for baseline of random pairing)





Track pairs' angular difference in
η (pseudorapidity), ϕ (azimuthal angle)



$$\frac{1}{N_{trk}^{corr}} \frac{d^2 N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

Two-particle correlation function
(per-trigger-particle associated yield)

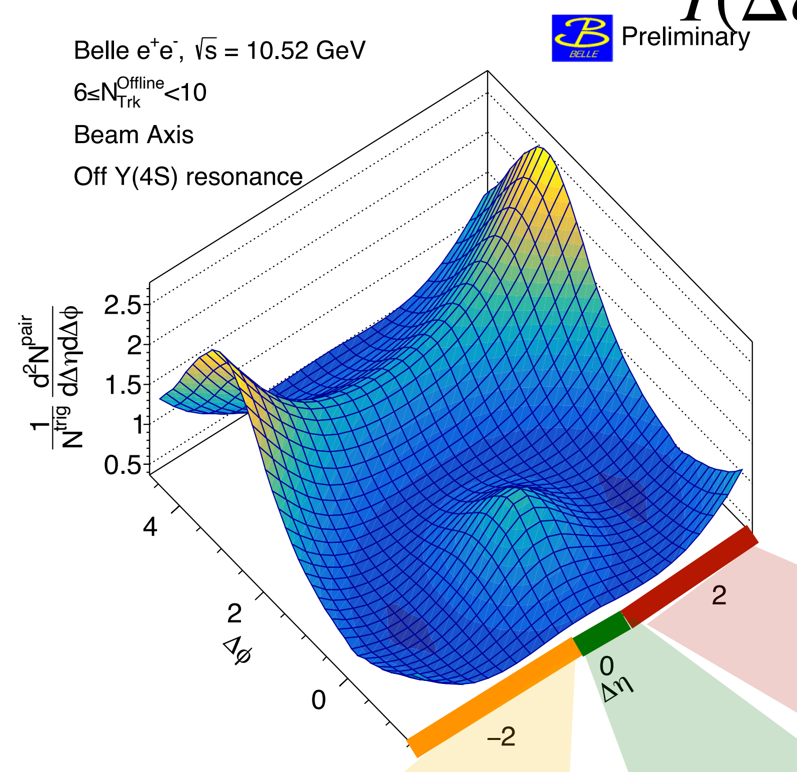
Azimuthal differential associated yield $Y(\Delta\phi)$

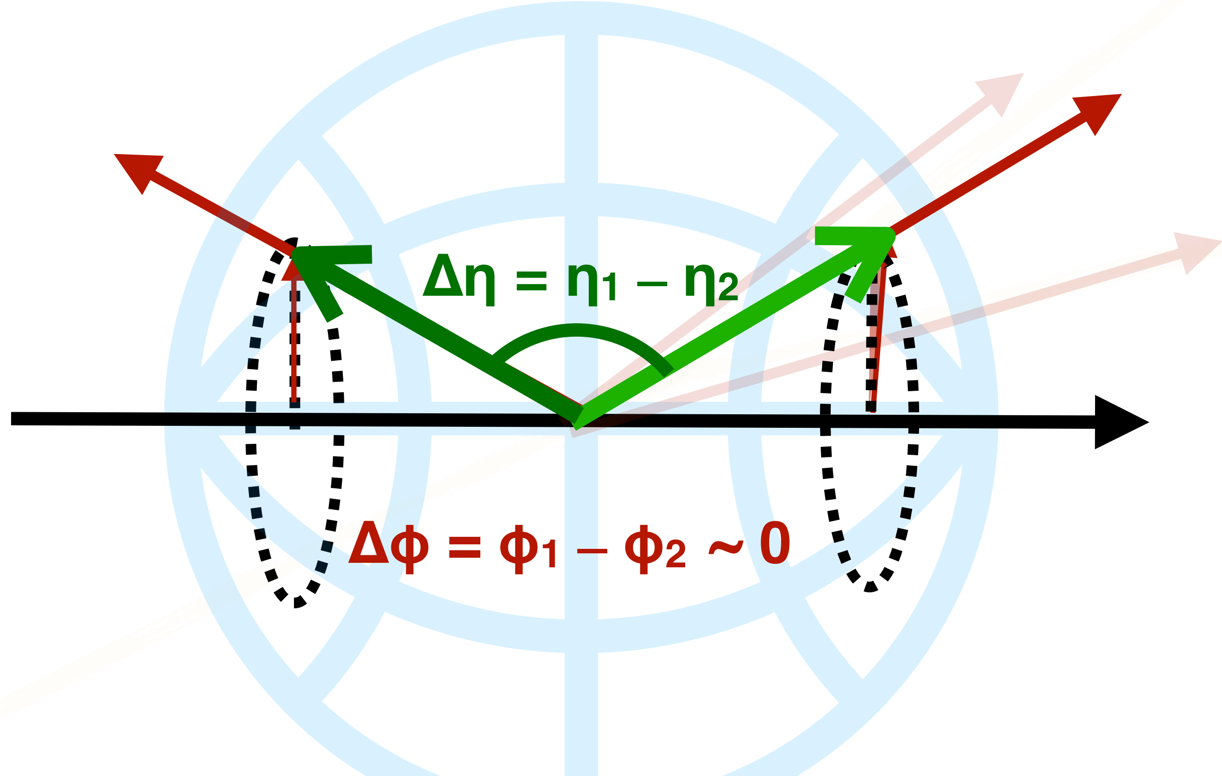
Two-particle correlation function (per-trigger-particle associated yield)

$$\frac{1}{N_{\mathrm{trig}}}\frac{d^2N^{\mathrm{pair}}}{d\Delta\eta d\Delta\phi}$$

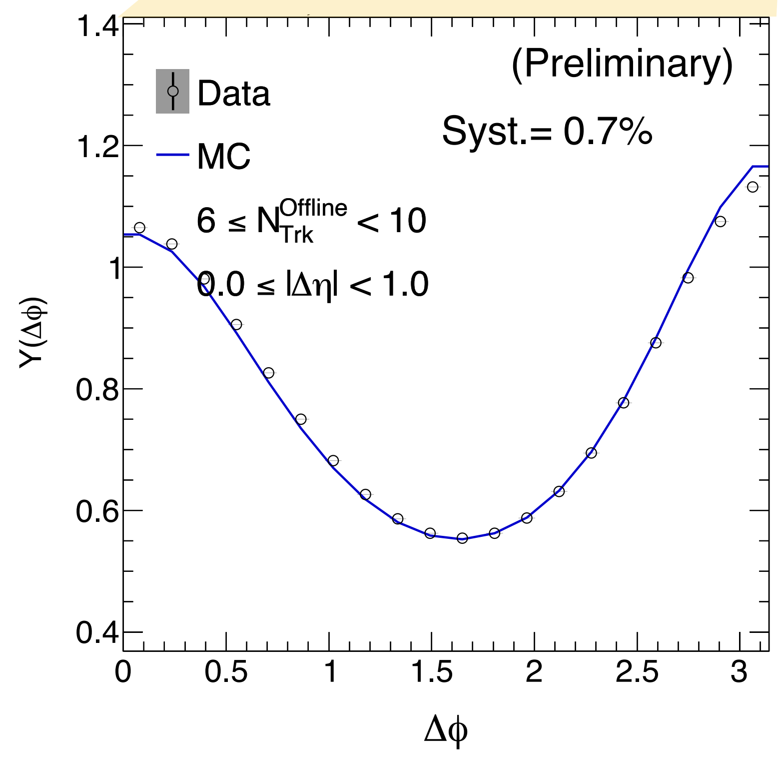
Associated yield vs. Δϕ

$$Y(\Delta\phi) = \frac{1}{N_{\mathrm{trig}}}\frac{dN^{\mathrm{pair}}}{d\Delta\phi} = \frac{1}{\Delta\eta_{\max}-\Delta\eta_{\min}}\int_{\Delta\eta_{\min}}^{\Delta\eta_{\max}}\frac{1}{N_{\mathrm{trig}}}\frac{d^2N^{\mathrm{pair}}}{d\Delta\eta d\Delta\phi}d\Delta\eta$$

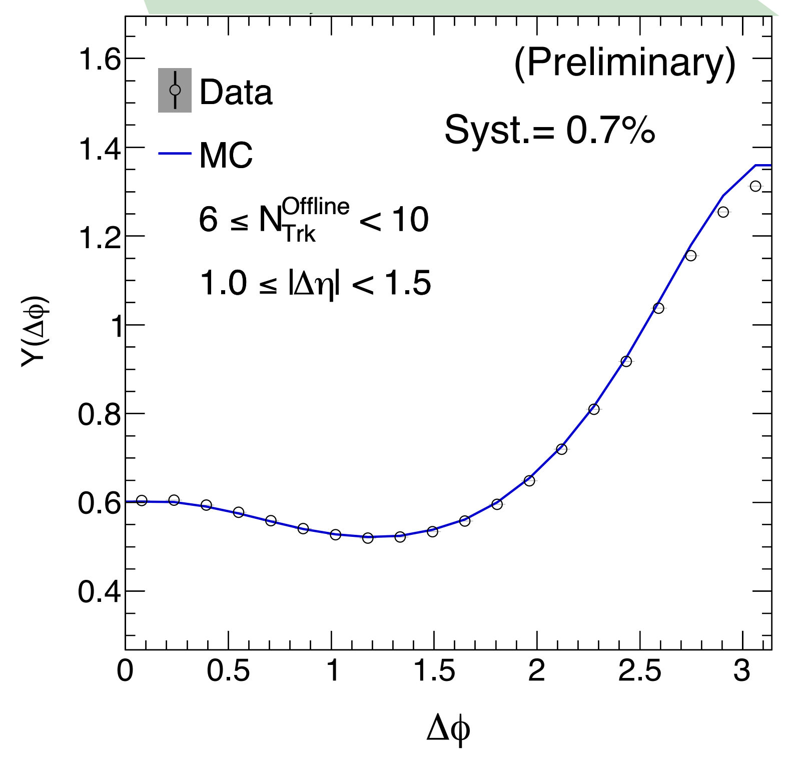




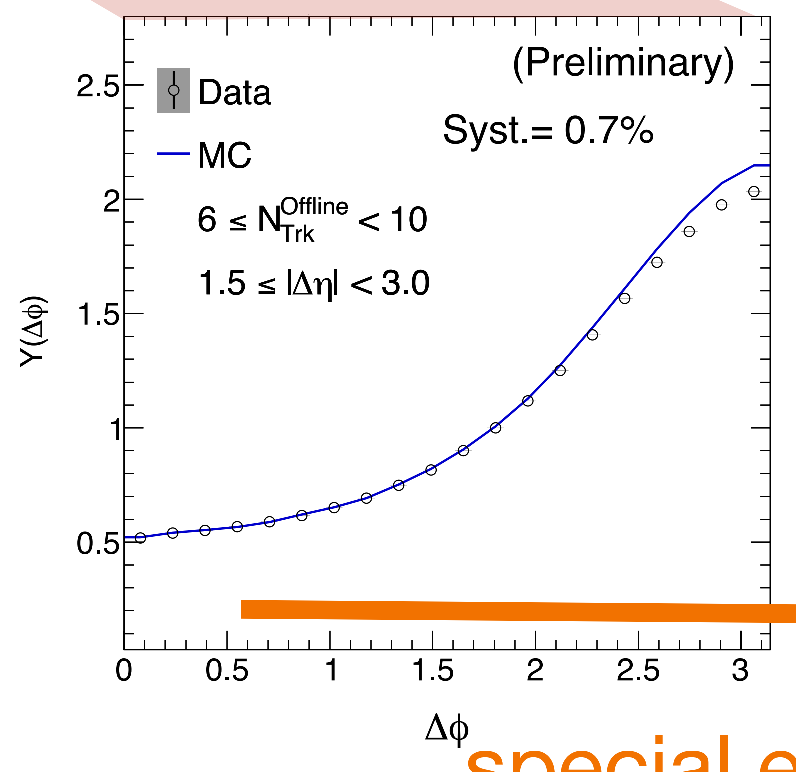
Short Range



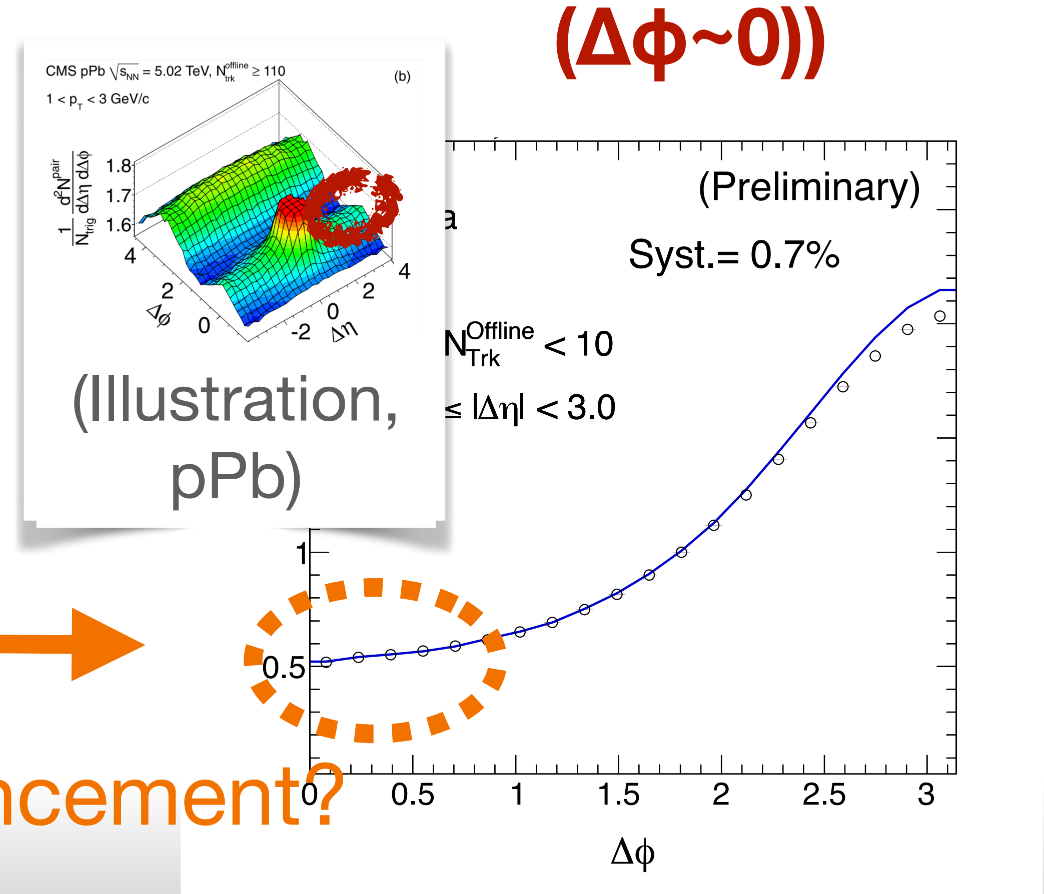
Middle Range



Long Range



Ridge Signal (long-range, near-side (Δϕ~0))



Corrections

Selection & efficiency correction

Two-particle correlations

1. Efficiency correction
2. Residual MC correction

- To calibrate the nonuniform detection efficiency and misconstruction bias
- Reconstructed tracks are weighted by the inverse of the efficiency correction factor:

$$\varepsilon(p_{\mathrm{T}}, \theta, \phi, \mathrm{N}_{\mathrm{trk}}^{\mathrm{rec}}) = \left[\frac{d^3\mathrm{N}^{\mathrm{reco}}}{dp_{\mathrm{T}} d\theta d\phi} \Big/ \frac{d^3\mathrm{N}^{\mathrm{gen}}}{dp_{\mathrm{T}} d\theta d\phi} \right]_{\mathrm{N}_{\mathrm{trk}}^{\mathrm{rec}}}$$

- A closure test is performed by comparing the p_{T}, θ, ϕ distributions of the generator level and those of the corrected reconstructed level

Corrections

Selection & efficiency correction

Two-particle correlations

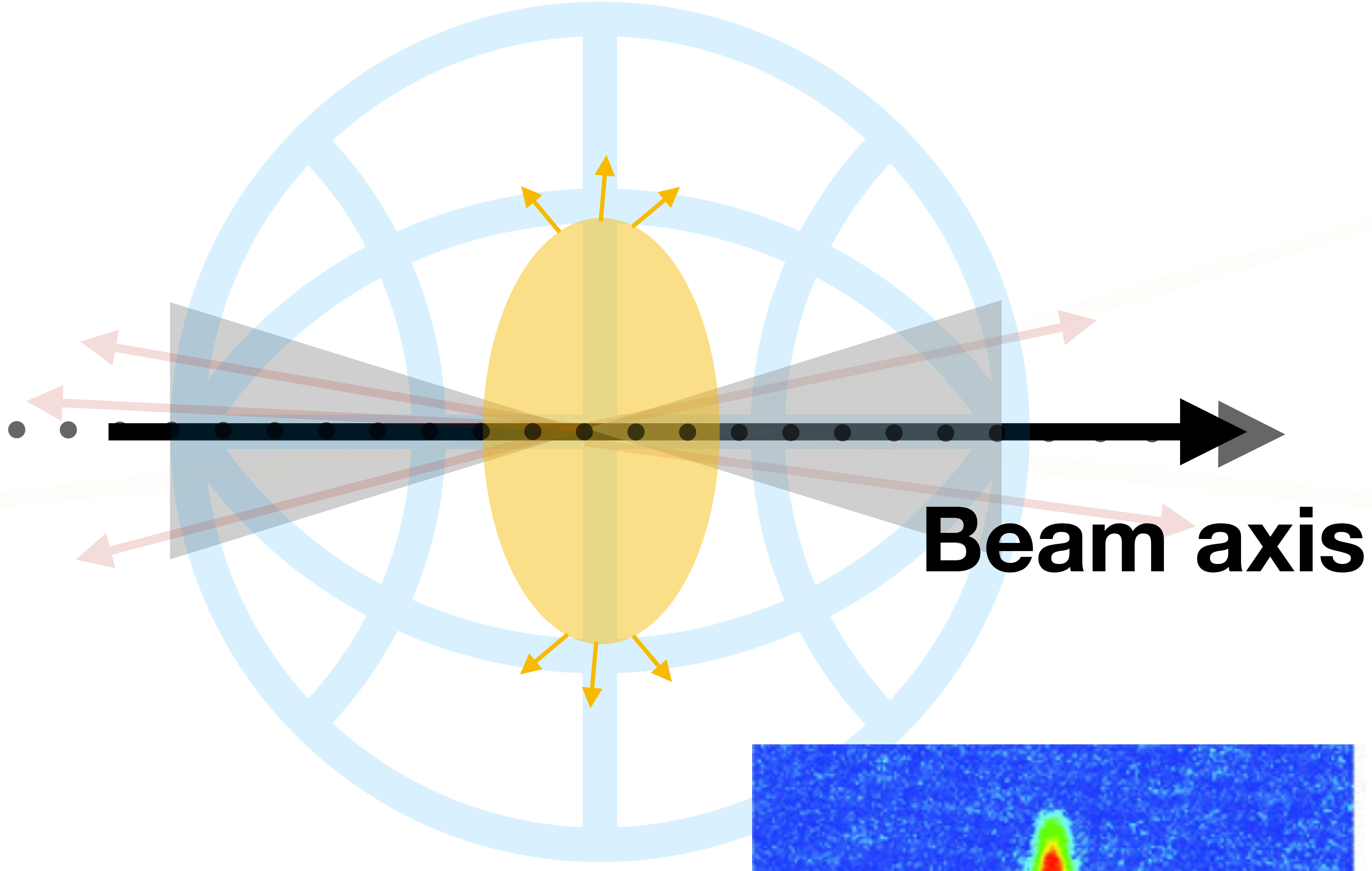
1. Efficiency correction
2. Residual MC correction

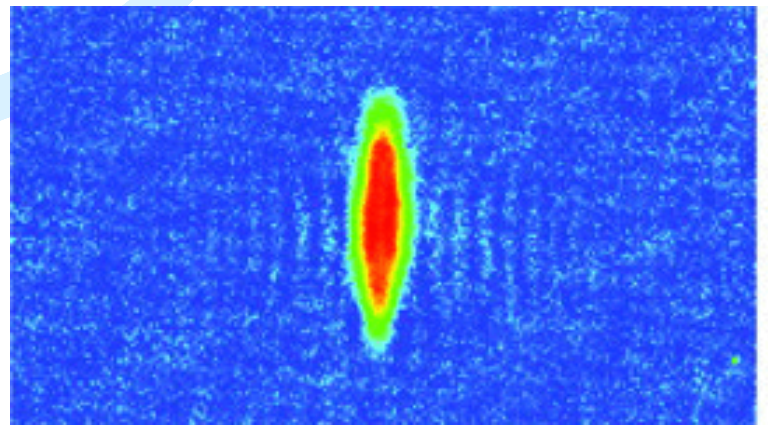
- To deal with remaining possible reconstruction effects
- Bin-by-bin correction: the correction factor is derived from the histogram ratio of MC correlation functions at the reconstruction and generator level as

$$\mathrm{C}(\Delta\phi) = \frac{Y(\Delta\phi)_{\mathrm{gen},i_g}}{Y(\Delta\phi)_{\mathrm{reco},i_r}}$$

- Final data correlation results are obtained from the multiplication of the original correlation function with the bin-by-bin correction factor

Perfect-fluid-like QGP expansion



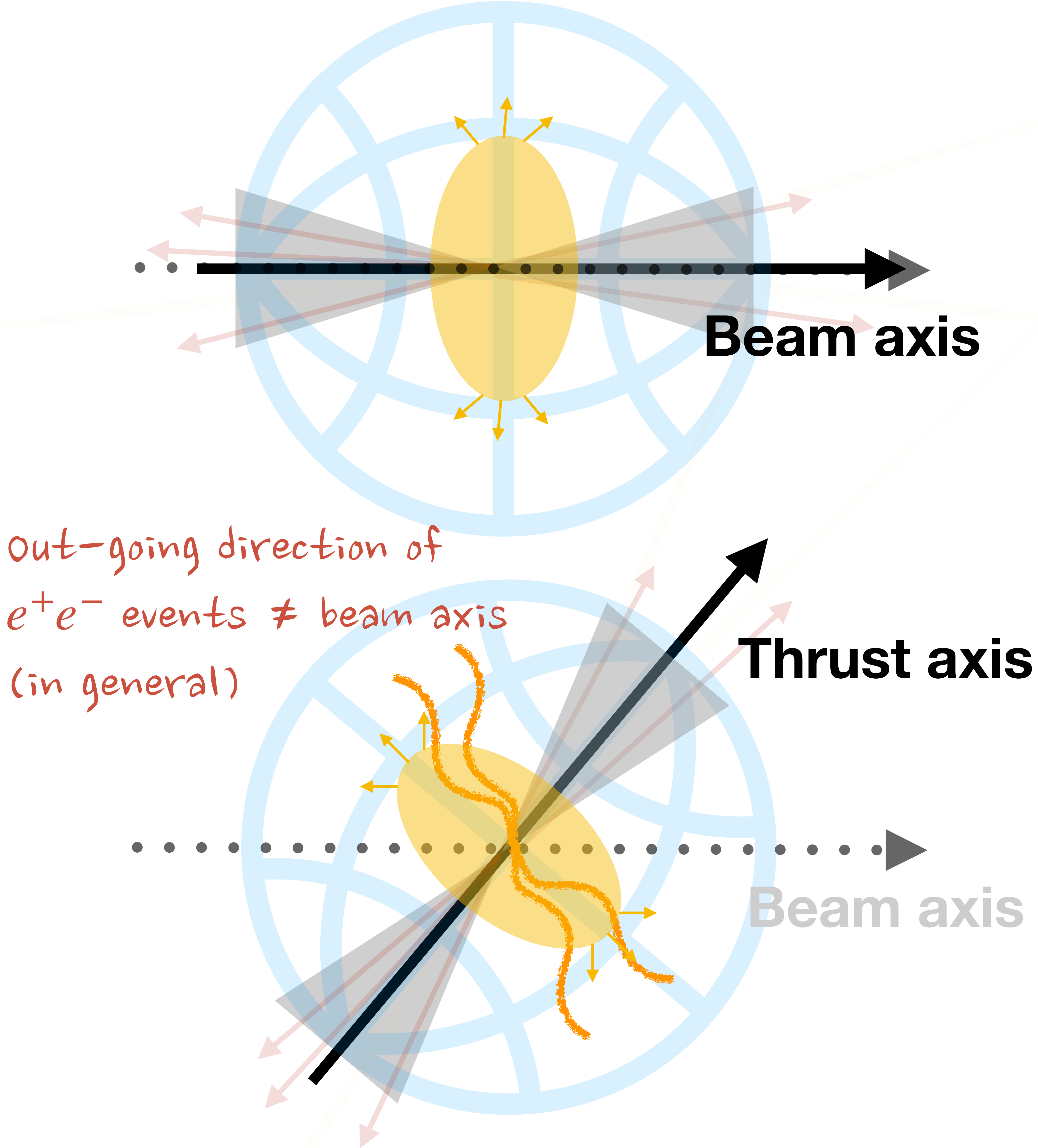


100 μs

2PC characterizes the medium expansion in the transverse region w.r.t. the reference axis:

- Beam axis analysis:
  hydrodynamic expansion of possible QGP medium in HI collisions

Hypothetical QGP in e^+e^-?



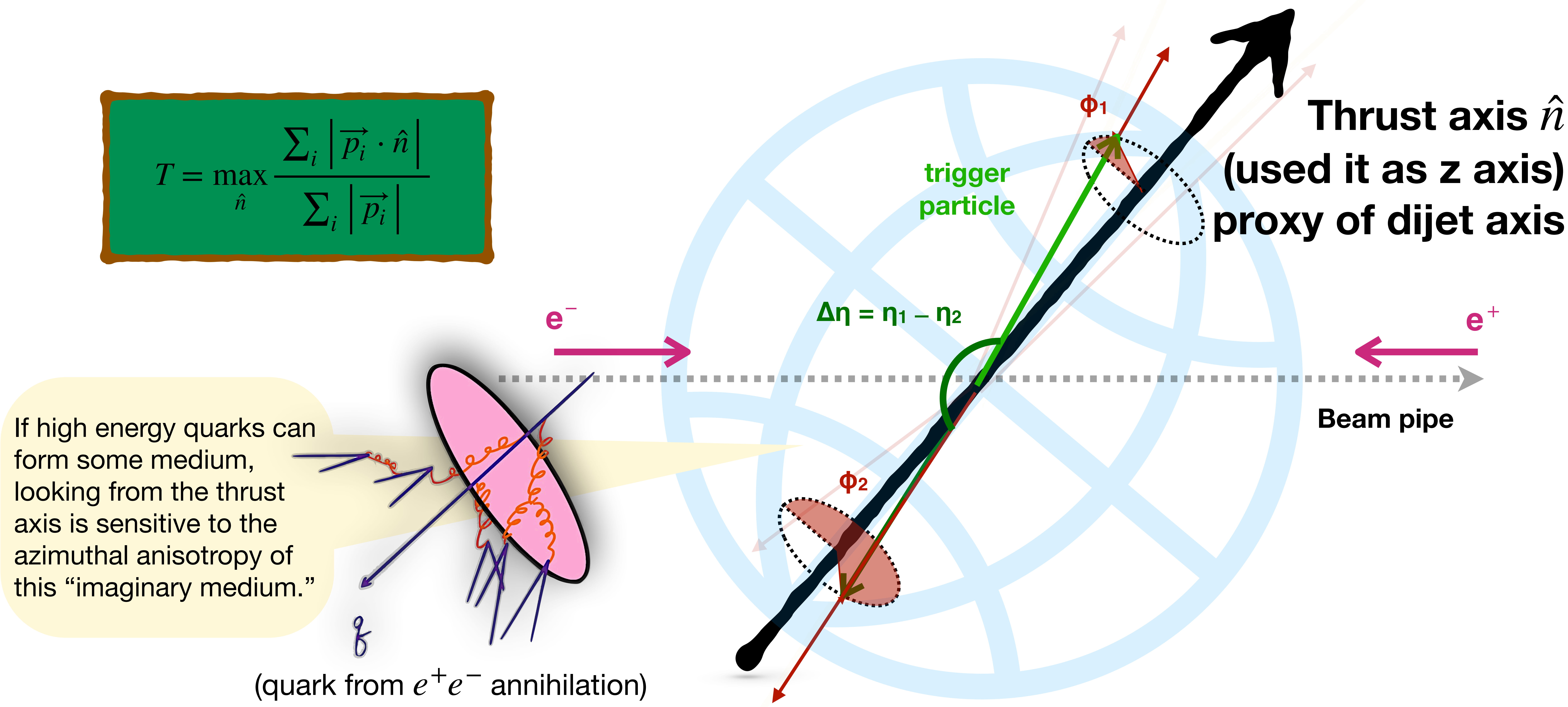
2PC characterizes the medium expansion in the transverse region w.r.t. the reference axis:

- Beam axis analysis:
  hydrodynamic expansion of possible QGP medium in HI collisions

- Thrust axis analysis:
  soft emissions or QGP in e^+e^- annihilation

Anisotropic correlation around thrust axis in e^+e^-?

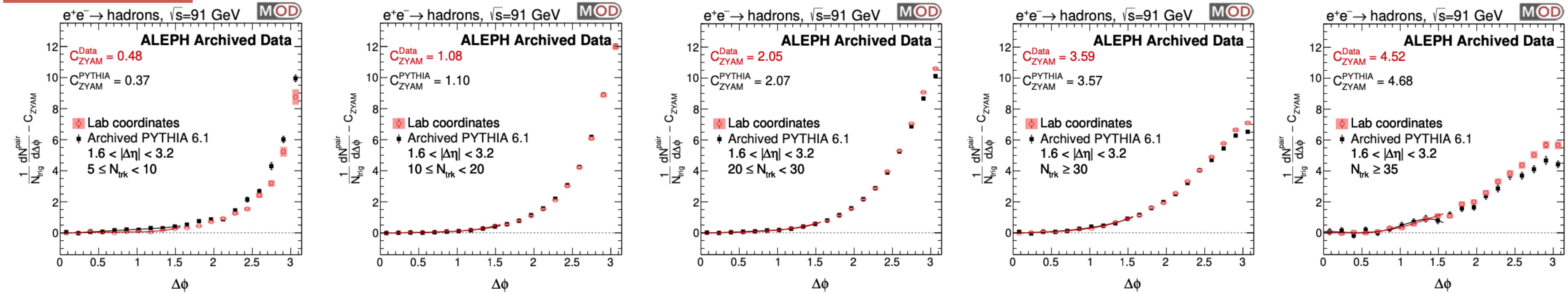
$$T = \max_{\hat{n}} \frac{\sum_i |\vec{p_i} \cdot \hat{n}|}{\sum_i |\vec{p_i}|}$$



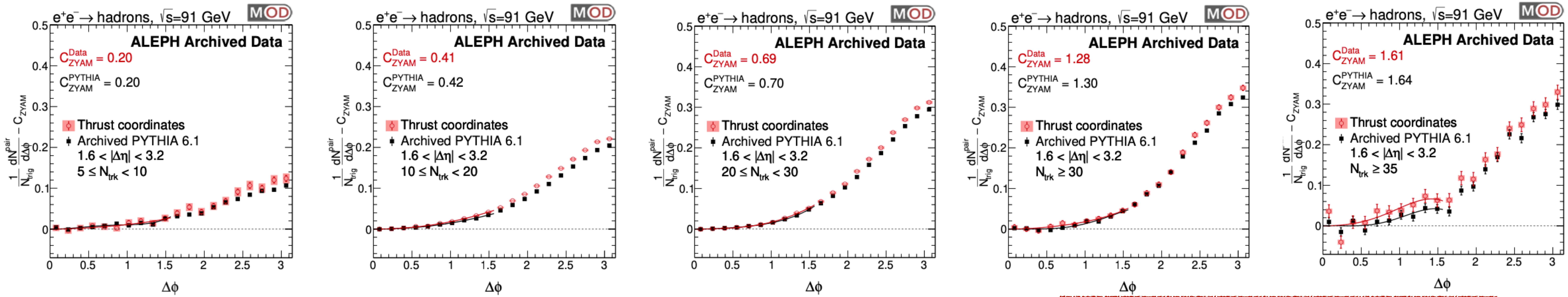
Long-range correlations (c.f. MC)

LEP1

Beam axis



$5 \leq N_{\rm trk} < 10$ $\quad 10 \leq N_{\rm trk} < 20$ $\quad 20 \leq N_{\rm trk} < 30$ $\quad N_{\rm trk} \geq 30$ $\quad N_{\rm trk} \geq 35$



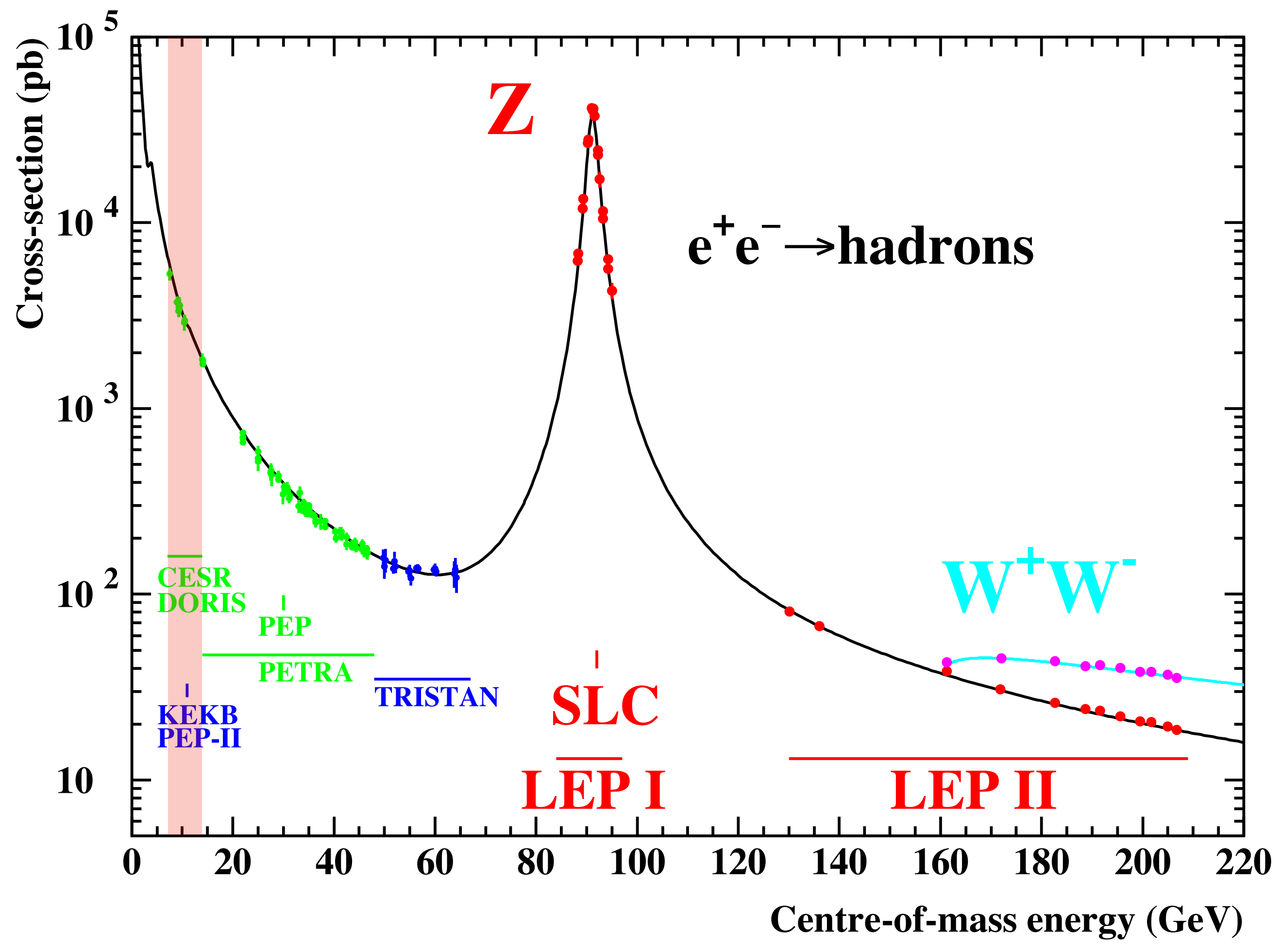
Thrust axis

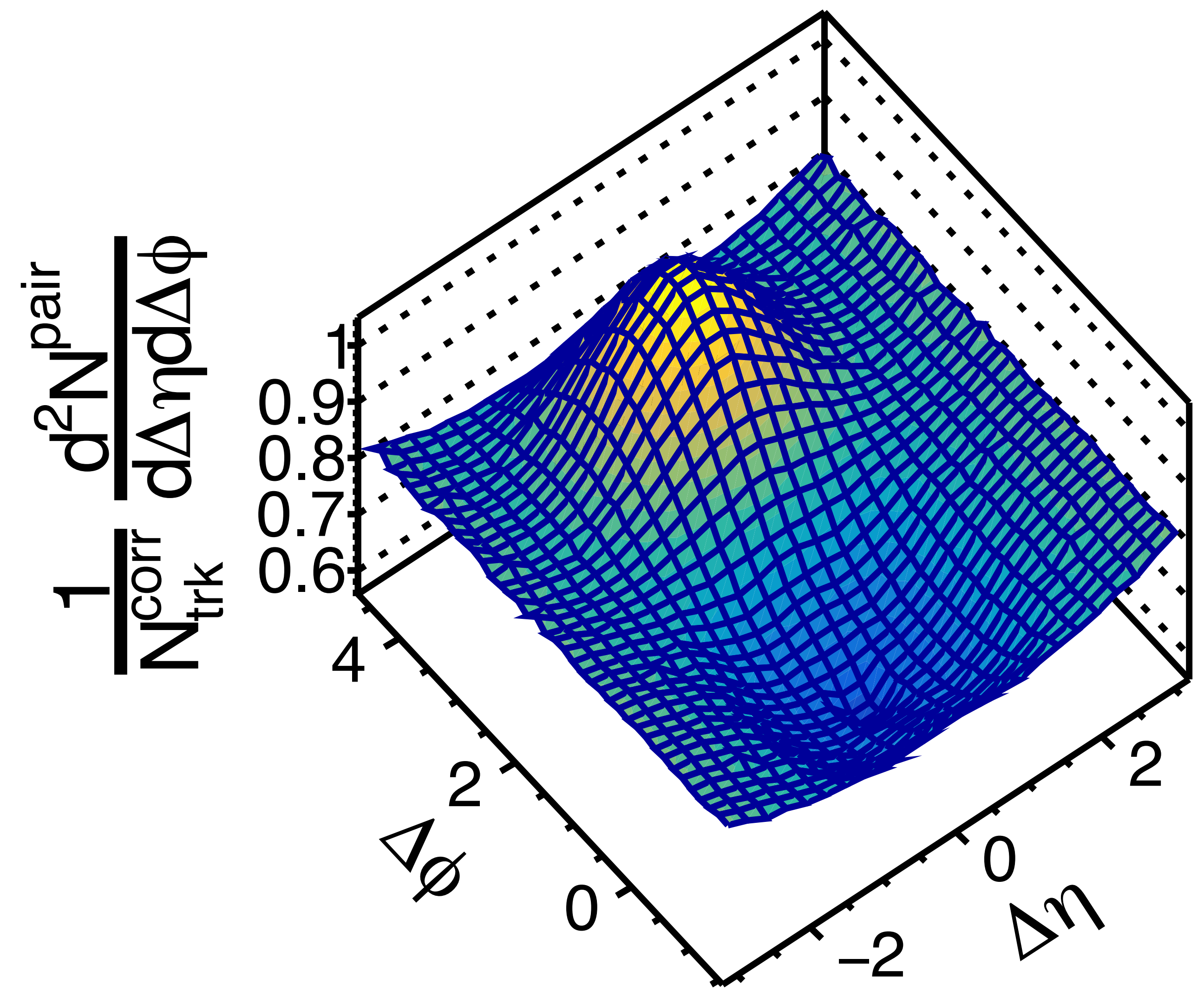
Good agreement with MC!

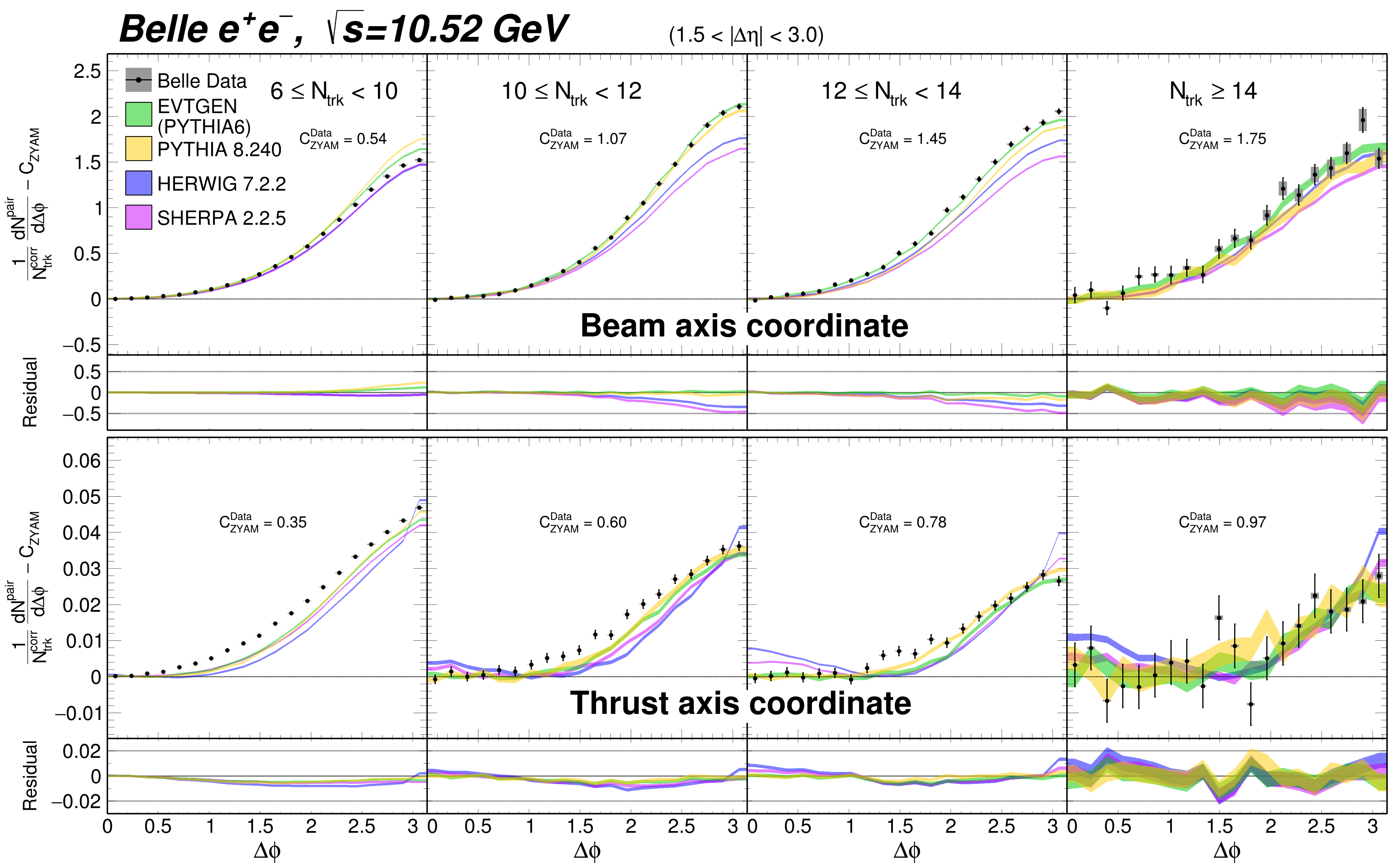
2PC — comparisons with the low-energy Belle experiment ($\sqrt{s}$=10.52 GeV)

Belle

Results





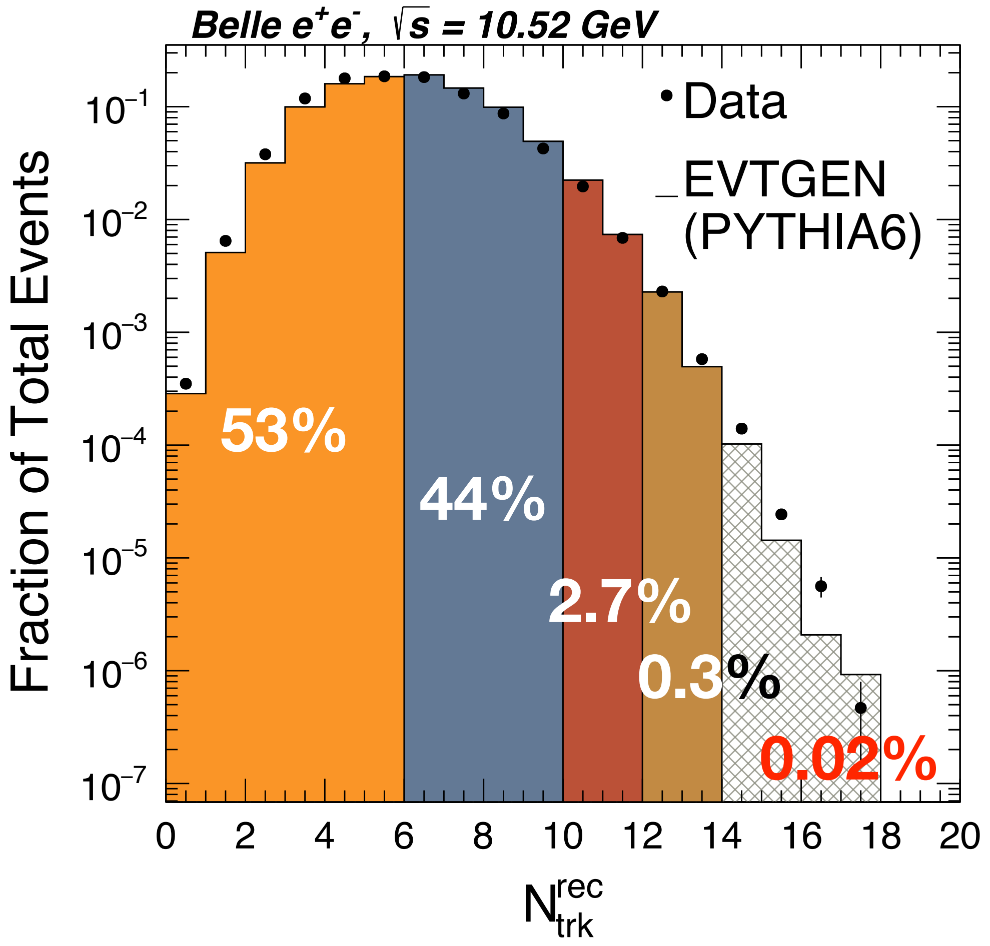


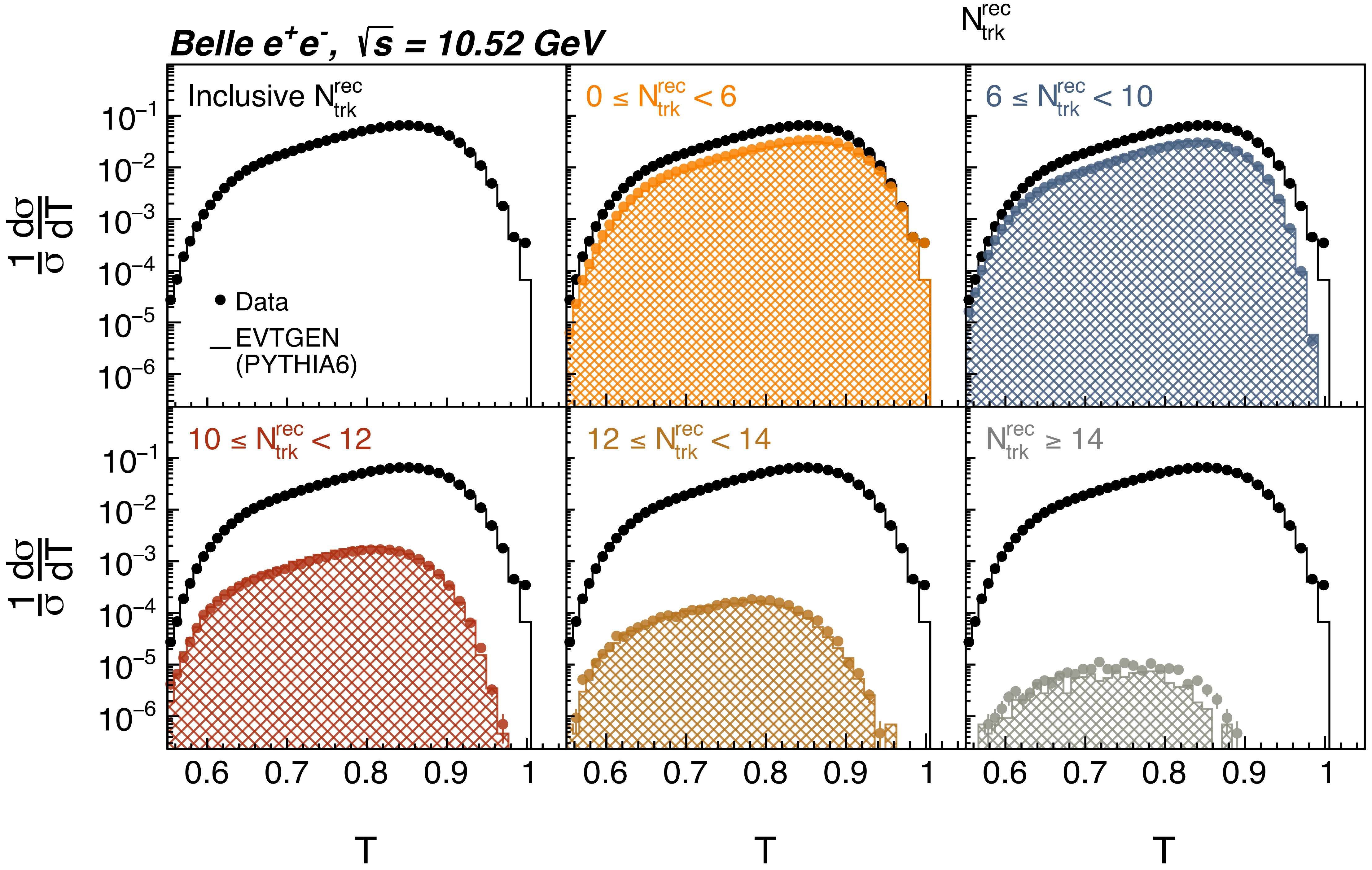
Compared with various fragmentation models

Belle e^+e^- [Phys. Rev. Lett. 128, 142005 (2022)]

c.f. MC

Belle



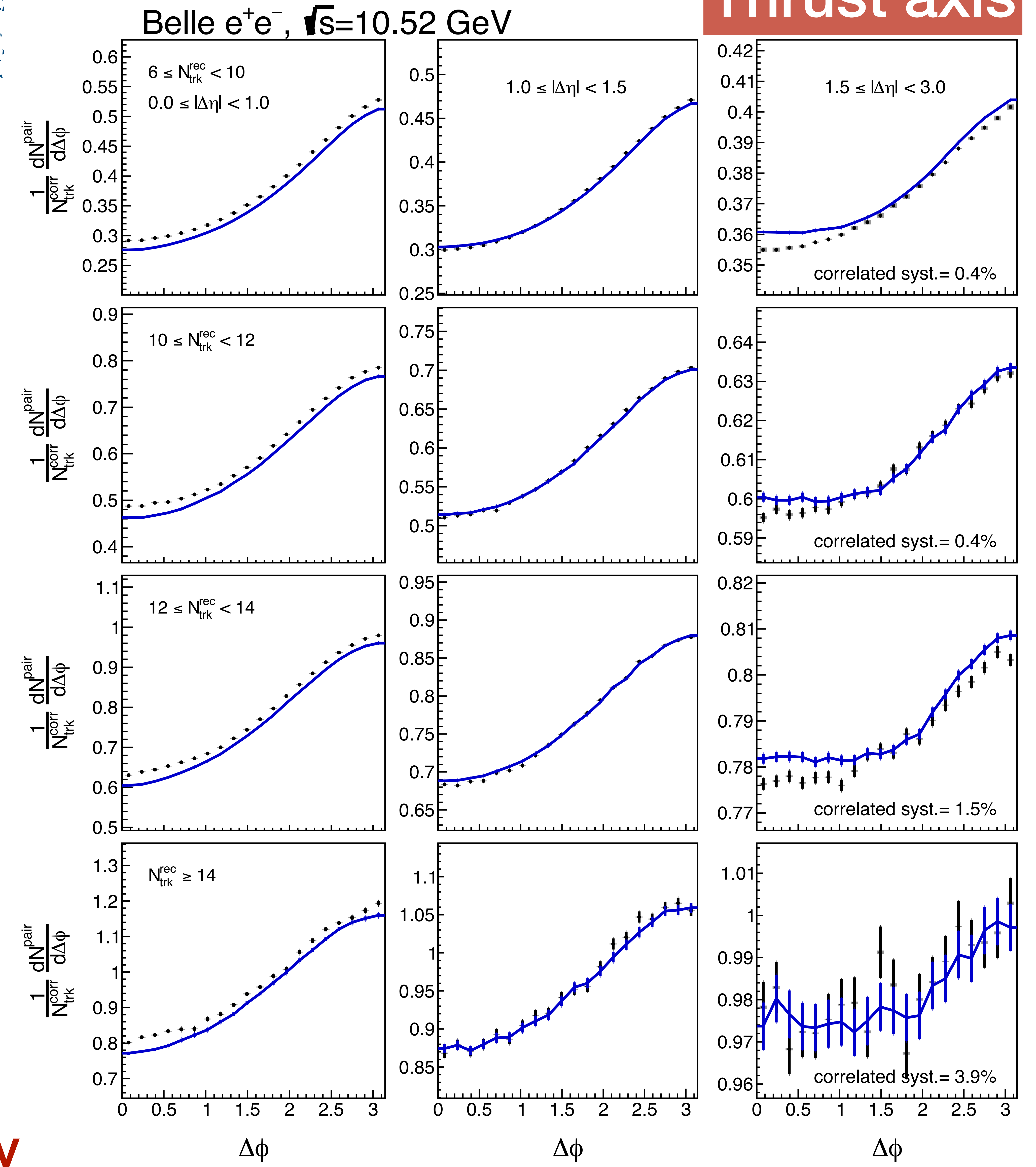


Data

PYTHIA6

High-multiplicity

Thrust axis



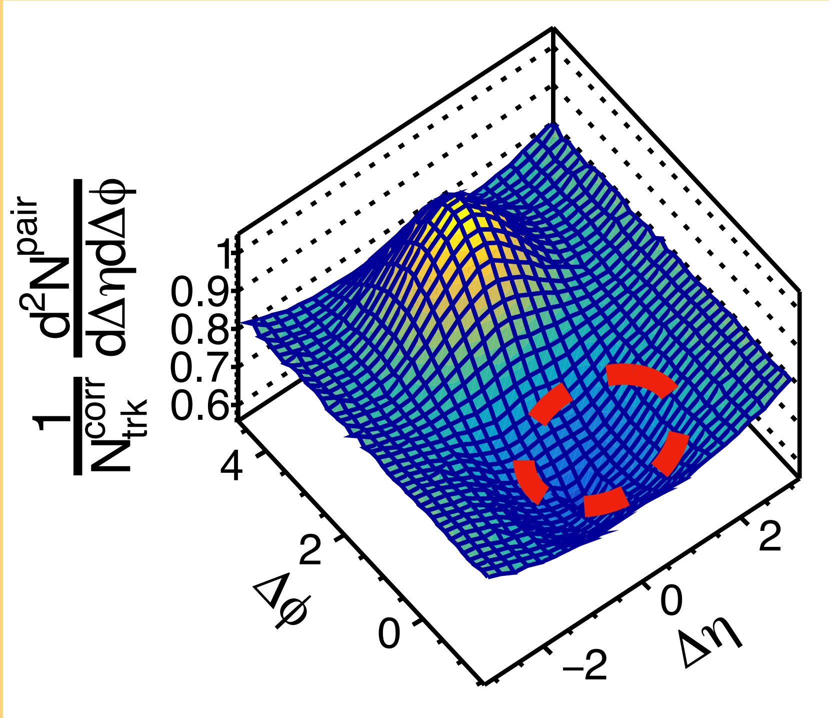
Short Range ($0 \le |\Delta\eta| < 1$)

Middle Range ($1 \le |\Delta\eta| < 1.5$)

Long Range ($1.5 \le |\Delta\eta| < 3.0$)

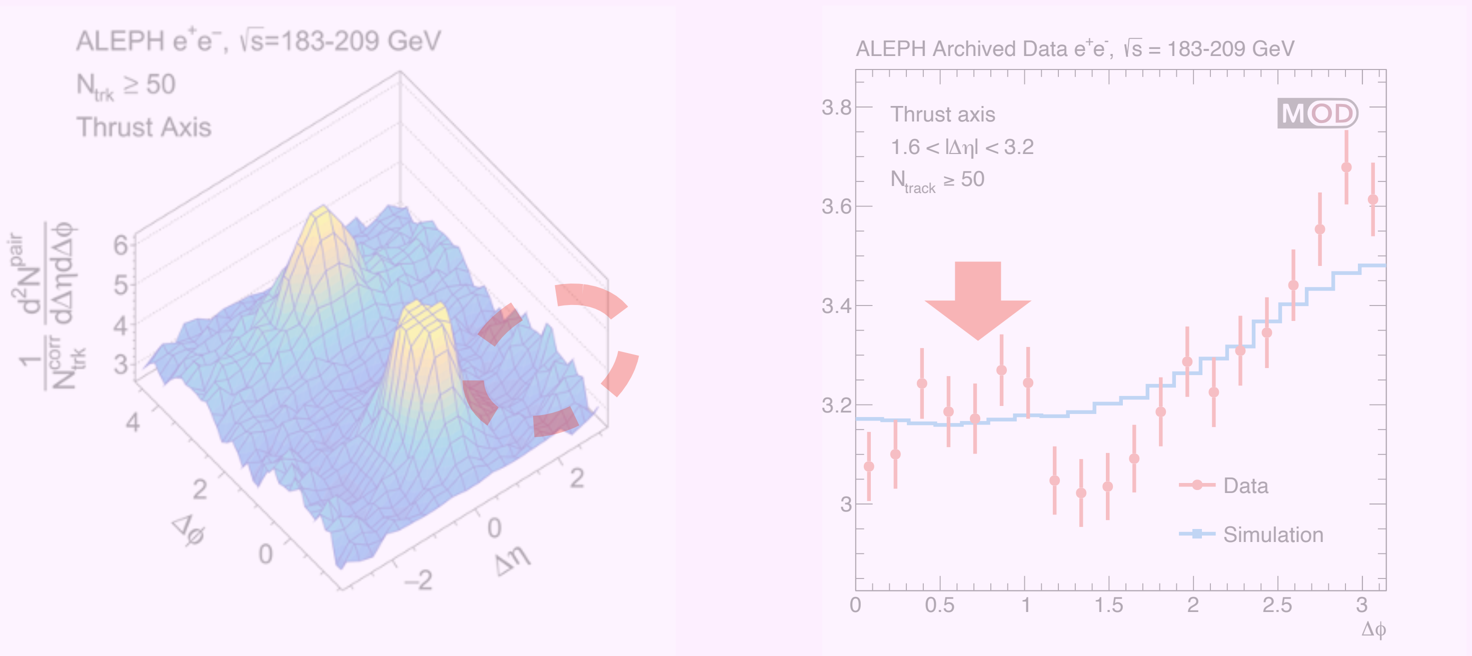
Puzzles we faced along the way…

Low-energy Belle data



Lack of jet-like correlation?

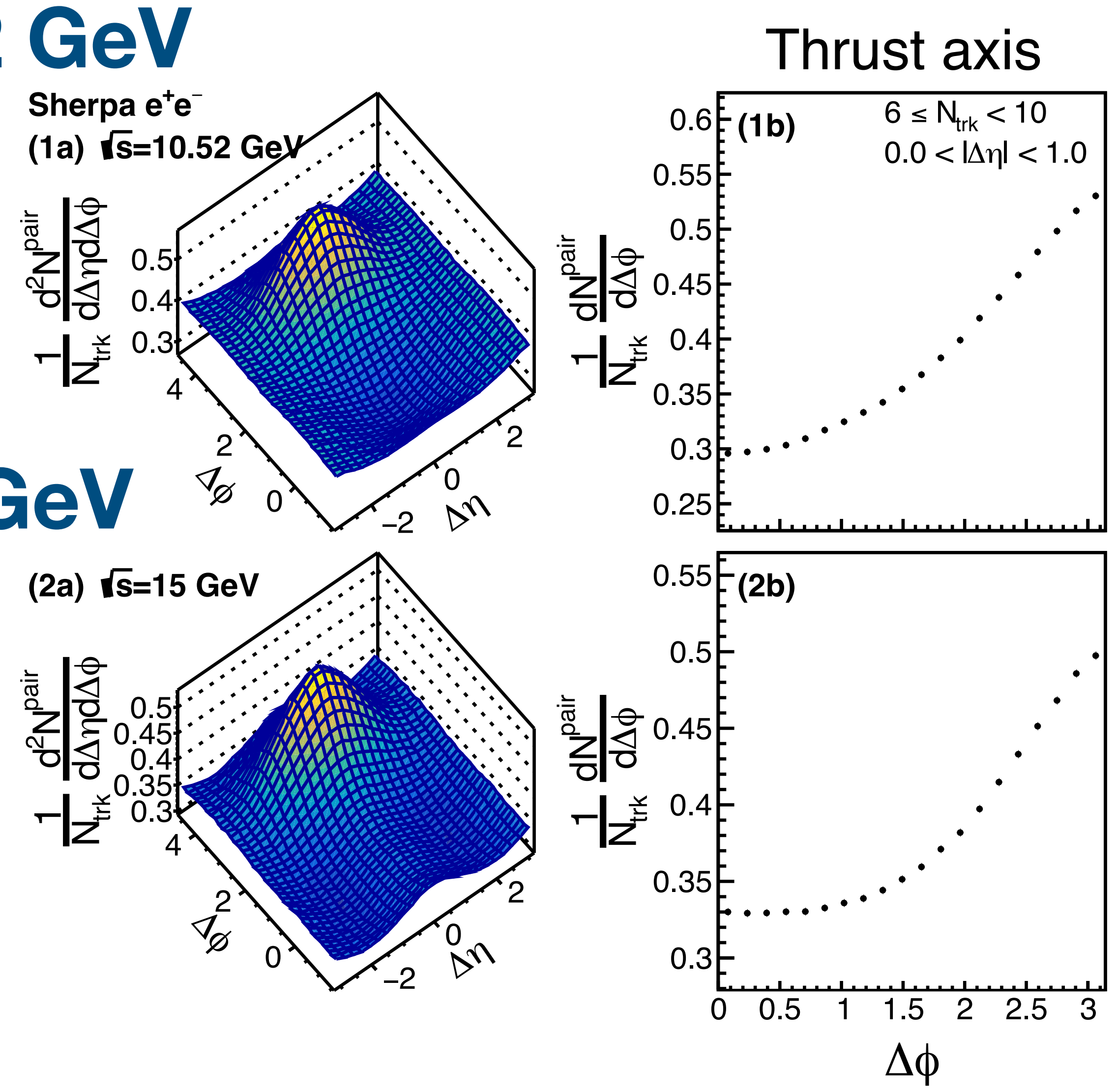
High-energy LEP 2 data



- Simulate by Sherpa generator on different $\sqrt{s}$:
  - Sharp origin-peak correlation evolved from null to significant intra-jet correlation as $\sqrt{s}$ goes high!

10.52 GeV

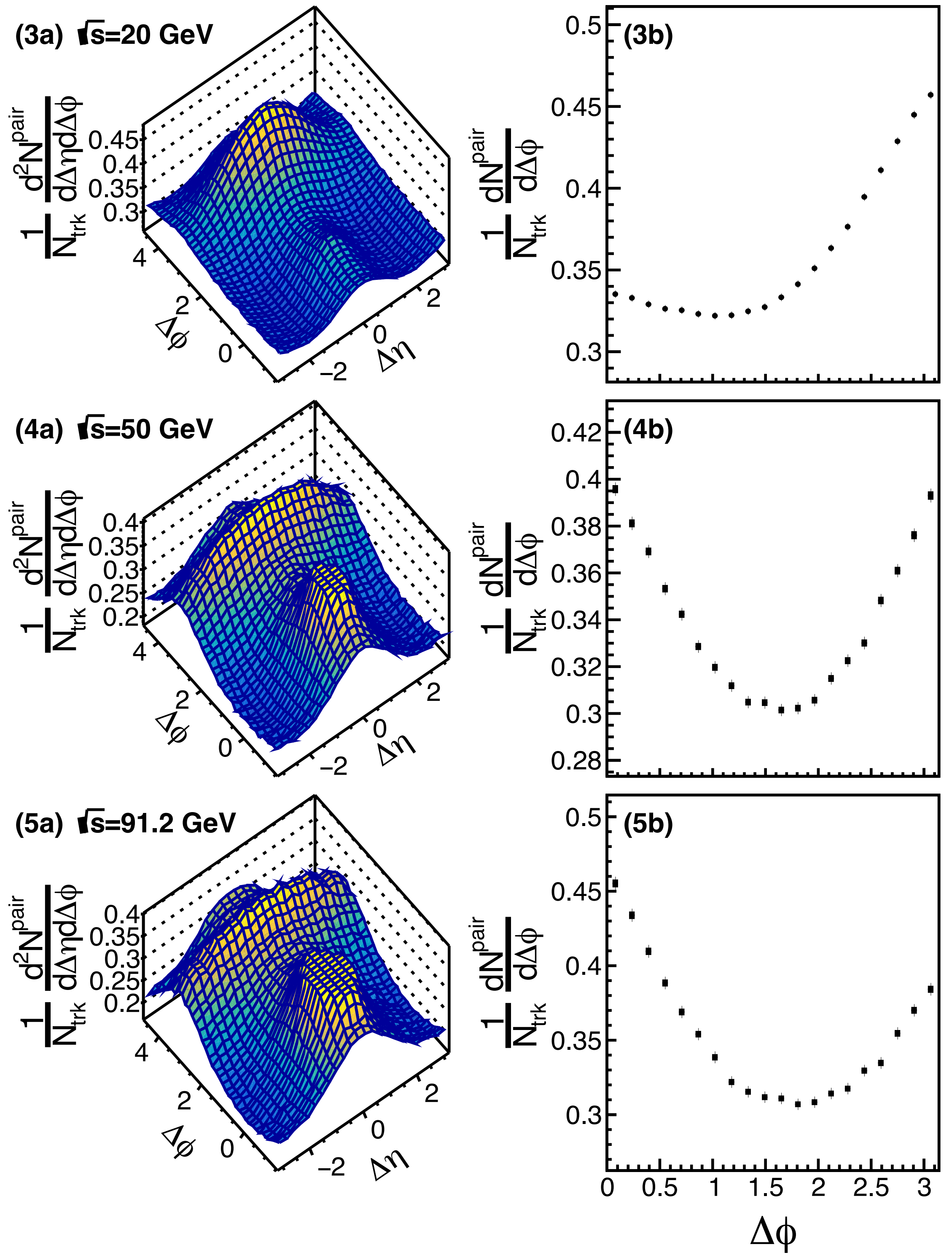
15 GeV



20 GeV

50 GeV

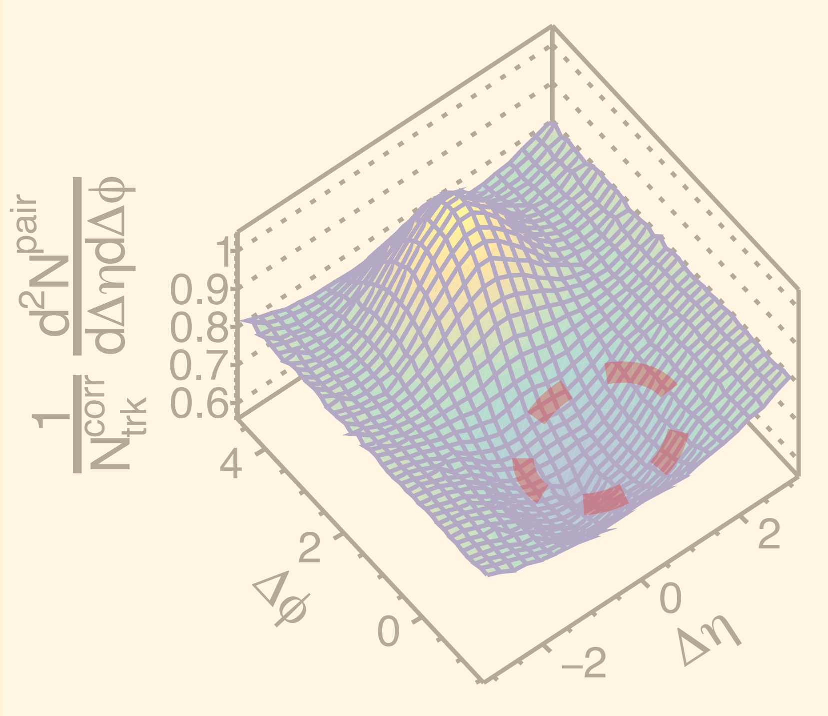
91.2 GeV (LEP1)



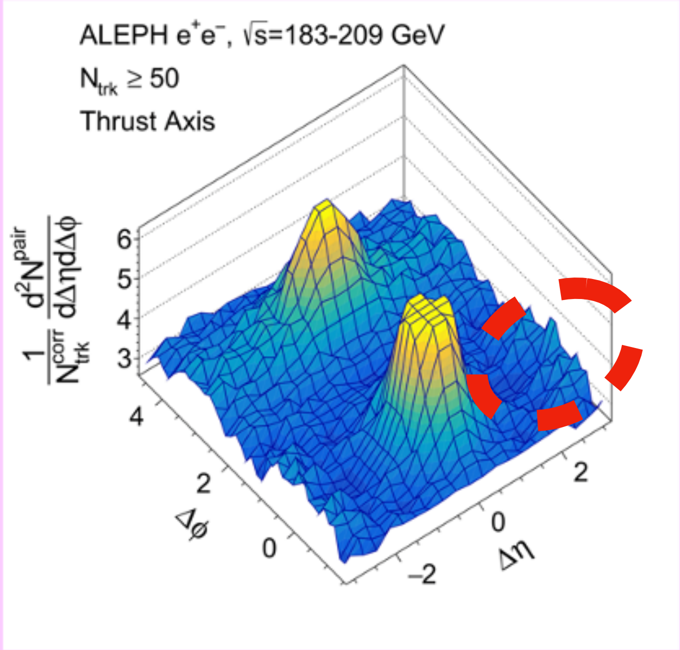
Understood!

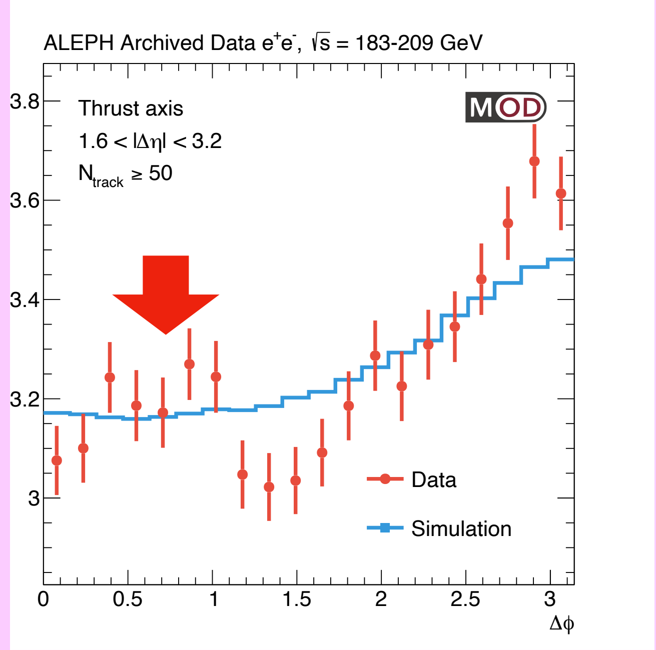
Puzzles we faced along the way…

Low-energy Belle data



High-energy LEP 2 data





Enhanced signals?

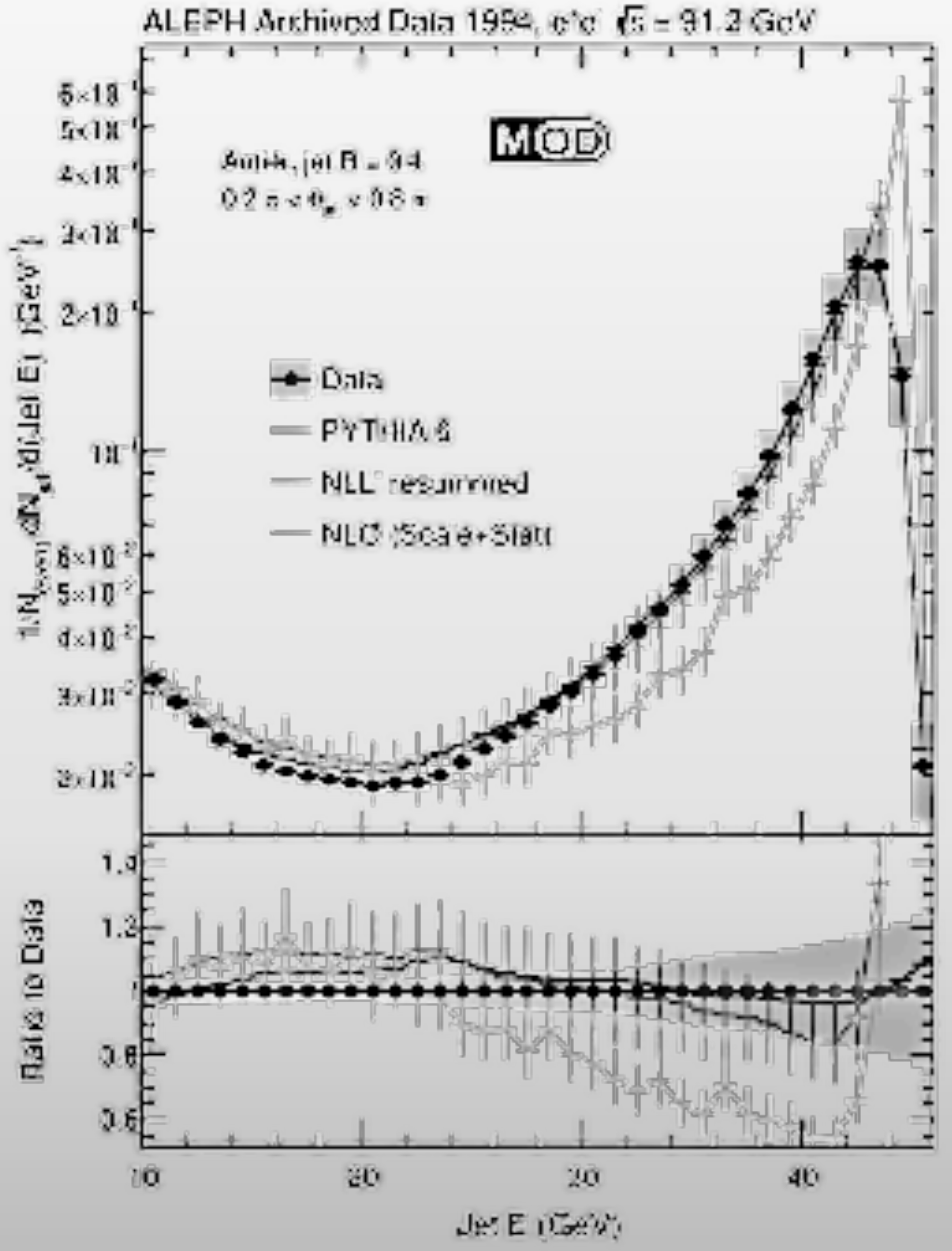
Difficulties of the analysis:

- Larger initial-state radiation effects (radiative return to the Z)
- Complicated physics processes above the di-boson production threshold (WW, ZZ)

Ongoing checks:

- Scanning of the long-range |Δη| projection window with MC
  To see if the signals really persist regardless the choice of the configuration
- Consistency check: look into the year-dependence (collision-energy-dependence)
- Compared with modern MC generators

Anti-k_T jet measurement



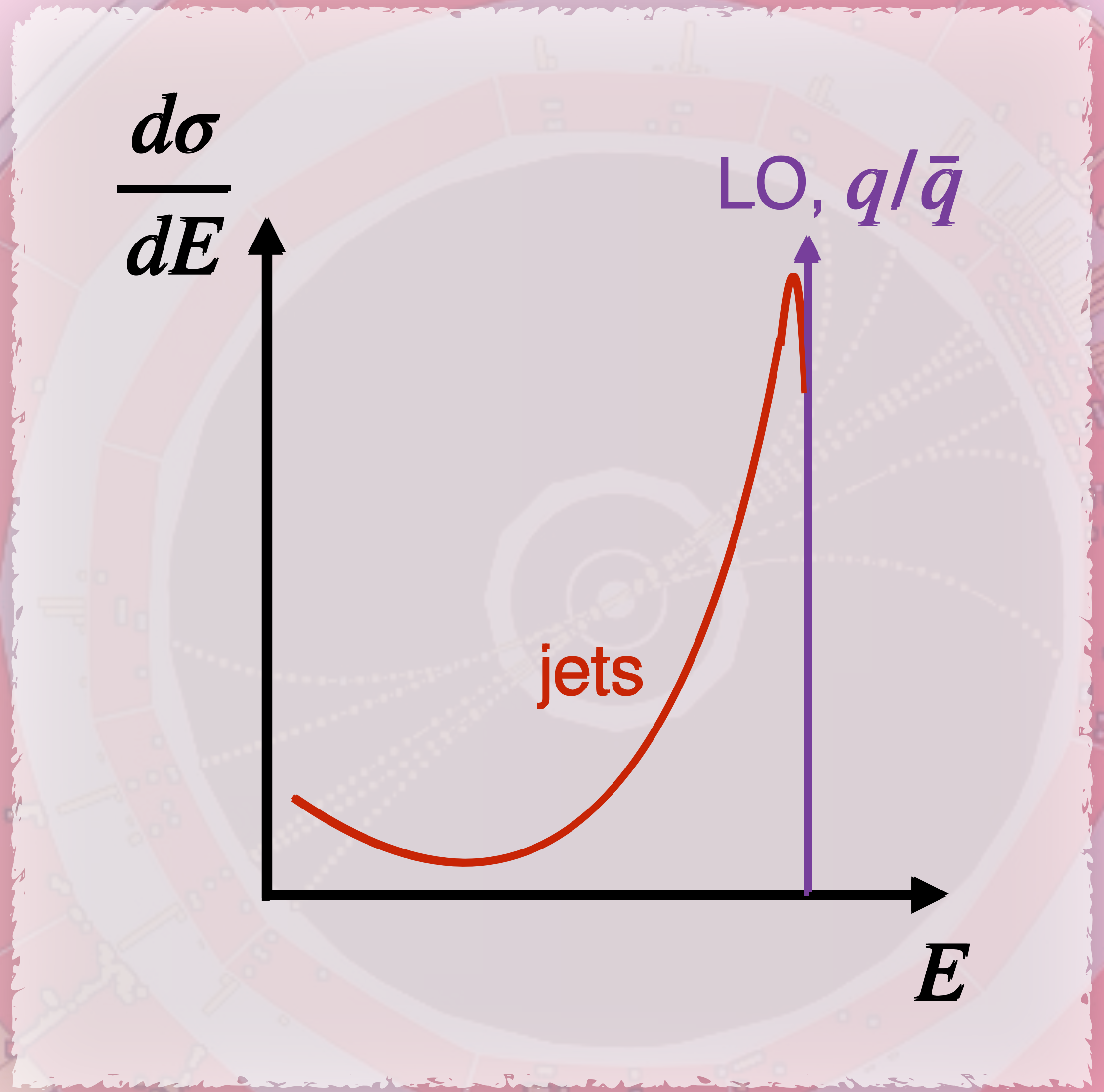
Motivation

Anti-k_T jet measurement

e^+e^- system offers cleanest tests of QCD

- Unambiguous inputs to pQCD calculation & pheno. models (PYTHIA / HERWIG / SHERPA)
- Unlike pp & HI, jet energy spectrum at e^+e^- is peaked (not smeared by PDF, gluonic ISR, etc)

⇒ sensitive to tunes/params. in fragmentation calculation



Great opportunity for jet re-analysis @ LEP

- Modern jet reco. & clustering algo. since the end of LEP
- Jets are important building blocks! (e.g., BSM searches at LHC, probes of quark-gluon plasma at RHIC)

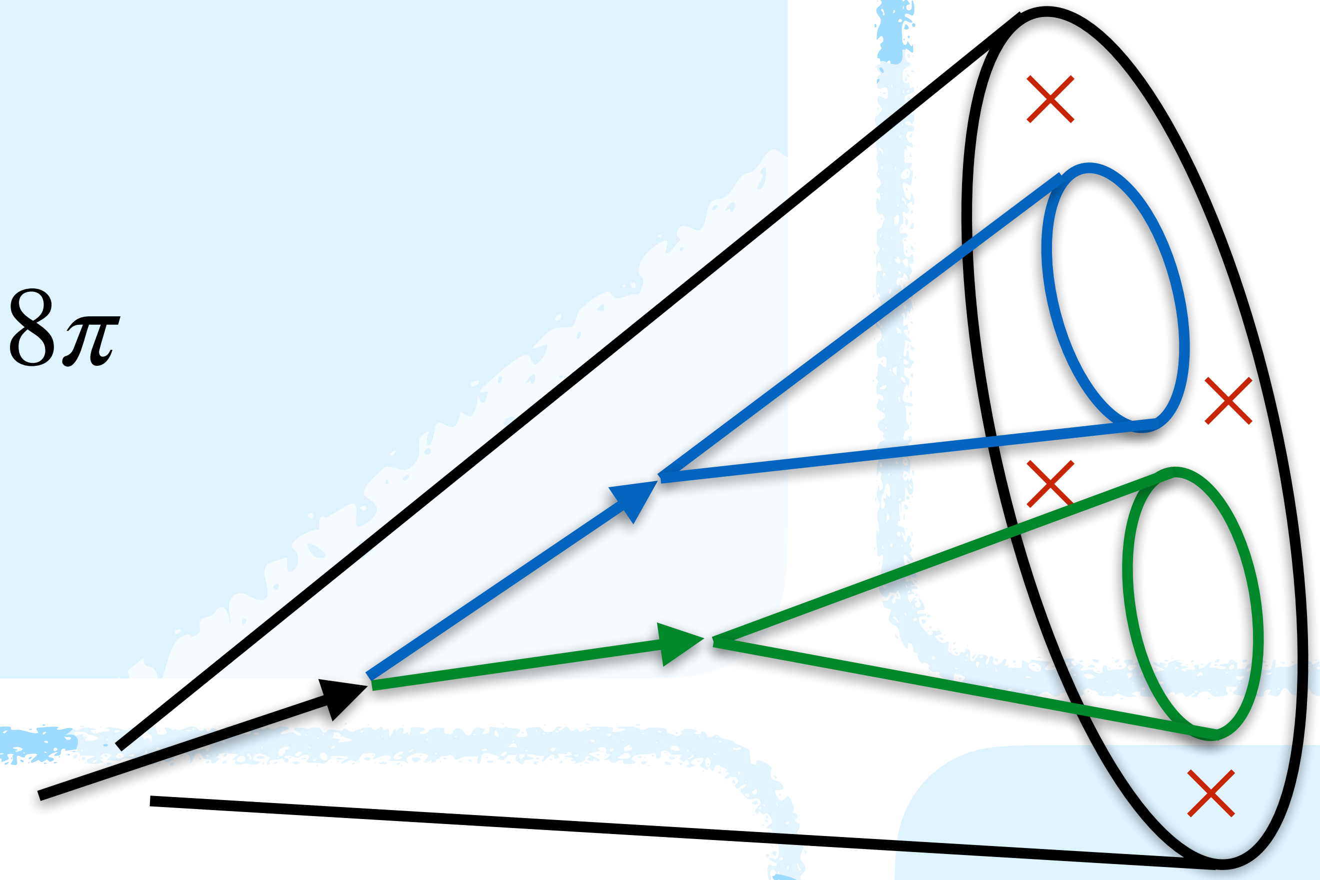
Analysis method: anti-k_T jet

Anti-k_T clustering

$R = 0.4$ $\left(R = \sqrt{\Delta\eta^2 + \Delta\phi^2}\right)$

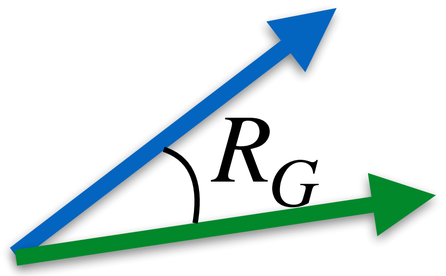
Acceptance cut: $0.2\pi < \theta_{\text{jet}} < 0.8\pi$

(avoid beam pipe)

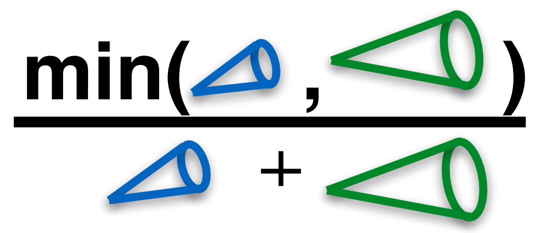


Grooming & substructure

Soft drop algorithm



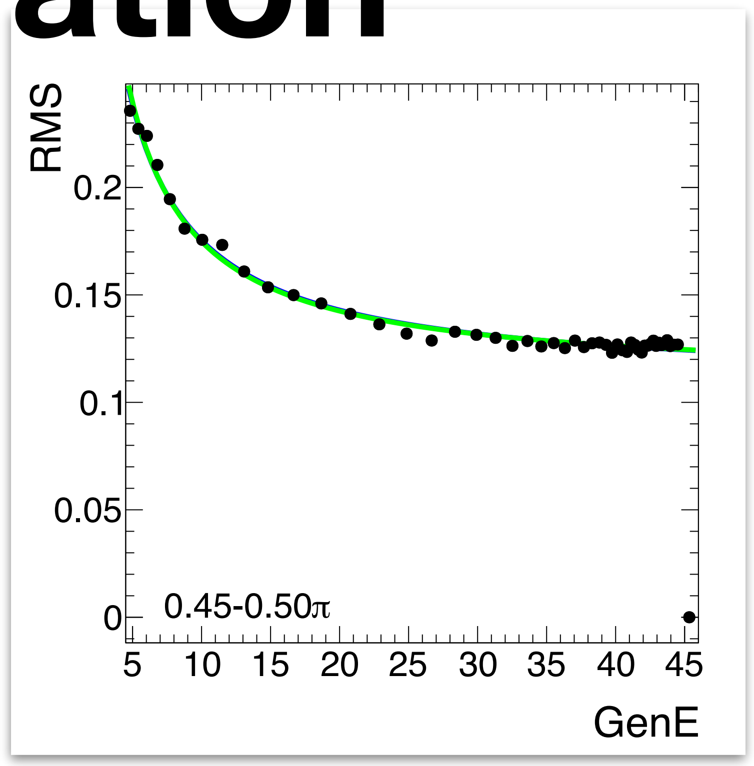
R_G = opening angle



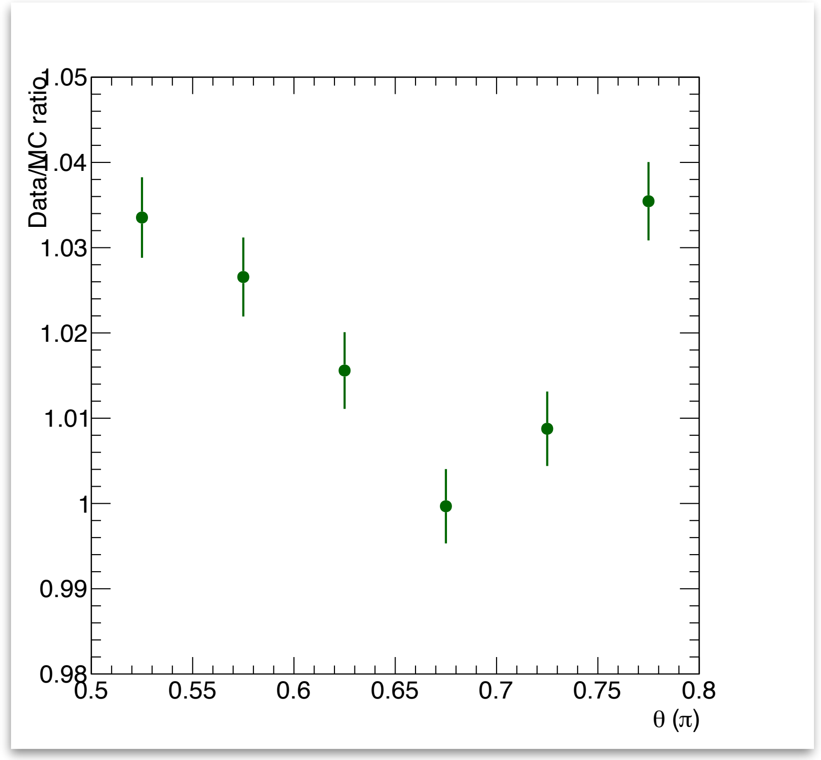
z_G = energy sharing

Calibration

Jet resolution

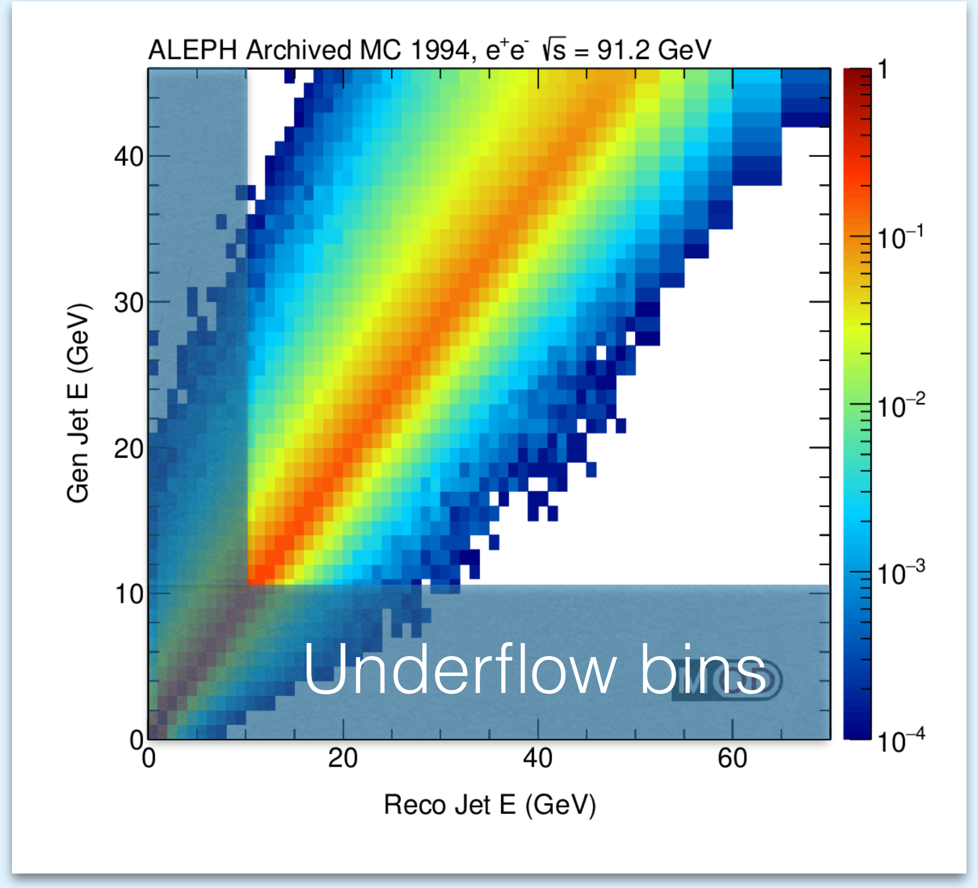


MC



Data / MC

Unfold to gen. level



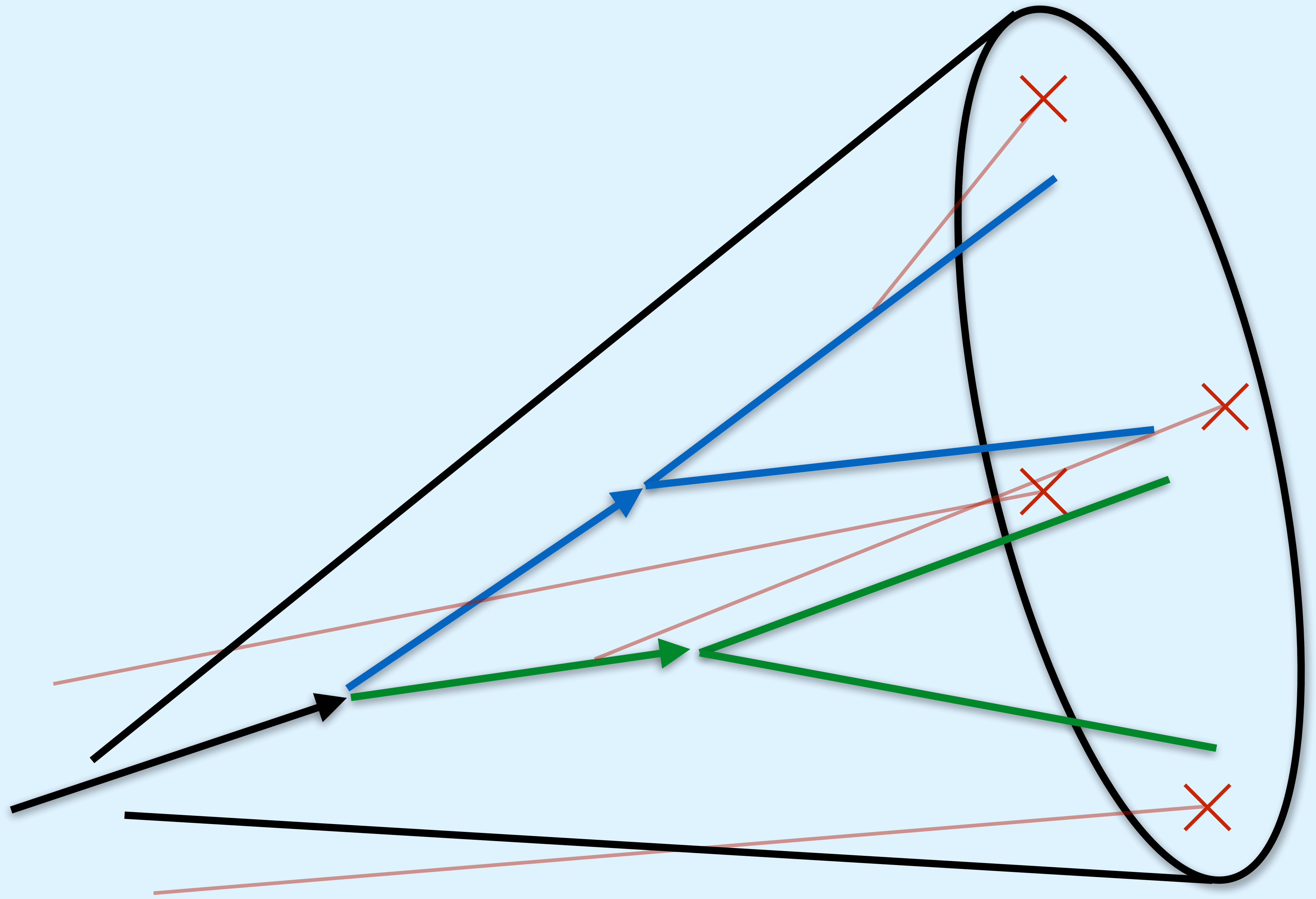
Ex: inclusive jet energy

Analysis method: anti-k$_T$ jet

Clustering

- Anti-k$_T$ algorithm, $R = 0.4$
  $\left(R = \sqrt{\Delta\eta^2 + \Delta\phi^2}\right)$
- Acceptance:
  (avoid beam pipe)
  $0.2\pi < \theta_{\text{jet}} < 0.8\pi$

Anti-k$_T$ clustering (FastJet)



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

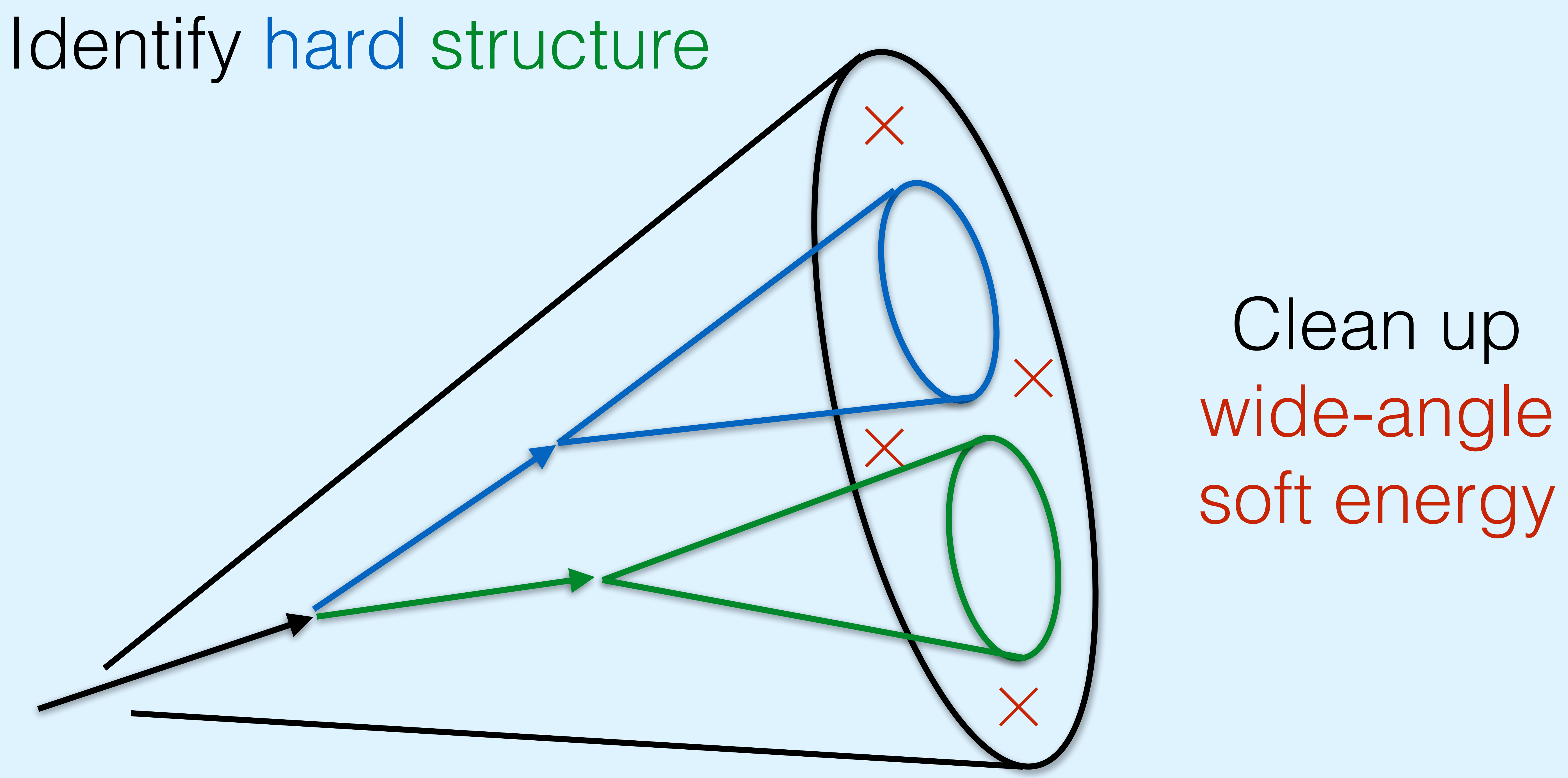
$$d_{iB} = E_i^{-2}$$

Analysis method: anti-k_T jet

Clustering

- Anti-k_T algorithm, $R = 0.4$

Grooming & substructure



JHEP 1405 (2014) 146
PRL 100 (2008) 242001

Analysis method: anti-k_T jet

Clustering

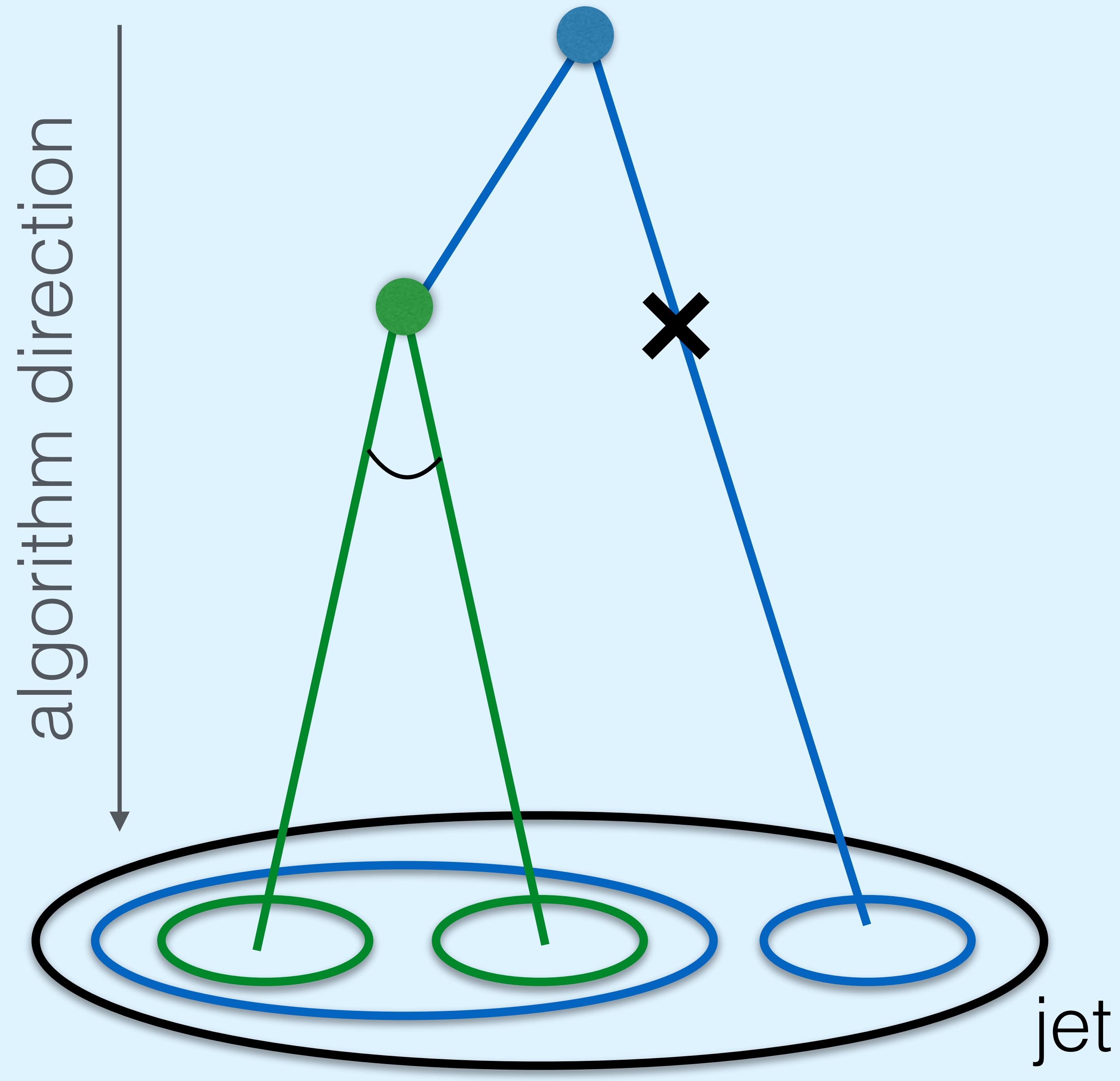
- Anti-k_T algorithm, $R = 0.4$

Grooming & substructure

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

JHEP 1405 (2014) 146
PRL 100 (2008) 242001

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

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

θ_{12} = opening angle btw sub-jet 1&2

Analysis method: anti-k_T jet

Clustering

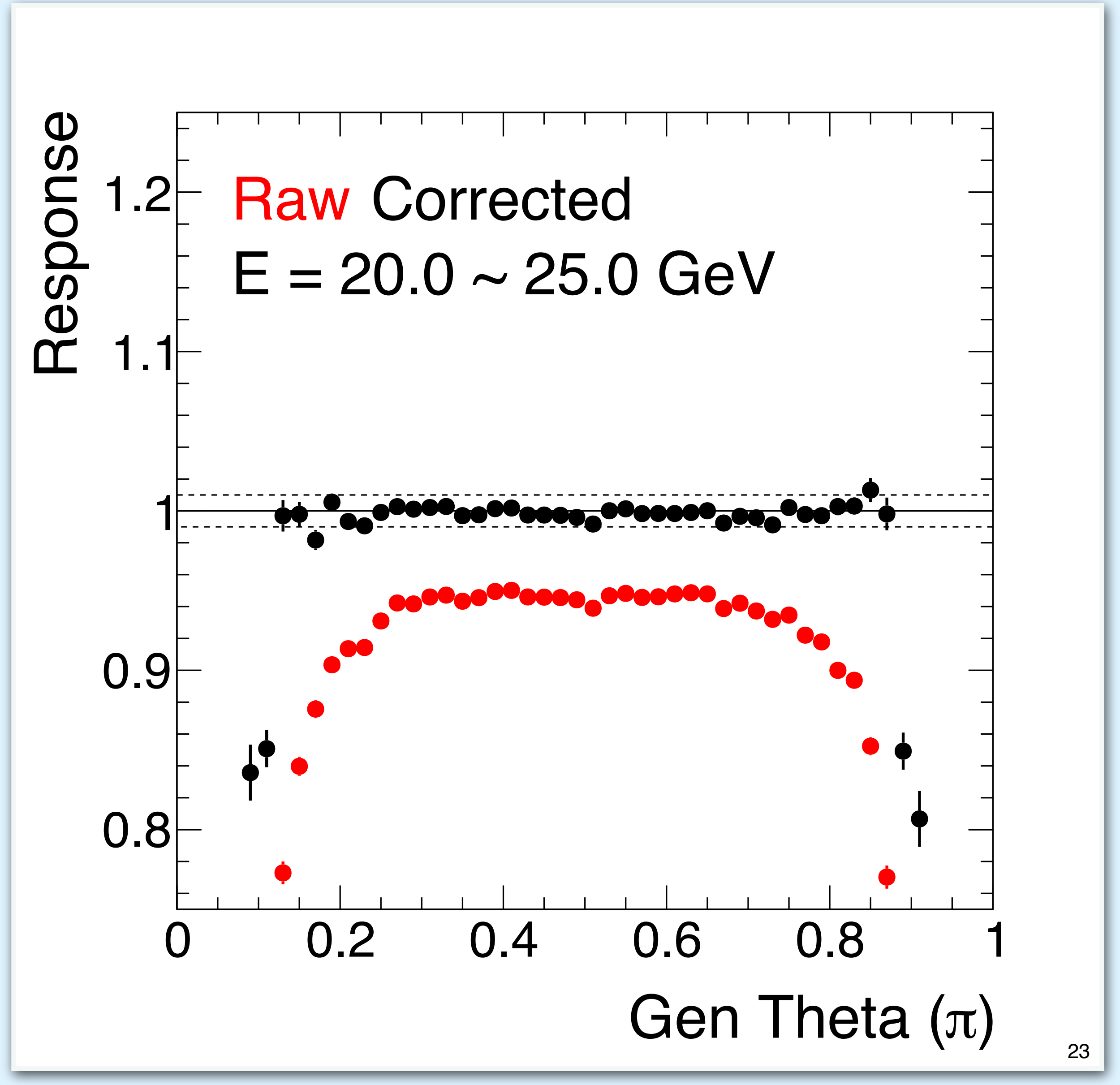
- Anti-k_T algorithm, $R = 0.4$

Grooming & substructure

- R_g = opening angle
- z_g = energy sharing

Calibration

MC-based calibration



Data/MC residual calibration

Monitoring on two variables:

- Forward-/ backward-side energy difference
- Multi jet mass

Analysis method: anti-k_T jet

Clustering

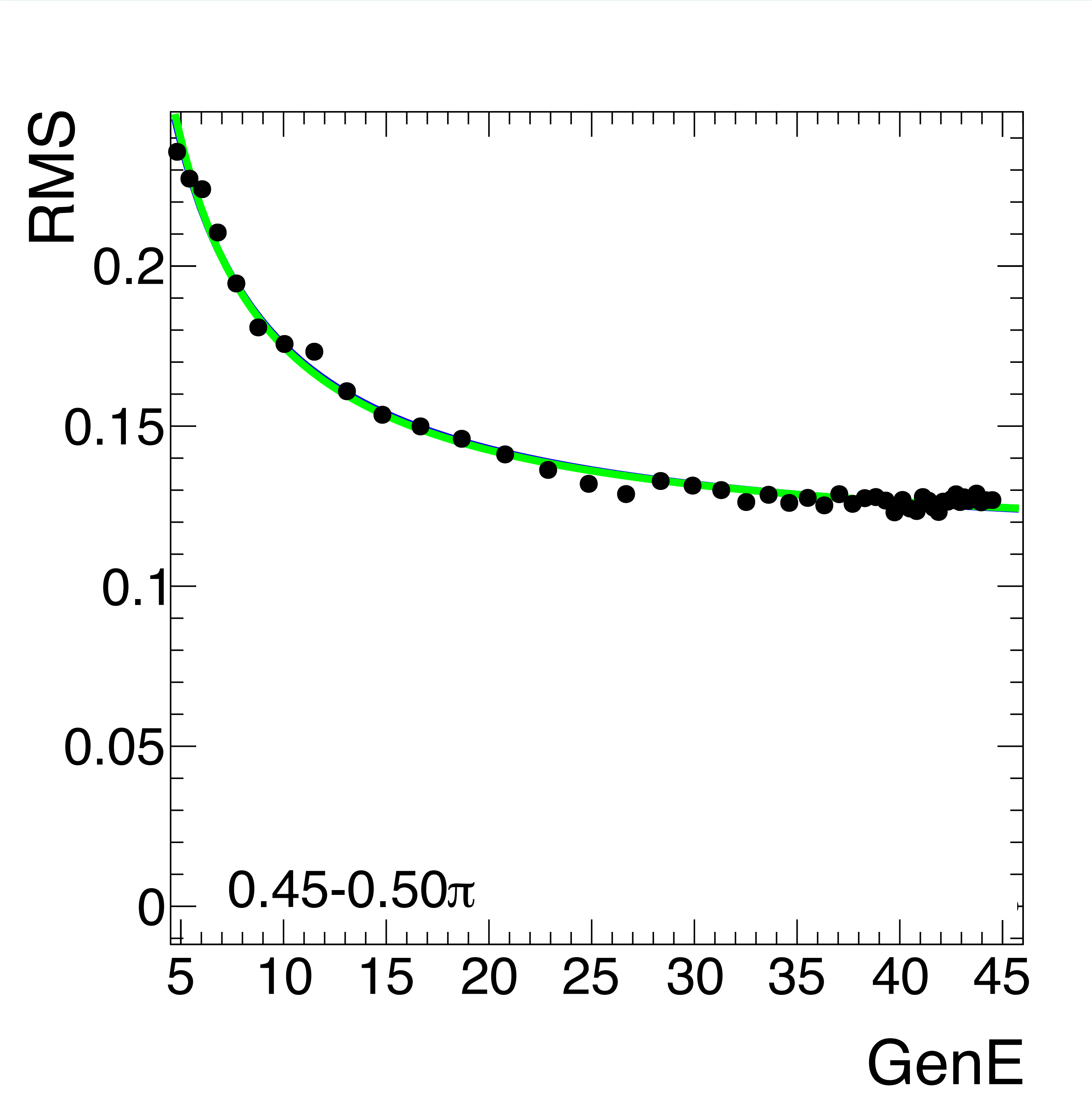
- Anti-k_T algorithm, $R = 0.4$

Grooming & substructure

- R_g = opening angle
- z_g = energy sharing

Calibration

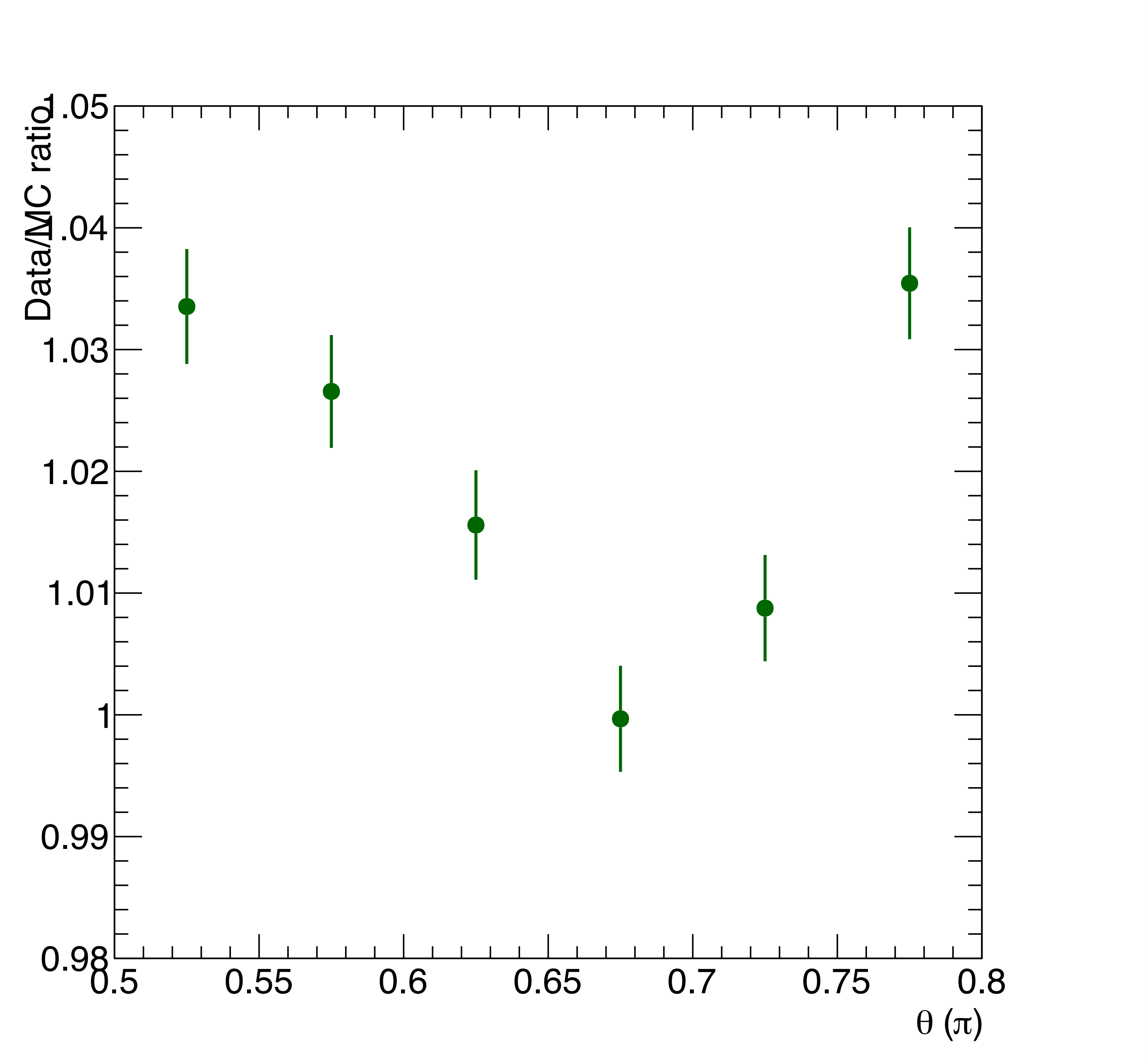
Jet resolution in simulation



Energy resolution: 10-25%

(Angular resolution: 0.01-0.05)

$\frac{\text{Data resolution}}{\text{MC resolution}}$



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

Analysis method: anti-k_T jet

Clustering

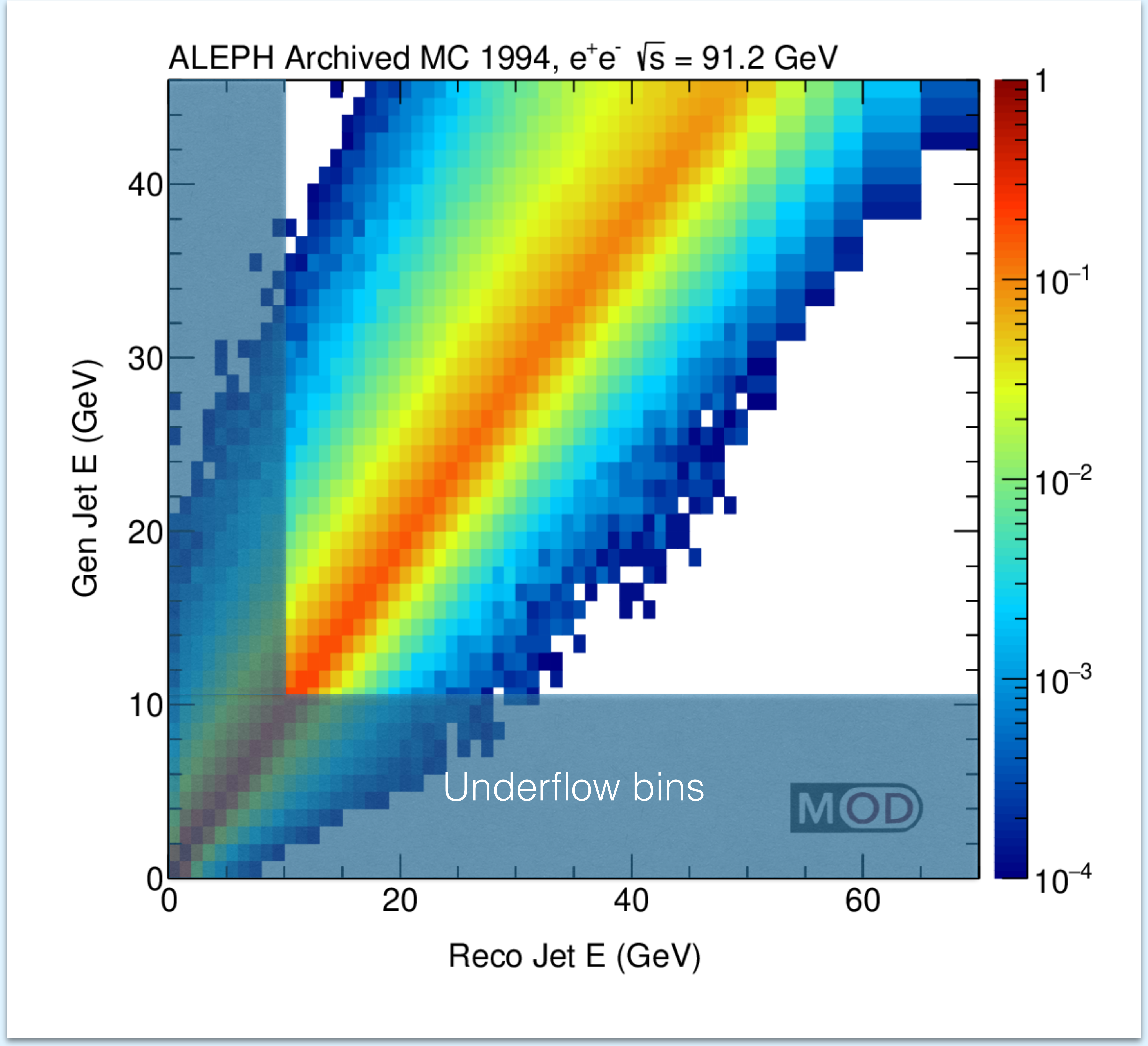
- Anti-k_T algorithm, $R = 0.4$

Grooming & substructure

- R_g = opening angle
- z_g = energy sharing

Calibration

Unfolding to gen. level



Example: inclusive jet energy

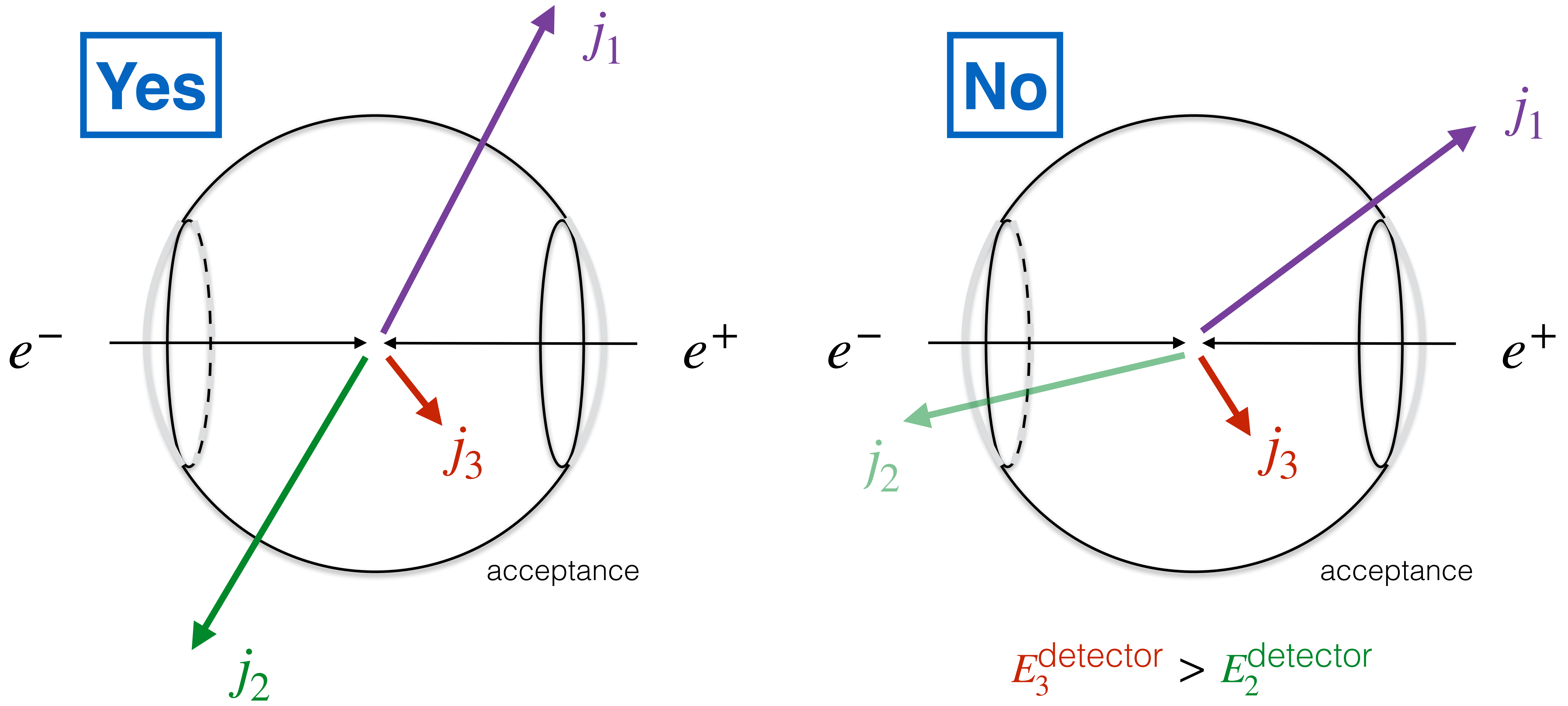
Jet measurement observables

sensitive to the soft radiation	sensitive to the hard part
Inclusive jets	Leading dijets
Energy spectra	Energy spectra
Full jet mass	Energy sum
Groomed jet angle	
Energy sharing	
Groomed jet mass	

Soft drop grooming

Global leading dijet

(slides from BOOST 2022 by Yi Chen)



We want to measure global leading dijet

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

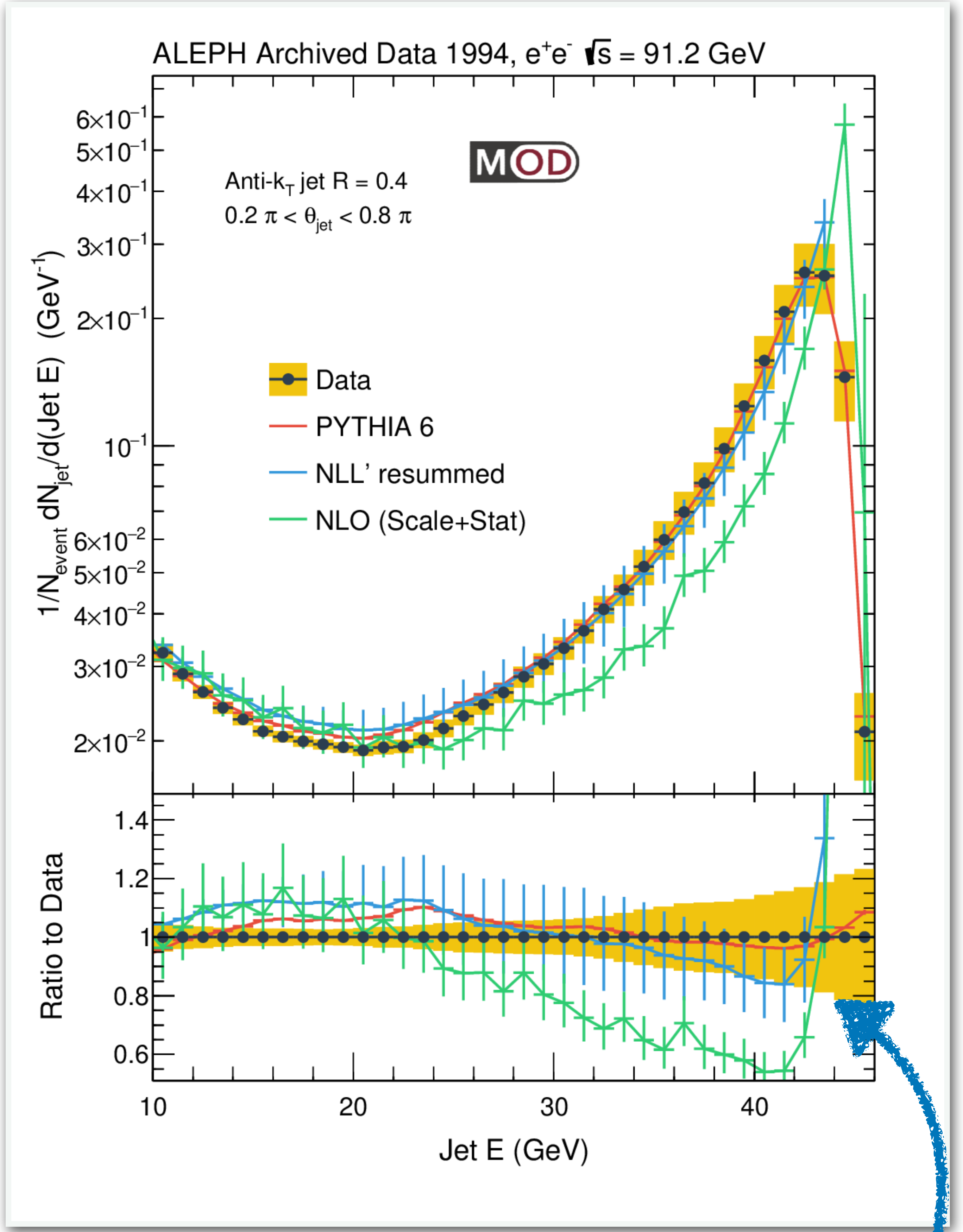
→ selection + correction

Jet energy spectrum

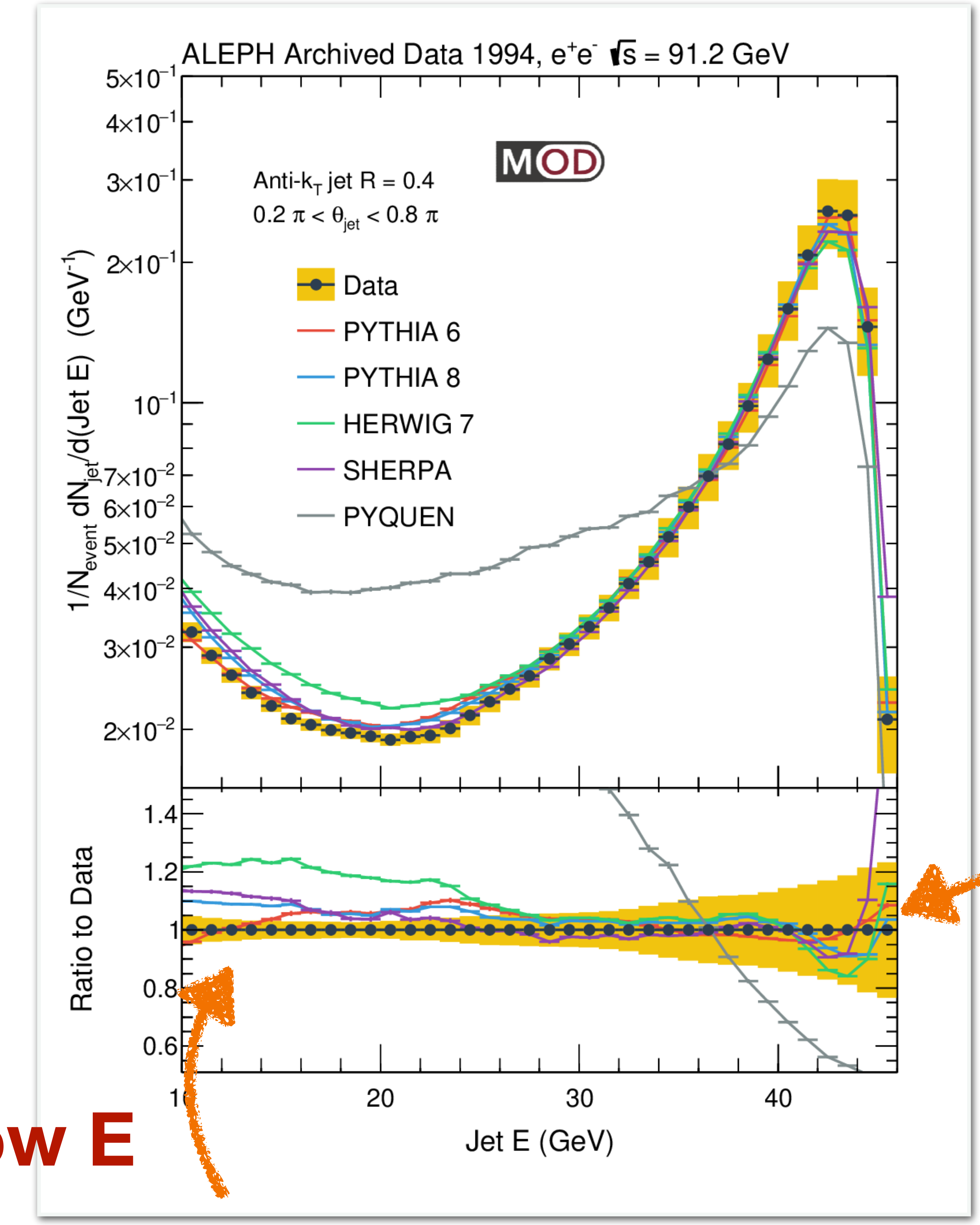
LEP1

Rising edge sensitive to jet function

c.f. analytical calculation



c.f. fragmentation models



@ high E

consistent within uncertainties

NLL'

[JHEP 07 (2021) 041]

NLL' resumed generally describes data

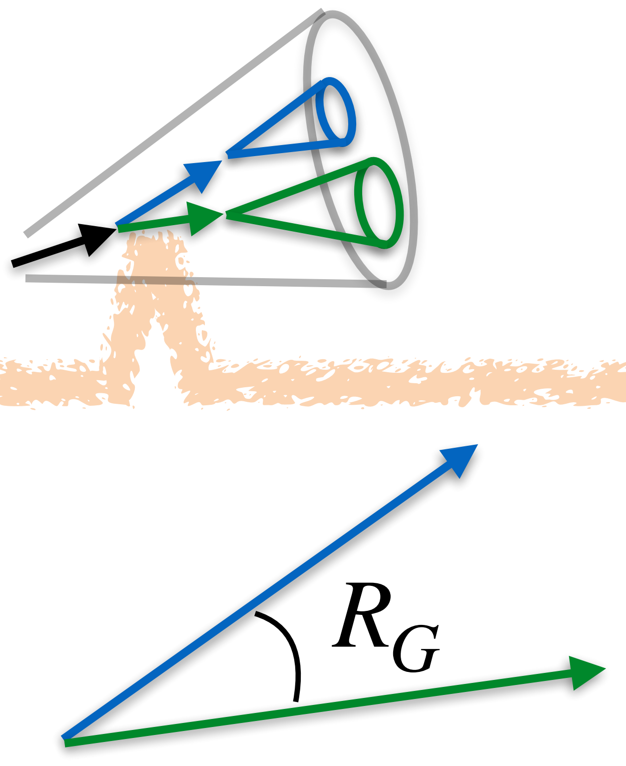
@ low E

10-20% disagreement

ALEPH jet

[JHEP 06 (2022) 008]

Jet substructure observables — R_G

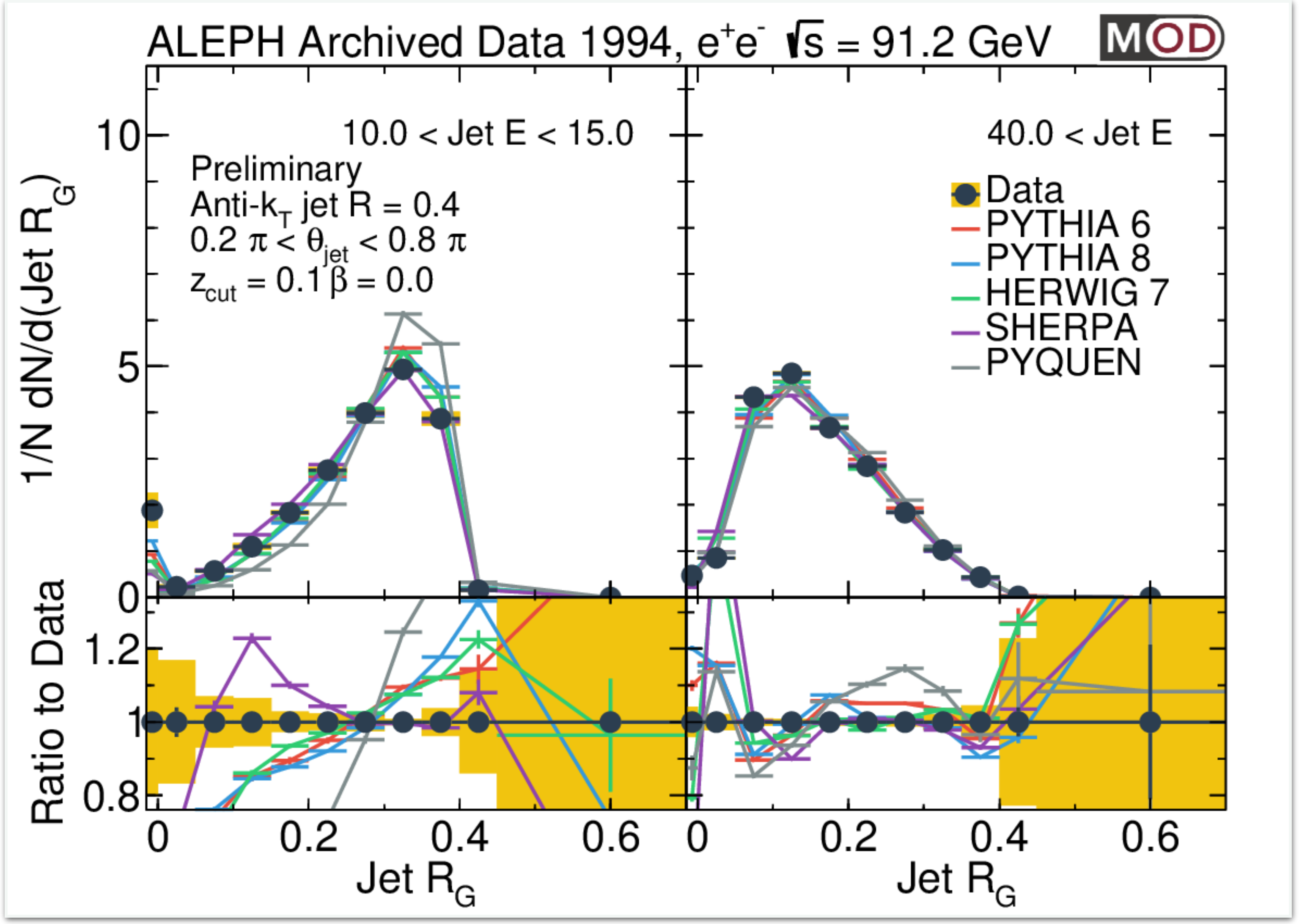


Opening angle (R_G)

@ low E
(soft radiation & combinatorial)

higher R_G

Worse MC/data agreement

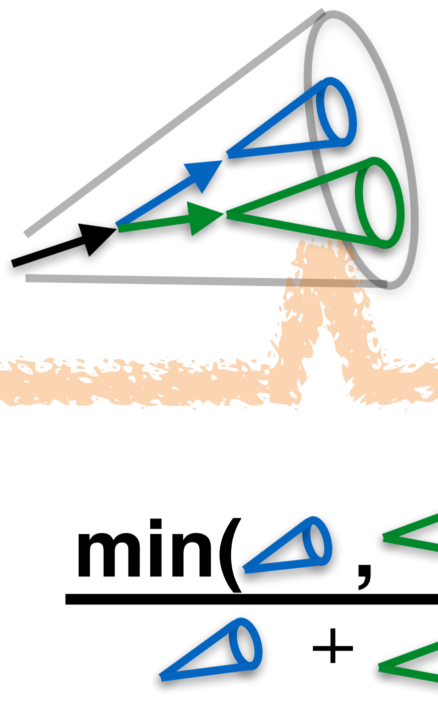


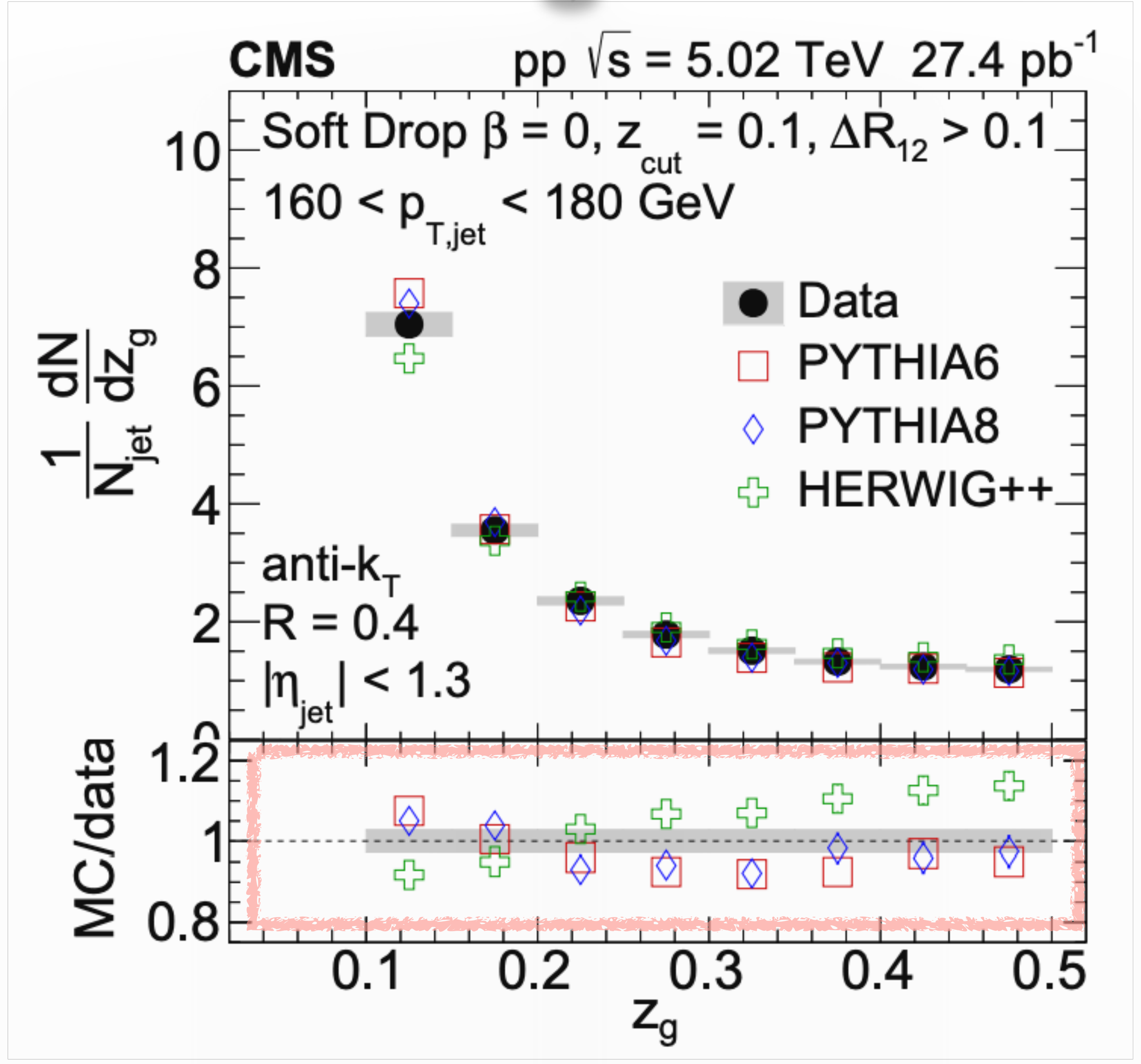
@ high E

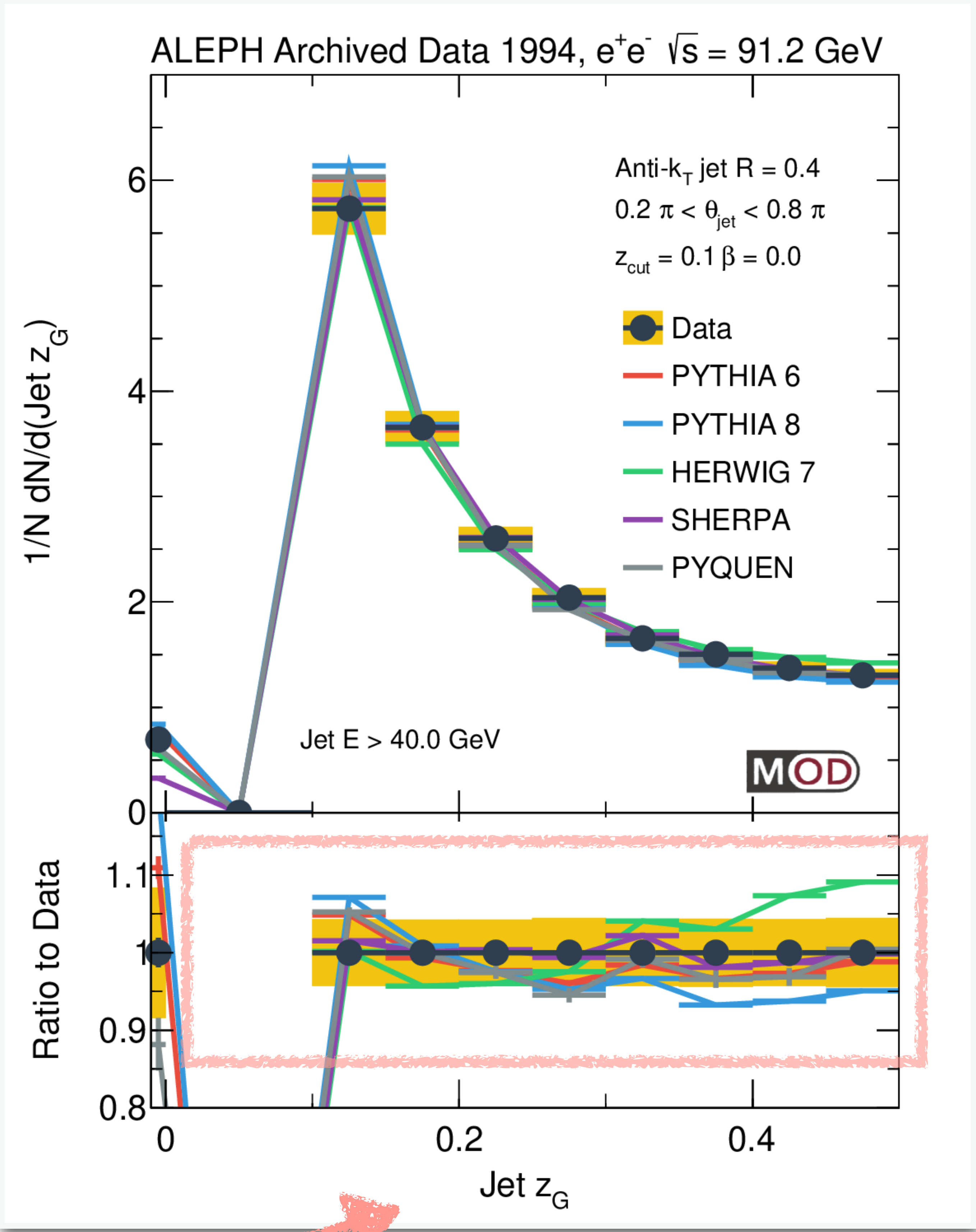
more similar to LHC/RHIC

ALEPH jet
[JHEP 06 (2022) 008]

Jet substructure observables — z_G







Similar trend btw e^+e^- & pp!

ALEPH jet

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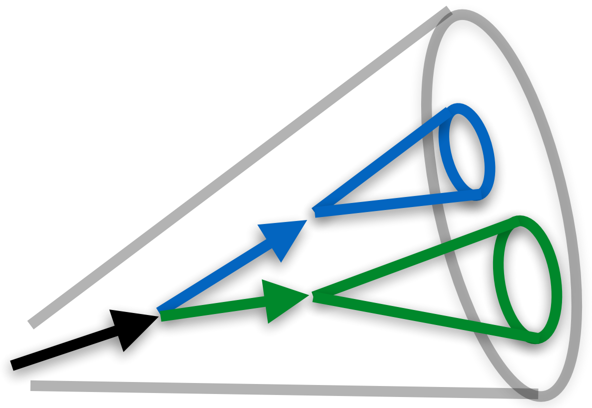
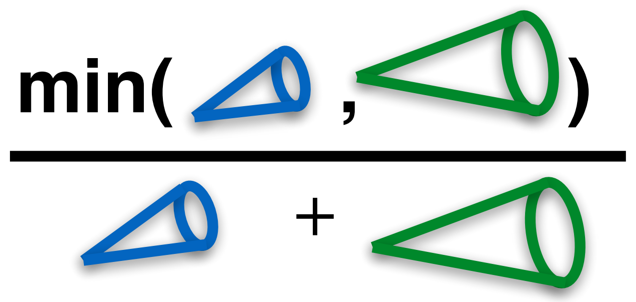
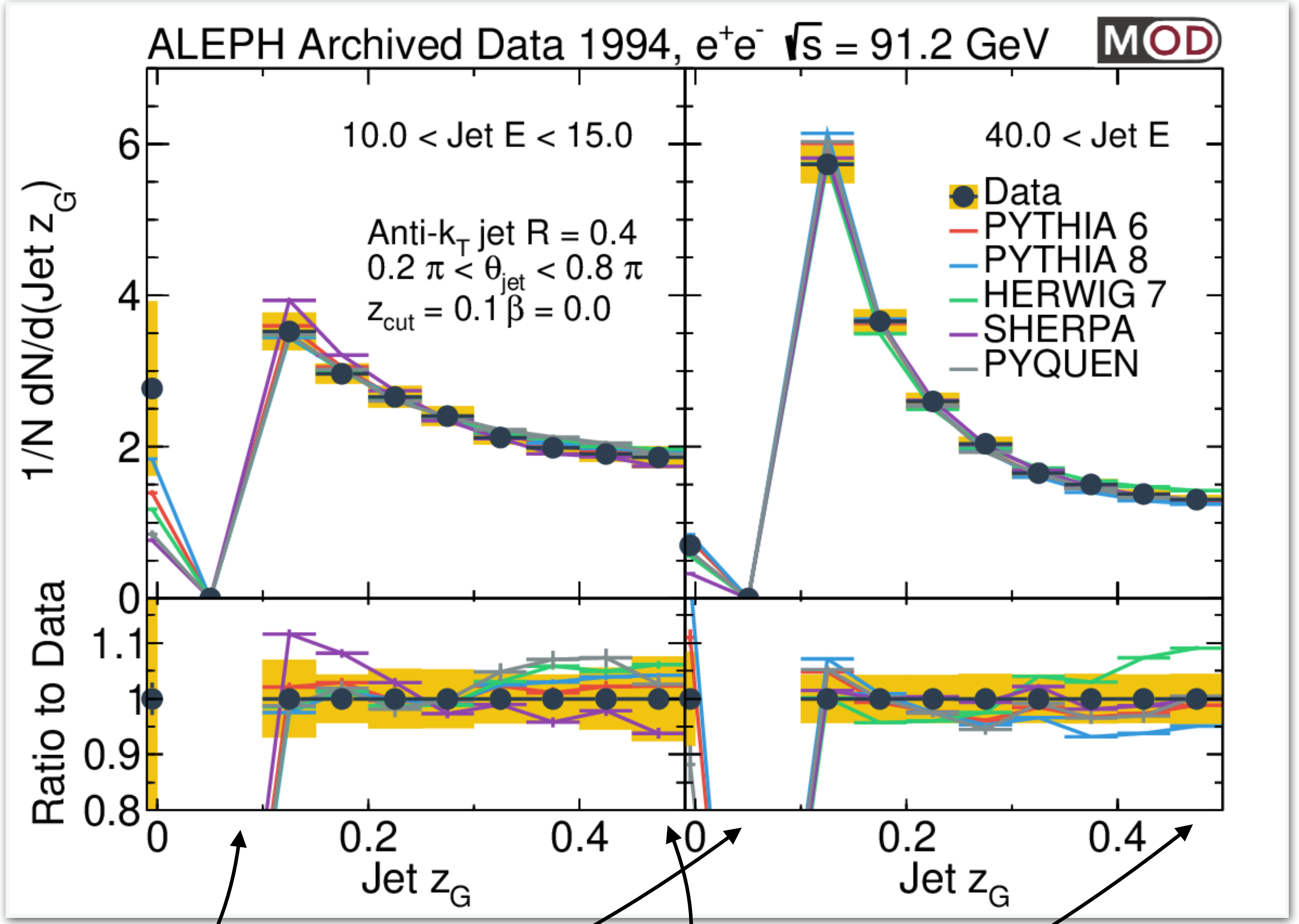
Energy sharing z_G

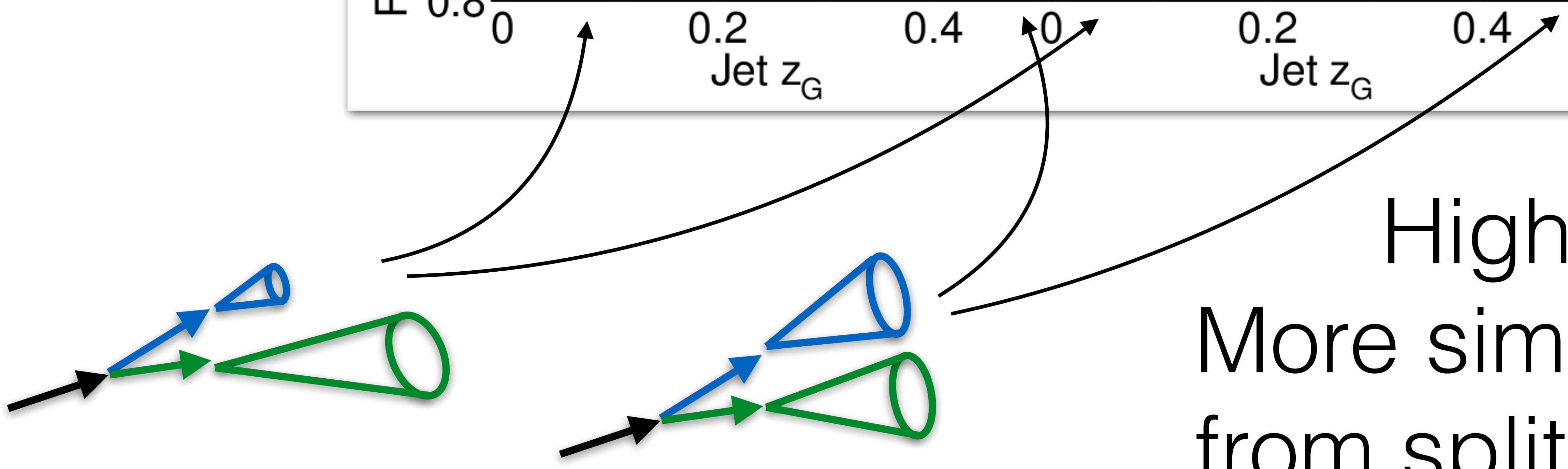
(slides from BOOST 2022 by Yi Chen)





Measurement binned in energy (most not shown)





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