Long-range Near-side Signal in High Multiplicity e^+e^- Collisions with ALEPH at 91-209 GeV

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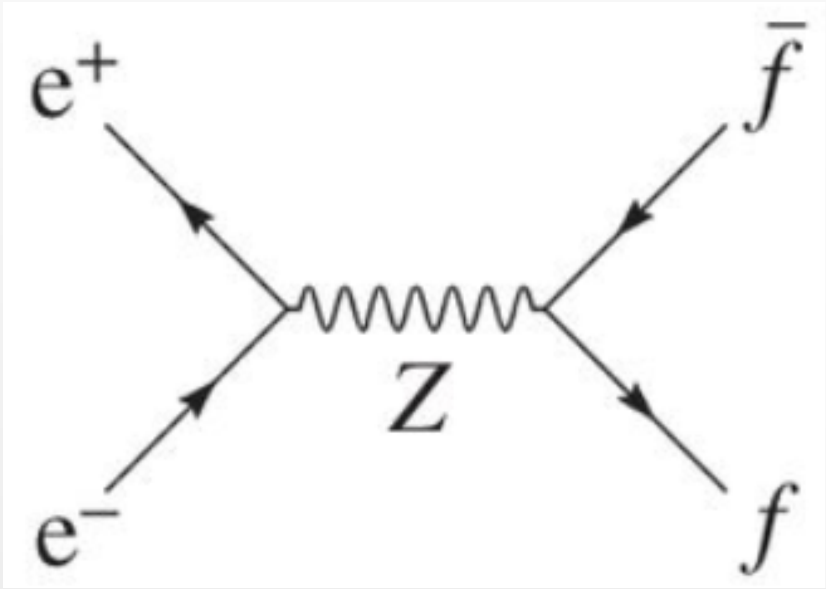
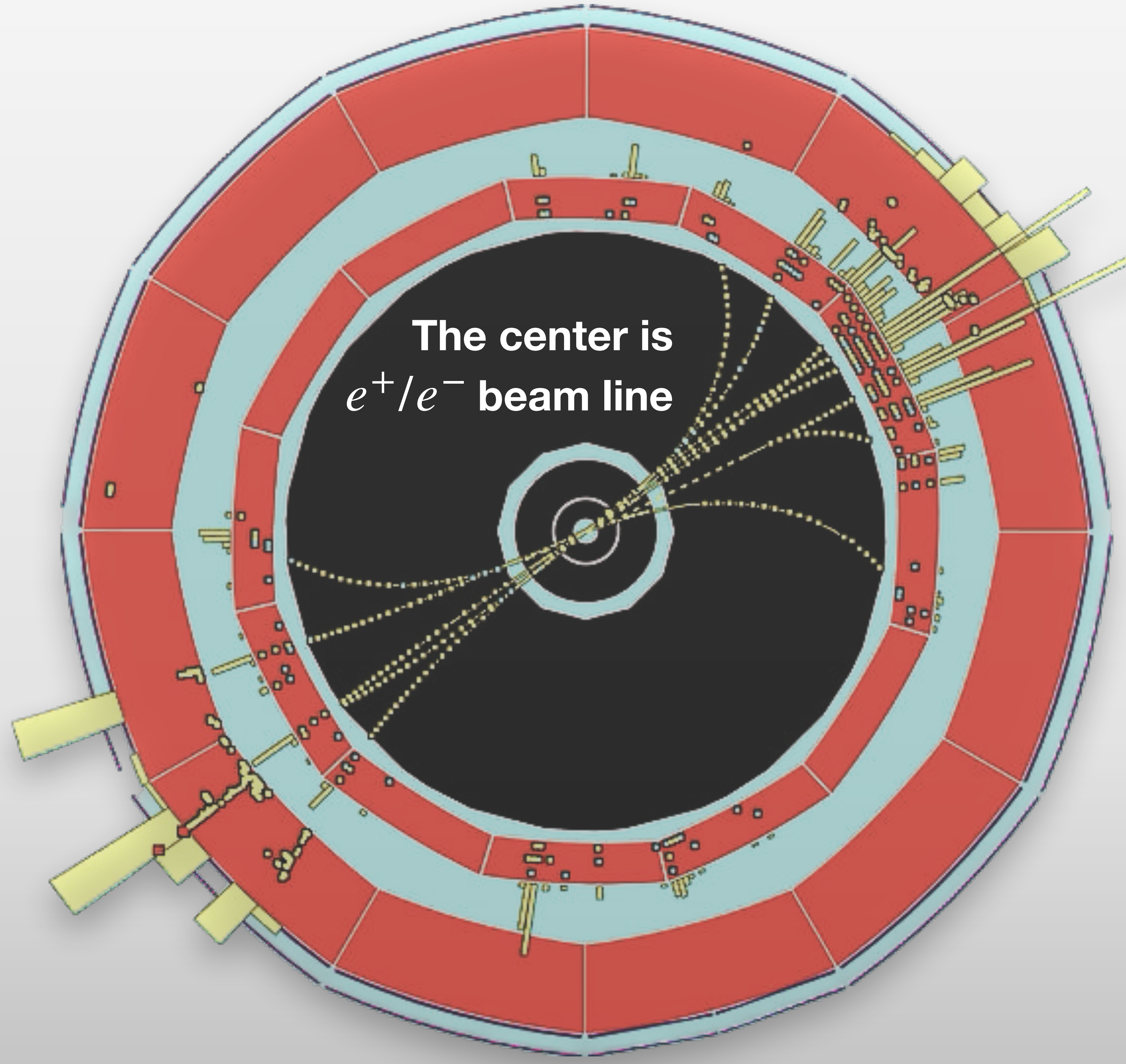
in collaboration with Austin Baty, Anthony Badea, Chris McGinn, Jesse Thaler, Gian Michelle Innocenti, and Tzu-An Sheng

- arXiv: 2312.05084
- Analysis note: 2309.09874
- Submitted to PRL

CMS & ALEPH mini-workshop, Feb. 28th

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





Structureless e^+/e^-

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

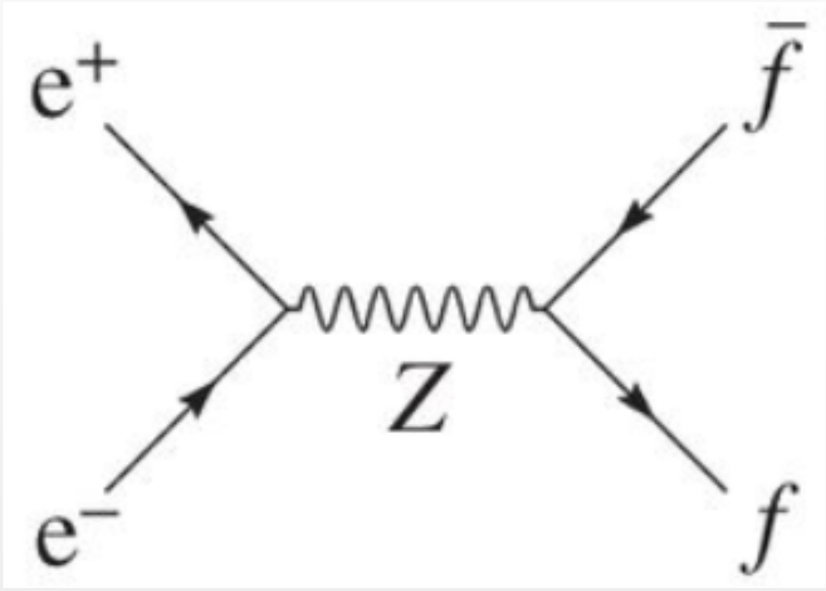
Negligible beam remnant

Controllable initial-state QED radiations

Color-neutral e^+/e^-

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

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



Structureless e^+/e^-

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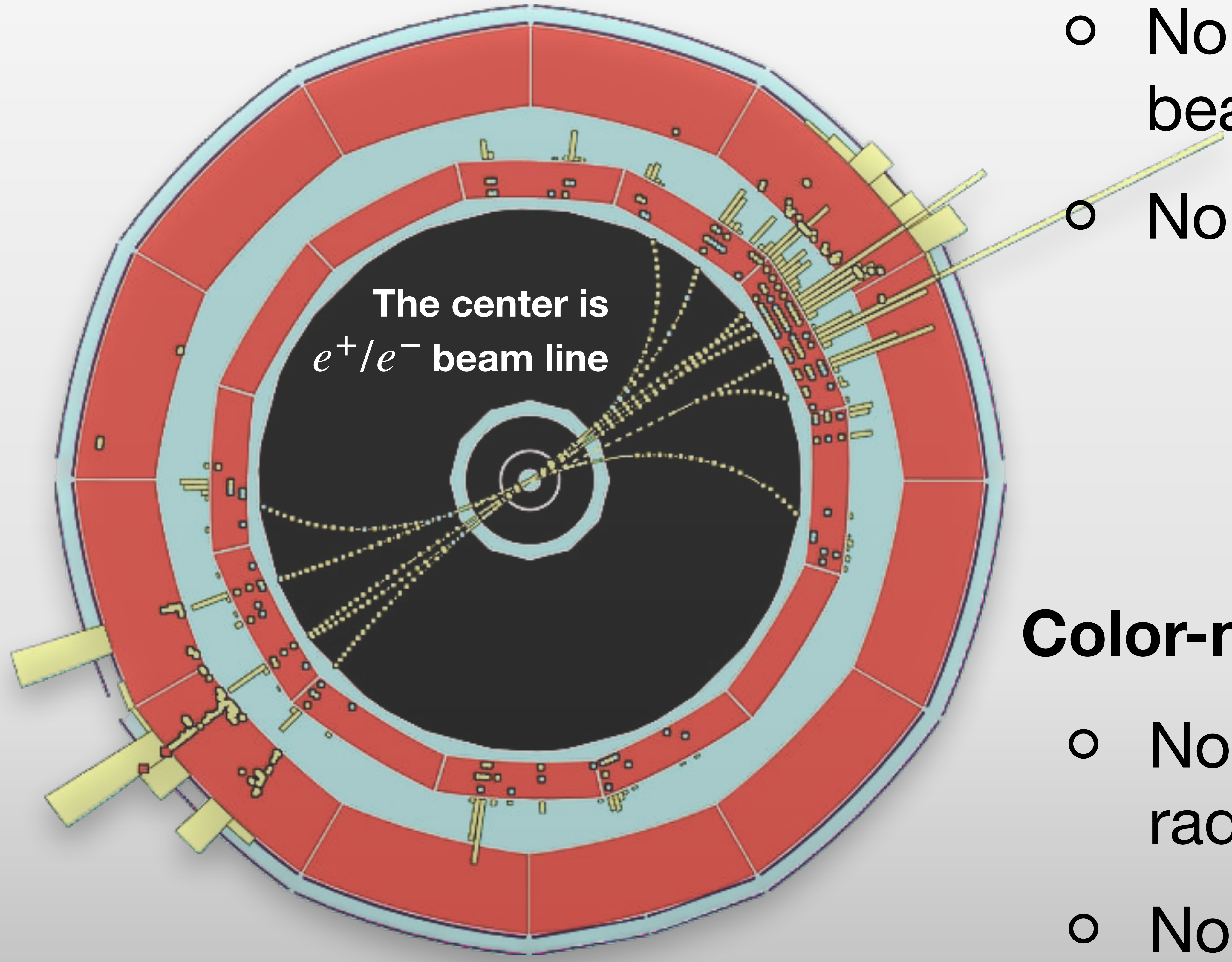


Negligible beam remnant

Controllable initial-state QED radiations

Color-neutral e^+/e^-

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

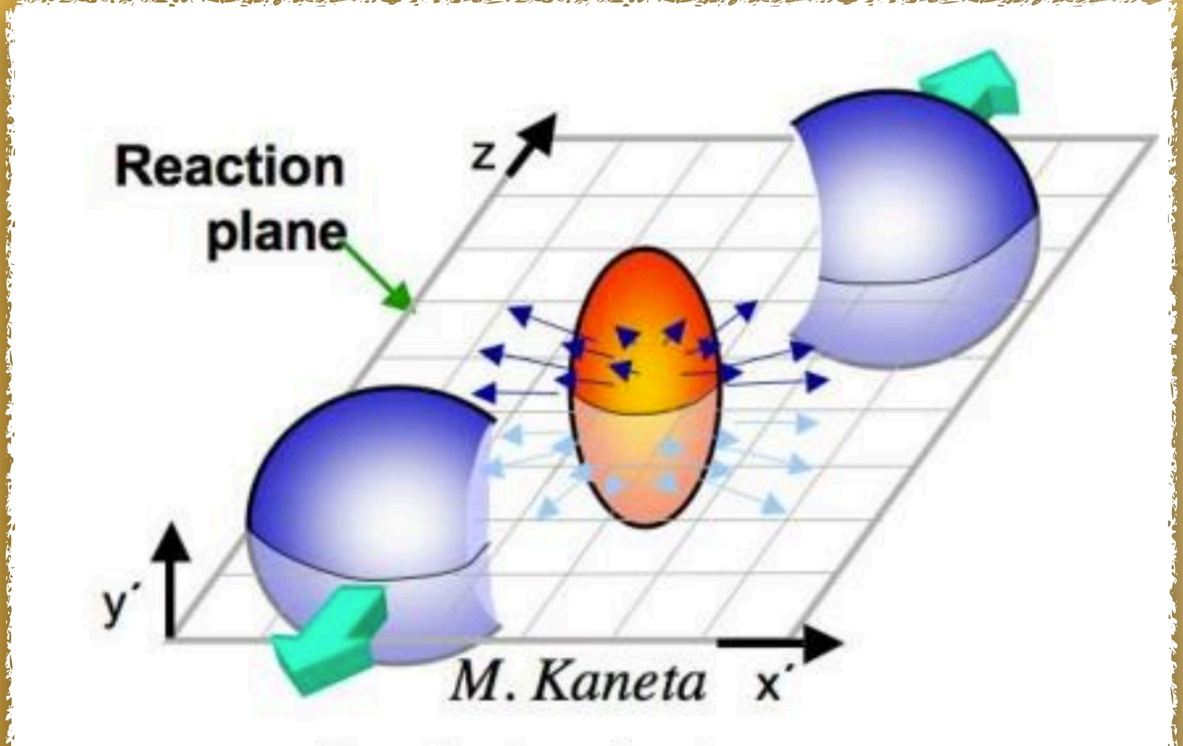
Unambiguous tests for heavy-ion & QCD phenomenology!

Two-particle correlations (2PC) in e^+e^- collisions

Two-particle correlation observable

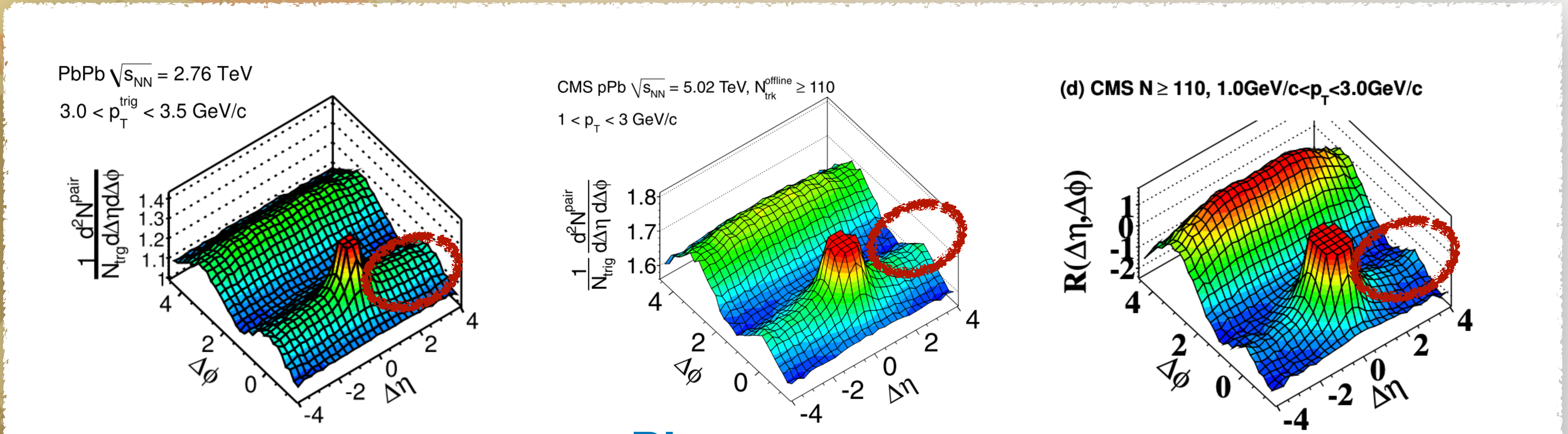
- Soft probe to study Quark-Gluon Plasma (QGP) in HI collisions
- Spatial anisotropy can happen as:

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!

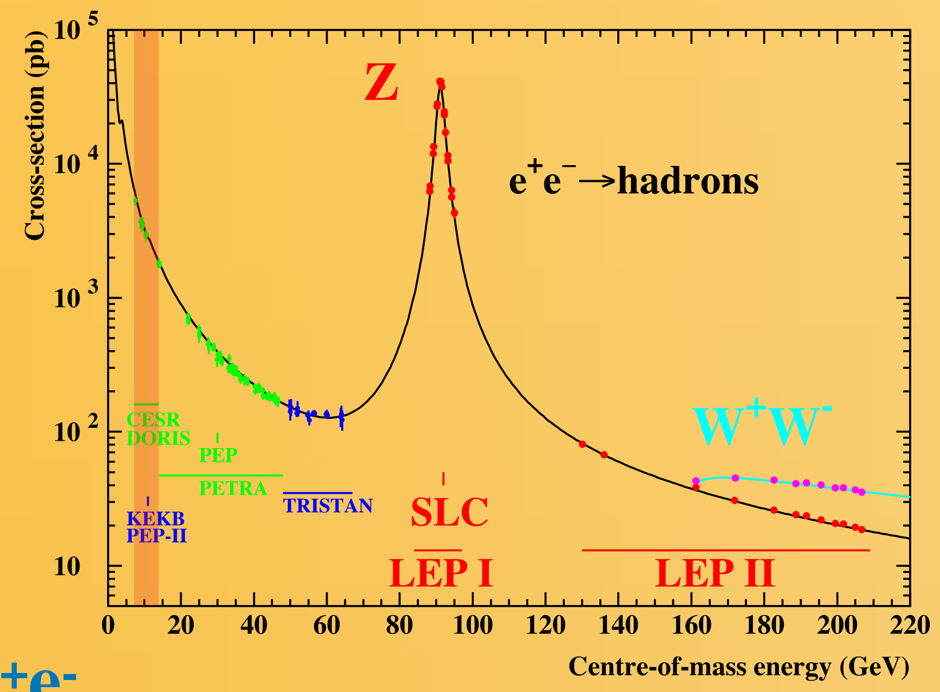


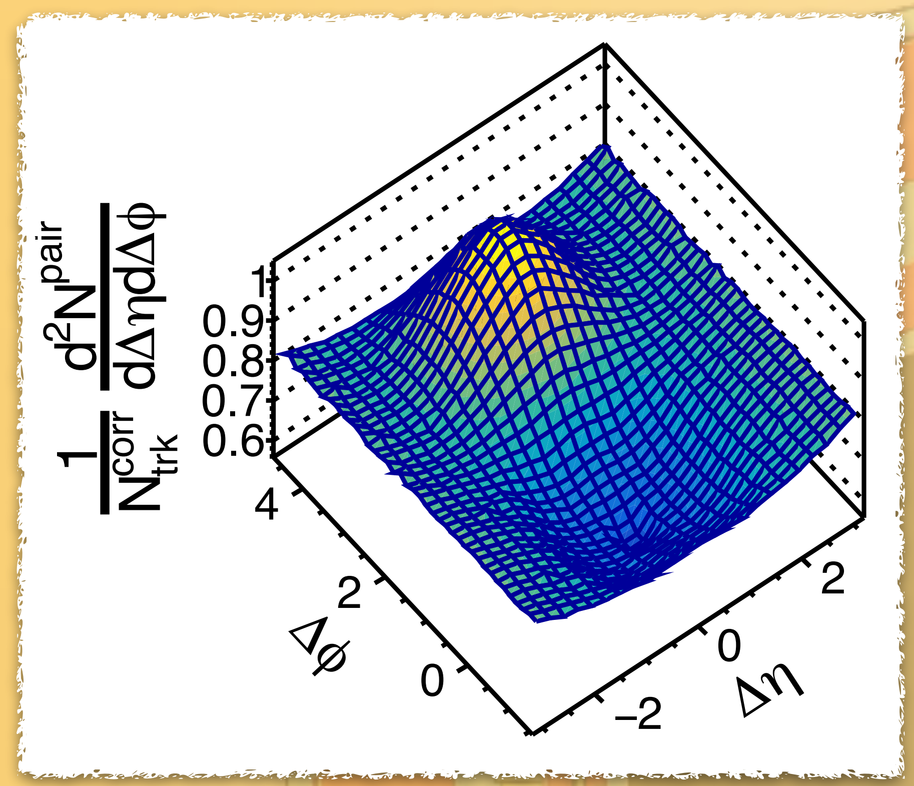
PbPb [Eur. Phys. J., C72] **pPb** [Phys. Lett. B718 (2013) 795-814] **pp** [JHEP 1009 (2010) 091]

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

Two-particle correlations (2PC) in e^+e^- collisions

- e^+e^- @ 10.52 GeV (Belle) gives stringent upper limits on ridge-like signals for N_{Trk} up to 14



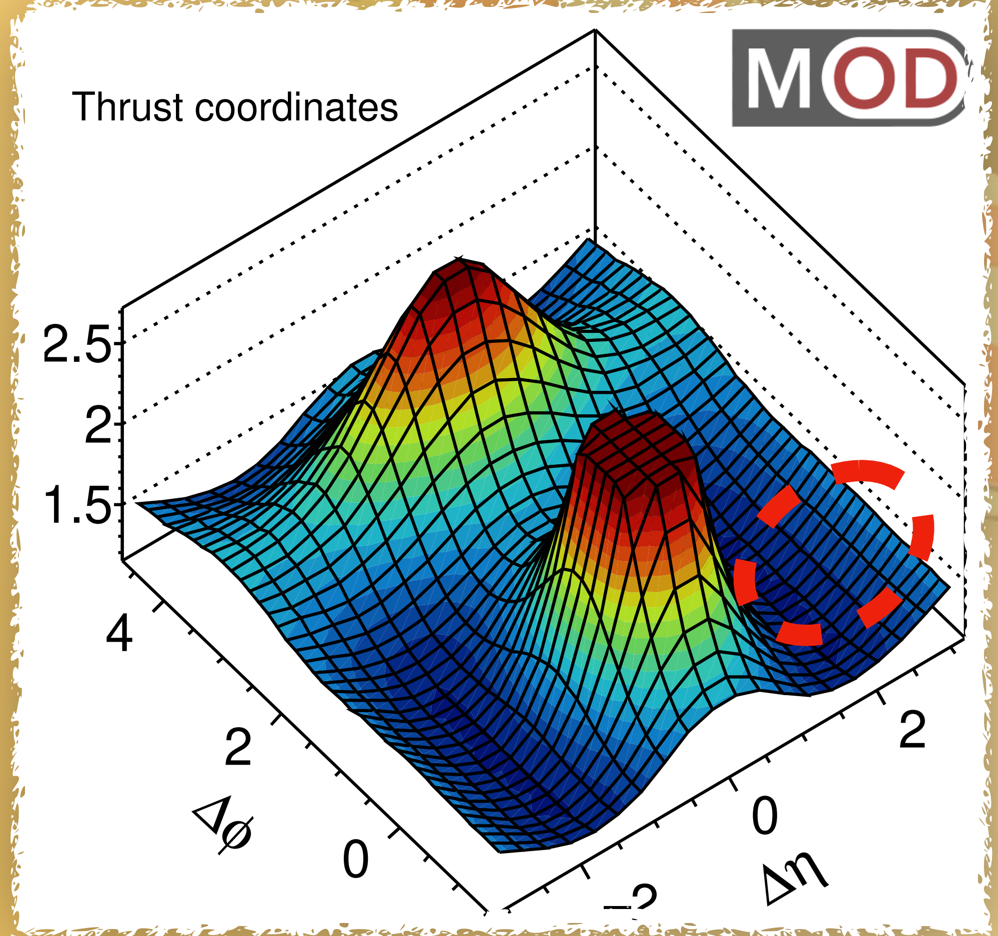


Belle e+e-
[Phys. Rev. Lett. 128, 142005 (2022)]

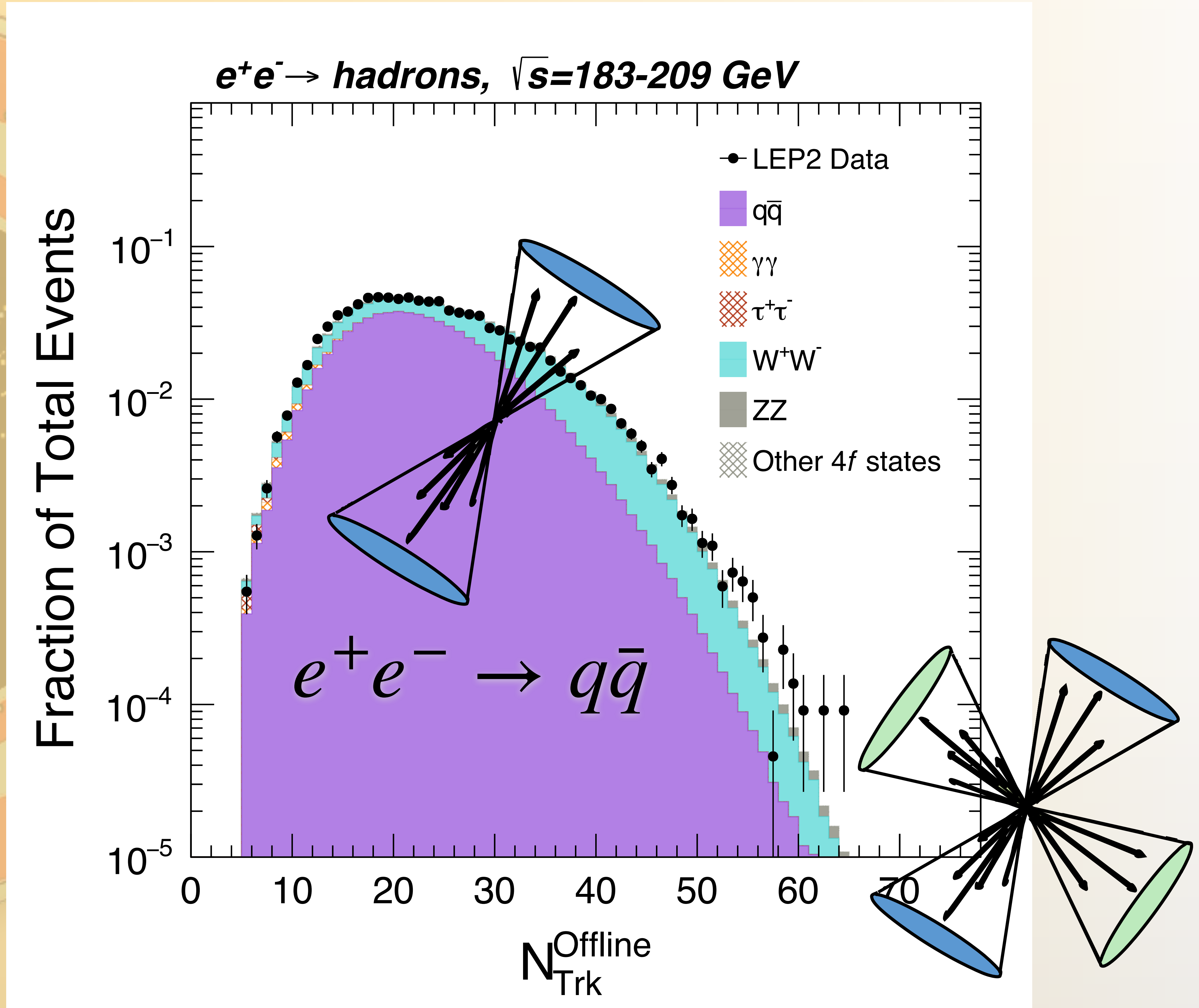
- e^+e^- @ 91 GeV (LEP1) shows no significant long-range near-side signals!

$N_{Trk} \geq 30$

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

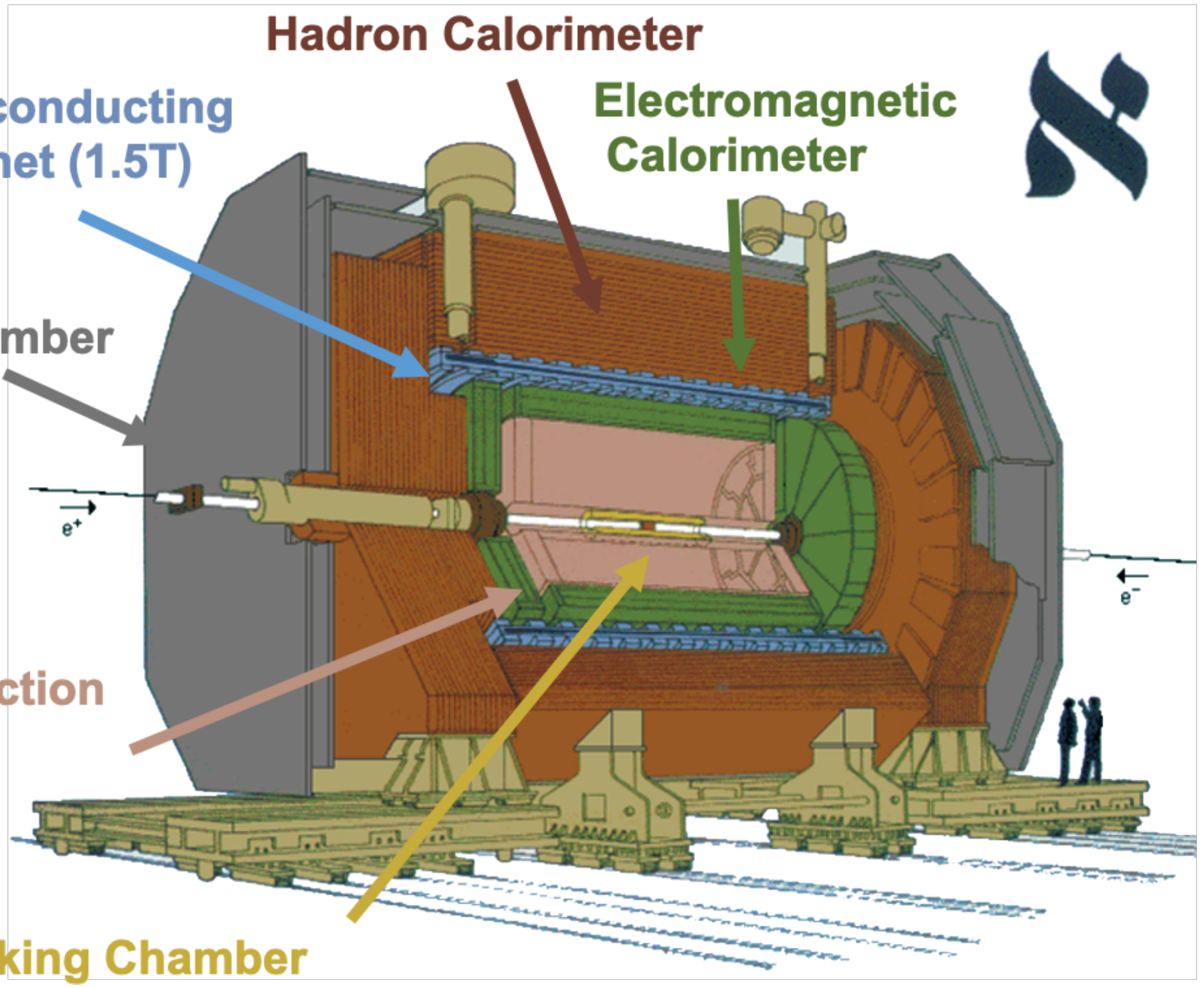


Towards higher energy ...



$e^+e^- \to W^+W^- \to 4f$

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

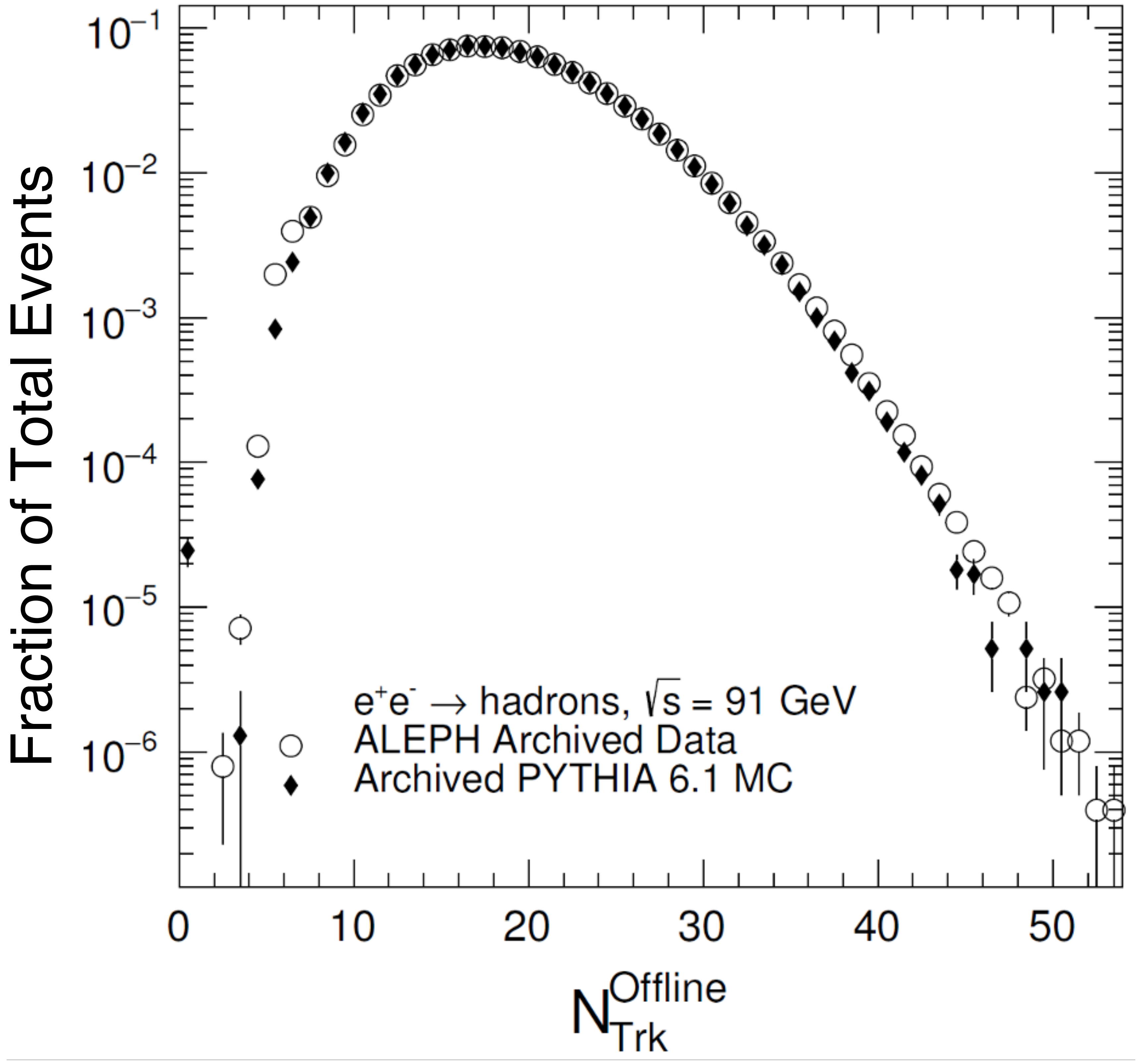
- $\sqrt{s} = 130\text{-}209$ GeV
- Above W^+W^- threshold (160 GeV) , more possible channels
- Radiative-return-to-Z $\Rightarrow$ effective COM energy $\sqrt{s'}$

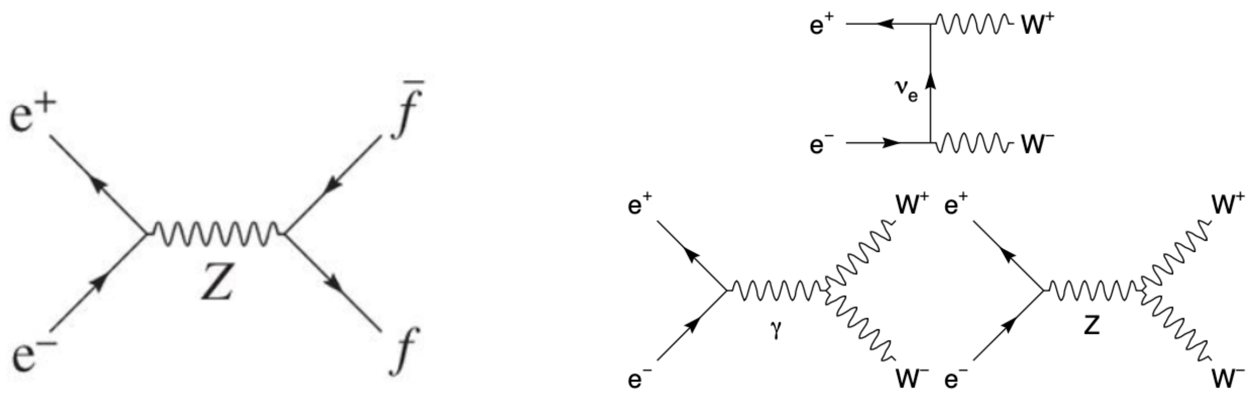
* There are also Z-resonance events in LEP2 sample

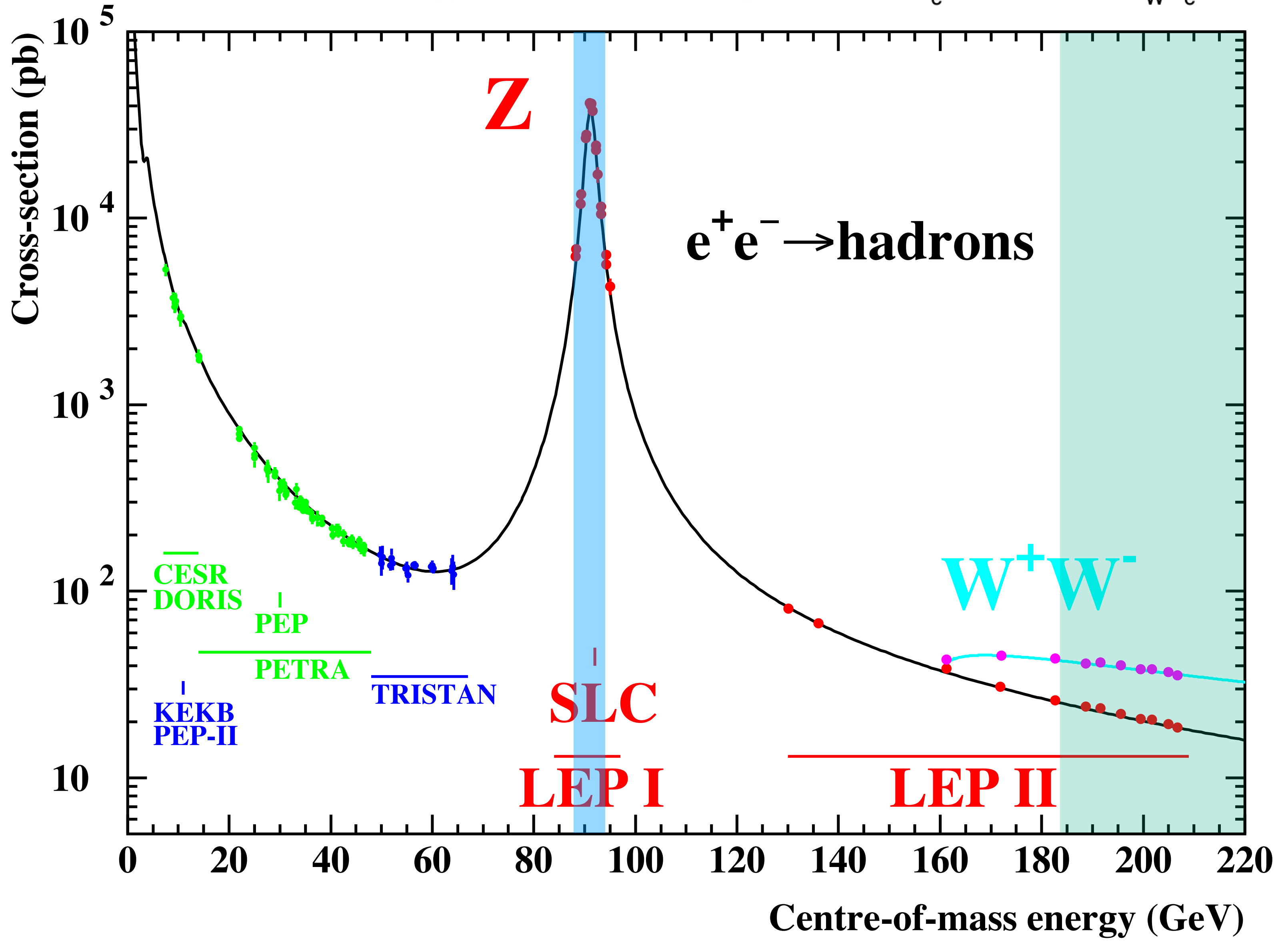
Charged multiplicity distributions

Z-resonance dataset

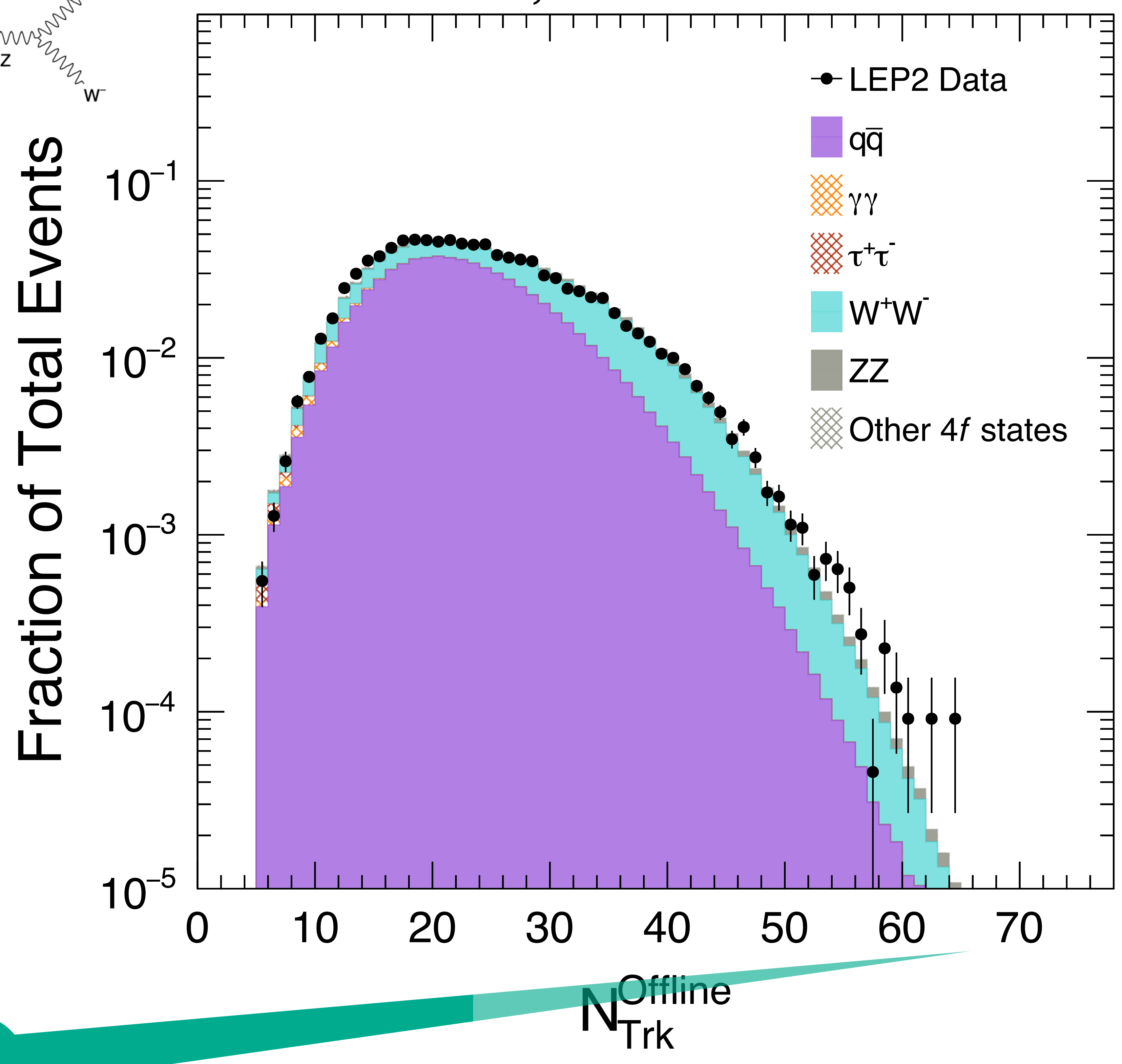
Clean!







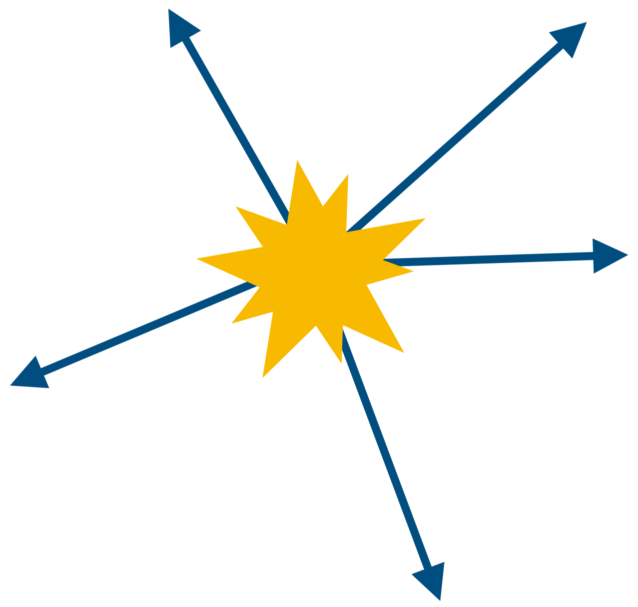
High-energy dataset

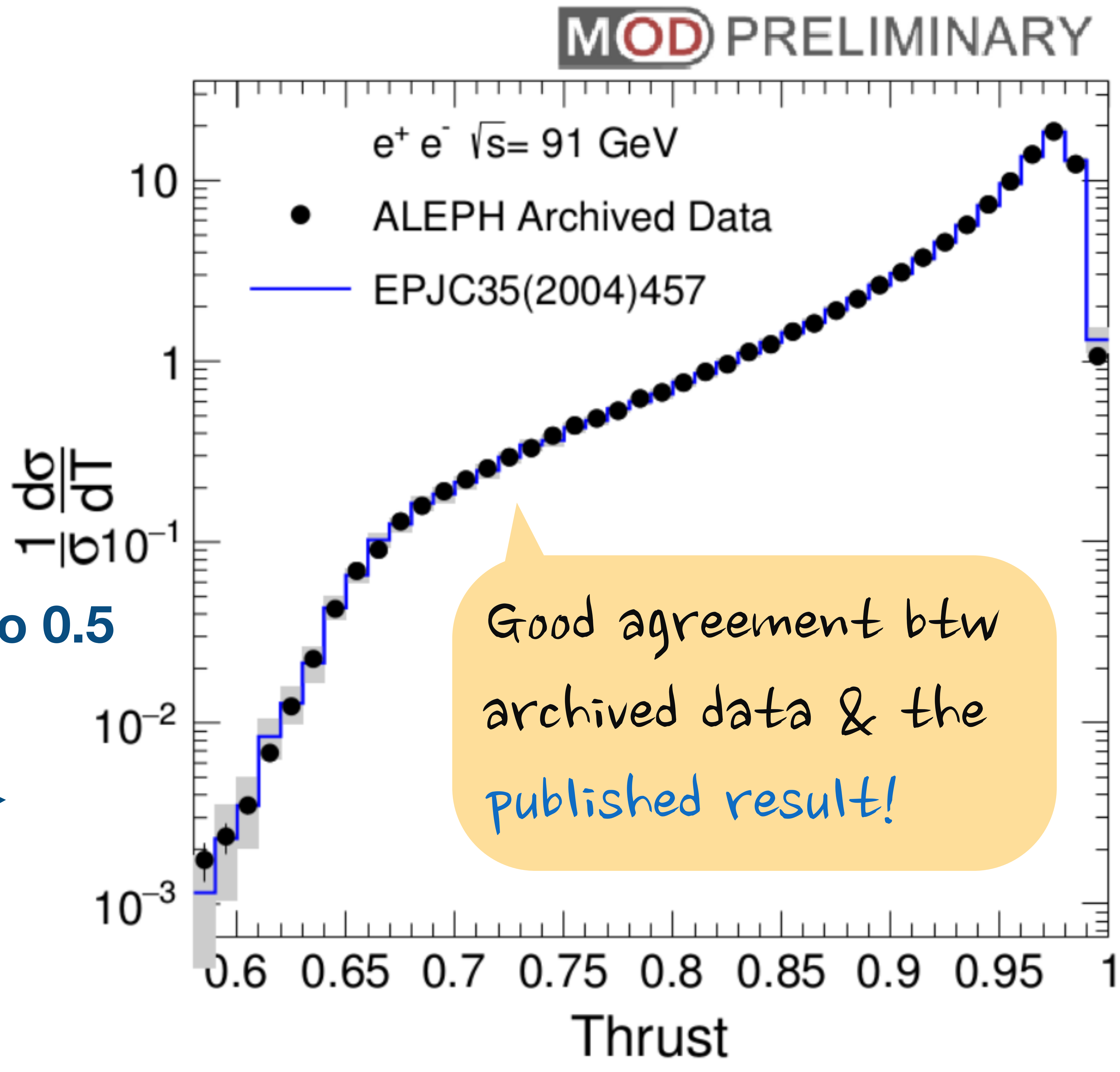


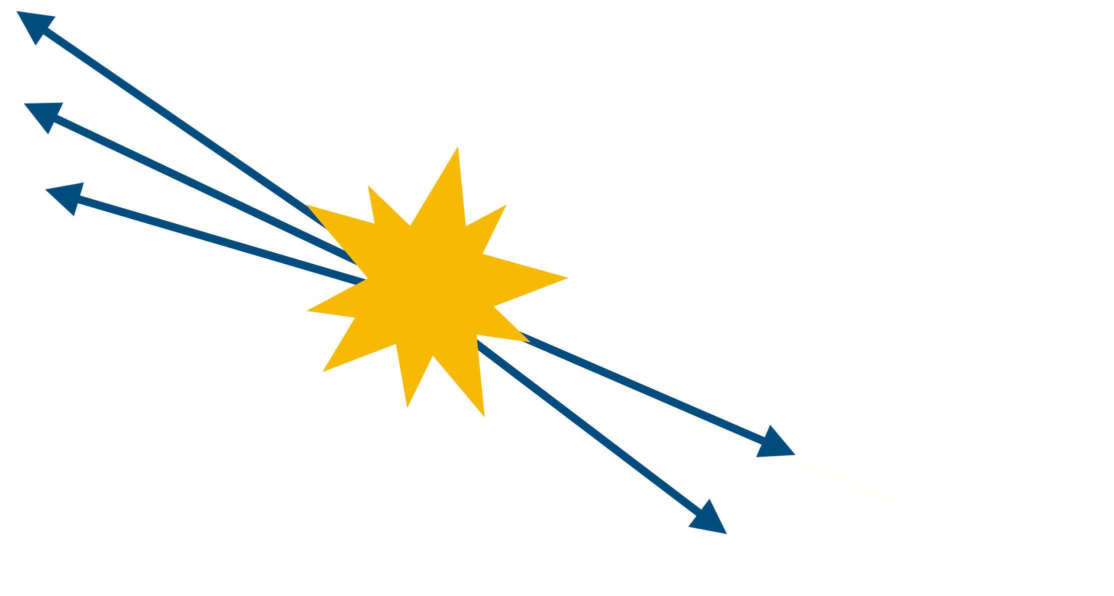
Higher multiplicity reach

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

Unfolded thrust distribution — Good quality data





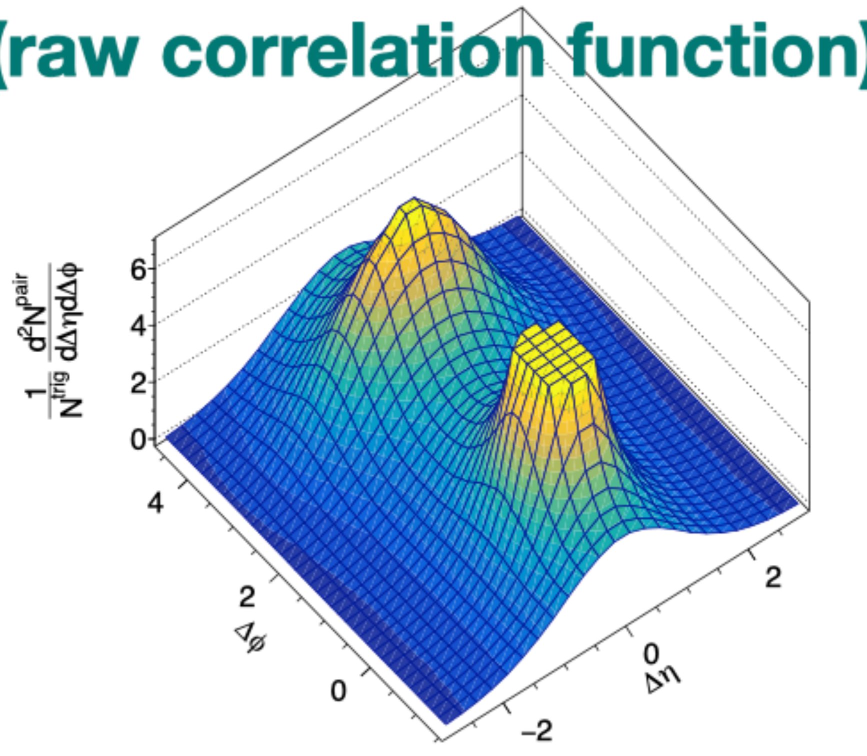


Thrust (T)

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

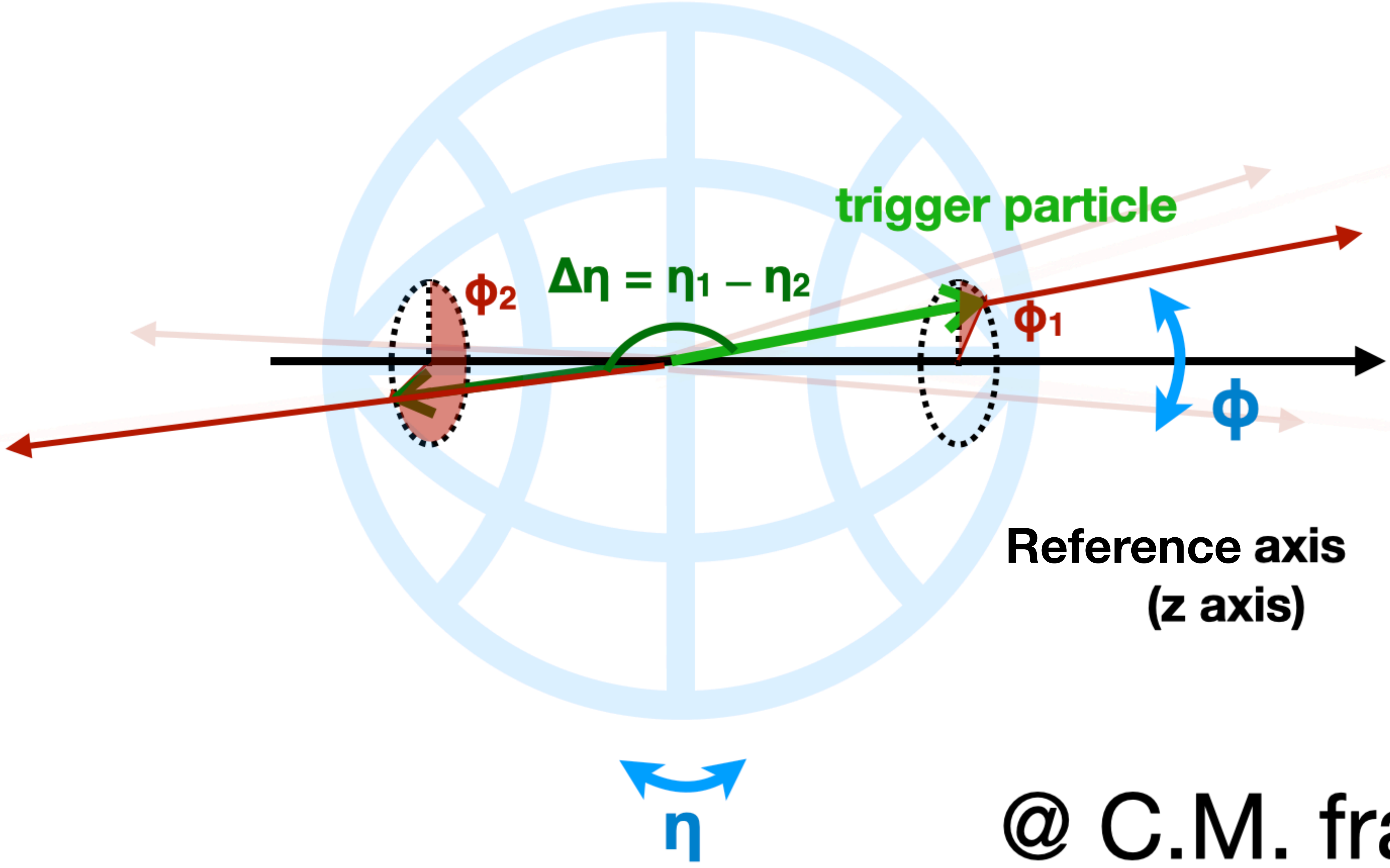
Analysis method: 2PC observable construction

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)

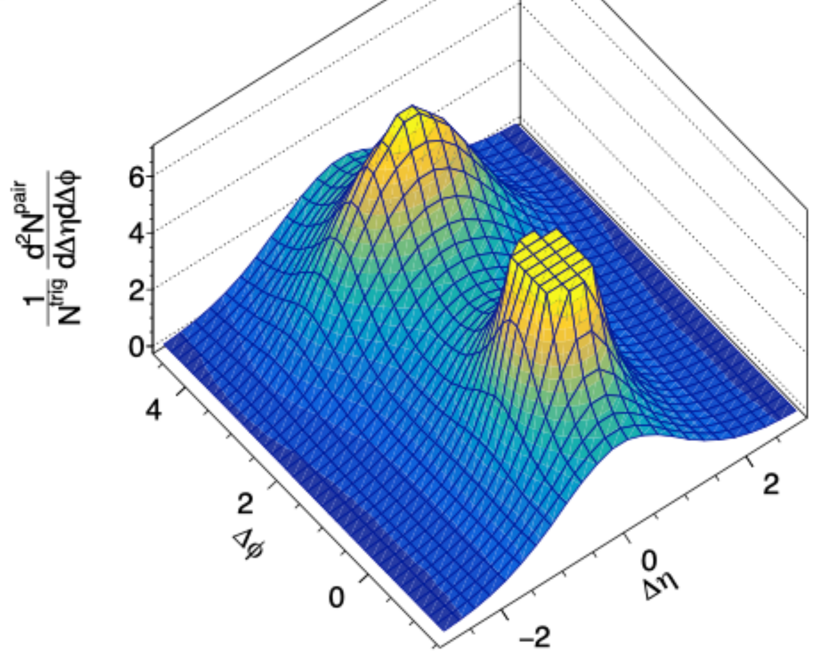


@ C.M. frame

(Illustrations in following slides are with Belle experiment (√s=10 GeV))

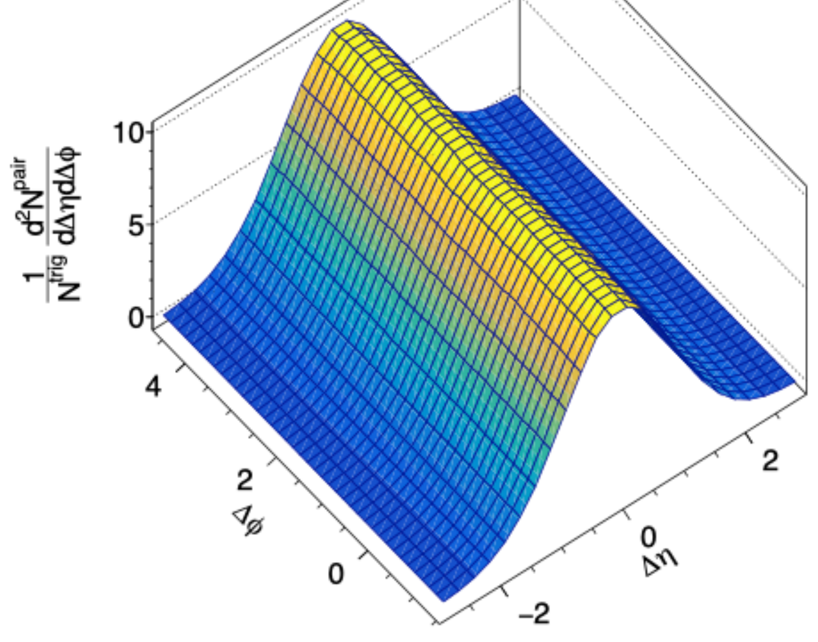
Analysis method: 2PC observable construction

Signal
(raw correlation function)



/

Background
(accounting for baseline of random pairing)



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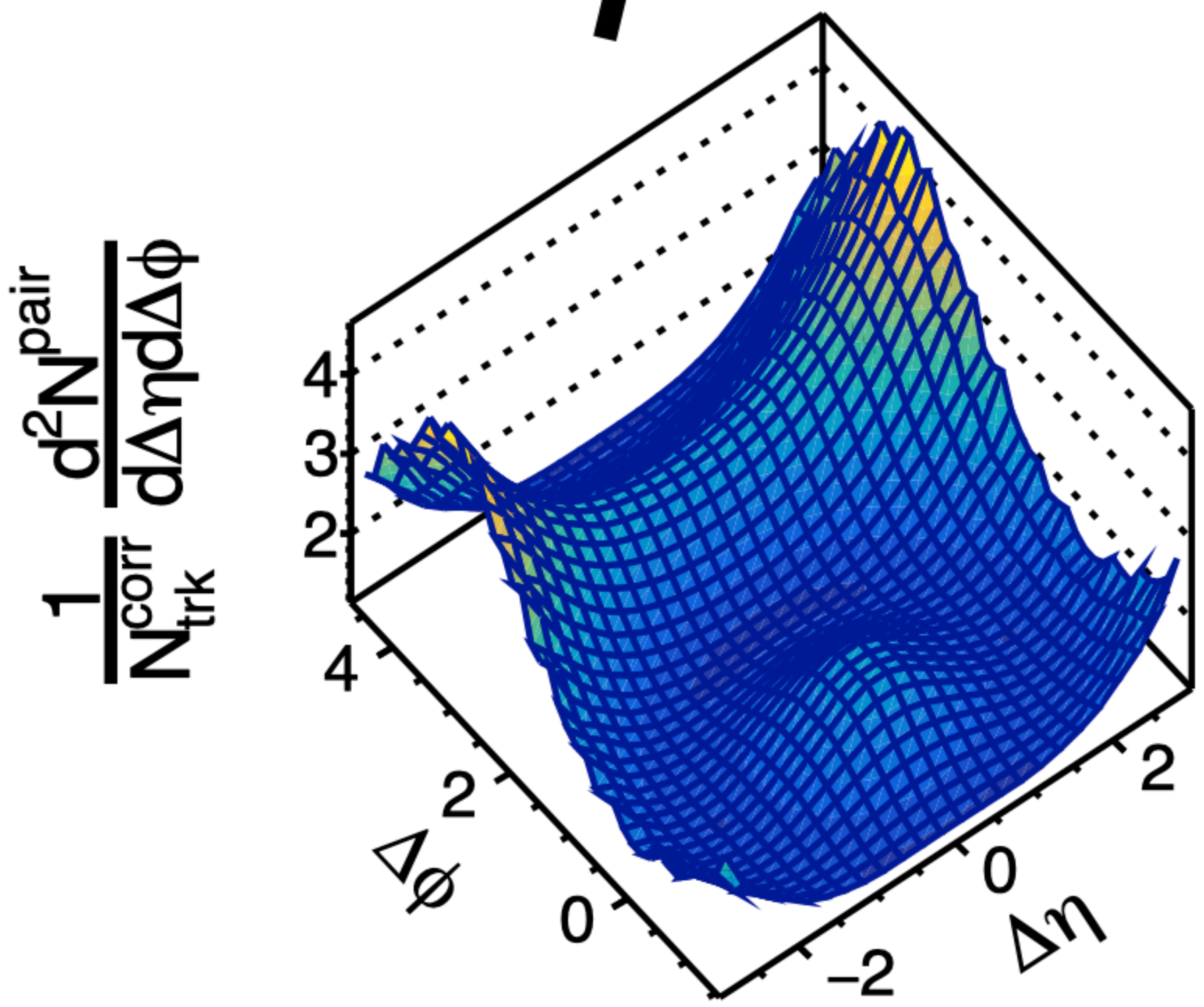
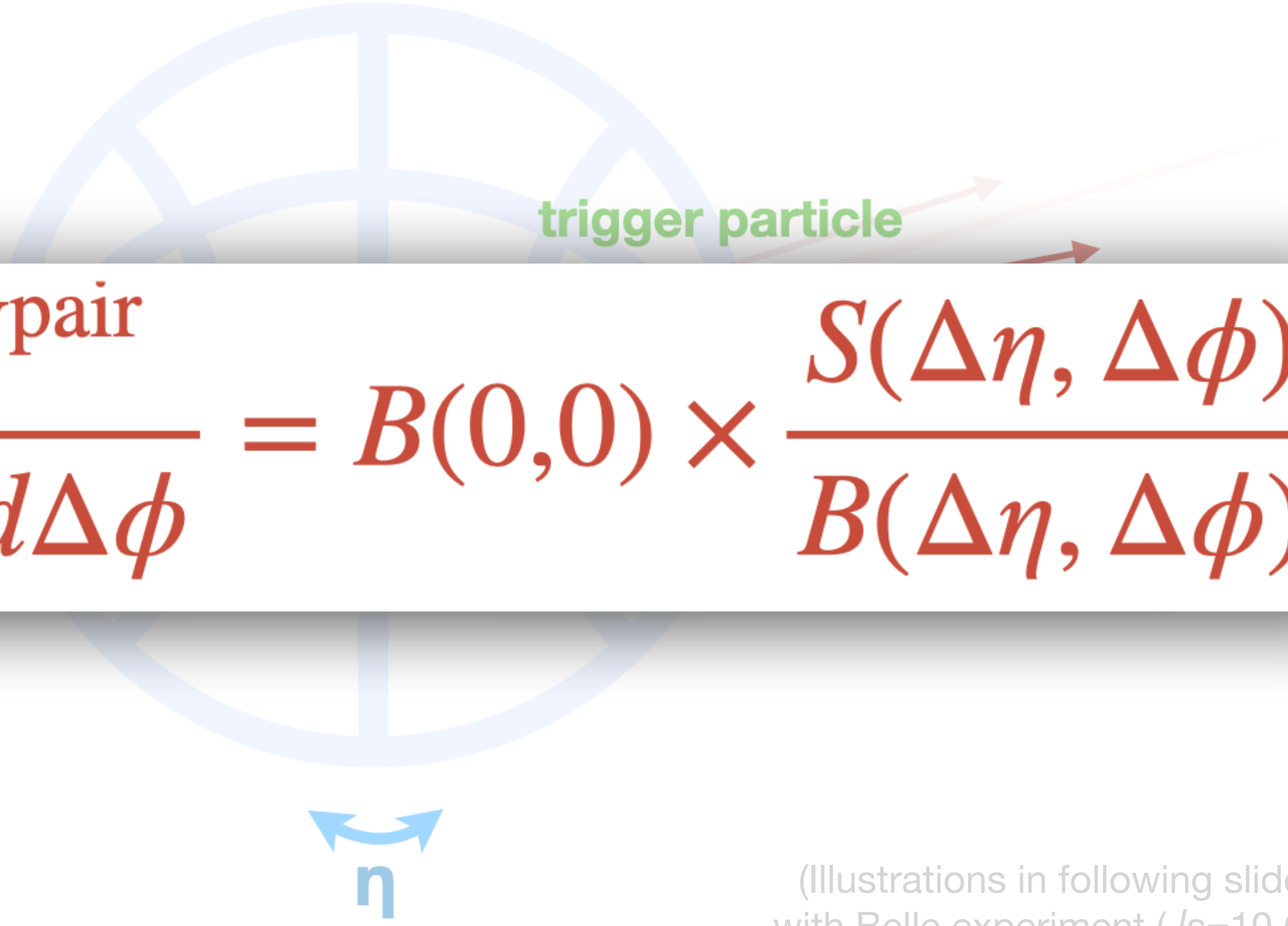


Two-particle correlation function
(per-trigger-particle associated yield)

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



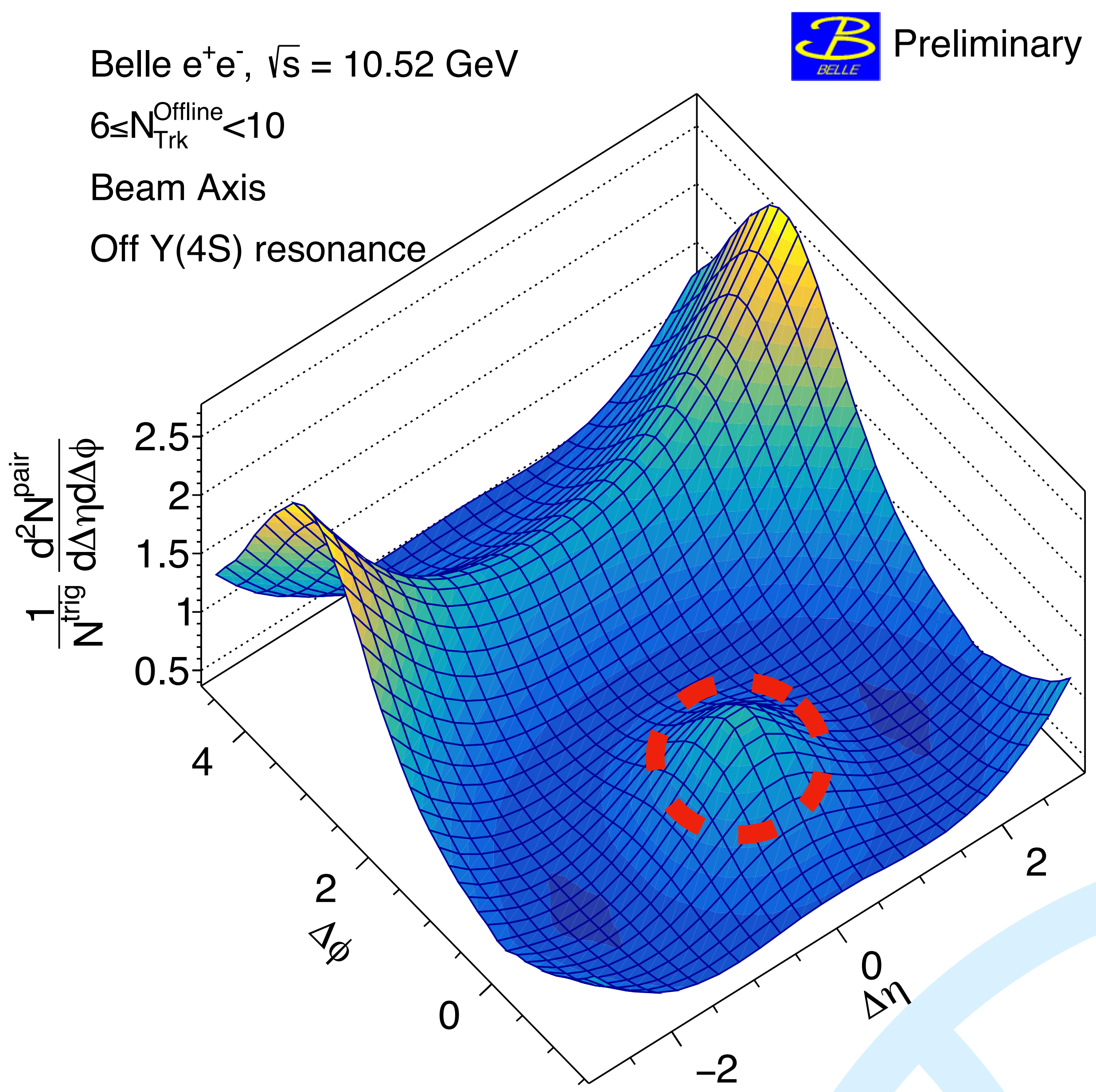
$$\frac{1}{N^{corr}_{trk}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0)\times\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

(Illustrations in following slides are with Belle experiment (√s=10 GeV))

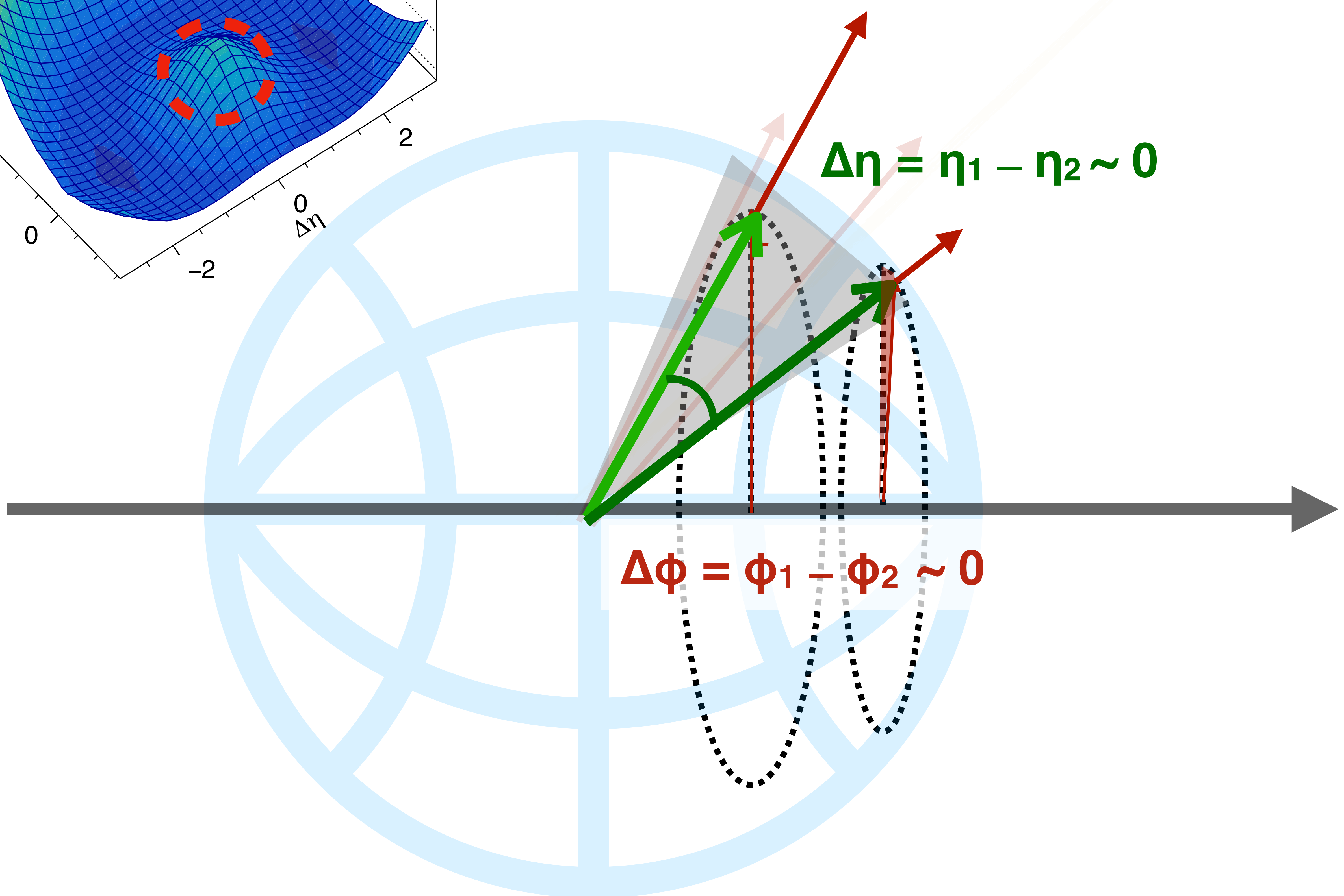
Understanding the 2PC

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

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



Origin-peak intra-jet correlations @ near side (Δη,Δϕ)~(0,0)

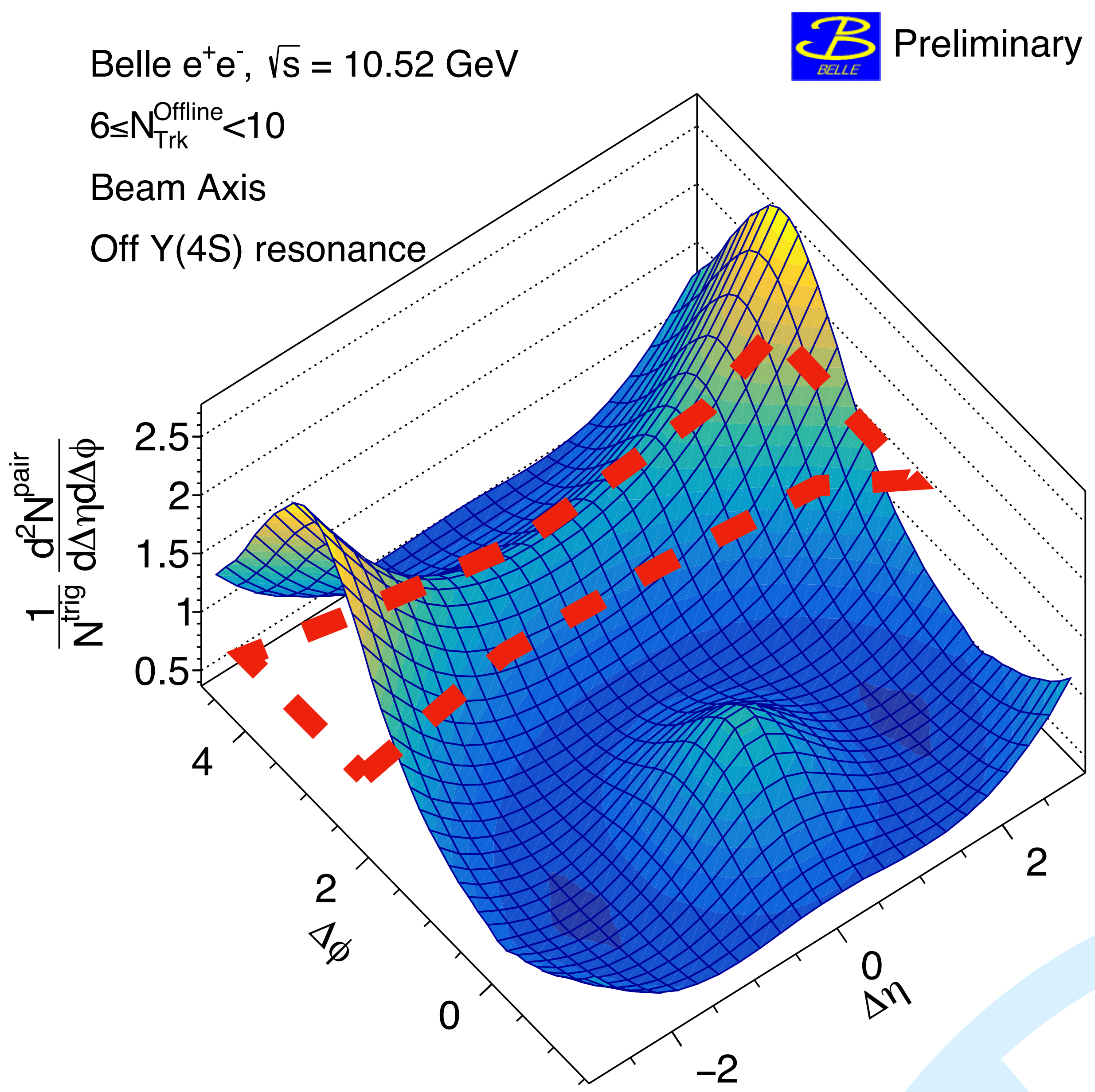


(Illustrations in following slides are with Belle experiment (√s=10 GeV))

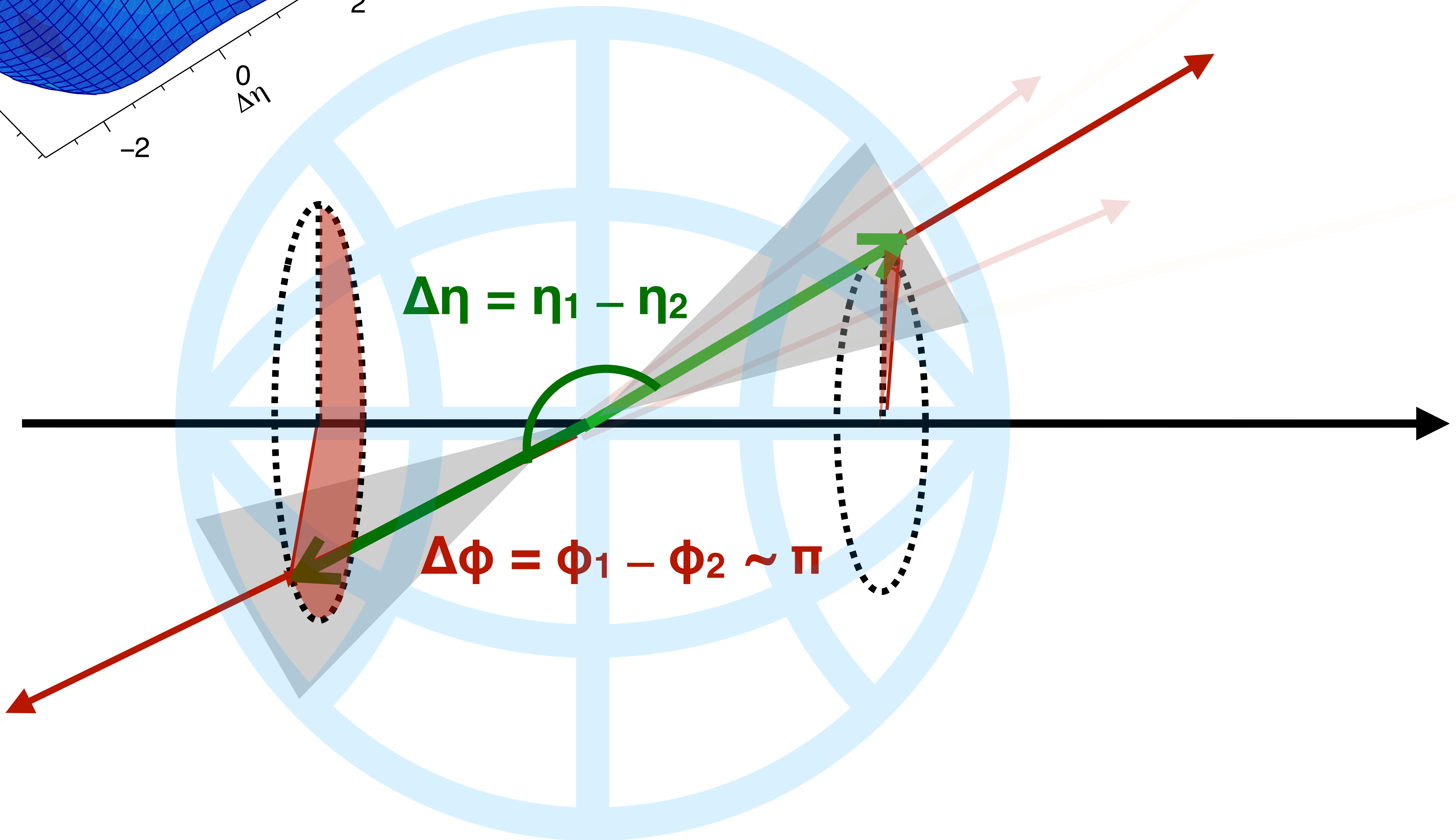
Understanding the 2PC

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

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



Inter-jet correlations @ away side (Δϕ~π)



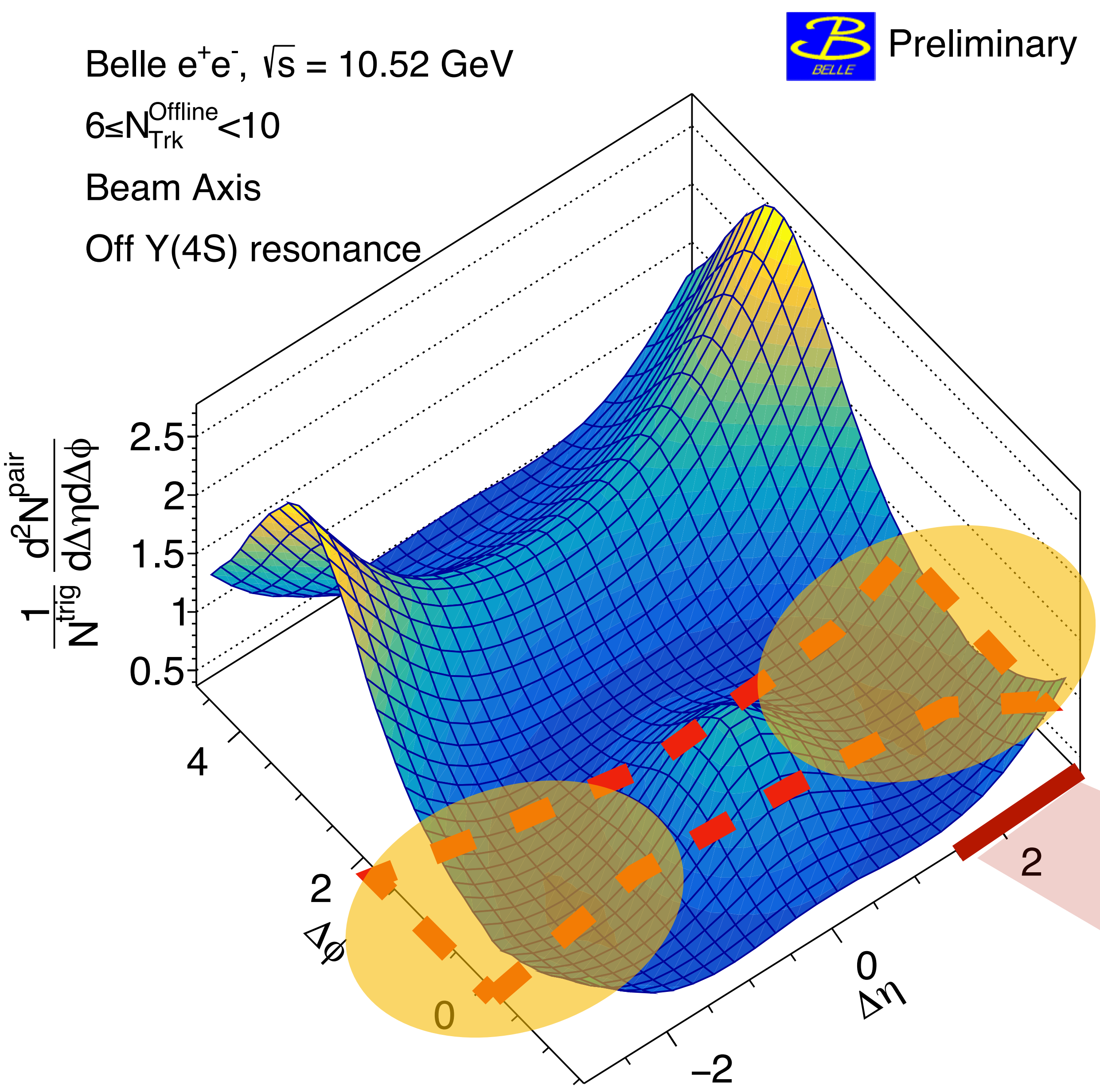
(Illustrations in following slides are with Belle experiment (√s=10 GeV))

Observable

Understanding the 2PC

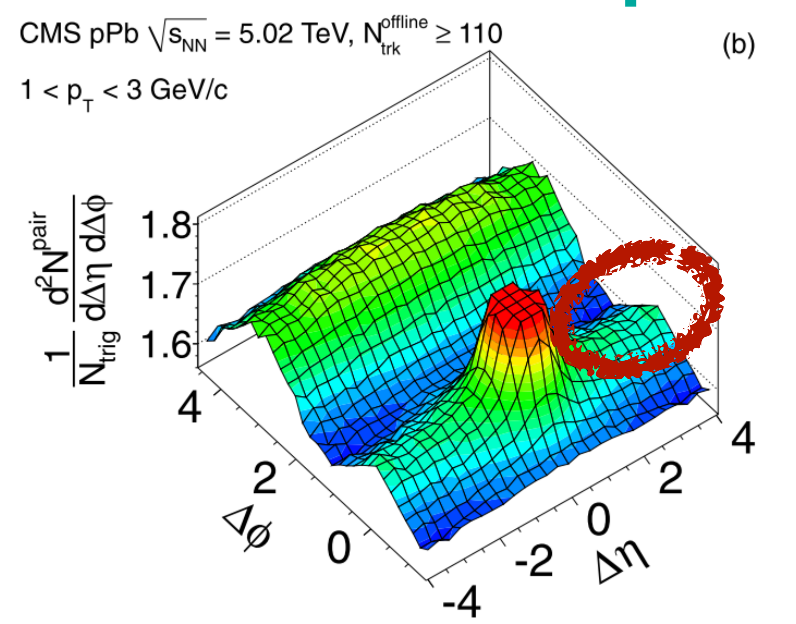
Two-particle correlation function (per-trigger-particle associated yield)

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

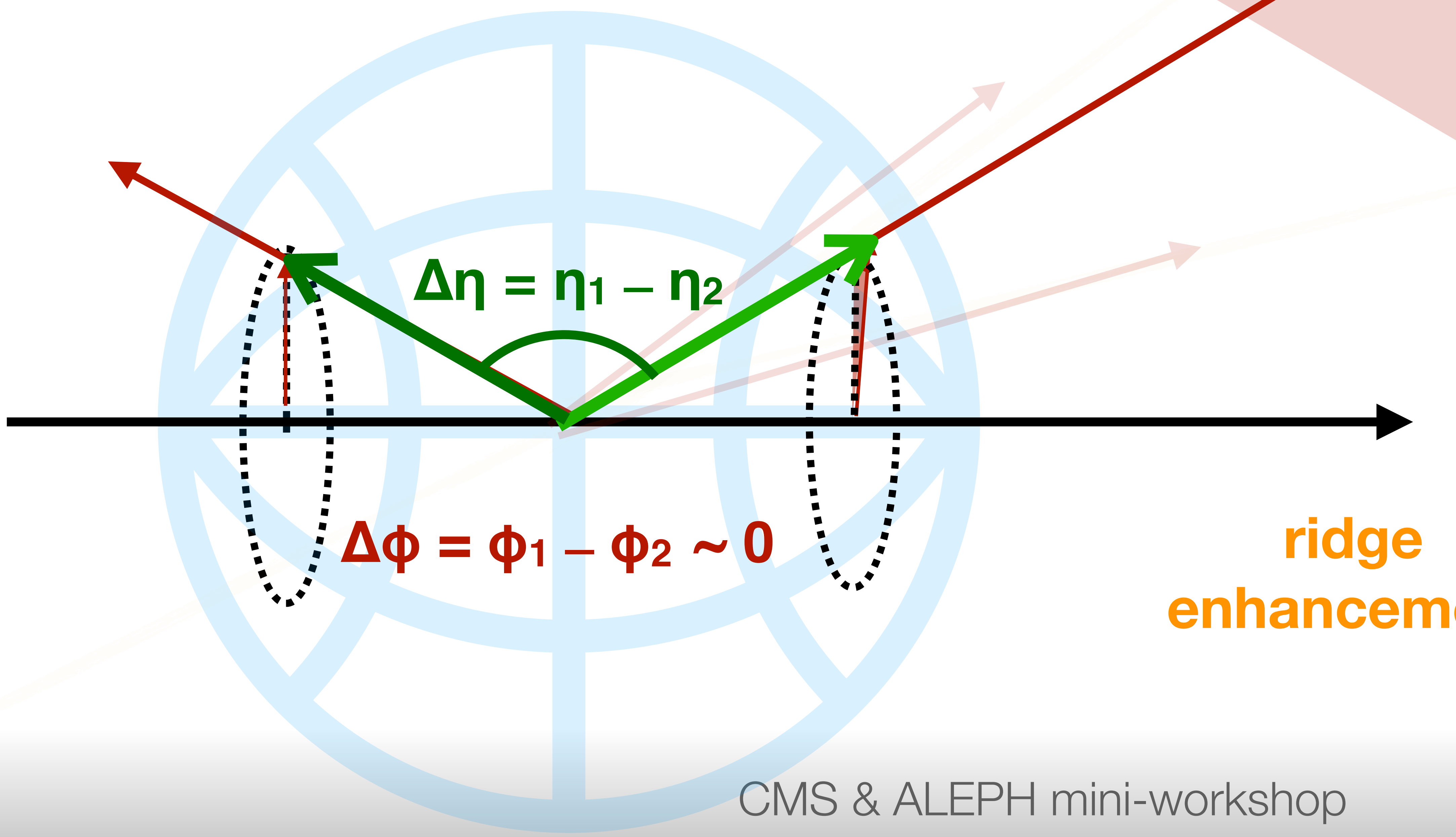


Ridge correlations @ long range, near side

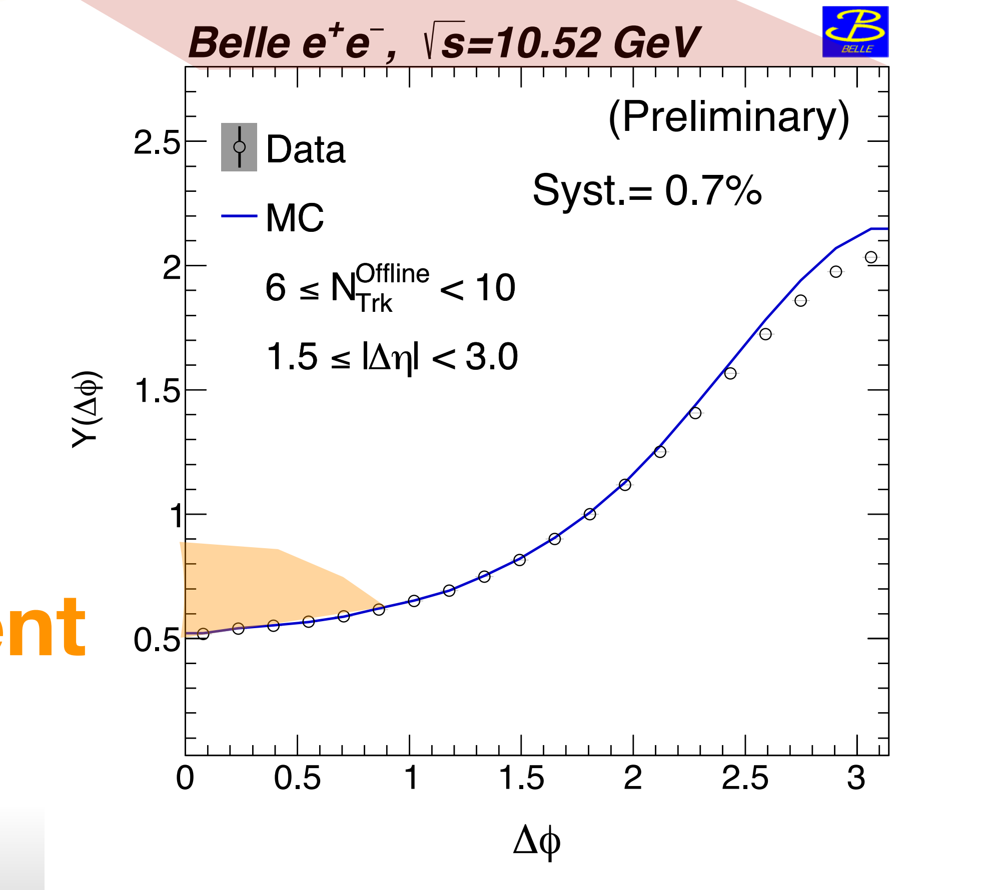
pPb



pA: Phys. Lett. B718 (2013) 795-814



long range in large |Δη|



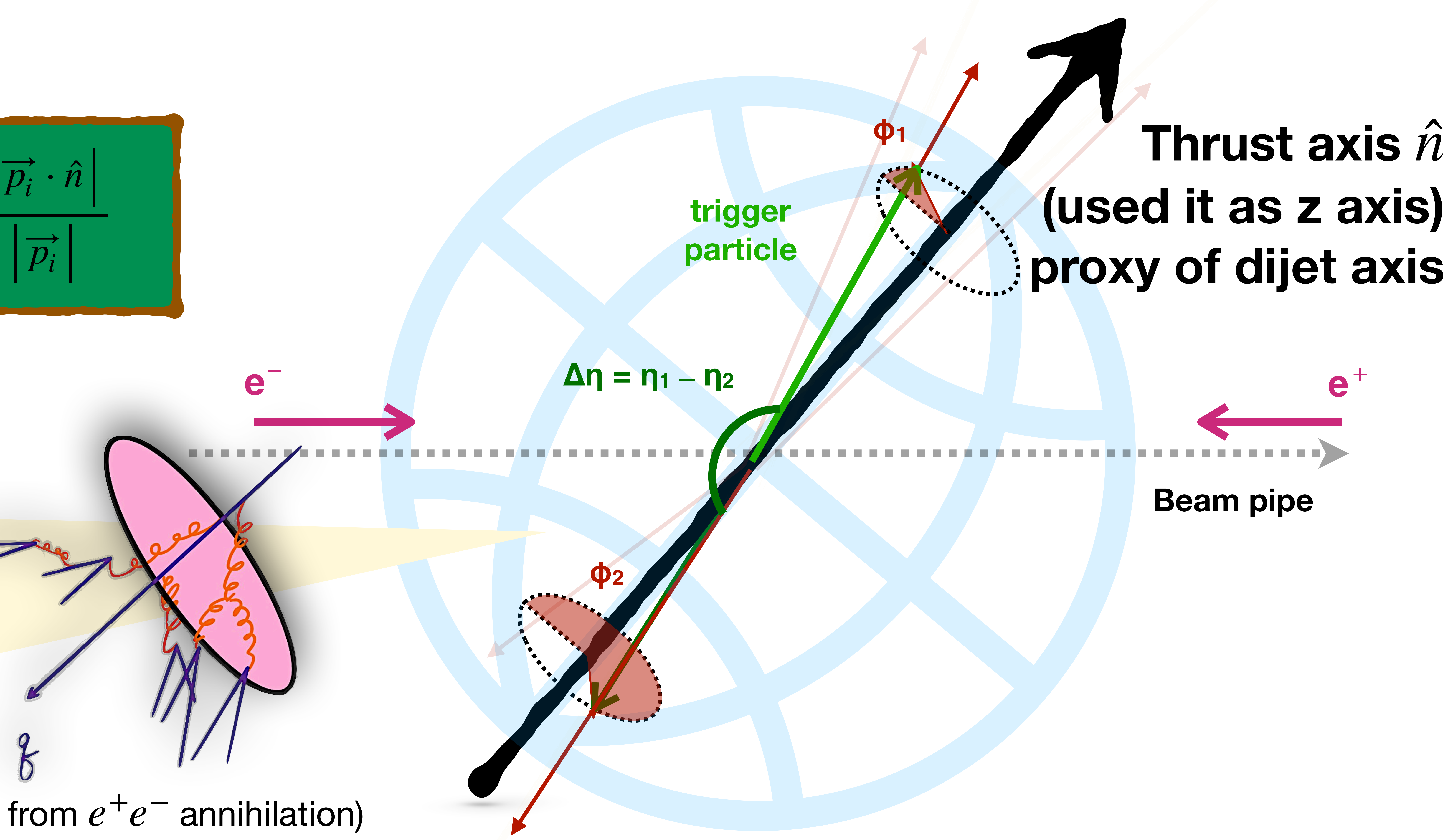
ridge enhancement

(Illustrations in following slides are with Belle experiment (√s=10 GeV))

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

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

If high energy quarks can form some medium, looking from the thrust axis is sensitive to the azimuthal anisotropy of this "imaginary medium."



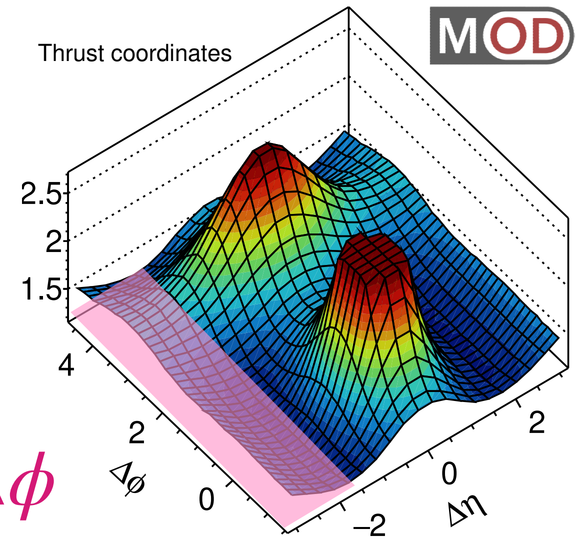
(quark from e^+e^- annihilation)

LEP1

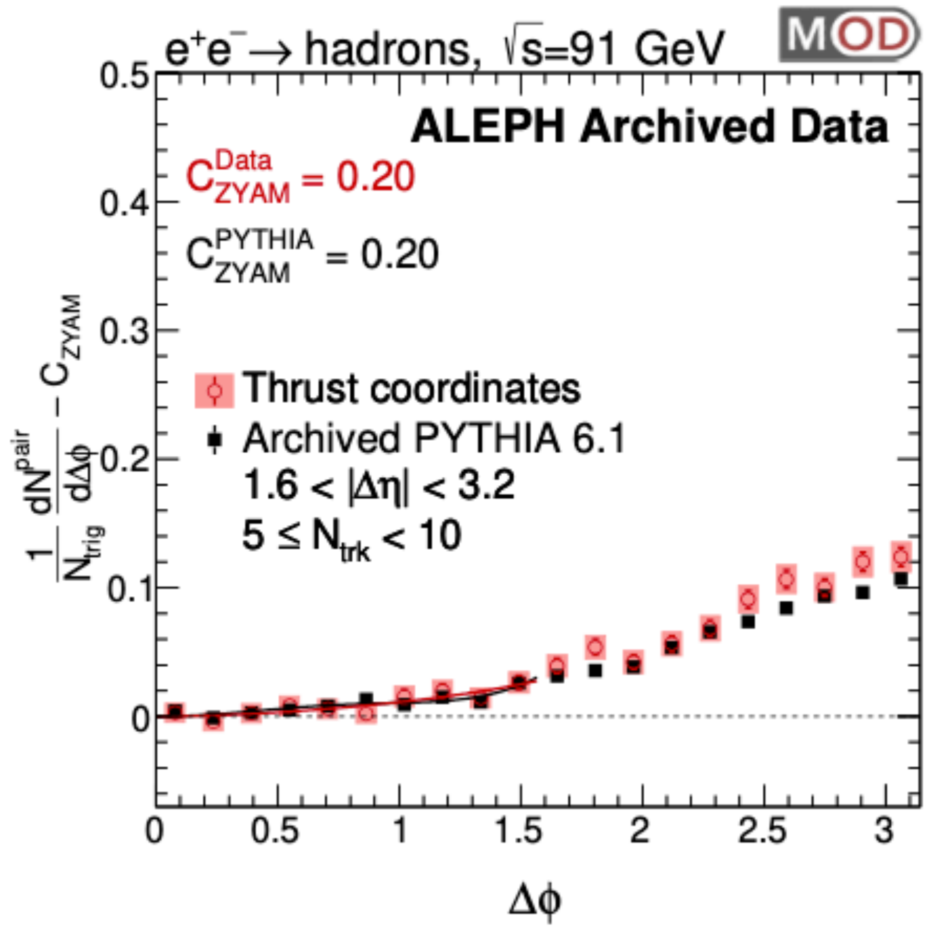
Long-range $(1.6 \leq |\Delta\eta| \leq 3.2)$ correlations

Data
PYTHIA6 MC

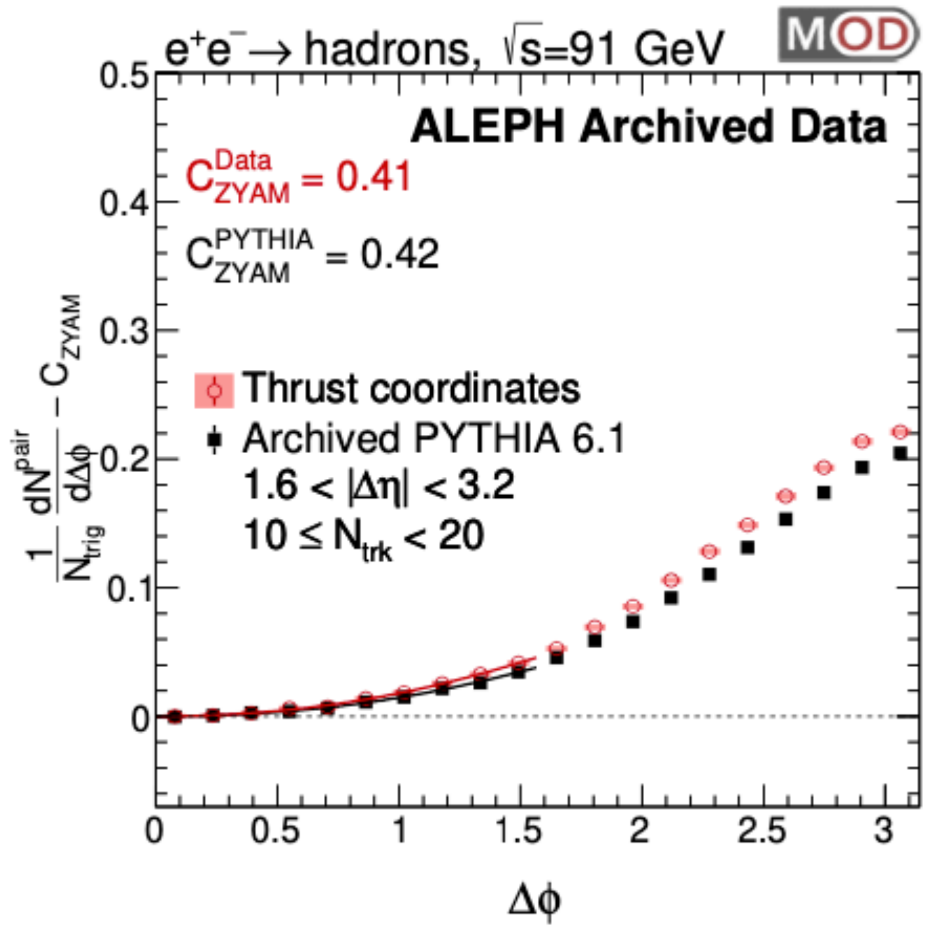
correlations projected in $\Delta\phi$



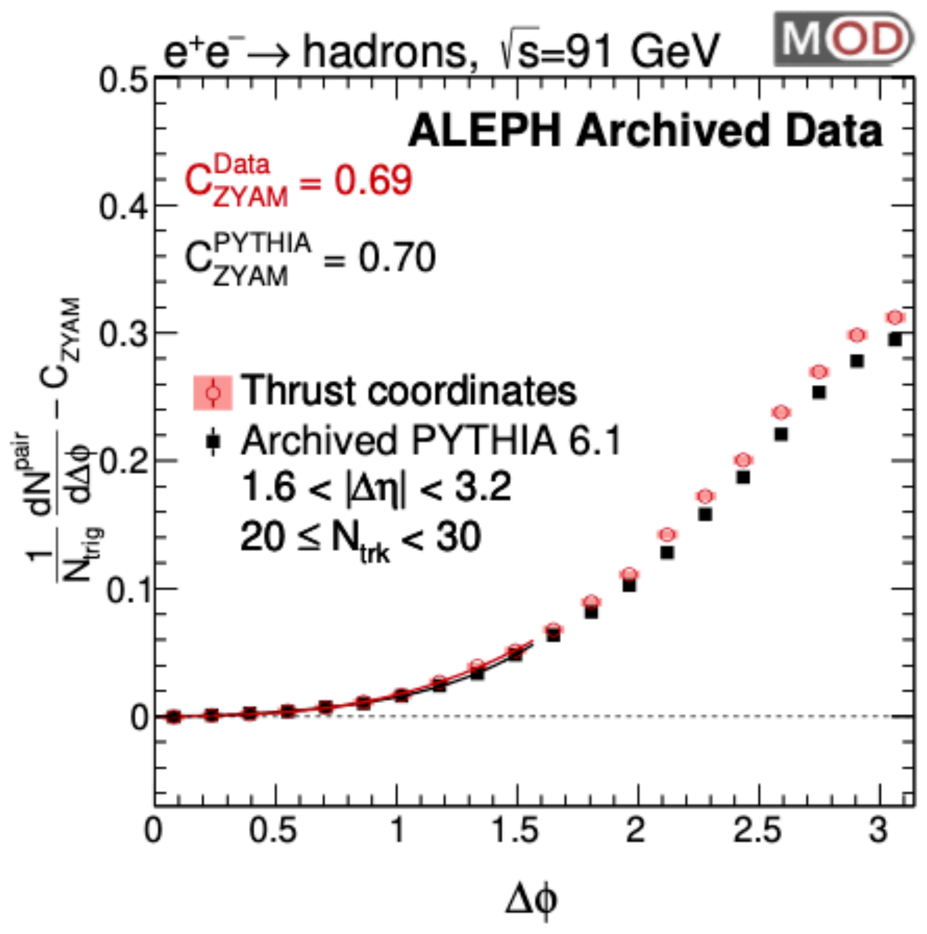
$5 \leq N_{trk} < 10$



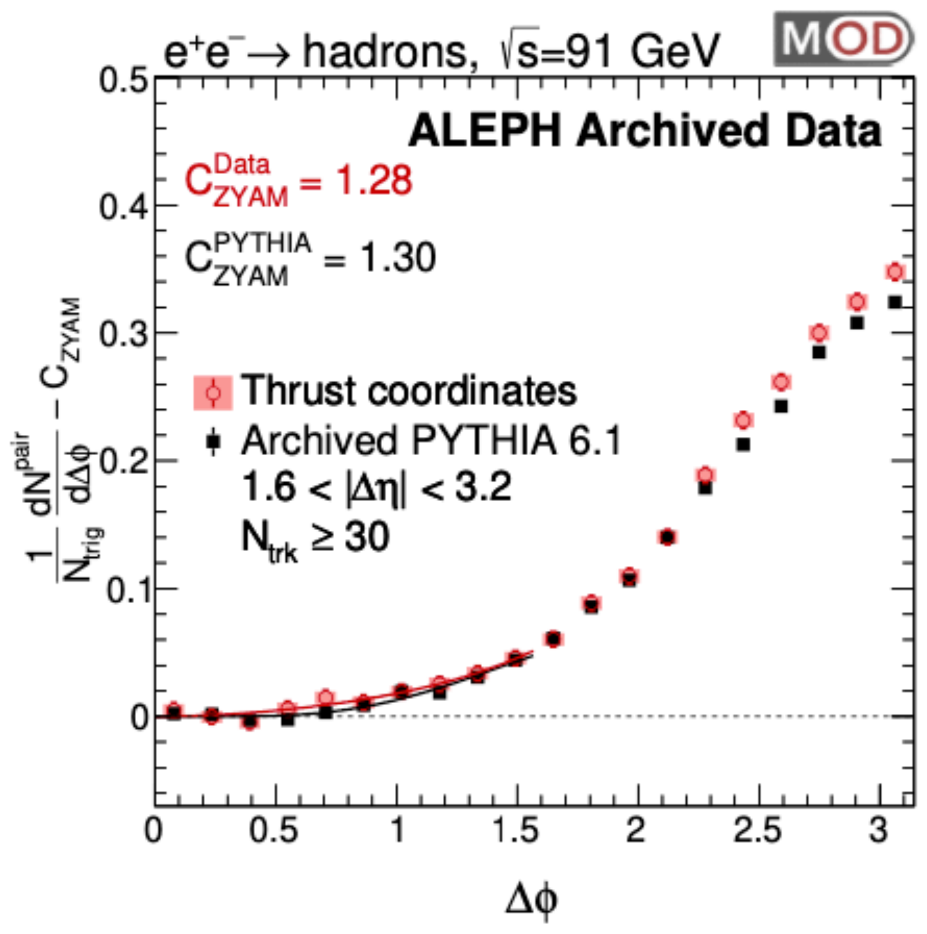
$10 \leq N_{trk} < 20$



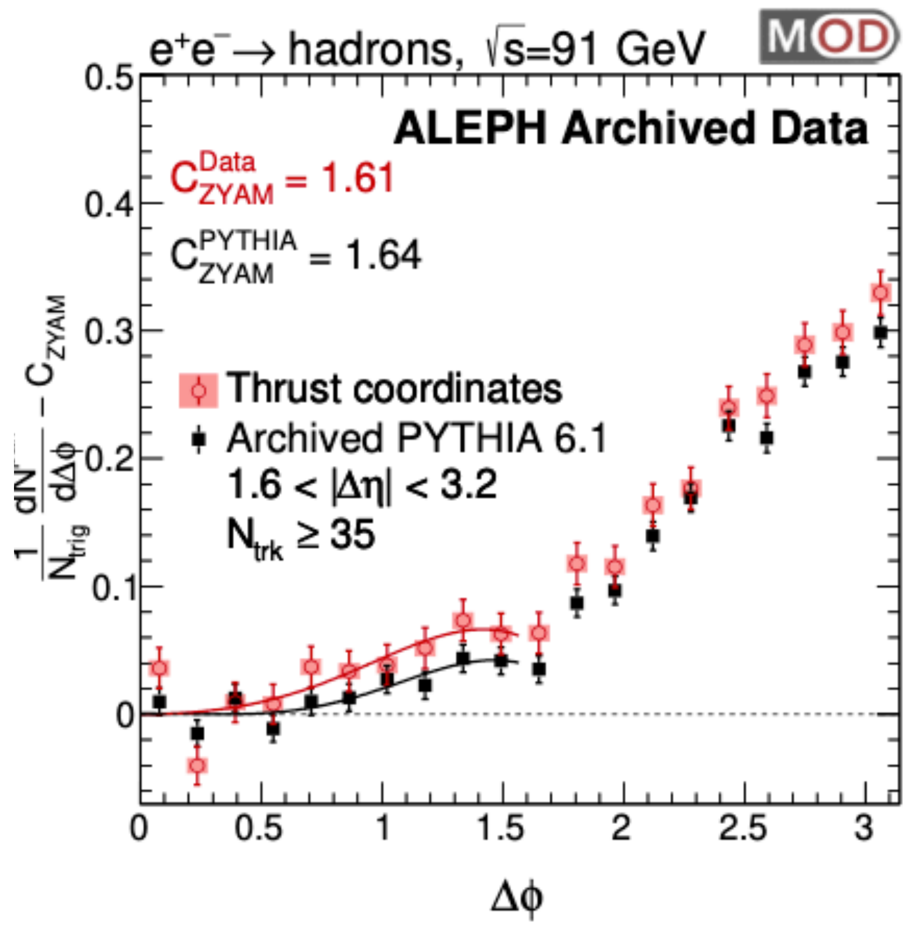
$20 \leq N_{trk} < 30$



$N_{trk} \geq 30$



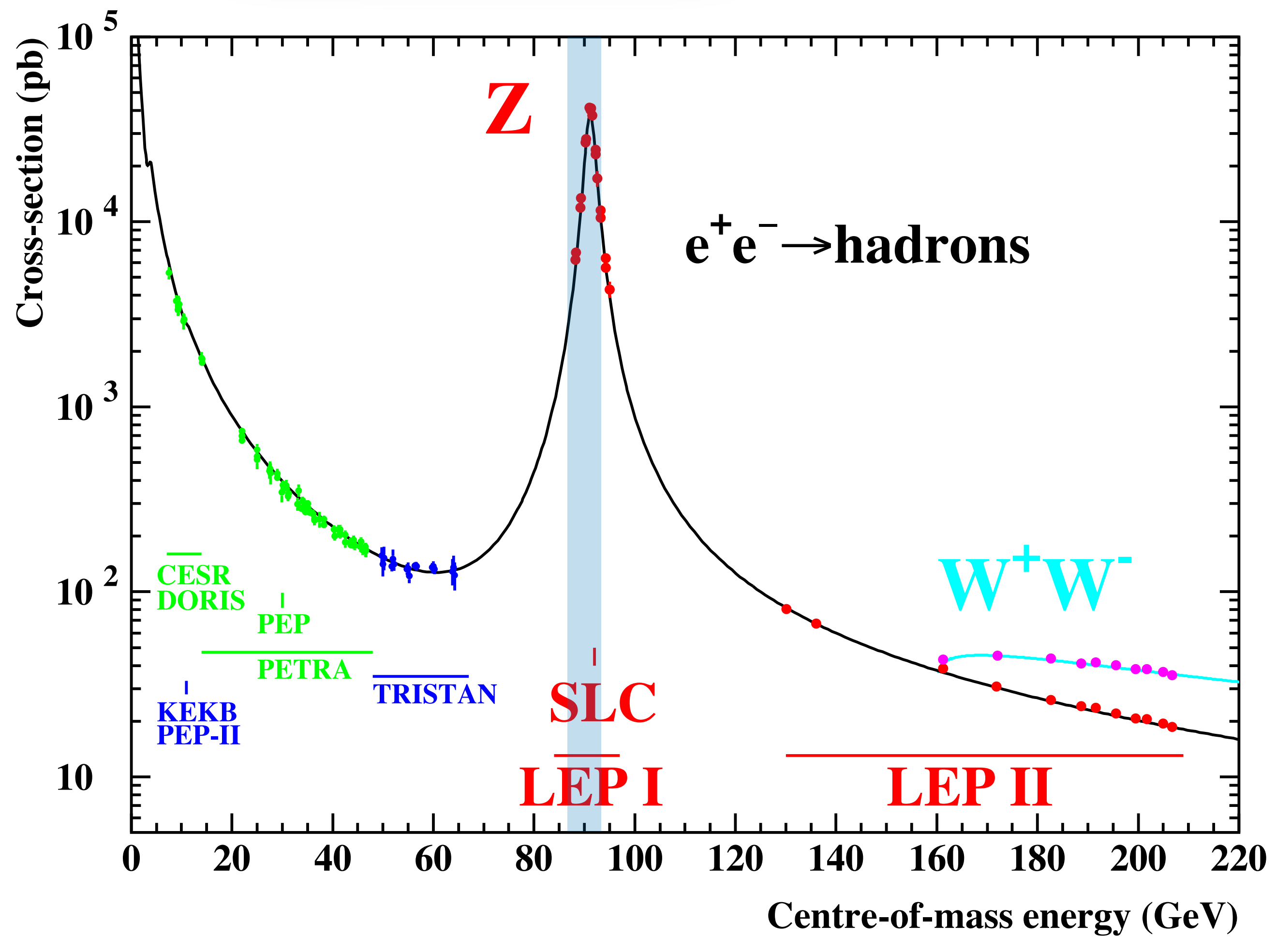
$N_{trk} \geq 35$

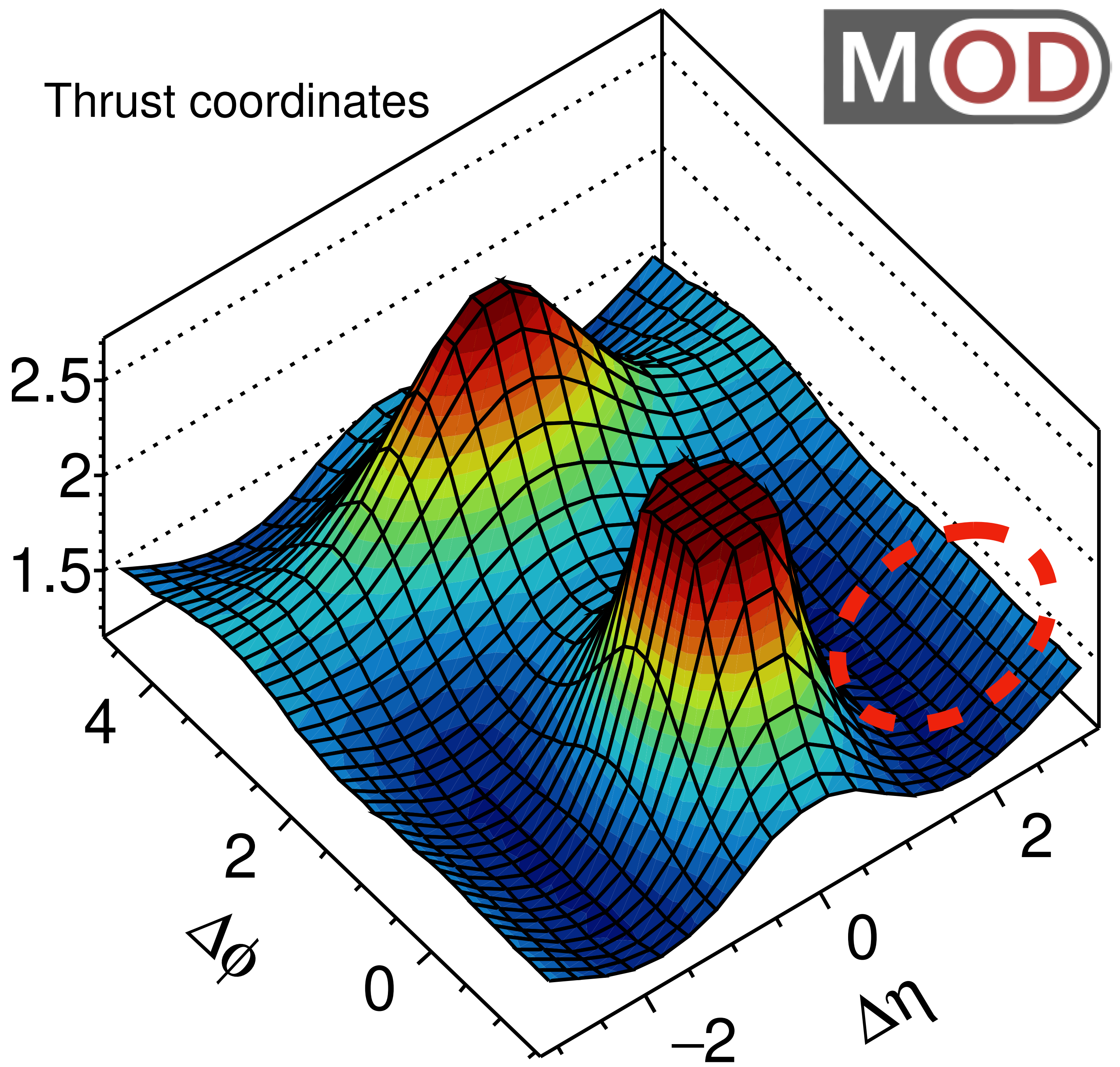


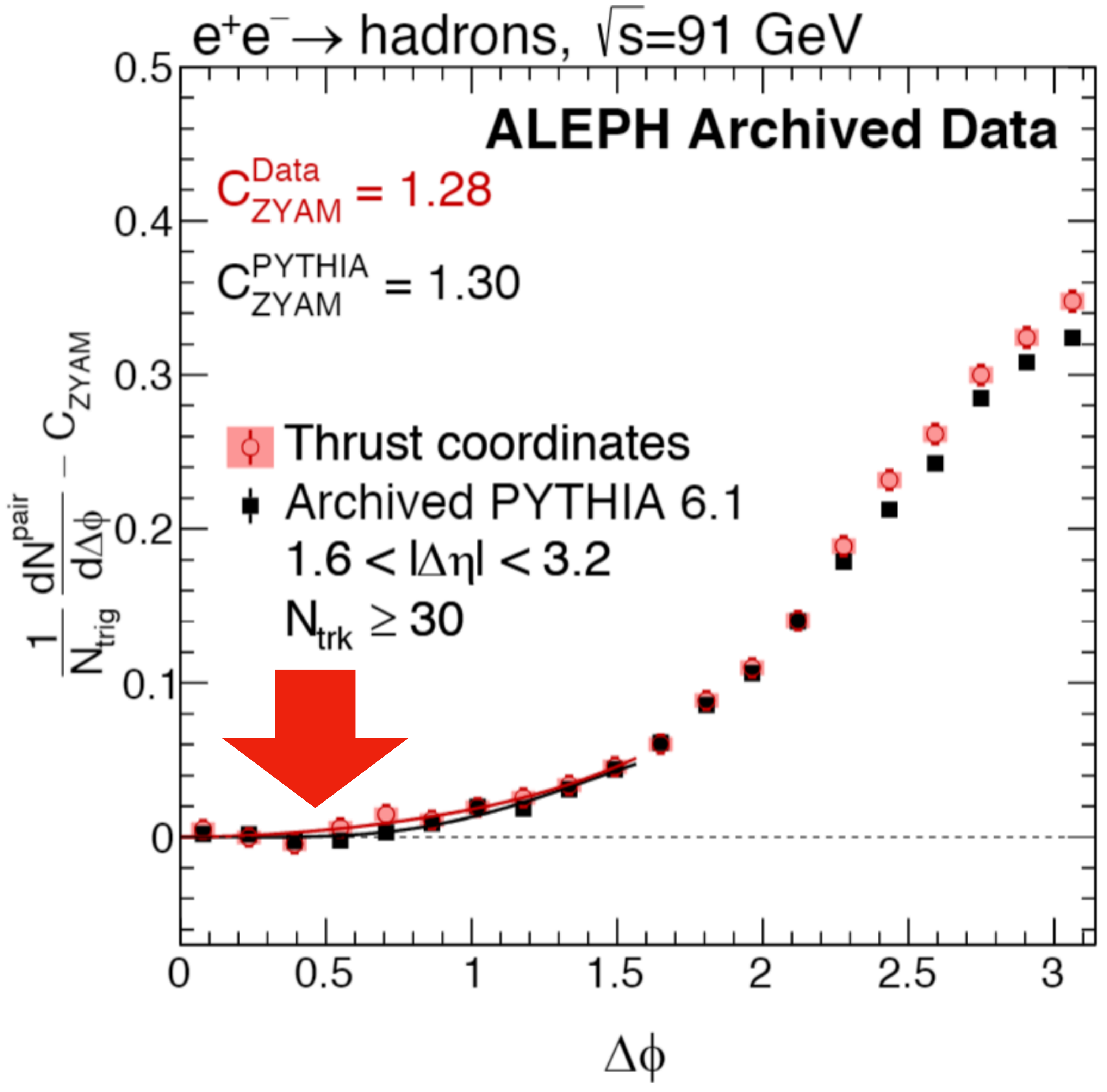
Good data/MC agreement!

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

LEP1 Results with high-multiplicity events





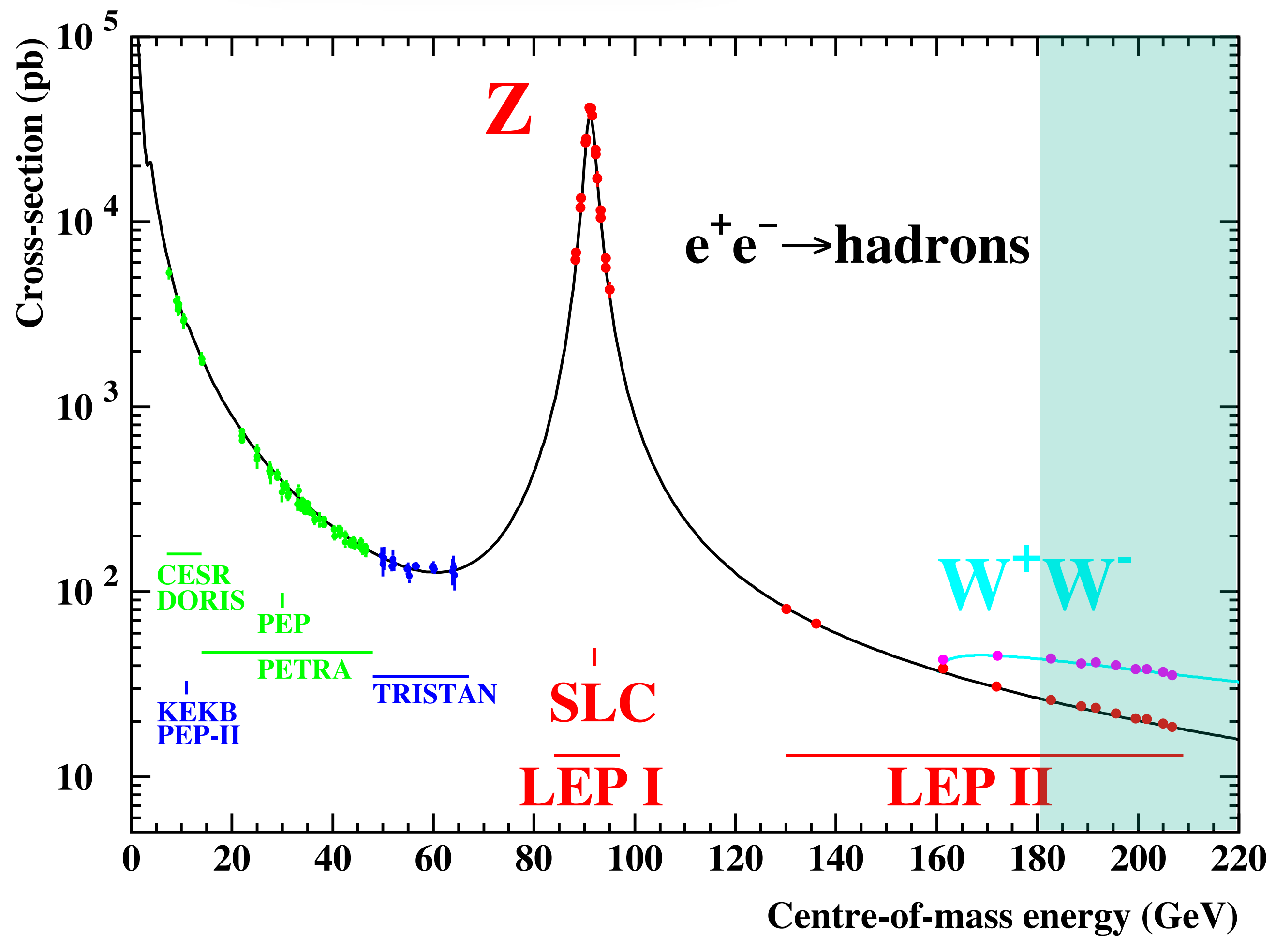


No significant ridge-like signal enhancement!

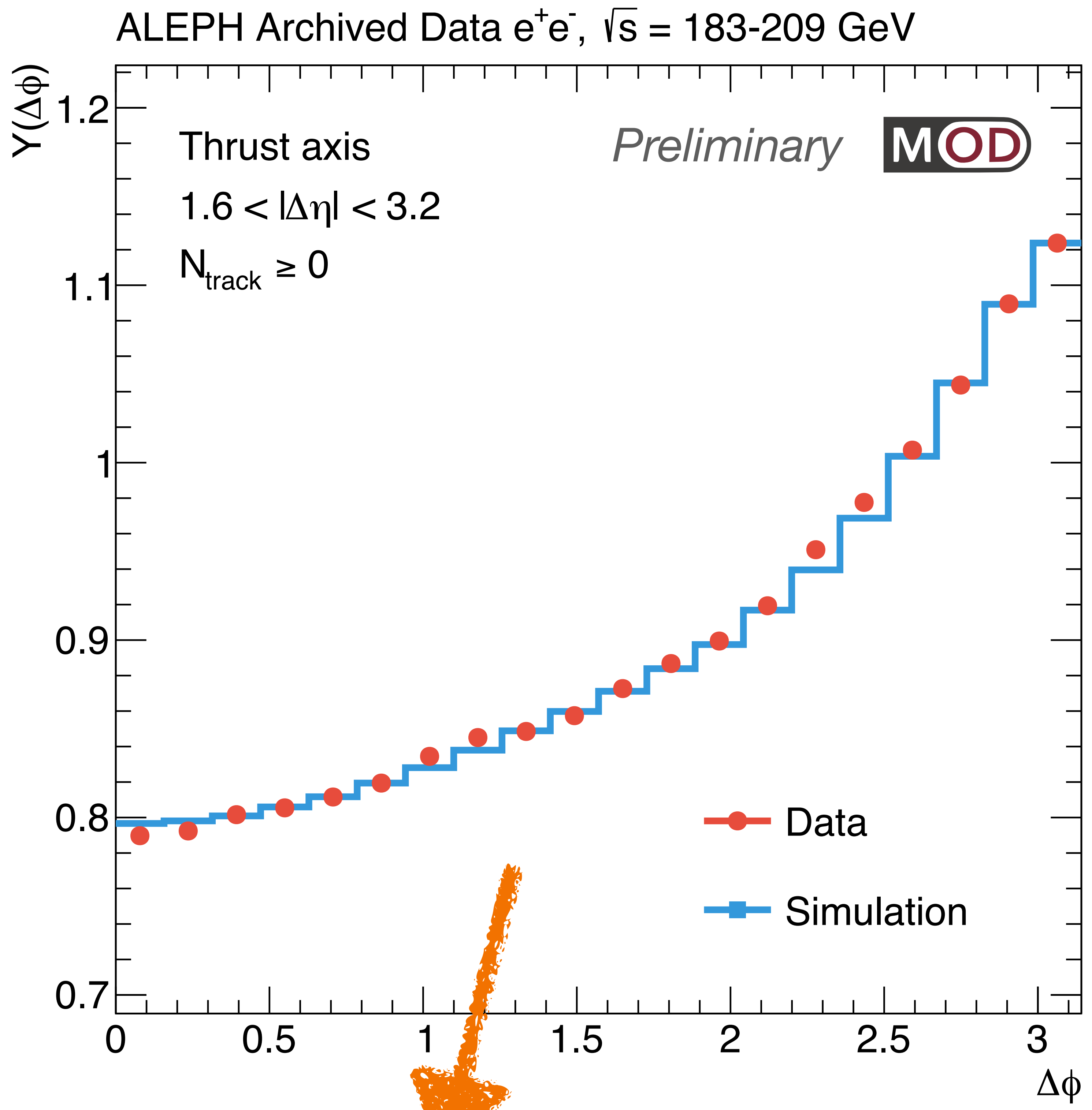
LEP1 e^+e^- 2PC

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

LEP2 High collision energy



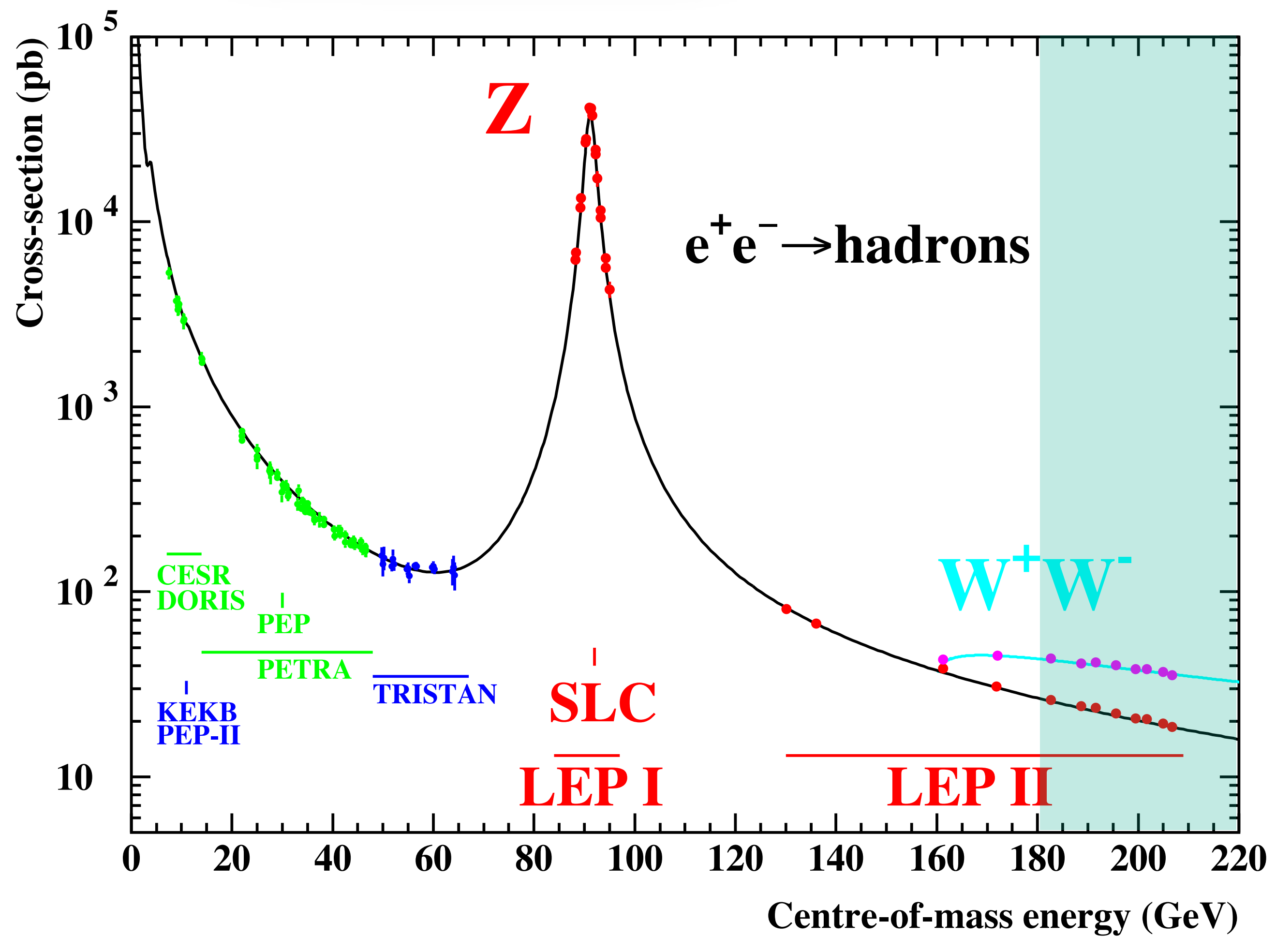
Inclusive in multiplicity

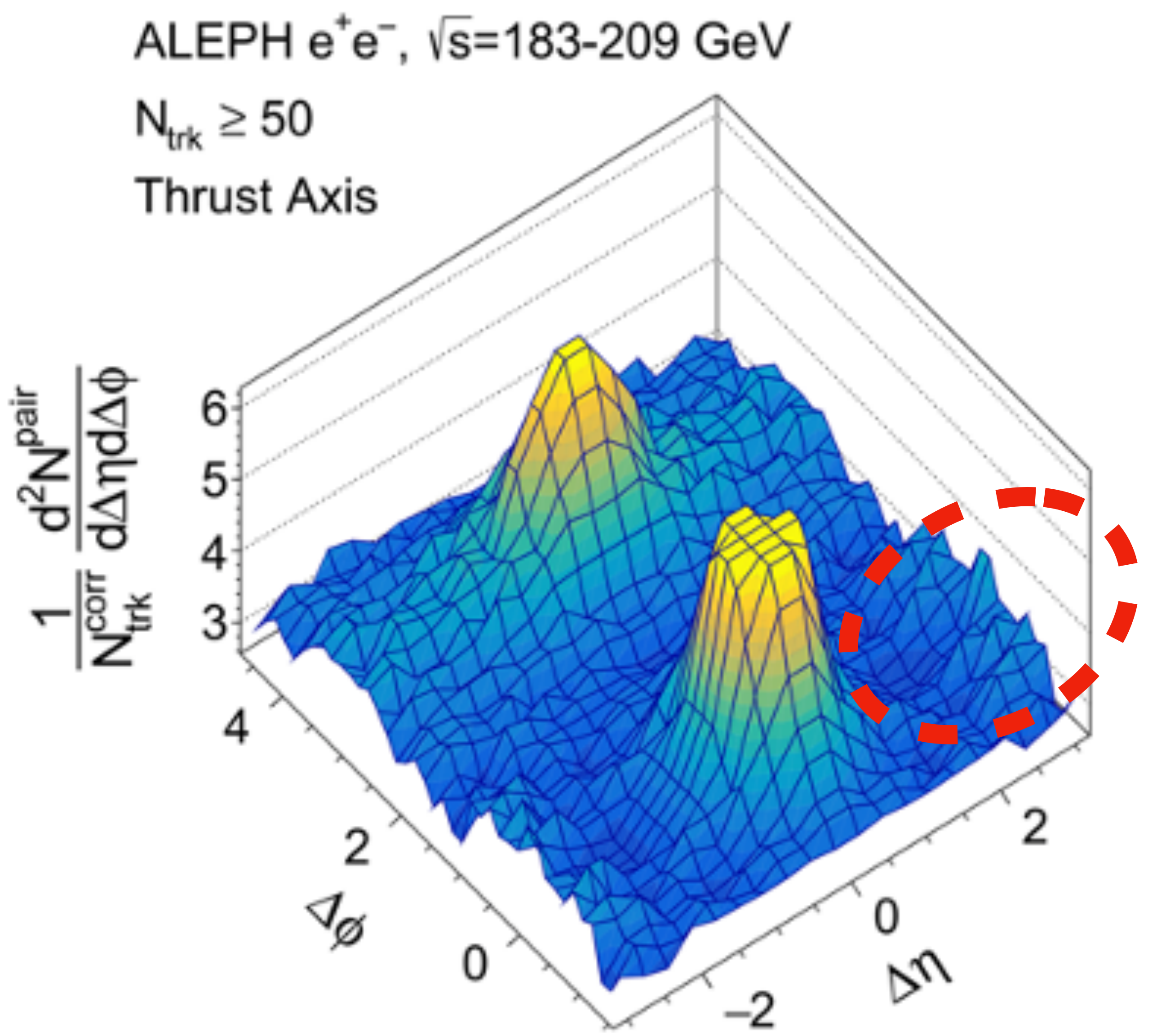


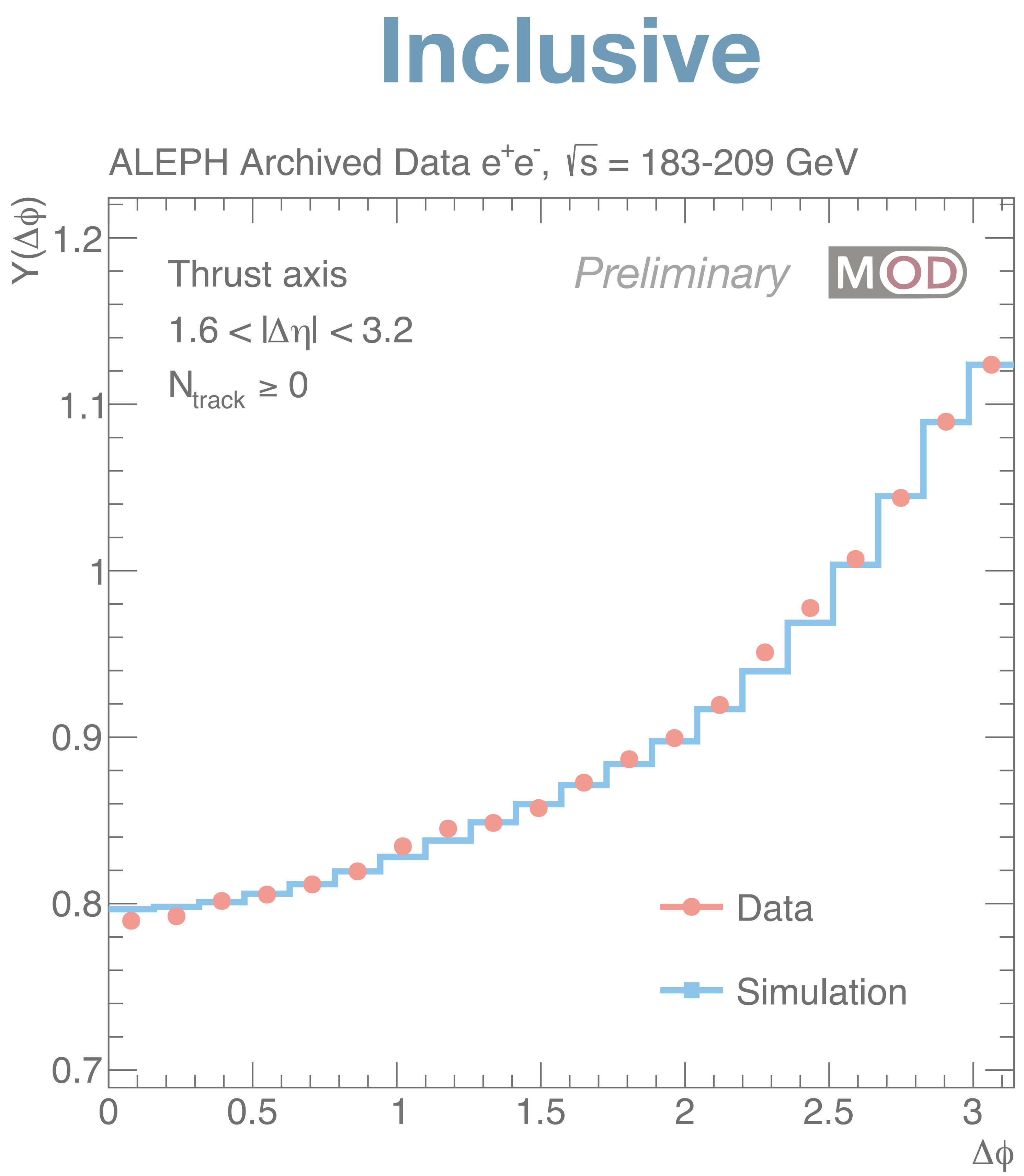
Fair data/MC agreement

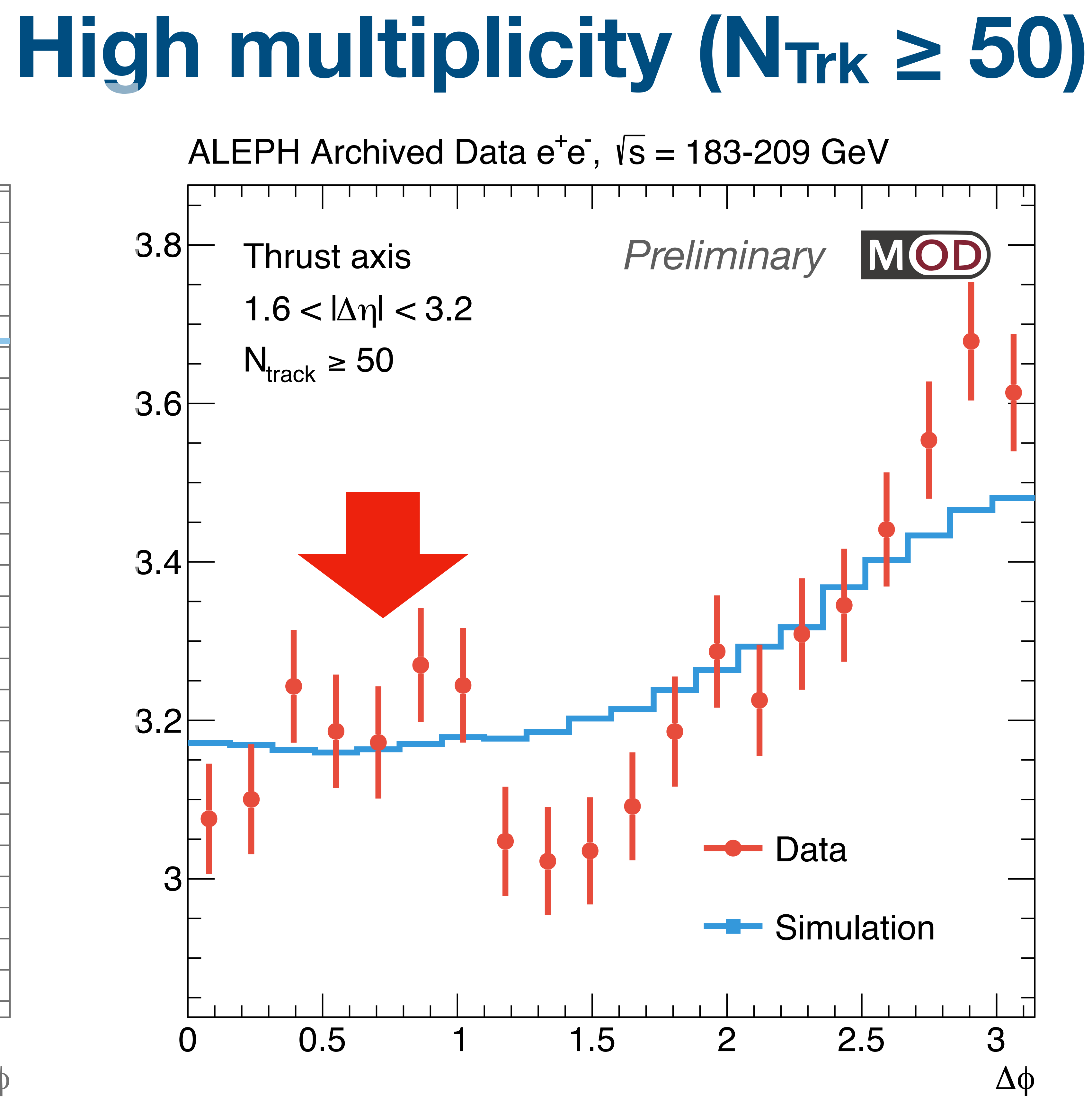
Preliminary!

LEP2 High collision energy & high multiplicity









Interesting structures in high-multiplicity events

Preliminary!

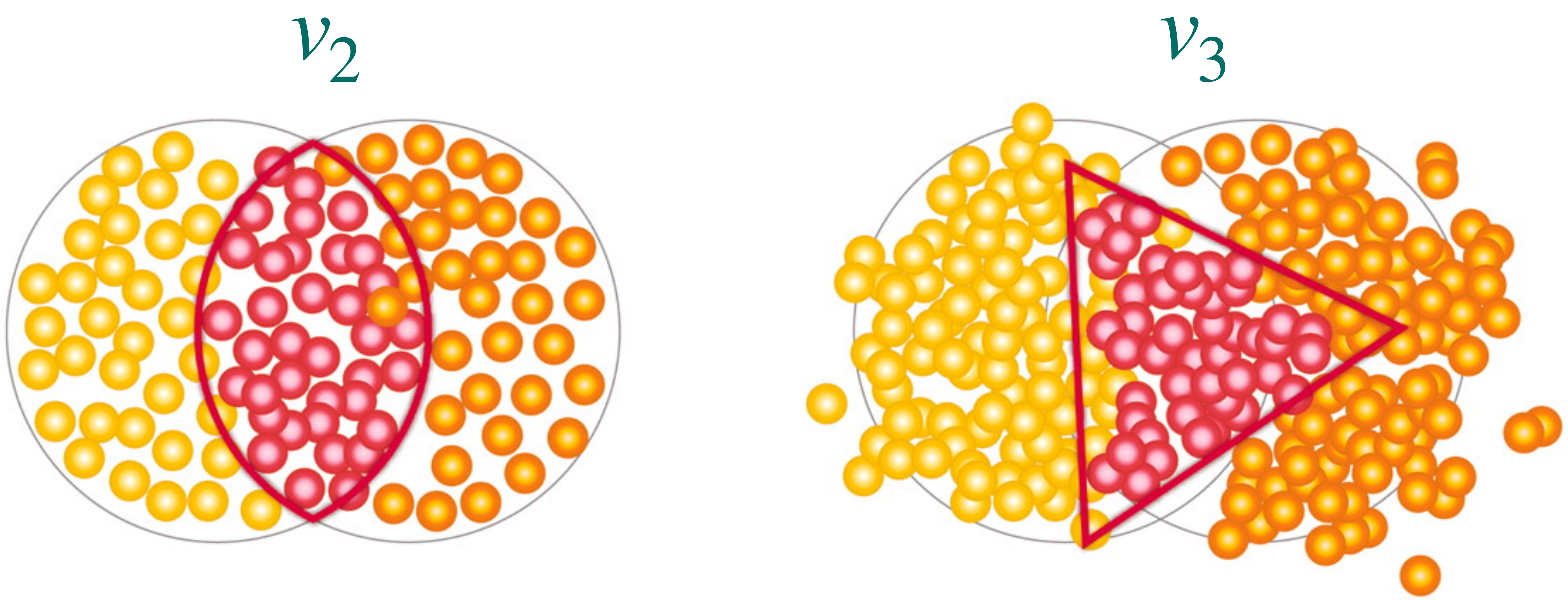
Flow coefficients — quantification of anisotropy

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

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

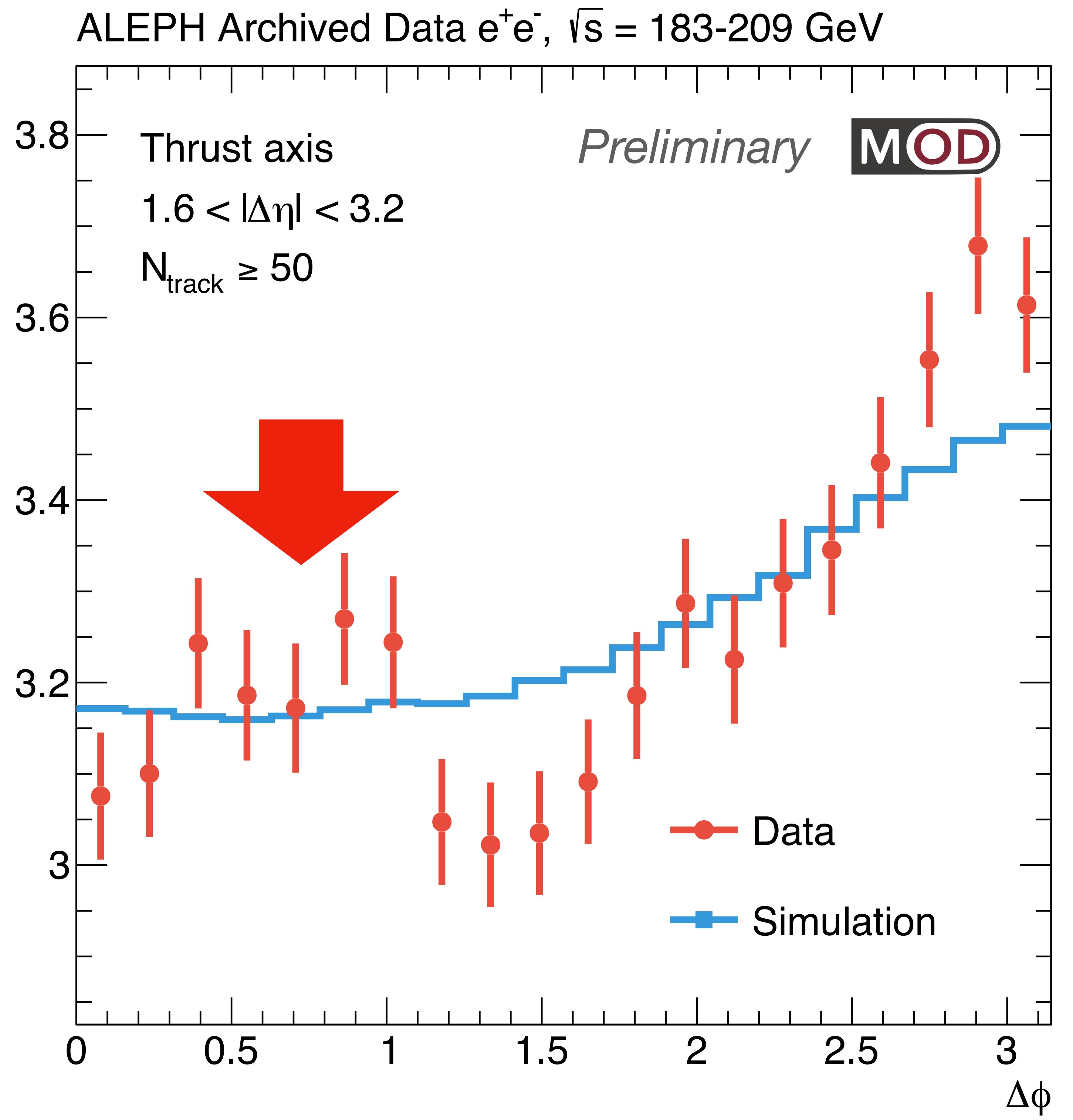
- The **flow coefficients** v_n correspond to different mode expansions:

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

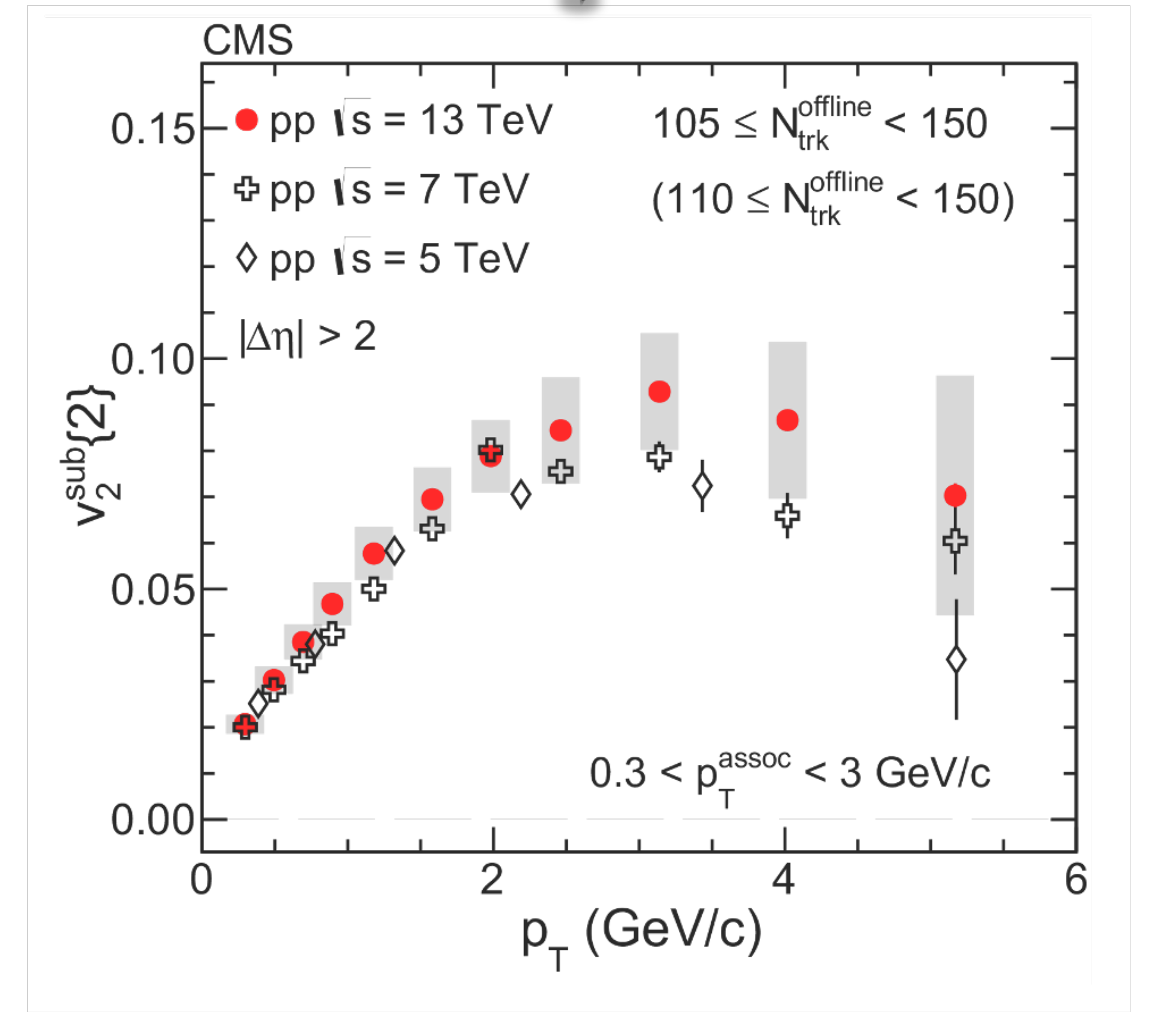


Elliptic flow

Triangular flow

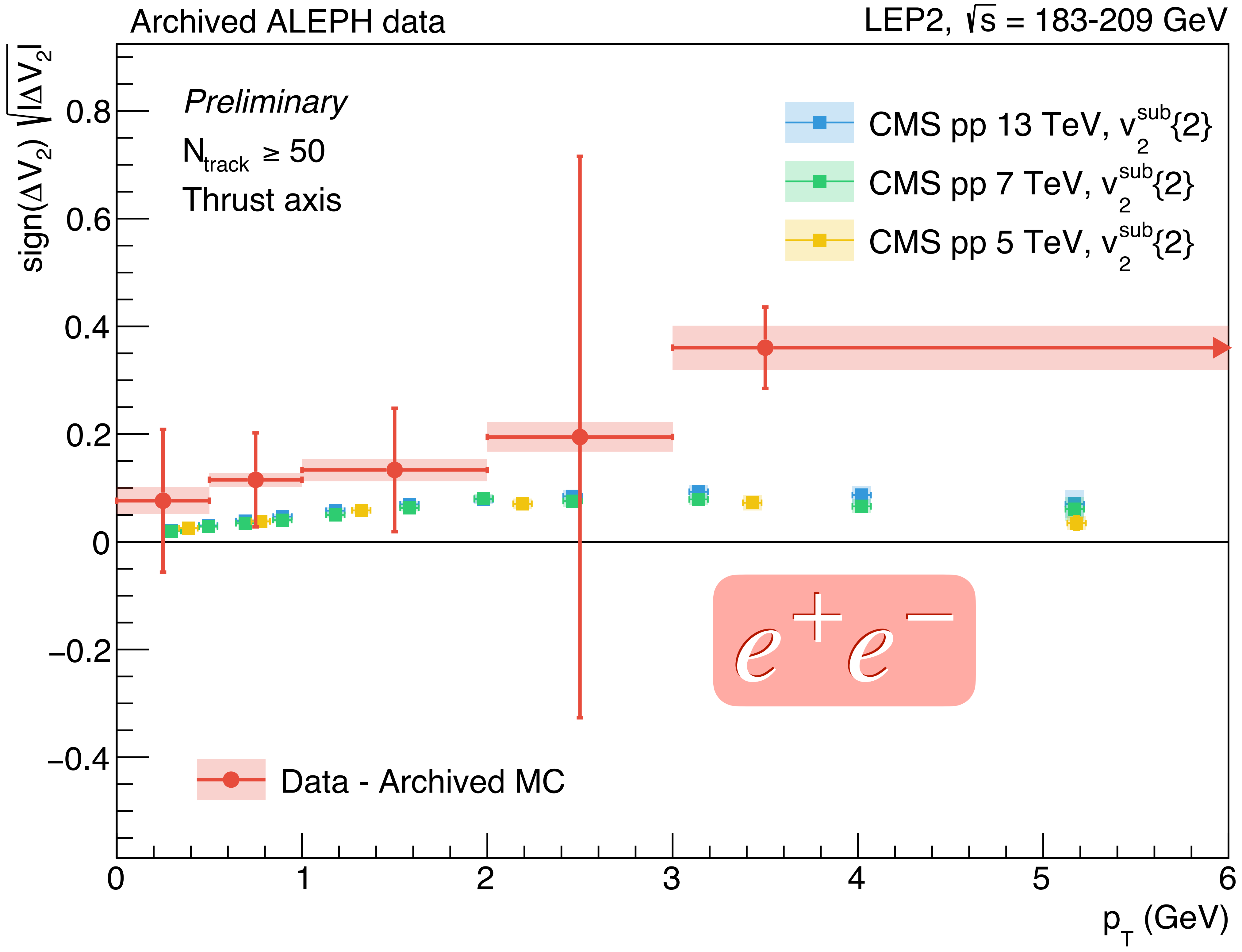


LEP2 Flow coefficients (v_2)



CMS pp [PLB 765 (2017) 193]

(overlap the data points taken from the CMS paper (left))



Excess of flow coefficient $\text{sign}(\Delta V_2)\sqrt{\Delta V_2}$,

where $\Delta V_2 = V_{2,\text{data}} - V_{2,\text{MC}}$

Intriguing similarity btw e^+e^- and pp data

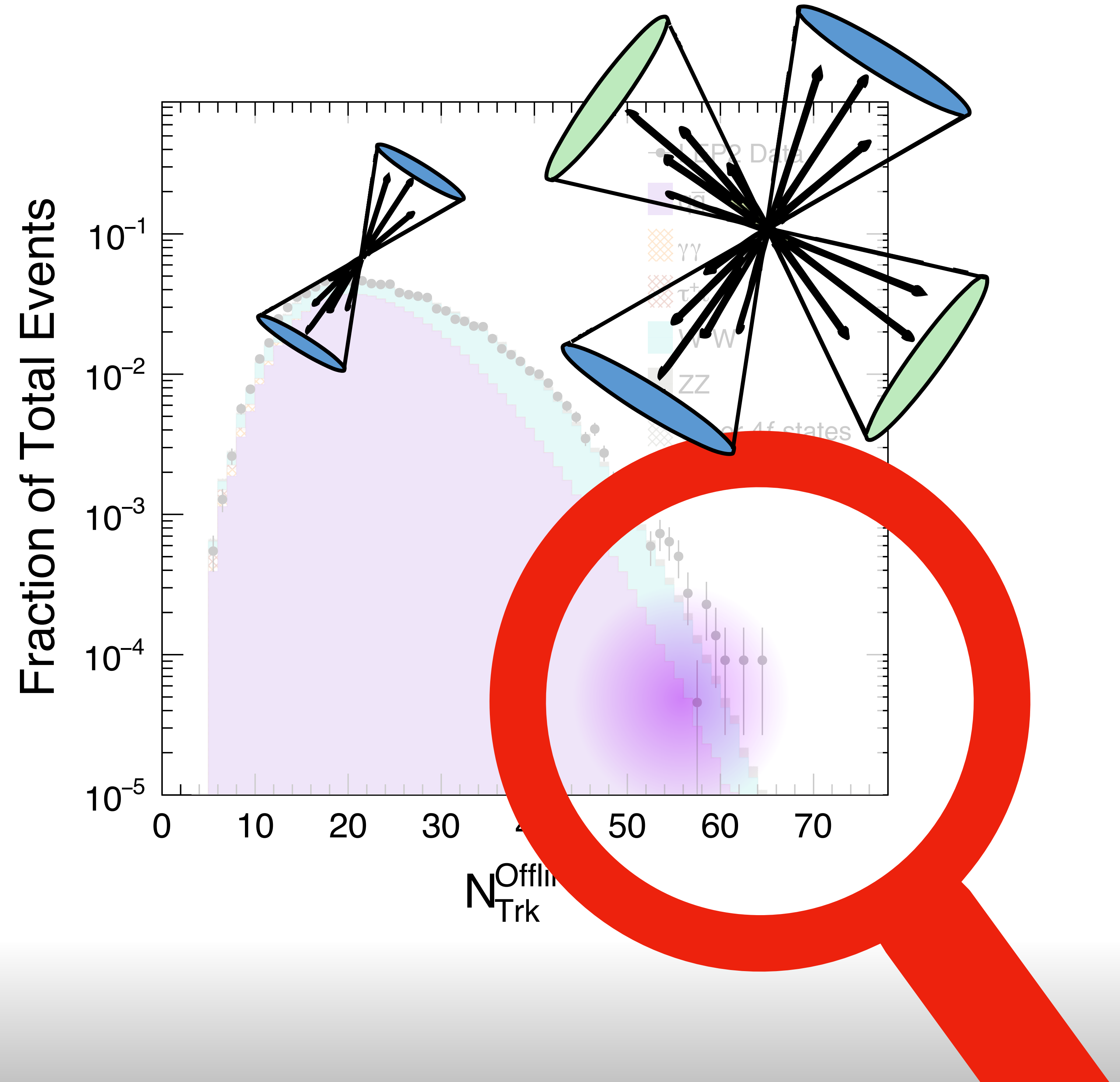
Long-range near-side excess & next steps

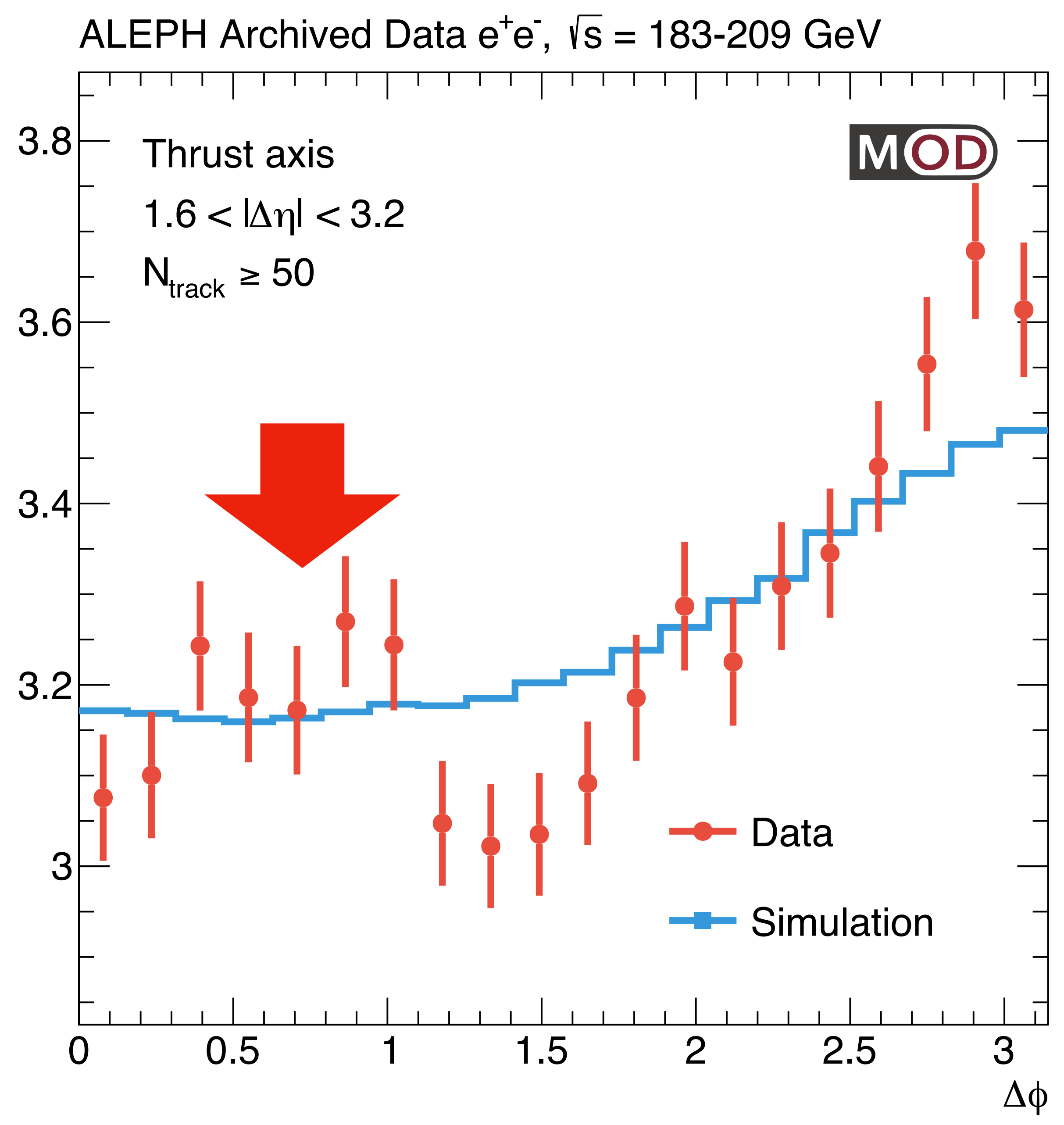
Now

High-multiplicity events in e^+e^- data show long-range near-side enhancement over MC

Next?

In e^+e^- configuration, it is possible to study more sophisticatedly with specialized selections and gain more understandings on W^+W^- in high-multiplicity events

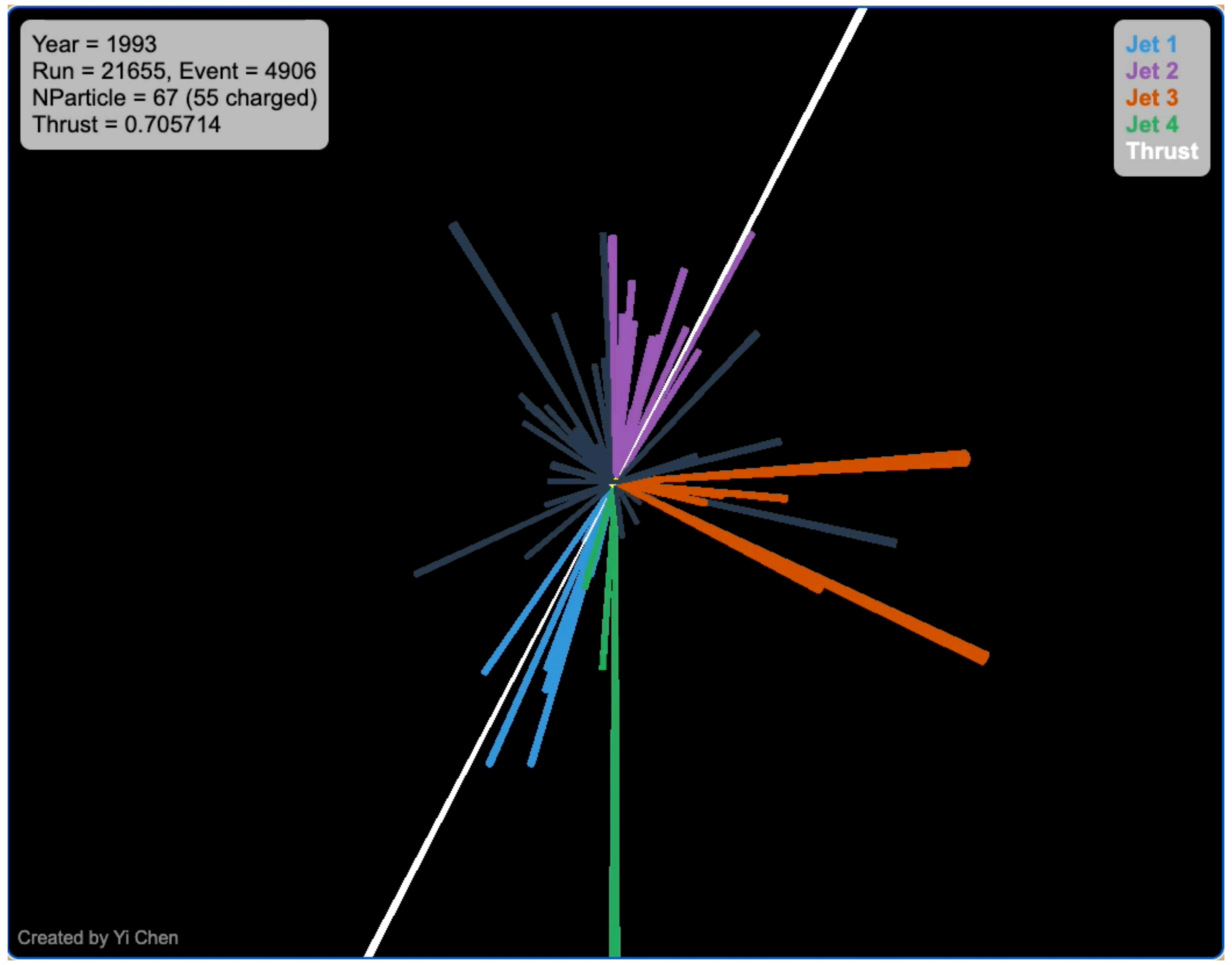




backup

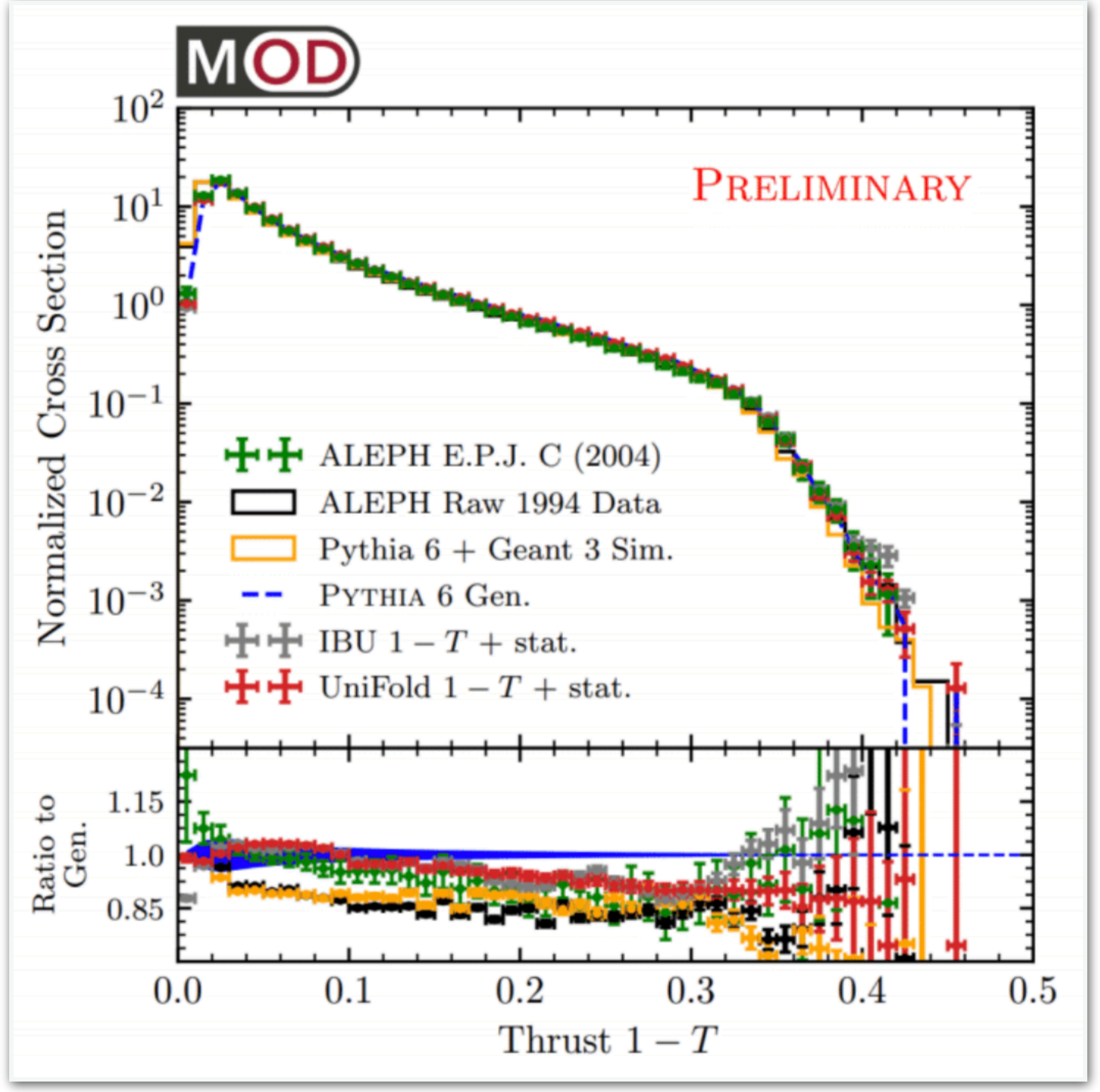
High quality archived data

(slides from BOOST 2022 by Yi Chen)



(to animation)

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



ALEPH: EPJC 35 (2004) 456

Published results can be reproduced

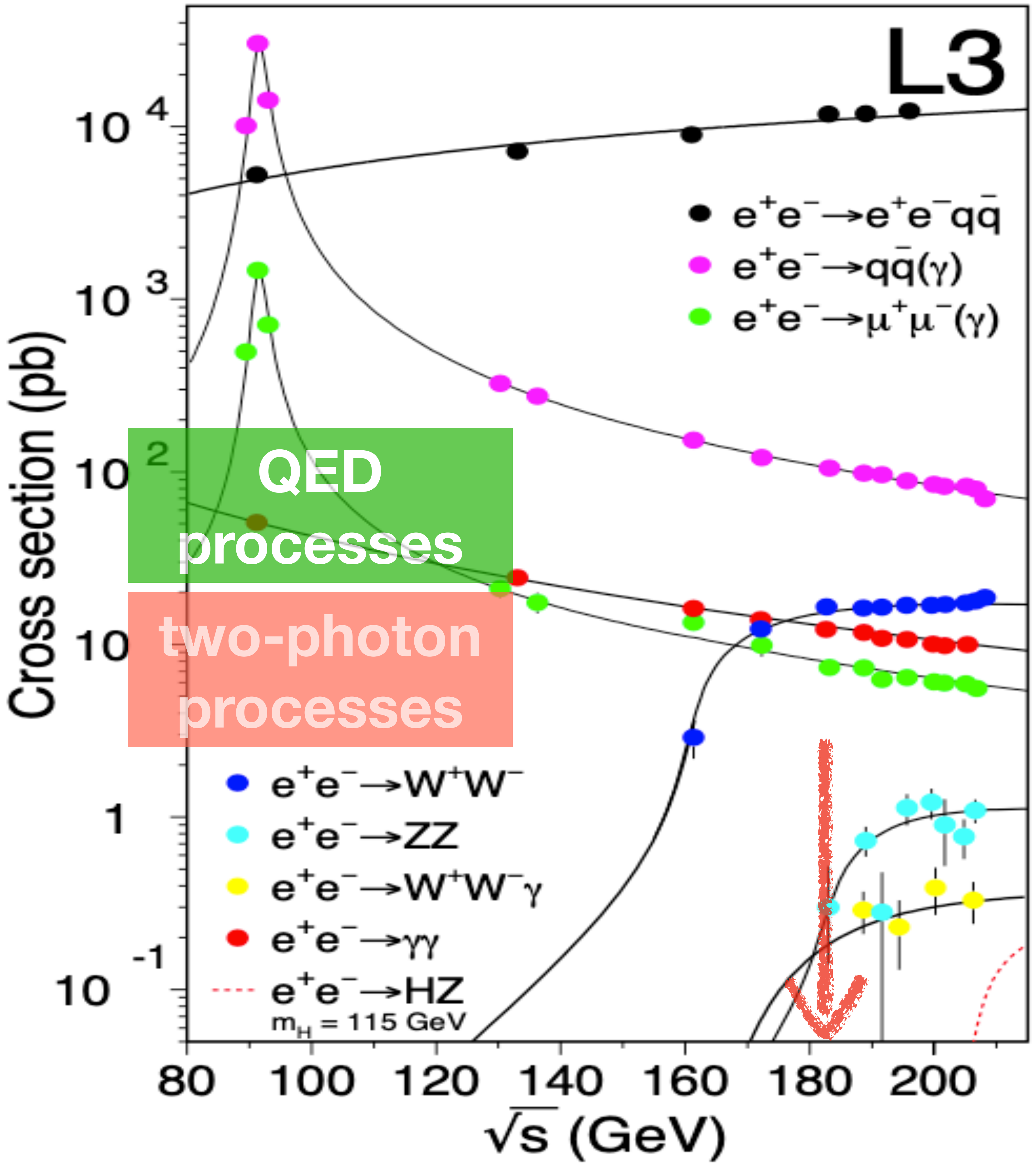
Big thanks to ALEPH collaboration and MIT open data

LEP 2 data & MC processes

Year *v.s.* $\sqrt{s}$ *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

$\sqrt{s}$ *v.s.* X-section

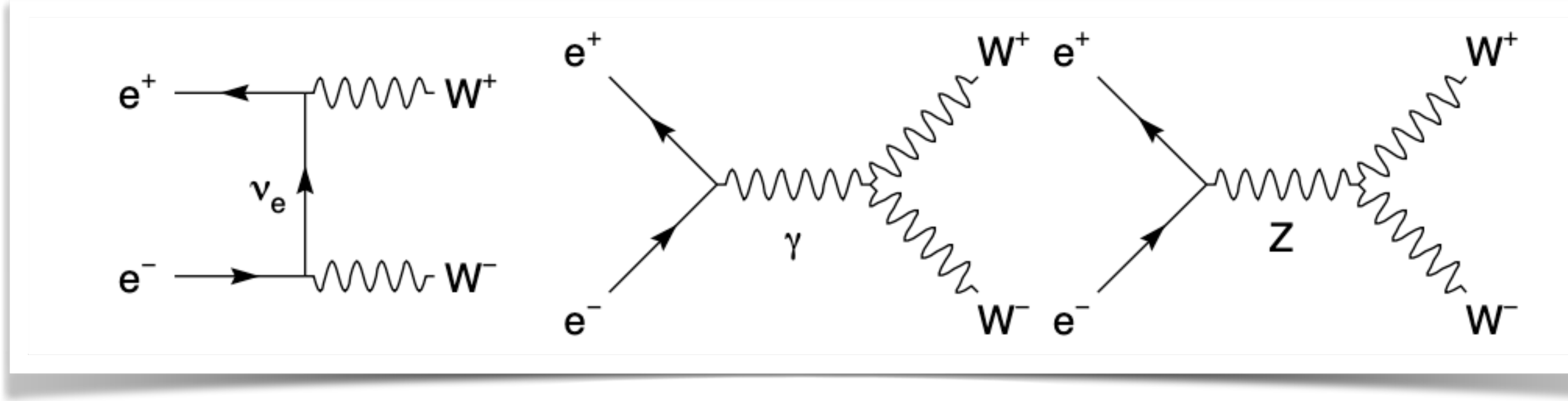


QED processes

two-photon processes

Hadronic $q\bar{q}$ production

Four fermion processes



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

LEP 2 event selections

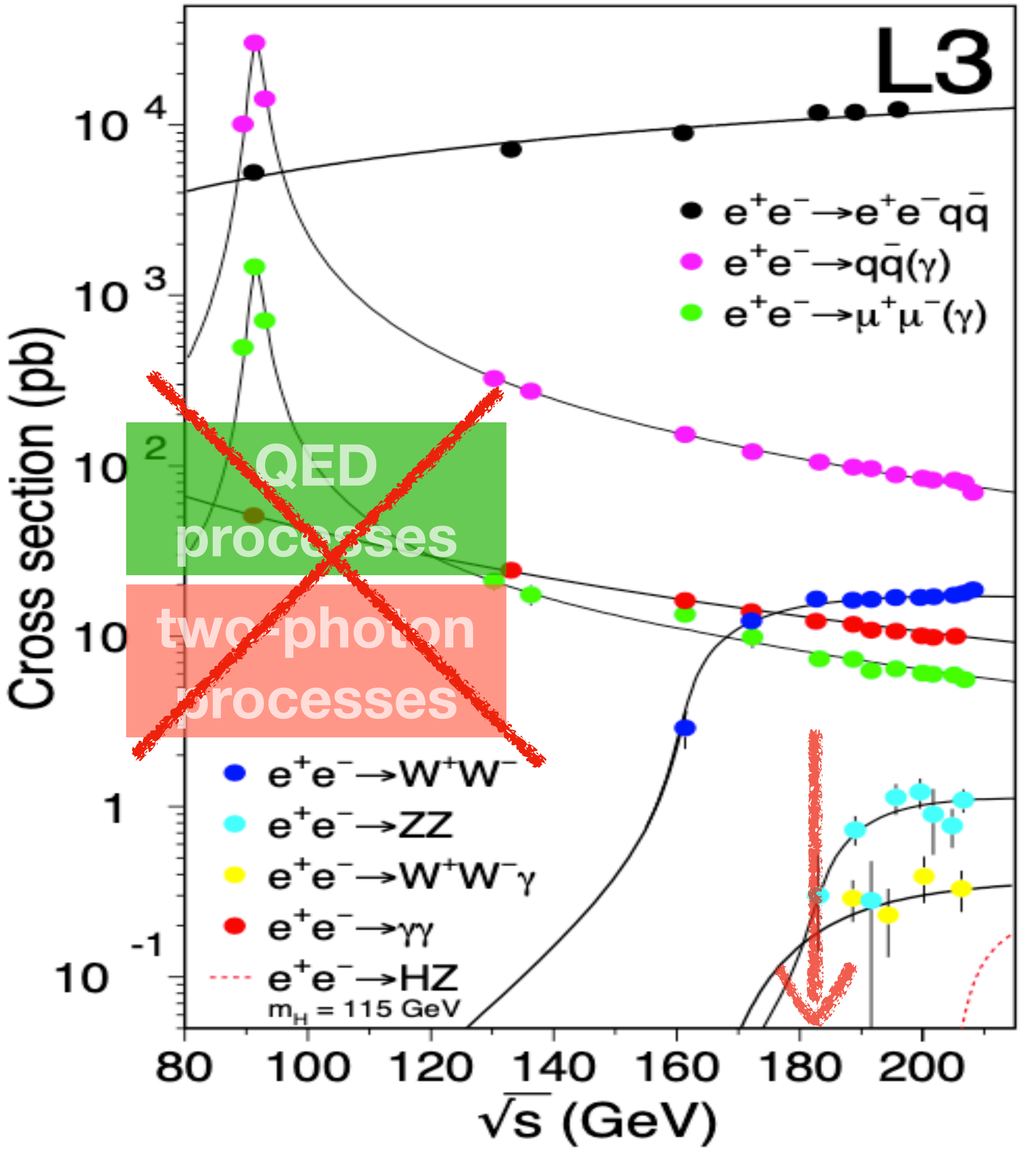
Acceptance

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

Hadronic event selection

$\geq$ 5 tracks

$E_{\text{chgd.}} \geq 15$ GeV



Hadronic $q\bar{q}$ production

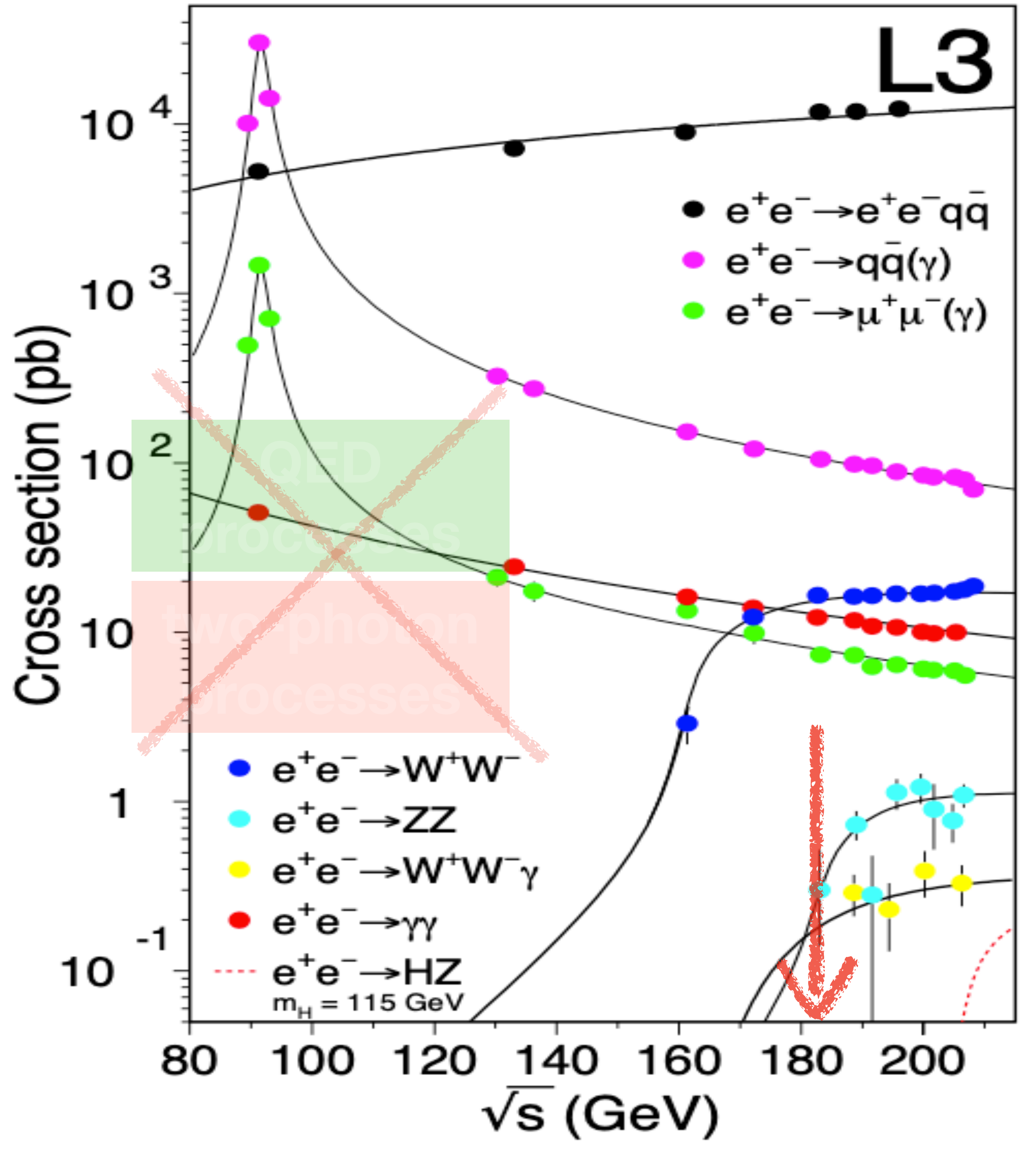
Four fermion processes

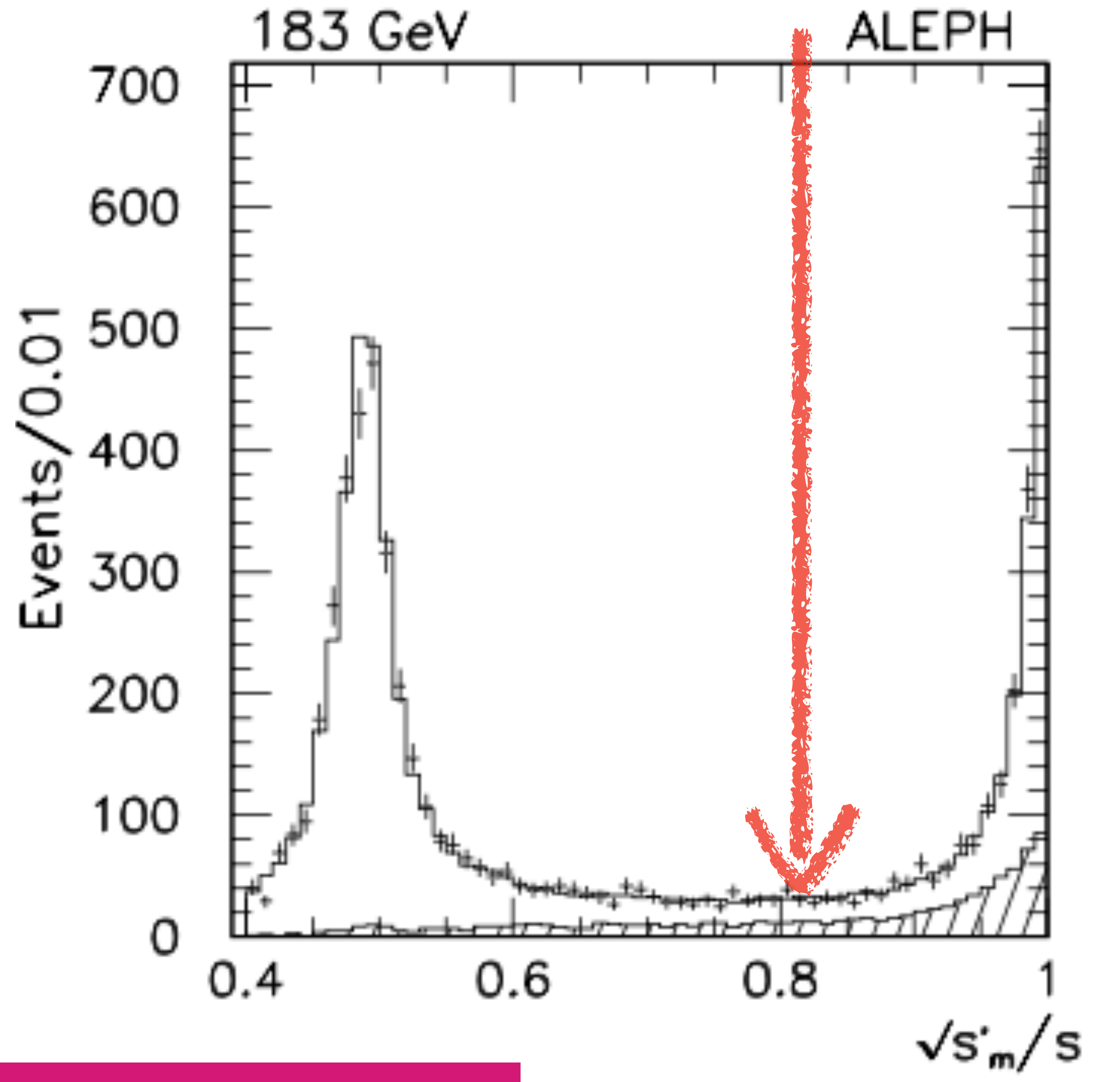
LEP 2 event selections

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

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

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





Ref: hep-ex/9904011

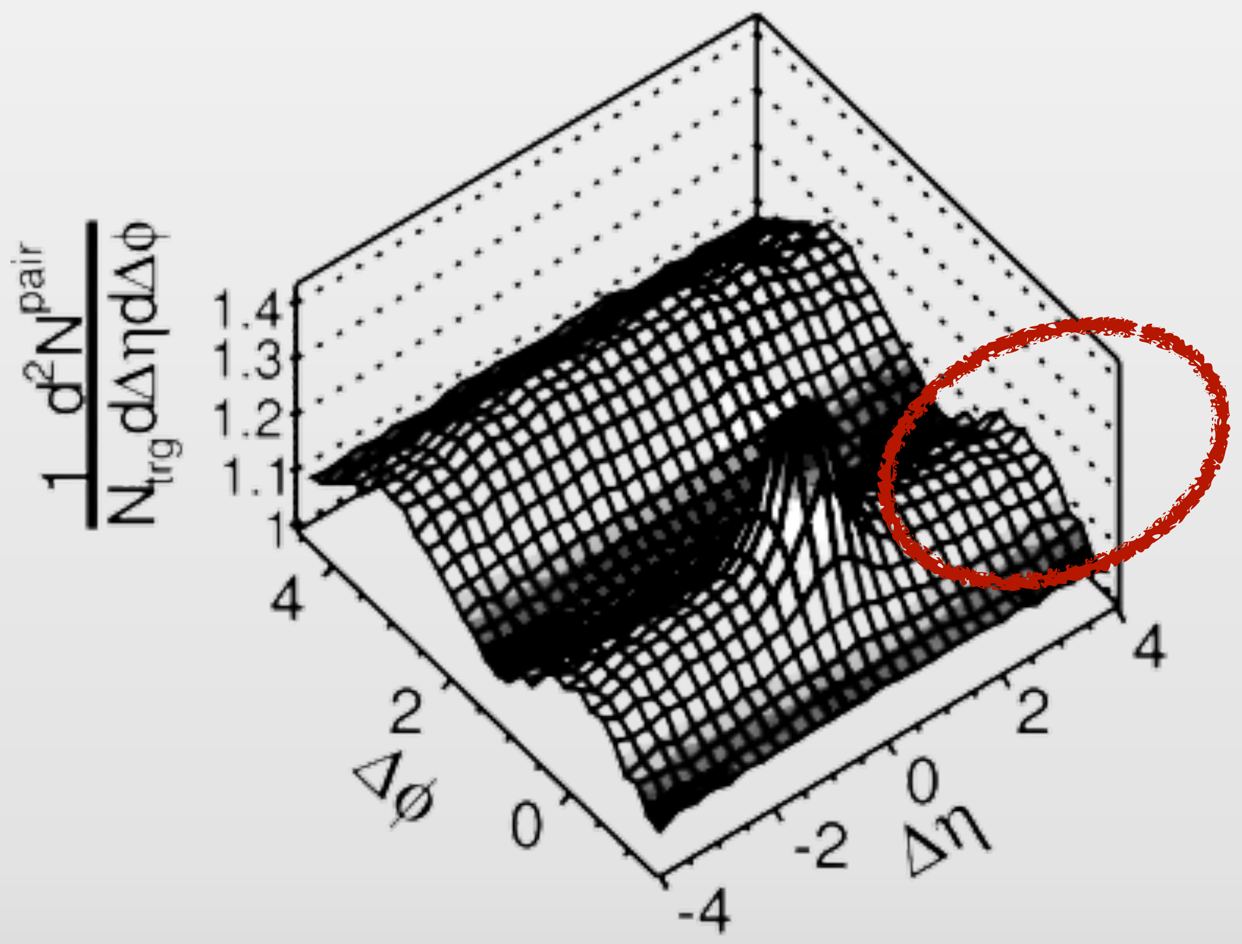
Hadronic $q\bar{q}$ production

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

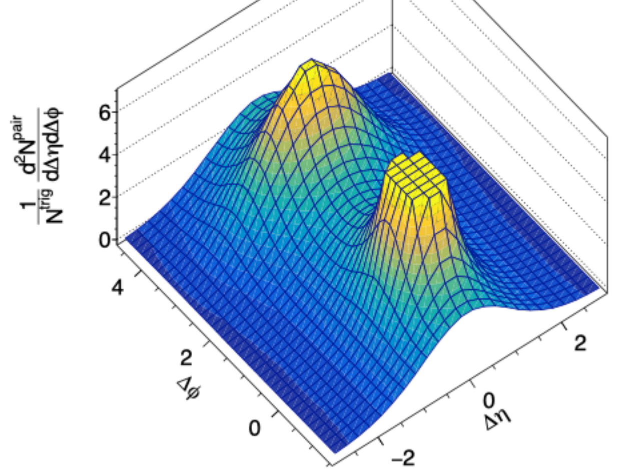
Selection

Two-particle correlations

Residual MC correction

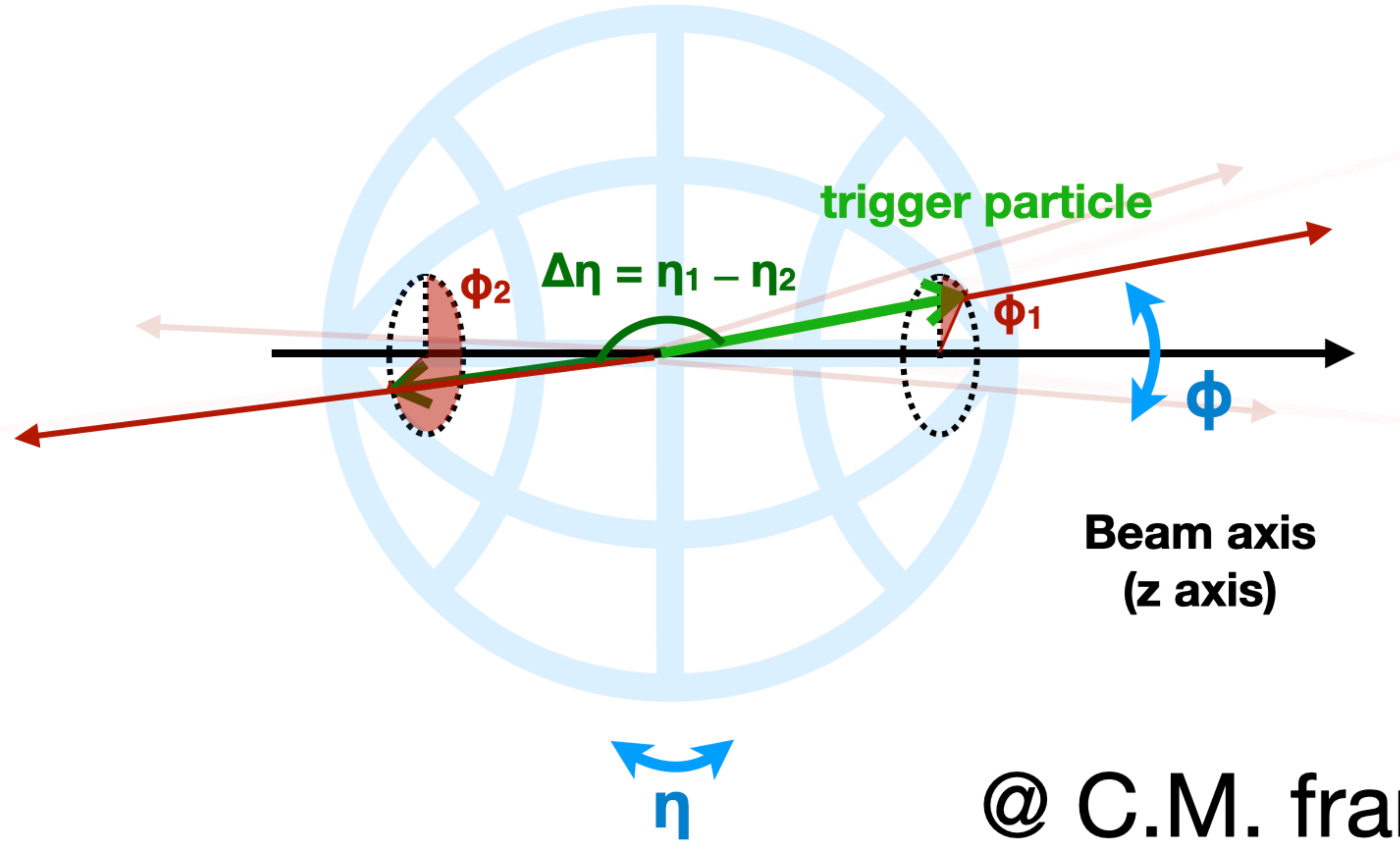
Signal

(raw correlation function)



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

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



@ C.M. frame

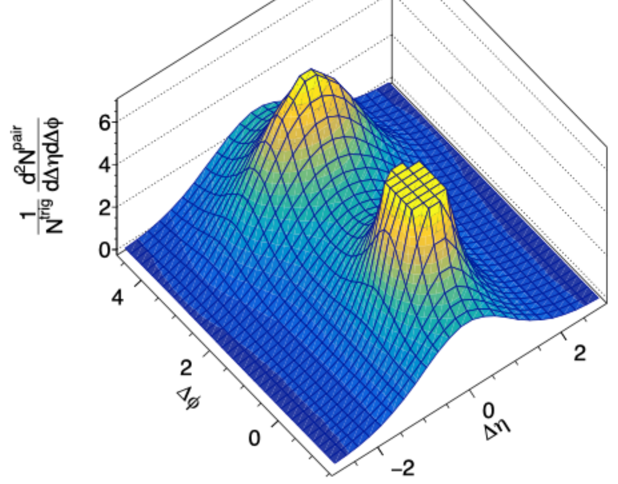
Analysis methods

Selection

Two-particle correlations

Residual MC correction

Signal
(raw correlation function)



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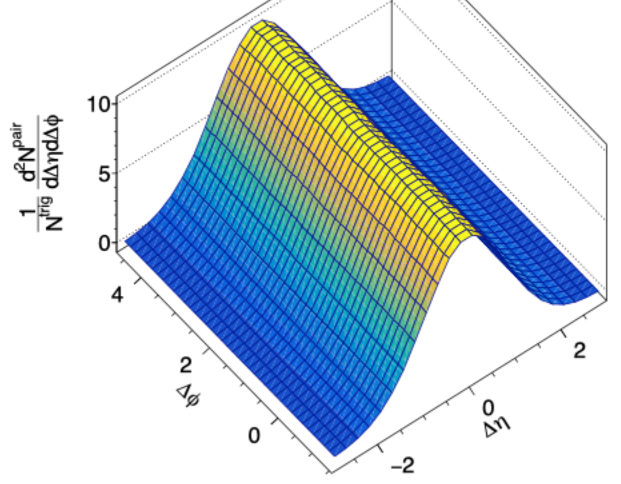
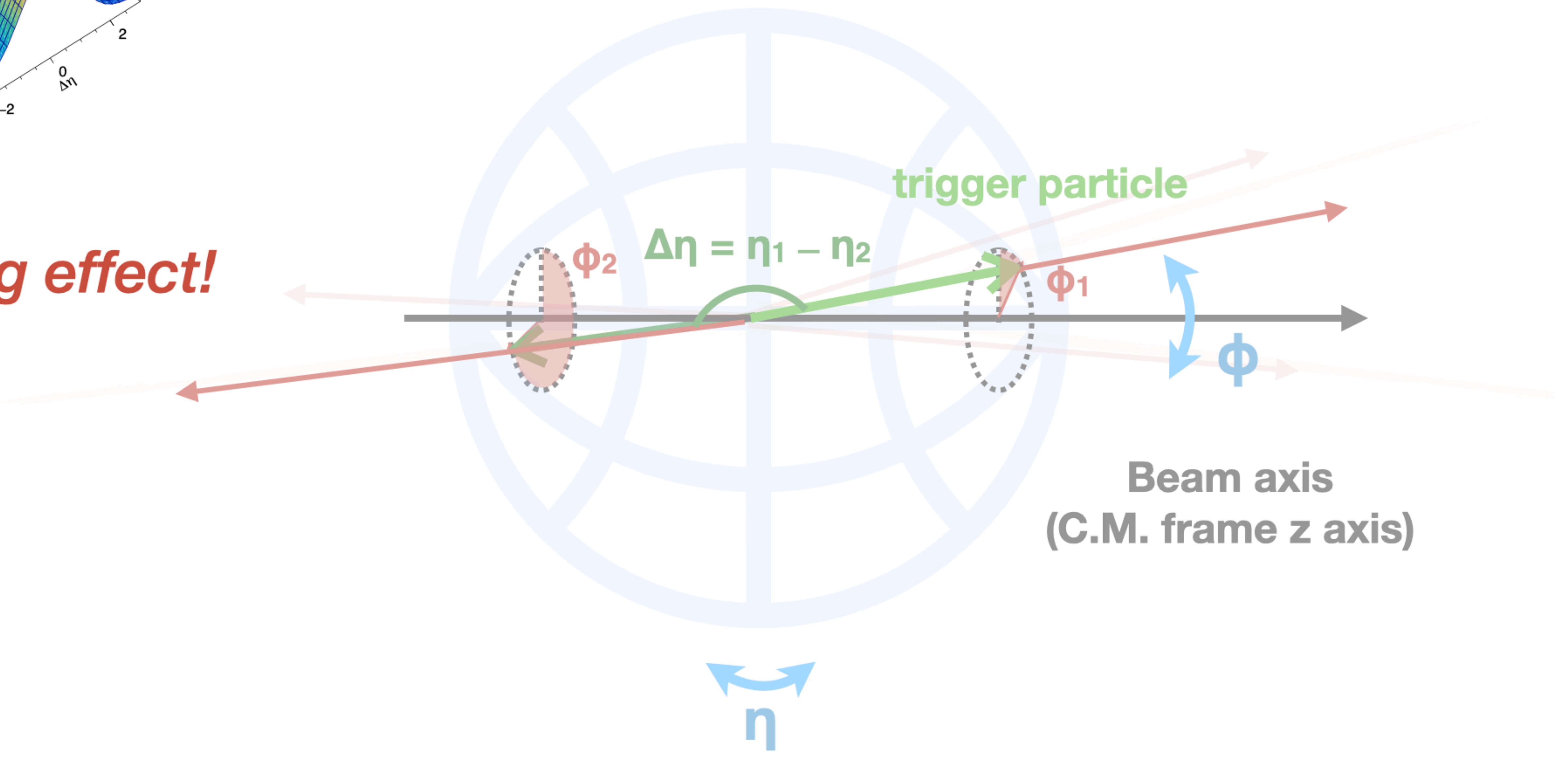
Background
(accounting for baseline of random pairing)



Factoring out the random pairing effect!

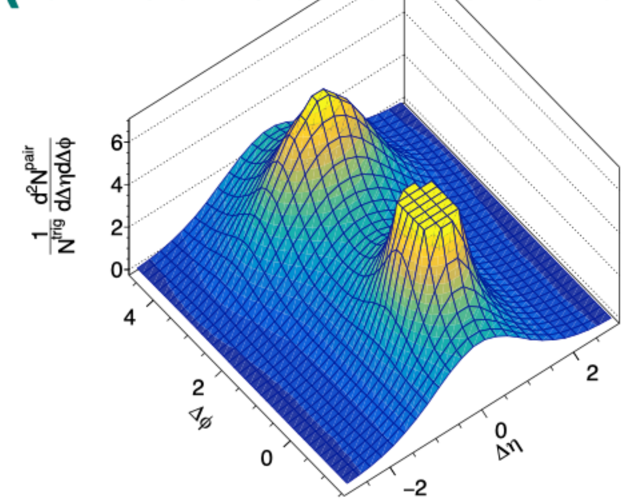
Track pairs' angular difference in
η (pseudorapidity), ϕ (azimuthal angle)



Analysis methods

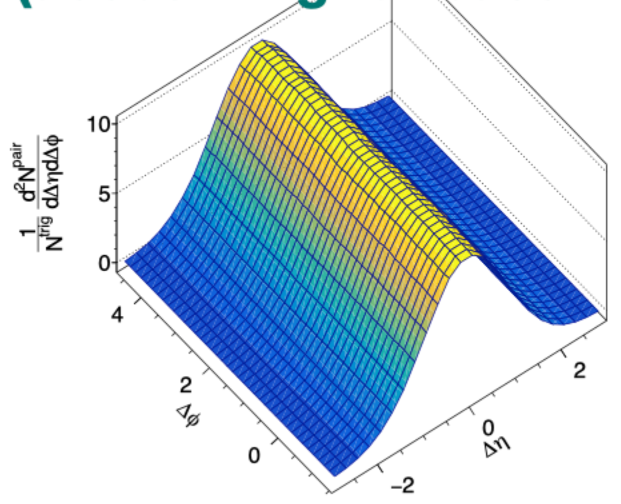
- Selection
- **Two-particle correlations**
- Residual MC correction

Signal
(raw correlation function)



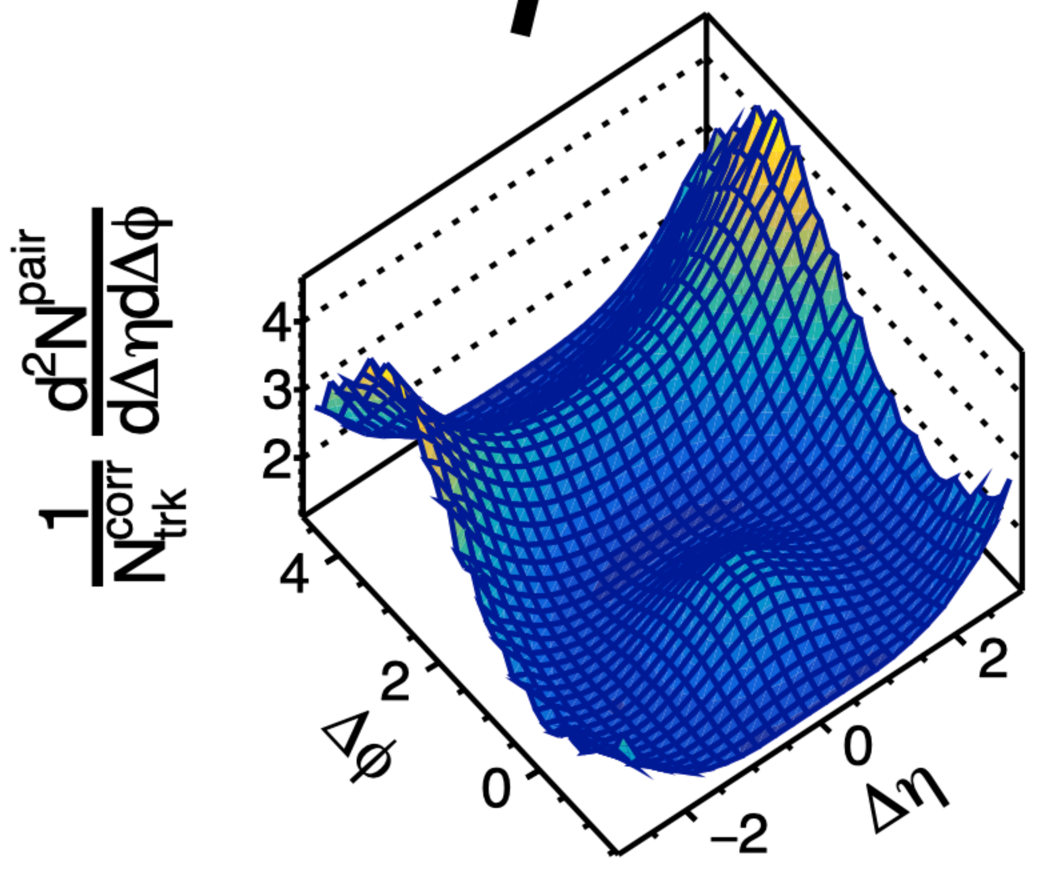
/

Background
(accounting for baseline of random pairing)

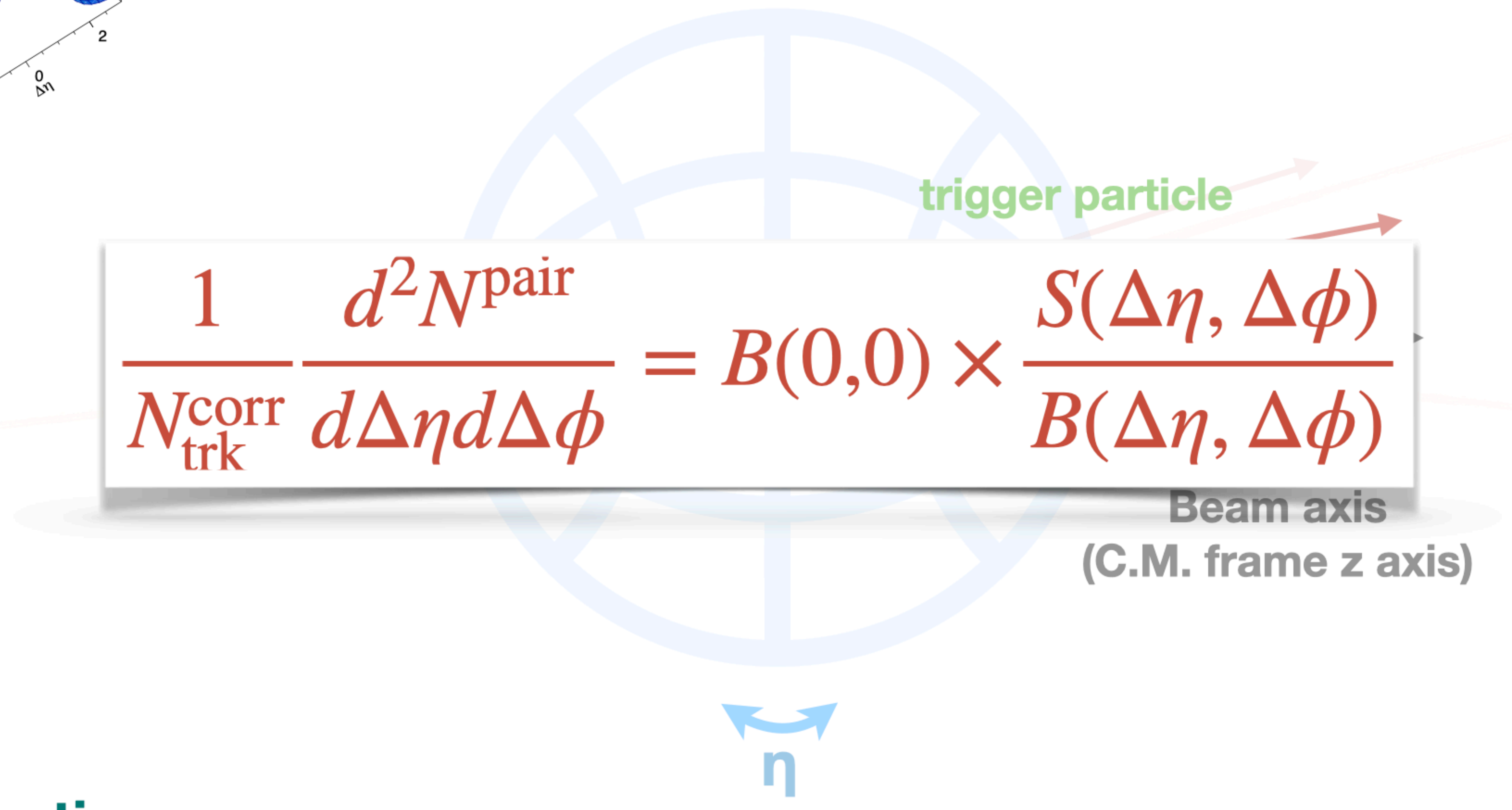


Track pairs' angular difference in η (pseudorapidity), ϕ (azimuthal angle)

⇒



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



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

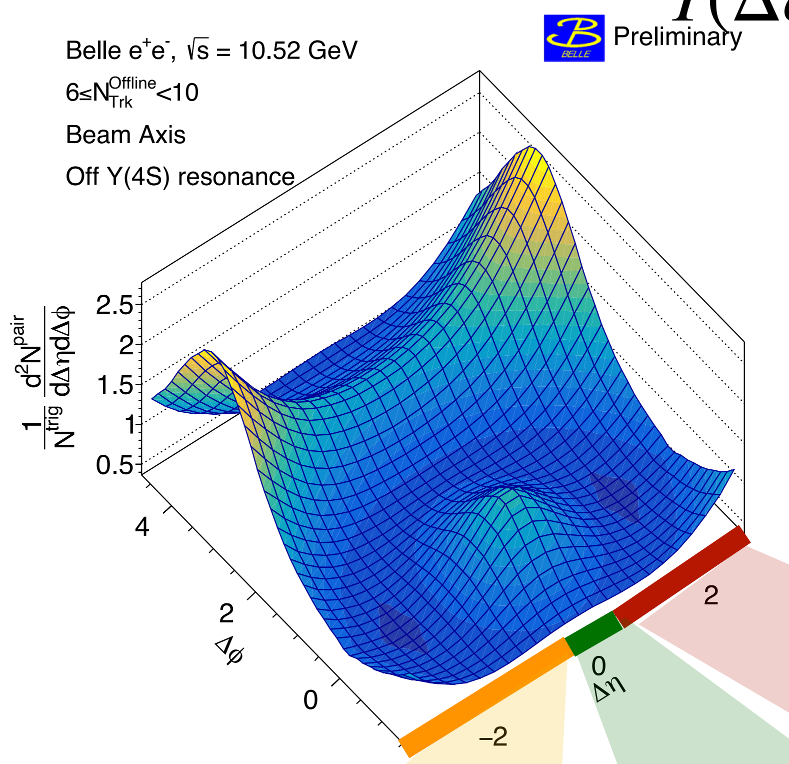
Azimuthal differential associated yield $Y(\Delta\phi)$

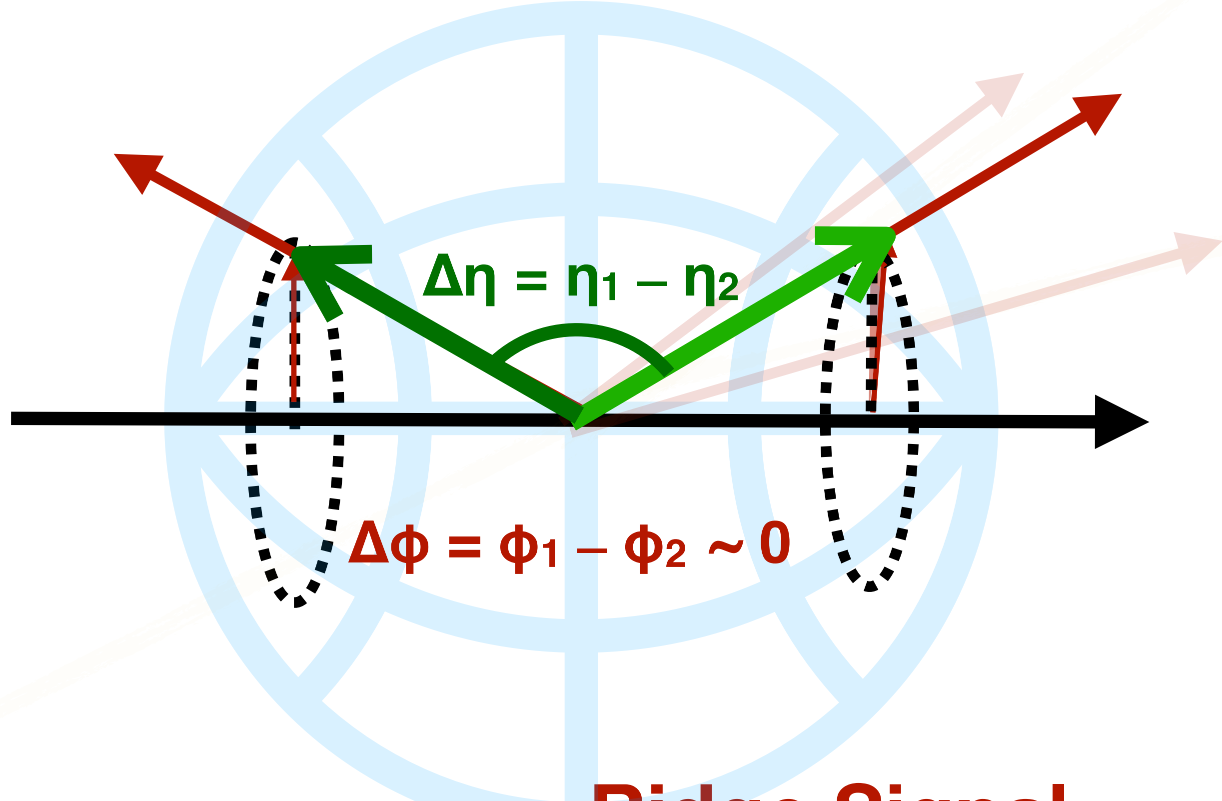
Two-particle correlation function (per-trigger-particle associated yield)

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

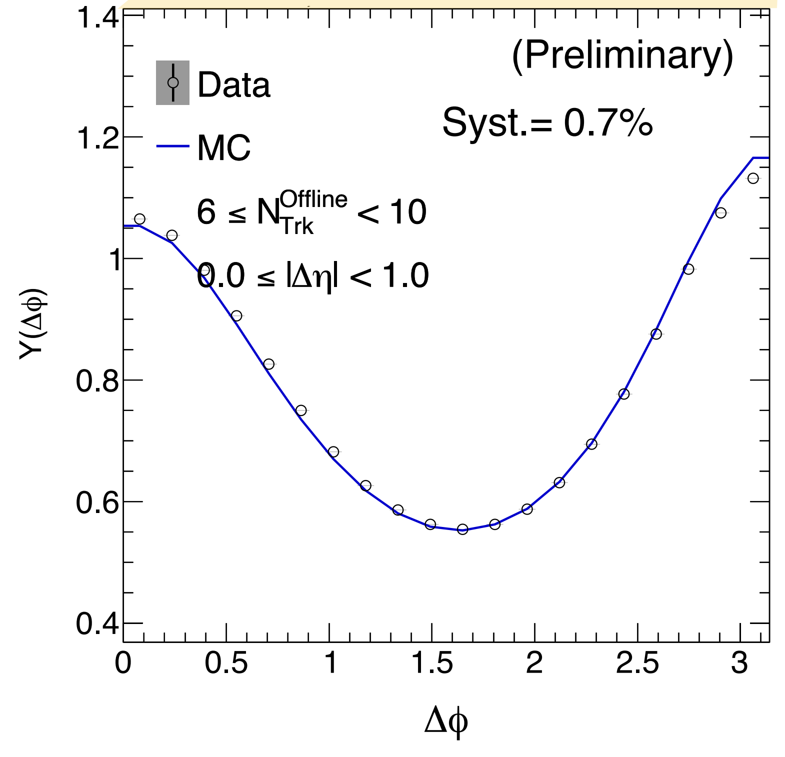
Associated yield vs. Δϕ

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

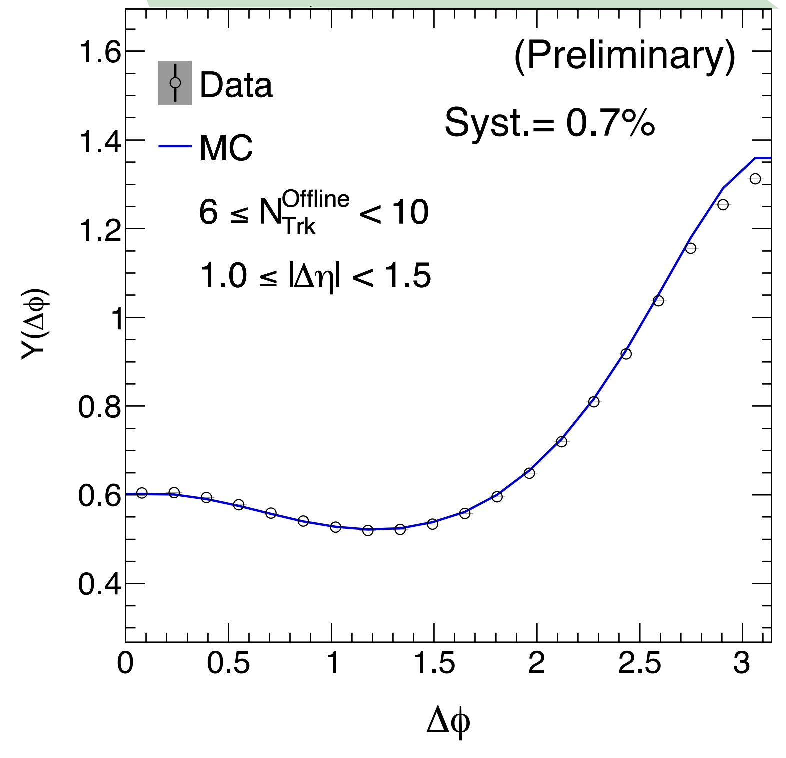




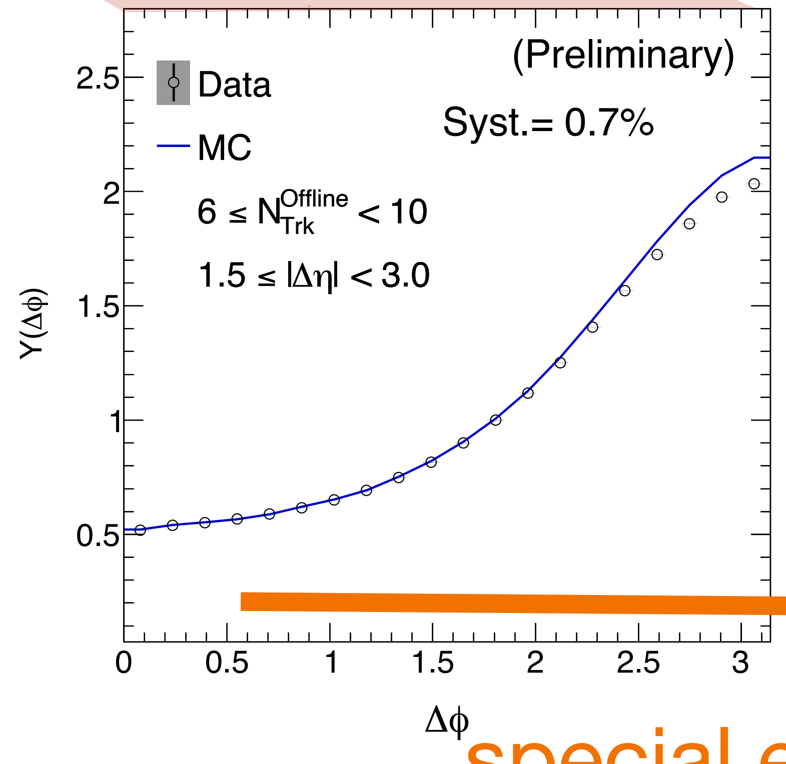
Short Range



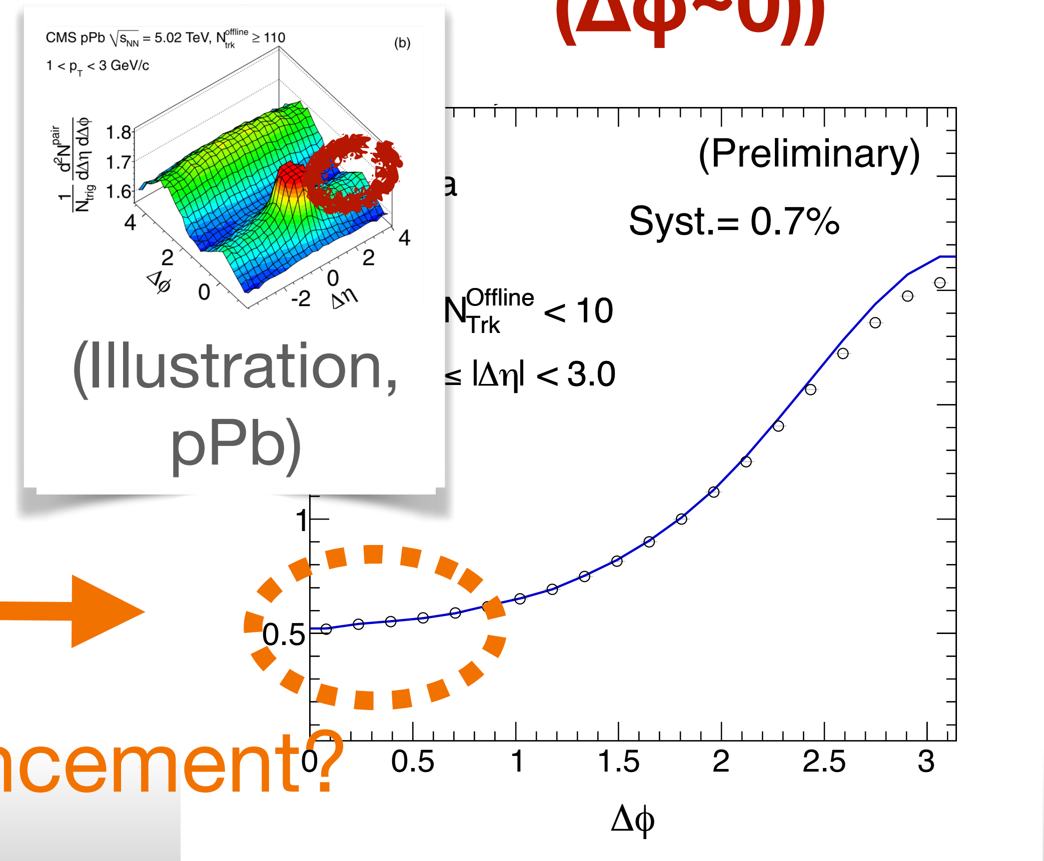
Middle Range



Long Range



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



special enhancement?

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:

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

- 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

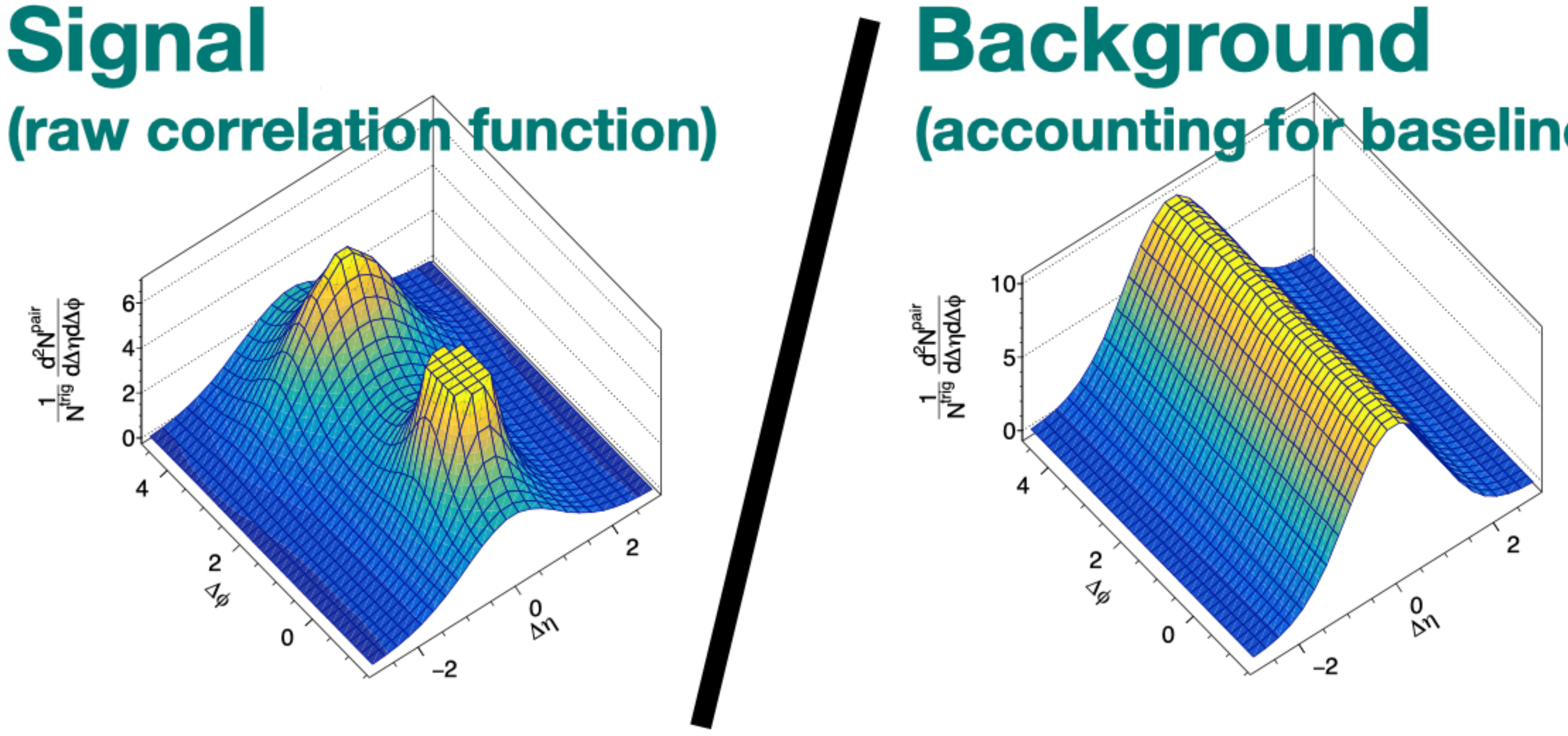
$$\mathrm{C}(\Delta\phi) = \frac{Y(\Delta\phi)_{\mathrm{gen},i_g}}{Y(\Delta\phi)_{\mathrm{reco},i_r}}$$

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

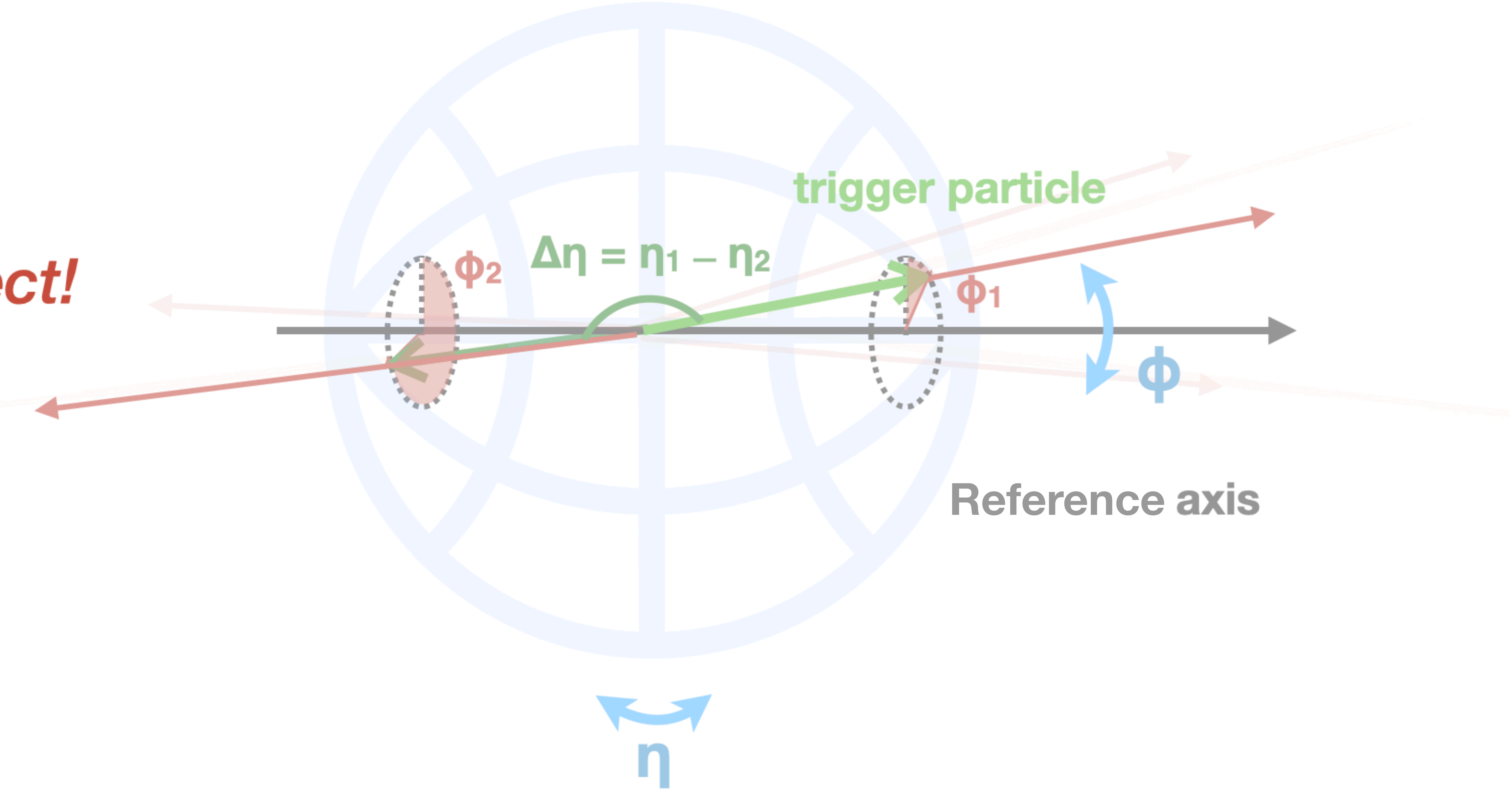
Analysis method: 2PC observable construction

Signal
(raw correlation function)

Background
(accounting for baseline of random pairing)

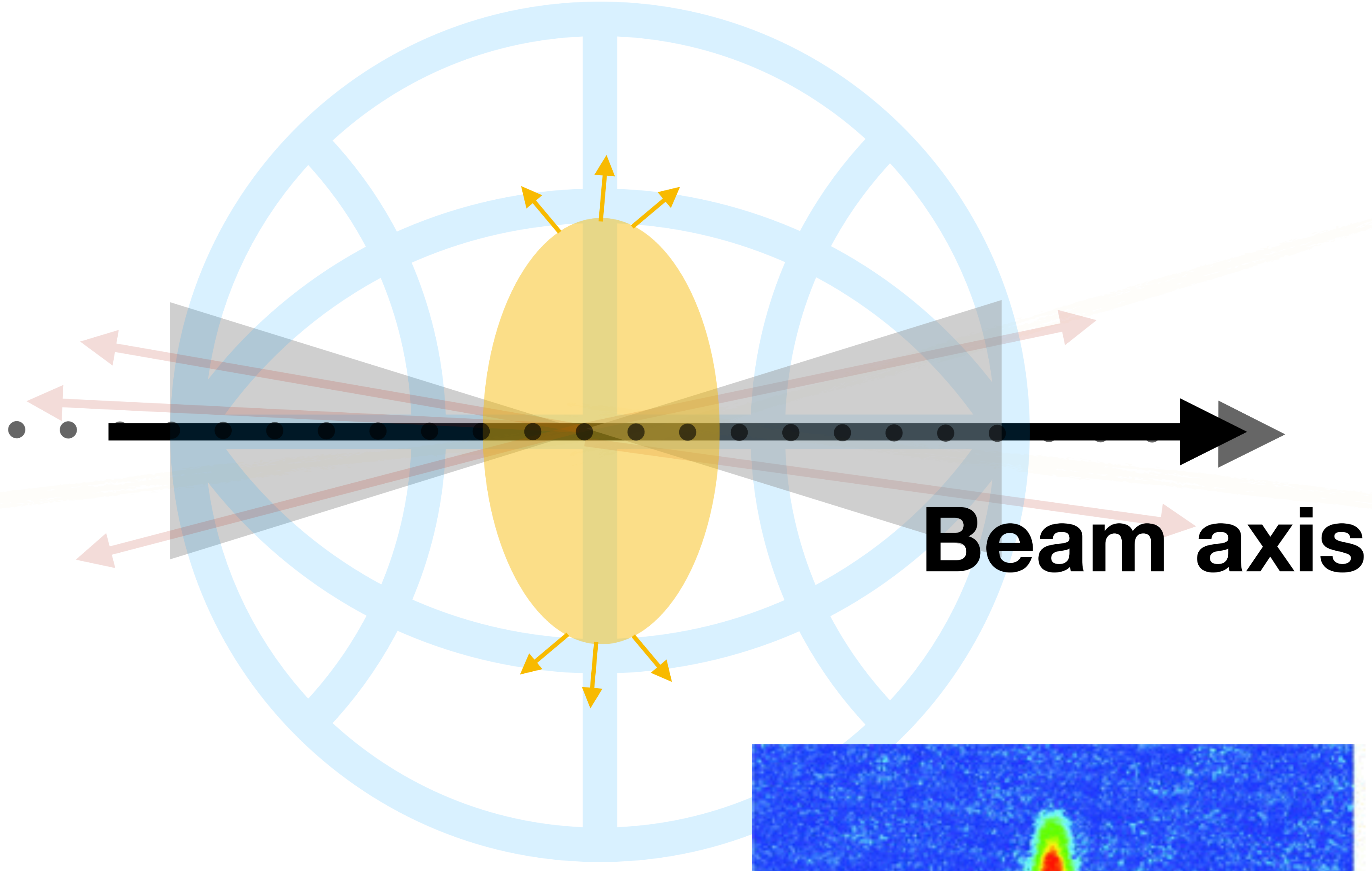


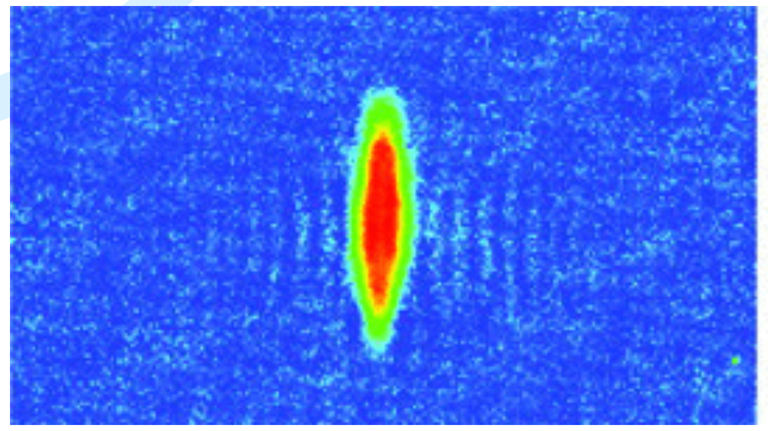
Track pairs' angular difference in
η (pseudorapidity), ϕ (azimuthal angle)



Factoring out the random pairing effect!

Perfect-fluid-like QGP expansion



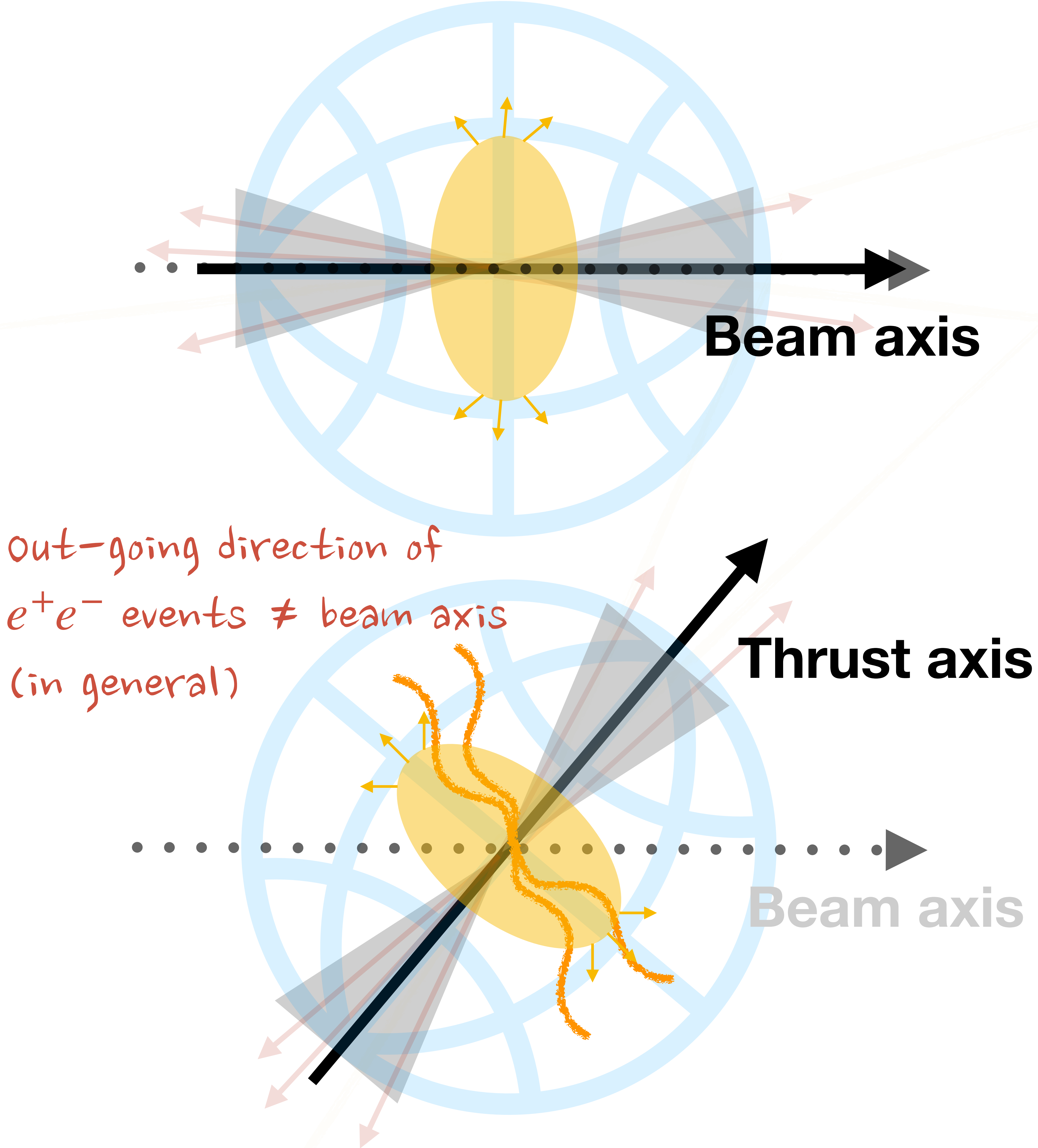


100 μs

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:

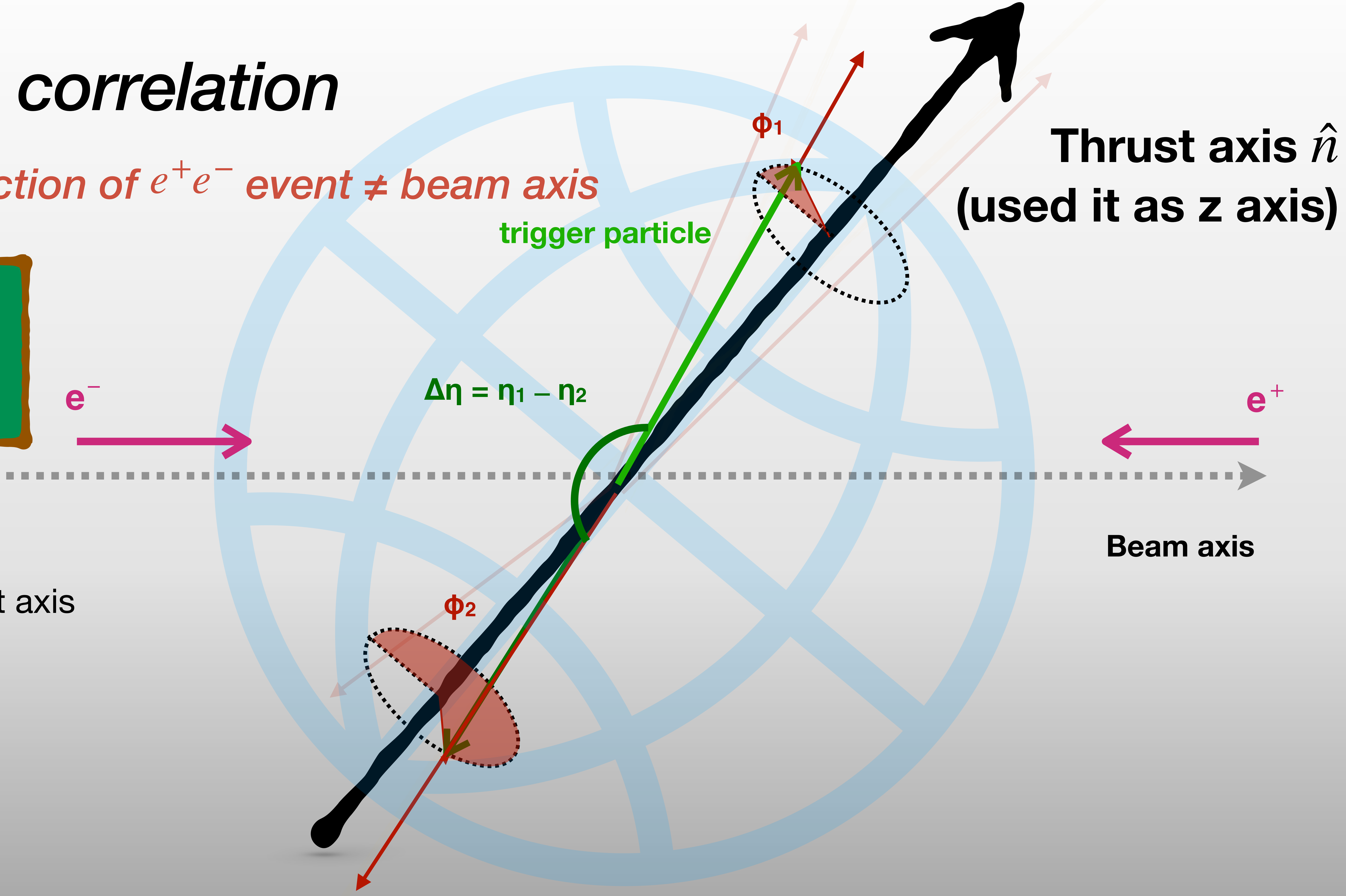
- Beam axis analysis:
  hydrodynamic expansion of possible QGP medium in HI collisions

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

Thrust-axis two-particle correlation

Out-going direction of e^+e^- event ≠ beam axis

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

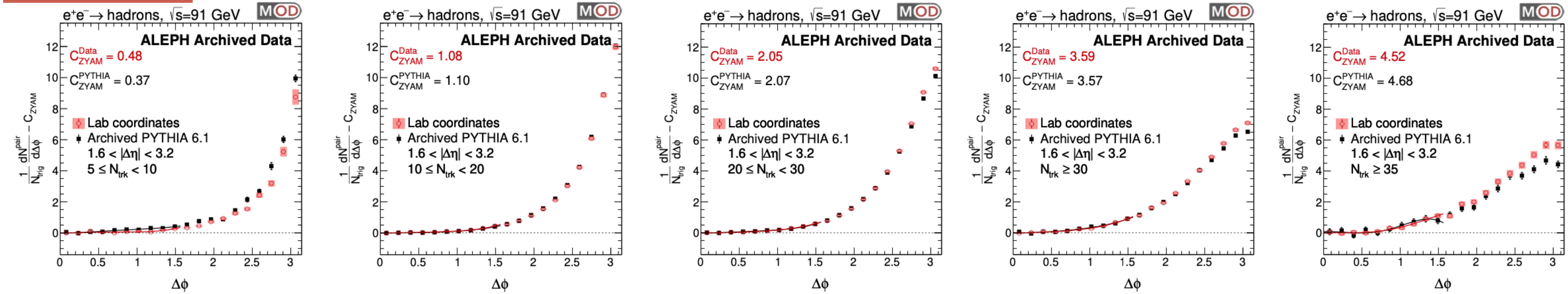


Particles (p_T,η,ϕ) are re-calculated w.r.t. thrust axis

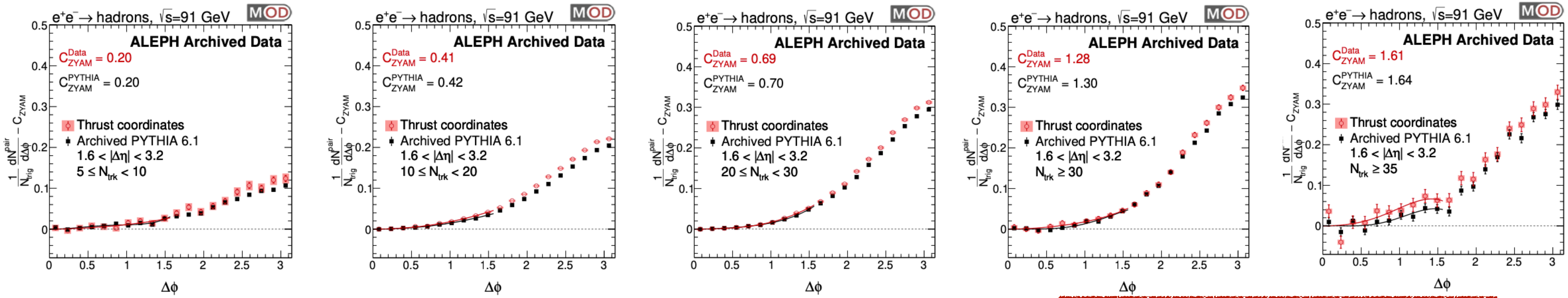
LEP1

Long-range correlations (c.f. MC)

Beam axis



$5 \leq N_{\text{trk}} < 10$ | $10 \leq N_{\text{trk}} < 20$ | $20 \leq N_{\text{trk}} < 30$ | $N_{\text{trk}} \geq 30$ | $N_{\text{trk}} \geq 35$

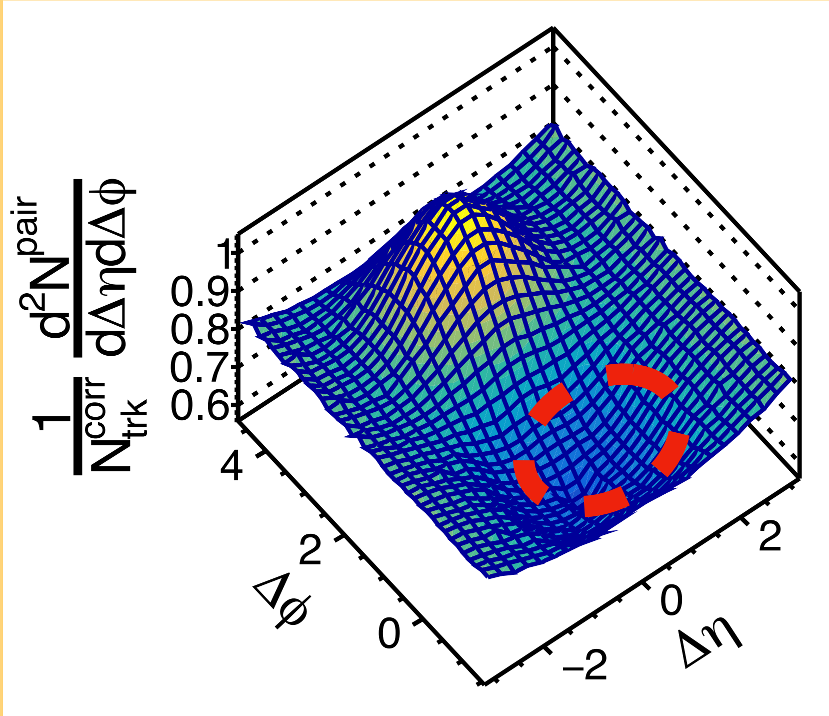


Thrust axis

Good agreement with MC!

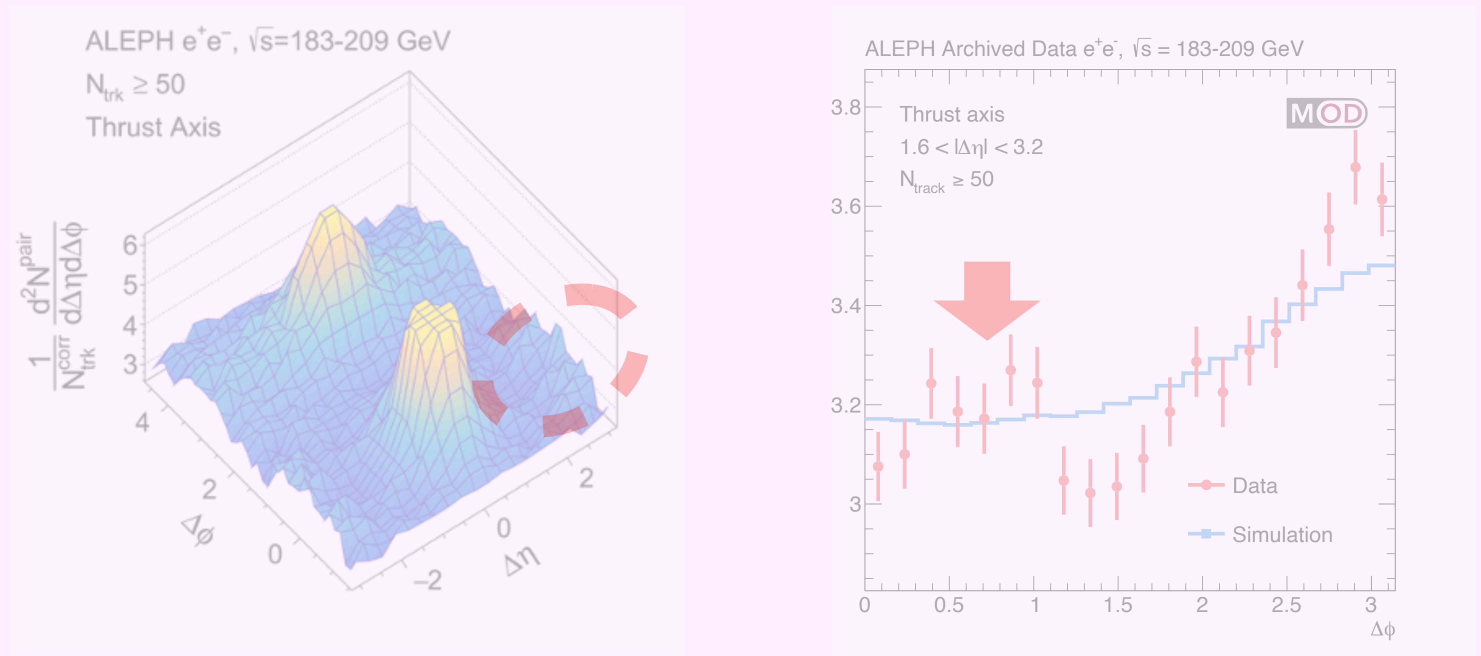
Puzzles we faced along the way…

Low-energy Belle data

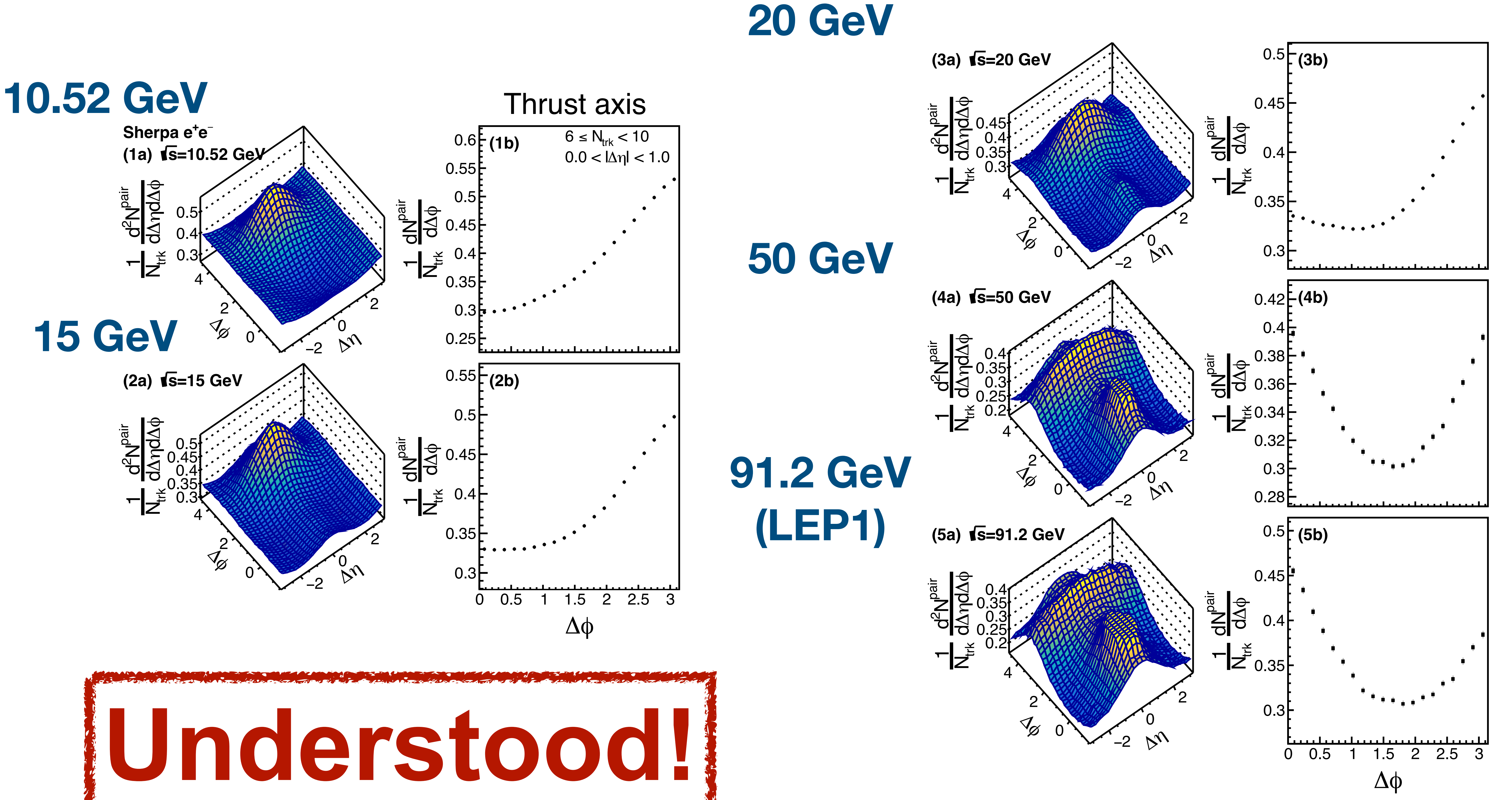


Lack of jet-like correlation?

High-energy LEP 2 data



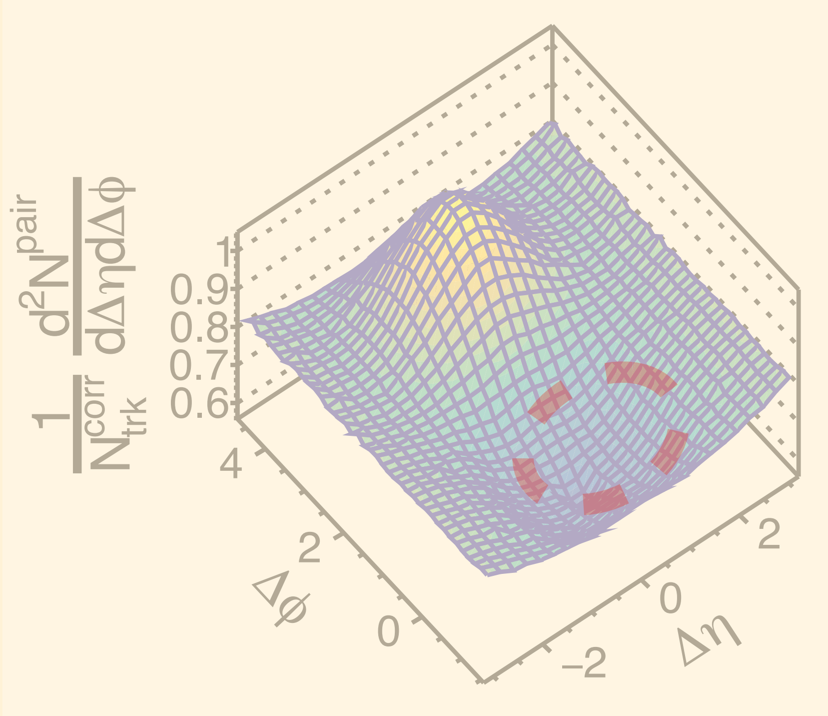
- Simulate by Sherpa generator on different √s:
  - Sharp origin-peak correlation evolved from null to significant intra-jet correlation as √s goes high!



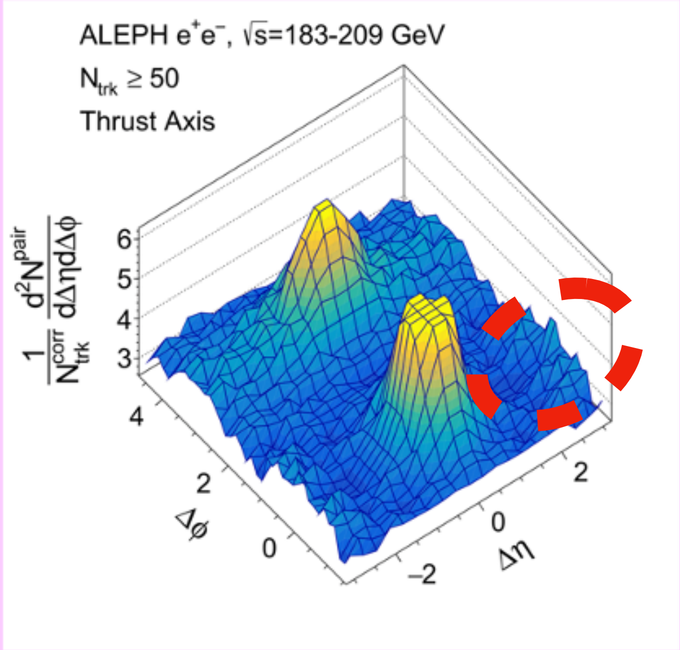
Understood!

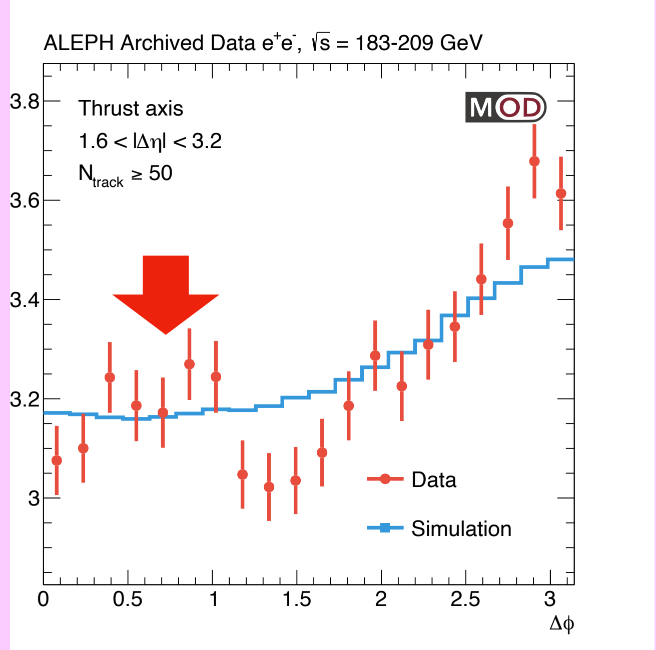
Puzzles we faced along the way…

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)

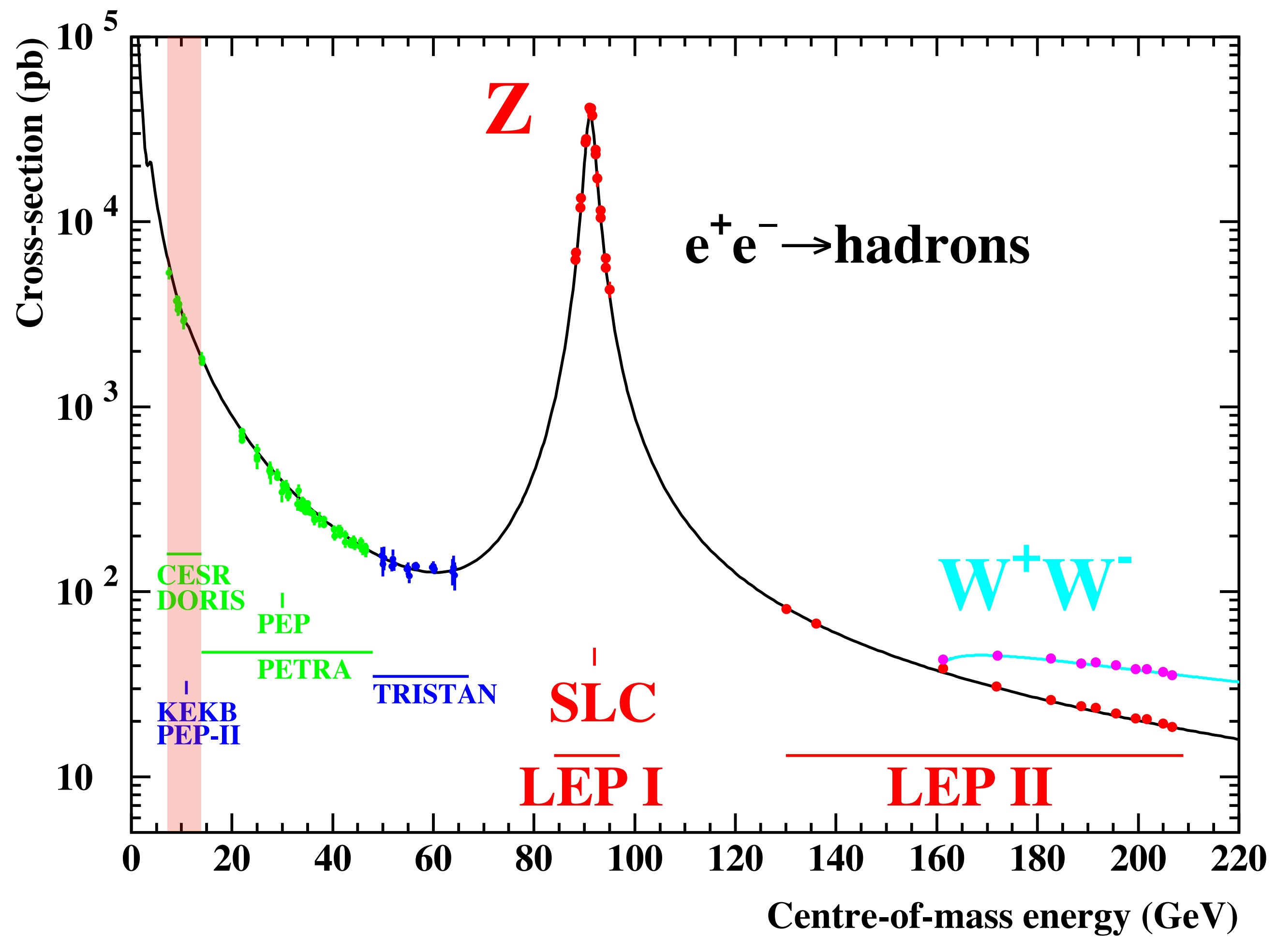
Ongoing checks:

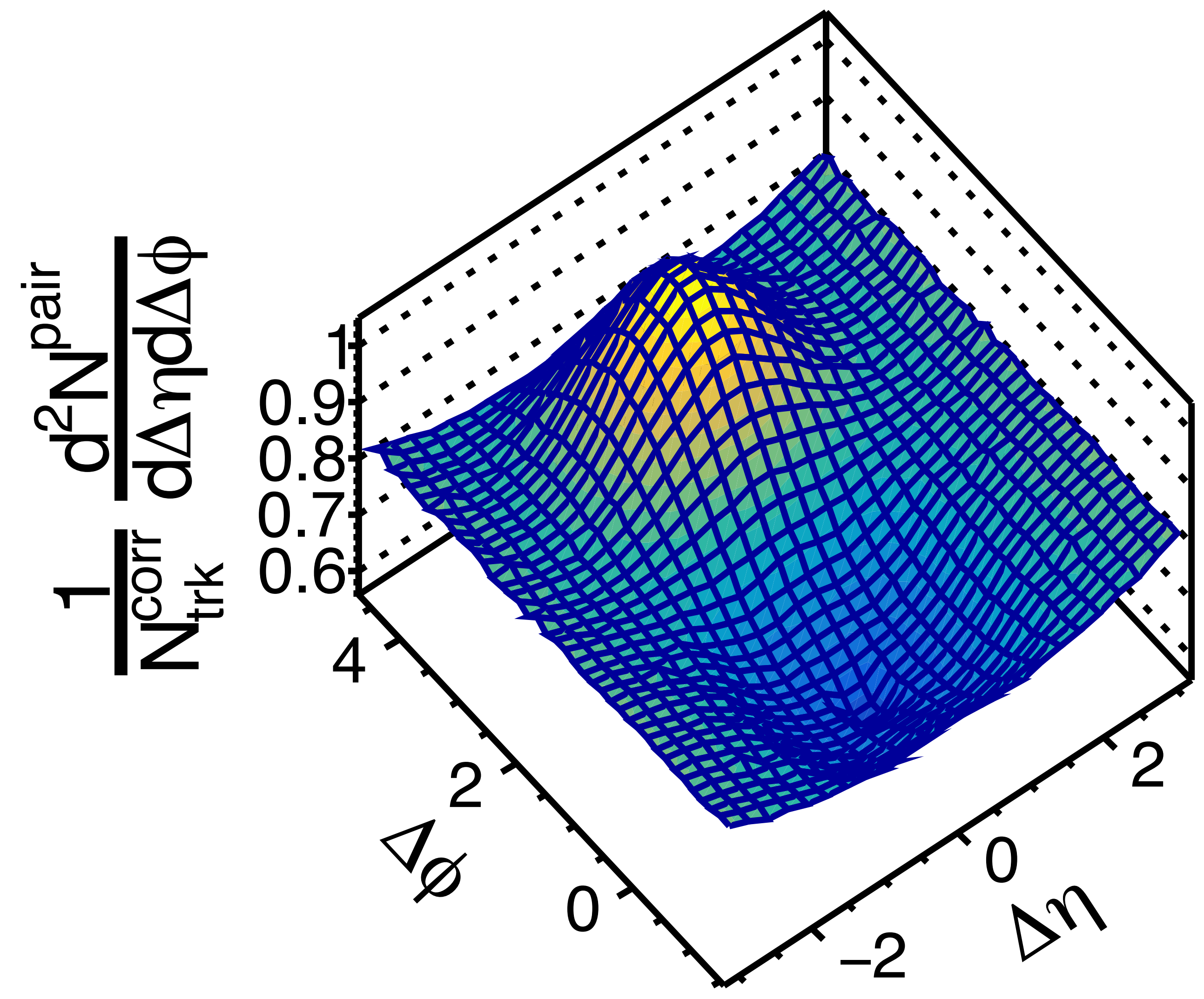
- Scanning of the long-range |Δη| projection window with MC
  To see if the signals really persist regardless the choice of the configuration
- Consistency check: look into the year-dependence (collision-energy-dependence)
- Compared with modern MC generators

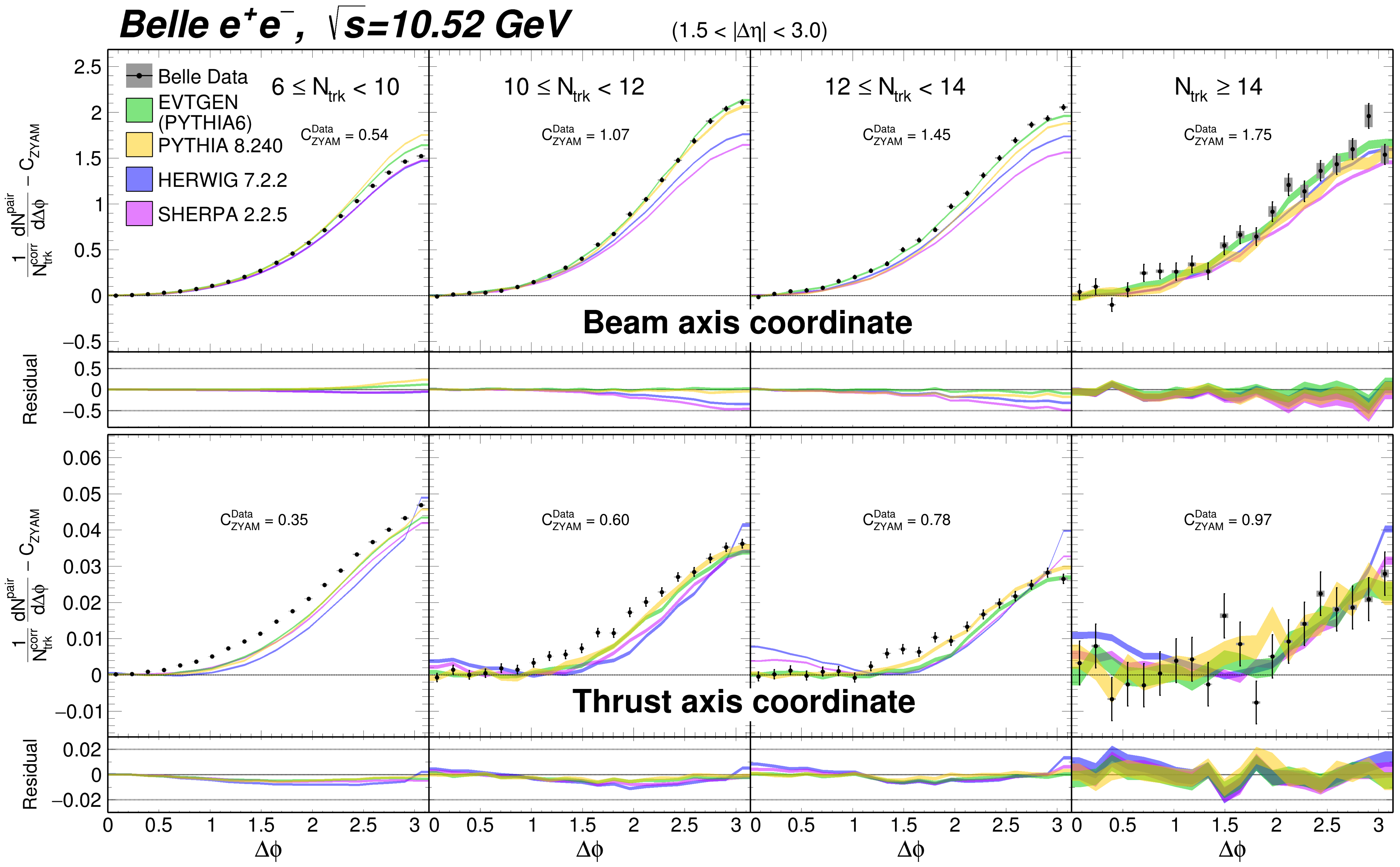
2PC — comparisons with the low-energy Belle experiment ($\sqrt{s}$=10.52 GeV)

Belle

Results



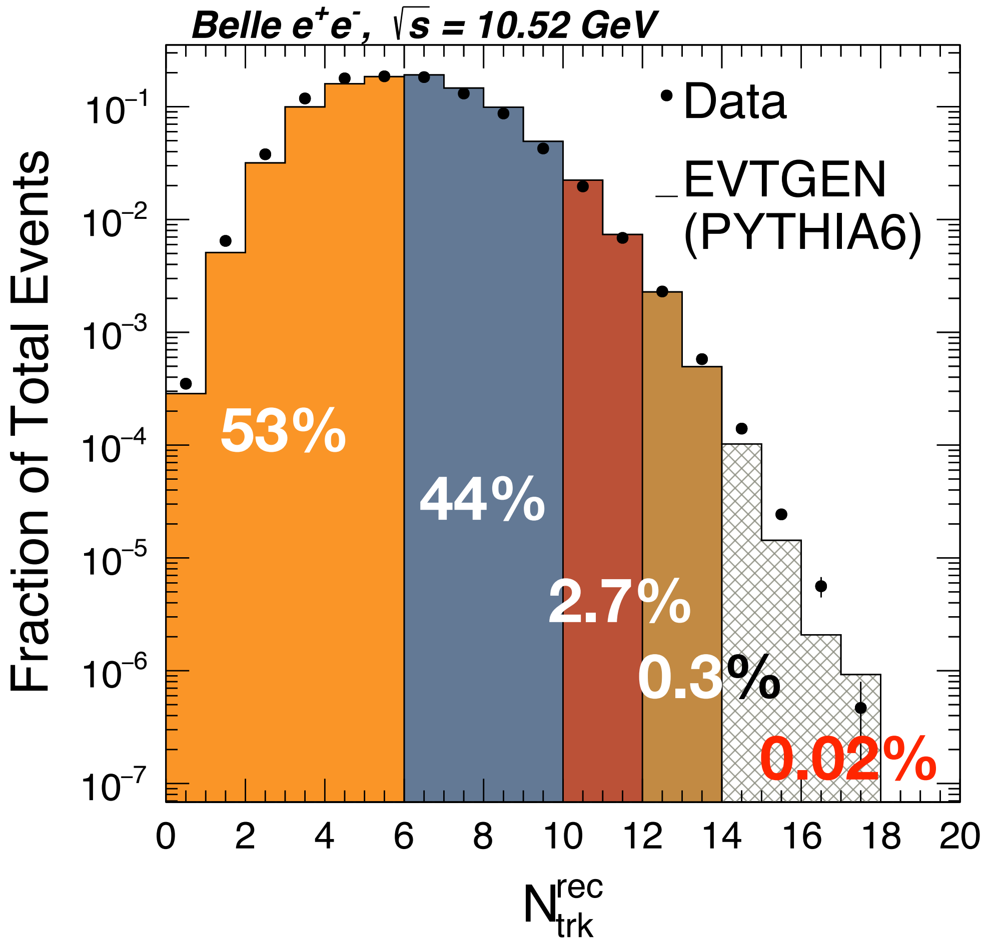


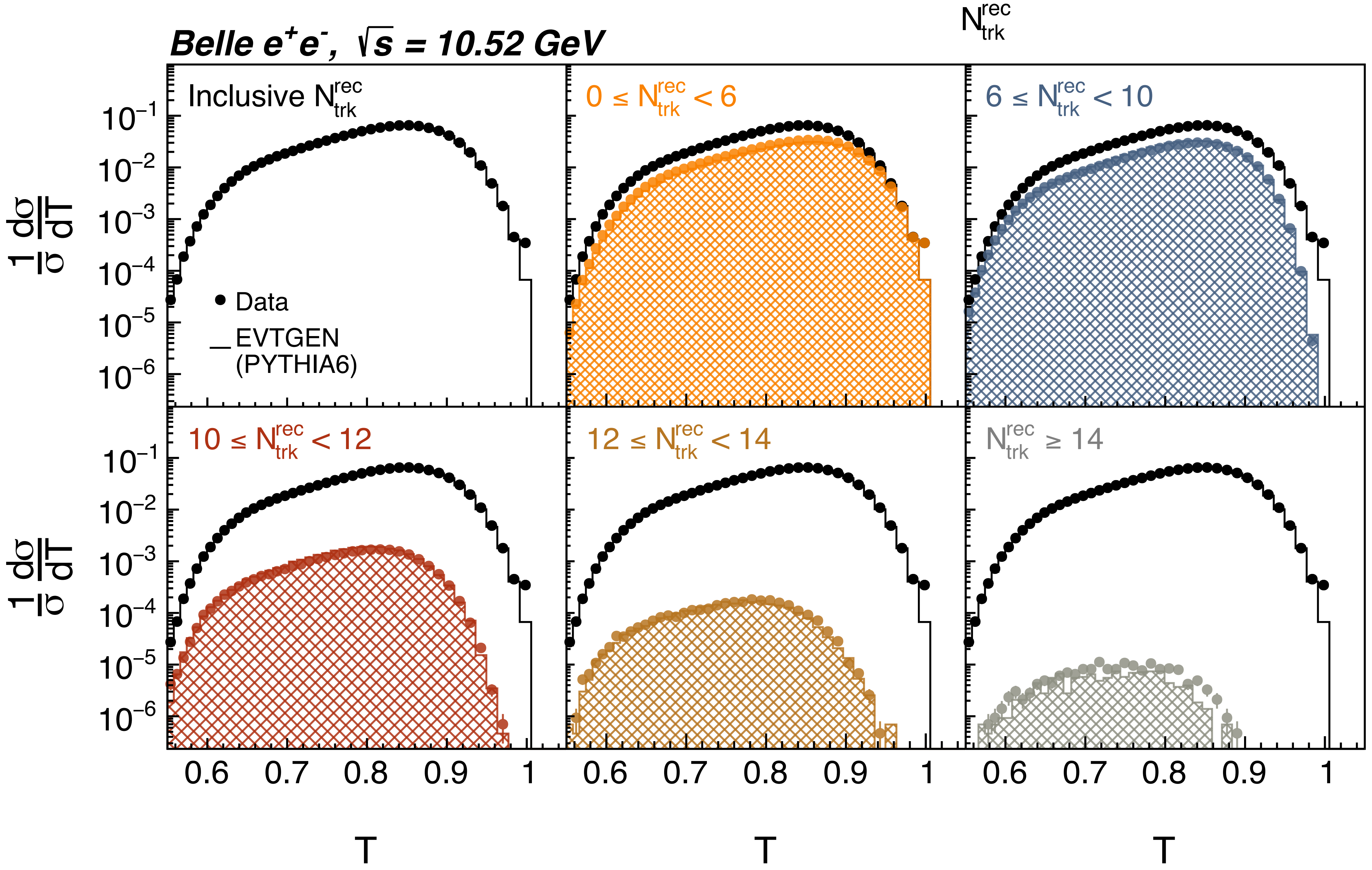


Compared with various fragmentation models

Belle

c.f. MC

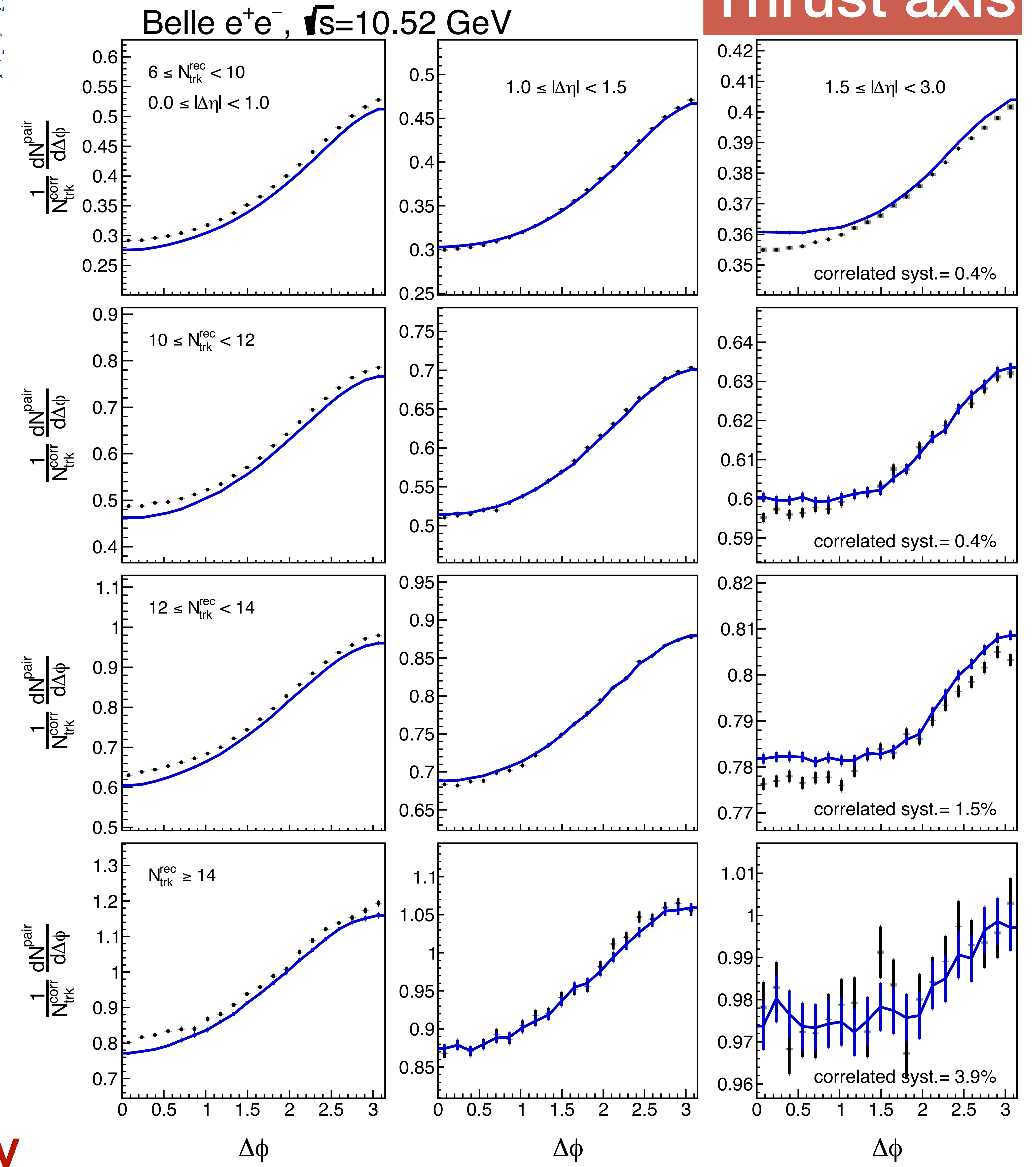




Data

PYTHIA6

High-multiplicity



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

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

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