Two-Particle Correlations in Hadronic e^+e^- Collisions at Belle and Their Implication

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on behalf of the Belle Collaboration

partial results in arXiv:2201.01694

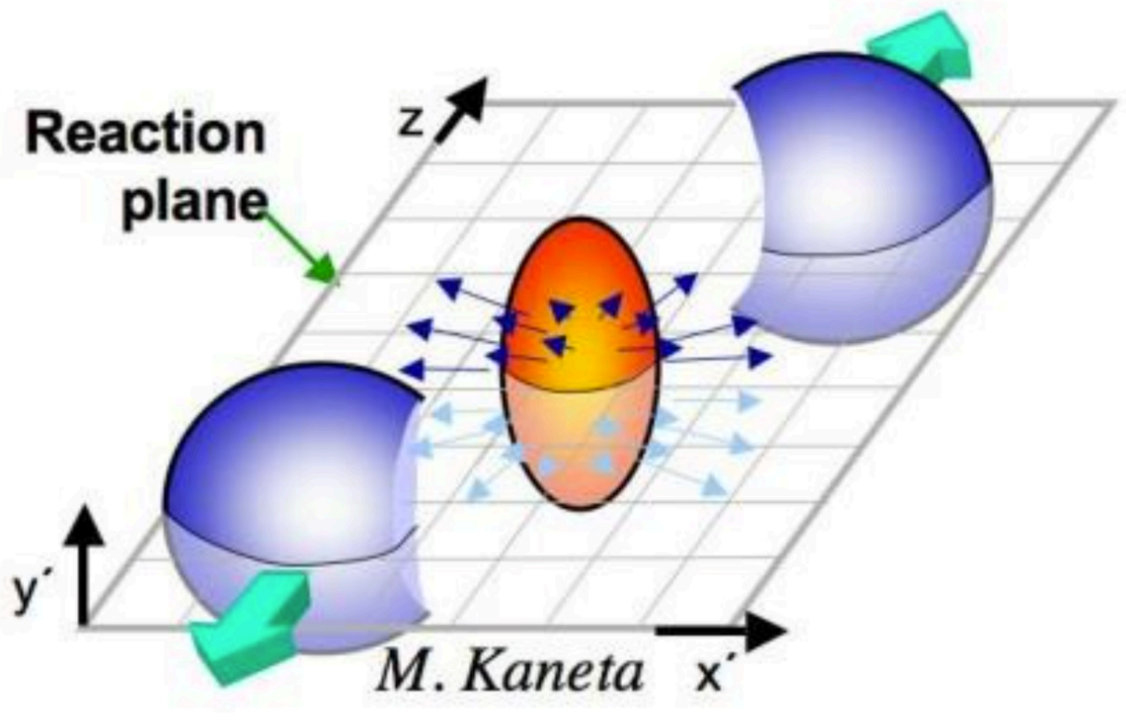
accepted by PRL

new paper in preparation (to be submitted to JHEP)

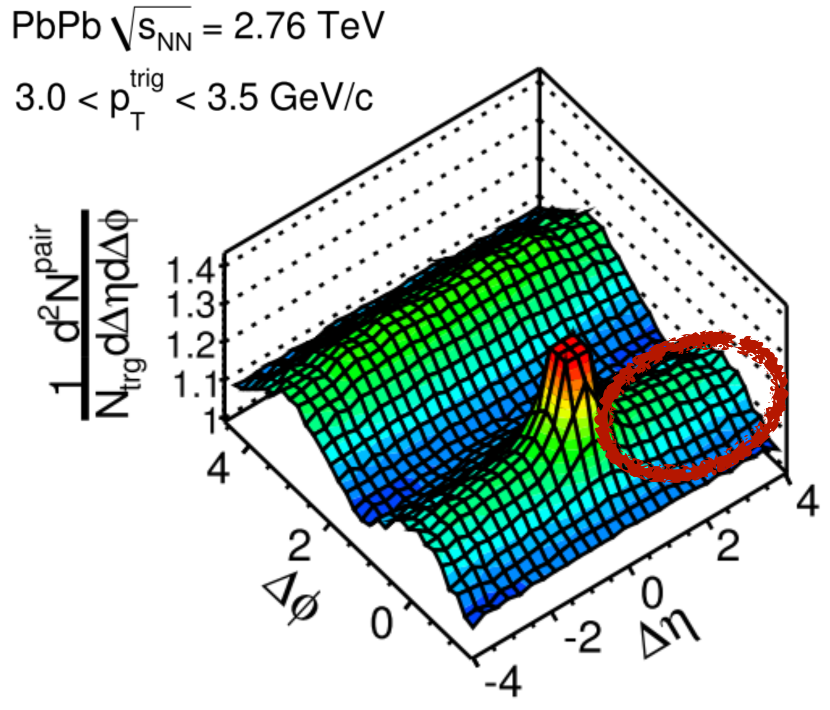
Quark Matter 2022, Apr. 6

Motivation

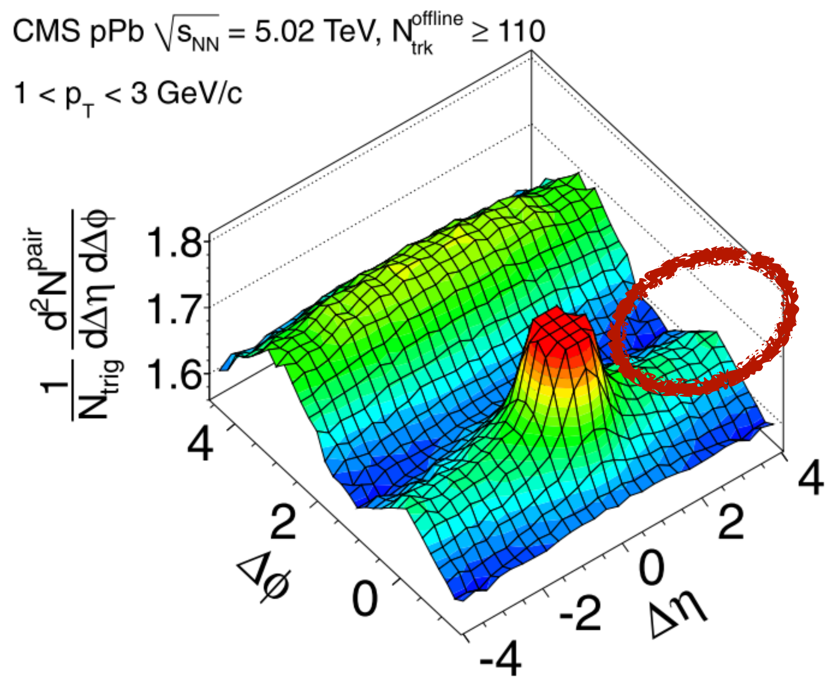
- Collectivity signal
  Two-particle correlation: soft probe for Quark-Gluon Plasma (QGP) in heavy ion collisions



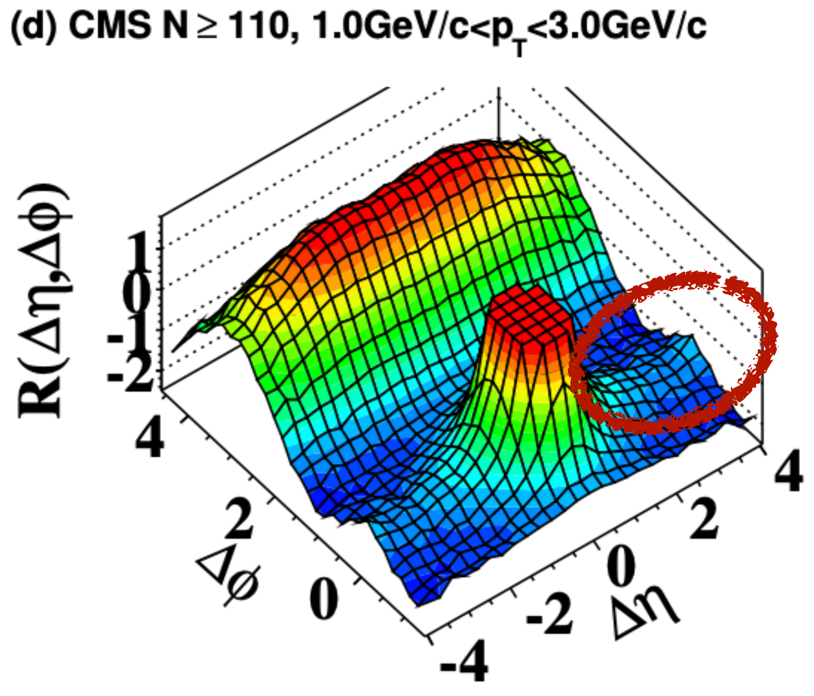
Spatial anisotropy



PbPb [Eur. Phys. J., C72]

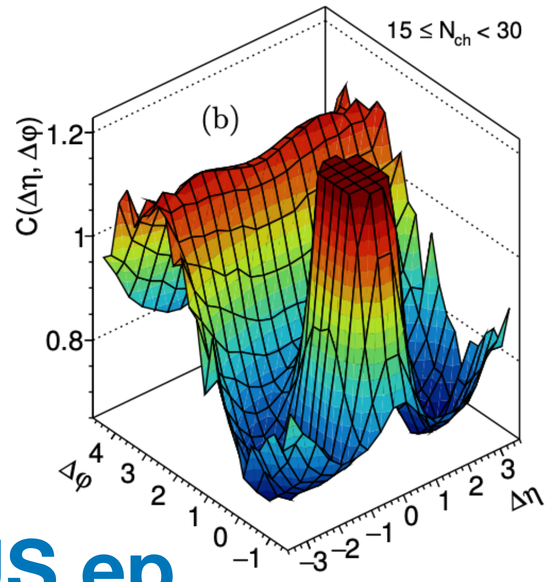


pPb [Phys. Lett. B718 (2013) 795-814]

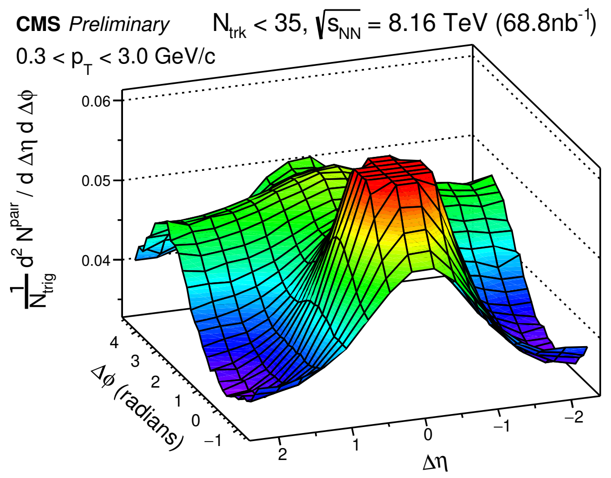


pp [JHEP 1009 (2010) 091]

- Minimal conditions for collectivity behavior [nucl-th:1707.02307]
  Smaller collision systems such as ep, e^+e^-, γp, γA, to the future EIC!



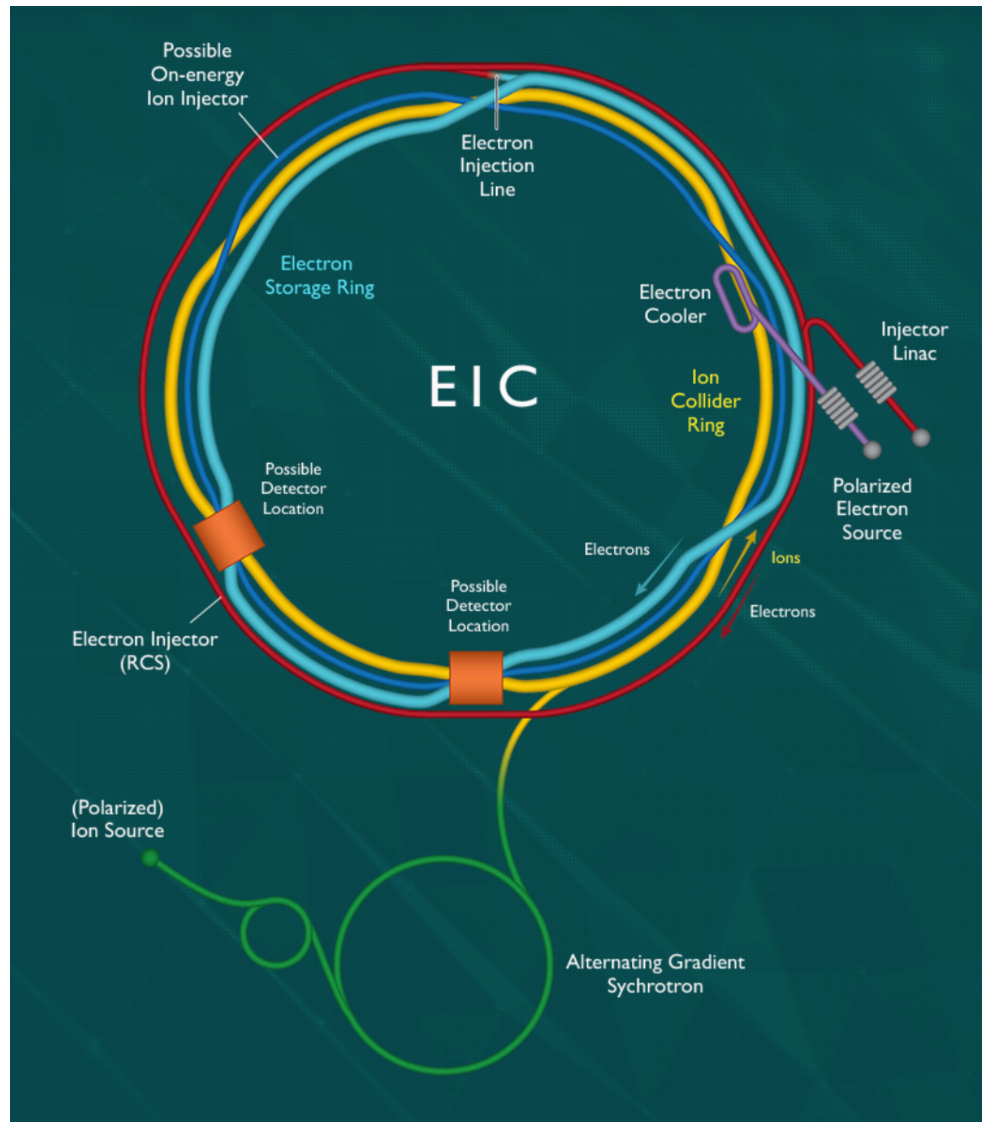
ZEUS ep
[JHEP 04 (2020) 070]



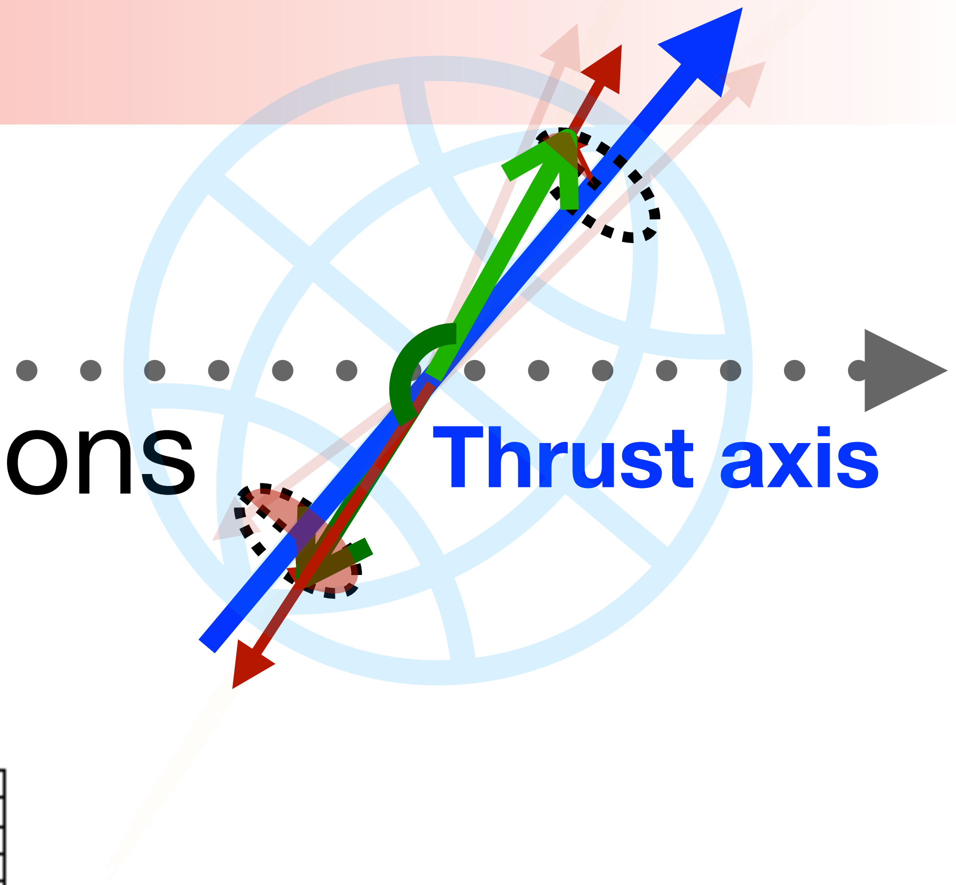
CMS γp
[CMS-PAS-HIN-18-008]

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

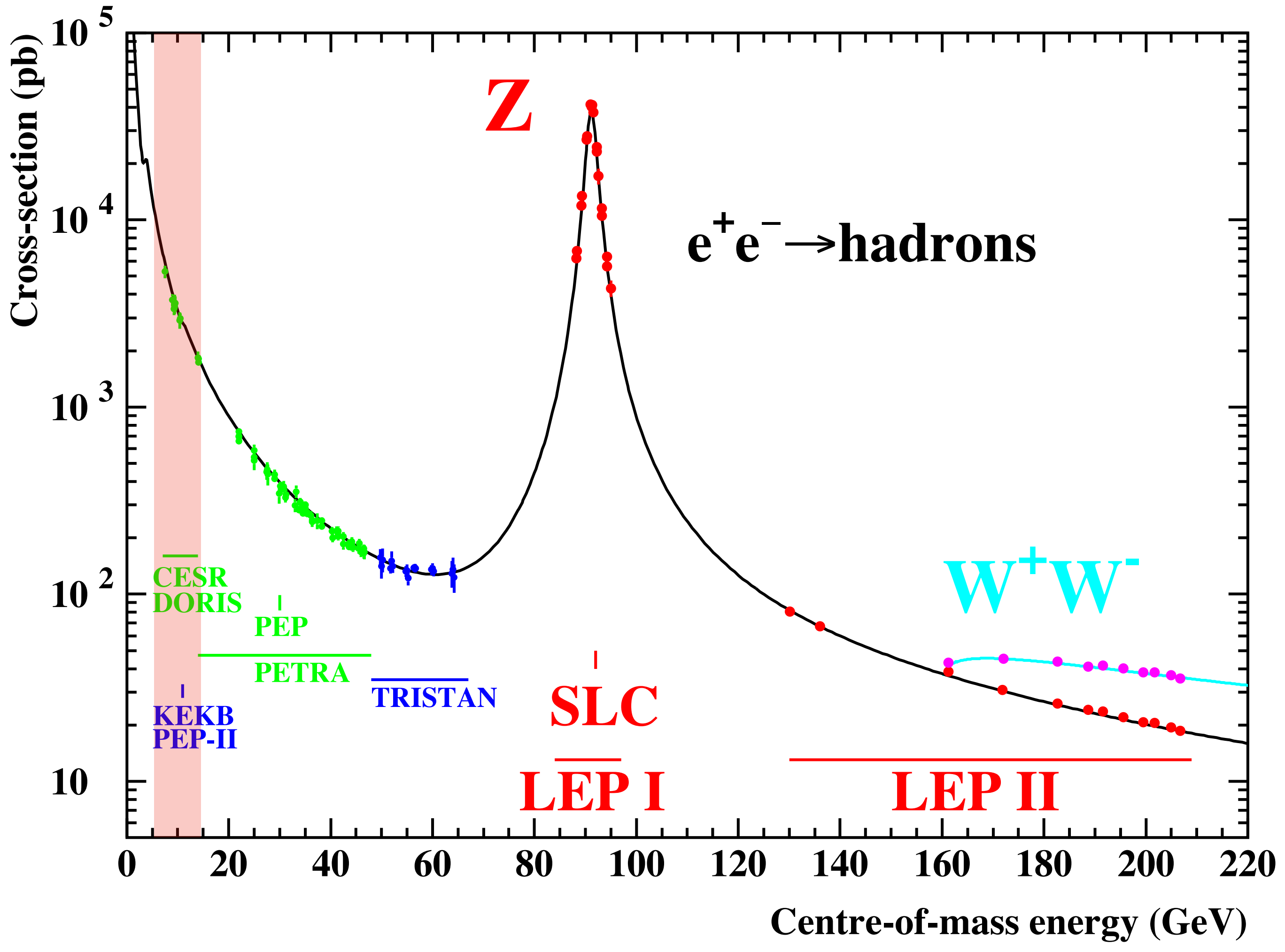
ATLAS γA [Phys. Rev. C. 104, 014903]

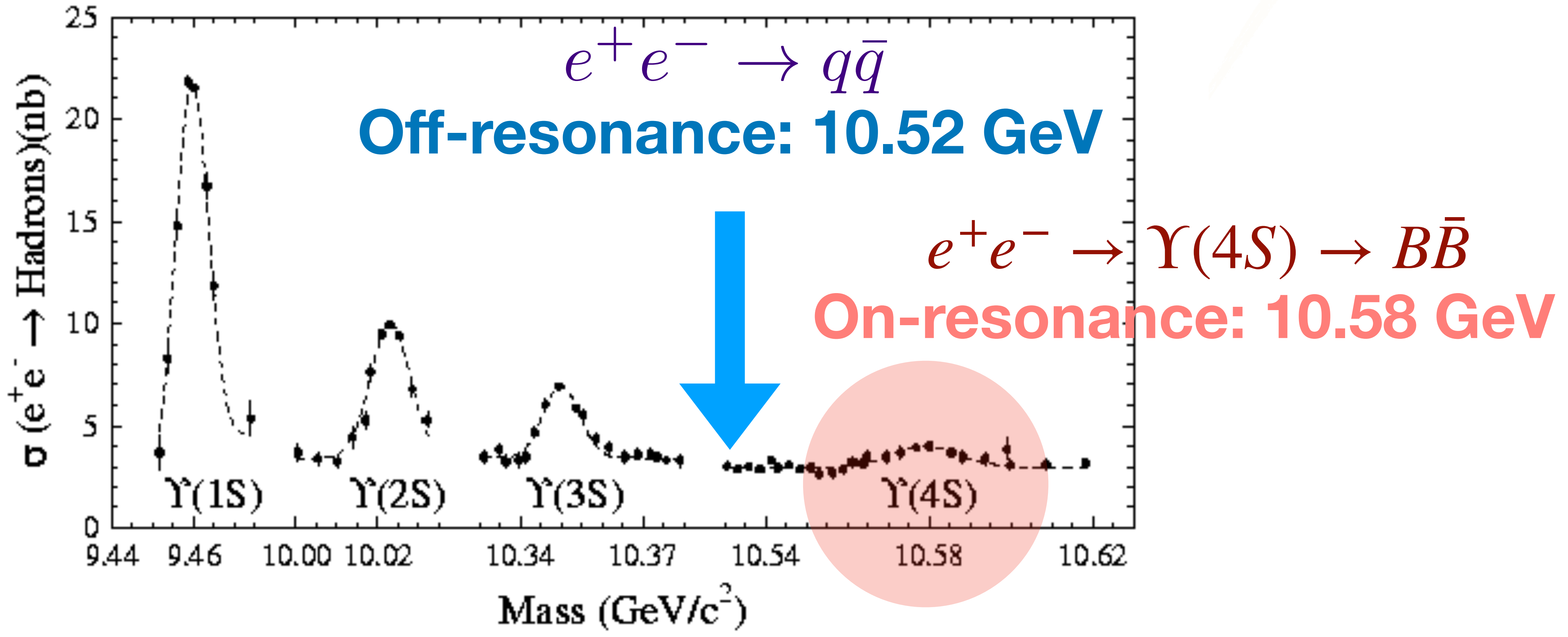


e^+e^- collisions



- Thrust-axis two-particle correlation:
  Search for medium expanding transverse to the out-going quark directions
- The first measurement at *B*-factory energy:





31.5 fb^{-1} 332.2 fb^{-1}
(statistics used in this analysis)

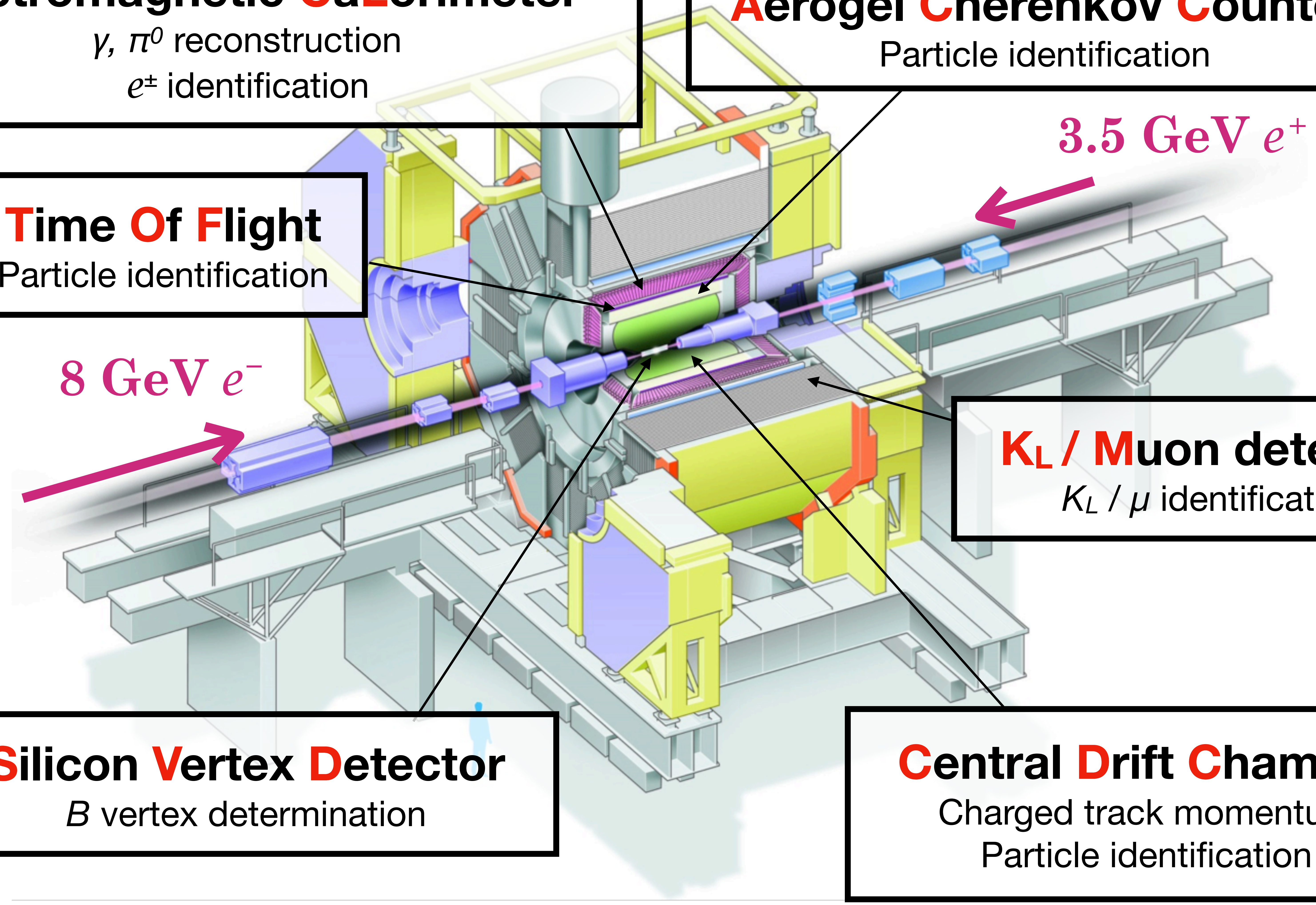
- The advantages:
  - Clean environment of e$^+$e$^-$ system: turn-off any possible CGC effect
  - New inputs to the phenomenological fragmentation models at low collision energy
  - Newly-devised "thrust axis analysis" is sensitive to soft emissions

Belle Detector

Electromagnetic CaLorimeter
γ, π^0 reconstruction
$e^{\pm}$ identification

Aerogel Cherenkov Counter
Particle identification

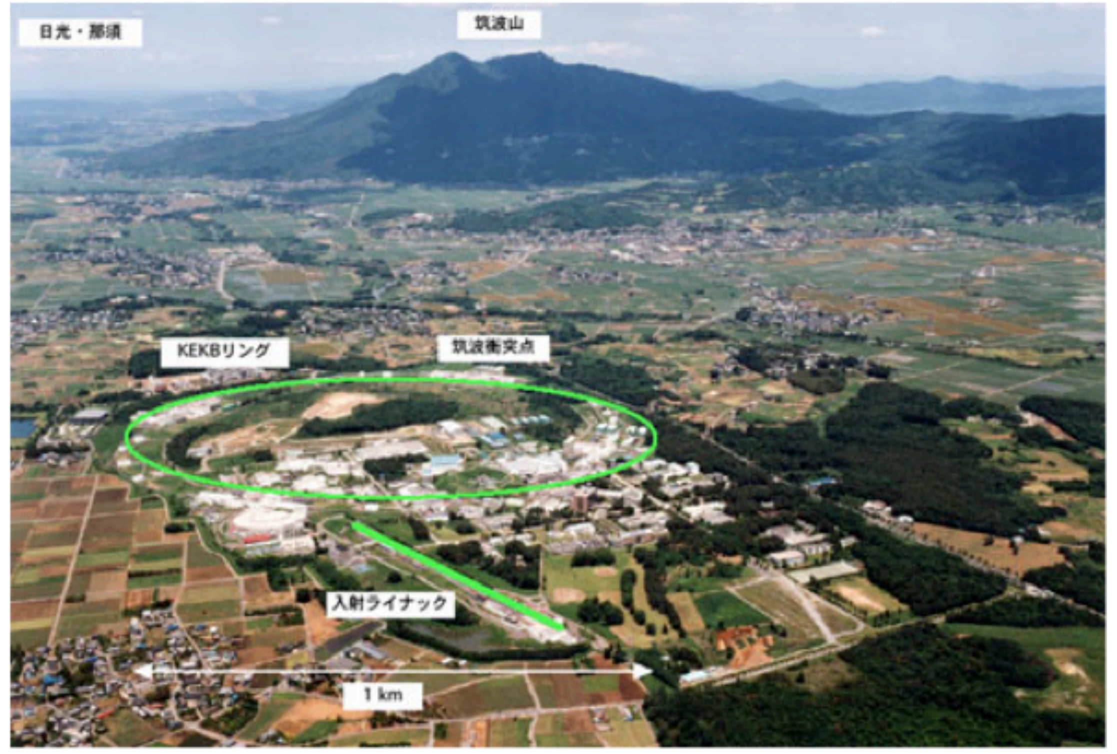
Time Of Flight
Particle identification



K_L / Muon detector
K_L / μ identification

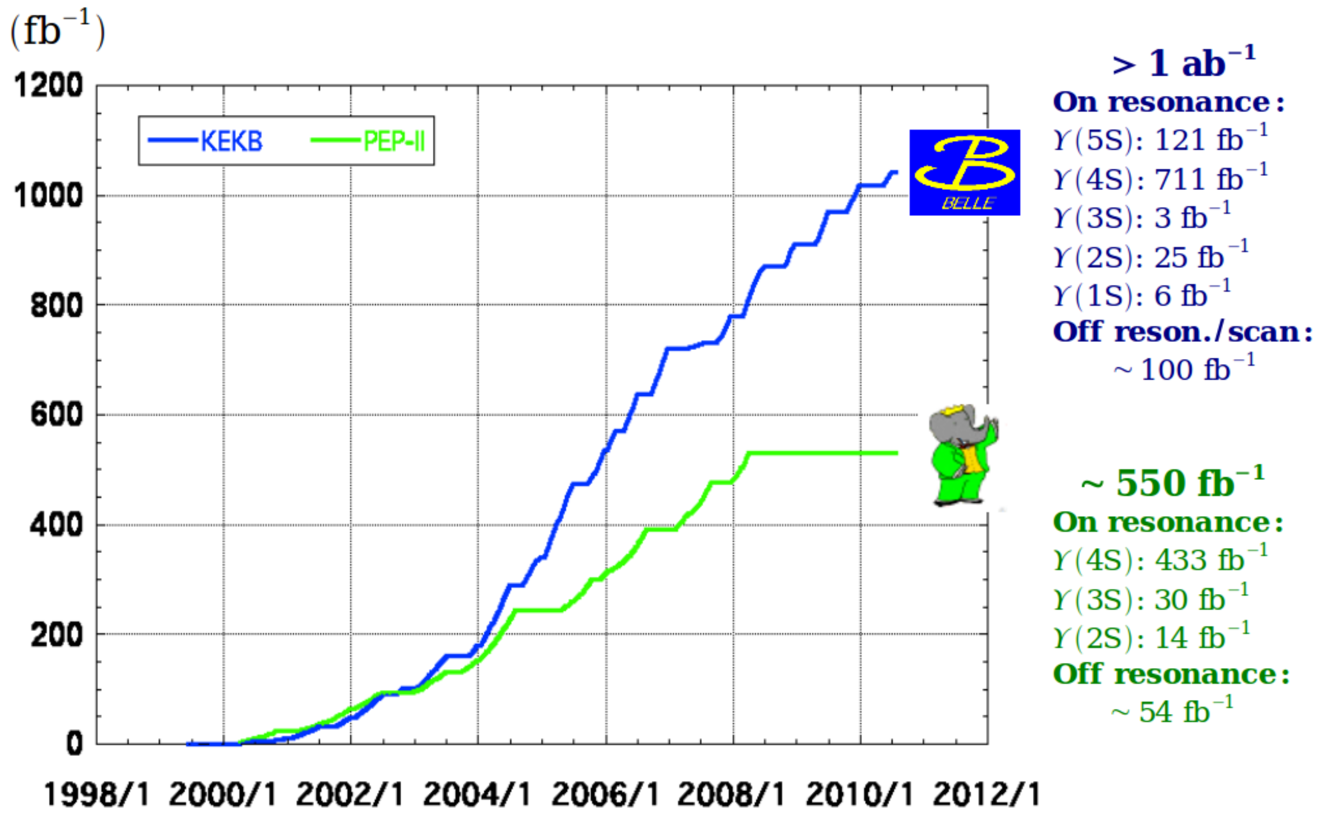
Silicon Vertex Detector
B vertex determination

Central Drift Chamber
Charged track momentum
Particle identification



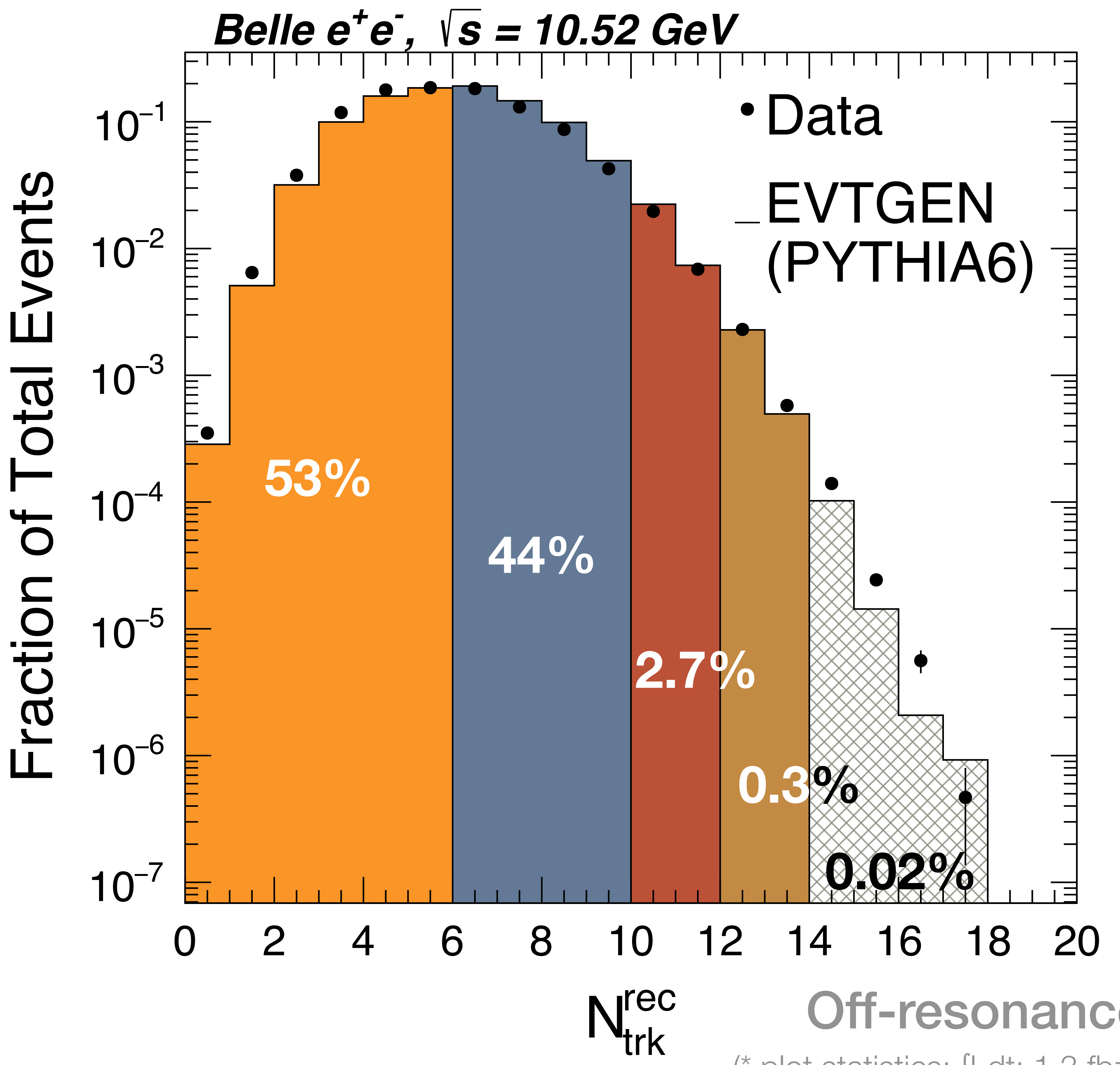
(KEK)

Boost to the CM frame for the correlation study!



Multiplicity distribution

- PYTHIA6-based Belle MC:
  - $q\bar{q}$ $(q = u, d, c$ and $s)$ fragmentation
  - $\Upsilon(4S)$ decays (by EVTGEN)
- Also simulated:
  - Radiative Bhabha events
  - Low multiplicity $e^+e^- \rightarrow l^+l^-$
  - Two-photon processes
- High statistics sample allows for probing the very stringent high-multiplicity class: $N_{trk}^{rec} \geq 14$ (**0.02%** of all events)



Off-resonance

(* plot statistics: ∫Ldt: 1.3 fb⁻¹)

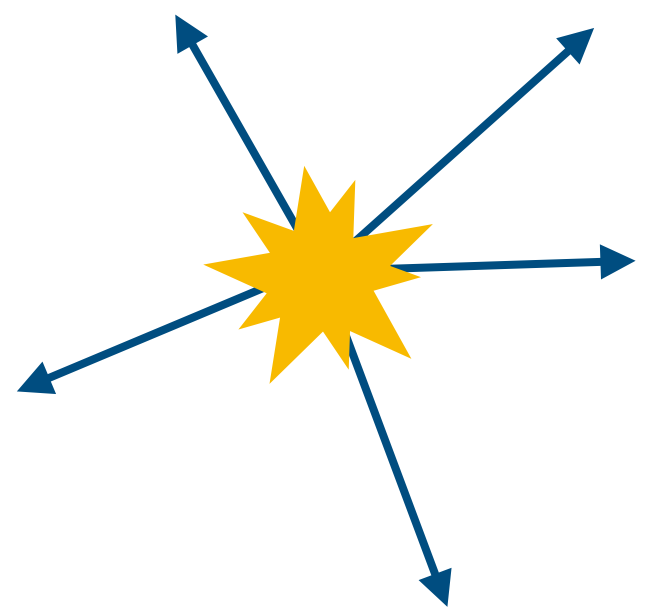
on-resonance see backup

Event thrust

Thrust axis is defined with the consideration of the missing momentum (MET):

$$T = \max_{\hat{n}} \frac{\sum_i \left| \vec{p_i} \cdot \hat{n} \right|}{\sum_i \left| \vec{p_i} \right|} \quad (i \in \text{charged, neutral particles and MET}) \qquad \vec{p}_{\text{MET}} = -\sum_{\text{neu,chg}} \vec{p}$$

T closes to 0.5

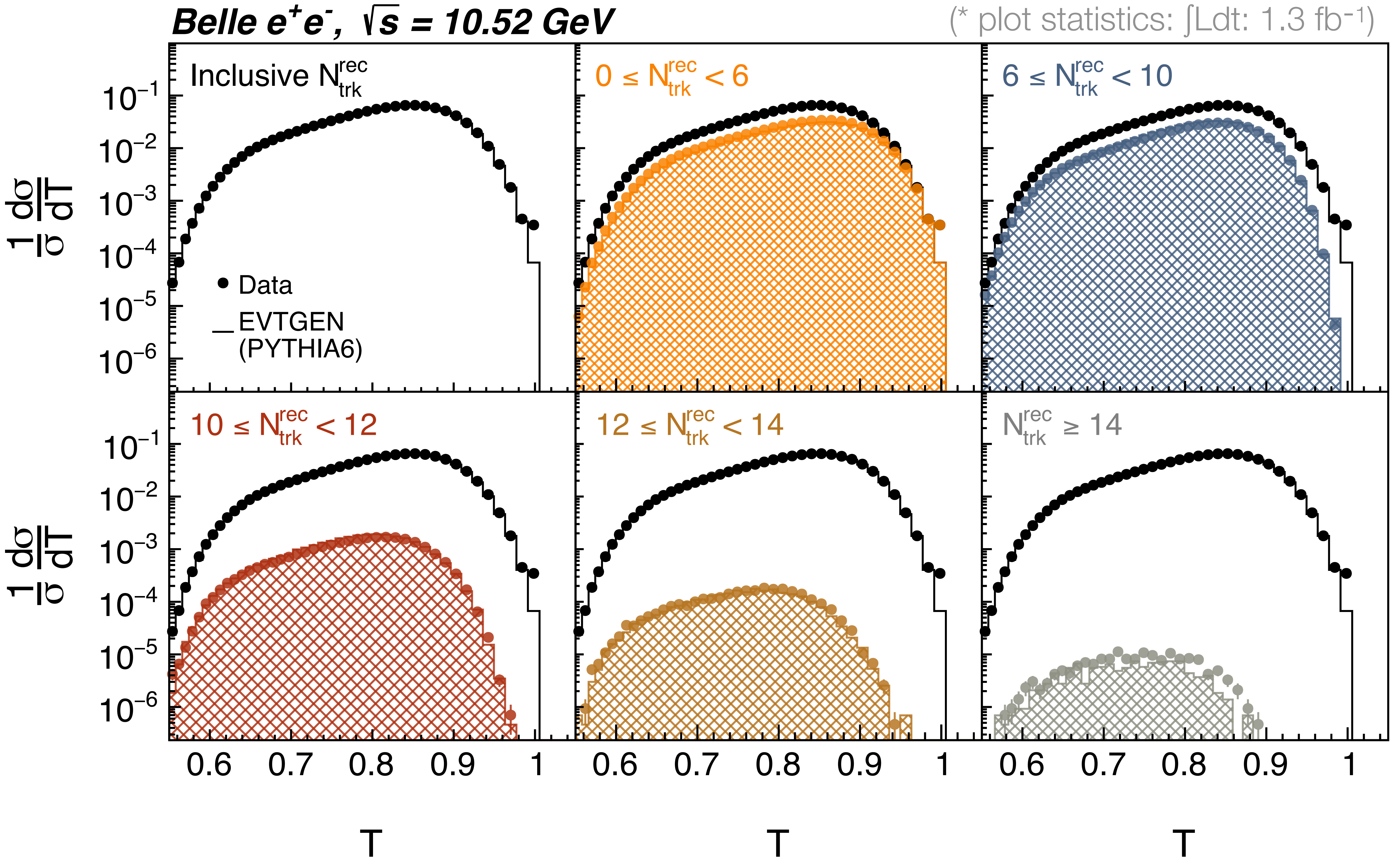


Spherical

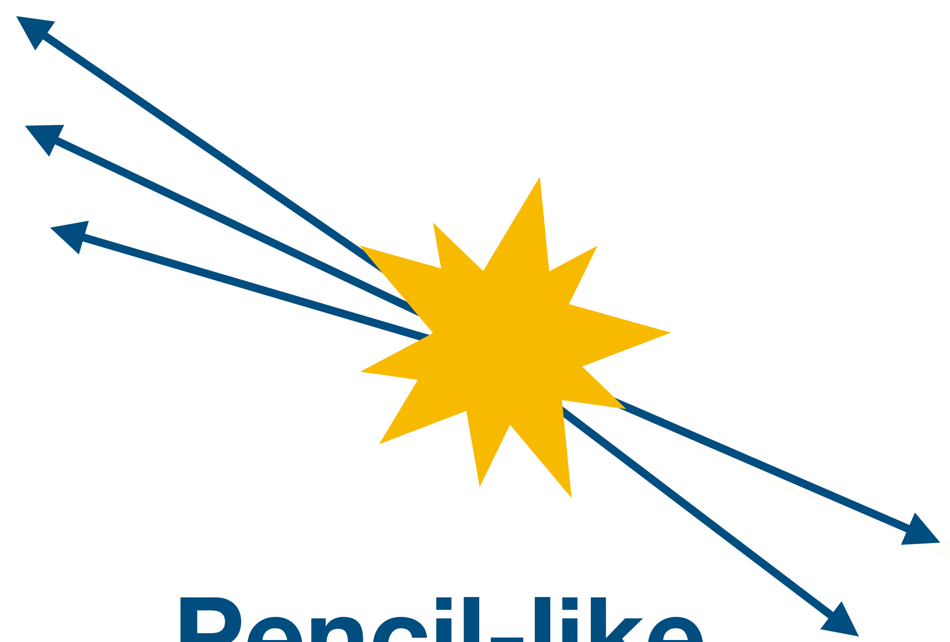
ex: B-decay

Off-resonance

(* plot statistics: ∫Ldt: 1.3 fb⁻¹)



T closes to 1



Pencil-like

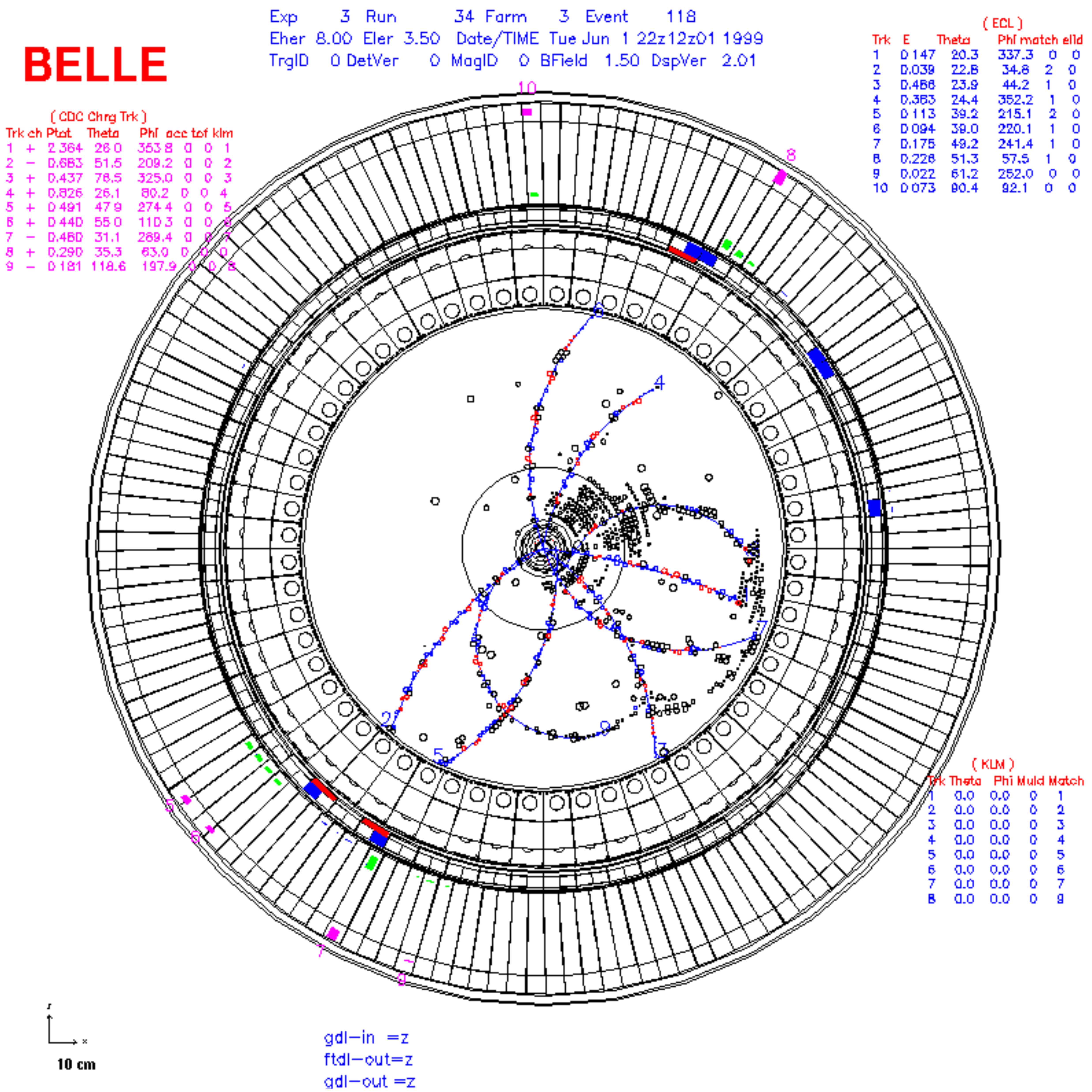
ex: $q\bar{q}$ fragmentation

on-resonance see backup

Sample

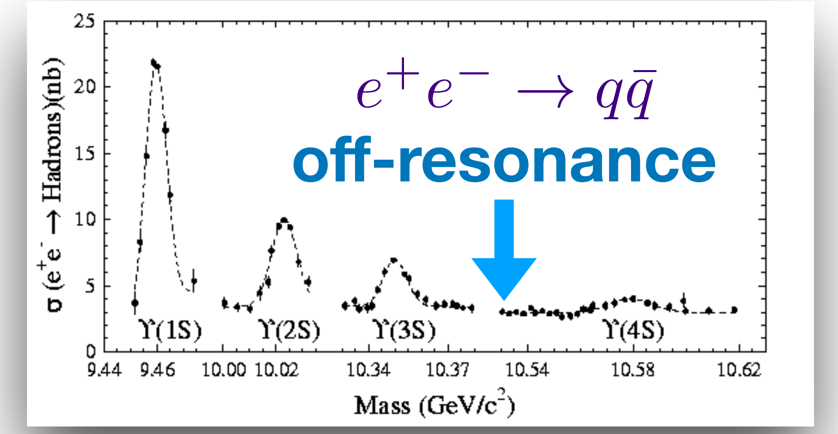
Hadronic event display

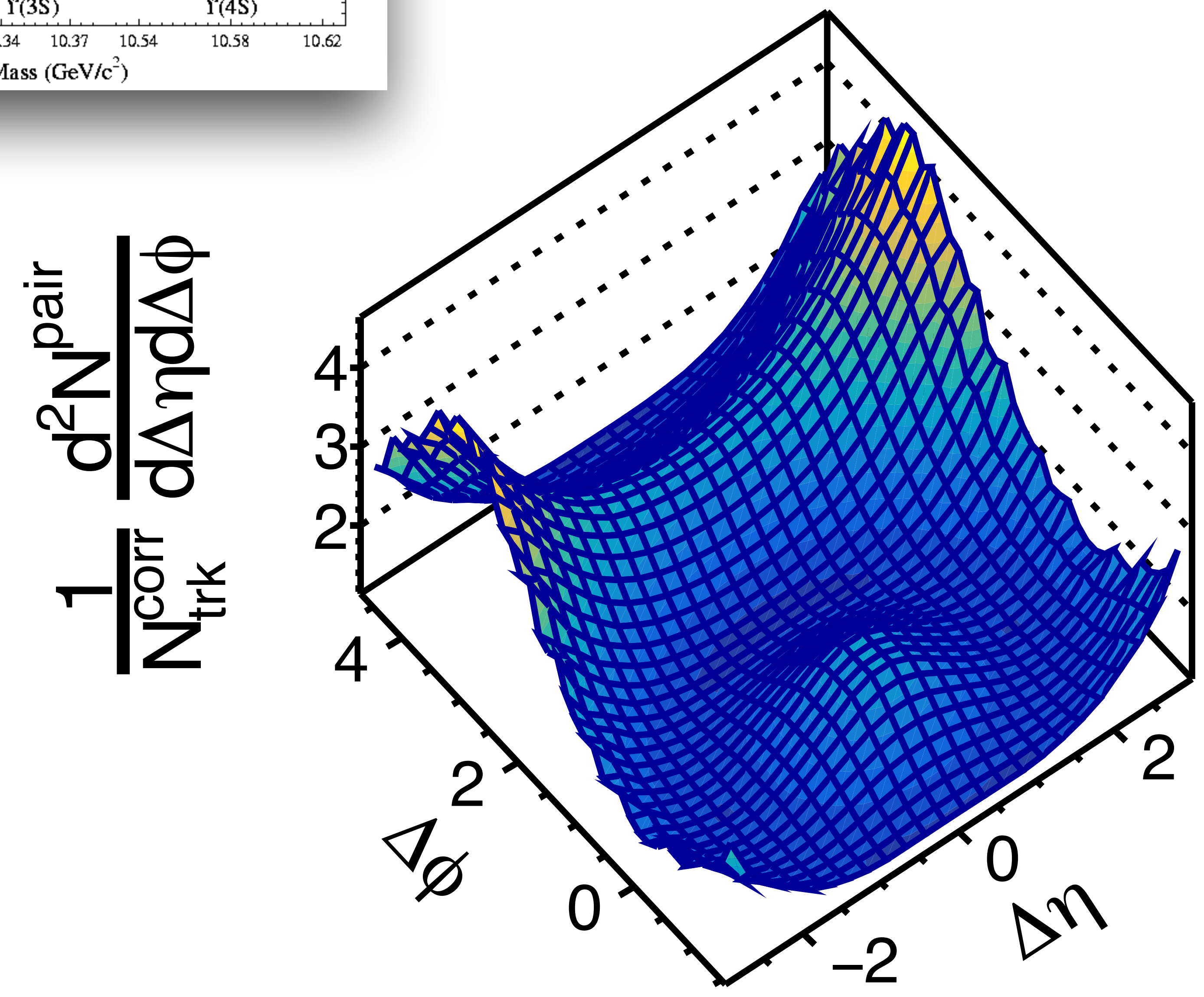
Belle has rather spherical events!



Beam-axis two-particle correlations — off-resonance ($\sqrt{s}$=10.52 GeV)

- Reasonable data and MC agreements
- Intriguing discrepancies in high-multiplicity events from short to the middle range



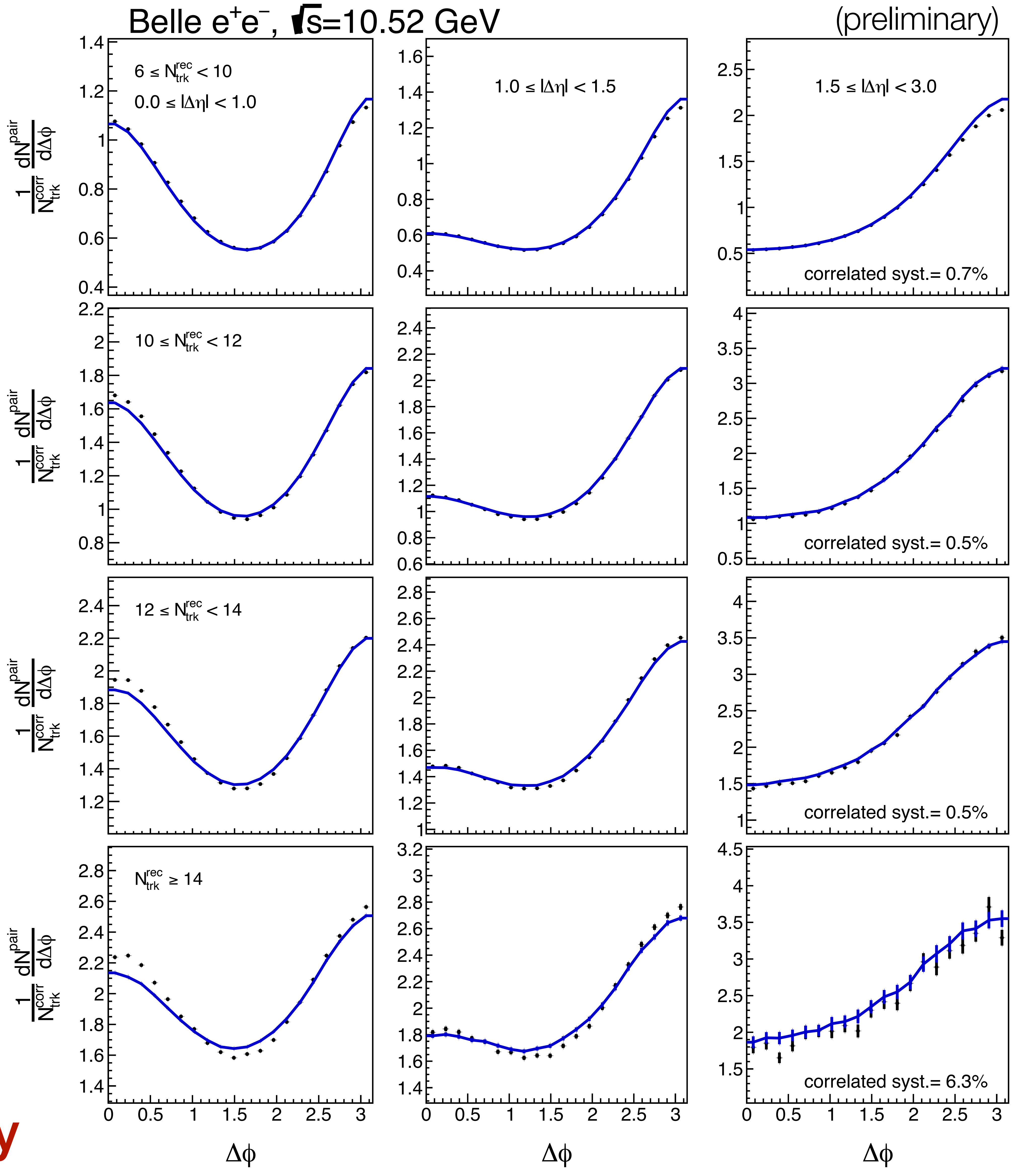


$$12 \leq N_{trk}^{rec} < 14$$

arXiv:2201.01694
accepted by PRL

Data
PYTHIA6

High-multiplicity



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

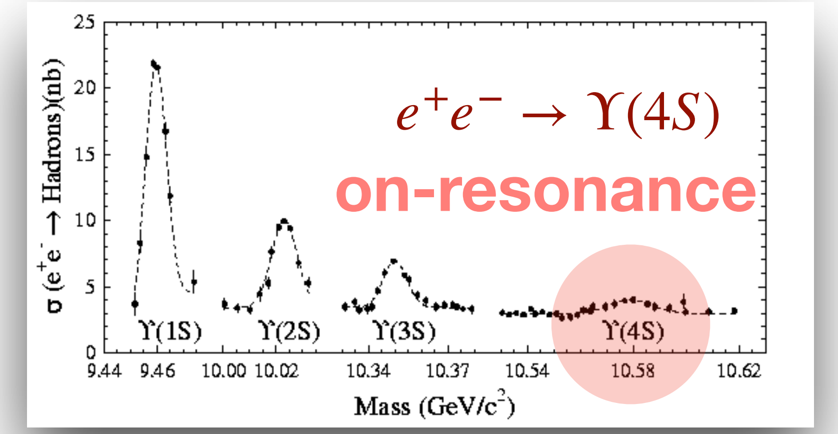
Middle Range ($1 \leq |\Delta\eta| < 1.5$)

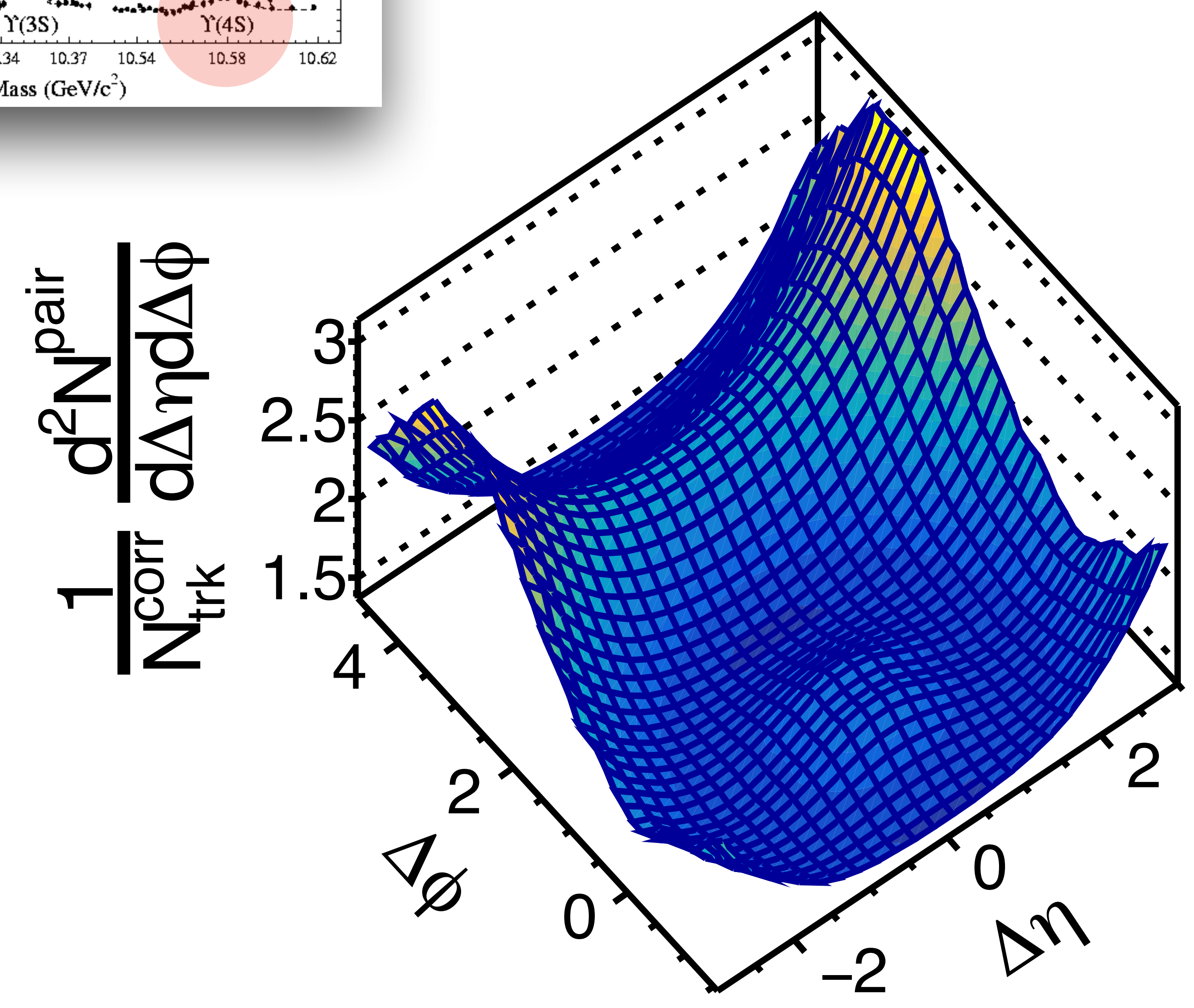
Long Range ($1.5 \leq |\Delta\eta| < 3.0$)

Result

Beam-axis two-particle correlations — on-resonance ($\sqrt{s}$=10.58 GeV)

- Larger discrepancies are observed btw data and PYTHIA6 in the near-side ($\Delta\phi \approx 0$) and away-side ($\Delta\phi \approx \pi$) peak values

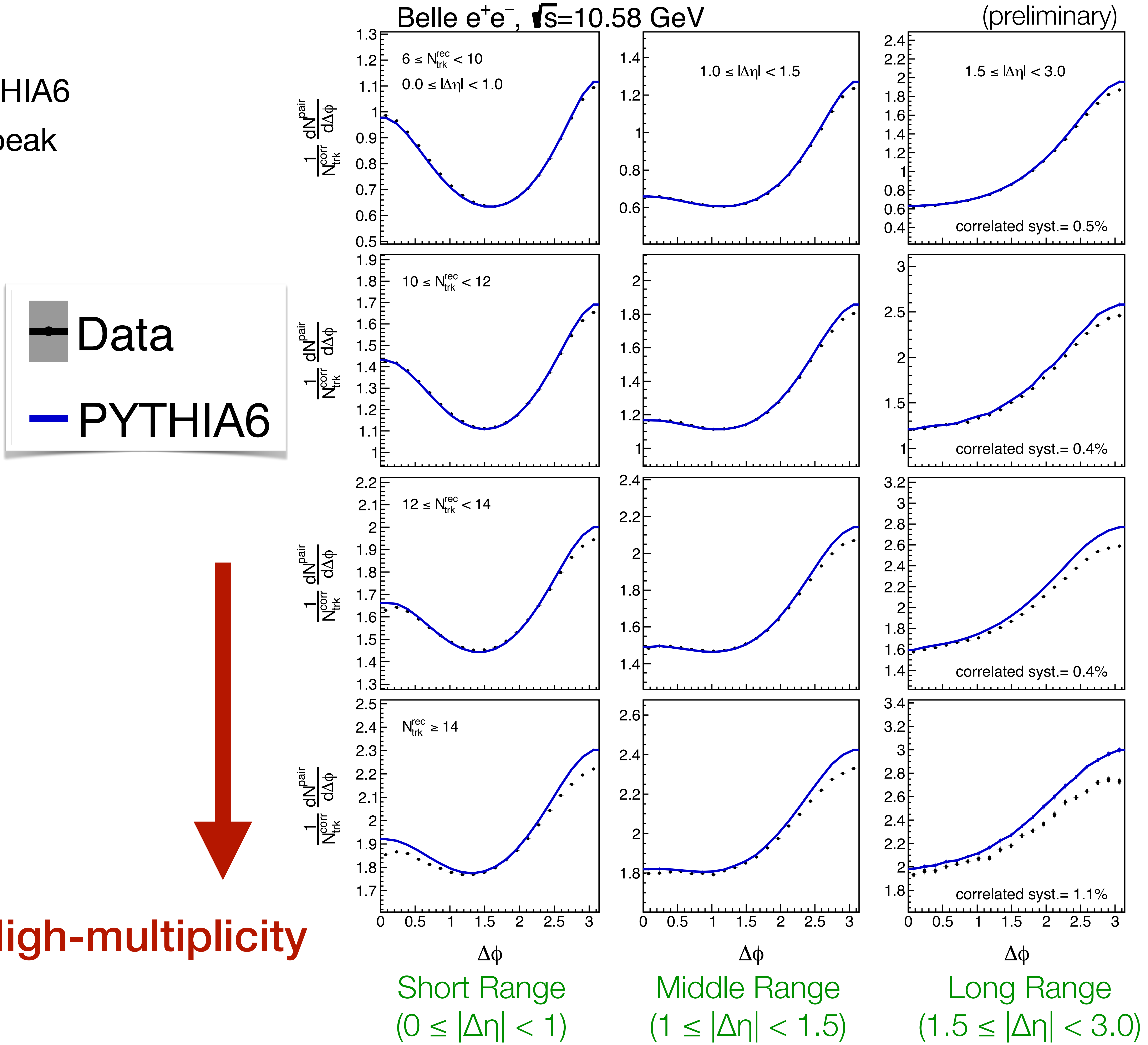




paper in preparation

$$12 \leq N_{trk}^{rec} < 14$$

High-multiplicity

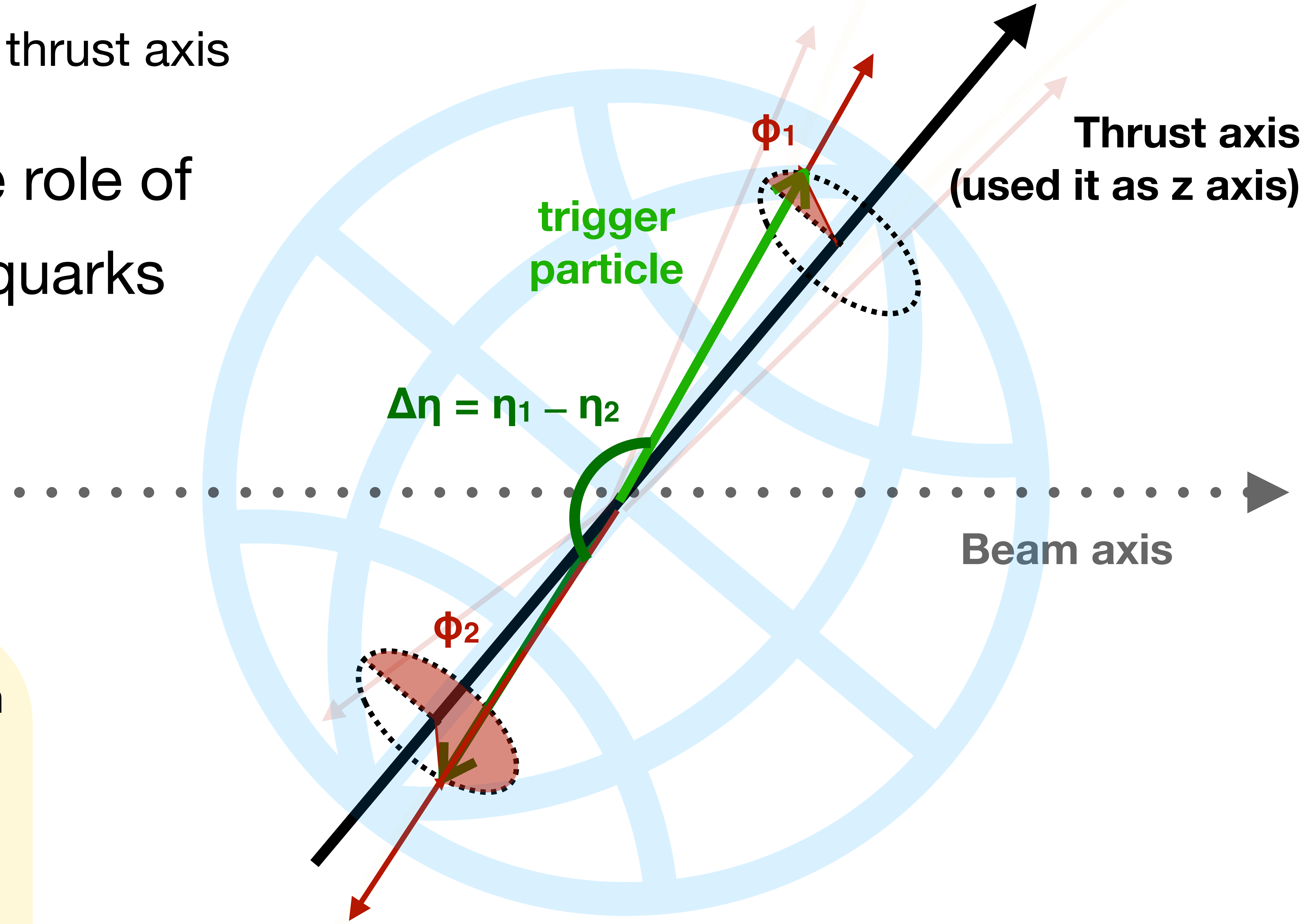


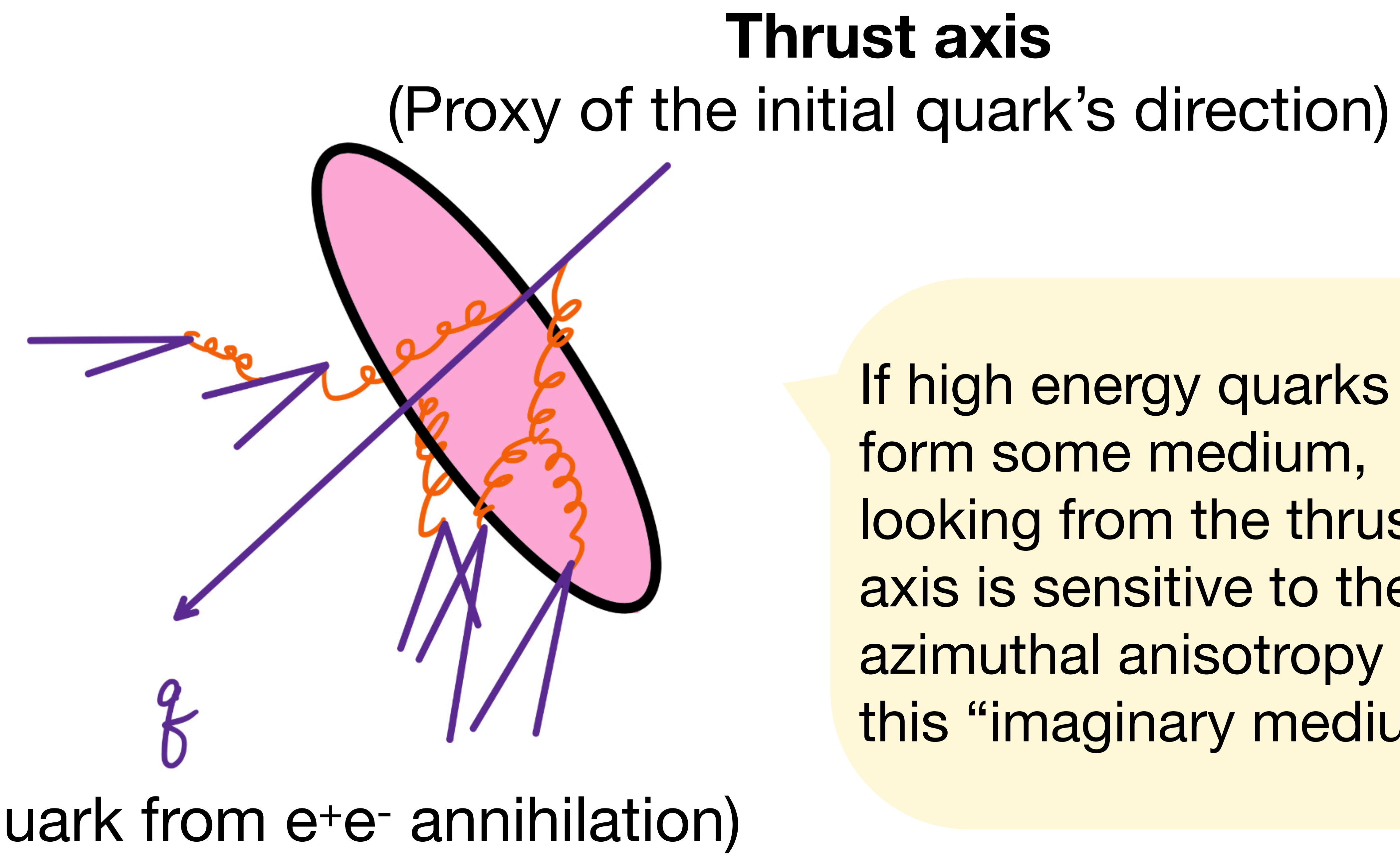
Thrust-axis two-particle correlation

- New reference z axis: event thrust axis

  particles (p_T, η, ϕ) are re-calculated with respect to thrust axis

- Similar to heavy-ion collisions study, the role of beam remnant is replaced by outgoing quarks

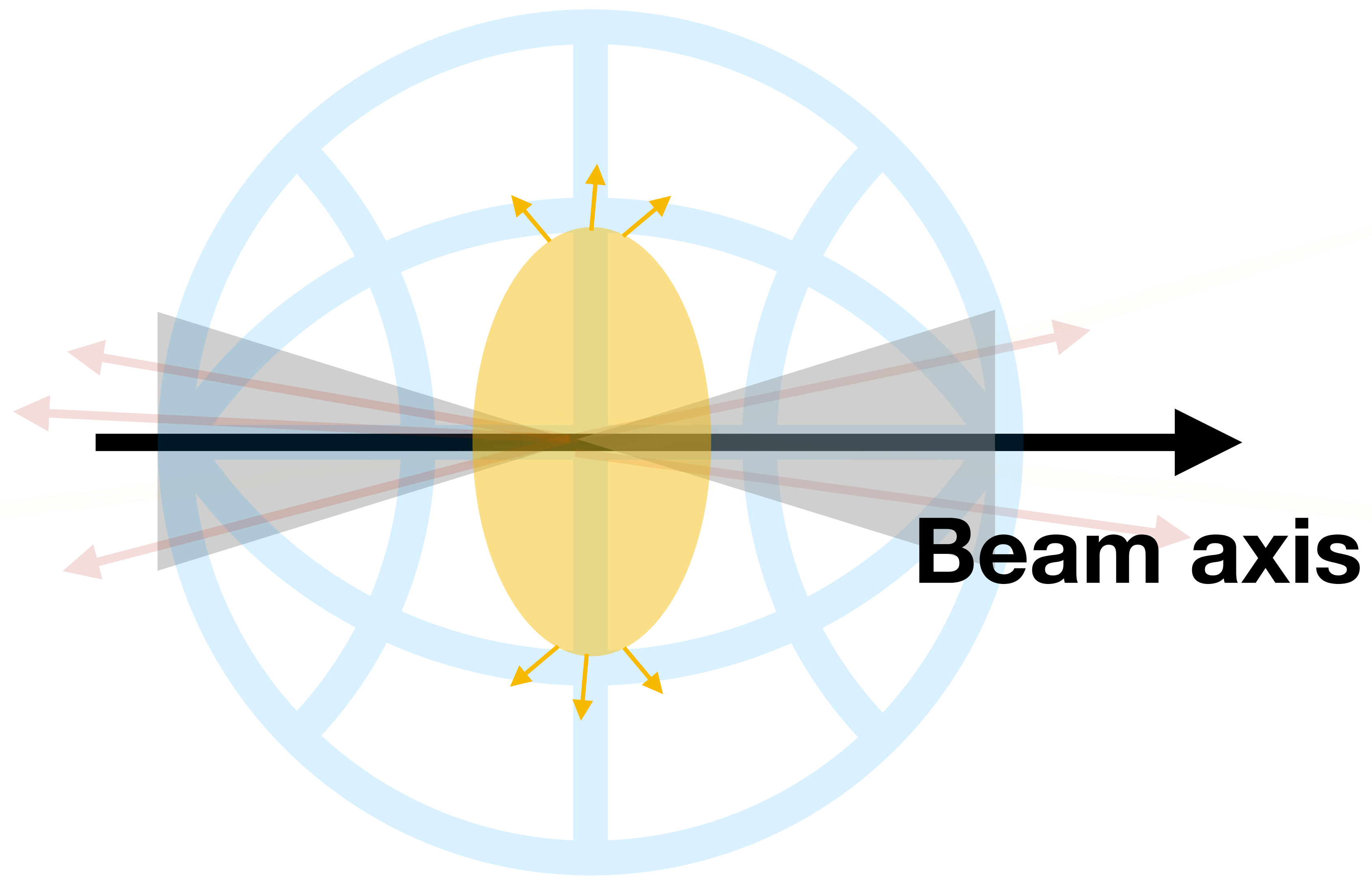




If high energy quarks can form some medium, looking from the thrust axis is sensitive to the azimuthal anisotropy of this "imaginary medium."

ALEPH
e^+e^-: Phys. Rev. Lett. 123, 212002 (2019)

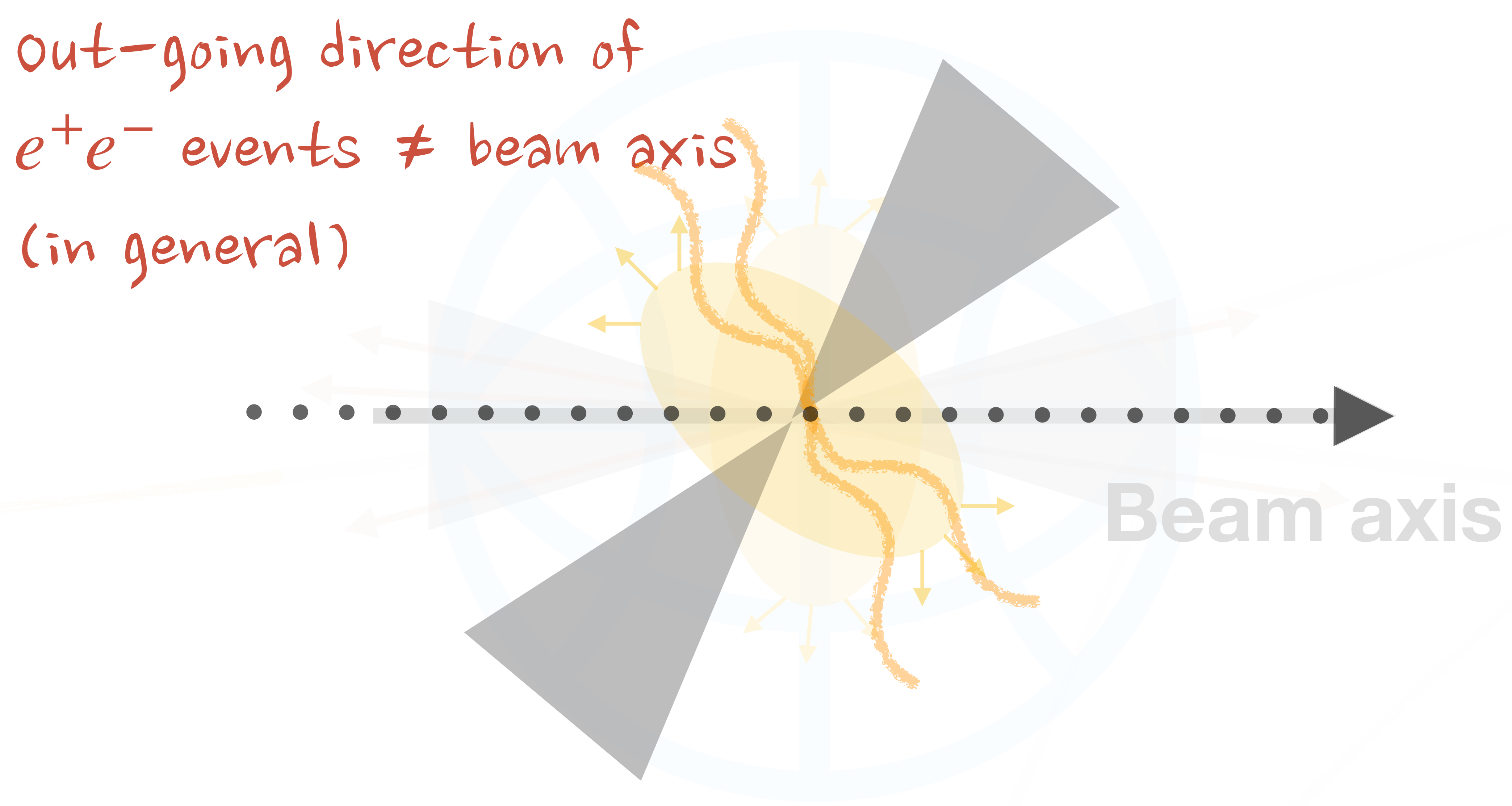
Thrust-axis two-particle correlation

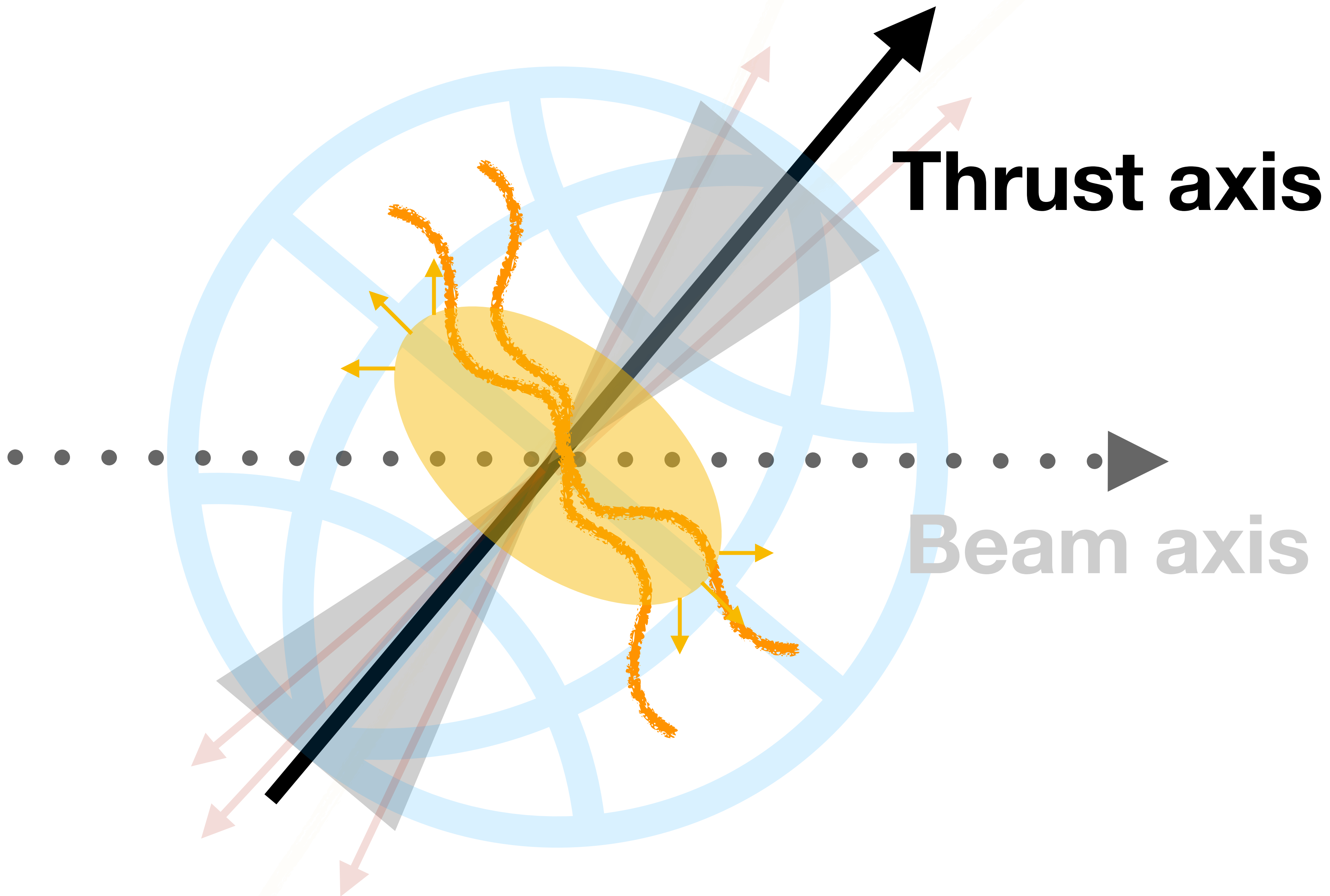


The **mid rapidity region** is where a correlation function sensitive to:

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

Thrust-axis two-particle correlation



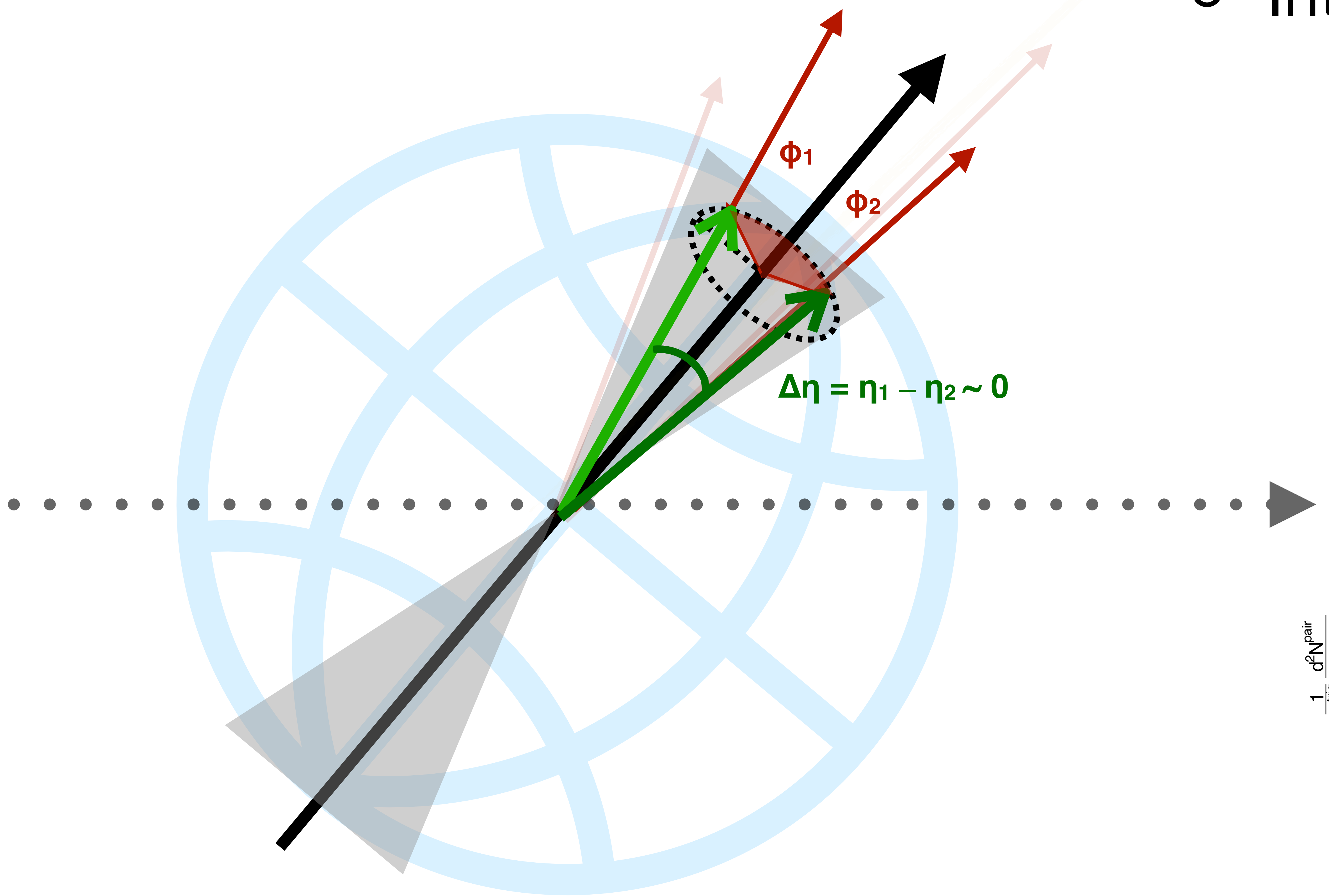


The **mid rapidity region** is where a correlation function sensitive to:

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

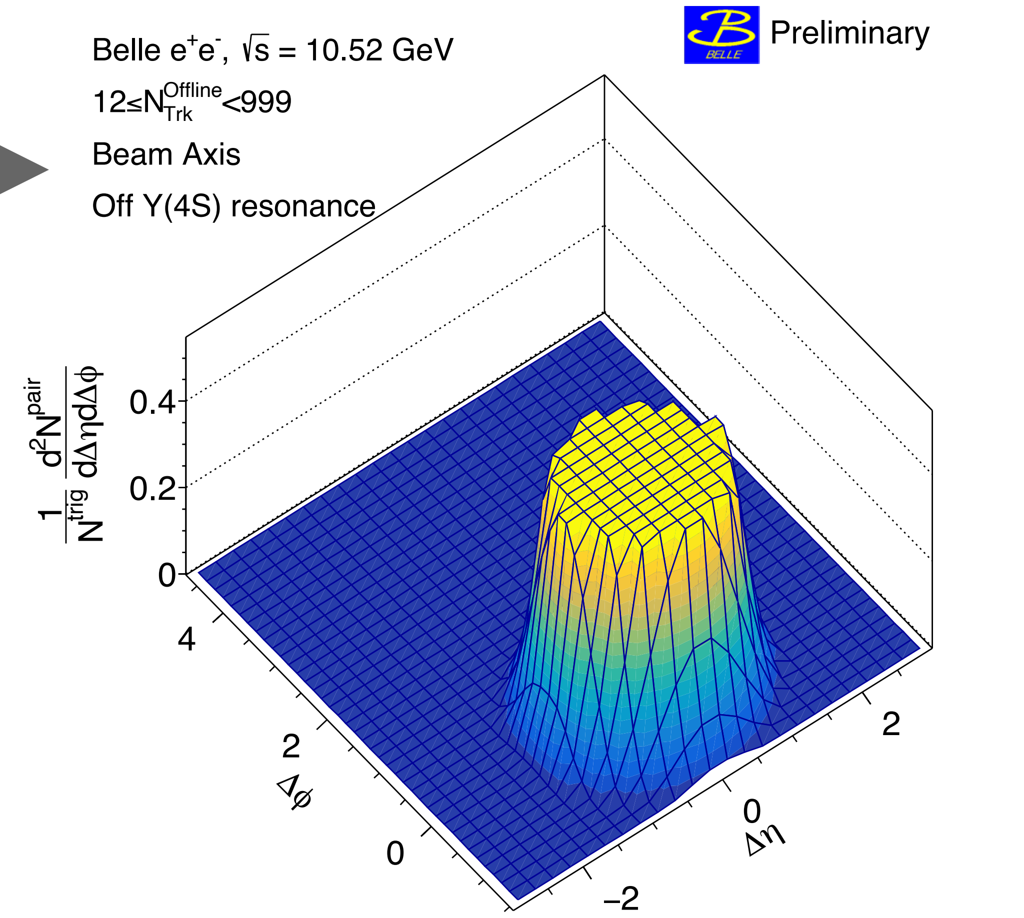
- Thrust axis analysis:
  soft emissions or QGP in e^+e^- annihilation

How to understand correlation function in thrust axis coordinate?

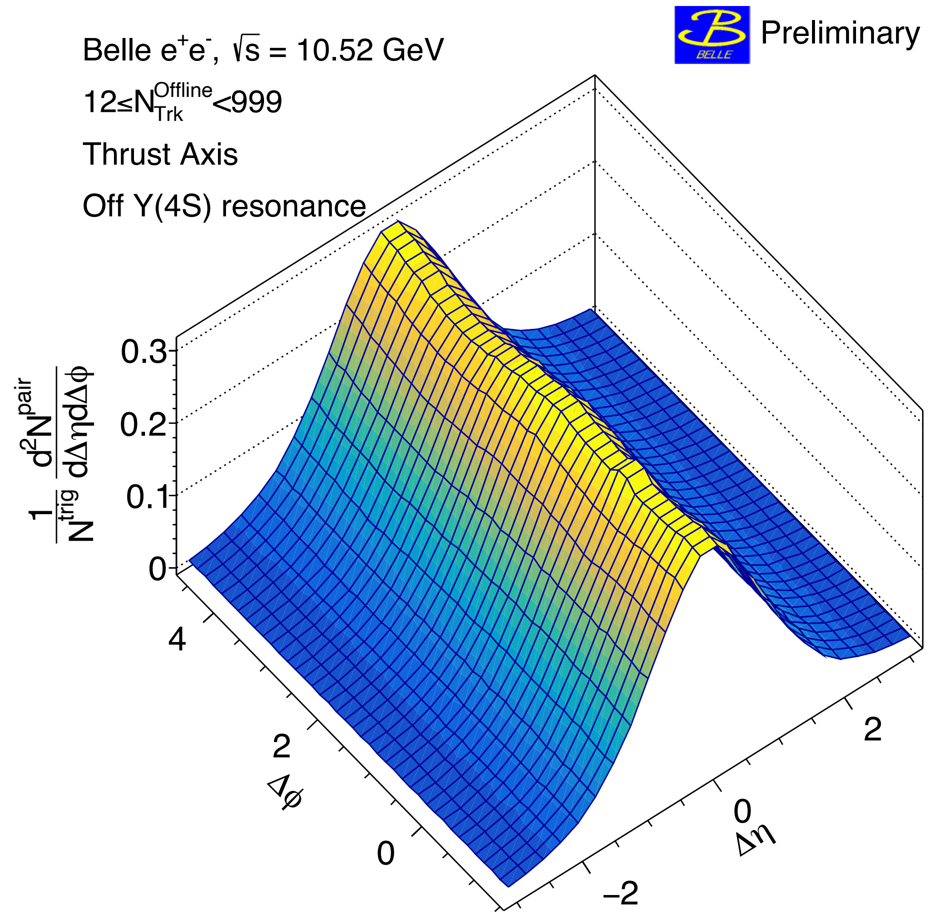


- Intra-jet correlation of on-axis jets is diluted!

Collinear leading intra-jet correlation dilutes along Δϕ

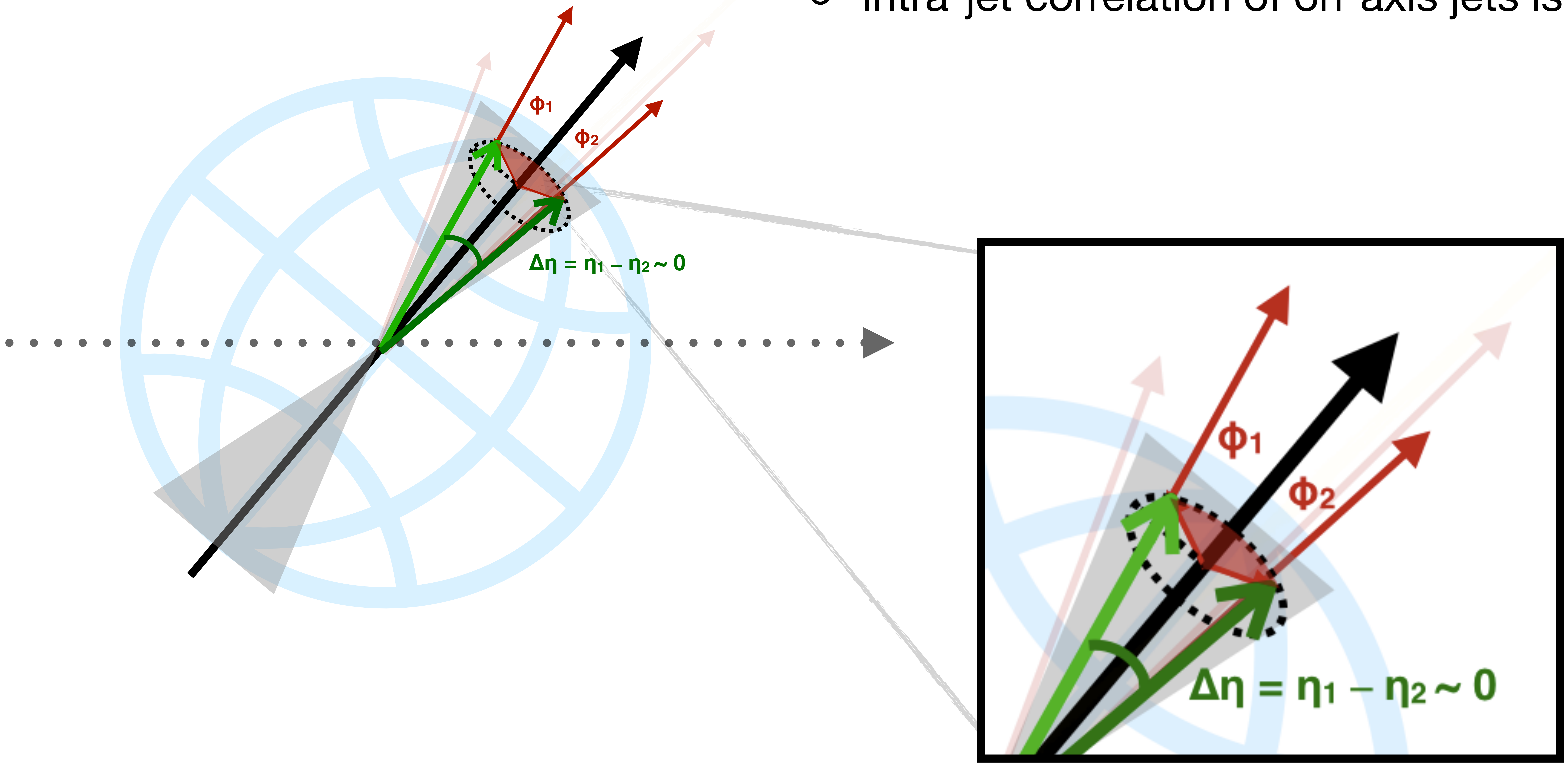


leading intra-jet correlation viewed @ beam coordinate



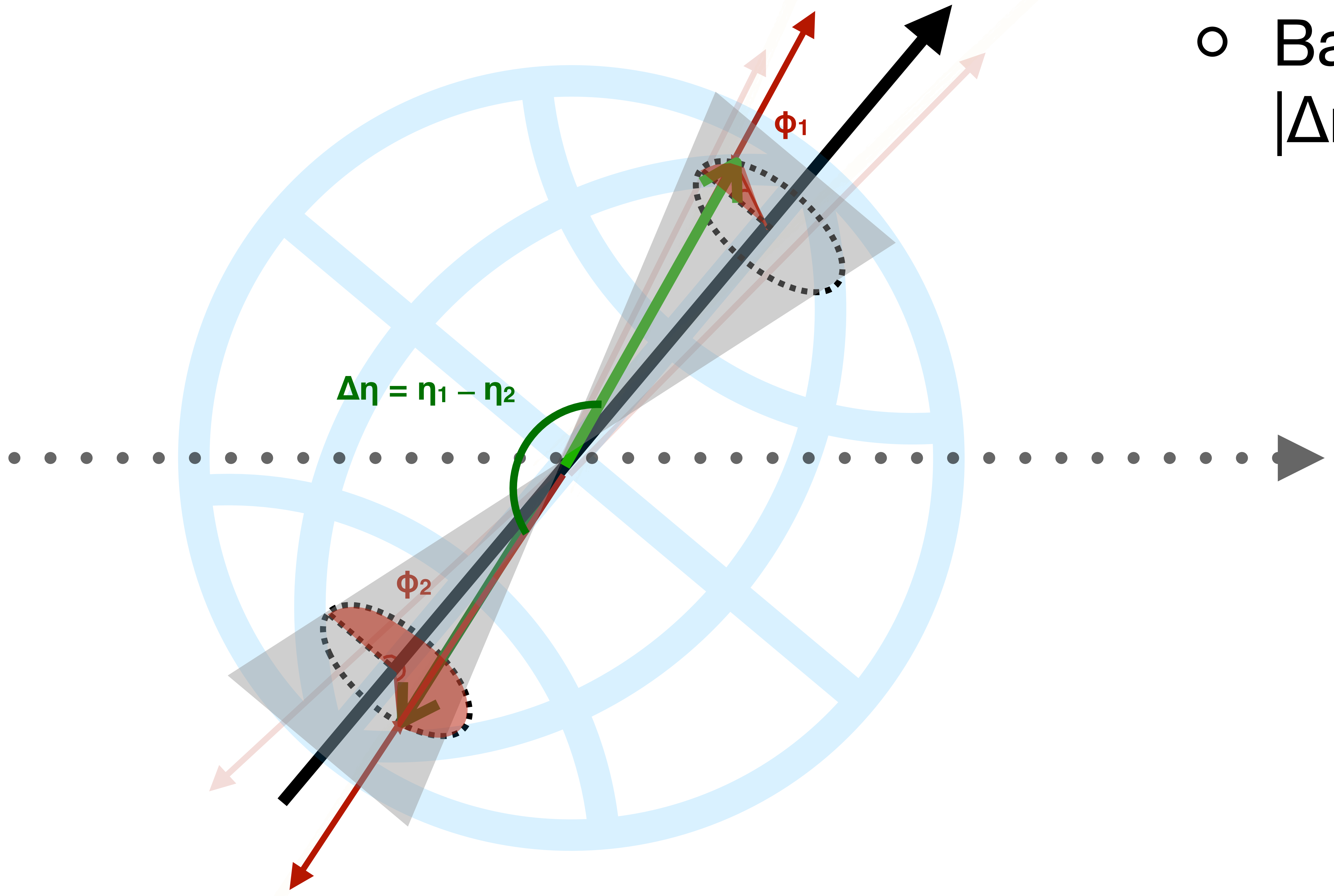
leading intra-jet correlation viewed @ thrust coordinate

A weakened jet correlation

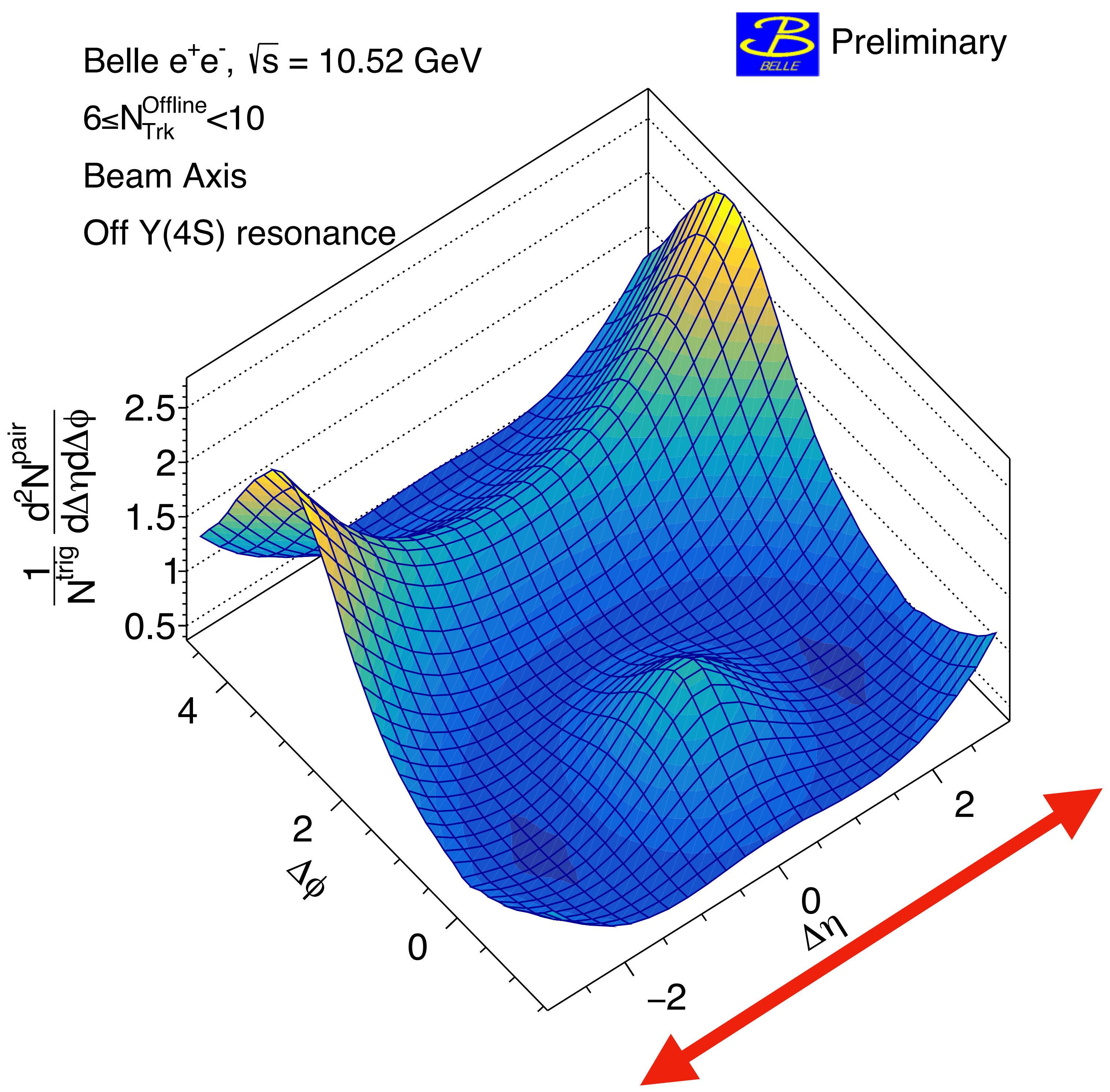


- Intra-jet correlation of on-axis jets is diluted!

A weakened jet correlation

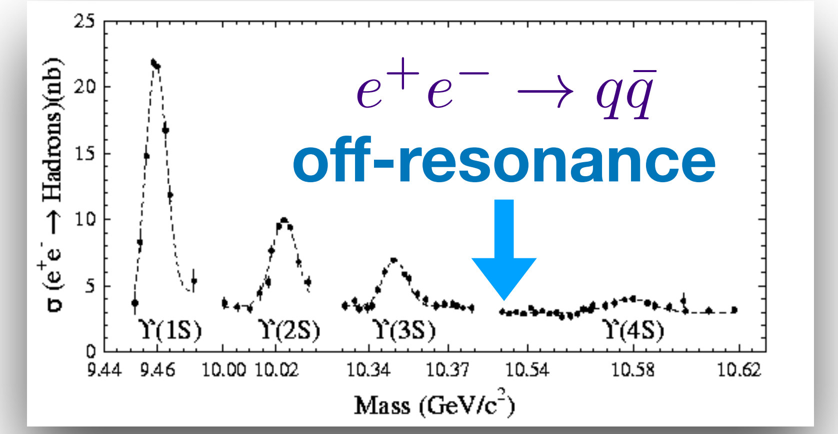


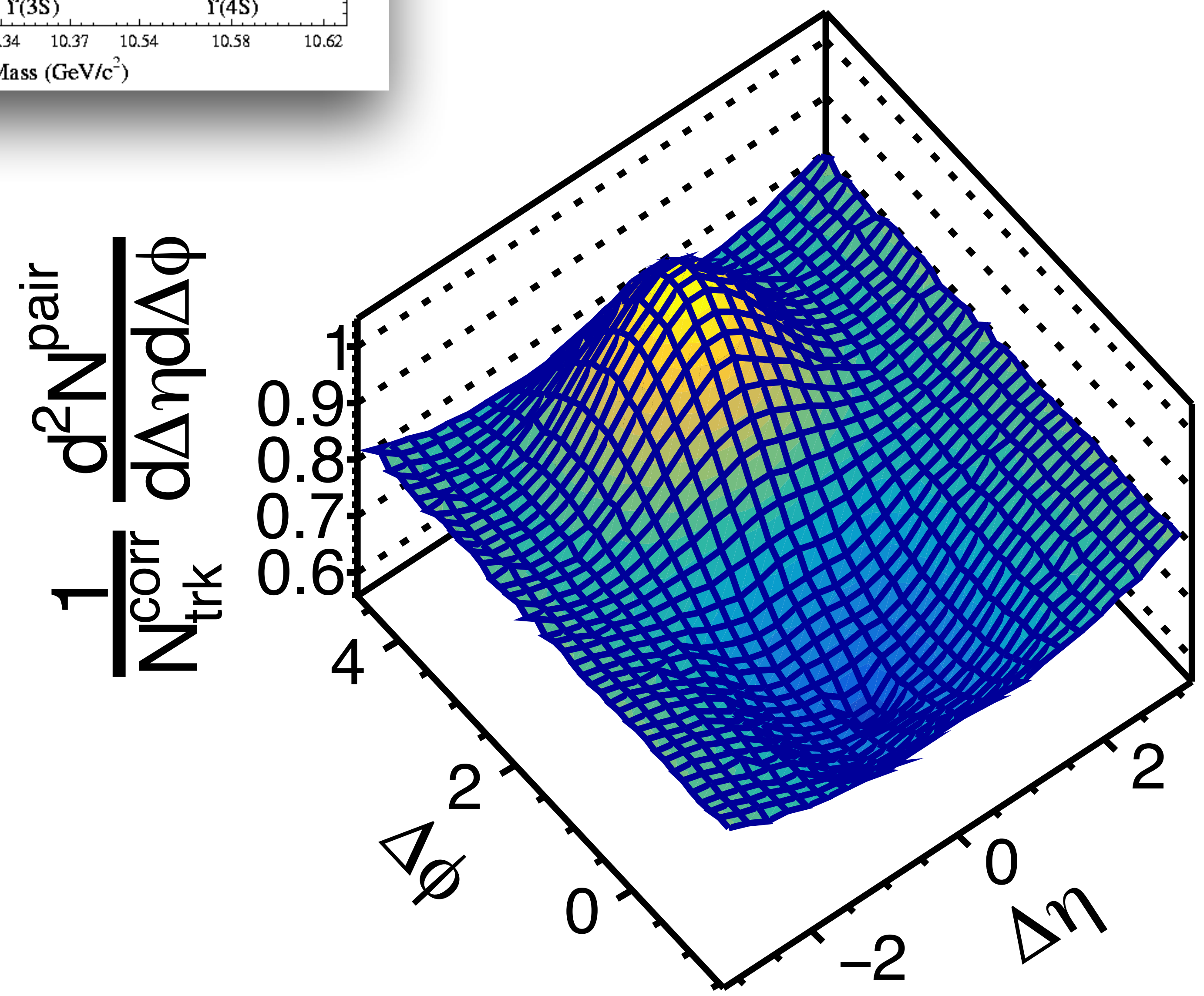
- Intra-jet correlation of on-axis jets is diluted!
- Back-to-back-jet correlation is excluded at finite $|\Delta\eta|$ region of interest



Thrust-axis two-particle correlations — off-resonance ($\sqrt{s}$=10.52 GeV)

- Sizable origin-peak is lacking
- Qualitatively good agreement in correlation function shape btw data and MC

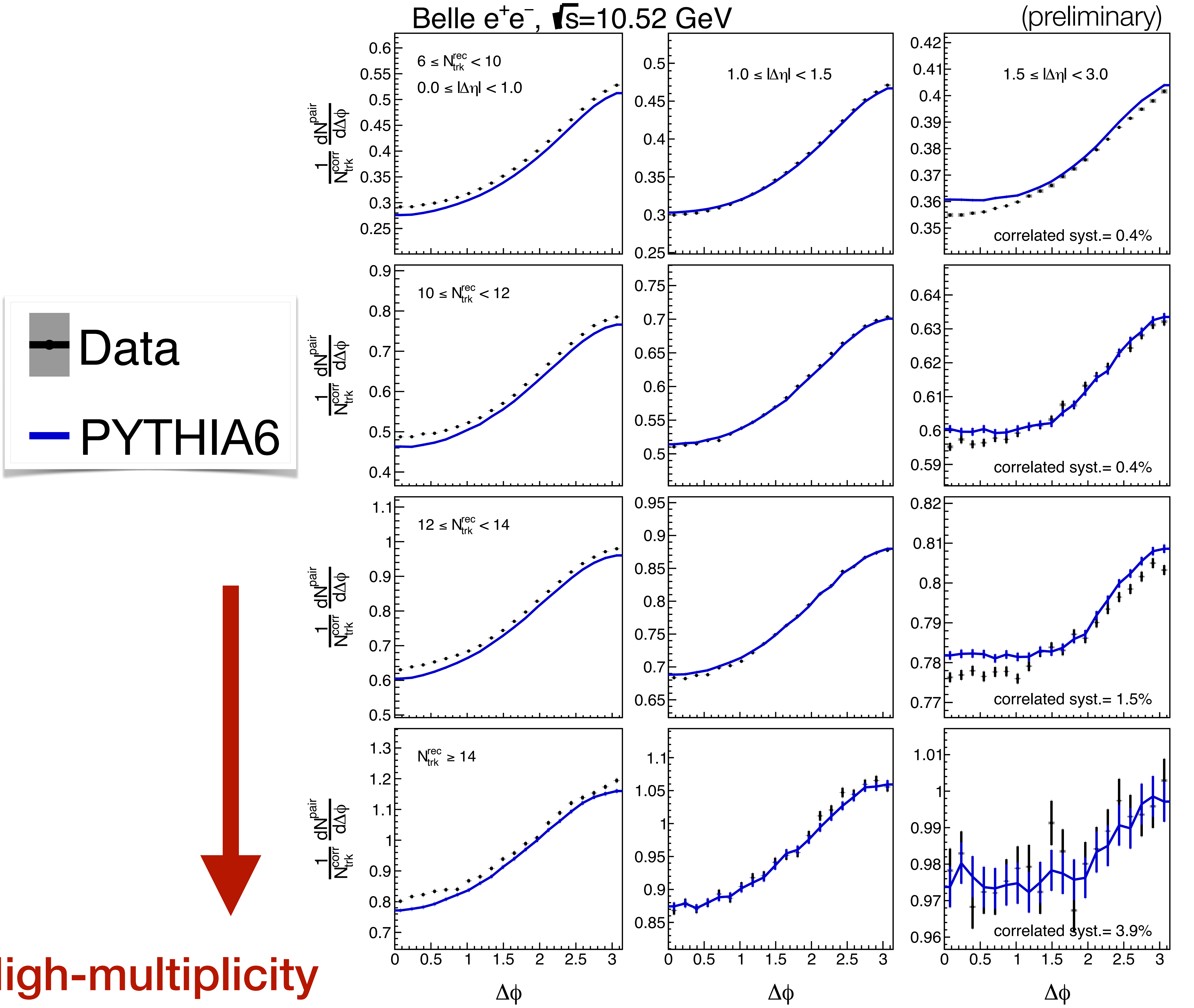




$12 \le N_{trk}^{rec} < 14$

arXiv:2201.01694
accepted by PRL

High-multiplicity



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

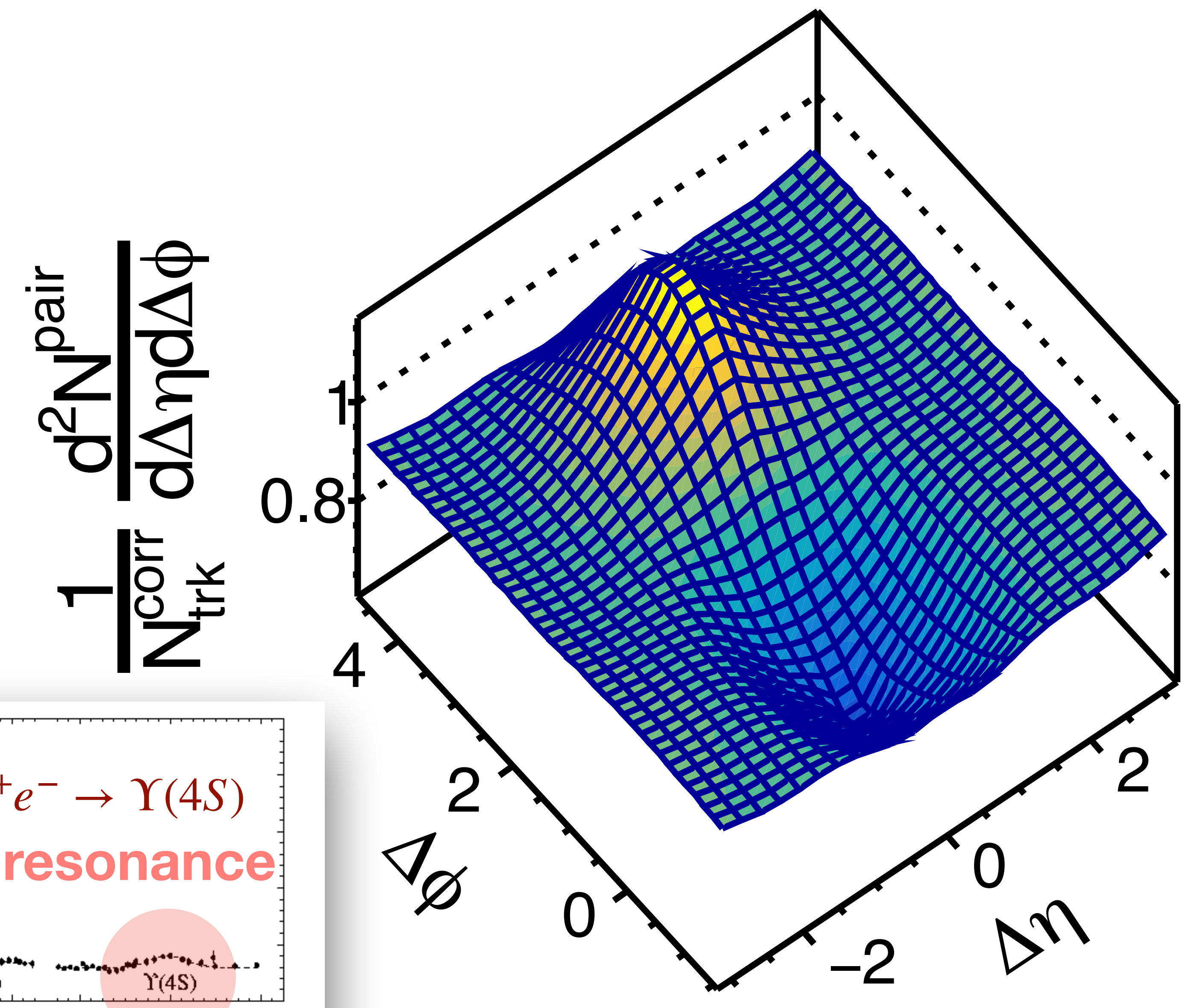
Middle Range ($1 \le |\Delta\eta| < 1.5$)

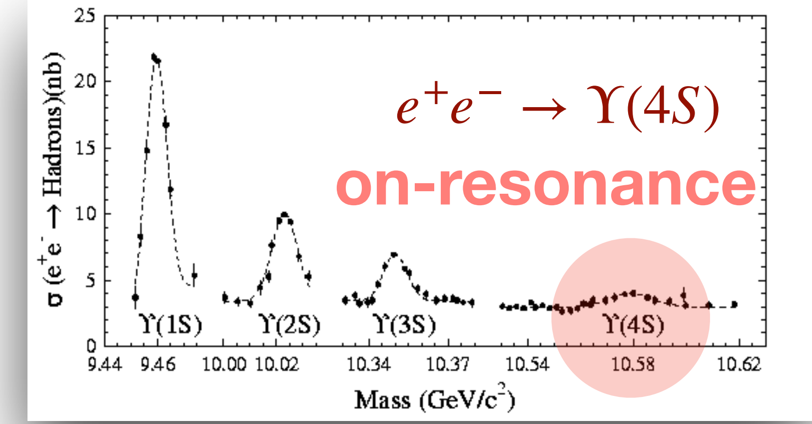
Long Range ($1.5 \le |\Delta\eta| < 3.0$)

Result

Thrust-axis two-particle correlations — on-resonance ($\sqrt{s}$=10.58 GeV)

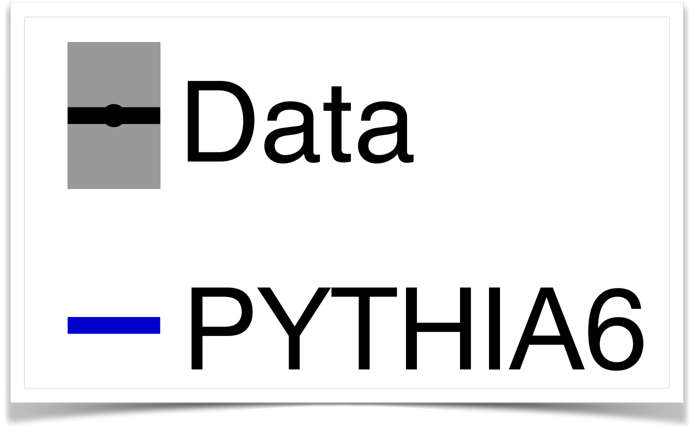
- Enhanced long-range near-side correlation, but does NOT resemble to typical ridge structure
- Similar enhancement seen in MC
- Up to 5% larger discrepancy seen in the correlation magnitude in the long-range region



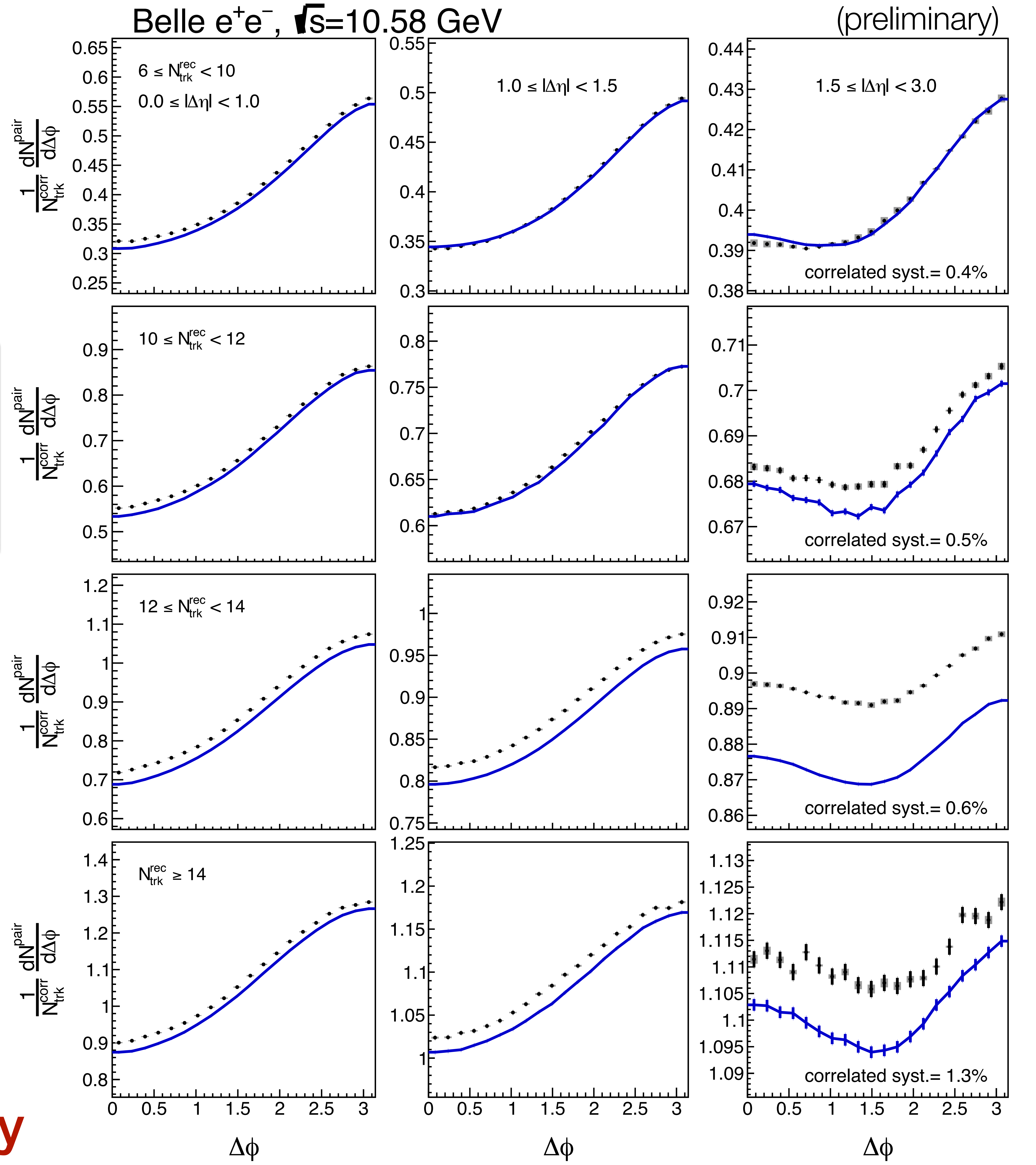


paper in preparation

$$12 \leq N^{rec}_{trk} < 14$$



High-multiplicity



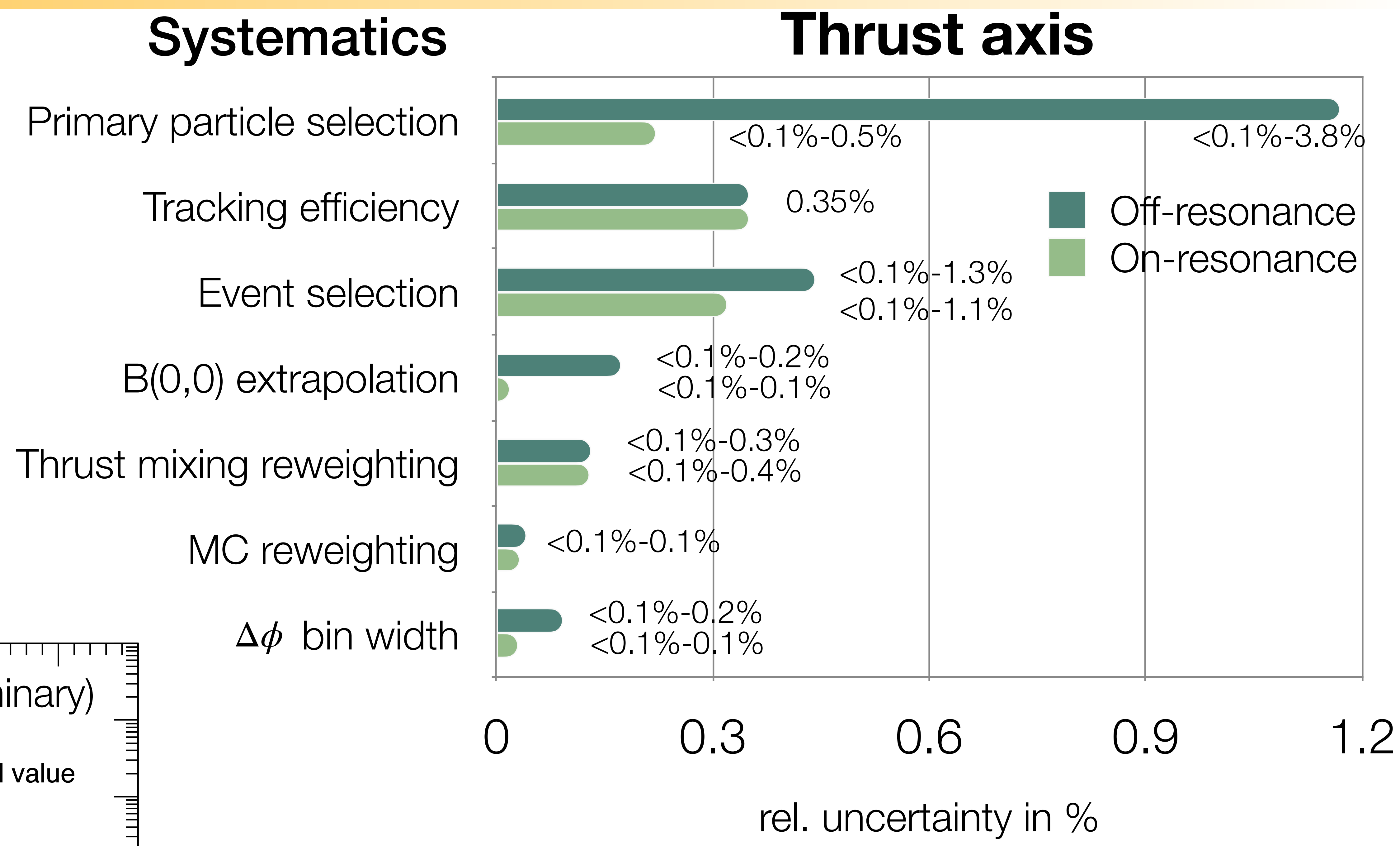
Short Range ($0 \leq |\Delta\eta| < 1$)

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

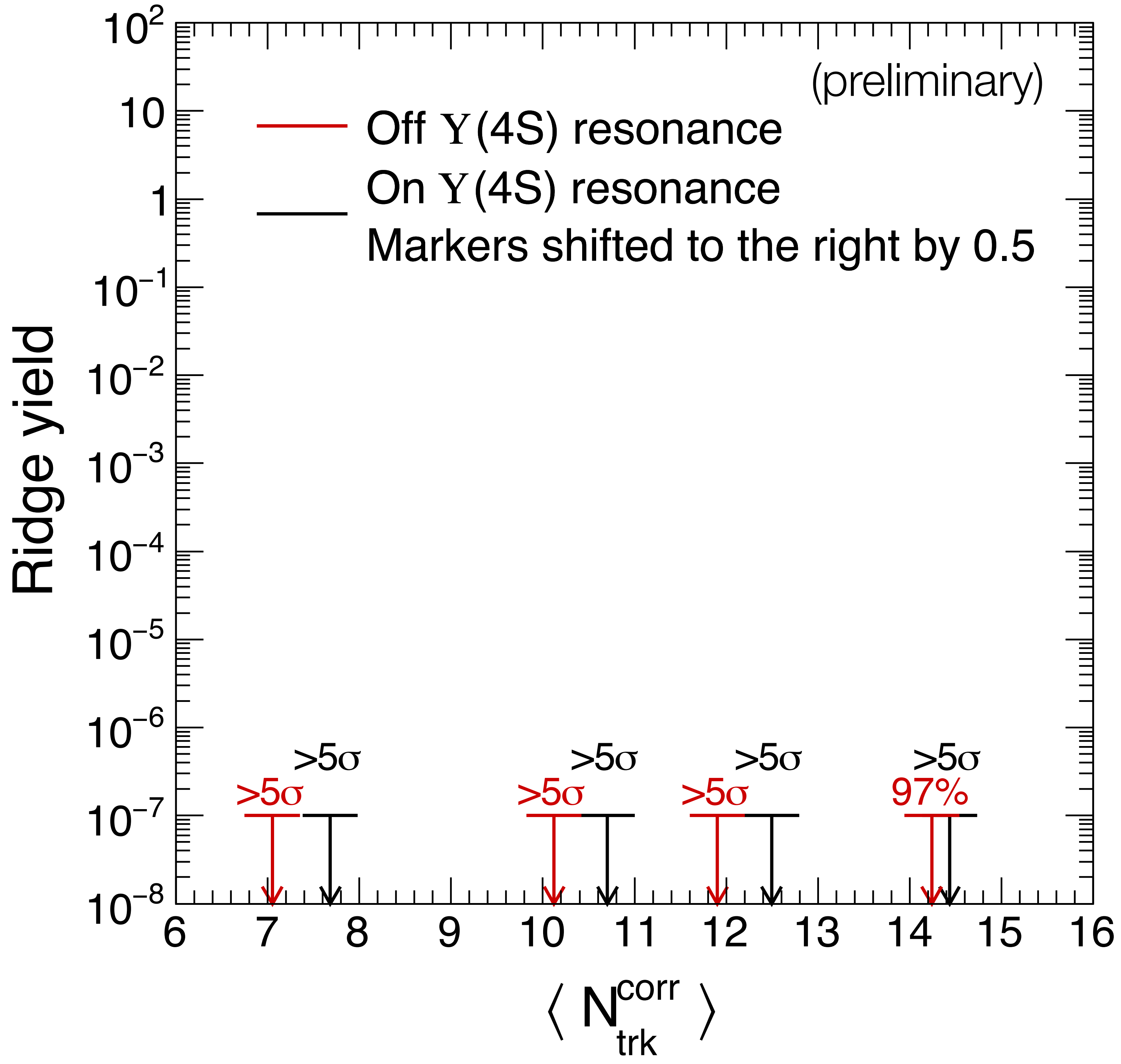
Long Range ($1.5 \leq |\Delta\eta| < 3.0$)

Ridge yield upper limits

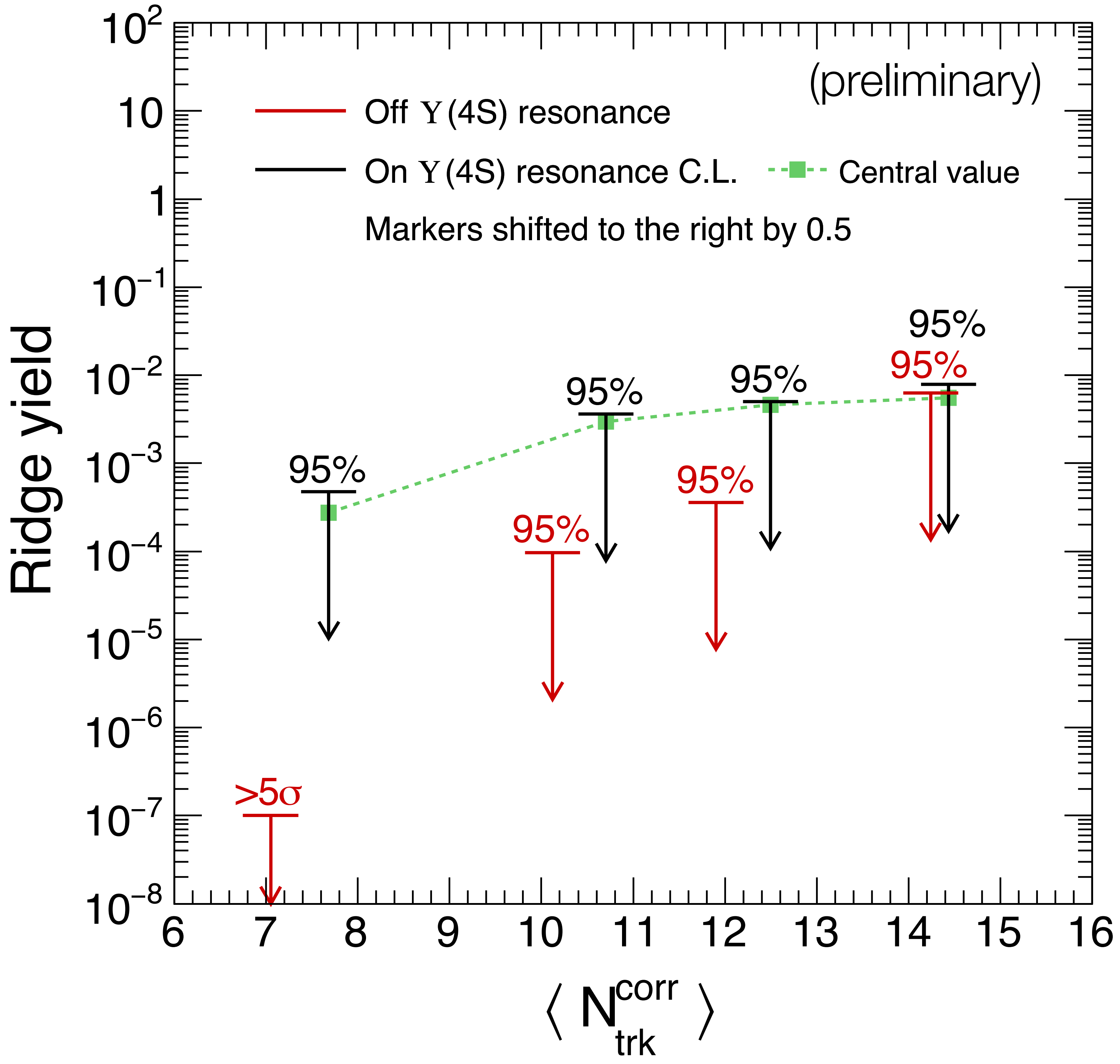
- Selections are the dominant systematics sources
- Beam axis analysis: >5σ exclusion of ridge signal



Beam axis



Thrust axis



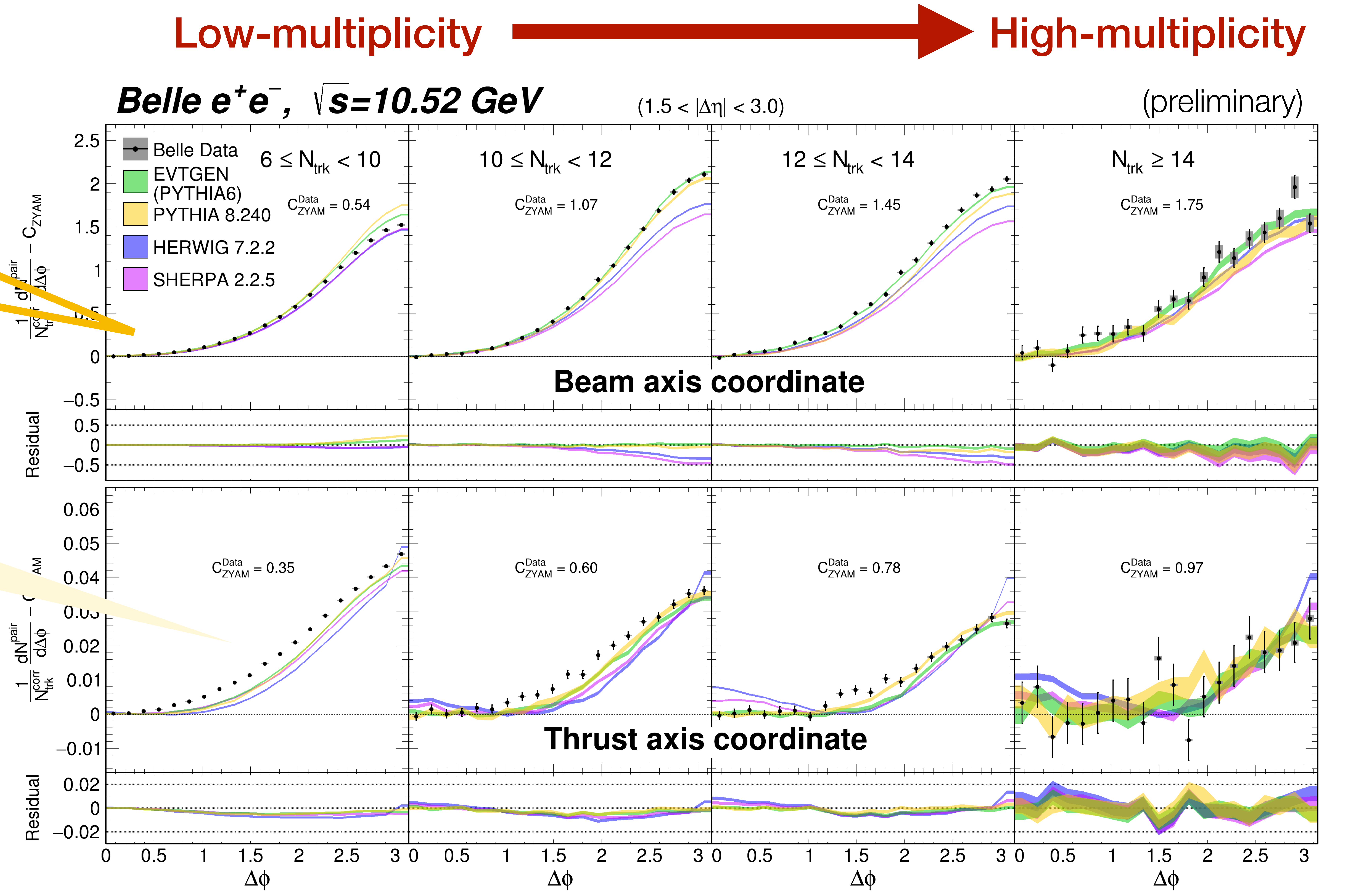
- Thrust axis analysis:
  - Off-resonance: no significant ridge signal, but C.L. in high-multiplicity bins are limited by statistics
  - On-resonance: low-scale long-range near-side enhancement

Off-resonance $Y(\Delta\phi)$

- MCs consistent with data in near side
- Discrepancies in the away-side magnitude

Differences in data & MC correlation shapes

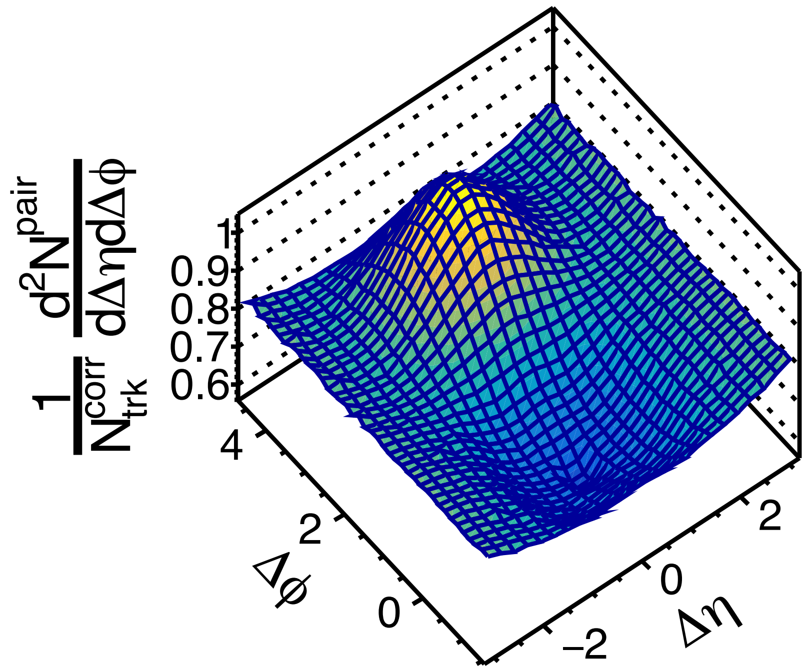
- PYTHIA6 agrees better with data than HERWIG & SHERPA
- PYTHIA8 has similar behavior as PYTHIA6

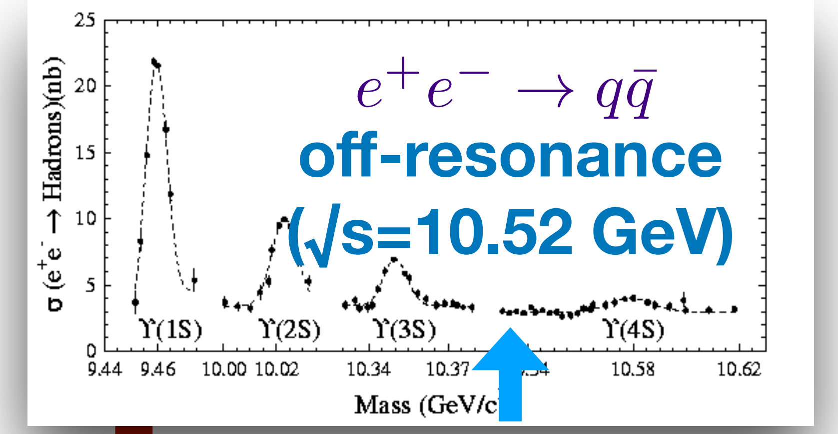


on-resonance see backup

Understanding the thrust-axis two-particle correlations

Lack of origin-peak jet correlation





- Sharp origin-peak correlation is recovered as √s goes high
- Thrust-axis analysis: from null to significant intra-jet correlation!

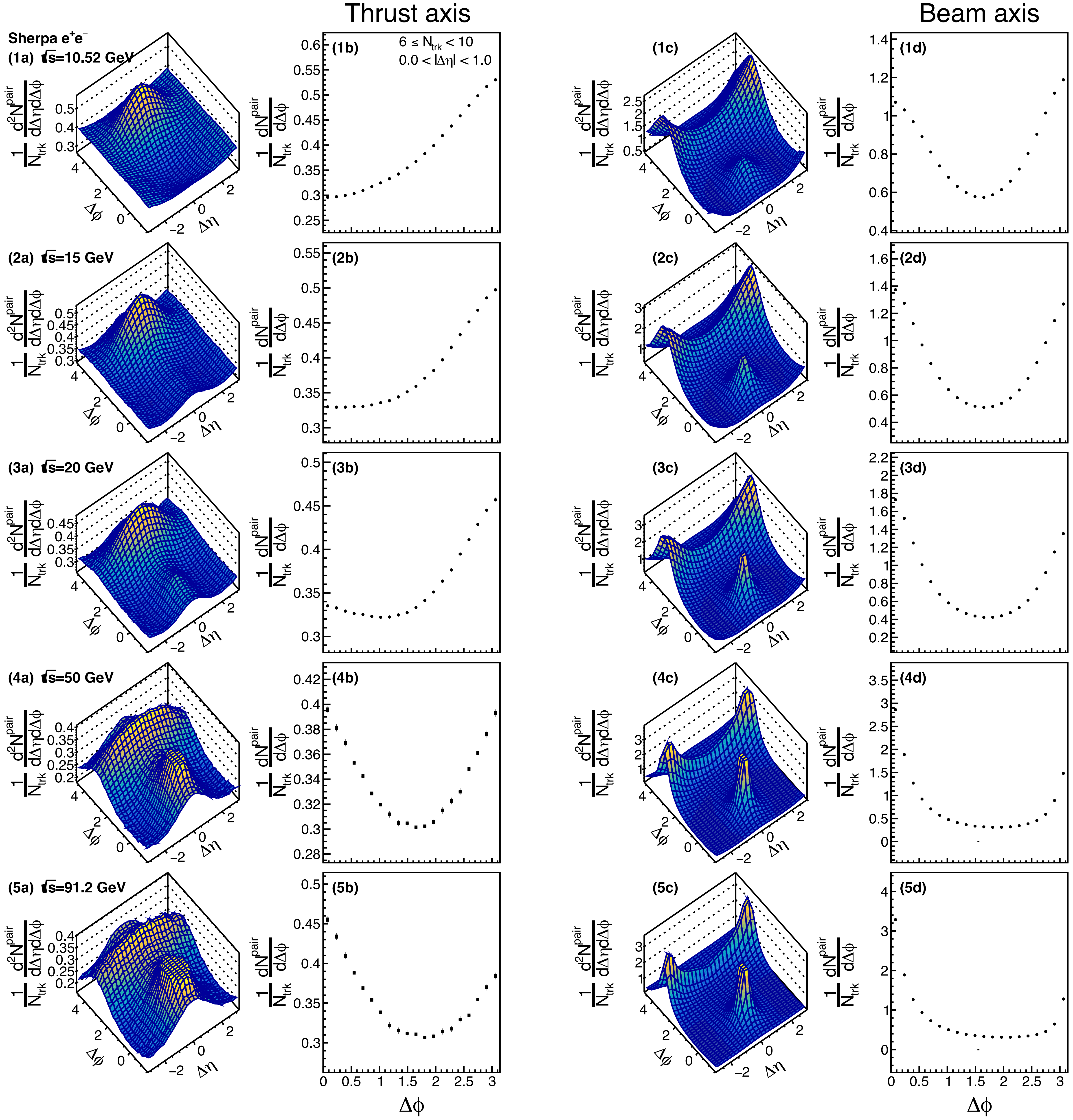
√s = 15 GeV

√s = 20 GeV

√s = 50 GeV

√s = 91.2 GeV (LEP1 energy)

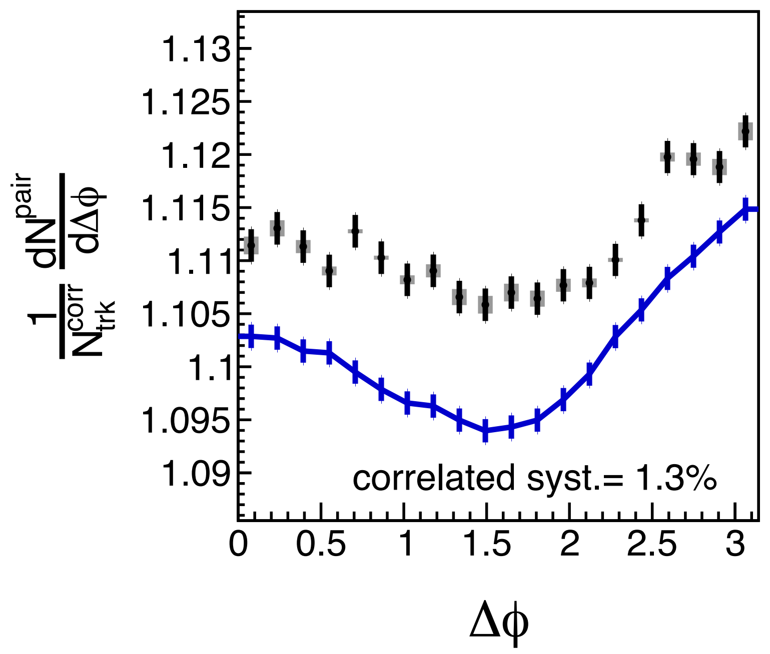
Larger origin peak correlation is found

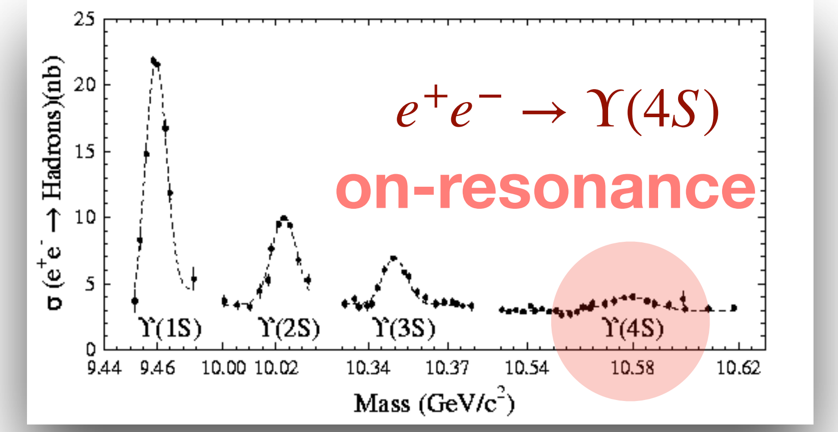


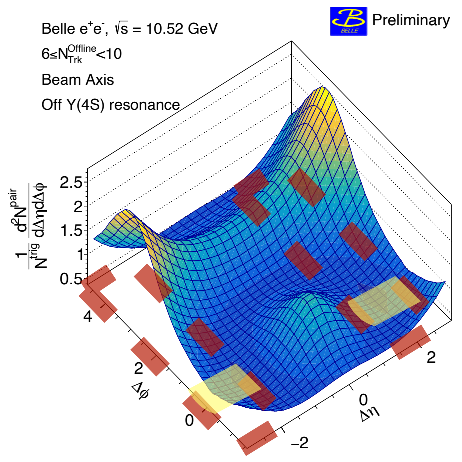
* Demonstrated with $6 \leq N_{trk} < 10$
This phenomenon is seen in all multiplicity ranges

Understanding the thrust-axis two-particle correlations

Long-range near-side enhancement in on-resonance sample

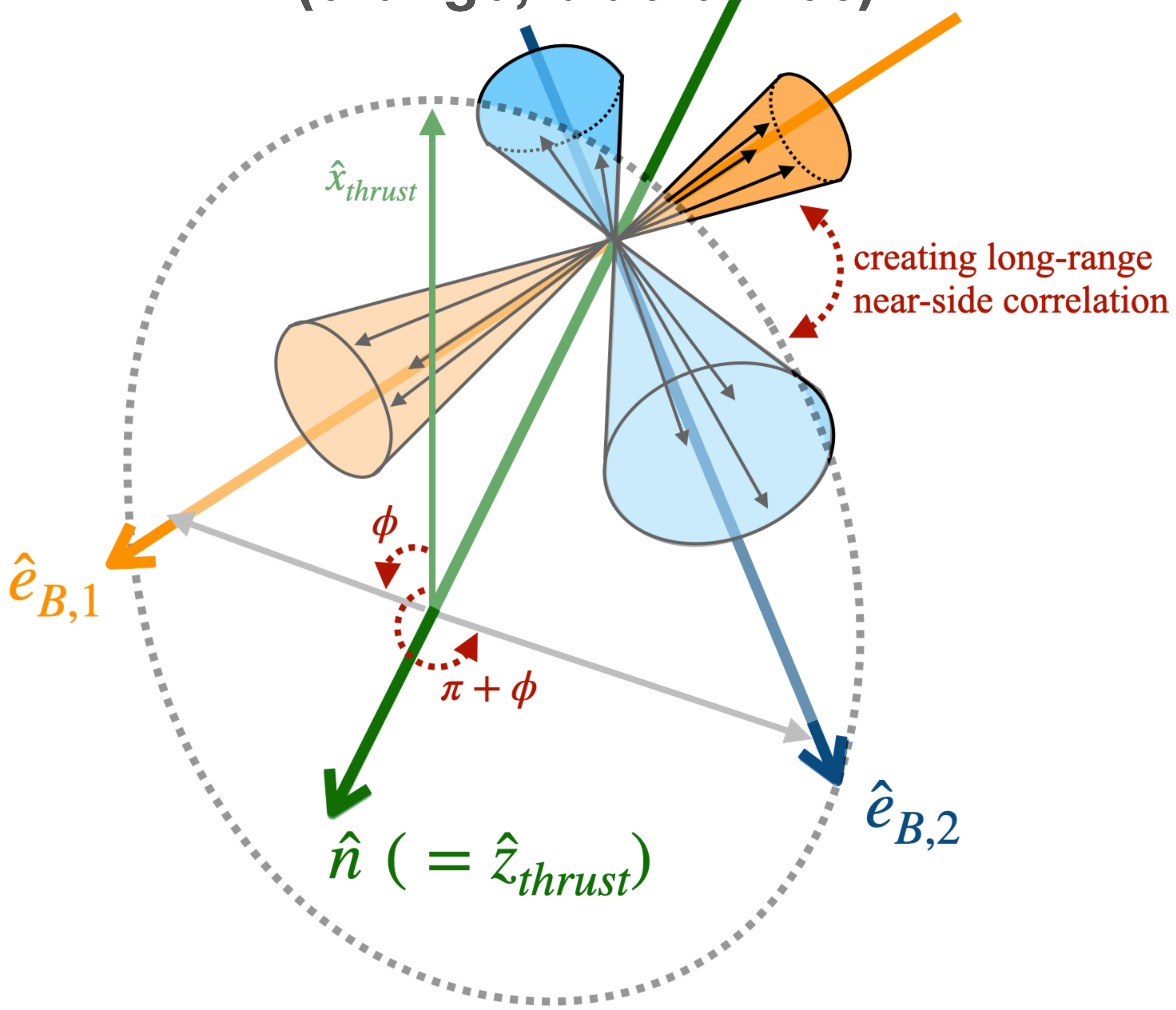


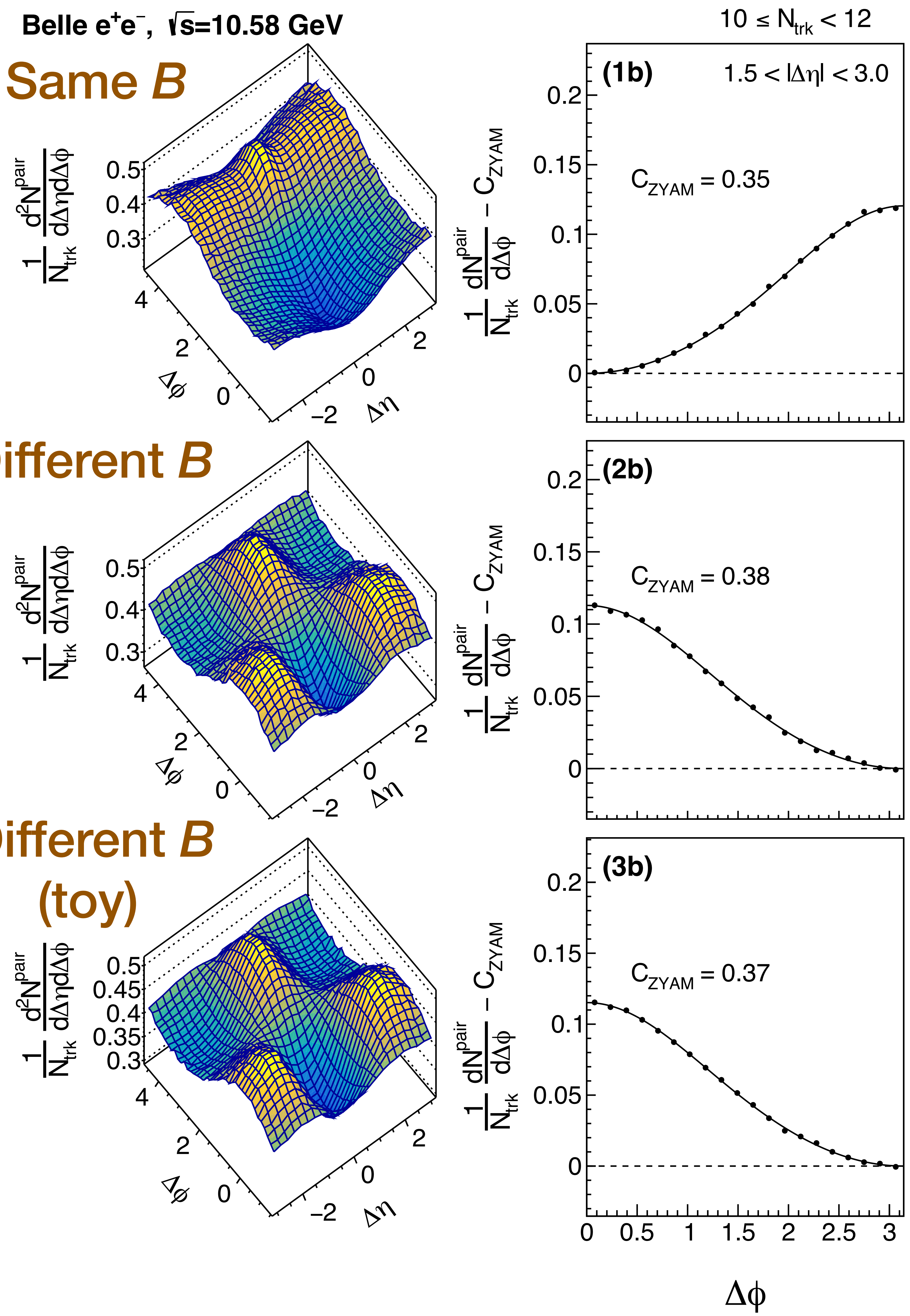




- Two *B*-meson decays: special event topology thrust axis alignment
- Toy sample pairing uncorrelated B's from different events shows similar enhancement!

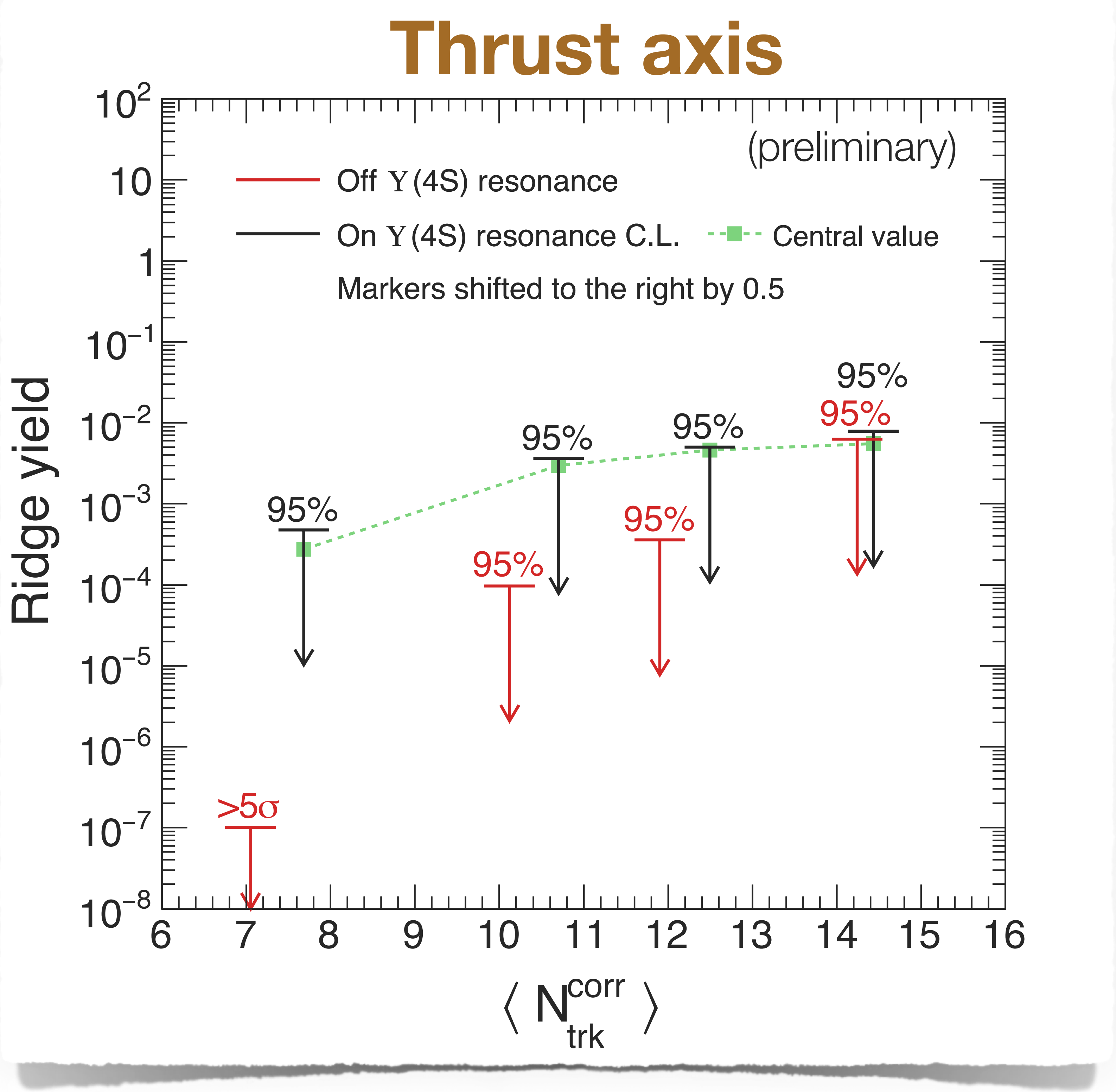
Schematic plot for $\Upsilon(4S) \to B\bar{B}$ (orange, blue cones)





Conclusion

- First results of two-particle correlations measured in both beam axis and thrust axis coordinates at Belle
- Beam axis analysis, strong exclusion of ridge signals
- Thrust axis analysis:
  - Off-resonance: no significant ridge signal, origin-peak jet correlation scales with collision energy
  - On-resonance: low-scale long-range near-side enhancement due to special decay topology of $\Upsilon(4S) \rightarrow B\bar{B}$ system, observed also on MC
- `PYTHIA` is in better agreement with data than `SHERPA` & `HERWIG`

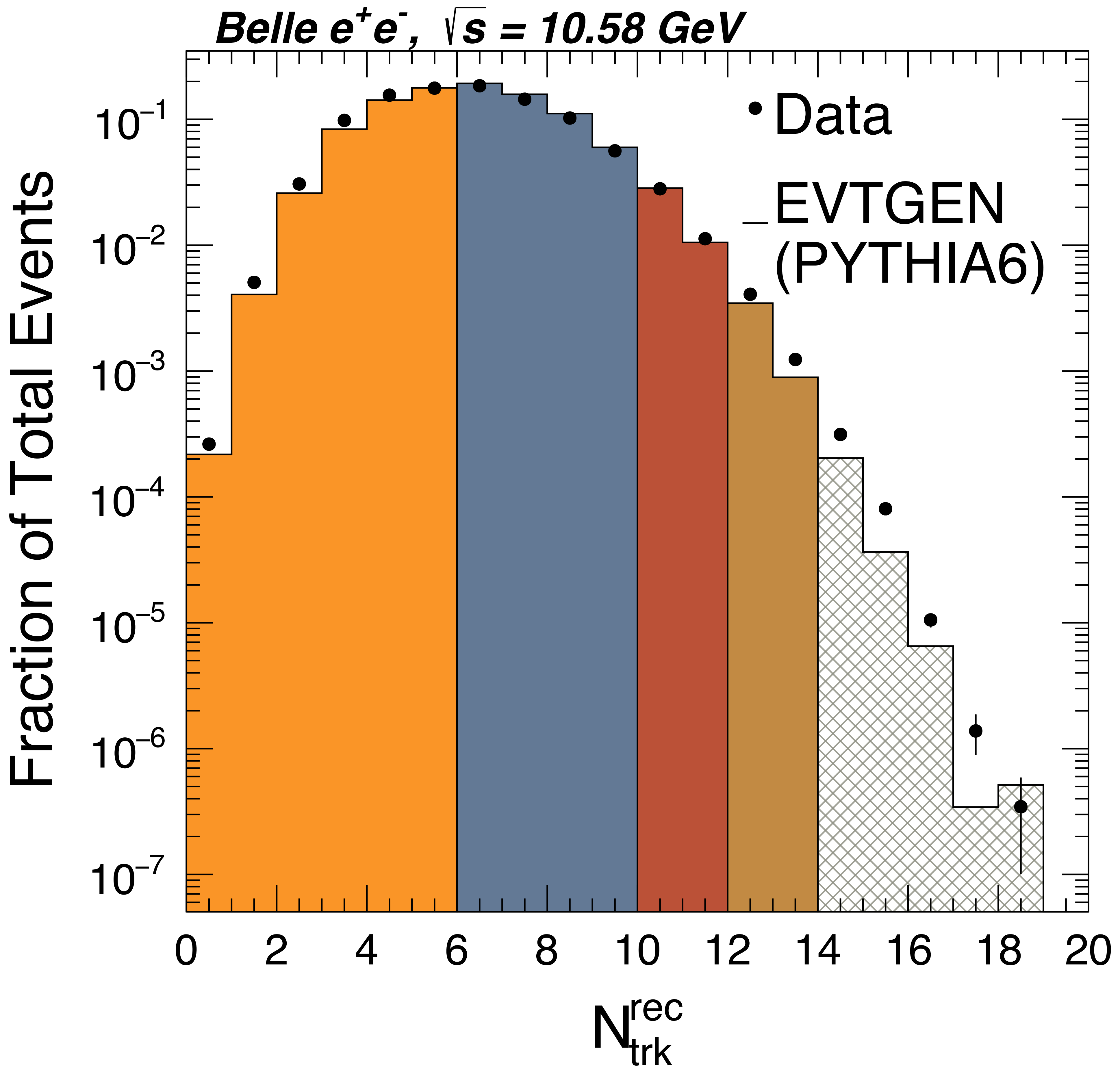


Backup

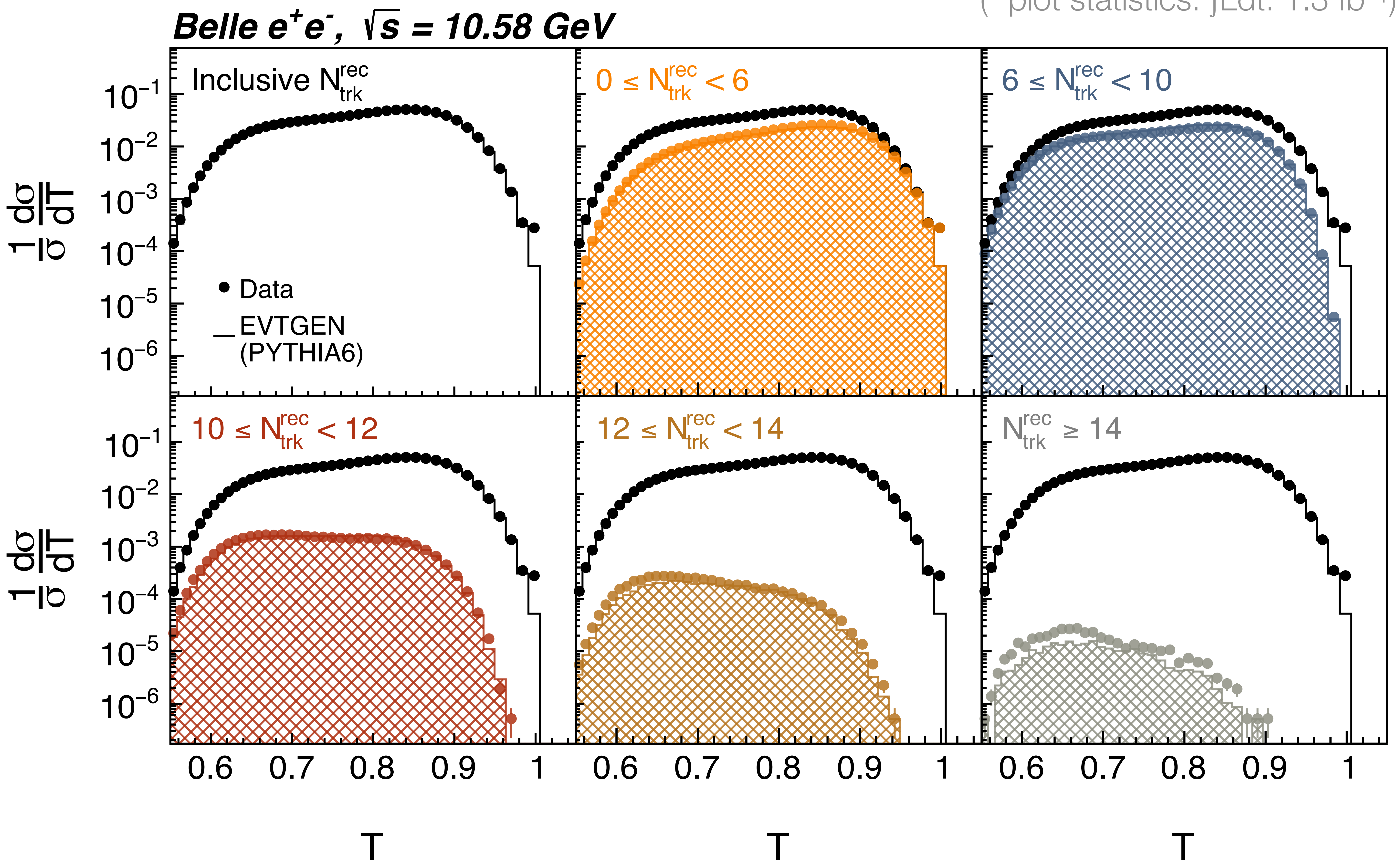
Sample

Charged particles	
Primary tracks	• [reconstructed] the distance in the transverse plane of the decay vertex from the primary vertex < 1 cm • [MC-truth] decay promptly or from particles with proper lifetime $\tau \leq 1$ cm/c
Acceptance	$17° \leq \theta \leq 150°$
High quality tracks	$p_T \geq 0.2$ GeV
Impact parameter	$\|\Delta r\| < 2$, $\|\Delta z\| < 5$
Duplicate track removal	veto the softer track of a low-momentum pair ($p_T < 0.4$ GeV) travelling with a small open angle δ: 1. same-sign charges with $\cos\delta > 0.95$ 2. opposite-sign charges with $\cos\delta < -0.95$
Photon conversion veto	veto track pairs which can form common vertices (V^0 objects) with 1. z distance between two tracks < 10 cm 2. reconstructed V^0's mass < 0.25 GeV 3. decay-vertex radius > 1.5 cm
Neutral particles (for thrust calculation)	
Cluster selection	No direct track-matching and tracks matched at cluster edges
Acceptance	$17° \leq \theta \leq 150°$
Energy cut	Forward endcap: $E < 0.10$ GeV Backward endcap: $E < 0.15$ GeV Barrel: $E < 0.05$ GeV

On-resonance multiplicity distribution and thrust distribution

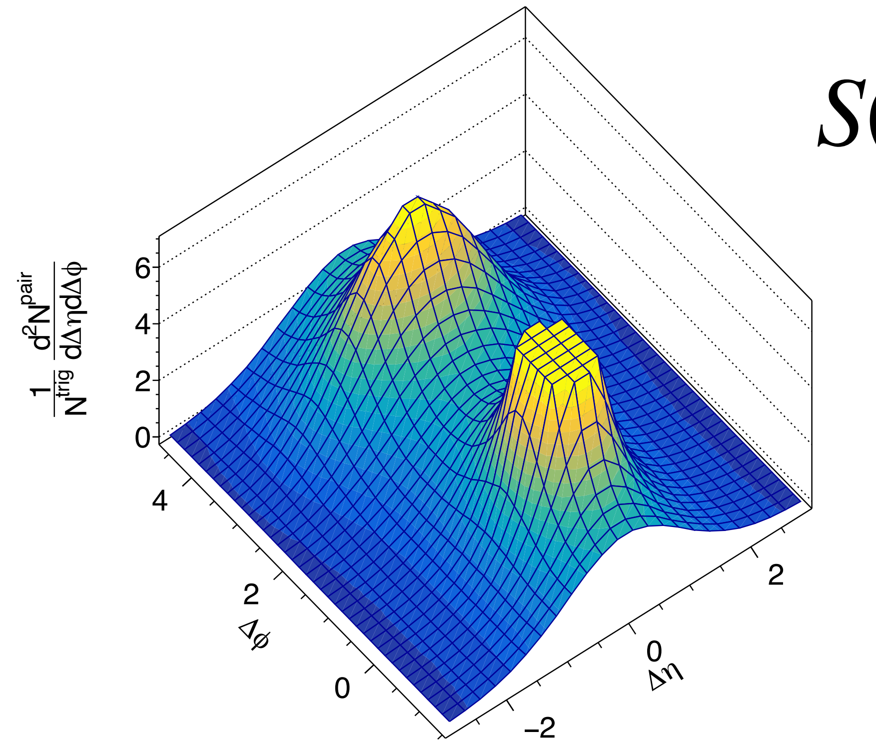


(* plot statistics: ∫Ldt: 1.3 fb⁻¹)



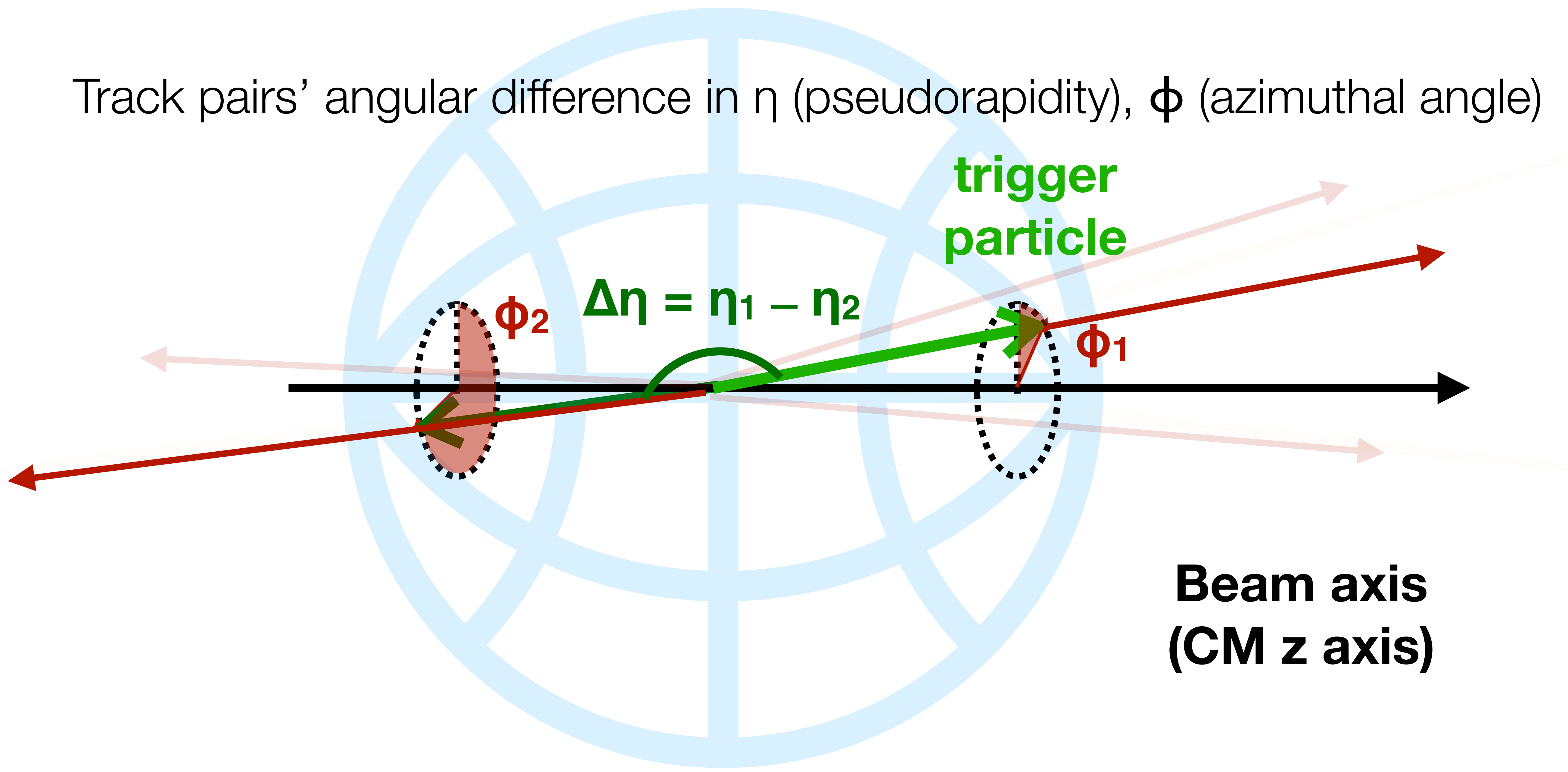
Two-particle correlation w.r.t. beam axis

Signal
(raw correlation function)

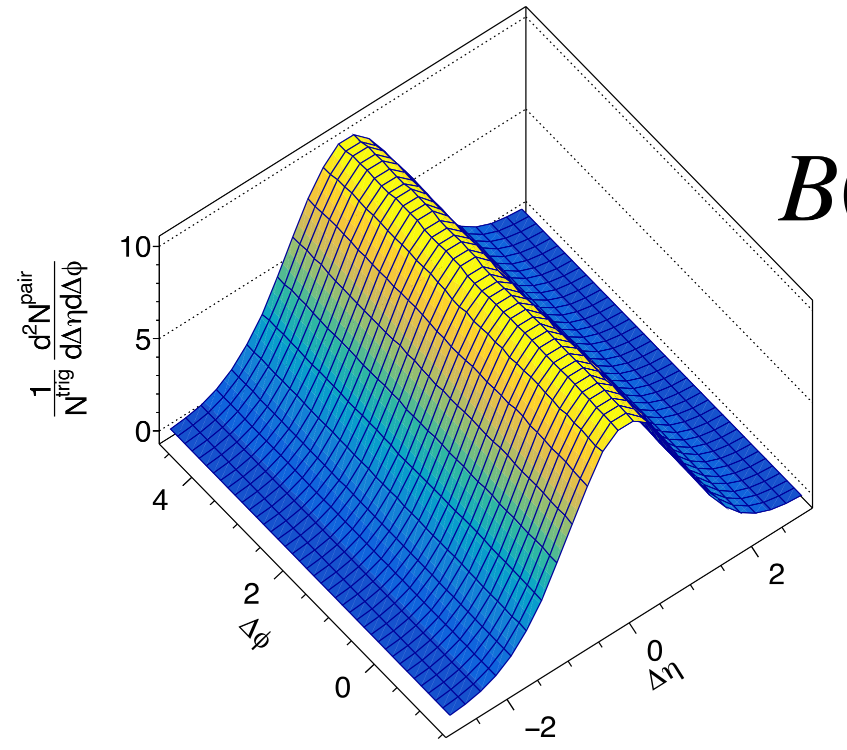


$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{\rm trk}^{\rm corr}} \frac{d^2N^{\rm same}}{d\Delta\eta d\Delta\phi}$$

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

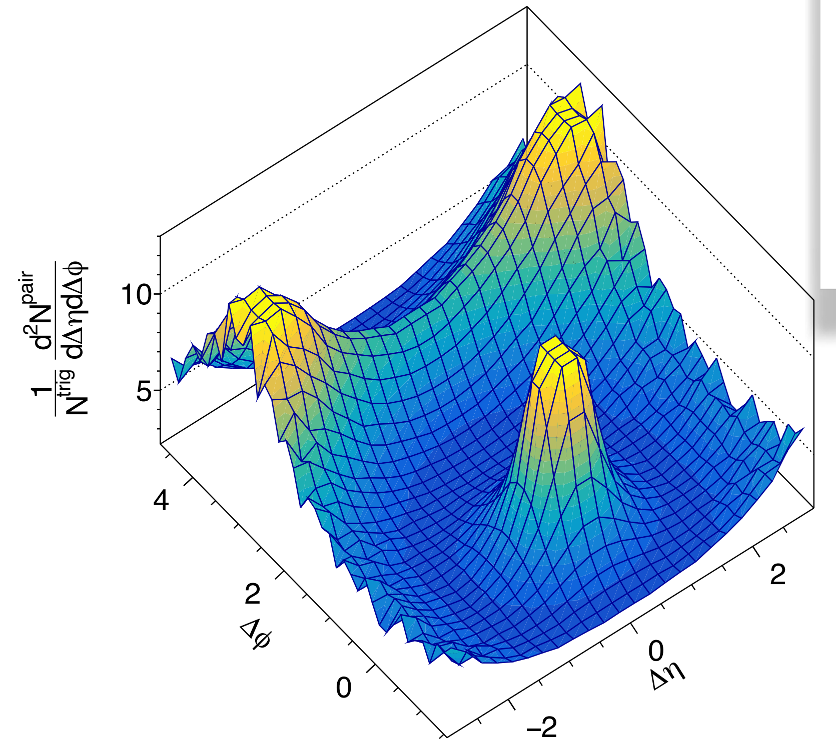


Background
(accounting for baseline of random pairing)



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

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



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

Observable

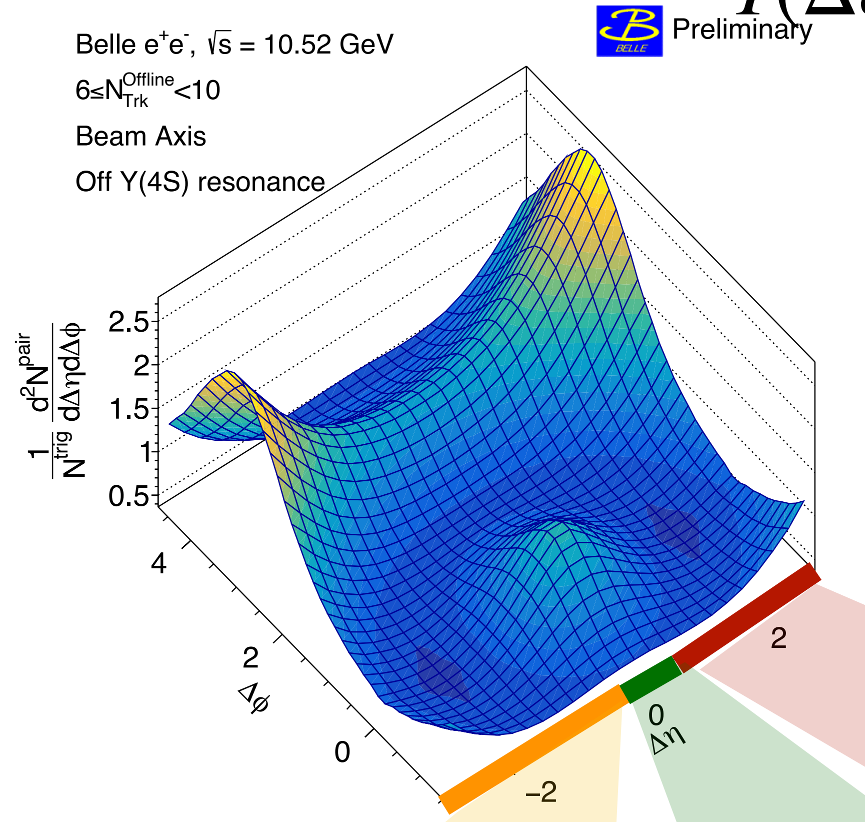
Azimuthal differential associated yield $Y(\Delta\phi)$

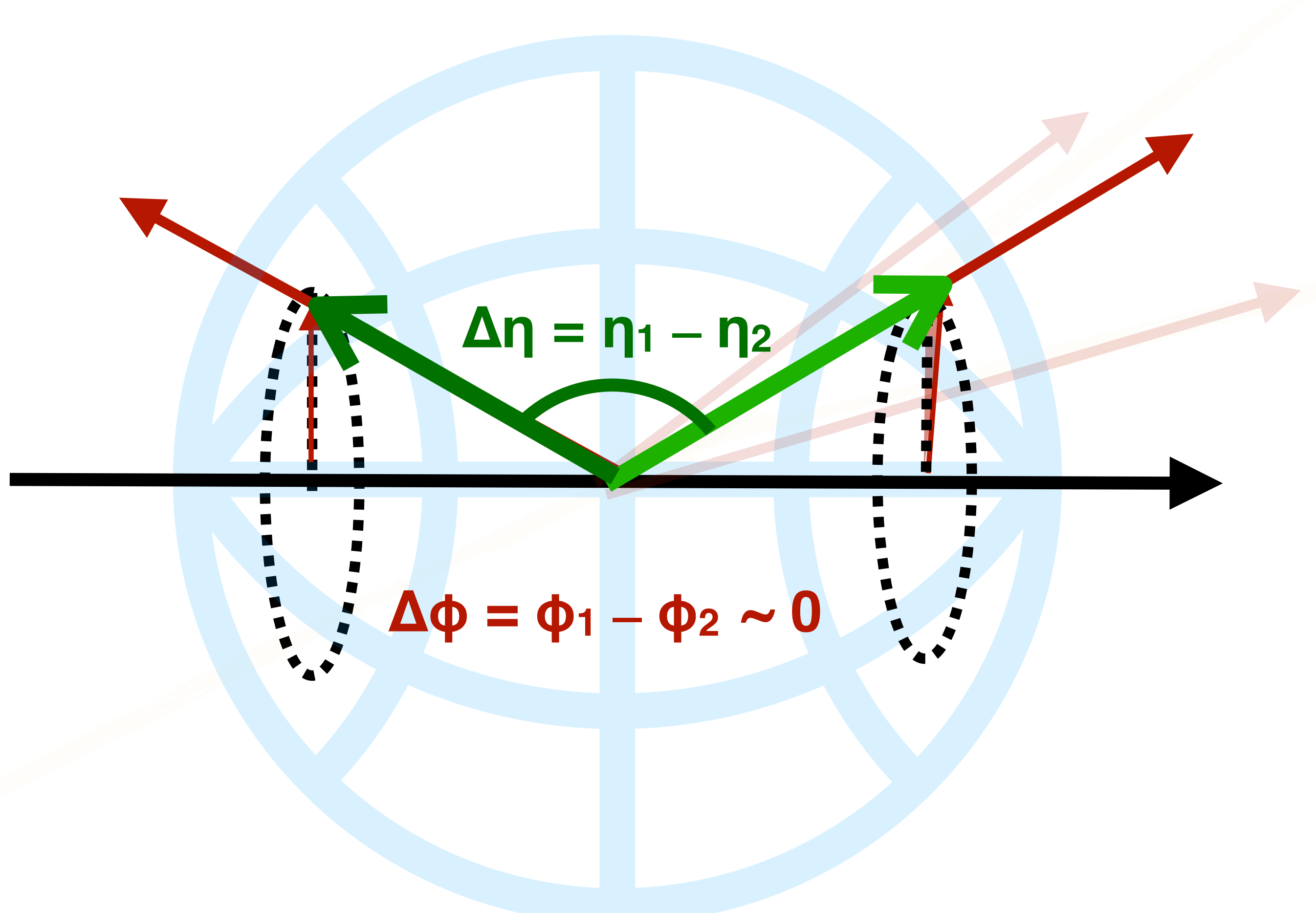
Two-particle correlation function (per-trigger-particle associated yield)

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

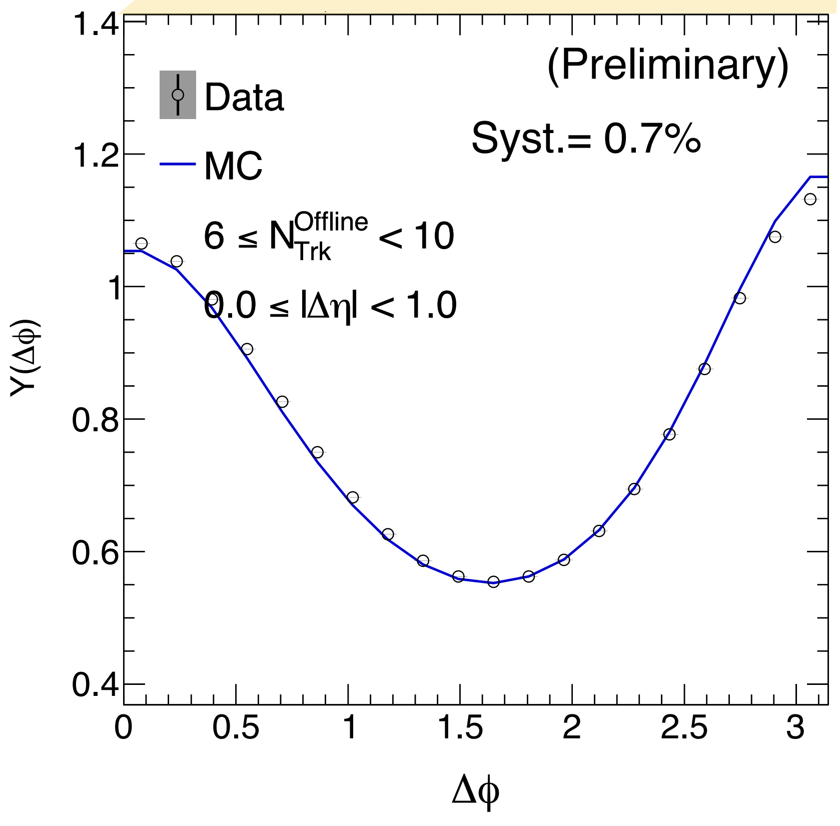
Associated yield vs. Δϕ

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

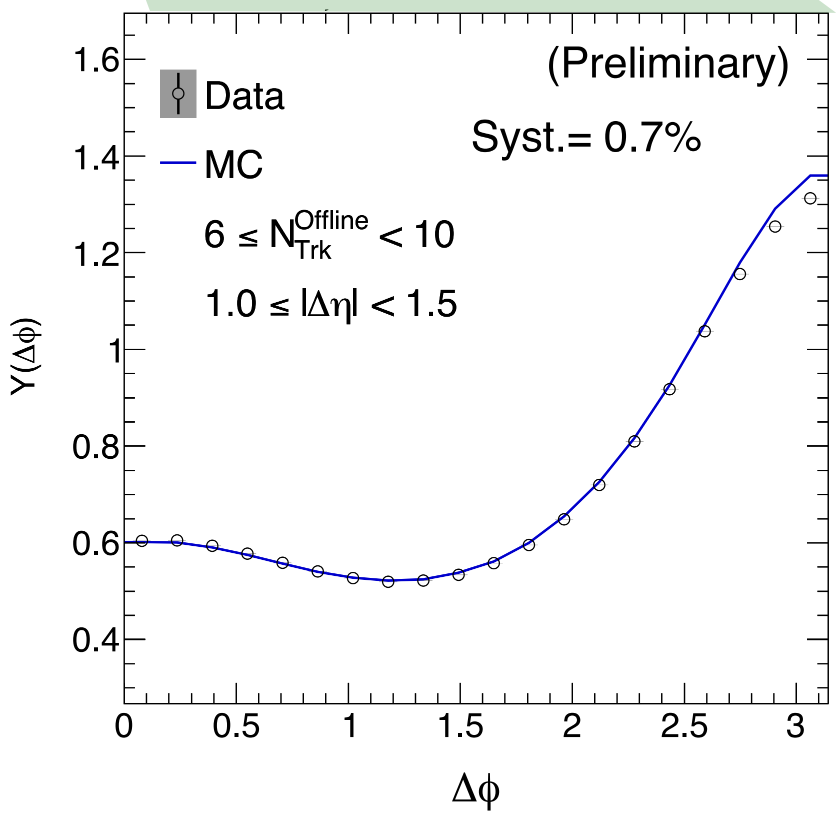




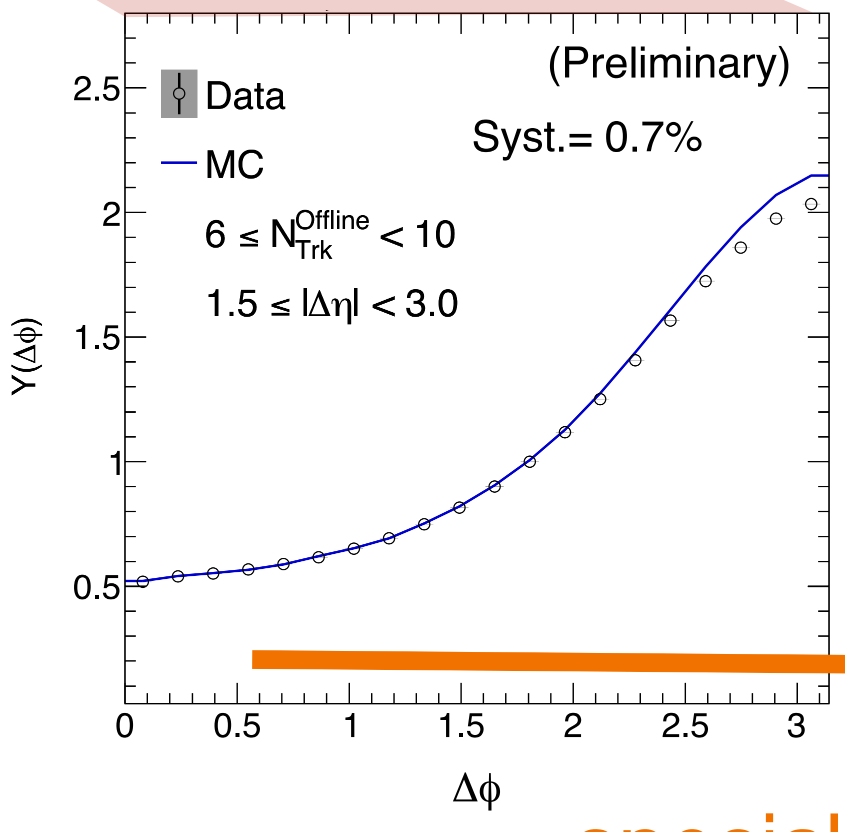
Short Range (0 ≤ |Δη| < 1)



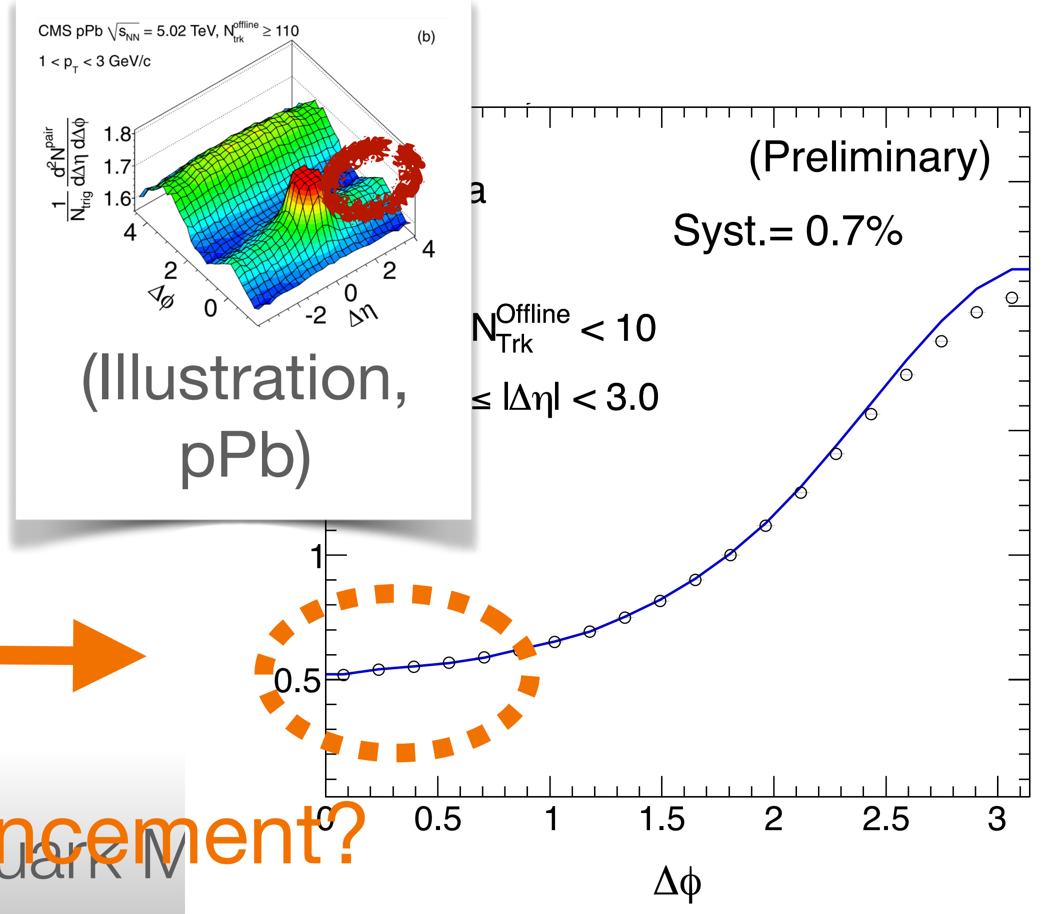
Middle Range (1 ≤ |Δη| < 1.5)



Long Range (1.5 ≤ |Δη| < 3.0)



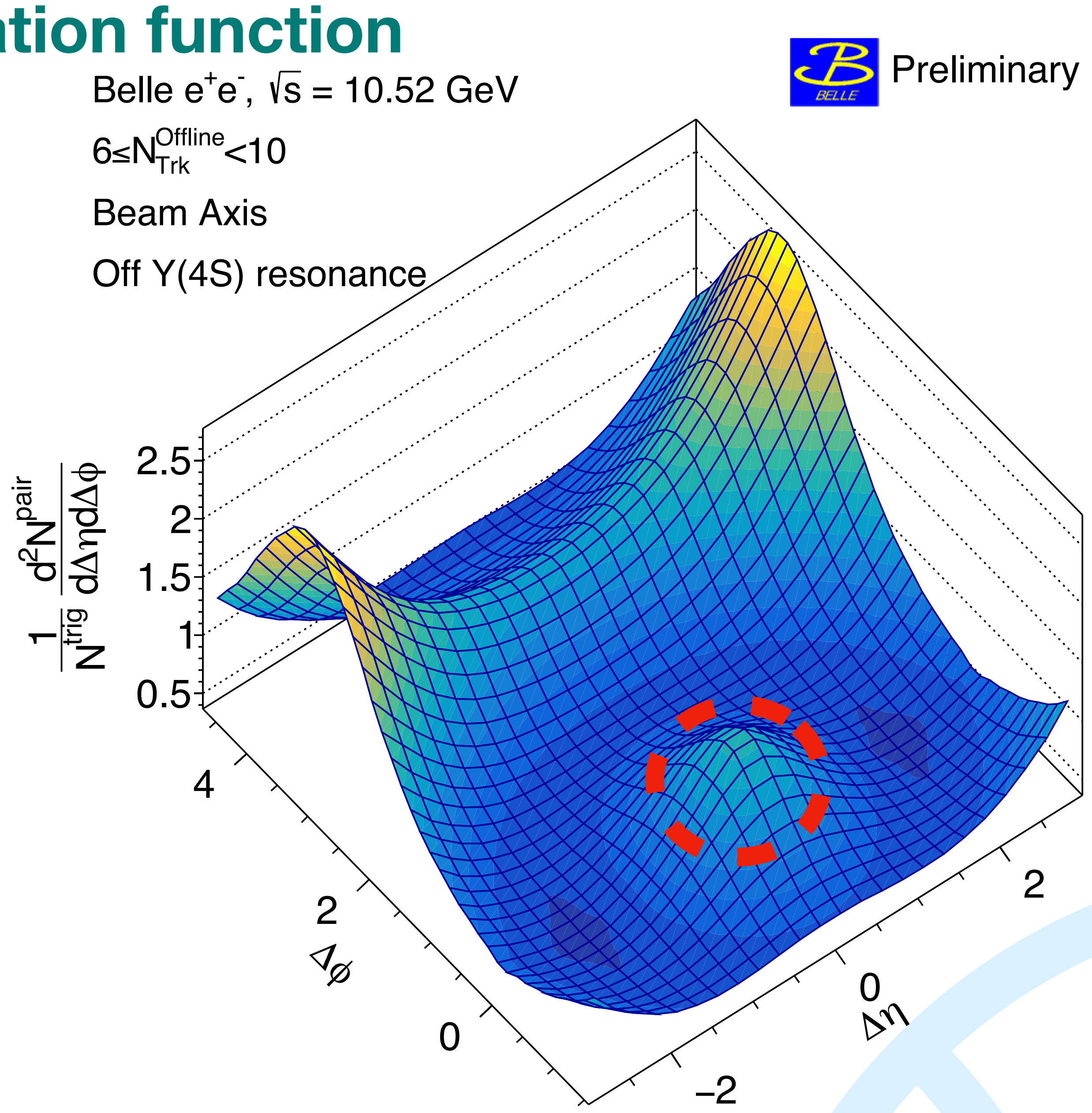
Ridge Signal (long-range, near-side (Δϕ~0))



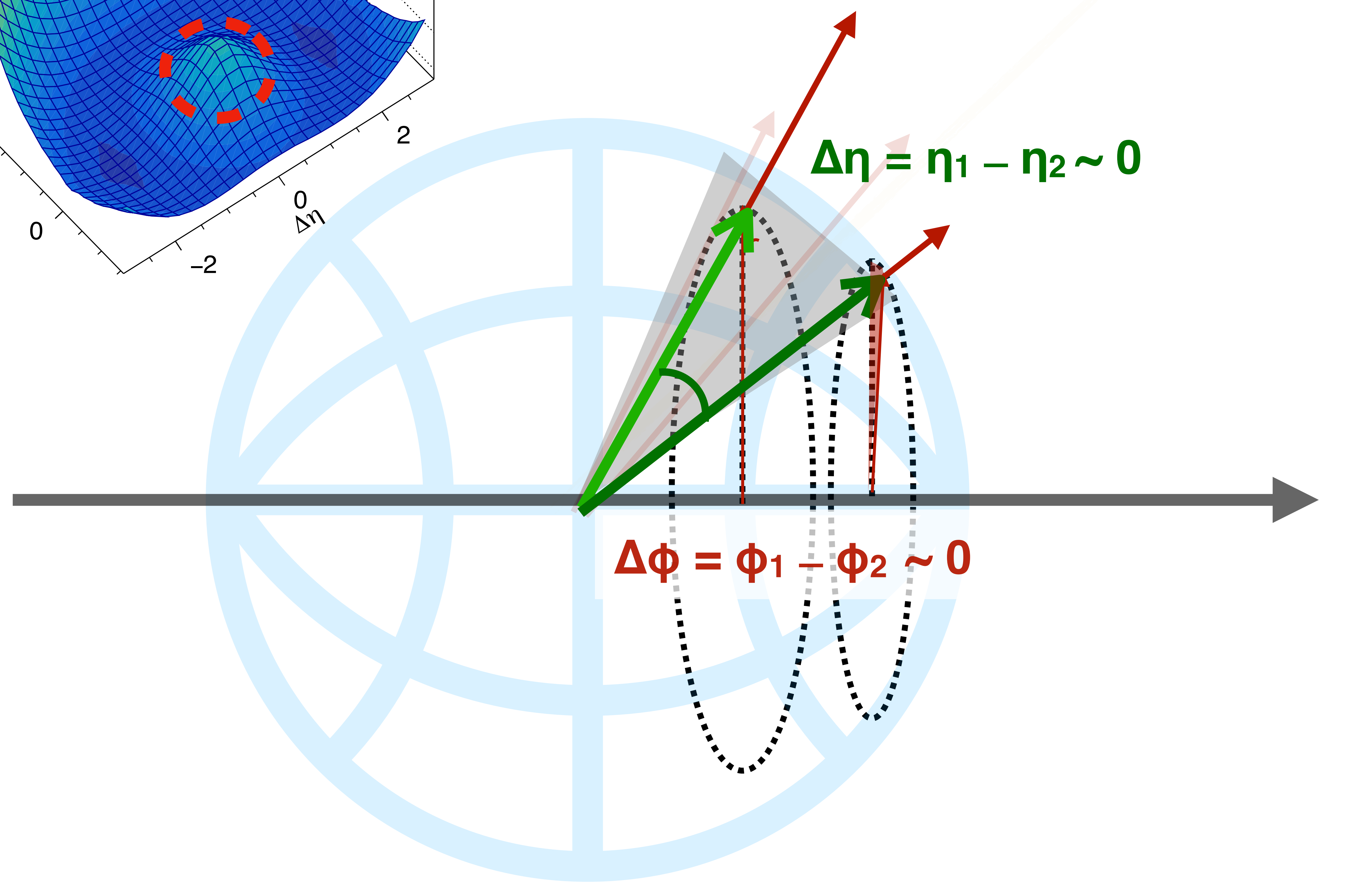
Azimuthal differential associated yield $Y(\Delta\phi)$

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

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



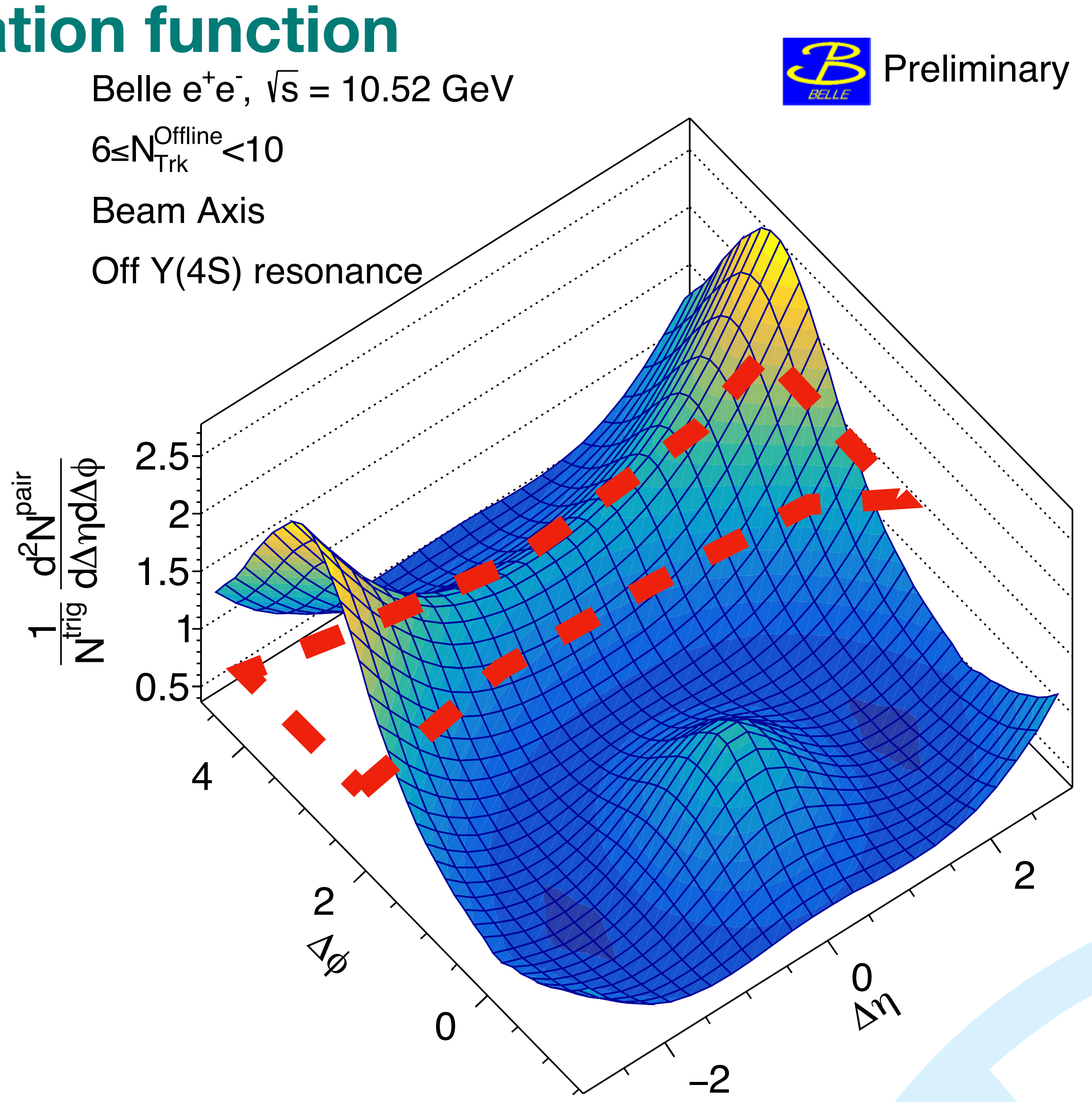
Origin-peak intra-jet correlations @ near side (Δη,Δϕ)~(0,0)



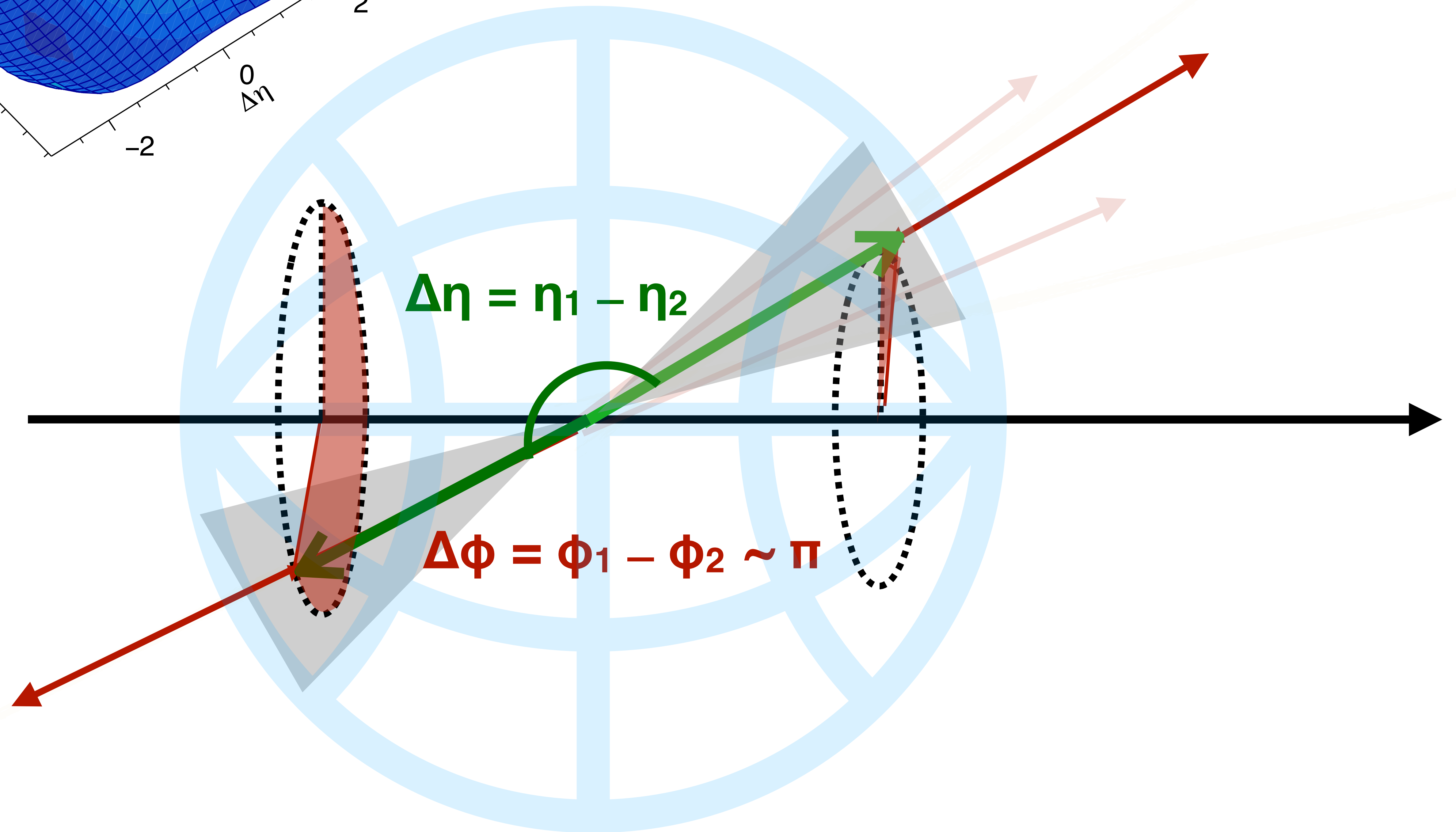
Azimuthal differential associated yield $Y(\Delta\phi)$

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

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



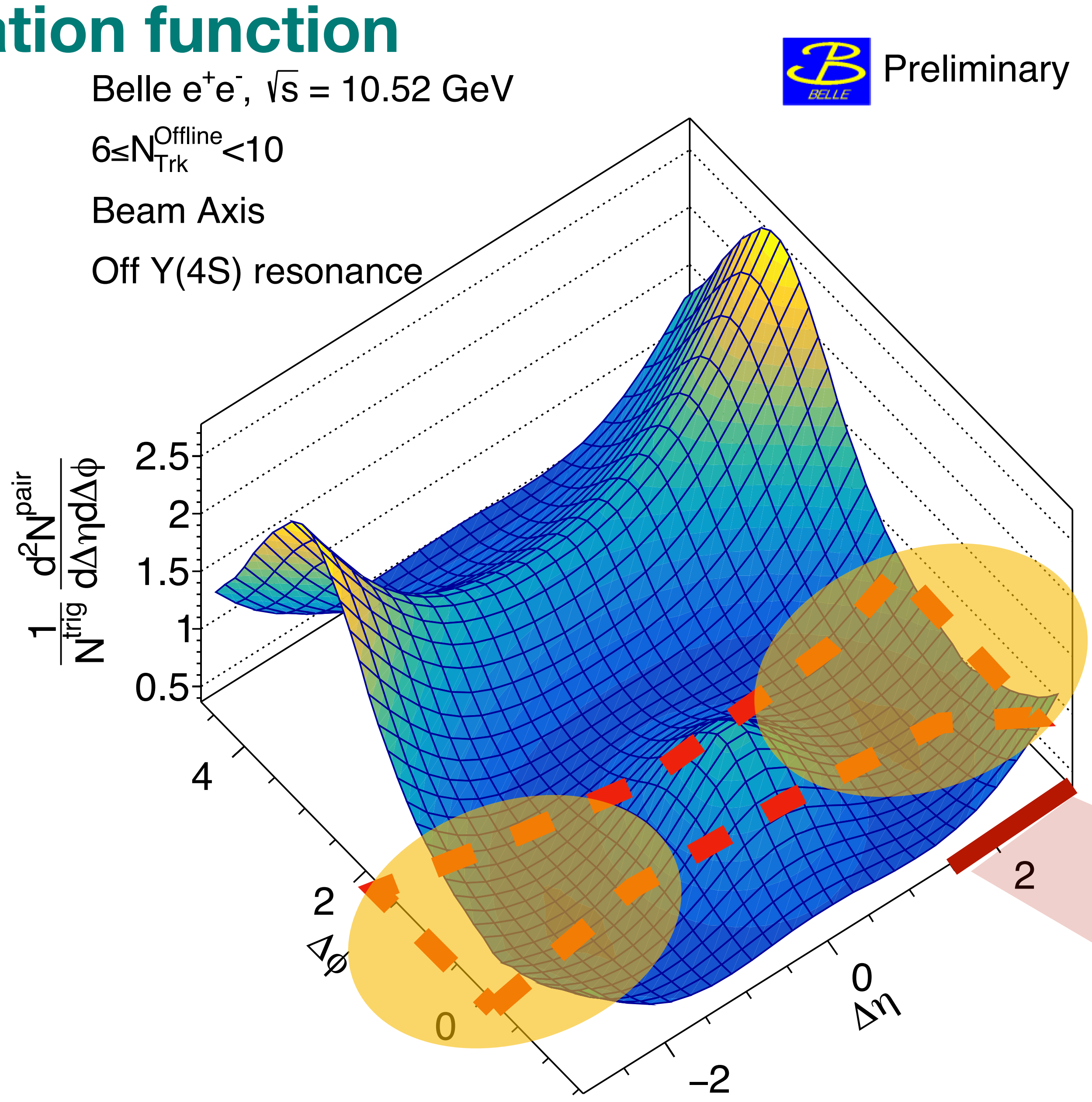
Back-to-back jet correlations @ away side (Δϕ~π)



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

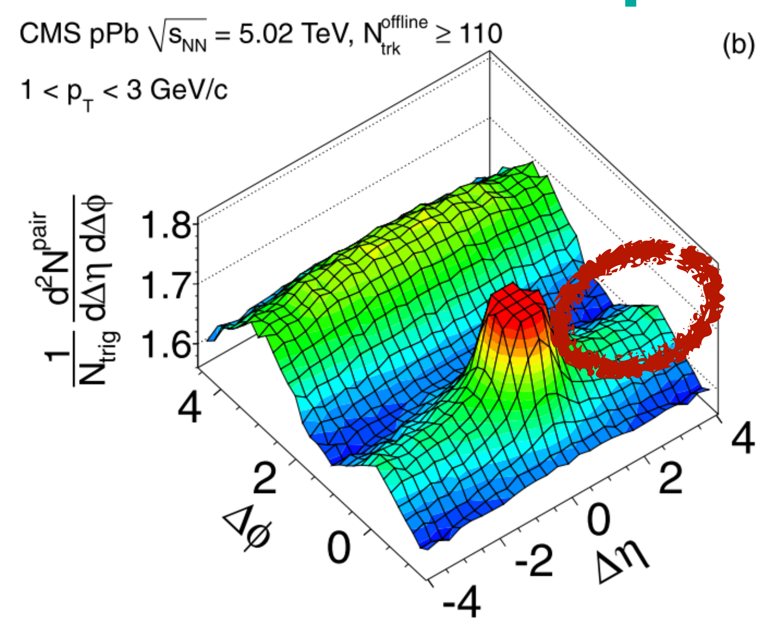
Two-particle correlation function (per-trigger-particle associated yield)

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

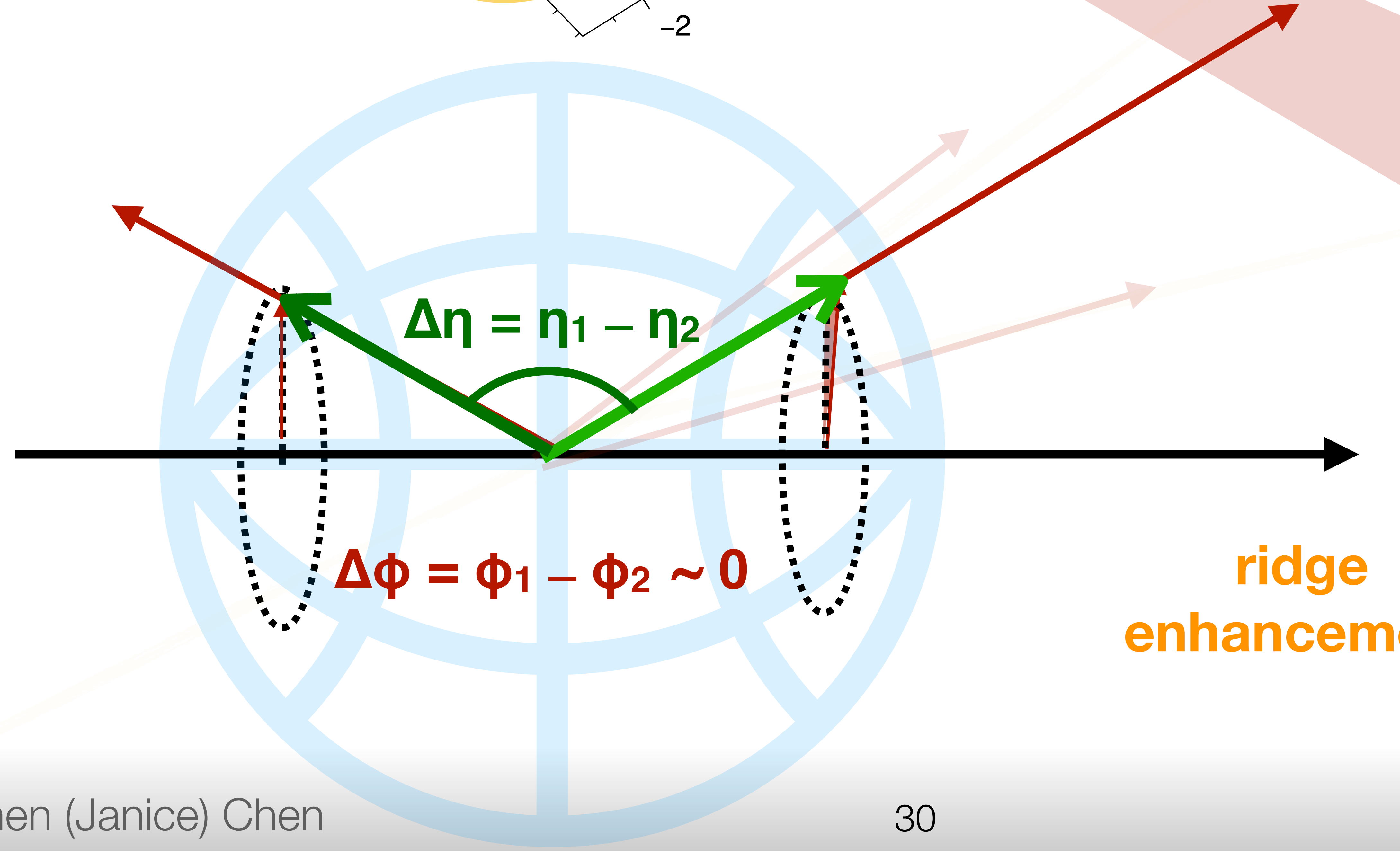


Ridge correlations @ long range, near side

pPb

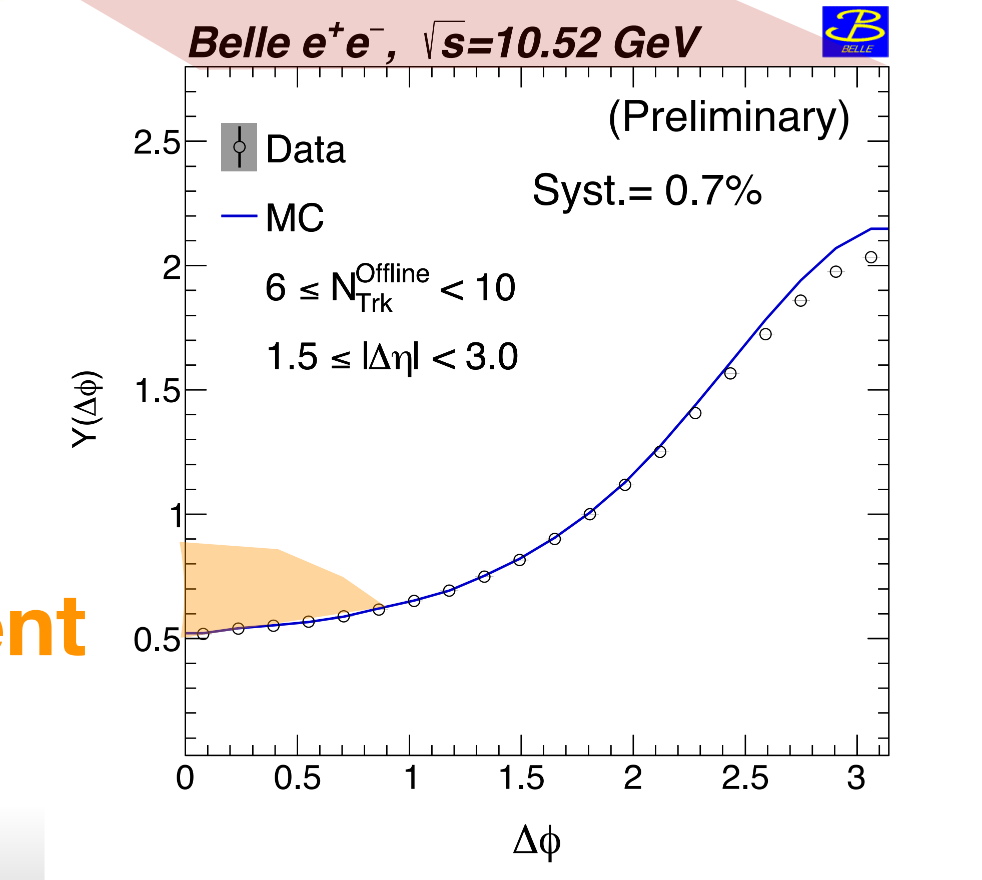


pA: [Phys. Lett. B718 (2013) 795-814]



long range (1.5 ≤ |Δη| < 3.0)

ridge enhancement



Systematics

Selections

1. Primary particle selection
   Vary the primary particle definition between the proper lifetime cut $\tau < 1\ \mathrm{cm}/c$ and the vertex cut $V_r < 1\ \mathrm{cm}$
2. Tracking efficiency
   Universal 0.35% uncertainty quoted for high p_T $(> 200\ \mathrm{MeV}/c)$ tracks
3. Event selection
   Vary the energy sum in ECL from $> 0.18\sqrt{s}$ to $> 0.23\sqrt{s}$

Histogramming imperfection

4. B(0,0) extrapolation and long-range correlation scaling
   Corrections of bin-size effect on the B(0,0) scaling factor and the magnitude of the long-range correlations are applied. Uncertainties of the correction factors are considered as sources of systematics
5. Δϕ bin width

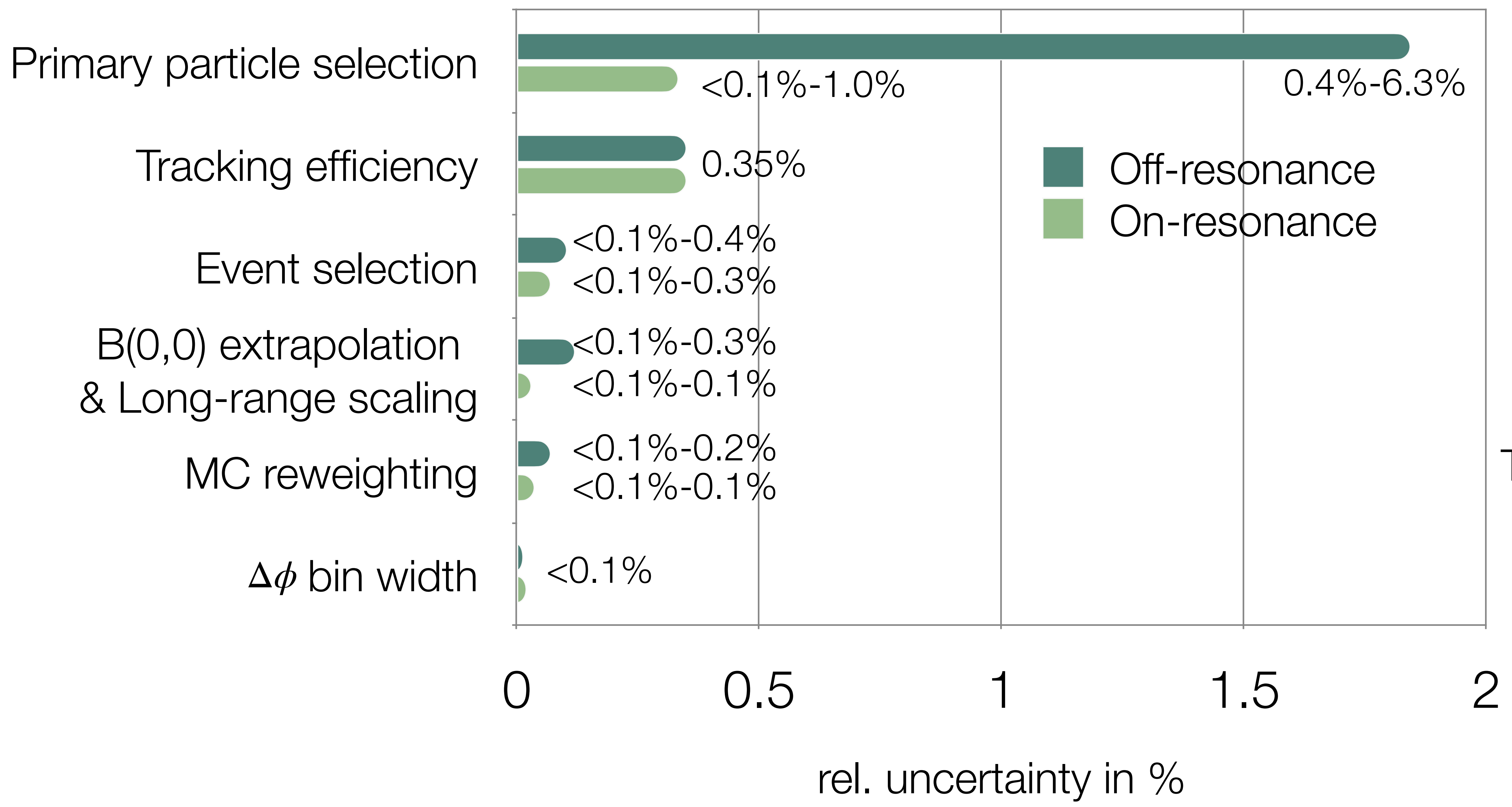
Reweighting

Accessing by reweighting factors with the alternative parametrization

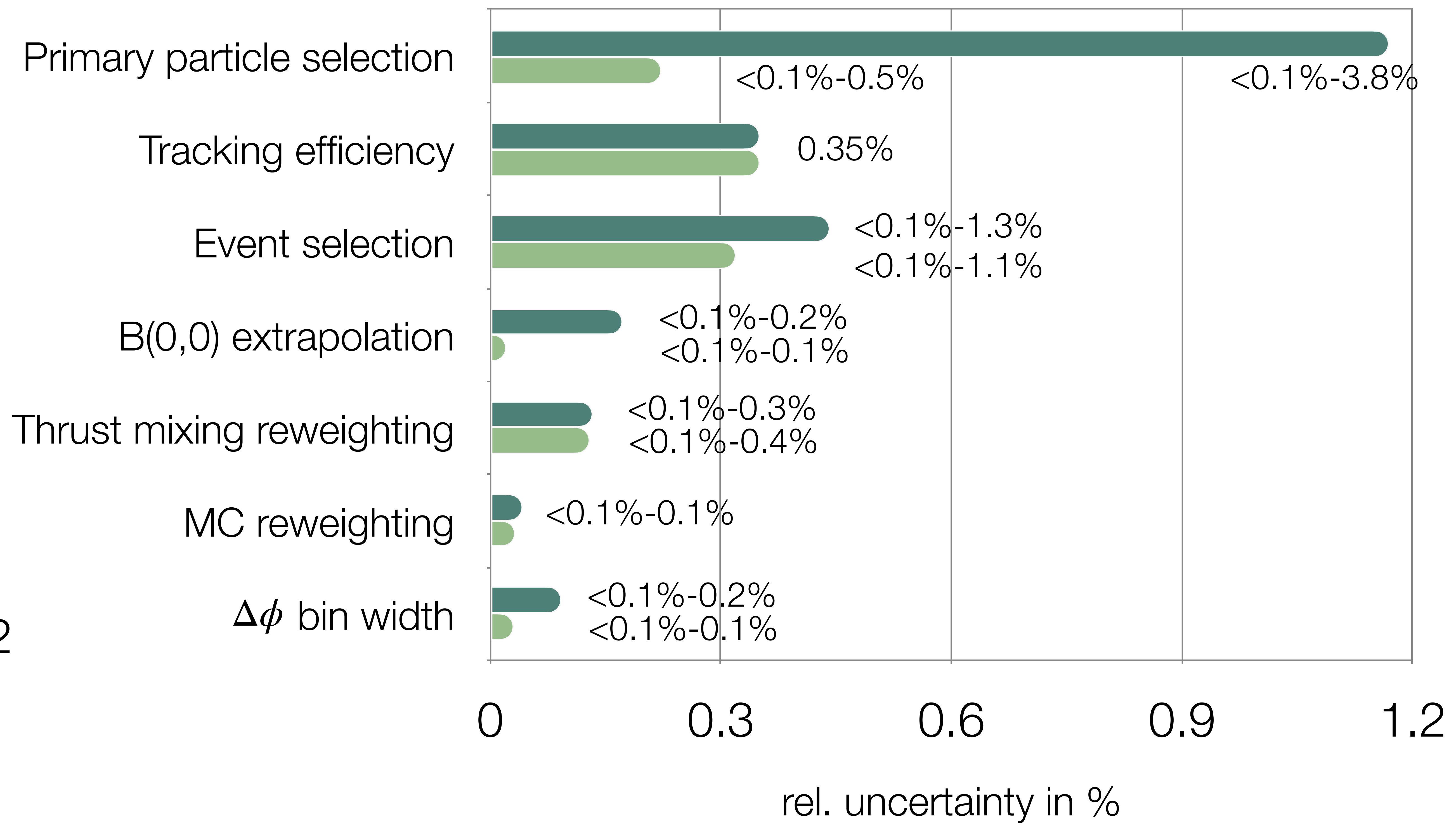
6. MC reweighting
7. Thrust mixing reweighting

- Selections (primary particle, tracking, and event selections) are the dominant systematics sources
- Others are comparably small: $O(10^{-4})$ up to 0.5%

Beam axis analysis



Thrust axis analysis



Quantifying ridge signal by ZYAM method

- ZYAM method (zero yield at minimum) is applied to calculate "ridge yield"

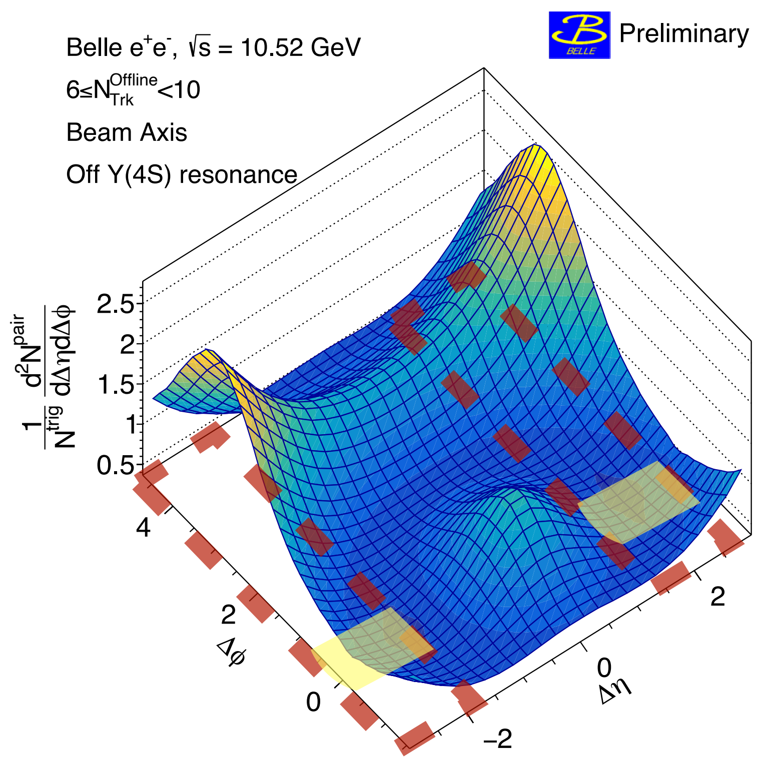
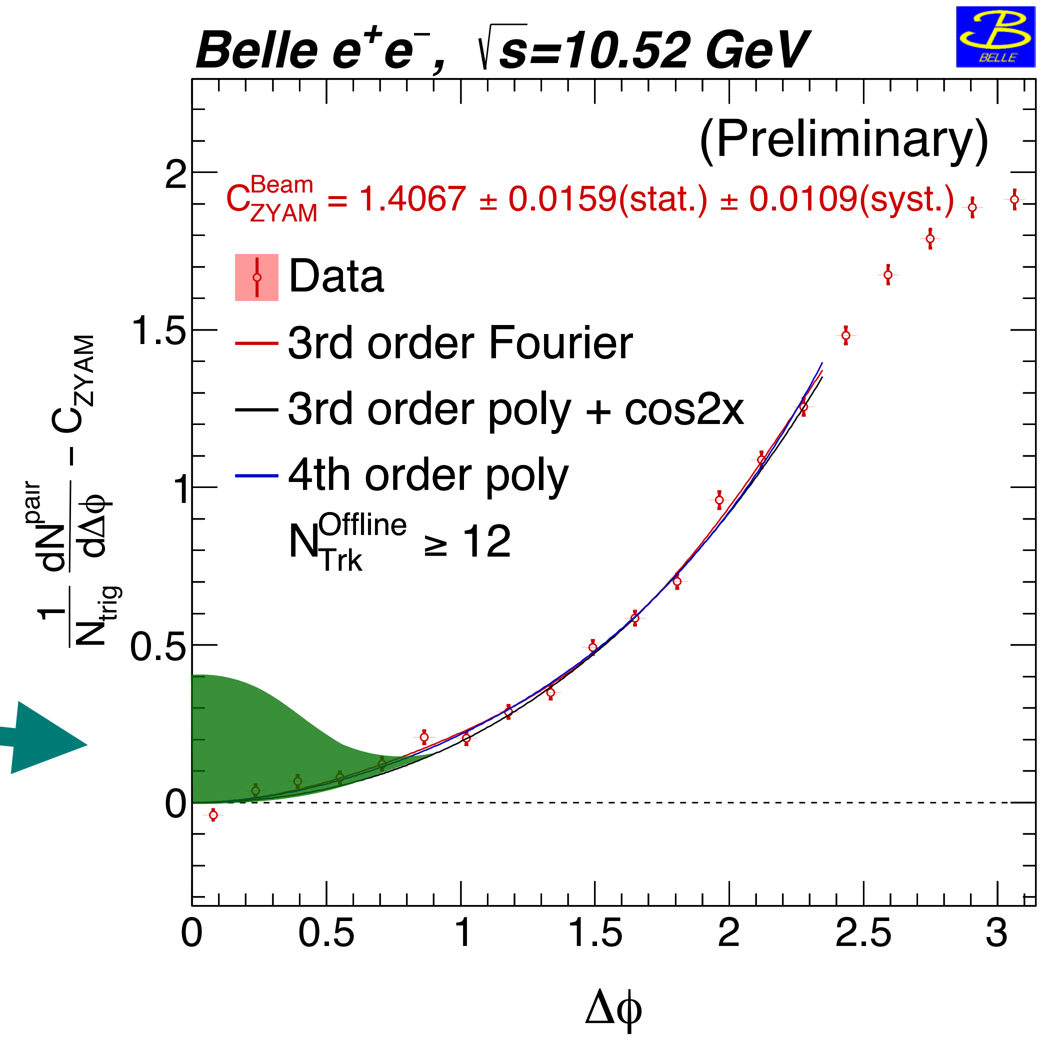
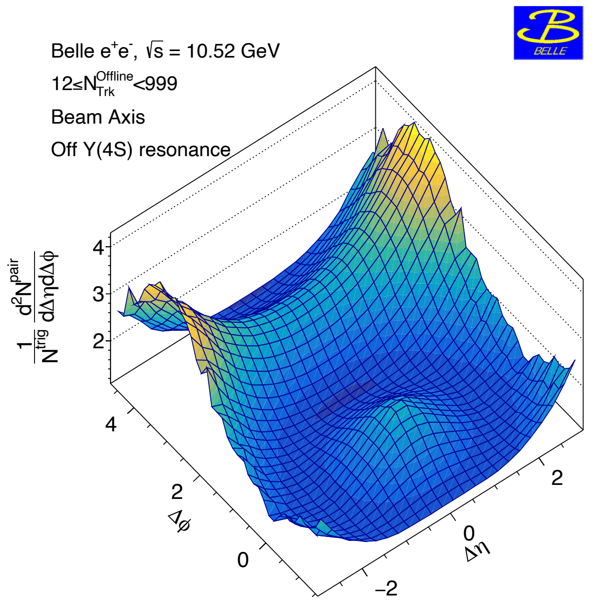


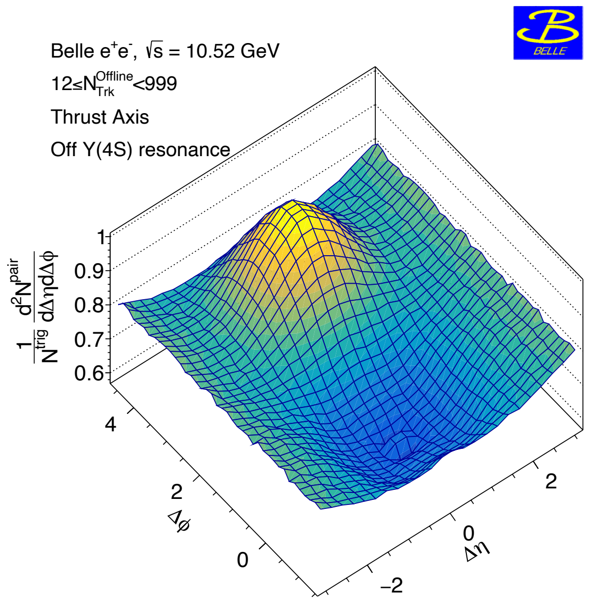
illustration of an enhanced ridge signal



- No significant ridge signals are observed in both beam, thrust axis coordinates
- Upper limits of ridge yield by the bootstrap method reported



(beam coordinates)



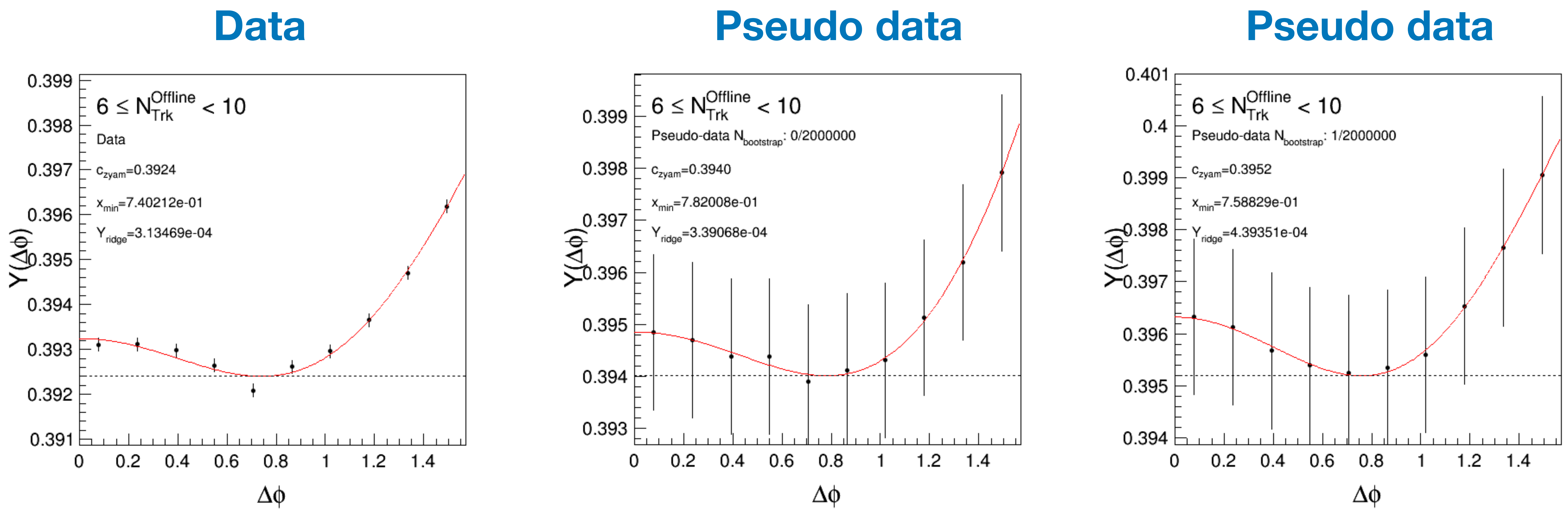
(thrust coordinates)

ZYAM
Phys.Rev. C72 (2005) 011902

bootstrap: [bootstrap]

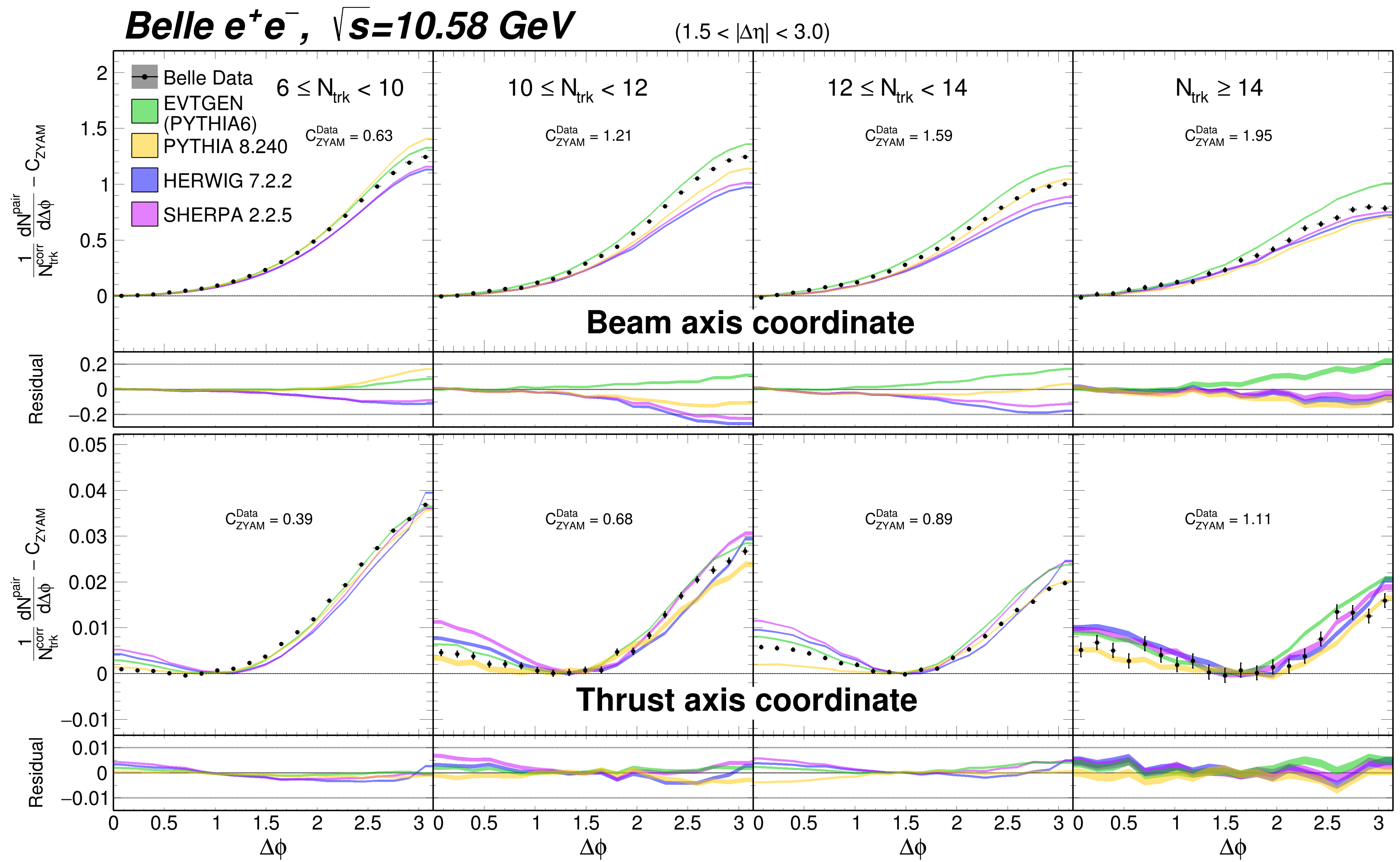
Bootstrap method

- Fit the long-range yield distribution Y(Δϕ).
- Vary the functional distribution by statistical and systematic uncertainties to construct a pseudo data.
- Refit the distribution with the same function and get a new ridge yield from this smeared distribution.
- Total 2M pseudo data are constructed.



Ref: [bootstrap]

On-resonance $Y(\Delta\phi)$



Kinematics distribution