Two-Particle Correlations of Hadrons in e^+e^- Collisions at Belle

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[a] *National Taiwan University*

[b] *Massachusetts Institute of Technology*

on behalf of the Belle Collaboration

[Phys. Rev. Lett. 128 (2022) 142005]
arXiv:2206.09440, submitted to JHEP

ICHEP 2022, Jul. 9th, Bologna Italy

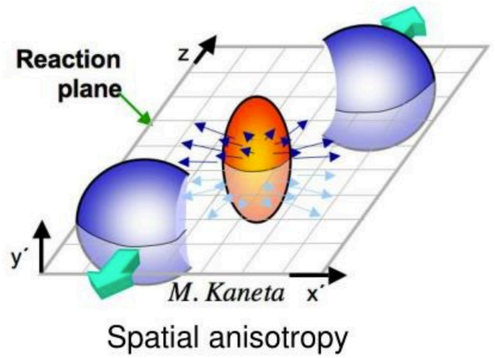
National Taiwan University

Motivation

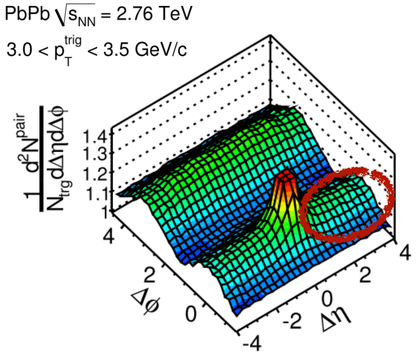
Small system (e^+e^-): minimal condition for azimuthal anisotropy

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

Ridge-like signal



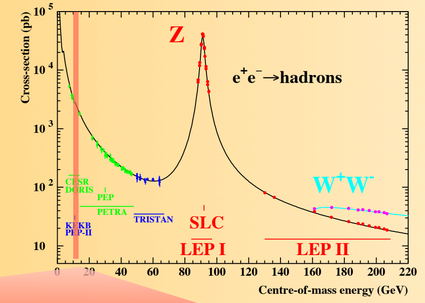
Spatial anisotropy

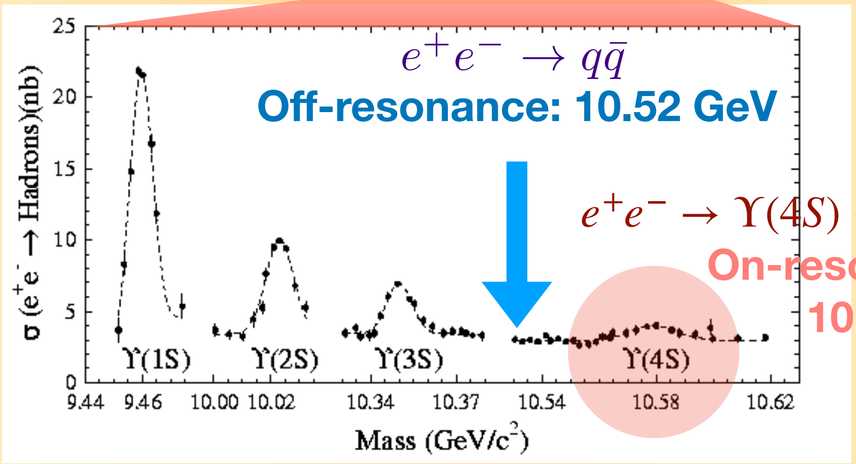


PbPb [Eur. Phys. J., C72]

- Also observed in pPb, pp
- Inspired searches in smaller systems (ep, e^+e^-, γp, γA …)
- Clean environment in e^+e^-: turn-off any possible CGC effect

Exploring low-energy region





Compared w/ event generators

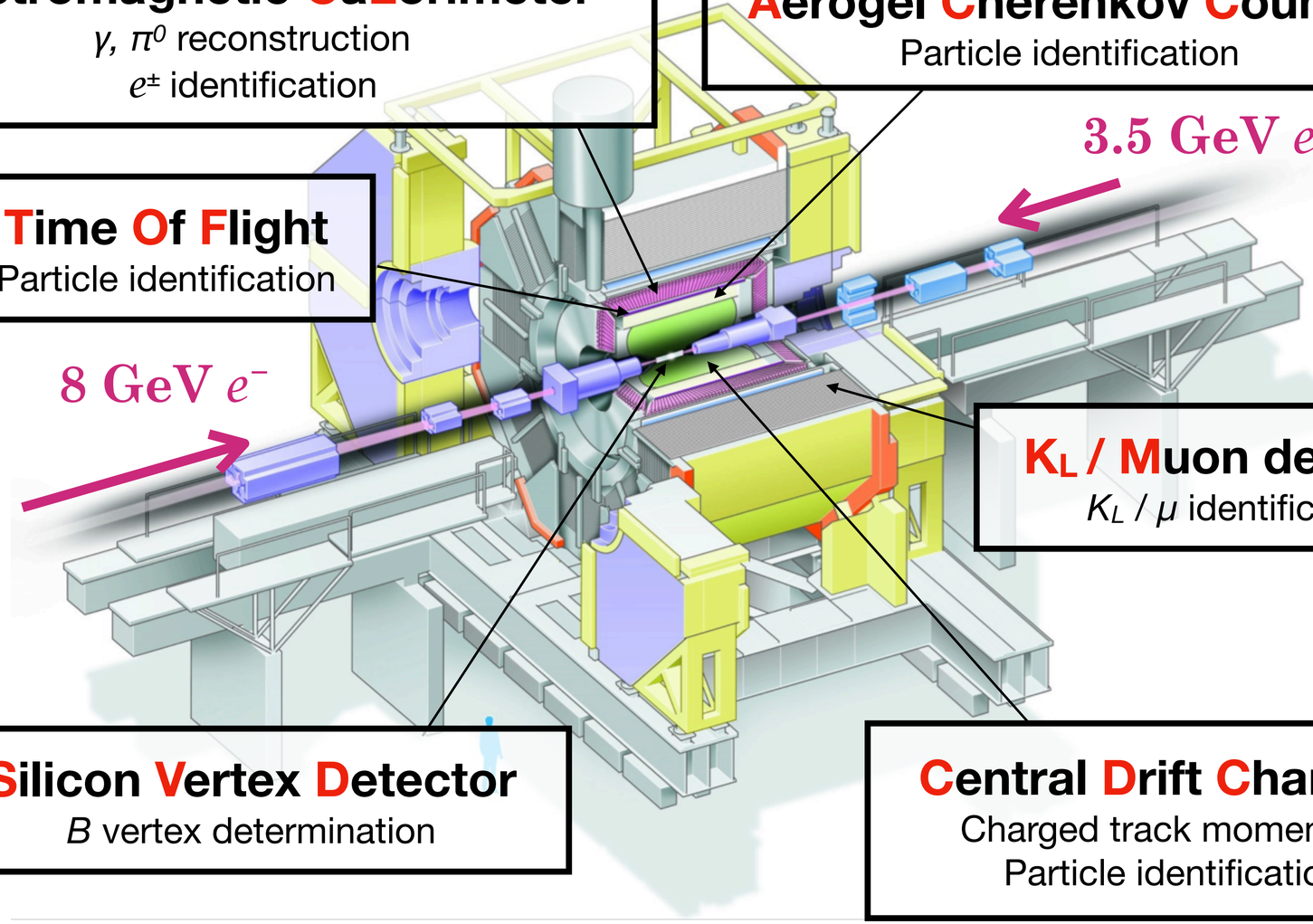
- Thrust-axis two-particle correlation: Search for medium expanding transverse to the out-going quark directions
- New inputs to the phenomenological fragmentation models at low collision energy

Belle Detector

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

Aerogel Cherenkov Counter
Particle identification

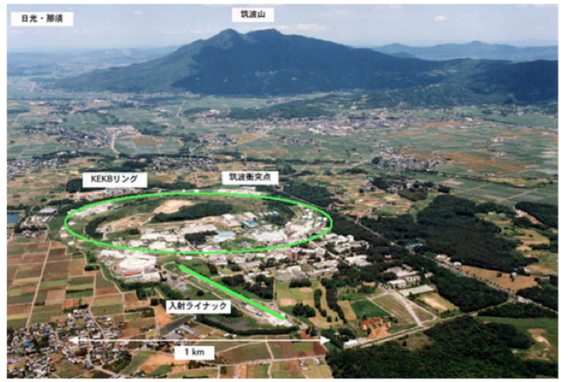
Time Of Flight
Particle identification



K_L / Muon detector
K_L / μ identification

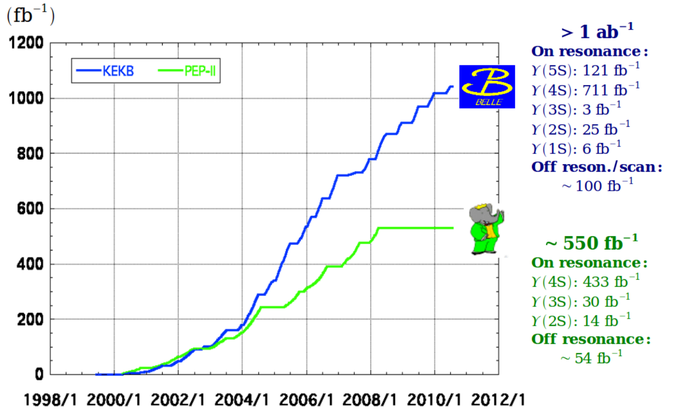
Silicon Vertex Detector
B vertex determination

Central Drift Chamber
Charged track momentum
Particle identification



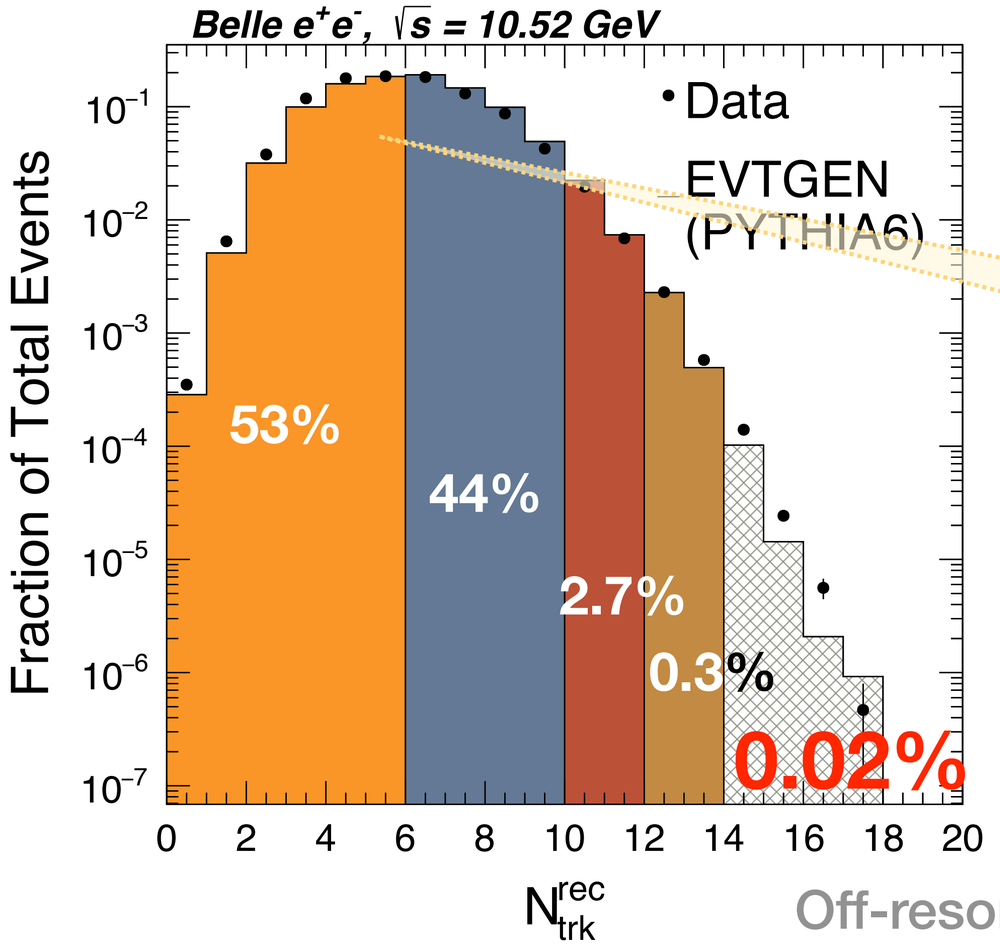
(KEK)

Boost to the C.M. frame for the correlation study!



Sample

Studying two-particle correlations as a function of multiplicity



Off-resonance

(* plot statistics: ∫Ldt: 1.3 fb^{-1})

- $q\bar{q}$ $(q = u, d, c$ and $s)$ fragmentation
- $\Upsilon(4S) \to B\bar{B}$ in on-resonance sample

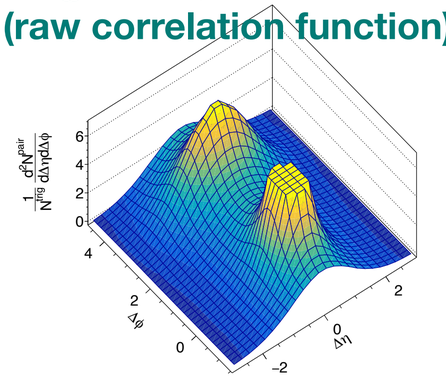
Low-multiplicity background

- Radiative Bhabha events
- $e^+e^- \to l^+l^-$ $(l = e, \mu)$
- Two-photon processes

on-resonance see backup

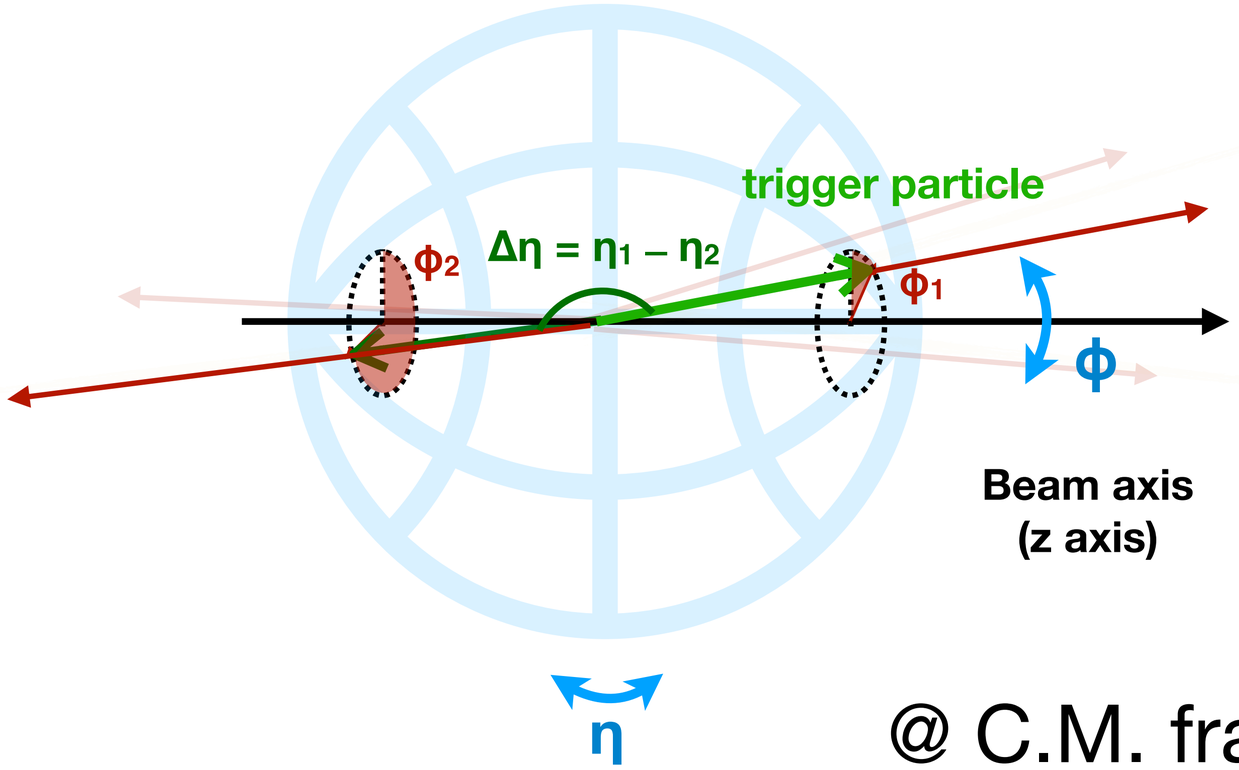
Two-particle correlation w.r.t. beam axis

Signal
(raw correlation function)



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

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

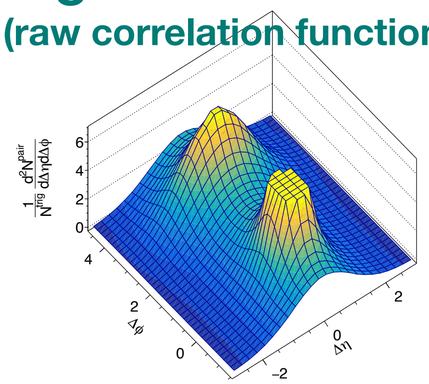


@ C.M. frame

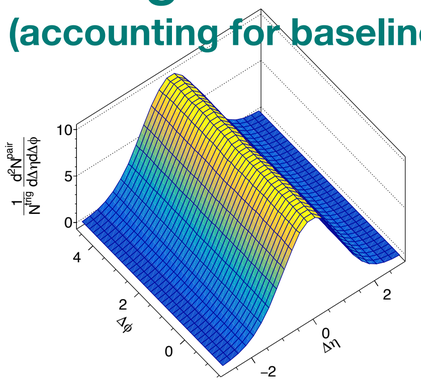
Observable

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

Signal
(raw correlation function)

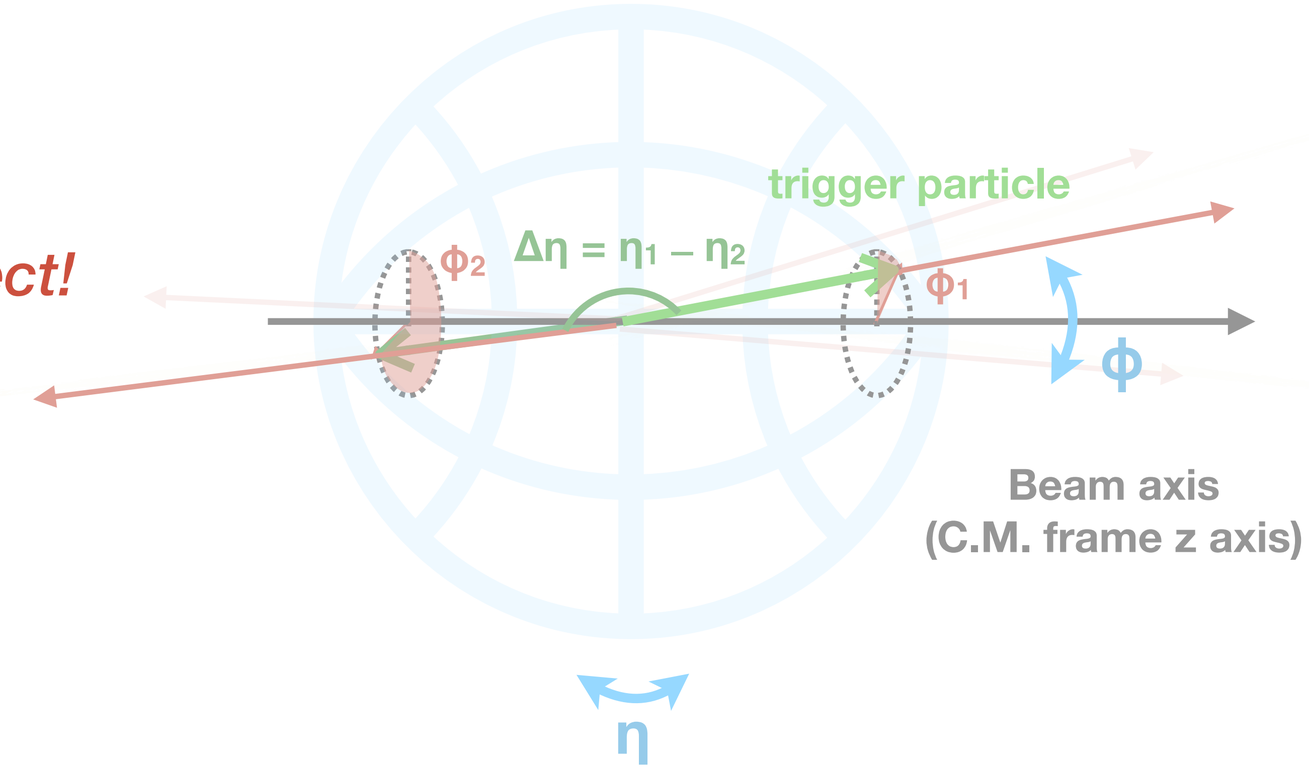


Background
(accounting for baseline of random pairing)



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

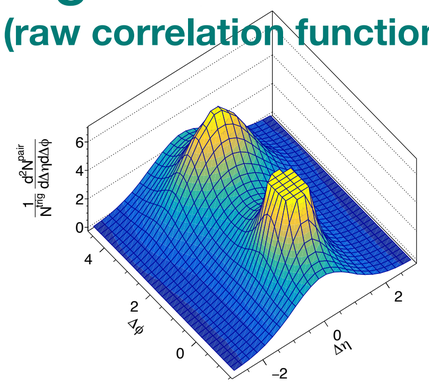
Factoring out the random pairing effect!



Observable

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

Signal
(raw correlation function)



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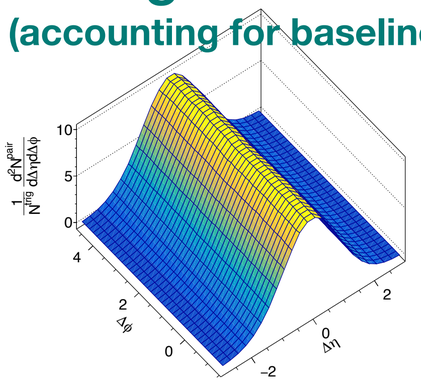
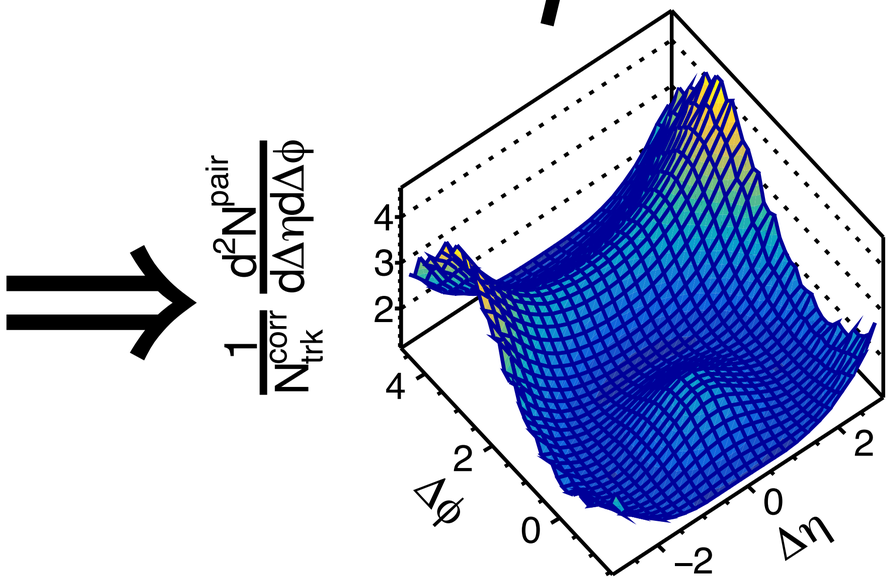
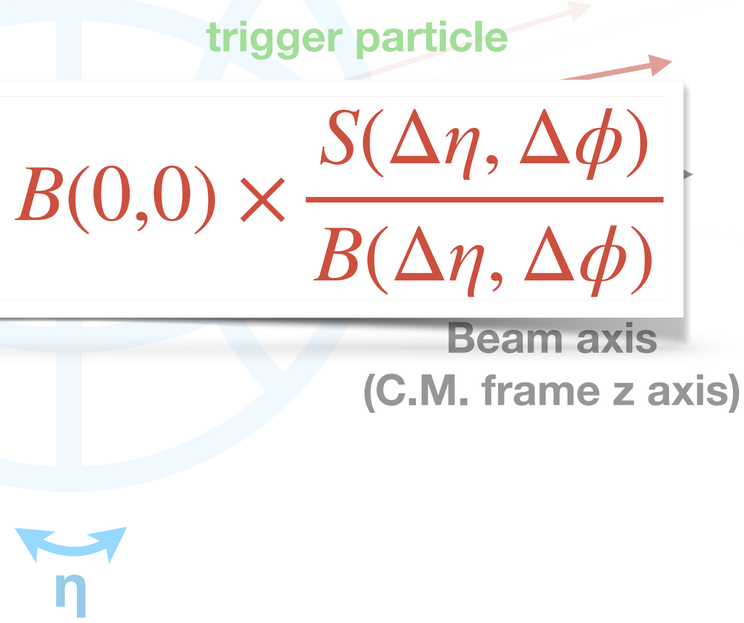


Track pairs' angular difference in
η (pseudorapidity), ϕ (azimuthal angle)

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

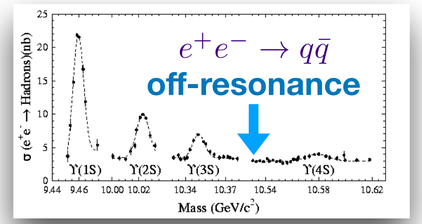




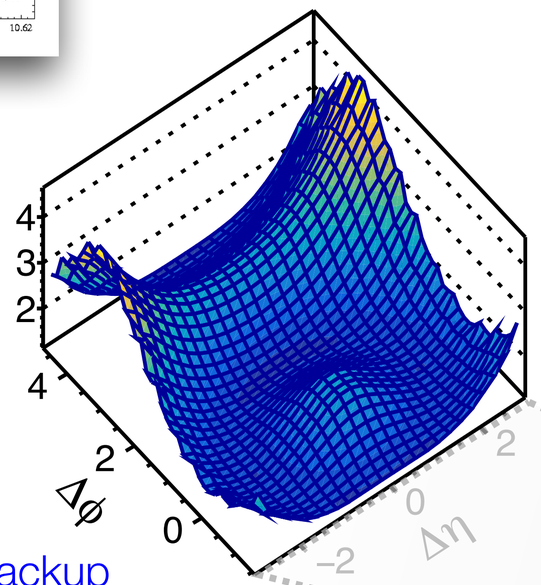
Two-particle correlation function
(per-trigger-particle associated yield)

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

Reasonable data and MC agreements!



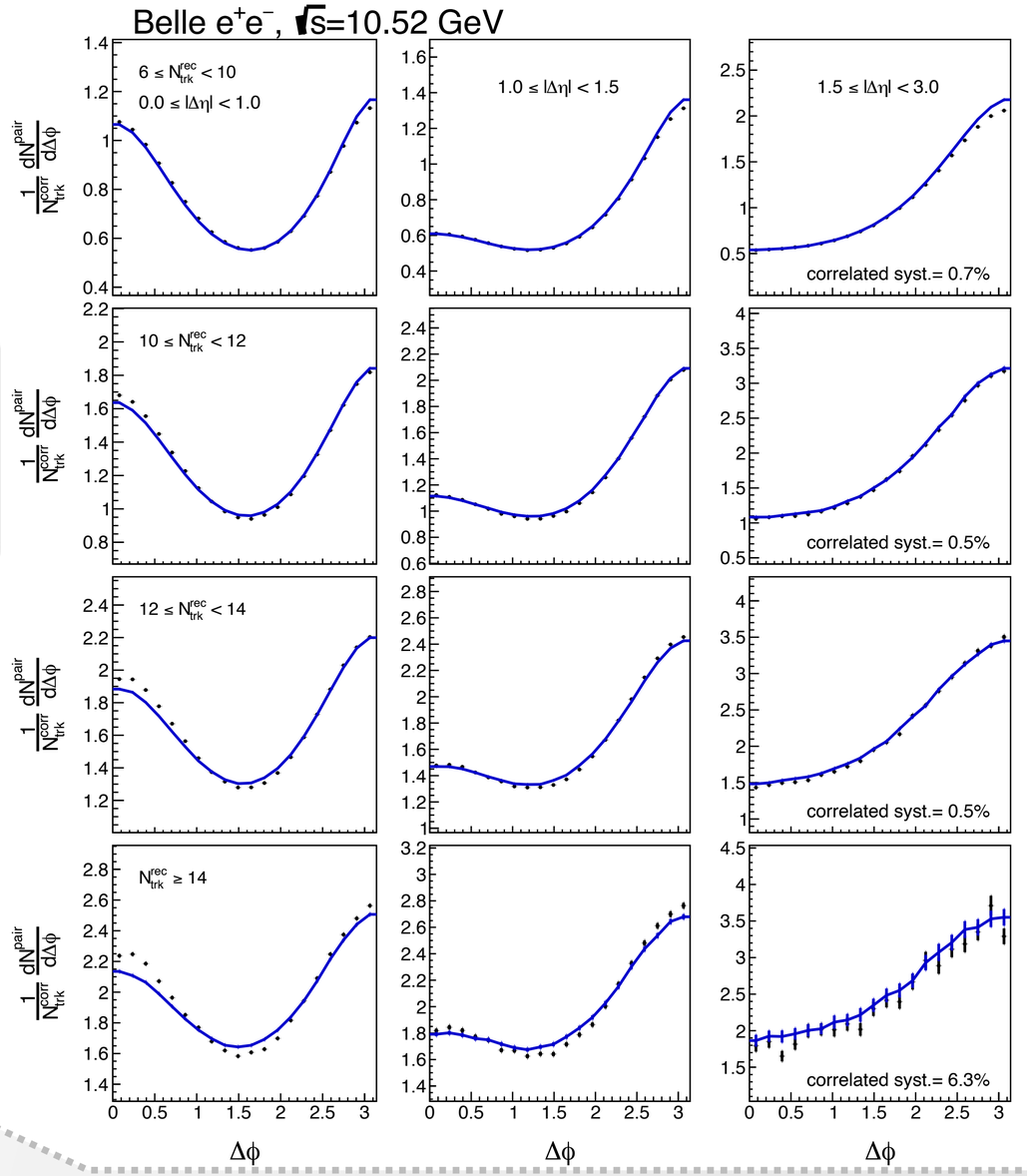
$$\frac{1}{N_{trk}^{corr}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi}$$



Data

PYTHIA6

High-multiplicity



on-resonance see backup

arXiv:2201.01694 [Phys. Rev. Lett. 128 (2022) 142005]

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

Short Range	Middle Range	Long Range
$(0 \le \lvert\Delta\eta\rvert < 1)$	$(1 \le \lvert\Delta\eta\rvert < 1.5)$	$(1.5 \le \lvert\Delta\eta\rvert < 3.0)$

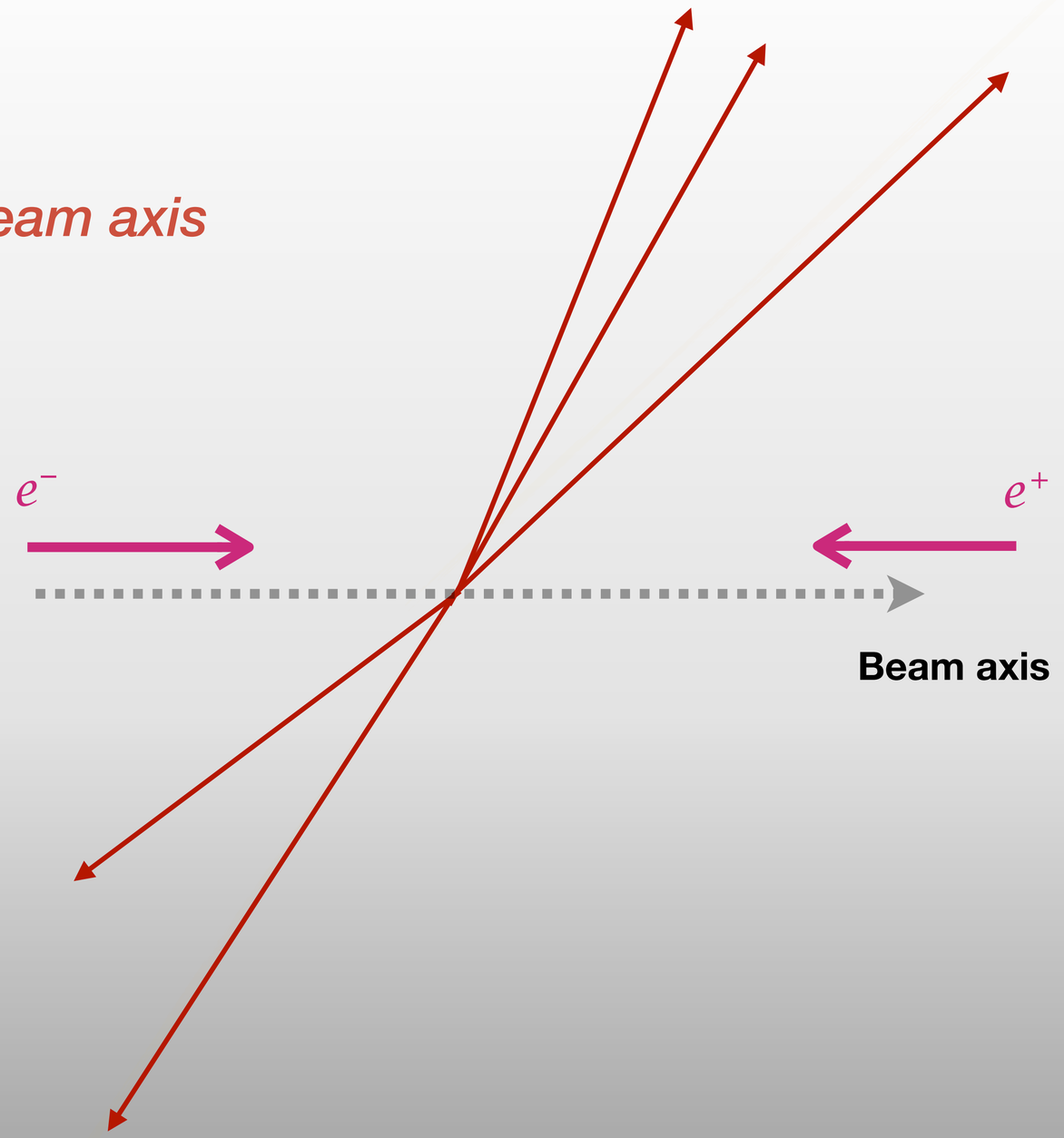
Thrust-axis two-particle correlation

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

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

($i \in$ charged, neutral particles and MET)

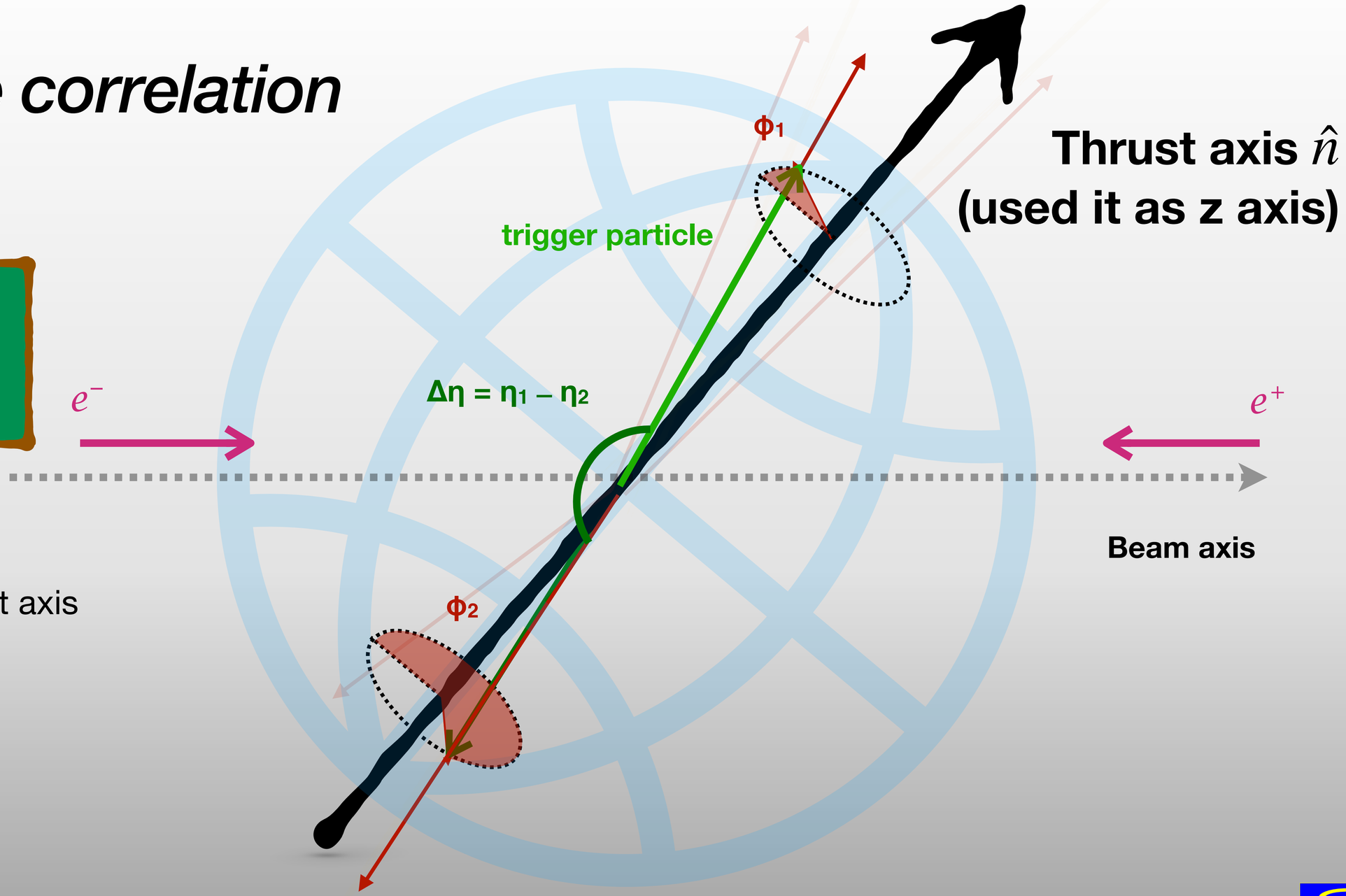
$$\vec{p}_{\mathrm{MET}} = -\sum_{\mathrm{neu,chg}} \vec{p}$$



Thrust-axis two-particle correlation

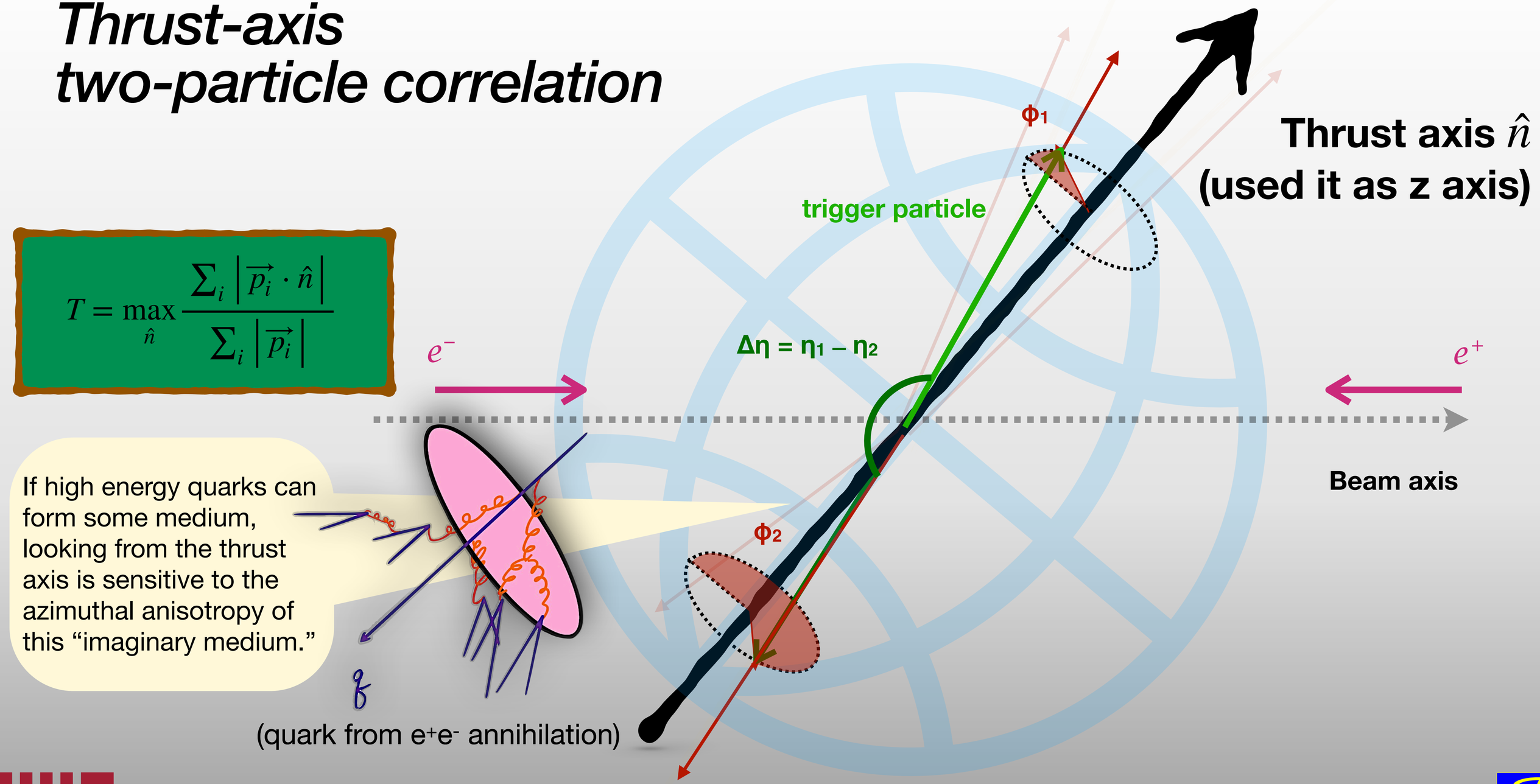
$$T = \max_{\hat{n}} \frac{\sum_i \left| \vec{p_i} \cdot \hat{n} \right|}{\sum_i \left| \vec{p_i} \right|}$$

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



Thrust-axis two-particle correlation

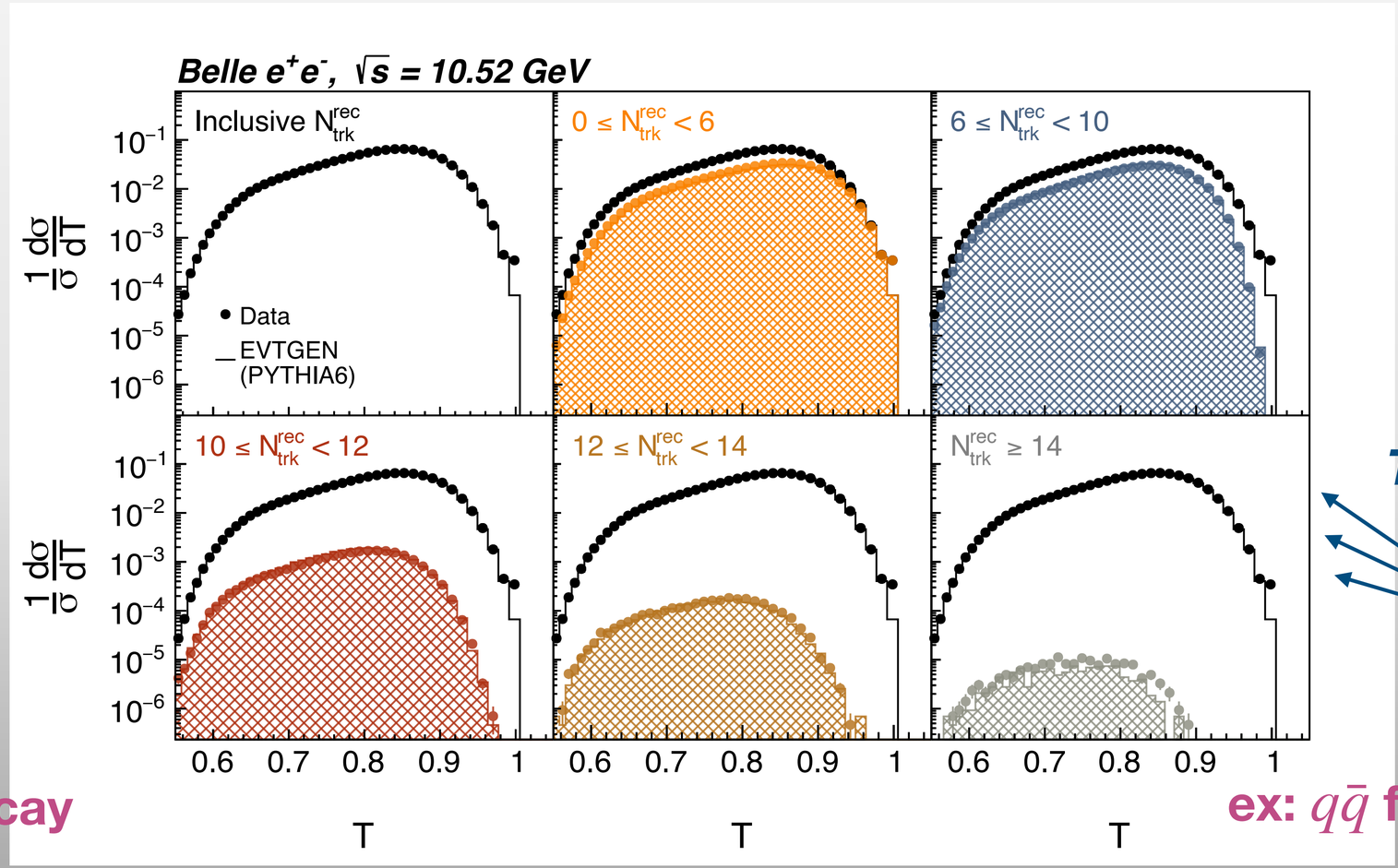
$$T = \max_{\hat{n}} \frac{\sum_i \left| \vec{p_i} \cdot \hat{n} \right|}{\sum_i \left| \vec{p_i} \right|}$$



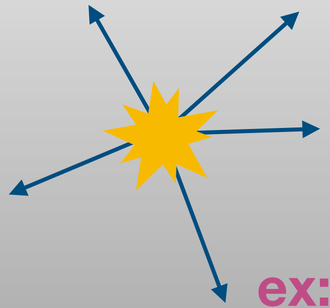
Thrust distribution

on-resonance see backup

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

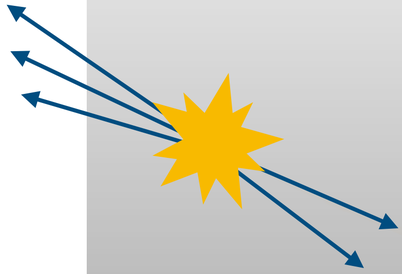


***T* closes to 0.5**



ex: *B*-decay

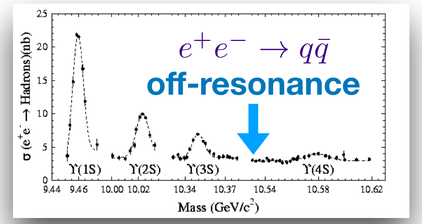
***T* closes to 1**

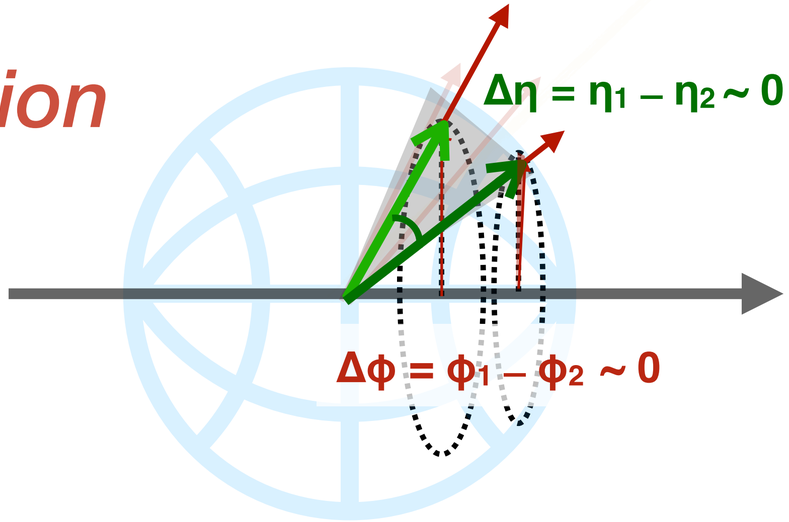


ex: $q\bar{q}$ fragmentation

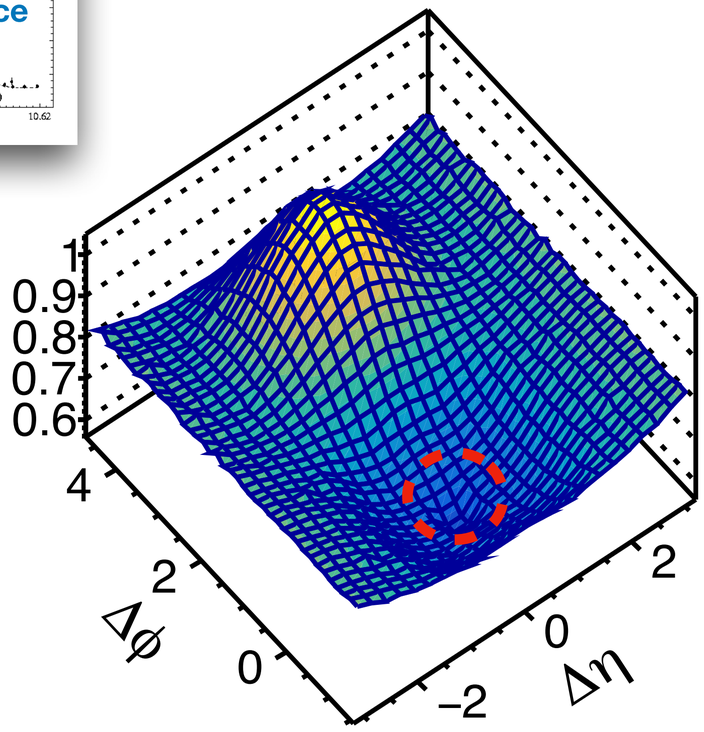
Thrust-axis two-particle correlations — off-resonance (√s=10.52 GeV)

Lack of origin-peak jet correlation



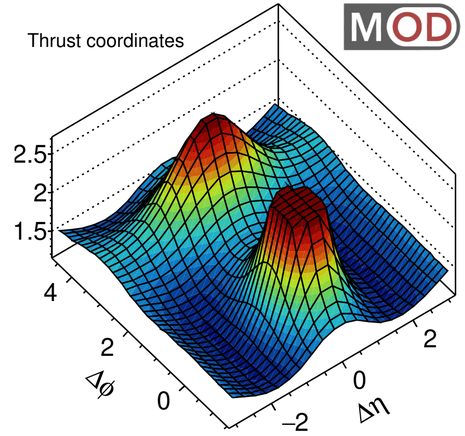


$$\frac{1}{N_{\rm trk}^{\rm corr}}\frac{d^2N^{\rm pair}}{d\Delta\eta d\Delta\phi}$$



c.f. e⁺e⁻ @ LEP1 (Z-pole energy)

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

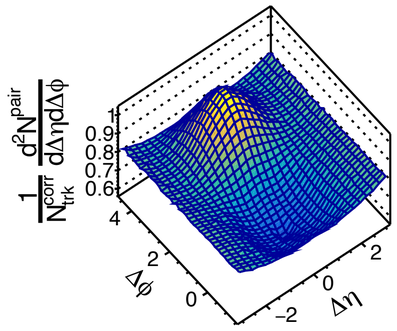


arXiv:2201.01694
PRL ref.

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

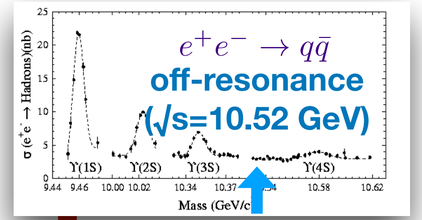
Lack of origin-peak jet correlation

- Simulate w/ Sherpa @ different √s



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

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



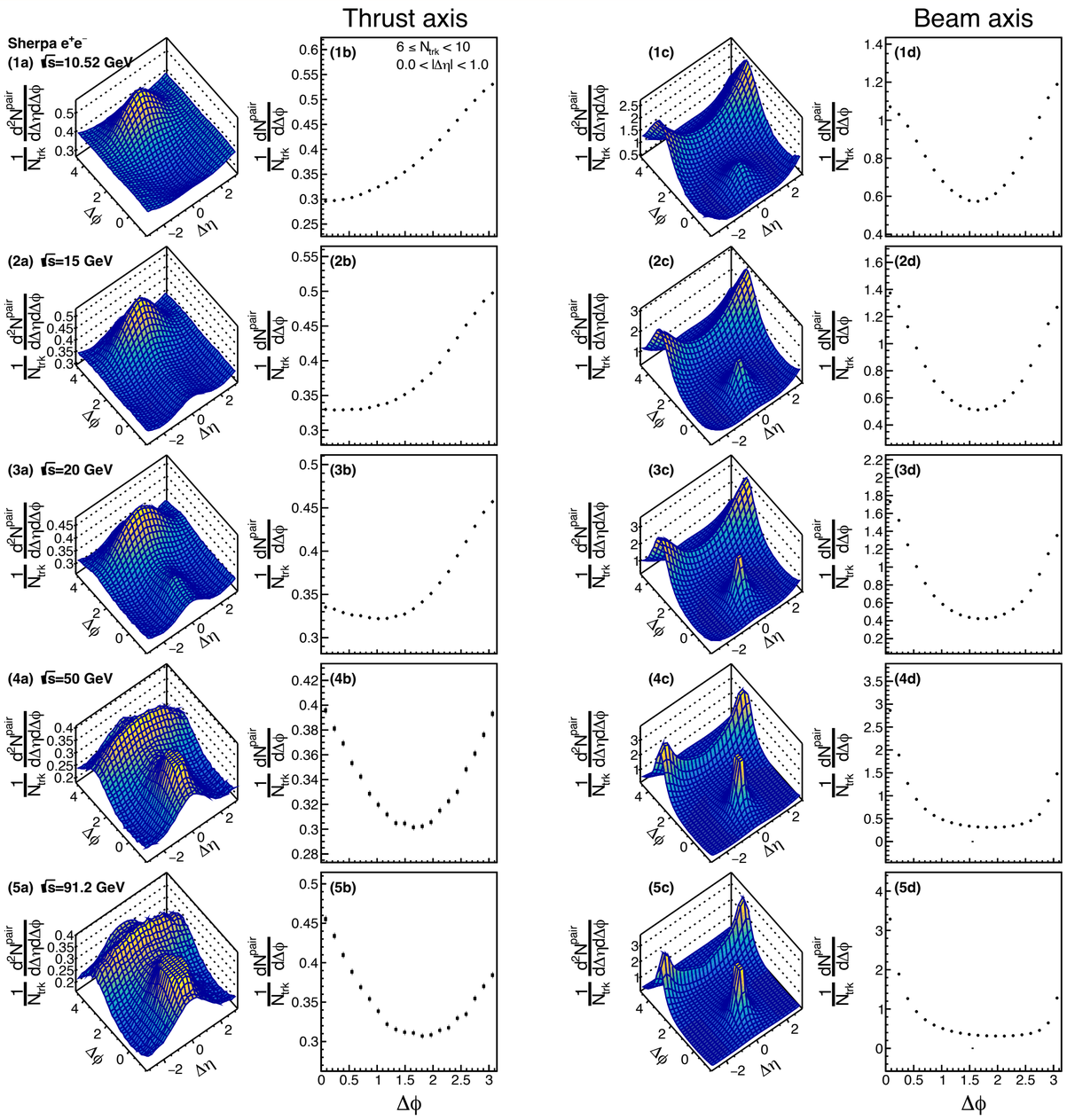
√s = 15 GeV

√s = 20 GeV

√s = 50 GeV

√s = 91.2 GeV (LEP1 energy)

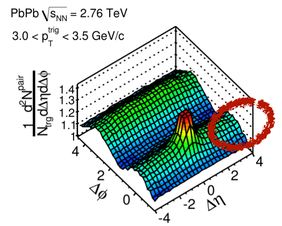
Larger origin peak correlation is found



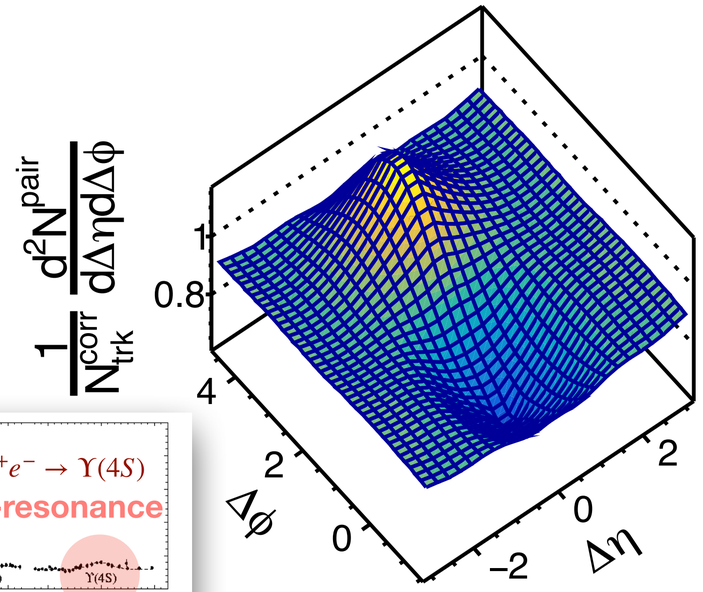
Result

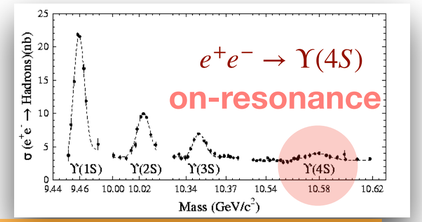
Thrust-axis two-particle correlations — on-resonance (√s=10.58 GeV)

- Enhanced long-range near-side correlation, but does NOT resemble to typical ridge structure
- Similar enhancement seen in MC



PbPb [Eur. Phys. J., C72]





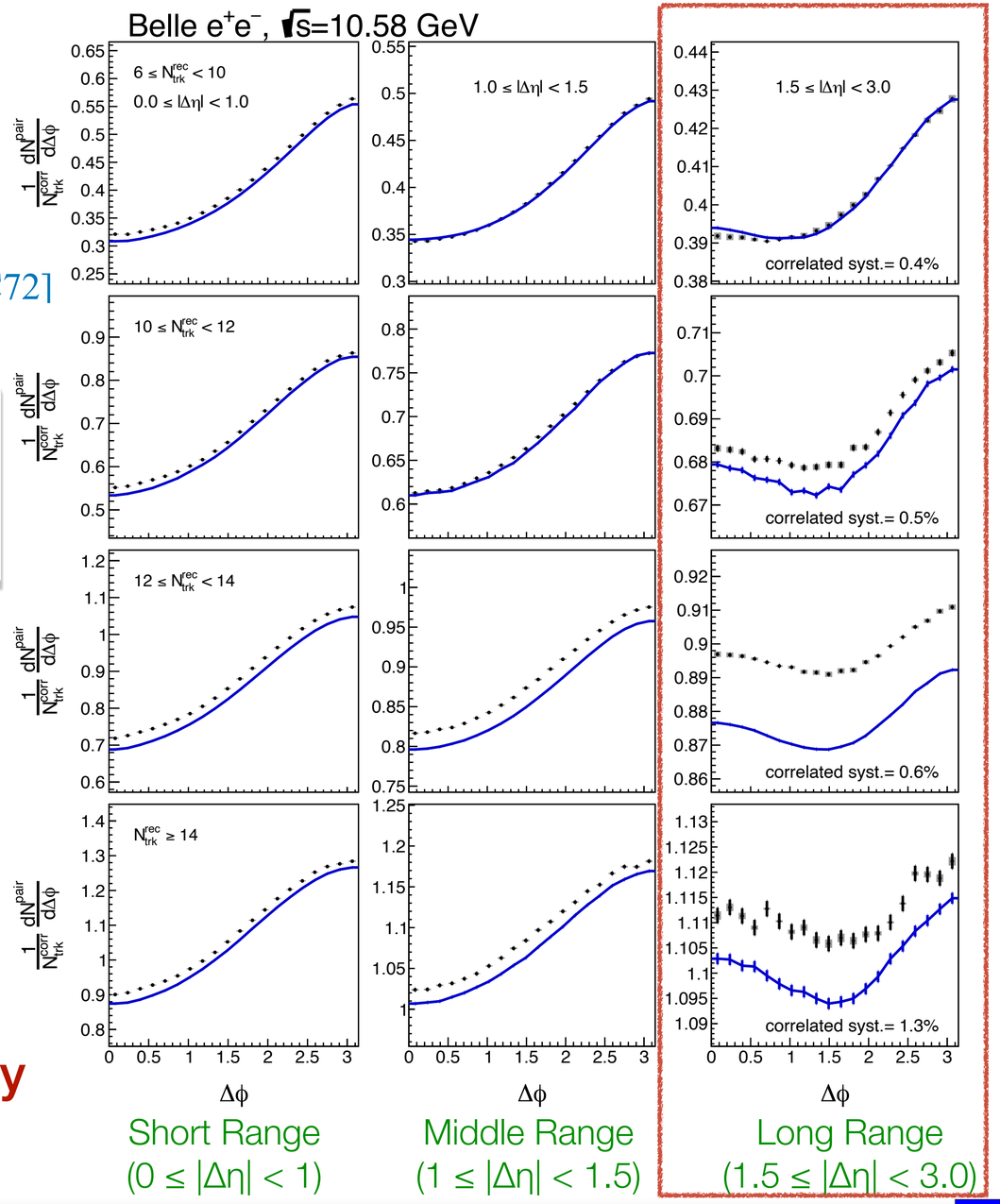
arXiv:2206.09440
submitted to JHEP

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

Data

PYTHIA6

High-multiplicity

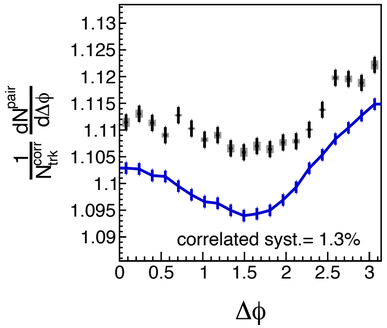


Short Range
(0 ≤ |Δη| < 1)

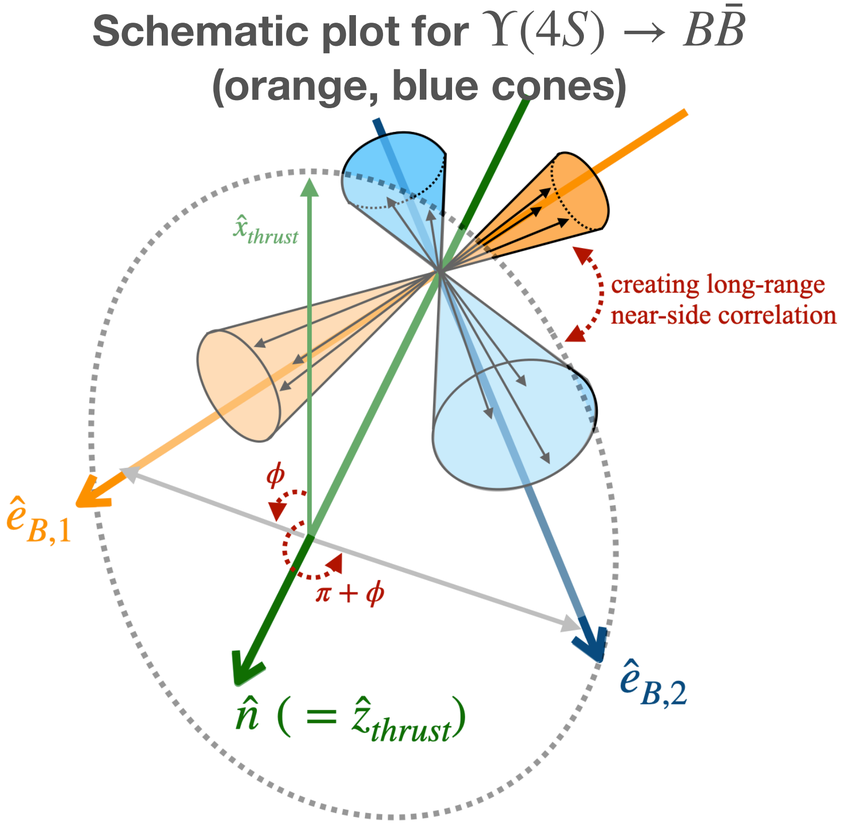
Middle Range
(1 ≤ |Δη| < 1.5)

Long Range
(1.5 ≤ |Δη| < 3.0)

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

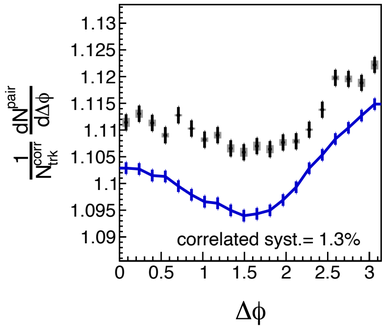


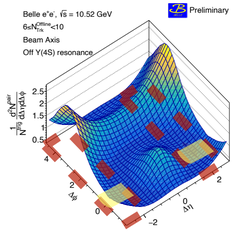
- Two *B*-meson decays: special event topology thrust axis alignment

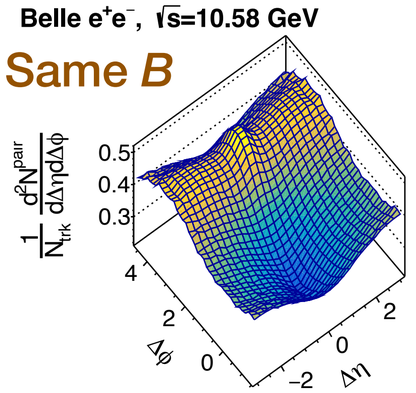


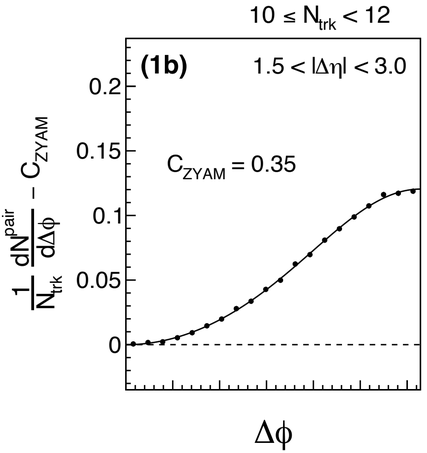
Generator study

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



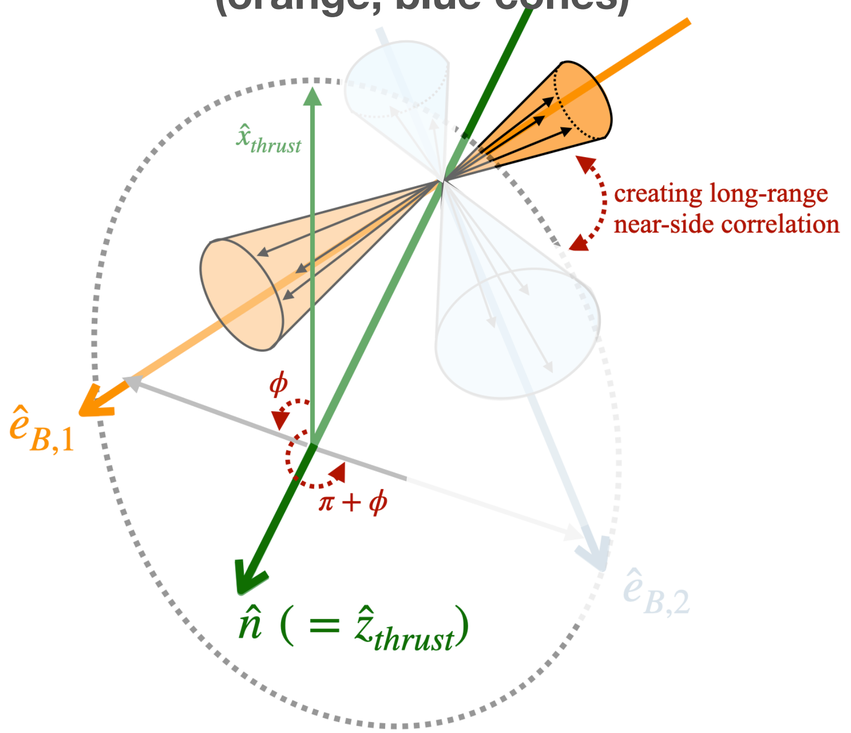






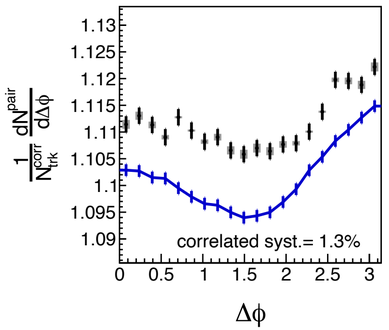
- Two *B*-meson decays: special event topology thrust axis alignment

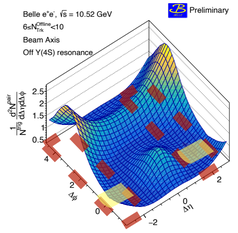
Schematic plot for $\Upsilon(4S) \to B\bar{B}$ (orange, blue cones)



Generator study

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





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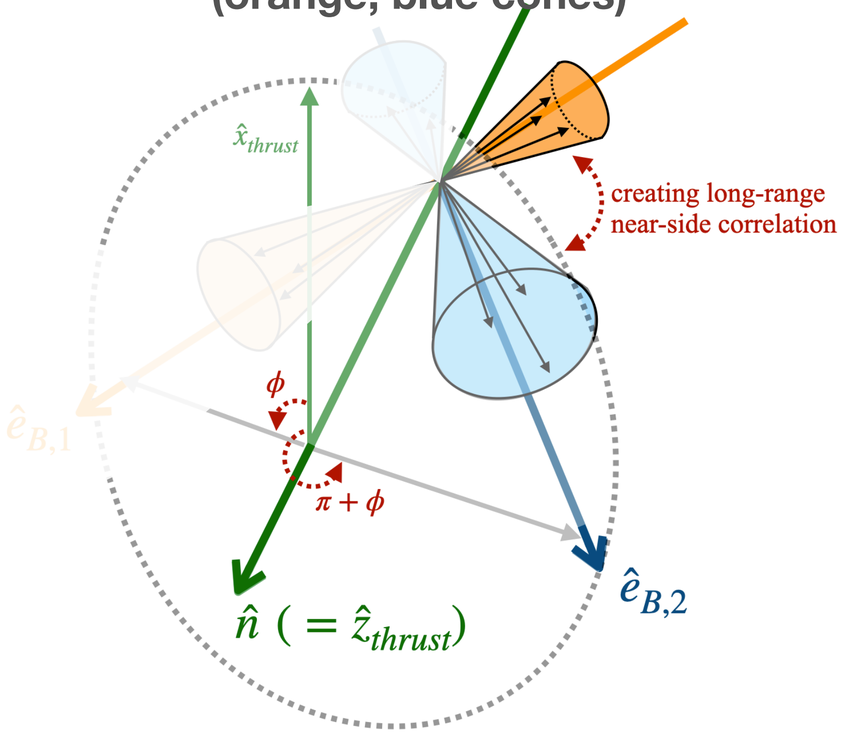
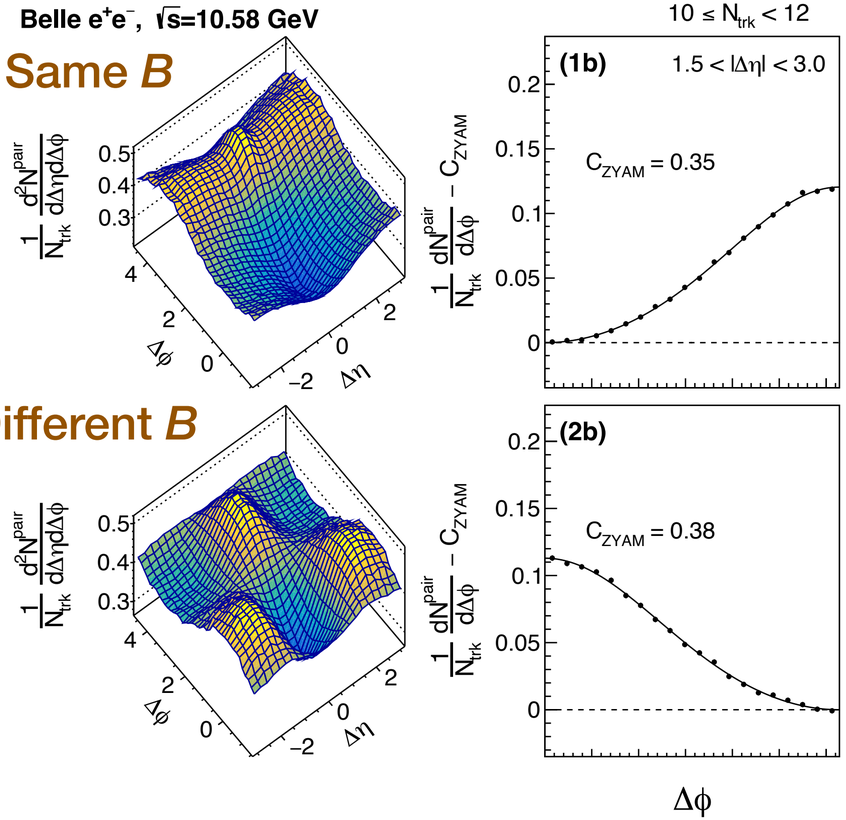
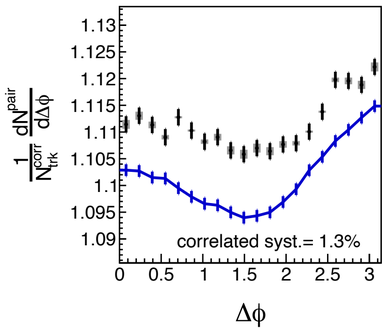
Schematic plot for $\Upsilon(4S) \to B\bar{B}$ (orange, blue cones)

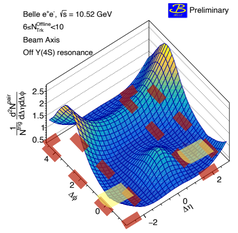




Generator study

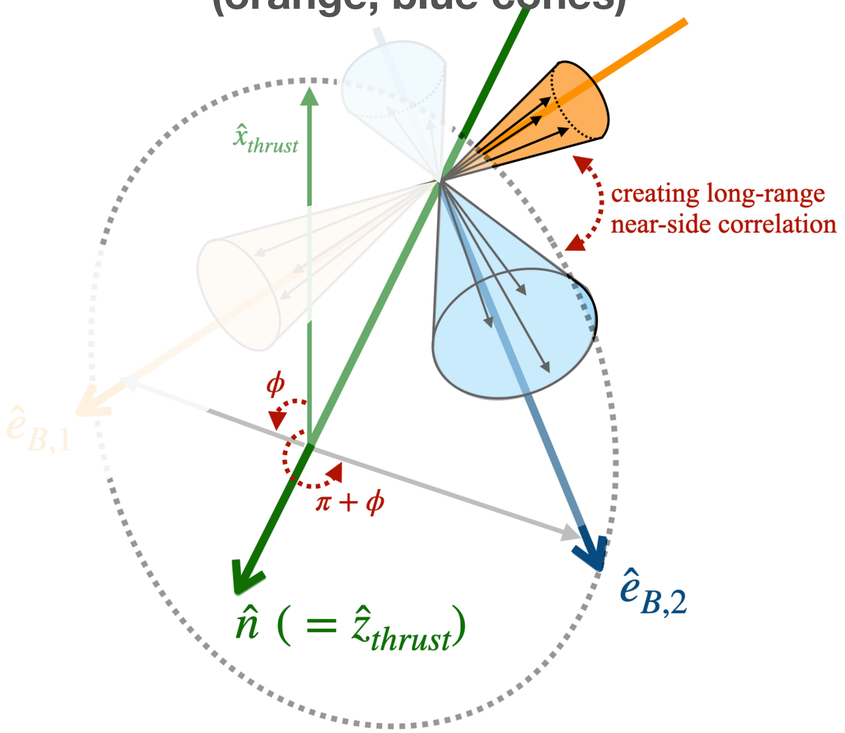
Long-range near-side enhancement in on-resonance sample

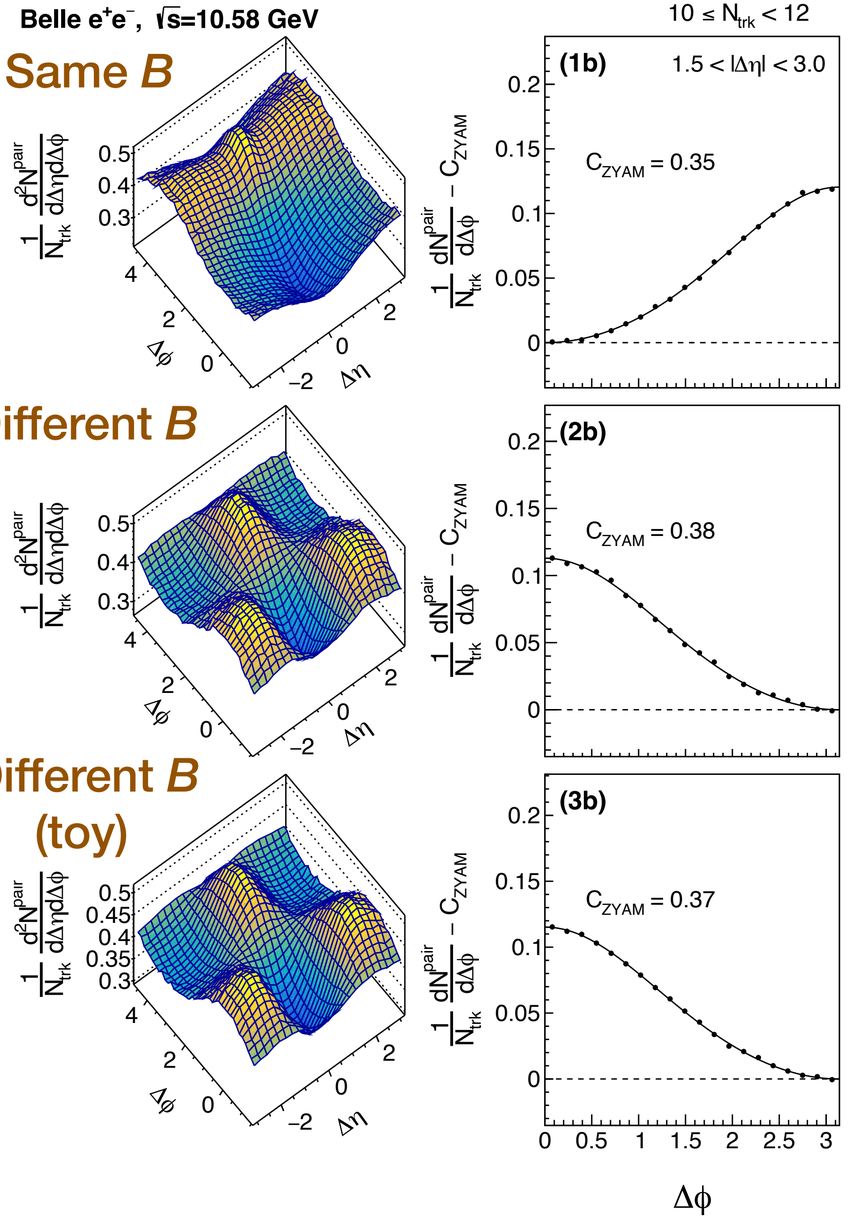




- Two *B*-meson decays: special event topology thrust axis alignment
- Toy sample pairing uncorrelated B's from different events shows similar enhancement!

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

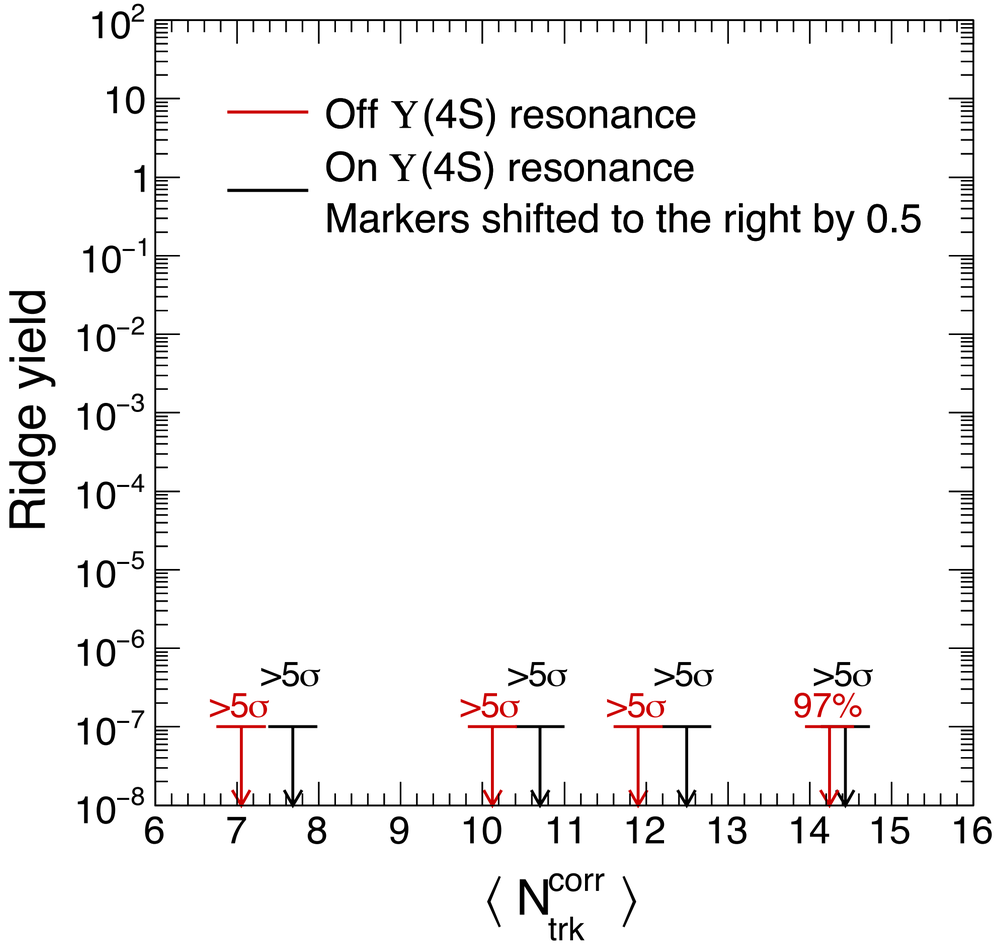




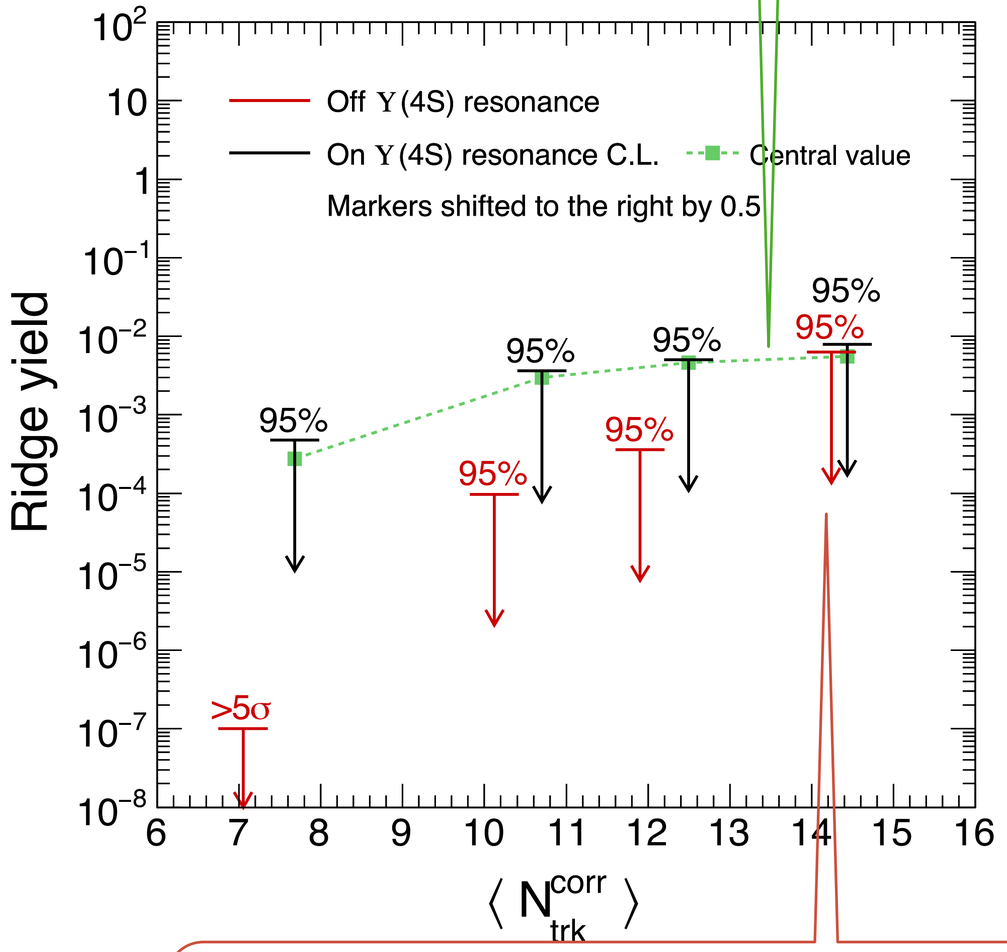
Quantification of ridge yields

On-resonance:
Low-scale long-range enhancement

Beam axis



Thrust axis



>5σ exclusion of ridge signal!

Off-resonance: No significant ridge signal
C.L. limited by statistics

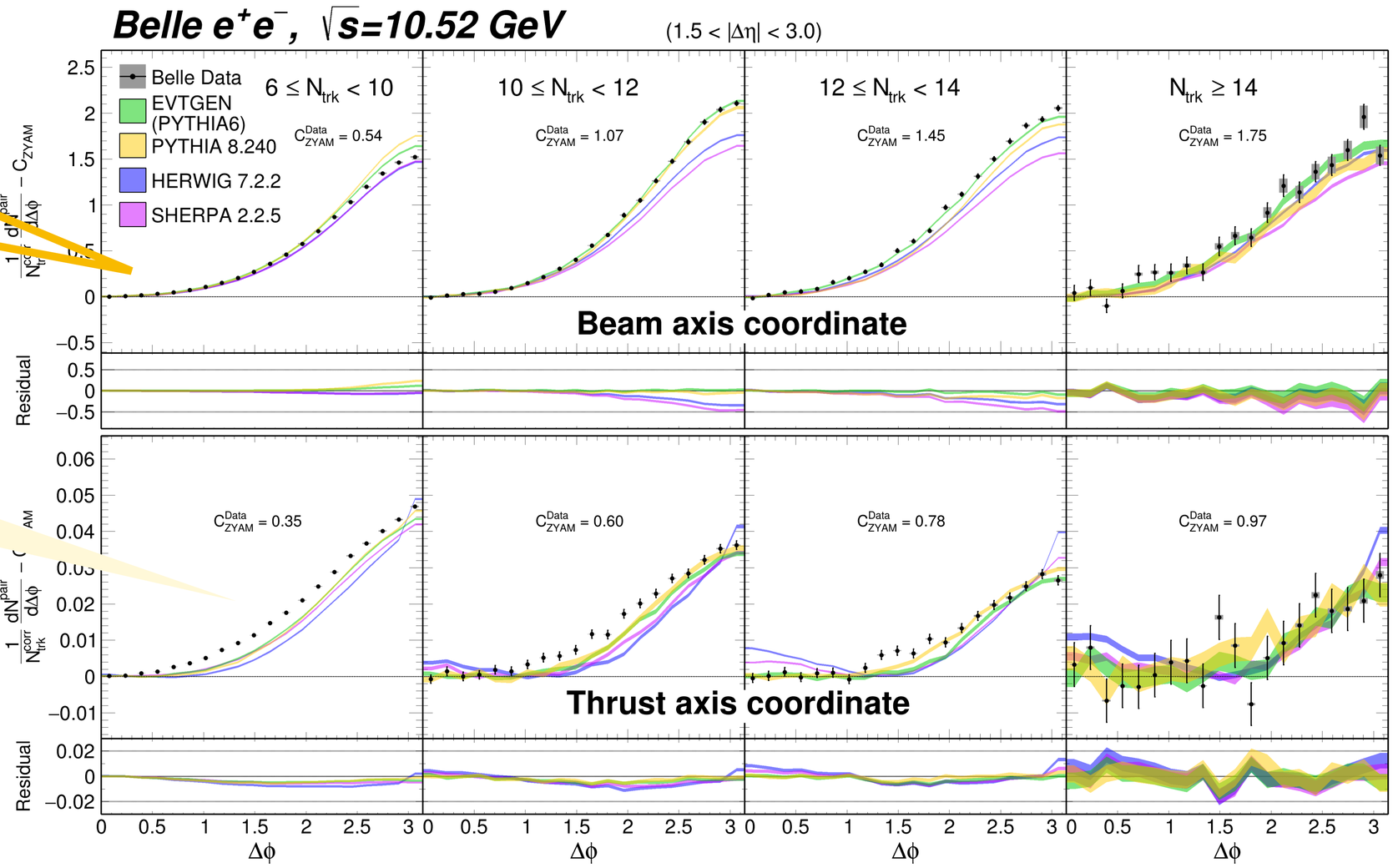
Off-resonance $Y(\Delta\phi)$

- 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

Low-multiplicity → High-multiplicity



on-resonance see backup

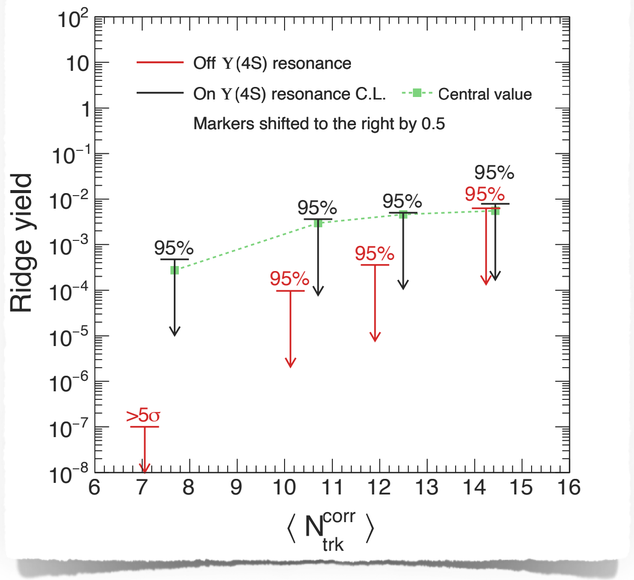
Conclusion

First two-particle correlation results at Belle!

e^+e^- system & minimal condition

- Upper limits for exclusion of ridge-like signals

Thrust axis



Exploring low-energy region

(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 $\Upsilon(4S) \to B\bar{B}$ system

Compared w/ event generators

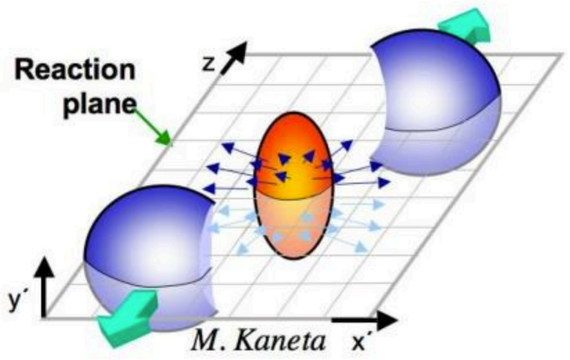
- `PYTHIA` is in better agreement with data than `SHERPA` & `HERWIG`

MITHIG group's work was supported by US DOE-NP

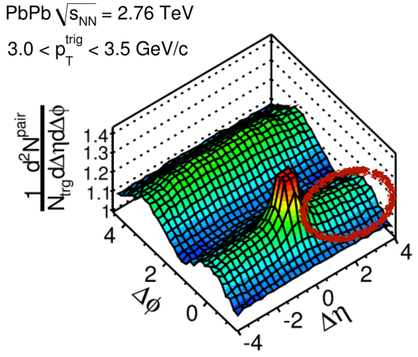
Backup

Motivation

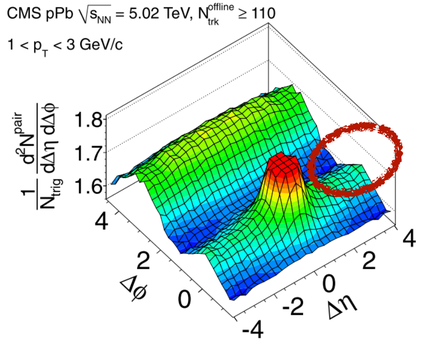
- Collectivity signal
  Two-particle correlation: soft probe for Quark-Gluon Plasma (QGP) in heavy ion collisions



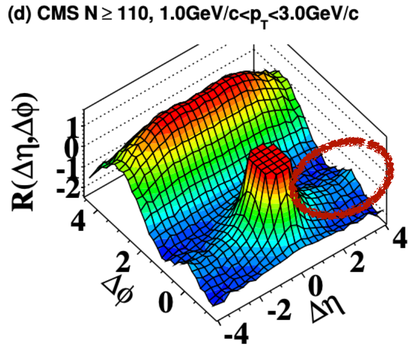
Spatial anisotropy



PbPb [Eur. Phys. J., C72]

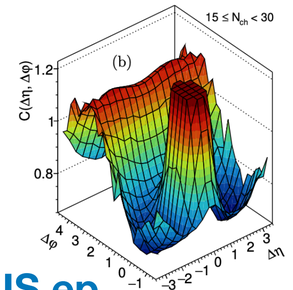


pPb [Phys. Lett. B718 (2013) 795-814]

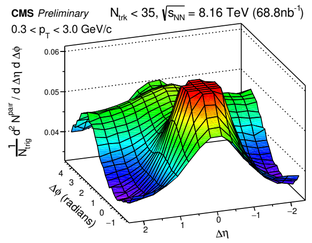


pp [JHEP 1009 (2010) 091]

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



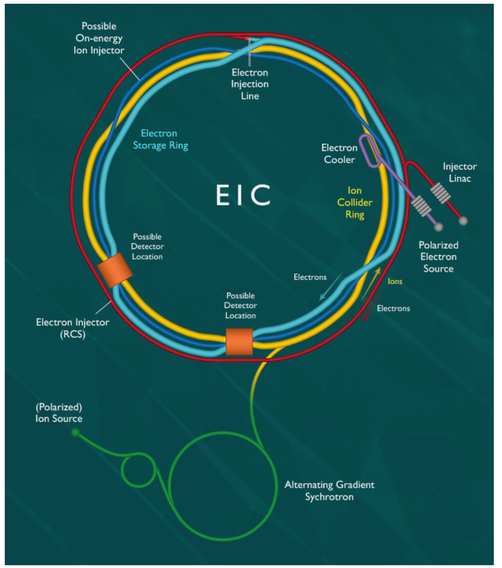
ZEUS ep
[JHEP 04 (2020) 070]



CMS γp
[CMS-PAS-HIN-18-008]

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

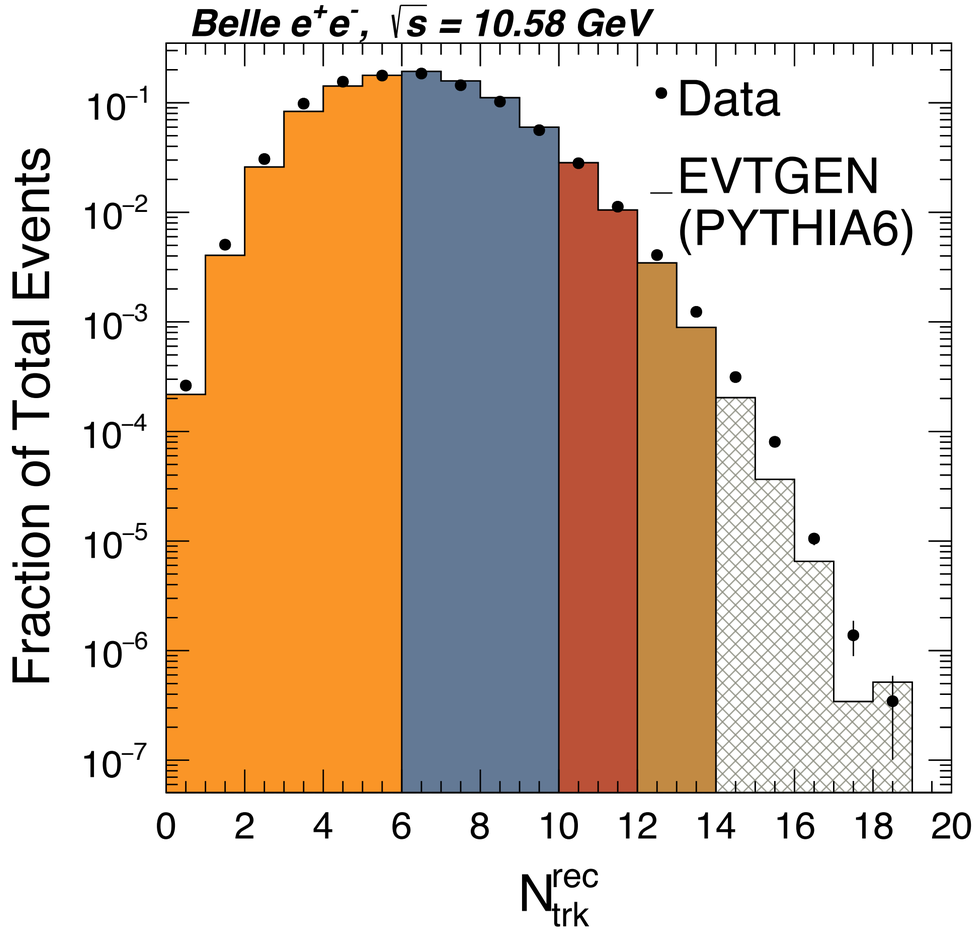
ATLAS γA [Phys. Rev. C. 104, 014903]



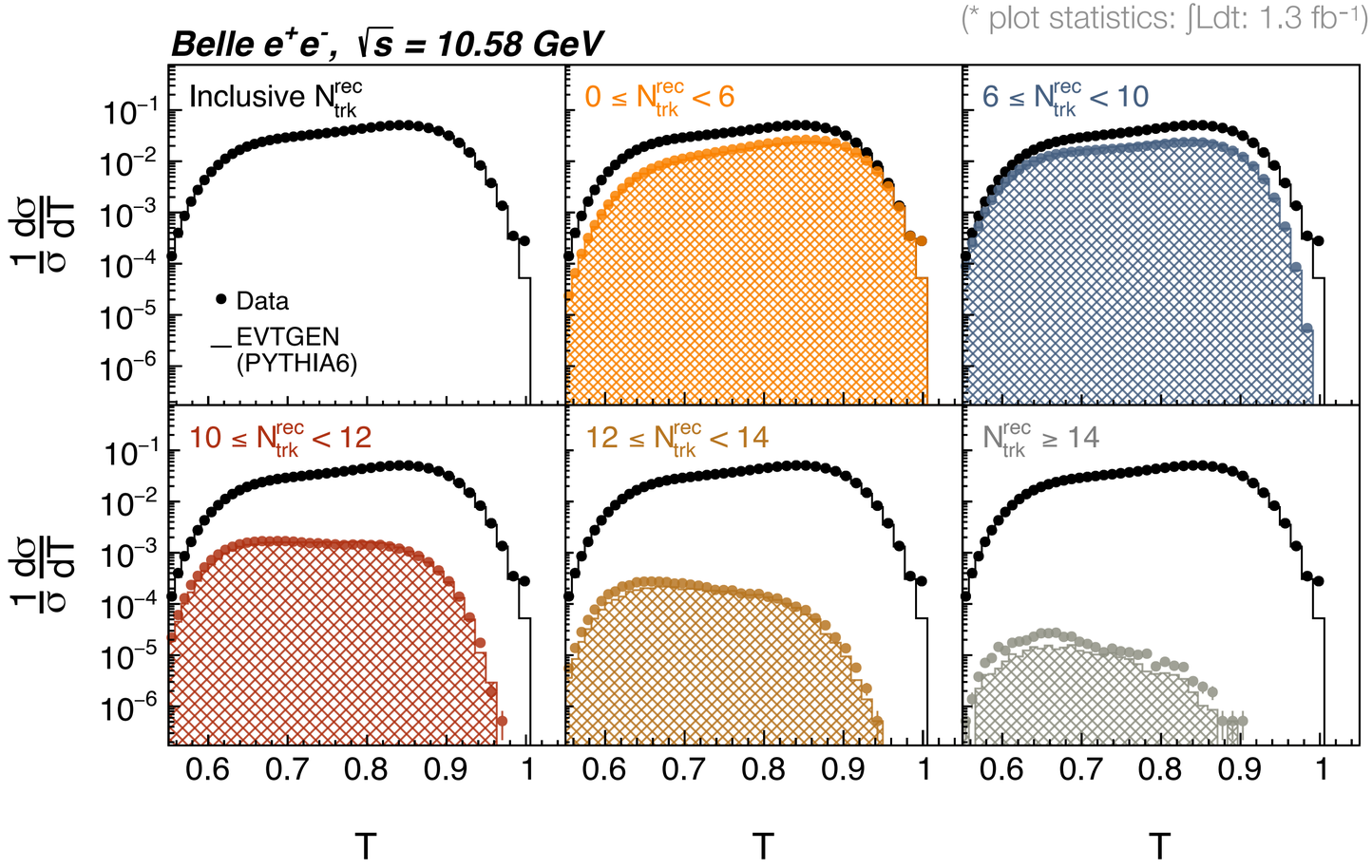
Sample

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	$p_{\mathrm{T}} \geq 0.2$ GeV
Impact parameter	$\lvert\Delta r\rvert < 2$, $\lvert\Delta z\rvert < 5$
Duplicate track removal	veto the softer track of a low-momentum pair ($p_{\mathrm{T}} < 0.4$ 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

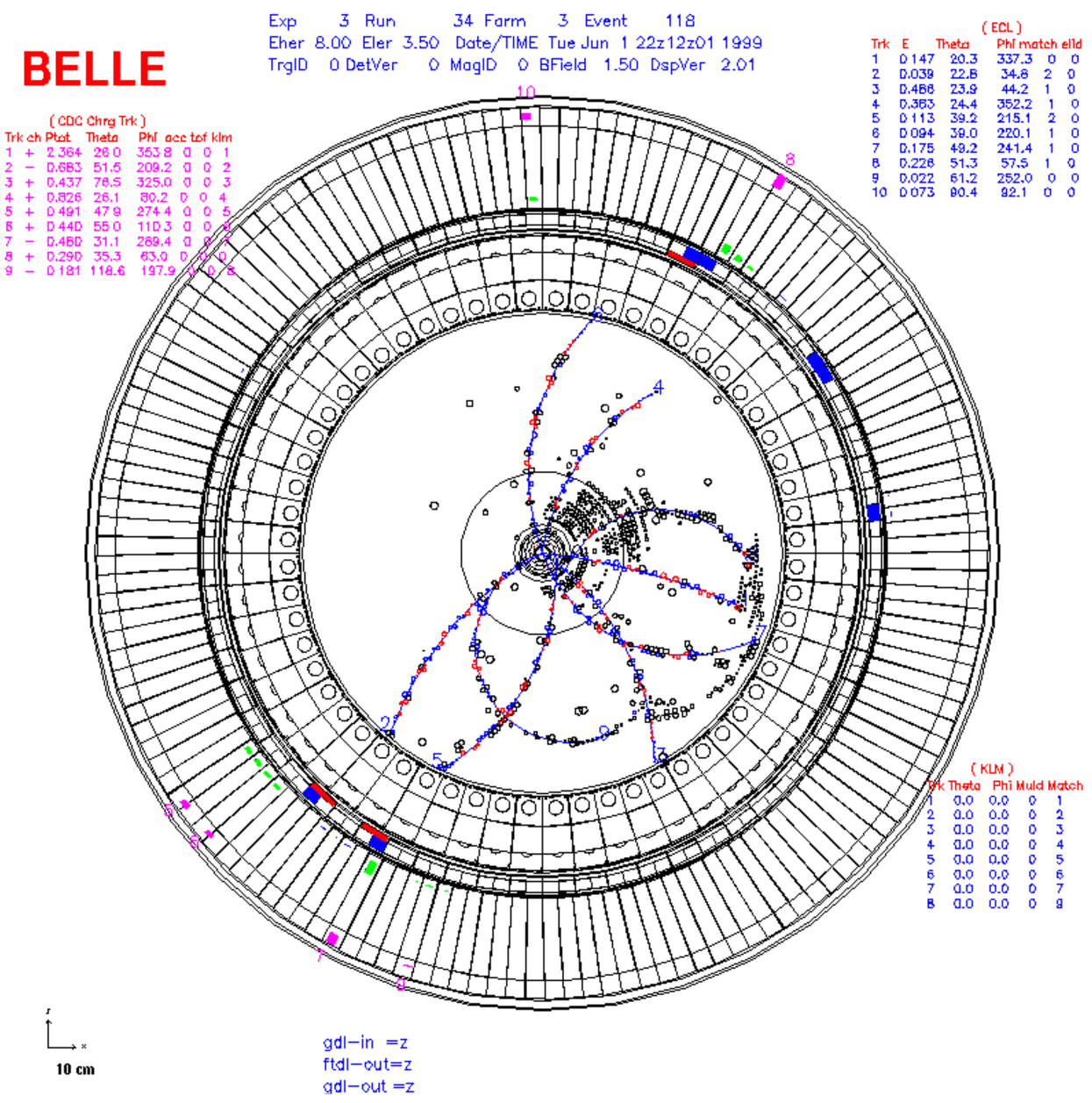


(* plot statistics: ∫Ldt: 1.3 fb^{-1})



Hadronic event display

Belle has rather spherical events!



Observable

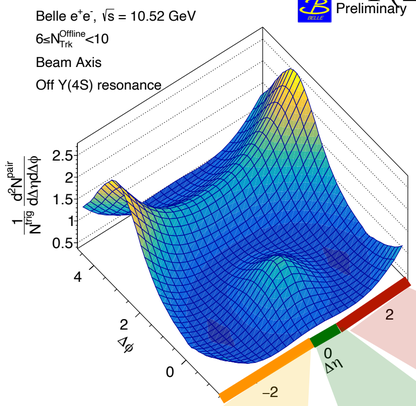
Azimuthal differential associated yield $Y(\Delta\phi)$

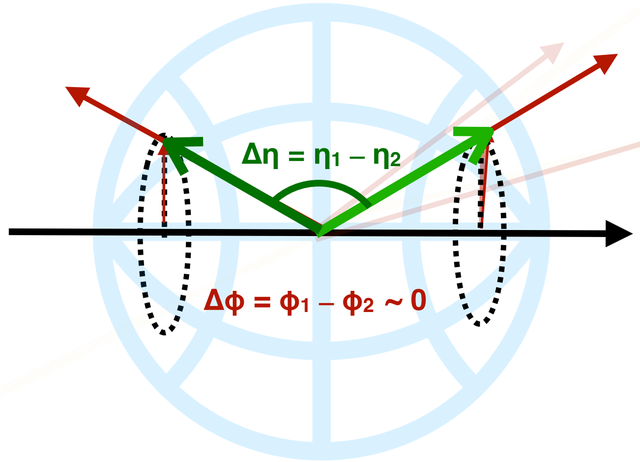
Two-particle correlation function (per-trigger-particle associated yield)

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

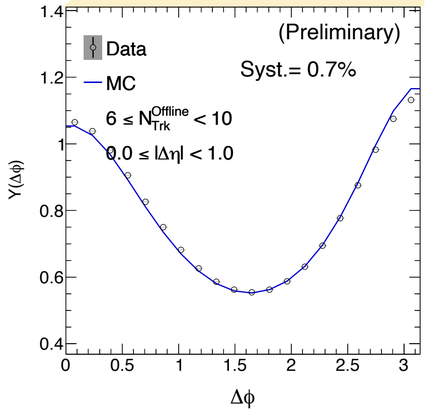
Associated yield vs. Δϕ

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

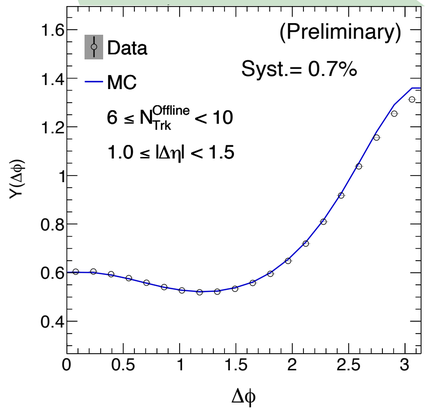




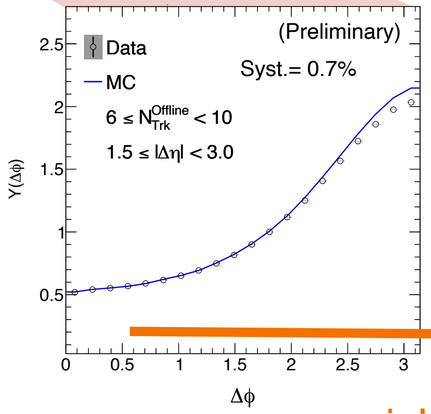
Short Range (0 ≤ |Δη| < 1)



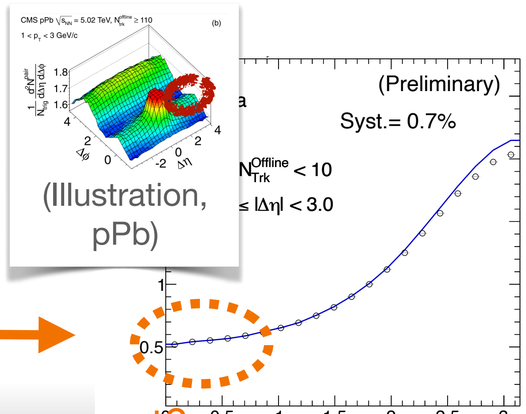
Middle Range (1 ≤ |Δη| < 1.5)



Long Range (1.5 ≤ |Δη| < 3.0)



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

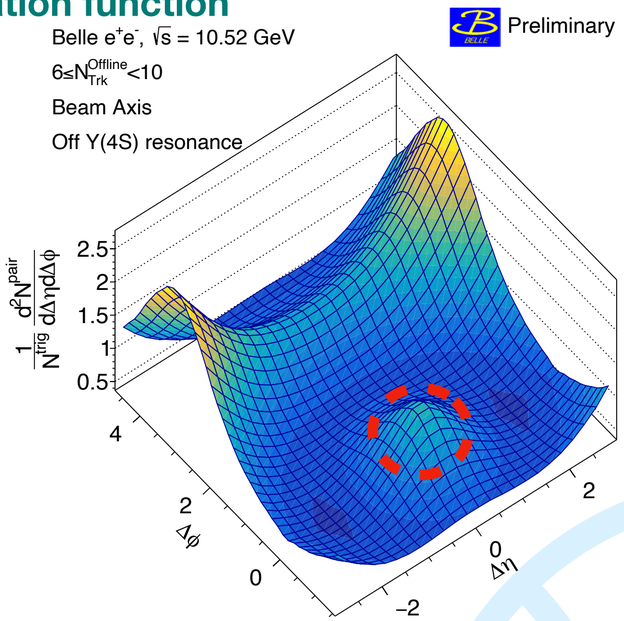


special enhancement?

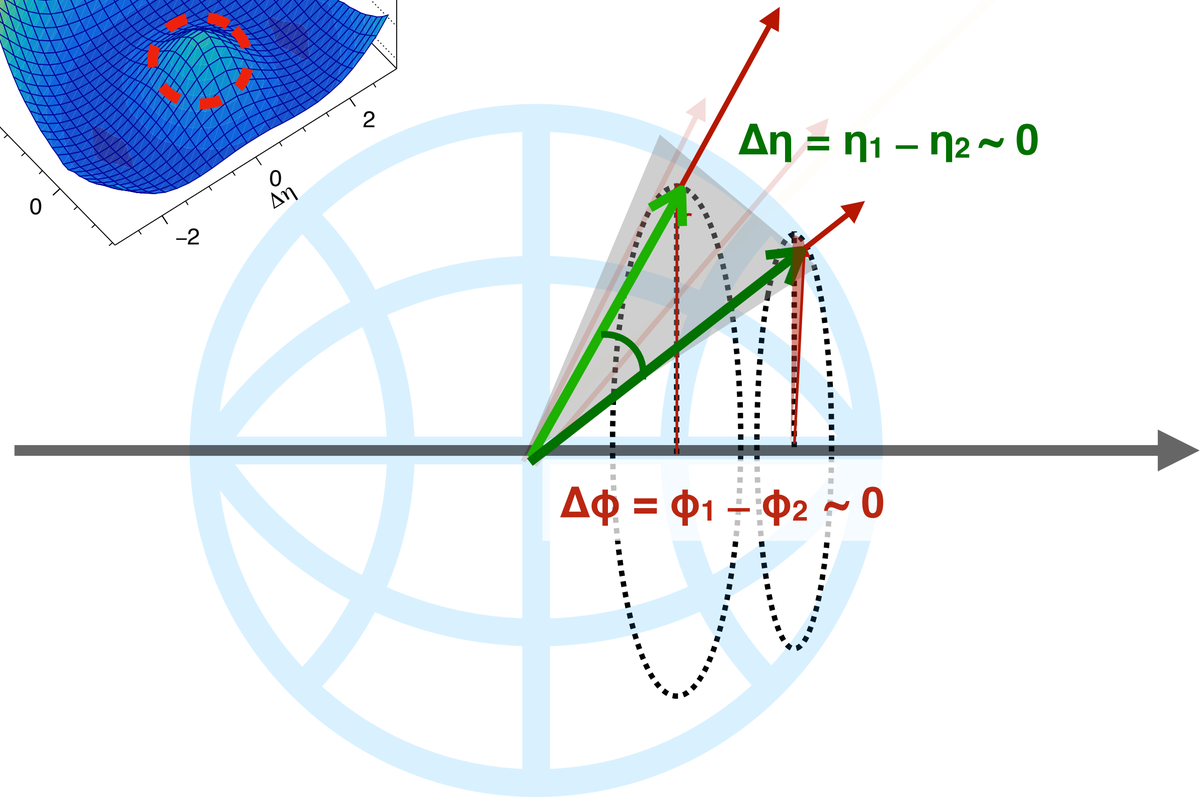
Azimuthal differential associated yield $Y(\Delta\phi)$

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

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



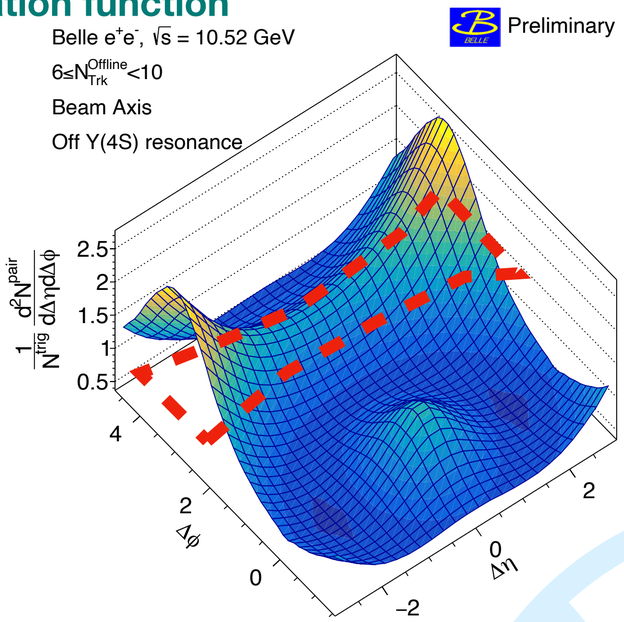
Origin-peak intra-jet correlations @ near side (Δη,Δϕ)~(0,0)



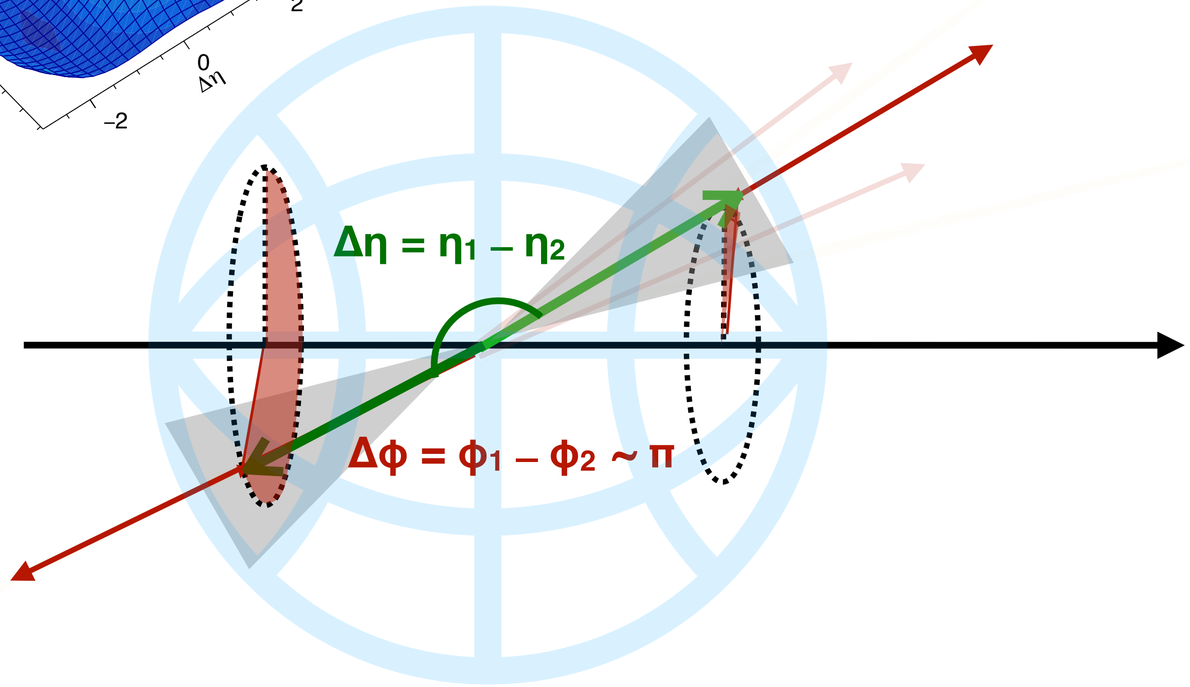
Azimuthal differential associated yield $Y(\Delta\phi)$

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

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



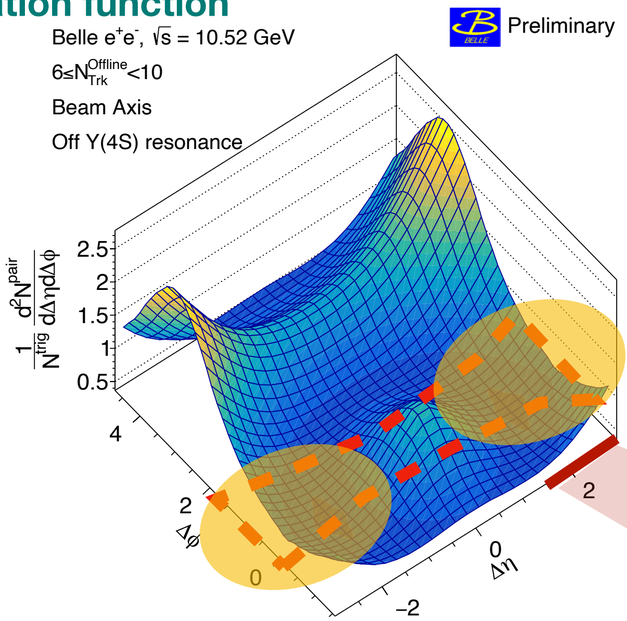
Back-to-back jet correlations @ away side (Δϕ~π)



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

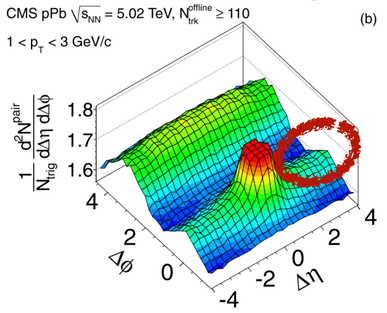
Two-particle correlation function (per-trigger-particle associated yield)

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

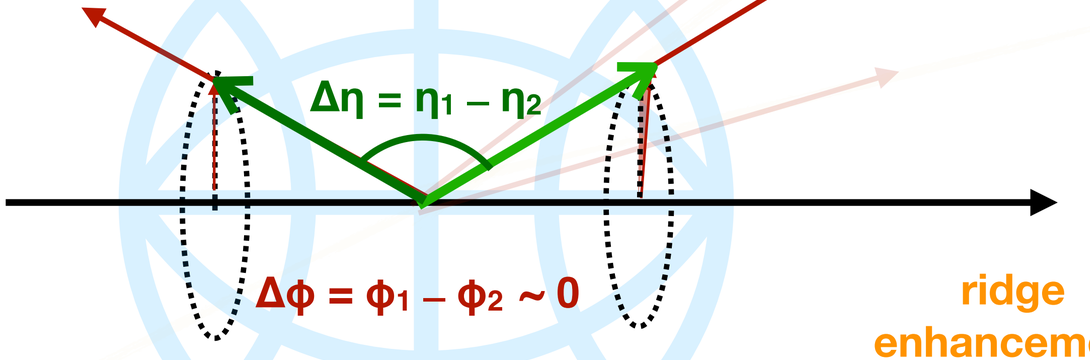


Ridge correlations @ long range, near side

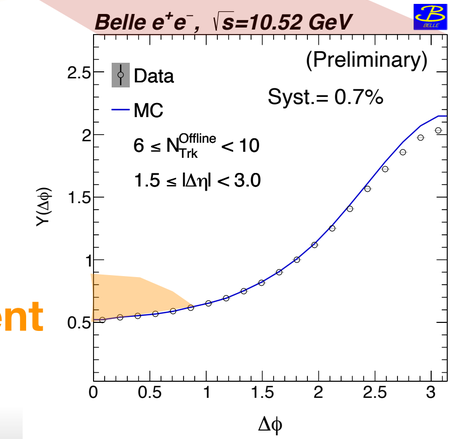
pPb



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

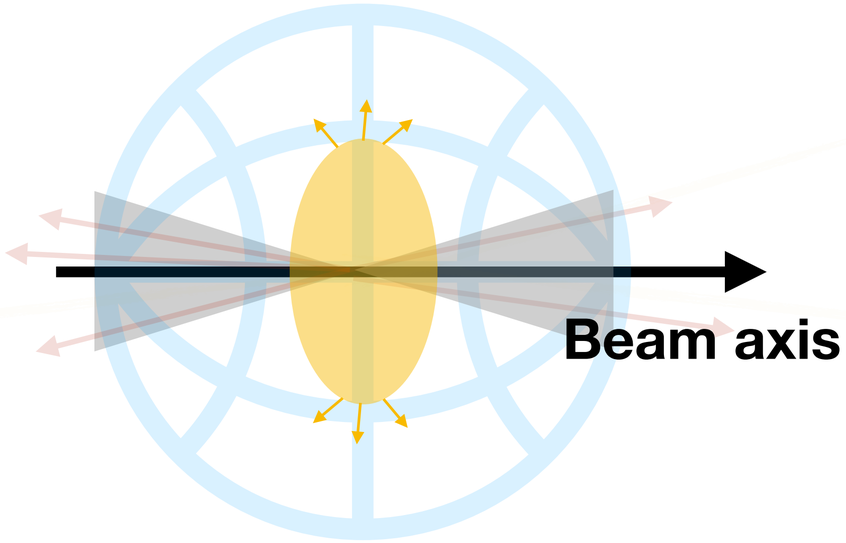


long range
(1.5 ≤ |Δη| < 3.0)



ridge enhancement

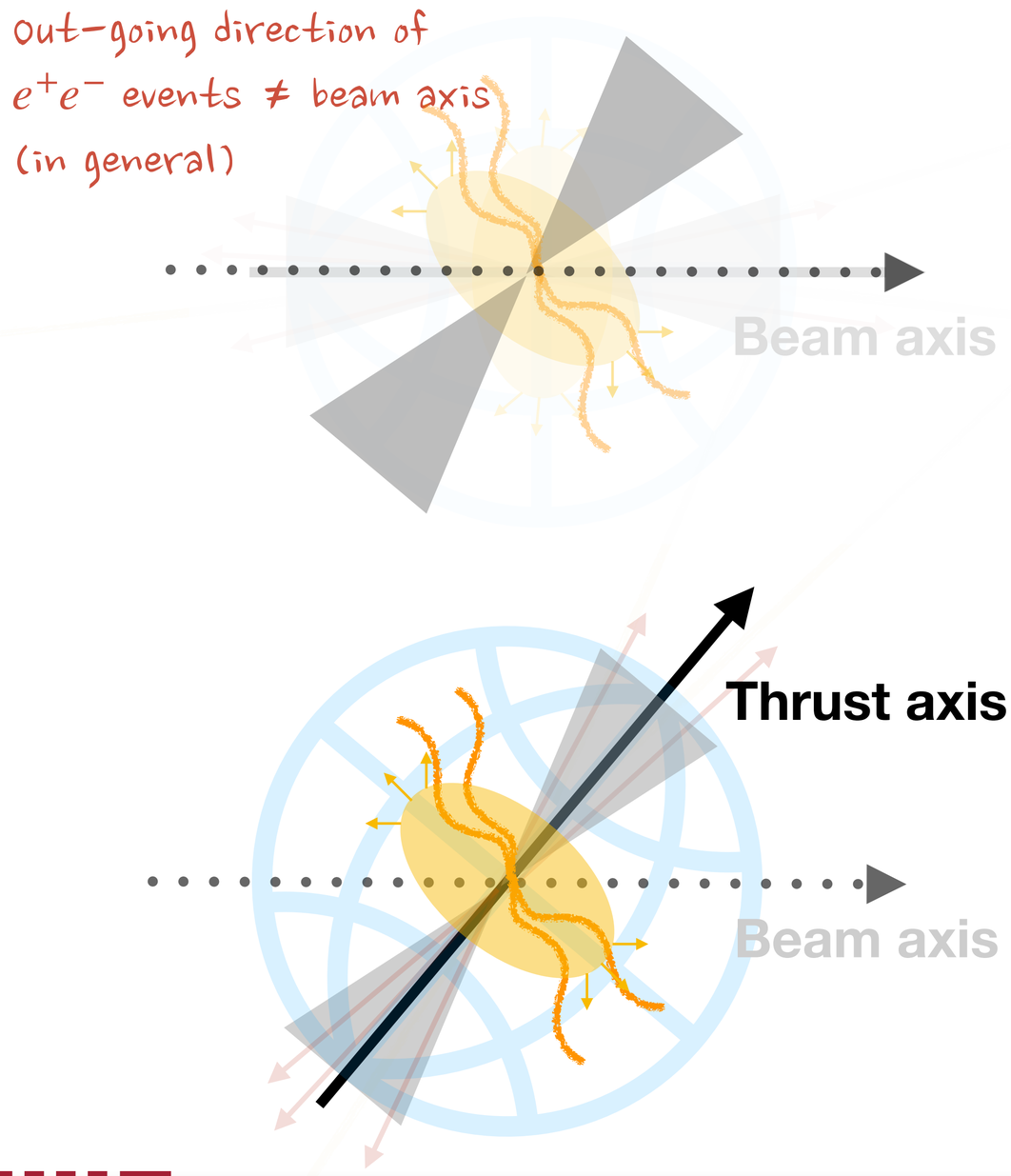
Thrust-axis two-particle correlation



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



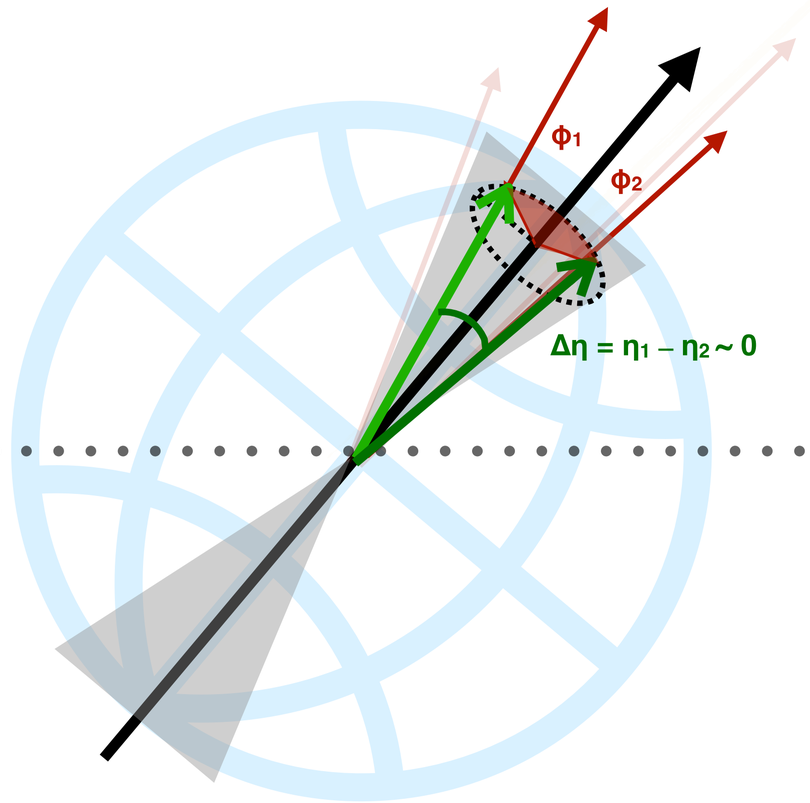
The **mid rapidity region** is where a correlation function sensitive to:

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

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

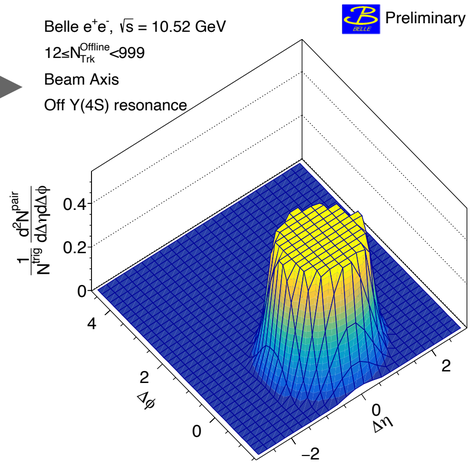
Working regions for correlation function

How to understand correlation function in thrust axis coordinate?

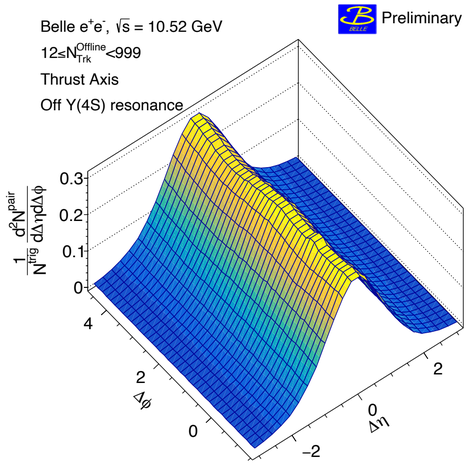


- Intra-jet correlation of on-axis jets is diluted!

Collinear leading intra-jet correlation dilutes along Δϕ



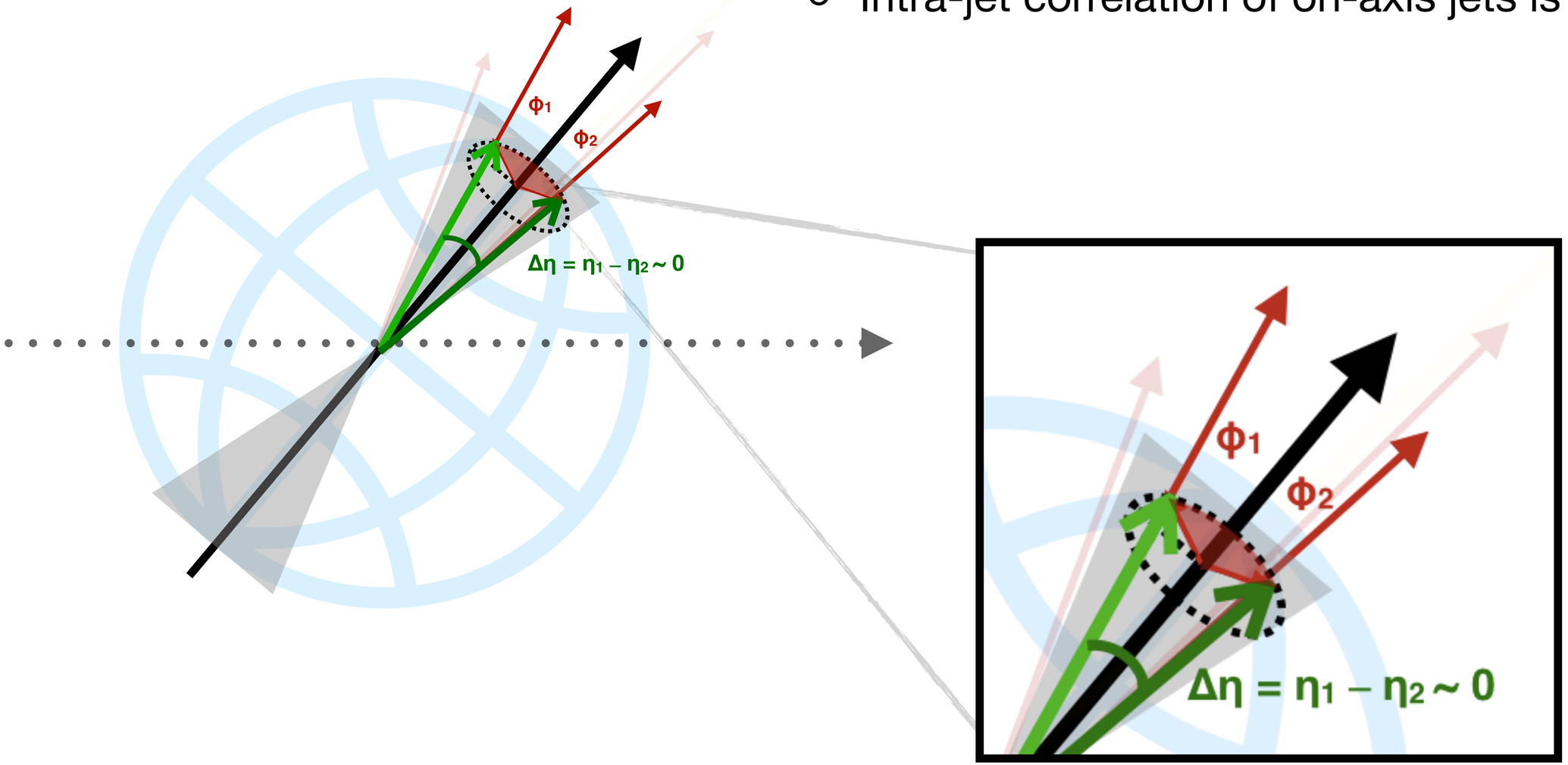
leading intra-jet correlation viewed @ beam coordinate



leading intra-jet correlation viewed @ thrust coordinate

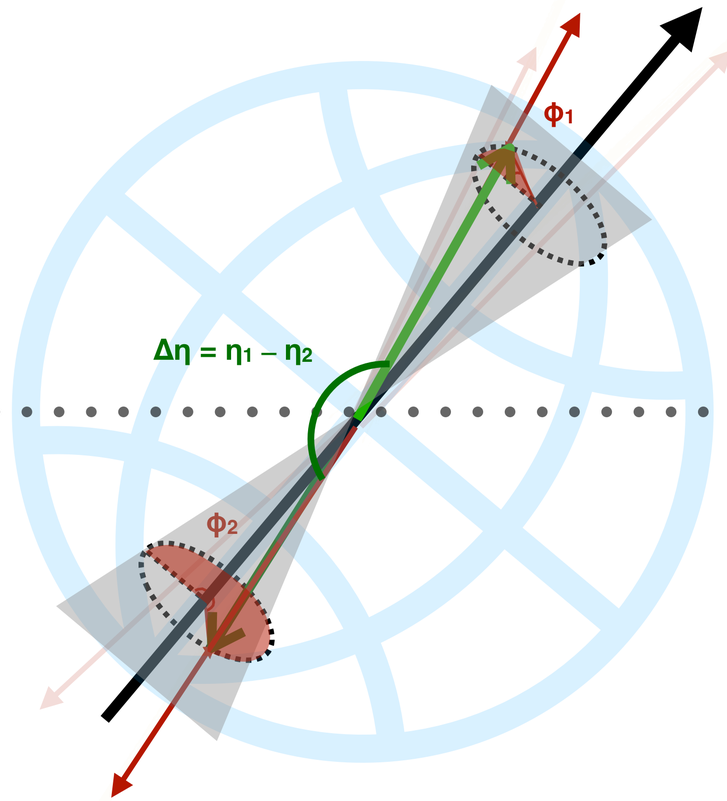
A weakened jet correlation

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

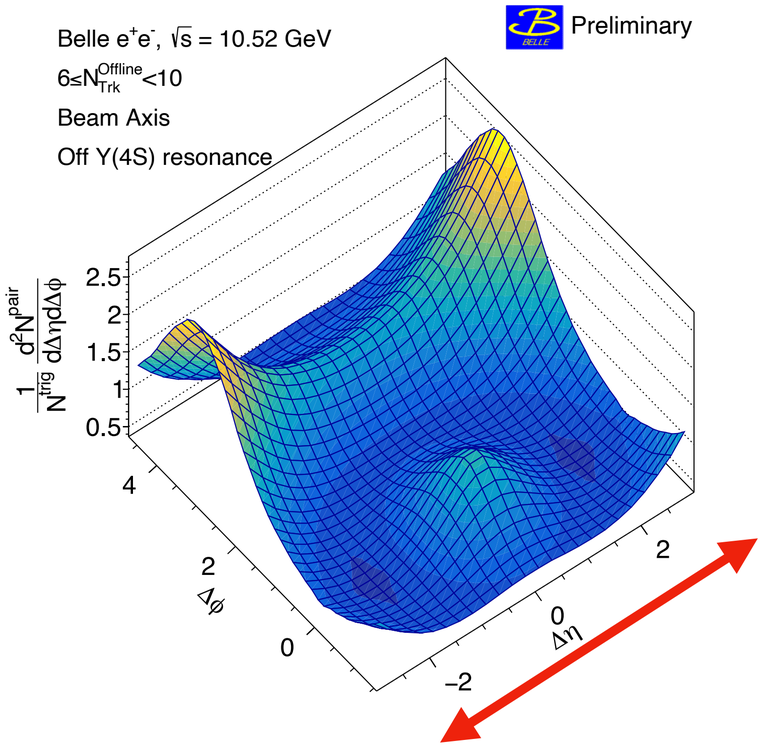


Working regions for correlation function

A weakened jet correlation



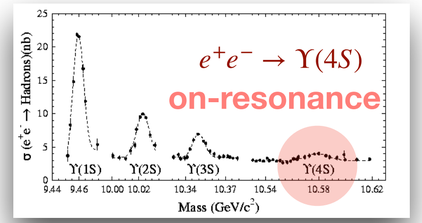
- Intra-jet correlation of on-axis jets is diluted!
- Back-to-back-jet correlation is excluded at finite |Δη| region of interest

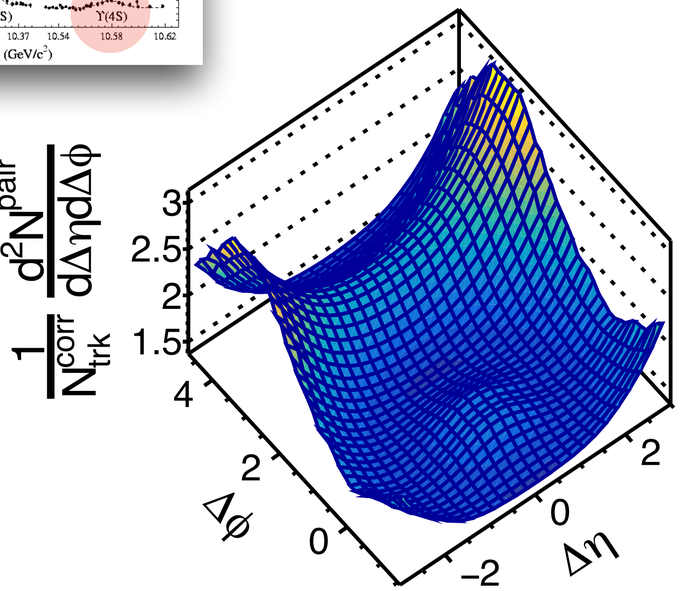


Result

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

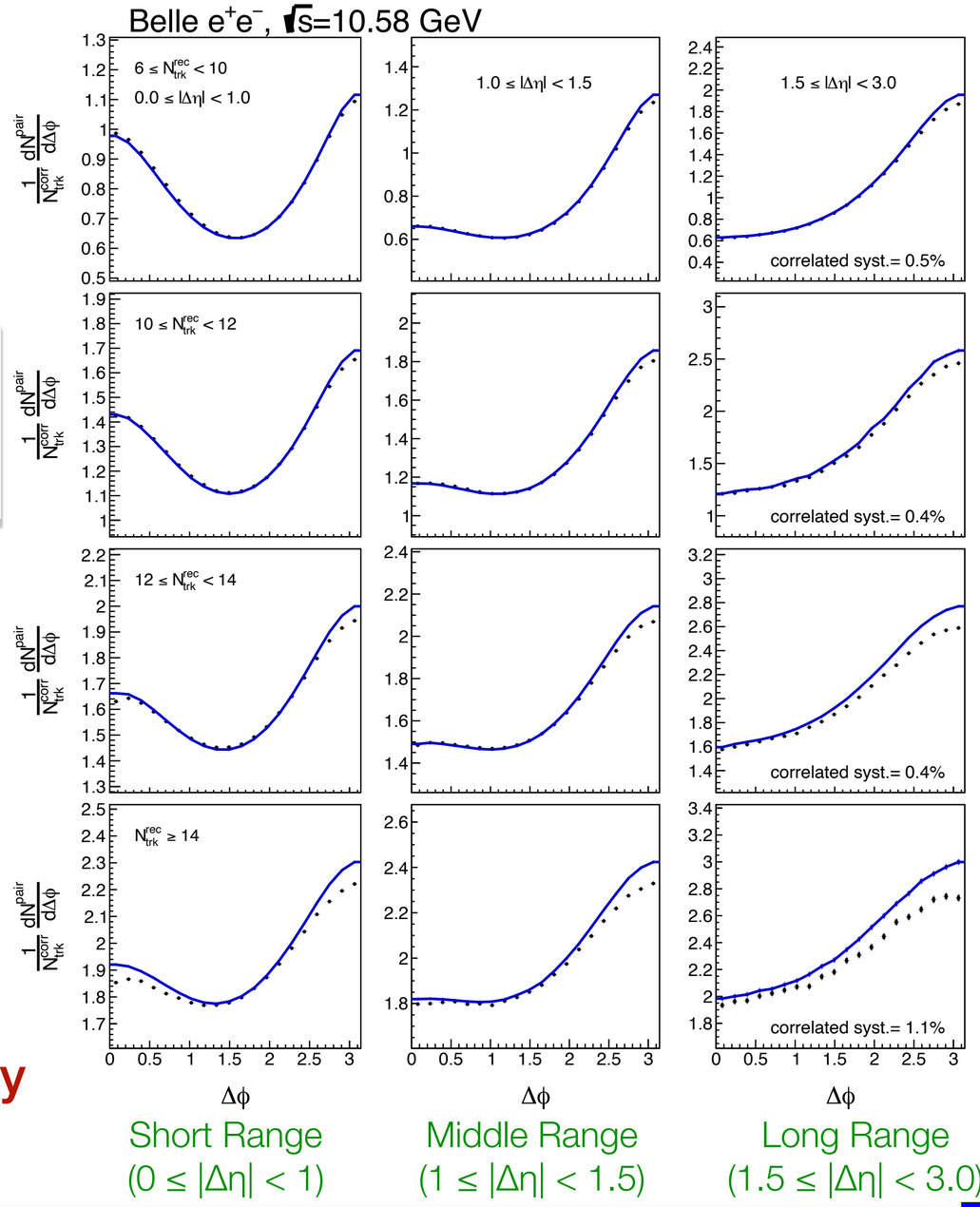




Data

PYTHIA6

High-multiplicity



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

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

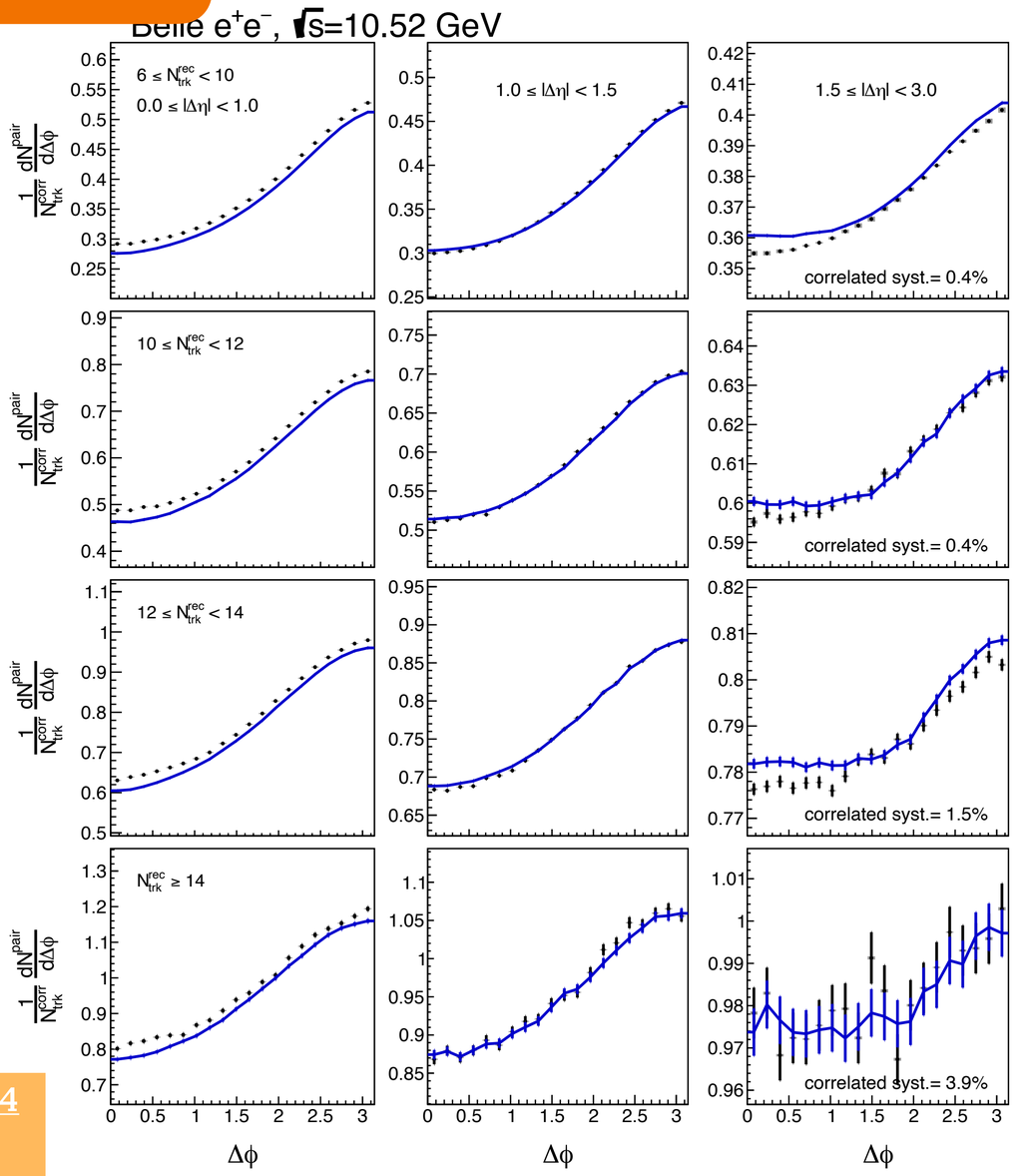
Long Range ($1.5 \le |\Delta\eta| < 3.0$)

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

arXiv:2206.09440
submitted to JHEP

Result

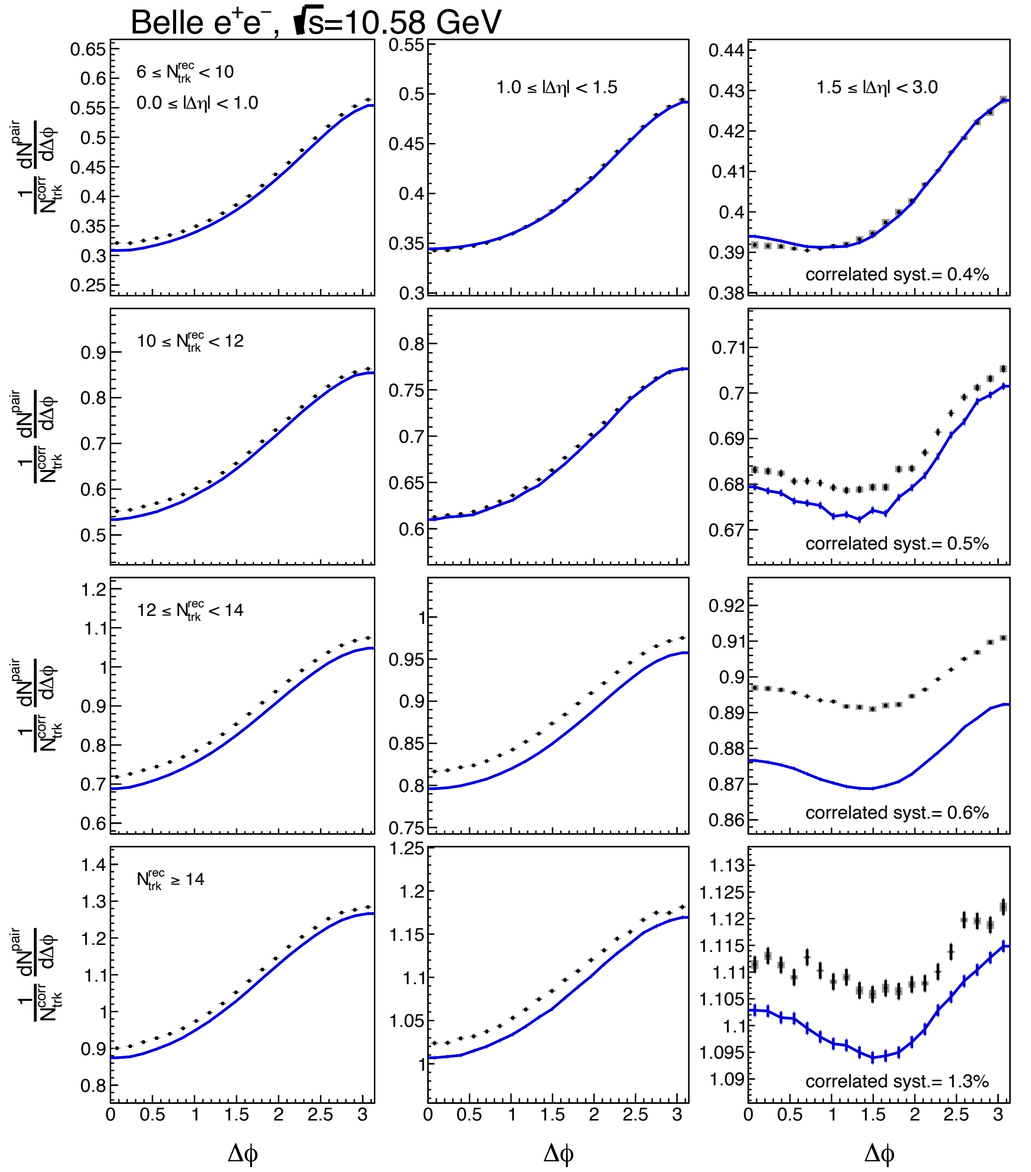
Thrust-axis two-particle correlations



Short Range (0 ≤ |Δη| < 1)

Middle Range (1 ≤ |Δη| < 1.5)

Long Range (1.5 ≤ |Δη| < 3.0)



Short Range (0 ≤ |Δη| < 1)

Middle Range (1 ≤ |Δη| < 1.5)

Long Range (1.5 ≤ |Δη| < 3.0)

arXiv:2201.01694
Phys. Rev. Lett. 128 (2022) 142005

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

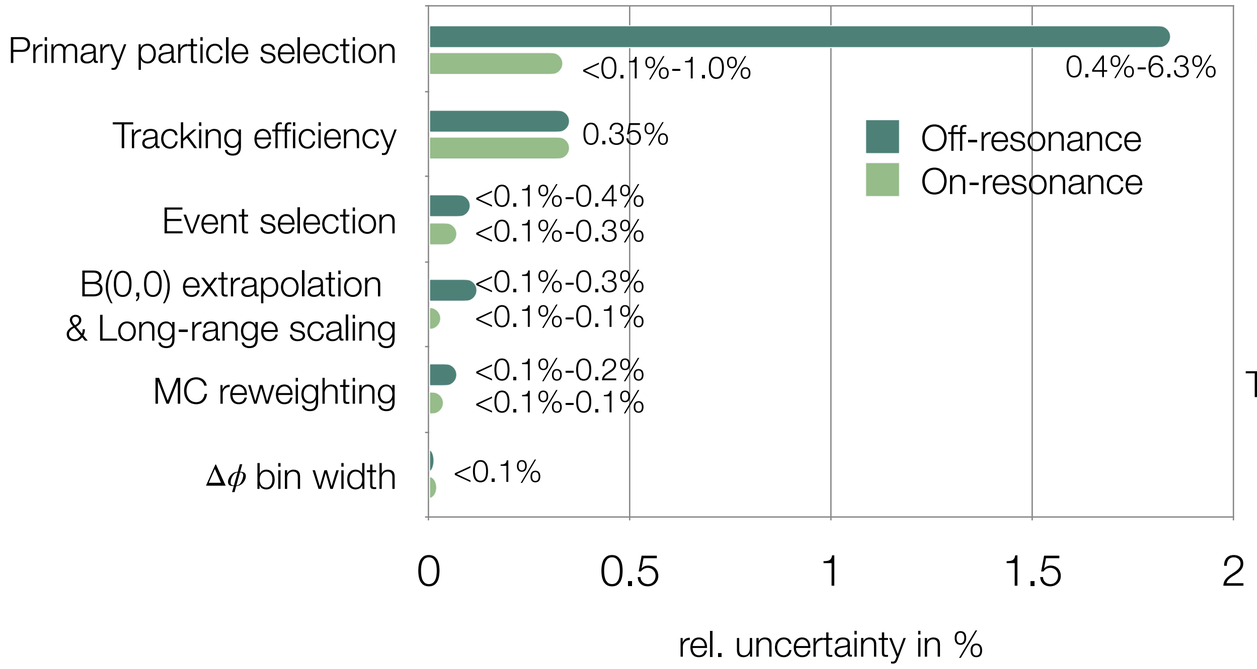
Accessing by reweighting factors with the alternative parametrization

6. MC reweighting
7. Thrust mixing reweighting

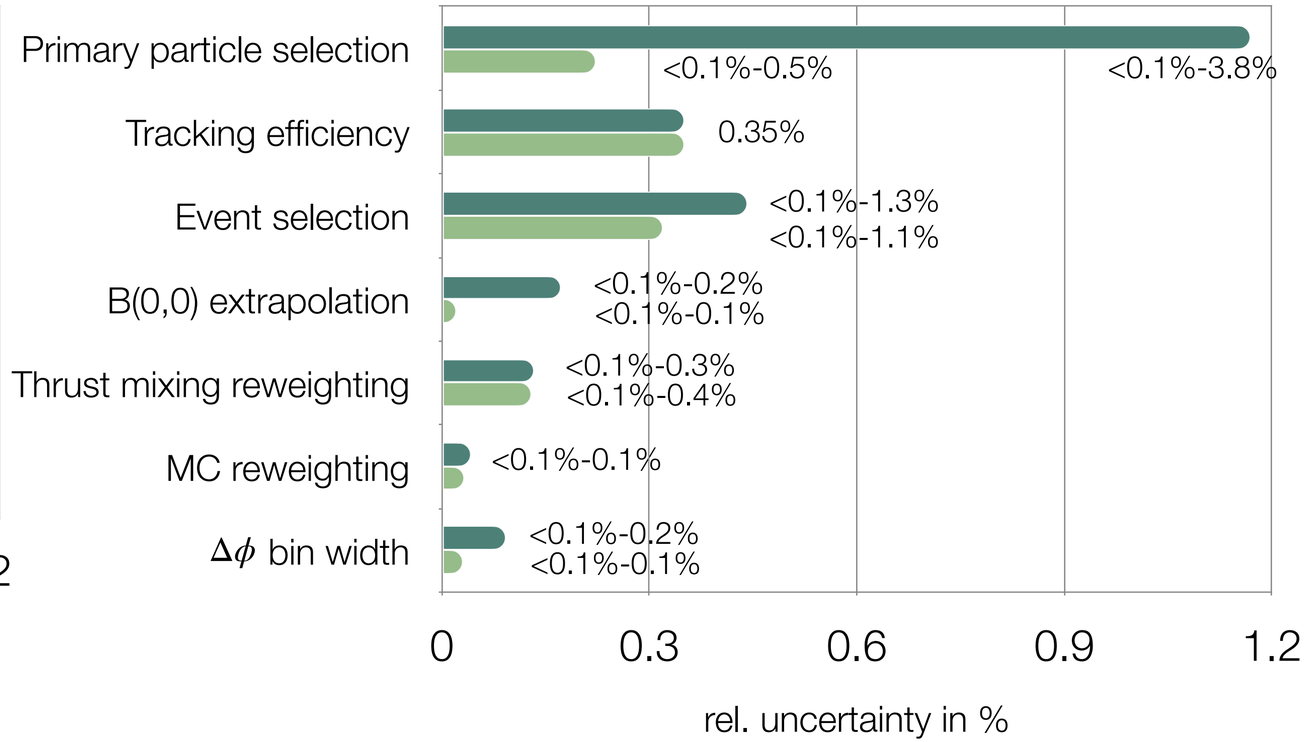
Systematics

- 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”

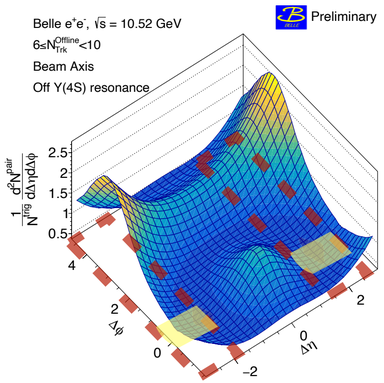
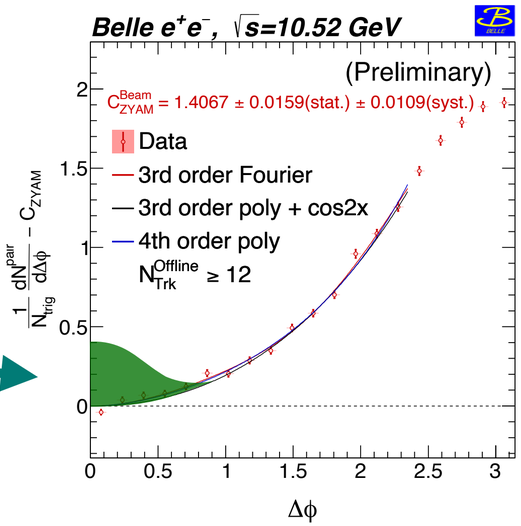
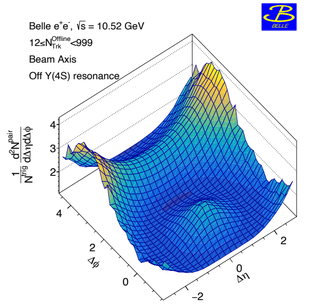


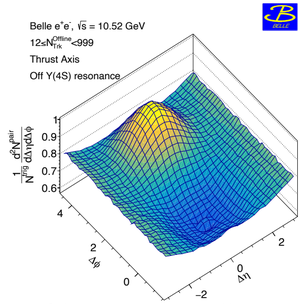
illustration of an enhanced ridge signal



- 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

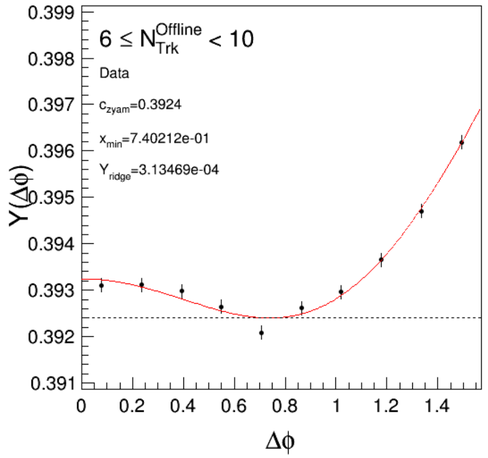
bootstrap: [bootstrap]

Quantifying ridge signal by ZYAM method

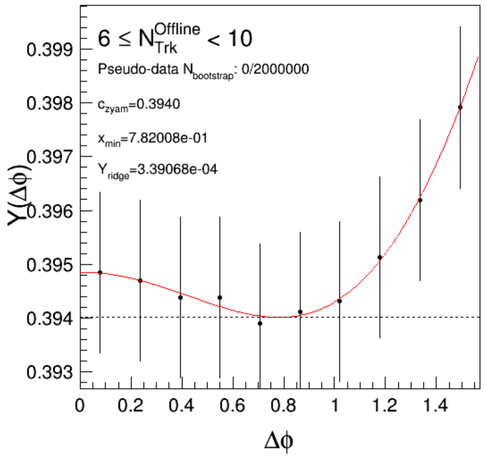
Bootstrap method

- 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.

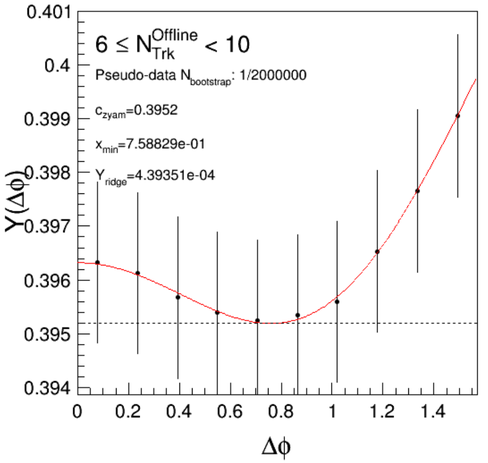
Data



Pseudo data

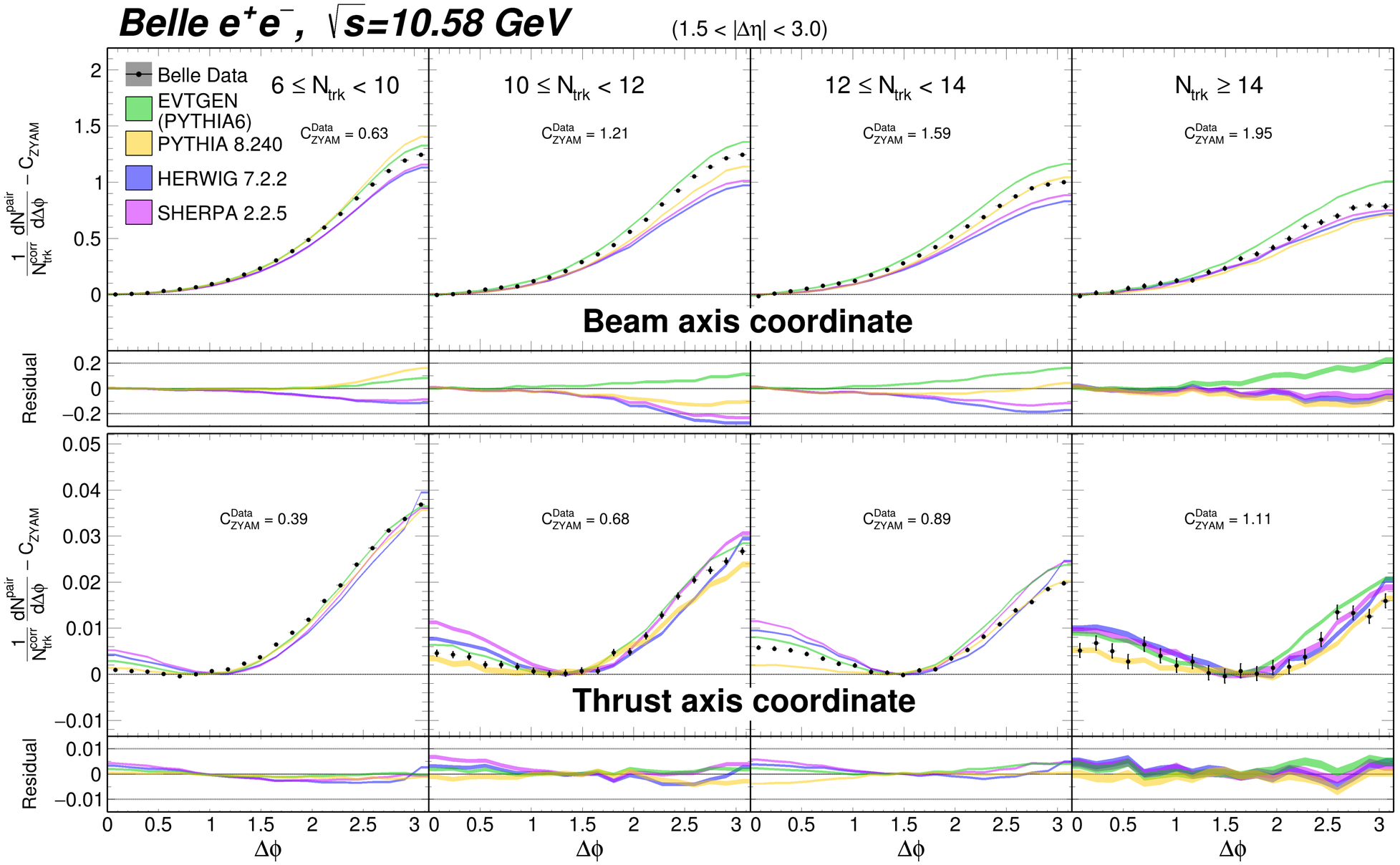


Pseudo data



Ref: [bootstrap]

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



Kinematics distribution