

International Workshop
On
QCD with Electron-Ion Collider-2020 (QEIC-2020)

Simulation studies of $R_2(\Delta\eta, \Delta\varphi)$ and $P_2(\Delta\eta, \Delta\varphi)$
correlation functions in p-p collisions with the PYTHIA
and HERWIG models

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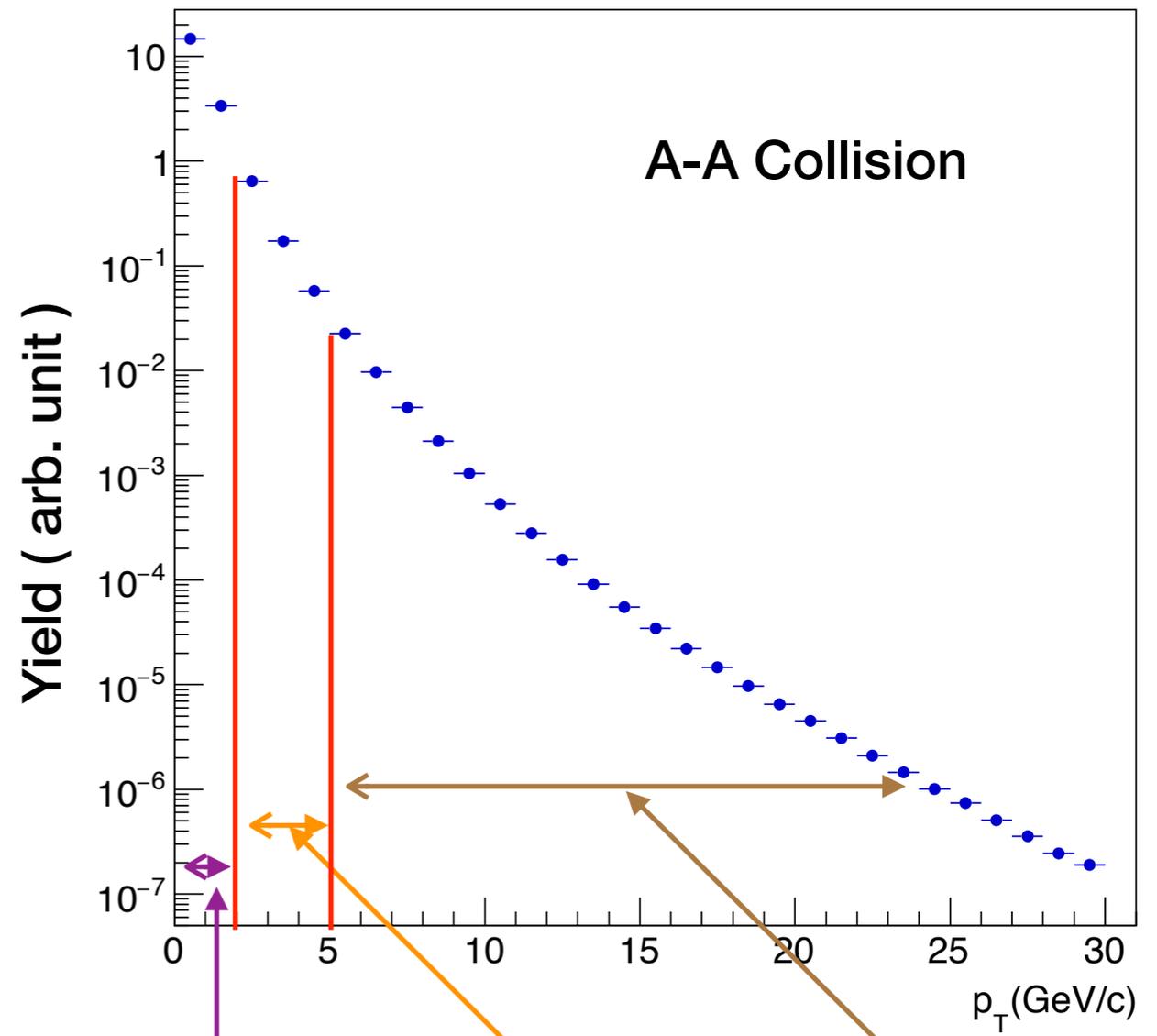
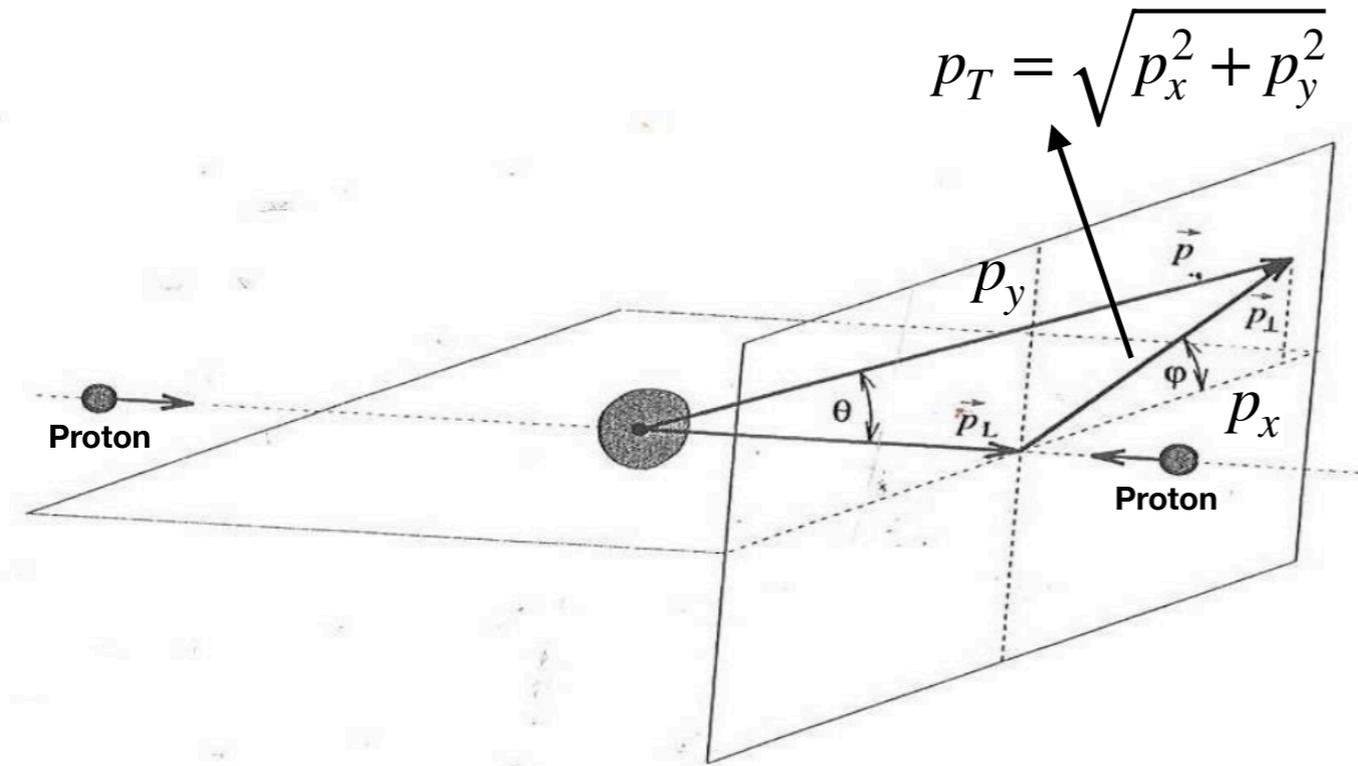
4-7 January 2020

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Outline:-

- ✓ **Introduction & Physics Motivation**
- ✓ **Definition of Observables**
- ✓ **Analysis Details**
- ✓ **Results**
- ✓ **Summary and outlook**

Introduction & Physics Motivation (I)



→ Why we study Two-particle Correlations ?

✓ These explore the underlying physics phenomena of particle production in collisions of both protons and heavy ions by measuring the distributions in $\Delta\eta\Delta\phi$ space.

→ Goal:

✓ How Two-particle correlation function behaves in these different p_T regions in small systems ?

1	2	3
Low p_T : 0.2 - 2.0 GeV/c (Relativistic Hydrodynamics)	Mid p_T : 2.0 - 5.0 GeV/c (Quark Coalescences)	High p_T : 5.0 - 30.0 GeV/c (Jets)

Introduction & Physics Motivation (II)

What we know about Two-particle correlations so far now ?

Correlation Function:

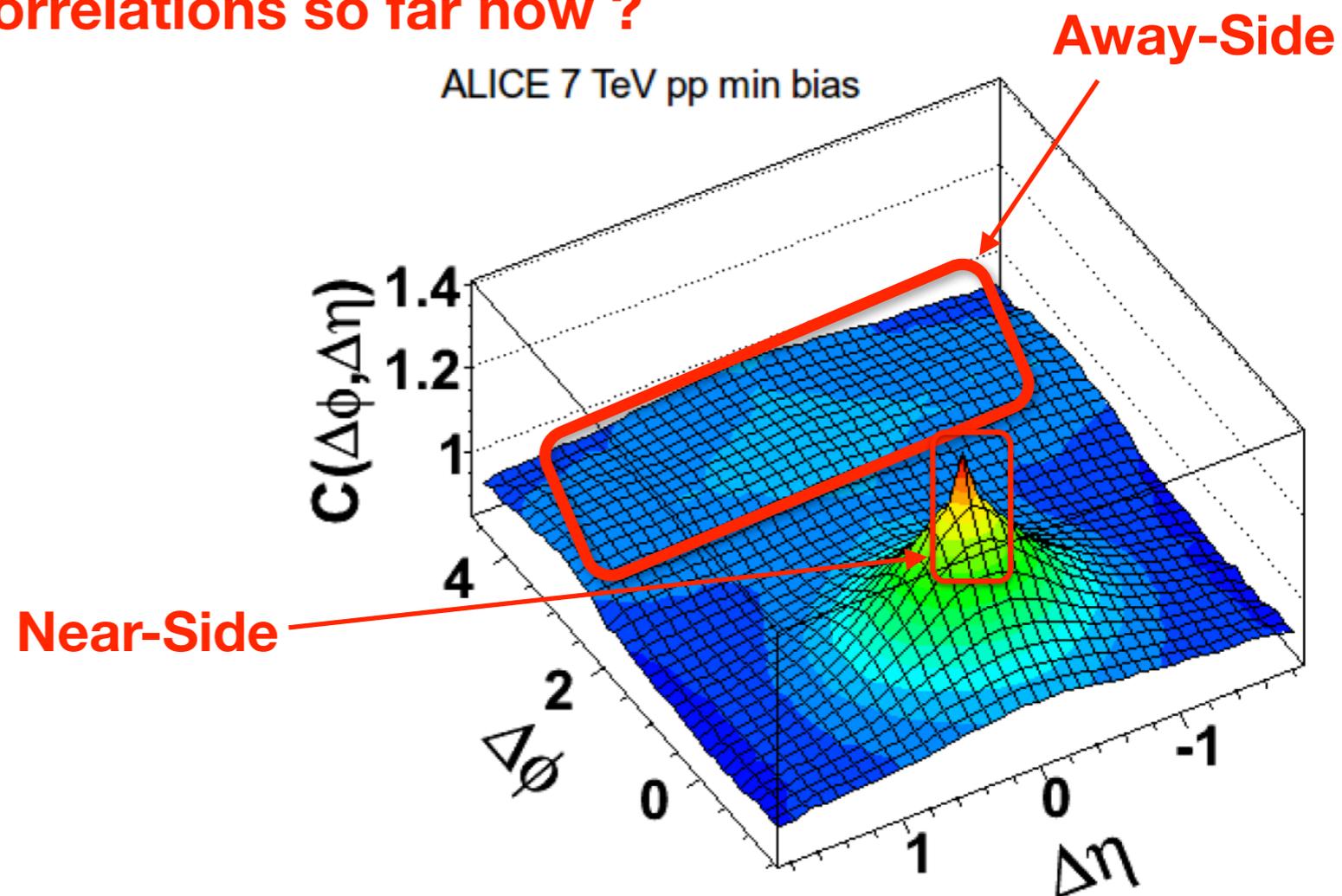
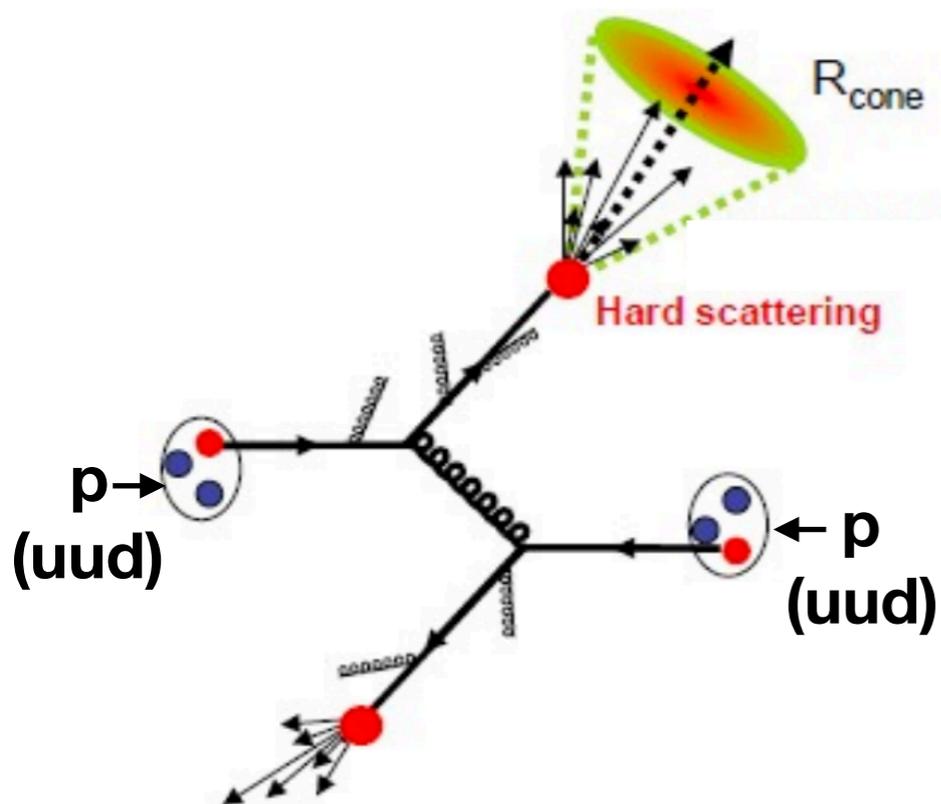
$$C(\Delta\eta, \Delta\phi) = \frac{N_{pairs}^{mixed} S(\Delta\eta, \Delta\phi)}{N_{pairs}^{signal} B(\Delta\eta, \Delta\phi)}$$

Where

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

$$\Delta\eta = \eta_1 - \eta_2$$

$$\Delta\phi = \phi_1 - \phi_2$$



→ Physics mechanism underlying all correlations:

✓ Conserved quantity:

Global conservation of energy, momentum, strangeness, baryon number and electric charge.

✓ Other phenomena:

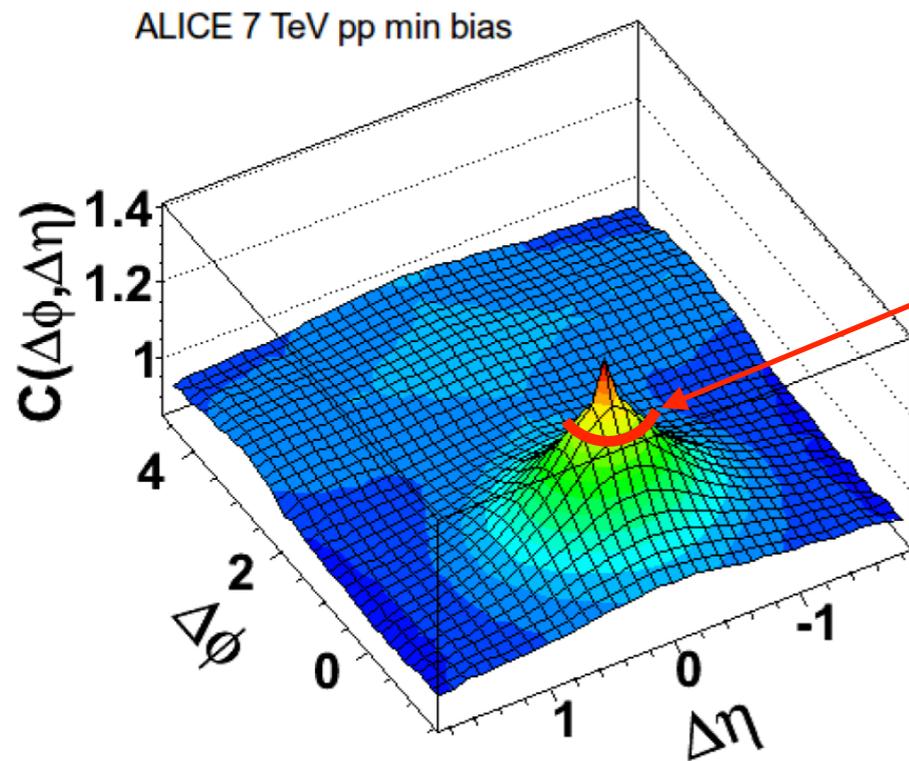
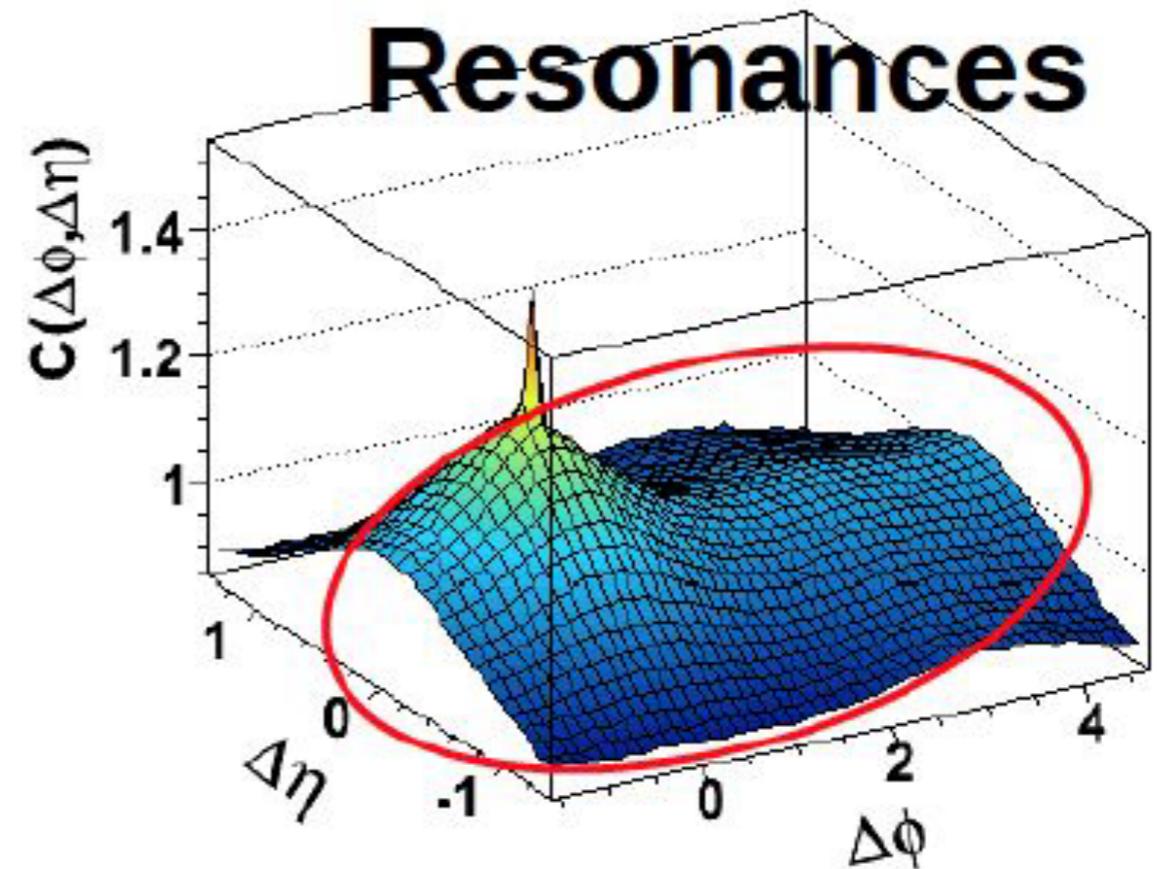
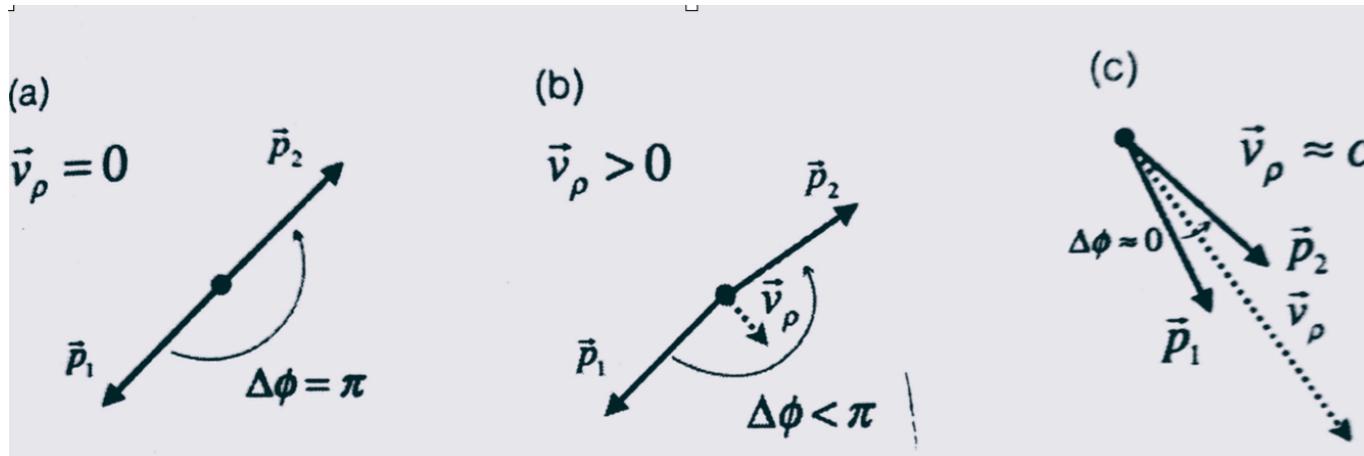
Mini-jets, jets, elliptic flow, Bose–Einstein correlations, resonance decays etc .

Ref: [ALICE Collaboration, Eur. Phys. J. C \(2017\) 77:569](#)

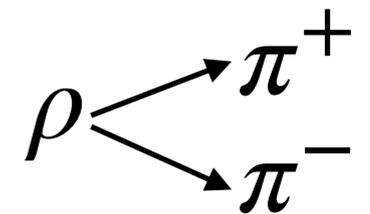
Introduction & Physics Motivation (III)

→ Resonance decay :

- ✓ It contributes to the near-side peak of the correlation function or produces a ridge at $\Delta\eta = 0$ extended in $\Delta\phi$



Bose-Einstein correlations:
 $(\Delta\eta, \Delta\phi) \approx (0, 0)$



- ✓ Quantum Statistics tells that pairs of identical bosons (i.e. $\pi^+\pi^+$) are likely to be emitted in same direction.

Ref: [ALICE Collaboration, Eur. Phys. J. C \(2017\) 77:569](#)

Definition of $R_2(\Delta\eta, \Delta\varphi)$ (I)

Kinematical Variables: $x \equiv \{\eta, \varphi, p_T\}$

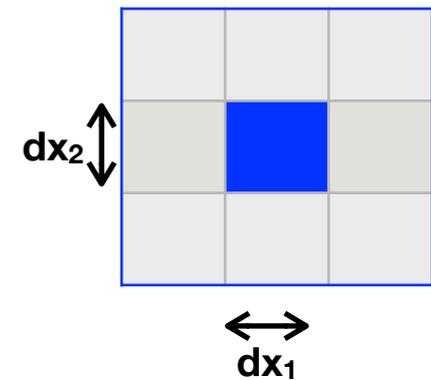
Single-Particle Density: $\rho_1(\mathbf{x}) = \frac{1}{N} \frac{dN}{d\mathbf{x}}$

Two-Particle Density: $\rho_2(\mathbf{x}_1, \mathbf{x}_2) = \frac{1}{N} \frac{d^2N}{d\mathbf{x}_1 d\mathbf{x}_2}$

✓ **1st Observable:**

Two-Particle Correlation:

$$C_2(\mathbf{x}_1, \mathbf{x}_2) = \rho_2(\mathbf{x}_1, \mathbf{x}_2) - \rho_1(\mathbf{x}_1) * \rho_1(\mathbf{x}_2)$$



Two-particle differential number Correlation [1]:

$$R_2(\Delta\eta, \Delta\varphi) = \frac{C_2(\Delta\eta, \Delta\varphi)}{\rho_1(\eta_1, \varphi_1) * \rho_1(\eta_2, \varphi_2)} = \frac{\rho_2(\Delta\eta, \Delta\varphi)}{\rho_1(\eta_1, \varphi_1) * \rho_1(\eta_2, \varphi_2)} - 1$$

✓ **Sensitive to particle production mechanisms**

Why we used R_2 ?

1. **Dimensionless quantity**

2. **Robust observable:**

Independent of detection efficiency [1]

[1] M. Sharma and C. A. Pruneau, [PRC 79, 024905 \(2009\)](#)

Definition of $P_2(\Delta\eta, \Delta\varphi)$ (II)

✓ 2nd Observable:

$$\left\langle \Delta\mathbf{p}_{T,1} * \Delta\mathbf{p}_{T,2} \right\rangle(\Delta\eta, \Delta\varphi) = \frac{\int \rho_2(\mathbf{x}_1, \mathbf{x}_2) \Delta\mathbf{p}_{T,1} \Delta\mathbf{p}_{T,2} d\mathbf{p}_{T,1} d\mathbf{p}_{T,2}}{\rho_2(\Delta\eta, \Delta\varphi)}$$

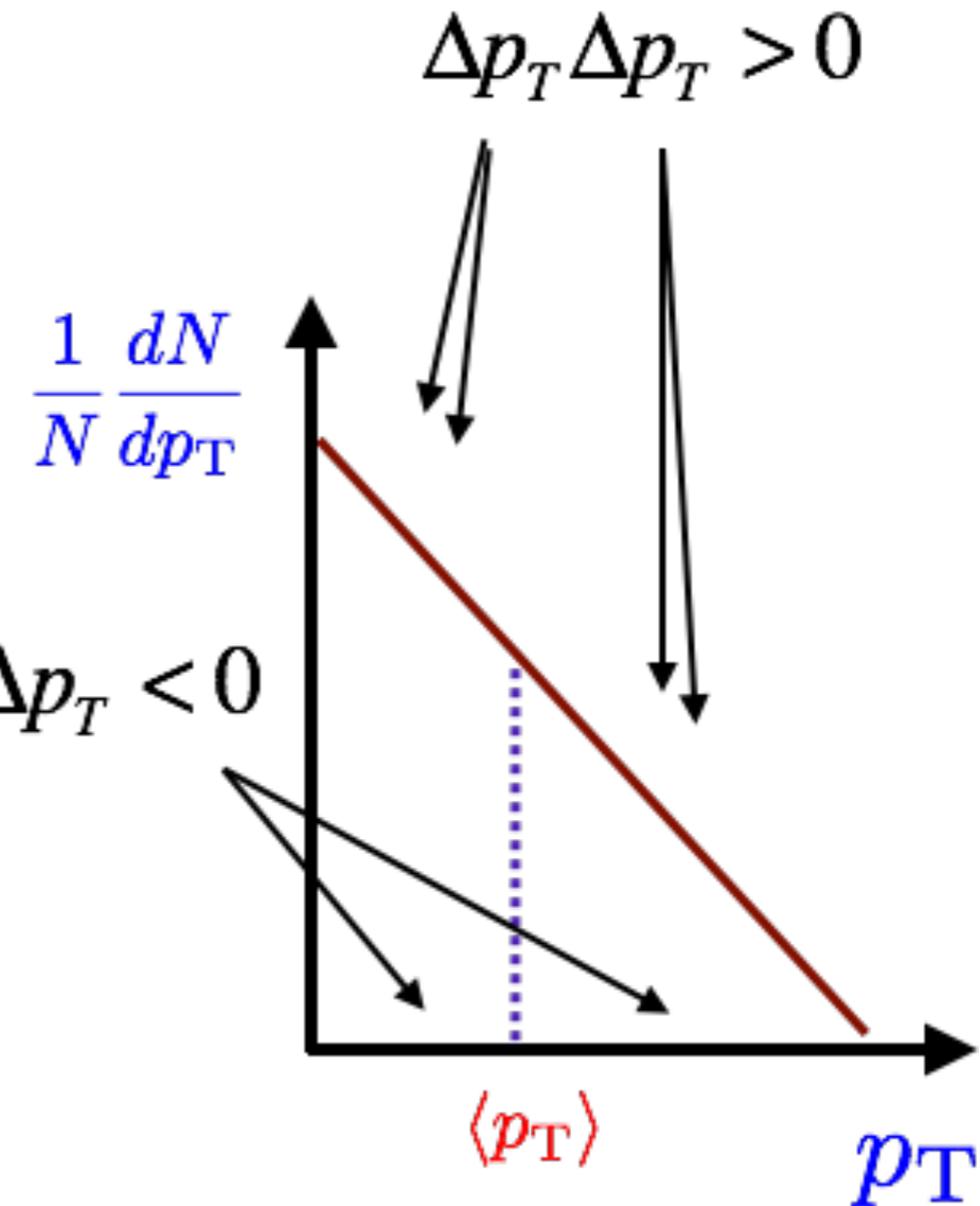
Two-particle differential transverse momentum Correlation [1]:

$$P_2(\Delta\eta, \Delta\varphi) = \frac{\left\langle \Delta\mathbf{p}_{T,1} * \Delta\mathbf{p}_{T,2} \right\rangle(\Delta\eta, \Delta\varphi)}{\left\langle \mathbf{p}_T \right\rangle^2} \text{ as } \mathbf{p}_{T,1} \approx \mathbf{p}_{T,2}$$

Where

$$\Delta\mathbf{p}_{T,i} = \mathbf{p}_{T,i} - \left\langle \mathbf{p}_T \right\rangle$$

✓ Sensitive to transverse momentum fluctuations



Why we used P_2 ?

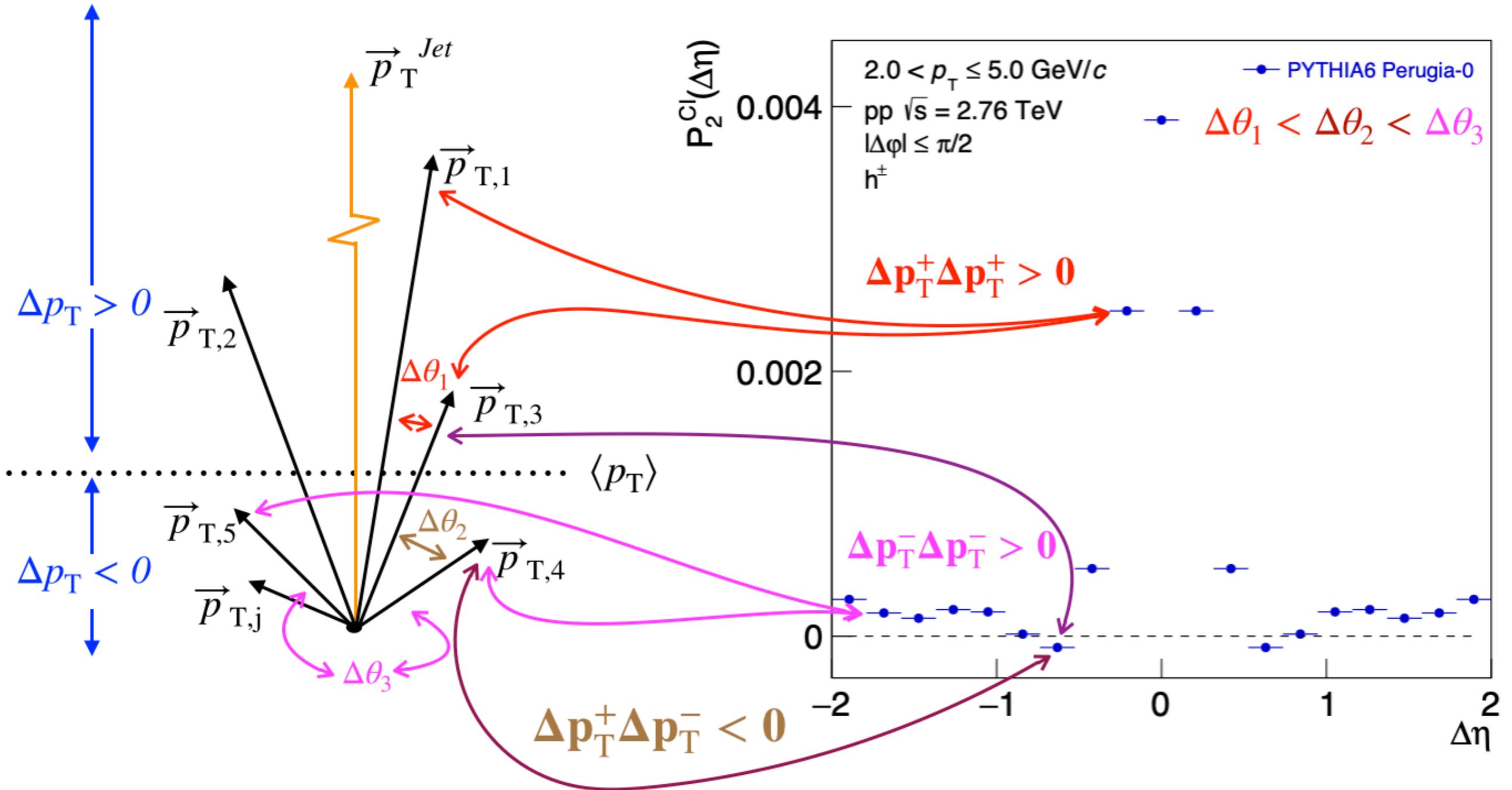
1. Dimensionless quantity
2. Robust observable:

Independent of detection efficiency [1]

[1] M. Sharma and C. A. Pruneau, [PRC 79, 024905 \(2009\)](#)

Angular Ordering

Angular Ordering: probe the internal structure of jets



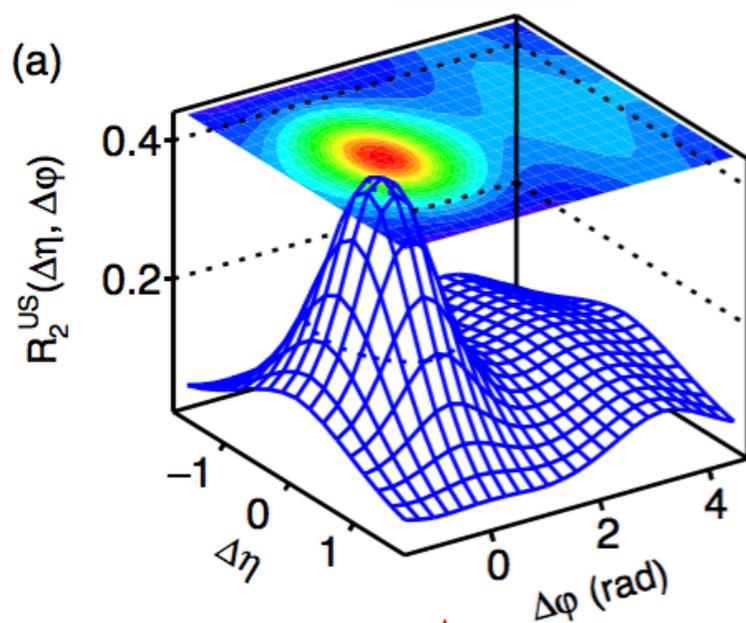
Definition of CI (III)

✓ 4 different charge combinations: (+ -), (- +), (+ +), (- -) $O \equiv (R_2, P_2)$

Unlike-Sign(US) pairs

$$O^{US} = \frac{1}{2}(O^{(+,-)} + O^{(-,+)})$$

US

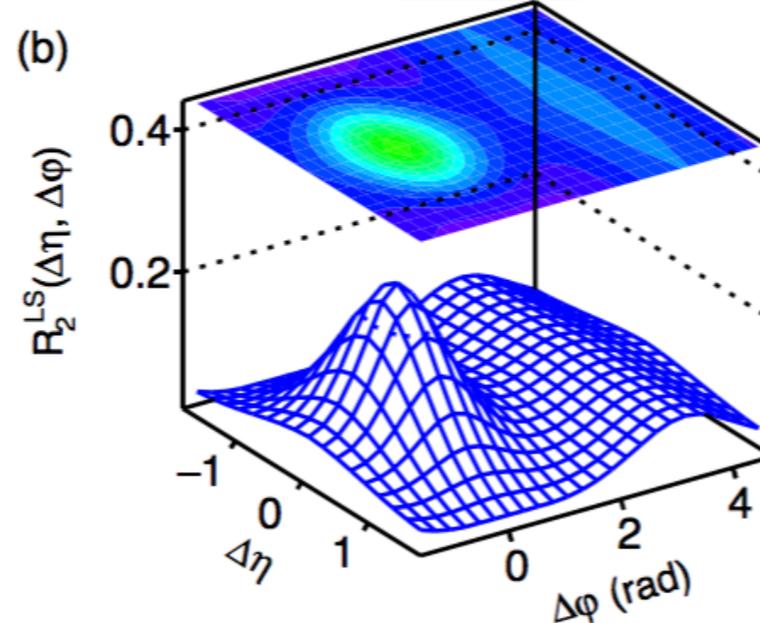


+

Like-Sign(LS) pairs

$$O^{LS} = \frac{1}{2}(O^{(+,+)} + O^{(-,-)})$$

LS

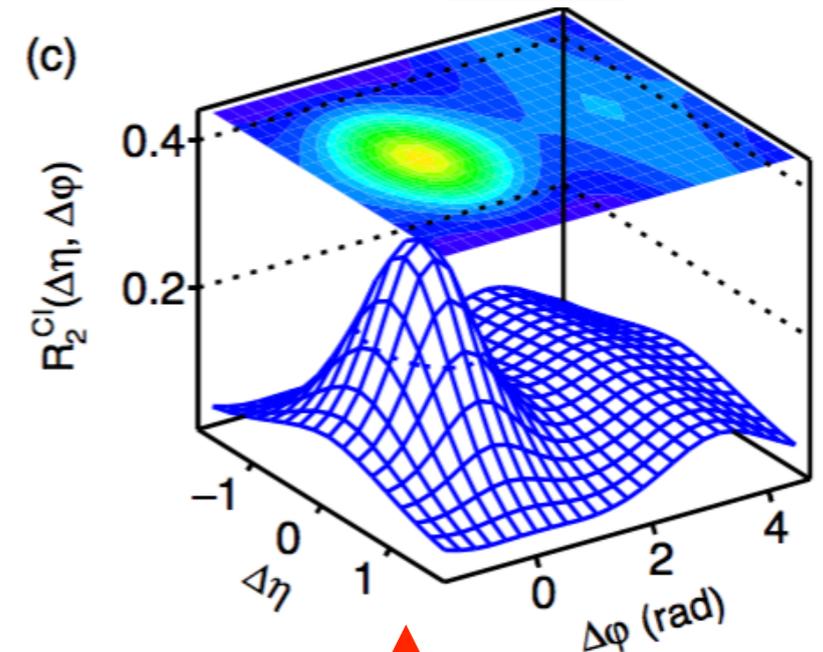


=

Charge Independent(CI)

$$O^{CI} = \frac{1}{2}(O^{US} + O^{LS})$$

CI



Coulomb Int.,
Jet, **Resonance**,
flow(In Heavy Ion) etc

Coulomb Int., Jet,
B-E corr.,
flow(In Heavy Ion) etc

Measures the average
correlation strength
between all charge particles.

[1] C. Pruneau, S. Gavin, and S. Voloshin, [Phys. Rev. C66, 044904 \(2002\)](#)

[2] S. Bass, P. Danielewicz, and S. Pratt, [Phys.Rev.Lett. 85, 2689 \(2000\)](#)

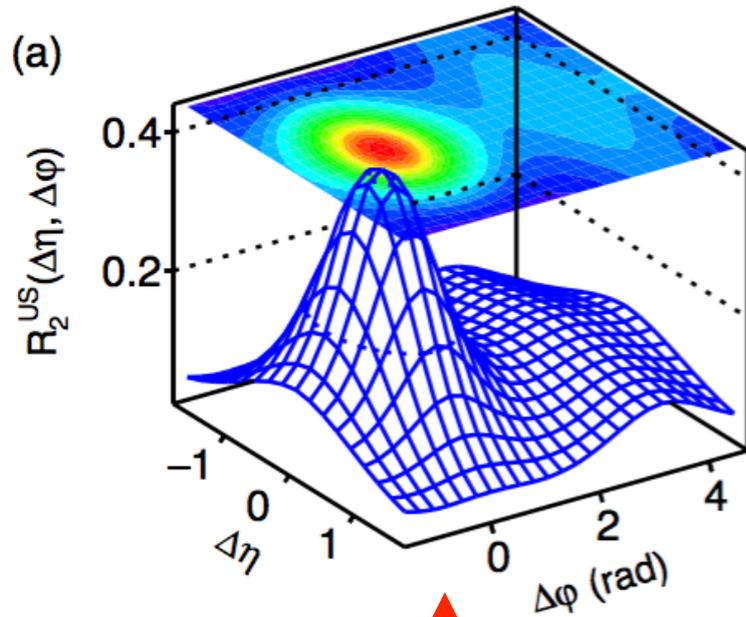
Definition of CD (IV)

✓ 4 different charge combinations: (+ -), (- +), (+ +), (- -) $O \equiv (R_2, P_2)$

Unlike-Sign(US) pairs

$$O^{US} = \frac{1}{2}(O^{(+,-)} + O^{(-,+)})$$

US

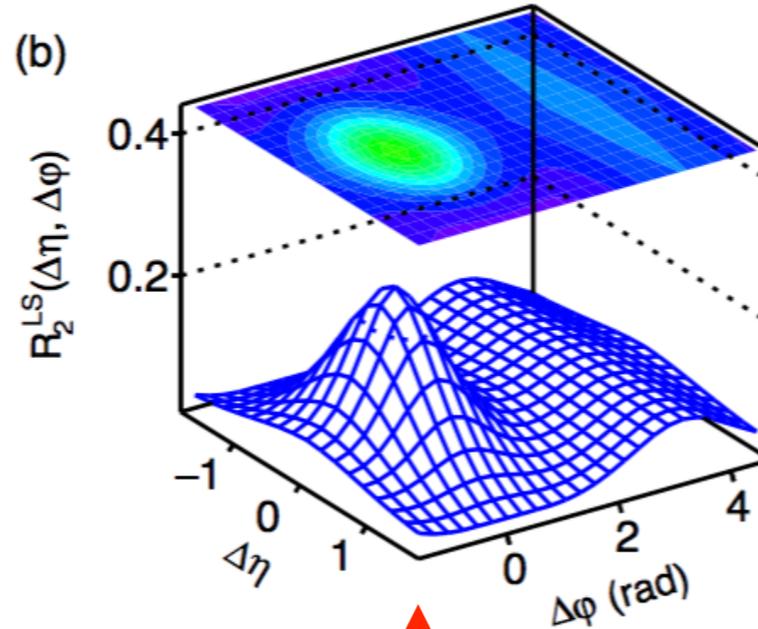


Coulomb Int.,
Jet, **Resonance**,
flow(In Heavy Ion) etc

Like-Sign(LS) pairs

$$O^{LS} = \frac{1}{2}(O^{(+,+)} + O^{(-,-)})$$

LS

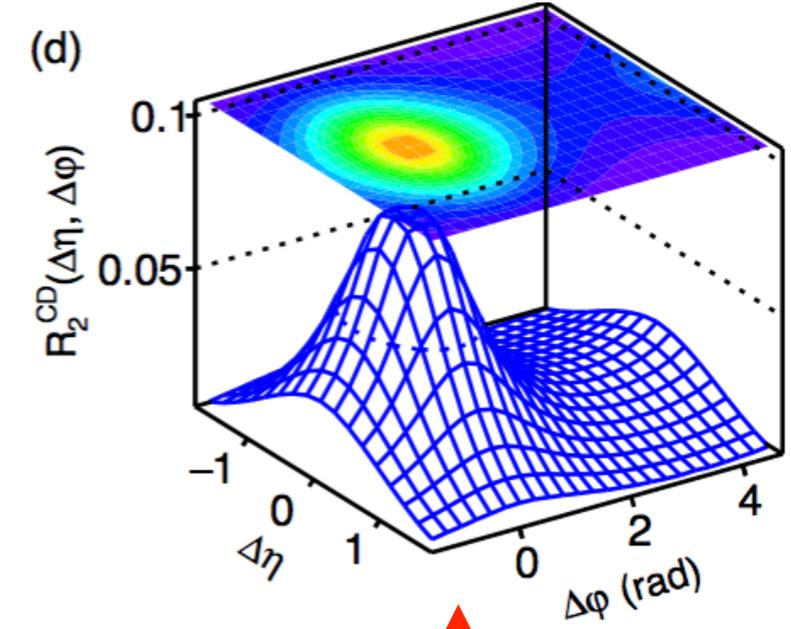


Coulomb Int., Jet,
B-E corr.,
flow(In Heavy Ion) etc

Charge Dependent(CD)

$$O^{CD} = \frac{1}{2}(O^{US} - O^{LS})$$

CD



effects
related to
balancing pairs

[1] C. Pruneau, S. Gavin, and S. Voloshin, [Phys. Rev. C66, 044904 \(2002\)](#)

[2] S. Bass, P. Danielewicz, and S. Pratt, [Phys.Rev.Lett. 85, 2689 \(2000\)](#)

Analysis Details

➡ $\sqrt{s} = 2.76$ TeV For p-p collision

➡ # of events = 200M

Event Generators:

HERWIG : Cluster model for hadronization

AliPythia6 Perugia0: String model for hadronization

✿ Particle selected = h^\pm

Low p_T cut:-

- ✓ p_T range : 0.2 – 2.0
- ✓ p_T bins = 18
- ✓ p_T bin width = 0.1

Mid p_T cut:-

- ✓ p_T range : 2.0 – 5.0
- ✓ p_T bins = 30
- ✓ p_T bin width = 0.1

High p_T cut:-

- ✓ p_T range : 5.0 – 30.0
- ✓ p_T bins = 250
- ✓ p_T bin width = 0.1

η Cut :-

- ✓ η range: -1.0-1.0
- ✓ η bins = 40(10)
- ✓ η bin width = 0.05(0.2)

φ Cut:-

- ✓ φ range : 0.0 – 2π
- ✓ φ bins = 72(24)
- ✓ φ bin width = 0.087(0.262)

Result (I): $R_2^{CI}(\Delta\eta, \Delta\varphi)$ & $P_2^{CI}(\Delta\eta, \Delta\varphi)$

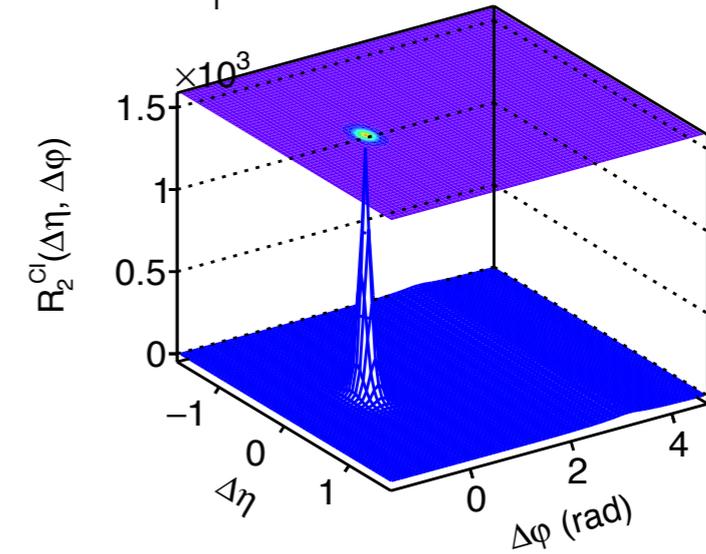
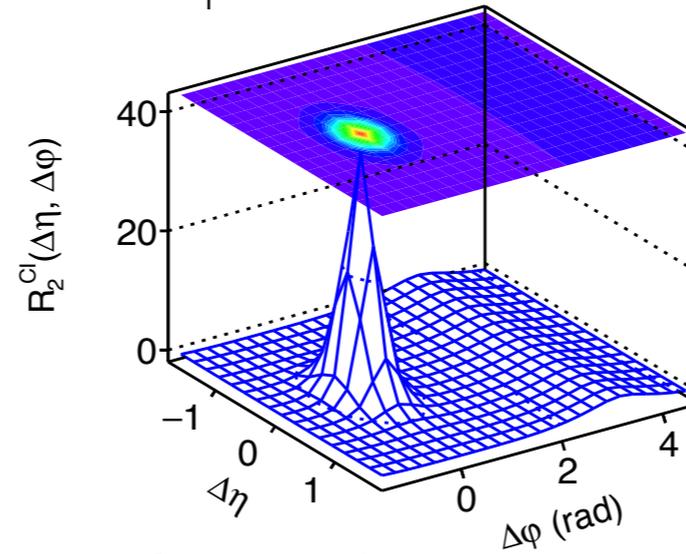
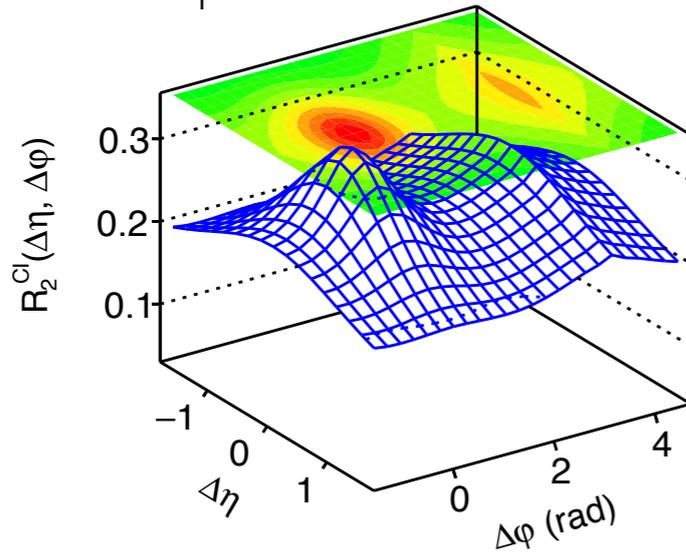
HERWIG, pp $\sqrt{s} = 2.76$ TeV

(a) $0.2 < p_T \leq 2.0$ GeV/c

(b) $2.0 < p_T \leq 5.0$ GeV/c

(c) $5.0 < p_T \leq 30.0$ GeV/c

$R_2^{CI}(\Delta\eta, \Delta\varphi)$



Increasing p_T

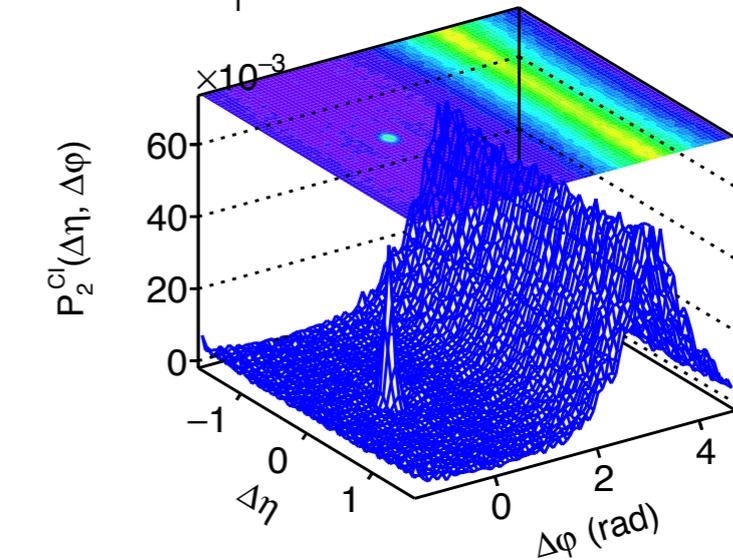
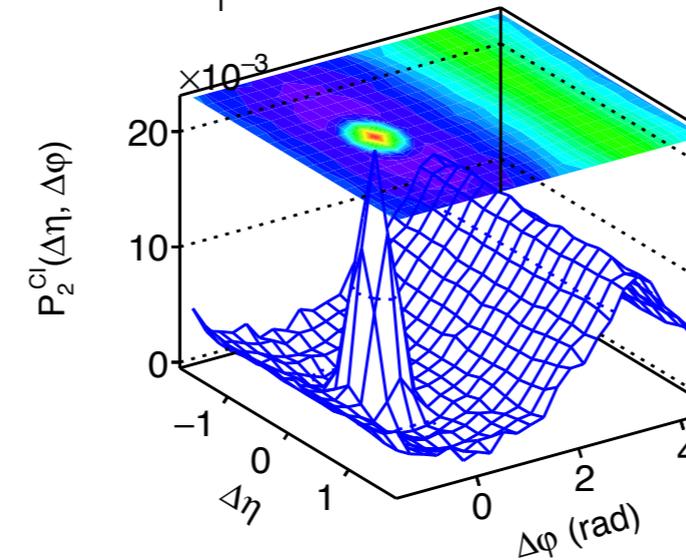
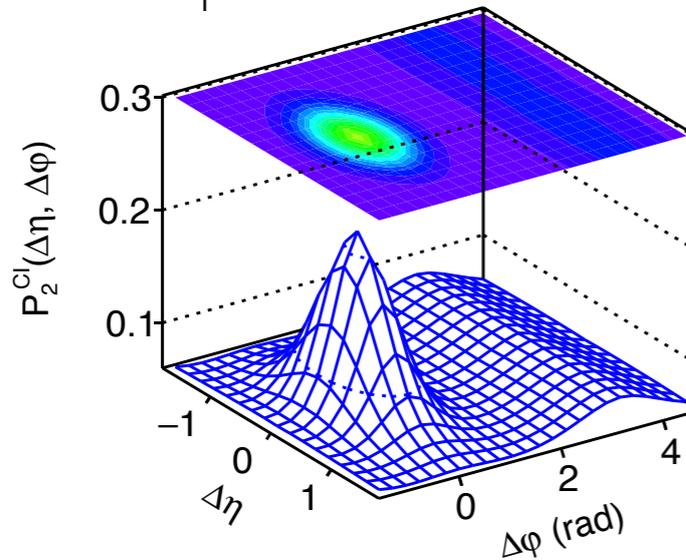
HERWIG, pp $\sqrt{s} = 2.76$ TeV

(a) $0.2 < p_T \leq 2.0$ GeV/c

(b) $2.0 < p_T \leq 5.0$ GeV/c

(c) $5.0 < p_T \leq 30.0$ GeV/c

$P_2^{CI}(\Delta\eta, \Delta\varphi)$

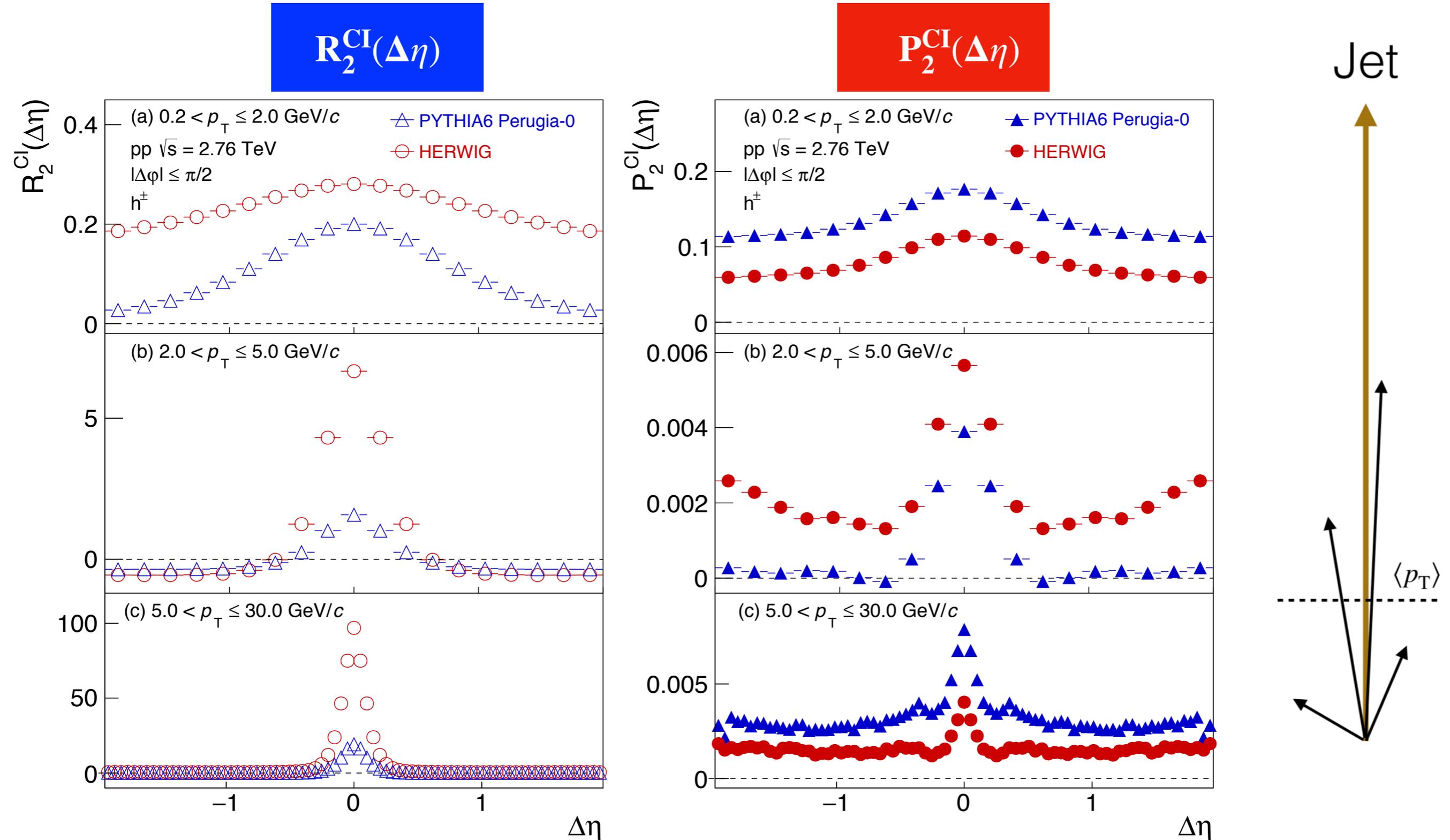


* Energy and momentum conservations are dominant here.

* Narrowing of the near-side peak with increasing p_T for CI with HERWIG.

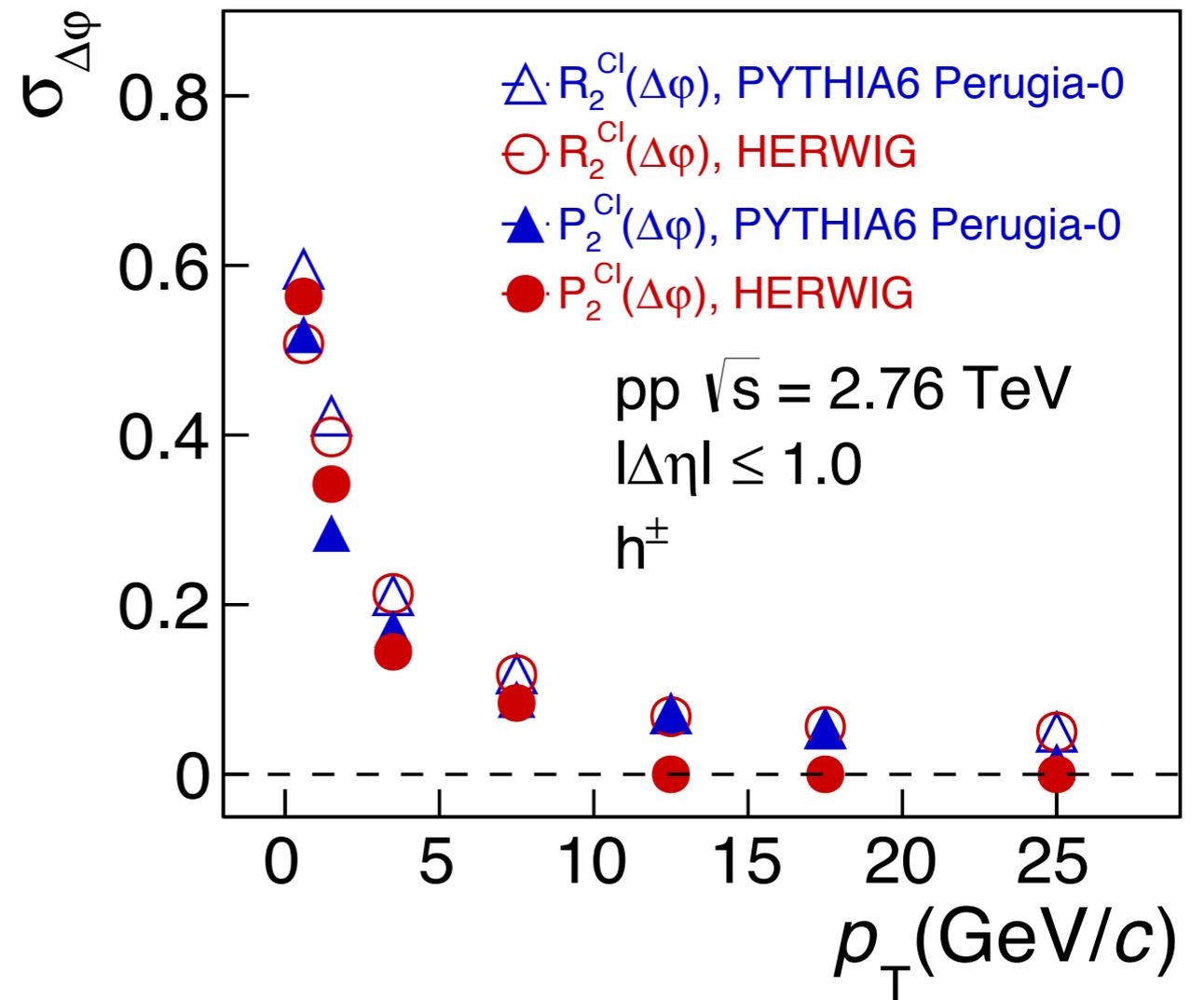
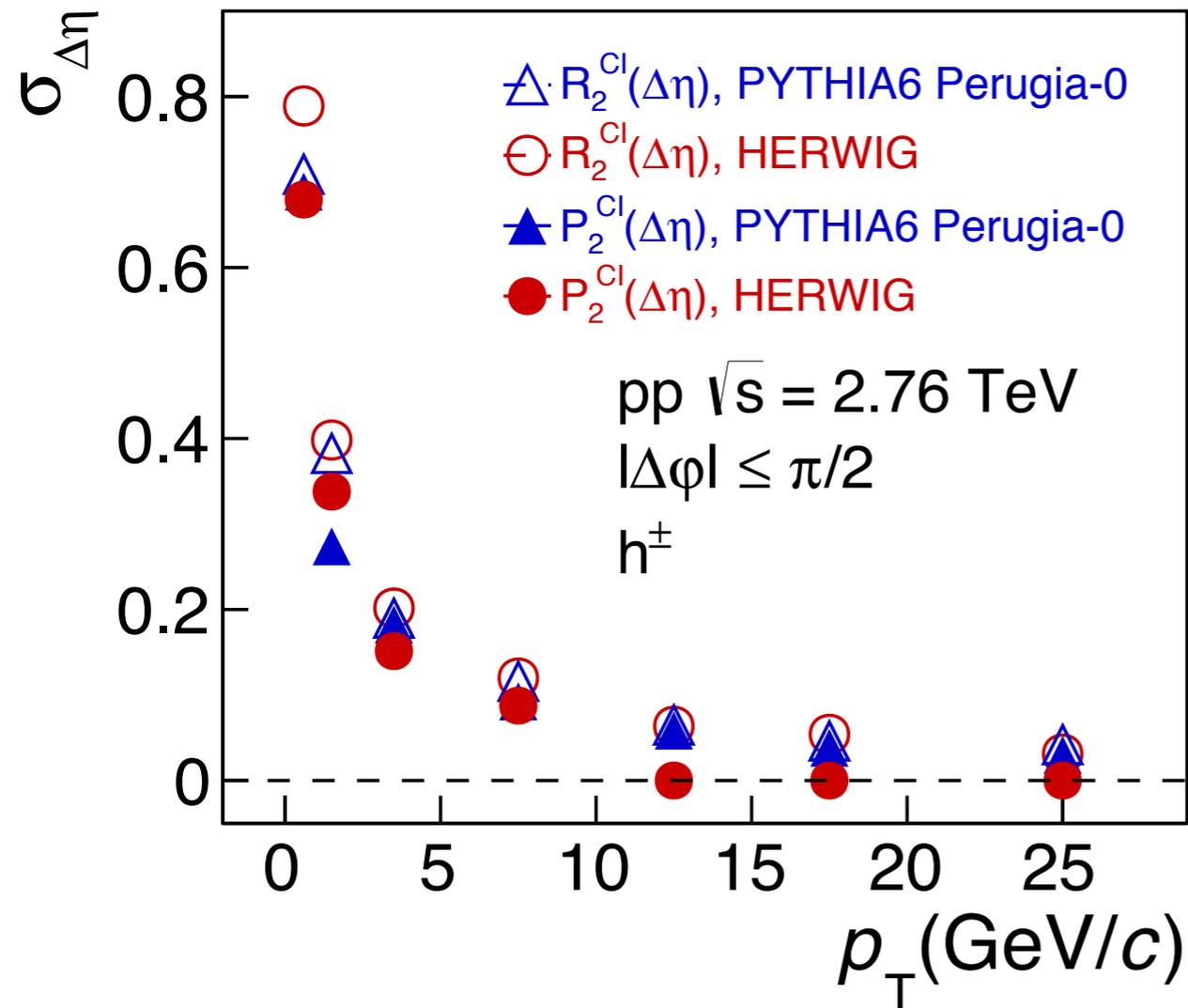
B. Sahoo et al. , Phys. Rev. C 100, 024909

Result (II) : Projection of $R_2^{\text{CI}}(\Delta\eta, \Delta\varphi)$ & $P_2^{\text{CI}}(\Delta\eta, \Delta\varphi)$ on $\Delta\eta$



*** $P_2^{\text{CI}}(\Delta\eta)$ is narrower than $R_2^{\text{CI}}(\Delta\eta)$ due to angular ordering which implies P_2 is more precise observable to probe the internal structure of jet.**

Result (III) : Width of CI



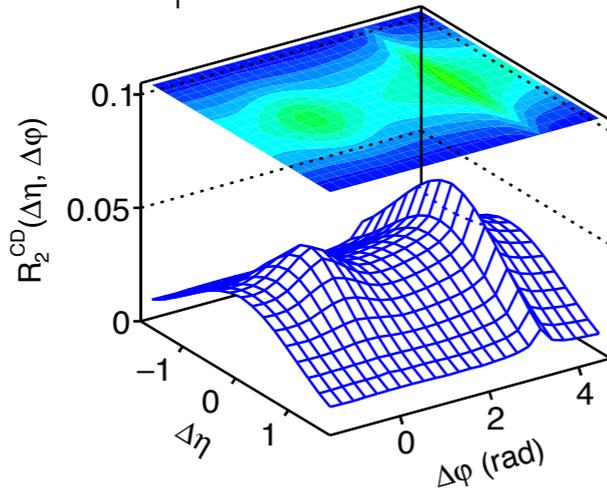
* Smooth fall of widths with increasing p_T .

* P_2 is narrower than R_2 , although for some p_T bins, it is broader.

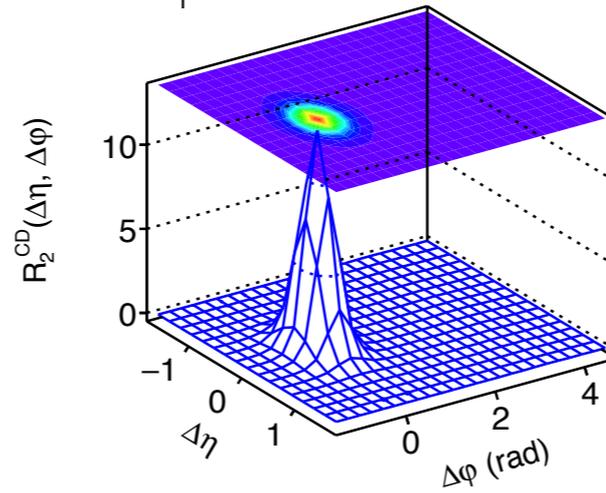
Result (IV) : $R_2^{\text{CD}}(\Delta\eta, \Delta\phi)$ & $P_2^{\text{CD}}(\Delta\eta, \Delta\phi)$

HERWIG, pp $\sqrt{s} = 2.76$ TeV

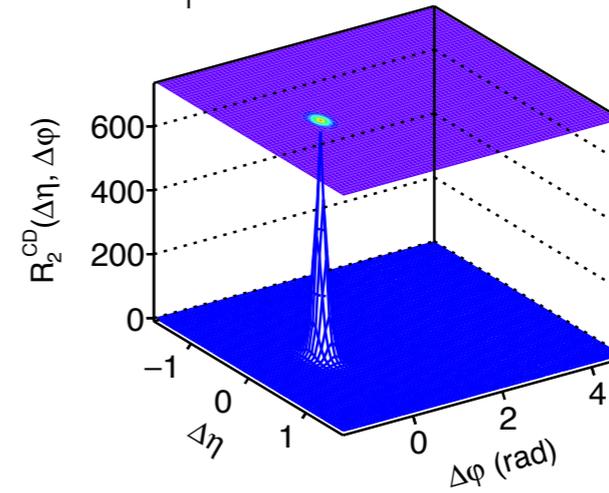
(a) $0.2 < p_T \leq 2.0$ GeV/c



(b) $2.0 < p_T \leq 5.0$ GeV/c



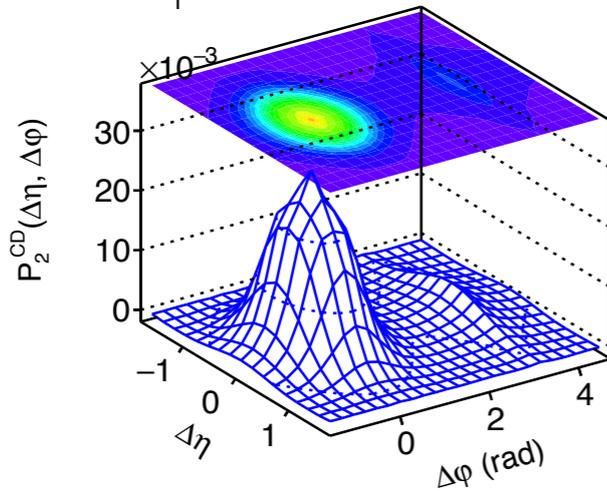
(c) $5.0 < p_T \leq 30.0$ GeV/c



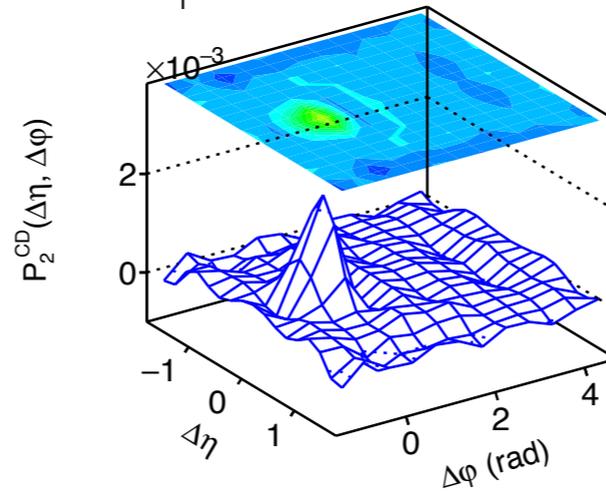
Increasing p_T

HERWIG, pp $\sqrt{s} = 2.76$ TeV

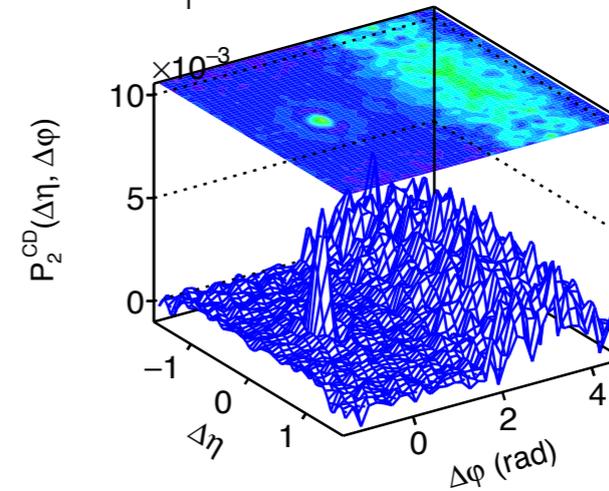
(a) $0.2 < p_T \leq 2.0$ GeV/c



(b) $2.0 < p_T \leq 5.0$ GeV/c



(c) $5.0 < p_T \leq 30.0$ GeV/c



$R_2^{\text{CD}}(\Delta\eta, \Delta\phi)$

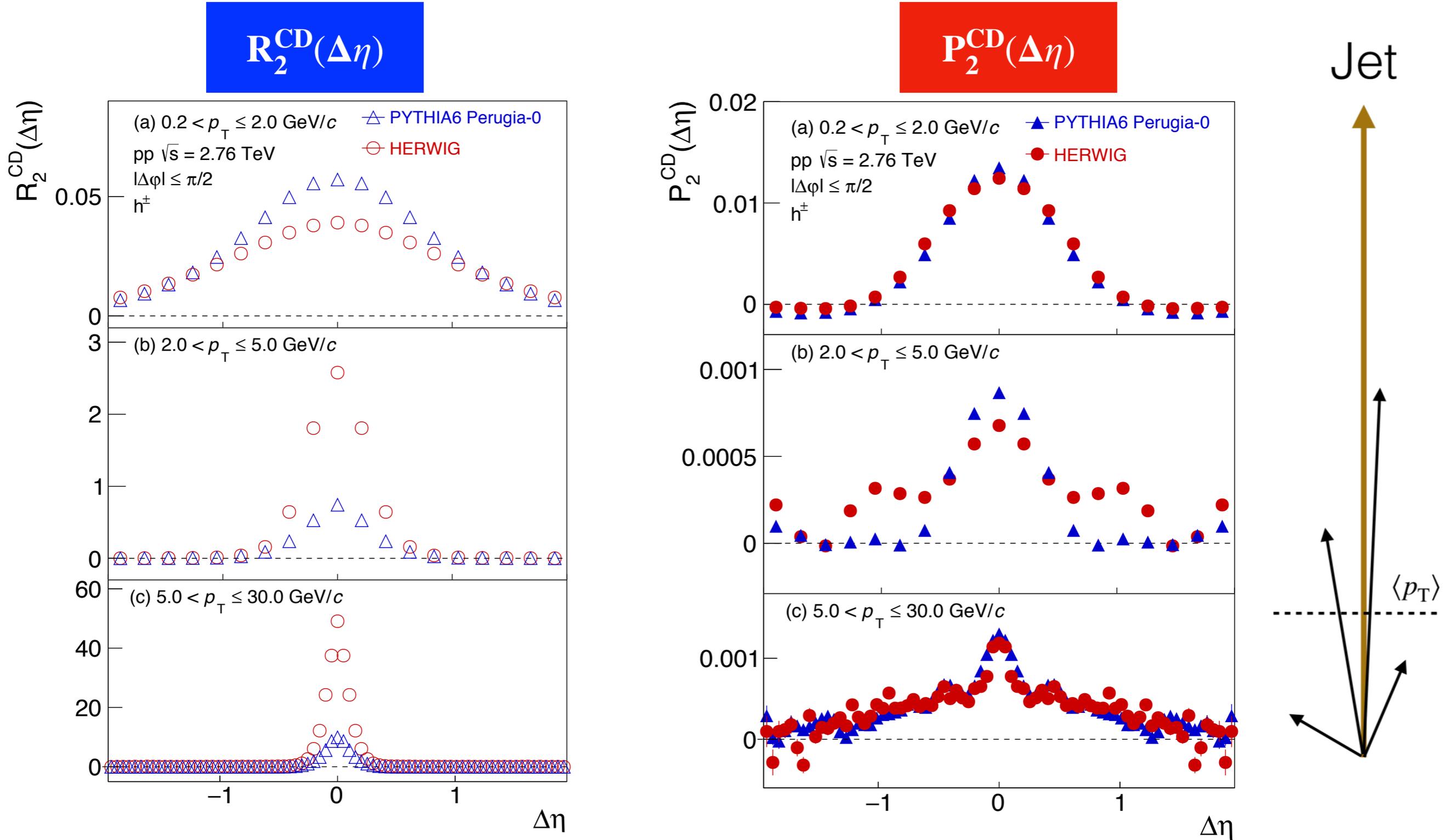
$P_2^{\text{CD}}(\Delta\eta, \Delta\phi)$

* Charge conservation is dominant here over energy and momentum conservations.

* Narrowing of the near-side peak with increasing p_T for CD with HERWIG.

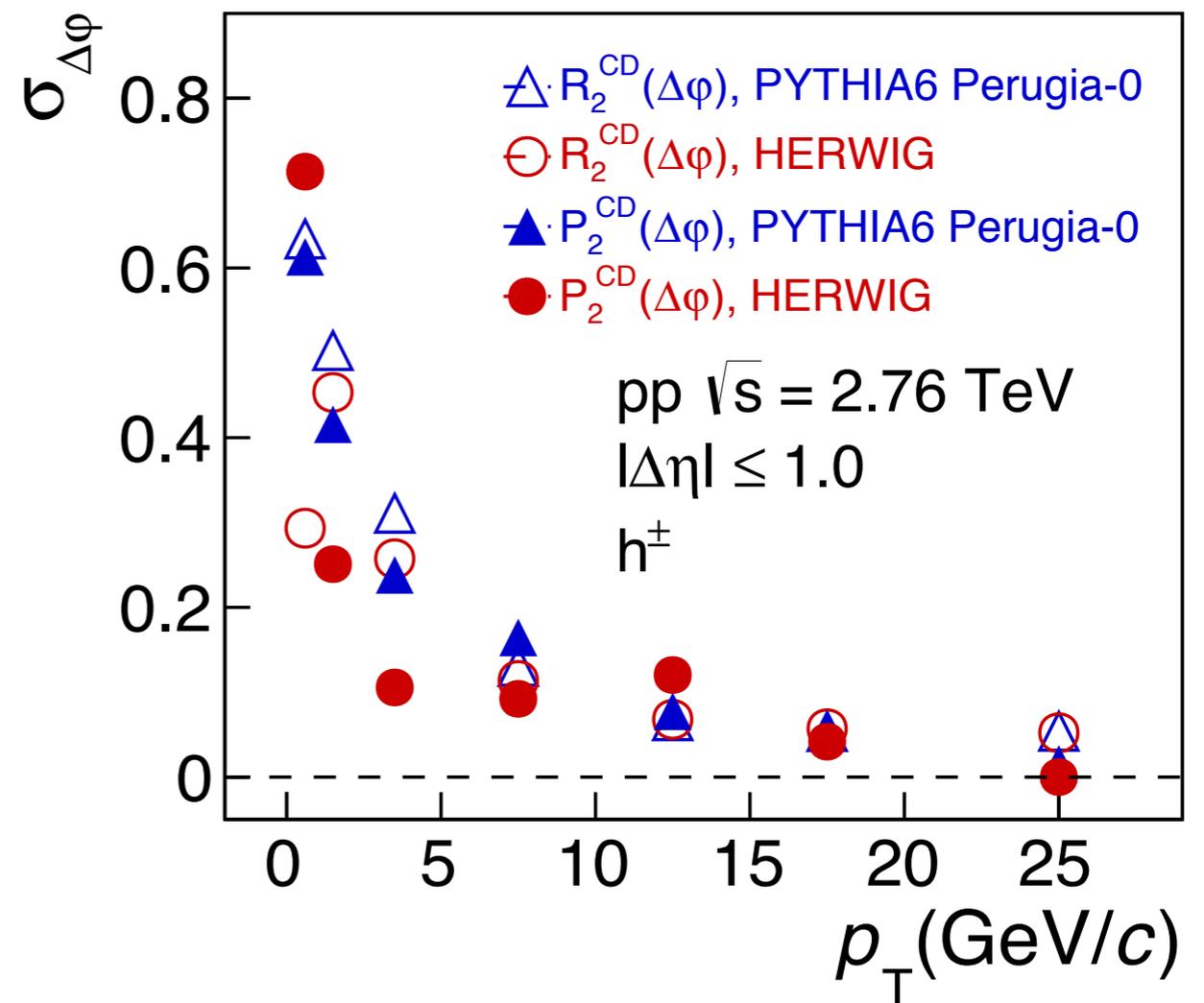
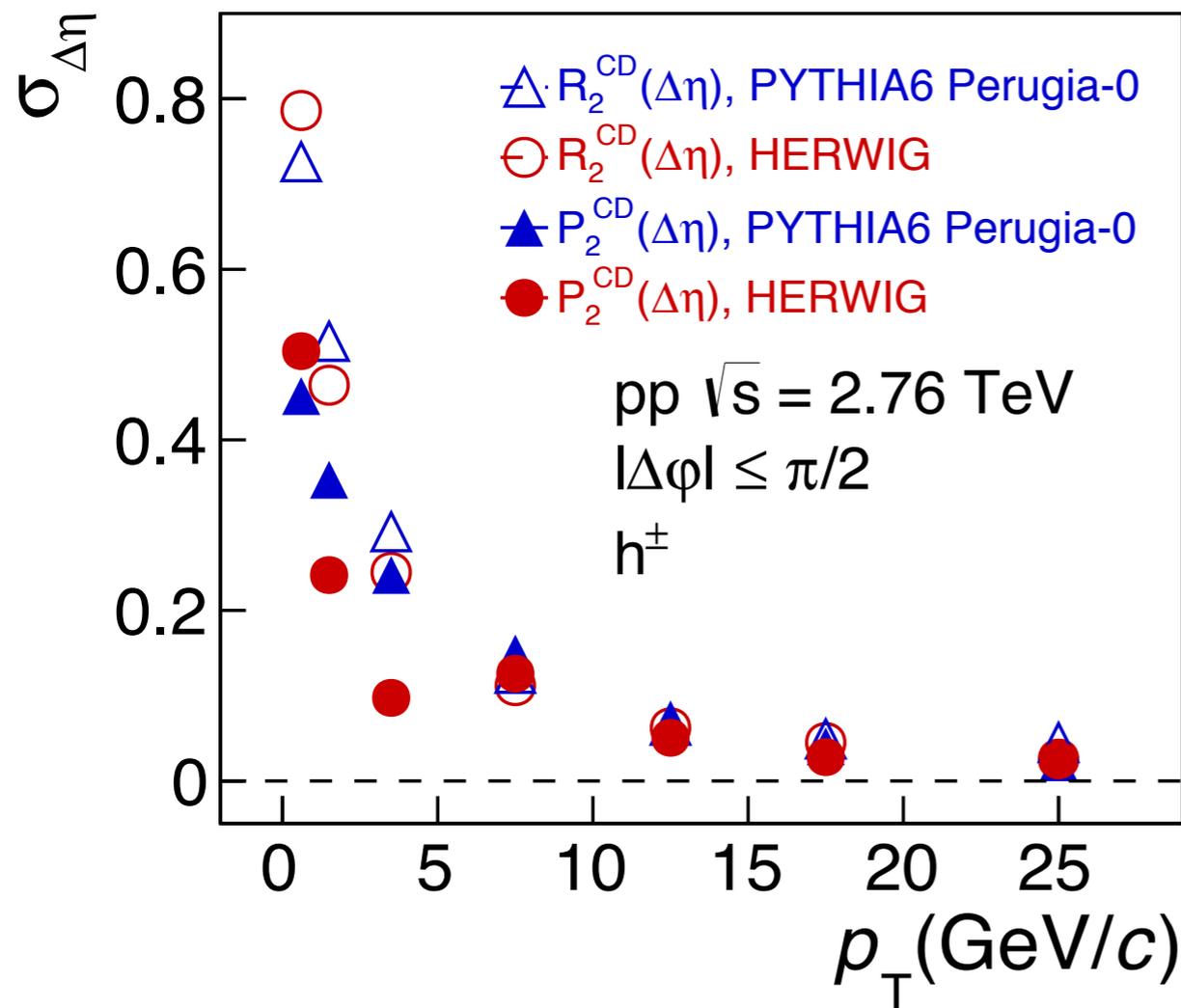
B. Sahoo et al. , Phys. Rev. C 100, 024909

Result (V) : Projection of $R_2^{CD}(\Delta\eta, \Delta\varphi)$ & $P_2^{CD}(\Delta\eta, \Delta\varphi)$ on $\Delta\eta$



*** $P_2^{CD}(\Delta\eta)$ is narrower than $R_2^{CD}(\Delta\eta)$ due to angular ordering which implies P_2 is more precise observable to probe the internal structure of jet.**

Result (VI) : Width of CD

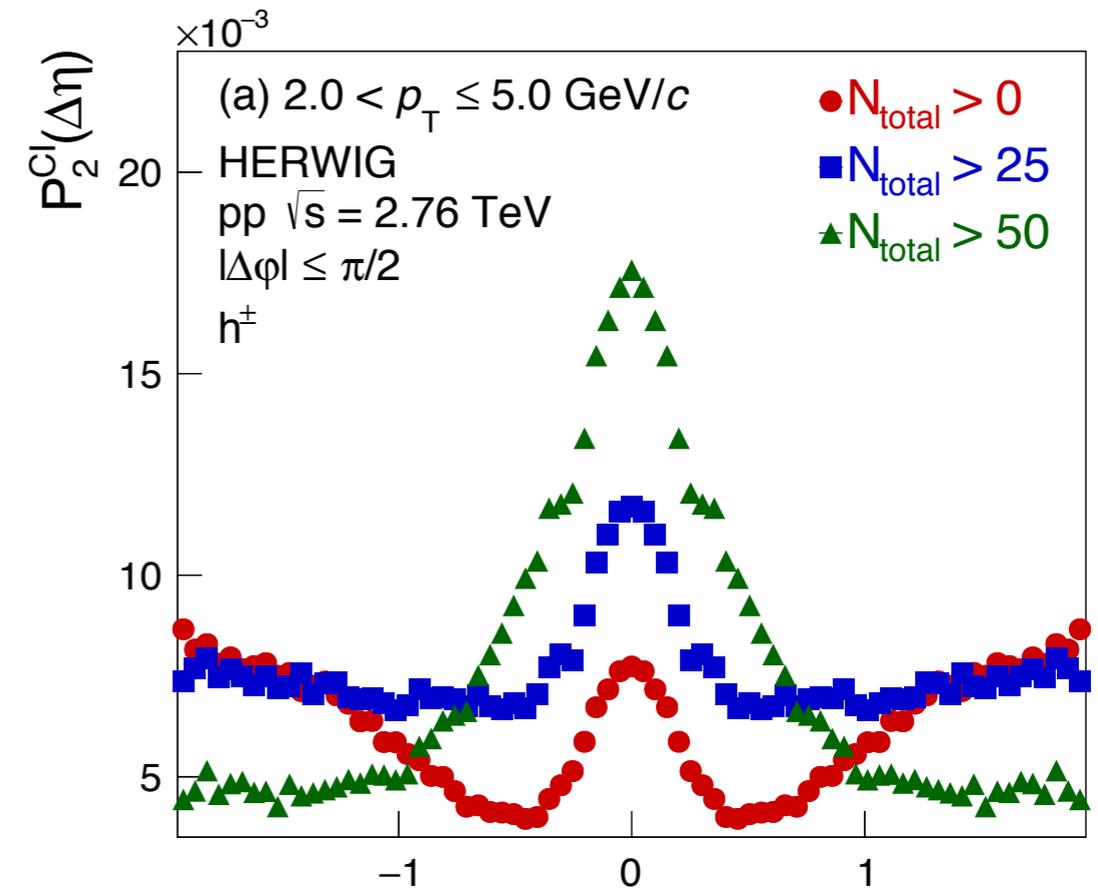
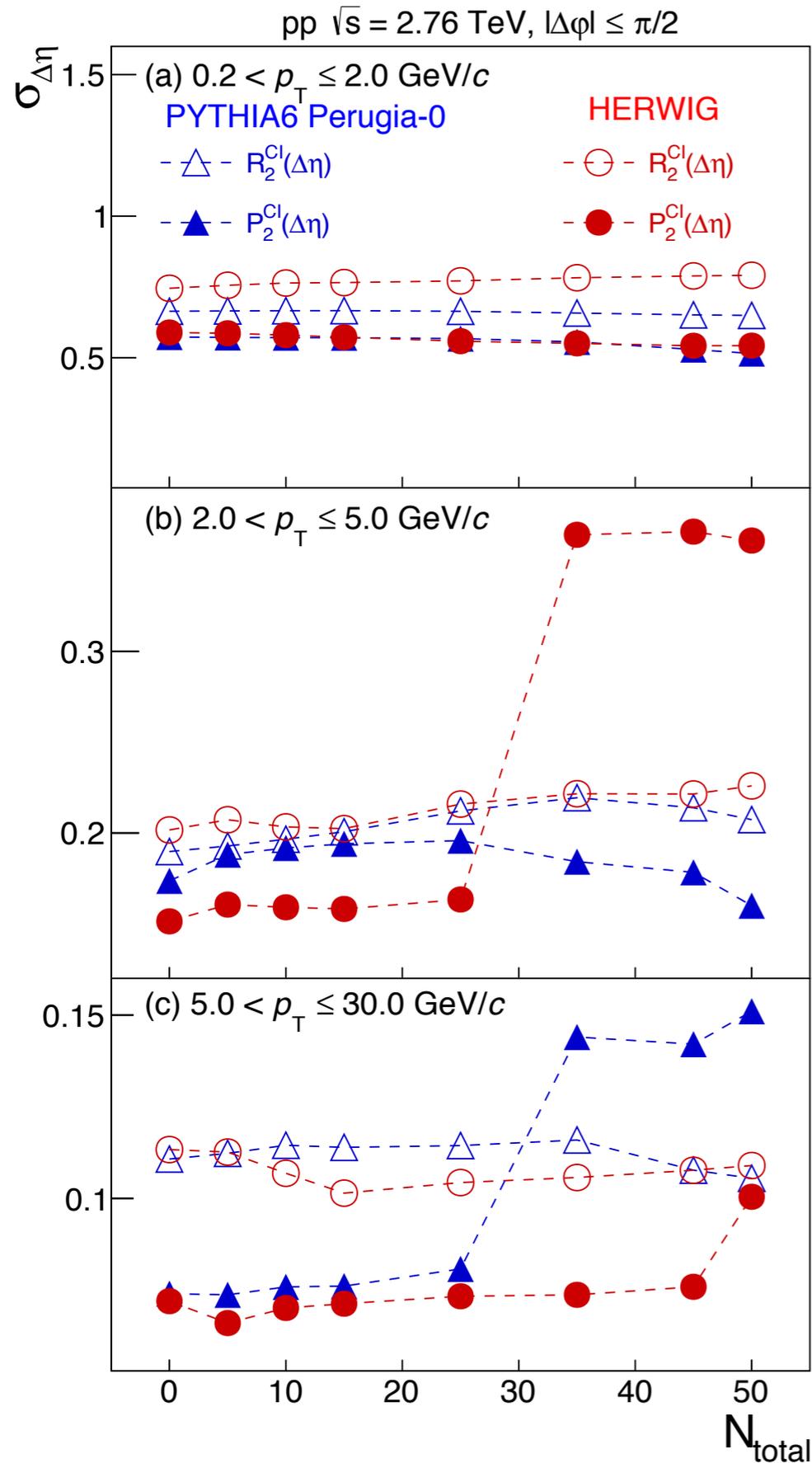


*** Smooth fall of widths with increasing p_T in PYTHIA.**

*** Irregular p_T dependence of widths in HERWIG.**

*** P_2 is narrower than R_2 , although for some p_T bins, it is broader.**

Result (VII) : Multiplicity wise study for CI



- * High-multiplicity events favour gluon jets.
- * Exhibit a discontinuity around $N_{total} = 30$.

B. Sahoo et al. , Phys. Rev. C 100, 024909

Summary

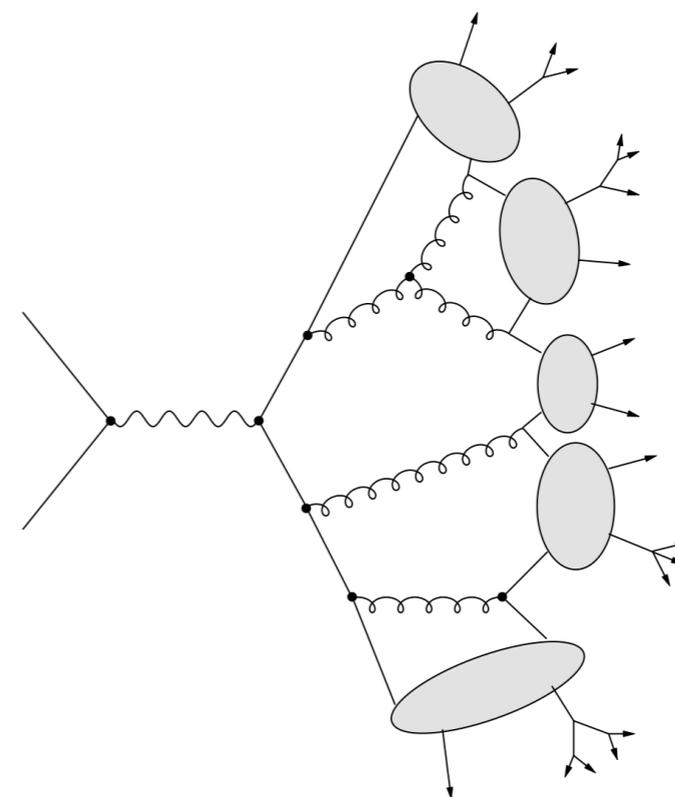
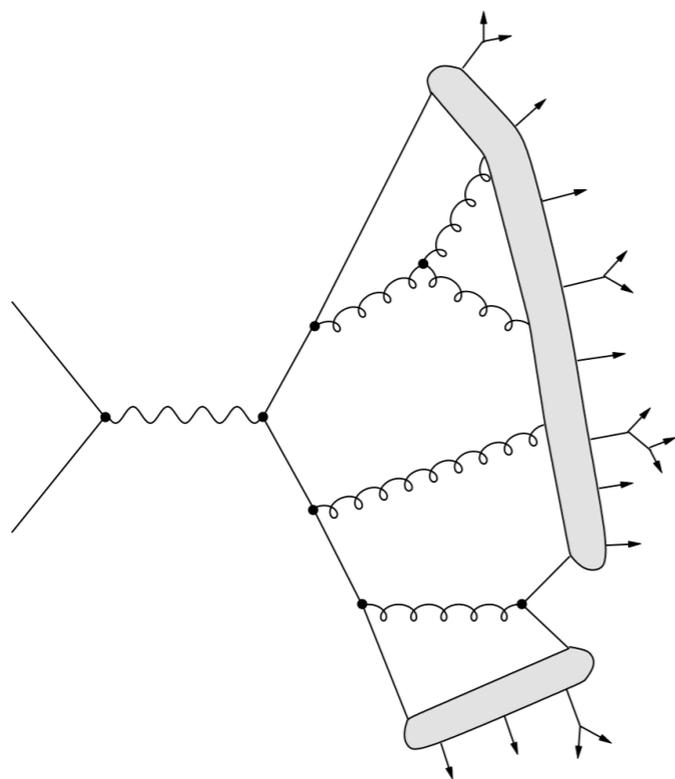
- ✓ P_2 is narrower than R_2 due to angular ordering, although in some p_T bins, P_2^{CD} is broader than R_2^{CD} .
- ✓ High-multiplicity events favour gluon jets.
- ✓ P_2^{CI} is a more precise observable to probe the internal structure of jet than R_2^{CI} .
- ✓ Analysis work is ongoing with ALICE data for pp@13 TeV.

Outlook

- ☑ It would be interesting to see the behavioural changes of these correlators when we probe low-x or gluon saturated regions.
- ☑ As fragmentation functions and mechanism of particle productions get changes. So, it would certainly change the correlation strength and shape both in number and momentum which could be studied as a discriminatory tool for separating particle production from quarks and gluons.

Thank you

Backup



http://www.scholarpedia.org/article/Parton_shower_Monte_Carlo_event_generators

Delta Eta Cut:-

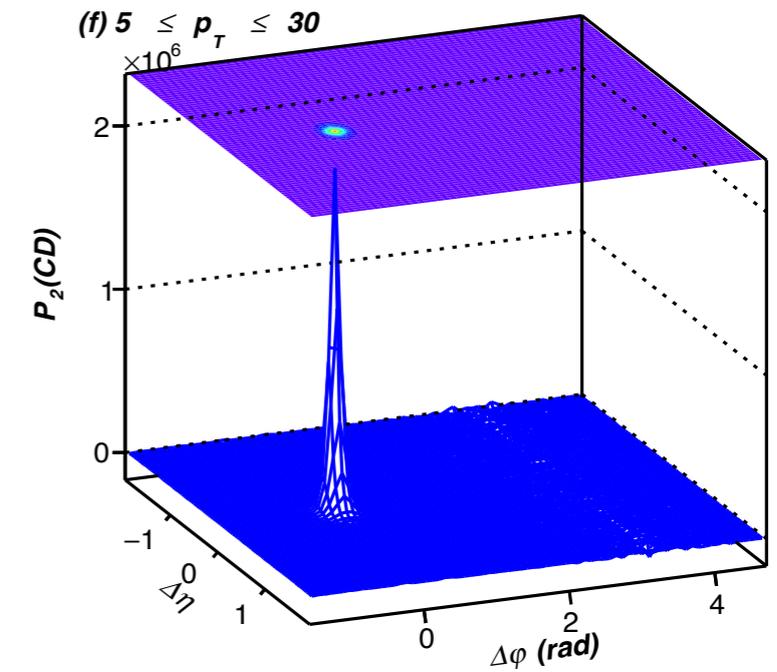
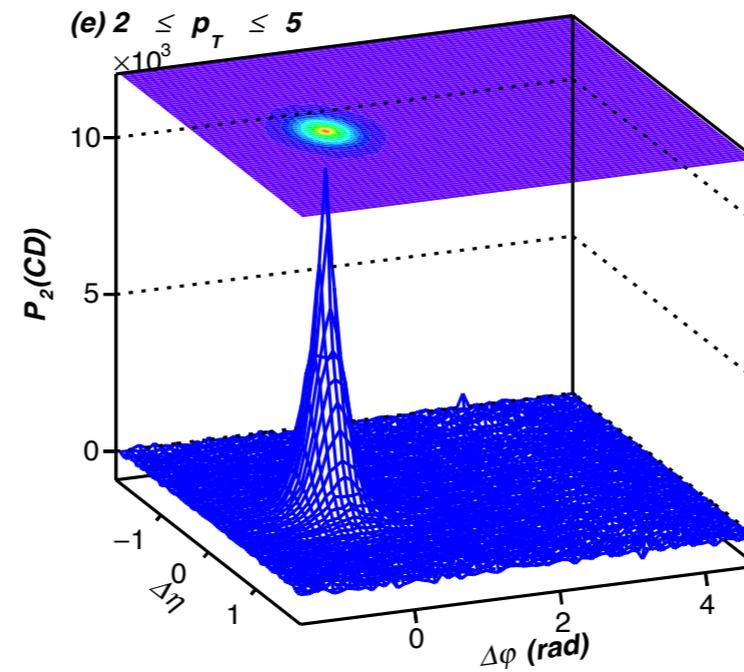
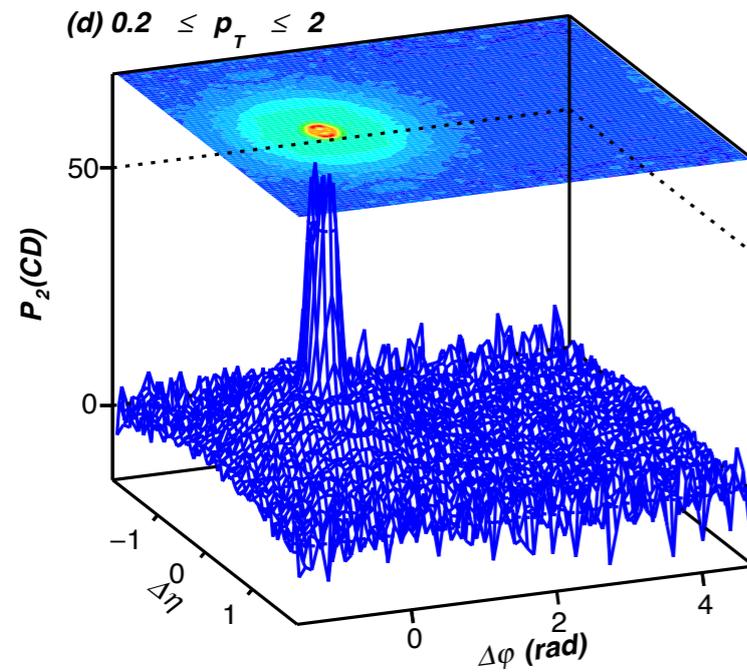
- ▶ Range : -2.0 to 2.0
- ▶ # of Bins = 79
- ▶ Bin Width = 0.05

$P_2^{CD}(\Delta\eta, \Delta\phi)$ for K^\pm

Delta Phi Cut:-

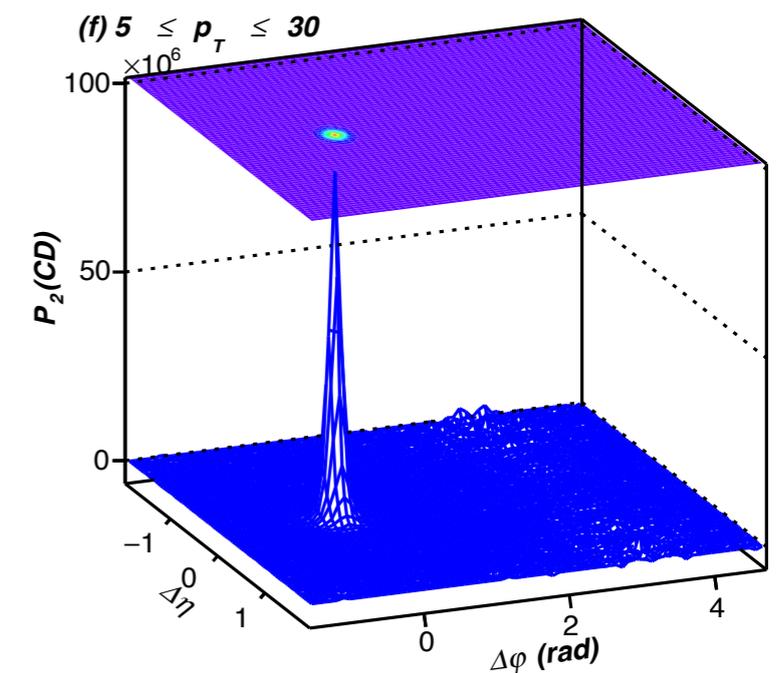
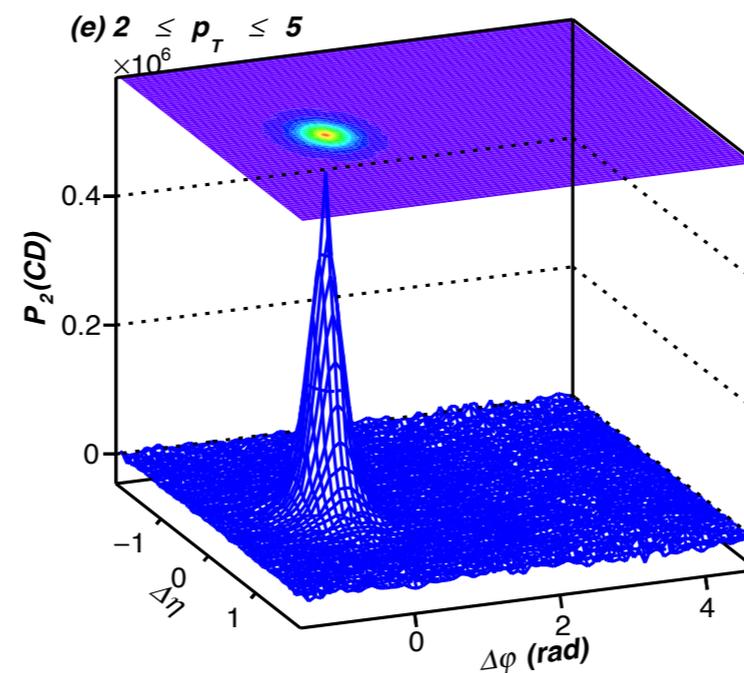
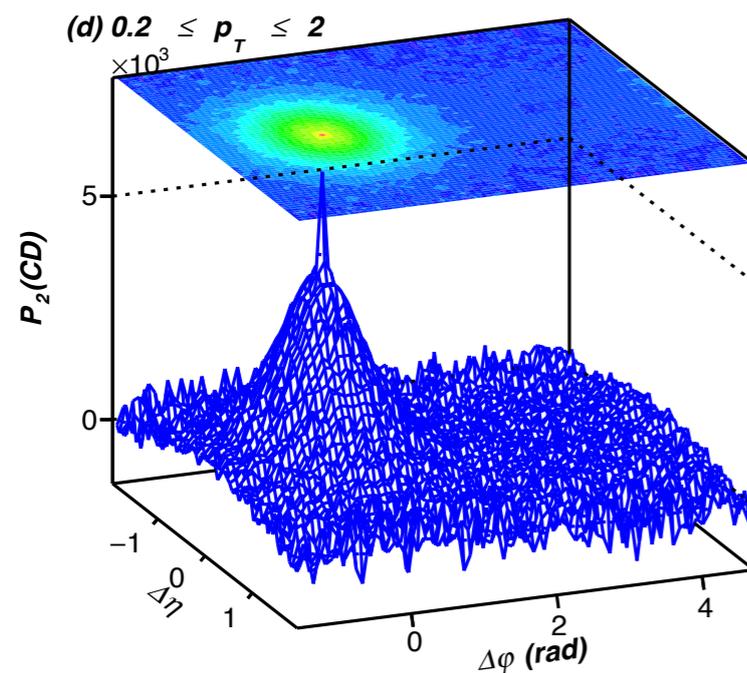
- ▶ Range : -0.5π to 1.5π
- ▶ # of Bins = 72
- ▶ Bin Width = 0.087

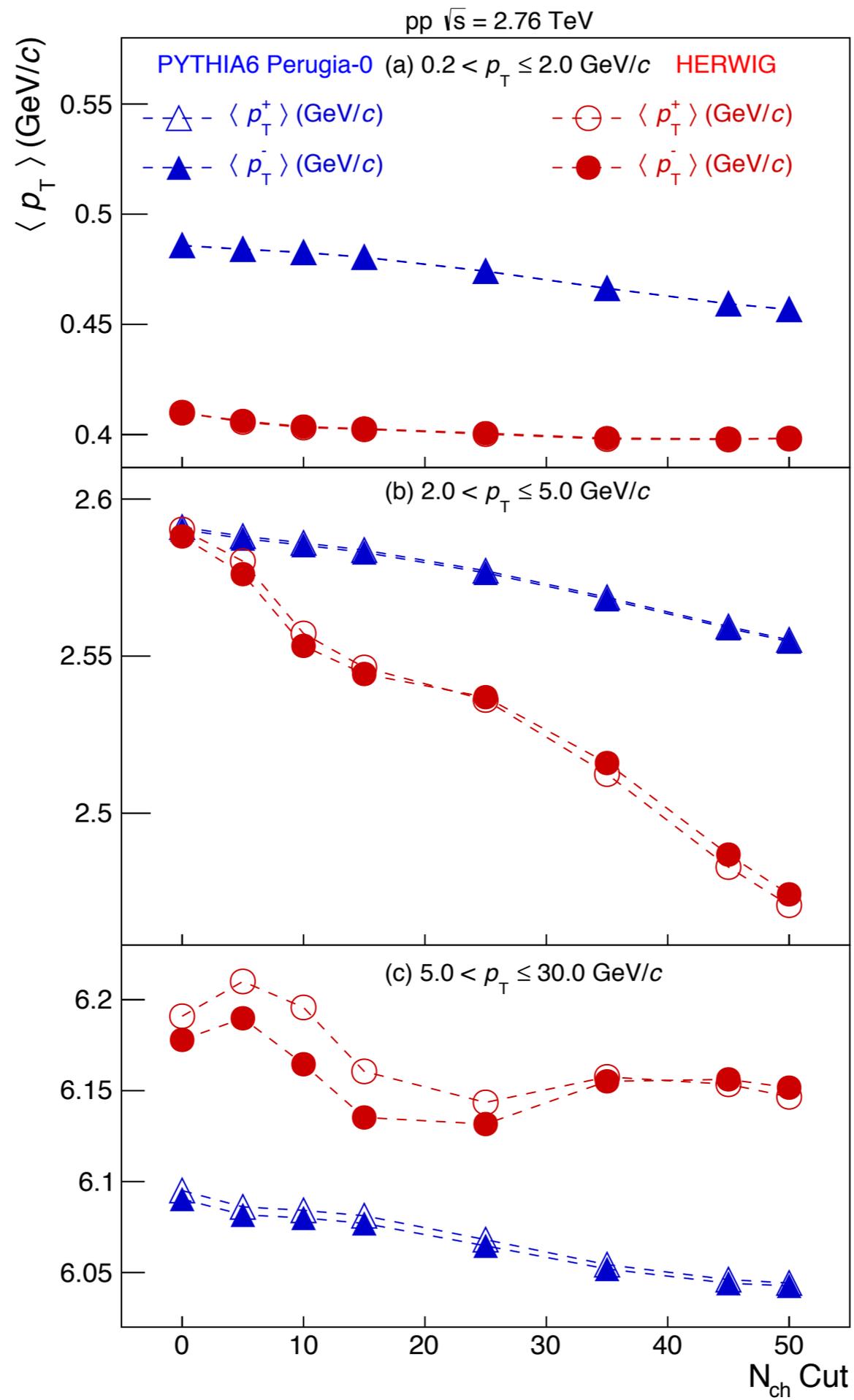
$\phi \rightarrow k^+ k^-$ - DecayOn

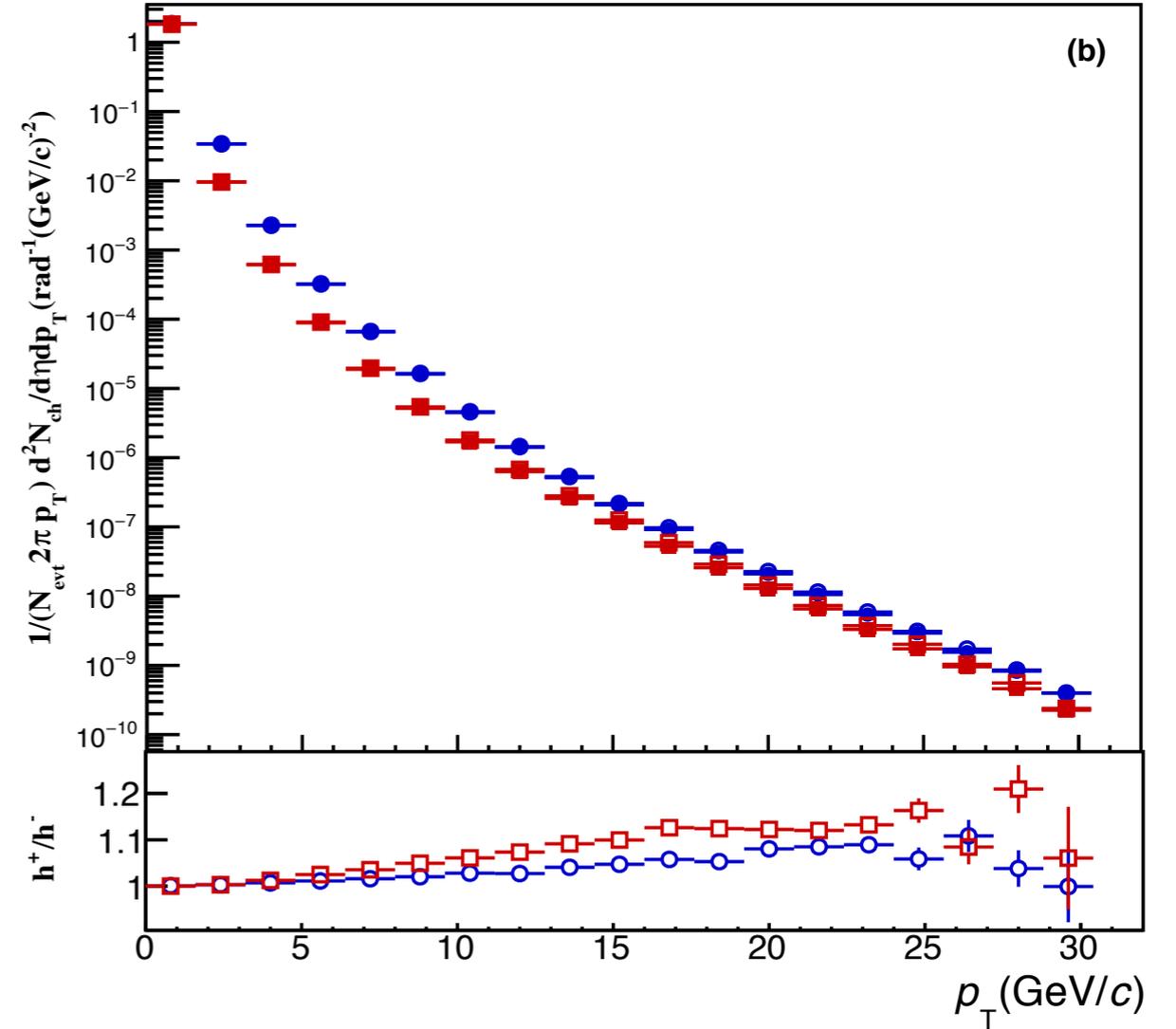
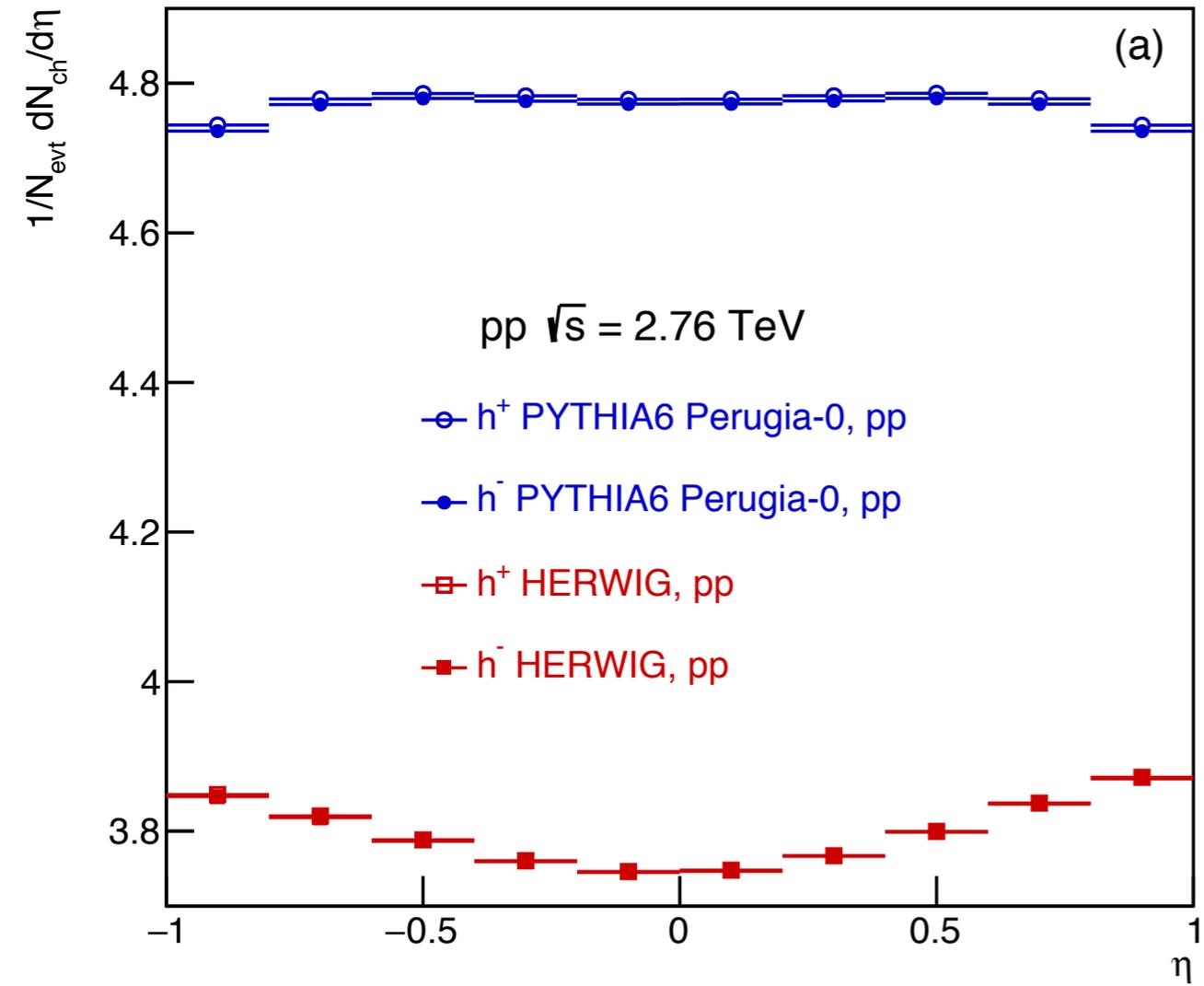


Increasing p_T

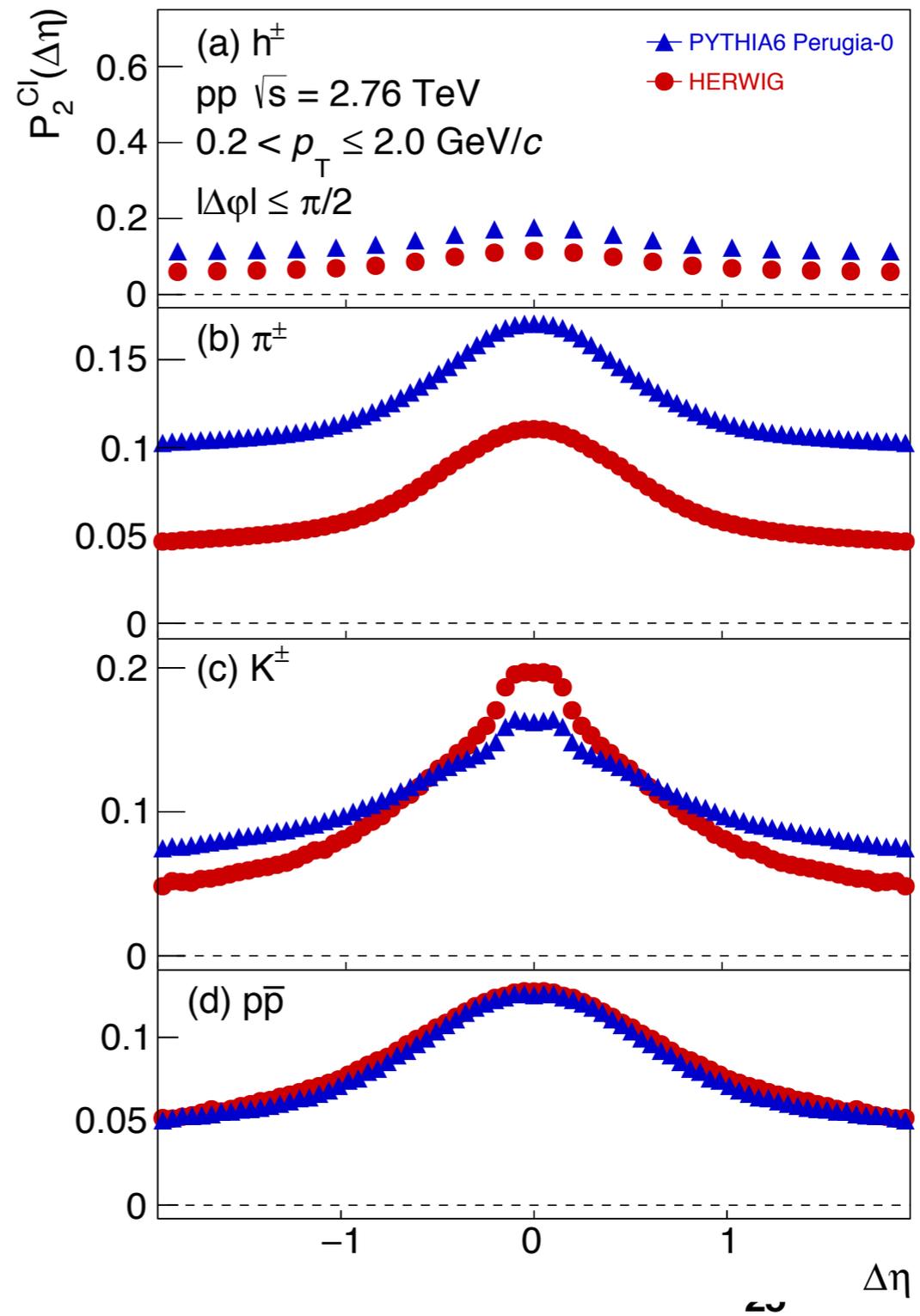
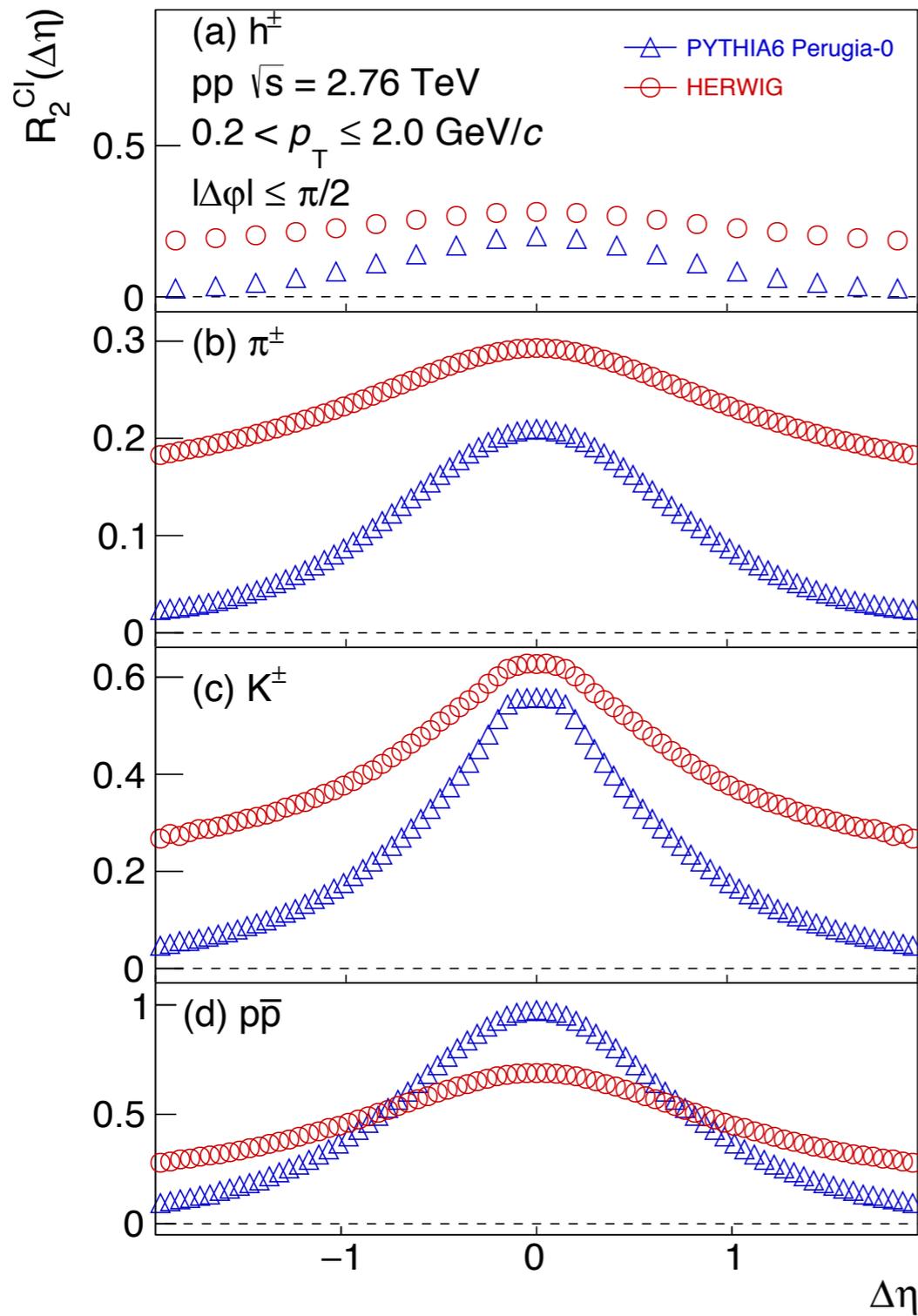
$\phi \rightarrow k^+ k^-$ - DecayOff





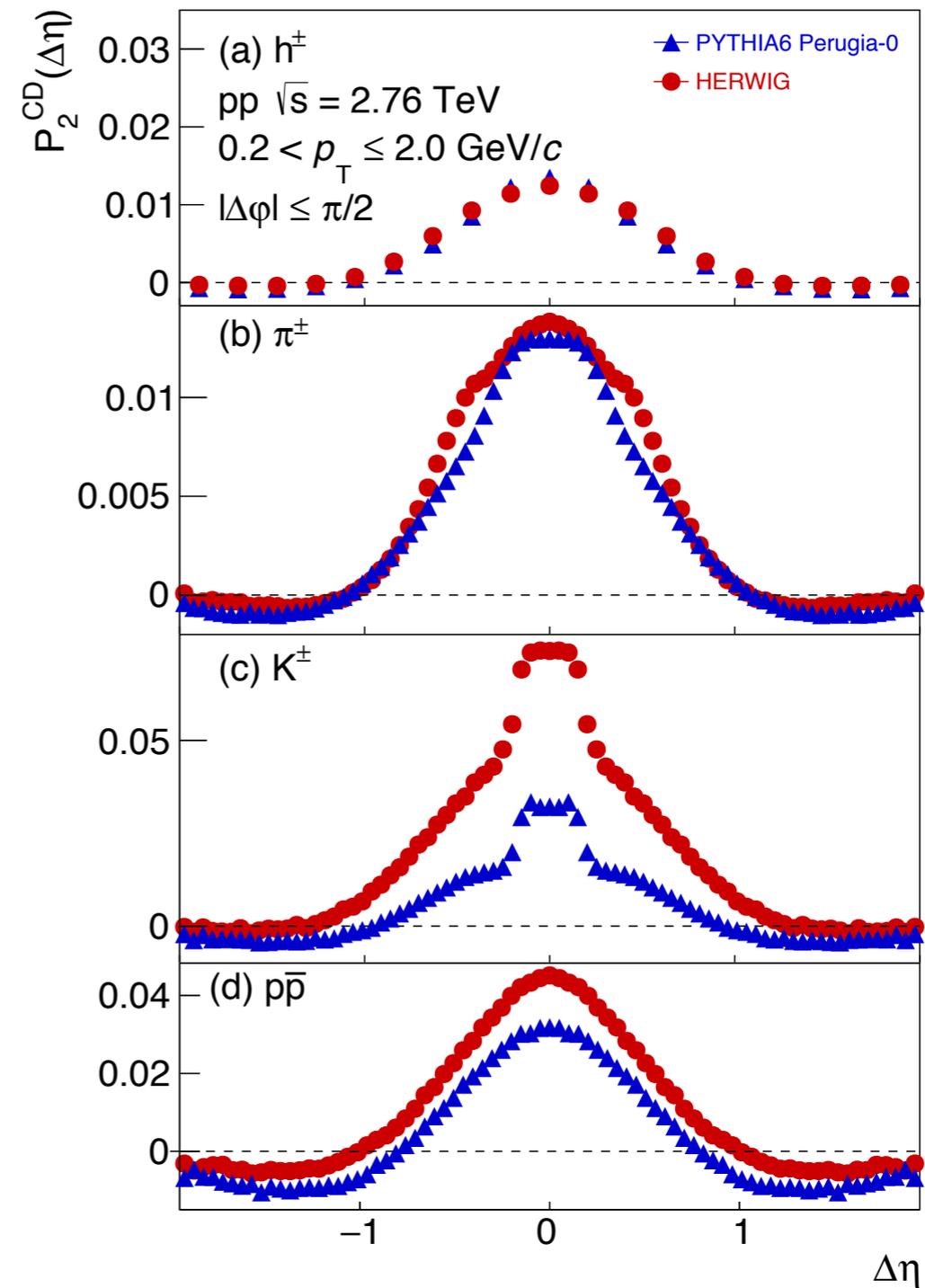
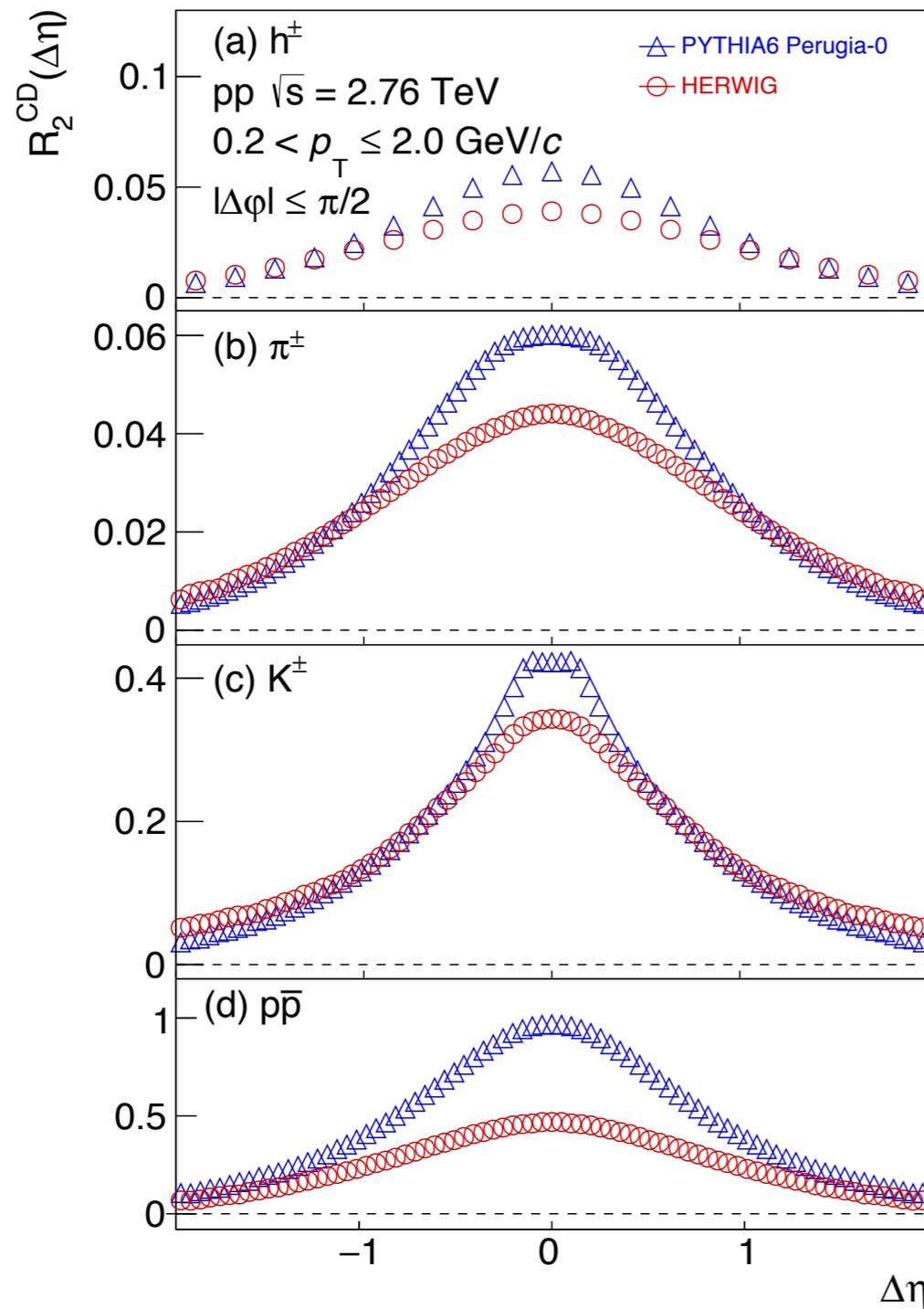


Result (VIII) : $R_2^{CI}(\Delta\eta)$ & $P_2^{CI}(\Delta\eta)$ for identified species



 **Resonance plays a vital role for kaons!**

Result (IX) : $R_2^{\text{CD}}(\Delta\eta)$ & $P_2^{\text{CD}}(\Delta\eta)$ for identified species



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 **Resonance plays a vital role for kaons!**

