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Topological studies of light-flavor hadron production in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC

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Instituto de Ciencias Nucleares, UNAM, Mexico City, Mexico

Introduction and Motivation

- Measurements at the LHC have revealed that small collision systems exhibit heavy-ion-like behavior, formerly thought to be a distinctive feature of heavy-ion collisions, where the data support the formation of sQGP.

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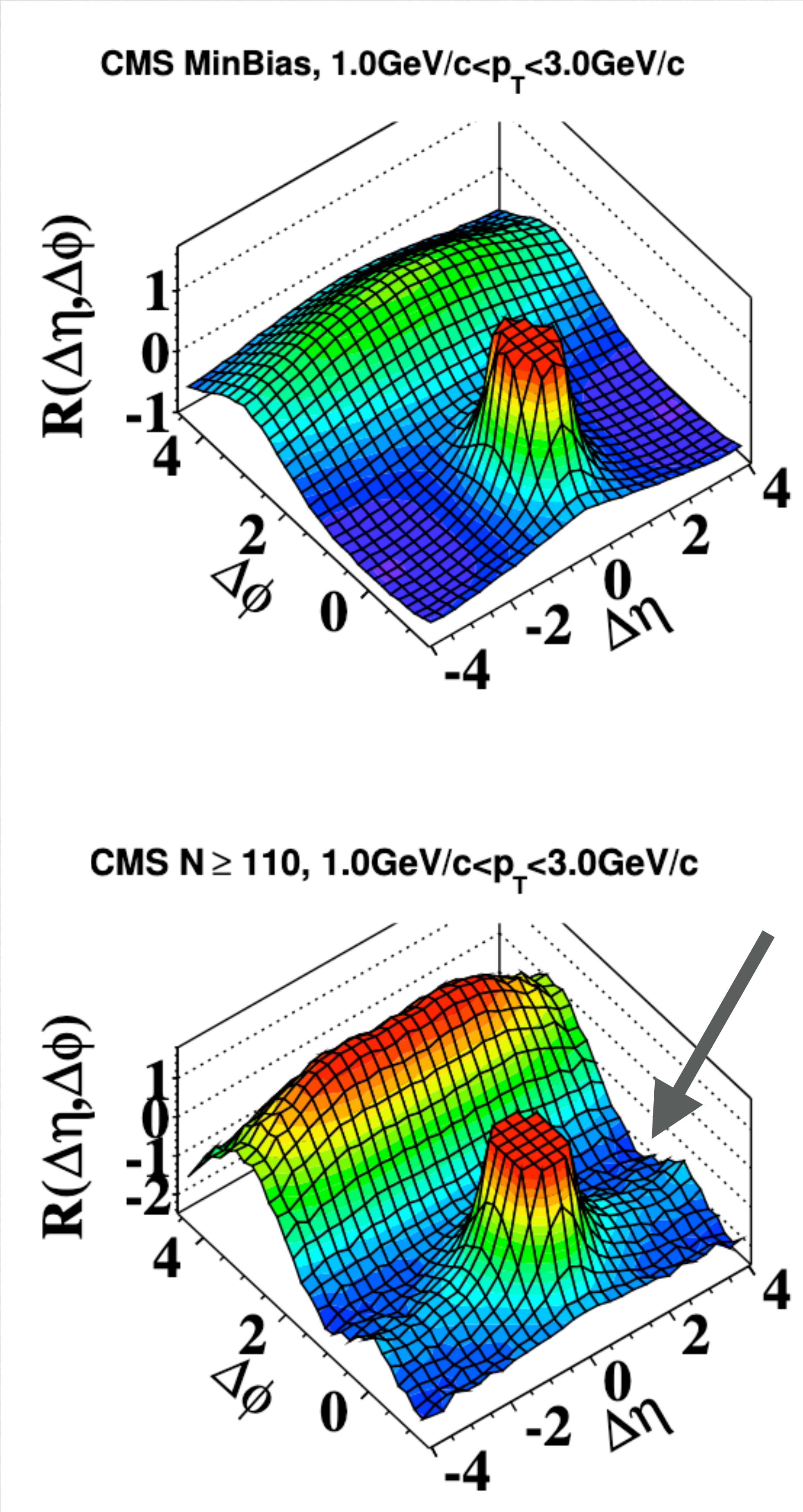
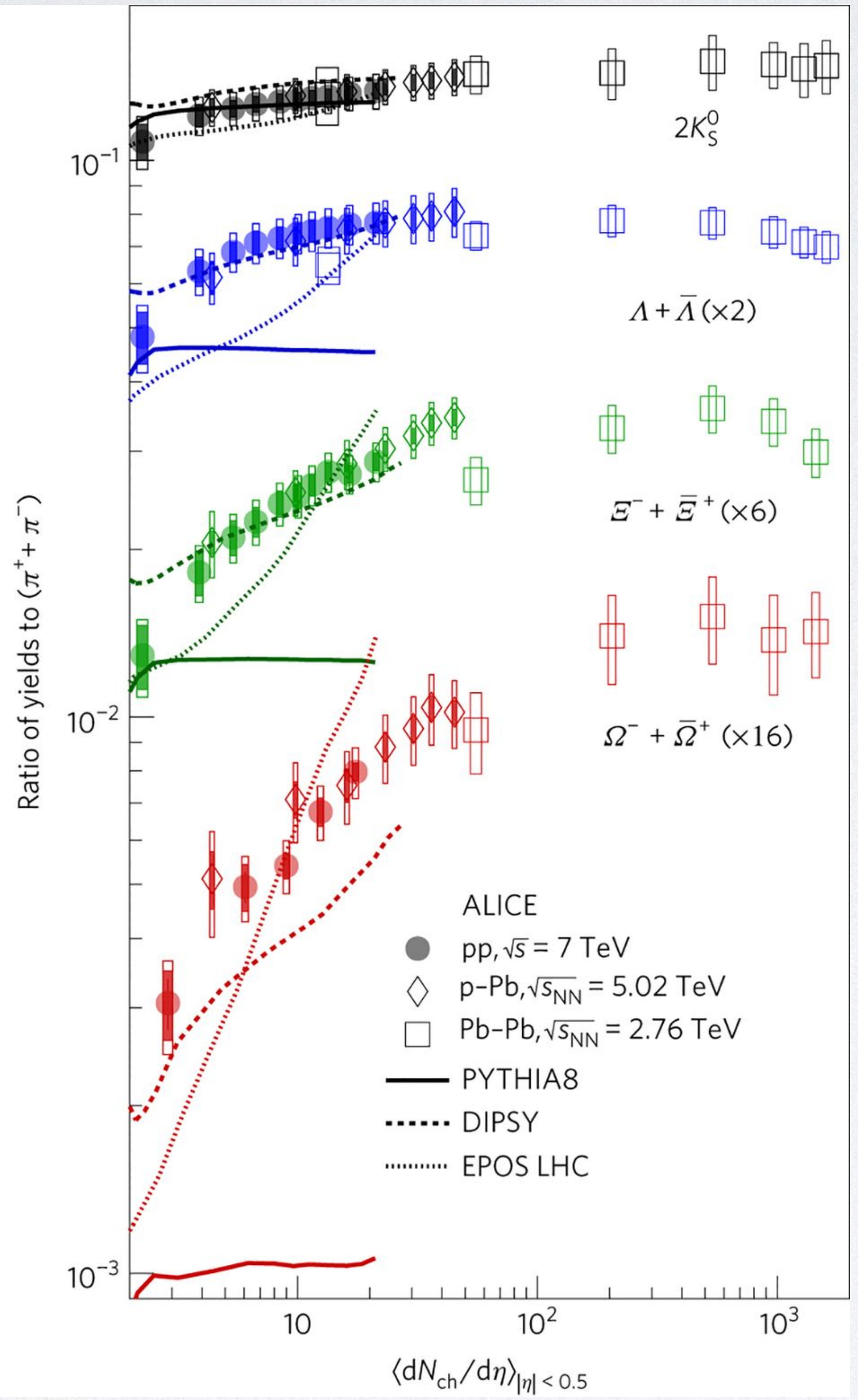
CMS, JHEP 1009:091,2010

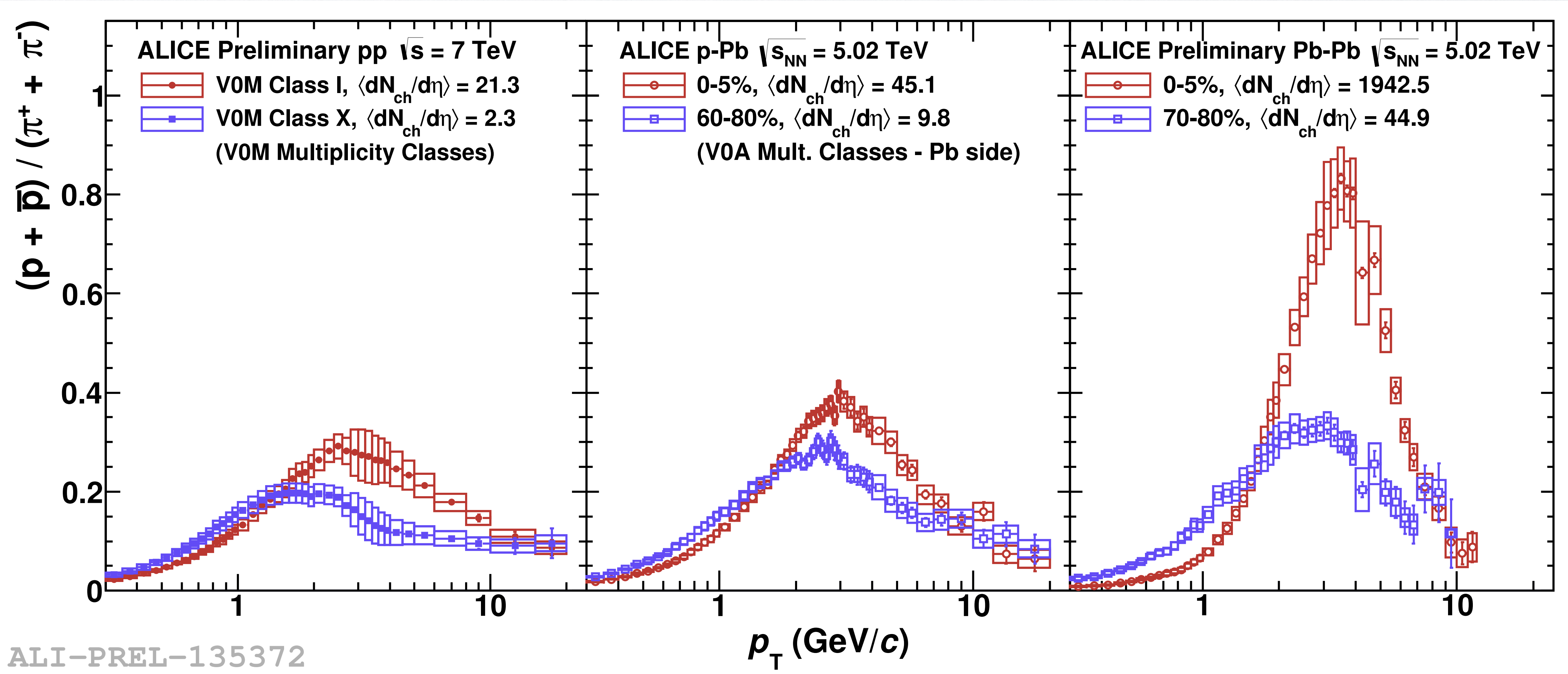


Ridge structure in high-multiplicity pp collisions

ALICE, Nature Physics 13, 535-539 (2017)



Strangeness enhancement in high multiplicity pp and p-Pb are similar to Pb-Pb



Similar features of baryon to meson ratios in pp, p-Pb and Pb-Pb collisions

Introduction and Motivation

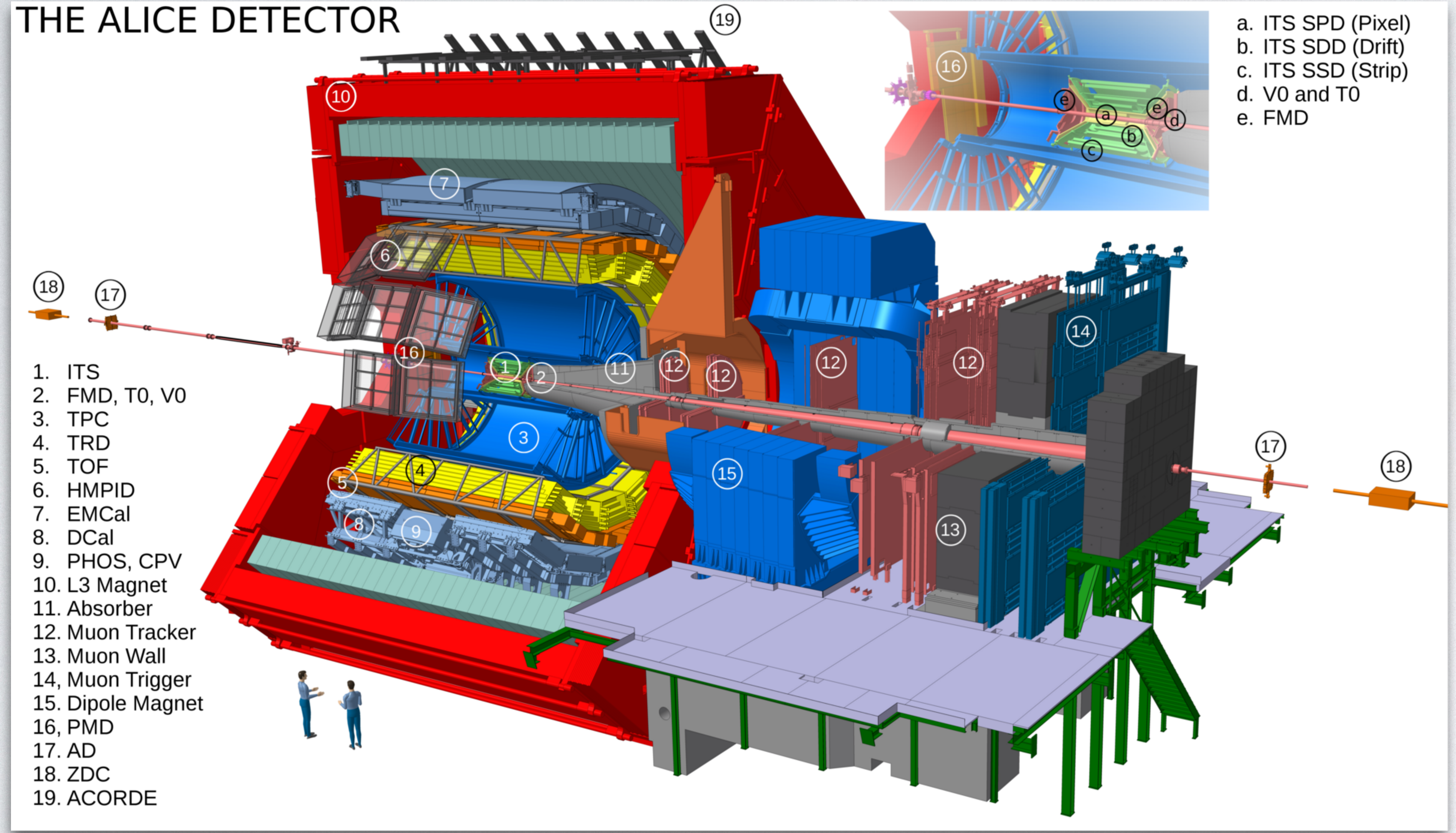
- Measurements at the LHC have revealed that small collision systems exhibit heavy-ion-like behavior, formerly thought to be a distinctive feature of heavy-ion collisions, where the data support the formation of sQGP.

- Traditionally, small collision systems are used as a baseline for the study of possible formation of QGP in heavy-ion collisions.

- The origin of the heavy-ion-like behavior in small systems is under debate. To get more insight on this, let us discuss the following scenario in this talk.
    - Isolating different physics regimes (soft and hard physics)
    - Test with microscopic (strings) and macroscopic (driven by hydrodynamics) models

The ALICE detector

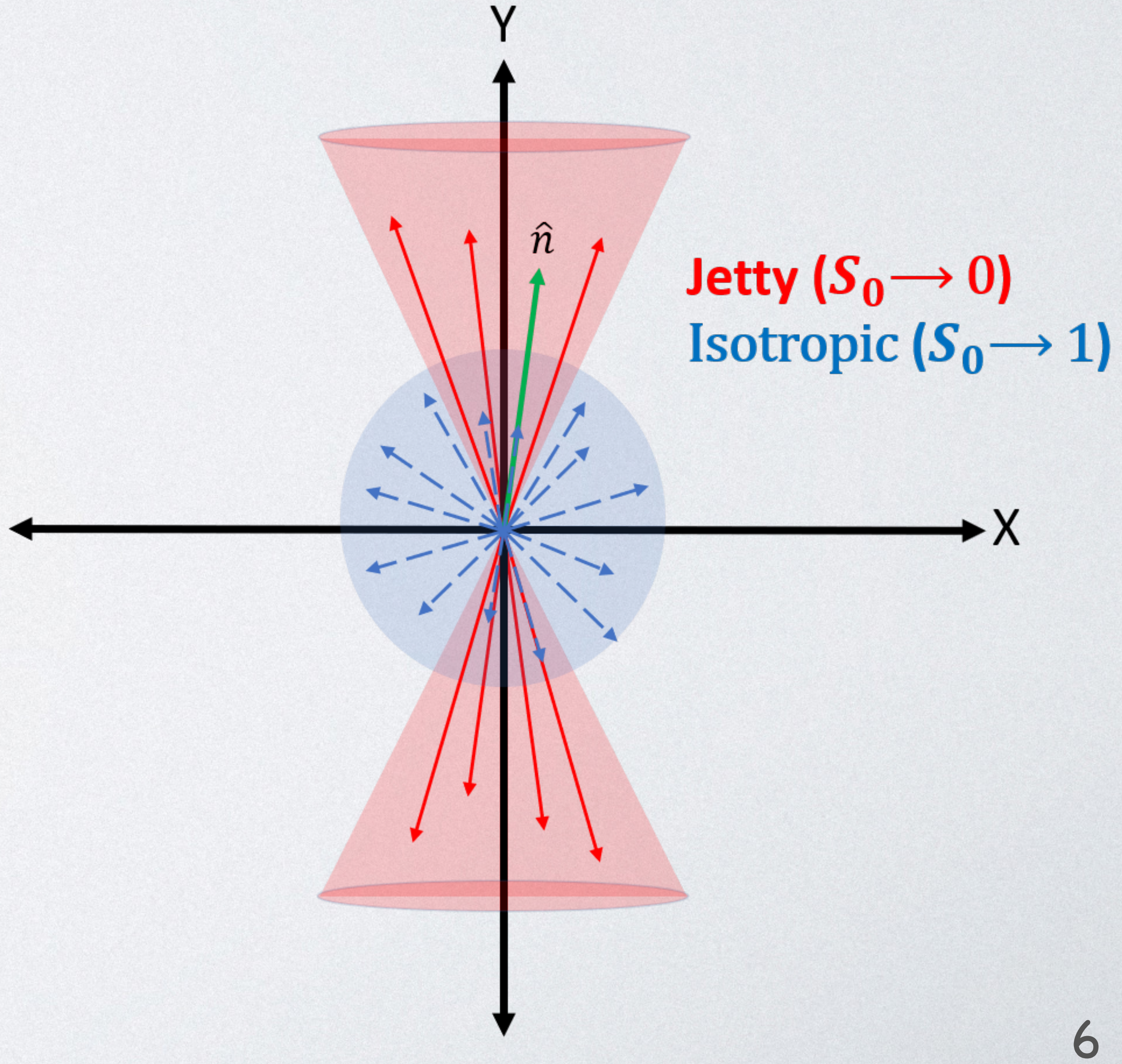
ALICE has collected data for pp, p-Pb, Xe-Xe and Pb-Pb collisions at several center of mass energies.



Detectors used for this analysis

- The Inner tracking system (ITS)
  - Trigger, tracking, vertex
  - Multiplicity estimator (N_{SPD}-mid rapidity)
- The Time Projection Chamber (TPC)
  - Tracking and PID (dE/dx)
- The Time-Of-Flight detector (TOF)
  - PID through particle time of flight
- V0-A and V0-C detectors
  - Trigger
  - Multiplicity estimator (V0M-forward rapidity)

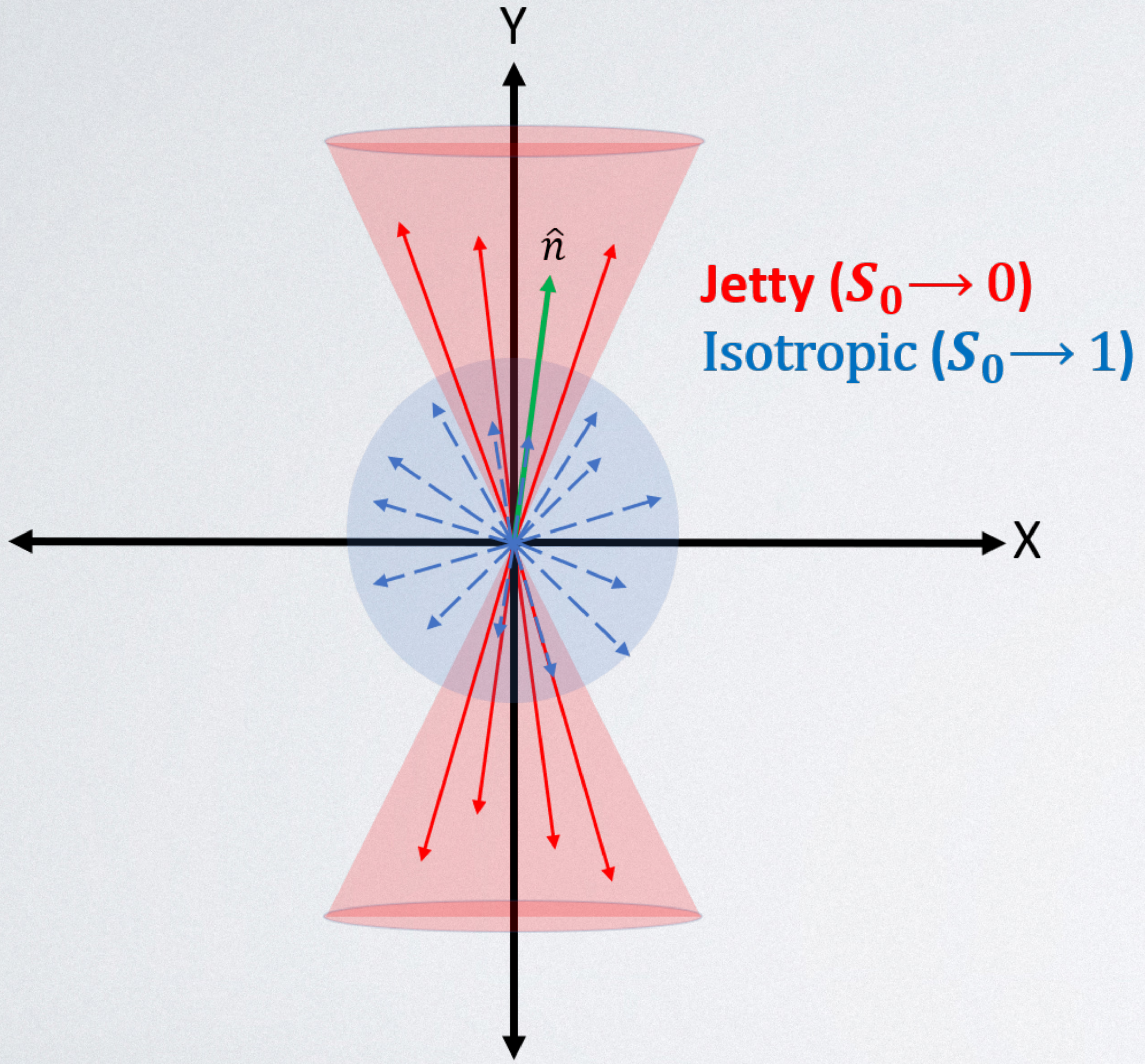
Identified particle production as a function of transverse spherocity



Event shape observables: Transverse Spherocity

Transverse Spherocity may discriminate between hard and soft processes.

- Jetty: Back-to-back structure, indication of hard QCD ($S_0 \rightarrow 0$)
- Isotropic: enhances underlying events, soft QCD ($S_0 \rightarrow 1$)



$$S_0 = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i |\overrightarrow{p_{\mathrm{Ti}}} \times \hat{n}|}{\Sigma_i p_{\mathrm{Ti}}} \right)^2$$

A. Ortiz, Adv.Ser.Direct.High Energy Phys. 29 (2018) 343.

A. Banfi, G. P. Salam and G. Zanderighi, JHEP 06 (2010) 038.

A. Ortiz, G. Paic. E. Cuautle, Nucl.Phys.A 941 (2015) 78.

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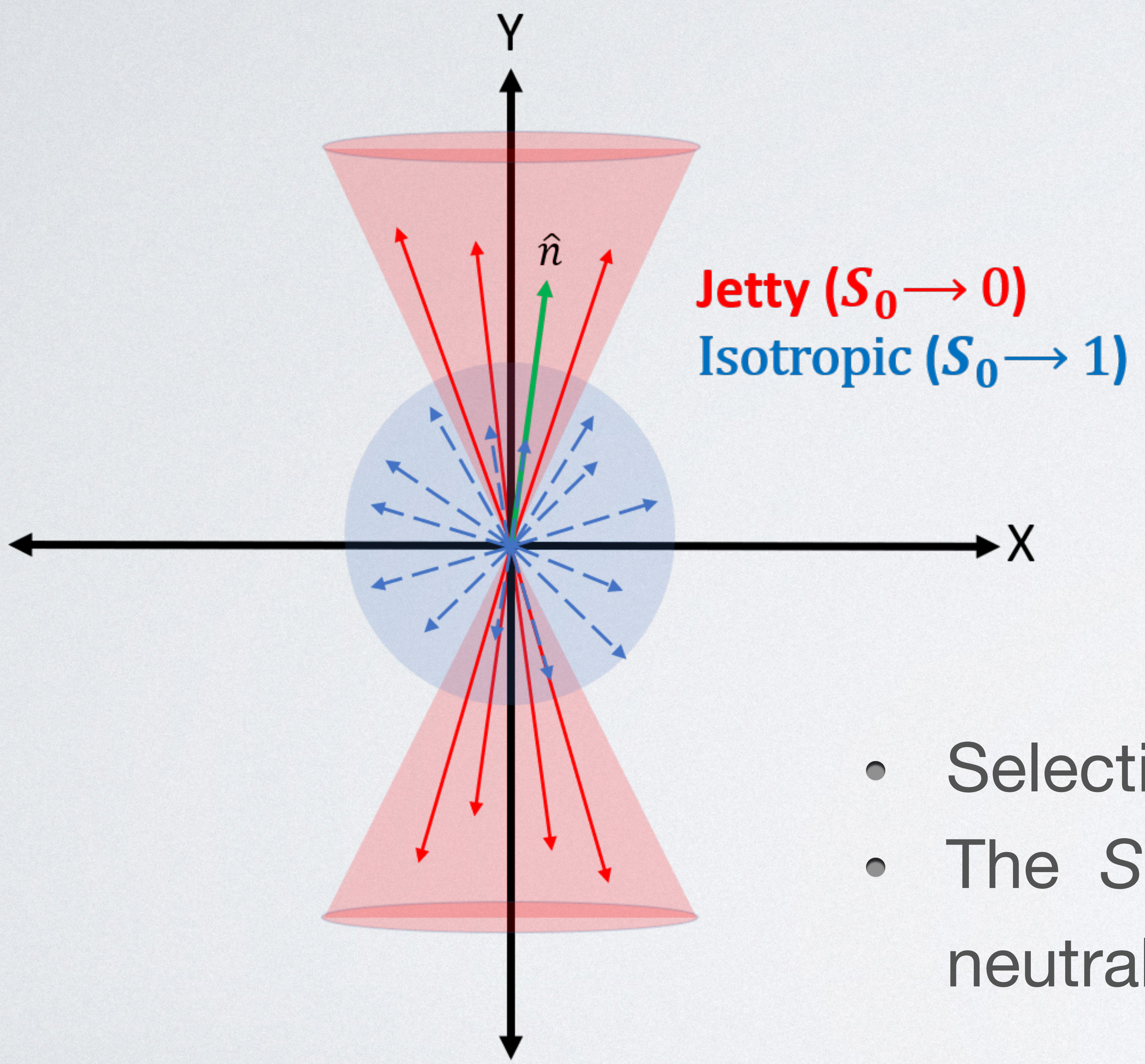

$$S_0 = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i |\overrightarrow{p_{\mathrm{Ti}}} \times \hat{n}|}{\Sigma_i p_{\mathrm{Ti}}} \right)^2$$

$$\downarrow$$

$$S_0^{p_{\mathrm{T}}=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i |\hat{p_{\mathrm{Ti}}} \times \hat{n}|}{N_{\mathrm{trk}}} \right)^2$$

Unweighted transverse spherocity
(only angular component is considered)

- Selecting events based on S_0 affects neutral and charged hadrons differently.
- The S_0 estimator was modified to reduce the bias on measurements of neutral particles such as K_S^0, ϕ, Λ etc.

A. Ortiz, Adv.Ser.Direct.High Energy Phys. 29 (2018) 343.
A. Banfi, G. P. Salam and G. Zanderighi, JHEP 06 (2010) 038.
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Identified particle production as a function of $S_0^{p_T=1}$ in pp collisions at 13 TeV

VOM forward-rapidity estimator

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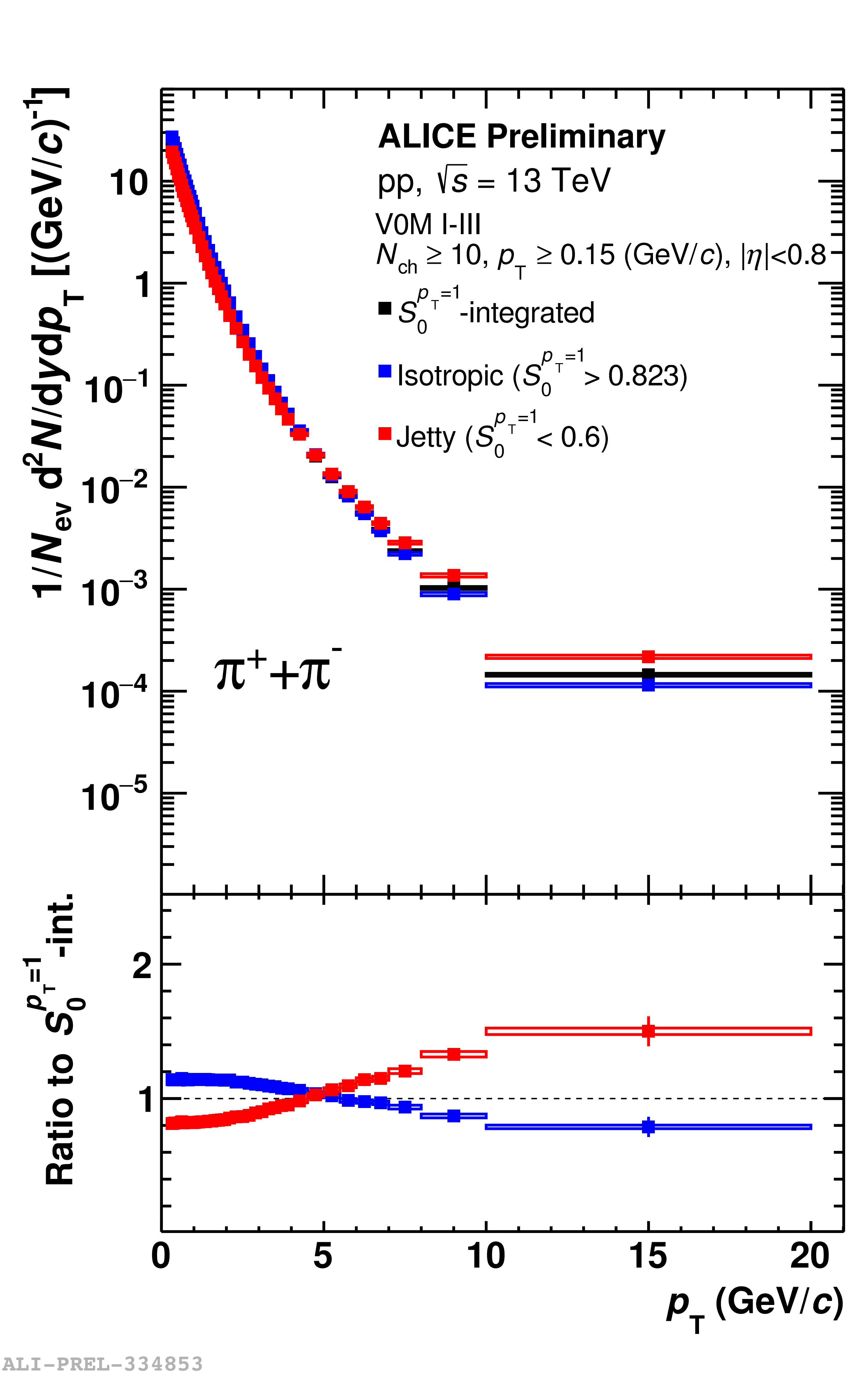
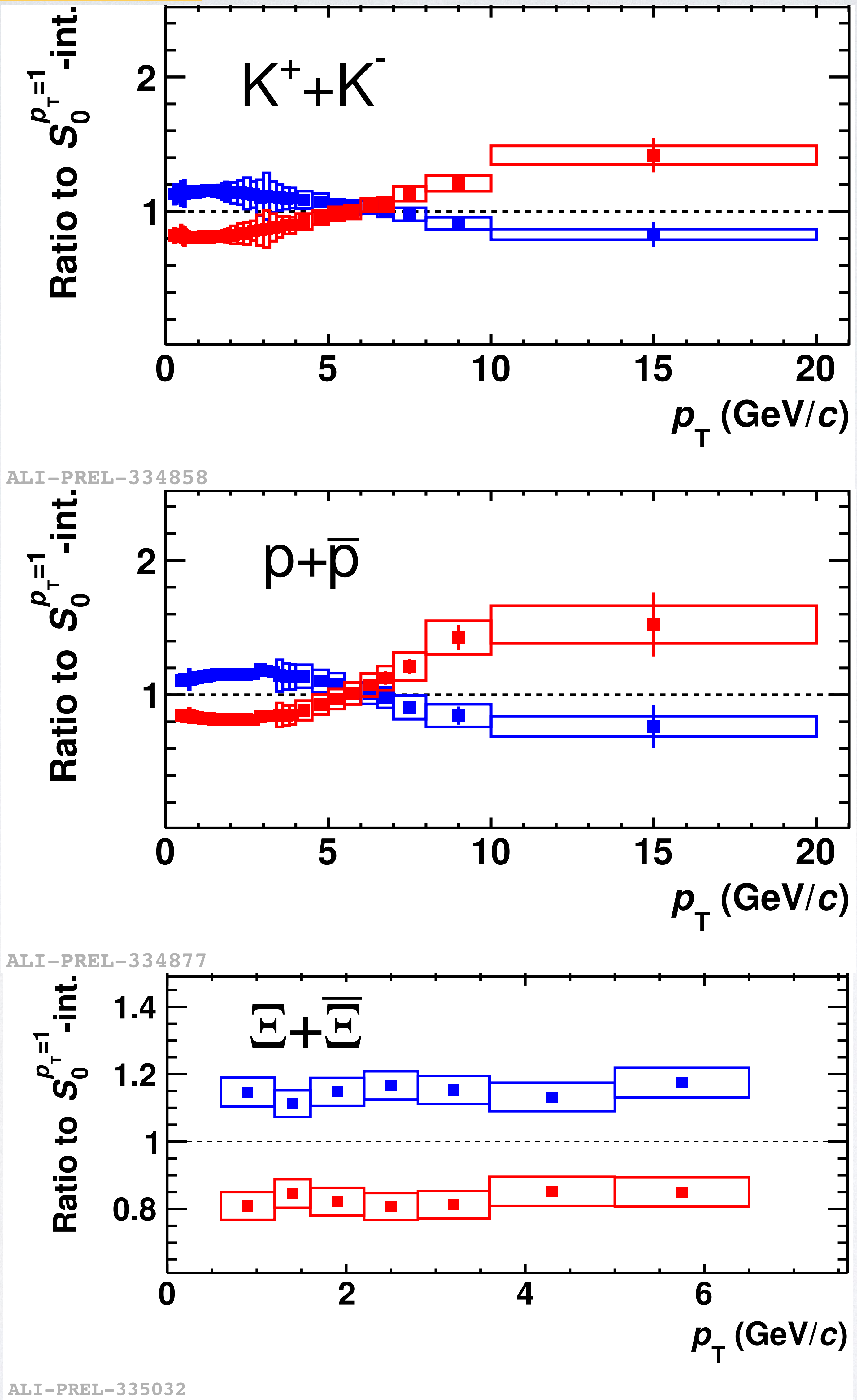
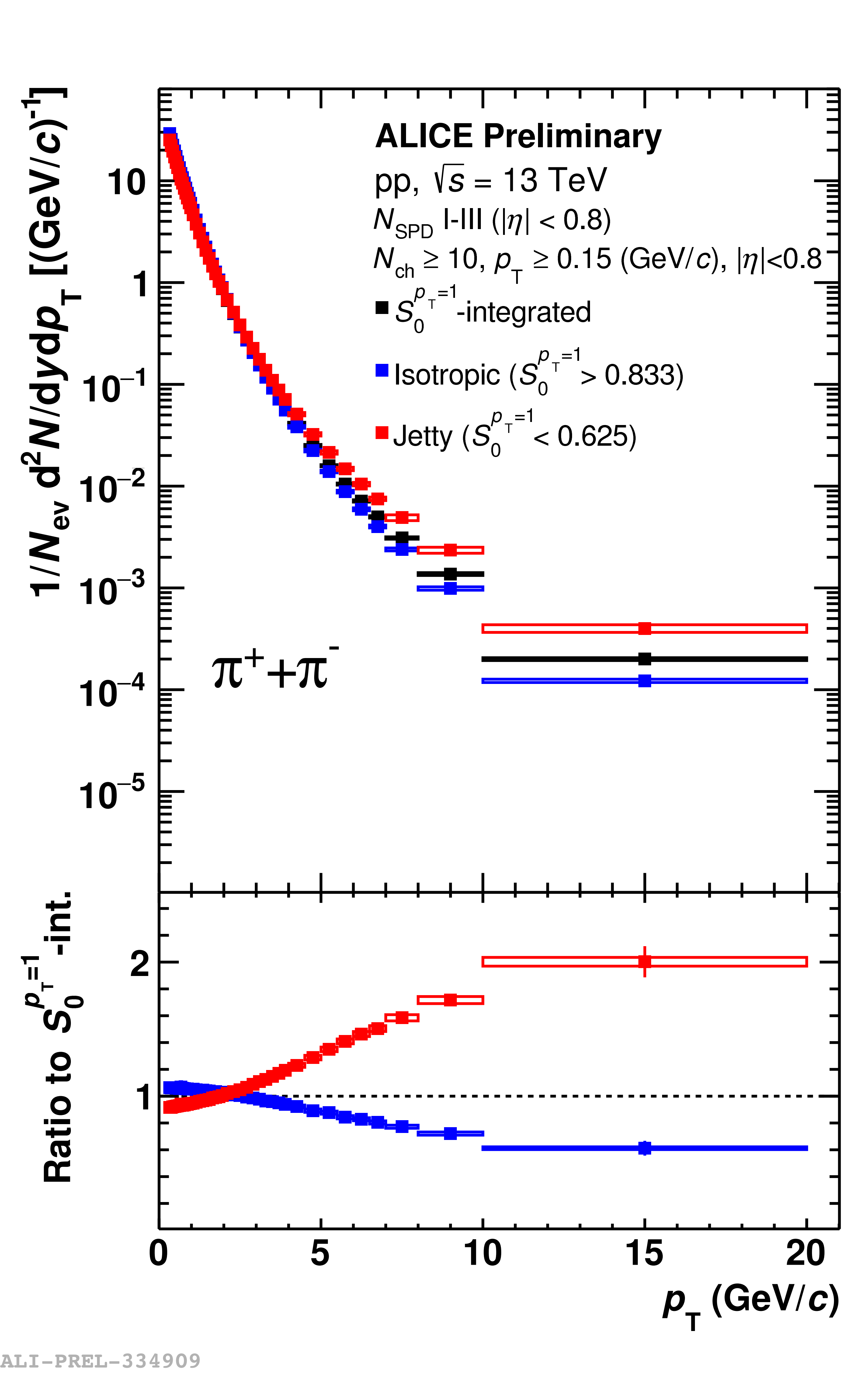


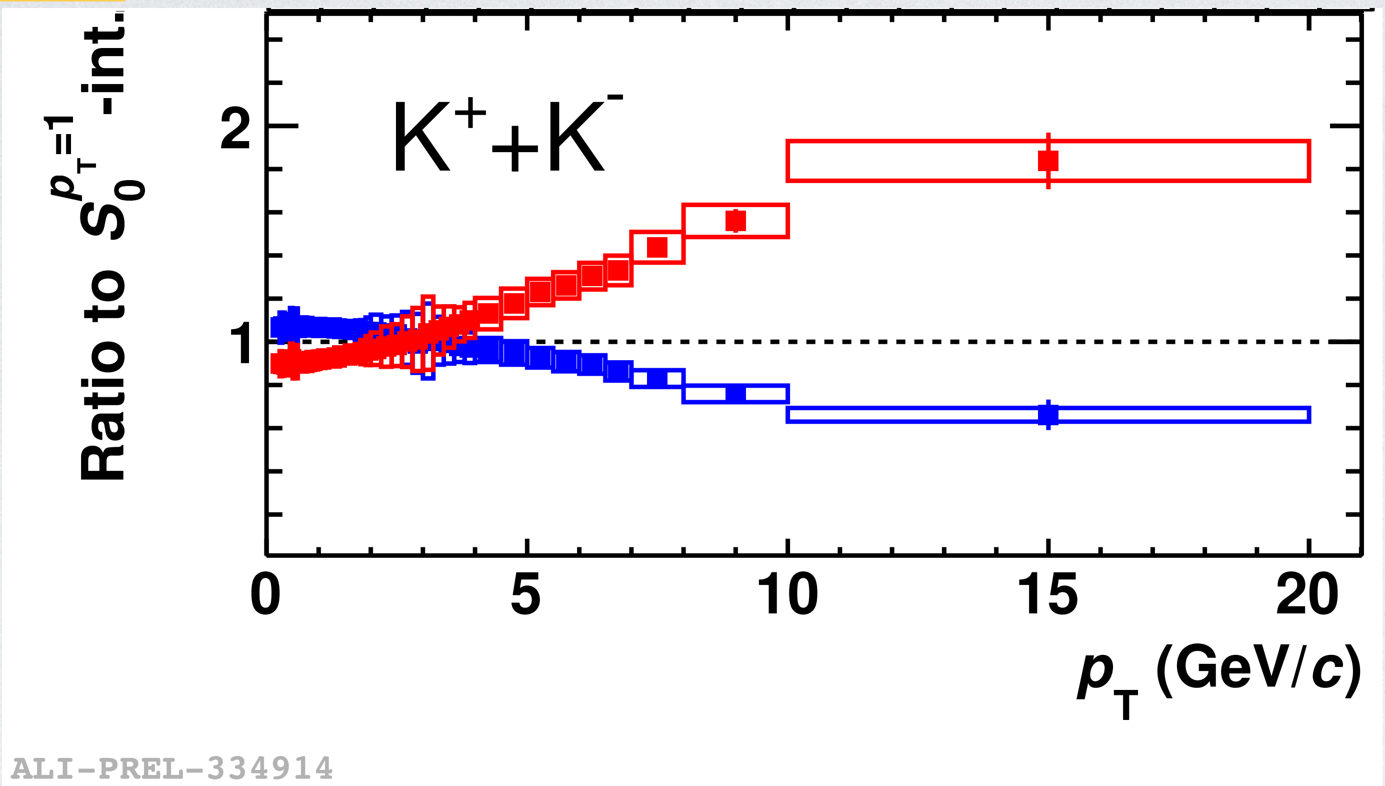


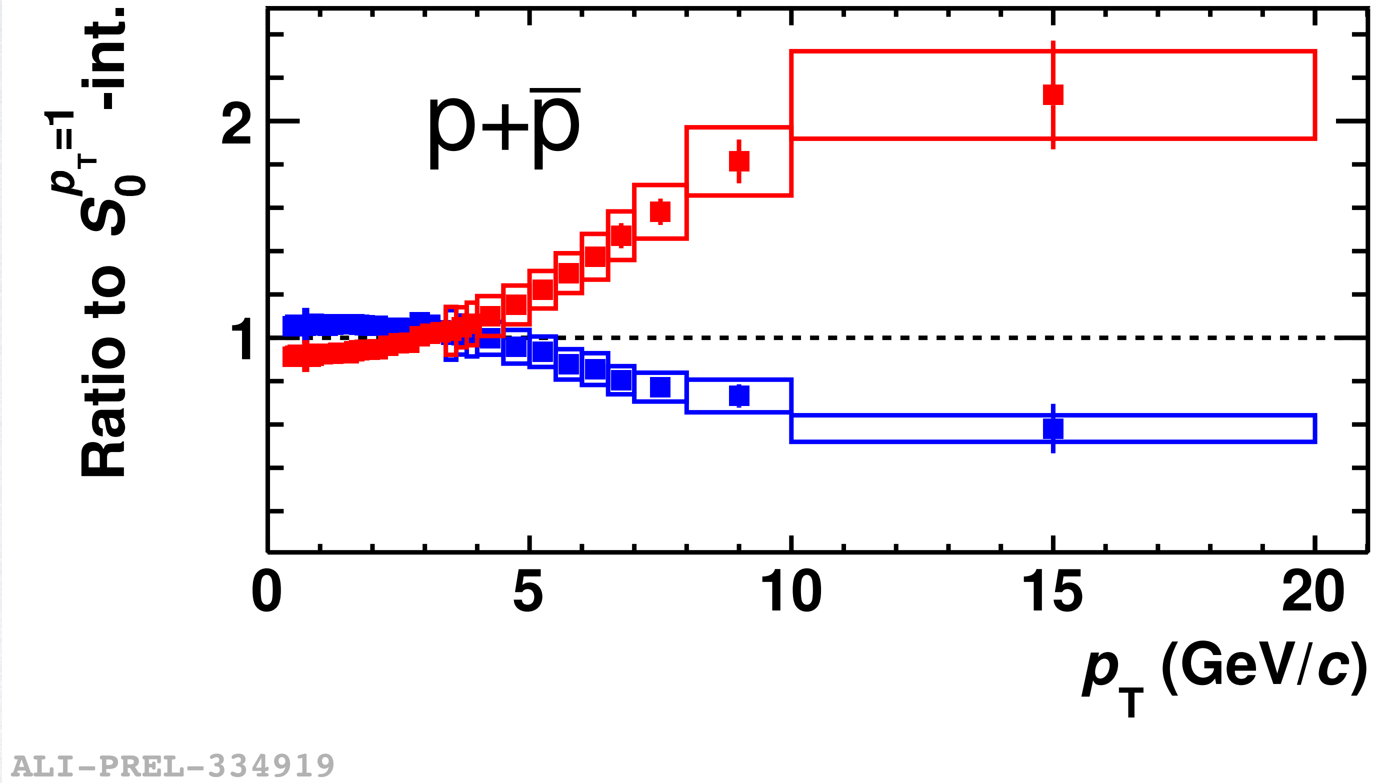
- Clear dependence of p_T spectra on $S_0^{p_T=1}$ and the ratio to the $S_0^{p_T=1}$-integrated events, isotropic and jetty events have distinct crossing points at low-p_T for pions, kaons and protons
- The ratios for Ξ appear to be more flat around unity (notice the different p_T range!) and no such crossing points are observed in the measured momentum range.

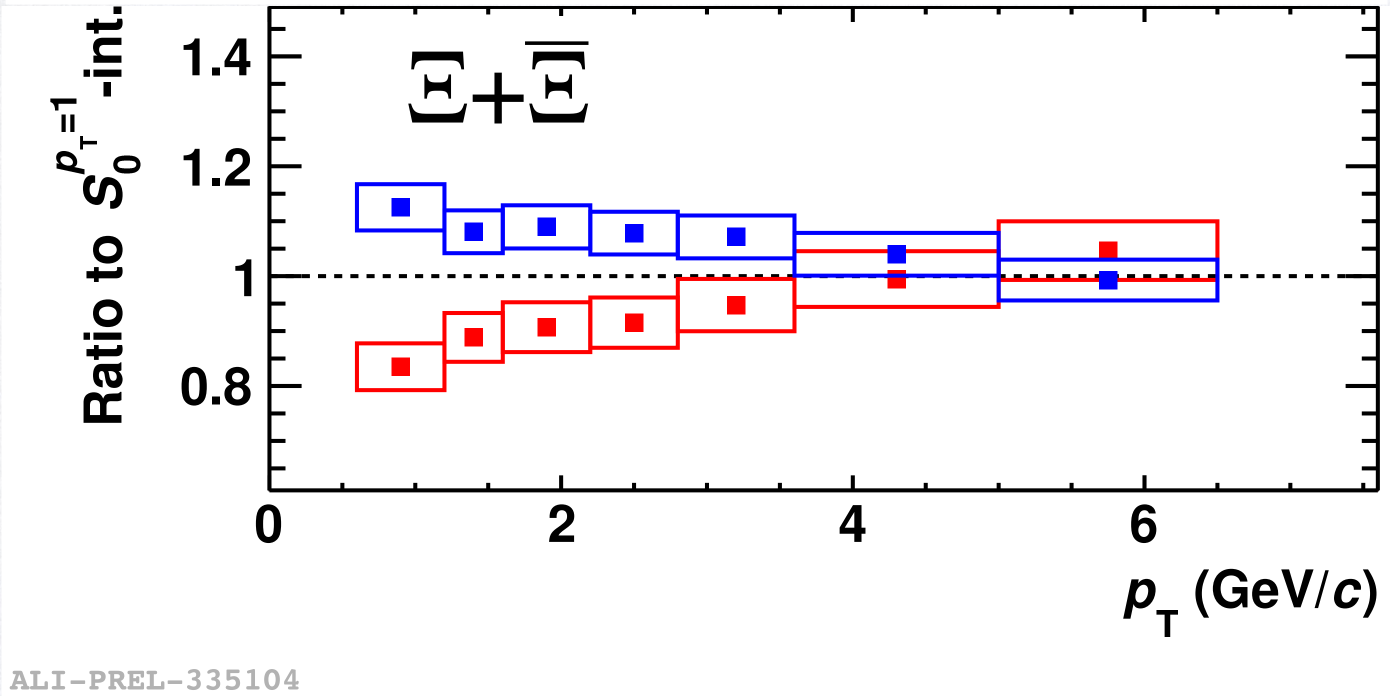
Identified particle production as a function of $S_0^{p_T=1}$ in pp collisions at 13 TeV

N_{SPD} mid-rapidity estimator









- For pions, kaons and protons, the particle production from jetty events dominates from a lower-p_T bin when compared to V0M estimator
- The ratios for Ξ appears to be converging to unity in the measured p_T range

Identified particle production as a function of $S_0^{p_T=1}$ in pp collisions at 13 TeV

N_{SPD} mid-rapidity estimator

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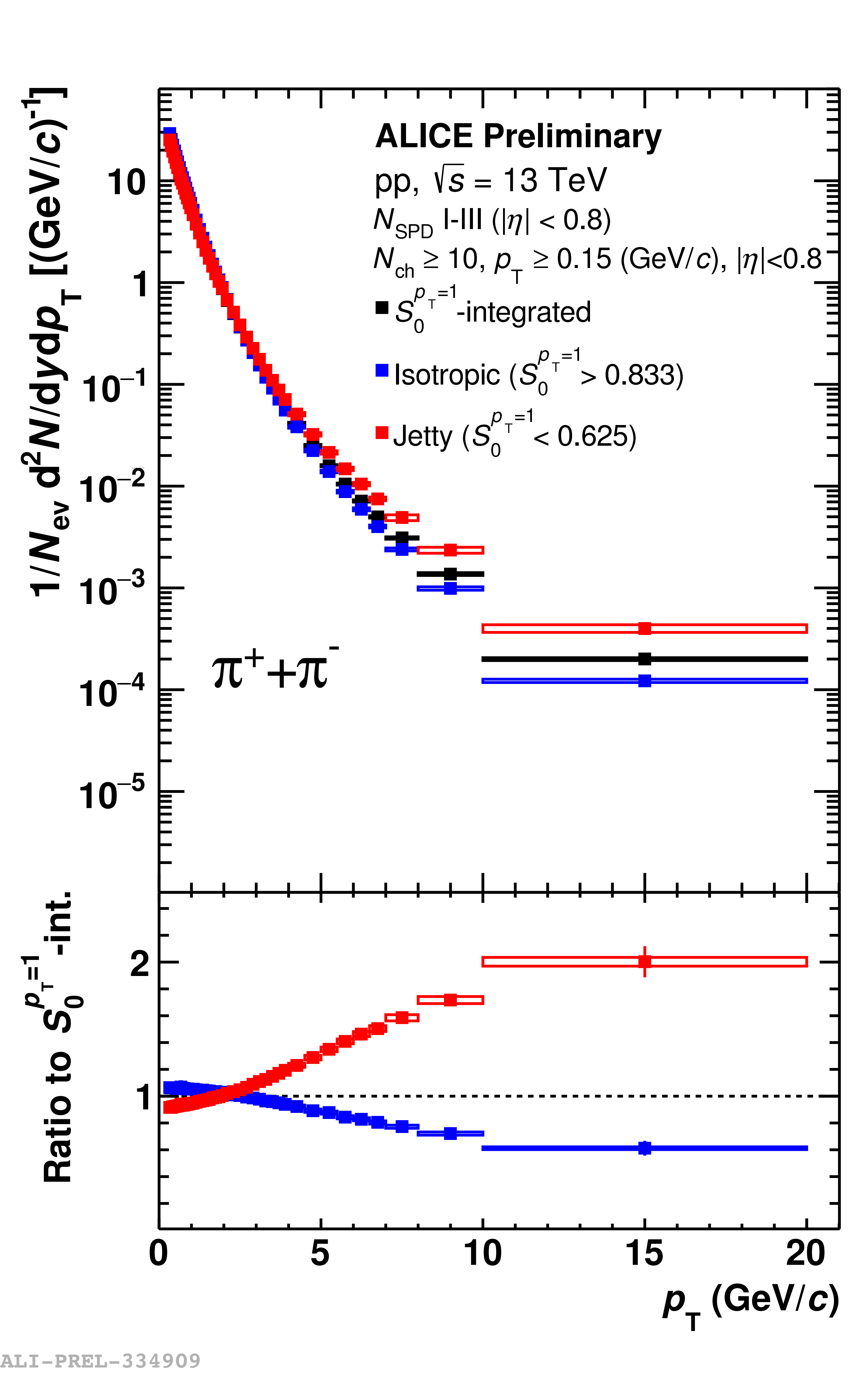

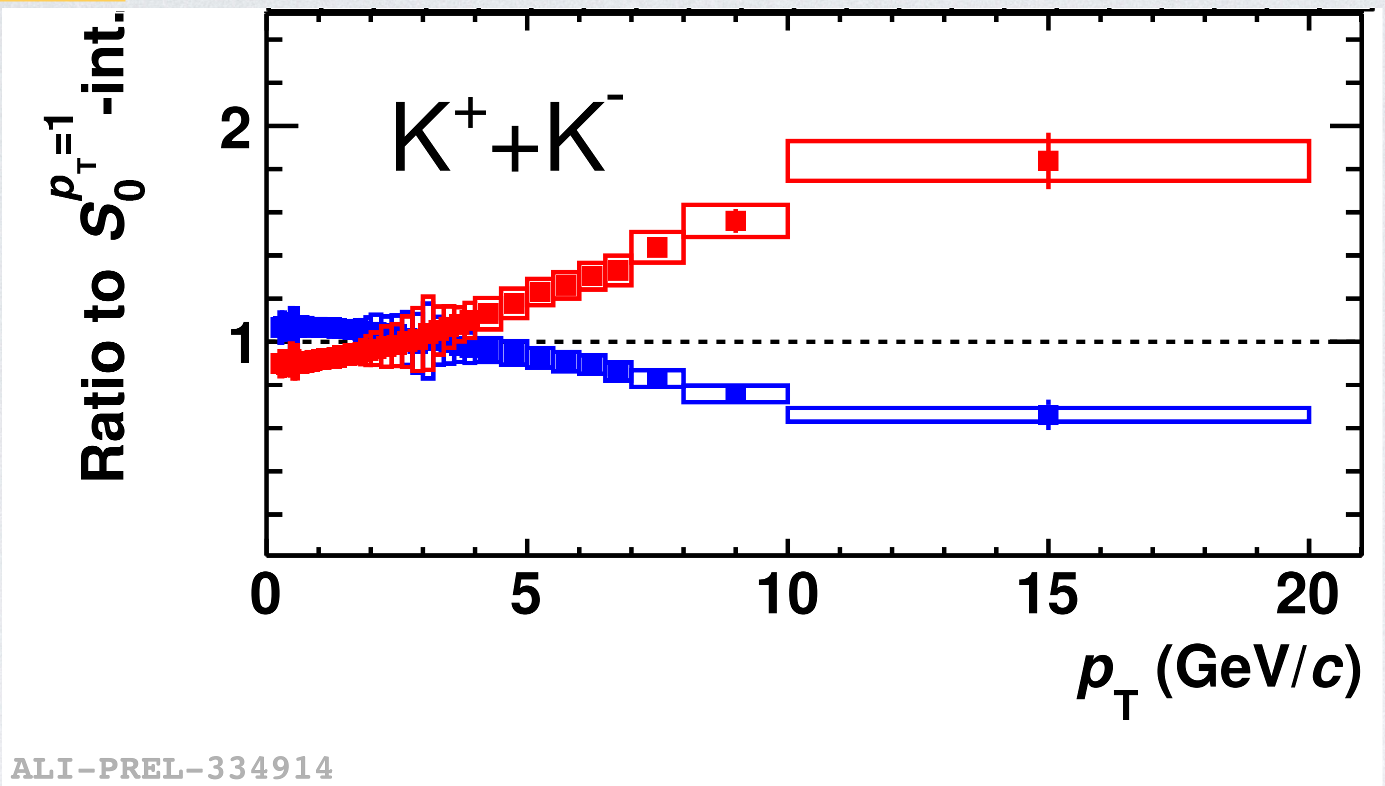

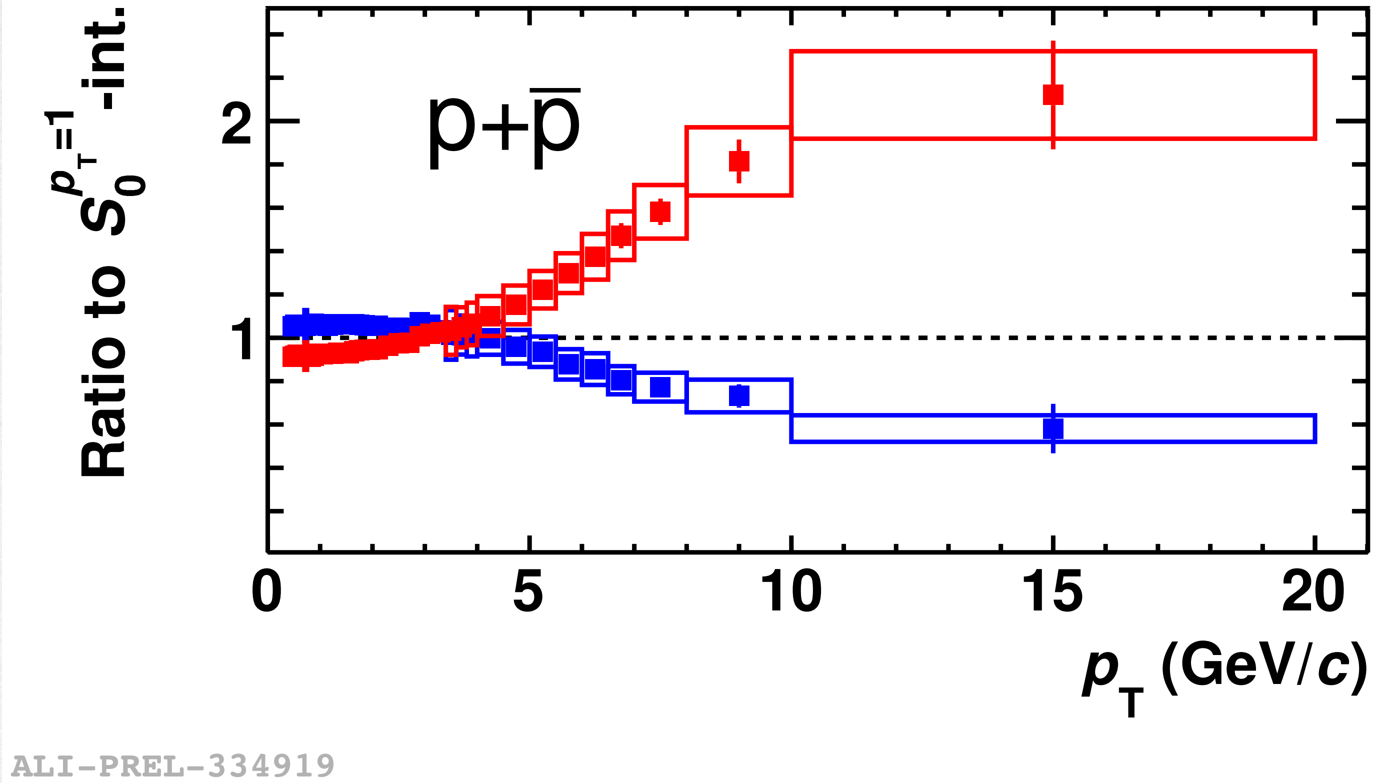

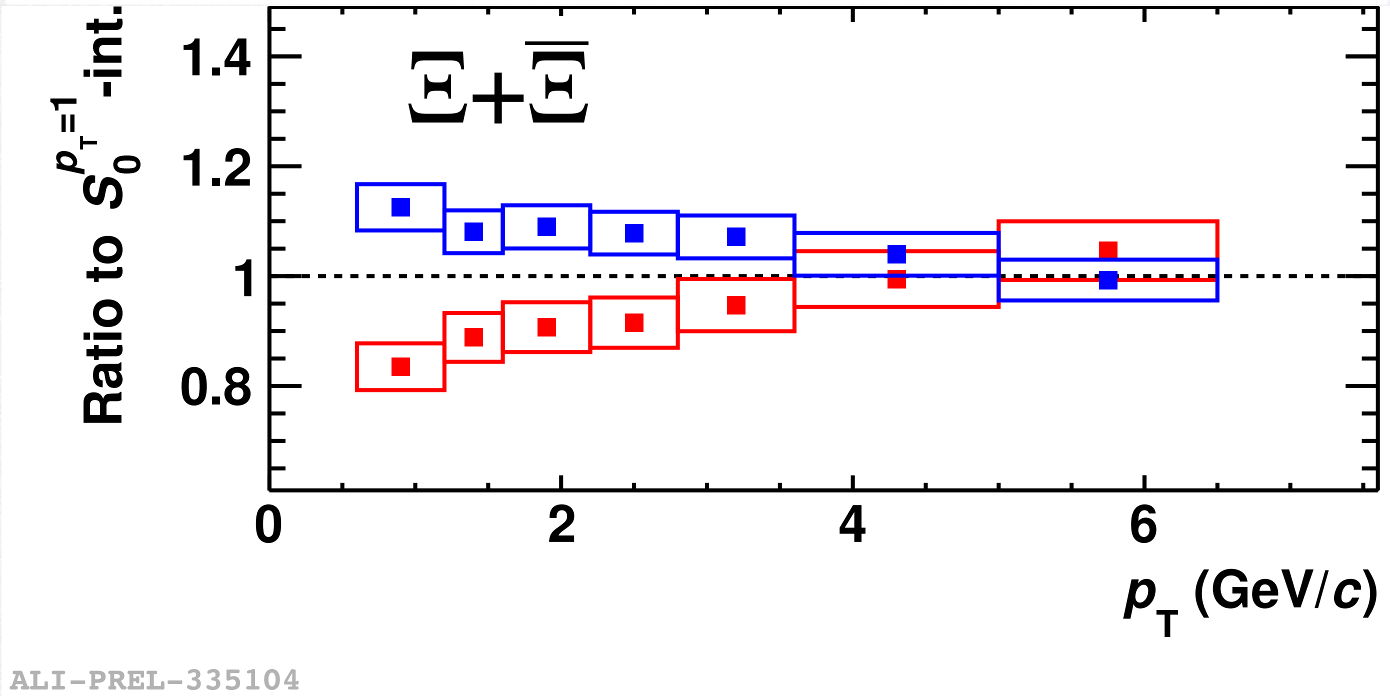

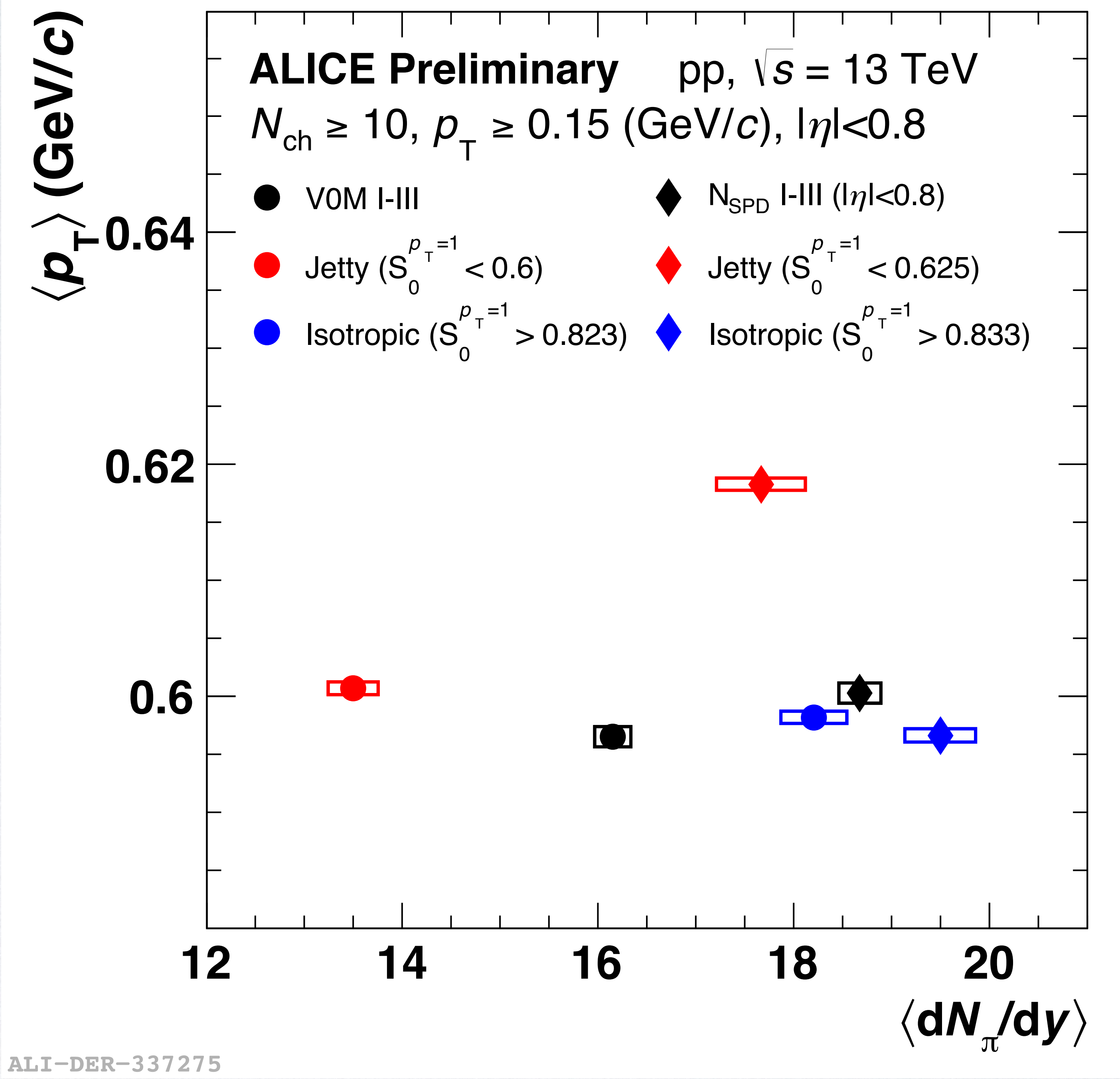

The V0M-triggered isotropic and jetty events have larger multiplicity difference while the N_{SPD}-triggered events disentangle soft and hard events more accurately in small multiplicity gap.

Identified particle ratios as a function of $S_0^{p_T=1}$ in pp collisions at 13 TeV

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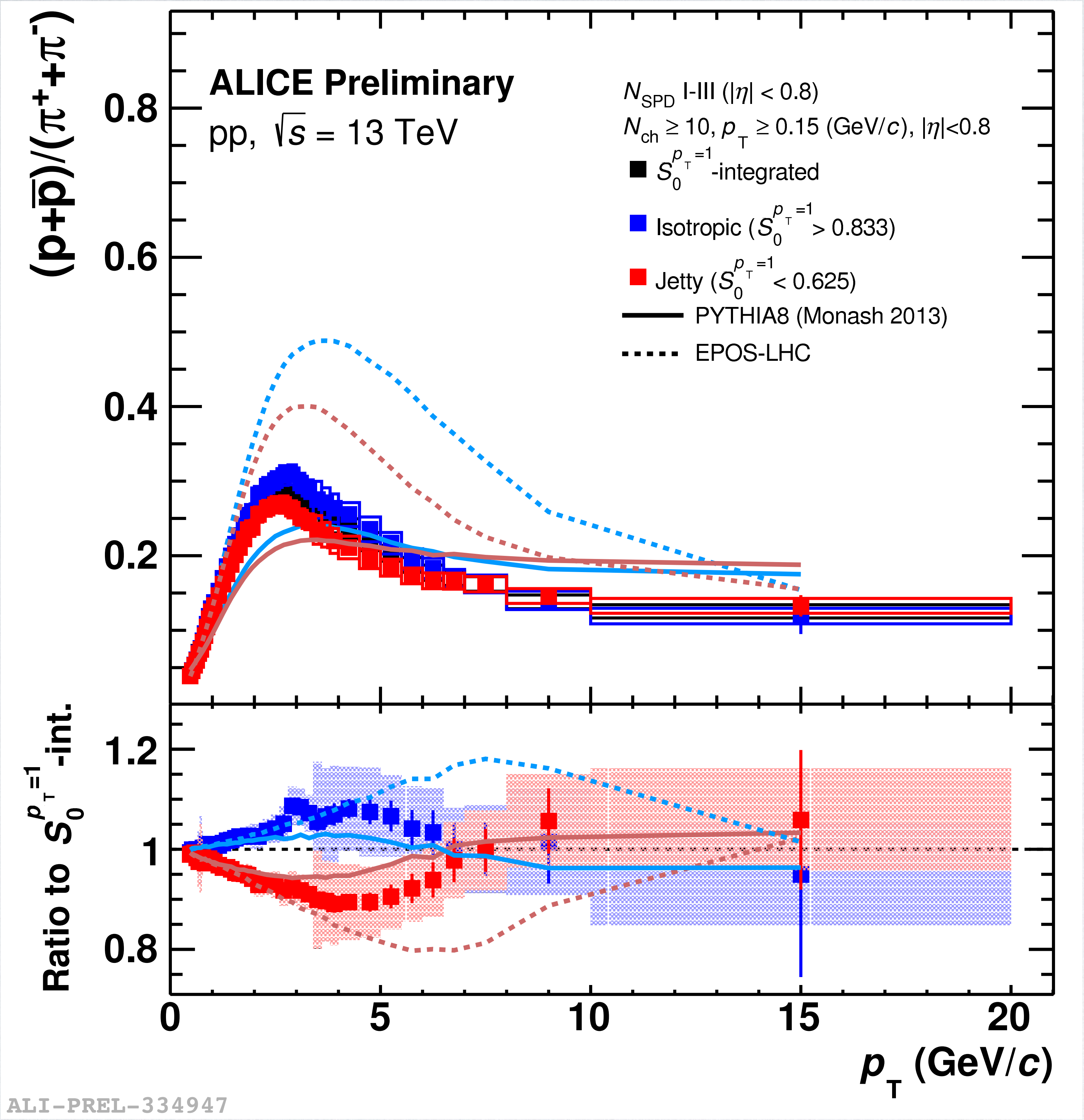
N_{SPD} (CL1) mid-rapidity estimator



- p/π ratio enhanced at intermediate p_T in isotropic events, reminiscent of similar effect in Pb-Pb collisions

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Identified particle ratios as a function of $S_0^{p_T=1}$ in pp collisions at 13 TeV

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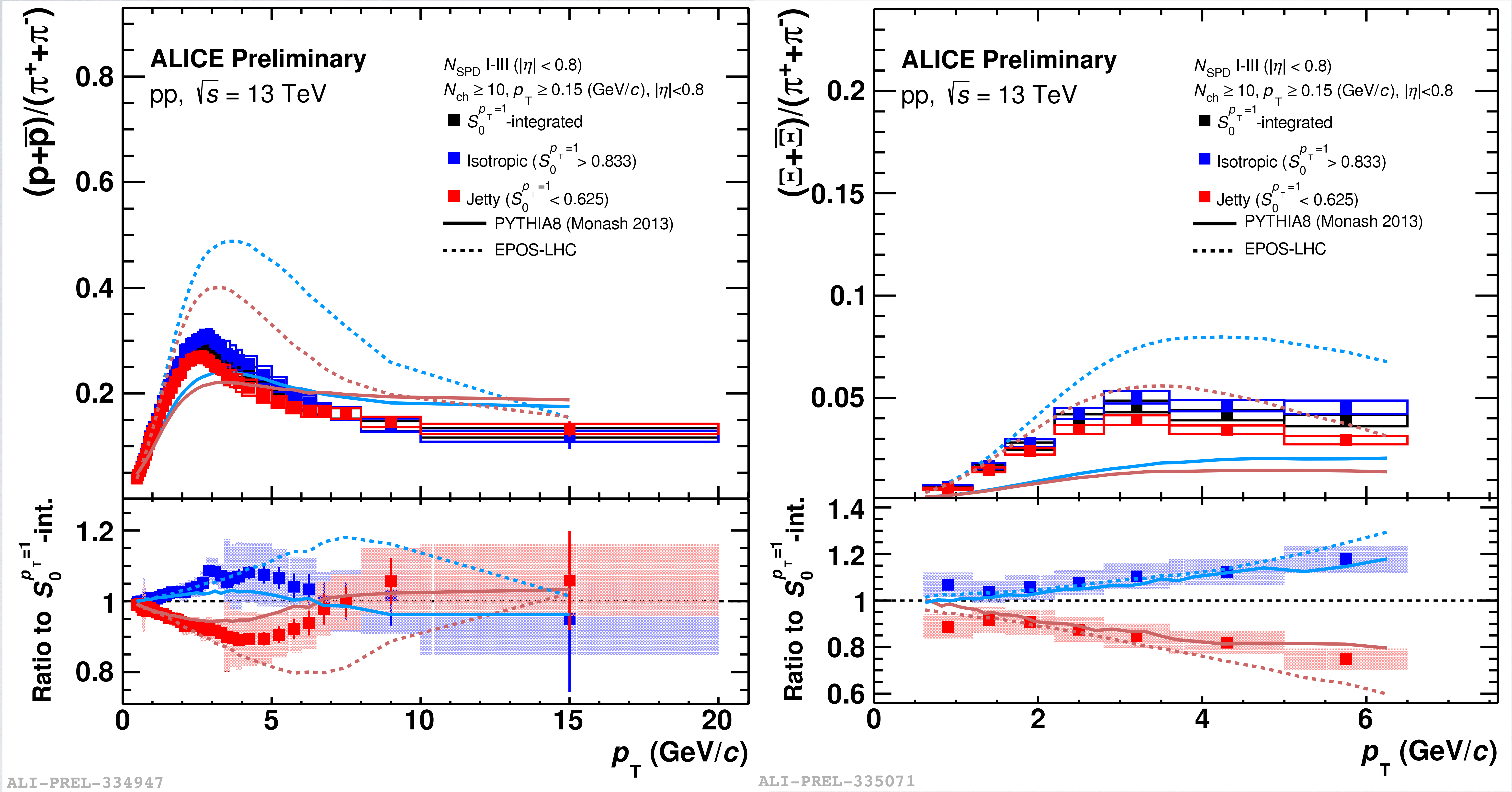

- p/π ratio enhanced at intermediate p_T in isotropic events, reminiscent of similar effect in Pb-Pb collisions

- Ξ/π ratio (notice the different p_T range!) suggests, the strange particle production is higher in isotropic compared to jetty events

Identified particle ratios as a function of $S_0^{p_T=1}$ in pp collisions at 13 TeV

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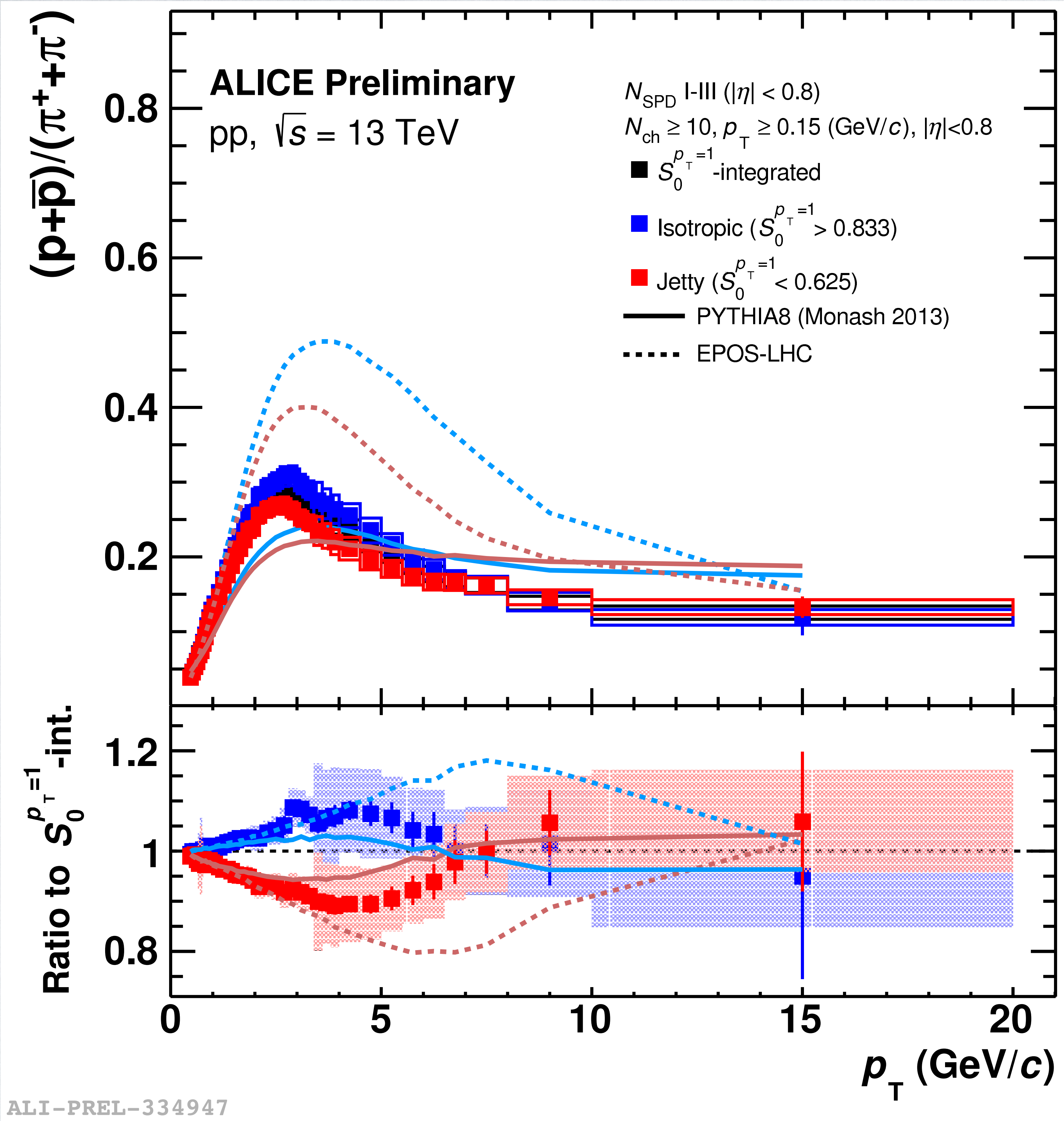
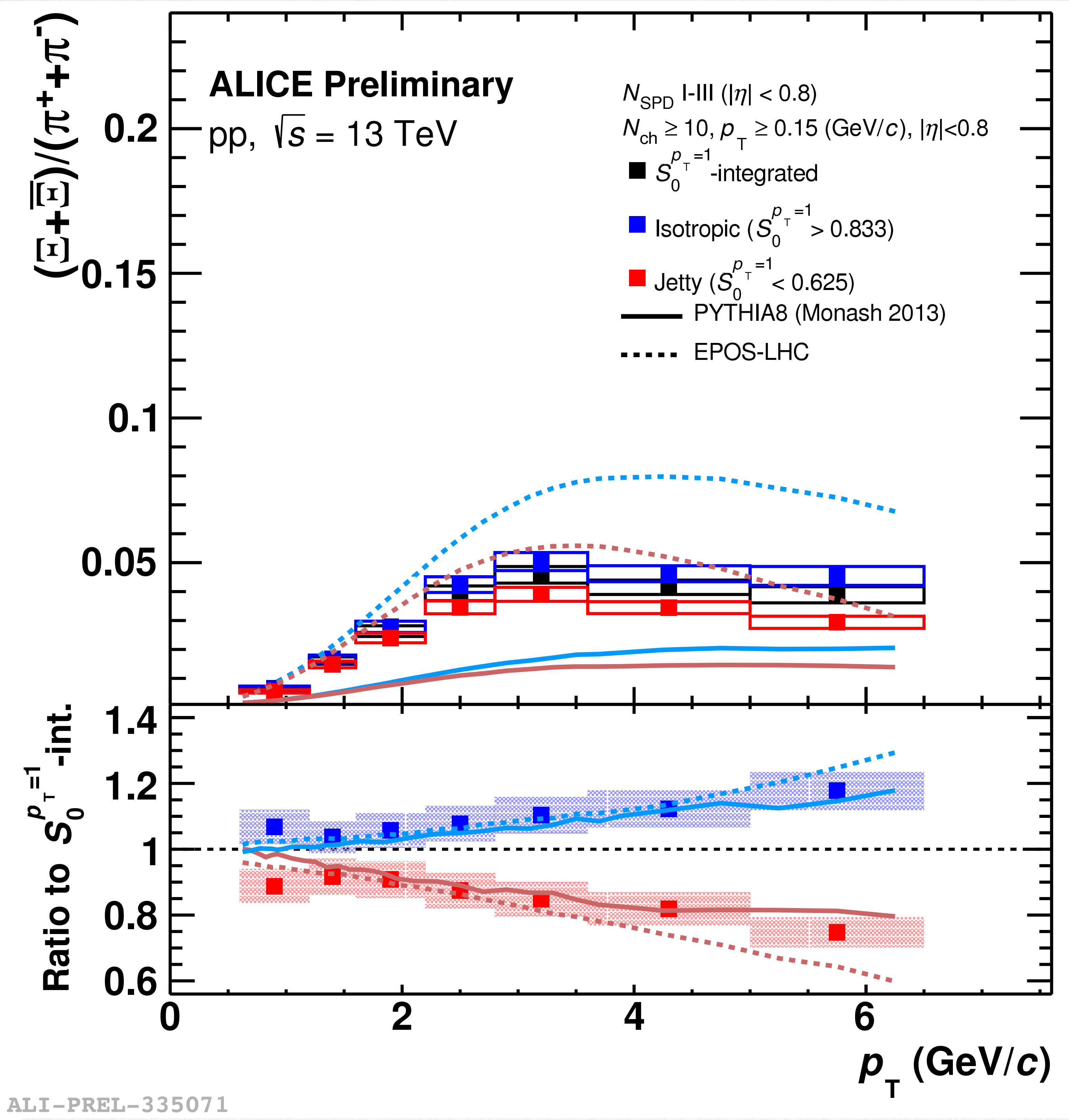
N_{SPD} (CL1) mid-rapidity estimator

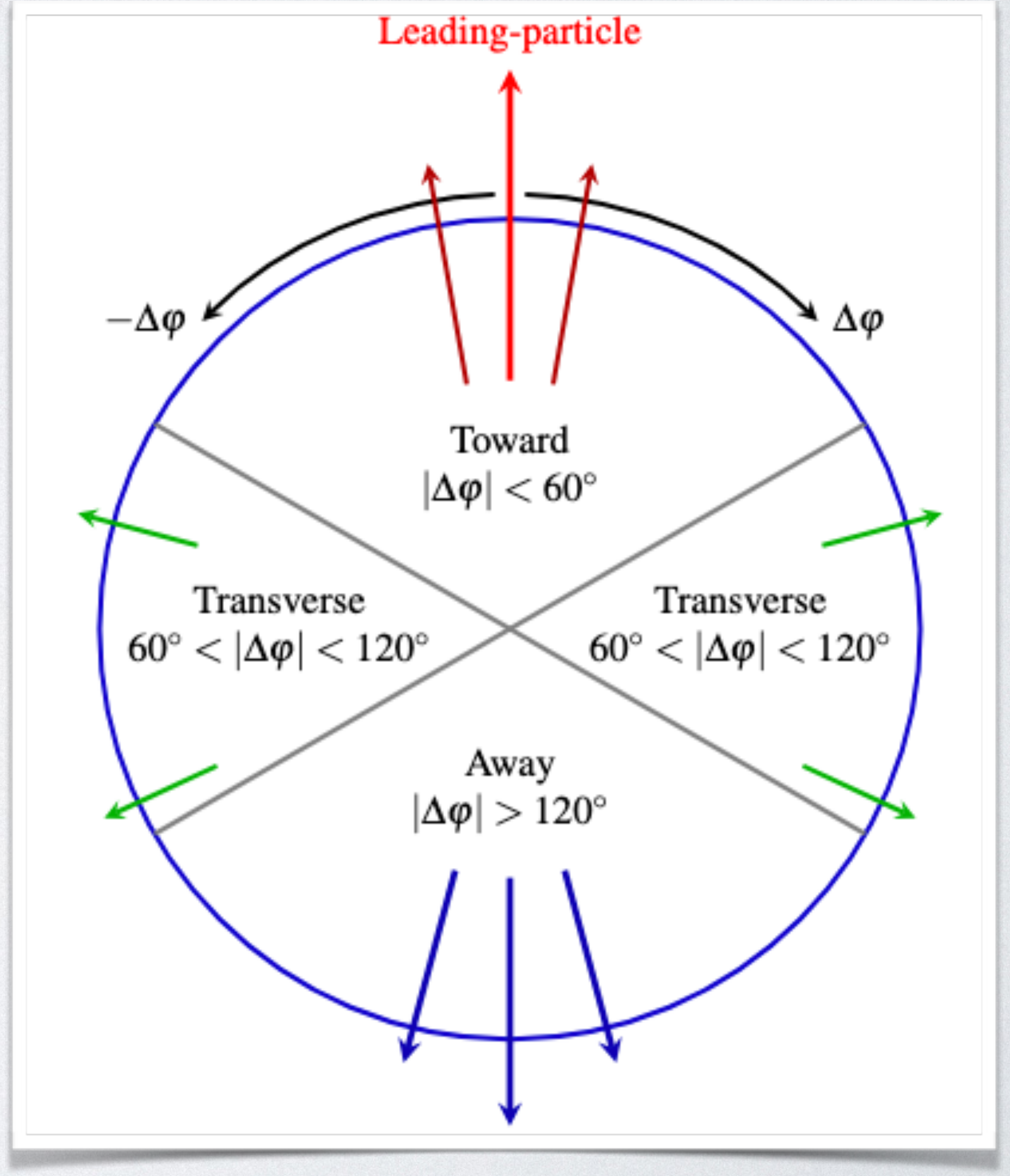




- p/π ratio enhanced at intermediate p_T in isotropic events, reminiscent of similar effect in Pb-Pb collisions
- Ξ/π ratio (notice the different p_T range!) suggests, the strange particle production is higher in isotropic compared to jetty events
- In general, the particle ratios are not described by PYTHIA8 and EPOS-LHC

- Pythia8 and EPOS-LHC seem to explain the trend of double ratios better
  - For p/π ratio in intermediate p_T range, PYTHIA8 is closer to unity compared to EPOS-LHC
  - For Ξ/π ratio, both the models have good agreement with the data except for the first p_T bin

System size dependence of charged particle production as a function of R_T: an attempt to unveil jet quenching in pp collisions



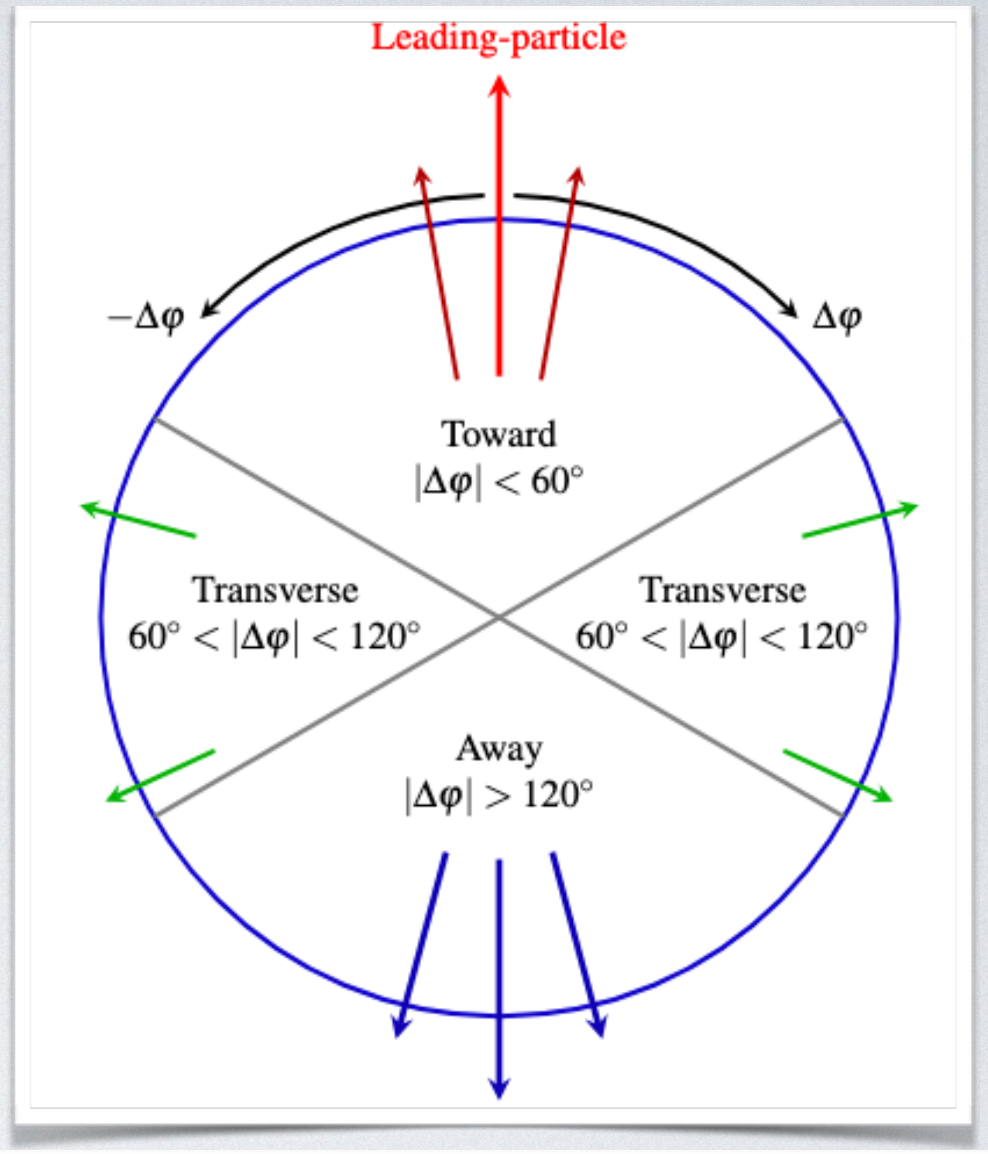
Event shape observables: Relative transverse activity classifier (R_T)

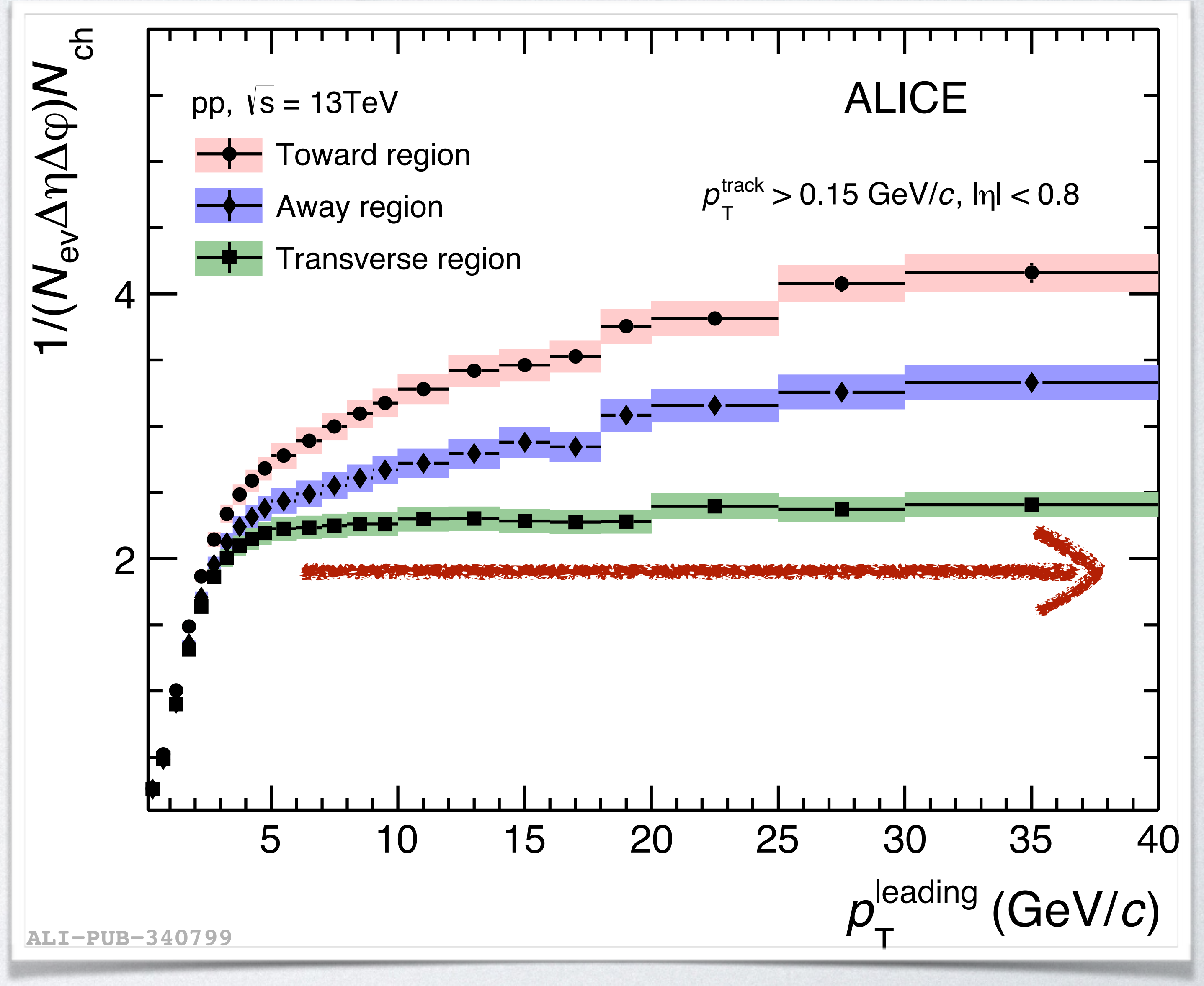
- $R_T = N_{ch}^{TS} / \langle N_{ch}^{TS} \rangle$, where N_{ch}^{TS} is the charged particle multiplicity in the transverse region.

- Using R_T, one can vary the magnitude of underlying events (UE) and study the particle production. $R_T \rightarrow 0$: Events with less UE (mostly dominated by jets).

- It is a useful tool to study:
  - Collective effects in events with low and high transverse activity
  - Events as a function of varying multi-partonic interactions (MPIs)
  - Auto-correlation effects

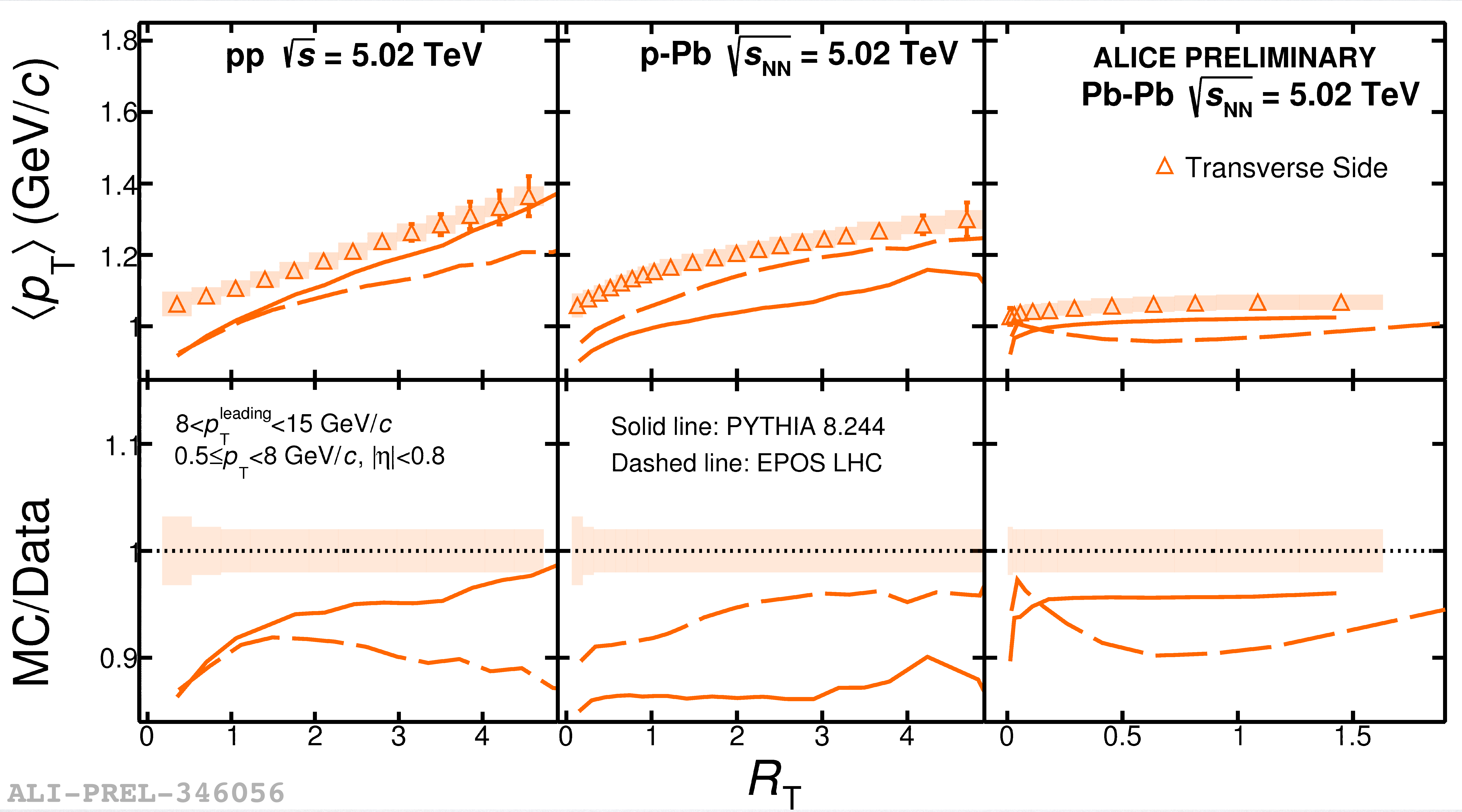
- A p_T cut for the leading particle is required to ensure a hard process: $8 < p_T^{leading} < 15$ GeV/c (this cut reduces the flow effects and the number density in transverse region remains nearly constant)





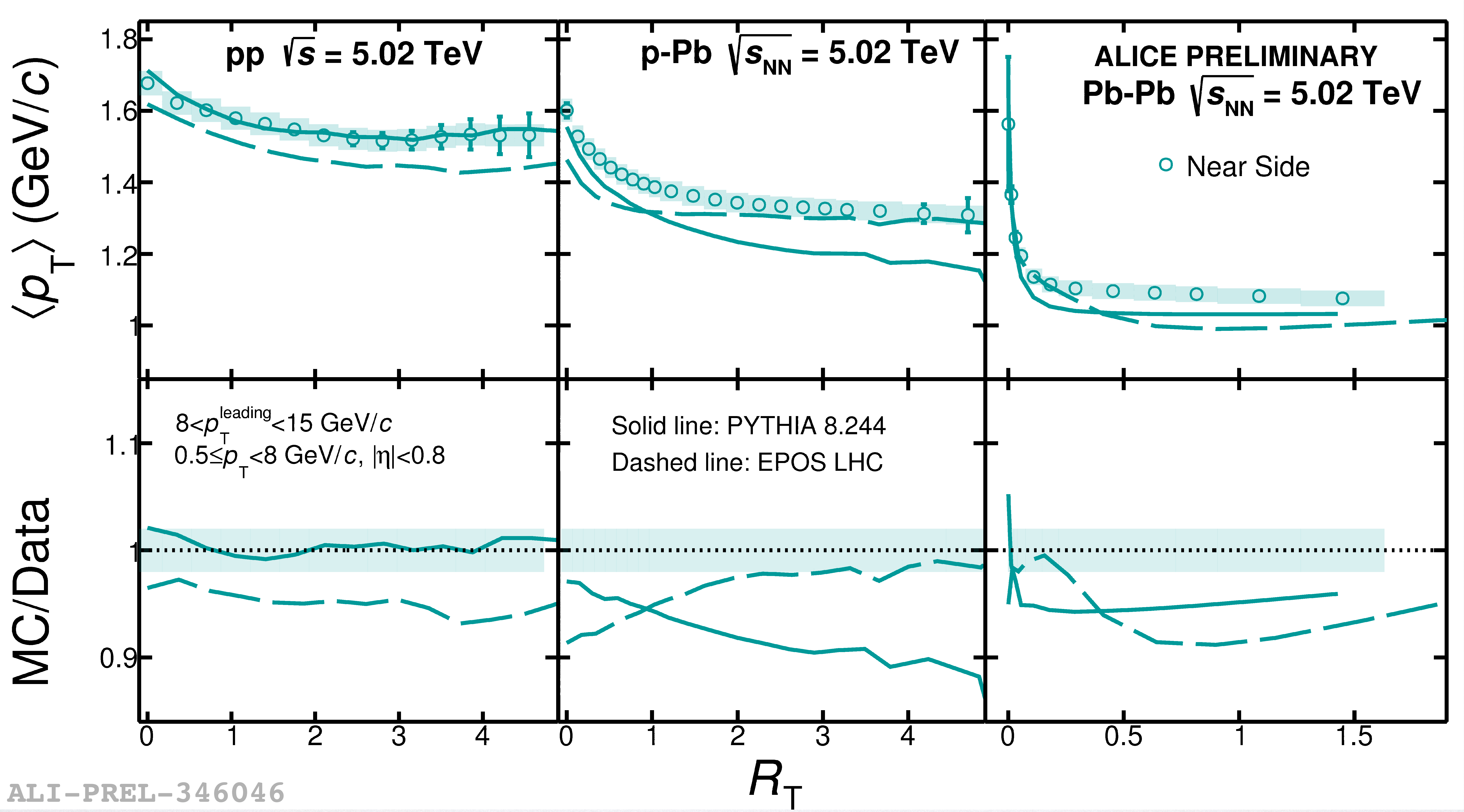
ALICE, JHEP04 (2020) 192

Mean transverse momentum



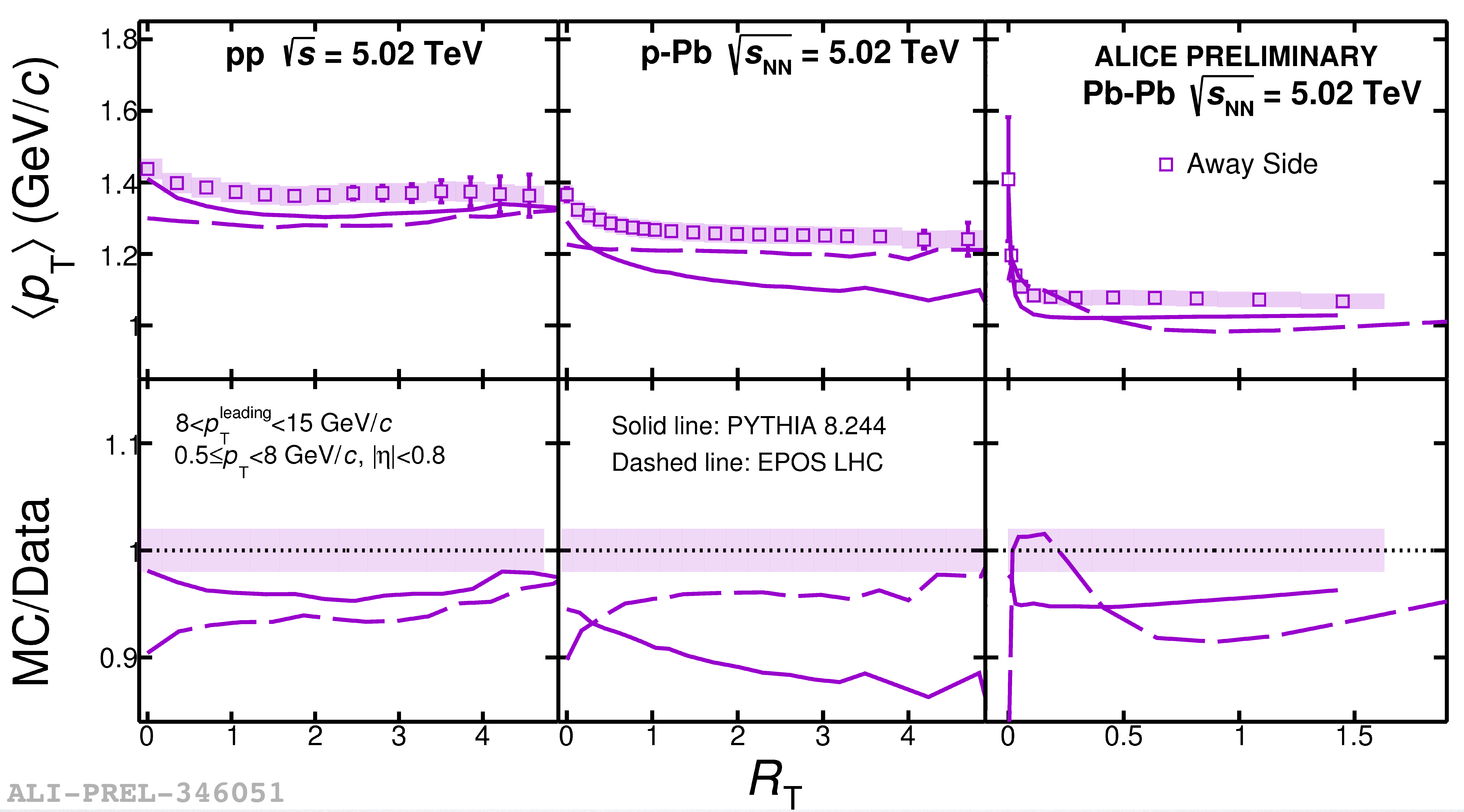
- $\langle p_T \rangle$ increases with increasing R_T.
- Models deviate 10-15 % from the data for the $\langle p_T \rangle$ across different collision systems.

Mean transverse momentum



- Slight decrease at low R_T and remains nearly flat afterwards.
- Models deviate 10-15 % from the data for the $\langle p_T \rangle$ across different collision systems.

Mean transverse momentum



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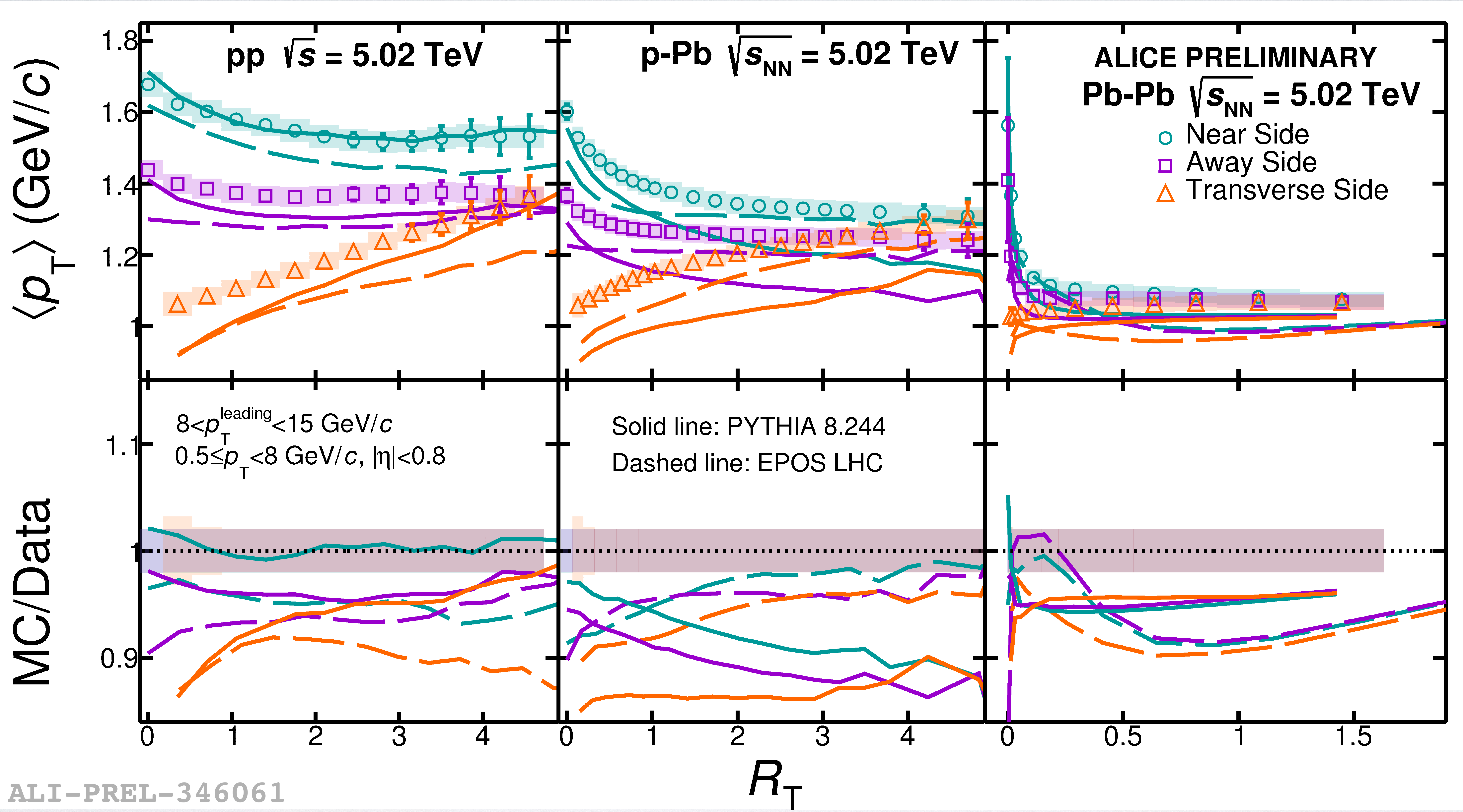
Mean transverse momentum



- The contribution from the near and away side jet dominates at low-R_T and the values are similar for all systems as one would naively expect for R_T -> 0
- For large R_T, the $<p_T>$ approach to a similar value in all three topological regions for a given system

Search for jet quenching effects in small collision systems

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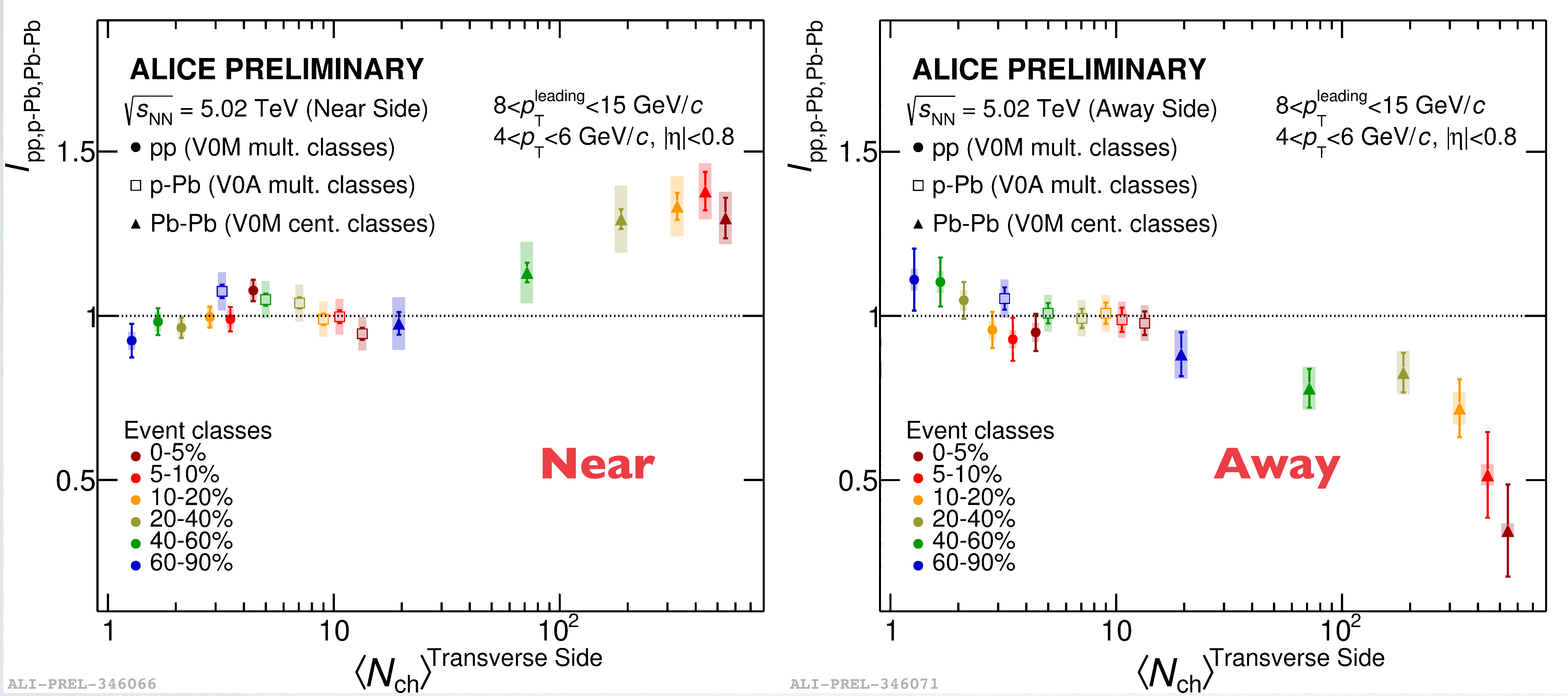
$$I_{\mathrm{pp,p-Pb,Pb-Pb}} = \frac{Y^{\mathrm{pp,p-Pb,Pb-Pb}} - Y_{\mathrm{TS}}^{\mathrm{pp,p-Pb,Pb-Pb}}}{Y^{\mathrm{pp\ min.bias}} - Y_{\mathrm{TS}}^{\mathrm{pp\ min.bias}}}$$

, Y is the yield in different topological regions



- $I_{\mathrm{pp,p-Pb,Pb-Pb}}$ is sensitive to medium effects. The suppression in away side would indicate the presence of jet quenching.
- Compatible with the ALICE I_{AA} results at Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV (ALICE, Phys. Rev. Lett. **108** (2012) 092301).

Note that for these results there is no direct selection on N_{ch}^{TS} cut. Instead, N_{ch}^{TS} is varied by selecting on the forward multiplicity.

Search for jet quenching effects in small collision systems

$$I_{\mathrm{pp,p-Pb,Pb-Pb}} = \frac{Y^{\mathrm{pp,p-Pb,Pb-Pb}} - Y^{\mathrm{pp,p-Pb,Pb-Pb}}_{\mathrm{TS}}}{Y^{\mathrm{pp\ min.bias}} - Y^{\mathrm{pp\ min.bias}}_{\mathrm{TS}}}$$

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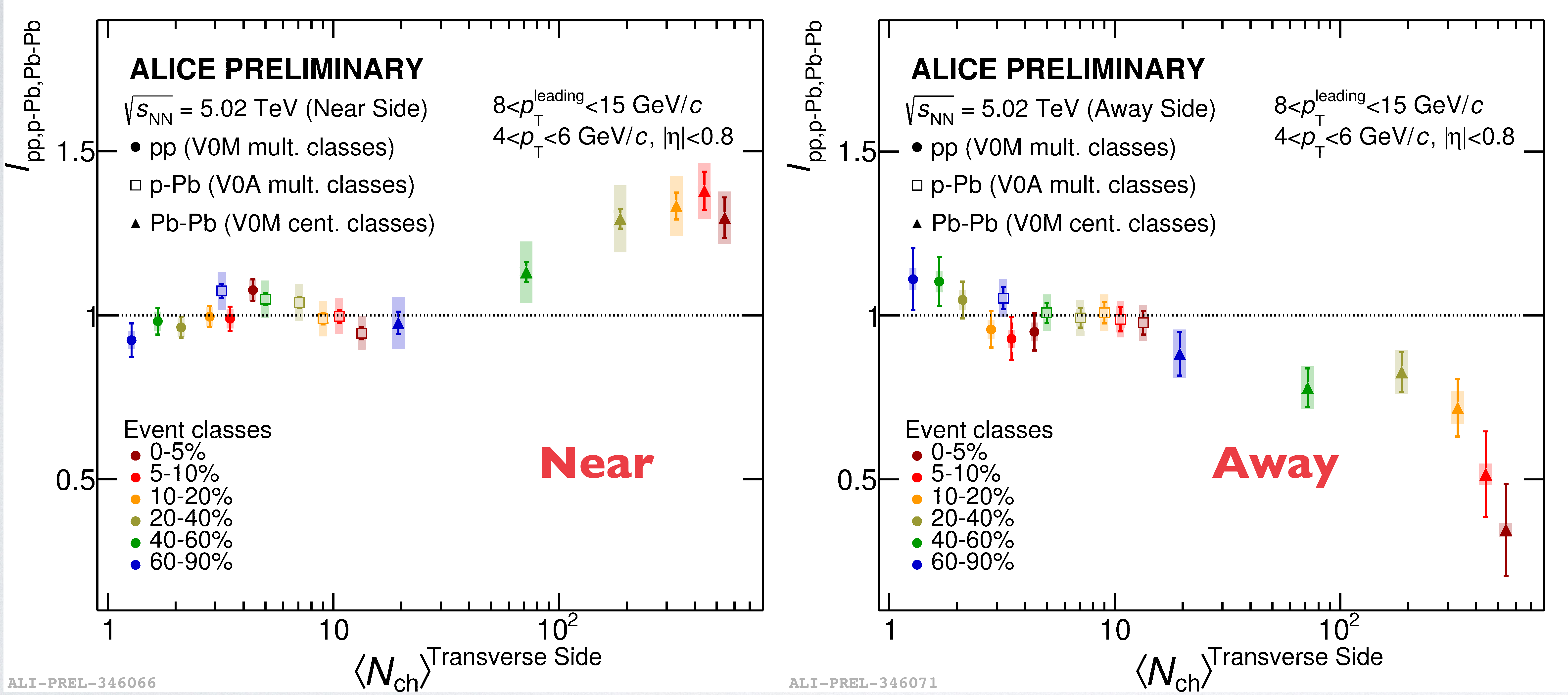

- $I_{\mathrm{pp,p\text{-}Pb,Pb\text{-}Pb}}$ is sensitive to medium effects. The suppression in away side would indicate the presence of jet quenching.
- Compatible with the ALICE I_{AA} results at Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV (ALICE, Phys. Rev. Lett. **108** (2012) 092301).

In contrast to Pb-Pb collisions, no enhancement (suppression) of $I_{\mathrm{pp,p\text{-}Pb,Pb\text{-}Pb}}$ is seen for NS (AS) in pp and p-Pb collisions. Based on these results, no hint of jet quenching in small systems is observed in the measured $\langle N_{ch}^{TS} \rangle$ range.

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Summary

- Using event shape observables like the Transverse spherocity and the Relative transverse activity classifier, one can vary the magnitude of the underlying event.
  - Clear dependence of light flavor particle production is observed as a function of event shape observables.

- System size dependence study of $\langle p_T \rangle$ suggests that the contribution of jets dominates in low-R_T while the $\langle p_T \rangle$ approach to a similar value for all topological regions.

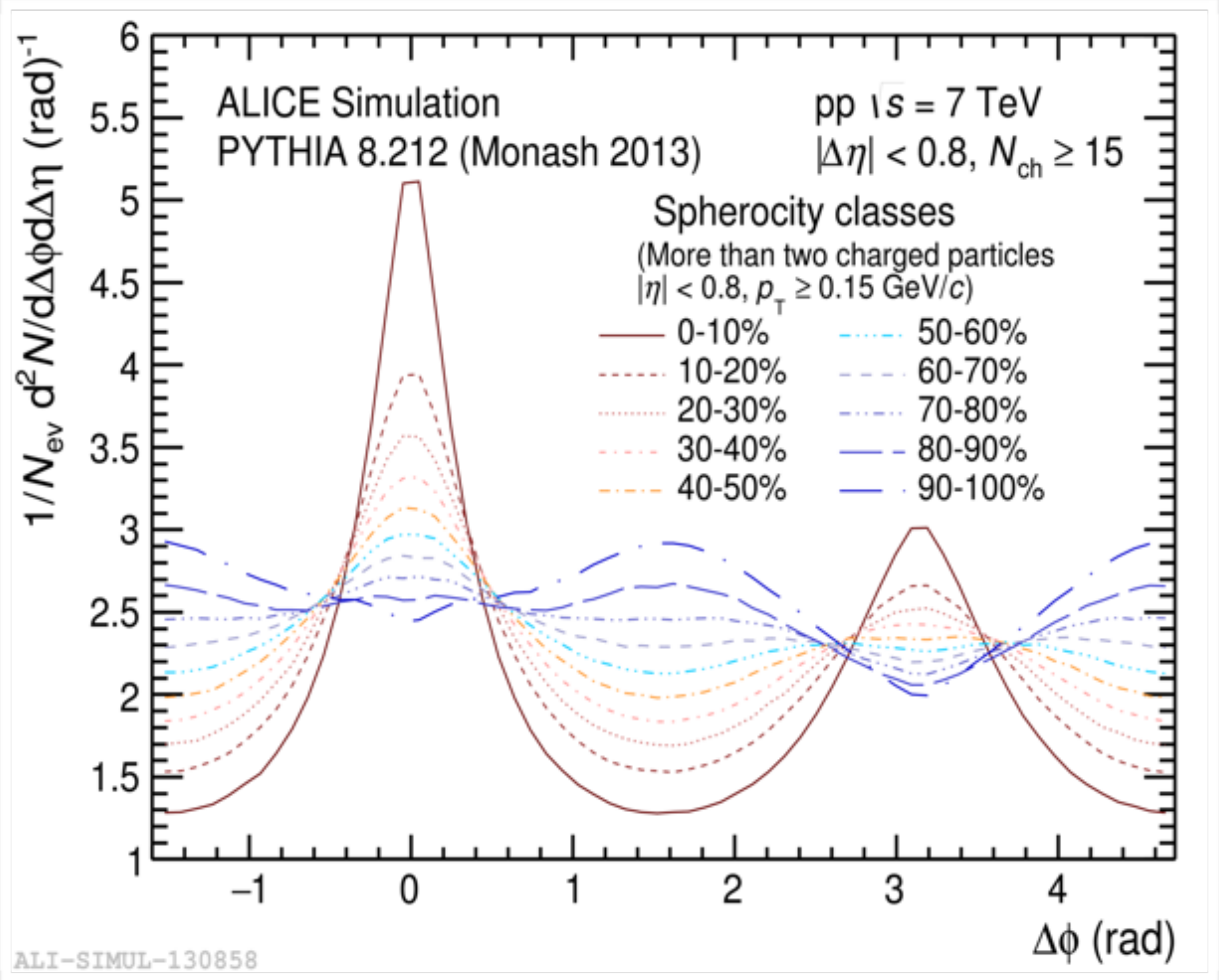
- In contrast to Pb-Pb collisions, no enhancement (suppression) of $I_{pp,p\text{-}Pb}$ is seen for Near (Away) side in pp and p-Pb collisions. Based on these results, no hint of jet quenching in small systems is observed in the measured $\langle N_{ch}^{TS} \rangle$ range.

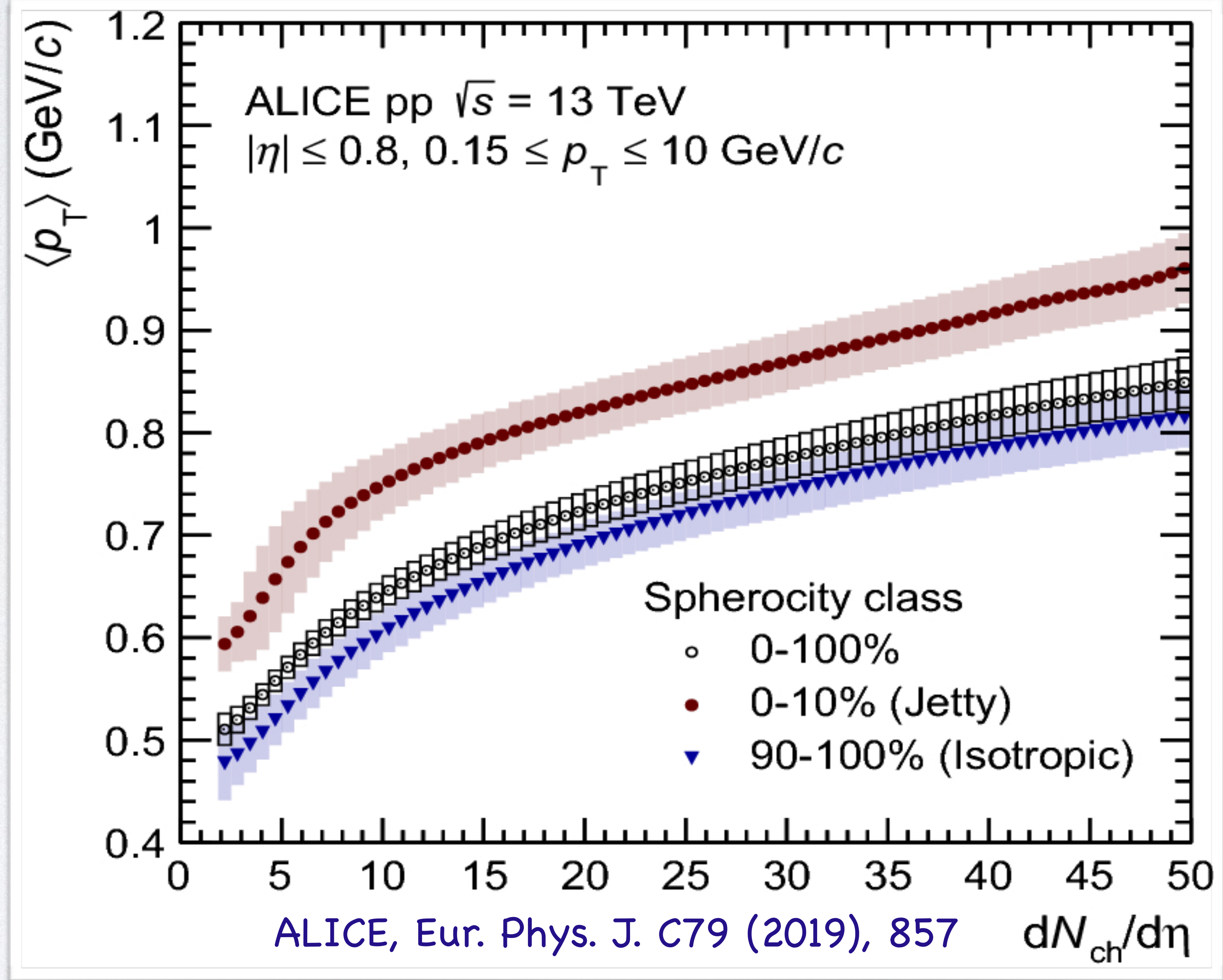
Thank you for your attention!

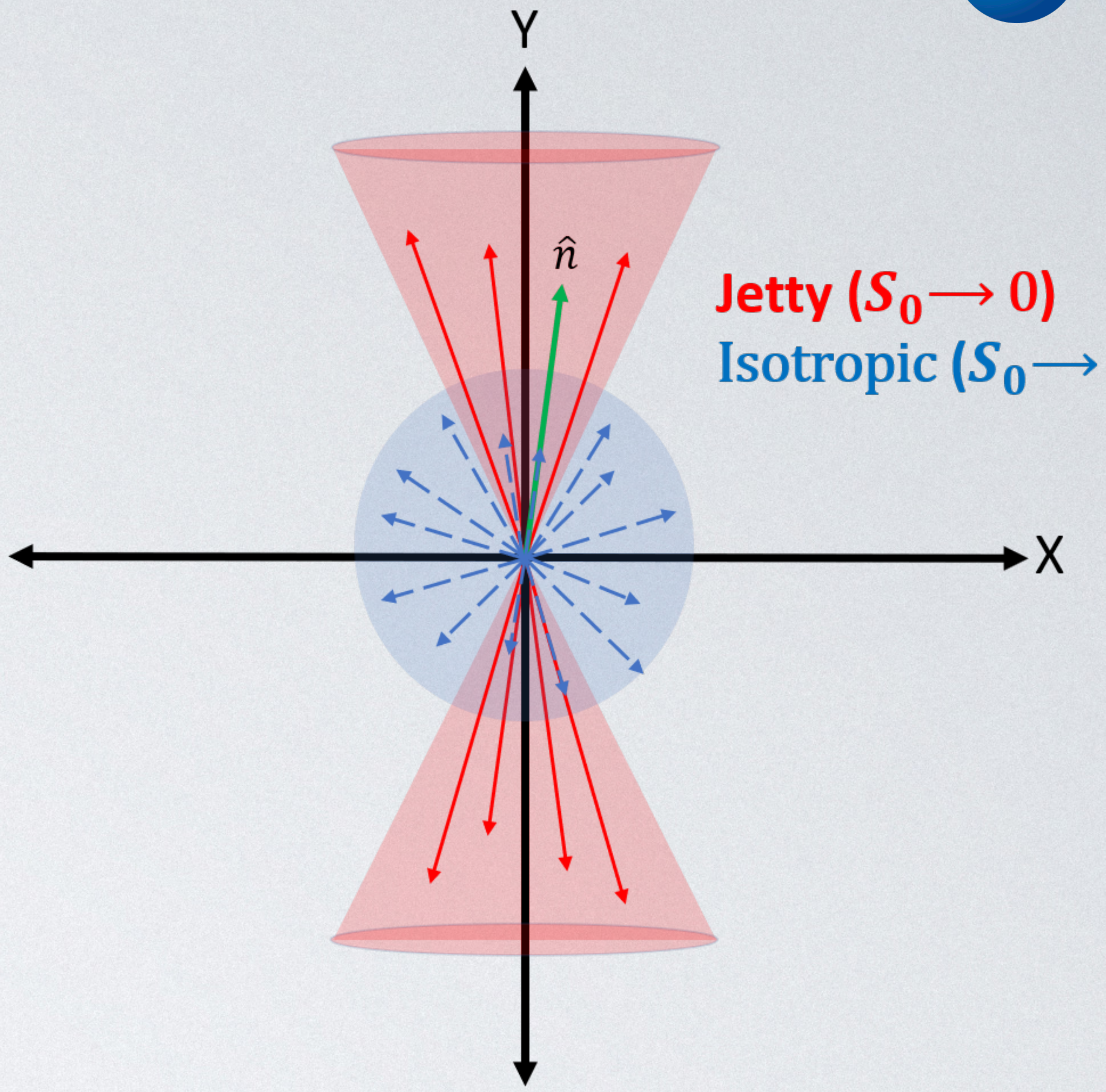
Back-up

Event shape observables: Transverse Spherocity

- Transverse Spherocity discriminates between hard and soft processes.
  - Jetty: Back-to-back structure, indication of hard QCD ($S_0 \rightarrow 0$)
  - Isotropic: enhances underlying events, soft QCD ($S_0 \rightarrow 1$)







$$S_0 = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i |\overrightarrow{p_{Ti}} \times \hat{n}|}{\Sigma_i p_{Ti}} \right)^2$$

↓

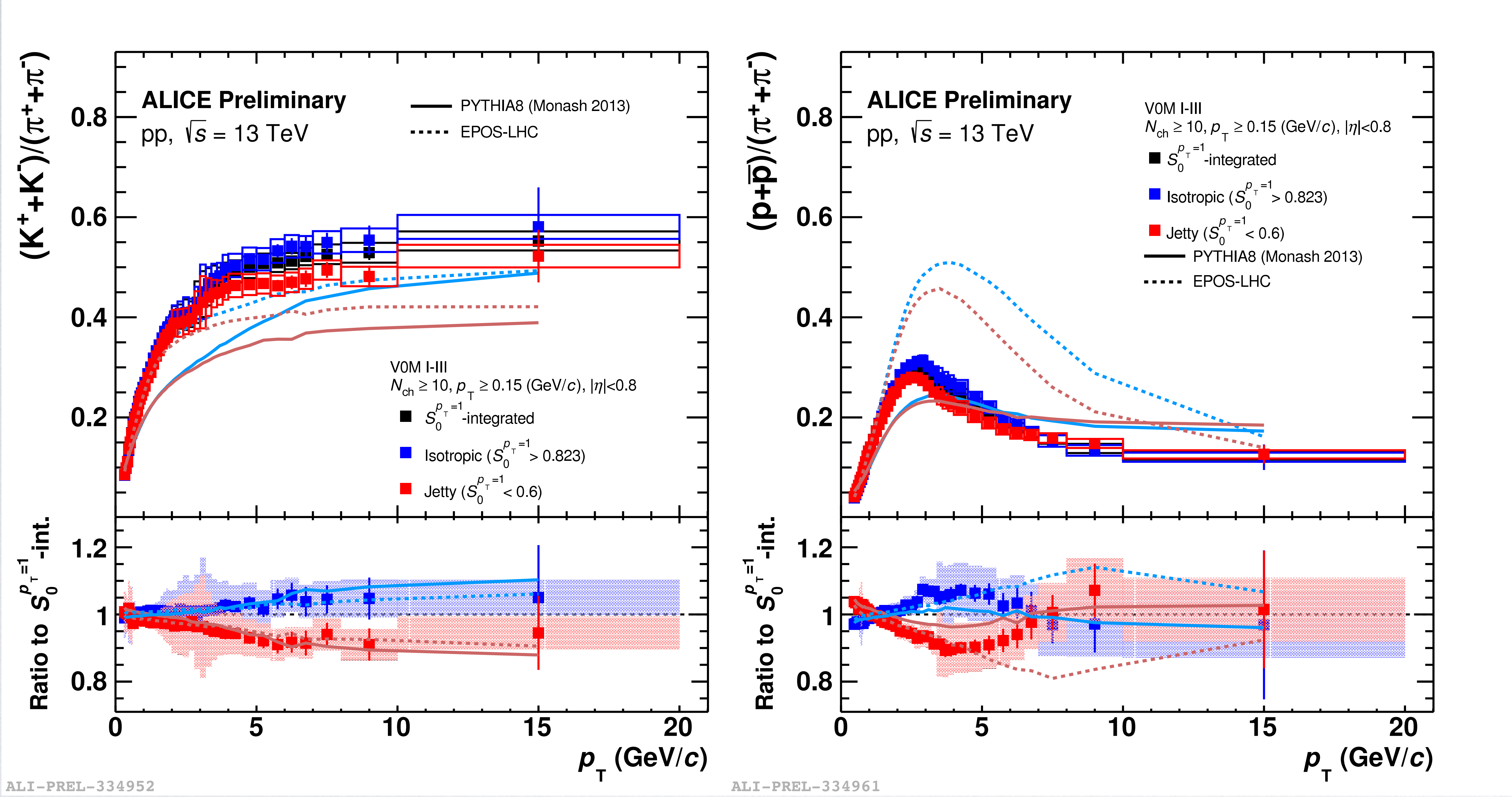
$$S_0^{p_T=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i |\hat{p_{Ti}} \times \hat{n}|}{N_{trk}} \right)^2$$

Unweighted transverse spherocity
(Only the angular component is considered)

- Selecting events based on S_0 affects neutral and charged hadrons differently.
- To study the neutral particles such as K_S^0, ϕ, Λ etc., the S_0 estimator had to be modified

Identified particle ratios as a function of $S_0^{p_{\mathrm{T}}=1}$ in high-multiplicity pp collisions at 13 TeV

V0M estimator



- K/π and p/π ratios: the ratios to $S_0^{p_{\mathrm{T}}=1}$-integrated events highlight the radial flow-like features.

In general, the particle ratios are not described by the models like PYTHIA8 and EPOS-LHC. However, they seem to explain the double ratios better.

Identified particle ratios as a function of $S_0^{p_T=1}$ in high-multiplicity pp collisions at 13 TeV

ALICE

VOM estimator

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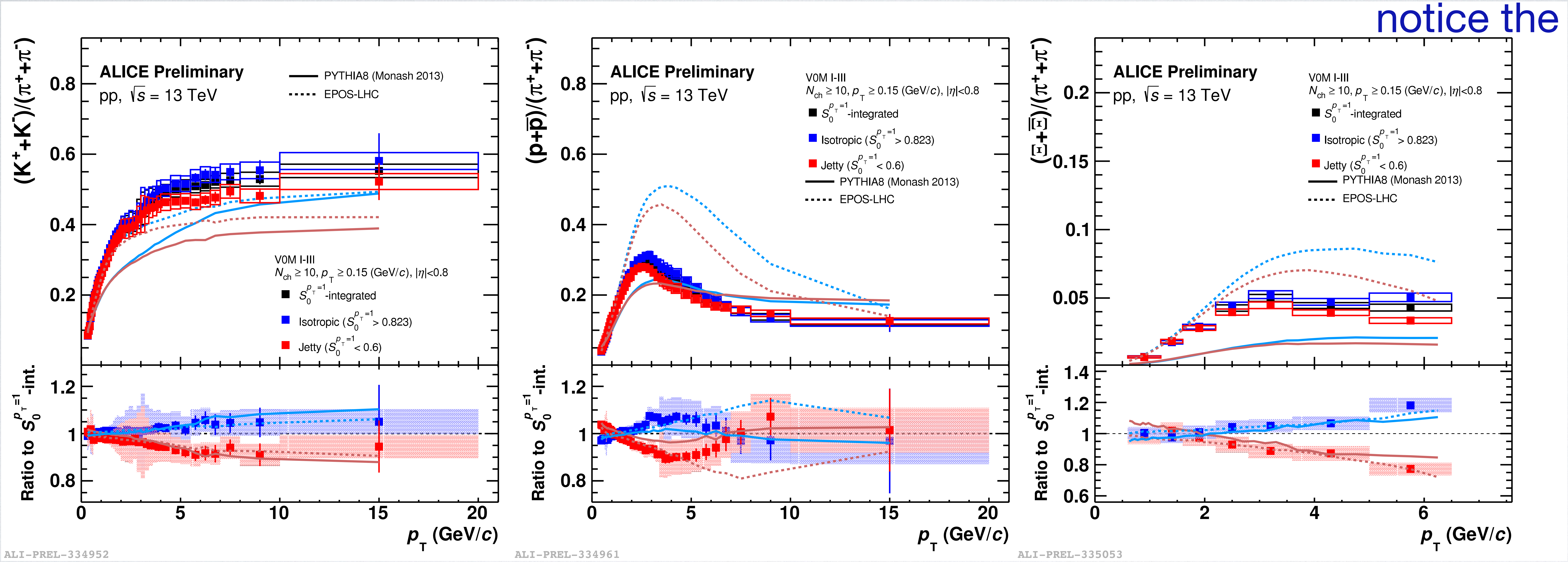
notice the change in p_T range!



- K/π and p/π ratios: the ratios to $S_0^{p_T=1}$-integrated events highlight the radial flow-like features.
- Ξ/π ratio: show a crossing point in the double ratio.

In general, the particle ratios are not described by the models like PYTHIA8 and EPOS-LHC. However, they seem to explain the double ratios better.

Identified particle ratios as a function of $S_0^{p_T=1}$ in high-multiplicity pp collisions at 13 TeV

VOM estimator

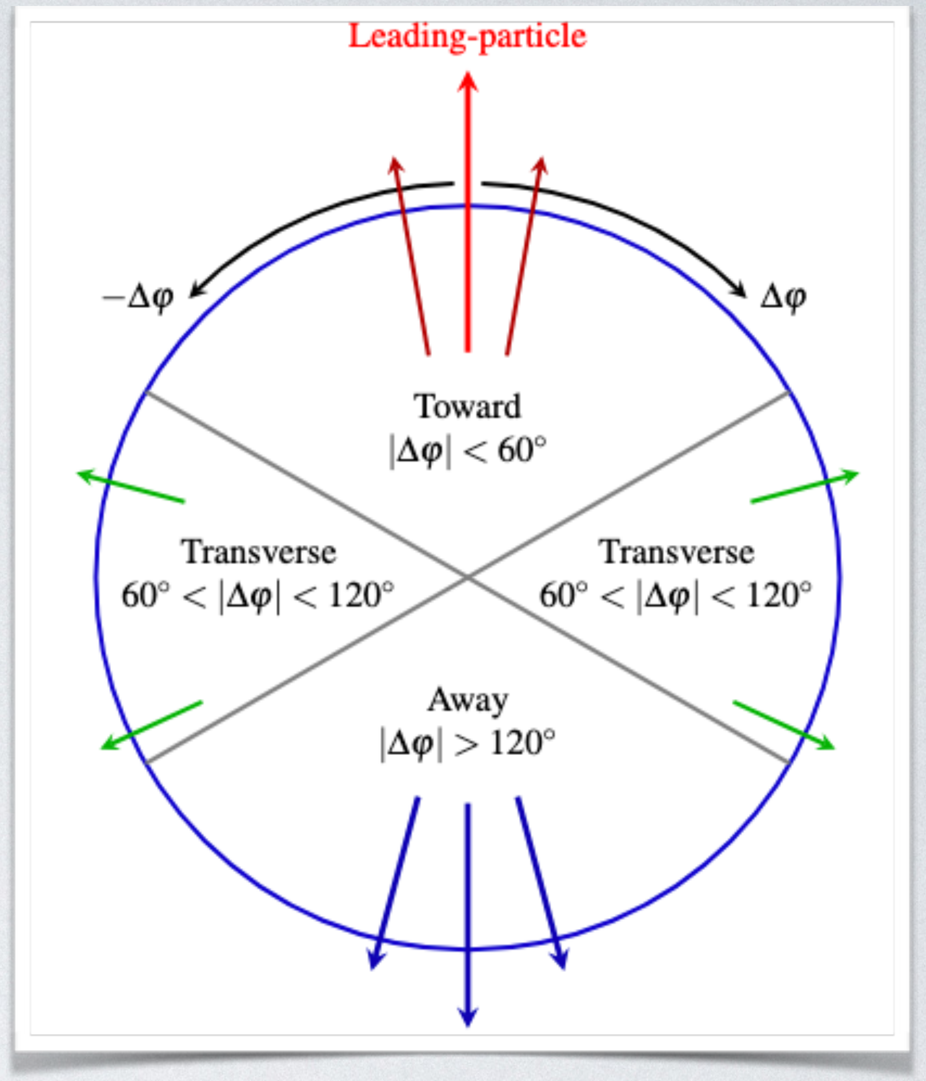
notice the change in p_T range!

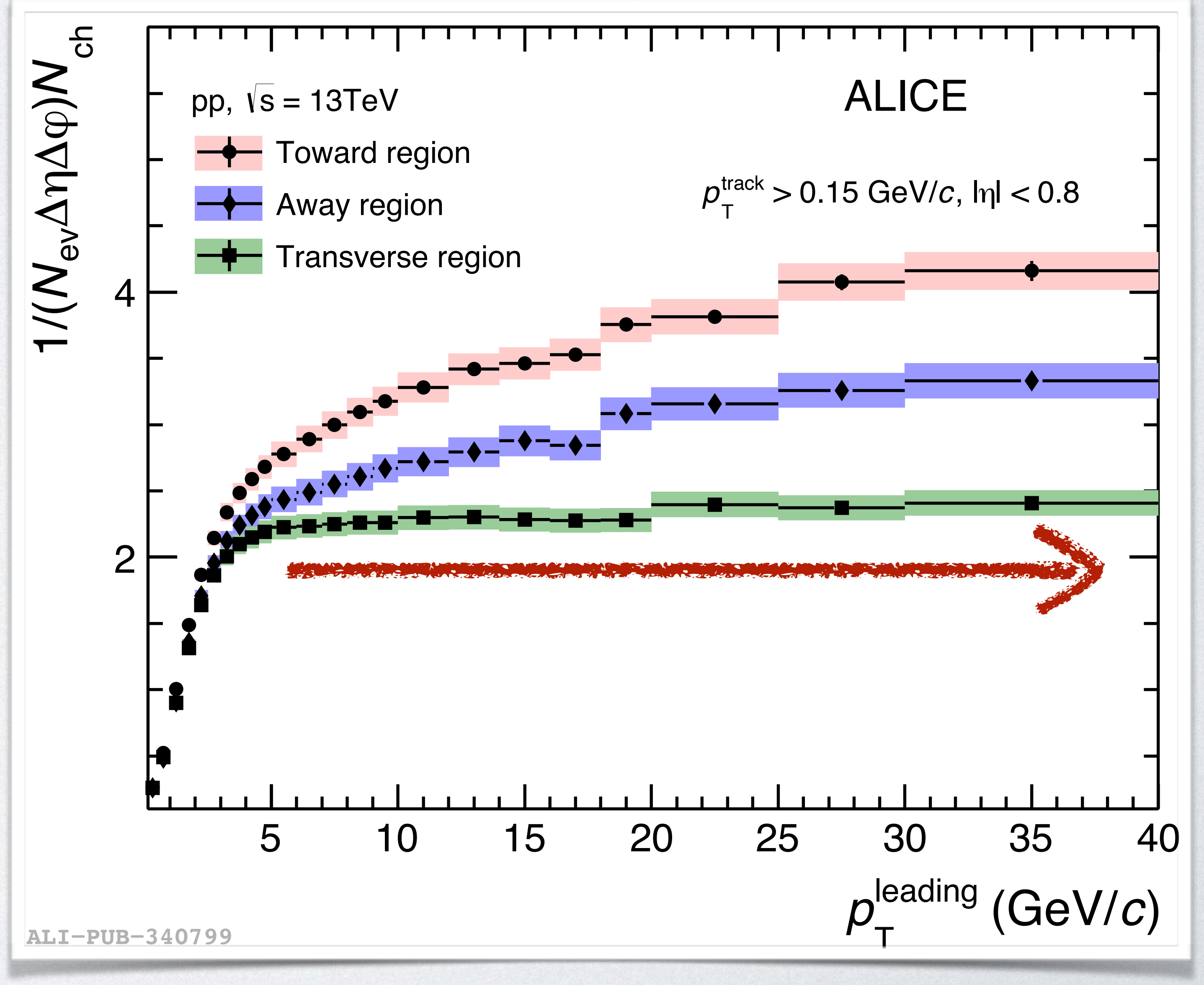
- K/π and p/π ratios: the ratios to $S_0^{p_T=1}$-integrated events highlight the radial flow-like features.
- Ξ/π ratio: show a crossing point in the double ratio.
- ϕ/π ratio: No significant dependence on spherocity unlike other particles.

In general, the particle ratios are not described by the models like PYTHIA8 and EPOS-LHC. However, they seem to explain the double ratios better.

Event shape observables: Relative transverse activity classifier (R_T)

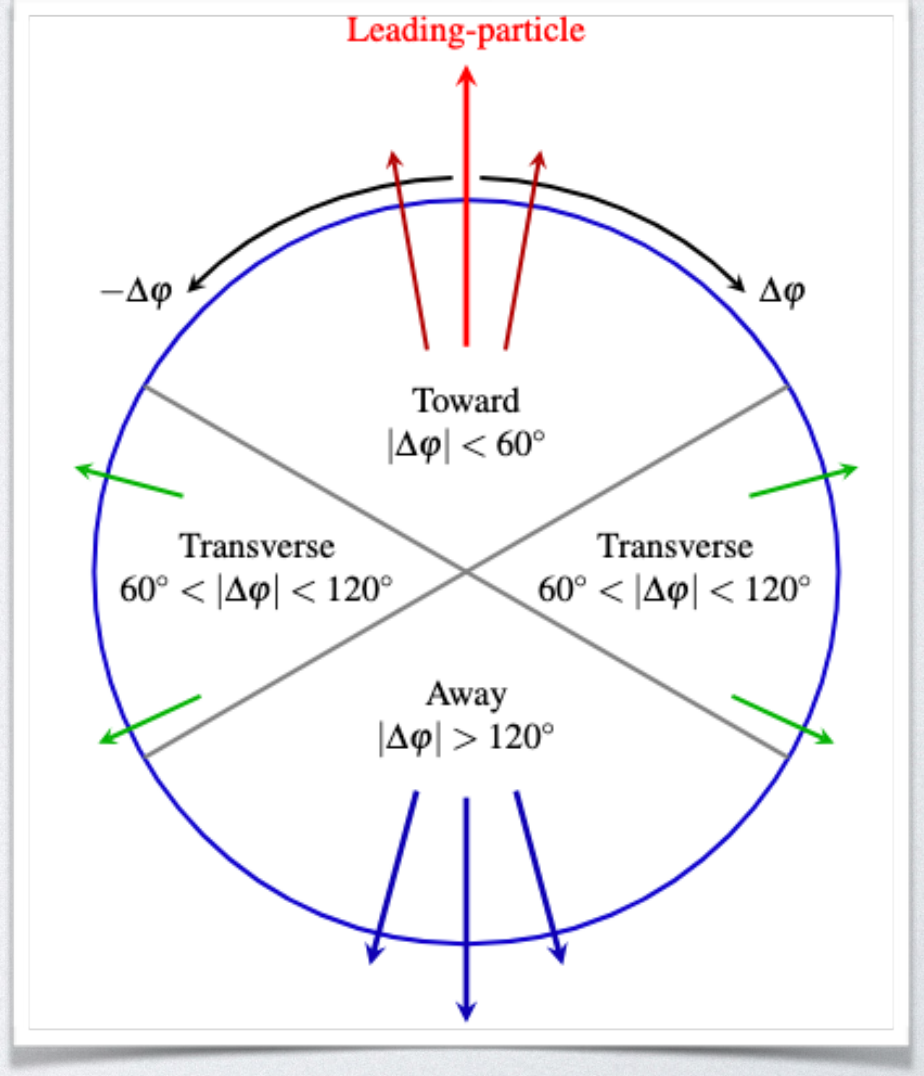
- $R_T = N_{ch}^{TS} / \langle N_{ch}^{TS} \rangle$, where N_{ch}^{TS} is the charged particle multiplicity in the transverse region.
- Using R_T, one can vary the magnitude of underlying events (UE). $R_T \rightarrow 0$: Events with less UE → expected to be compatible with the results from jetty-like events based on transverse spherocity.
- It is an useful tool to study:
  - Collective effects in events with low and high transverse activity
  - Events as a function of varying multi-partonic interactions (MPIs)
  - Interplay between soft and hard interactions
  - Auto-correlation effects
- A p_T cut for the leading particle is required to ensure a hard process
  - For identified particle analysis: $p_T^{leading} > 5$ GeV/c
  - For un-identified charged particle analysis: $8 < p_T^{leading} < 15$ GeV/c (this hard cut reduces the flow effects, required for searches for jet quenching effects)



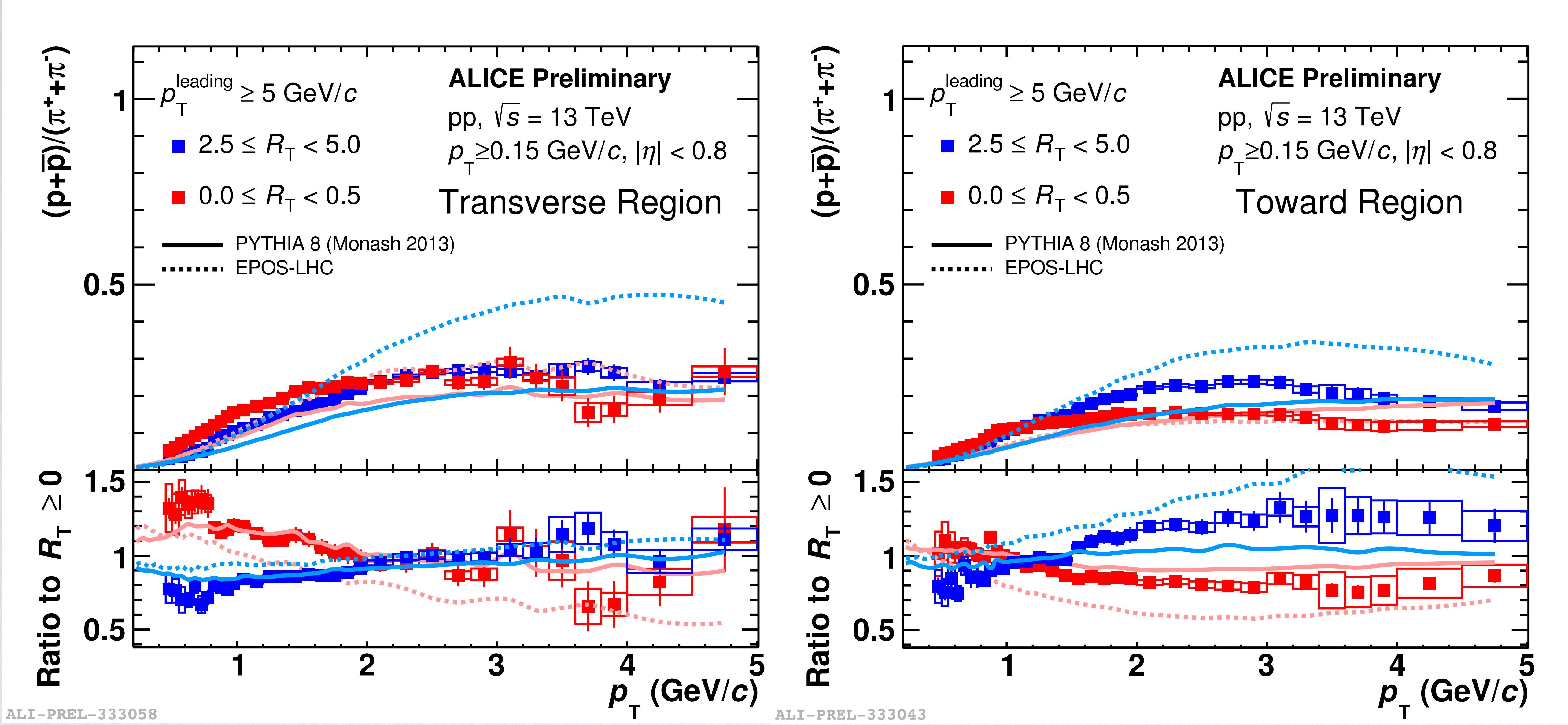


ALICE, JHEP04 (2020) 192

Identified particle production as a function of Relative transverse activity classifier (R_T)



Identified particle ratios as a function of R_T in pp collisions at 13 TeV



- p/π ratio:
  - Radial flow-like features in both the regions. However, this feature is stronger in the Transverse region.
  - Low-R_T trend is somewhat described by models. However, both of them fail to describe the high-R_T trend.

Identified particle ratios as a function of R_T in pp collisions at 13 TeV

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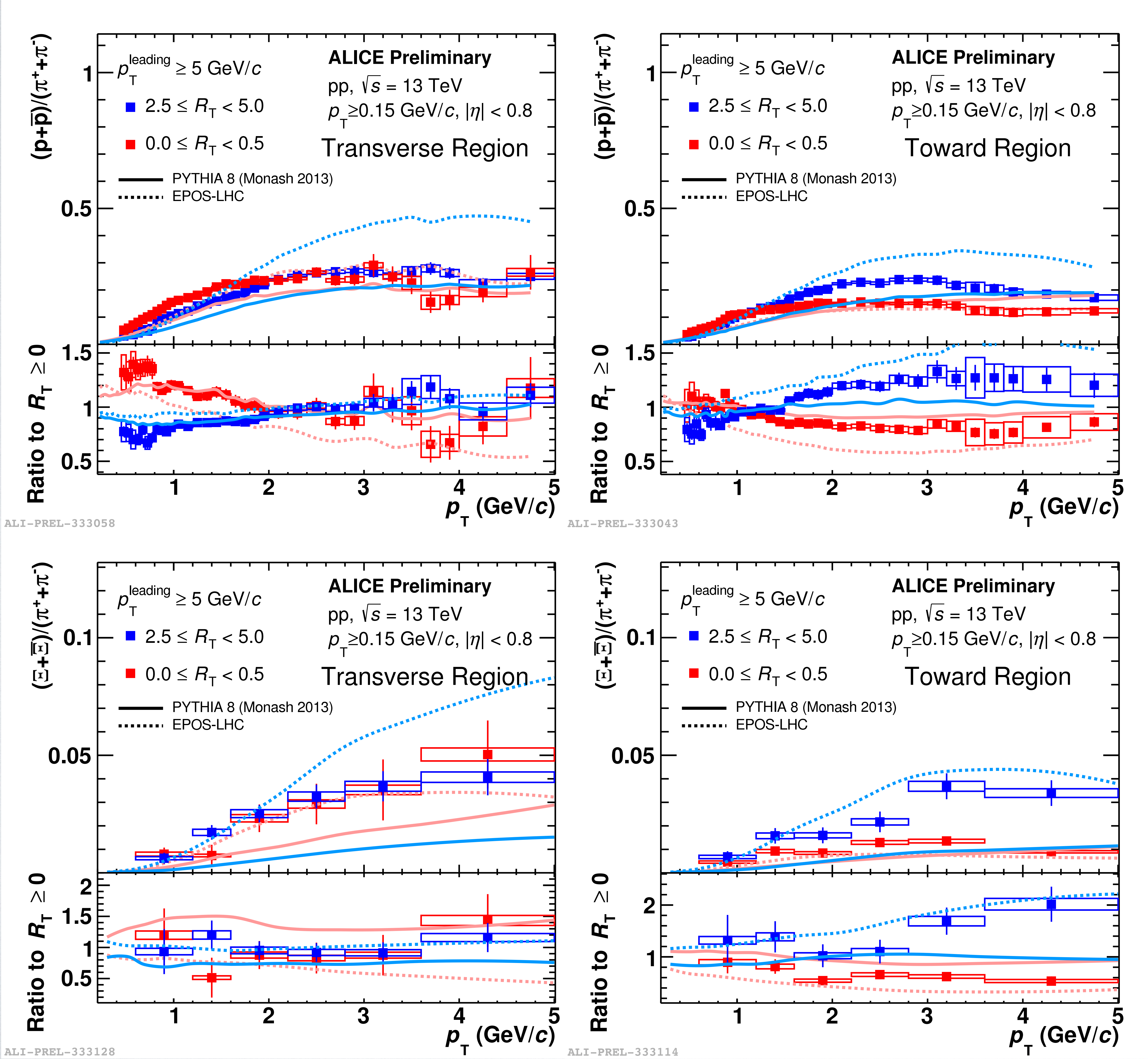
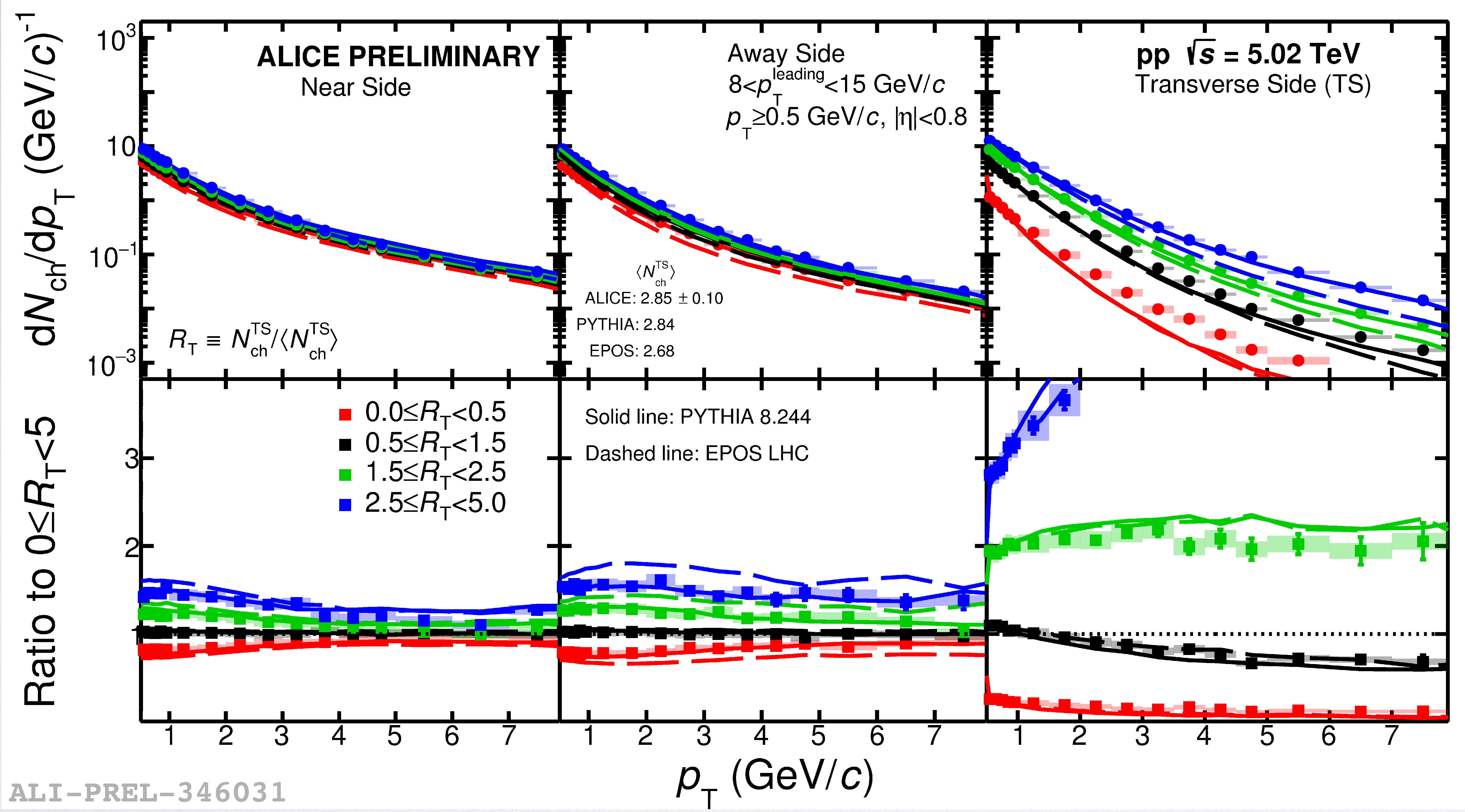


- p/π ratio:
  - Radial flow-like features in both the regions. However, this feature is stronger in the Transverse region.
  - Low-R_T trend is somewhat described by models. However, both of them fail to describe the high-R_T trend.
- Ξ/π ratio:
  - show a similar trend as the p/π ratio.
  - high-R_T toward region approaches the results in Transverse region.
  - In general, EPOS-LHC does better than PYTHIA8.

Charged particle production as a function of R_T in pp collisions at 5.02 TeV



- For the transverse side, the ratio of p_T spectra to the $0<R_T<5$ spectra rises with increase in R_T.
- Near and away side high-p_T yields are nearly independent. However, at low-p_T, the R_T dependence is significant.

Both PYTHIA 8.244 and EPOS-LHC models describe data qualitatively.

Charged particle production as a function of R_T in p-Pb collisions at 5.02 TeV

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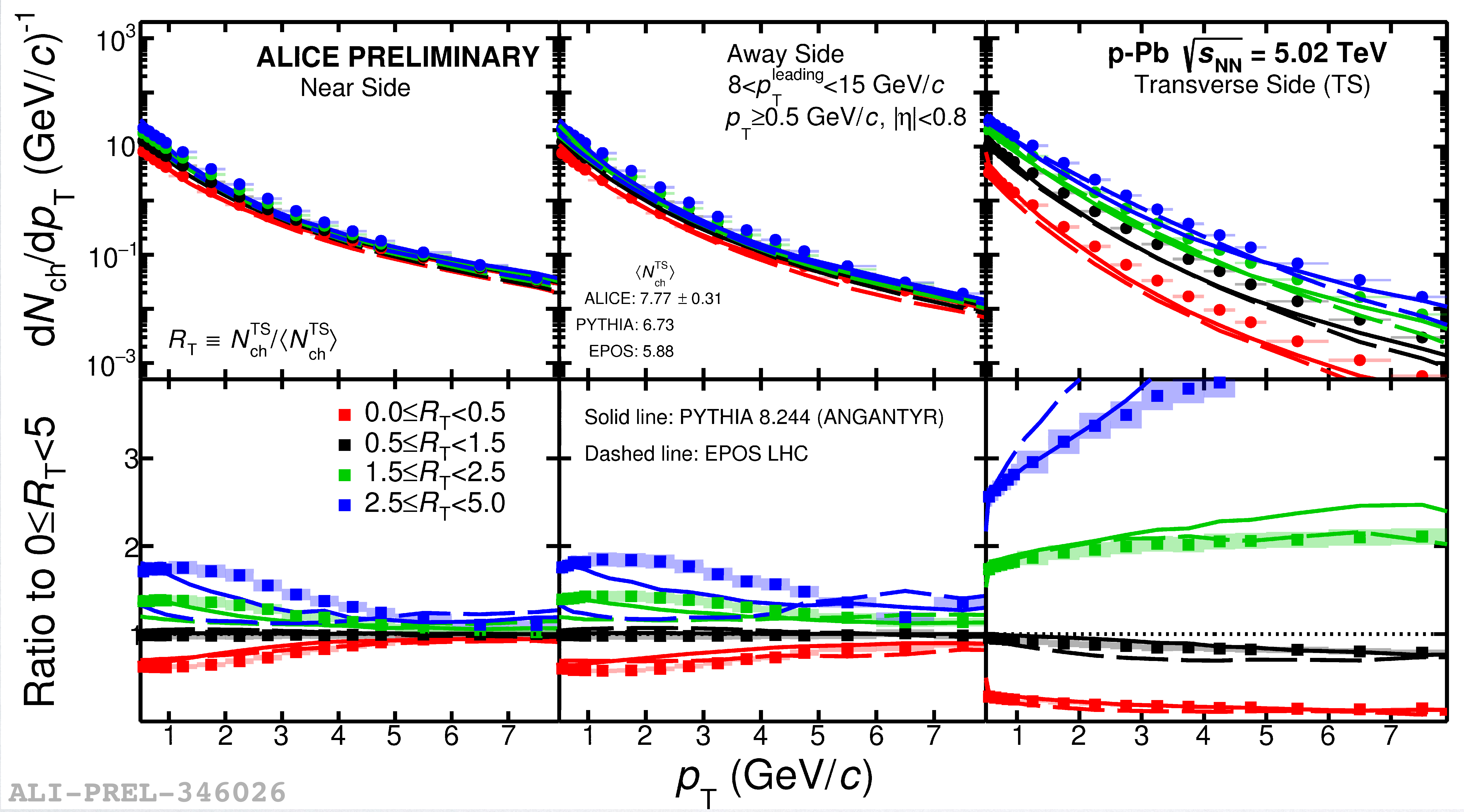
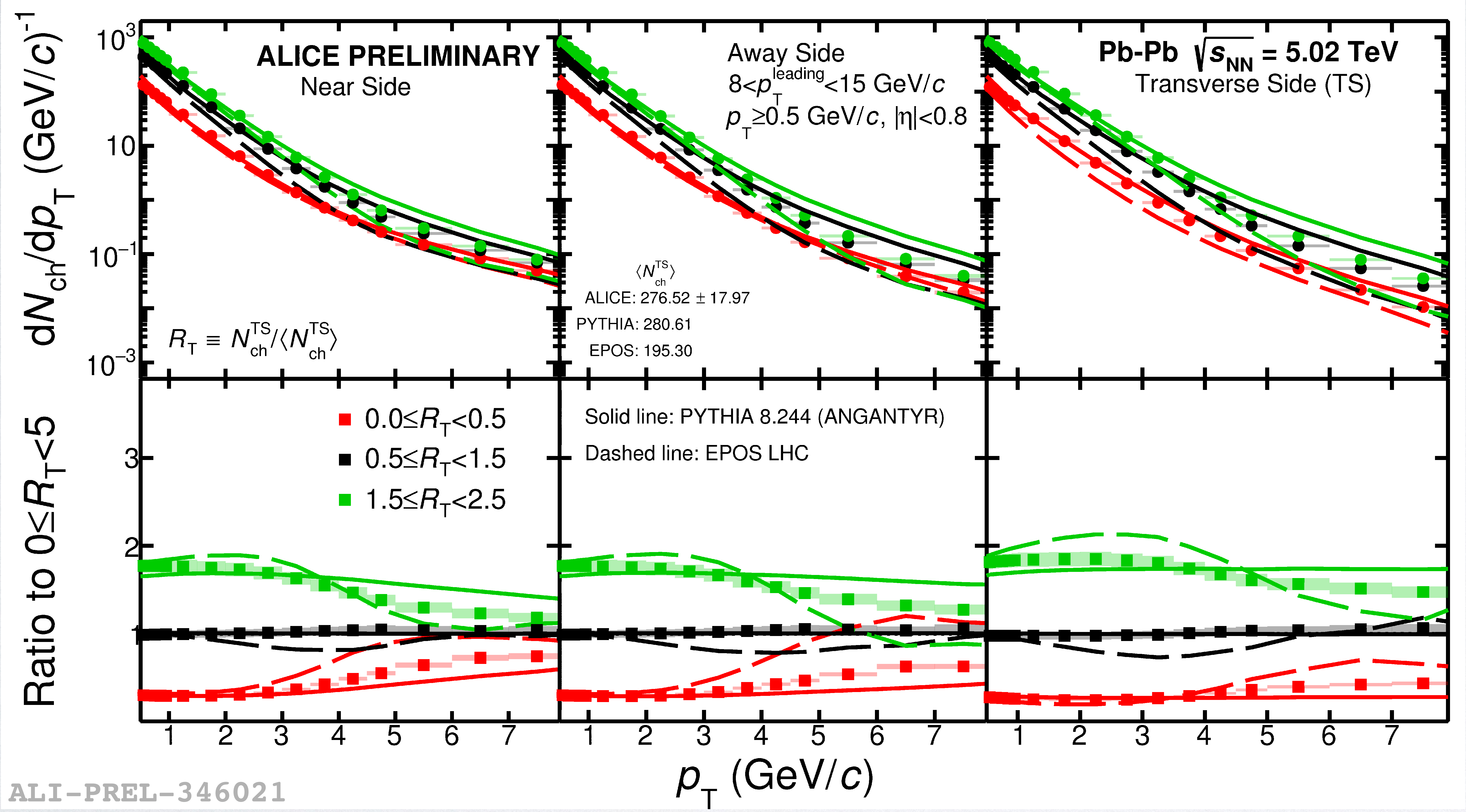


- Similar trend in p_T spectra for pp and p-Pb collisions on transverse side. The rise of the ratio to R_T-integrated is less steep for p-Pb
- For near and away side at low-p_T the R_T dependence is more significant in p-Pb compared to pp.

Both PYTHIA 8.244 and EPOS-LHC models describe data qualitatively.

Charged particle production as a function of R_T in Pb-Pb collisions at 5.02 TeV



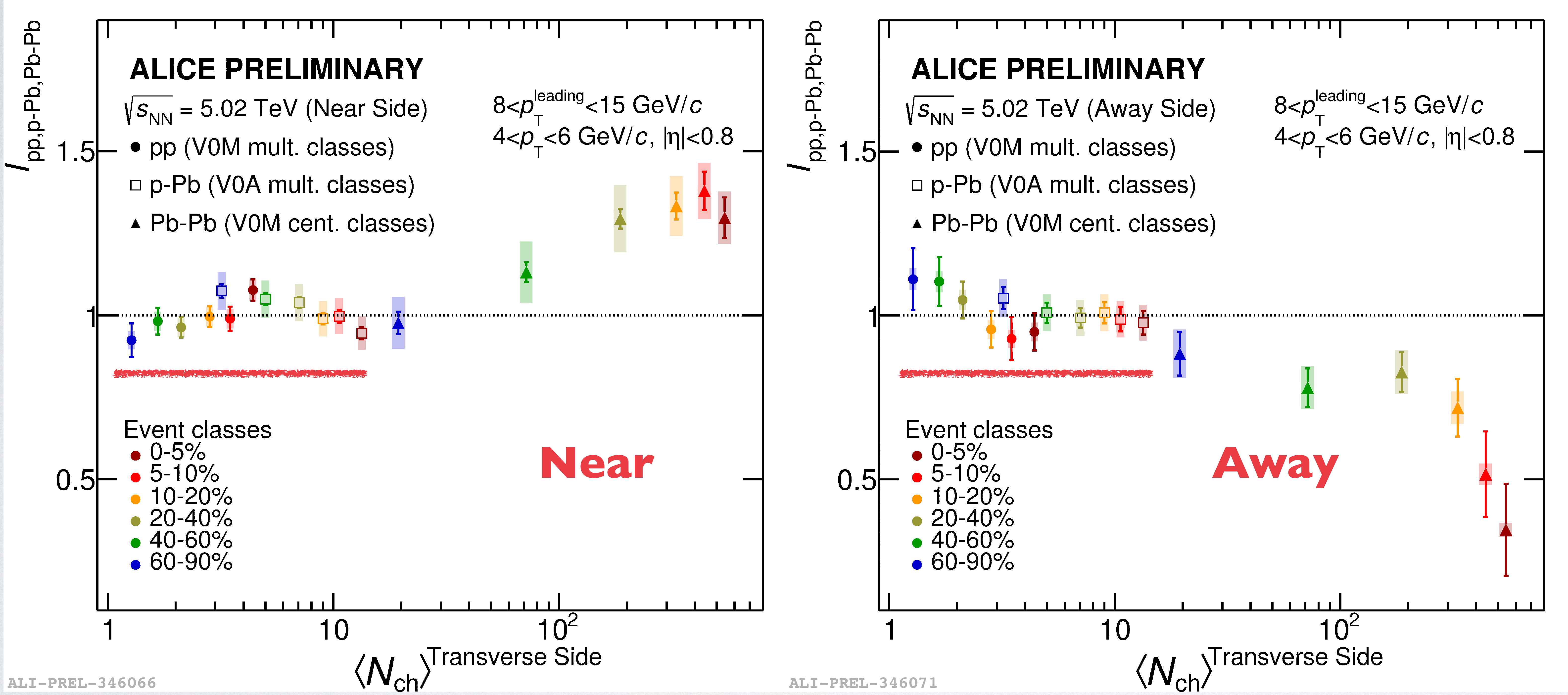
- Results for all topological regions in Pb-Pb collisions are qualitatively consistent with each other.
- As R_T is calculated mostly with low-p_T particles, R_T is more sensitive to soft physics.
- Due to high $<N_{ch}^{TS}>$, the maximum reach of $R_T \approx 2.5$ in Pb-Pb collisions.

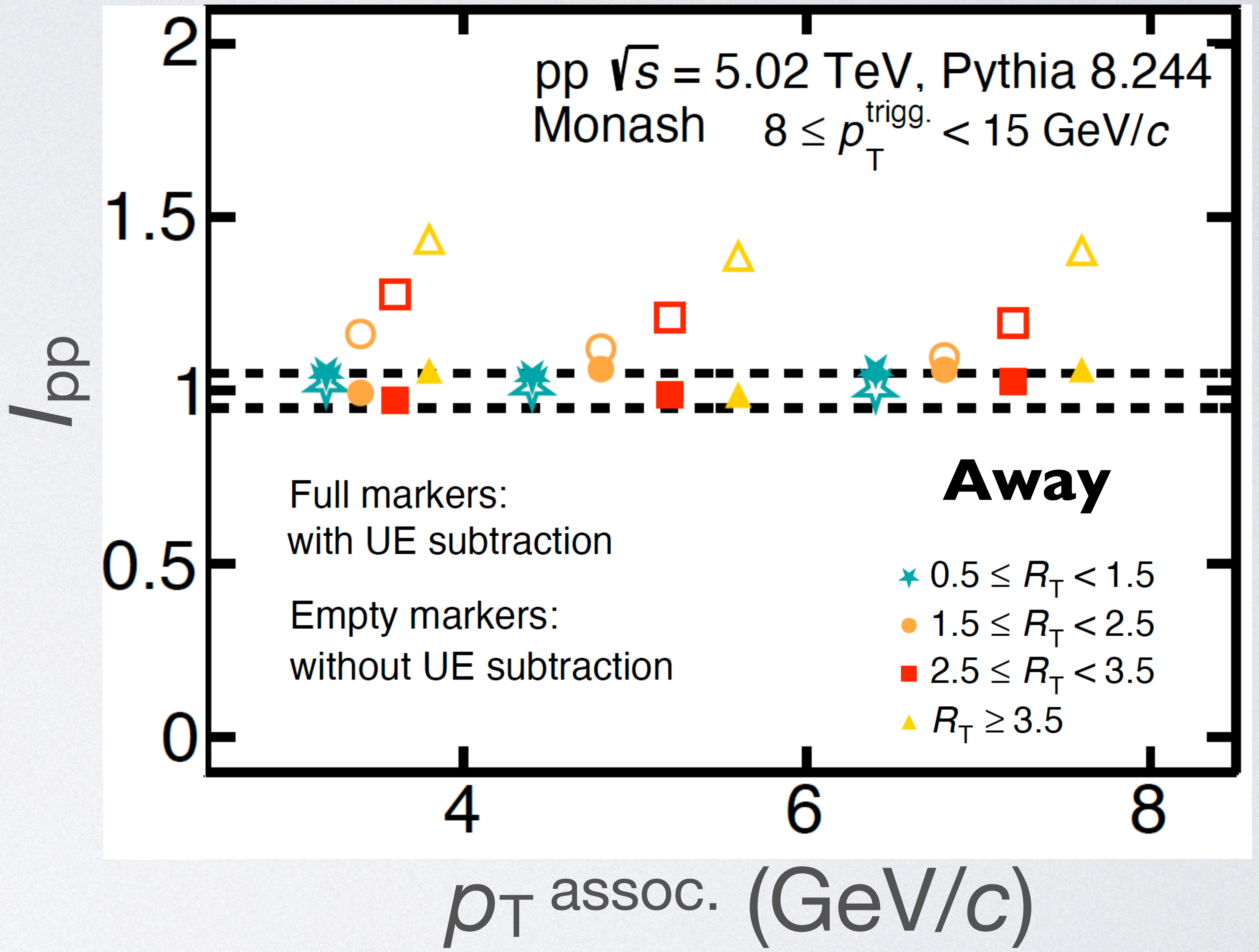
Both PYTHIA 8.244 and EPOS-LHC models describe data qualitatively.

Search for jet quenching effects in small collision systems

$$I_{\mathrm{pp,p-Pb,Pb-Pb}} = \frac{Y^{\mathrm{pp,p-Pb,Pb-Pb}} - Y^{\mathrm{pp,p-Pb,Pb-Pb}}_{\mathrm{TS}}}{Y^{\mathrm{pp\ min.bias}} - Y^{\mathrm{pp\ min.bias}}_{\mathrm{TS}}}$$

A. Ortiz, S. Tripathy and G. Benecdi, arXiv:2007.03857 [hep-ph]



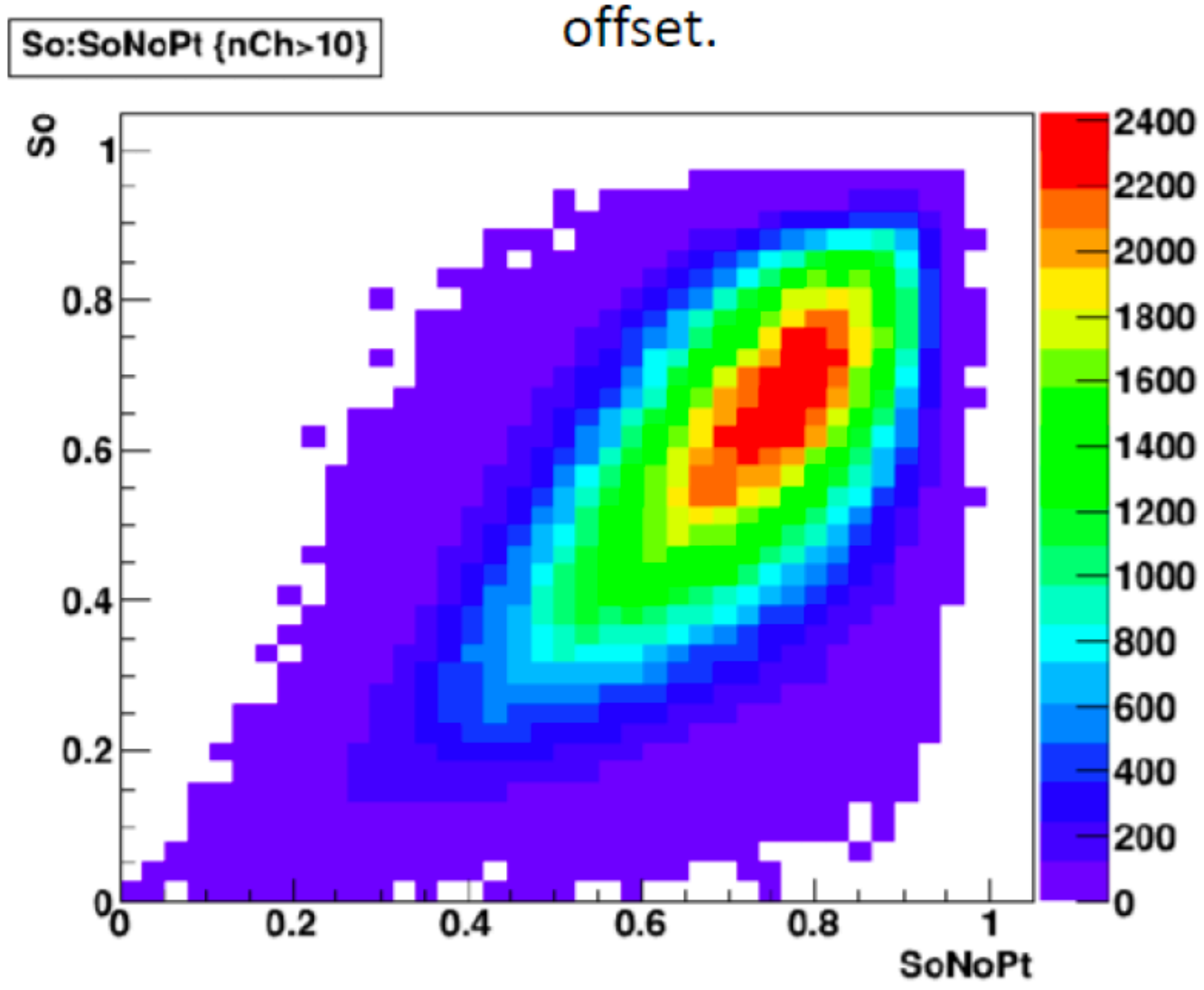


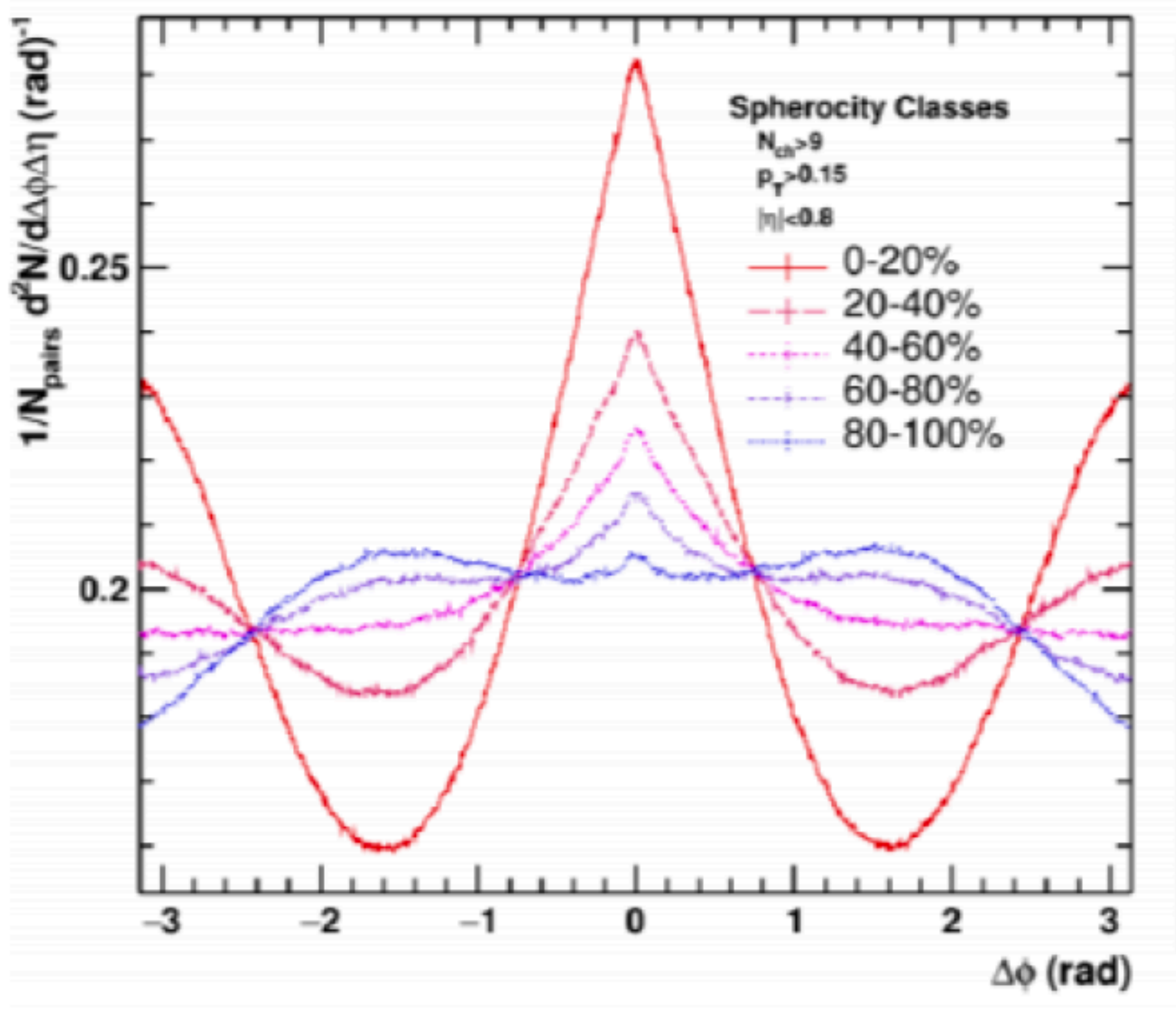
In contrast to Pb-Pb collisions, no enhancement (suppression) of $I_{\mathrm{pp,p-Pb,Pb-Pb}}$ is seen for NS (AS) in pp and p-Pb collisions. Based on these results, no hint of jet quenching in small systems is observed.

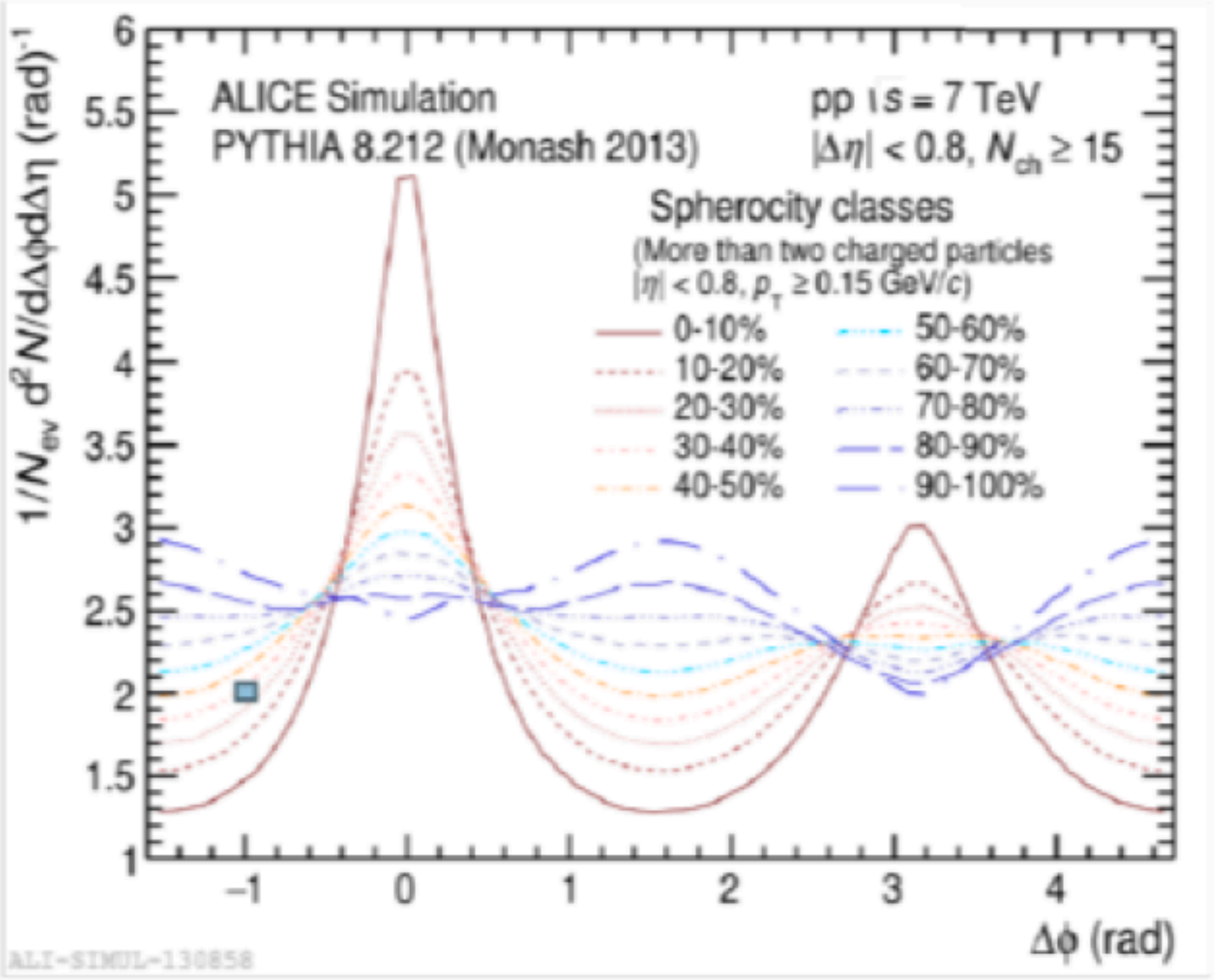
Predictions from Pythia 8 (Monash tune) is consistent with data

$S_O^{p_T=1}$ MC Studies - $S_O^{p_T=1}$ vs S_O

Correction matrix between $S_O^{p_T=1}$ and S_O linear with an initial offset.



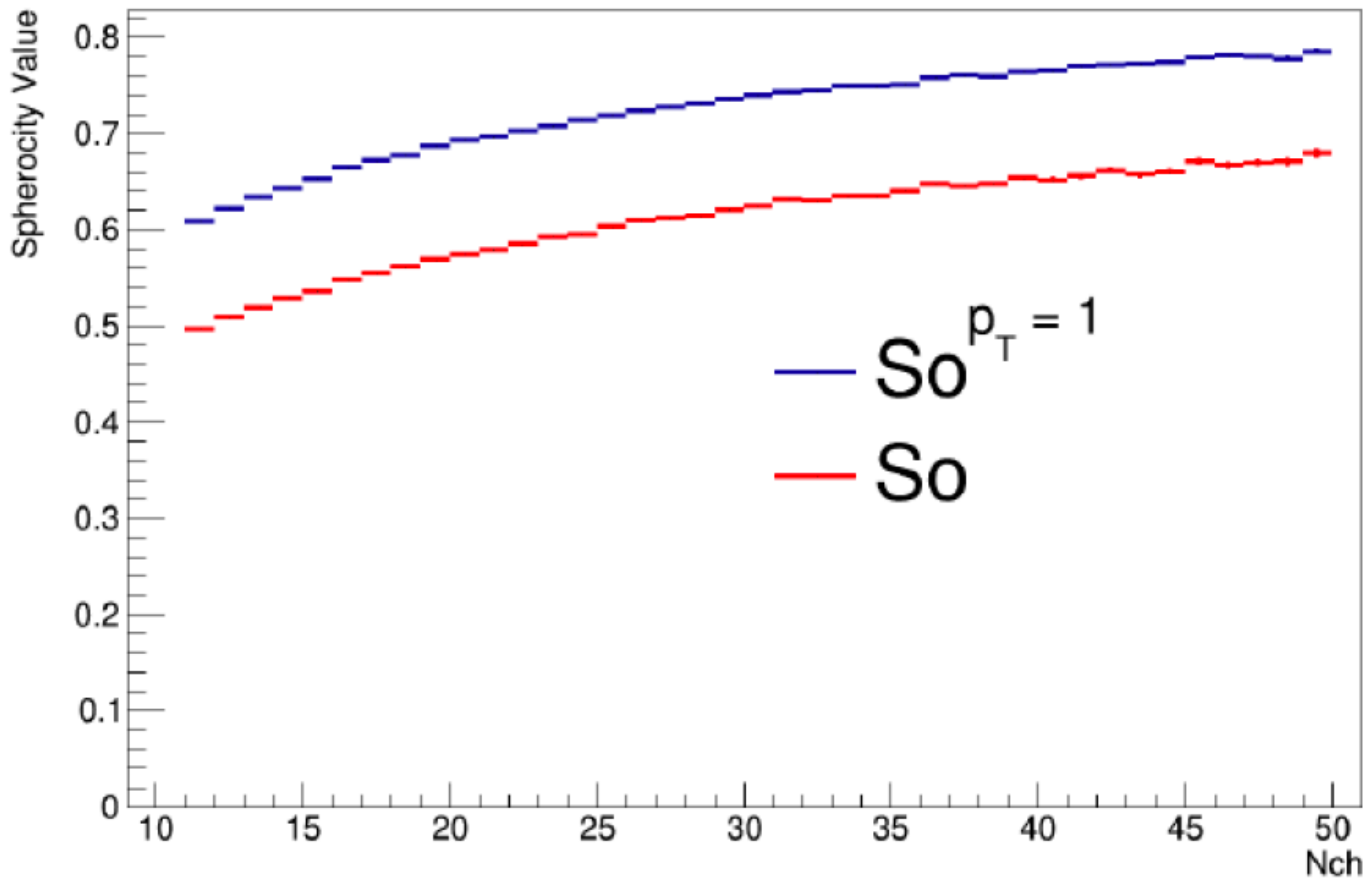


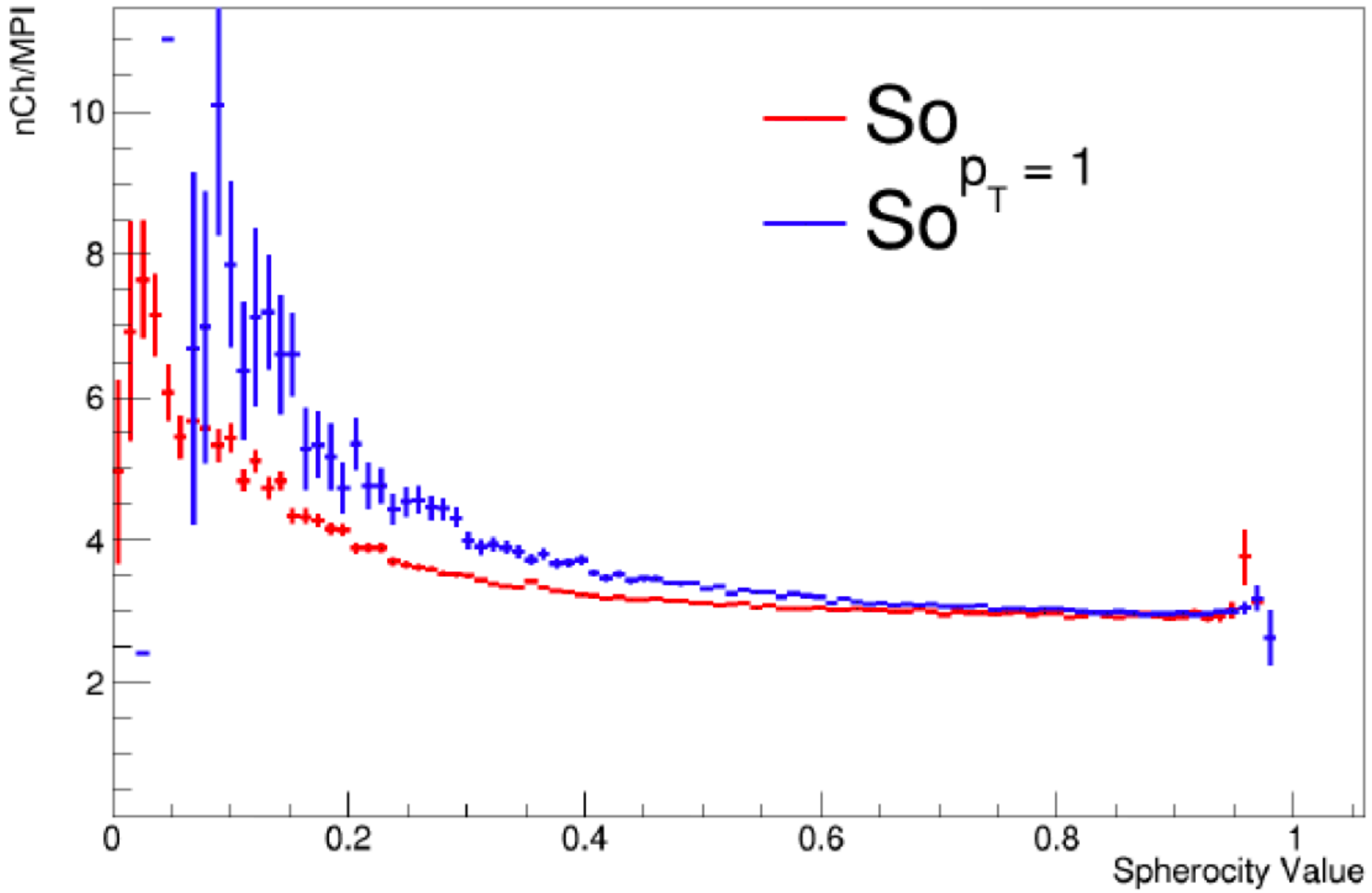


$S_O^{p_T=1}$ MC Studies - $S_O^{p_T=1}$ vs S_O

Qualtitatively similar
Nch/MPI distributions

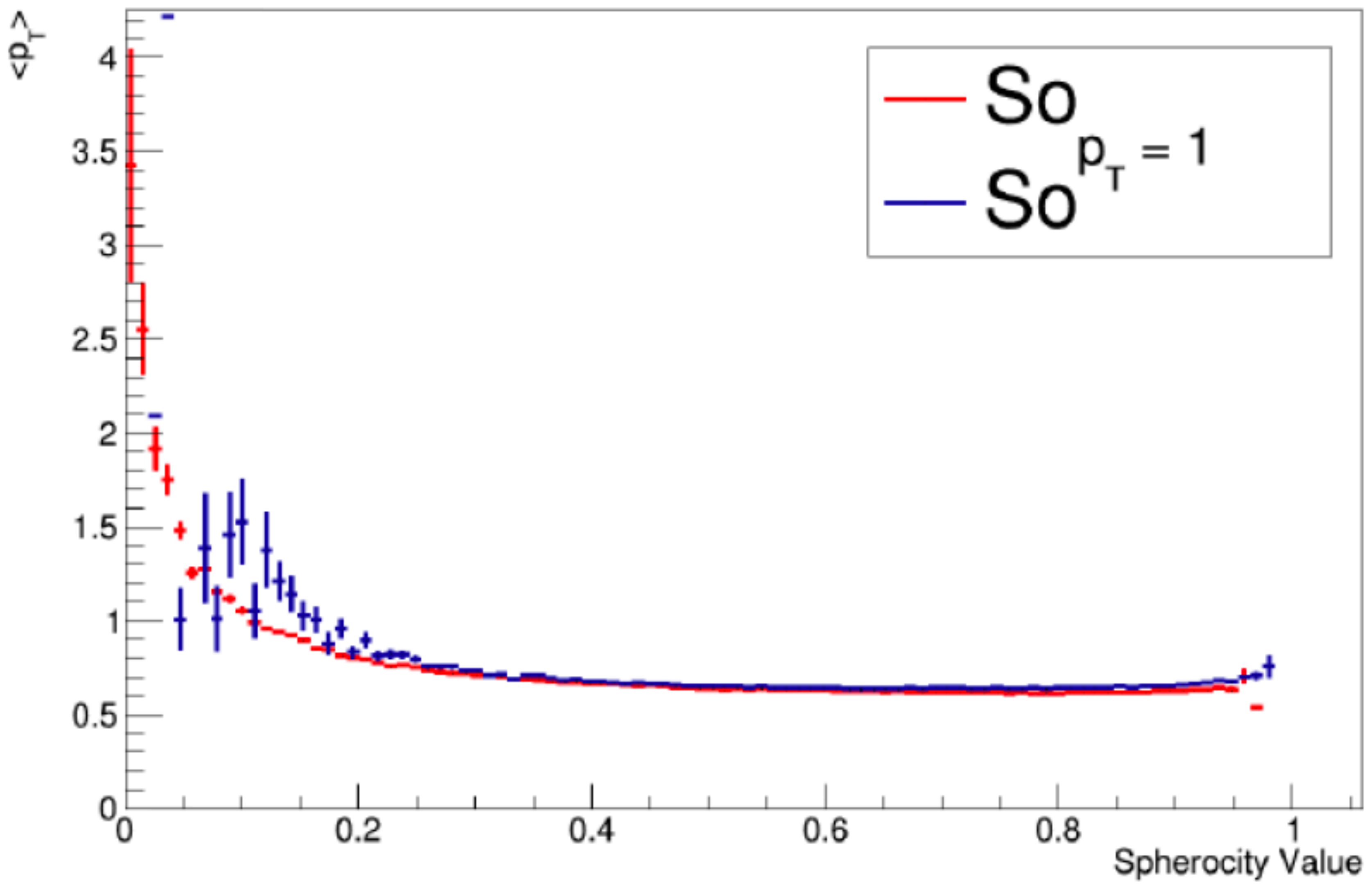
Qualitatively similar
Nch distributions

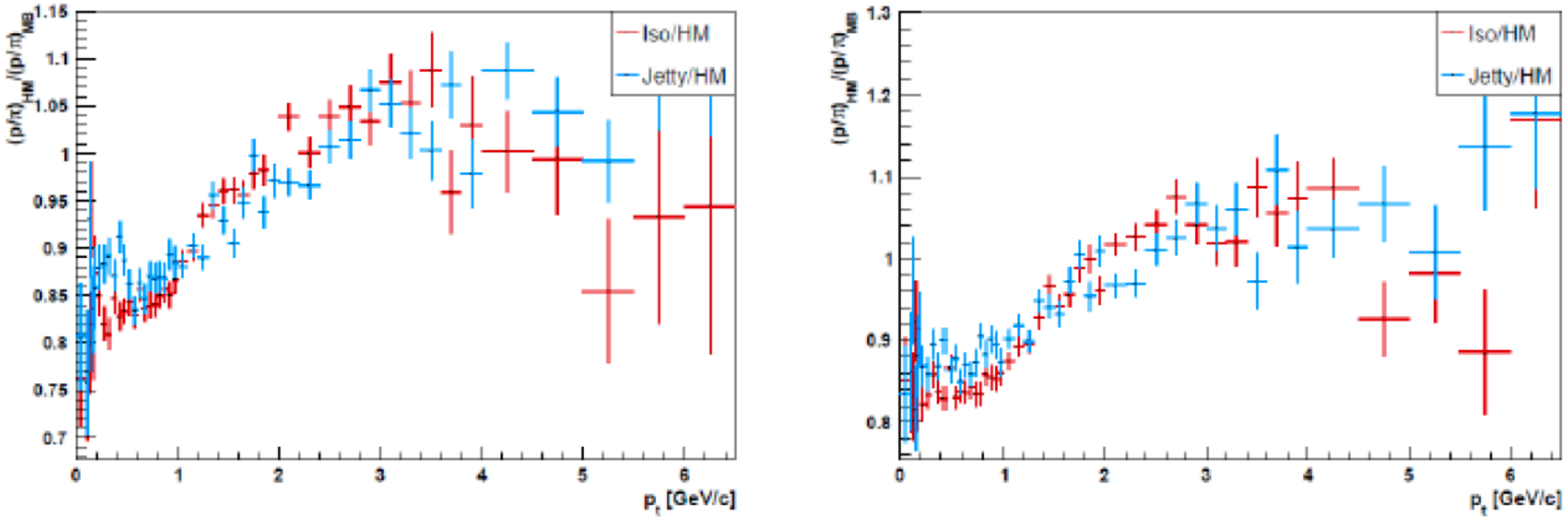




$S_O^{p_T=1}$ MC Studies - $S_O^{p_T=1}$ vs S_O

Qualtitatively similar
$\langle p_T \rangle$ distributions



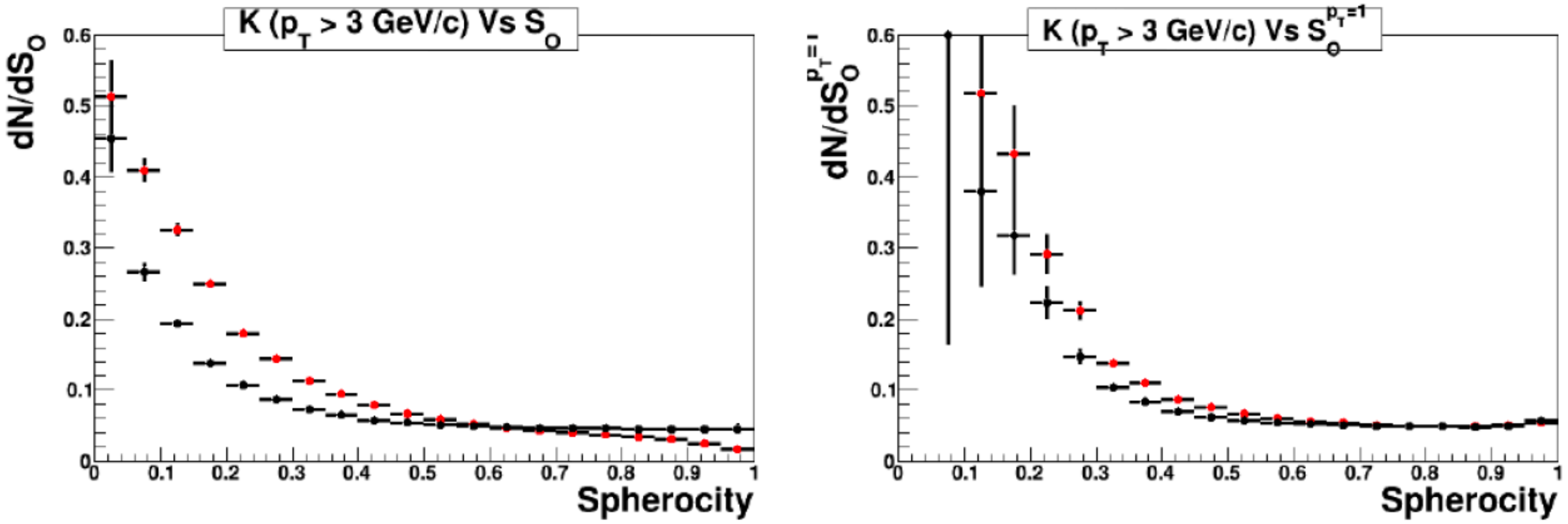


(a) Spherocity (b) Spherocity $p_T = 1$

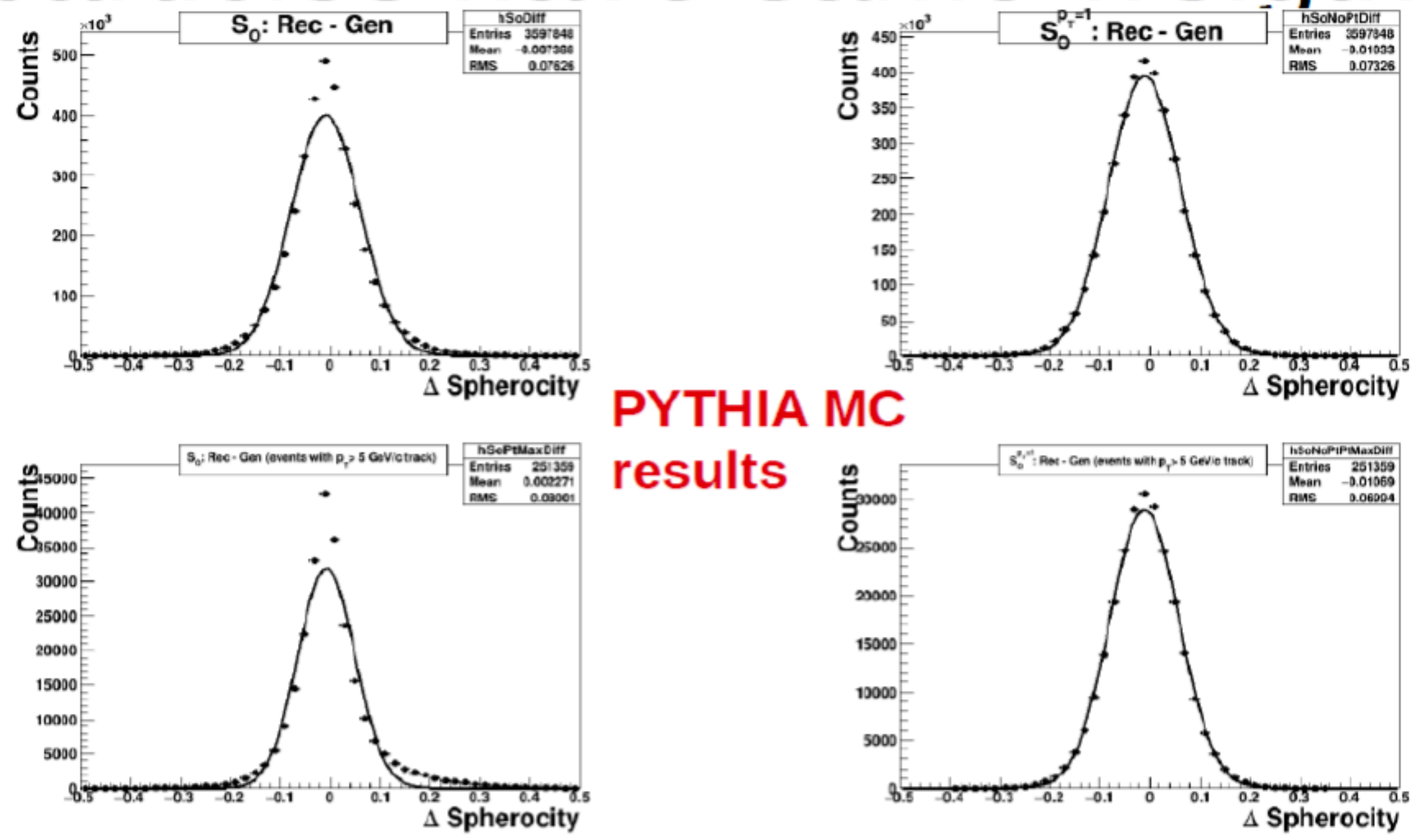
$S_O^{p_T=1}$ MC Studies – Charged Vs Neutral

K^+ and K^0_s with p_T>3 GeV/c

PYTHIA MC results (generator level)



$S_{O,pT=1}$ is more “robust”: all particles have same weigth



PYTHIA MC results