# Probing strangeness production in small systems through new multi-differential measurements with ALICE at the LHC

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On Behalf of The ALICE Collaboration

*2nd of March, 2020*

# Introduction: Isolating Hard & Soft Physics

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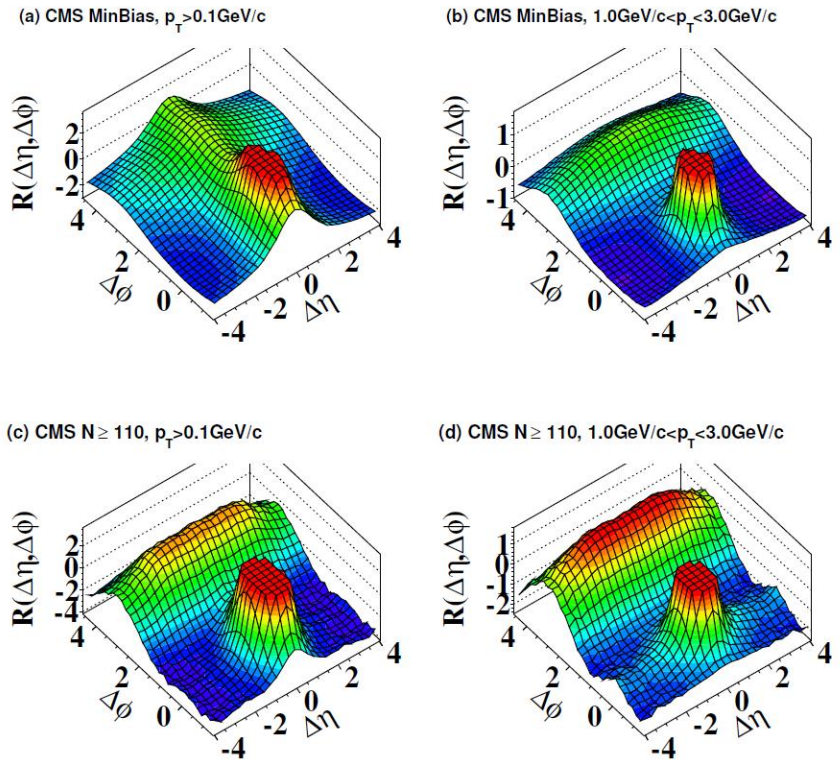
  - Correlations




JHEP 1009:091,2010

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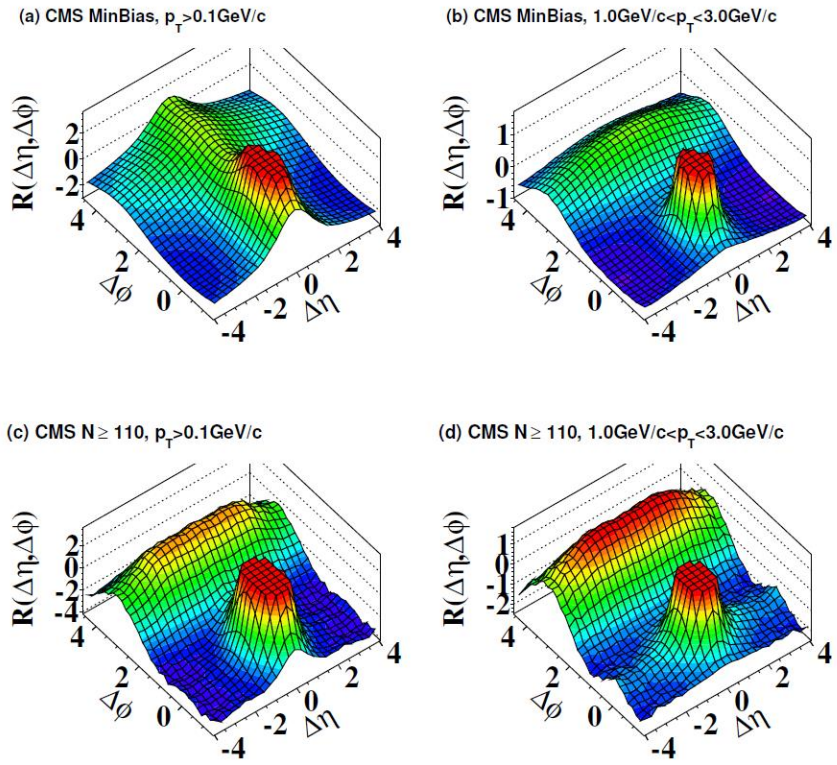


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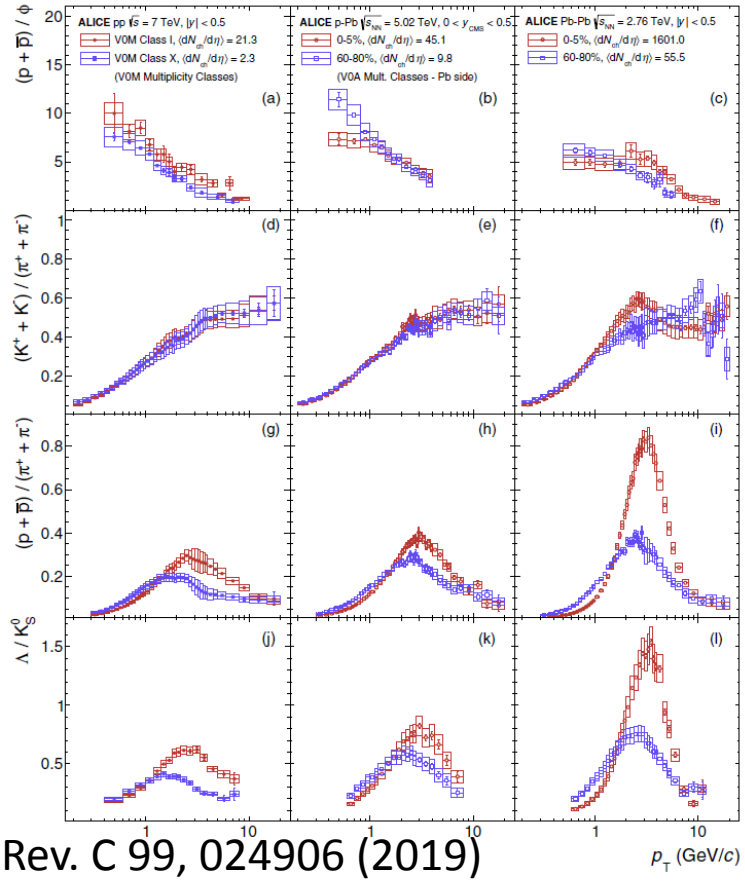


Phys. Rev. C 99, 024906 (2019)

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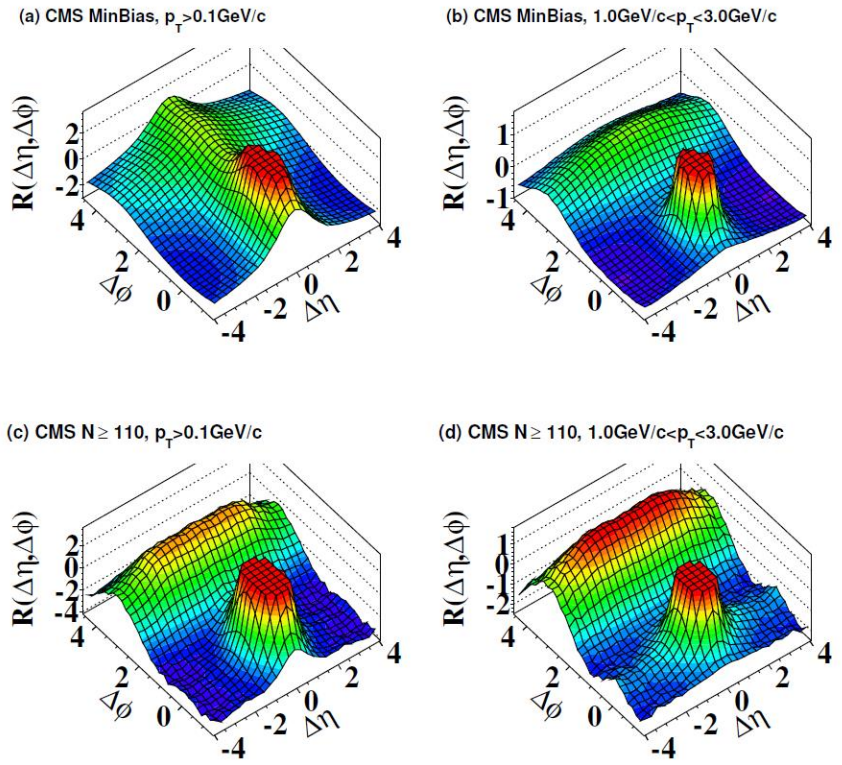


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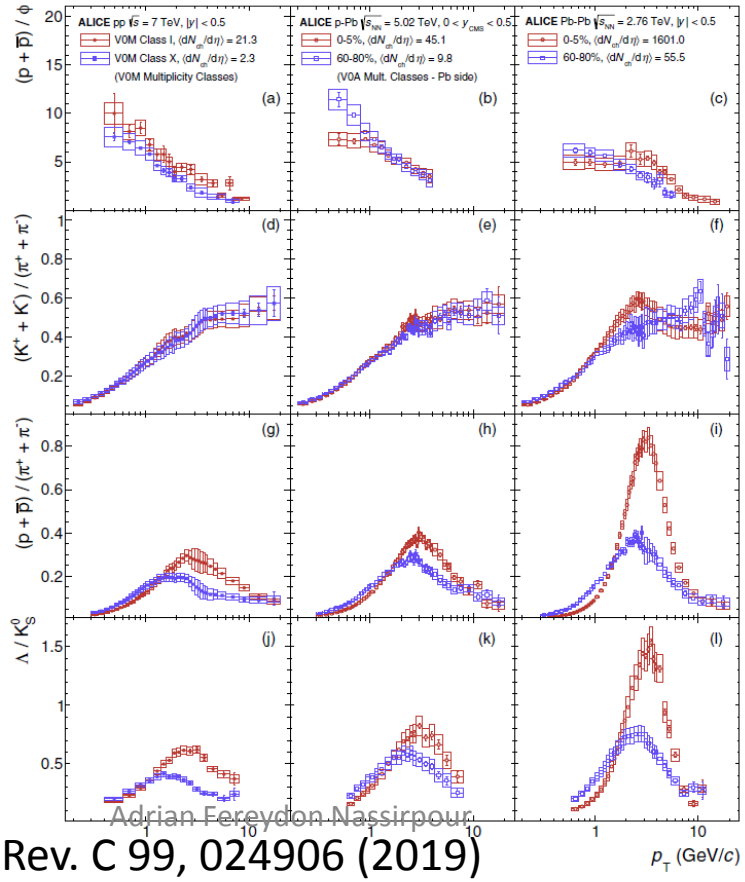


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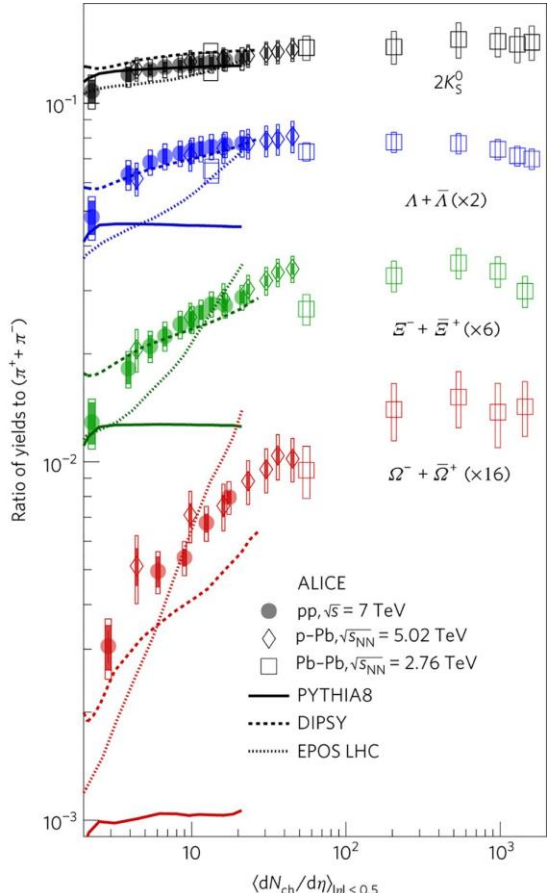


Nature Physics 13 (2017) 535-539

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- Experimental observations have found collective-like behaviour in pp & p-Pb collisions.
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- In A-A systems, the same observations are interpreted as signatures of the formation of a strongly interacting medium (Quark-Gluon Plasma).
- However, it has historically been thought that the system produced in pp collisions could not form a strongly interacting medium.
  - The medium would be too short-lived/the volume too small.
  - Can enough temperature/baryon density be achieved?

# Introduction: Isolating Hard & Soft Physics

- How do we pinpoint the underlying mechanisms of collective behaviour and strangeness enhancement?
  - Can we isolate the different physics regimes (soft vs hard)?
  - Can we test pp (strings) vs A-A (hydro) ideas?

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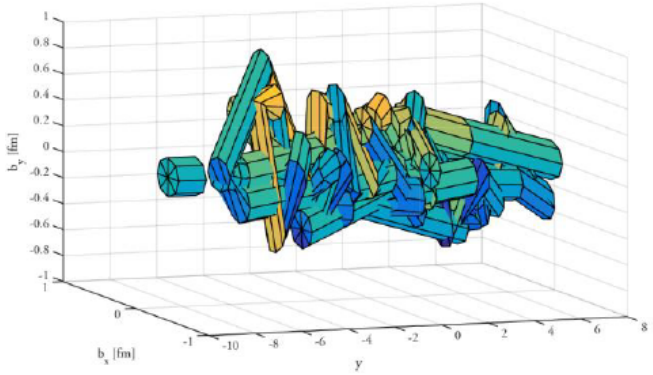
Explicit details of hadronization.

How are strange quarks produced in the collision? Canonical suppression?

Are "collective effects" a signature of the QGP? Can effects be reproduced by string-like models?

Microscopic vs Macroscopic

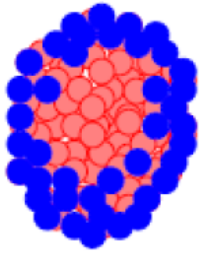


Picture from C. Bierlich
(string radii ~3.5 times too small!)

Low mult pp

corona
core

High mult pp



Pictures from K. Werner

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- During this talk I will present 3 new differential measurements from ALICE that can give insight into light-flavour particle production.
  - $\pi/\mathrm{K}/\mathrm{p}/\phi/\Xi$ production as a function of Transverse Spherocity $S_O^{p_\mathrm{T}=1}$.
  - $\pi/\mathrm{K}/\mathrm{p}/\phi/\Xi$ production as a function of $R_T$.
  - $\pi/\mathrm{K}-\Xi$ angular correlations.

# $\pi/K/p/\phi/\Xi$ production as a function Transverse Spherocity $S_O$

- This measurement aims to study how the production of light-flavour hadrons changes depending on the event topology.

- I'm taking two underlying assumptions into account:

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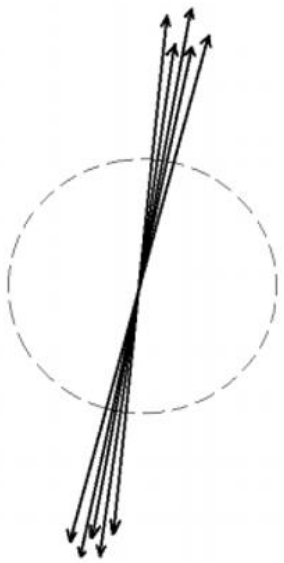

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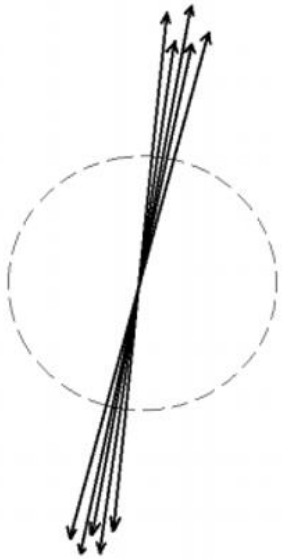
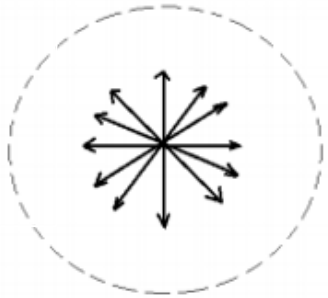
  - Hadrons produced from several soft collisions:
    - Azimuthal isotropic distribution of particles.





# $\pi/K/p/\phi/\Xi$ production as a function Transverse Spherocity $S_0$

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

- Transverse Spherocity $S_0$ is used to separate different event topologies

- $S_0 \rightarrow 0$: Describes events with jet-like topologies
  → Dominated by hard physics

- $S_0 \rightarrow 1$: Describes events with isotropic topologies
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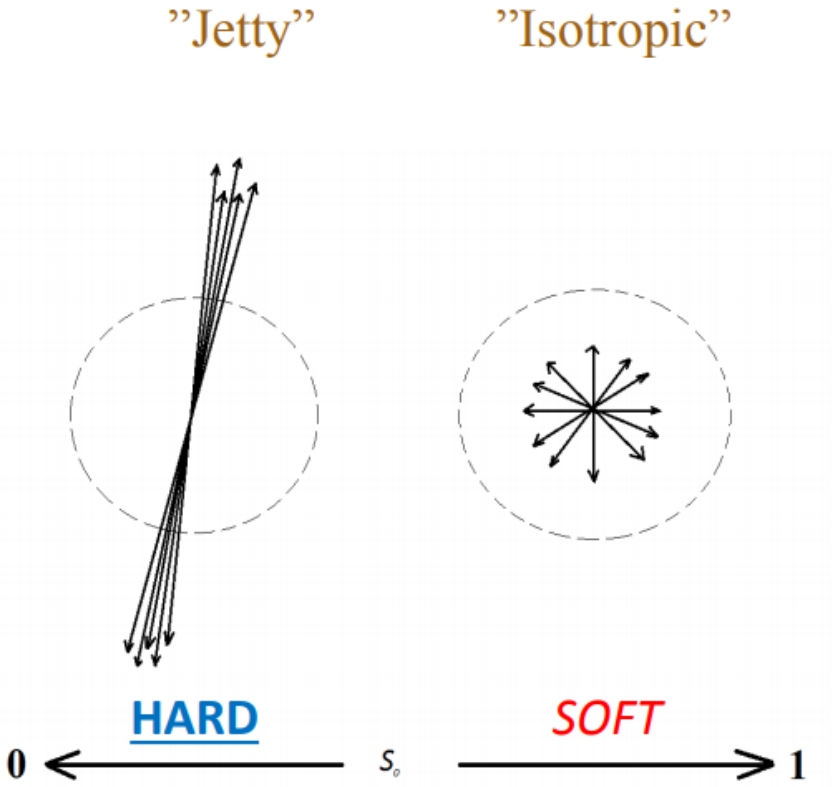

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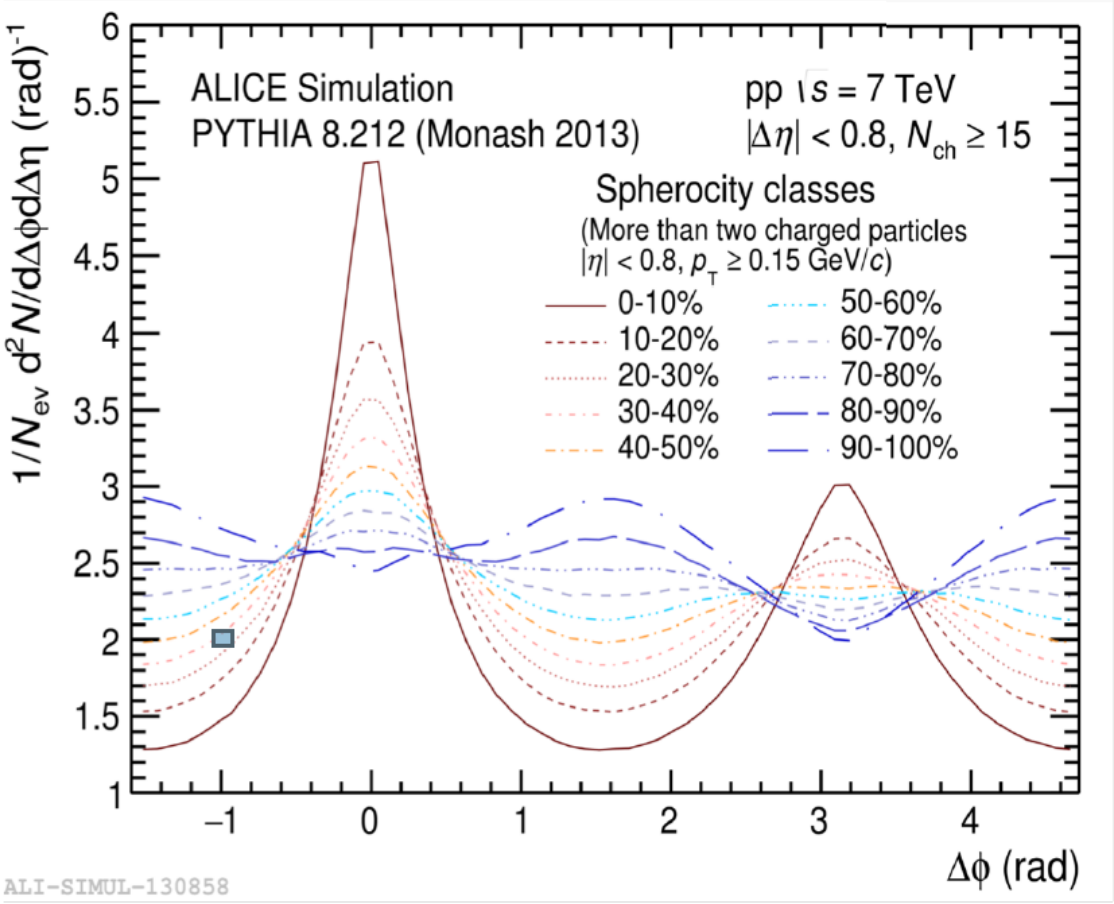

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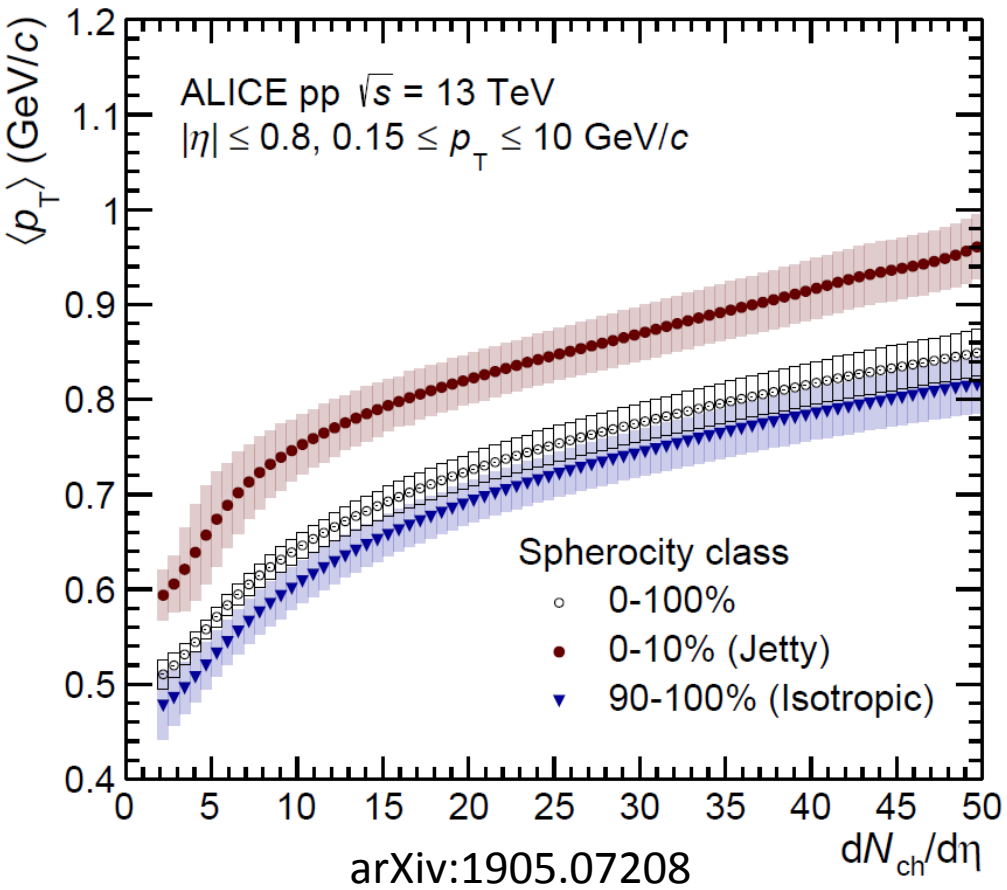
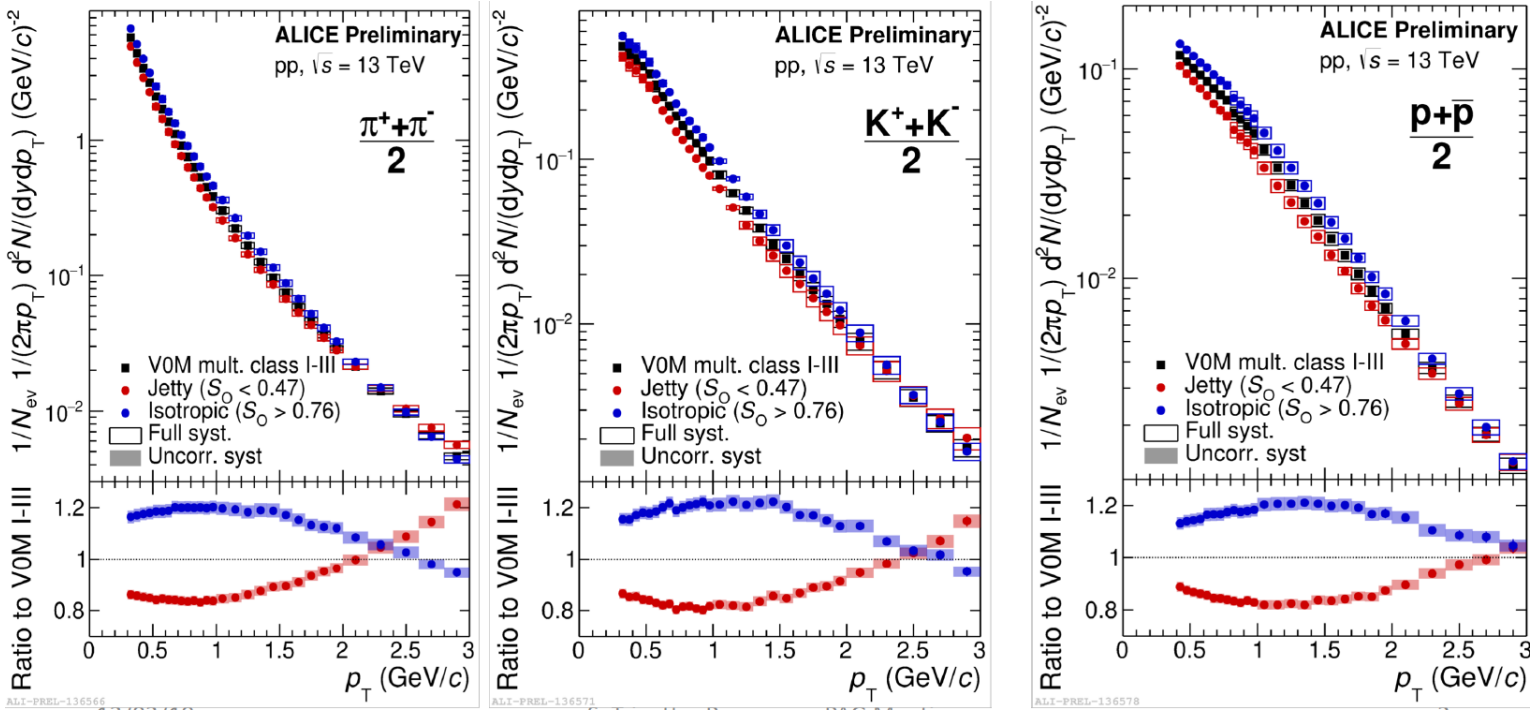



arXiv:1905.07208

# $\pi/K/p/\phi/\Xi$ production as a function Transverse Spherocity $S_O$

- A previous study of $\pi/K/p$ as a function of $S_O$ released in 2017.

- However, selecting events based on $S_O$ affects neutral and charged hadrons differently.
  - $S_O$ defined by $N_{ch}$.



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$$S_O = \frac{\pi^2}{4} \min_{\hat{n}} \left( \frac{\Sigma_i |p_T \times \hat{n}|}{\Sigma_i p_{T_i}} \right)^2 \rightarrow S_O^{p_T=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left( \frac{\Sigma_i |\hat{p}_T \times \hat{n}|}{N_{trk}} \right)^2$$

**$S_O^{p_T=1}$: Unweighted Transverse Spheroctiy.**
**Only the angular component is taken into account!**

- However, selecting events based on $S_O$ affects neutral and charged hadrons differently.
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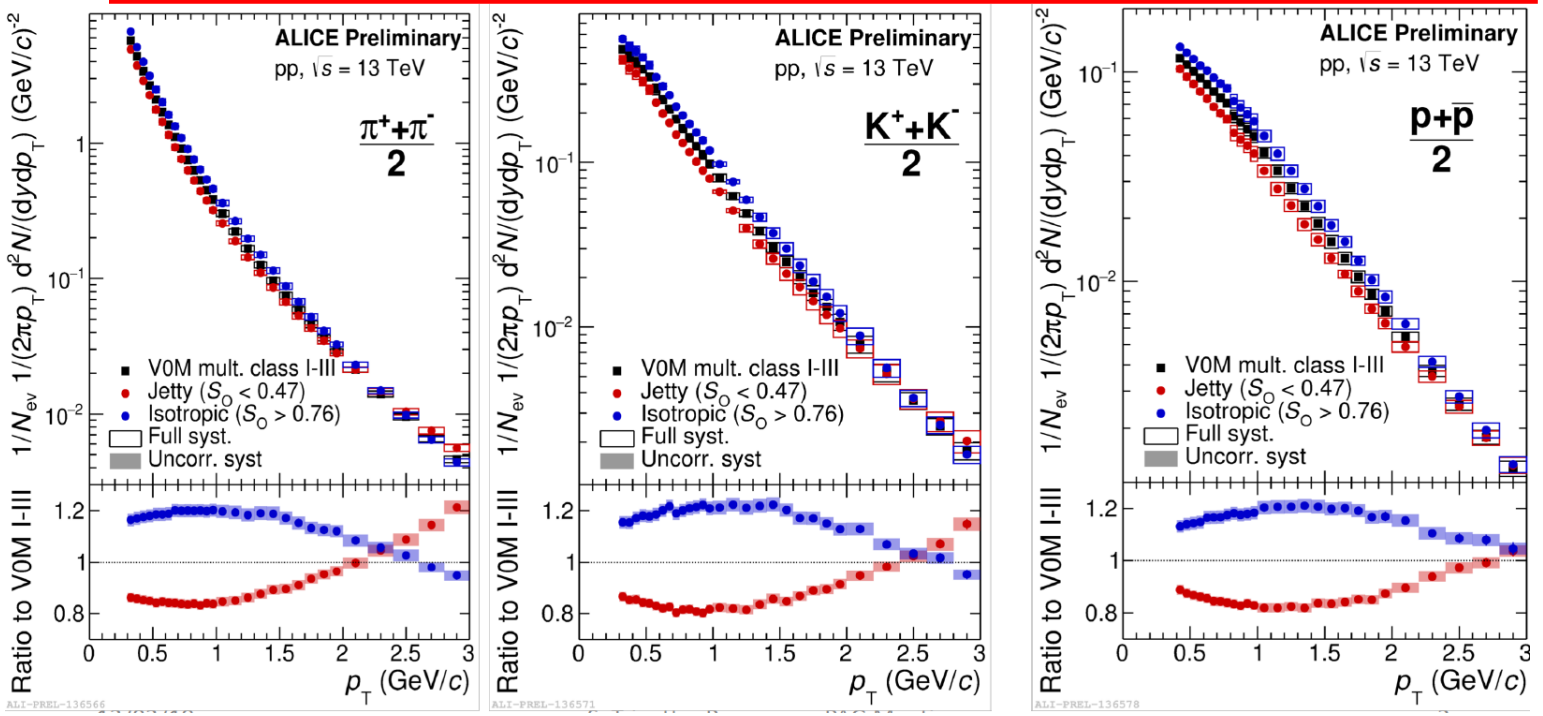
- In order to accomodate other particles ($K_s^0/\phi/\Lambda/\Xi$), the $S_O$ estimator had to be modified (details in backup).

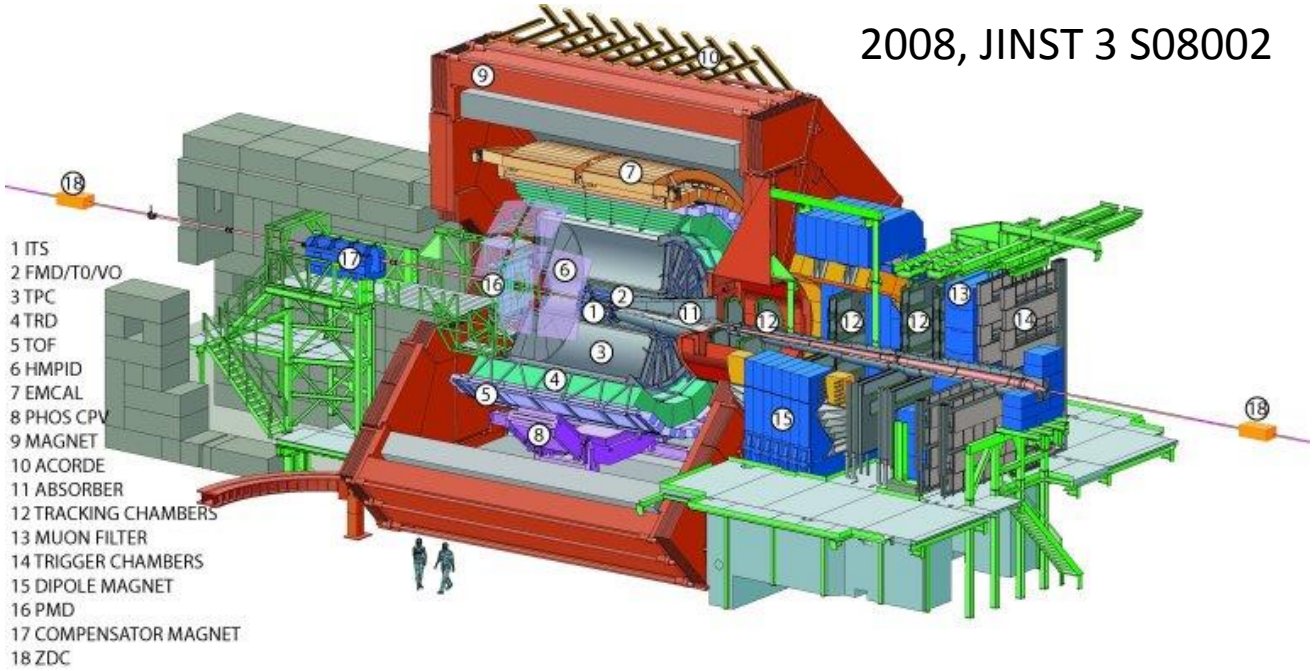


# Introduction: ALICE

- The ALICE detector at the LHC used to study pp, p-A and AA collisions at different centre-of-mass energies.

- The main detector systems used for this analysis are:
  - The Time Projection Chamber (TPC)
  - The Time-of-Flight (TOF)
  - The Inner Tracking System (ITS)

2008, JINST 3 S08002

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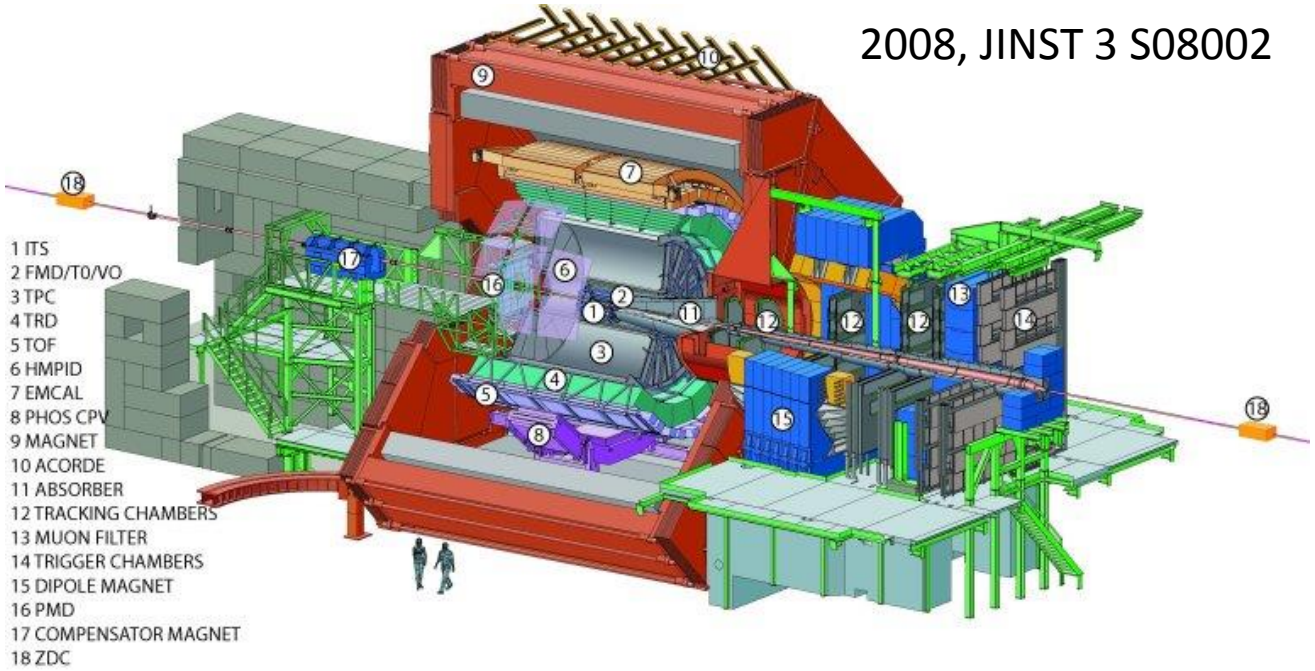
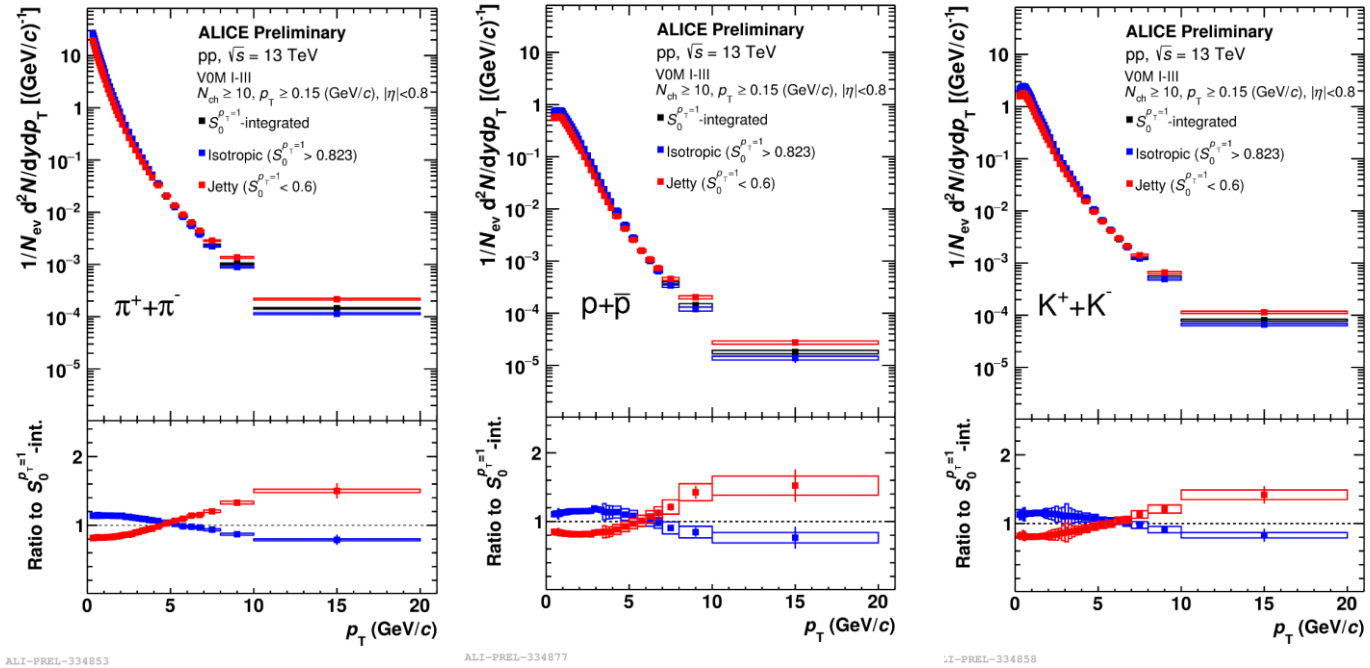



- We are interested in high-multiplicity events, so we mainly consider the 0-10% multiplicity percentile.
  - V0A/V0C (V0M) are scintillators that measure the charged particle multiplicity at forward rapidity ($2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$)
  - CL1 measures the number of short tracks segments in the ITS, $N_{\mathrm{spd}}$, at mid-rapidity ($|\eta| < 0.8$)
  - High-multiplicity particle production can be characterized by different physics in the two rapidity regions
    - Mid-rapidity particle production will be more sensitive to local fluctuations (auto-correlations, jets).
    - Slicing multiplicity at far-rapidity, but measuring at mid-rapidity is more robust against fluctuations.

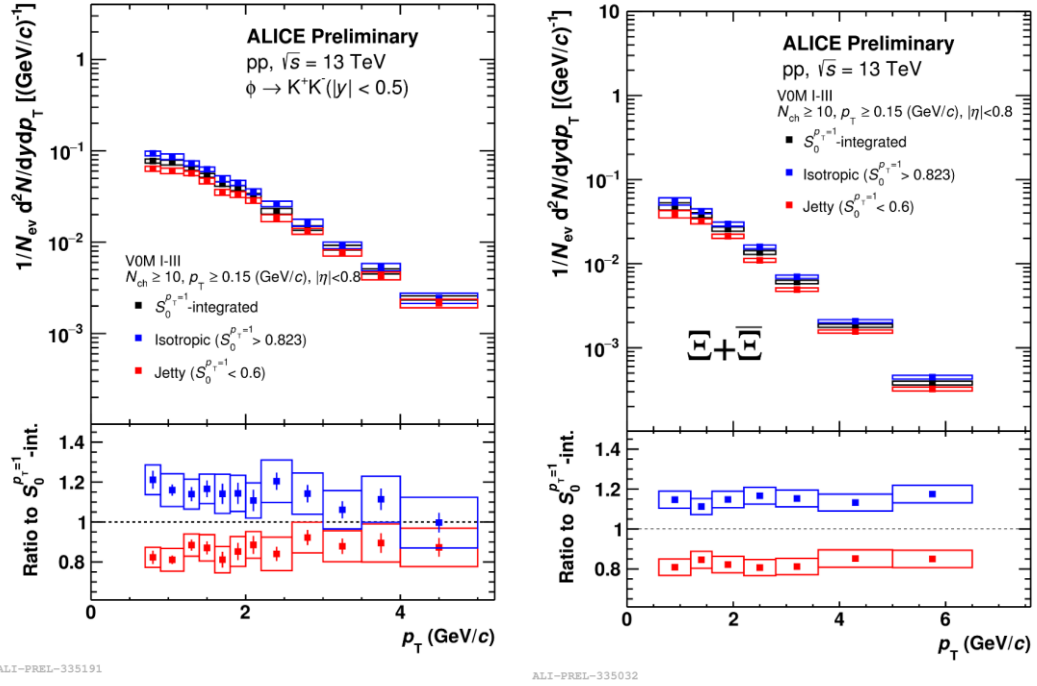
# Unweighed Transverse Spherocity $S_0^{p_T=1}$ – Results

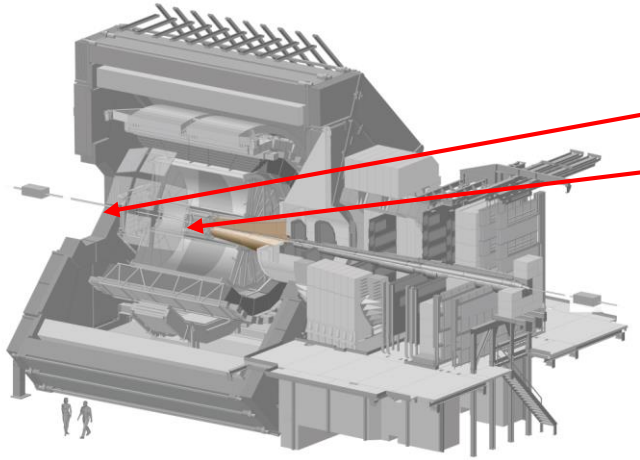
## V0M 0 – 10%




Distinct difference between Jetty and Isotropic events!

$\pi/K/P$ has distinct crossing point.
$\phi/\Xi$ appears to be more flat around unity.
(notice $p_T$ range)



$2.8 < \eta < 5.1$

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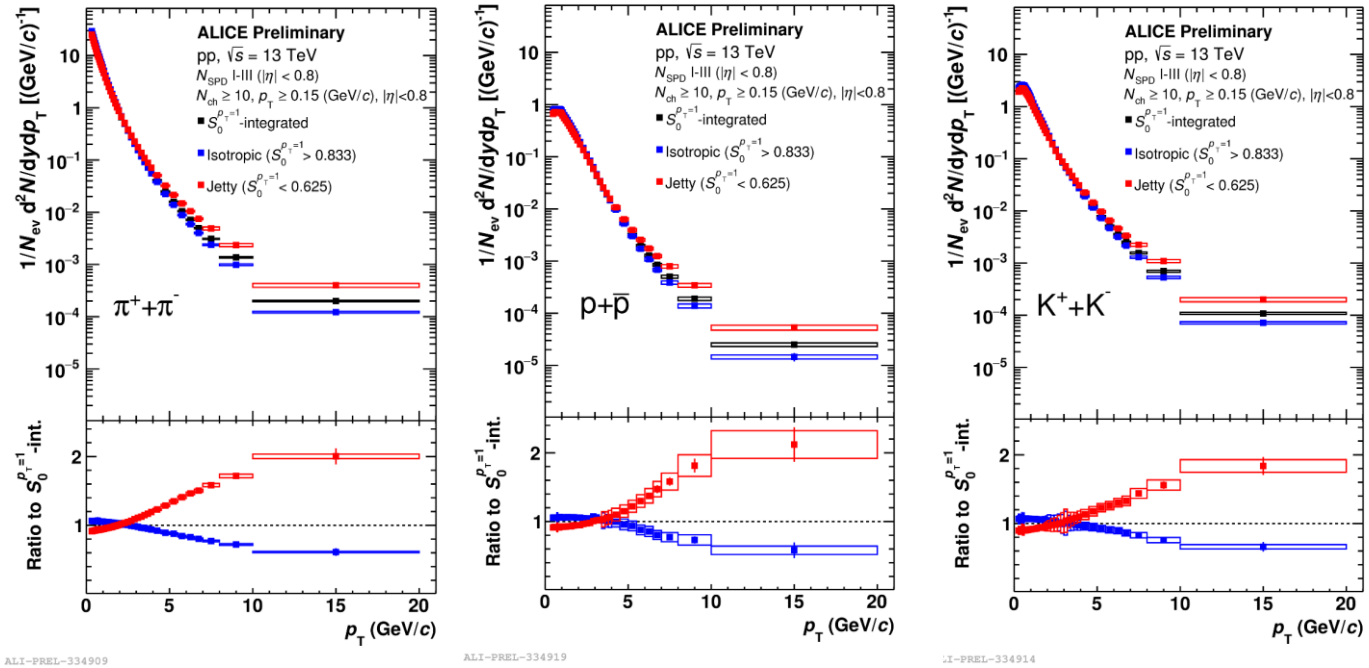
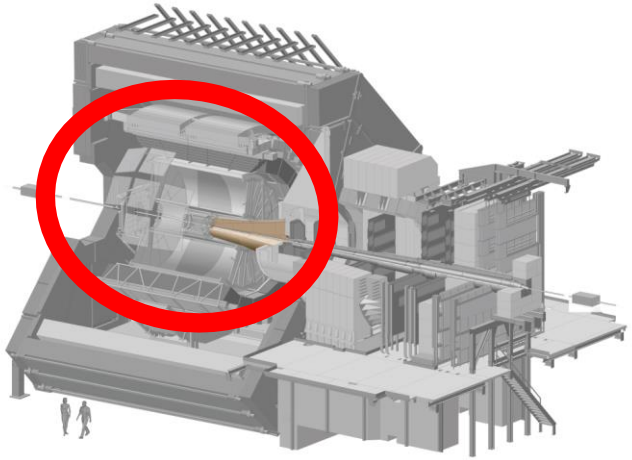
# Unweighed Transverse Spherocity $S_0^{p_T=1}$ – Results CL1 0 – 10%




$|\eta| < 0.8$

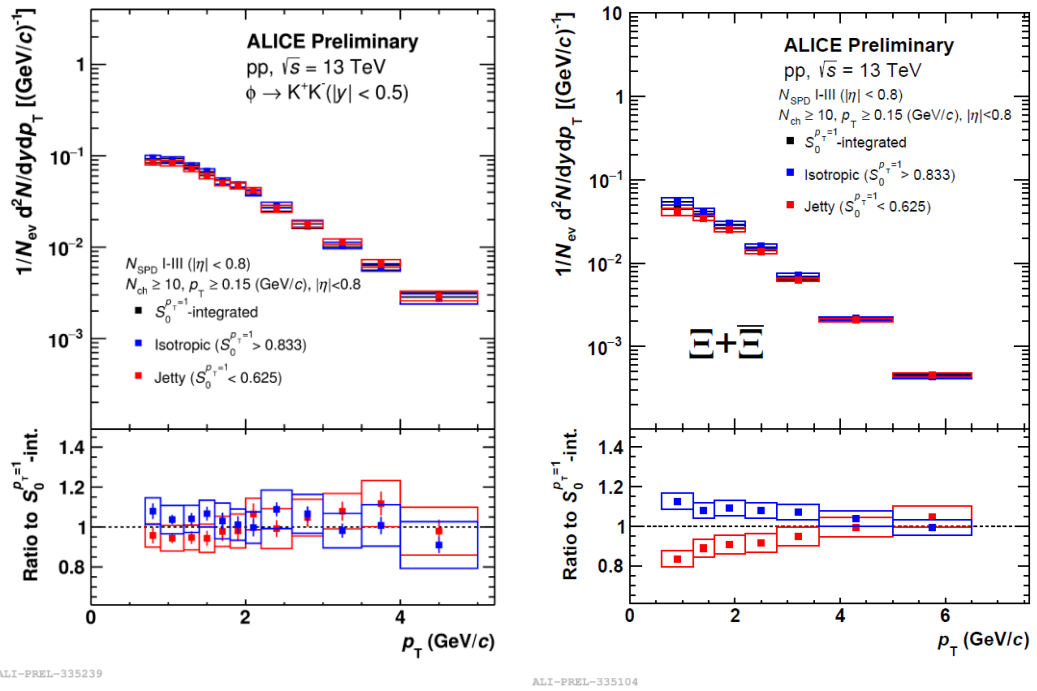


Difference between Isotropic and Jetty are now less distinct at low $p_T$.

$\pi/K/P$ show stronger $p_T$ dependence .

$\Xi$ converge to unity.

$\phi$ shows little or no $S_0^{p_T=1}$ dependence



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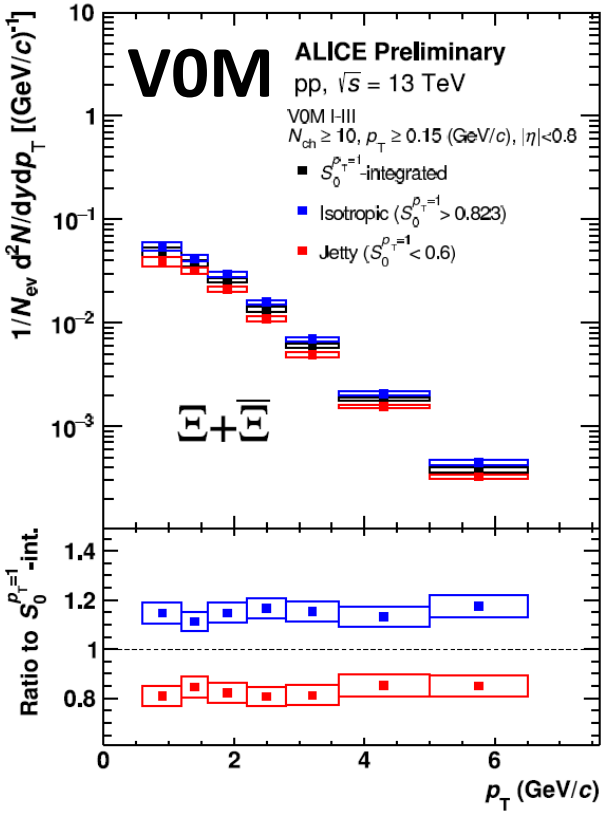


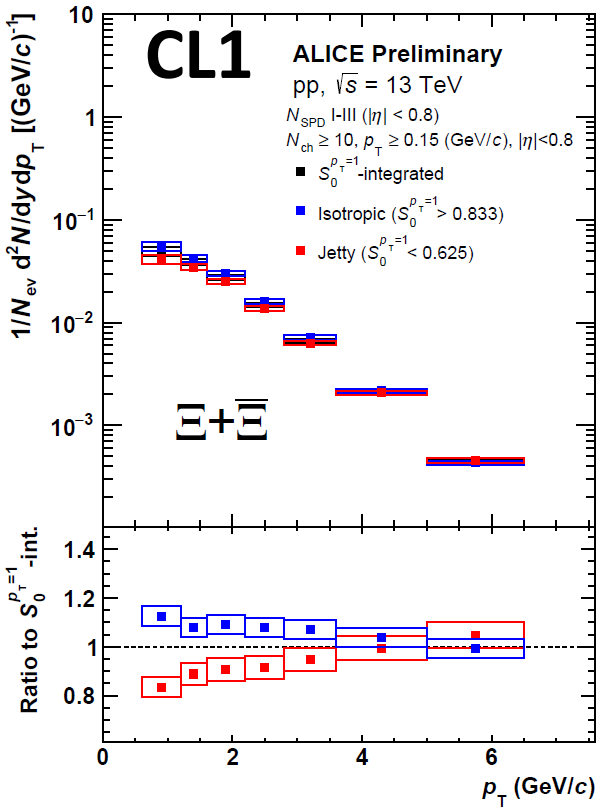


Let's take Ξ as an example to delve deeper into the V0M vs CL1 difference.

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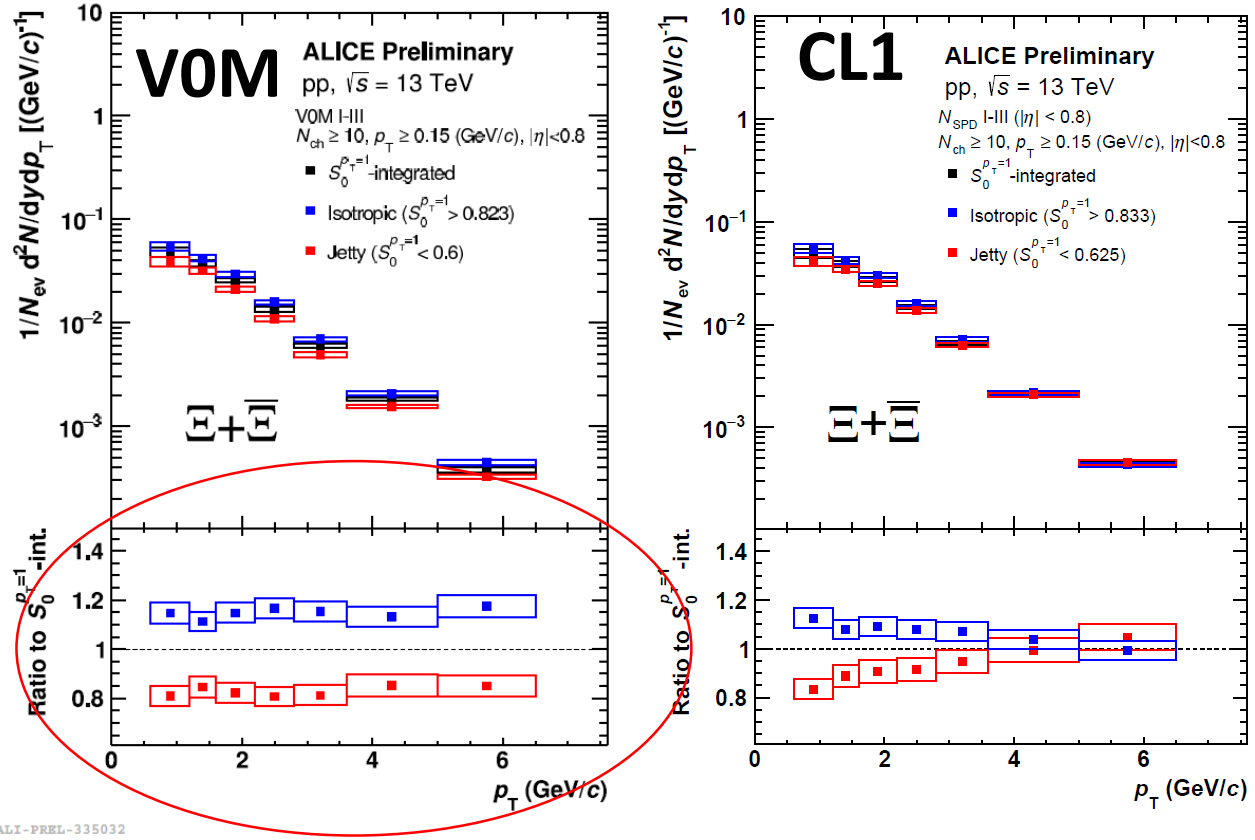


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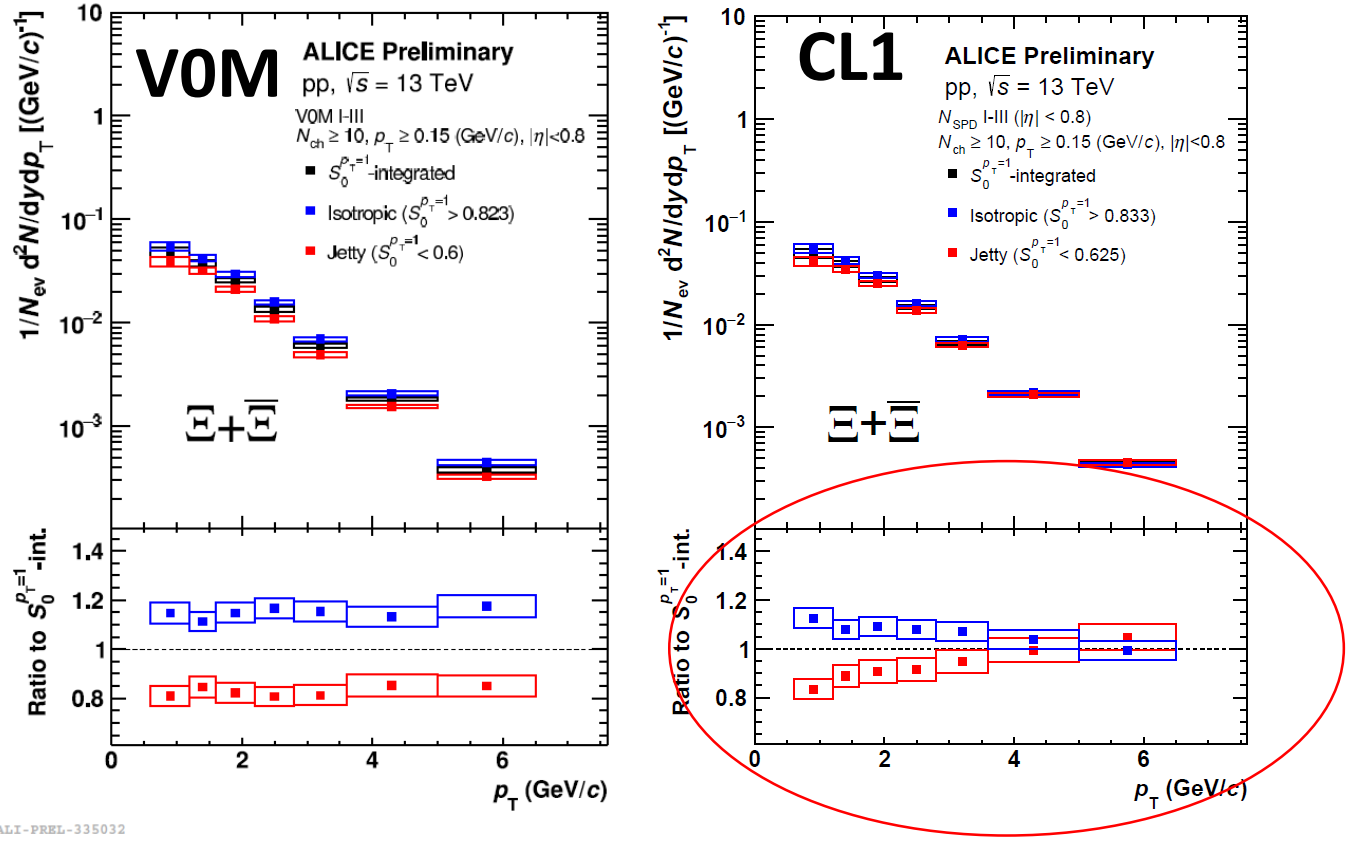


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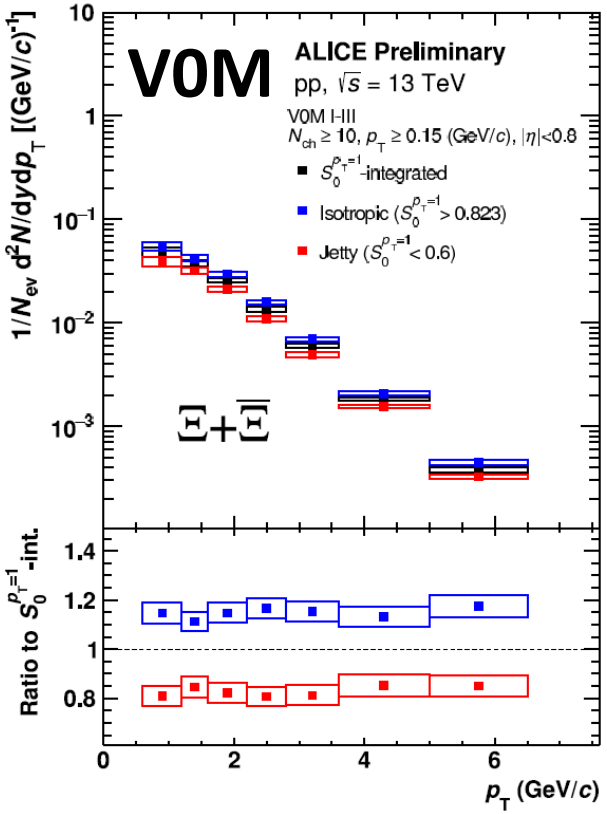


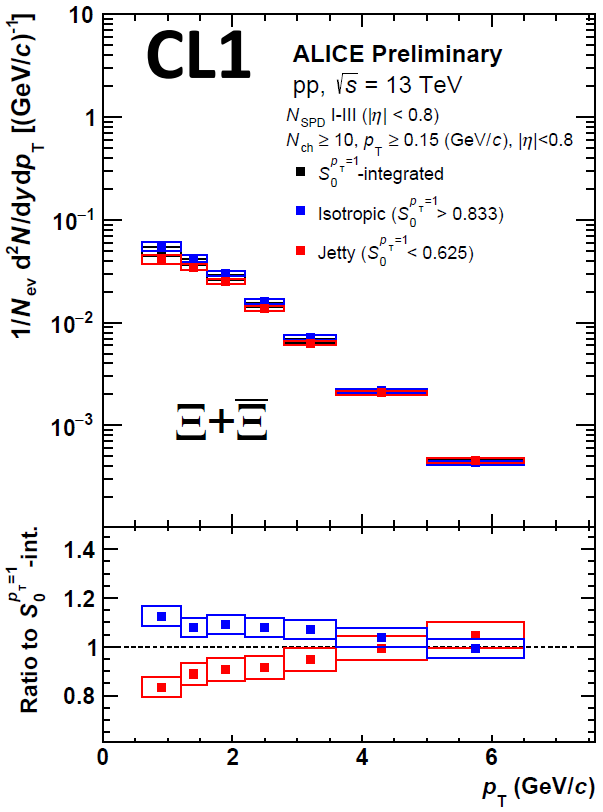


ALI-PREL-335032

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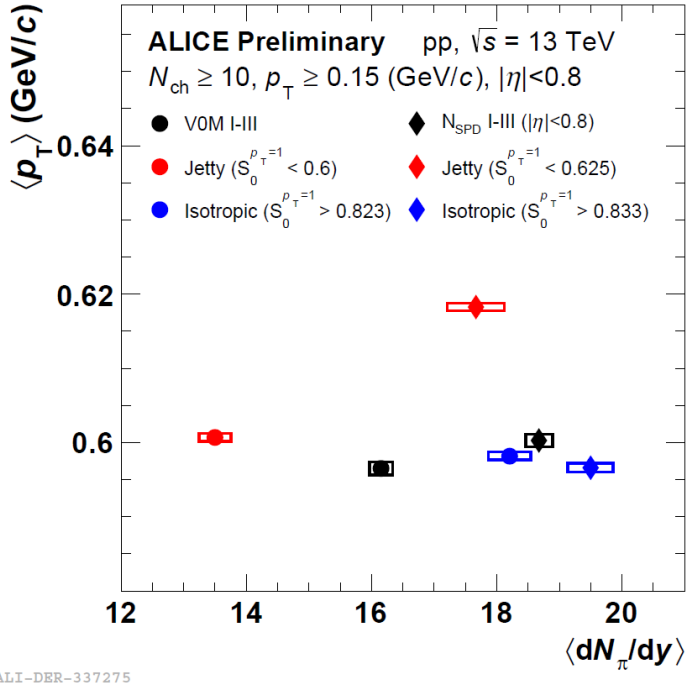
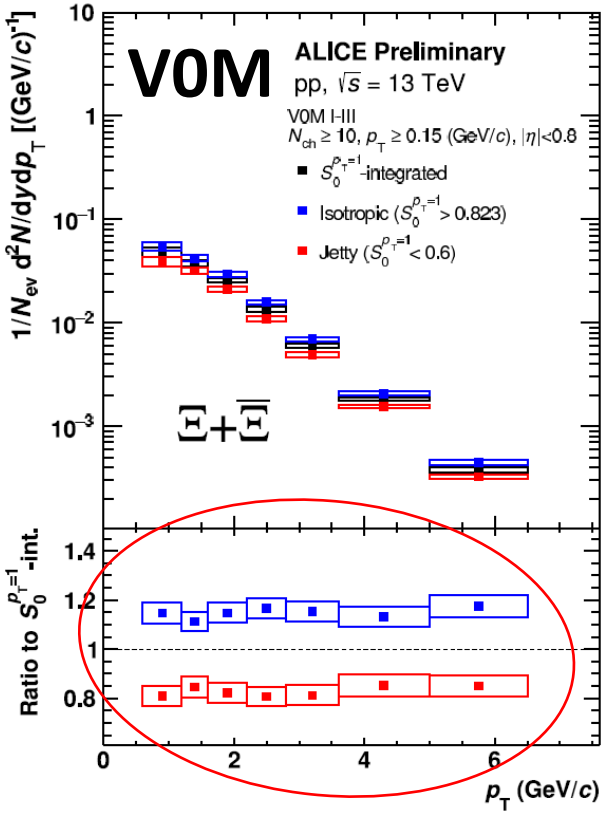
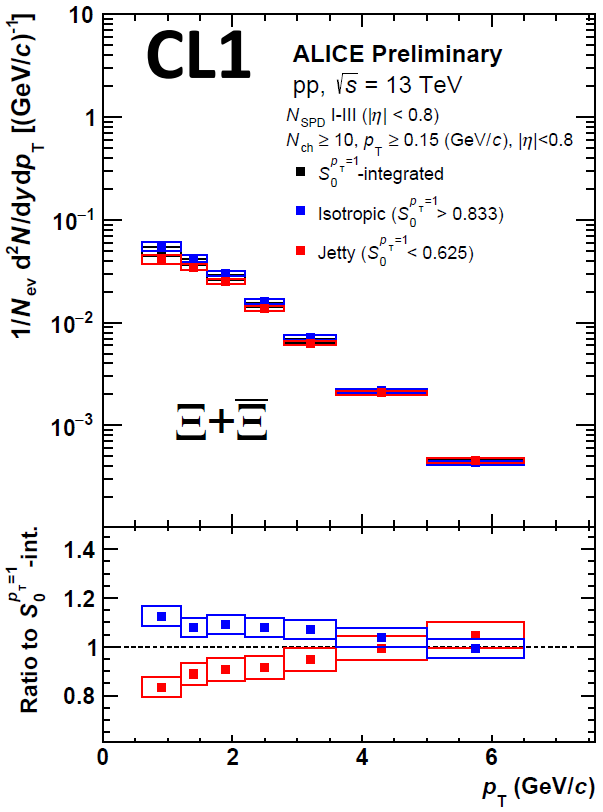



ALI-DER-337275

# Unweighed Transverse Spherocity $S_0^{p_T=1}$ – Results V0M Vs CL1

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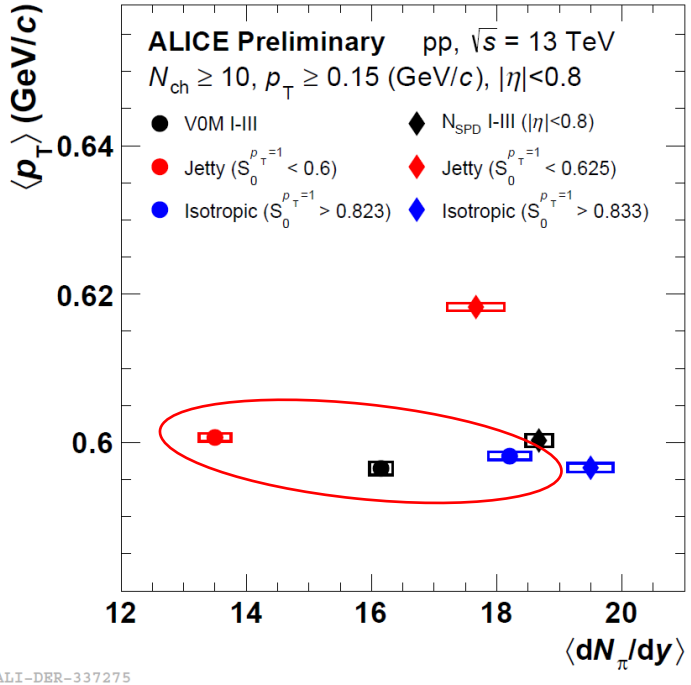


V0M triggered $S_0^{p_T=1}$ events have a large multiplicity difference, but exhibits similar $< p_T >$.

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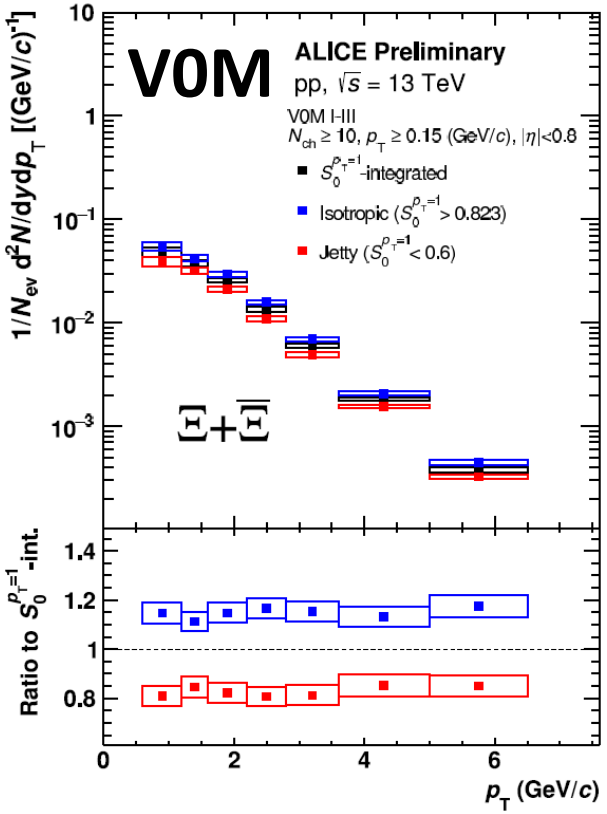


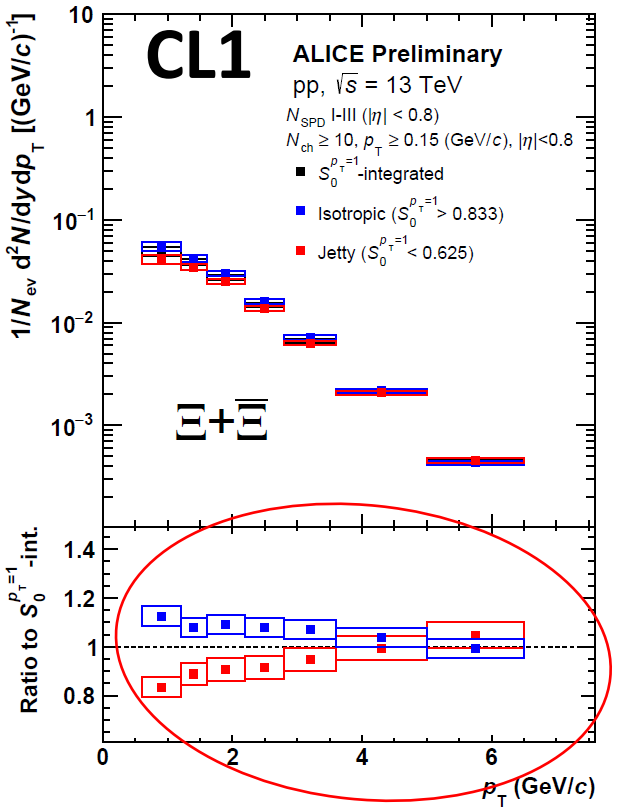


ALI-PREL-335032

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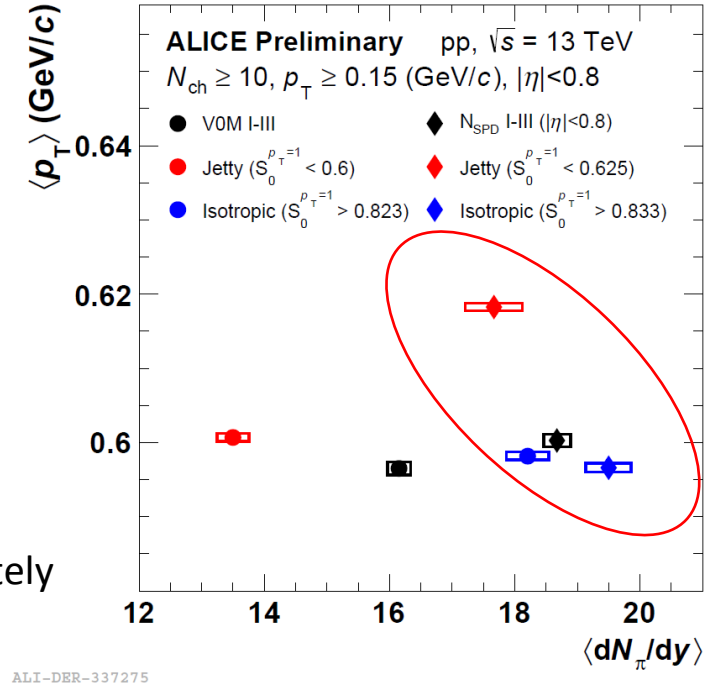


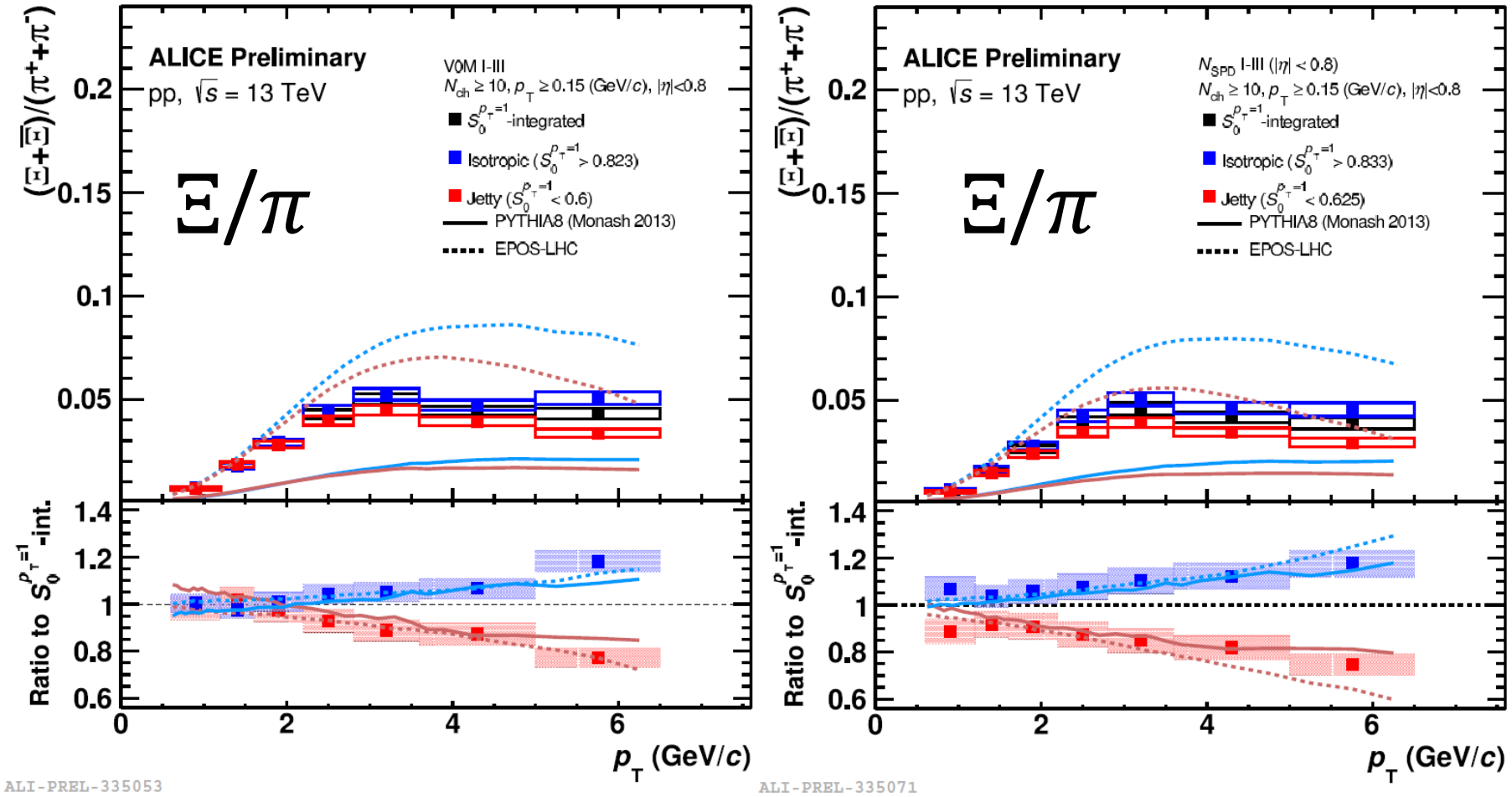

ALI-DER-337275

V0M triggered $S_0^{p_T=1}$ events have a large multiplicity difference, but exhibits similar $< p_T >$.

CL1 triggered $S_0^{p_T=1}$ events have a small multiplicity difference, and is able to accurately disentangle events based on hardness.

# Unweighed Transverse Spherocity $S_0^{p_T=1}$ – Results

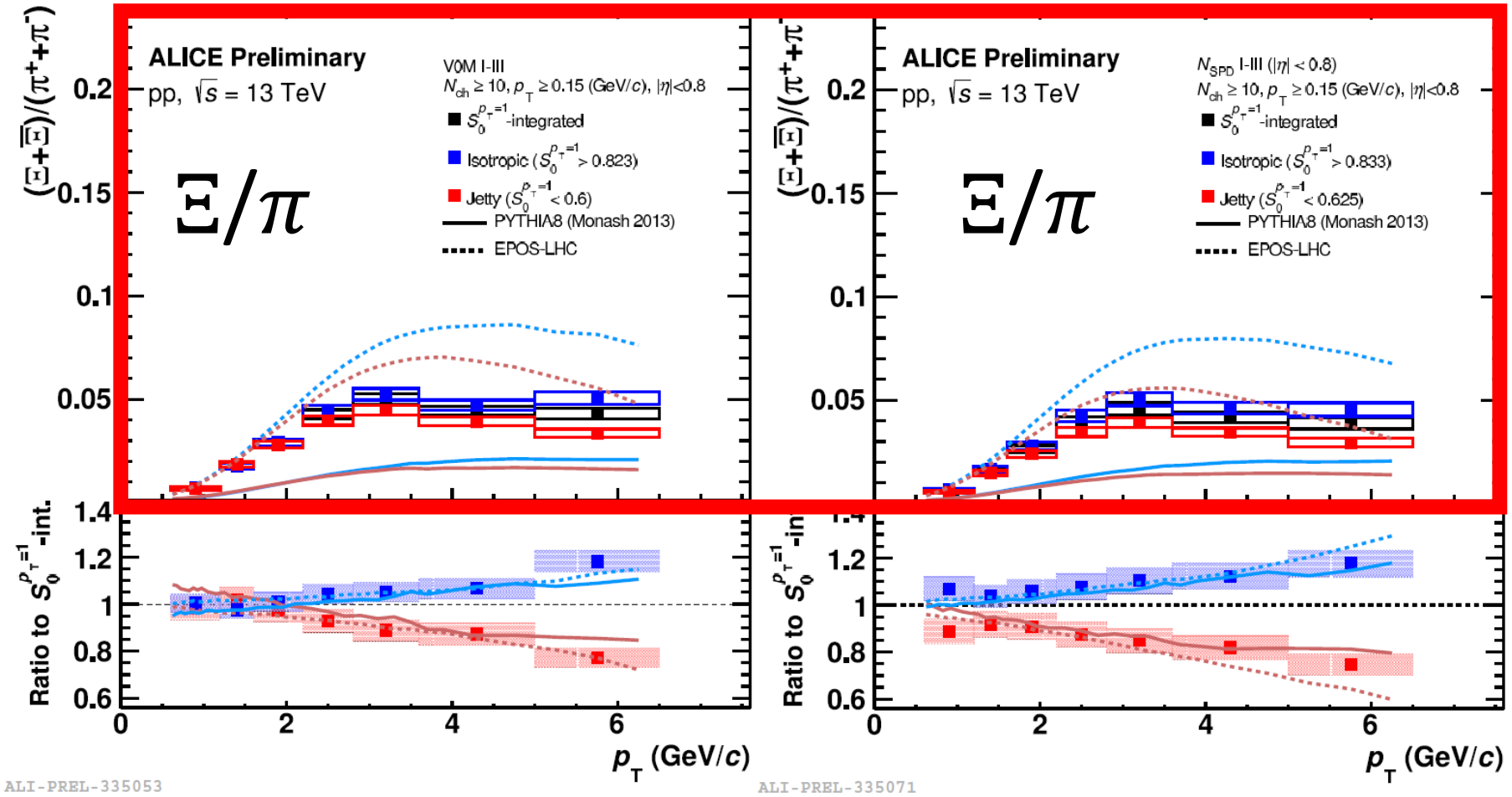
## Ratio to Pions – $\Xi/\pi$




Spherocity Integrated
Jetty
Isotropic
PYTHIA/EPOS

# Unweighed Transverse Spherocity $S_0^{p_T=1}$ – Results

## Ratio to Pions – $\Xi/\pi$




- Spherocity Integrated
- Jetty
- Isotropic
- PYTHIA/EPOS

The CL1 results suggest that one can enhance or suppress the strangeness enhancement by selecting on $S_0^{p_T=1}$

The generators do not describe the $p_T$ evolution

# Unweighed Transverse Spherocity $S_0^{p_T=1}$ – Results

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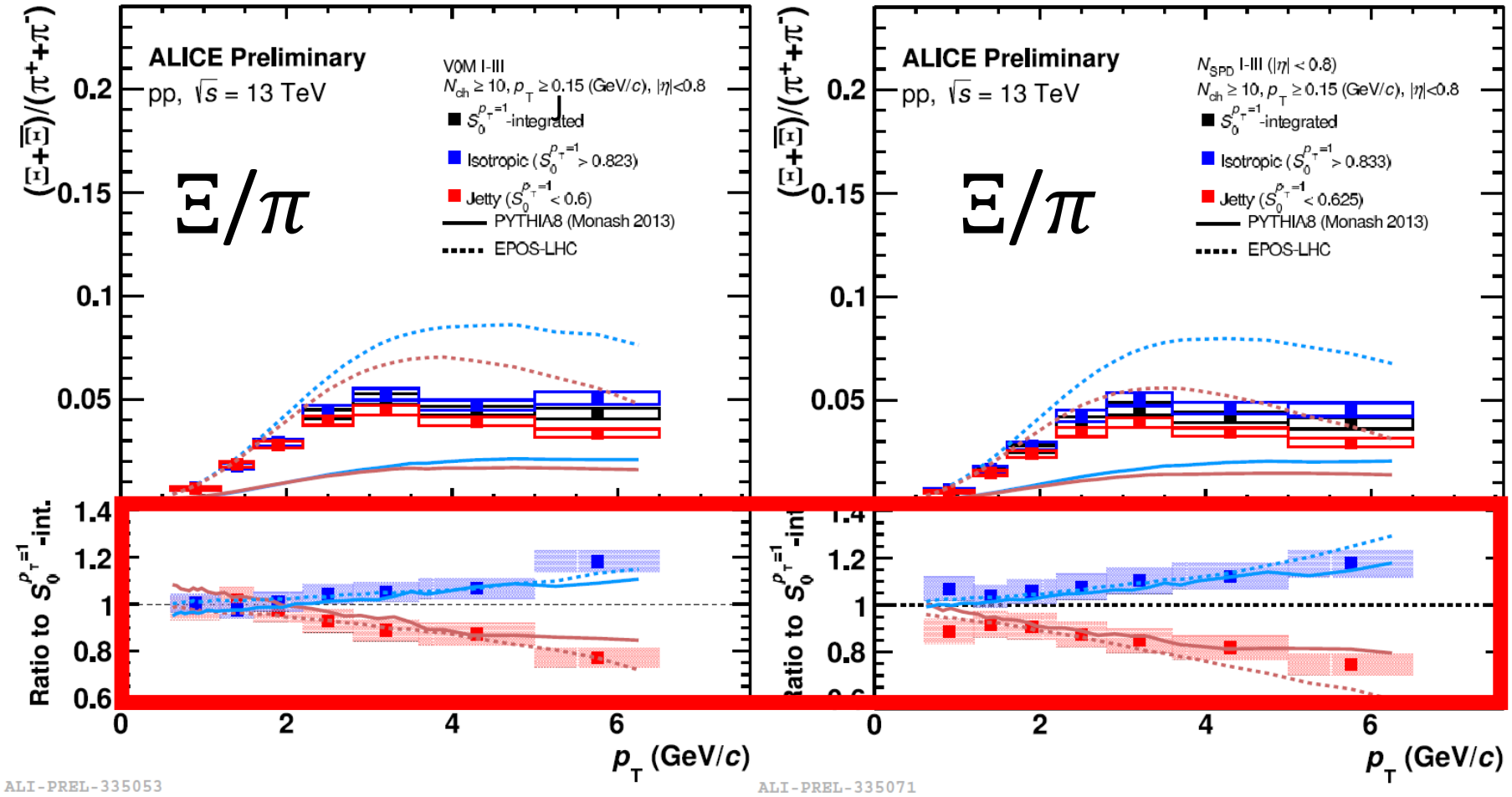



Spherocity Integrated
Jetty
Isotropic
PYTHIA/EPOS

The CL1 results suggest that one can enhance or suppress the strangeness enhancement by selecting on $S_0^{p_T=1}$

The generators do not describe the $p_T$ evolution

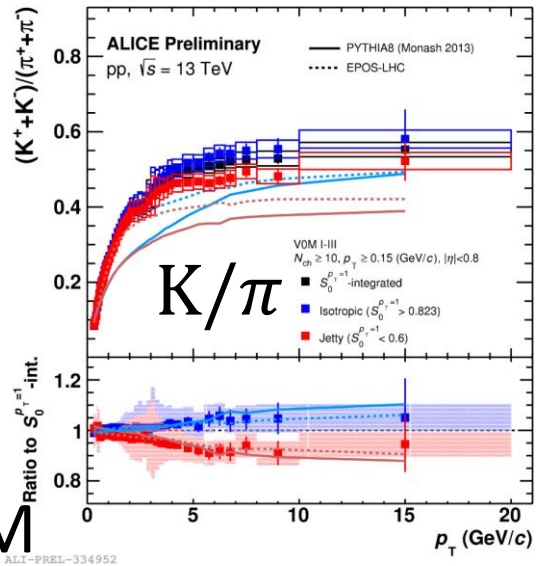
V0M results show a crossing between the two $S_0^{p_T=1}$ event classes, whereas one can observe a clear separation when using CL1

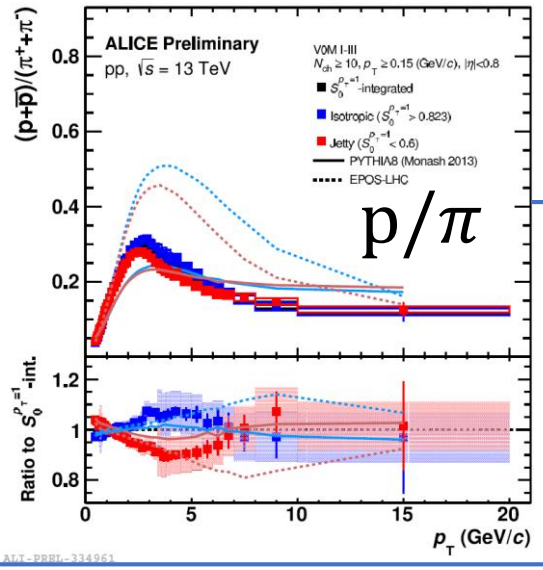
Both generators describe the double-ratio better

# Unweighed Transverse Spherocity $S_0^{p_T=1}$ – Results

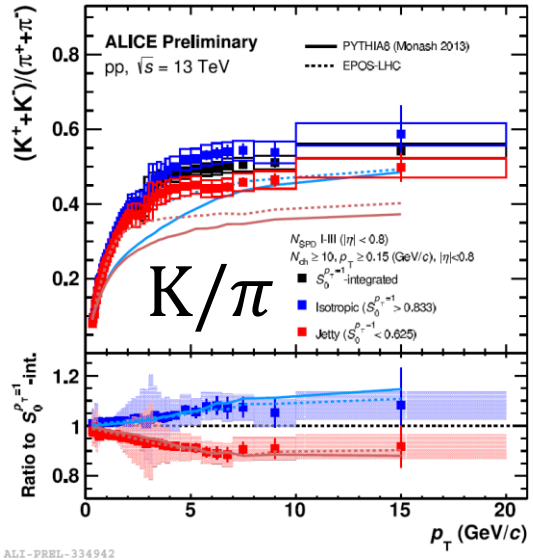
## Ratio to Pions - $K/\pi$ and $p/\pi$

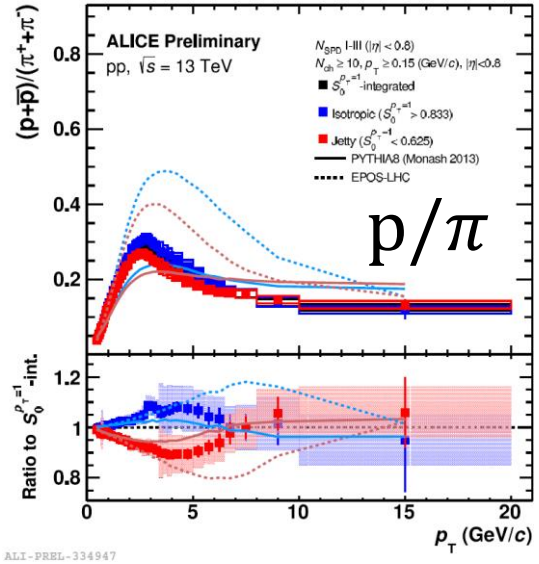
V0M




CL1



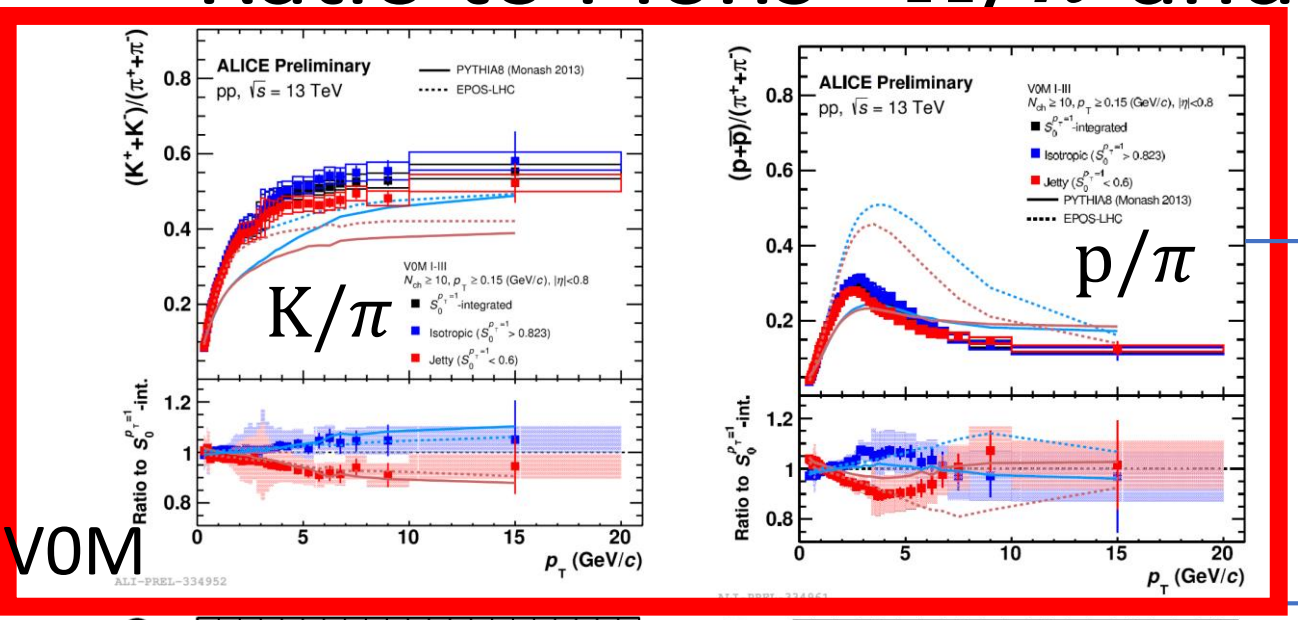

Spherocity Integrated
Jetty
Isotropic
PYTHIA/EPOS

The $K/\pi$ and $p/\pi$ ratios exhibit different features when triggering on CL1 or V0M.

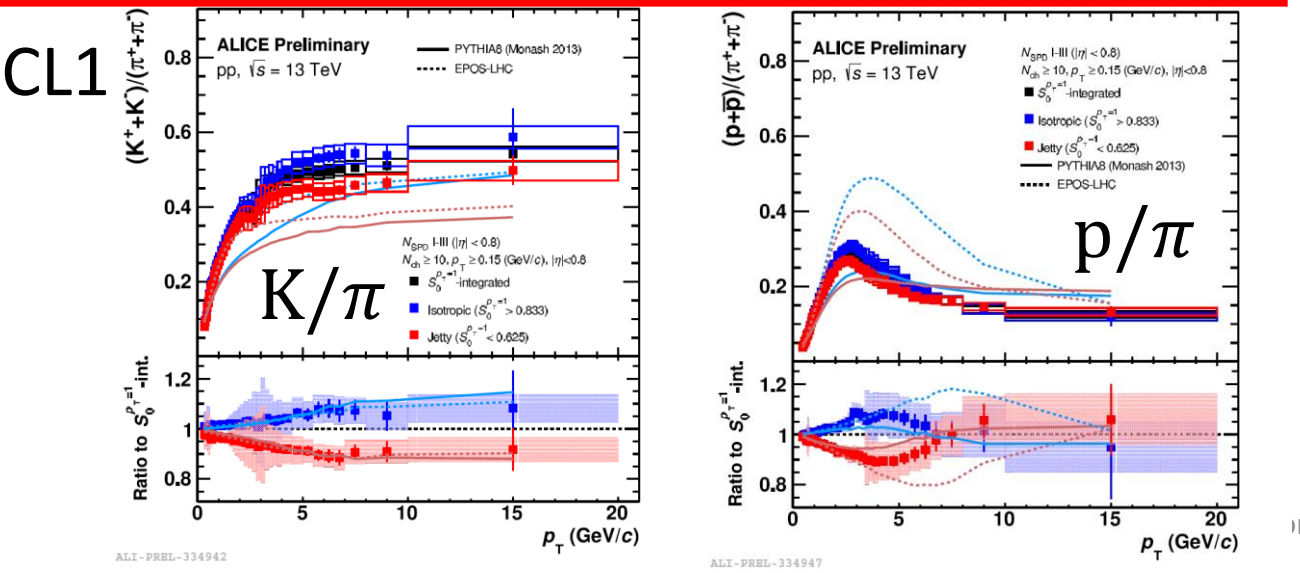
The ratios to $S_0^{p_T=1}$-integrated highlights a "radial flow"-like behavior in the V0M triggered events.

# Unweighed Transverse Spherocity $S_0^{p_T=1}$ – Results

## Ratio to Pions - $K/\pi$ and $p/\pi$




V0M




CL1

- Spherocity Integrated
- Jetty
- Isotropic
- PYTHIA/EPOS

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# Unweighed Transverse Spherocity $S_0^{p_T=1}$ – Results

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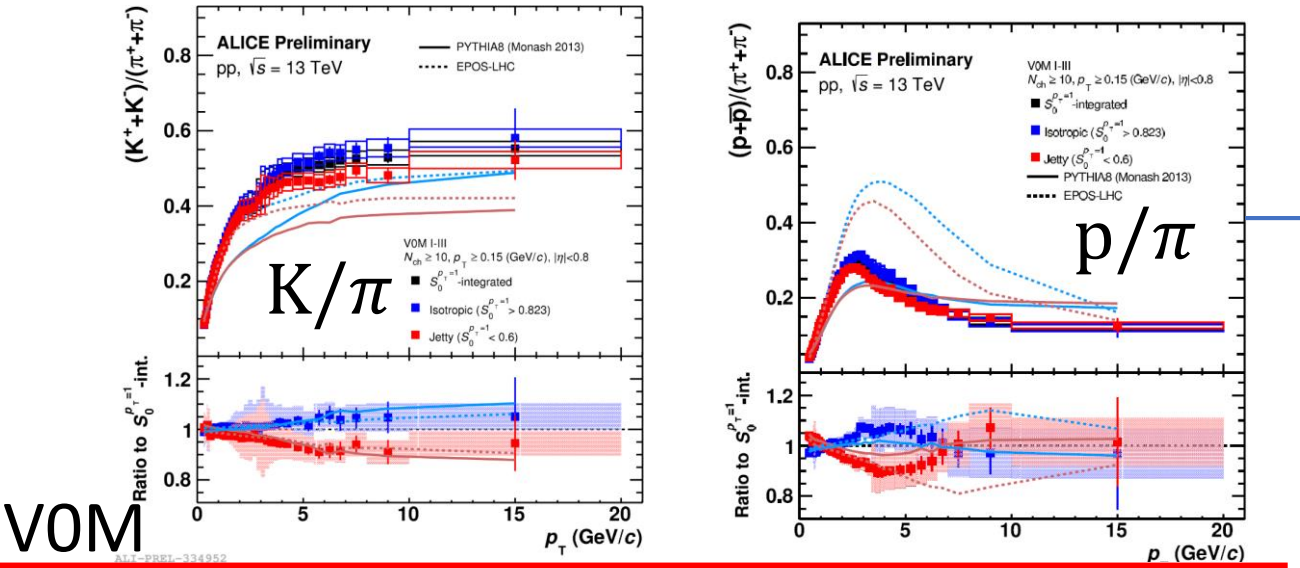
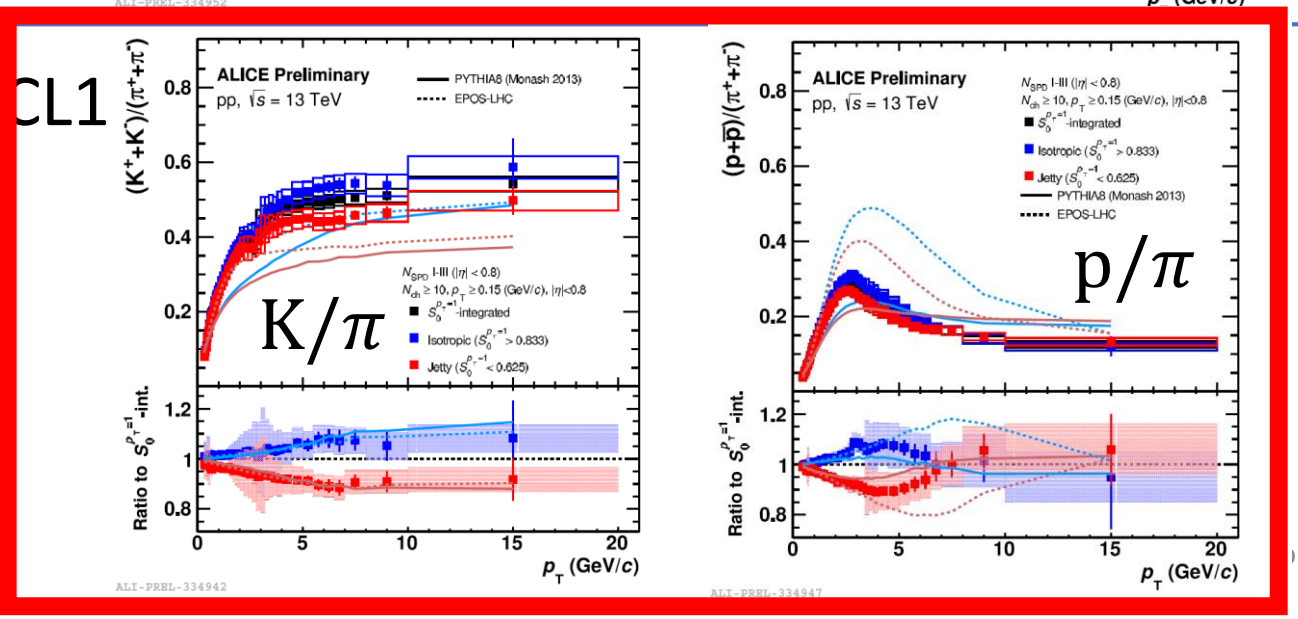



V0M




CL1

- Spherocity Integrated
- Jetty
- Isotropic
- PYTHIA/EPOS

The $K/\pi$ and $p/\pi$ ratios exhibit different features when triggering on CL1 or V0M.

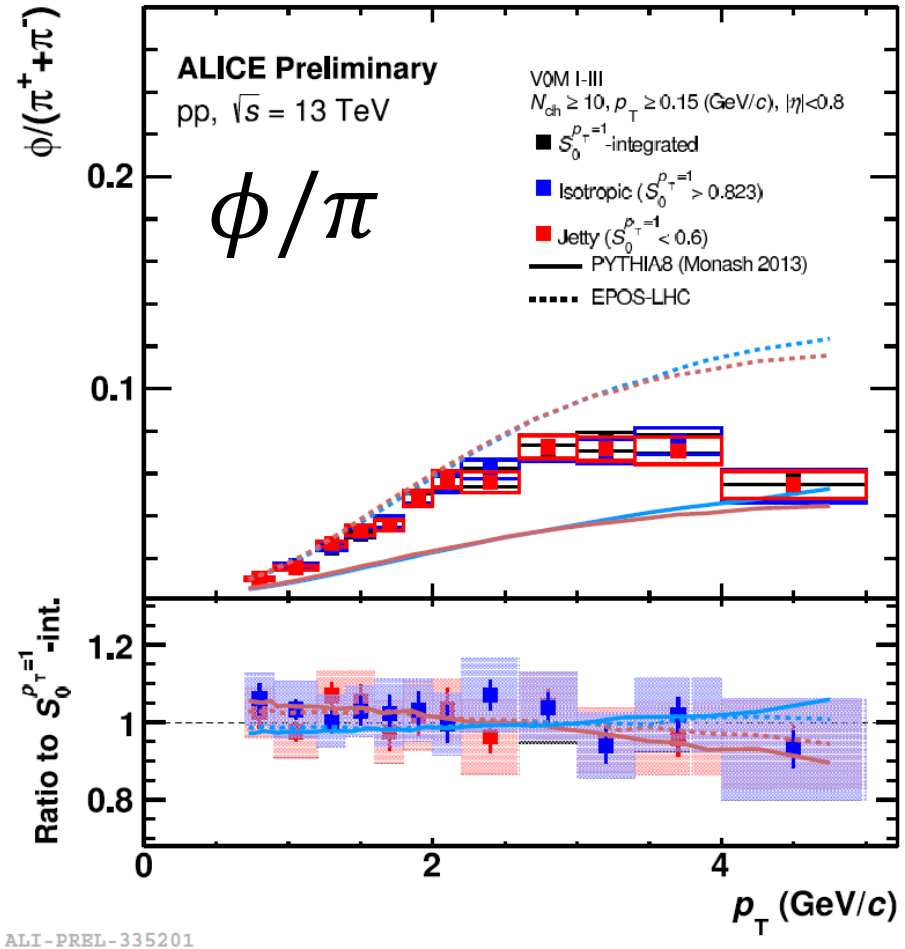
The ratios to $S_0^{p_T=1}$-integrated highlights a "radial flow"-like behavior in the V0M triggered events.

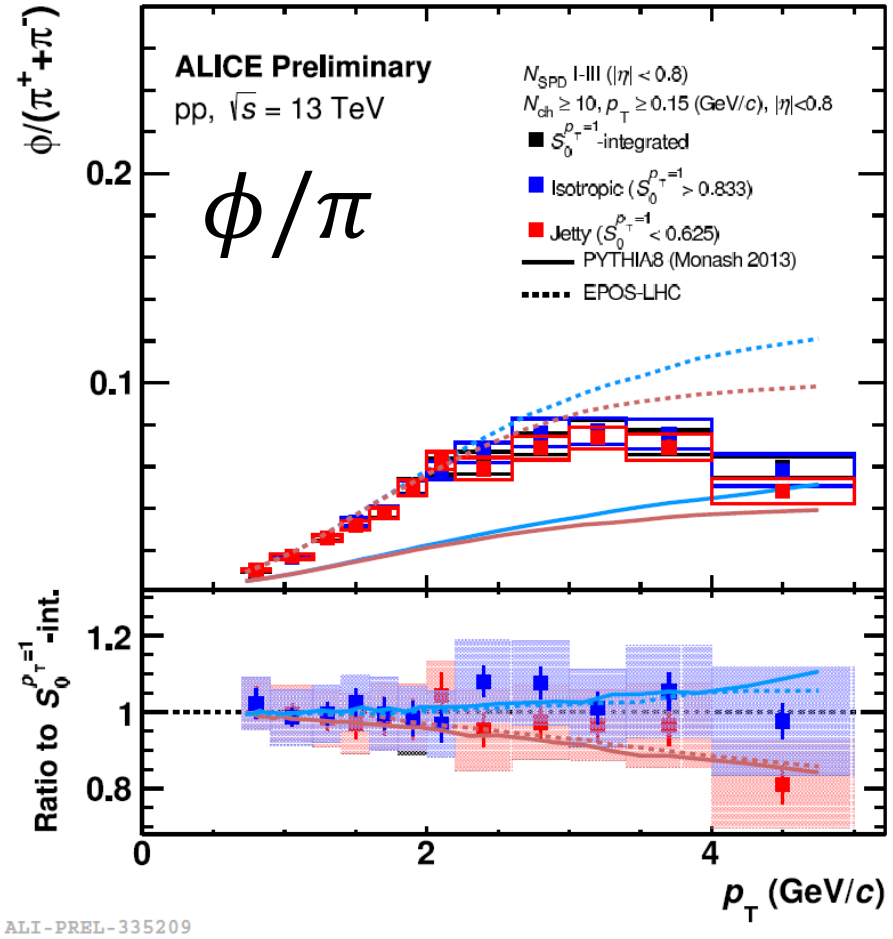
The CL1 ratios suggests a general softening or hardening.

The jetty CL1 events show behaviour similar to the jet $p_T$ evolution
→ fragmentation "pushes" kaons and protons to higher $p_T$.

# Unweighed Transverse Spherocity $S_0^{p_T=1}$ – Results

## Ratio to Pions - $\phi/\pi$



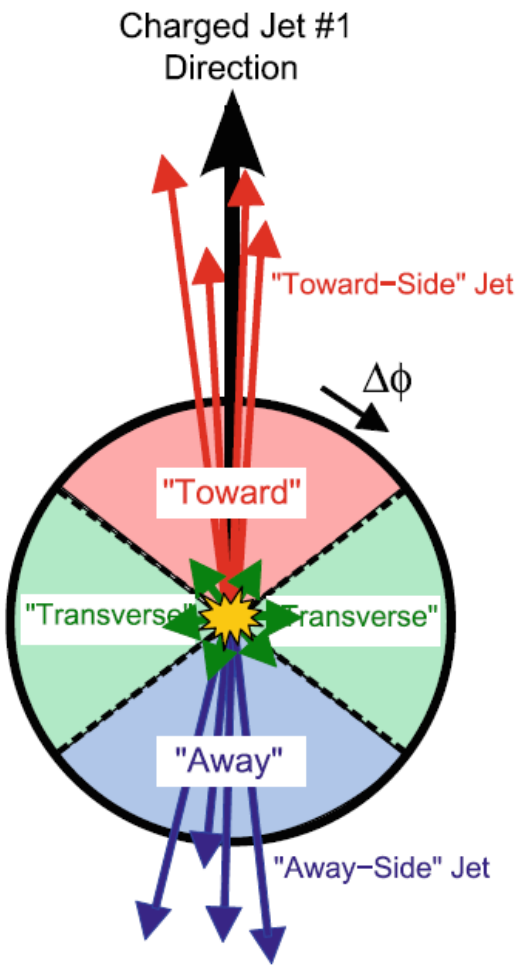

Unlike the K/p/Ξ, the $\phi$ does not give a clear picture.

There seems to be no significant difference of $\phi$ production in Jetty or Isotropic events.

There is also no difference between V0M and CL1 triggered events.

# $\pi/K/p/\phi/\Xi$ Production as a Function of $R_T$

- $R_T$ aims to measure the hadron production by varying the amount of underlying event.

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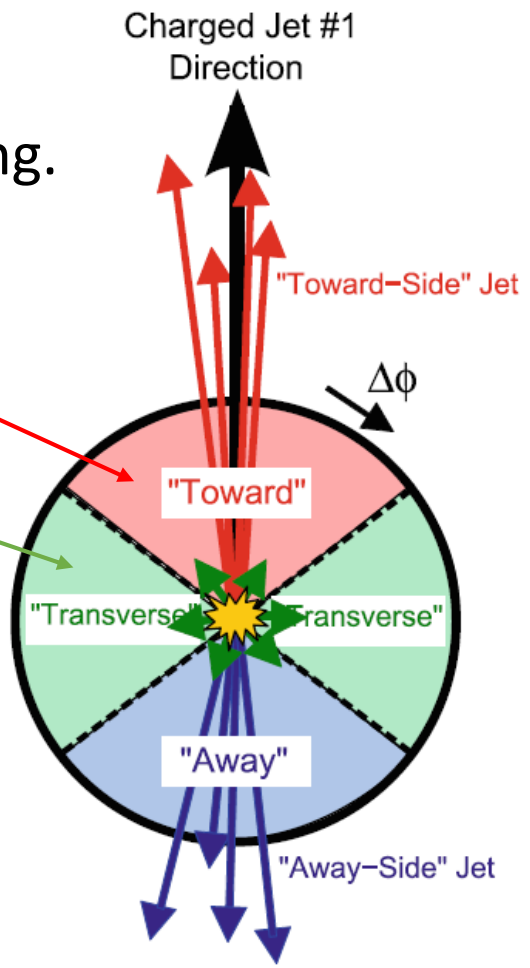
# $\pi/K/p/\phi/\Xi$ Production as a Function of $R_T$

- $R_T$ aims to measure the hadron production by varying the amount of underlying event.

- 5 GeV trigger particle is required to ensure hard scattering.
  - Event is sliced into different sectors, relative to leading trigger particle.
    - ”Toward” region contains hard scattering + UE.
    - ”Transverse” region consists mostly of UE.




Eur. Phys. J. C62 (2009), 237

# $\pi/K/p/\phi/\Xi$ Production as a Function of $R_T$

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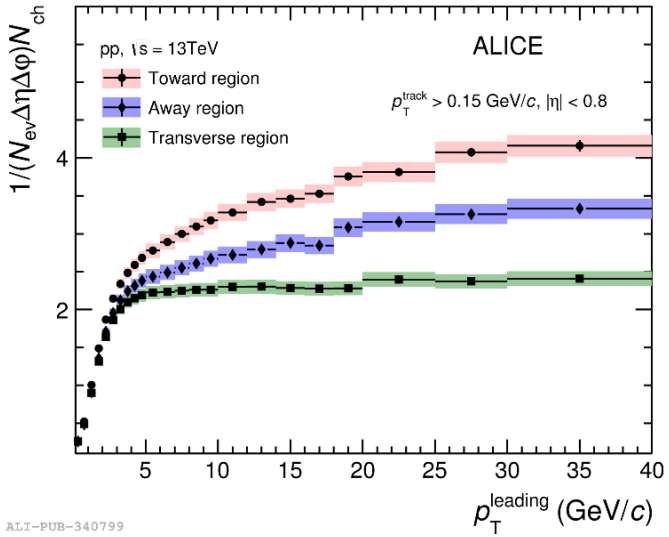
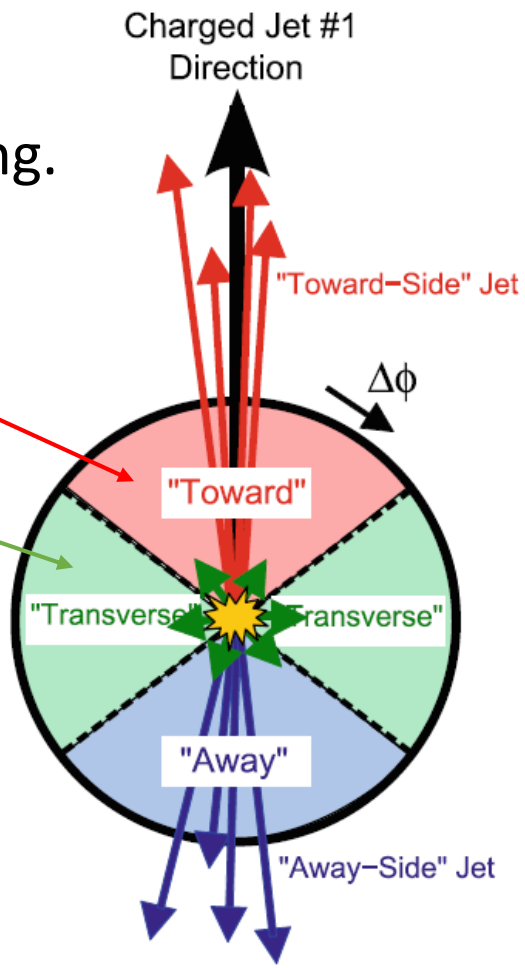



Number of MPIs is relatively stable in Transverse when trigger particle is >5 GeV.




Eur. Phys. J. C62 (2009), 237

# $\pi/K/p/\phi/\Xi$ Production as a Function of $R_T$

- $R_T$ aims to measure the hadron production by varying the amount of underlying event.

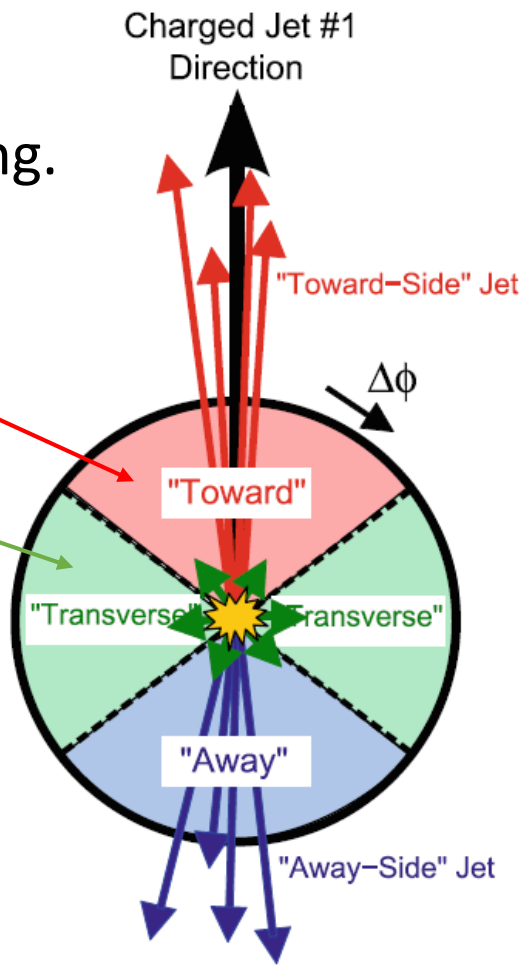
- 5 GeV trigger particle is required to ensure hard scattering.
  - Event is sliced into different sectors, relative to leading trigger particle.
    - ”Toward” region contains hard scattering + UE.

- The UE is then controlled by varying $R_T$ in each region.

- $$R_T = \frac{N_T}{<N_T>}$$

  ← Charged particles in ”Transverse”

  ← Average charged particles in ”Transverse”

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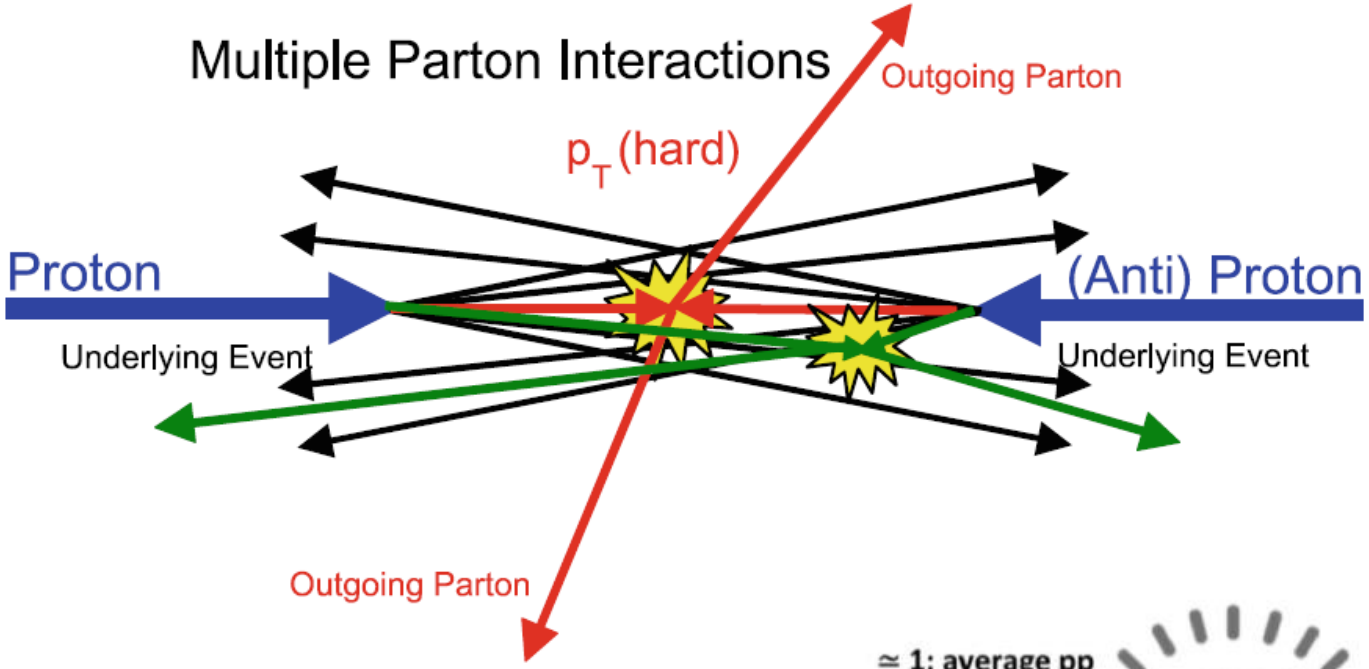
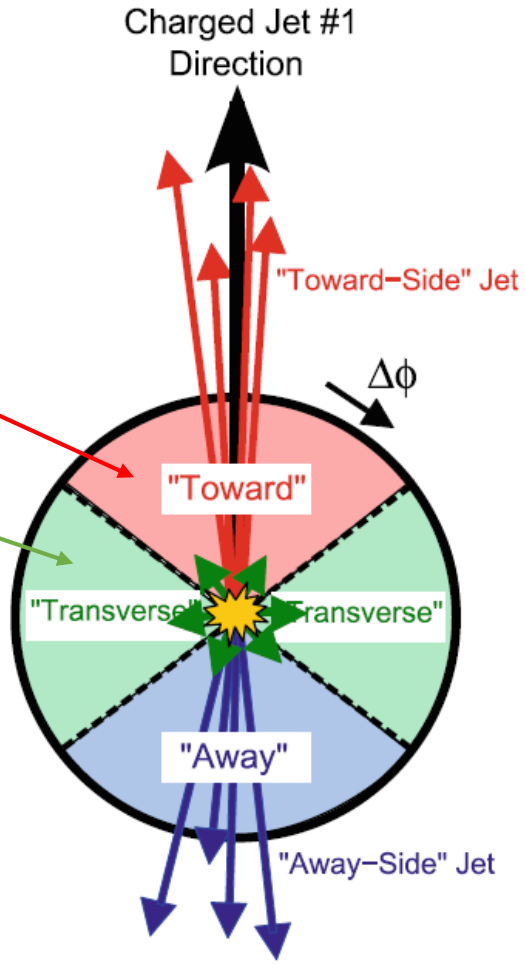
# $\pi/K/p/\phi/\Xi$ Production as a Function of $R_T$

The idea is that with $R_T$, you can now gauge the UE, which in models like PYTHIA is related to the number of Multiple-Parton Interactions (MPIs).





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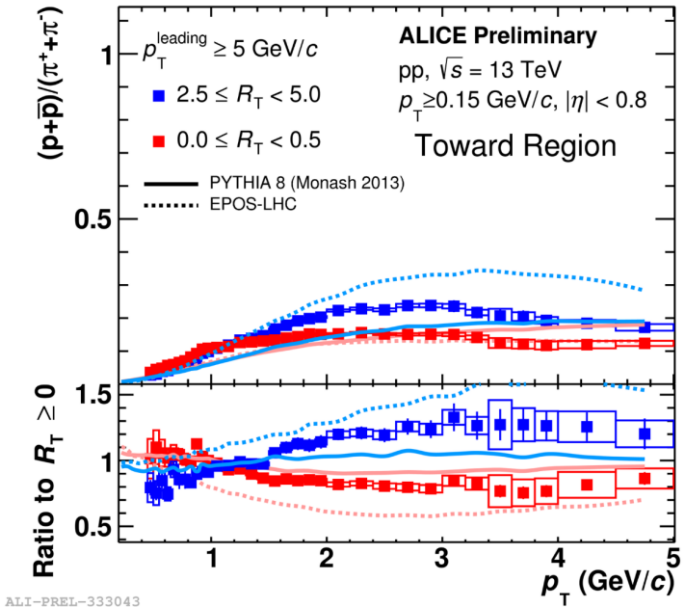
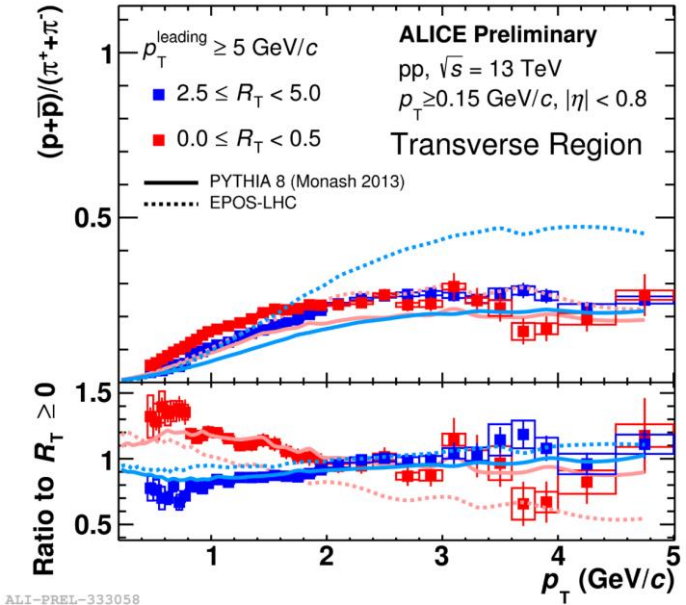
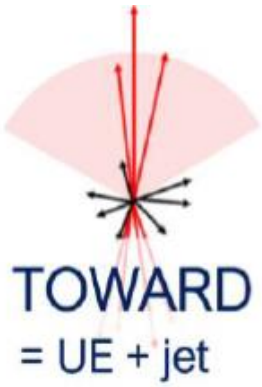
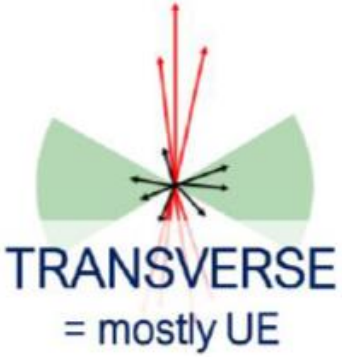
# $R_T$ – Results



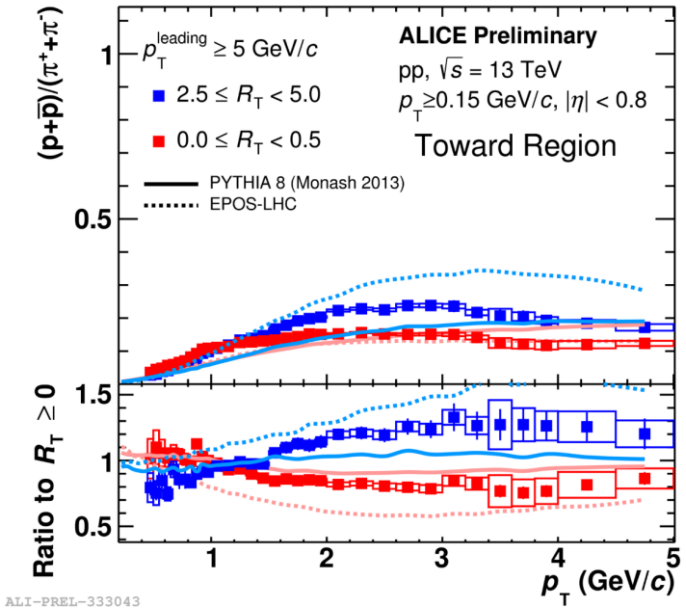



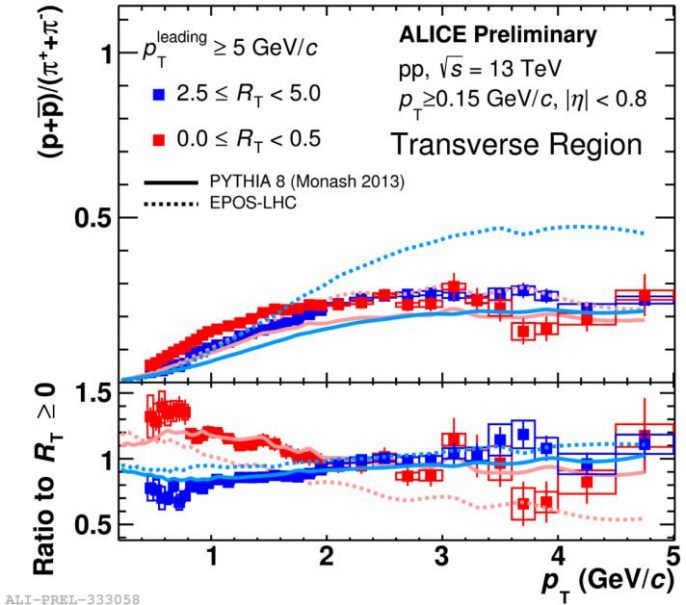



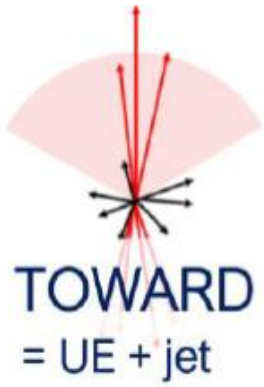



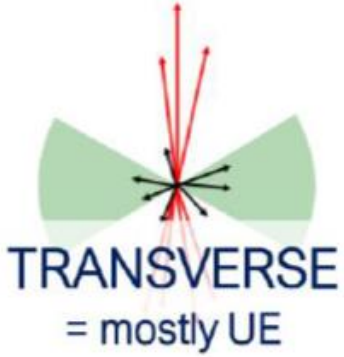

- The proton-to-pion ratio indicates a radial flow-like behaviour between the two $R_T$ cases.
  - This effect is stronger in the Transverse region.

# $R_T$ – Results



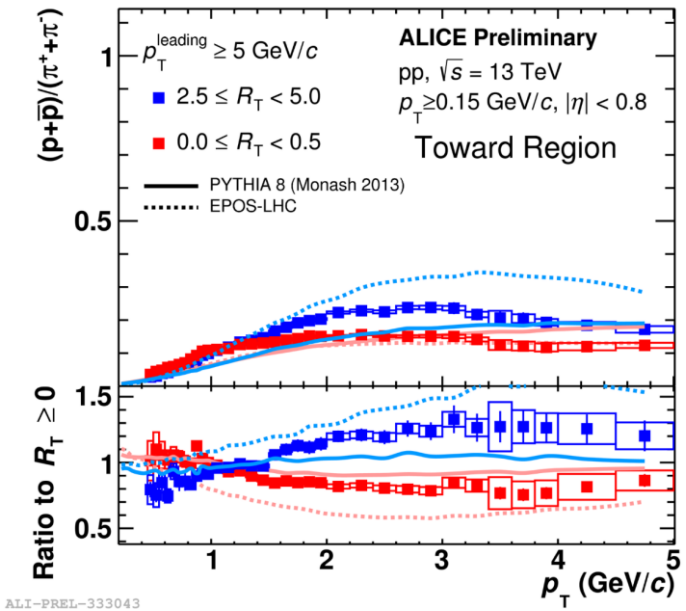



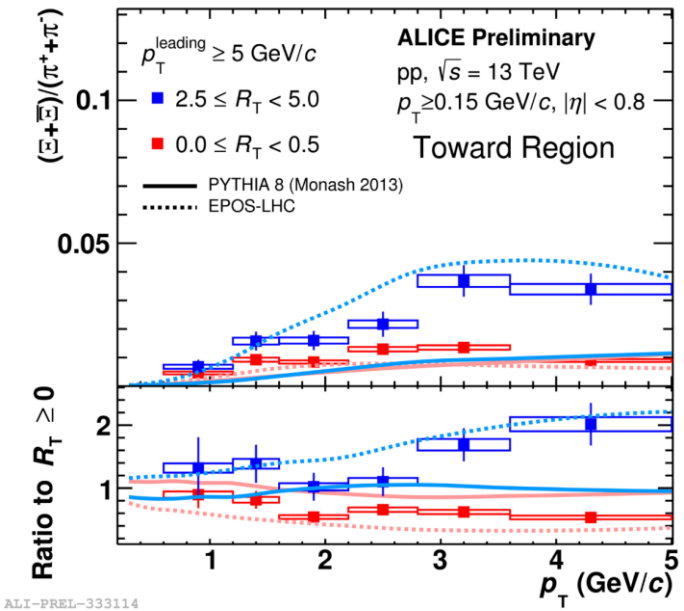



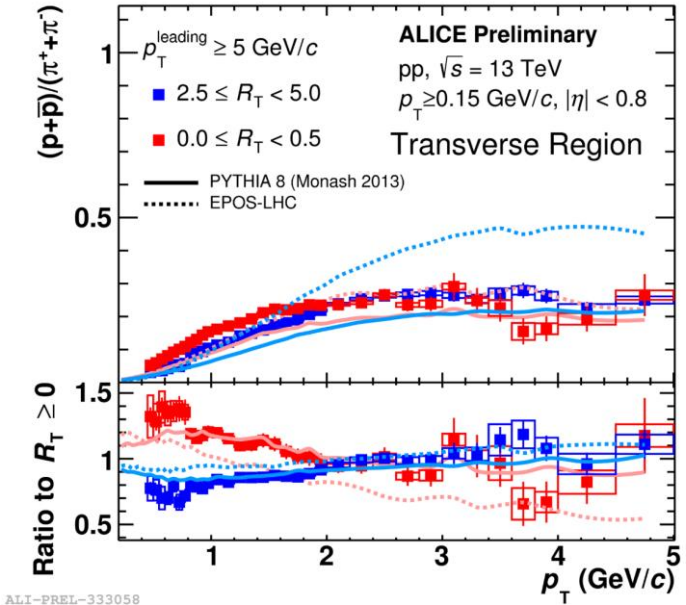



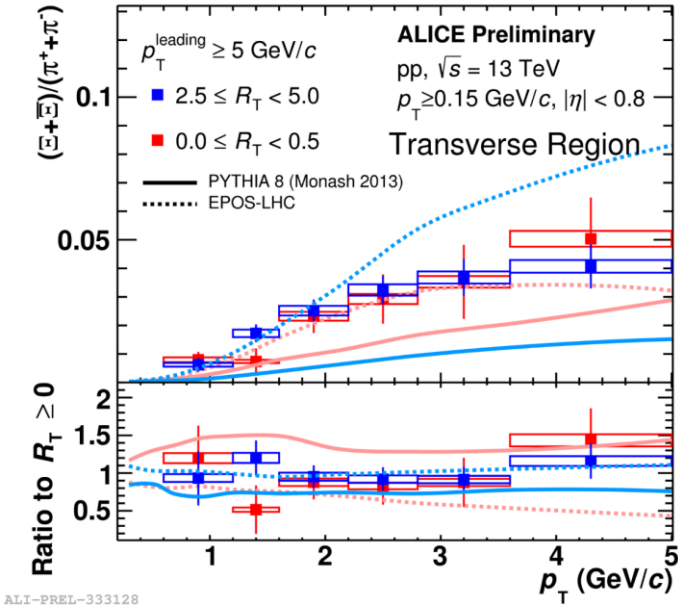

- The proton-to-pion ratio indicates a radial flow-like behaviour between the two $R_T$ cases.
  - This effect is stronger in the Transverse region.
- Both models are able to somewhat reproduce the low-$R_T$ trend.
  - These events are most likely dominated by (hard) ee physics.
- However, both models fail to describe the high-$R_T$ trend.
  - EPOS performs a bit better qualitative job than PYTHIA.

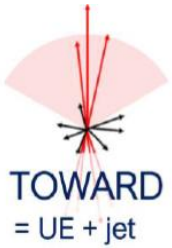
# $R_T$ – Results

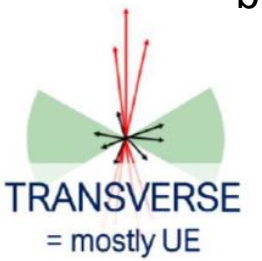


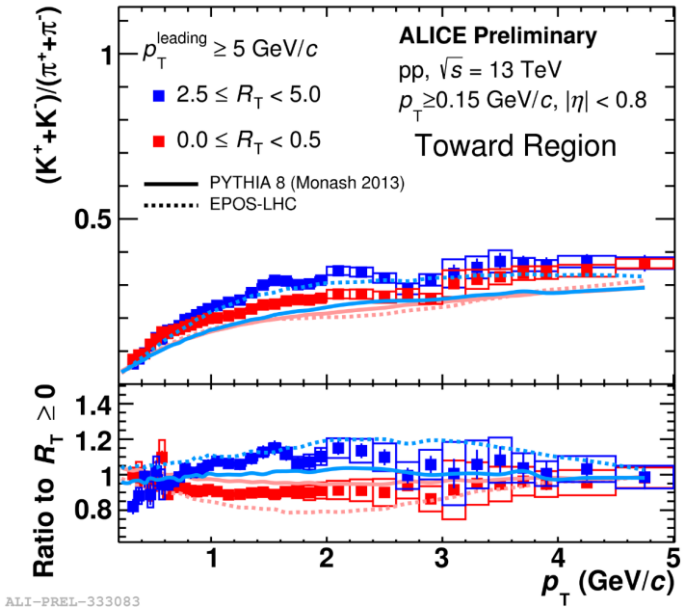



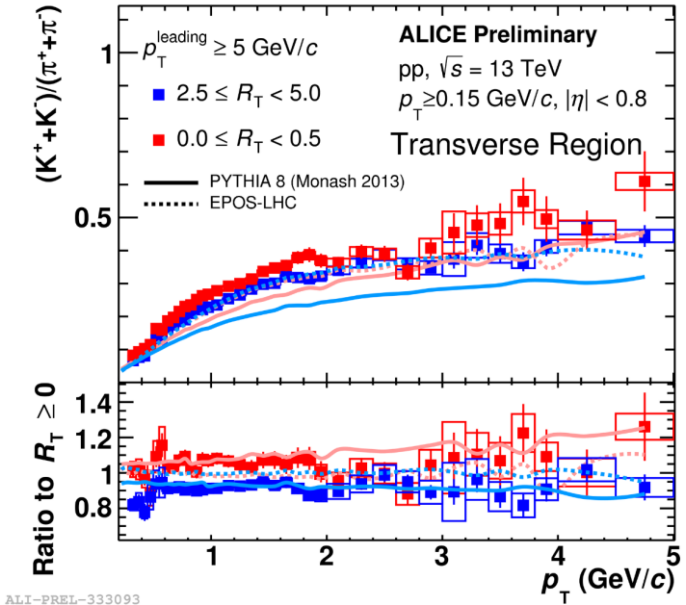



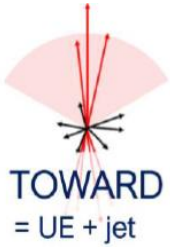

- The proton-to-pion ratio indicates a radial flow-like behaviour between the two $R_T$ cases.
  - This effect is stronger in the Transverse region.
- Both models are able to somewhat reproduce the low-$R_T$ trend.
  - These events are most likely dominated by (hard) ee physics.
- However, both models fail to describe the high-$R_T$ trend.
  - EPOS performs a bit better qualitative job than PYTHIA.

- The $\Xi$ -to-pion ratio also show similar behaviour, but more enhanced.
  - high-$R_T$ for Xi-to-pion in Toward approaches the Transverse values.
  - EPOS accurately describes the high-$R_T$ Toward region.

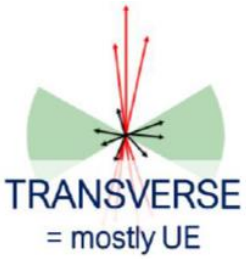
# $R_T$ – Results



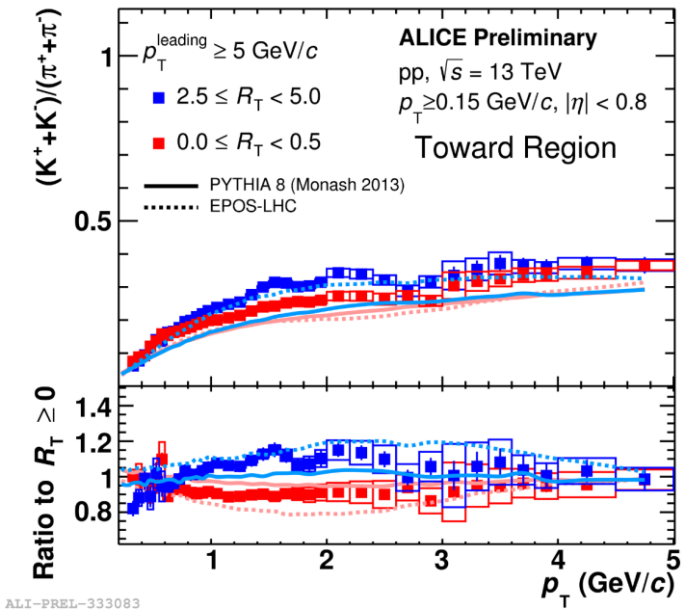



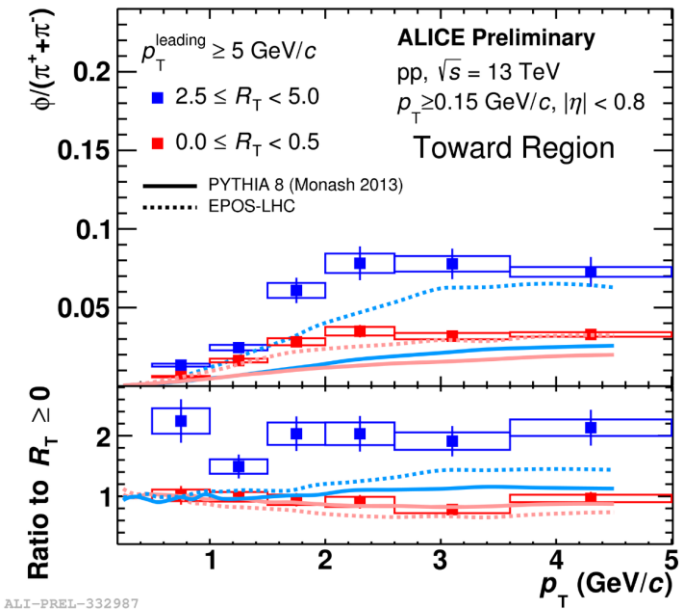



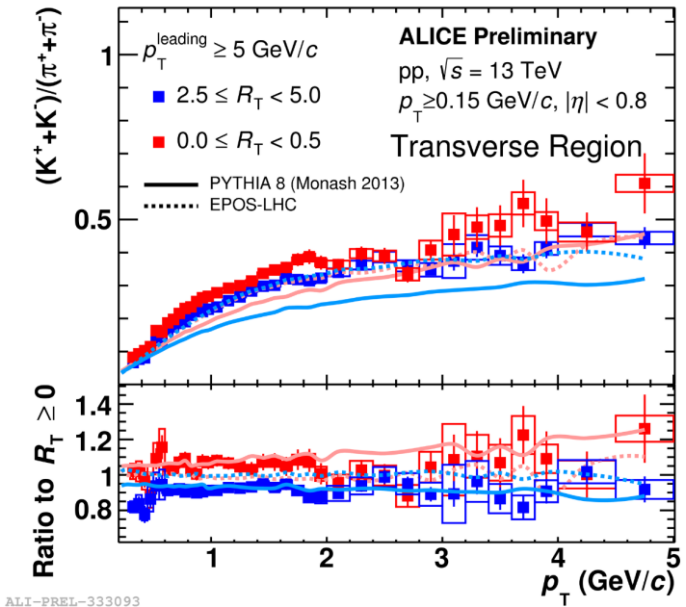

- Kaon-to-pion ratio contain similar effects seen in proton-to-pion ratio.
  - Both generators are able to somewhat predict the double-ratio.
  - Also exhibits a radial flow-like effect.

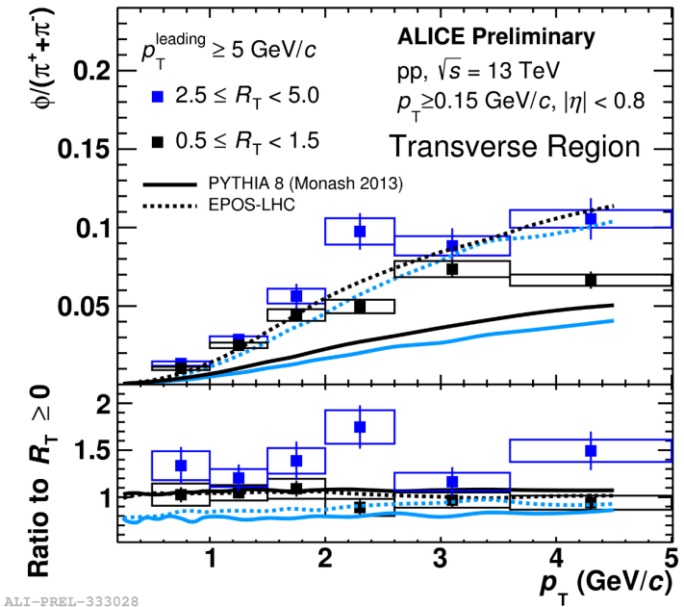


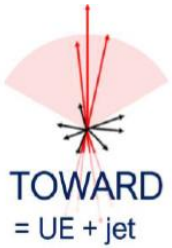
# $R_T$ – Results



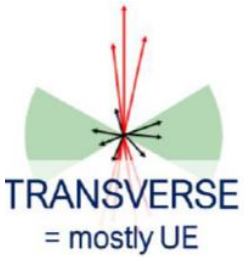




- Kaon-to-pion ratio contain similar effects seen in proton-to-pion ratio.
  - Both generators are able to somewhat predict the double-ratio.
  - Also exhibits a radial flow-like effect.

- The Phi-to-pion ratio exhibit a large boost in both high-$R_T$ ratios.
  - Toward region has significant enhancement that is neither generator can accurately describe.
  - EPOS seems to be able to capture the overall trend.



# $\Xi - \pi/K$ Correlations

- $\Xi$ – h correlations can shed light on the microscopic picture of light-flavour hadron production.

MICRO
(PYTHIA)

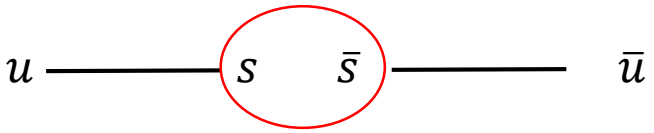
MACRO
(EPOS)

# Ξ – π/K Correlations

- Ξ – h correlations can shed light on the microscopic picture of light-flavour hadron production.

MICRO
(PYTHIA)

- Hadron flavour conserved locally.
  - In effect, flavour is calculated canonically.




**The production of a single Ξ will have a lot of associated strangeness in near rapidity.**

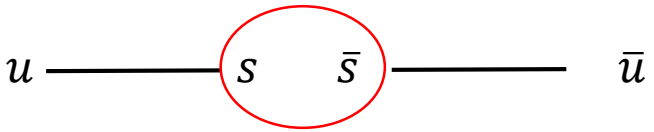
MACRO
(EPOS)

# Ξ – π/K Correlations

- Ξ – h correlations can shed light on the microscopic picture of light-flavour hadron production.

MICRO
(PYTHIA)

- Hadron flavour conserved locally.
  - In effect, flavour is calculated canonically.




**The production of a single Ξ will have a lot of associated strangeness in near rapidity.**

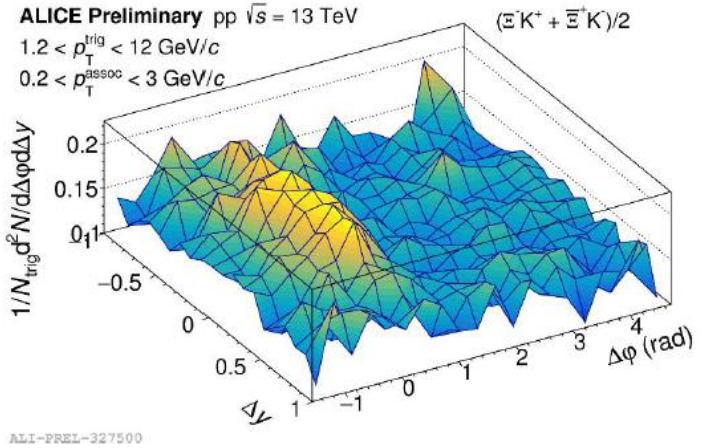
MACRO
(EPOS)

- Hadron flavour calculated using a grand canonical ensemble.
  - Conserves strangeness globally.

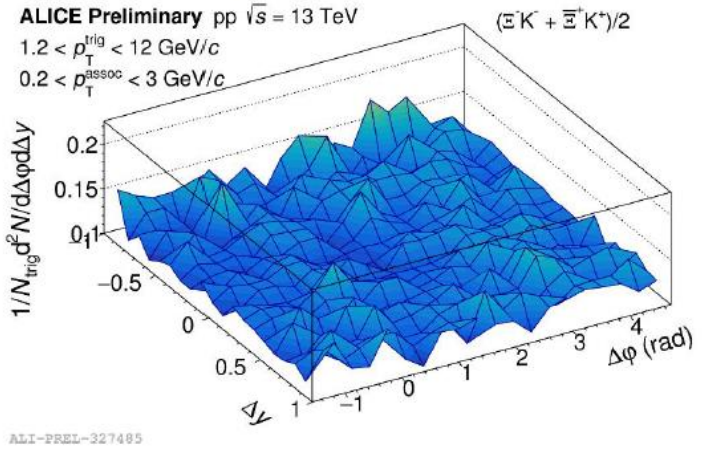

**There is no strict constraint on associated strangeness production when a multi-strange particle is produced.**

# $\Xi - \pi/K$ Correlations

Opposite sign (OS), e.g., $\Xi^-/ssd - K^+/\bar{s}d$




Same sign (SS), e.g., $\Xi^-/ssd - K^-/\bar{d}s$




- Two-particle correlation function between opposite and like-sign $\boldsymbol{\Xi^-}$ -$\boldsymbol{K^\pm}$.

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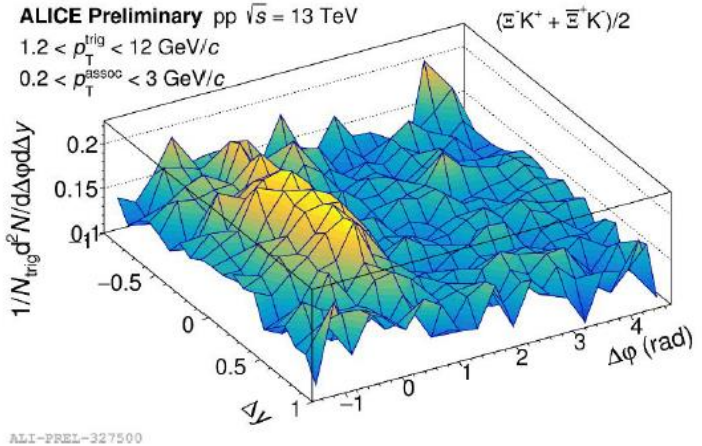


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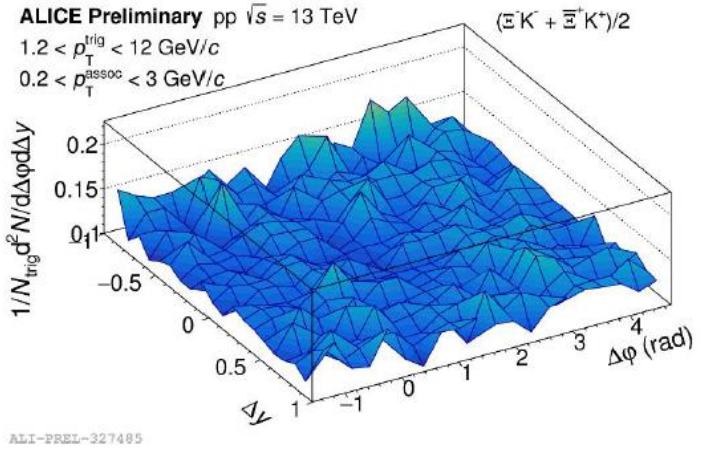


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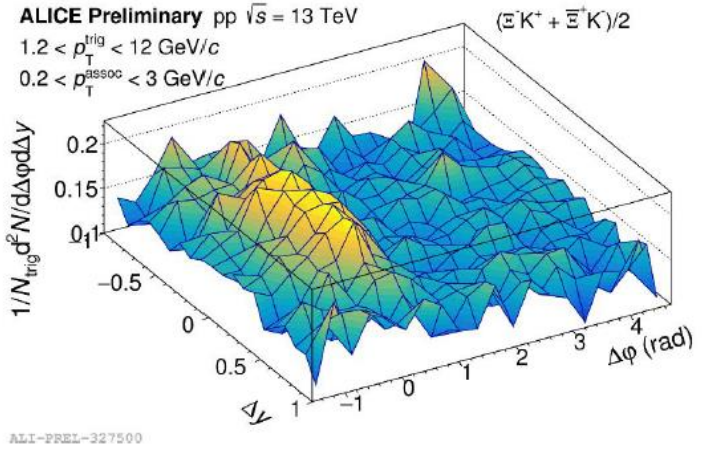


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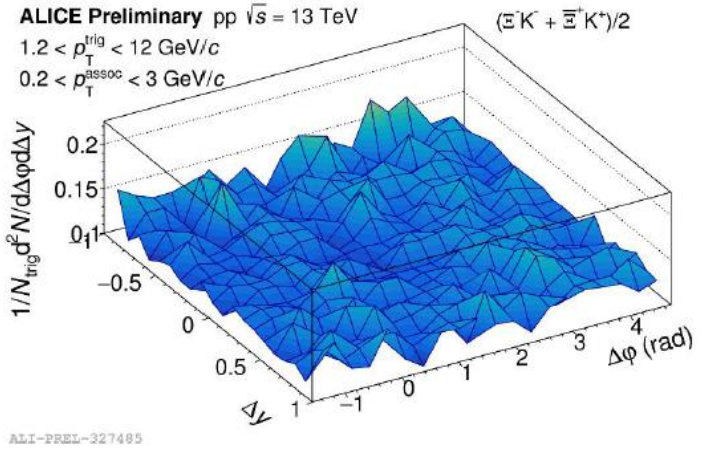
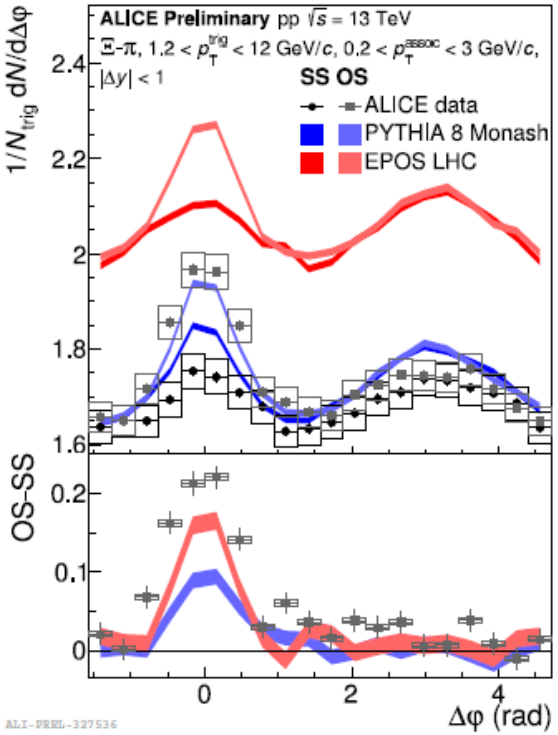



- Two-particle correlation function between opposite and like-sign $\boldsymbol{\Xi^-}$ -$\boldsymbol{K^{\pm}}$.
  - Flat behaviour, small away-side ridge.
  - All of the strange quarks have the same strangeness quantum number.

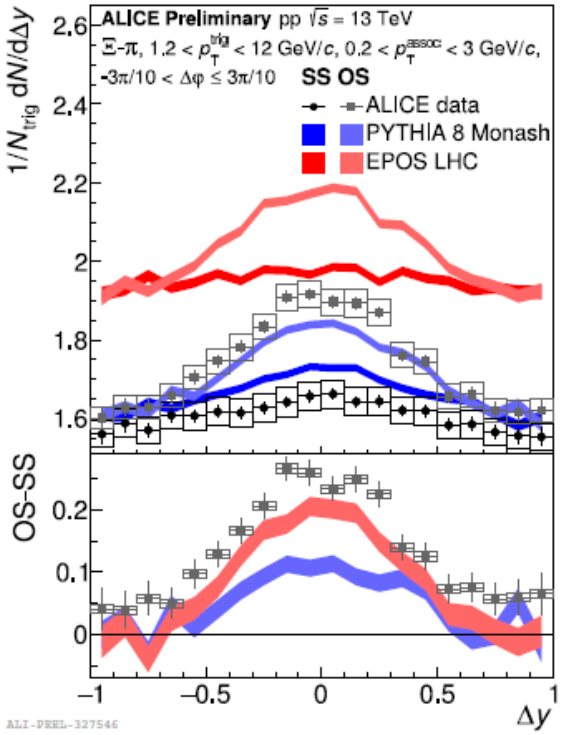
  - Opposite-sign channel (OS) instead has a very clear peak in near $\Delta\phi, \Delta y$ space.

# Ξ – π Correlations

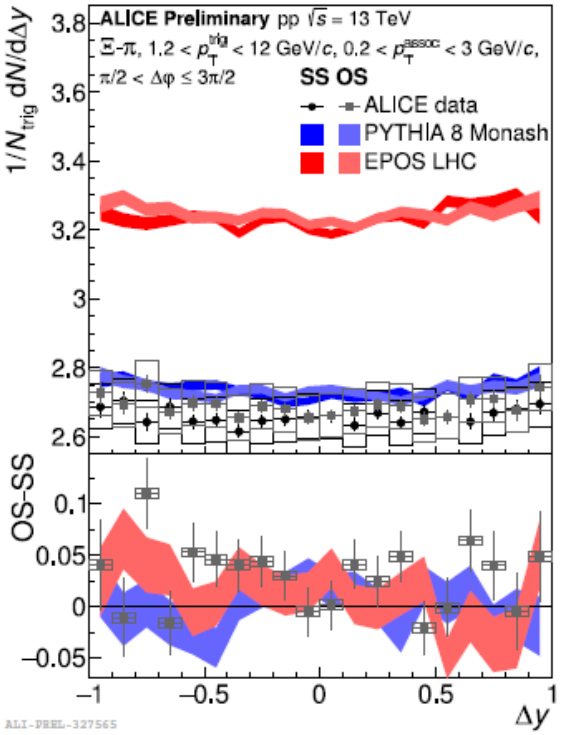
**Δy PROJECTION**




**NEAR-SPACE Δϕ**




**FAR-SPACE Δϕ**



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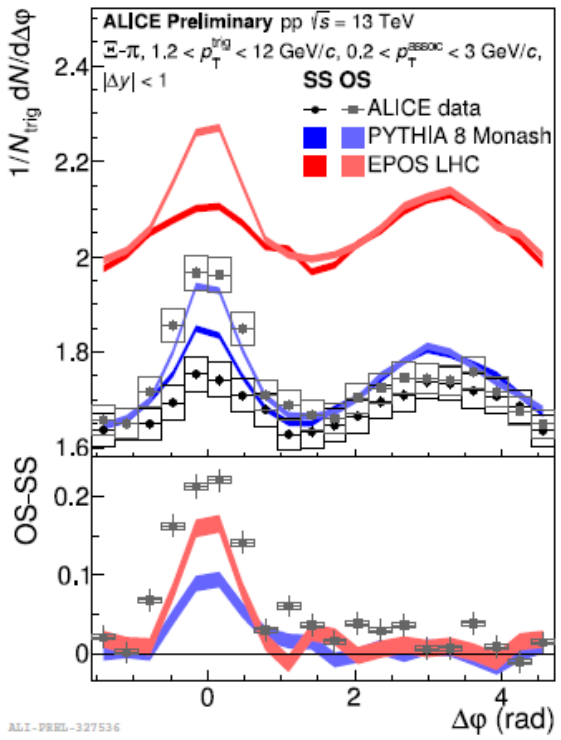


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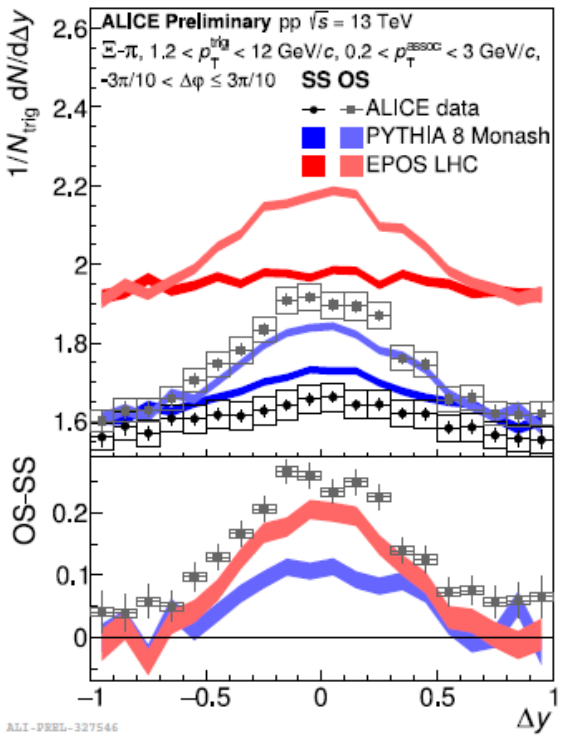


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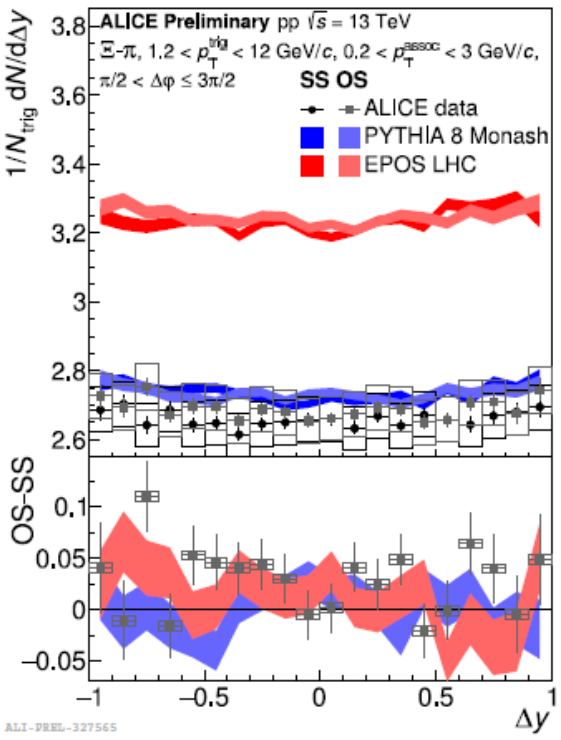


- Correlation around near Δϕ mostly due to minijet correlations & jet fragmentation.

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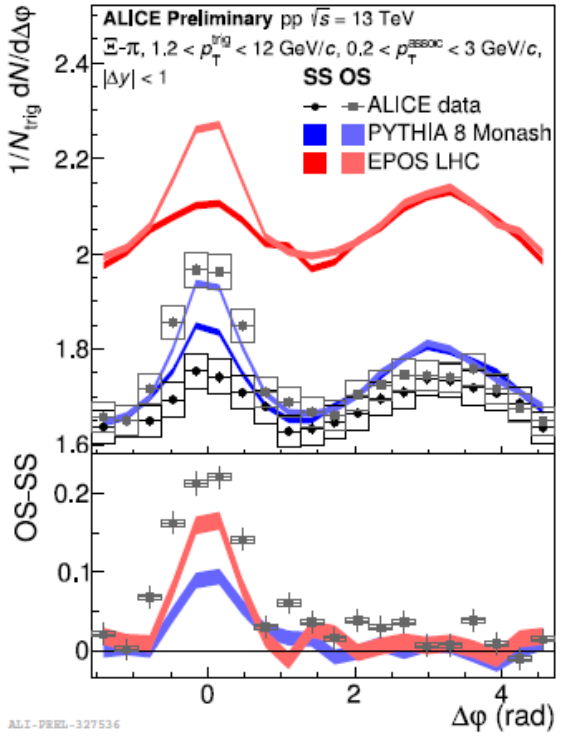


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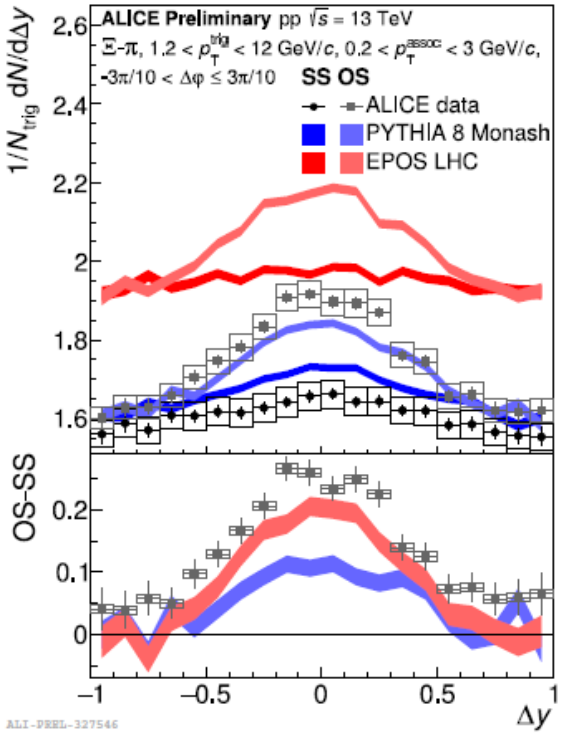


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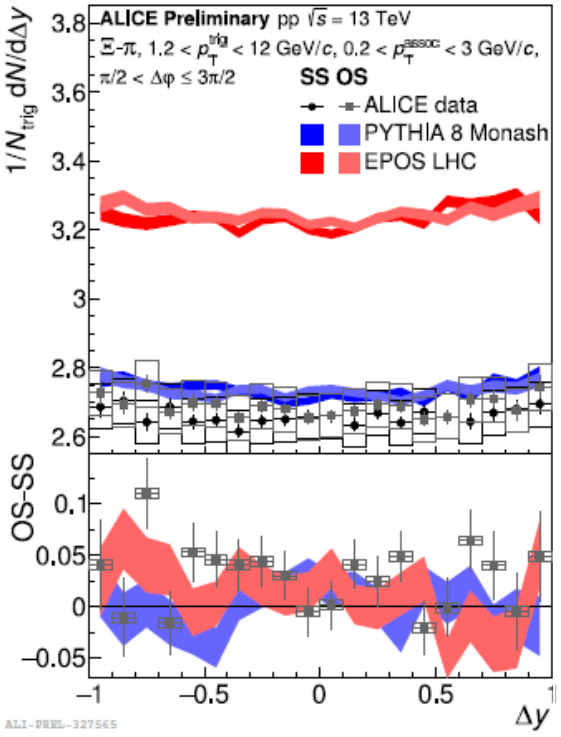


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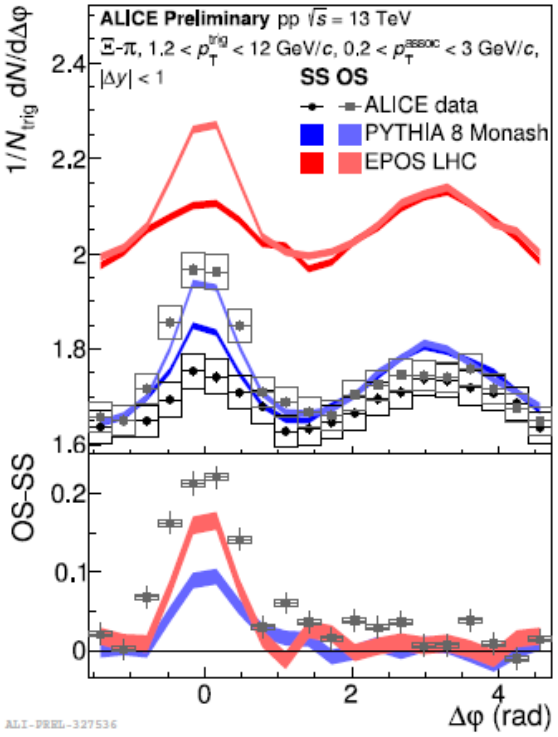


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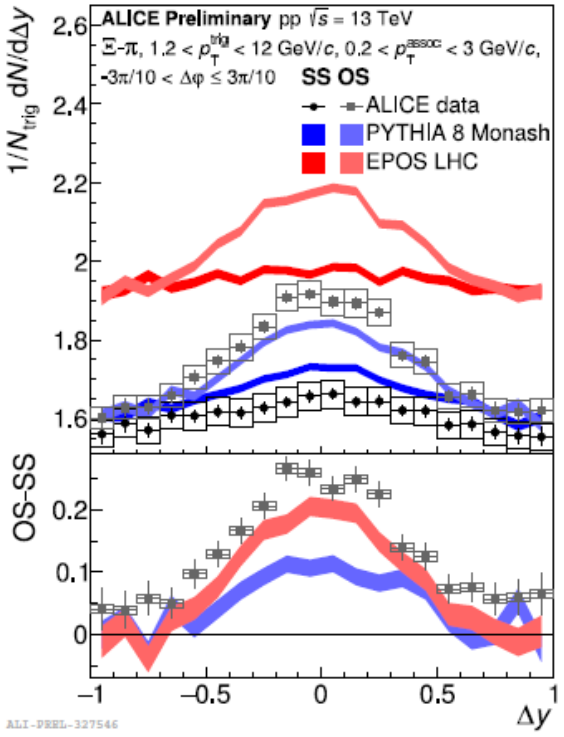


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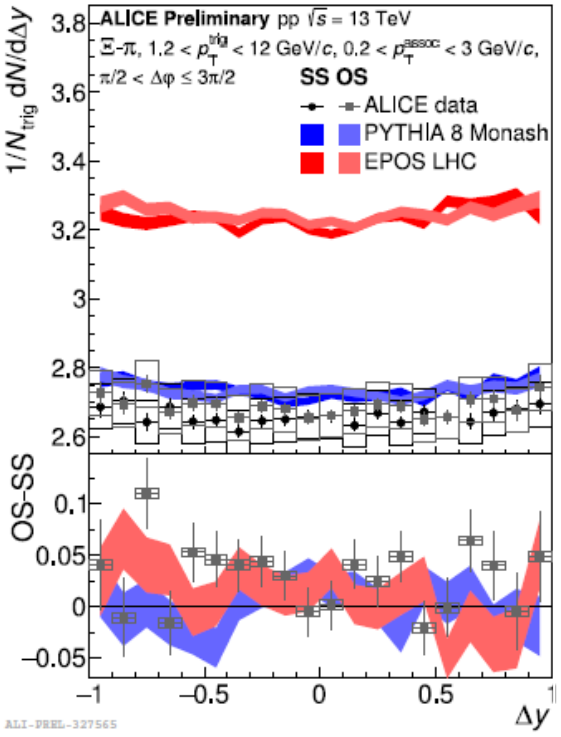
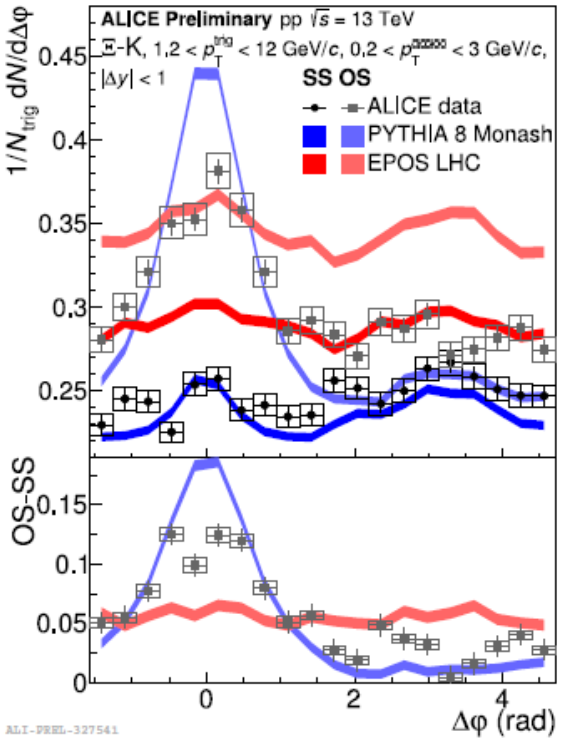



- Correlation around near Δϕ mostly due to minijet correlations & jet fragmentation.
- PYTHIA is good at describing the correlation, but underestimates OS-SS imbalance.

- EPOS quantitatively overestimates correlation, but manages to describe OS-SS imbalance better than PYTHIA.

# Ξ – K Correlations

**Δy PROJECTION**

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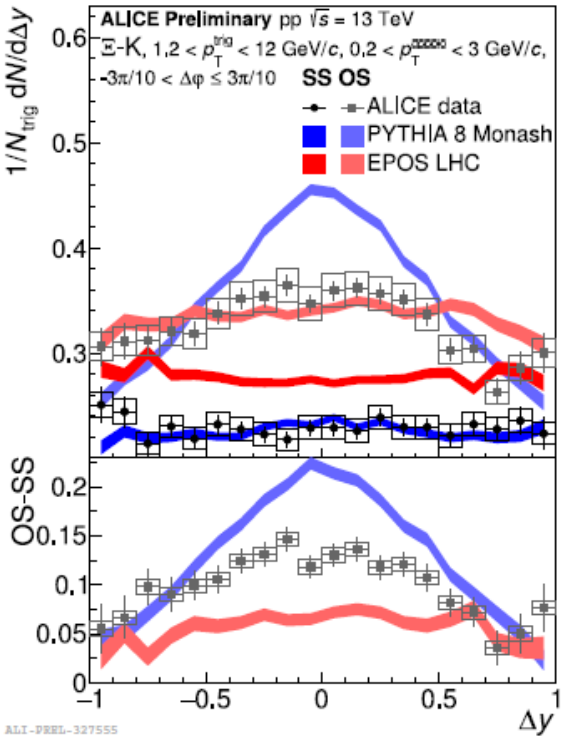


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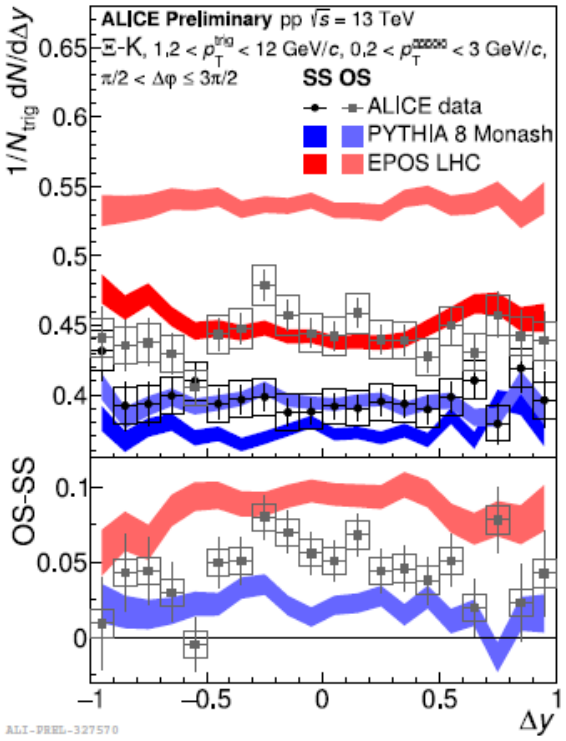

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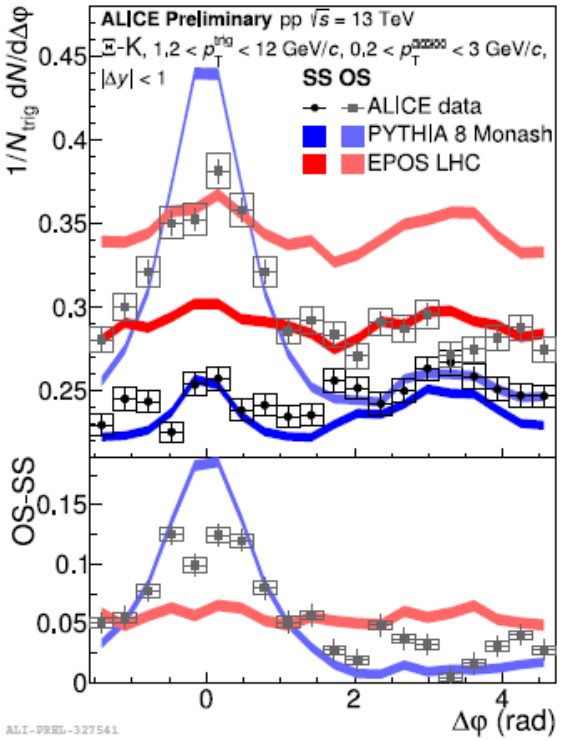


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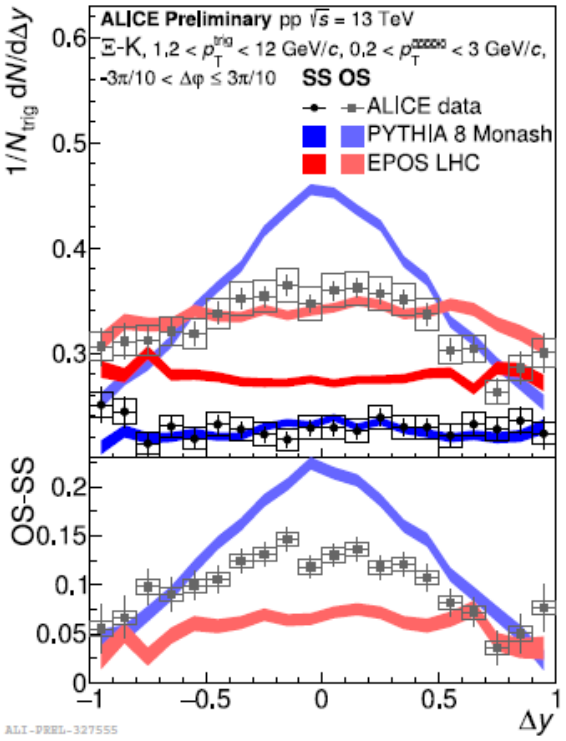


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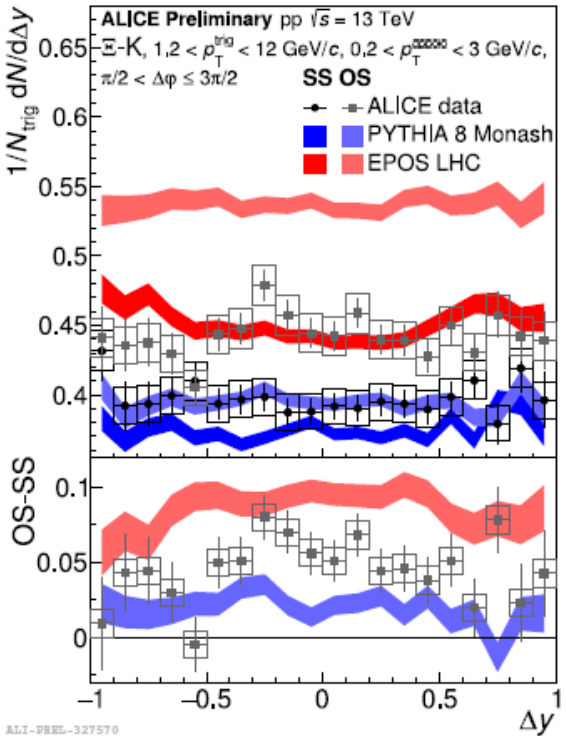


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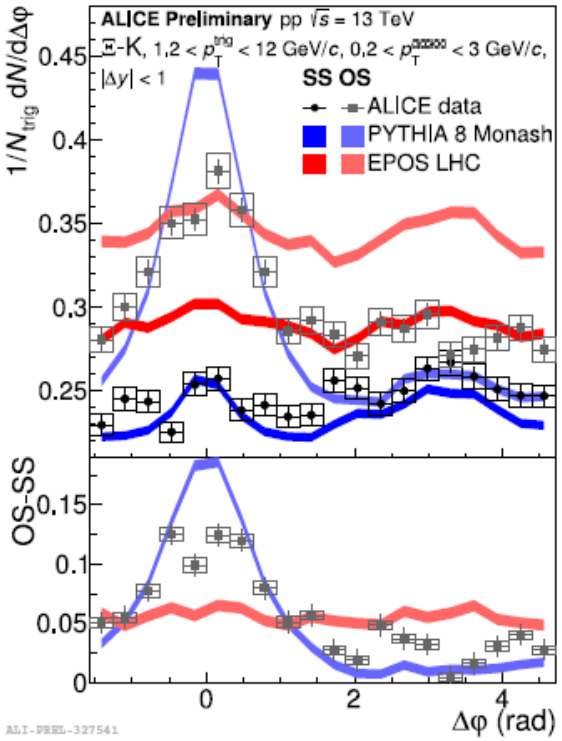


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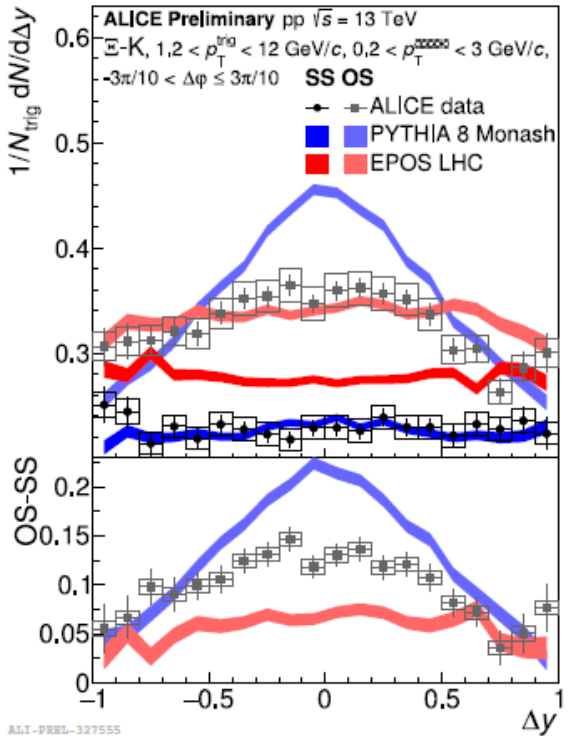


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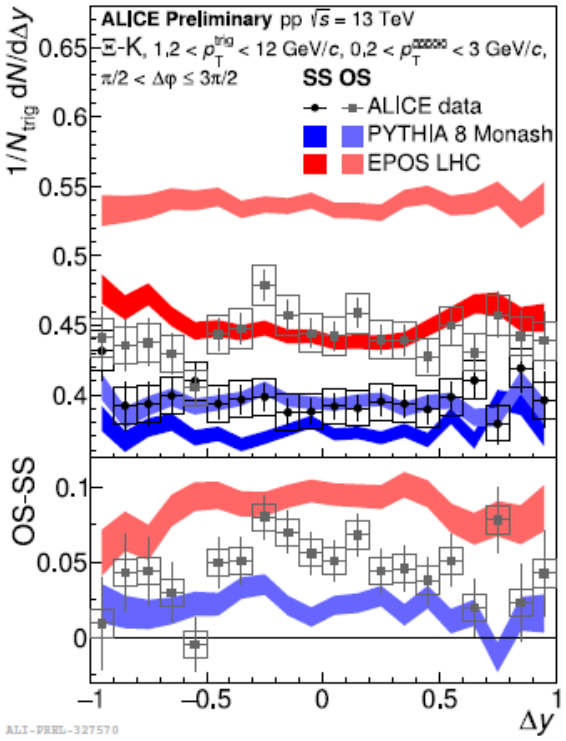


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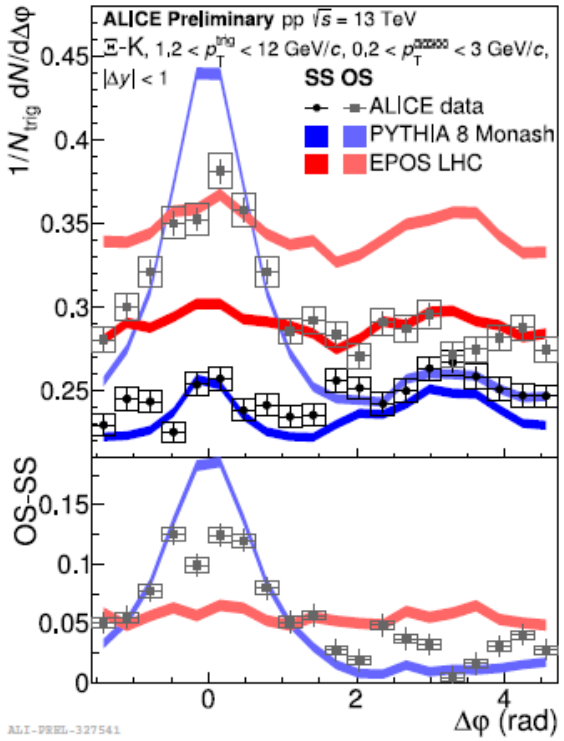


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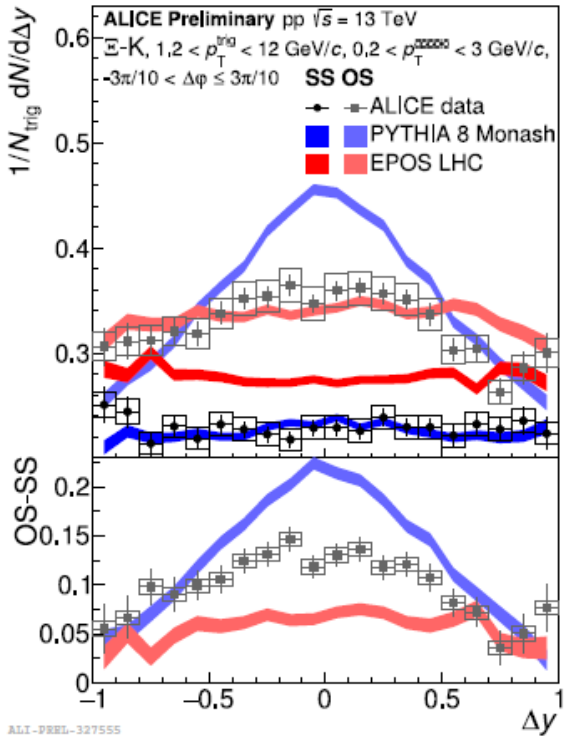


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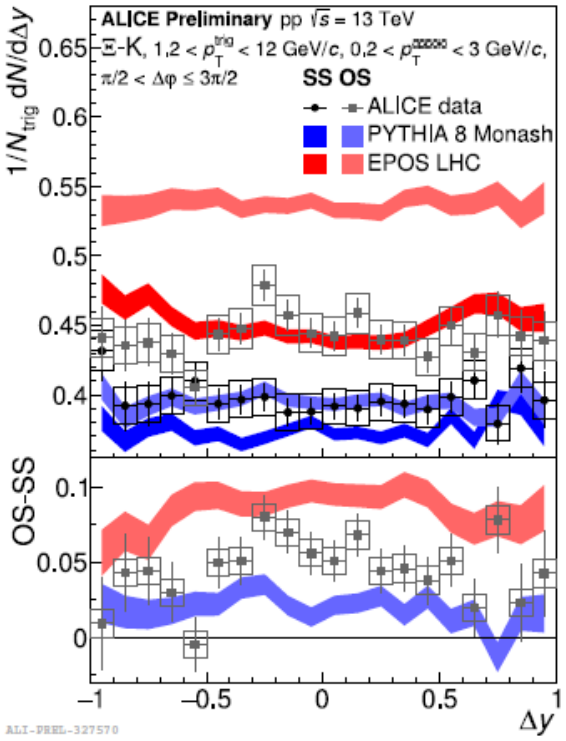


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- Almost complete decorrelation of strangeness production in EPOS.
- Ξ – K correlations has the potential to constrain the strangeness production mechanism.

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- **<u>These analyses are currently being improved to encompass a larger set of particle species and measurements.</u>**

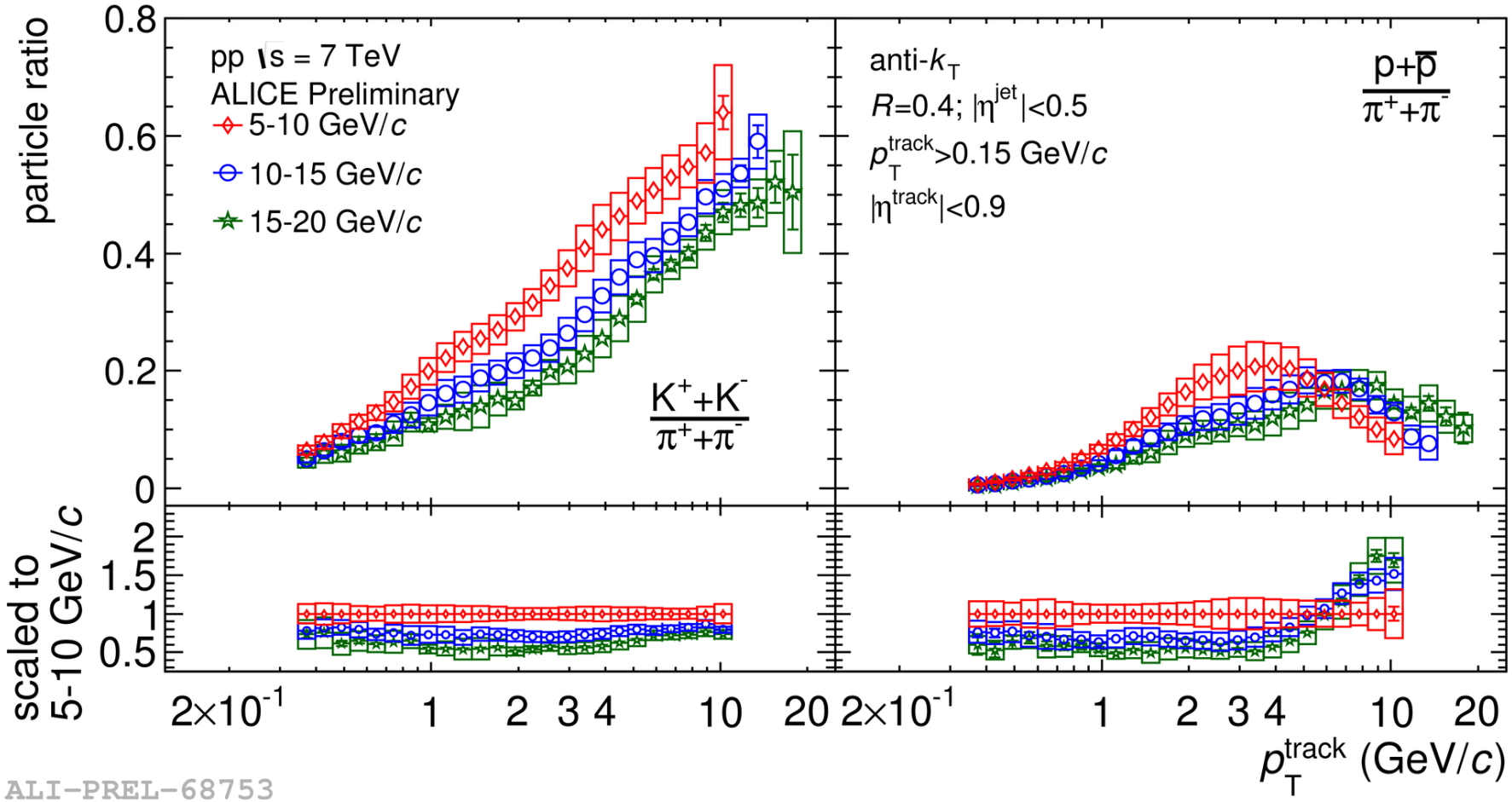
# Thank you for your time!

ALICE

LUNDS UNIVERSITET

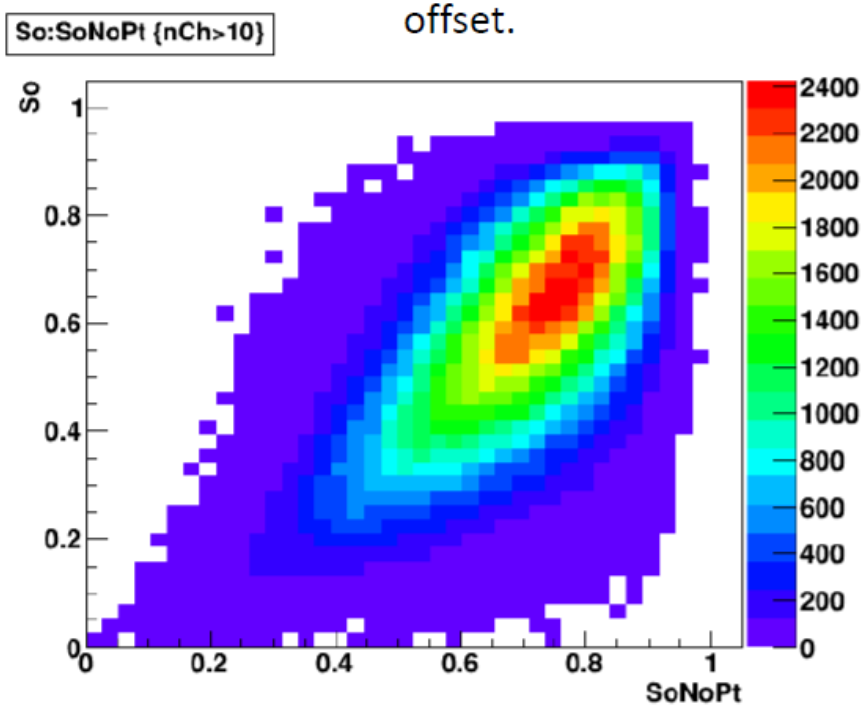
# BACKUP

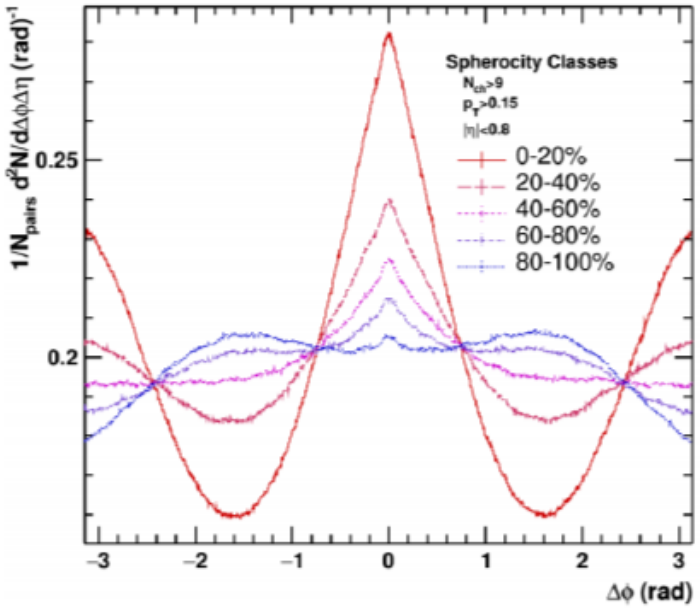
# Jet Pt Evolution

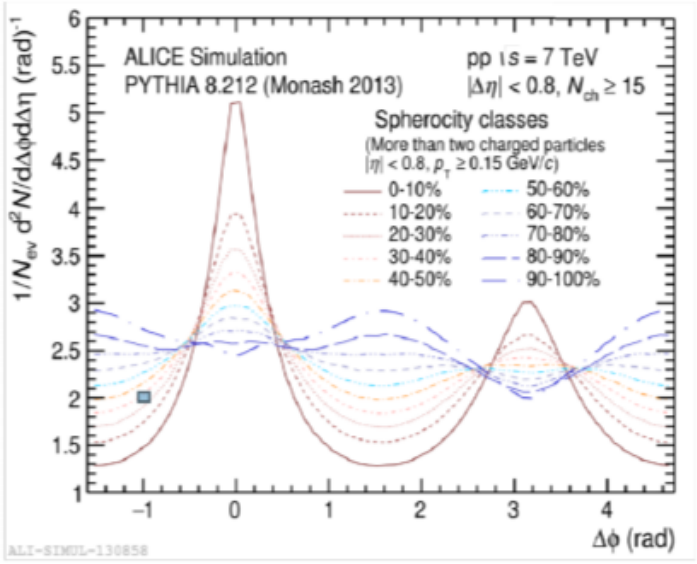


# $S_O^{p_T=1}$ MC Studies - $S_O^{p_T=1}$ vs $S_O$

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



# Identified Vs Unidentified Hadrons

- There is a non-trivial difference in the $S_O$ measurement for Identified and Unidentified hadrons

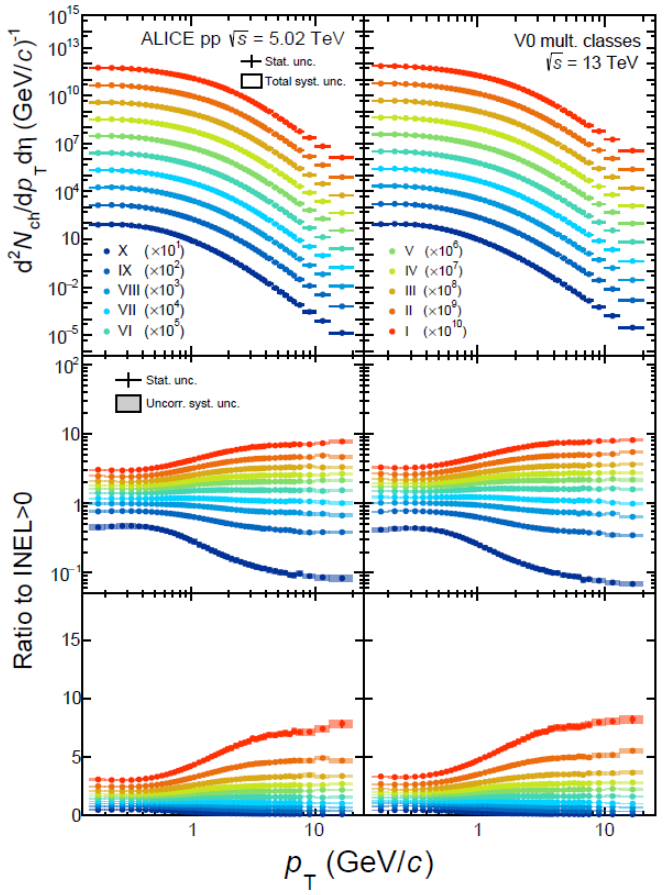
$N_{ch}$

Events require at least 10 (3) charged primary tracks.

$$S_O = \frac{\pi^2}{4} \min_{\hat{n}} \left( \frac{\Sigma_i |p_T \times \hat{n}|}{\Sigma_i p_{T_i}} \right)^2$$

- Primary Unidentified hadrons enter both the yield extraction and $S_O$

arXiv:1905.07208



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$$\pi/K/\mathrm{p}/N_{\mathrm{ch}}$$

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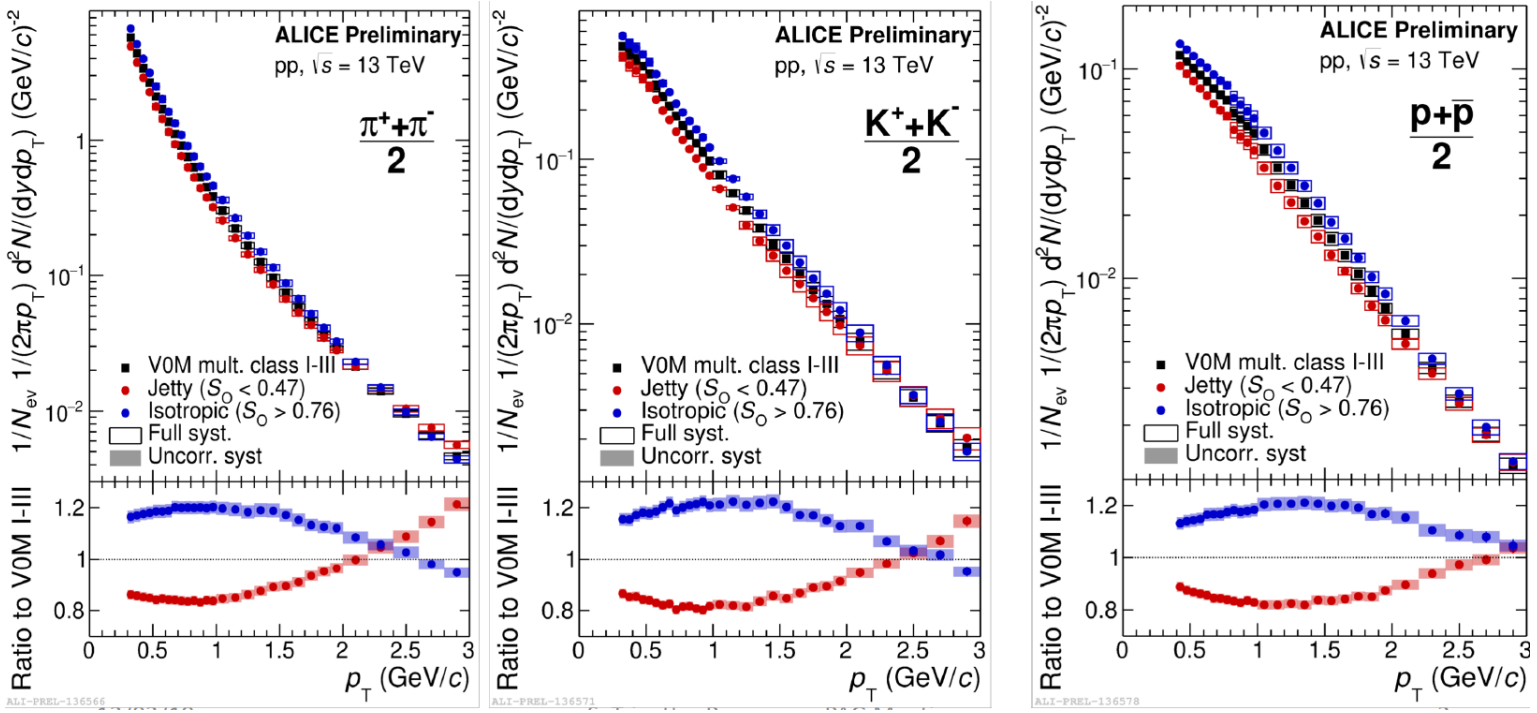

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$\Xi$

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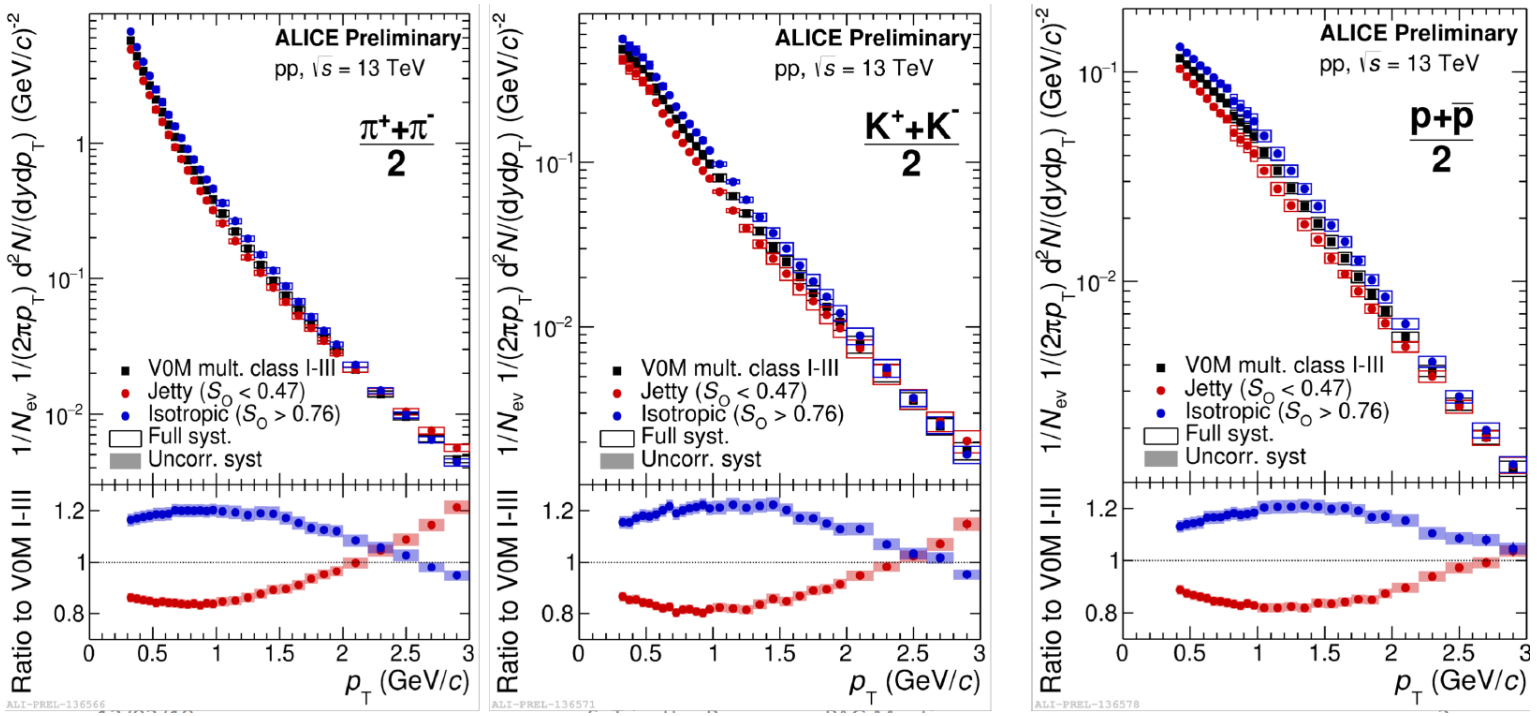
- **But this does NOT apply to Ξ!**



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$\phi$ $\Xi$ $\pi/K/\mathrm{p}/N_{\mathrm{ch}}$

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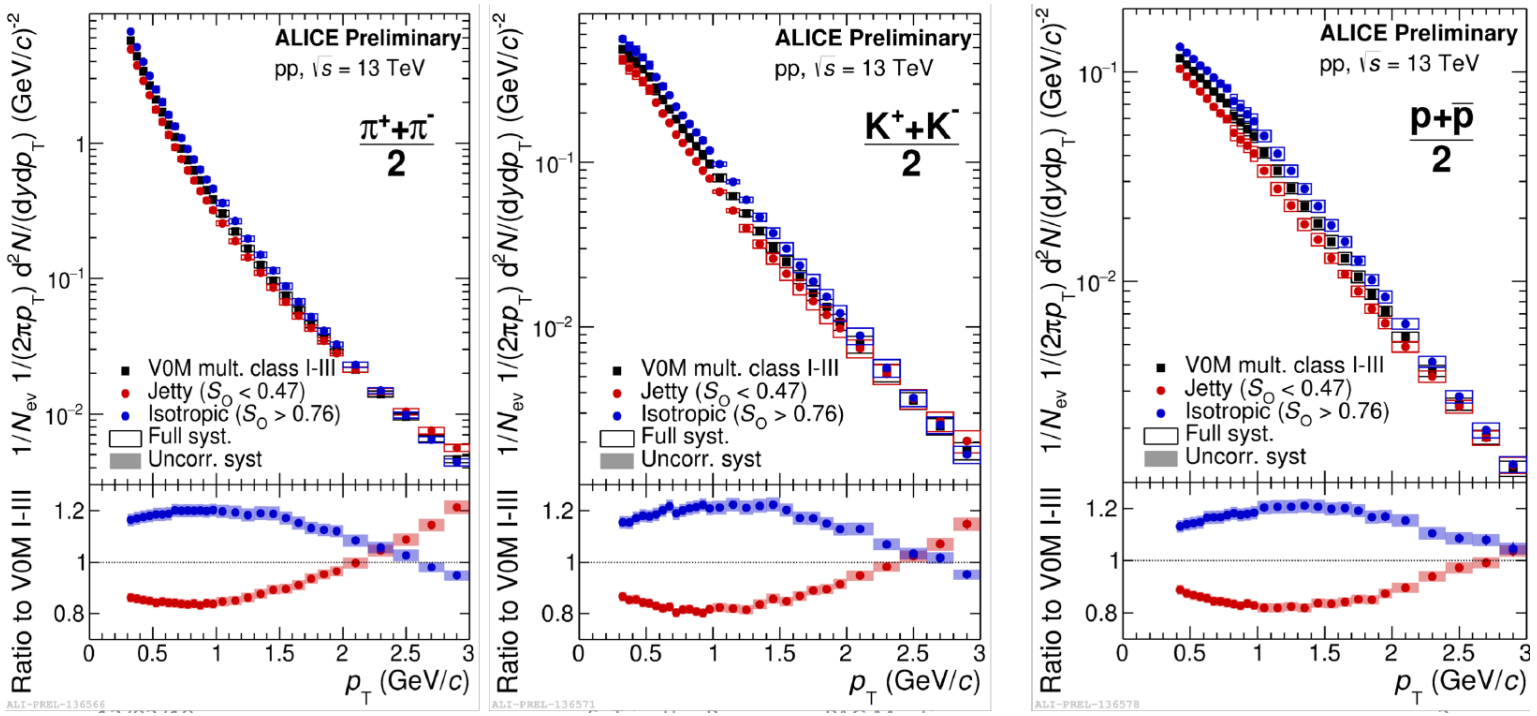
- **<u>But this does NOT apply to Ξ!</u>**
- $\phi$ enters twice! ($K^+ K^-$)



# Unweighed Transverse Spherocity $S_O^{p_T=1}$

- $S_O^{p_T=1}$ is measured as $S_O$, but only considers the angular component.

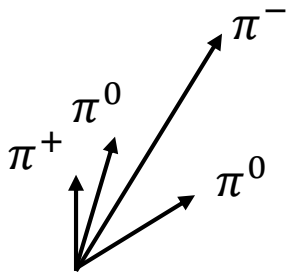
$$S_O = \frac{\pi^2}{4} \min_{\hat{n}} \left( \frac{\Sigma_i |p_T \text{ x } \hat{n}|}{\Sigma_i p_{T_i}} \right)^2 \quad \rightarrow \quad S_O^{p_T=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left( \frac{\Sigma_i |\hat{p}_T \text{ x } \hat{n}|}{N_{trk}} \right)^2$$

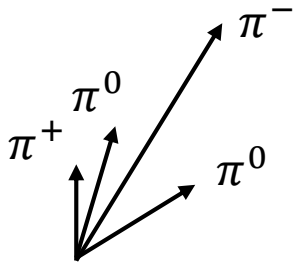
# Unweighed Transverse Spherocity $S_O^{p_T=1}$

- $S_O^{p_T=1}$ is measured as $S_O$, but only considers the angular component.

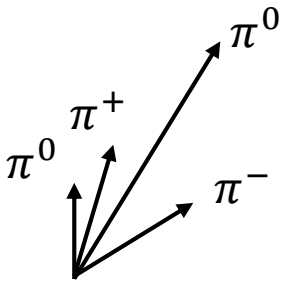
$$S_O = \frac{\pi^2}{4} \min_{\hat{n}} \left( \frac{\Sigma_i |p_T \times \hat{n}|}{\Sigma_i p_{T_i}} \right)^2 \quad \rightarrow \quad S_O^{p_T=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left( \frac{\Sigma_i |\hat{p}_T \times \hat{n}|}{N_{trk}} \right)^2$$

$S_{O,1}$

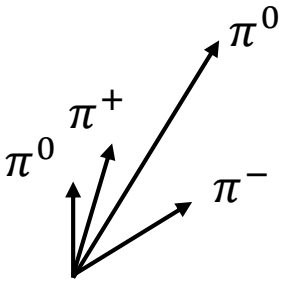



$S_{O,1}^{p_T=1}$




$S_{O,2}$




$S_{O,2}^{p_T=1}$

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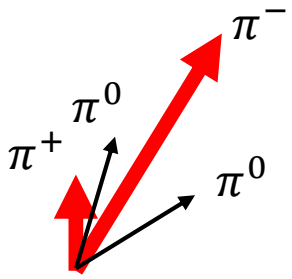
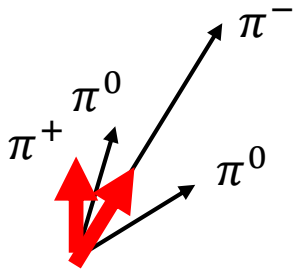
$S_{O,1}$

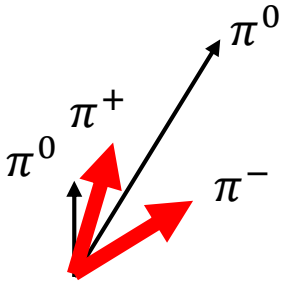


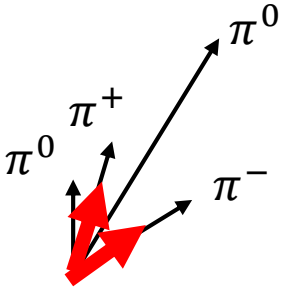




$S_{O,1}^{p_T=1}$

$S_{O,1}$ and $S_{O,2}$ will describe two completely different topologies!

$S_{O,1}^{p_T=1}$ and $S_{O,2}^{p_T=1}$ will describe two similar topologies.



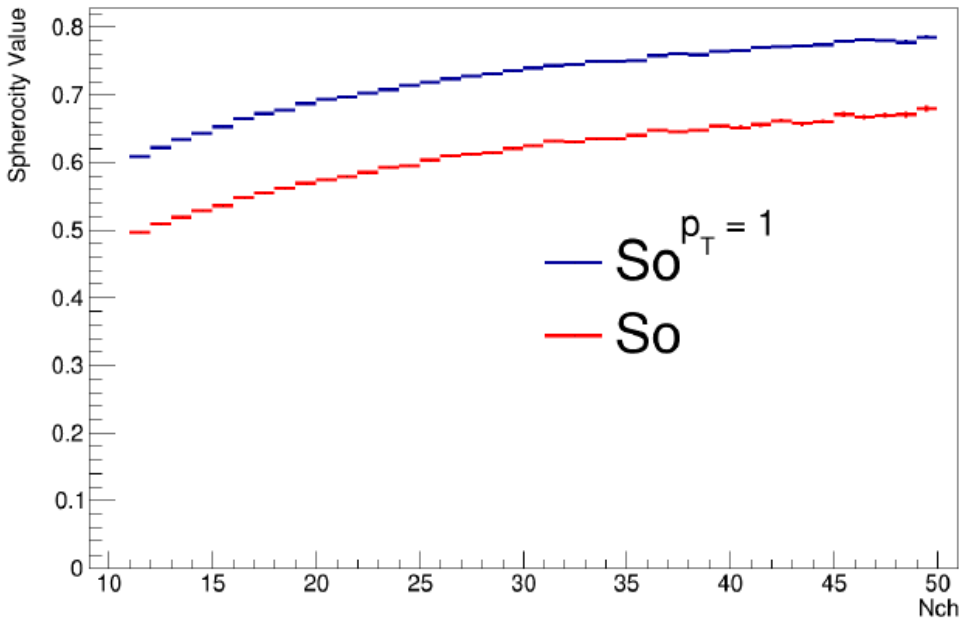




$S_{O,2}$

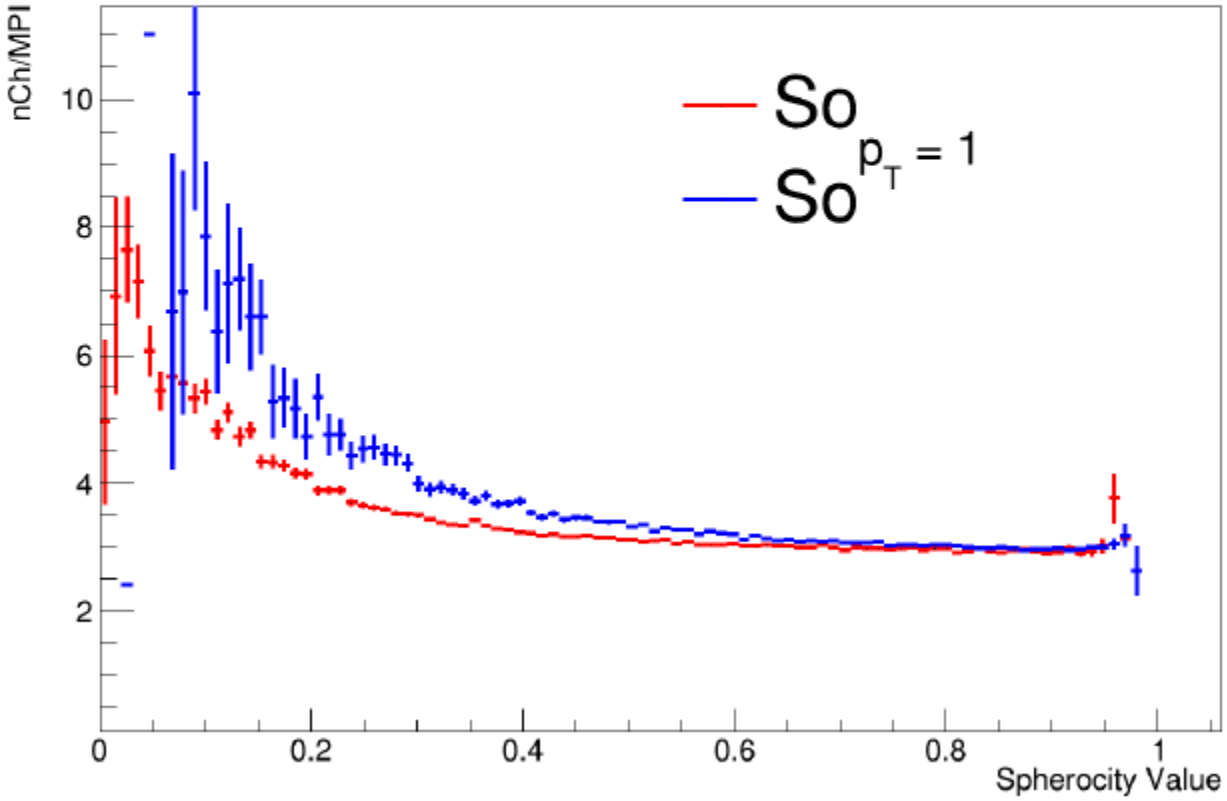
$S_{O,2}^{p_T=1}$

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

Qualitatively similar
Nch distributions

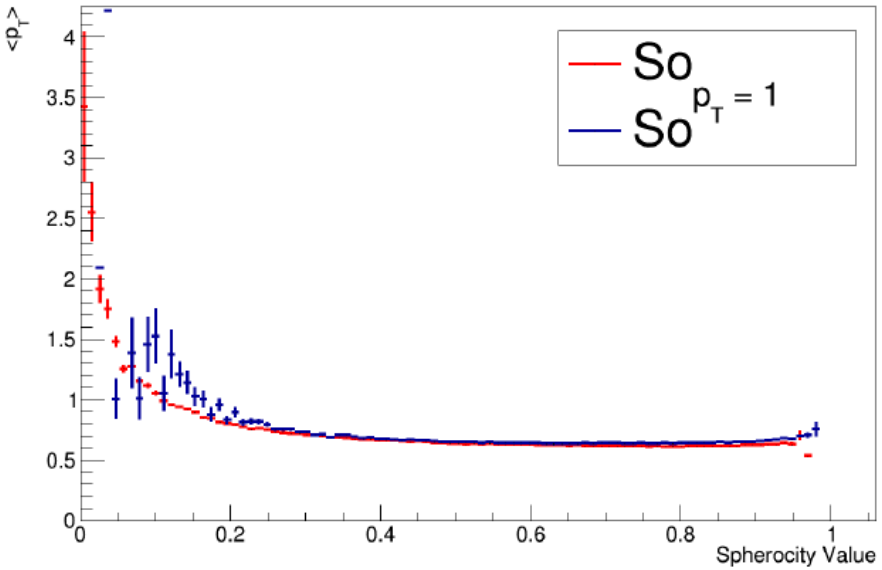


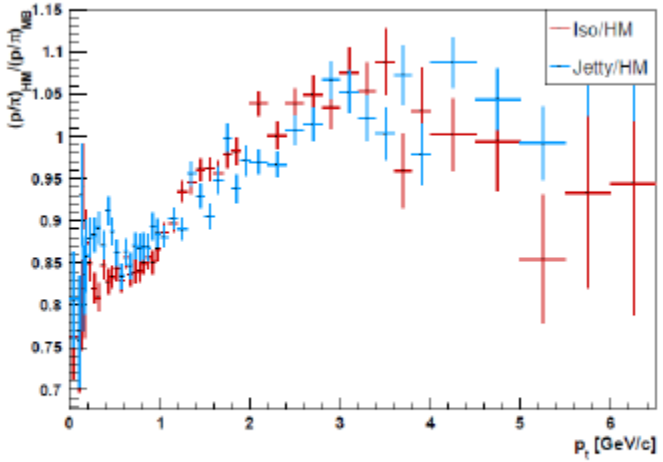

Qualtitatively similar
Nch/MPI distributions



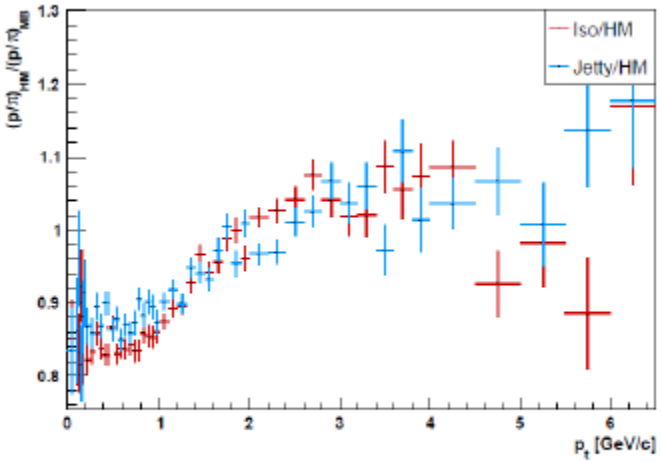
# $S_O^{p_T=1}$ MC Studies - $S_O^{p_T=1}$ vs $S_O$

Qualtitatively similar
<$p_T$> distributions




(a) Spherocity

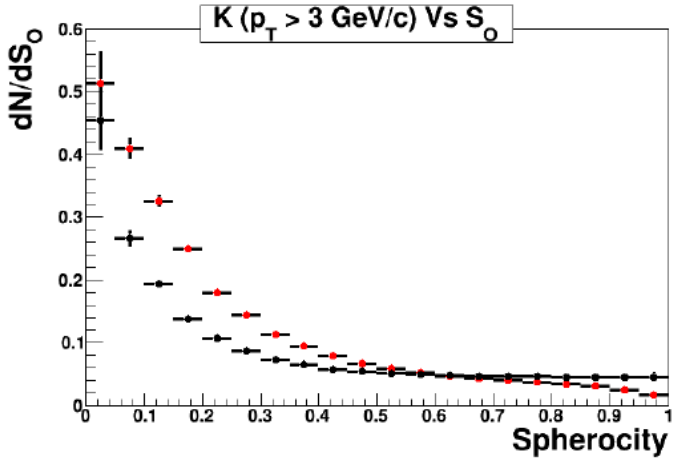


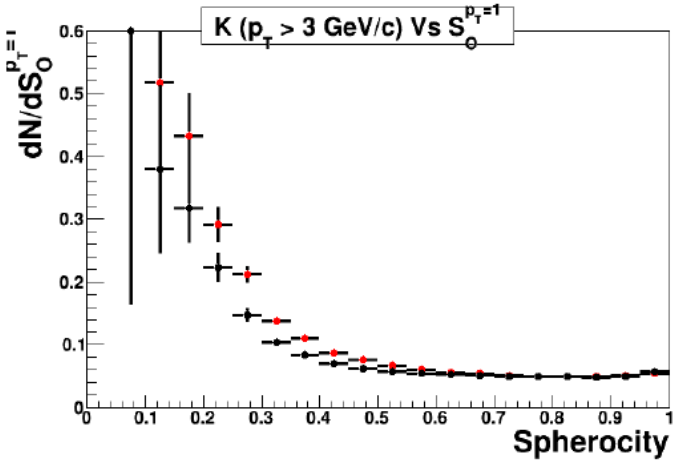

(b) Spherocity $p_T = 1$

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

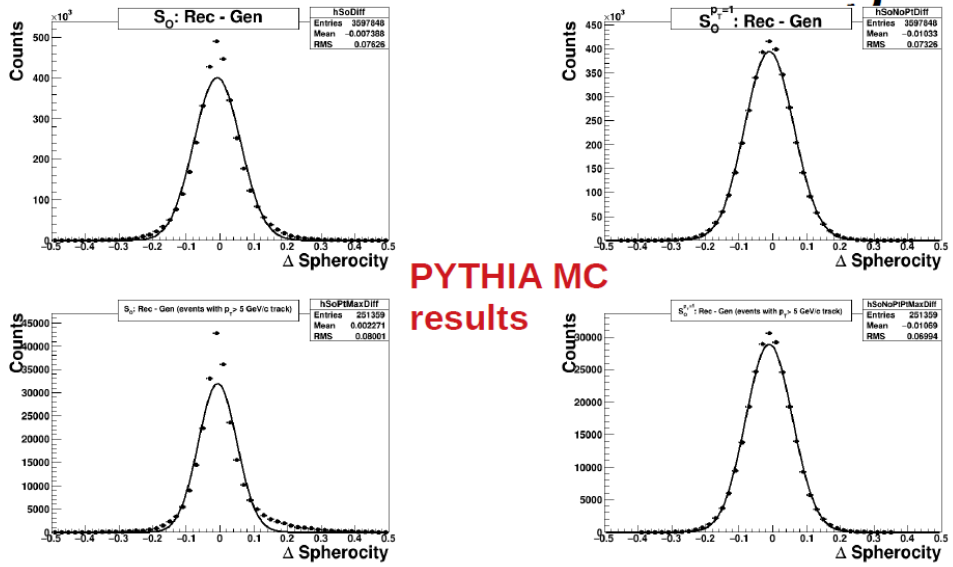
## $K^+$ and $K^0_s$ with $p_T$>3 GeV/c

**PYTHIA MC results (generator level)**




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

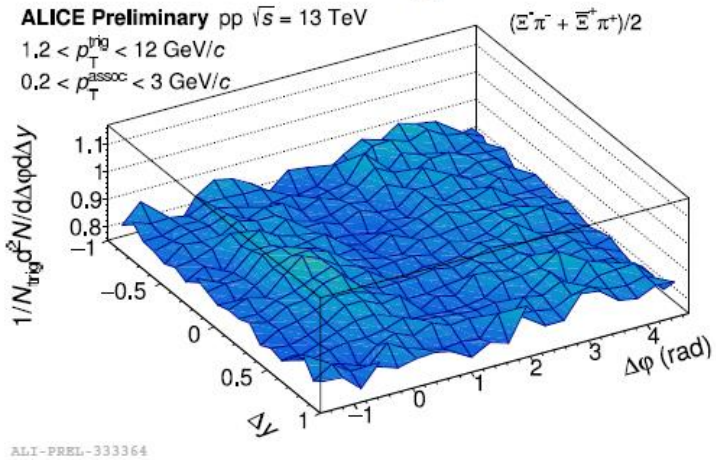



**PYTHIA MC results**

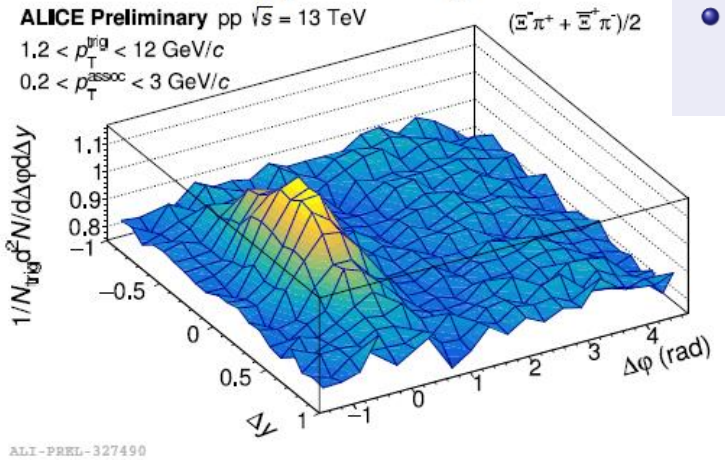
# Backup: Correlations

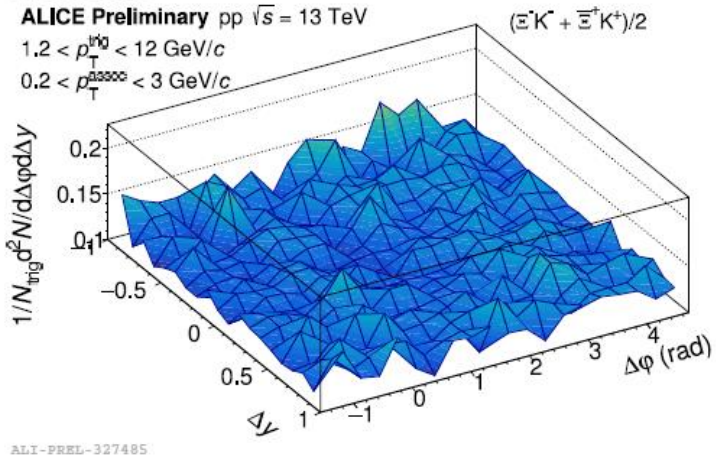
- Correlation function: $\mathbb{C}(\Delta\eta, \Delta\varphi) = \frac{1}{N_{\text{pairs}}} \frac{\mathrm{d}^2 N_{\text{pairs}}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\varphi}$, number of pairs is normalised to unity
- Per-trigger yield: $\mathbb{Y}(\Delta y, \Delta\varphi) = \frac{1}{N_{\text{trig}}} \frac{\mathrm{d}^2 N_{\text{trig-assoc pairs}}}{\mathrm{d}\Delta y \mathrm{d}\Delta\varphi}$, normalised to number of triggers

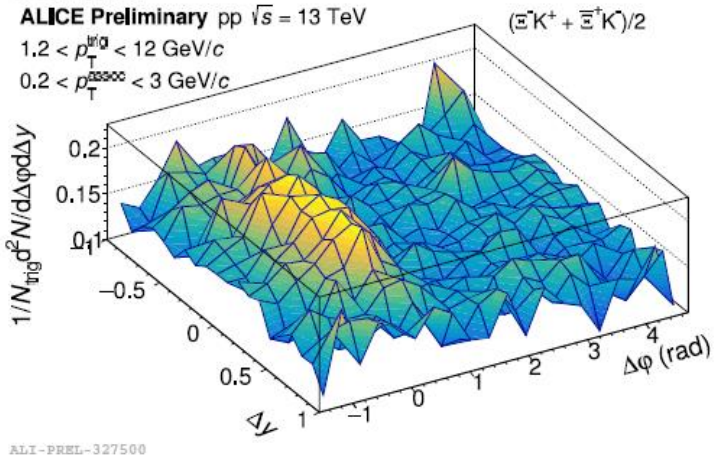
Same sign:




Opposite sign:




- Balance function:
$$\mathbb{B}(\Delta y, \Delta\varphi) = \frac{1}{2}\left(\mathbb{Y}_{(+,-)} + \mathbb{Y}_{(-,+)} - \mathbb{Y}_{(+,+)} - \mathbb{Y}_{(-,-)}\right)$$