Studying (multi-)strange hadron correlation and production with event topology using the ALICE detector

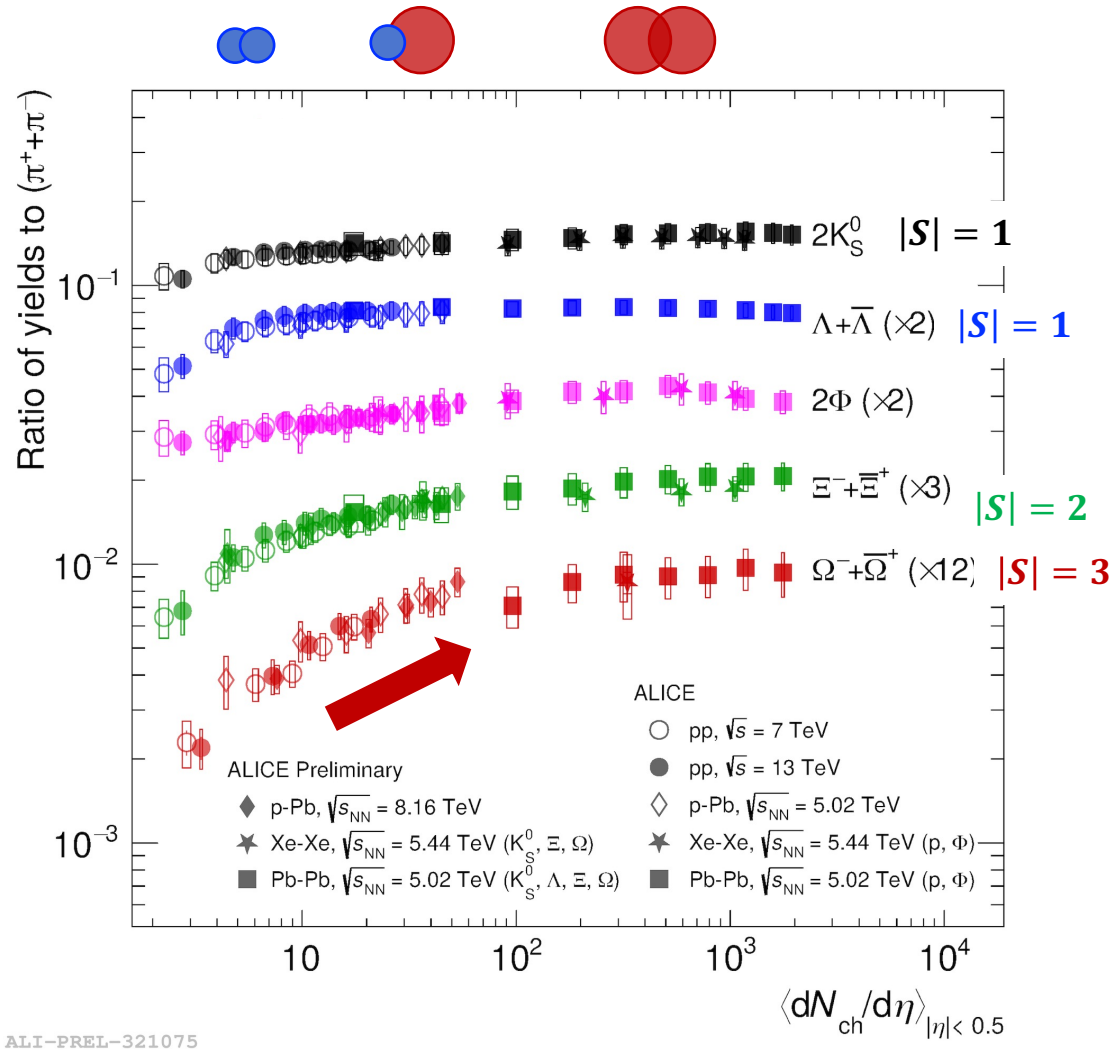
Chiara De Martin on behalf of the ALICE Collaboration

University and INFN - Trieste

SQM 2024 Strasbourg

Strangeness in Quark Matter

Physics motivation

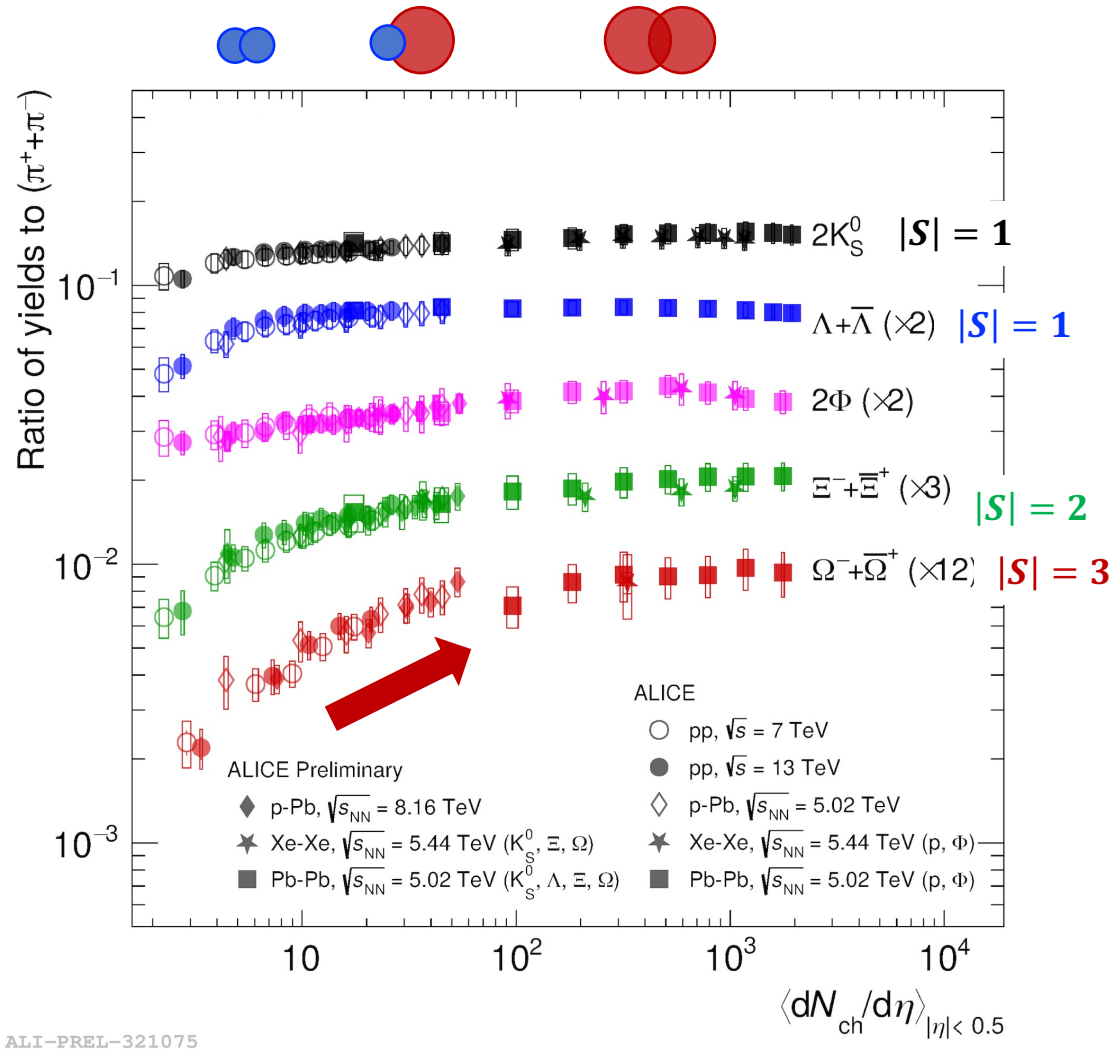


Strangeness enhancement:
The ratio between (multi-)strange hadron yields and pion yields is enhanced in heavy-ion collisions with respect to minimum bias pp collisions

- Smooth evolution with the multiplicity of charged particles across different collision systems (pp, p—Pb, Pb—Pb)
- No dependence on the collision energy at the LHC
- The enhancement is larger for particles with larger strangeness content ($\Omega > \Xi > \Lambda \sim K^0_S$)

ALICE, Nature Phys 13, 535–539 (2017)
ALICE, Eur.Phys.J.C 80, 167 (2020)

Physics motivation



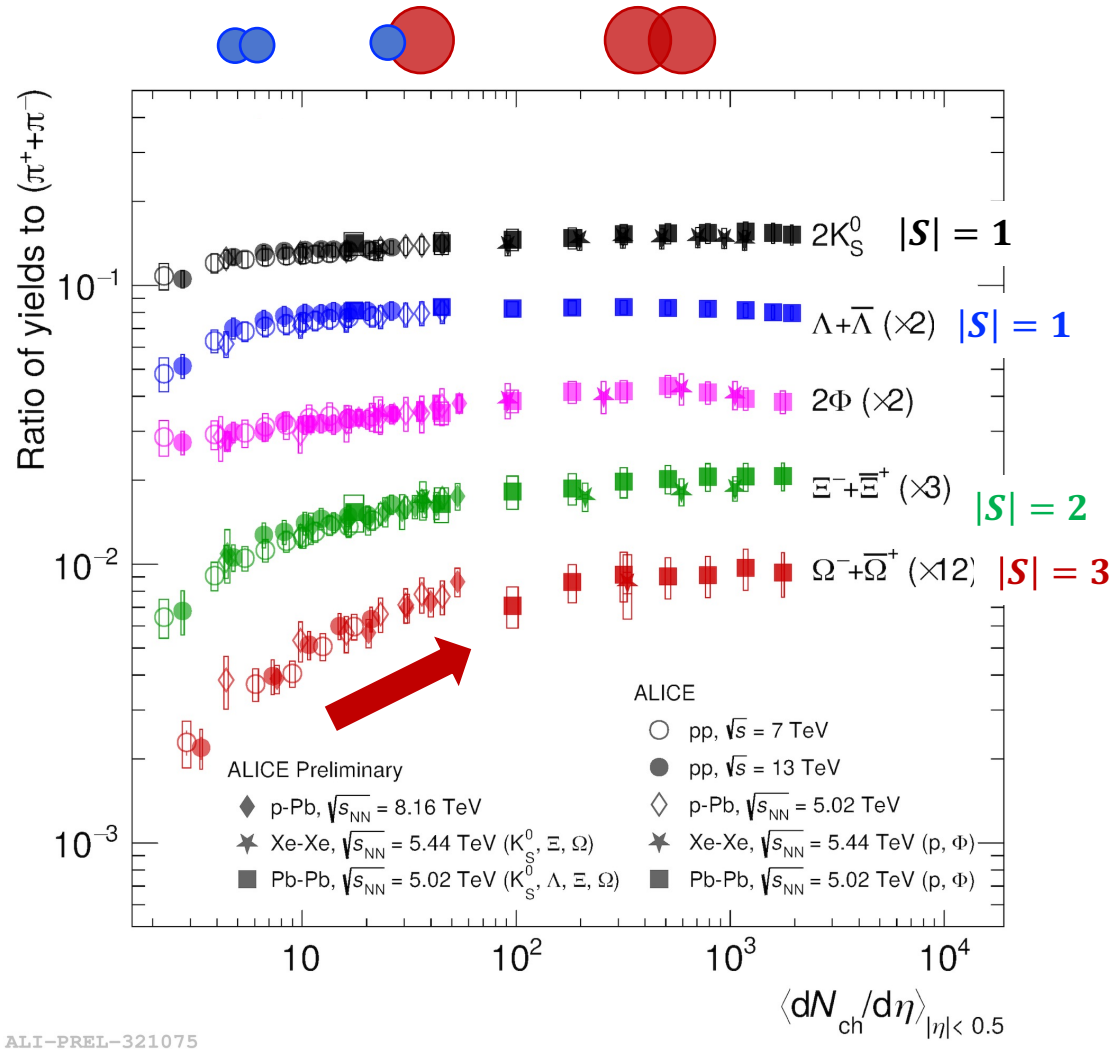
Strangeness enhancement:
The ratio between (multi-)strange hadron yields and pion yields is enhanced in heavy-ion collisions with respect to minimum bias pp collisions

- Smooth evolution with the multiplicity of charged particles across different collision systems (pp, p—Pb, Pb—Pb)
  - ➢ Enhanced production of strangeness in Pb—Pb collisions is traditionally considered a signature of quark-gluon plasma (QGP), which is not expected to form in pp collisions

See previous talk by Roman Nepeivoda Track1-LF, today 11:20

ALICE, Nature Phys 13, 535–539 (2017)
ALICE, Eur.Phys.J.C 80, 167 (2020)

Physics motivation



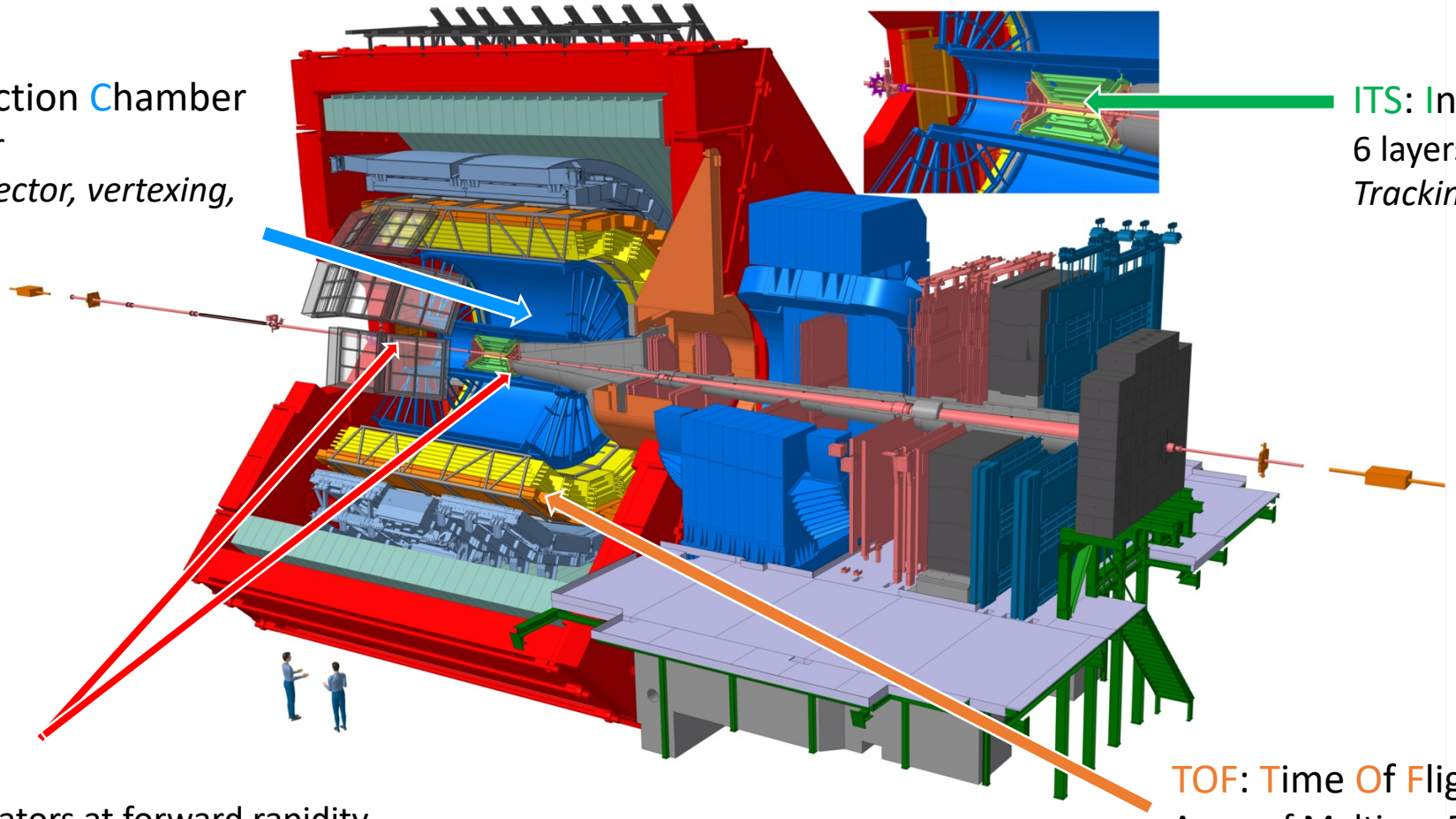
Strangeness enhancement:
The ratio between (multi-)strange hadron yields and pion yields is enhanced in heavy-ion collisions with respect to minimum bias pp collisions

- What is the microscopic origin of strangeness enhancement **in pp collisions**?
- Is it related to hard processes, such as jets, to the underlying event, or to both?

ALICE, Nature Phys 13, 535–539 (2017)
ALICE, Eur.Phys.J.C 80, 167 (2020)

ALICE at the LHC in Run 2

TPC: Time Projection Chamber
Gas-filled detector
Main tracking detector, vertexing, PID (dE/dx)



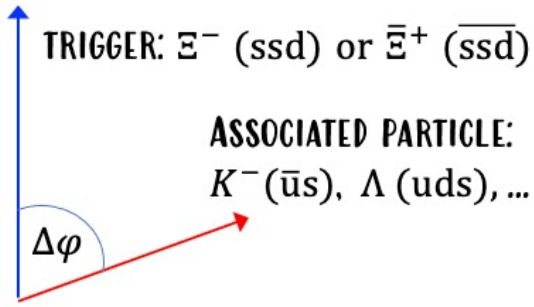
ITS: Inner Tracking System
6 layers of silicon detectors
Tracking, triggering, vertexing

V0A and V0C
Arrays of scintillators at forward rapidity
Triggering, multiplicity estimators

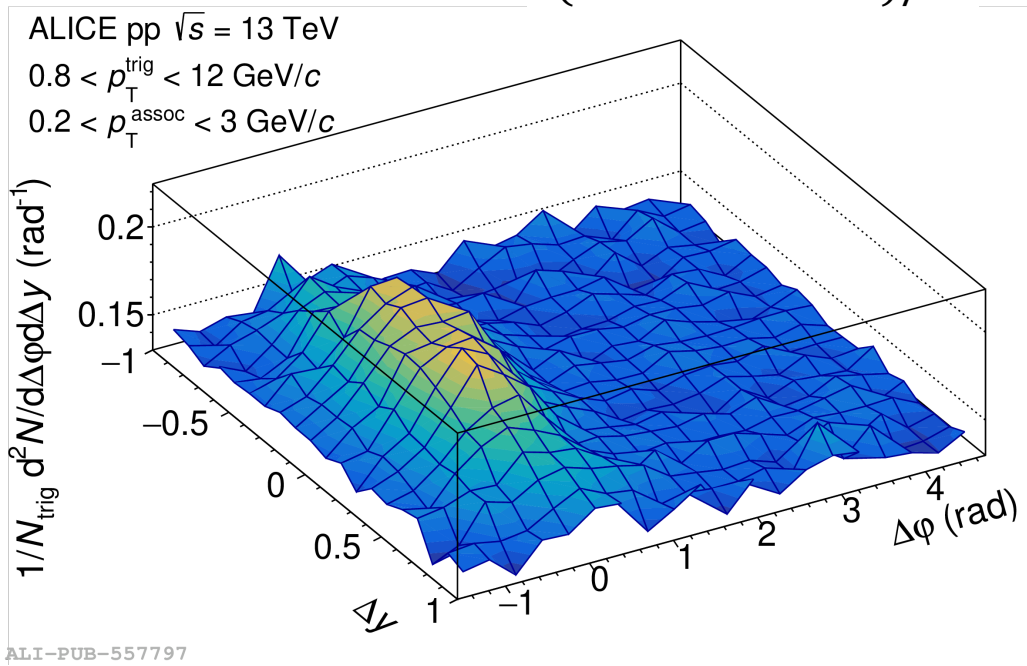
TOF: Time Of Flight
Array of Multigap Resistive Plate Chambers
PID, out-of-bunch pile-up rejection

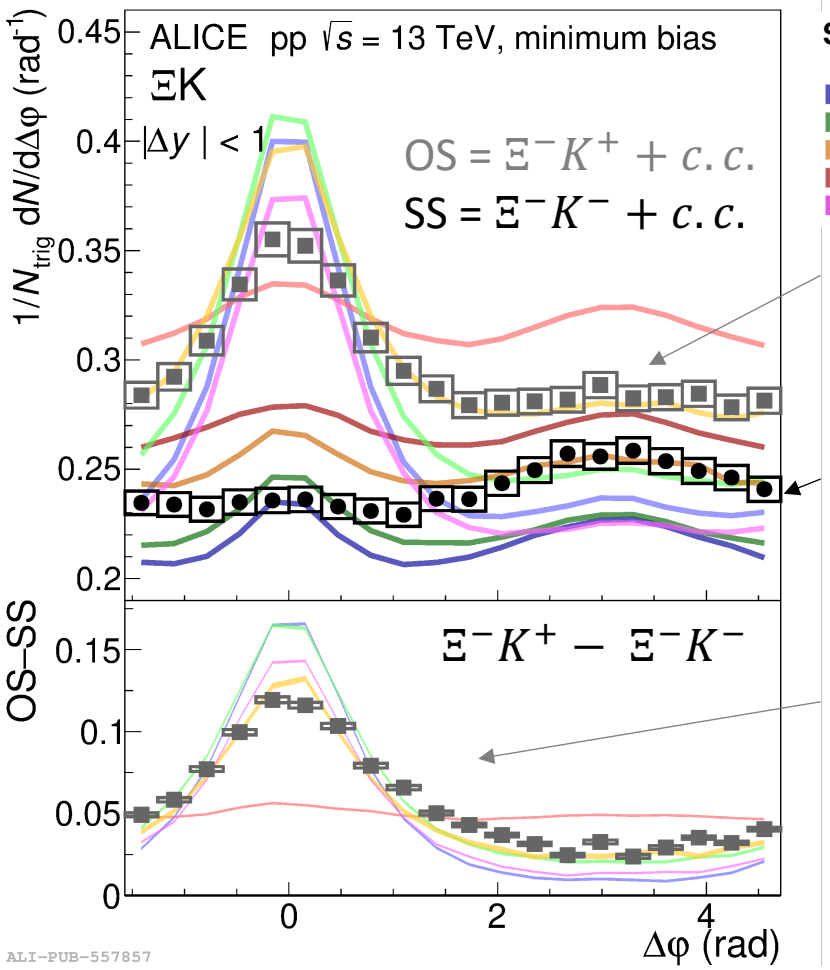
Angular correlations between Ξ and identified hadrons in pp collisions at $\sqrt{s} = 13$ TeV

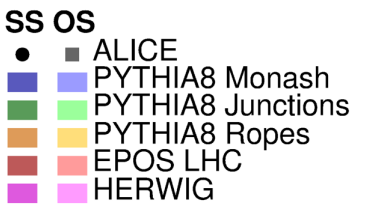
Angular correlations of strange hadrons



$(\Xi^-K^+ + \bar{\Xi}^+K^-)/2$







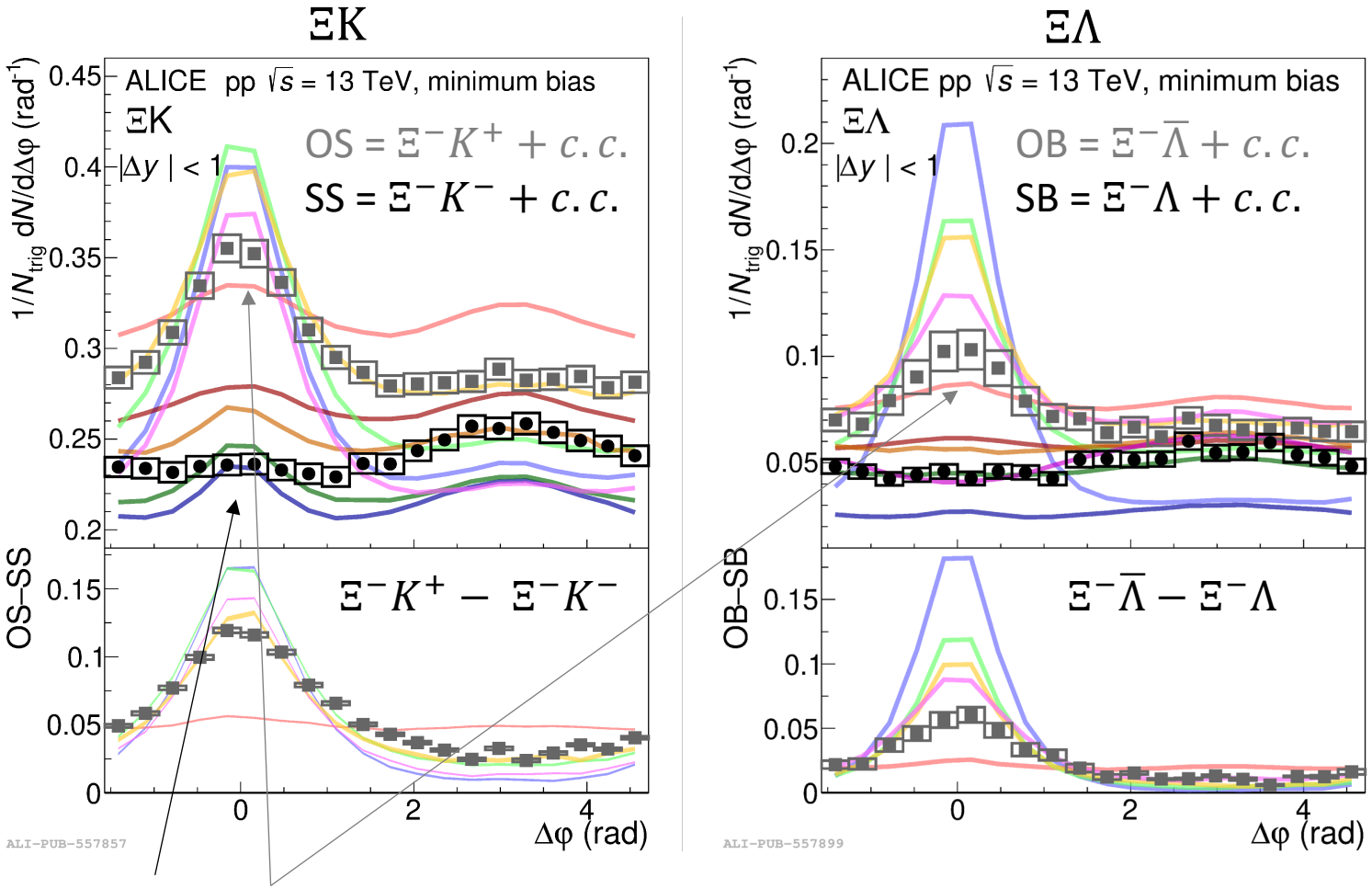
OS = correlation between particles with **opposite-sign** *S* quantum number

SS = correlation between particles with **same-sign** *S* quantum number

OS – SS to **isolate quantum-number dependent correlation** and remove flow and (mini-)jet correlations

arXiv:2308.16706

Balancing of strangeness quantum number



OS correlation attributed to $s\bar{s}$ pair

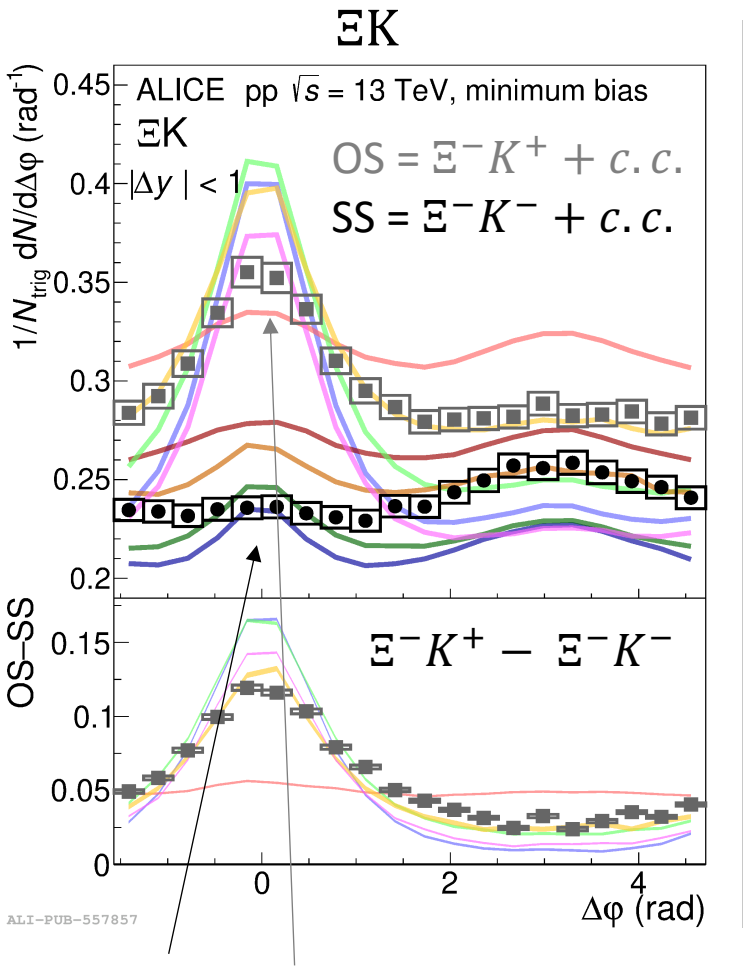
No SS near-side peak (no shared $q\bar{q}$)

SS OS

- ALICE
- PYTHIA8 Monash
- PYTHIA8 Junctions
- PYTHIA8 Ropes
- EPOS LHC
- HERWIG

arXiv:2308.16706

Balancing of strangeness quantum number



OS correlation attributed to $s\bar{s}$ pair

No SS near-side peak (no shared $q\bar{q}$)

Can correlations help distinguish between the phenomenological models capable of predicting strangeness enhancement (SE) in pp collisions?

PYTHIA8 (string hadronization model)

→ predicts SE if ropes/junctions are included

HERWIG (cluster hadronization model)

→ qualitatively predicts SE with baryonic ropes mechanism

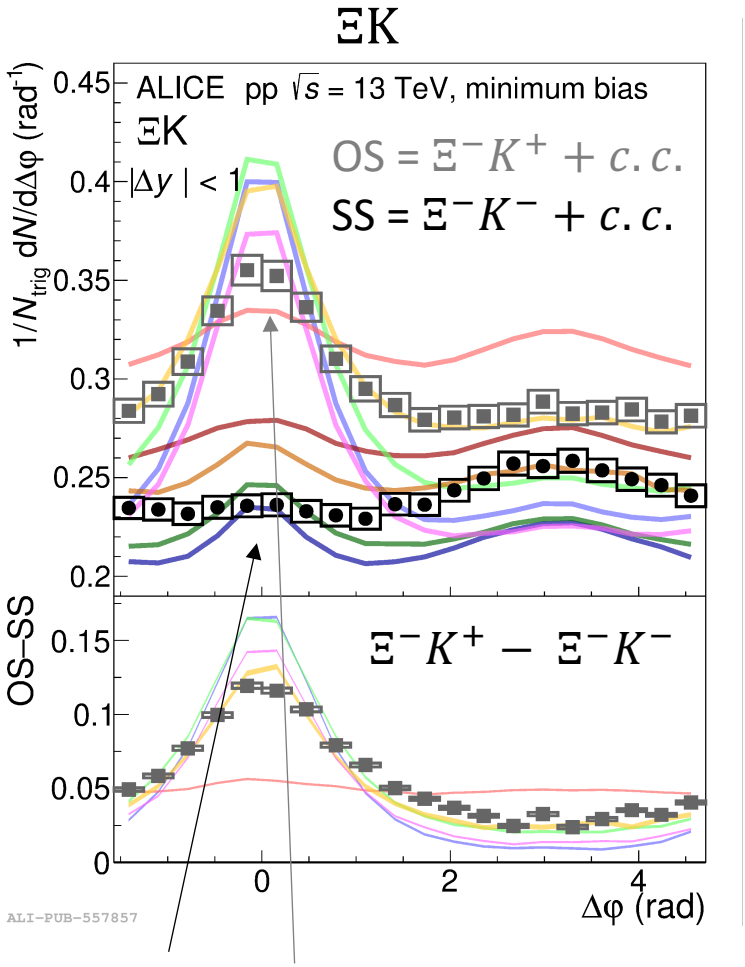
→ $\boldsymbol{s\bar{s}}$ are produced in pairs and remain **correlated** in final state

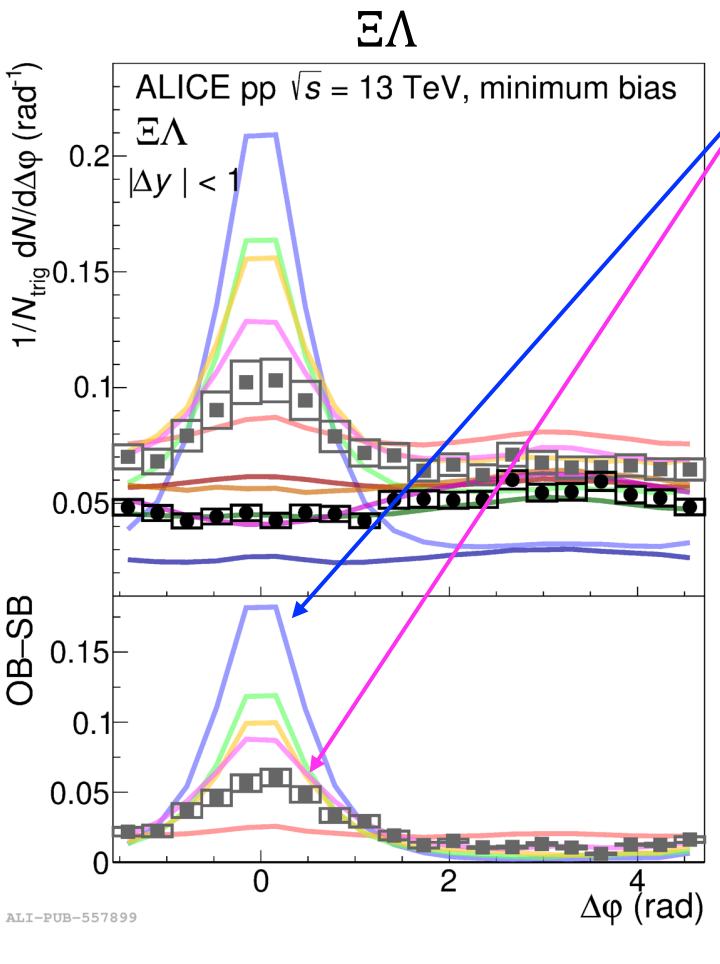
EPOS LHC (core-corona model)

→ describes SE as an increase of the "core" part (thermalised medium with global strangeness conservation) wrt "corona"(string-breaking)

→ **decorrelation of *s* quarks**

Balancing of strangeness quantum number





PYTHIA8 and HERWIG predict narrower and taller near-side (NS) peaks
→ **effects of string breaking too large**

OS correlation attributed to $s\bar{s}$ pair
No SS near-side peak (no shared $q\bar{q}$)

Production of multiple baryons within same (mini)jet is disfavoured

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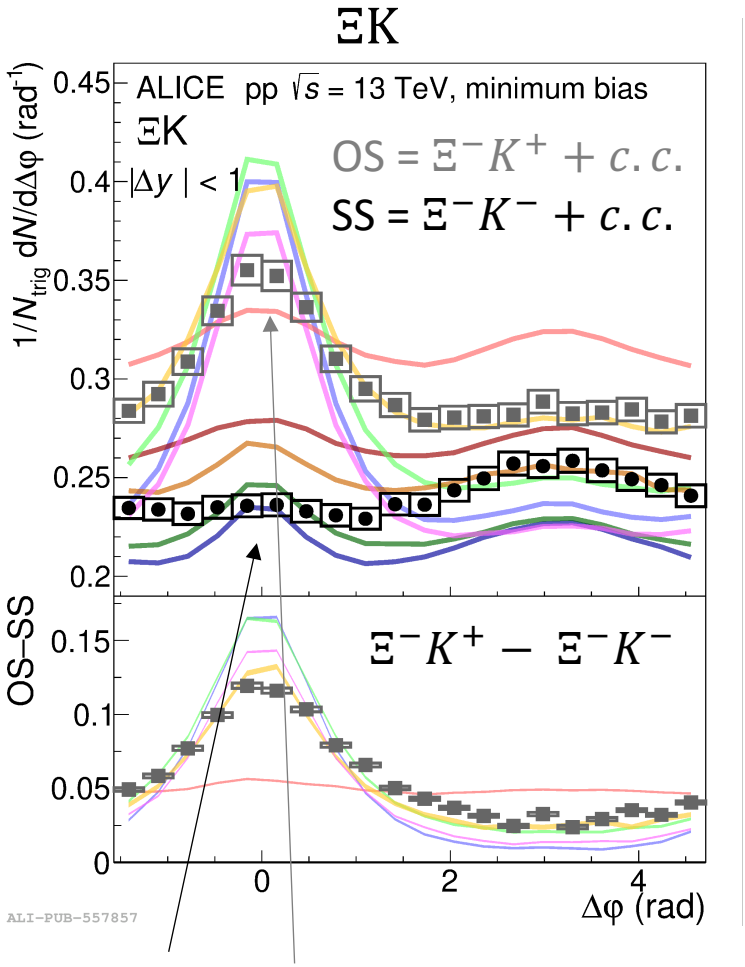
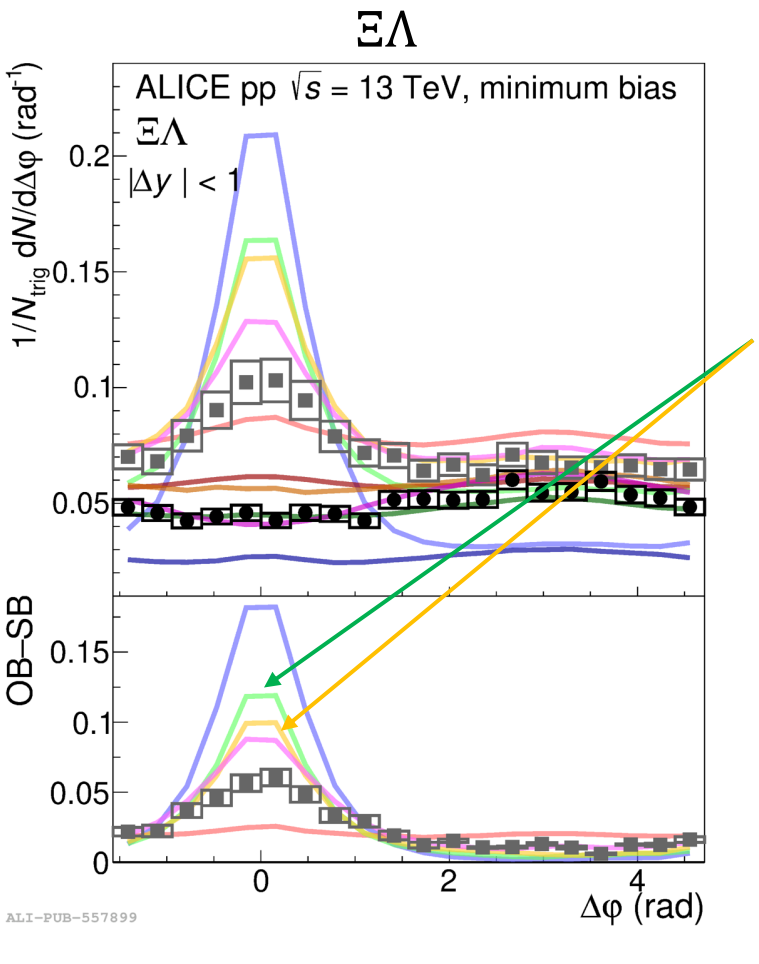
arXiv:2308.16706

Balancing of strangeness quantum number





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PYTHIA8 with ropes and junctions provide better description than Monash
→ **diquark breaking mechanism is not enough** to describe the data

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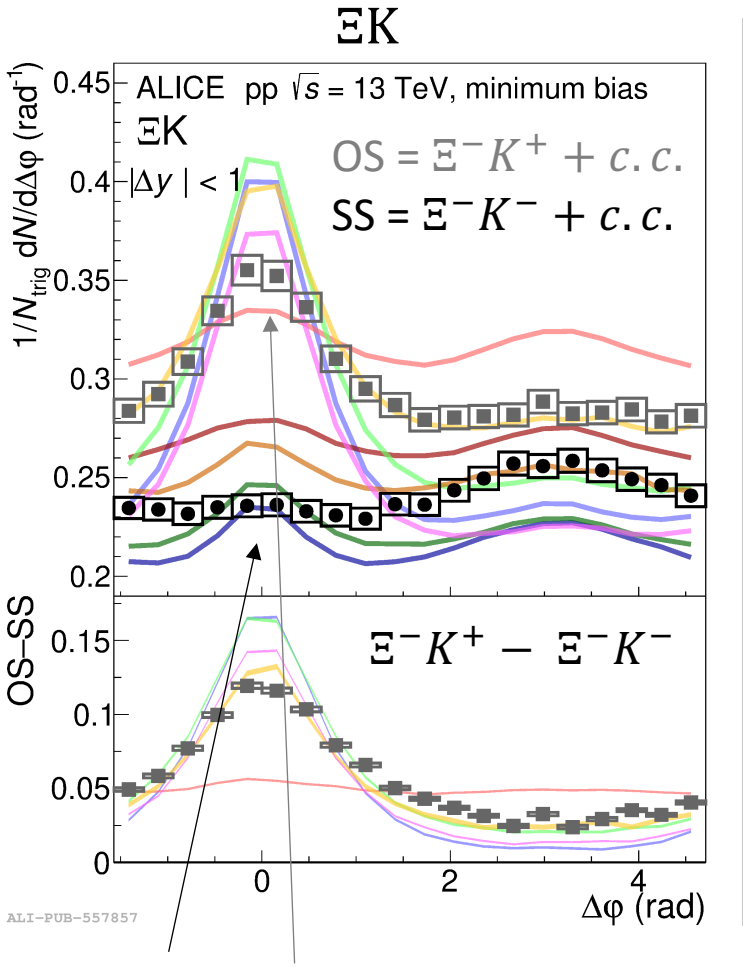

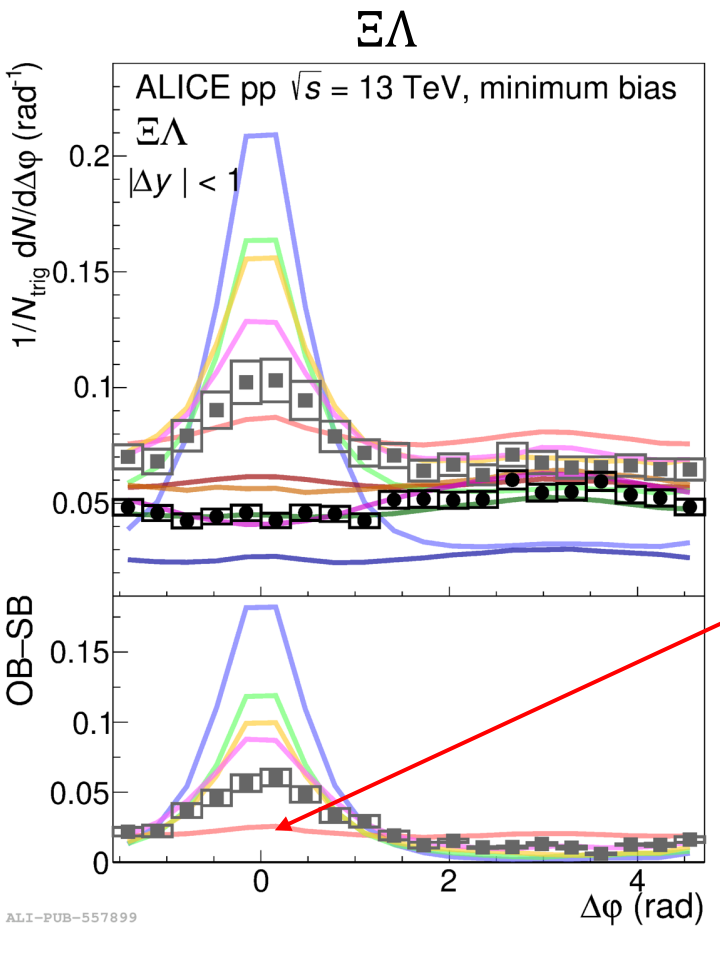

PYTHIA8 and HERWIG predict narrower and taller near-side (NS) peaks
→ **effects of string breaking too large**

PYTHIA8 with ropes and junctions provide better description than Monash
→ **diquark breaking mechanism is not enough** to describe the data

EPOS LHC predicts broader NS peaks
→ consequence of **decorrelation**

OS correlation attributed to $s\bar{s}$ pair
No SS near-side peak (no shared $q\bar{q}$)

Production of multiple baryons within same (mini)jet is disfavoured

SS OS
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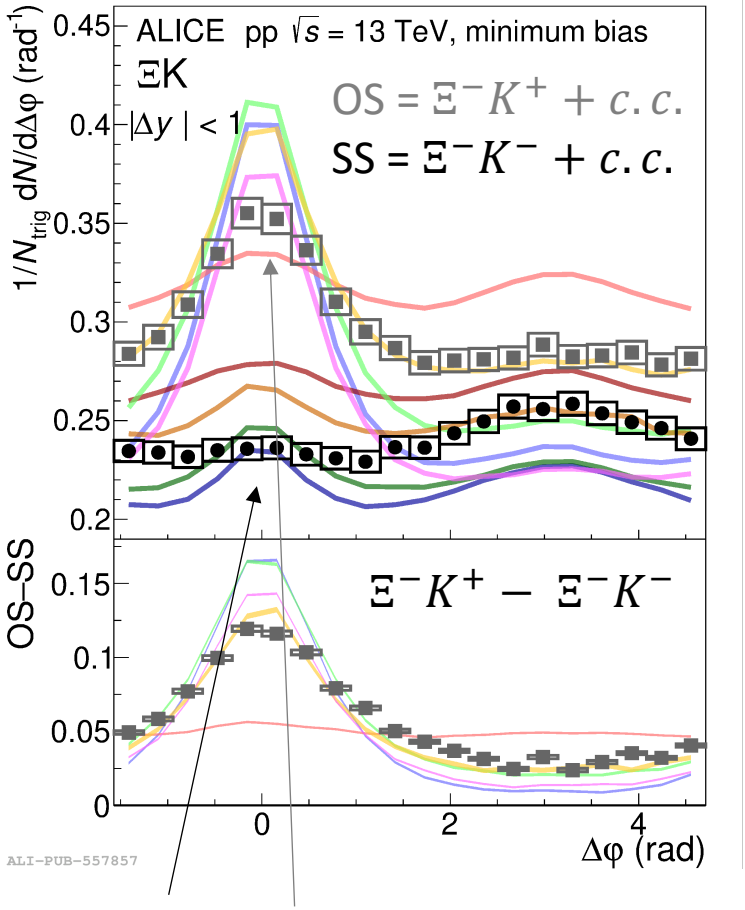
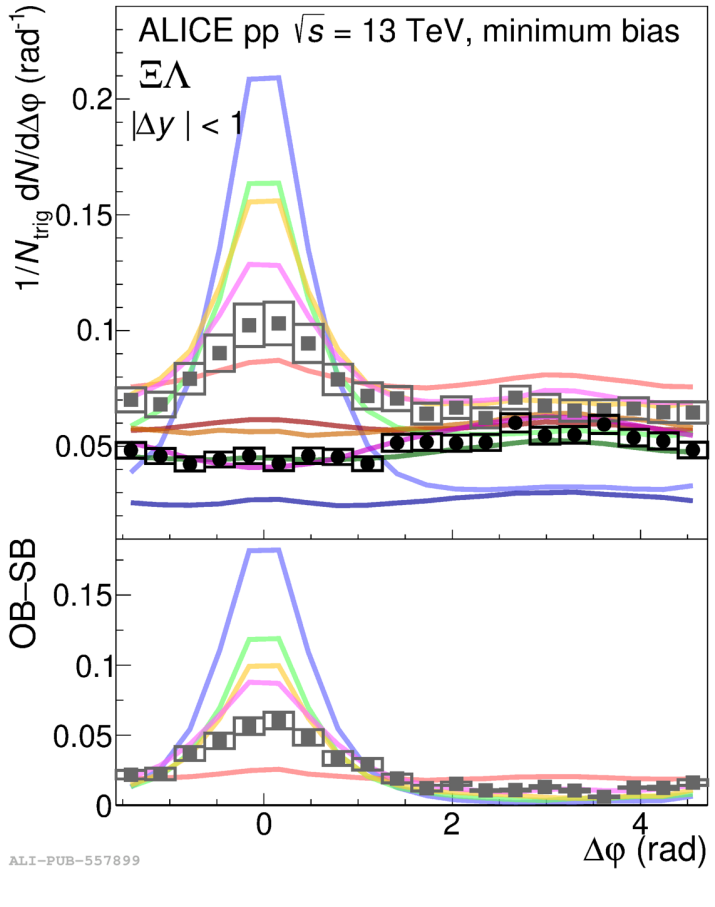




OS correlation attributed to $s\bar{s}$ pair
No SS near-side peak (no shared $q\bar{q}$)

Production of multiple baryons within same (mini)jet is disfavoured

TAKE-HOME MESSAGE #1

The data show locally correlated $s\bar{s}$ production. EPOS LHC predicts wider correlations, PYTHIA8 and HERWIG narrower ones.

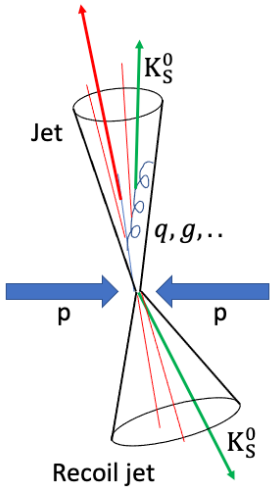
SS OS
ALICE
PYTHIA8 Monash
PYTHIA8 Junctions
PYTHIA8 Ropes
EPOS LHC
HERWIG

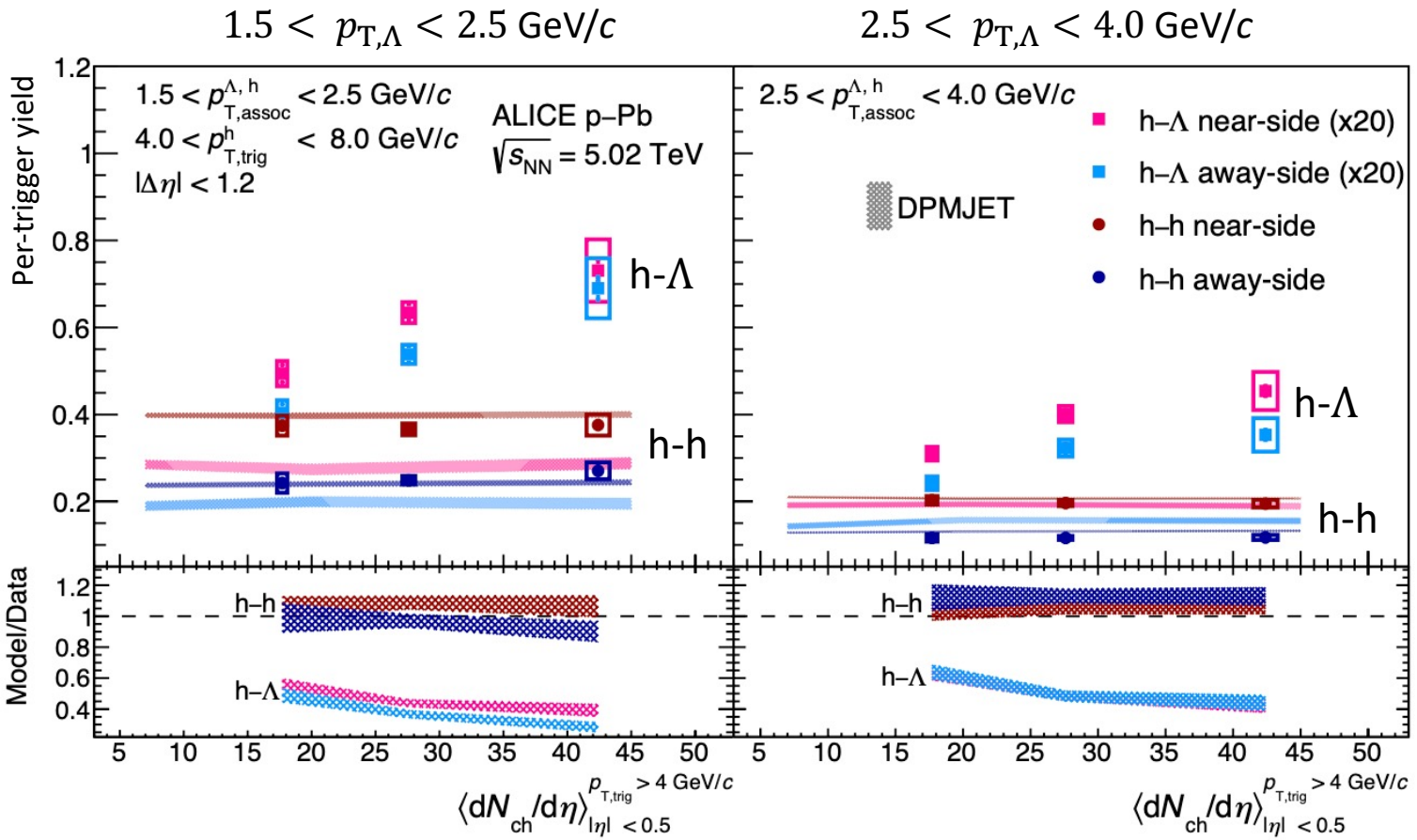
arXiv:2308.16706

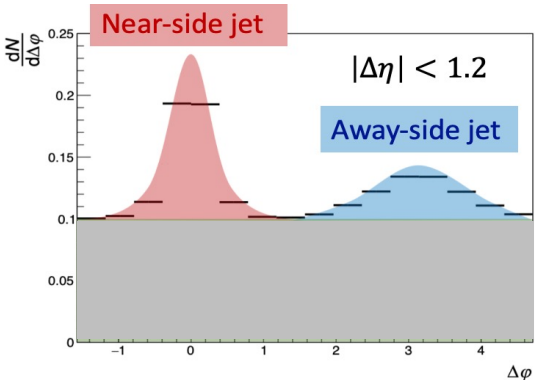
Angular correlations for in- and out-of-jet strange hadron production vs $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle_{|\eta|<0.5}$

$\mathrm{h}-\mathrm{h}$ and $\mathrm{h}-\Lambda$ yields vs multiplicity in p–Pb collisions

trigger particle:
$h^{\pm}$ with $p_{\mathrm{T}} > 4$ GeV/c
~jet axis



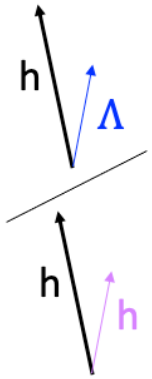


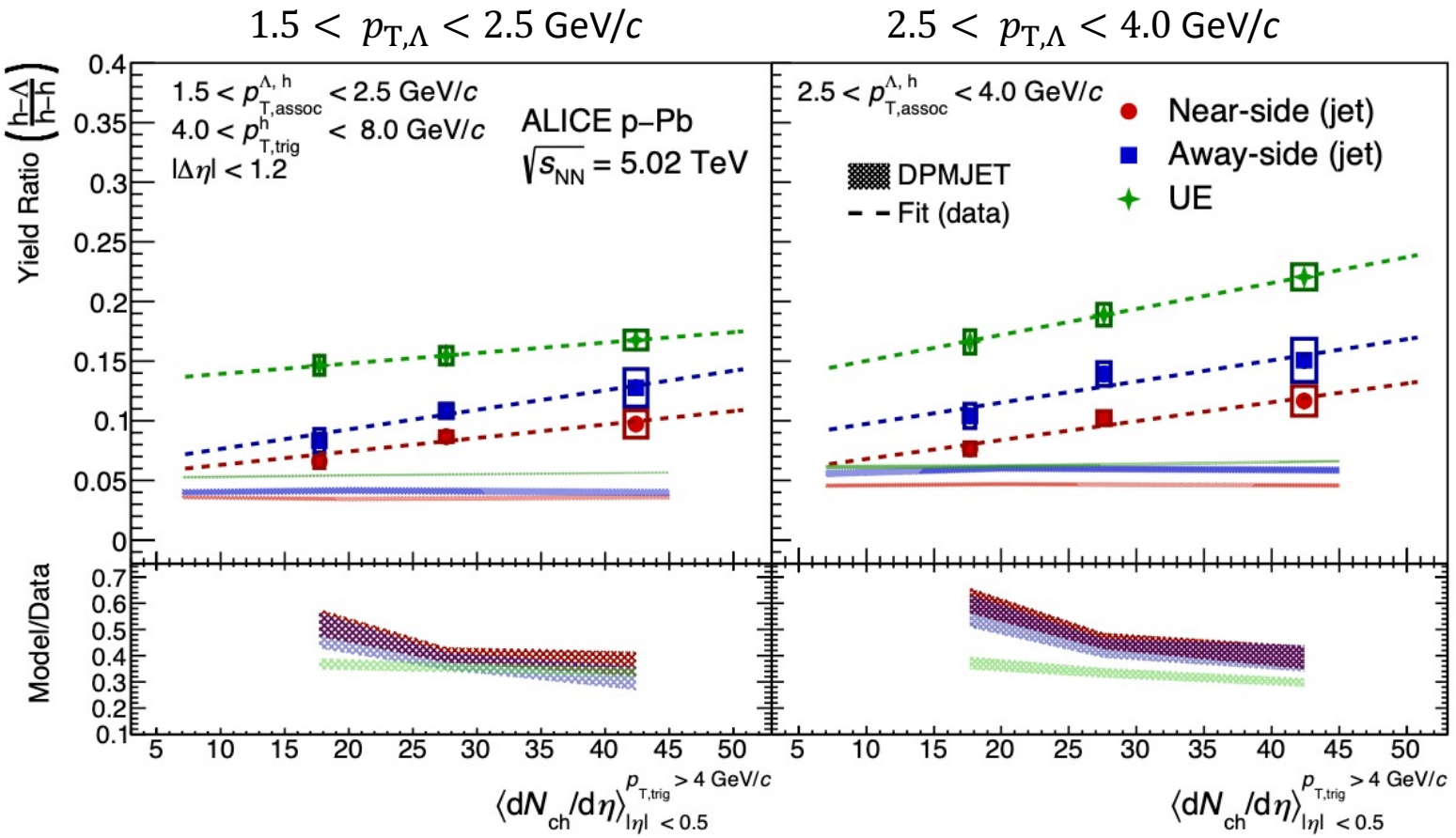


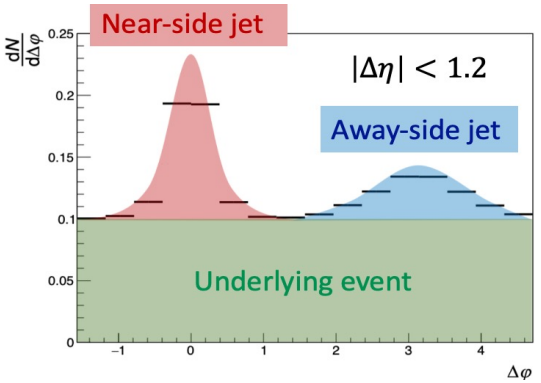
NEW!
arXiv:2405.19855

- The near-side and the away-side $\mathrm{h}-\Lambda$ yields **increase with multiplicity**, whereas the $\mathrm{h}-\mathrm{h}$ yields do not show any significant multiplicity dependence
- **DPMJET** fairly reproduces the $\mathrm{h}-\mathrm{h}$ yields, but largely underestimates the $\mathrm{h}-\Lambda$ yields

$\mathrm{h}-\Lambda/\mathrm{h}-\mathrm{h}$ yield ratios vs multiplicity in p–Pb collisions





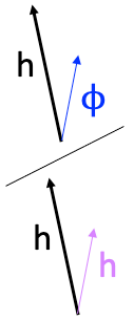


NEW!

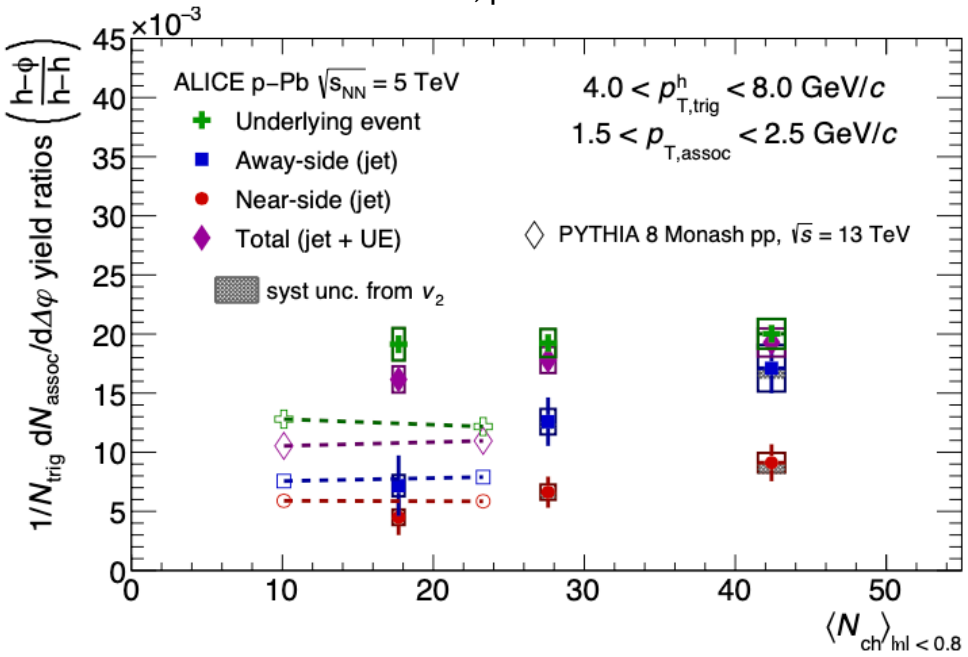
arXiv:2405.19855

- The underlying event ratios **increase with multiplicity** in both p_{T} intervals
- The near-side and the away-side ratios show a **hint of increase with multiplicity**
- **DPMJET** reproduces the ordering UE > AS > NS, but not the magnitude nor the multiplicity dependence

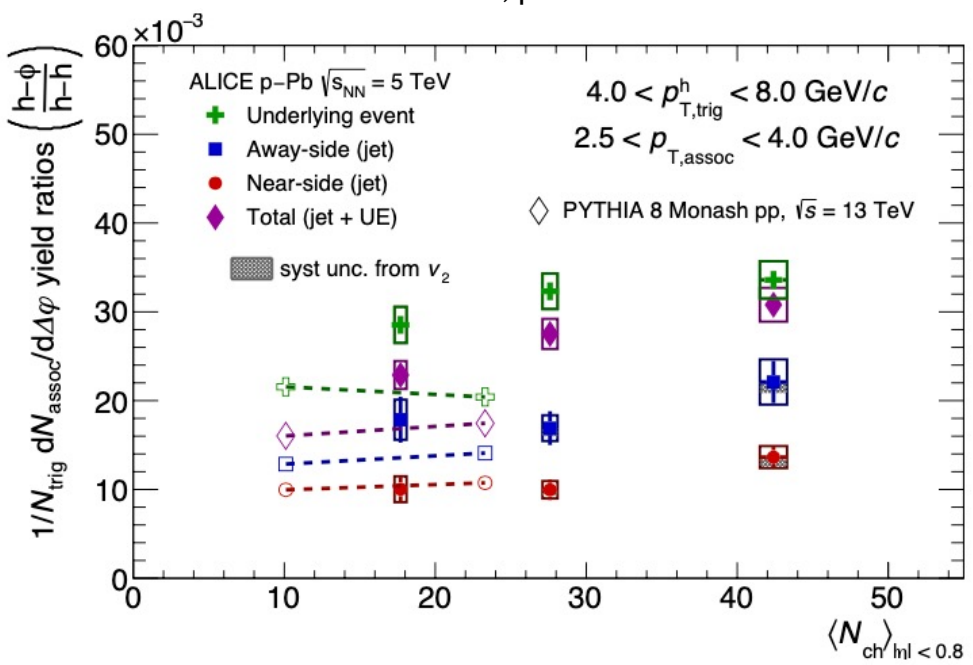
$\mathbf{h-\phi}$ /$\mathbf{h-h}$ yield ratios vs multiplicity in p–Pb collisions



$1.5 < p_{\mathrm{T},\phi} < 2.5$ GeV/c

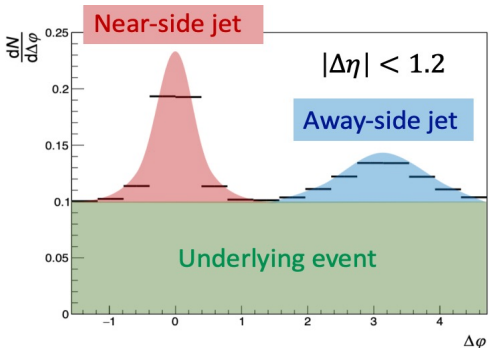


$2.5 < p_{\mathrm{T},\phi} < 4.0$ GeV/c



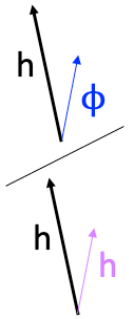
NEW!

arXiv:2405.14491



- The same ordering UE > AS > NS is also observed in the $\mathbf{h-\phi/h-h}$ **ratios**
- The AS and NS ratios show a hint of increase with multiplicity in the lowest p_{T} interval
- The total ratio is predominantly determined by the underlying event production

h − ϕ /h − h yield ratios vs multiplicity in p–Pb collisions



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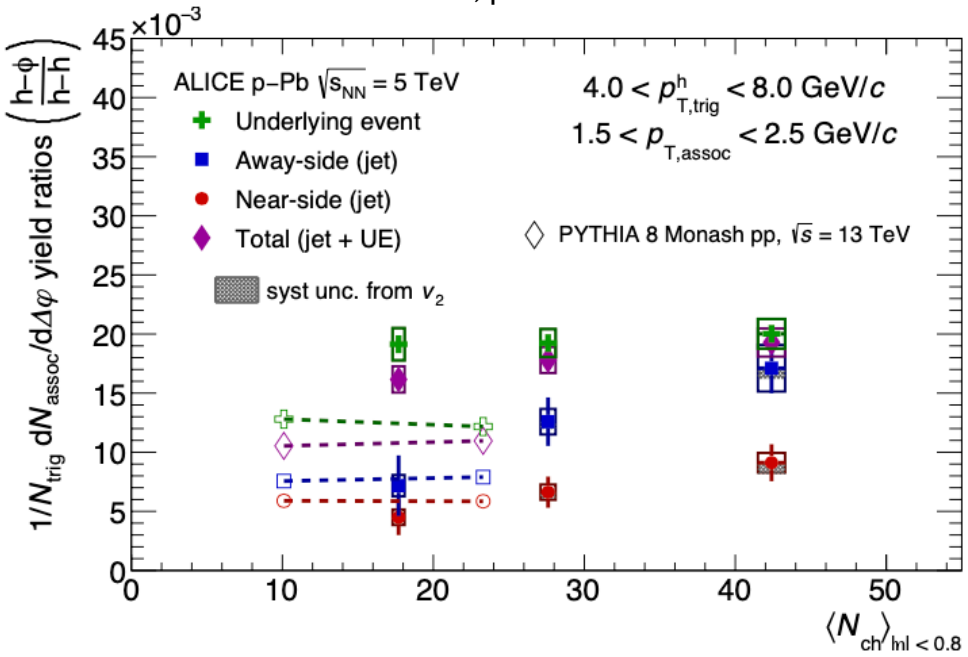

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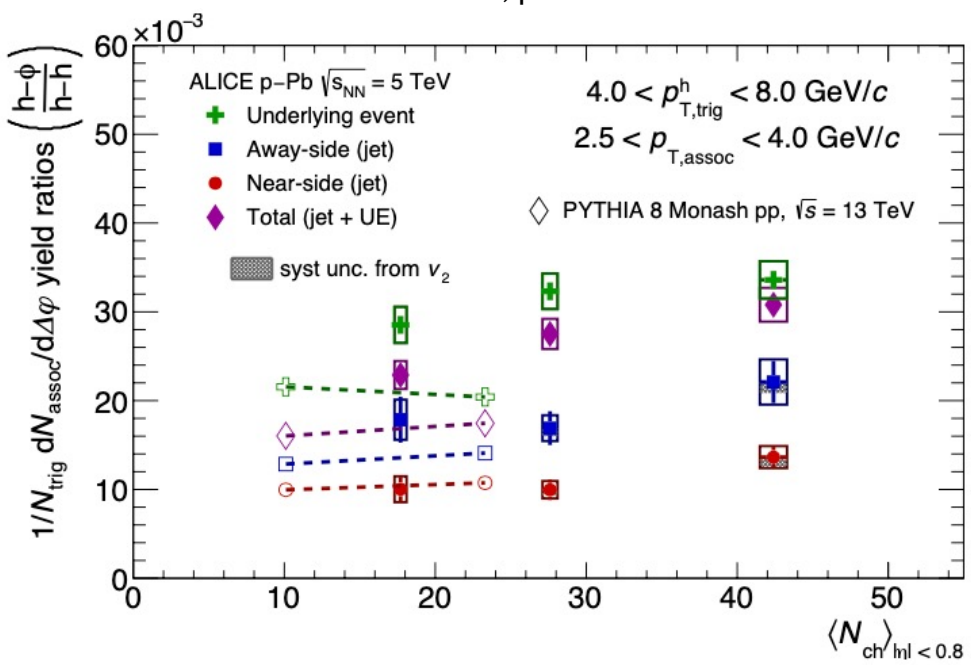
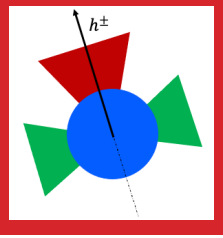


NEW!

arXiv:2405.14491

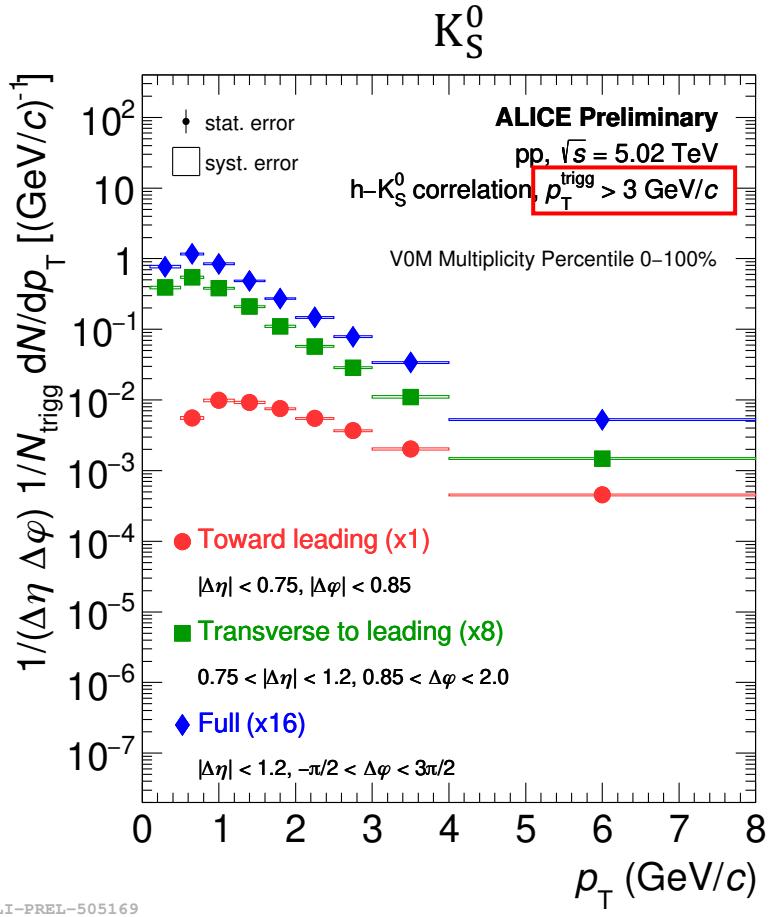
TAKE-HOME MESSAGE #2

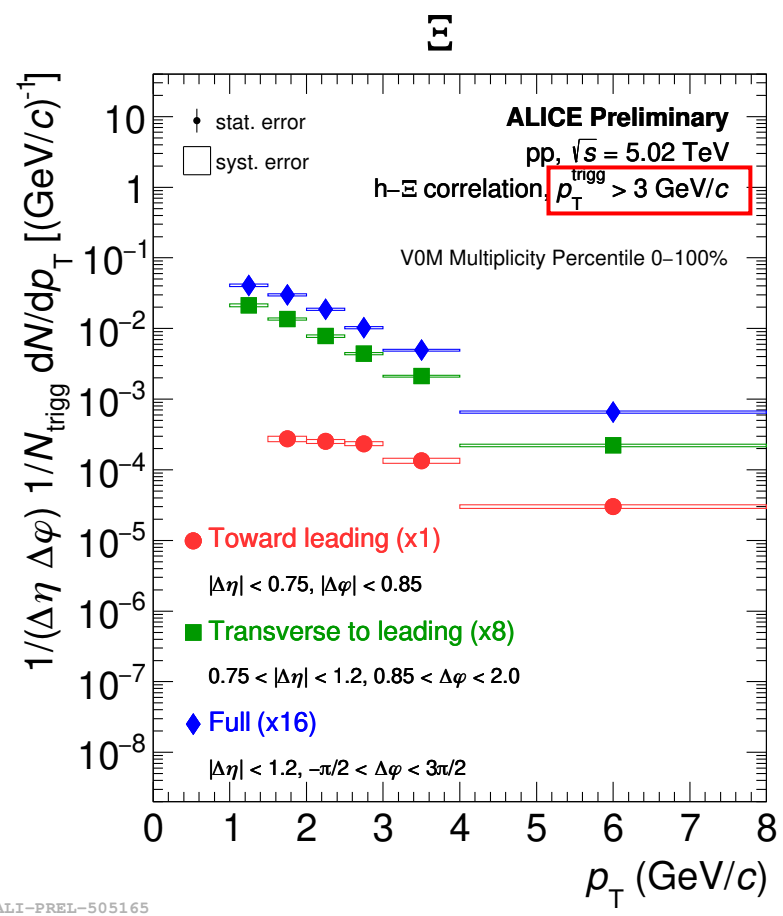
The relative production of strange hadrons is **larger in the underlying event** than in hard scattering processes

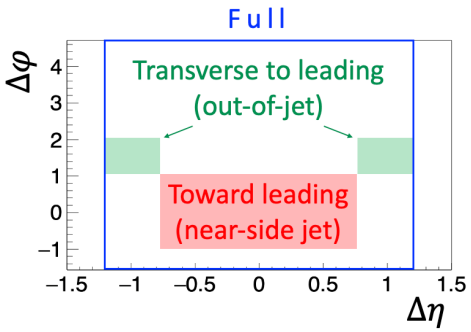


Toward, transverse-to-leading and full p_T spectra of K^0_S and Ξ in pp collisions

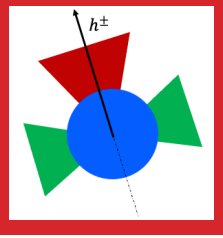
ALICE







- Toward-leading spectra of K^0_S (Ξ) are harder than transverse-to-leading spectra of K^0_S (Ξ)
- Same feature observed in different multiplicity classes and different centre-of-mass energies



Toward, transverse-to-leading and full p_T spectra of K^0_S and Ξ in pp collisions

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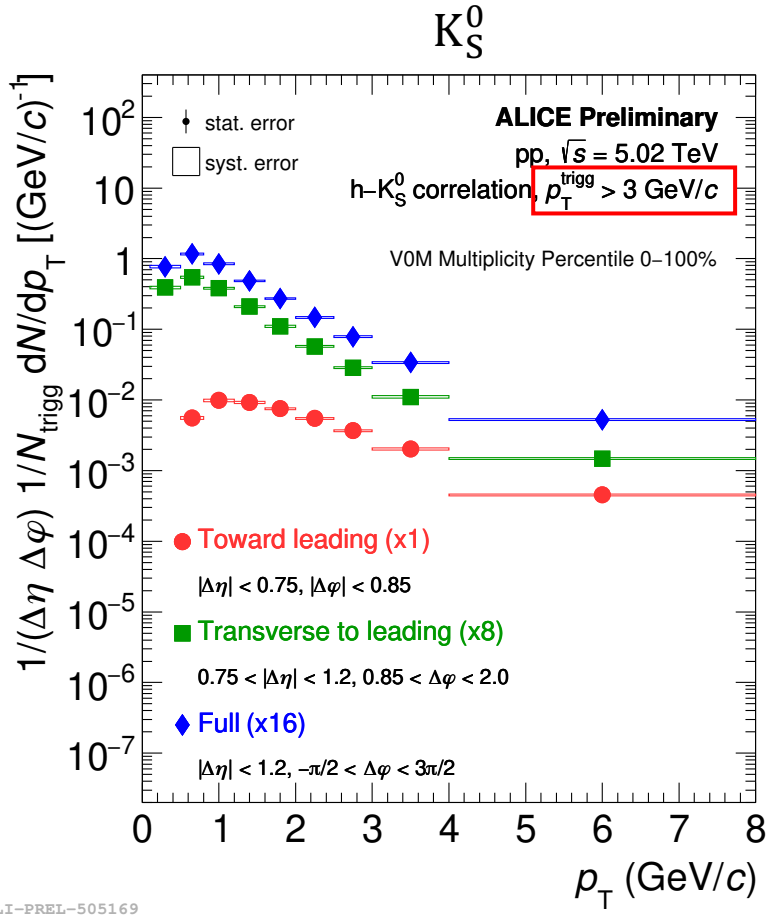
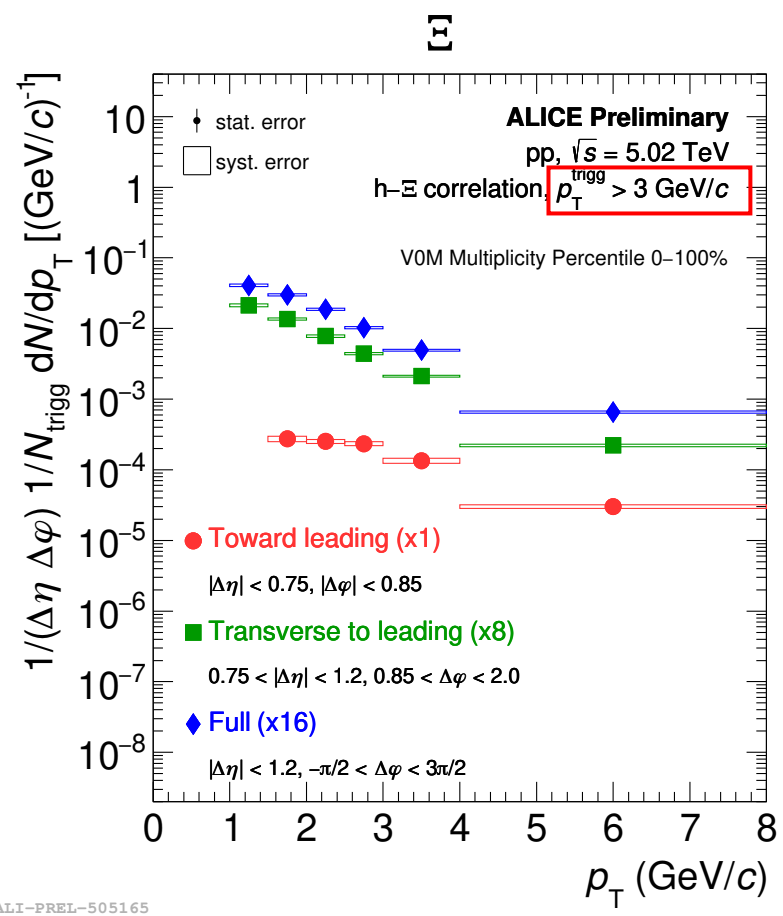
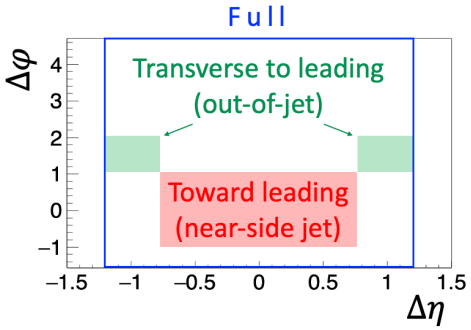
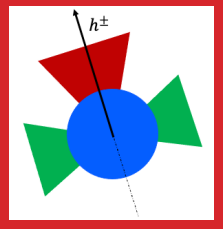






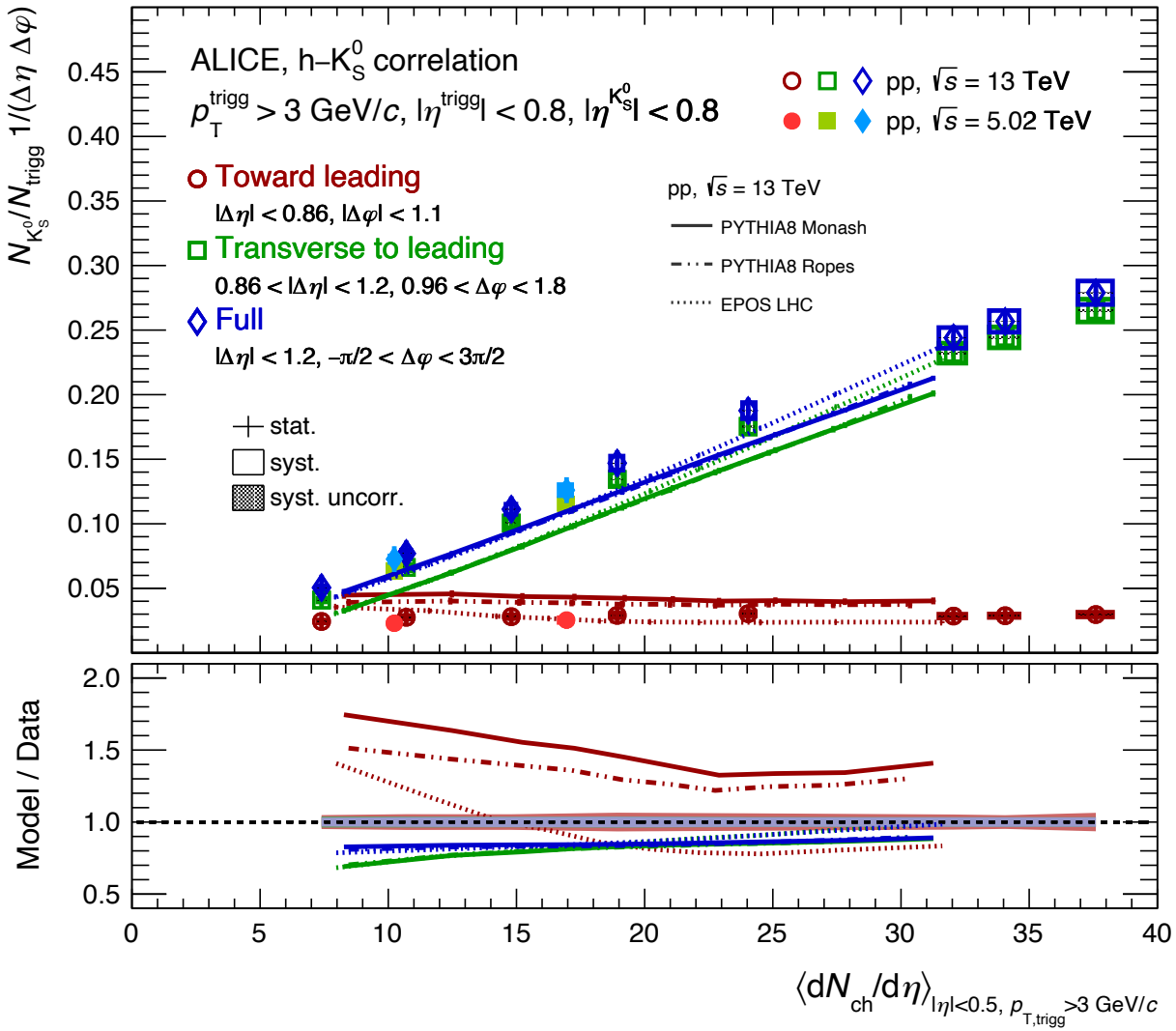
See also the talk by Gijs van Weelden Track1-LF, Wed 9:50

- Toward-leading spectra of K^0_S (Ξ) are harder than transverse-to-leading spectra of K^0_S (Ξ)
- Same feature observed in different multiplicity classes and different centre-of-mass energies



K^0_S vs charged-particle multiplicity

ALICE

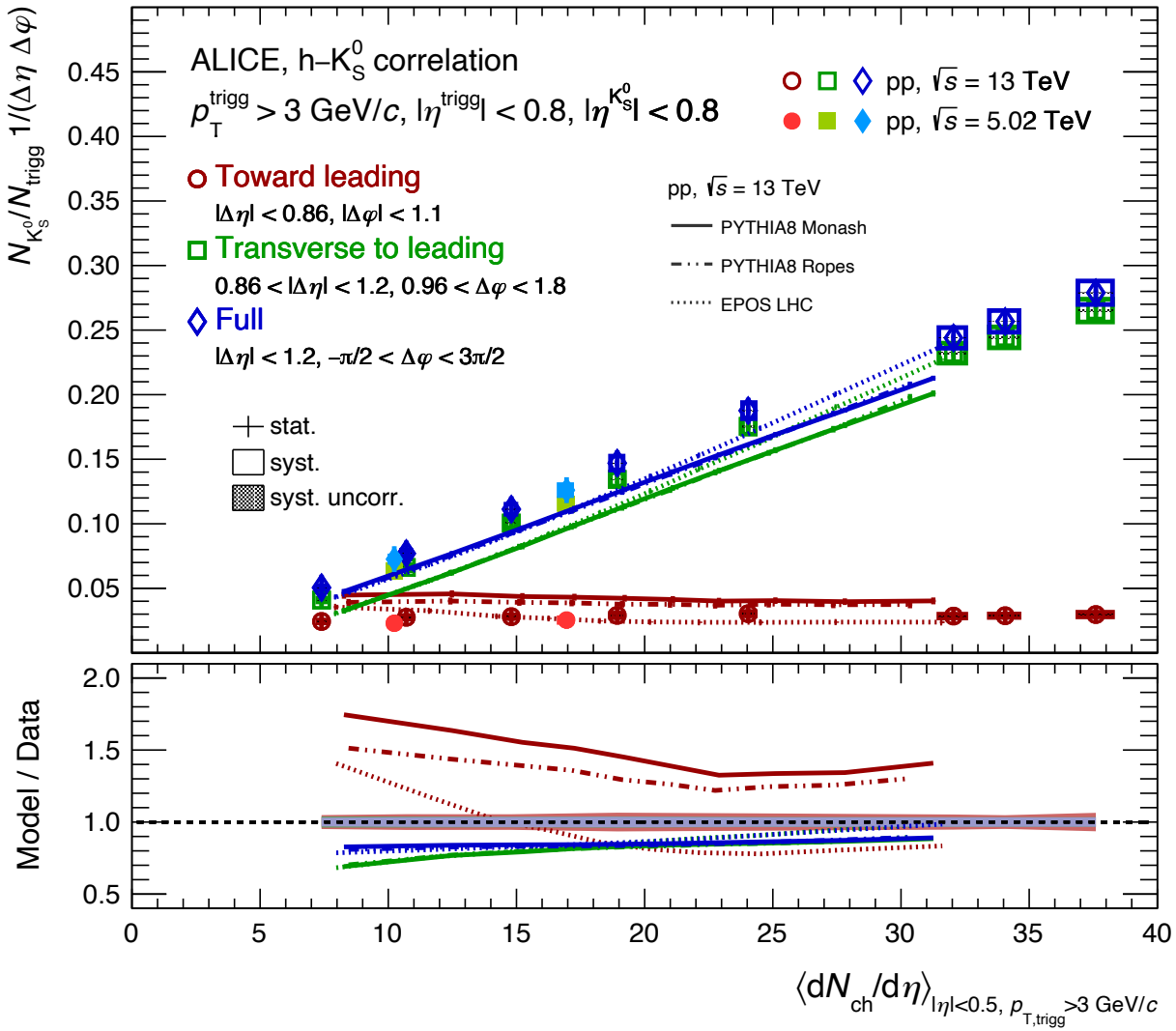


- Both full and transverse-to-leading yields increase with the multiplicity
- Milder increase with multiplicity of the toward-leading yield
- The yields show no dependence on the centre-of-mass energy

NEW!

arXiv:2405.14511

K^0_S vs charged-particle multiplicity

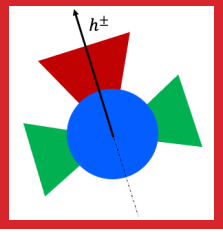


- Both full and transverse-to-leading yields increase with the multiplicity
- Milder increase with multiplicity of the toward-leading yield
- The yields show no dependence on the centre-of-mass energy

TAKE-HOME MESSAGE #3

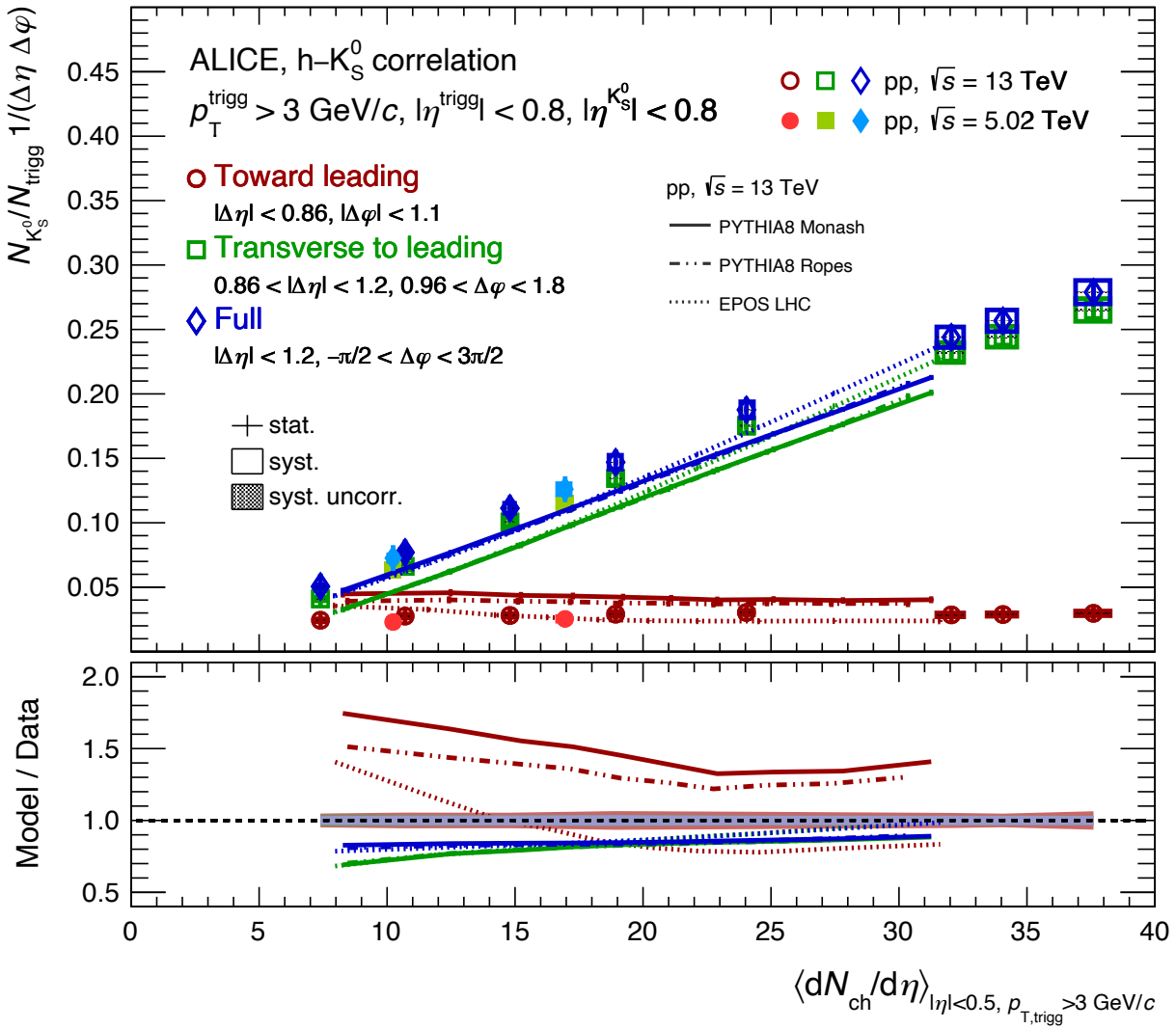
The contribution of transverse-to-leading wrt toward-leading production increases with multiplicity

NEW!
arXiv:2405.14511



K^0_S vs multiplicity: model comparison

ALICE



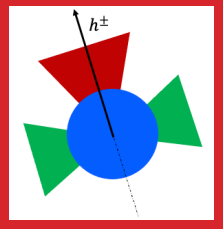
PYTHIA8 with ropes and **EPOS LHC** can qualitatively describe the strangeness enhacement in pp collisions

PYTHIA8 Monash predicts flat strange-hadron-to-pion ratios vs multiplicity

How do they describe the toward-leading and transverse-to-leading production of strange hadrons?

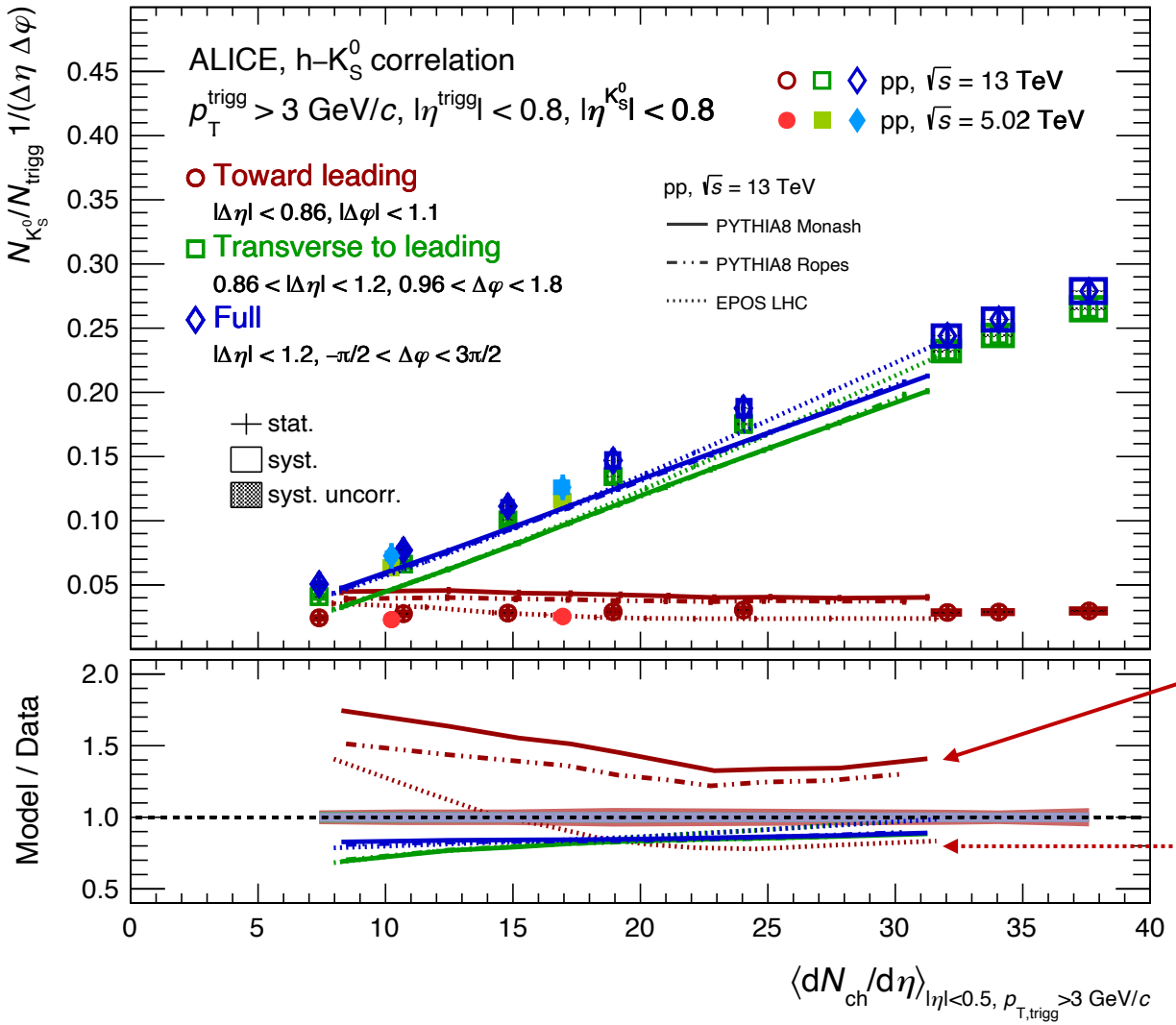
NEW!

arXiv:2405.14511



K^0_S vs multiplicity: model comparison

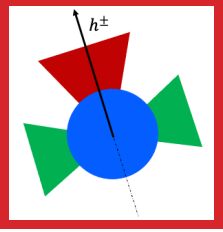
ALICE



All **models underestimate** the transverse-to-leading and the full production of up to 30%

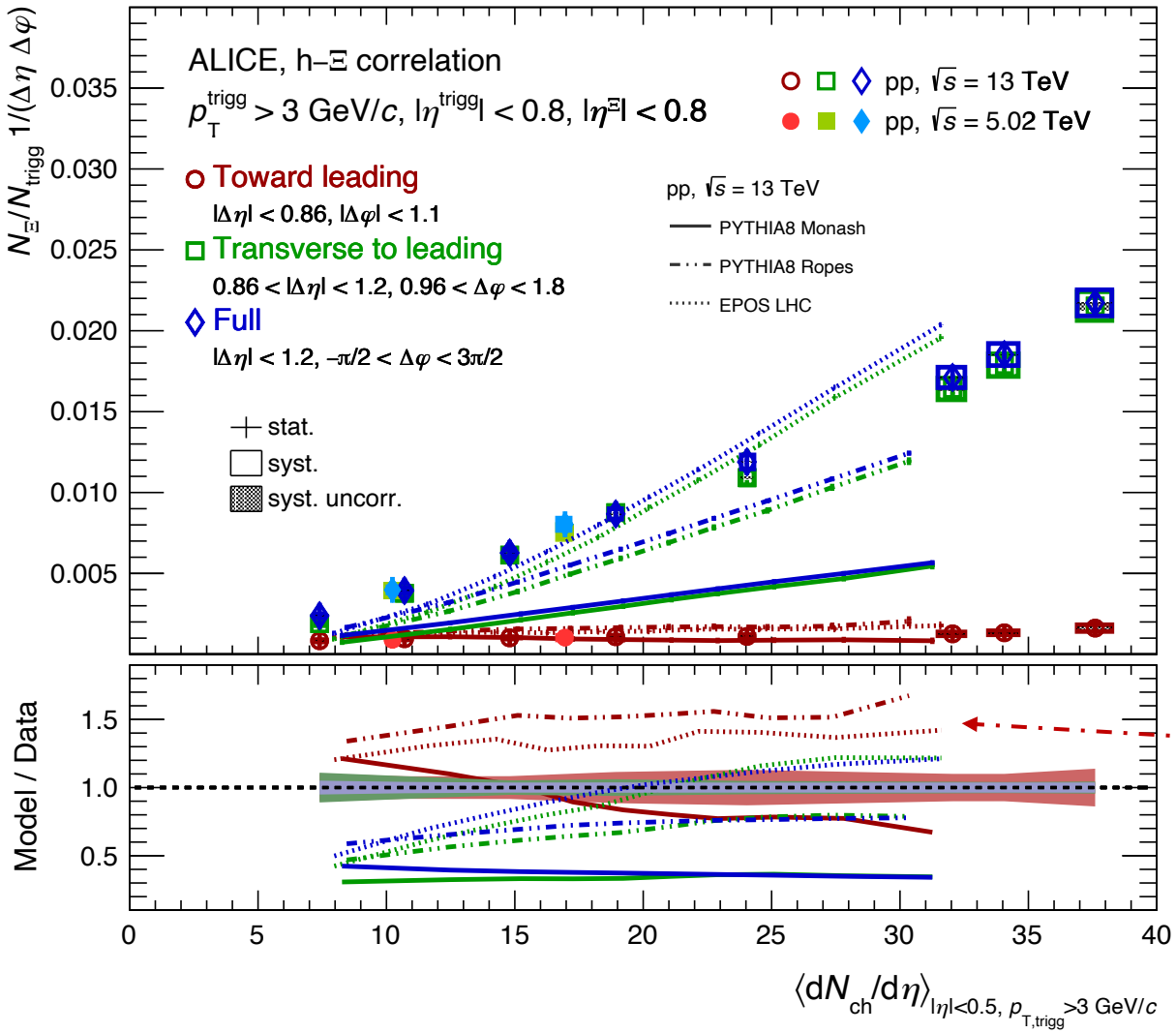
Both **PYTHIA8 models overestimate** the toward-leading production

EPOS LHC cannot describe the toward-leading increase with multiplicity



$\Xi^{\pm}$ vs charged-particle multiplicity

ALICE



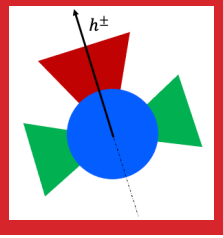
Also for Ξ the full and transverse-to-leading yields increase with multiplicity faster than the toward-leading yields

The deviation of the models from the full and transverse-to-leading yields is **larger** than for K^0_S

PYTHIA8 with ropes and **EPOS LHC** reproduce the toward-leading **increase** with multiplicity

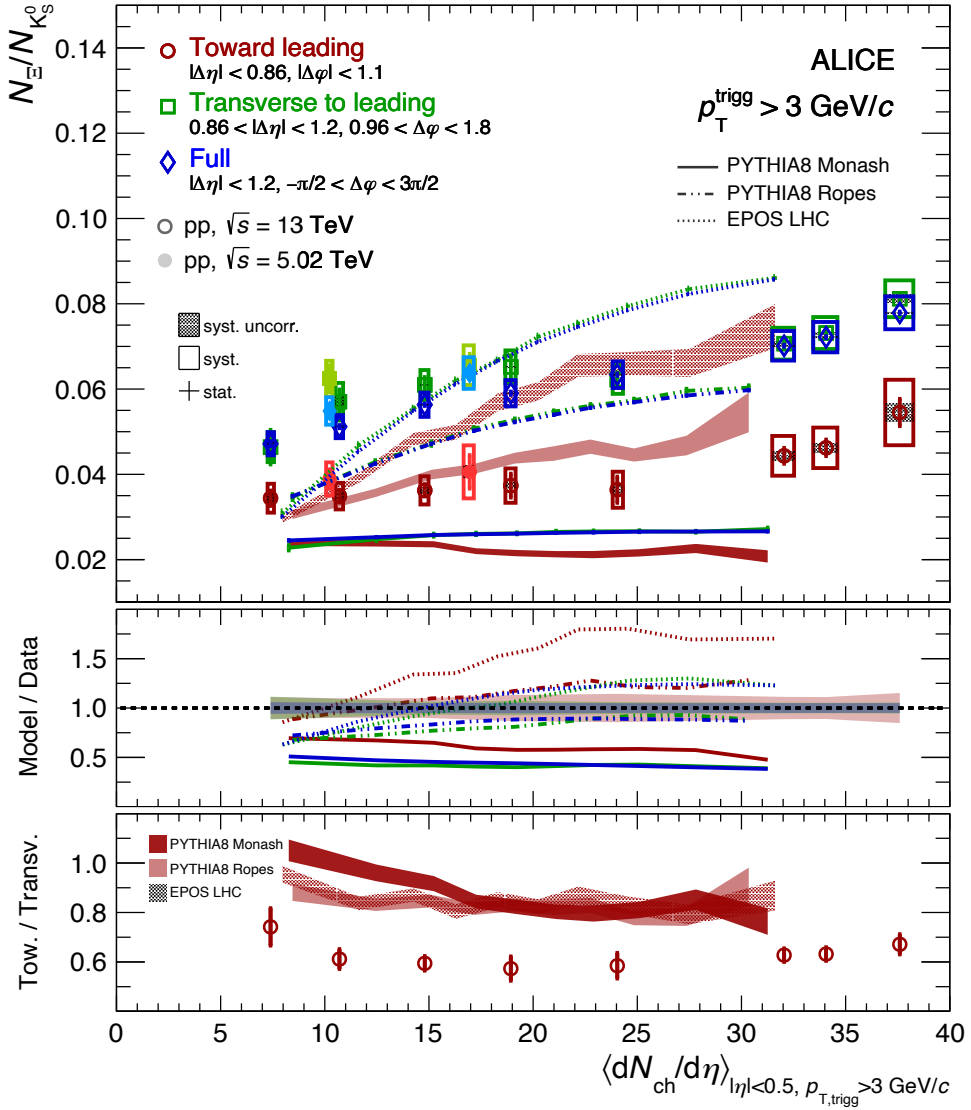
NEW!

arXiv:2405.14511



Ξ/K^0_S yield ratio vs multiplicity

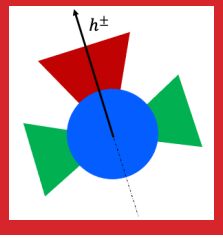
ALICE



- The strangeness enhancement in the ratio of full yields is attributed to the larger strangeness content of Ξ ($|S| = 2$) with respect to K^0_S ($|S| = 1$)
- The transverse-to-leading Ξ/K^0_S yield ratio **increases with the multiplicity** and is compatible with the ratio of full yields
- The toward-leading yield ratio is **smaller** than the transverse-to-leading one and **increases with multiplicity** in a compatible way

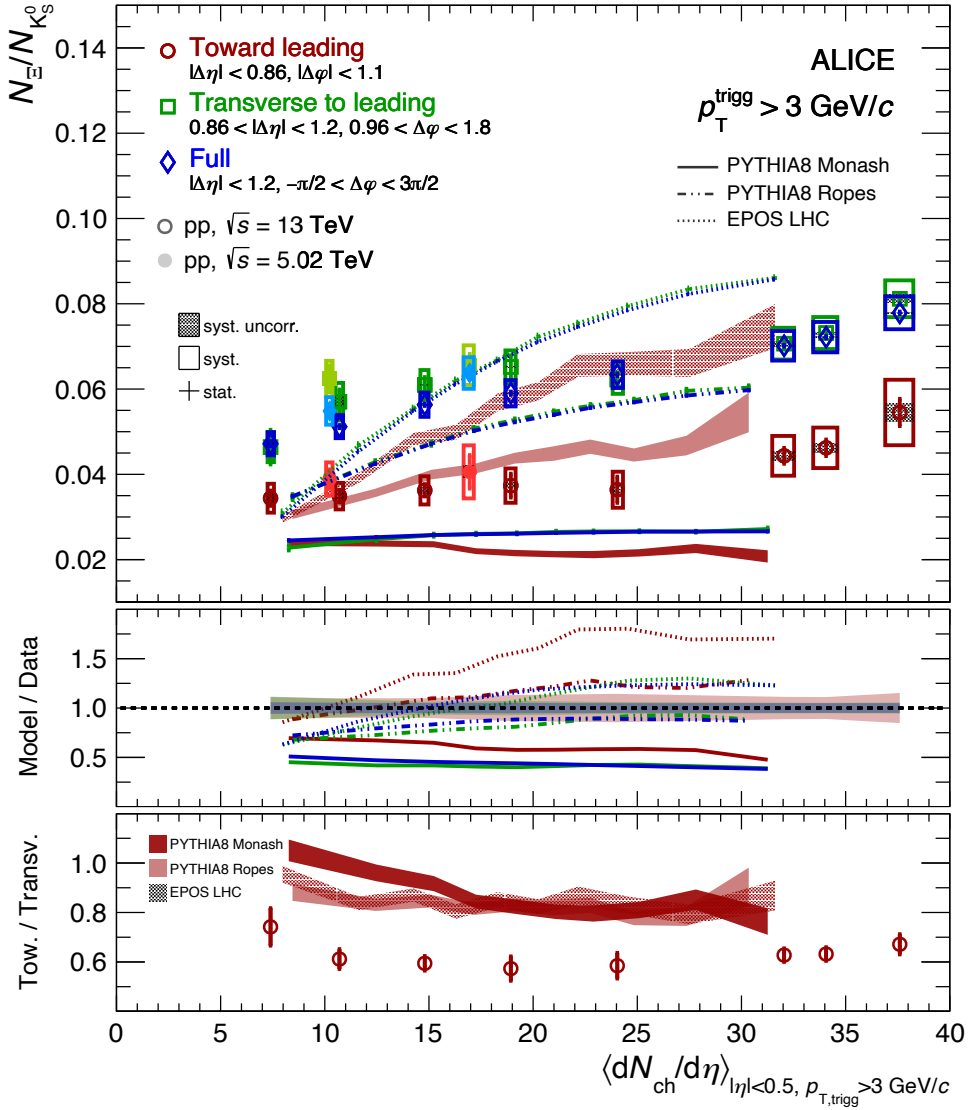
PYTHIA8 Monash
PYTHIA8 Ropes
EPOS LHC

NEW!
arXiv:2405.14511



Ξ/K^0_S yield ratio vs multiplicity

ALICE



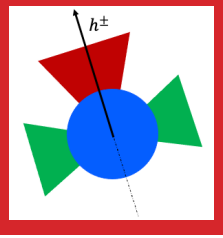
TAKE-HOME MESSAGE #4

→ Transverse-to-leading processes give the **dominant contribution** to the Ξ/K^0_S full yield ratio in pp collisions

→ The toward-leading and transverse-to-leading Ξ/K^0_S yield ratios **increase with multiplicity** in a compatible way

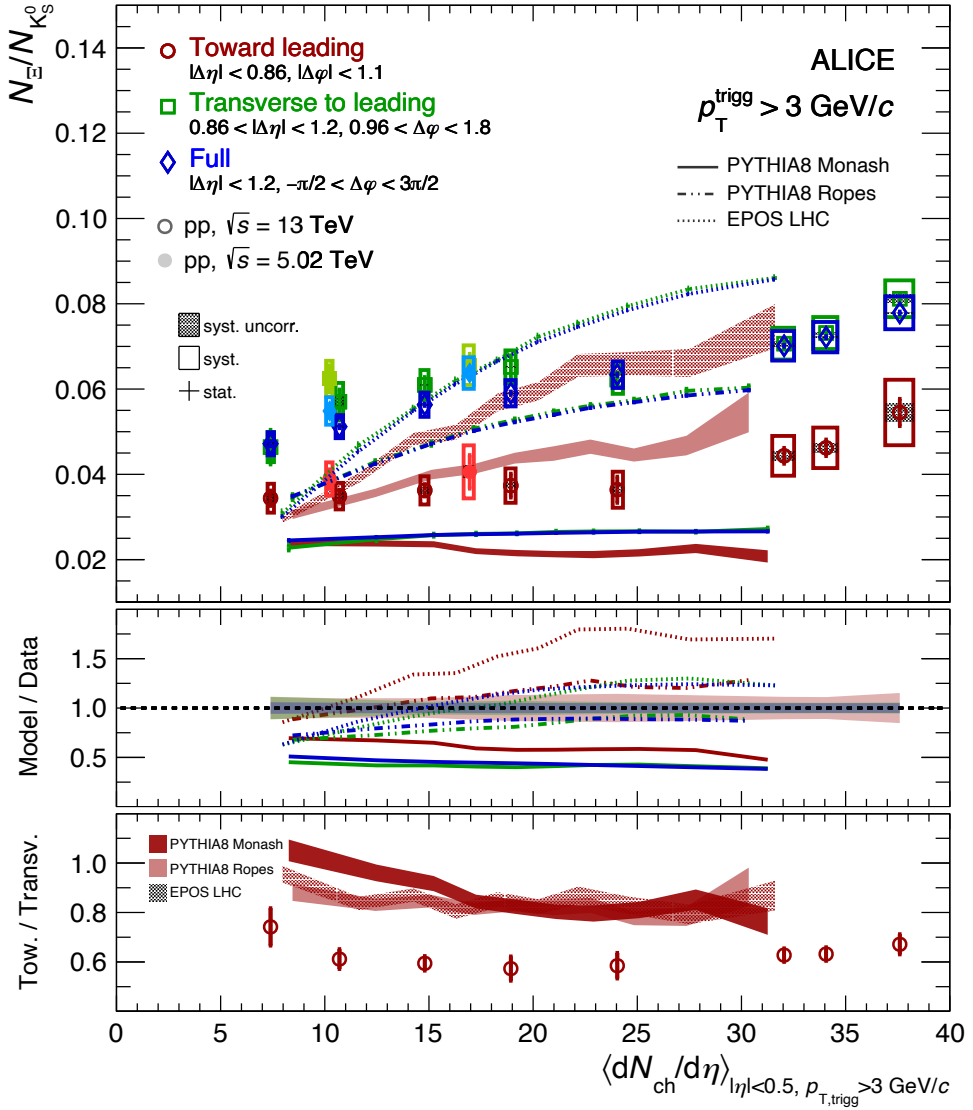
PYTHIA8 Monash
PYTHIA8 Ropes
EPOS LHC

NEW!
arXiv:2405.14511



Ξ/K^0_S yield ratio vs multiplicity

ALICE



PYTHIA8 Monash **underestimates** the ratios

PYTHIA8 with ropes qualitatively reproduces the **increasing trends with multiplicity** but underestimates the full and transverse-to-leading ratios

EPOS LHC **overestimates the increase** with multiplicity of the ratios

PYTHIA8 Monash
PYTHIA8 Ropes
EPOS LHC

TAKE-HOME MESSAGE #5

None of the considered models **quantitatively describe strange hadron** production in **hard scattering** processes or in the **underlying event**

Summary

- **Locally correlated $s\bar{s}$ production** in pp collisions **overestimated by string breaking** models and **underestimated by models with thermalised medium**
- **The underlying event** gives the **dominant contribution to strange particle production** in pp and p—Pb collisions
- **Strangeness enhancement** with multiplicity is observed both in the **toward-leading** and **transverse-to-leading** regions
- **Phenomenological models cannot quantitatively describe** strange hadron production in **hard scattering processes** or in the **underlying event**

Summary

- **Locally correlated $s\bar{s}$ production** in pp collisions **overestimated by string breaking** models and **underestimated by models with thermalised medium**
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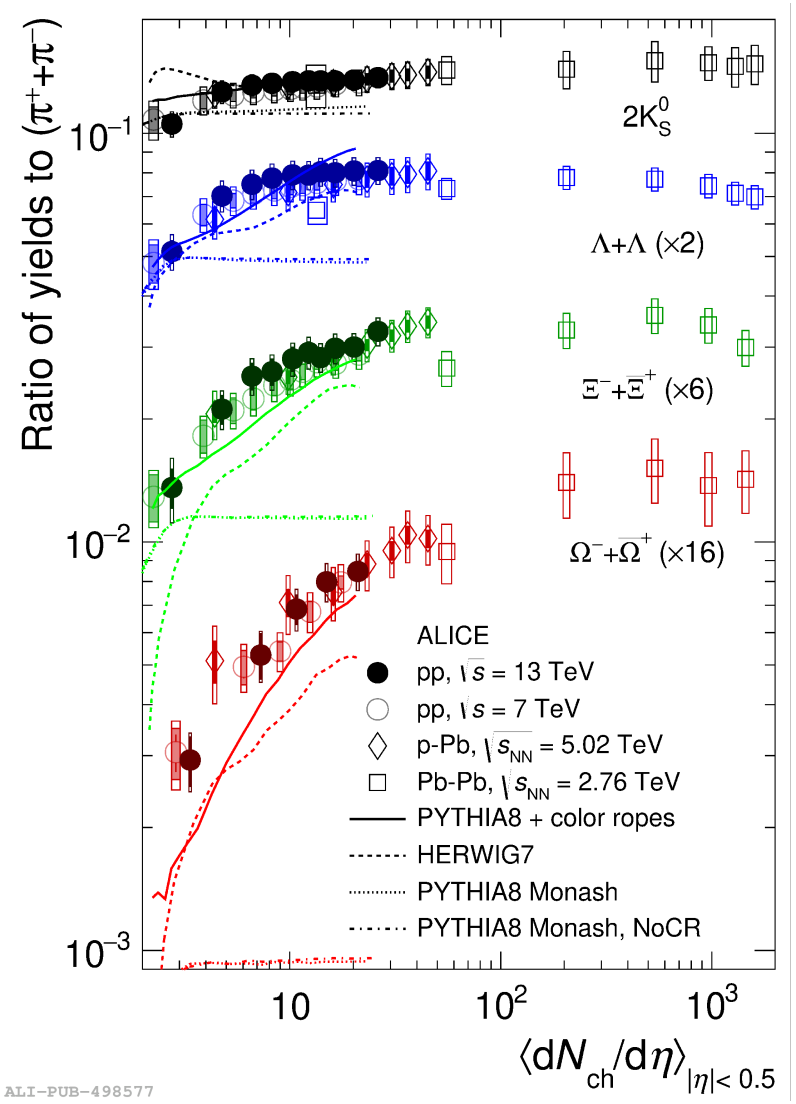
- **Strangeness enhancement** with multiplicity is observed both in the **toward-leading** and **transverse-to-leading** regions
- **Phenomenological models cannot quantitatively describe** strange hadron production in **hard scattering processes** or in the **underlying event**

Studies of strangeness production in pp collisions are profiting from the large amount of data that ALICE is collecting during Run 3

→ e.g. > 10^3 increase of $\Omega^{\pm}$ for in- and out-of-jet analysis at the end of Run 3

Backup

Model description of strangeness enhancement



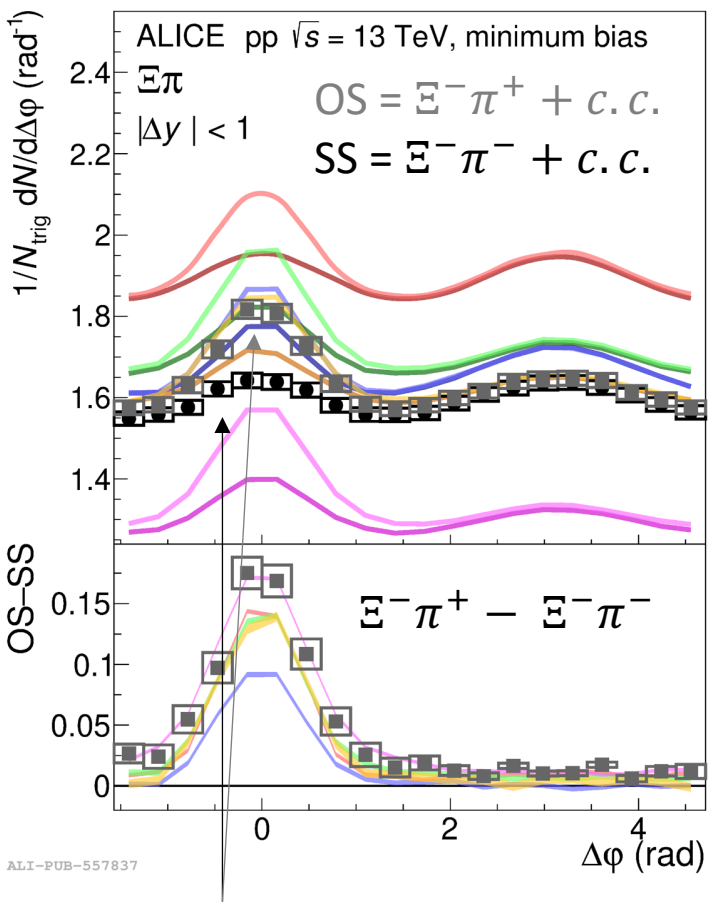
PYTHIA8 (string hadronization model)
→ predicts SE if ropes/junctions are included

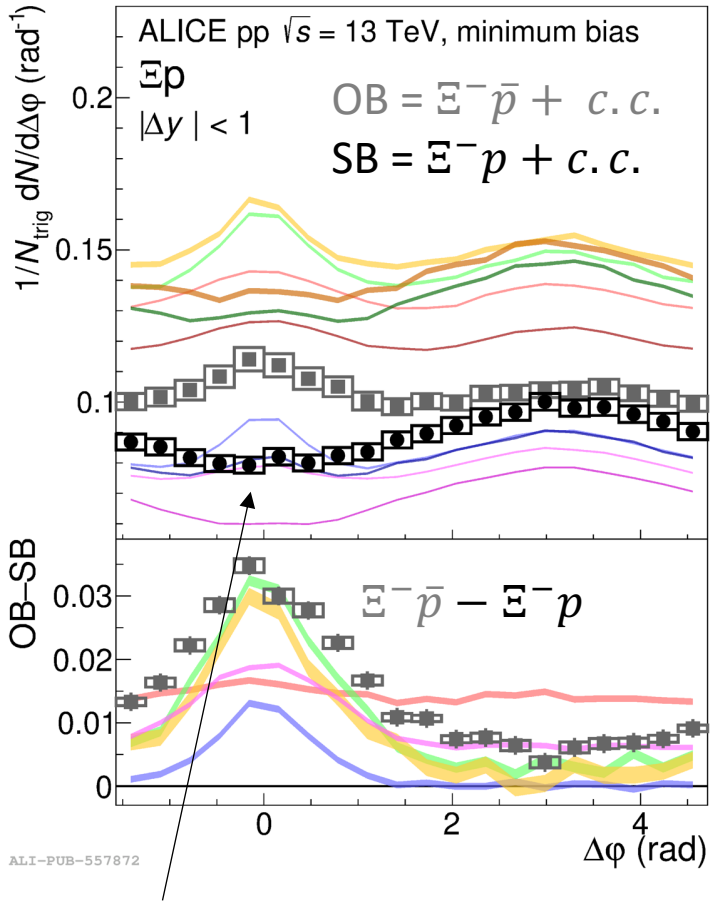
HERWIG (cluster hadronization model)
→ qualitatively predicts SE with baryonic ropes mechanism

EPOS LHC (core-corona model)
→ describes SE as an increase of the "core" part (thermalised medium with global strangeness conservation) wrt "corona"(string-breaking)

ALICE, Nature Phys 13, 535–539 (2017)
ALICE, Eur.Phys.J.C 80, 167 (2020)

Ξπ and Ξp angular correlations



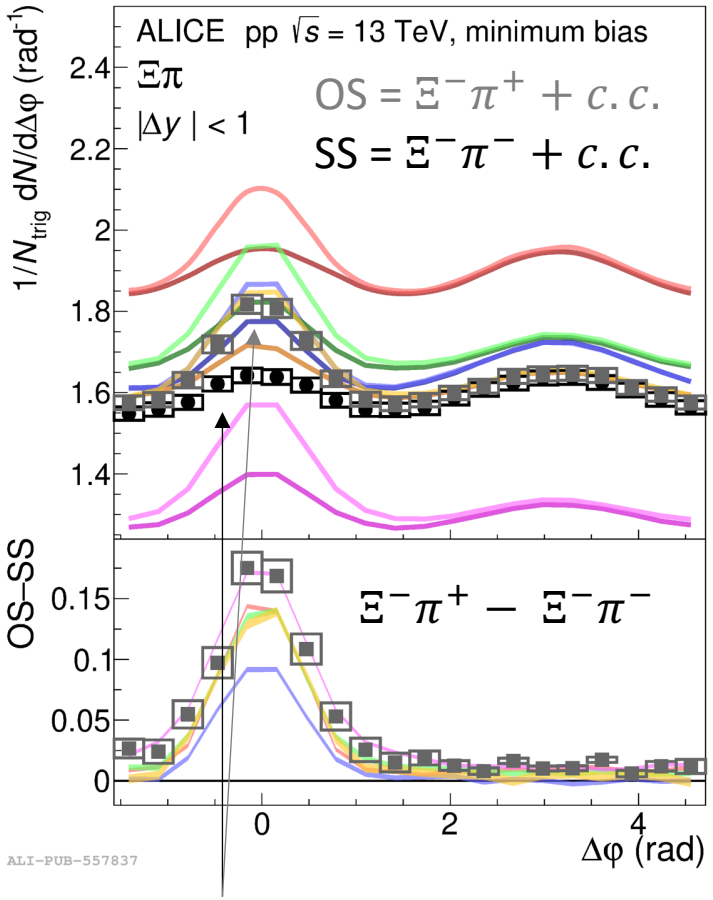


OS correlation attributed to $d\bar{d}$ pair
SS correlation attributed to dd pair

Production of multiple baryons within same (mini)jet is disfavoured

SS OS
ALICE
PYTHIA8 Monash
PYTHIA8 Junctions
PYTHIA8 Ropes
EPOS LHC
HERWIG

Ξπ and Ξp angular correlations



OS correlation attributed to $d\bar{d}$ pair
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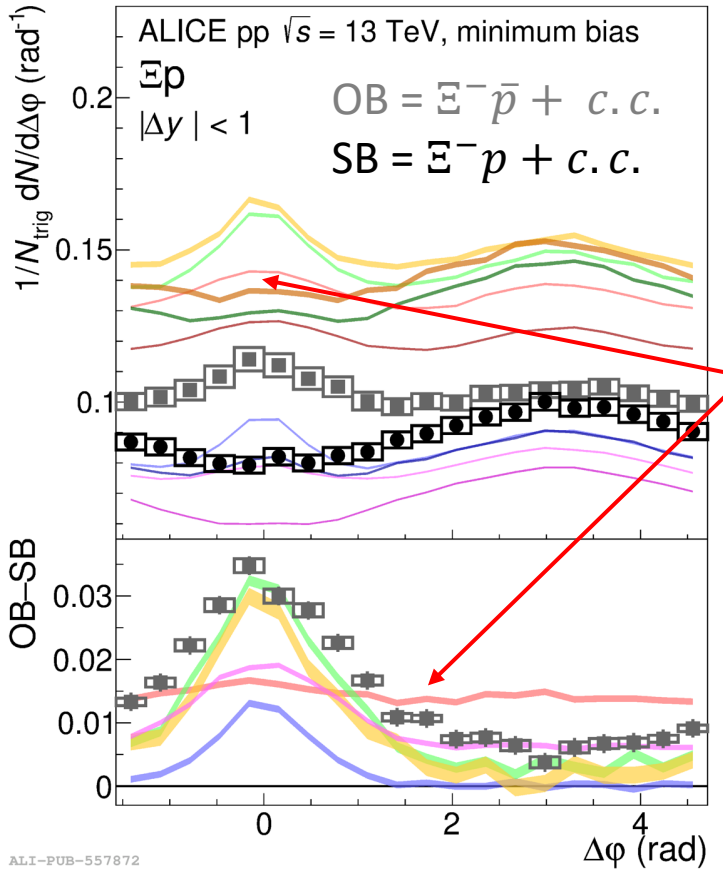


Production of multiple baryons within same (mini)jet is disfavoured

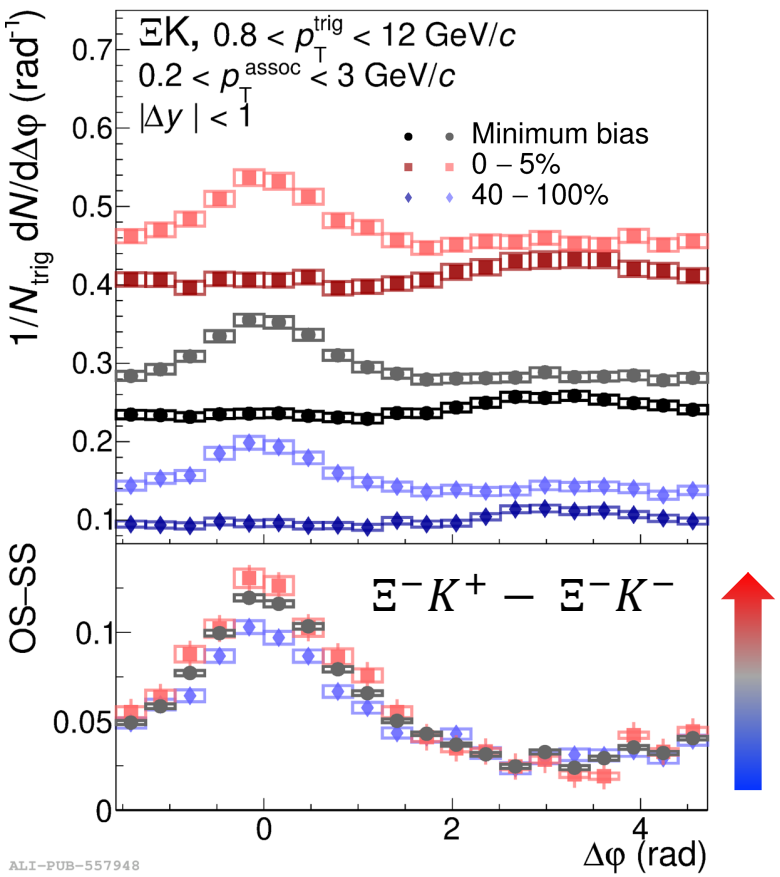
Shape of near-side (NS) and away-side (AS) Ξπ peaks well predicted by PYTHIA, HERWIG and EPOS LHC.
Ξπ underlying event magnitude not described by EPOS LHC and HERWIG

EPOS LHC predicts **broader NS Ξp peaks** → consequence of decorrelation in the "core", where quantum numbers are conserved globally and not locally

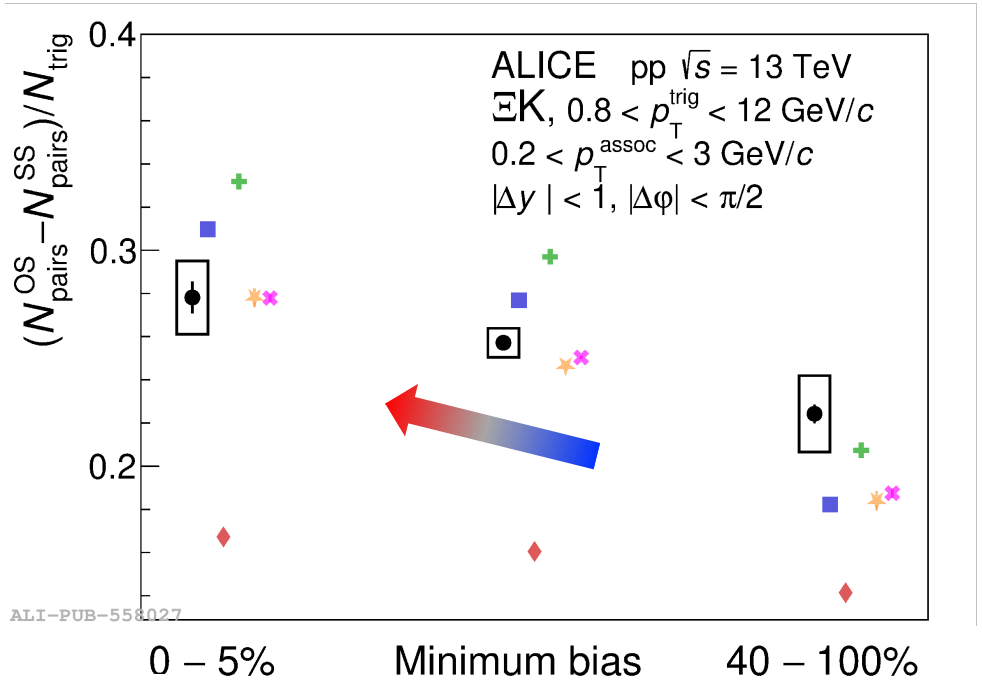
SS OS
ALICE
PYTHIA8 Monash
PYTHIA8 Junctions
PYTHIA8 Ropes
EPOS LHC
HERWIG

Multiplicity dependence of the balance function

ΞK

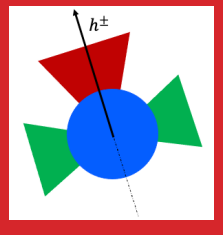


Near-side peak narrower and taller with increasing multiplicity
→ consistent with radial flow



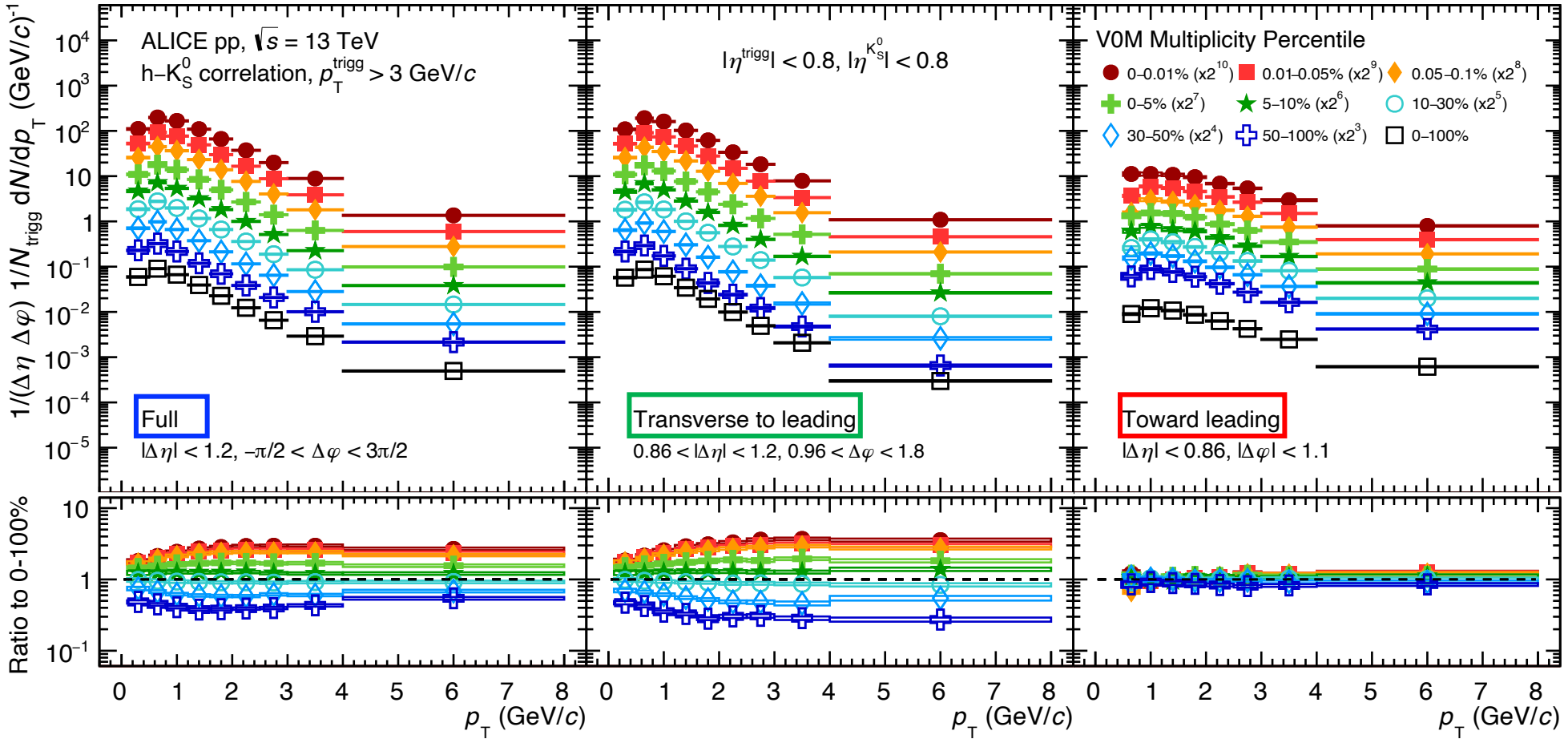
EPOS LHC shows little multiplicity dependence
→ global strangeness conservation not enough to describe strangeness production

PYTHIA and HERWIG qualitatively reproduce the increase with multiplicity



Full, transverse and toward-leading p_{T} spectra of $\mathrm{K}^0_{\mathrm{S}}$

ALICE

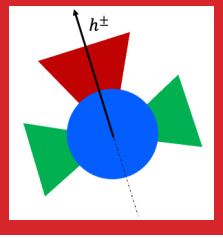


High multiplicity

Low multiplicity

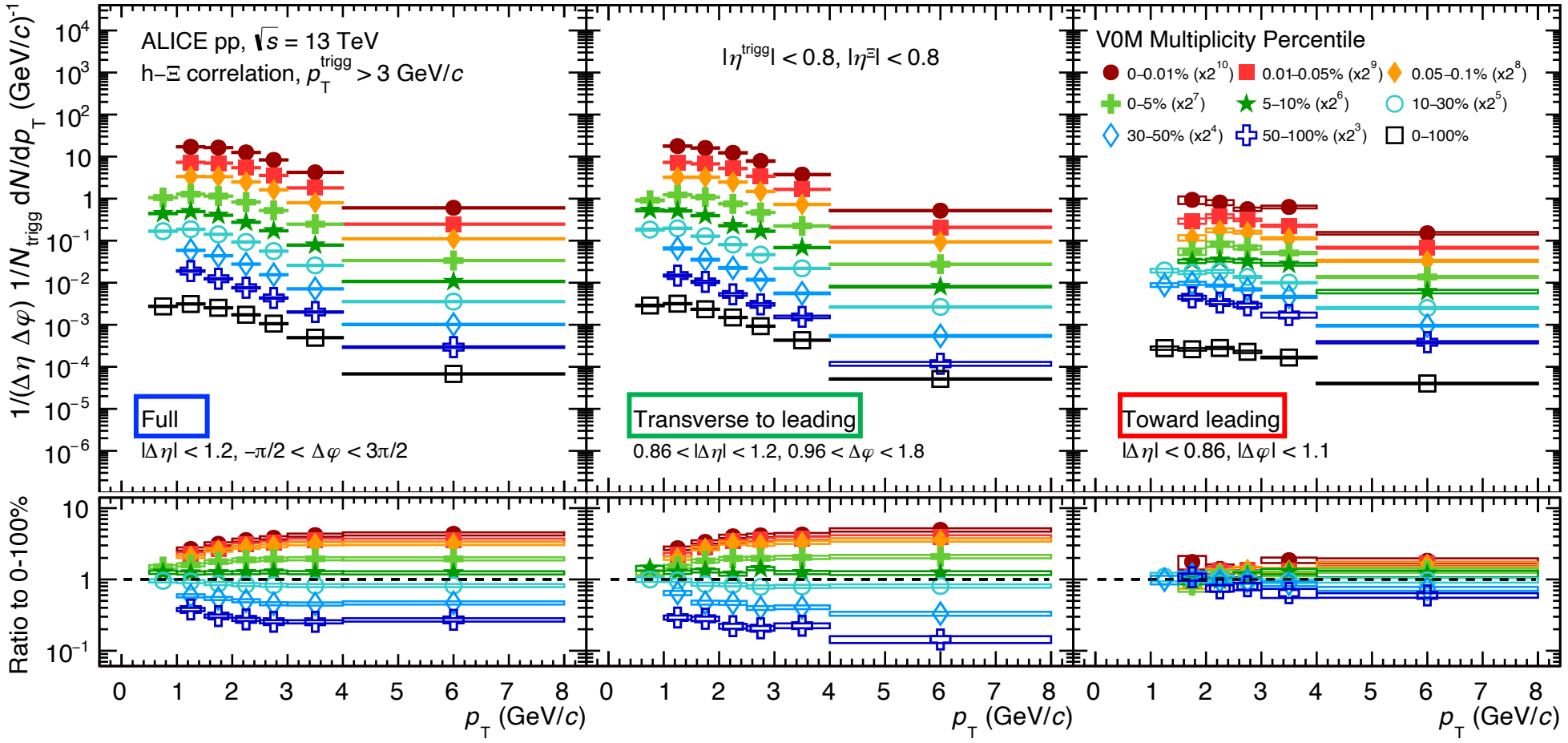
Full and **transverse-to-leading** spectra of $\mathrm{K}^0_{\mathrm{S}}$ **increase with multiplicity**

Toward-leading spectra show smaller multiplicity dependence



Full, transverse and toward-leading p_{T} spectra of $\Xi^{\pm}$

ALICE



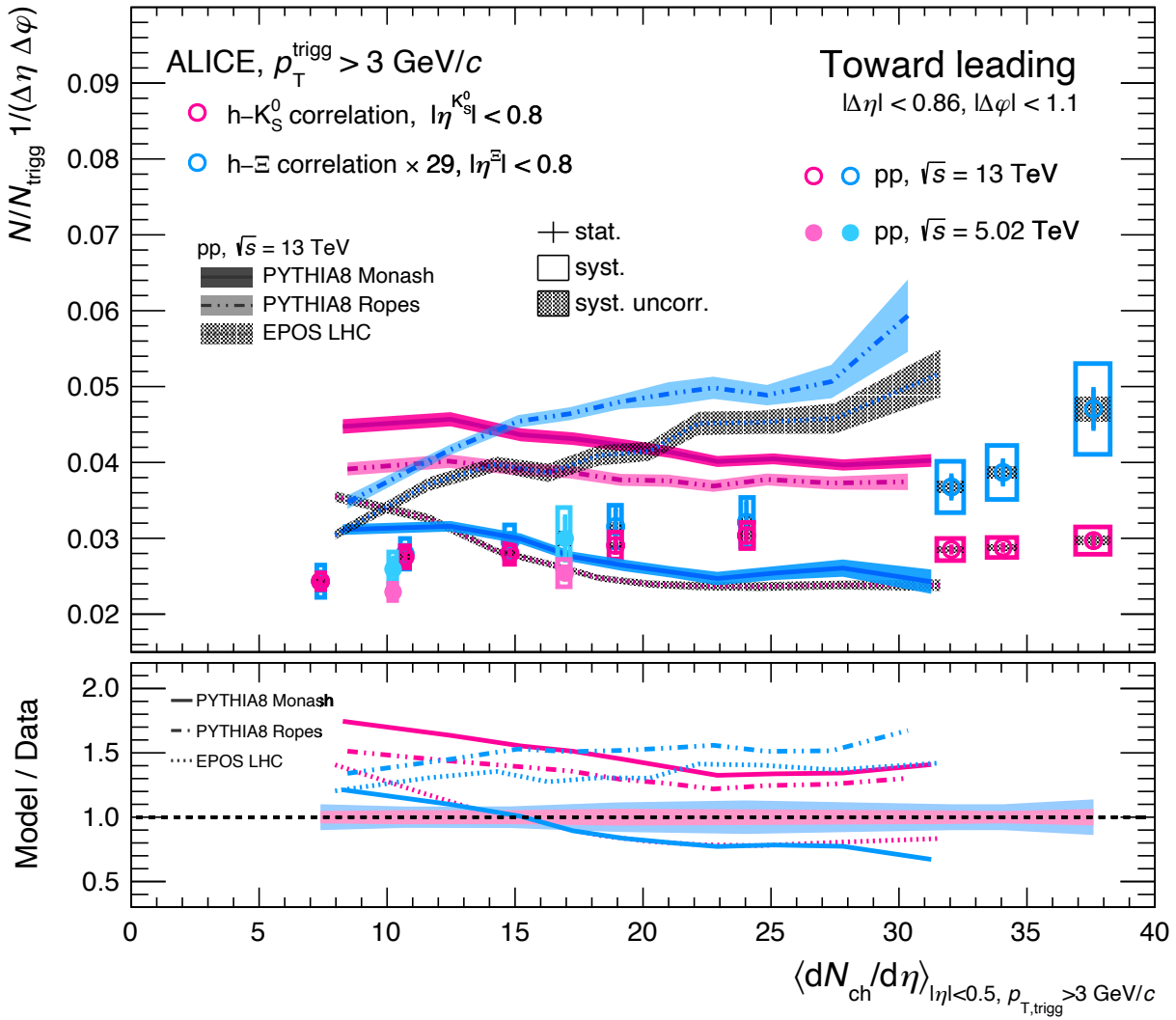
High multiplicity

Low multiplicity

Full and **transverse-to-leading** spectra of $\Xi^{\pm}$ **increase with multiplicity**

Toward-leading spectra show smaller multiplicity dependence

K^0_S and $\Xi^{\pm}$ toward-leading yields vs multiplicity



The Ξ toward-leading yield increases with multiplicity **faster than the K^0_S one**

Model Comparison

None of the models **can describe the increase** with multiplicity of the K^0_S toward-leading yield

Pythia with ropes and EPOS LHC **overestimate** the toward-leading production of Ξ but reproduce the **increasing trend** with multiplicity

Pythia Monash does not reproduce the Ξ toward-leading trend with multiplicity

NEW!

arXiv:2405.14511