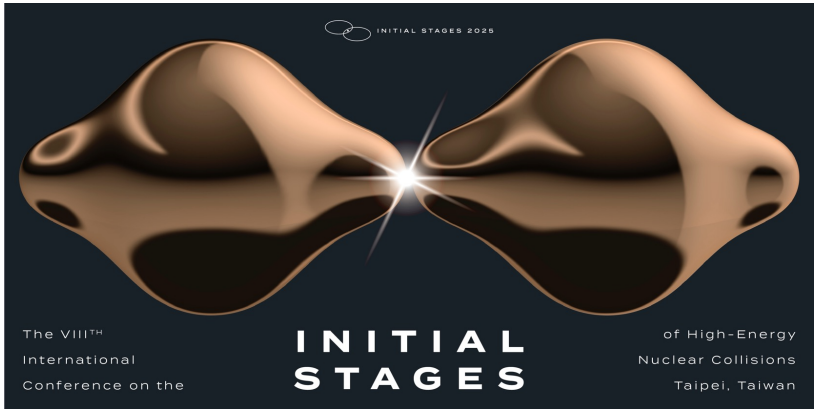
Probing strangeness enhancement in proton-proton collisions using rapidity correlations among a ϕ meson and a strange hadron with ALICE

Stefano Cannito[1] on behalf of the ALICE Collaboration
[1]University & INFN, Trieste, Italy

Initial Stages 2025, Taipei, 10/09/2025

ALICE

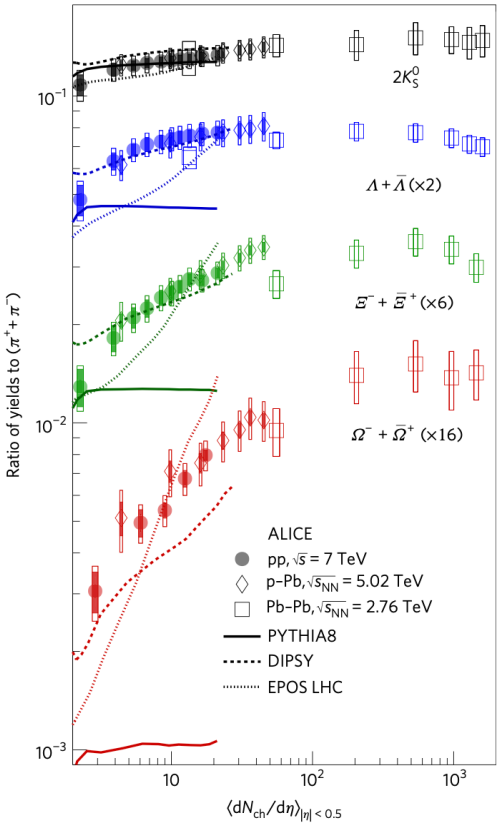
INFN



UNIVERSITÀ DEGLI STUDI DI TRIESTE

Local vs global conservation of strangeness

Strangeness enhancement in pp collisions



$K^0_S = (d\bar{s} + s\bar{d})/\sqrt{2}$

|S| = 1

$\Lambda = (uds)$

|S| = 1

$\Xi^- = (dss)$

|S| = 2

$\Omega^- = (sss)$

|S| = 3

The **enhanced production of (multi-)strange hadrons** compared to non-strange meson is traditionally considered as a probe of **quark-gluon plasma (QGP)** formation

Strangeness enhancement observed in pp collisions as function of **charged-particle multiplicity** $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$

- **Smooth transition** from pp to Pb-Pb
- Stronger effect for increasing **strangeness content S**

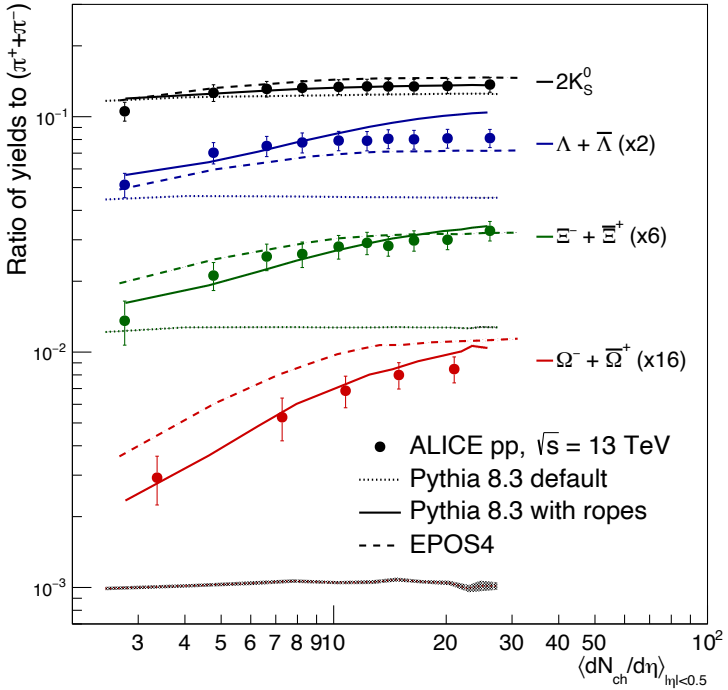
ALICE Collaboration, *Nature Phys.* 13 (2017) 535-539

State of the art

Two very different types of models perform well in reproducing the overall strangeness enhancement:

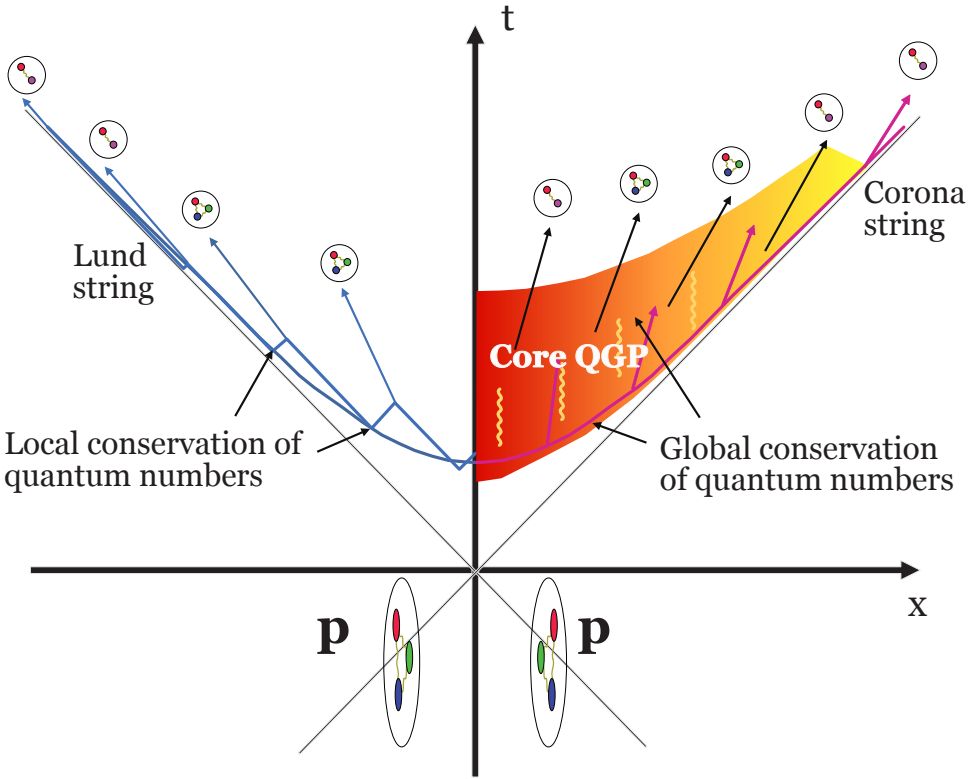
- Core-corona models with hydrodynamical evolution of core similar to QGP fluid → **EPOS4**
- Models of microscopic interactions of strings (no QGP) → **PYTHIA 8.3**

How can we advance further?



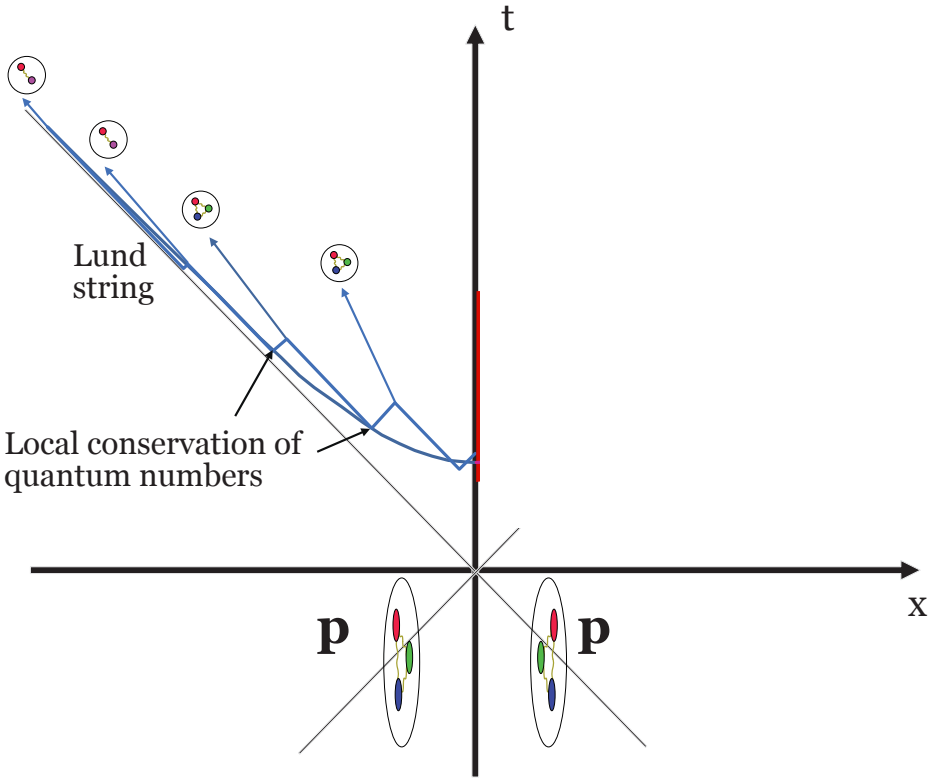
ALICE Collaboration, *Eur. Phys. J. C* 80 (2020) 8, 693

Lund strings vs QGP



C. Bierlich, S. Cannito, V. Zaccolo, *Eur. Phys. J. C* 84 (2024) 996

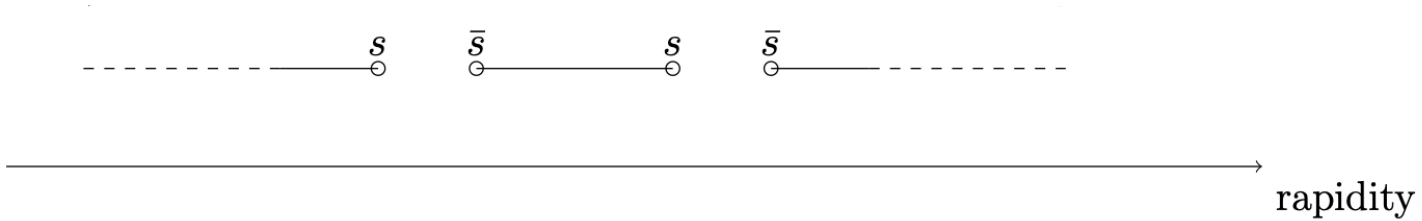
Lund strings vs QGP



C. Bierlich, S. Cannito, V. Zaccolo, *Eur. Phys. J. C* 84 (2024) 996

The special role of the ϕ meson

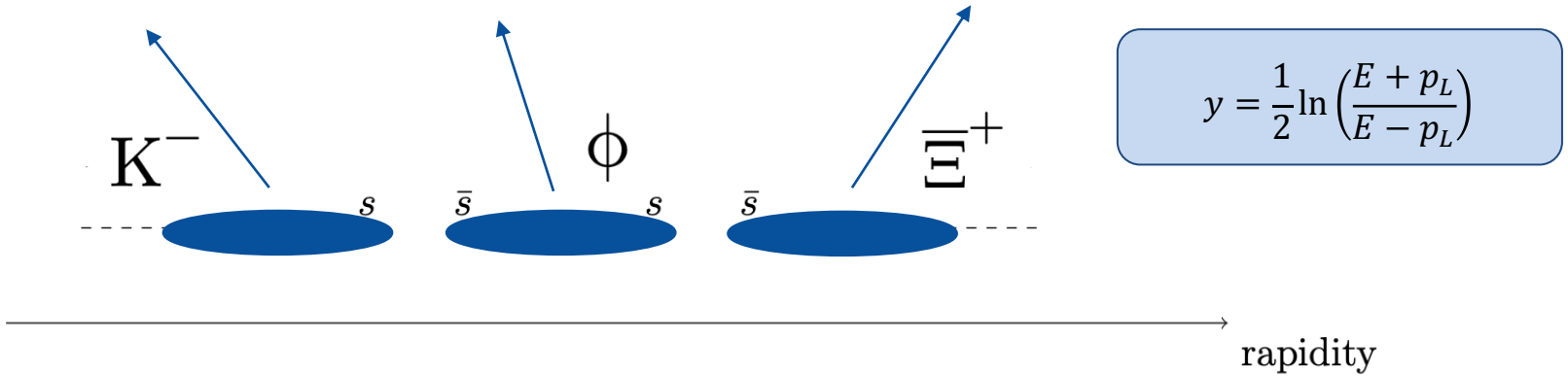
Special events characterised by the presence of at least one ϕ meson among the final particles to study **rapidity correlations among a ϕ meson and a (multi-)strange hadron**



In a **string scenario**, the **ϕ-meson production**, requires two $s\bar{s}$ breaks and the neighboring hadrons will include the leftover (anti-)strange quarks

The special role of the ϕ meson

Special events characterised by the presence of at least one ϕ meson among the final particles to study **rapidity correlations among a ϕ meson and a (multi-)strange hadron**

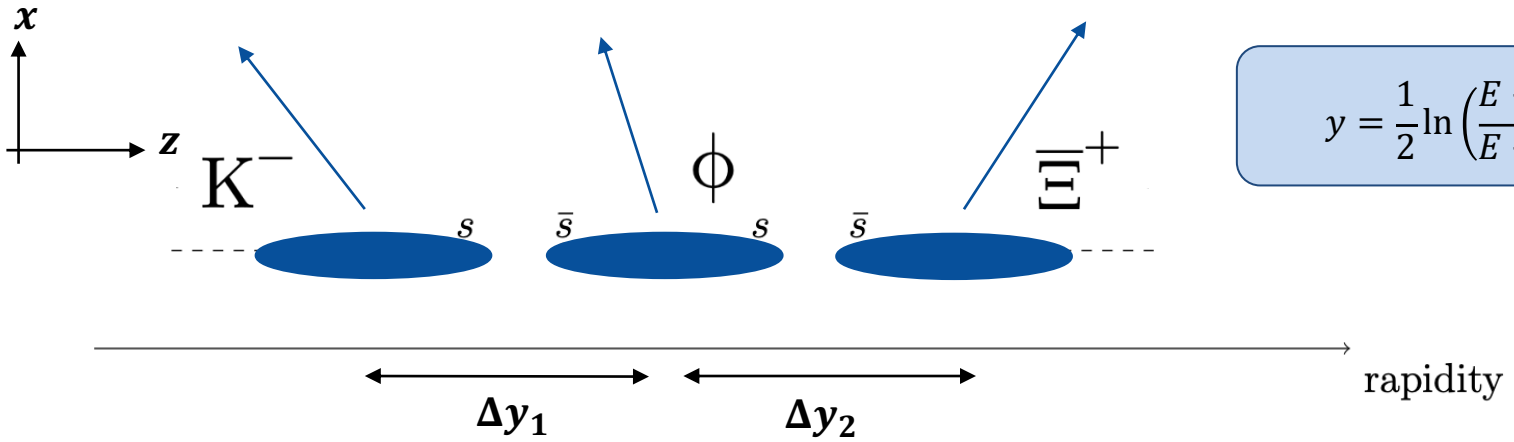


$$y = \frac{1}{2}\ln\left(\frac{E + p_L}{E - p_L}\right)$$

In a **string scenario**, the **ϕ-meson production**, requires two $s\bar{s}$ breaks and the neighboring hadrons will include the leftover (anti-)strange quarks

The special role of the ϕ meson

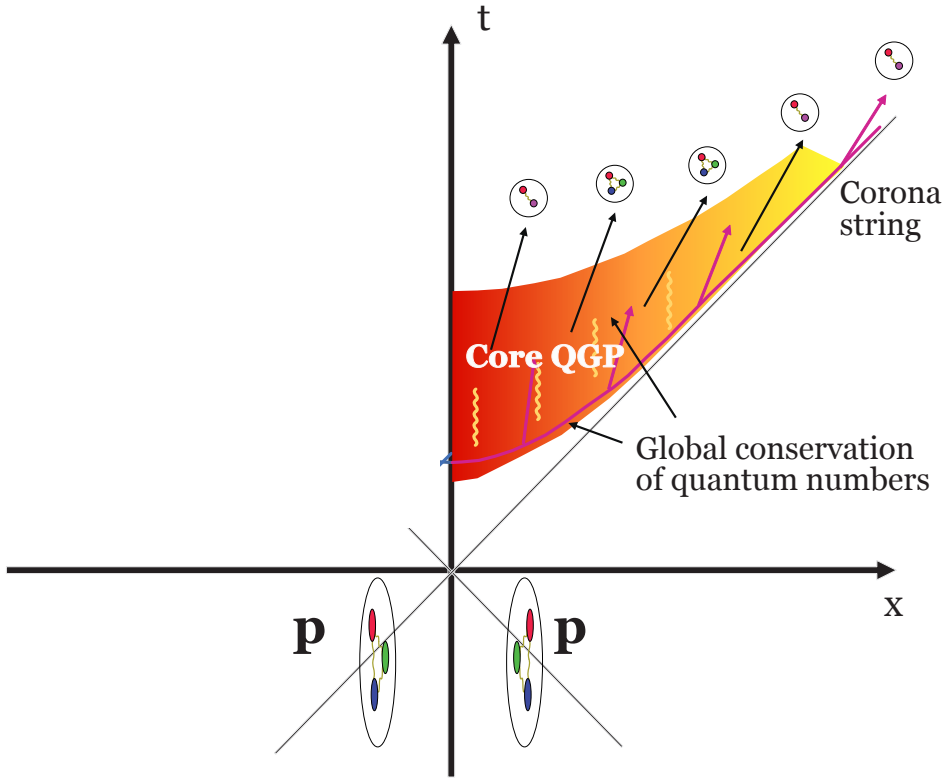
Special events characterised by the presence of at least one ϕ meson among the final particles to study **rapidity correlations among a ϕ meson and a (multi-)strange hadron**



$$y = \frac{1}{2}\ln\left(\frac{E + p_L}{E - p_L}\right)$$

Rapidity correlations highlighting **local conservation of quantum numbers** like, **strangeness**

Lund strings vs QGP



C. Bierlich, S. Cannito, V. Zaccolo, *Eur. Phys. J. C* 84 (2024) 996

$K^0_S/\pi^{\pm}$ in events with ϕ

Multiplicity-dependent $K^0_S/\pi^{\pm}$ yield ratio in **different rapidity intervals around the triggered ϕ meson**

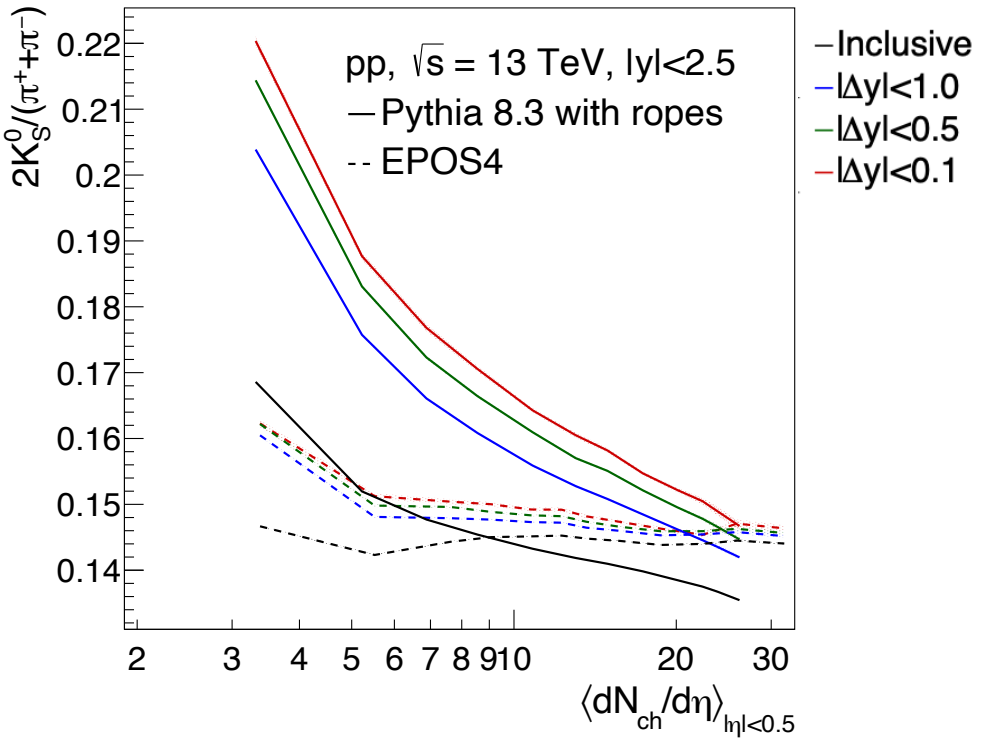
PYTHIA 8.3

Local strangeness conservation
→ **ordered structure** in ratio of yields with respect to charged pions

Decreasing trend in multiplicity

EPOS4

Global strangeness conservation
→ **almost no rapidity correlations** with ϕ



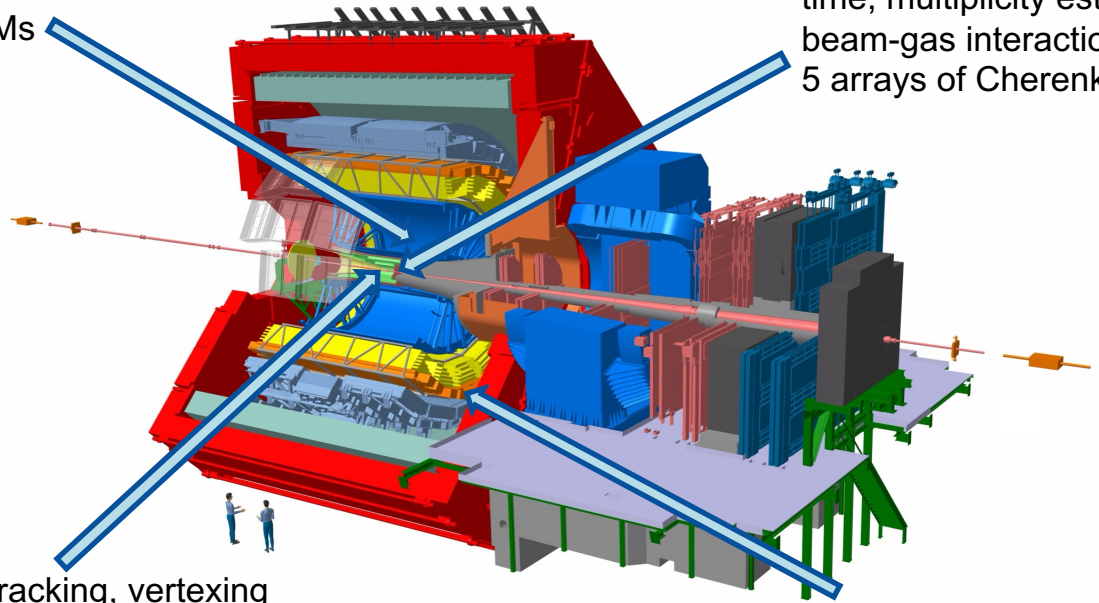
C. Bierlich, S. Cannito, V. Zaccolo, *Eur. Phys. J. C* 84 (2024) 996

ϕ - K_S^0 rapidity correlations in pp collisions at 13.6 TeV with ALICE

The ALICE detector in Run 3

Upgraded TPC: tracking, PID (d*E*/d*x*)
continuous readout up to 1.1 MHz pp interaction rate
thanks to new GEMs

New Fast Interaction Trigger (FIT): collision time, multiplicity estimation and rejection of beam-gas interactions
5 arrays of Cherenkov radiators and scintillators



Upgraded ITS: tracking, vertexing
7 layers of silicon detectors with improved performance

Upgraded TOF: PID (time of flight) upgrade to accomplish continuous readout of data based on MRPCs

Analysis procedure

Data sample: ~ 1.5 x 10^{10} pp collisions @ 13.6 TeV collected during LHC Run 3 data-taking campaign

Analysis steps:

1. Selection of good-quality pp collisions
2. Identification of ϕ meson (trigger particle) and K^0_S meson or $\pi^\pm$ (associated particle)

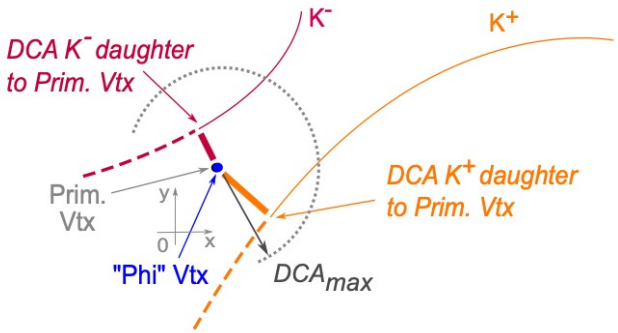
$$\phi \rightarrow \mathrm{K}^+\mathrm{K}^- \quad \mathrm{K}^0_\mathrm{S} \rightarrow \pi^+\pi^- \quad \pi^\pm : \mathrm{d}E/\mathrm{d}x \ \& \ \mathrm{TOF}$$

3. Signal extraction and correction for ϕ purity
4. Correction of raw results for the effects of the detector and extrapolation to low p_T
5. Computation of $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle_{|\eta|<0.5}$ values for events with a ϕ candidate decaying into $\mathrm{K}^+\mathrm{K}^-$
6. Computation of systematic uncertainties

ϕ identification

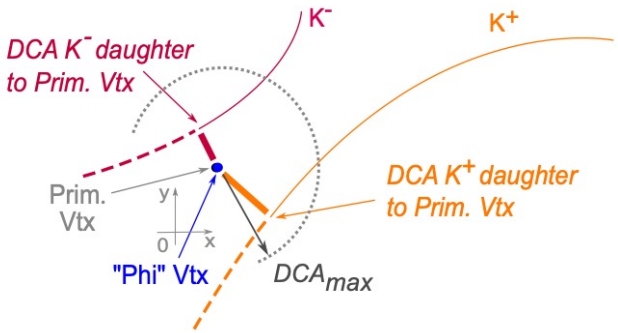
$$\phi \rightarrow K^{+}K^{-} \quad \text{(BR = 48.9\%)}$$

The ϕ meson has a mean lifetime of $\sim 10^{-22}$ s
→ **not feasible to distinguish the secondary decay vertex from the primary vertex**



ϕ identification

$$\phi \rightarrow K^+K^- \quad (BR = 48.9\%)$$



The ϕ meson has a mean lifetime of $\sim 10^{-22}$ s
→ **not feasible to distinguish the secondary decay vertex from the primary vertex**

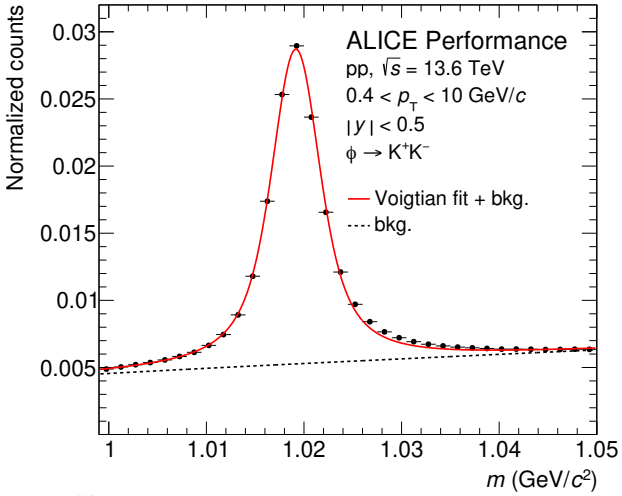
Modellisation of the **ϕ meson invariant mass $m_{K^+K^-}$ distribution**:

- **Signal** model: **Voigtian function**

$$f_{sig} = f_{Voigt} = \int f_{BW}(m'_{K^+K^-}) f_{Gaus}(m'_{K^+K^-} - m_{K^+K^-}) dm'_{K^+K^-}$$

- **Combinatorial background** model:

$$f_{bkg} = a + b m_{K^+K^-} + c\sqrt{m_{K^+K^-} - 0.987}$$

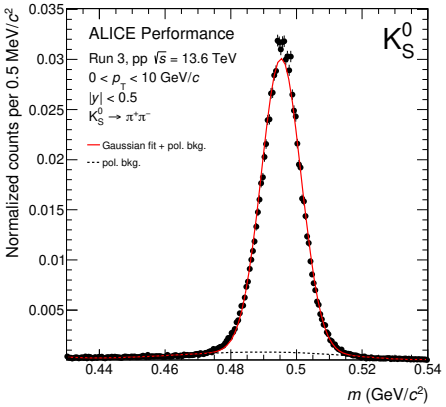


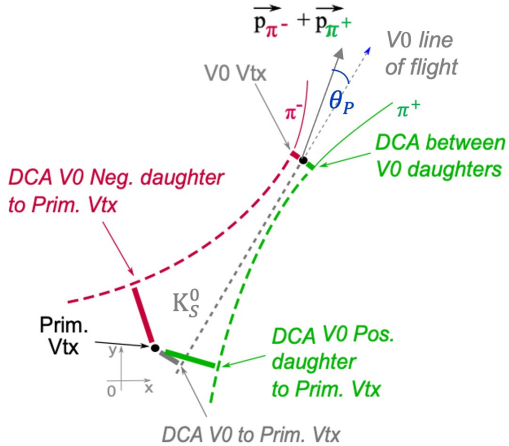
Associated particles identification

$$K^0_S \rightarrow \pi^+\pi^- \text{ (BR = 69.2\%)}$$

Identification techniques:

- **Topology of a K^0_S (V^0) decay** which allows for a selection on the **DCA** of the daughter tracks to the primary vertex, between themselves, **pointing angle θ_P**, and **radius**
- **Secondary pion identification**





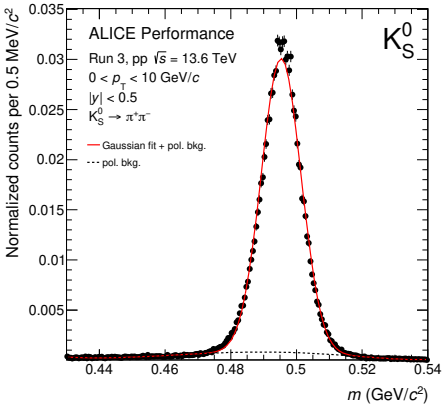
ALI-PERF-528877

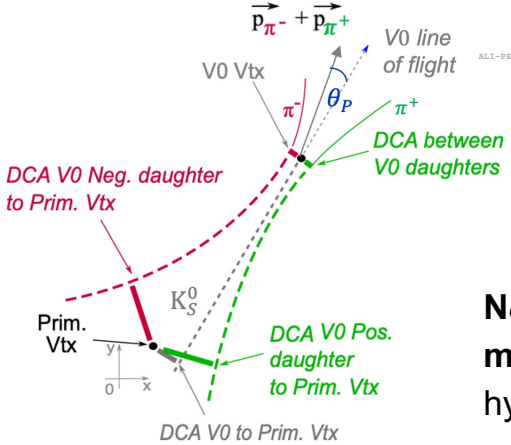
Associated particles identification

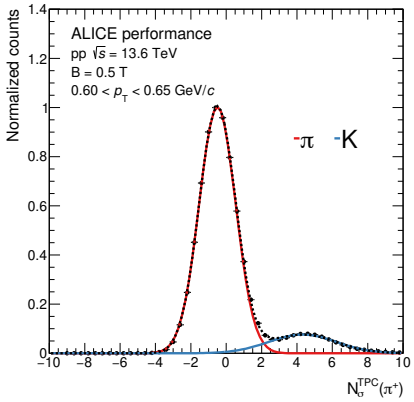
$$K^0_S \rightarrow \pi^+\pi^- \text{ (BR = 69.2\%)}$$

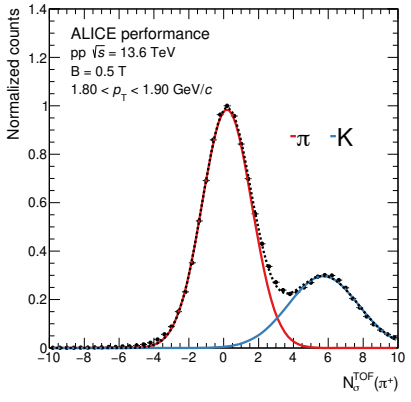
Identification techniques:

- **Topology of a K^0_S (V^0) decay** which allows for a selection on the **DCA** of the daughter tracks to the primary vertex, between themselves, **pointing angle θ_P**, and **radius**
- **Secondary pion identification**









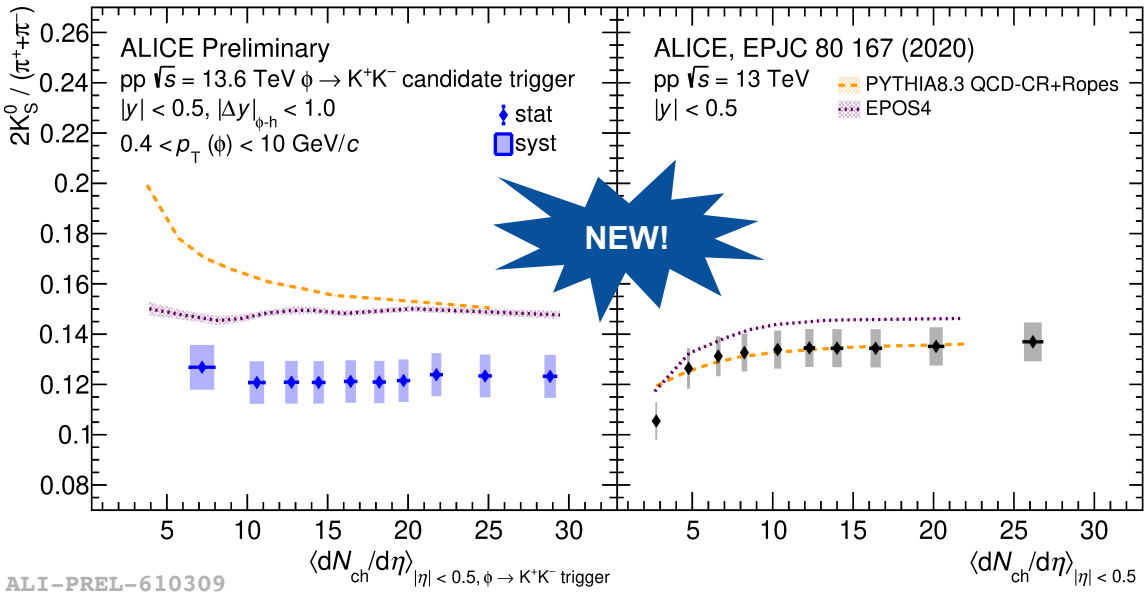
TPC **TOF**

$$\pi^{\pm} : \mathrm{d}E/\mathrm{d}x \ \& \ \mathrm{TOF}$$

N$\sigma^{\mathrm{TPC/TOF}}(\pi^{\pm})$ defined as the **deviation from the mean value** of the d*E*/d*x* (TOF) distribution in the pion hypothesis in **units of standard deviation**

Ratio $2K^0_S/(\pi^+ + \pi^-)$ in events with ϕ

First measurement of $K^0_S/\pi^{\pm}$ in pp collisions with at least one ϕ meson produced has been performed using a sample of ~1.5 x 10^{10} pp collisions collected during LHC Run 3 in 2024



The ratio of yields with respect to charged pions is **compatible with the minimum bias result at 13 TeV**

It shows **a flat trend as function of the charged-particle multiplicity in the event** which resembles the one predicted by **EPOS4**, but deviates by ~ 15%

In contrast, the **non-flat behaviour predicted by PYTHIA 8.3 is put under test** by these results

Outlook: strange-baryons/$\pi^{\pm}$ in events with ϕ

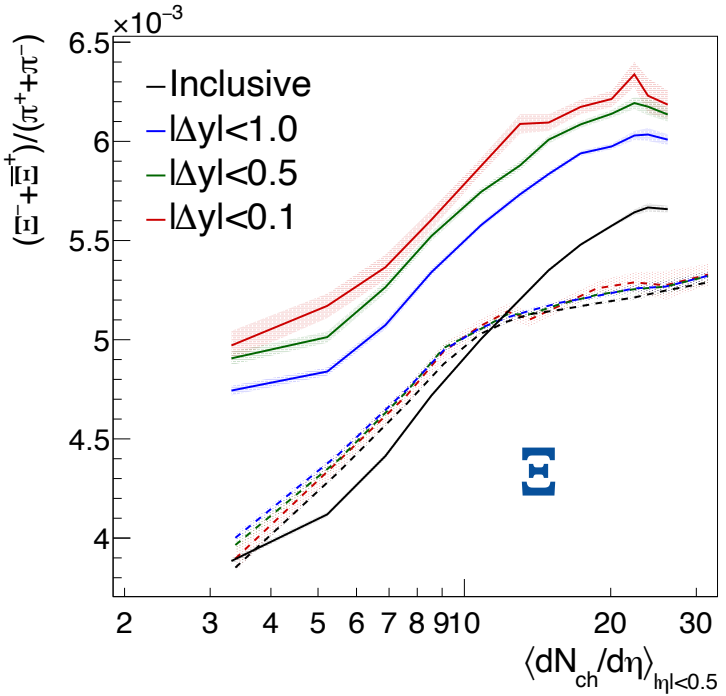
Ξ study case

pp, $\sqrt{s}$ = 13 TeV, |y|<2.5
— Pythia 8.3 with ropes
-- EPOS4

- **EPOS4**: curves collapse into a single one
  → global strangeness conservation

- **PYTHIA 8.3**: a marked enhancement with saturation is seen moving from the inclusive sample and closer to the ϕ
  → local strangeness conservation

Increasing trend in multiplicity



C. Bierlich, S. Cannito, V. Zaccolo, *Eur. Phys. J. C* 84 (2024) 996

Conclusions

- MC simulations shows that **studying the strange hadron production in events with a ϕ meson effectively distinguishes among the different strangeness production approaches**

Conclusions

- MC simulations shows that **studying the strange hadron production in events with a ϕ meson effectively distinguishes among the different strangeness production approaches**

- The **first preliminary measurement of the $K^0_S/\pi^{\pm}$ ratio in events with a ϕ trigger** has been provided by analysing pp collisions @ 13.6 TeV collected by the ALICE Collaboration during the LHC Run 3 :
  - The results are compatible within uncertainties with those without the trigger measured in Run 2
  - They show a **flat trend as function of the charged-particle multiplicity in the event** which resembles the one predicted by **EPOS4**, but deviates by ~ 15%
  - The **non-negligible multiplicity dependency of PYTHIA 8.3 predictions is challenged** by these results

Conclusions

- MC simulations shows that **studying the strange hadron production in events with a ϕ meson effectively distinguishes among the different strangeness production approaches**

- The **first preliminary measurement of the $K_S^0/\pi^{\pm}$ ratio in events with a ϕ trigger** has been provided by analysing pp collisions @ 13.6 TeV collected by the ALICE Collaboration during the LHC Run 3 :
  - The results are compatible within uncertainties with those without the trigger measured in Run 2
  - They show a **flat trend as function of the charged-particle multiplicity in the event** which resembles the one predicted by **EPOS4**, but deviates by ~ 15%
  - The **non-negligible multiplicity dependency of PYTHIA 8.3 predictions is challenged** by these results

- The next step will be to assess the **feasibility of measuring the same observable in more than one rapidity-gap class** and to perform the **same measurement with (multi-)strange baryons (hyperons), e.g. $\Lambda, \overline{\Lambda}, \Xi, \Omega$**

Backup

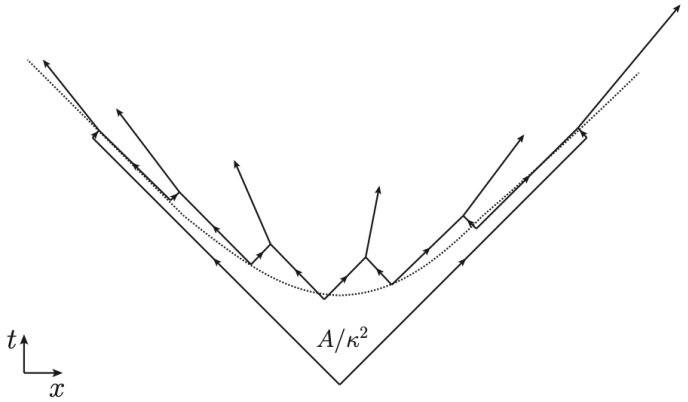
The Lund string model in PYTHIA 8.3

In the final state of the collision **the strong coupling constant α_s is $O(1)$** → perturbative approach not feasible

Lund string phenomenological model:

- **Strings** spanned between $q\bar{q}$ pairs with tension $\kappa \approx 1\ \mathrm{Gev/fm}$, which fragment to produce several hadrons
- Strange quarks suppressed with respect to up or down by a factor:

$$\rho = \exp\left(-\frac{\pi({m_s}^2 - {m_u}^2)}{\kappa}\right)$$



C. Bierlich *et al.*, *SciPost Phys.Codeb. 2022 (2022) 8*

Rope hadronisation in PYTHIA 8.3

When several strings overlap:

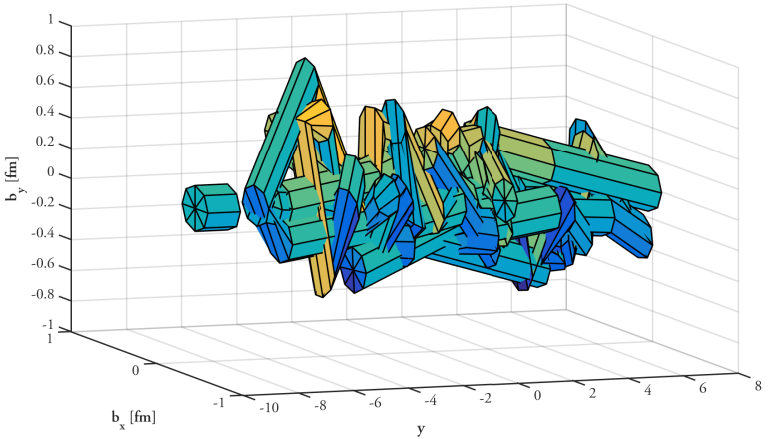
- A **rope structure** is formed in colour space

Two aspects to consider:

- The **effective string tension** in each individual string break increases by:

$$\kappa_{\text{eff}} = \frac{2p + q + 2}{4}\kappa$$

$\boldsymbol{p}$ and $\boldsymbol{q}$ are the number (anti-)strings of the same colour which compose the rope



C. Bierlich, G. Gustafson, L. Lönnblad, A. Tarasov *JHEP* 03 (2015) 148

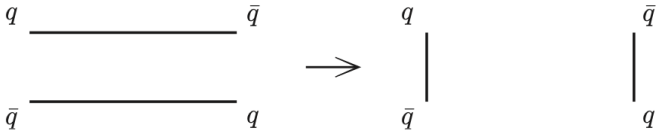
Rope hadronisation in PYTHIA 8.3

When several strings overlap:

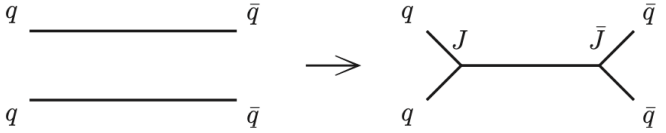
- A **rope structure** is formed in colour space

Two aspects to consider:

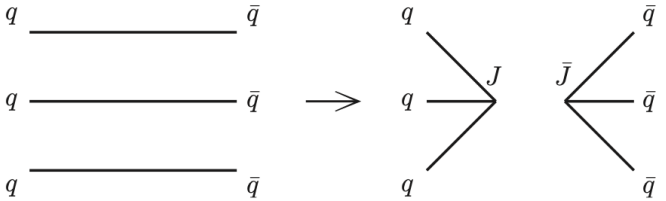
- **Junction topologies**, which carry an **intrinsic baryon number**, can be dynamically formed



(a) Type I: ordinary dipole-style reconnection



(b) Type II: junction-style reconnection



(c) Type III: baryon-style junction reconnection

[J. R. Christiansen, P. Z. Skands, *JHEP* 08 (2015) 003]

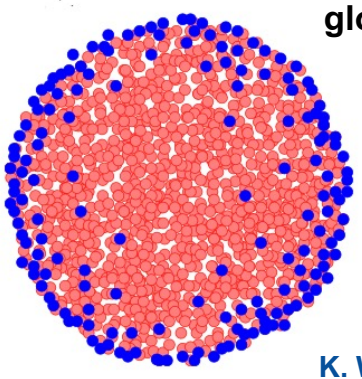
Core-corona production in EPOS4

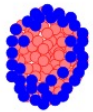
Parton scatterings lead to the formation of **prehadrons whose density determines the methods that handle the event evolution**:

- If it is high, prehadrons are treated as **core** which thermalizes and expands collectively
- If they are close to the surface, or escape the bulk with large p_{T}, they are treated as **corona**, i.e. as in vacuum

AA

Microcanonical partition function with only **global conservation of the quantum numbers**





pp

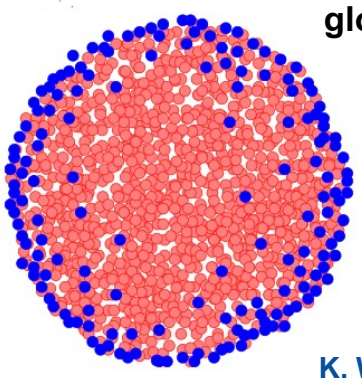
K. Werner, *Phys. Rev. C* 109 (2024) 1, 014910

Core-corona production in EPOS4

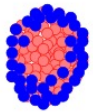
Parton scatterings lead to the formation of **prehadrons whose density determines the methods that handle the event evolution**:

- If it is high, prehadrons are treated as **core** which thermalizes and expands collectively
- If they are close to the surface, or escape the bulk with large p_{T}, they are treated as **corona**, i.e. as in vacuum

AA

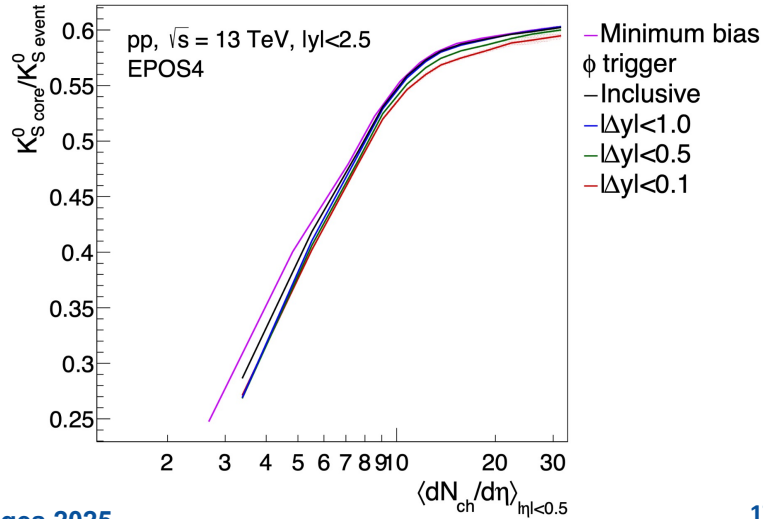


Microcanonical partition function with only **global conservation of the quantum numbers**

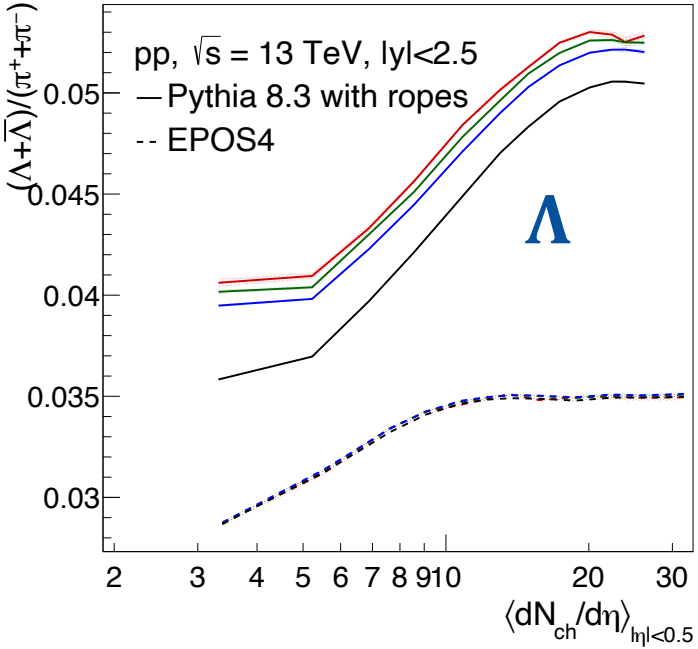


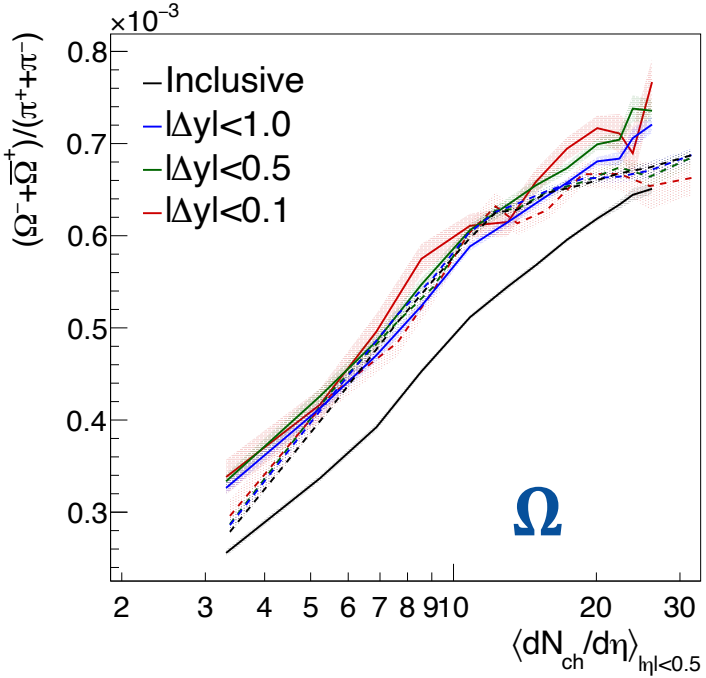
pp

K. Werner, *Phys. Rev. C* 109 (2024) 1, 014910



$\Lambda/\pi^{\pm}$ & $\Omega/\pi^{\pm}$ in events with ϕ





C.Bierlich, S.Cannito, V.Zaccolo, arXiv:2403.00511