Enhanced production of multi-strange hadrons in high-multiplicity pp collisions

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29th Rencontres de Blois

May 28 – Jun 2, 2017

Blois – Loire Valley, France

FAPESP

FUNDAÇÃO DE AMPARO À PESQUISA
DO ESTADO DE SÃO PAULO

(supported by FAPESP Grant 2014/09167-8)

Outline

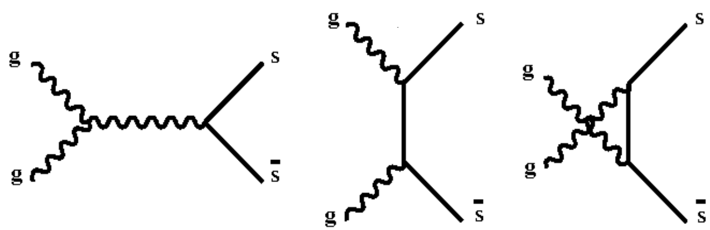
- Introduction and Motivation
- The ALICE Experiment
- Strange Hadron Measurements
- Results
- Summary

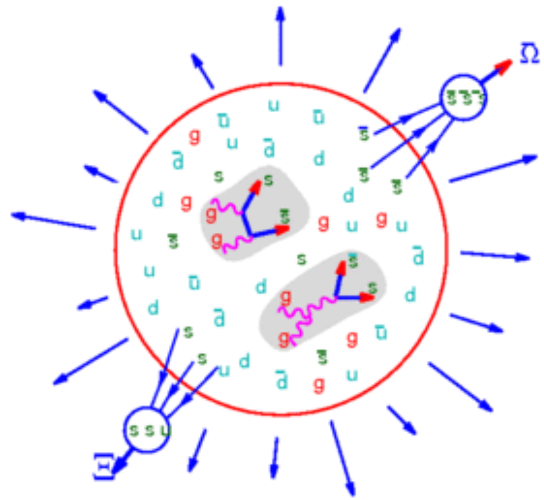
Introduction and Motivation

ALICE

→ Strangeness enhancement

- The enhanced production of strangeness relative to *u* and *d* quarks was one of the first proposed signatures of QGP formation
    - *Thermal strangeness equilibration in a QGP regime can be achieved due to gluon fusion processes*





J. Rafelski and B. Müller, PRL48, 1066 (1982)
P. Koch, B. Müller, J. Rafelski, Phys. Rep. 142, 167 (1986)

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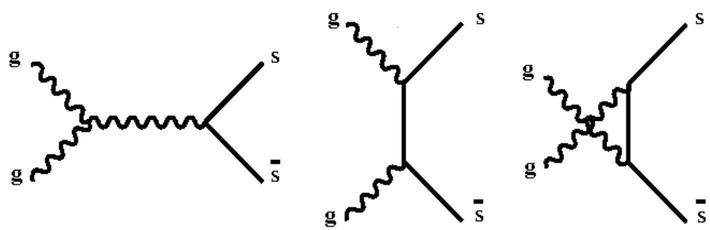

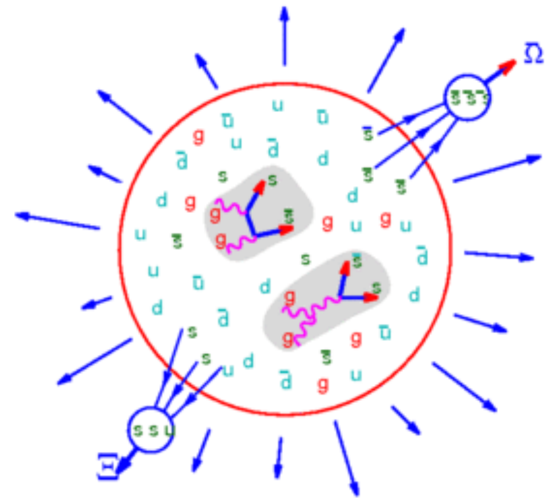

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P. Koch, B. Müller, J. Rafelski, Phys. Rep. 142, 167 (1986)

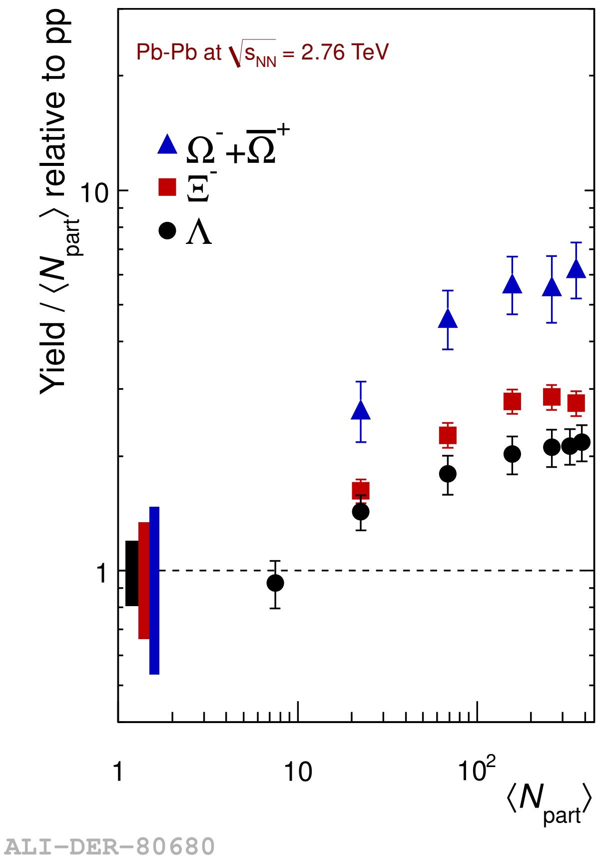
→ Strangeness canonical suppression (in a *hadronic* equilibrium thermal model)

- In small systems, multi-strange baryons should be highly suppressed
  - *Conservation laws must be implemented locally – Canonical Formulation*
  - *The canonical conservation of quantum numbers severely reduces the phase space available for particle production*

S. Hamieh, K. Redlich, A. Tounsi, Phys. Lett. B 486 (2000) 61
A. Tounsi, K. Redlich, arXiv:hep-ph/0111159

Introduction and Motivation

→ Strangeness enhancement in A-A



Introduction and Motivation

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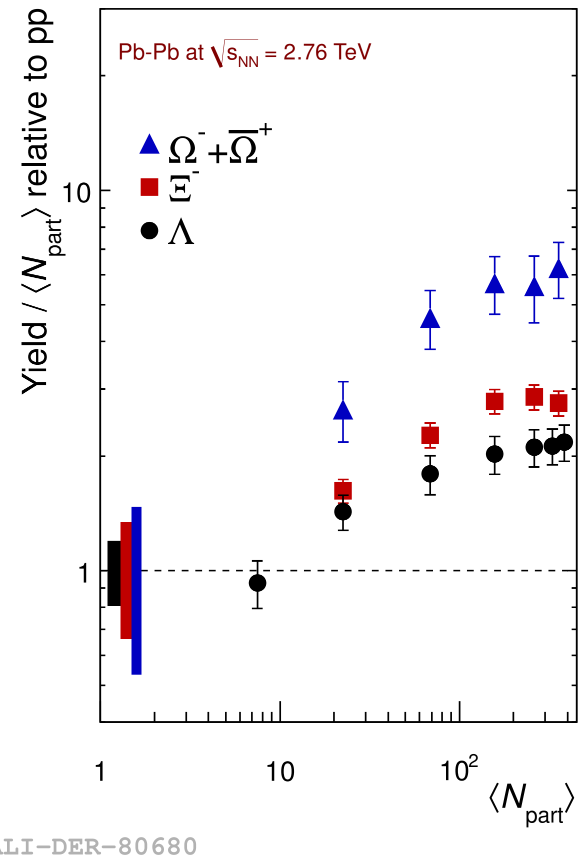
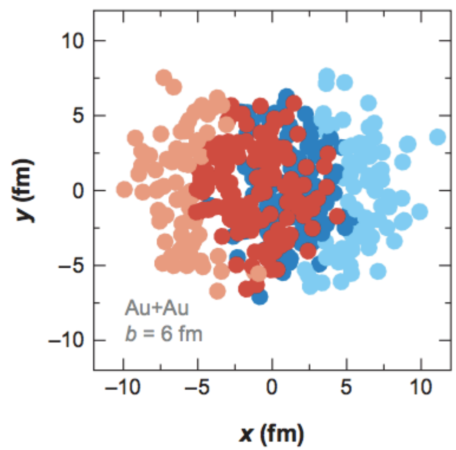
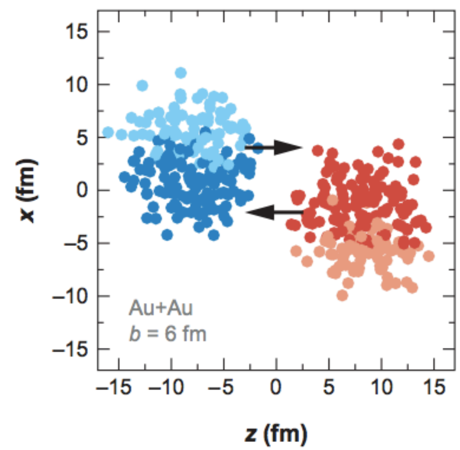


Glauber Model calculations

N_{part} → number of participants nucleons

mapped onto centrality intervals expressed as percentages of the cross section





Introduction and Motivation

ALICE

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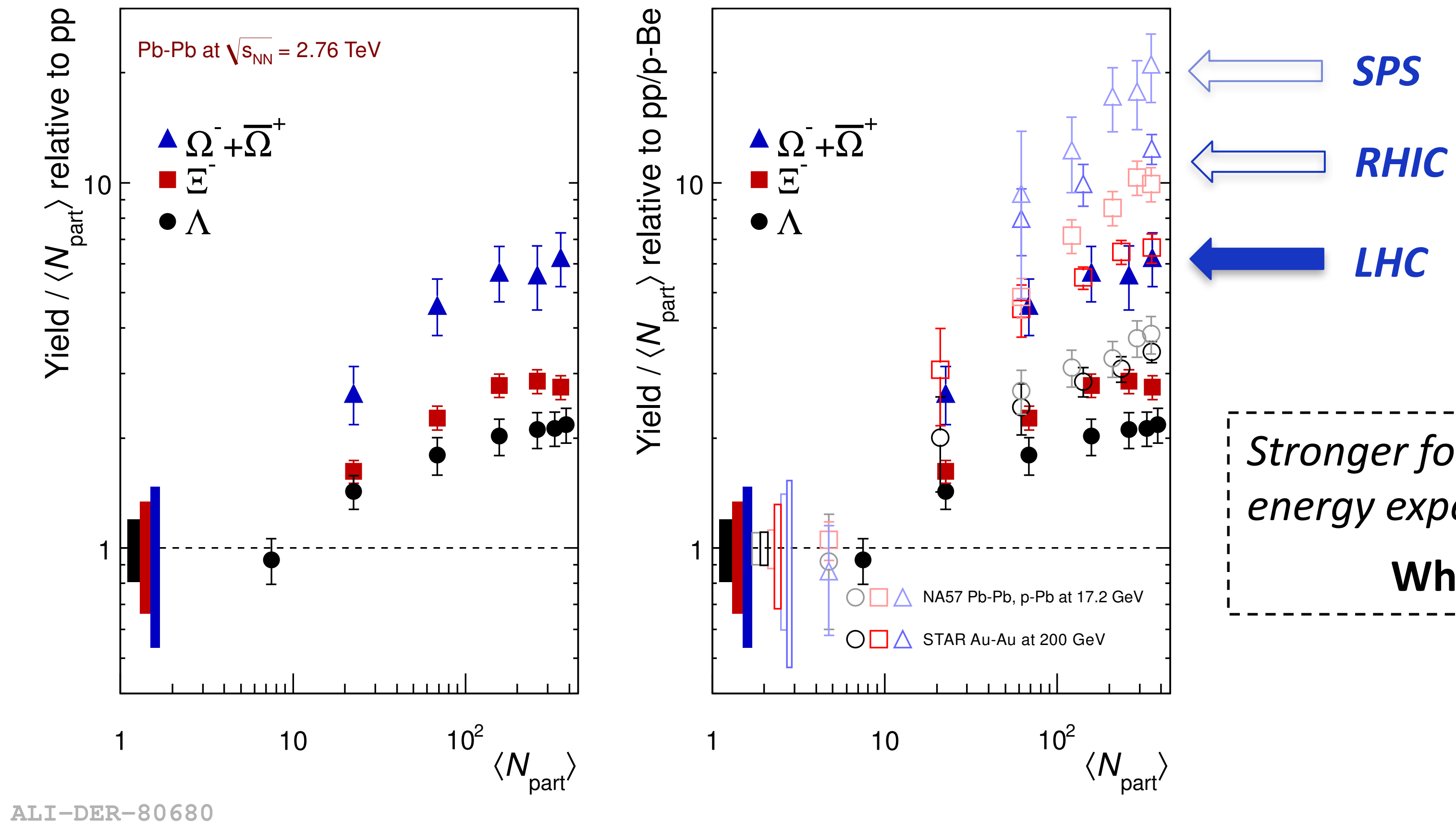
Phys. Lett. B 728 (2014) 216–227



Stronger for lower energy experiments!

Why?

Introduction and Motivation

ALICE

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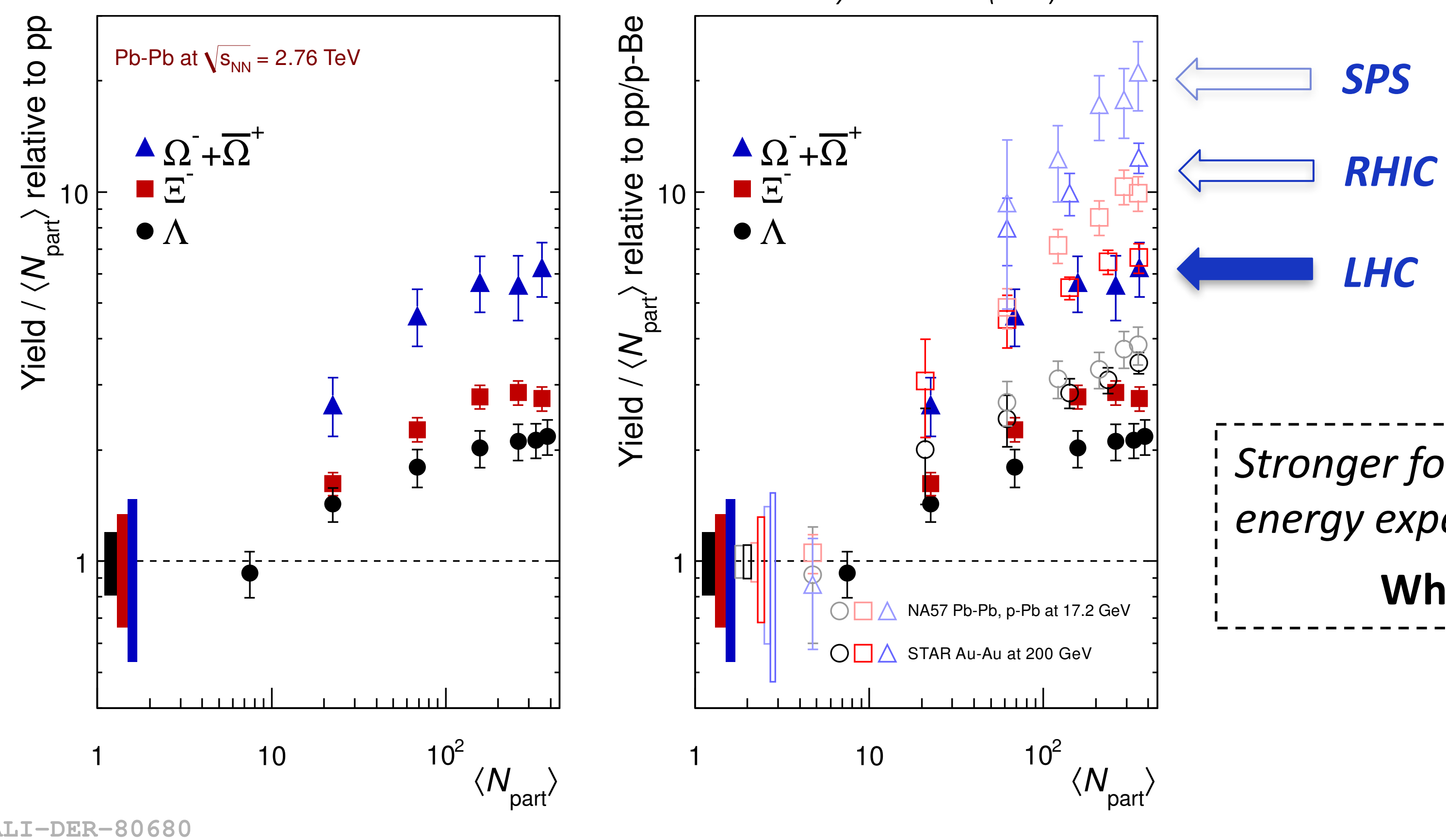


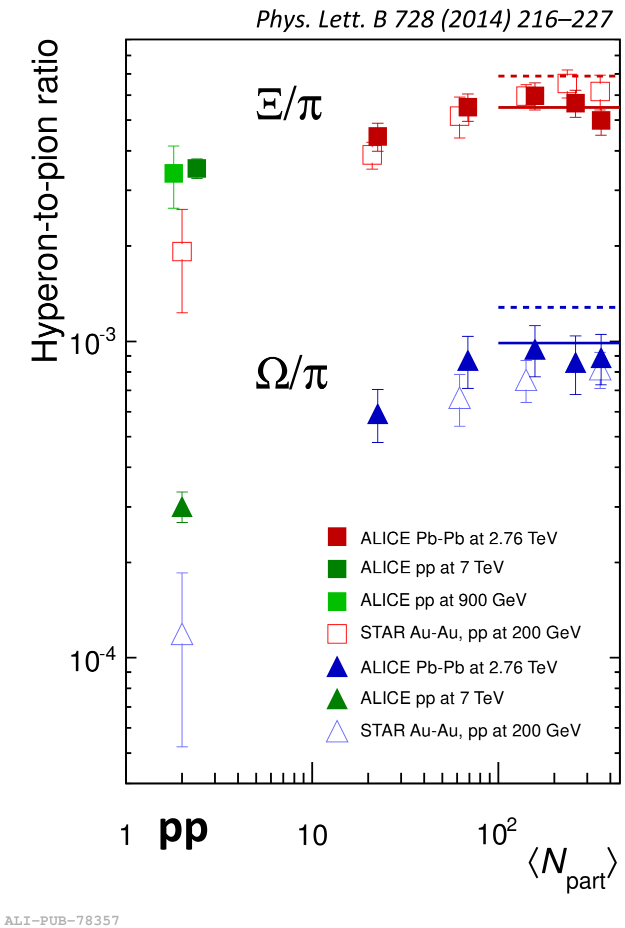
Stronger for lower energy experiments!

Why?

Possible explanation: *the enhancement in A-A actually comes from a suppression in pp, which is more important for lower energies*

Introduction and Motivation

→ **Strangeness enhancement: *hyperon-to-pion ratio***



- Clear increase of strange hadron production relative to pions is observed in A-A collisions as a function of the collision centrality

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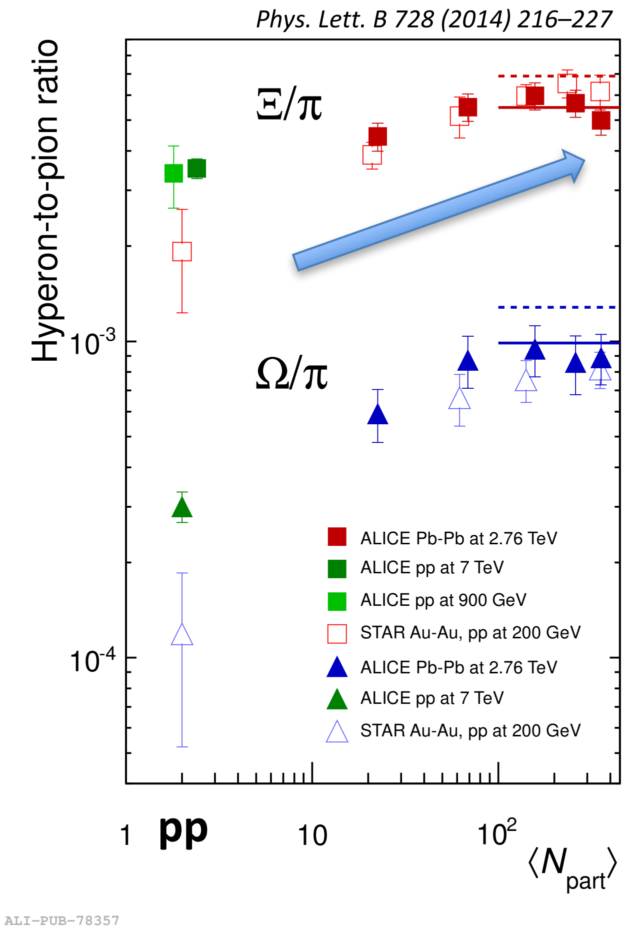

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- The ratios saturate towards central A-A collisions (larger systems), matching with predictions from thermal approaches using Grand-Canonical (GC) formulation

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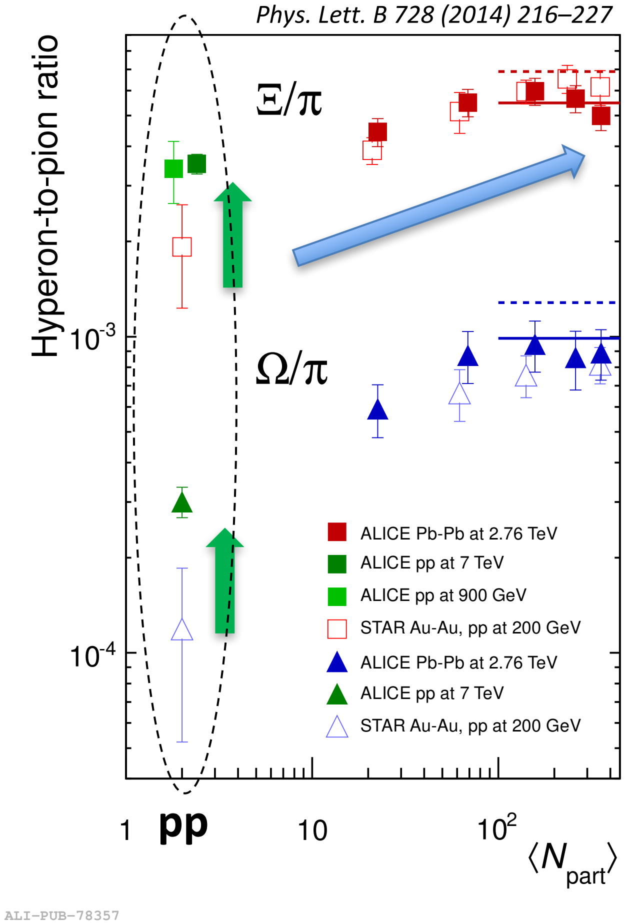

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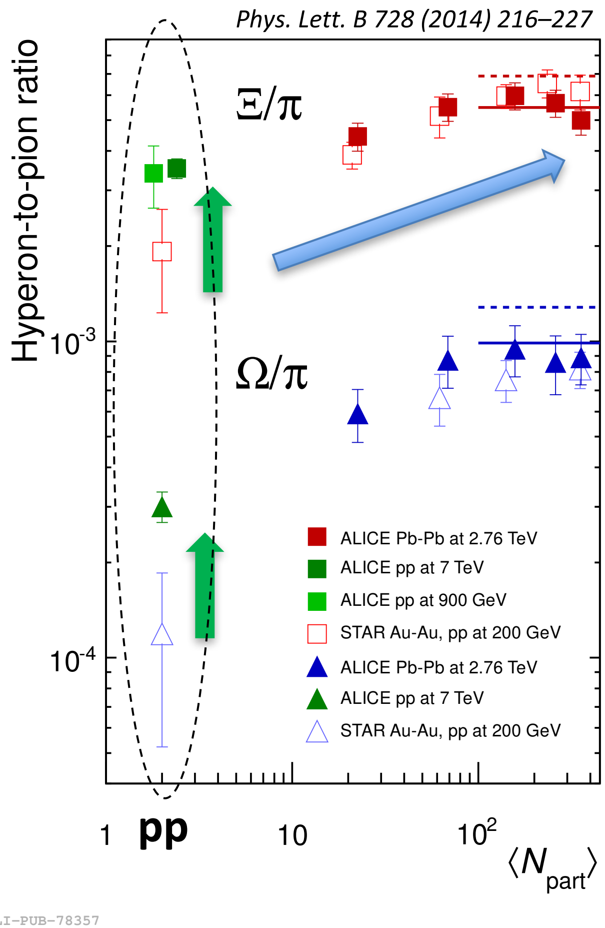

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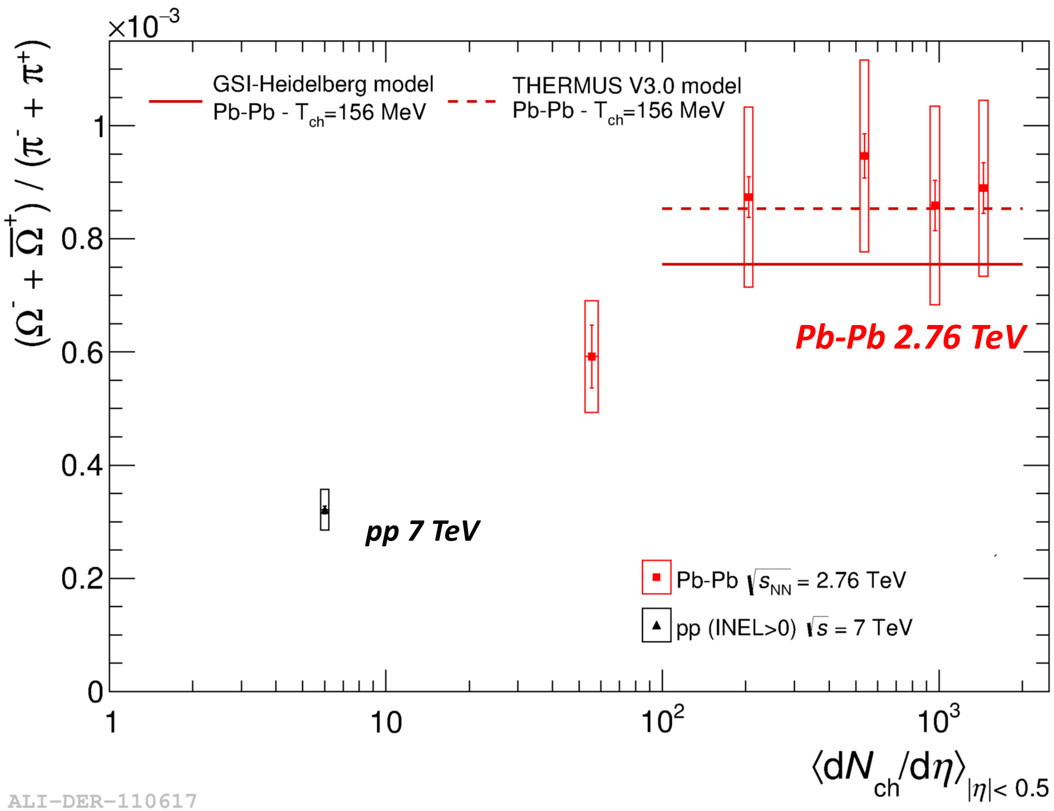
Can we further explore the transition between pp and A-A collisions?

Introduction and Motivation

→ Strangeness enhancement: *multiplicity dependence*



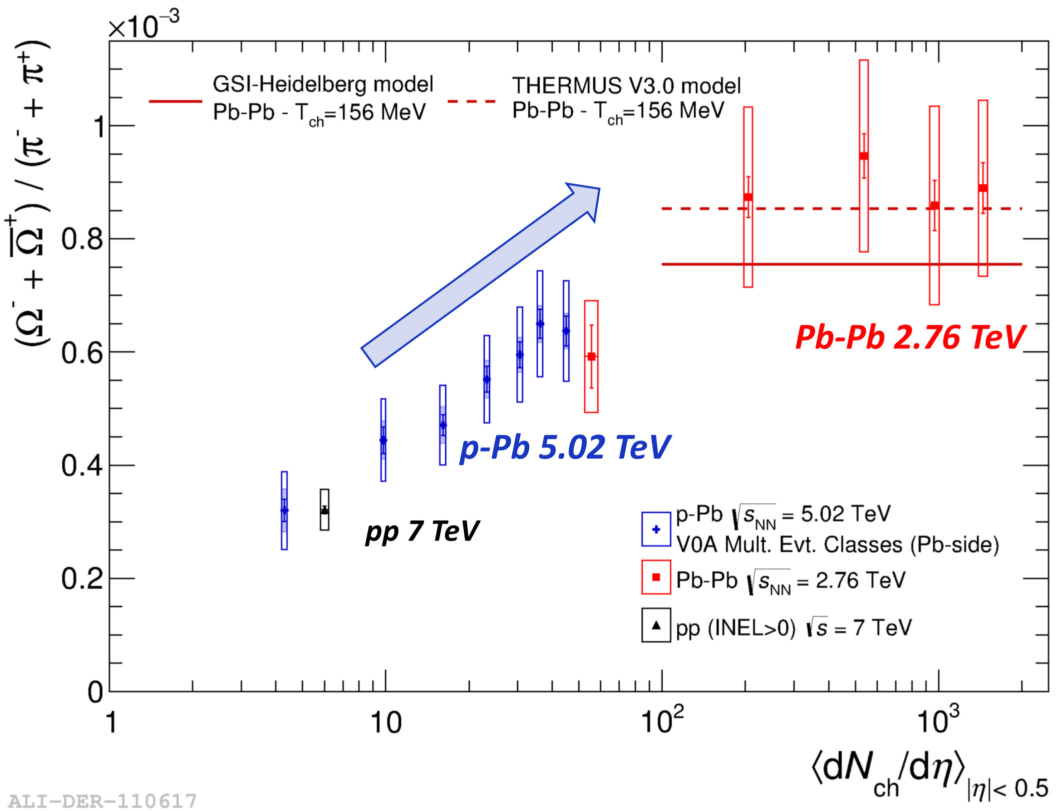
- Hyperon-to-pion ratio as a function of the average charged multiplicity density $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ at midrapidity ($|\eta| < 0.5$)

In the following slides, we will use the ***multiplicity density at midrapidity*** *as a proxy for the* ***system size***

Introduction and Motivation

ALICE

→ **Strangeness enhancement: *multiplicity dependence***



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- **p-Pb results:**
  (PLB 758 (2016) 389-401)
  - *Consistent with **pp** at low multiplicities and with **Pb-Pb** at high multiplicities*

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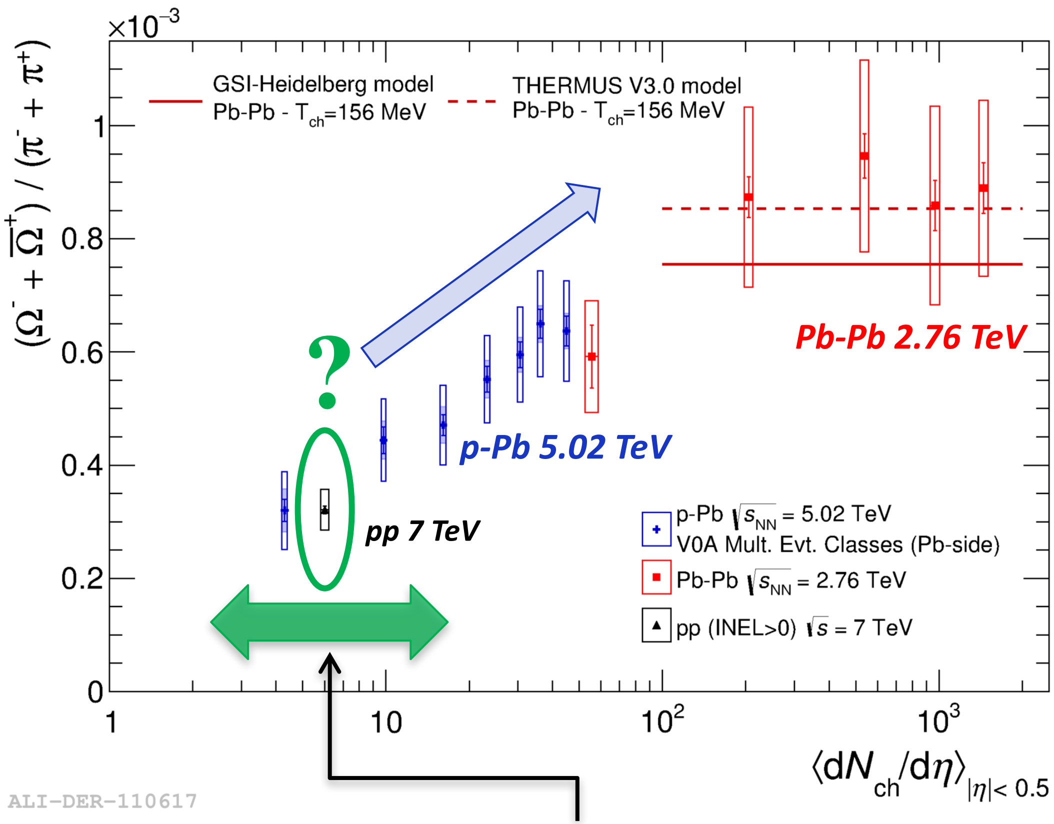

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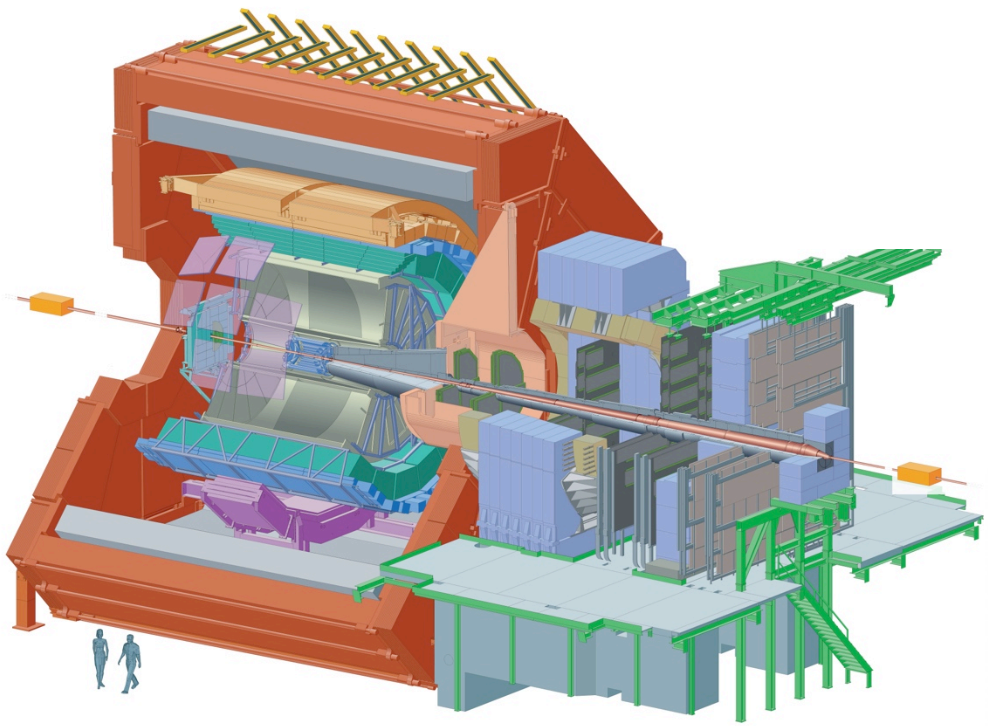
→ What about multiplicity dependence in pp?
→ Is hadrochemistry independent of $\sqrt{s}$?

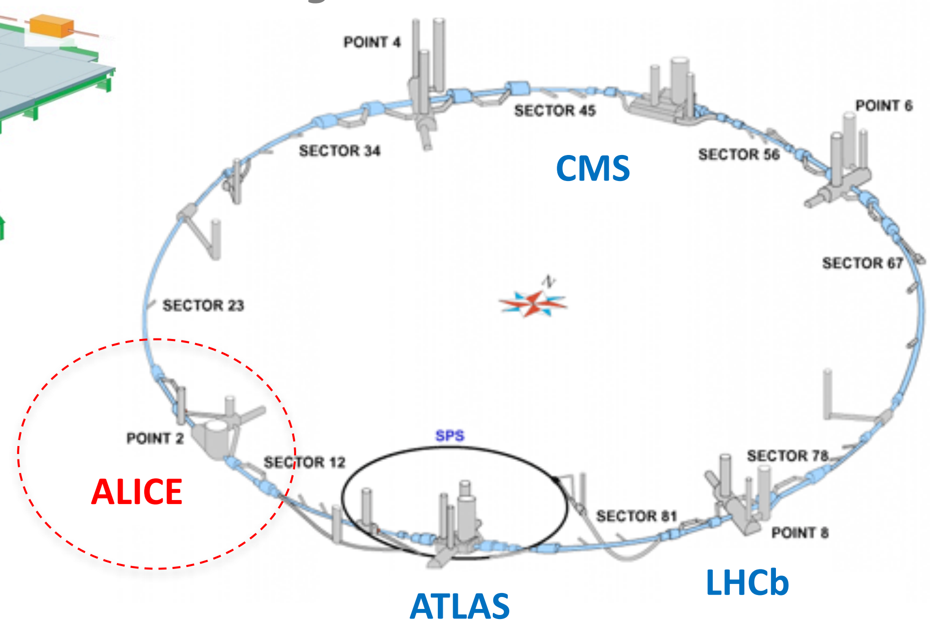
The ALICE Experiment

➔ **Dedicated experiment to study QGP properties**



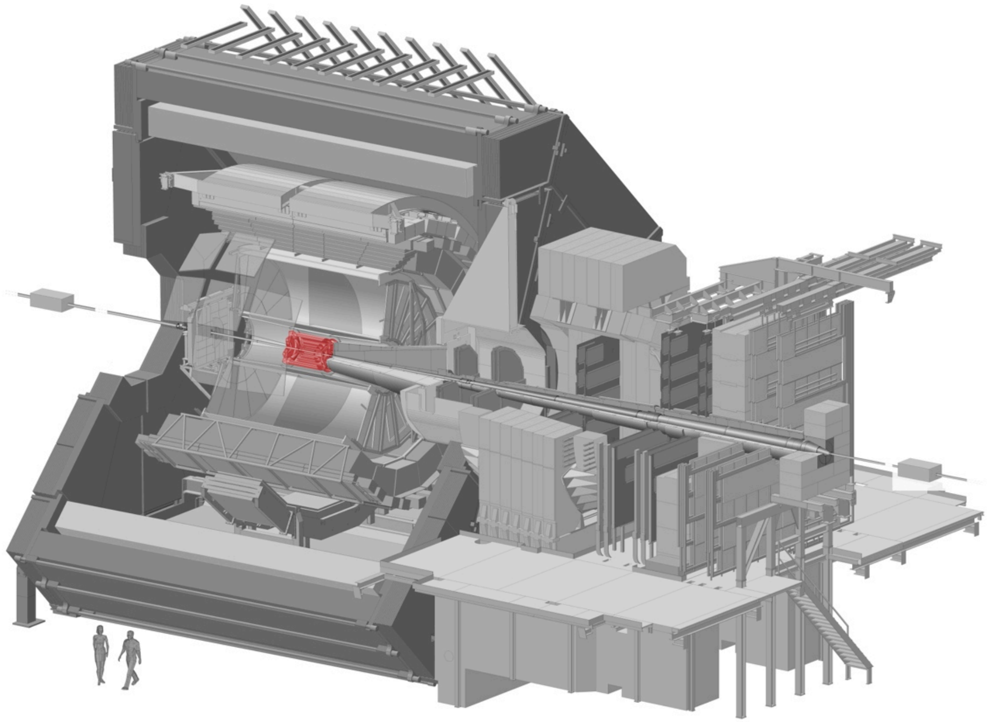
Optimized for charged particle tracking and **hadron identification**

Large Hadron Collider



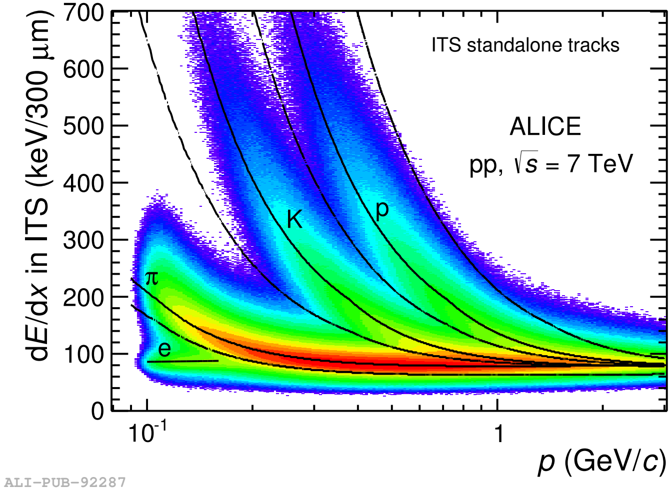
The ALICE Experiment

➔ **Particle Identification:** π, K and p



ITS ($|\eta|$<0.9)

- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)



ITS dE/dx

10^{-1} 1 10 10^{2}

p_T (GeV/c)

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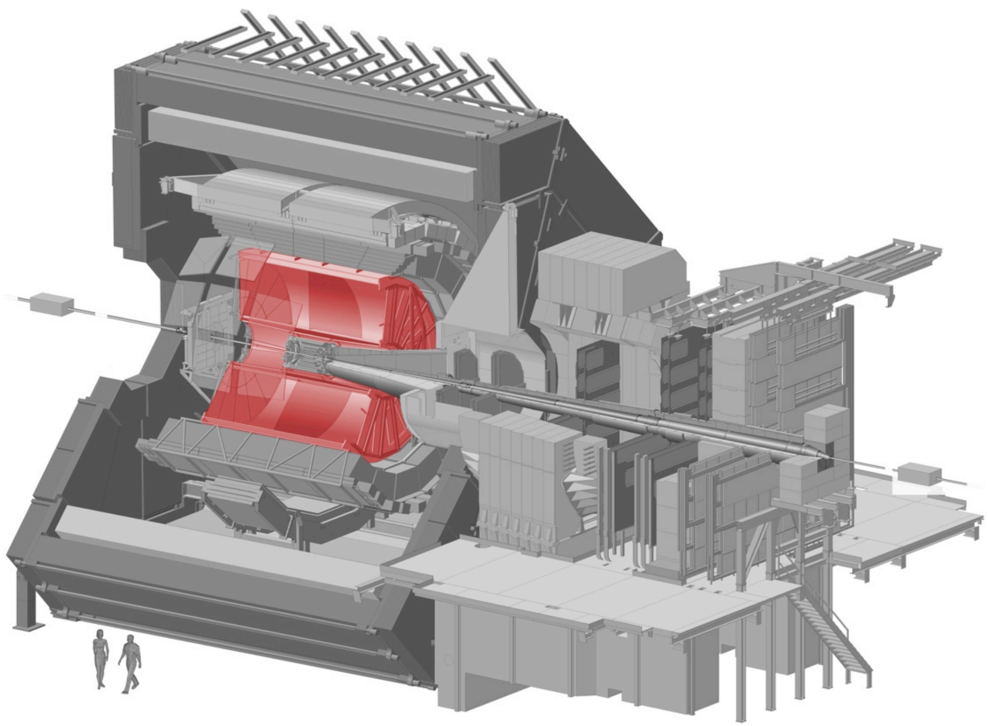

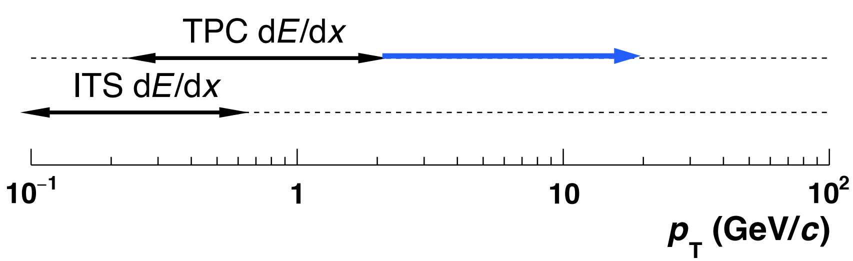

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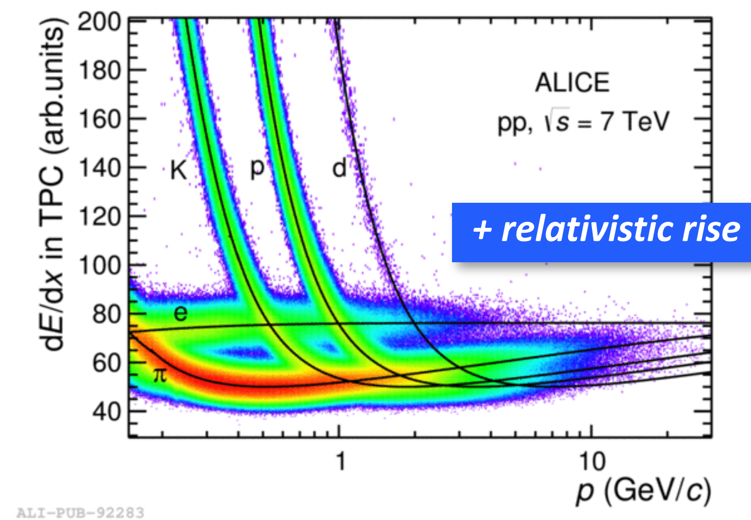
TPC ($|\eta|$<0.9)

- Gas-filled ionization detection volume
- Tracking, vertex, PID (dE/dx)



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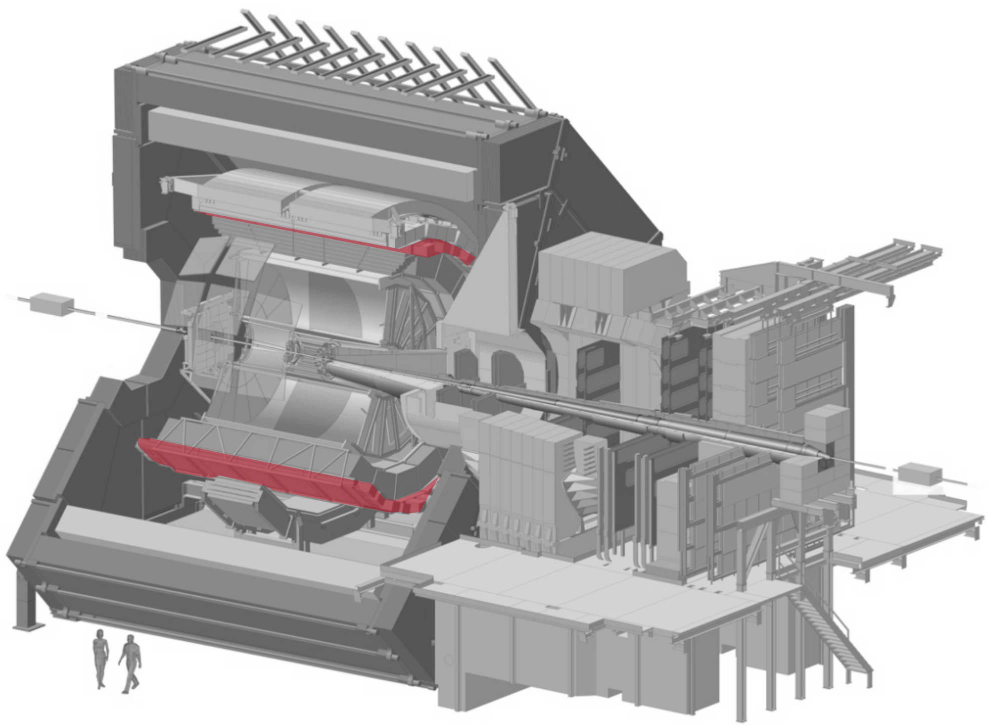

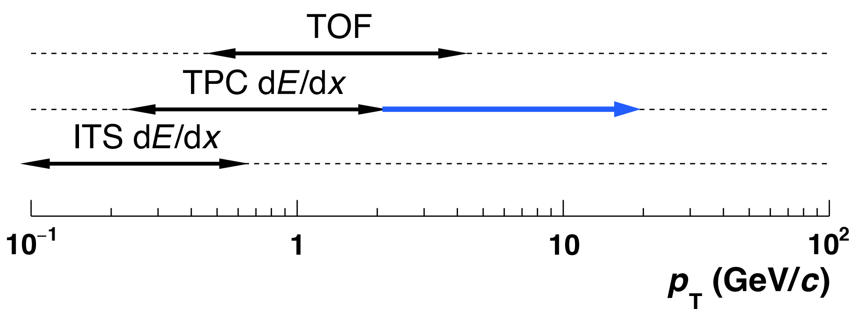

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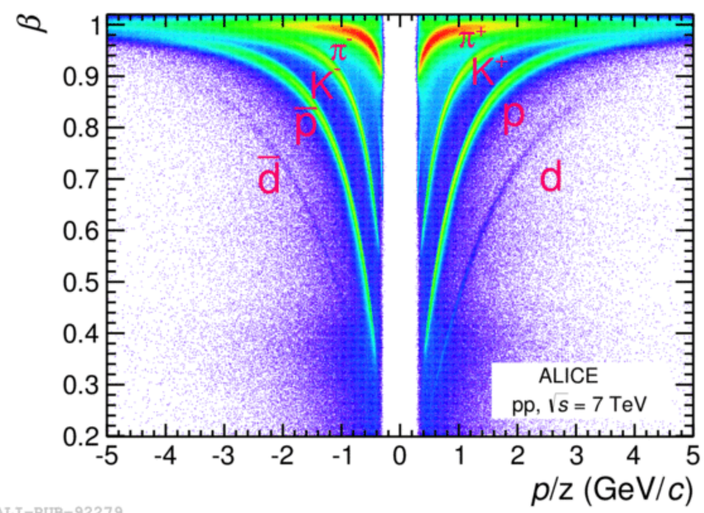
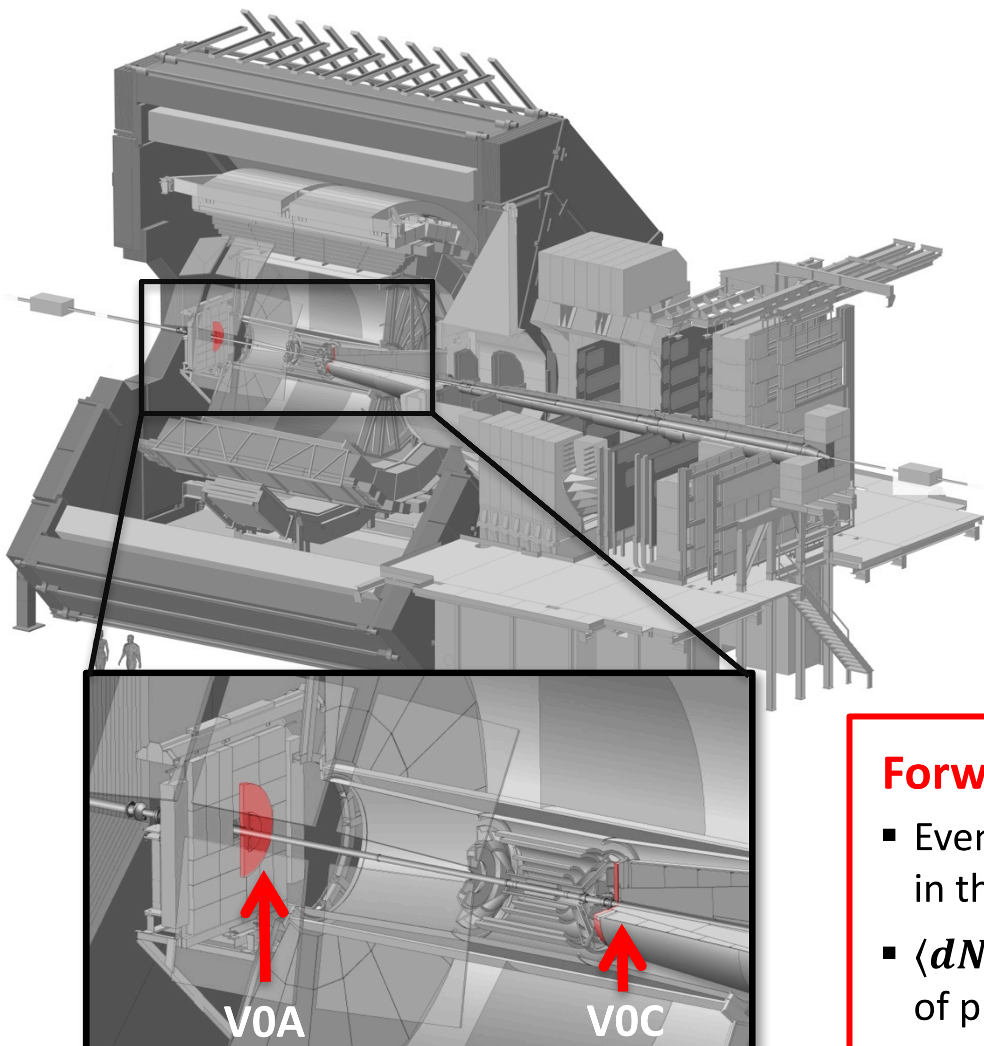
TOF ($|\eta|<0.9$)

- Multi-gap resistive plate chambers
- PID



The ALICE Experiment

➔ Multiplicity Selection



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V0 [V0A (2.8<η<5.1) & V0C (-3.7<η<-1.7)]
- Forward arrays of scintillators
- Trigger, beam gas rejection
- *Multiplicity estimator* ←

Forward Multiplicity Estimator

- Event selection based on total charge deposited in the **V0A** and **V0C** detectors ("**V0M**")
- $\langle dN_{\mathrm{ch}}/d\eta \rangle$ estimated as the average number of primary charged tracks in $|\eta| < 0.5$

Strange Hadron Measurements

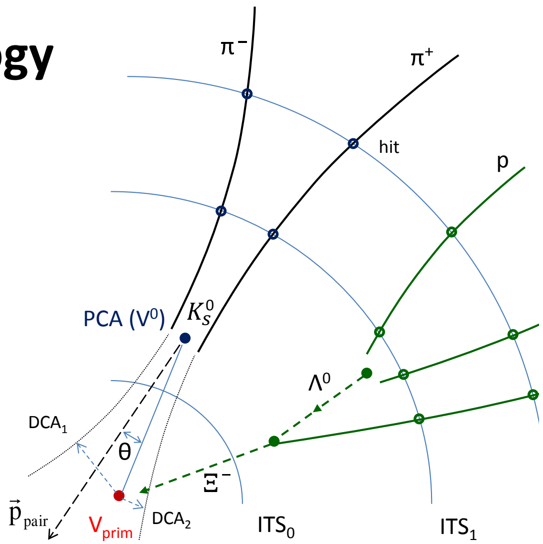
V^0's and Cascades reconstruction via decay topology

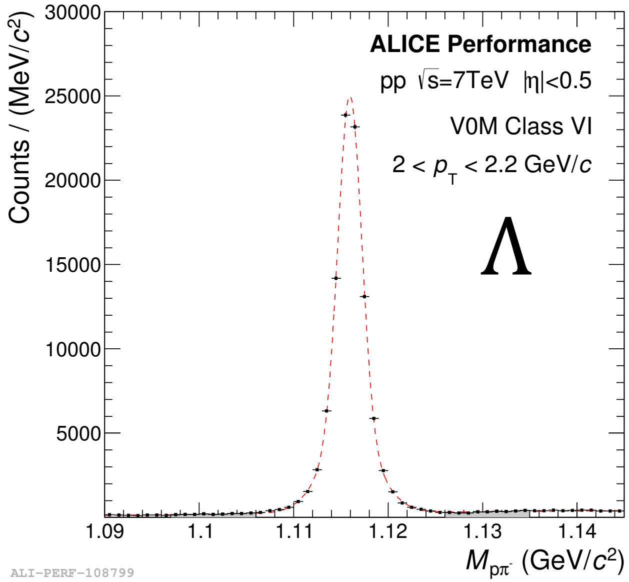
$K_S^0 \rightarrow \pi^+ + \pi^-$
– **B.R.:** 69.2%

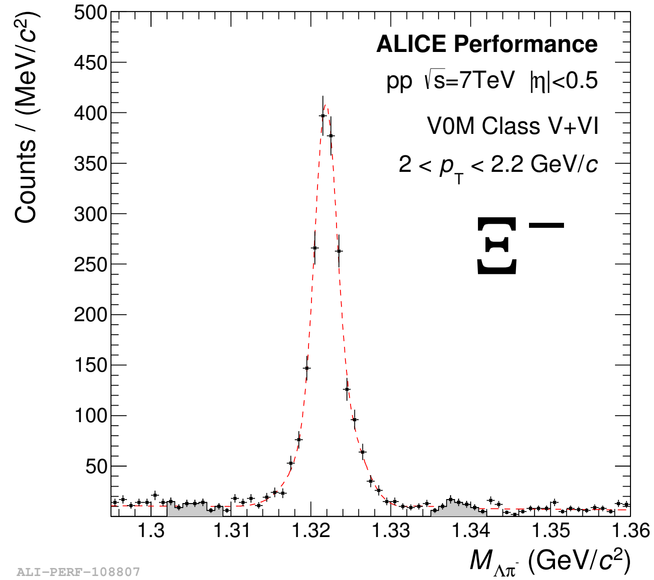
$\Xi^- \rightarrow \Lambda + \pi^-$
– **B.R.:** 99.9%

$\Lambda \rightarrow p + \pi^-$
– **B.R.:** 63.9%

$\Omega^- \rightarrow \Lambda + K^-$
– **B.R.:** 67.8%





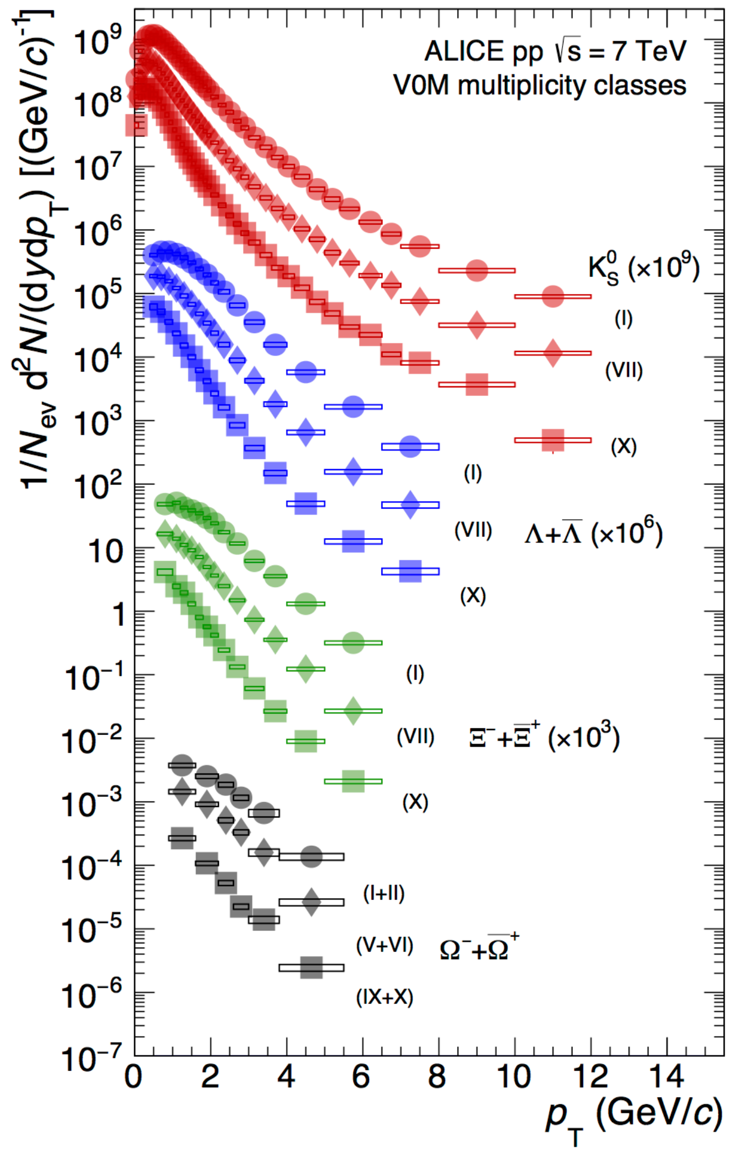


Transverse momentum spectra

- **V0M Multiplicity Classes:**
  - → *10 multiplicity classes*

$$\begin{cases} \boldsymbol{I} \rightarrow \langle \mathbf{d}N_{\mathbf{ch}}/\mathbf{d}\eta \rangle \approx 3.5 \times \langle \mathbf{d}N_{\mathbf{ch}}/\mathbf{d}\eta \rangle^{\mathbf{INEL>0}} \\ \vdots \\ \boldsymbol{X} \rightarrow \langle \mathbf{d}N_{\mathbf{ch}}/\mathbf{d}\eta \rangle \approx 0.4 \times \langle \mathbf{d}N_{\mathbf{ch}}/\mathbf{d}\eta \rangle^{\mathbf{INEL>0}} \end{cases}$$

$$\left(\langle \mathbf{d}N_{\mathbf{ch}}/\mathbf{d}\eta \rangle^{\mathbf{INEL>0}} \approx 6.0 \right)$$



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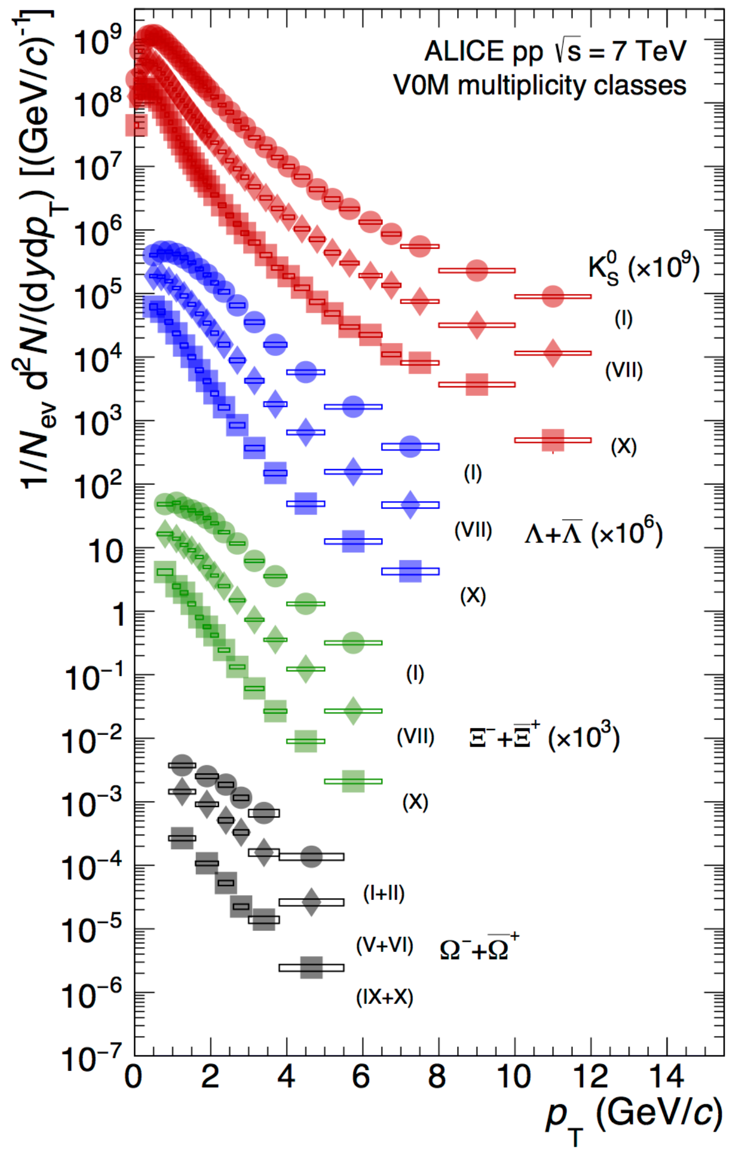
- **Spectra get harder with increasing multiplicity**

  (similar to A-A collisions)



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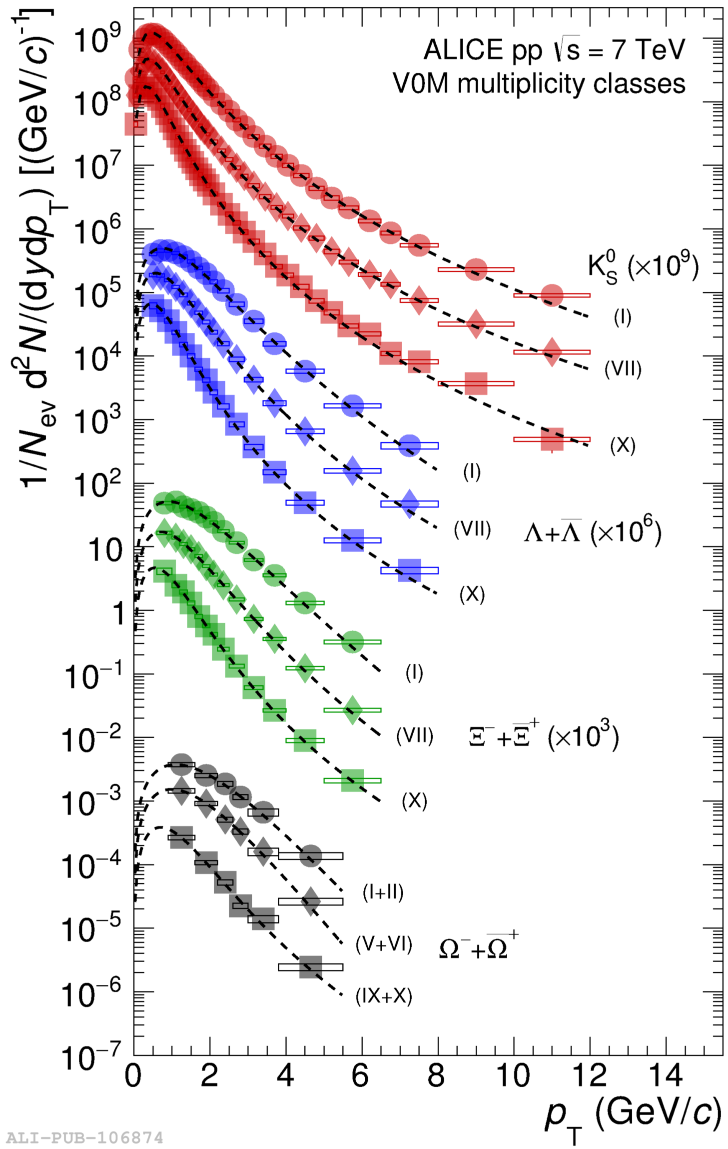
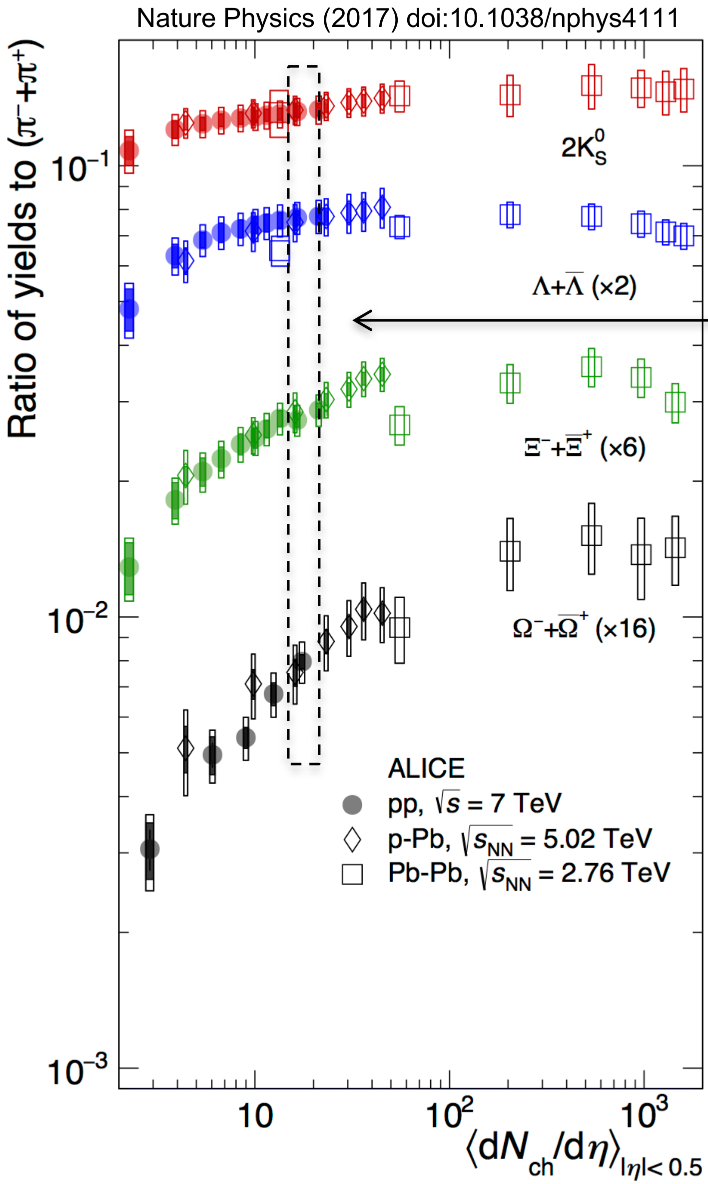
- **Extrapolation to low-p_{T} for computing integrated yields**
  - → *Lévy-Tsallis fit to data*
    (dashed lines in the plot)



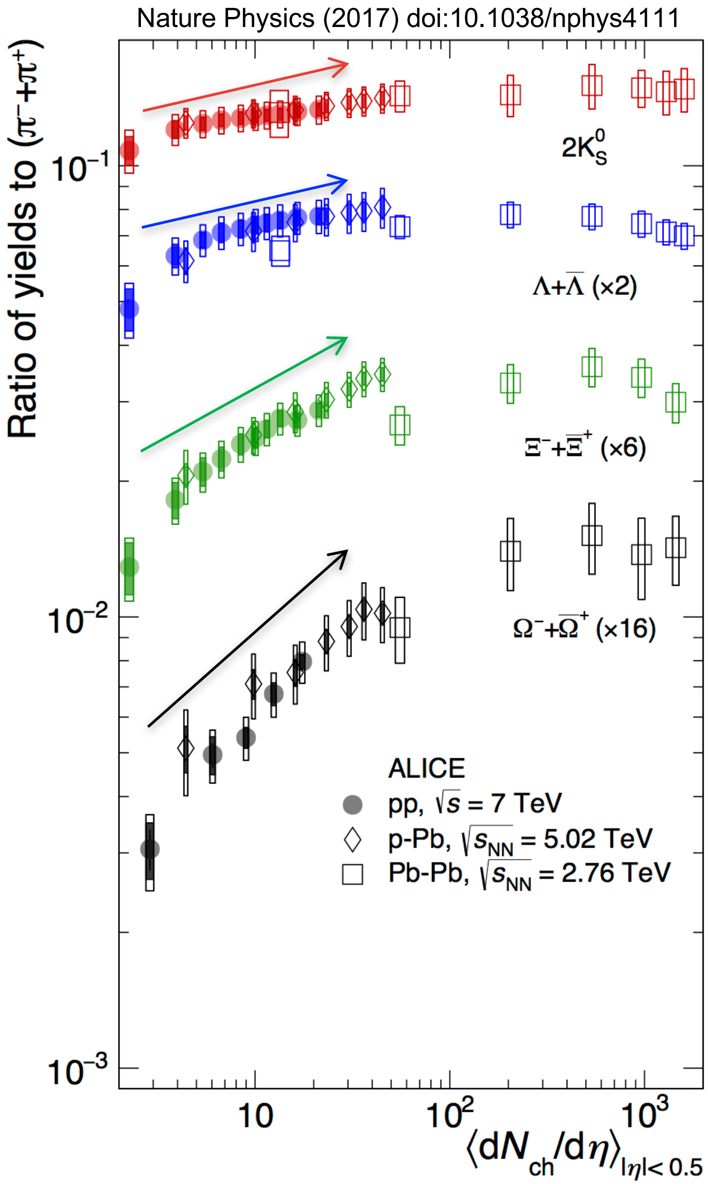
Ratios of Integrated Yields



- ***Consistent pattern*** observed between ***pp, p-Pb*** and ***Pb-Pb***

At fixed final state multiplicity, identical particle chemistry is observed independent of the system geometry

Ratios of Integrated Yields



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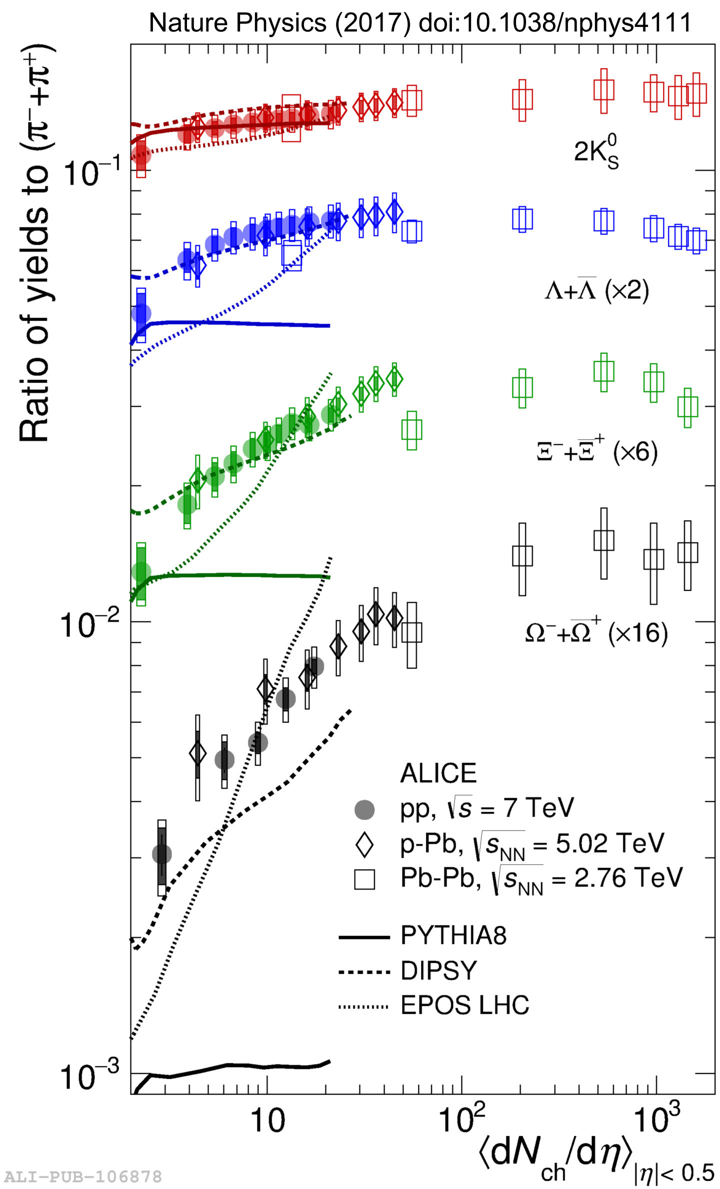
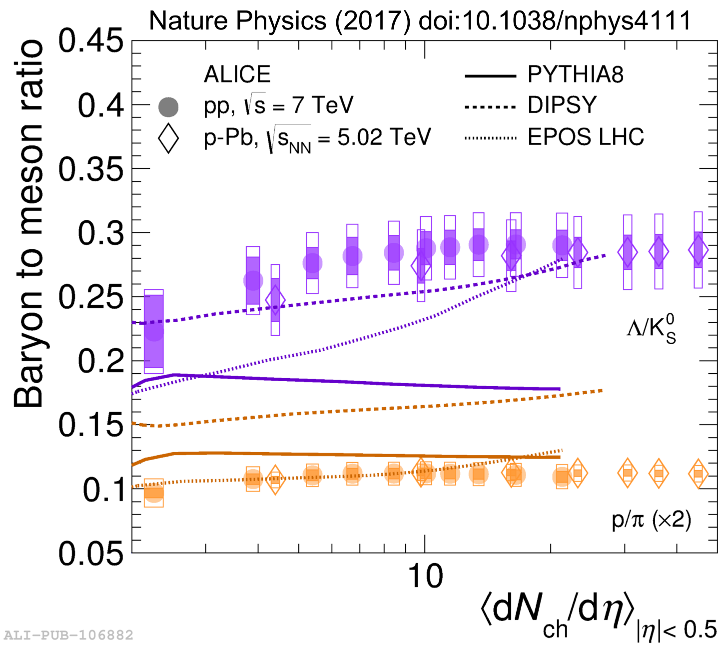


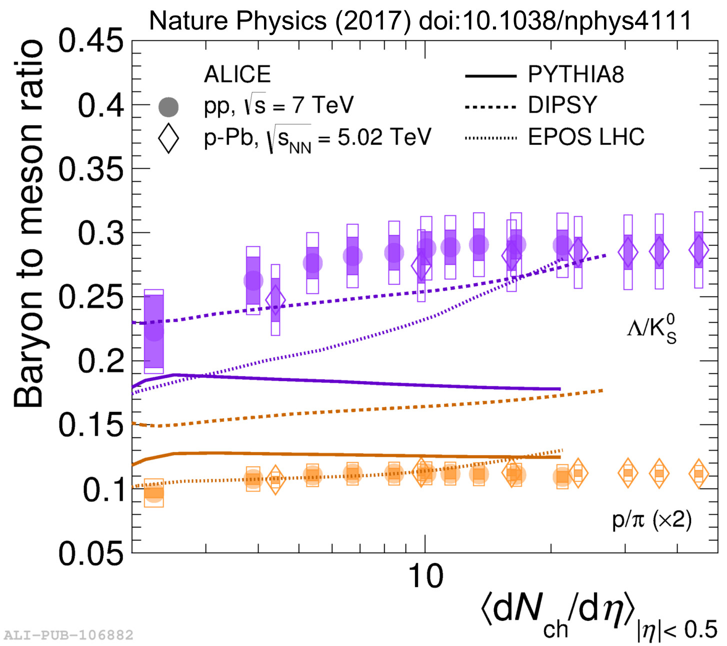
- ***Consistent pattern*** observed between ***pp, p-Pb*** and ***Pb-Pb***
- ***Significant enhancement*** of strange to non-strange hadron production in ***pp***
- ***MC models*** fail to describe the data
  - *PYTHIA8 (Color Reconnection) completely misses the behavior of the data* (independent of switching ON or OFF CR mechanism)
  - *DIPSY (Color Ropes) cannot simultaneously reproduce the observed enhancement for all four strange hadrons* (overpredicts the protons – see next slide →)
  - *EPOS LHC (Core-corona approach) only qualitatively describes the trend*

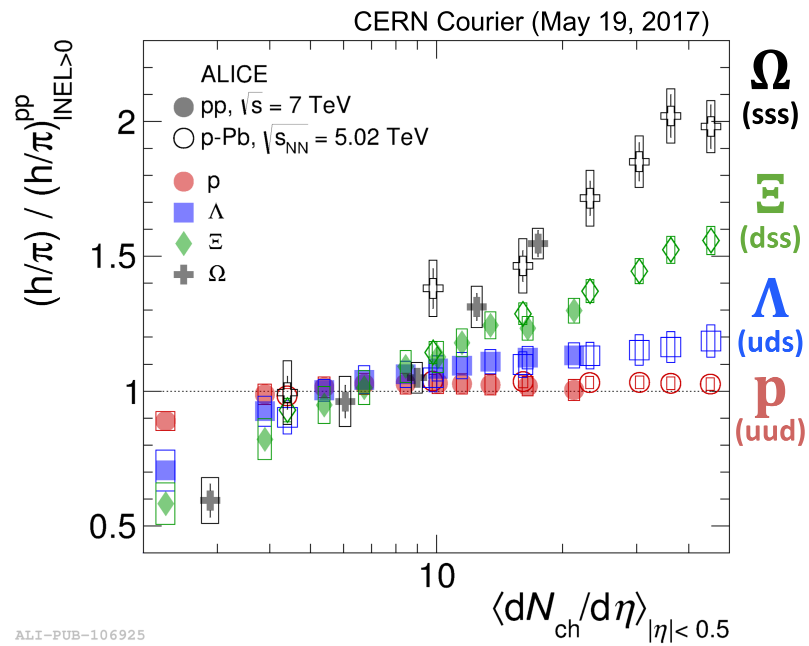
Strangeness Enhancement



- ***The enhancement is strangeness rather than mass related***

Strangeness Enhancement



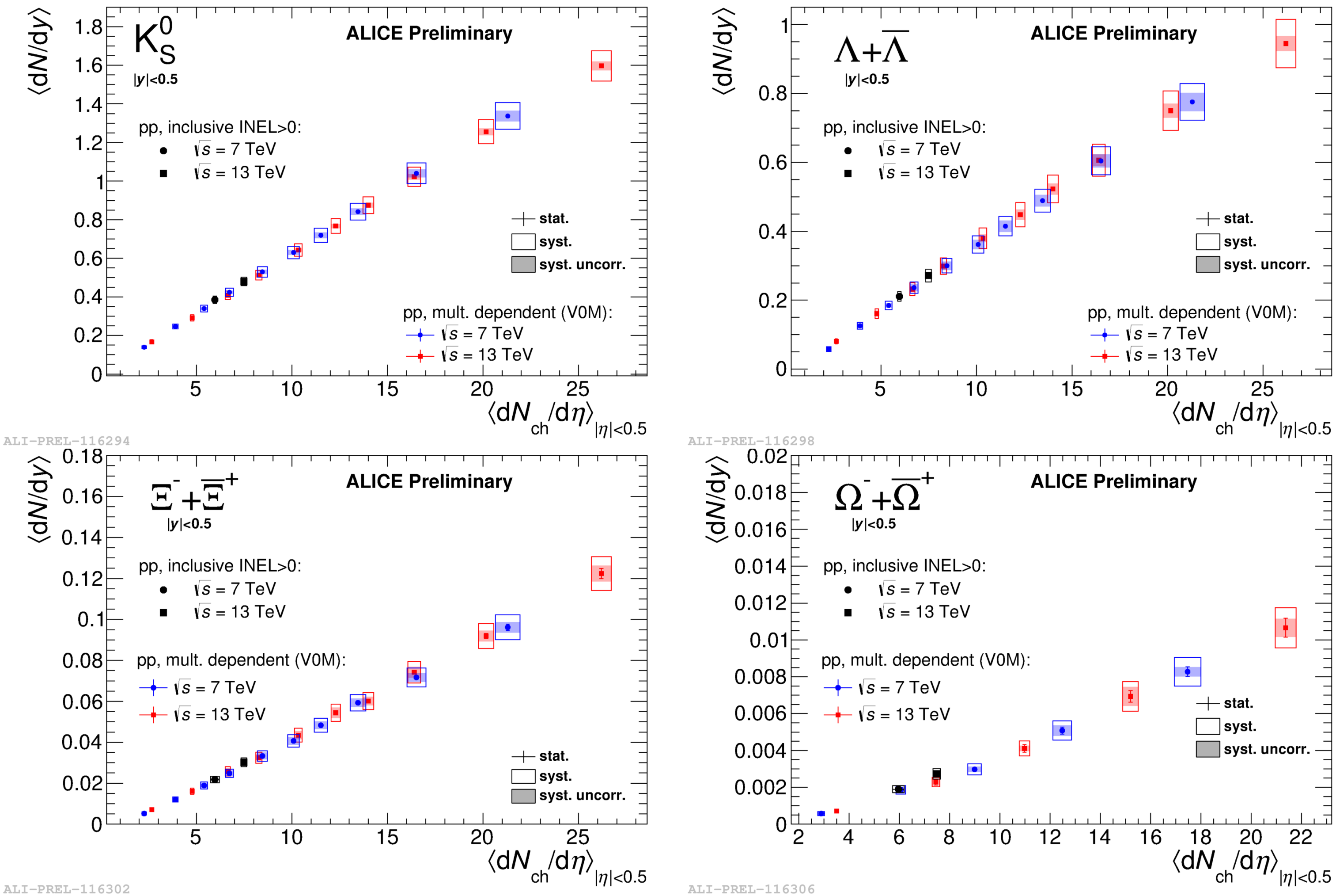


- ***The enhancement is strangeness rather than mass related***
- ***And it is proportional to the strangeness content of the hadron***

Hadrochemistry (in)dependence with $\sqrt{s}$

ALICE

→ *Preliminary results from pp collisions at 13 TeV*



→ *Multiplicity is the only driving quantity!*

Conclusions and Outlook

- **Enhancement of strange hadron production is observed towards high multiplicity pp events**
  - Observed enhancement of massive hadrons is due to ***strangeness*** – and not due to ***mass***
  - QCD inspired MC generators fail to describe the observed enhancement of strange hadrons
  - *Color Reconnection (PYTHIA)? Color Ropes (DIPSY)? Collective Radial Expansion (EPOS)?*

[Nature Physics (2017) doi:10.1038/nphys4111]

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  - Ridge at $\Delta\phi$=0 → collective flow of an expanding QGP?
  - Common hydrodynamic origin for Pb-Pb, p-Pb and pp?

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- **Is the QGP formed in collisions of small systems?**
  - The study of hadrochemistry across different colliding system is a powerful tool to investigate the thermal properties of QCD matter
  - We can't remove the question mark yet, but we have added another piece in puzzle

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[Nature Physics (2017) doi:10.1038/nphys4111]

- **Results from high multiplicity pp collisions at the LHC are revealing many interesting features (even unexpected for such small systems)**
  - Ridge at $\Delta\phi=0$ → collective flow of an expanding QGP?
  - Common hydrodynamic origin for Pb-Pb, p-Pb and pp?

- **Is the QGP formed in collisions of small systems?**
  - The study of hadrochemistry across different colliding system is a powerful tool to investigate the thermal properties of QCD matter
  - We can't remove the question mark yet, but we have added another piece in puzzle

thank you!

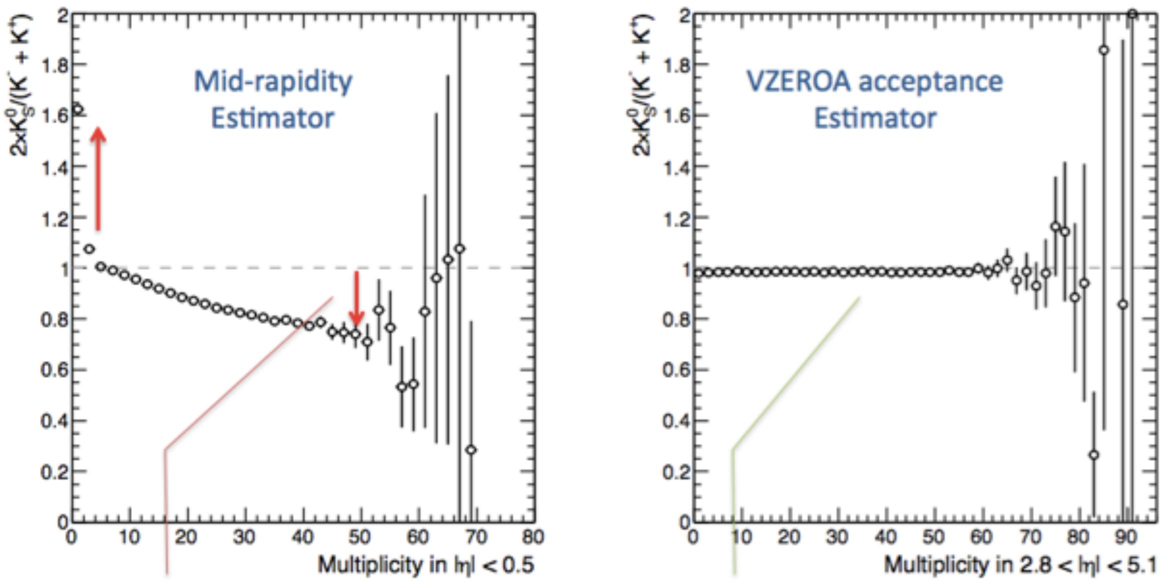
Backup

The ALICE Experiment

➔ Forward Multiplicity Estimator

Why is this important?

- Using mid-rapidity multiplicity estimators may introduce *self-correlation biases*, in particular towards charged particles
- For instance, it can be verified in simulations that the integrated yield ratio of charged to neutral kaons deviates from unity when selecting with mid-rapidity estimators



(~20-30% difference) (produced in equal amounts)

MC Studies: Estimator Biases

- PYTHIA Perugia-2011 (Tune 350)
- pp 7 TeV
- $K^{\pm}, K^0_S$ test

V0M Multiplicity Classes

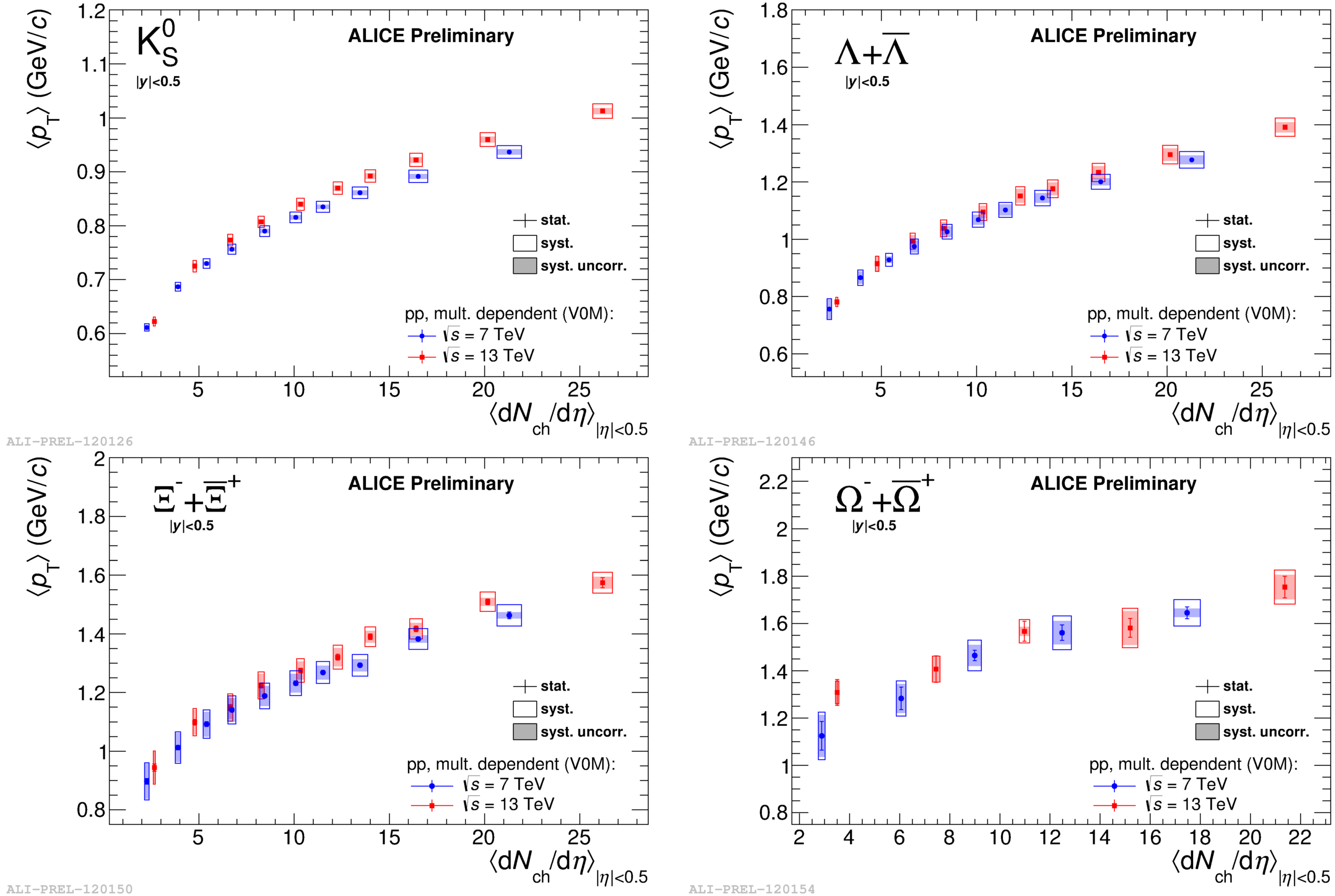
- *pp at 7 TeV vs multiplicity*

Fractions of the *INEL>0* cross-section:

π, K^0_S, Λ, Ξ			Ω		
V0M Class	$\frac{\sigma}{\sigma_{\mathrm{INEL}>0}}$	$\left\langle\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}\right\rangle$	**V0M Class**	$\frac{\sigma}{\sigma_{\mathrm{INEL}>0}}$	$\left\langle\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}\right\rangle$
I	0-0.95%	21.3±0.6	**I+II**	0.0-4.7%	17.5±0.5
II	0.95-4.7%	16.5±0.5			
III	4.7-9.5%	13.5±0.4	**III+IV**	4.7-14%	12.5±0.4
IV	9.5-14%	11.5±0.3			
V	14-19%	10.1±0.3	**V+VI**	14-28%	8.99±0.27
VI	19-28%	8.45±0.25			
VII	28-38%	6.72±0.21	**VII+VIII**	28-48%	6.06±0.19
VIII	38-48%	5.40±0.17			
IX	48-68%	3.90±0.14	**IX+X**	48-100%	2.89±0.14
X	68-100%	2.26±0.12			

Hadrochemistry (in)dependence with $\sqrt{s}$

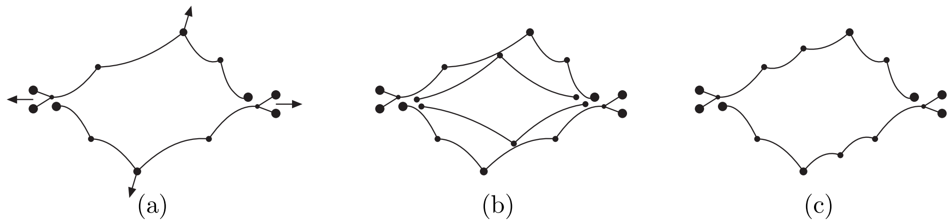
→ Preliminary results from pp collisions at 13 TeV



higher collision energy → higher $<p_T>$

Developments in microscopic modeling

Multi-Parton Interactions (MPI) and Color Reconnection (CR) mechanisms:

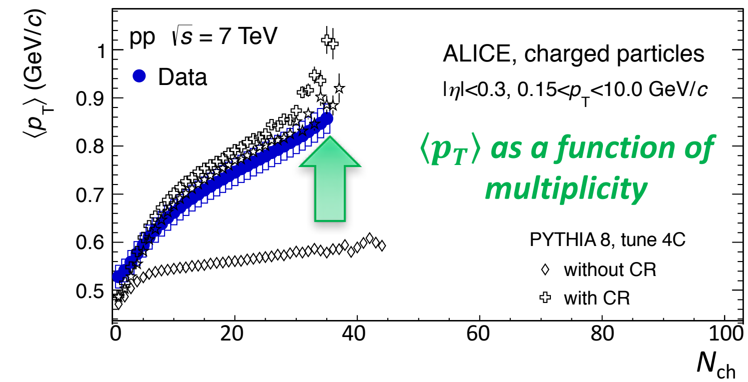


a) In a hard gluon-gluon subcollision, the outgoing gluons will be color-connected to the projectile and target remnants. Initial state radiation may give extra gluon kinks, which are ordered in rapidity

b) A second hard scattering would naively be expected to give two new strings connected to the remnants

c) In the fits to data, the gluons are color reconnected, so that the total string length becomes as short as possible

B. Abelev et al. (ALICE), PLB 727 (2013) 371



B. Abelev et al. (ALICE), PLB 728 (2013) 25