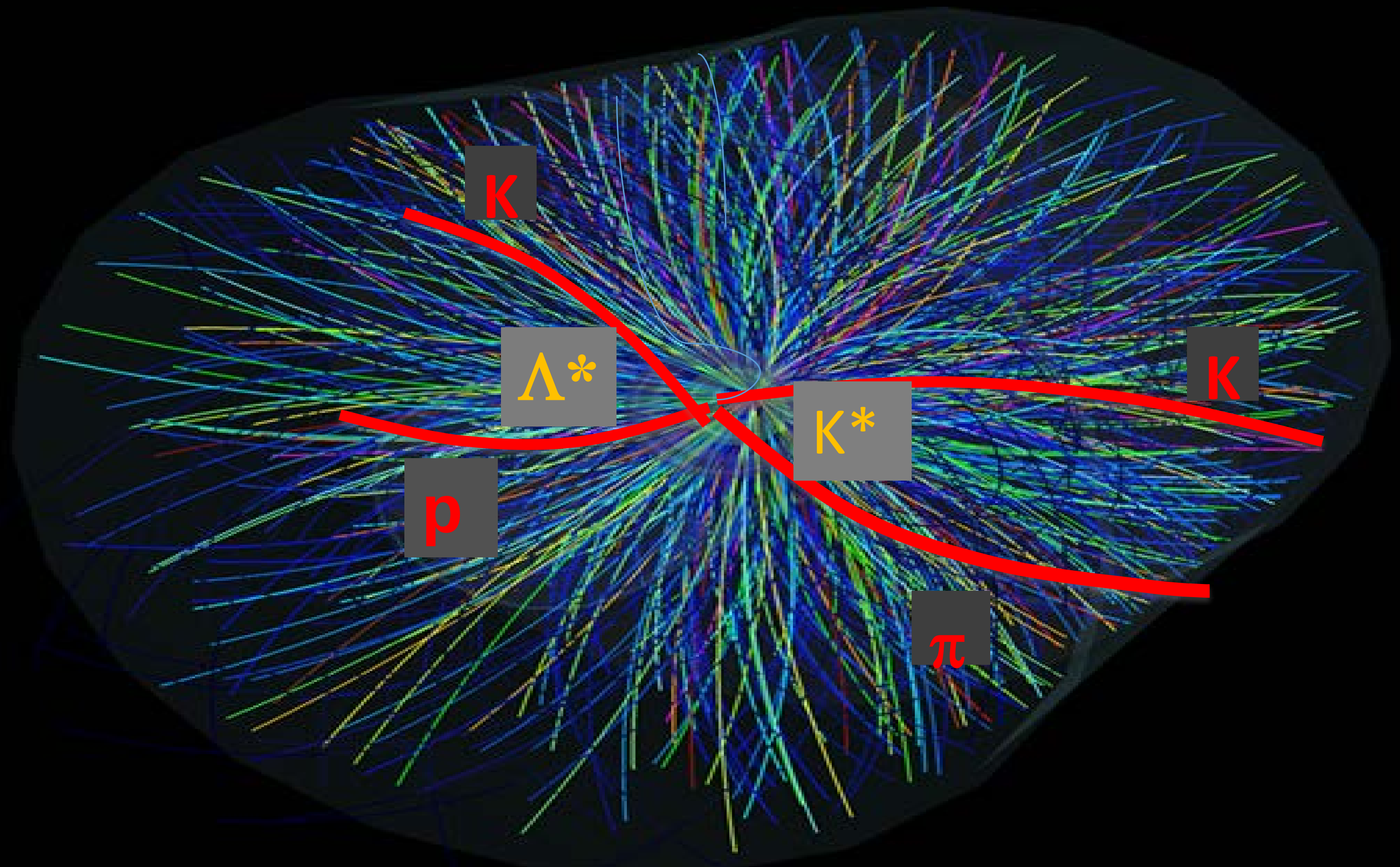
Latest results on hadronic resonance production with ALICE at the LHC

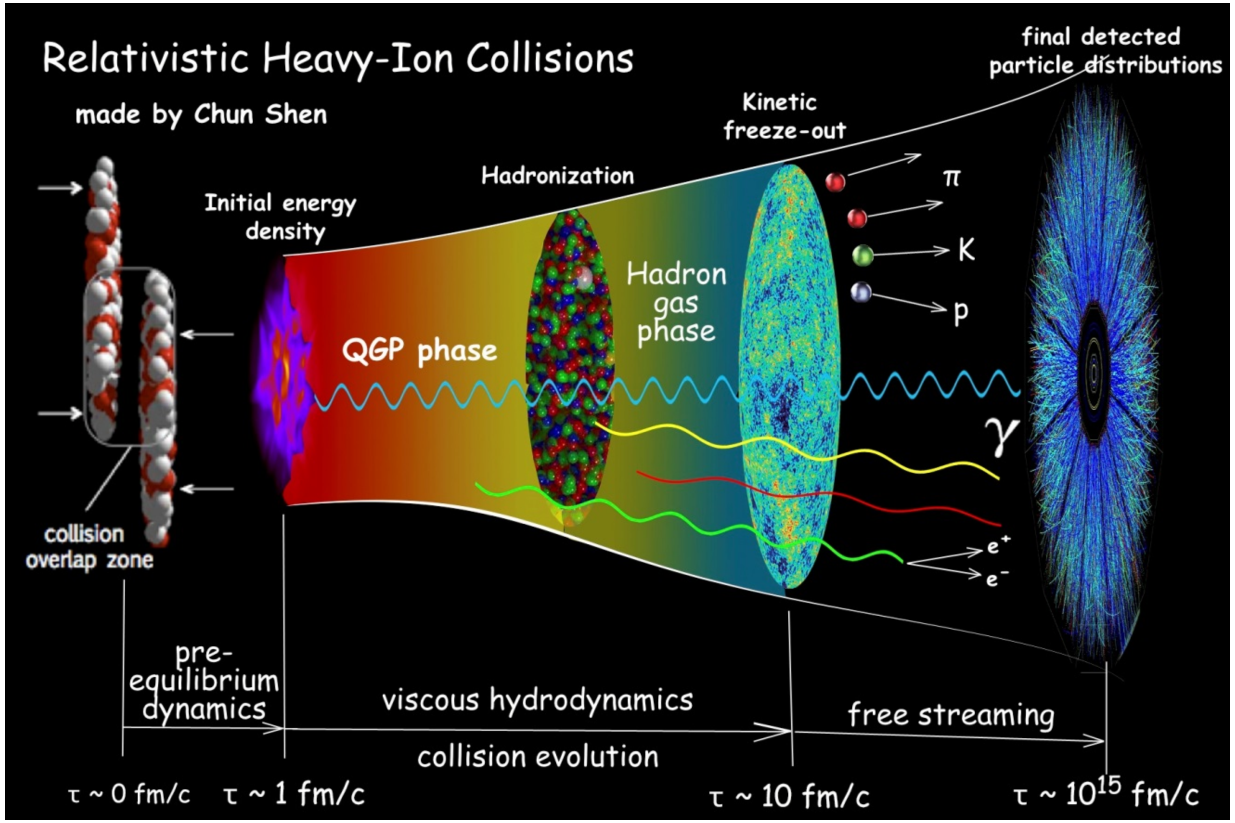


Angela Badalà for the
ALICE Collaboration
INFN Sezione di Catania

Talk outline

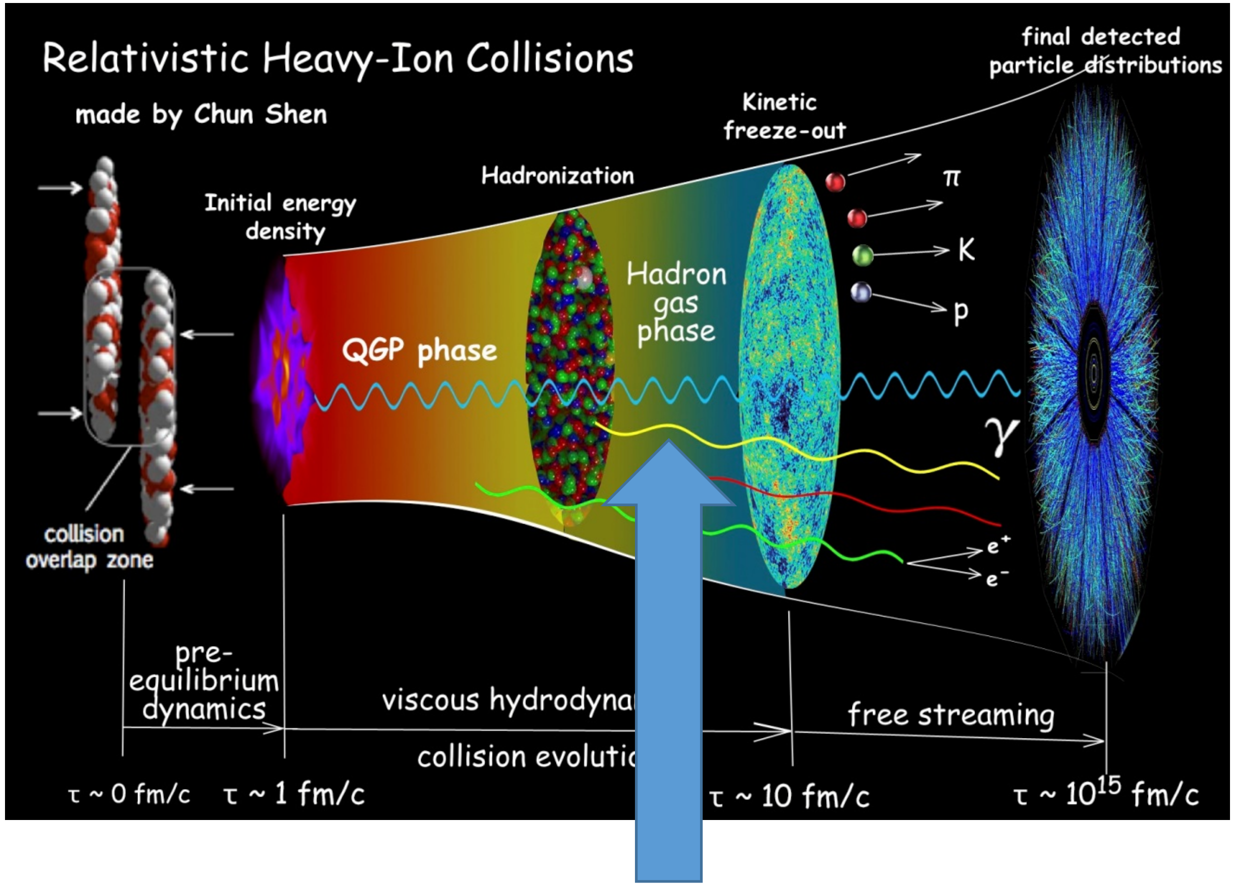
- Motivation
- Resonance results
- Summary and future

Relativistic heavy-ion collision evolution



- Initial hot and dense partonic matter rapidly expands
- Collective flow develops and the system cools down
- Phase transition (crossover) to hadron gas takes place at T_{critical}
- Chemical freeze-out takes place when inelastic collisions stop
- Kinetic freeze-out happens after the chemical freeze-out once elastic collisions stop

Relativistic heavy-ion collision evolution



Focus on this region with resonance studies

- Initial hot and dense partonic matter rapidly expands
- Collective flow develops and the system cools down
- Phase transition (crossover) to hadron gas takes place at T_{critical}
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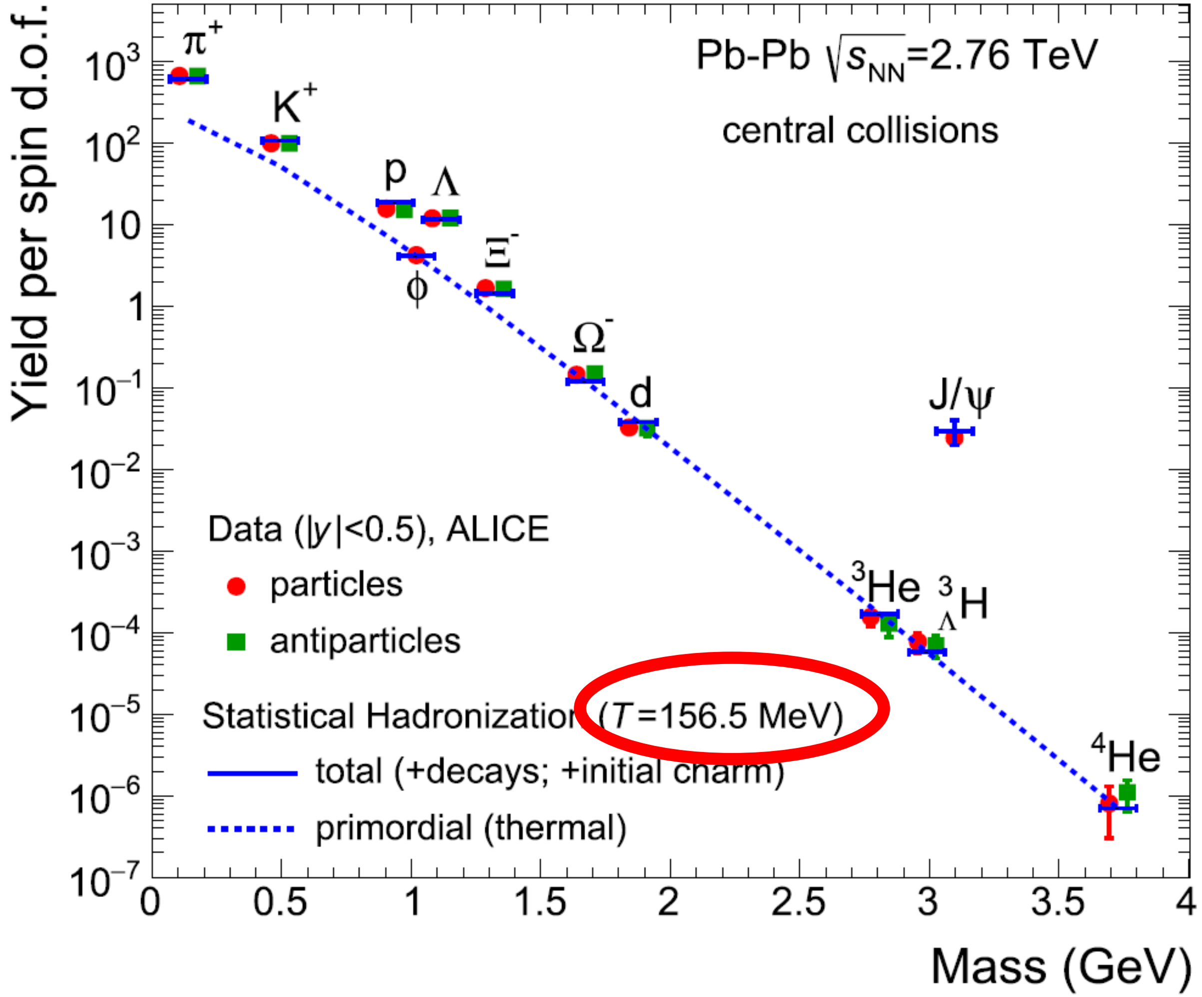
Hadronic resonances in ALICE

lifetime →

Resonance	$\rho(770)^0$	$K^*(892)^\pm$	$K^*(892)^0$	$f_0(980)$	$\Sigma(1385)^\pm$	$\Xi(1820)^\pm$	$\Lambda(1520)$	$\Xi(1530)^0$	$\phi(1020)$
Quark composition	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$u\bar{s}, \bar{u}s$	$d\bar{s}, \bar{d}s$	unknown	uus, dds	uss	uds	uss	$s\bar{s}$
τ(fm/c)	1.3	3.6	4.2	large unc.	5-5.5	8.1	12.6	21.7	46.4
Decay	π π	K^0_S π	K π	$\pi^+\pi^-$	Λ π	Λ K	p K	Ξ π	K K
B.R.(%)	100	33.3	66.6	46	87	unknown	22.5	66.7	48.9

Resonances have lifetimes of about a few fm/c → $\tau_{\text{resonance}} \sim \tau_{\text{fireball}} > \tau_{\text{hadronic-phase}}$

Hadronization and thermal equilibrium

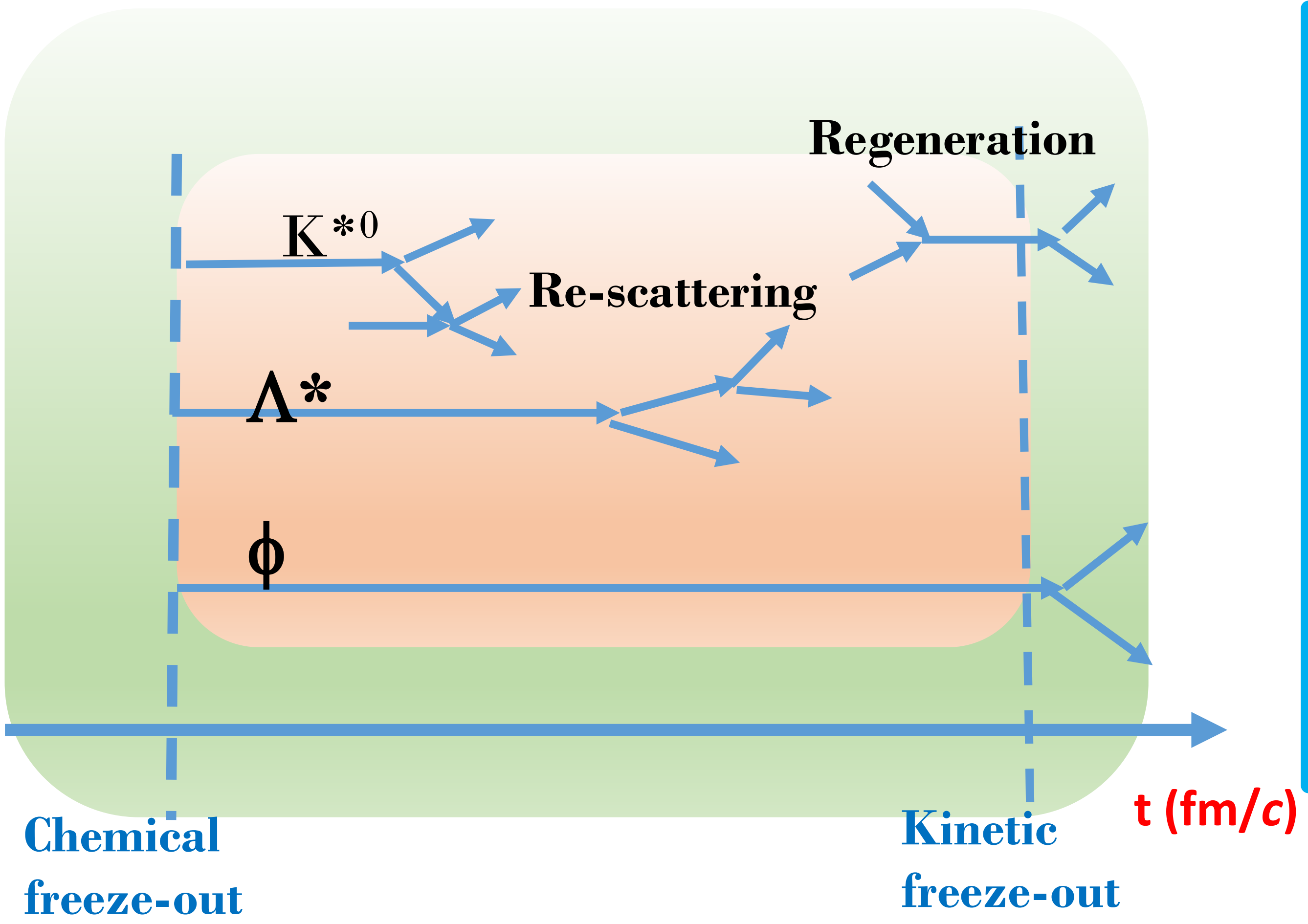


A. Andronic et al., Phys. Lett. B797 (2019) 134836

- At hadronization, system is close to thermal equilibrium
- A rapid freeze-out takes place at the phase boundary
- Hadron yields described well by thermal model over 9 order of magnitude
- Even loosely bound objects as light nuclei are well described

Resonances in hadronic phase

Re-scattering (elastic or pseudo-elastic scattering of the decay products) and regeneration modify the yield of reconstructible resonances.



- **Regeneration**:

pseudo-elastic scattering of decay products → increase of resonance measured yield

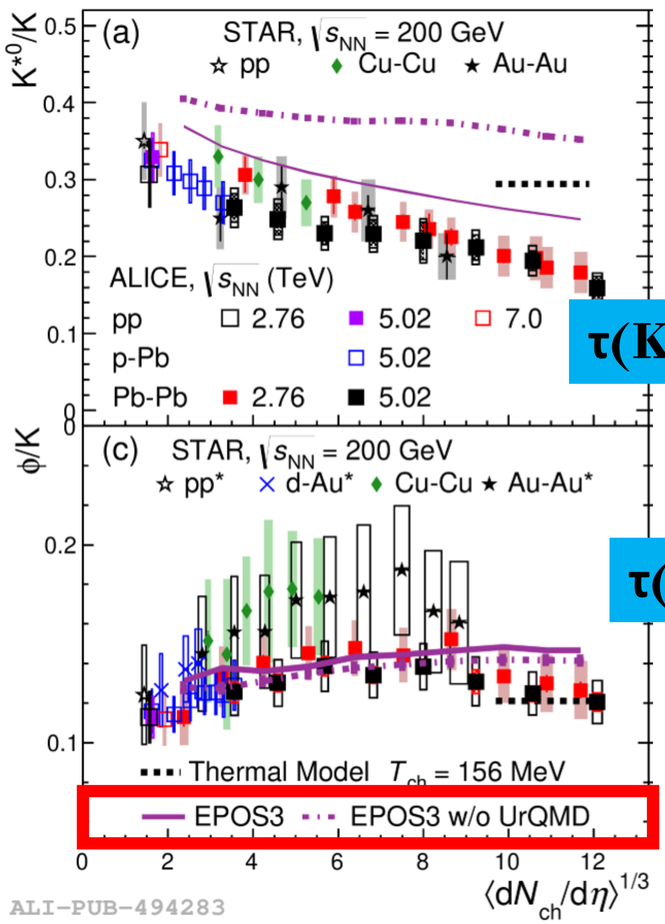
- **Re-scattering**:

Resonance decay products undergo elastic scattering or pseudo elastic scattering through different resonances → Resonance can not be reconstructed through invariant mass → decrease of resonance measured yield

Resonance suppression: hadronic phase effects

Ratio resonance yield to ground-state hadrons with similar quark content

Phys. Rev. C 106 (2022) 034907



$\tau(K^{*0})$ = 4.2 fm/c

$\tau(\phi)$ = 46.4 fm/c

Significant suppression of K*/K from pp-> p–Pb → Pb–Pb

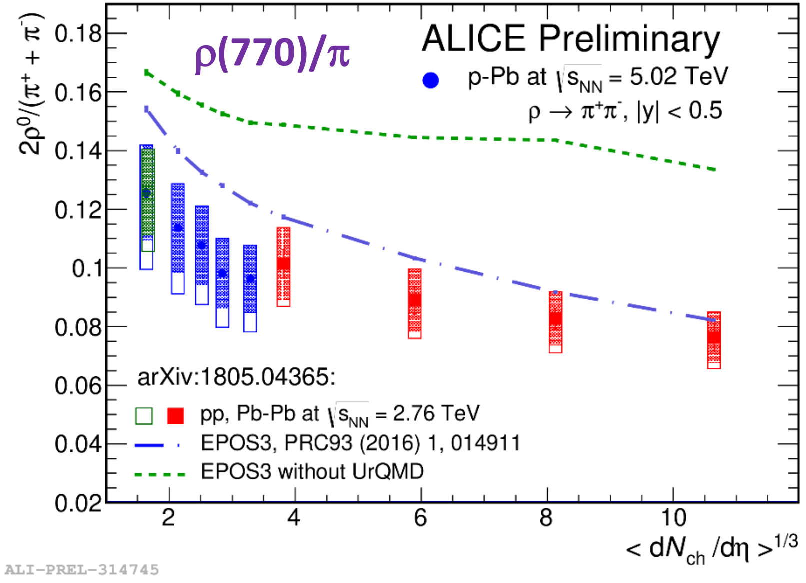
Presence of hadronic interaction: re-scattering dominant effect compared to regeneration

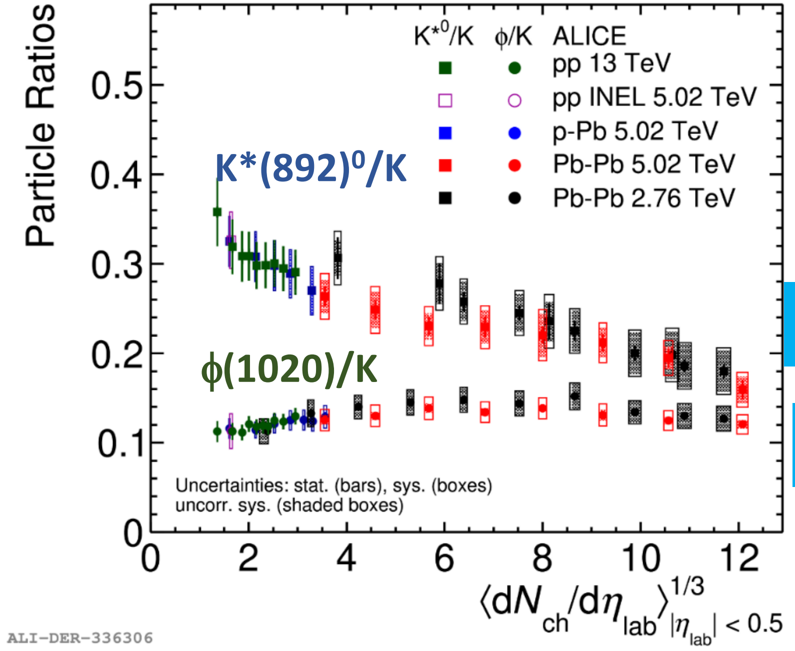
What drives this decrease?

- The **lifetime of the resonance**
- The **cross sections for re-scattering and regeneration** processes
- The **time duration** of the **hadronic phase**

Resonances in small collision systems

$\tau(\rho^0) = 1.3$ fm/c





$\tau(K^{*0}) = 4.2$ fm/c

$\tau(\phi) = 46.4$ fm/c

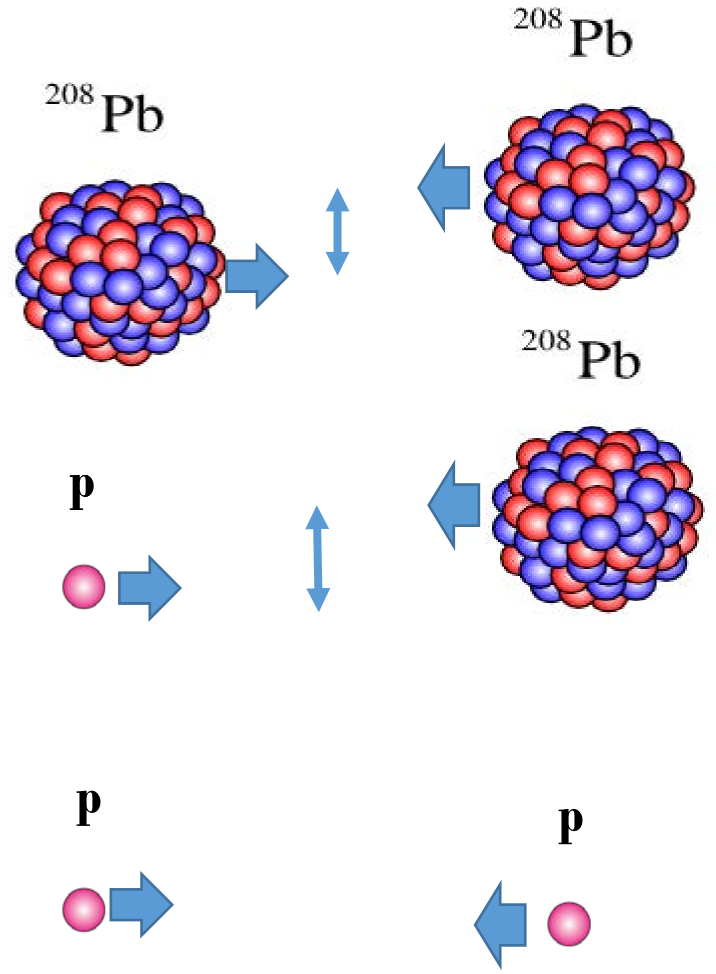
Small collision systems (pp and p–Pb):

➢ Used as a **baseline** for heavy-ion collisions

➢ **Recent results** show some **typical** phenomena **of heavy-ion collisions (collectivity, strangeness enhancement, hint of resonance suppression in high multiplicity events, etc..)**

Collision systems

Run 1: 2010-2013
Run 2: 2015- 2018
Run3: 2022 -



Pb–Pb collisions
Hot QCD matter studies
$\sqrt{s_{NN}}$ = **2.76**, **5.02 TeV +**
Xe–Xe $\sqrt{s_{NN}}$ = **5.44 TeV**

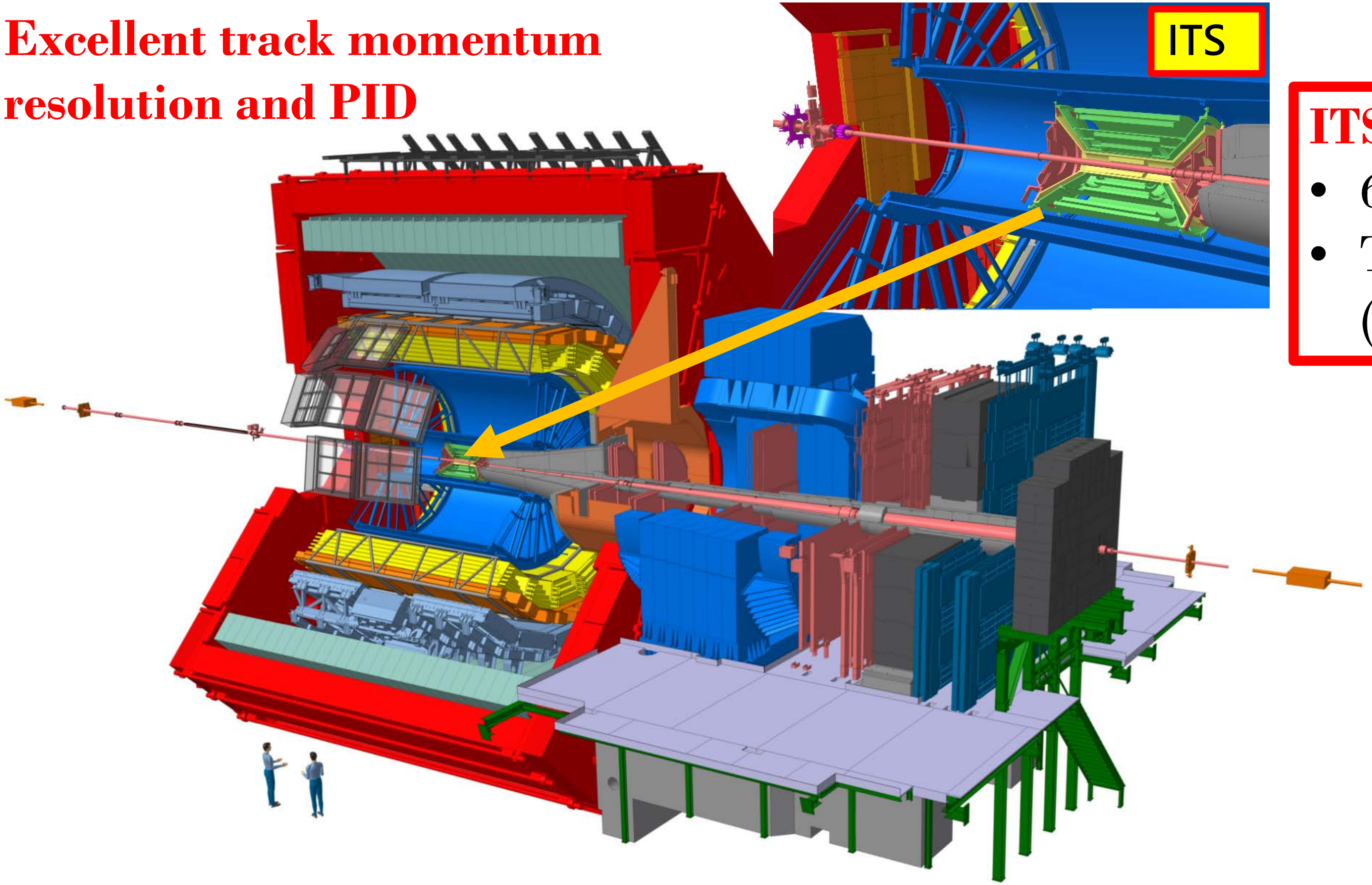
p–Pb collisions
Cold nuclear matter effects
$\sqrt{s_{NN}}$ = **5.02**, **8.16 TeV**

pp collisions
Standard QCD reference
$\sqrt{s}$ = **0.9, 2.76, 5.02, 7**, **13 TeV**

Are QGP effects really absent here?

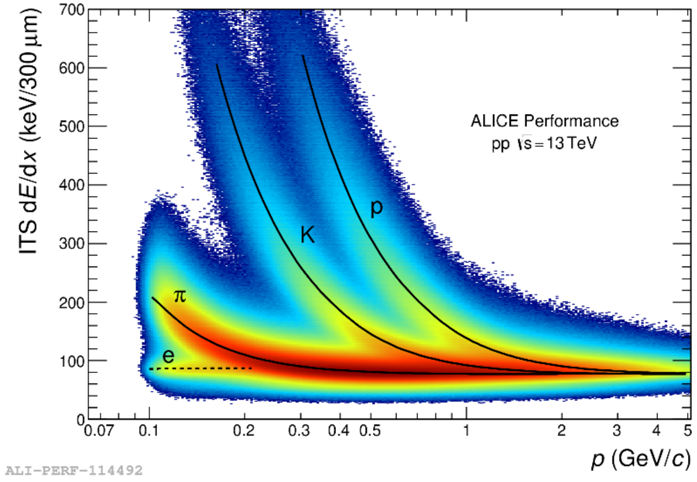
The ALICE detector

Excellent track momentum resolution and PID

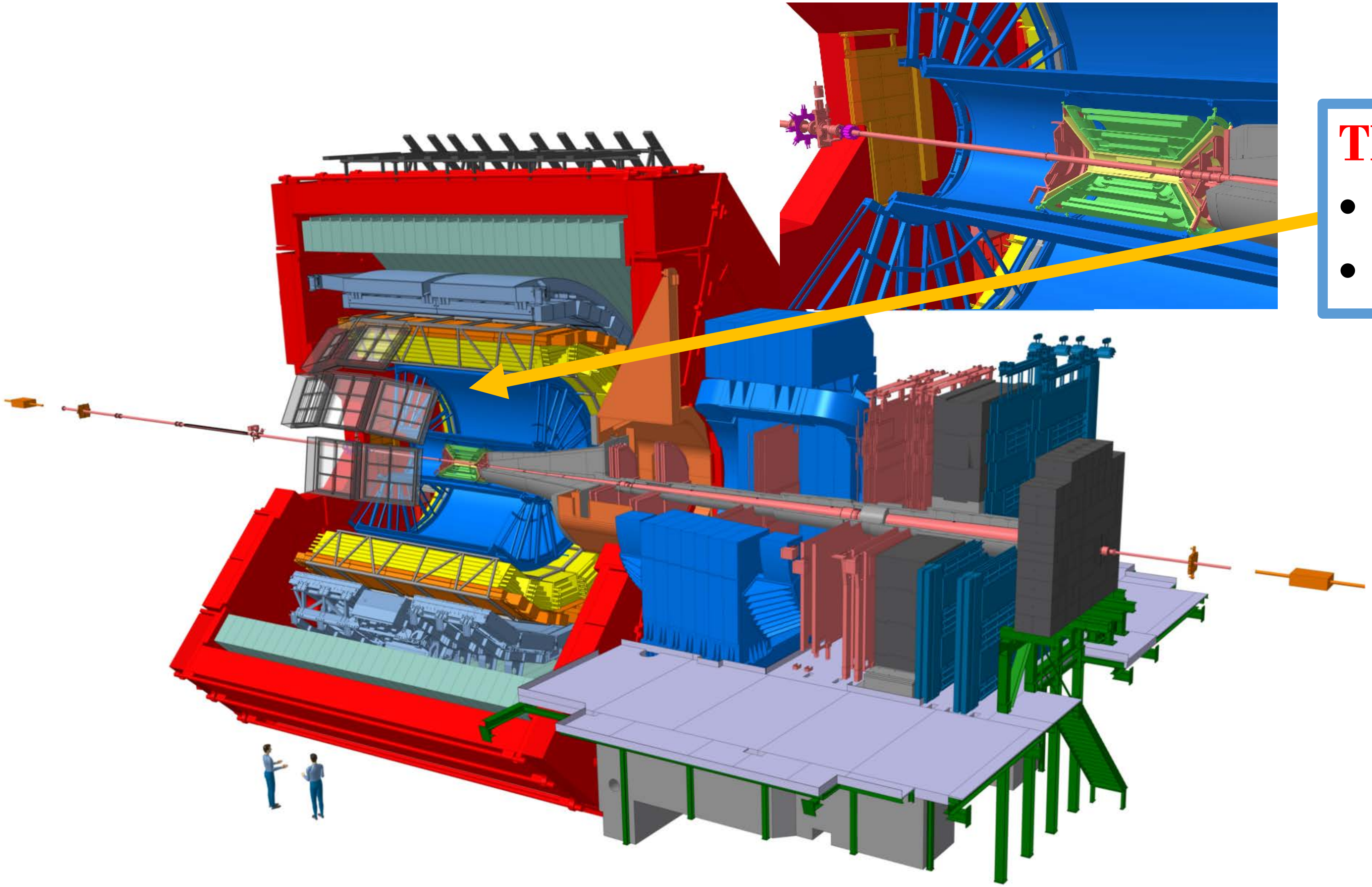


ITS (Inner Tracking System)

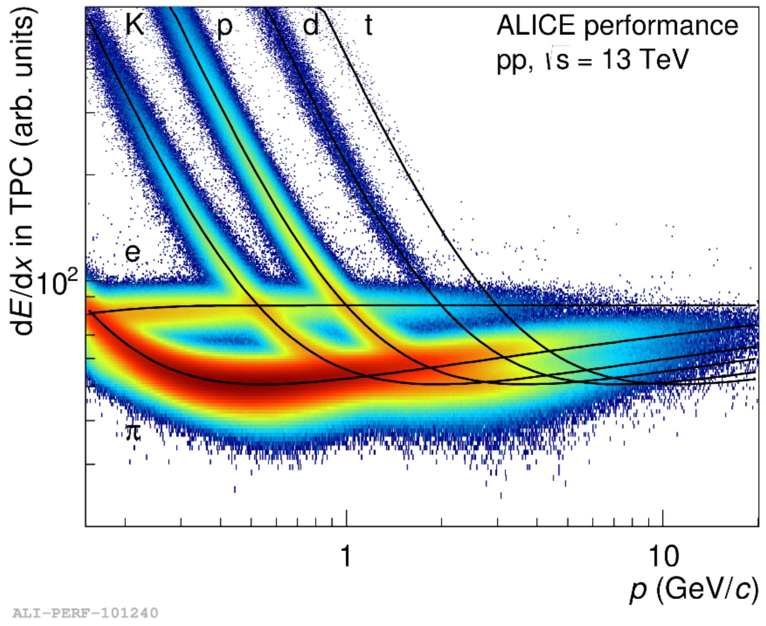
- 6 layers of silicon detectors
- Trigger, tracking, vertex, PID (dE/dx)



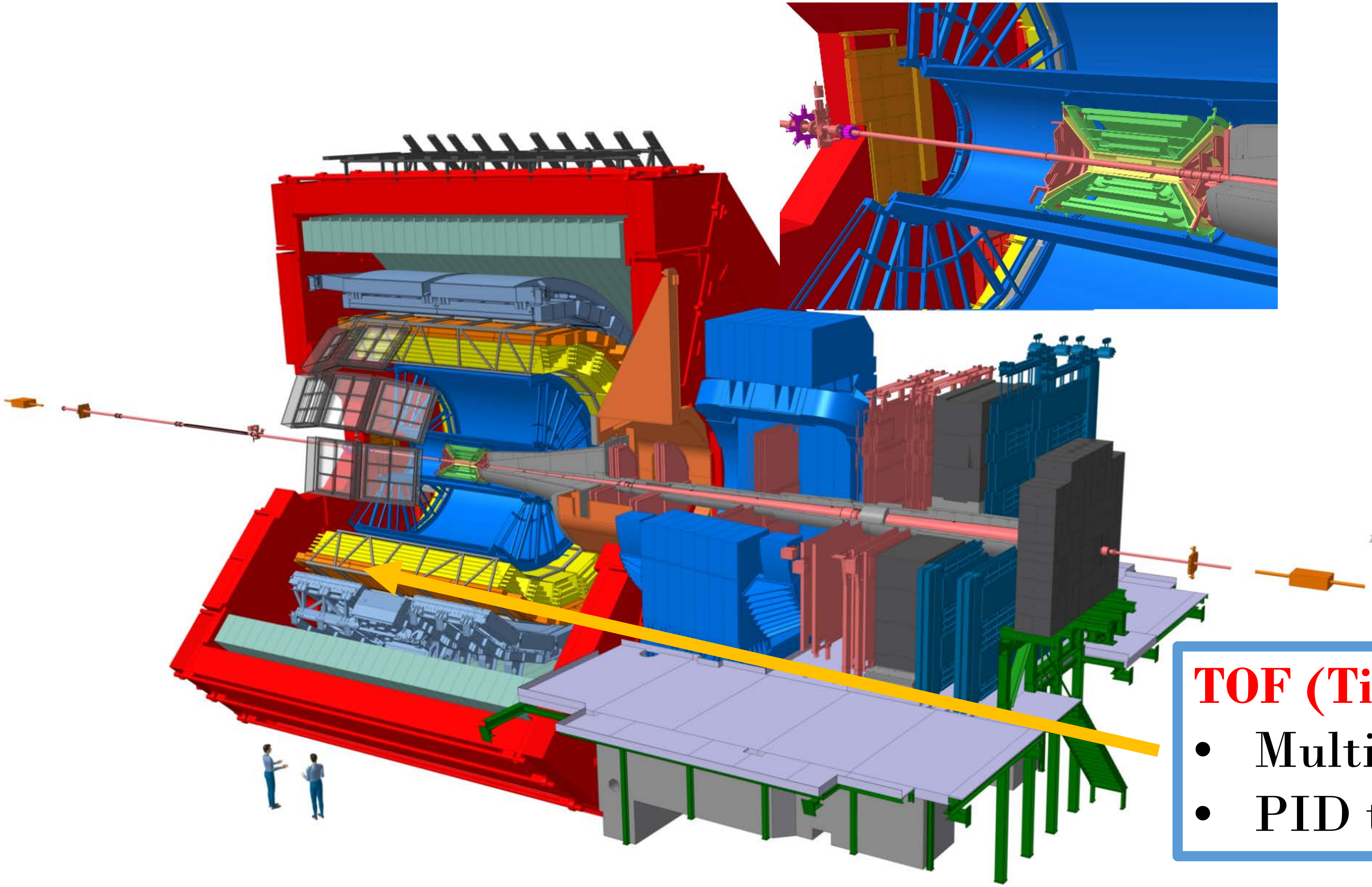
The ALICE detector

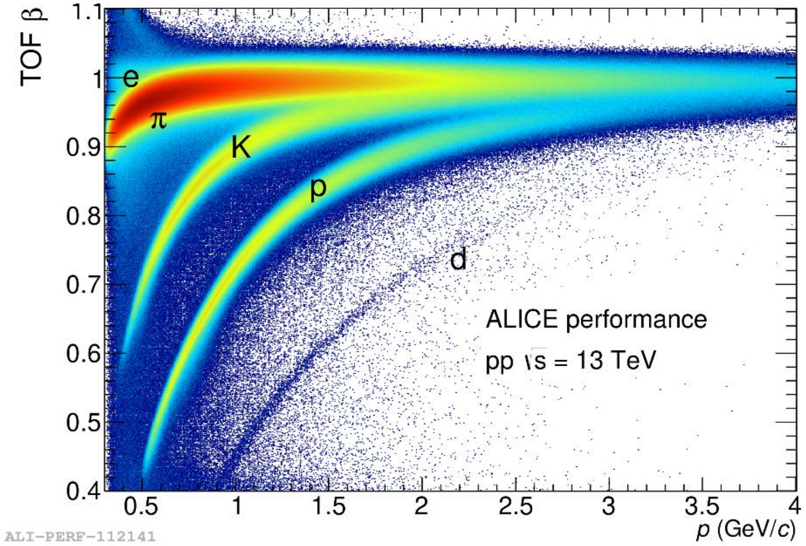


TPC (Time Projection Chamber)
- Gas-filled ionization detector
- Tracking and PID (dE/dx)



The ALICE detector

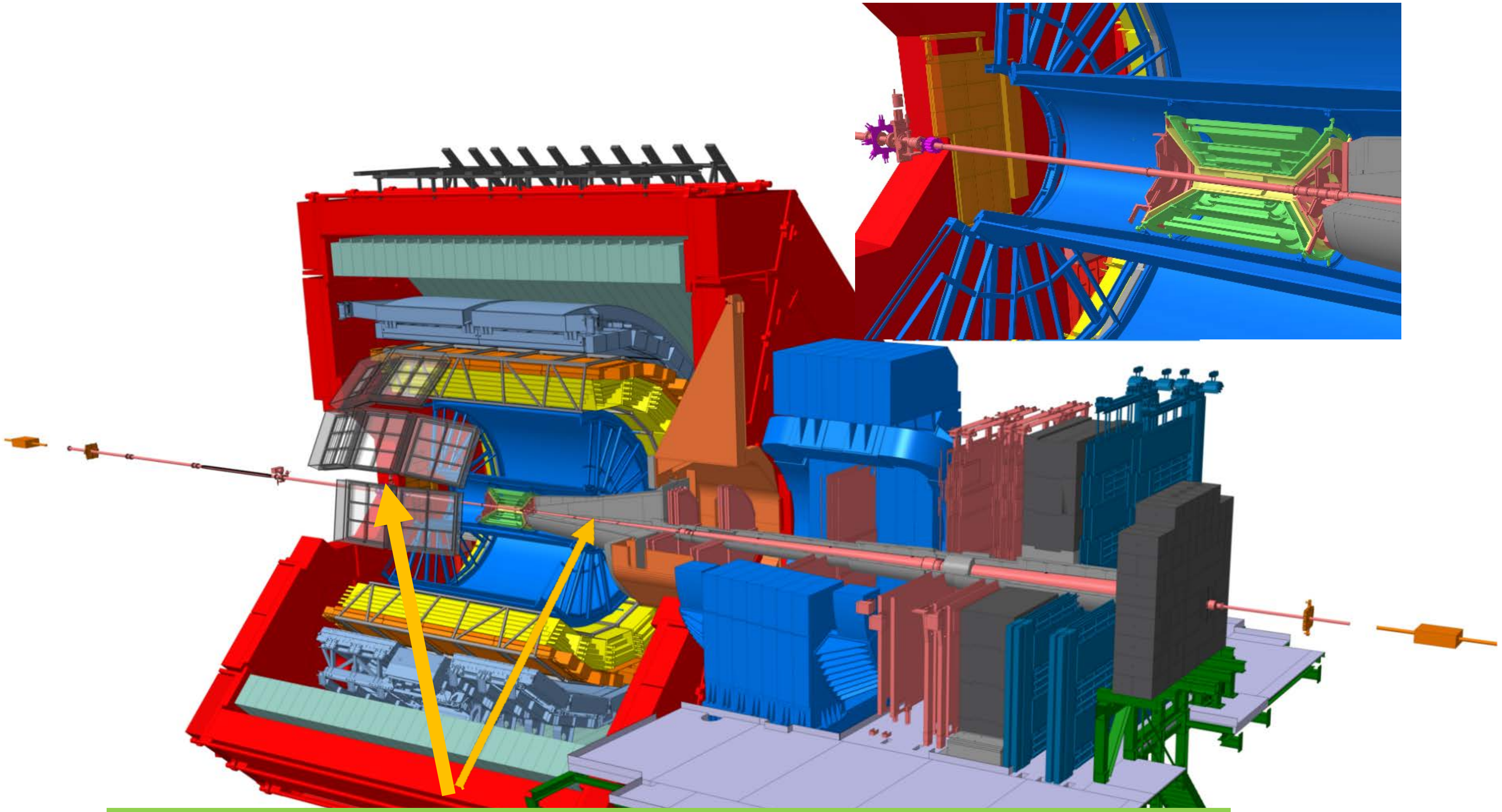


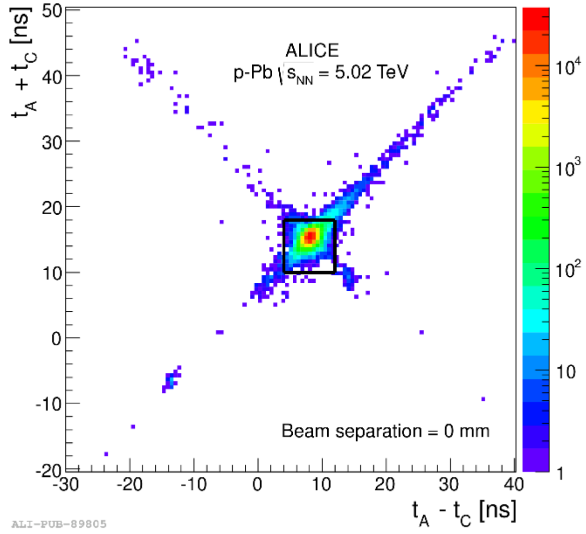


TOF (Time Of Flight)

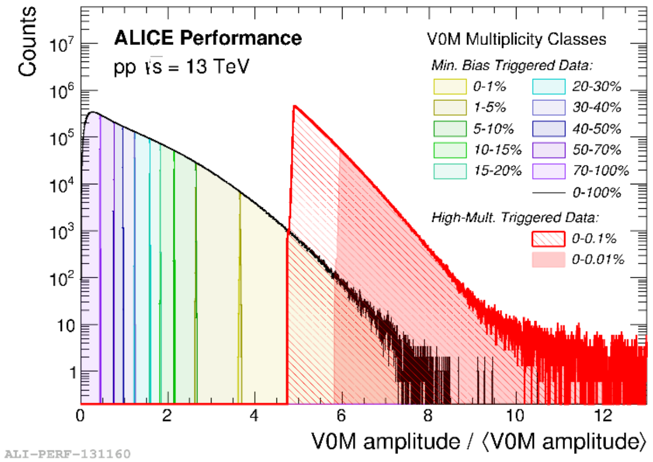
- Multi-gap Resistive Plate Chamber
- PID through particle time-of-flight

The ALICE detector





ALICE Coll. JINST 9 (2014) 1100



V0A and V0C

- 2 arrays of plastic scintillator hodoscopes
- Trigger, Centrality/Multiplicity estimator

Resonance reconstruction

Resonance are reconstructed via their **invariant mass**

$$M_{inv} = \sqrt{(E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2}$$

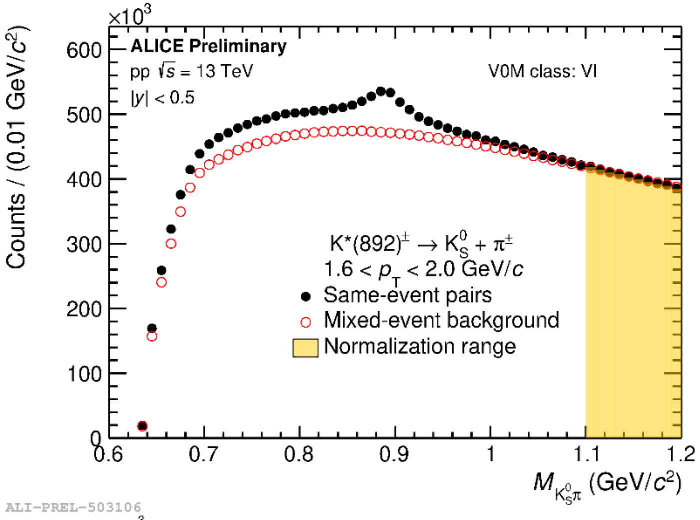
Uncorrelated background is estimated via **event -mixing** or **like-sign** techniques

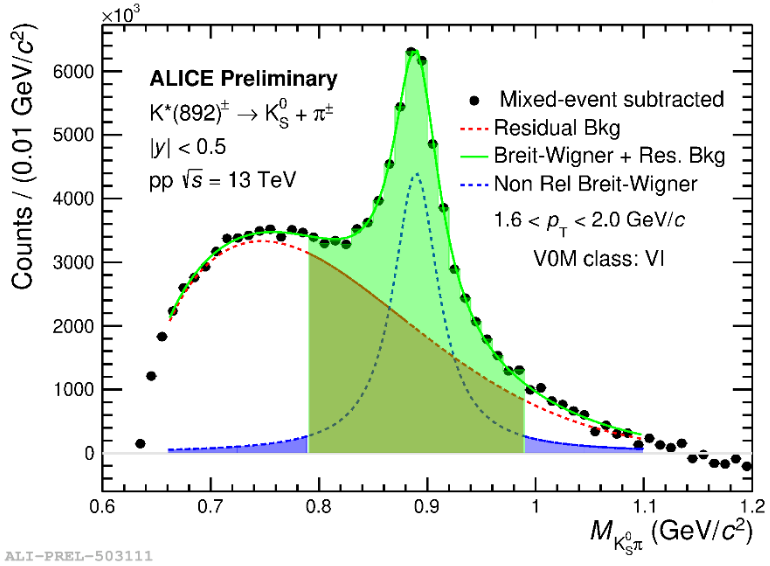
PID from TPC, TOF for the **daughter tracks. V0 or Cascade topology** for K^0_s, Λ, Ξ

Residual background Correlated pairs or misidentified decay products, usually modelled by a polynomial function

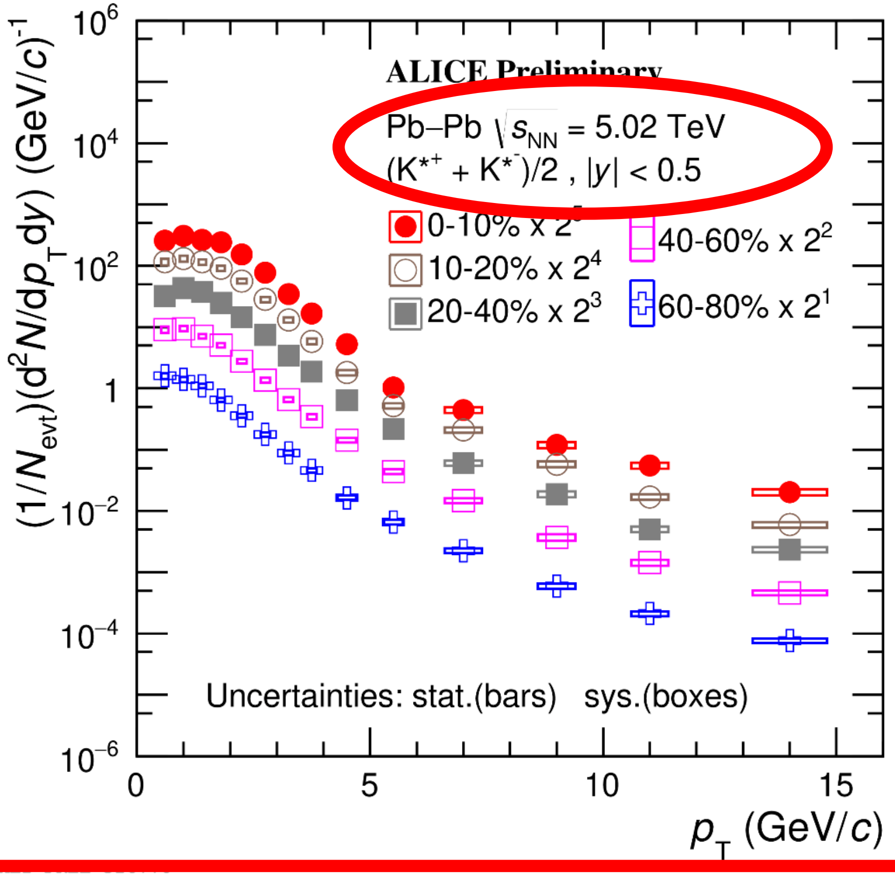
Signal: Fit the event-mixing (or like-sign) subtracted distribution with a Breit-Wigner or Voigtian function (signal function) and the residual background

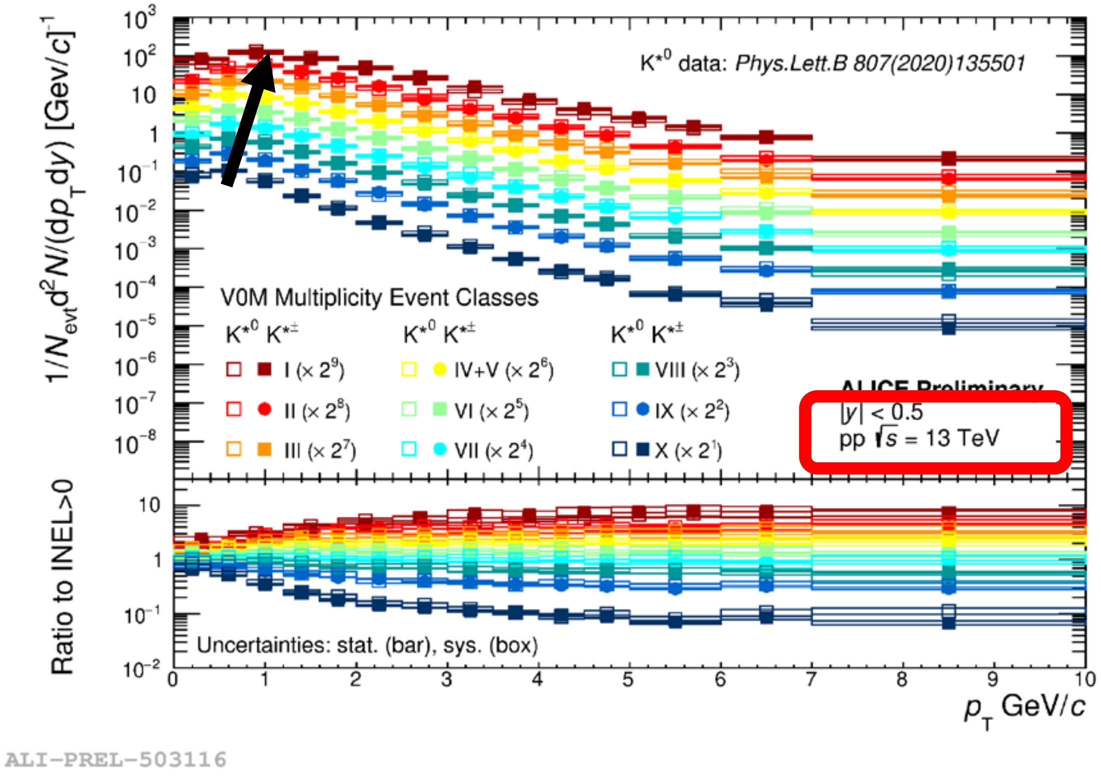
Yields are calculated integrating the signal function





K*± p_T spectra

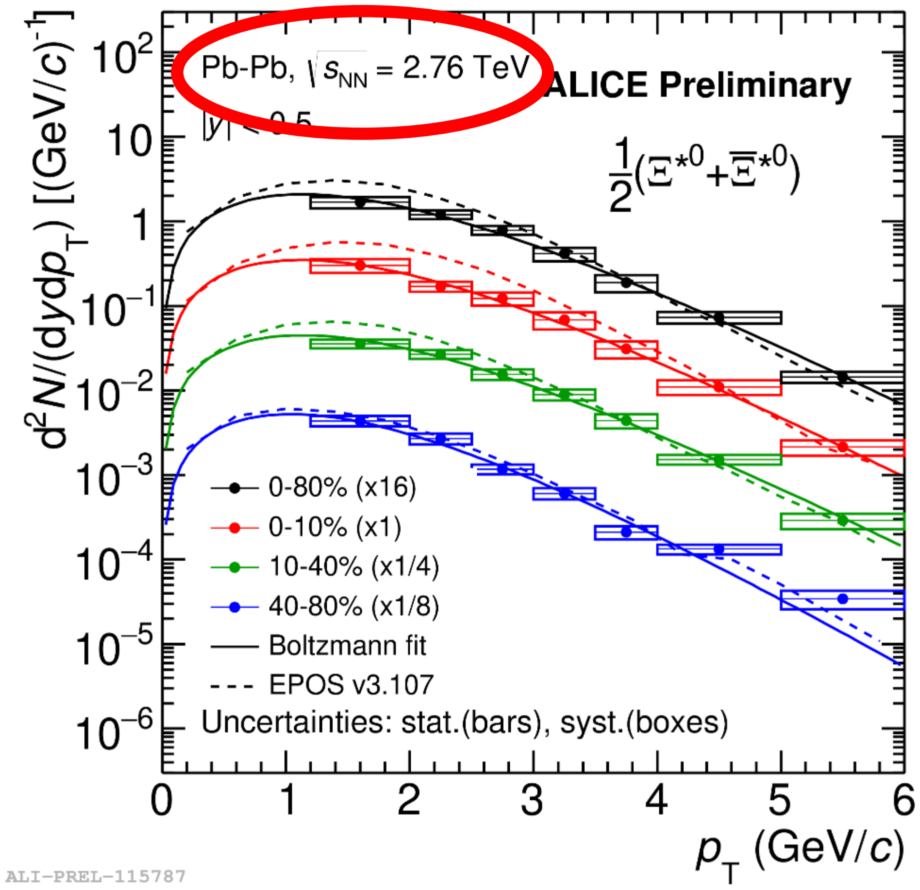


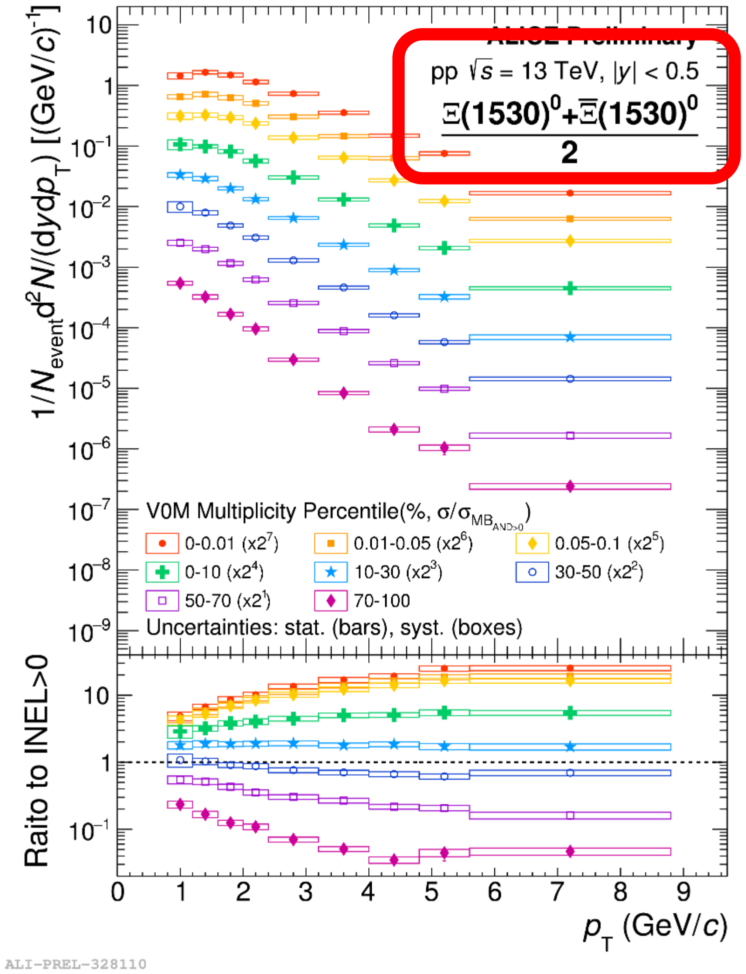


Hardening of spectra with increasing centrality of the collision → caused by radial flow. Observed for all produced hadrons.

Hardening of p_T spectra and maximum shifts with increasing multiplicity → flow-like effects in small collision systems

Ξ (1530)^0 p_T spectra

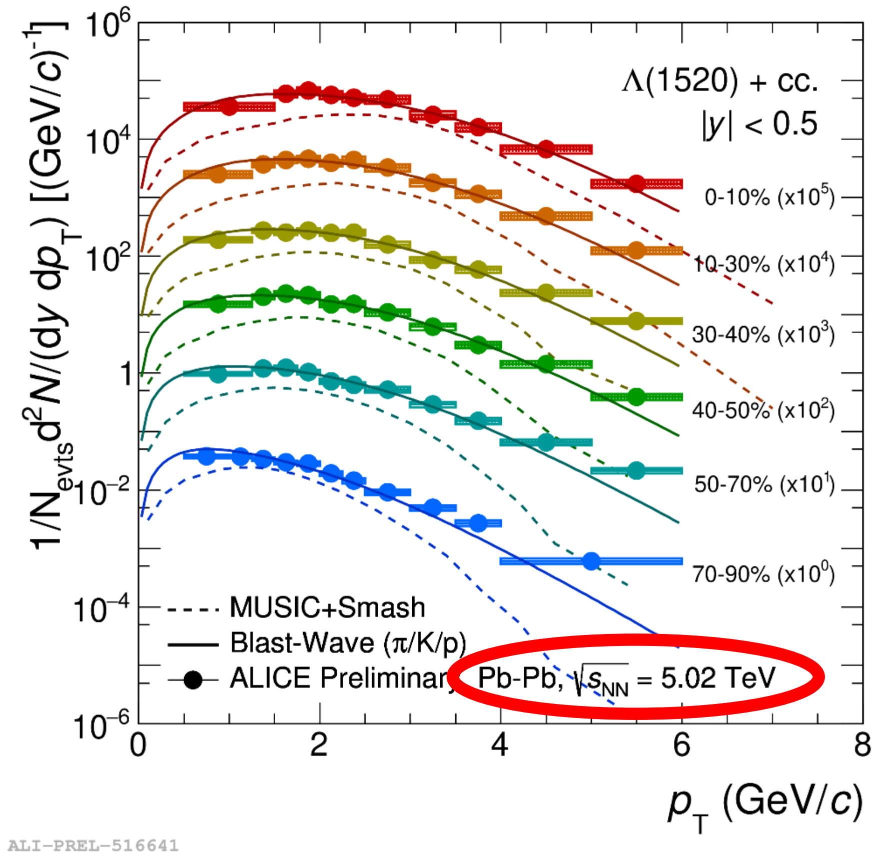




The process causing spectra variation is dominant at low p_T

Similar behavior as K*

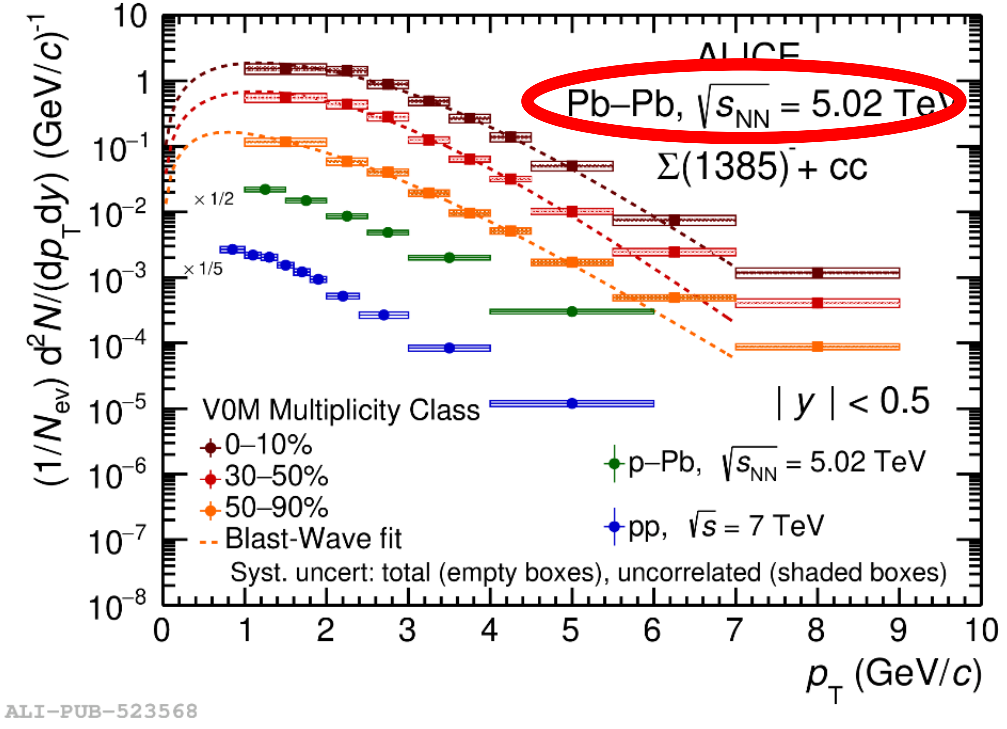
Λ(1520) p_T spectra

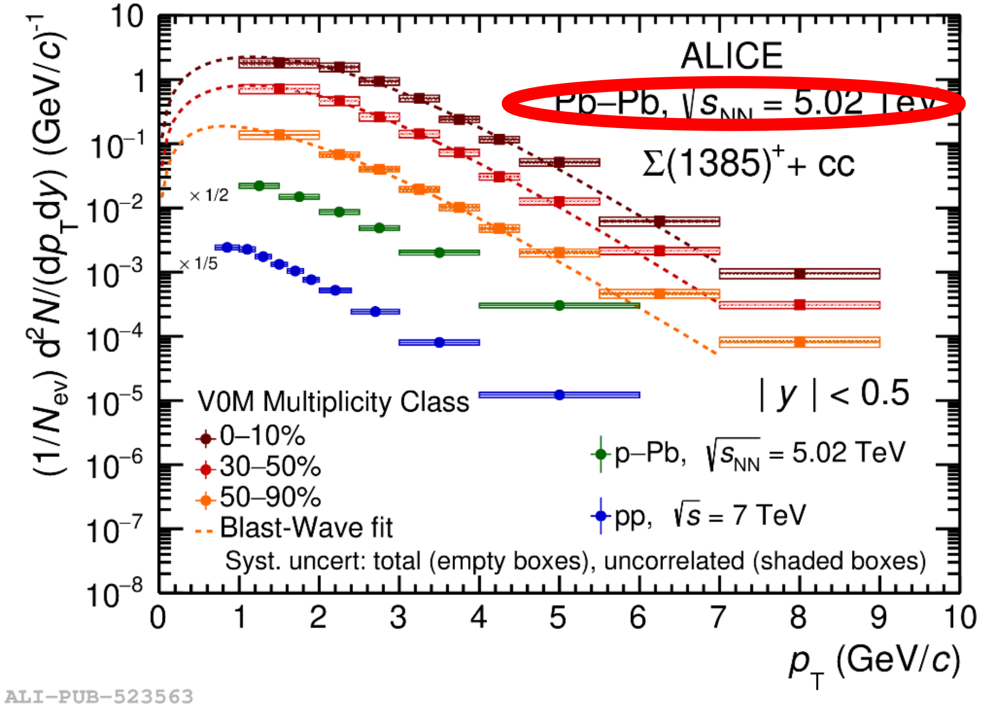


Comparison with hydrodynamic models:

- Spectral shapes are in agreement with Blast-Wave model (from π, K, p)
- MUSIC +SMASH afterburner predictions underestimate the measurements

$\Sigma(1385)^{\pm}$ p_T spectra in Pb–Pb collisions

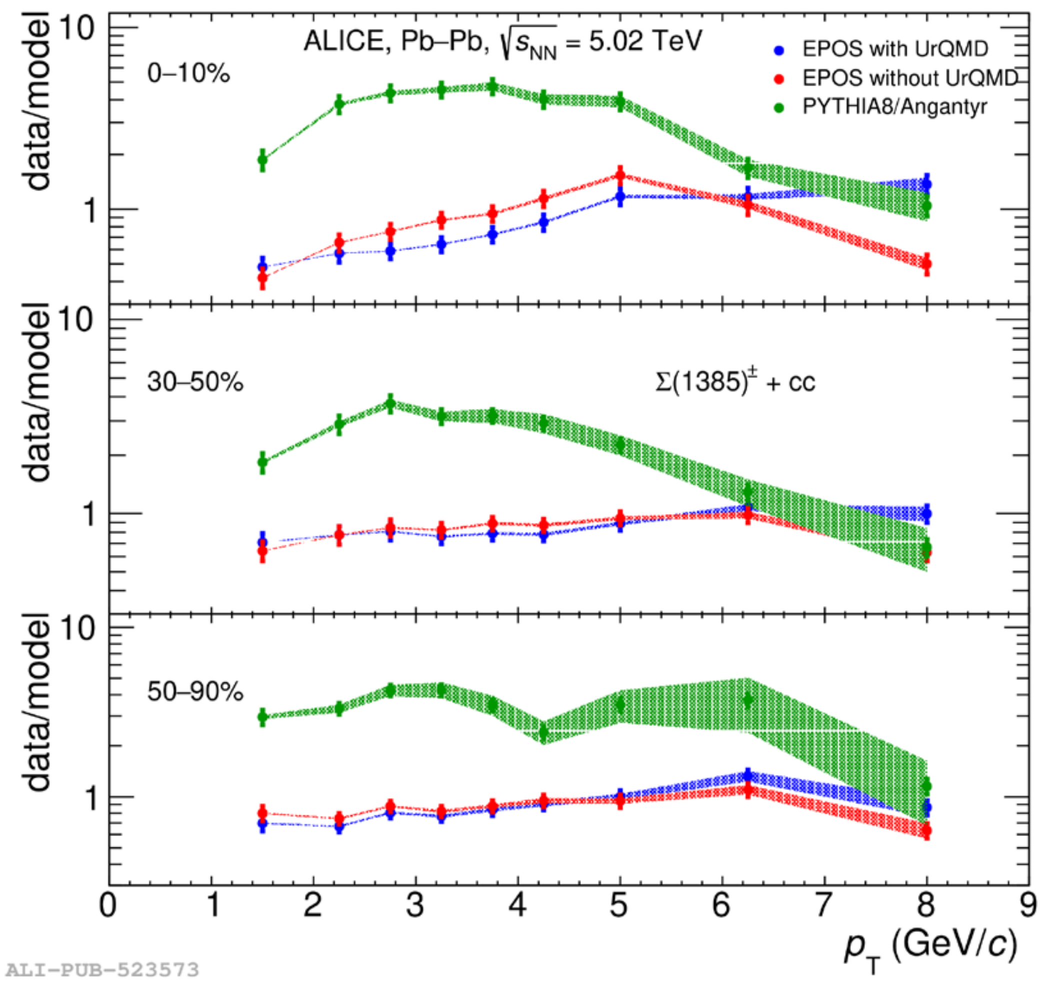




arXiv:2205.13998

$\Sigma(1385)^{\pm}$ p_T spectra in Pb–Pb collisions

ALICE Coll. arXiv:2205.13998



EPOS3 [1] :

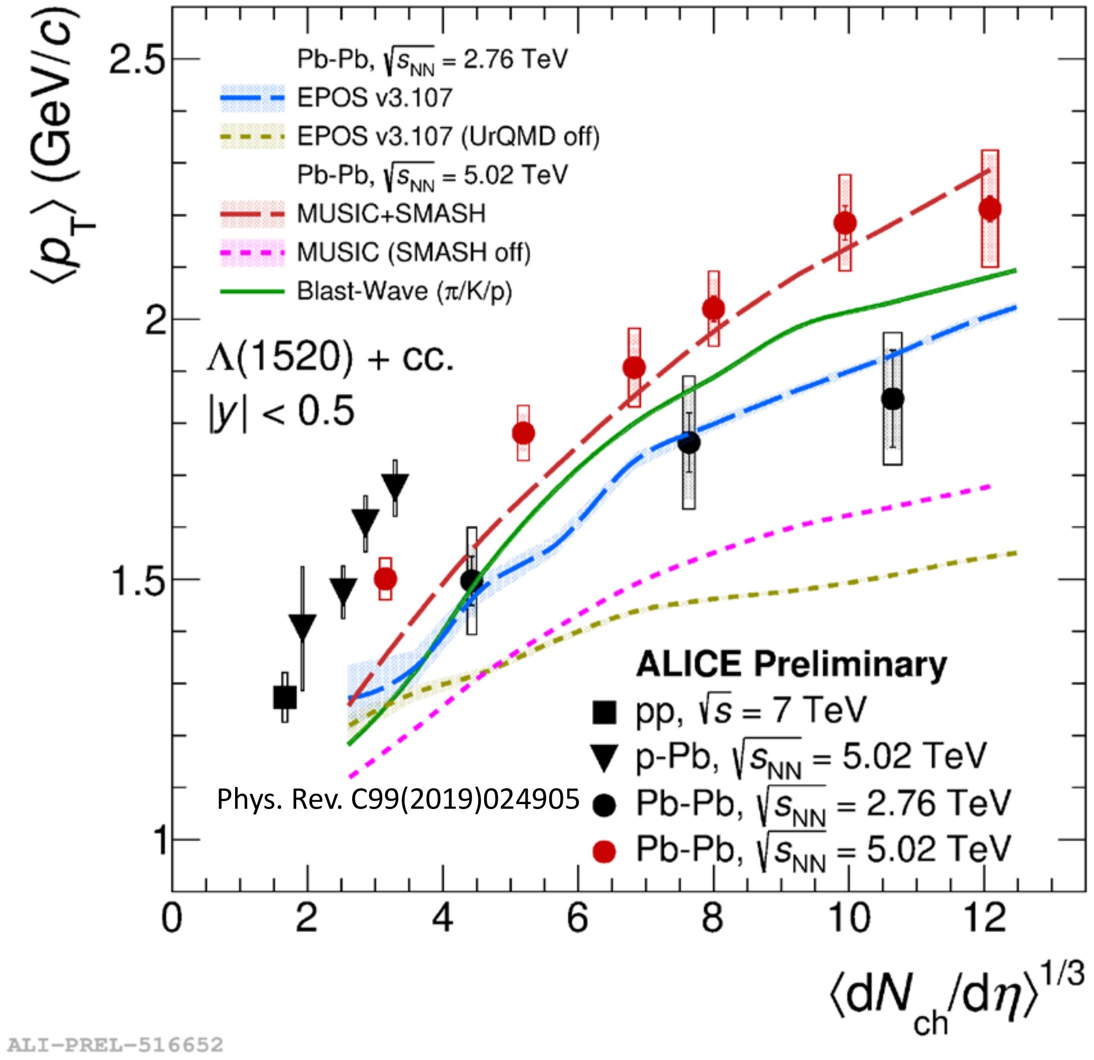
Semicentral and peripheral collisions:
No significant difference is observed between the calculation with the UrQMD afterburner and without it. Data are described within 20-30%

The $\Sigma(1385)^{\pm}$ production is overestimated by ~60% in **most central collisions and p_T < 5 GeV/c**

PYTHIA8/Angantyr [2]:
The $\Sigma(1385)^{\pm}$ production is underestimated by a factor 3 to 4 up to p_T ~ 6-7 GeV/c

[1] K. Werner et al., Phys. Rev. C89 (2014) 064903
[2] T. Sjöstrand et al., Compt. Phys. Comm. 191 (2015) 159

Mean transverse momentum



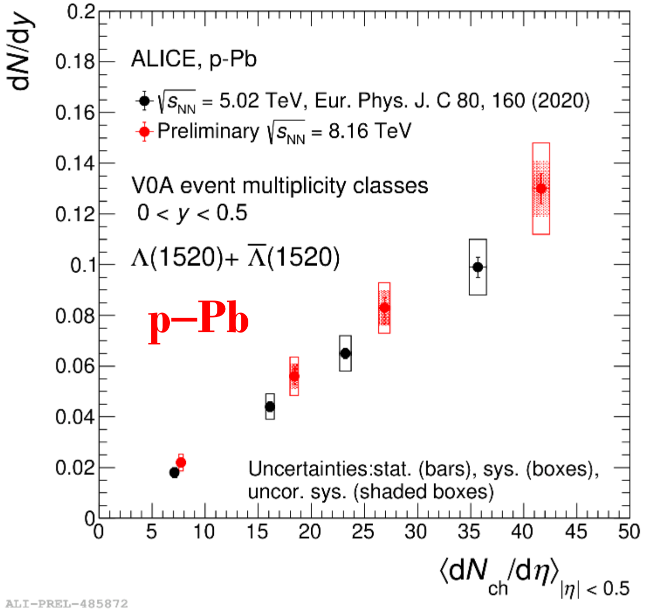
Mean transverse momentum provides first-order characterization of the spectral shapes

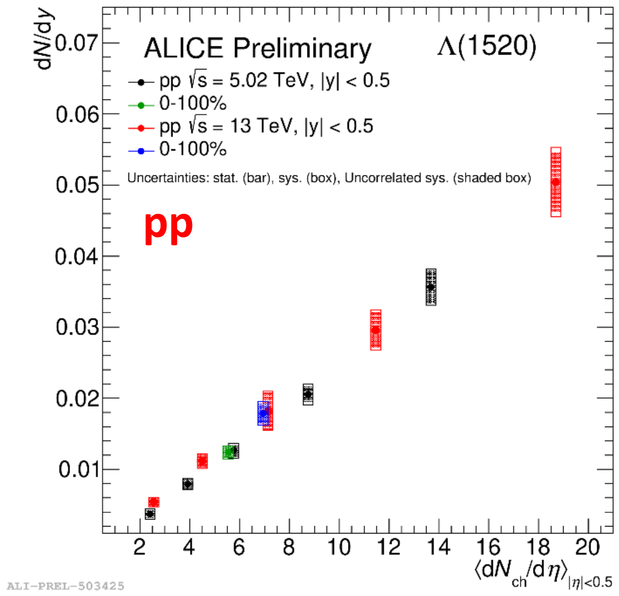
$<p_T>$ values increase with increasing multiplicity and are higher for the higher centre-of-mass energy

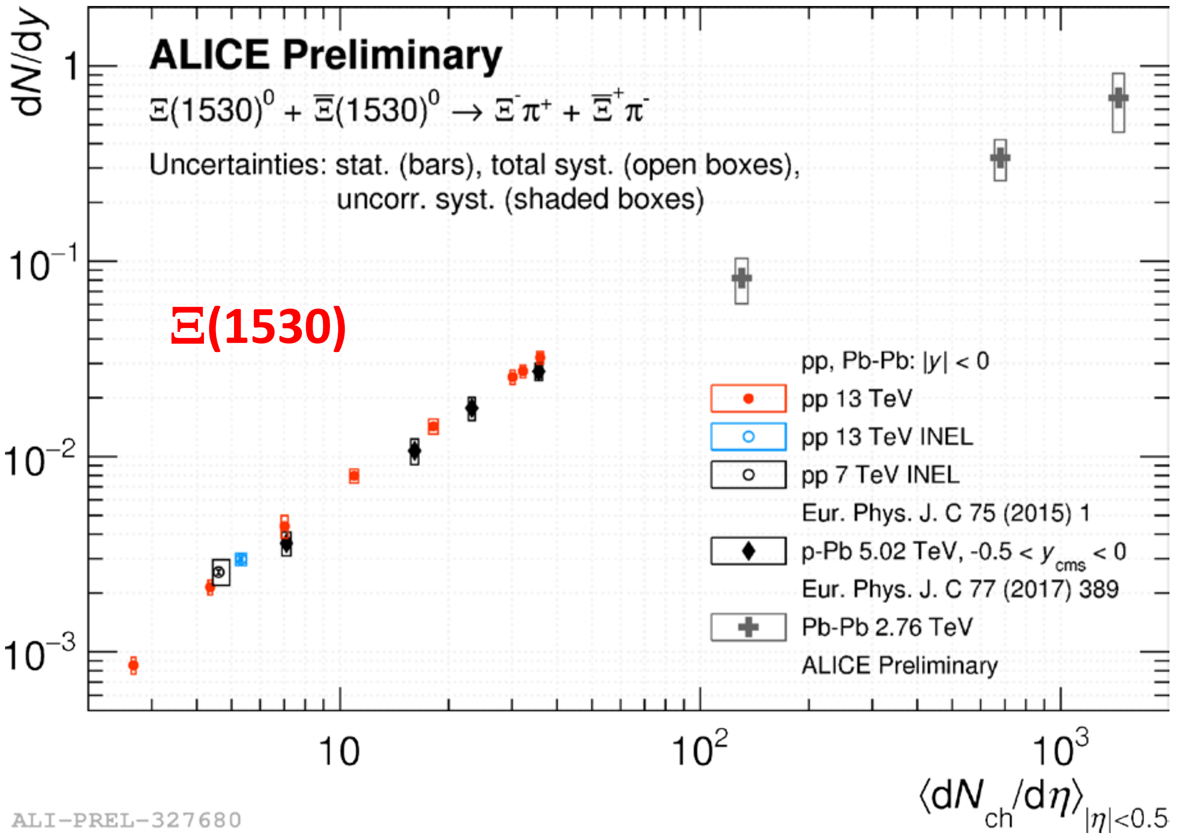
Models that do not include a hadronic afterburner do not reproduce the data

Integrated yields

Λ(1520)



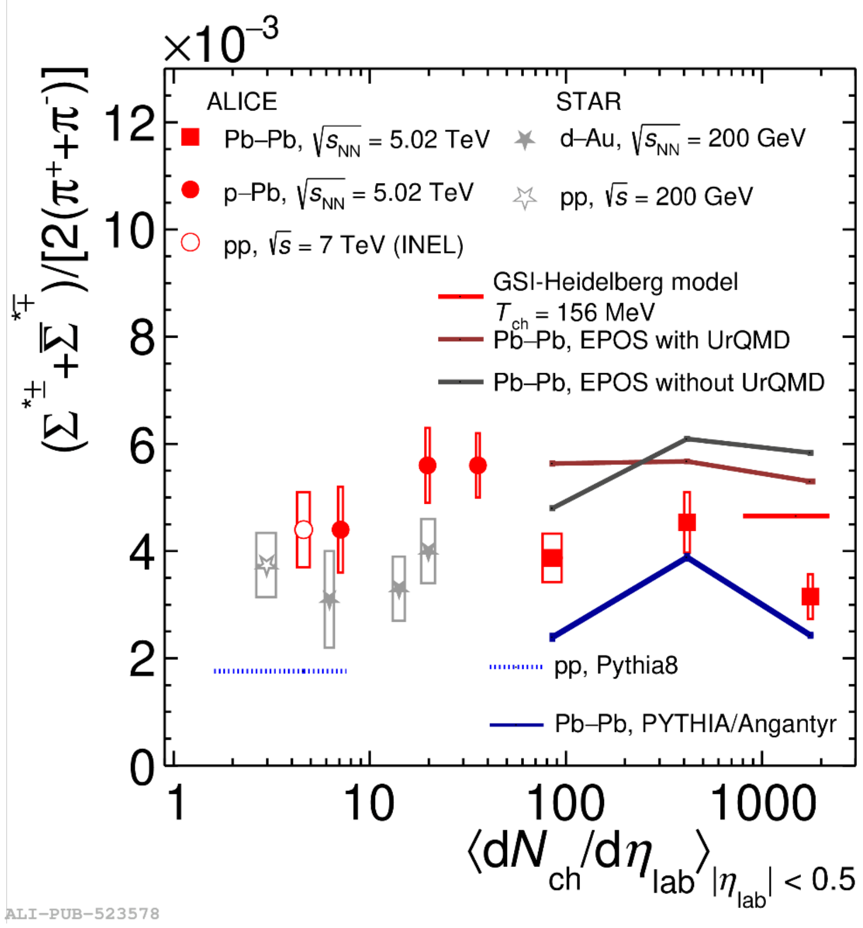




Resonance production is driven by the multiplicity. It doesn't depend on the system size or the centre of mass energy

Ratio Σ*/π

τ(Σ*) = 5 fm/*c*



arXiv:2205.13998

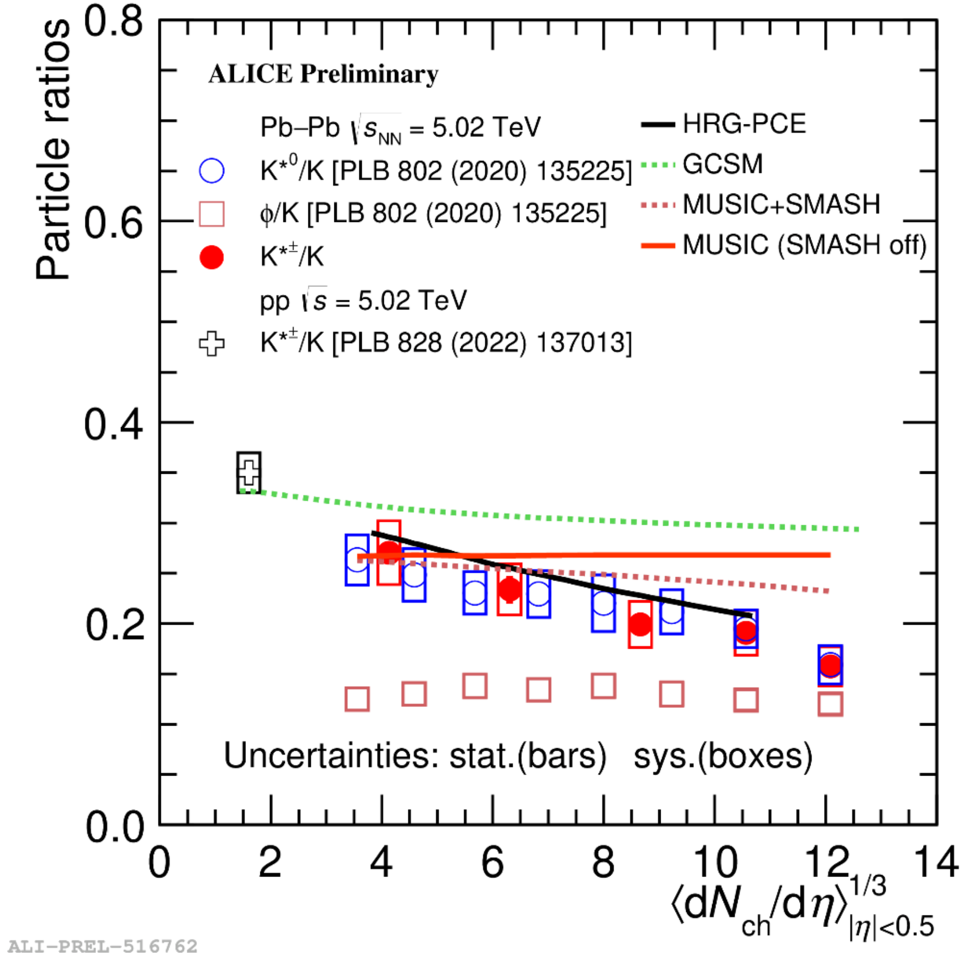
Suppression of $\Sigma^{*\pm}/\pi^{\pm}$ yield ratio in central Pb–Pb collisions wrt pp and p–Pb

Thermal model and EPOS + UrQMD overestimate the measurement

Suppression at al level of 3.6σ in 0–10% central Pb–Pb collisions with respect to statistical thermal model

Ratio K*/K

τ(K*⁰) = 4.2 fm/*c*



$K^{*\pm}$ shows a ~55% suppression going from peripheral Pb–Pb collisions to most central Pb–Pb → consistent with the re-scattering of the daughters as the dominant effect

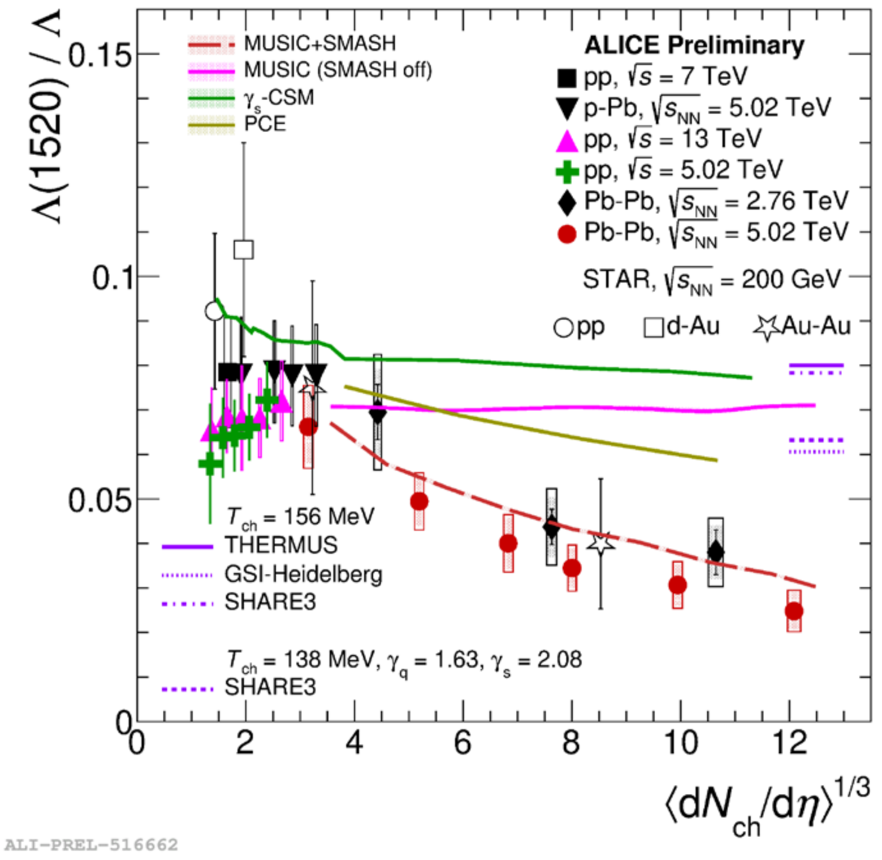
Models with re-scattering effects qualitatively describe the data

$K^{*\pm}$ measurement is consistent with previous results for K^{*0}

MUSIC: D. Olinychenko, arXiv: 2105.07539
PCE: A. Motornenko, Phys. Rev. C102 (2020) 024909
GCSM: V. Vovchenko, Phys. Rev. C 100 (2019) 054906

Ratio Λ*/Λ

τ(Λ*) = 12.6 fm/*c*



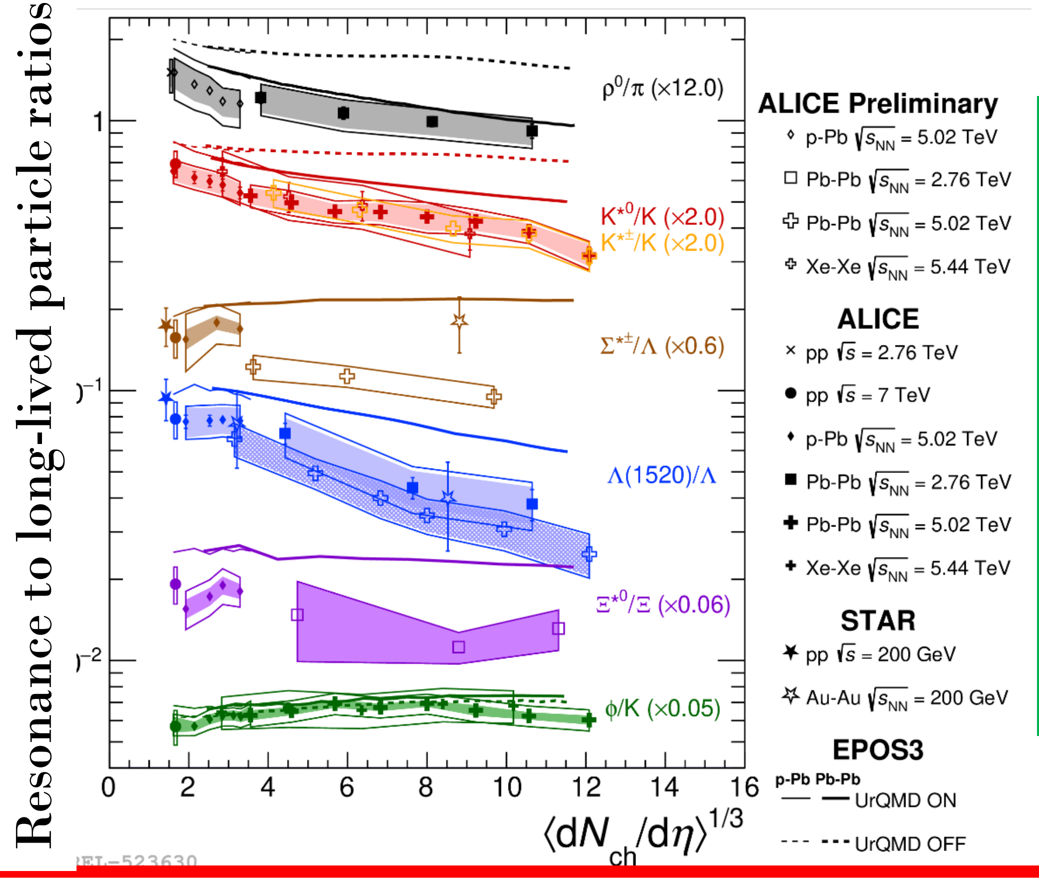
- Λ*/Λ shows a ~ 70% suppression going from peripheral to central Pb–Pb collisions → Consistent with the rescattering of the daughters as the dominant effect
- Λ* suppression larger than $K^{*\pm}$ (~ 55%) although τ(Λ*) ~3τ(K*) → Regeneration may play a more important role in K* than in Λ*
- MUSIC + SMASH reproduces the multiplicity suppression trend
- Thermal models overestimate the ratio in central Pb–Pb collisions

MUSIC: D. Olinychenko, arXiv: 2105.07539
PCE: A. Motornenko, Phys. Rev. C102 (2020) 024909
GCSM: V. Vovchenko, Phys. Rev. C 100 (2019) 054906

Probing the late hadronic phase

Lifetime(fm/c): ρ(1.3) < K*⁰(4.2) < Σ*(5.5) < Λ*(12.6) < Ξ*(21.7) < ϕ(46.2)

Lifetime



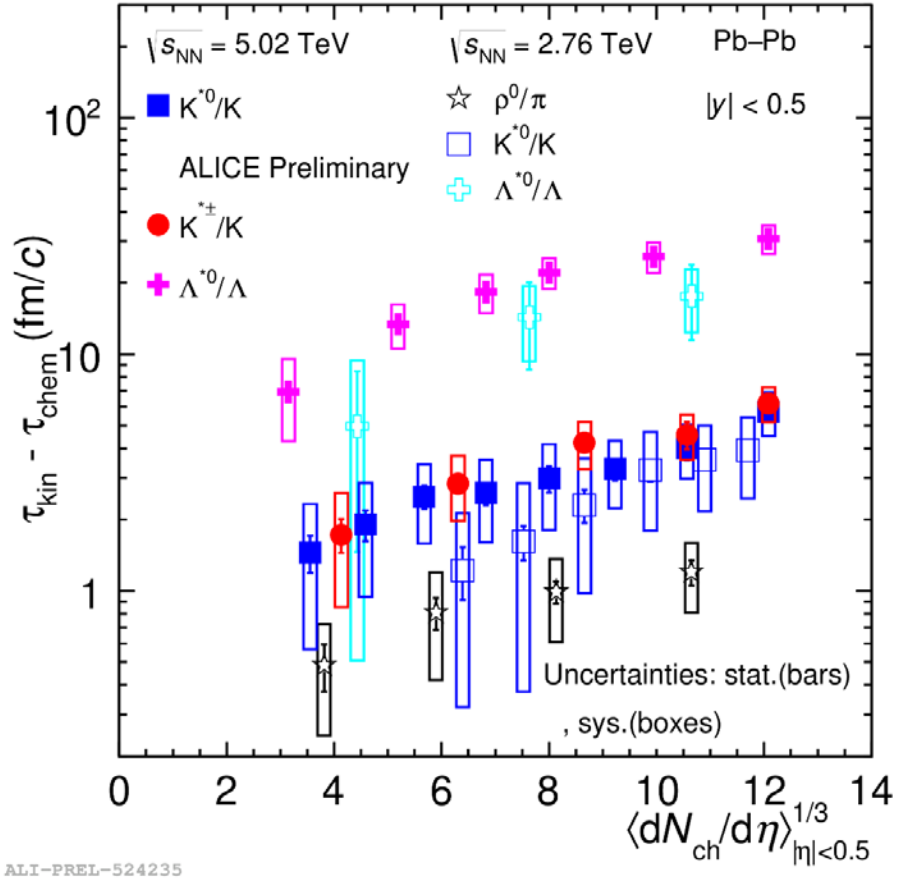
Ξ*/Ξ and **ϕ/K** (longer lifetime) no significant centrality dependence across the different collision systems.

ρ⁰/π, K*⁰/K, Σ*/Λ, Λ*/Λ in Pb–Pb: suppression in central Pb–Pb collisions -> dominance of re-scattering over regeneration.

In most cases EPOS3 with UrQMD as afterburner describes the trend qualitatively

A.G. Knospe et al., Phys. Rev. C 93 (2016) 014911

Measuring the lifetime of the hadronic phase



Lifetime of hadronic phase smoothly increases with multiplicity

Estimation of the lower limit of the timespan between chemical and kinetic freeze-out by exponential law:

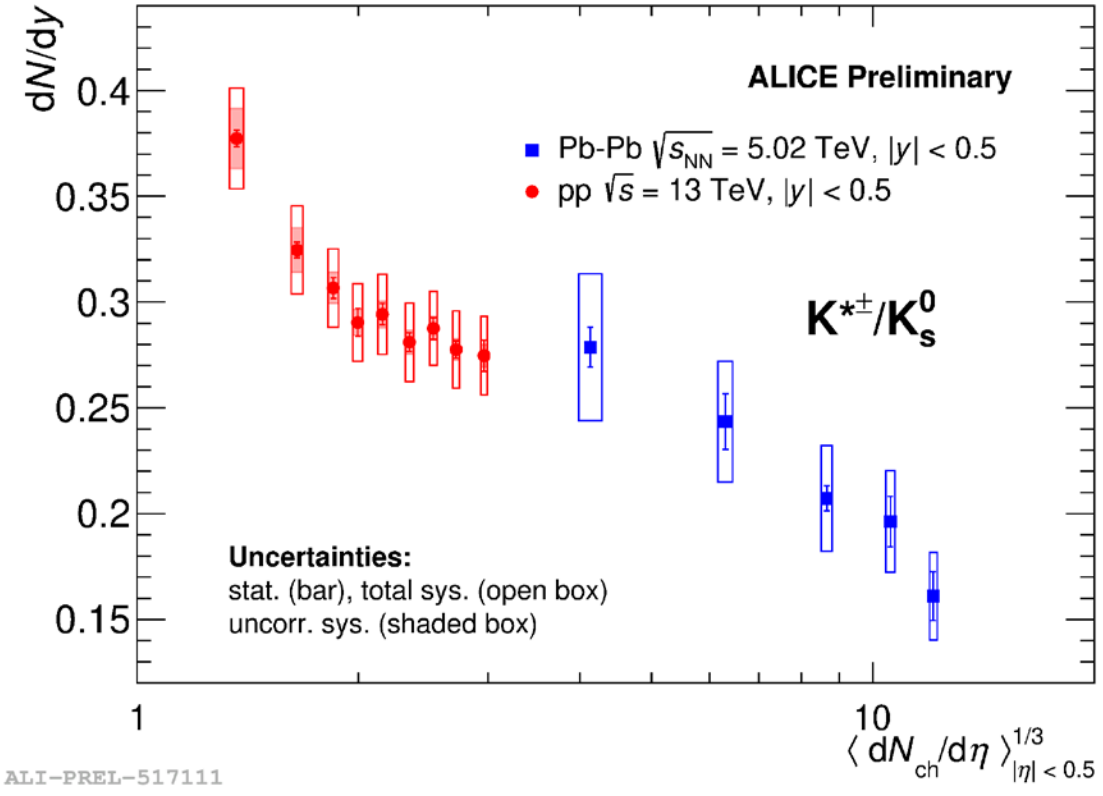
$$r_{kin} = r_{chem} \times \exp(-(\tau_{kin} - \tau_{chem})/\tau_{res}$$

- r_{kin} = measured yield ratios in Pb–Pb collisions
- r_{chem} = measured yield ratios in pp collisions
- τ_{res} = lifetime of resonance

Assumptions:

- Simultaneous freeze-out for all particles
- Negligible regeneration

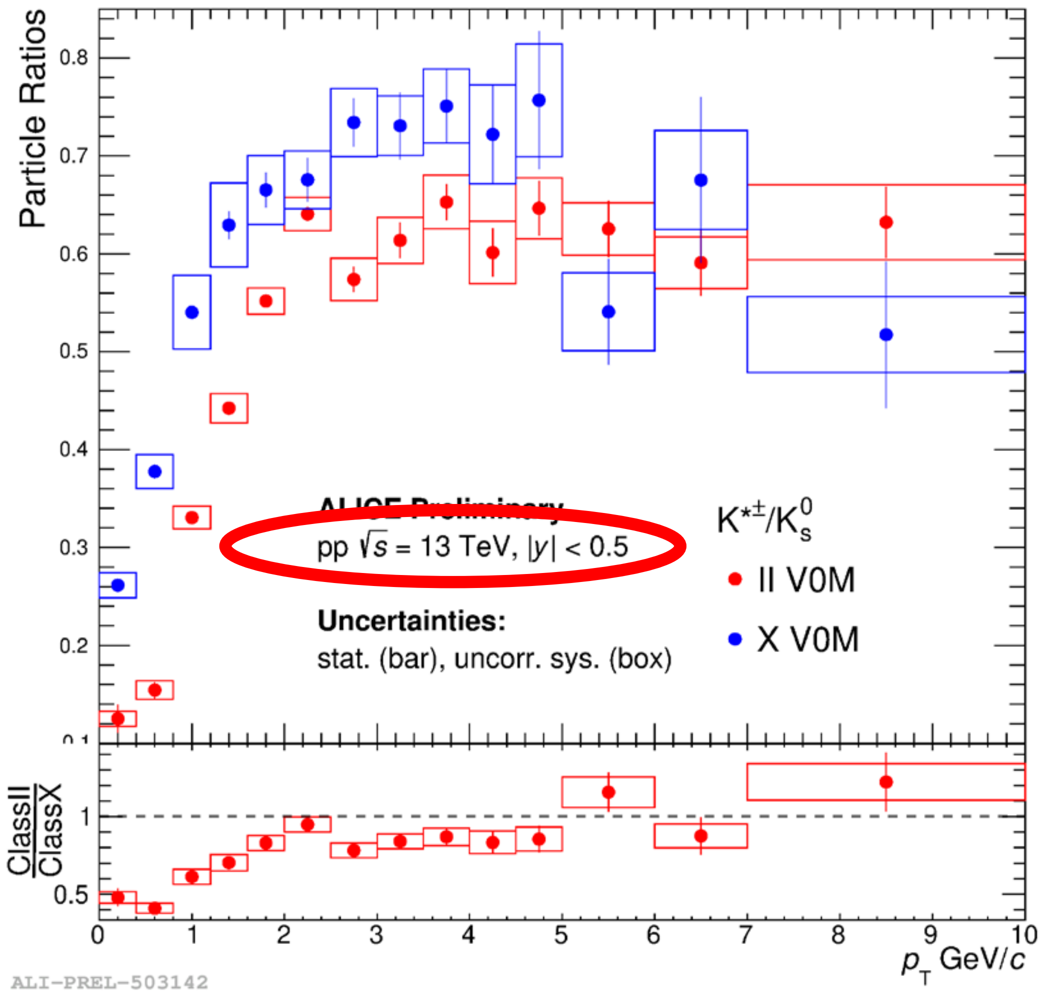
$K^*(892)^{\pm}/K^0_s$ ratio versus event multiplicity



Suppression of $\mathbf{K^{*\pm}/K^0_s}$ with increasing multiplicity **in pp** and **Pb–Pb** collisions

$K^{*\pm}$ analysis in pp@13 TeV confirms, with lower systematic uncertainties, suppression observed for K^{*0} (Phys. Lett. B807 (2020) 135501)

$K^{*\pm}/K^0_S$ for low and high multiplicity classes



Results consistent with those obtained for K^{*0}

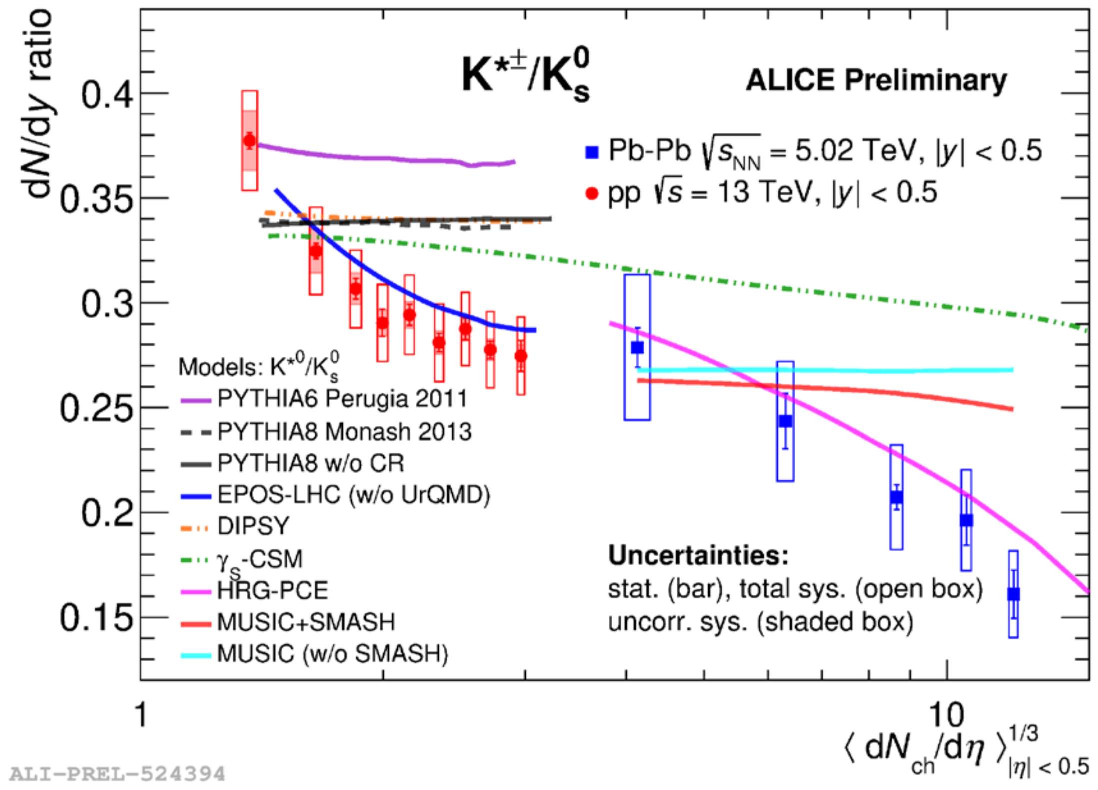
Phys. Lett. B807 (2020) 135501

Important $K^{*\pm}/K^0_s$ suppression for $p_T < 2.5$ GeV/c

In AA collisions stronger suppression at low p_T is a signature for rescattering effects

Hint of a hadronic phase in pp collisions?

Model comparison for $K^*(892)^{\pm}/K^0_s$ ratio versus event multiplicity



Model prediction estimated for K^{*0}

Best description: EPOS-LHC for pp and HRG in Partial Chemical Equilibrium[1] for Pb–Pb collisions

EPOS-LHC: same treatment for pp, pA and AA systems → two regions: core (high density) and corona (low density)

Core can form in pp collisions: critical density reached due to parton multiple scattering

HRG-PCE: A. Motornenko et al., Phys. Rev. C102 (2020) 024909
EPOS-LHC: T. Pierog et al, Phys. Rev. C92 (2015) 034906

Summary

ALICE has measured a comprehensive set of resonance particles in pp, p–Pb and Pb–Pb collisions at various energies

Resonance production is **independent** of the collision **energy** and system and it is **driven** by the event **multiplicity**

Re-scattering is the **dominant process** in the hadronic phase for short – lived resonances (τ<15 fm/c)

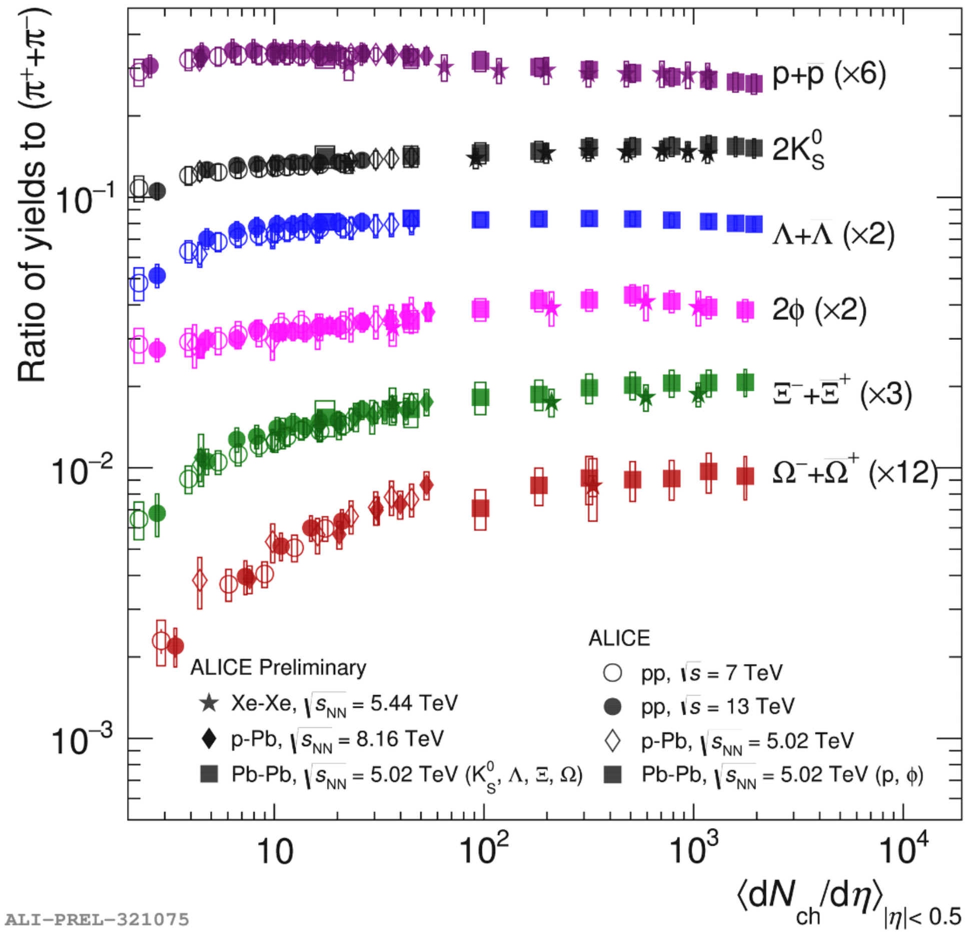
Rough estimate of **lifetime of hadronic phase** is obtained. It shows a smoothly increase with multiplicity

Hint of suppression for short-lived resonances in **high multiplicity pp and p–Pb** collisions. **Hadronic phase presence? QGP formation?**

Thank you

Backup slides

Strangeness production



Smooth evolution vs. multiplicity in pp, p–Pb, Xe–Xe and Pb–Pb collisions from different energies

Strangeness enhancement increases with strangeness content