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Recent results on hadronic resonance production with the ALICE experiment

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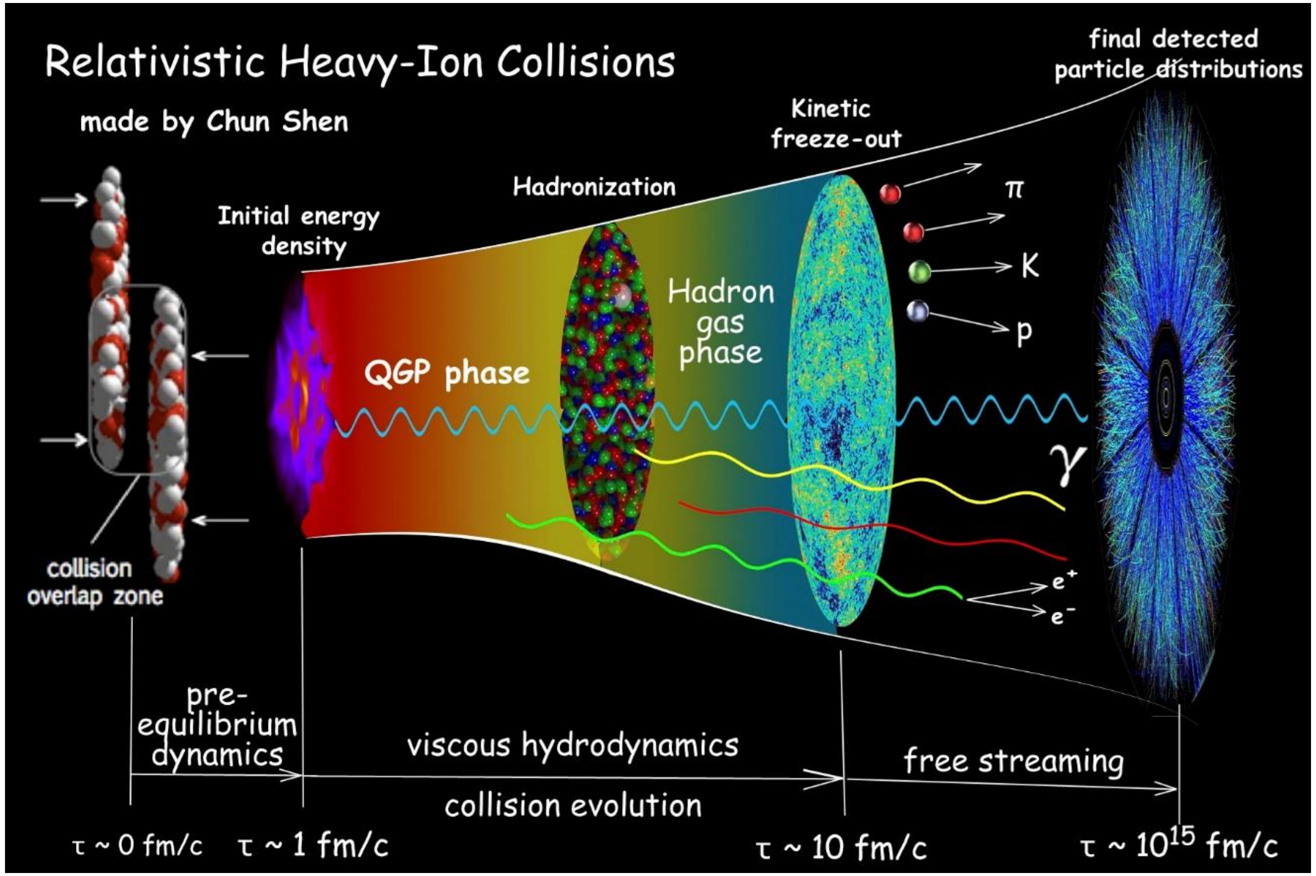
Heavy-ion collisions and Quark Gluon Plasma

Ultrarelativistic heavy-ion collisions: critical value of temperature (T_C ~170 MeV) and energy density (ε_C ~1 GeV/fm^3) → Quark Gluon Plasma (**QGP**) formation

Fireball evolution:

- **Pre-equilibrium:** Hot and dense partonic matter created in the collision region
- **QGP:** plasma of quarks and gluons. The fireball expands because of the pressure gradients
- **Hadronization:** The system cools down and the energy density decreases. Quarks and gluons become confined → Interacting Hadron gas
- **Chemical freeze-out:** the energy is too low to allow inelastic processes
- **Kinetic freeze-out:** occurs after the chemical freeze-out, when also the elastic interactions stop

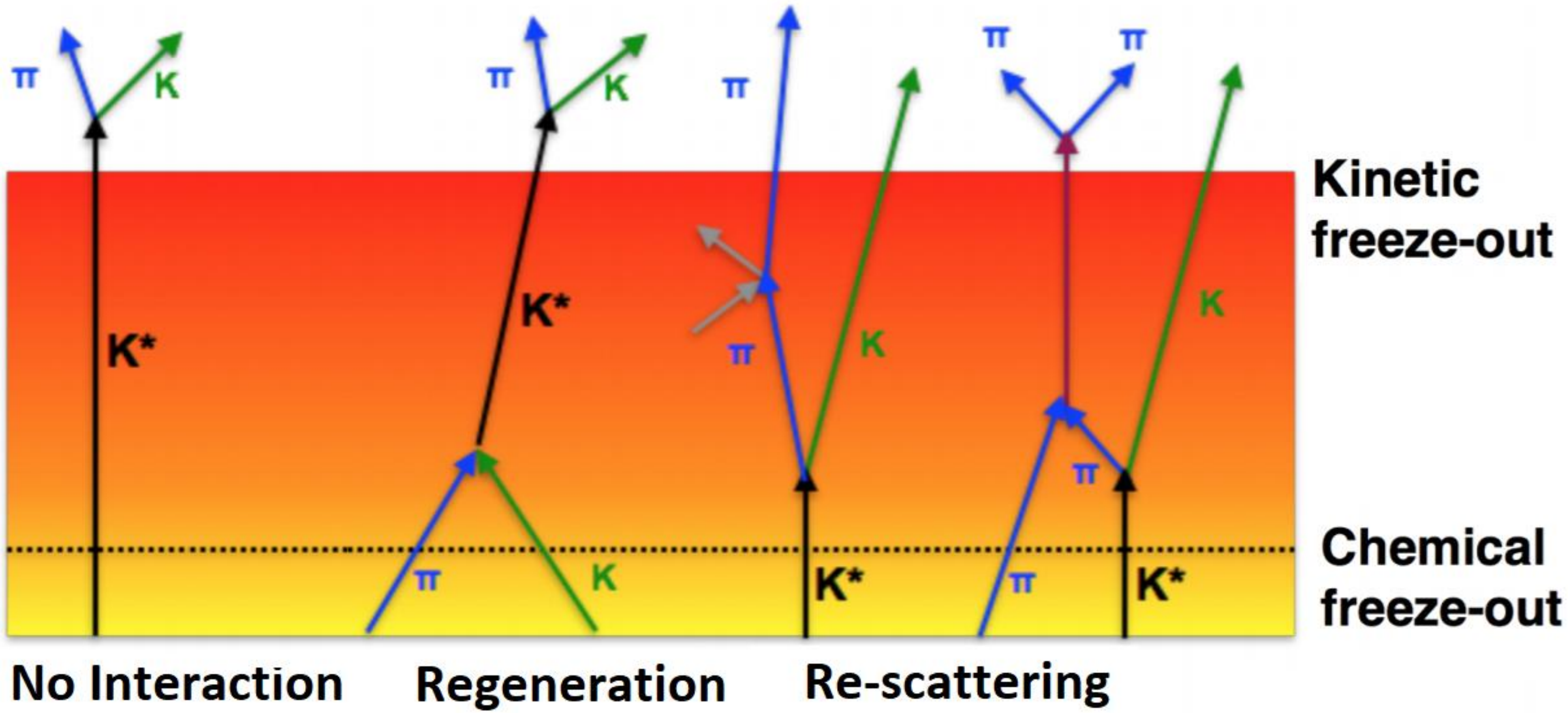


Then particles can be detected

Hadronic Phase

- The phase between chemical and kinetic freeze-out is known as hadronic phase

- During this stage, processes like **re-scattering** or **regeneration** may affect resonance measured yield



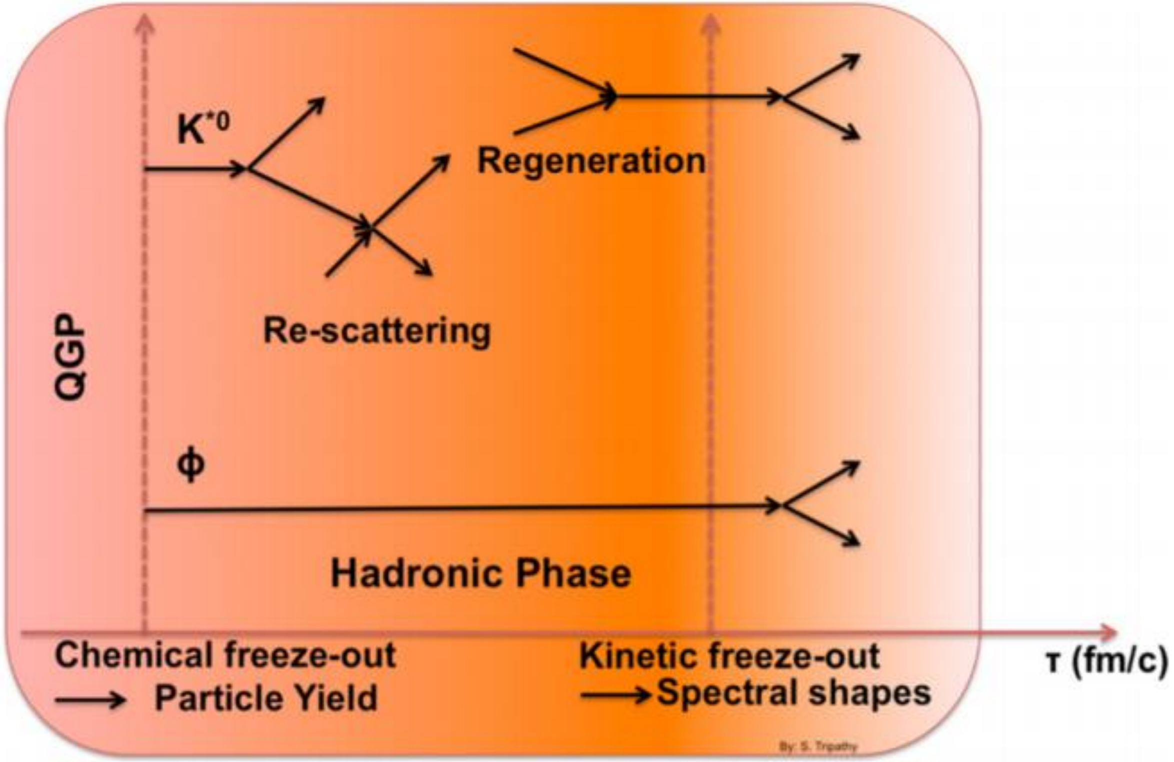
Regeneration: a given resonance can be regenerated as a consequence of pseudo-elastic collisions of the particles medium $\rightarrow$ signal gain: yield enhancement.

Re-scattering: resonance decay daughters interact with other particles in the hadronic medium $\rightarrow$ signal loss: yield suppression.

Why study hadronic resonances?

- Long-lived resonances, decaying outside the hadronic medium do not undergo any such processes
- Resonances with a lifetime comparable to the fireball ($\tau \sim 10$ fm/c) instead are sensitive to these competitive effects
- Resonances with different lifetimes can help in estimating the hadronic phase lifetime
- Measurement of production of resonances with different masses, quantum numbers and quark content are useful to explore the particle production mechanisms

Resonances are the perfect probes to characterize the late-stage evolution of the system formed in A-A collisions at ultrarelativistic energies



Main resonaces studied by ALICE

Yields at kinetic freeze-out depend on:

- Resonance and hadronic phase lifetime
- Yields at the chemical freeze-out
- Scattering cross sections of decay products

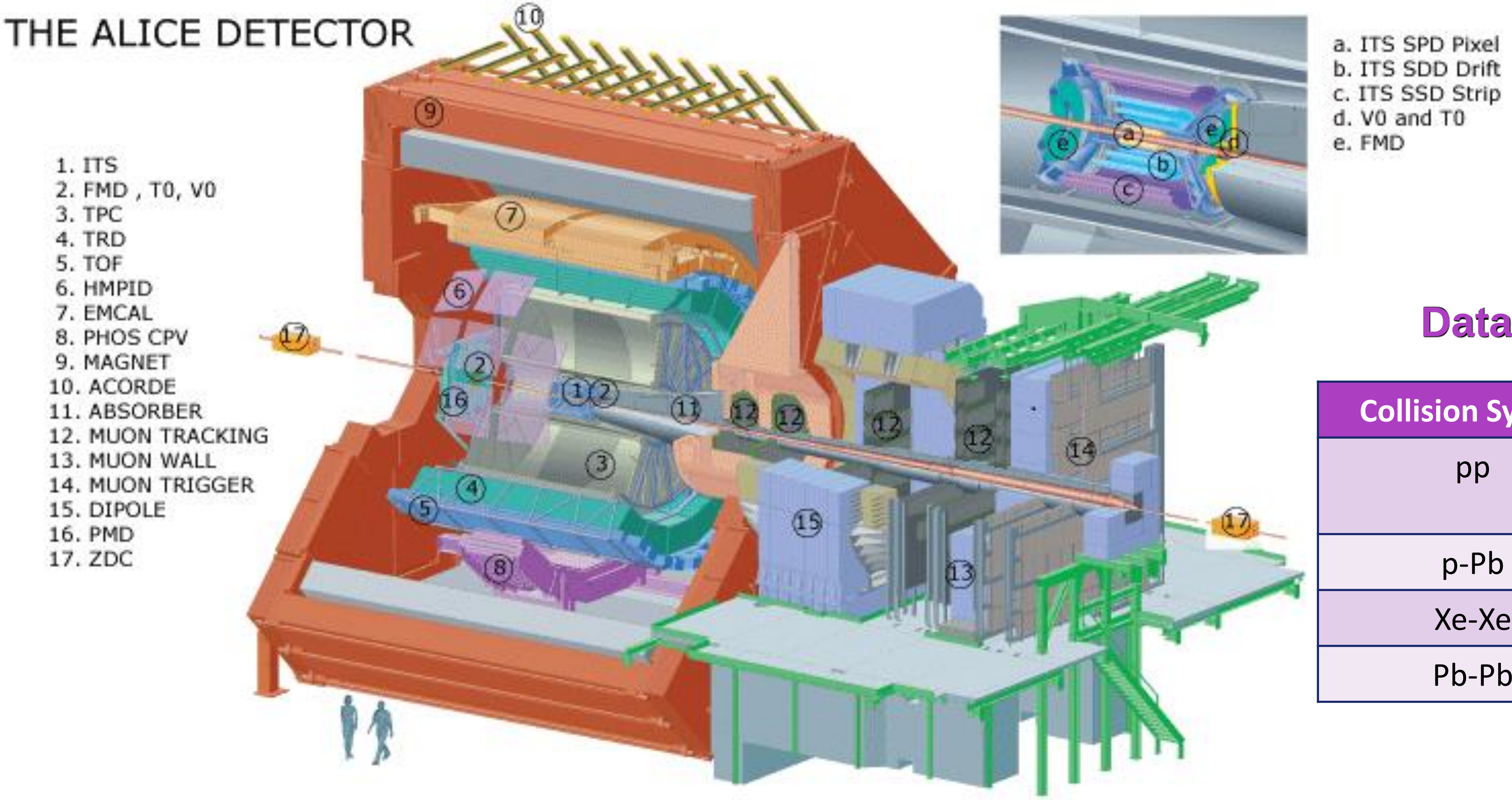
Resonance yields encode the effects of interaction during the hadronic phase!

Lifetime →

Resonance	ρ(770)⁰	K*(892)±	K*(892)⁰	f₀(990)	Σ(1385)±	Ξ(1820)±	Λ(1520)	Ξ(1530)⁰	ϕ(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	dss	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

Fireball lifetime: τ ~ 10 fm/c at LHC energies

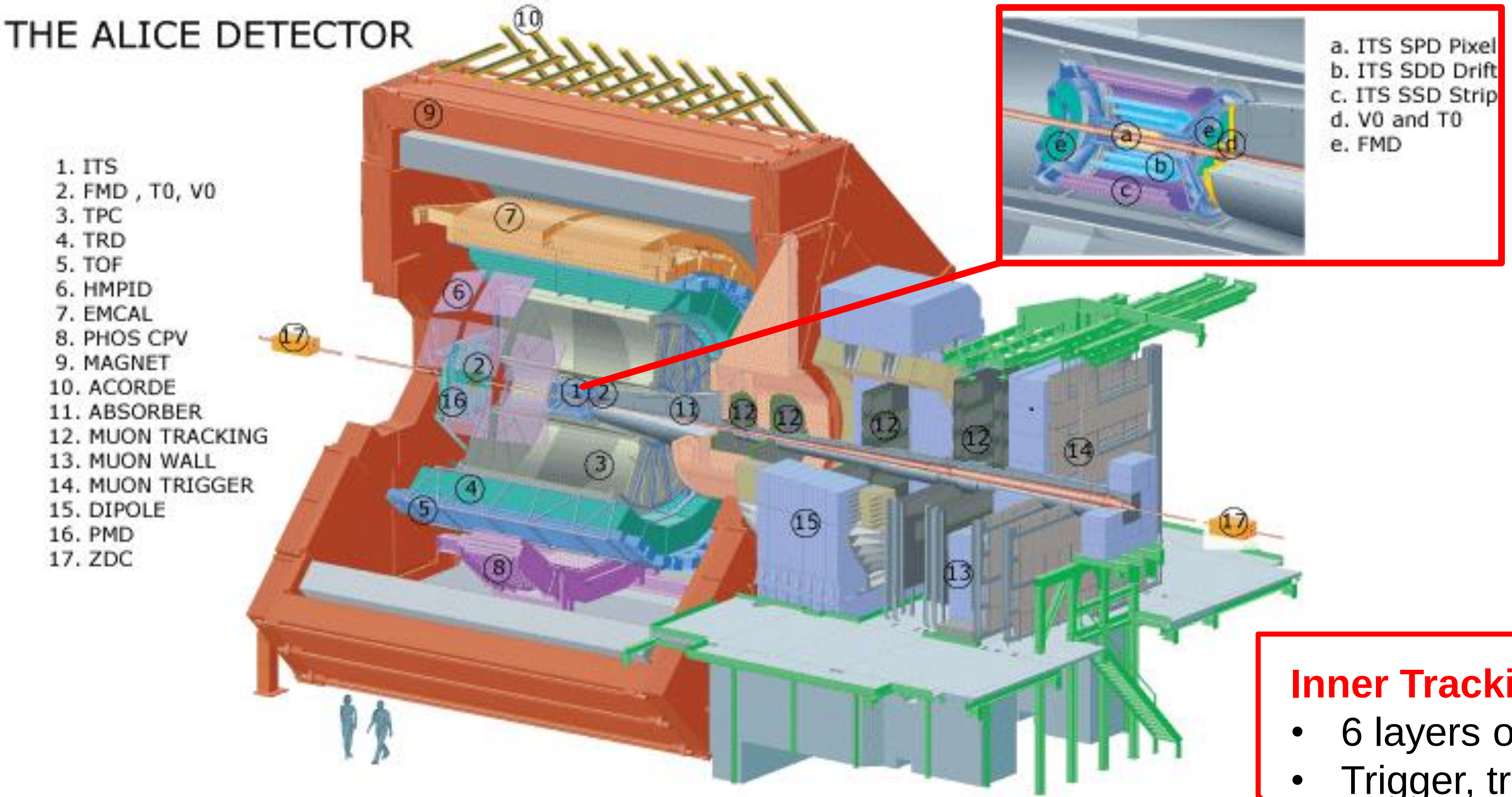
The ALICE detector



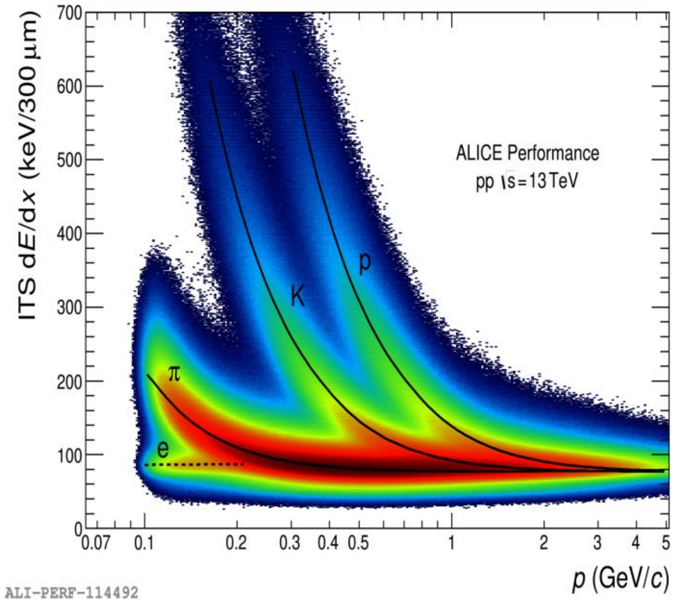
Data collected from:

Collision System	$\sqrt{s_{NN}}$ (TeV)
pp	0.9, 2.76, 5.02, 7, 8,13
p-Pb	5.02, 8.16
Xe-Xe	5.44
Pb-Pb	2.76, 5.02

Main detectors for resonance reconstruction



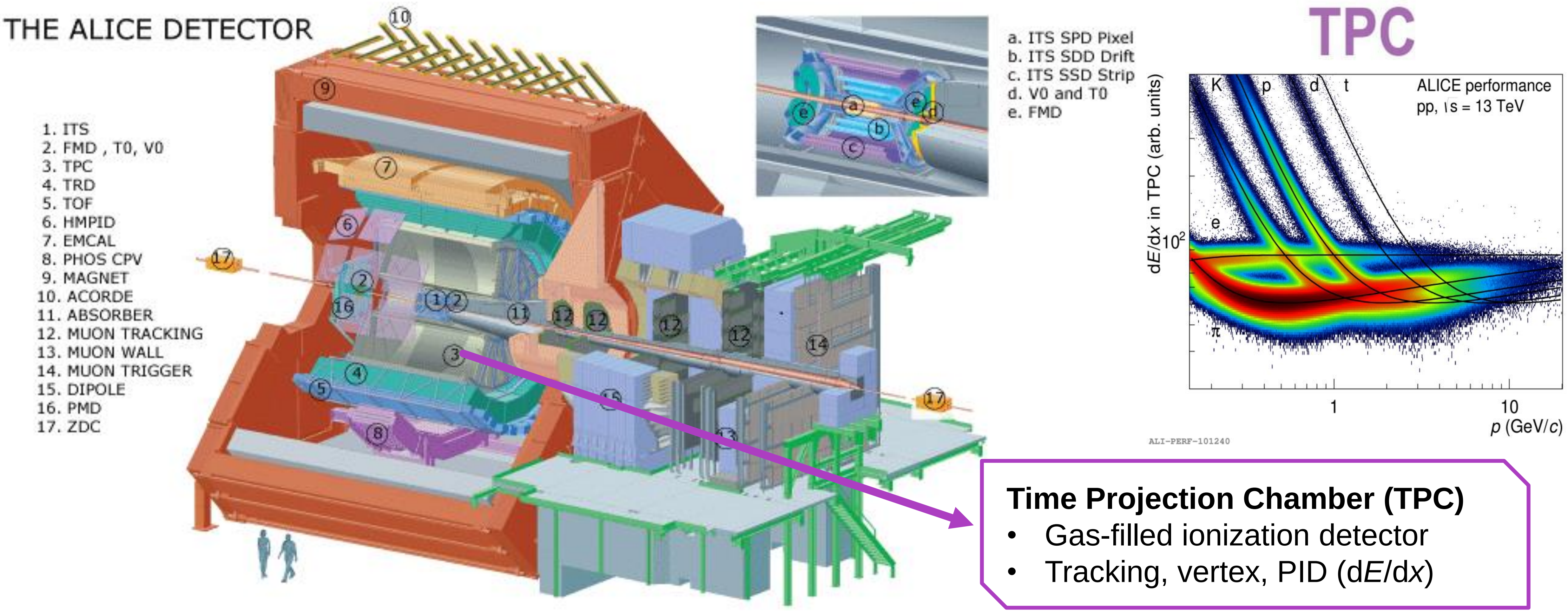
ITS



Inner Tracking System (ITS)

- 6 layers of Silicon detectors
- Trigger, tracking, vertex, PID (d*E*/d*x*)

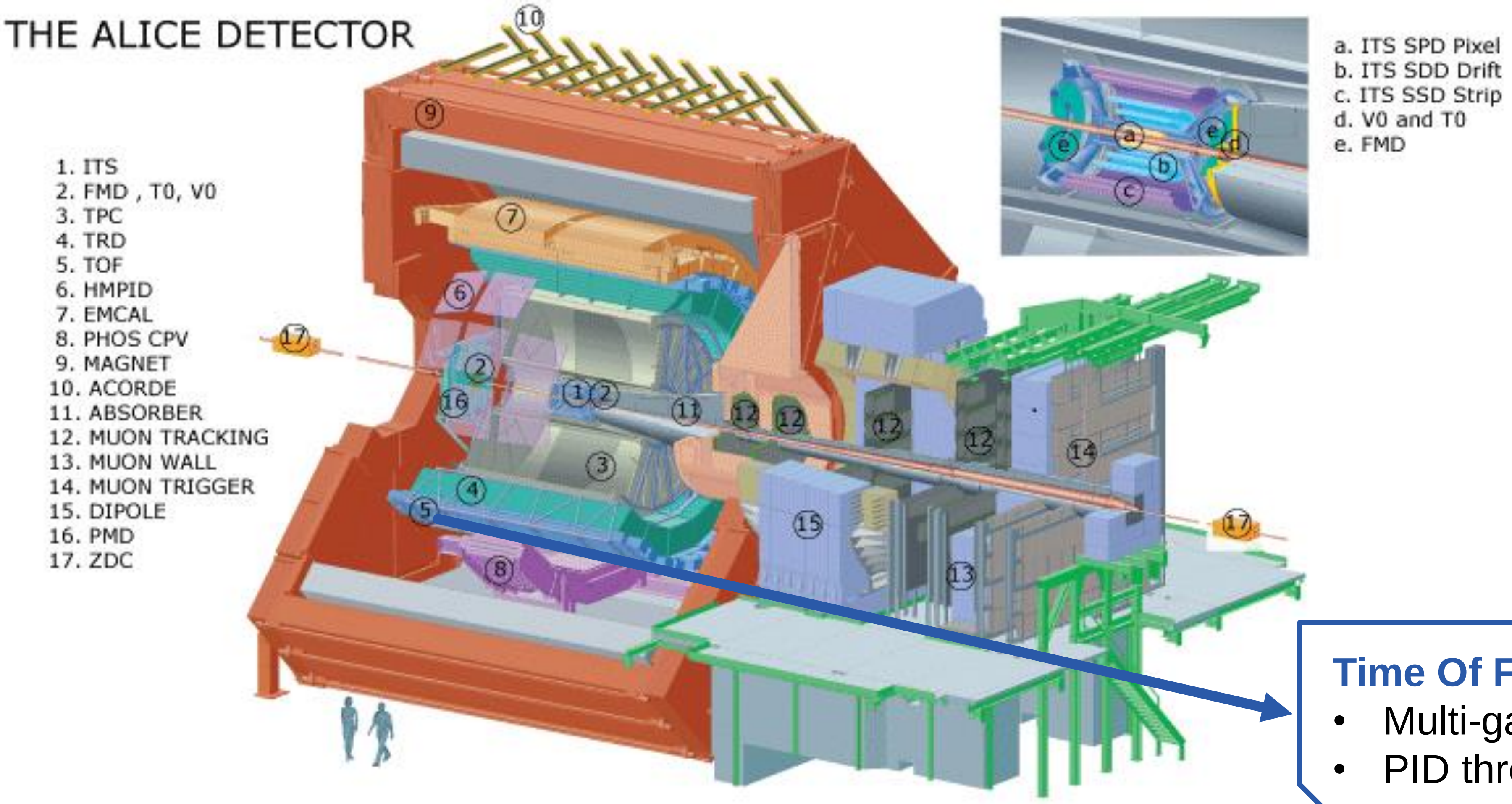
Main detectors for resonance reconstruction

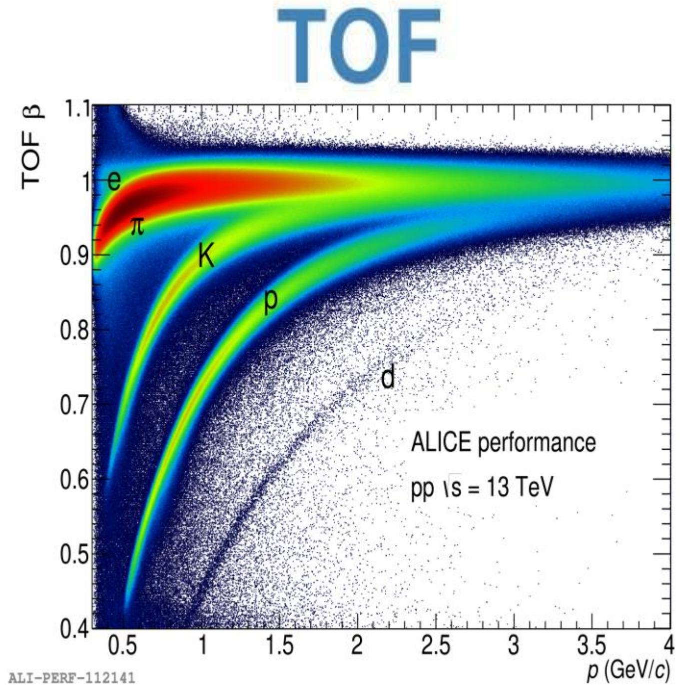


Time Projection Chamber (TPC)

- Gas-filled ionization detector
- Tracking, vertex, PID (d*E*/d*x*)

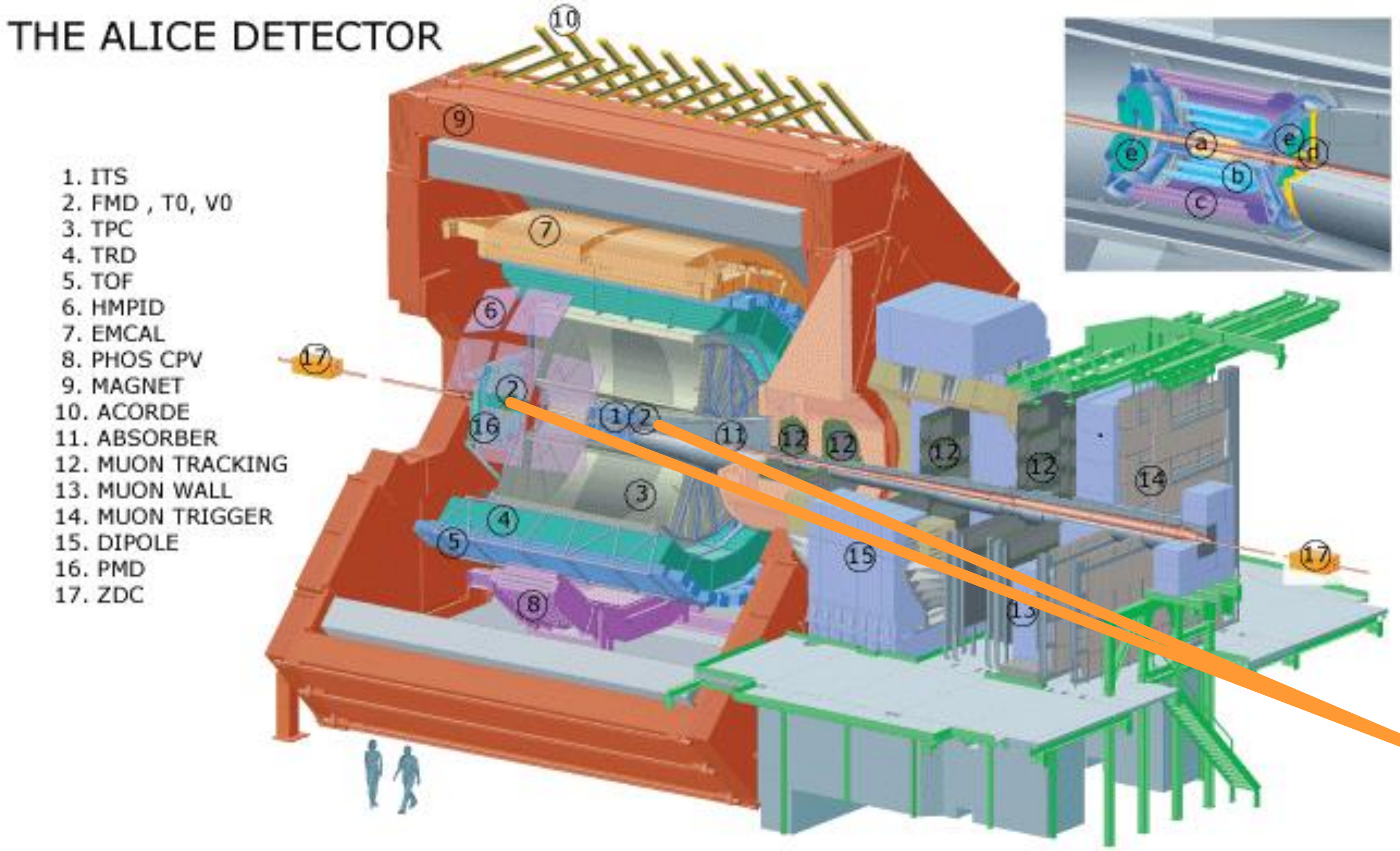
Main detectors for resonance reconstruction



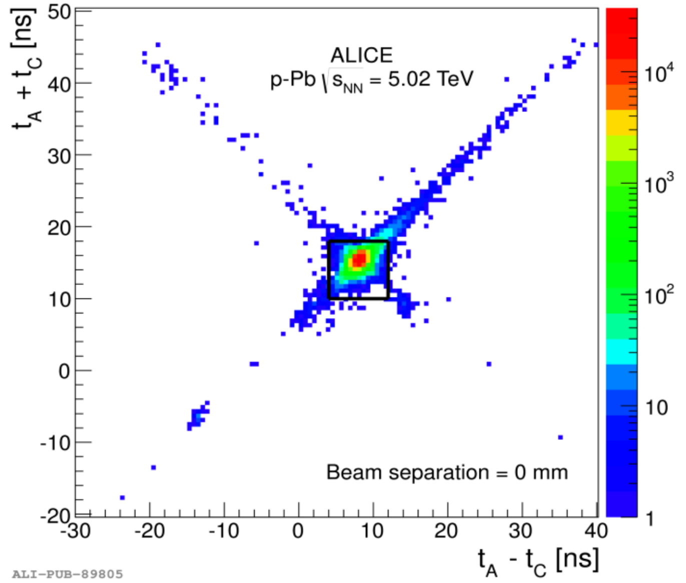


Time Of Flight (TOF)
- Multi-gap Resistive Plate Chamber
- PID through particle time of flight

Main detectors for resonance reconstruction



V0A - V0C



The ALICE collaboration 2014 JINST 9 P11003

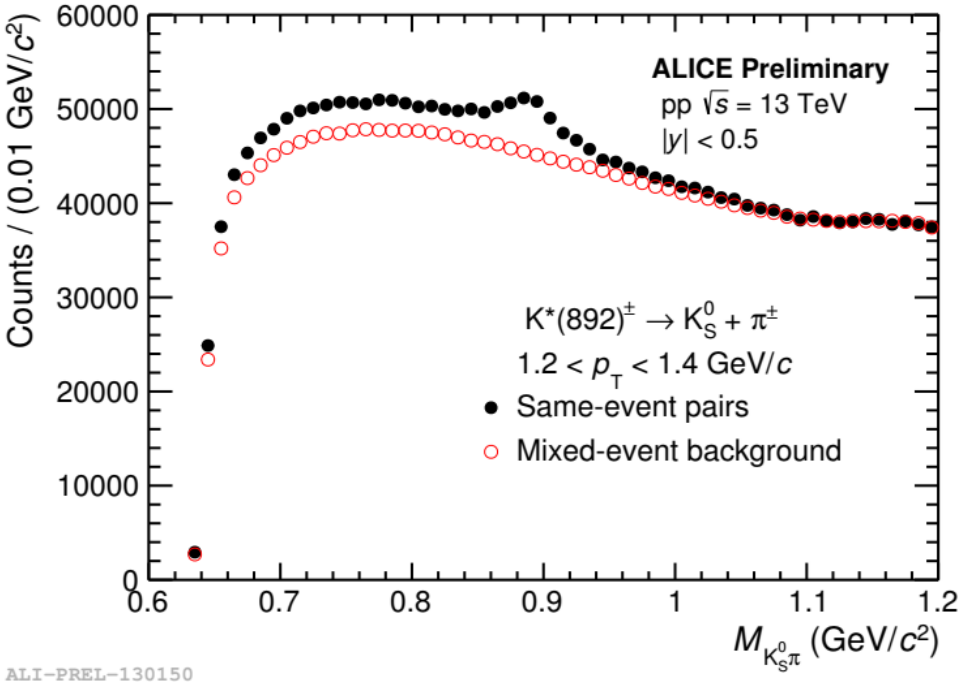
V0A and V0C

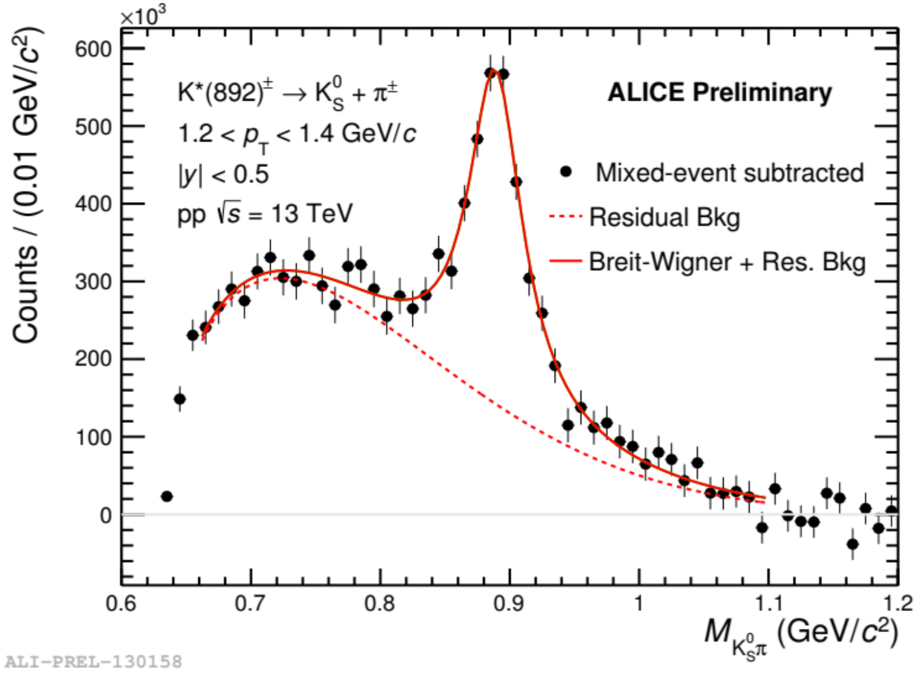
- 2 arrays of plastic scintillator hodoscopes
- Trigger, centrality/multiplicity estimator

Signal extraction

Resonance yield extraction via invariant mass distribution of the decay daughters identified with TPC/TOF and topological selection criteria

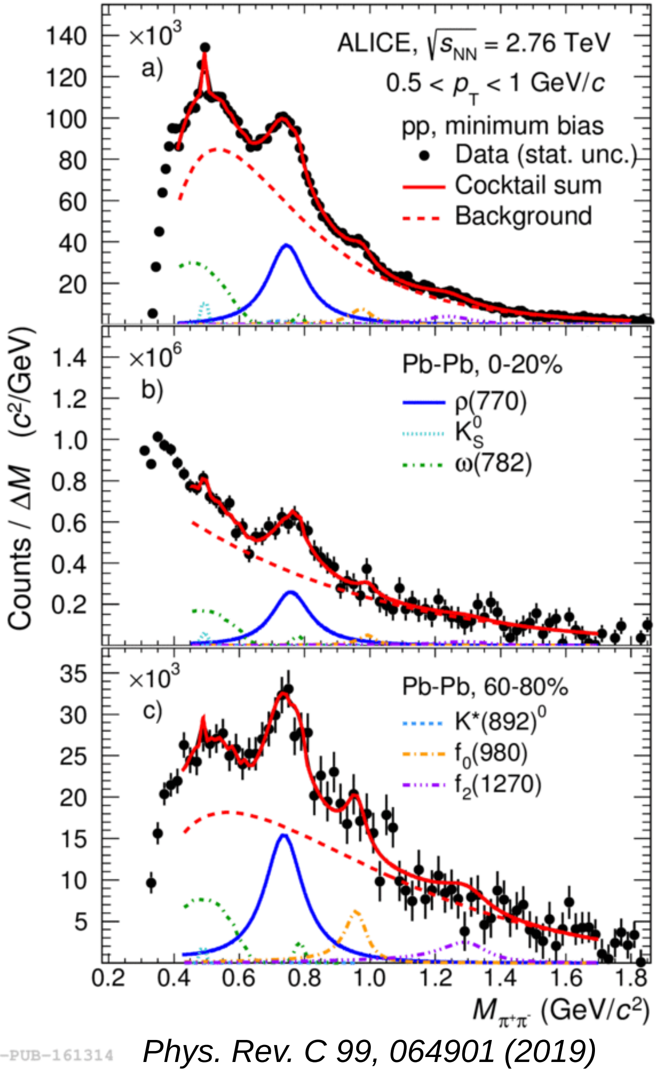
- Uncorrelated background calculated via event mixing technique or like-charge method
- After subtracting the uncorrelated background, the remaining distribution is fitted with a suitable function for the residual background and a Breit-Wigner (or a Gaussian, or a Voigtian) for the signal





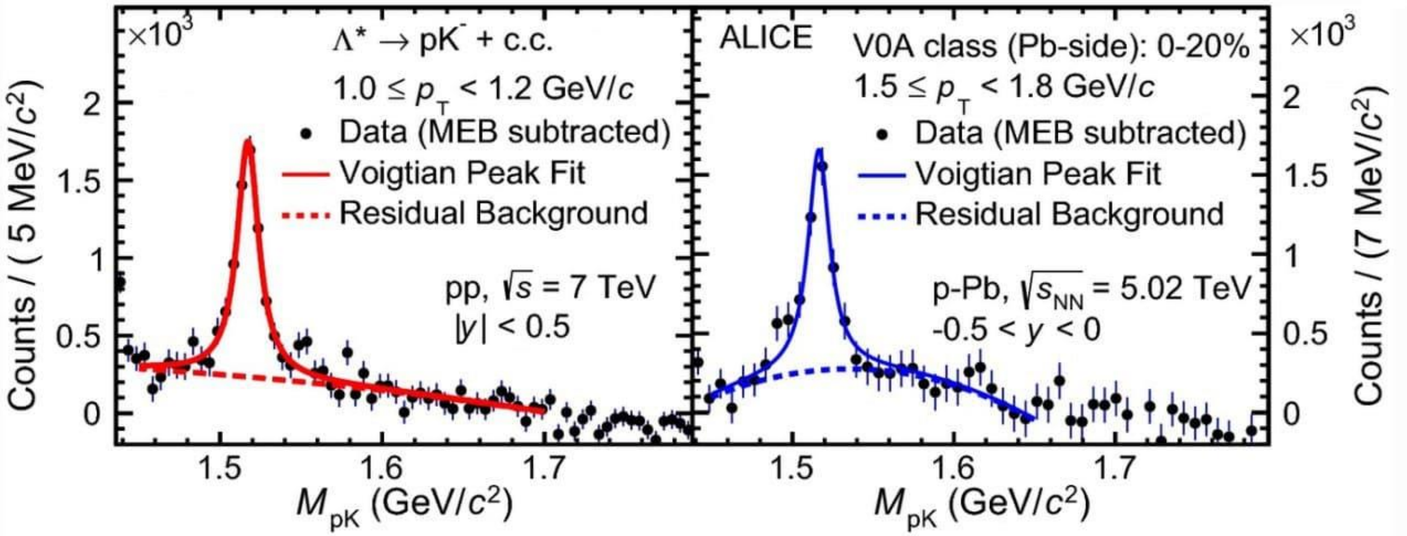
Signal extraction

ρ(770)⁰ Pb-Pb@2.76 TeV

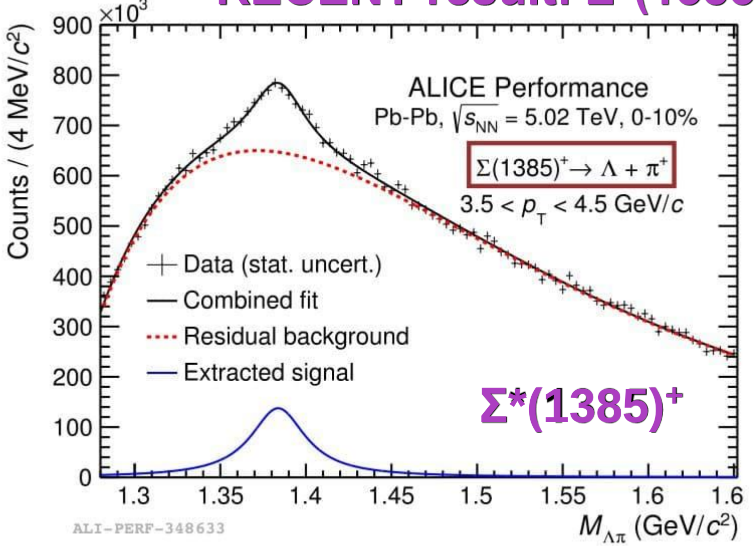


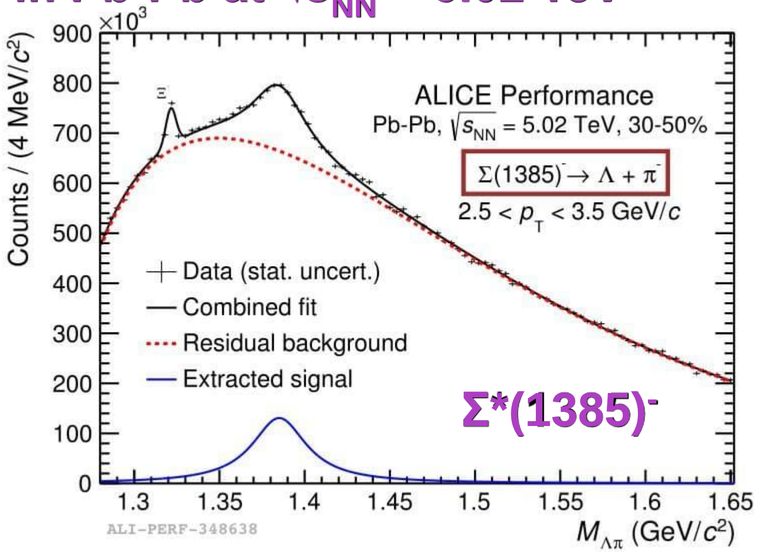
Phys. Rev. C 99, 064901 (2019)

pp@7 TeV **Λ(1520)** p-Pb@5.02 TeV *Eur. Phys. J. C 80, 160 (2020)*



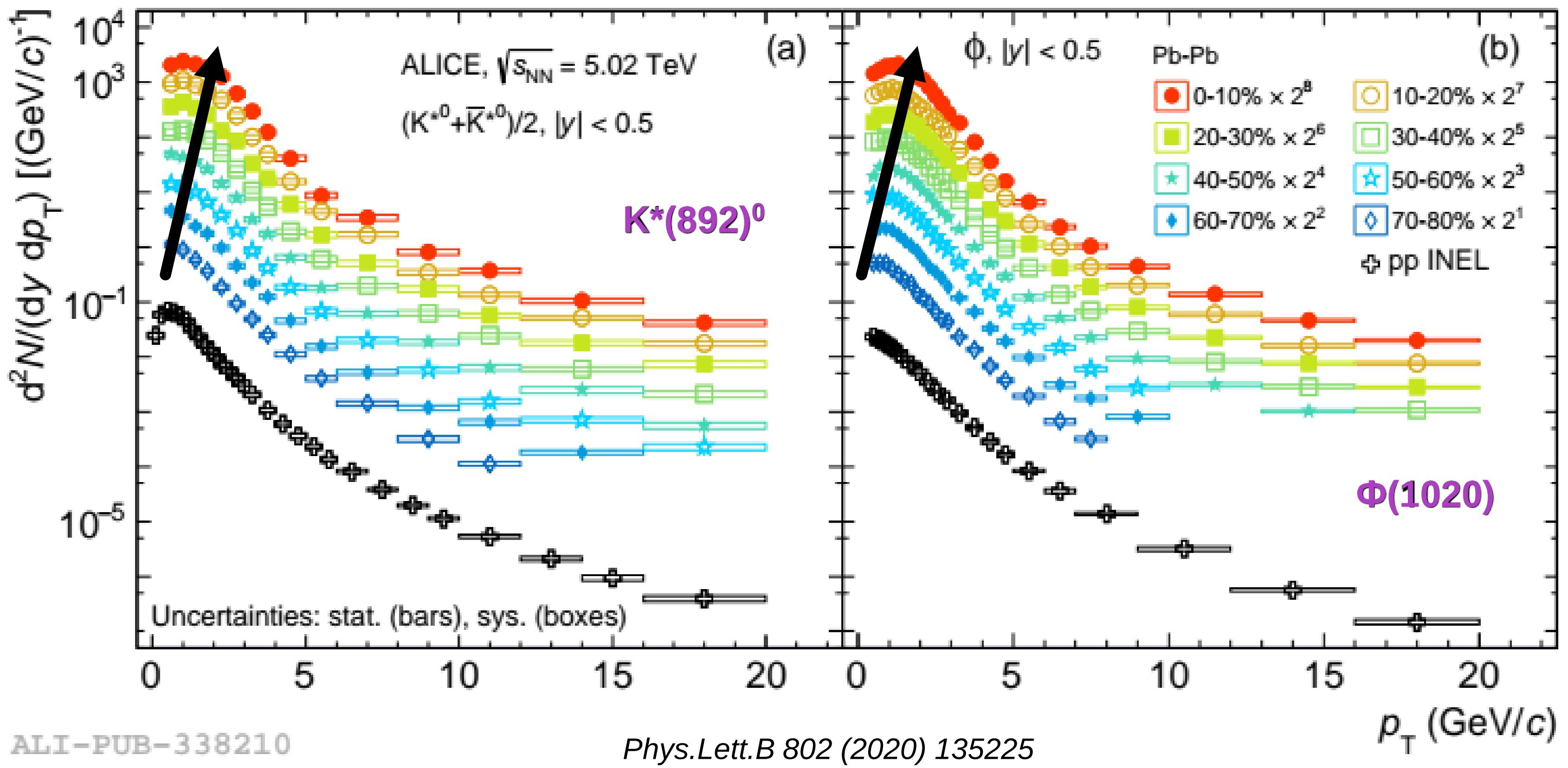
RECENT result: Σ*(1385)$^\pm$ in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV





p_T spectra in heavy-ion collisions

Pb-Pb@5.02 TeV



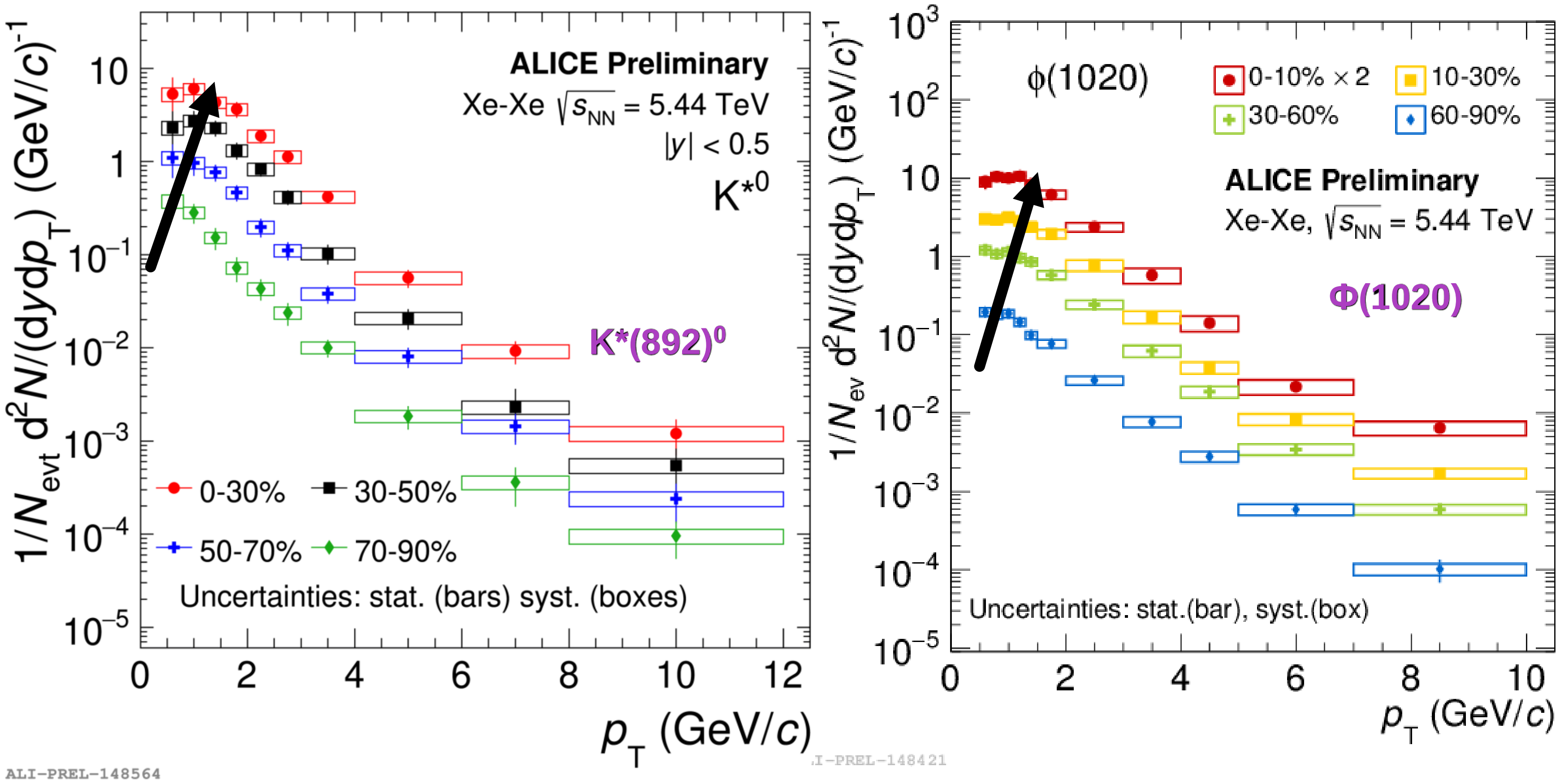
Phys.Lett.B 802 (2020) 135225

- Multiplicity event class definition based on forward/backward V0 estimator.
- p_T spectra get harder with increasing multiplicity (from peripheral to central collisions)
- Similar spectra obtained also for the other hadron species

→ In **heavy-ion collision**: effect due to collective expansion

p_T spectra in heavy-ion collisions

Xe-Xe@5.44 TeV

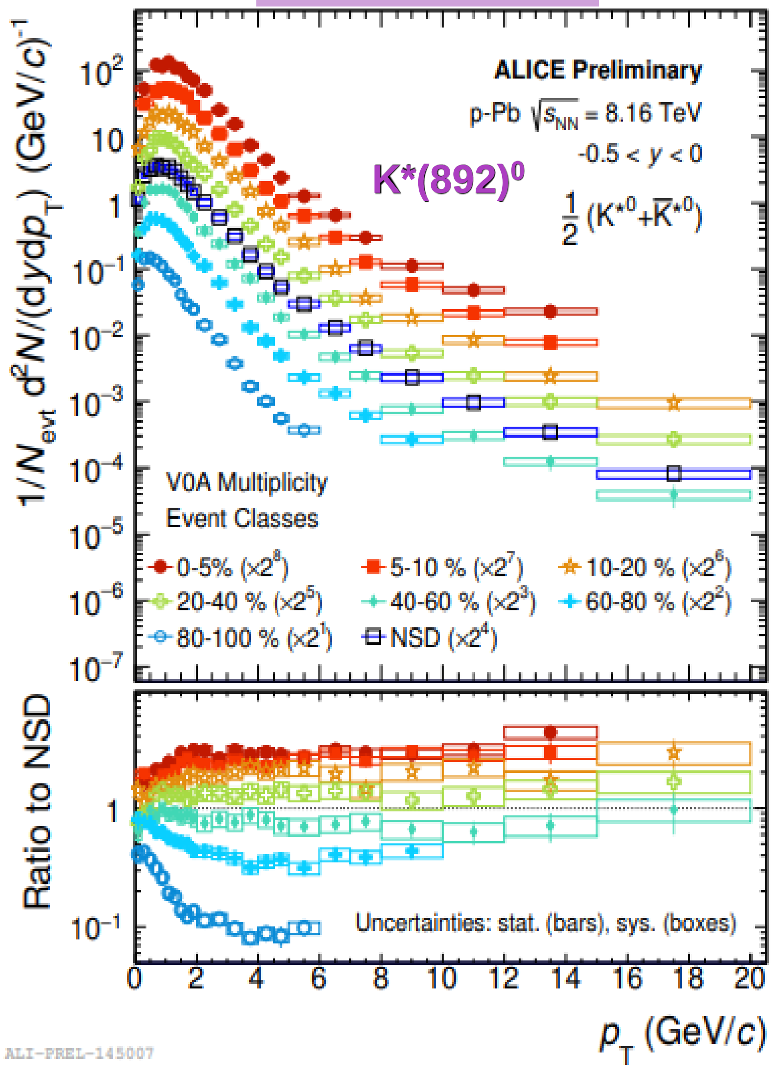


- Multiplicity event class definition based on forward/backward V0 estimator.
- p_T spectra get harder with increasing multiplicity (from peripheral to central collisions)
- Trend confirmed also in Xe-Xe collisions

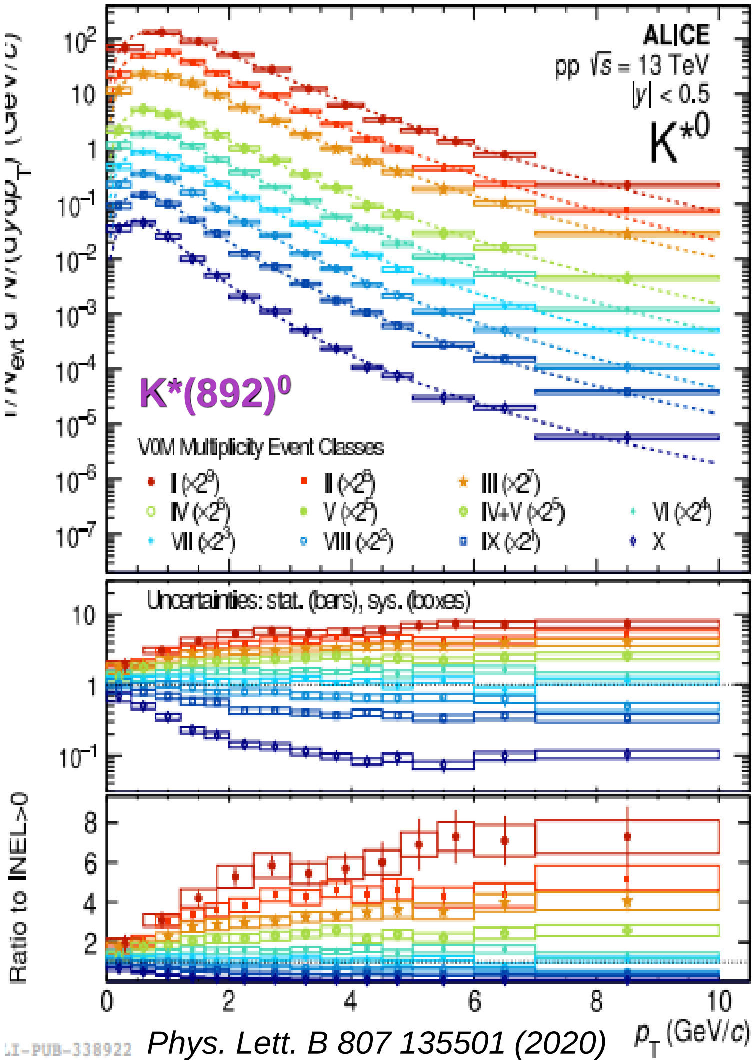
→ In **heavy-ion collision**: effect due to collective expansion

p_T spectra in small collision systems

p-Pb@8.16 TeV



pp@13 TeV



Phys. Lett. B 807 135501 (2020)

- pp and p-Pb collisions are typically used as baseline for A-A collisions
- p_T spectra get harder with increasing multiplicity: qualitatively similar to **Pb-Pb**
- **Lower panels:** ratios of p_T spectra to NSD (p-Pb collisions) and to INEL>0 (pp collisions)

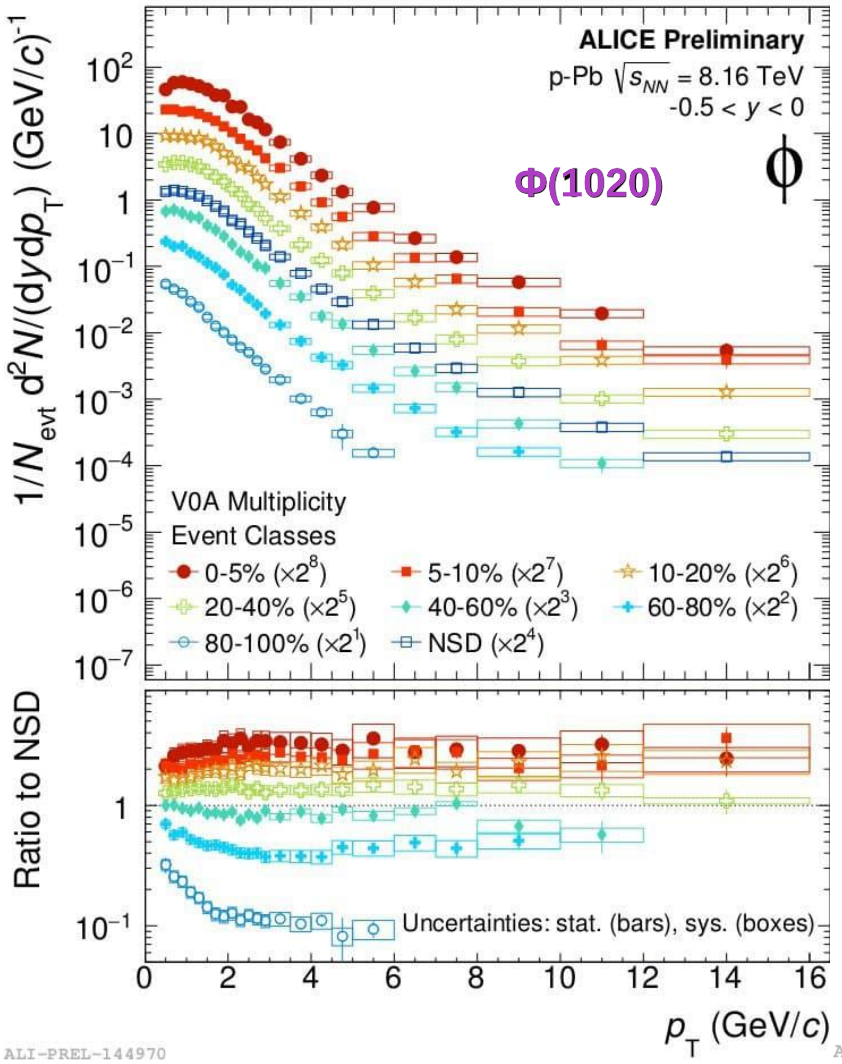
p_T < 5 GeV/*c*: p_T spectra increase from low to high multiplicity classes

p_T > 5 GeV/*c*: same spectral shapes for all multiplicity classes

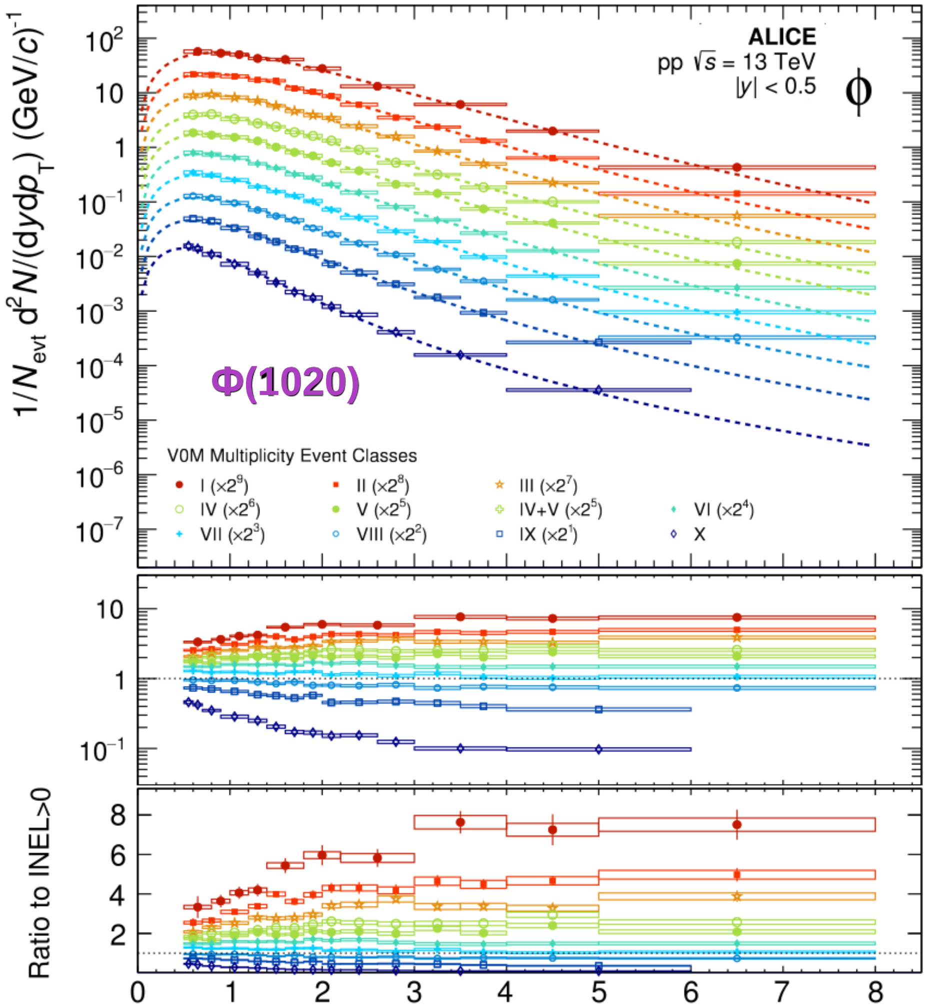
Process dominant at low p_T

p_T spectra in small collision systems

p-Pb@8.16 TeV



pp@13 TeV

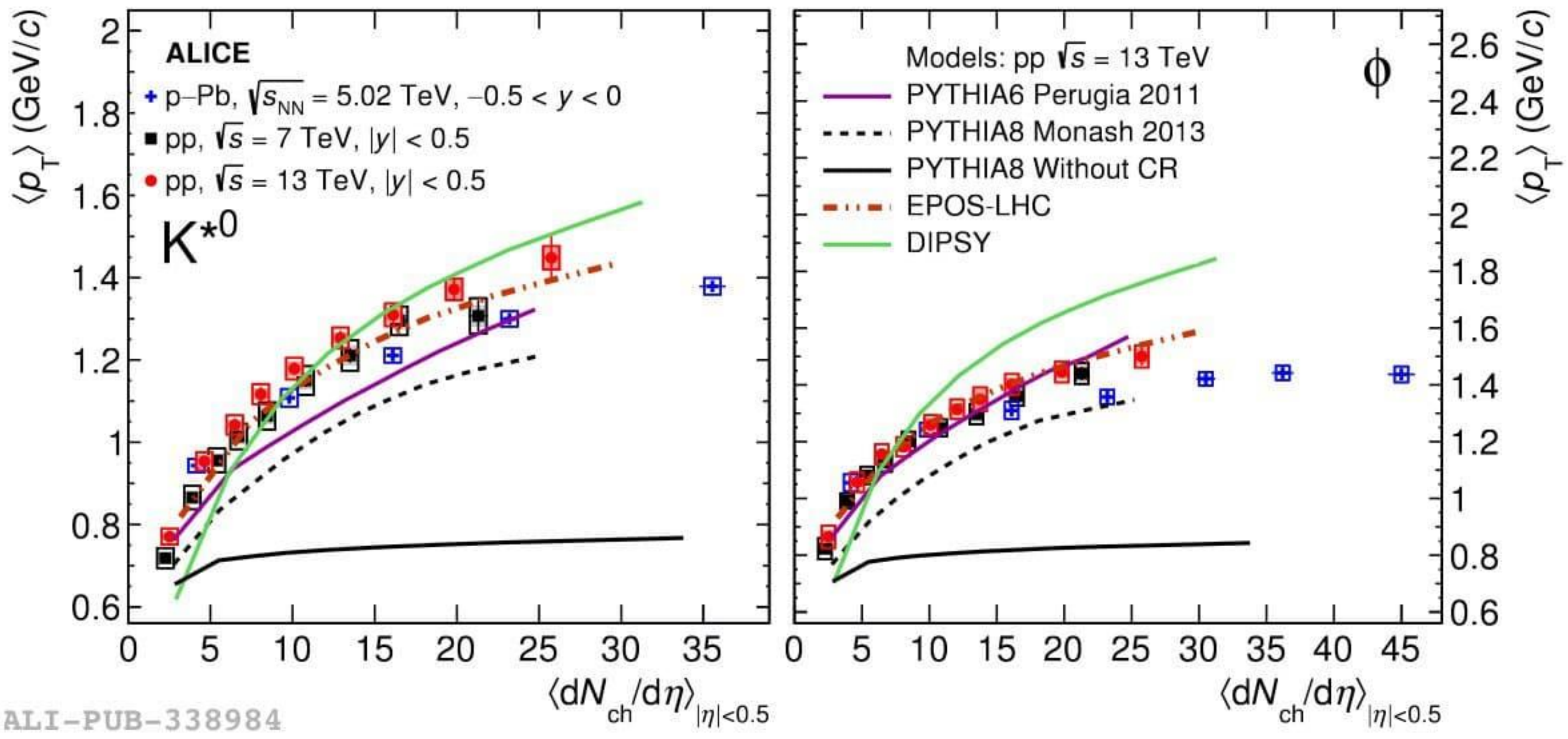


Phys. Lett. B 807 135501 (2020)

- Same trend observed also for Φ(1020)
- pp and p-Pb collisions show typical features of heavy-ion collisions as flow-like effects
- Colour reconnection mechanism can mimic the effect of collective-like behaviour.

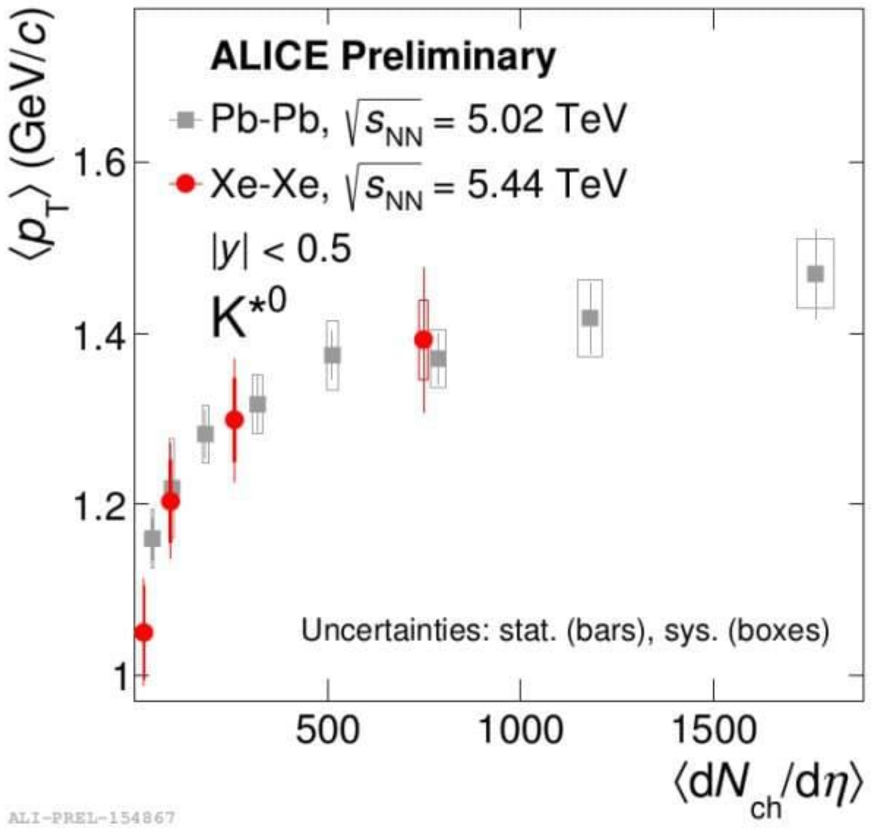
Spectra mean p_T in small collision systems

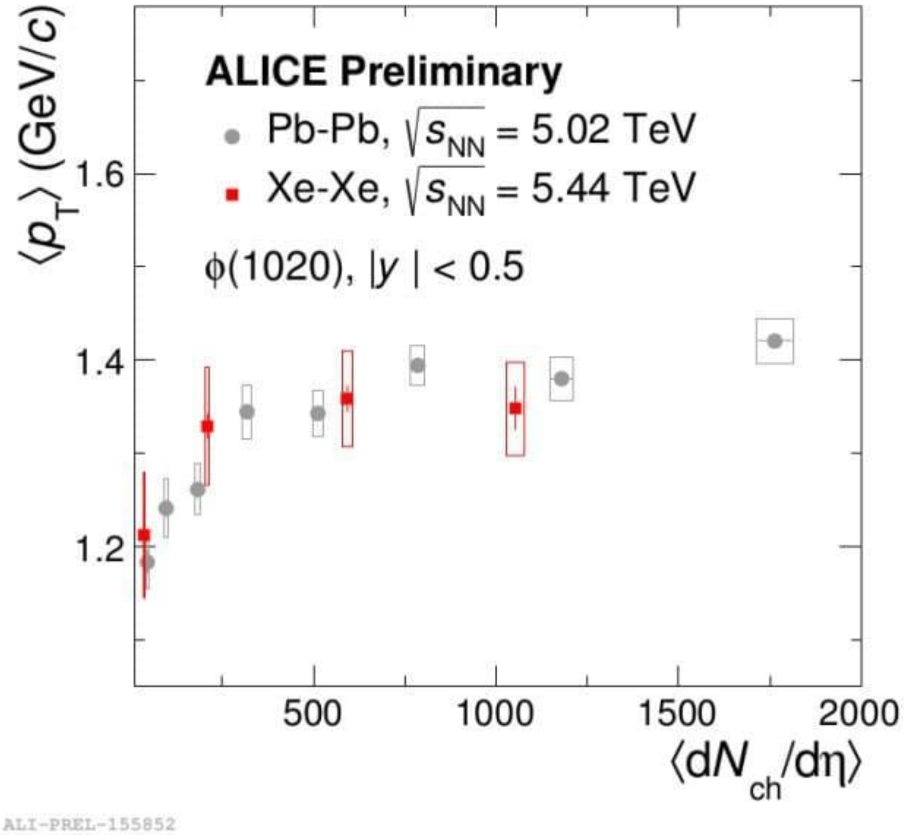
Phys. Lett. B 807 135501 (2020)



- $\langle p_T \rangle$ values in pp collision at $\sqrt{s}$ = 7 TeV and 13 TeV follow approximately the same trend and rise faster as a function of $\langle dN_{ch}/d\eta \rangle$ than in p-Pb collisions
- Among the different models EPOS-LHC gives the best agreement with data, however the predictions slightly underestimate values for K^{*0}

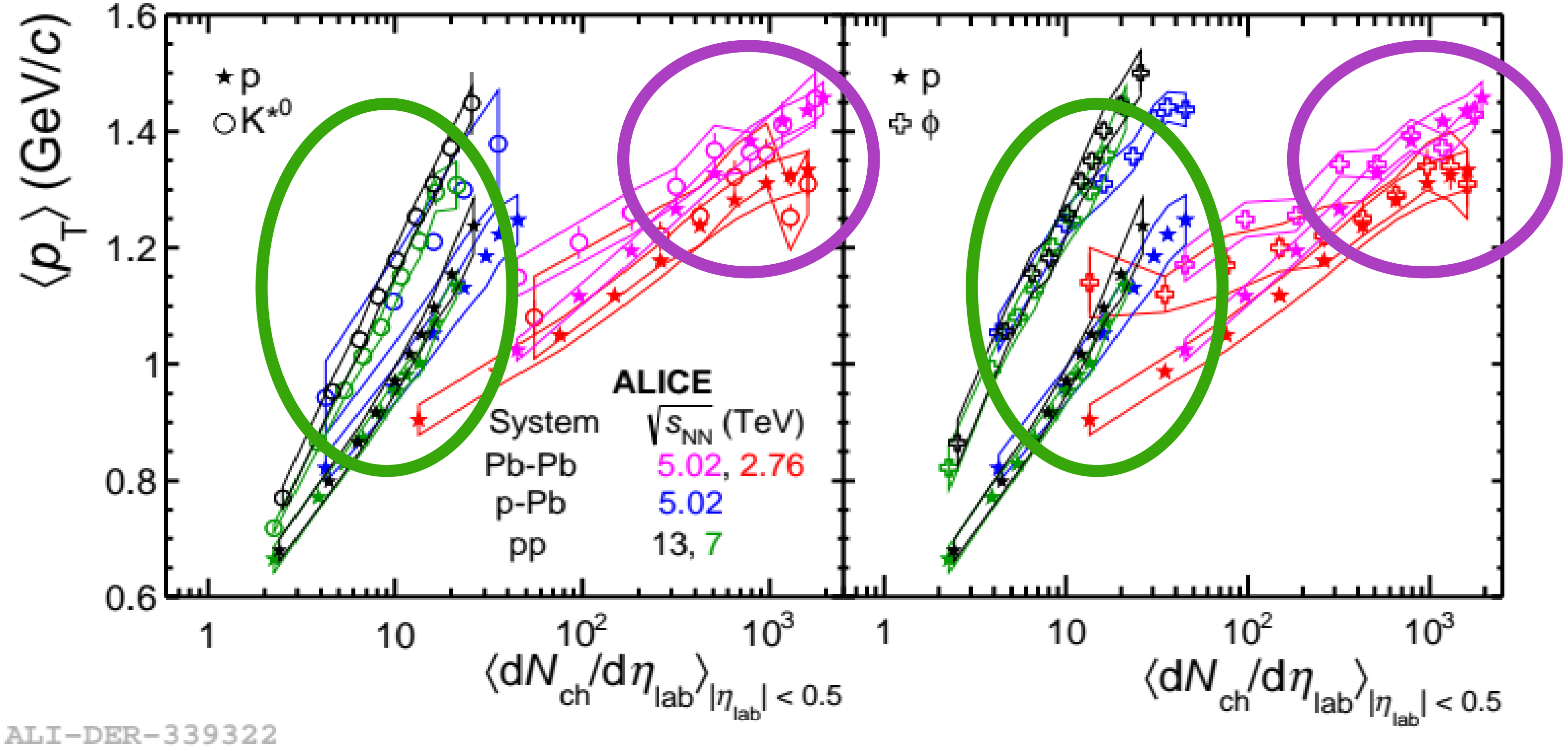
Spectra mean p_T in heavy-ion collisions





- Similar evolution in Pb-Pb and Xe-Xe collisions
- Independent of colliding nucleus size (Xe-Xe aligns with Pb-Pb)

Spectra mean p_T spectra



$\langle p_T \rangle$ in pp and p–Pb rise faster than in Pb–Pb collisions

Central Pb-Pb collisions (high multiplicity):

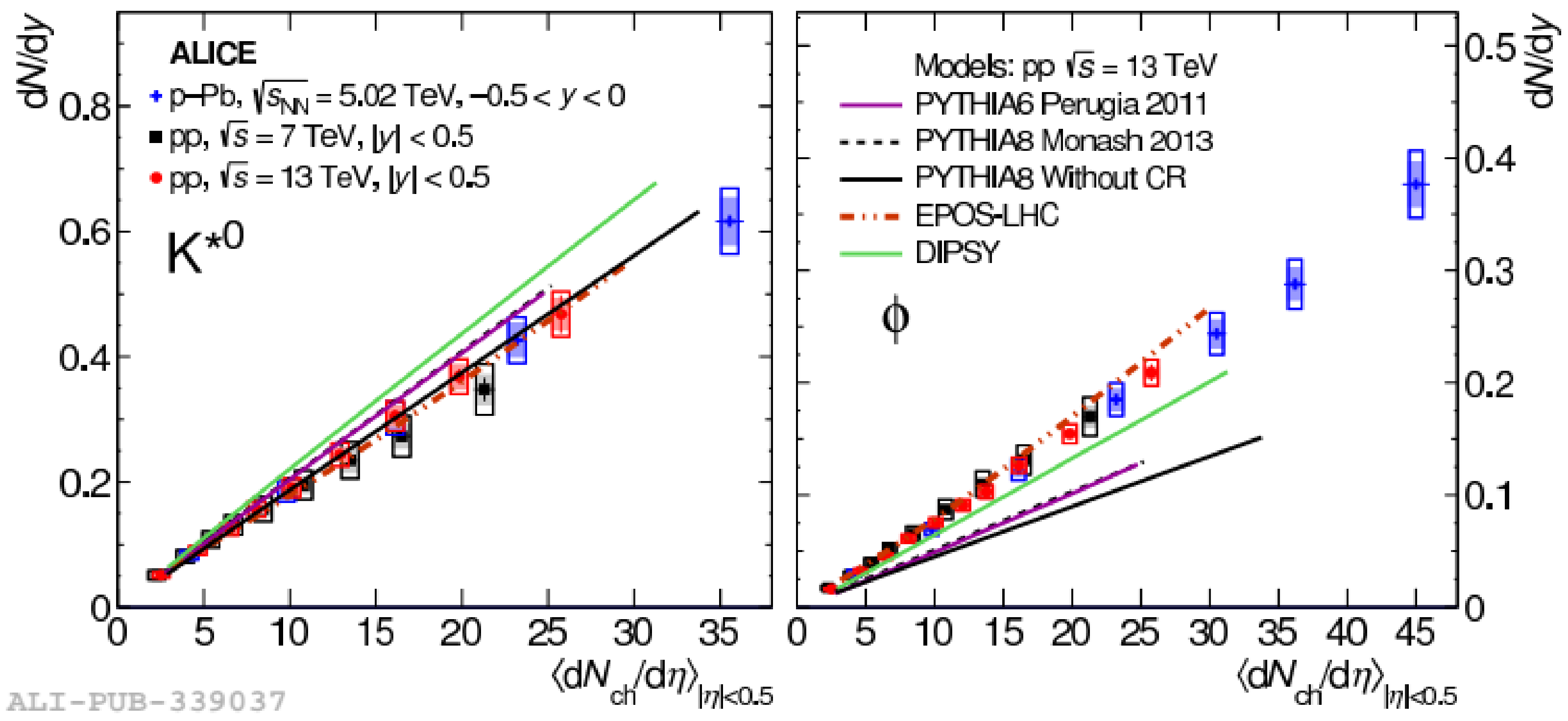
- **mass ordering:** particles with similar masses have similar $\langle p_T \rangle$ → indicative of radial flow.

Peripheral Pb-Pb and small collision systems (pp; p-Pb):

- **mass ordering breaks down:** lower $\langle p_T \rangle$ for p than K^{*0} and Φ.

Integrated yield in small collision systems

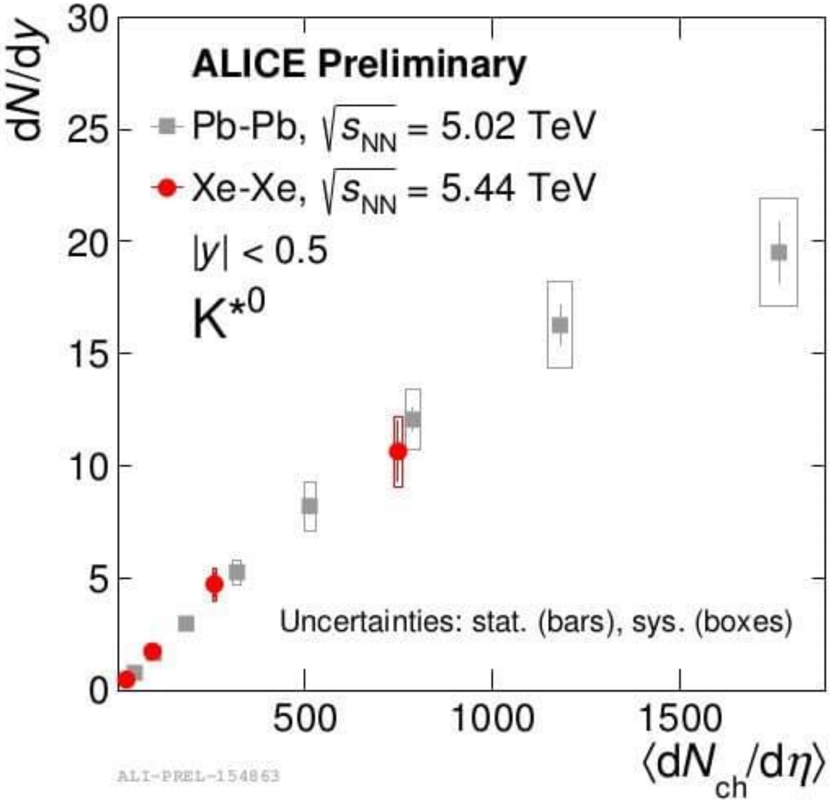
Phys. Lett. B 807 135501 (2020)

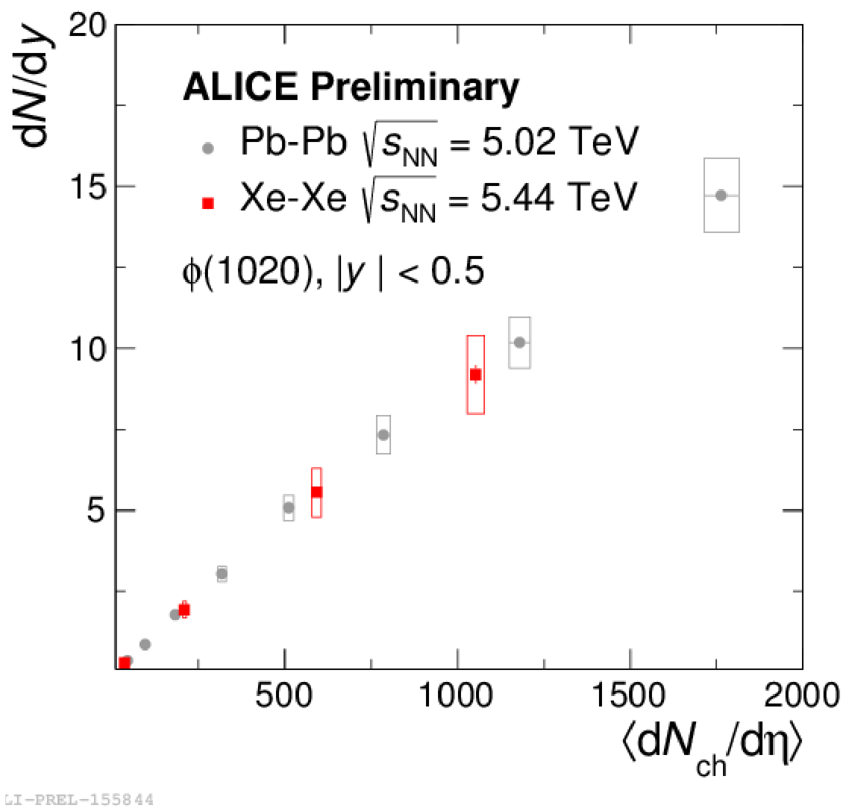


- For both particles, dN/dy exhibits a linear increase with increasing $\langle dN_{ch}/d\eta \rangle$
- Results for **pp @ 7 and 13 TeV** and for **p–Pb @ 5.02 TeV** are almost **overlapped**
- Similar results also for other hadron species

- EPOS-LHC and PYTHIA8 without colour reconnection describe K^{*0} data well
- Φ data are slightly overestimated by EPOS-LHC and underestimated by PYTHIA

Integrated yield in heavy-ion collisions



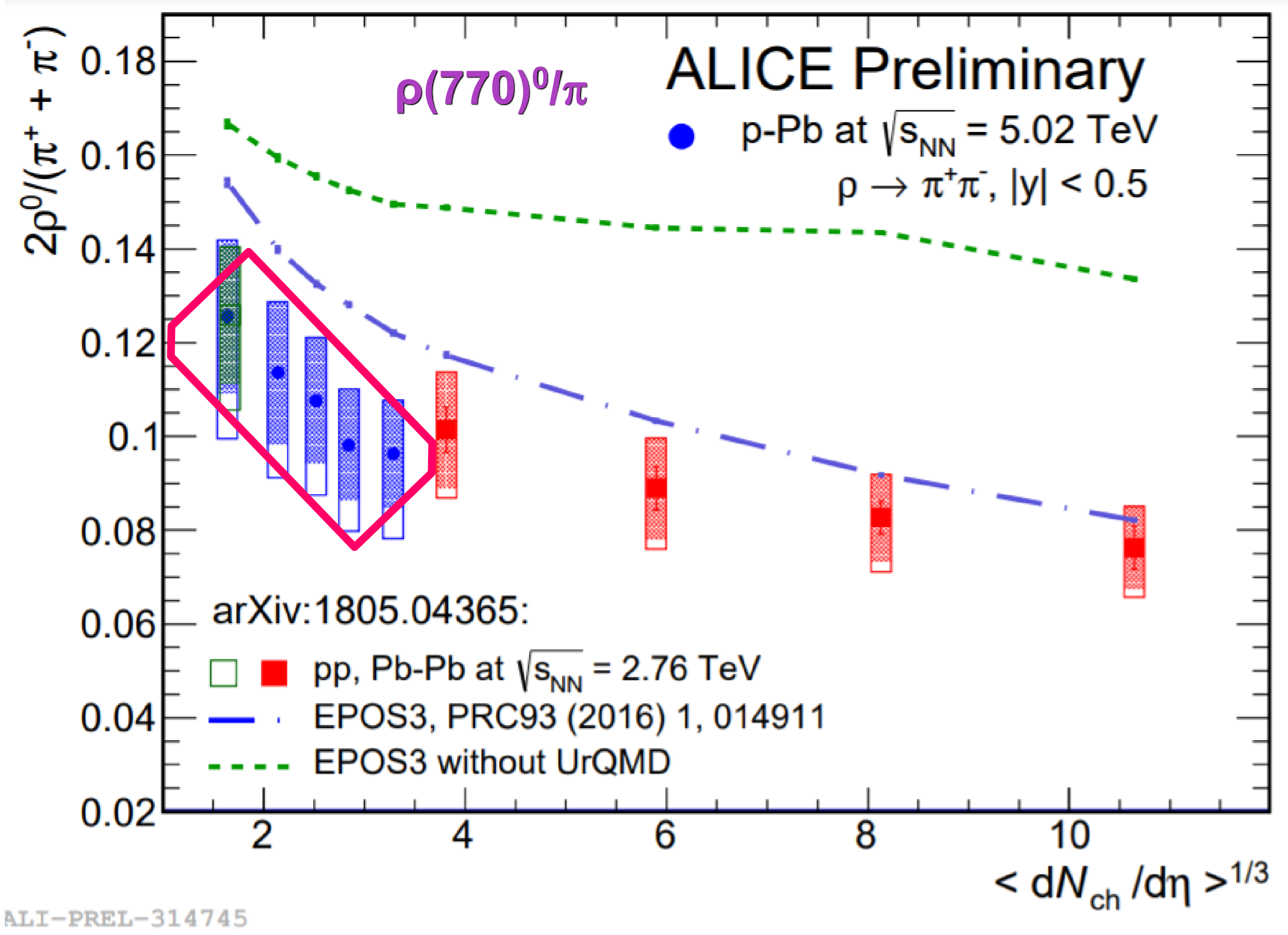


- As for pp and p-Pb, the yields in **Pb-Pb @ 5.02 TeV** and **Xe-Xe @ 5.44 TeV** lie on the **same line**

Particle production rate does not depend on collision system or energy → it depends only on event multiplicity

- Similar results also for other hadron species

Ratios to long-lived particle yields



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

Resonance yield can be compared to long-lived particles with similar quark content to study the system size dependence.

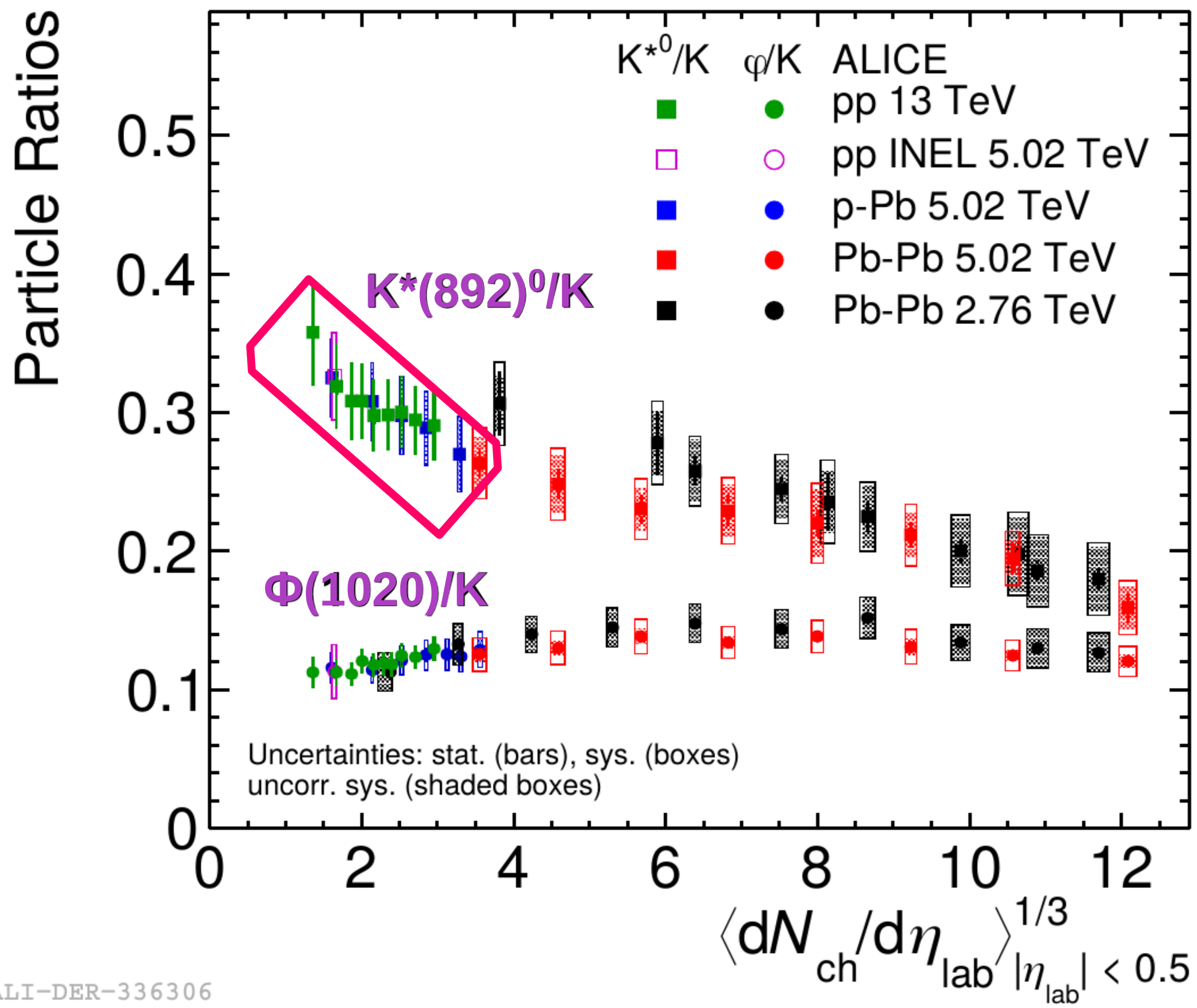
- **Significant suppression** going from pp, p-Pb, and peripheral Pb-Pb to central Pb-Pb collisions (i.e. increasing system size)

- **Hint of suppression** also for high multiplicity p-Pb collisions

→ dominance of re-scattering over regeneration

- EPOS3, although systematically higher than the data, qualitatively describes the decreasing trend

Ratios to long-lived particle yields



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

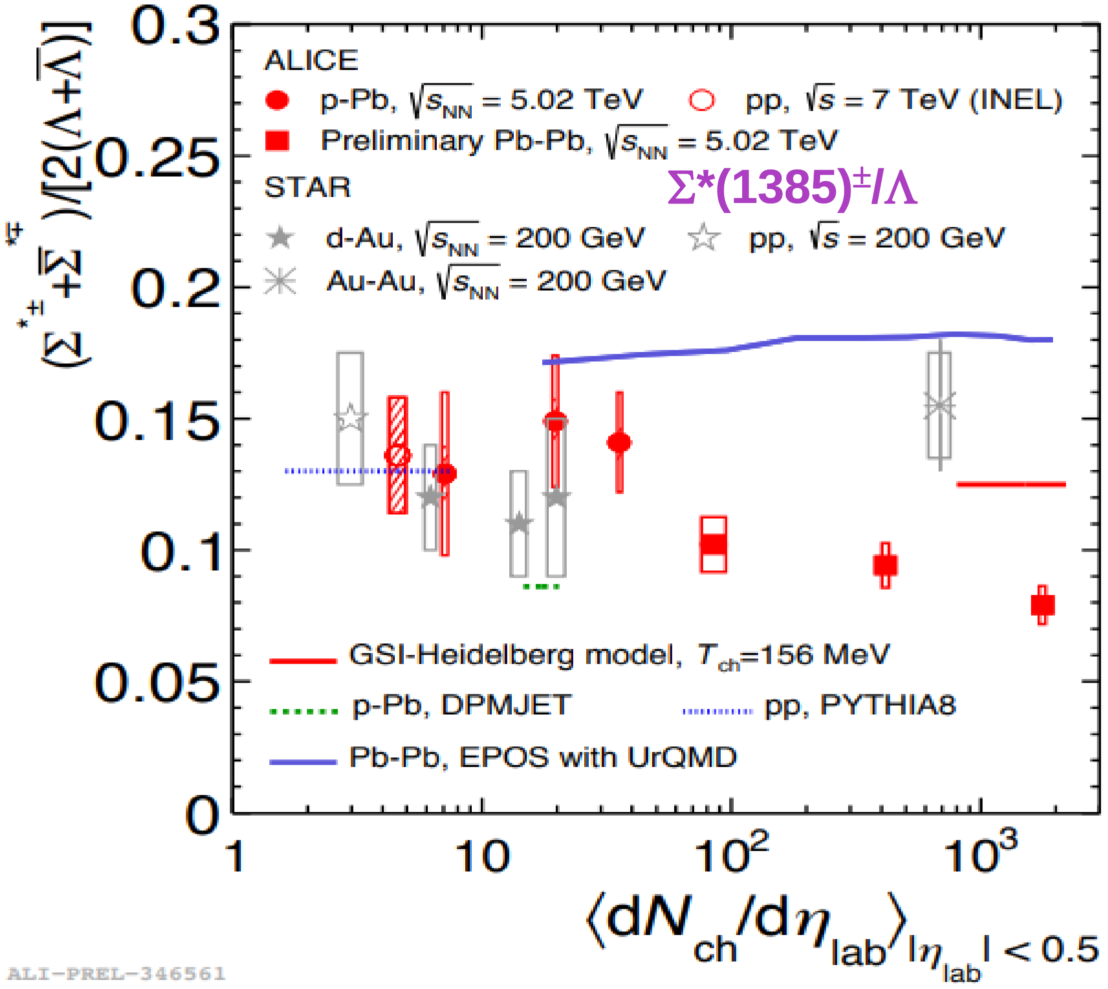
- **Significant suppression** of K^{*0}/K going from pp, p-Pb, and peripheral Pb-Pb to central Pb-Pb collisions →K^{*0} re-scattering dominant over regeneration
- As for ρ/π **hint of suppression** in high multiplicity pp and p-Pb collisions → **hadronic phase effect in small systems as well?**

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

- Flat behaviour for Φ/K for each collision system → larger Φ lifetime: it probably decays after the end of the hadronic phase

Ratios to long-lived particle yields

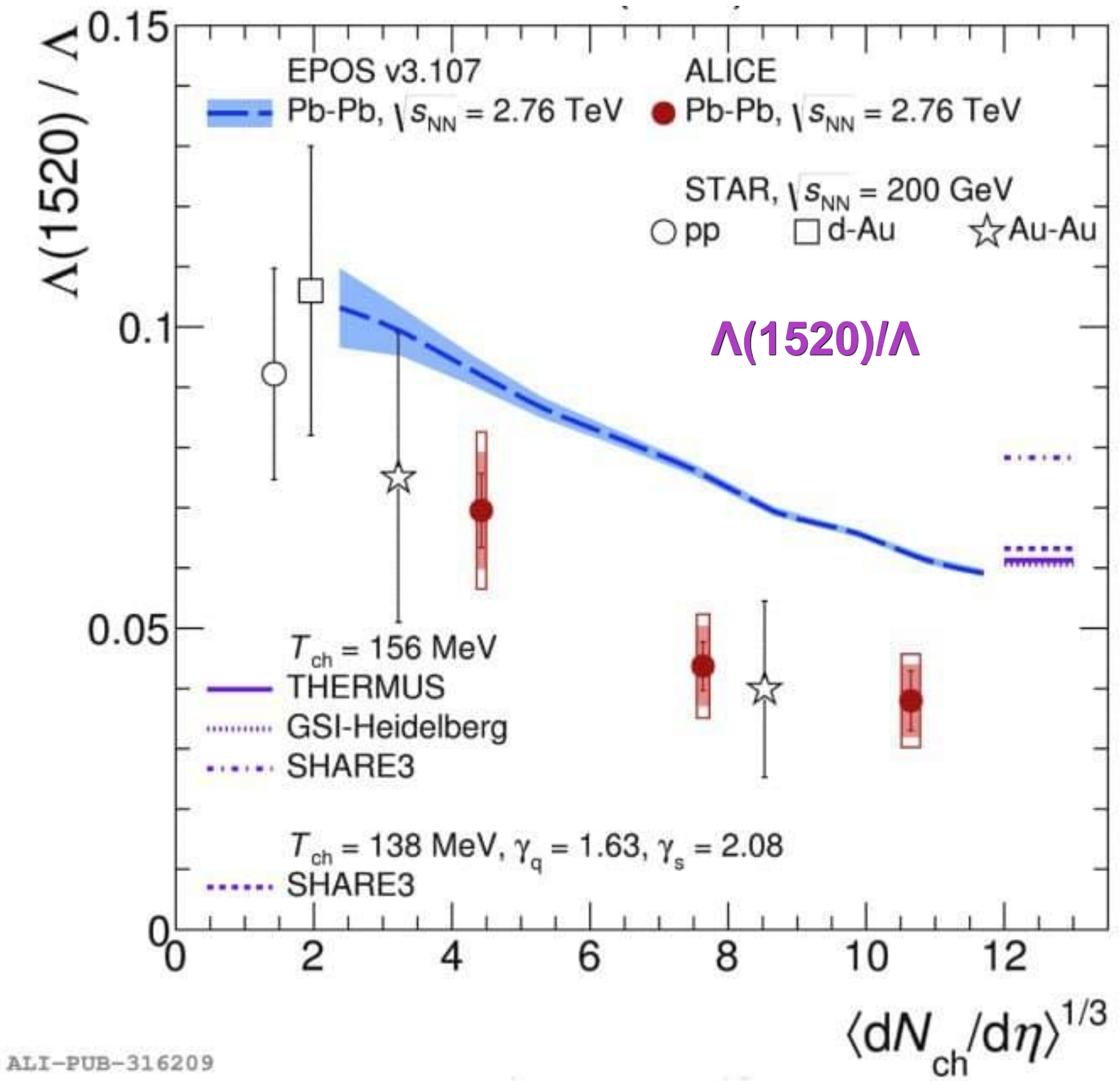
RECENT result: $\Sigma^*(1385)^{\pm}$ in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



$\tau(\Sigma^{*\pm})$ = 5-5.5 fm/c

- The ratio $\Sigma^{*\pm}/\Lambda$ remains flat in small collisions systems
- **A suppression is observed for the first time in central Pb-Pb collisions**
- The suppression is not predicted by EPOS or thermal model
- Pb-Pb data are lower than STAR Au-Au value

Ratios to long-lived particle yields



$\tau(\Lambda^*)$ = 12.6 fm/c

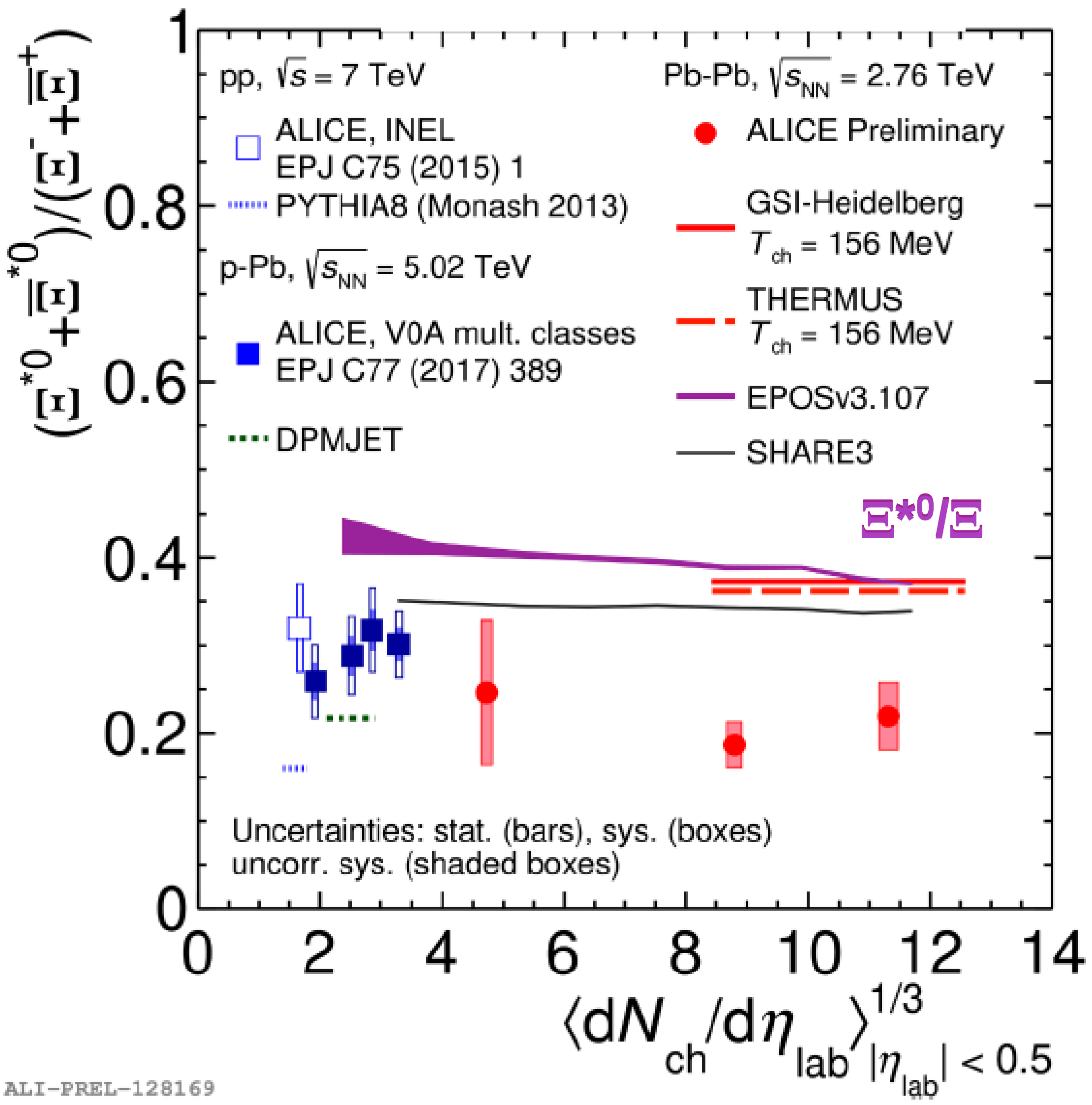
- Significant decrease of Λ*/Λ with increasing charged-particle multiplicity from peripheral to central Pb-Pb collisions

- The trend of suppression is similar to the one seen from STAR data in Au-Au collisions @ 200 GeV

→ Consistent with re-scattering as dominant effect

- EPOS3, although systematically higher than the data, qualitatively describes the decreasing trend

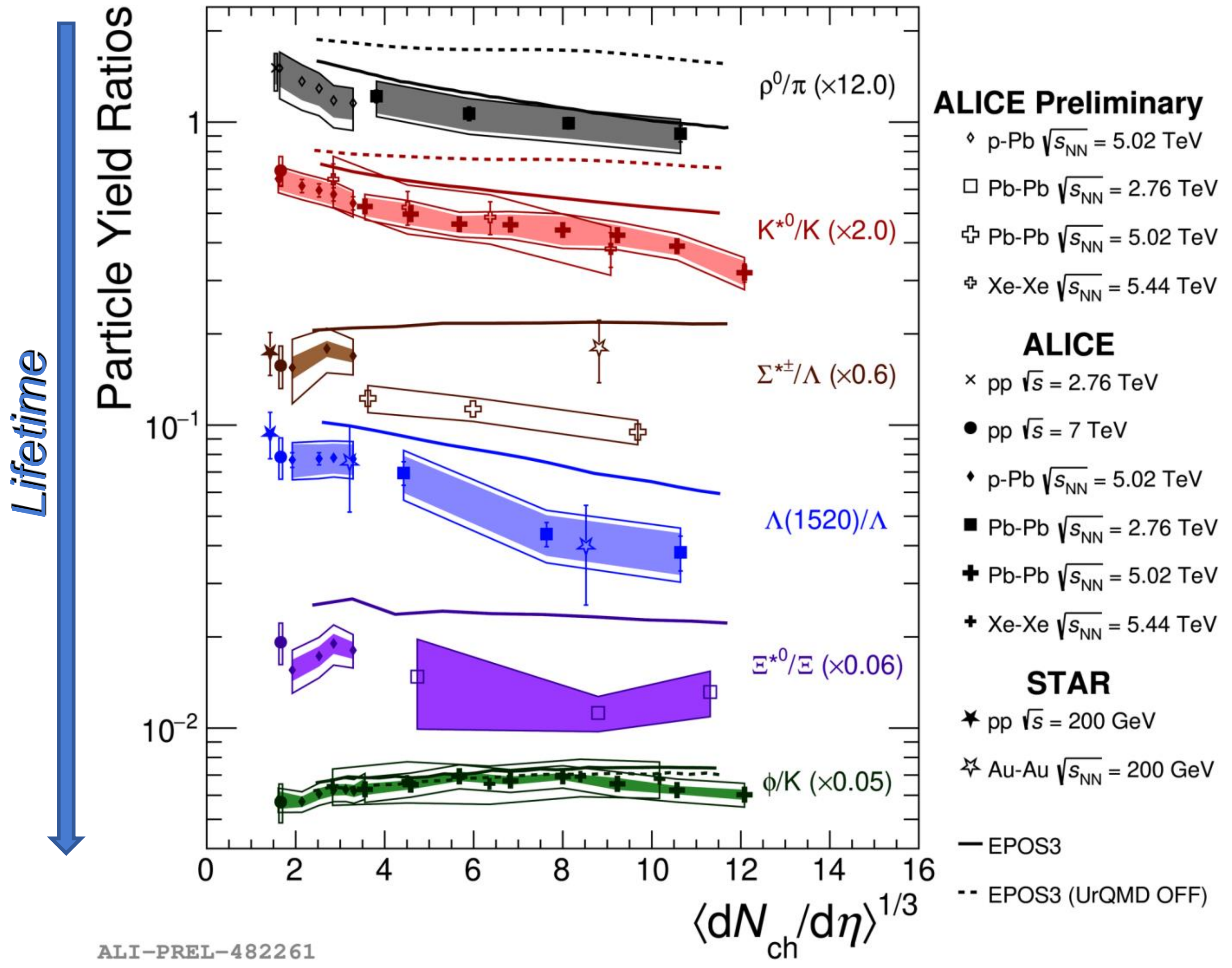
Ratios to long-lived particle yields



$\tau(\Xi^{*0})$ = 21.7 fm/c

- Like Φ/K, the Ξ^{*0}/Ξ ratio also does not show remarkable suppression in Pb-Pb nor in elementary collisions
- Ξ^{*0} probably decays outside the hadronic medium
- Models overestimate data

Ratios to long-lived particle yields: overview



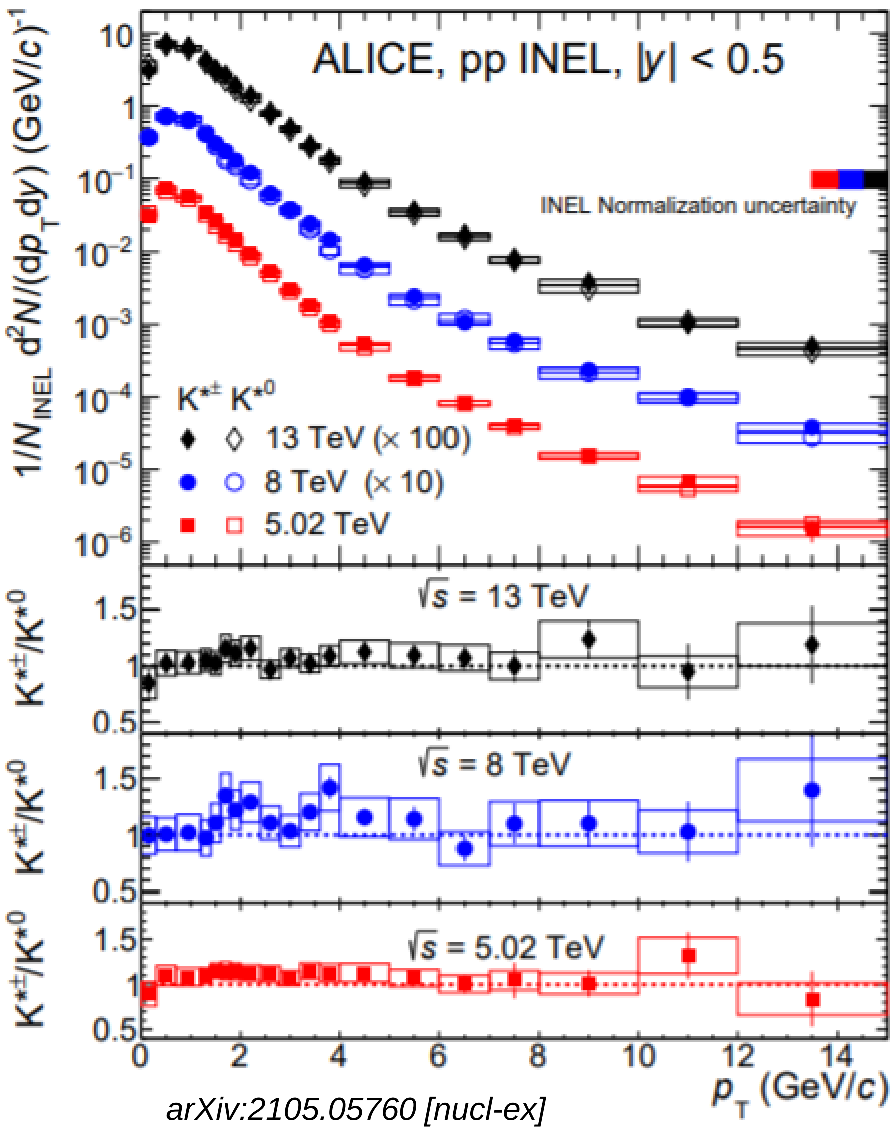
Small collision systems (pp, p-Pb):

- **Φ/K Σ*±/Λ Λ(1520)/Λ**, and **Ξ*⁰/Ξ** ratios are independent of charged particle multiplicity
- **ρ⁰/π**, **K*⁰/K** → hint of suppression (possible re-scattering effect)

Heavy-ion collision systems (Pb-Pb, Xe-Xe):

- **ρ⁰/π**, **K*⁰/K**, **Σ*±/Λ**,and **Λ(1520)/Λ** ratios are suppressed with respect to pp, p-Pb and peripheral Pb-Pb: dominance of re-scattering compared to regeneration
- **Φ/K** and **Ξ*⁰/Ξ** no suppression: larger lifetime → decay outside the medium

K*(892)$^{\pm}$: recent results and ongoing analysis



arXiv:2105.05760 [nucl-ex]

- K*(892)$^{\pm}$ reconstructed via $K^{*\pm} \rightarrow K^0_S + \pi^{\pm}$ with $\mathbf{K^0_S \rightarrow \pi^+ + \pi^-}$
  NOTE: K*(892)^0 reconstructed via $K^{*0} \rightarrow K^{\mp} + \pi^{\pm}$
- Lower systematic uncertainties on K^0_S measurement than $K^{\pm}$ due to the different strategies used for their identification in ALICE
- The spectra of $K^{*\pm}$ and K^{*0} are consistent within the uncertainties
- These measurements complement and confirm the previous results for K^{*0} **with smaller systematic uncertainties**

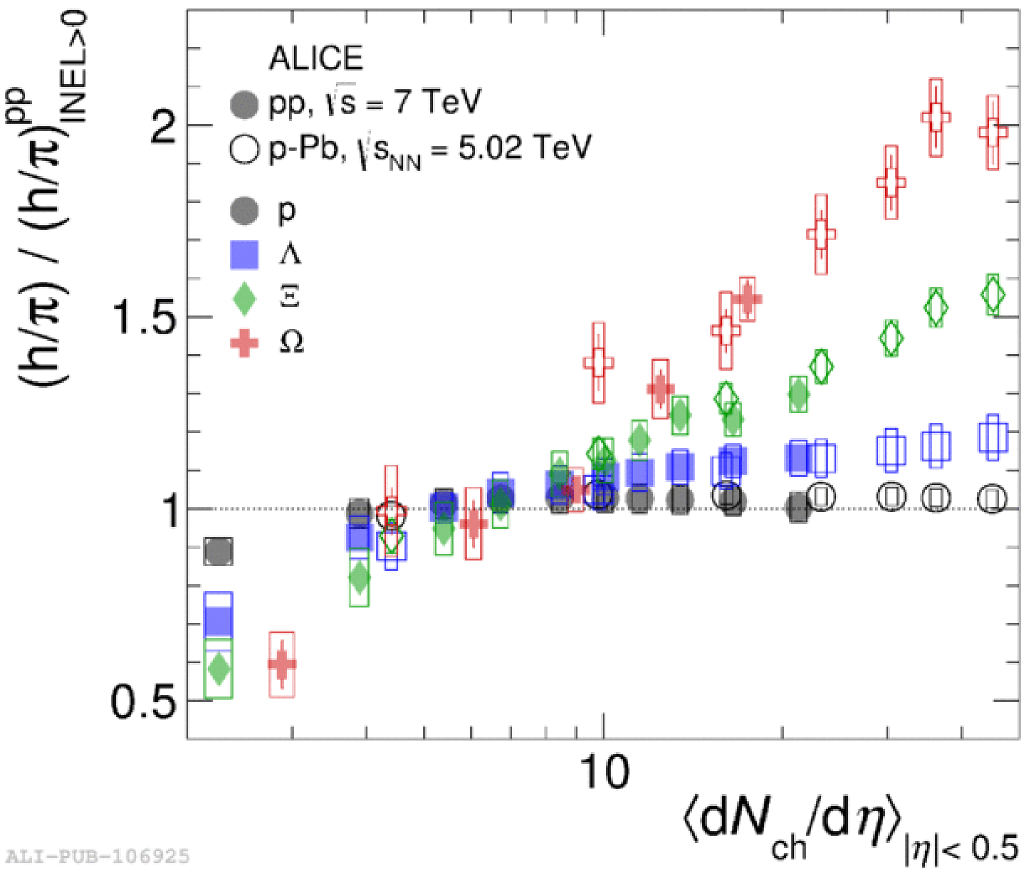
K*(892)$^{\pm}$ multiplicity-dependent analysis in pp collisions @ 13 TeV is ongoing

f_0(980) resonance production with ALICE

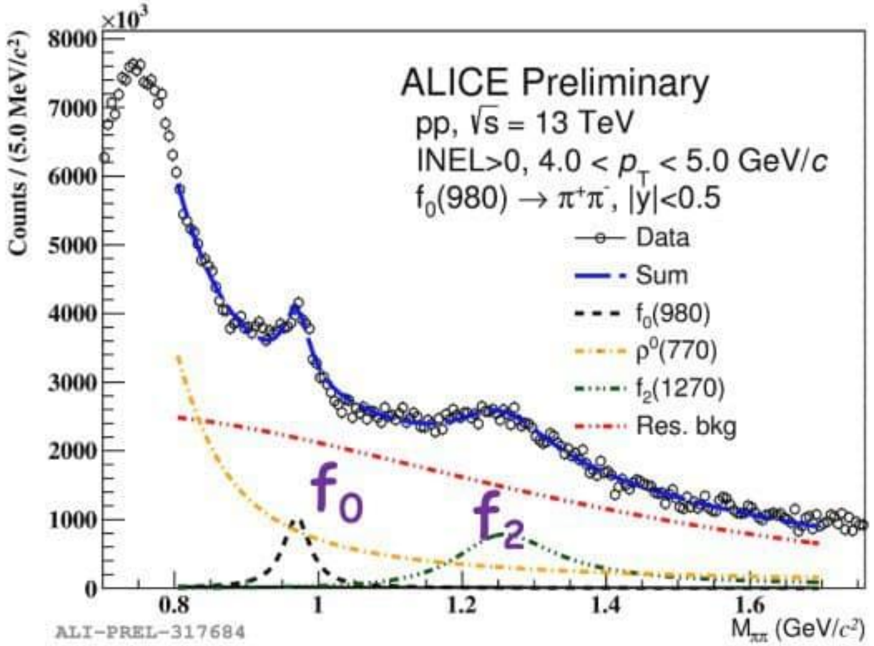
- f_0(980) quark structure is still controversial
- It has been considered as a $(q)^2(\bar{q})^2$ tetraquark and as a mixture of $q\bar{q}$ and tetraquark
- The analysis in pp collisions can provide a baseline for measurement in larger collision systems (p−Pb, Pb−Pb)
- In addition enhancement of particles containing strange quarks has been observed even in small systems

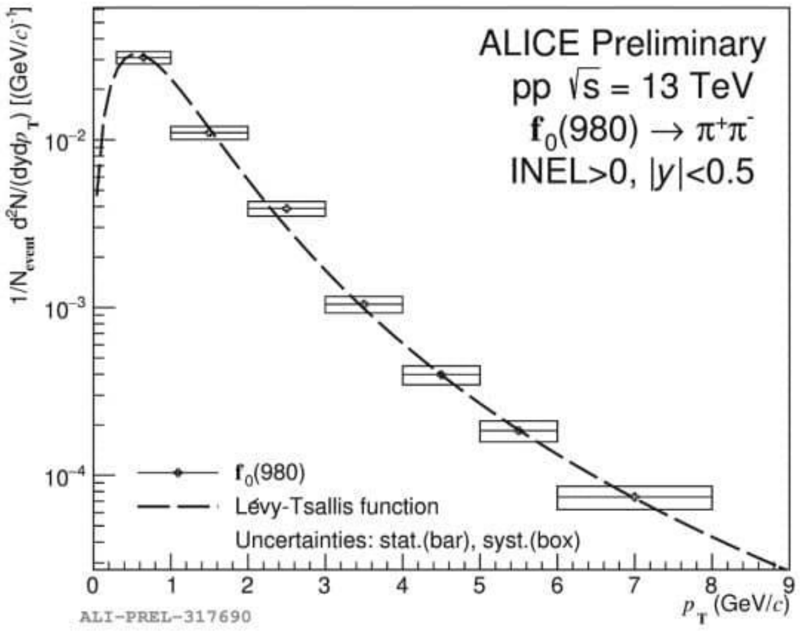
Measurement of f_0(980) enhancement would give a hint of its quark content

Nature Phys. 13 (2017) 535-539



f_0(980) resonance production with ALICE





- Resonance reconstruction via $f_0(980) \to \pi^+\pi^-$
- Large contribution by other resonances in the considered invariant mass window → very challenging signal extraction
- The f_0(980) peak is parametrized with a relativistic Breit-Wigner function
- Overlap with the broad ρ^0(770) and f_2(1270) → two additional relativistic Breit-Wigner functions are included
- The residual combinatorial background is computed with a Maxwell-Boltzmann distribution
- Results on f_0(980) production in pp @ 5.02 TeV will be soon available!

Summary

Rich set of resonances measured by ALICE for several collision systems and energies

- Resonance production is independent of collision system and collision energy at LHC energies and it is driven by the event multiplicity
- The hardening of p_T spectra with increasing multiplicity is observed also in small collision systems
- Similar $\langle p_T \rangle$ is measured for p, K^{*0} and Φ in central Pb-Pb collisions, as expected from hydrodynamics since they have similar masses. Steeper increase of $\langle p_T \rangle$ with multiplicity in small systems. Mass ordering, observed for central Pb-Pb, breaks down for small systems.
- Short-lived resonances (ρ^0 , K^{*0}, $\Sigma^{*\pm}$, and Λ^0) are suppressed in the most central heavy-ion collisions compared to small collision systems. No suppression for longer-lived resonances [$\tau(\Xi^{*0})$ = 21.7 fm/c and $\tau(\Phi)$ = 46.4 fm/c]
- Hint of suppression for short-lived resonances (ρ^0 and K^{*0}) in high multiplicity pp and p-Pb collisions → non zero lifetime of hadronic phase in small systems?
- Exotic resonances like $f_0(980)$ and Ξ(1820) are beeing explored

Thank you for your attention