Latest results on the production of hadronic resonances with ALICE at the LHC

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Sezione di Bologna

ALICE

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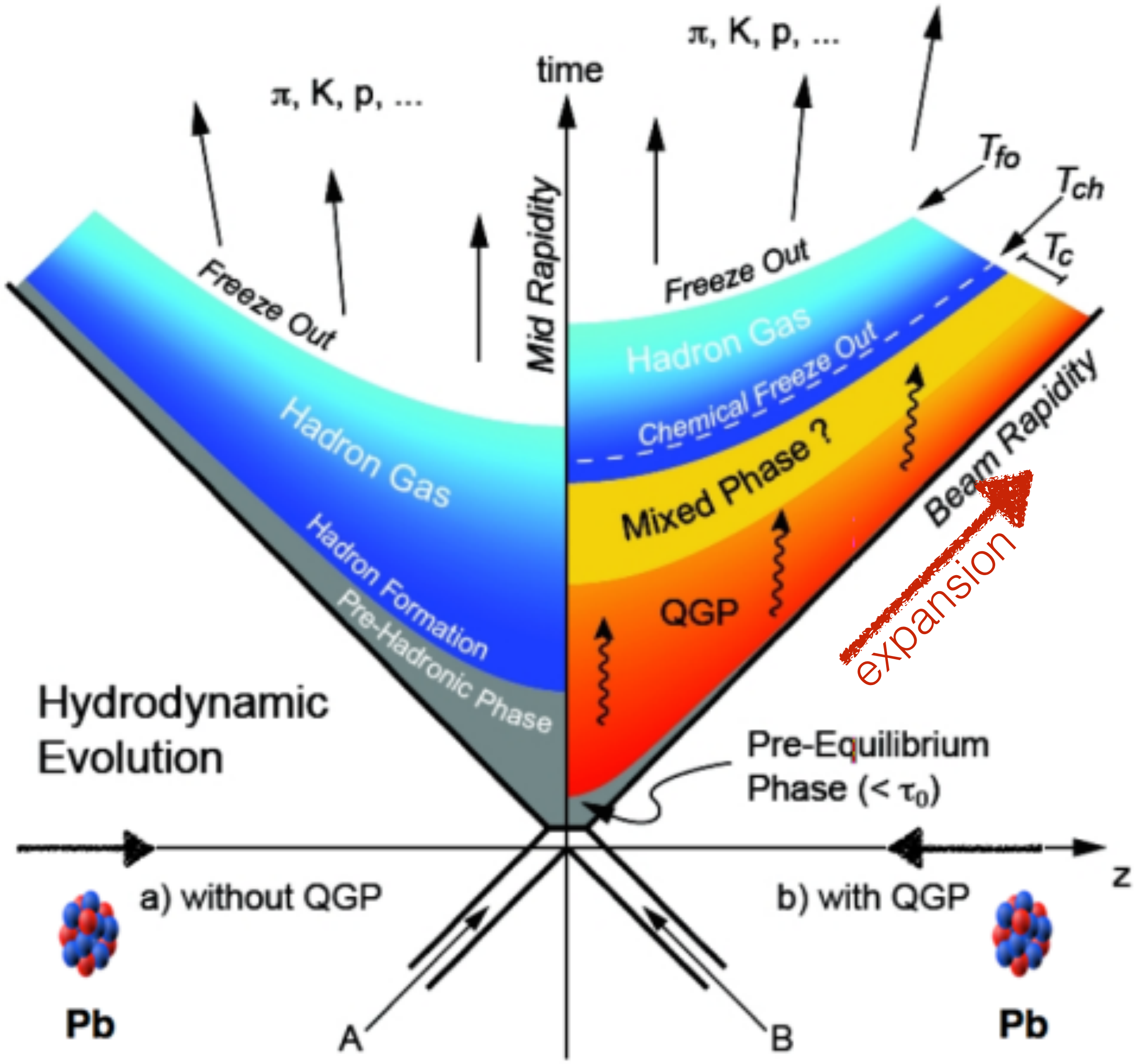
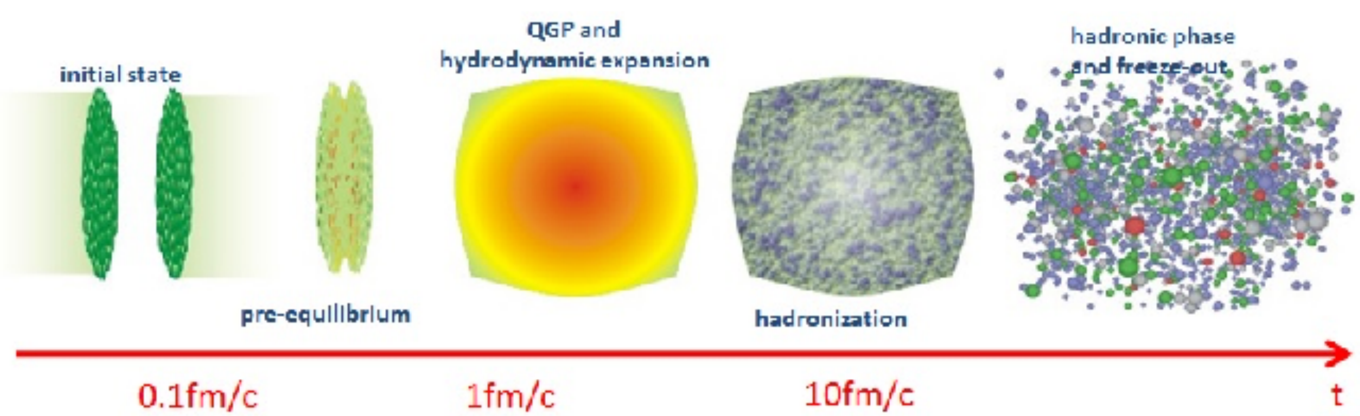
Heavy-ion collision





Initial state

- ions travelling with velocity near the speed of light

Nuclei collide

- parton-parton scattering: a large amount of energy is deposited in a small volume of space

Partonic phase

- QGP ~ few fm/c

Hadronisation

- QGP to hadron gas

Chemical freeze-out

- inelastic collisions stop
- fixed chemical composition
- followed by hadron-resonance gas

Kinetic freeze-out (~10 fm/*c*)

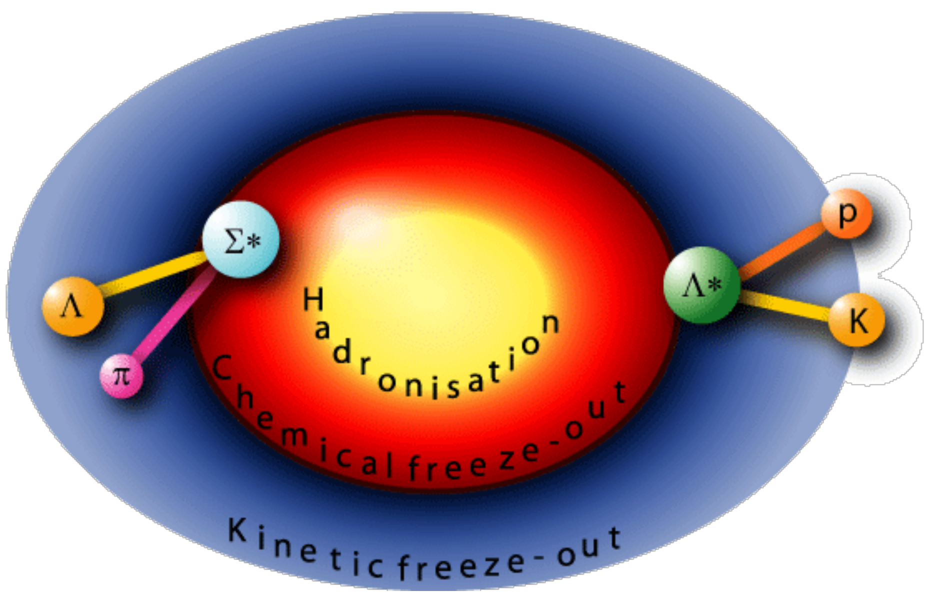
- no more collisions
- fixed momentum distributions

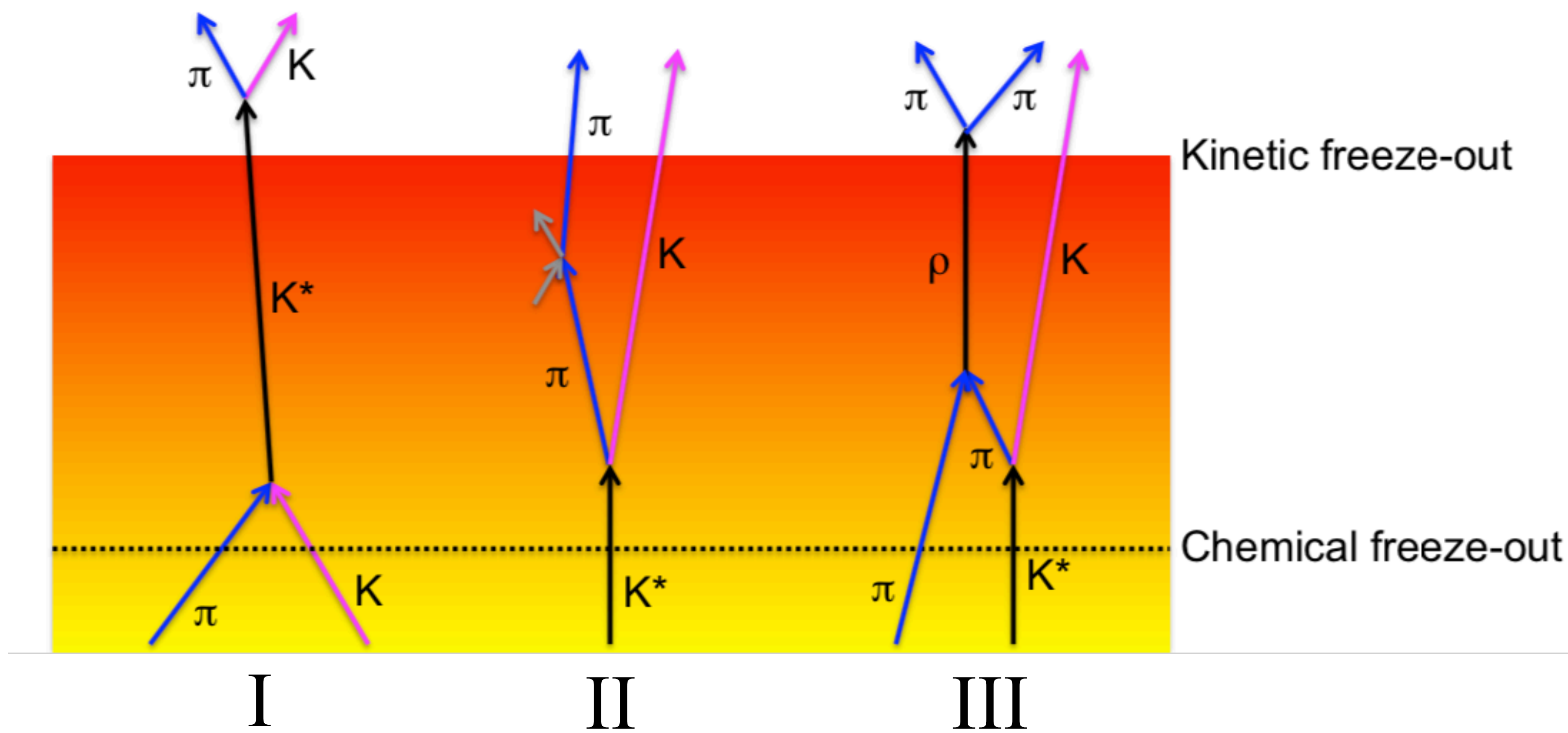
Free hadrons

- experimental measurement

Hadronic phase of heavy-ion collisions

The phase **between chemical and kinetic freeze-out** can be probed with hadronic resonances (short lifetimes ~ τ of hadronic phase)



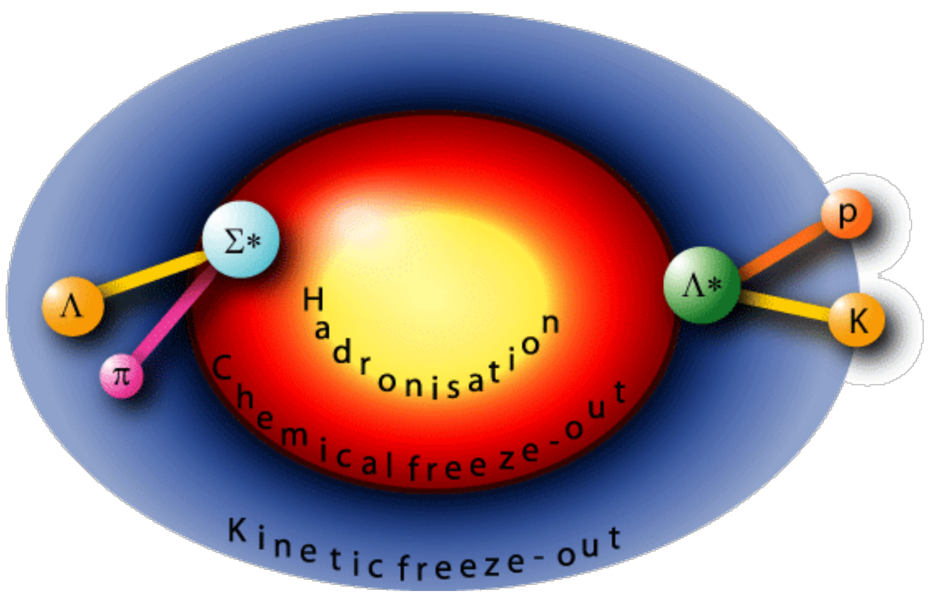


Elastic **re-scattering** of decay daughters smears out mass peak (case - II)
Pseudo-elastic scattering through a resonance state (e.g. ρ) (case - III)
→ **signal loss** of original resonance

Re-generation by pseudo-elastic scattering through resonance state (case - I)
(eg: Kp ⟶ Λ(1520) ⟶ Kp)
→ **signal gain**

Hadronic phase of heavy-ion collisions

The phase **between chemical and kinetic freeze-out** can be probed with hadronic resonances (short lifetimes ~ τ of hadronic phase)



Final yield at kinetic freeze-out depends on
- chemical freeze out temperature (T_{ch}) : fixes initial yield
- time span between kinetic and chemical freeze-out
- lifetime of resonance and scattering cross sections of decay daughters

resonance (excited state) yield can be compared to **long-lived particles** with **similar quark content** but different masses

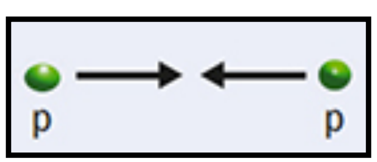
resonance yields encode the **effects of interactions** in the **hadronic phase** created in heavy-ion collisions

Resonances in ALICE

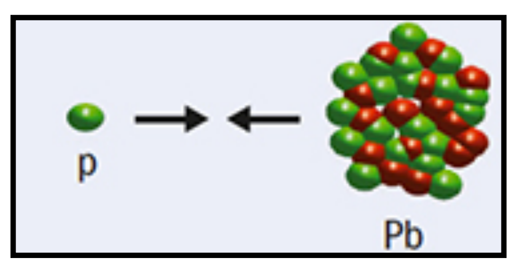
Light flavoured hadronic resonances

- chemical composition **u/d/s** quarks

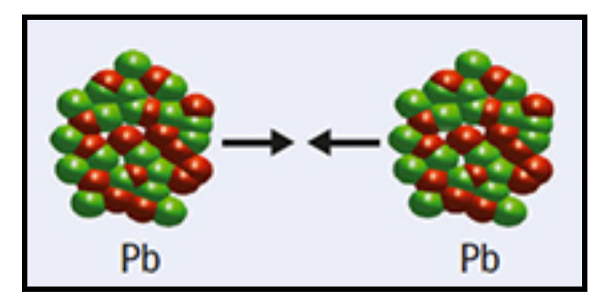
Resonance	$\rho(770)^0$	$K^*(892)$	$\Sigma(1385)$	$\Lambda(1520)$	$\Xi(1530)^0$	$\Phi(1020)$
Lifetime (fm/*c*)	1.3	4.2	5.0 - 5.5	12.6	21.7	46.4
Quark cont.	$(uu+dd)/\sqrt{2}$	$d\bar{s}$	uus/dds	uds	uss	$s\bar{s}$
Decay	$\pi\pi$	$K_s^0\,\pi$	$\Lambda\pi$	pK	$\Xi\pi$	KK
BR(%)	100	33.3	87	22.5	66.7	49.2



pp collisions
$\sqrt{s}$ = **2.76, 5, 7, 8, 13** TeV

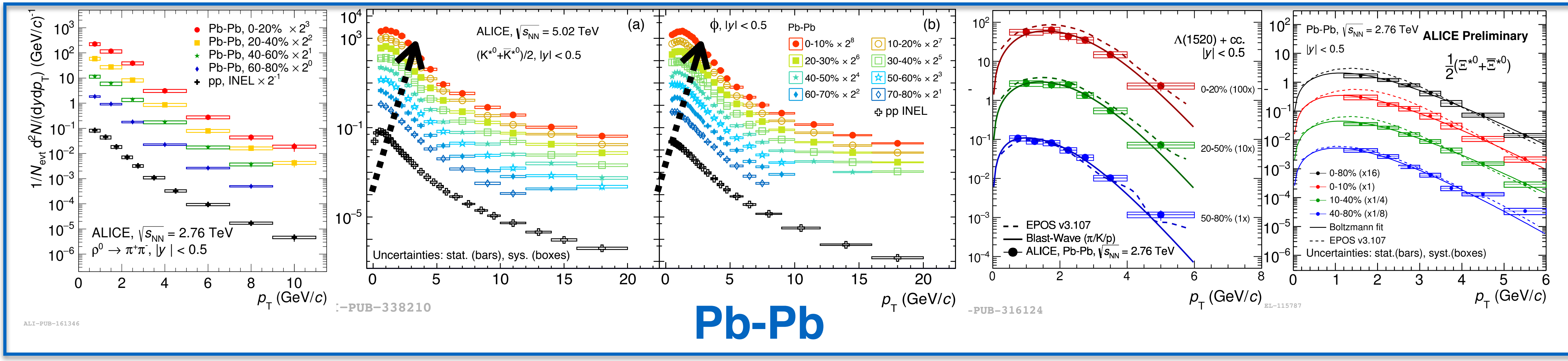


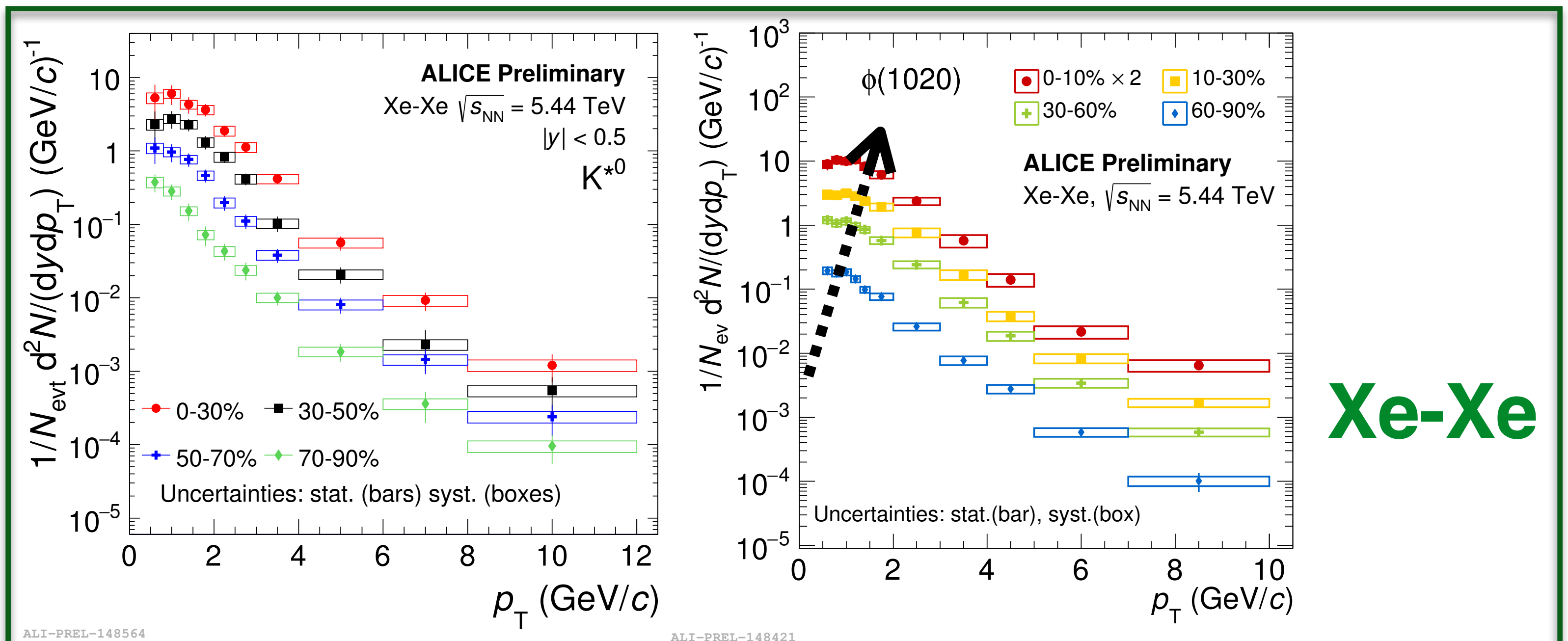
p-Pb collisions
$\sqrt{s_{NN}}$ = **5.02, 8.16** TeV



Pb-Pb (Xe-Xe) collisions
$\sqrt{s_{NN}}$ = **2.76, 5.02, (5.44)** TeV

Plenty of p_T spectra: Heavy-ion collisions





- Multiplicity event class definition based on forward/backward V0 estimator
- $\langle dN_{ch}/d\eta \rangle$ measured in central rapidity region for each class

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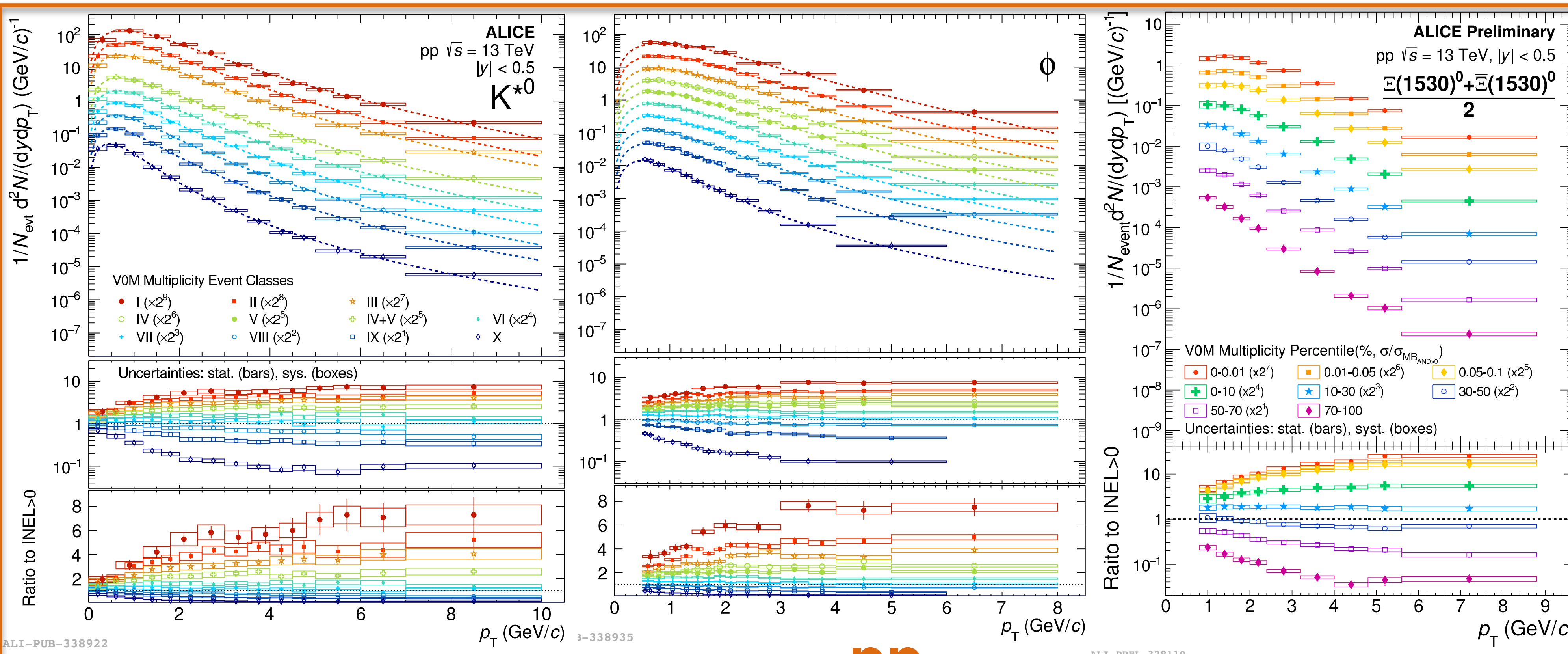
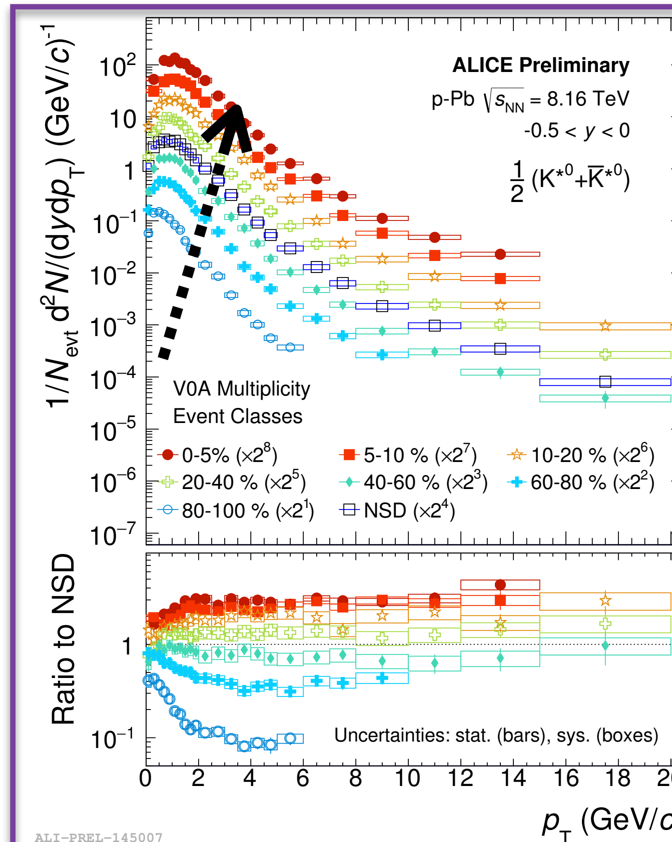
Phys. Rev. C 91 (2019) 024905
arXiv:1910.14419

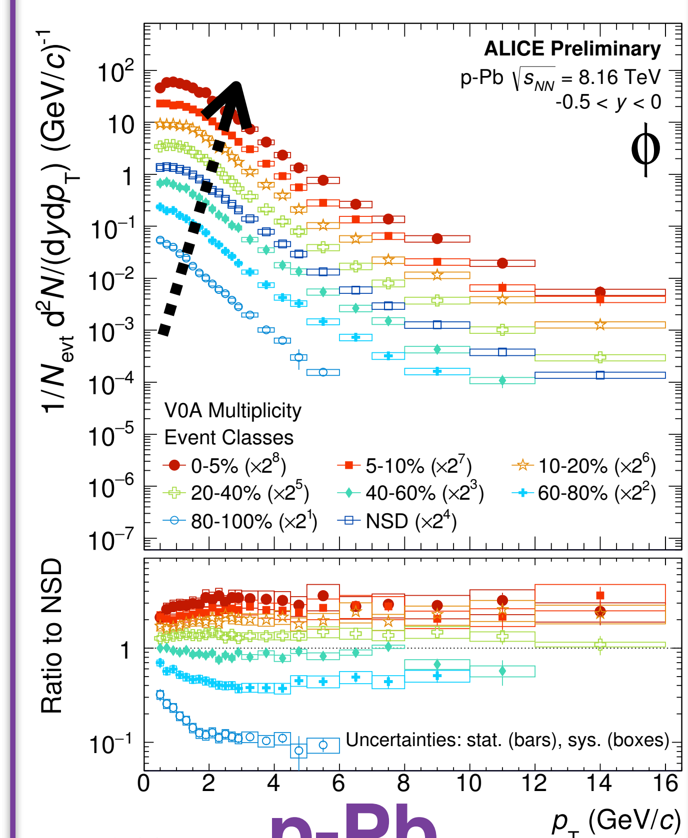
- ***p_T-spectra***
  → get harder with increasing multiplicity/collision centrality for $p_T < 5$ GeV/c
  → similar shape across multiplicity/collision centrality for $p_T > 5$ GeV/c

Plenty of p_T spectra: pp and p-Pb collisions



pp





p-Pb

p_T-spectra

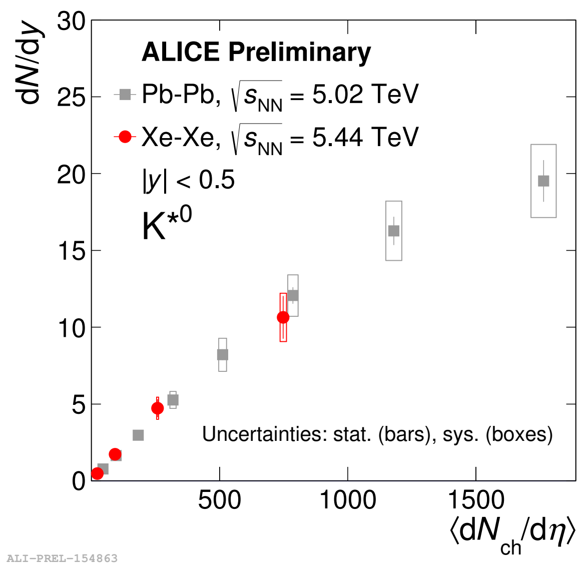
→get harder with increasing multiplicity/collision centrality for p_T < 5 GeV/c

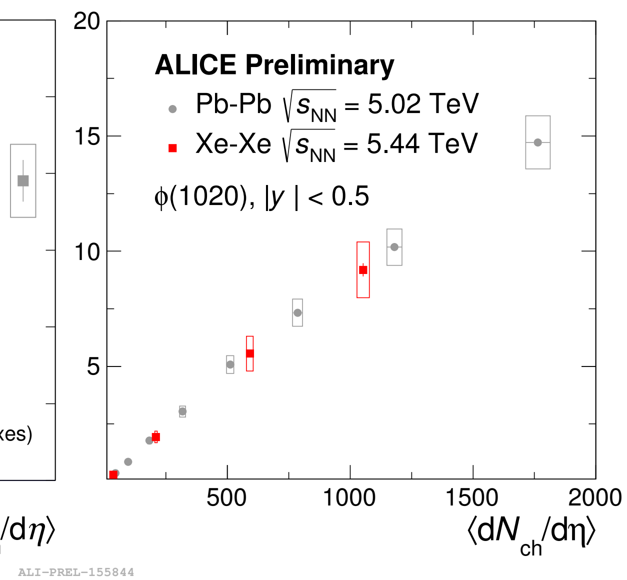
→ similar shape across multiplicity/collision centrality for p_T > 5 GeV/c

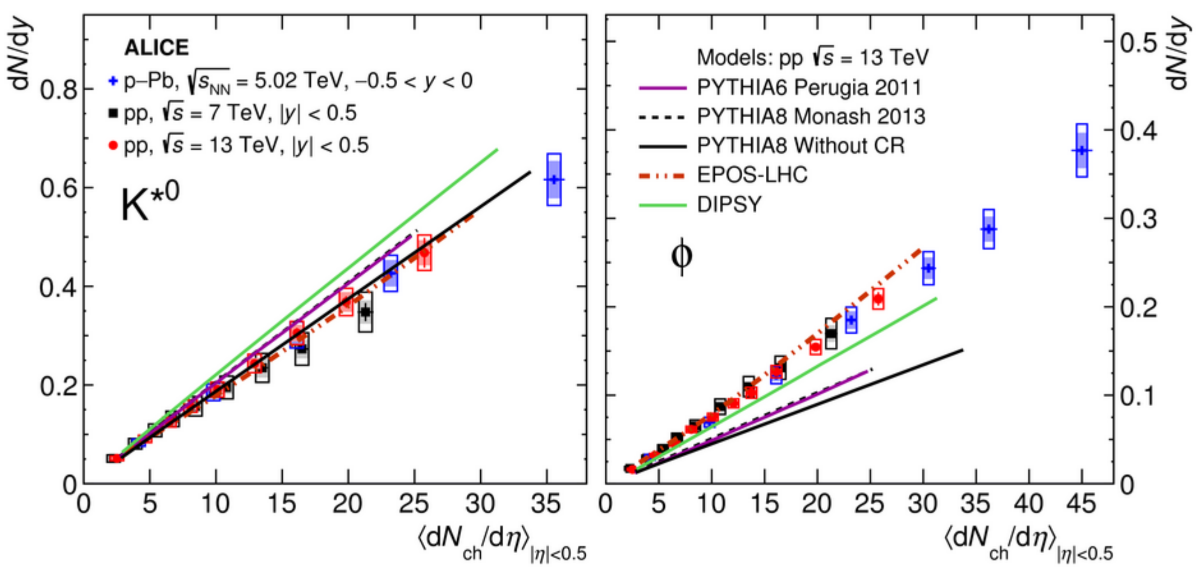
→ qualitatively similar hardening in Pb-Pb, p-Pb and pp collision systems

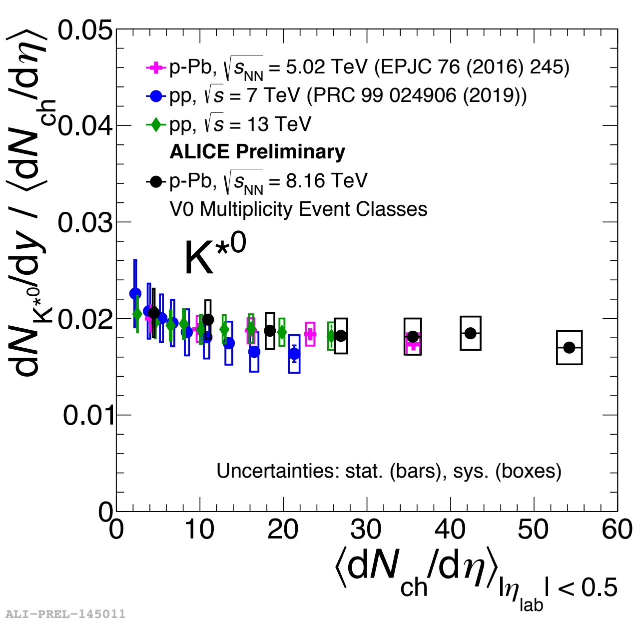
arXiv:1910.14397

Integrated Yields - d*N*/d*y*









- **K* and ϕ: linear increases** towards higher multiplicity
- **K*: in agreement** with prediction of EPOS3 model and Pythia8 without colour reconnection
  - charged particle normalised yield is independent to collision energy and system
- **ϕ: is slightly overestimated** with EPOS3 and underestimated by DIPSY model predictions
- Charge particle **multiplicity class determines** the **resonance production independent** of collision energy and system

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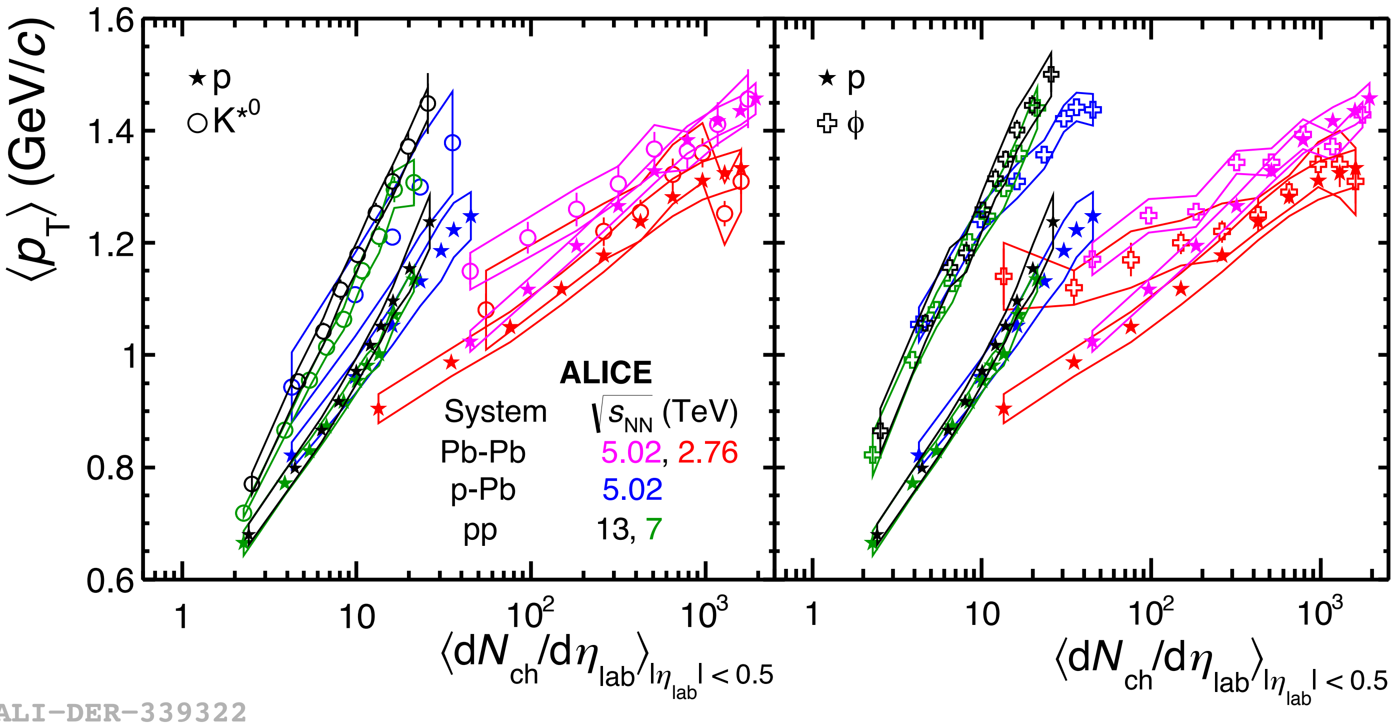
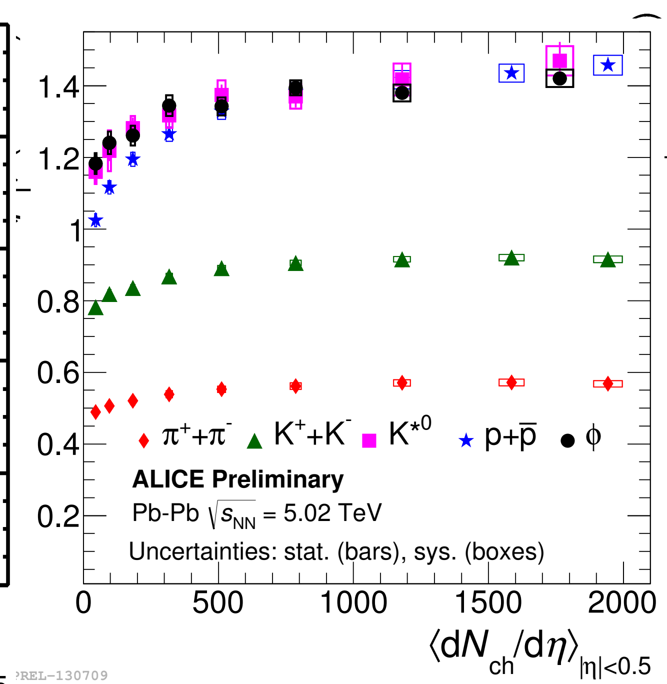
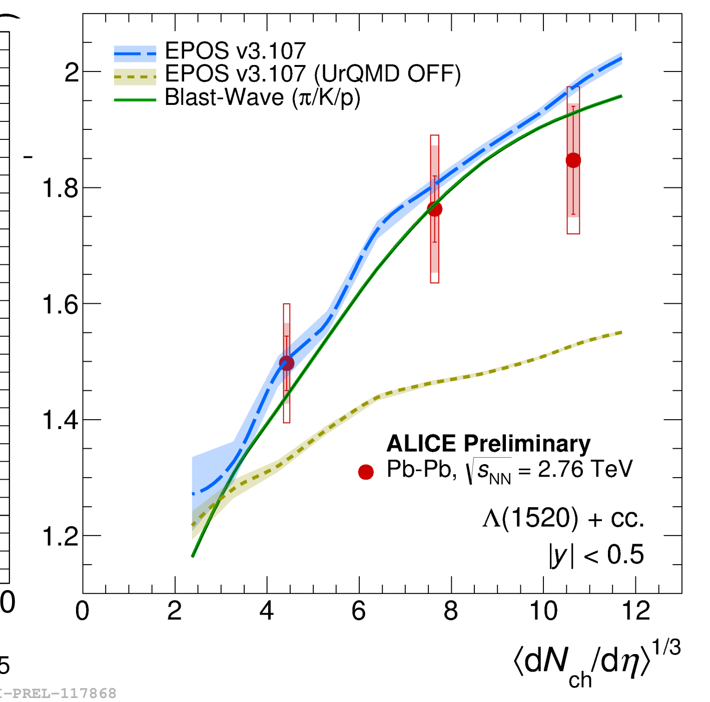
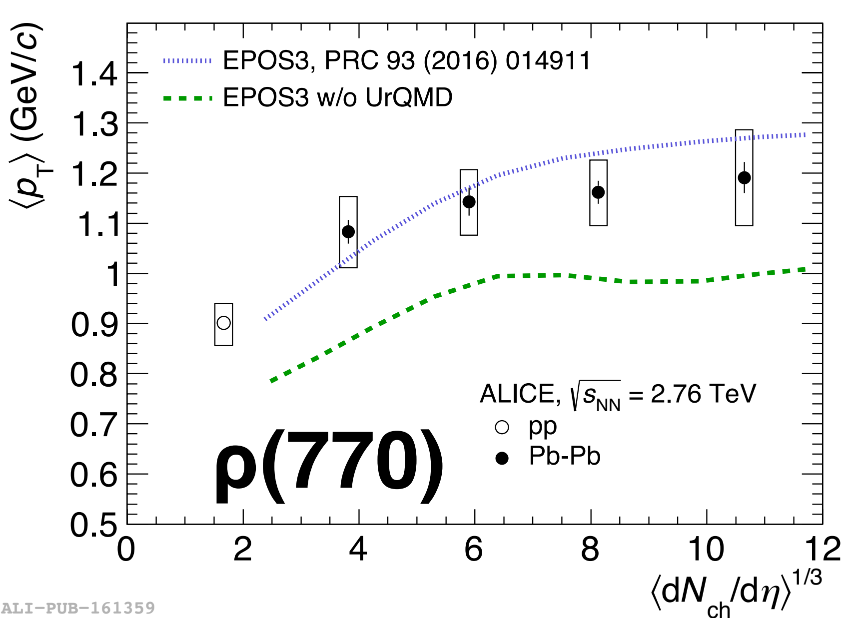
Mean Transverse Momentum - ⟨p_T⟩









- **ϕ, K*: increases** towards higher multiplicity
  - **consistent values** in 2.76 and 5.02 TeV Pb-Pb collision data

- **Follows mass ordering**
  - indicative of radial flow in central
  - violated in peripheral (ϕ > p)

- **ρ, Λ(1520): in agreement** with EPOS3 (with UrQMD) and Blast Wave (π/K/p)
  - EPOS3 fails to predict the data if UrQMD is off

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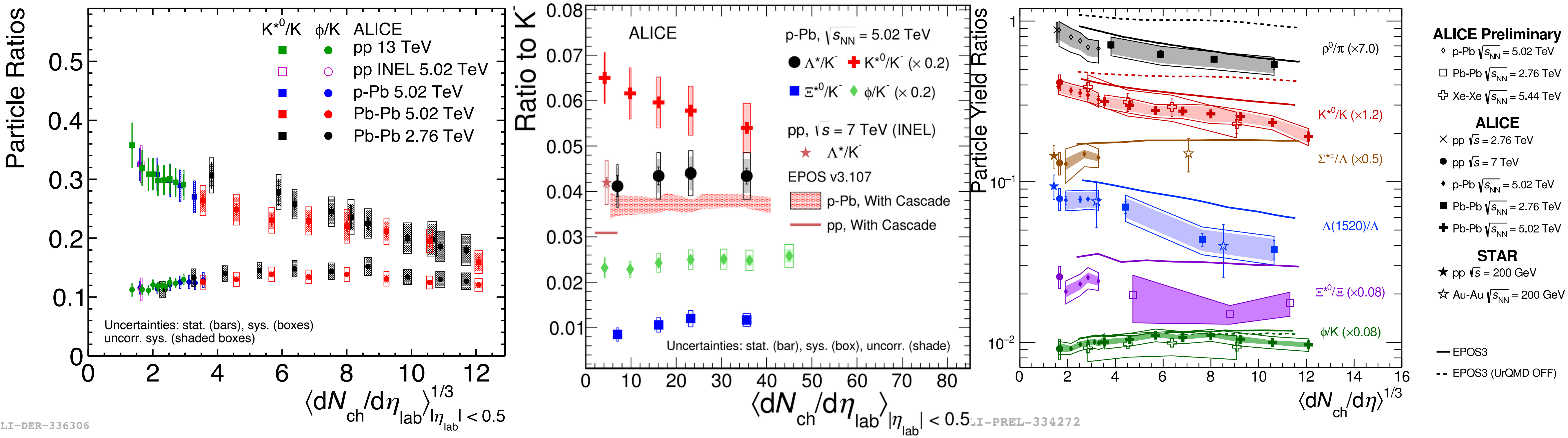
Particle ratio



- **Small collision system (pp, p-Pb)**
  - **φ/K, Λ(1520)/K, Ξ*0/Ξ** ratios are **independent** of charged **particle multiplicity**
  - **ρ/π, K*/K** shows a hint of suppression (possible re-scattering effect?)

- **Heavy-Ion collision system (Pb-Pb, Xe-Xe)**
  - **ρ/π, K*/K, Λ(1520)/Λ, (Ξ*0/Ξ)** ratios are suppressed (slightly) with respect to pp, p-Pb and peripheral Pb-Pb: Dominance of re-scattering compared to re-generation
  - **φ/K no suppression** suggest decay outside of medium, no significant re-scattering effect
  - trends qualitatively described by EPOS3+UrQMD model
  - EPOS3 fails to predict the data if UrQMD is off

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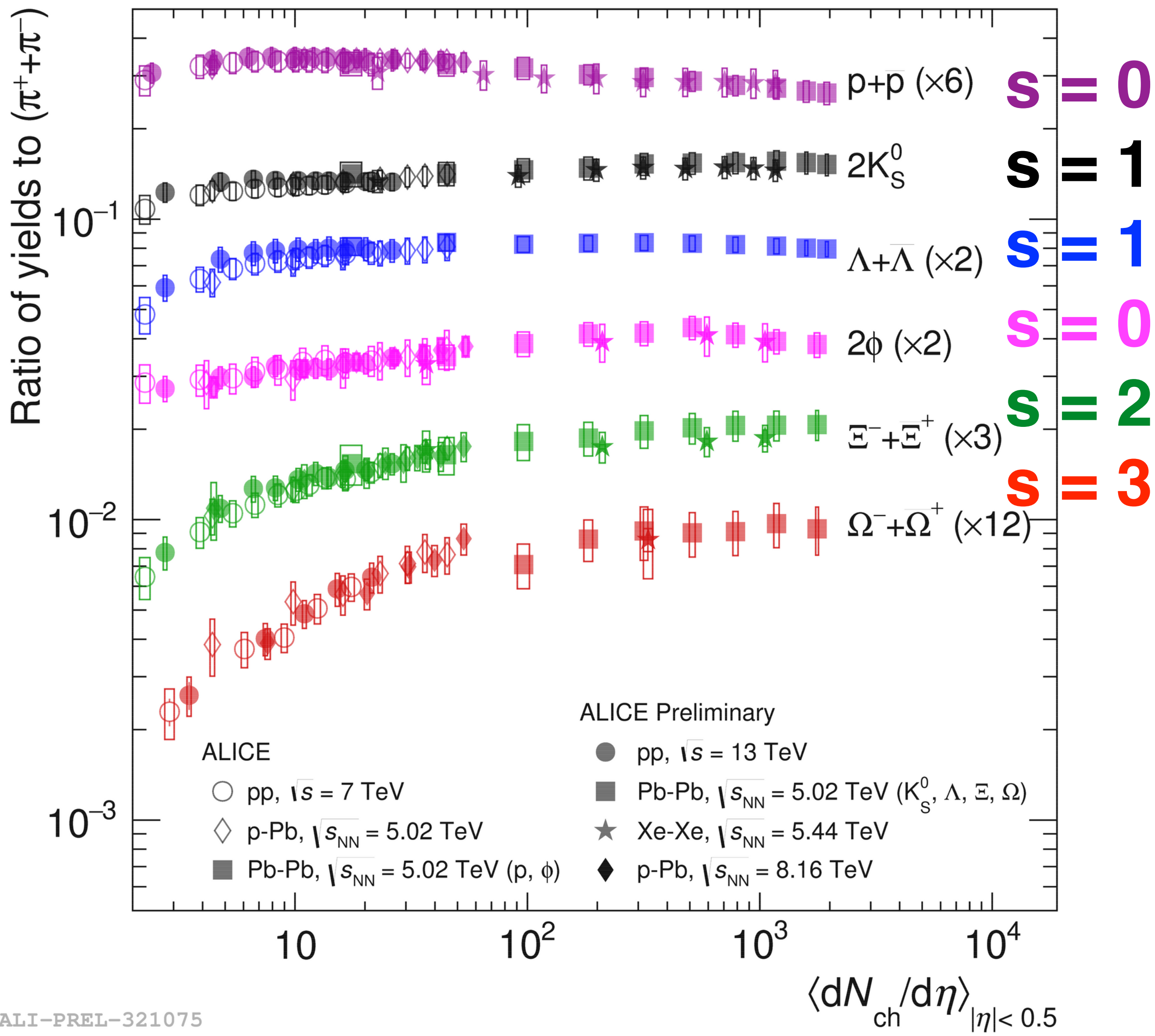
Strangeness production



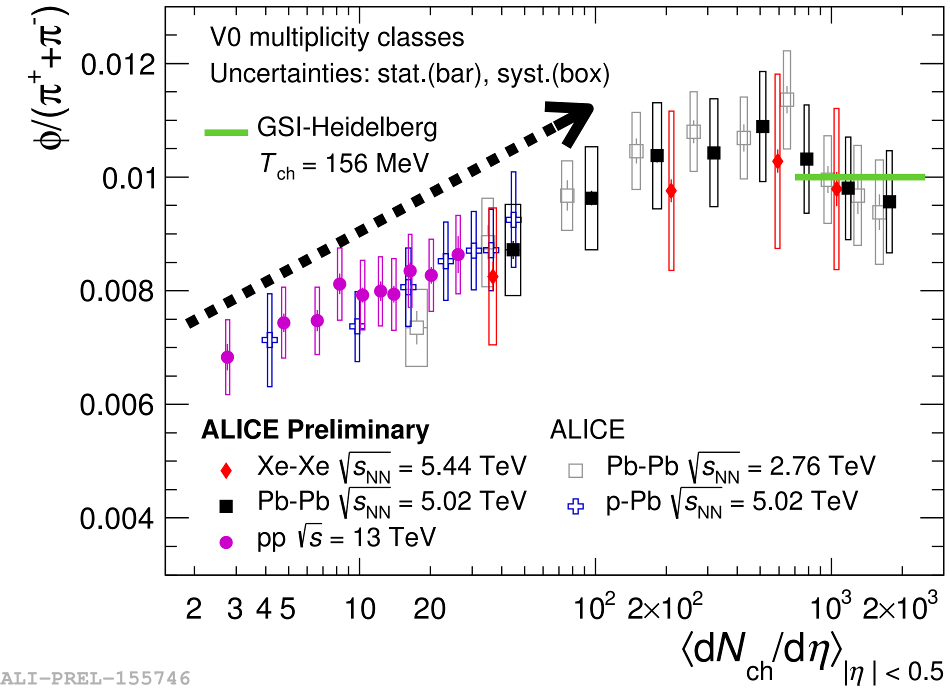
- **Strangeness enhancement**
  - one of the first proposed QGP signatures
  (Rafelski, PRL 48 (1982) 1066)
- **Strange particle** production in pp relative to pions **increases** significantly with $dN_{ch}/d\eta$
  - remarkable **agreement** with **p-Pb**
  - **smooth evolution** from low multiplicity pp, p-Pb **reached Pb-Pb values**
- Phenomenon related to event multiplicity of the **final system**

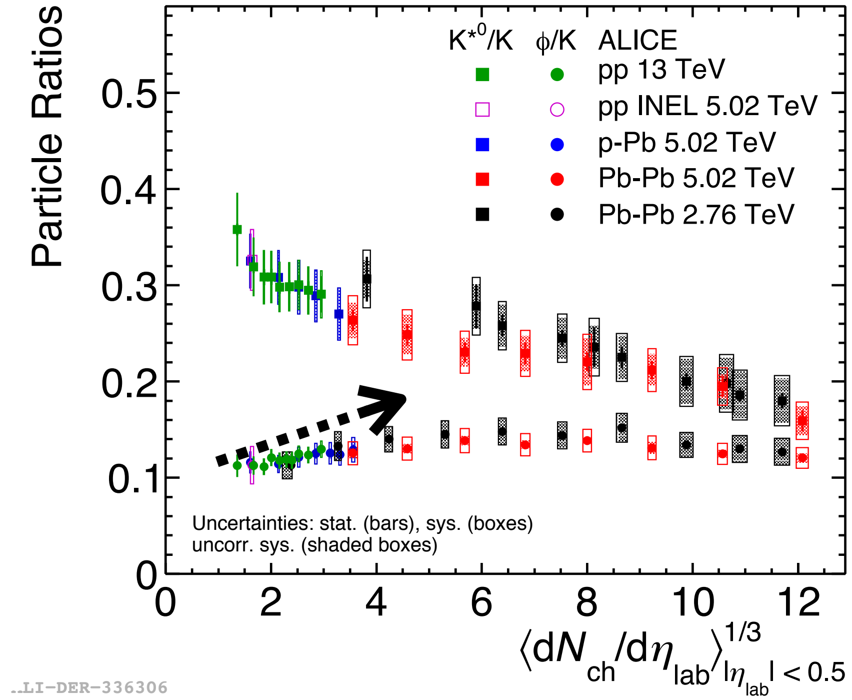
- Strangeness-content hierarchy: **not strange not enhanced!**
  - **Ξ(dss) enhanced, Ω(sss) more enhanced**
  - indicate that strangeness control the production rate rather than mass

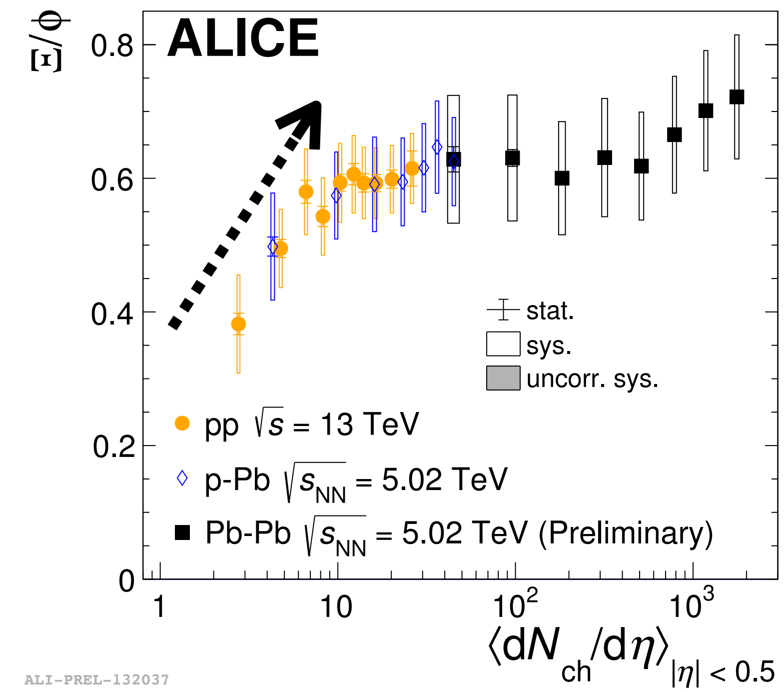
ALICE, Nature Phys. 13 (2017) 535
Phys. Lett. B 758 (2016)
Phys. Lett. B 728 (2014)

- **Evolution of ϕ ($s\bar{s}$):** behave as strangeness = 2 or 0?

Strangeness production: ϕ-meson







- Ratio of **ϕ ($s = 0$) to π ($s = 0$)**
  - smooth increase from pp to p-Pb values and saturates in Pb-Pb
  - consistent with thermal model predictions

- Ratio of **ϕ ($s = 0$) to K ($s = 1$)**
  - slight **increase in pp** which suggests to behave S > 1 particle

- Ratio of **Ξ ($s = 2$) to ϕ ($s = 0$)**
  - slight **increase in pp, p-Pb**, S < 2 particle
  - flat for multiplicity of Pb-Pb, S ~ 2 particle

- **ϕ behave as if it had effective strangeness 1 - 2 units**

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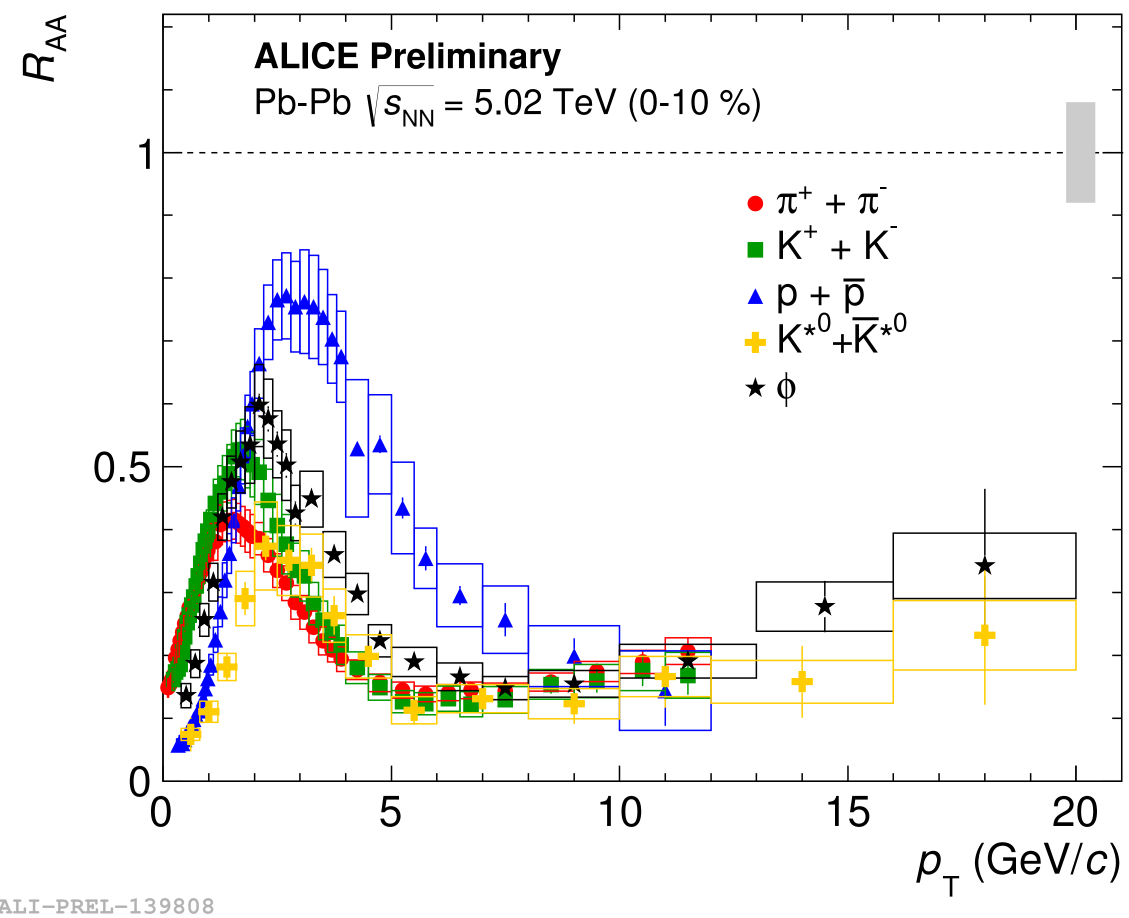
Nuclear Modification factor



- **partons** produced by high Q^2 processes **lose their energy while traversing the medium**

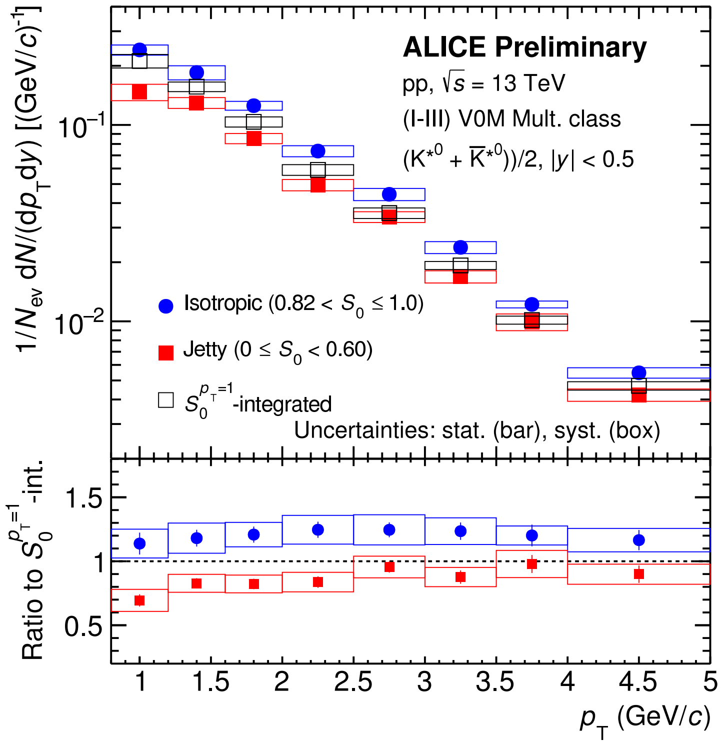
- **suppression of high-pT production**
  - can be observed by comparing with pp results
  - observable is nuclear modification factor **(R_{AA})**
  - **R_{AA} = 1** for hard processes in absence of nuclear medium effects
  - confirmed in Pb-Pb collisions at LHC (direct γ, $W^{\pm}$, Z^0)

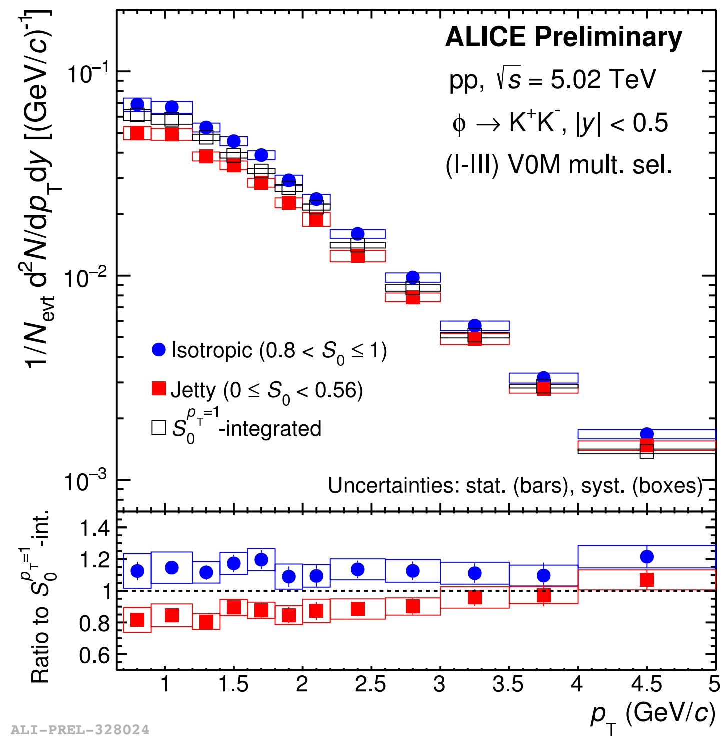
$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{(1/N_{evt}^{AA}) d^2N^{AA}/dydp_T}{(1/N_{evt}^{pp})) d^2N^{pp}/dydp_T}$$

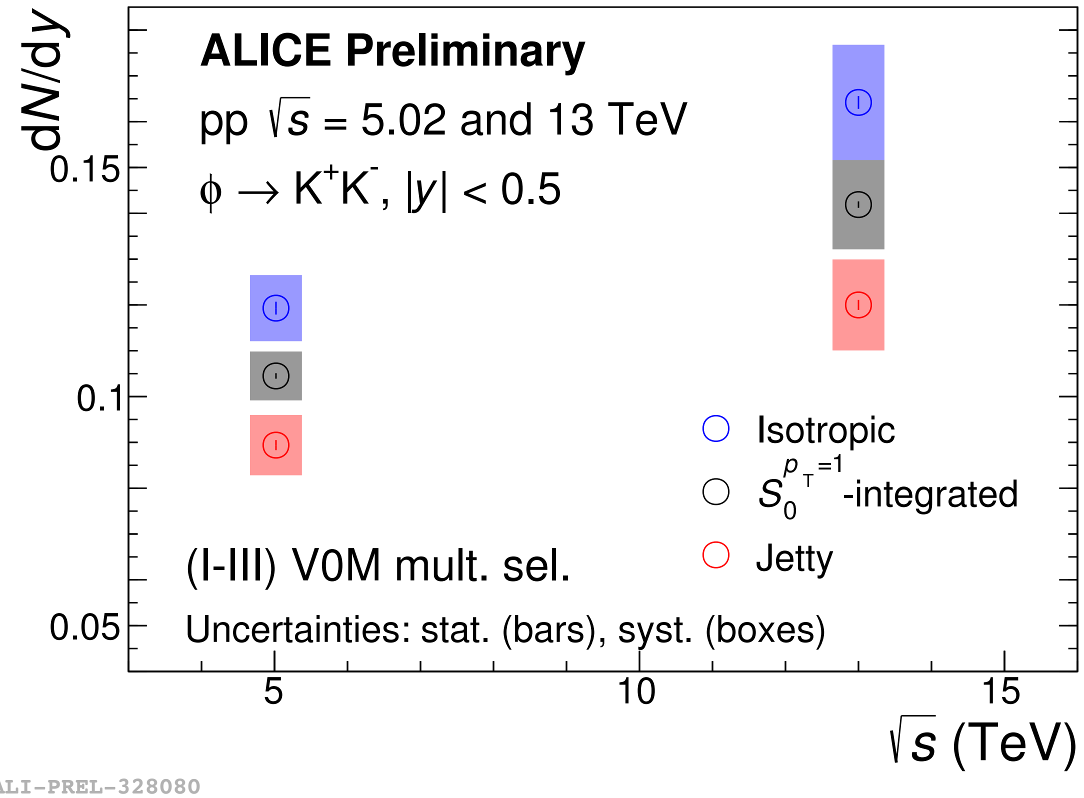
- ***p_T* > 8 GeV/*c*** all light-flavoured hadrons ($\pi^{\pm}$, $K^{\pm}$, p), K*, ρ and ϕ-meson are **equally suppressed** by a factor of 4-5
  - not dependent on hadron species/properties like mass, quark content or baryon number

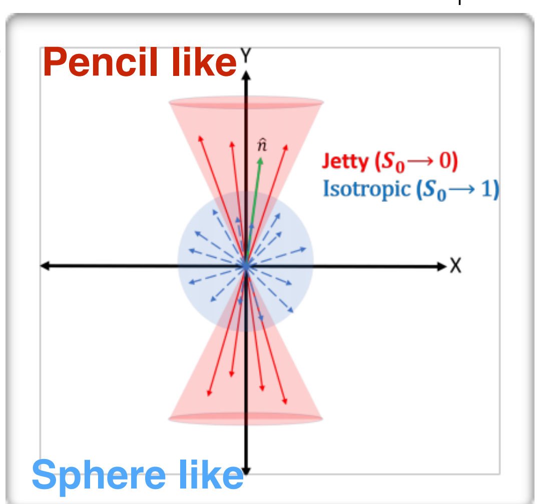
- ***p_T* < 8 GeV/*c* : Baryon-meson splitting**
  - *K**, ϕ are closer to other mesons than to baryons
  - possible mass ordering among mesons

Transverse spherocity









Spherocity is defined for a unit vector $\hat{n} = (n_x, n_y, 0)$

such that $$S_o = \frac{\pi^2}{4} \min_{\hat{n}=(n_x,n_y,0)} \left(\frac{\sum_i |\vec{p}_{Ti} \times \hat{n}|}{\sum_i p_{Ti}} \right)^2$$

$S_0(p_T=1) \to 0$ jetty limit

$S_0(p_T=1) \to 1$ isotropic limit

- a new observable which **reduces the bias** in sphericity calculations for **leading neutral particle** in the collision, measured unweighted transverse spherocity
  - significantly different yield among different sphericity classes
  - K* and ϕ production is larger at low Pt for isotropic events as compared to jetty events
  - integrated yield of ϕ meson is maximum for isotropic events at 5.02 and 13 TeV pp collisions

Summary

- **A rich set of resonances measured by ALICE in various collisions system and energies**
  -observed hardening of p_T spectra, event multiplicity class determines the particle production independently of collision system and energy

- **Suppression for most short-lived resonances: ρ, K*, Λ(1520)**
  - in central Pb-Pb collisions with respect to pp, p-Pb and peripheral Pb-Pb
  - suggests that re-scattering is dominant over regeneration

- **No Suppression for longer lived Φ-meson**
  - suggest decay outside of medium and re-scattering effects not significant
  - behave as a particle of effective strangeness 1-2 units

- **Parton energy loss is independent of hadron species or properties**

- **Results support the existence of a hadronic phase**
  - lasting long enough to cause a significant reduction of the reconstructible yield of short lived resonances