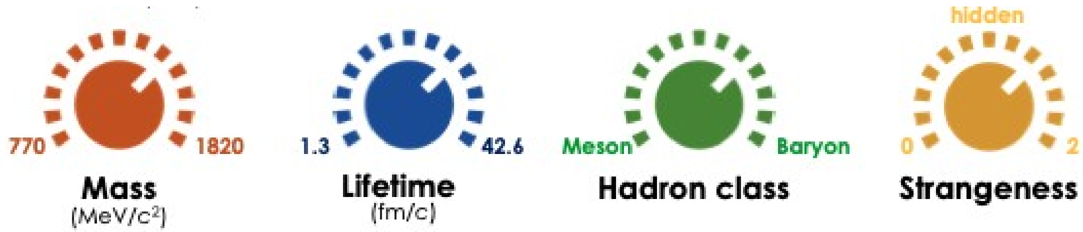
Latest results on hadronic resonance production with ALICE at the LHC

Dukhishyam Mallick (for the ALICE Collaboration)
National Institute of Science Education and Research
HBNI, Jatni, INDIA

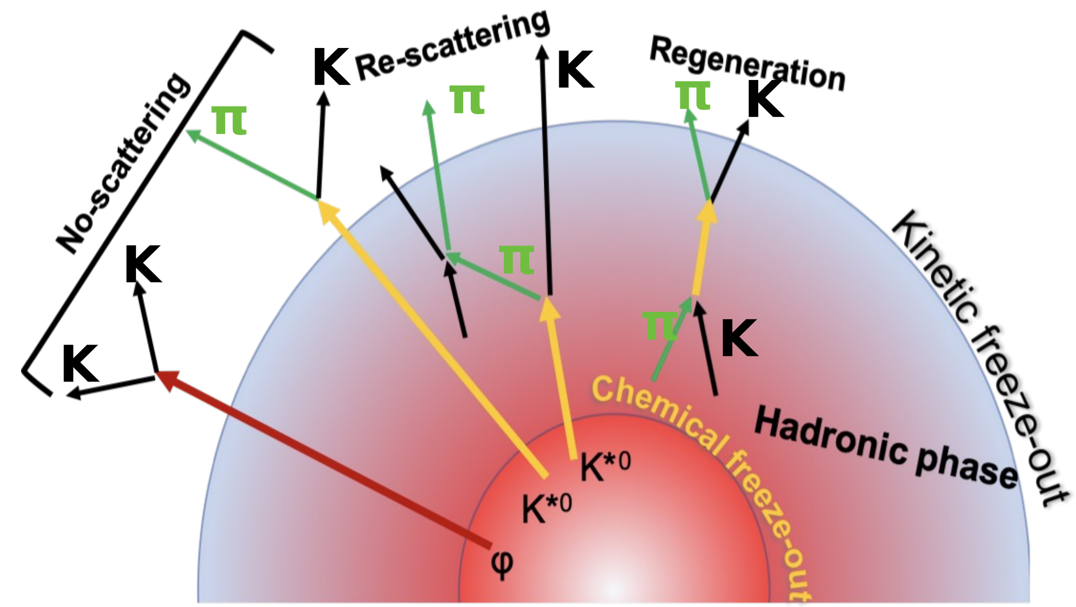
Why resonances ?

Lifetime (fm/c): ρ^0 (1.3) < $K^{*\pm}$ (3.6) < K^{*0} (4.16) < $\Sigma^{*\pm}$ (5.0-5.5) < Λ^* (12.6) < Ξ^{*0} (21.7) < ϕ(46.2)



Particles that are unstable against decay by the **strong interaction** (lifetime: ~10^{-23} seconds (~1fm/c))

Hadronic phase: Phase between chemical and kinetic freeze-out



Physics topics:

i. Hadrochemistry of particle production

ii. Modification of yields: Rescattering vs regeneration

iii. Estimate the lifetime of the hadronic phase

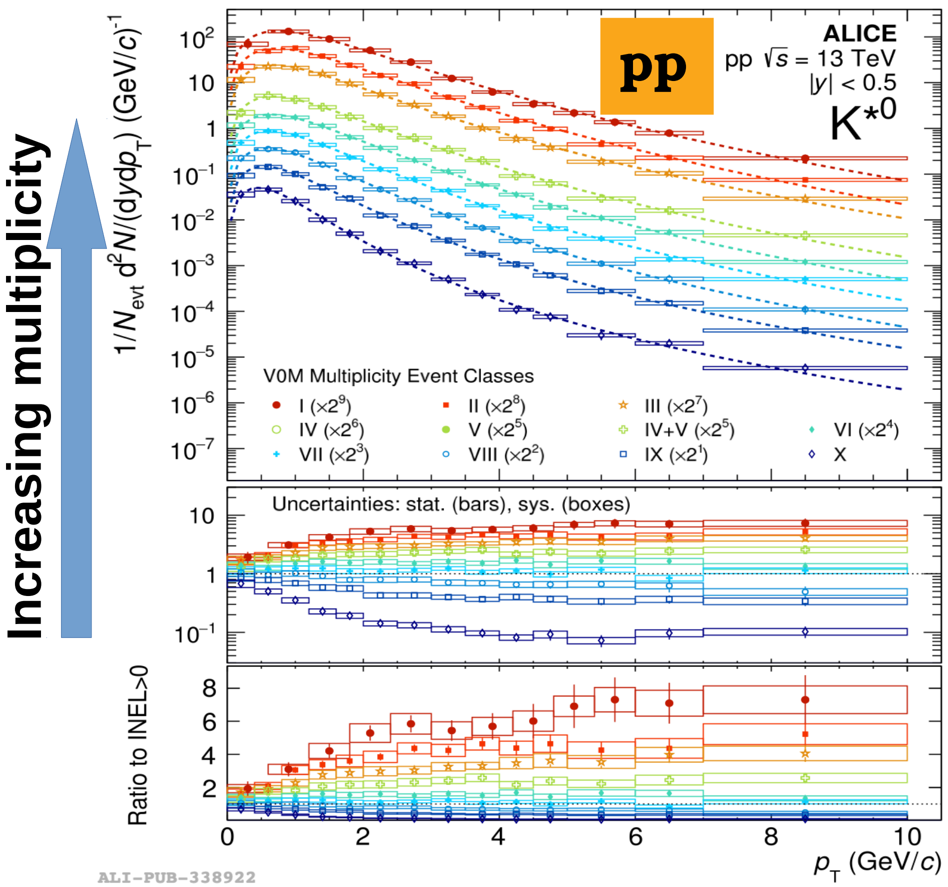
iv. Study of in medium energy loss of partons

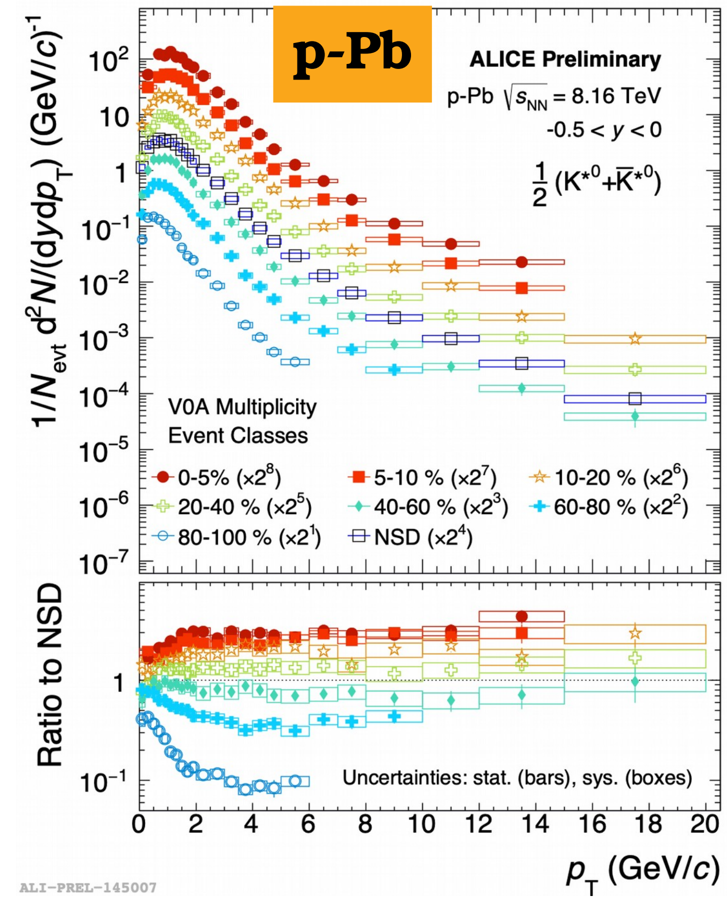
v. Spin alignment: probing initial condition of collisions

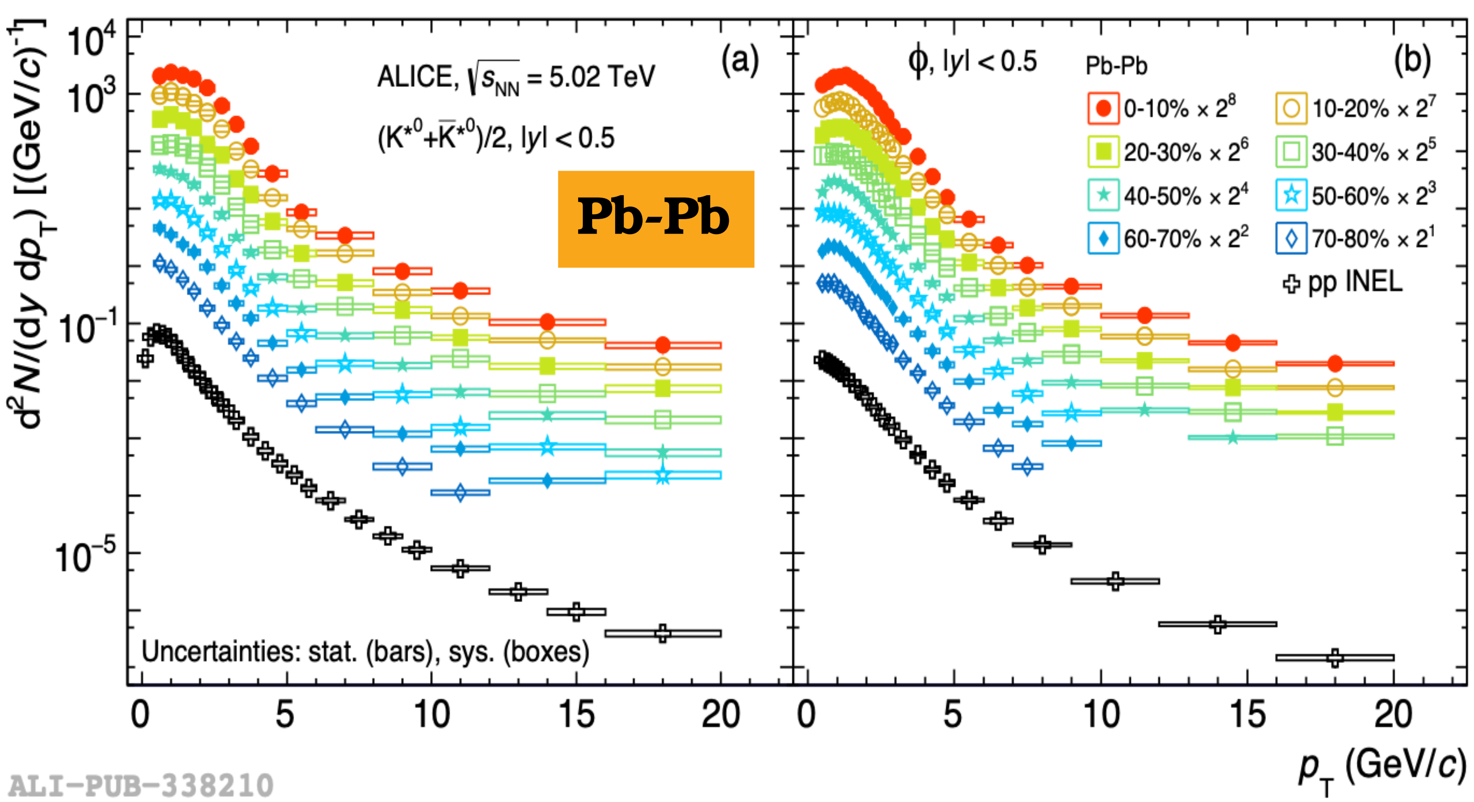
References:

1. PLB 802 (2020) 135225
2. PLB 807 (2020) 135501
3. Phys. Rev. Lett. 125, 012301 (2020)
4. Phys. Rev. C 102 (2020) 024912
5. arXiv:2105.05760
6. arXiv:2106.13113

p_T spectra in high energy collisions







[1] PLB 807 (2020) 135501

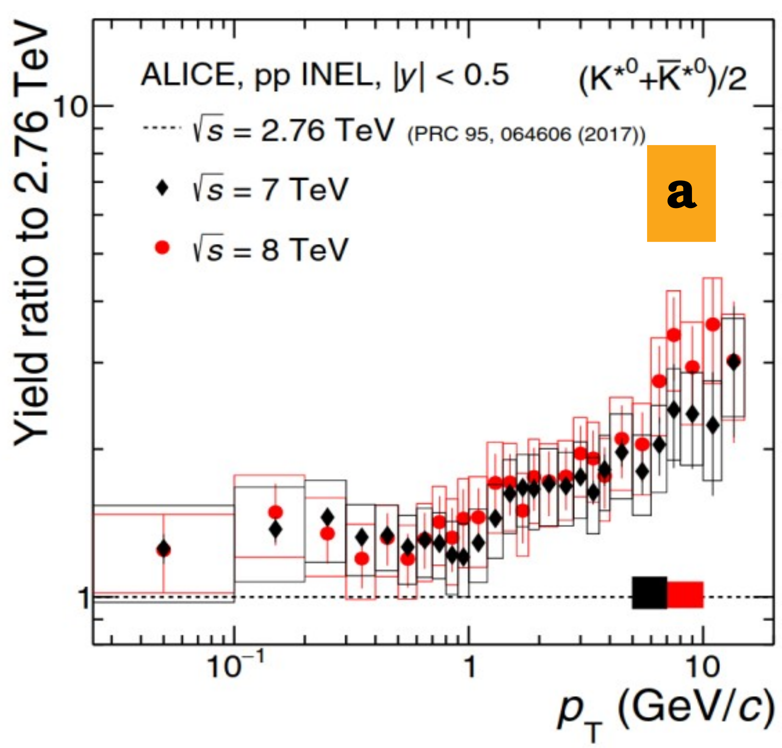
[2] *Eur.Phys.J.C* 76 (2016) 5, 245

[3] arXiv:2106.13113

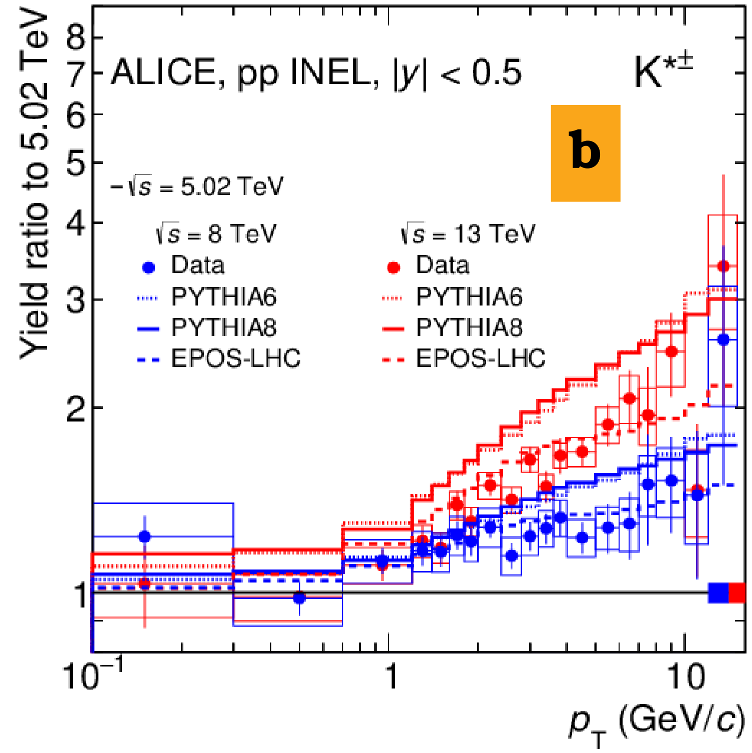
- Spectra get harder as multiplicity (or centrality) increases
- Evolution of spectral shape is qualitatively similar in pp [1], p-Pb[2] and Pb-Pb[3] collisions

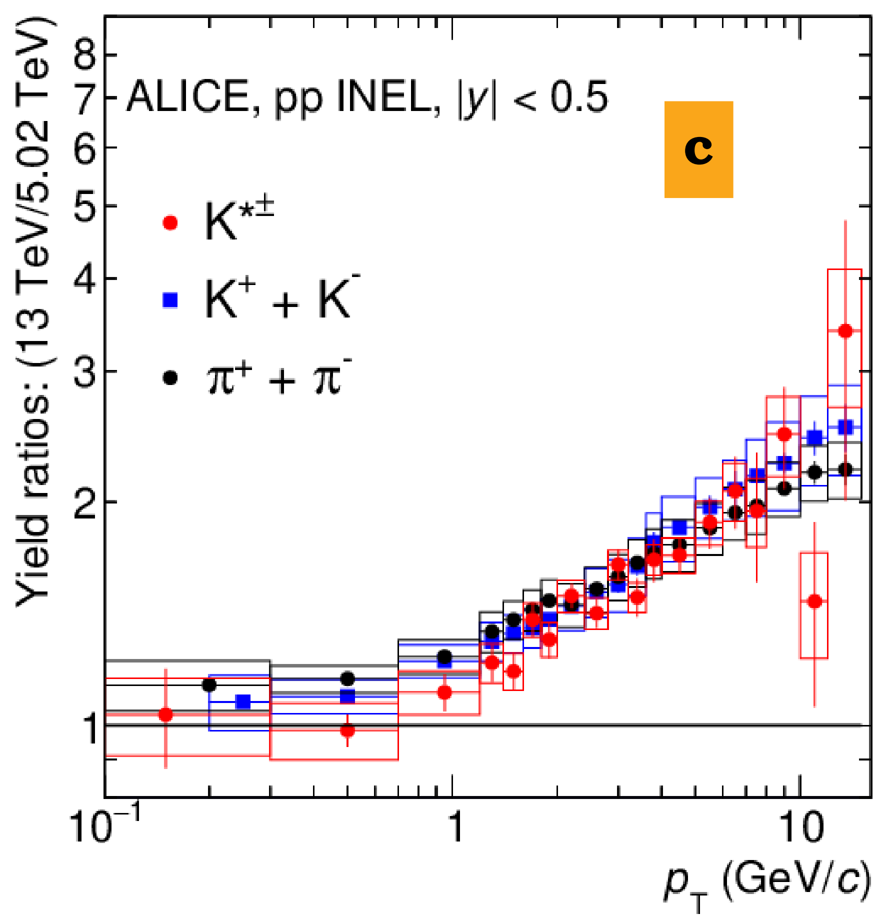
Energy dependence of resonance production

PRC 102, 024912 (2020)



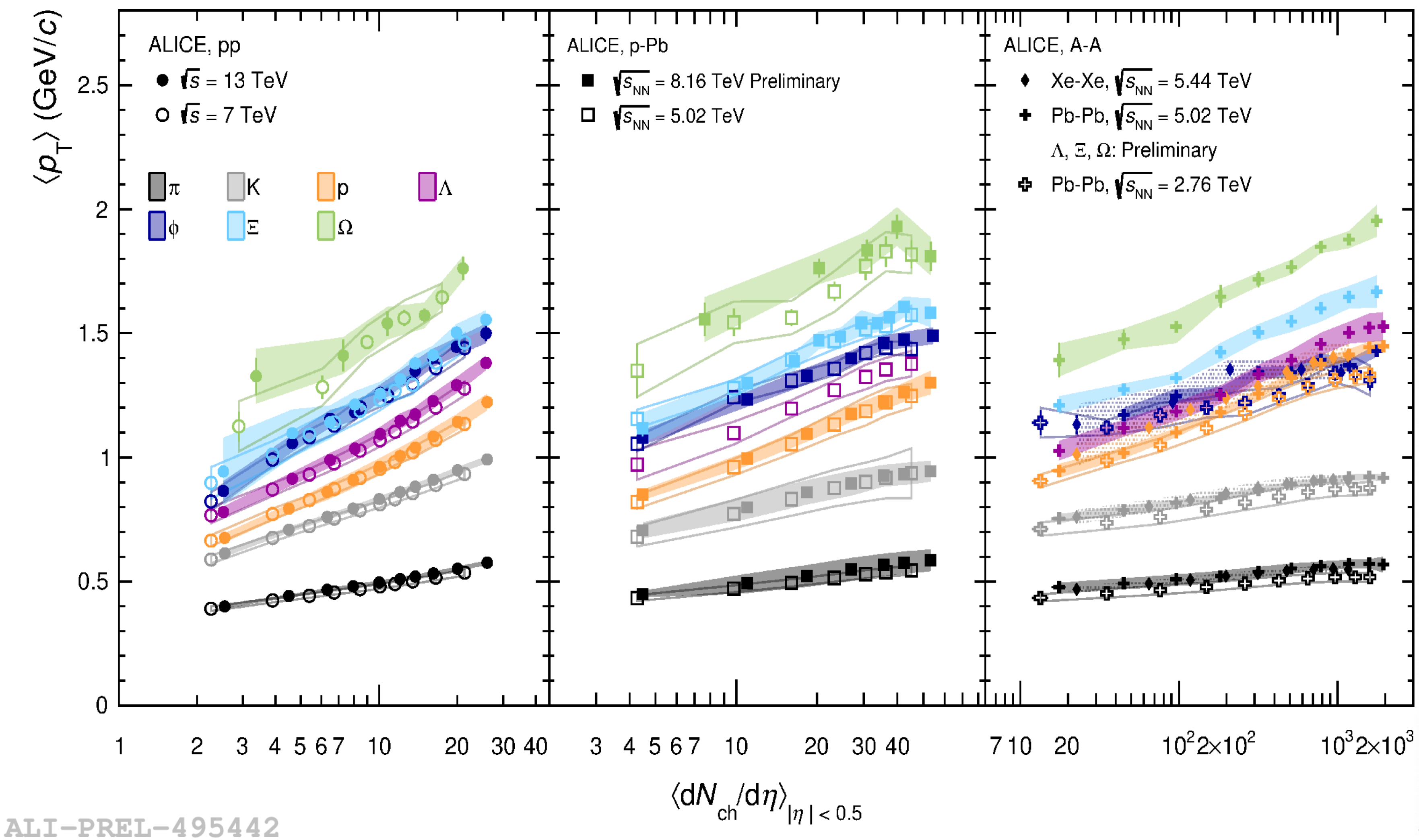
arXiv:2105.05760



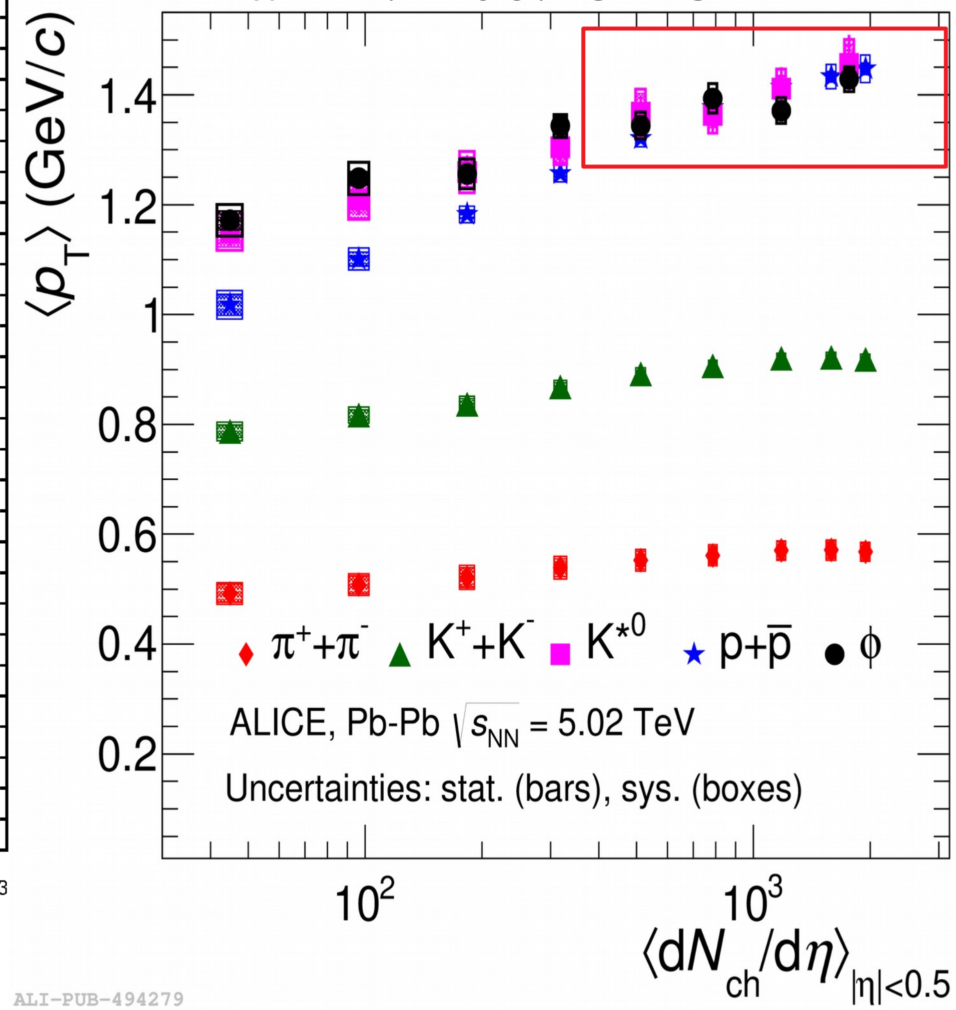


- ❖ For p_T < 1 GeV/c
  → No strong collision energy dependence
- ❖ For p_T >1 GeV/c
  →Ratio increases with p_T and depends on collision energy
- ❖ Similar behavior observed for resonances and other light-flavor hadrons (c)
- ❖ PYTHIA qualitatively reproduces the measurements, which are quantitatively better described by EPOS-LHC (b)

Mean transverse momenta (<p$_T$>)



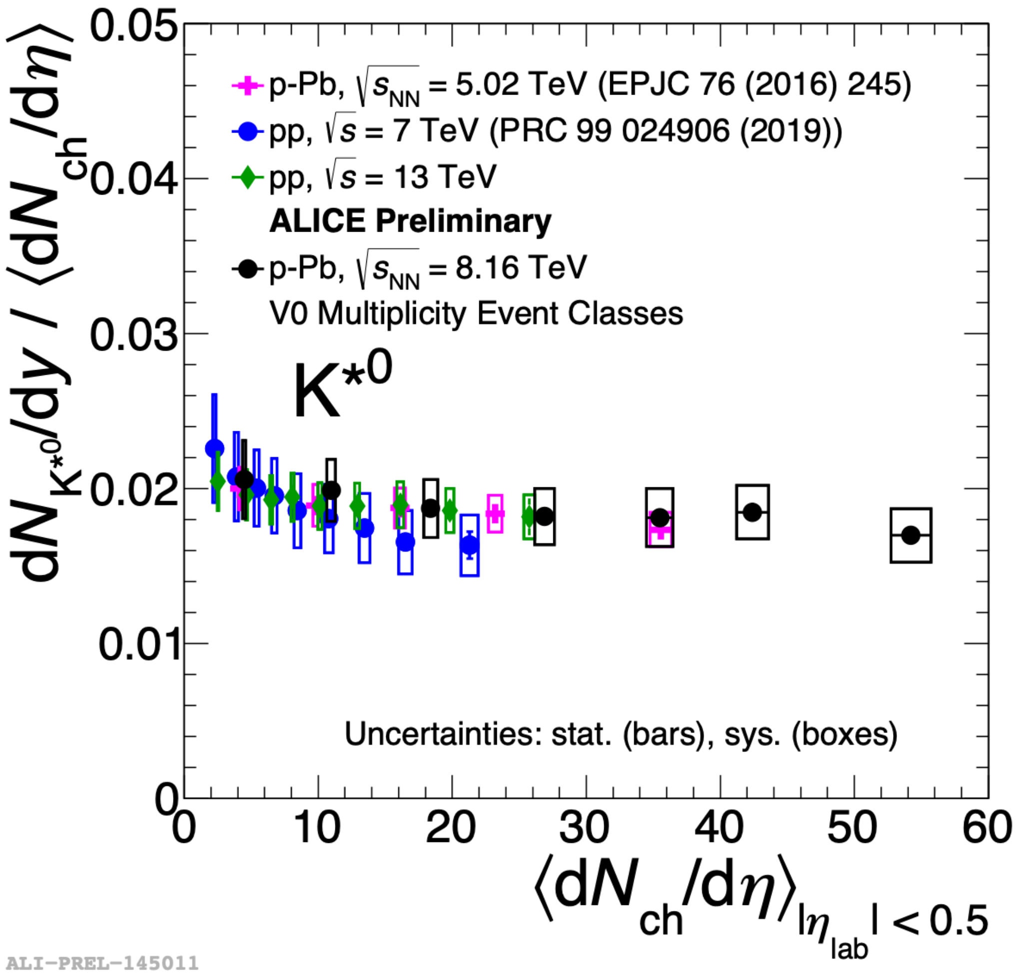
arXiv:2106.13113

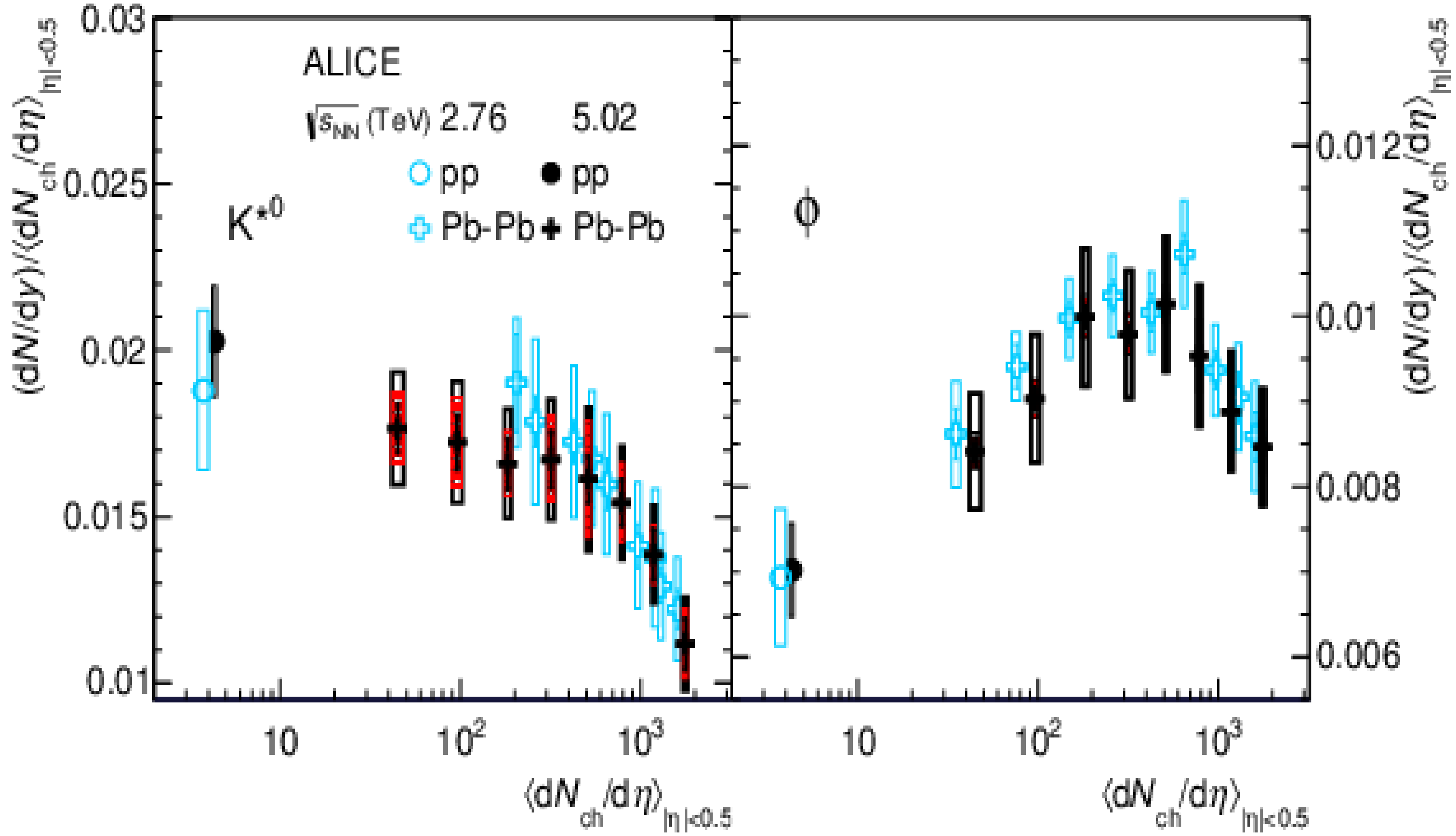


- ❖ <p$_T$> increases with multiplicity
- ❖ <p$_T$> rises faster in small collisions compared to heavy-ion collisions
- ❖ <p$_T$> increases with mass of hardons, **mass ordering** in central heavy-ion collisions (Pb-Pb, Xe-Xe)
- ❖ **Mass ordering breaks down** for hadron with similar mass (p, K^{*0},ϕ) in peripheral Pb-Pb, p-Pb and pp collisions
- ❖ For similar multiplicity, <p$_T$>$_{Pb-Pb}$ ~ <p$_T$> $_{Xe-Xe}$

Integrated yield (dN/dy)

arXiv:2106.13113



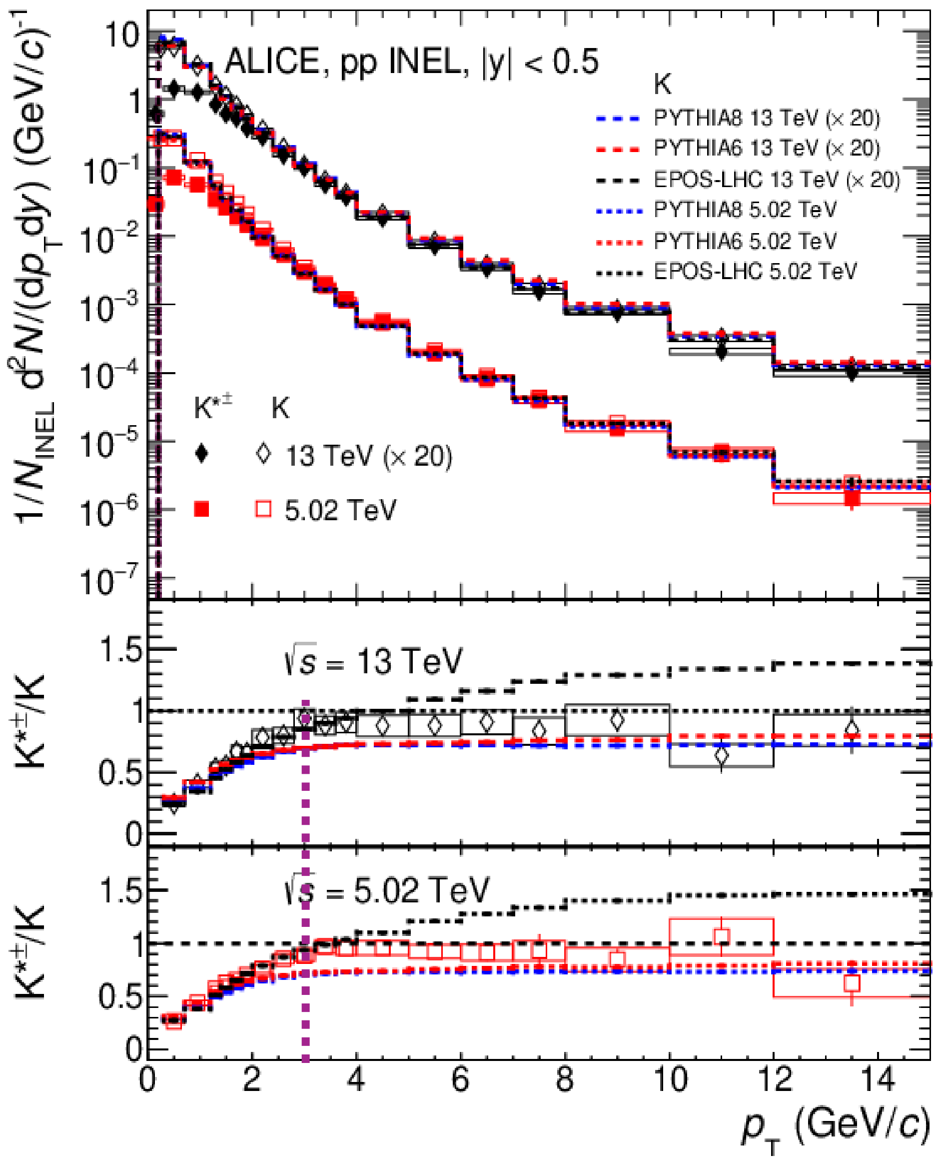


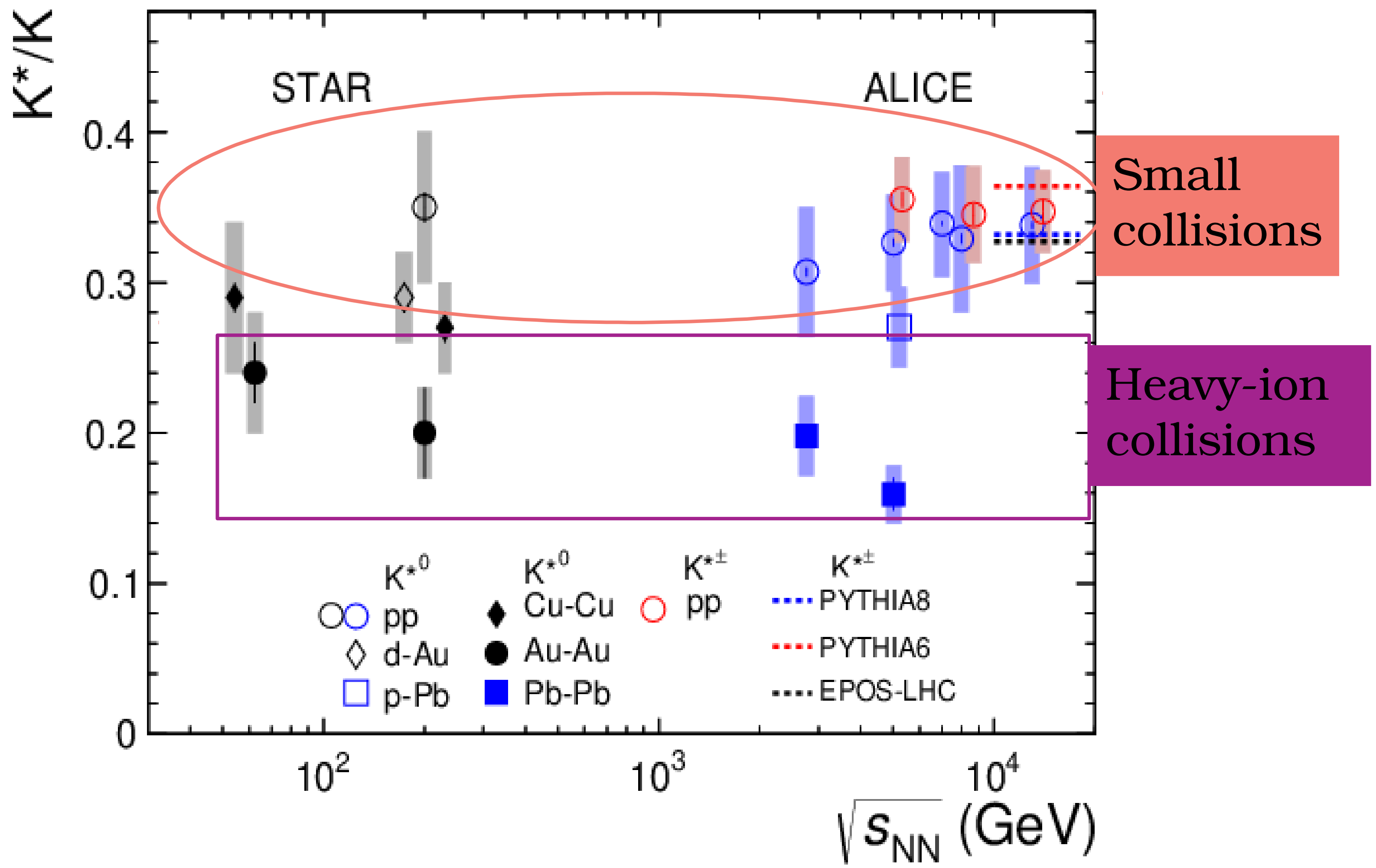
❖ For given multiplicity, self-normalized yields (dN/dy /$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$) are similar irrespective of colliding systems and energies

→ **Event multiplicity drives resonance yield**

Resonances to long lived particle ratios ($K^{*0,+-}/K$)

arXiv:2105.05760





p_T-differential ratios (K^{*+-}/K) in pp:

❖ For p_T < 3 GeV/c → Suppressed

❖ For p_T > 3 GeV/c

→ ~ Unity

→ No significant energy dependence

❖ Models qualitatively reproduce the data

p_T-integrated ratios (K^*/K):

❖ Small collisions: Ratios are similar and consistent with model predictions

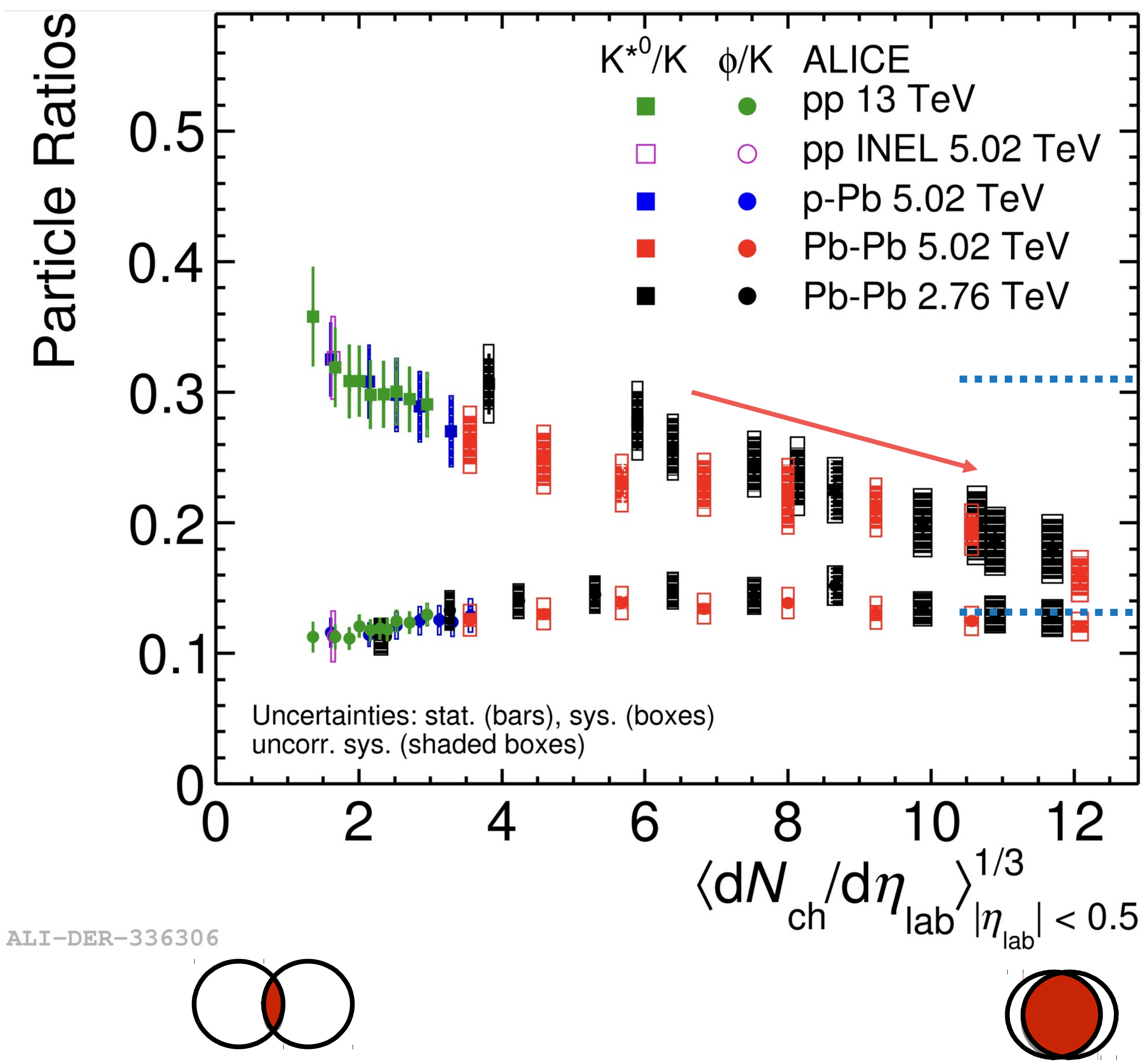
❖ Heavy-ion collisions: Small decrease with collision energy and weak dependence on system size

Resonances to long lived particle ratios

Lifetime (fm/c): ρ^0 (1.3) < $K^{*\pm}$ (3.6) < K^{*0} (4.16) < $\Sigma^{*\pm}$ (5.0-5.5) < Λ^* (12.6) < Ξ^{*0} (21.7) < ϕ(46.2)

- ❖ K^{*0}/K ratio decreases with system size and values below statistical model predictions in central Pb-Pb collisions
- ❖ In contrast, ϕ/K constant across multiplicities in Pb-Pb, p-Pb and pp collisions, consistent with statistical model predictions in central Pb-Pb collisions
  →Lifetime of ϕ = 10 x longer than K^{*0}
  → **Rescattering** dominant over **regeneration**
- ❖ K^{*0}/K ratio slightly decreasing with multiplicity in pp and p–Pb
  → Hint for non-zero lifetime of hadronic phase in small collision systems

PLB 802 (2020) 135225 PLB 807 (2020) 135501



$<dN_{ch}/d\eta>^{1/3}$: Proxy for system size

Extract lifetime of hadronic phase

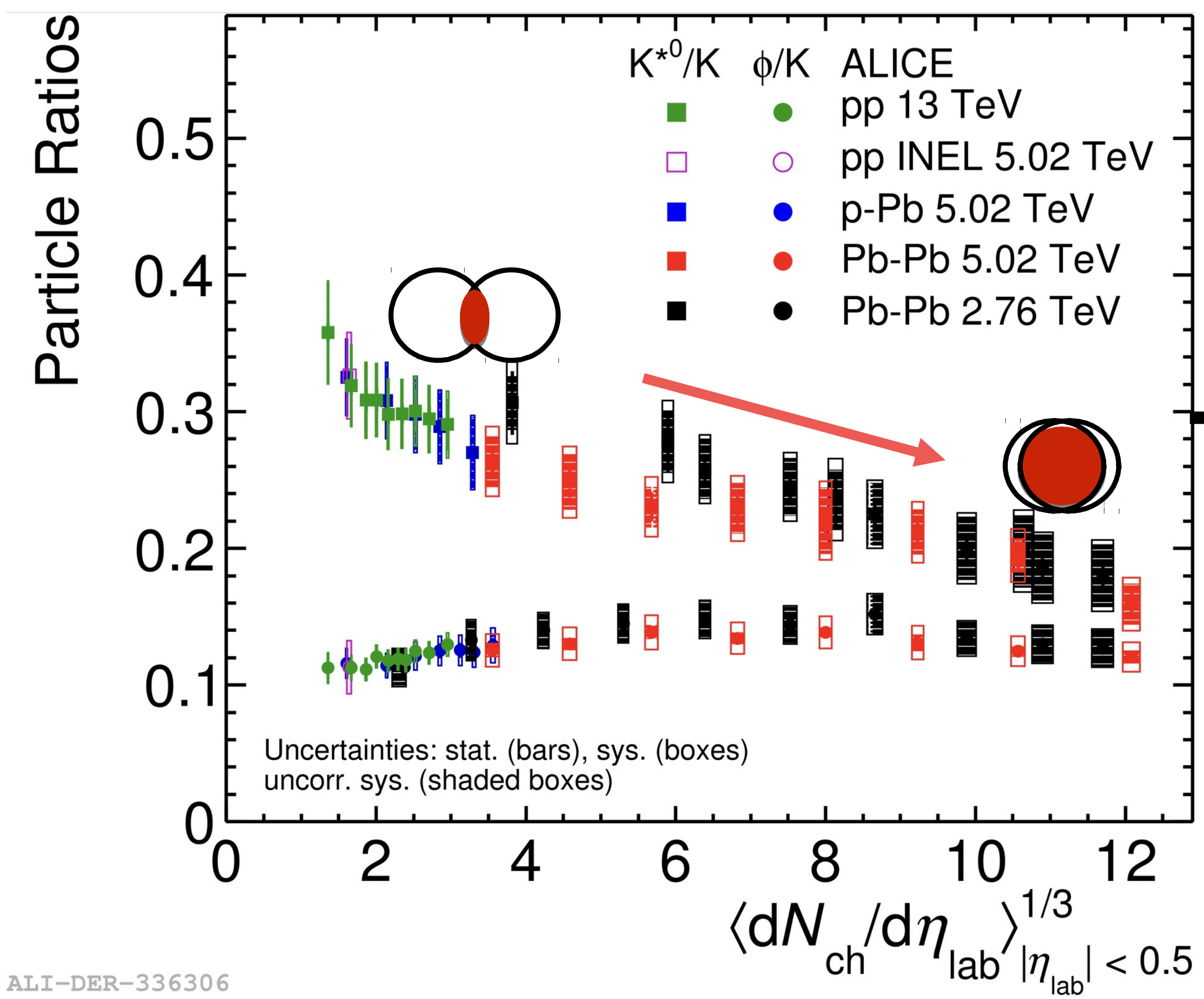
Assumption : No regeneration effects between chemical and kinetic freeze-out

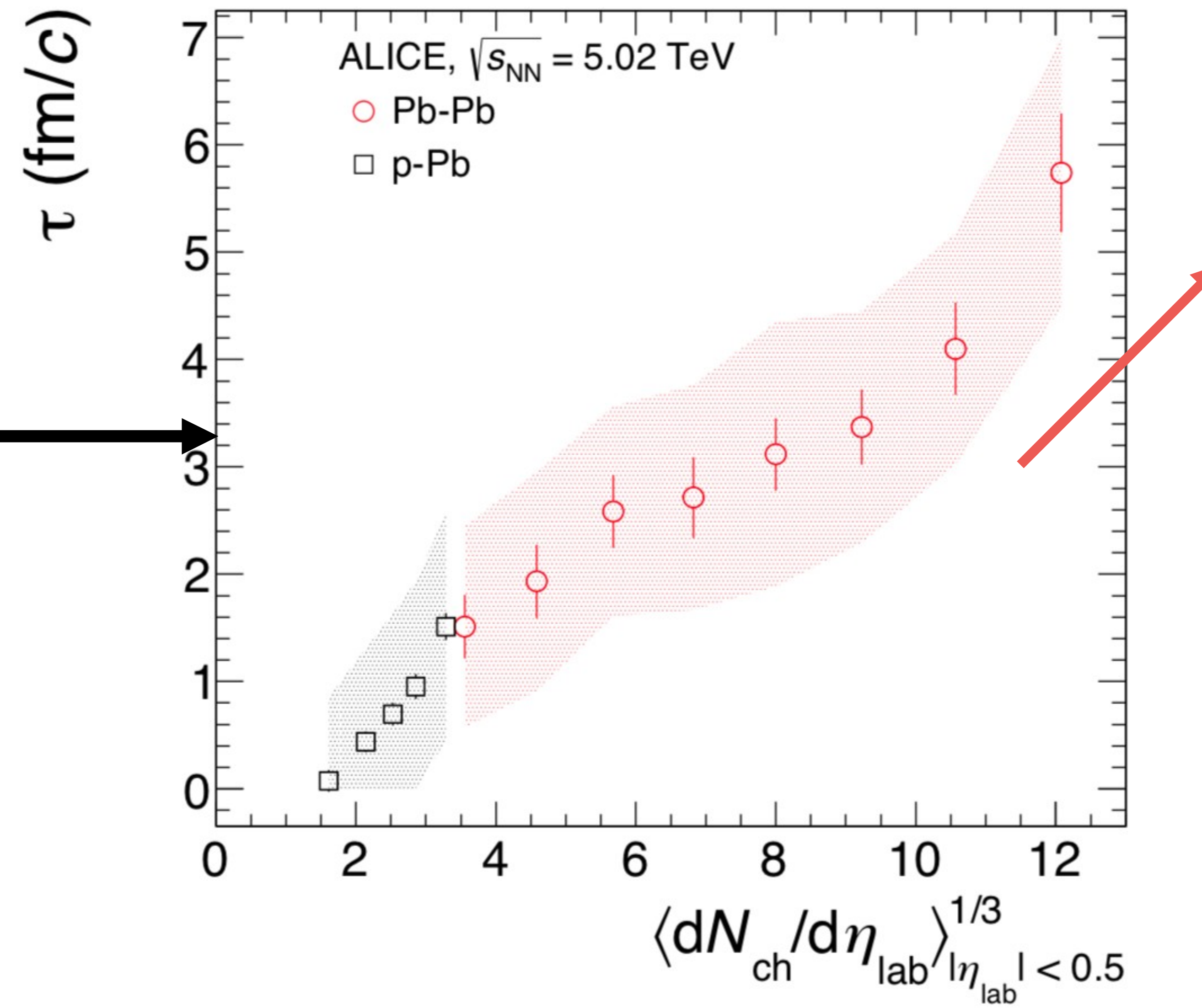
$$[\frac{K^{*0}}{K}]_{kinetic(Pb-Pb)} = [\frac{K^{*0}}{K}]_{chemical(pp)} \times exp(-\tau/\tau_K^{*0})$$

τ_K^{*0} = Lifetime of K^{*0}

τ = Timespan between chemical and kinetic freeze out

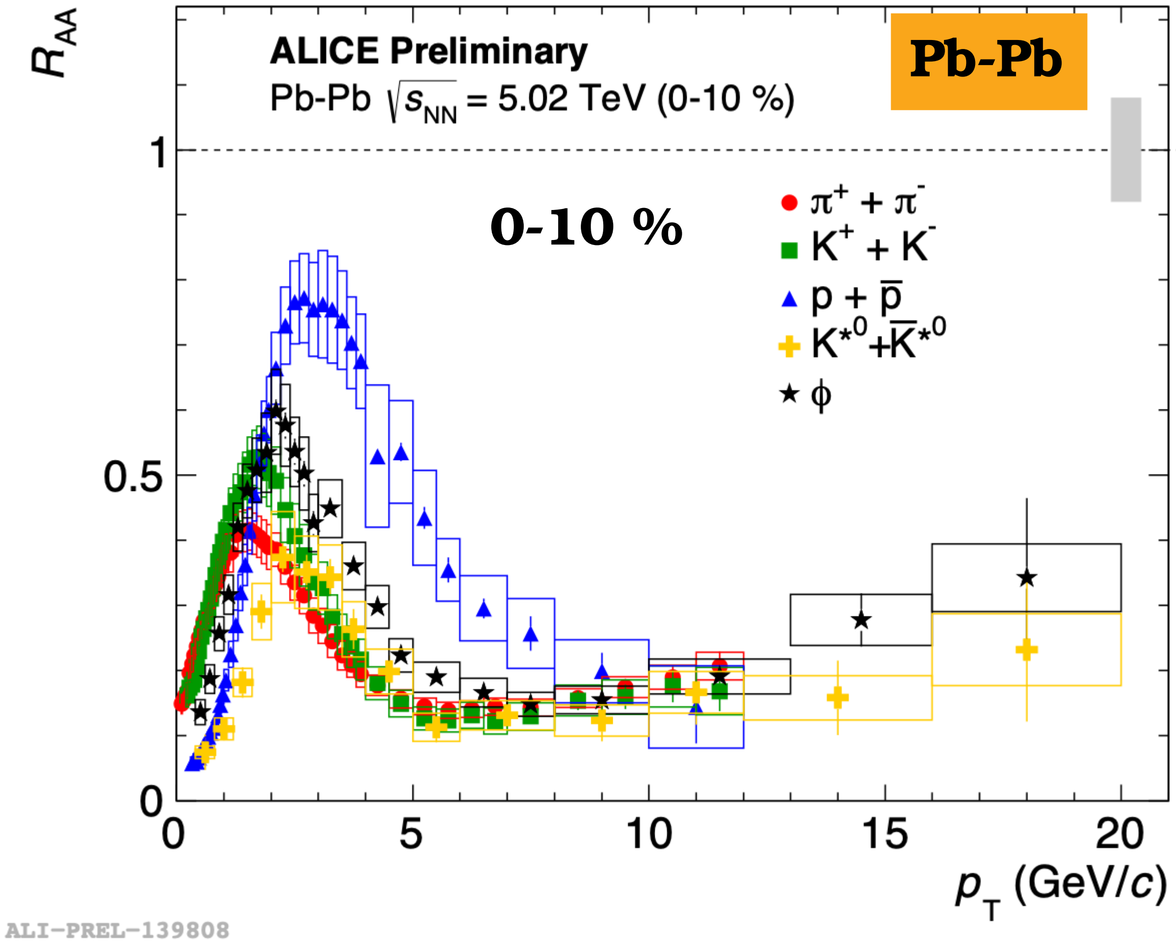
PLB 802 (2020) 135225





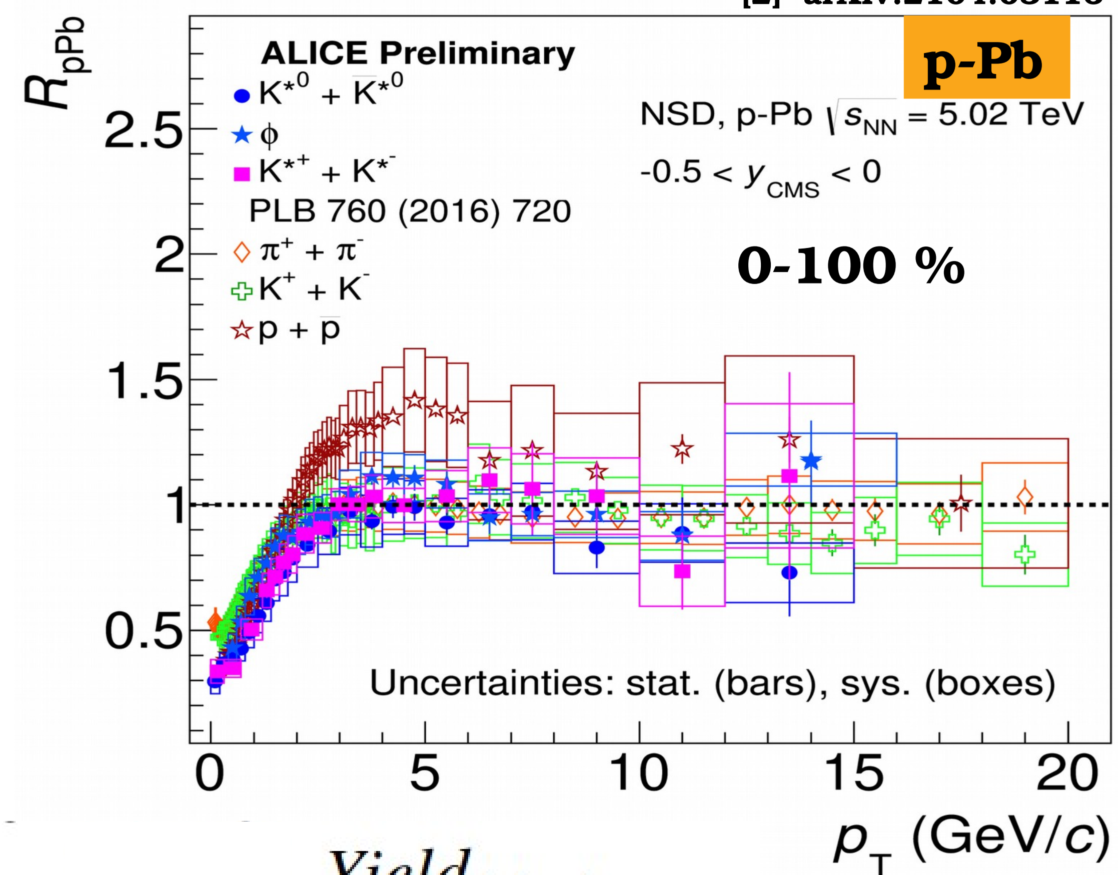
A smooth increase of τ (fm/c) with system size from p–Pb to Pb–Pb collisions observed

Nuclear modification factors (R_{AA} or R_{pPb})



[1] JHEP 03 (2016)082

[2] arXiv:2104.03116



$$R_{AA,pA} = \frac{Yield_{AA,pA}}{\langle N_{coll} \rangle \times Yield_{pp}}$$

❖For $p_T > 6$ GeV/c

→ $R_{AA} < 1$, suppression in central Pb-Pb collisions

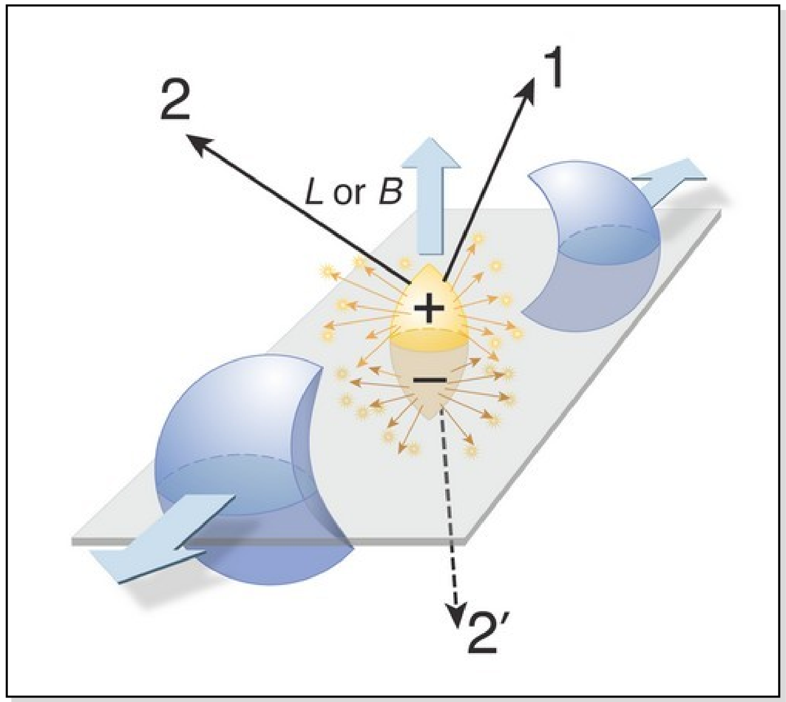
→ $R_{AA} = 1$, no suppression in p-Pb collisions

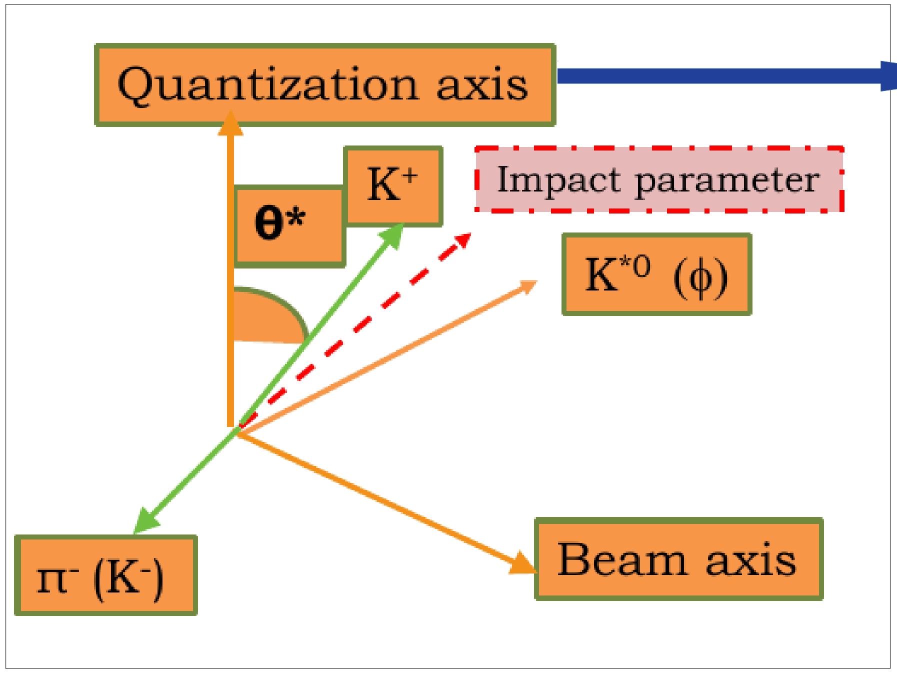
→ Similar R_{AA} or R_{pA} regardless of the quark content of hadron

Similar R_{AA} or R_{pA} values are observed for charmed mesons in Pb-Pb collisions [1] and in p-Pb collisions [2] π^0 at high p_T

Spin alignment of vector mesons

Non-central heavy-ion collisions:





Quantization axis
- Normal to production plane (Momentum of vector meson and beam axis)
- Normal to reaction plane (Impact parameter and beam axis)

❖ Large angular momentum (~ $10^7\hbar$) due to medium rotation in participant nucleons [1],

❖ High magnetic field (~10^{15} T) formed for a short time due to spectator nucleons [2] is expected In the initial stage of heavy-ion collisions at LHC energy.

[1] PRC 77 (2008) 024906, Beccattini et al.

[2] NPA 803 (2008), Kharzeev et al.

Observable:
Anisotropies in angular distribution of decay daughters

K. Schilling et al., Nucl. Phys. B 15 (1970) 397

$$\frac{dN}{dcos\theta^*} = N_0[1-\rho_{00}+\cos^2\theta^*(3\rho_{00}-1)]$$

ρ_{00}: Probability of vector meson is in spin state = 0

ρ_{00} = 1/3 : No spin alignment

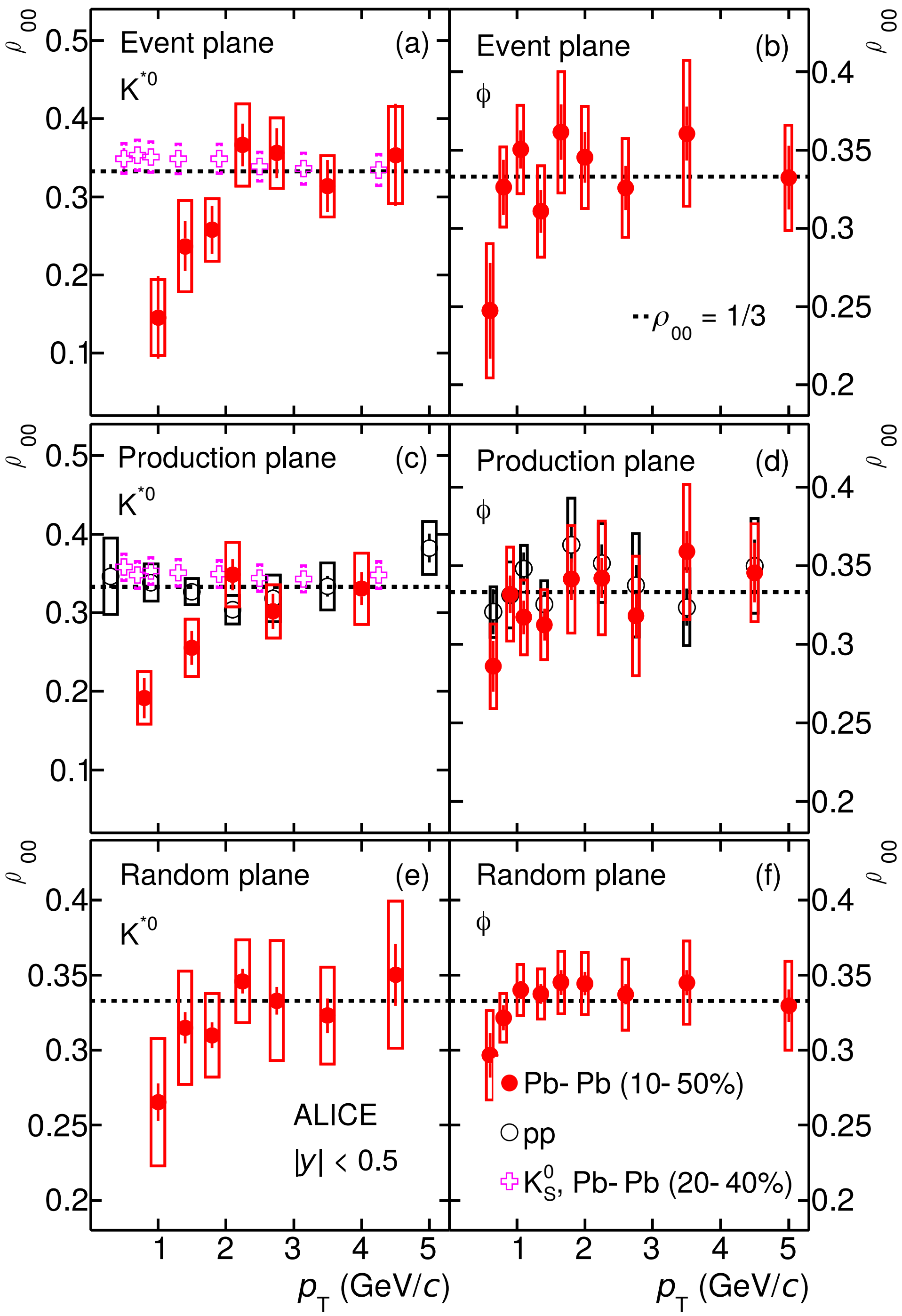
Angular distribution of decay daughters of vector (spin=1) meson gets modified in presence of large angular momentum

$\rho_{00} \neq 1/3$: spin alignment

Spin alignment: ρ_{00} vs. p_T

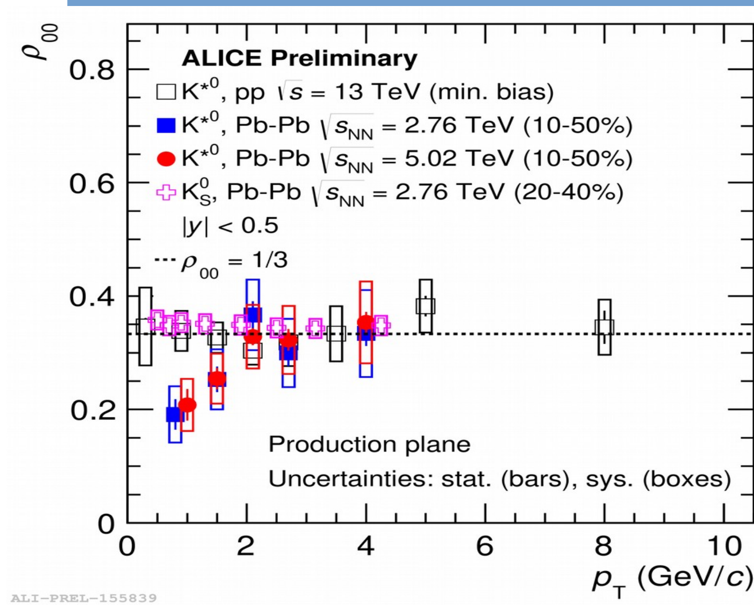
[1] ALICE: Phys. Rev. Lett. 125, 012301

[2] Z. Liang et. al., Phys. Lett. B629, 20 (2005)



- ❖ Spin Alignment (ρ_{00} < 1/3) observed at a lebel of **3σ (for K*0) and 2σ (for ϕ)** for vector mesons at low momentum mid-central collisions
- ❖ No spin alignment (ρ_{00} ~ 1/3)
  - → High-p_T
  - → For spin 0 particle (K^0_s)
  - → In proton-proton collisions
  - → For random planes

p_T and centrality dependence of ρ_{00} *are* qualitatively consistent with predictions from quark-recombination [2].



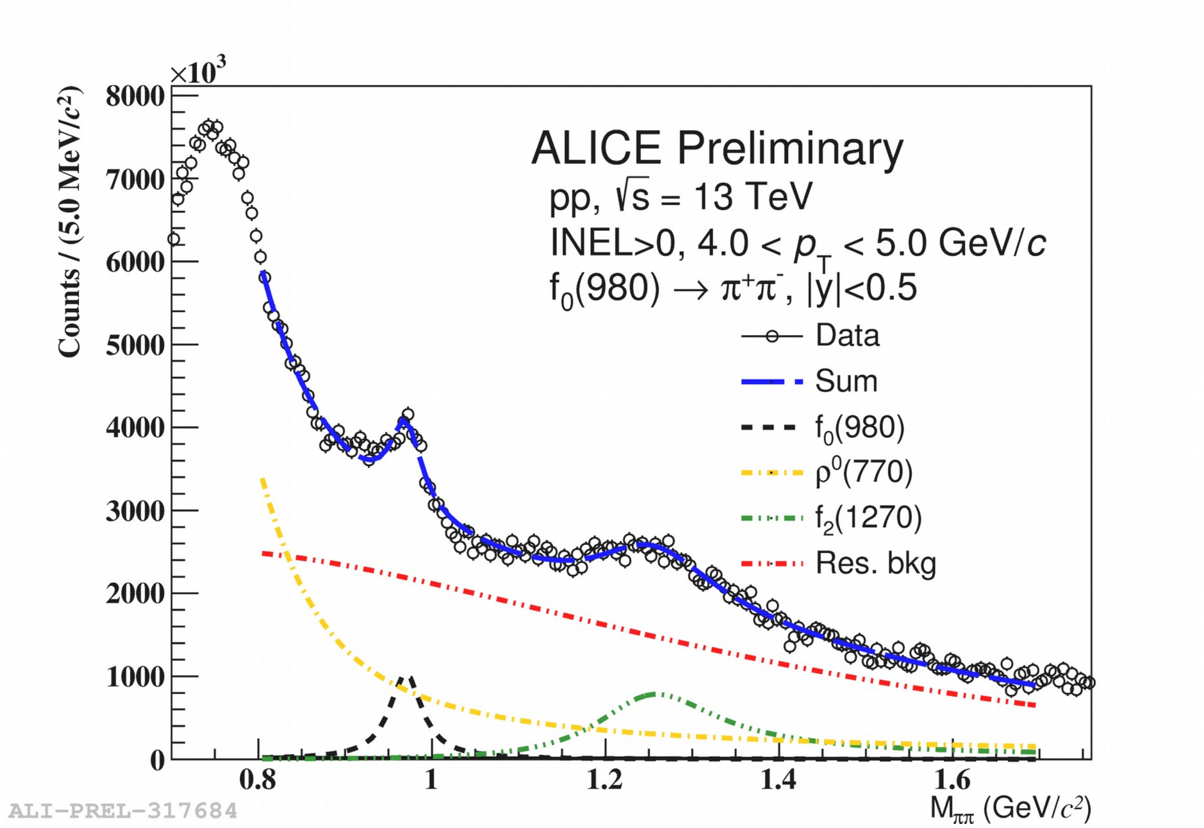
Similar behavior observed with measurements Pb-Pb @5.02 TeV (Run1 (2015)).

High statistics in Pb-Pb @5.02 TeV (Run 2 (2018)) in progress
-Provide further precision measurement, energy dependence and spin alignment of K*+-

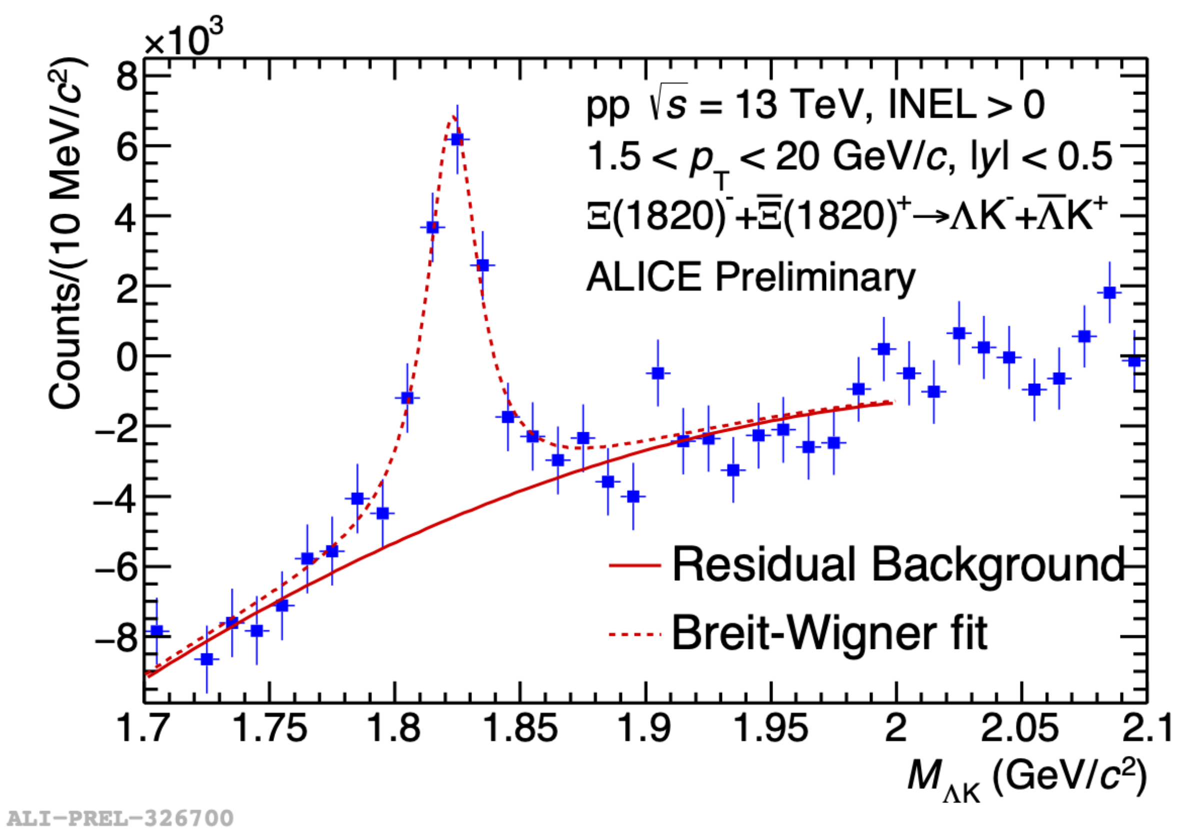
Explore new resonances

[1] Tanabashiet al. (PDG), Phys. Rev. D 98 (2018) 030001

[2] G. Aarts et al., Arxiv: 1710.00566v1



$f_0(980)$: tetraquark candidate[1]
Mass (M) : (0.99 ± 0.02) GeV/c^2
Full width Γ from 0.01 to 0.1 GeV/c^2



Ξ(1820): Candidate for chiral symmetry restoration[2]
Measurement of Ξ(1820) in progress in pp, p-Pb and Pb-Pb collisions (ΛK channels)

Search for higher mass resonance $K^{0*}(1420)$ and $K_2^*(1430)$, $f_2(1525)$ are ongoing

Summary and outlook

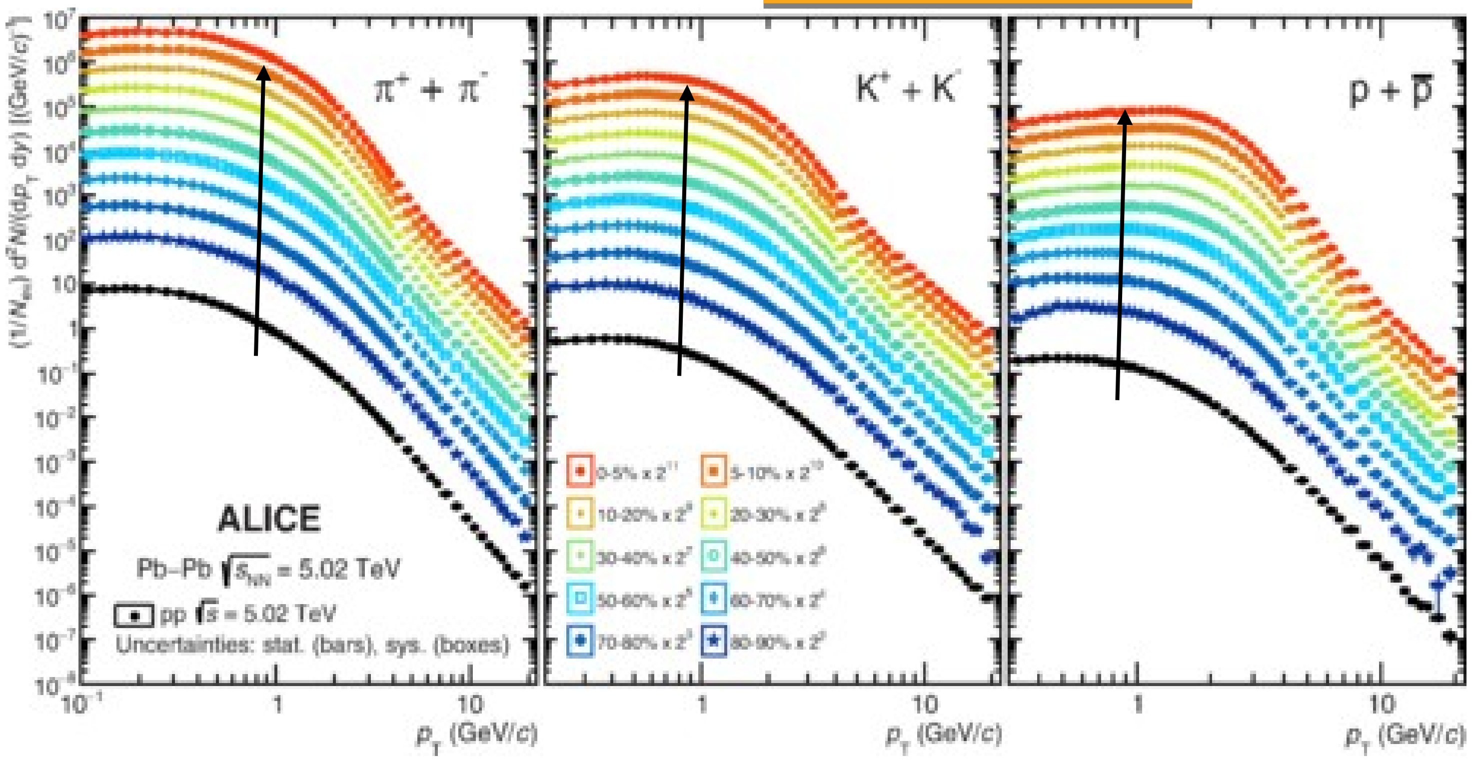
- **Spectra shape evolution with multiplicity** at low p_T. No changes at high p_T
- The contribution of **hard scattering processes** to particle production **increases with energy**
- **Event multiplicity drives** resonance production
- $< p_T >$ follows **mass ordering** in central Pb-Pb and Xe-Xe collisions
- Evidence of rescattering effects in **K^{*0}/K** for **central Pb-Pb** collisions. Hint of **non-zero lifetime** of hadronic phase in **high multiplicity** small collisions
- Presence of **in medium effects** in Pb-Pb collisions emerging from the study of R_{AA}
- **Spin alignment (ρ_{00}<1/3)** of vector mesons are observed in heavy-ion collisions **at low p_T in mid-central Pb-Pb collisions** → Precision studies with high statistics in progress
- Spin alignment of vector mesons **qualitatively** consistent with **quark recombination**, more theoretical efforts are required for comprehensive quantitative comparison
- **Study of higher mass and rare resonances** will be explored exploiting **Run2 and high statistics Run3 data**

Back up

p_T spectra in heavy-ion collisions

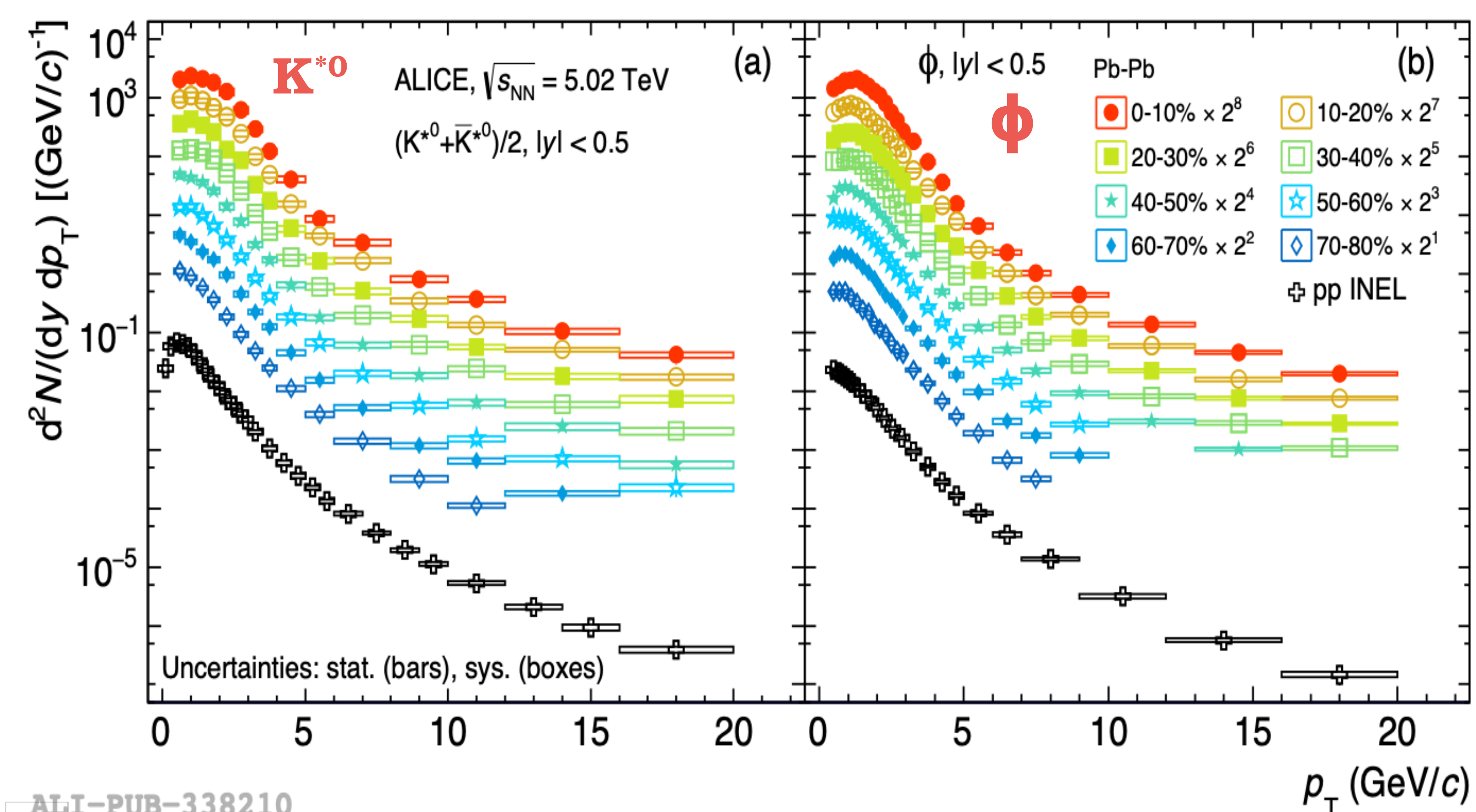
Phys. Rev. C 101, 044907

Pb-Pb



- p_T spectra become harder with increasing multiplicity, flatten at low-p_T, pronounced more for heavier particles.
  →Expected from collective hydrodynamic expansion (hint presence of radial flow)

arXiv:2106.13113

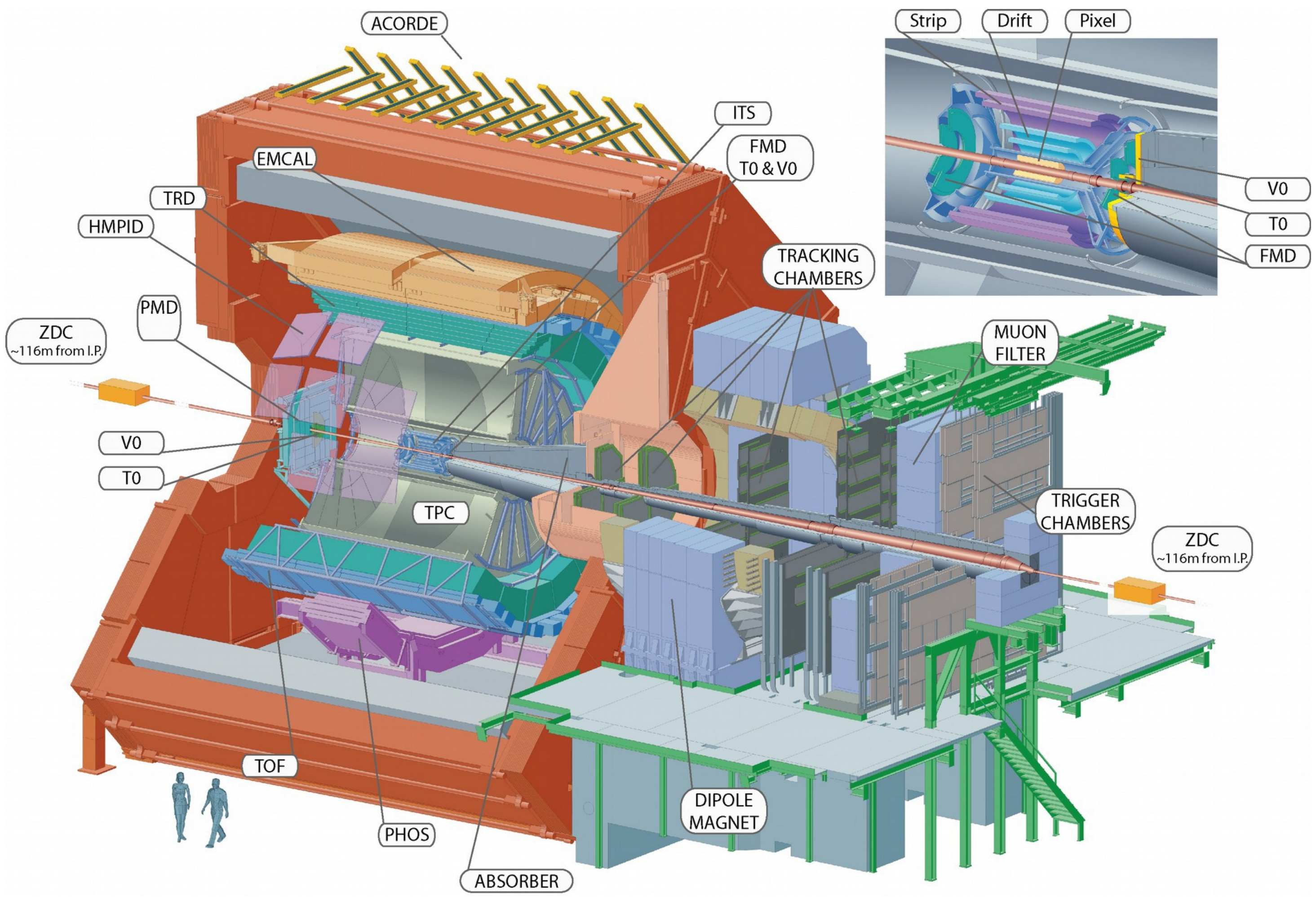


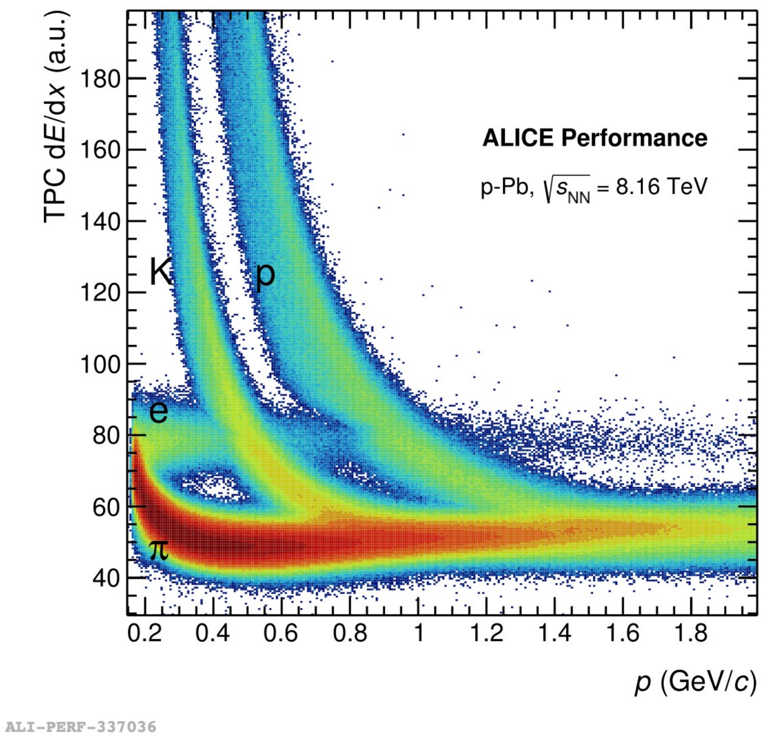
Similar hardening of spectra have been observed in high-multiplicity pp and p-Pb collisions

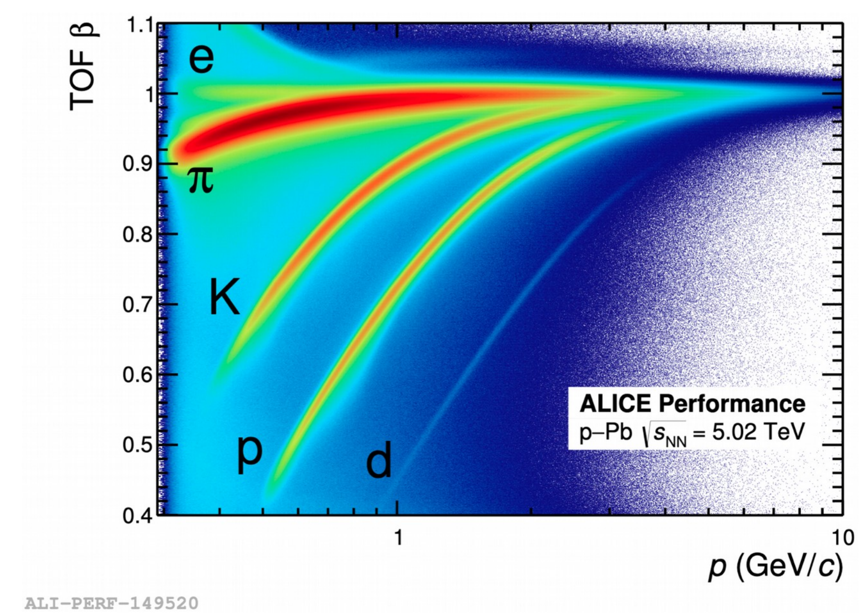
ALICE Detector

Inner Tracking System(ITS): (|η| < 0.9)

- ❖ 6 layers of silicon detector
- ❖ Tracking, vertex, PID (dE/dx)







Forward detector (V0): V0A($2.8<\eta<5.1$)&V0C($-3.7<\eta<-1.7$)

- ❖ Trigger, centrality estimator

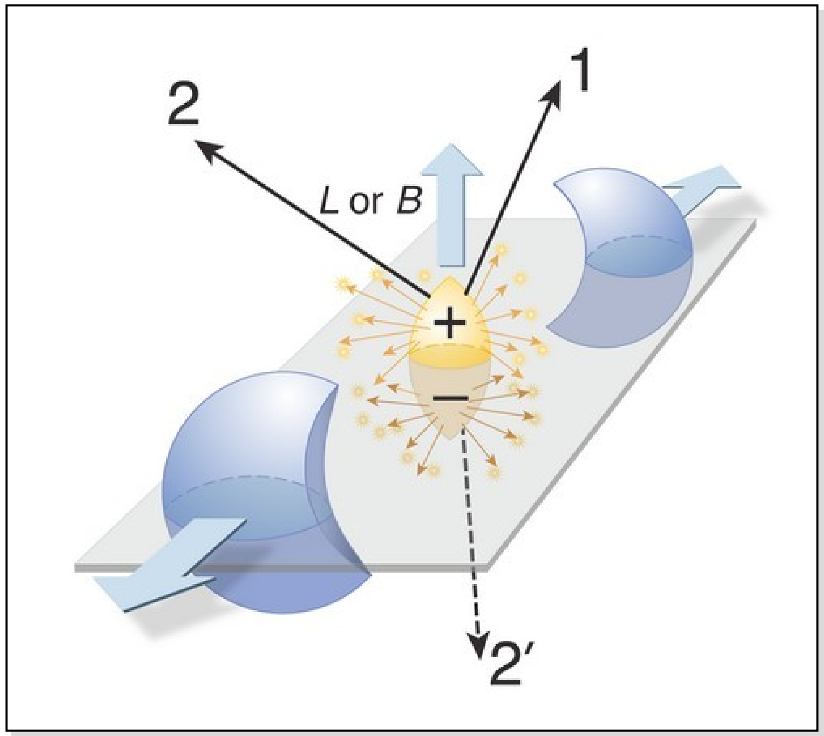
TimeProjectionChamber (TPC): (|η| < 0.9)

- ❖ Primary vertex determination
- ❖ Main tracking device
- ❖ PID (dE/dx) in gas

Time-Of-Flight (TOF): (|η| < 0.9)

- ❖ PID (time-of-flight measurement)

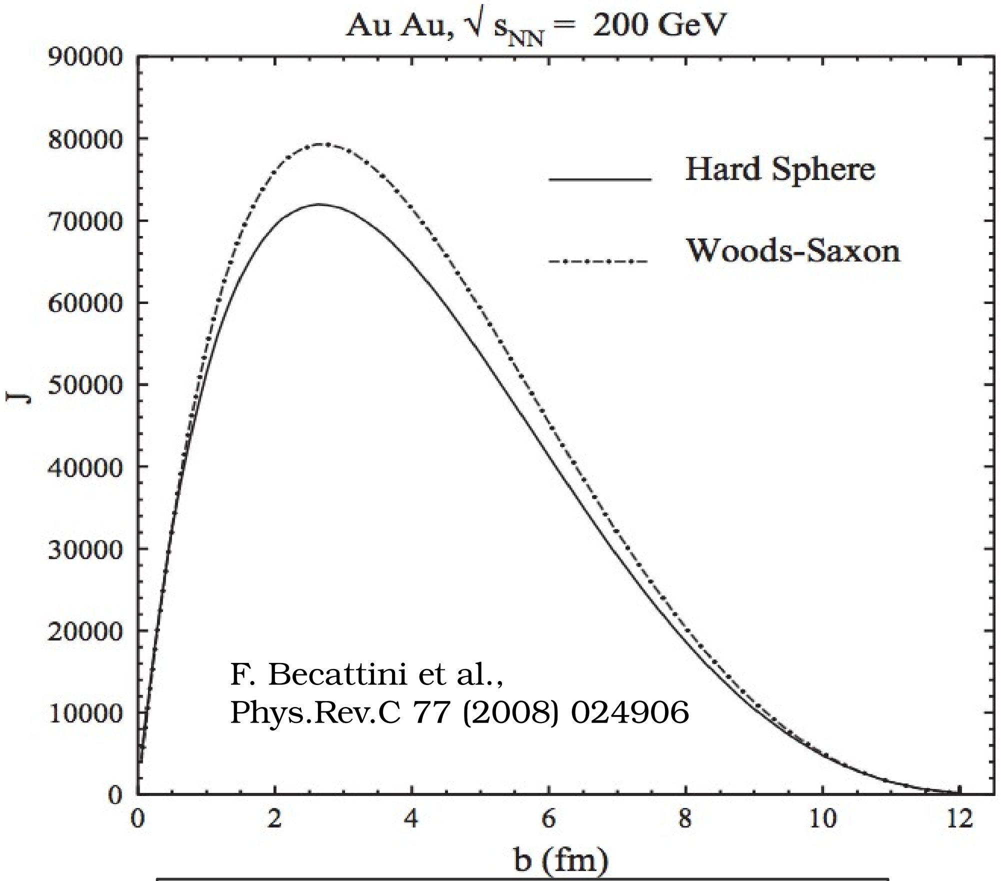
Heavy-Ion Collisions and Initial State



Reaction plane: Impact parameter and beam axis

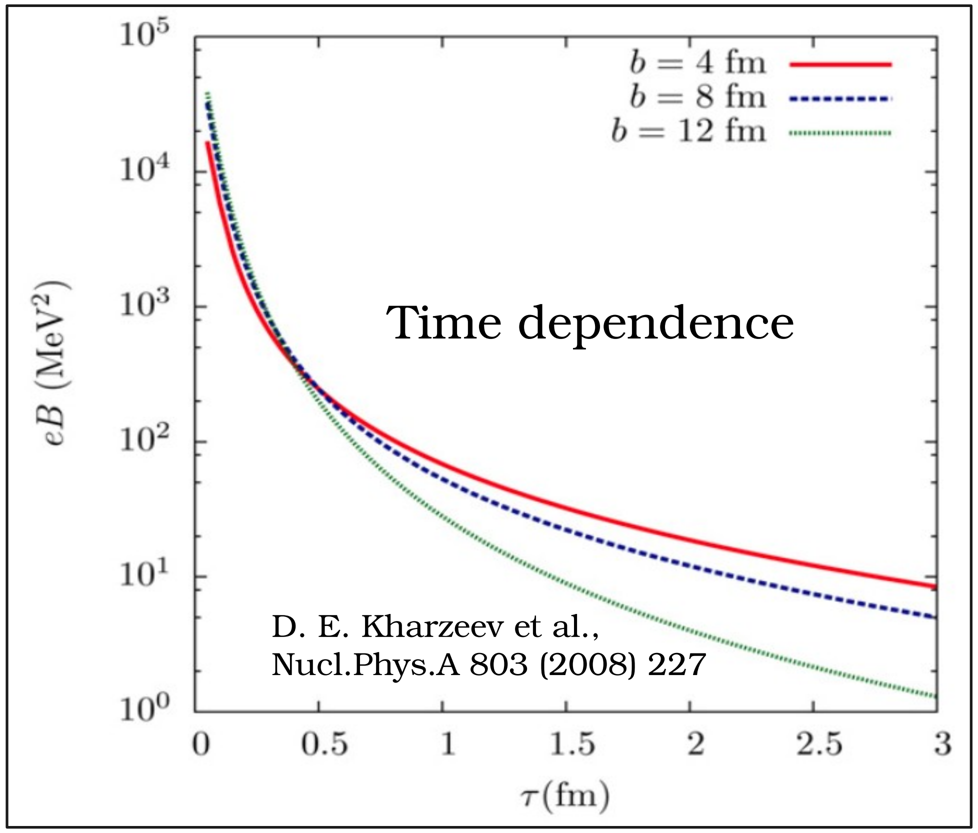
L and B perpendicular to reaction plane

Impact parameter dependence



Large angular momentum (Conserved Quantity)

Au Au ,$\sqrt{s_{NN}}$ = 200 GeV



Large magnetic field

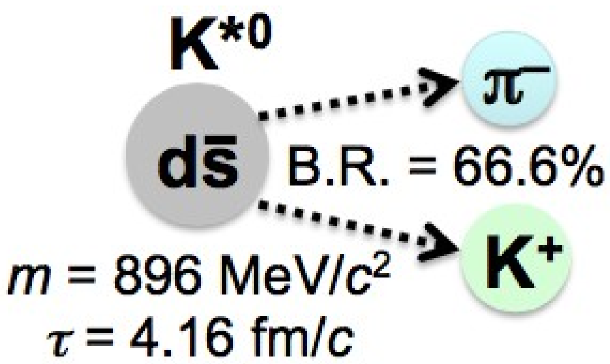
Focus of the study is to see the effect of large angular momentum (L) and magnetic field (B) in heavy-ion collisions

Goal: How can probe these effects in experiments

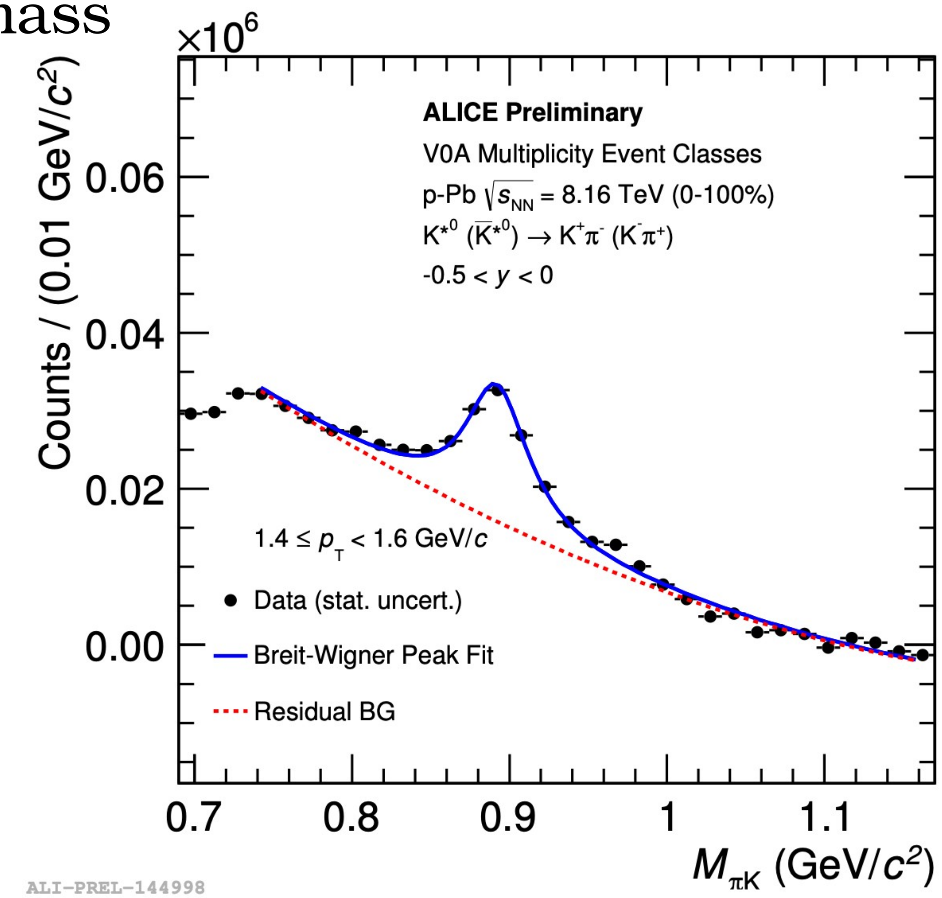
$M^2_\pi \sim 2 \times 10^4$ MeV^2 ~ 3×10^{14} Tesla ~ 3×10^{18} Gauss

Analysis details: resonance reconstruction

1. Short-lived particles reconstructed through invariant mass method (example : $K^{*0} \longrightarrow K^{+} + \pi^{-}$)



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



2. Identify all decay products, add 4 momentum of each pair and find the mass

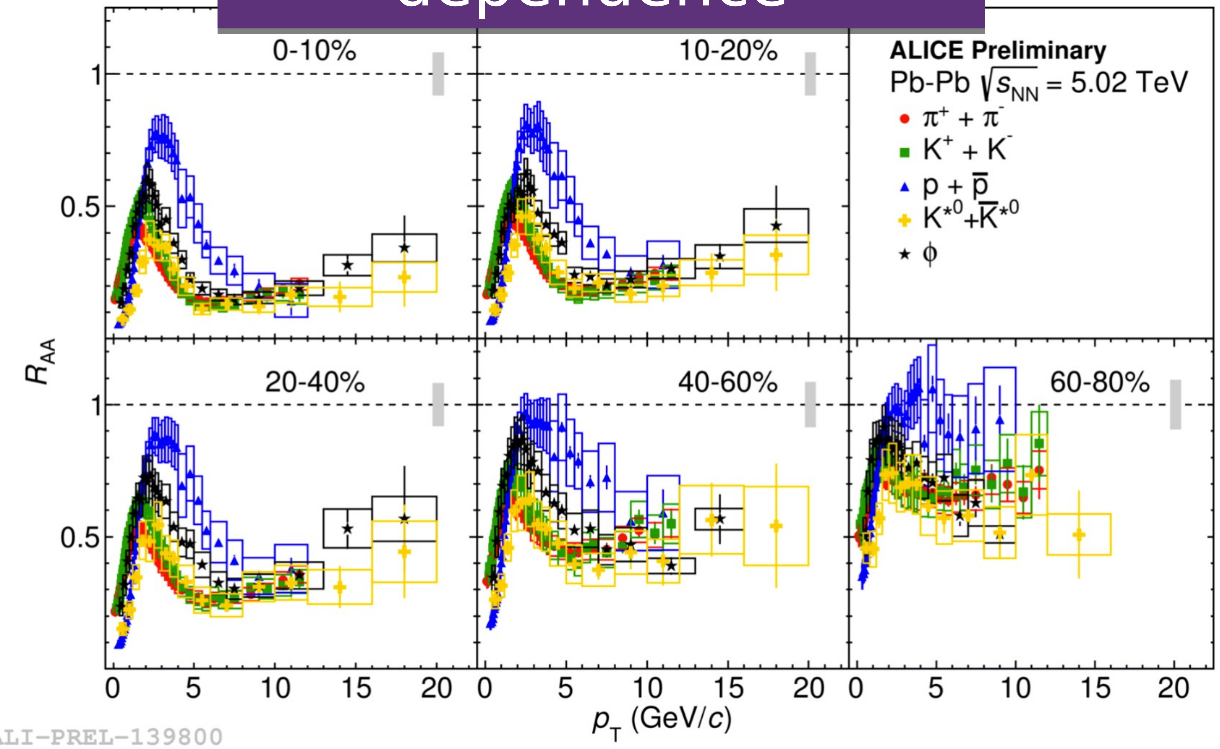
3. Look for a peak on top of combinatorial background
4. Estimate of the combinatorial background distribution using different techniques (like-charge , event mixing , rotational method)

i) Same event (signal+ background) and normalised mixed event distribution
ii)Same event distribution after mixed event background subtraction
iii) K^{*0}: Breit-Wigner + Residual background function (pol2)
iv) Yield is calculated as a function of p_T for various multiplicity/centrality classes

Yield : Area under the BW

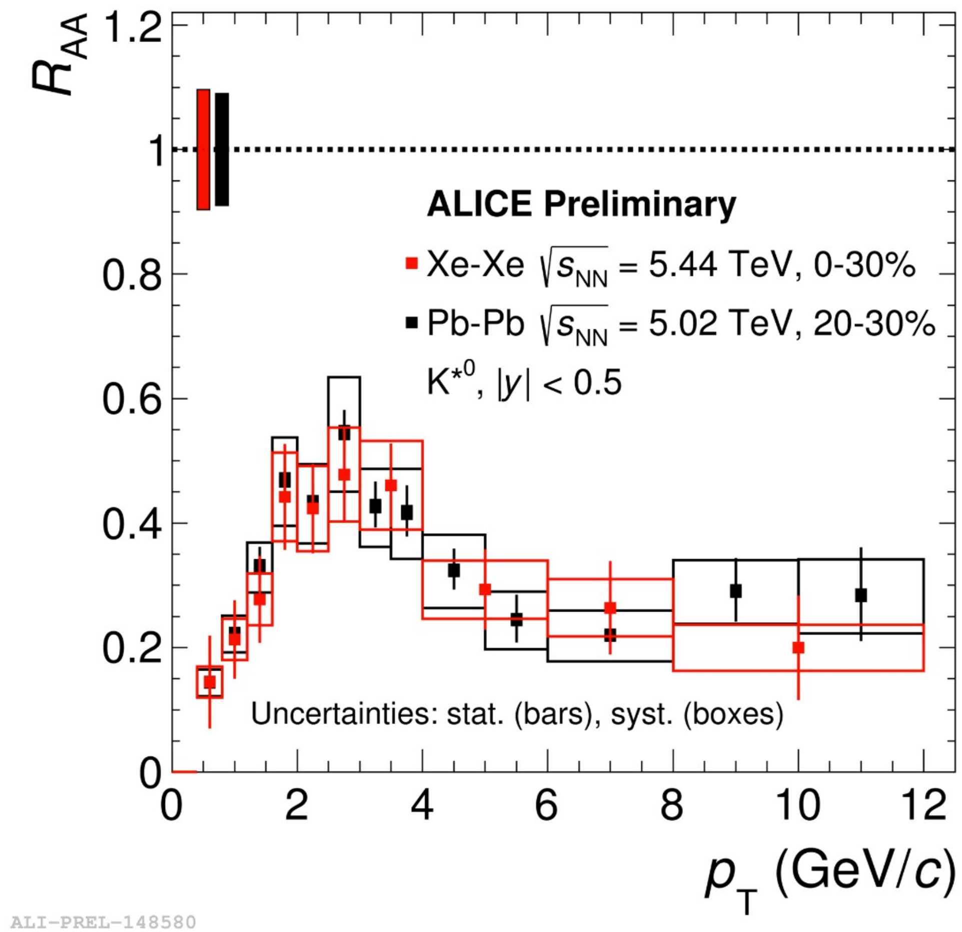
R_{AA} vs Centrality, Energy and System size

Centrality dependence



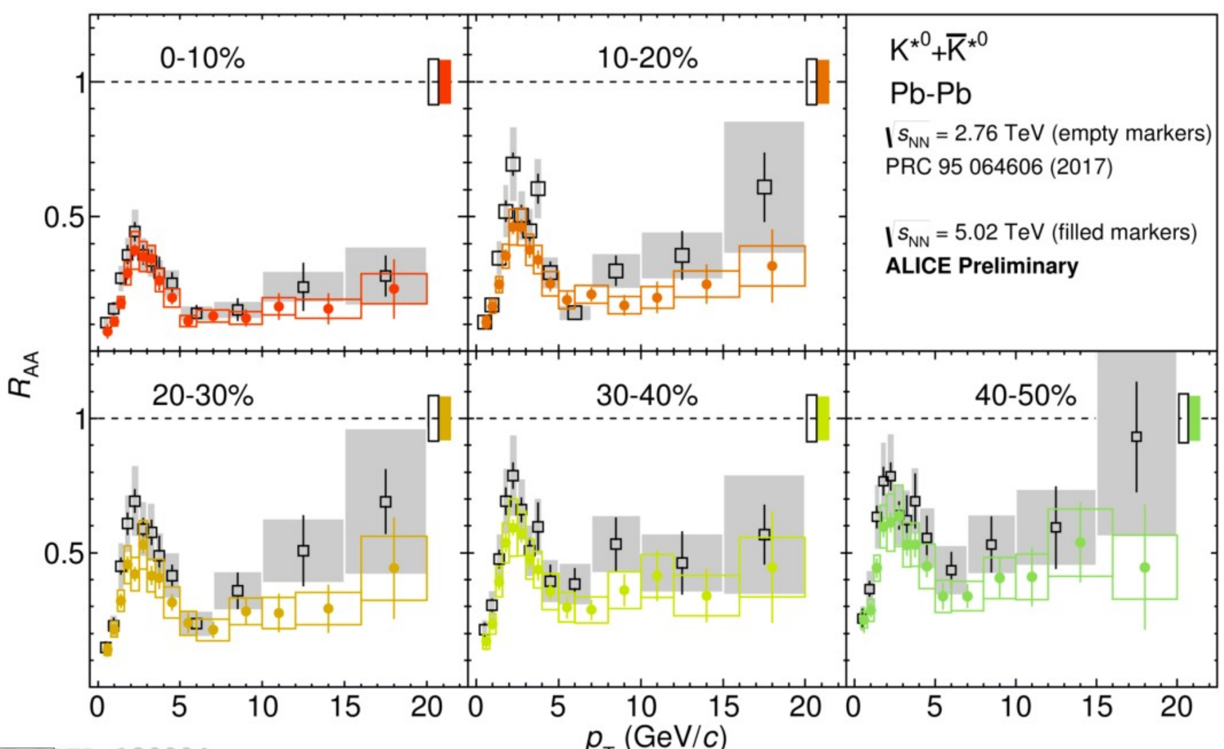
ALI-PREL-139800

System size dependence



ALI-PREL-148580

Energy dependence



ALI-PREL-139804

❖ **R_{AA} :**

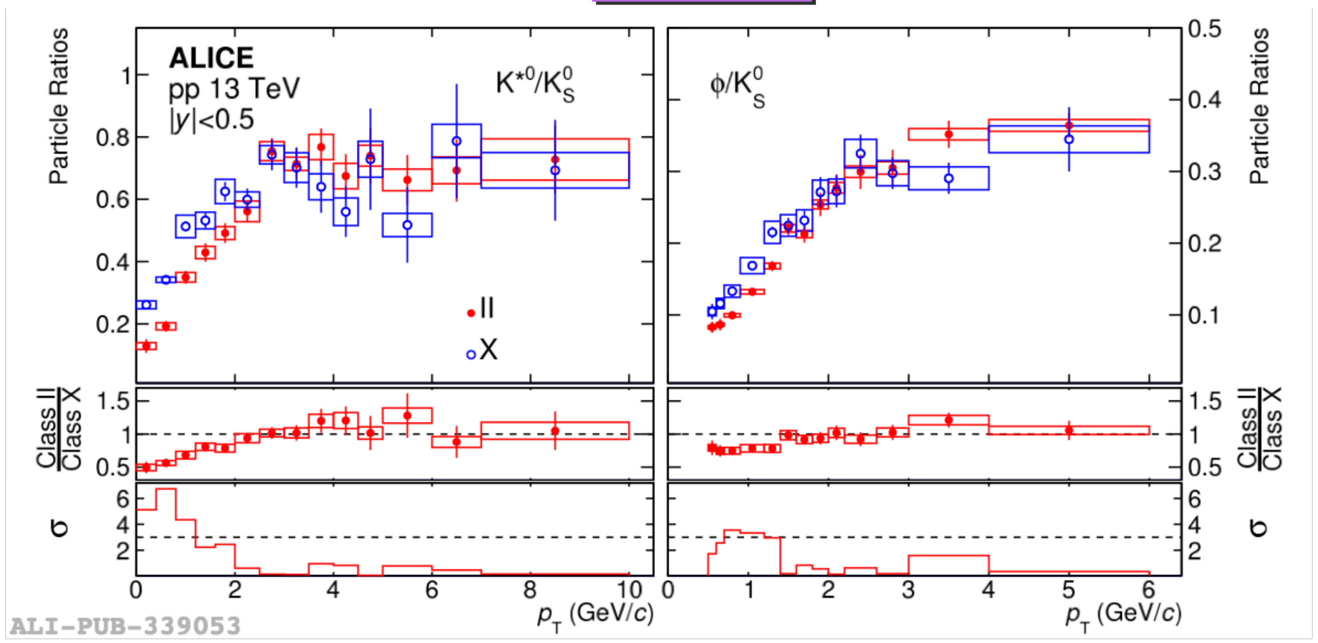
-> Suppression decreases from most central to peripheral

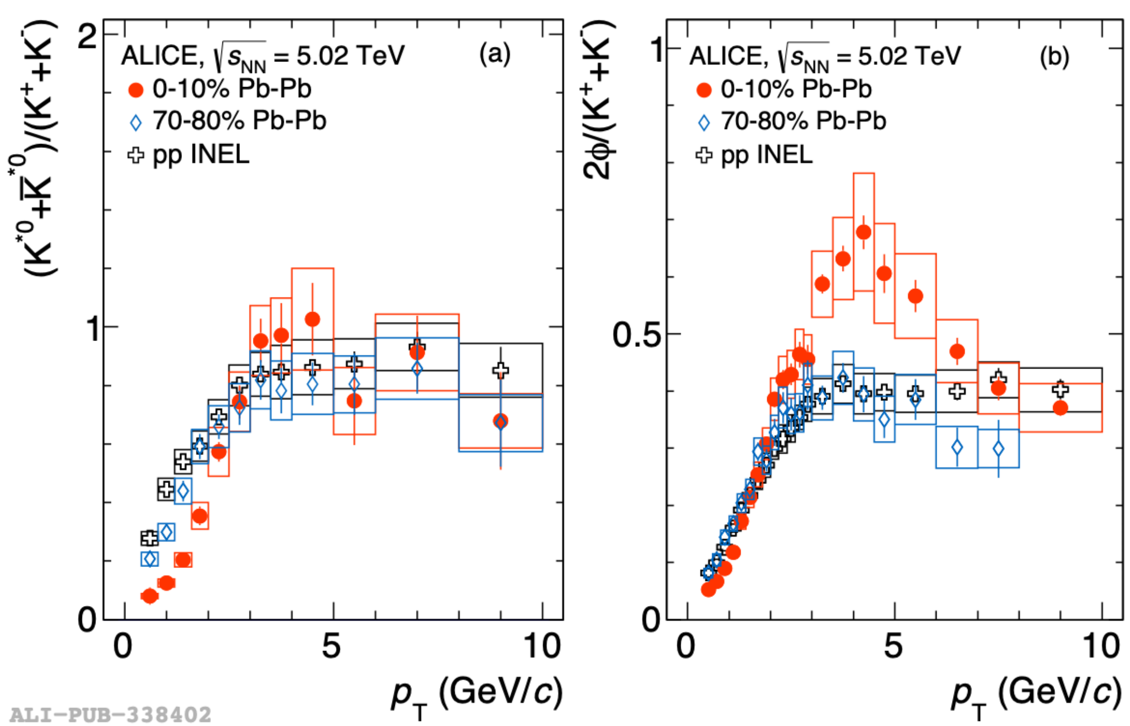
-> No significant energy dependence for all centrality classes

-> No system size dependence at similar multiplicity

p_T -differential particle ratios

pp





At low p_T : K^{*0}/K for central collisions are lower than

peripheral (pp) collisions whereas ϕ/K are comparable

within the uncertainties —> due to re-scattering

process in the

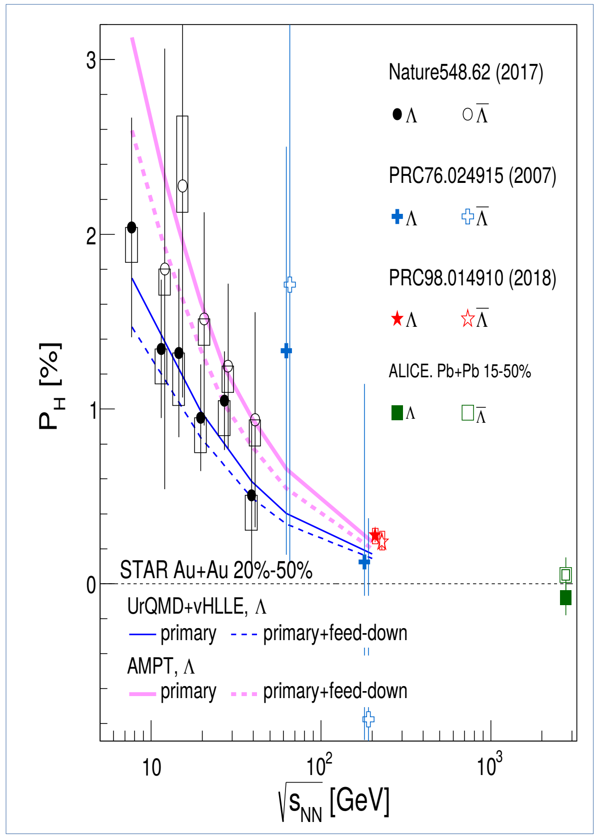
hadronic phase must effect on low momentum

Intermediate p_T :

→ Ratios show greater enhancement for central Pb-Pb collisions than peripheral and pp collisions (more for ϕ than K^{*0})

Energy dependence

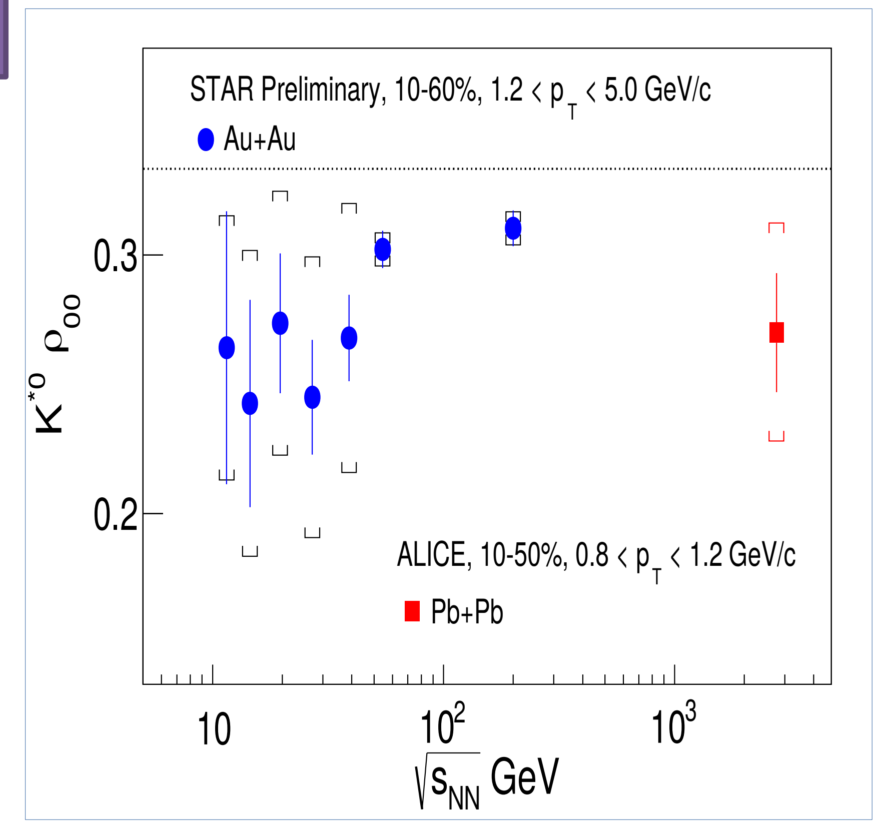
1.



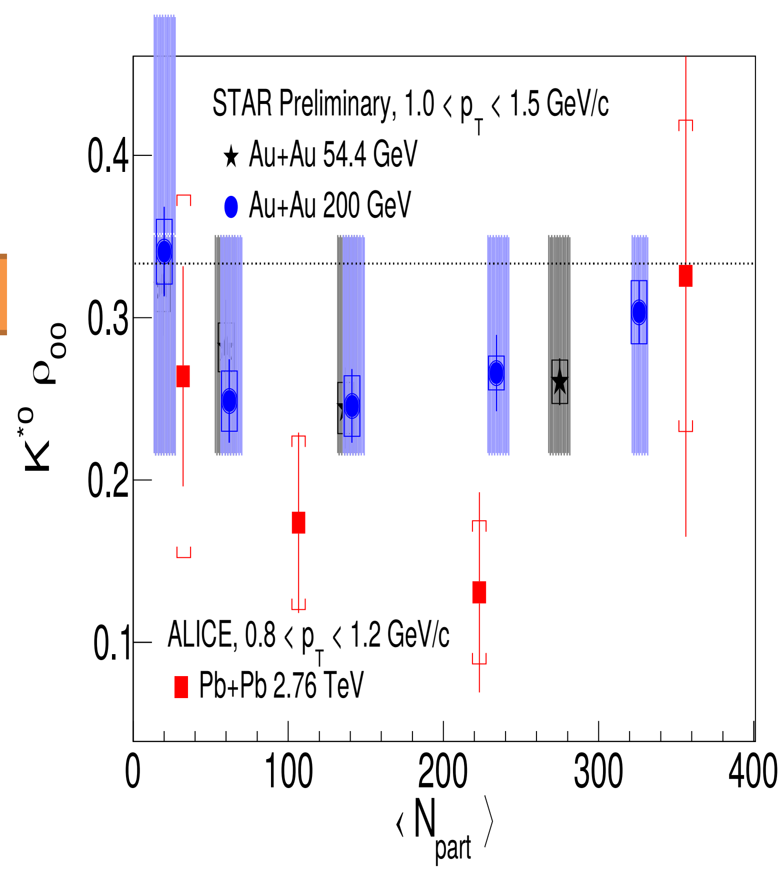
$P_H \sim P_q$ and $\rho_{00} \sim P_q^2$

ρ_{00} ~ 1/3

ρ_{00} energy dependence ?



2.



ALICE: Phys. Rev. Lett. 125, 012301

STAR: S. Singha, QM2019

K^{*0} versus ϕ meson at RHIC and LHC