System Size and Energy Dependence of Resonance production

Jihye Song
Pusan National University

HaPhy 2021

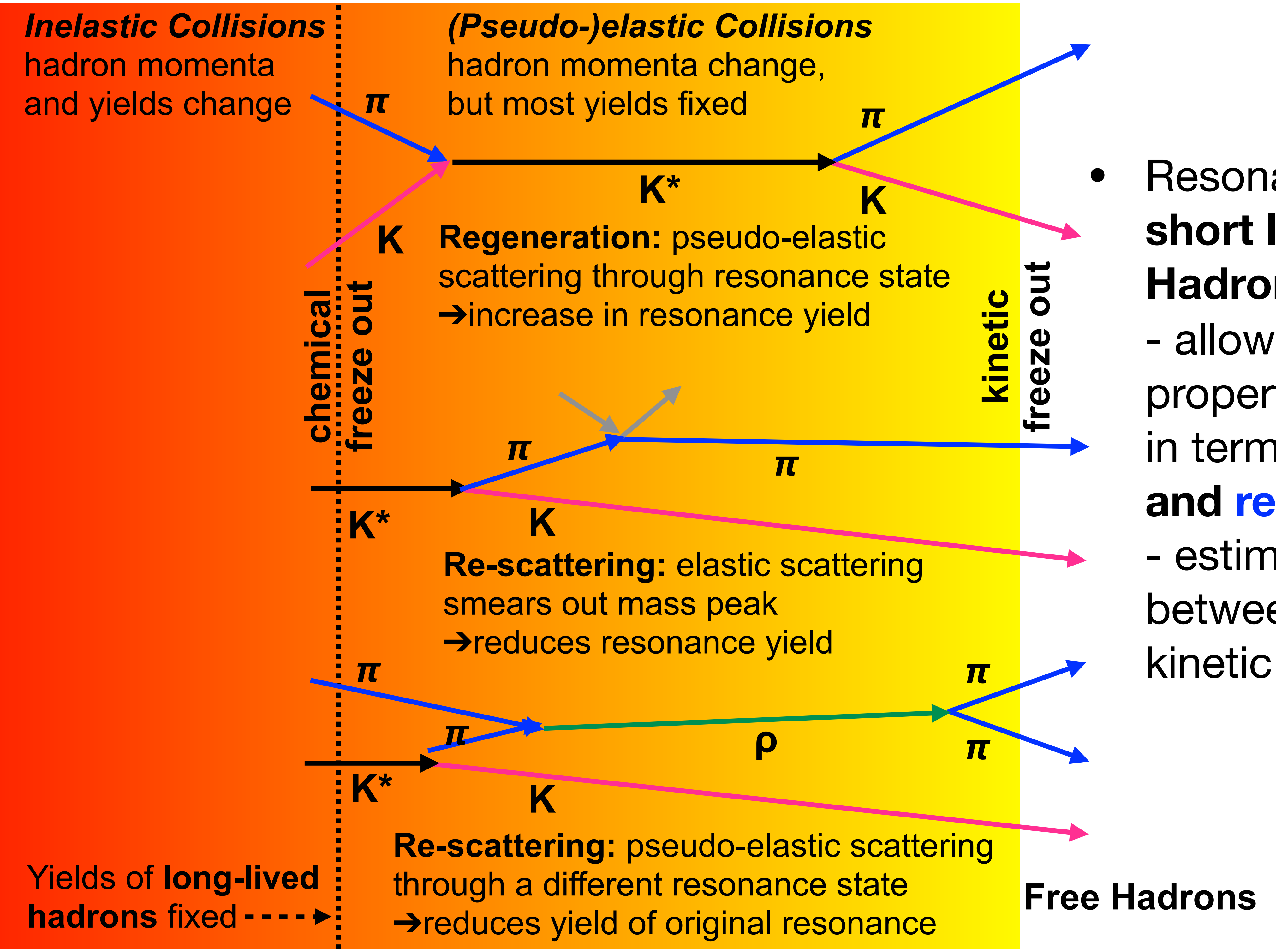
19 November 2021

Outline

- Motivation
- Resonance production
  - system size
  - energy
  - lifetime
- Probing the hadronic phase
- Strangeness production
- Spin alignment
- Summary and outlook

Motivation

1. Probing the properties of hadronic phase



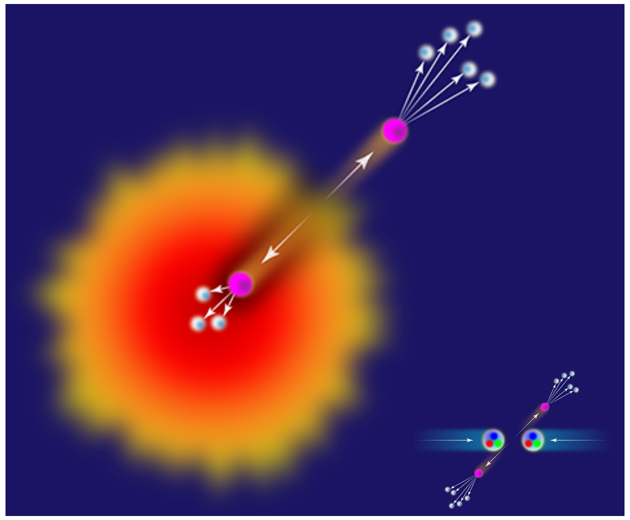
- Resonances have different **short lifetimes** similar to **Hadronic phase**
  - allows the study of properties of hadronic phase in terms of **regeneration** and **re-scattering** effects
  - estimate the duration between chemical and kinetic freeze-out

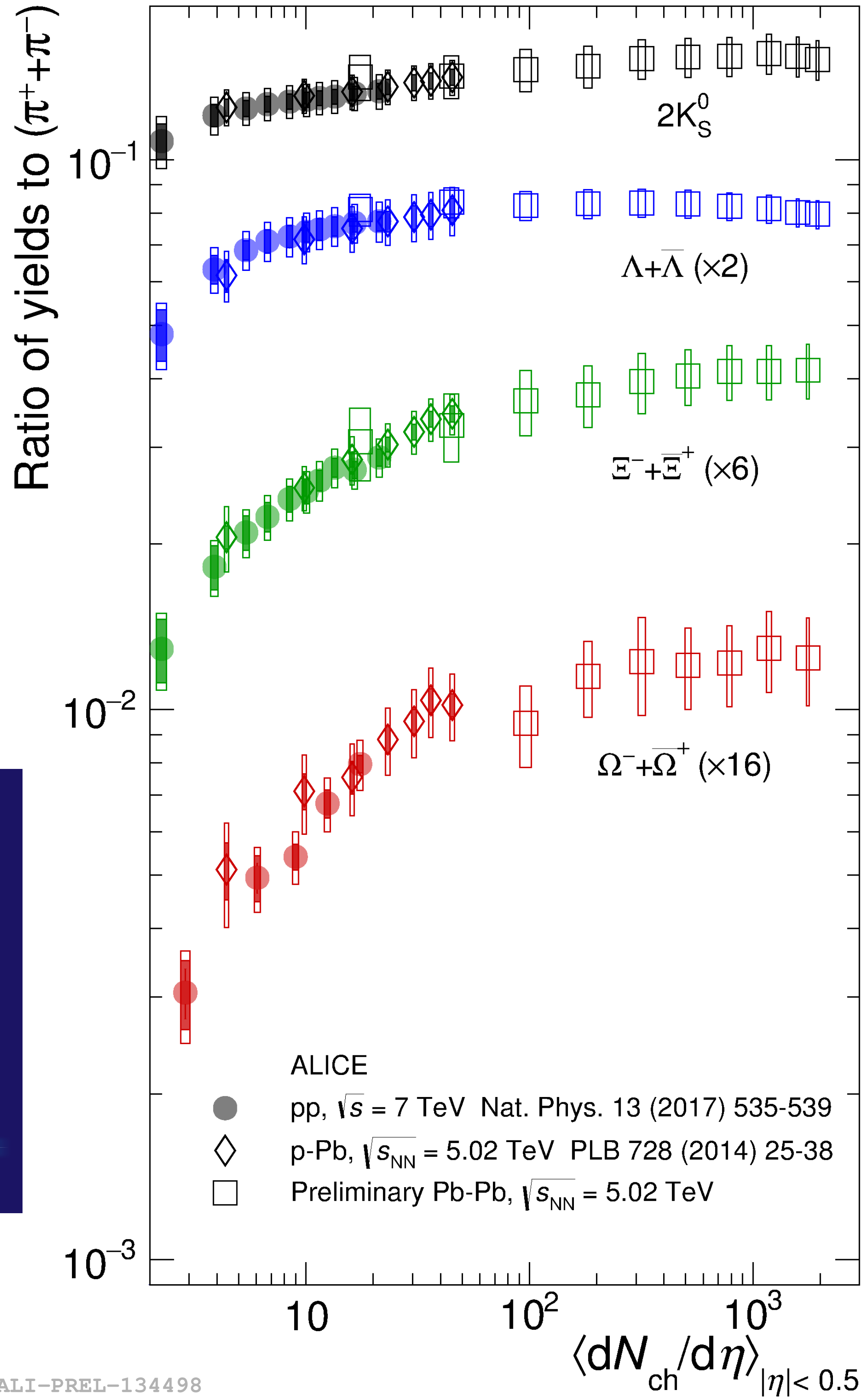
Lifetime(fm/c): **ρ(1.3)** < **K*⁰(4.2)** < **Σ*(5.5)** < **Λ*(12.6)** < **Ξ*(21.7)** < **ϕ(46.4)**

Motivation

2. Strangeness production

- Resonances have same quark content as the ground state particles, but different masses
  - help to understand **strangeness production** by factorizing mass and strangeness related effects





3. In-medium energy loss

4. Spin Alignment

5. Chiral symmetry restoration

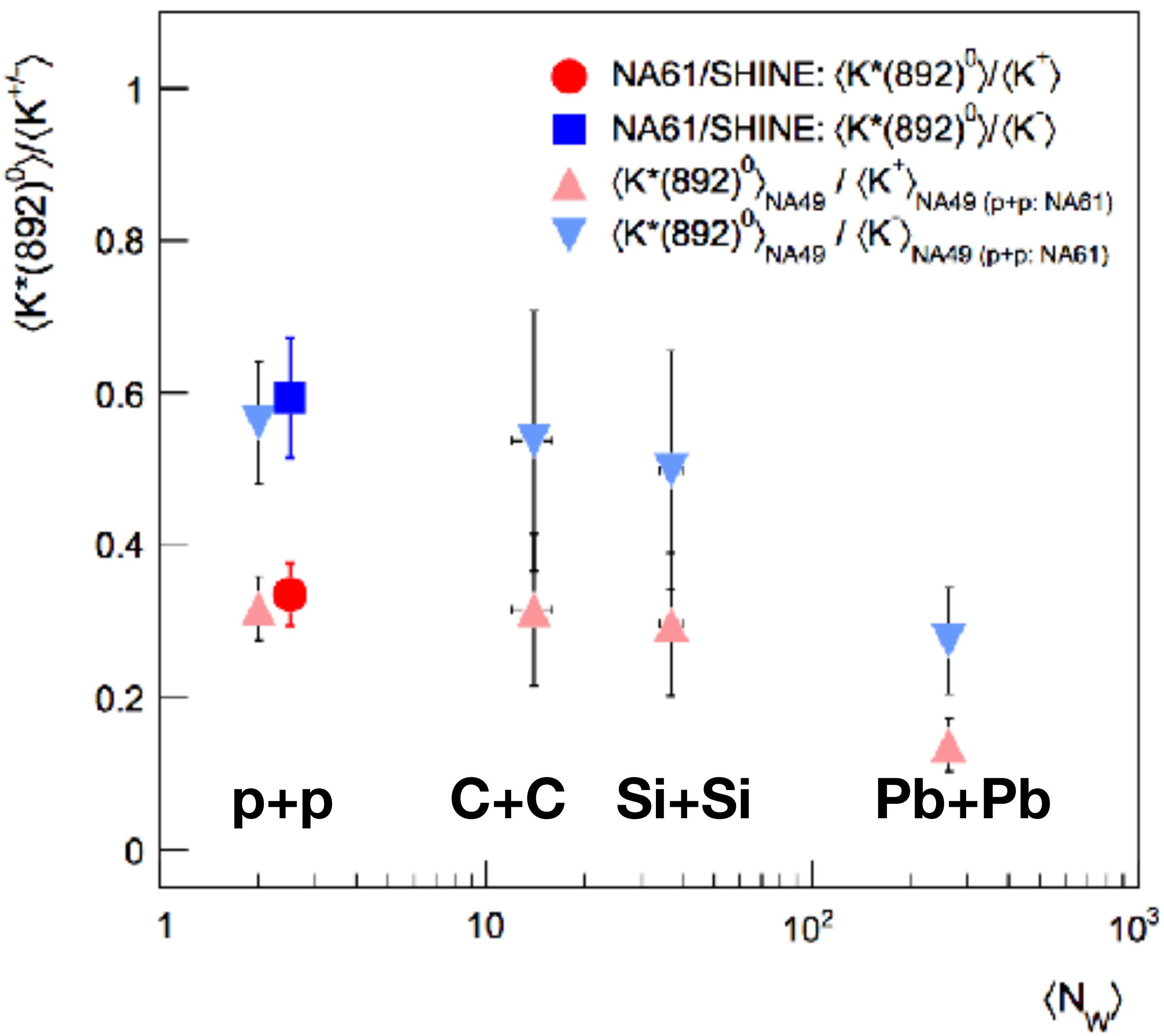
Resonances (particle & decay)

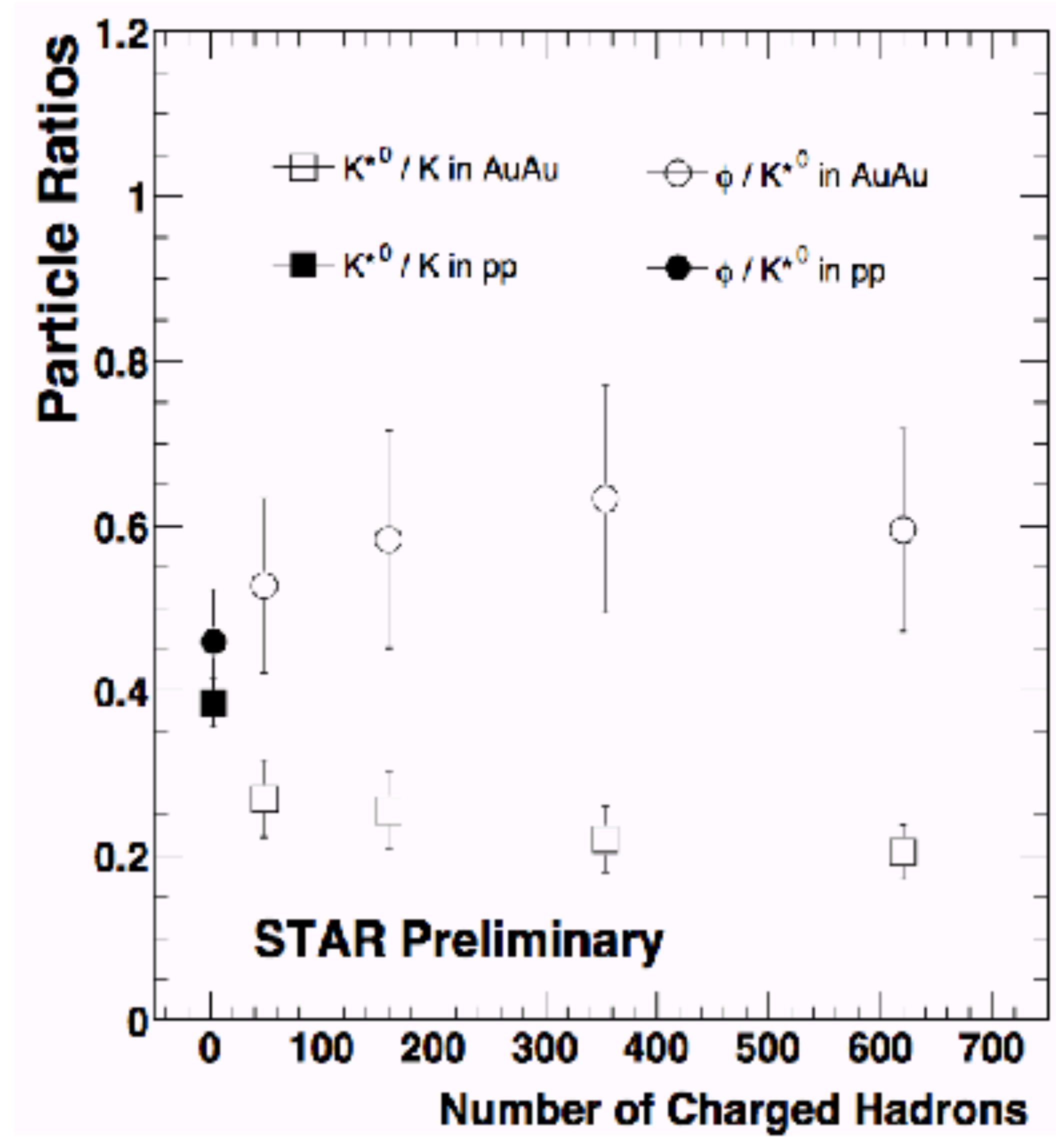
Meson	quark content	Decay modes	B.R.
$\rho(770)^0$	$(u\bar{u}+d\bar{d})/\sqrt{2}$	$\pi^+\pi^-$	100
$K^*(892)^0$	$d\bar{s}$	$K^+\pi^-$	66.6
$K^*(892)^\pm$	$u\bar{s}$	$K^0_s\pi^+$	33.3
$f_0(980)$, $f_2(1270)$	unknown	$\pi^+\pi^-$	46(84)
$K^*_{0,2}(1430)^0$	$d\bar{s}$	$K^+\pi^-$	93(49.4)
$\phi(1020)$	$s\bar{s}$	K^+K^-	48.9

Baryon	quark content	Decay modes	B.R.
$\Sigma(1385)^+$	uus	$\Lambda\pi^+$	87
$\Sigma(1385)^-$	dds	$\Lambda\pi^-$	87
$\Lambda(1520)$	uds	pK^-	22.5
$\Xi(1530)^0$	uss	$\Xi^-\pi^+$	66.7
$\Xi(1820)^{\mp,0}$	dss (uss)	$\Lambda K^\mp$ (ΛK^0_s)	unknown
$\Omega(2012)^\mp$	sss	$\Xi^\mp K^0_s$	unknown

Lifetime(fm/c): **ρ(1.3) < K^{*0}(4.2) < Σ^*(5.0-5.5) < Λ^*(12.6) < Ξ^*(21.7) < ϕ(46.2)**

Particle ratios: system size



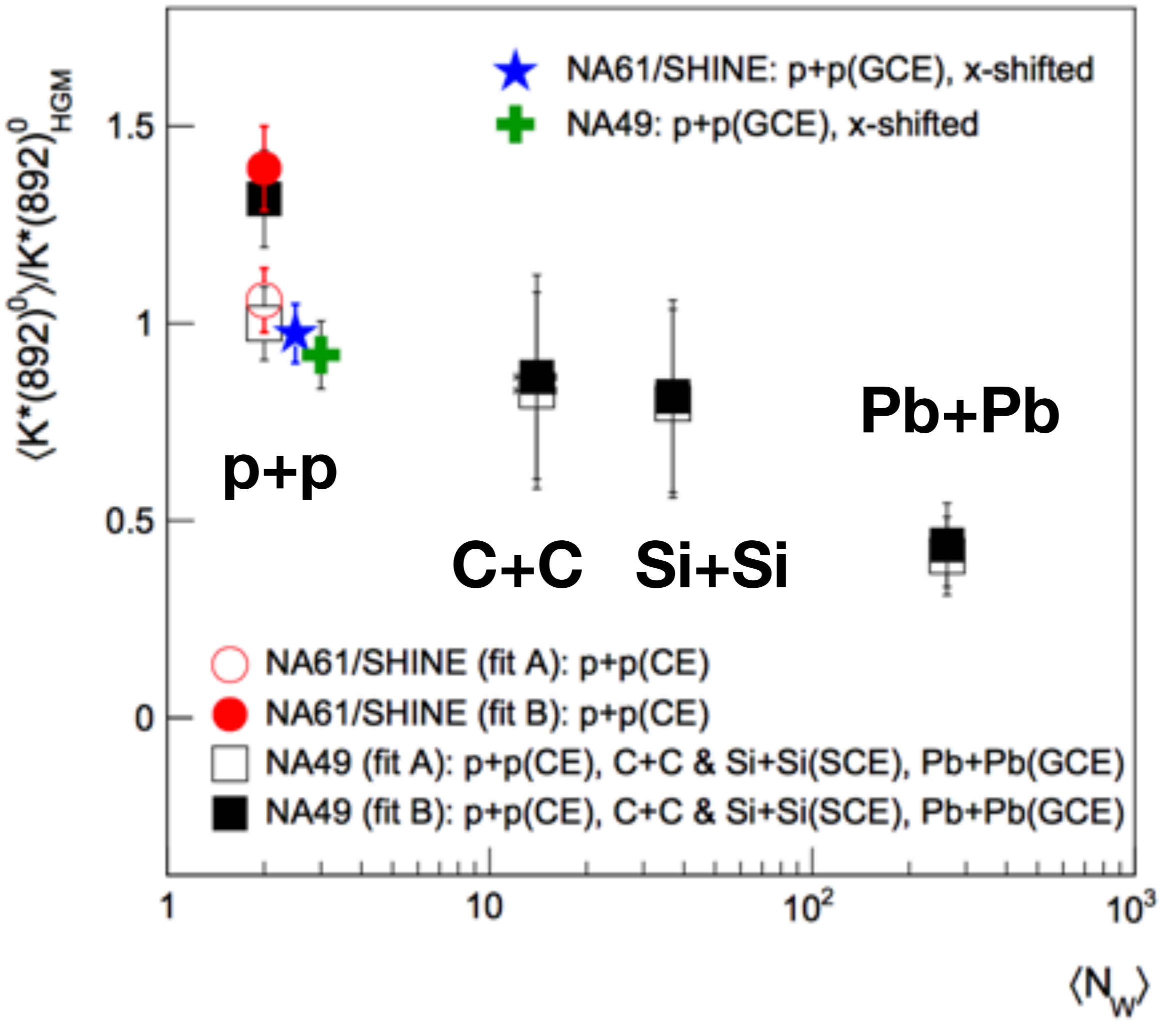


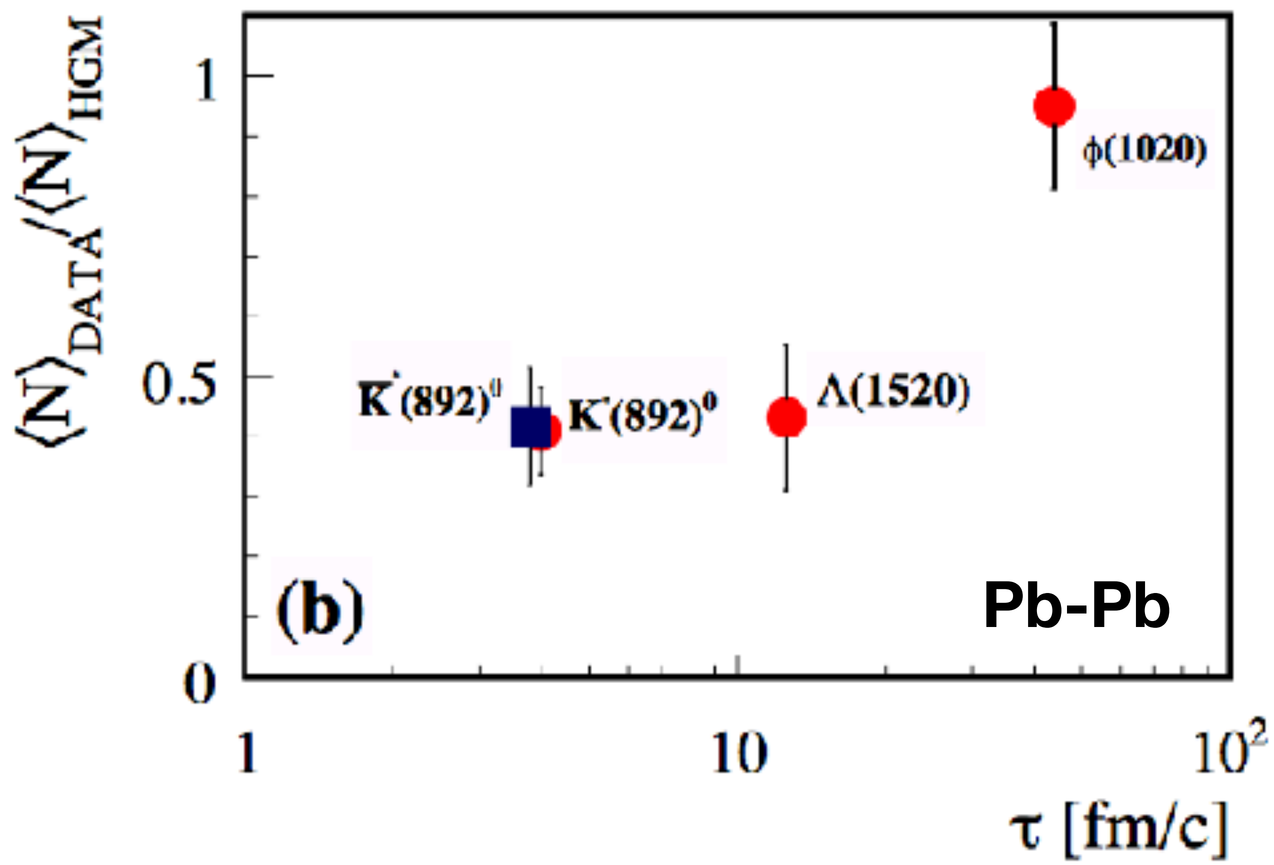
- Suppression of K^{*0} is observed in different collision systems from various experiments (NA49, NA61/SHINE, STAR)
  - more suppression for larger collision systems

Eur. Phys. J. C (2020) 80:460

J. Phys. G: Nucl. Part. Phys. 30 S577

Particle ratios: system size





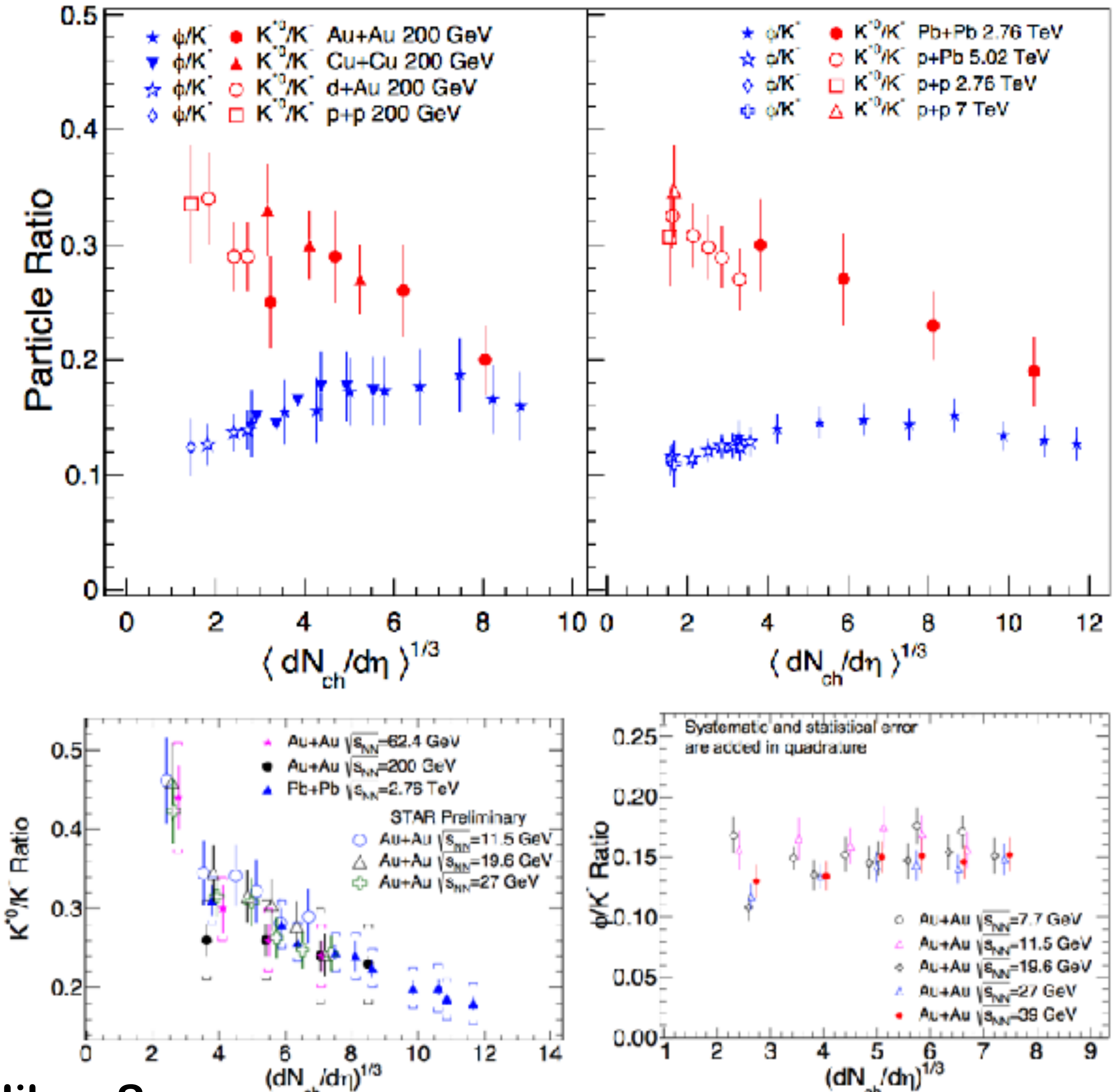
- Suppression of K^{*0} w.r.t. the statistical Hadron Resonance Gas Models(HGM) is observed for heavier system

- Suppression of Λ(1520) while no suppression for ϕ w.r.t. the HGM from NA49 measurement

Eur. Phys. J. C (2020) 80:460
NA49, Phys. Rev. C84 (2011) 064909

Particle ratios: energy dep.

M. Nasim, J. Zhao(SQM2019)

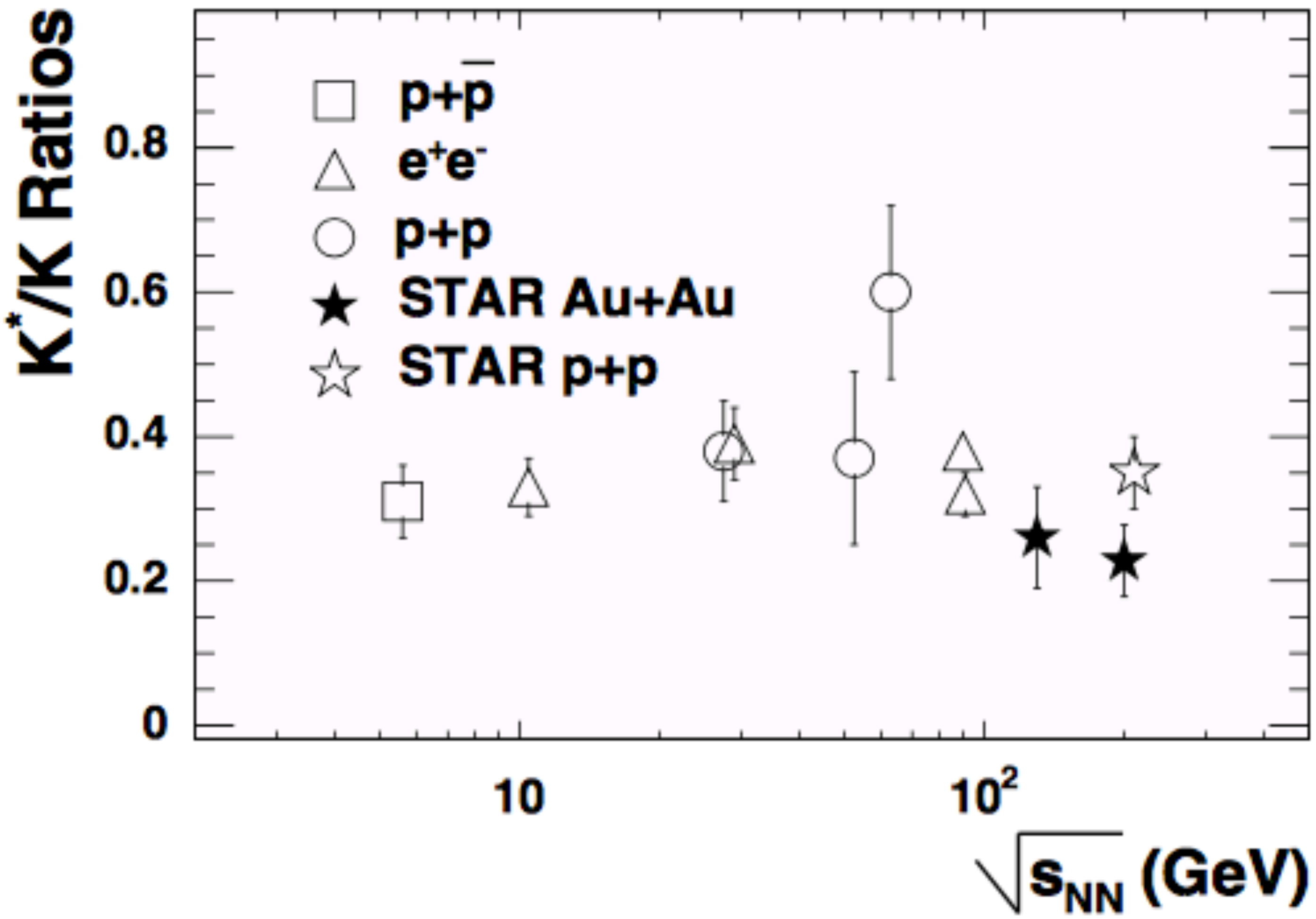


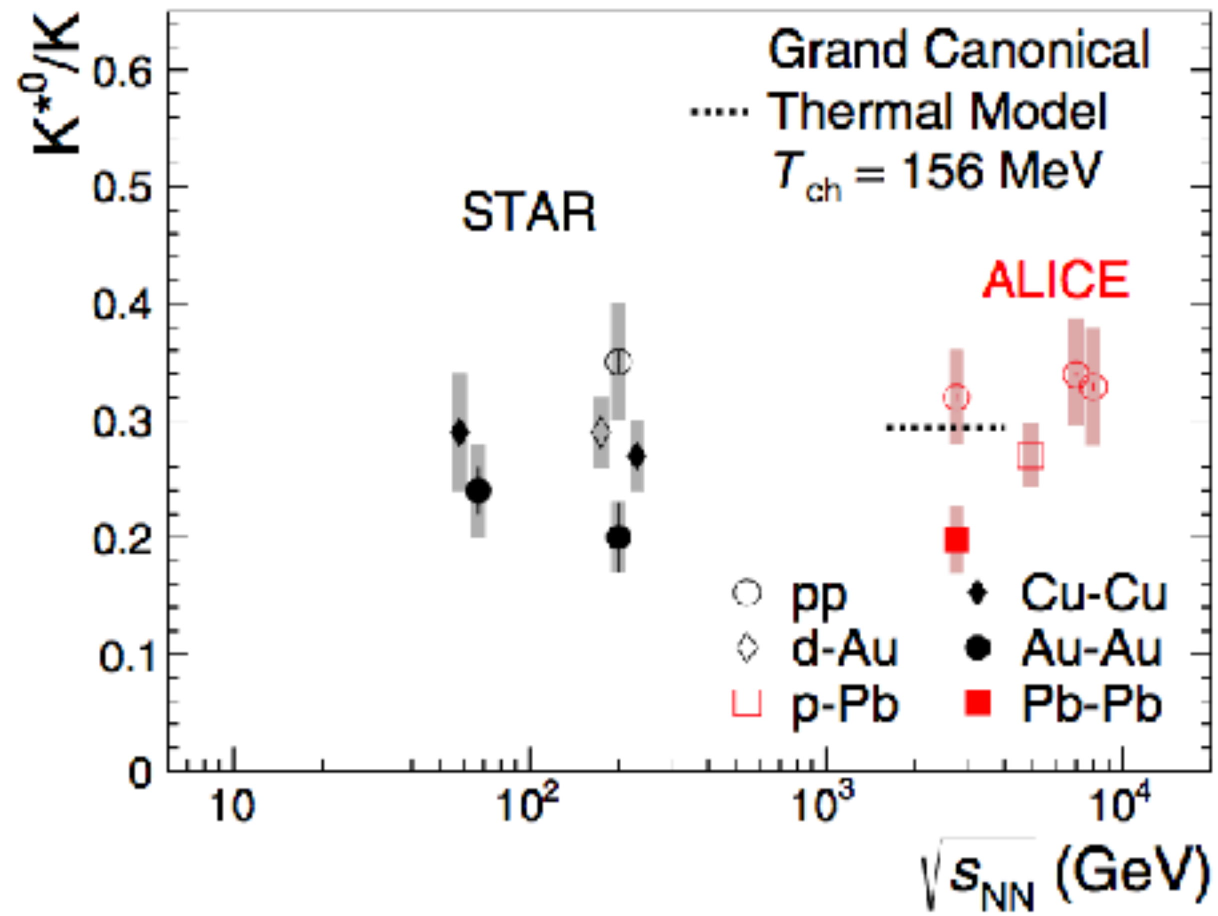
K^{*0}/K and ϕ/K ratios have been measured at different energies in STAR and ALICE

- no clear energy dependence from RHIC to LHC

PLB 802 (2020) 135225

Particle ratios: energy dep.





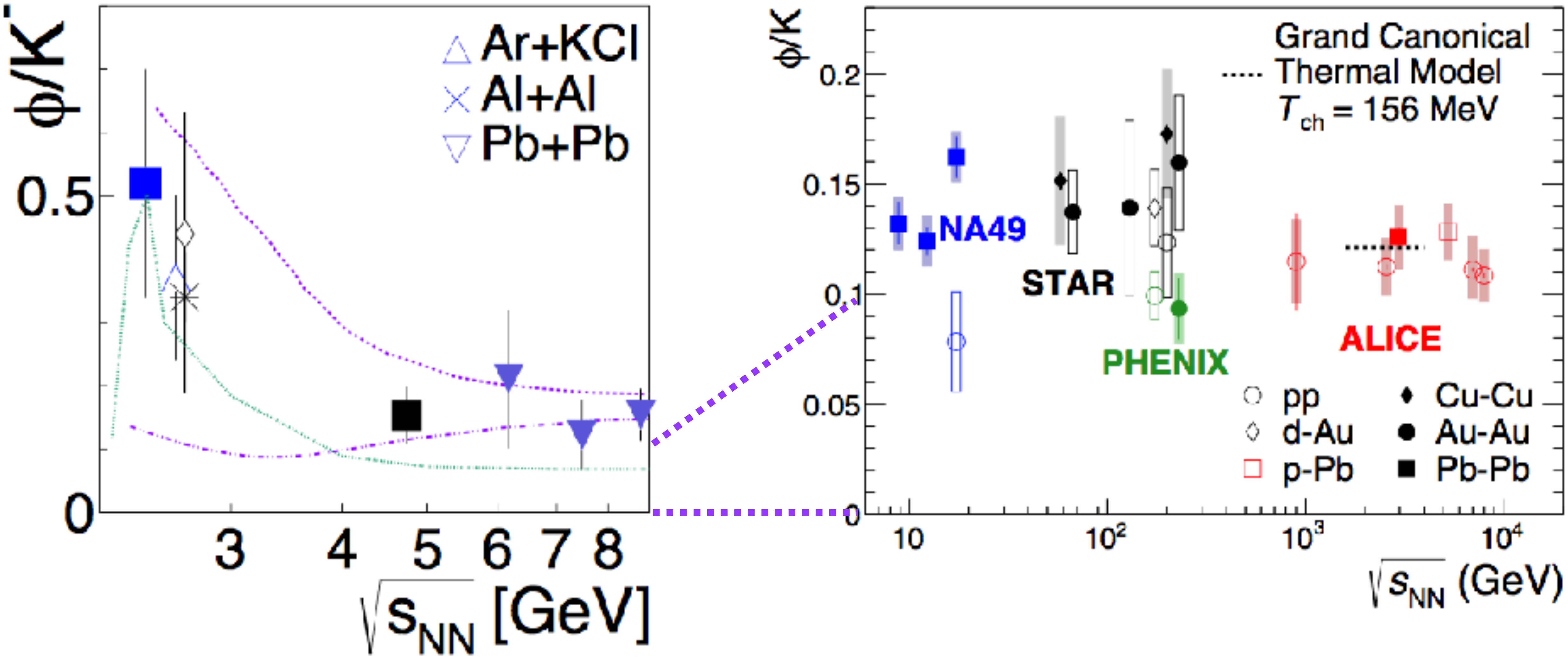
- Flat behavior in wide range of energy for small collision systems
- Yield ratios for central Au+Au and Pb-Pb collisions are significantly lower than the pp collisions

Phys.Rev.C71:064902,2005

PHYSICAL REVIEW C 102, 024912 (2020)

Particle ratios: energy dep.

HADES *Phys.Lett.B* 778 (2018)



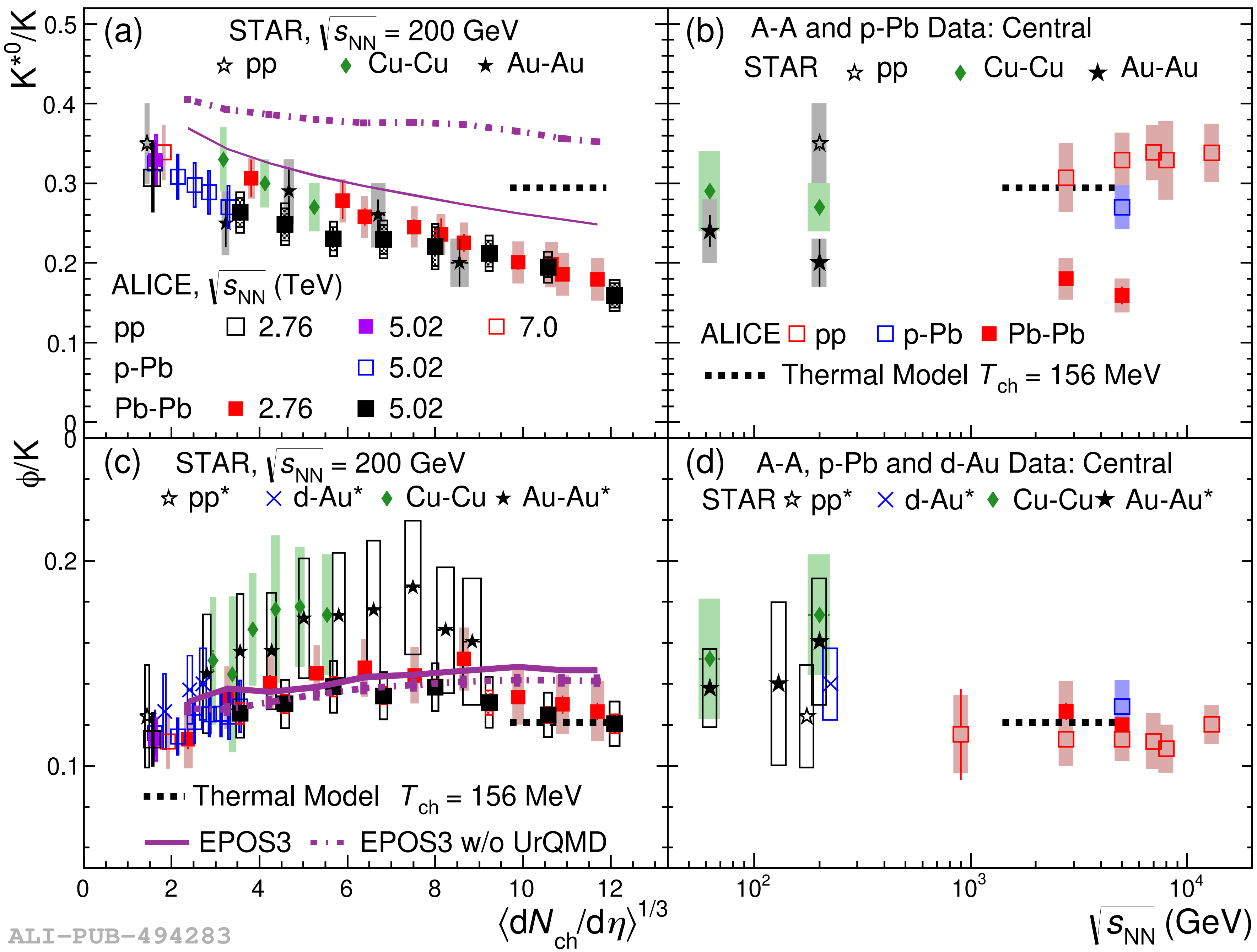
- Flat behavior in wide range of energy (~10-10^4 GeV)

- Increase for low energies due to canonical suppression
  - reproduced by statistical model calculation with strangeness correlation radius parameter R_c = 2.2fm

Phys.Rev.C71:064902,2005

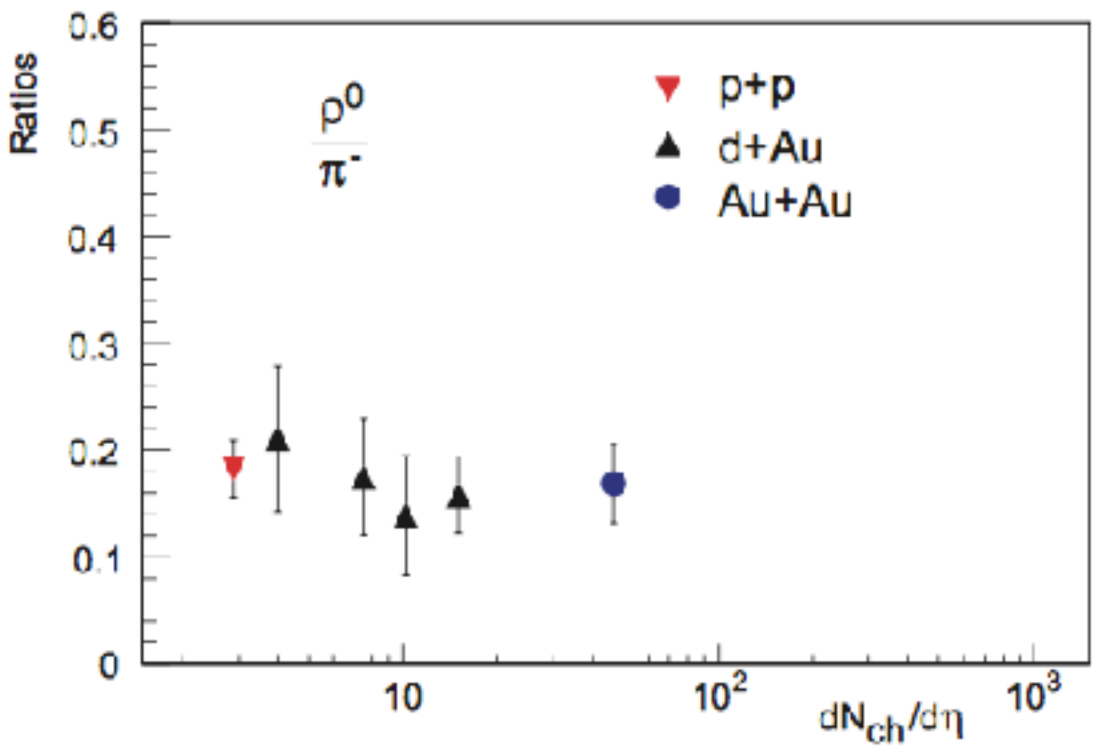
PHYSICAL REVIEW C 102, 024912 (2020)

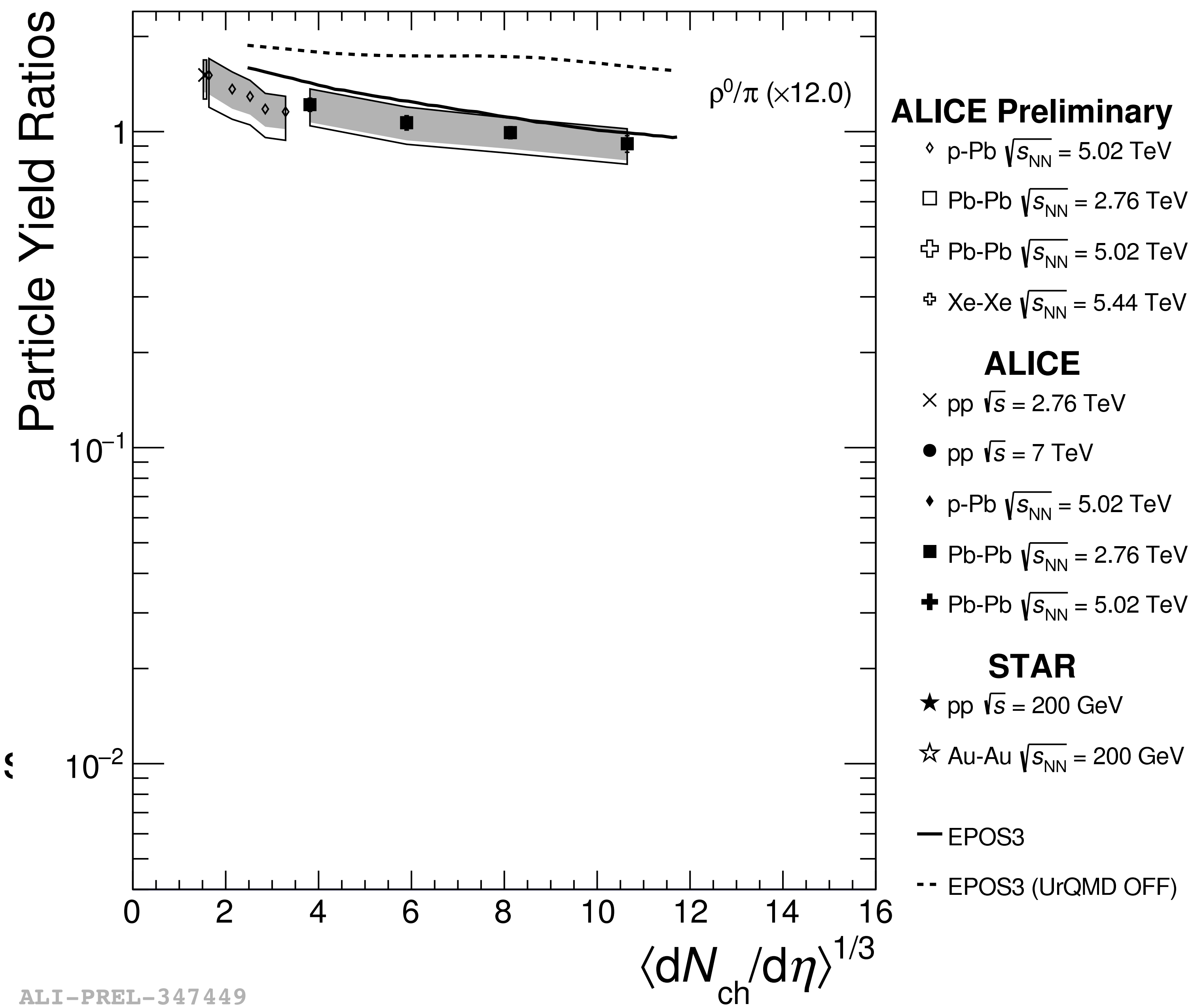
Particle ratios



- **K*⁰/K**
  - decrease with increasing multiplicity (system size)
  - larger in central Cu-Cu than central Au-Au
  - higher in pp collisions than in central Au-Au and Pb-Pb
- **ϕ/K**
  - constant as a function of multiplicity
  - slightly larger in Au-Au and Cu-Cu than Pb-Pb
  - independent of collision energy and system from RHIC to LHC energies

Resonance to long-lived particle ratios



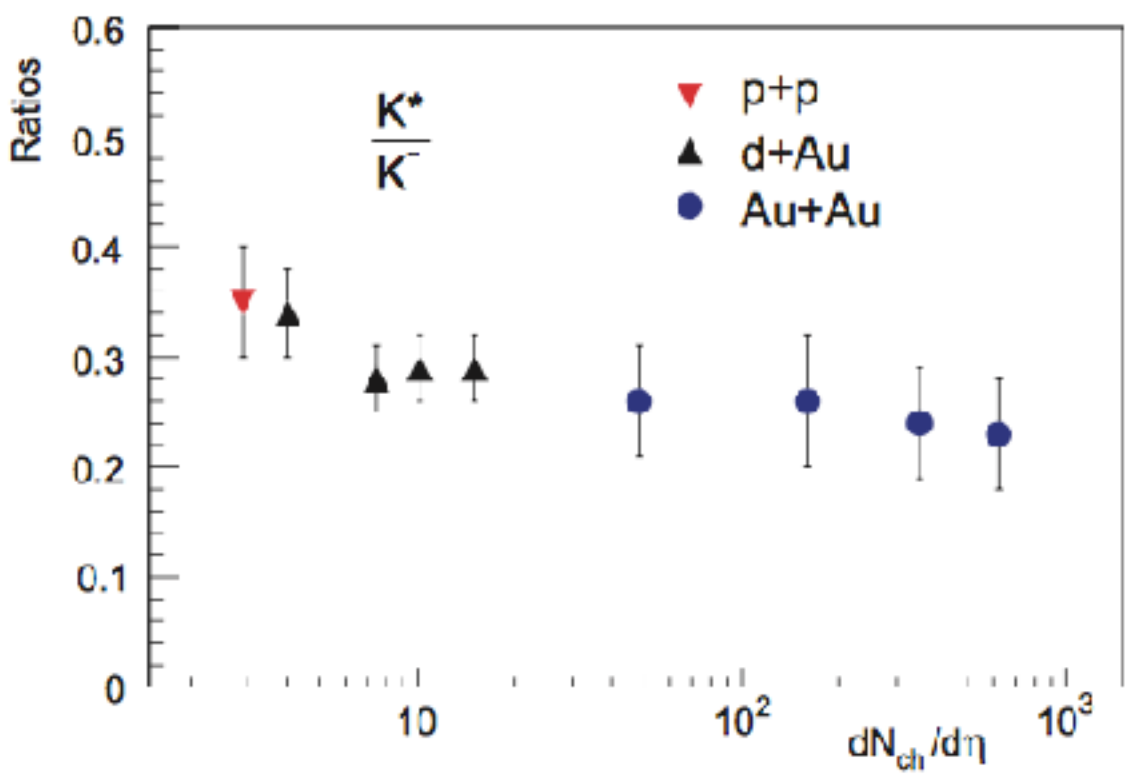


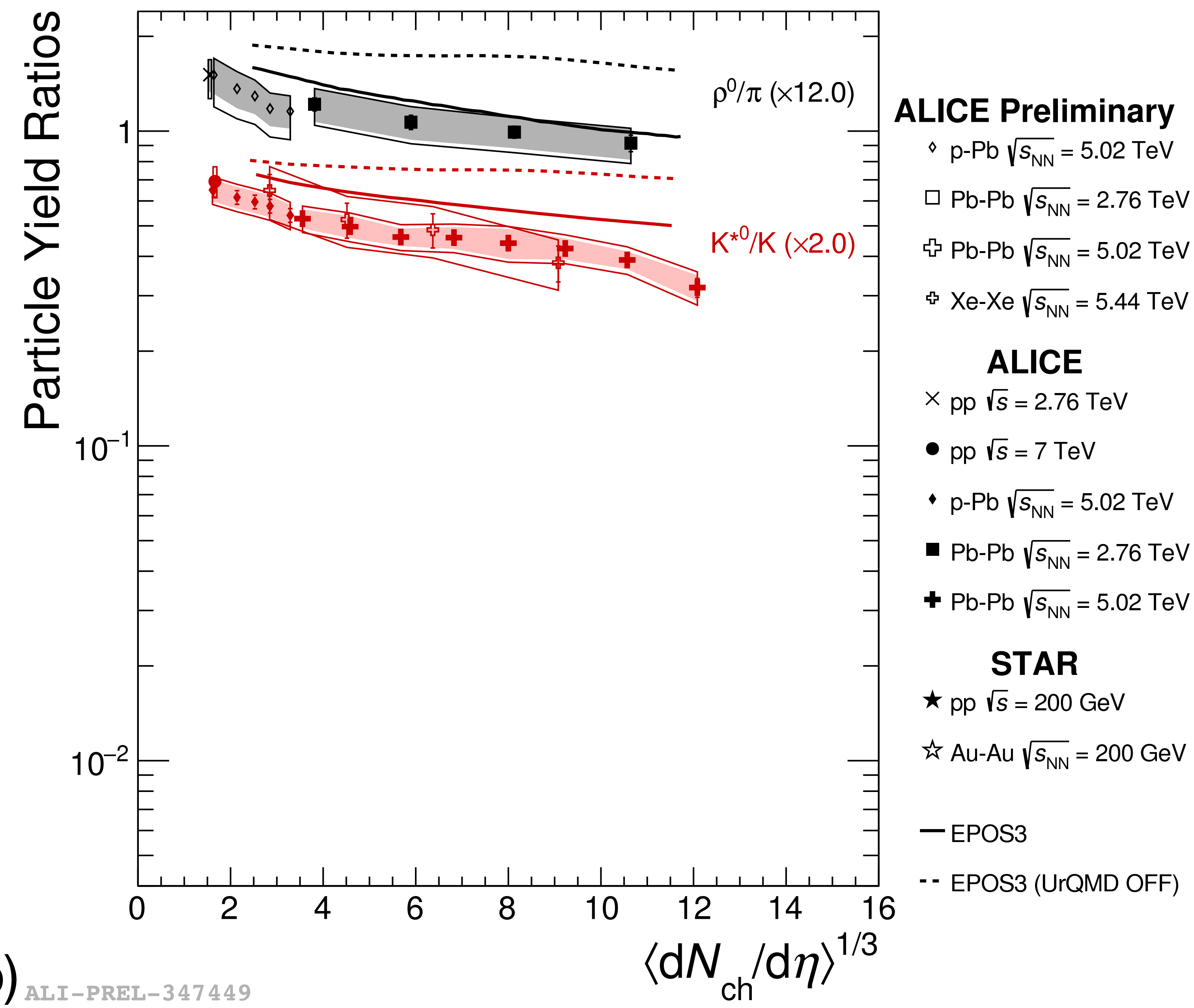
- No multiplicity dependence of ρ^0/π at RHIC in p+p, d+Au and Au+Au collisions
- ρ^0/π is suppressed at LHC with increasing multiplicity
  - qualitatively described by EPOS with UrQMD

Lifetime(fm/c): **ρ(1.3)**

Phys.Rev.C78:044906,2008

Resonance to long-lived particle ratios



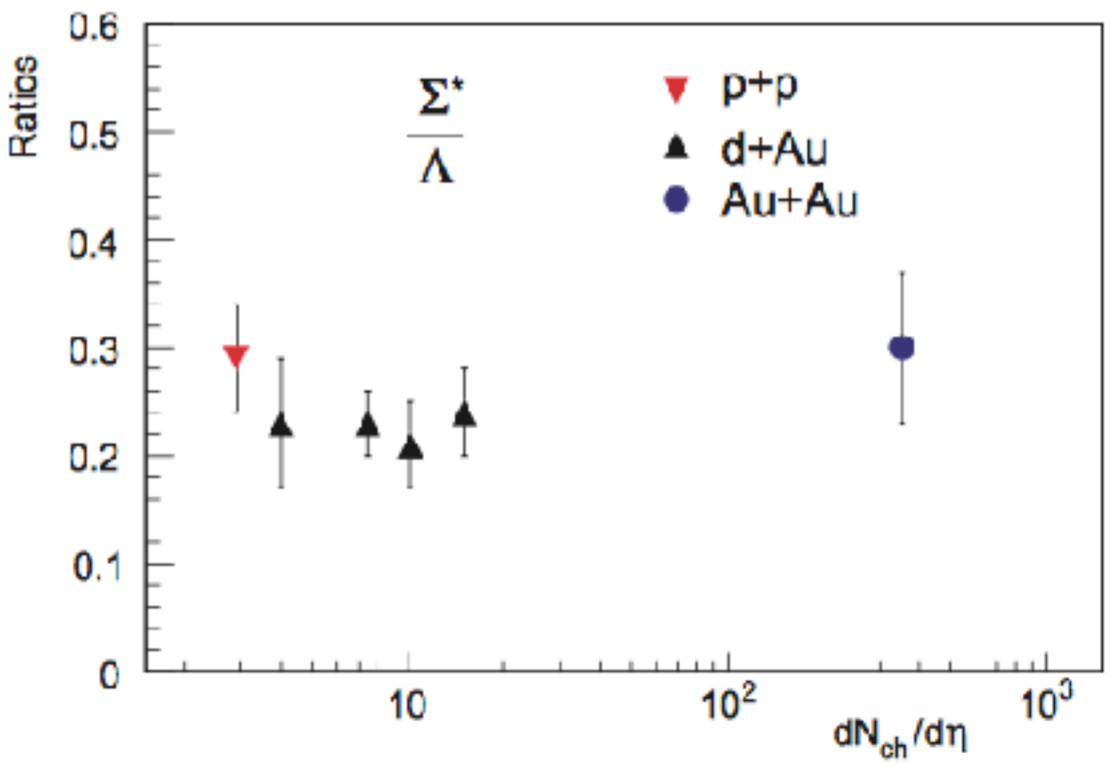


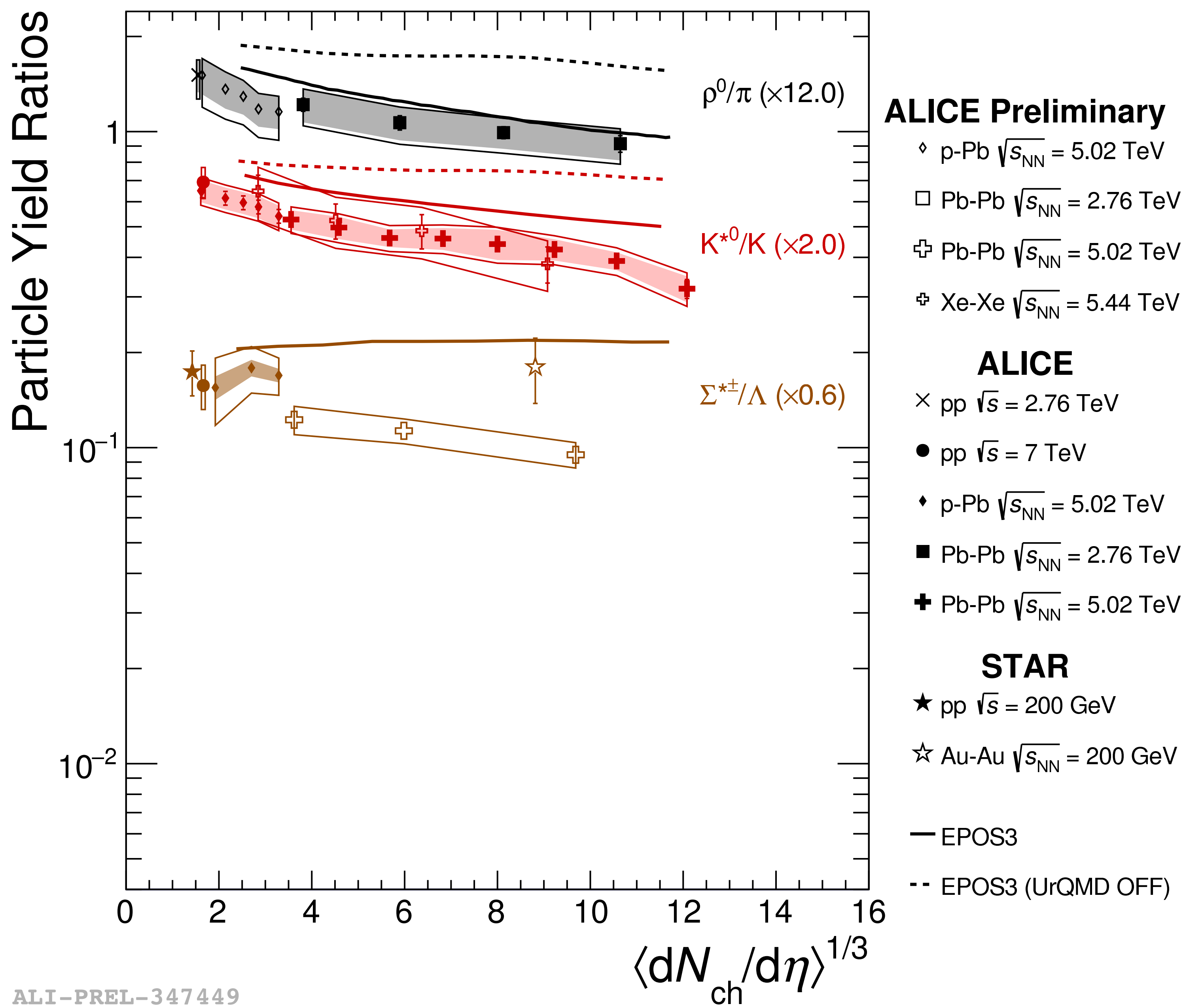
- Multiplicity dependence of K^{*0}/K at RHIC and LHC
  - smooth trend:
  p+p→d+Au(p+Pb)→Au+Au(Pb+Pb)

Lifetime(fm/c): **ρ(1.3)** < **K^{*0}(4.2)**

Phys.Rev.C78:044906,2008

Resonance to long-lived particle ratios

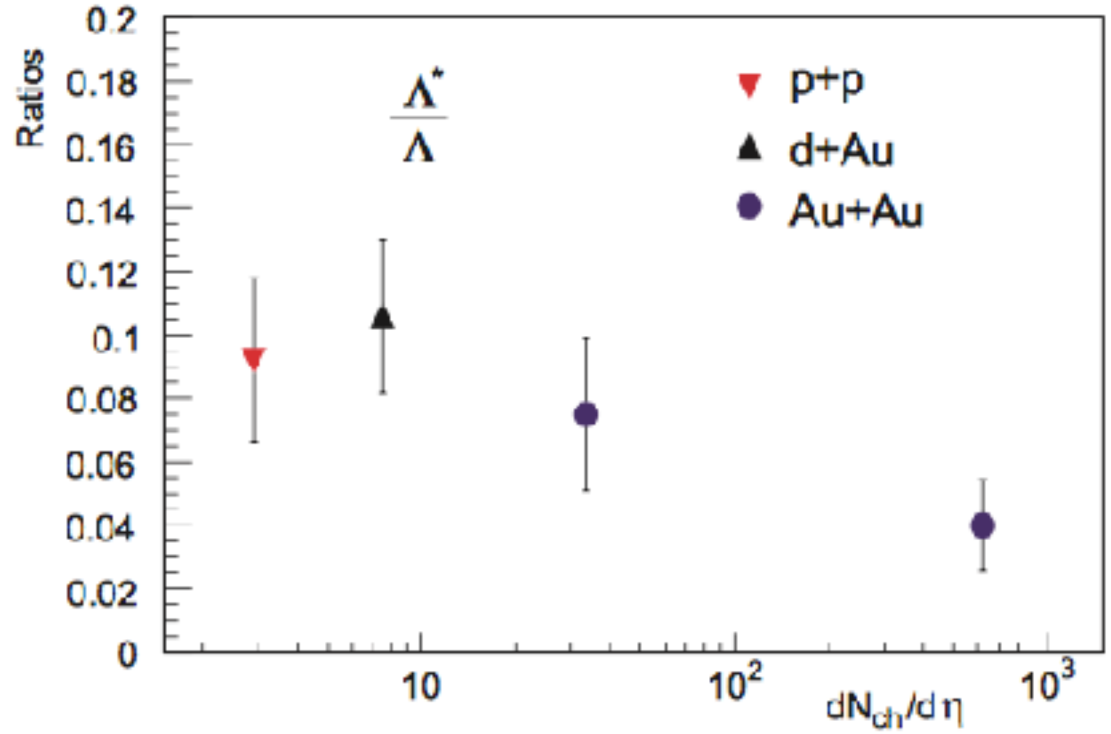


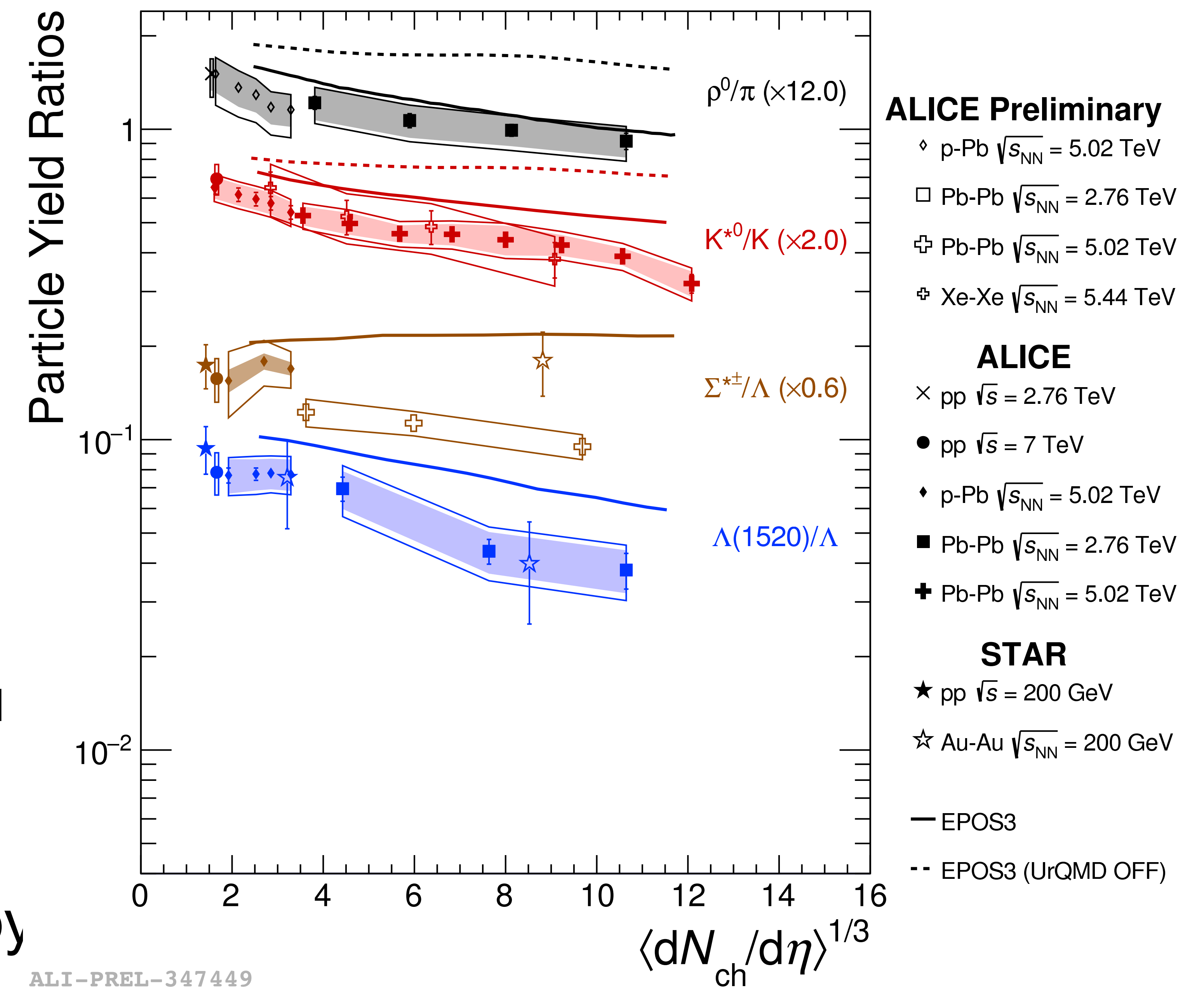


- No modification of Σ^*/Λ at d+Au, p+Pb and Au+Au
- while suppression of Σ^*/Λ is observed in Pb+Pb
  - not described by EPOS3

Lifetime(fm/c): **ρ(1.3)** < **K*⁰(4.2)** < **Σ*(5.5)**

Resonance to long-lived particle ratios



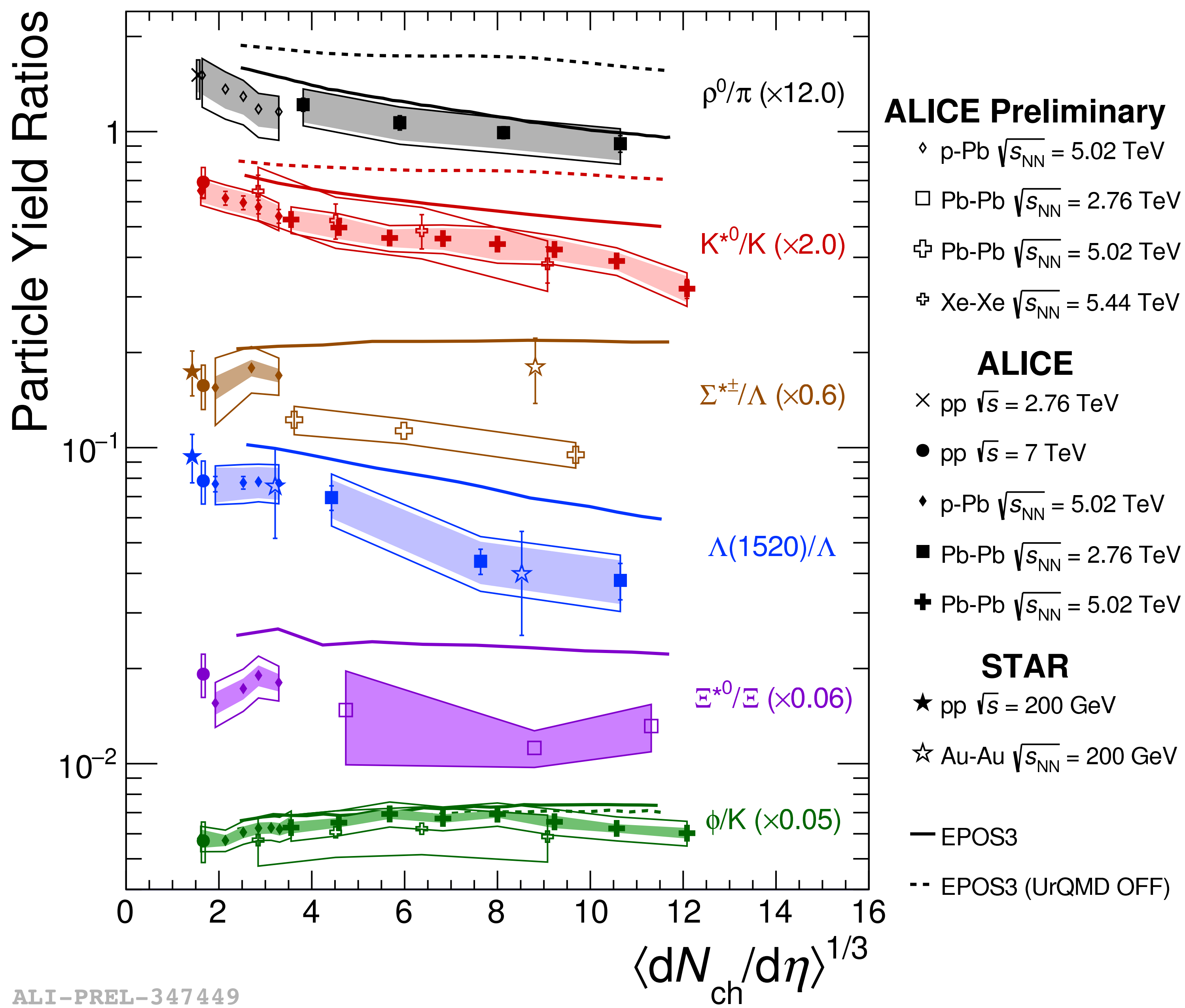


- Suppression of Λ^*/Λ at Au+Au Pb+Pb
- A+A: qualitatively described by EPOS with UrQMD

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

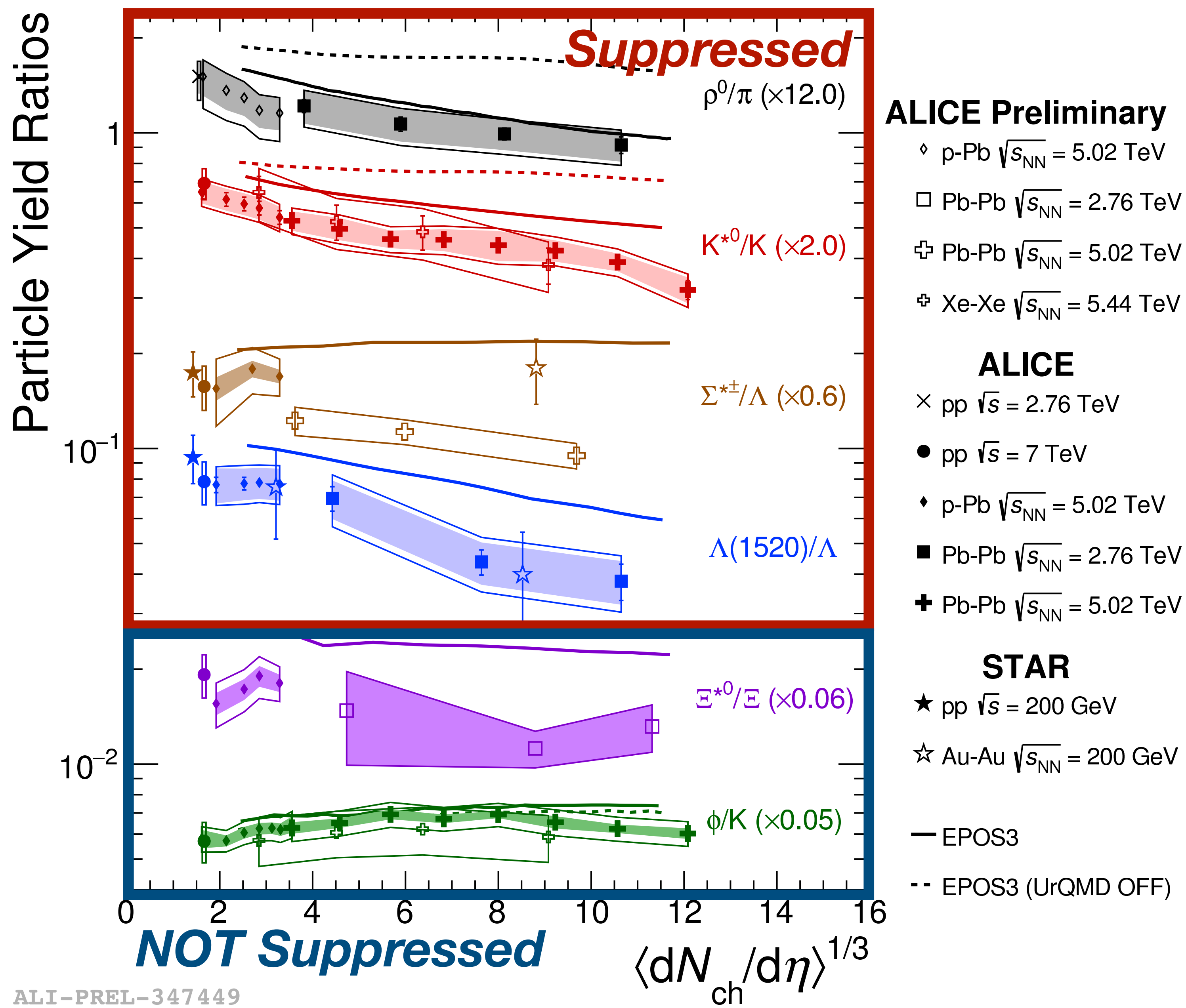
Resonance to long-lived particle ratios

- **Ξ*/Ξ** and ***ϕ*/K**: no significant centrality dependence across the different collision systems



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

Resonance to long-lived particle ratios



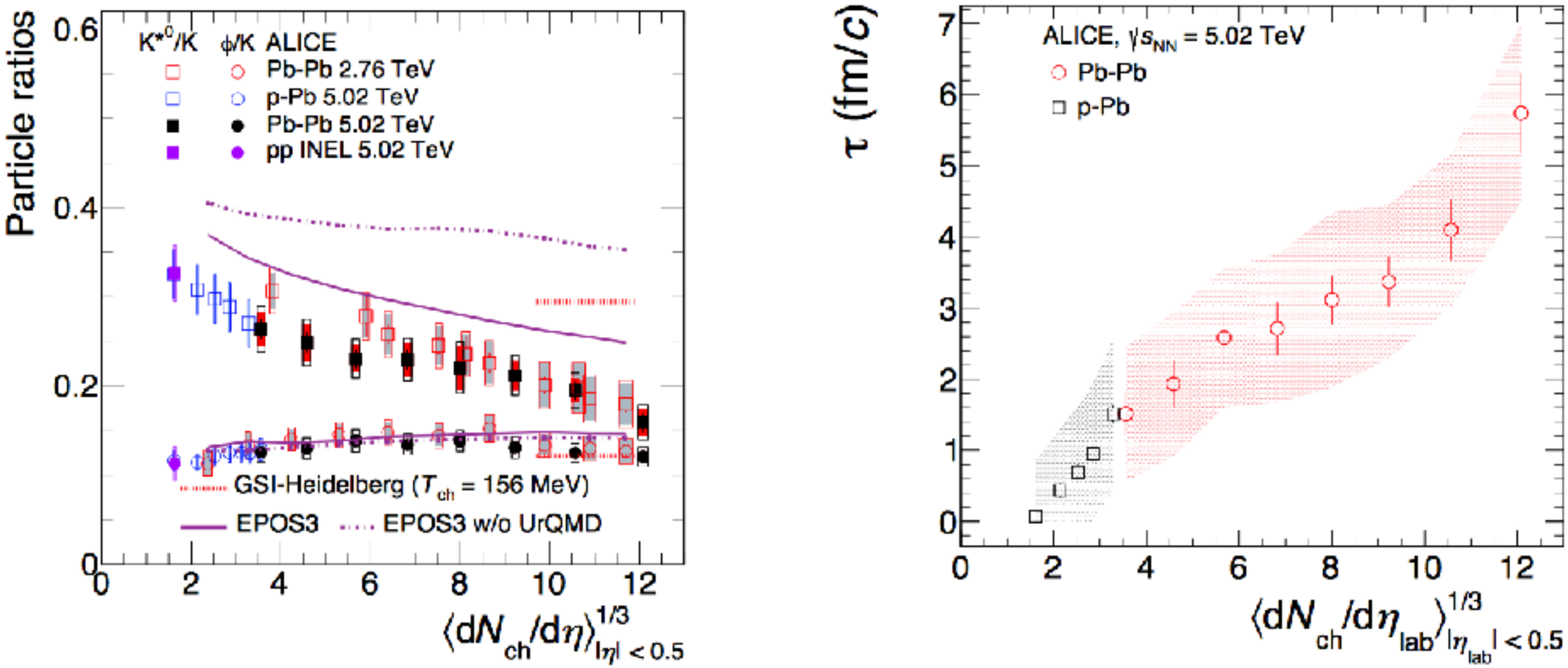
Summary

ρ^0/π, K^{*0}/K, Σ^*/Λ and **Λ^*/Λ in Pb-Pb**: suppression in central Pb-Pb collisions indicates *dominance of re-scattering over regeneration for short lived resonances*

Ξ^*/Ξ and **ϕ/K**: no significant centrality dependence

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

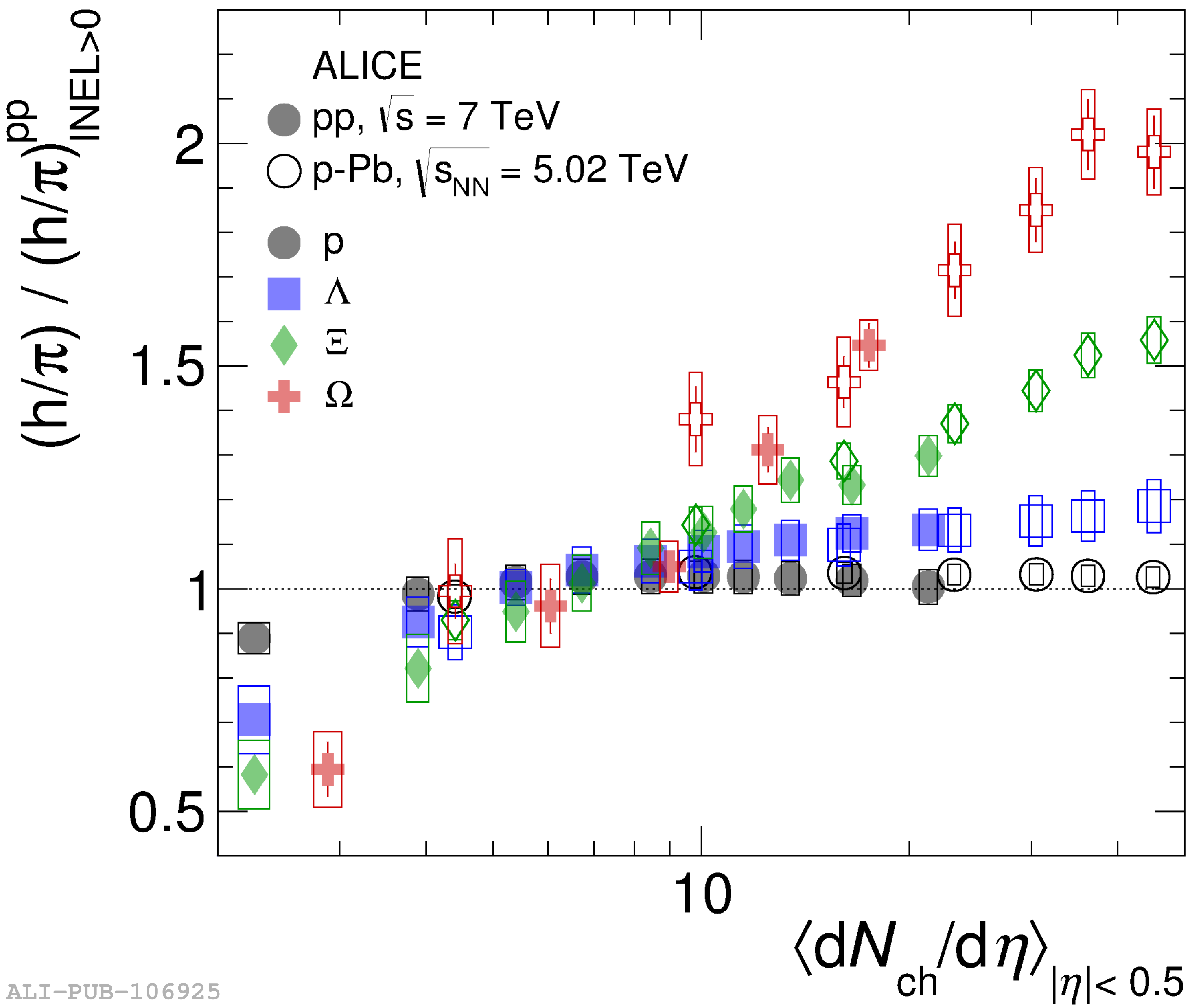
Probing the hadronic phase



$$[K^{*0}/K]_{\text{kinetic(pPb, PbPb)}} = [K^{*0}/K]_{\text{chemical(pp)}} \times e^{-\tau/\tau_{K^{*0}}}$$

- Estimate the time duration between chemical and kinetic freeze-out from the measurement of K^{*0}/K ratios in Pb-Pb and pp collisions
  - found to be ~4-7 fm/*c* for central collisions

Strangeness in small system



What causes the enhancement?
mass vs. strangeness

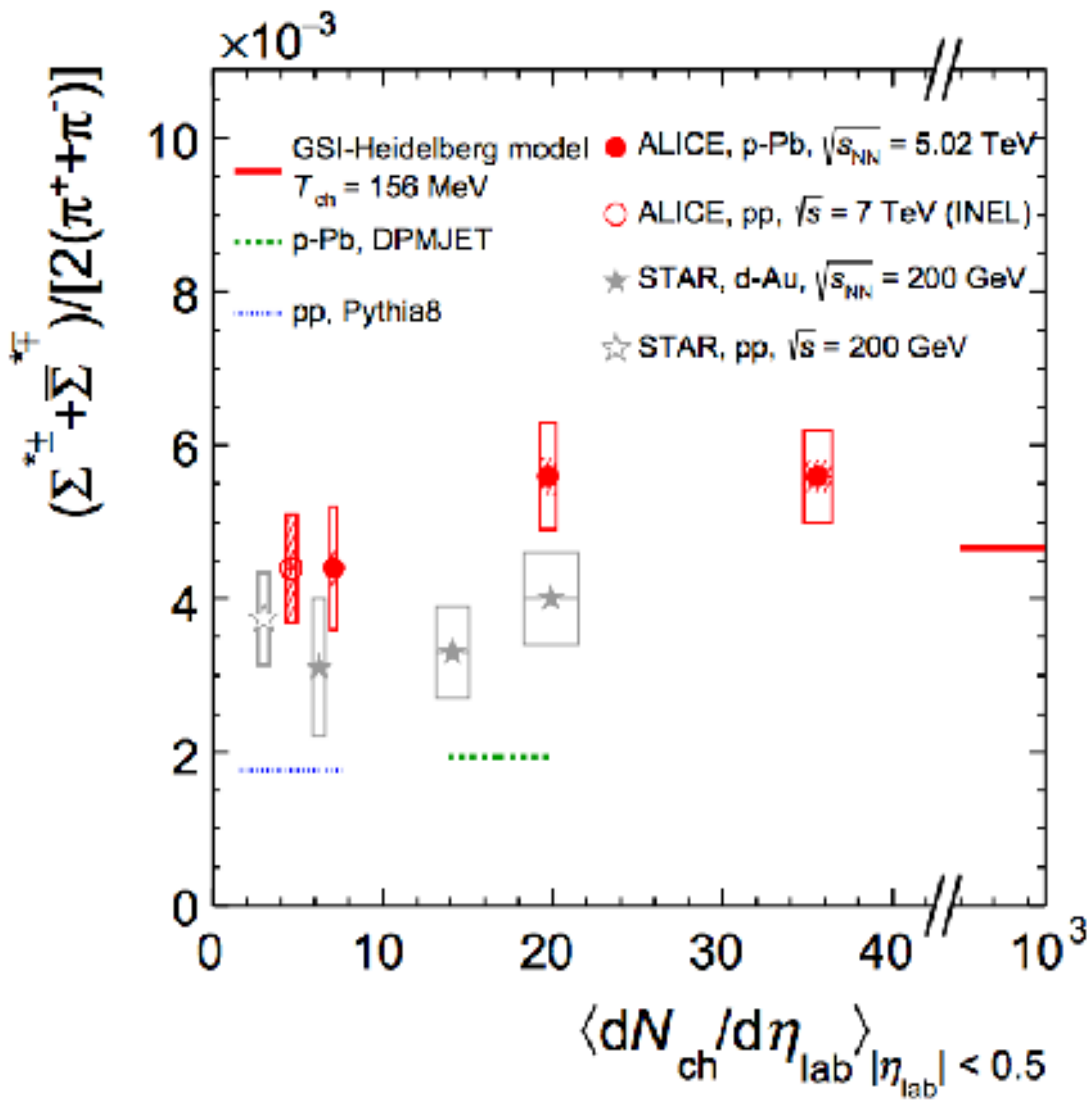
Ground state

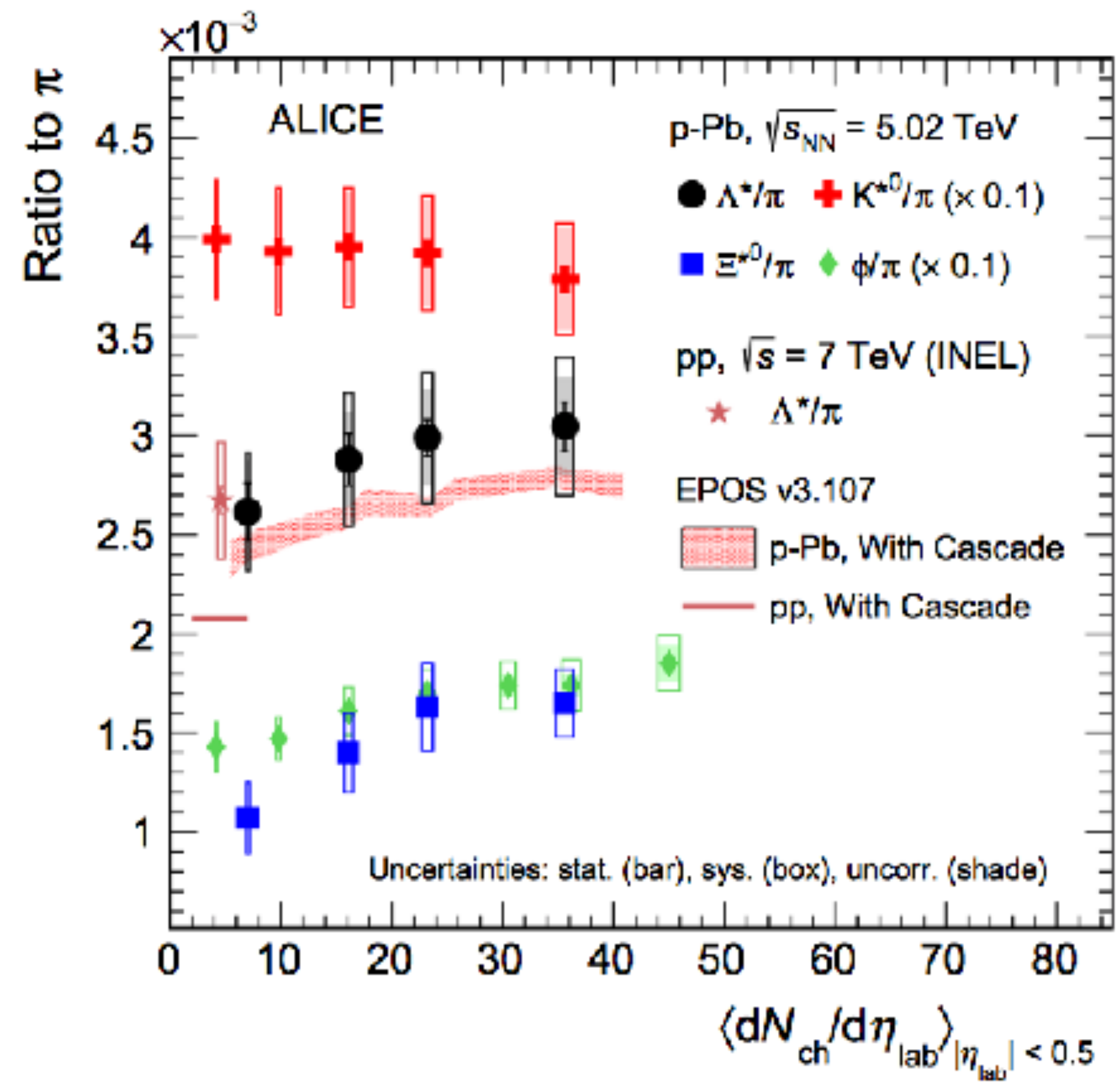
s=1: Λ(1116)
s=2: Ξ(1320)
s=3: Ω(1670)

Resonances

s=1: $\Sigma^*(1385)^{\pm}$, $\Lambda^*(1520)$
s=2: $\Xi^*(1530)^0$
s=3: $\Omega(2012)^{\mp}$

Strangeness in small system





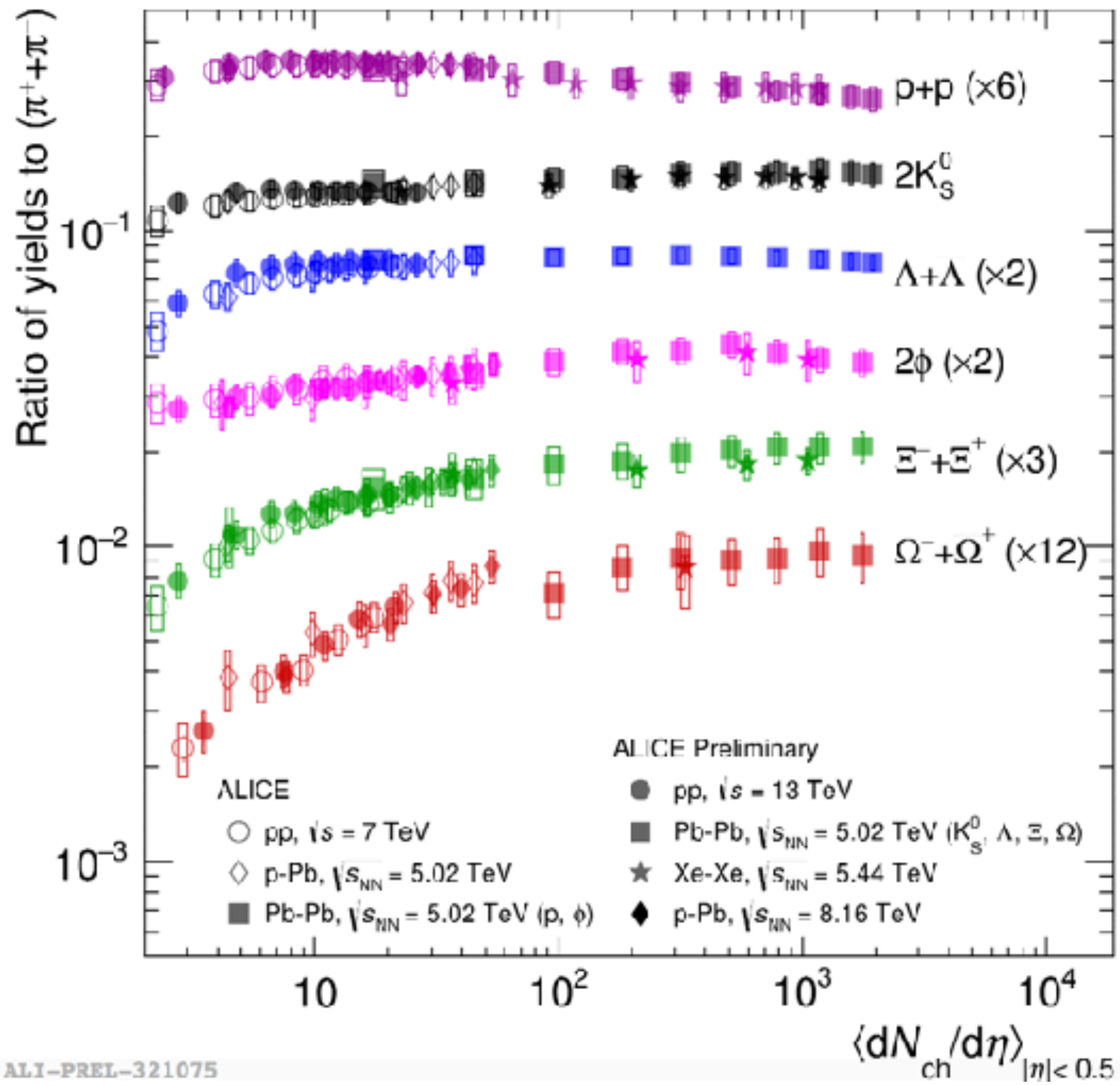
Σ(1385)$^{\pm}$:
- Same strangeness content as Λ
- Mass is similar to Ξ
- Σ*/π is compatible with Λ/π

Λ(1520):
- Same strangeness content as Λ
- Mass is larger than Ξ
- Λ*/π is compatible with Λ/π

Ξ(1530)^{0}:
- Same strangeness content as Ξ
- Mass is between Ξ & Ω
- Ξ*/π is compatible with Ξ/π

Increases in small system is not related to mass and is due to ***Strangeness content***

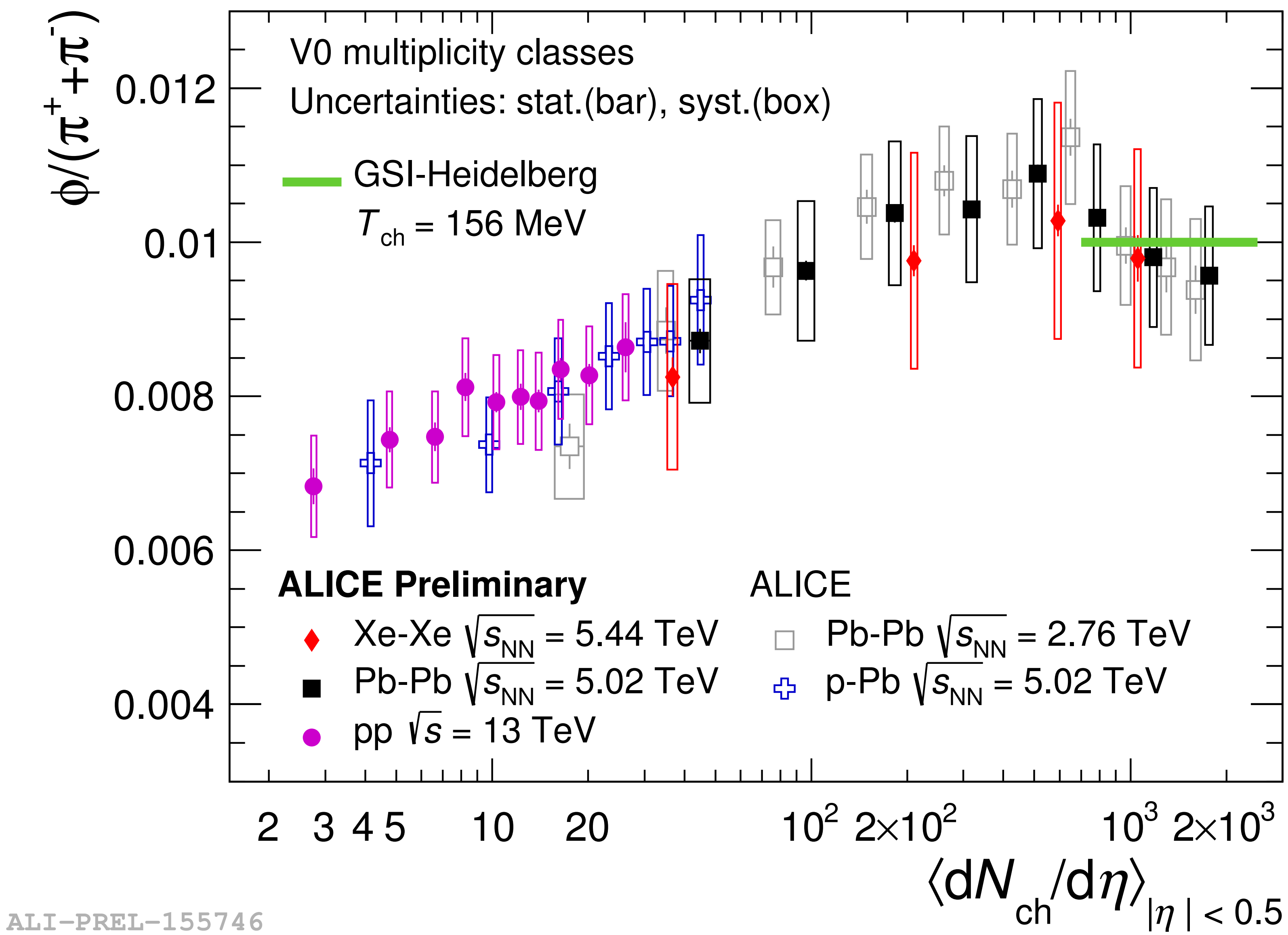
Strangeness enhancement



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

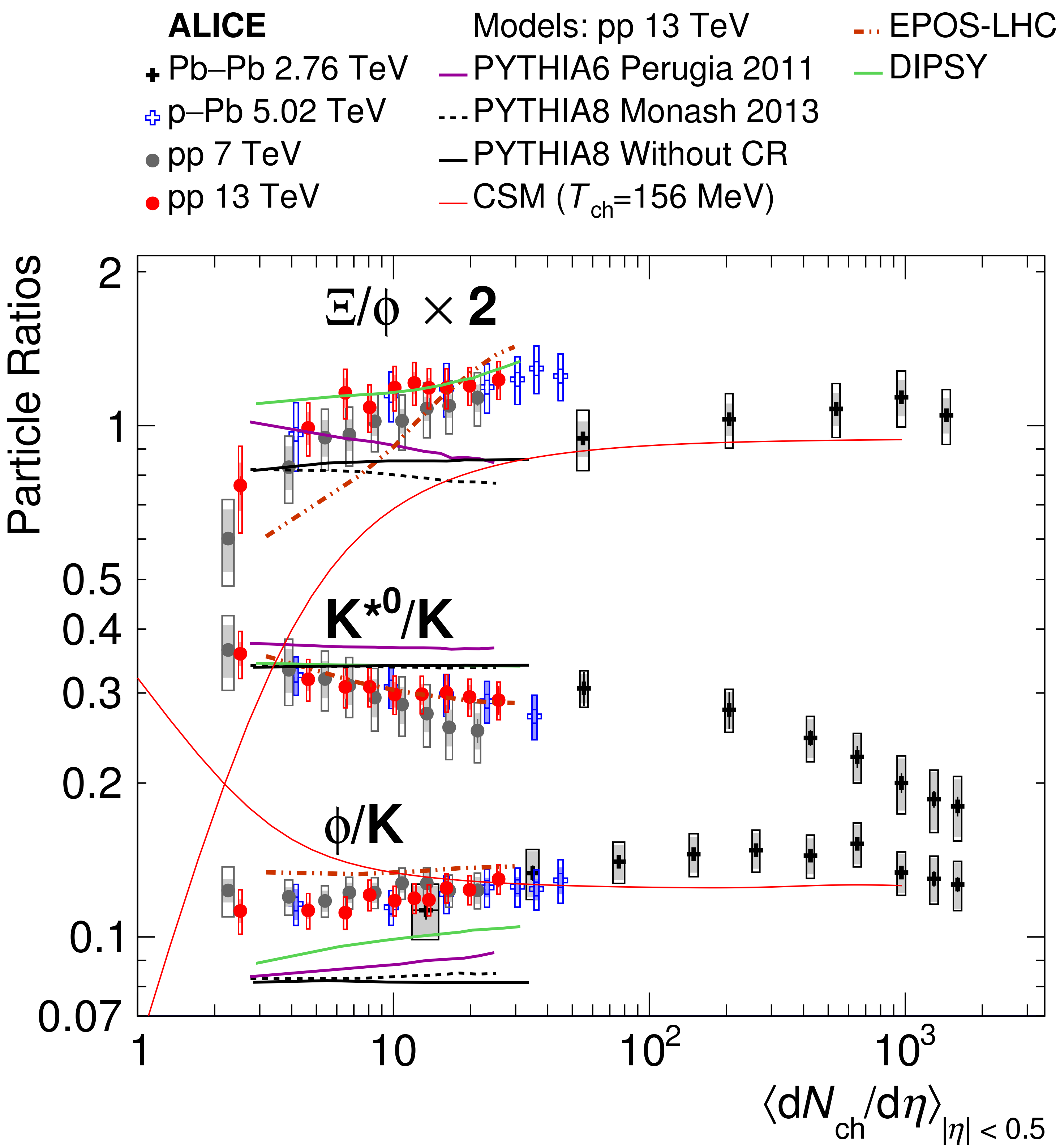
- Strangeness enhancement increases with strangeness content
  - what about ϕ meson?

Strangeness enhancement: ϕ



- ϕ/π (|S|=0)/(|S|=0)
  - large systems: described by thermal model
  - small systems: increase with multiplicity

Strangeness enhancement: ϕ

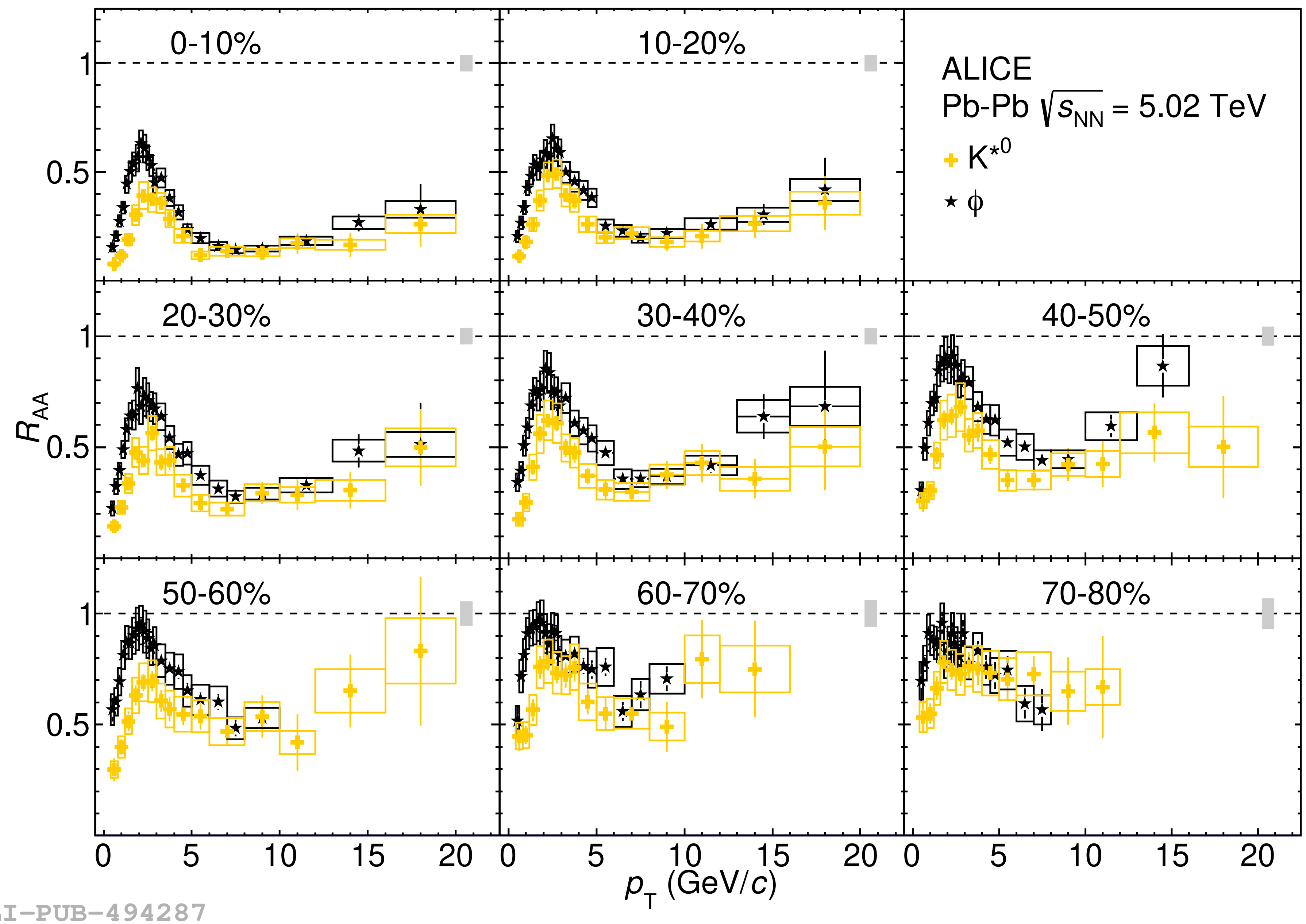


- ϕ/K (|S|=0)/(|S|=1)
  - flat or slightly increasing at lowest multiplicities
  - suggest ϕ behaves like a S ≧ 1 particle
- Ξ/ϕ (|S|=2)/(|S|=0)
  - increase for low multiplicity collisions
  - fairly flat across wide multiplicity range
- The ϕ has "effective strangeness" of 1-2 units

Nuclear modification factor (R_{AA})

R_{AA} helps in understanding the evolution of parton energy loss in the medium

Centrality dependence

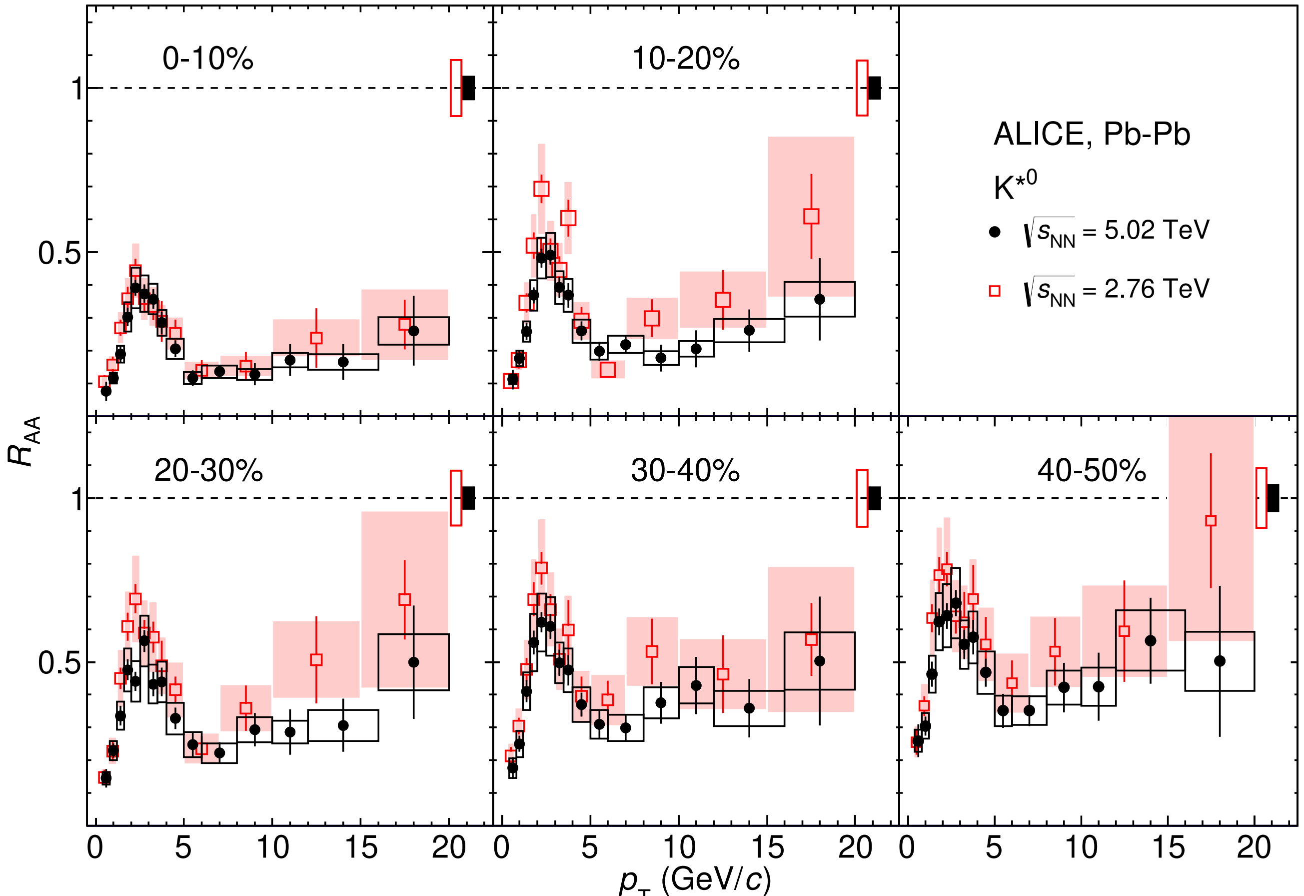


$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\text{Yield}_{pp}(p_T) \times \langle N_{coll} \rangle}$$

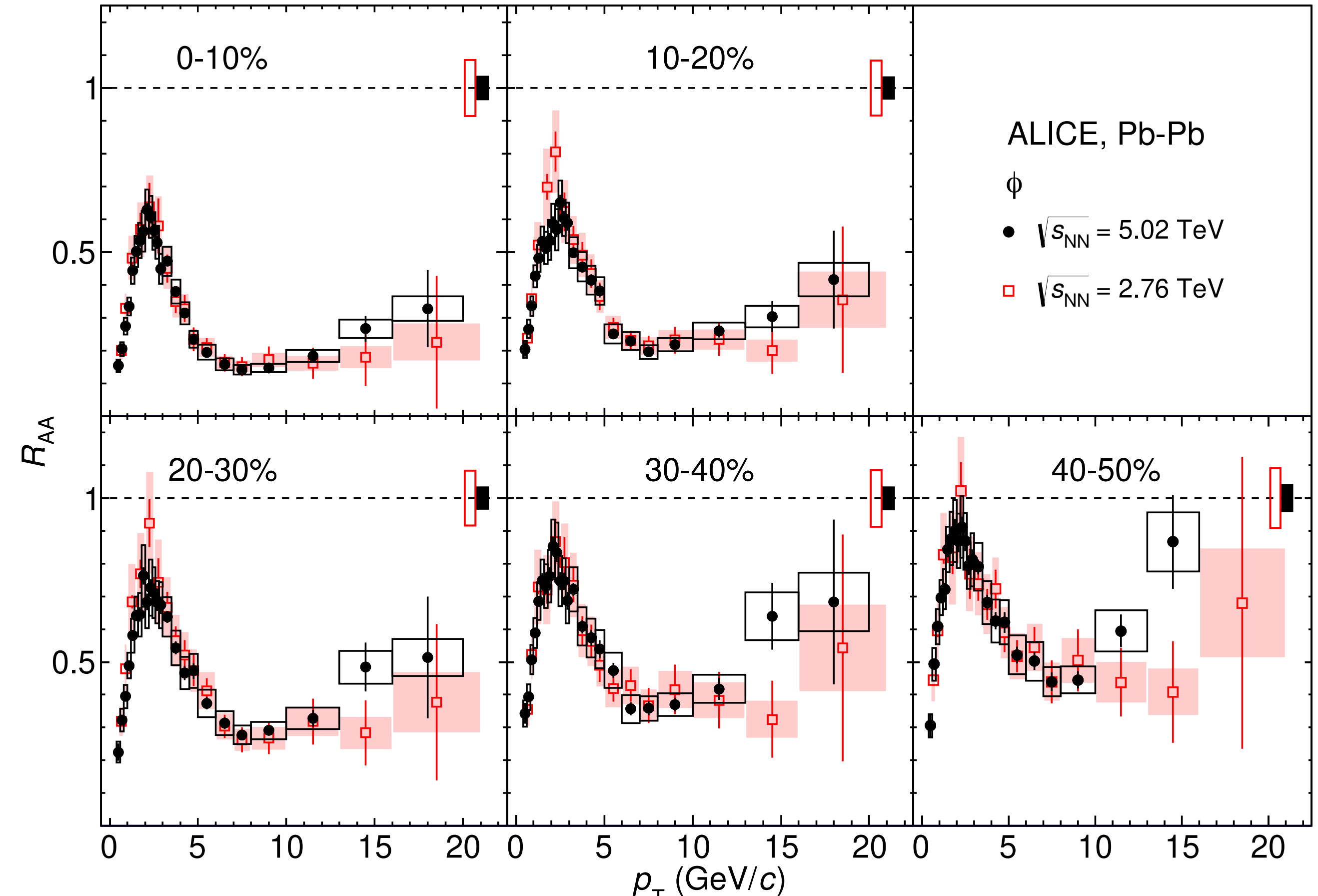
- **p_T < 5 GeV/c**
  - R_{AA} of K^{*0} is lower than ϕ
  - dominance of re-scattering effect
- **p_T > 6 GeV/c**
  - R_{AA} of K^{*0} and ϕ are comparable within uncertainties
  - suppression due to parton energy loss
  - pronounced suppression in the most central collisions

Nuclear modification factor (R_{AA})

Center-of-mass energy dependence



ALI-PUB-494291

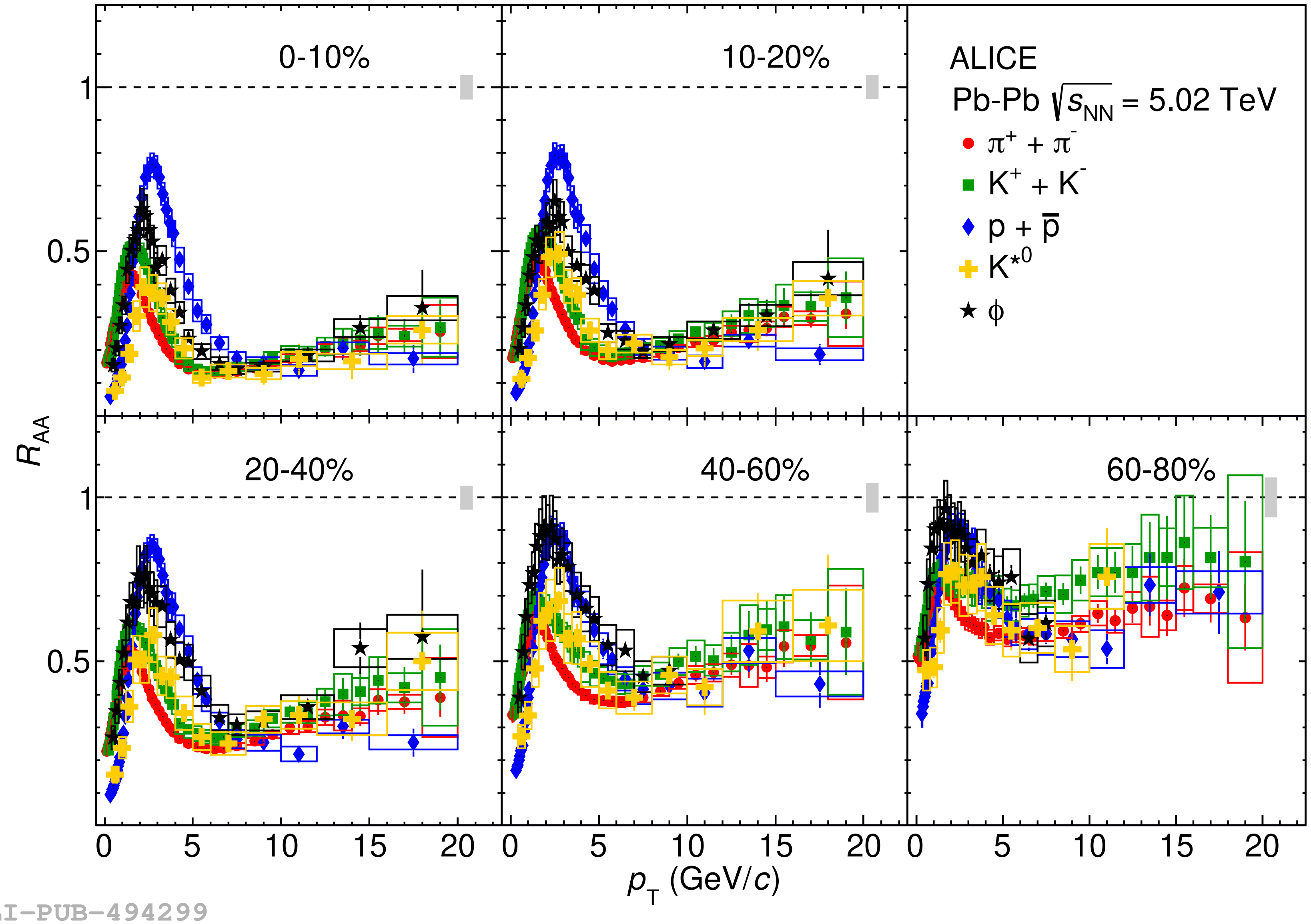


ALI-PUB-494295

- R_{AA} values for $\sqrt{s_{NN}}$ = 5.02 TeV are compared to the values at $\sqrt{s_{NN}}$ = 2.76 TeV
- No significant differences for both the K^{*0} and ϕ are observed
- measurement of other mesonic and baryonic resonances ($\rho(770)^0$, $\Delta(1232)^{++}$, $\Sigma(1385)$, $\Lambda(1520)$) are required to further support

Nuclear modification factor (R_{AA})

Hadron species dependence

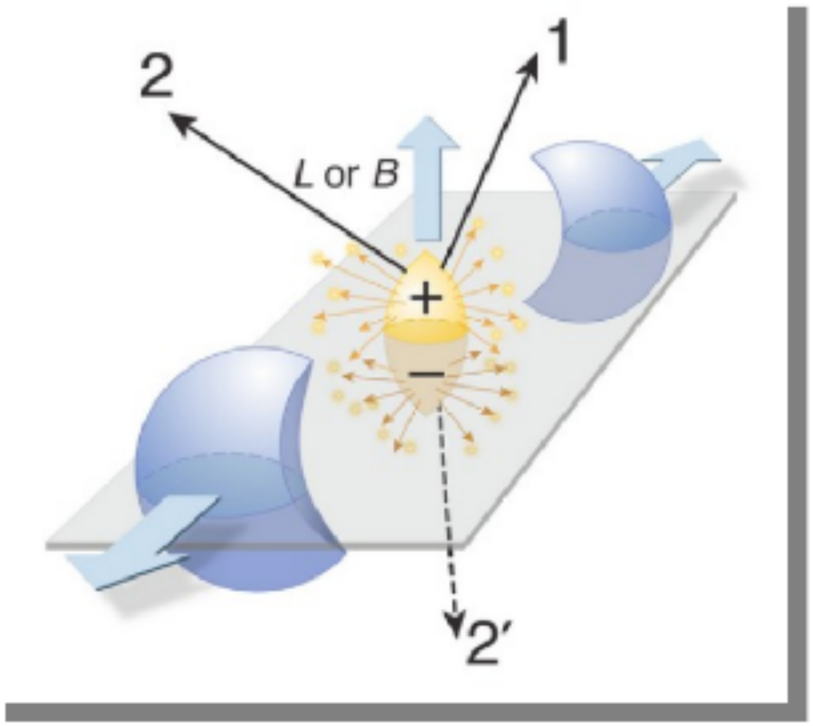


Intermediate-p_T (2 < p_T < 8 GeV/c)
- baryon-meson splitting
- hint of **mass ordering** among mesons
- higher R_{AA} values for proton (might be due to baryon-meson effect)

High-p_T (>8 GeV/c)
- similar **suppression** for different light flavor hadrons
- No flavor (u,d,s) dependence

Spin alignment

Resonance production contributes spin alignment in heavy-ion collisions



Experimental observable

$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

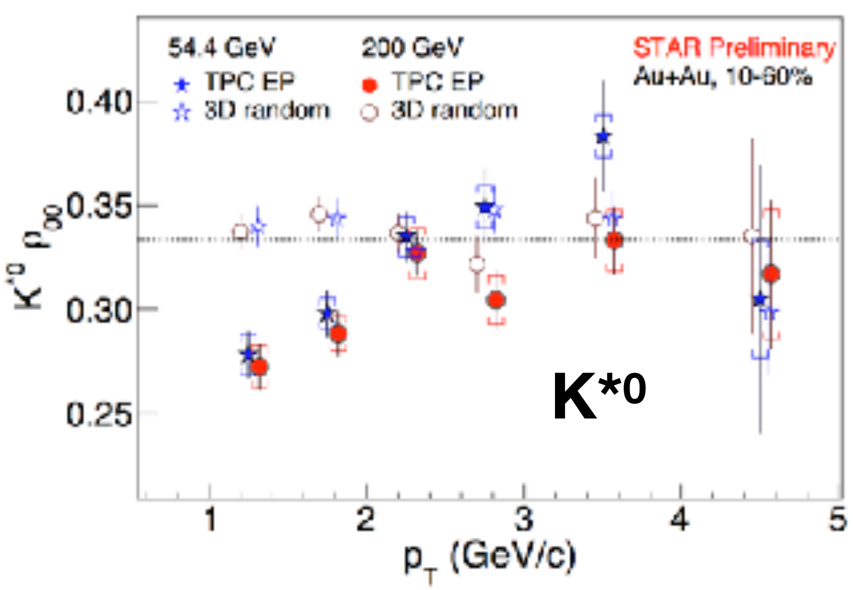
ρ_{00}: Element of spin density matrix
if $\rho_{00} = 1/3$, No spin alignment

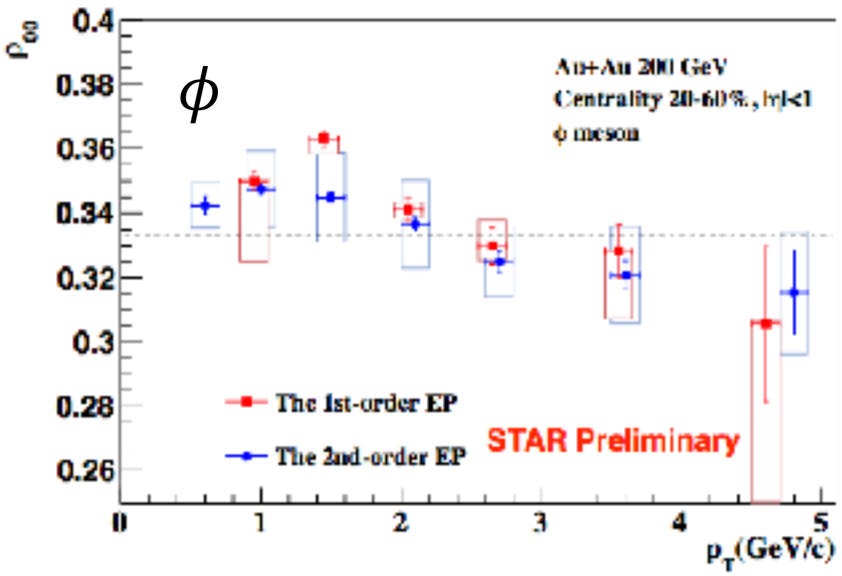
- Large angular momentum [1] and intense magnetic field [2] is expected in initial stage of heavy-ion collisions
  - spin alignment of vector meson could occur

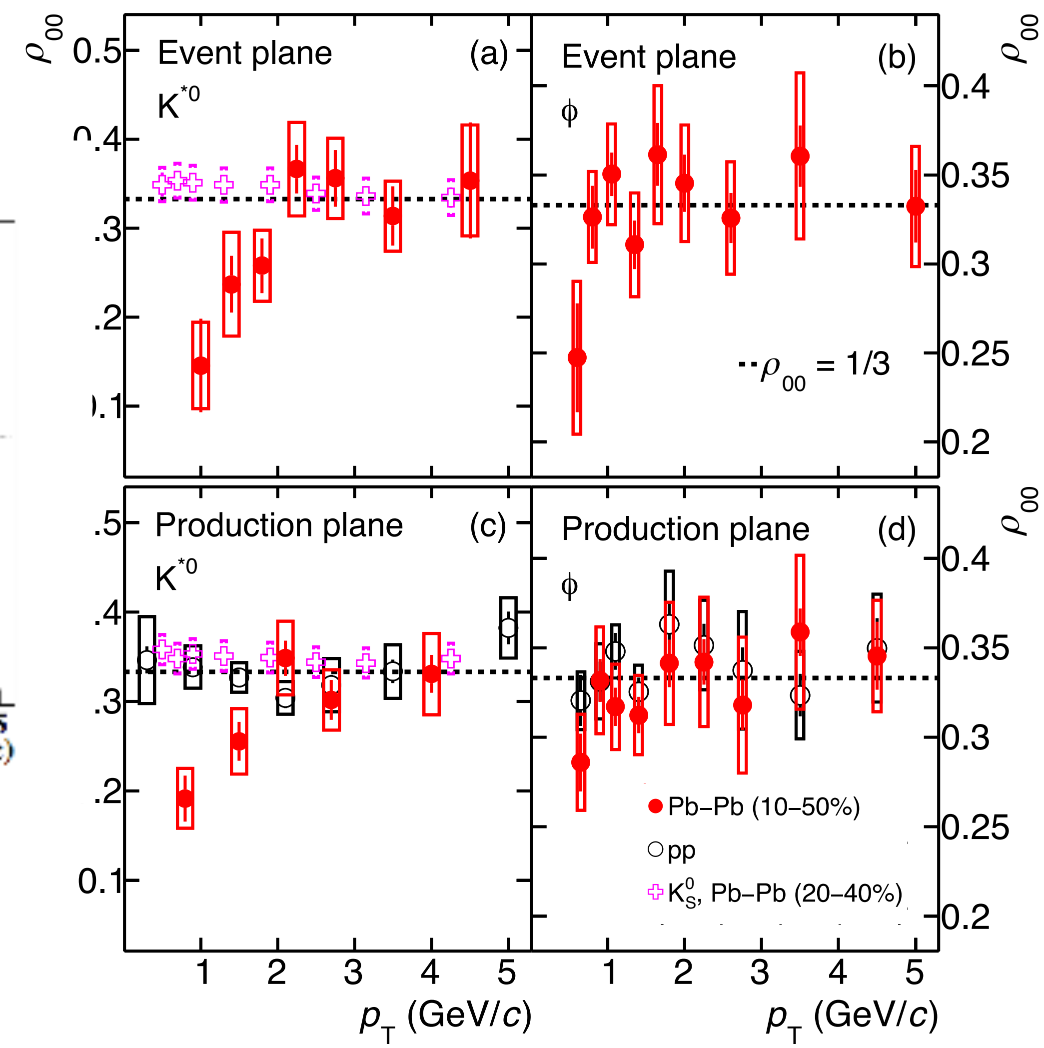
[1] F. Becattini et al.,Phys.Rev.C 77 (2008) 024906
[2] D. E. Kharzeev et al., Nucl.Phys.A 803 (2008) 227

Nucl. Phys. B 15, 397 (1970)

Spin alignment: ρ_{00} vs. p_T



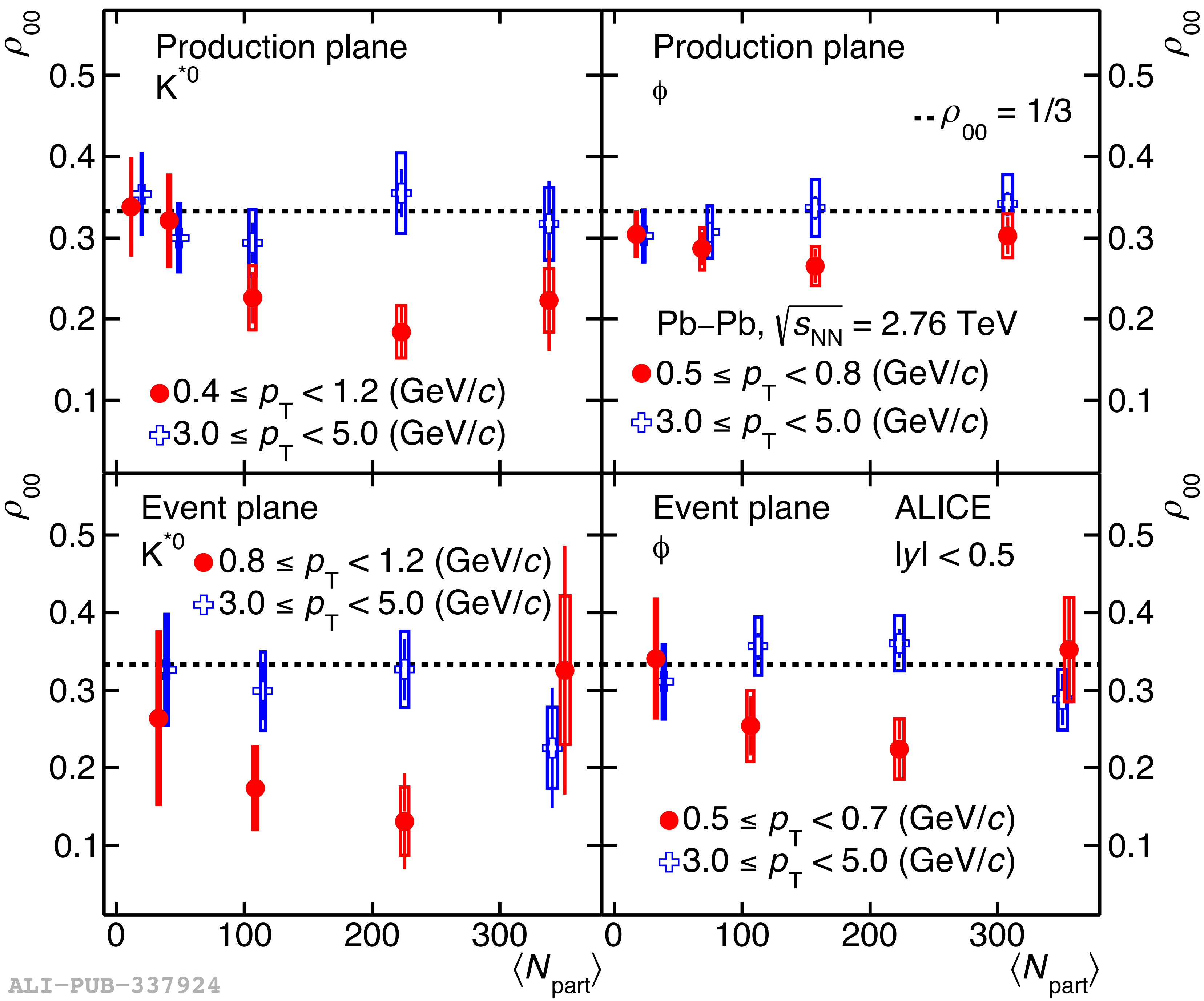


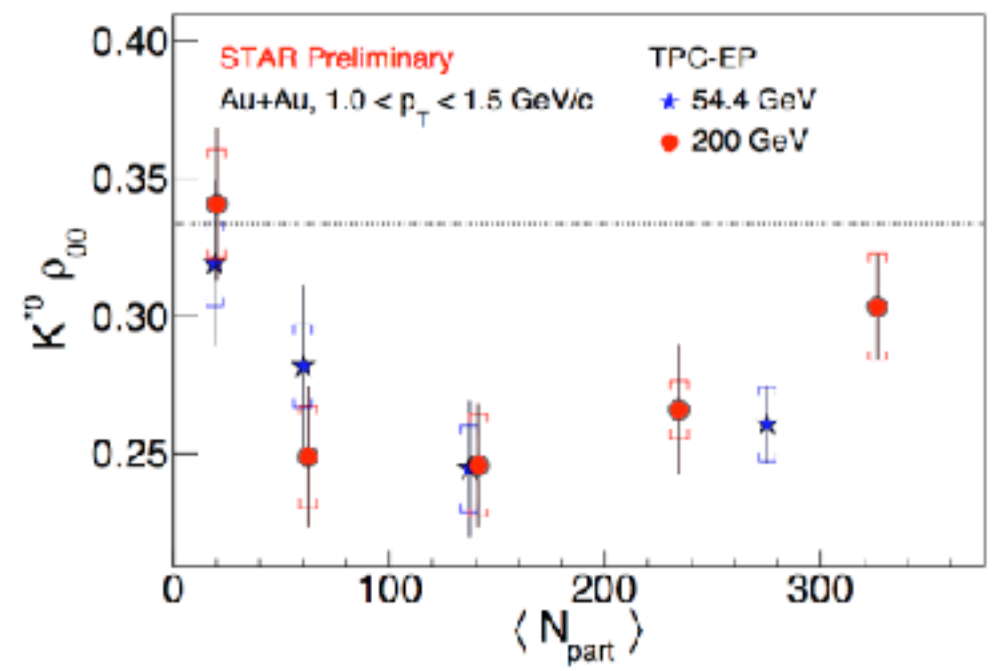


- RHIC
  - ρ_{00}<1/3 for **K*0** and consistent with 1/3 for ϕ
- LHC
  - spin alignment (ρ_{00}<1/3) of vector meson in heavy-ion collisions at low p_T
  - no spin alignment for vector meson in pp collisions
  - no spin alignment for spin 0 hadron (**K^0_S**)

C. Zhou / NPA 982 (2019) 559–562
PhysRevLett.125.012301 (2020)
NPA 1005 (2021) 121733

Spin alignment: ρ_{00} vs. $\langle N_{part} \rangle$

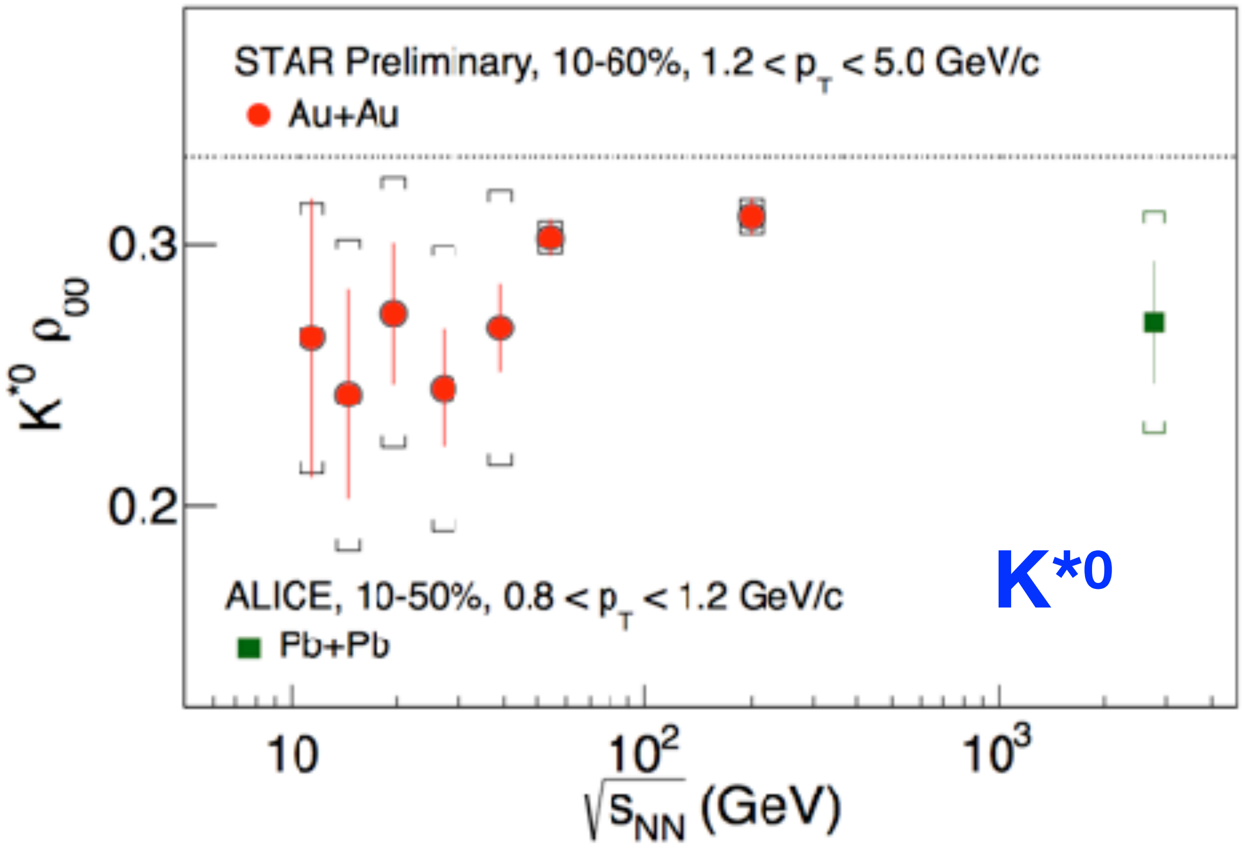


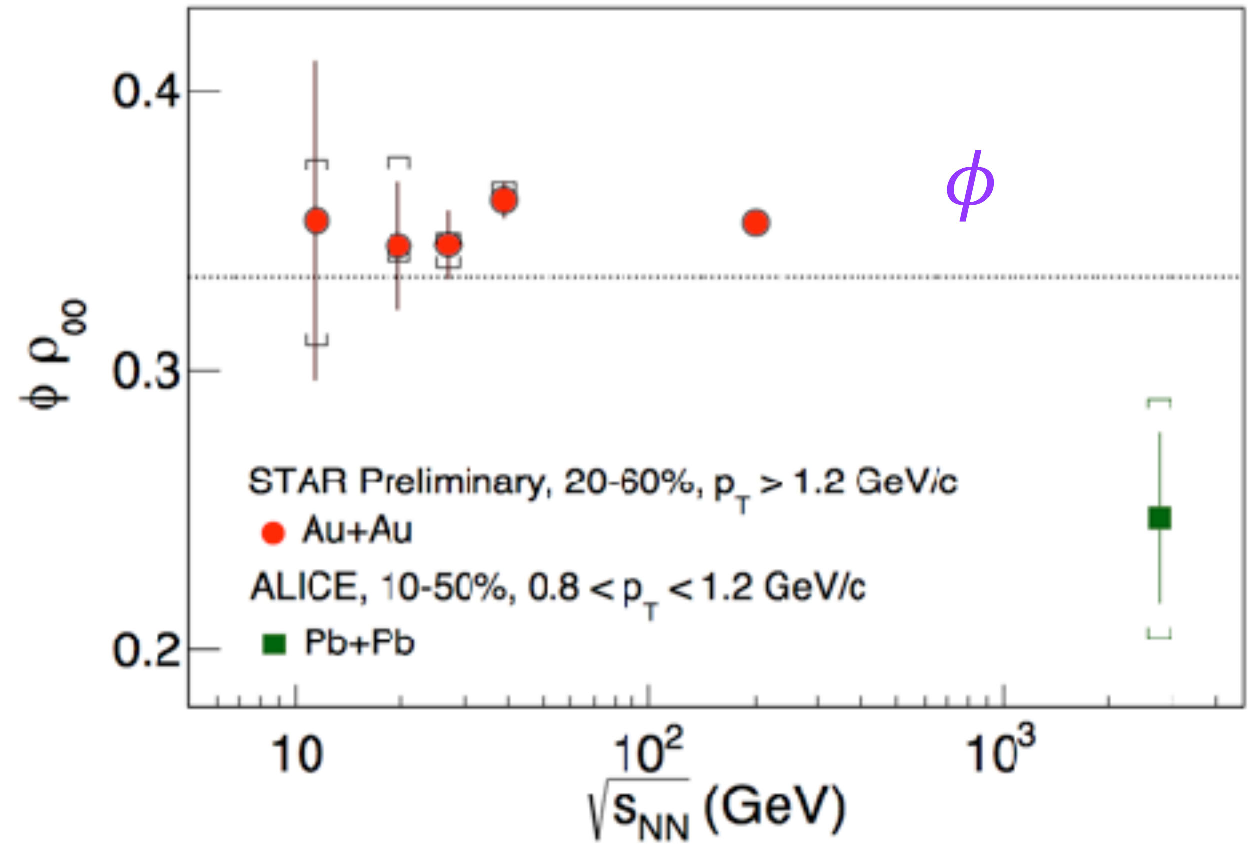


- spin alignment (ρ_{00}<1/3) of vector meson in heavy-ion collisions at low p_T
- ρ_{00} ~ 1/3 at high-p_T
- ρ_{00} ~ 1/3 in central and peripheral collisions

PhysRevLett.125.012301 (2020)
NPA 1005 (2021) 121733

Spin alignment: ρ_{00} vs. energy





$$\sqrt{s_{NN}} = 11.5 - 200 \text{ GeV/c}$$

- **K^{*0} ρ_{00}**
  - low-p_T and in mid central collisions is smaller than 1/3
  - no beam-energy dependence is observed

- **ϕ ρ_{00}**
  - larger than 1/3 at RHIC energies (~ 3σ significance at 200 GeV)
  - smaller than 1/3 at LHC energy (~ 2σ significance)

PRD 101, 096005 (2020)

Conclusion

- Hadronic **resonances** are valuable probes to study the **properties of hadronic phase and strangeness production** (in medium energy loss, spin alignment, chiral symmetry restoration, etc.)

- **Suppression of short-lived resonances** in large collision systems
  - dominance of re-scattering over regeneration
  - no suppression observed for the longer-lived resonances

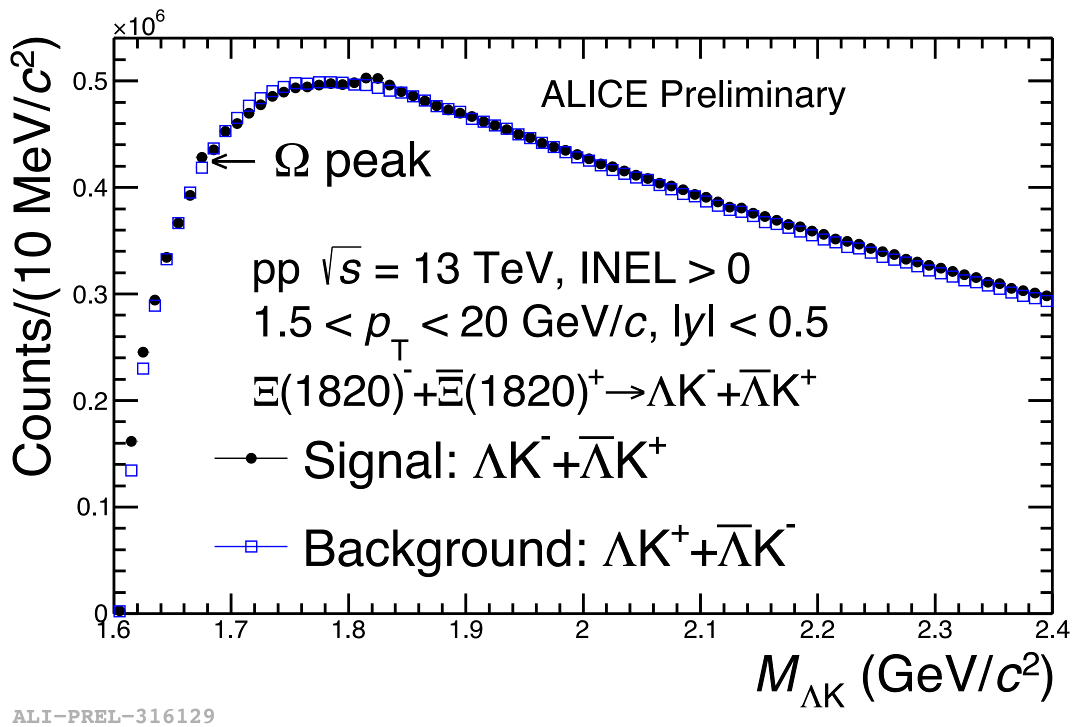
- **Enhancement of strange baryon** with multiplicity is due to strangeness content
  - confirmed by comparing ground state particle & resonances

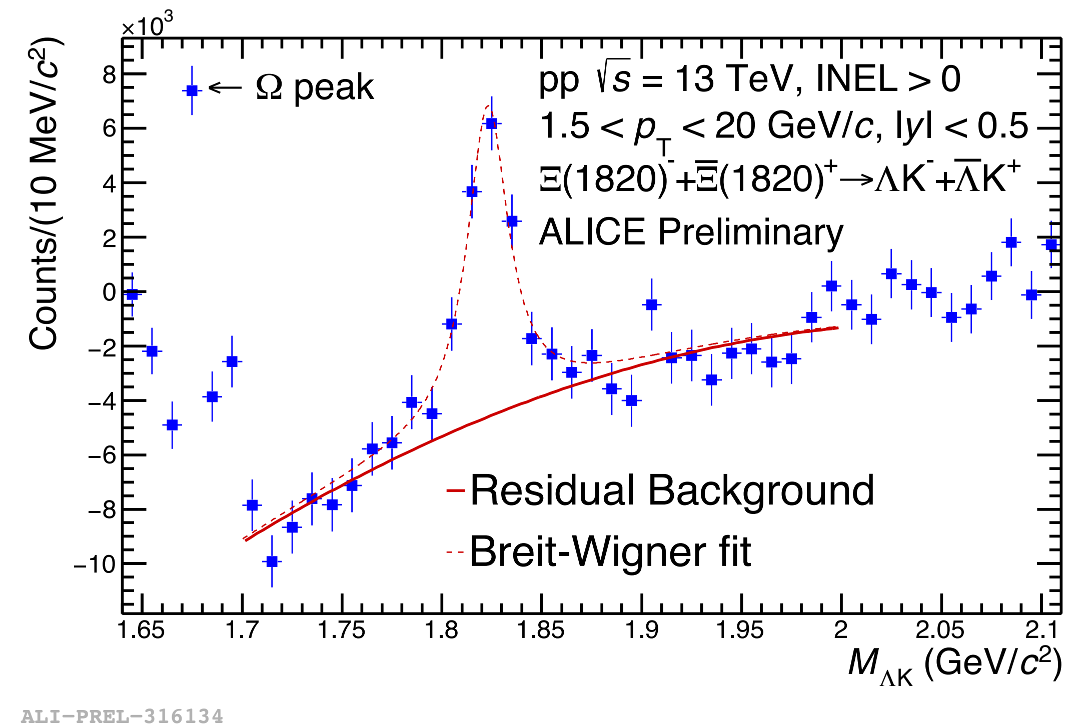
- **High-p_T particle suppression** is observed for Pb-Pb
  - No flavor(u/d/s) dependencies (ground state particles & resonances)

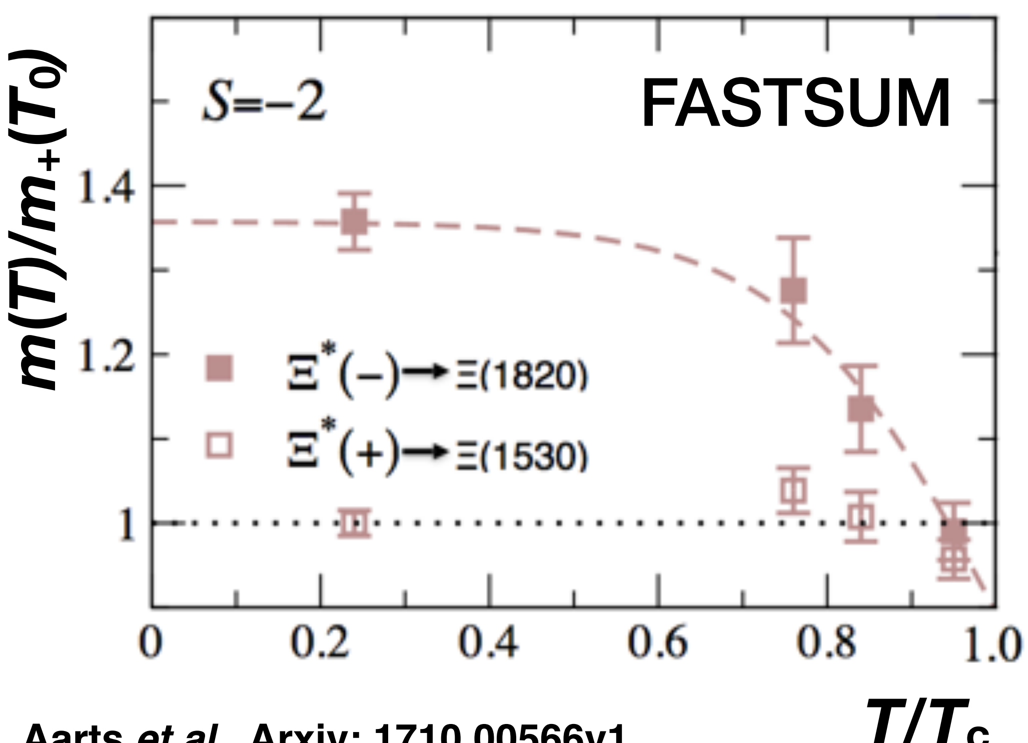
- **Spin alignment (ρ_{00}<1/3) of vector meson** is found in heavy-ion collisions at low p_T in mid-central Pb-Pb collisions

Backup

Chiral symmetry restoration: Ξ(1820)



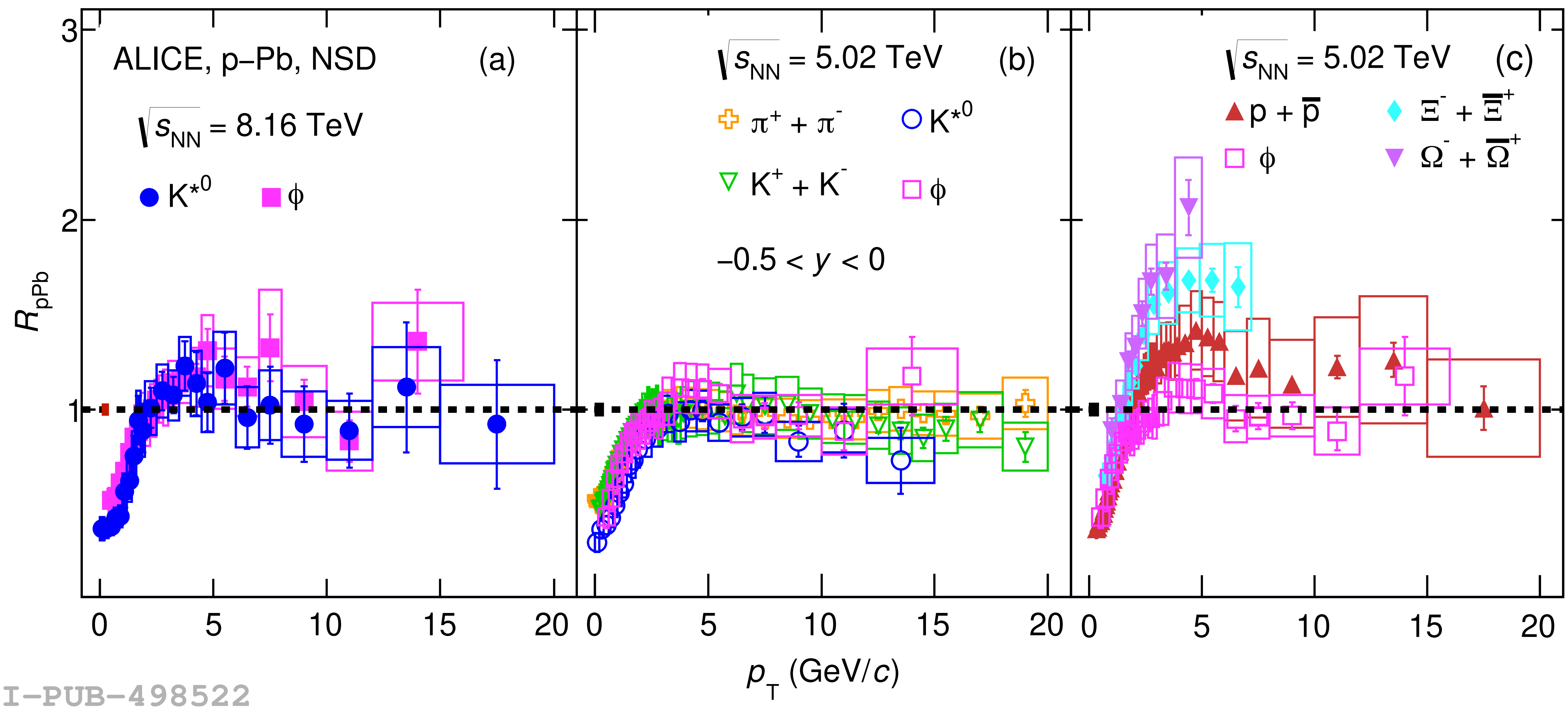




G. Aarts *et al.*, Arxiv: 1710.00566v1

- First measurement of Ξ(1820) from a collider experiment
- Calculation from FASTSUM Collaboration shows potential parity doubling
  - signature of chiral symmetry restoration in heavy-ion collisions
  - expected signal: mass shift, width broadening or change in yield ratio between Ξ(1820) and Ξ(1530)

Nuclear modification factor (R_{pA})



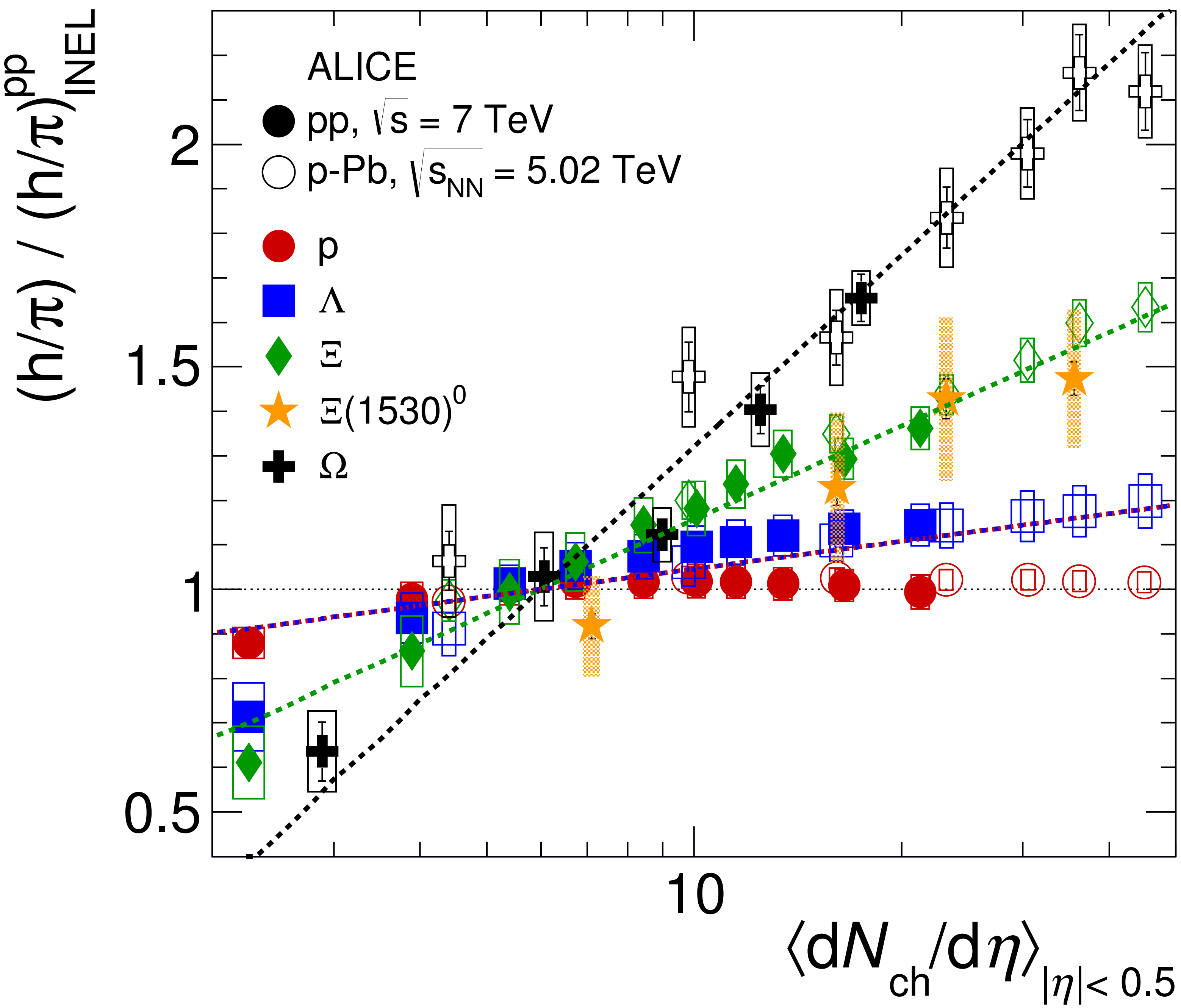
Intermediate-p_T ($2 < p_T < 8$ GeV/c)

- **mass dependent** for strange baryons

High-p_T (>8 GeV/c)

- **no suppression** for different light flavor hadrons
- No flavor (u,d,s) dependence

Strangeness production



Increases in small system is related to ***Strangeness content***