SQM2022

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Resonance production and interaction from low to high energy

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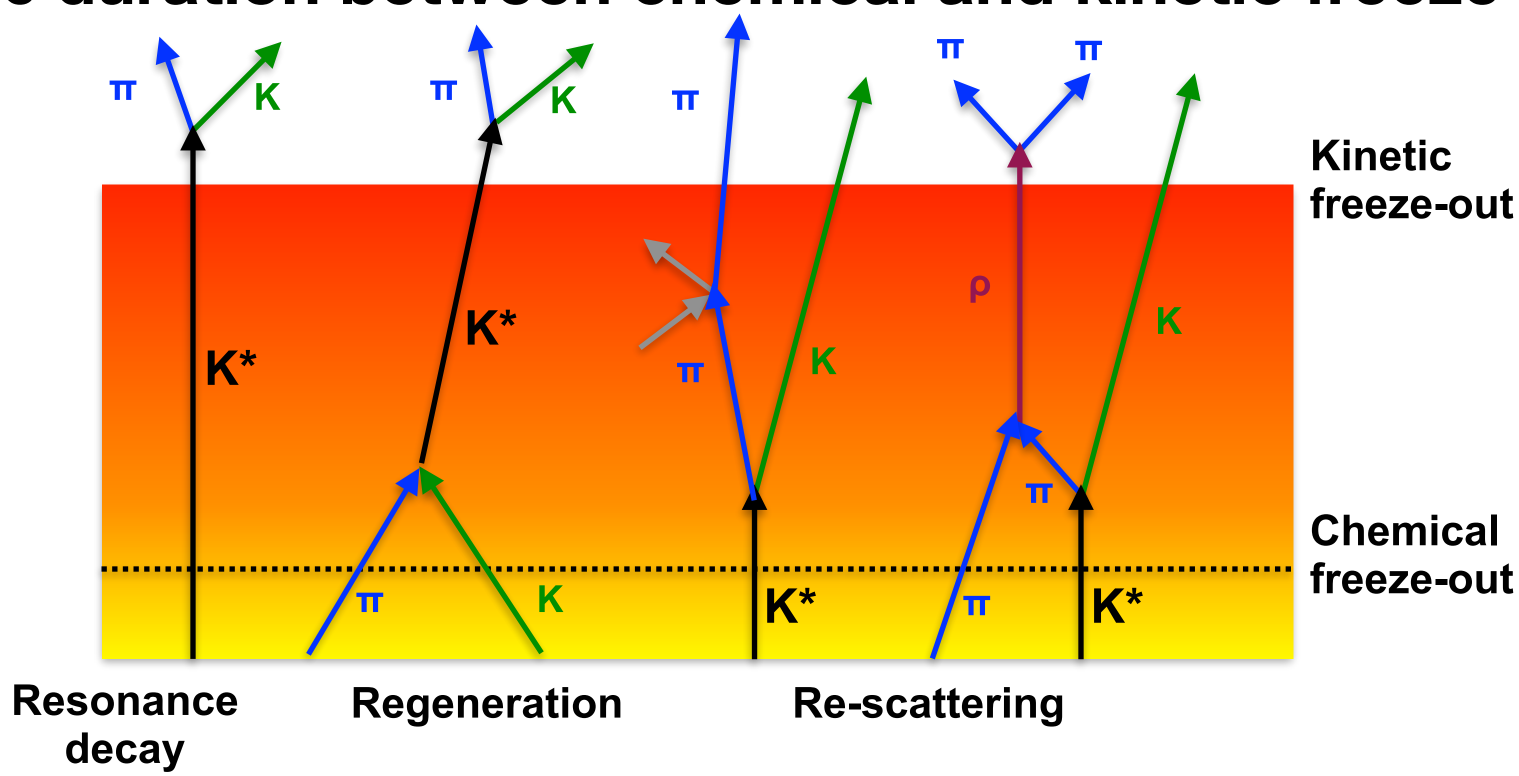
Motivation

1. Probing the properties of hadronic phase

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



Regeneration: pseudo-elastic scattering of decay products

→ ***Enhanced*** yield

Re-scattering: resonance decay products undergo elastic scattering or pseudo-elastic scattering through a different resonance state

→ Not reconstructed through invariant mass

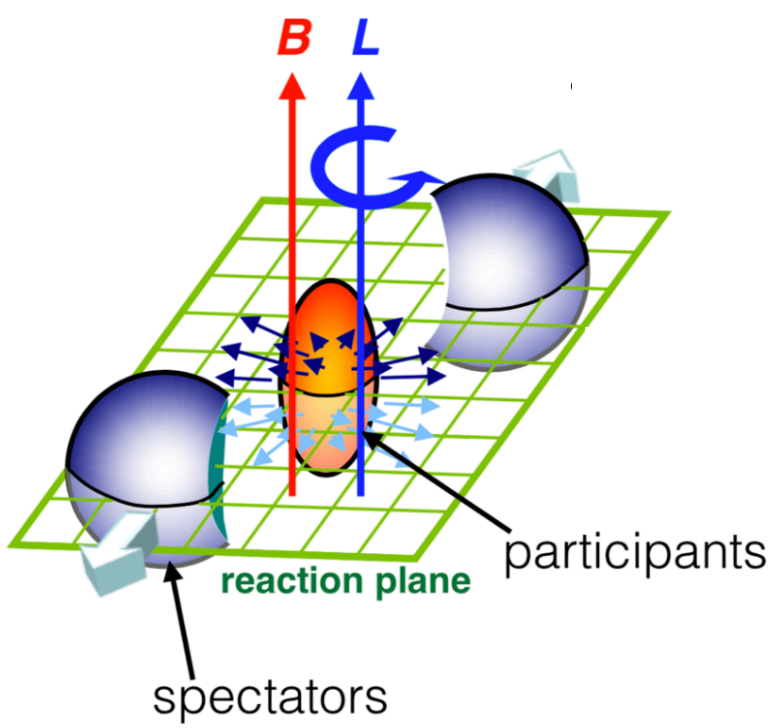
→ ***Reduced*** yield

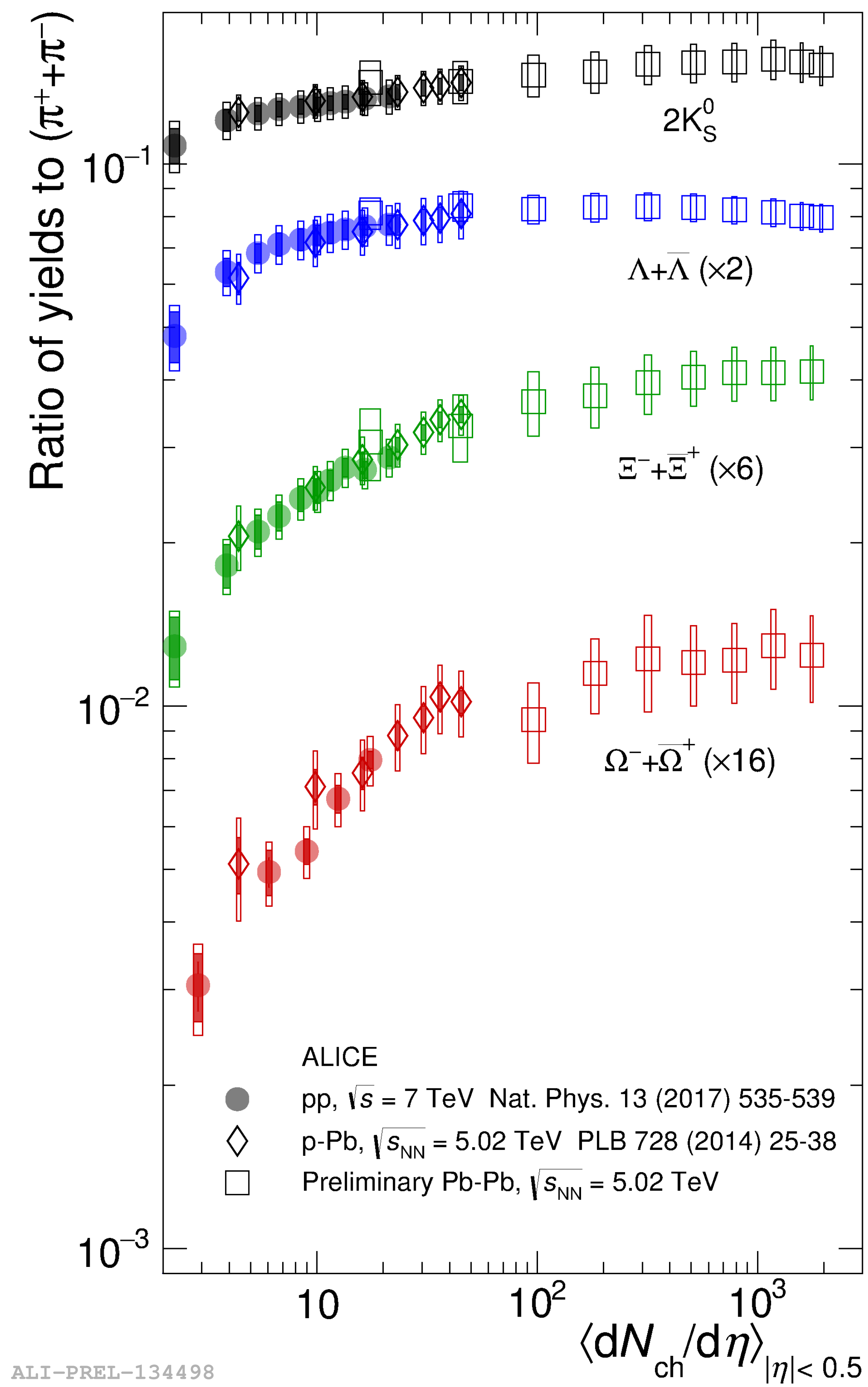
Motivation

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. Spin alignment of vector mesons

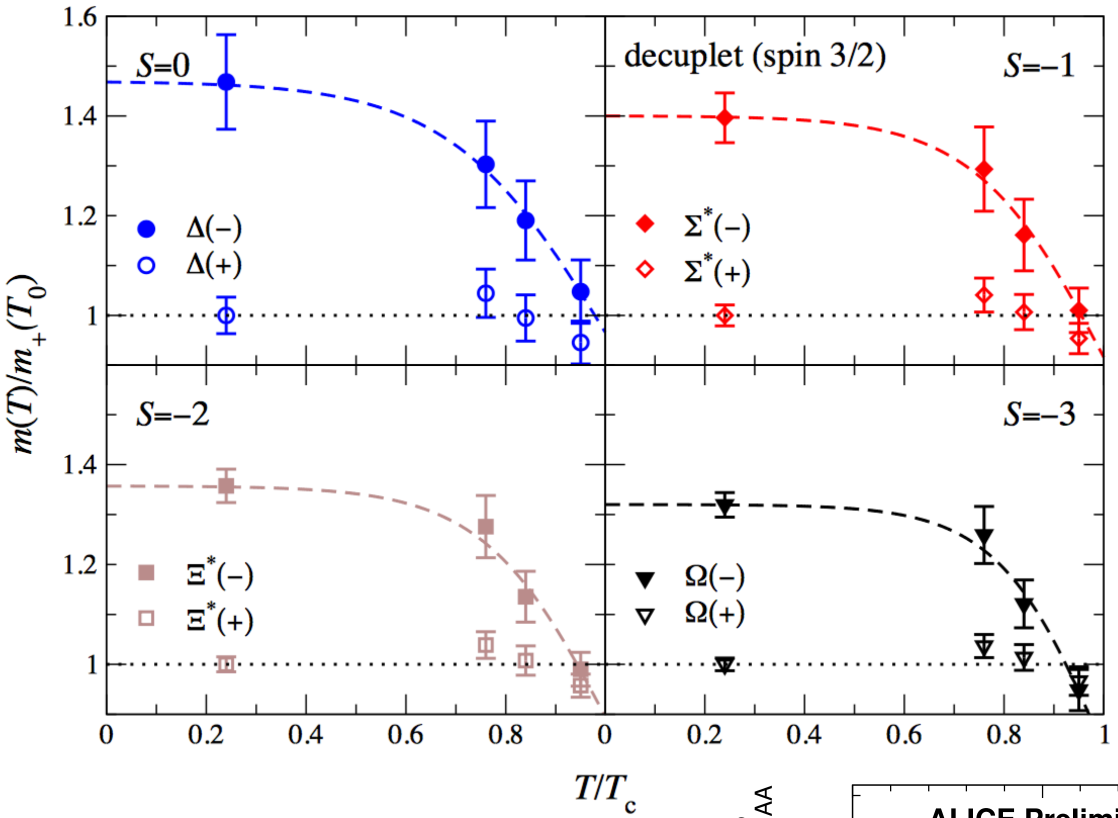




Motivation

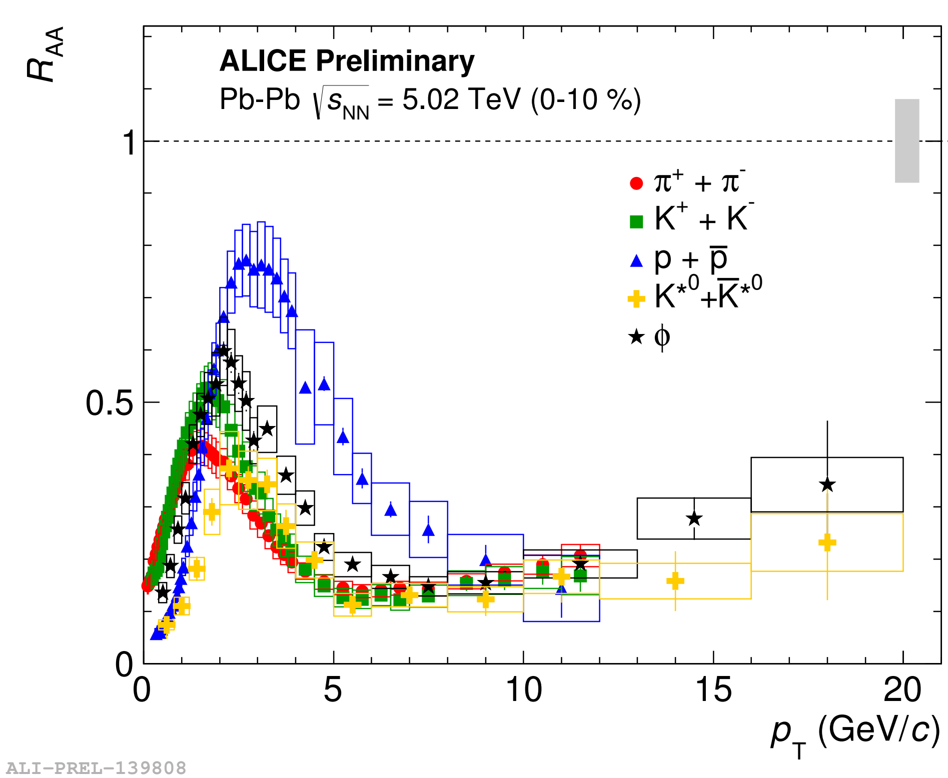
PRD 99 (2019) 074503

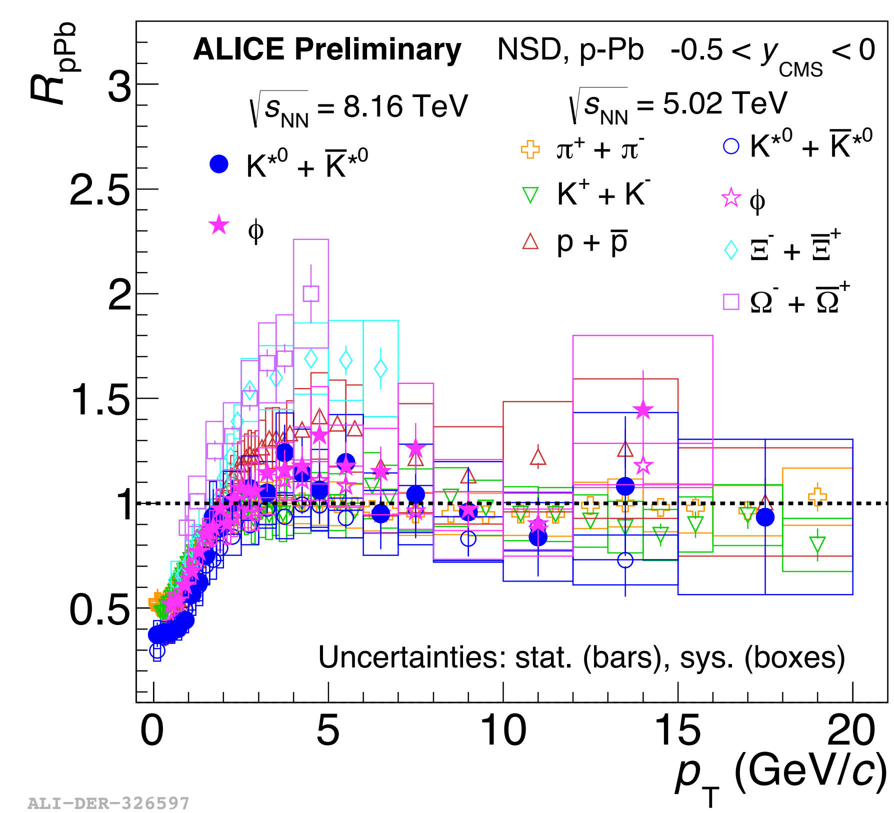
4. Chiral symmetry restoration



- Calculation from FASTSUM Collaboration shows potential parity doubling
  - signature of chiral symmetry restoration in heavy-ion collisions

5. In-medium energy loss





Resonances (particles & decay)

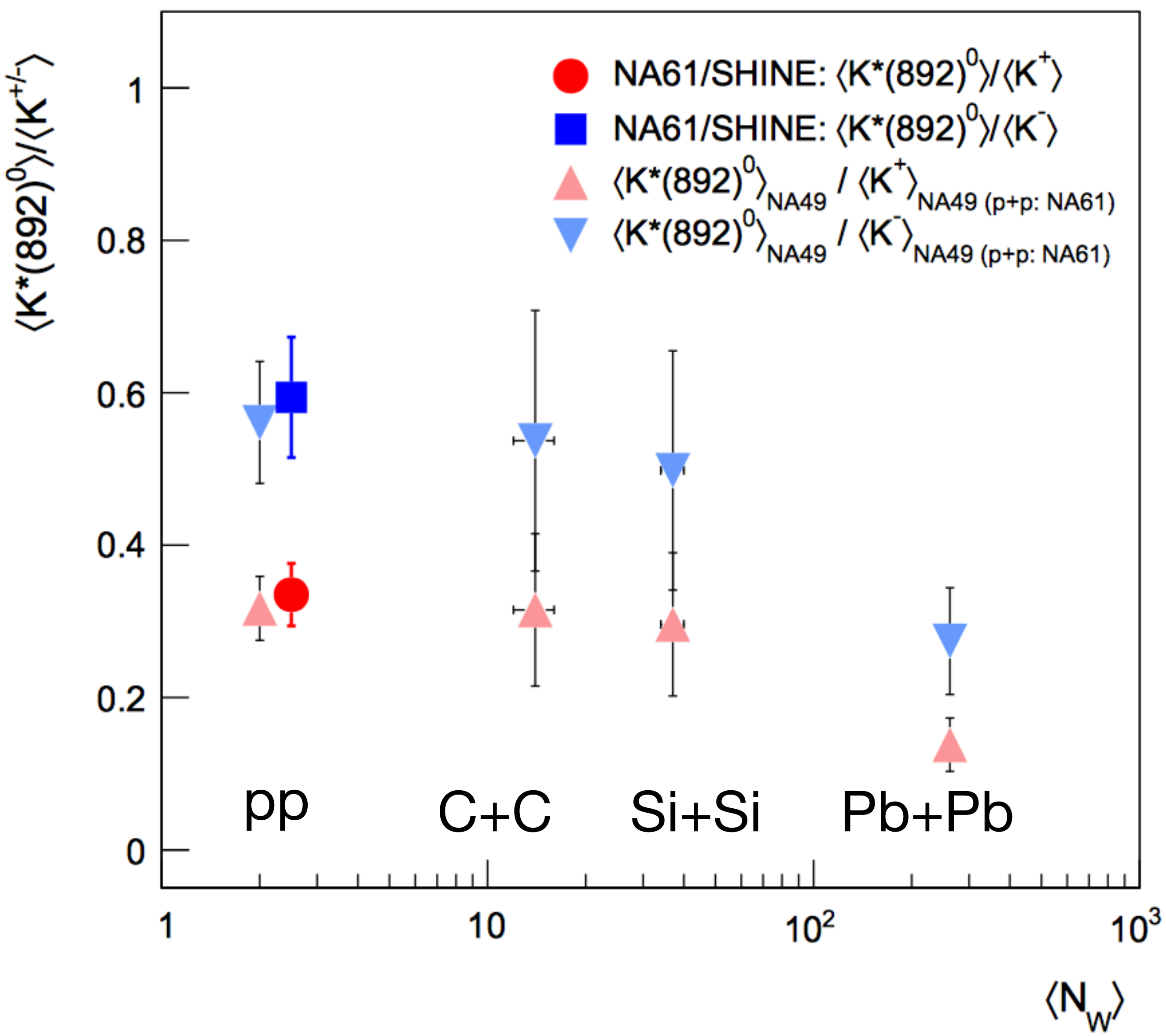
Meson	quark content	Decay modes	B.R.
$\rho(770)^0$	$(u\bar{u}+d\bar{d})/\sqrt{2}$	$\pi^+\pi^-$	100
$K^*(892)^0$	$d\bar{s}$	$K^+\pi^-$	66.6
$K^*(892)^\pm$	$u\bar{s}$	$K^0_S\pi^+$	33.3
$f_0(980)$, $f_2(1270)$	unknown	$\pi^+\pi^-$	46(84)
$K^*_{0,2}(1430)^0$	$d\bar{s}$	$K^+\pi^-$	93(49.4)
$\phi(1020)$	$s\bar{s}$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

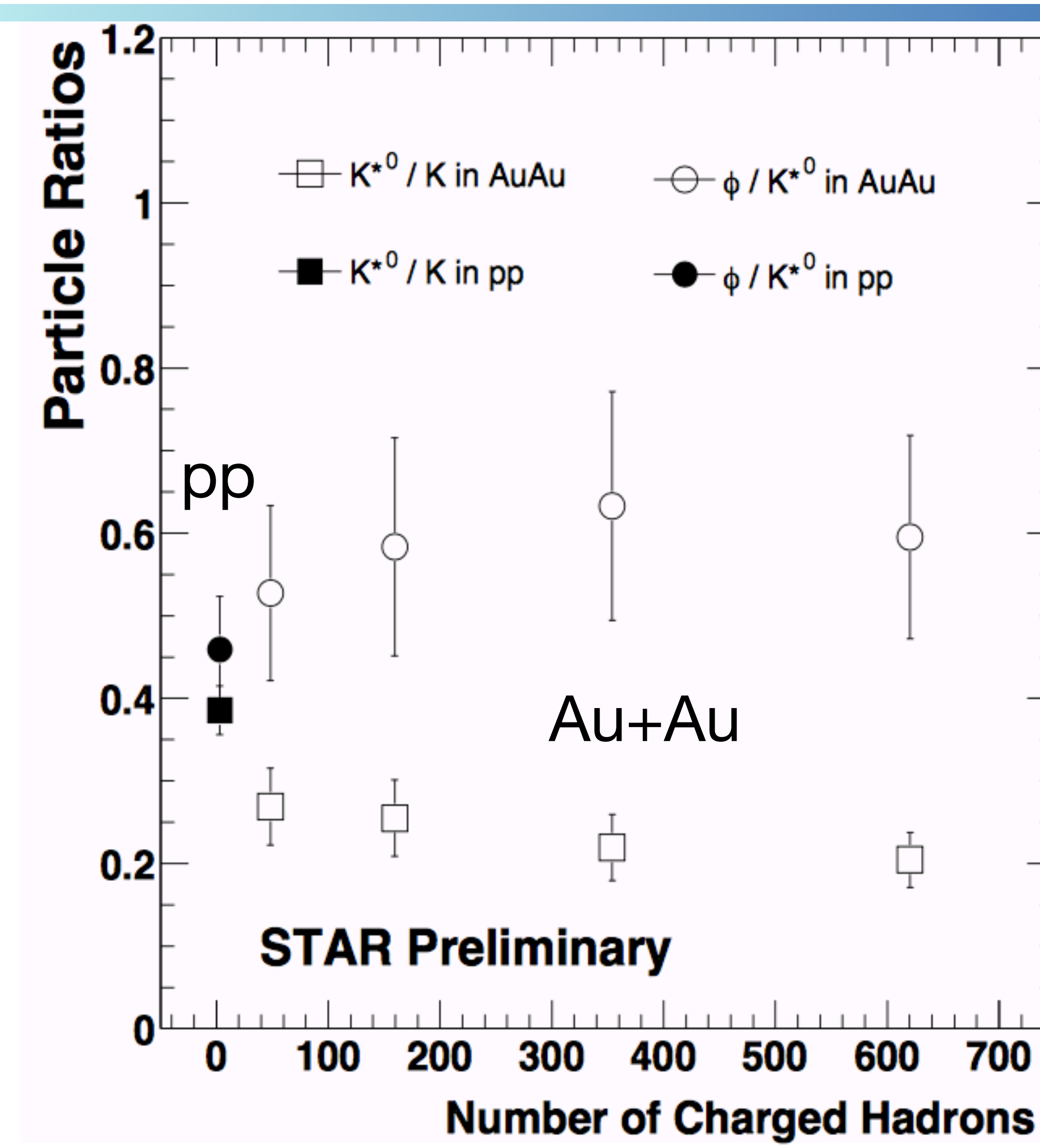
Baryon	quark content	Decay modes	B.R.
$\Sigma(1385)^+$	uus	$\Lambda\pi^+$	87
$\Sigma(1385)^-$	dds	$\Lambda\pi^-$	87
$\Lambda(1520)$	uds	pK^-	22.5
$\Xi(1530)^0$	uss	$\Xi^-\pi^+$	66.7
$\Xi(1820)^{\mp,0}$	dss (uss)	$\Lambda K^\mp$ (ΛK^0_S)	unknown
$\Omega(2012)^\mp$	sss	$\Xi^\mp K^0_S$	unknown

Lifetime(fm/c)

$\rho(1.3) < K^{*\pm}(3.6) < K^{*0}(4.2) < \Sigma^{*\pm}(5.0\text{-}5.5) < \Lambda^*(12.6) < \Xi^*(21.7) < \phi(46.2)$

Resonance suppression: K^{*0}



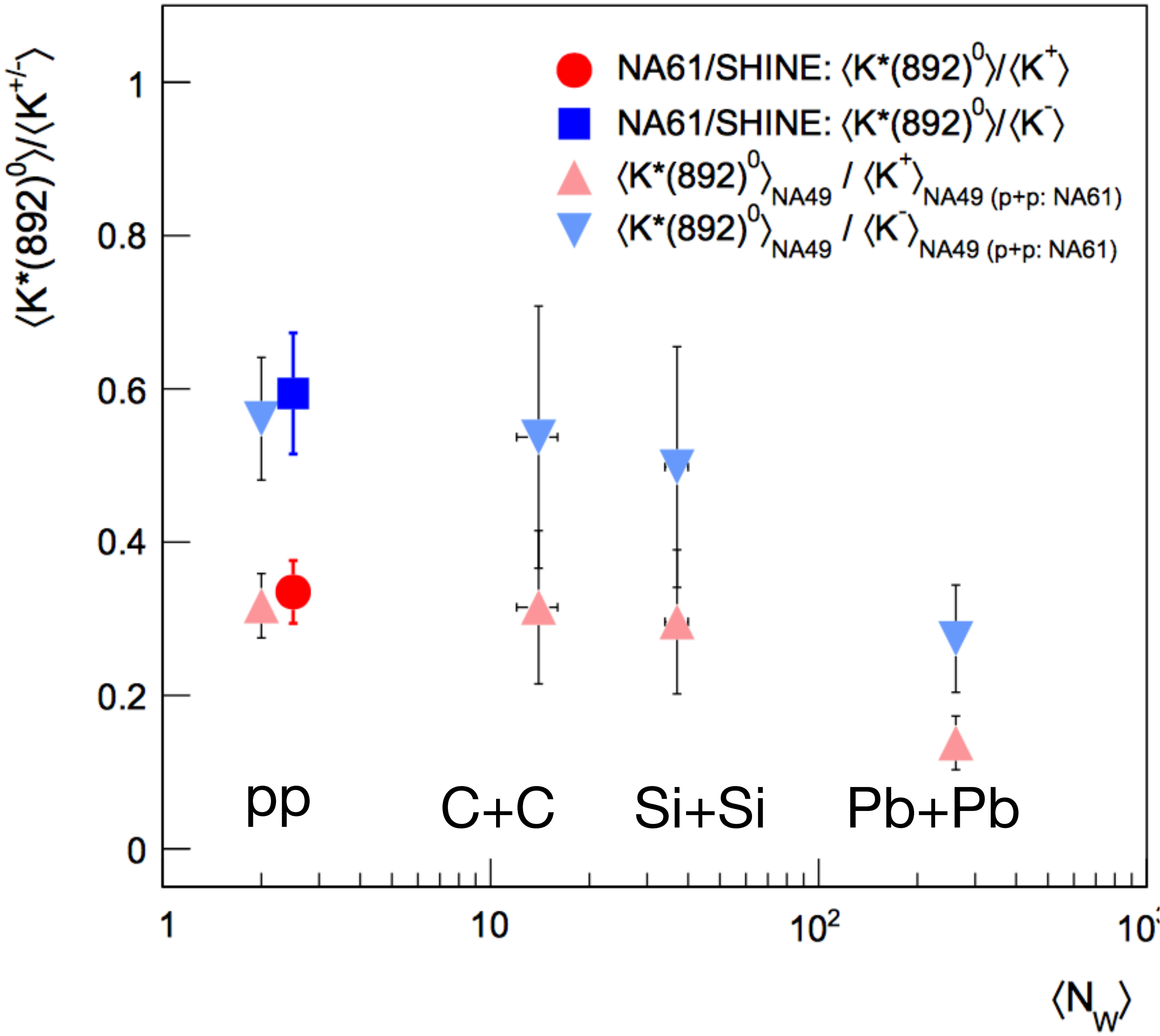


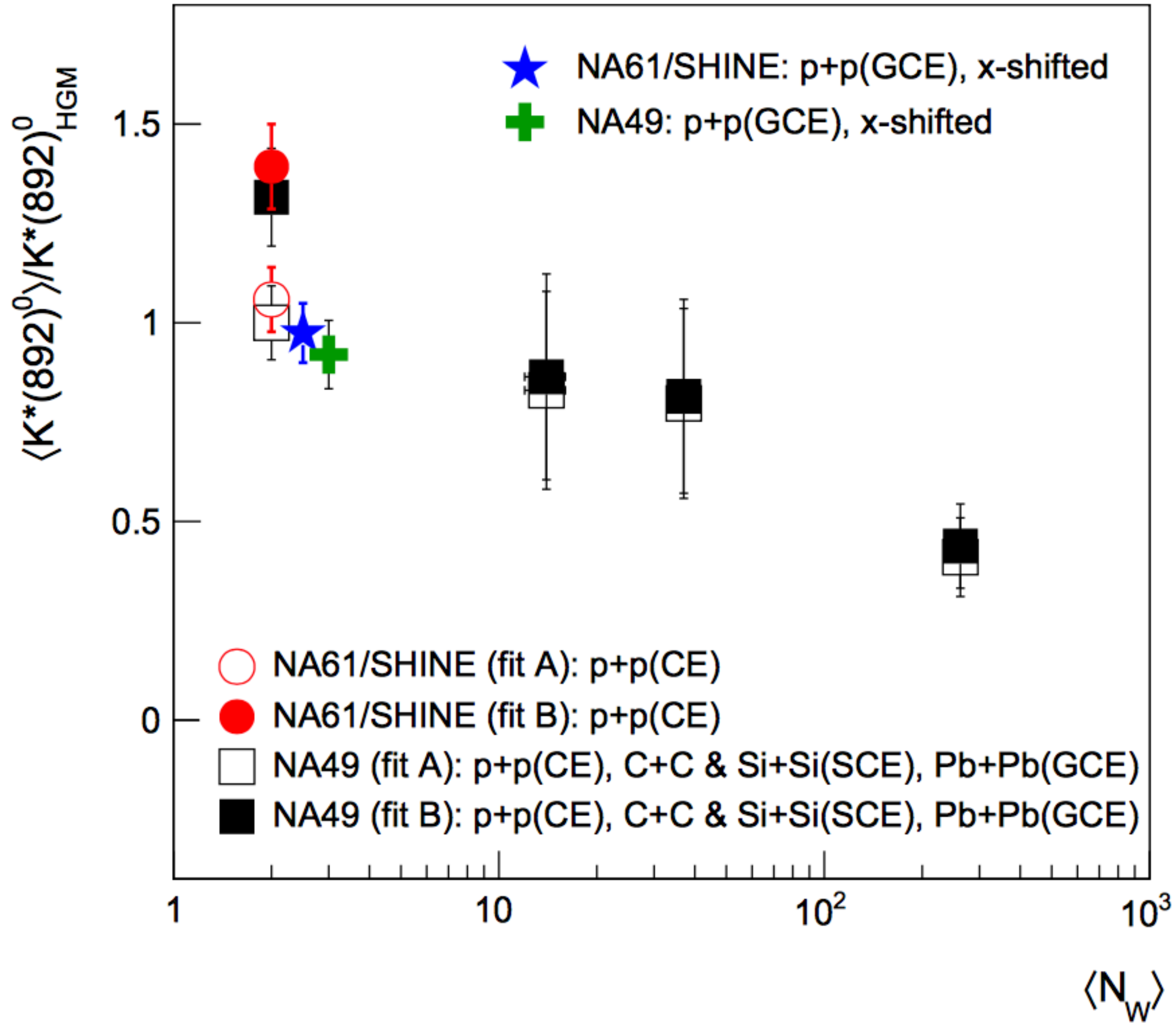
- **Suppression** of K^{*0} is observed in different collision systems from various experiments (NA49, NA61/SHINE, STAR)
  - more suppression for larger collision systems

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

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

Resonance suppression: K^{*0}

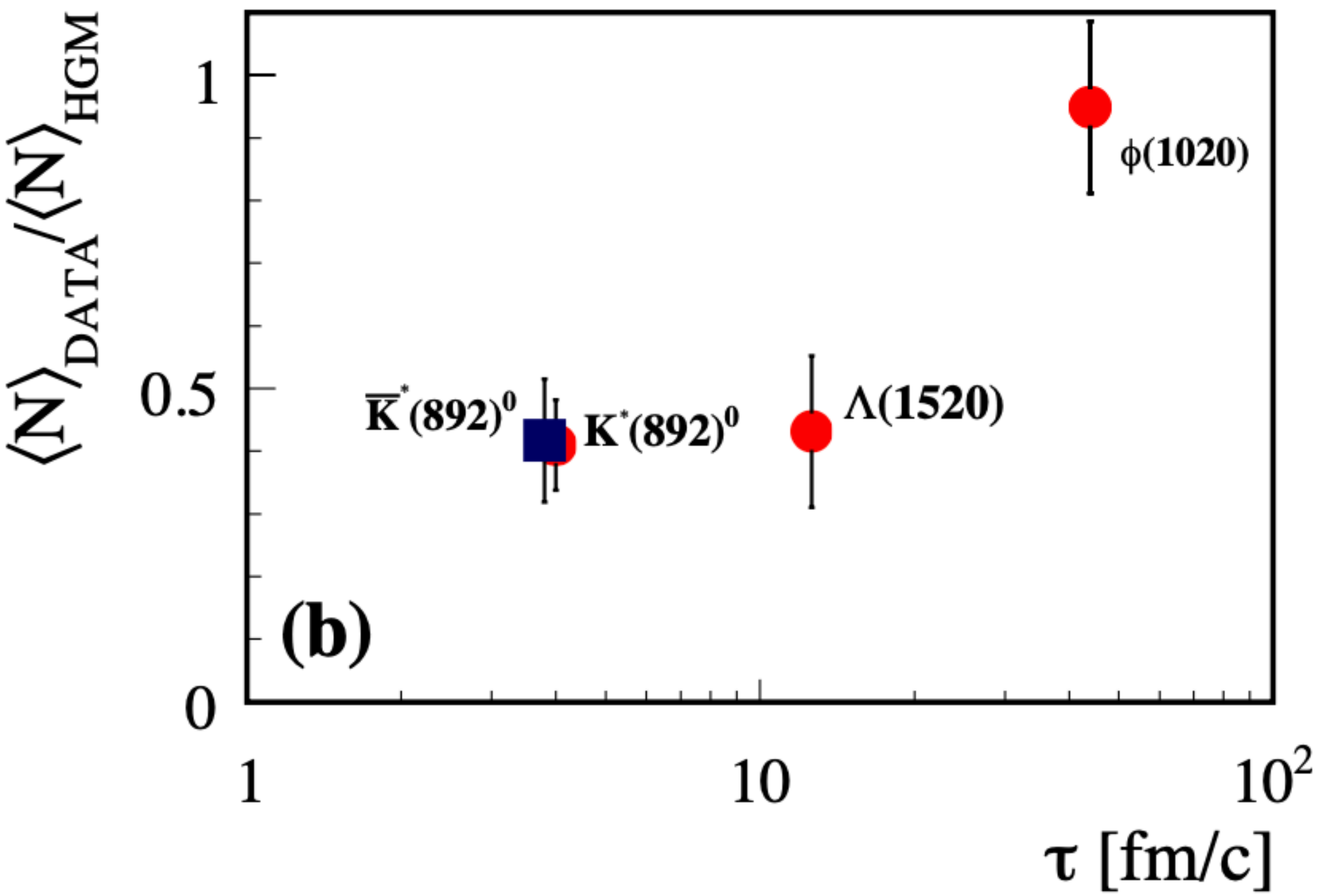


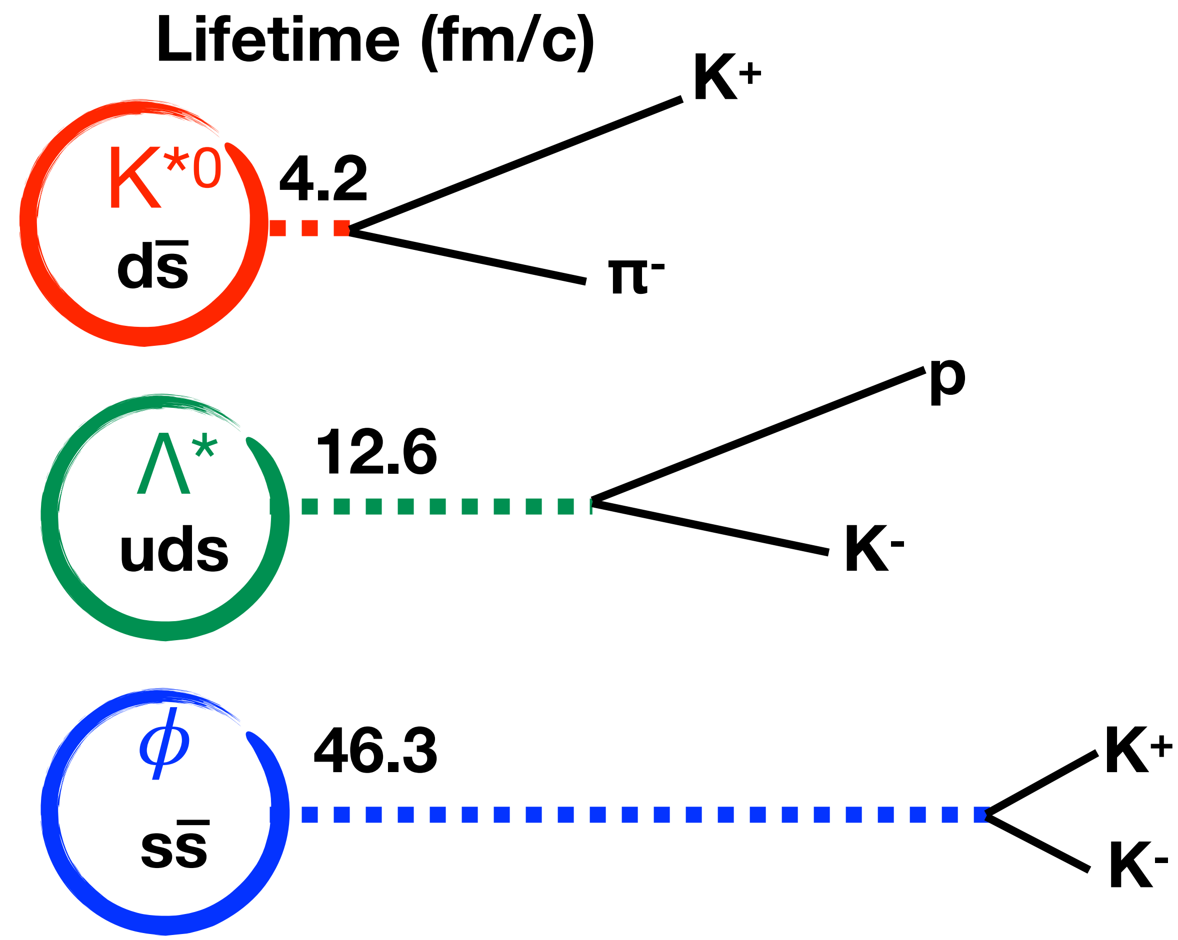


- **Suppression** of K^{*0} is observed in different collision systems from various experiments (NA49, NA61/SHINE, STAR)
  - more suppression for larger collision systems
- **Suppression** of K^{*0} w.r.t. the statistical **Hadron Resonance Gas Models**(HGM) is observed for heavier system

Eur. Phys. J. C (2020) 80:460 Phys.Rev.C 102 (2020) 2, 024909 Phys. Rev. C 73, 044905 (2006)

Resonance suppression





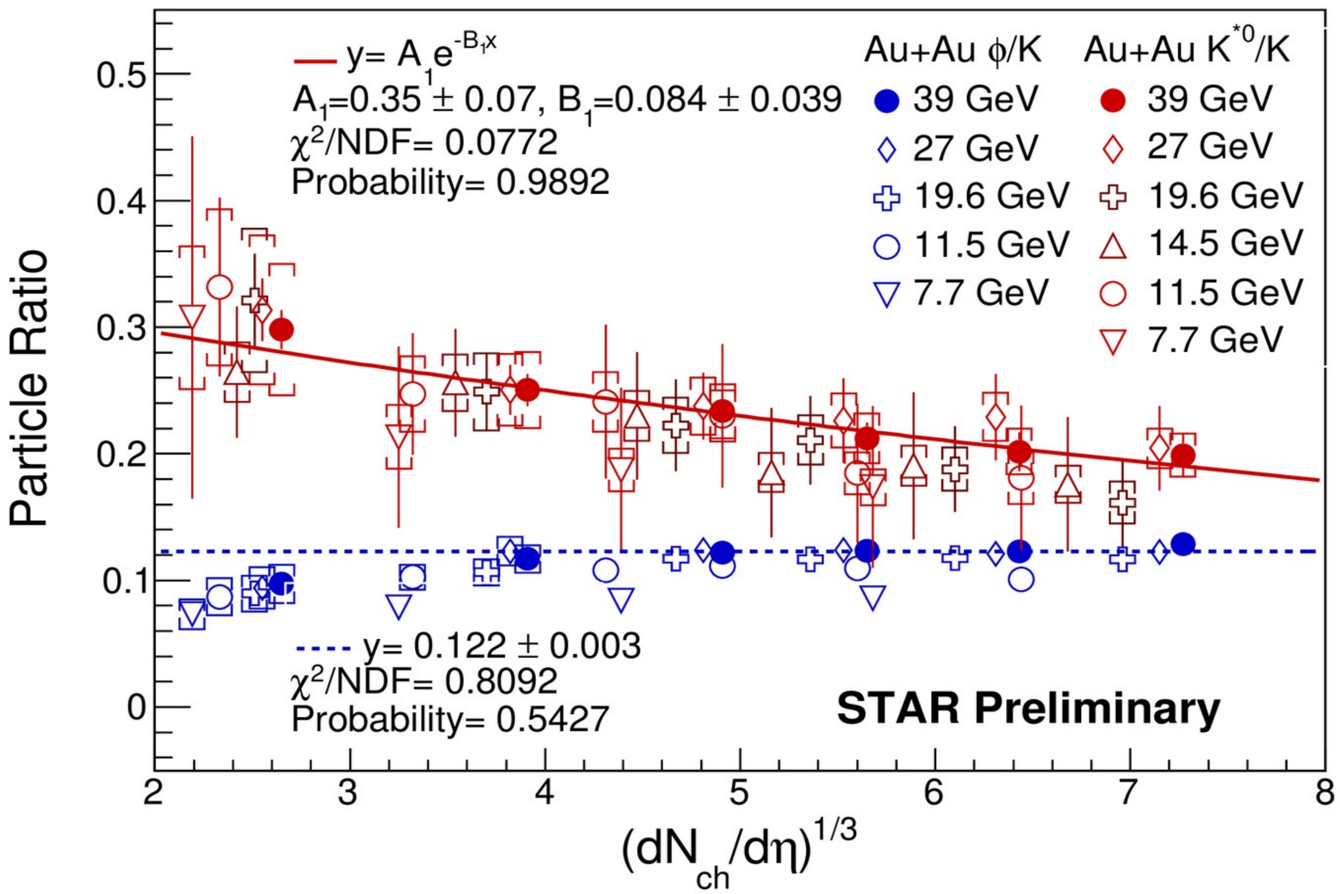
- **Suppression** of K^{*0} and $\Lambda^*(1520)$ w.r.t. the statistical Hadron Resonance Gas Models(HGM) while **no suppression** for ϕ w.r.t. the HGM

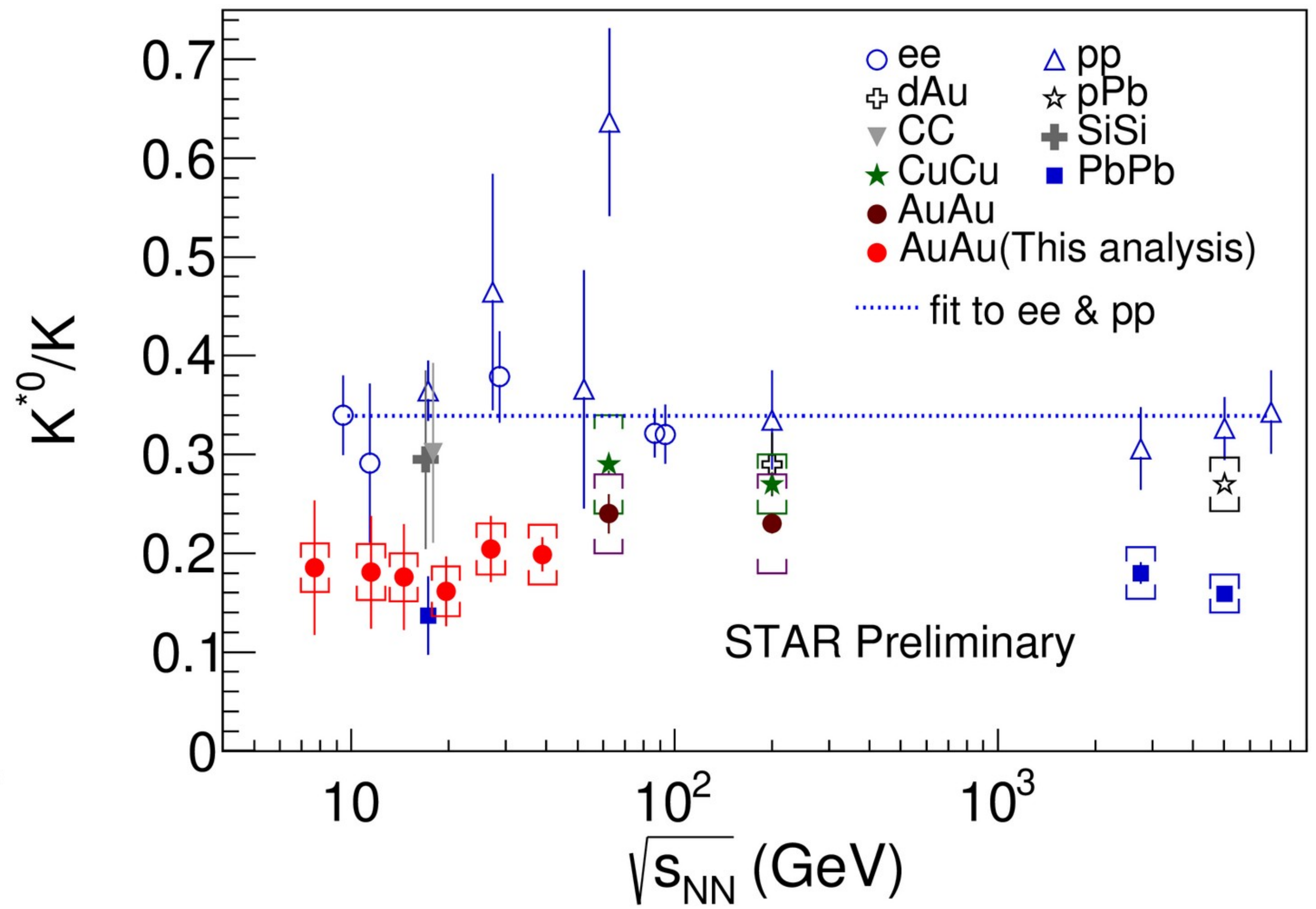
- Suppression effect might be related to the lifetime of the resonances

https://arxiv.org/pdf/1105.3109.pdf

Resonance suppression: energy dependence (K^{*0}/K)

A. K. Sahoo (QM2022)

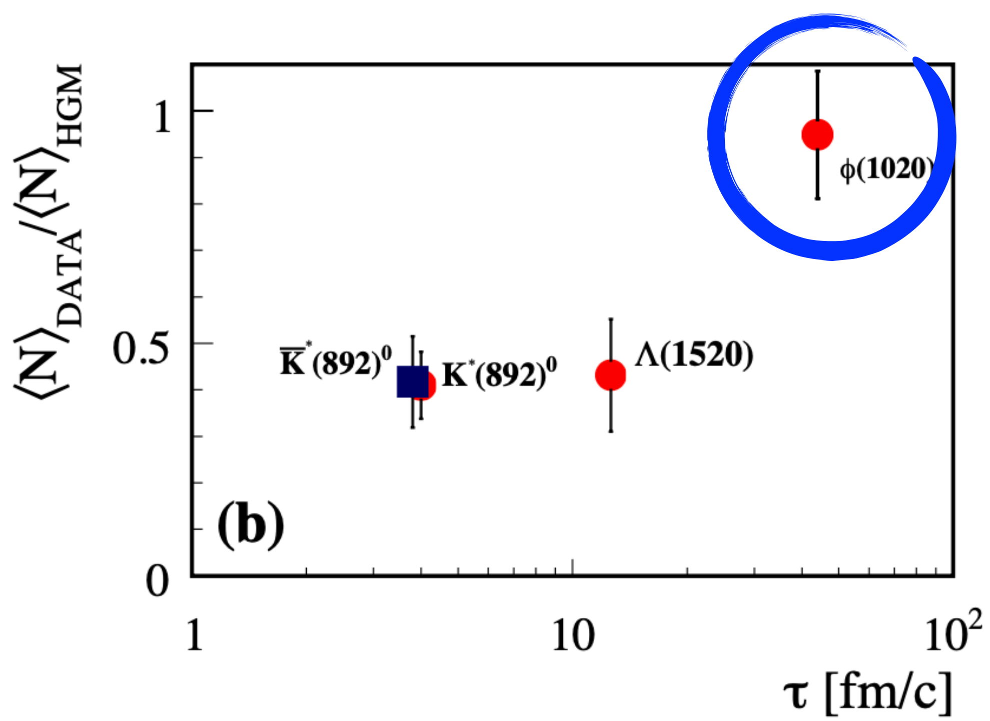


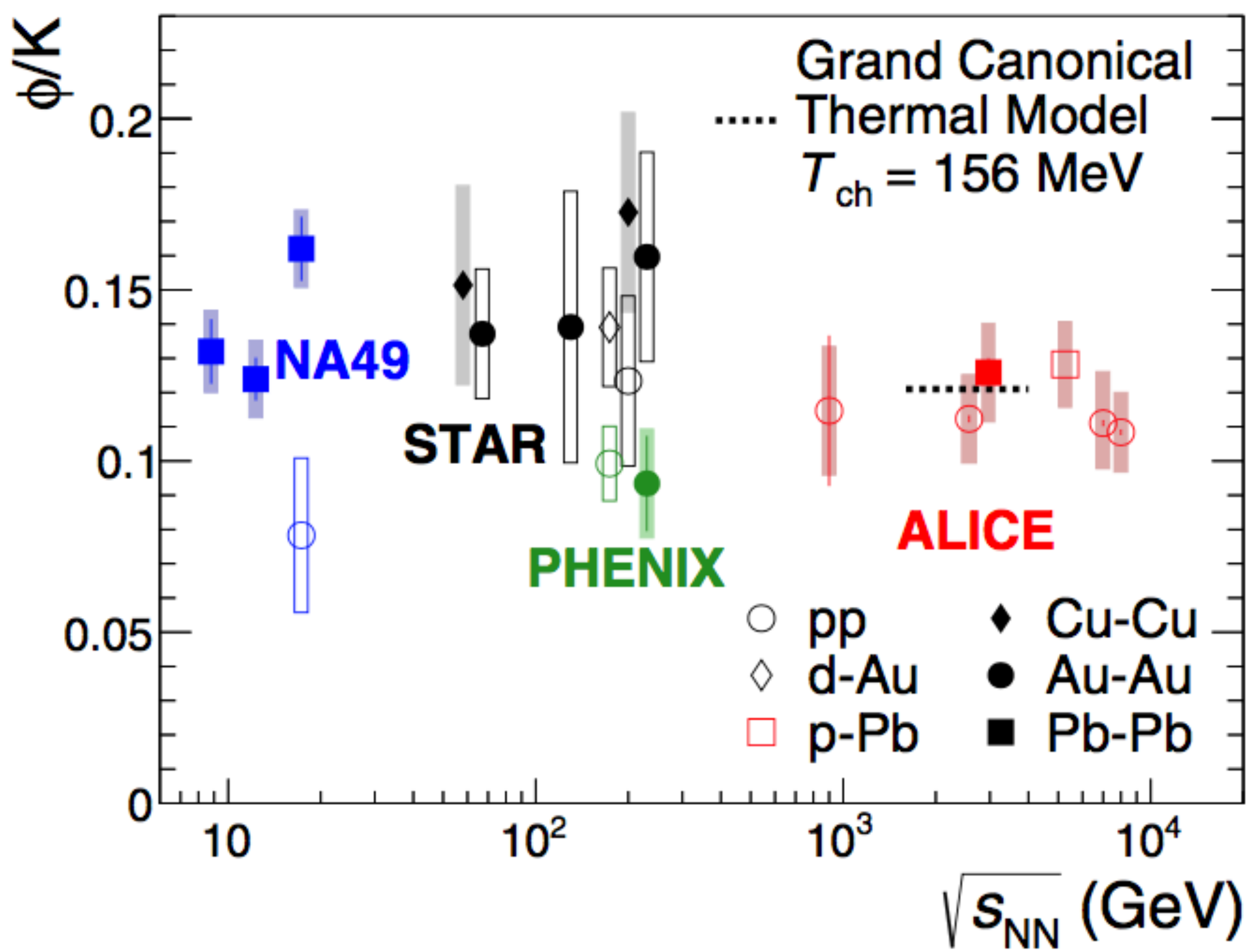


- K^{*0}/K and ϕ/K ratios have been measured at different energies
  - K^{*0}/K: decreasing with increasing multiplicity
  - ϕ/K: independent of multiplicity

- K^{*0}/K ratios in central collisions are smaller than the ratios from pp & ee collisions
  (ratios for AA collisions are results from most central collisions. e.g. 0-10% or 0-20%)
  -no clear energy dependence from 7.7 GeV/c to 5.02 TeV

Resonance suppression: energy dependence (ϕ/K)





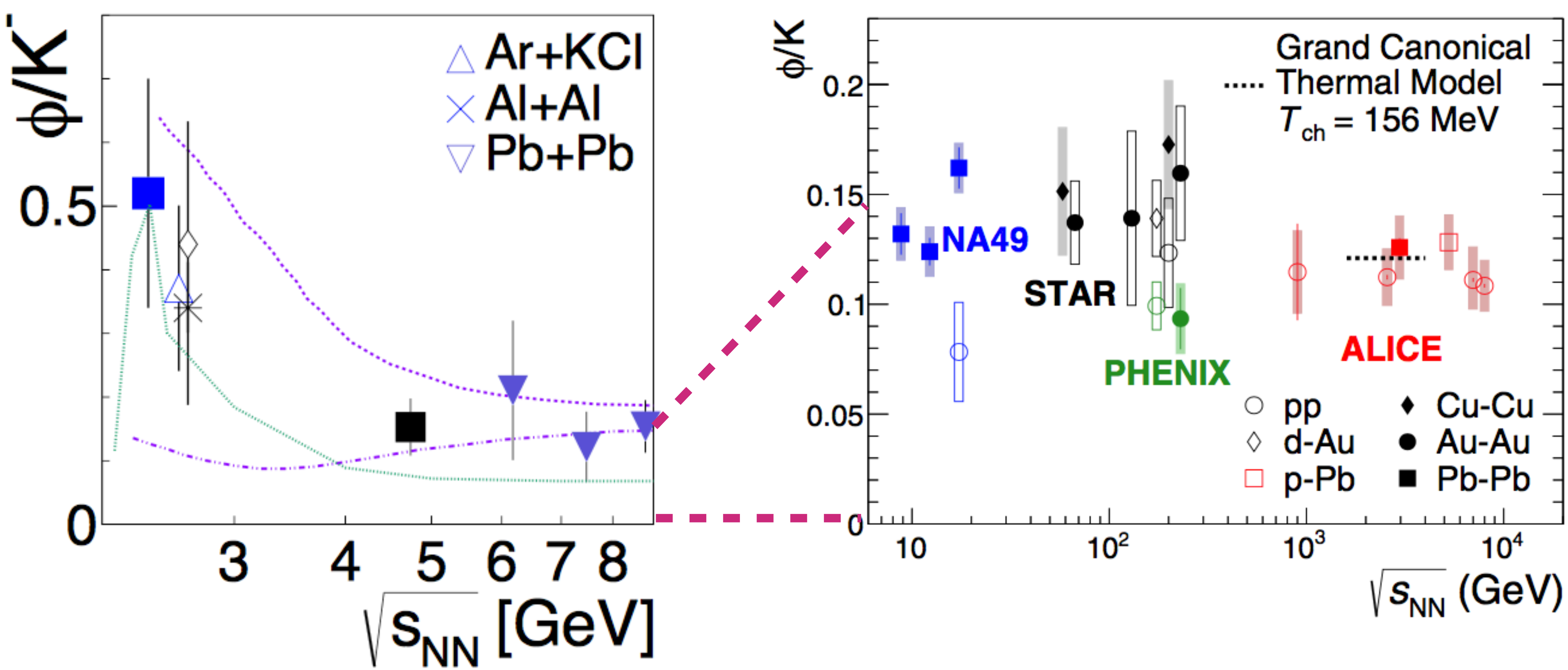
- Flat behavior in a wide range of energy (~10-10^4 GeV) and different collision systems

https://arxiv.org/pdf/1105.3109.pdf

PHYSICAL REVIEW C 102, 024912 (2020)

Resonance suppression: energy dependence (ϕ/K)

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



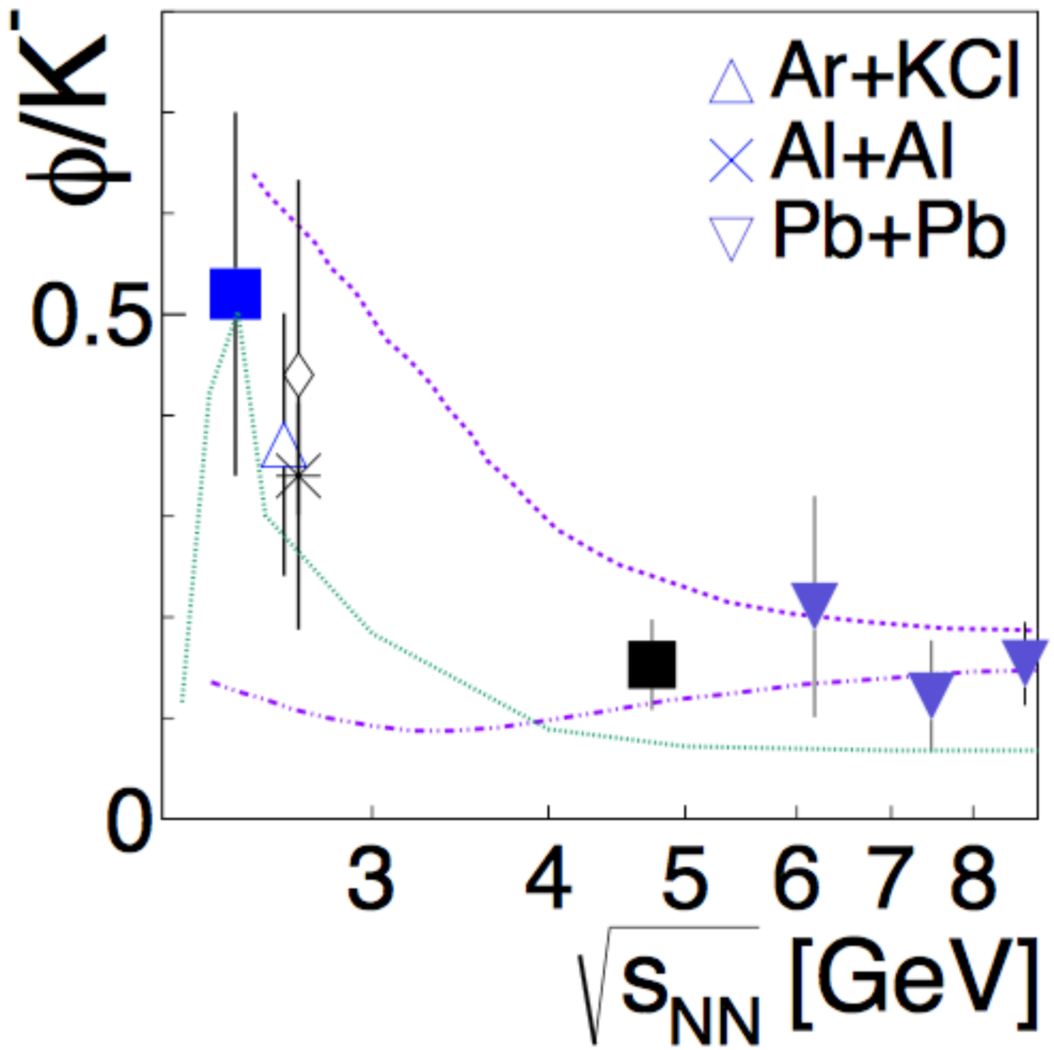
- Increase for low energies due to canonical suppression
  - reproduced by statistical model calculation with strangeness correlation radius parameter R_c = 2.2fm (purple dashed curve)

https://arxiv.org/pdf/1703.08418v1.pdf

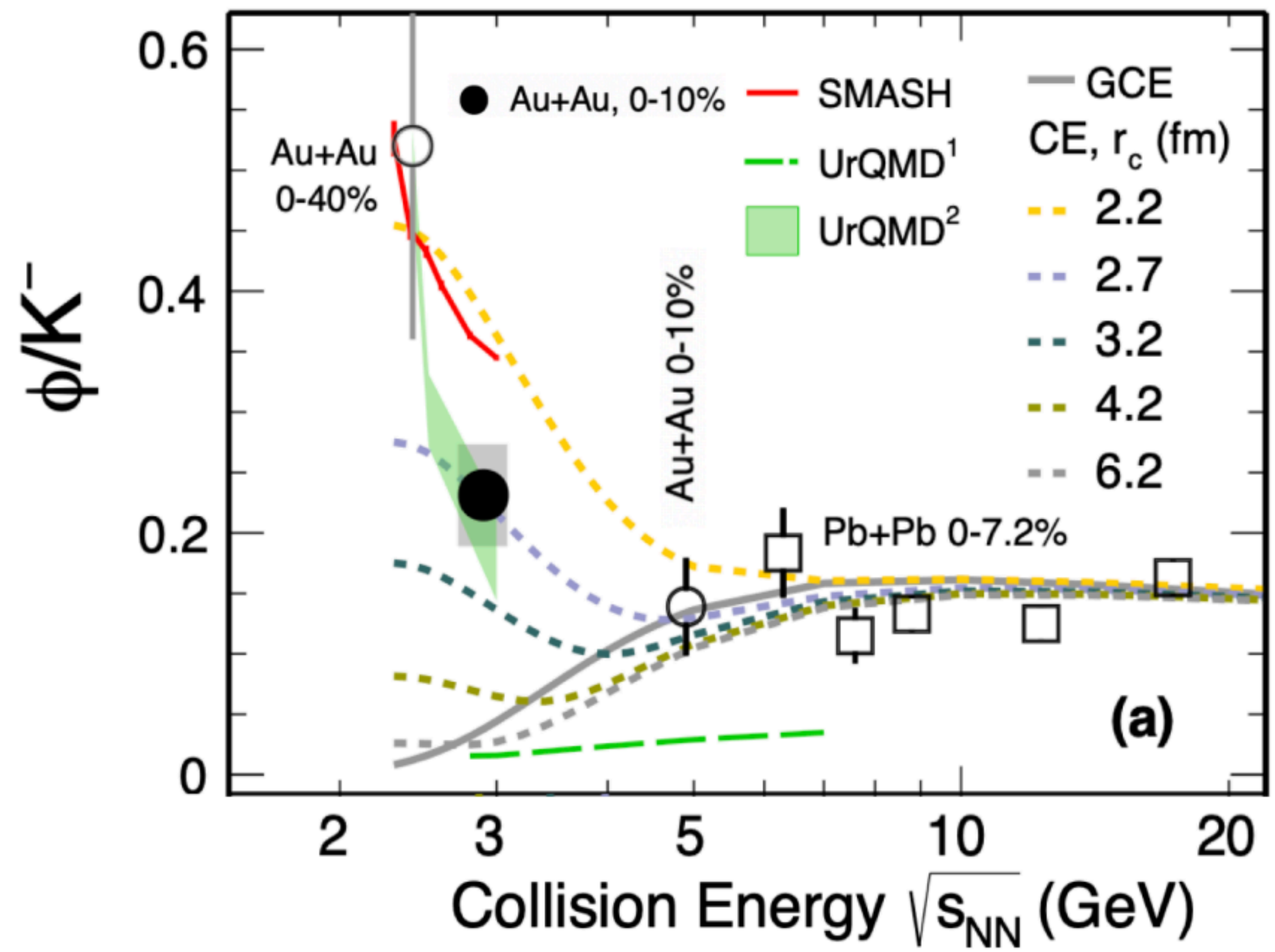
PHYSICAL REVIEW C 102, 024912 (2020)

Resonance suppression: energy dependence (ϕ/K)

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

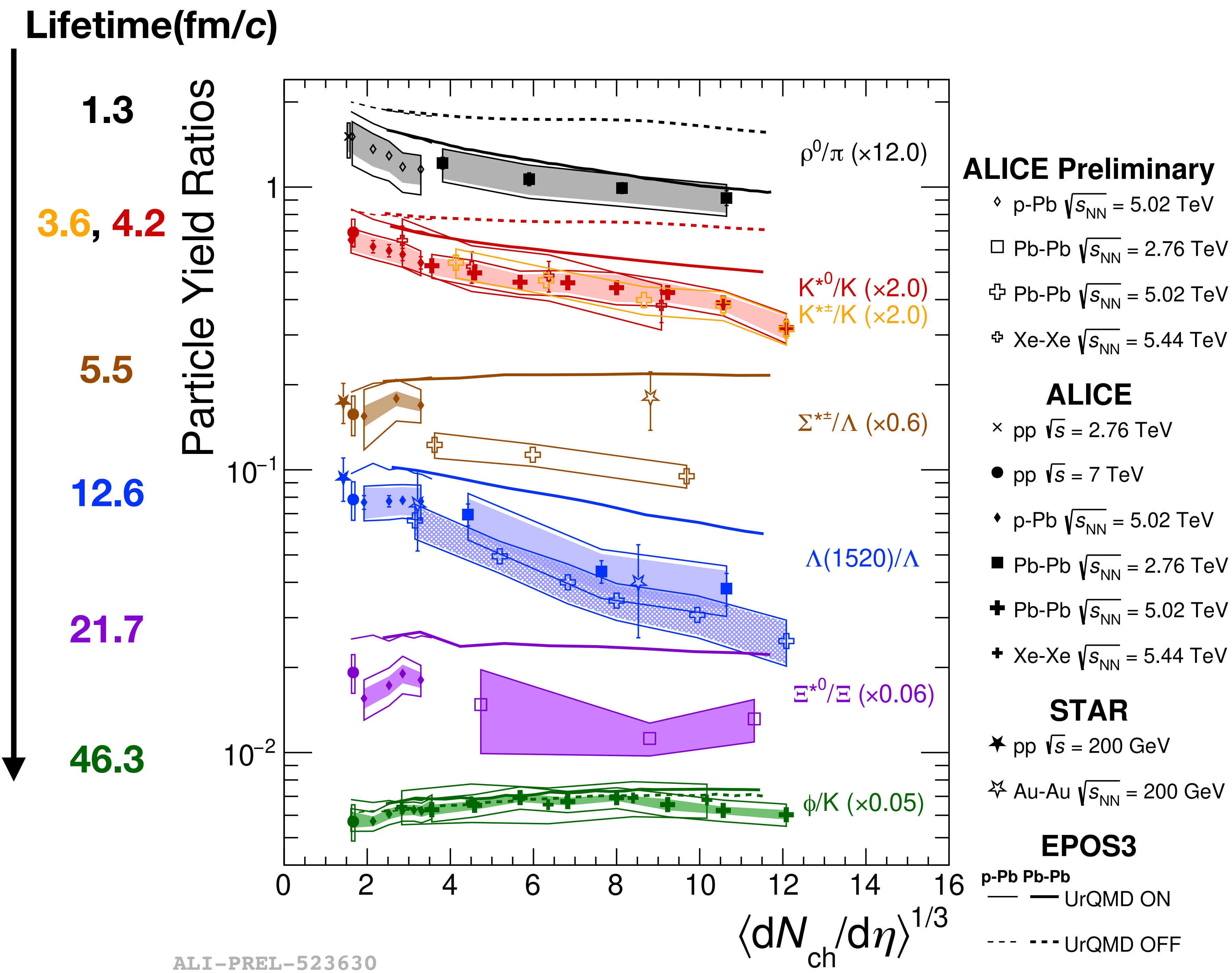


STAR *Phy.Lett.B* 831 (2022) 137152



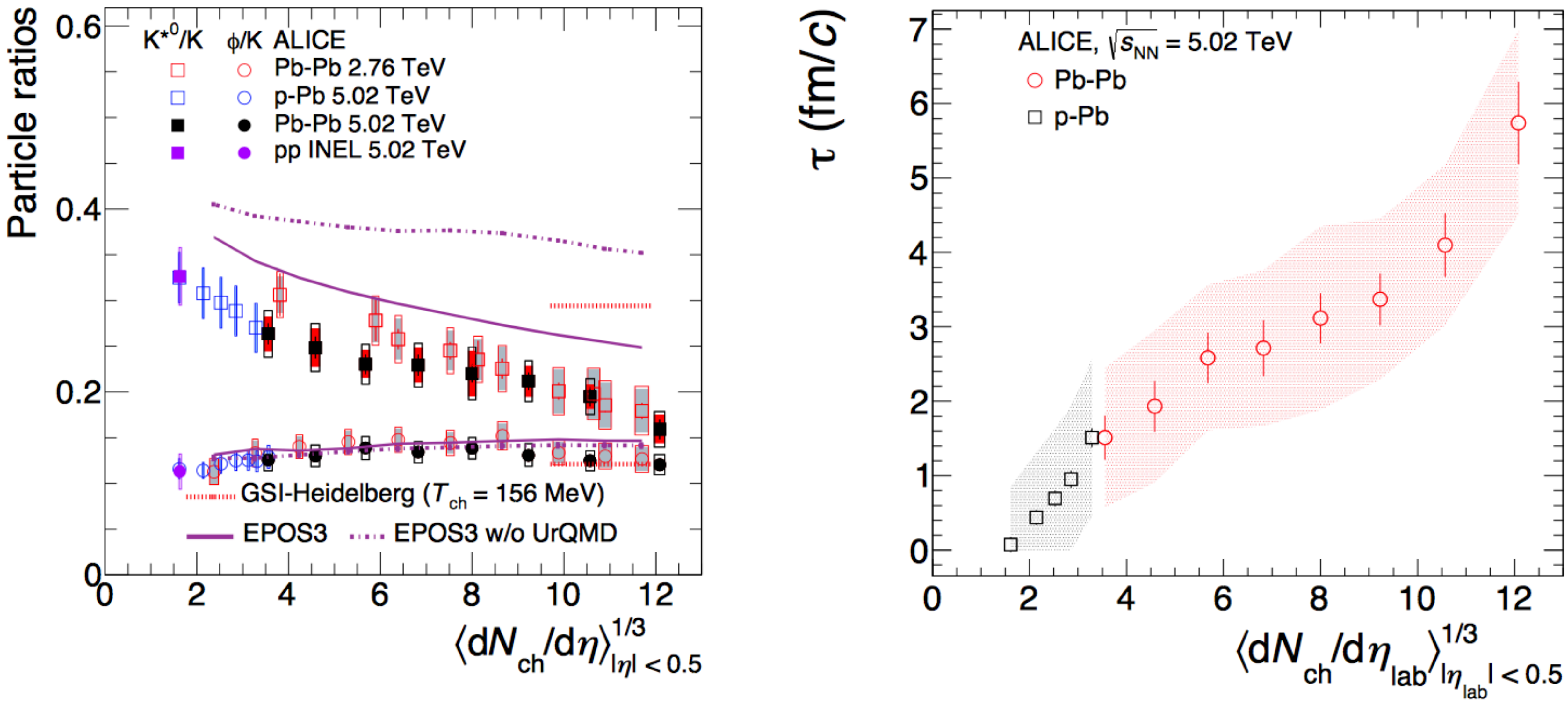
- GCE underestimates data at low energy
- Thermal model with CE gives a good description of data at $\sqrt{s_{NN}}$=3 GeV
- SMASH&UrQMD² calculations reproduce ϕ/K at $\sqrt{s_{NN}}$=3 GeV

Resonance to long-lived particle ratios



- **suppression** of the ratios of **short-lived resonances** in central Pb-Pb collisions
  - indicates <u>*dominance of re-scattering over regeneration*</u>
- no significant centrality dependence for long-lived resonances e.g. Ξ^*,ϕ
- **no energy dependence** from RHIC to LHC
- smooth trend: pp→pA→AA

Probing the hadronic phase

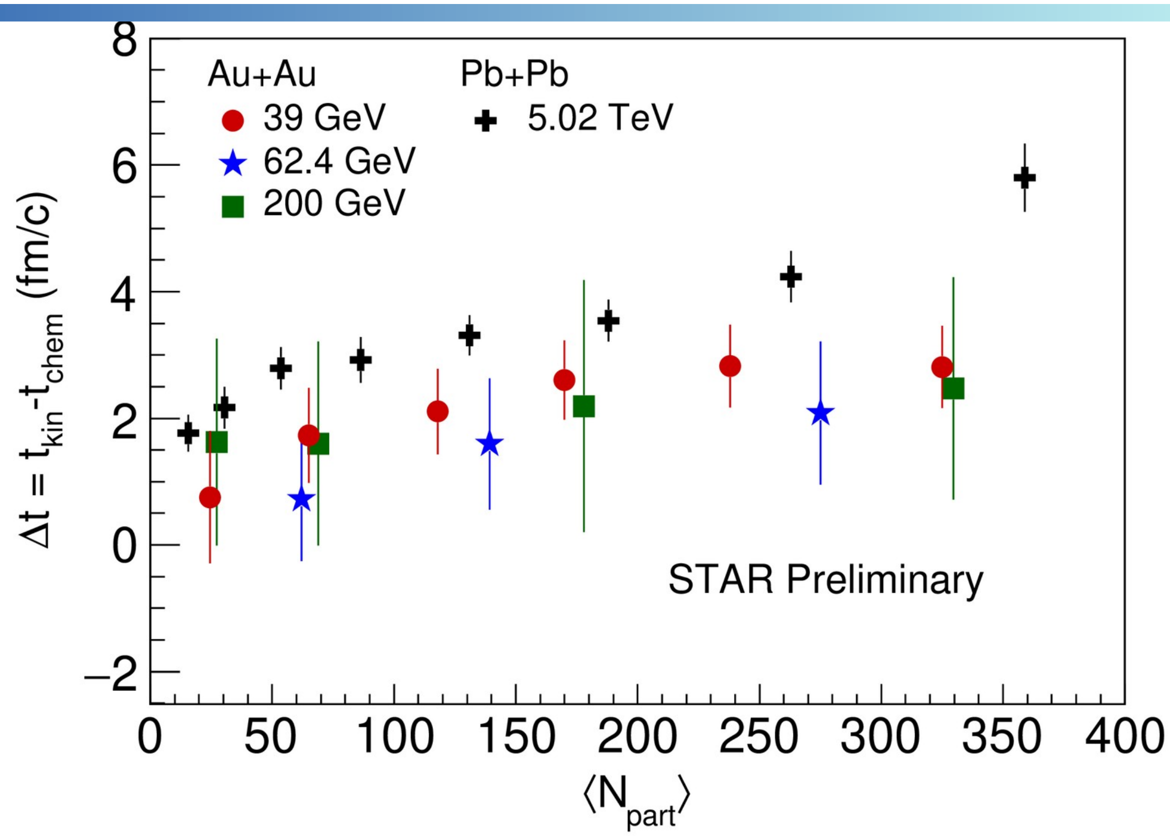


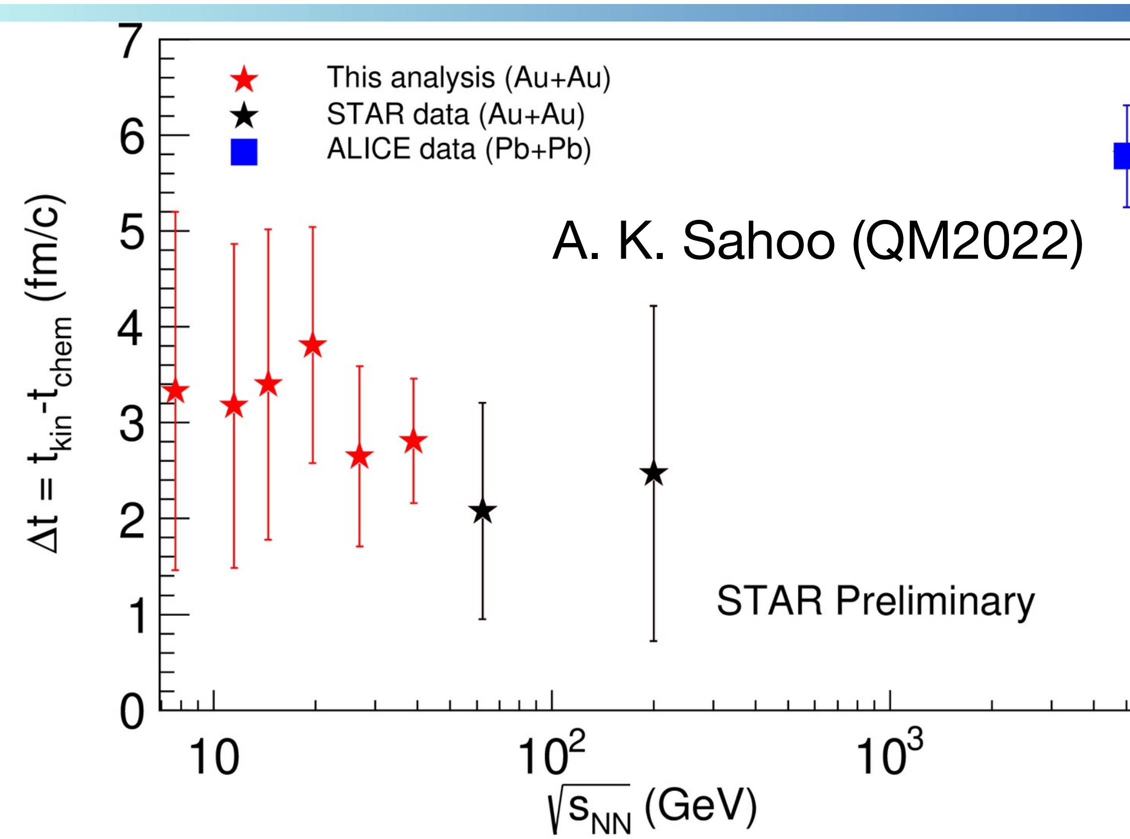
$$[K^{*0}/K]_{kinetic(Pb\text{-}Pb)} = [K^{*0}/K]_{chemical(pp)} \times e^{-\tau/\tau_{K^{*0}}}$$

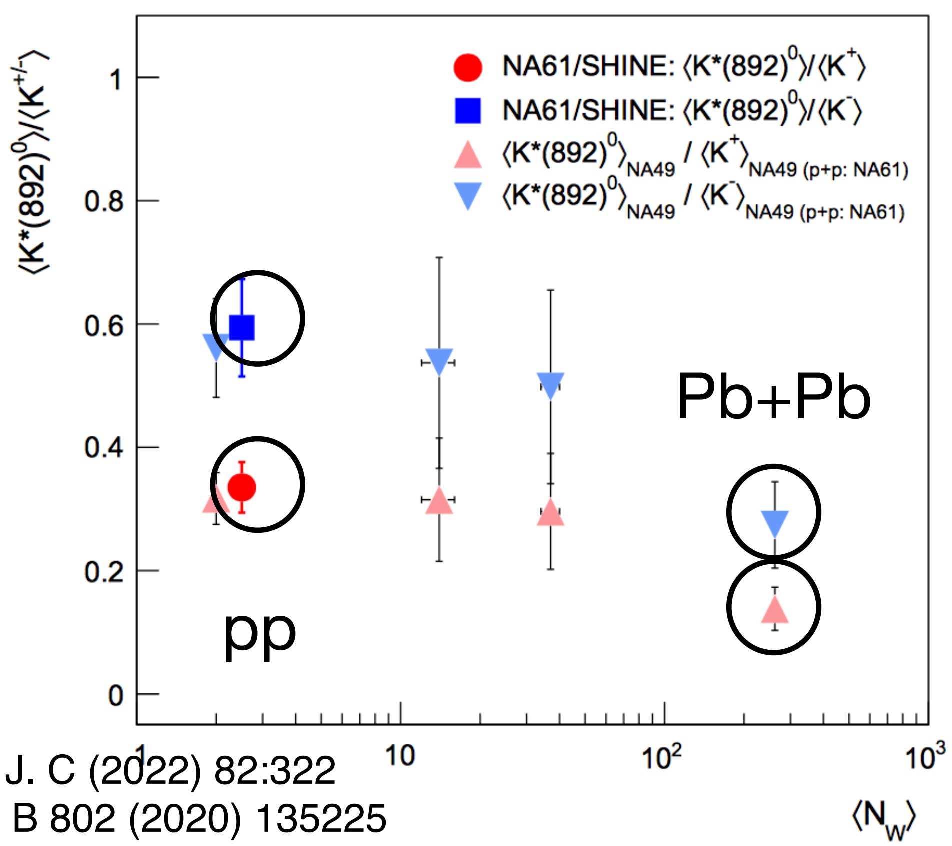
- Estimate the **time duration between chemical and kinetic freeze-out** from the measurement of K^{*0}/K ratios in Pb-Pb and pp collisions
  - lifetime of hadronic phase smoothly increases with multiplicity
  - found to be ~4-7 fm/*c* for central collisions

PLB 802 (2020) 135225

Probing the hadronic phase





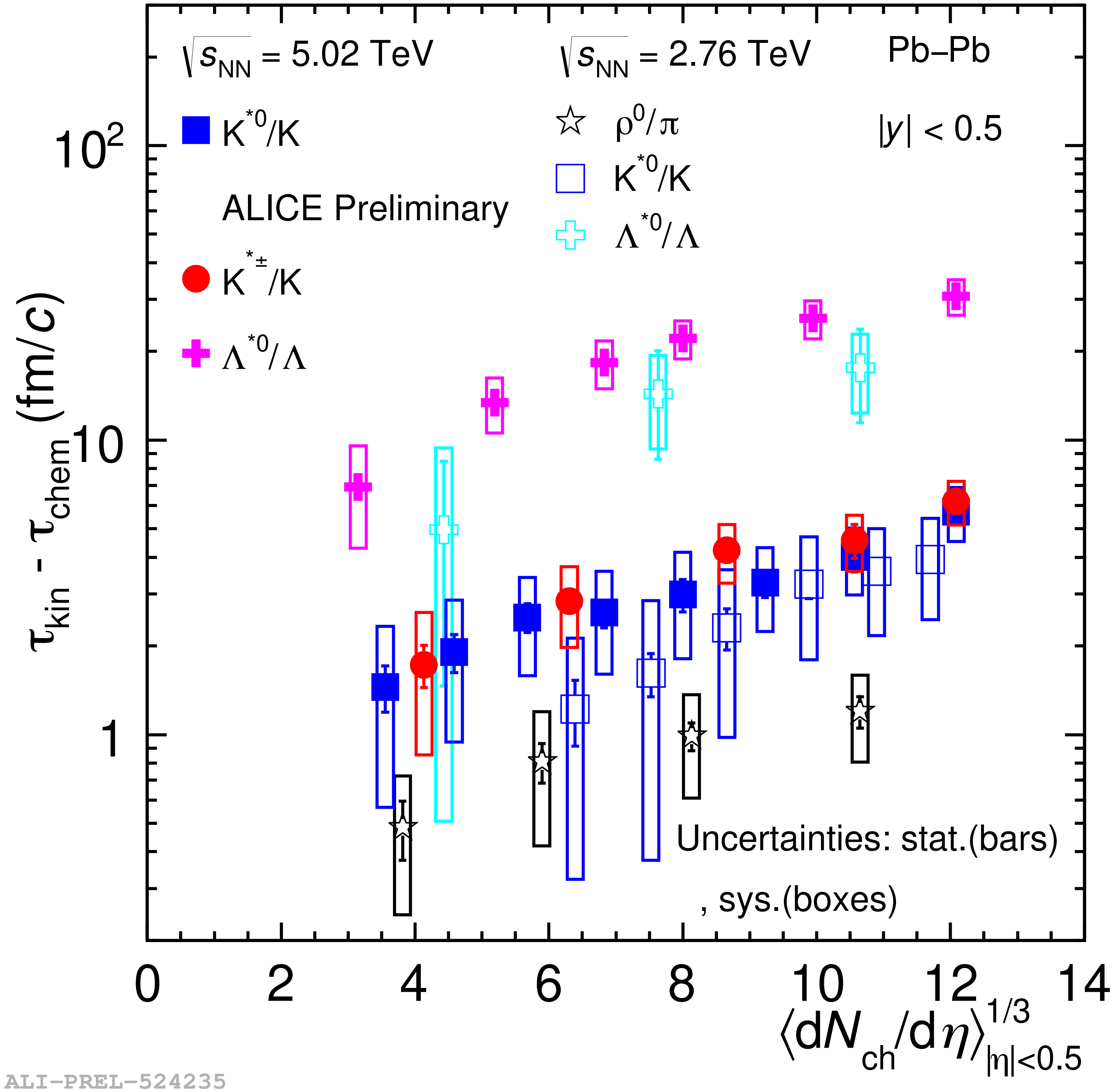


- There seems no energy dependence from 39 GeV to 200 GeV at RHIC
- Hadronic lifetime (Δt) at RHIC seems to be smaller than at LHC
- Δt measured from NA61/SHINE is comparable with RHIC
  - K^{*0}/K^+: 3.7±1.2 fm/*c*
  - K^{*0}/K^-: 3.2±1.2 fm/*c*

Eur. Phys. J. C (2022) 82:322
Phys. Lett. B 802 (2020) 135225
Phys. Rev. C 84:034909 (2011)

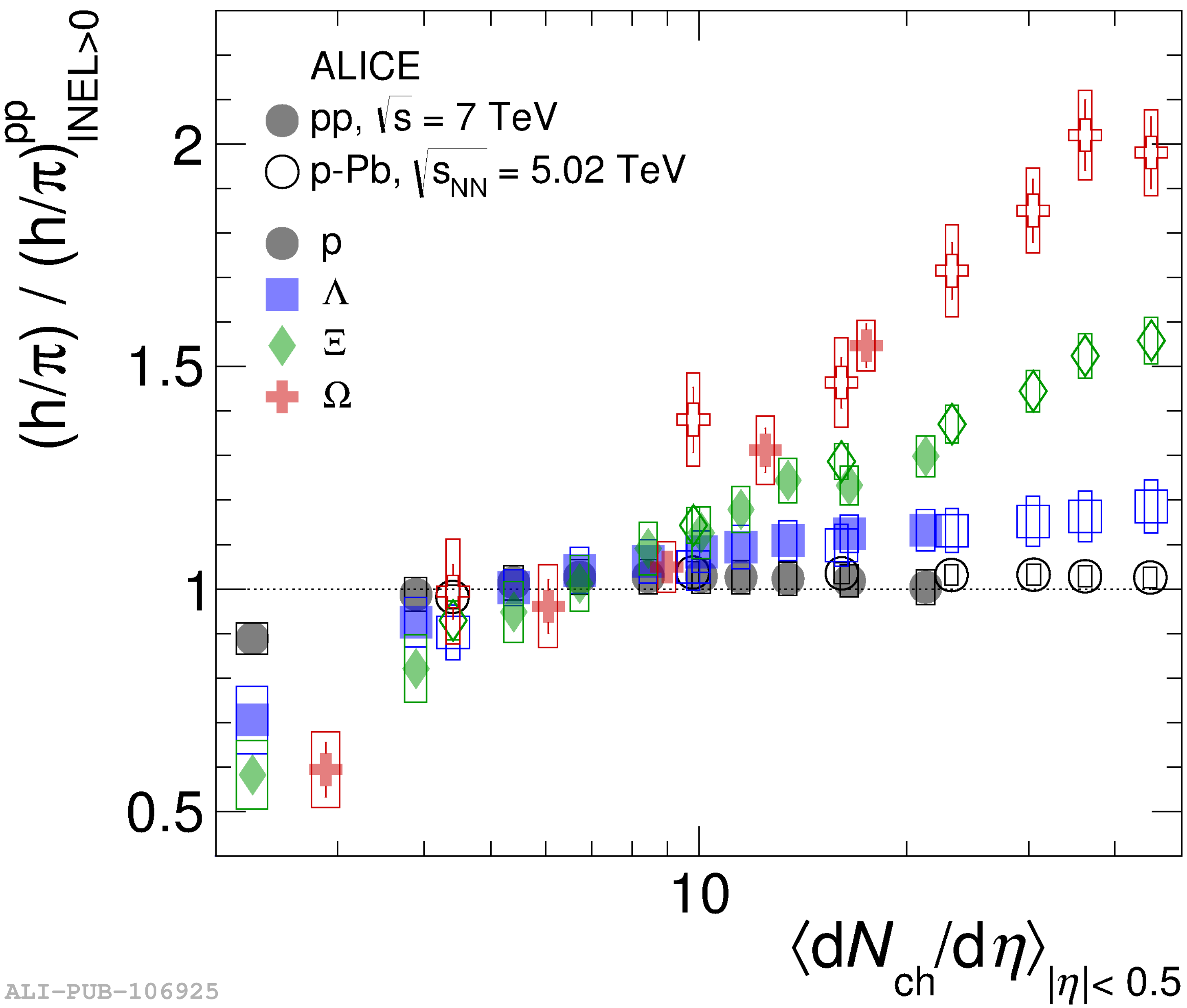
Probing the hadronic phase

Dukhishyam Mallic (SQM2022: PA-Resonances and Hyper-nuclei)



- Summary of estimation of the lower limit of hadronic phase for ρ^0/π, K^{*0}/K, $K^{*\pm}/K$, and Λ^*/Λ
- Estimated time duration measured in $\sqrt{s_{NN}}$=5.02 TeV energy seems larger than those from $\sqrt{s_{NN}}$=2.76 TeV
  - But within the systematic error
- Need theory input to have better understanding

Strangeness enhancement in small system



ALI-PUB-106925

What causes the enhancement? mass vs. strangeness

Ground state

s=1: Λ(1116)

s=2: Ξ(1320)

s=3: Ω(1670)

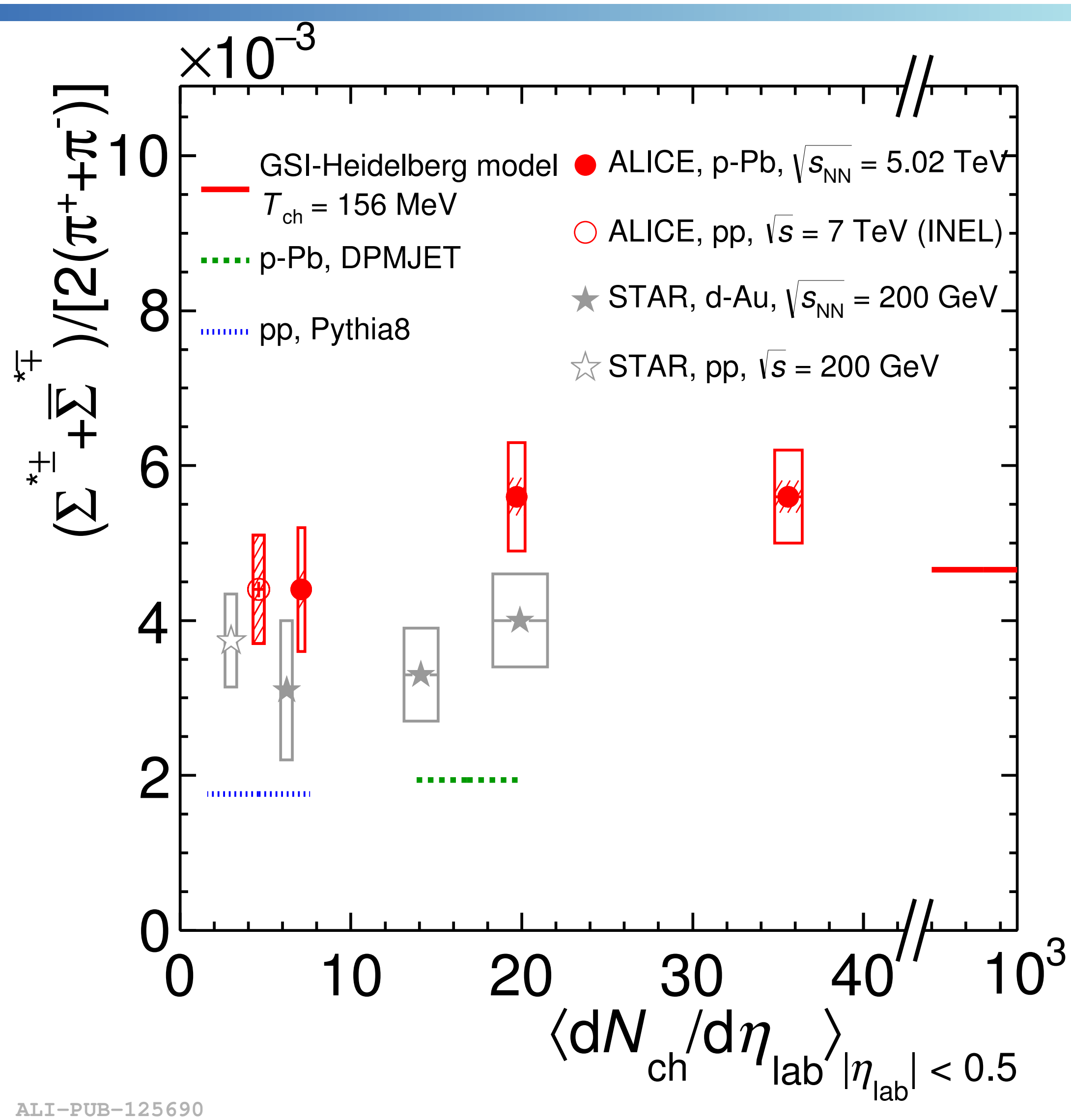
Resonances

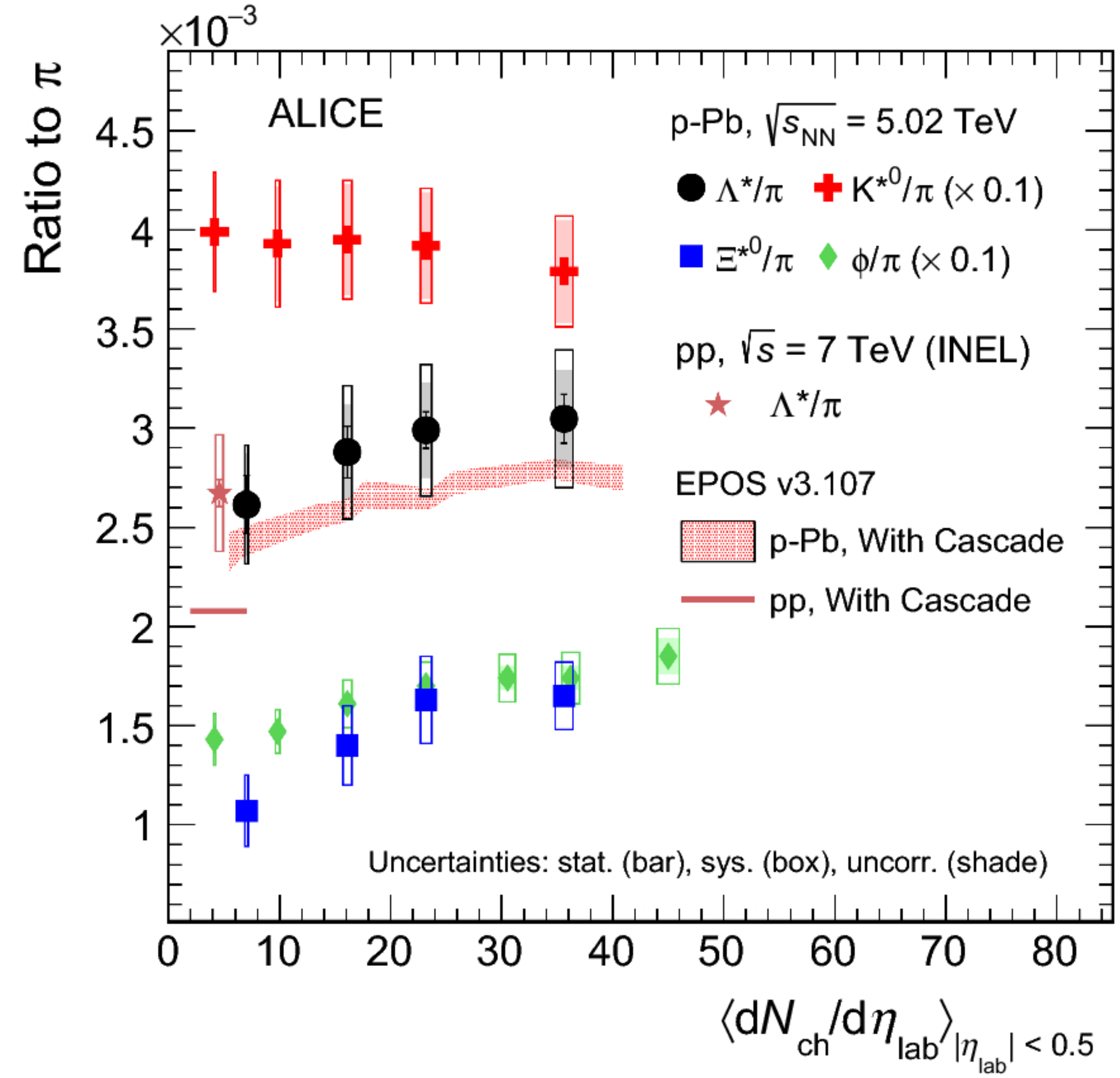
s=1: $\Sigma^*(1385)^{\pm}$, $\Lambda^*(1520)$

s=2: $\Xi^*(1530)^0$

s=3: $\Omega(2012)^{\mp}$

Strangeness enhancement in small system





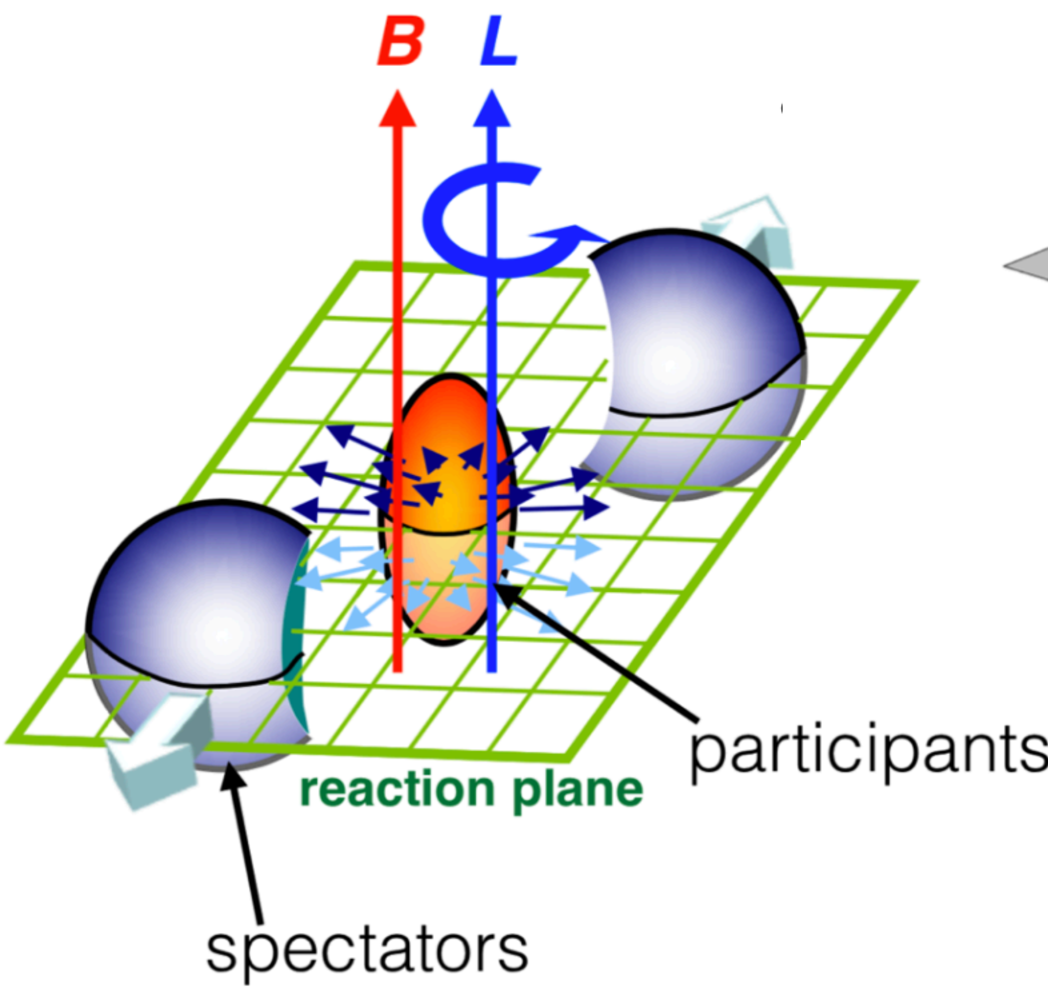
Σ(1385)$^{\pm}$, Λ(1520):
- Same strangeness content as Λ
- Mass is similar(grater) to Ξ
- Σ*/π and Λ*/π are compatible with Λ/π

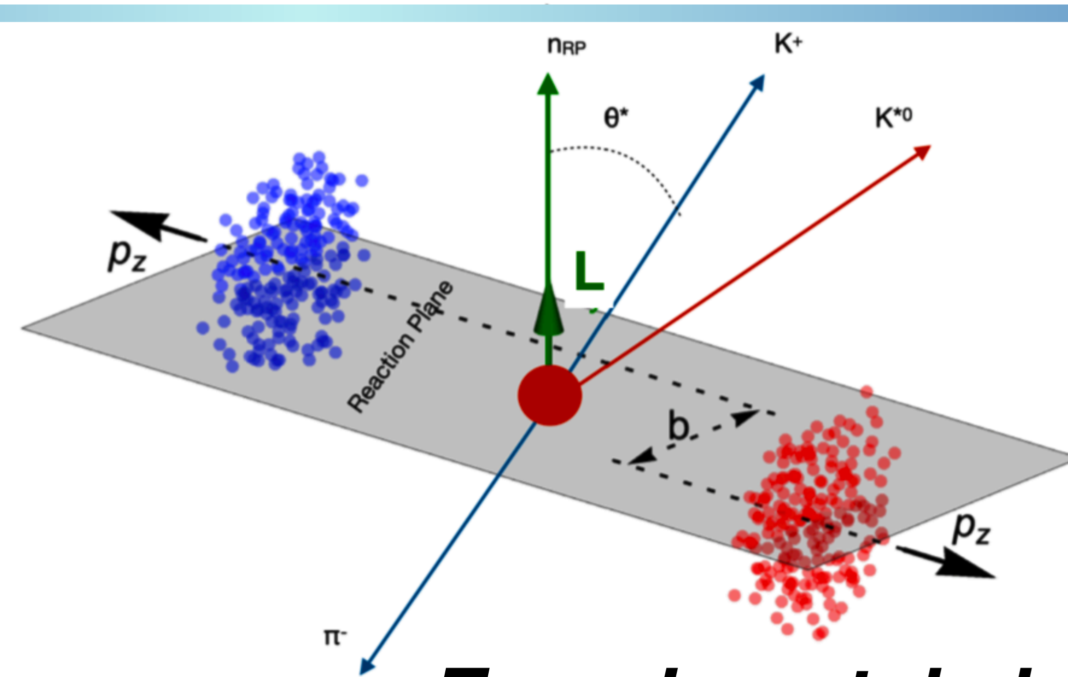
Ξ(1530)^{0}:
- Same strangeness content as Ξ
- Mass is between Ξ & Ω
- Ξ*/π is compatible with Ξ/π

- **Relative strangeness production** increases with the multiplicity
- ***enhancement of hyperons is due to their strangeness content*** (not a mass effect)

Eur. Phys. J. C (2020) 80:160 Eur. Phys. J. C (2017) 77:389

Spin alignment





Experimental observable

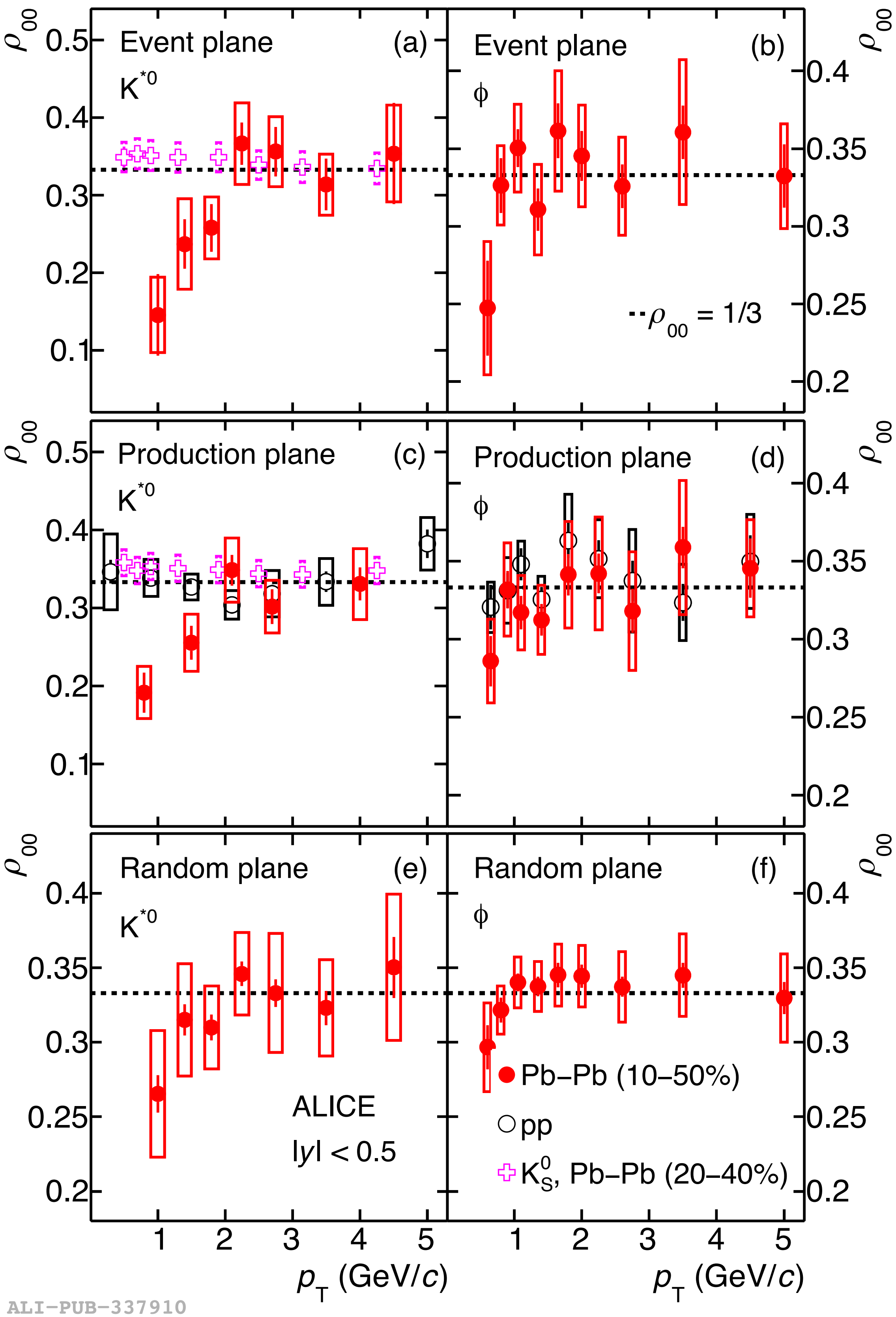
$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

ρ_{00}: Element of spin density matrix
if ρ_{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

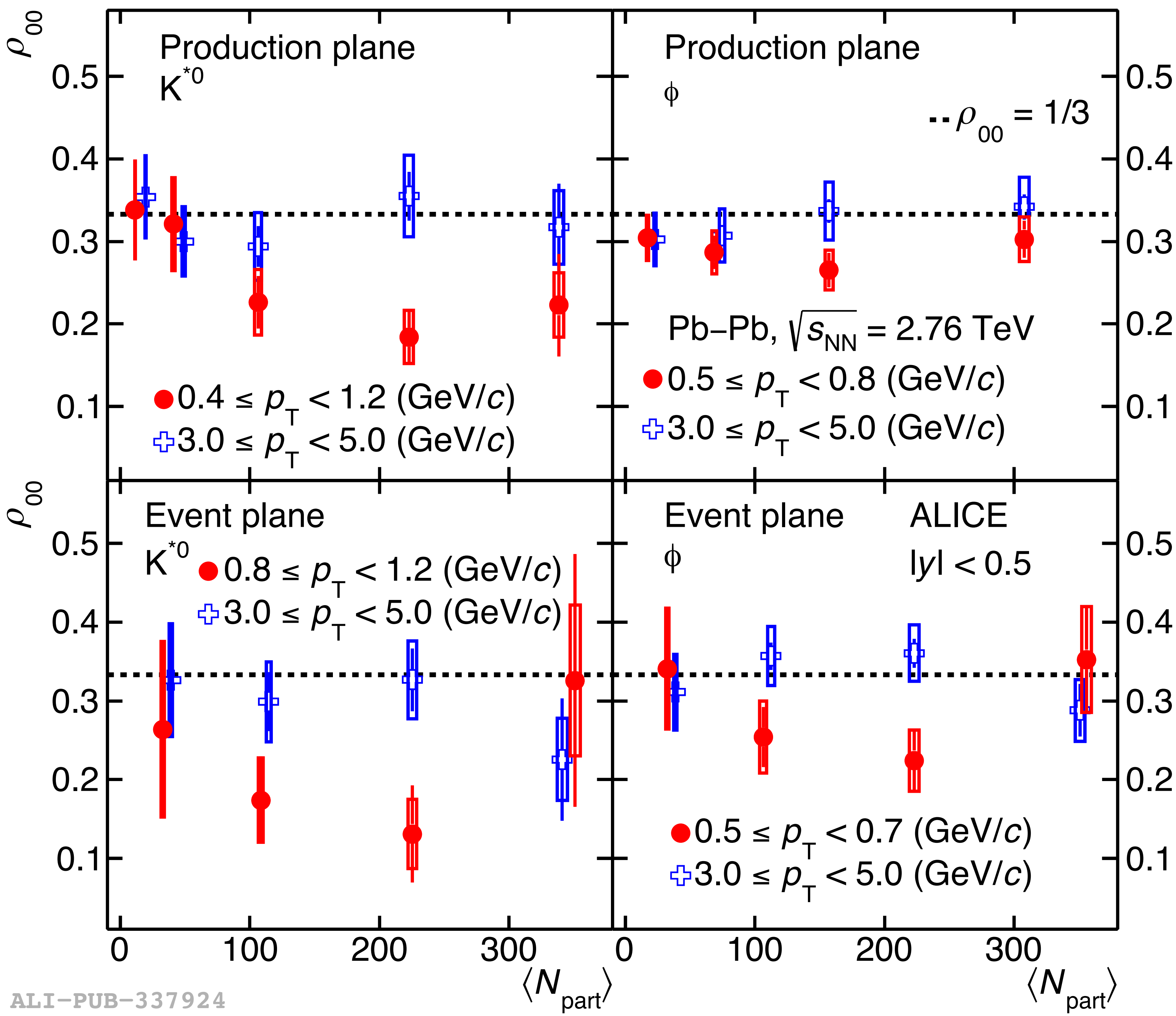
Spin alignment: ρ_{00} vs. p_T



- 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 meson (K^0_s)
- Measurements with Random Event Plane consistent with 1/3 (a small deviation at lowest p_T bin: residual effect of event plane)

PhysRevLett.125.012301 (2020)

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)

Conclusion

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

- K^{*0}/K and ϕ/K ratios are observed in different collision systems from various experiments
  - **more suppression of K^{*0}/K for the larger system**
  - **no energy dependence** of K^{*0}/K and ϕ/K ratios in a wide range (10-10^4 GeV)

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

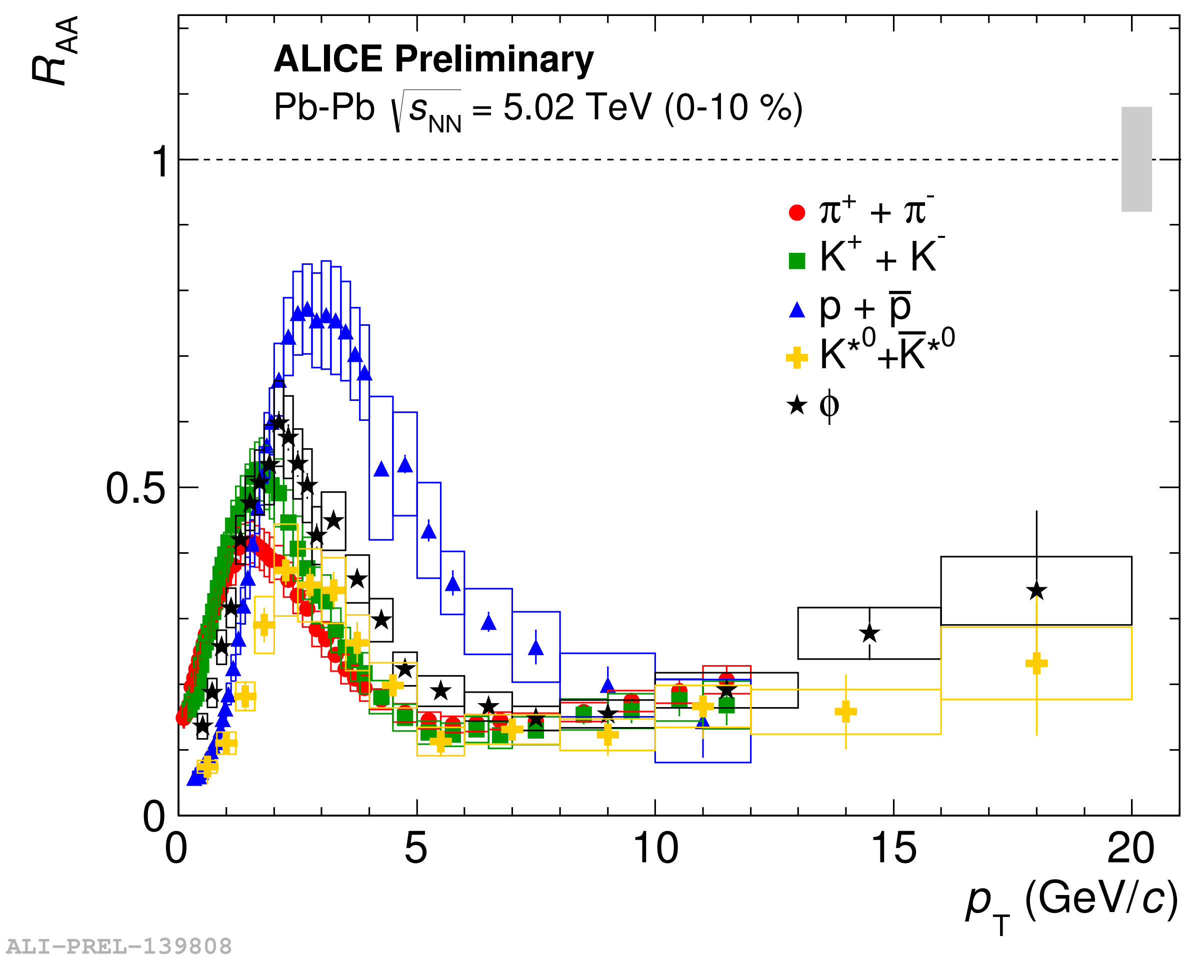
- **Enhancement of strange baryon** with multiplicity is **due to strangeness content**
  - confirmed by comparing ground state particle & resonances

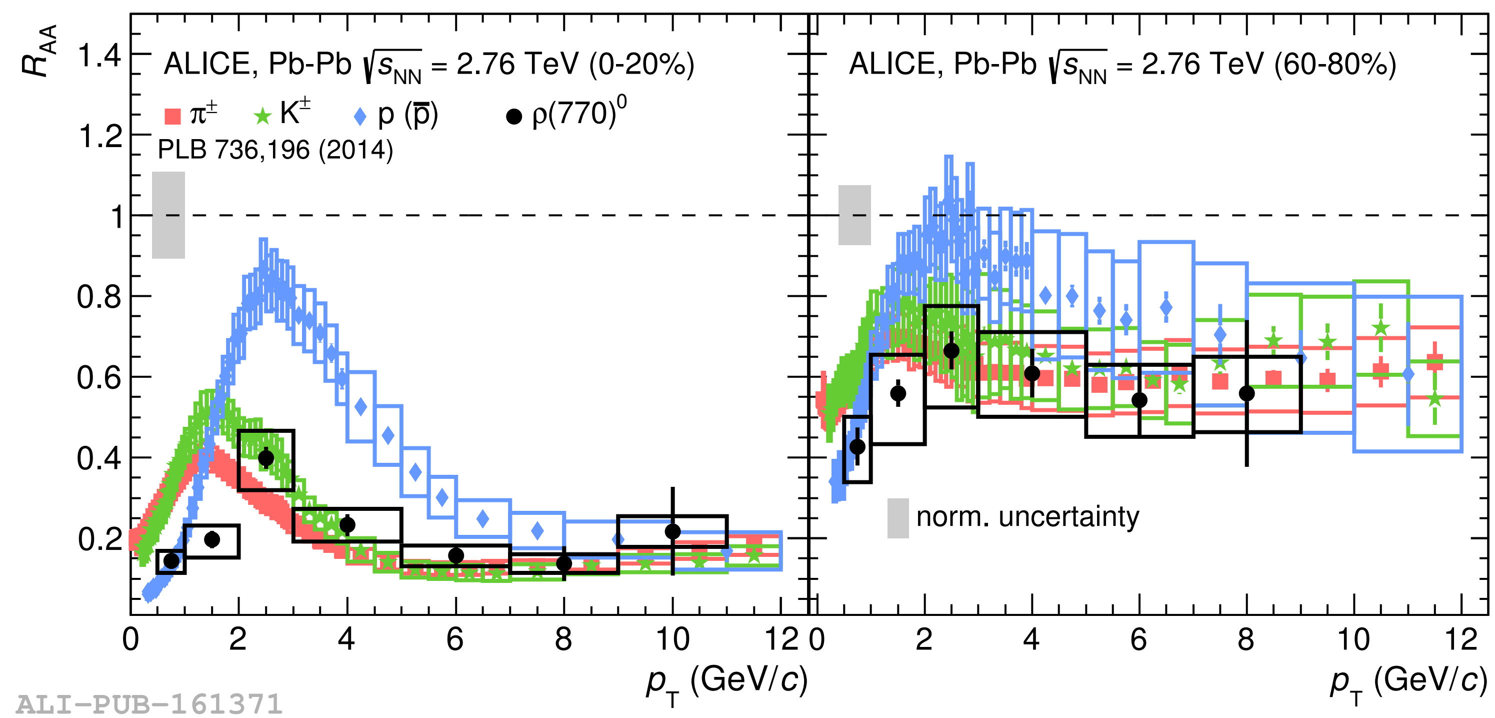
- **Spin alignment** ($\rho_{00}<1/3$) of vector meson is found in heavy-ion collisions **at low p_T in mid-central Pb-Pb collisions**

Backup

Nuclear Modification Factor (R_{AA}, R_{pA})

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



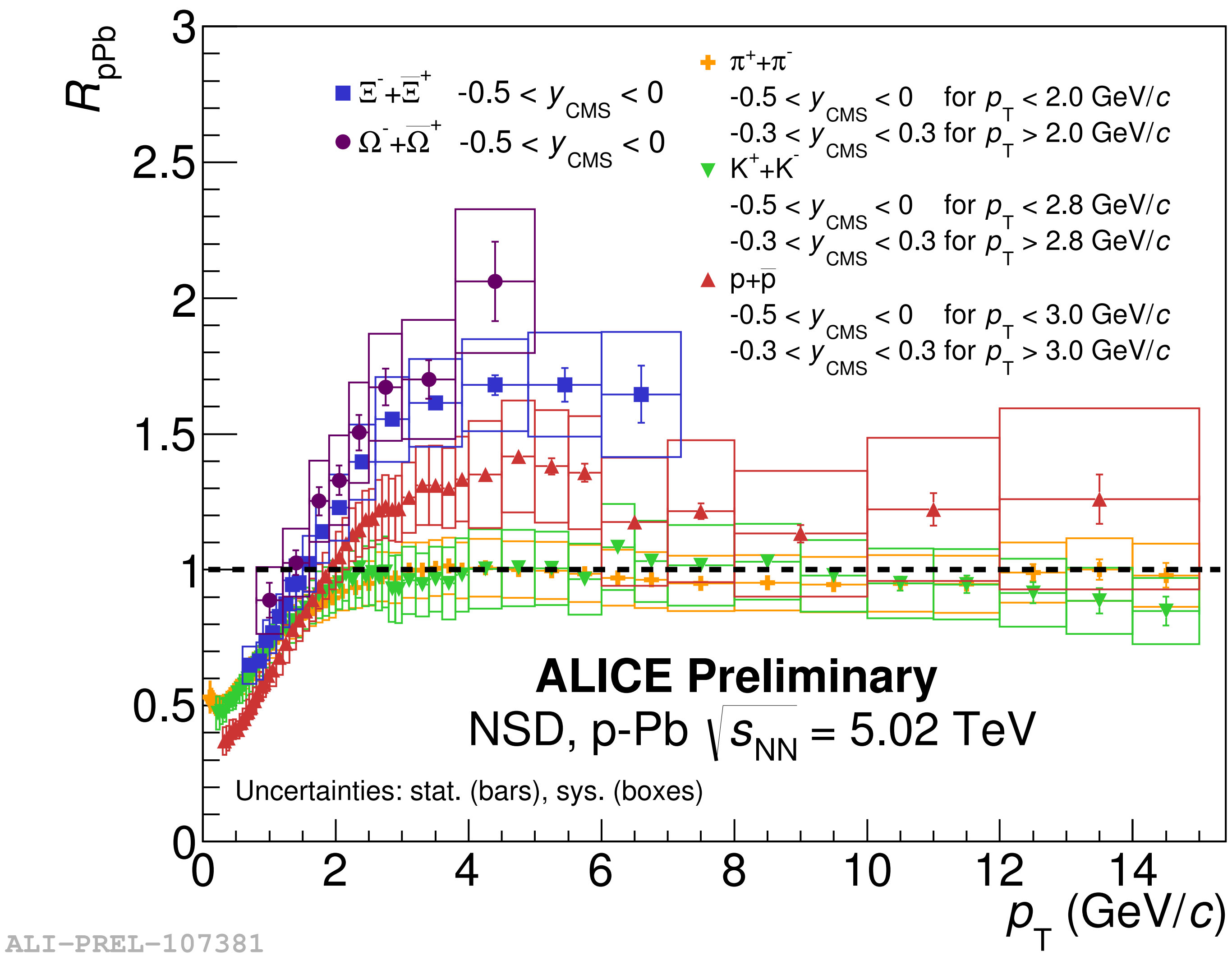


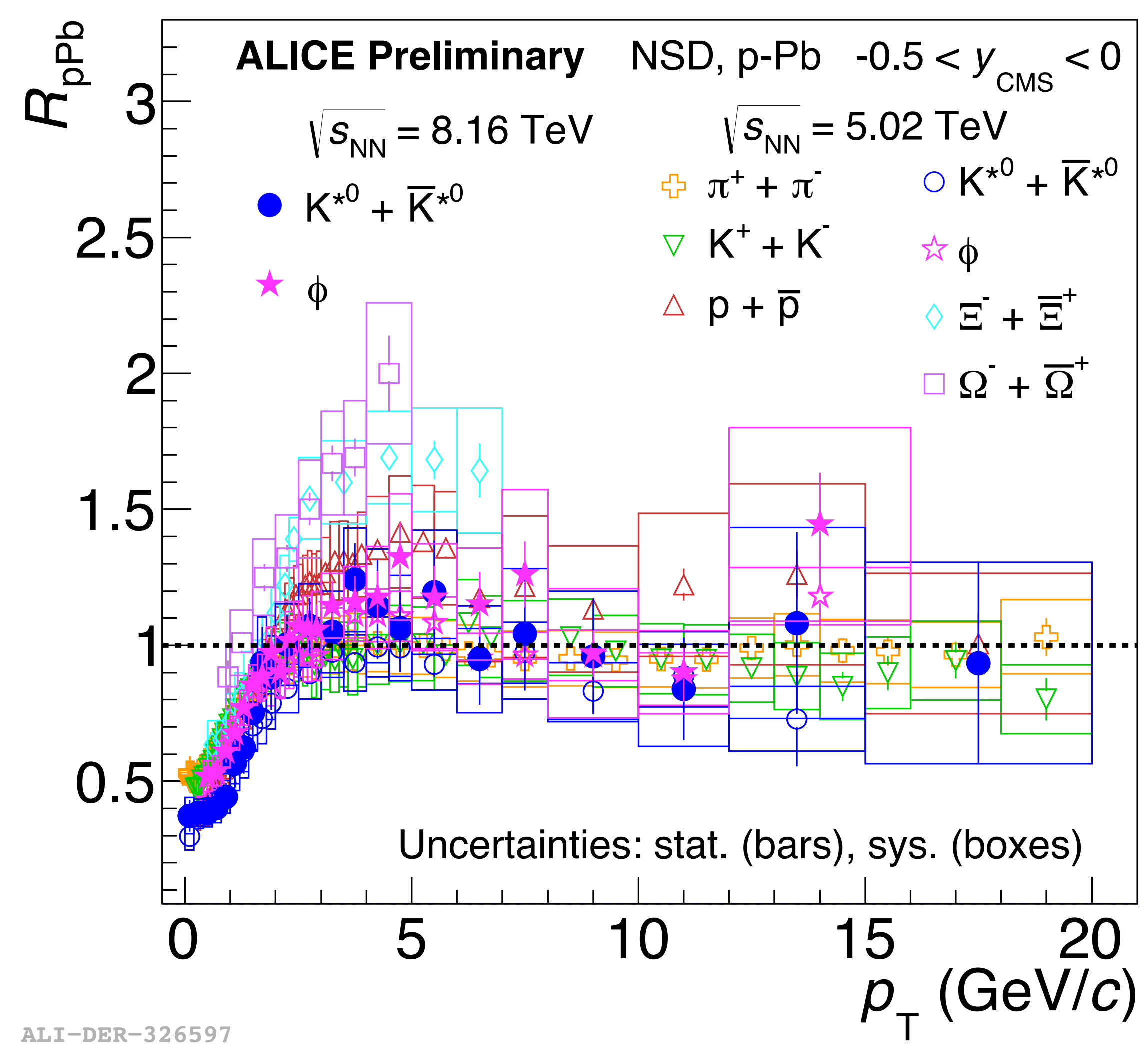
Phys. Rev. C 99, 064901 (2019)

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

Nuclear Modification Factor (R_{AA}, R_{pA})

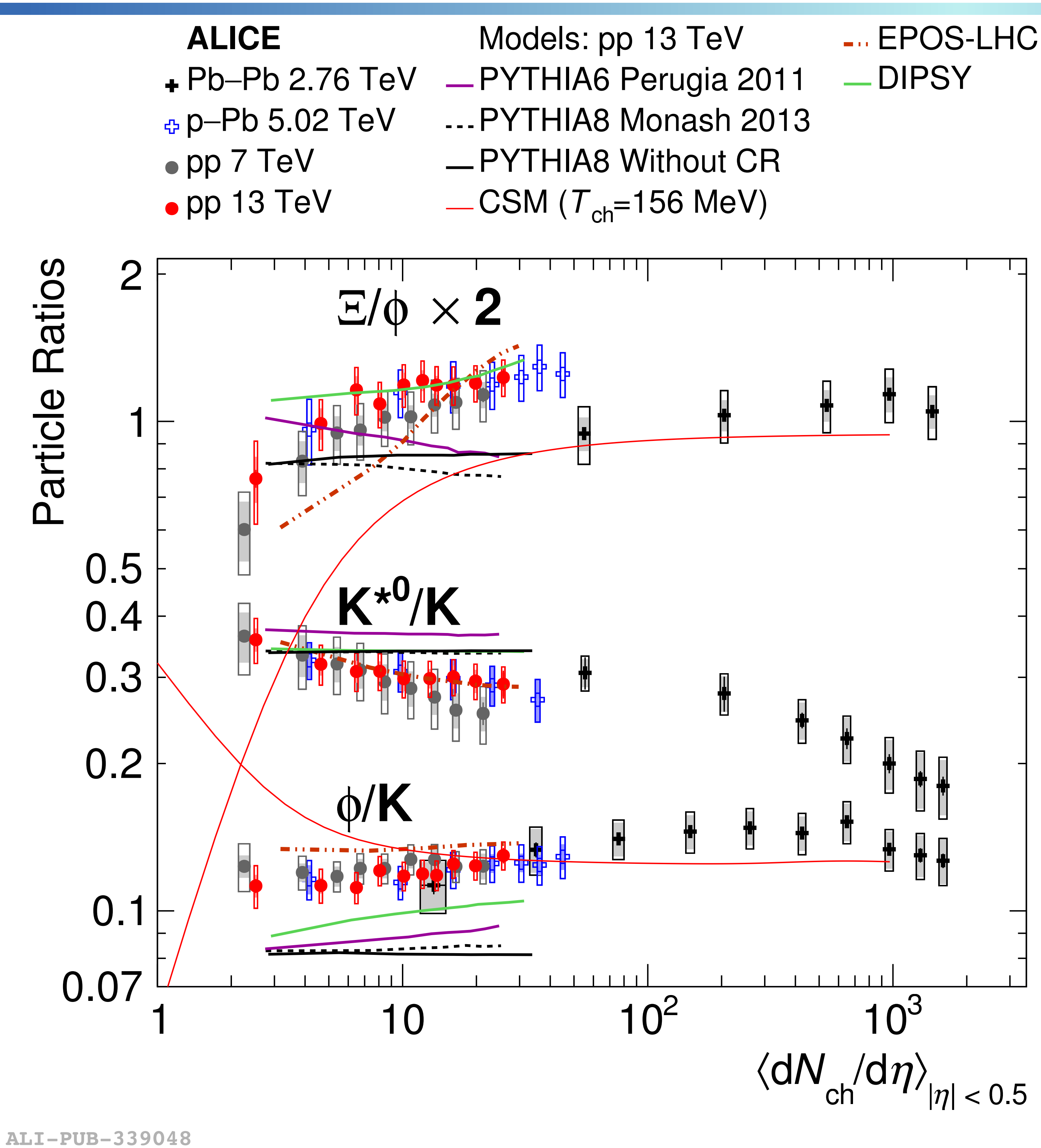




- **Intermediate-p_T (2 < p_T < 8 GeV/c)**
  - **mass dependent** for strange baryons

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

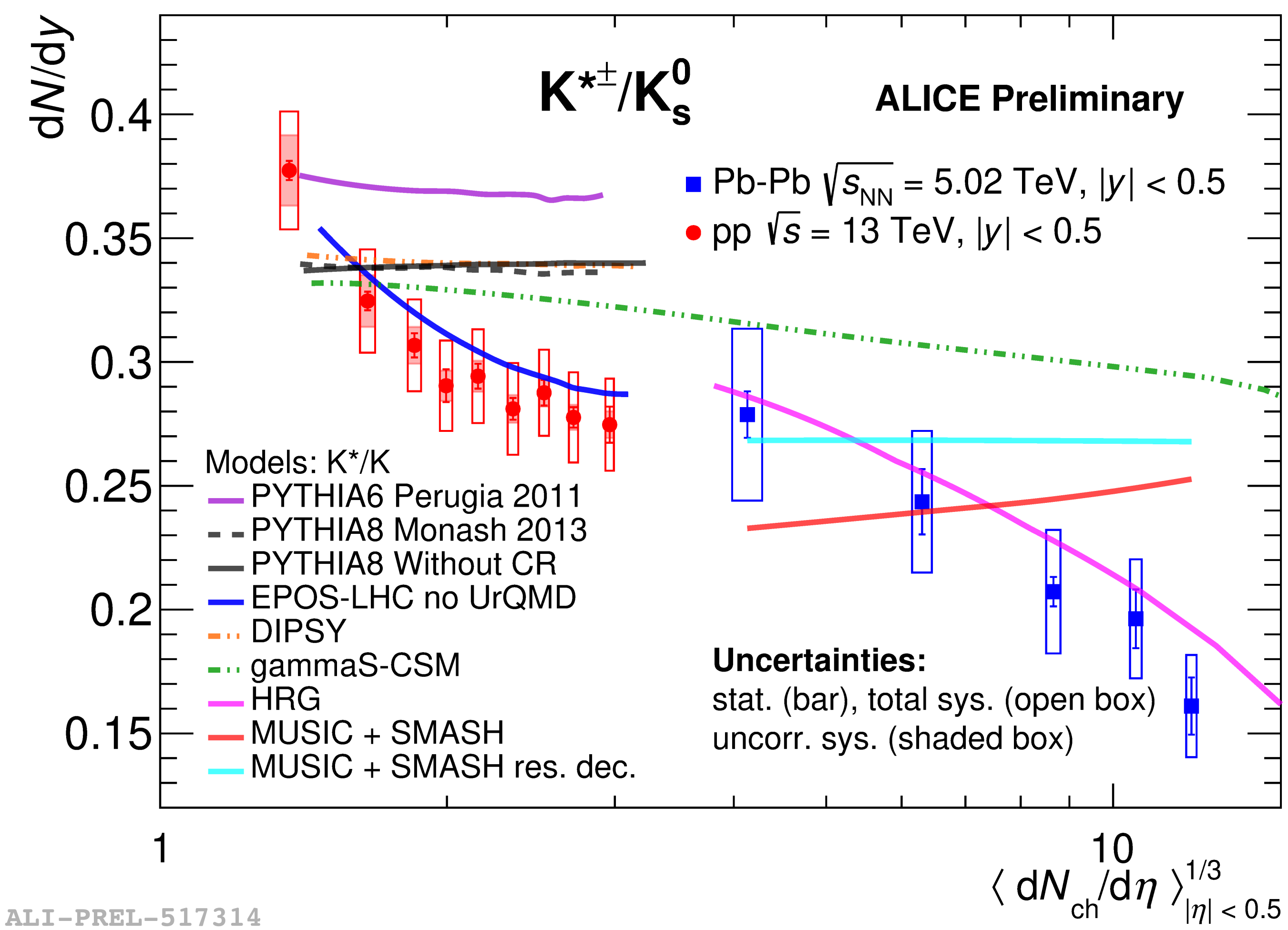
Strangeness enhancement: ϕ



- 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

Resonance to long-lived particle ratios

Antonina Rosano, Prottay Das (QM2022)



Neelima Agrawal, Sonali Padhan (QM2022)