Resonance Production in Heavy-Ion collisions

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Exotics and Exotic Phenomena in Heavy Ion Collisions (ExHIC)

APCTP, Pohang Korea
30 Sep. 2022

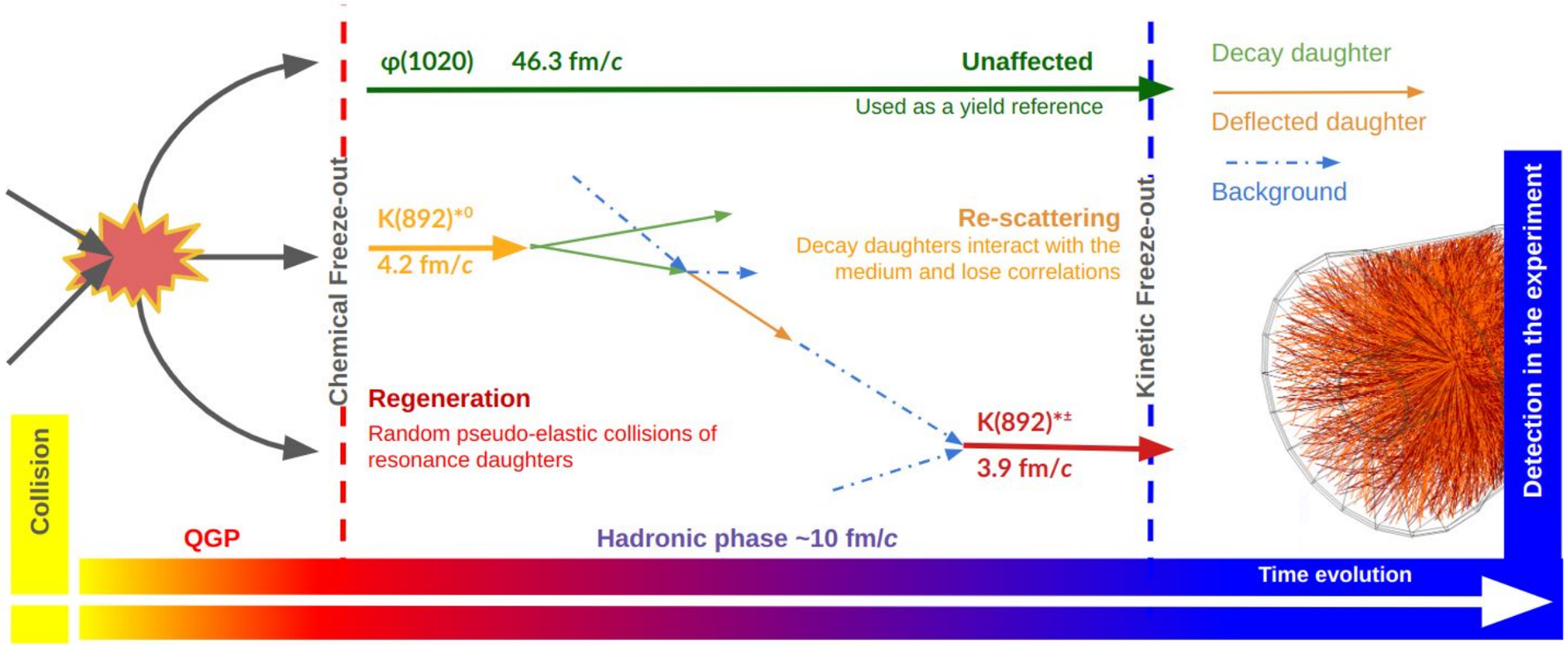
Outline

- Motivation
- Particle yield ratios
  - system size dependences
  - energy dependences
- Probing the hadronic phase
- Spin alignment
- Conclusion and outlook

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

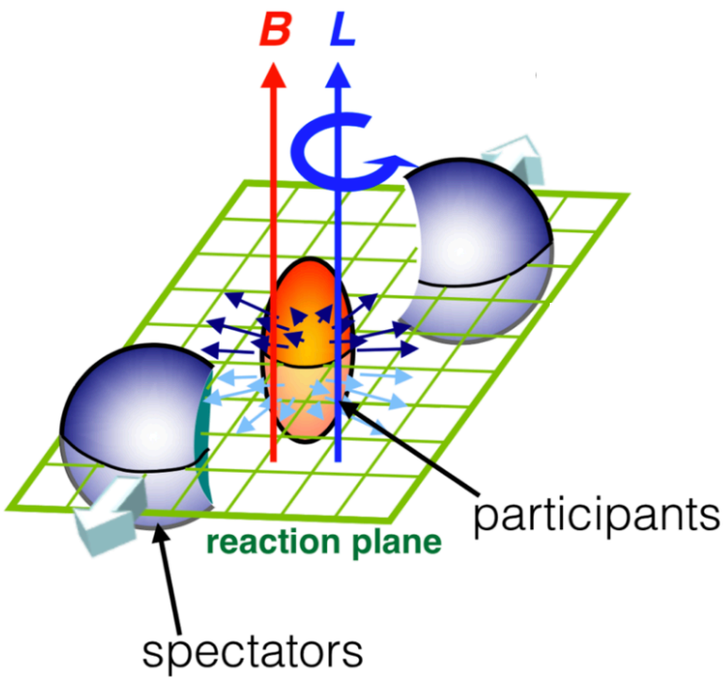
→ ***Reduced*** yield

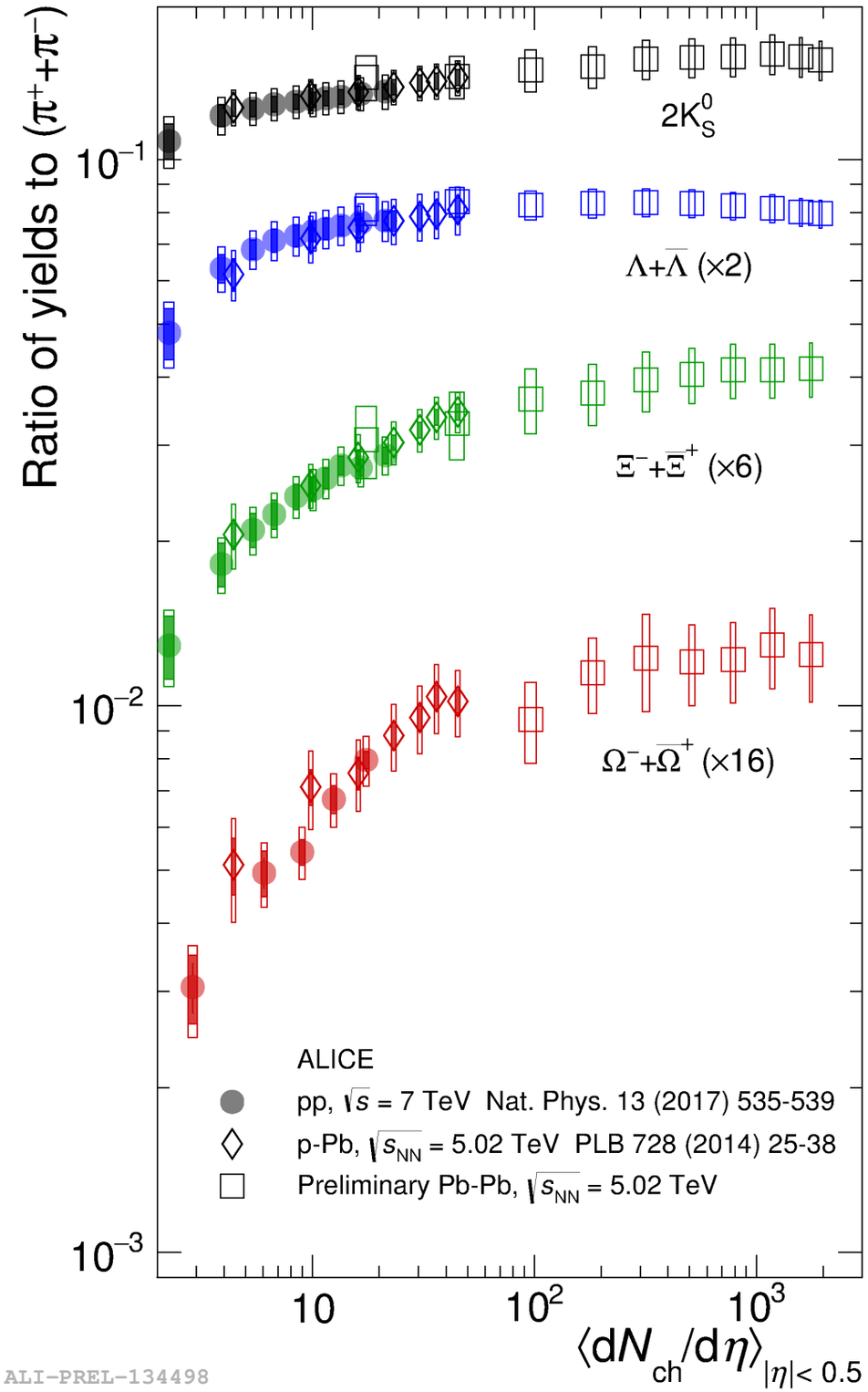
Motivation

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

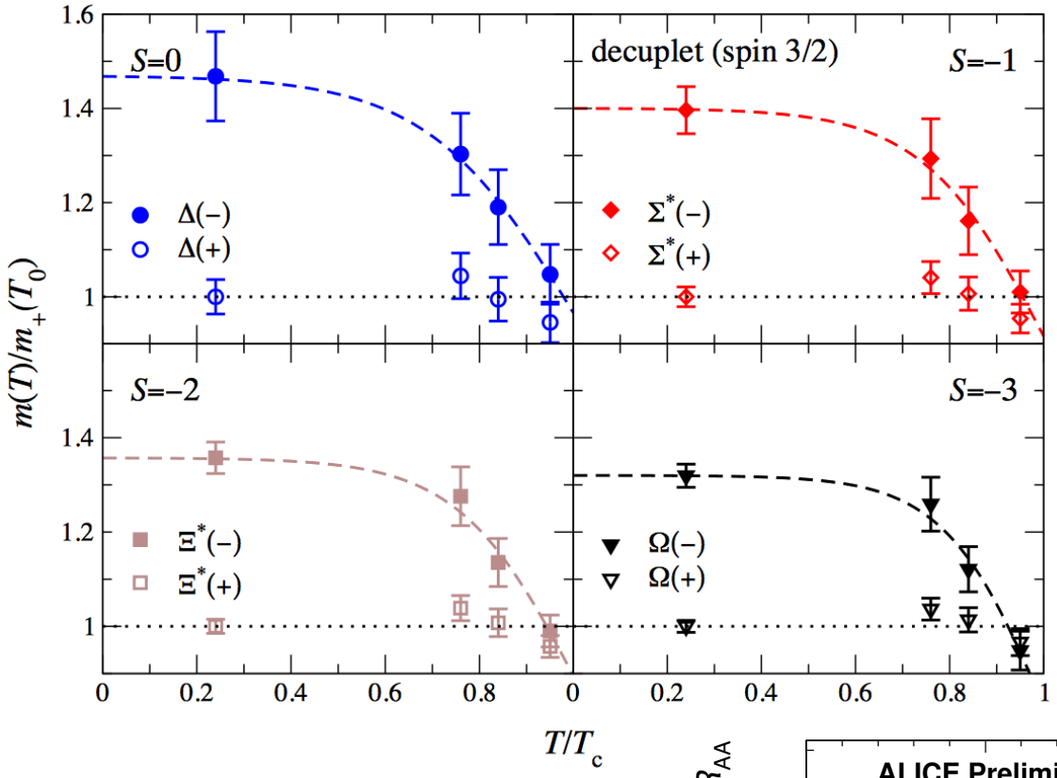




Motivation

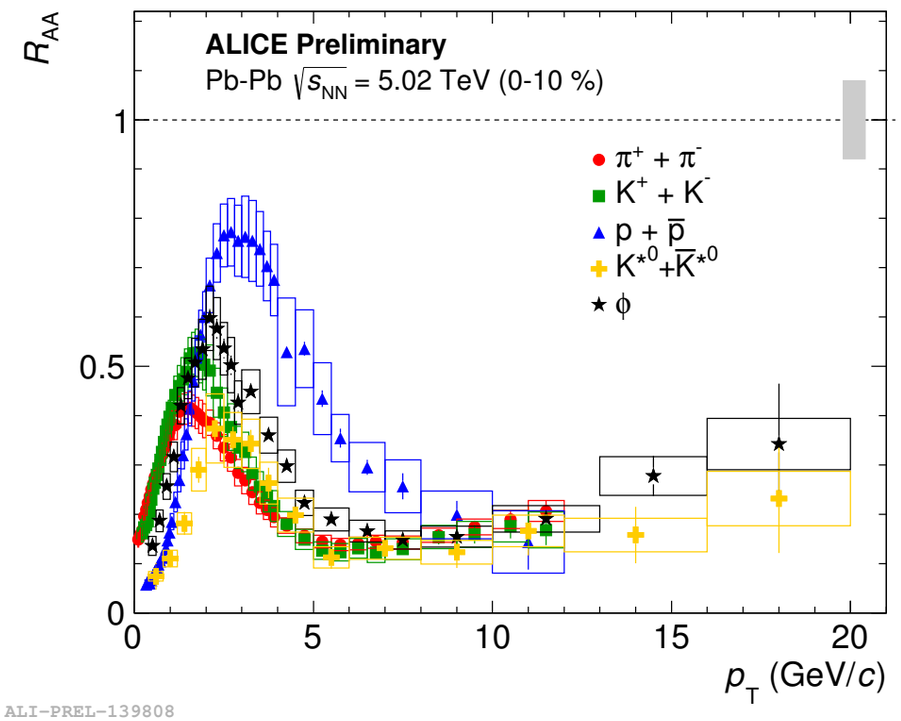
4. Chiral symmetry restoration

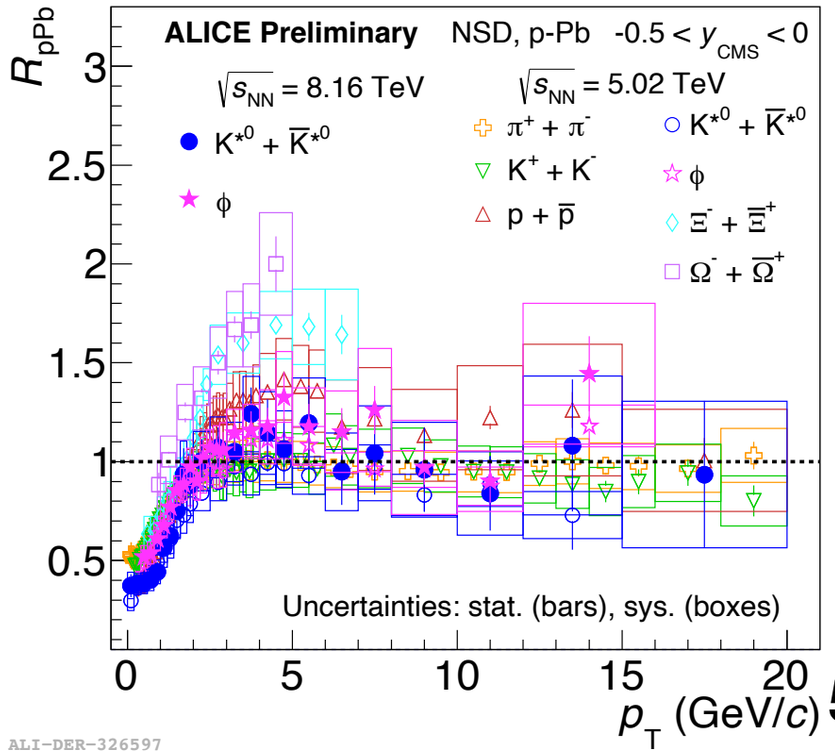
PRD 99 (2019) 074503



- 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)

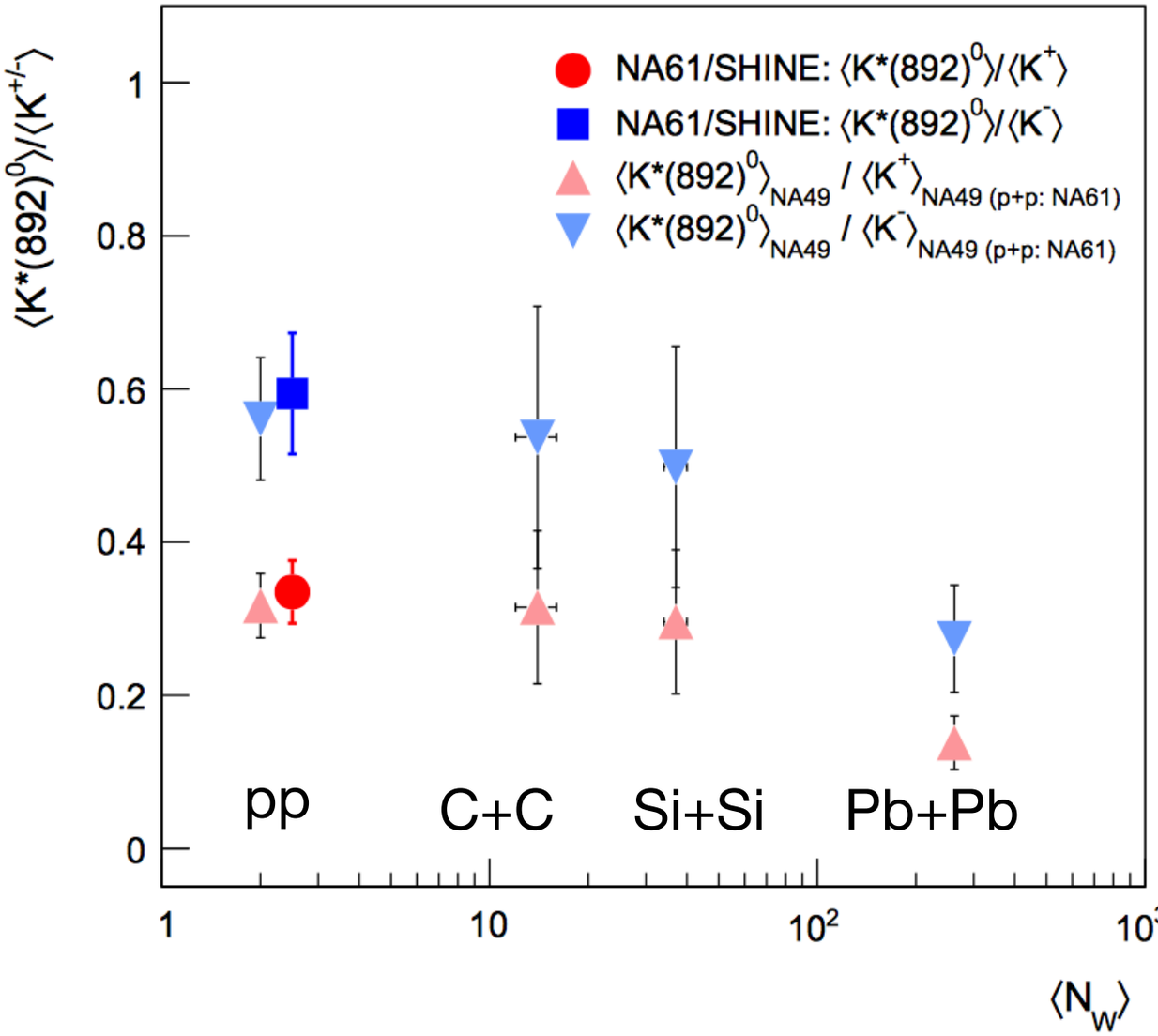
Meson	quark content	Decay modes	B.R.
ρ(770)⁰	$(u\bar{u}+d\bar{d})/\sqrt{2}$	$\pi^+\pi^-$	100
K*(892)⁰	$d\bar{s}$	$K^+\pi^-$	66.6
K*(892)±	$u\bar{s}$	$K^0_s\pi^+$	33.3
f_0(980), f_2(1270)	unknown	$\pi^+\pi^-$	46(84)
K*$_{0,2}$(1430)⁰	$d\bar{s}$	$K^+\pi^-$	93(49.4)
ϕ(1020)	$s\bar{s}$	K^+K^-	48.9

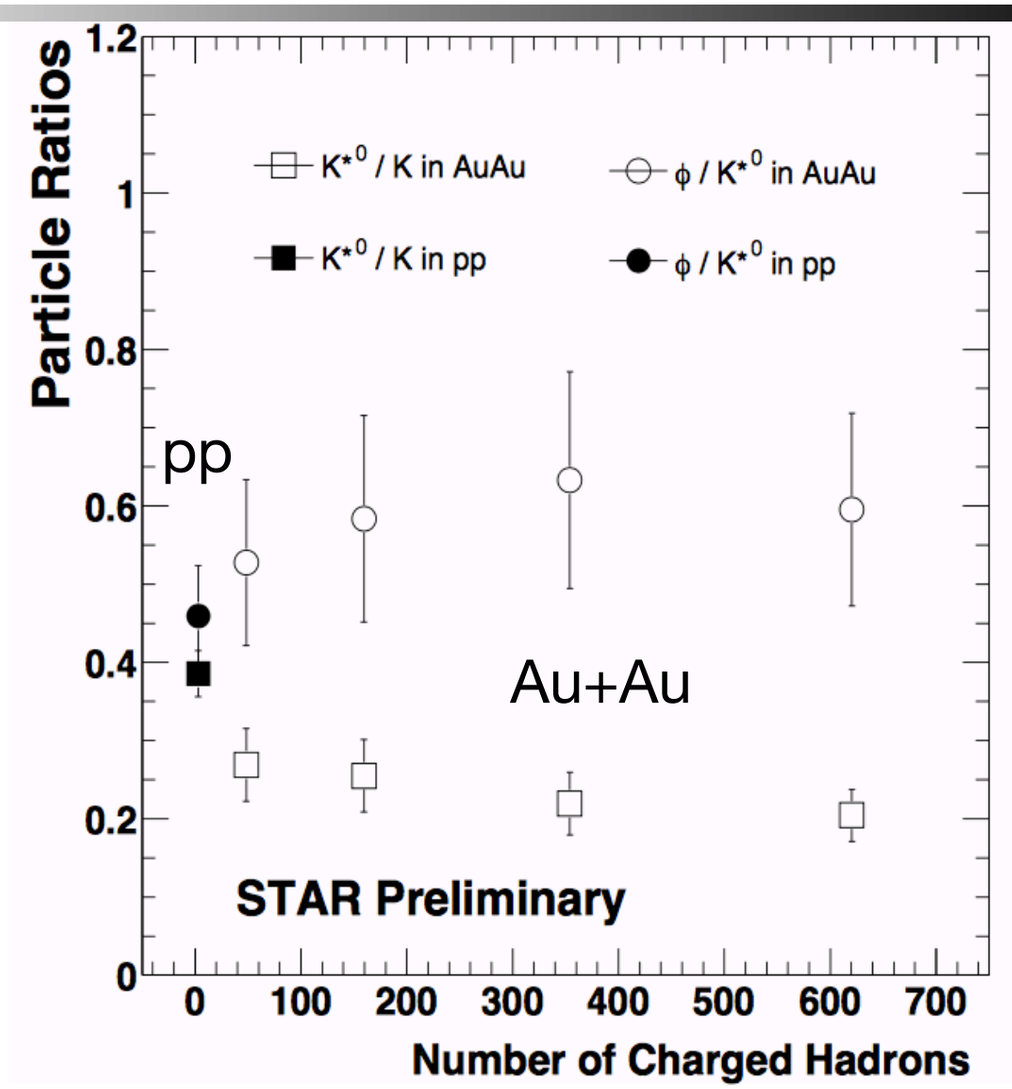
Baryon	quark content	Decay modes	B.R.
Σ(1385)⁺	uus	$\Lambda\pi^+$	87
Σ(1385)⁻	dds	$\Lambda\pi^-$	87
Λ(1520)	uds	pK^-	22.5
Ξ(1530)⁰	uss	$\Xi^-\pi^+$	66.7
Ξ(1820)∓,0	dss (uss)	$\Lambda K^\mp$ (ΛK^0_s)	unknown
Ω(2012)∓	sss	$\Xi^\mp K^0_s$	unknown

Lifetime(fm/c)

ρ(1.3) < K*±(3.6) < K*⁰(4.2) < Σ*±(5.0-5.5) < Λ*(12.6) < Ξ*(21.7) < ϕ(46.2)

Resonance suppression



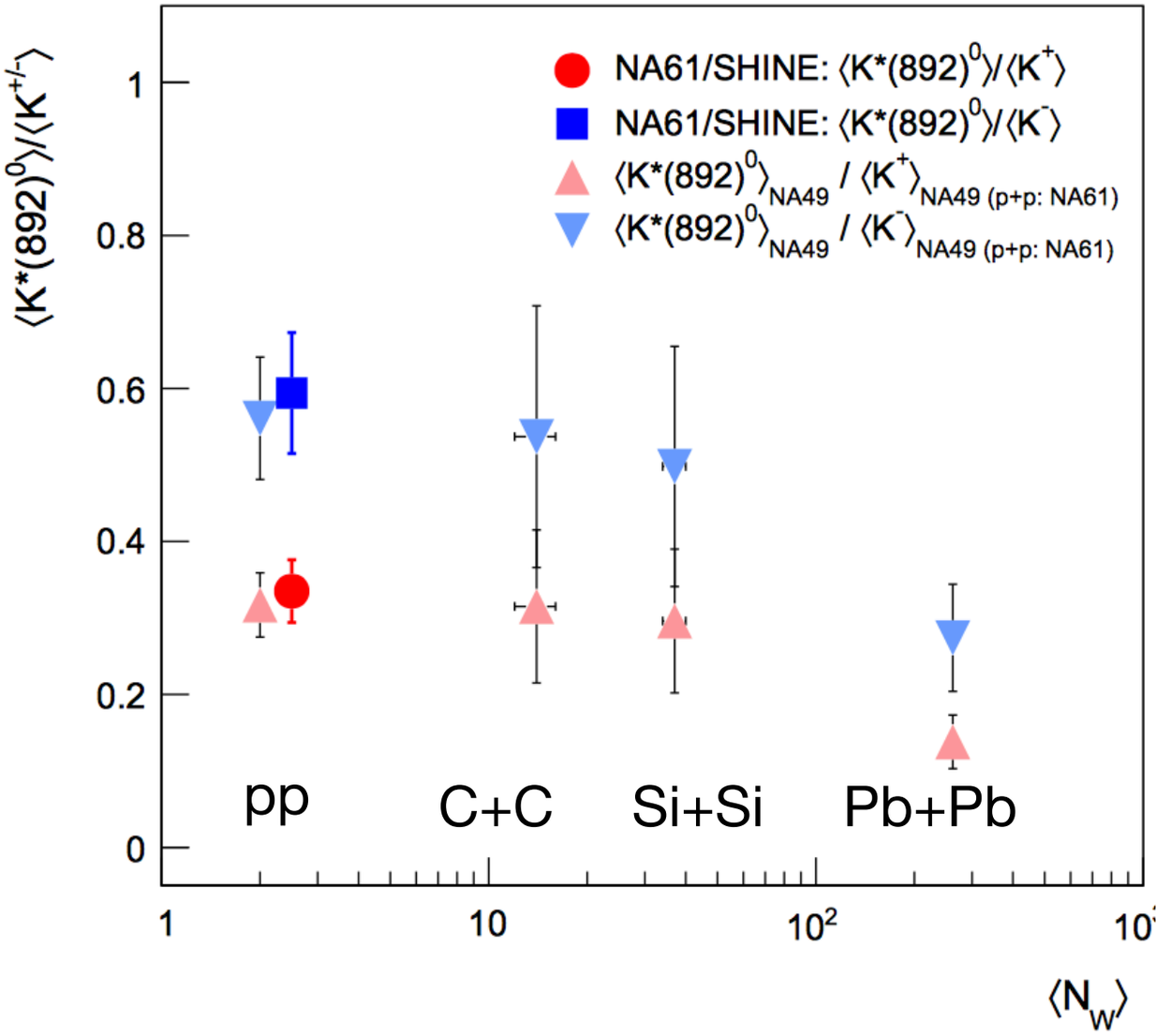


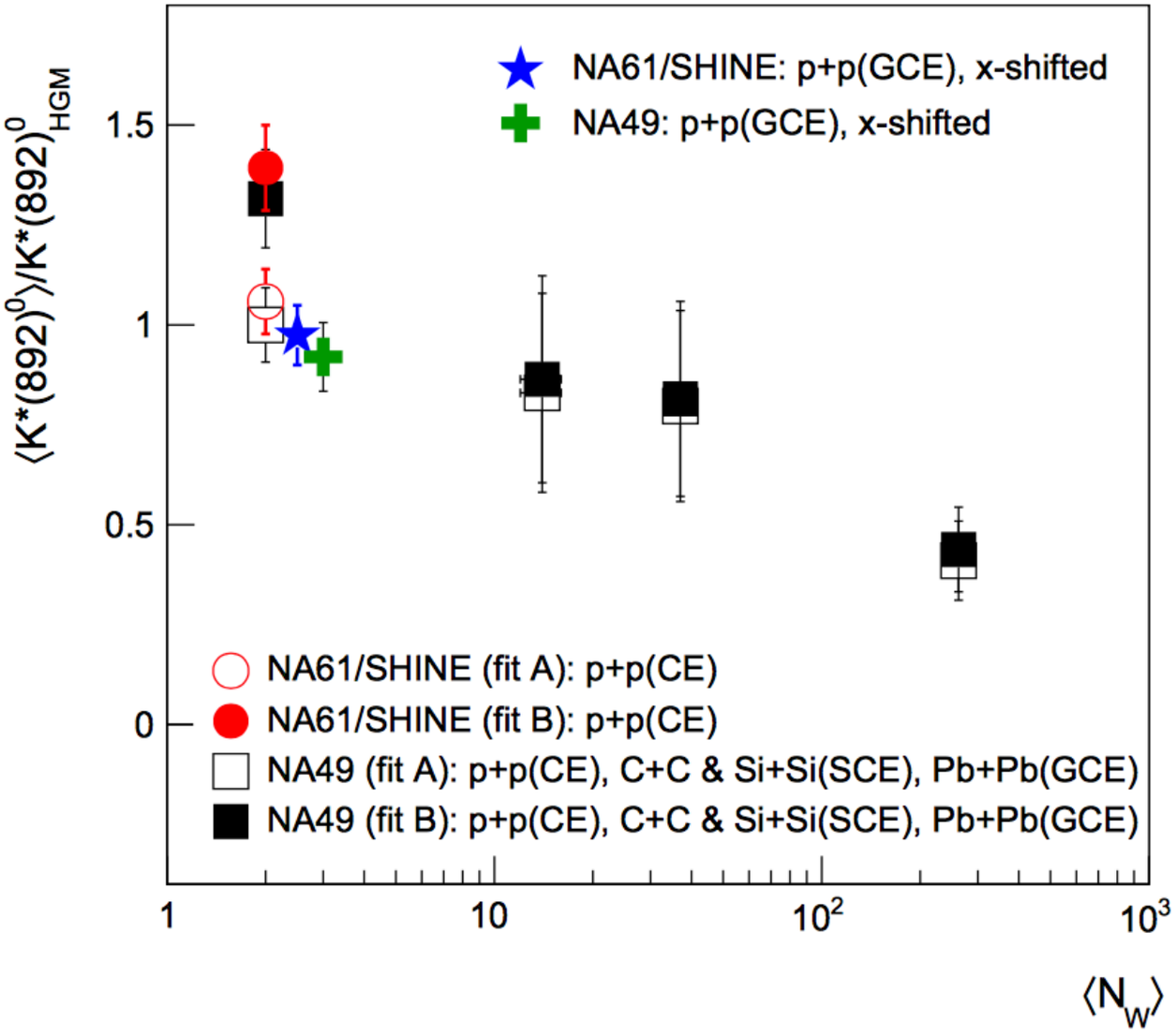
- **Suppression** of K*0 is observed in different collision systems from various experiments (NA49, NA61/SHINE, STAR)
  - more suppression for larger collision systems

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

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

Resonance suppression

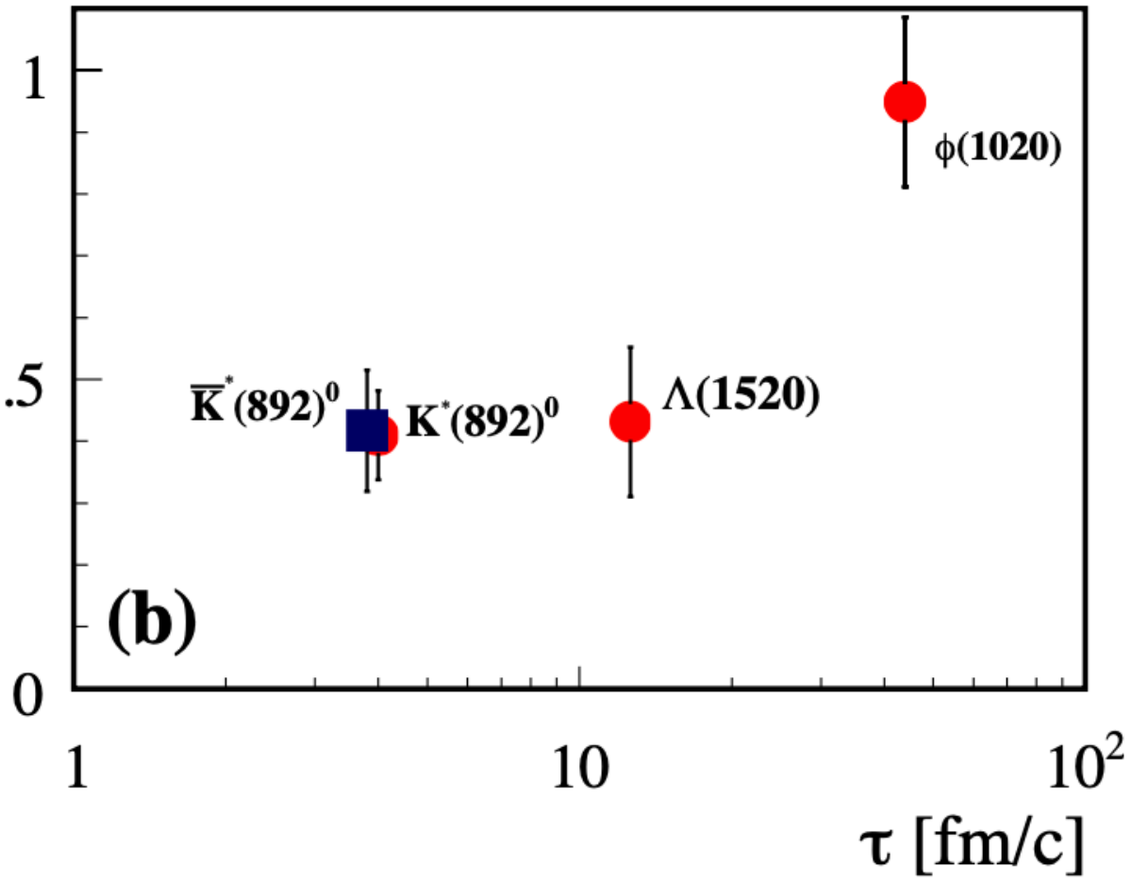


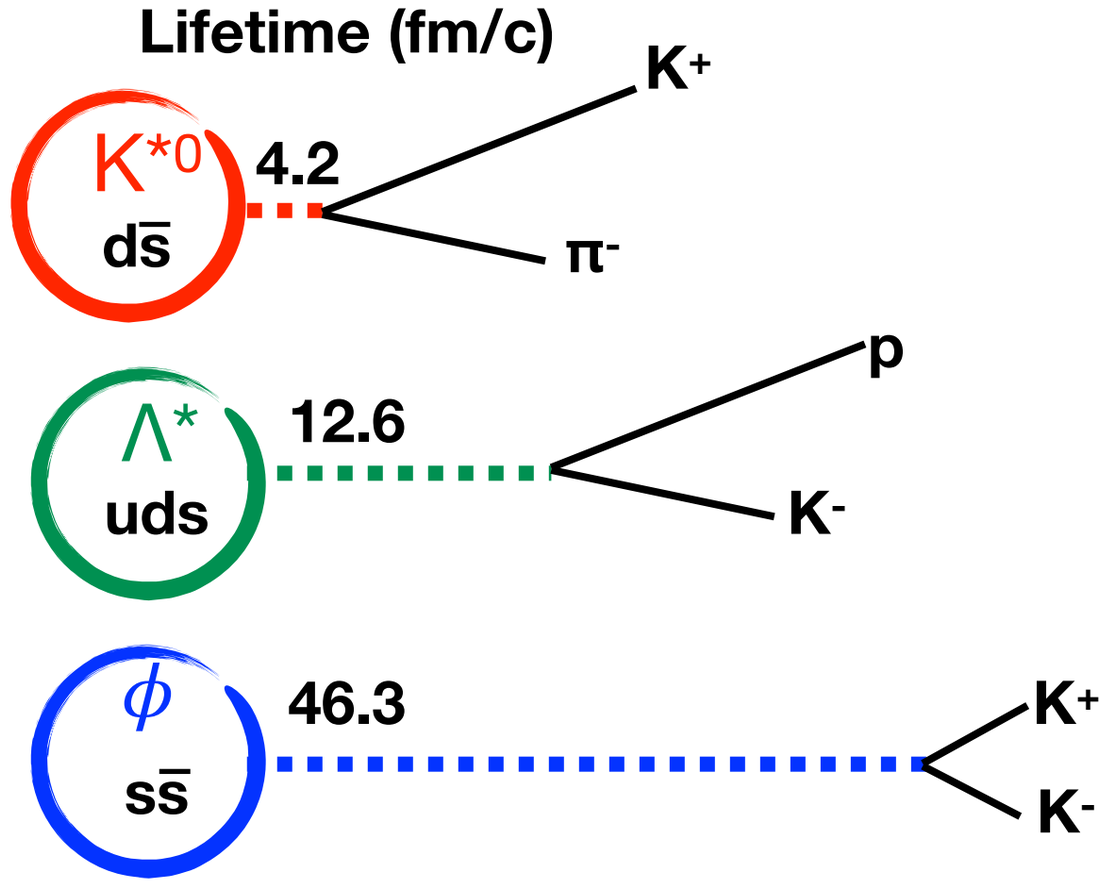


- **Suppression** of K*0 is observed in different collision systems from various experiments (NA49, NA61/SHINE, STAR)
  - more suppression for larger collision systems
- **Suppression** of K*0 w.r.t. the statistical **Hadron Resonance Gas Models**(HGM) is observed for heavier system

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

Resonance suppression





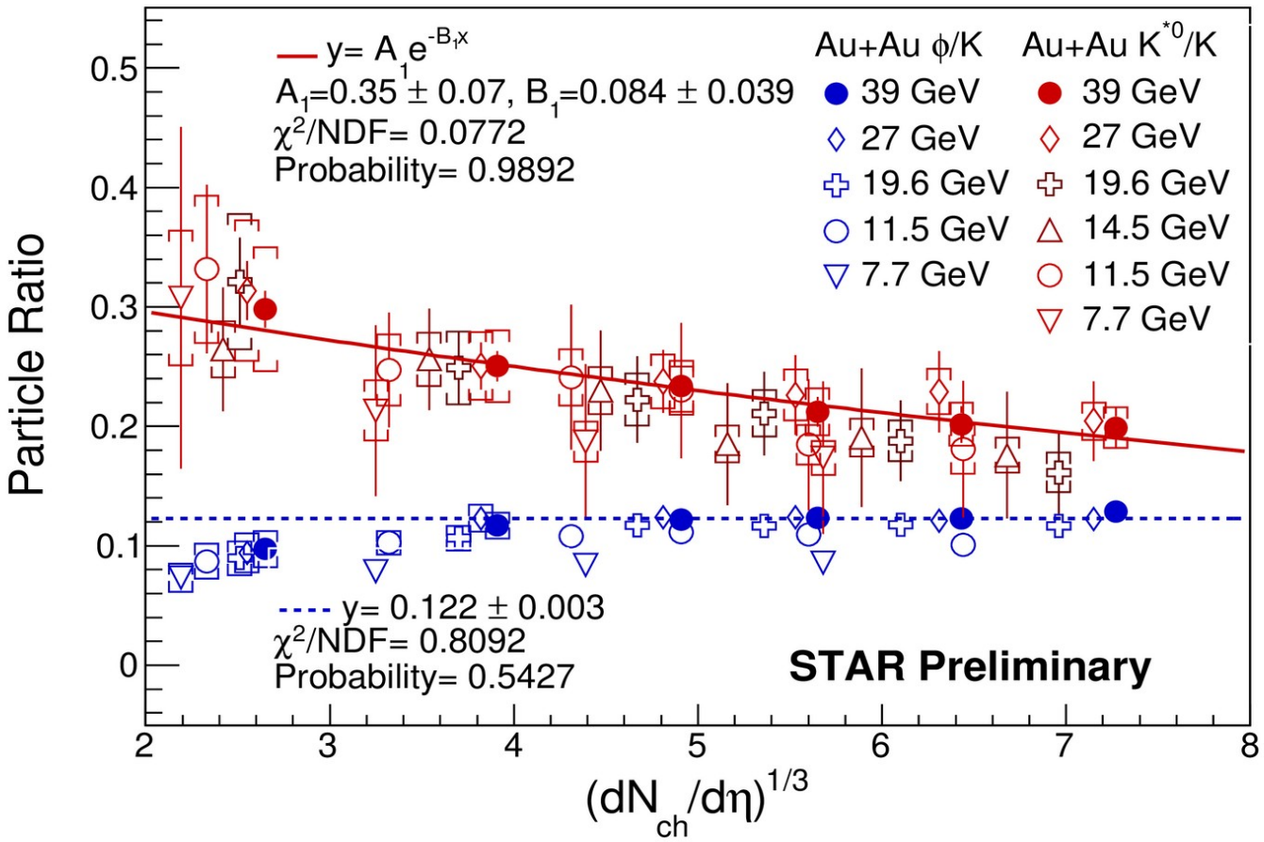
- **Suppression** of K^{*0} and $\Lambda^{*}(1520)$ w.r.t. the statistical Hadron Resonance Gas Models(HGM) while **no suppression** for ϕ w.r.t. the HGM

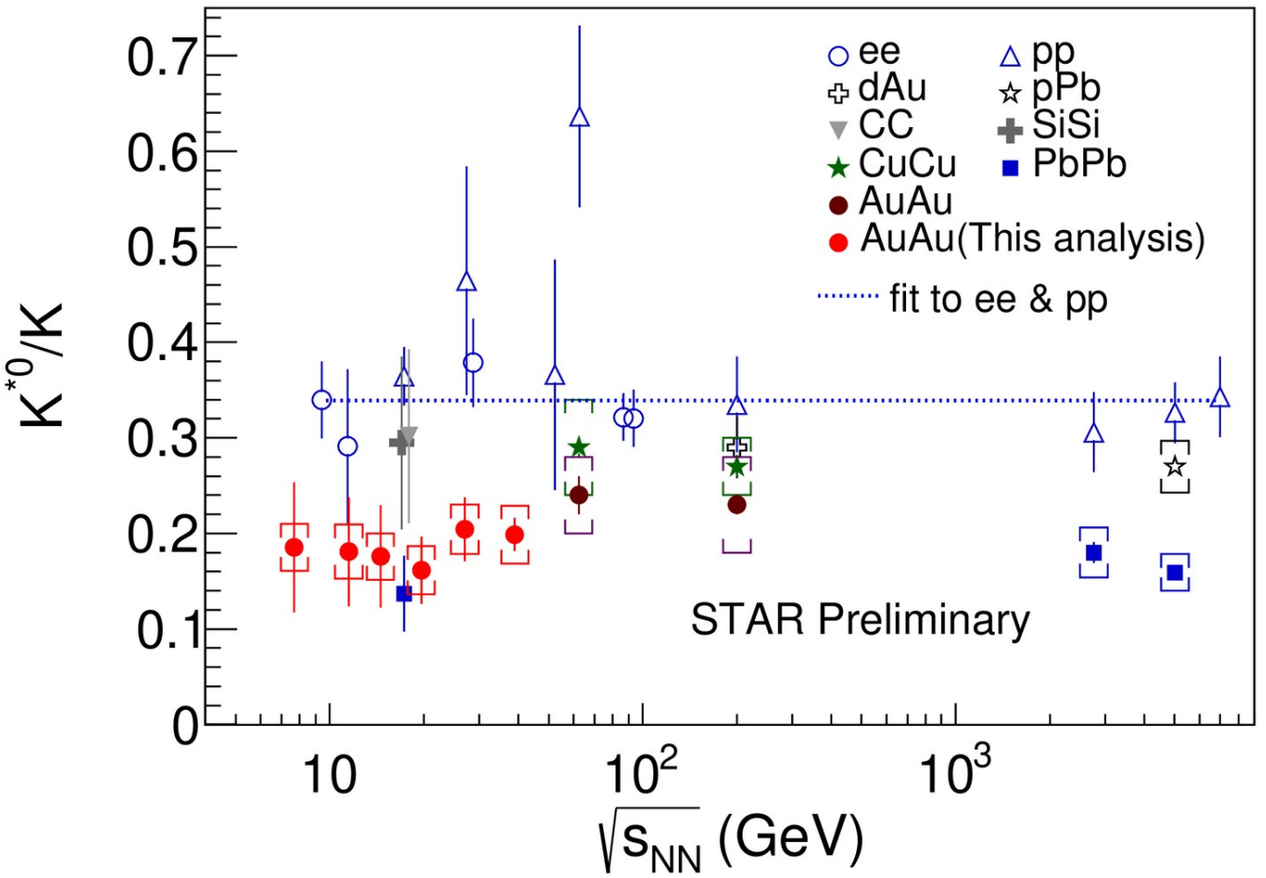
- Suppression effect might be related to the lifetime of the resonances

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

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

A. K. Sahoo (QM2022)

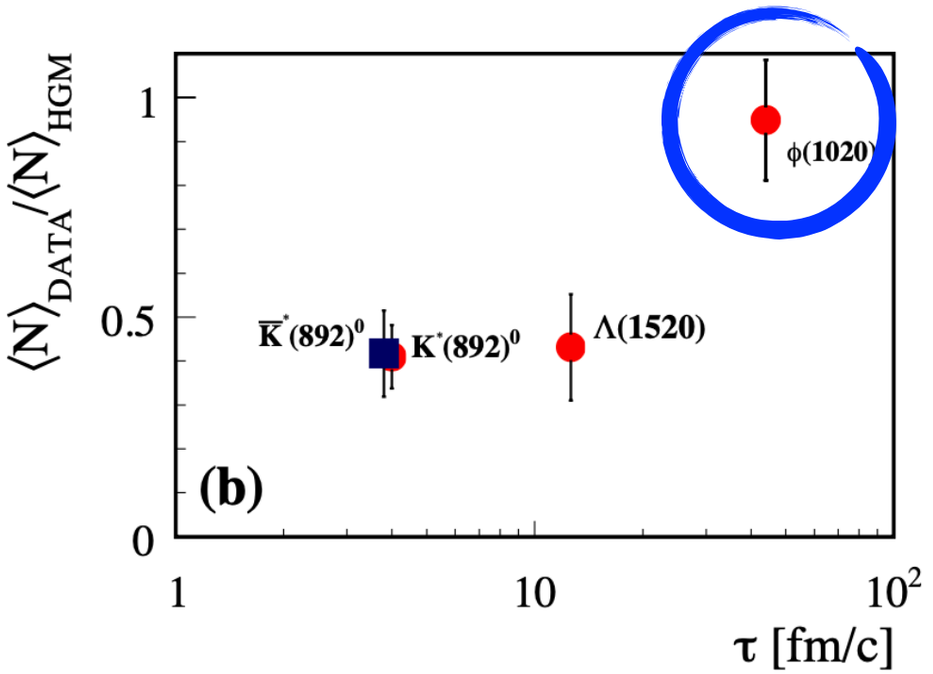


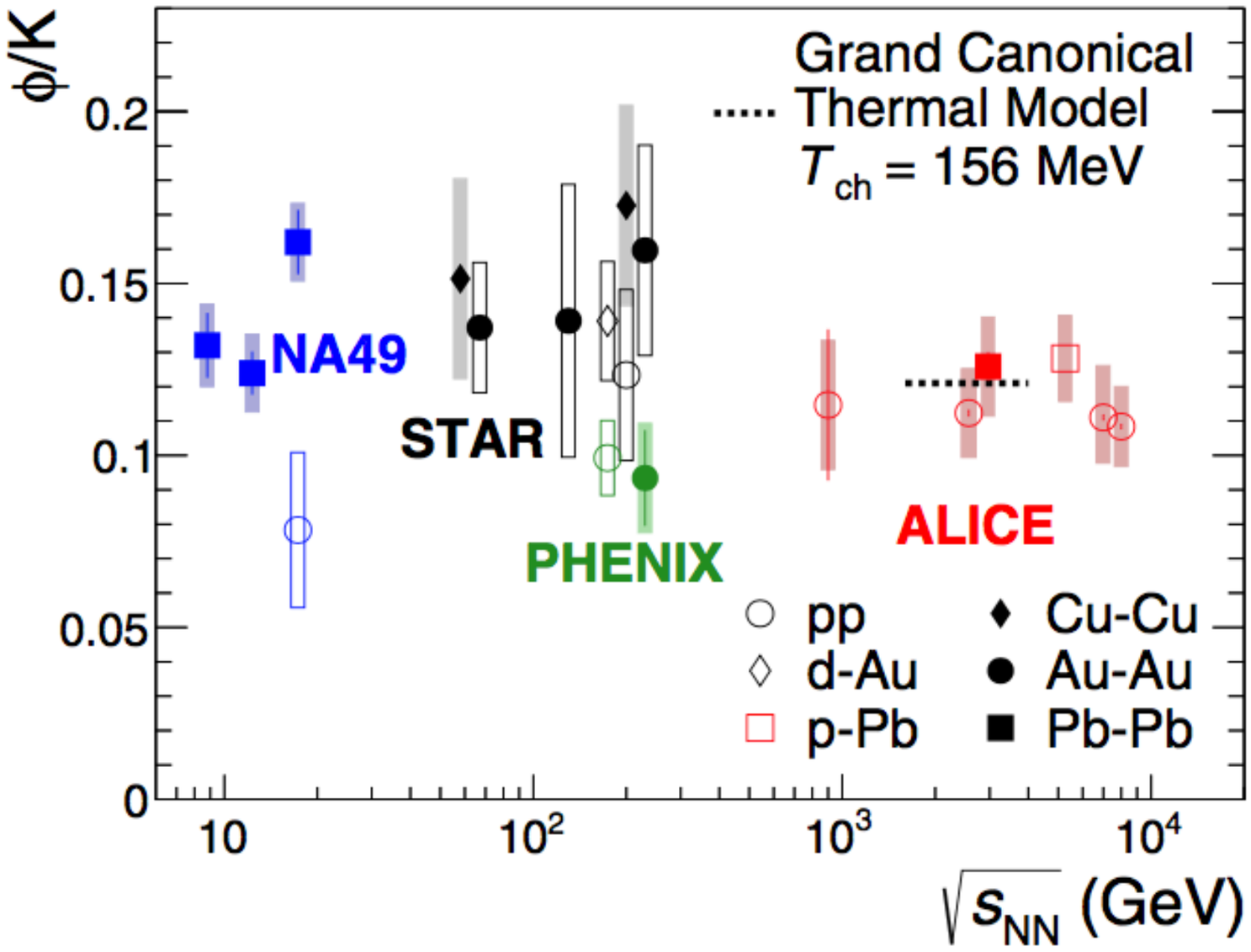


- K^{*0}/K and ϕ/K ratios have been measured at different energies
  - K^{*0}/K: decreasing with increasing multiplicity
  - ϕ/K: independent of multiplicity

- 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)



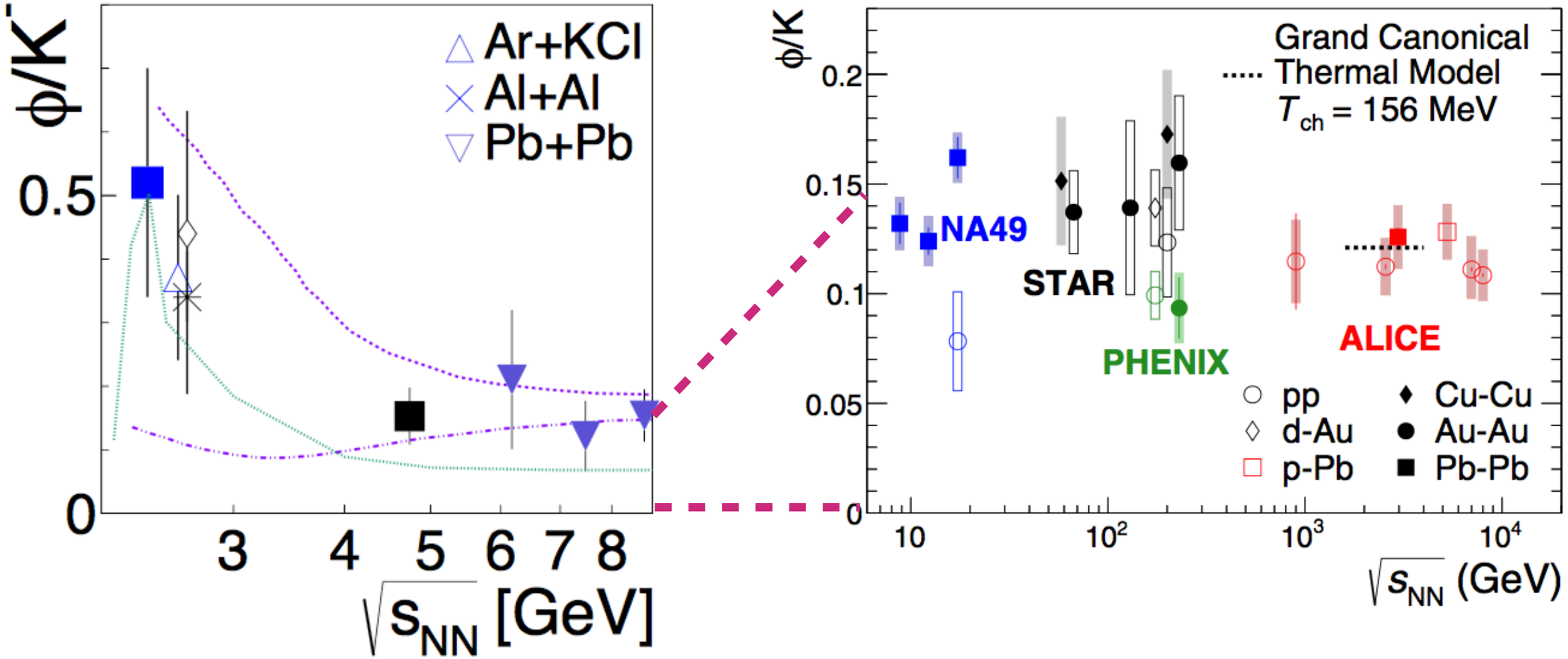


- Flat behavior in a wide range of energy (~10-10^4 GeV) and different collision systems

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)

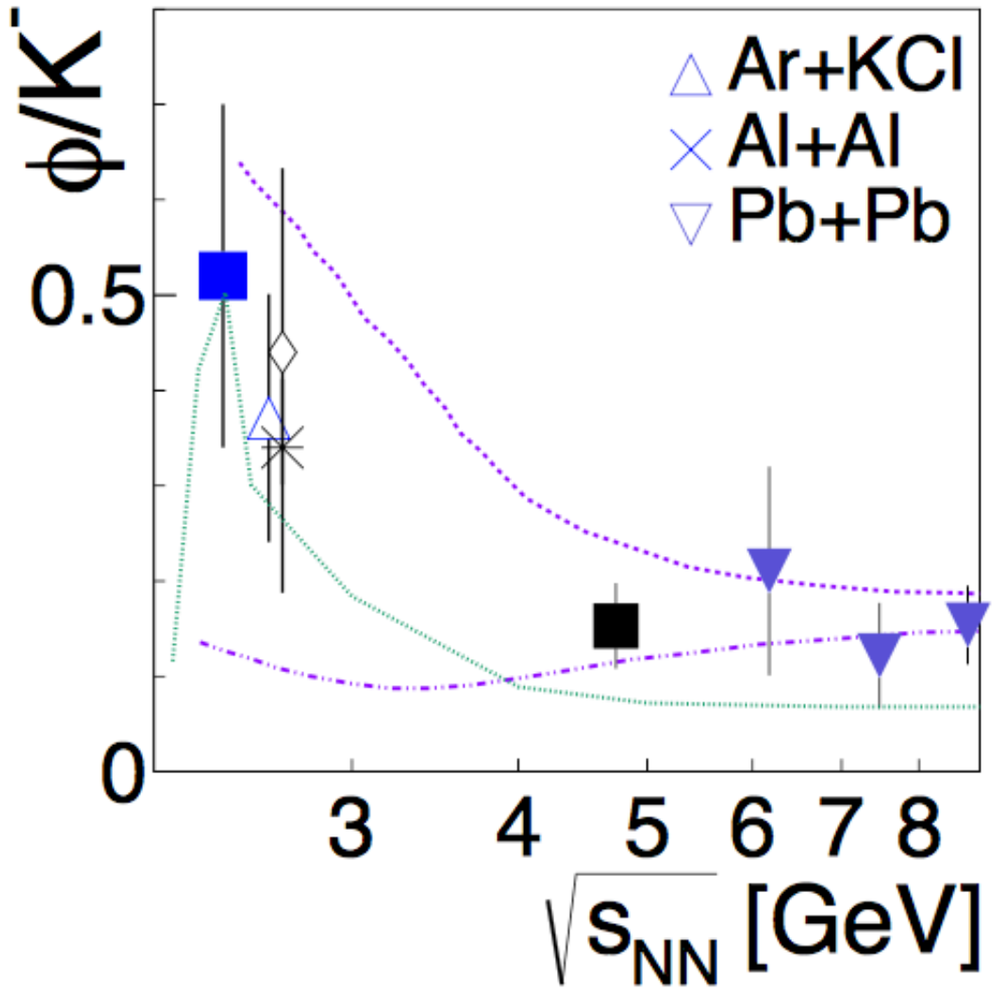


- Increase for low energies due to canonical suppression
  - reproduced by statistical model calculation with strangeness correlation radius parameter R_c = 2.2fm (purple dashed curve)

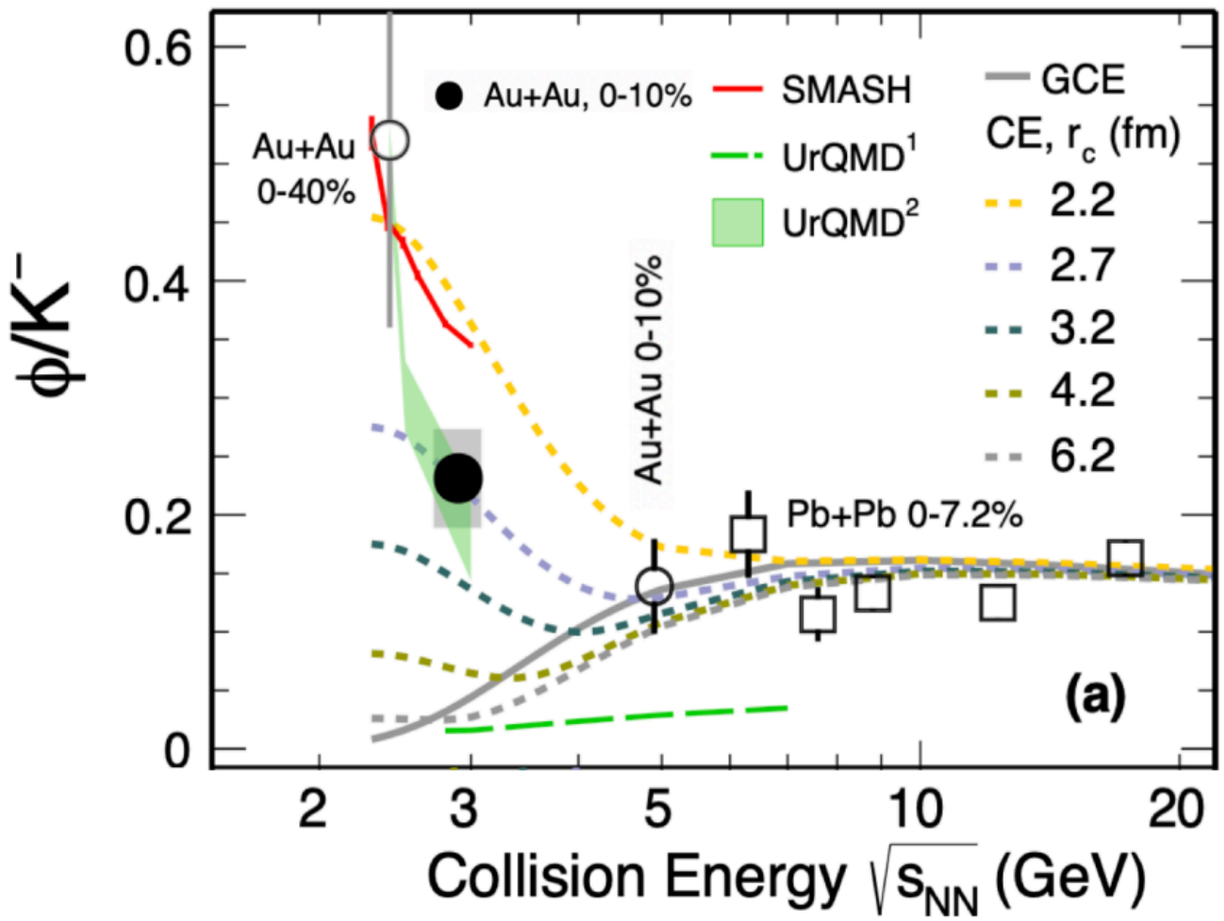
https://arxiv.org/pdf/1703.08418v1.pdf
PHYSICAL REVIEW C 102, 024912 (2020)

Resonance suppression: energy dependence (ϕ/K)

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

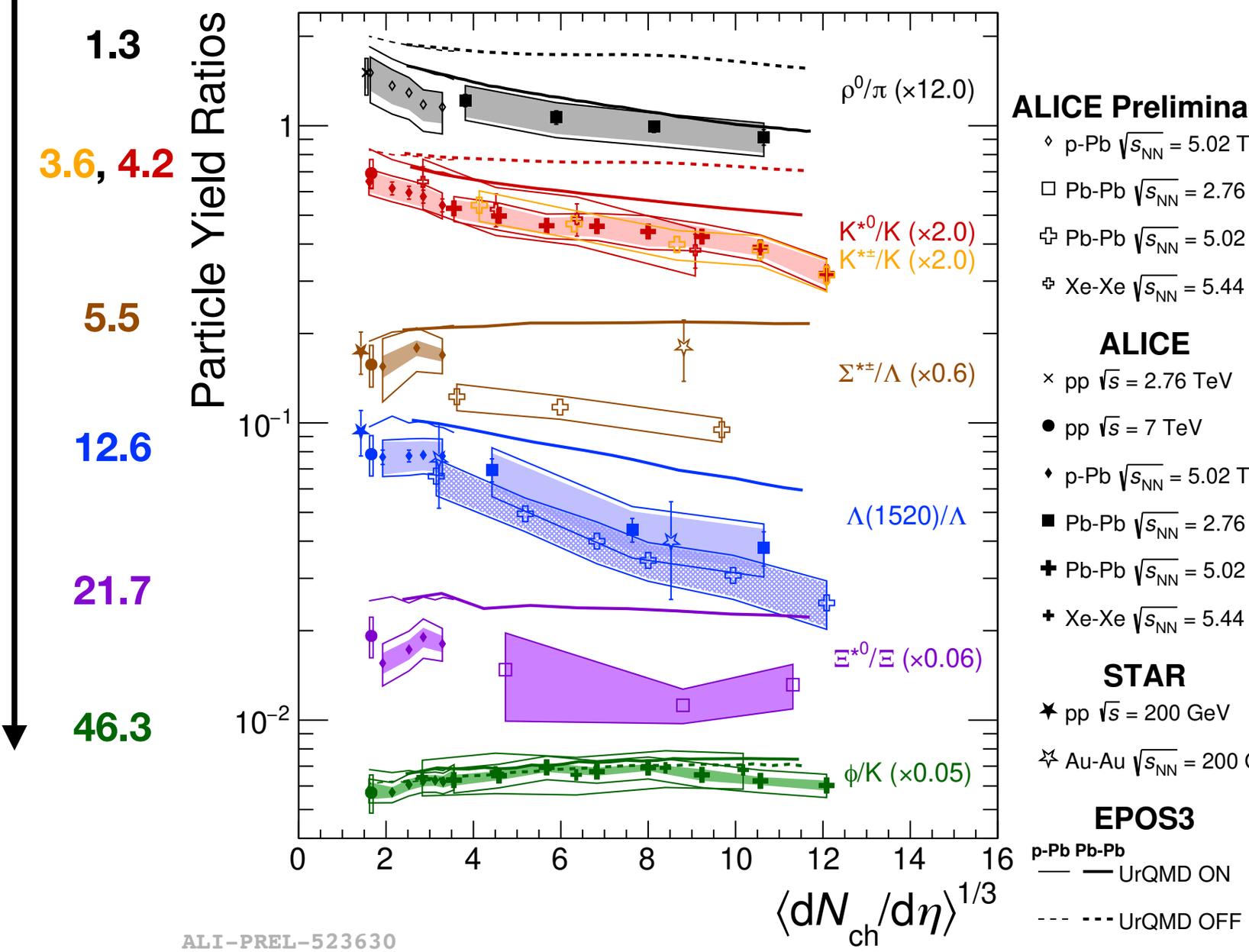


STAR *Phy.Lett.B* 831 (2022) 137152



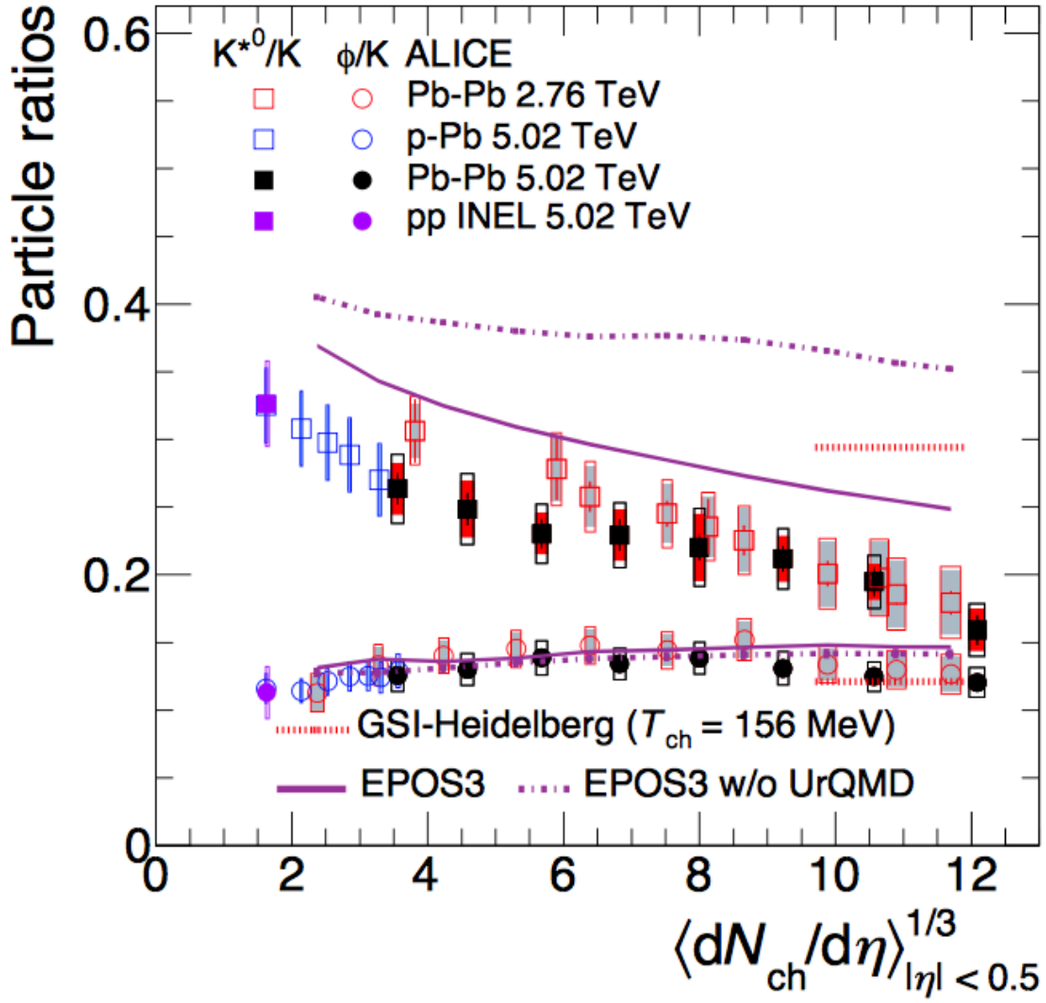
- GCE underestimates data at low energy
- Thermal model with CE gives a good description of data at $\sqrt{s_{NN}}$=3 GeV
- UrQMD[2] calculations reproduce ϕ/K at $\sqrt{s_{NN}}$=3 GeV

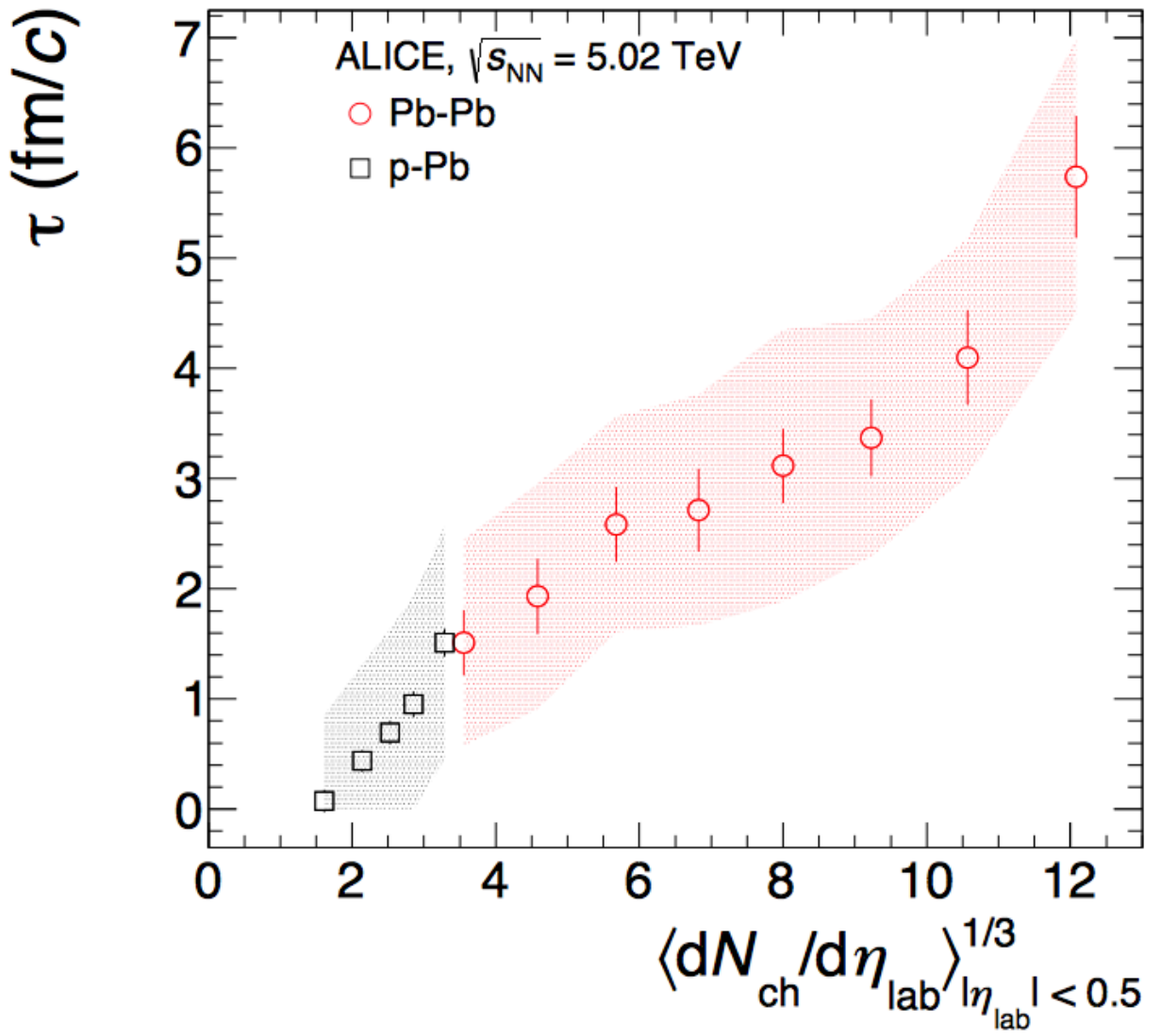
Resonance to long-lived particle ratios



- **suppression** of the ratios of **short-lived resonances** in central Pb-Pb collisions
  - indicates *dominance of re-scattering over regeneration*
- 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



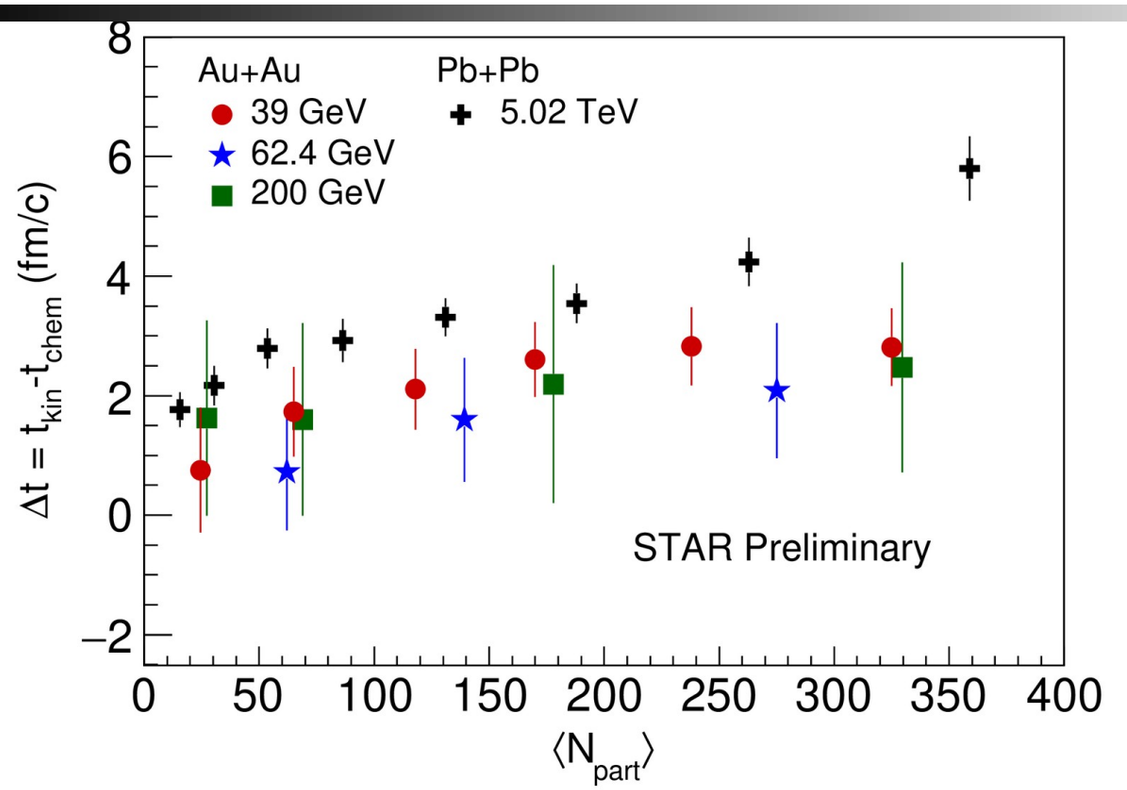


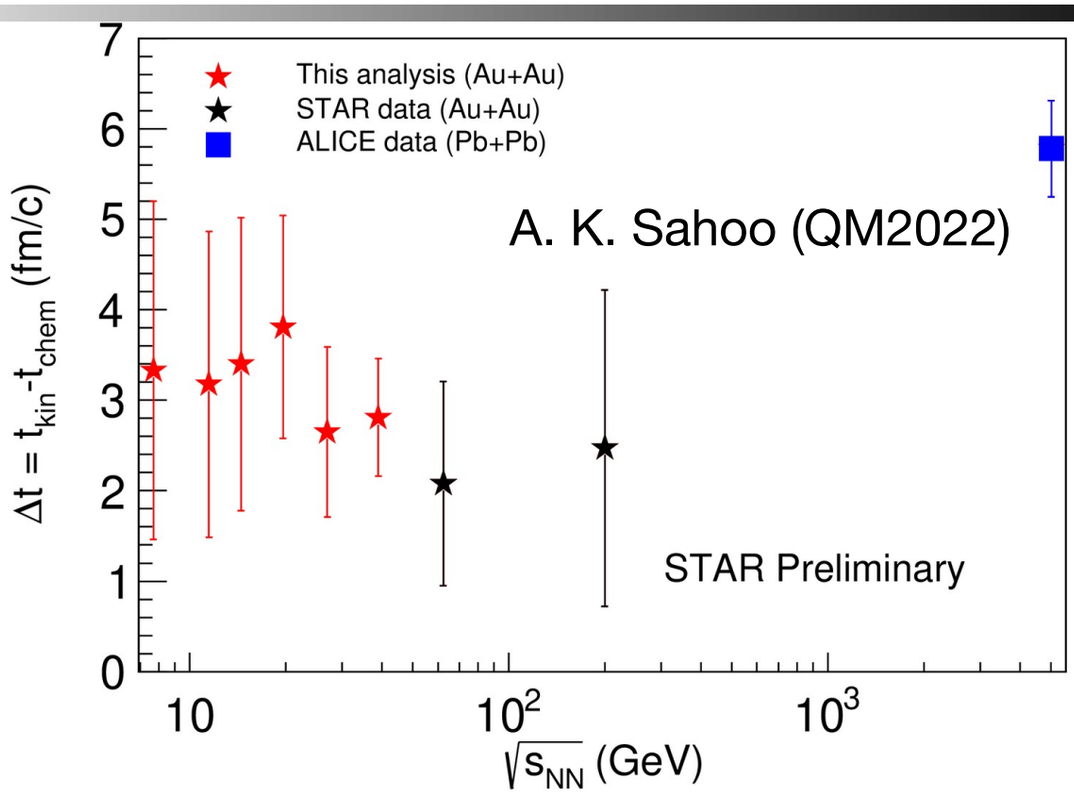
$$[K^{*0}/K]_{\text{kinetic(Pb-Pb)}} = [K^{*0}/K]_{\text{chemical(pp)}} \times e^{-\tau/\tau_{k^{*0}}}$$

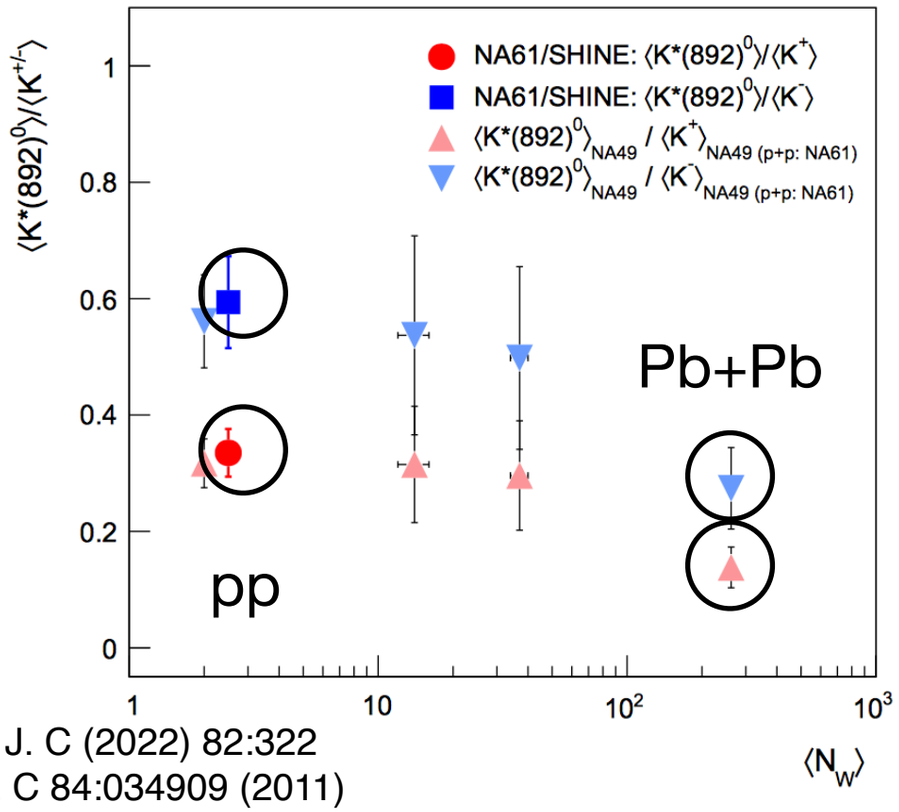
- Estimate the **time duration between chemical and kinetic freeze-out** from the measurement of K^{*0}/K ratios in Pb-Pb and pp collisions
  - lifetime of hadronic phase smoothly increases with multiplicity
  - found to be ~4-7 fm/*c* for central collisions

PLB 802 (2020) 135225

Probing the hadronic phase





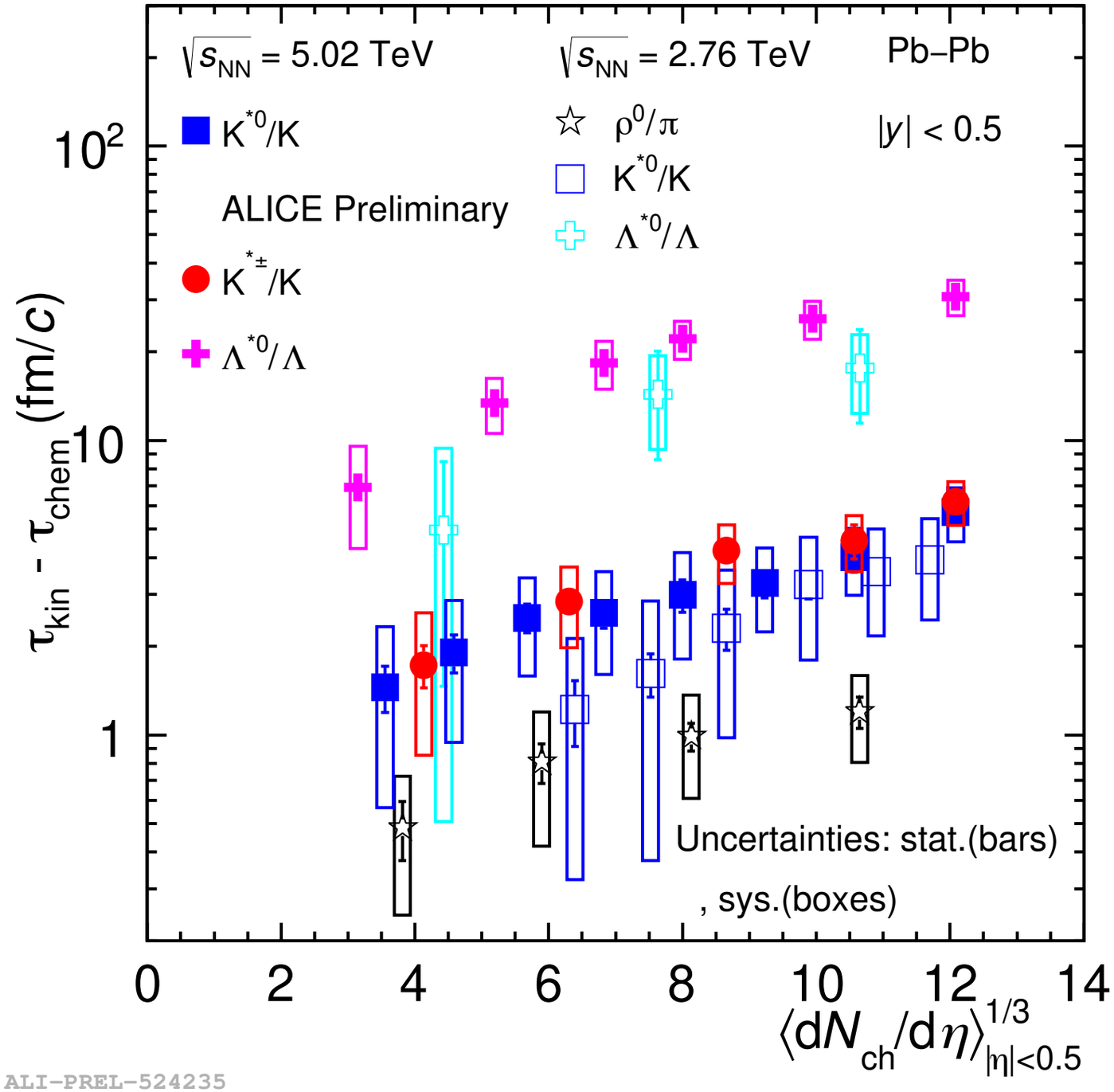


- There seems no energy dependence from 39 GeV to 200 GeV at RHIC
- Hadronic lifetime (Δt) at RHIC seems to be smaller than at LHC
- Δt measured from NA61/SHINE is comparable with RHIC
  - K^{*0}/K^{+}: 3.7±1.2 fm/*c*
  - K^{*0}/K^{-}: 3.2±1.2 fm/*c*

Eur. Phys. J. C (2022) 82:322
Phys. Rev. C 84:034909 (2011)

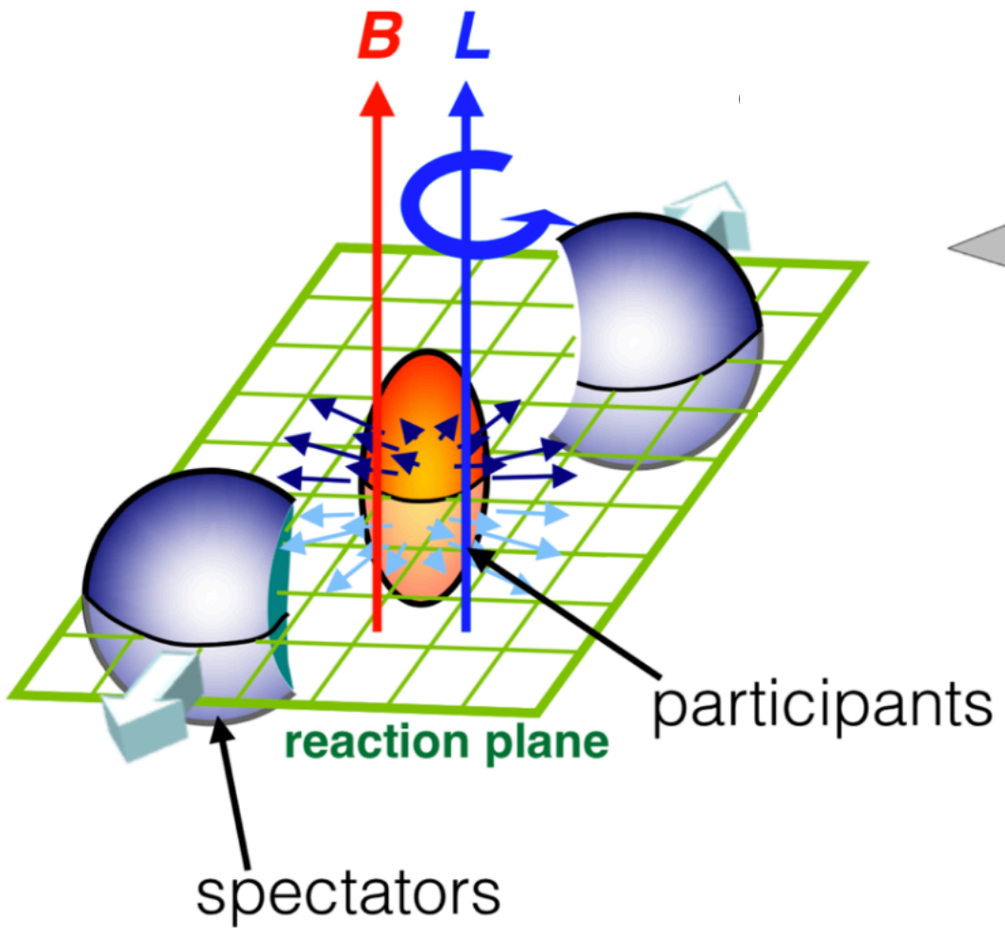
Probing the hadronic phase

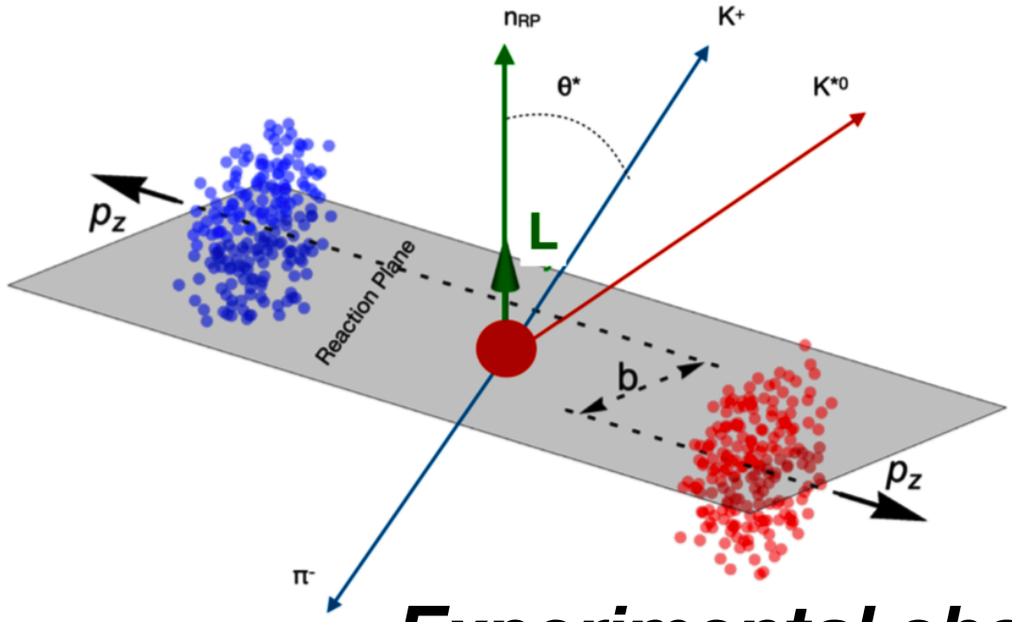
Dukhishyam Mallic (SQM2022: PA-Resonances and Hyper-nuclei)



- 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

Spin alignment





Experimental observable

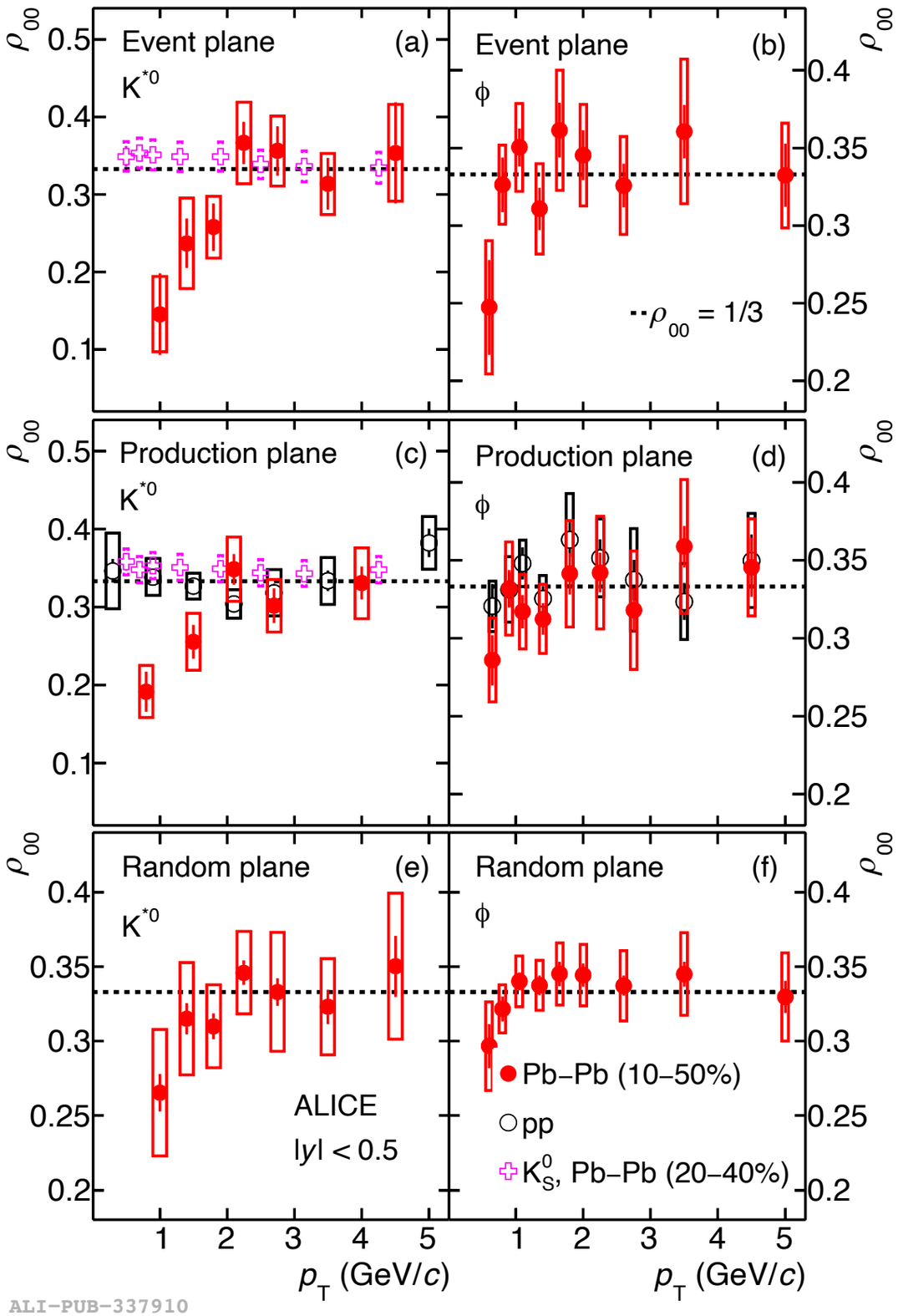
$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

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

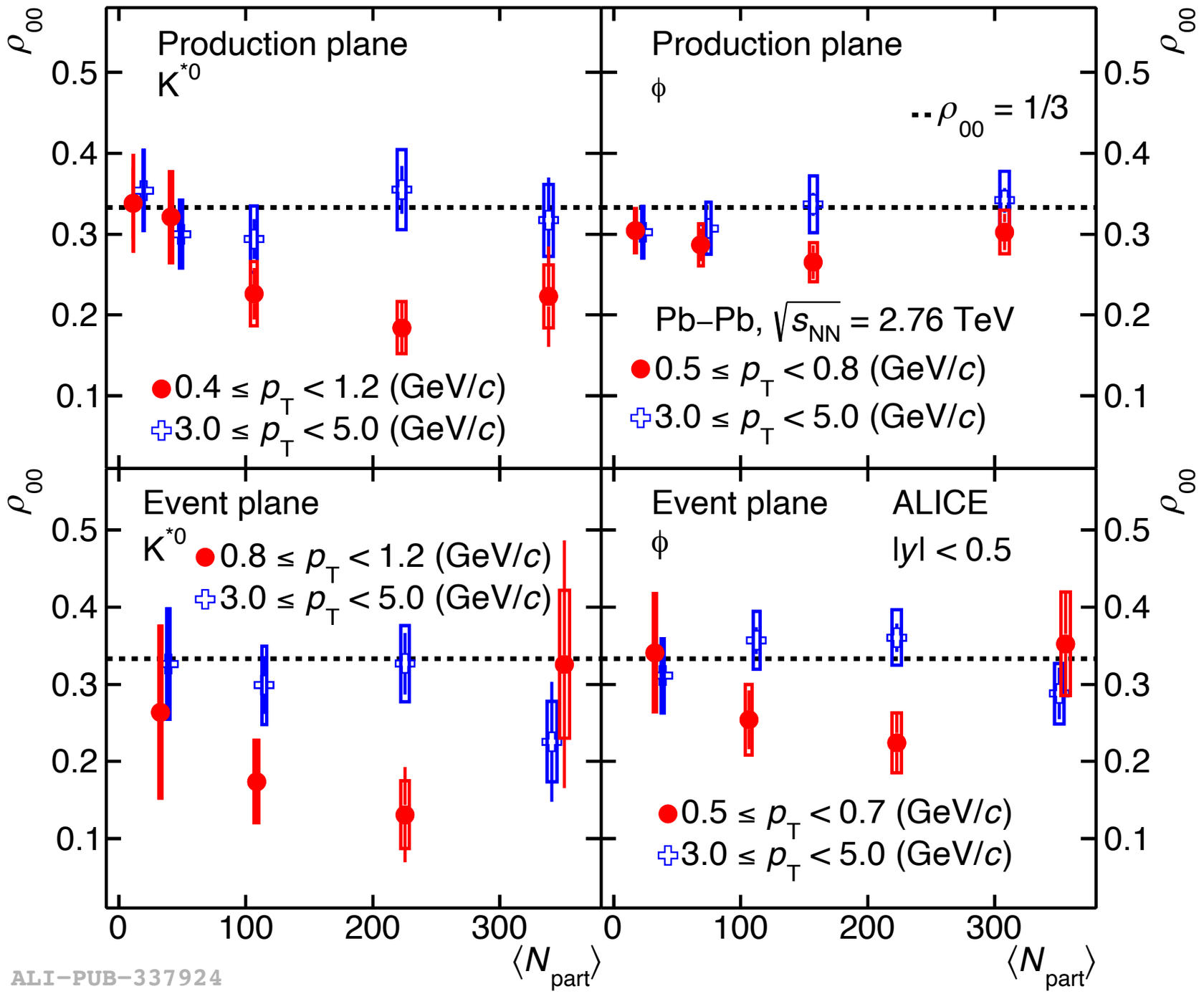


ALI-PUB-337910

- 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. $\langle N_{\text{part}} \rangle$



- 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

- 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 energy (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

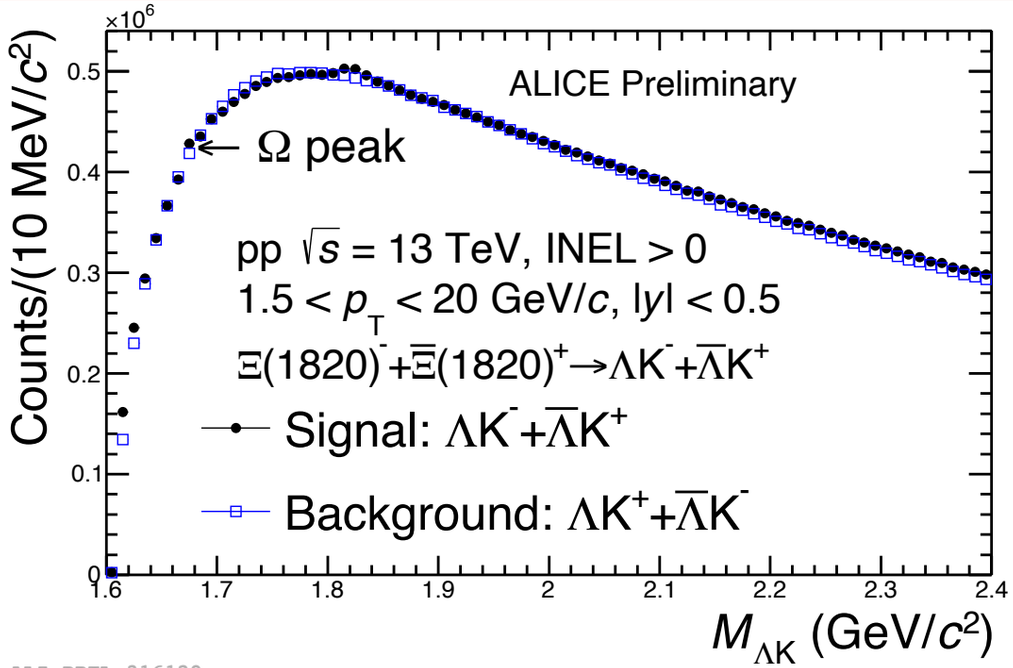
- **time duration between chemical and kinetic freeze-out** is estimated with resonances

- **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**

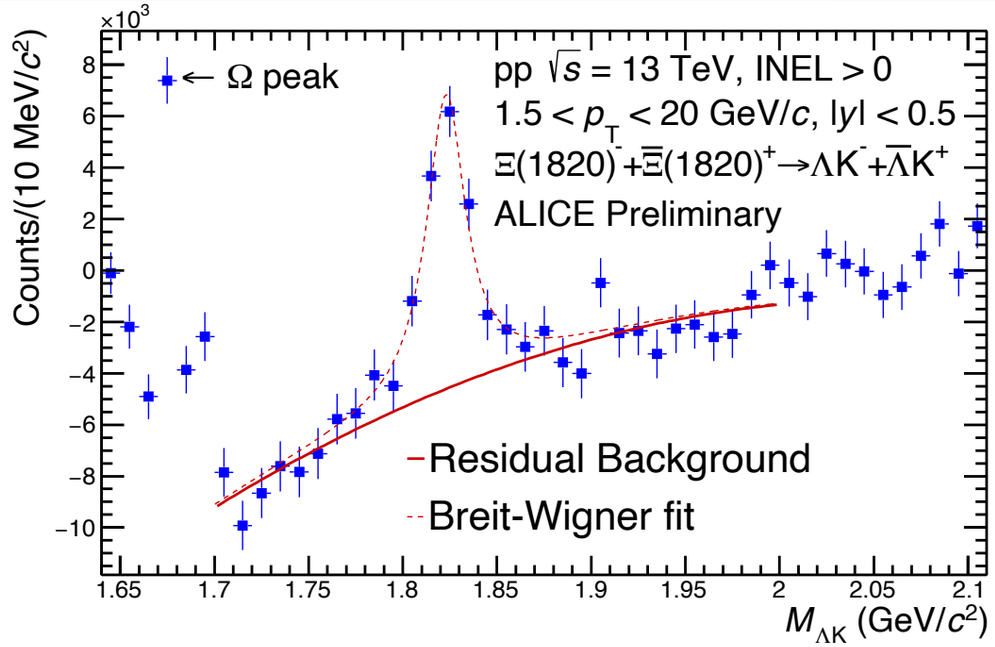
- **Higher mass resonances** could be measured with new data

Backup

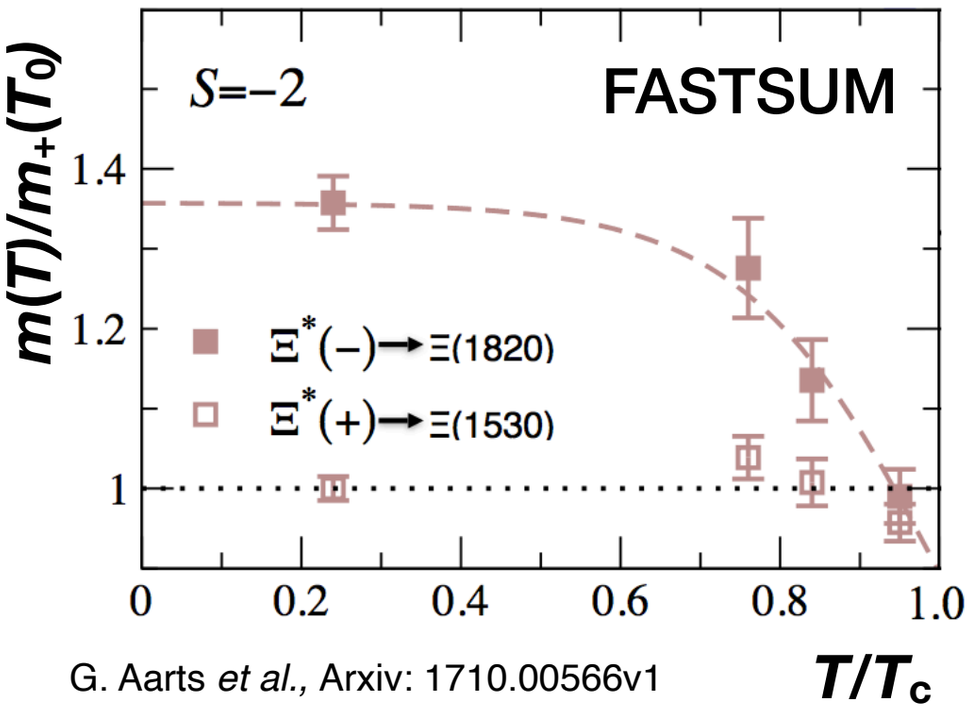
Reconstruction of Ξ(1820)



ALI-PREL-316129



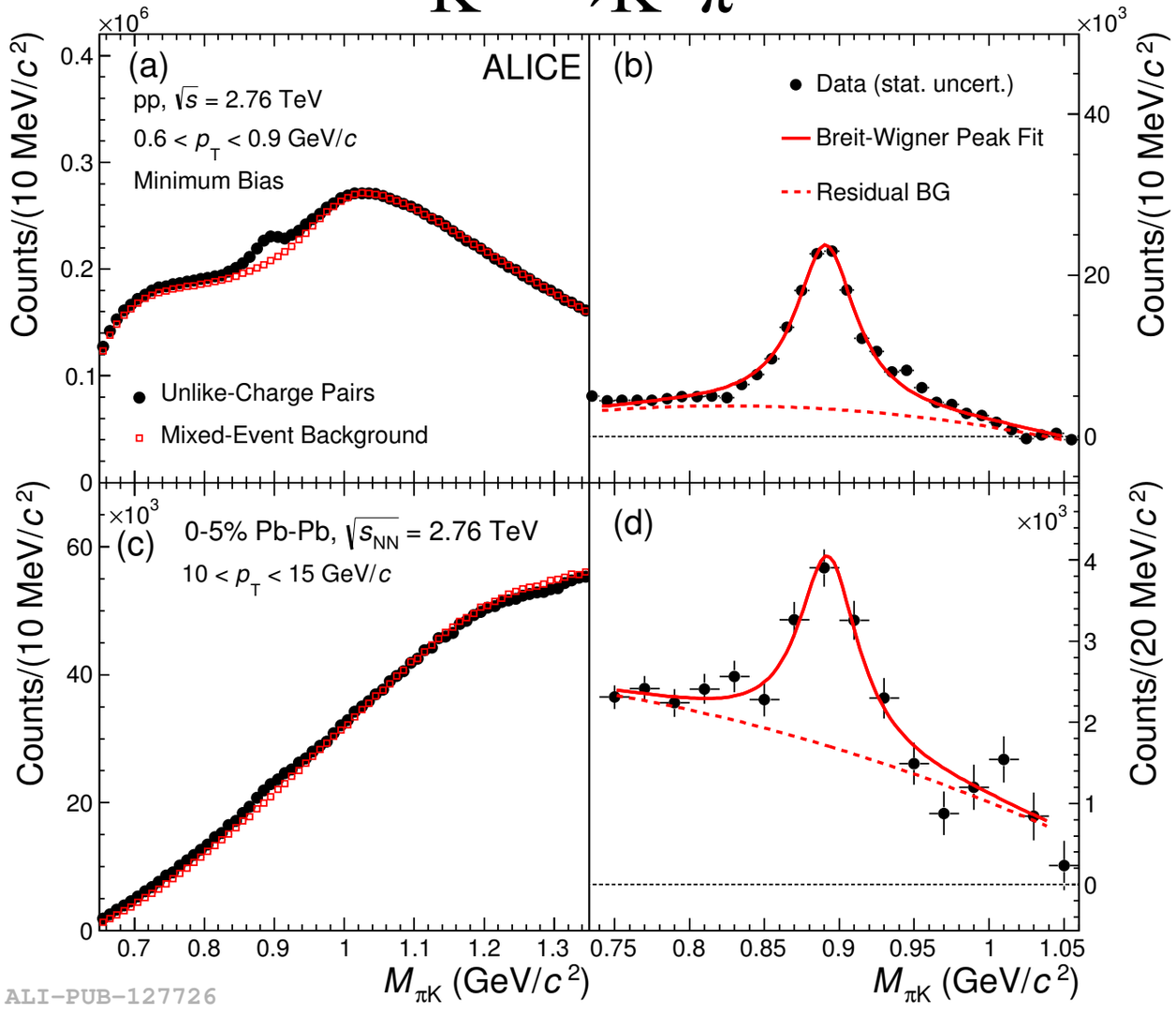
ALI-PREL-316134

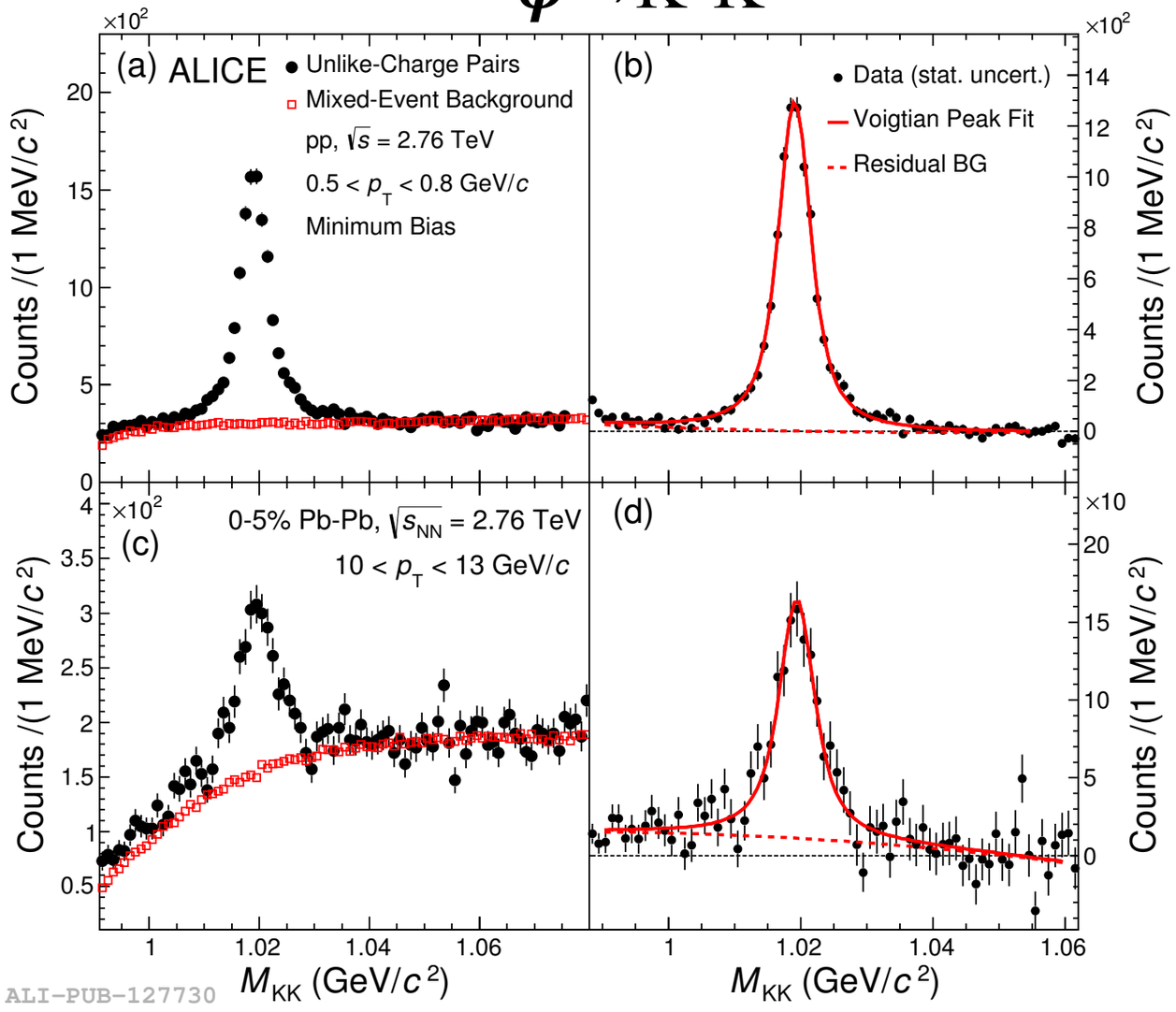


G. Aarts *et al.*, Arxiv: 1710.00566v1

- 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)

Invariant mass distribution: K^{*0} and ϕ

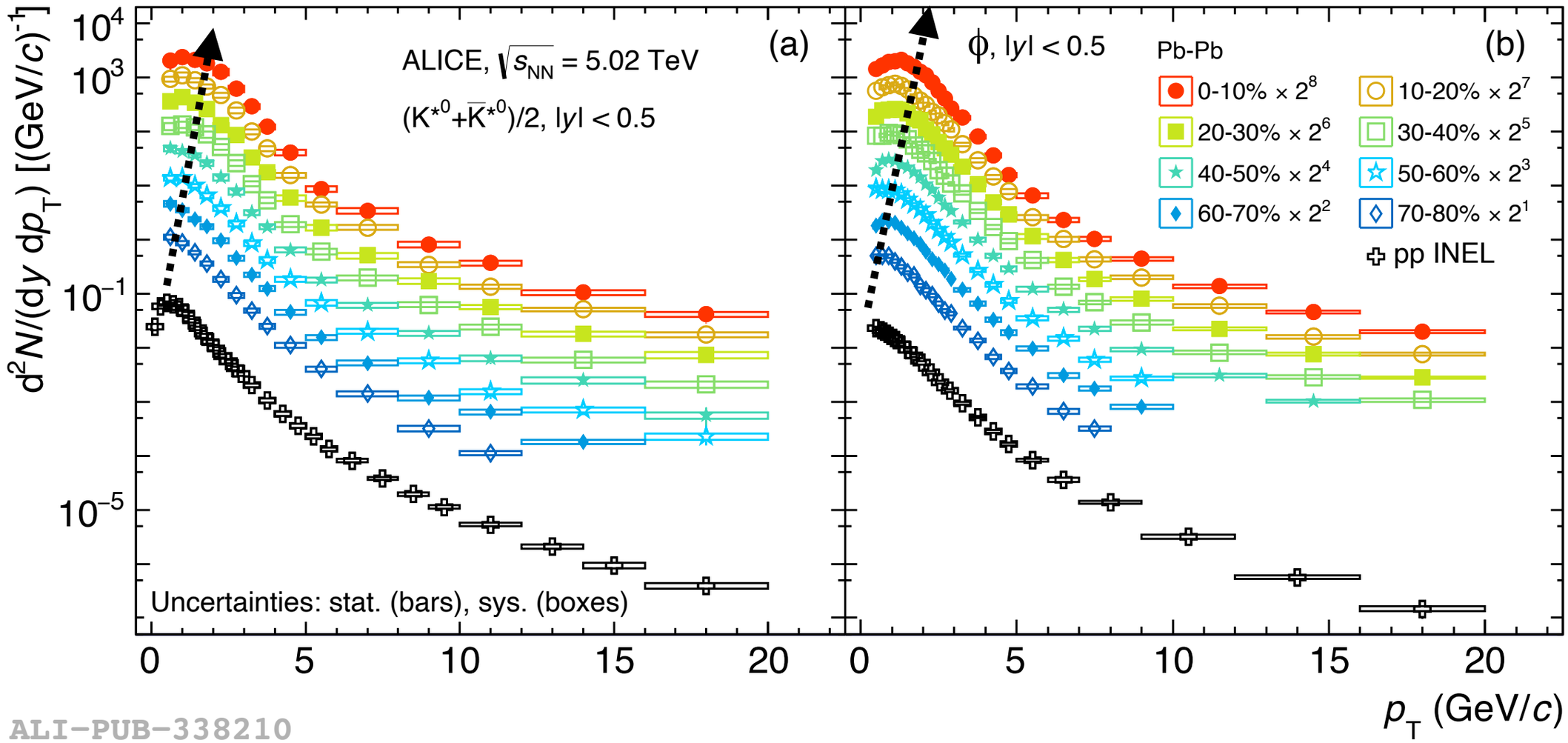




- Event-mixing background/like-sign background methods are applied to estimate the background
- Breit-Wigner/Voigtian fits are used for residual background estimation

Phys. Rev. C 95 064606 (2017)

p_T-spectra in heavy-ion(Pb-Pb) collisions

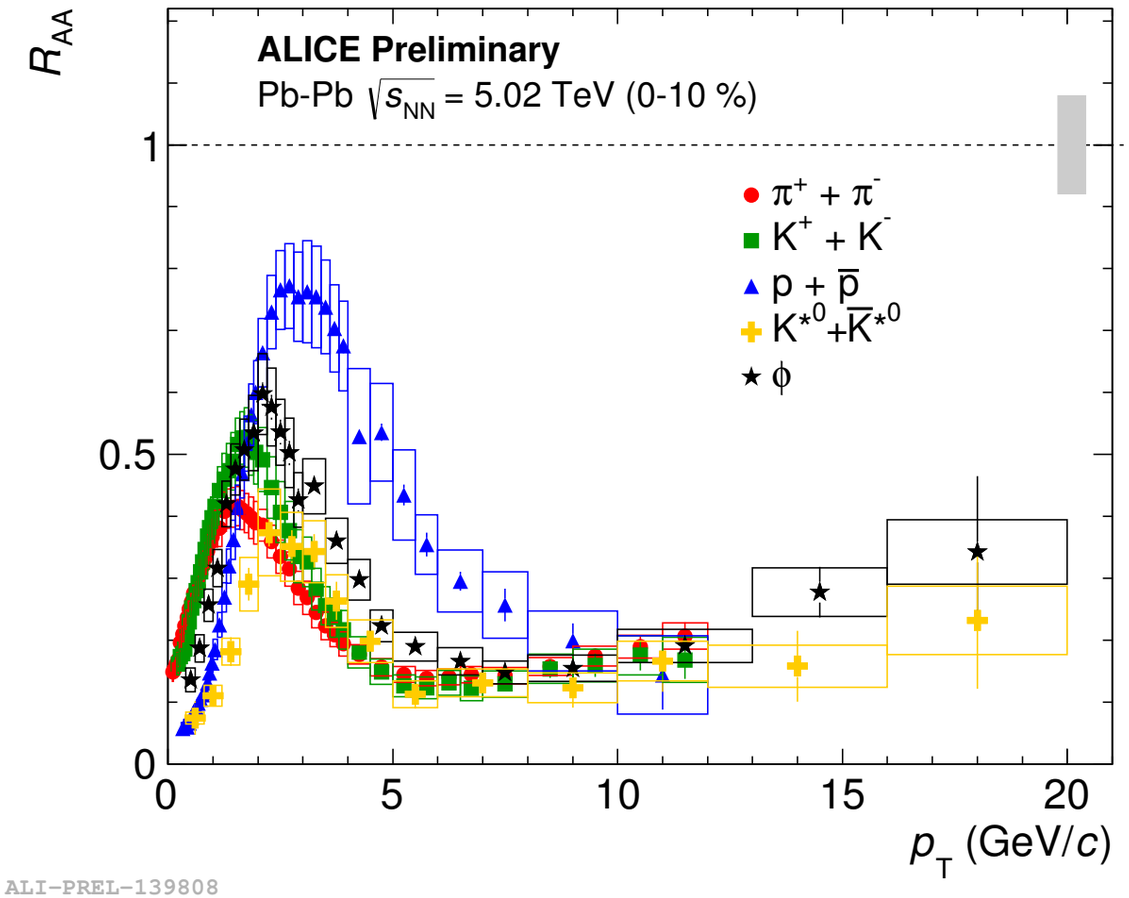


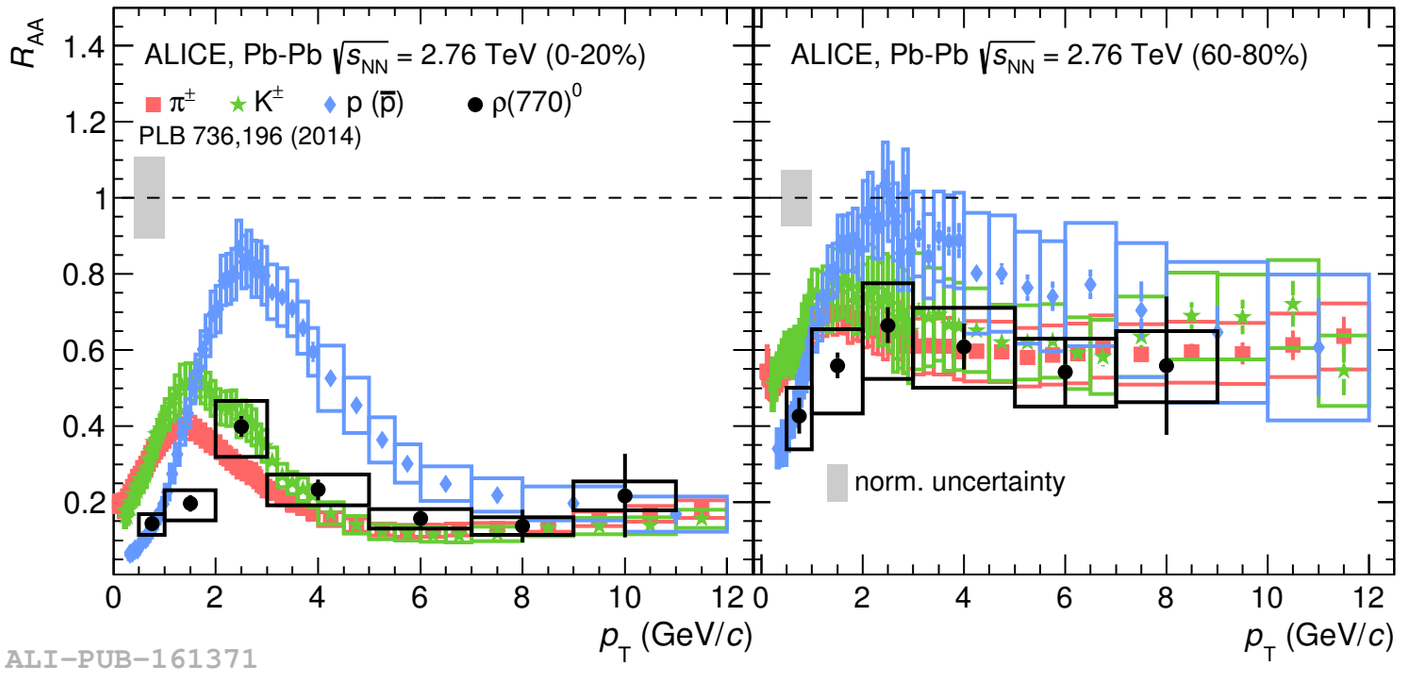
- Hardening of particle spectra from peripheral to central collisions

PLB.2020.135225

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)

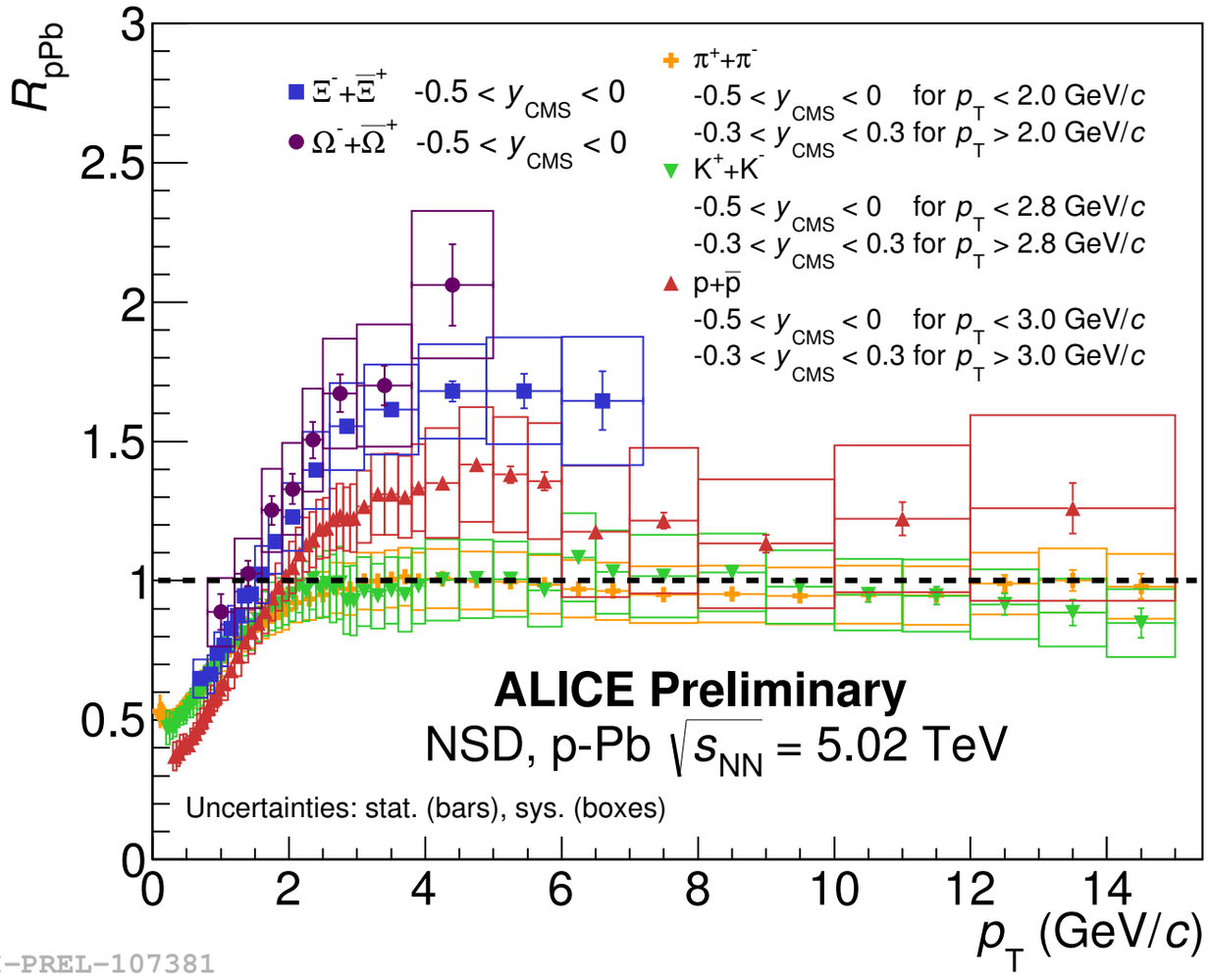
Intermediate-p_T ($2 < p_T < 8$ GeV/c)

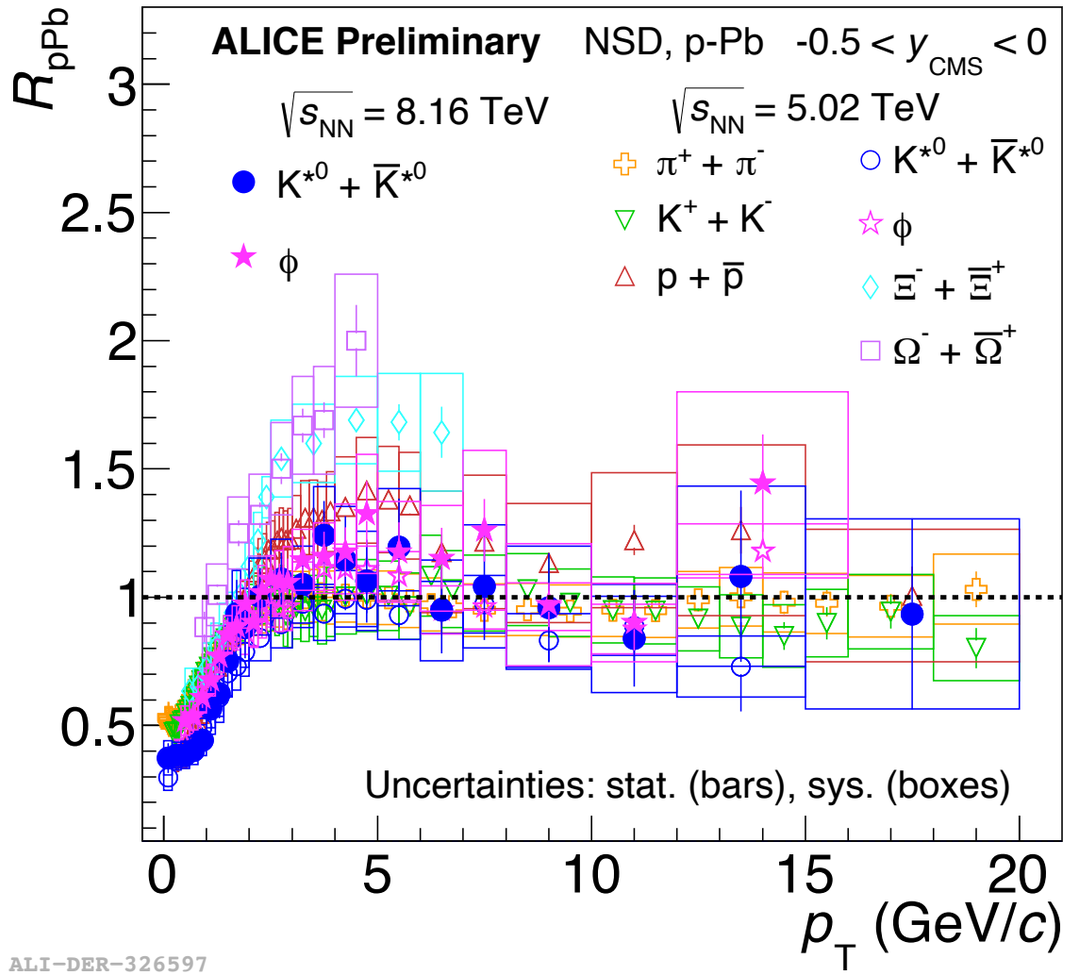
- baryon-meson splitting
- hint of **mass ordering** among mesons
- higher R_{AA} values for proton (might be due to baryon-meson effect)

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})



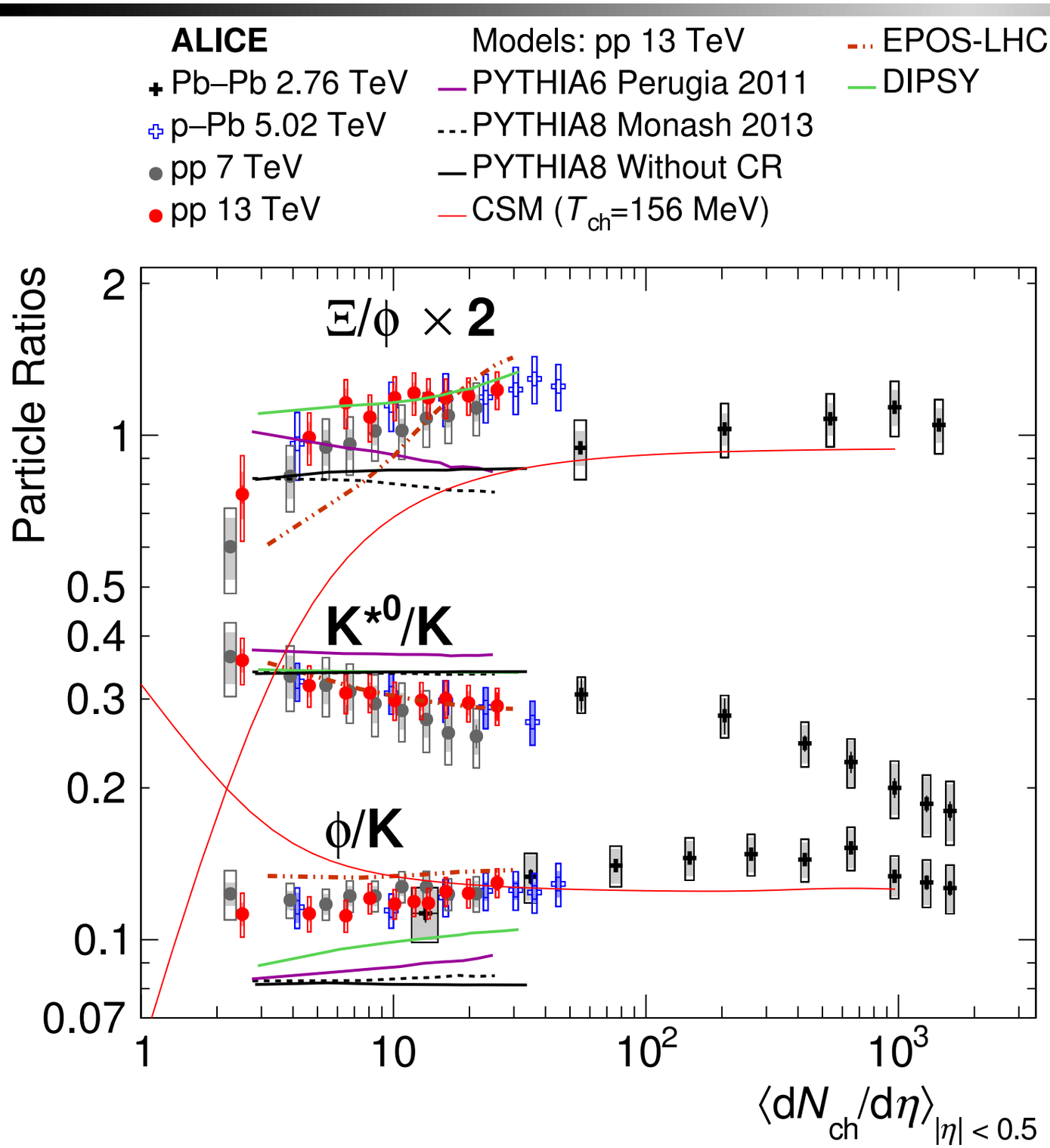


- **Intermediate-p_T (2 < p_T < 8 GeV/c)**
  - **mass dependent** for strange baryons

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