Strange Resonances & Exotic States

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Outline

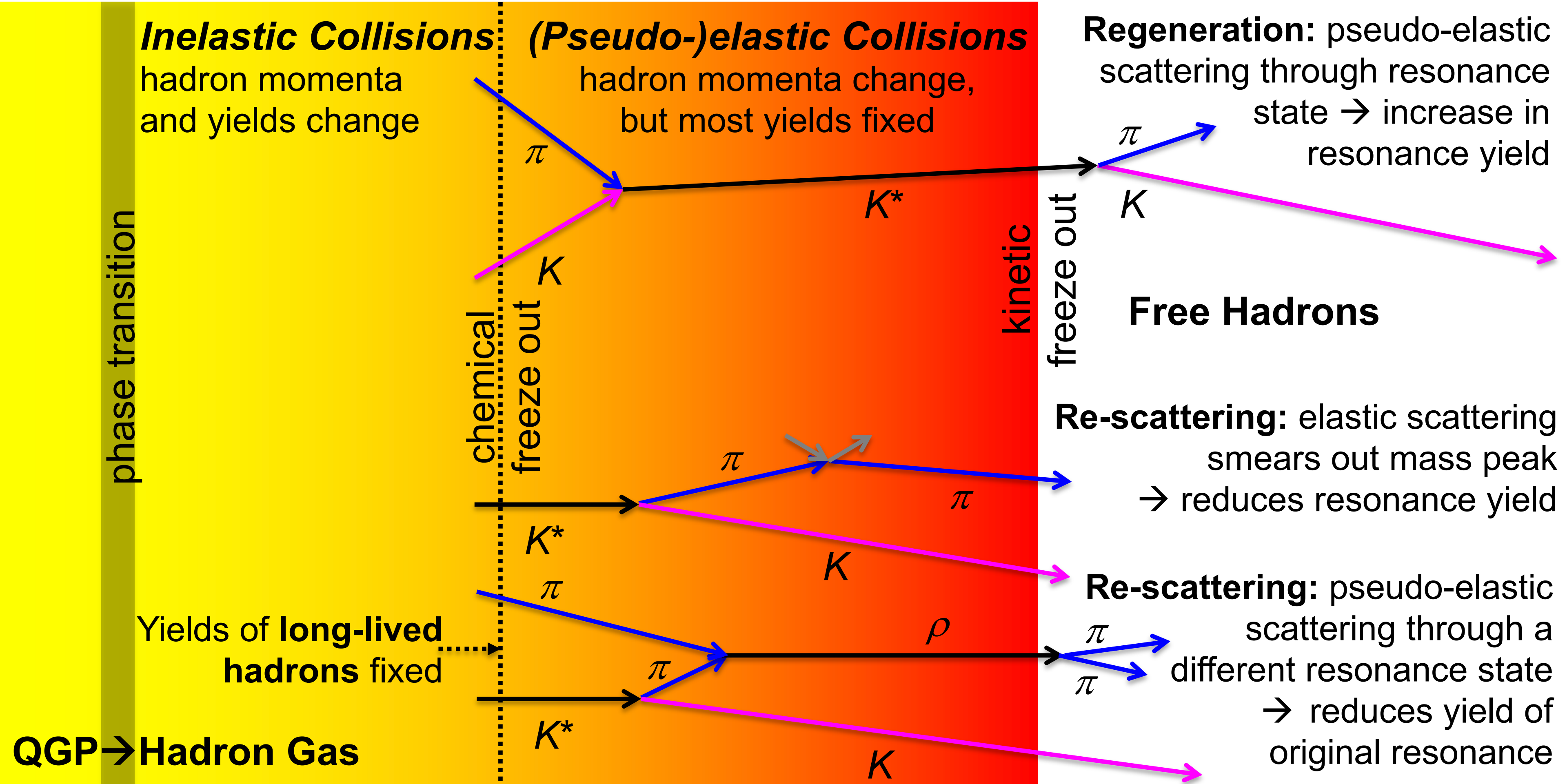
How can do we use resonances to study…

- Hadronic Phase
- Hadrochemistry
- Hadron Structure
- Flow & Vorticity

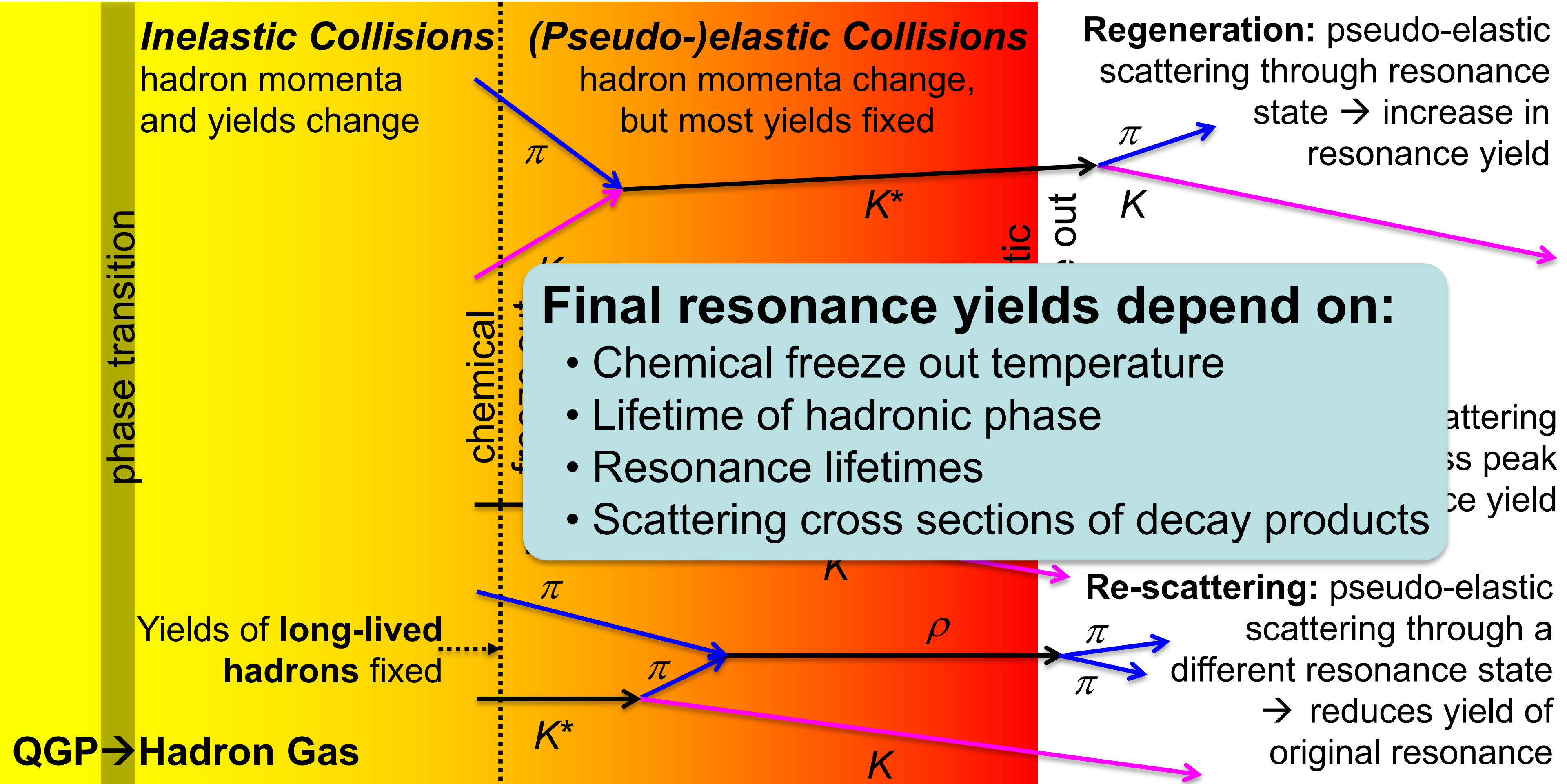
My own biased & incomplete selection of (mostly recent) results…

Hadronic Phase

Hadronic Phase



Hadronic Phase



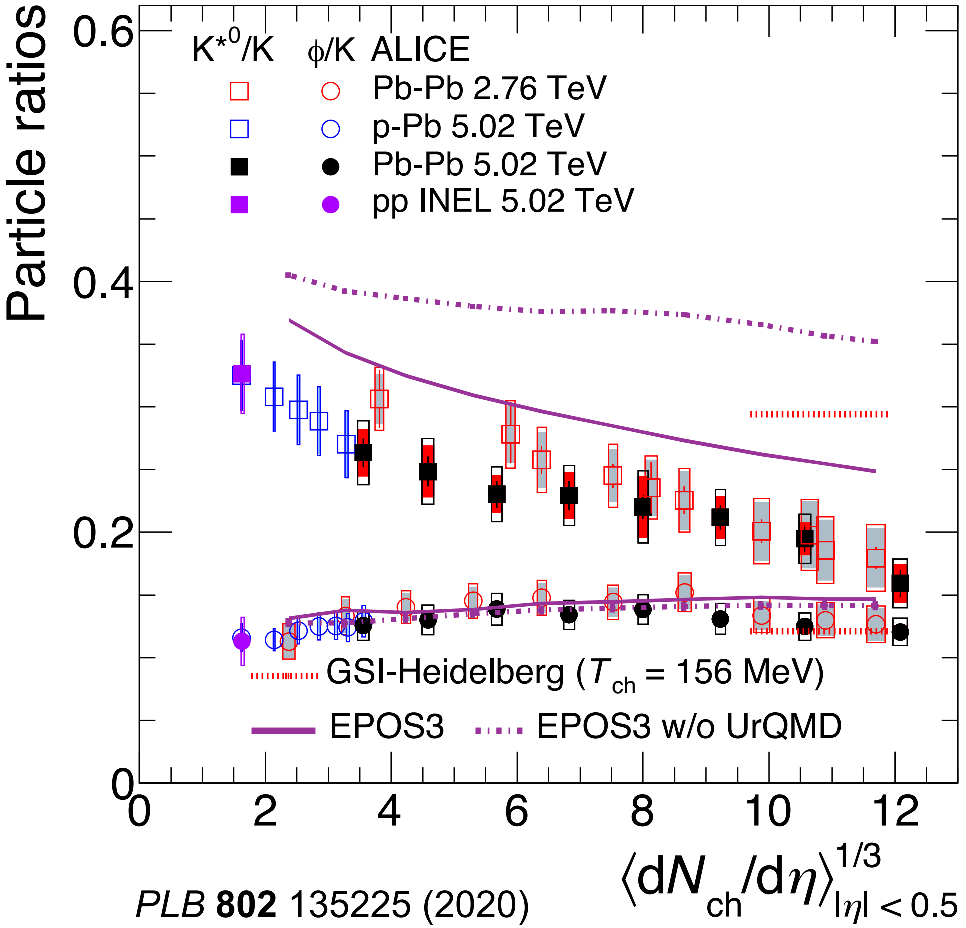
Final resonance yields depend on:

- Chemical freeze out temperature
- Lifetime of hadronic phase
- Resonance lifetimes
- Scattering cross sections of decay products

K^{*0} & ϕ

- Suppression of K^{*0}/K in central A+A collisions
  - Below p+p, p+Pb, and statistical-model predictions
  - Suggests that re-scattering is dominant over regeneration

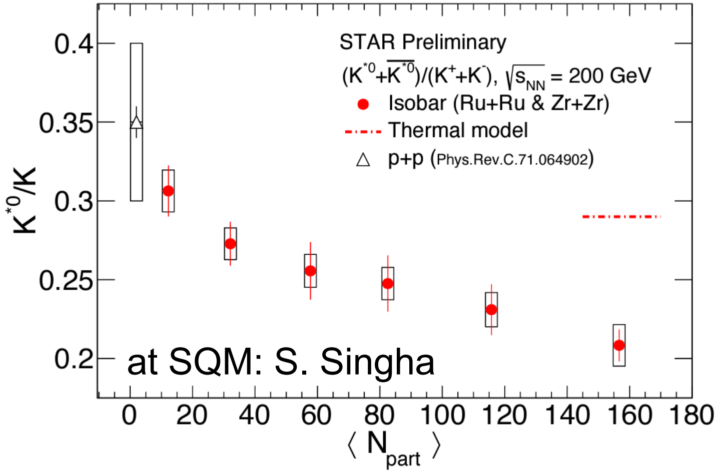
- In contrast, ϕ/K not suppressed
  - Consistent w/ statistical models
  - Lifetime of ϕ ~10 × longer than K^{*0}
  - Re-scattering effects not significant



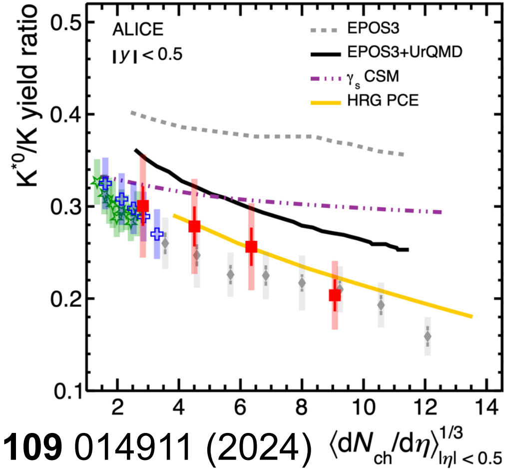
PLB **802** 135225 (2020)

K^{*0}: Intermediate Nuclei

- New STAR result: K^{*0}/K ratio in isobar (Ru+Ru & Zr+Zr) collisions at 200 GeV.
- Ratio decreases with increasing $\langle N_{\text{part}} \rangle$, consistent with other observations from STAR, including Au+Au and Cu+Cu.



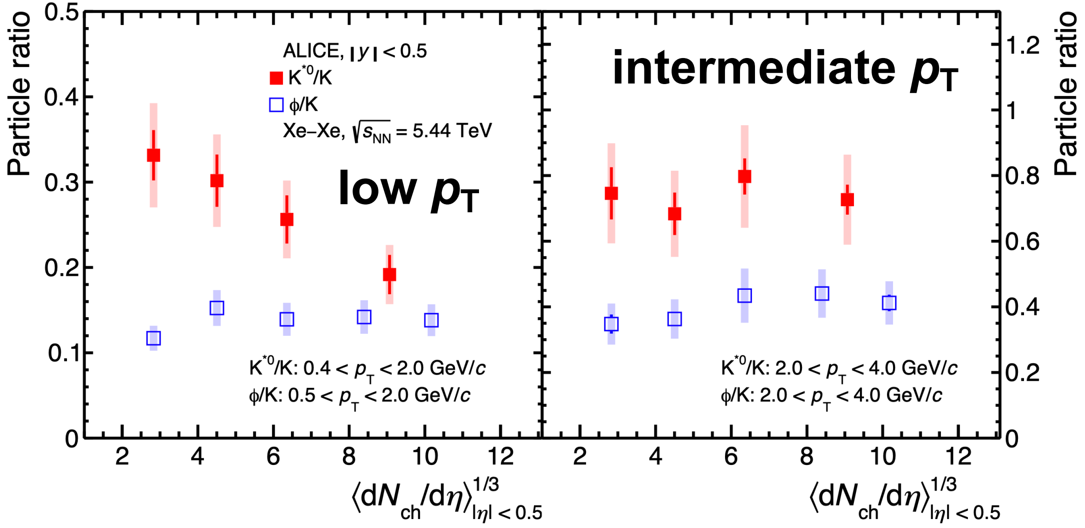
- Also consistent with results in Xe+Xe collisions at 5.44 TeV from ALICE.
- Identities of the colliding nuclei don't matter: yield & suppression controlled by $\langle N_{\text{part}} \rangle$ or multiplicity



PRC **109** 014911 (2024)

K^{*0} & ϕ: p_T Dependence

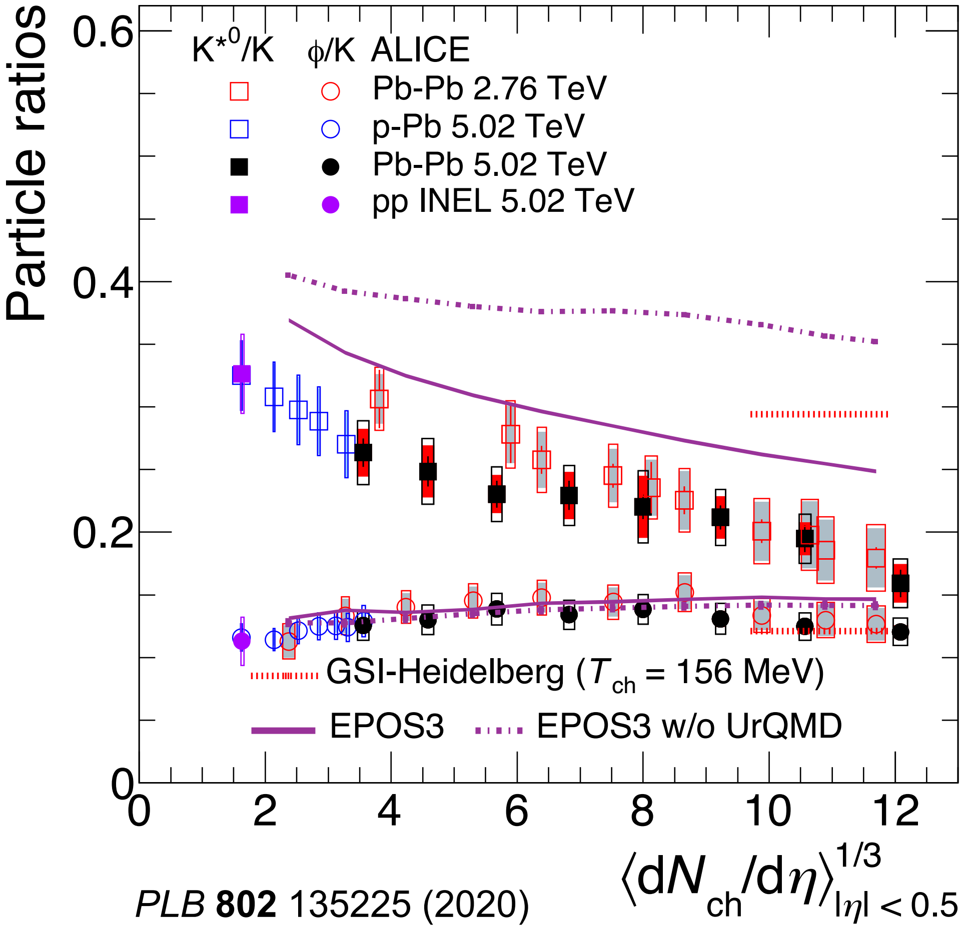
- K^*/K and ϕ/K ratios calculated in two different p_T ranges.
- Suppression of K^*/K observed for $0.4<p_T<2$ GeV/c, but not $2<p_T<4$ GeV/c.
- No suppression of ϕ/K for either range.
- Suggests that re-scattering is more important at low p_T.



PRC **109** 014911 (2024)

K^{*0} & ϕ: EPOS

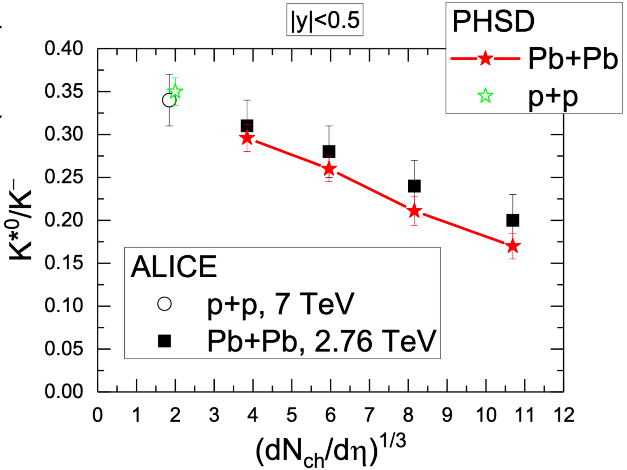
- EPOS:
  - Scattering effects modeled with UrQMD
  - Qualitatively describes falling K^{*0}/K ratio, largely flat ϕ/K
  - Turning off UrQMD: K^{*0}/K described less well, little effect on ϕ/K



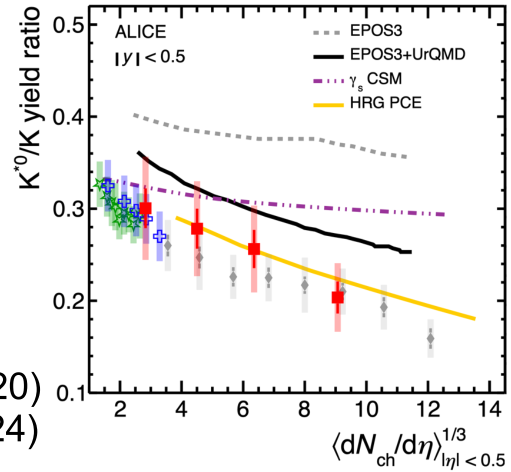
PLB **802** 135225 (2020)

K^{*0} & ϕ: Models

- PHSD:
  - Re-scattering and absorption of decay products in hadronic phase
  - Suppression of K^{*0}/K
  - Better agreement with ALICE data than EPOS



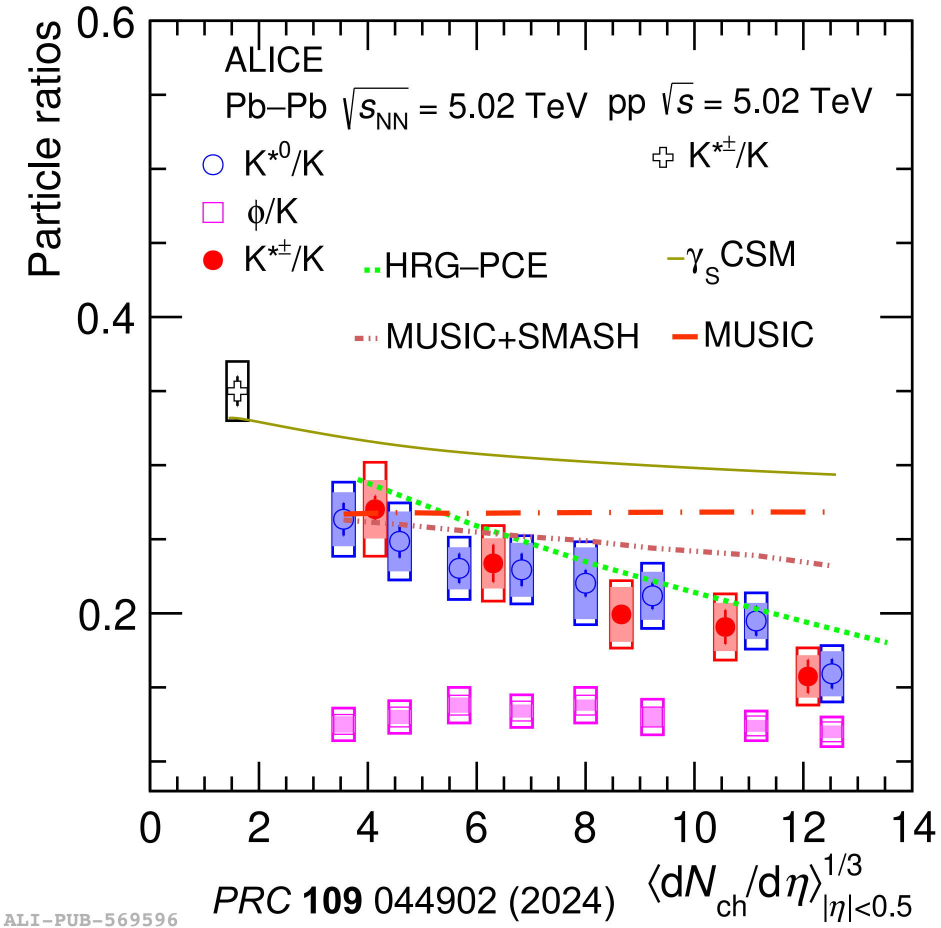
- HRG PCE
  - Hadron Resonance Gas in Partial Chemical Equilibrium
  - Good agreement with ALICE measurement



PRC **102** 024909 (2020)
PRC **109** 014911 (2024)

$K^{*\pm}$ & Models

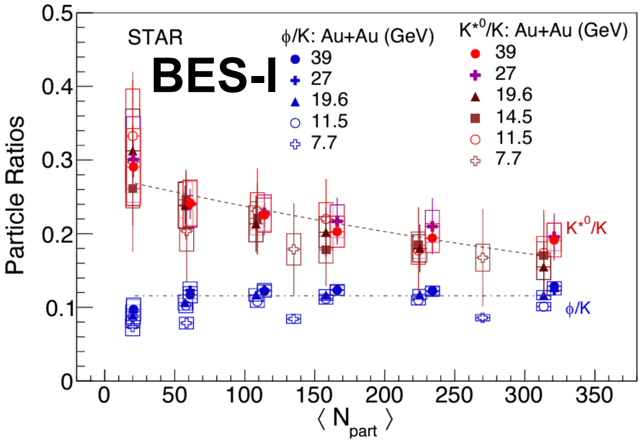
- New measurements of $K^{*\pm}$
  - Very similar behavior to K^{*0}
  - $K^{*\pm}/K$ ratio follows same trend as K^{*0}/K vs. multiplicity
- γ_S Canonical Statistical Model predicts only a slow decrease in the K^{*}/K ratio [*PRC* **100** 054906 (2019)]
- MUSIC [arXiv:2105.07539]
  - w/o SMASH afterburner: flat prediction
  - w/ SMASH afterburner: slower decrease in K^{*}/K than measurement
- HRG PCE
  - Predicts decrease in K^{*}/K vs. multiplicity
  - Good agreement with measurement

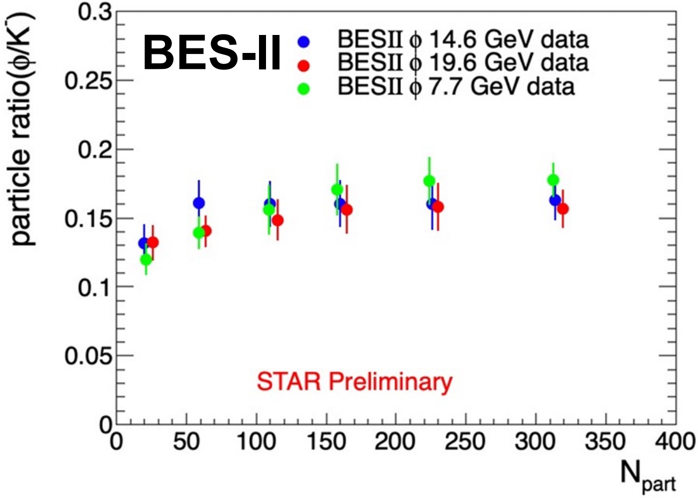


PRC **109** 044902 (2024)

K^{*0} & ϕ: Low Energy

- STAR Beam Energy Scan: measurements of K^{*0} & ϕ
- BES-I: K^{*}/K and ϕ/K ratios consistent with results from full RHIC energy & LHC.
  - Apparent decrease of K^{*}/K with increasing $\langle N_{\mathrm{part}} \rangle$, although uncertainties must be considered.
  - Little energy dependence.
- BES-II: little energy or centrality dependence in ϕ/K ratio.

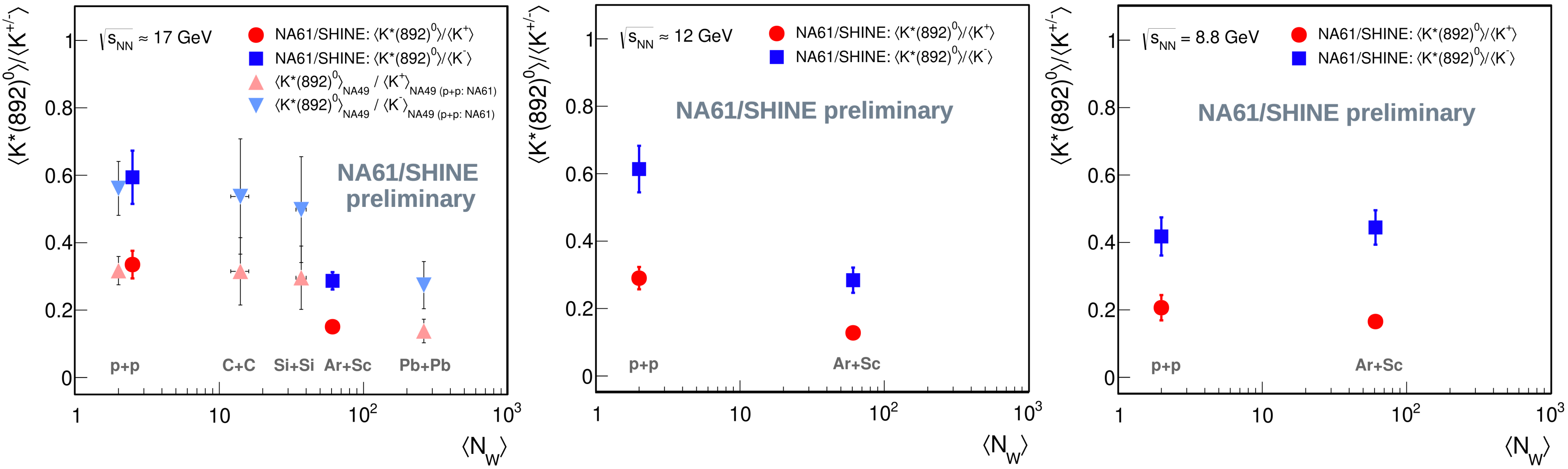




K^{*0}: Low Energy

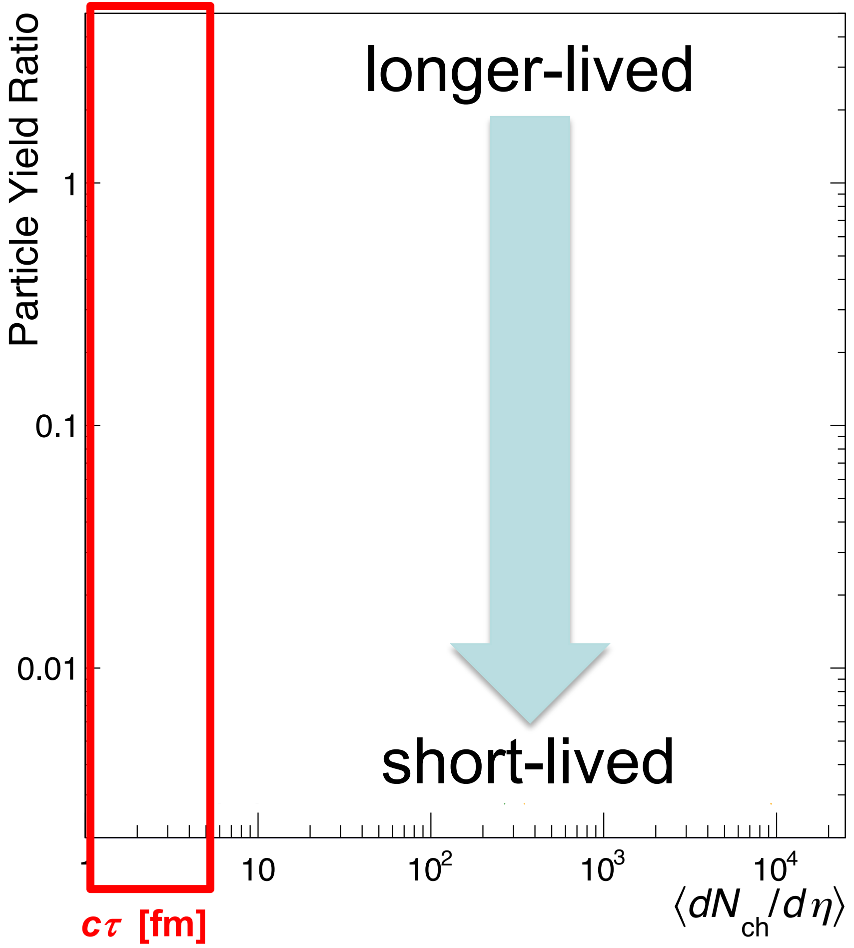
- NA61/SHINE observes suppression w.r.t. *p+p* of K^{*0}/K ratios in Ar+Sc collisions at $\sqrt{s_{NN}}$ = 17 and 12 GeV.
- But that suppression turns off for $\sqrt{s_{NN}}$ = 8.8 GeV
  – Shorter lifetime for hadronic phase → less influence of re-scattering.

at SQM: B. Kozłowski



Summary Plot

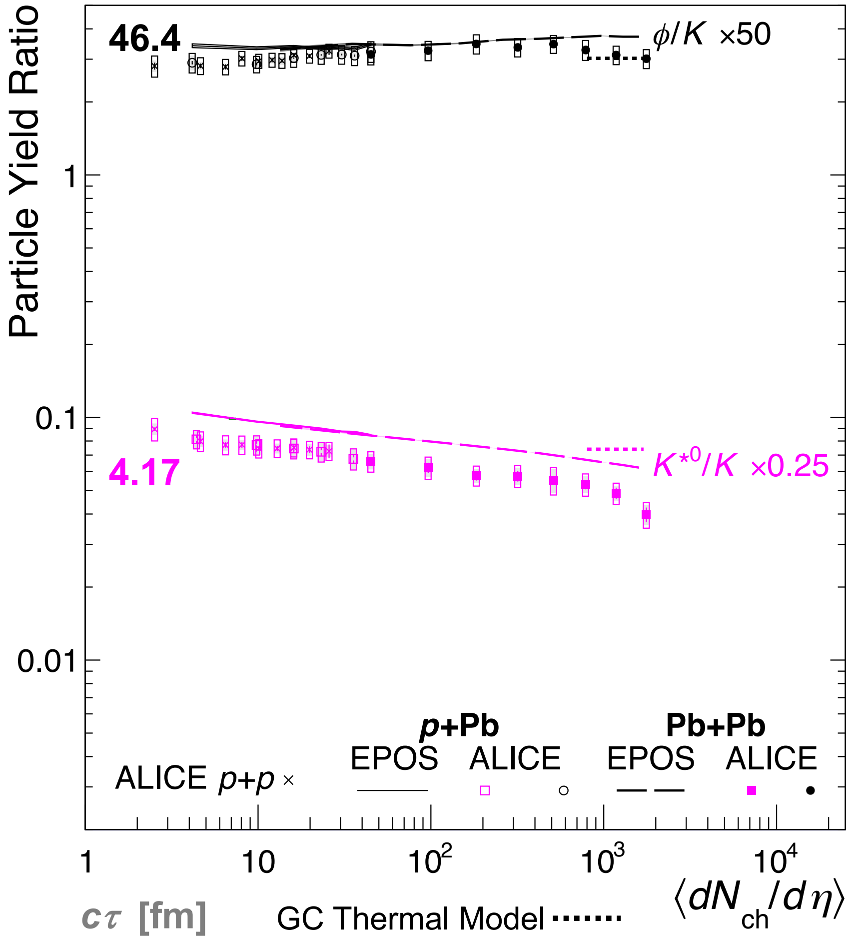
- Many results, not just K^* & ϕ, to discuss
- Let's collect the various yield ratios on this summary plot:
  - Yield ratios (scaled for visibility) vs. multiplicity
  - Numerator & denominator particle should have same strangeness & baryon number
  - From low-multiplicity *p+p* to central *A+A*
  - Resonance lifetimes decrease from top to bottom.
  - $c\tau$ will be listed on left
  - Not all measurements shown.
  - Mostly showing ALICE, but some STAR data will appear too.
  - Compare to EPOS & GC Thermal Model



Summary Plot

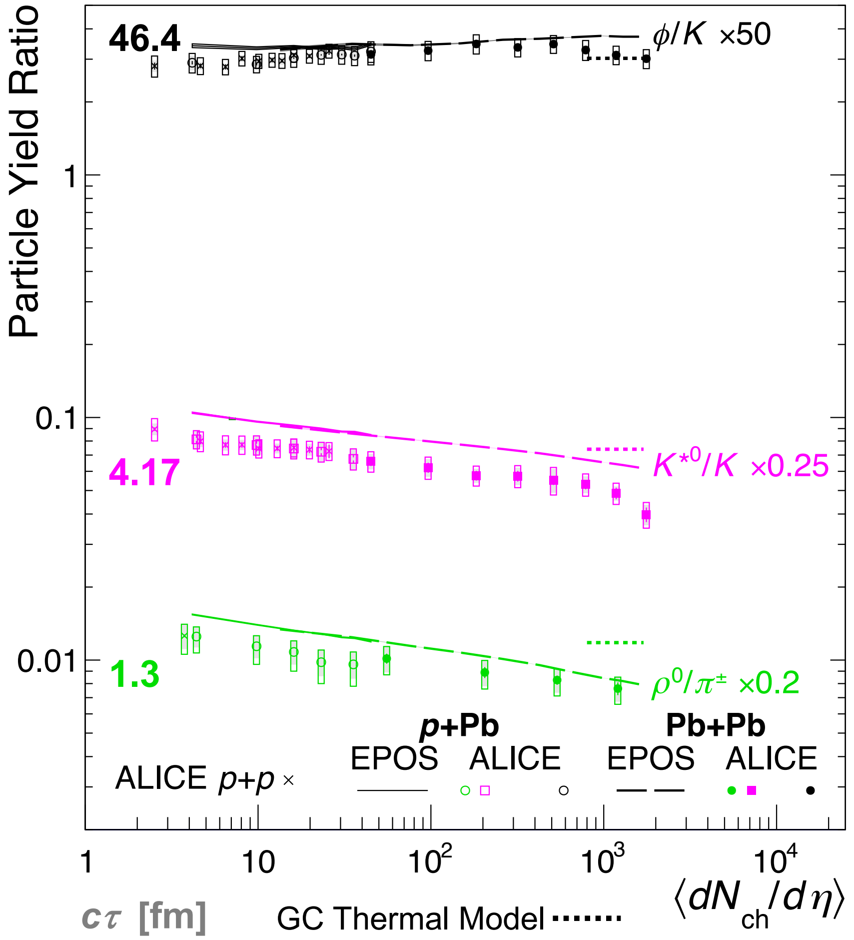
- ϕ/K: little multiplicity dependence

- K^*/K: decreases with increasing multiplicity, clear suppression in A+A



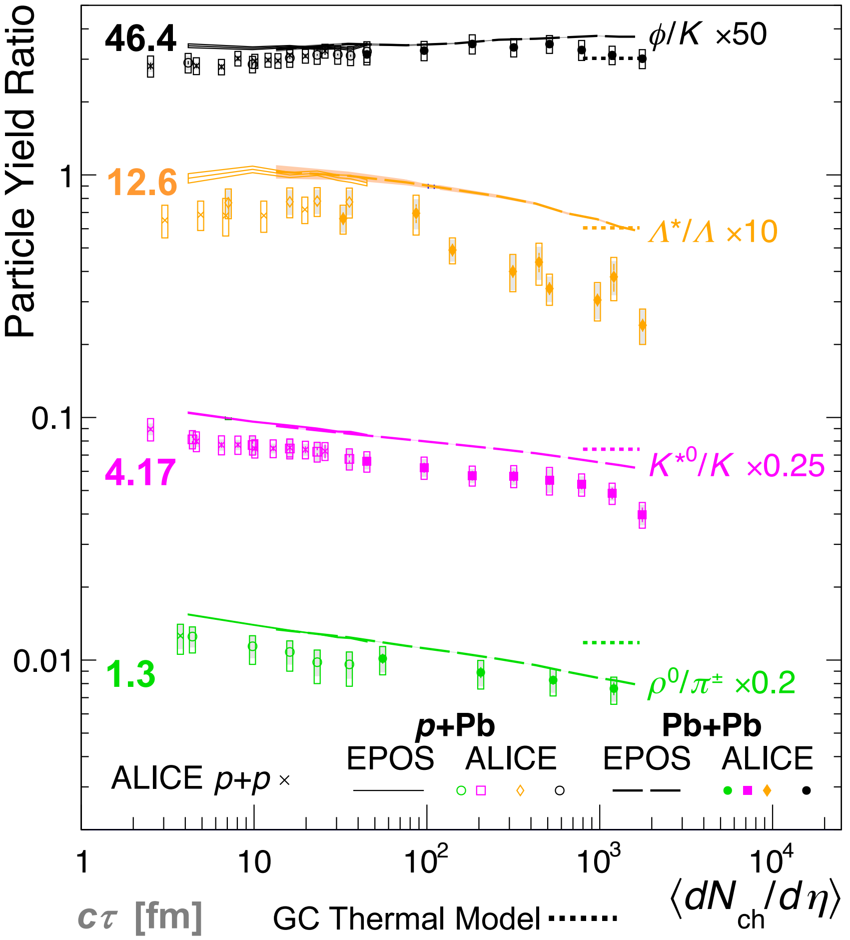
Summary Plot

- ϕ/K: little multiplicity dependence
- *K*/K*: decreases with increasing multiplicity, clear suppression in *A+A*
- ρ/π : decreases with increasing multiplicity, clear suppression in *A+A*



Summary Plot

- ϕ/K: little multiplicity dependence
- $\Lambda(1520)/\Lambda$: clear suppression in *A*+*A*
- K^*/K: decreases with increasing multiplicity, clear suppression in *A*+*A*
- ρ/π : decreases with increasing multiplicity, clear suppression in *A*+*A*



Summary Plot

- ϕ/K: little multiplicity dependence
- Ξ^*/Ξ: possible weak suppression in *A+A*
- $\Lambda(1520)/\Lambda$: clear suppression in *A+A*
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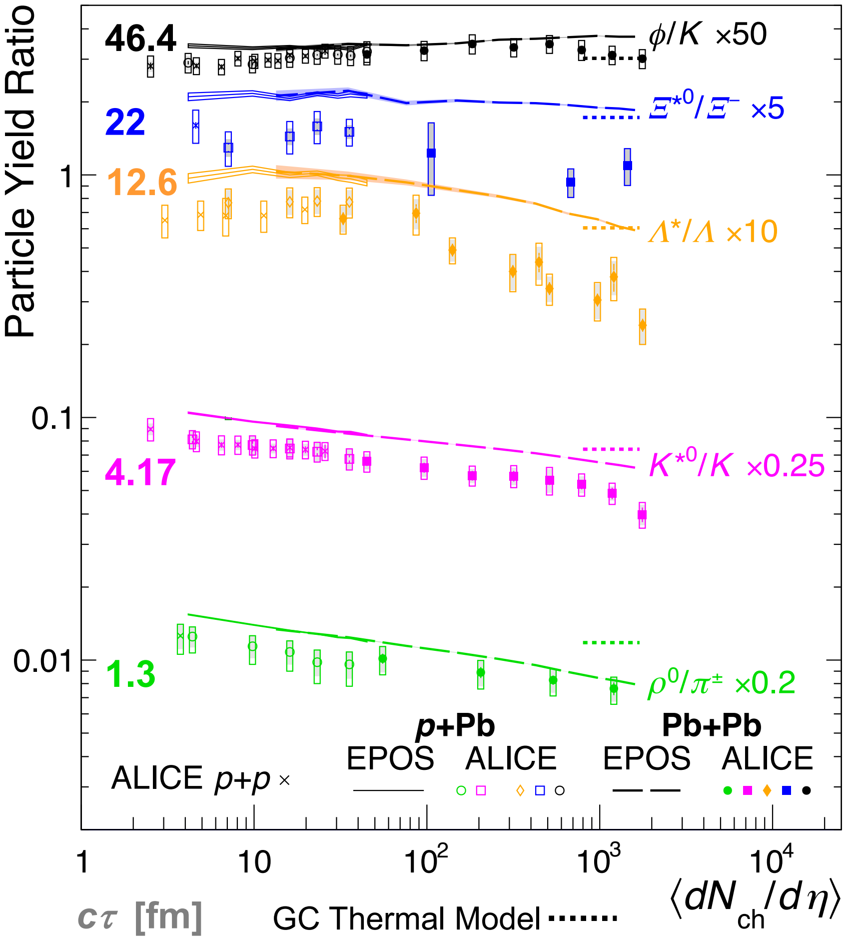
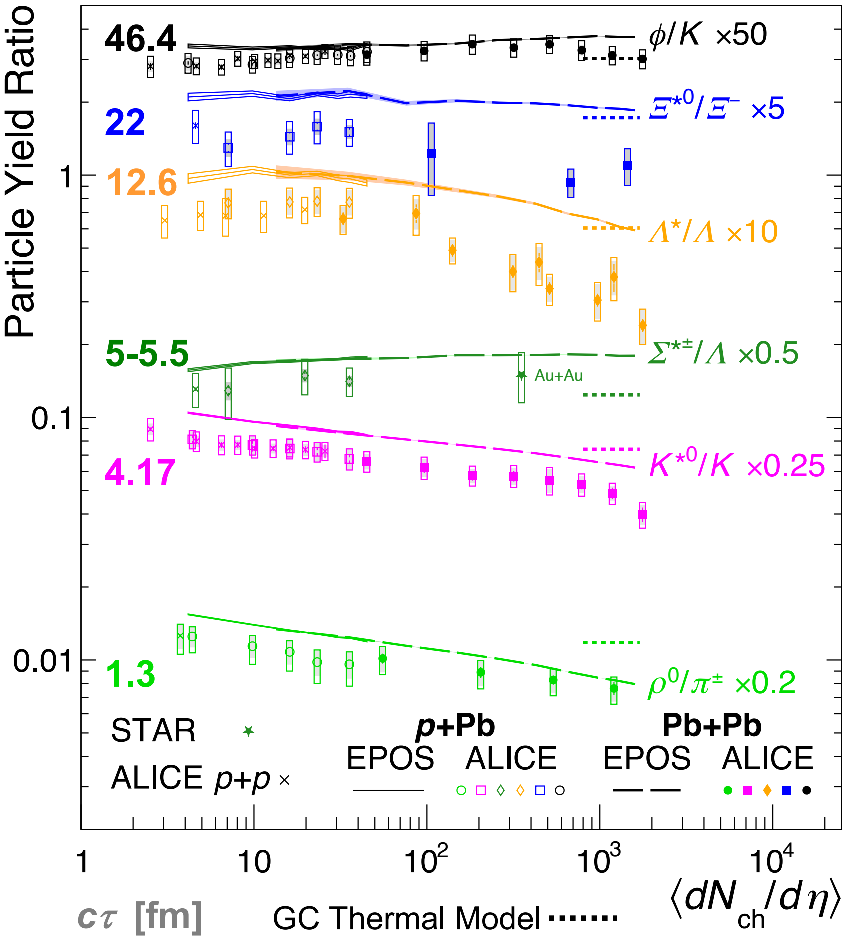
- ρ/π: decreases with increasing multiplicity, clear suppression in *A+A*



Summary Plot

- ϕ/K: little multiplicity dependence
- Ξ^*/Ξ: possible weak suppression in *A+A*
- $\Lambda(1520)/\Lambda$: clear suppression in *A+A*
- Σ^*/Λ: flat in small systems, STAR observes no suppression in *A+A*, ALICE: weak suppression in *A+A*?
- K^*/K: decreases with increasing multiplicity, clear suppression in *A+A*
- ρ/π: decreases with increasing multiplicity, clear suppression in *A+A*



Summary Plot

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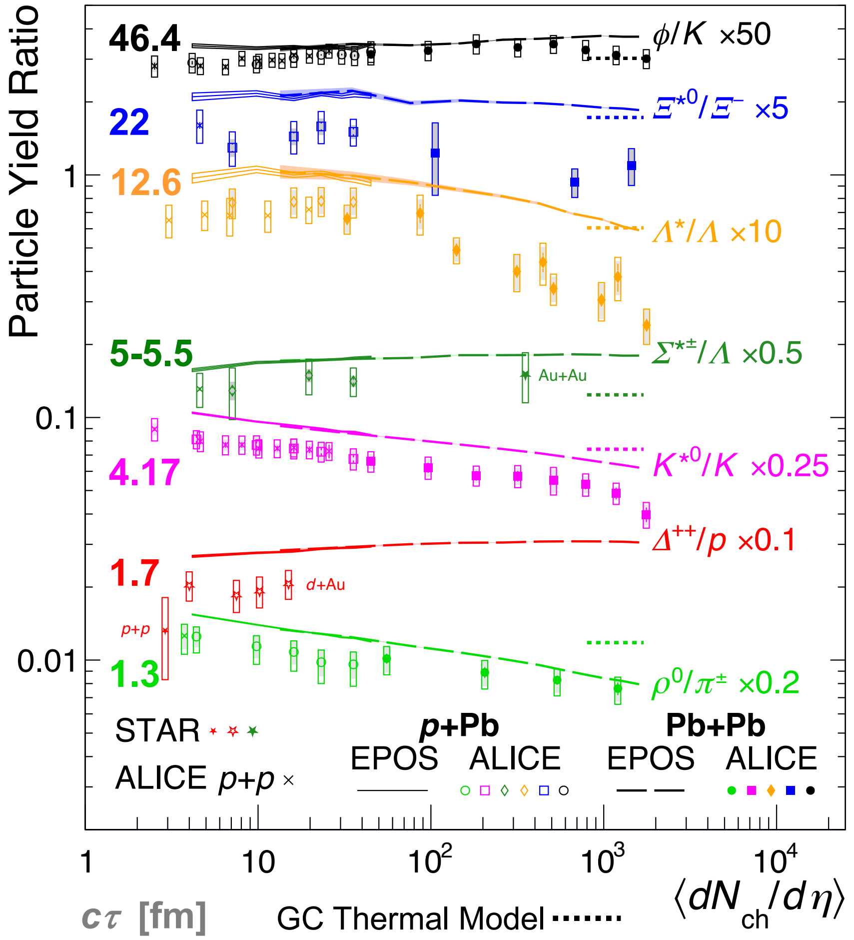
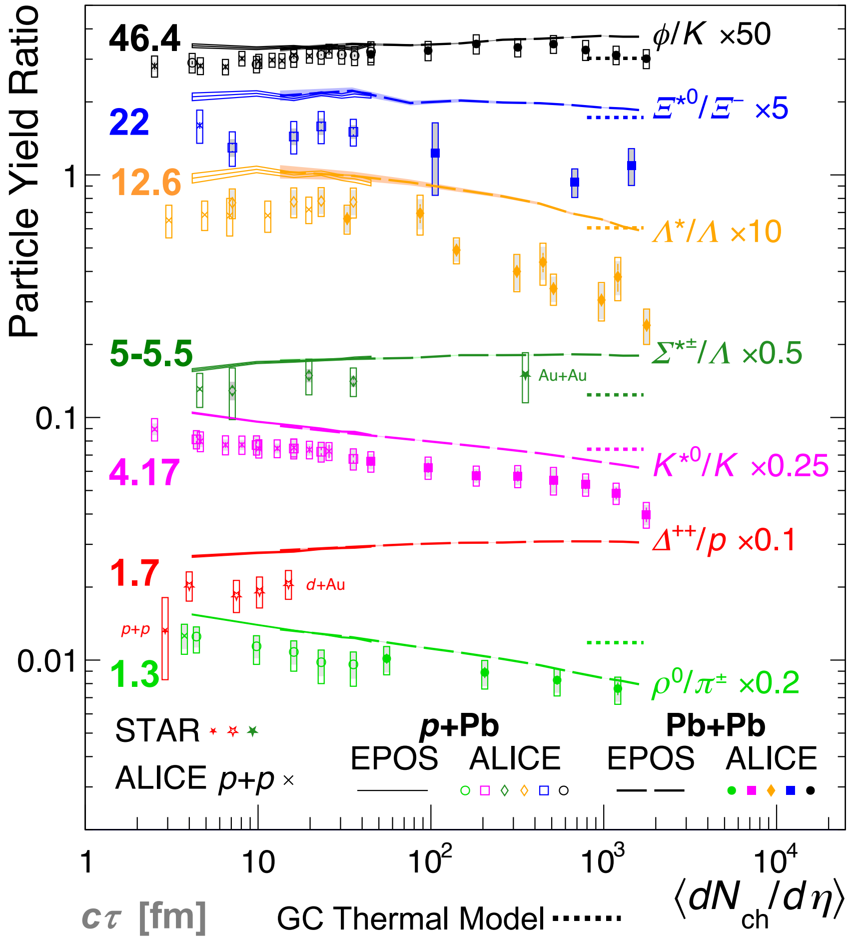
- Σ^*/Λ: flat in small systems, STAR observes no suppression in *A*+*A*, ALICE: weak suppression in *A*+*A*?
- K^*/K: decreases with increasing multiplicity, clear suppression in *A*+*A*
- Δ/p: flat in small systems, EPOS predicts no suppression in *A*+*A*
- ρ/π: decreases with increasing multiplicity, clear suppression in *A*+*A*



Summary Plot

- Several short-lived resonances are suppressed in central *A+A* collisions w.r.t. small systems thermal model
  - A suppression trend is sometimes also visible even in the small systems.
  - Suppression trends are at least qualitatively described by models that include descriptions of the hadronic phase (EPOS, MUSIC+SMASH, PHSD, …)
- However, not all short-lived resonances are expected to be suppressed
- And the relationship between resonance lifetime and suppression is not simple

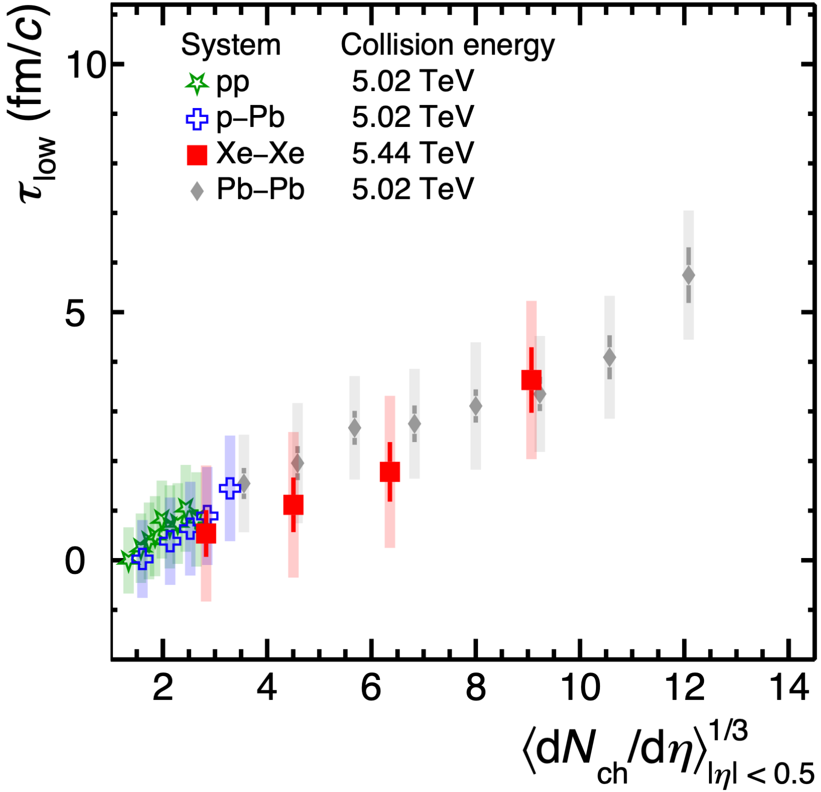


Hadronic Phase

- Can estimate lower limit hadronic phase lifetime τ_{low} from exponential decay law, scaled by a Lorentz factor:

$$\left(\frac{K^*}{K}\right)_{\text{kin}} = \left(\frac{K^*}{K}\right)_{\text{chem}} \times \exp\left(-\frac{\tau_{\text{low}}}{\tau_{K^*}}\right)$$

  - Assumes simultaneous freeze out of all particles, negligible regeneration
- Roughly linear increase in lifetime with cube root of multiplicity (proxy for system radius)
- Smooth transitions between systems
- Values range from 0 in small systems to 6 fm/*c* in large systems



PRC **102** 024909 (2020)
PRC **109** 014911 (2024)

Hadronic Phase

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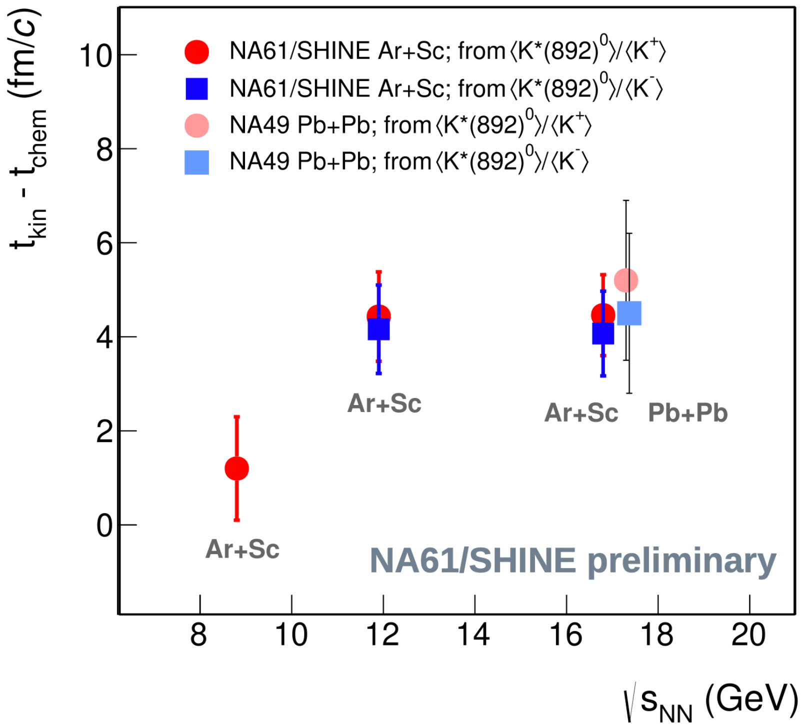
  - Assumes simultaneous freeze out of all particles, negligible regeneration
- Same technique employed by NA61/SHINE to extract hadronic lifetime in Ar+Sc collisions.
  - Lifetime at $\sqrt{s_{NN}}$ = 8.8 GeV near 0.



at SQM: B. Kozłowski

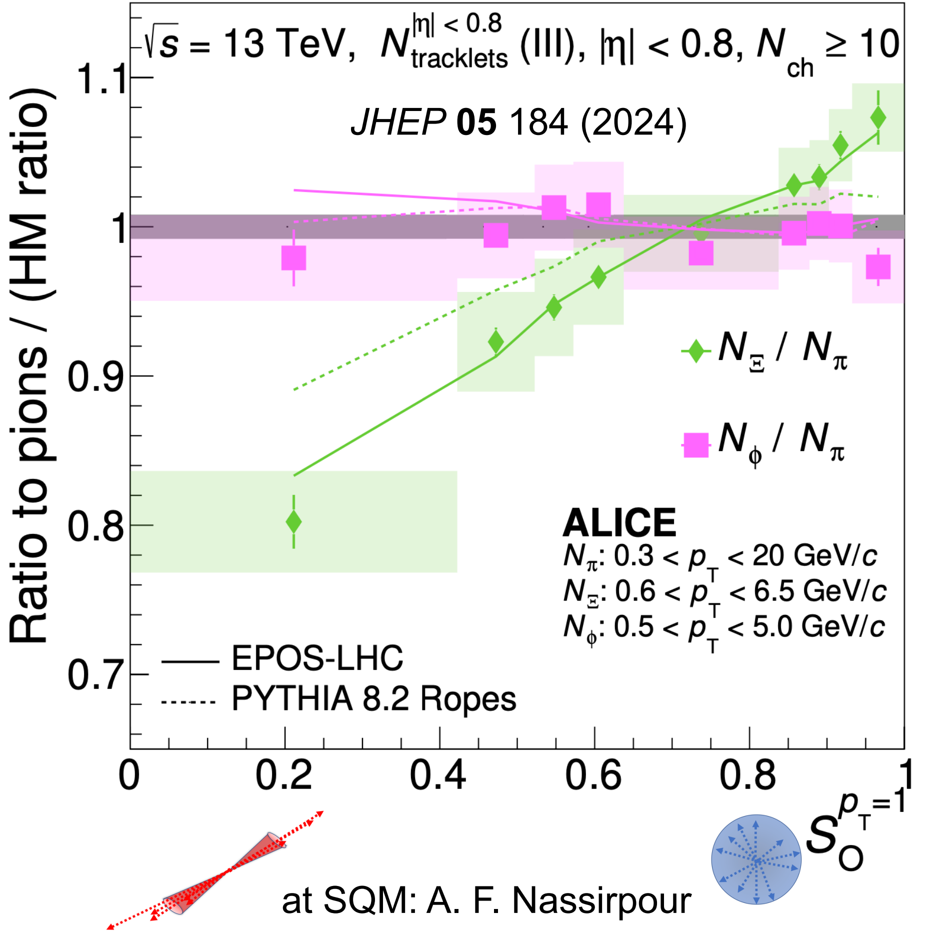
Hadrochemistry

Spherocity & ϕ

- The study observes that strange-hadron production is suppressed in jet-like events.
  - Strangeness enhancement connected to underlying event and soft processes.
- For 0–10% highest mult. pp, split sample into spherocity classes.
- Calculate the double ratio:

$$\frac{(h/\pi)_{\text{spherocity classes}}}{(h/\pi)_{\text{spherocity integrated}}}$$

- Double ratio increases for Ξ
- But not for ϕ: behaves like S=0 particle in this context.

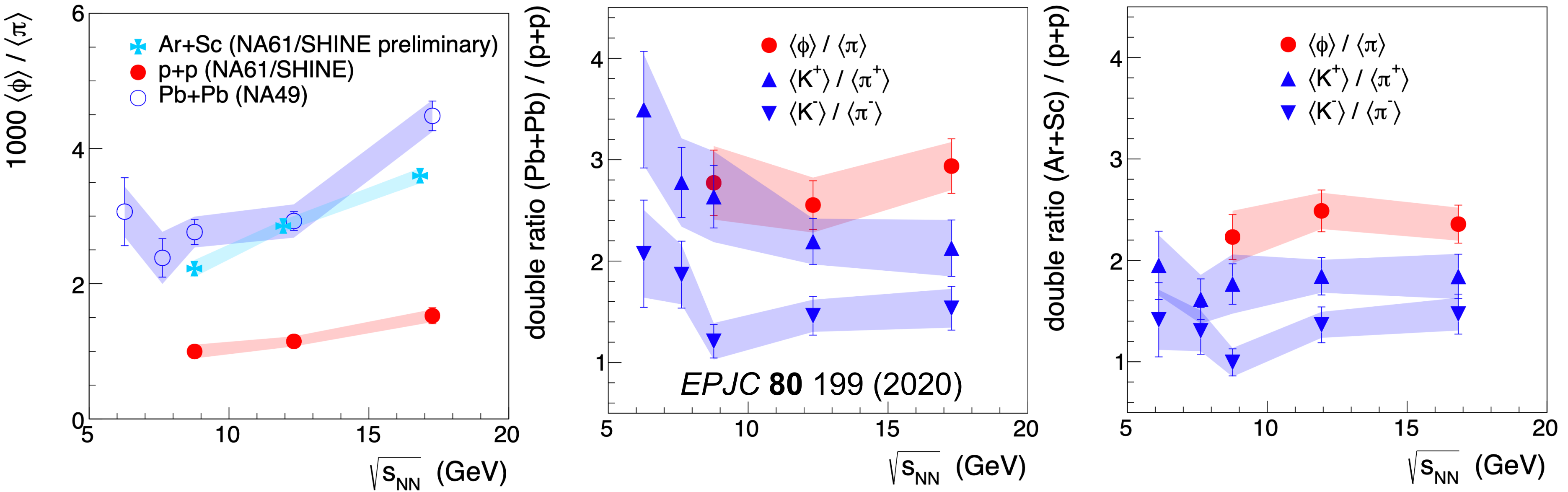


at SQM: A. F. Nassirpour

ϕ Enhancement: NA61/SHINE

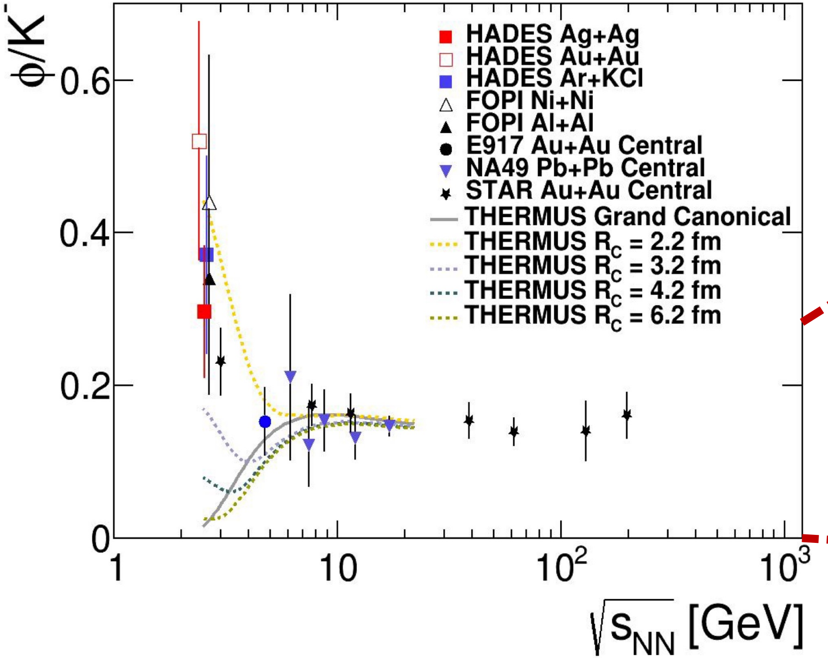
- The ϕ/π ratio increases w/ energy
- Ratio is higher in Ar+Sc & Pb+Pb collisions than in *p+p*.
- The ϕ/π ratio is higher than the $K^{\pm}/\pi^{\pm}$ ratios at the same energies.

at SQM: Ł. Rozpłochowski

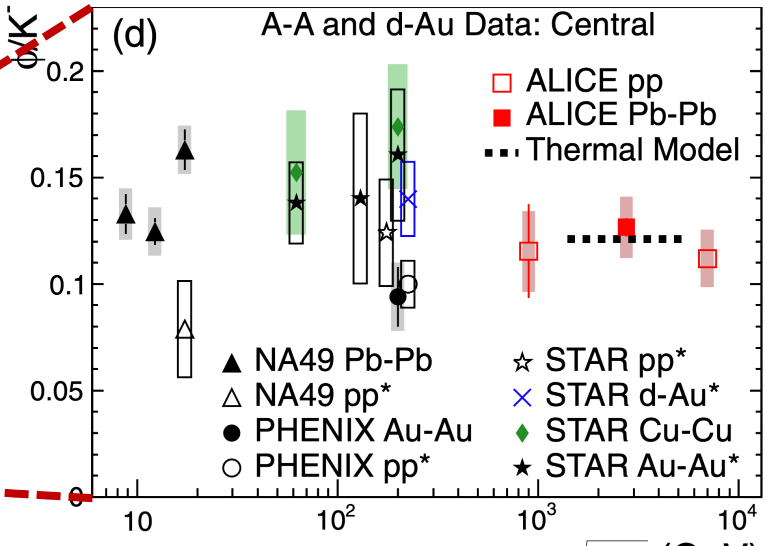


ϕ: Low Energy

- HADES, FOPI, & STAR measurements of ϕ/K around 3 GeV are greater than higher energy measurements → canonical suppression of K
- Measurements can be used to estimate correlation radius r_c in CSM, but disagreement between r_c values from ϕ/K^- and ϕ/Ξ ratios.



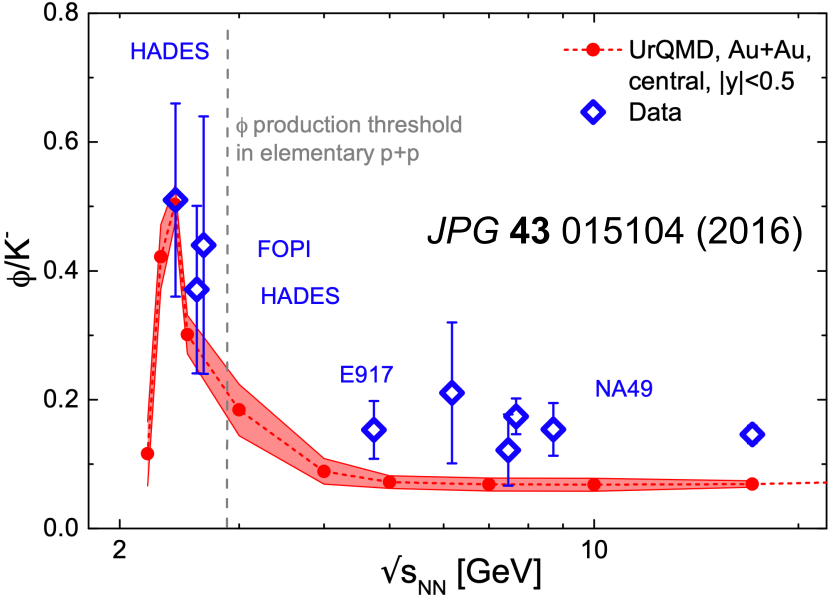
at SQM: M. Lorenz, S. Spies, M. Kohls

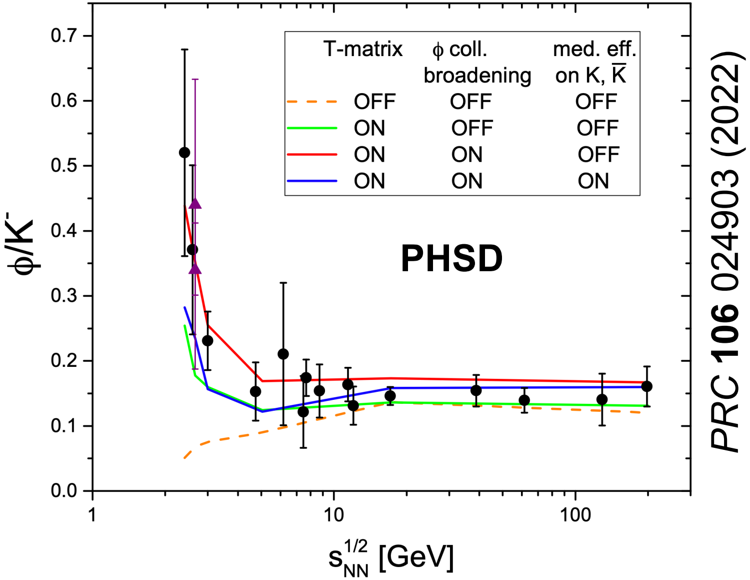


PRC **91** 024609 (2015)

ϕ: Low Energy

- UrQMD describes the observed behavior
  - Includes *N** resonances that decay to ϕ
- PHSD also describes the observed behavior
  - Introduces *T*-matrix approach and includes modified *K* mass as function of baryon density

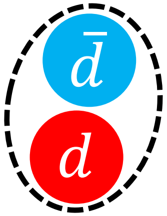




Hadron Structure

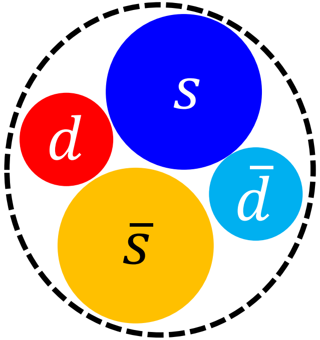
Exotic Mesons

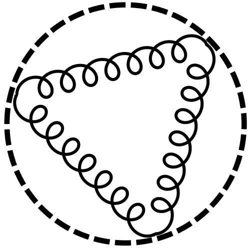
- Internal structures are unclear: “vanilla” meson, tetraquark, glueball, hybrid?



“vanilla” meson

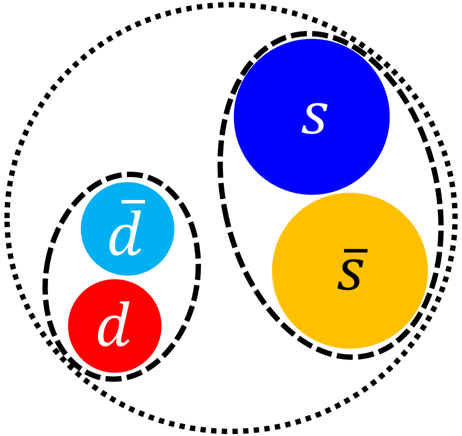
tetraquark



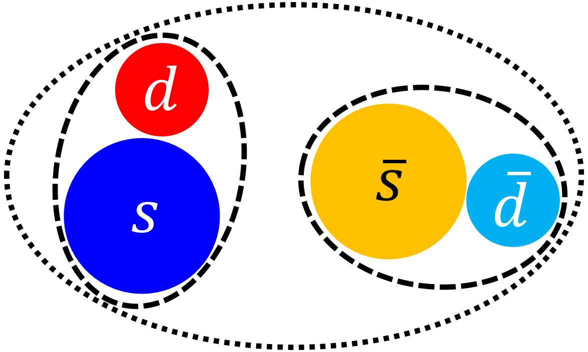


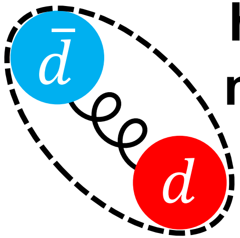
glueball

meson-meson molecule



diquark-antidiquark molecule

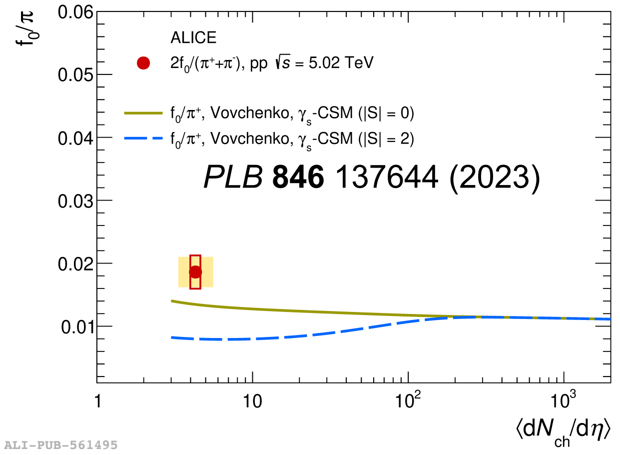


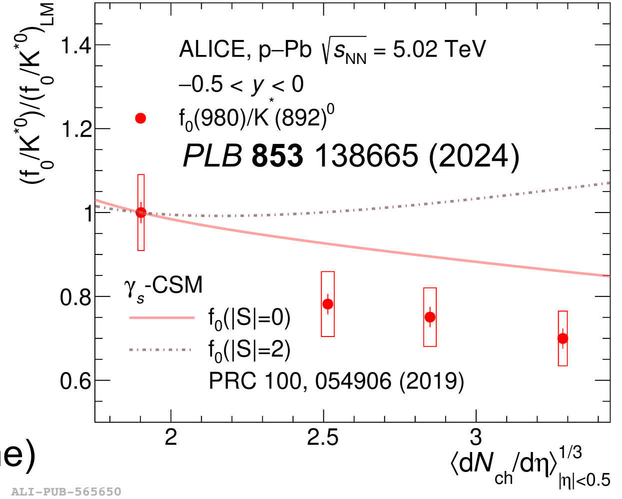


hybrid meson

$f_0(980)$

- Reconstructed via decay $f_0(980) \to \pi^+\pi^-$.
- ALICE *p*+*p*
  - Ratio $f_0(980)/\pi$ is underestimated by γ_S-CSM
  - Measured value disfavors the configuration with |*S*|=2 (particle is $s\bar{s}$)
- ALICE *p*+Pb
  - Ratio $f_0(980)/K^{*0}$ decreases with increasing multiplicity
  - Normalize ratio to low-multiplicity value:
  - γ_S-CSM predicts slow decrease w/ multiplicity for |*S*|=0
  - γ_S-CSM predicts slow increase w/ multiplicity for |*S*|=2
  - ALICE data favor |*S*|=0 (no strangeness) configuration
  - Also: measurements of nuclear modification factor do not exhibit Cronin enhancement → suggests that $f_0(980)$ has 2-(anti)quark structure



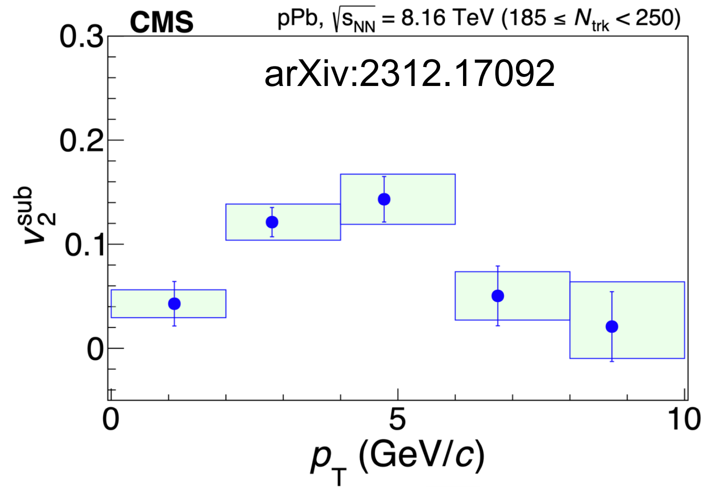


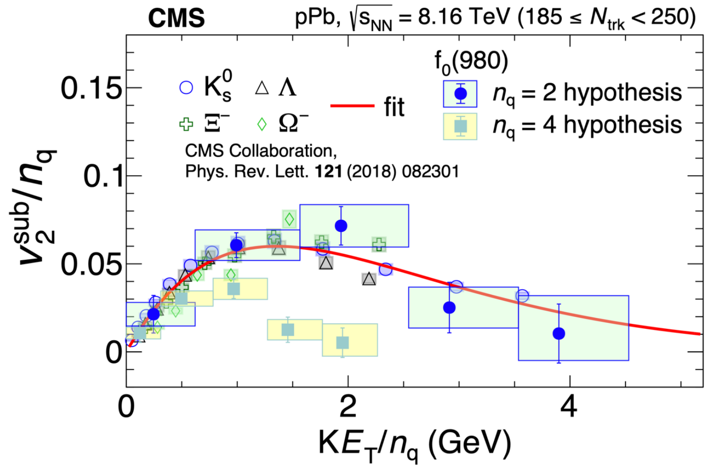
at SQM: P. Das (5 June)

$f_0(980)$

- CMS measures v_2 of $f_0(980)$ in p+Pb
- Then does NCQ scaling under different hypotheses for the number of valence partons inside the $f_0(980)$
  - "Vanilla" meson: n_q=2 ($q\bar{q}$)
  - Hybrid meson: n_q=3 ($q\bar{q}g$)
  - Tetraquark: n_q=4 ($q\bar{q}q\bar{q}$ or $K\bar{K}$ molecule)
  - Perform fit with n_q as a free parameter
- Preferred n_q value is near 2
  - n_q=3 excluded at 3.5σ level
  - n_q=4 disfavored

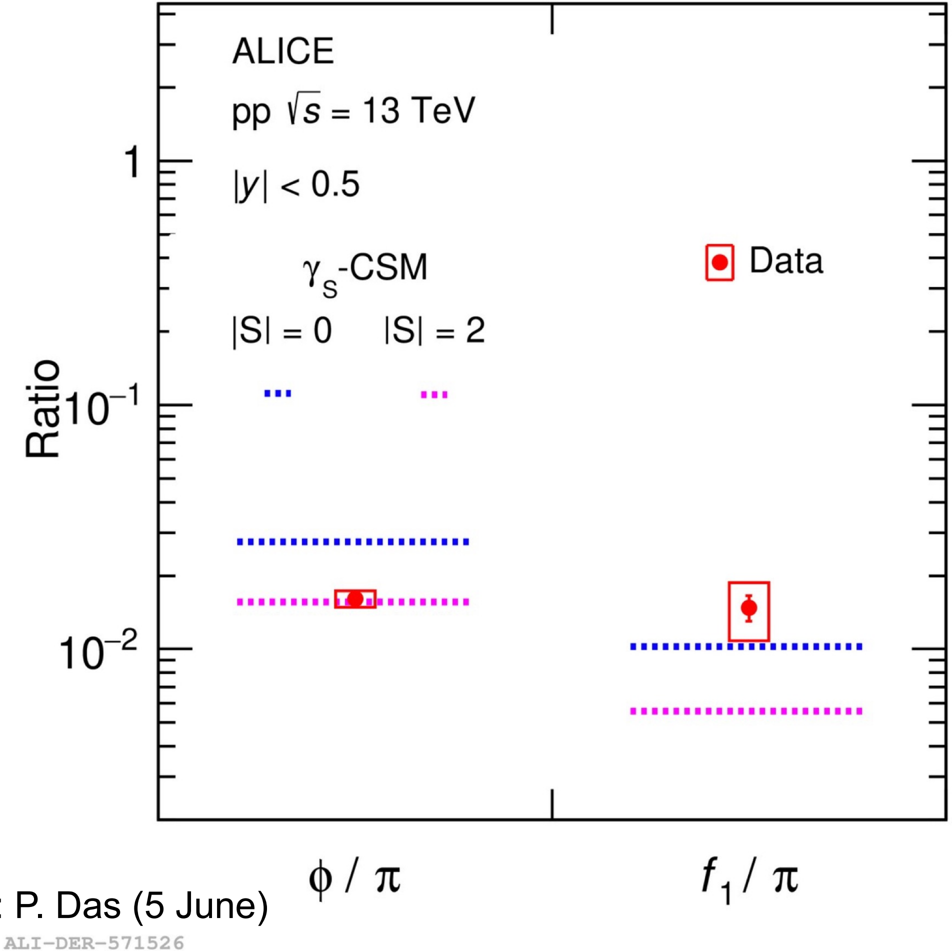
"we find strong evidence that the $f_0(980)$ hadron is a normal quark-antiquark state."





$f_1(1285)$

- ALICE: $f_1(1285) \rightarrow K_S^0 K^{\pm}\pi^{\mp}$ in *p*+*p*
- The γ_S-CSM preproduces the measured ϕ/π ratio under the |S|=2 assumption ($\phi = s\bar{s}$)
- The γ_S-CSM agrees better with ALICE measurement of $f_1(1285)/\pi$ ratio for |S|=0 assumption.



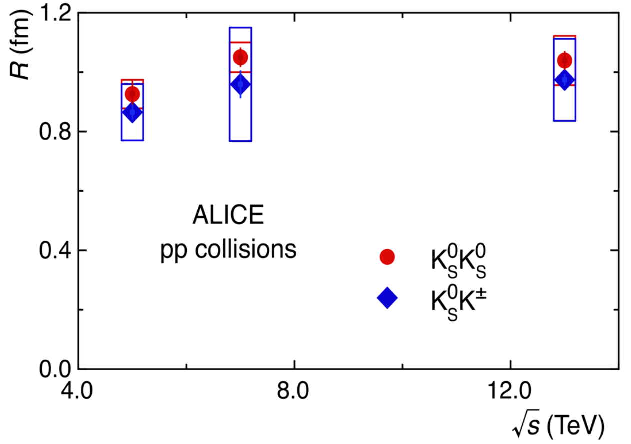
at SQM: P. Das (5 June)

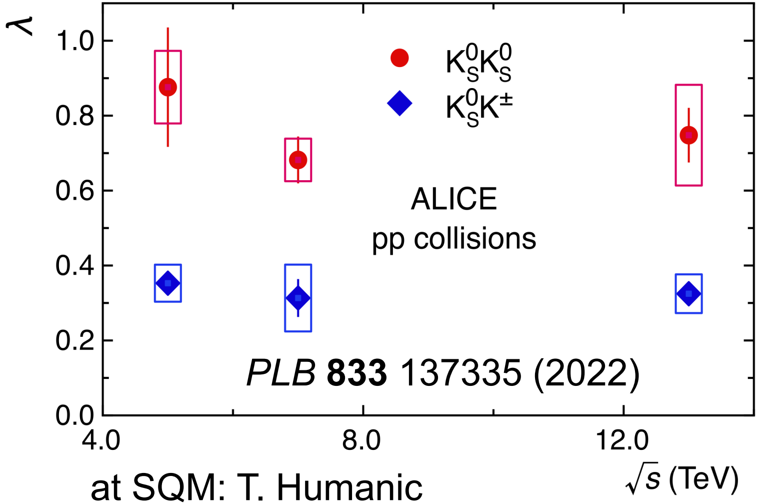
$a_0(980)^{\pm}$

- ALICE femtoscopy studies: measure correlation function of $K_S^0 K_S^0$ and $K_S^0 K^{\pm}$ pairs in *p*+*p*.

$$f_0(980) \rightarrow K_S^0 K_S^0$$
$$a_0(980)^{\pm} \rightarrow K_S^0 K^{\pm}$$

- Extract source radius *R* and correlation strength λ.
- No energy dependence.
- While *R* is same for both correlations, λ is significantly lower for $K_S^0 K^{\pm}$ pairs.
  - Suggests that $a_0(980)^{\pm}$ may be a tetraquark.





at SQM: T. Humanic

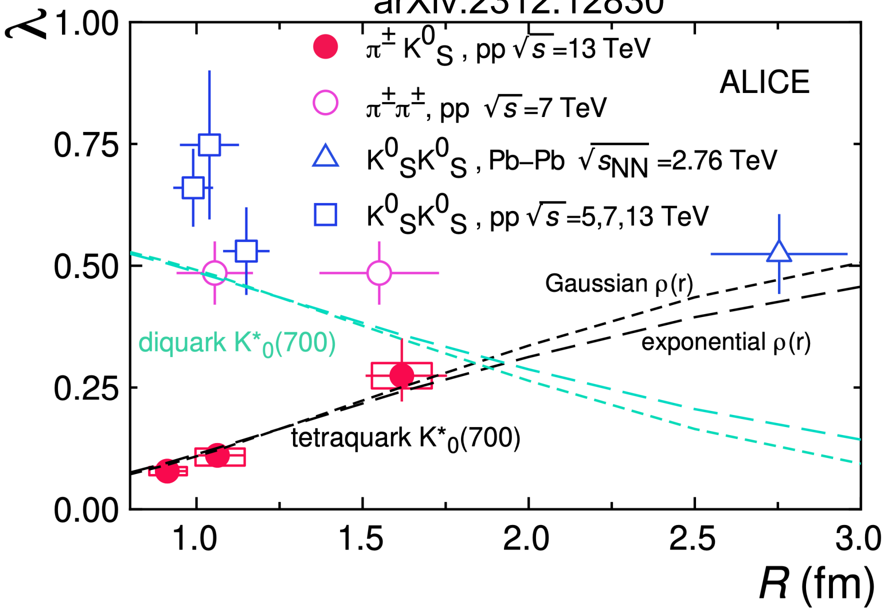
$K_0(700)^{\pm}$

- ALICE femtoscopy studies: measure correlation function $K_S^0\pi^{\pm}$ pairs in *p+p*.

$$K_0(700)^{\pm} \rightarrow K_S^0\pi^{\pm}$$

- Extract source radius *R* and correlation strength λ.
- Correlation strength λ is smaller than for $K_S^0K_S^0$ and $\pi^{\pm}\pi^{\pm}$ pairs.
- And λ increases with increasing *R* → this behavior is expected if $K_0(700)^{\pm}$ is a tetraquark.

arXiv:2312.12830

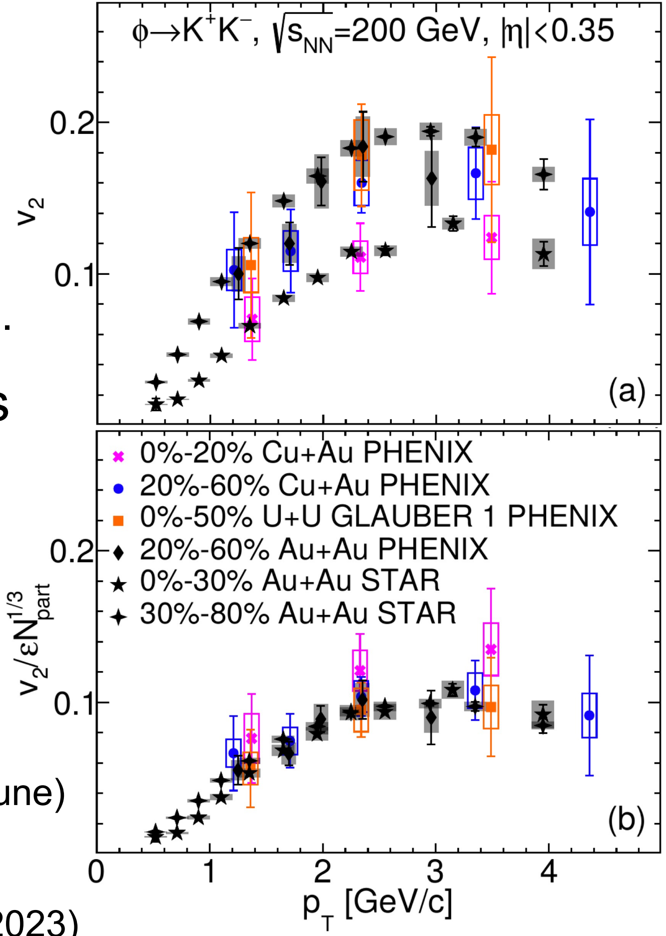


at SQM: T. Humanic

Flow & Vorticity

ϕ Meson v_2 at PHENIX

- PHENIX measures v_2 of ϕ mesons in Cu+Au and U+U collisions.
- v_2 values evolve with centrality and colliding species
  - Result for 0-50% U+U comparable to 30-80% Au+Au.
- But scaling by the empirical factor $\varepsilon N_{\mathrm{part}}^{1/3}$ gives a single curve.
- Also measurements of ϕ nuclear modification factors in Cu+Cu and U+U.

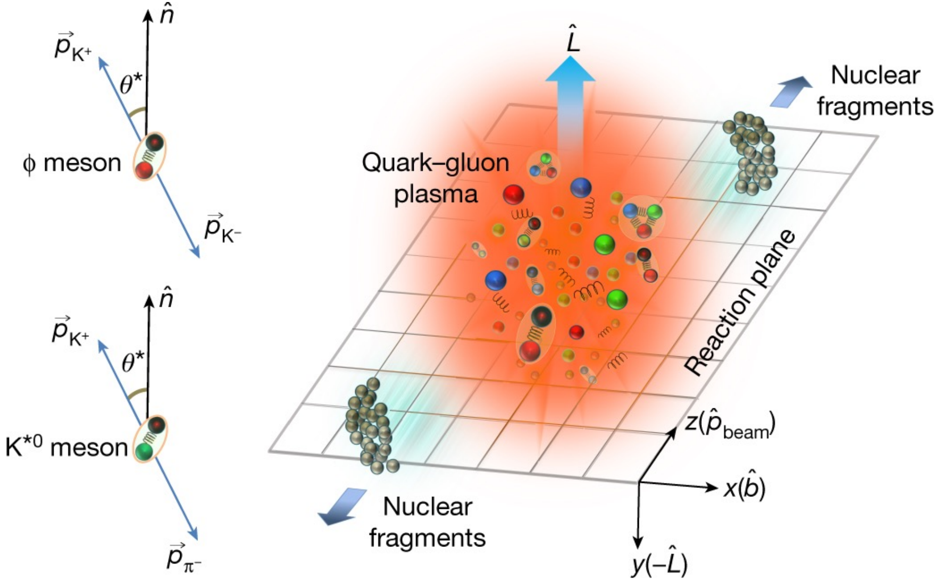


at SQM: R. Nouicer (4 June)

PRC **107** 014907 (2023)

Spin Alignment of Vector Mesons

- A+A collisions with non-zero impact parameter have large orbital angular momentum $\hat{L}$, which is ⊥ reaction plane
- Leads to vorticity in QGP
  → global polarization of quarks
  → global polarization of hadrons
  (Λ, vector mesons)
- For K^{*0} & ϕ :
  - Measure distributions of decay products as function of θ^*: angle w.r.t. quantization axis ($\hat{L}$).
  - Fit to extract ρ_{00}, element of spin density matrix →



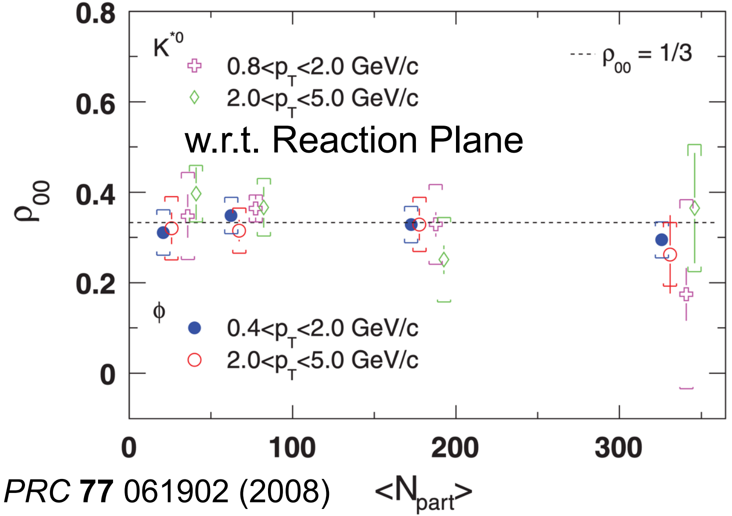
STAR, *Nature* **614** 244–248 (2023)

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

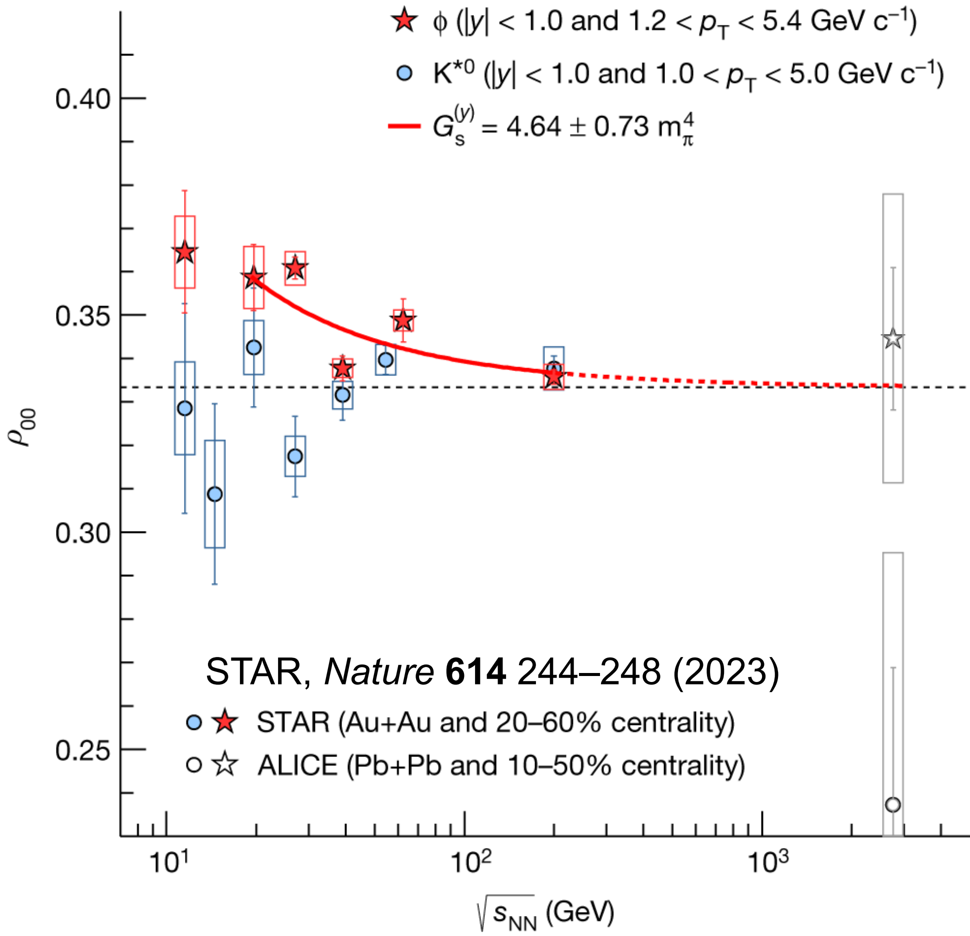
$\rho_{00} = \frac{1}{3}$ means no polarization

Spin Alignment of Vector Mesons

- STAR measures ρ_{00} for K^{*0} & ϕ in Au+Au collisions, 11.5 to 200 GeV
- 200-GeV measurements consistent with no polarization
- But lower energy (11.5 to 62 GeV) data have $\rho_{00} > \frac{1}{3}$ at 7.4σ for ϕ.

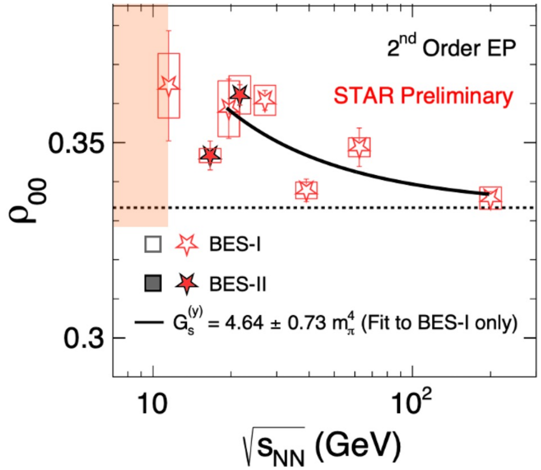


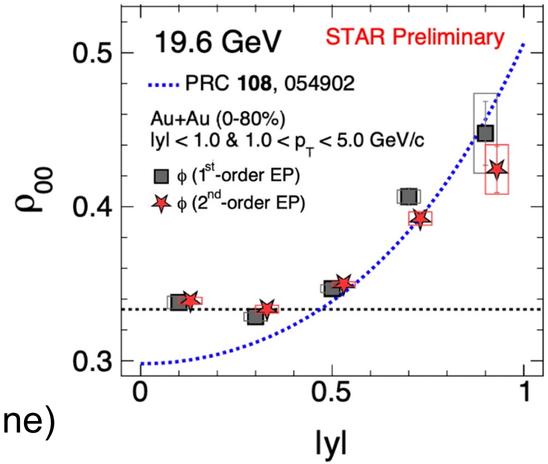
STAR, *PRC* **77** 061902 (2008)



Spin Alignment of Vector Mesons

- Preliminary STAR measurements in BES-II confirm $\rho_{00} > \frac{1}{3}$ deviation for ϕ.
- Rapidity dependence: deviations become larger with larger $|y|$.
  - Consistent with theoretical prediction.
  - Particles moving with larger $|y|$ see larger field fluctuations in direction ⊥ motion.





at SQM: G. Wilks (5 June)

Conclusions

- Resonances give us multiple ways to probe the properties of ion-ion collision systems (both large and small).
- Experimentalists have accumulated a useful collection of many different types of results on many different resonances.
- Theorists are continuing to come up with ingenious ways to describe these measurements and predict new things to search for.
- Looking ahead, improvements in detectors and accelerators will allow us to add new, rare resonances to the toolbox.

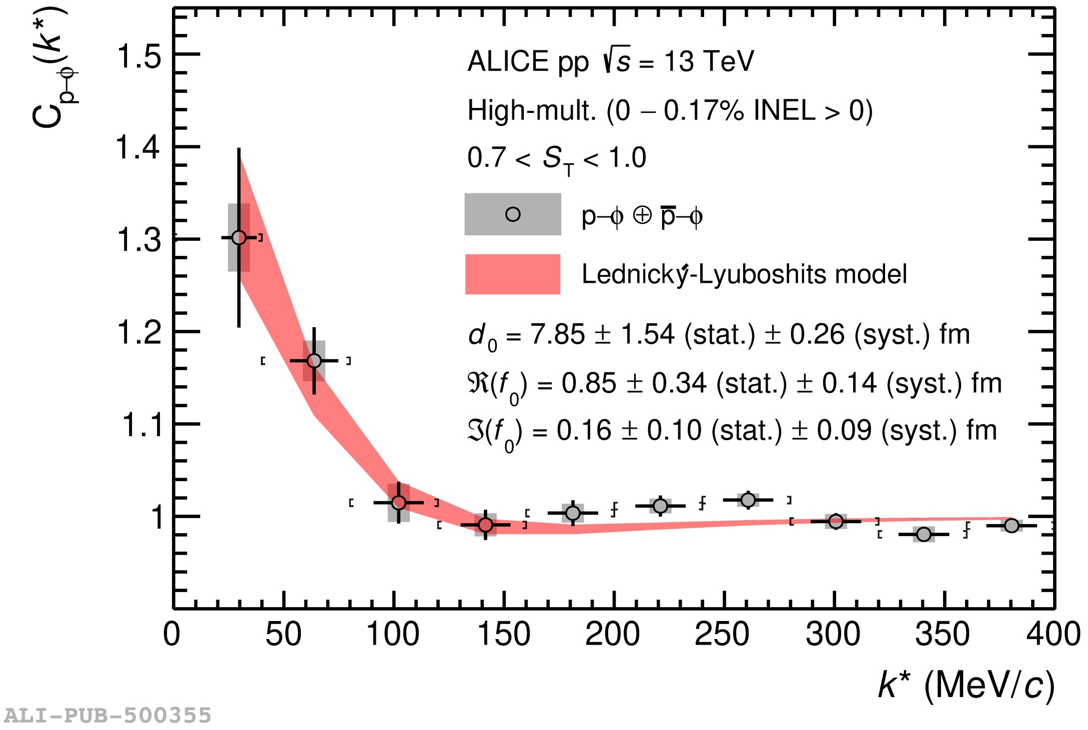
- Thanks to the many people and groups whose plots I used!
- Thanks to the organizers for giving me the opportunity to speak today!

Backup Material

p–ϕ interaction

- ϕ proposed as mediator for repulsive hyperon-hyperon force
  - Important for neutron star EoS
- Attraction between p & ϕ in pp collisions (first measurement)
- Scattering parameters extracted
- Extracted Yukawa-type coupling constant for N–ϕ interaction

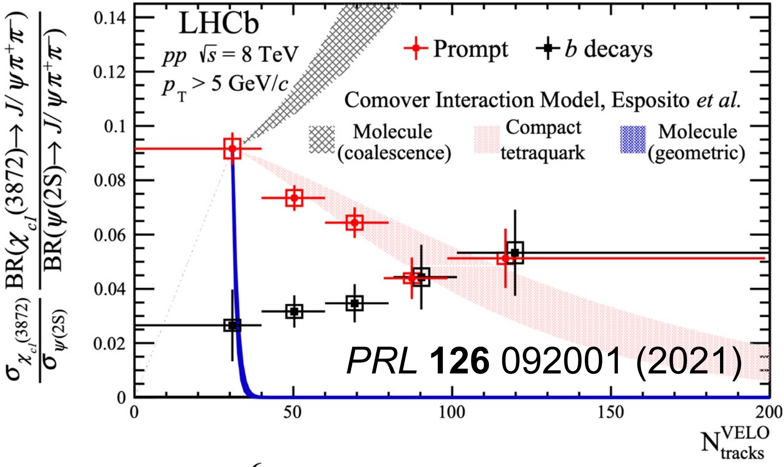
  $g_{N-\phi}$ = 0.14 ± 0.03 (stat.) ± 0.02 (syst.)
- ALICE: Observation seems to be incompatible with bound state.
- Subsequent studies suggest a possible bound state in $^2S_{1/2}$ channel (E_B of 10–70 MeV).
  - At SQM: K. Kuroki (5 June)

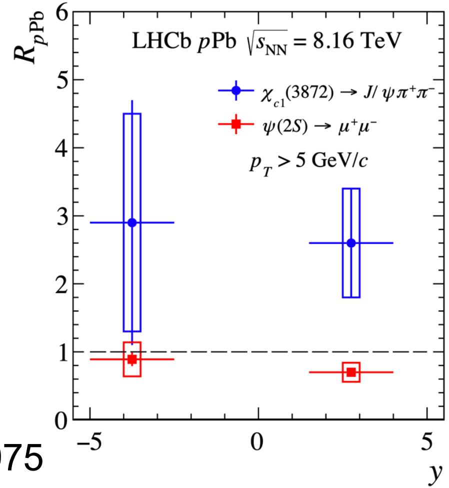


PRL **127** 172301 (2021)

$\chi_{c1}(3872)$

- Long-standing questions about structure of $\chi_{c1}(3872)$.
- LHCb observes gradual decrease of $\chi_{c1}(3872)/\psi(2S)$ ratio with increasing multiplicity.
  - Consistent w/ compact tetraquark structure → dissociation stronger as mult. increases.
  - Not enough coalescence in p+p.
- LHCb observes enhancement of $\chi_{c1}(3872)$ in p+Pb.
  - Different behavior than $\psi(2S)$.
  - Also consistent w/ compact tetraquark structure.
  - Greater importance of coalescence in this collision system.

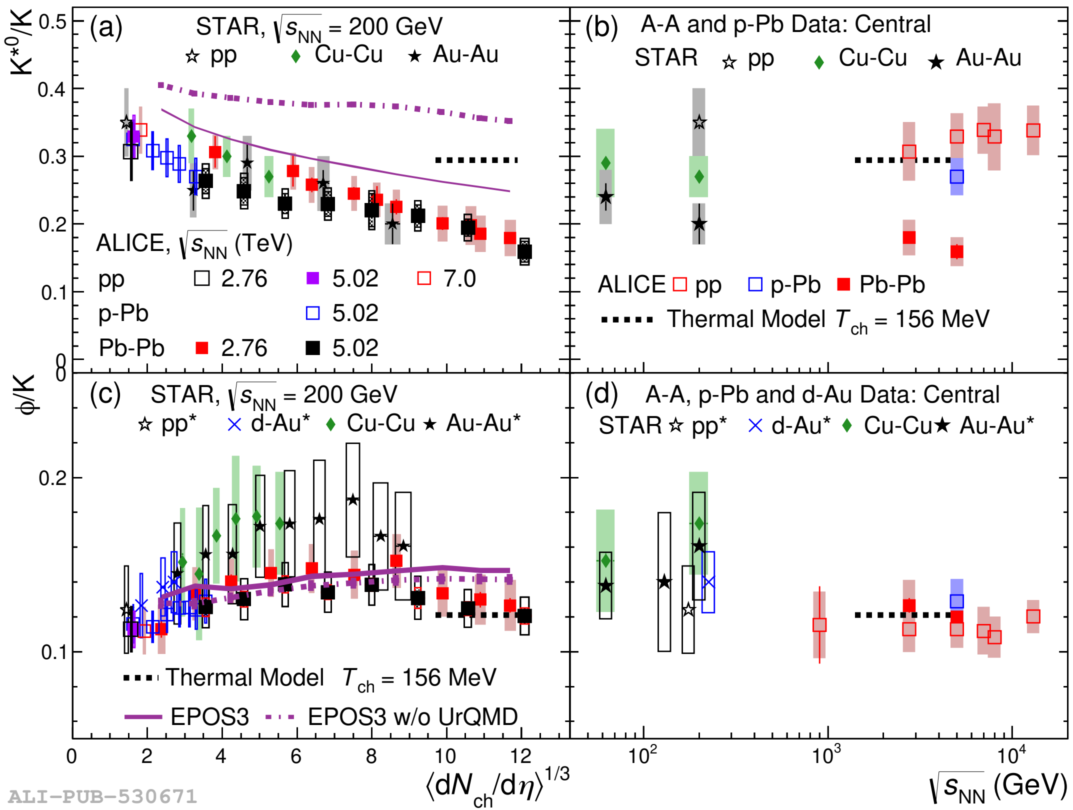




arXiv:2402.14975

K^{*0} & ϕ: Energy Dependence

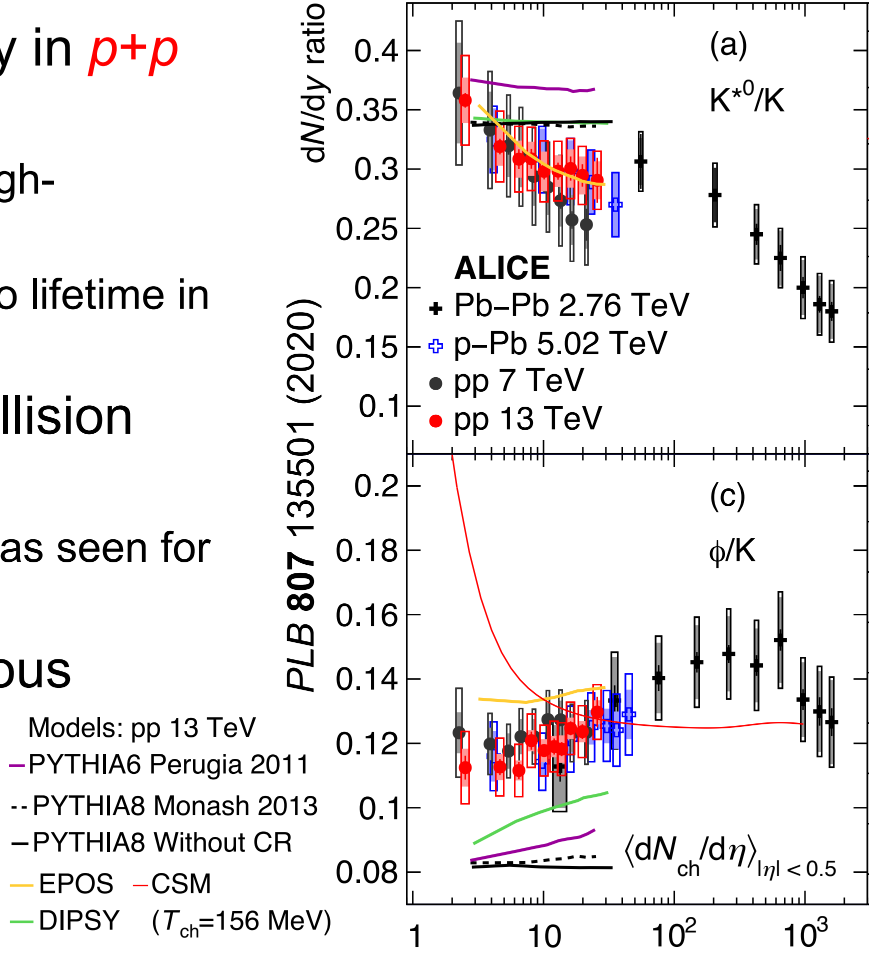
- These ratios have also been measured by STAR in p+p, d+Au, Cu+Cu, & Au+Au
  - STAR also observes smooth transitions between collision systems → resonance yield ratios controlled by multiplicity
  - No clear energy dependence for RHIC up to LHC energies
  - One possible exception: STAR ϕ/K measurements are systematically higher than ALICE in A+A collisions



PLB **807** 135501 (2020)

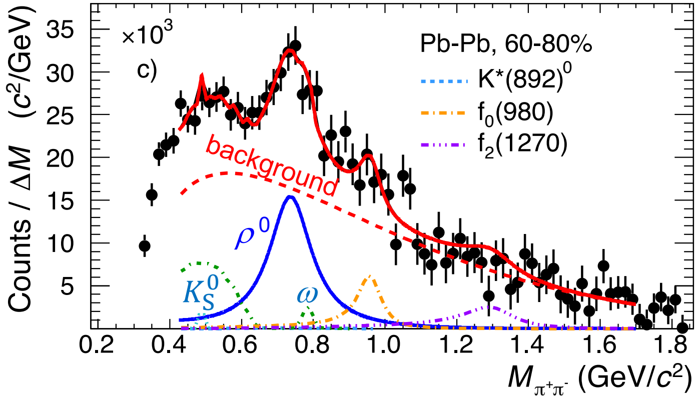
K^{*0} & ϕ: Small Systems

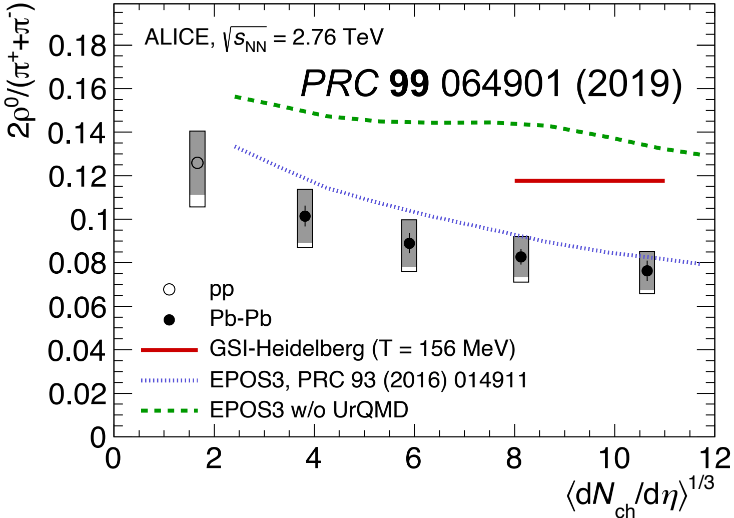
- Measurements of K^{*0} & ϕ vs. multiplicity in *p+p* and *p+Pb* collisions
  - Intriguing suggestion of K^{*0} suppression in high-multiplicity *p+p*, *p+Pb*
  - Could be hint of hadronic phase with non-zero lifetime in small systems
- Smooth transitions between different collision systems as function of multiplicity
  - Resonance yields controlled by system size (as seen for yields of longer-lived hadrons)
- For *p+p* at 13 TeV: comparisons to various models
  - EPOS-LHC provides best description of K^*/K



Short-Lived: ρ^0

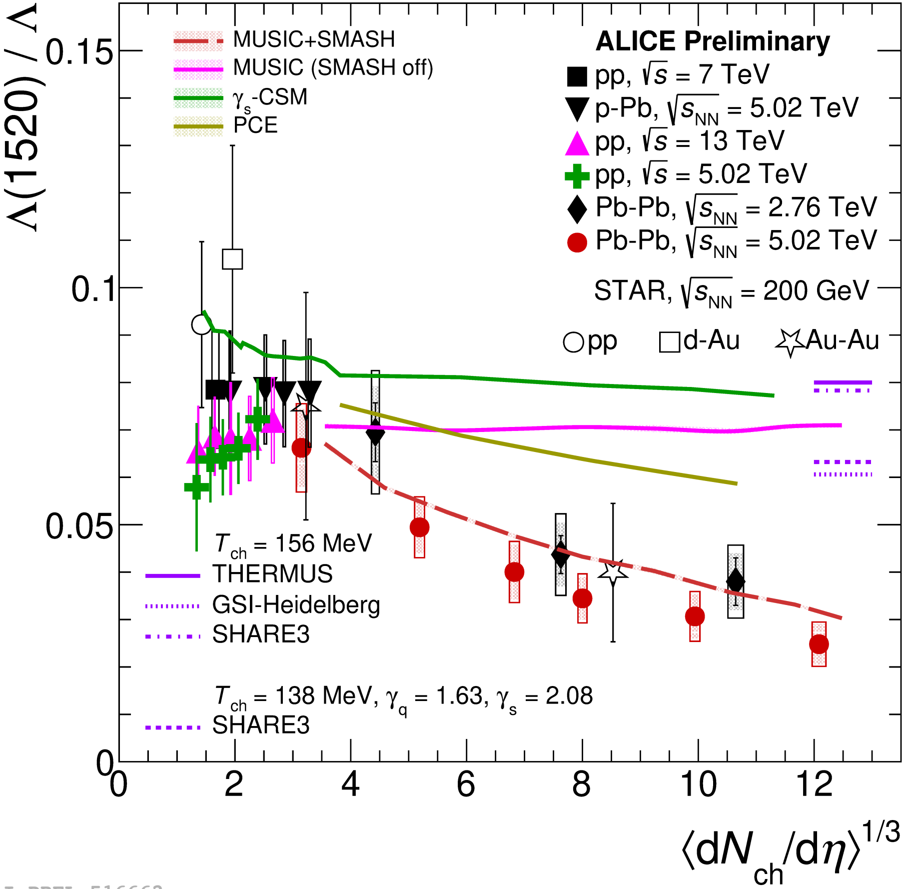
- A wide resonance → complicated to fit
- Like *K**, observe decreasing trend with increasing multiplicity
  - Suppression of ρ^0/π in central Pb+Pb collisions
  - And hint of decrease in *p*+Pb
- EPOS
  - EPOS w/o UrQMD: ρ^0/π decreases only weakly
  - EPOS w/ UrQMD: good qualitative agreement, but systematically above ALICE measurement
- Consistent with resonance suppression in hadronic phase, effects of re-scattering dominant over regeneration





Short-Lived: $\Lambda(1520)$

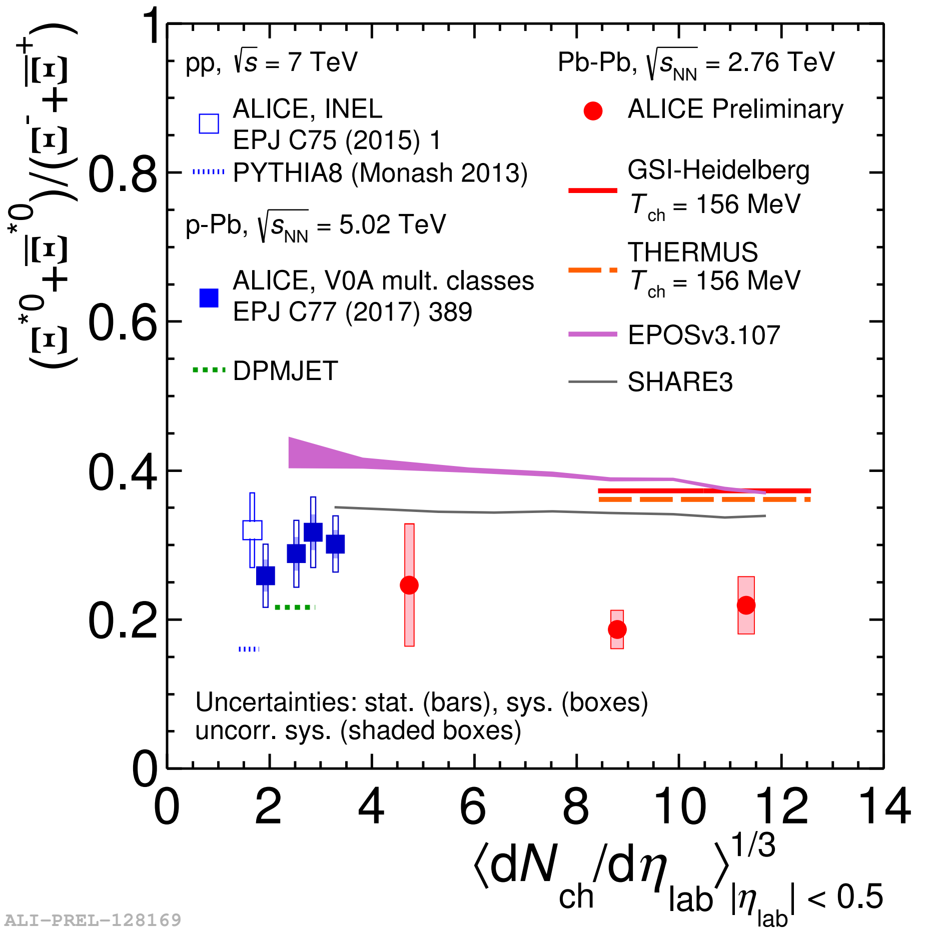
- Suppression of $\Lambda(1520)/\Lambda$ in central *A*+*A* w.r.t. *p*+*p*, *p*+Pb, and thermal models
- Flat (or increasing w/ multiplicity) for small systems
- No energy dependence for RHIC→LHC
- Model Comparisons:
  - Qualitatively described by EPOS
  - Decent description by MUSIC+SMASH
  - PCE, γ_S CSM do not describe the suppression
  - Or suppression of *p*-wave baryons [$\Lambda(1520)$] in recombination model [*PRC* **74** 061901(R) (2006)]



ALI-PREL-516662

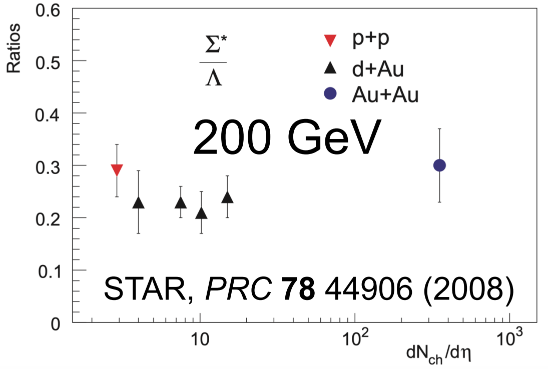
Intermediate Lifetime: Ξ^{*0}

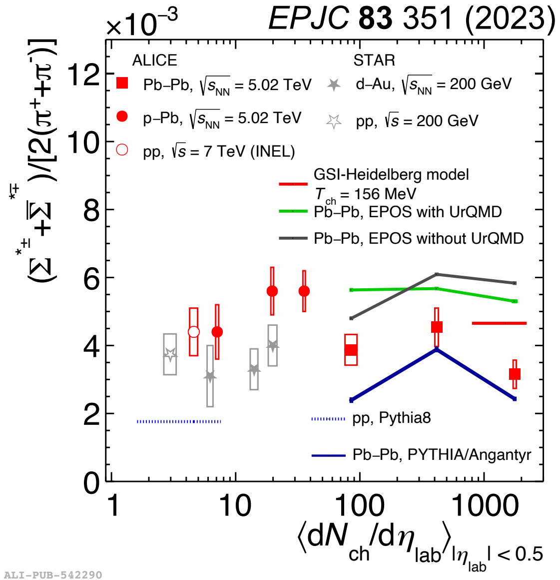
- In Pb+Pb:
  - No significant centrality dependence
  - Flat trend qualitatively described by EPOS and SHARE3
  - Systematically lower in (mid-)central Pb+Pb than in *p*+*p* and *p*+Pb
  - Below thermal model
  - Weak suppression?
- In *p*+*p* and *p*+Pb: No clear multiplicity dependence



Short Lifetimes: $\Sigma^{*\pm}$

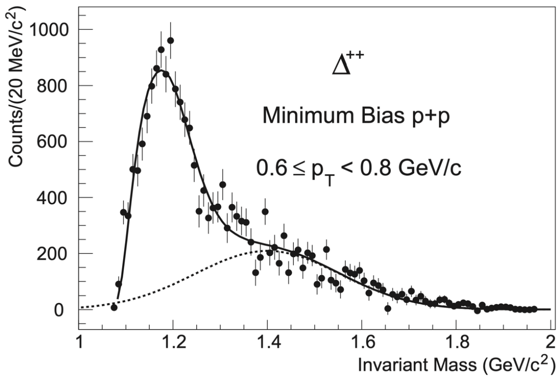
- STAR observes flat $\Sigma^{*\pm}/\Lambda$ ratio from p+p & d+Au to Au+Au collisions
- ALICE: no multiplicity dependence in small systems
- ALICE has not reported final $\Sigma^{*\pm}/\Lambda$ ratio in Pb+Pb yet.
  - The $\Sigma^{*\pm}/\pi^{\pm}$ ratio deviates below thermal model for central collisions
  - But shows only weak centrality dependence in Pb+Pb
  - Does re-scattering balance out strangeness enhancement?
- EPOS overpredicts the value, but can describe the shape
- PYTHIA8 + Angantyr also describes the shape

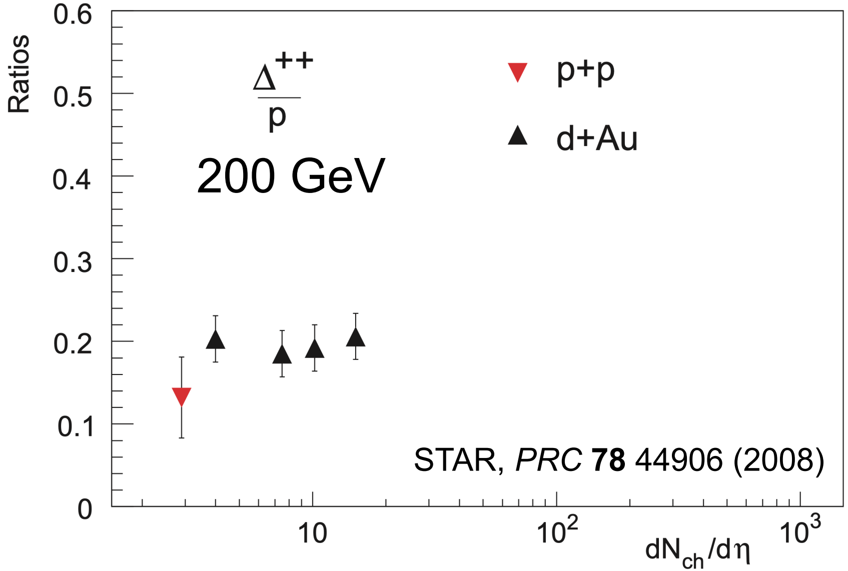




Short Lifetimes: Δ

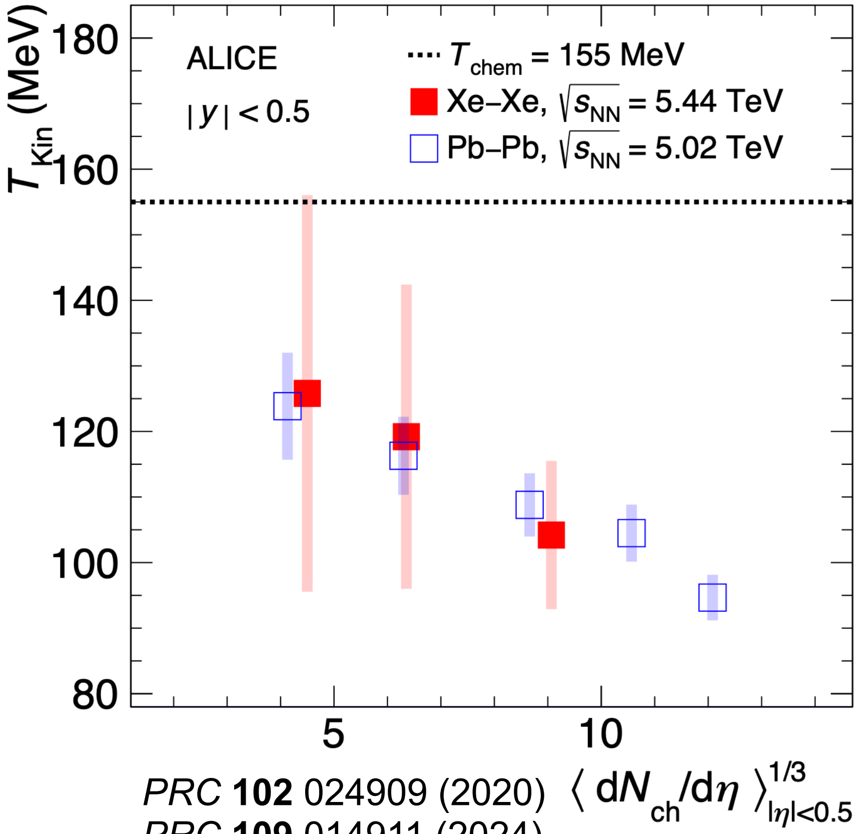
- Difficult to measure (background)
- STAR observes no clear multiplicity dependence in Δ^{++}/p ratio in *p+p* and *d*+Au collisions
- EPOS predicts no significant suppression as function of multiplicity (at LHC energies)
- Would be an interesting missing piece to fill in if we could do it.





Hadronic Phase

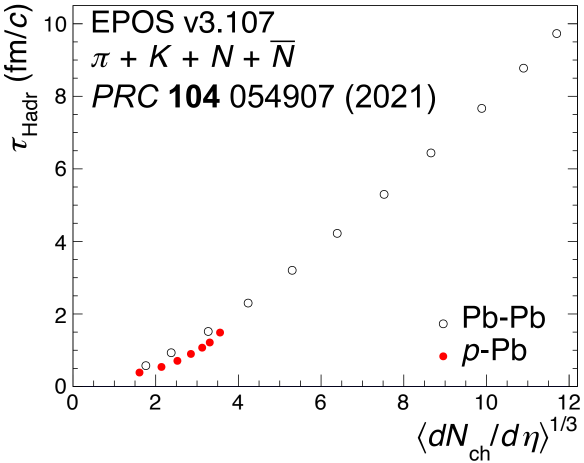
- Use HRG PCE model to fit measured yields of $\pi^{\pm}$, $K^{\pm}$, p, ϕ, & K^{*0}
- Extract kinetic freeze-out temperature in Pb+Pb and Xe+Xe collisions at LHC energies
- Values range from 90 to 130 MeV, somewhat lower than T_{chem}
- T_{kin} decreases as collision centrality increases, consistent with a longer-lived hadronic phase
- Values for the two collision systems are consistent for similar multiplicities.

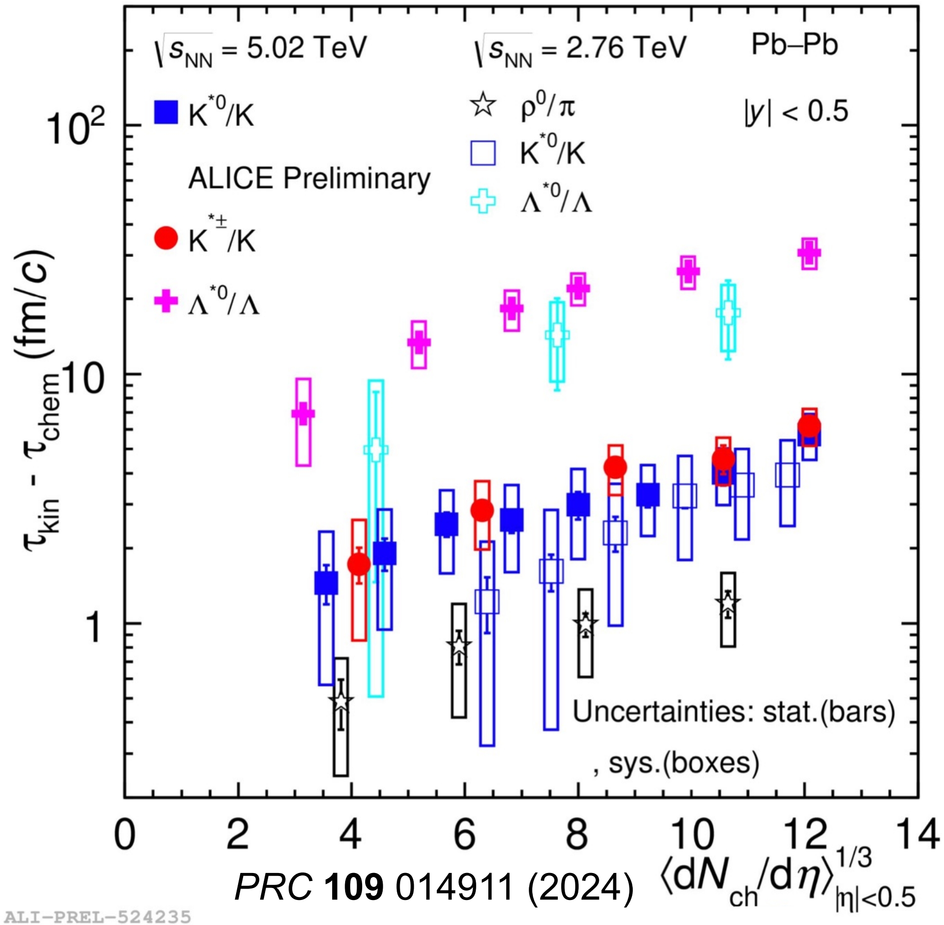


PRC **102** 024909 (2020)
PRC **109** 014911 (2024)

Hadronic Phase

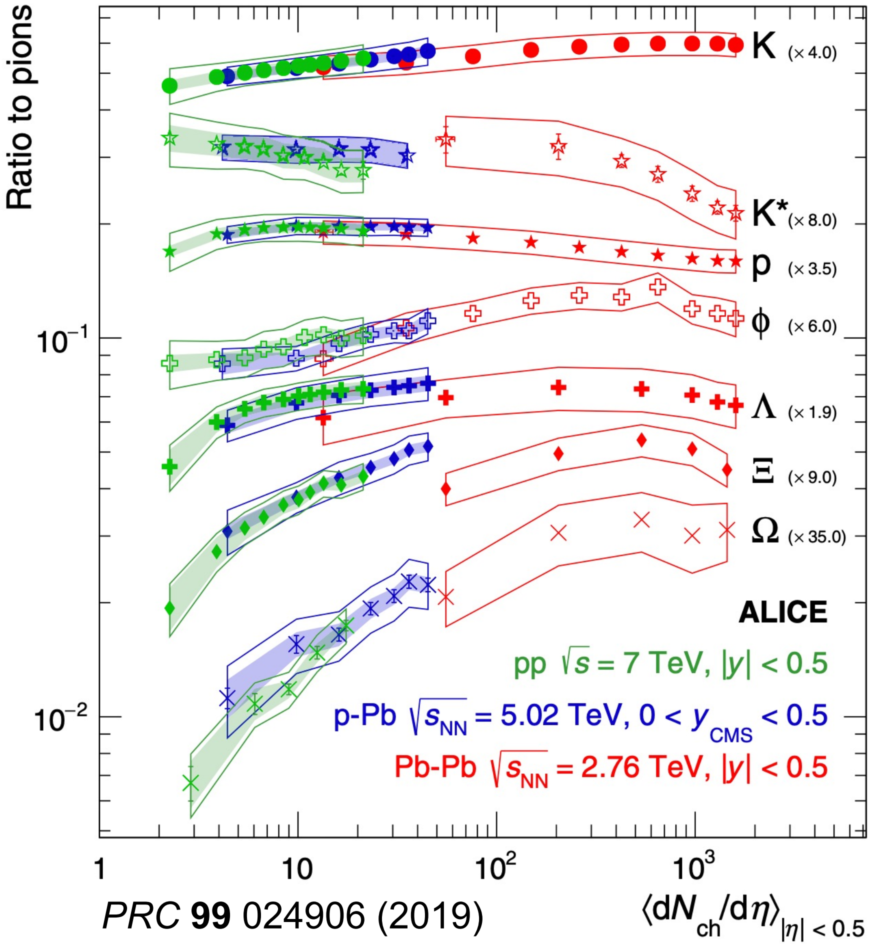
- Procedure can be extended to other particles [$K^{*\pm}$, ρ^0, $\Lambda(1520)$]
- For each class of particle, the lifetime increases smoothly with multiplicity
- Earlier study estimated hadronic phase lifetime in EPOS:





ϕ Enhancement

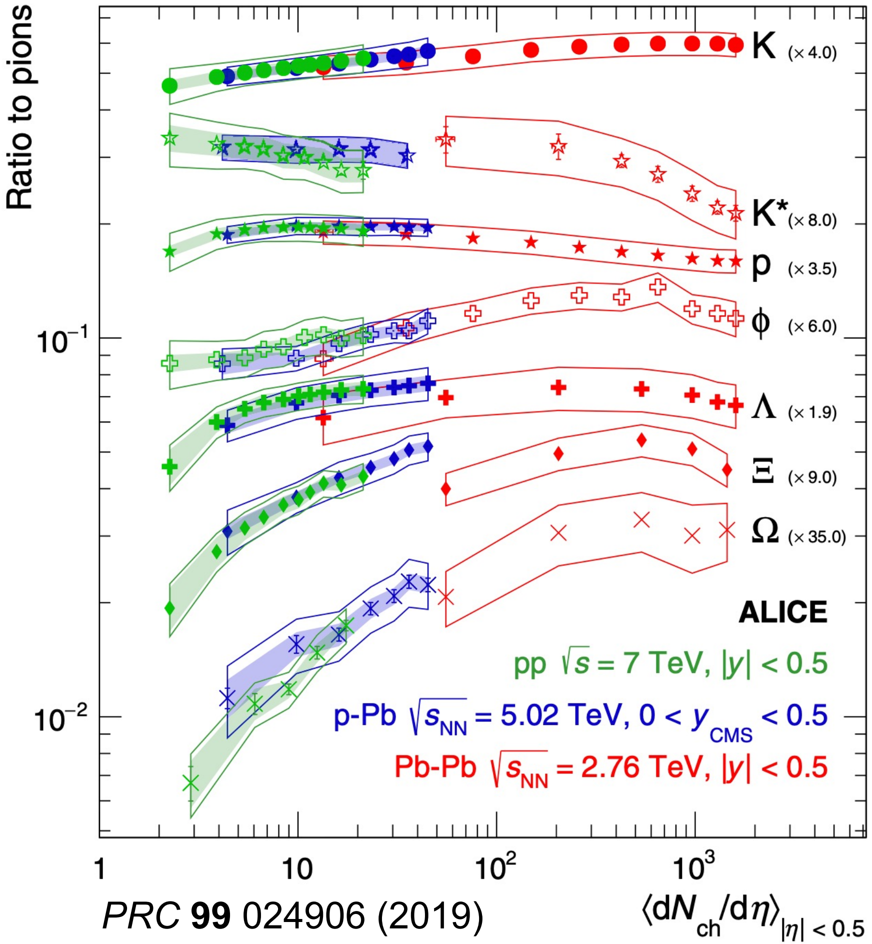
- Strange particle production increases with increasing system size
- And particles containing more *s* squarks are enhanced more.
- How does the ϕ meson ($s\bar{s}$) fit?
  - Does it behave like an *S*=0 particle?
  - Or *S*=2? Or some effective strangeness between 0 & 2?
  - Different theoretical treatments (canonical suppression, color ropes, …) may give different answers.



PRC **99** 024906 (2019)

ϕ Enhancement

- The ϕ/π ratio is not flat → ϕ does not seem to behave like *S*=0 particle.
  - Models where the strangeness evolution is due to canonical suppression at low multiplicity predict a flat ratio.
- ϕ/K ratio is pretty flat, although ϕ may be enhanced slightly more than *K*.
  - Canonical suppression of *K* → higher ϕ/K ratio at low mult.: inconsistent w/ data.
- ϕ is enhanced less than Ξ (*S*=2).
- So does the ϕ have an "effective strangeness" between 1 and 2?
  - A recent spherocity study by ALICE may complicate the interpretation…

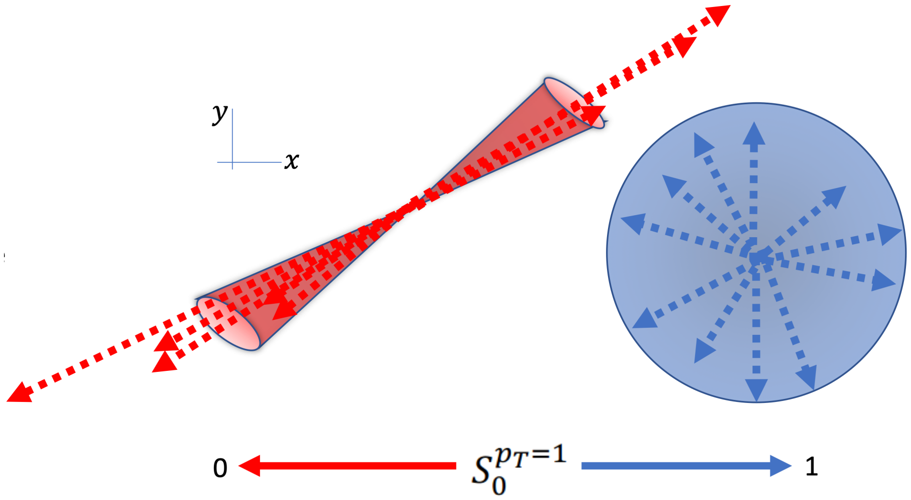


PRC **99** 024906 (2019)

Spherocity

- Spherocity $S_0^{p_{\mathrm{T}}=1}$ quantifies extent to which a given event is
  - Azimuthally isotropic ($S_0^{p_{\mathrm{T}}=1}$=1) or
  - Back-to-back “jet-like” ($S_0^{p_{\mathrm{T}}=1}$=0).
- ALICE performed a study of hadron production (π, K, p, ϕ, K^{*}, Λ, Ξ) in high-multiplicity pp collisions.
  - *JHEP* **05** 184 (2024)
  - The resonances are part of a comprehensive study → see A. F. Nassirpour’s talk (4 June) for full details.
  - But let’s look at one ϕ result…

$$S_0^{p_{\mathrm{T}}=1} = \frac{\pi^2}{4} \min_{\hat{n}} \sum_i \left(\frac{|\hat{p}_{\mathrm{T},i} \times \hat{n}|}{N_{\mathrm{trk}}} \right)$$



at SQM: A. F. Nassirpour