Resonance production and interaction from low to high energy

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Introduction

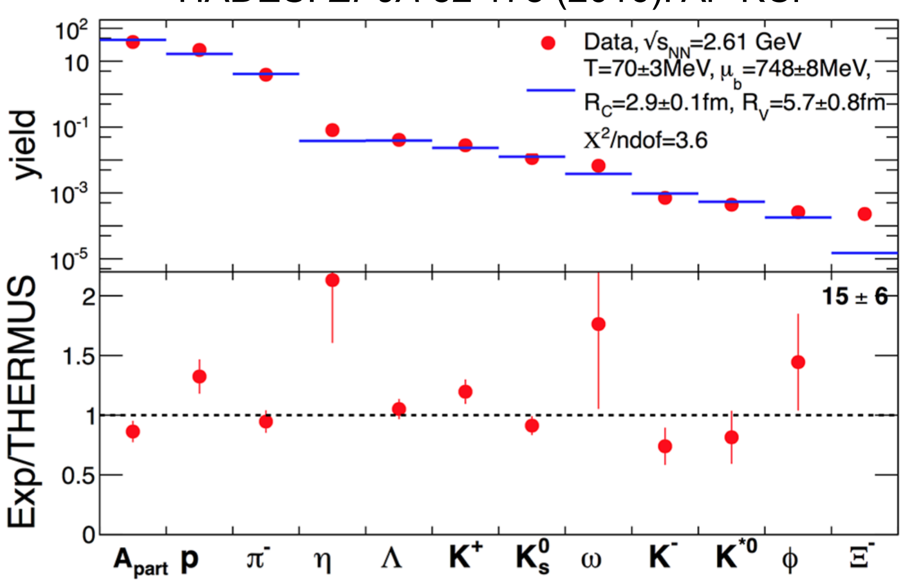
- Hadrochemistry
  - What controls it? How does it evolve from small to large systems?
  - Strangeness enhancement
  - Hadronic phase and resonance suppression
  - Hadron spectroscopy
- How are resonance properties modified by strongly interacting medium?
  - Chiral symmetry restoration, collisional broadening
  - Low-mass dileptons and ρ broadening
  - Parity doubling

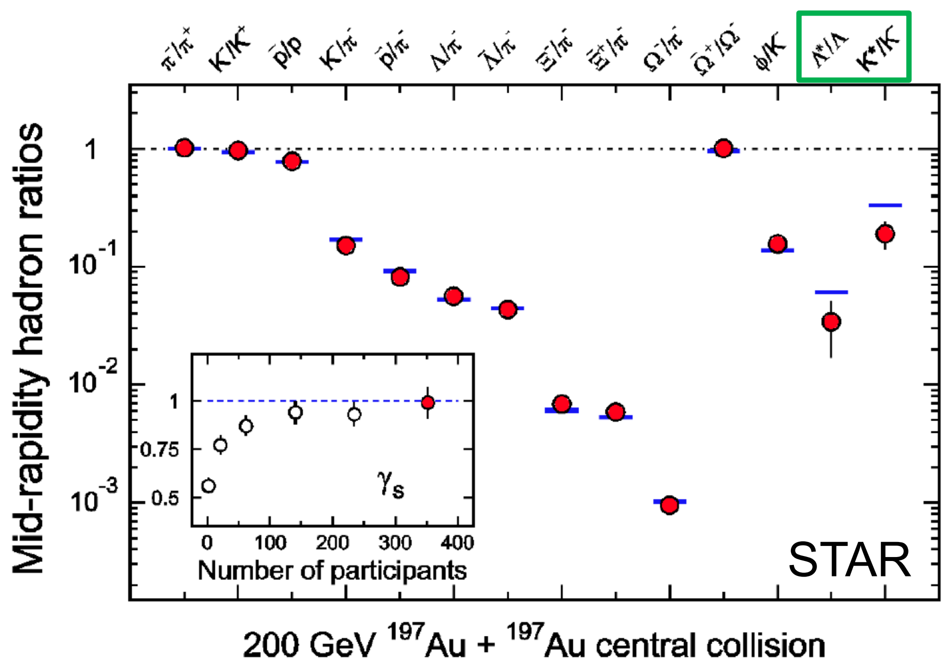
Hadrochemistry

Thermal Models

- Most light-flavor hadron yields described fairly well by thermal models
- Sometimes need mechanisms to suppress strangeness (γ_S, R_C)
- Short-lived resonances (K^{*0}, Λ^*) tend to deviate (may be excluded from fits)
- Work from low energies…

HADES: *EPJA* **52** 178 (2016): Ar+KCl





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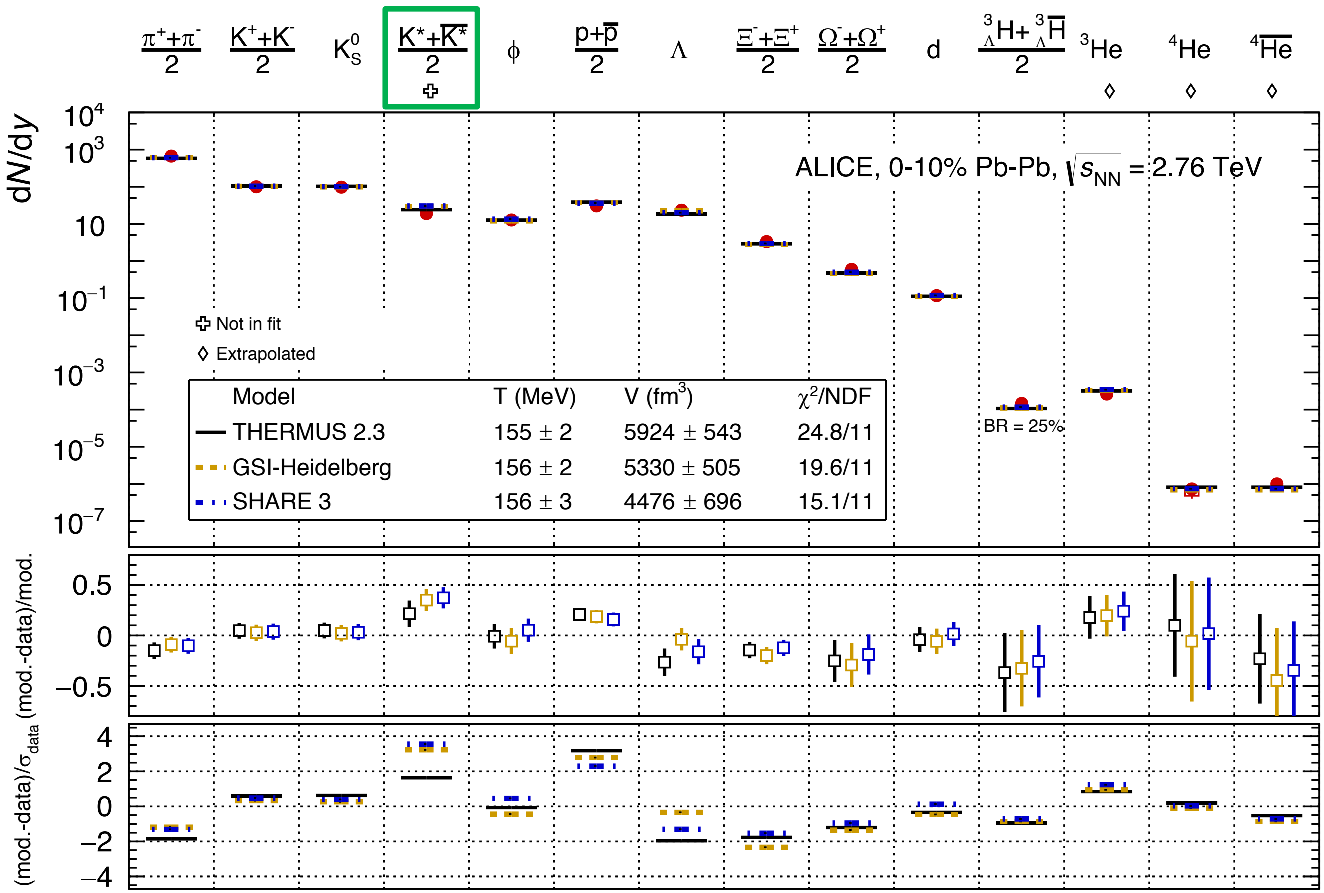
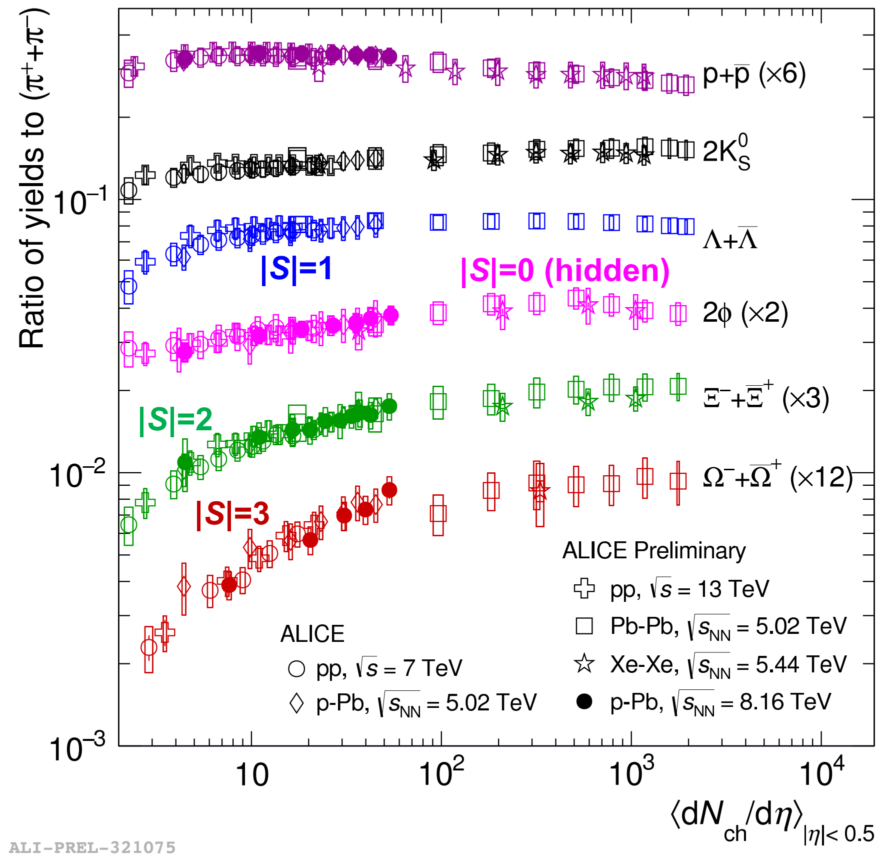
- Work from low energies up to high energies



Nucl. Phys. A **971** 1-20 (2018)
THERMUS: Wheaton *et al.*, *Comput. Phys. Commun.* **180** 84 (2009)
GSI-Heidelberg: Andronic *et al.*, *PLB* **673** 142 (2009)
SHARE: Petran *et al.*, *Comput. Phys. Commun.* **185** 2056 (2014)

Strangeness Production

- Increase of strange-particle production for small systems, saturation around thermal-model values for large systems
  - Magnitude of strangeness enhancement increases with strange-quark content
- Smooth evolution of particle production with charged-particle multiplicity across *p*+*p*, *p*+Pb, Xe+Xe, and Pb+Pb collisions
  - No energy dependence
  - Hadron chemistry is driven by the multiplicity (system size)



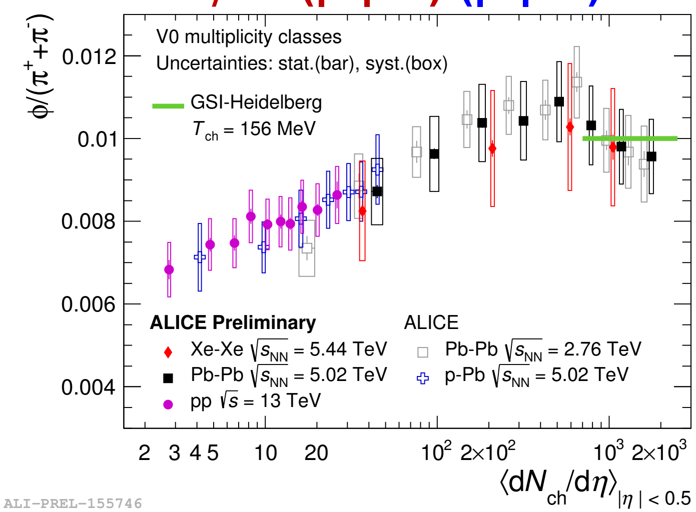
New version of this plot.

Hadrochemistry: ϕ

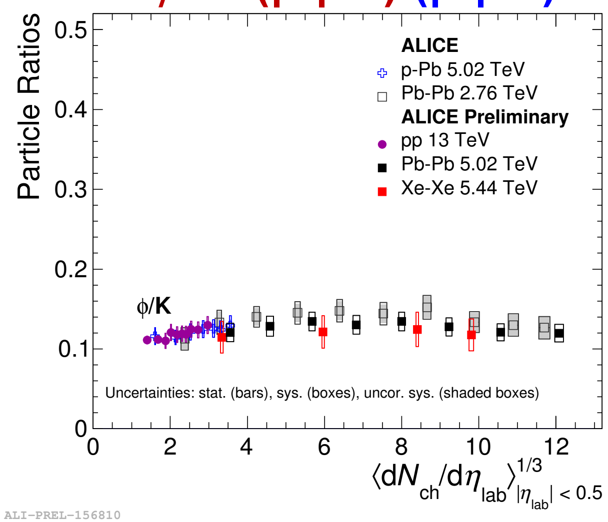
- The ϕ meson ($s\bar{s}$) has hidden strangeness and is a key probe in studying strangeness production
  - Does ϕ evolve as S=0 particle, or as if it had open strangeness?
- Large systems: ϕ production described by thermal models
- Small systems: increase in ϕ/π ratio with multiplicity
- Ratios ϕ/K and Ξ/ϕ fairly flat across wide multiplicity range
  - The ϕ has "effective strangeness" of 1–2 units

Also at SQM19: J. Blair (Thursday)

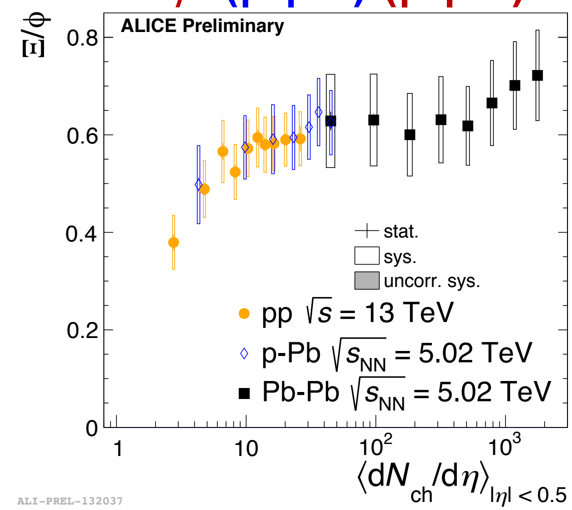
ϕ/π: (|S|=0)/(|S|=0)



ϕ/K: (|S|=0)/(|S|=1)

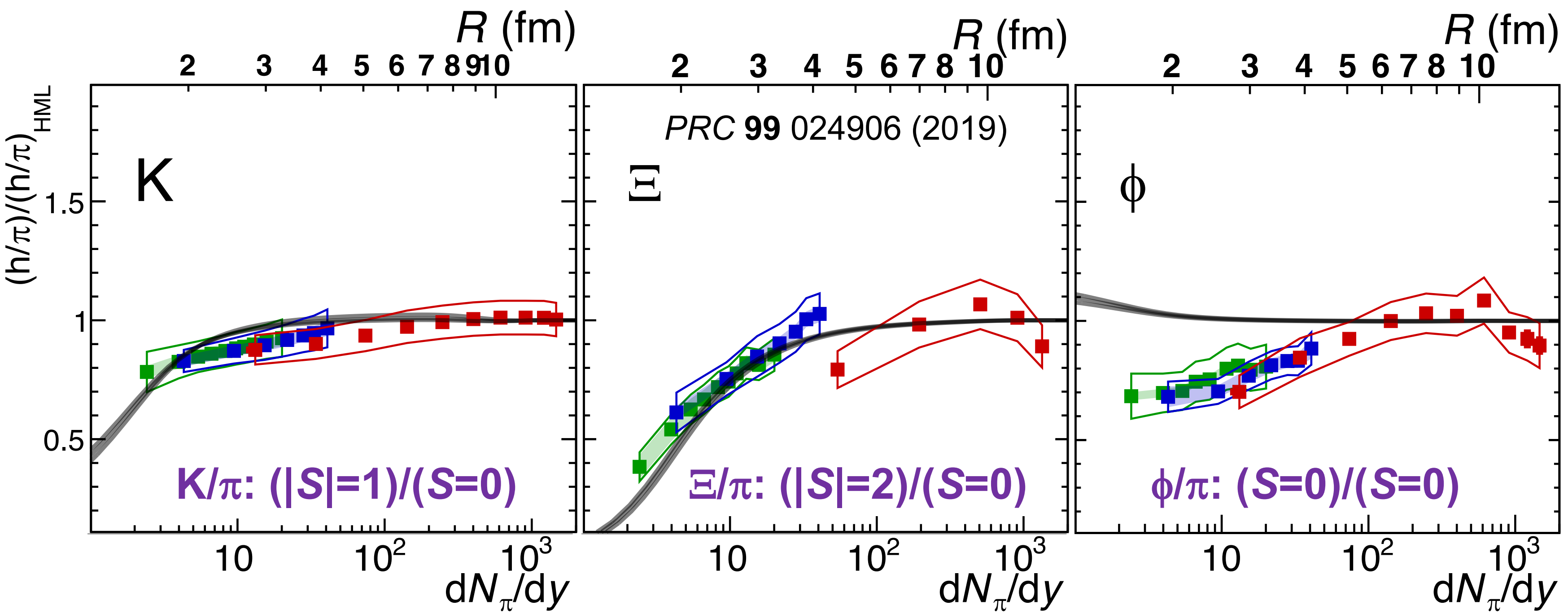


Ξ/ϕ: (|S|=2)/(|S|=0)



Canonical Suppression

- Small systems: particles with open strangeness subject to canonical suppression, while ϕ is not
- ALICE observes increase in ϕ/π w/ multiplicity in *p*+*p*
  - Not expected for simple canonical suppression
  - Does system drop out of equilibrium?



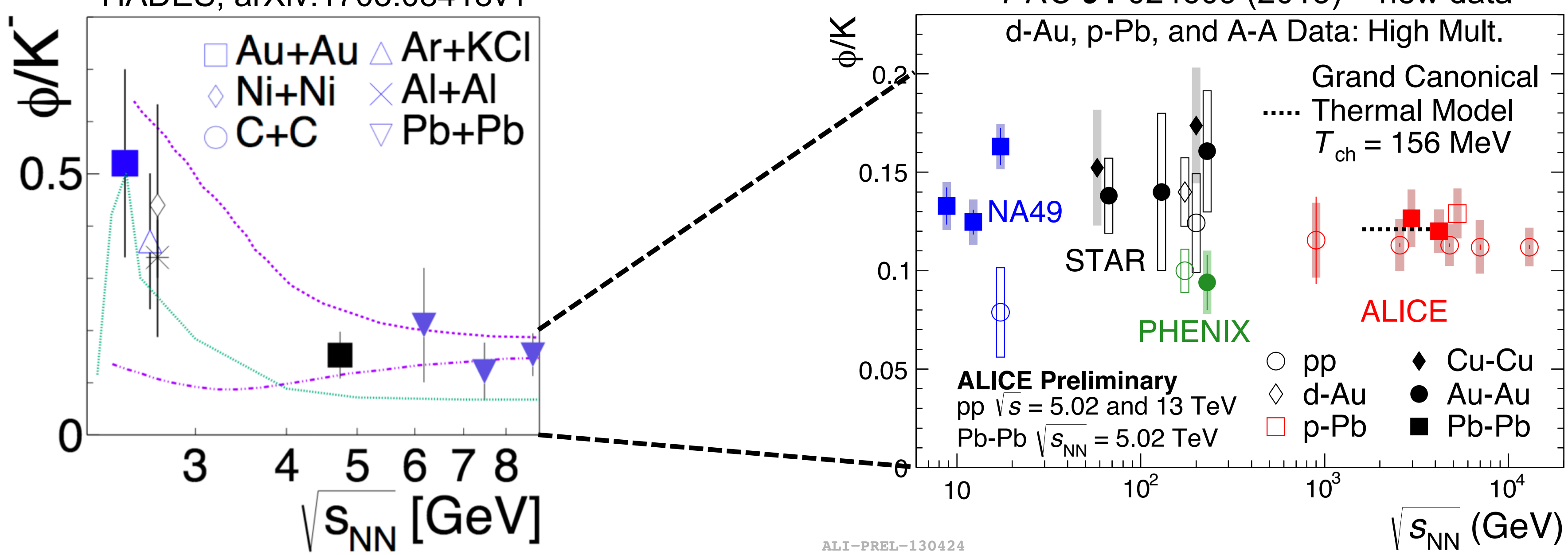
Energy Dependence

- ϕ/K ratio ~constant in *A*+*A* over 3 orders of magnitude in energy
- Increase for low energies: can be explained by statistical model with strangeness correlation radius $R_c \approx 2.2$ fm
  - Onset of canonical suppression in *A*+*A* at low energies

HADES, FOPI, E917, NA49

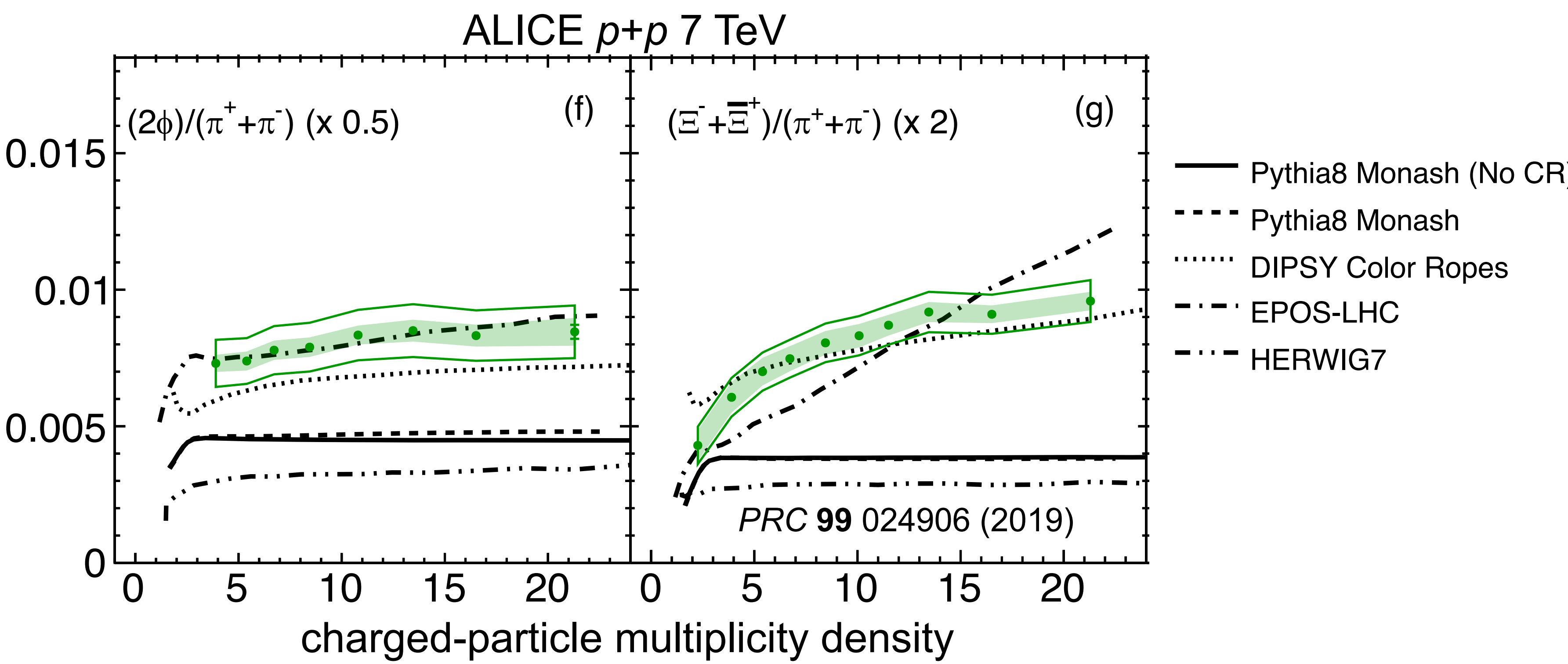
HADES, arXiv:1703.08418v1

PRC **91** 024609 (2015) + new data



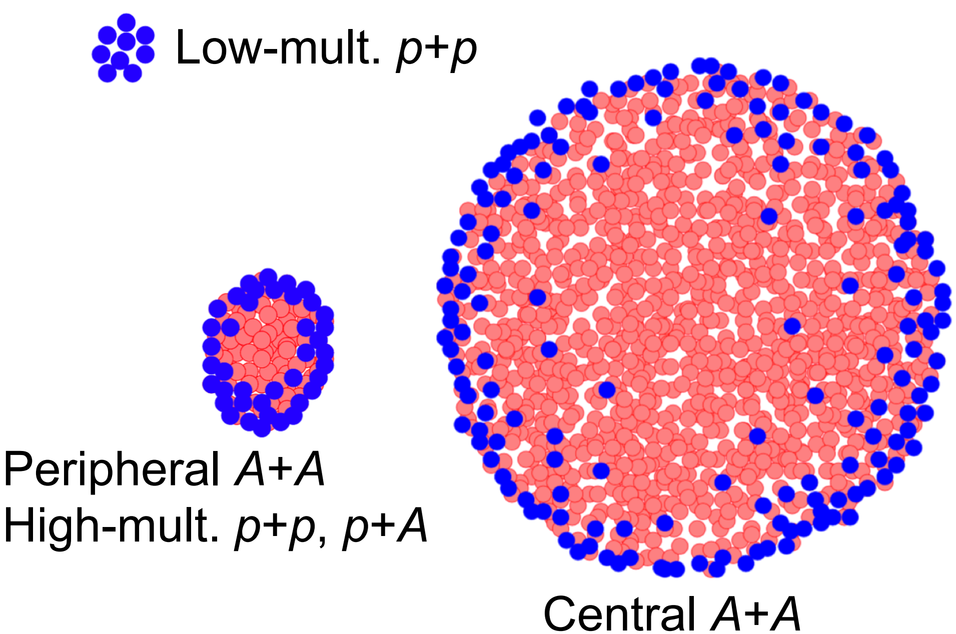
Rope Hadronization

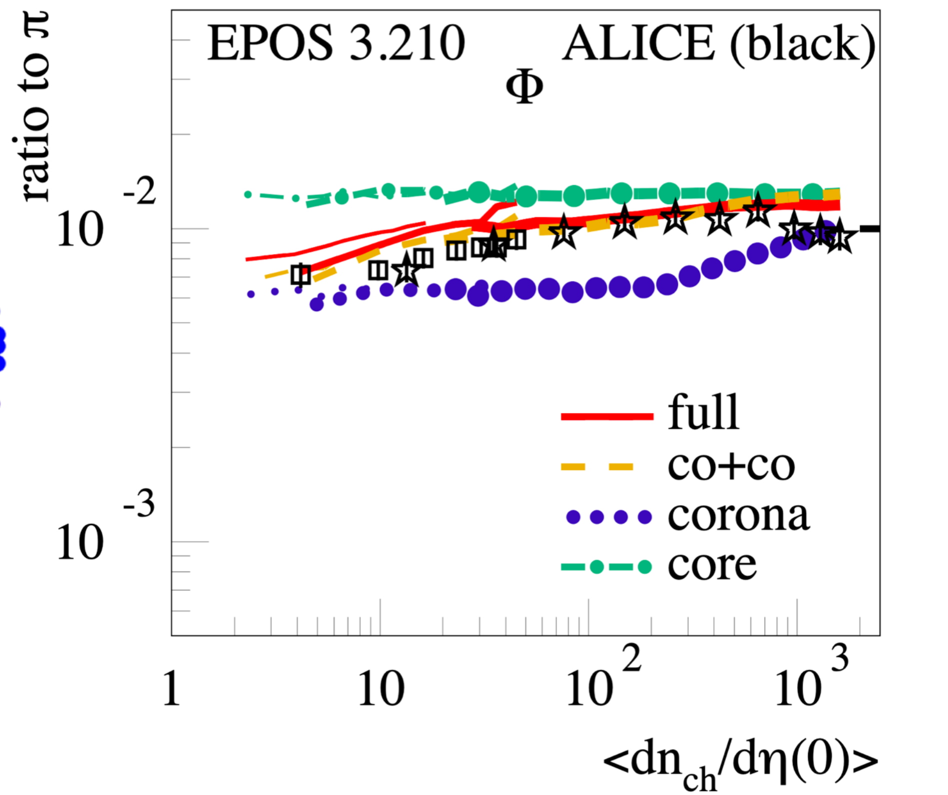
- Groups of overlapping strings fragment with higher effective string tension
  - Enhances strange-particle production
  - Enhancement of ϕ similar to open-strangeness hadrons
  - DIPSY (color ropes) qualitatively describes increase of ϕ/π with multiplicity



Core/Corona Effects

- EPOS: describes *p+p*, *p+A*, and *A+A* collisions with common framework
  - Collision divided into a core (QGP) and a corona of jets
  - Core evolves hydrodynamically
  - Hadronic phase with re-scattering and regeneration (UrQMD)



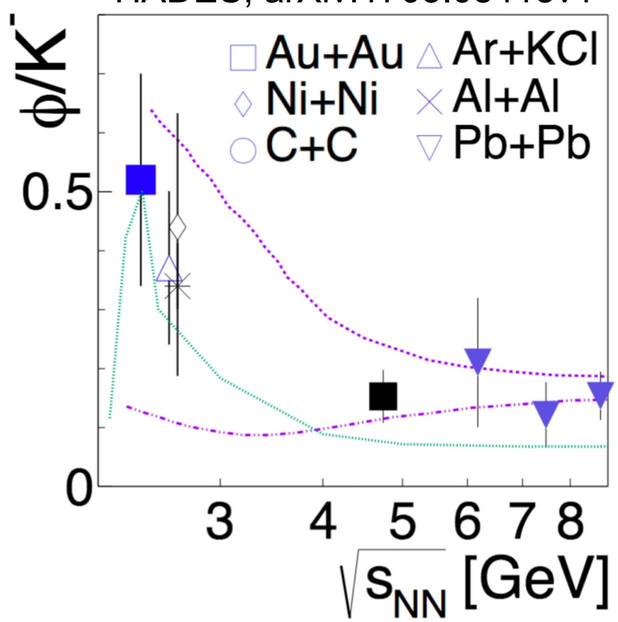


ϕ at Low Energies

- Onset of canonical suppression in *A+A* at low energies

HADES, FOPI, E917, NA49

HADES, arXiv:1703.08418v1



ϕ at Low Energies

- Onset of canonical suppression in *A*+*A* at low energies
- Suppression of K^- in nuclei, ϕ/K^- ratio similar in π+C and π+W collisions → ϕ absorption in nuclear matter

HADES, FOPI, E917, NA49

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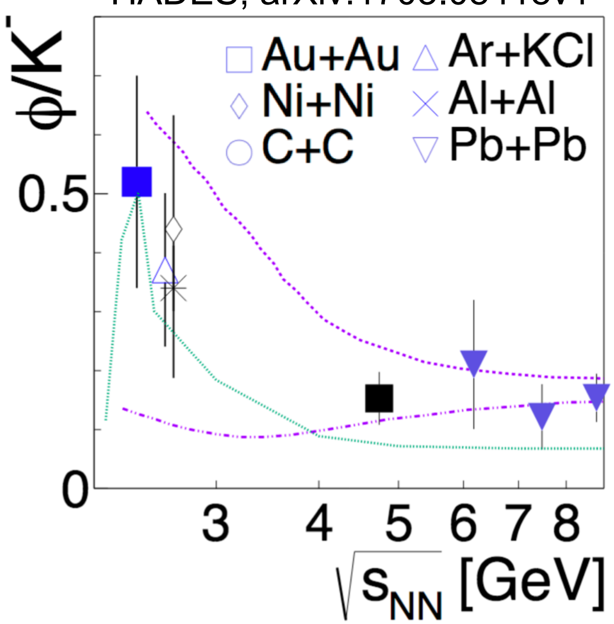
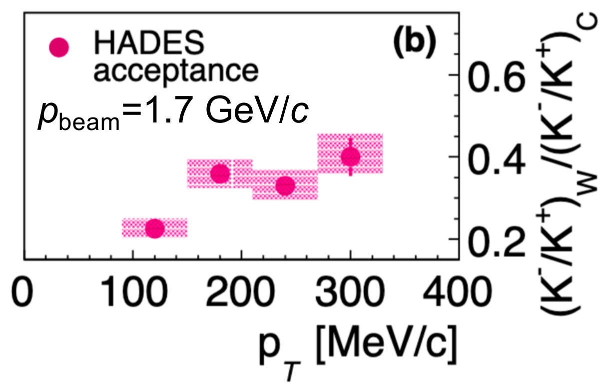


arXiv:1812.03728



$(\phi/K^-)_{\pi+C} = 0.55\pm0.04^{+0.06}$

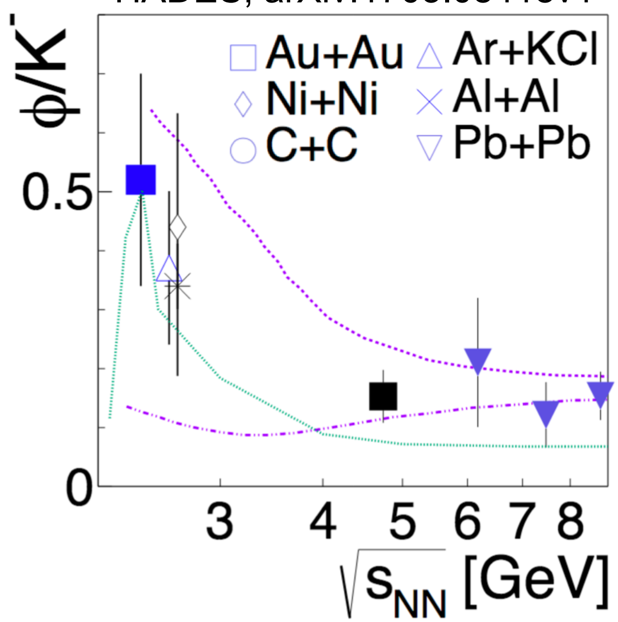
$(\phi/K^-)_{\pi+W} = 0.63\pm0.06\pm0.11$

-0.07

ϕ at Low Energies

- Onset of canonical suppression in *A*+*A* at low energies
- Suppression of K^- in nuclei, ϕ/K^- ratio similar in π+C and π+W collisions → ϕ absorption in nuclear matter
- Universal scaling of strangeness production with $\langle A_{part}\rangle$ for $|S|=1$ particles & ϕ (*i.e.* ϕ evolves like particles with open strangeness)

HADES, FOPI, E917, NA49
HADES, arXiv:1703.08418v1



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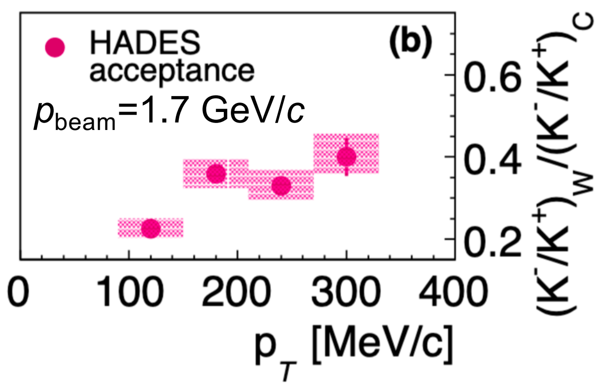

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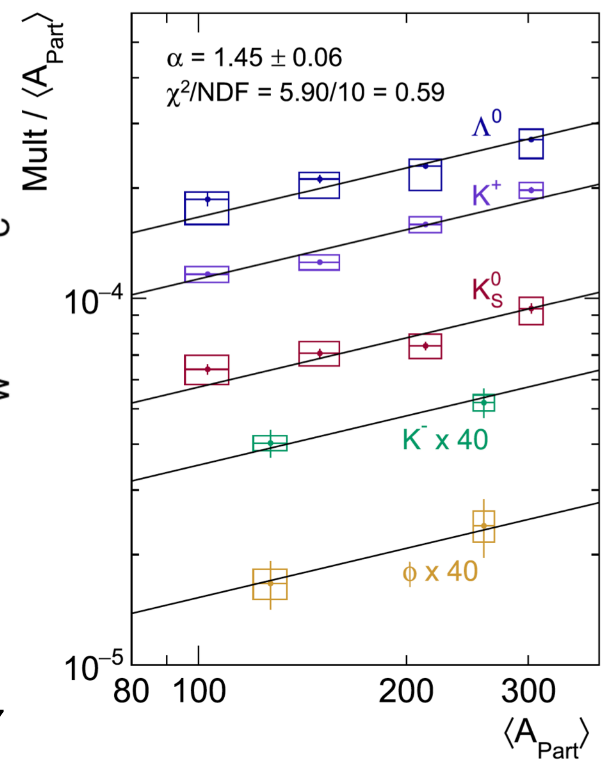
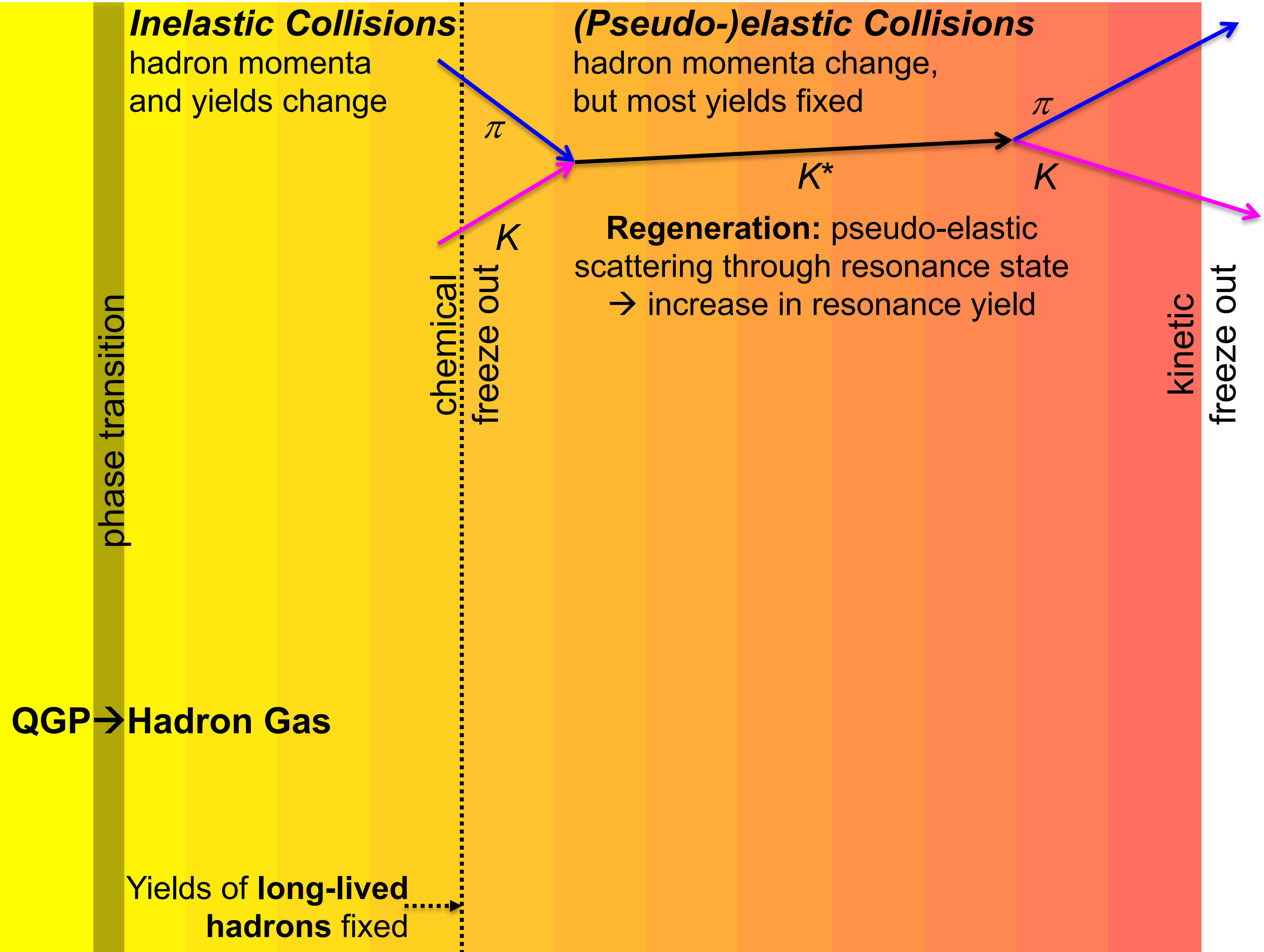
PLB **793** 457-463 (2019)



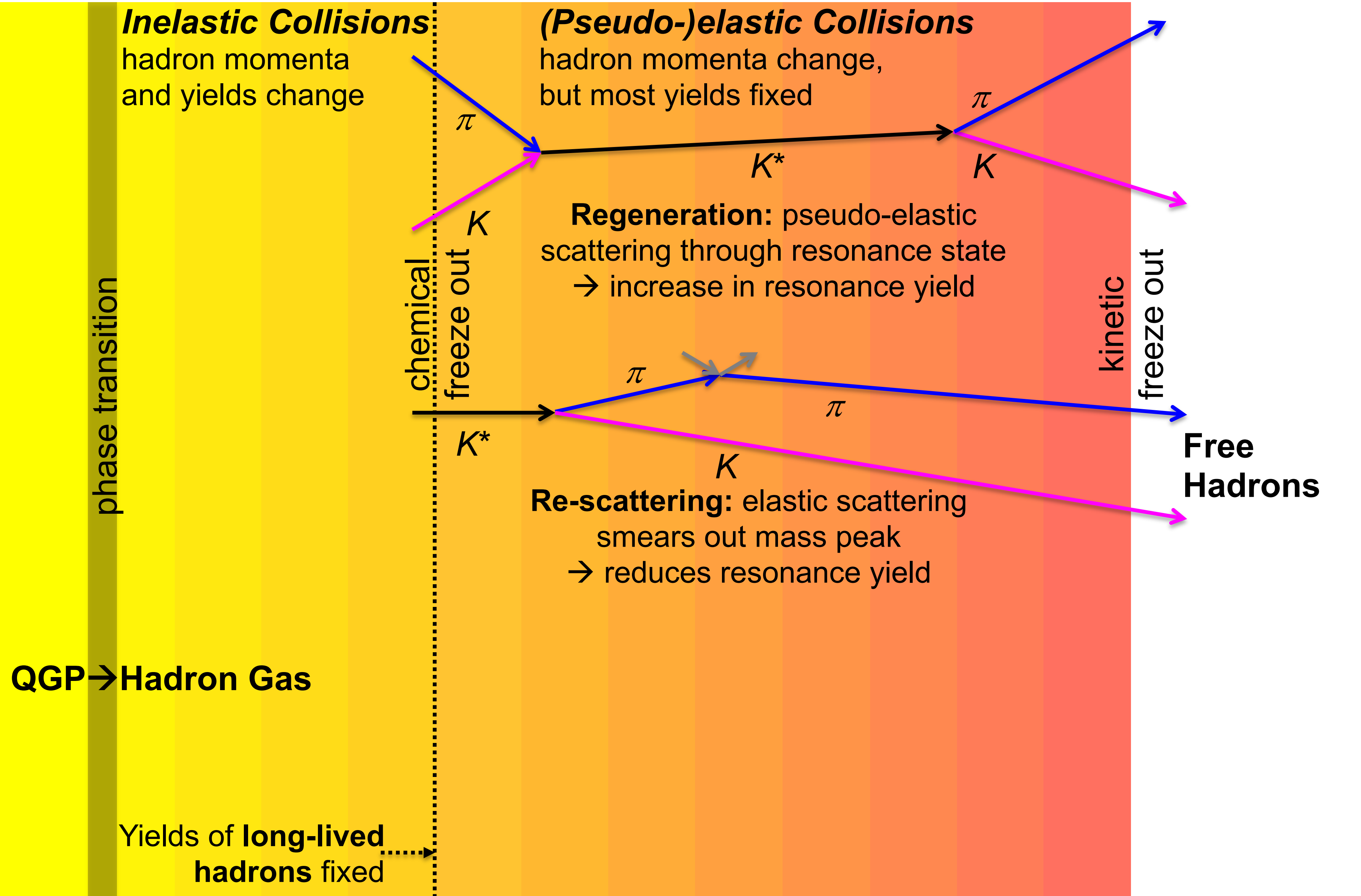
HADES Au+Au $\sqrt{s_{NN}}$=2.4 GeV

Hadronic Phase & Resonance Suppression

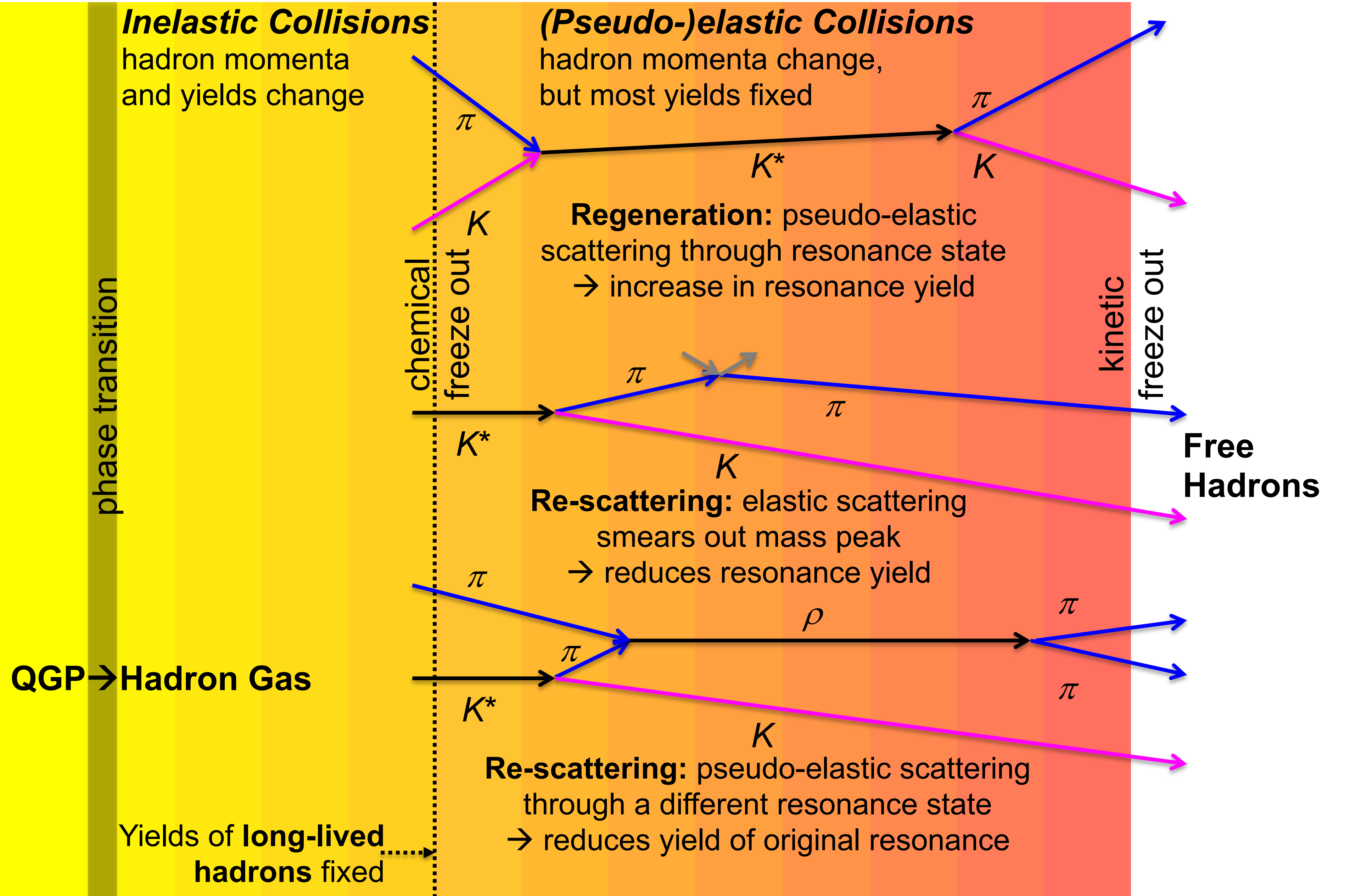
Hadronic Phase



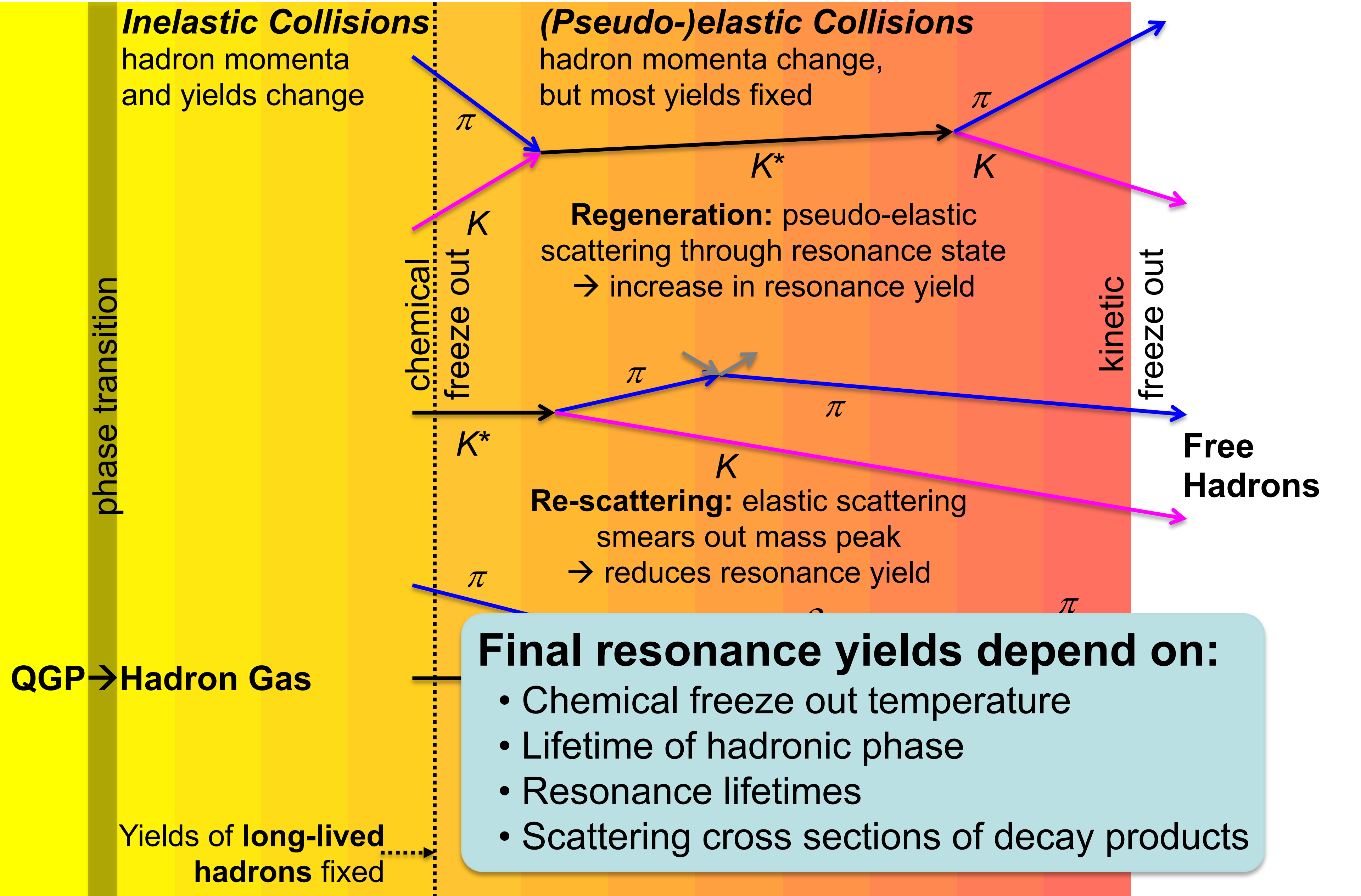
Hadronic Phase



Hadronic Phase



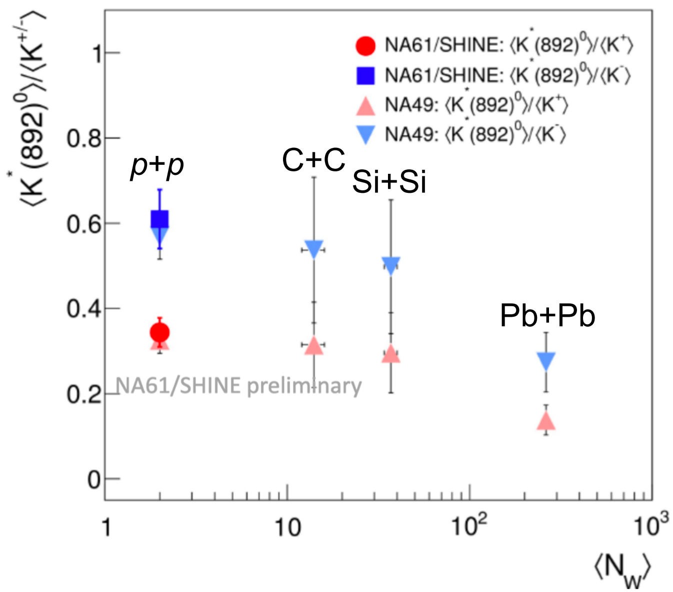
Hadronic Phase



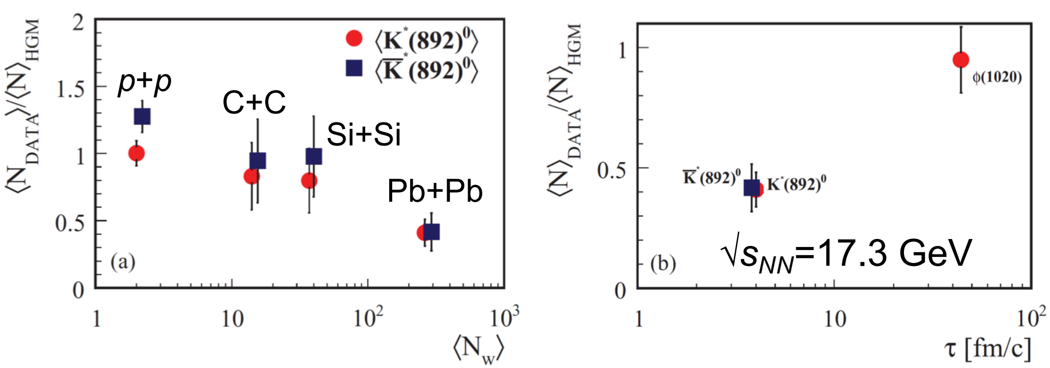
Final resonance yields depend on:

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

Resonance Suppression



EPJC **77** 671 (2017), *PRC* **84** 064909 (2011), *EPJC* **68** 1 (2010), *PRL* **94** 052301 (2005), *PRC* **66** 054902 (2002)



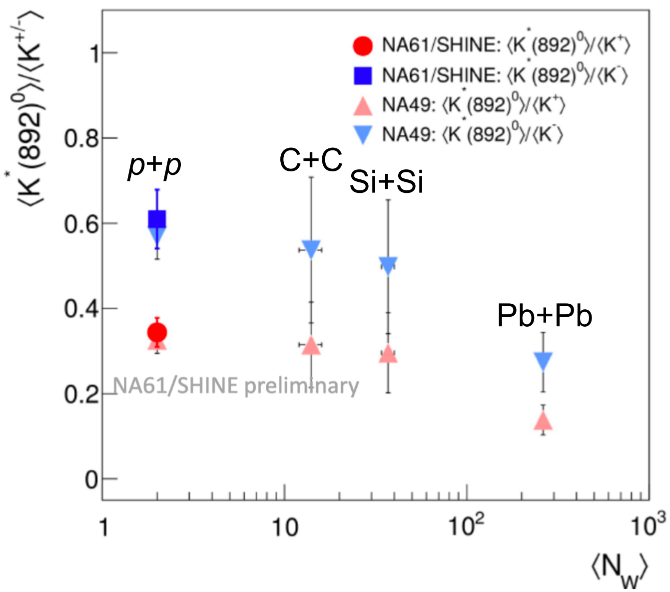
NA49, *PRC* **84** 064909 (2011)

NA49 + NA61/SHINE

- Suppression of K^{*0}:
  - More suppression for larger systems
  - Suppressed w.r.t. HGM value
- No suppression of ϕ w.r.t. HGM

At SQM19: S. Pulawski (Monday), A. Tefelska (Thursday)

Resonance Suppression



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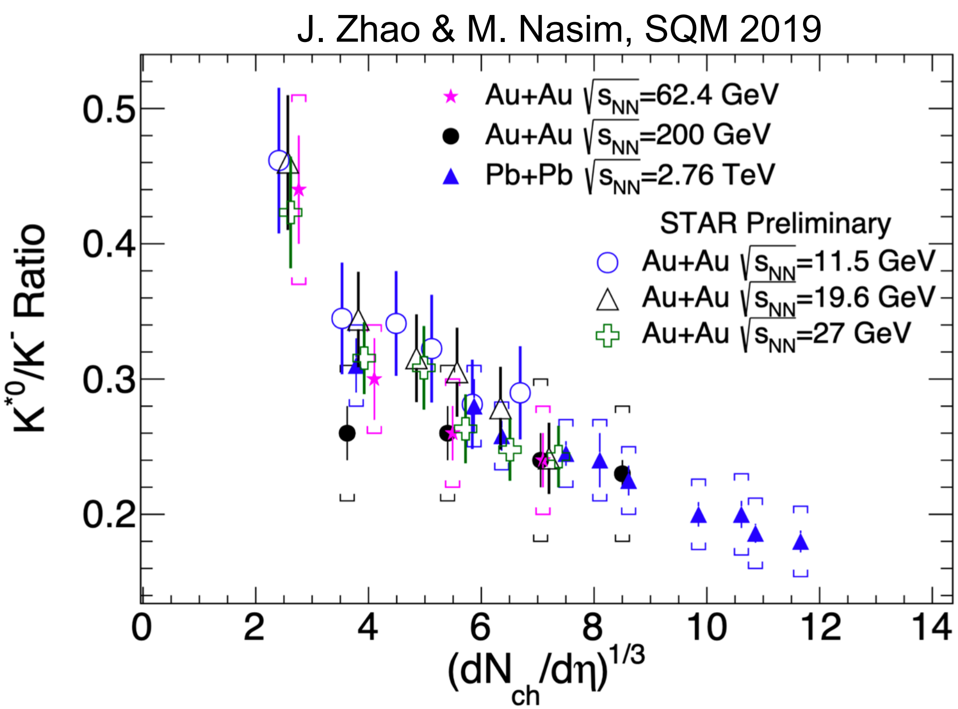
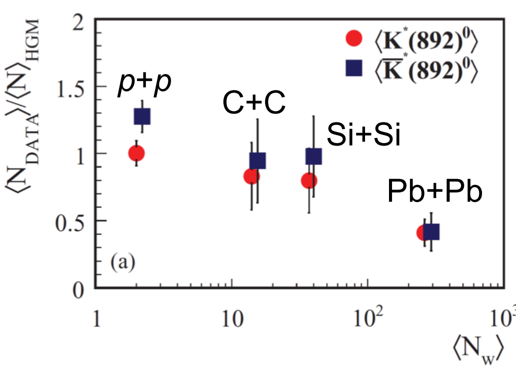
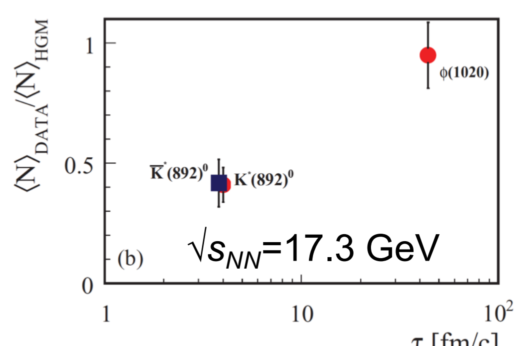






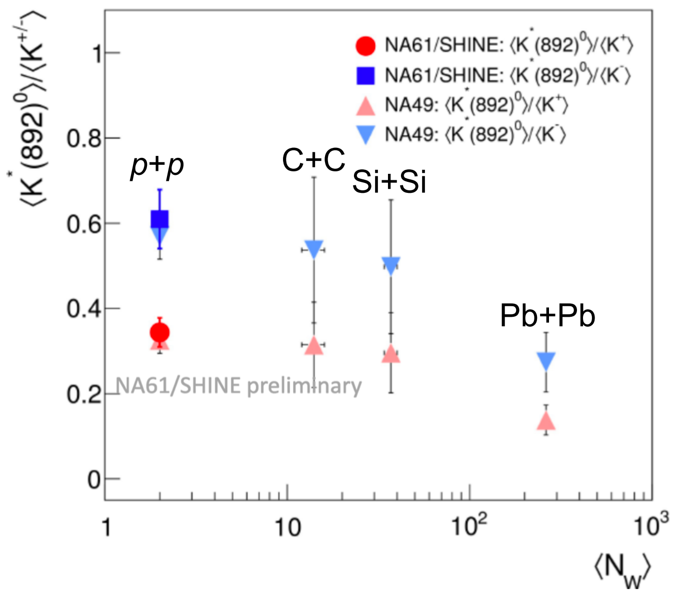
NA49, *PRC* **84** 064909 (2011)

STAR + ALICE

- Suppression of K^{*0}:
  - More suppression for larger systems
  - Suppressed w.r.t. GC thermal model
  - Controlled by multiplicity: no clear energy dependence within or between RHIC & LHC

At SQM19: S. Tripathy & M. Nasim (Thursday)

Resonance Suppression



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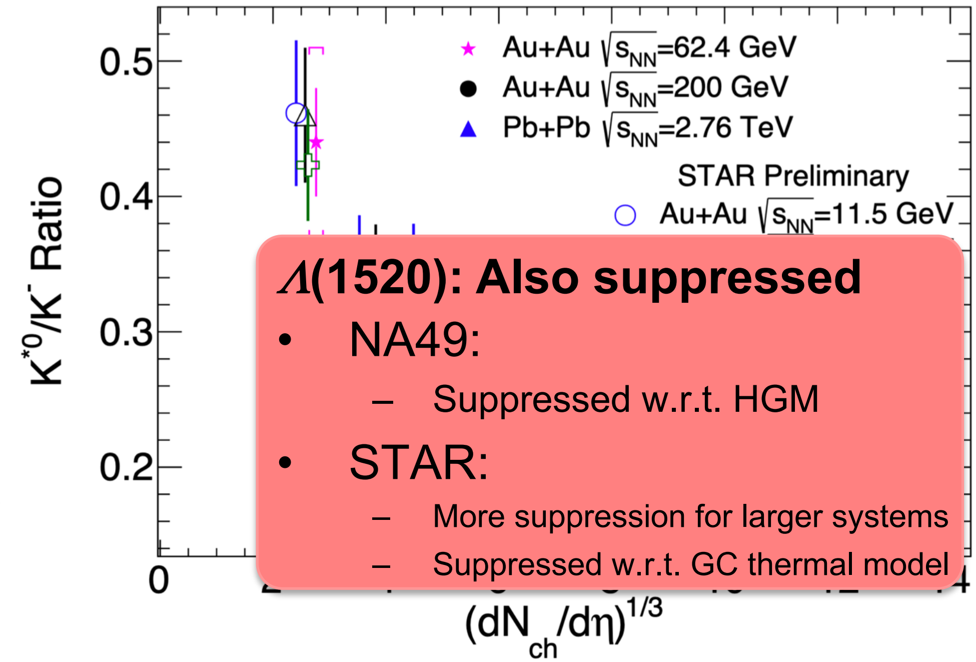
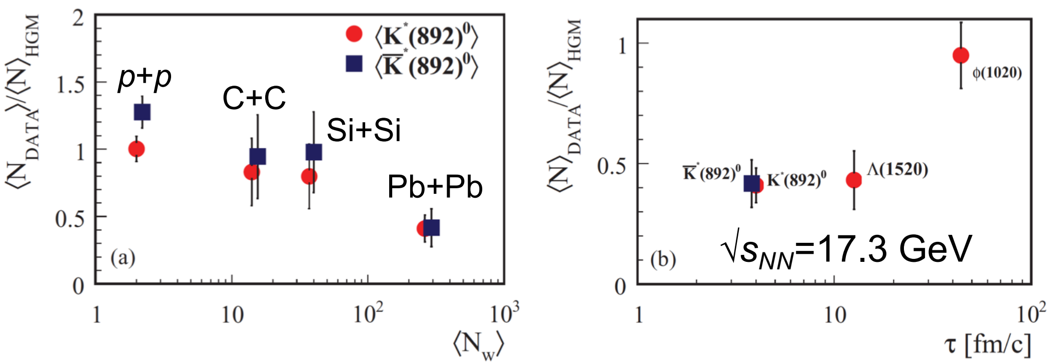
J. Zhao & M. Nasim, SQM 2019

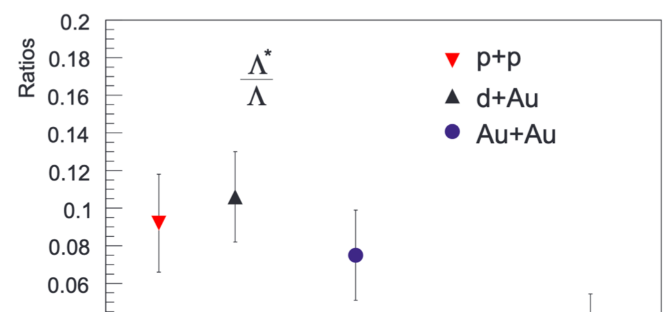


Λ(1520): Also suppressed

- NA49:
  - Suppressed w.r.t. HGM
- STAR:
  - More suppression for larger systems
  - Suppressed w.r.t. GC thermal model



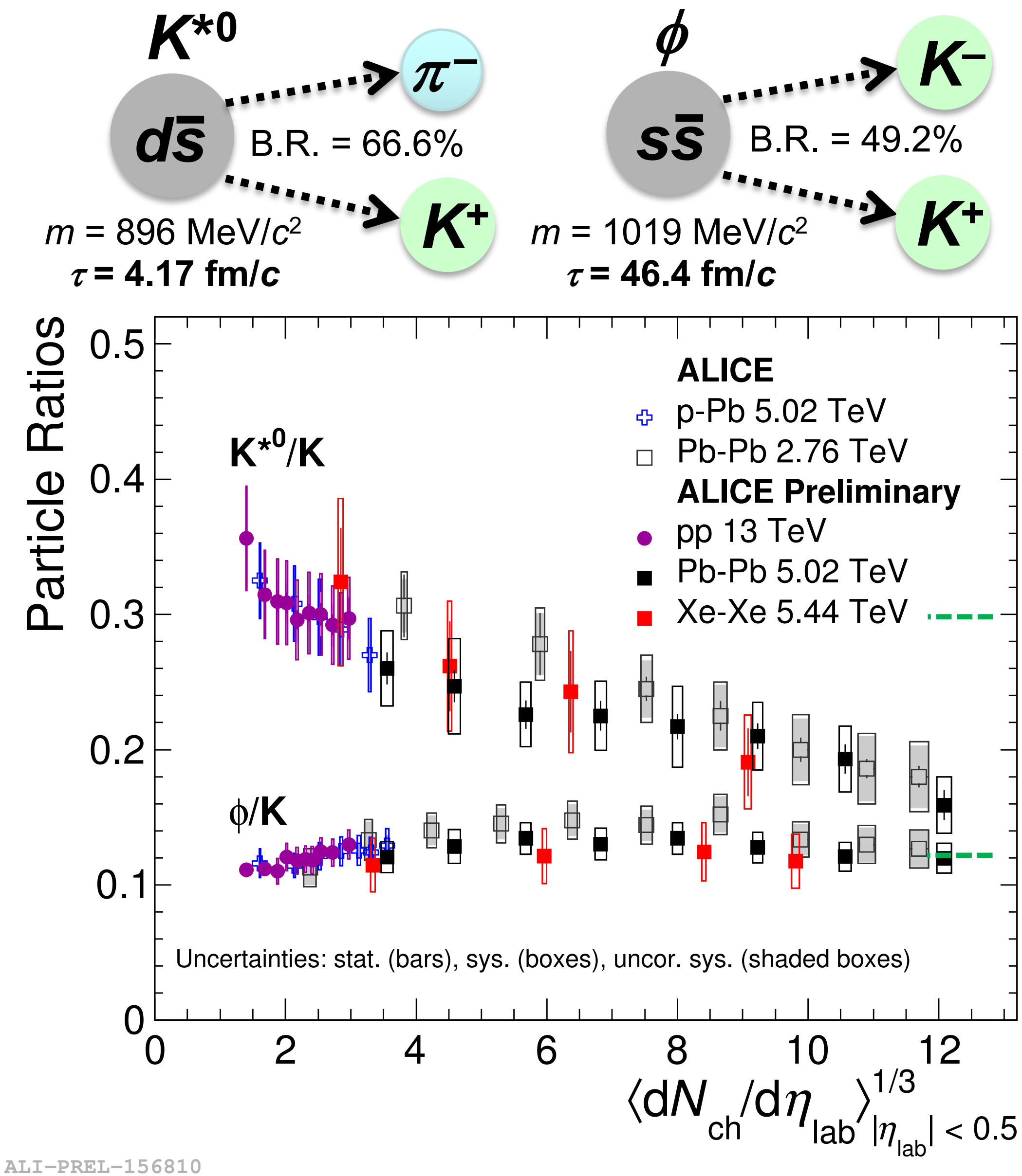
NA49, *PRC* **84** 064909 (2011)



PRC **78** 044906 (2008)

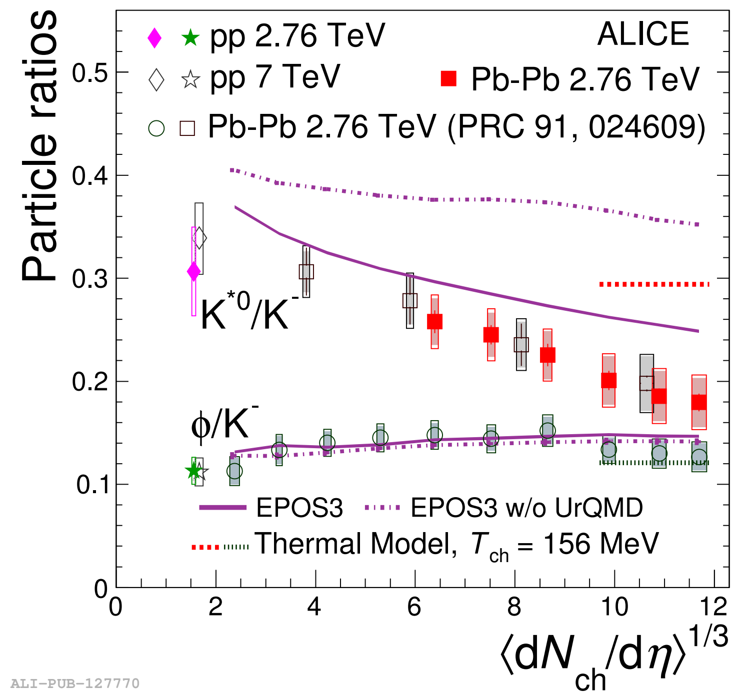
K^{*0} & ϕ

- Suppression of K^{*0}/K in central $A+A$ collisions
  - Below $p+p$ and statistical-model predictions
  - Suggests that re-scattering is dominant over regeneration
- In contrast, ϕ/K not suppressed
  - Consistent w/ stat. models
  - Lifetime of ϕ ~10× longer than K^{*0}
  - Re-scattering effects not significant



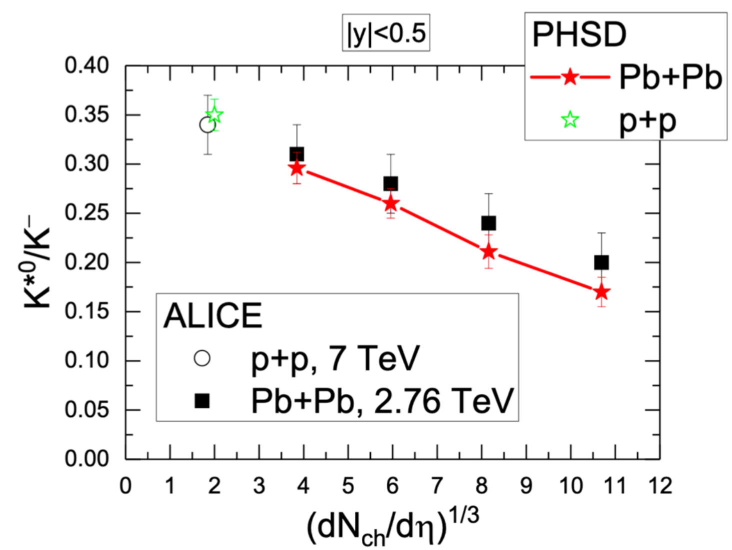
K^{*0} & ϕ: Theory

- 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



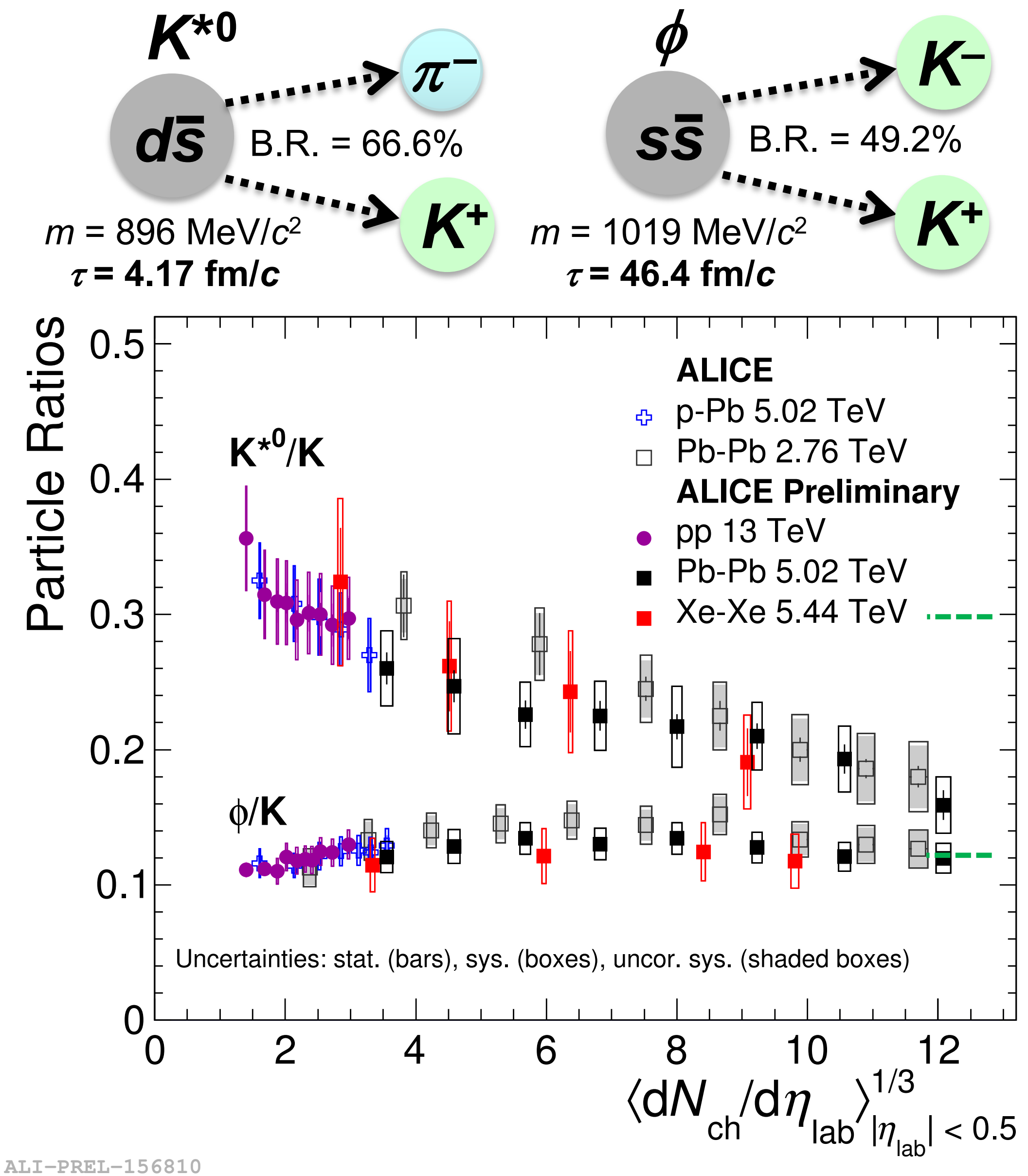
Also at SQM19:
C. Bierlich (Thursday)

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



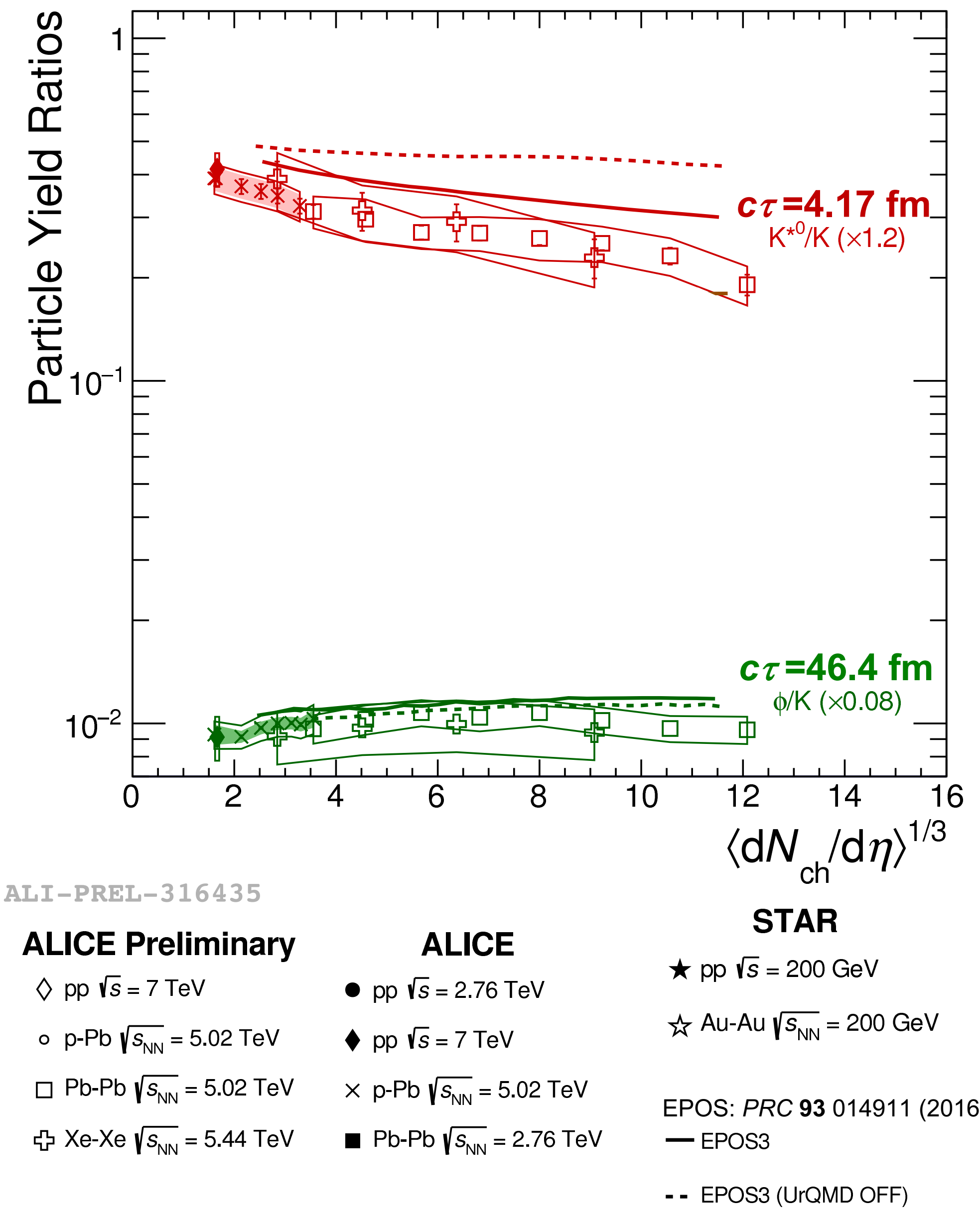
K^{*0} & ϕ: Small Systems

- Small systems: 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



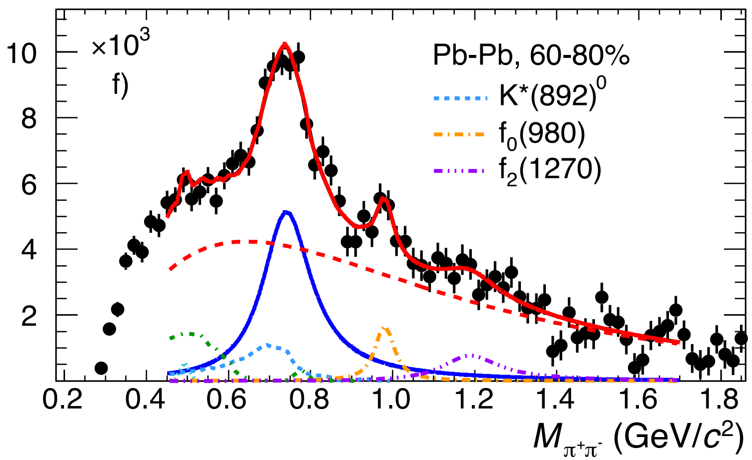
Other Resonances

Increasing Lifetime

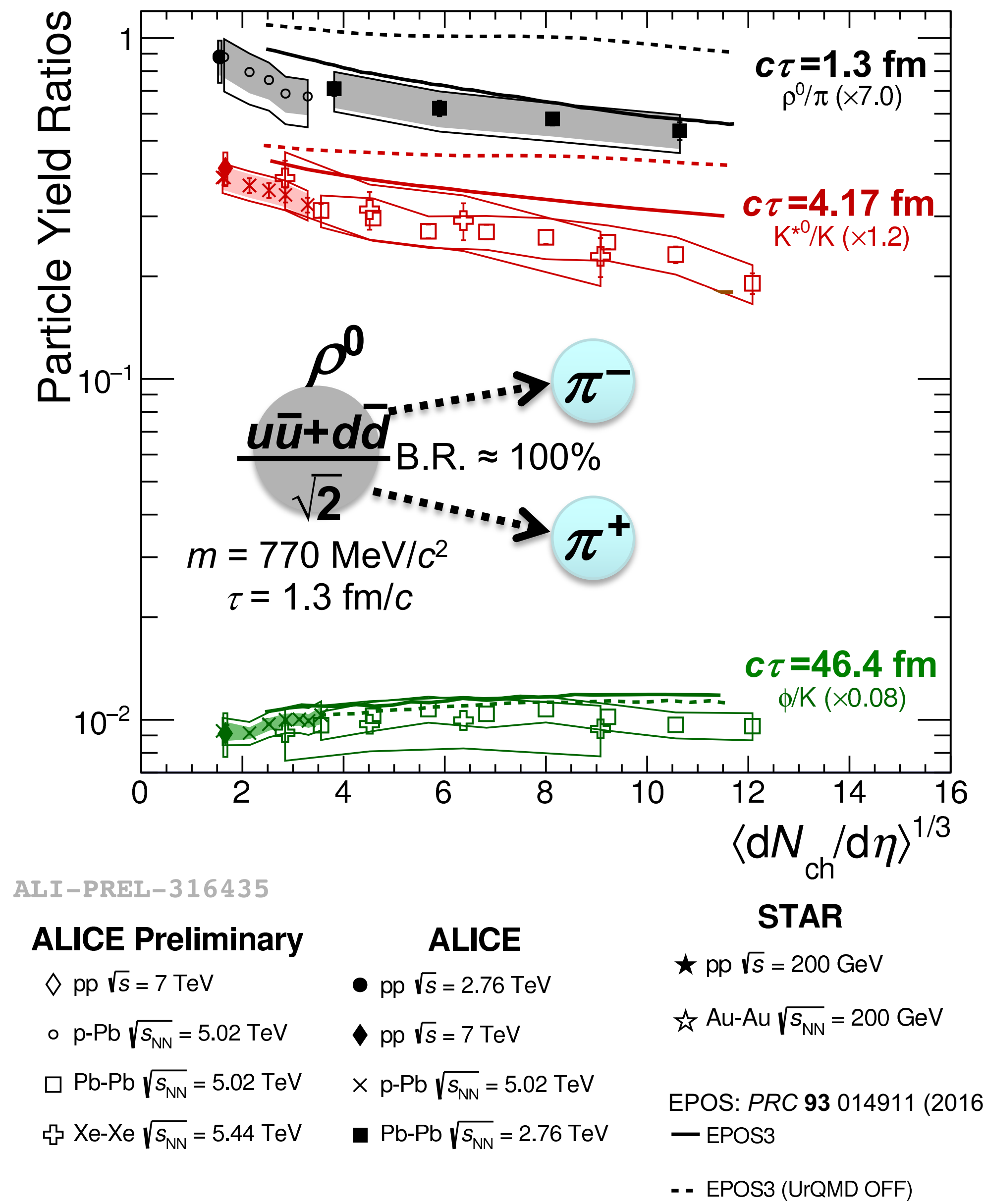


Short Lifetime: ρ^0

- Reconstruction: wide peak w/ complicated cocktail for correlated background

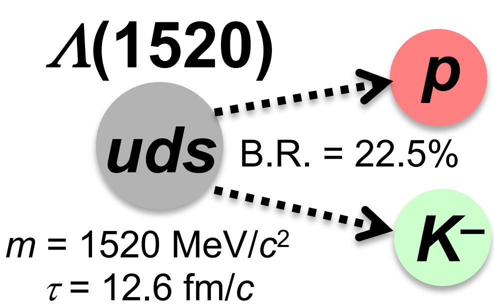


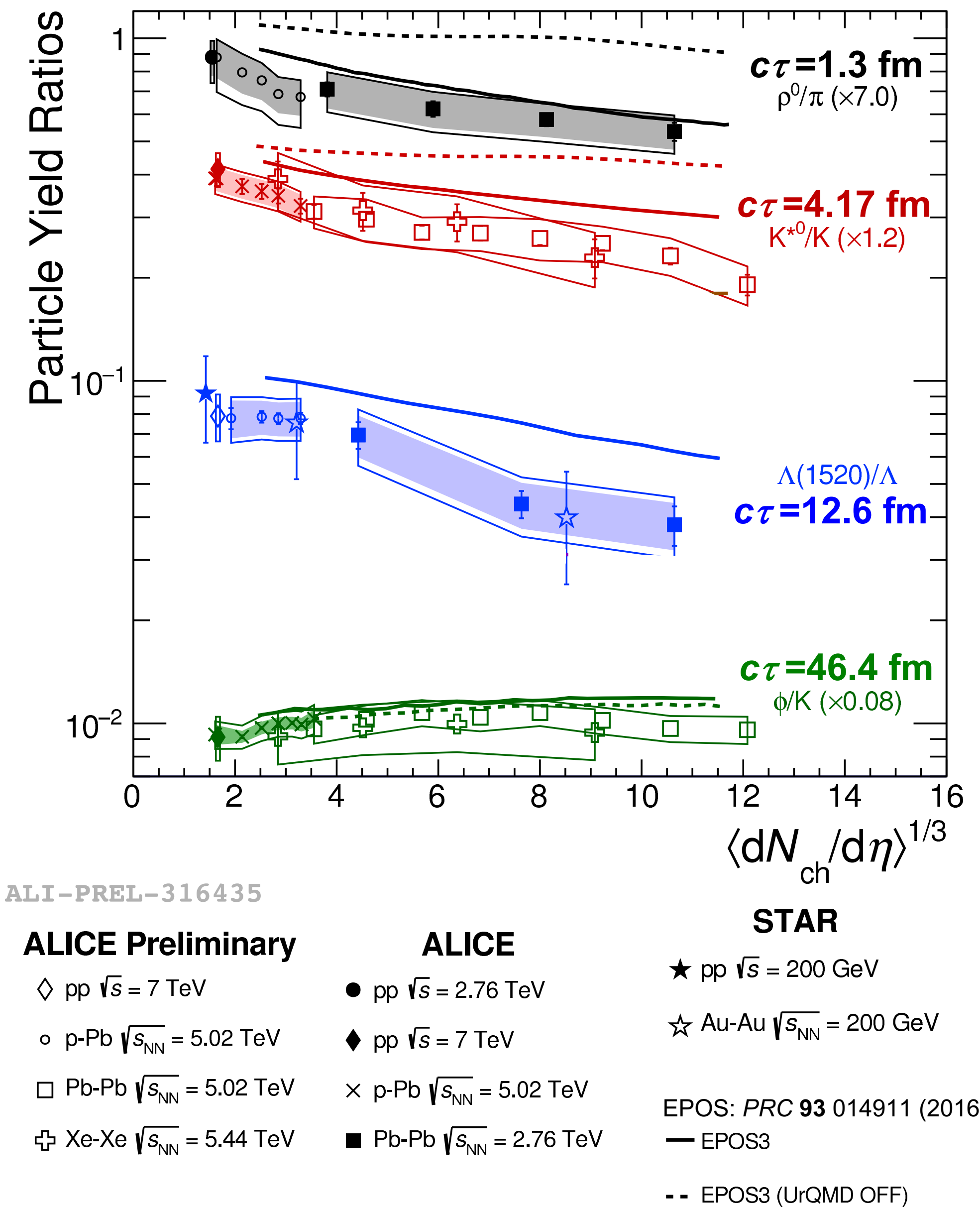
- Suppression of ρ^0/π ratio in central Pb+Pb w.r.t. *p*+*p* and thermal model
  - Qualitatively described by EPOS with UrQMD
- Suggestion of suppression in high-multiplicity *p*+Pb
  - New for SQM 2019



Short Lifetime: $\Lambda(1520)$

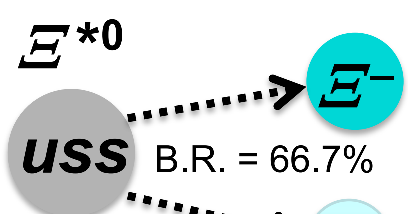
- Suppression of $\Lambda(1520)/\Lambda$ in central *A*+*A* w.r.t. *p*+*p*, *p*+Pb, and thermal model
- No energy dependence for RHIC→LHC
- No multiplicity dependence in *p*+Pb
- Qualitatively described by EPOS
- Or suppression of *p*-wave baryons [$\Lambda(1520)$] in recombination model [*PRC* **74** 061901(R) (2006)]



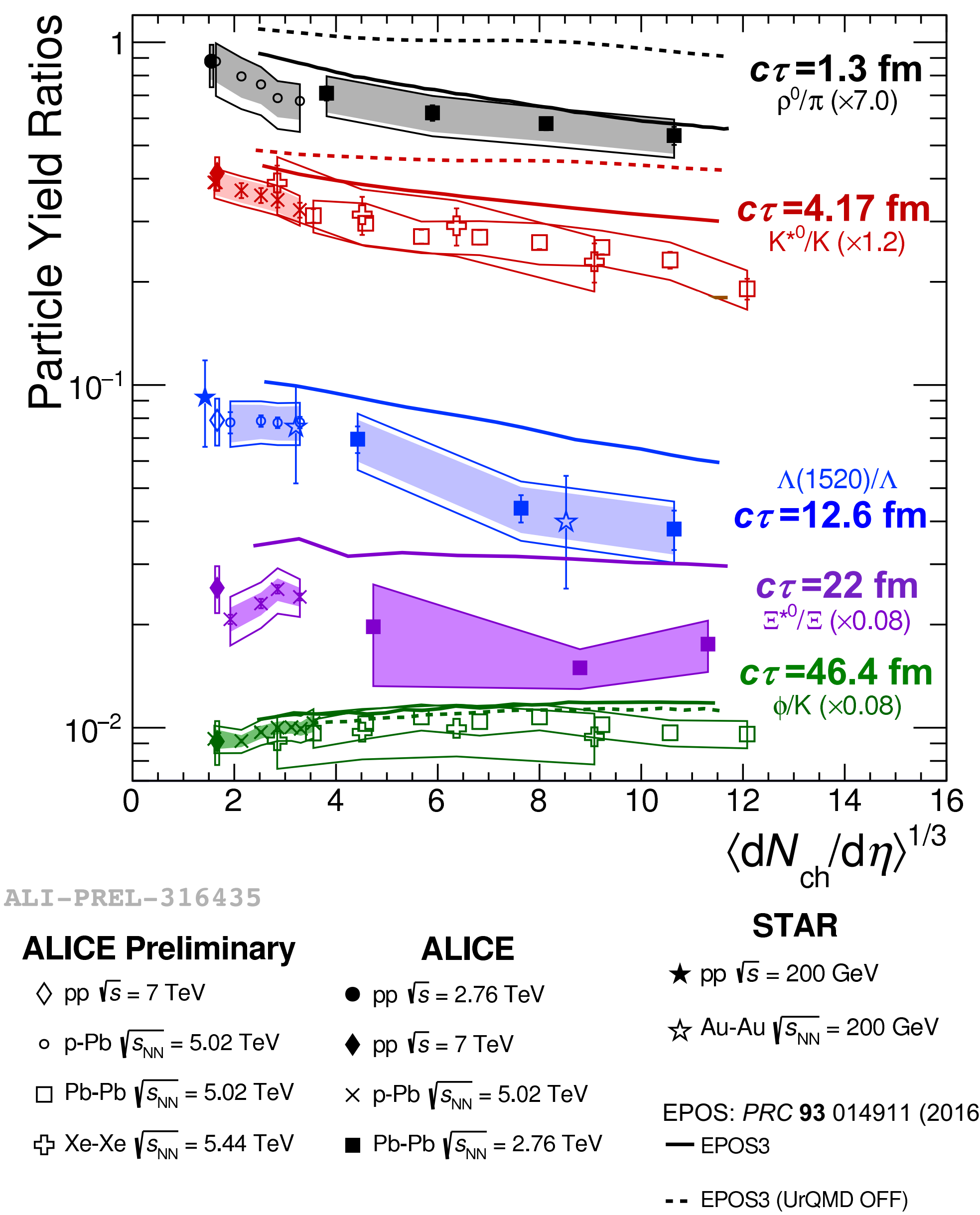


Intermediate Lifetime: Ξ^{*0}

- In Pb+Pb:
  - No significant centrality dependence
  - 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 mult. dependence

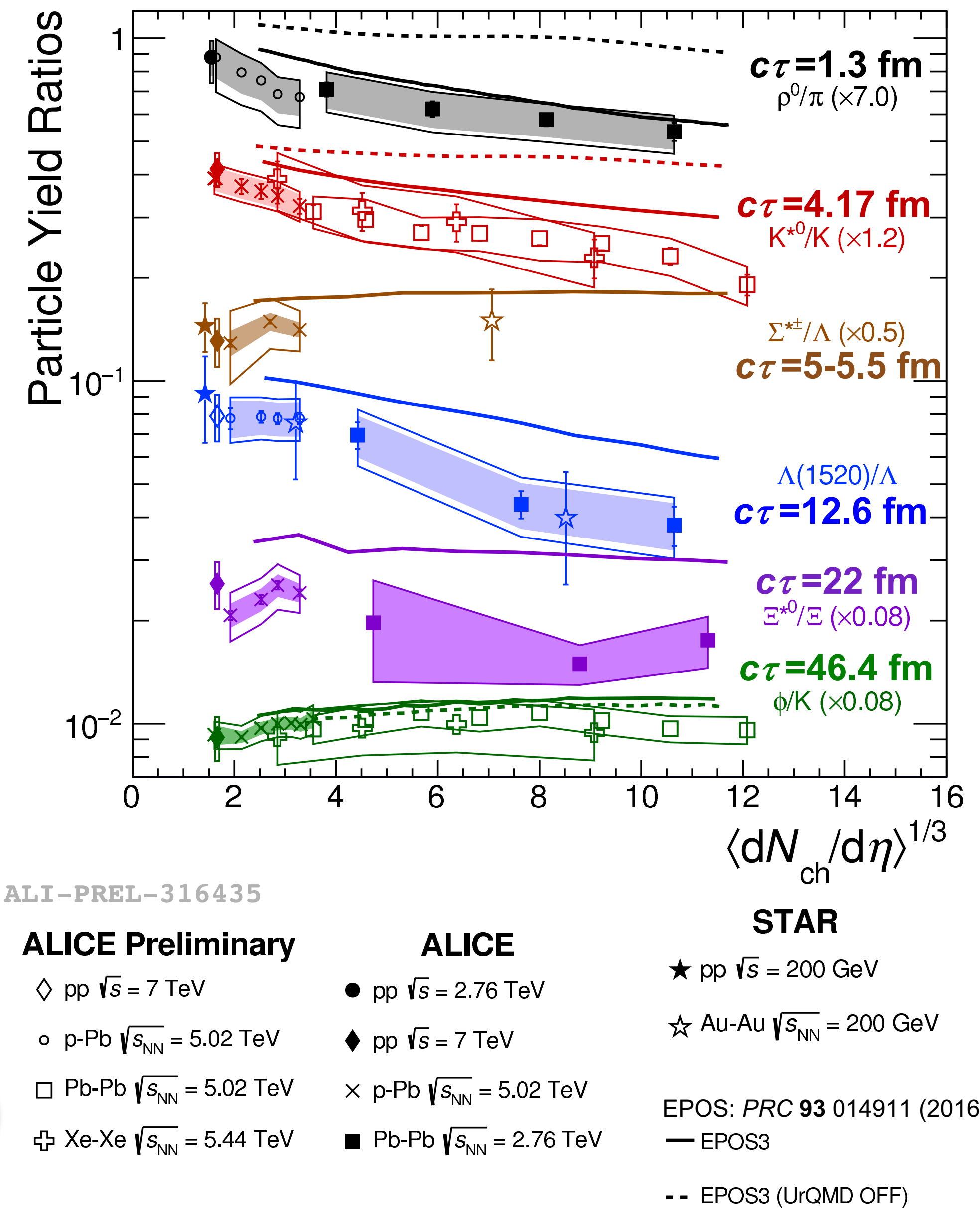


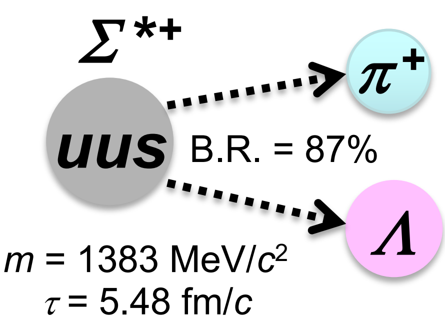
m = 1532 MeV/c^2
τ = 22 fm/c

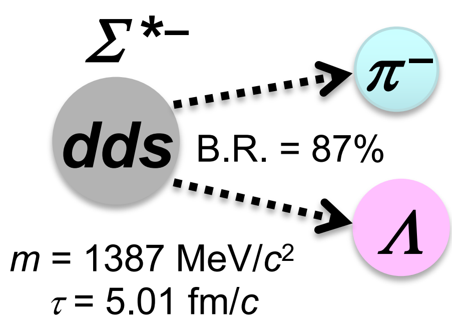


Short Lifetimes: $\Sigma^{*\pm}$

- No modification of $\Sigma^{*\pm}/\Lambda$ in *d*+Au and *p*+Pb
  - No energy dependence RHIC→LHC
- No suppression of $\Sigma^{*\pm}/\Lambda$ seen in in Au+Au
- No suppression predicted by EPOS! (also for Δ^{++})
  - Regeneration, different scattering cross sections…
- Lifetime is not the only consideration: to be tested in Pb–Pb collisions at LHC





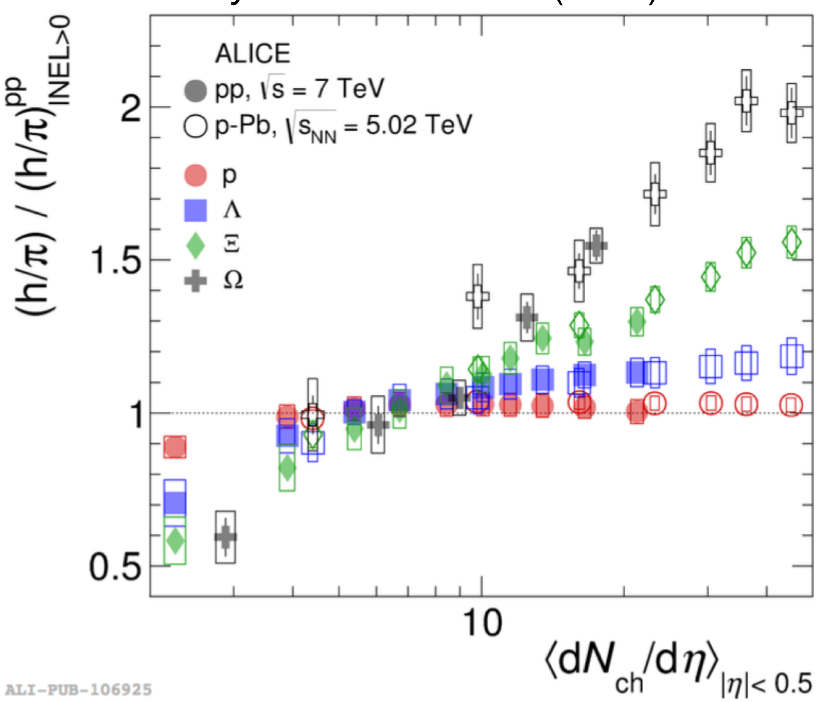


Strangeness Production

- Is the enhancement really controlled by strangeness? What about baryon number or mass?
- p/π ratio is ~constant → enhancement not related to baryon number
- $\Sigma^{*\pm}$ and Ξ^{*0}: greater masses than ground-state counterparts
- Recall: $\Sigma^{*\pm}/\Lambda$ and Ξ^{*0}/Ξ constant in *p*+Pb
- Strangeness increase in *p*+Pb is due to strangeness content, not mass or baryon number.

Nature Physics **13** 535-539 (2017)
Phys. Lett. B **758** 389 (2016)

Baryon	Mass (MeV/c^2)	$\|S\|$
Ω	1672	3
Ξ^{*0}	1530	2
$\Sigma^{*\pm}$	1385	1
Ξ^-	1322	2
Λ	1116	1
p	938	0



Ω/π: $|S|=3$
Ξ/π: $|S|=2$
Λ/π: $|S|=1$
p/π: $S=0$

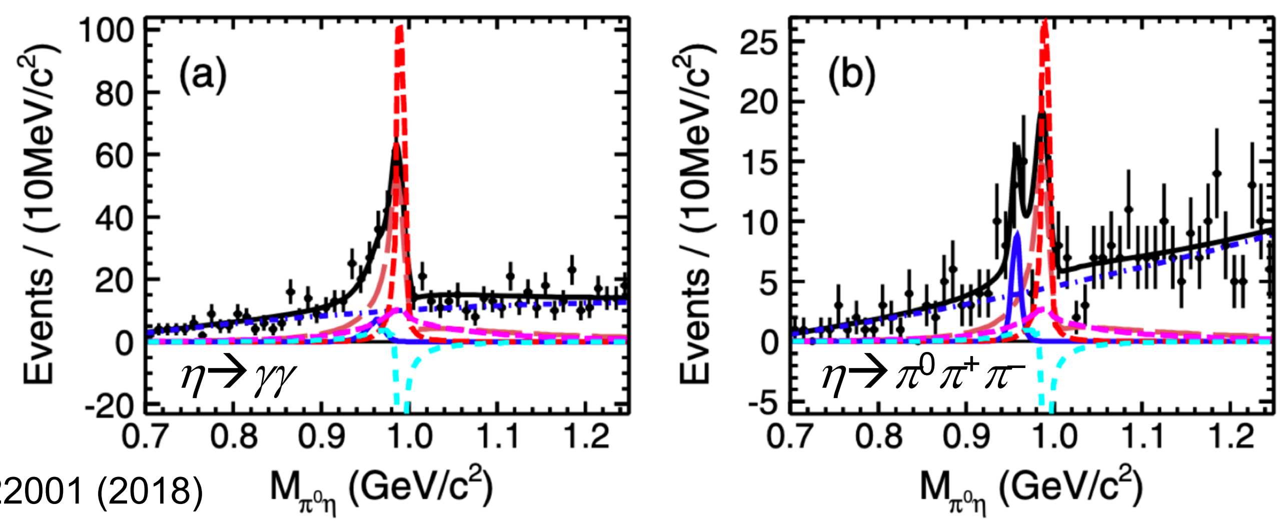
Hadron Spectroscopy

$a_0(980)^0 \leftrightarrow f_0(980)$ Mixing

- $a_0(980)^0$ (I=1) and $f_0(980)$ (I=0) similar properties, different isospin
  - Mixing → narrow (~8 MeV wide) structure in invariant-mass distributions: can study with precise measurement of lineshape
  - Important problem in light-hadron spectroscopy: what is the nature of a_0 and f_0?

$a_0(980)^0 \leftrightarrow f_0(980)$ Mixing

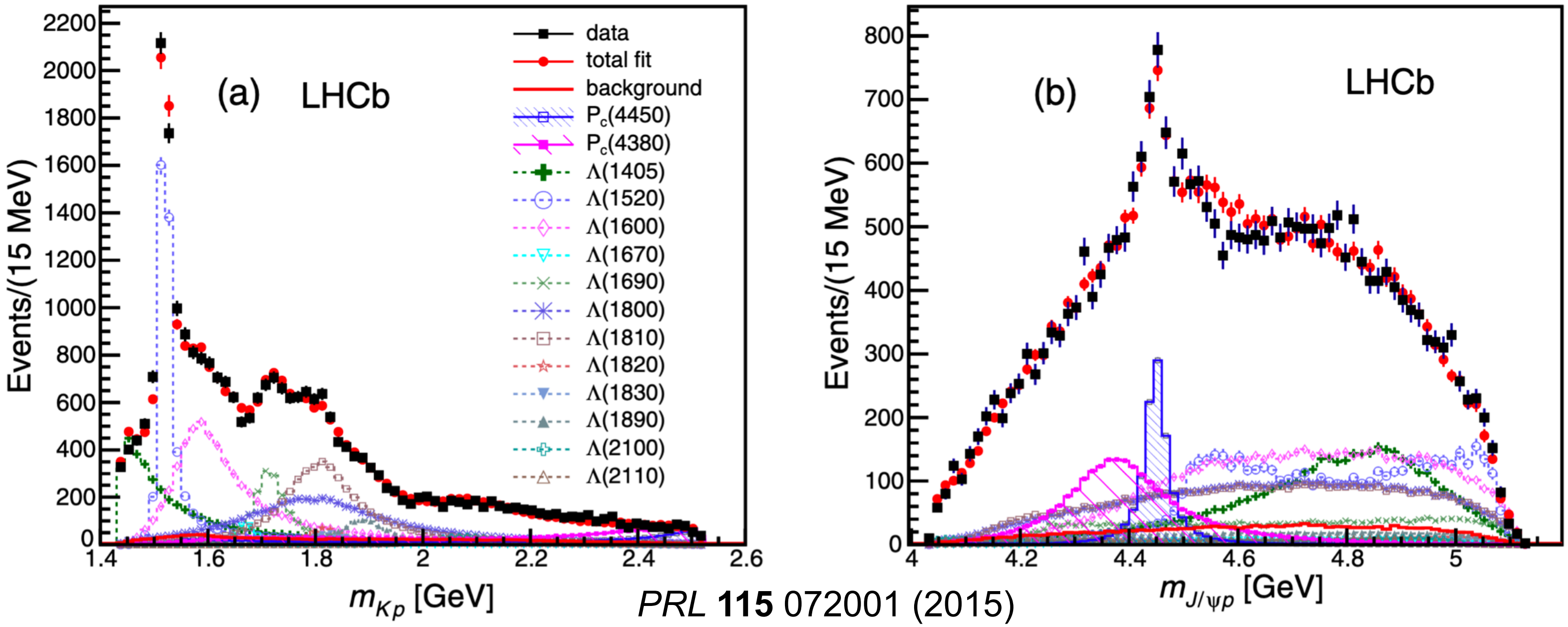
- $a_0(980)^0$ (I=1) and $f_0(980)$ (I=0) similar properties, different isospin
  - Mixing → narrow (~8 MeV wide) structure in invariant-mass distributions: can study with precise measurement of lineshape
  - Important problem in light-hadron spectroscopy: what is the nature of a_0 and f_0?
- Studied by BESIII at Beijing Electron-Positron Collider (BEPCII)
  - Using $\pi^0\eta$ pairs in $J/\psi \rightarrow \phi f_0(980) \rightarrow \phi a_0(980)^0 \rightarrow \phi\pi^0\eta$ decays
  - And $\pi^+\pi^-$ pairs in $\chi_{c1} \rightarrow \pi^0 a_0(980)^0 \rightarrow \pi^0 f_0(980) \rightarrow \pi^0\pi^+\pi^-$ decays
  - Fits using different contributions to peak (including mixing)
  - First observations of mixing: $f_0 \rightarrow a_0^0$ (7.4σ) and $a_0^0 \rightarrow f_0$ (5.5σ)



PRL **121** 022001 (2018)

Pentaquarks

- 2015: LHCb observed P_c^+ pentaquark states in $\Lambda_b \rightarrow J/\psi p K^-$ decays
  - Multidimensional fit (m_{Kp}, $m_{J/\psi p}$, helicity & decay-plane angles)
  - Large background from $\Lambda_b \rightarrow J/\psi \Lambda^*$, but distributions cannot be described with only these decays: resonant structures in $m_{J/\psi p}$ needed: pentaquarks
  - Reported $P_c(4380)^+$ and $P_c(4450)^+$ states



PRL **115** 072001 (2015)

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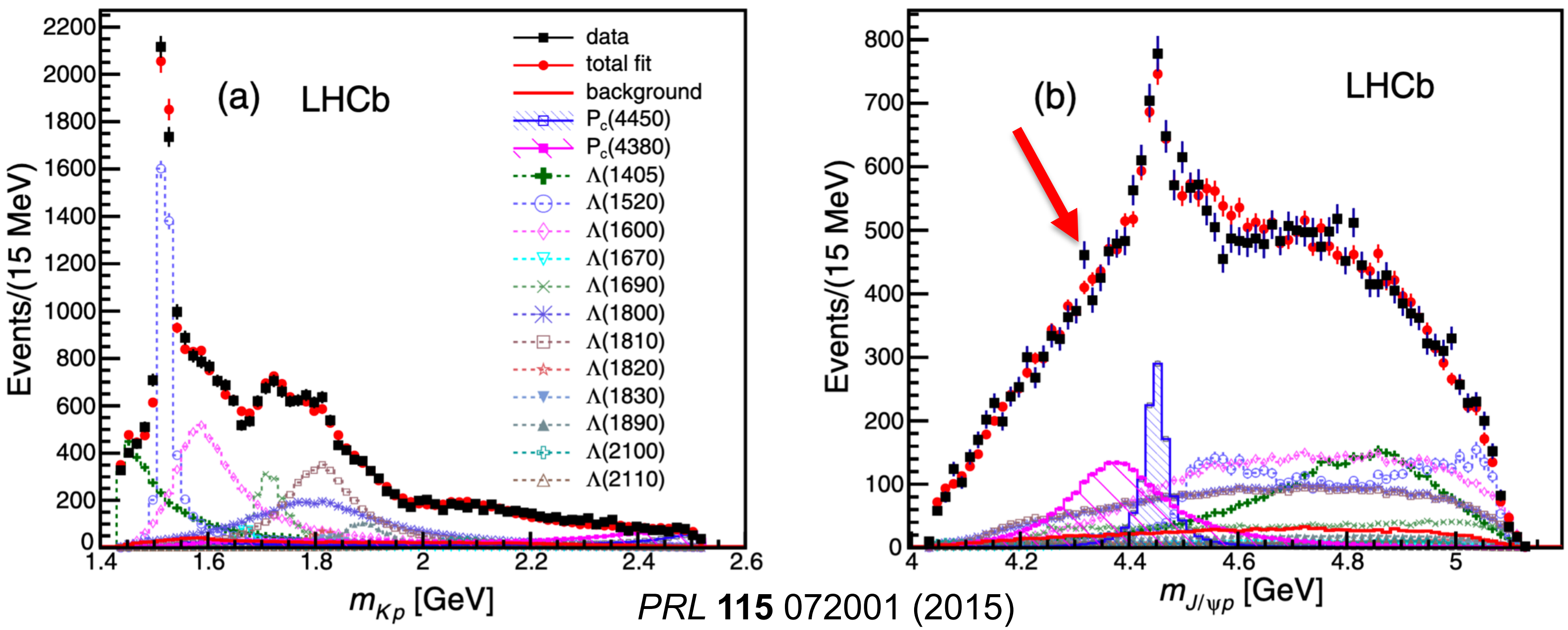
- 2019: 9x more events (7 + 8 + 13 TeV p+p) + finer binning
  - This "peak" (not significant in 2015)…



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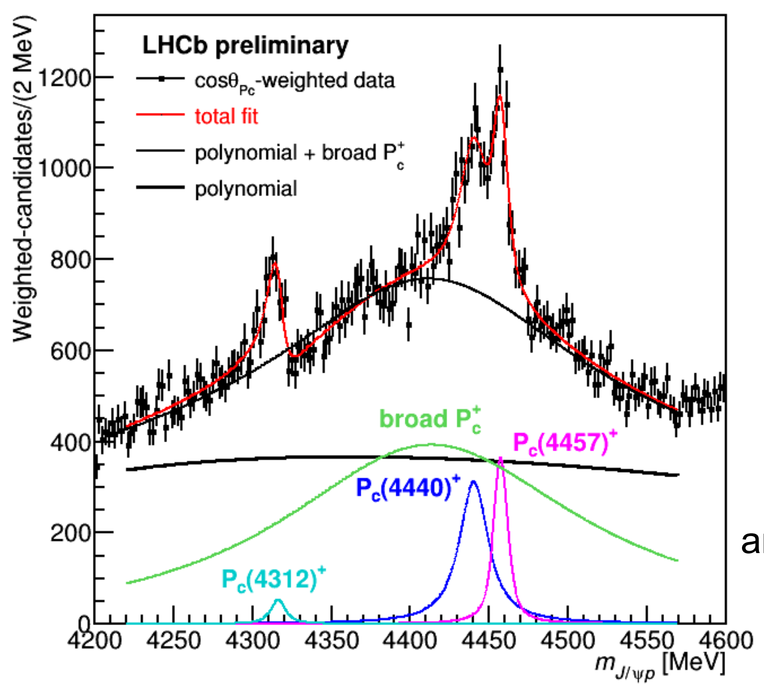
  - This "peak" (not significant in 2015) is a new $P_c(4312)^+$ state (7.3σ)
  - The $P_c(4450)^+$ actually two narrow states: $P_c(4440)^+$ & $P_c(4457)^+$



arXiv:1904.03947

Pentaquarks

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  - Multidimensional fit (m_{Kp}, $m_{J/\psi p}$, helicity & decay-plane angles)
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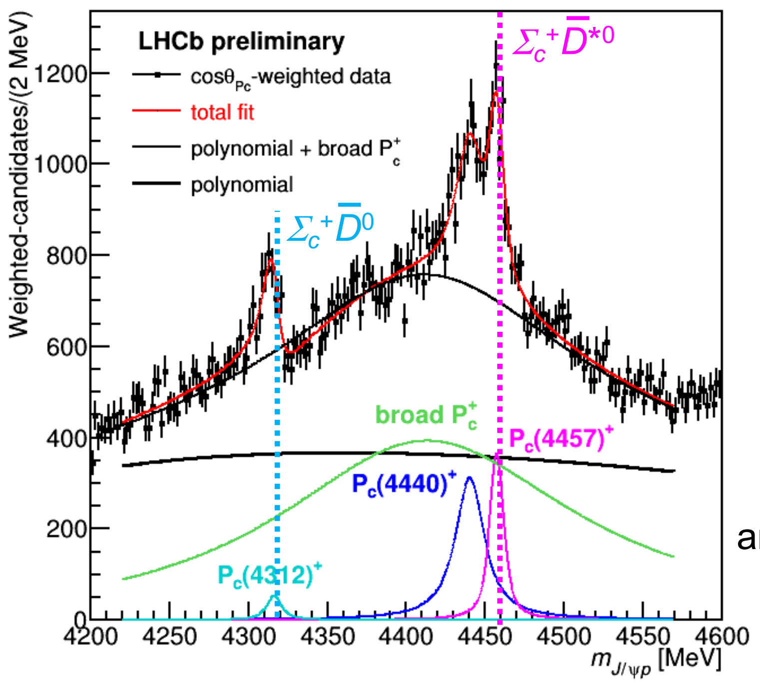
  - The $P_c(4450)^+$ actually two narrow states: $P_c(4440)^+$ & $P_c(4457)^+$
  - Masses lie just below $\Sigma_c^+\bar{D}^0$ and $\Sigma_c^+\bar{D}^{*0}$ thresholds → baryon-meson molecules?



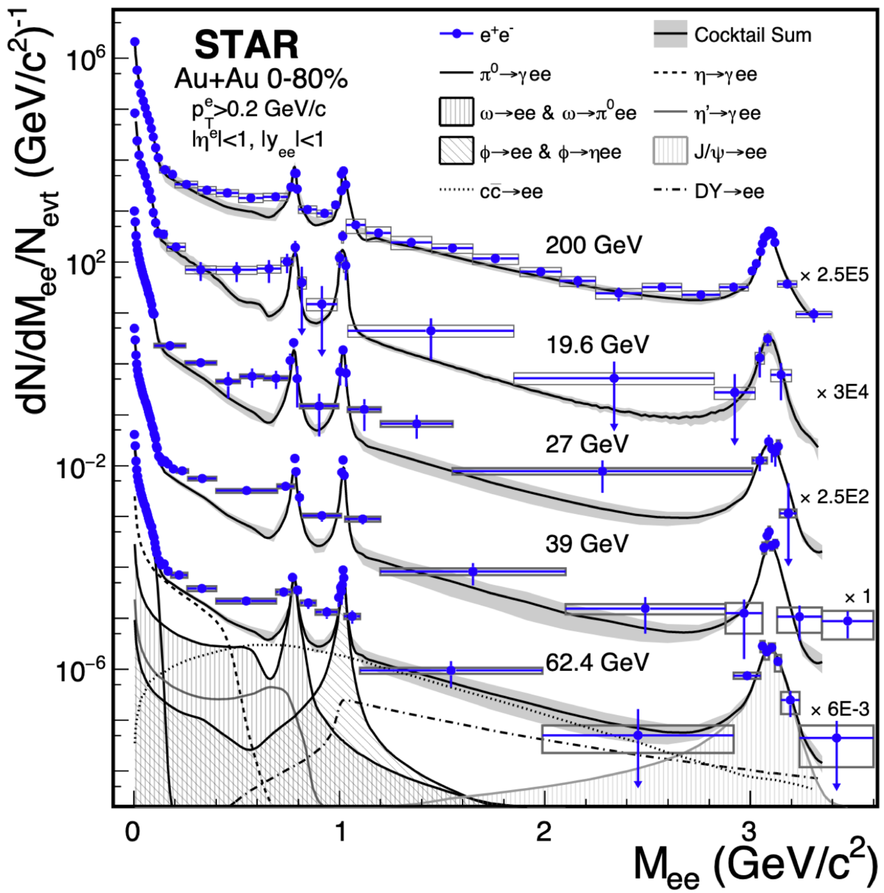
arXiv:1904.03947

Lineshape Modifications

Low-mass Dielectrons: STAR

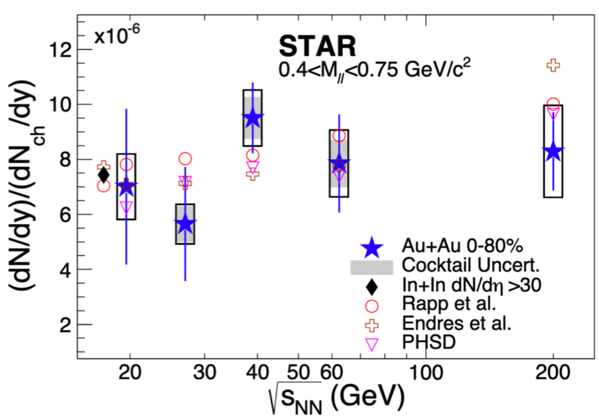
- Measurements of $e^{-}e^{+}$ distributions over broad momentum range, Au+Au at different energies
- Compared to cocktail from known sources (excluding vacuum ρ^0)
- Clear excess seen in low-mass region

arXiv: 1810.10159

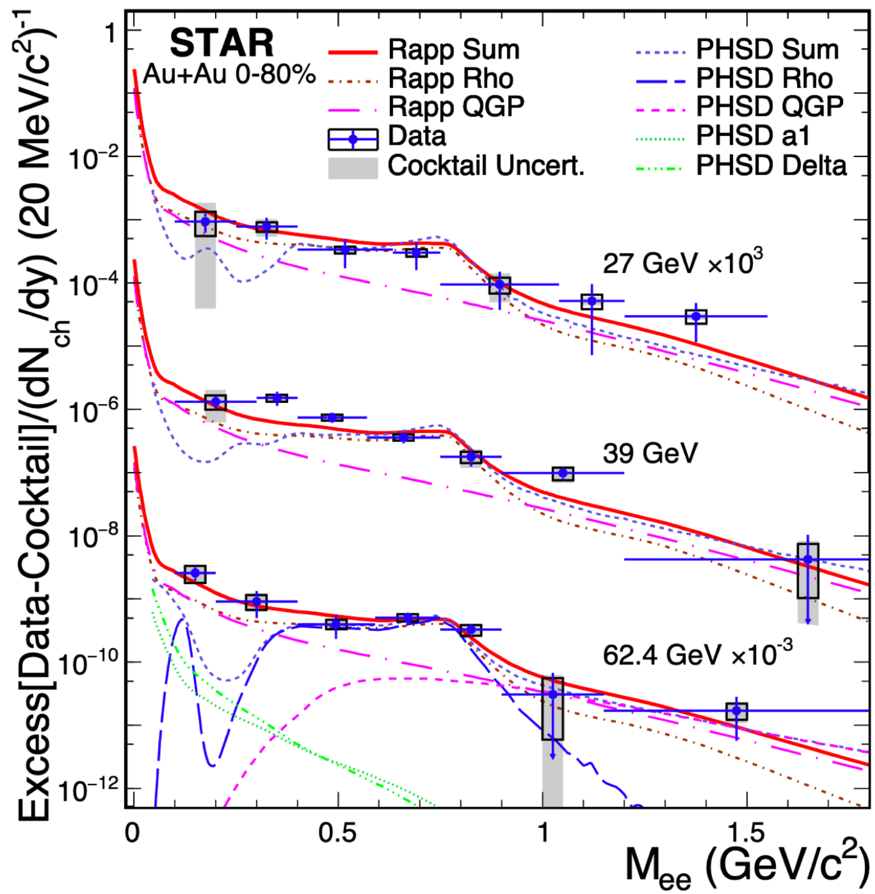


Low-mass Dielectrons: STAR

- Excess compared to Rapp & PHSD calculations
  - Contributions from broadened ρ^0, other decays, QGP radiation
  - Both calculations describe excess well for $0.4<M_{ee}<0.75$ GeV/c^2
  - Good agreement over broad energy range (also for NA60 In+In)



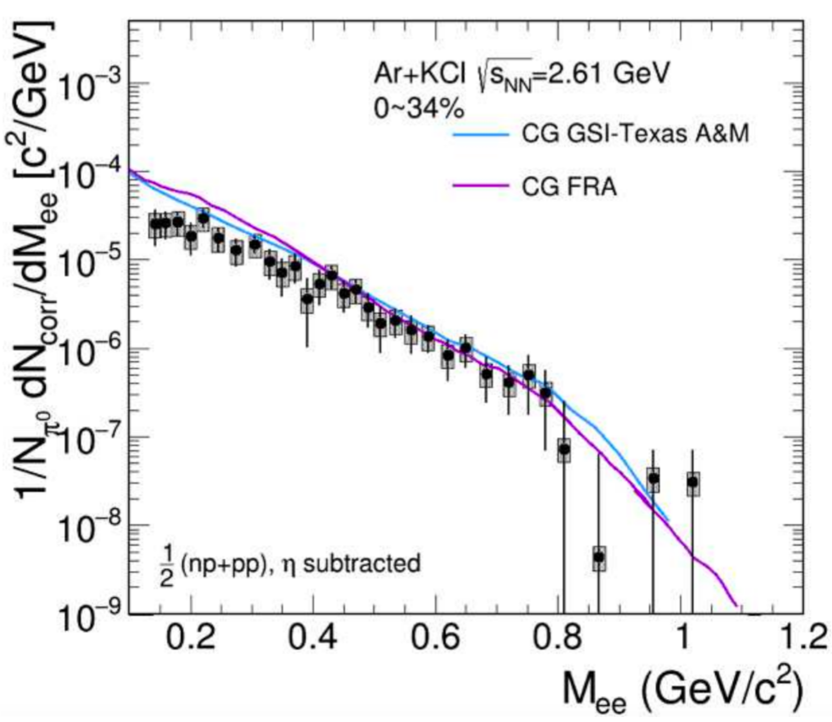
arXiv: 1810.10159

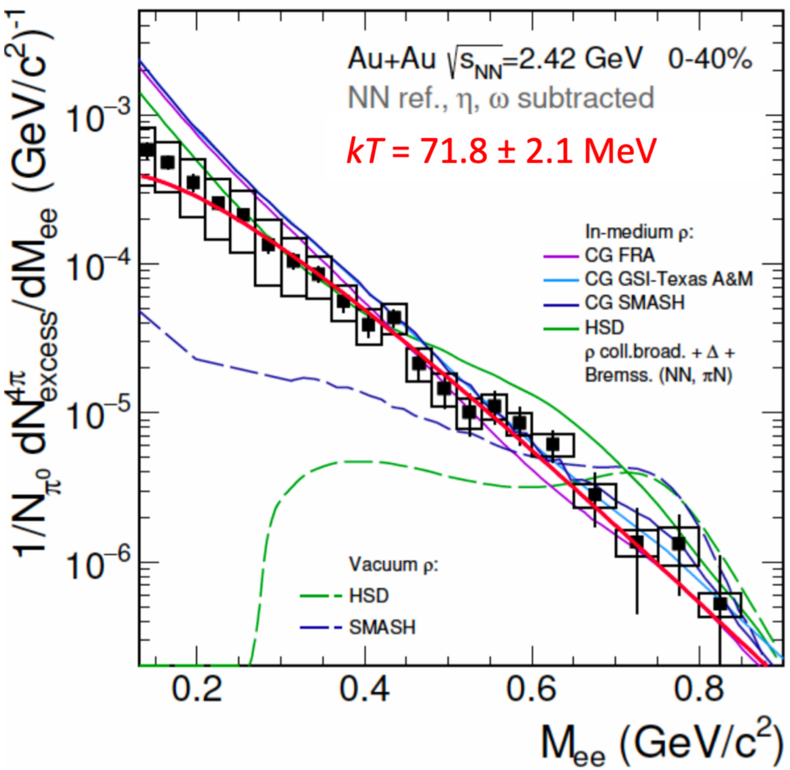


But: low-mass e^-e^+ yield for $p_T < 0.15$ GeV/c not explained by cocktail w/ broadened ρ [*PRL* **121** 132301 (2018)]

Low-mass Dielectrons: HADES

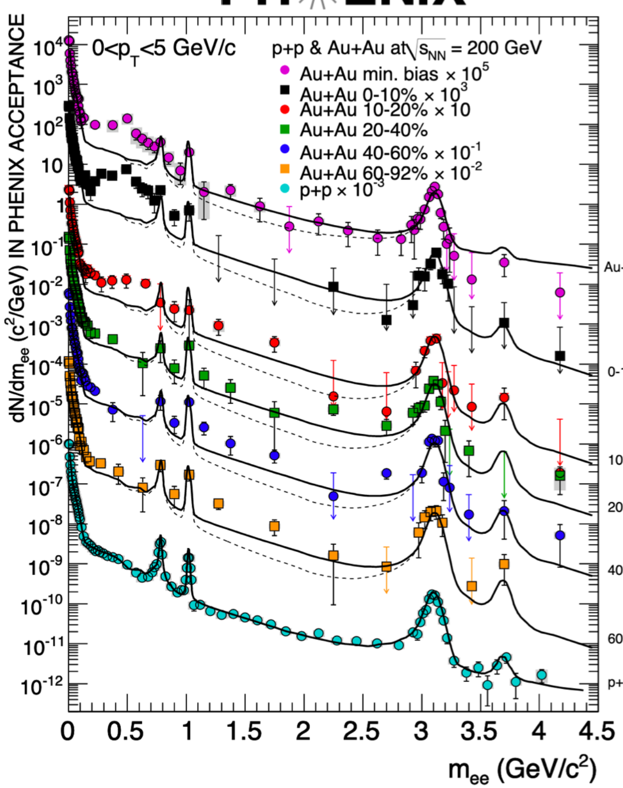
- HADES measures dielectron excess in low mass region
- Excess described using
  - Coarse-graining approach for evolution of fireball
  - Broadening of ρ : interactions with baryon-rich medium



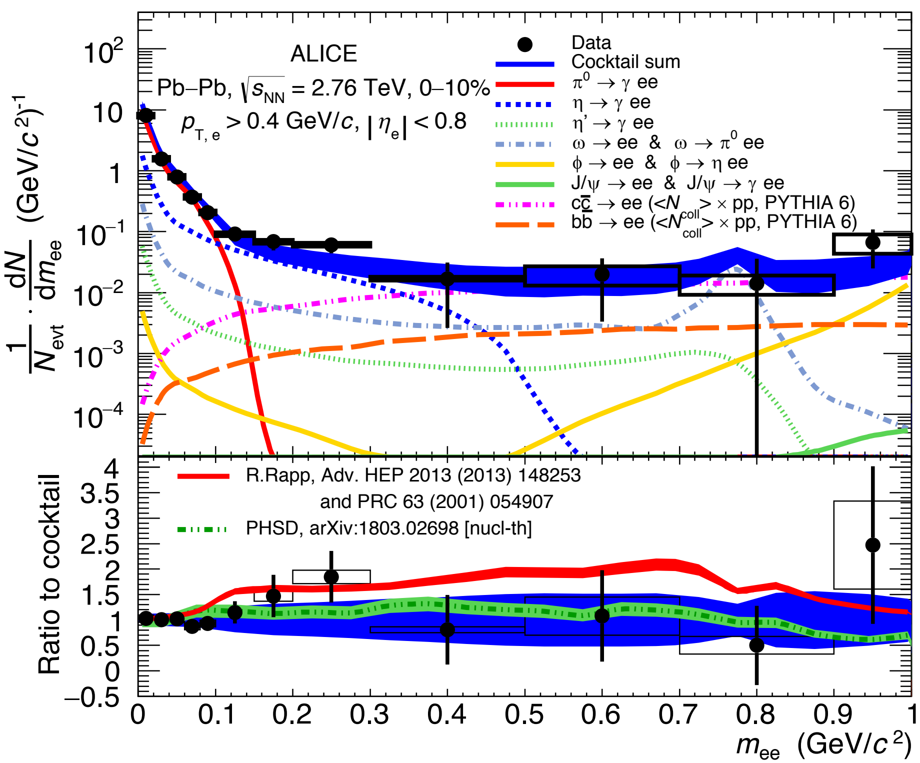


Low-mass Dielectrons

- Similar conclusions drawn at other experiments…



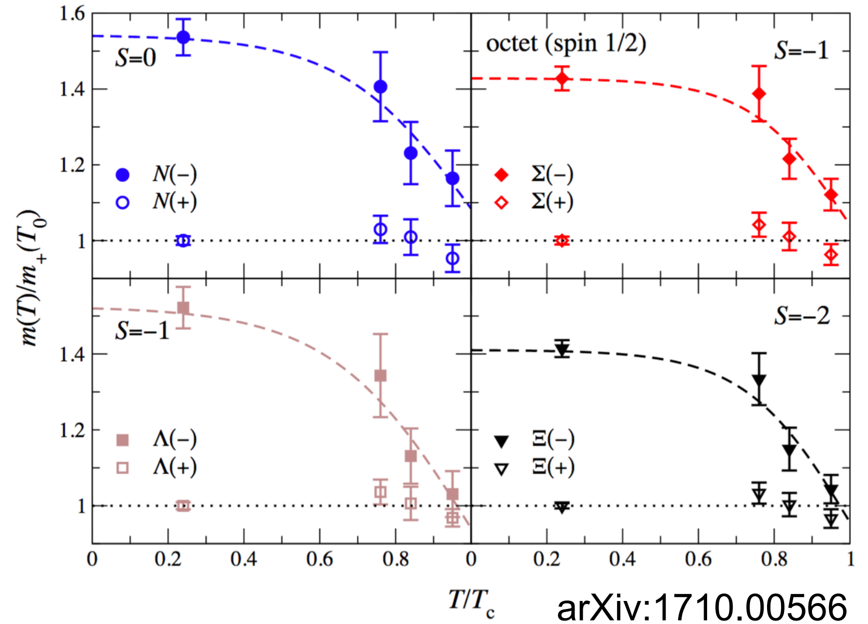
PRC **81** 034911 (2010)



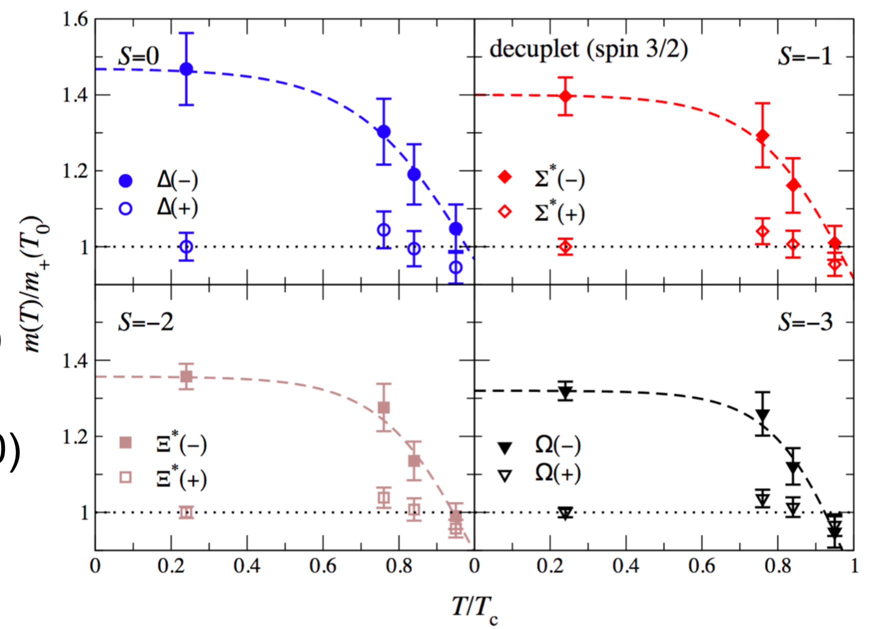
PRC **99** 024002 (2019)

Parity Doubling

- FASTSUM Collaboration calculates mass degeneracy for chiral partners around T_C.
  - Positive-parity masses independent of temperature.
  - Negative-parity masses decrease with increasing temperature.
- Candidates in the octet:
  - Λ: $J^P={}^1/_2{}^+$: measured many times
  - $\Lambda(1405)$: $J^P={}^1/_2{}^-$: difficult to measure, decays to $\Sigma\pi$
- Candidates in the decuplet:
  - $\Xi(1530)$: $J^P={}^3/_2{}^+$: measured in pp, p–Pb, and Pb–Pb
  - $\Xi(1820)$: $J^P={}^3/_2{}^-$: (difficult) measurement in progress at ALICE in pp (ΛK channels)
  - Potential to measure mass shift, width broadening, or change in $\Xi(1820)/\Xi(1530)$ ratio with system size
  - See poster of C. Myers at SQM 2019



arXiv:1710.00566



Summary

- Hadrochemistry controlled by system size at RHIC & LHC energies
  - ϕ/π ratio increases with multiplicity → consistent with rope hadronization or core-corona effects
  - ϕ/K^{-} at low energies: signs of canonical suppression
- Suppression of short-lived resonances [K^{*0}, ρ^{0}, $\Lambda(1520)$] in large collision systems
  - Re-scattering dominant over regeneration
  - Hints of similar behavior in high-multiplicity *p*+*p* and *p*+Pb
  - But lifetime is not the only consideration (see $\Sigma^{*\pm}$)
- Pentaquarks: new states announced
- Low-mass dielectron studies: evidence for ρ broadening

- Hadron Resonances Session: Thurs. 16:10 Sala A+A1

Additional Material

Resonances

We study hadronic resonances with different…

masses (MeV/c^2)

ρ^0	770
K^{*+}	892
K^{*0}	896
$f_0(980)$	990
ϕ	1019
Δ	1232
Σ^{*+}	1383
Σ^{*-}	1387
$\Lambda(1520)$	1520
Ξ^{*0}	1532

And many other resonances…

Resonances

We study hadronic resonances with different…

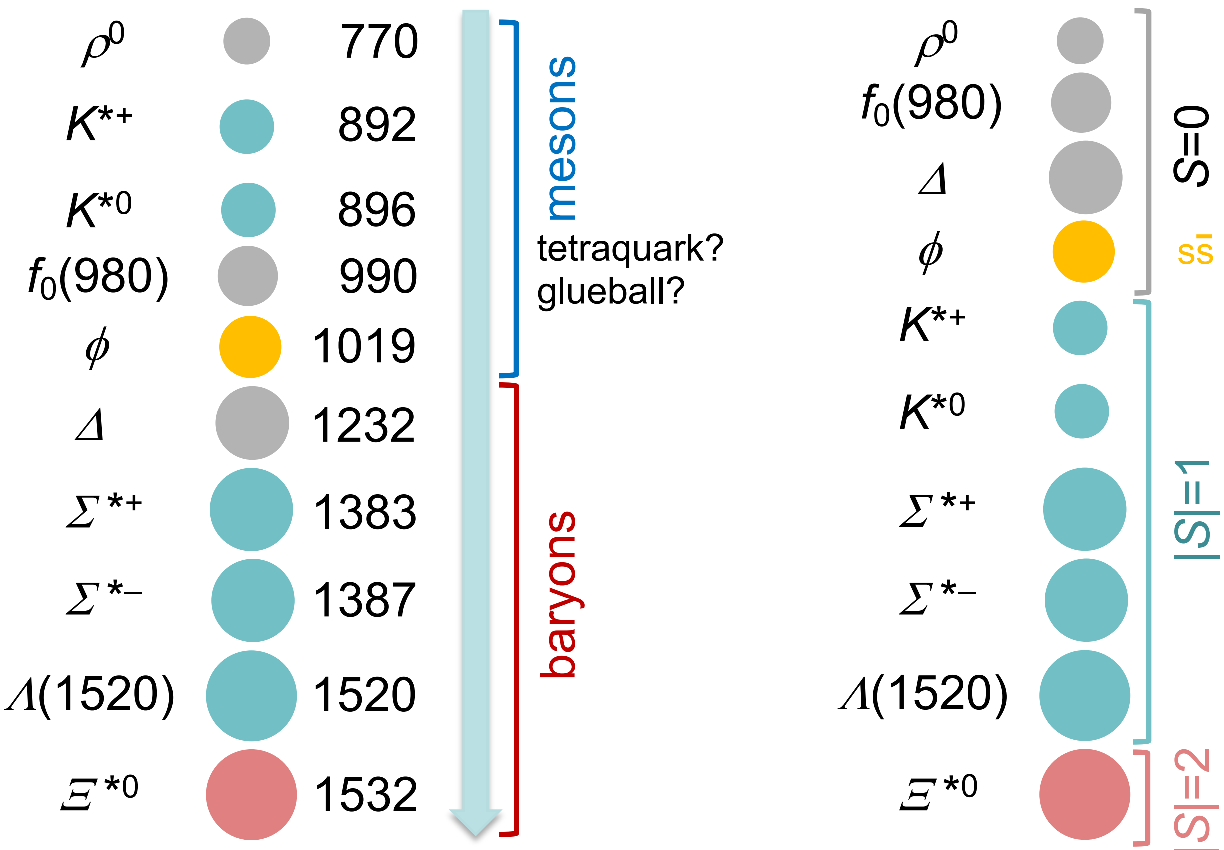
	masses (MeV/c^2)	quark content
ρ^0	770	mesons
K^{*+}	892	mesons
K^{*0}	896	mesons
$f_0(980)$	990	mesons; tetraquark? glueball?
ϕ	1019	mesons
Δ	1232	baryons
Σ^{*+}	1383	baryons
Σ^{*-}	1387	baryons
$\Lambda(1520)$	1520	baryons
Ξ^{*0}	1532	baryons

And many other resonances…

Resonances

We study hadronic resonances with different…

masses (MeV/c^2) quark content strangeness



And many other resonances…

Resonances

We study hadronic resonances with different…

masses (MeV/c^2) / quark content

ρ^0	770	mesons
K^{*+}	892	mesons
K^{*0}	896	mesons
$f_0(980)$	990	mesons (tetraquark? glueball?)
ϕ	1019	mesons
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Σ^{*+}	1383	baryons
Σ^{*-}	1387	baryons
$\Lambda(1520)$	1520	baryons
Ξ^{*0}	1532	baryons

strangeness

ρ^0	S=0
$f_0(980)$	S=0
Δ	S=0
ϕ	S=0 ($s\bar{s}$)
K^{*+}	|S|=1
K^{*0}	|S|=1
Σ^{*+}	|S|=1
Σ^{*-}	|S|=1
$\Lambda(1520)$	|S|=1
Ξ^{*0}	|S|=2

lifetimes (fm/c)

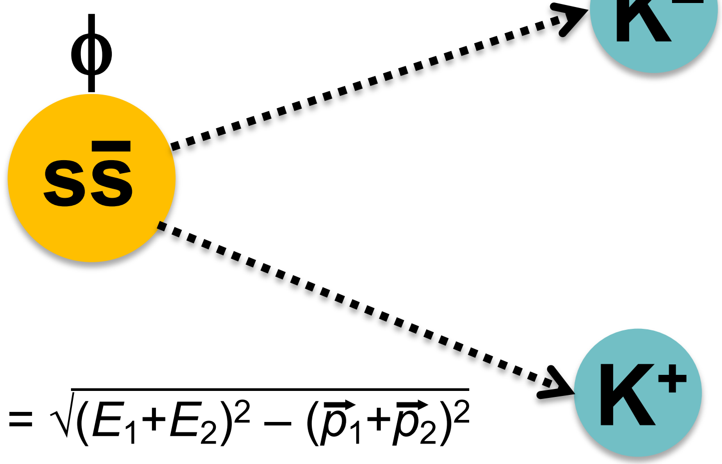
ρ^0	1.3
Δ	1.69
$f_0(980)$	2–20
K^{*+}	3.92
K^{*0}	4.17
Σ^{*-}	5.01
Σ^{*+}	5.48
$\Lambda(1520)$	12.6
Ξ^{*0}	22
ϕ	46.4

~ fireball lifetime!

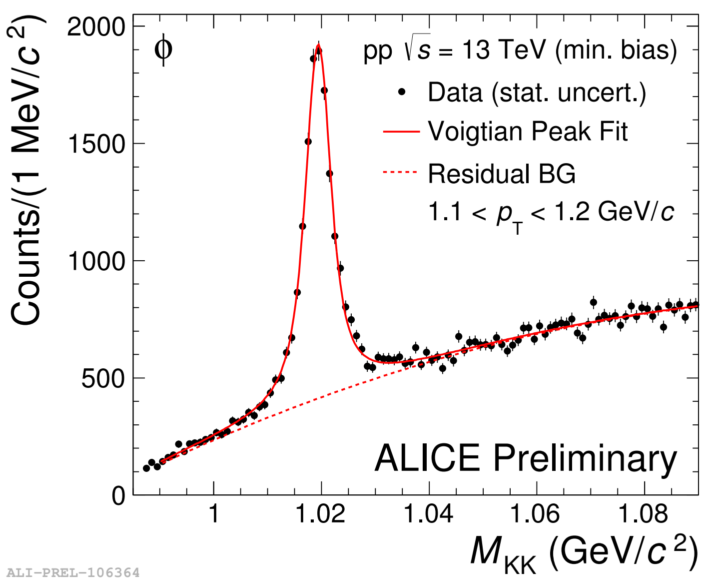
And many other resonances…

Reconstructing Resonances

- Long-lived charged particles ($\pi^{\pm}$, $K^{\pm}$, p, $e^{\pm}$, $\mu^{\pm}$) & γ reach detector components and can be measured directly
- Short-lived particles reconstructed through invariant-mass analysis (example: $\phi \rightarrow K^{-}K^{+}$)
  - Identify all possible decay products
  - Add the 4-momenta for each pair and find mass
  - Look for a peak on top of combinatorial background

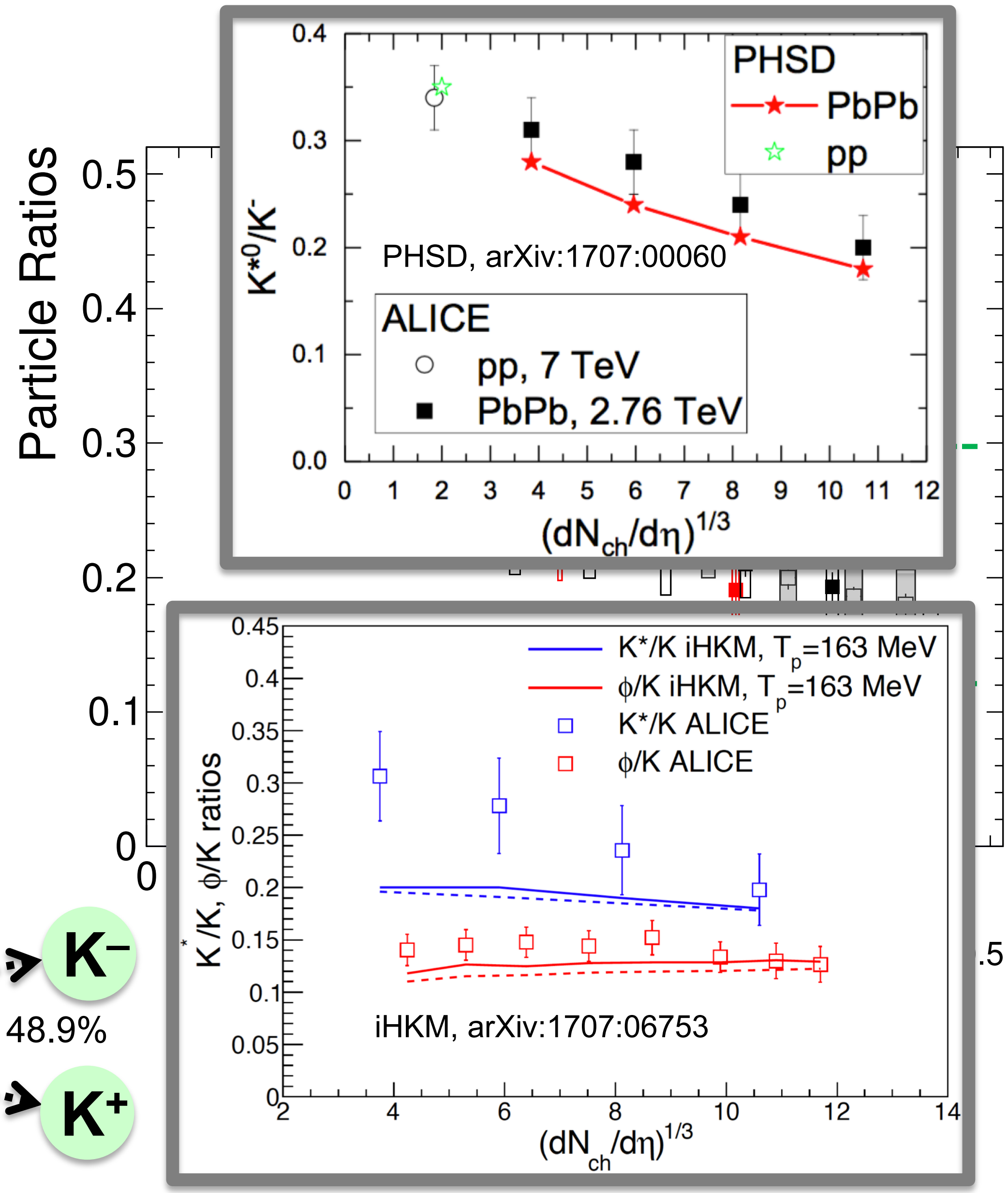


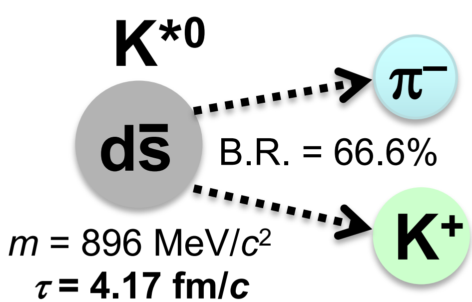
$$M_{inv} = \sqrt{(E_1+E_2)^2 - (\vec{p}_1+\vec{p}_2)^2}$$

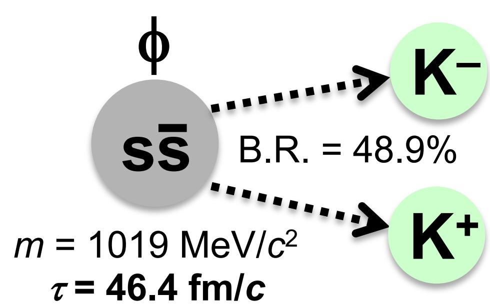


K*0 & ϕ

- Suppression K^{*0}/K in central Pb–Pb collisions
  - Below pp, p–Pb, and GSI-Heidelberg prediction
  - Suggests that re-scattering is dominant over regeneration
- In contrast, ϕ/K not suppressed
  - Consistent w/ GSI-Heidelberg
  - Lifetime of ϕ ~10 × longer than K*0
  - Re-scattering effects not significant
- Suppression described by EPOS, PHSD, & central iHKM

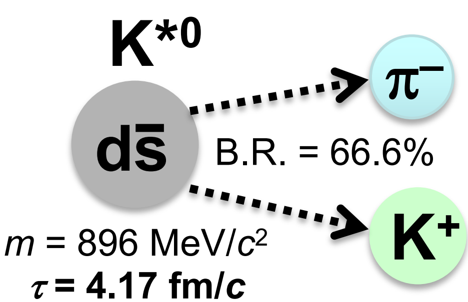


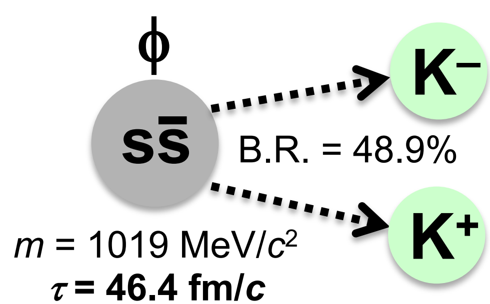


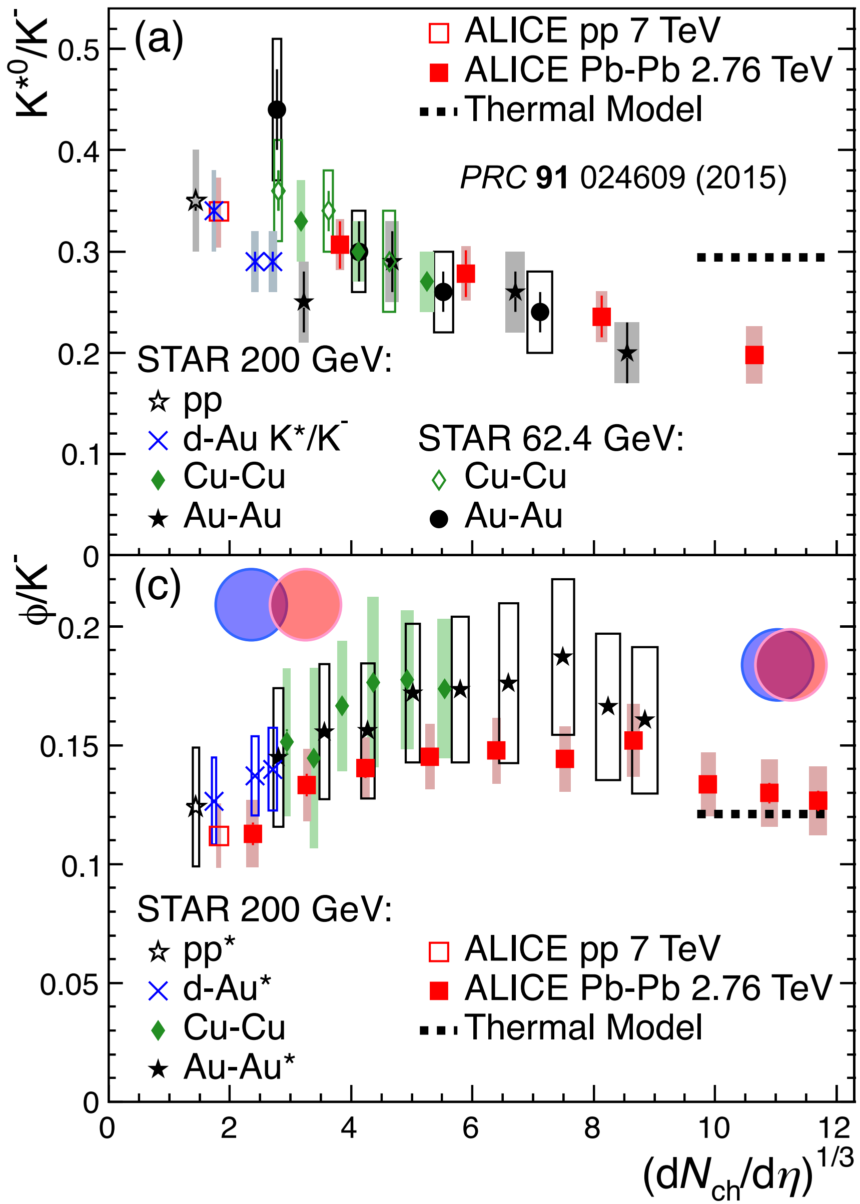


K*0 & ϕ: Coll. Energy

- Similar trends at LHC & RHIC
- K*0/K:
  - No clear energy dependence
  - Smaller ALICE uncertainties give clearer picture of suppression
- ϕ/K:
  - Maybe a weak decrease with energy for A–A

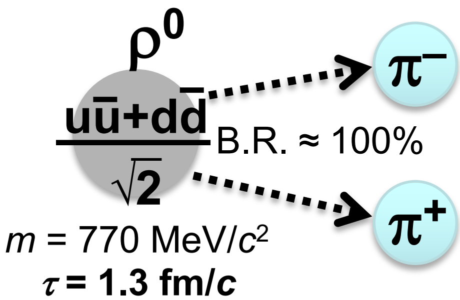






Short Lifetime: ρ^0

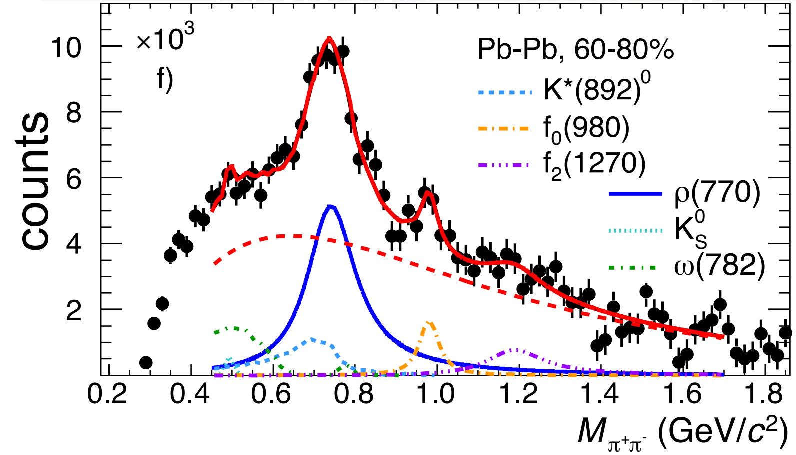
- Reconstruction: wide peak on with a complicated cocktail of correlated background sources

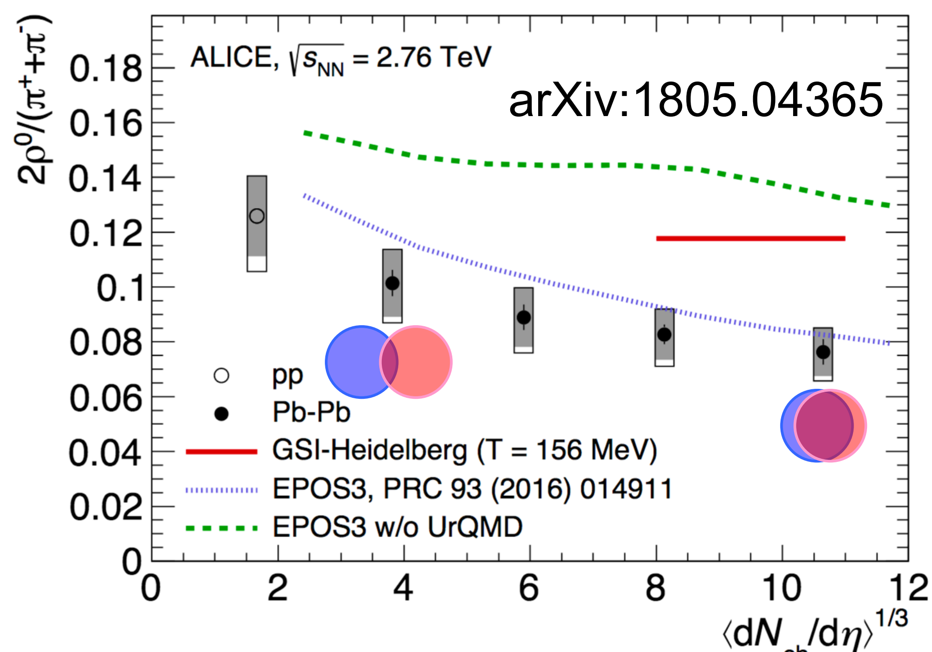


- Suppression of ρ^0/π ratio in central Pb–Pb w.r.t. pp and thermal model (GSI-Heidelberg)
  - Qualitatively described by EPOS with UrQMD
- Suggestion of suppression in high-multiplicity p–Pb
  - Shown later…
- Energy Dependence: RHIC values above LHC

ρ^0 Δ^{++} K^{*0} $\Sigma^{*\pm}$ $\Lambda(1520)$ Ξ^{*0} ϕ

Lifetime→

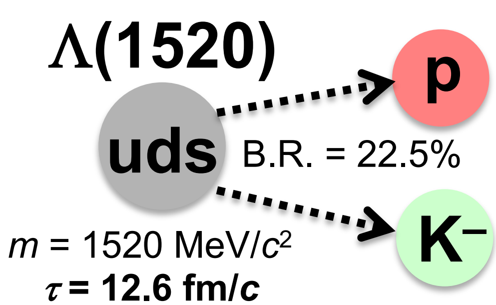


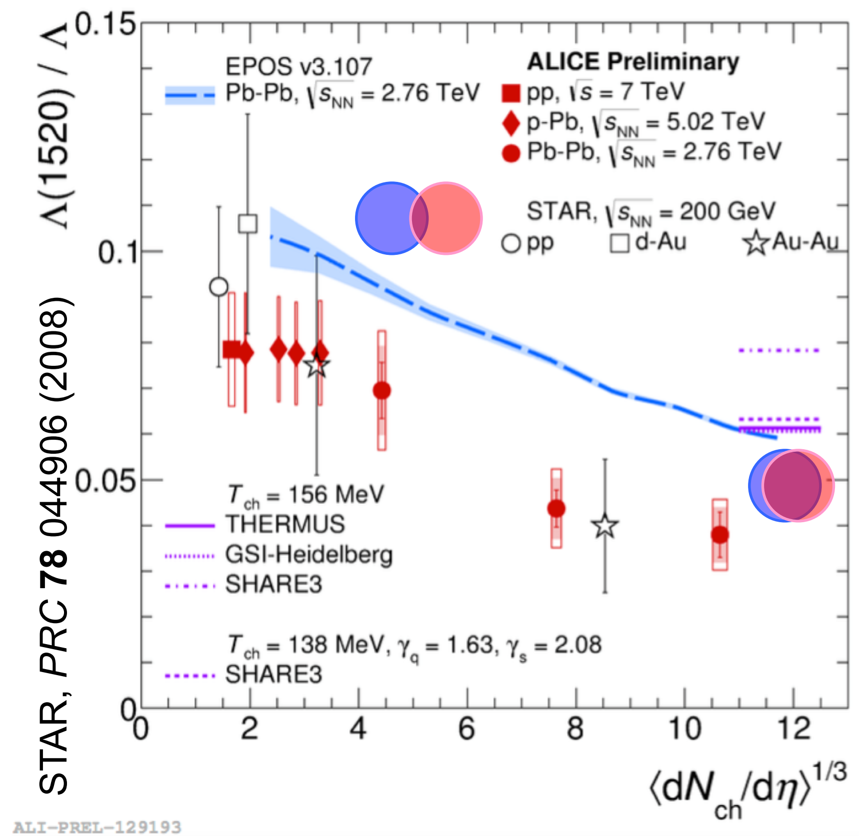


Short Lifetime: Λ(1520)

ρ^0 Δ^{++} K*^{0} Σ*$^{\pm}$ Λ(1520) Ξ*^{0} ϕ
Lifetime→

- Suppression of Λ(1520)/Λ in central Pb–Pb
- No energy dependence for RHIC→LHC
- No multiplicity dependence in p–Pb
- Qualitatively described by EPOS
- Or suppression of *p*-wave baryons [Λ(1520)] in recombination model [*PRC* **74** 061901(R) (2006)]

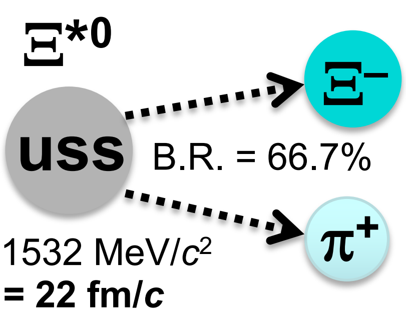


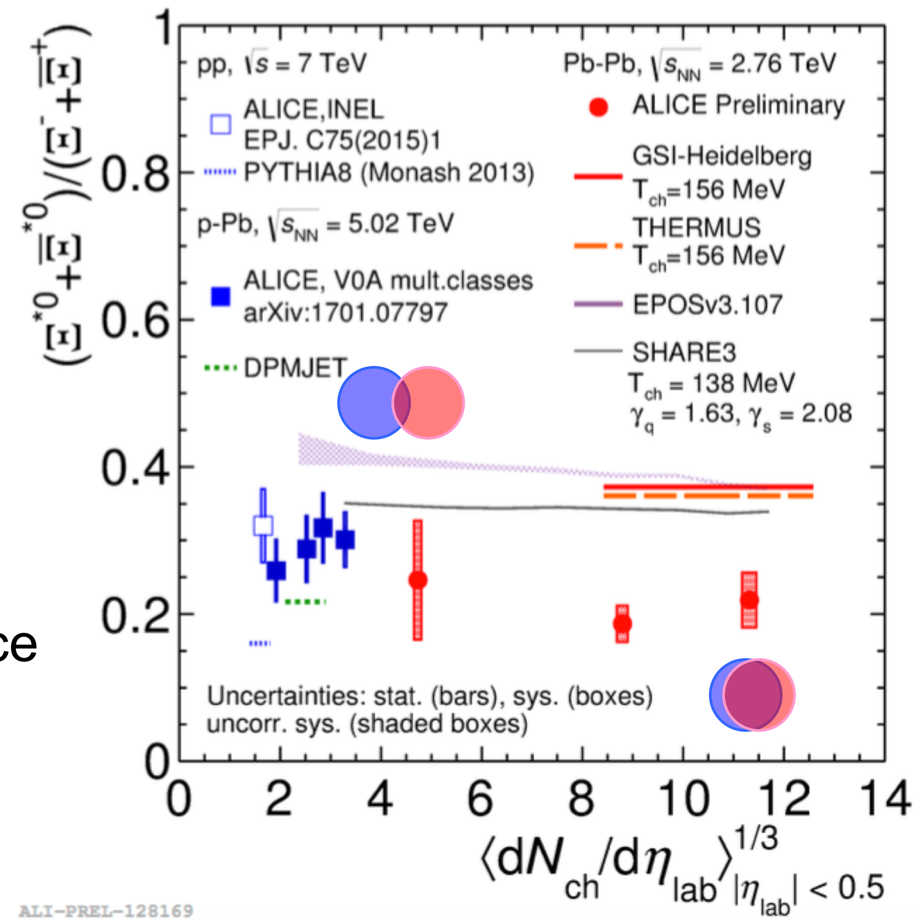


Intermediate Lifetime: Ξ^{*0}

ρ^0 Δ^{++} K^{*0} $\Sigma^{*\pm}$ $\Lambda(1520)$ Ξ^{*0} ϕ
Lifetime→

- In Pb–Pb:
  - No significant centrality dependence
    - Qualitatively described by EPOS and SHARE3
  - Systematically lower in (mid-)central Pb–Pb than in pp and p–Pb
  - Lower than thermal models
  - Possible weak suppression
- In pp and p–Pb:
  - No clear multiplicity dependence

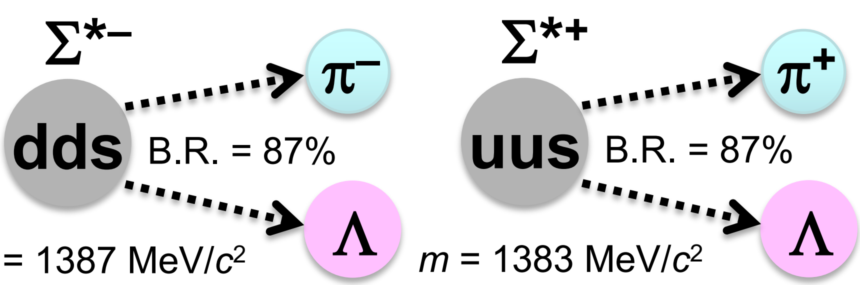




Short Lifetimes: $\Sigma^{*\pm}$

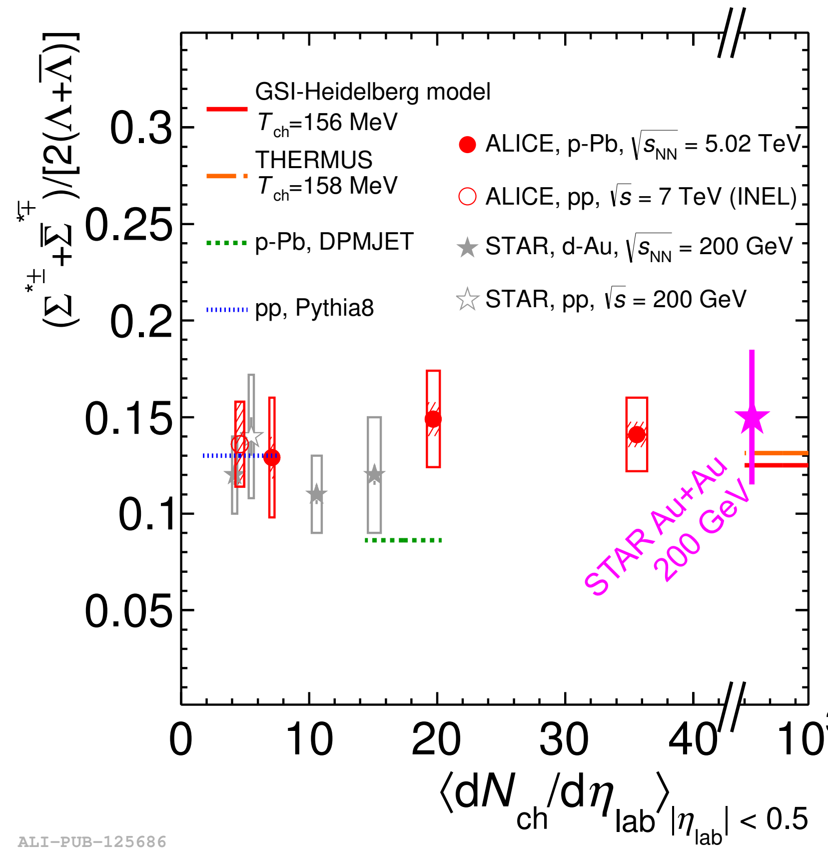
ρ^0 Δ^{++} K^{*0} $\Sigma^{*\pm}$ $\Lambda(1520)$ Ξ^{*0} ϕ
Lifetime→

- No modification of $\Sigma^{*\pm}/\Lambda$ in d–Au and p–Pb
  - No energy dependence RHIC→LHC
- No suppression of $\Sigma^{*\pm}/\Lambda$ seen in in Au–Au
- Pb–Pb measurement in progress



m = 1387 MeV/c^2
τ = 5.01 fm/c

m = 1383 MeV/c^2
τ = 5.48 fm/c

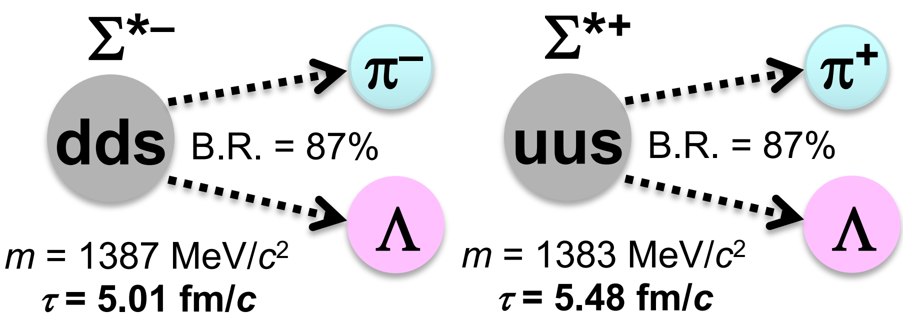


STAR, *PRC* **78** 044906 (2008)
ALICE, *EPJC* **77** 389 (2017)

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

ρ^0 Δ^{++} K^{*0} $\Sigma^{*\pm}$ $\Lambda(1520)$ Ξ^{*0} ϕ
Lifetime→

- No modification of $\Sigma^{*\pm}/\Lambda$ in d–Au and p–Pb
  - No energy dependence RHIC→LHC
- No suppression of $\Sigma^{*\pm}/\Lambda$ seen in in Au–Au
- Pb–Pb measurement in progress
- No suppression predicted by EPOS!

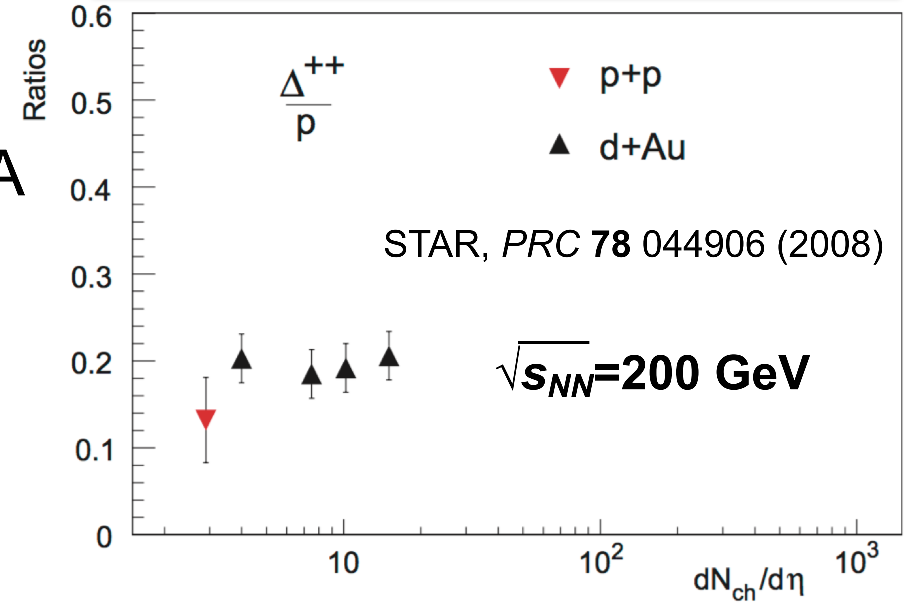


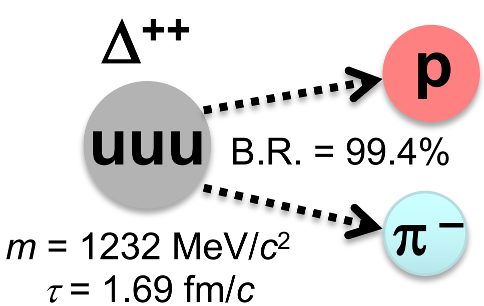
Short Lifetime: Δ^{++}

- No suppression seen in d–Au
- EPOS: no suppression (for LHC energies)
- Measurements difficult in A–A
  - Difficult to control correlated background under peak

ρ^0 Δ^{++} K^{*0} $\Sigma^{*\pm}$ $\Lambda(1520)$ Ξ^{*0} ϕ

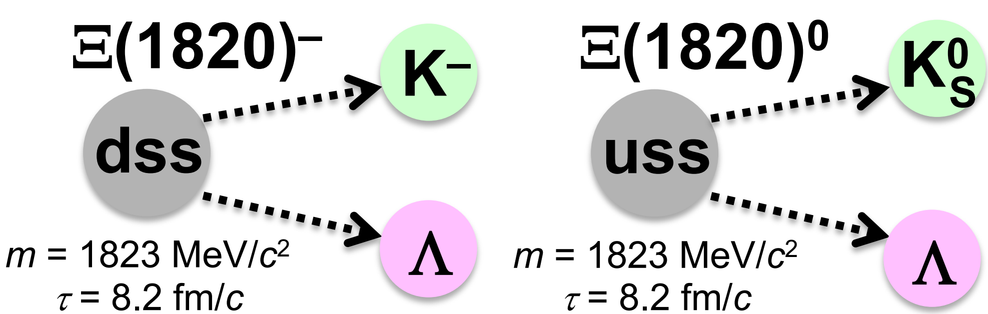
Lifetime→

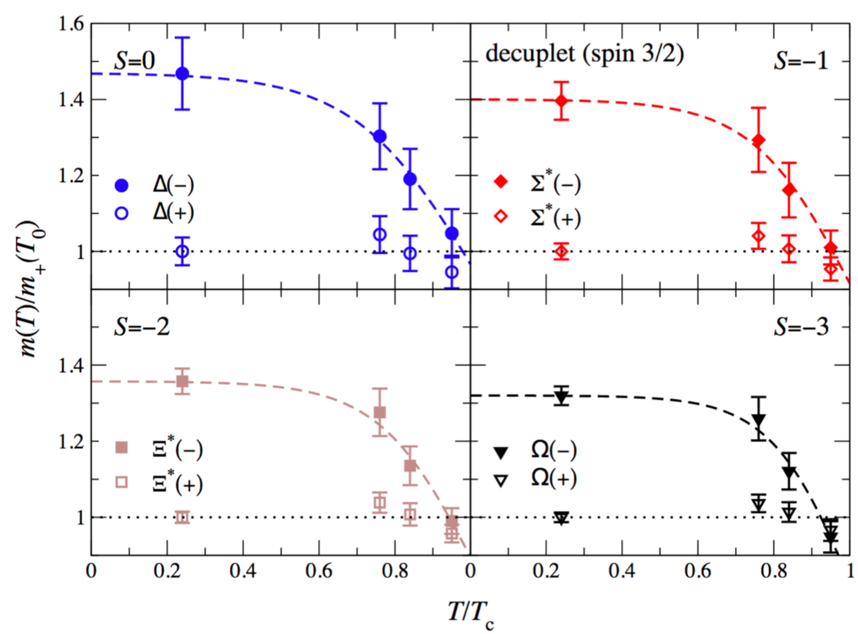




Ξ(1820)

- Motivation
  - Lifetime between K* and Λ(1520) → might be suppressed
  - Understand spectrum of excited hadronic states (for HRG calculations)
  - Improve knowledge of properties: last PDG reference from 1999
  - Possible mass shift in QGP: masses of *P*=–1 states may shift towards *P*=+1 partners (FASTSUM, arXiv:1710.00566)
    - Ξ(1530): $(3/2)^+$ vs. Ξ(1820): $(3/2)^-$



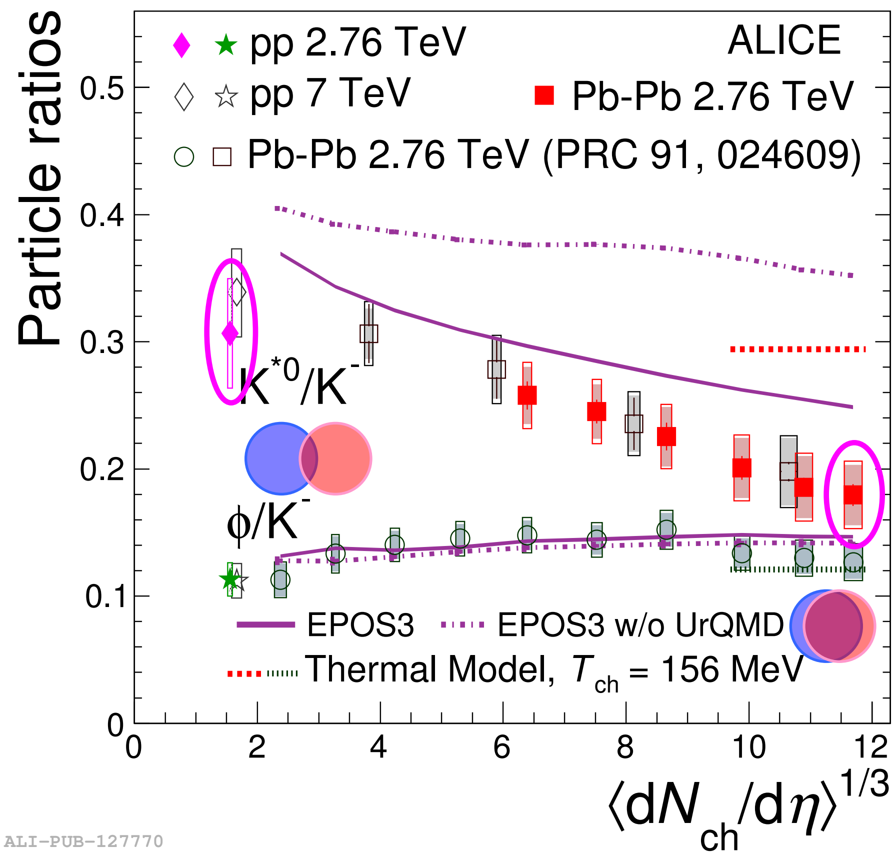


Hadronic Phase

- Simple calculation: assume any K^{*0} decaying before kinetic freeze out is lost (re-scattering), neglect regeneration and time dilation
  - Exponential decrease in yield (τ = 4.2 fm/c)

$$(\text{Final}) = (\text{Initial}) \times \exp(-\Delta t/\tau)$$

  - Use inelastic pp as initial value, central Pb–Pb as final value
    → lifetime of hadronic phase $\Delta t \geq 1$ fm/c



Mean p_T

- Mass ordering of <p_T> in central Pb–Pb
  - <p_T> for p and ϕ similar → expected from hydro
  - M(p) = 938 MeV/c^2 vs. $M(\phi)$ = 1019 MeV/c^2
- Mass ordering breaks down for smaller collision systems.
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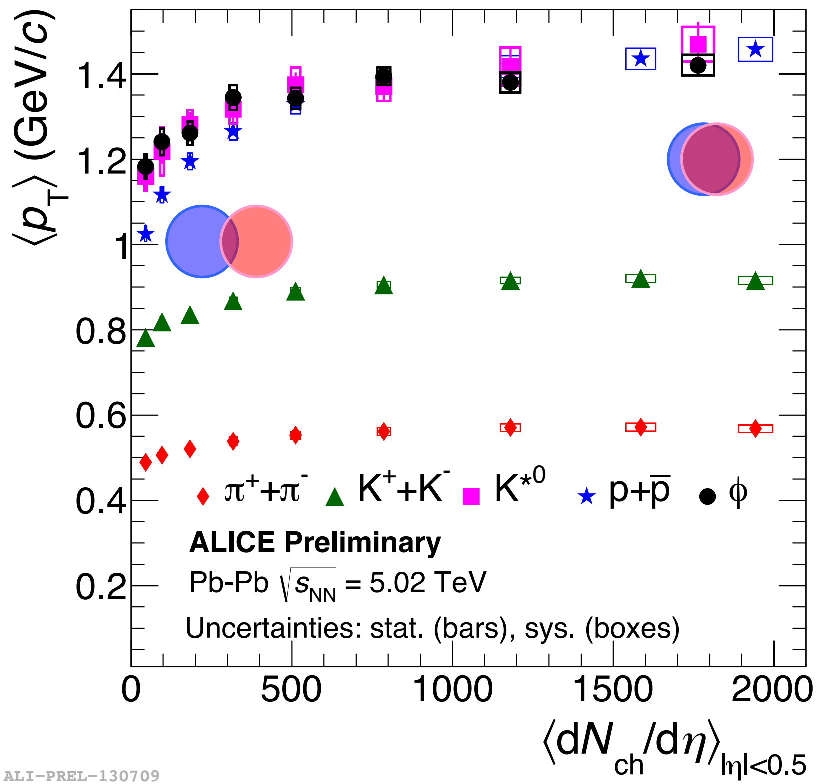
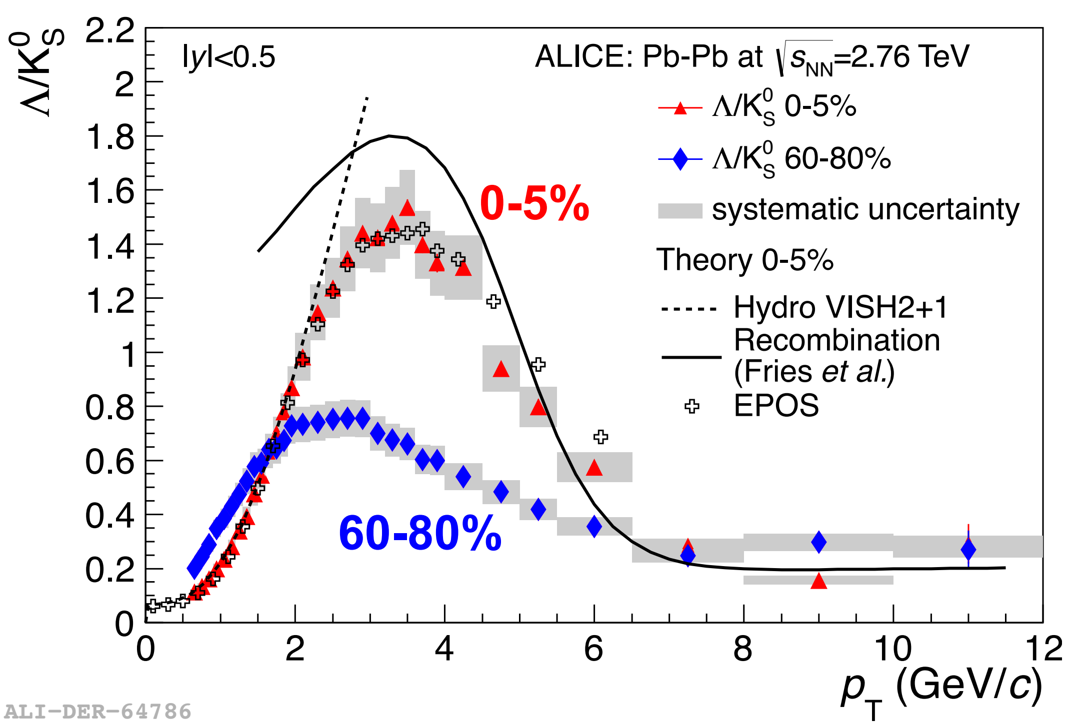
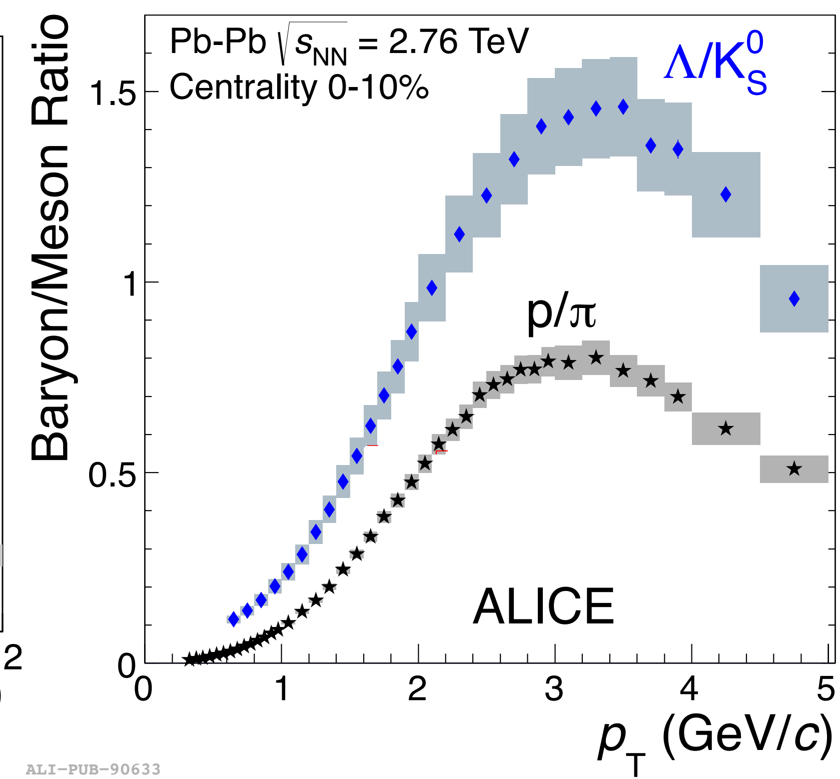


Baryon/Meson Ratios

- p/π and Λ/K^0_S ratios in Pb–Pb
- What causes intermediate p_T (~3 GeV/c) enhancement (for Λ/K^0_S)?
  - Recombination qualitatively describes enhancement
  - Low-p_T rise described by hydrodynamics (VISH 2+1)
  - EPOS consistent with measured enhancement → radial flow





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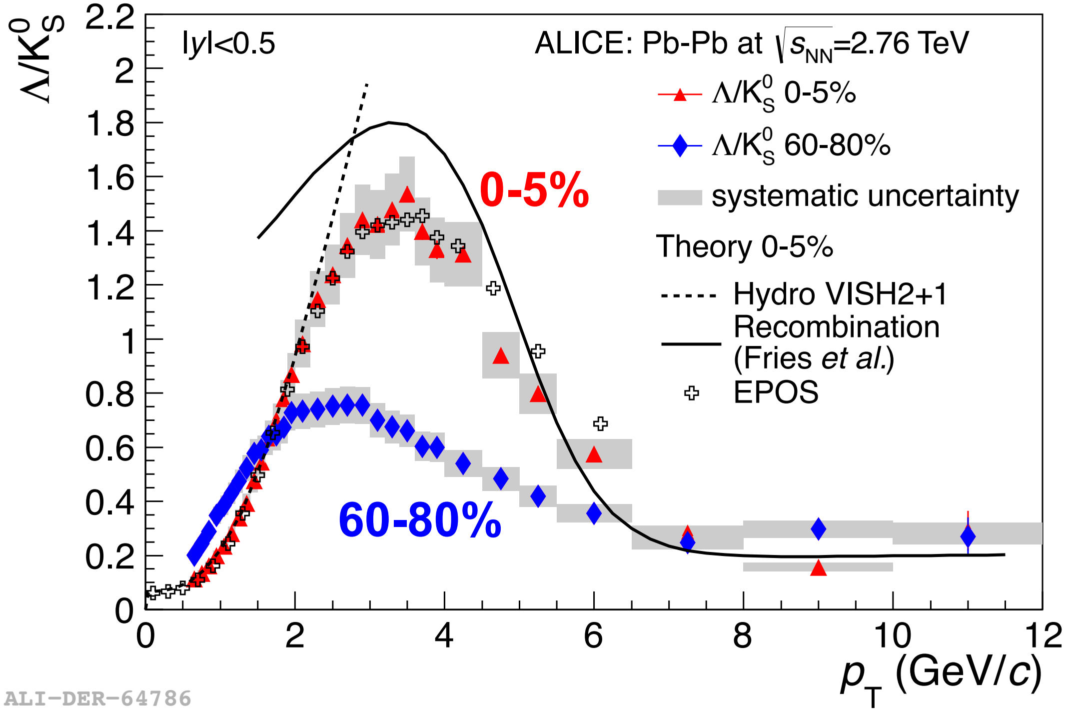
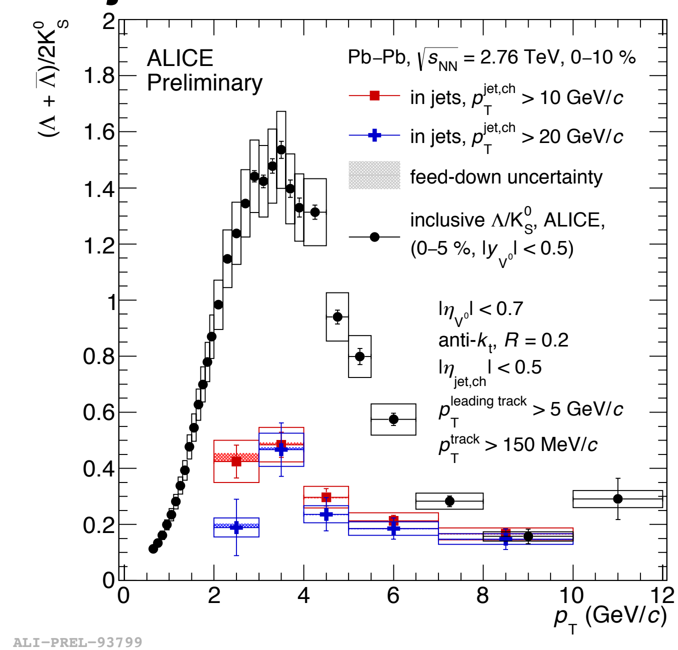
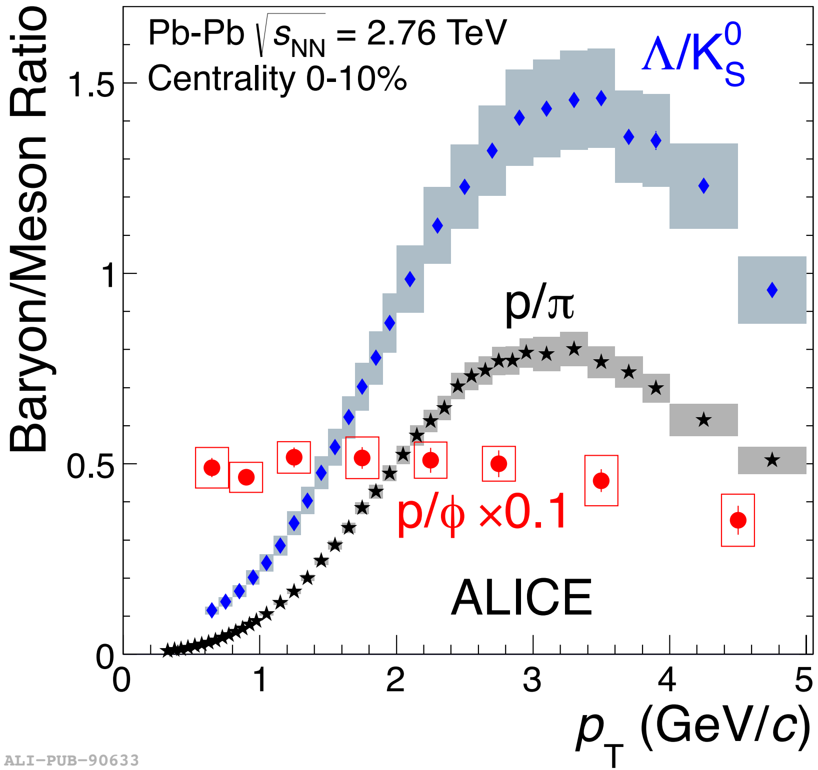


Note: much less prominent in jets → bulk effect



Baryon/Meson Ratios

- p/ϕ ratio ($m_p \approx m_\phi$): flat for p_T < 4 GeV/c (cent. 0-10%)
  - Particle masses determine spectra → expected from hydro
  - Some recombination models (+ fragmentation) can also describe this behavior
    - *e.g.*, Minissale *et al.*, *Phys. Rev. C* **92** 054904 (2015)



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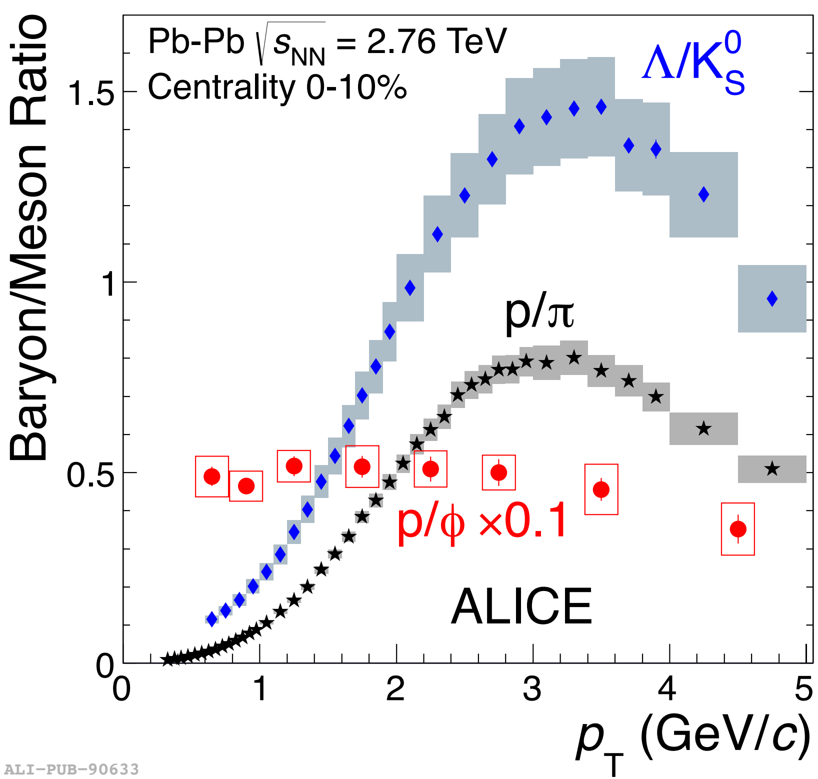
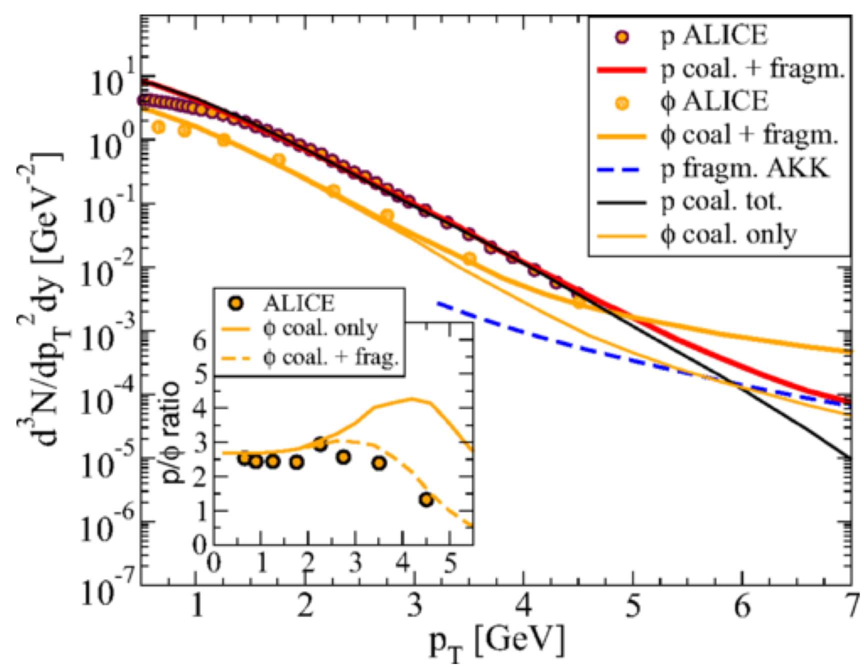
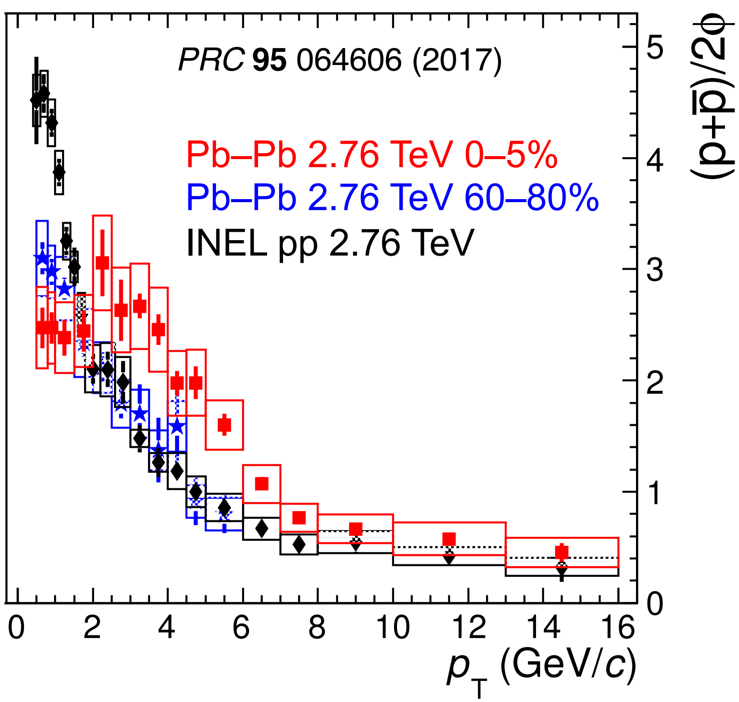




Baryon/Meson Ratios

- Extend p/ϕ measurement to high p_T
  - Flat in p_T for p_T<4 GeV/*c*
    - Hydrodynamics or recombination
  - Drop-off towards high p_T, Pb–Pb consistent w/ pp
    - Jets, fragmentation

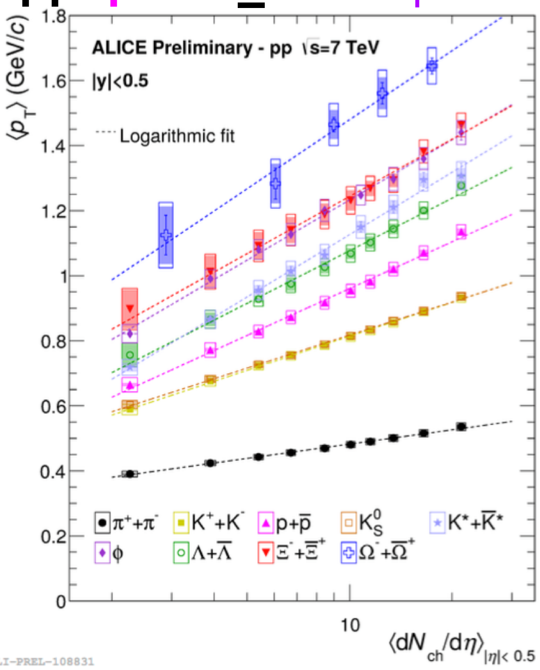


Mean p_T

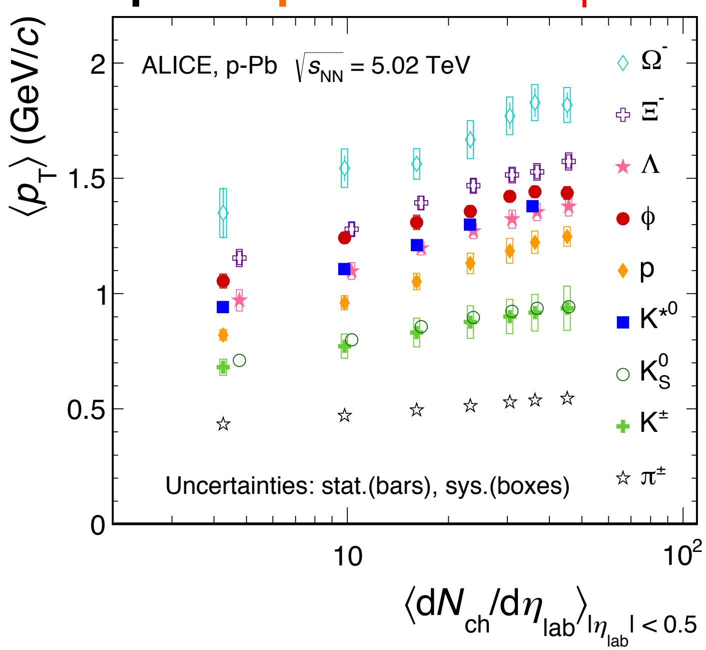
- Mass ordering of $\langle p_T \rangle$ in central Pb–Pb
  - $\langle p_T \rangle$ for p and ϕ similar → expected from hydro
  - M(p) = 938 MeV/c^2 vs. $M(\phi)$ = 1019 MeV/c^2
- Mass ordering breaks down for smaller collision systems.
  - In pp: $\langle p_T(\phi) \rangle \approx \langle p_T(\Xi) \rangle$ despite 30% mass difference

$\langle p_T \rangle$ ordering:

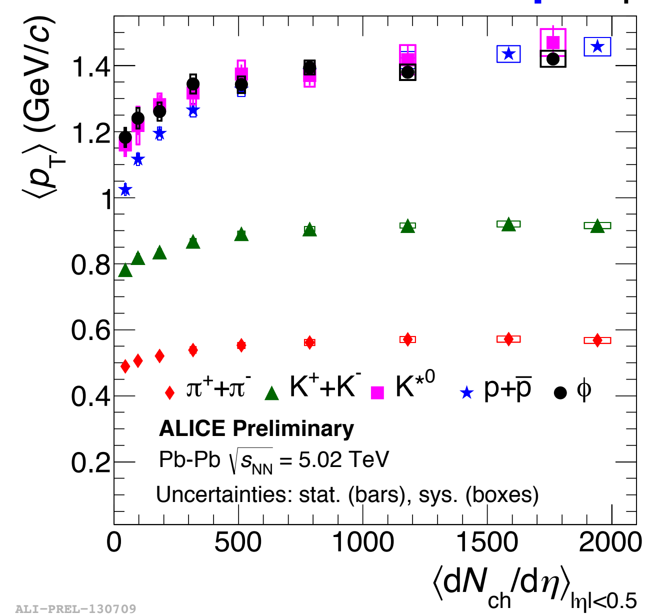
pp: p < Λ ≤ K^{*0} < φ ≈ Ξ^-



p–Pb: p < Λ ≈ K^{*0} < φ < Ξ^-



Central Pb–Pb: K^{*0} ≈ p ≈ φ



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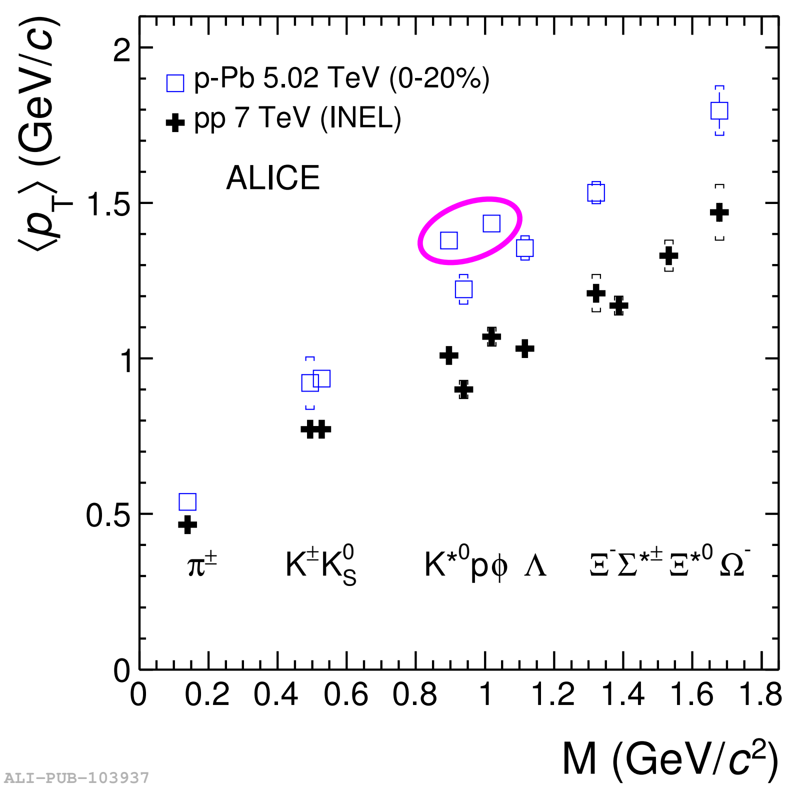
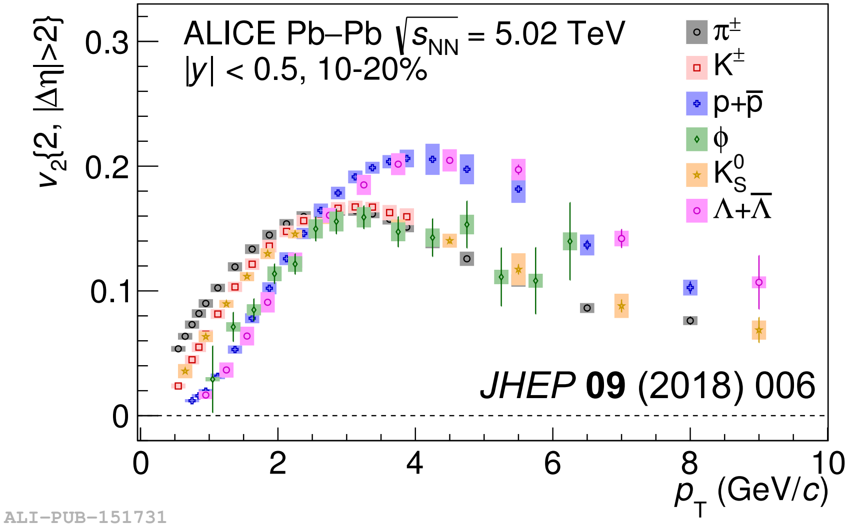
  - Baryon/meson differences? Different behavior for resonances?



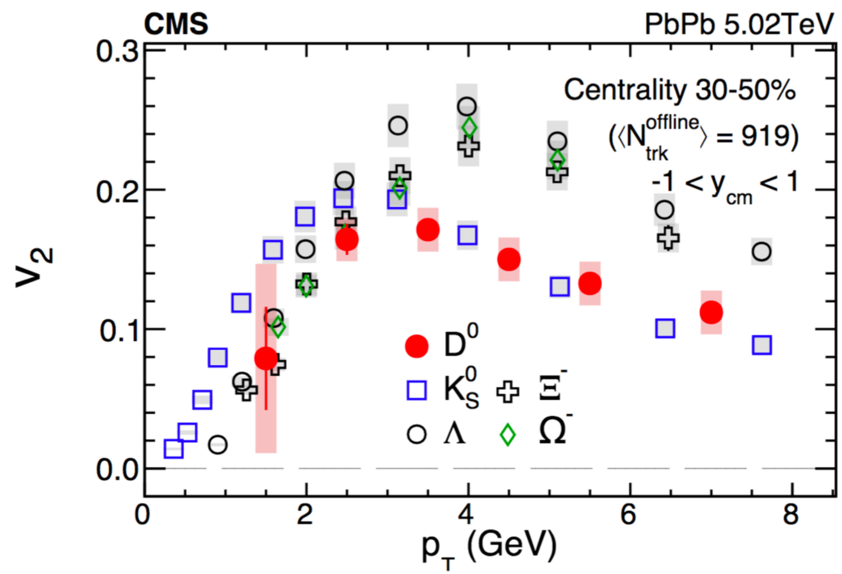
Elliptic Flow

- v_2 of identified hadrons in Pb–Pb
  - Low p_T: mass ordering: $v_2^p \approx v_2^\phi \approx v_2^\Lambda$
  - Hight p_T: baryon-meson splitting
  - Also for other centralities, lower energies
  - The ϕ is a key probe for verifying this.



JHEP **09** (2018) 006

- See also D^0 meson flow (CMS)
  - $m(D^0)$=1.865 GeV/c^2
  - Baryon-meson splitting at high p_T
  - Consistent with mass ordering at low p_T, but large uncertainties

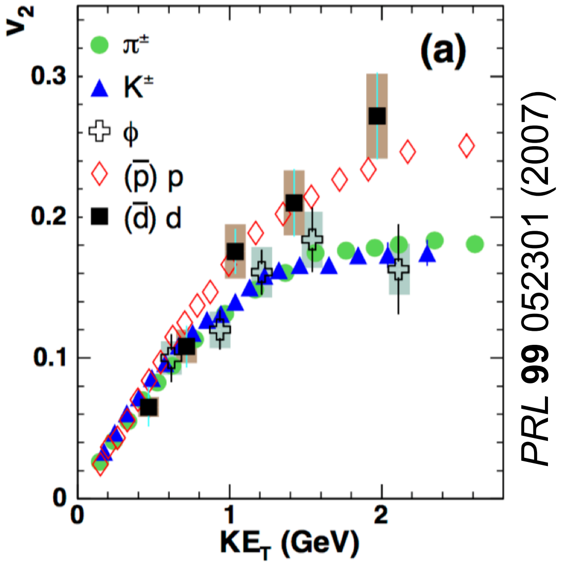


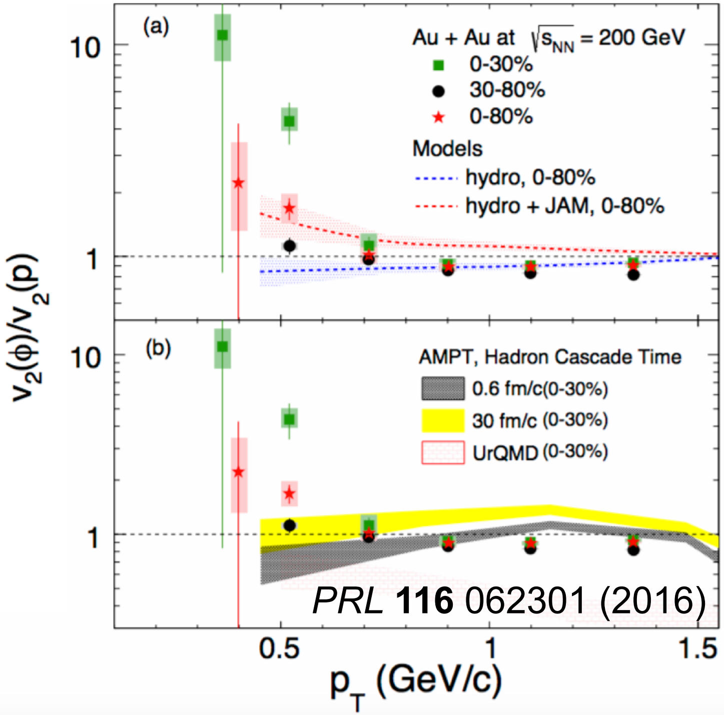
PRL **121** 082301 (2018)

Elliptic Flow

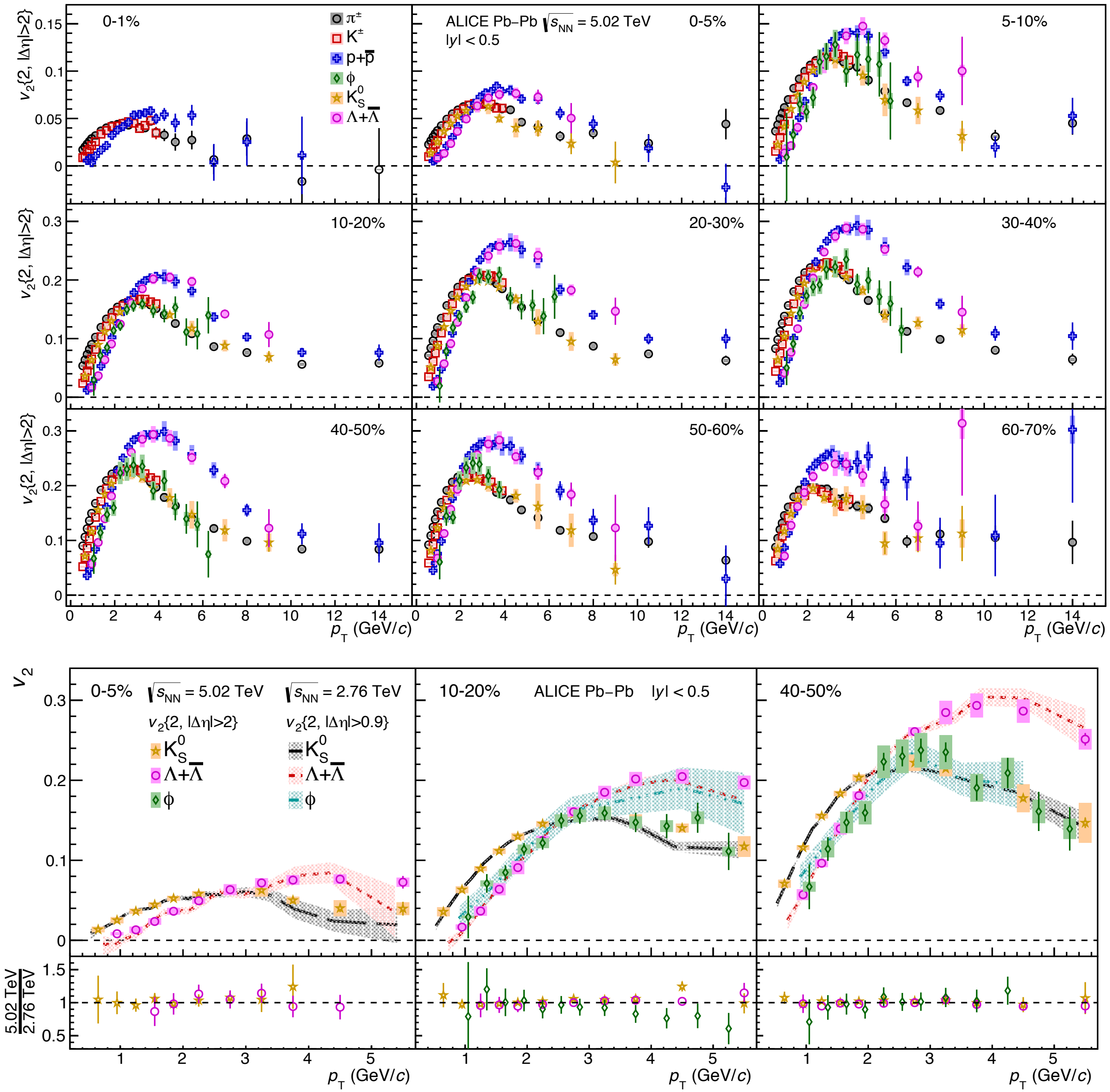
- PHENIX: $v_2(KE_T)$ for ϕ follows other mesons for p_T>0.8 GeV/c

- STAR: violation of mass ordering: $v_2(\phi)$>$v_2(p)$ at low p_T
  - Hadronic re-scattering for p?

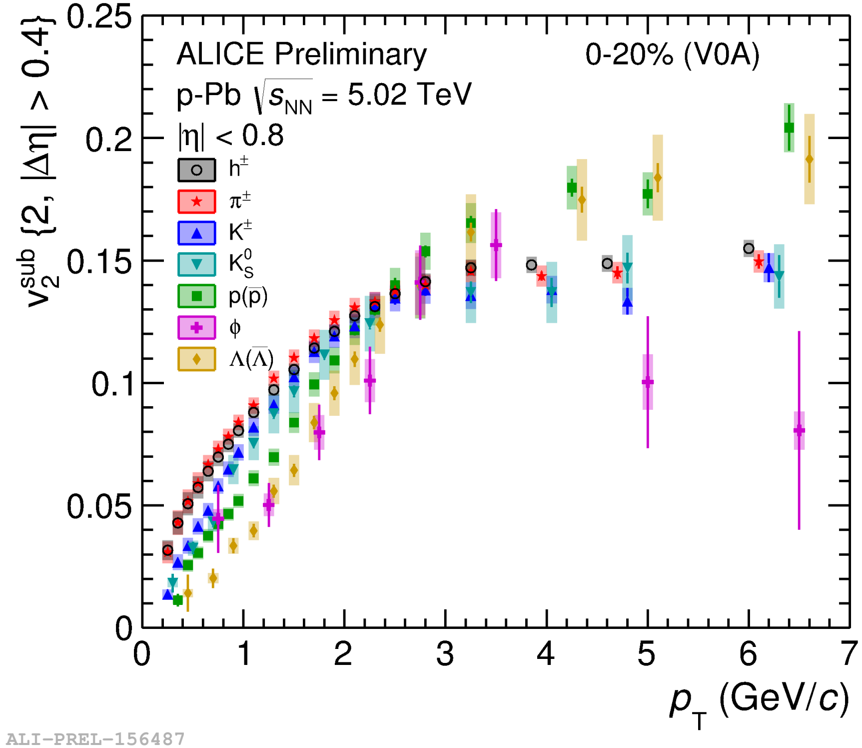


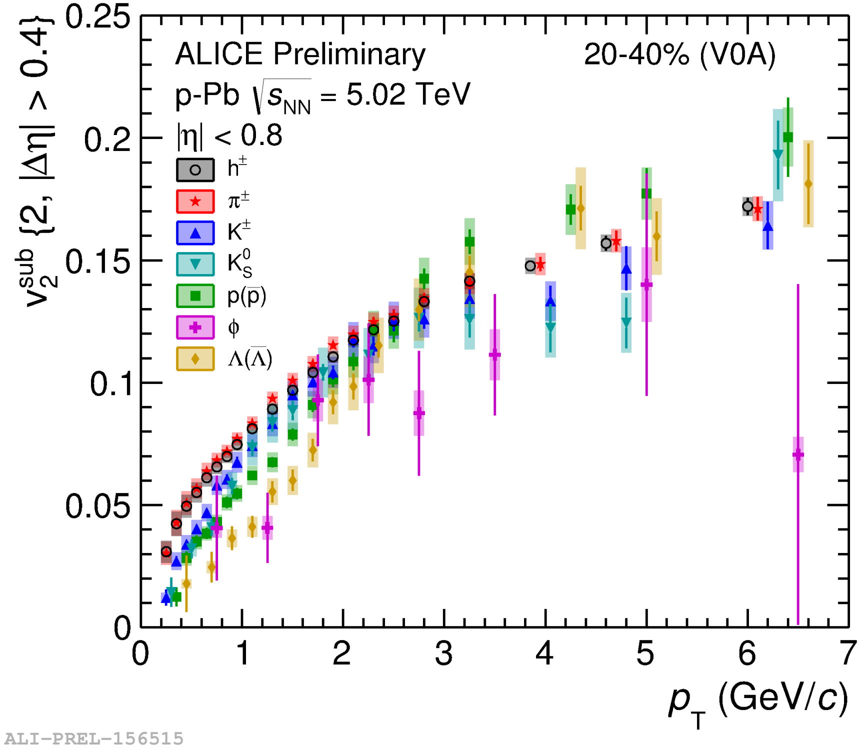


ϕ Elliptic Flow: Pb–Pb



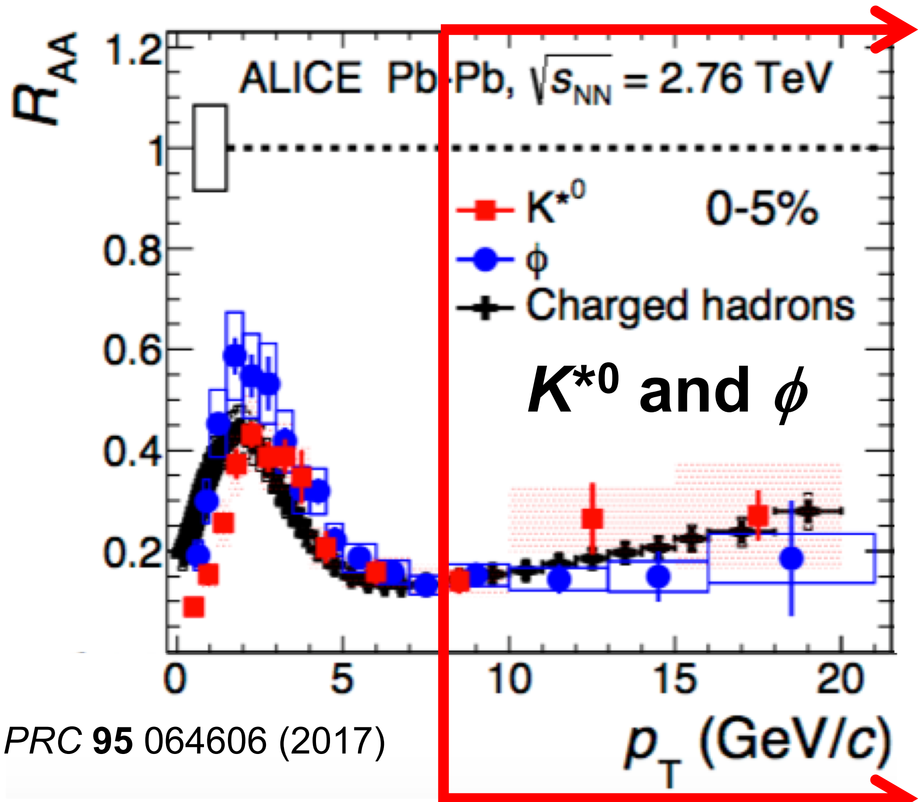
ϕ Elliptic Flow: p–Pb





Nuclear Modification Factor

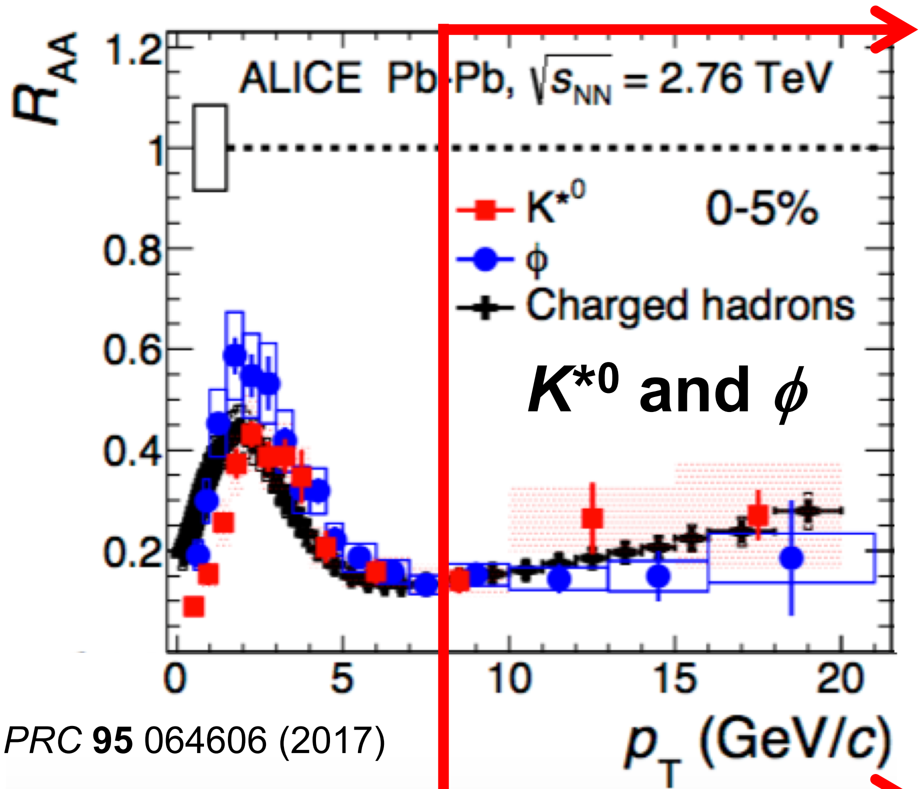
- High p_T (>8 GeV/c)
  - Charged hadrons ($\pi^{\pm}+K^{\pm}+p$) suppressed by factor of 4–5
  - As are K^{*0} and ϕ (and ρ^0)



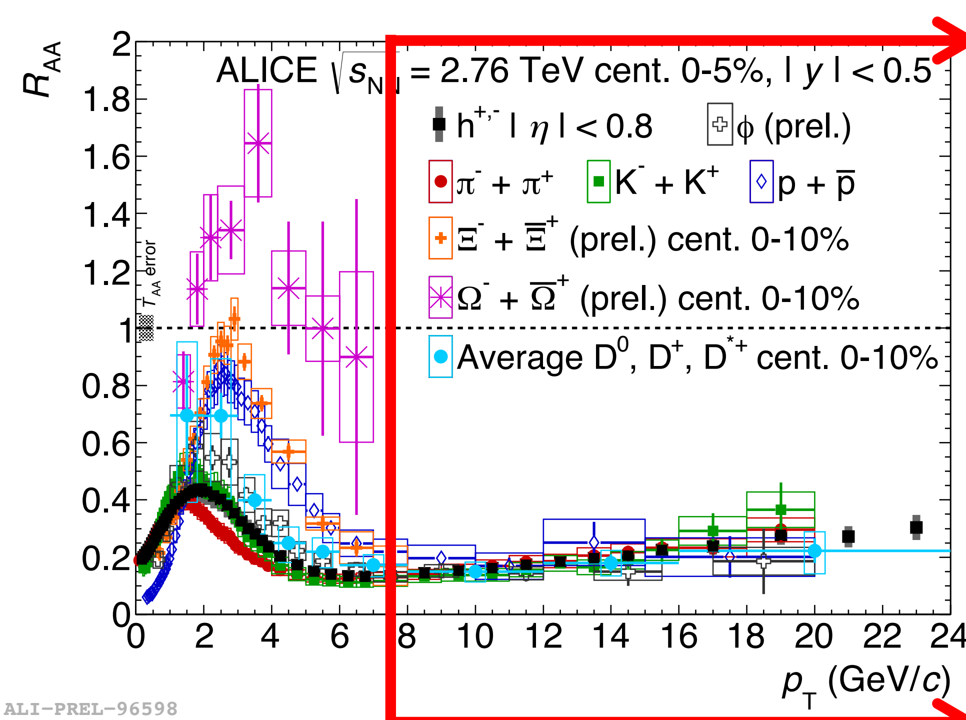
PRC **95** 064606 (2017)

Nuclear Modification Factor

- High p_T (>8 GeV/c)
  - Charged hadrons ($\pi^{\pm}+K^{\pm}+p$) suppressed by factor of 4–5
  - As are K^{*0} and ϕ (and ρ^0) and most other hadron species.
  - Suppression not influenced by hadron properties (mass, baryon number, *u*/*d*/*s*/*c* quark content)



PRC **95** 064606 (2017)



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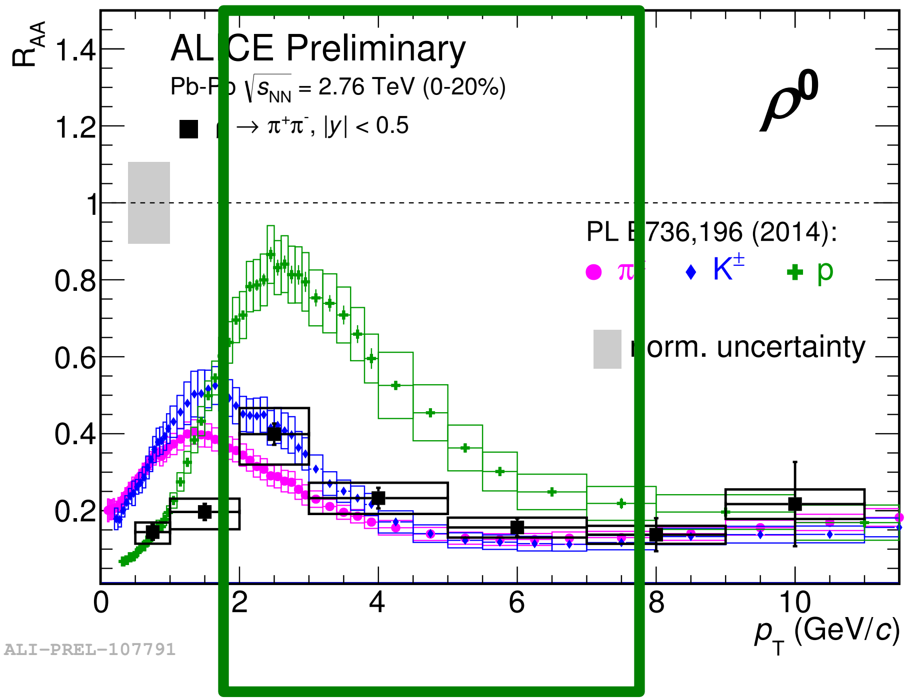
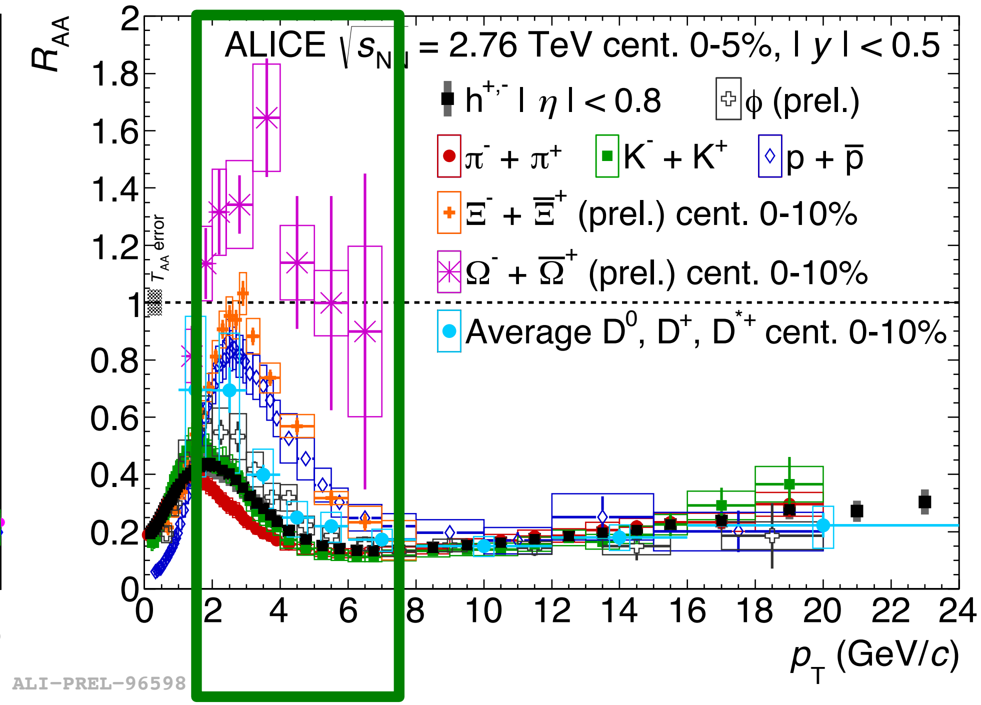
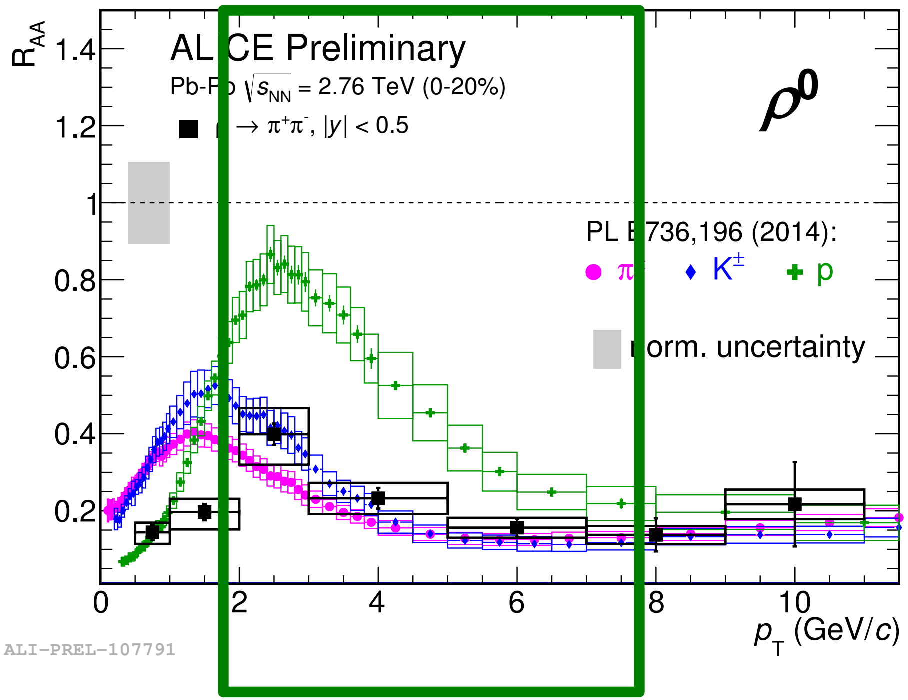
- Intermediate p_T ($2 < p_T < 8$ GeV/c)
  - Baryon-meson splitting: ρ^0, K^{*0}, ϕ, and even D are closer to other mesons than to baryons

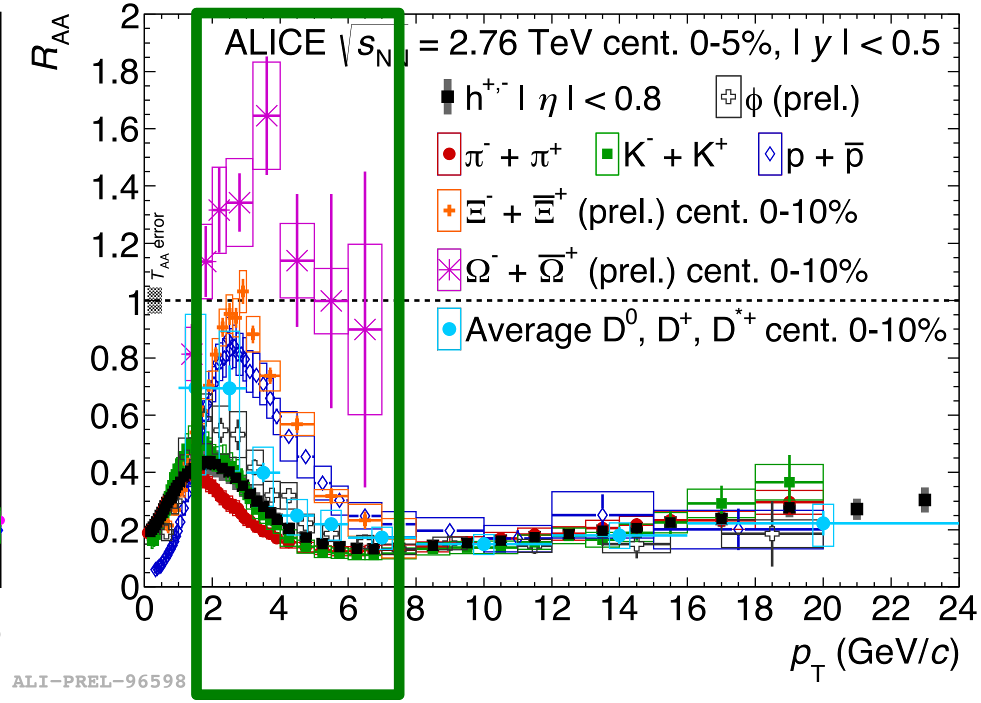




Nuclear Modification Factor

- Intermediate p_T ($2 < p_T < 8$ GeV/c)
  - Baryon-meson splitting: ρ^0, K^{*0}, ϕ, and even D are closer to other mesons than to baryons; possible mass ordering among mesons
  - Indications of similar behavior at RHIC [PHENIX, *PRC* **83** 024909 (2011)]
  - Differences between p and ϕ R_{AA} were taken as evidence for recombination in A+A → in fact, due to different p+p baselines





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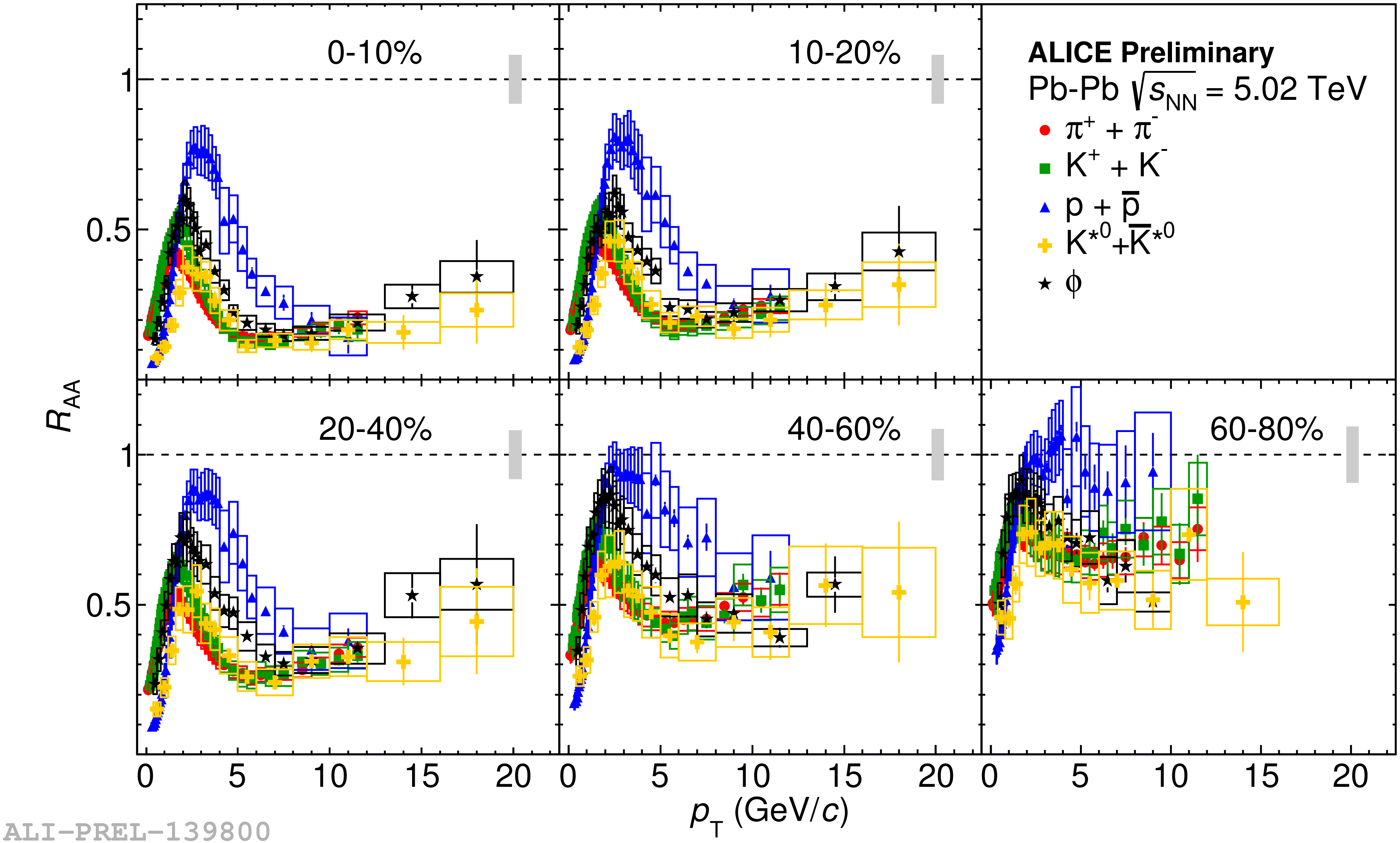
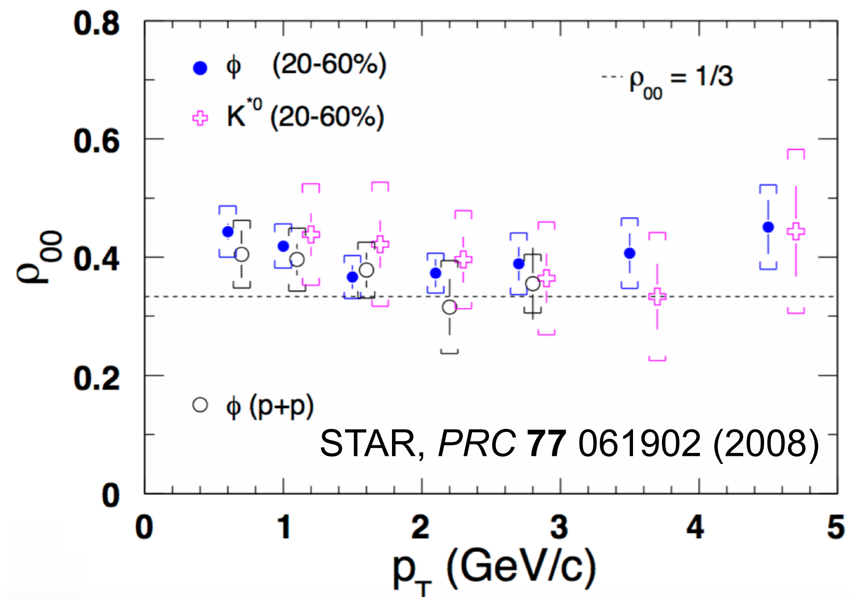
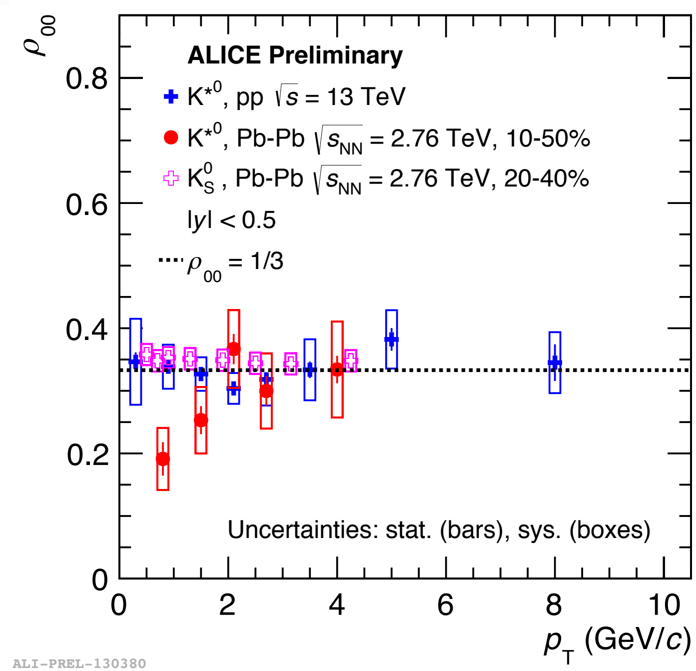


Spin Alignment

- RHIC
  - Matrix element ρ_{00} consistent with ⅓ (no polarization) for K^{*0} and ϕ
  - Results in *p*+*p* and Au+Au consistent
- LHC
  - No polarization for K^{*0} in *p*+*p*
  - No polarization for K^0_S (pseudoscalar)
  - Hint (2.5σ) of ρ_{00}<⅓ for K^{*0} in Pb+Pb

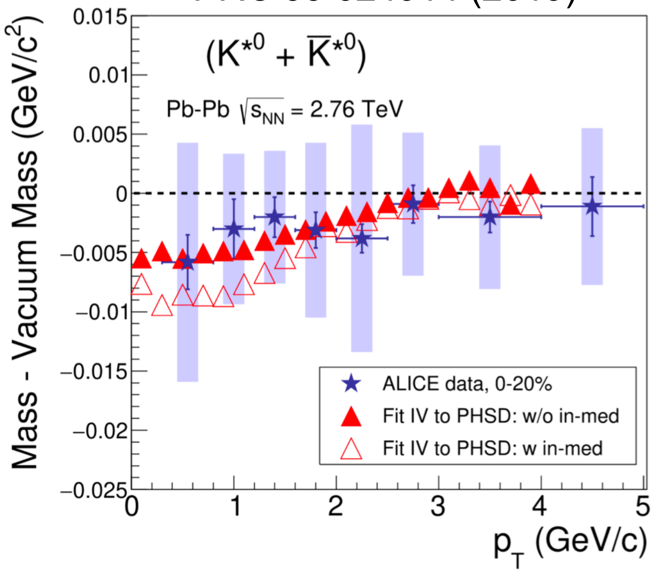




Lineshape Modification

- PHSD: gives small change in K^{*0} mass at LHC energies, compatible with ALICE
  - Caused by K^* interaction with baryonic medium (greater net effect for smaller energies) & re-scattering of decay products

PRC **99** 024914 (2019)



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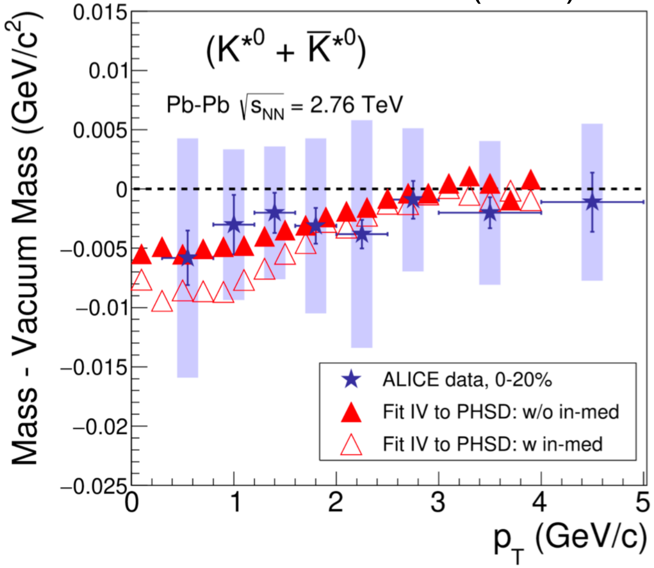
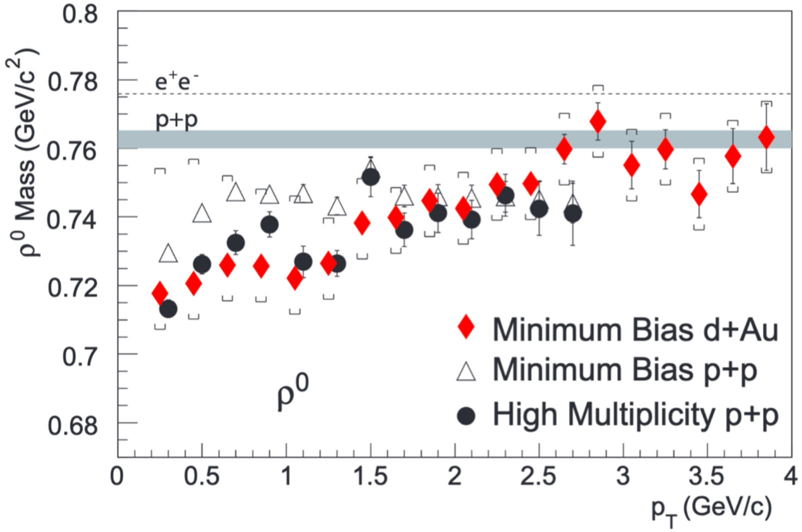
  - Caused by K^* interaction with baryonic medium (greater net effect for smaller energies) & re-scattering of decay products
- STAR: mass decrease for ρ^0 (& Δ^{++}) observed in p+p and d+Au
  - Hint of multiplicity-dependence
  - Interactions w/ hadronic medium, interference, re-scattering, Bose-Einstein correlations

PRC **99** 024914 (2019)





PRC **78** 44906 (2008)

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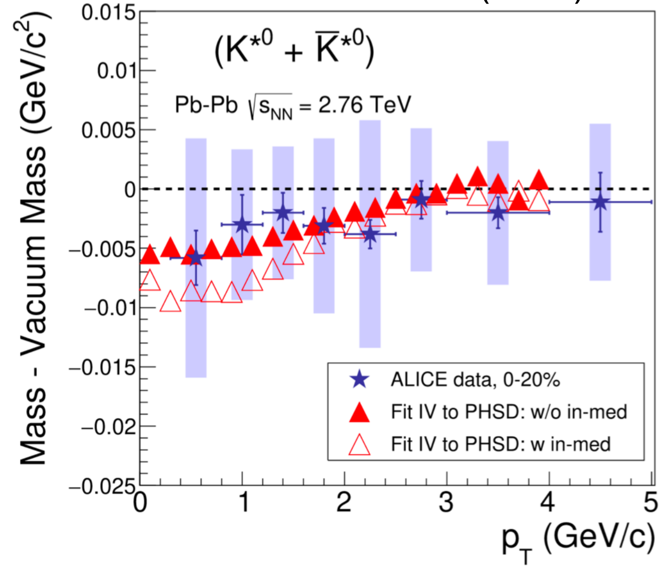
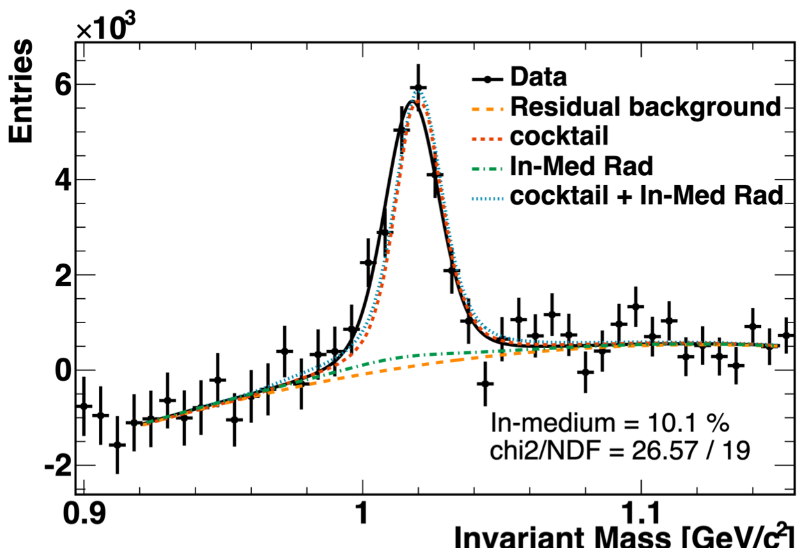
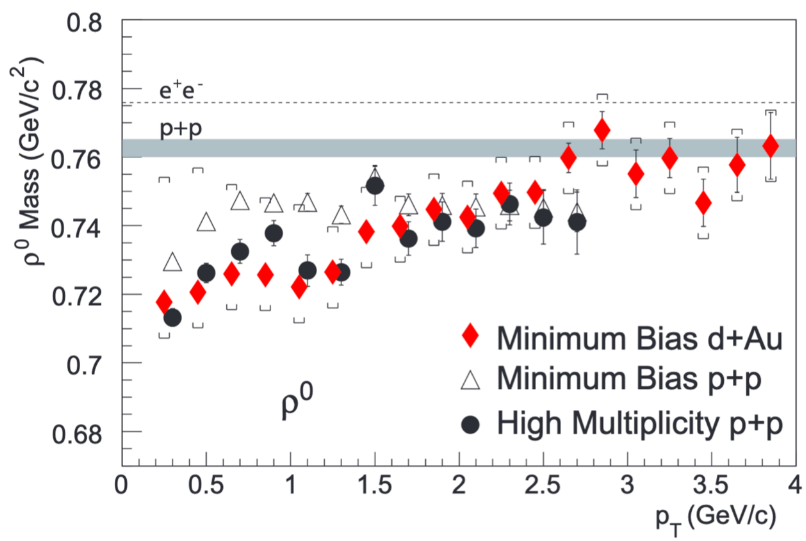
- STAR: mass decrease for ρ^0 (& Δ^{++}) observed in p+p and d+Au
  - Hint of multiplicity-dependence
  - Interactions w/ hadronic medium, interference, re-scattering, Bose-Einstein correlations
- STAR: ϕ in dielectron decay channel: data compatible with small medium-modified component

PRC **99** 024914 (2019)





arXiv:1503.04217



PRC **78** 44906 (2008)