

# Resonance Production in Heavy-Ion Collisions

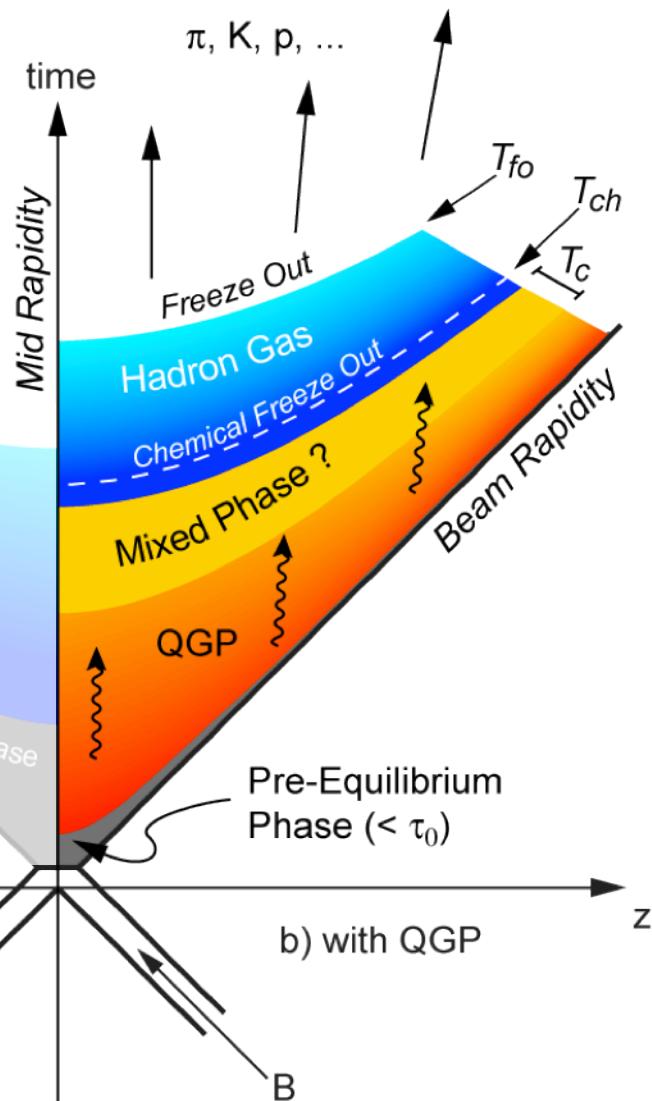
A. G. Knospe

The University of Houston

14 July 2017



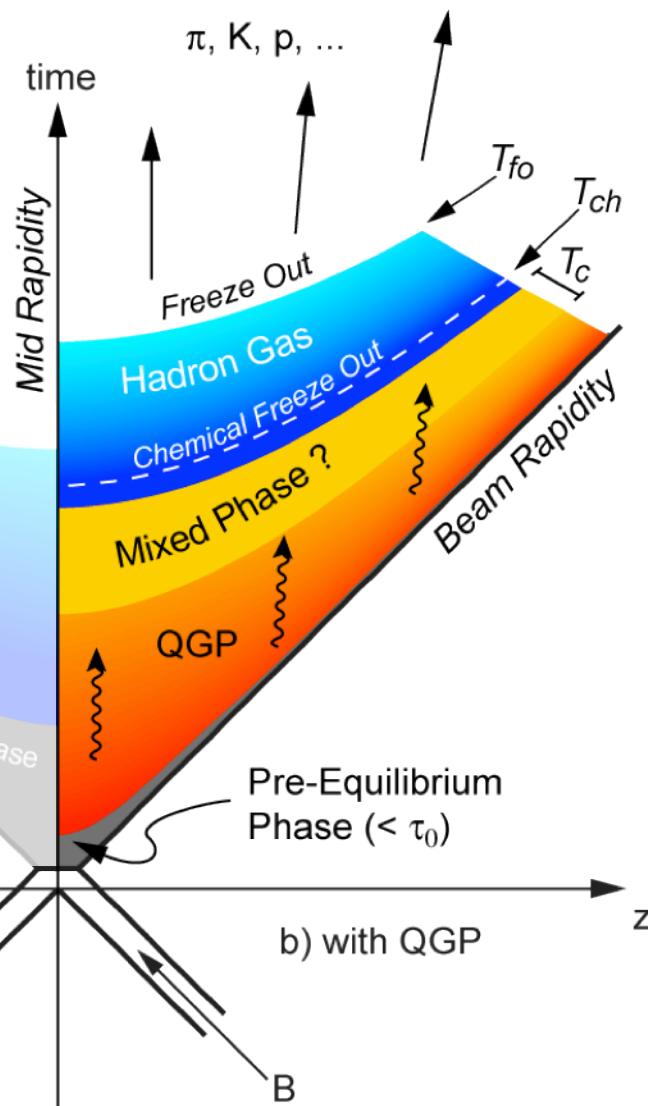
# Motivation



## Why study resonances?

- Short lifetimes
- Compare ground and excited states: same quark content but different masses
- Compare particles with similar masses, but different quark content (e.g.,  $p$  and  $\phi$ )
- Unique quark content:  $\phi$  composed entirely of valence  $s$  (anti)quarks, but is not affected by canonical suppression

# Motivation



Properties of hadronic phase

- Next slide...

Strangeness Production

What shapes particle  $p_T$  spectra?

- Hydrodynamics, recombination, ...

In-medium energy loss

Spin Alignment

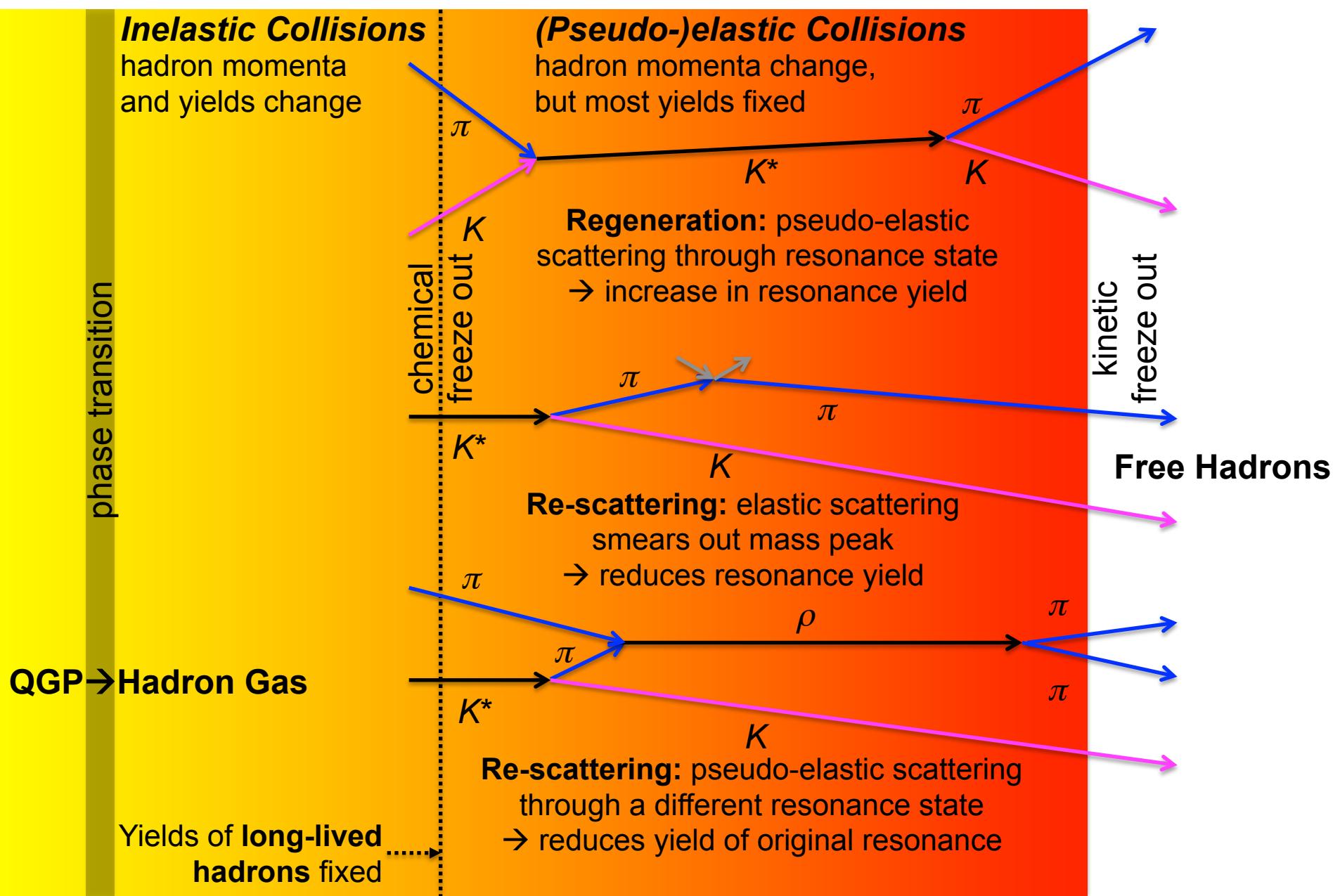
Modification of Lineshapes

Elliptic Flow

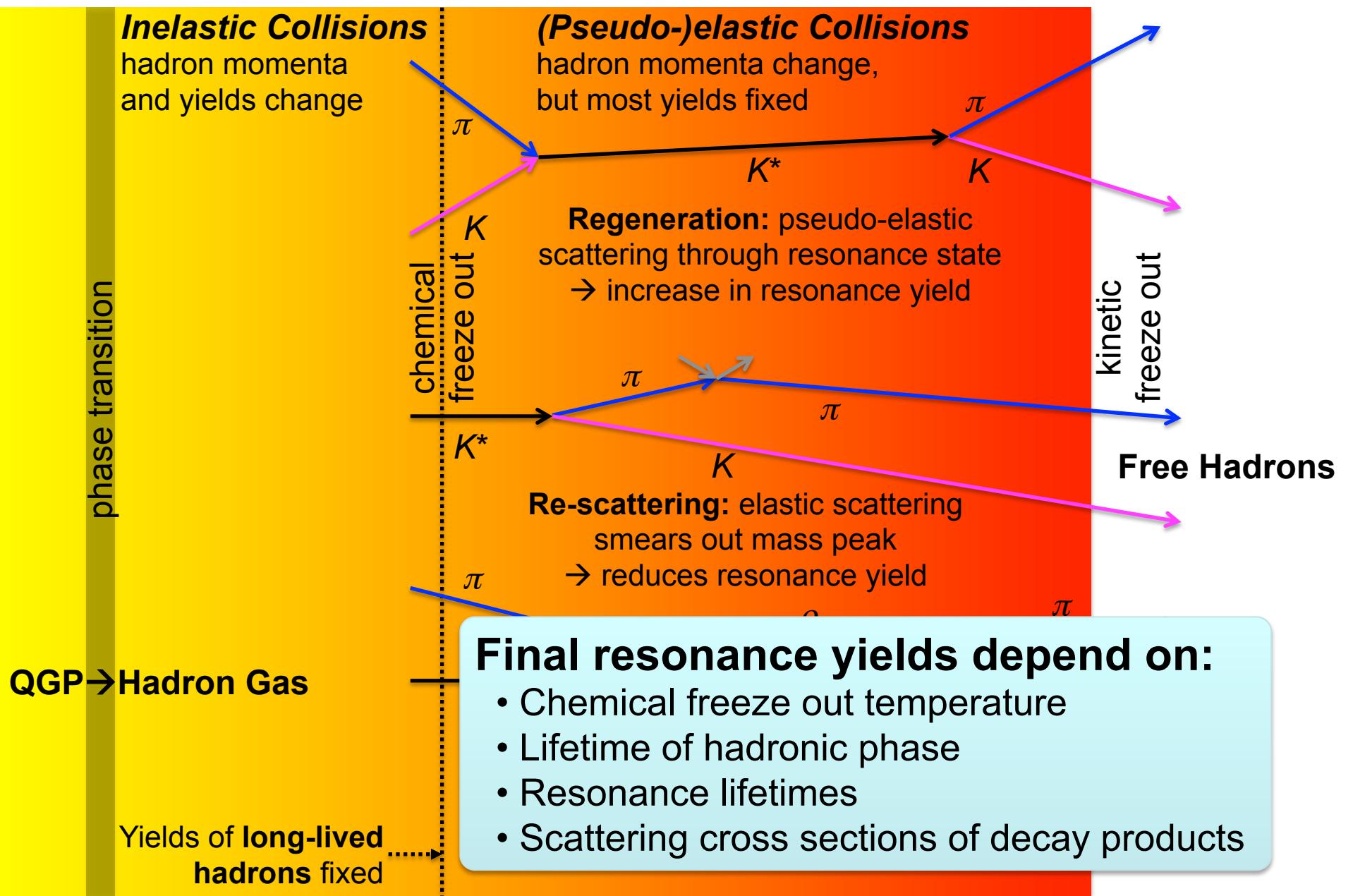
Small Systems:

- Baselines for  $A+A$
- Data to tune event generators
- Look for collective effects

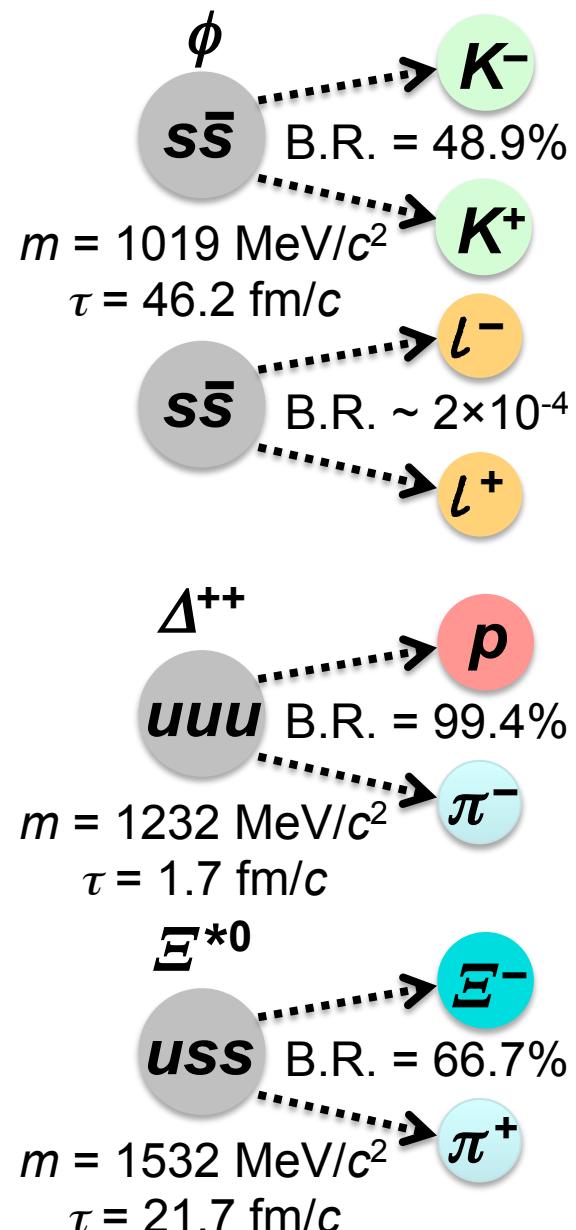
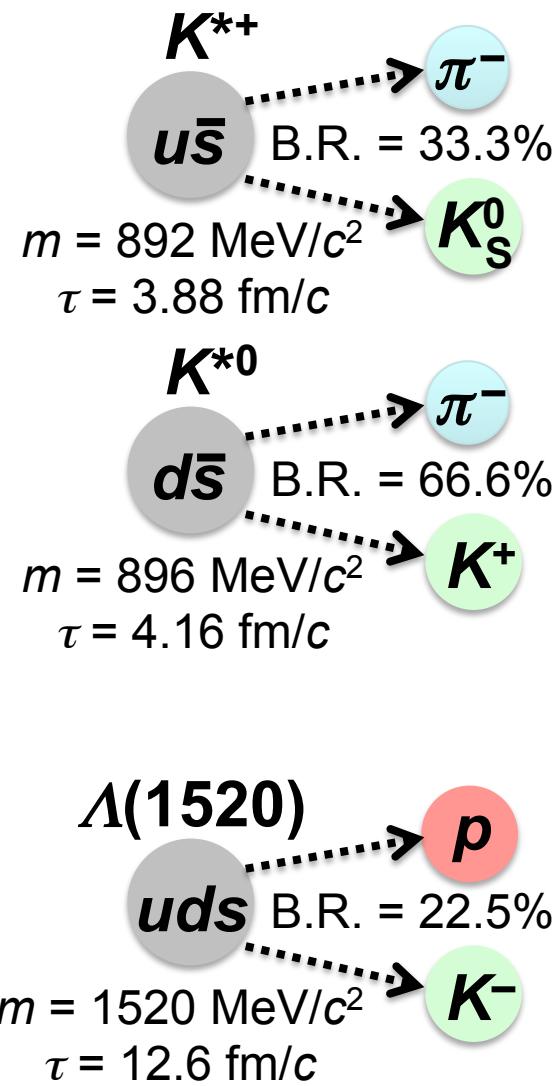
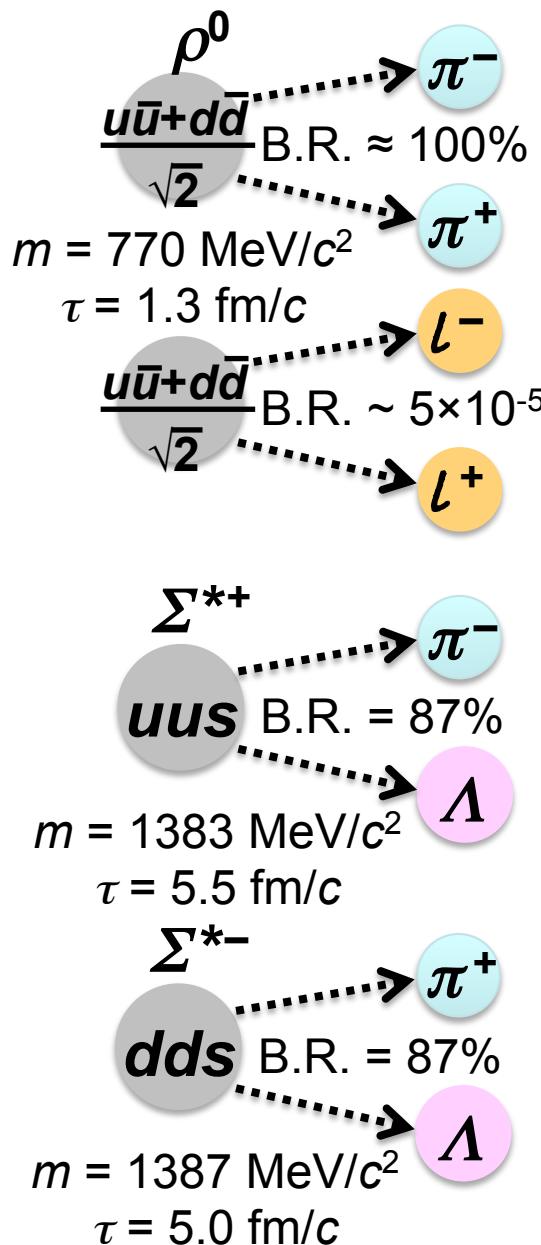
# Hadronic Phase



# Hadronic Phase

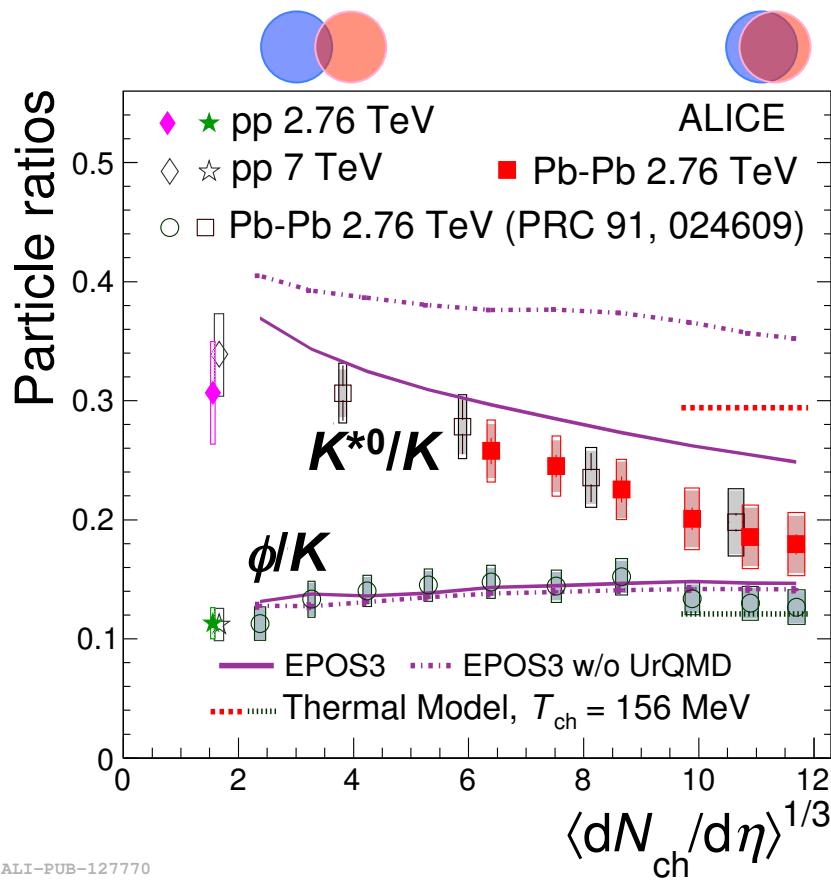


# Particles & Decays



# Particle Yield Ratios

- Suppression of  $K^{*0}/K$  in central Pb+Pb w.r.t. peripheral Pb+Pb,  $p+p$  and thermal model
  - Qualitatively described by EPOS with UrQMD
- No suppression of  $\phi/K$ 
  - Central Pb+Pb consistent with thermal model
- Suggests that  $K^{*0}$  re-scattering is dominant over regeneration
  - Lifetime of  $K^{*0} = 4.16 \text{ fm}/c$
  - Lifetime of  $\phi = 46.2 \text{ fm}/c$
  - Re-scattering not significant for  $\phi$
- Estimate hadronic phase lifetime (model-dependent):  $\Delta t \geq 2.4 \text{ fm}/c$ 
  - Details in backup



Plotted as function of  $\langle dN_{ch}/d\eta \rangle^{1/3}$ : proxy for system radius (cf. femtoscopy studies)

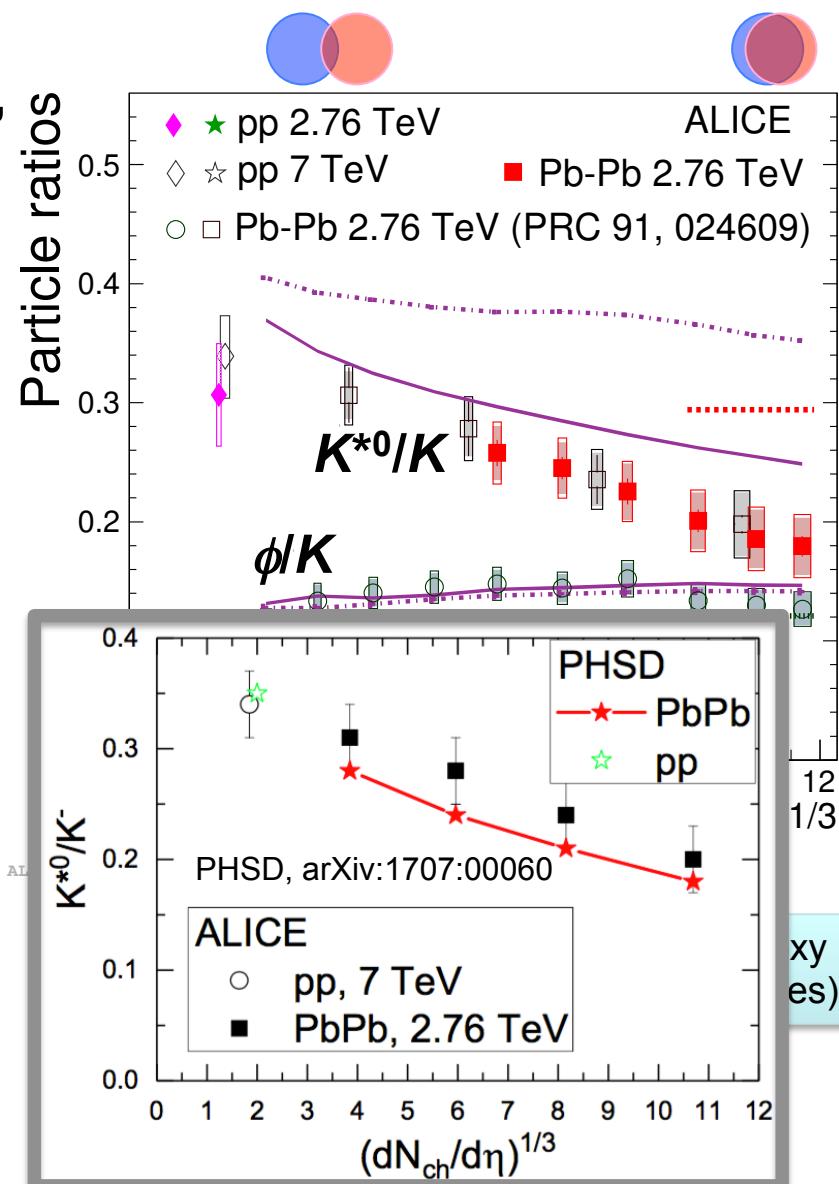
PRC 91 024609 (2015)

PRC 95 064606 (2017)

EPOS: PRC 93 014911 (2016)

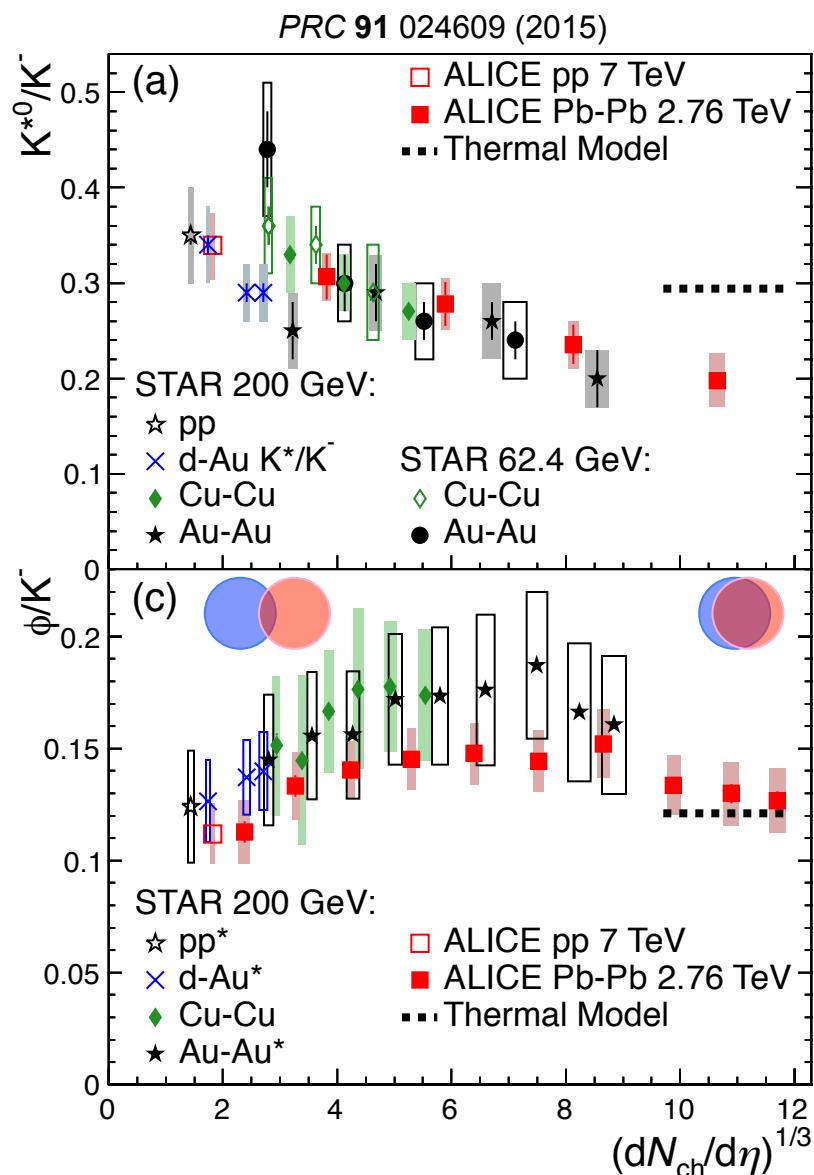
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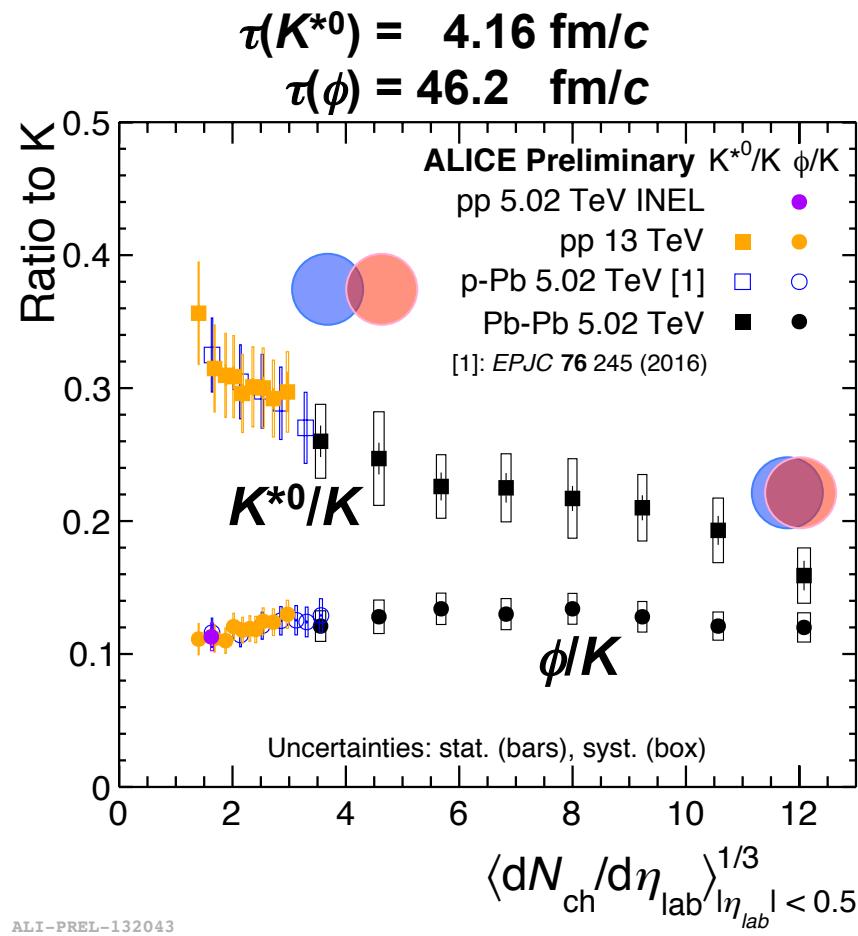
# Energy Dependence

- $K^*/K$ : for given multiplicity, no clear energy dependence from RHIC  $\rightarrow$  LHC

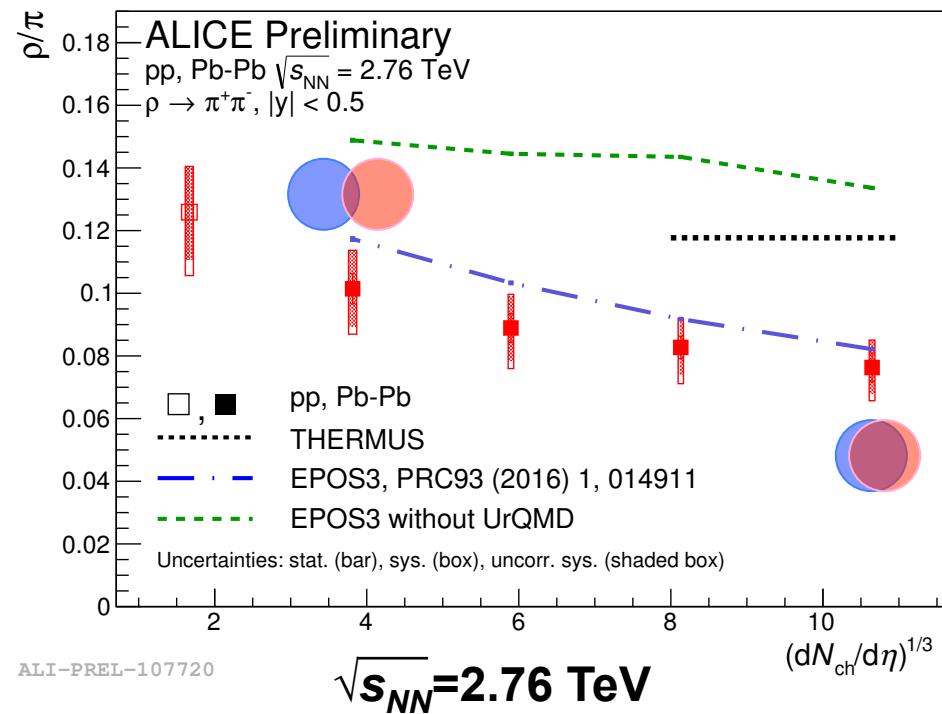
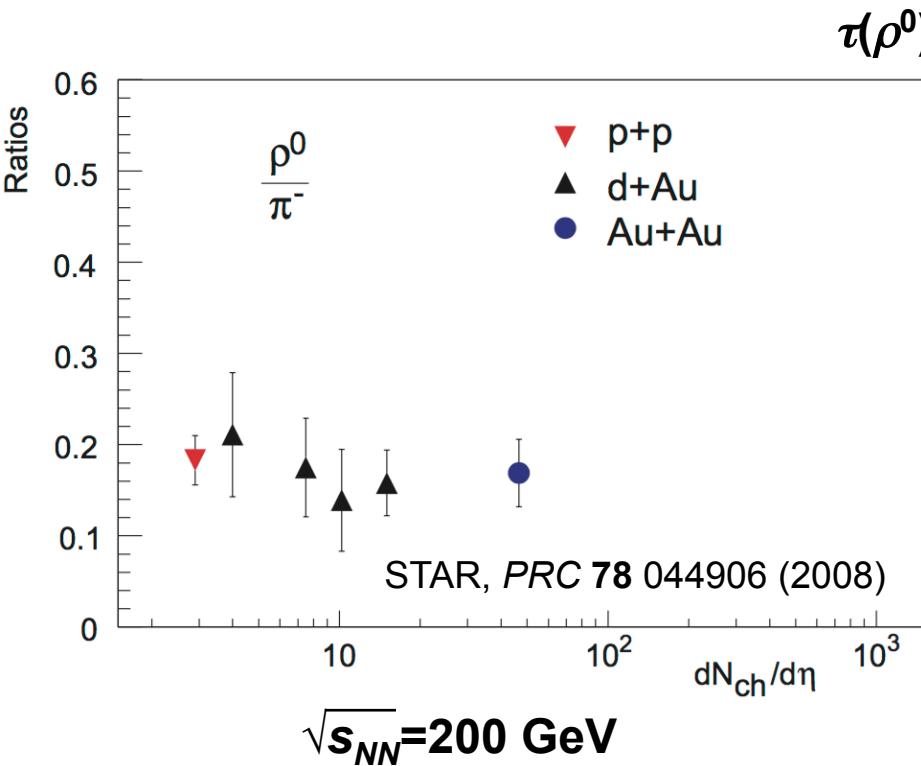


# Small Systems

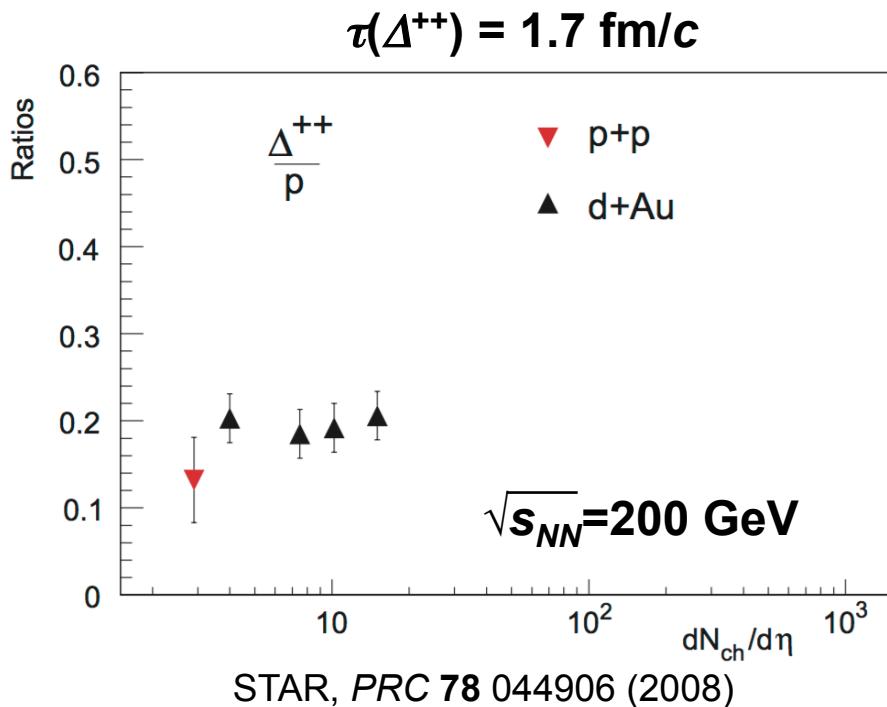
- Multiplicity-dependent suppression of  $K^{*0}/K$  in  $p+p$  and  $p+Pb$  collisions
  - Is the same physics (re-scattering) responsible?
- For both ratios, smooth trends:  $p+p \rightarrow p+Pb \rightarrow Pb+Pb$



- No clear multiplicity dependence in  $\rho^0/\pi$  at RHIC
  - Au+Au: only peripheral
- Suppression of  $\rho^0/\pi$  ratio in central LHC Pb+Pb w.r.t.  $p+p$  and thermal model
  - Qualitatively described by EPOS with UrQMD
- Energy Dependence: RHIC values above LHC

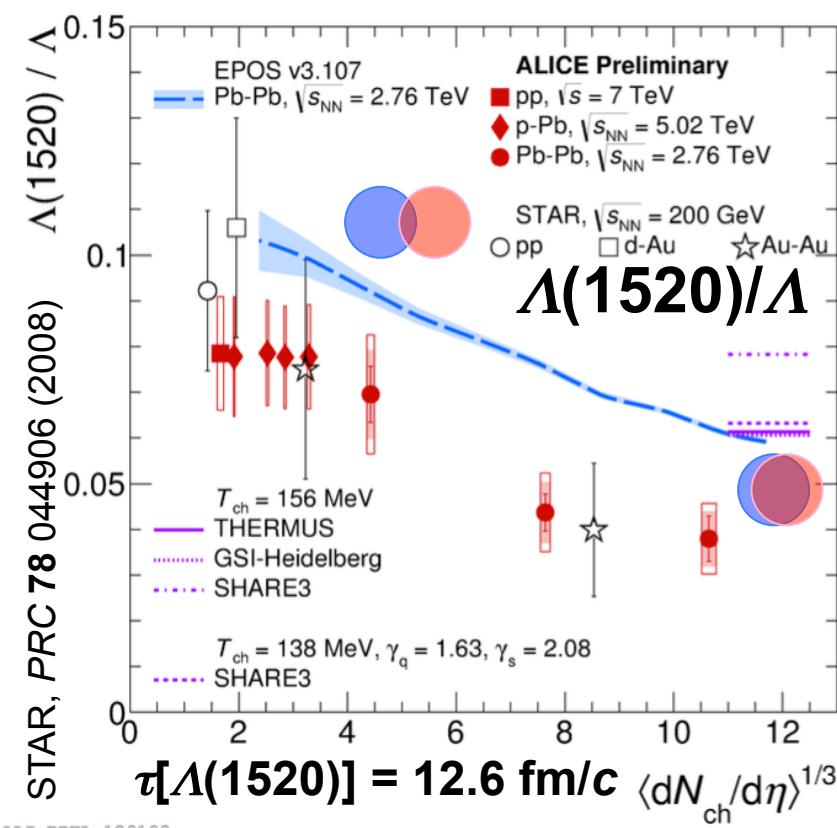
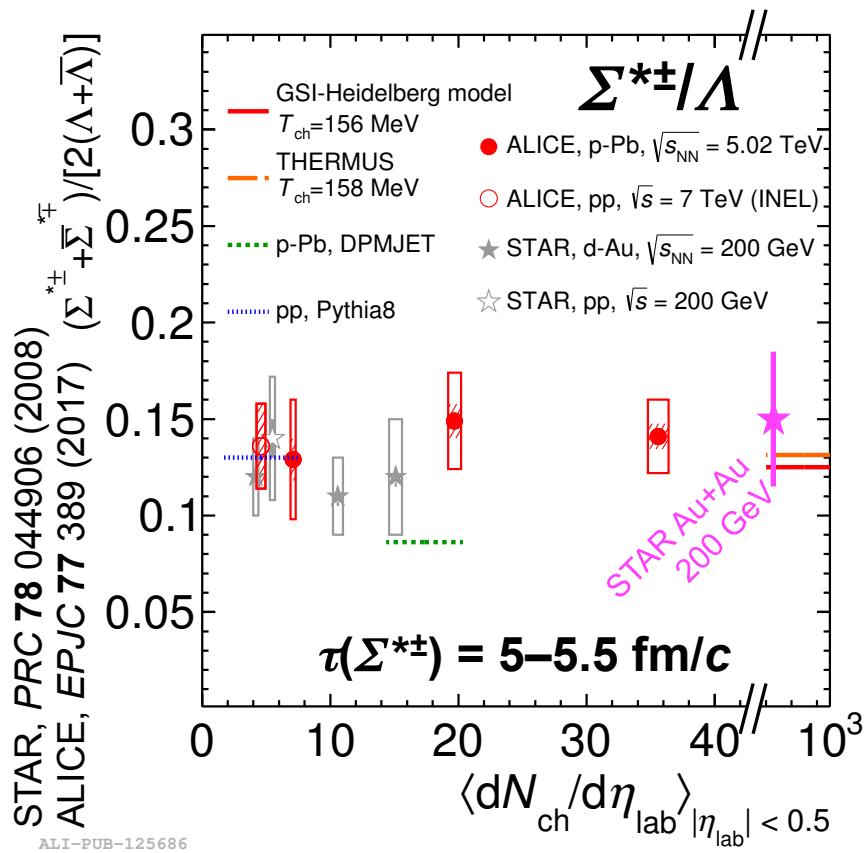


- No suppression observed in  $d+Au$
- EPOS predicts no suppression (for LHC energies)
- Measurements difficult in  $A+A$

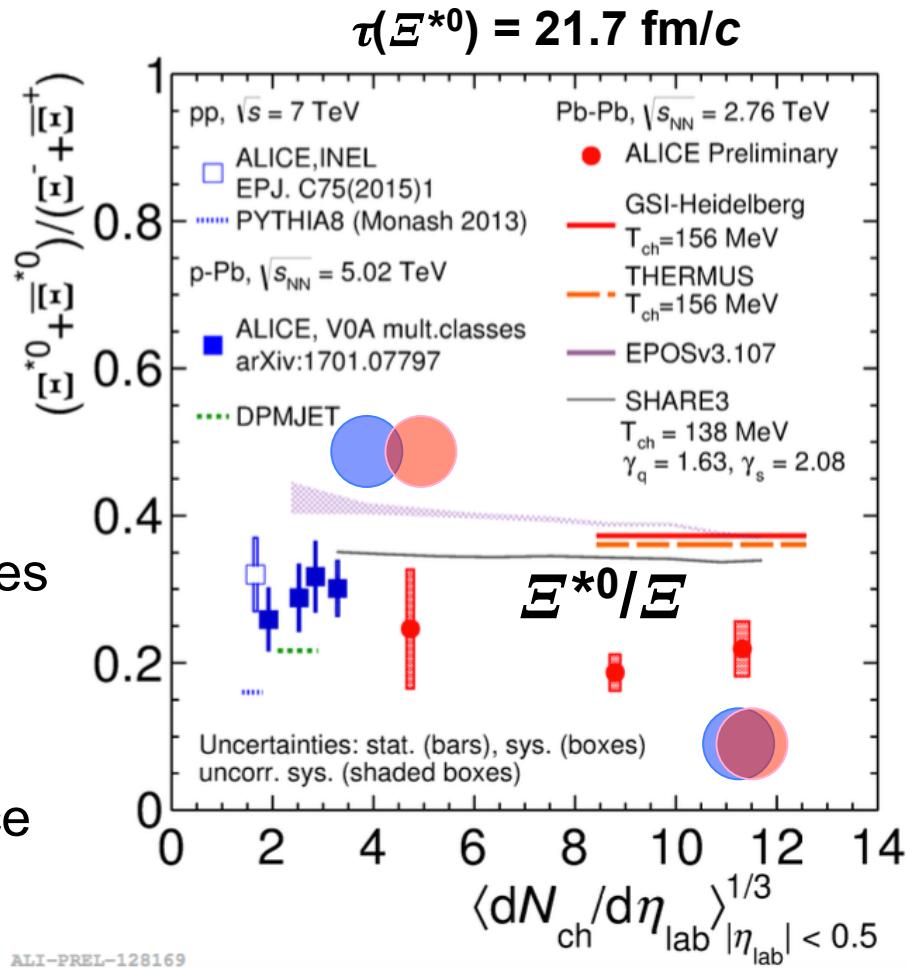


# $\Sigma^{*\pm}$ and $\Lambda(1520)$

- No modification of  $\Sigma^{*\pm}/\Lambda$  in  $d+Au$ ,  $p+Pb$ , and  $Au+Au$
- Suppression of  $\Lambda(1520)/\Lambda$  in central  $Pb+Pb$
- No energy dependence for (RHIC $\rightarrow$ LHC)
- $A+A$ : qualitatively described by [EPOS](#) with UrQMD
- Or suppression of  $p$ -wave baryons [ $\Lambda(1520)$ ] in recombination model  
[PRC 74 061901(R) (2006)]



- $\Xi^*0/\Xi$  in Pb+Pb:
  - No significant centrality dependence
    - Qualitatively described by EPOS and SHARE3
  - Systematically lower in (mid-)central Pb+Pb than  $p+p$  and  $p+\text{Pb}$
  - Lower than thermal model values
  - Possible weak suppression
- In  $p+p$  and  $p+\text{Pb}$ :
  - No clear multiplicity dependence



NOTE: ALICE  $\Xi$  yields being re-analyzed.

# Particle Yield Ratios

- Summary:

	<b>Not suppressed in <math>d+Au</math></b>	<b>Not suppressed</b>	<b>Not suppressed</b>
<b>Resonance:</b>	$\rho^0$	$\Delta^{++}$	$K^{*0}$
<b>Lifetime (fm/c):</b>	1.3	1.7	4.16

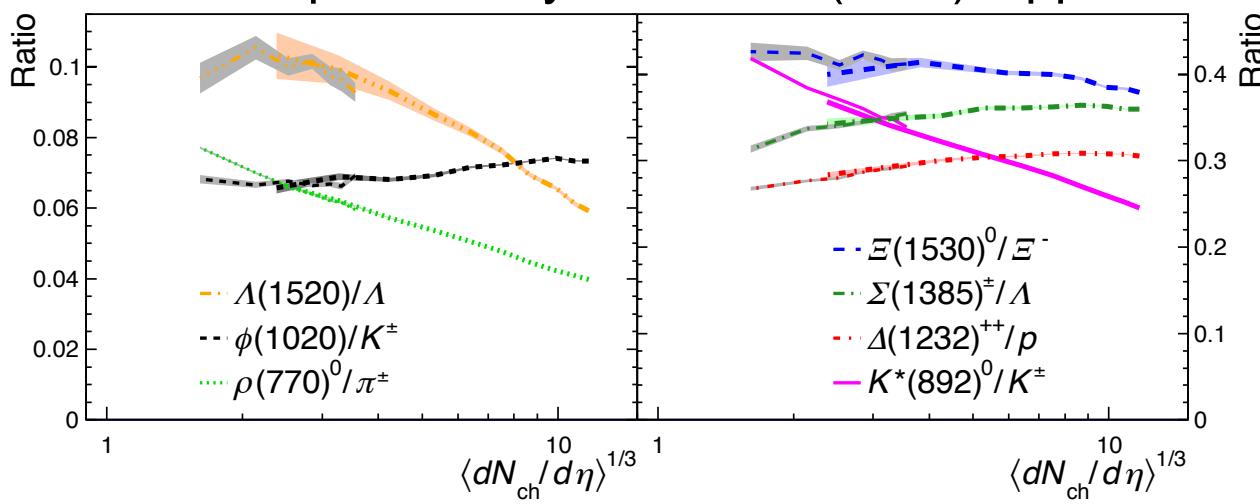
  

<b>Resonance:</b>	$\Sigma^{*\pm}$	$\Lambda(1520)$	$\Xi^{*0}$	$\phi$
<b>Lifetime (fm/c):</b>	5	12.6	21.7	46.2

↓ Not suppressed in  $d+Au$     
 ↓ Not suppressed    
 ↓ Not suppressed

Suppressed    
 Possible weak suppression

- Shorter-lived resonances suppressed, but lifetime not only factor
  - Scattering cross sections
  - Competition between regeneration and re-scattering
- EPOS w/ UrQMD qualitatively describes (non-)suppression patterns

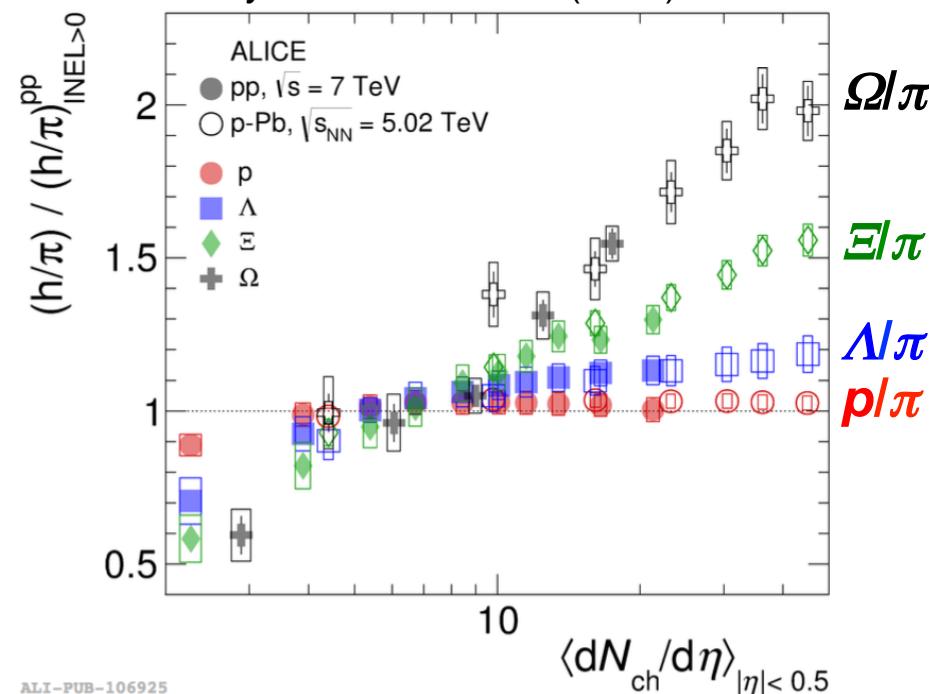


# Strangeness Production

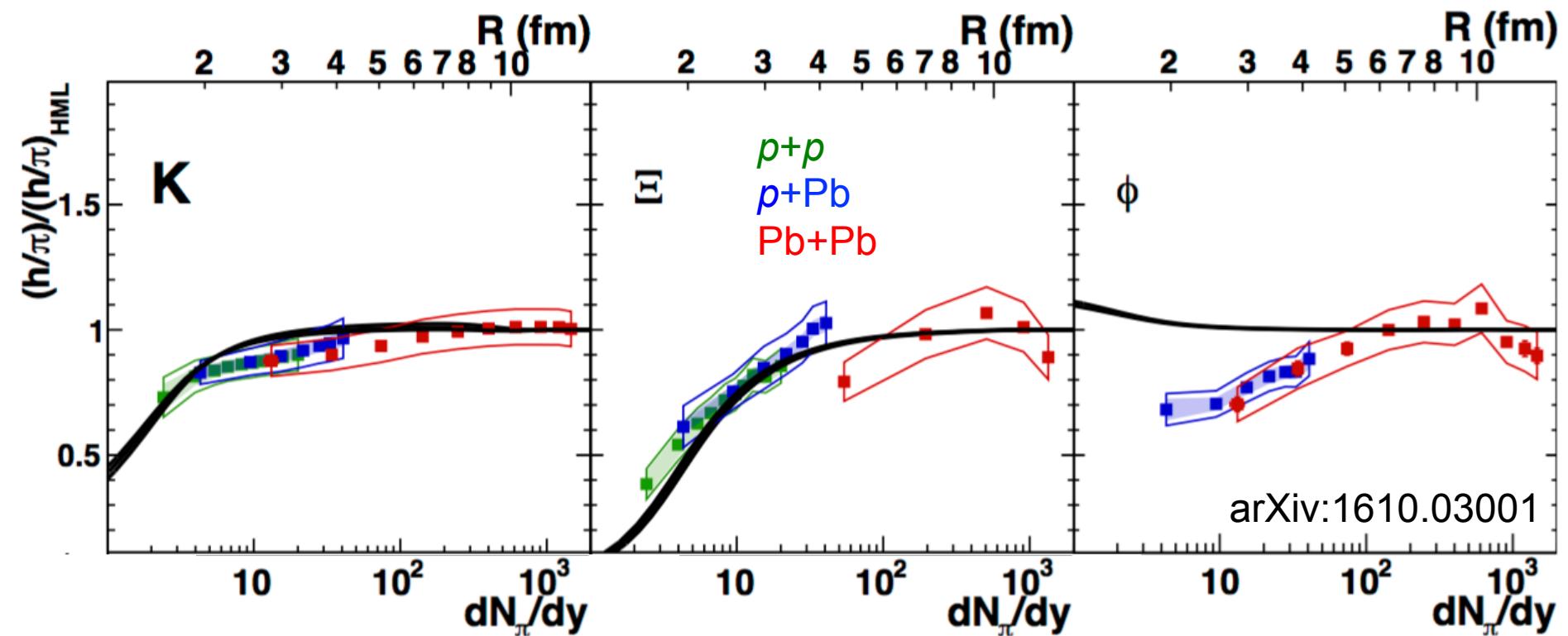
- What causes enhancement? Strangeness? Mass? Baryon number?
- $p/\pi$  ratio is constant → enhancement not related to baryon number
- $\Sigma^{*\pm}$  and  $\Xi^{*0}$ : greater masses than ground-state counterparts
- $\Sigma^{*\pm}/\Lambda$  and  $\Xi^{*0}/\Xi$  constant in  $p+\text{Pb}$
- Strangeness increase in  $p+\text{Pb}$  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 <sup>2</sup> )	S
$\Omega$	1672	3
$\Xi^{*0}$	1530	2
$\Sigma^{*\pm}$	1385	1
$\Xi$	1322	2
$\Lambda$	1116	1
$p$	938	0

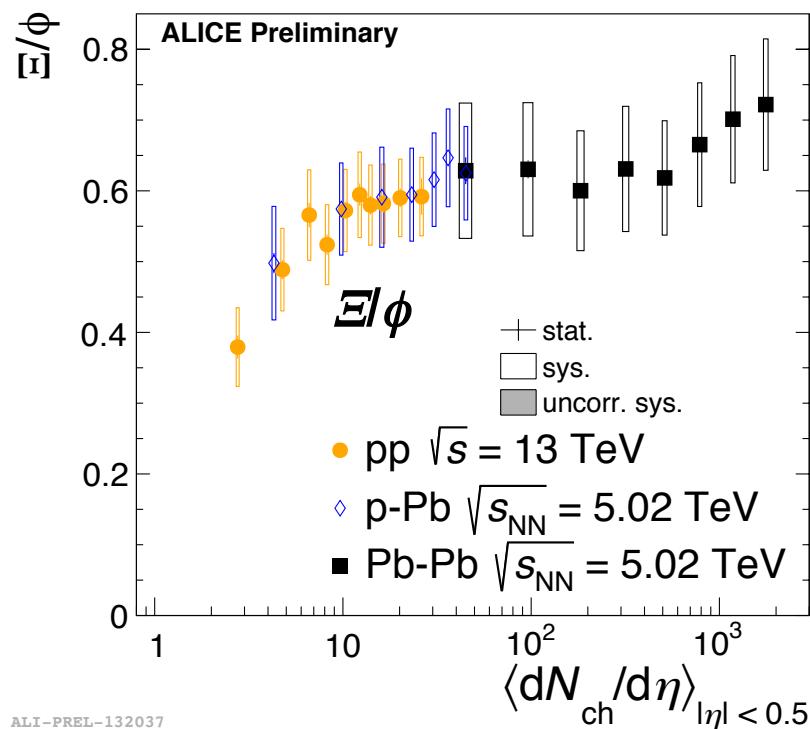
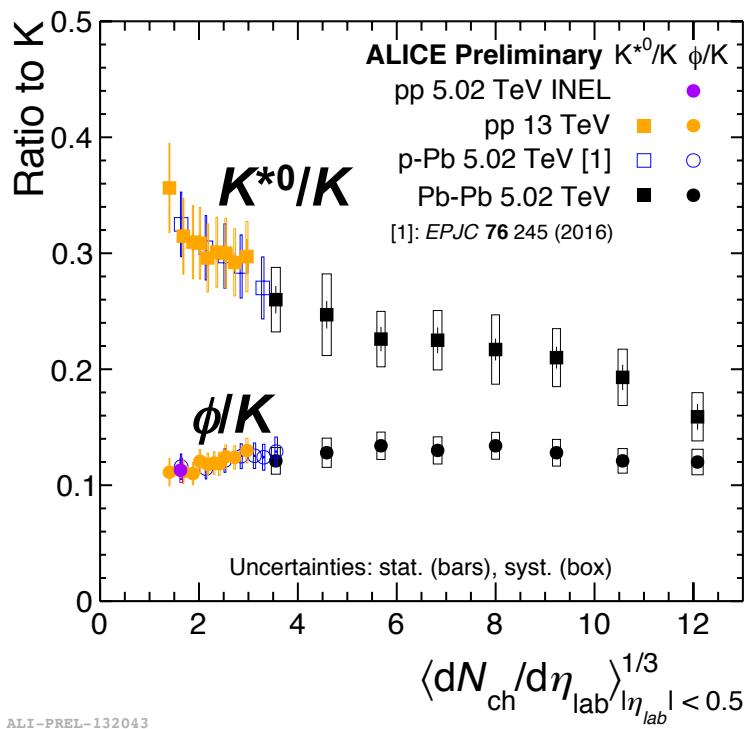
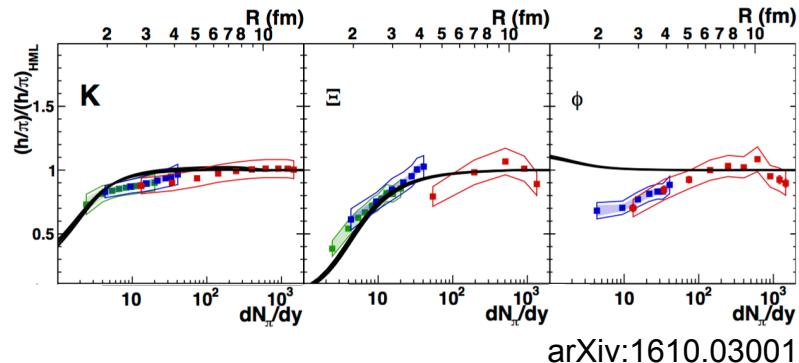


# Canonical Suppression



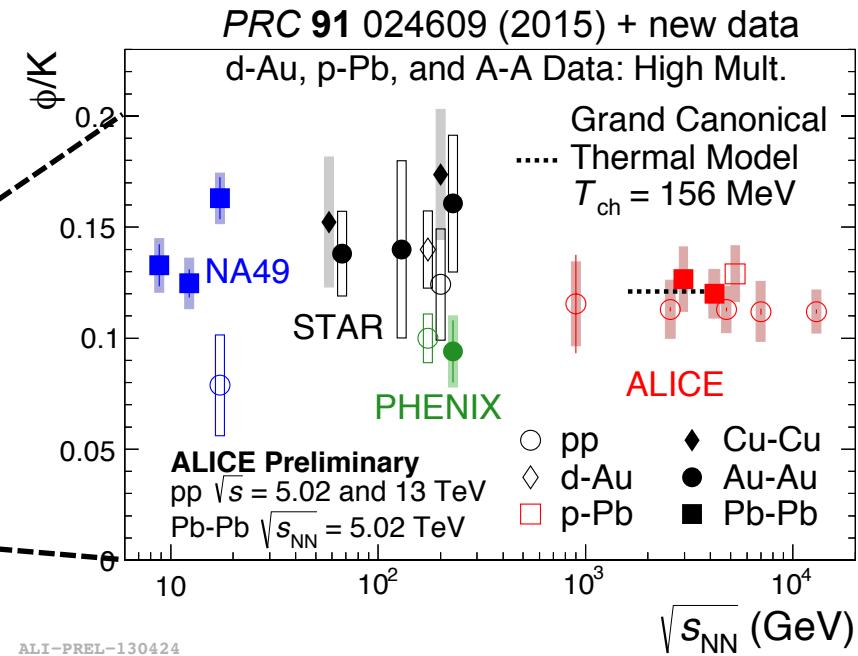
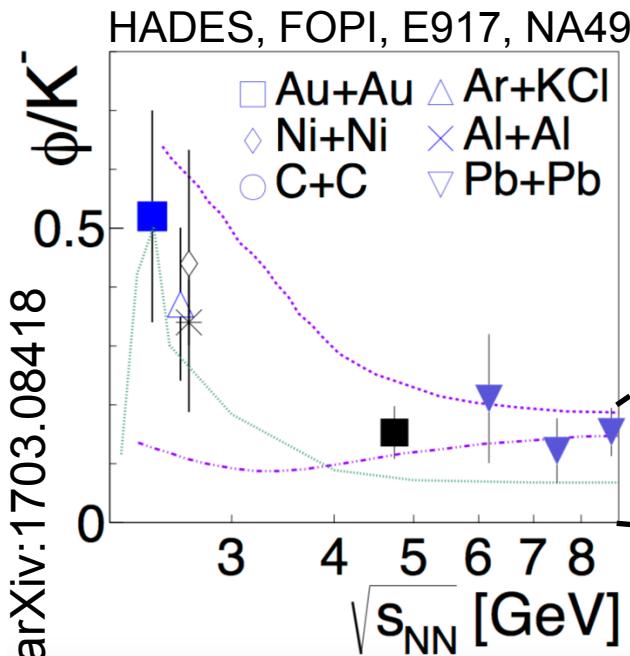
# Canonical Suppression

- $\phi$  enhanced more than  $K$ , less than  $\Xi$ 
  - Effective strangeness  $1 \leq |S| \leq 2$
- Why does  $\phi$  follow particles affected by canonical suppression?



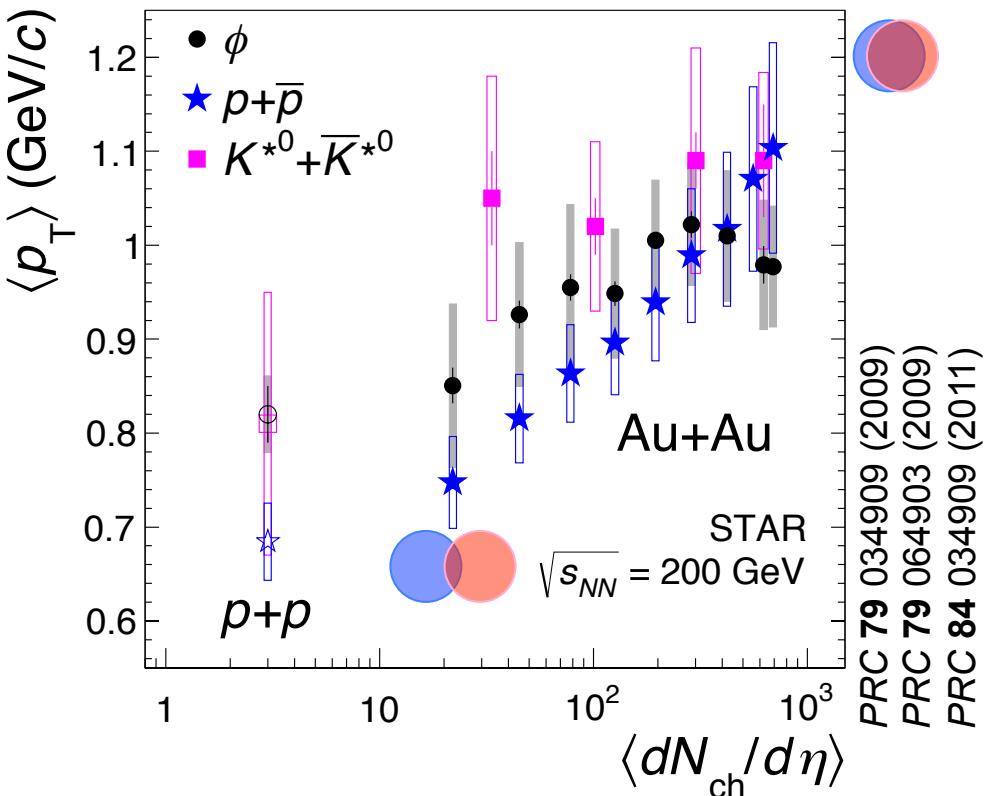
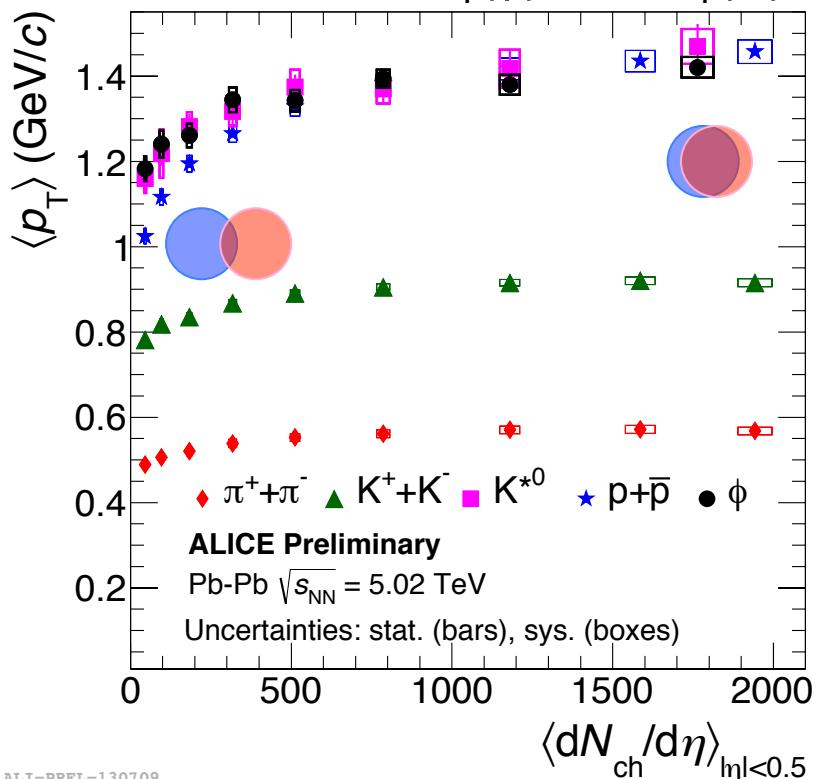
# Energy Dependence

- $\phi/K$  ratio  $\sim$ constant in  $A+A$  over 3 orders of magnitude
- Increase for low energies: can be explained by statistical model with strangeness correlation radius  $R_C \approx 2.2$  fm
  - Strangeness conserved in small volume  $\rightarrow K^-$  suppressed, but  $\phi$  not affected
- Sizeable  $\phi$  feed-down contribution to  $K^-$  at low energies  $\rightarrow$  may (partially) explain different slopes of  $K^+$  and  $K^-$  slopes at low energies



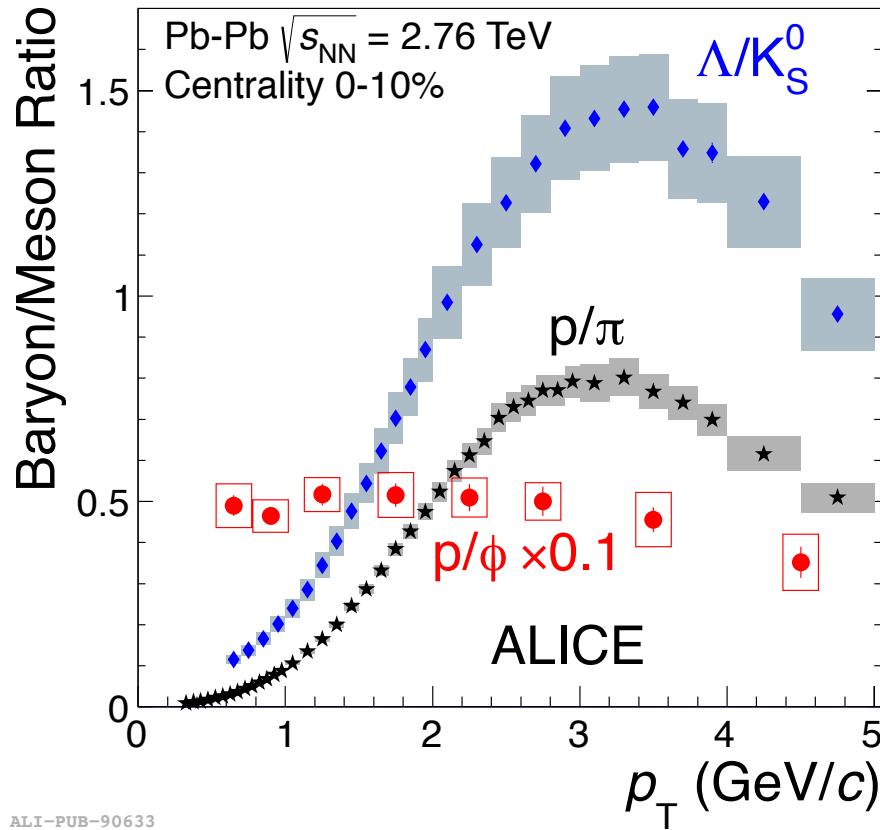
# Mean $p_T$

- Mass ordering of  $\langle p_T \rangle$  in central Pb+Pb
- $\langle p_T \rangle$  for  $p$  and  $\phi$  similar  $\rightarrow$  expected from hydro
  - $M(p) = 938 \text{ MeV}/c^2$  vs.  $M(\phi) = 1019 \text{ MeV}/c^2$
- Mass ordering breaks down for smaller collision systems.
  - Hints of similar behavior at RHIC
  - In  $p+p$ :  $\langle p_T(\phi) \rangle = \langle p_T(\Xi) \rangle$  despite 30% mass difference



# Baryon/Meson Ratios

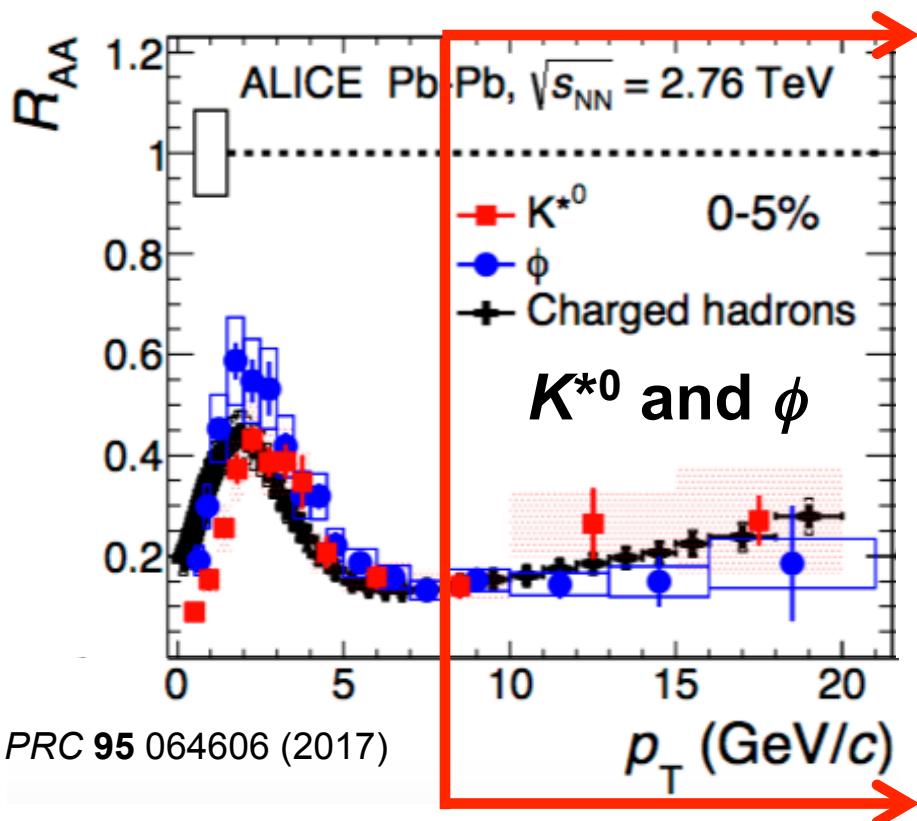
- **$p/\phi$  ratio** ( $m_p \approx m_\phi$ ): flat for  $p_T < 4$  GeV/c (cent. 0-10%)
  - Particle masses determine spectra → expected from hydrodynamics
  - Some recombination models can also describe this behavior
    - e.g., *Phys. Rev. C* **92** 054904 (2015)
  - Strong  $p_T$  dependence for smaller collision systems (not shown)



*PRC* **91** 024609 (2015)  
*CERN Courier* **55**,  
 No. 2, pp. 9 (2015)

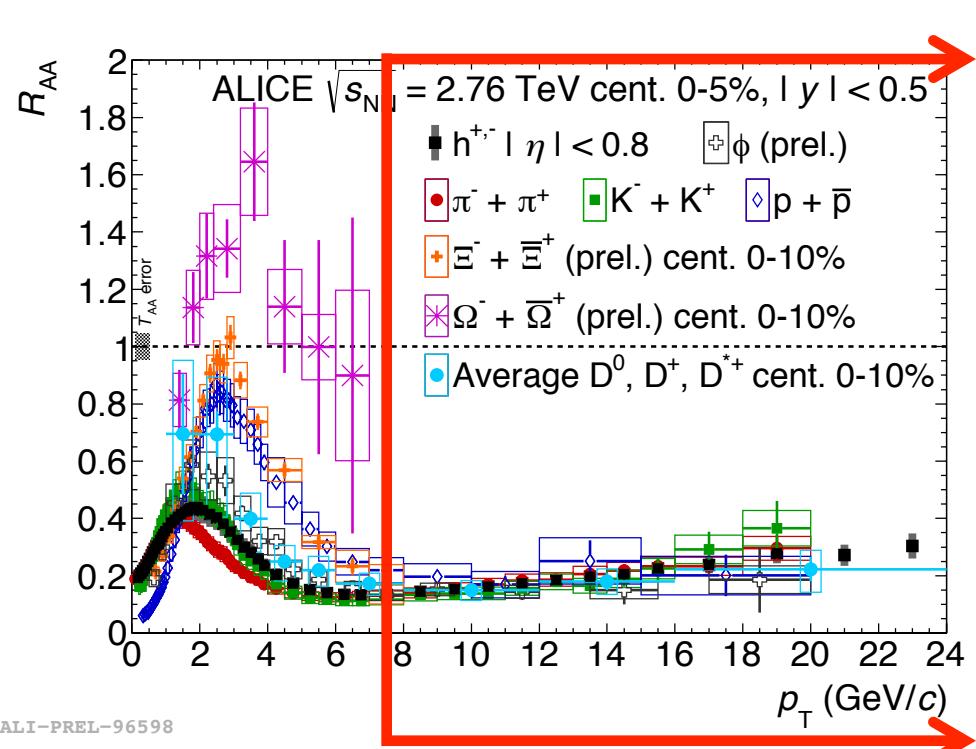
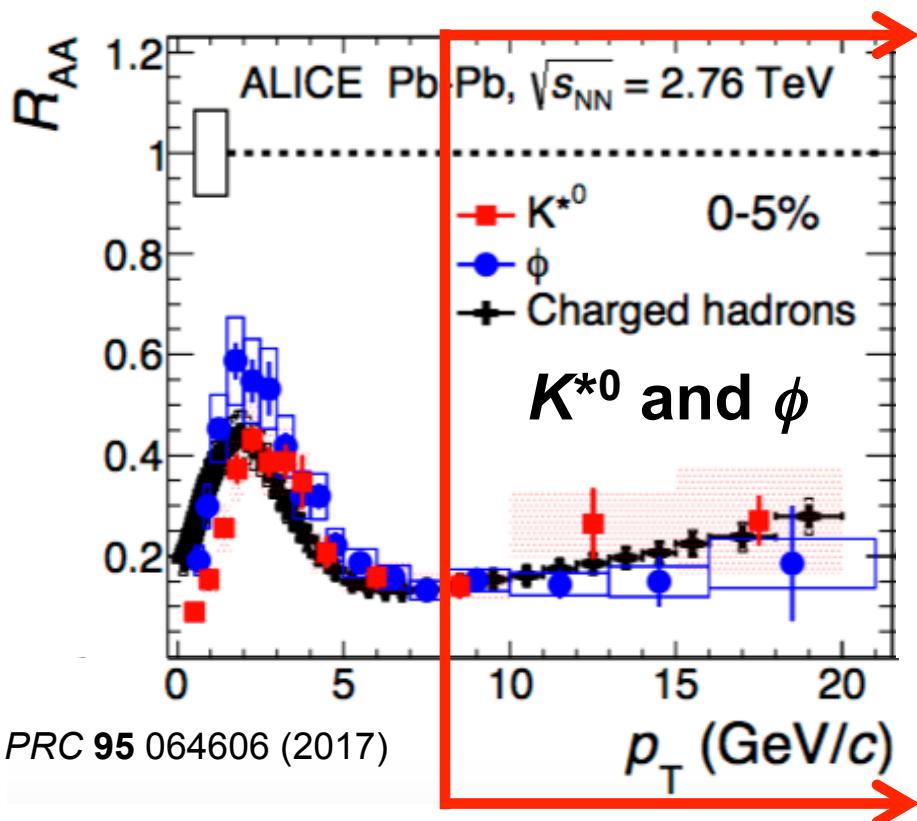
# Nuclear Modification Factor

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



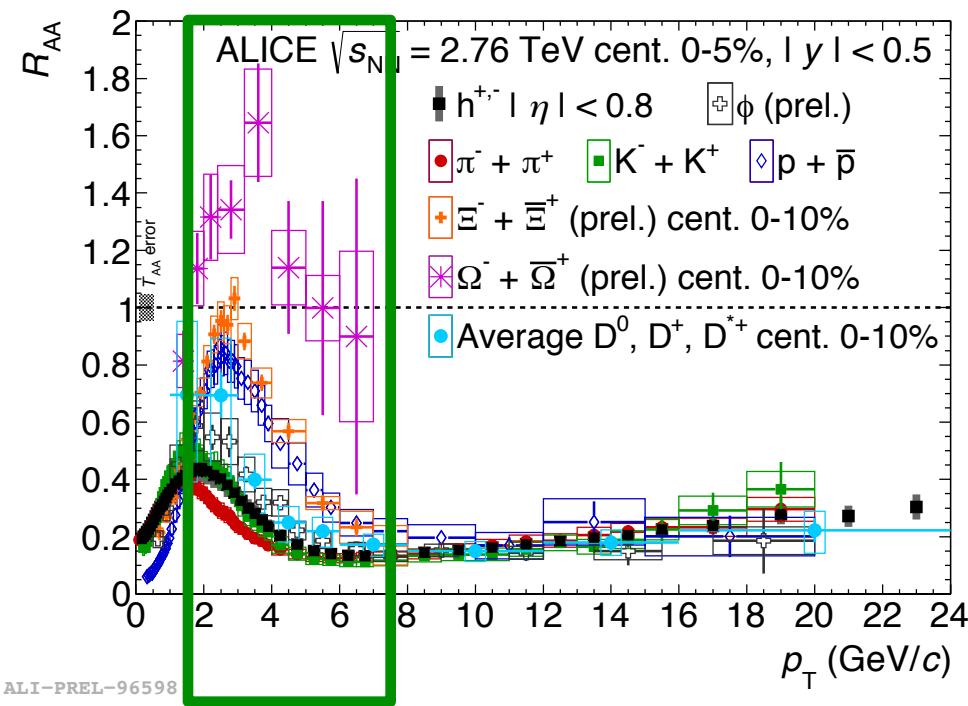
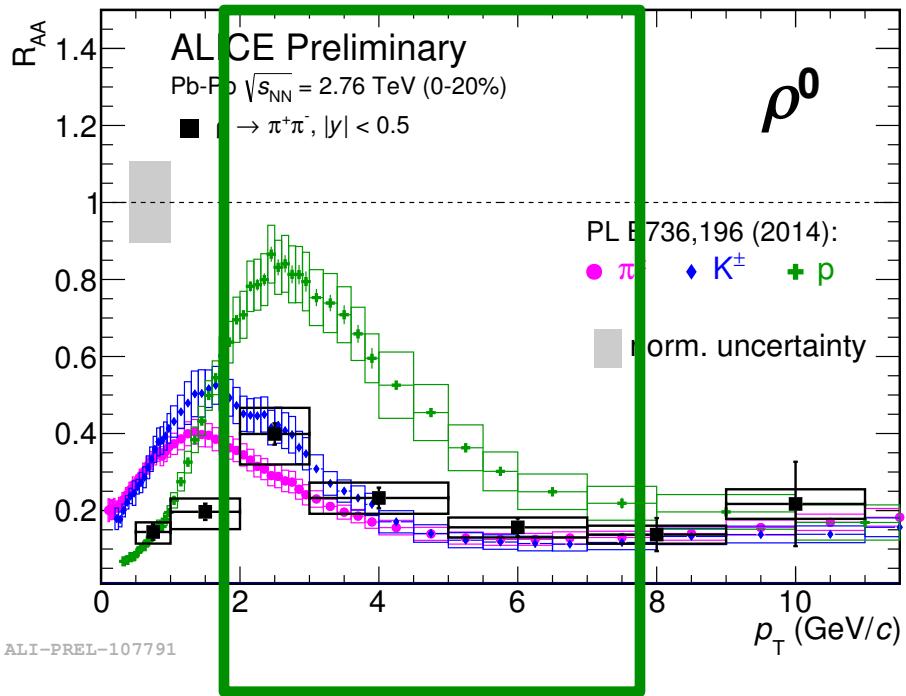
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  - Charged hadrons ( $\pi^\pm + K^\pm + p$ ) suppressed by factor of 4–5
  - As are  $K^{*0}$  and  $\phi$  (and  $\rho^0$ ) and most other hadron species.
  - Suppression not influenced by hadron properties (mass, baryon number,  $u/d/s/c$  quark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



# Nuclear Modification Factor

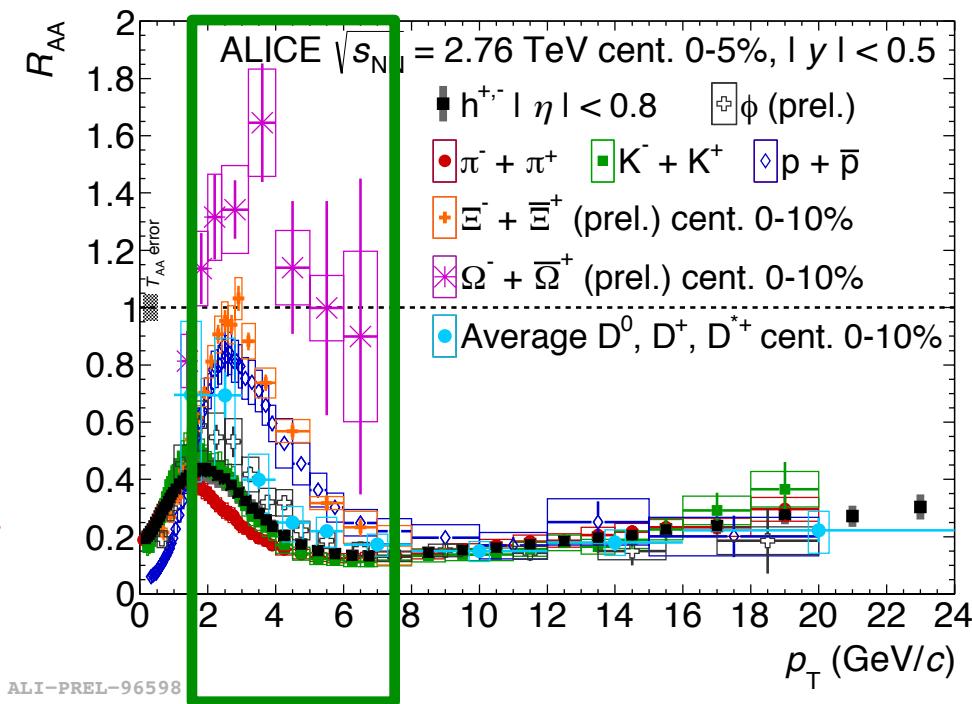
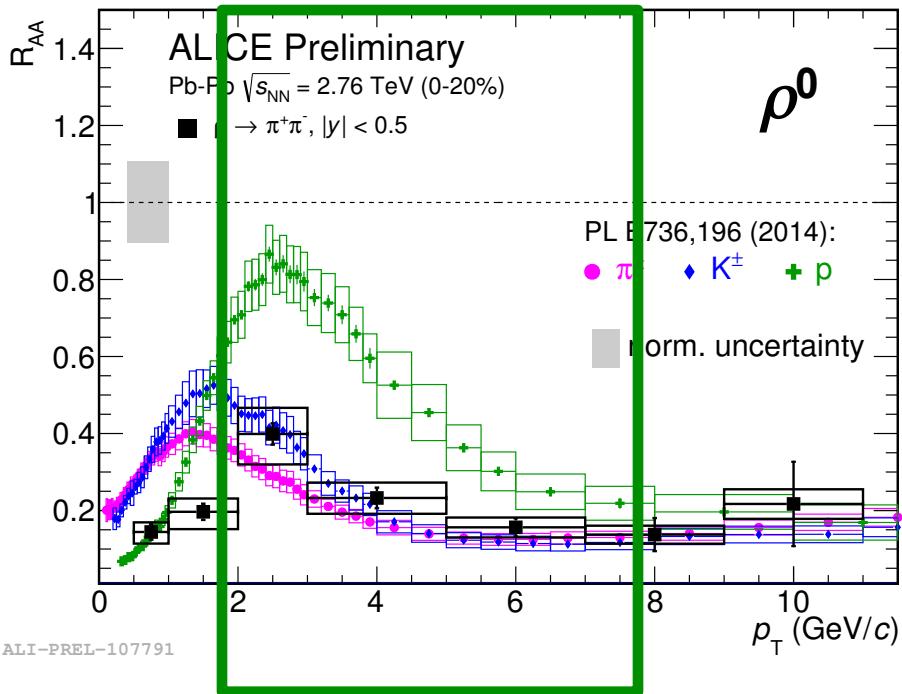
- Intermediate  $p_T$  ( $2 < p_T < 8 \text{ GeV}/c$ )
  - Baryon-meson splitting:  $\rho^0$ ,  $K^{*0}$ ,  $\phi$ , and even  $D$  are closer to other mesons than to baryons



# Nuclear Modification Factor

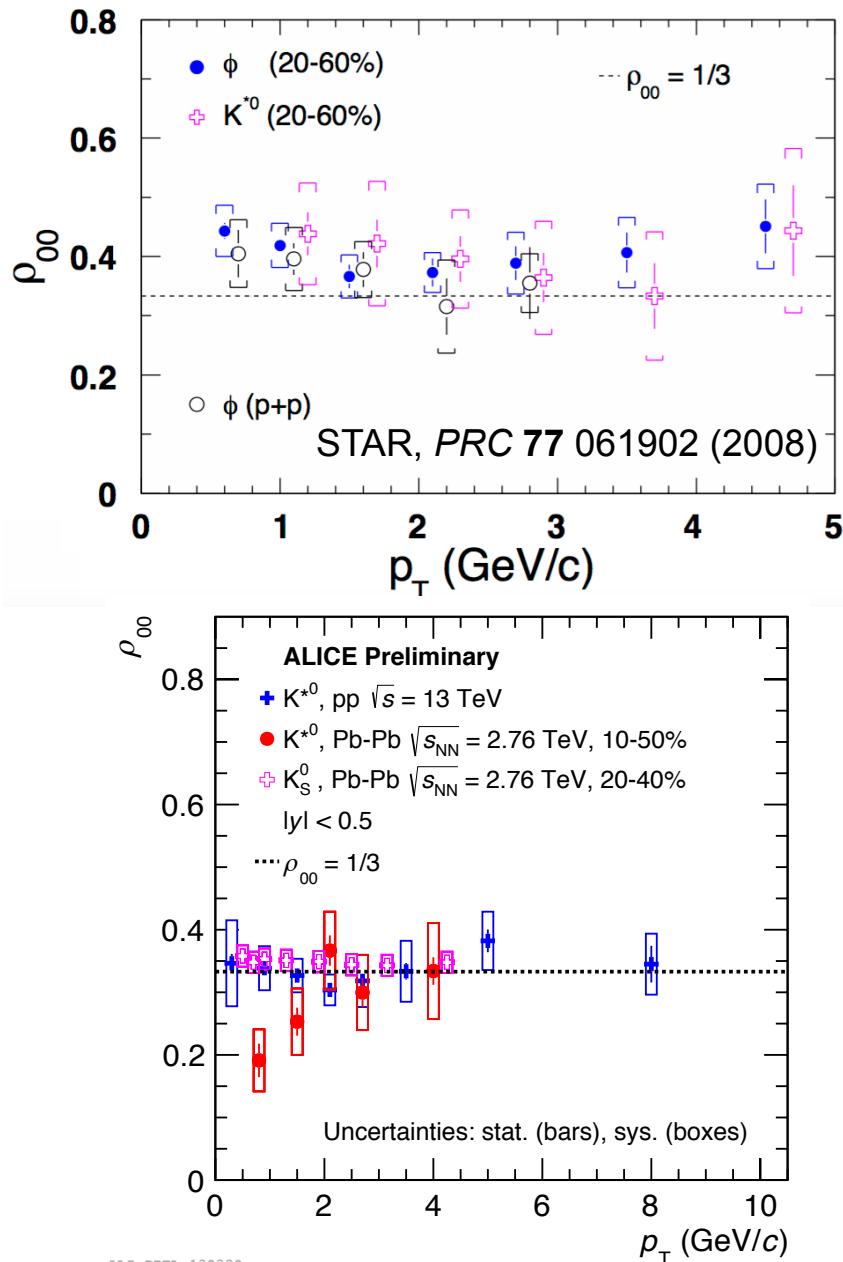
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- Baryon-meson splitting:  $\rho^0$ ,  $K^{*0}$ ,  $\phi$ , and even  $D$  are closer to other mesons than to baryons; possible mass ordering among mesons
- Indications of similar behavior at RHIC [PHENIX, *PRC* **83** 024909 (2011)]
- Differences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



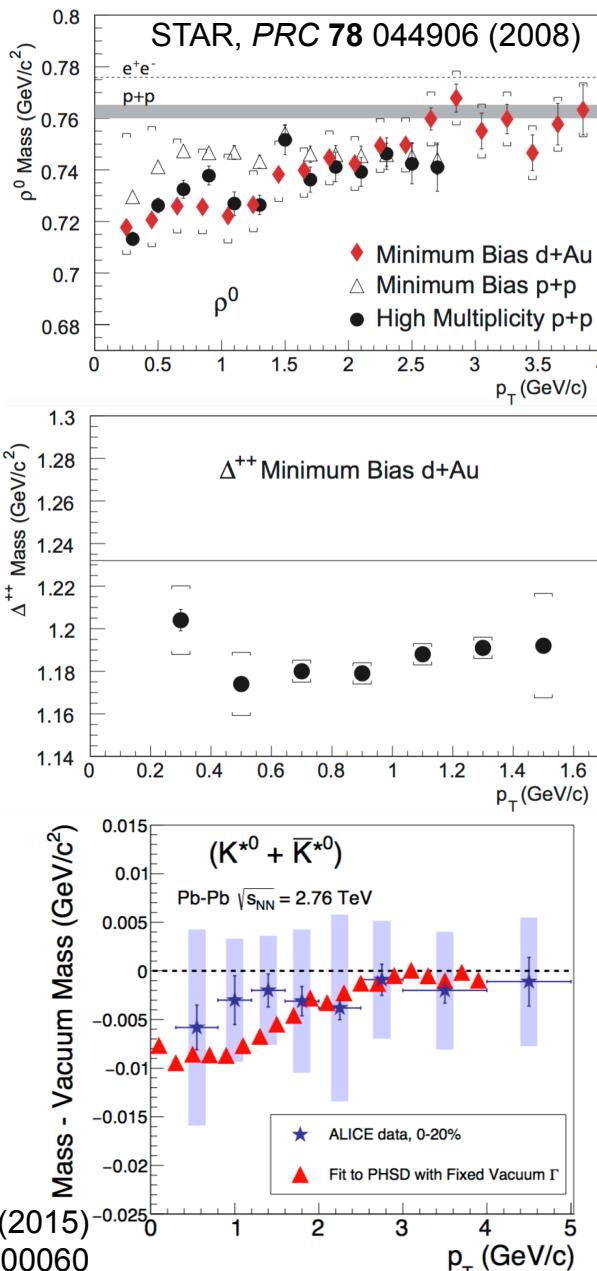
# Spin Alignment

- RHIC
  - Matrix element  $\rho_{00}$  consistent with  $1/3$  (no polarization) for  $K^{*0}$  and  $\phi$
  - Results in  $p+p$  and  $Au+Au$  consistent
- LHC
  - No polarization for  $K^{*0}$  in  $p+p$
  - No polarization for  $K_S^0$  (pseudoscalar)
  - Hint ( $2.5\sigma$ ) of  $\rho_{00} < 1/3$  for  $K^{*0}$  in  $Pb+Pb$
- See also
  - Poster: S. Shi
  - Talk: B. Tu today at 14:35
  - Talk: B. Mohanty today at 14:55



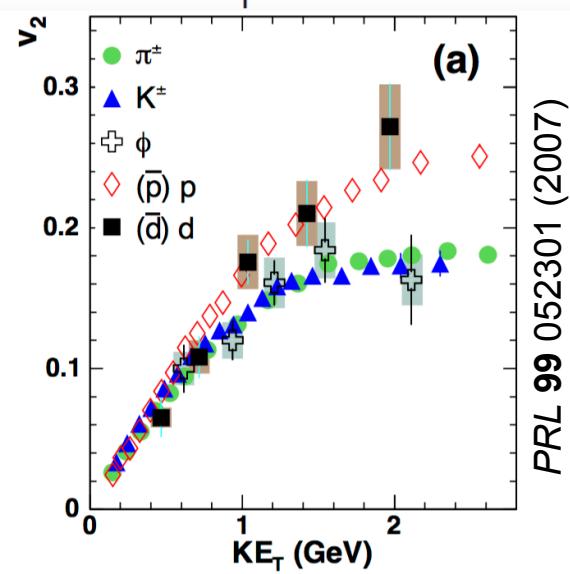
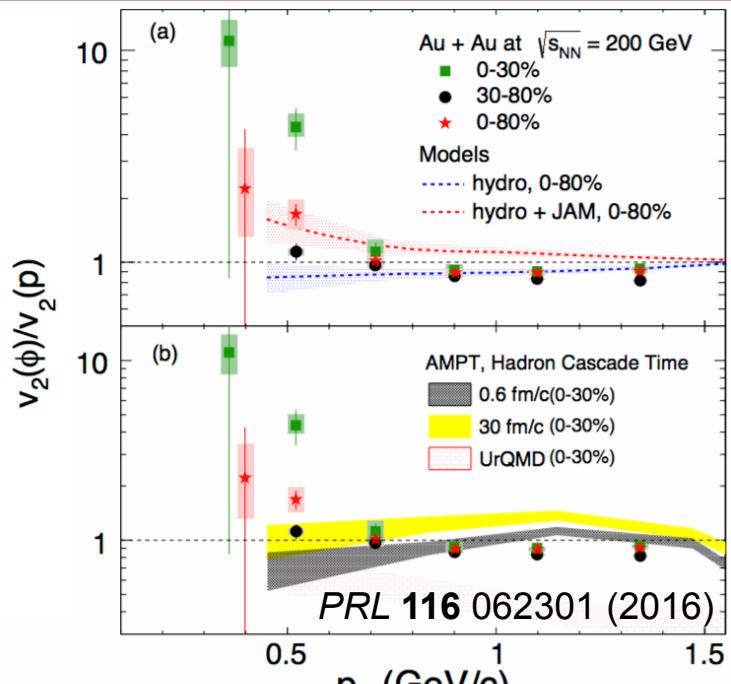
# Lineshape Modification

- Low-mass excess of dileptons in  $A+A$ 
  - Possible melting of  $\rho^0$
- $p_T$ -dependent negative shift of masses for  $\rho^0$ ,  $K^*$ ,  $\Delta^{++}$ , &  $\Sigma^{*\pm}$  observed in  $p+p$  and  $d+Au$ 
  - Possible interpretations: interference, re-scattering, Bose-Einstein correlations
  - Hint of multiplicity-dependence
- Hint of  $p_T$ -dependent negative shift of mass for  $K^{*0}$  in Pb+Pb
  - New PHSD paper attributes this to medium modification of spectral function and re-scattering & absorption in hadronic phase



# Elliptic Flow

- STAR: violation of mass ordering:  $v_2(\phi) > v_2(p)$  at low  $p_T$ 
  - Hadronic re-scattering for  $p$ ?
- PHENIX:  $v_2(KE_T)$  for  $\phi$  follows other mesons for  $p_T > 0.8 \text{ GeV}/c$ 
  - Similar trend seen in ALICE (Run 2)



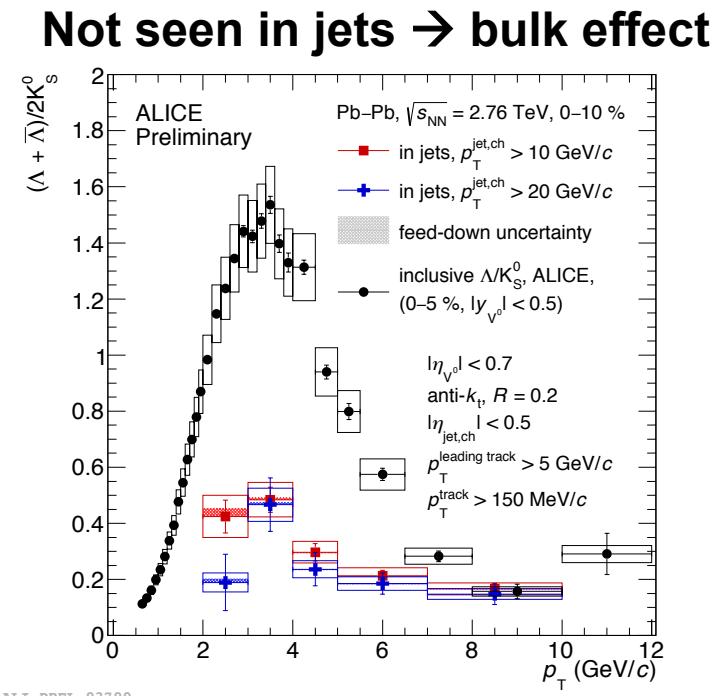
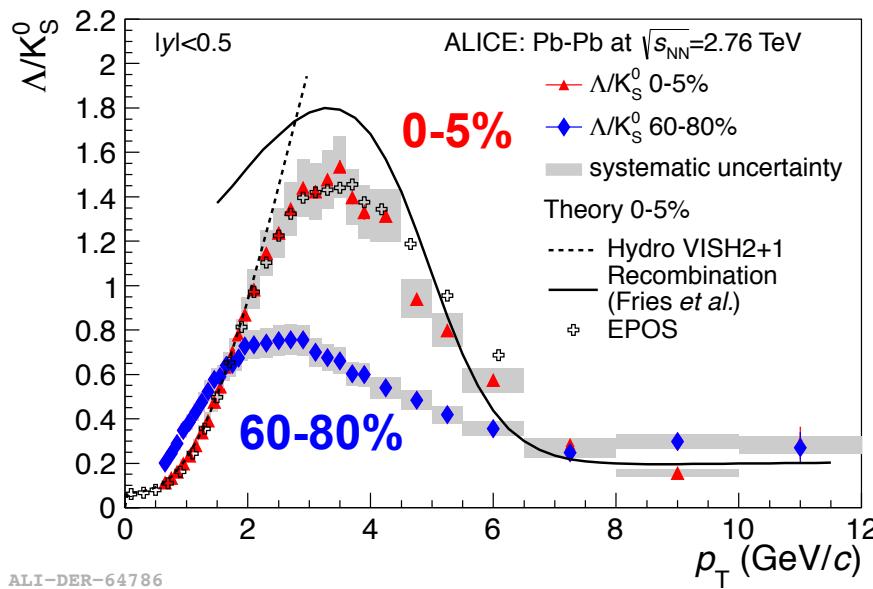
# Summary

- Resonance (non-)suppression:
  - $\rho^0$ ,  $K^*$ ,  $\Lambda(1520)$ , maybe  $\Xi^{*0}$  suppressed in central  $A+A$ 
    - Re-scattering dominant over regeneration
  - $\phi$ ,  $\Delta^{++}$ ,  $\Sigma^{*\pm}$  not suppressed
  - Trends described by models (EPOS, PHSD) with scattering
  - Multiplicity-dependent suppression in small collision systems
- Enhancement of strange baryons in  $p+A$  is indeed due to **strangeness content** (not baryon number or mass)
- Constant  $p/\phi$  ratio and mass ordering of  $\langle p_T \rangle$  in central  $A+A$ : consistent with hydrodynamics
- High- $p_T$  particle suppression does not depend on hadron properties (mass, baryon number,  $u/d/s/c$  quark content).
- $p_T$ - (and multiplicity?) dependent mass shifts observed

# Additional Material

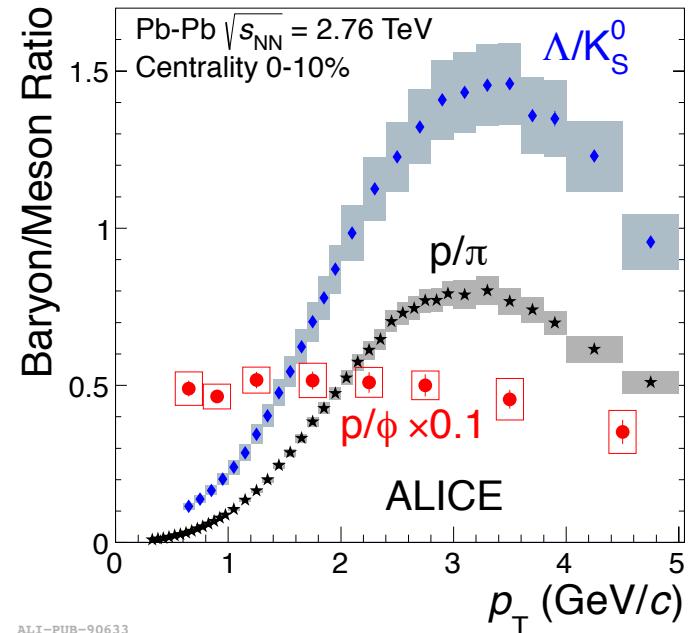
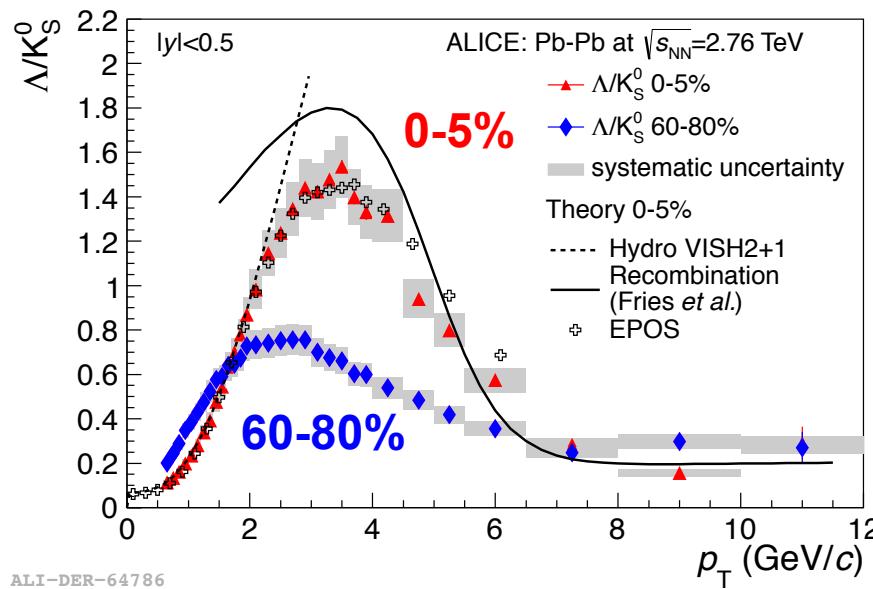
# Baryon/Meson Ratios

- Pb–Pb  $\Lambda/K_S^0$  ratio:
  - Low- $p_T$  rise described by hydrodynamics (VISH 2+1)
  - Recombination qualitatively describes enhancement
  - EPOS consistent with measured enhancement → radial flow



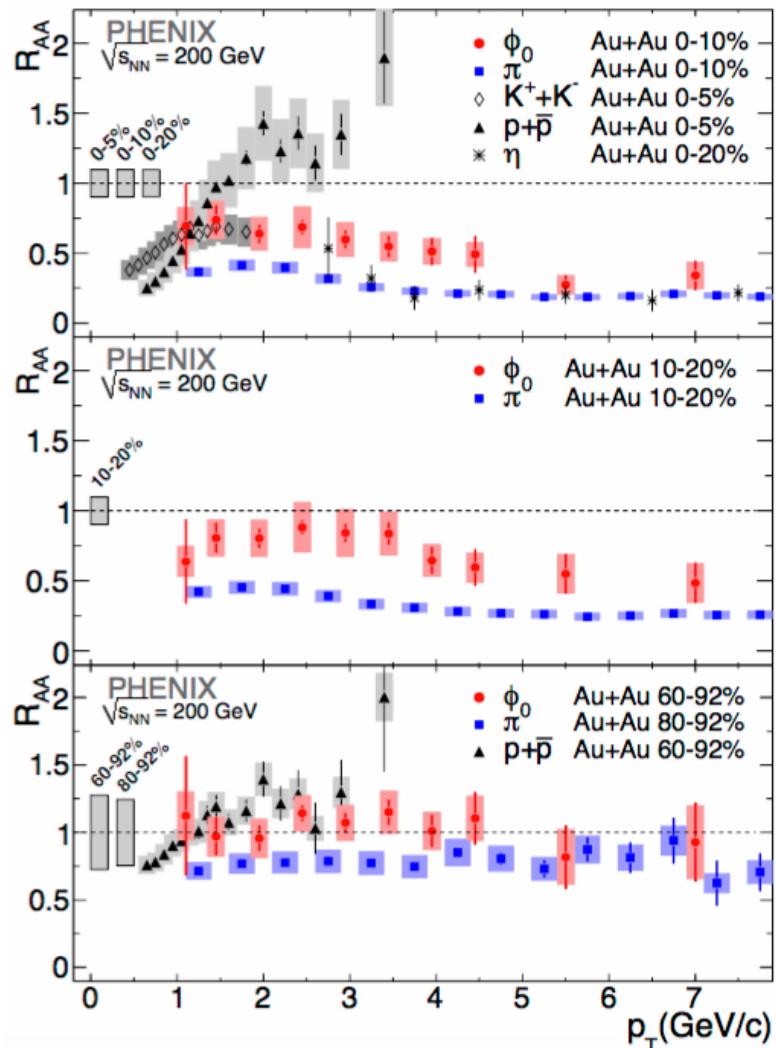
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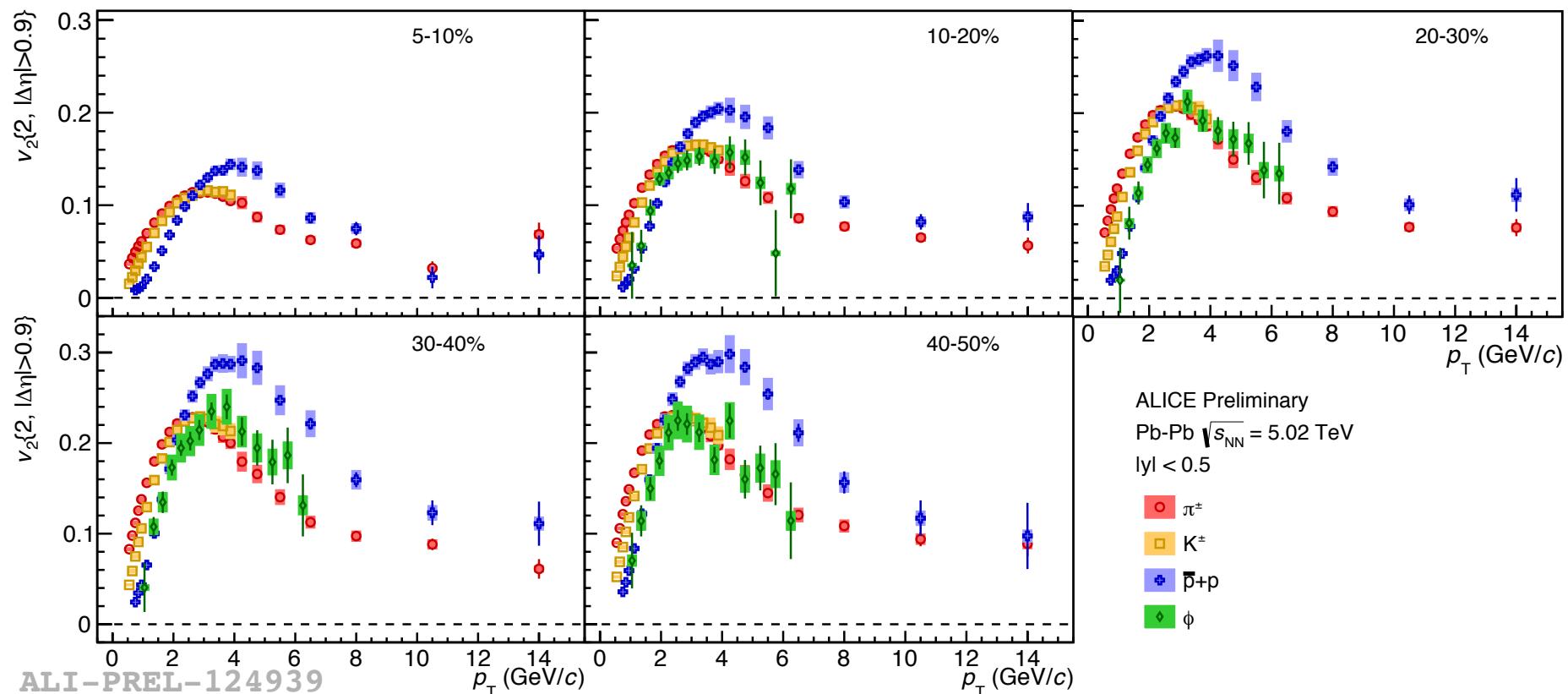
# Nuclear Modification Factor

- $R_{AA}(\phi) < R_{AA}(p)$  at intermediate  $p_T$ , closer to other mesons
- $R_{AA}(\phi)$  approaches  $\pi^0$  and  $\eta$  at high  $p_T$

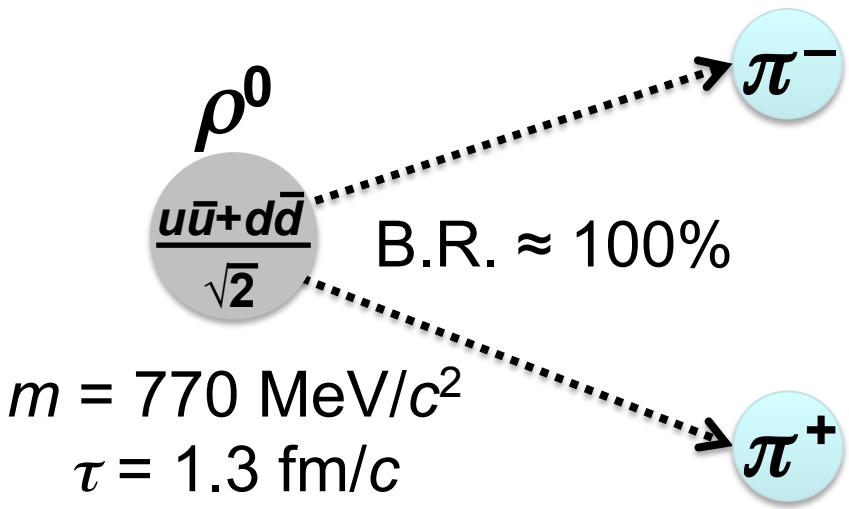


PHENIX, *PRC* 83 024909 (2011)

# Elliptic Flow: ALICE



# $\rho^0$ Reconstruction at ALICE



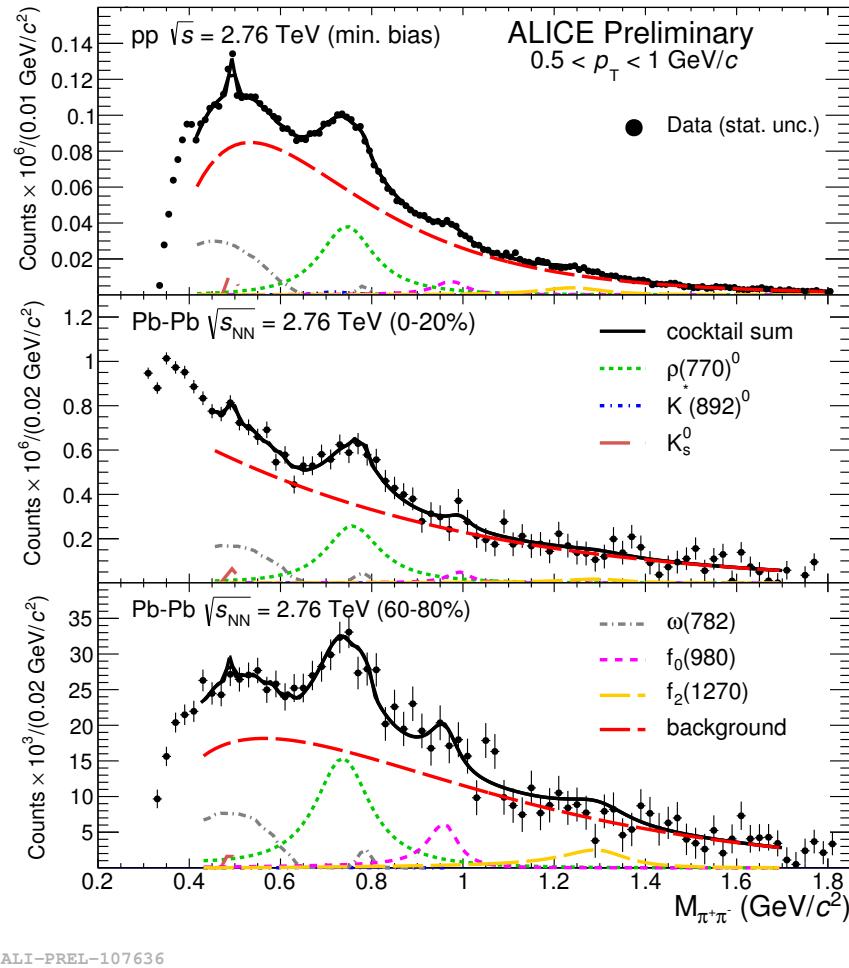
- Analyzed in pp and Pb–Pb collisions at 2.76 TeV
- Subtract like-charge combinatorial background
- Fit with **residual background** + cocktail ( $K_s^0$ ,  $K^{*0}$ ,  $\omega$ ,  $f_0$ ,  $f_2$ )
- Peak Model:

*Relativistic  
Breit-Wigner*

*Phase Space*

*Mass-Dependent  
Efficiency*

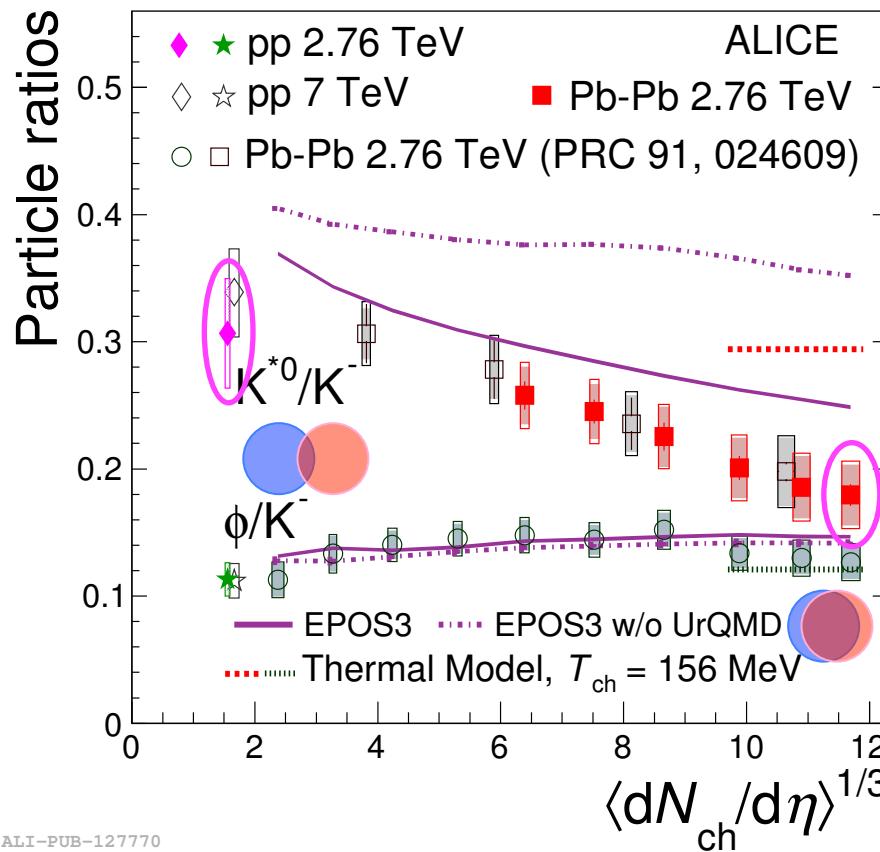
*Söding  
Interference Term*



ALICE-PREL-107636

# 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 ( $\tau = 4.2 \text{ fm/c}$ )
 
$$\text{(Final)} = \text{(Initial)} \times \exp(-\Delta t/\tau)$$
  - Use inelastic  $p+p$  as **initial value**, central  $\text{Pb+Pb}$  as **final value**  
 $\rightarrow$  lifetime of hadronic phase  $\Delta t \geq 1 \text{ fm/c}$



# Hadronic Phase

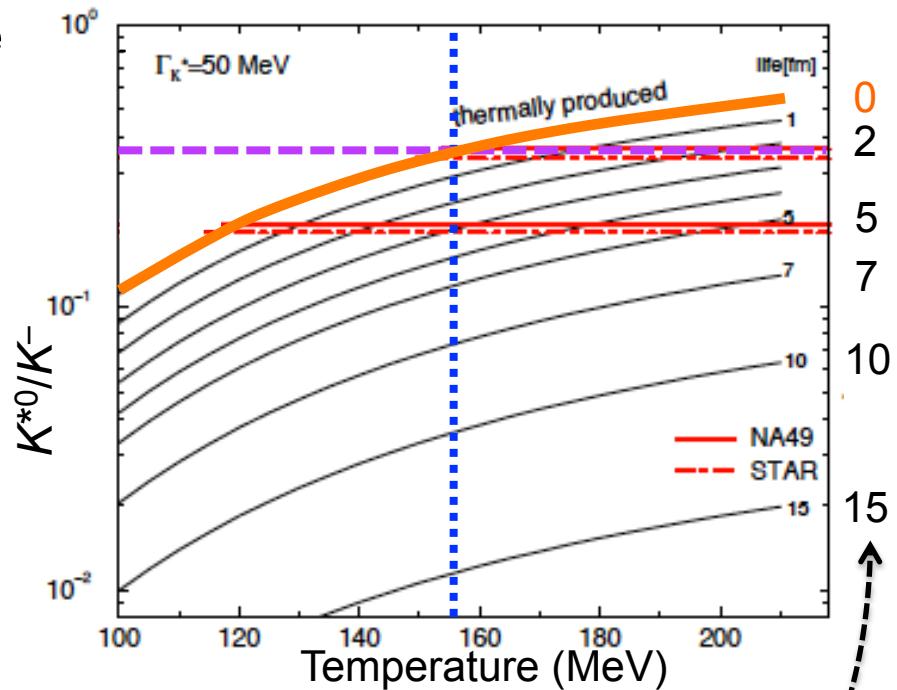
- Model of Torrieri, Rafelski, *et al.* predicts particle ratios as functions of chemical freeze-out temperature and lifetime of hadronic phase
- Model Predictions:

Torrieri/Rafelski [1-3]  
no re-scattering  
 $T_{ch} = 156$  MeV

Prediction:  
 $K^{*0}/K^- = 0.35$

- $T_{ch}$ : assumption, based on thermal-model fits of ALICE data
- Prediction: consistent with  $p+p$  value, much larger than measured Pb+Pb value:  $0.180 \pm 0.027$

- [1] *J. Phys. G* **28**, 1911 (2002)  
[2] *Phys. Rev. C* **65**, 069902(E) (2002)  
[3] arXiv:hep-ph/0206260v2 (2002)



**Curves:** different hadronic phase lifetimes (fm/c)

## Inelastic Collisions

QGP → Hadron Gas

chemical  
freeze out

## (Pseudo-)elastic Collisions

regeneration & re-scattering

kinetic  
freeze out

# Hadronic Phase

- Model of Torrieri, Rafelski, *et al.* predicts particle ratios as functions of chemical freeze-out temperature and lifetime of hadronic phase
- Model Predictions:

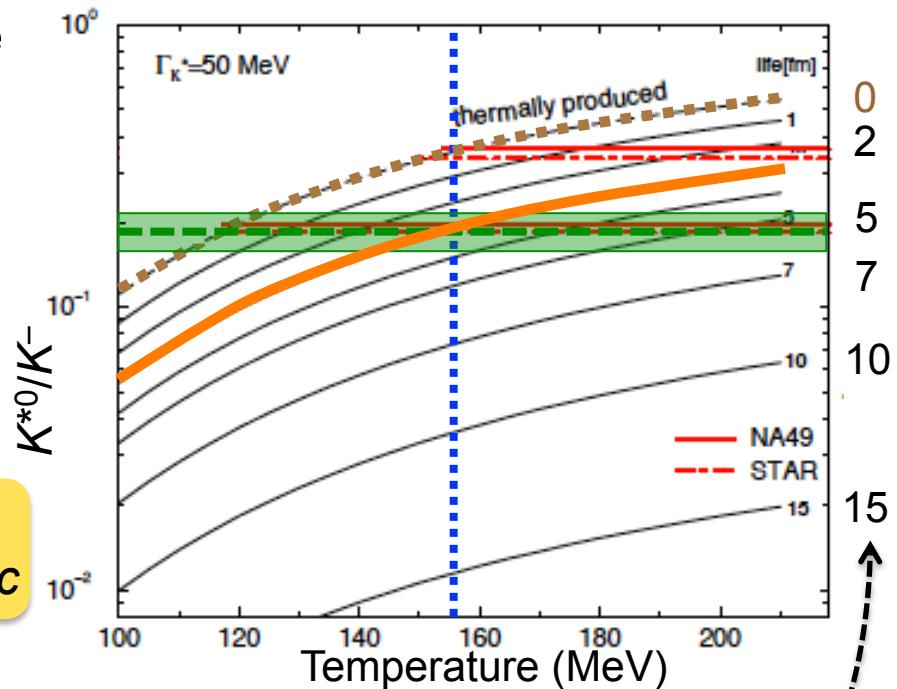
Torrieri/Rafelski [1-3]  
no re-scattering  
 $T_{ch} = 156$  MeV

Prediction:  
 $K^{*0}/K^- = 0.35$

Torrieri/Rafelski [1-3]  
measured  $K^{*0}/K^-$   
 $T_{ch} = 156$  MeV

Prediction:  
Lifetime  $\geq 2.4$  fm/c

- [1] *J. Phys. G* **28**, 1911 (2002)  
[2] *Phys. Rev. C* **65**, 069902(E) (2002)  
[3] arXiv:hep-ph/0206260v2 (2002)



**Curves:** different hadronic phase lifetimes (fm/c)

**Inelastic Collisions**

**(Pseudo-)elastic Collisions**

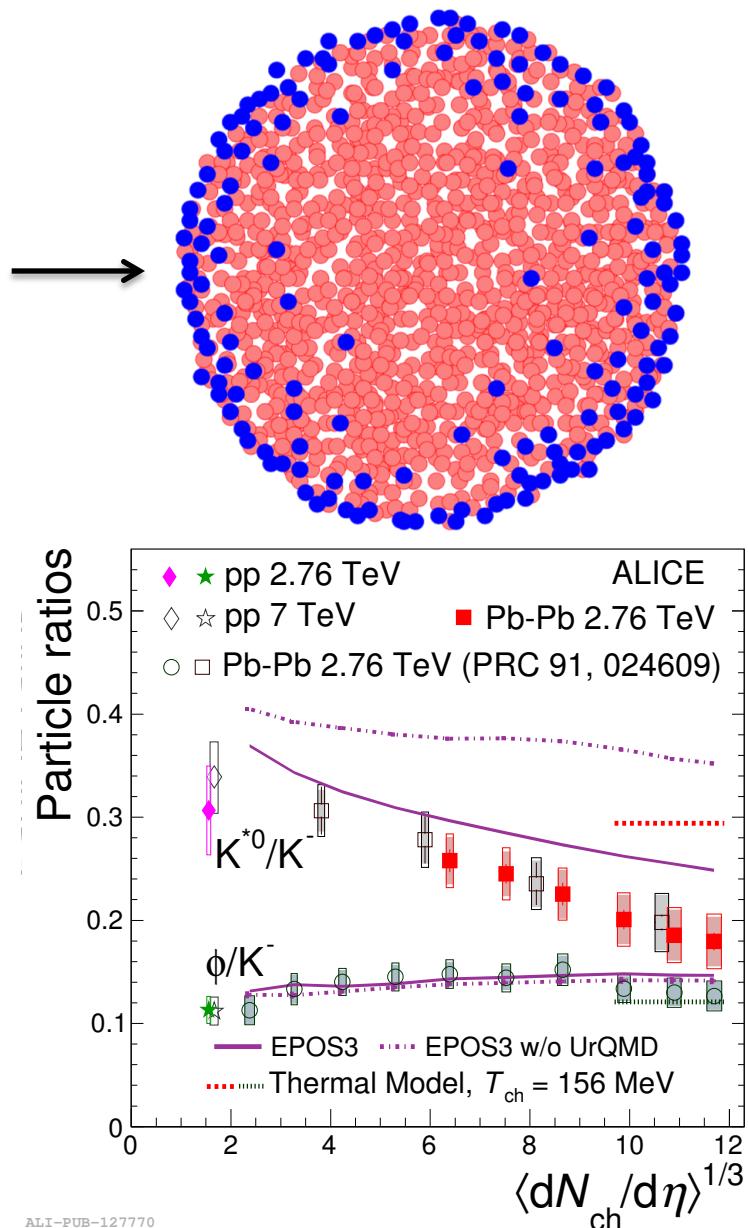
regeneration & re-scattering

$\text{QGP} \rightarrow \text{Hadron Gas}$

chemical  
freeze out

kinetic  
freeze out

- 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)
  - Possible to turn off UrQMD to test importance of scattering processes

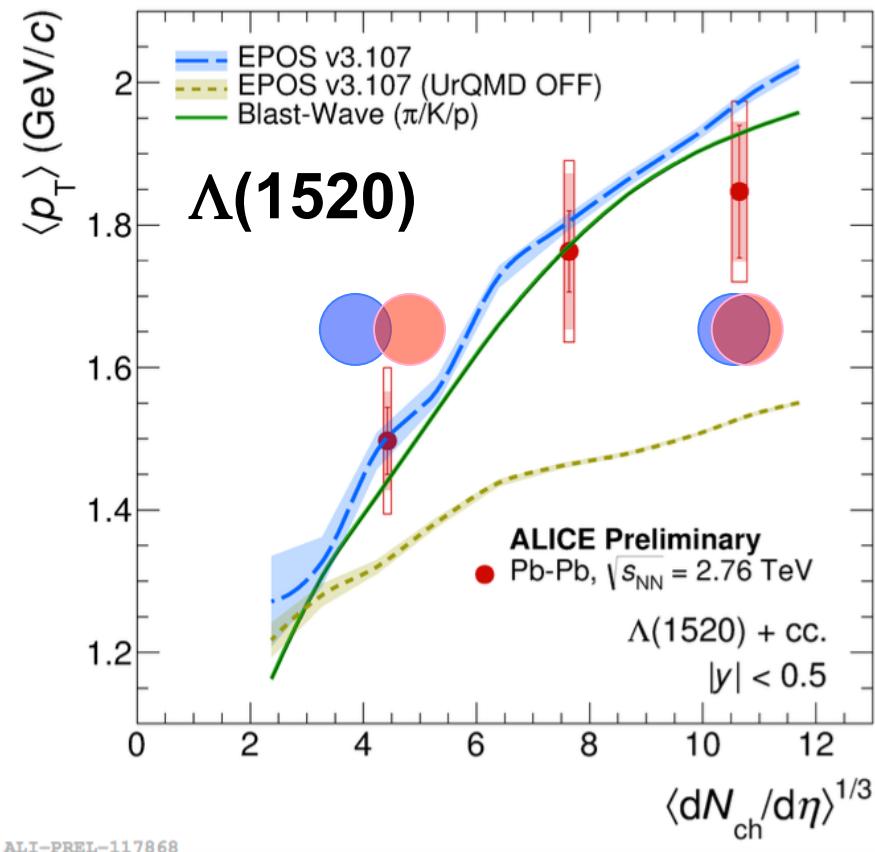
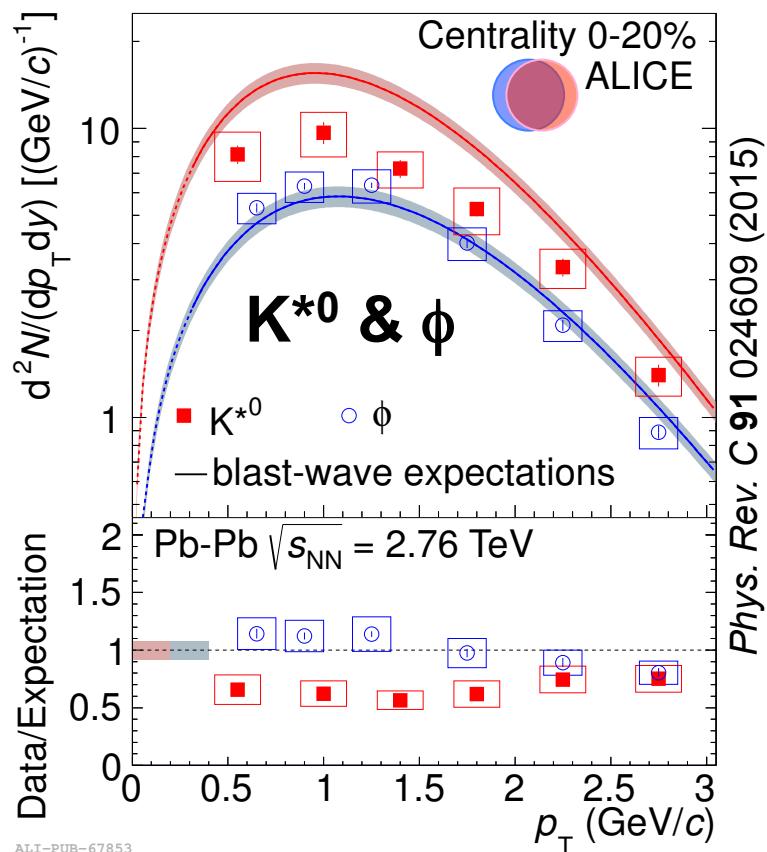


# Suppression: $p_T$ Dependence<sup>Knospe</sup>

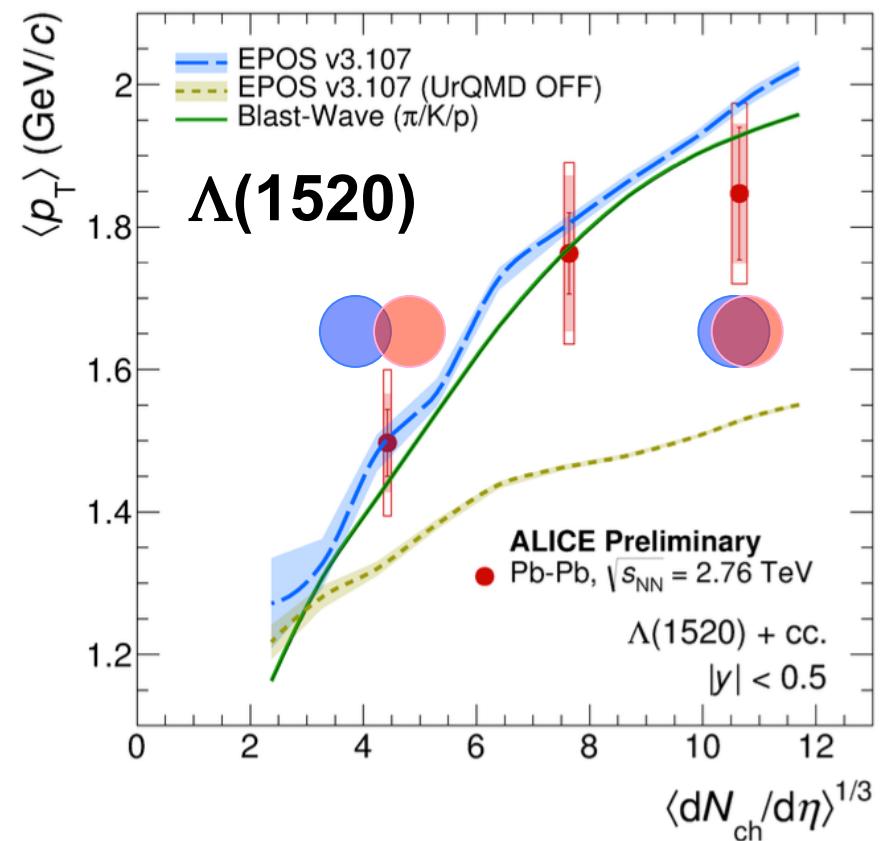
- In UrQMD, resonance modification by regeneration and re-scattering mostly at low  $p_T$  ( $< 2 \text{ GeV}/c$ ).
- Can we see this?

# Blast-Wave Model

- Expected  $p_T$  distributions from blast-wave model using fits of  $\pi/K/p$
- $K^{*0}$  suppressed for  $p_T < 3 \text{ GeV}/c$
- $\langle p_T \rangle$  of  $\Lambda(1520)$  well described
- Comparison to blast-wave model implies **no strong  $p_T$  dependence** of resonance suppression.

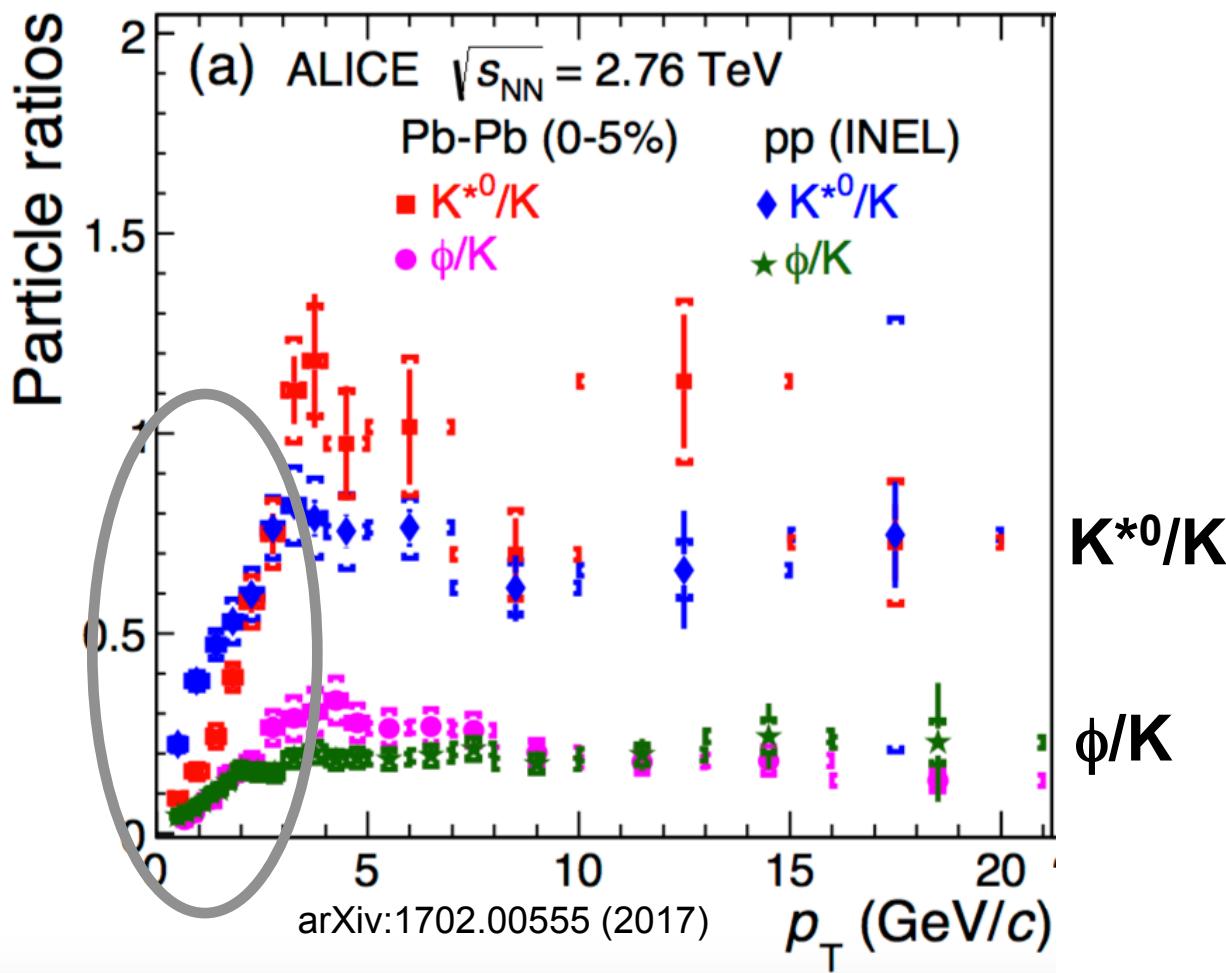


- EPOS with UrQMD describes  $\langle p_T \rangle$  of  $\Lambda(1520)$
- UrQMD off:  $\langle p_T \rangle$  of  $\Lambda(1520)$  underestimated
- Similar situation for  $\rho^0$
- Suggests more suppression of resonances for  $p_T < 2 \text{ GeV}/c$ .
- However, turning off UrQMD also decreases  $\langle p_T \rangle$  of most long-lived particles.



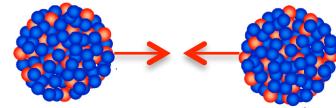
# Changing System Size

- Low- $p_T$   $K^{*0}/K$  decreases from pp to central Pb–Pb
- But  $\phi/K$  does not decrease from pp to Pb–Pb
- Suggests short-lived resonance suppression at low  $p_T$ .



# Nuclear Modification Factor

- How do we quantify particle suppression?

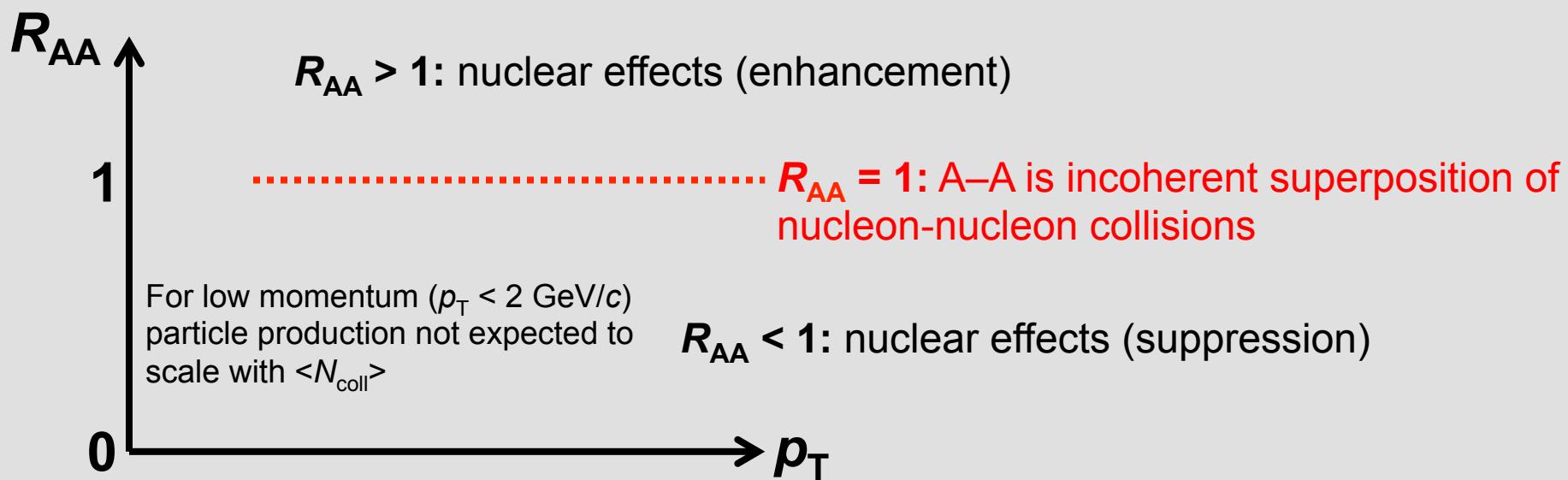


particle yield in nucleus-nucleus collisions

$$R_{AA} = \frac{Y(A-A)}{Y(pp) \times \langle N_{coll} \rangle}$$

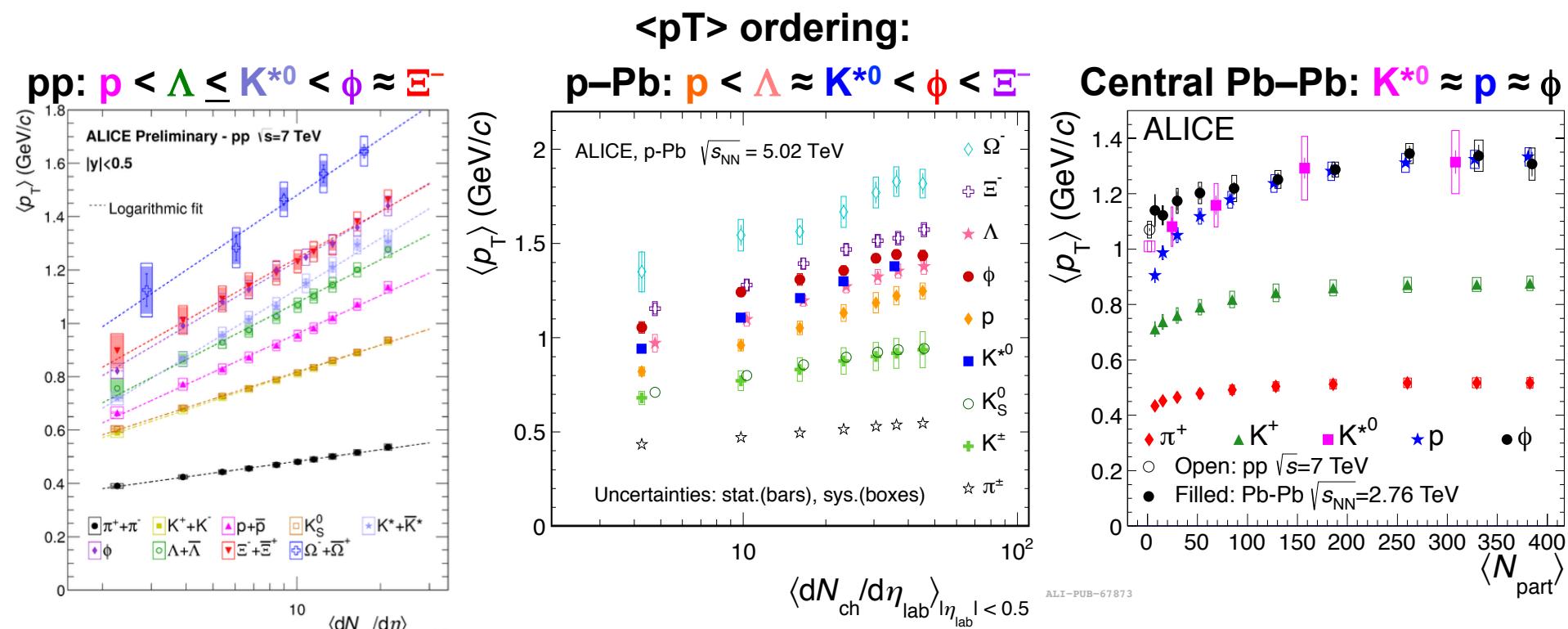
particle yield in proton-proton collisions (baseline)

number of binary nucleon-nucleon collisions in nucleus-nucleus collisions (calculated from models)



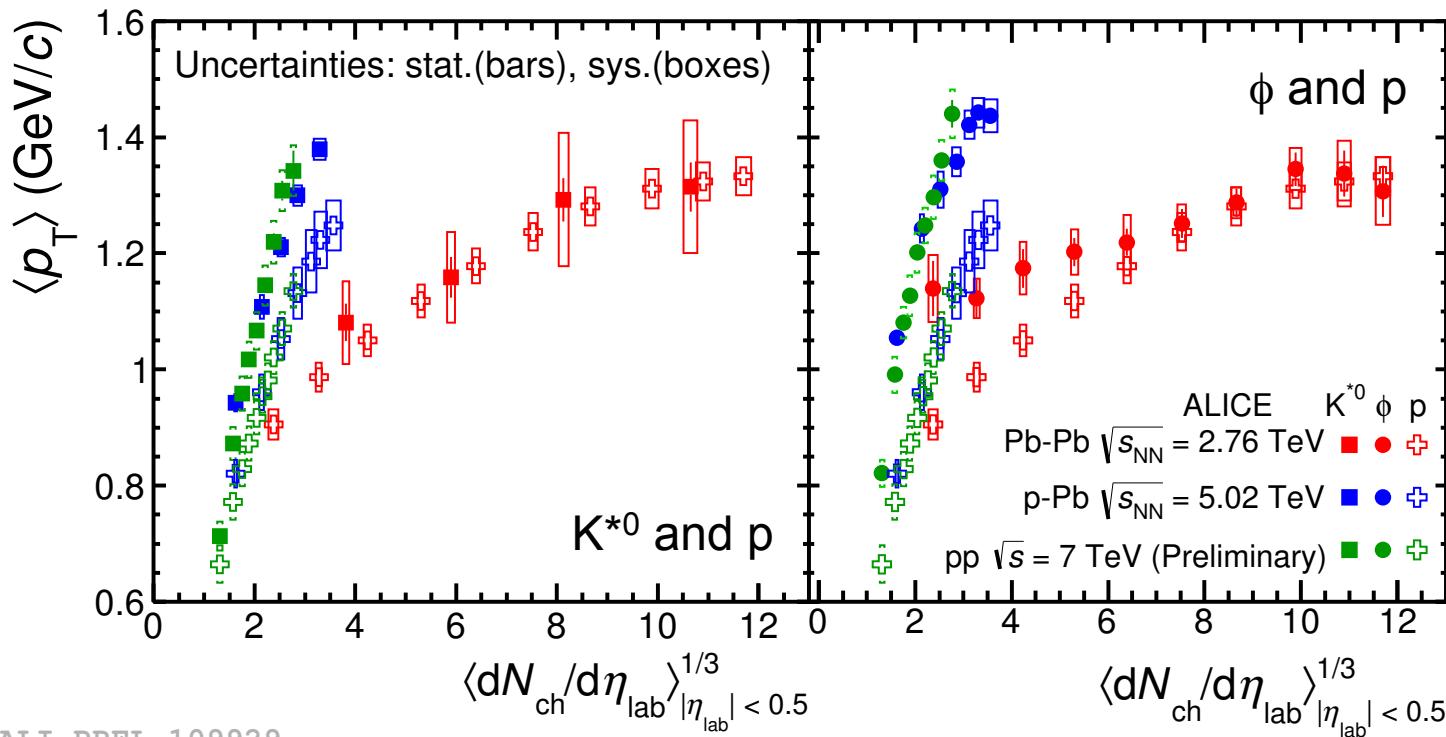
# Mean $p_T$

- Mass ordering of  $\langle p_T \rangle$  in central Pb–Pb
  - $\langle p_T \rangle$  for  $K^{*0}$ ,  $p$ , and  $\phi$  similar  $\rightarrow$  expected from hydro (similar masses)
- Mass ordering only approximate for peripheral Pb–Pb, p–Pb, and pp
  - Resonances different from long-lived particles? Baryon/meson difference?



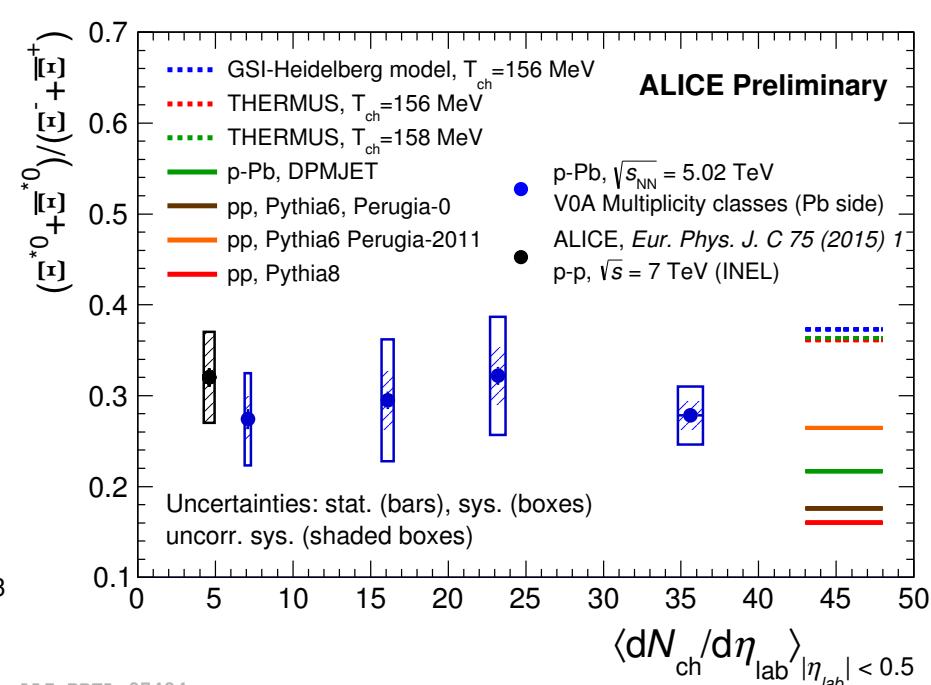
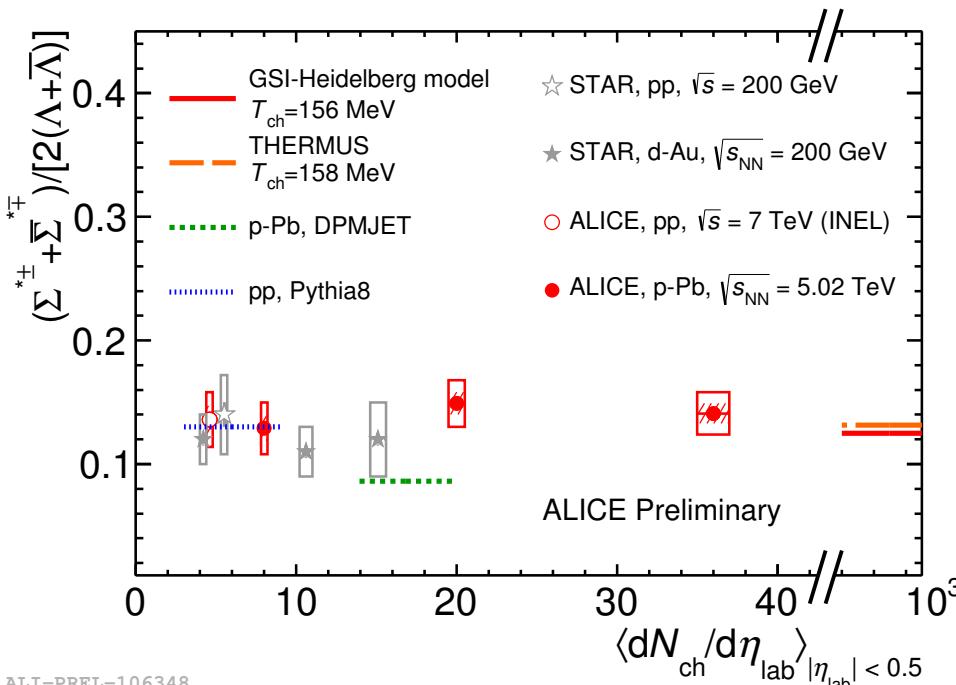
# Mean $p_T$

- Mass ordering of  $\langle p_T \rangle$  in central Pb–Pb
  - $\langle p_T \rangle$  for  $K^{*0}$ , p, and  $\phi$  similar → expected from hydro (similar masses)
- Mass ordering only approximate for peripheral Pb–Pb, p–Pb, and pp
  - Resonances different from long-lived particles? Baryon/meson difference?
- $\langle p_T \rangle$  of  $K^{*0}$ , p, and  $\phi$ :
  - pp and p–Pb follow same trends vs. multiplicity, different trend for Pb–Pb
  - Reach or exceed central Pb–Pb values in high multiplicity pp & p–Pb



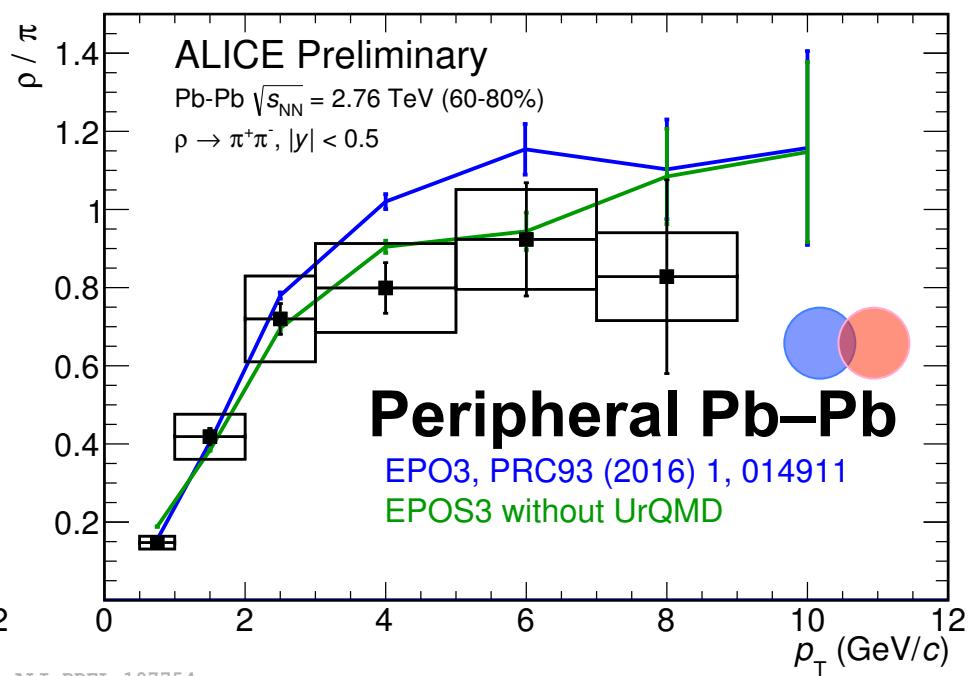
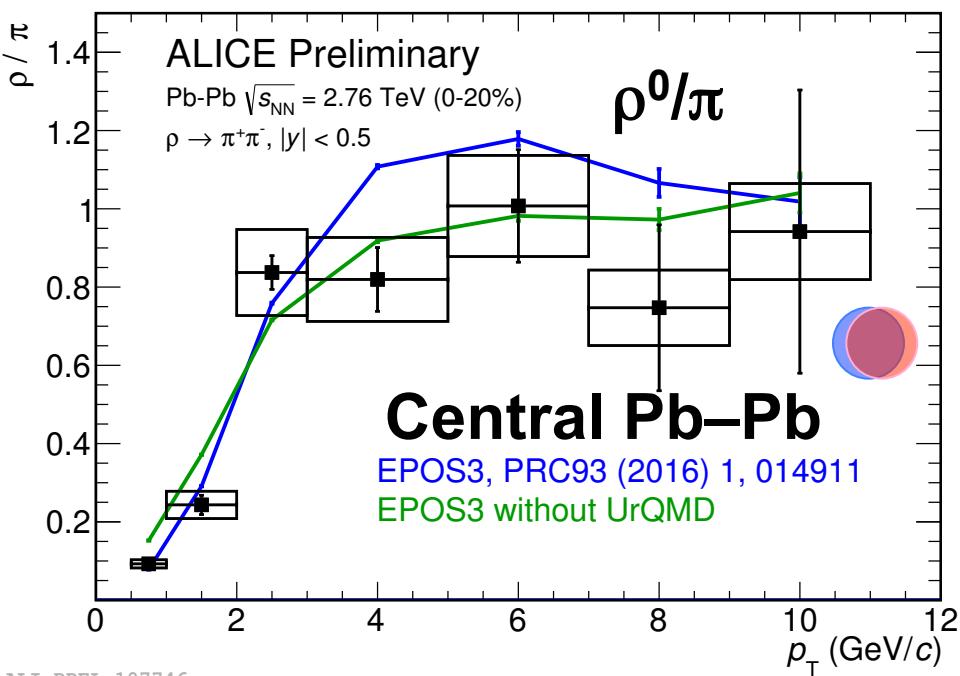
# Strangeness Production

- New measurements of  $\Sigma^{*\pm}$  and  $\Xi^{*0}$  in p–Pb collisions at 5.02 TeV
  - Measurements in progress for Pb–Pb collisions at 2.76 TeV
- No strong dependence of  $\Sigma^{*\pm}/\Lambda$  on energy or system size
  - Values consistent with thermal model and PYTHIA predictions
- No system size dependence of  $\Xi^{*0}/\Xi$  at LHC
  - Values in pp and p–Pb tend to be below thermal model predictions
- Strangeness enhancement in p–Pb collisions due to strangeness content, not mass



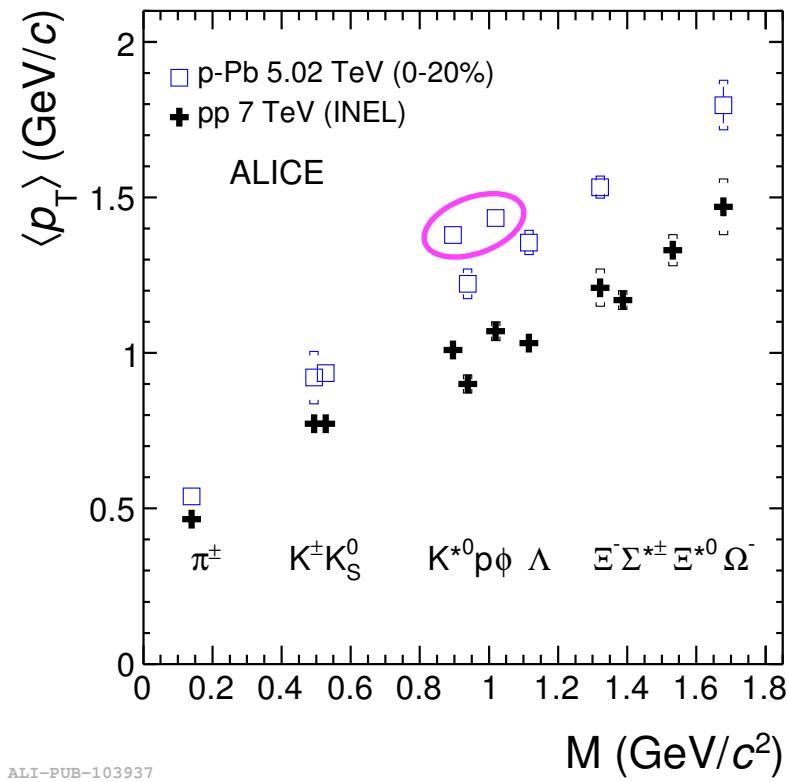
# Changing System Size

- Low- $p_T$   $\rho^0/\pi$  decreases from peripheral to central Pb–Pb

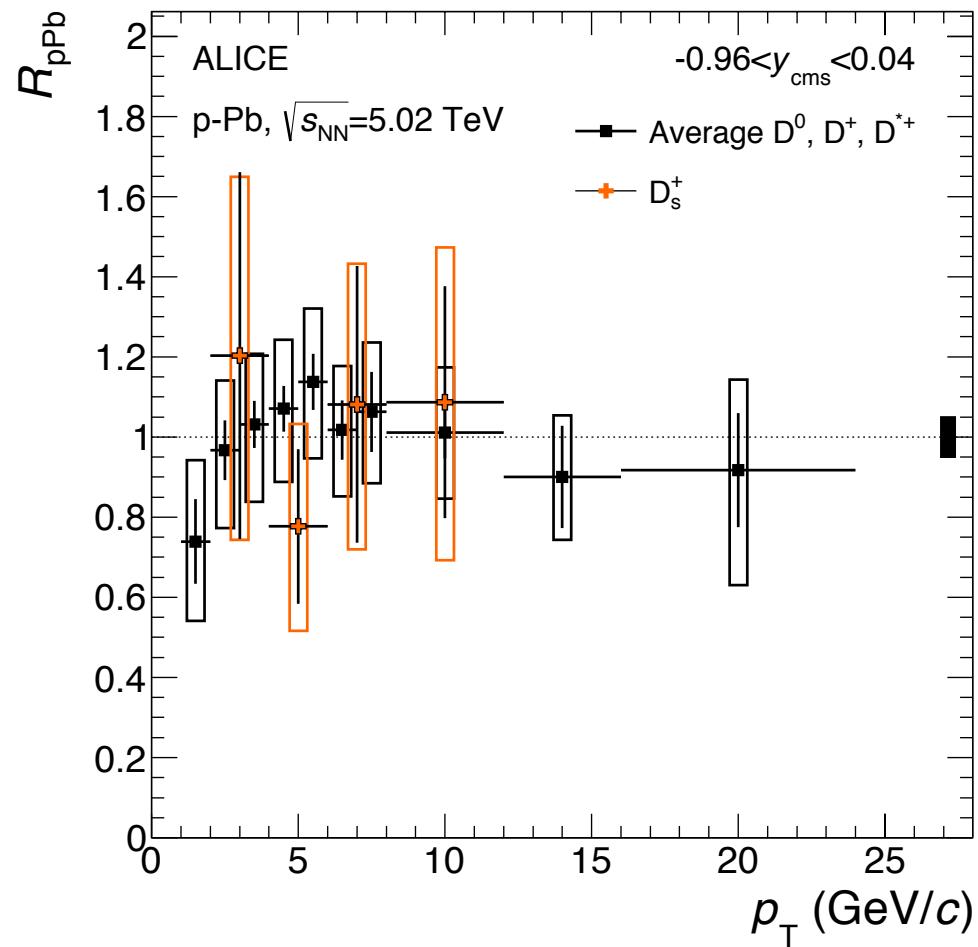


# Mean $p_T$

- **Central Pb–Pb:**  $K^{*0}$ ,  $p$ ,  $\phi$  have same  $\langle p_T \rangle$  → consistent with hydrodynamics
- **Small systems:**
  - $p$ – $Pb$  and  $pp$ :  $\langle p_T \rangle$  values rise faster with mult. than  $Pb$ – $Pb$ , reach similar values at high multiplicity as central  $Pb$ – $Pb$ 
    - Different **particle production mechanisms?** Harder scattering?
  - Mass ordering violated:  $K^{*0}$  and  $\phi$  have larger  $\langle p_T \rangle$  values than  $p$  and  $\Lambda$
  - Is there a **baryon/meson difference**, or do resonances not obey mass ordering?

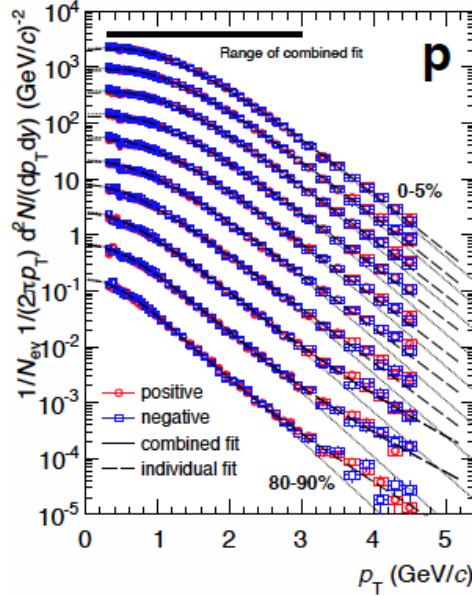
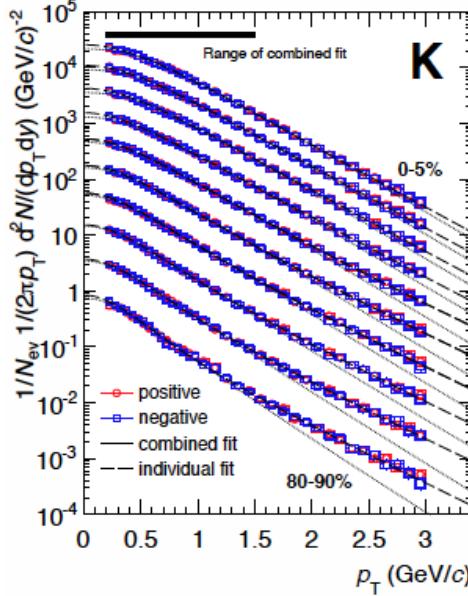
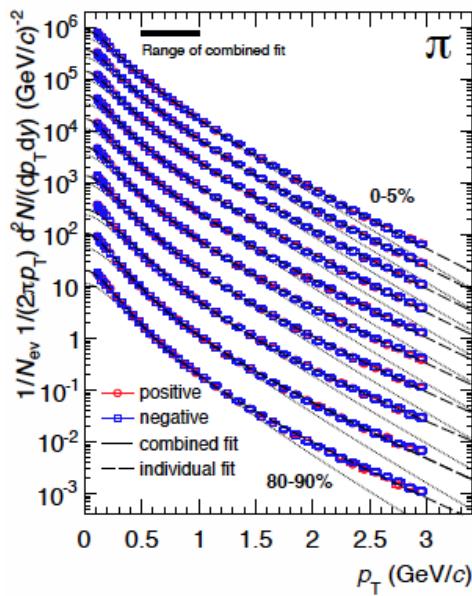


# D $R_{\text{pPb}}$



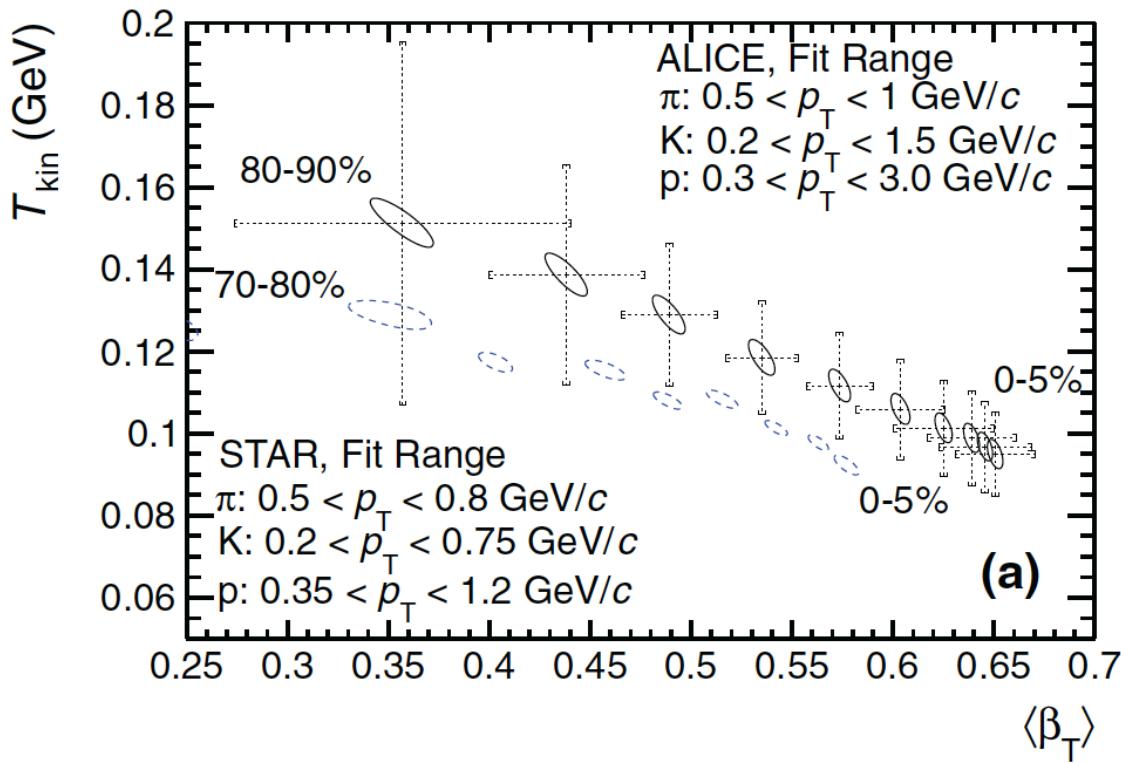
# $\pi/K/p$ Blast-Wave Fits

- Combined fits of  $\pi^\pm$ ,  $K^\pm$ , and (anti)protons in Pb–Pb collisions
  - *Phys. Rev. C* **88** 044910 (2013)



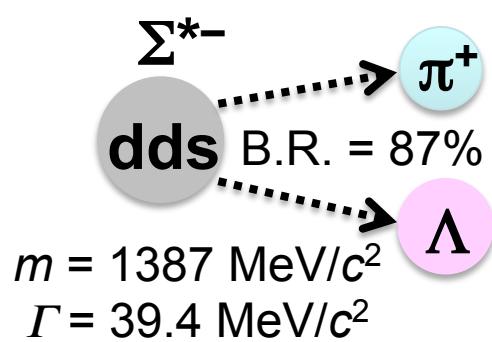
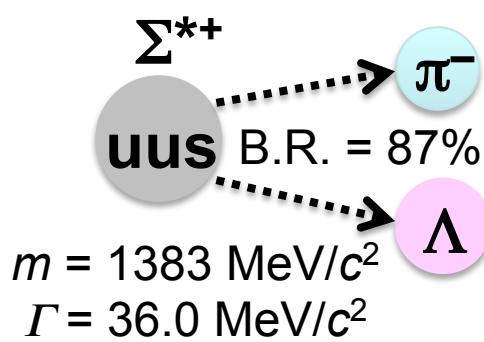
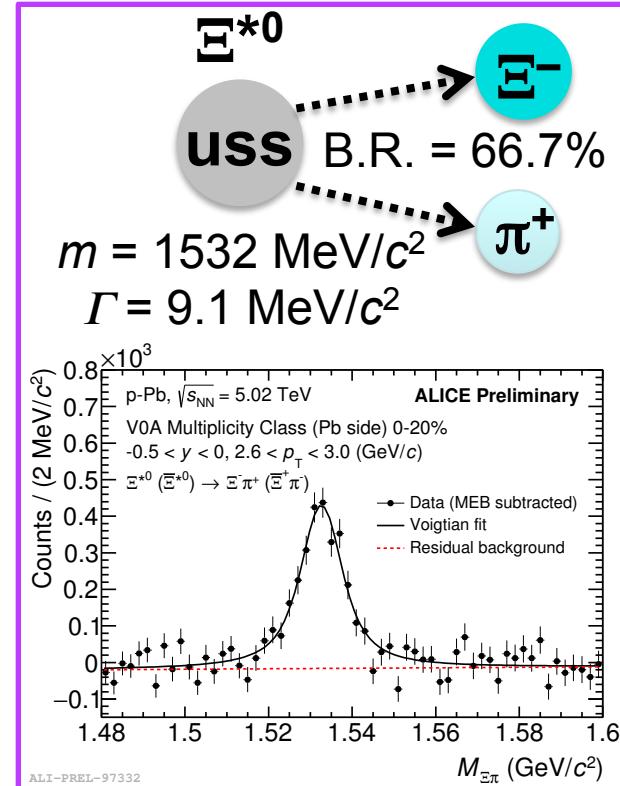
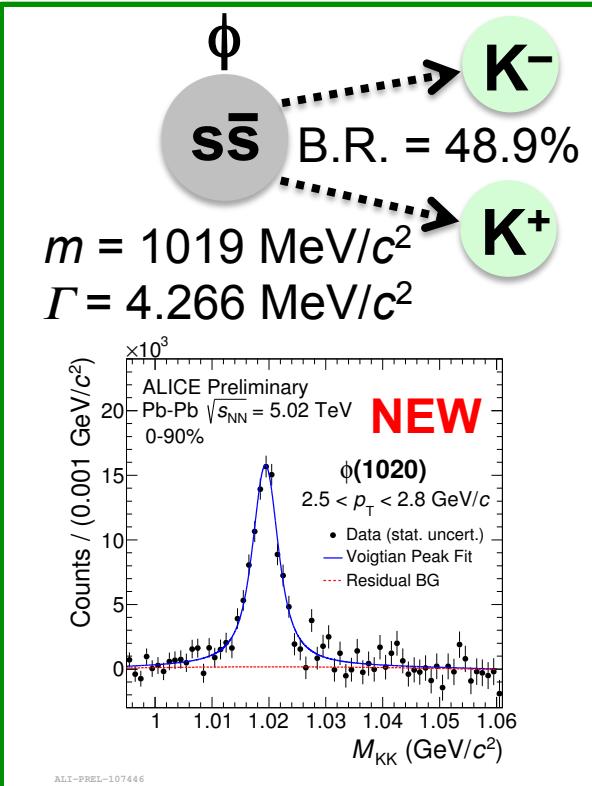
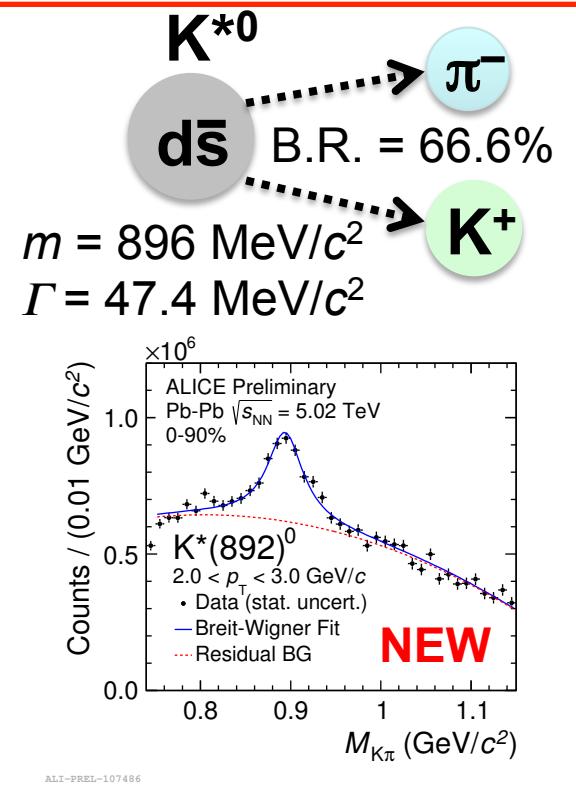
# $\pi/\text{K}/\text{p}$ Blast-Wave Fits

- Combined fits of  $\pi^\pm$ ,  $\text{K}^\pm$ , and (anti)protons in Pb–Pb collisions
  - *Phys. Rev. C* **88** 044910 (2013)



# Resonances

# Other Resonances

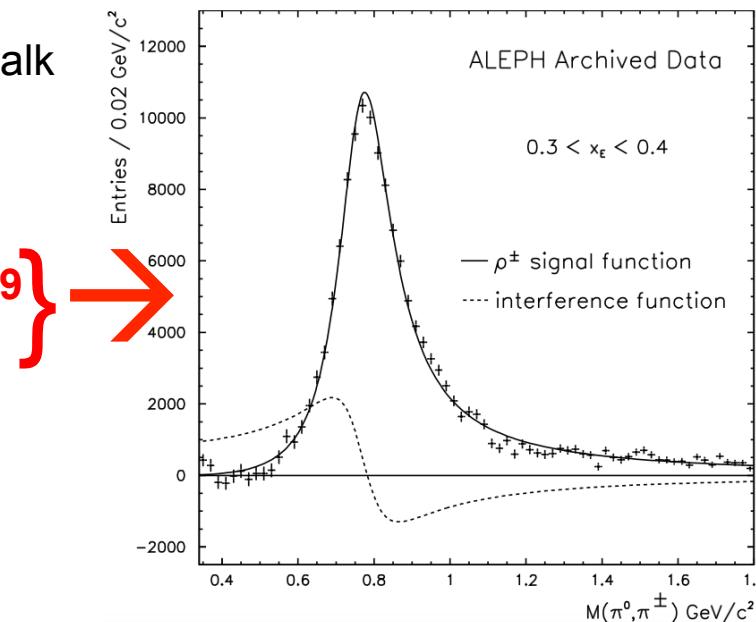


# $\rho^0$ : Söding Interference Term Knospe

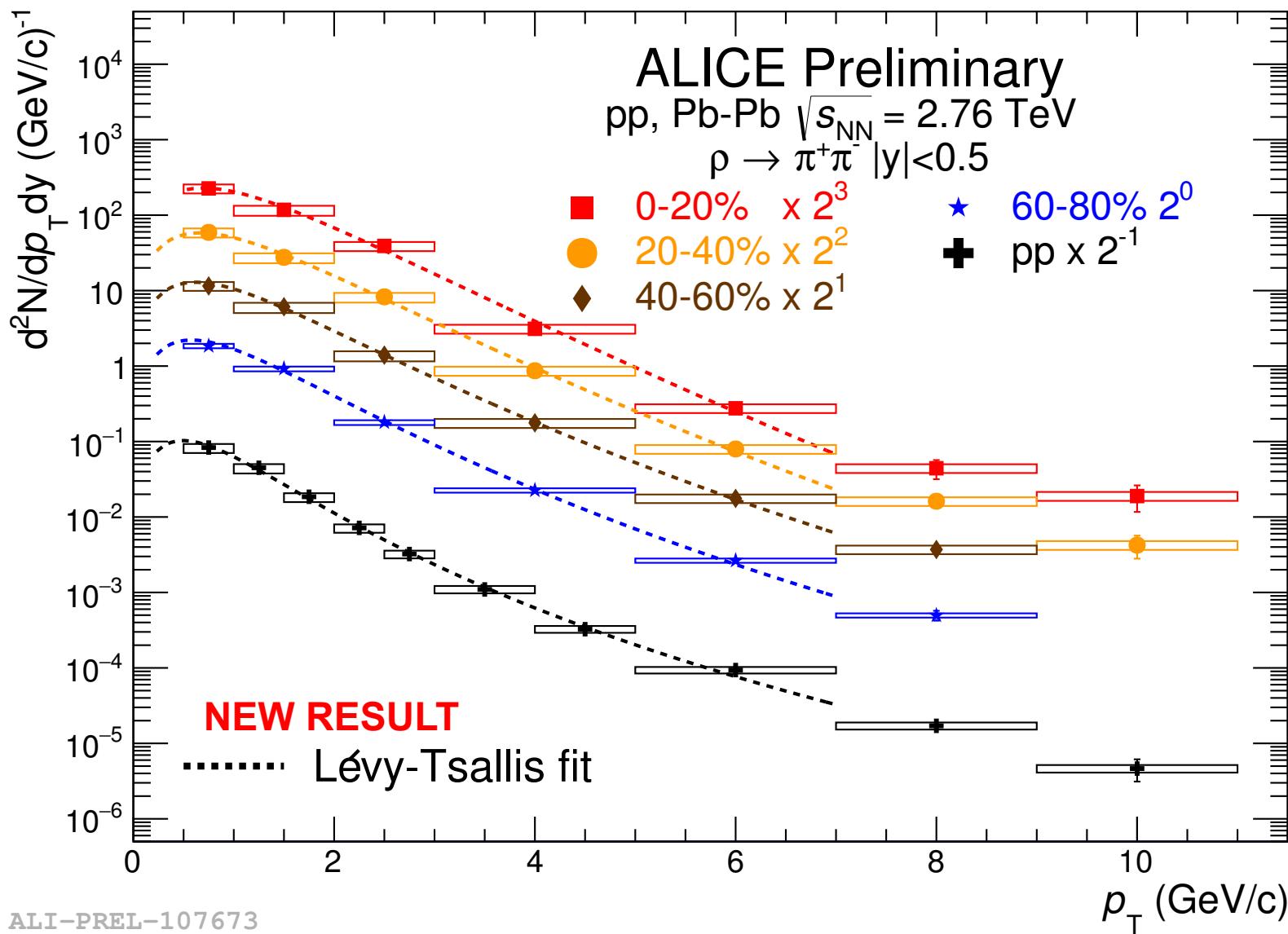
- Accounts for Bose-Einstein correlations between pions produced in  $\rho$  decays and other identical pions nearby in phase space

$$f_i(m) = C \left( \frac{m_0^2 - m^2}{m \Gamma(m)} \right) f_s(m)$$

- Used for
  - ALICE for  $\rho^0$  in ultra-peripheral collisions: see talk of O. Villalobos Baillie, SQM 2016
  - OPAL: *Z. Phys. C* **56** 521-535 (1992); *Z. Phys. C* **60** 559-666 (1993)
  - ALEPH [Archived Data]: *Acta Phys. Polon. B* **39**} 173-180 (2008)
  - DELPHI: *Z. Phys. C* **65** 587-602 (1995)

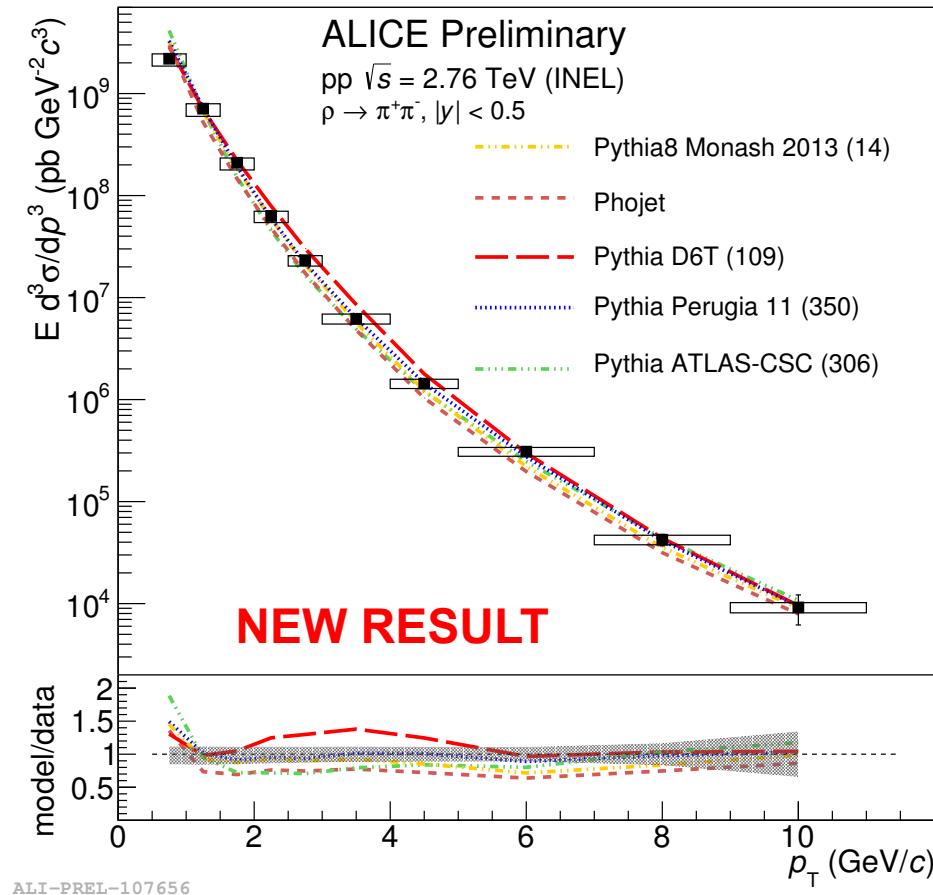


# $\rho^0 p_T$ Spectra



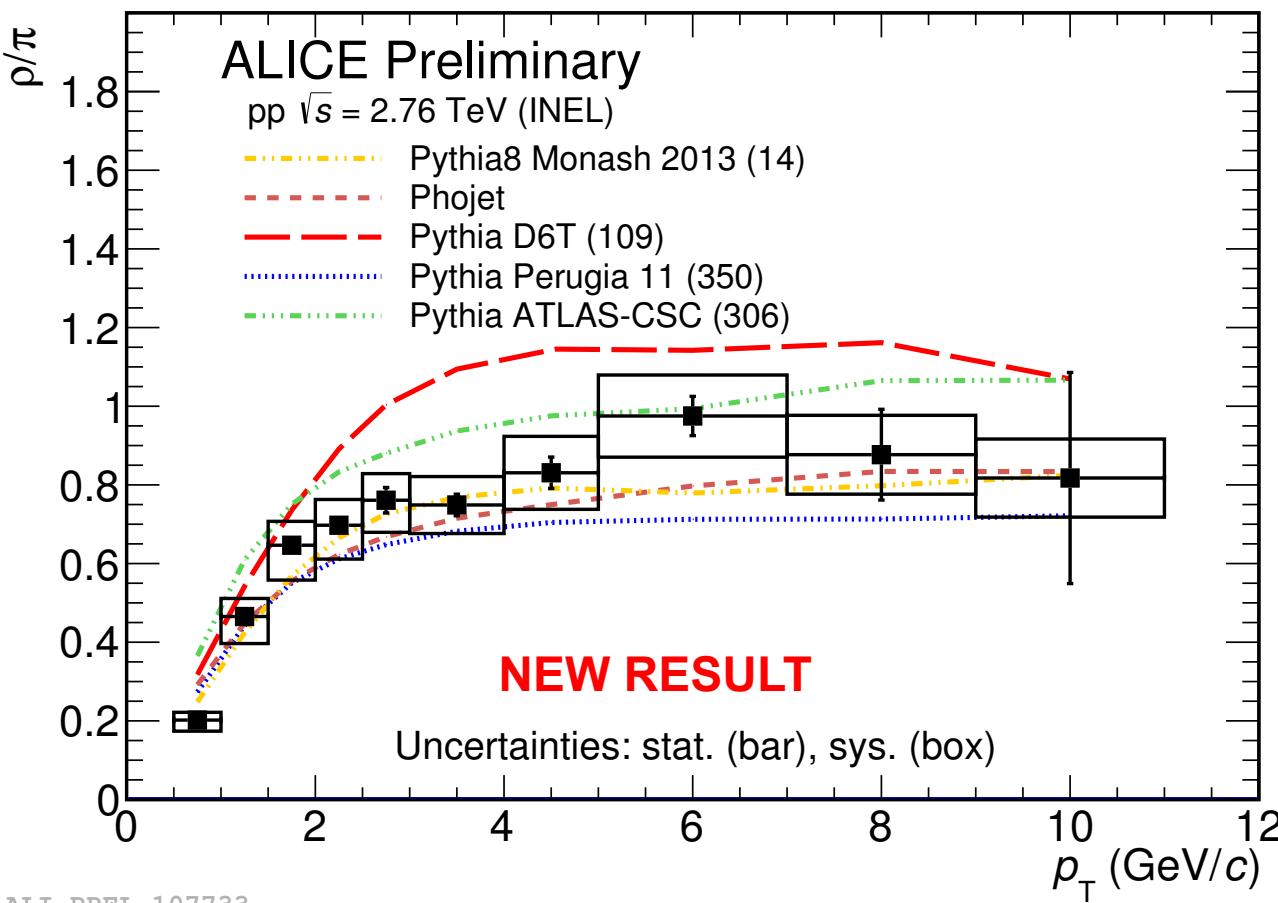
# $\rho^0$ in pp: Model Comparisons Knospe

- $\rho^0$  in pp collisions at 2.76 TeV: all models predict softer spectrum than observed
  - PHOJET, PYTHIA ATLAS-CSC, & PYTHIA Monash 2013 tend to under-predict yields for  $p_T > 1 \text{ GeV}/c$
  - PYTHIA D6T over-predicts yield for  $2 < p_T < 5 \text{ GeV}/c$
  - PYTHIA Perugia 11 describes data within uncertainties for  $p_T > 1 \text{ GeV}/c$



# $\rho^0/\pi$ Ratio vs. $p_T$ (pp)

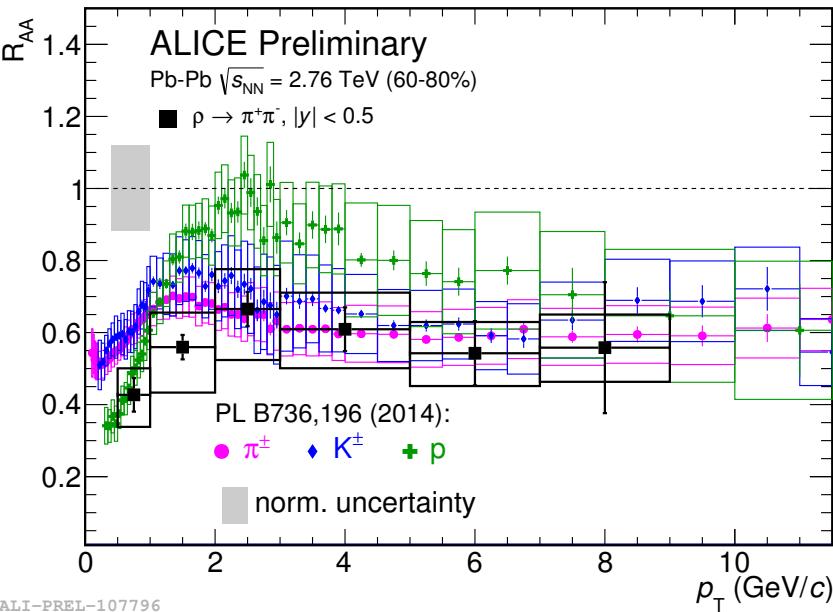
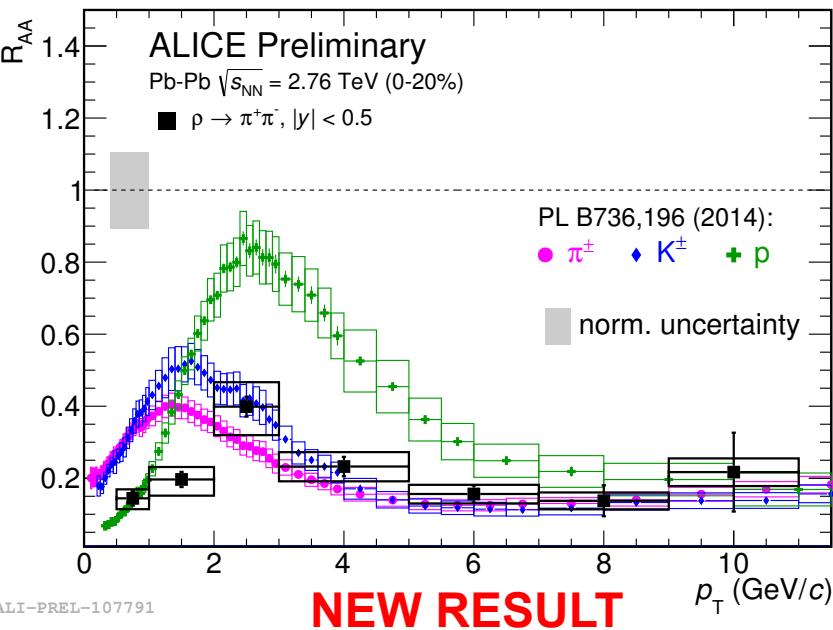
- Measured  $\rho^0/\pi$  ratio in pp collisions at 2.76 TeV compared to models:
  - PYTHIA D6T and ATLAS-CSC over-predict
  - PHOJET and PYTHIA Perugia 11 under-predict
  - Best Description by PYTHIA Monash 2013



# $\rho^0$ Nuclear Modification

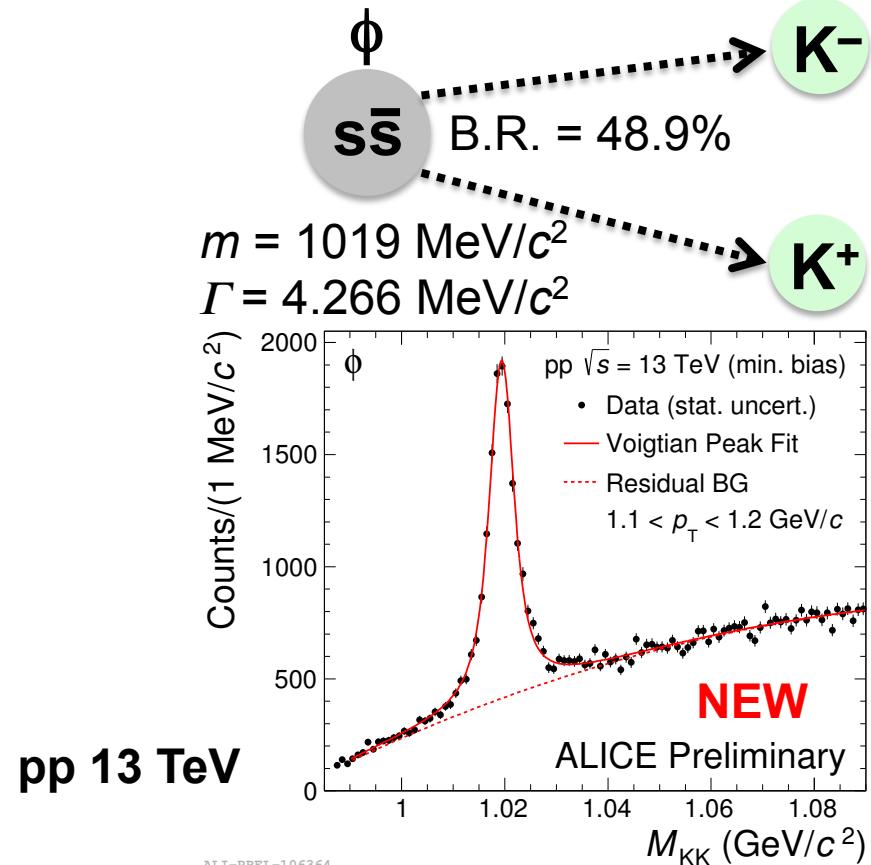
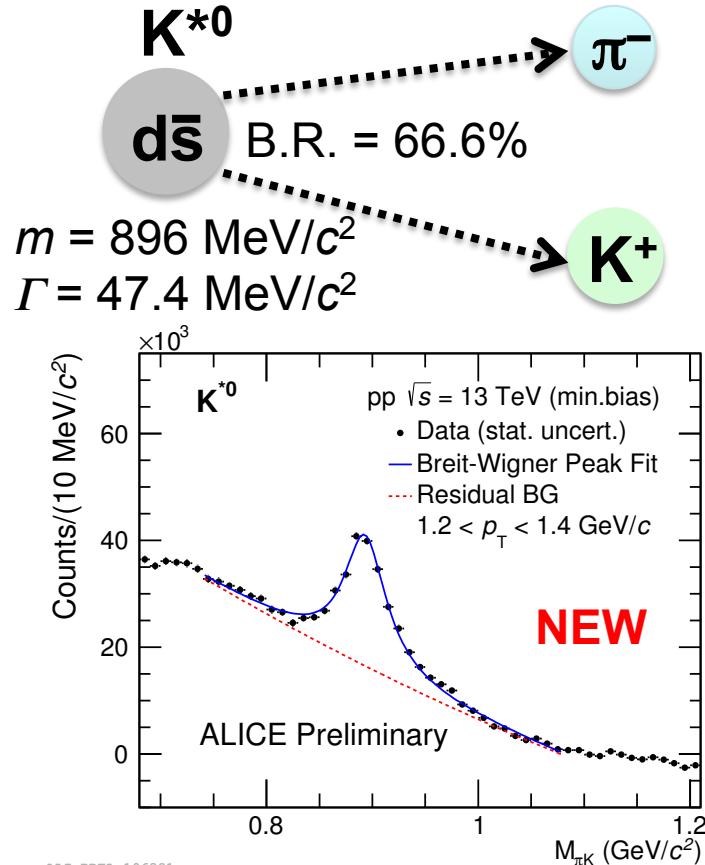
- **New measurements at 2.76 TeV**
- High  $p_T$ : consistent with light  $h^\pm$
- Consistent with other mesons over wider  $p_T$  range than p
- Distorted by radial flow and suppression at low  $p_T$

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



# $K^{*0}$ and $\phi$ Reconstruction

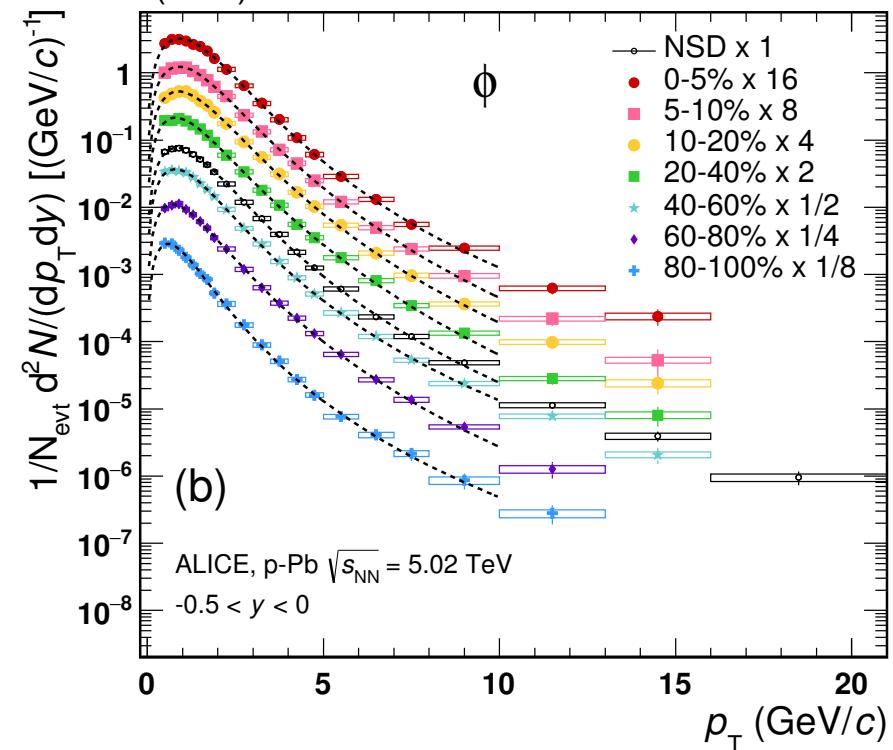
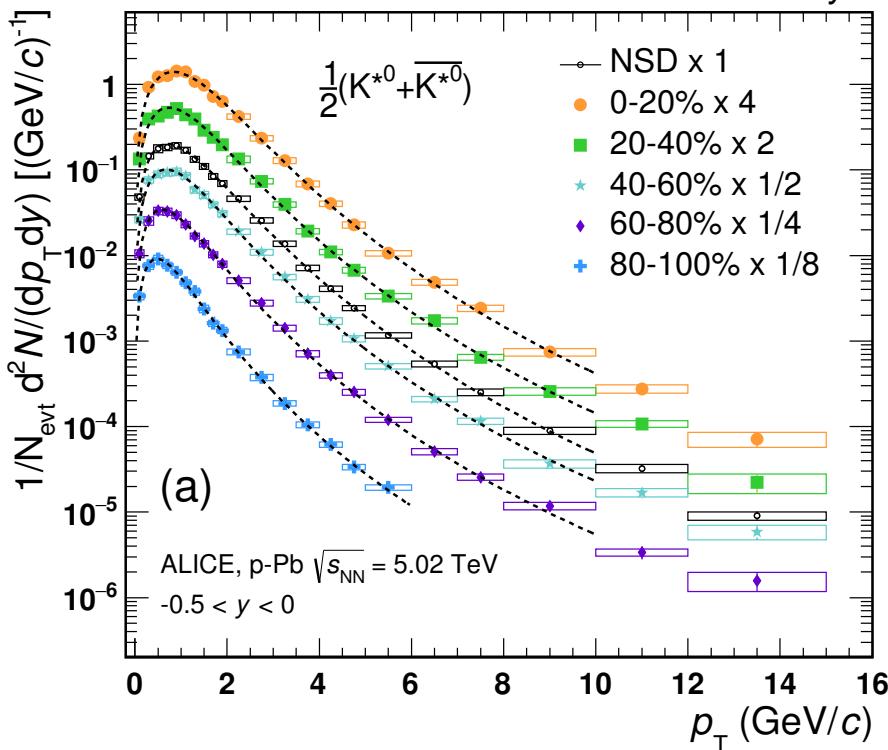
- Analyzed in pp collisions at 0.9, 7 (vs. multiplicity), 13 TeV; p–Pb collisions at 5.02 TeV; Pb–Pb collisions at 2.76 & 5.02 TeV
- Subtract mixed-event or like-charge combinatorial backgrounds
- Polynomial residual background
- Peaks: Breit-Wigner ( $K^{*0}$ ) or Voigtian ( $\phi$ )



# $K^{*0}$ and $\phi$ Reconstruction

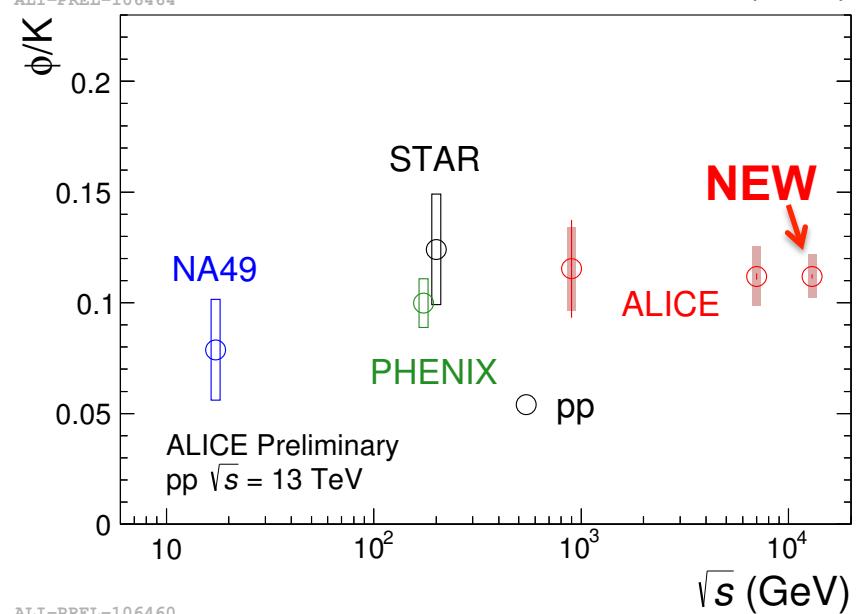
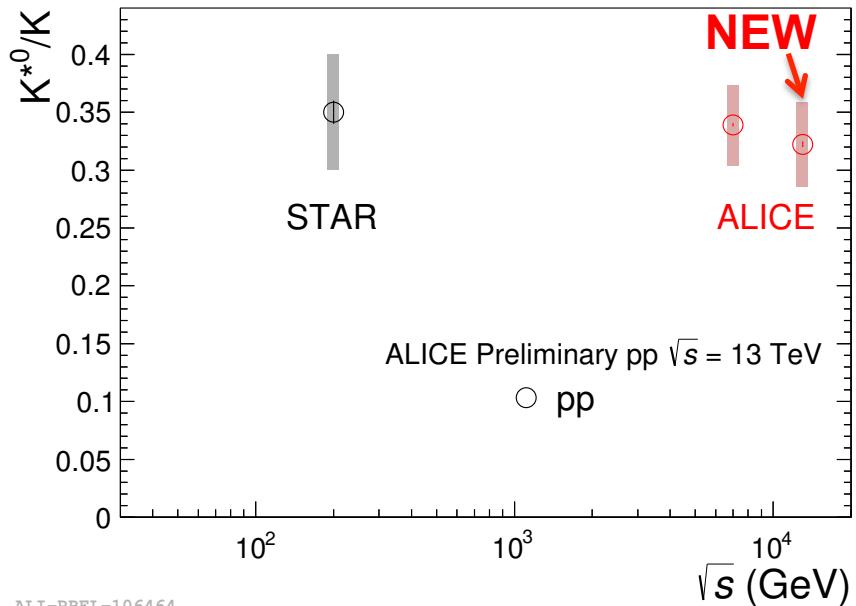
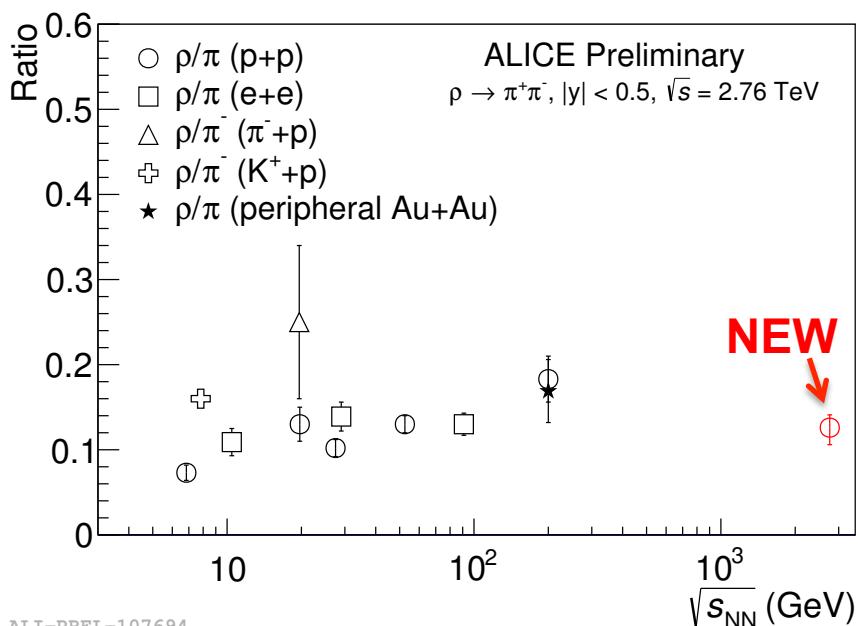
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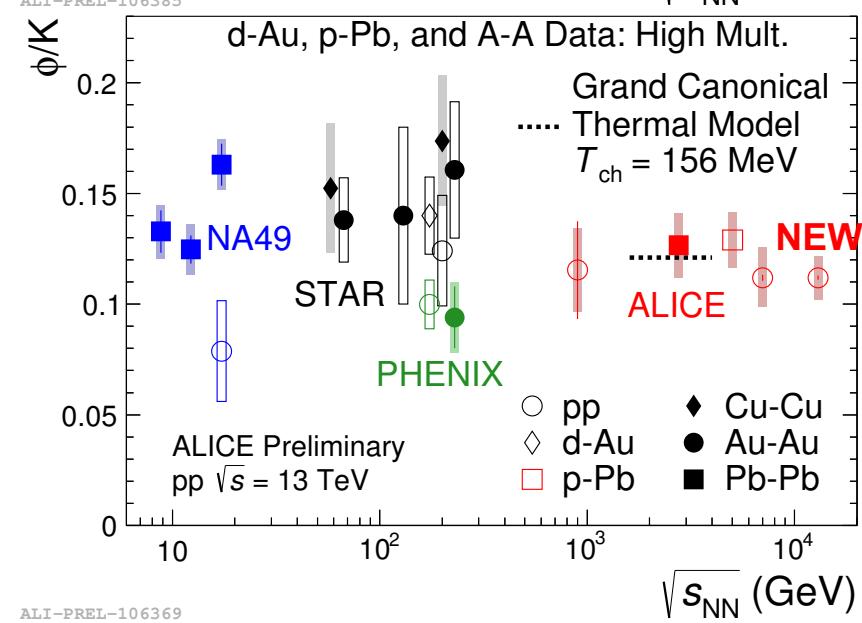
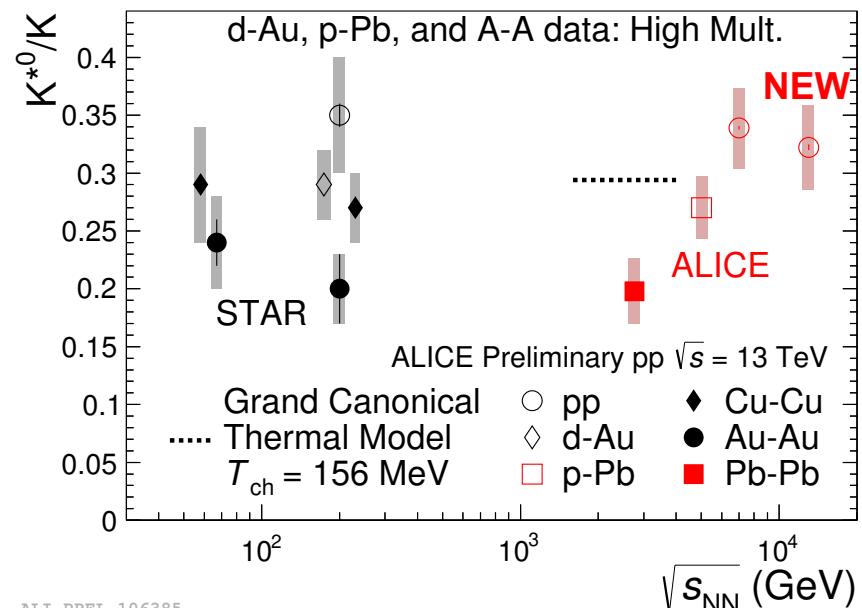
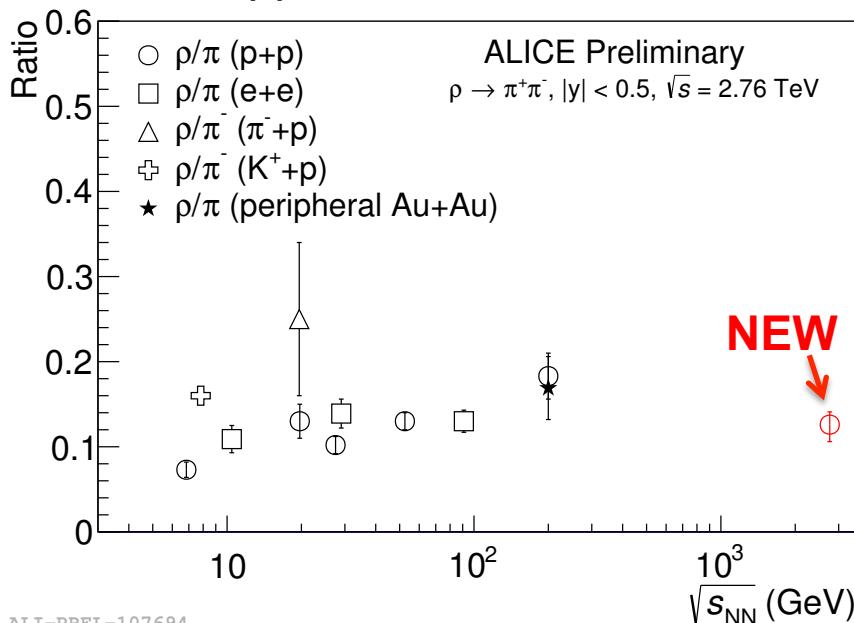
# Ratios to Stable Hadrons (pp) <sup>Knospe</sup>

- Ratios in pp: **new ALICE**  
measurements of  $\rho^0/\pi$  at 2.76 TeV,  
 $K^{*0}/K$  and  $\phi/K$  at 13 TeV:  
  - No energy dependence through  
2-3 orders of magnitude



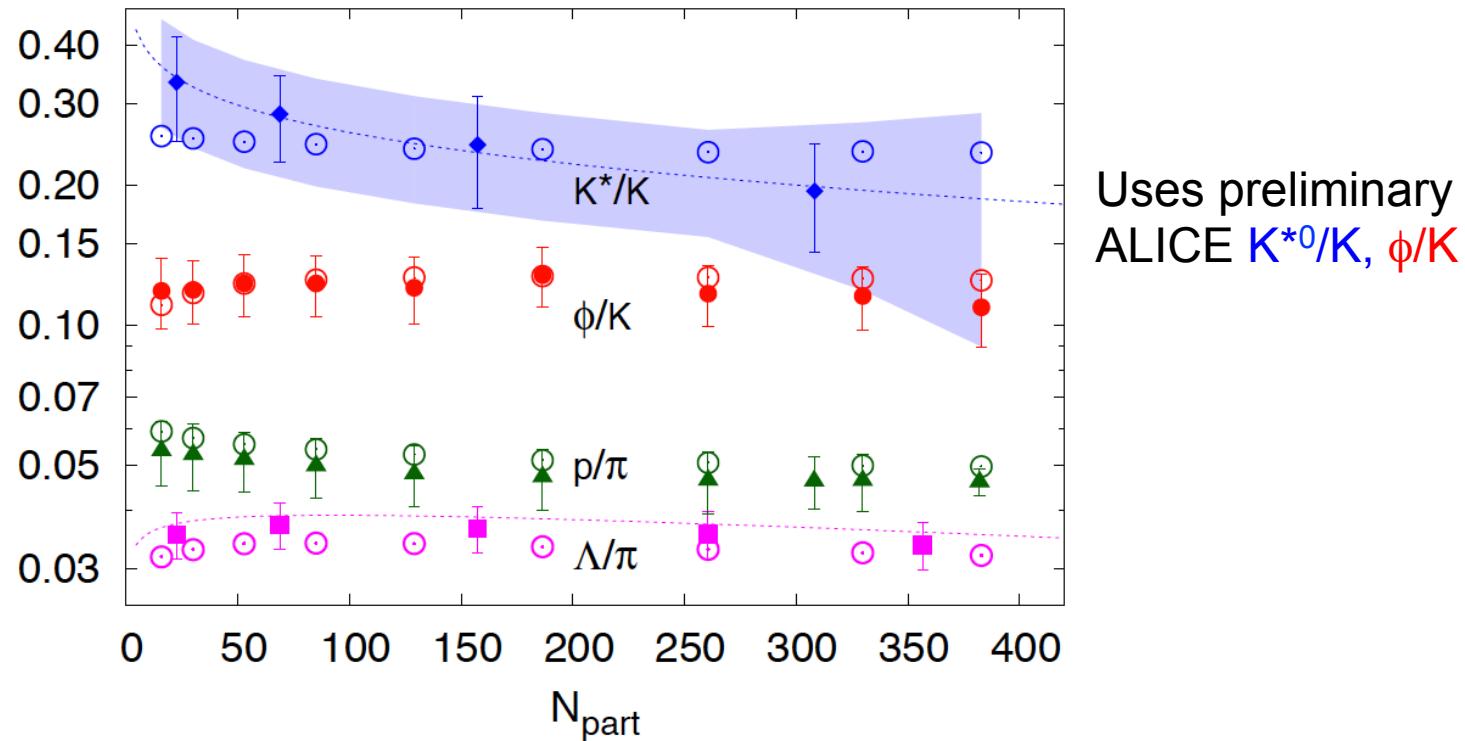
# Ratios to Stable Hadrons

- Ratios in pp: new ALICE measurements of  $\rho^0/\pi$  at 2.76 TeV,  $K^{*0}/K$  and  $\phi/K$  at 13 TeV:
  - No energy dependence through 2-3 orders of magnitude
- Ratios in larger collision systems:
  - No clear dependence of  $\phi/K$  on energy or system size at RHIC and LHC
  - Suppression of  $K^{*0}/K$  observed...



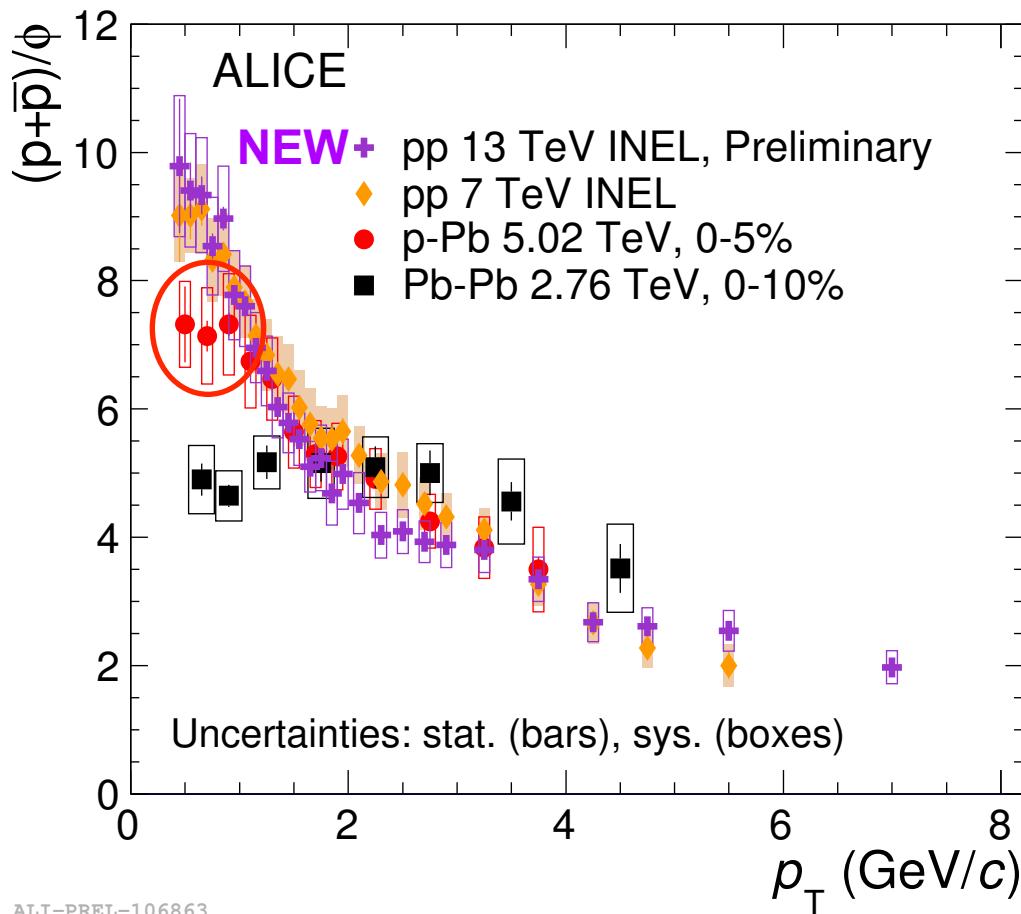
# Non-equilibrium Model

- Chemical non-equilibrium statistical hadronization model
  - Phys. Rev. C* **88**, 034907 (2013)
- Factors  $\gamma_q \neq 1$  and  $\gamma_s \neq 1$  that modify u/d and s pair yields w.r.t. equilibrium values
  - $\gamma_q \neq 1$  when "source of hadrons disintegrates faster than the time necessary to re-equilibrate the yield of light quarks present."
- Gives  $\sim$ flat  $K^*/K$  ratio, may be inconsistent with measured  $K^{*0}/K^-$



# p/φ Ratio vs. $p_T$

- **New measurement** in pp collisions at 13 TeV
- p/φ **flat for central collisions** for  $p_T < 3\text{-}4 \text{ GeV}/c$ 
  - Consistent with **hydrodynamic evolution**, some recombination models can also describe it
- p/φ in high-multiplicity p–Pb:
  - For  $p_T > 1 \text{ GeV}/c$ : similar to pp and peripheral Pb–Pb (not shown)
  - For  $p_T < 1 \text{ GeV}/c$ : decrease (flattening?) in p/φ: hint of onset of collective behavior in high-multiplicity p–Pb?

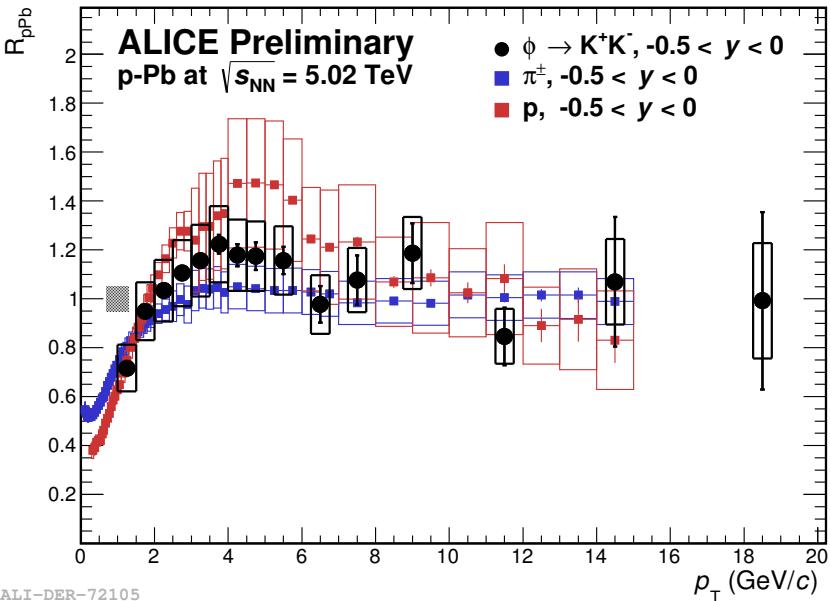
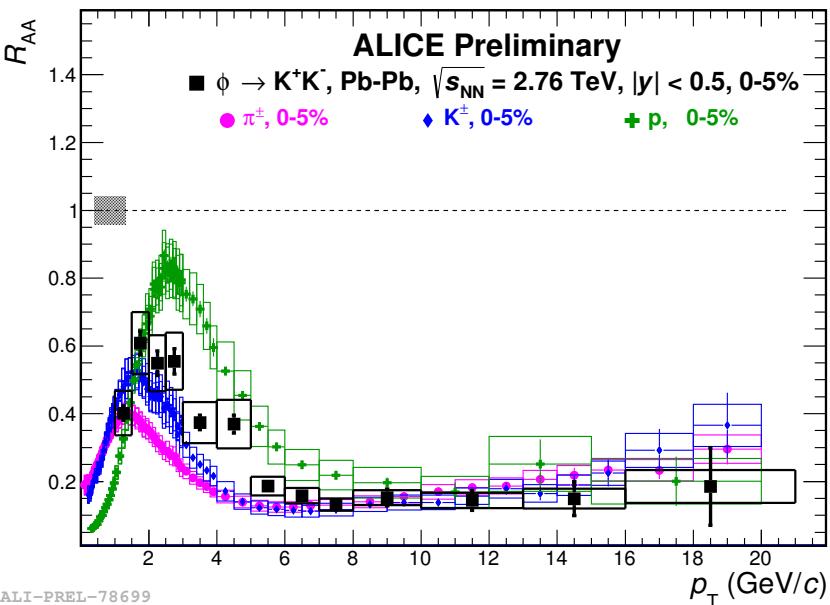


Phys. Rev. C **91** 024609 (2015)  
 Eur. Phys. J. C **76** 245 (2016)

# $\phi$ Nuclear Modification

- In Pb–Pb:
  - Shape differences between  $p$  and  $\phi$  due to differences in reference (pp) spectra
  - Strong suppression of all hadrons at high  $p_T$

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

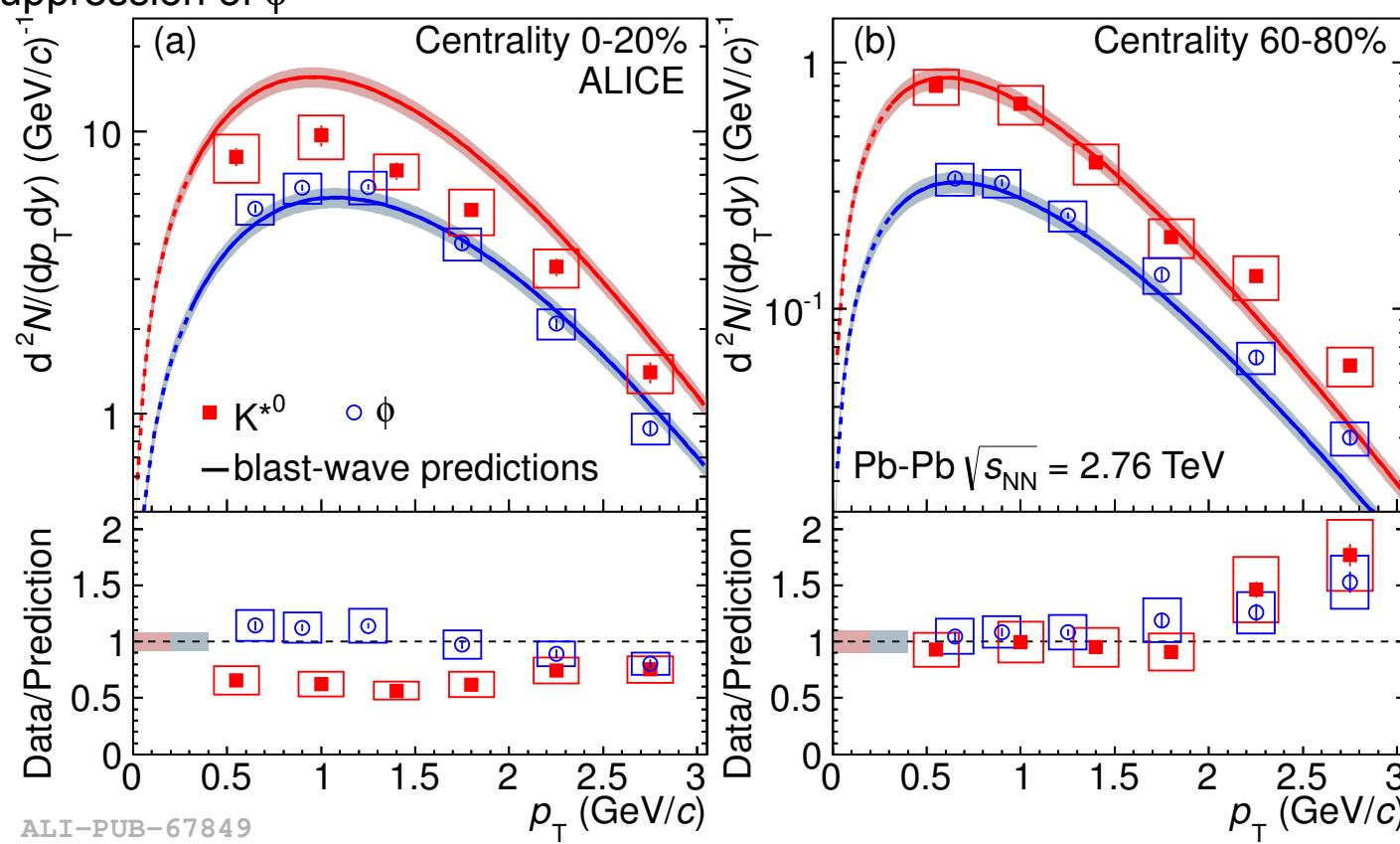


$R_{pPb}$

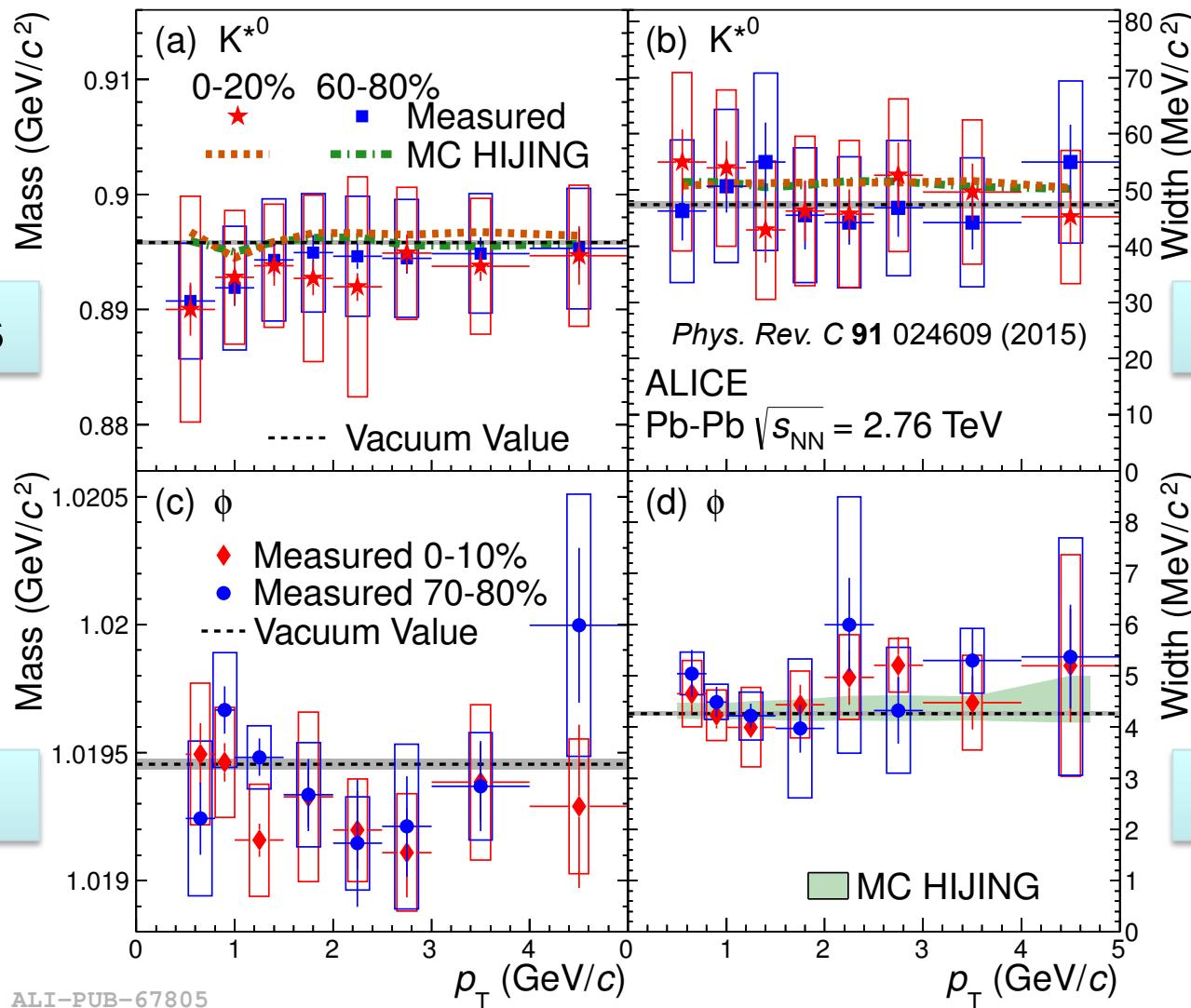
# Resonance Suppression

- Does  $K^{*0}$  suppression depend on  $p_T$ ? UrQMD: re-scattering strongest for  $p_T < 2 \text{ GeV}/c$ .
- Expected  $p_T$  distribution from blast-wave model:
  - Shape: parameters ( $T_{\text{kin}}$ ,  $n$ ,  $\beta$ ) from combined fits of  $\pi/K/p$  in Pb–Pb (\*)
  - Normalization: K yield  $\times K^{*0}/K$  ratio from thermal model ( $T_{\text{ch}} = 156 \text{ MeV}$ )
- Central:  $K^{*0}$  suppressed for  $p_T < 3 \text{ GeV}/c$ , but no strong  $p_T$  dependence
- Peripheral:  $K^{*0}$  not suppressed
- No suppression of  $\phi$

\*PRC 88 044910 (2013)



# Mass and Width (Pb–Pb)

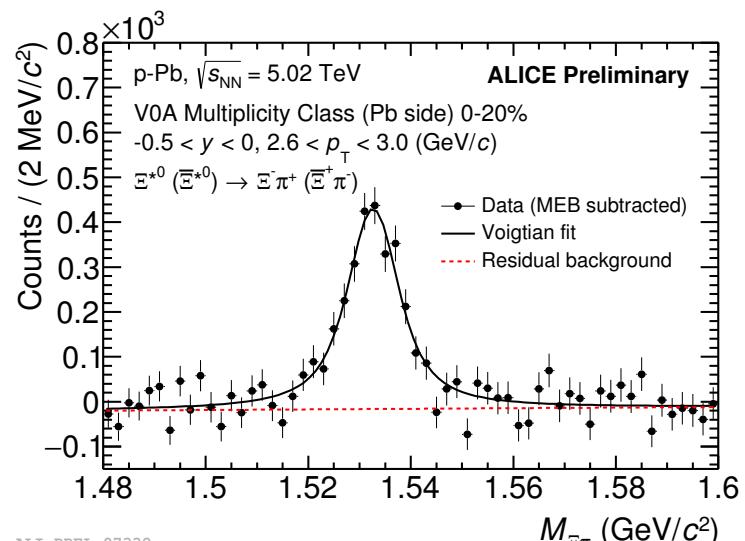
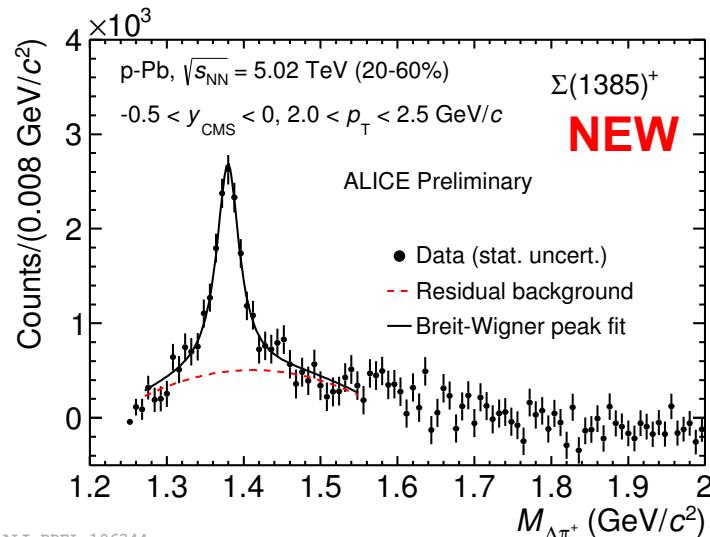
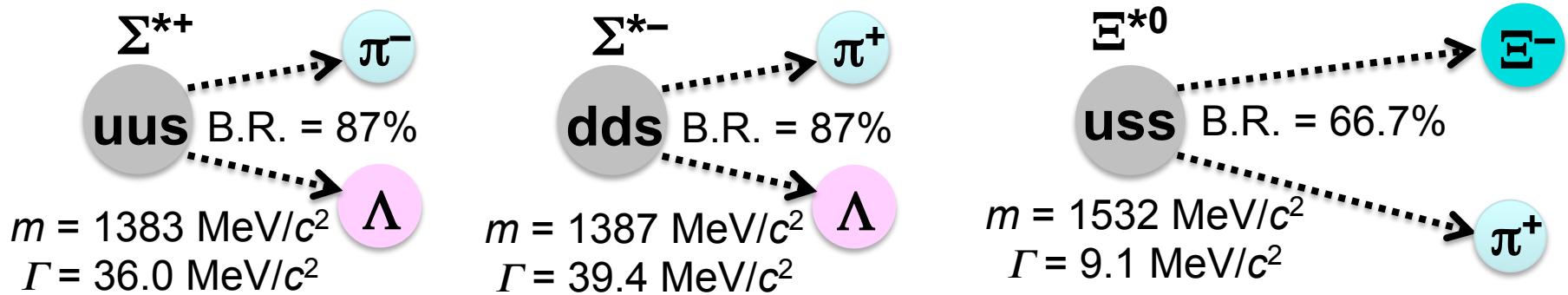
**K<sup>\*</sup>0 Mass** **$\phi$  Mass** **$\phi$  Width**

No significant mass or width shifts observed.  
No centrality dependence of mass or width.

ALI-PUB-67805

# $\Sigma^{*\pm}$ and $\Xi^{*0}$ Reconstruction

- Analyzed in pp collisions at 7 TeV & p–Pb collisions at 5.02 TeV (Pb–Pb collisions at 2.76 TeV in progress)
- Subtract mixed-event combinatorial background
- Polynomial residual background
- Peaks: Breit-Wigner ( $\Sigma^{*\pm}$ ) or Voigtian ( $\Xi^{*0}$ )



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