Resonances as Probes of Heavy-Ion Collisions at ALICE

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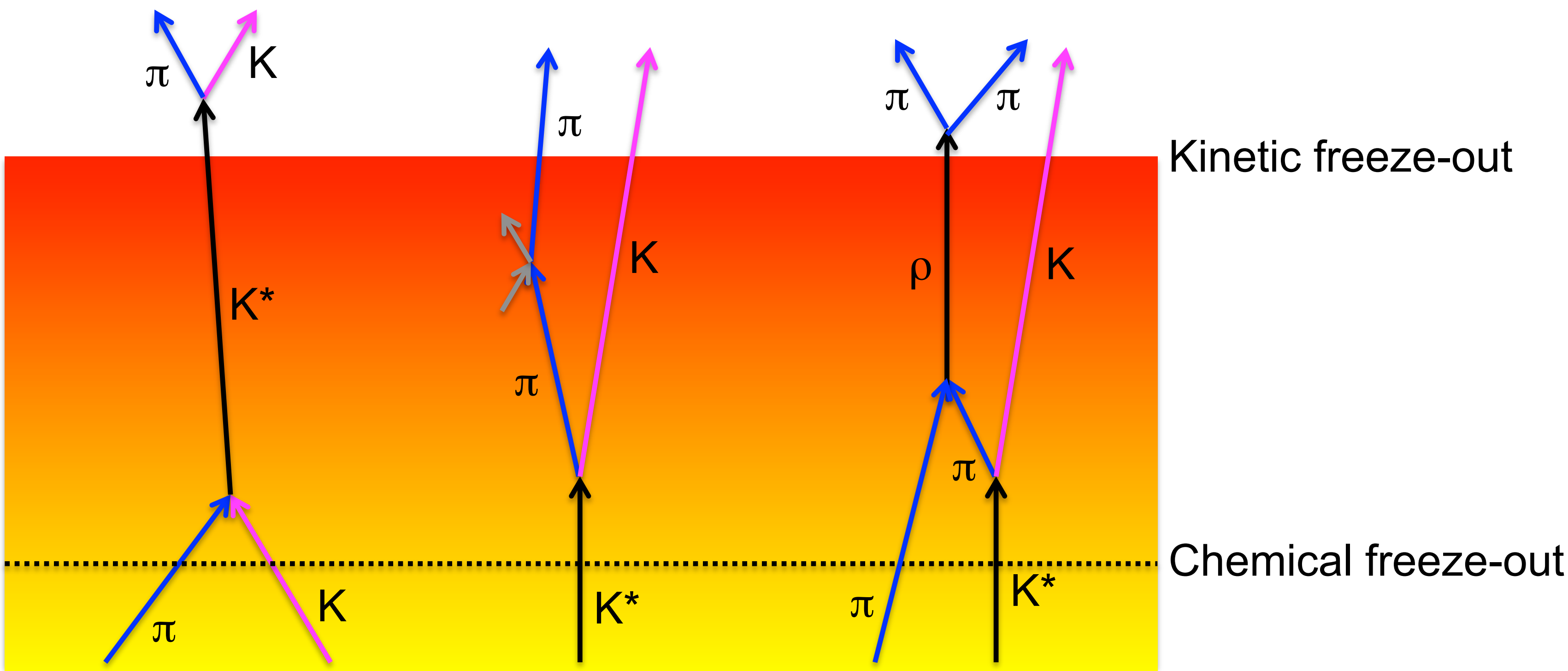
Introduction

- pp and p–Pb collisions:
  - Baseline measurements for heavy-ion collisions
  - R_{pPb}: System size dependence and cold nuclear matter effects
- Chiral Symmetry Restoration:
  - expect mass shift and width broadening for those resonances that decay when chiral symmetry restored
- Particle Production Mechanisms:
  - Hydrodynamics: particle masses determine shapes of p_{T} spectra
  - Recombination: baryon/meson differences in shapes of p_{T} spectra
- In-Medium Energy Loss:
  - R_{AA}: Study Nuclear Modification Factor (flavor dependence)
- Properties of Hadronic Phase…

Hadronic Phase

- Reconstructible resonance yields affected by hadronic processes after chemical freeze-out:
  - **Regeneration:** pseudo-elastic scattering of decay products
    - e.g., $\pi K \rightarrow K^* \rightarrow \pi K$
  - **Re-scattering:**
    - Resonance decay products undergo elastic scattering
    - Or pseudo-elastic scattering through a different resonance (e.g. ρ)
    - Resonance not reconstructed through invariant mass



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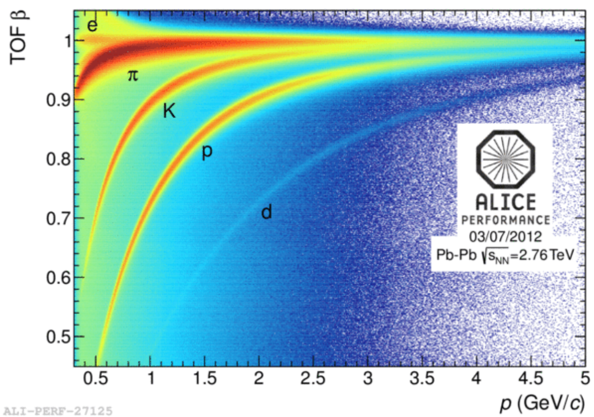
- Final yields at kinetic freeze-out depend on
  - Chemical freeze-out temperature
  - Time between chemical and kinetic freeze-out
  - Resonance lifetime
- Re-scattering and regeneration expected to be most important for $p_T < 2$ GeV/c (UrQMD)

ALICE Detector

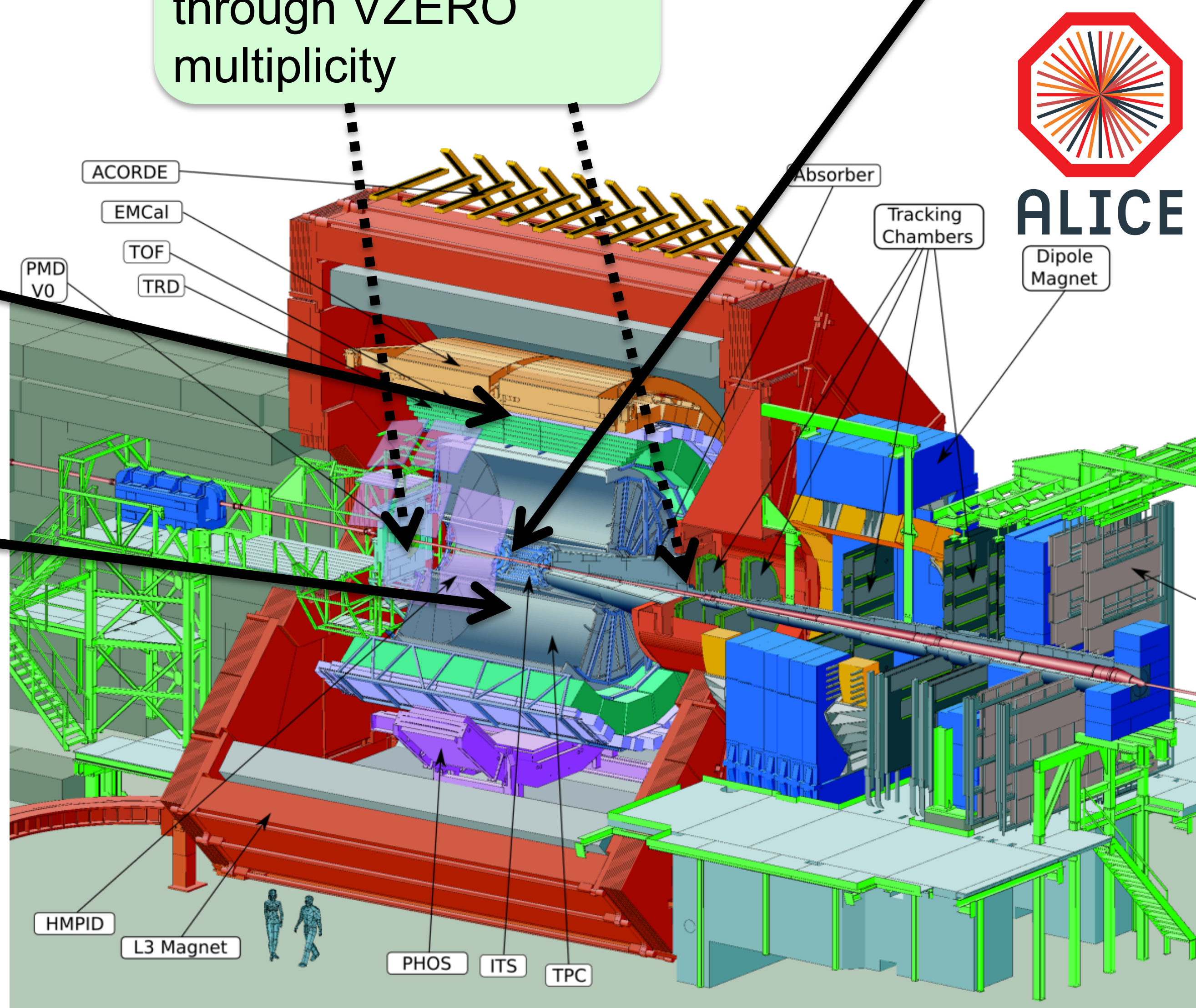


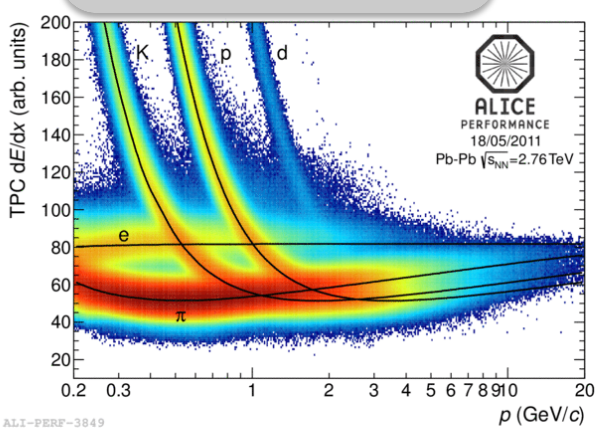
TOF: PID through particle time of flight

VZERO (scintillators): centrality estimate through VZERO multiplicity

ITS (silicon): Tracking and Vertexing

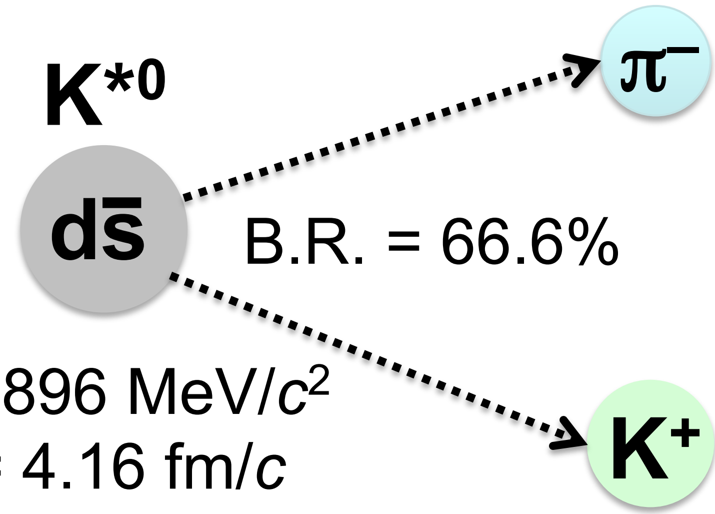
TPC: Tracking and PID through d*E*/dx



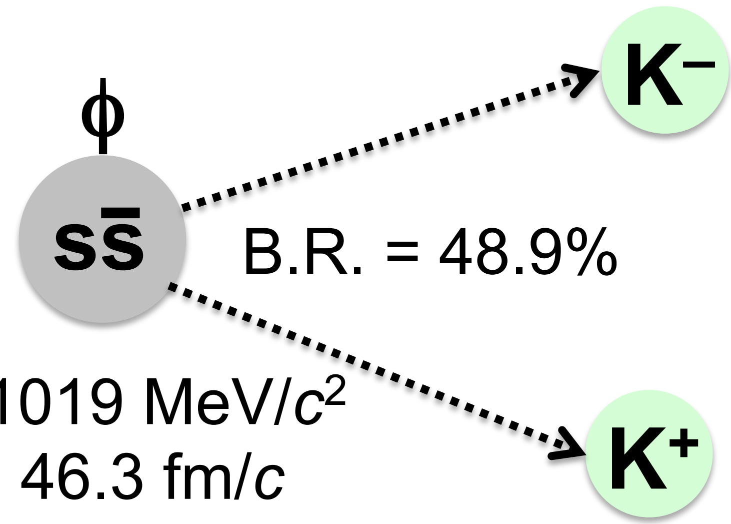


Resonance Reconstruction

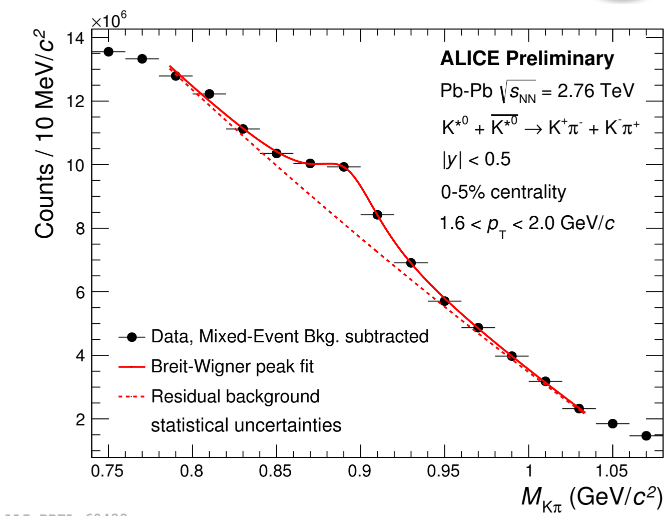
- Invariant-mass reconstruction through hadronic decays
- Resonances measured in pp (0.9, 2.76, 7 TeV) , p–Pb (5.02 TeV), and Pb–Pb (2.76 TeV) collisions

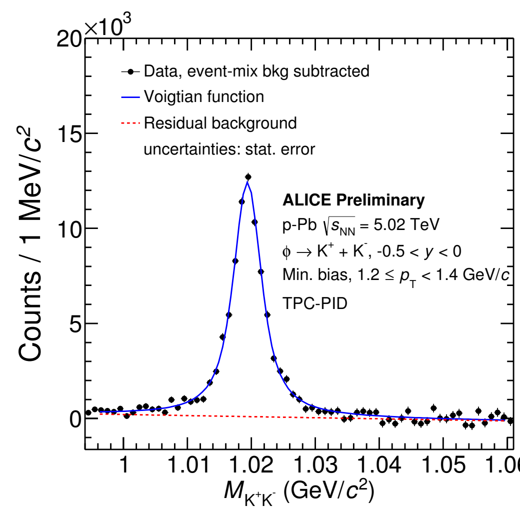


m = 896 MeV/c^2
τ = 4.16 fm/c



m = 1019 MeV/c^2
τ = 46.3 fm/c





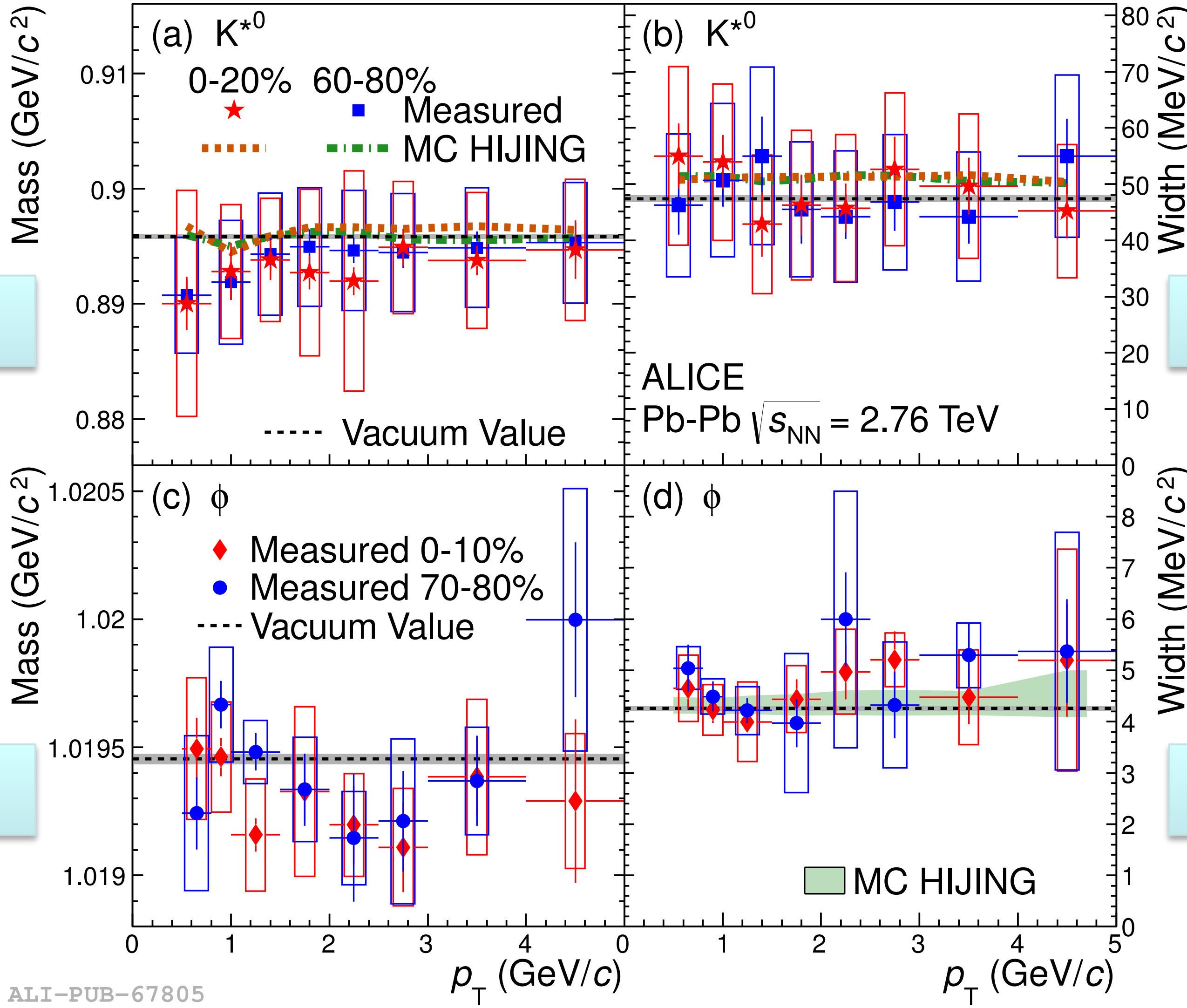
Mass and Width (Pb–Pb)

K*0 Mass

K*0 Width

ϕ Mass

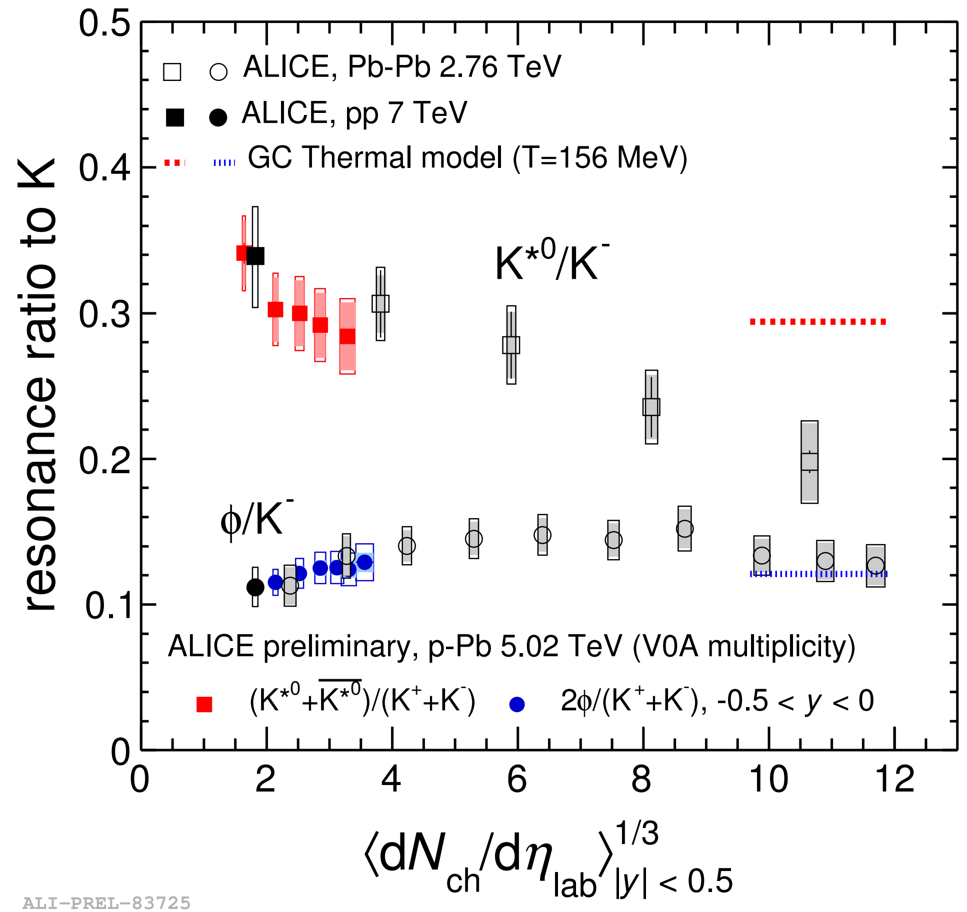
ϕ Width



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

Ratios of Yields

- K^{*0}/K
  - In Pb–Pb: strongly suppressed in central collisions w.r.t. peripheral, pp, p–Pb, or thermal model
  - Consistent with the hypothesis that re-scattering is dominant over regeneration
- ϕ/K
  - No strong dependence on centrality or collision system
  - ϕ lifetime ~10× longer than K^{*0}, re-scattering effects not significant
  - Ratio for central Pb–Pb consistent with thermal model
- Ratios in p–Pb consistent with trend from pp to peripheral Pb–Pb

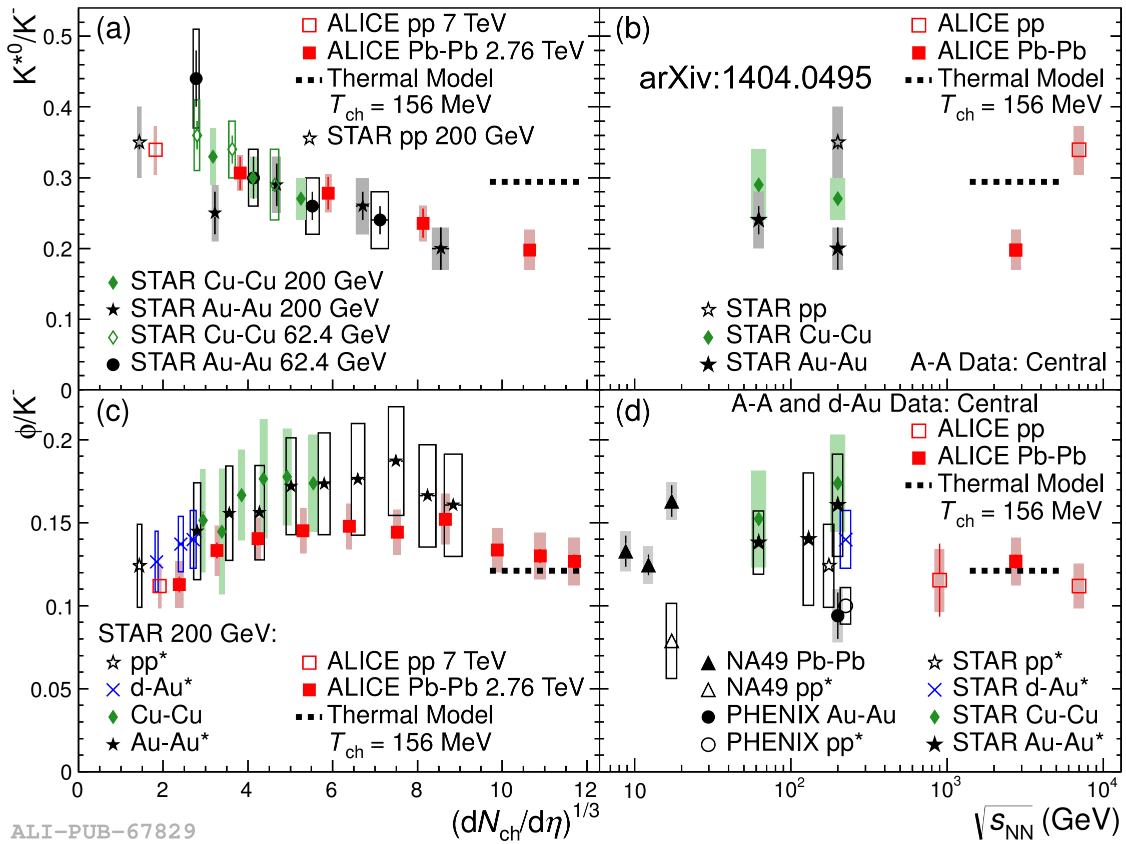


Plotted as function of $(dN_{ch}/d\eta)^{1/3}$, proxy for system radius

References:
pp: *EPJC* **72** 2183 (2012)
Pb–Pb: arXiv:1404.0495 (2014)
Thermal Model: J. Stachel *et al.*, SQM 2013

Ratios of Yields

- K^{*0}/K
  - Values appear to follow same trend for both RHIC and LHC
  - Similar suppression of signal between pp and central A–A
- ϕ/K
  - Similar shapes in RHIC Au–Au and LHC Pb–Pb. Au–Au values tend to be larger than Pb–Pb, but consistent within uncertainties.
  - Ratio in d–Au fits into trend between pp and Au–Au (*cf.* p–Pb at LHC)
  - No strong energy or collision-system dependence between RHIC and LHC

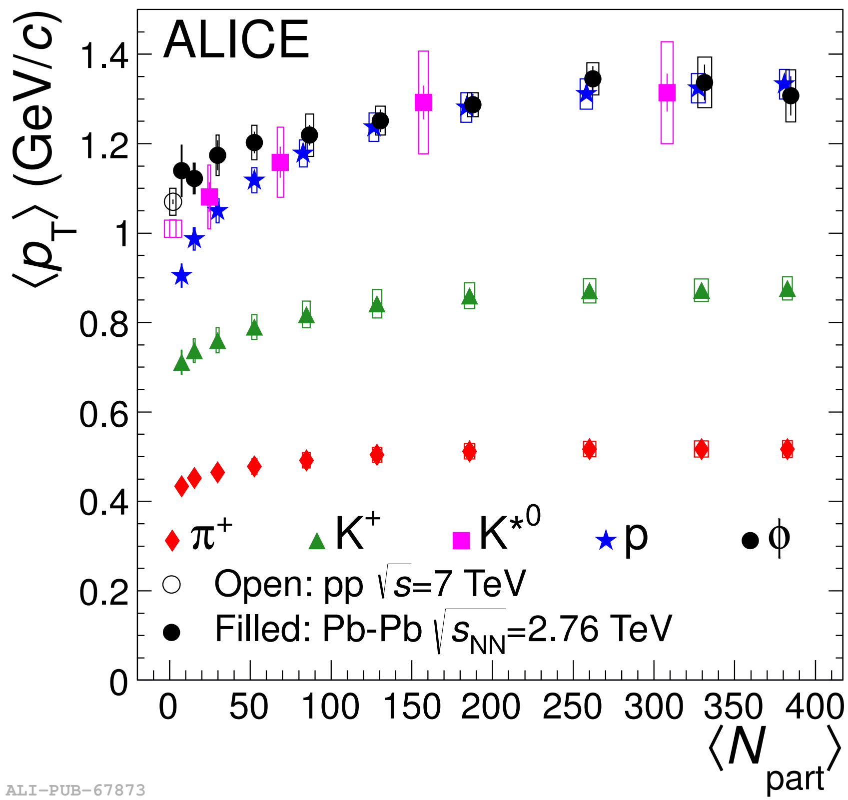


- Estimate hadronic phase lifetime*
  - Initial yields from thermal model
  - Predict effect of re-scattering on K^{*0}/K
  - Lower limit on lifetime: 2 fm/c

Phys. Rev. C **65**, 069902(E) (2002), arXiv:hep-ph/0206260v2 (2002)

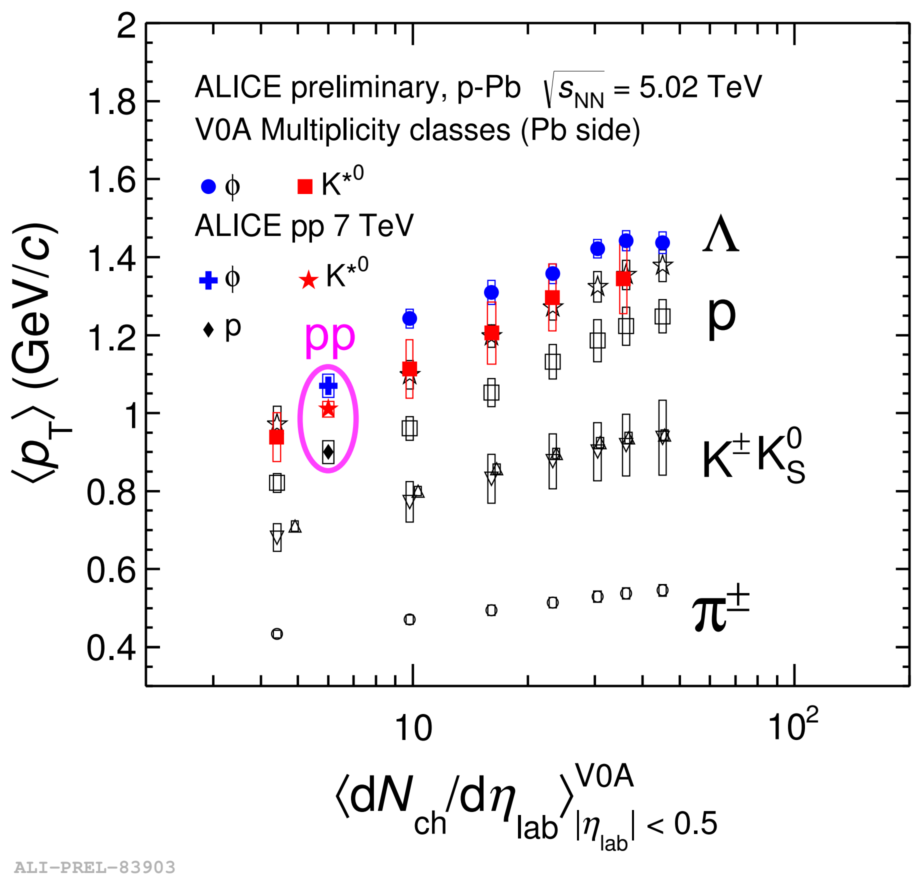
Mean p_T in Pb–Pb

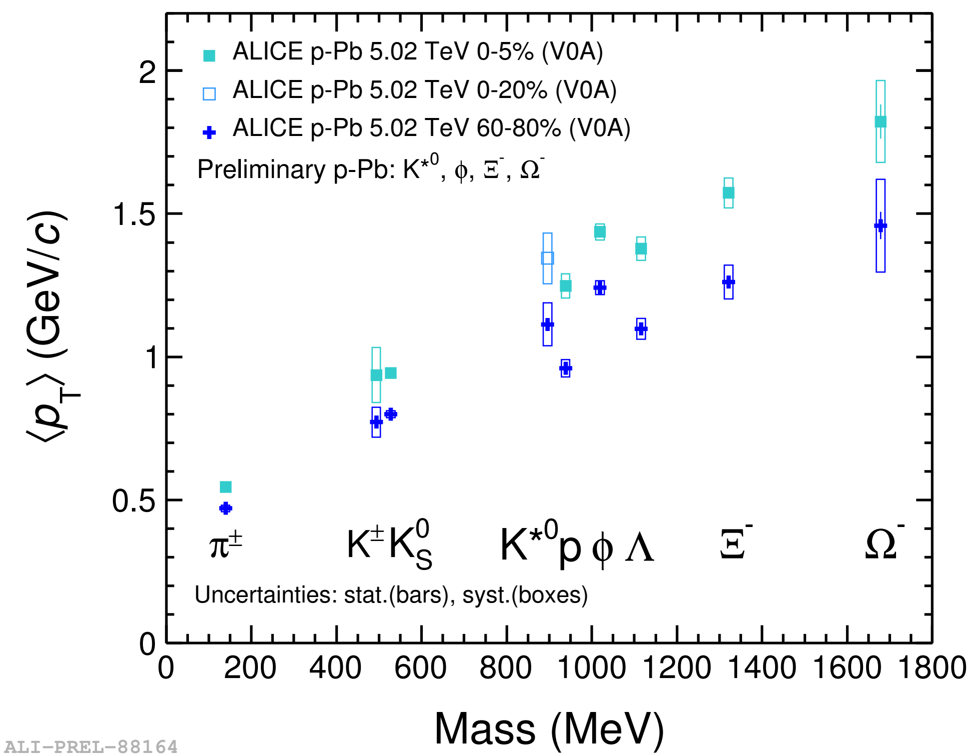
- Mass ordering of $<p_T>$ observed
- $<p_T>$ of K^{*0}, p, and ϕ is similar for central Pb–Pb
  - Consistent with hydrodynamics
- $<p_T>$ splitting between p and ϕ for peripheral Pb–Pb
- Increase in $<p_T>$ from peripheral to central:
  - For $\pi^{\pm}$, $K^{\pm}$, K^{*0}, and ϕ: ~20% – For p: ~50%



Mean p_T in p–Pb

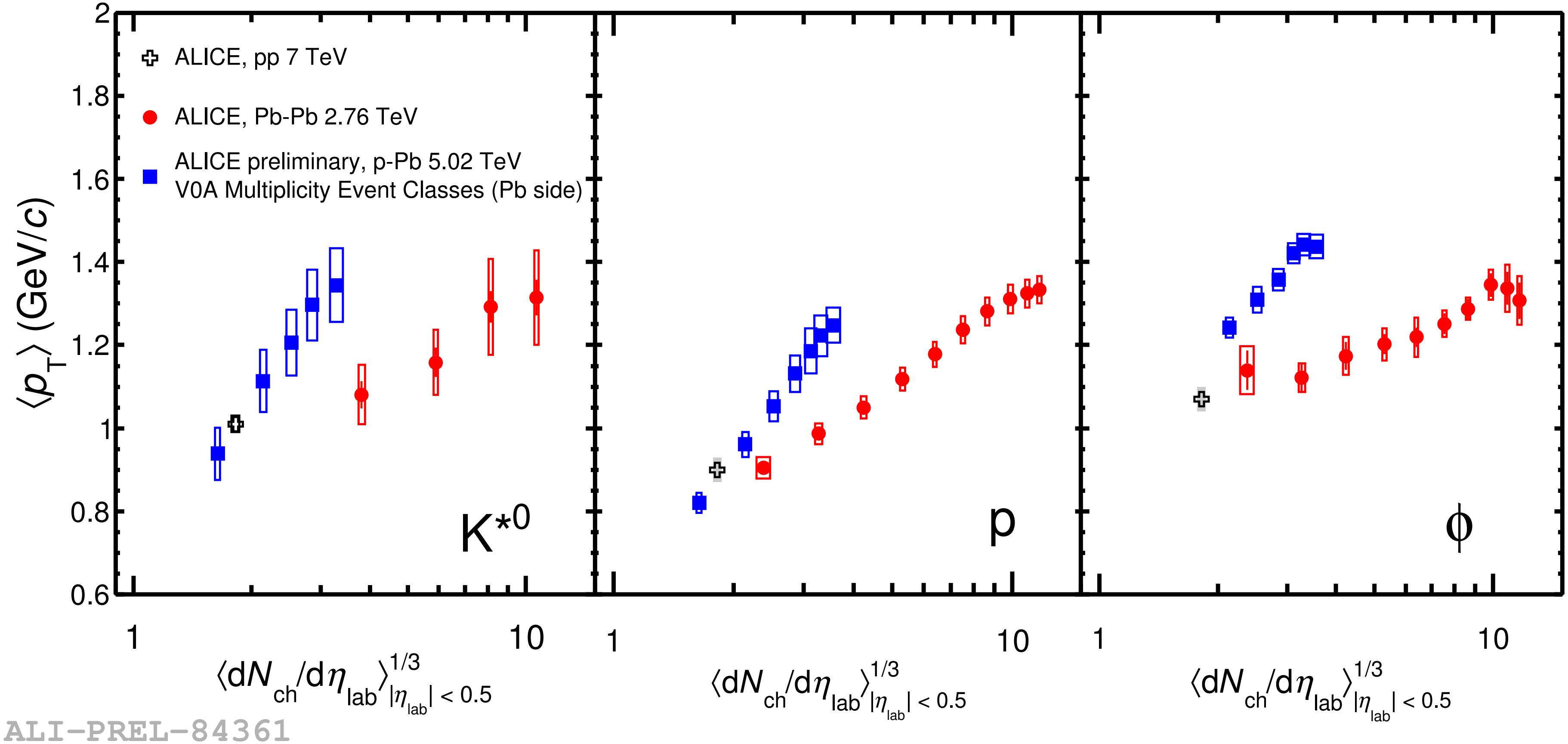
- Approximate mass ordering in $<p_T>$
  - But $<p_T>$ of K^{*0} and ϕ greater than p and Λ
  - Is there a baryon/meson difference, or do resonances not obey mass ordering?
  - Same trend observed in pp





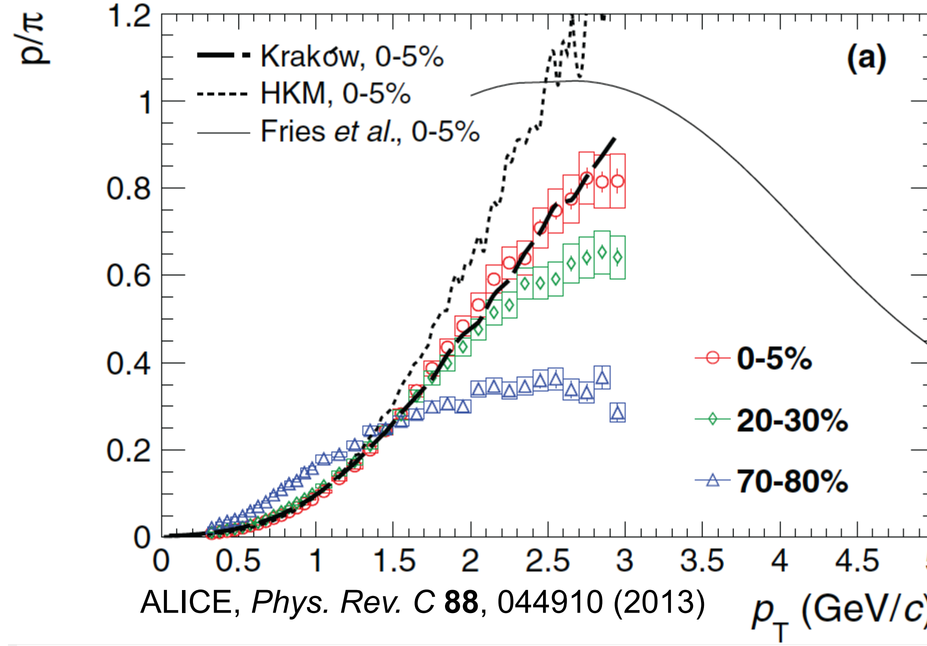
Mean p_T

- High-multiplicity p–Pb reaches similar $\langle p_T \rangle$ values as central Pb–Pb
- $\langle p_T \rangle$ in p–Pb increases more rapidly than Pb–Pb as a function of multiplicity
- Differences in $\langle p_T \rangle$ due to difference in particle production mechanisms? Harder scattering in p–Pb? (*PLB* **727** 371–380 (2013))

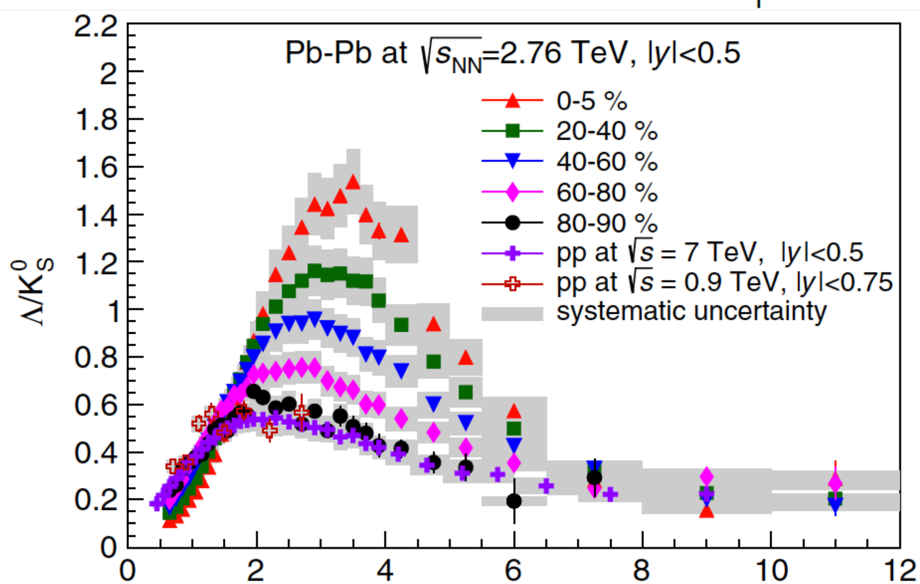


Particle Production

- p/π and Λ/K^0_S vs. p_T from :
- What causes the shape of these ratios?
  - Particle masses (hydro)?
  - Quark content/baryon vs. meson (recombination)?
- To test: need a meson with a mass similar to the proton:
  - Nature has given us such a meson: ϕ



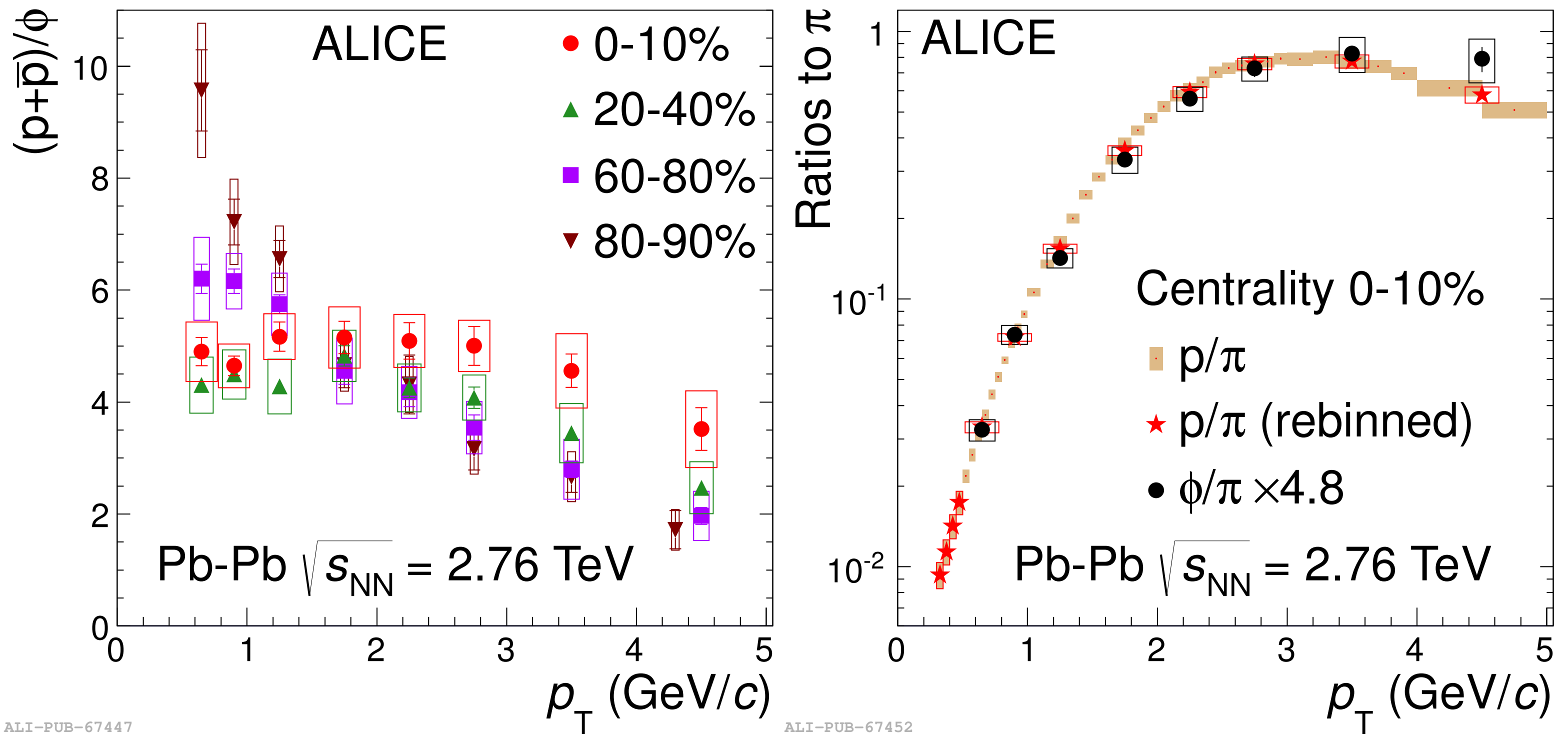
ALICE, *Phys. Rev. C* **88**, 044910 (2013)



ALICE, *Phys. Rev. Lett* **111**, 222301 (2013)

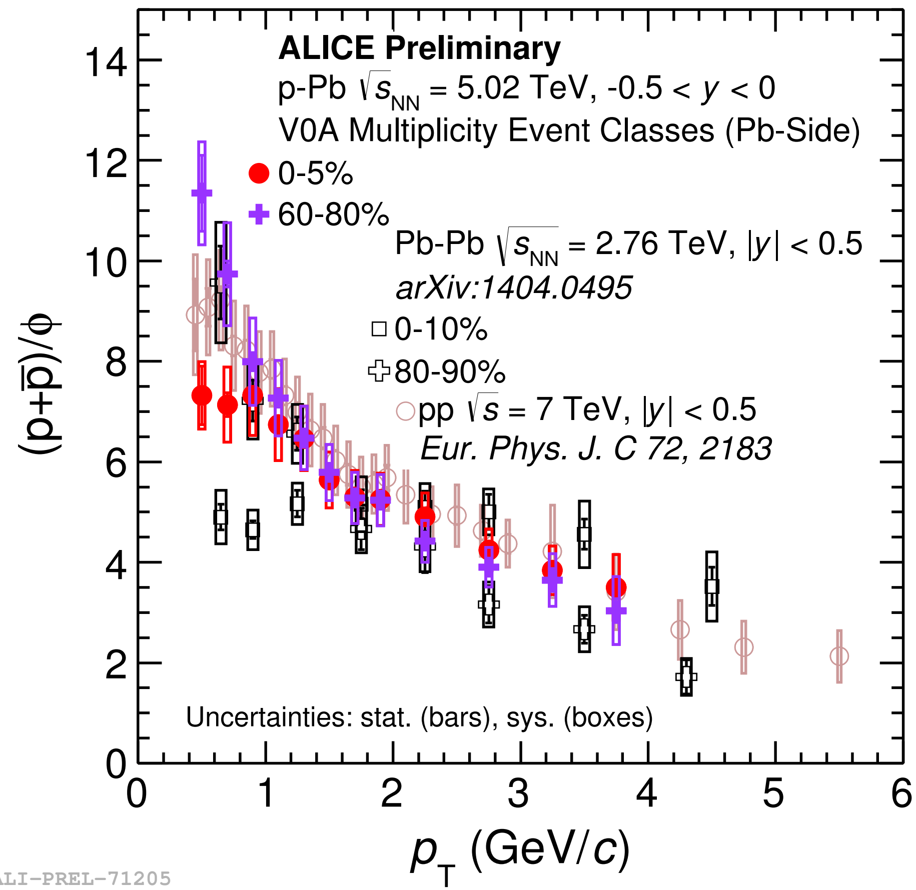
p/φ vs. p_T in Pb–Pb

- p/φ flat for central collisions for p_T < 3-4 GeV/*c*
  - Baryon/meson difference goes away if the two particles have the same mass. Consistent with hydrodynamical production
- Increasing slope for peripheral collisions
- Peripheral Pb–Pb similar to pp (7 TeV)
- Same trend seen in <p_T> (p and φ different for peripheral Pb–Pb)
- Different production mechanism for p, φ in central vs. peripheral, pp?



p/ϕ vs. p_T in p–Pb

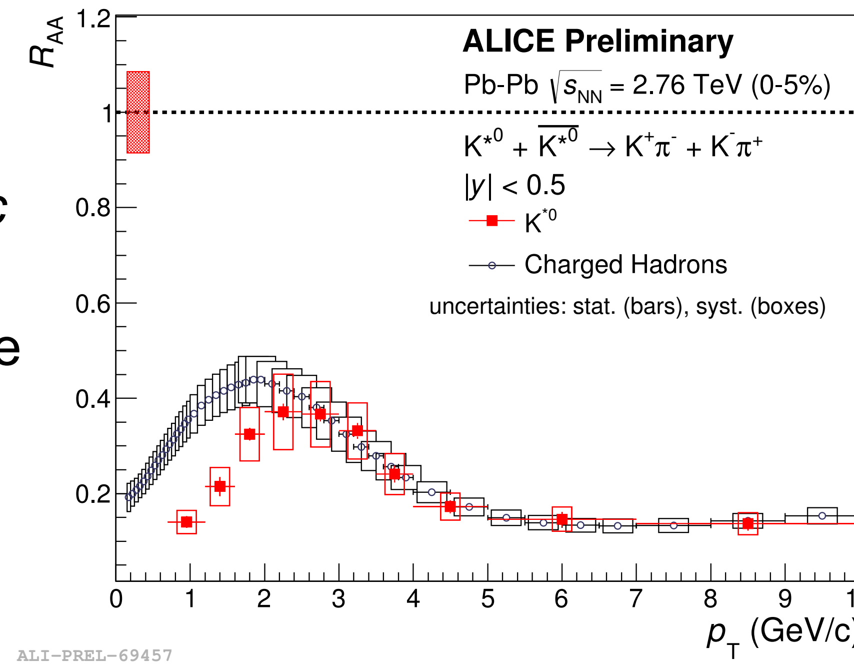
- p/ϕ in low-multiplicity p–Pb similar to peripheral Pb–Pb and pp
- For p_T > 1 GeV/c: no multiplicity dependence in p–Pb
- For p_T < 1 GeV/c: decrease of p/ϕ for high-multiplicity
  - Possible flattening of ratio: hint of onset of collective behavior in high-multiplicity p–Pb?

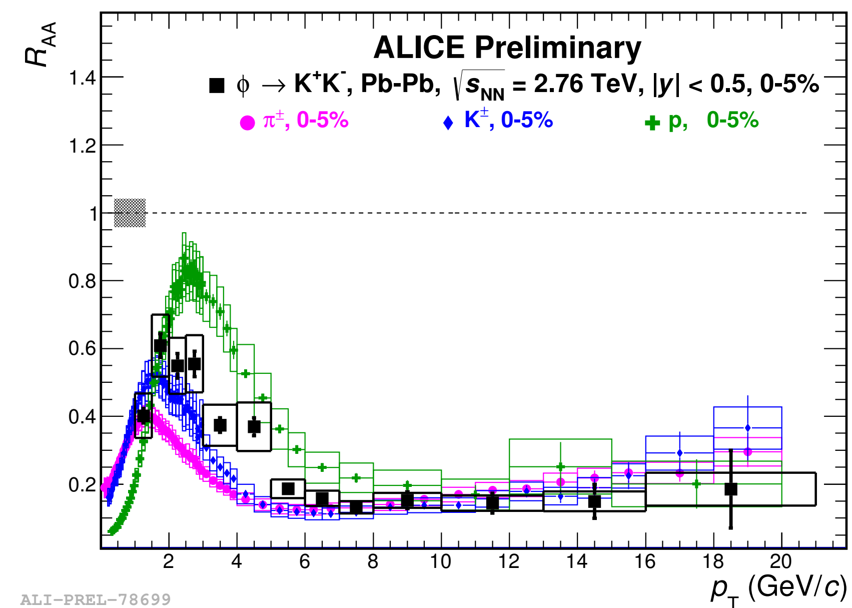


Nuclear Modification Factors

- In Pb–Pb:
  - More suppression of K^{*0} than of charged hadrons for p_T<2 GeV/c (consistent with re-scattering)
  - Differences between p and ϕ due to differences in reference (pp) spectra
  - Strong suppression of all hadrons at high p_T

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





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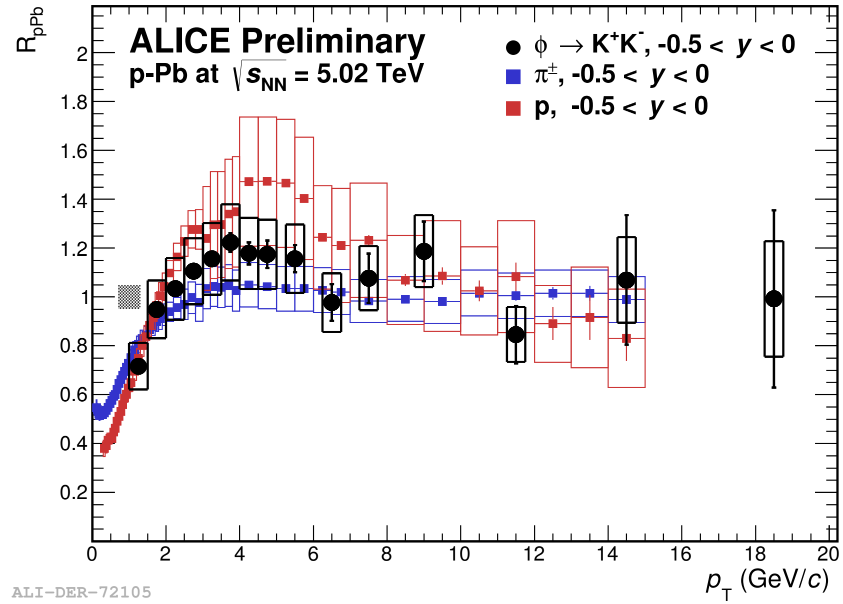
  - Differences between p and ϕ due to differences in reference (pp) spectra
  - Strong suppression of all hadrons at high p_T
- In p–Pb:
  - No suppression of ϕ w.r.t. pp for p_T > 1.5 GeV/c
  - Intermediate p_T: Cronin peak for p, smaller peak for ϕ
  - Possible mass dependence or baryon/meson differences in R_{pPb}



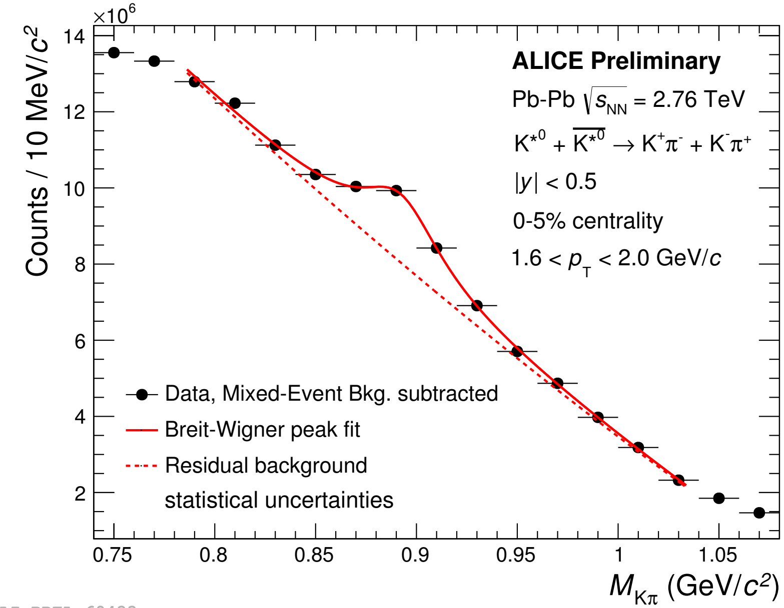
Conclusions

- Central Pb–Pb: K^{*0} suppressed (re-scattering) ϕ not suppressed (longer lifetime)
- K^{*0}/K and ϕ/K ratios in p–Pb follow trend from pp to peripheral Pb–Pb
- $\langle p_T \rangle$ in p–Pb and Pb–Pb follow different trends
- For central Pb–Pb: $\langle p_T(K^{*0}) \rangle \approx \langle p_T(p) \rangle \approx \langle p_T(\phi) \rangle$ (consistent with hydrodynamics)
- Mass ordering violated for pp, p–Pb, peripheral Pb–Pb: $\langle p_T(K^{*0},\phi) \rangle > \langle p_T(p,\Lambda) \rangle$
  - Baryon/meson difference?
- p/ϕ ratio flat vs. p_T for central Pb-Pb collisions (p_T<3-4 GeV/c)
  - consistent with hydrodynamics
- Hint of p/ϕ flattening at low p_T for high-multiplicity p–Pb: possible onset of collective effects?
- Nuclear Modification Factors:
  - High-p_T suppression observed in central Pb–Pb (R_{AA}) but not in p–Pb
  - High-p_T behavior of resonances similar to stable hadrons
  - Differences in p and ϕ R_{AA} due to reference (pp) spectra

Hot Quarks History

Backup Material

K^{*0} Peaks and Spectra



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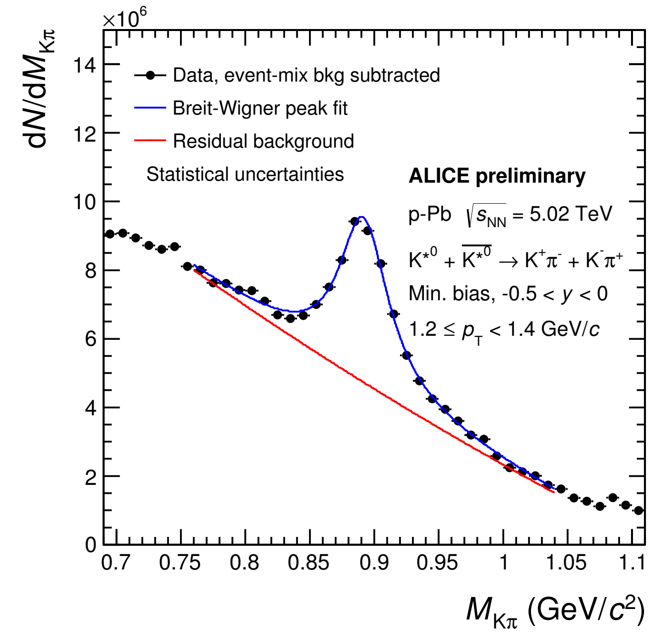
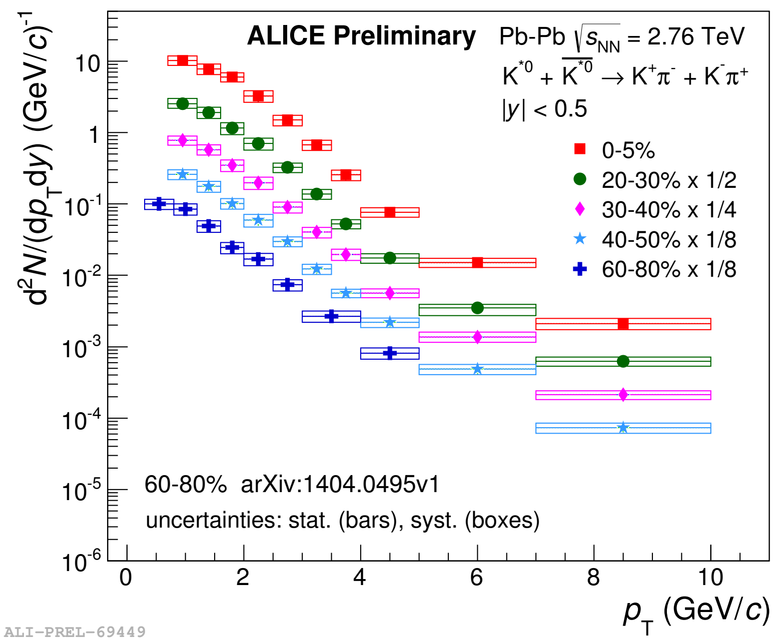
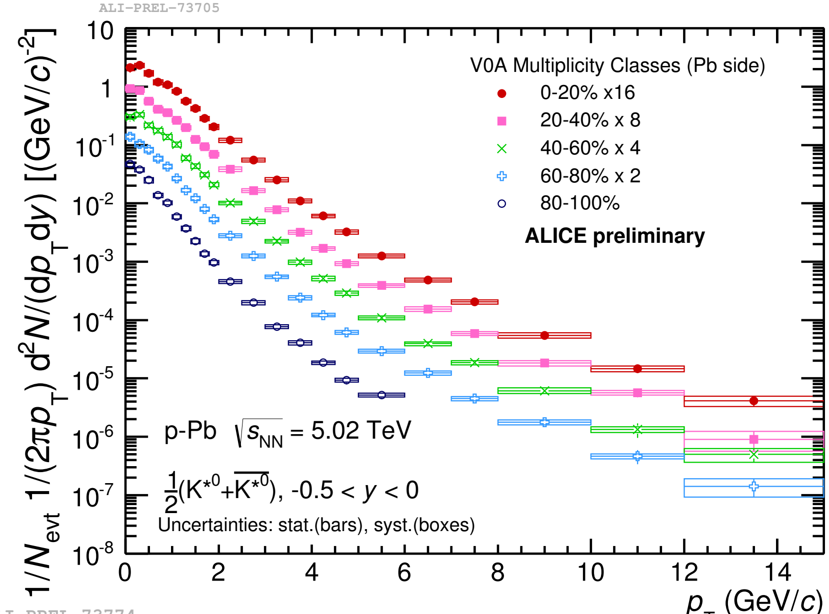


ALI-PREL-73705



ALI-PREL-69449



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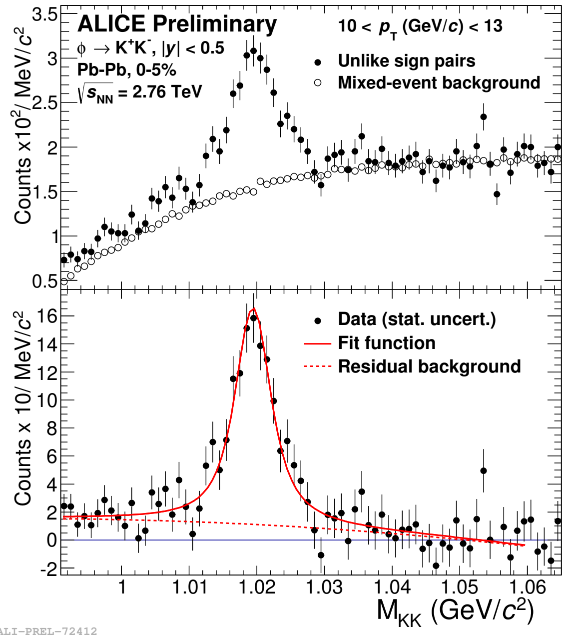
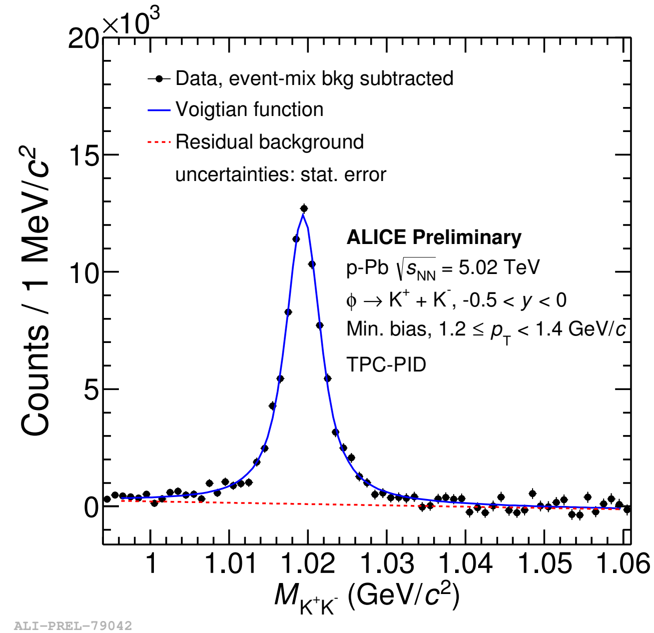
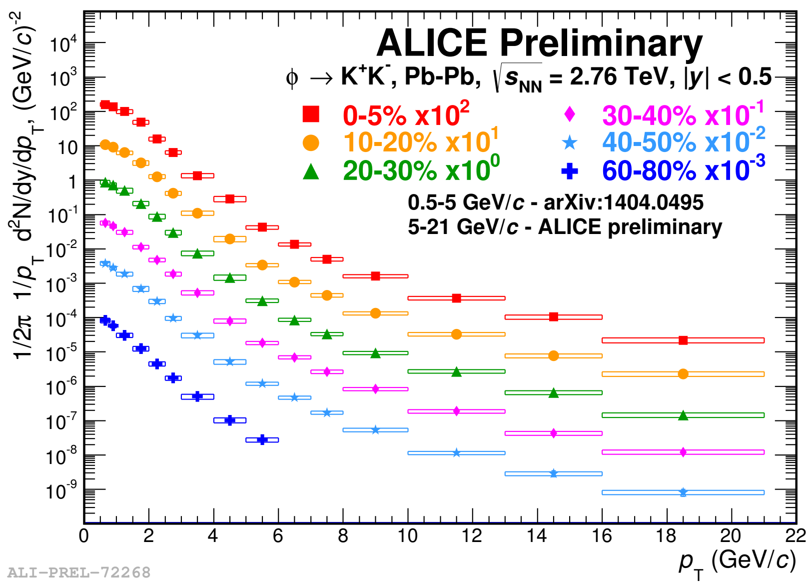
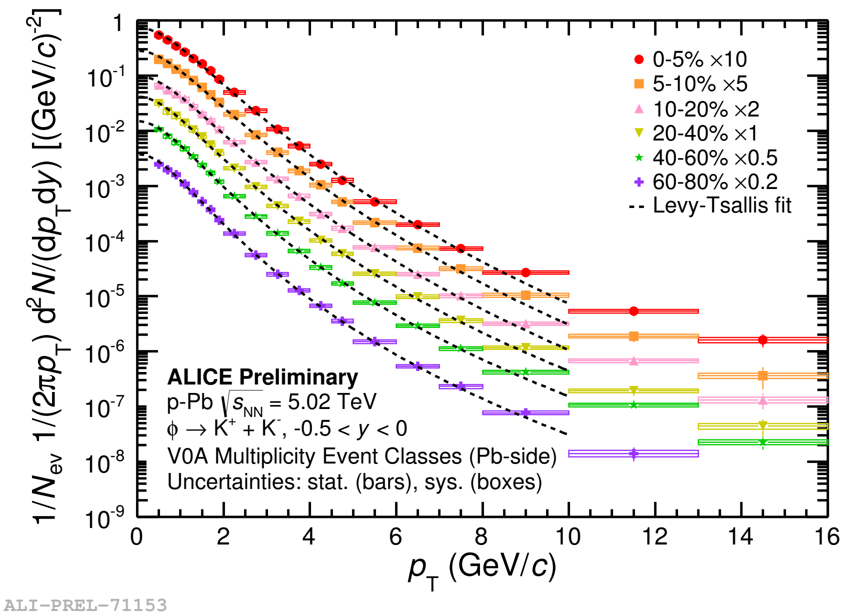
φ Peaks and Spectra







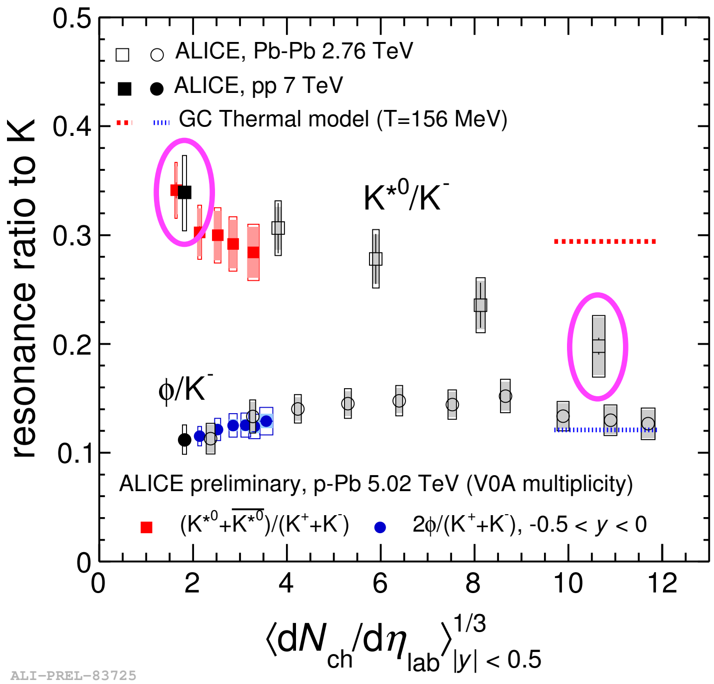


Properties of Hadronic Phase

- Simple model:
  - Assume that any K^{*0} that decays before kinetic freeze-out will be lost due to re-scattering, neglect regeneration, neglect lifetime increase due to time dilation
  - Simple exponential decrease in yield (τ = 4.16 fm/c) :

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

  - Take K^{*0}/K in pp as initial value, central Pb–Pb as final value: lifetime of hadronic phase would be Δt = 2.25 ± 0.75 fm/c
    - But since we neglect re-scattering and time dilation, treat this as a lower limit: Δt > 1.5 fm/c



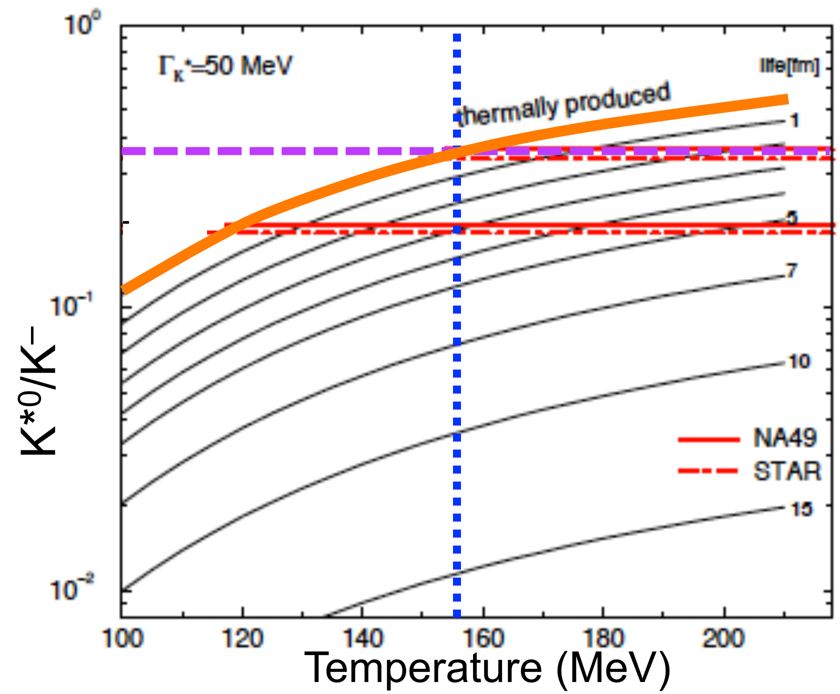
Properties of Hadronic Phase

- Recall: 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

our assumption, based on thermal-model fits of ALICE data



[1] *J. Phys. G* **28**, 1911 (2002)
[2] *Phys. Rev. C* **65**, 069902(E) (2002)
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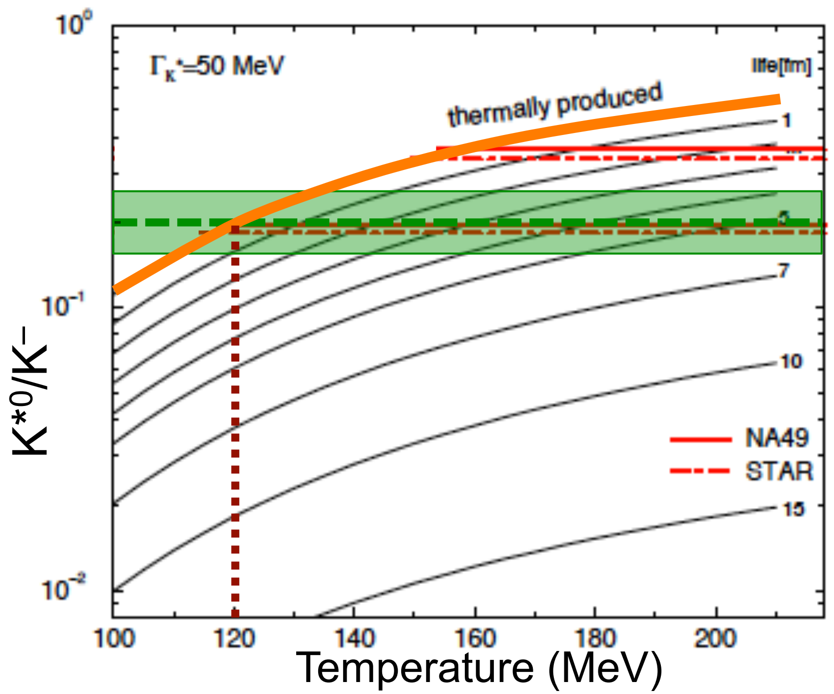
Torrieri/Rafelski [1-3]
no re-scattering
measured K^{*0}/K^{-}

→ Prediction:
T_{ch} = 120±7 MeV

K^{*0}/K^{-} = 0.20 ± 0.01 (stat.) ± 0.03 (sys.)



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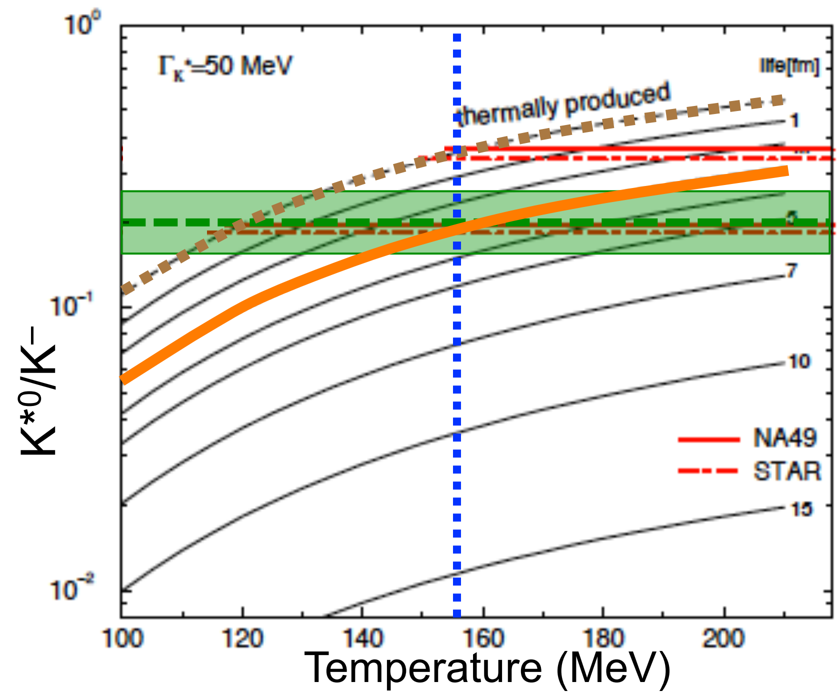
Torrieri/Rafelski [1-3]
measured K^{*0}/K^{-}
T_{ch} = 156 MeV
→ Prediction: Lifetime ≥ 2 fm/c



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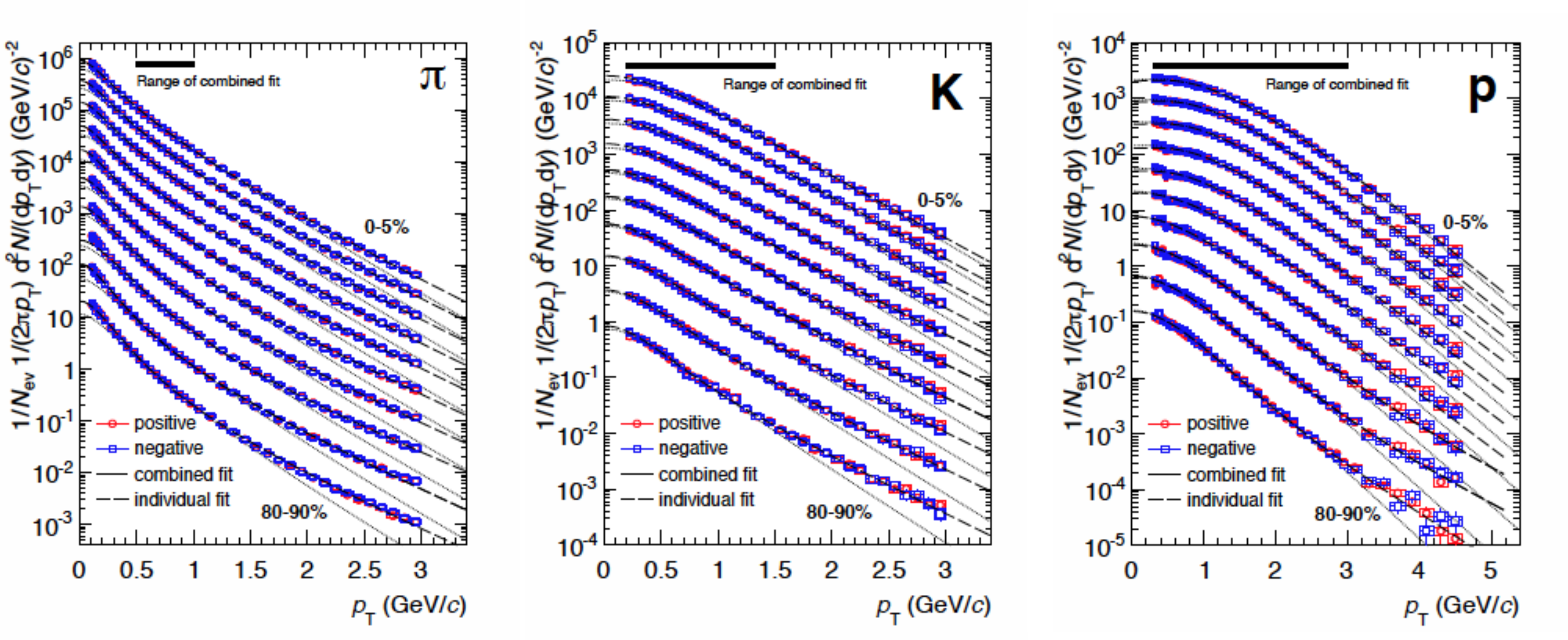
πKp Blast-Wave Fits

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



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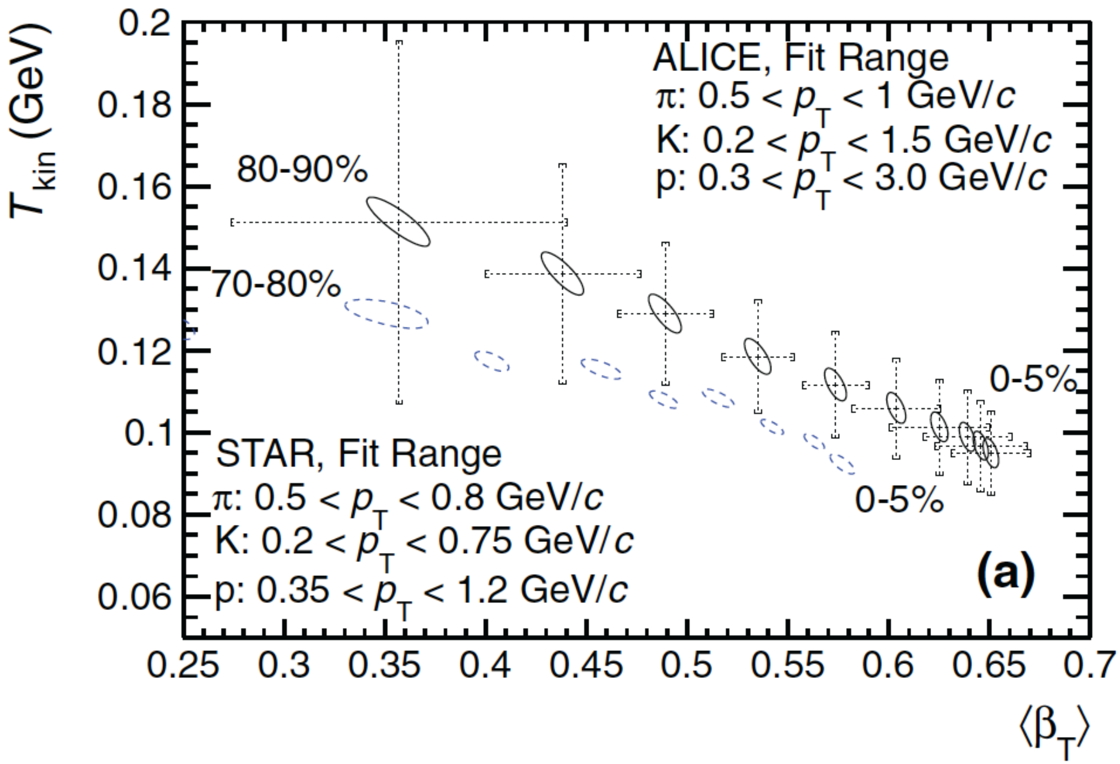
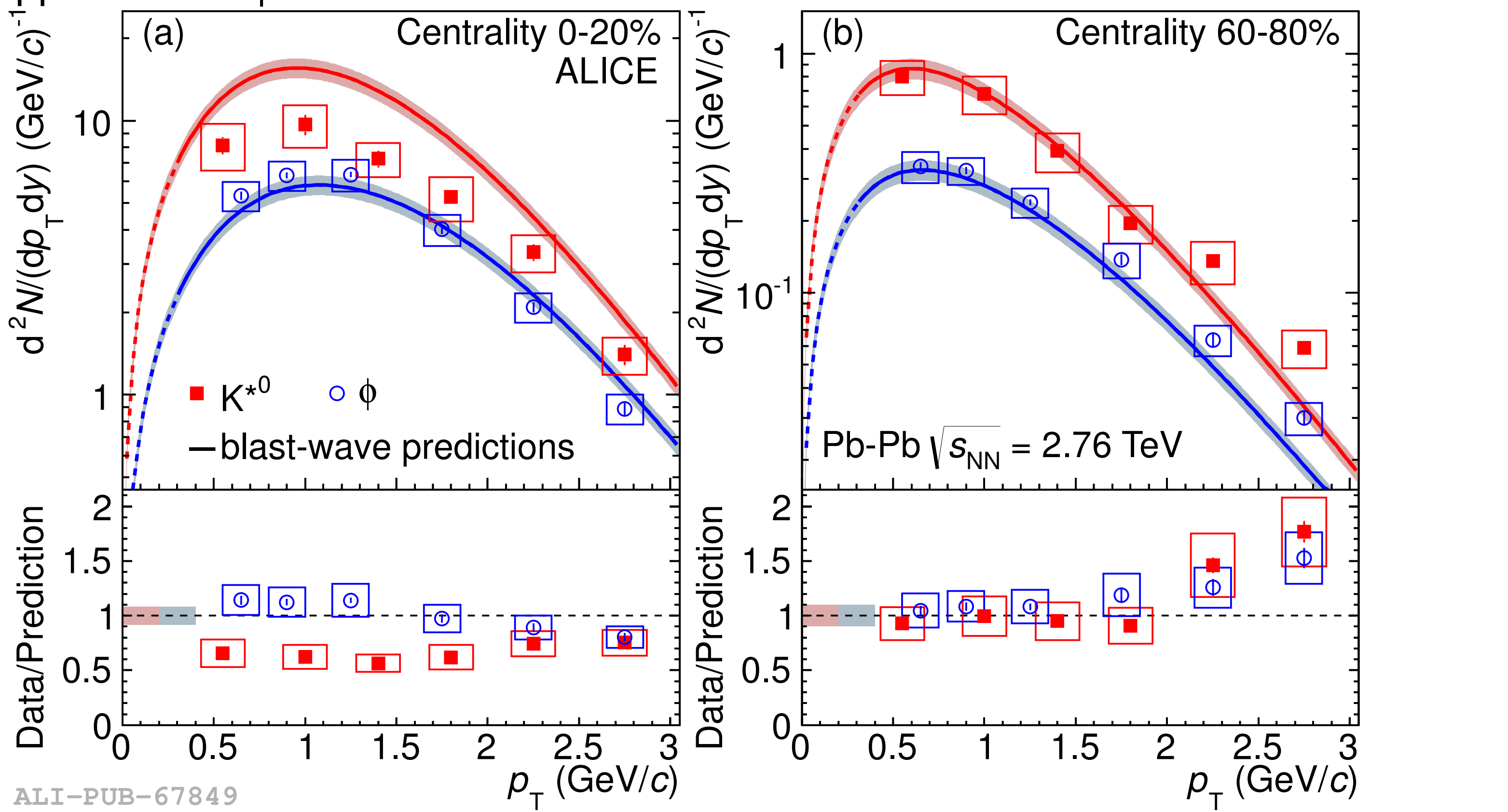


Resonance Suppression

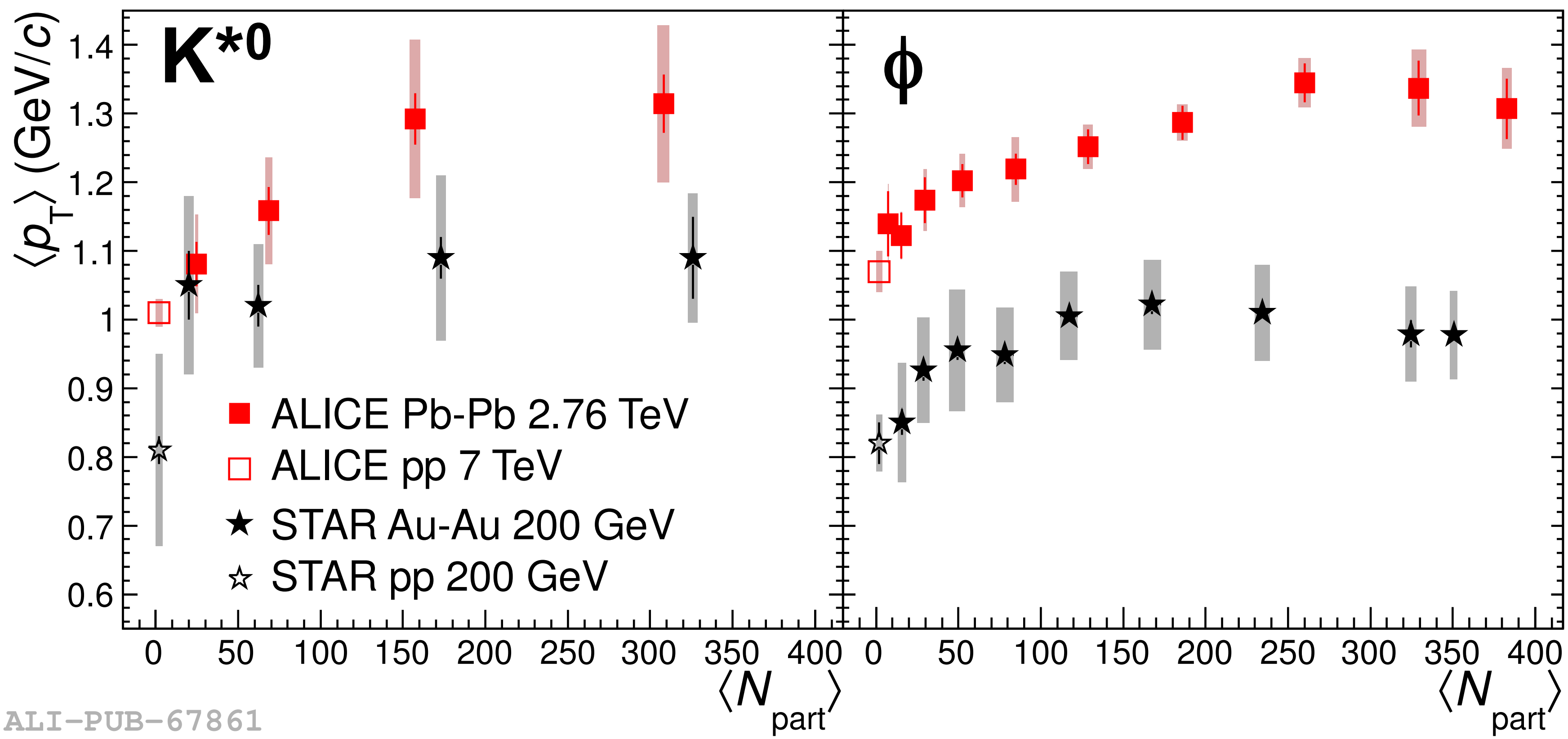
- Does K^{*0} suppression depend on p_T? UrQMD: re-scattering strongest for p_T<2 GeV/c.
- Expected p_T distribution from blast-wave model:
  - Shape: parameters (T_{kin}, n, β) from combined fits of π/K/p in Pb–Pb (*)
  - Normalization: K yield × K^{*0}/K ratio from thermal model (T_{ch}=156 MeV)
-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

*PRC **88** 044910 (2013)



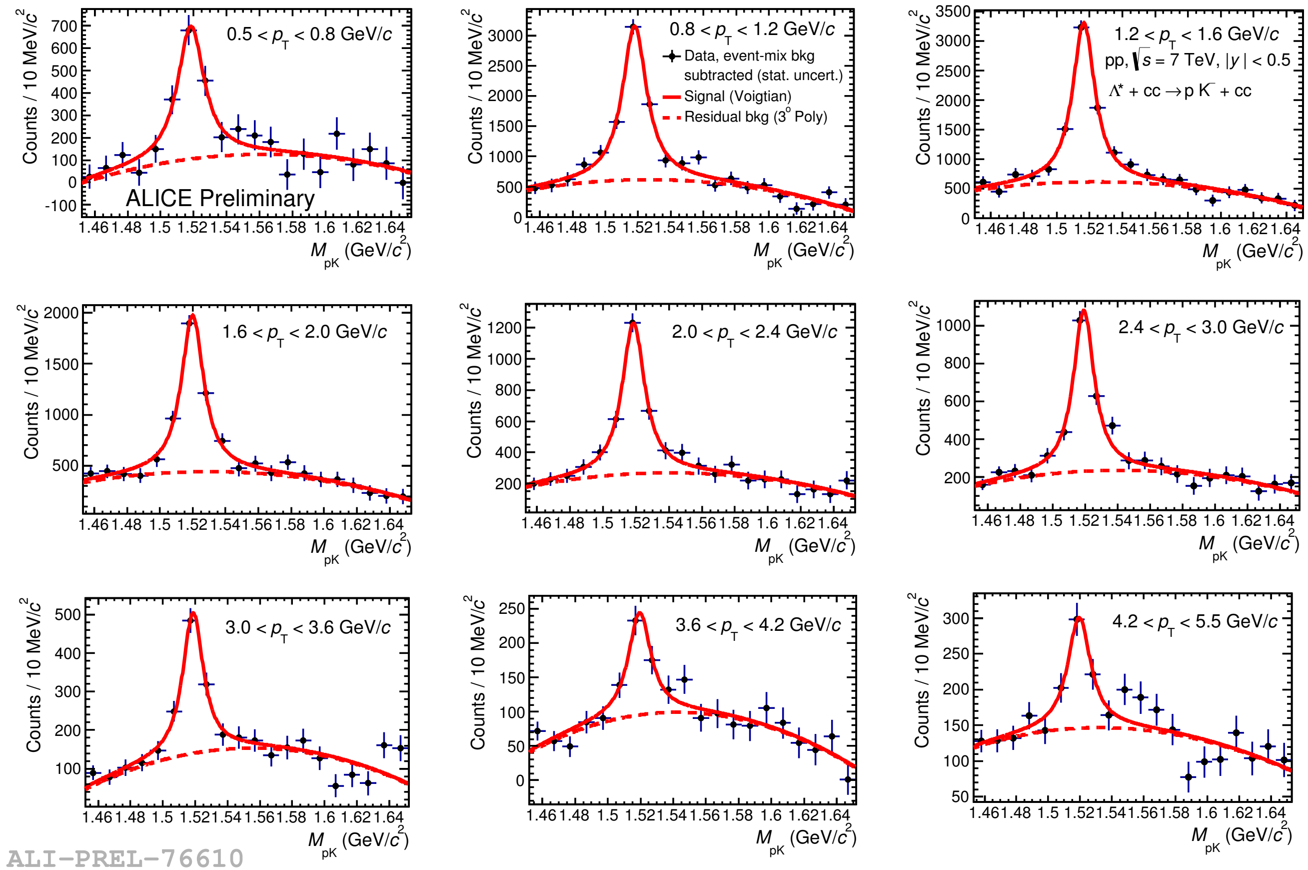
Mean p_T in A–A

- $\langle p_T \rangle$ appears to increase for more central Pb–Pb collisions w.r.t. peripheral and pp
- $\langle p_T \rangle$ greater at LHC than RHIC
  - For K^{*0}: 20% larger   For ϕ: 30% larger
- ALICE π,K,p spectra: global blast-wave fit shows ~10% increase in radial flow w.r.t. RHIC



Λ(1520)

- Reconstruction in pp 2.76 TeV, pp 7 TeV, p–Pb 5.02 TeV, and Pb–Pb 2.76 TeV
- Decay channel: Λ(1520)→pK⁻
  - Decay products identified using TPC and TOF
- Mass from invariant-mass fits in pp and p–Pb: good agreement with vacuum value
- More information can be found in poster of R. C. Baral at Quark Matter 2014: https://indico.cern.ch/event/219436/session/2/contribution/197/material/poster/0.pdf



Σ^0

- Reconstruction in pp 7 TeV
- Decay channel: $\Sigma^0 \rightarrow \Lambda\gamma$
  - Photon identified through measurement of its conversion, and in PHOS (calorimeter)
- More information can be found in poster of A. Borissov at Quark Matter 2014: https://indico.cern.ch/event/219436/session/2/contribution/196/material/slides/0.pdf