An Overview of Resonance Measurements at the ALICE Experiment

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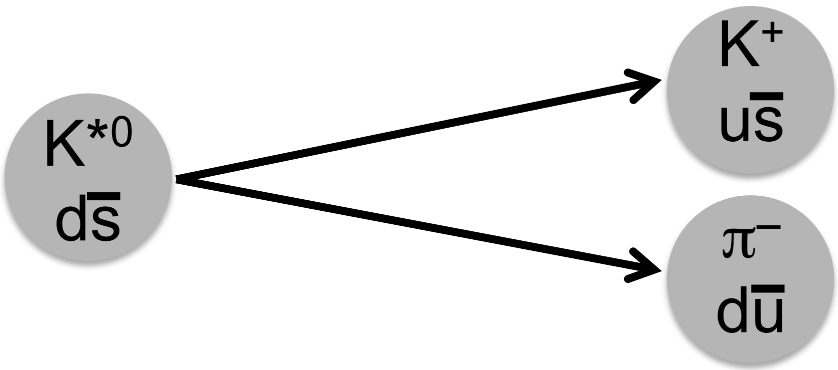
Resonances

- What particles do we study?
  - Excited hadronic states
  - Short Lifetimes (~ Lifetime of Fireball)
  - For practical reasons, we prefer resonances with only charged particles at the end of the decay chain.



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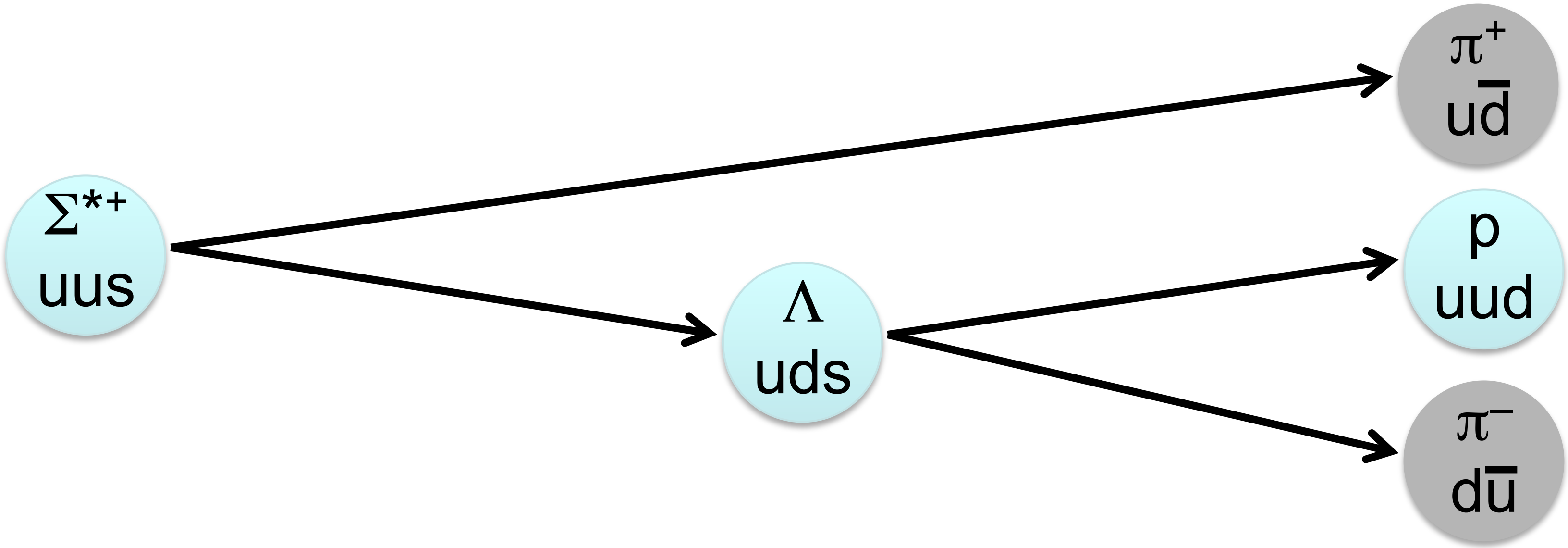


ALICE Resonance Program

Comprehensive studies: pp, p–Pb, Pb–Pb

- K^{*0}: $d\bar{s}$
- ϕ: $s\bar{s}$

Results for pp, ongoing studies for p–Pb and Pb–Pb

- Σ^{*-}: dds
- Σ^{*+}: uus
- Ξ^{*0}: uss

Ongoing studies in pp, p–Pb, and Pb–Pb

- ρ^0: $\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$
- $\Lambda(1520)$: uds

Ongoing studies in pp

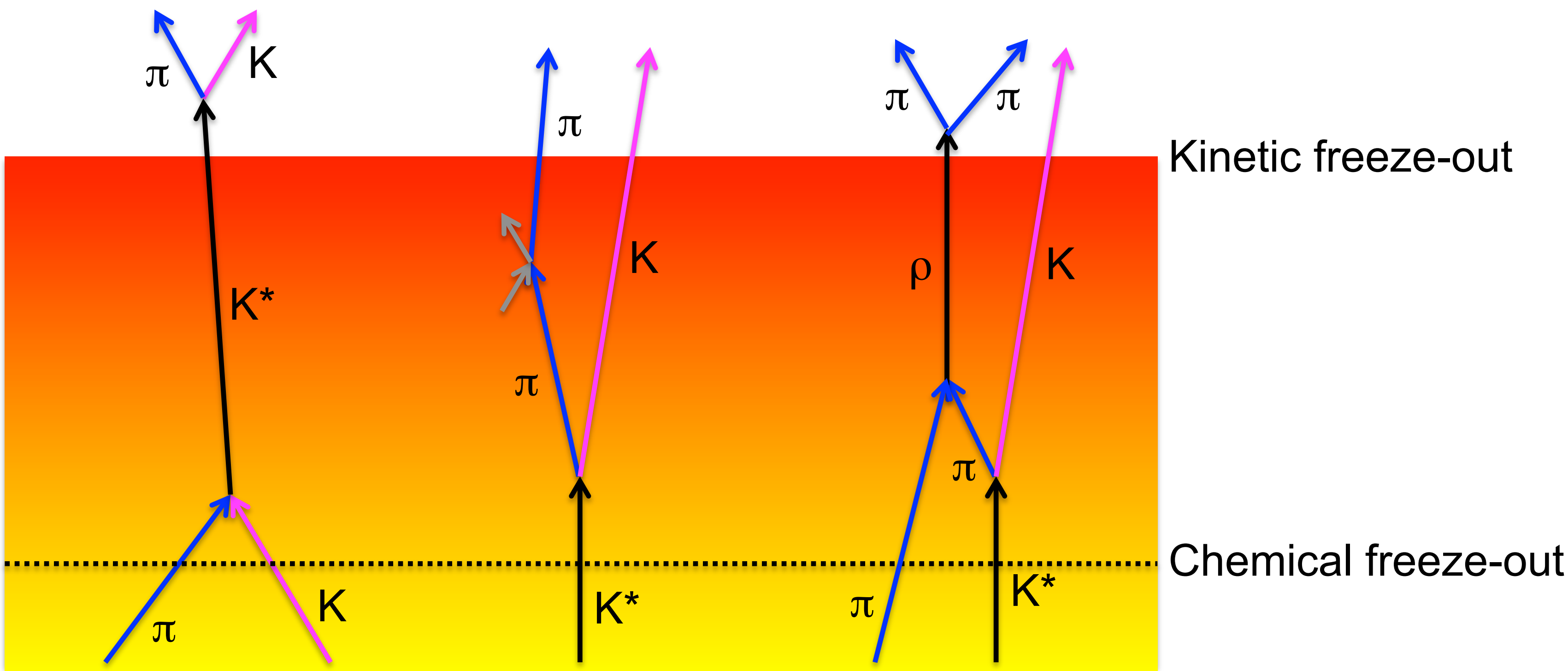
- Δ^{++}: uuu
- Σ^0: uds

Motivation

- pp and p–Pb collisions:
  - Baseline measurements for A–A
  - R_{pPb}: initial-state nuclear matter effects, system size dependence
- In-Medium Energy Loss:
  - R_{AA}: Study Nuclear Modification Factor (flavor dependence)
- Shapes of Particle p_{T} Spectra:
  - Hydrodynamics: particle masses determine shapes of spectra
  - Recombination: baryon/meson differences in shapes p_{T} spectra
- Chiral Symmetry Restoration:
  - expect mass shift and/or width broadening for resonances that decay when chiral symmetry (partially) restored
  - ALICE Results for K^{*0} and ϕ in Pb–Pb: mass and width show no significant modification and no centrality dependence
- Properties of Hadronic Phase…

Hadronic Phase

- Reconstructible resonance yields may be changed by hadronic processes after chemical freeze-out:
  - **Regeneration:** pseudo-elastic scattering of decay products
    - e.g., πK → K* → πK
  - **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



Hadronic Phase

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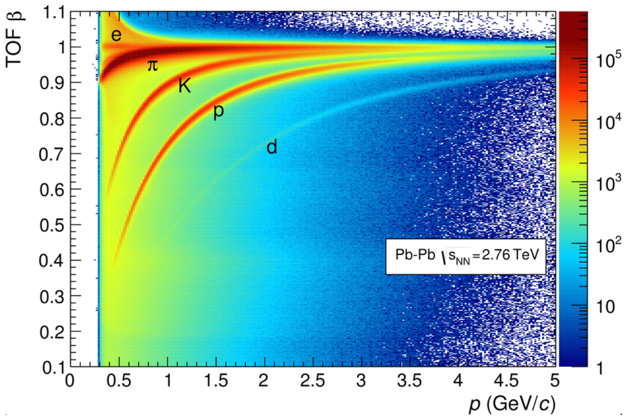
  - **Regeneration:** pseudo-elastic scattering of decay products
    - e.g., $\pi K \rightarrow K^* \rightarrow \pi K$
  - **Re-scattering:**
    - Resonance decay products undergo elastic scattering
    - Or pseudo-elastic scattering through a different resonance (e.g. ρ)
    - Resonance not reconstructed through invariant mass
- Final yields at kinetic freeze-out depend on
  - Initial Yields: chemical freeze-out temperature
  - Elapsed time between chemical and kinetic freeze-out
  - Resonance lifetime
  - Scattering cross-sections of decay products
- Re-scattering and regeneration expected to be most important for $p_T < 2$ GeV/c (UrQMD)

ALICE Detector

Knospe



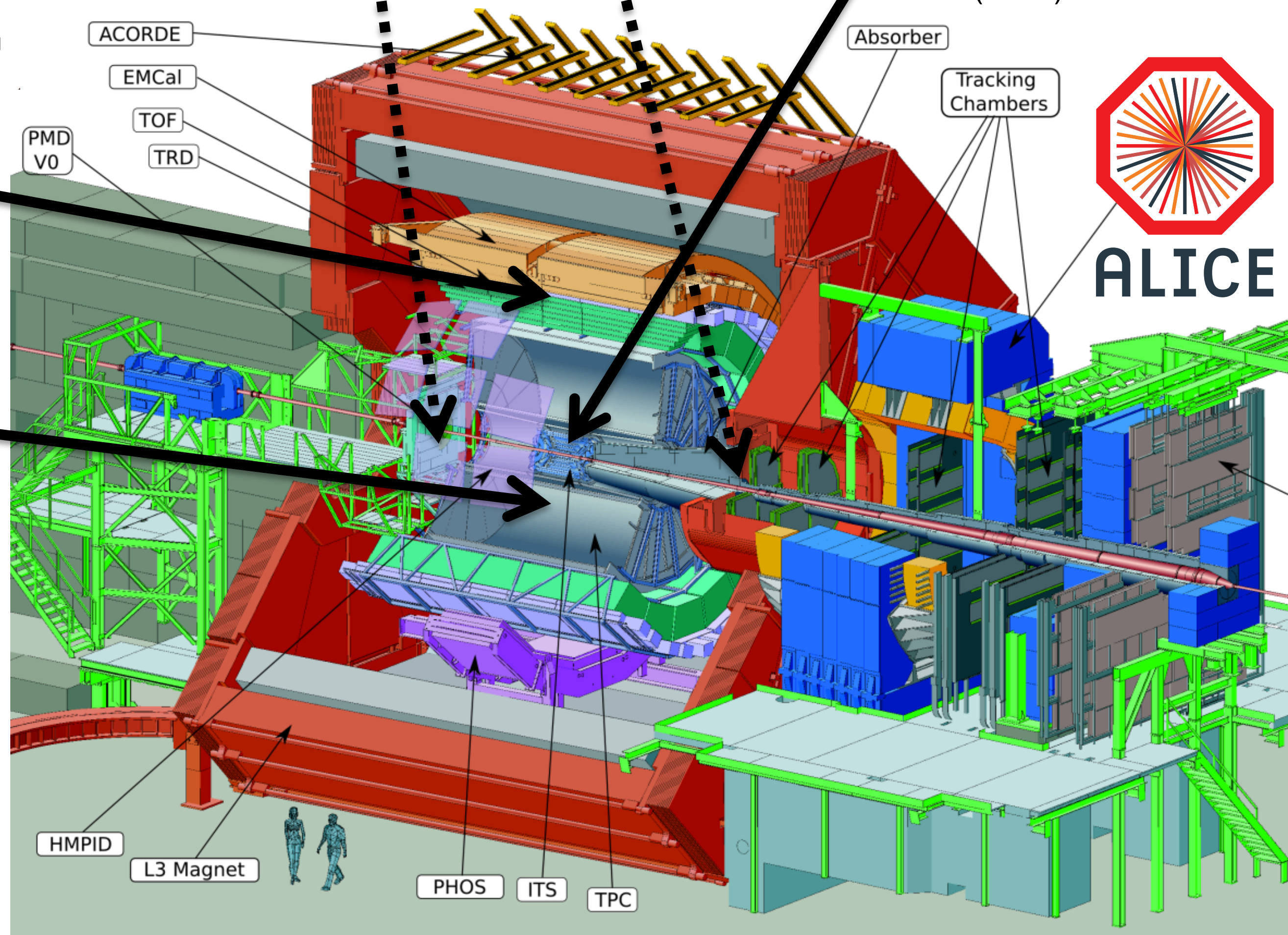
VZERO (scintillators): centrality estimate through energy deposition (→multiplicity)

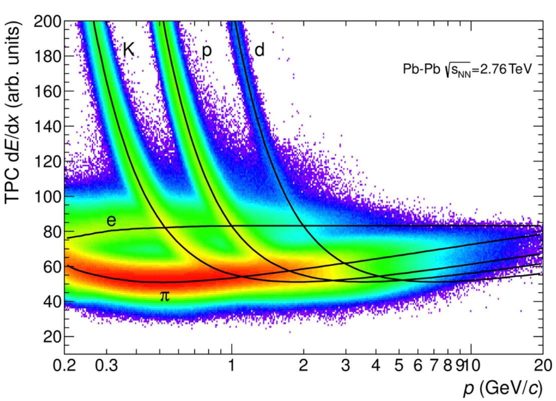
ITS (silicon): Tracking and Vertexing

ALICE, *Int. J. Mod. Phys. A* **29** 1430044 (2014)

TOF: PID through particle velocity measurement

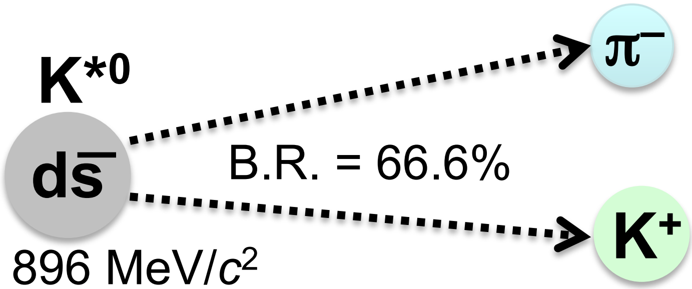
TPC: Tracking and PID through d*E*/d*x*



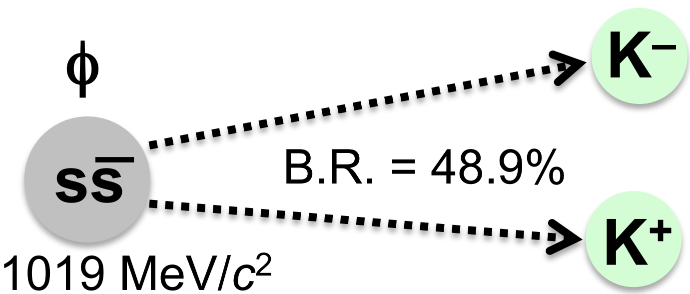


Resonance Reconstruction

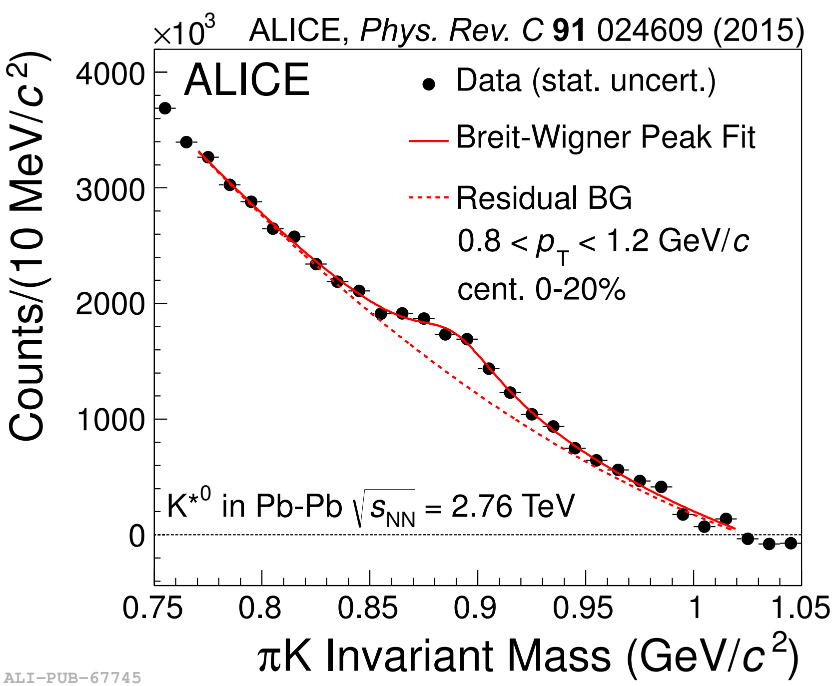
- Invariant-mass reconstruction through hadronic decays
- Resonances measured in pp (0.9, 2.76, 7 TeV) , p–Pb (5.02 TeV), and Pb–Pb (2.76 TeV) collisions

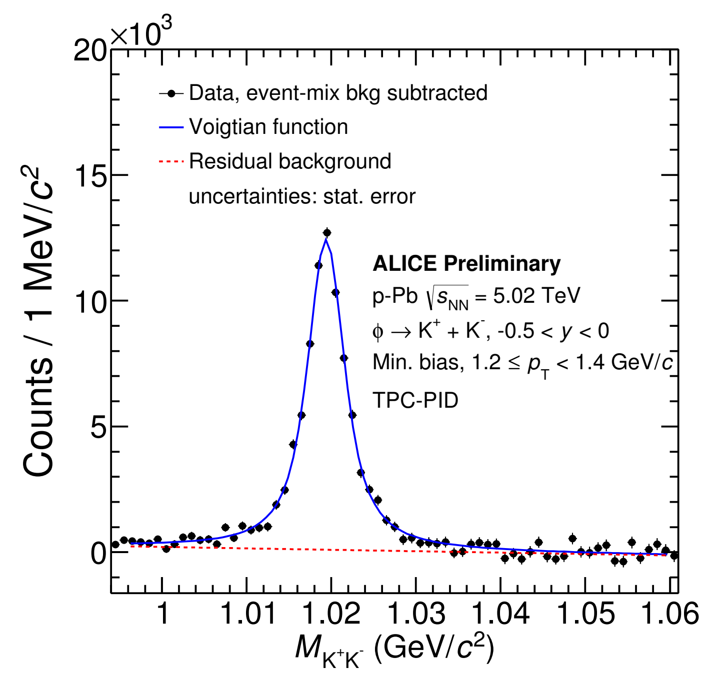


m = 896 MeV/c^2
τ = 4.16 fm/c



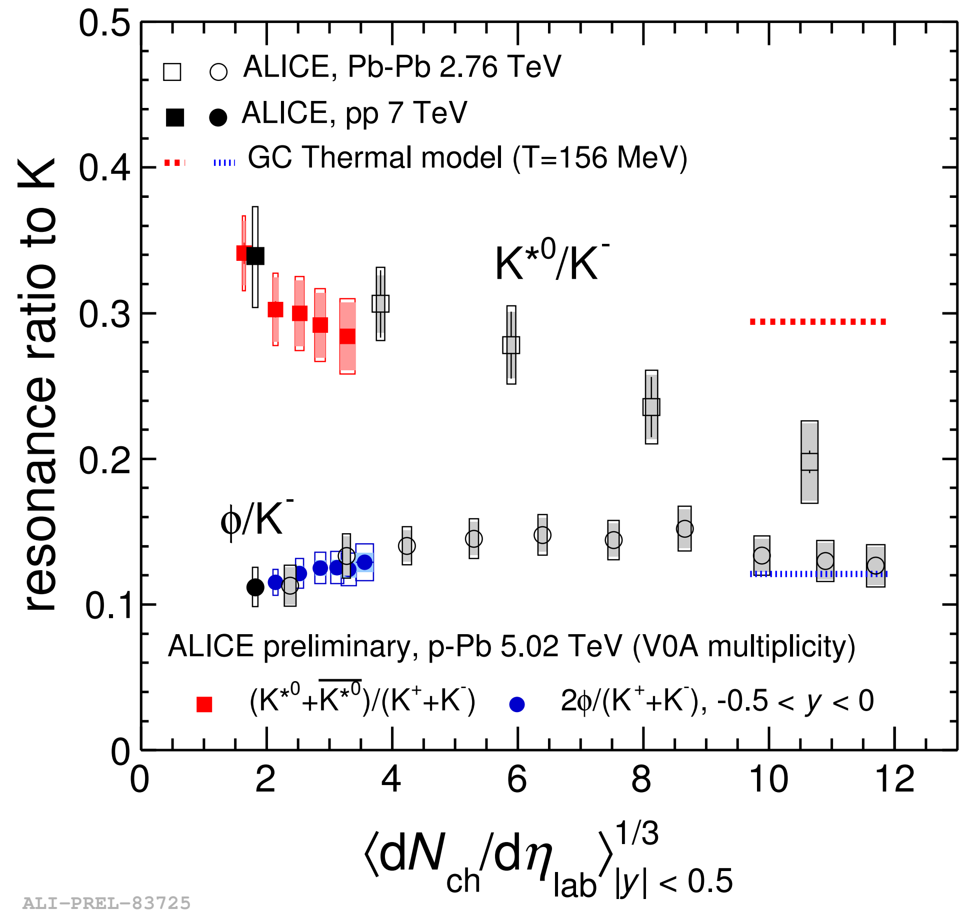
m = 1019 MeV/c^2
τ = 46.3 fm/c





Ratios of Yields

- K^{*0}/K
  - Central Pb–Pb: significantly suppressed 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

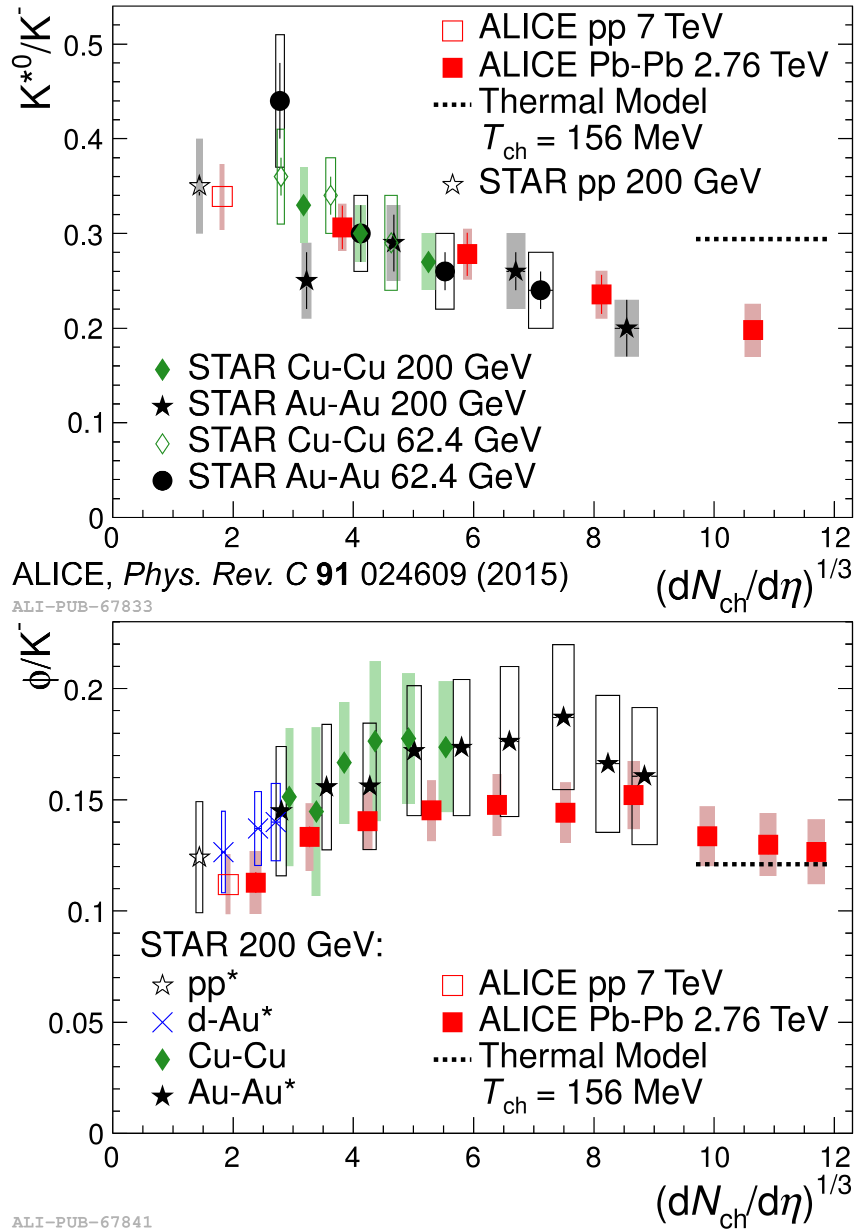


Plotted as function of $(dN_{ch}/d\eta)^{1/3}$, proxy for system radius

References:
pp: ALICE, *Eur. Phys. J. C* **72** 2183 (2012)
Pb–Pb: ALICE, *Phys. Rev. C* **91** 024609 (2015)
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

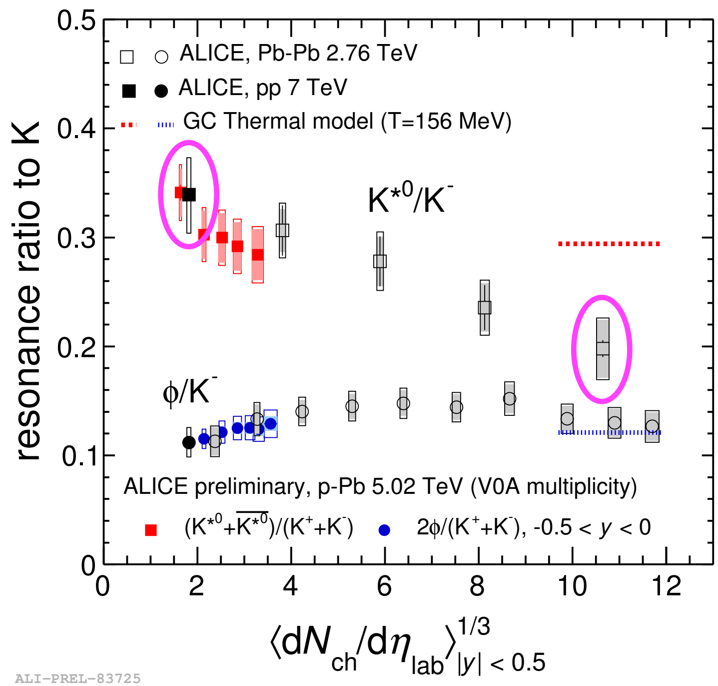


Properties of Hadronic Phase

- 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



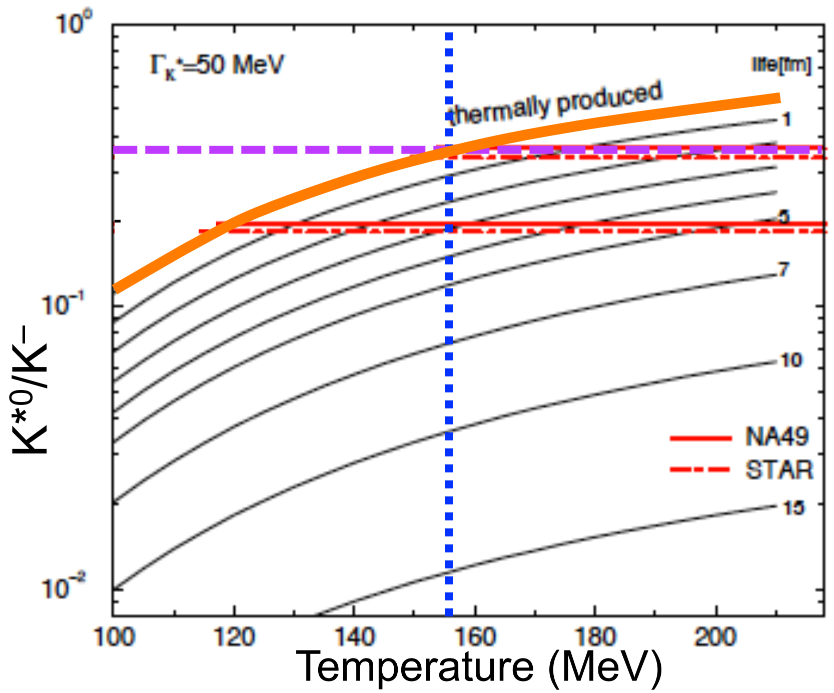
Properties of Hadronic Phase

- 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*
no re-scattering
T_{ch} = 156 MeV

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

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



*References:
G. Torrieri and J. Rafelski, *J. Phys. G* **28**, 1911 (2002)
J. Rafelski *et al.*, *Phys. Rev. C* **64**, 054907 (2001)
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C. Markert *et al.*, arXiv:hep-ph/0206260v2 (2002)

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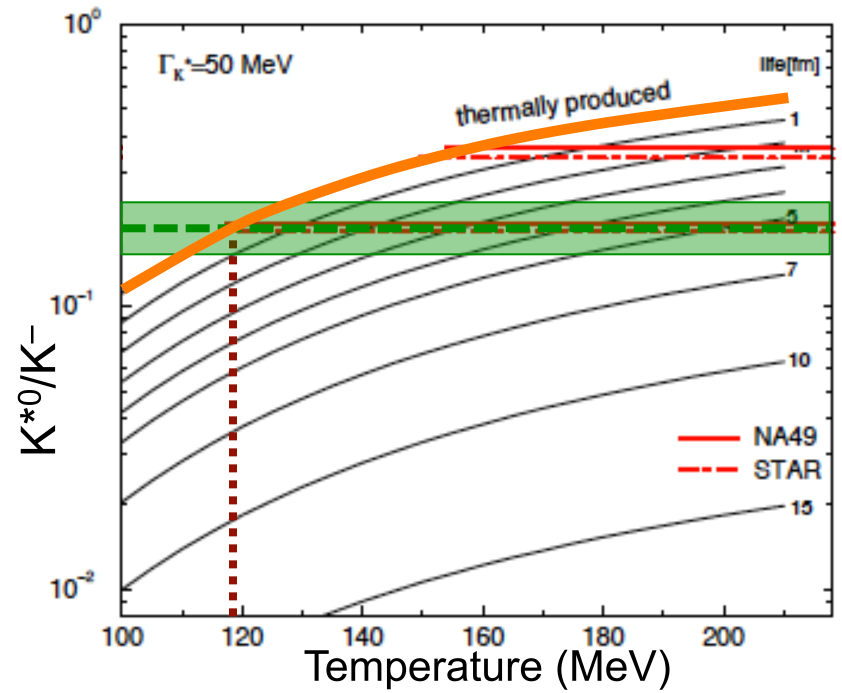
Torrieri/Rafelski*
no re-scattering
measured K^{*0}/K^{-}

→ Prediction:
T_{ch} = 120±7 MeV

K^{*0}/K^{-} = 0.20 ± 0.01 (stat.) ± 0.03 (sys.)
[ALICE, *Phys. Rev. C* **91** 024609 (2015)]



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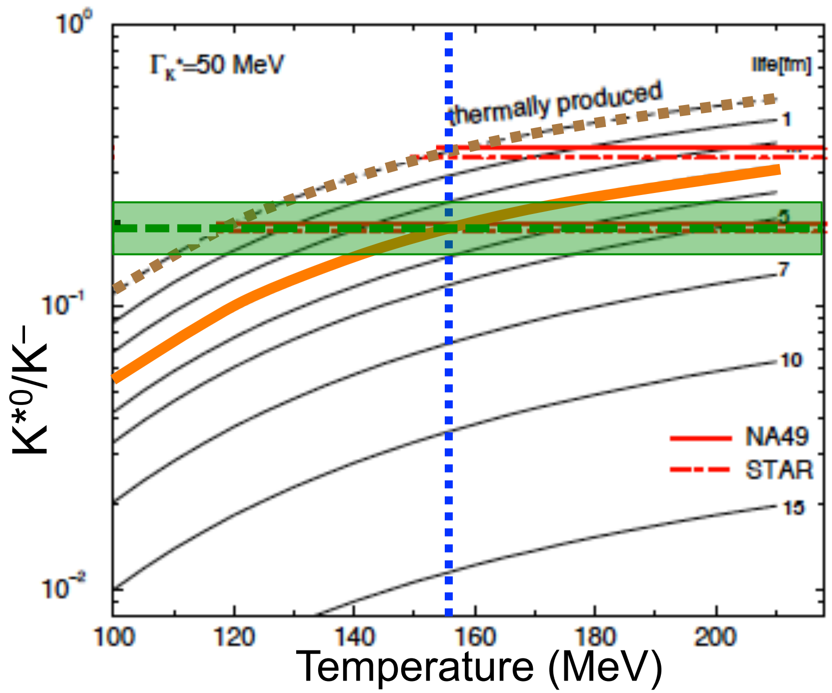
Torrieri/Rafelski*
measured K^{*0}/K^{-}
T_{ch} = 156 MeV
→ Prediction: Lifetime $\geq$ 2 fm/c



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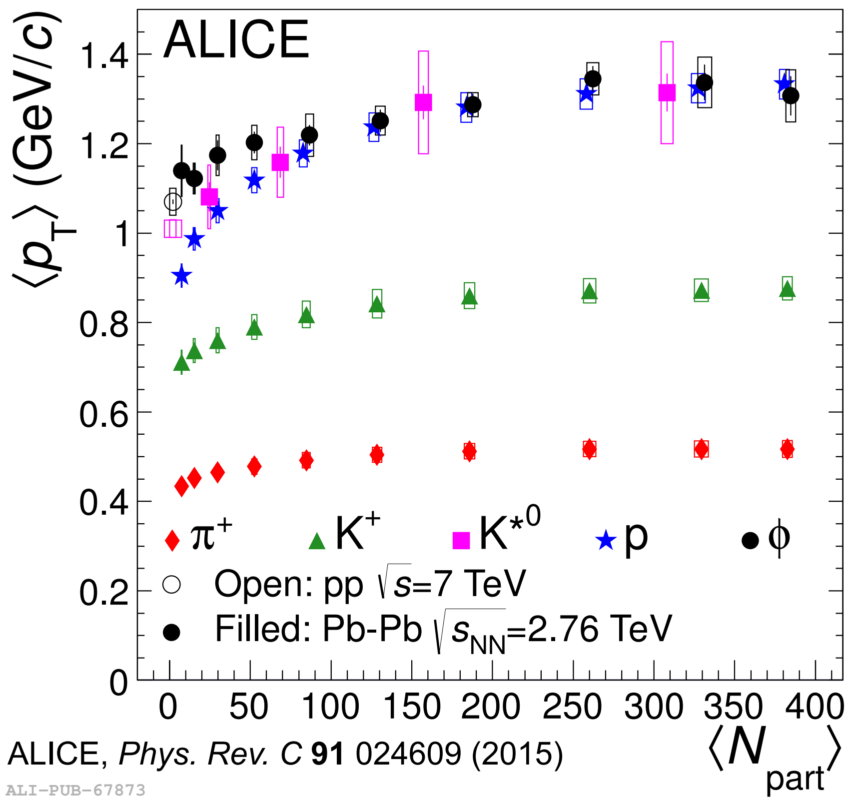
Mean p_T in Pb–Pb

- 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%

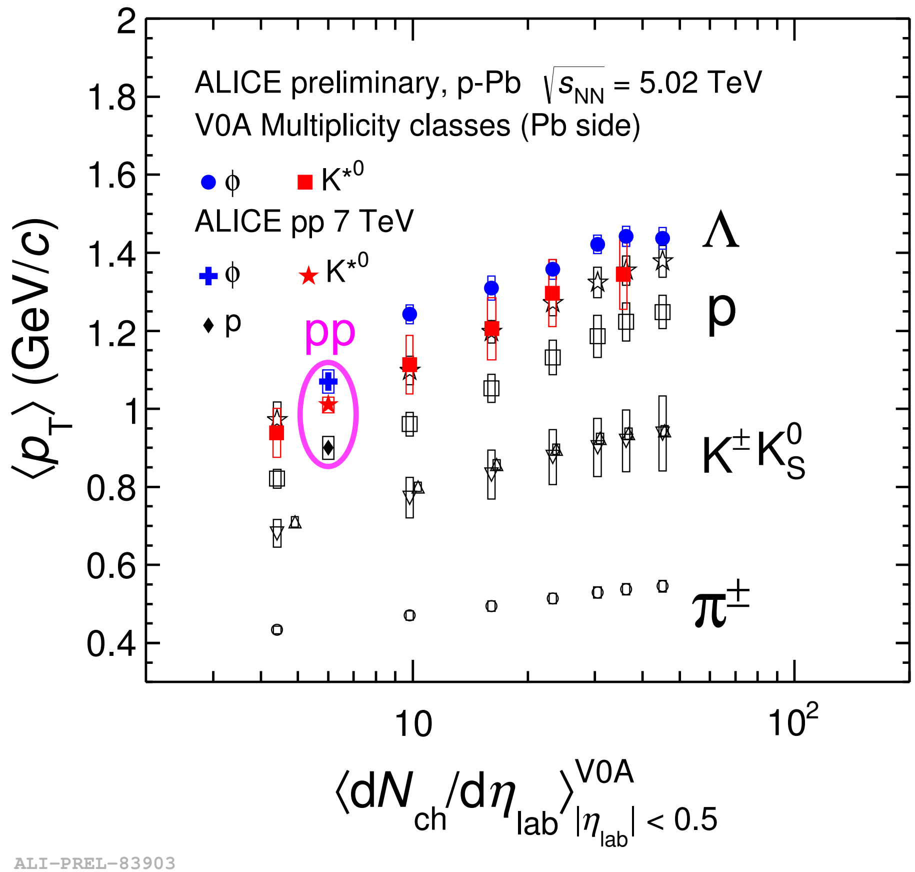


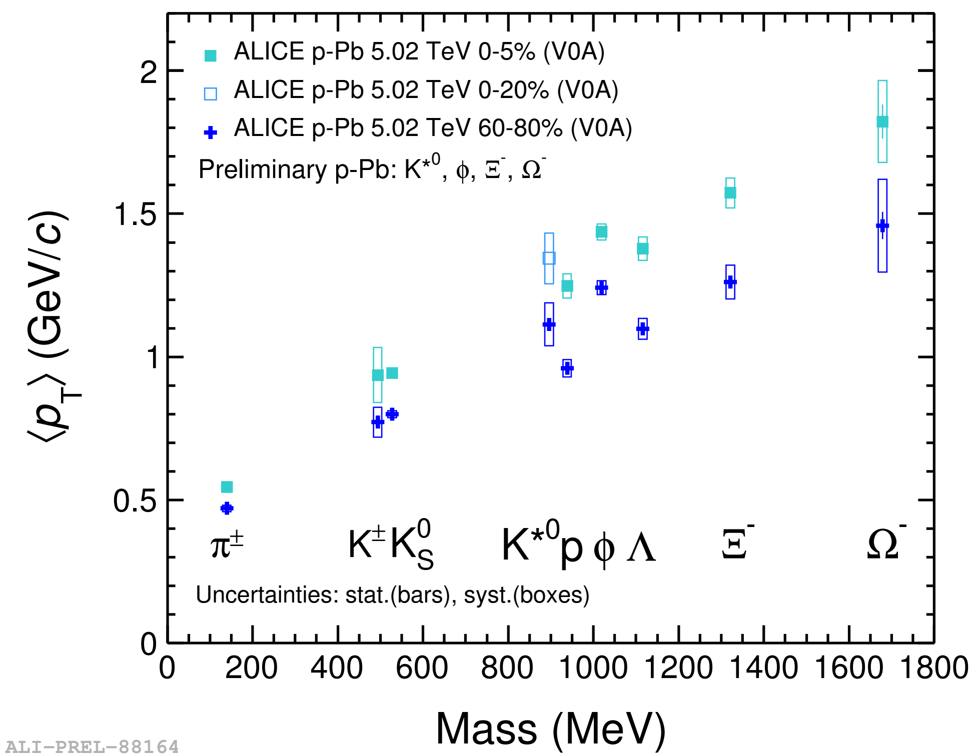
ALICE, *Phys. Rev. C* **91** 024609 (2015)

ALI-PUB-67873

Mean p_T in p–Pb

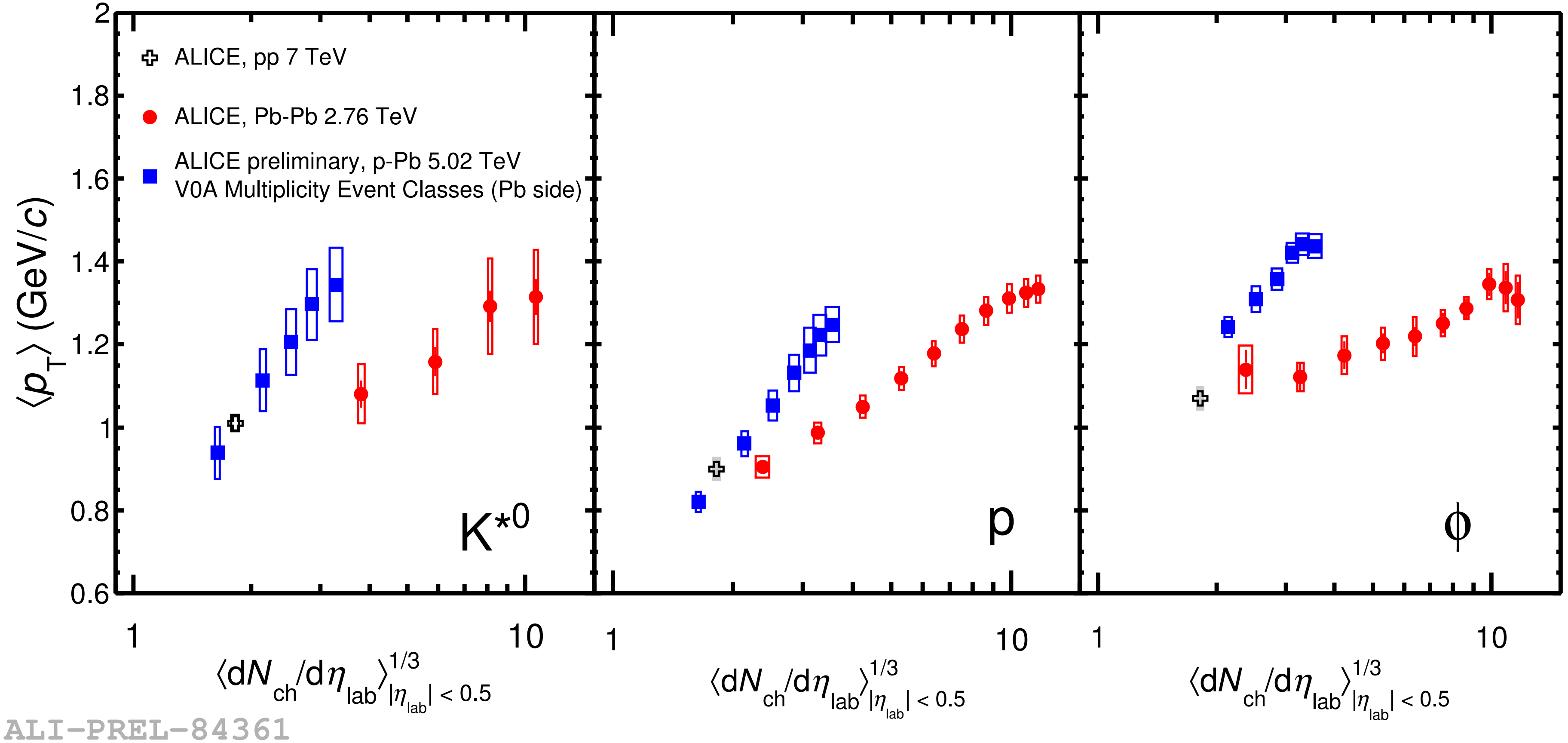
- Approximate mass ordering in $\langle p_T \rangle$
  - But $\langle p_T \rangle$ of K^{*0} and ϕ greater than p and Λ
  - Is there a baryon/meson difference, or do resonances not obey mass ordering?
  - Same trend observed in pp





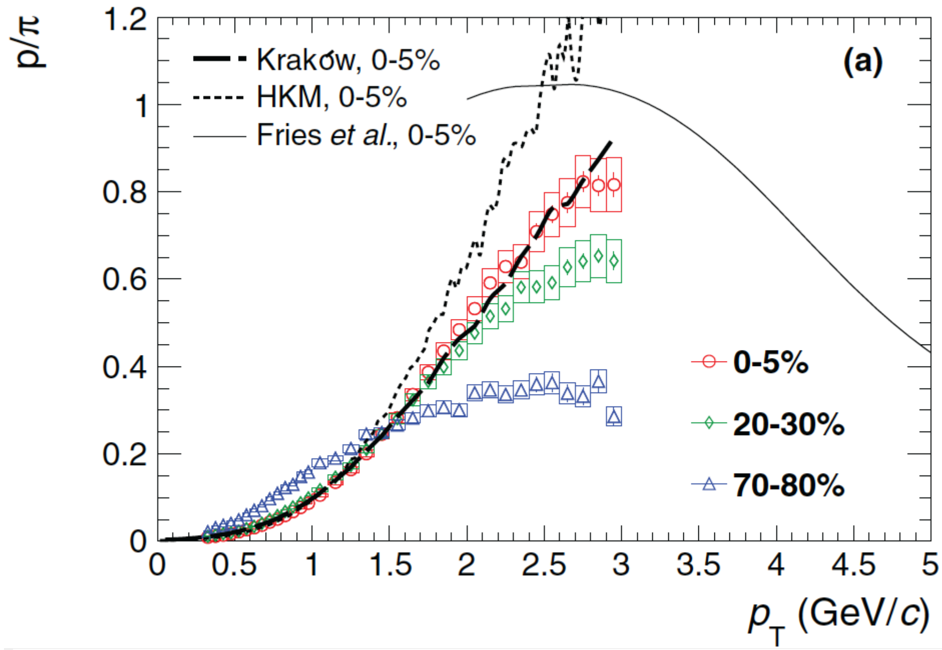
Mean p_T

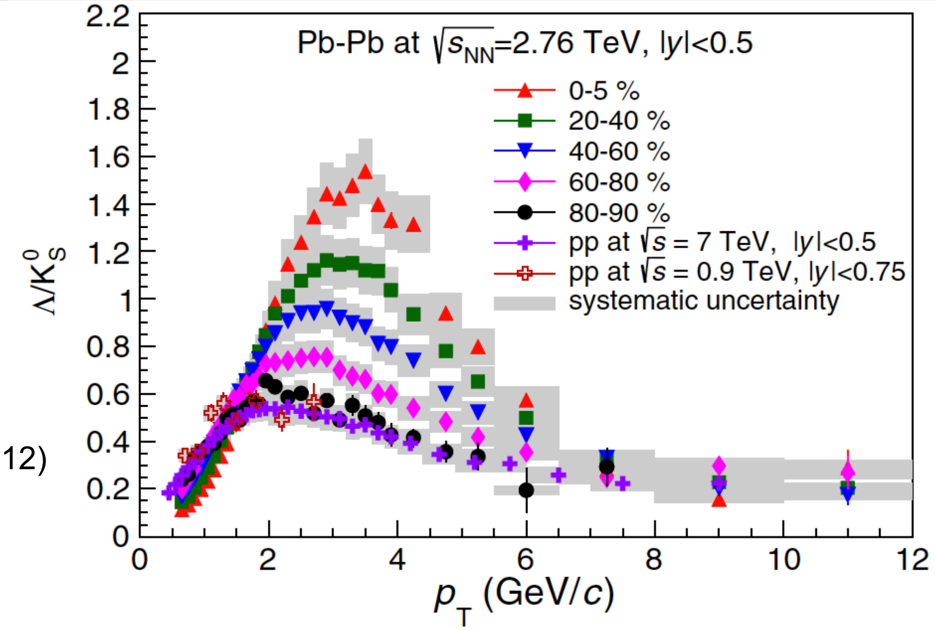
- High-multiplicity p–Pb reaches similar $\langle p_T \rangle$ values as central Pb–Pb
- $\langle p_T \rangle$ in p–Pb increases more rapidly than Pb–Pb as a function of multiplicity
- Differences in $\langle p_T \rangle$ due to difference in particle production mechanisms? Harder scattering in p–Pb?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



Particle Production

- p/π and Λ/K^0_S vs. p_T:
- 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





References:

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

P. Bozek and I. Wyskiel-Piekarska, *Phys. Rev. C* **85** 064915 (2012)

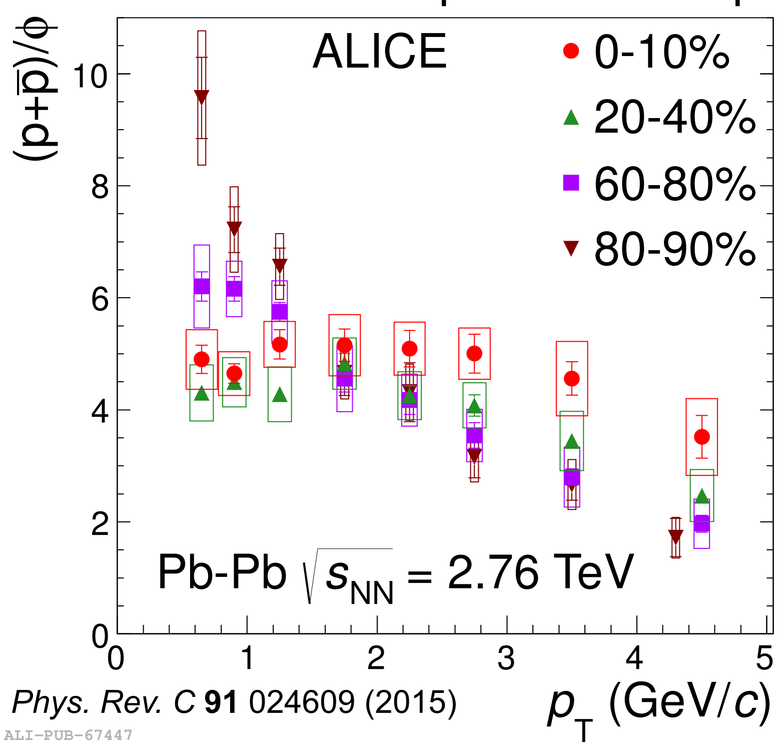
I. Karpenko *et al.*, *Phys. Rev. C* **87** 024914 (2013)

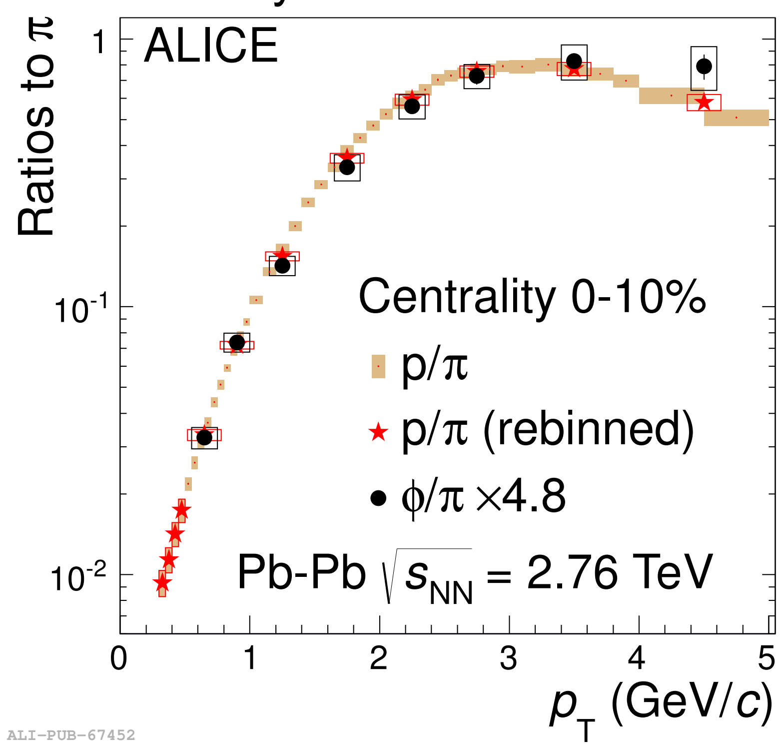
R. Fries *et al.*, *Phys. Rev. Lett.* **90** 202303 (2003)

Lower plot: 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?
- Extended hadronic phase with expansion velocity in central Pb–Pb

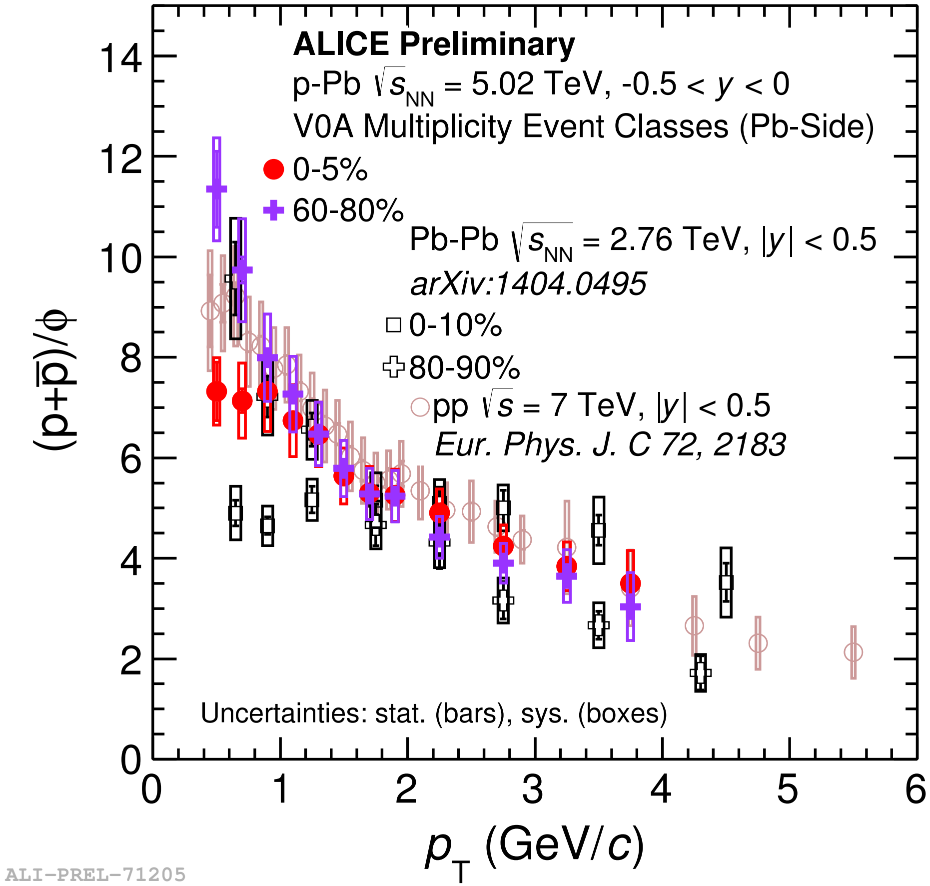




ALICE, *Phys. Rev. C* **91** 024609 (2015)

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?

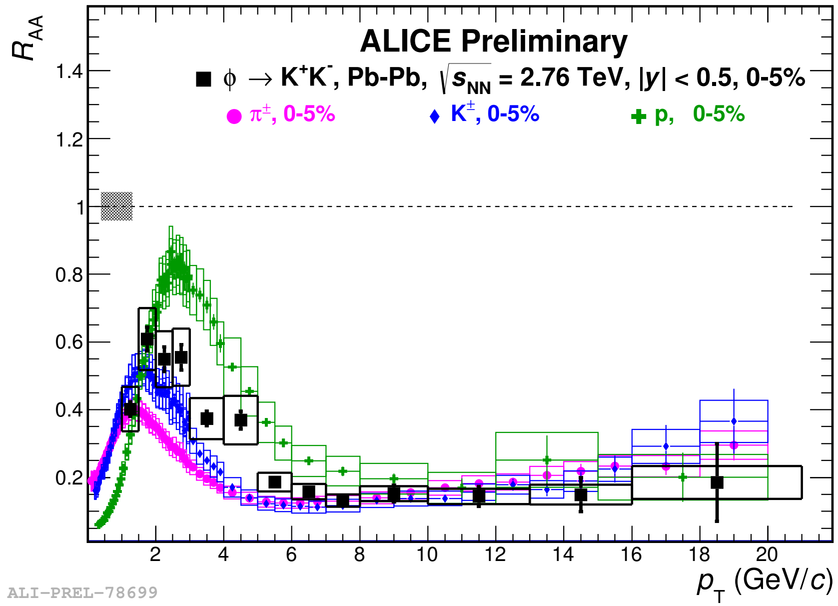


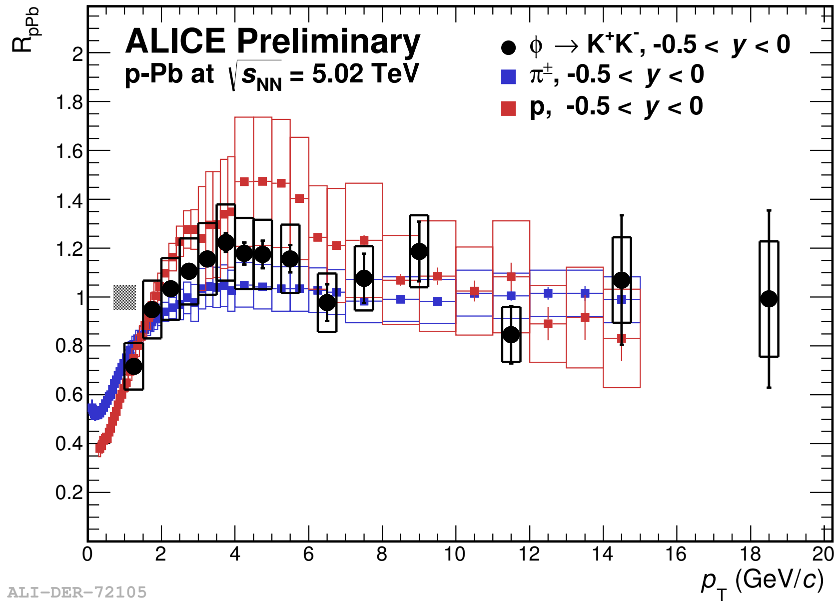
Nuclear Modification Factors

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

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

- 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}



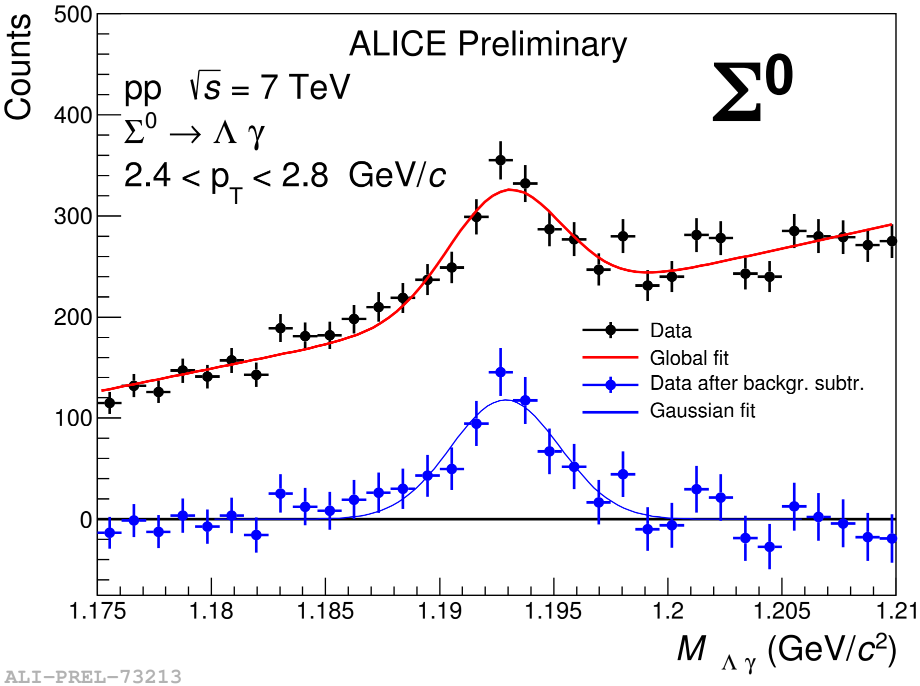


Conclusions

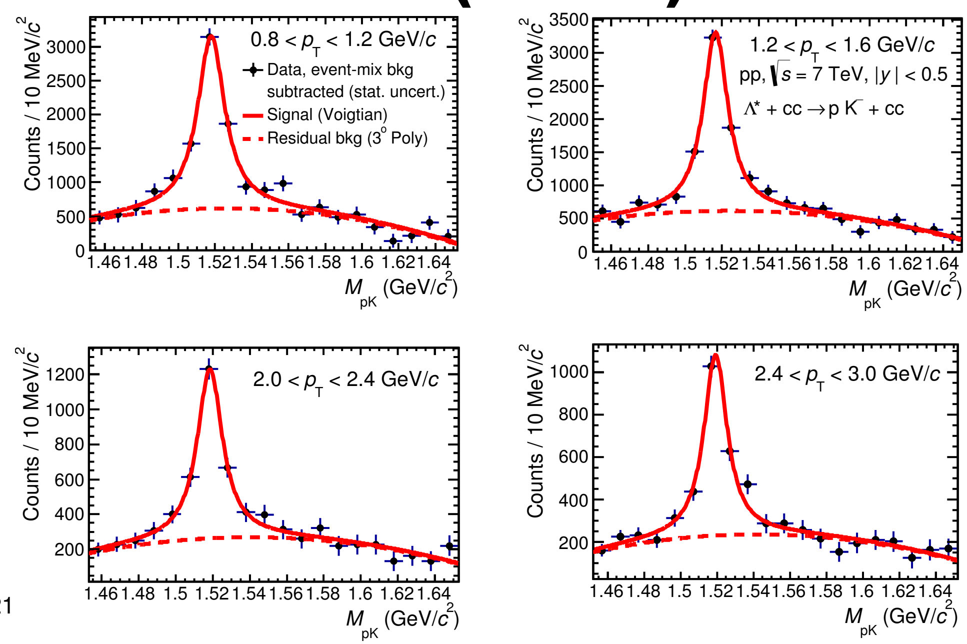
- Resonance Suppression:
  - Central Pb–Pb: K^{*0} suppressed (re-scattering) ϕ not suppressed (longer lifetime)
    - From K^{*0}/K^{-} ratio: lower limit on lifetime of hadronic phase: 2 fm/*c*
  - p–Pb: K^{*0}/K and ϕ/K ratios follow trend from pp to peripheral Pb–Pb
- Mean p_T:
  - $\langle p_T \rangle$ in p–Pb and Pb–Pb follow different trends
  - For central Pb–Pb: $\langle p_T \rangle$ of $K^{*0} \approx p \approx \phi$ consistent with hydrodynamics
  - Mass ordering violated for pp, p–Pb, peripheral Pb–Pb:
    - $\langle p_T \rangle$ of $K^{*0} \approx \phi > p \approx \Lambda$
    - Baryon/meson difference?
- p/ϕ ratio:
  - Flat vs. p_T for central Pb-Pb (p_T<3-4 GeV/*c*), consistent with hydrodynamics
  - Hint of 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

Outlook

- Other studies in pp, p–Pb, and Pb–Pb collisions:
  - ρ^0, Σ^0, $\Sigma^{*\pm}$, $\Lambda(1520)$, Ξ^{*0}
  - Allows study of modification of yields of several different resonances → better understanding of properties of hadronic phase
- Extension of K^{*0} and ϕ measurements to high p_T
- LHC Run 2 data at 13 TeV

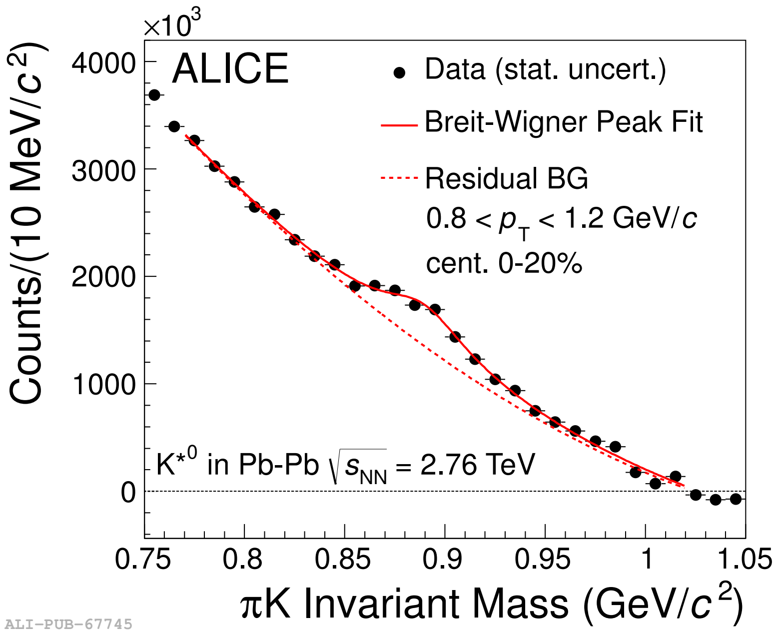


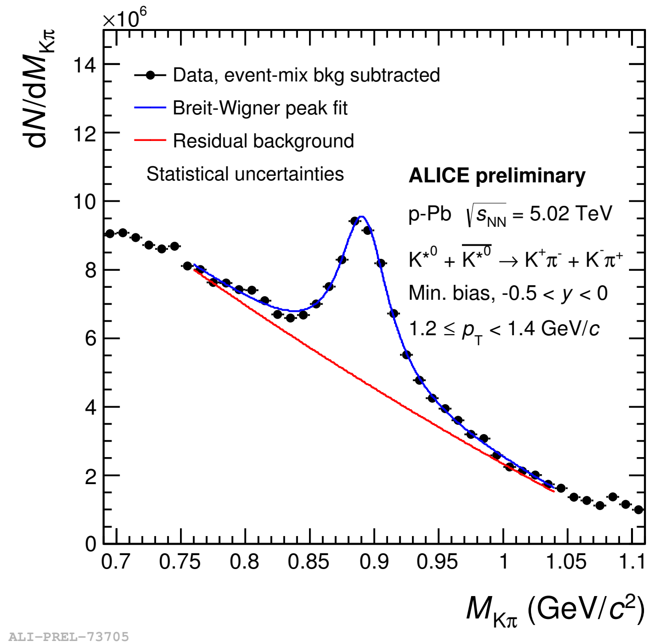
Λ(1520)

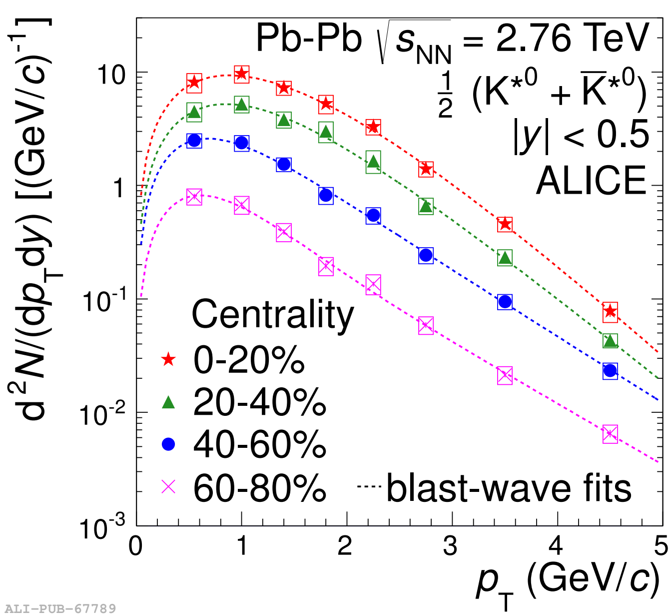


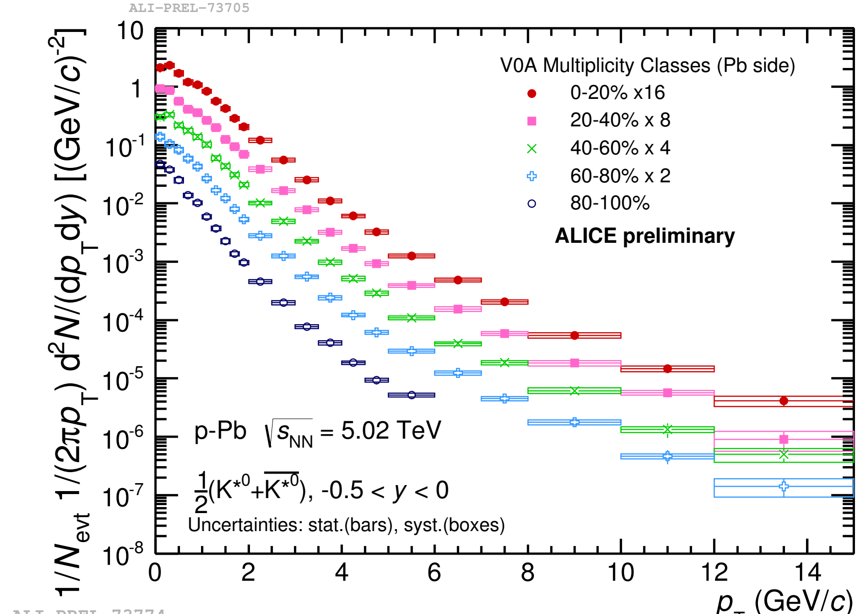
Backup Material

K*0 Peaks and Spectra

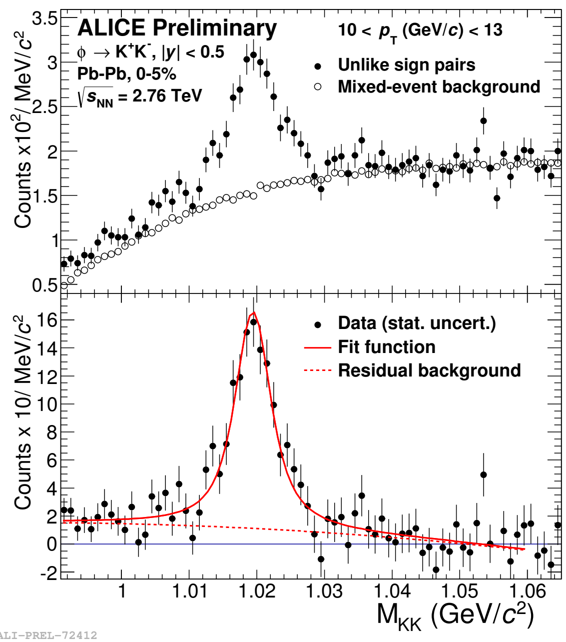


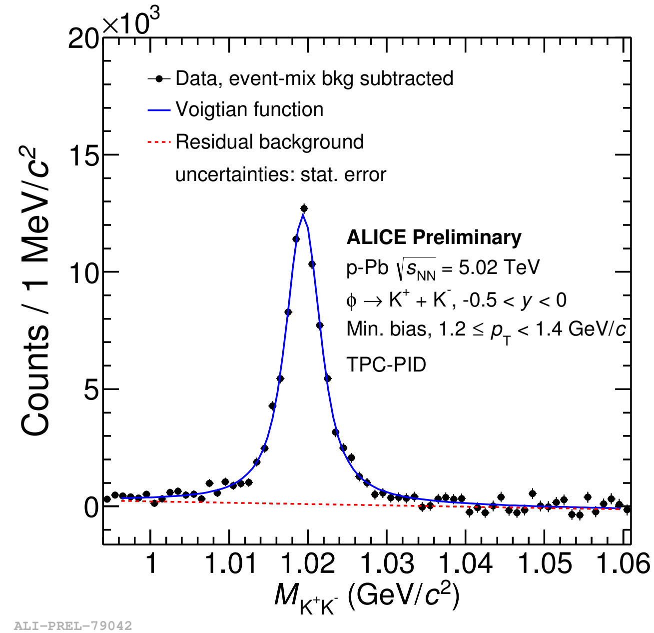


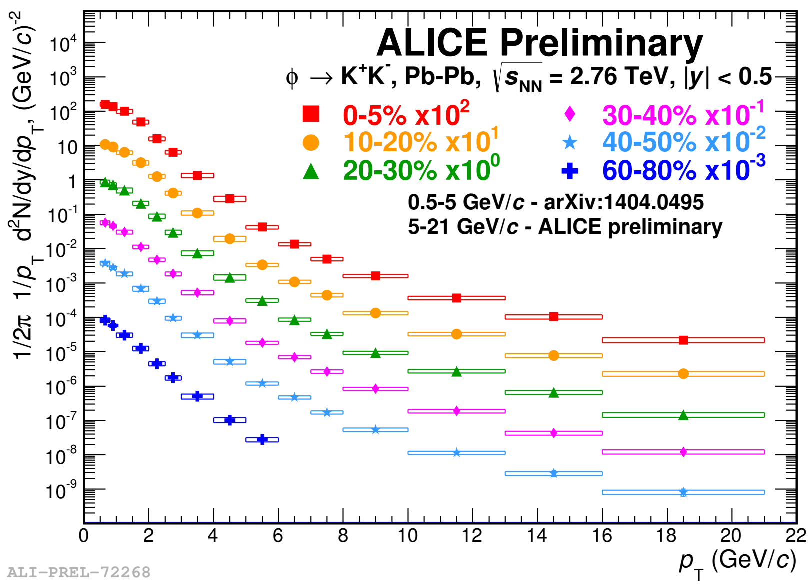


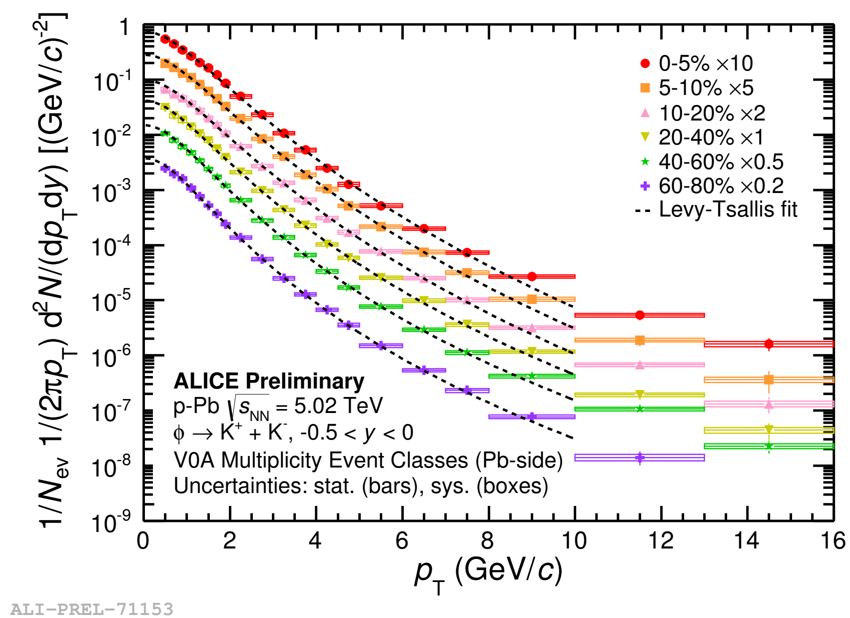


ϕ Peaks and Spectra





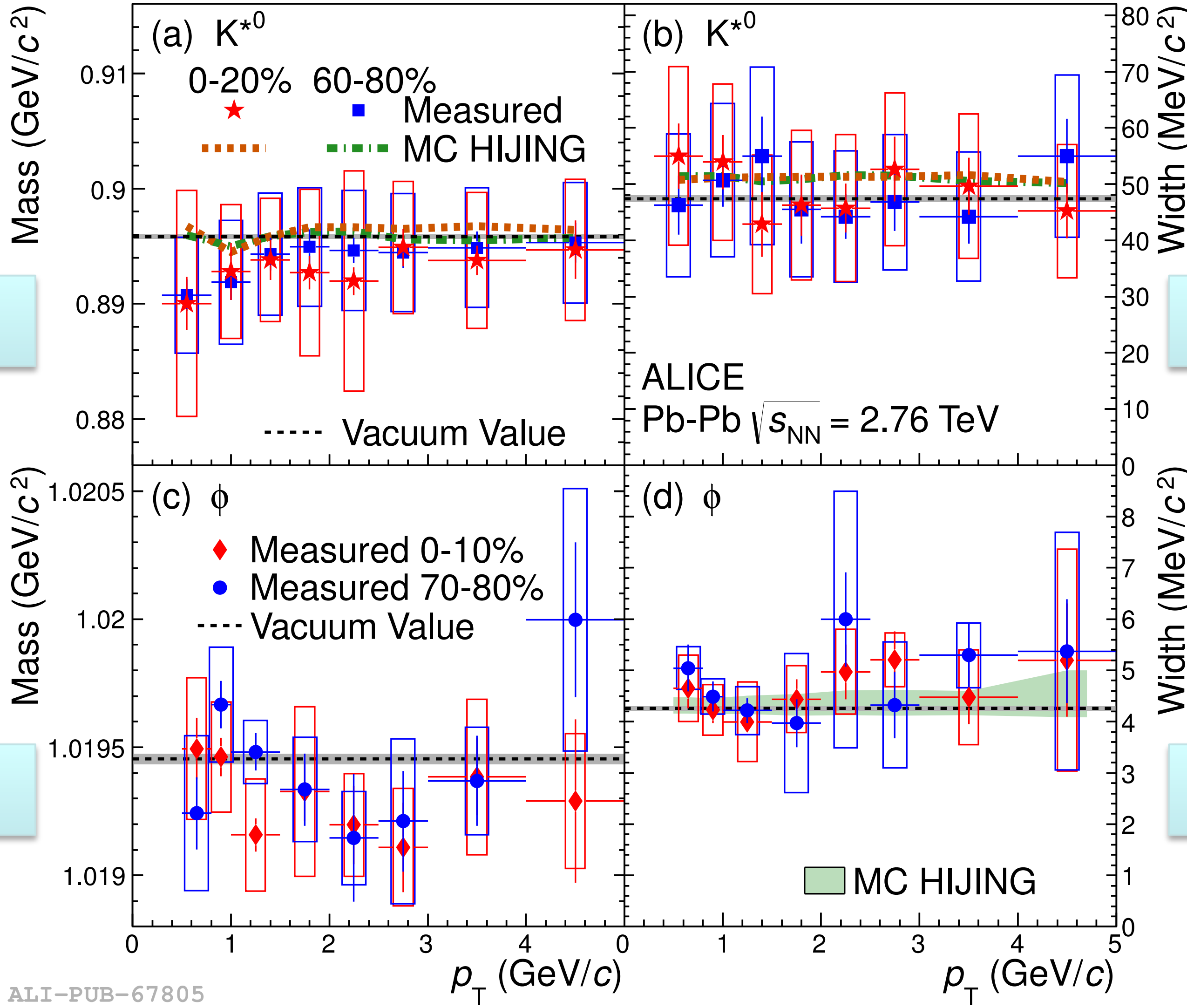




Mass and Width (Pb–Pb)

K*0 Mass

K*0 Width



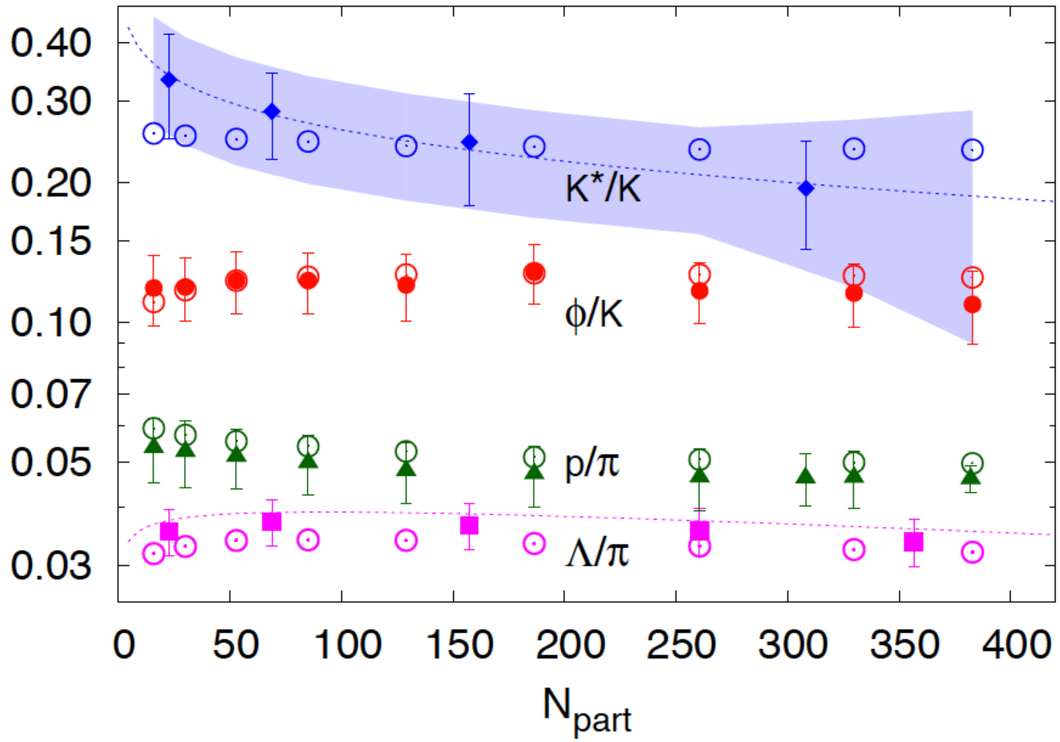
ϕ Mass

ϕ Width

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

Non-equilibrium Model

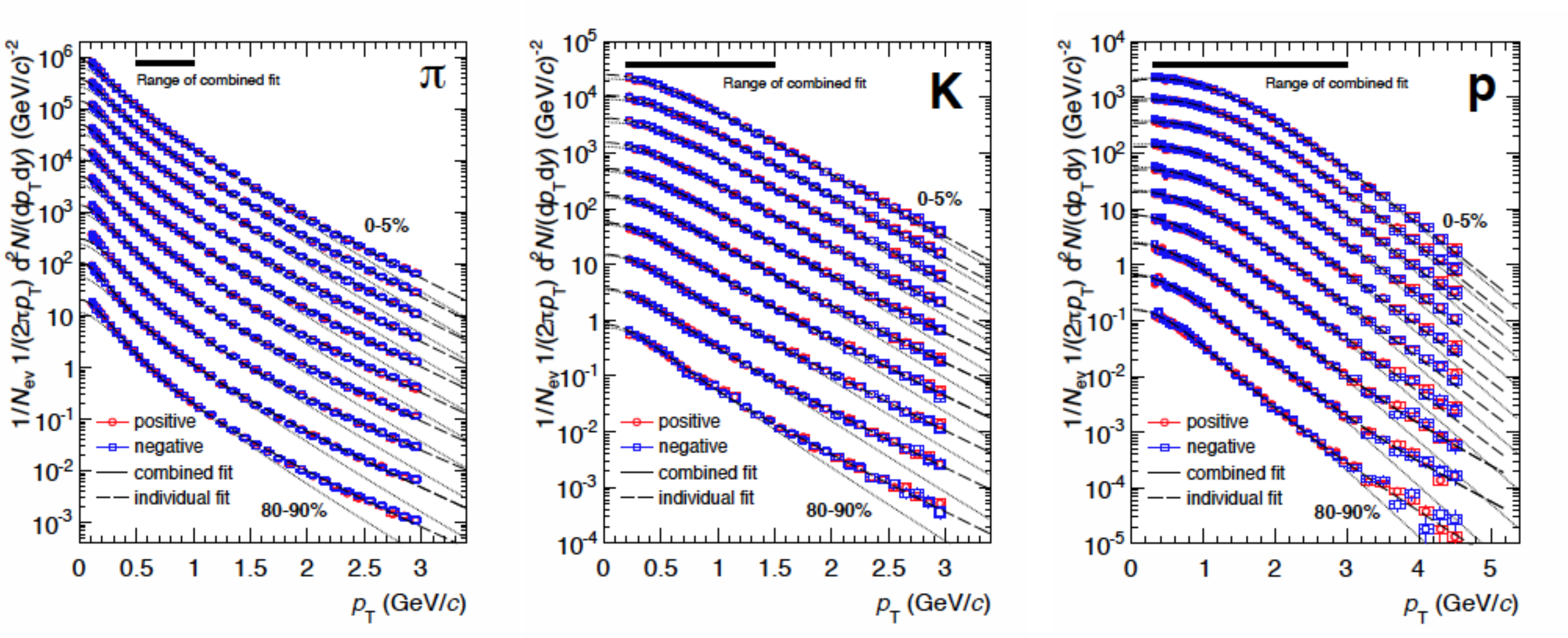
- Chemical non-equilibrium statistical hadronization model
  - *Phys. Rev. C* **88**, 034907 (2013)
- Factors $\gamma_q \neq 1$ and $\gamma_s \neq 1$ that modify u/d and s pair yields w.r.t. equilibrium values
  - $\gamma_q \neq 1$ when "source of hadrons disintegrates faster than the time necessary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



Uses preliminary ALICE K^{*0}/K, ϕ/K

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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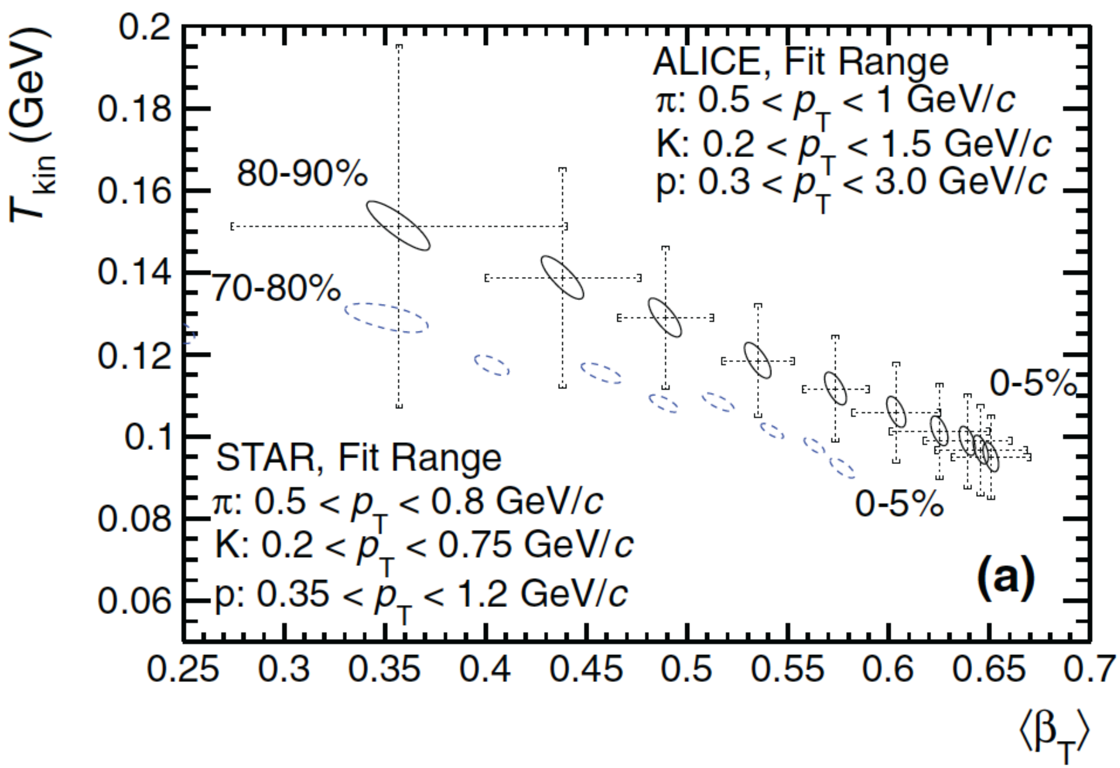

Resonance Suppression

- 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

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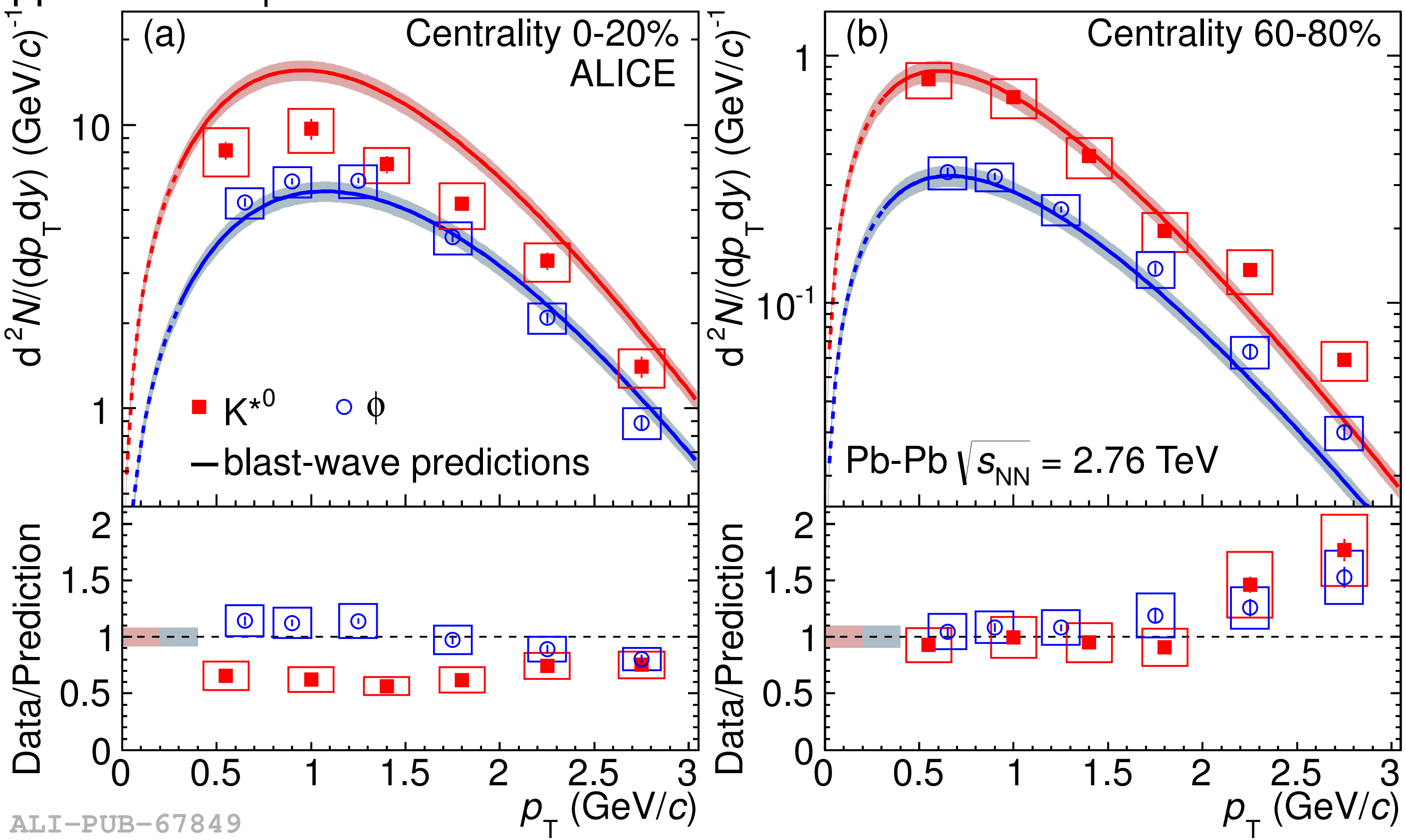
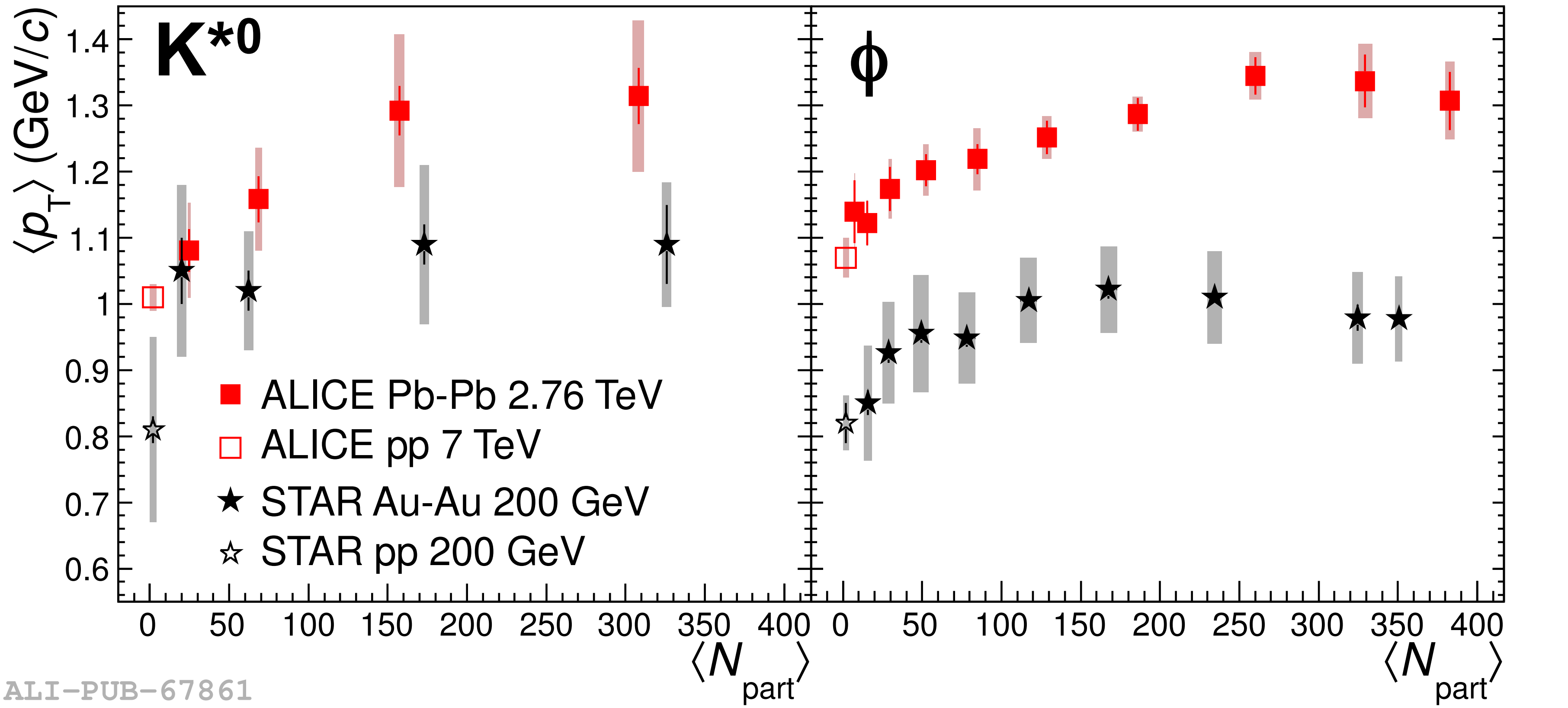


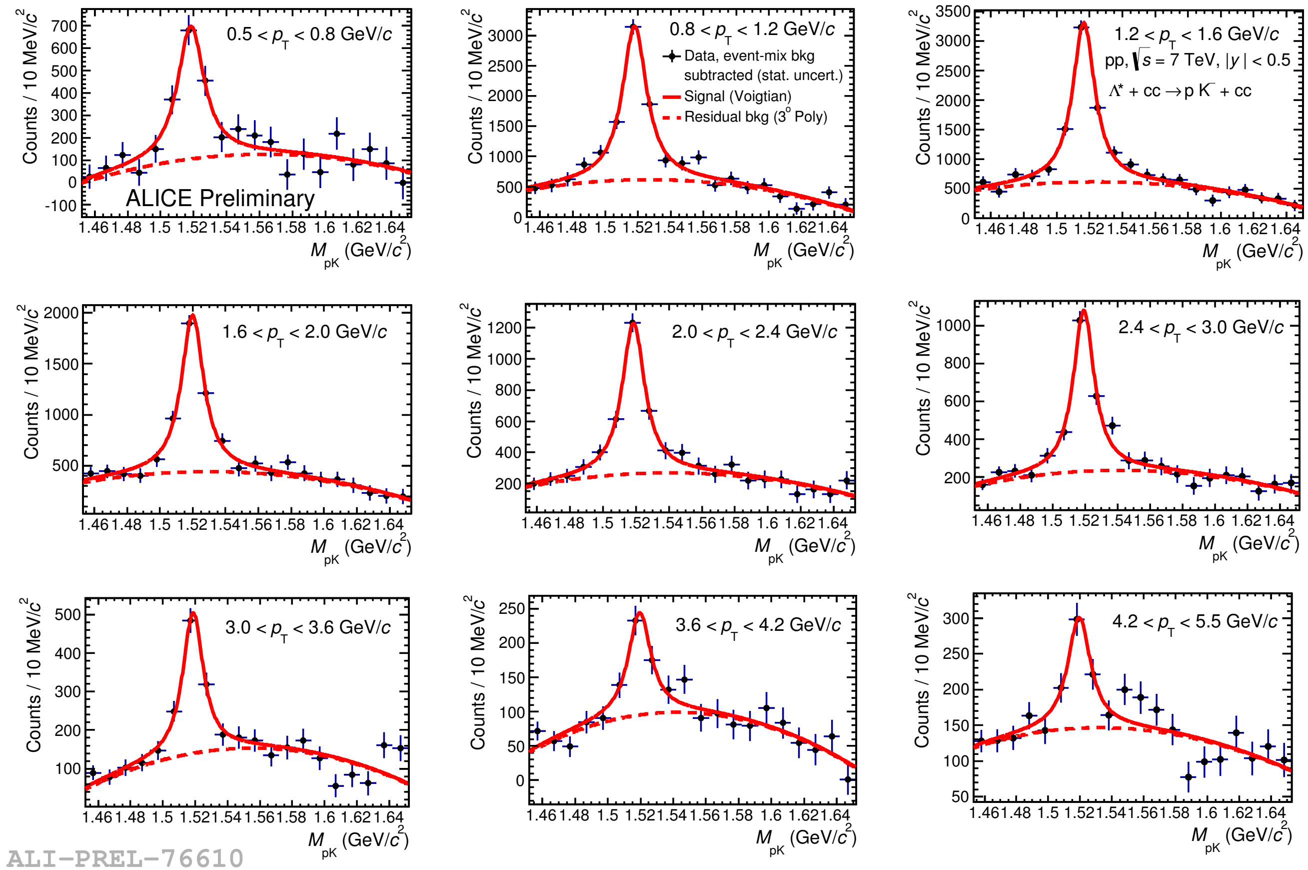
Mean p_T in A–A

- $<p_T>$ appears to increase for more central Pb–Pb collisions w.r.t. peripheral and pp
- $<p_T>$ 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 this poster from 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 this poster from Quark Matter 2014: https://indico.cern.ch/event/219436/session/2/contribution/196/material/slides/0.pdf