Resonance production in pp, p-Pb and Pb-Pb collisions measured by ALICE at the LHC

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JOINT INSTITUTE FOR NUCLEAR RESEARCH
Strangeness in Quark Matter
06 July - 11 July 2015
SQM DUBNA 2015

Outline

- Motivations
- Results on K^{*0} and ϕ production in pp, p-Pb and Pb-Pb:
  - ✓ p_T spectra, $\langle p_T \rangle$, dN/dy
  - ✓ particle ratios
  - ✓ nuclear modification factors
- Summary & Outlook

Motivation

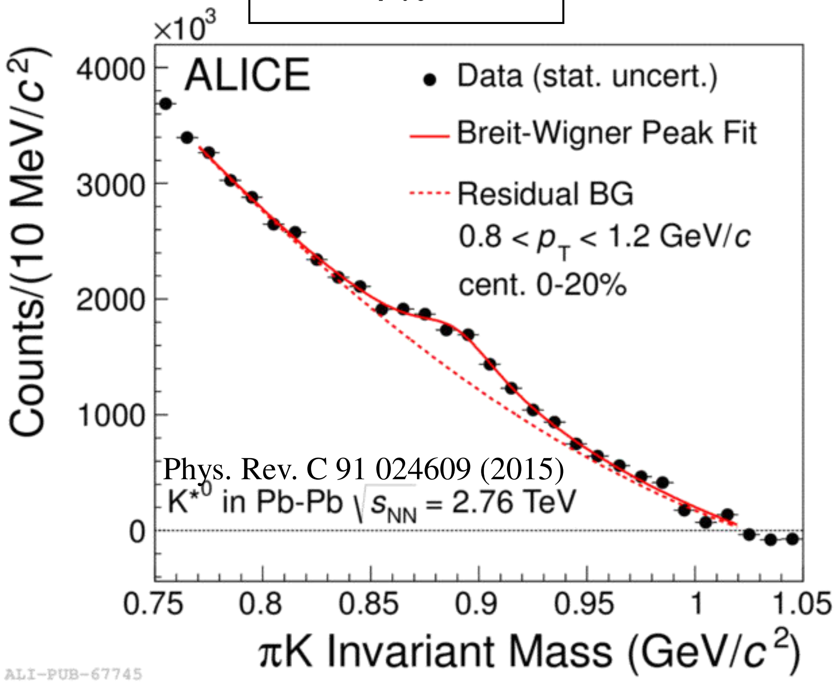
- Resonances are excited hadronic states with lifetimes comparable to that of the fireball
- Copiously produced and measurable in different collision systems even at top multiplicities
- pp: baseline measurements, tests of QCD
- p-Pb: nPDFs, parton rescattering, onset of collectivity
- Pb-Pb: properties of hot and dense matter
  - ✓ parton energy loss, flavor dependence
  - ✓ baryon anomaly, hydro vs. recombination
  - ✓ hadronic phase: lifetime, density
  - ✓ chiral symmetry partial restoration, mass/width modifications

→ *ALICE does not observe any significant modifications of K^{*0} and ϕ line shapes from pp to central Pb-Pb collisions*

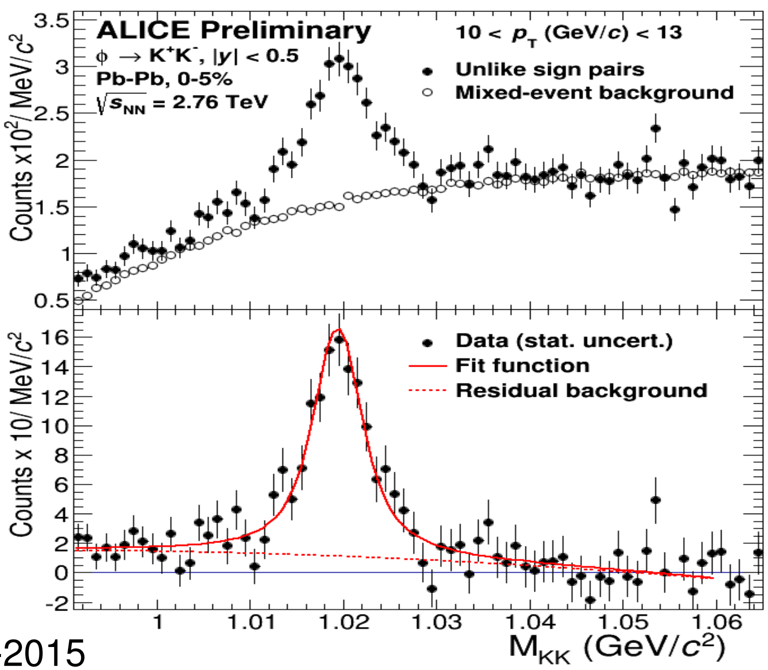
Resonance reconstruction

- Hadronic decays with large BR and charged particles in the final state
  - ✓ $\phi \to K^+K^-$ (BR ~ 49 %); $K^{*0} \to \pi^{+-}K^{-+}$ (BR ~ 67%)
- Different collision systems and energies:
  - ✓ pp at $\sqrt{s}$ = 2.76 and 7 TeV
  - ✓ p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV, different multiplicities
  - ✓ Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV, different centralities

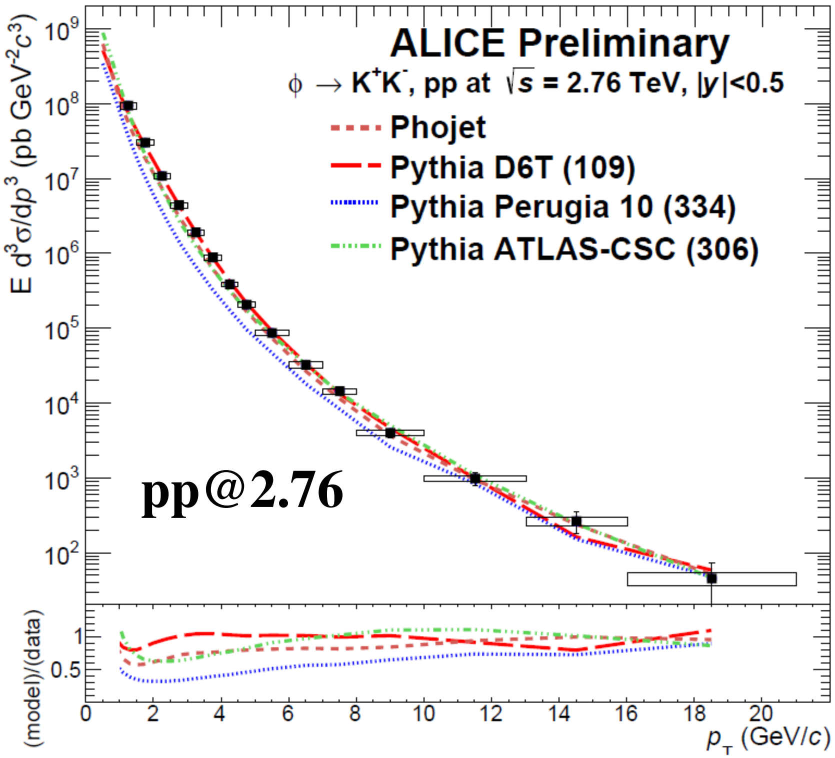
$K^{*0} \to \pi^{+-}K^{-+}$



$\phi \to K^+K^-$



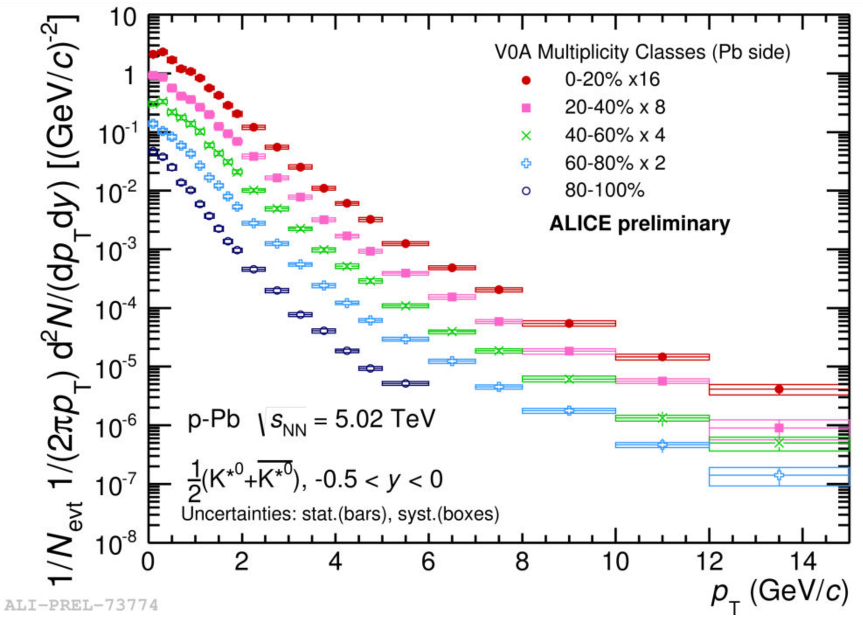
K^{*0} and ϕ spectra in pp collisions



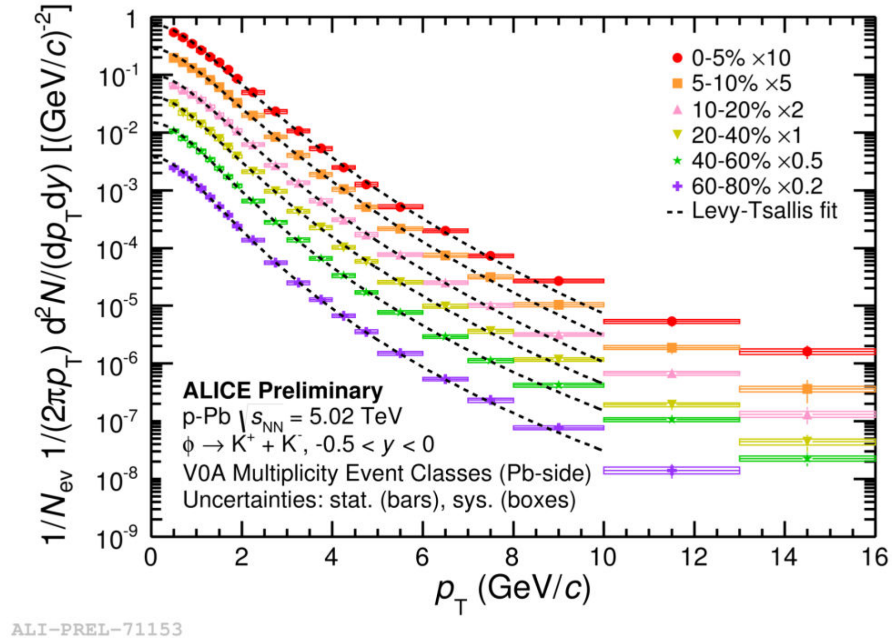
- First measurement of ϕ meson production at high p_T, up to 21 GeV/c in pp@2.76 TeV
- Pythia and Phojet are consistent with a measurement at high p_T
- ϕ and K^{*0} production was previously measured in pp@7 TeV (Eur.Phys.J. C72:2183, 2012)
- Used as a reference for calculation of nuclear modification factors (R_{pPb} and R_{AA})

K^{*0} and ϕ spectra in p-Pb@5.02 TeV

$K^{*0} \rightarrow \pi^{+-} K^{-+}$



$\phi \rightarrow K^{+}K^{-}$

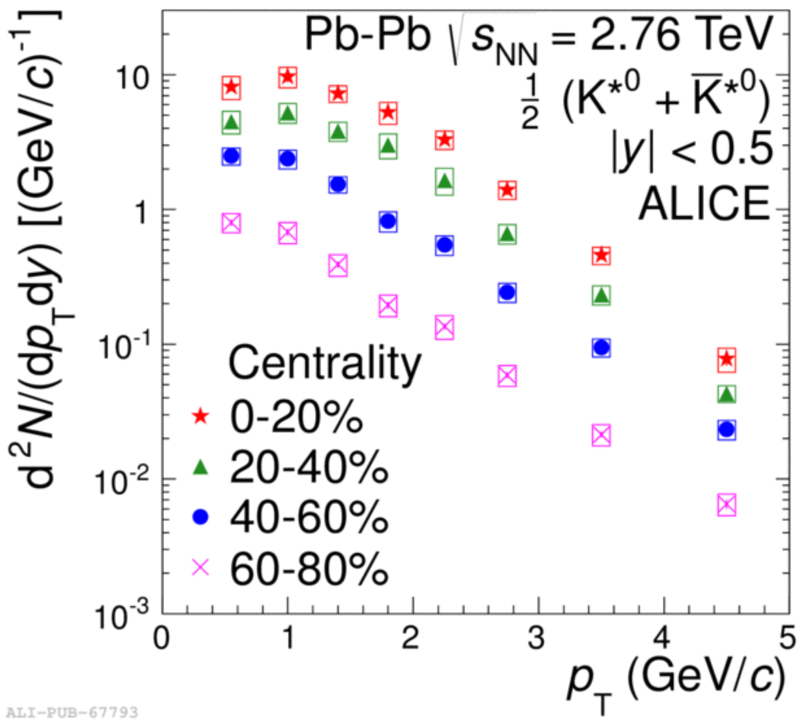


- K^{*0} and ϕ production is measured in a wide p_T range:
  - ✓ K^{*0}: 0-15 GeV/c (TPC + TOF PID)
  - ✓ ϕ: 0.2-3 GeV/c (TPC + TOF PID) + 3-16(21) GeV/c (no PID)
- Measurements performed in different multiplicity bins

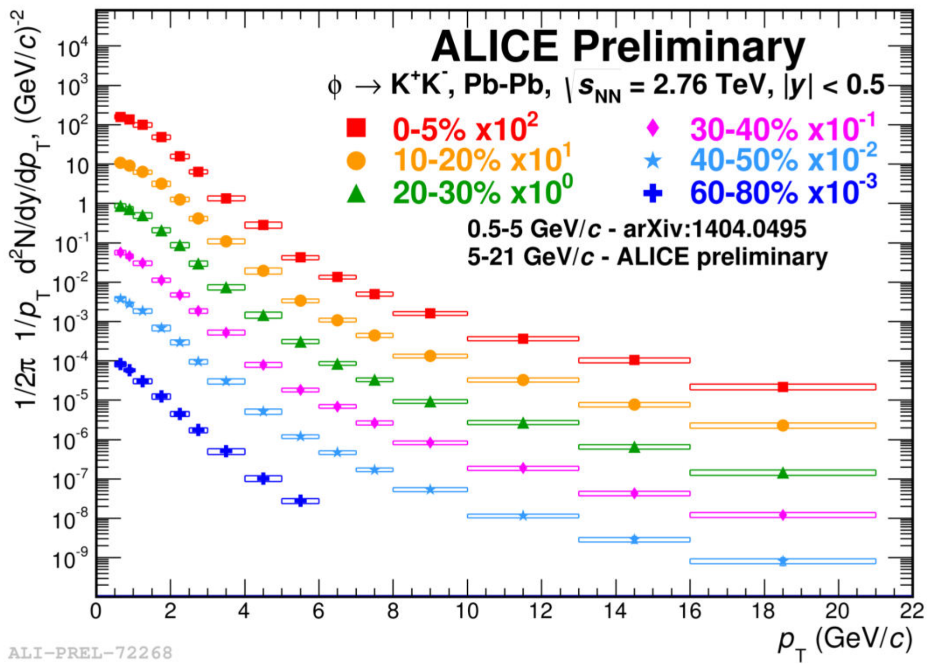
K^{*0} and ϕ spectra in Pb-Pb@2.76 TeV

$K^{*0} \rightarrow \pi^{+-}K^{-+}$

Phys. Rev. C 91 024609 (2015)



$\phi \rightarrow K^+K^-$



- 2010 Pb-Pb data analysis: $p_T \leq 5$ GeV/c
- 2011 Pb-Pb data analysis: extends p_T coverage up to 21 GeV/c for ϕ

Mean p_T: Pb-Pb collisions

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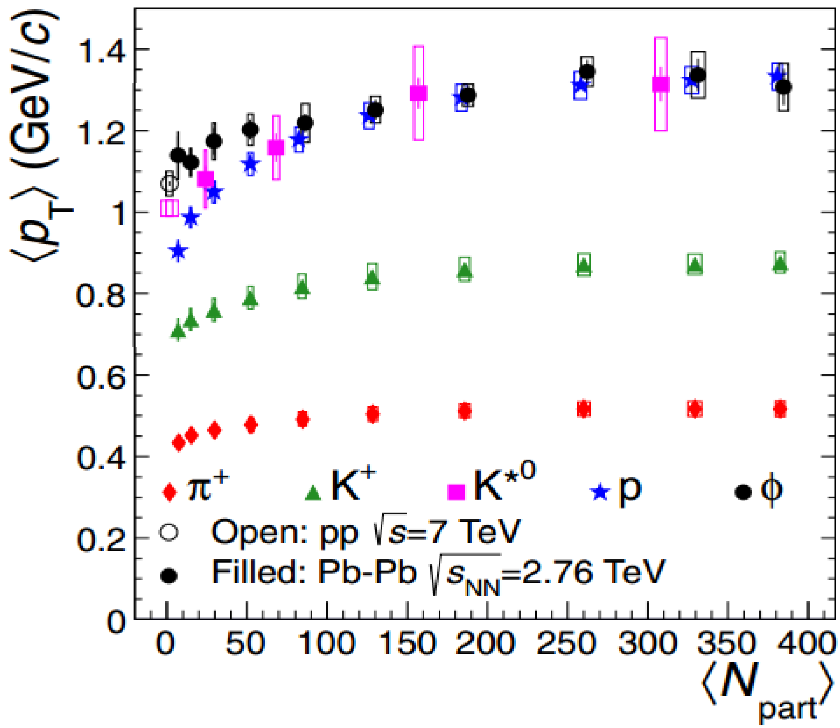
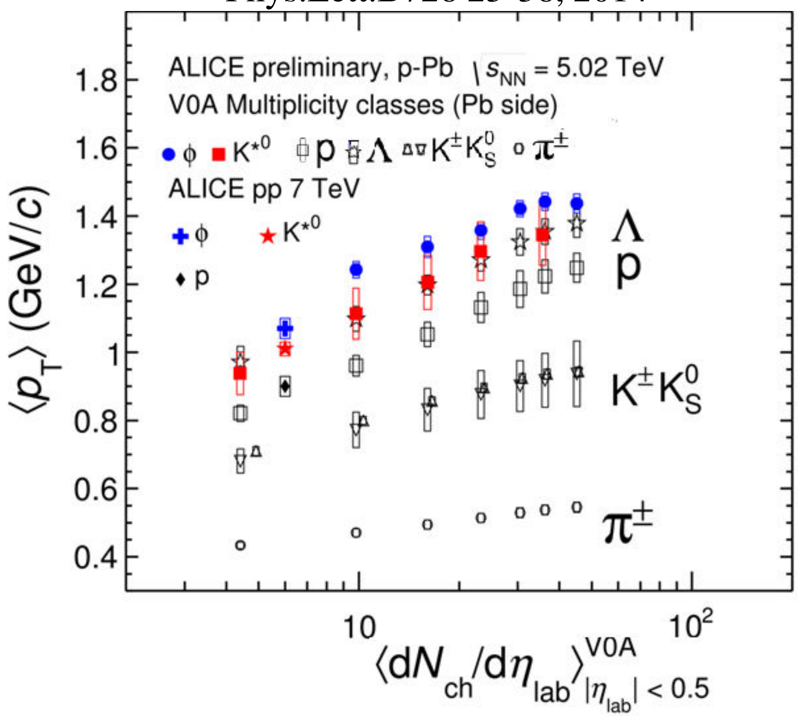
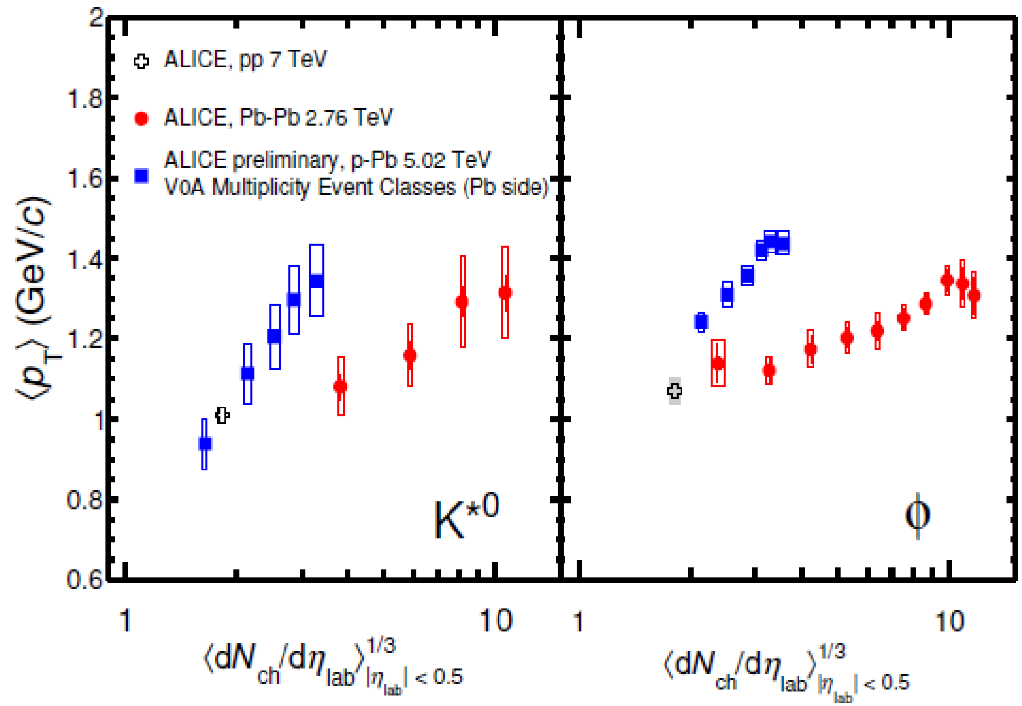


- Mass ordering of <p_T> is observed
- <p_T> for K^{*0}, ϕ and p is similar in central collisions → consistent with hydro
- Splitting of <p_T> in peripheral collisions, protons are lower
- <p_T> increases by 20% for mesons and by 50% for protons from peripheral to central

Mean p_T: pp, p-Pb and Pb-Pb collisions

Phys.Lett.B728 25-38, 2014





- Approximate mass ordering but $<p_T>$ for K^{*0} and ϕ is larger than for protons
  → baryon/meson difference ?
- $<p_T>$ in p–Pb increases more rapidly with multiplicity than in Pb–Pb
- In highest multiplicity p-Pb collisions $<p_T>$ reaches similar values to central Pb–Pb
  → stronger radial flow, different particle production mechanisms ?

Particle ratios and hadronic phase

- Reconstructed resonance yields in heavy ion collisions are defined by:
  - ✓ resonance yields at chemical freeze-out
  - ✓ hadronic processes between chemical and kinetic freeze-outs
    → rescattering of daughter particles (loss of signal)
    → regeneration: $\pi K \rightarrow K^{*0}$, $KK \rightarrow \phi$ etc. (increased yields)
- Effect of hadronic processes depends on:
  - ✓ lifetime of hadronic phase
  - ✓ resonance lifetime
  - ✓ scattering cross sections
- Resonances with lifetimes comparable to that of the fireball are a very promising tool to study properties of the hadronic phase

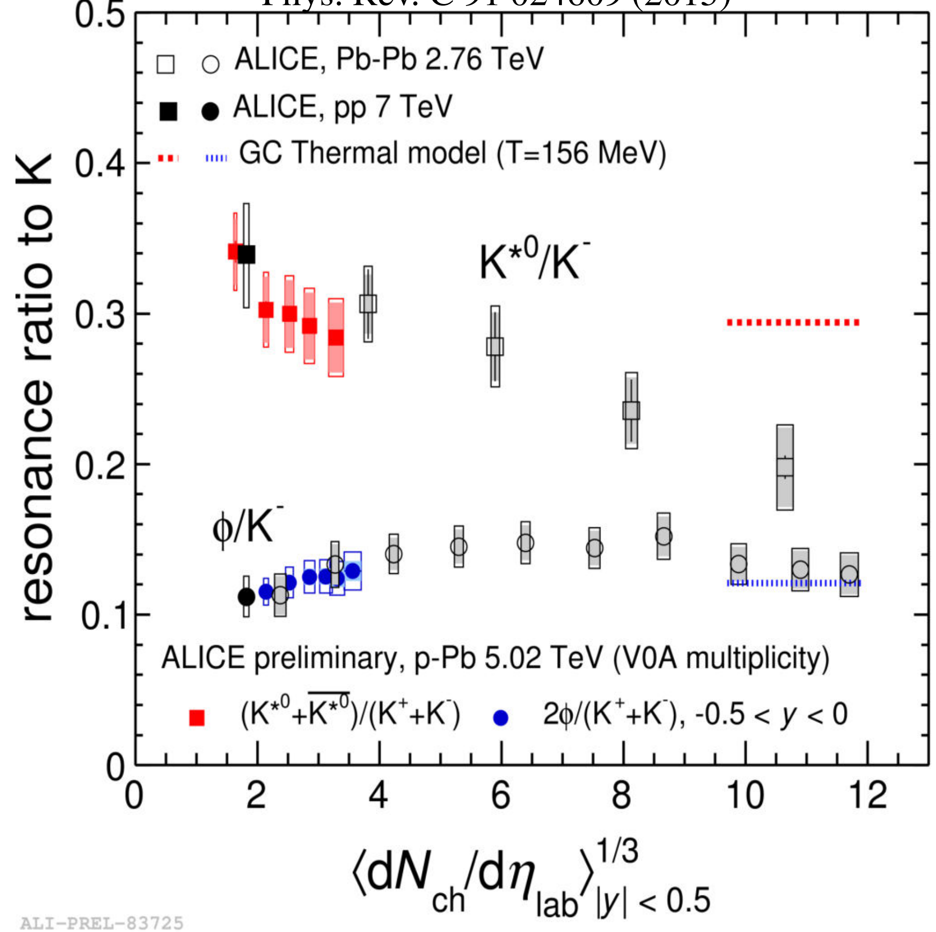
	ρ(770)	**K*(892)**	**Σ(1385)**	**Λ(1520)**	**Ξ(1530)**	**ϕ(1020)**
cτ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi \sigma_\pi$	$\sigma_\pi \sigma_K$	$\sigma_\pi \sigma_\Lambda$	$\sigma_K \sigma_p$	$\sigma_\pi \sigma_\Xi$	$\sigma_K \sigma_K$

- UrQMD: rescattering and regeneration are most prominent at $p_T < 2$ GeV/c
  → focus is on low p_T measurements

Particle ratios: K^{*0}/K, ϕ/K

- ϕ/K:
  - ✓ no strong centrality dependence
  - ✓ consistent for pp, p-Pb and Pb-Pb
  - ✓ consistent with thermal models*
- K^{*0}/K:
  - ✓ significant suppression going from pp and peripheral Pb-Pb to central Pb-Pb collisions
  - ✓ Central Pb-Pb results are inconsistent with thermal models [1]
- Drop of K^{*0}/K ratio is consistent with expectations from rescattering of decay products in hadronic phase
- No such effect for ϕ/K because of much longer lifetime, $\tau(\phi) >> \tau(K^{*0})$

Eur. Phys. J. C 72 2183 (2012)
Phys. Rev. C 91 024609 (2015)



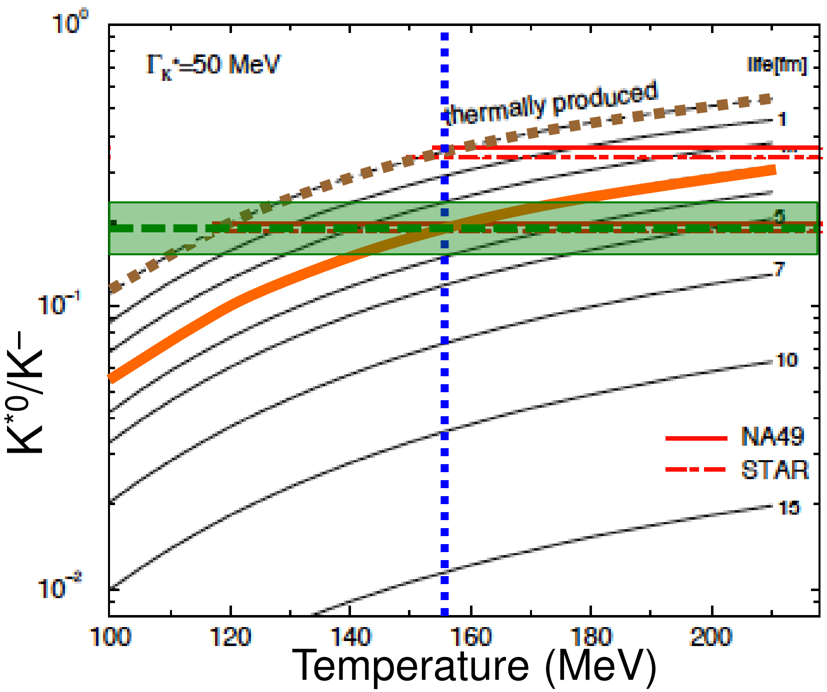
[1] Andronic et al., J. Phys. G38(2011)124081

Hadronic phase

- Simple model:
  - ✓ all K^{*0} that decayed before kinetic freeze-out are lost due to rescattering
  - ✓ regeneration and time dilation are ignored
  - ✓ Yield(central Pb-Pb) = Yield(pp)·exp(-Δt/τ), τ = 4.16 fm/*c* → Δt = 2.25±0.75 fm/*c*
  - ✓ Lower limit for hadronic phase lifetime: **Δt > 1.5 fm/*c***

- More advanced models [1,2] couple particle ratios to temperature and hadronic phase lifetime Δt:
  - ✓ T = 156 MeV from thermal fits
  - ✓ K^{*0}/K= 0.2 ±0.01 (stat) ± 0.03 (syst)

  → **Δt > 2 fm/*c***



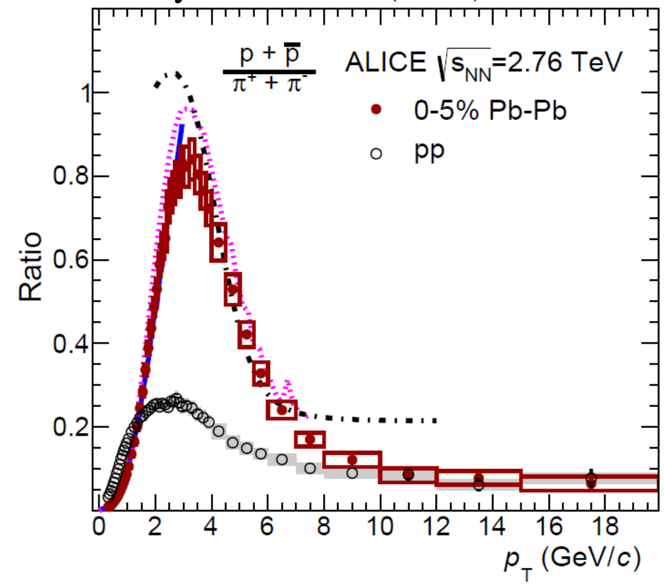
[1] G. Torrieri and J. Rafelski, J. Phys. G 28, 1911 (2002)

[2] C. Markert et al., arXiv:hep-ph/0206260v2 (2002)

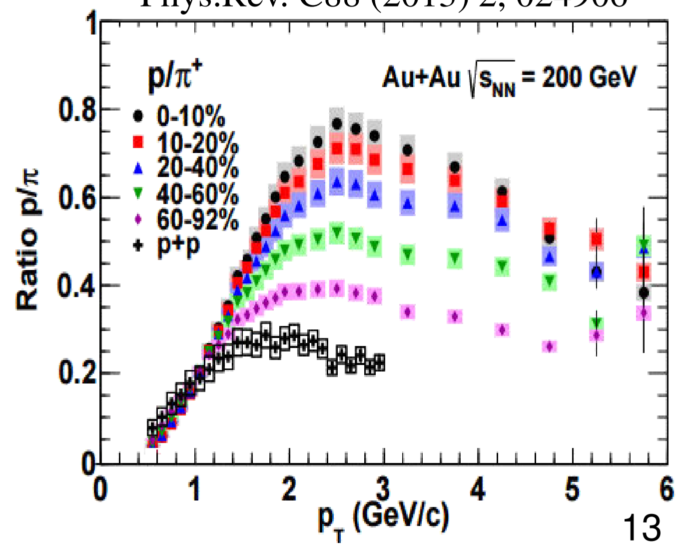
Intermediate p_T range

- Baryon anomaly region manifested in increased p/π and Λ/K_s^0 ratios at RHIC and the LHC
- Driving force of enhancement is not yet fully understood:
  - ✓ particle mass (hydro)?
  - ✓ quark count (baryons vs. mesons)?
- ϕ and K^{*0} are well suited for tests as mesons with masses very close to that of a proton:
  - ✓ $\Delta m_\phi \sim 80$ MeV/c^2, $\Delta m_{K^{*0}} \sim -45$ MeV/c^2

Phys.Lett. B736 (2014) 196-207

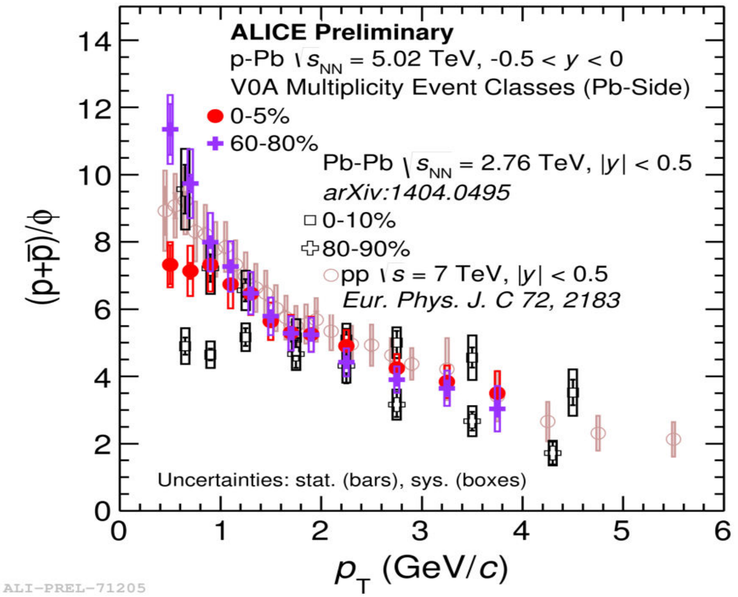


Phys.Rev. C88 (2013) 2, 024906

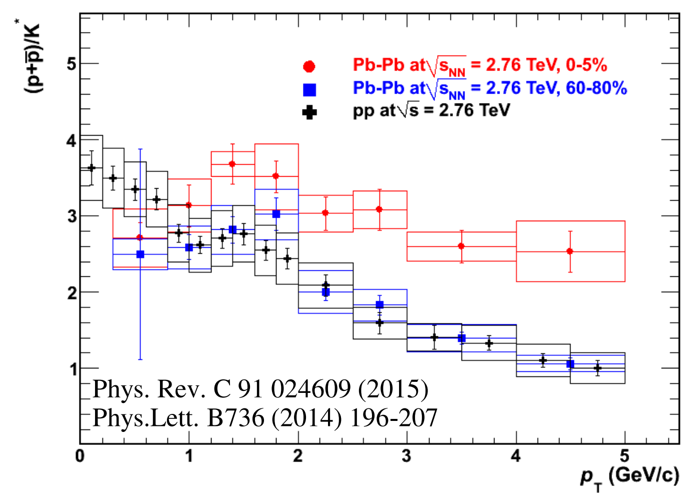


Particle ratios: p/$\phi(p_T)$, p/$K^{*0}(p_T)$

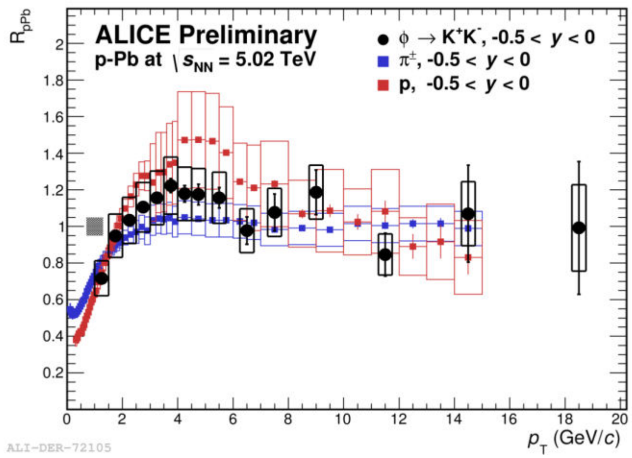
- Both ratios, p/$\phi(p_T)$ and p/$K^{*0}(p_T)$ show clear centrality dependence and flattening in most central Pb-Pb collisions
  → similar spectral shapes of p, K^{*0} and ϕ
  → shapes are determined by masses

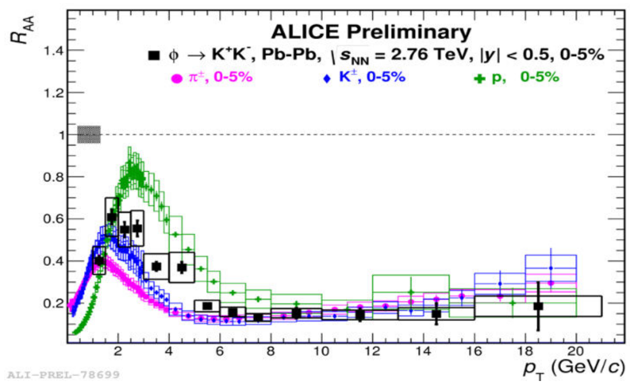


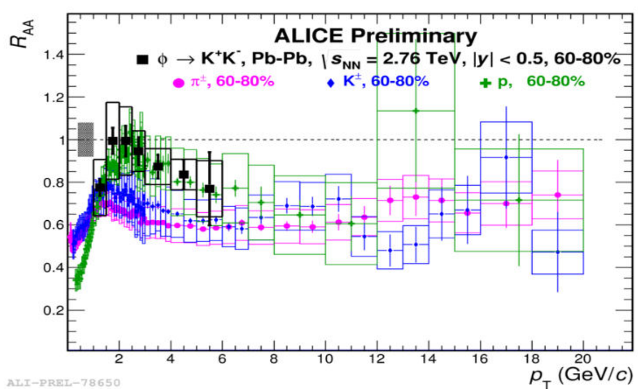
- p/ϕ in p-Pb 0-5% indicates flattening of the ratio at $p_T < 1.5$ GeV/c
  → onset of collective behaviour in p-Pb?



Nuclear modification factors







- Nuclear modification factor: $R_{AA}(p_T) = \dfrac{Yield_{A-A}(p_T)}{Yield_{pp}(p_T) \cdot N_{coll}}$

- p-Pb:
  - ✓ R_{pPb} ~ 1 at high p_T > 6-8 GeV/c
  - ✓ Cronin enhancement at intermediate p_T
  - ✓ species dependence of enhancement
    → mass or baryon/meson effect ?
  - ✓ magnitude of enhancement is smaller at the LHC compared to RHIC and SPS

- Pb-Pb:
  - hadrons are similarly suppressed at p_T > 10 GeV/c
  - species dependence of R_{AA} at intermediate p_T
  - R_{AA} of ϕ approaches R_{AA} of proton as centrality evolves from central to peripheral collisions
  - In most central collisions difference of R_{AA} for ϕ and p is governed by difference of pp references (p/ϕ ratio is flat)

Summary

K^{*0} and ϕ have been measured in a wide momentum range in
pp, p-Pb and Pb-Pb collisions at the LHC, as a function of multiplicity (centrality)

- ✓ In pp, p-Pb and Pb-Pb we observe clear evolution of production spectra shapes with multiplicity reflected in change of $\langle p_T \rangle$. In pp and p-Pb $\langle p_T \rangle$ for resonances does not follow the mass ordering while it is the case for central Pb-Pb.
- ✓ We observe signs of rescattering effect in the hadronic phase, K^{*0}/K ratio is significantly suppressed in central Pb-Pb while ϕ/K ratio stays unchanged. Lower limit for the hadronic phase lifetime $\Delta t > 1.5\text{-}2$ fm/c.
- ✓ p/ϕ and p/K^{*0} ratios indicate that shapes of particle spectra are mostly defined by particle masses that is consistent with hydrodynamical models. The flattening of p/ϕ in central p-Pb at low p_T can be a hint of onset of collective effects usually expected for heavy ion collisions.
- ✓ In central Pb-Pb production of all hadrons is similarly suppressed at high transverse momentum.
- ✓ In p-Pb we observe a species dependent Cronin effect at intermediate p_T similar to that observed at lower collision energies at RHIC and SPS but smaller in amplitude.

Backup slides

ALICE experiment

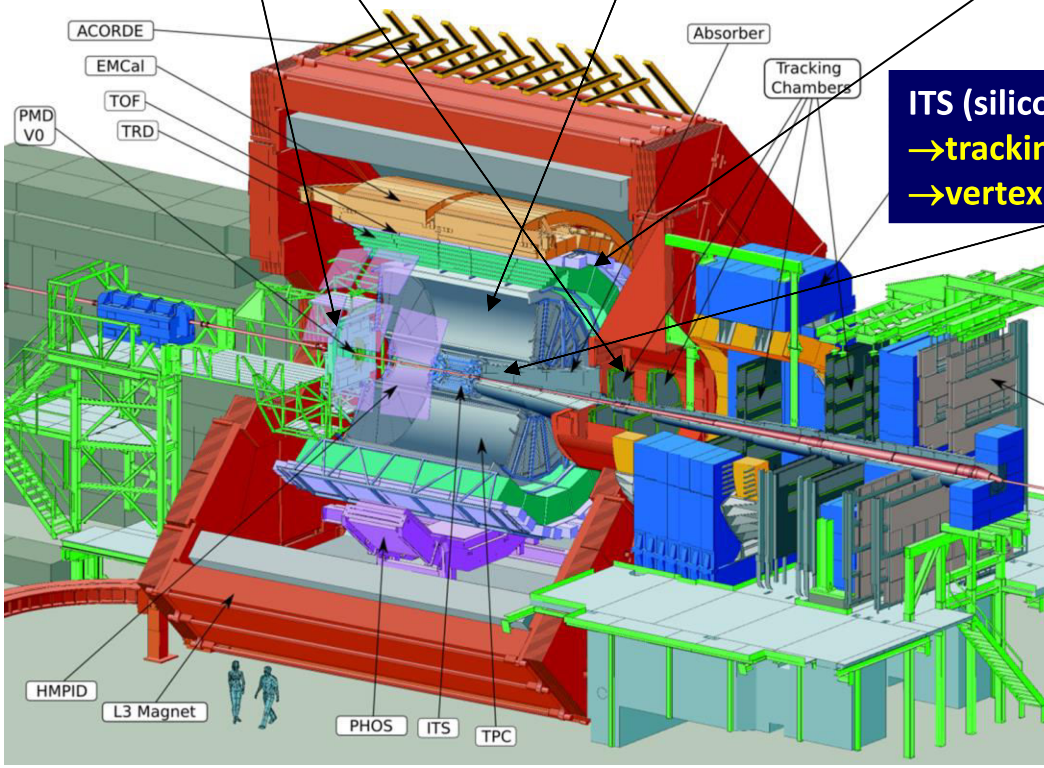
Int. J. Mod. Phys. A 29 1430044 (2014)

VZERO scintillator detectors:
→**centrality** determination in Pb-Pb
→**multiplicity event classes** in p-Pb

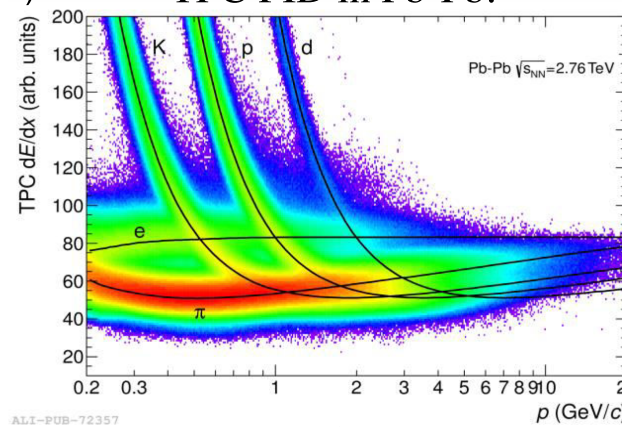
TPC:
→tracking
→PID through dE/dx

TOF:
→PID through momentum and ToF

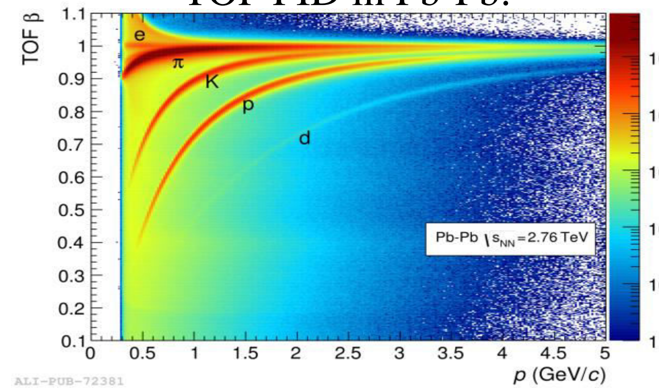
ITS (silicon):
→tracking
→vertexing



TPC PID in Pb-Pb:



TOF PID in Pb-Pb:



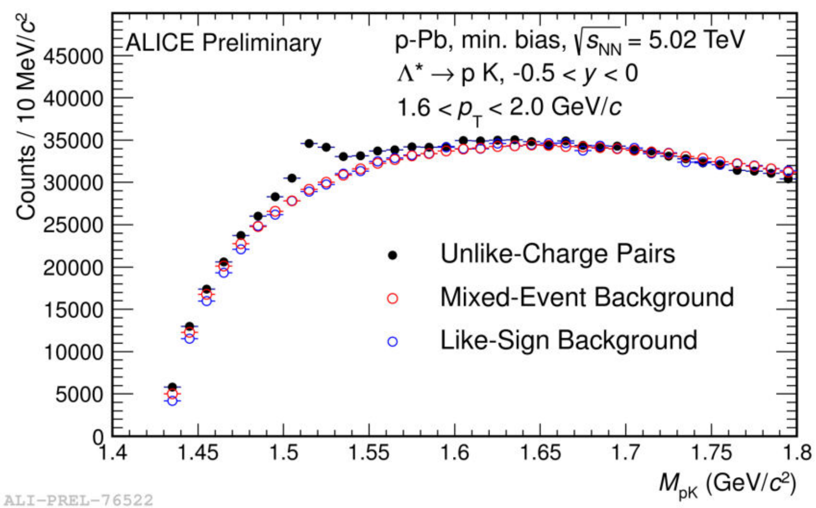
p_T ranges for 3σ separation

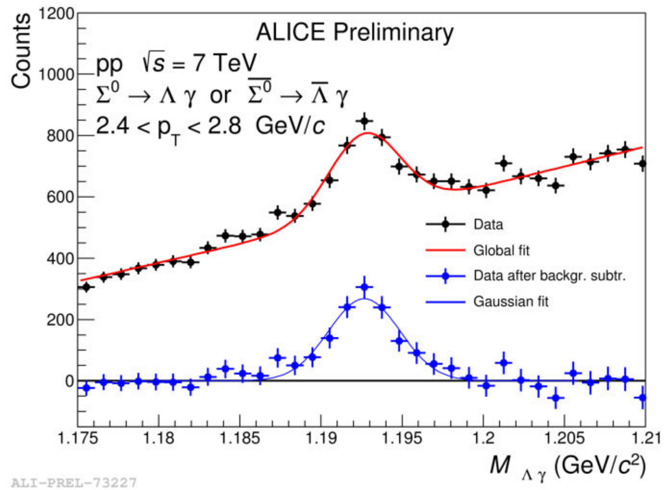
	TPC	TOF
π	0.2 - 0.7	0.5 - 2.0
K	0.3 - 0.6	0.5 - 2.0
p	0.5 - 1.0	0.5 - 2.5

Outlook

- New analyses are ongoing in pp, p-Pb and Pb-Pb using available data sets:
  - ✓ finalizing high-p_T results for ϕ and K*0
  - ✓ new resonances: ρ, Λ^*, $\Sigma^{*\pm}$, Σ^0, Ξ^{*0} having different lifetimes

→ better understanding of hadronic phase, parton energy loss, baryon anomaly …



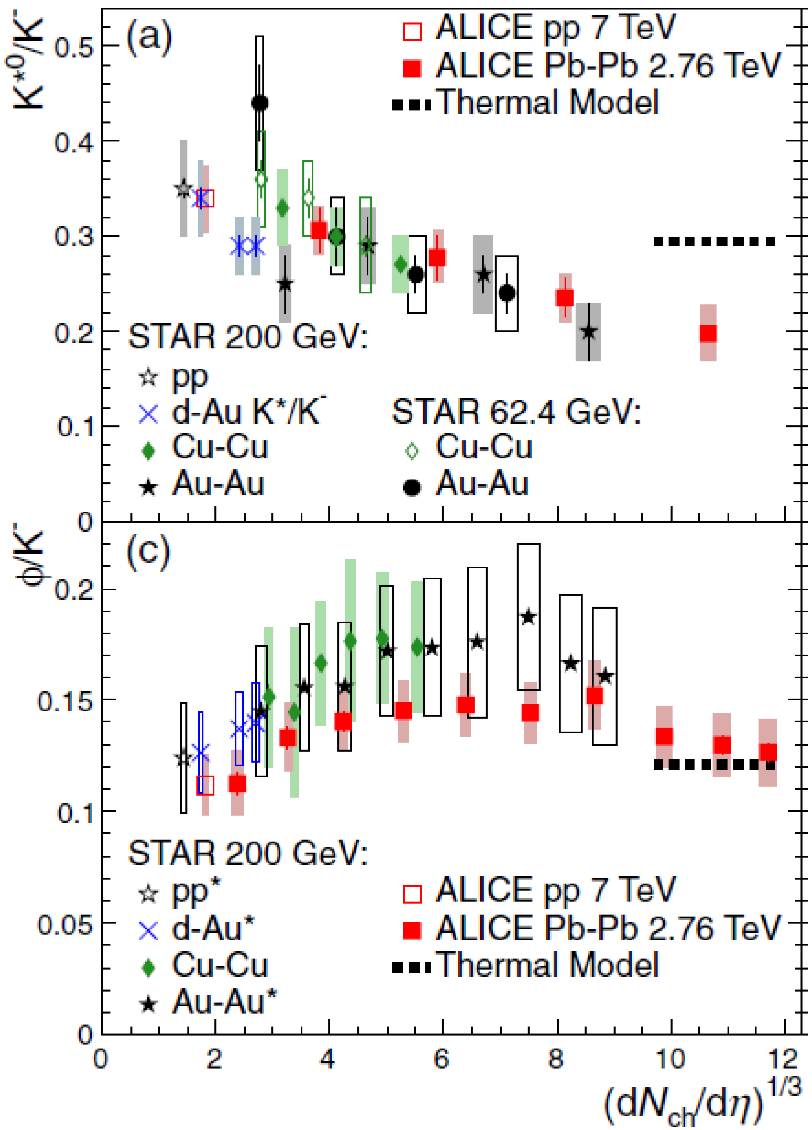


- New data samples in Run2:
  - ✓ hotter and denser matter
  - ✓ smaller uncertainties from larger data sets

Comparison to RHIC

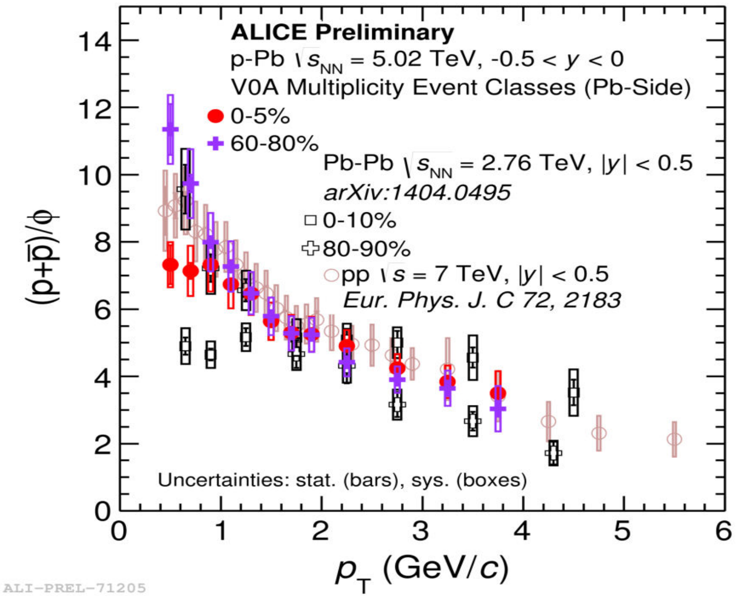
- ϕ/K and K*0/K follow the same trend at RHIC and the LHC, ratios are consistent within uncertainties
- Results for ρ and Λ* are coming soon
- Particle ratios compared to model predictions can help to better understand properties of the hadronic phase

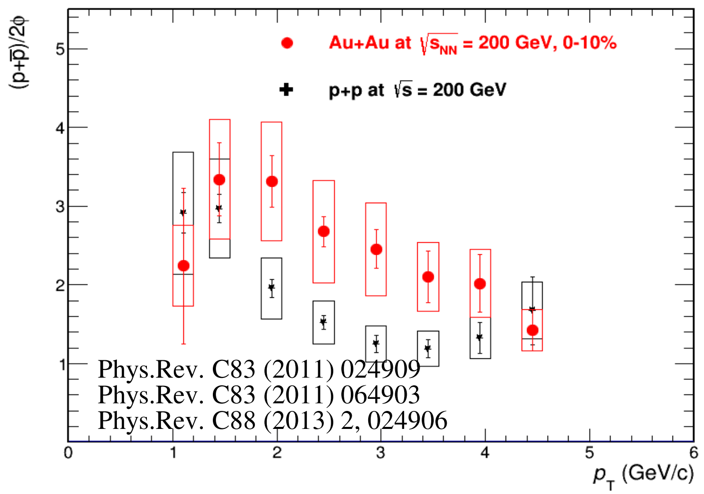
Phys. Rev. C 91 024609 (2015)



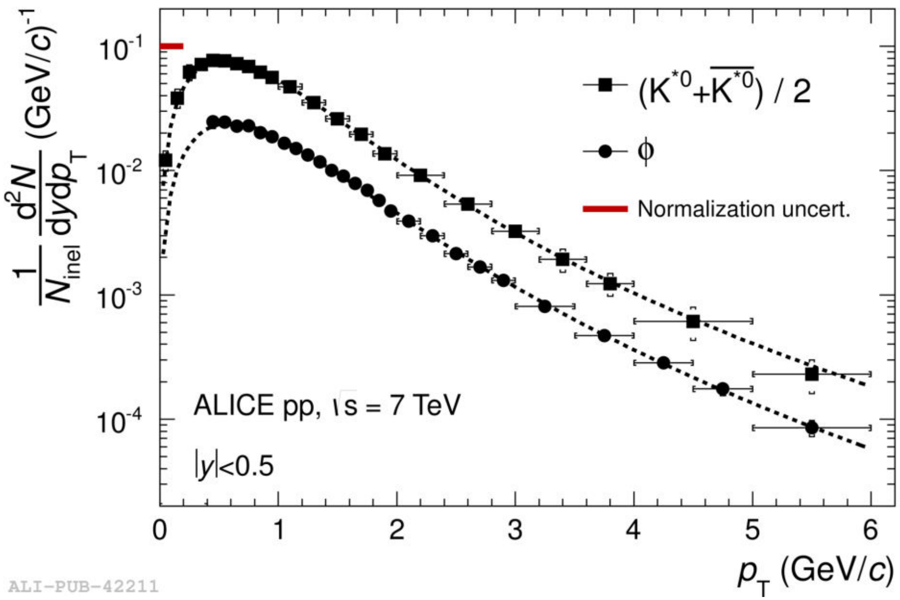
Particle ratios: p/$\phi(p_T)$, p/K*0(p_T)

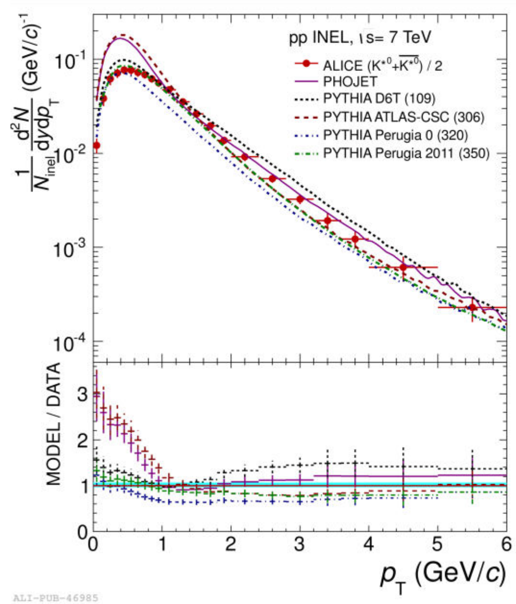
- Both ratios, p/$\phi(p_T)$ and p/K*0(p_T) show clear centrality dependence and flattening in most central Pb-Pb collisions
  →similar spectral shapes of p, K*0 and ϕ
  → shapes are determined by masses
- Similar flattening for p/$\phi(p_T)$ at lower $\sqrt{s_{NN}}$ at RHIC although in narrower p_T range

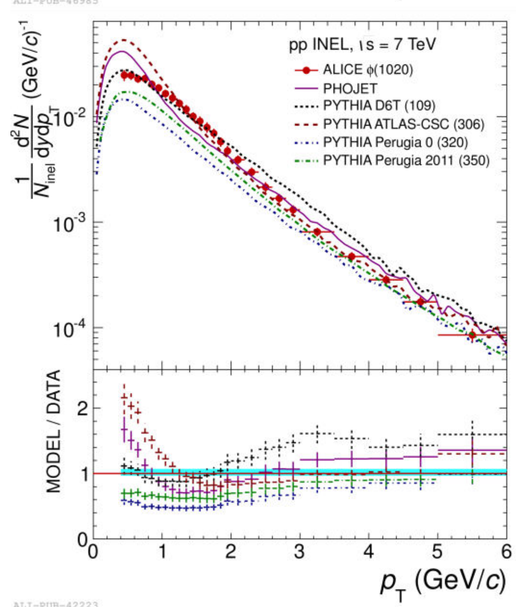




ϕ And K^{*0} in pp@7







Nuclear modification factor: R_{pA}

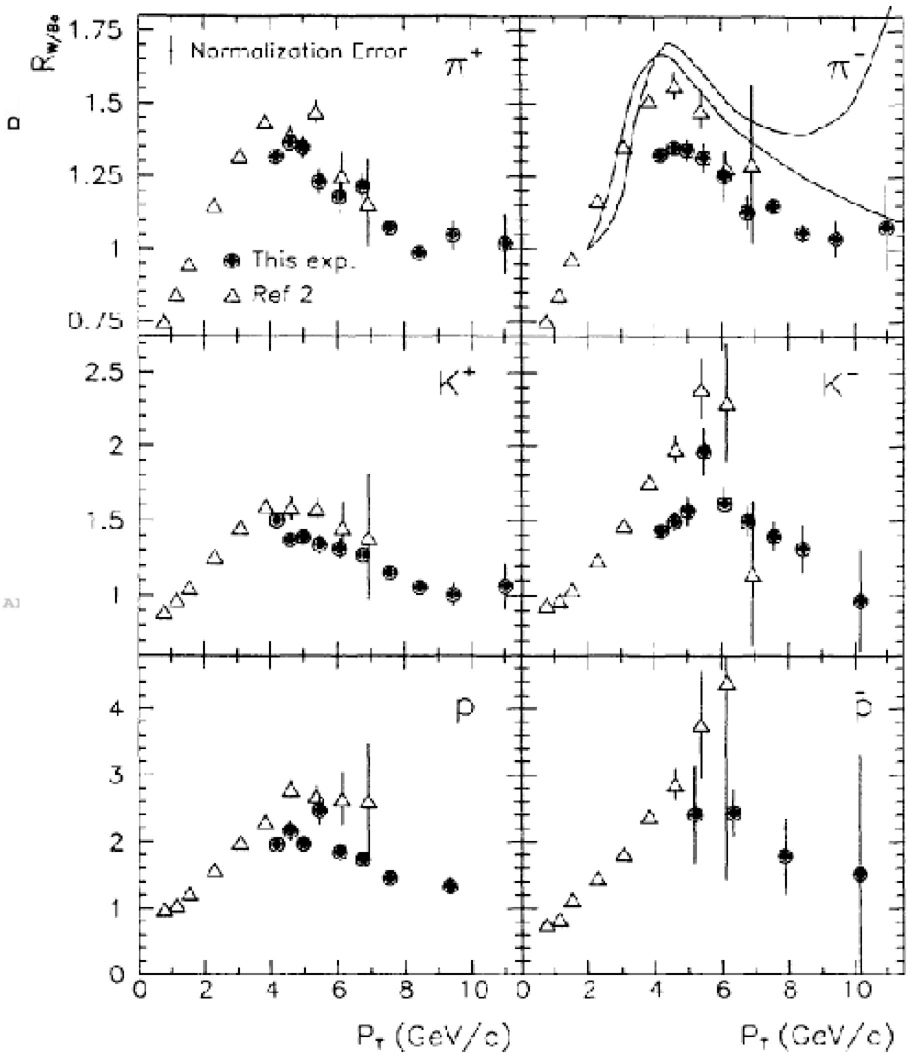
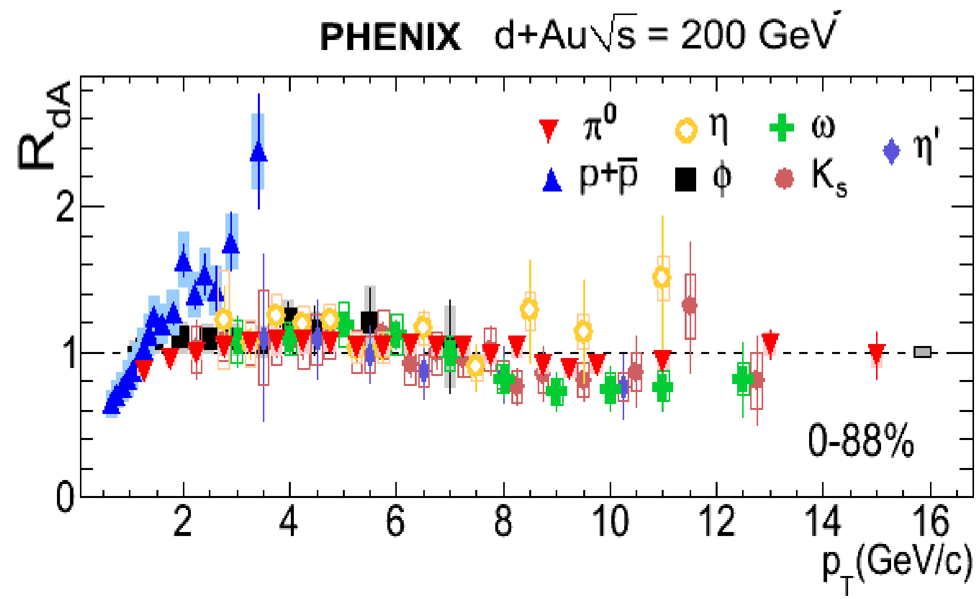


Figure 9.8: W-to-Be ratio of per-nucleon cross sections, $R_{W/Be}$ vs p_T for each hadron species at $\sqrt{s} = 38.8$ GeV from [7] . Also shown are results from [6] at $\sqrt{s} = 27.4$ GeV and model calculations [109] for π^- at $\sqrt{s} = 27.4$ GeV (upper curve) and $\sqrt{s} = 51.3$ GeV (lower curve).



Phys.Rev.C83:024909, 2011