Recent Hadronic Resonance Measurements at ALICE

A. G. Knospe
The University of Houston
on behalf of the ALICE Collaboration

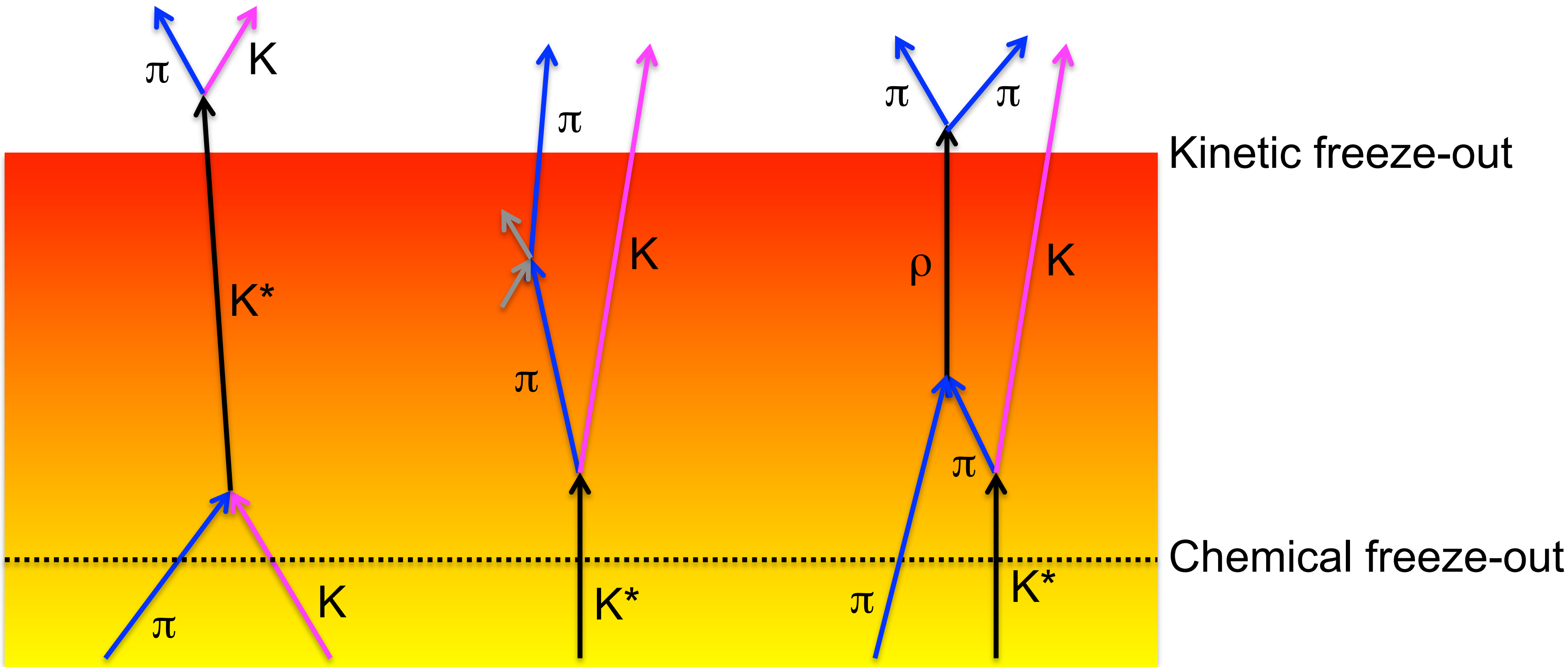
28 June 2016

Motivation

- pp and p–Pb collisions:
  - Baseline measurements for A–A
  - Input for event generators
  - R_{pPb}: system size dependence
- In-Medium Energy Loss:
  - R_{AA}: Study flavor dependence
- Shapes of Particle p_T Spectra:
  - Hydrodynamics: particle masses determine shapes of spectra
  - Recombination: possible baryon/meson differences
- Properties of Hadronic Phase…

Hadronic Phase

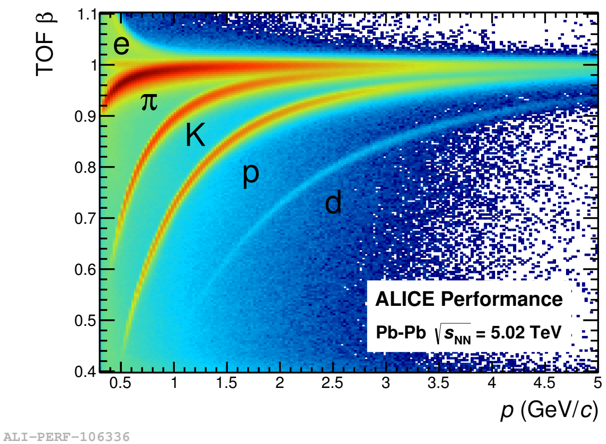
- Reconstructible resonance yields may be changed by hadronic scattering processes after chemical freeze-out:
  - **Regeneration:** pseudo-elastic scattering of decay products
    - e.g., πK → K* → πK
  - **Re-scattering:**
    - Resonance decay products undergo elastic scattering
    - Or pseudo-elastic scattering through a different resonance (e.g. ρ)
    - Resonance not reconstructed through invariant mass



Hadronic Phase

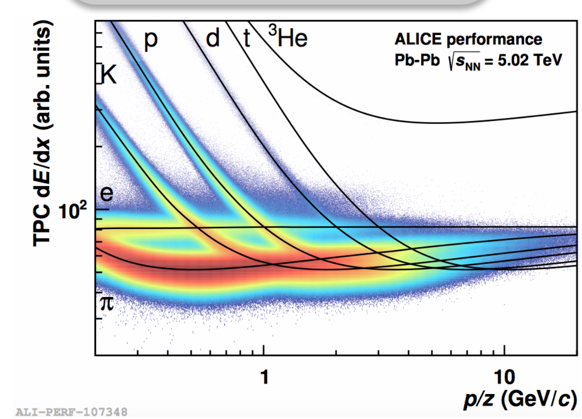
- Reconstructible resonance yields may be changed by hadronic scattering processes after chemical freeze-out:
  - **Regeneration:** pseudo-elastic scattering of decay products
    - e.g., $\pi K \rightarrow K^* \rightarrow \pi K$
  - **Re-scattering:**
    - Resonance decay products undergo elastic scattering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



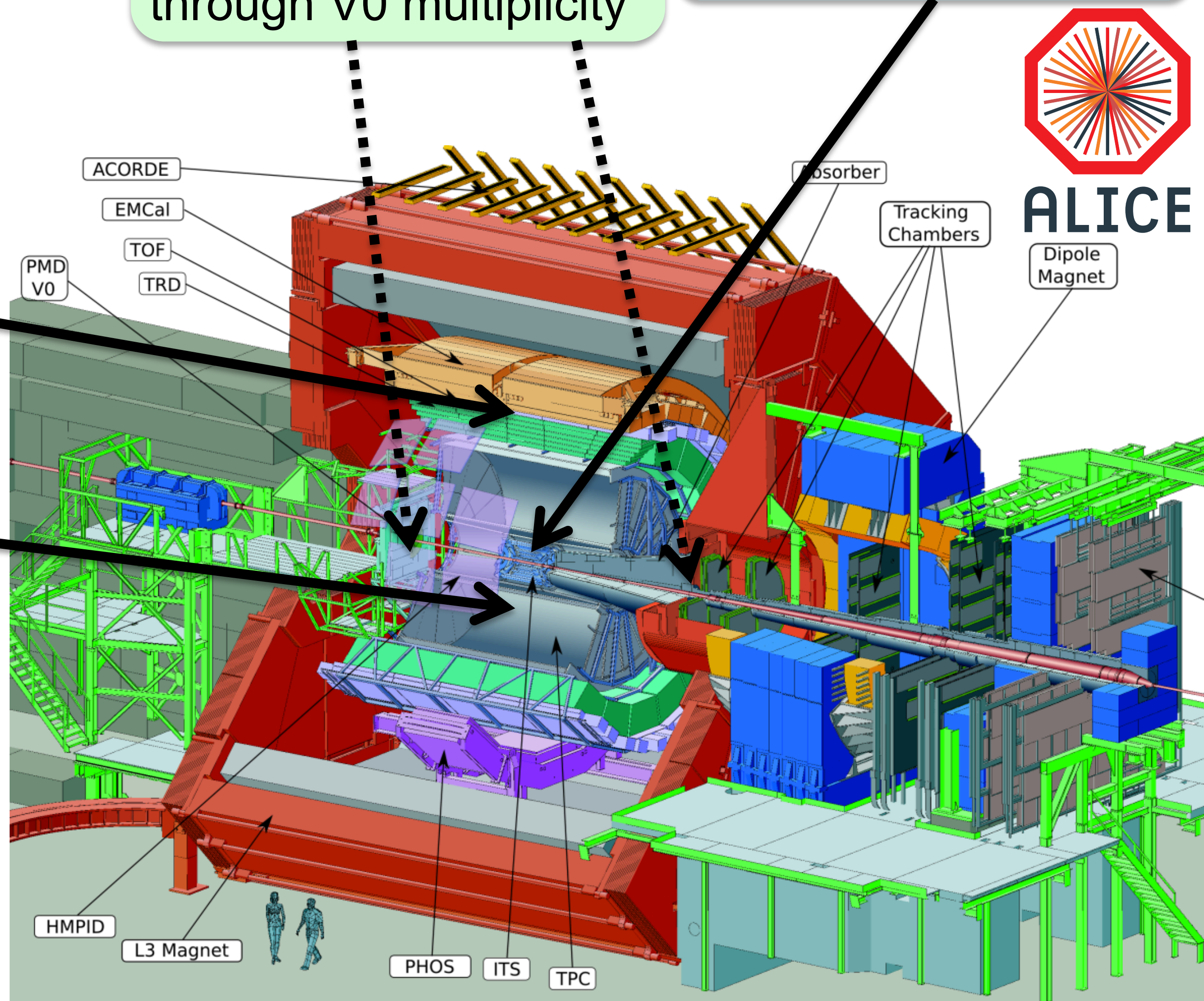
TOF: PID through particle time of flight

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



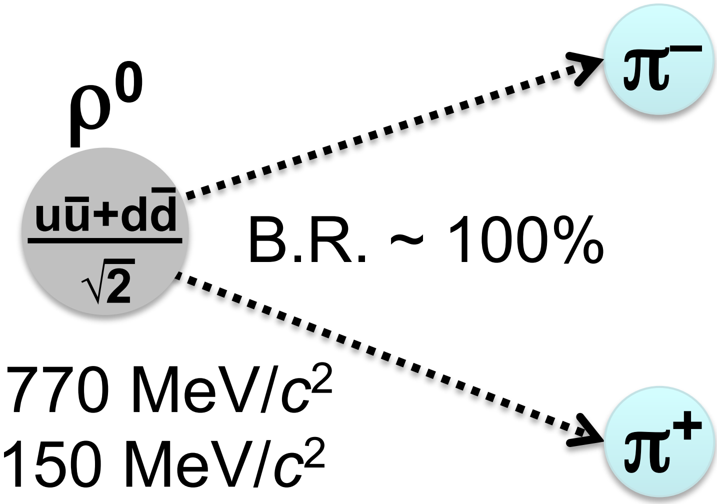
V0 (scintillators): centrality estimate through V0 multiplicity

ITS (silicon): Tracking and Vertexing



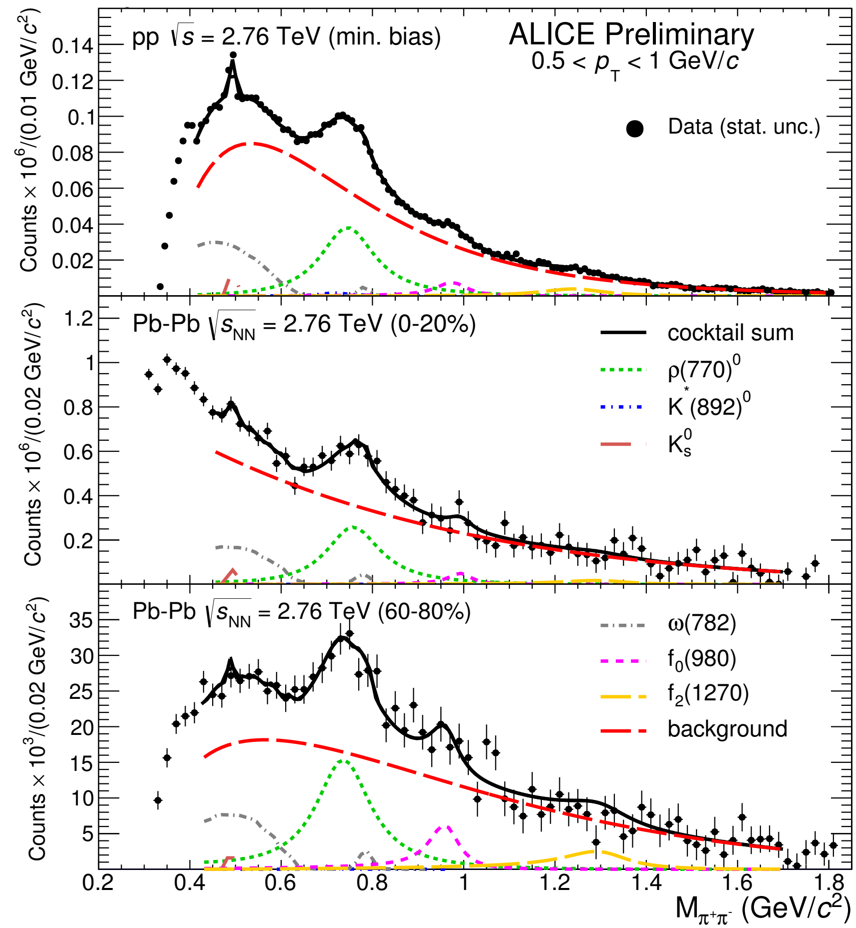
ρ^0 Reconstruction

Knospe



m = 770 MeV/c^2
Γ = 150 MeV/c^2

NEW RESULT

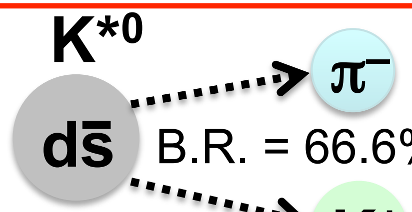


ALI-PREL-107636

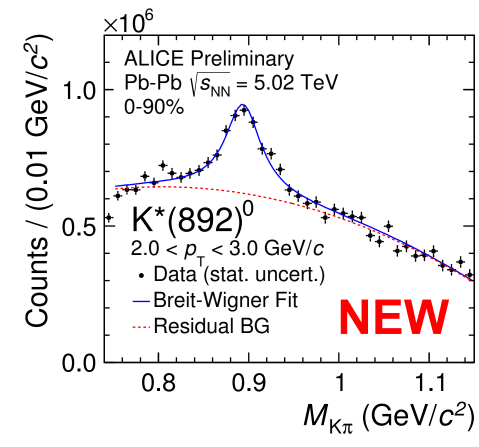
- Analyzed in pp and Pb–Pb collisions at 2.76 TeV
- Subtract like-charge combinatorial background
- Fit with residual background + cocktail (K^0_S, K^{*0}, ω, f_0, f_2)
- Peak Model:

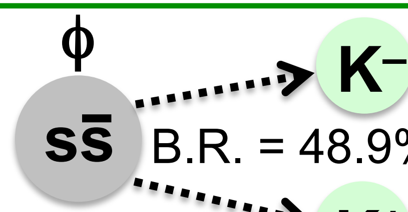
Relativistic Breit-Wigner × **_Phase Space_** × **_Mass-Dependent Efficiency_** × **_Söding Interference Term_**

Other Resonances

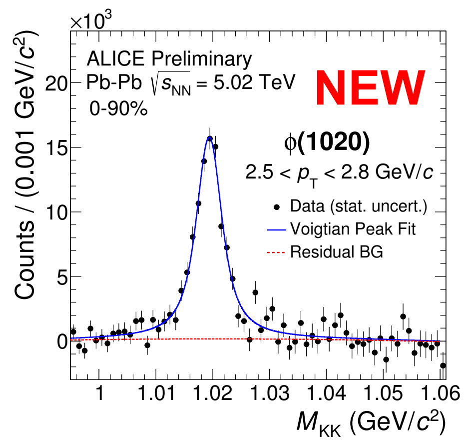


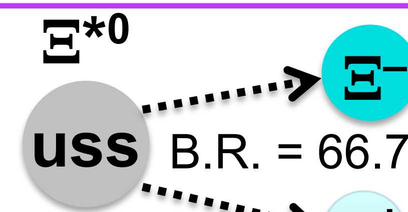
m = 896 MeV/c^2
Γ = 47.4 MeV/c^2



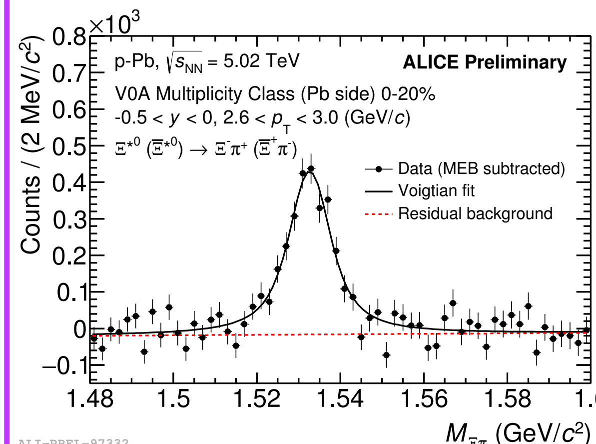


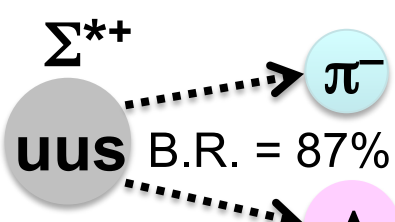
m = 1019 MeV/c^2
Γ = 4.266 MeV/c^2



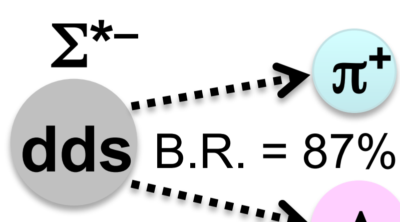


m = 1532 MeV/c^2
Γ = 9.1 MeV/c^2

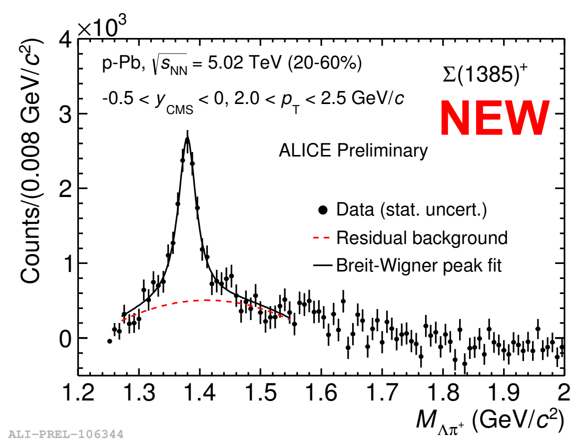




m = 1383 MeV/c^2
Γ = 36.0 MeV/c^2



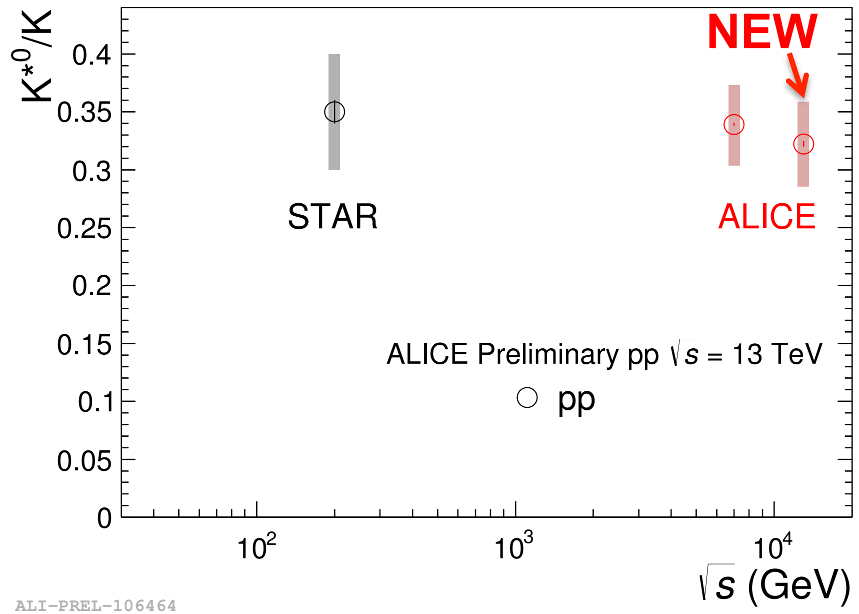
m = 1387 MeV/c^2
Γ = 39.4 MeV/c^2

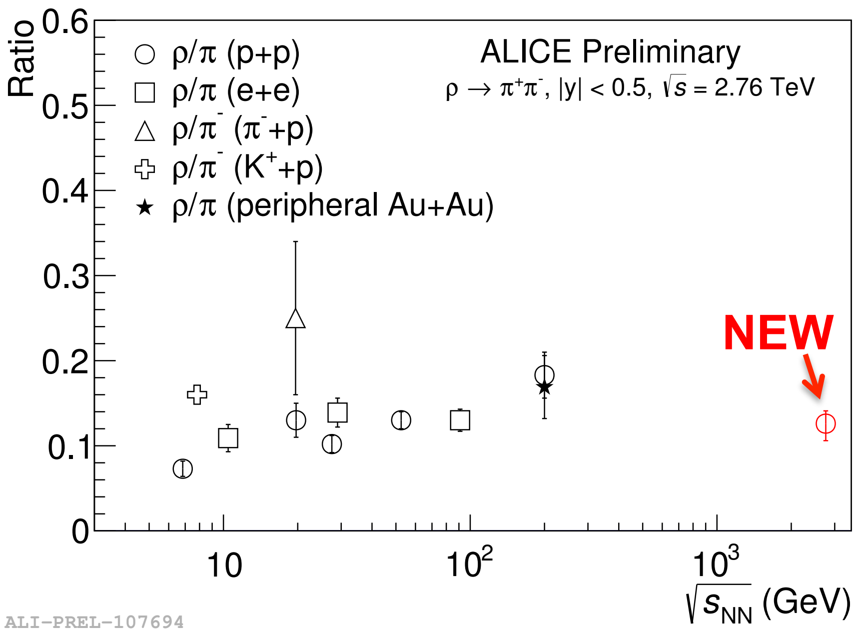


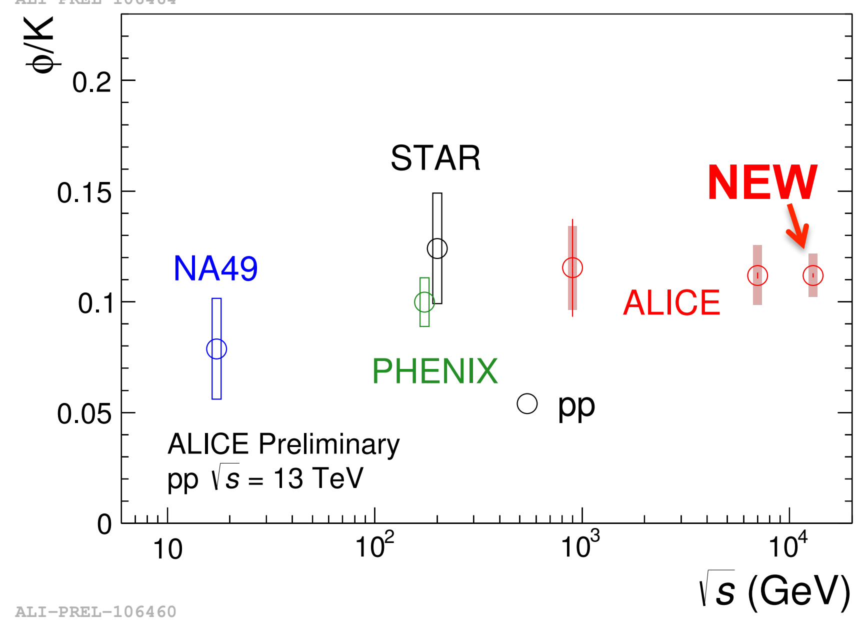
Ratios to Stable Hadrons (pp)

Knospe

- Ratios in pp: new ALICE measurements of ρ^0/π at 2.76 TeV, K^{*0}/K and ϕ/K at 13 TeV:
  - No energy dependence through 2-3 orders of magnitude

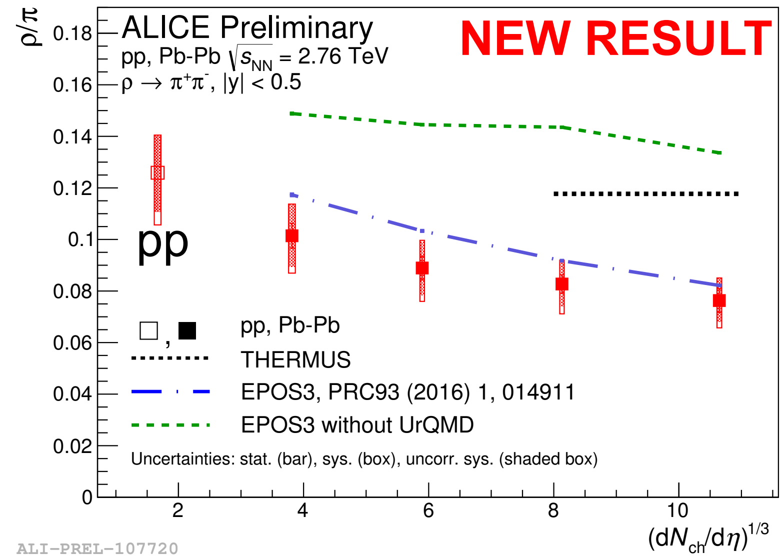


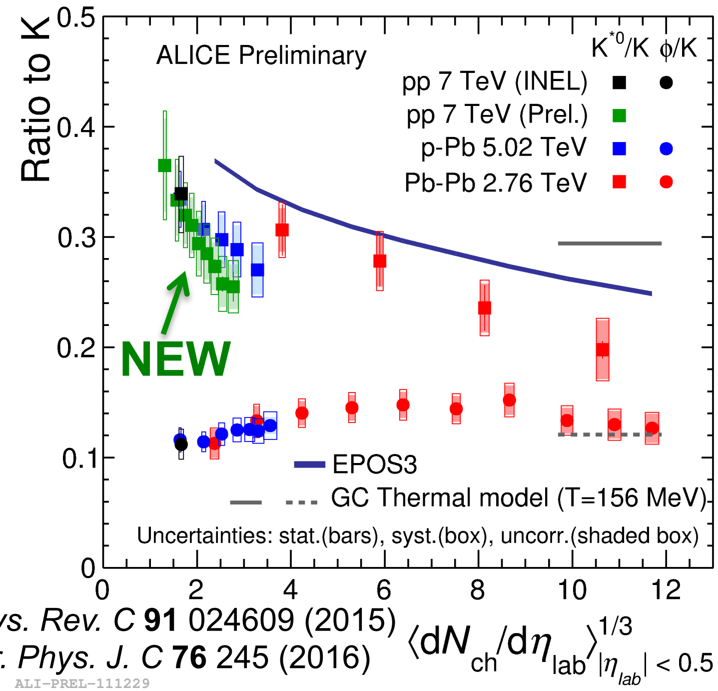




Ratios to Stable Hadrons

- Suppression of ρ^0/π and K^{*0}/K in central Pb–Pb w.r.t. peripheral, pp, p–Pb, thermal model
  - Suggests that re-scattering is dominant over regeneration
  - Well described by EPOS w/ UrQMD
- K^{*0}/K in small systems:
  - decreasing trend observed in p–Pb (slope not consistent with 0)
  - Multiplicity-dependent suppression in pp
- No suppression of ϕ/K, no strong centrality dependence
  - Central Pb–Pb consistent w/ thermal model
  - Lifetime of ϕ ~10× longer than K^{*0}, ~35× longer than ρ^0 → re-scattering effects not significant
  - Ratio in p–Pb consistent with trend from pp to peripheral Pb–Pb
- Additional Material: See backup slides for ρ^0 R_{AA} and multiplicity dependence of K^{*0} p_T spectra in pp collisions at 7 TeV.





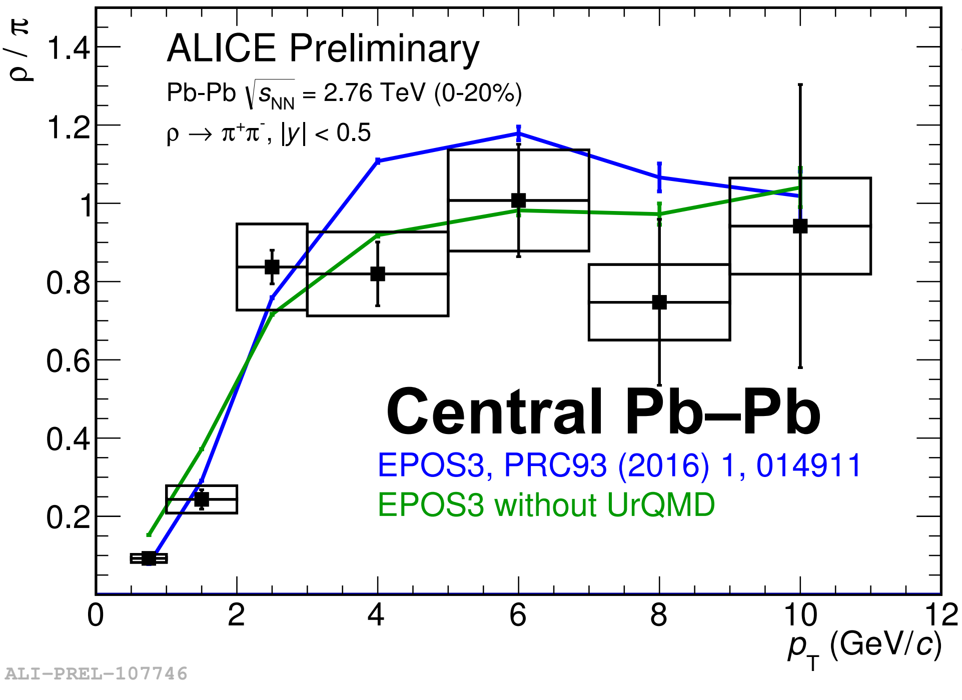
Phys. Rev. C **91** 024609 (2015)
Eur. Phys. J. C **76** 245 (2016)

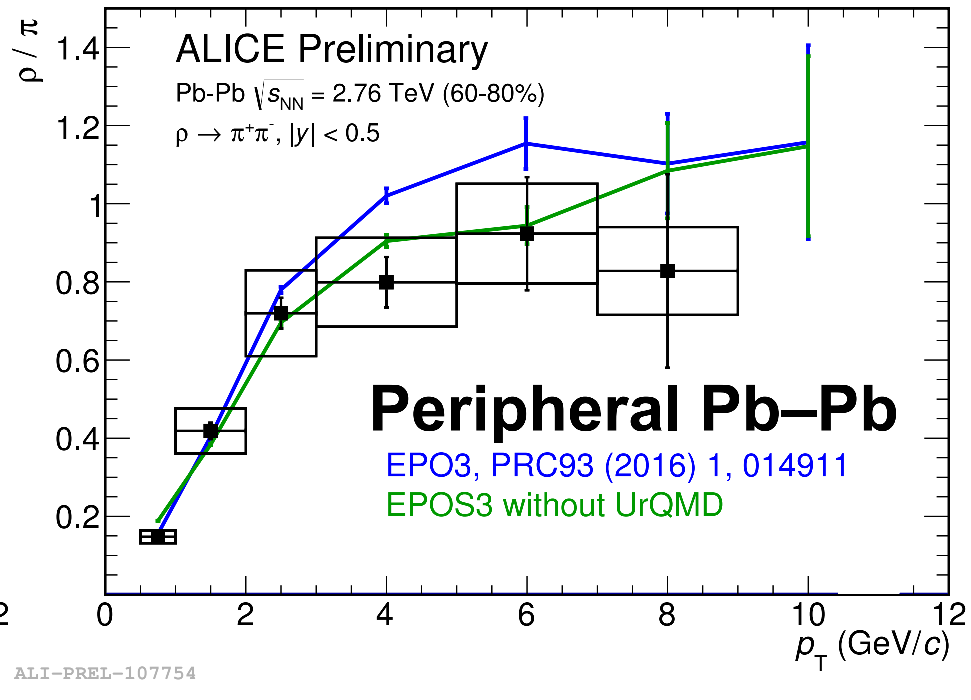
ALI-PREL-111229

ρ^0/π Ratio vs. p_T

- In Pb–Pb:
  - Fair description by EPOS3 with UrQMD
  - Central: EPOS without UrQMD overestimates ratio at low p_T → reduction of ρ^0 yield due to re-scattering
  - Peripheral: both EPOS calculations describe low-p_T ratio
- In pp: see backup for comparisons to PYTHIA, PHOJET

NEW RESULT

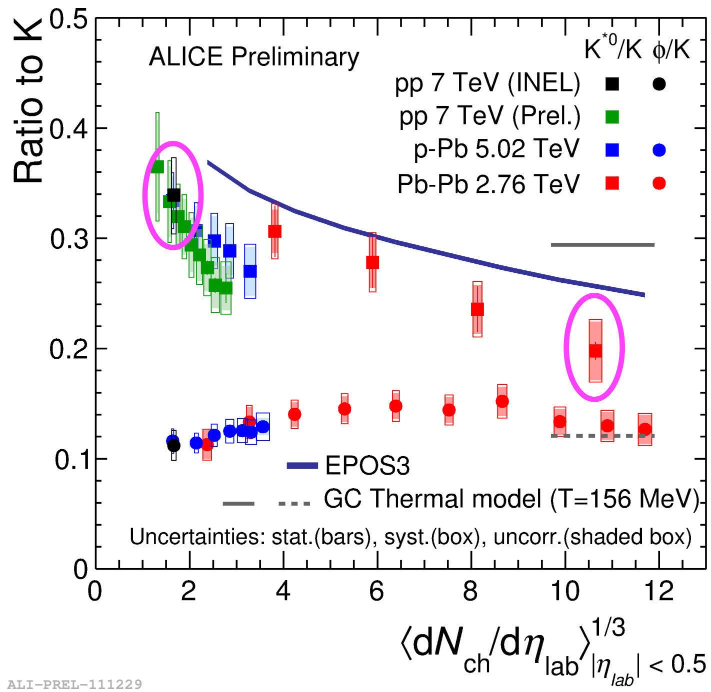


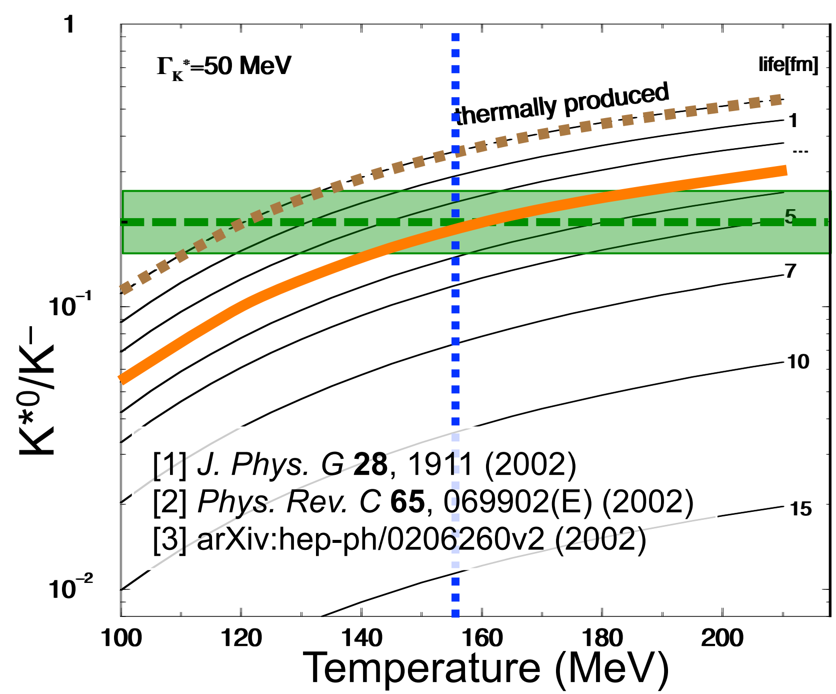


Properties of Hadronic Phase

Knospe

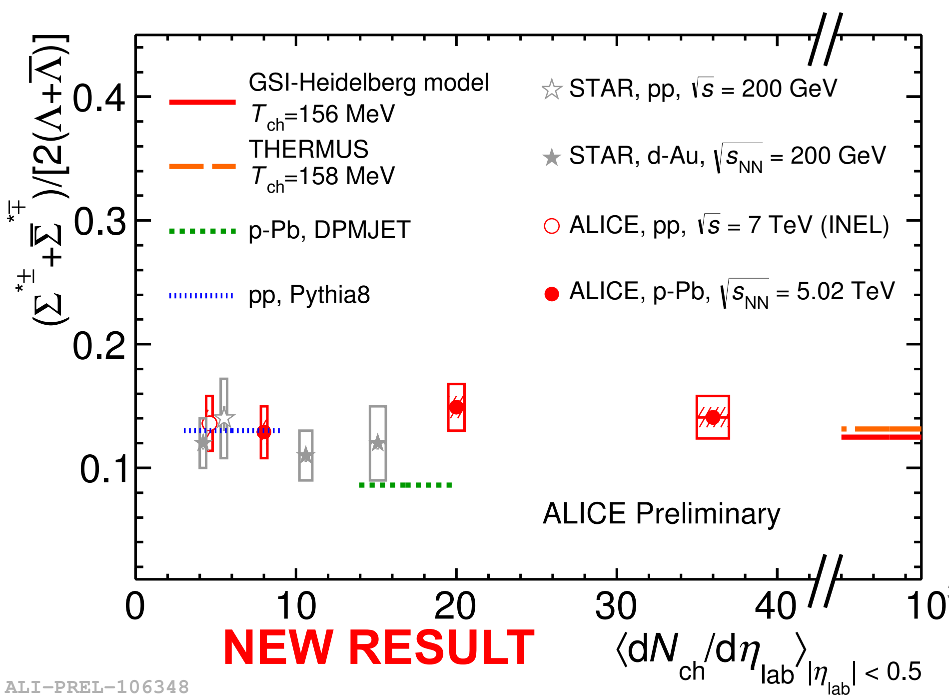
- Toy Model: assume any K^{*0} that decays before kinetic freeze-out is lost due to re-scattering, neglect regeneration and time dilation
  - Exponential decrease in yield (τ = 4.2 fm/c)
  - Use MB pp as initial value, central Pb–Pb as final value → lifetime of hadronic phase $\Delta t \geq$ 1.5 fm/c
- Model of Torrieri, Rafelski, *et al.*: K^{*0}/K as function of T_{ch} and Δt
  - Assume Δt = 0, Measured K^{*0}/K → T_{ch} = 120 MeV
  - Assume T_{ch} = 156 MeV, Measured K^{*0}/K → $\Delta t \geq$ 2 fm/c

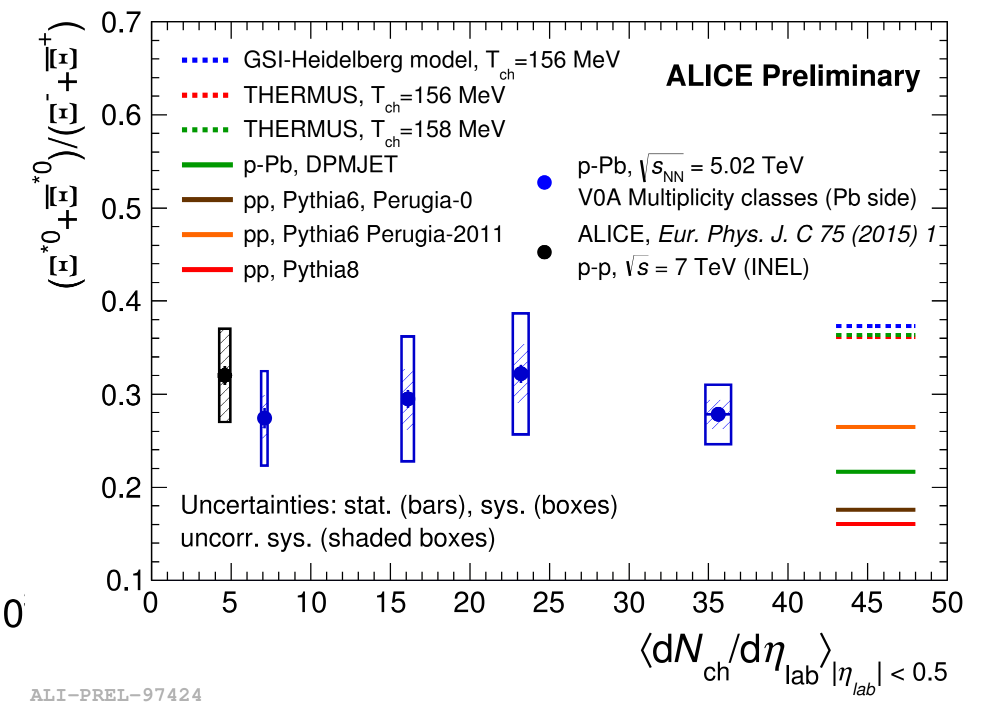




Ratios to Stable Hadrons

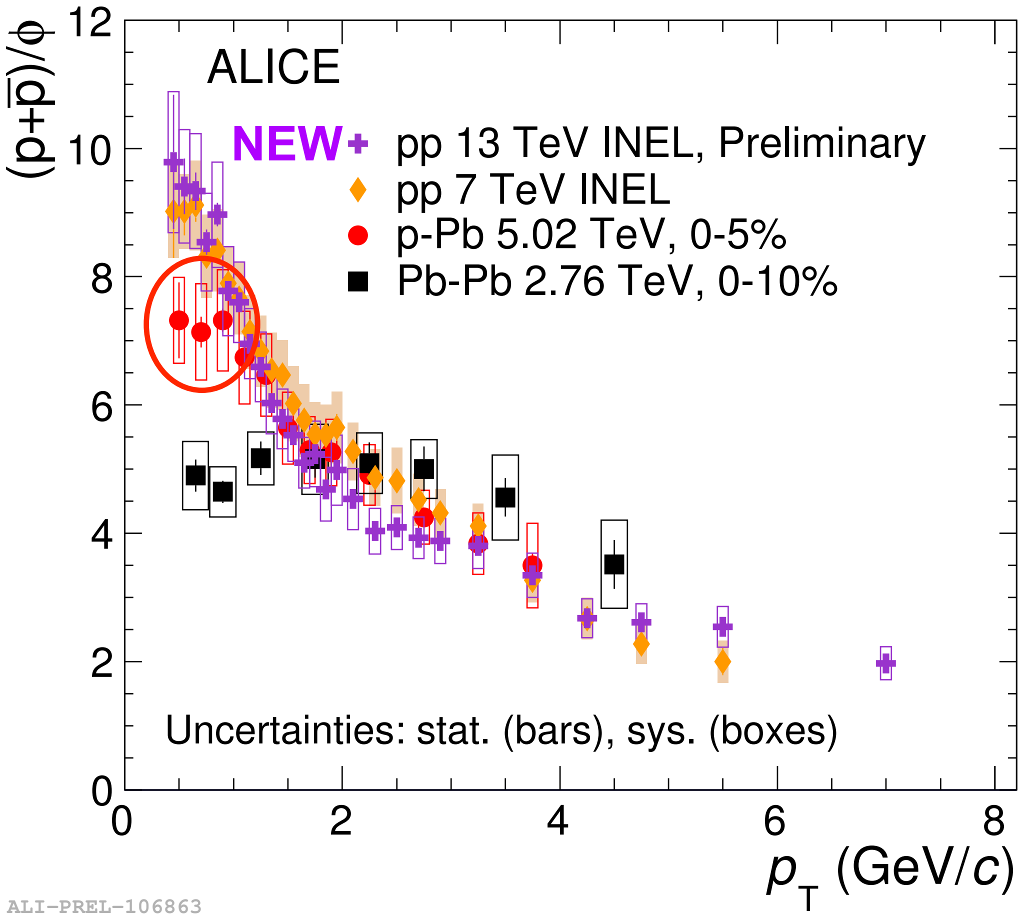
- New measurements of $\Sigma^{*\pm}$ and Ξ^{*0} in p–Pb collisions at 5.02 TeV
  - Measurements in progress for Pb–Pb collisions at 2.76 TeV
- No strong dependence of $\Sigma^{*\pm}/\Lambda$ on energy or system size
  - Values consistent with thermal model and PYTHIA predictions
- No system size dependence of Ξ^{*0}/Ξ at LHC
  - Values in pp and p–Pb tend to be below thermal model predictions





p/ϕ Ratio vs. p_T

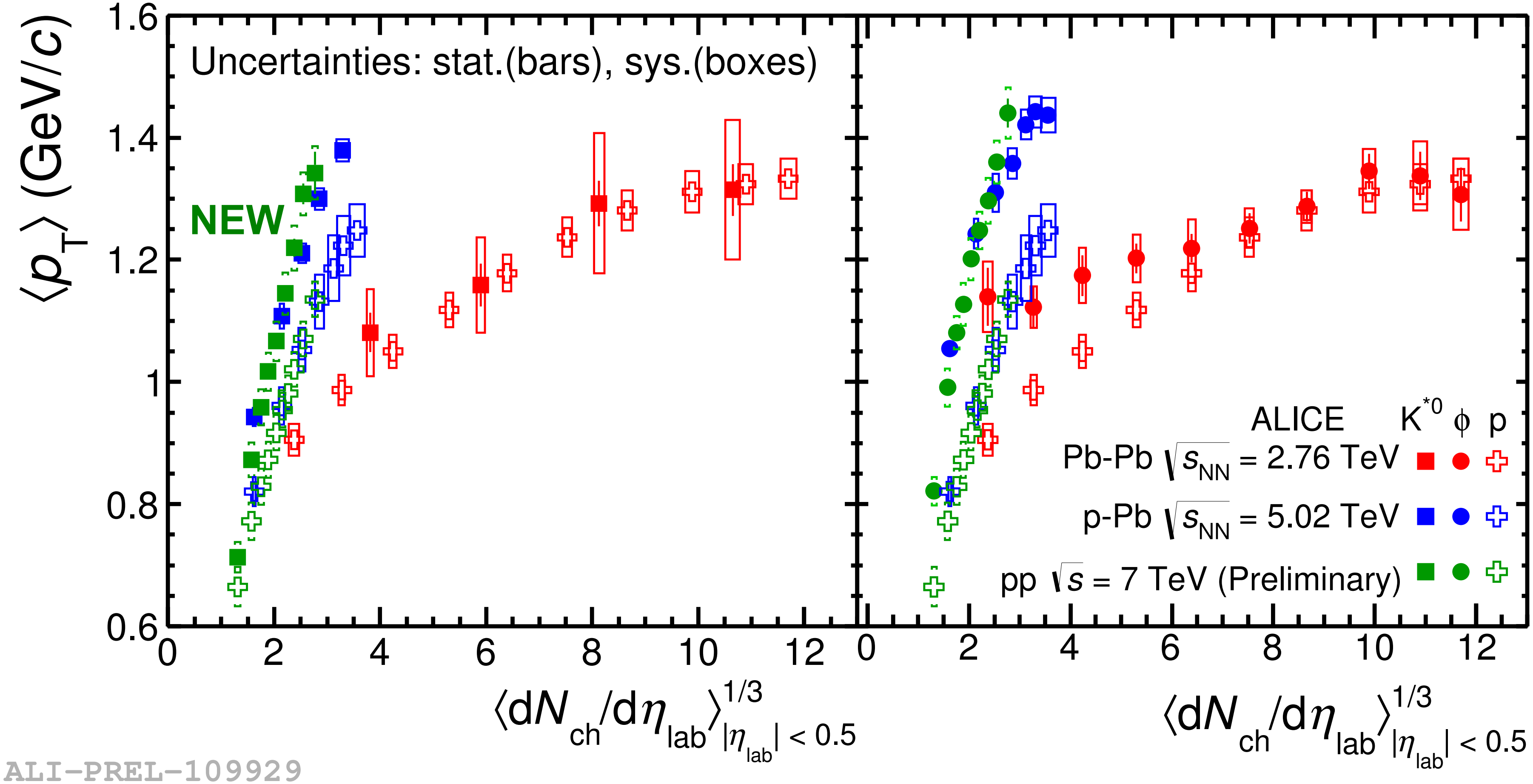
- **New measurement** in pp collisions at 13 TeV
- p/ϕ flat for central collisions for p_T < 3-4 GeV/*c*
  - Consistent with hydrodynamic evolution, some recombination models can also describe it
- p/ϕ in high-multiplicity p–Pb:
  - For p_T > 1 GeV/*c*: similar to pp and peripheral Pb–Pb (not shown)
  - For p_T < 1 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)

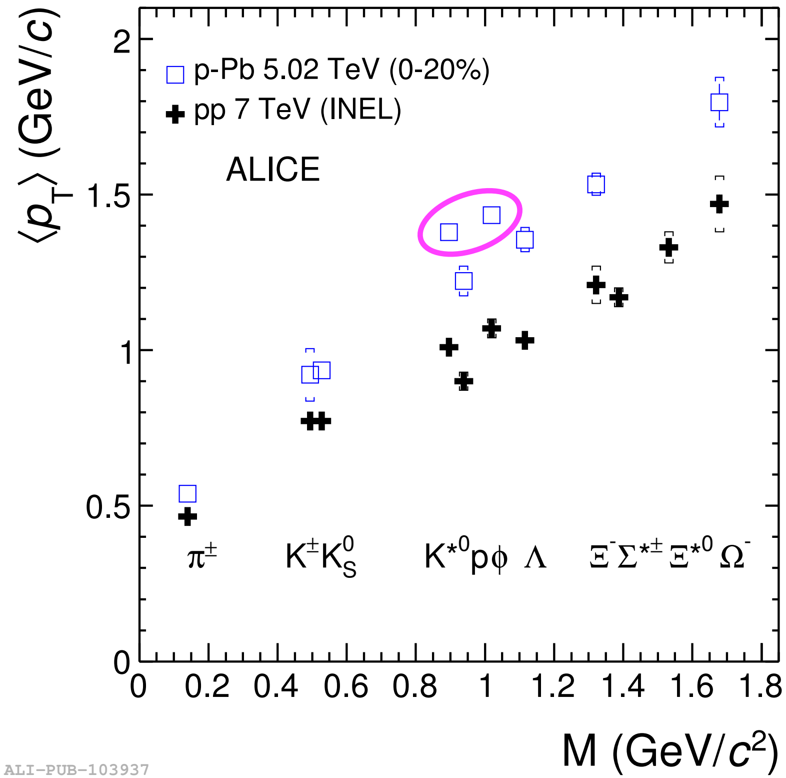
Mean p_T

- Central Pb–Pb: K^{*0}, p, φ have same $<p_T>$ → consistent with hydrodynamics
- Small systems:
  - p–Pb and pp: $<p_T>$ values rise faster with mult. than Pb–Pb, reach similar values at high multiplicity as central Pb–Pb
    - Different particle production mechanisms? Harder scattering?



Mean p_T

- Central Pb–Pb: K^{*0}, p, ϕ 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 ϕ have larger $\langle p_T \rangle$ values than p and Λ
  - Is there a baryon/meson difference, or do resonances not obey mass ordering?

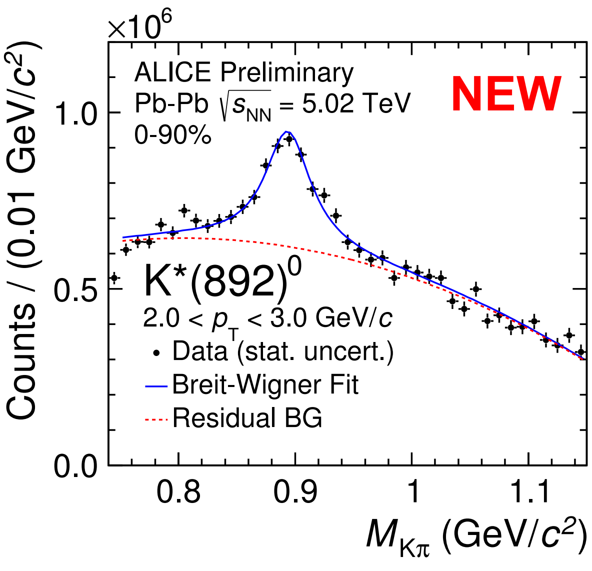


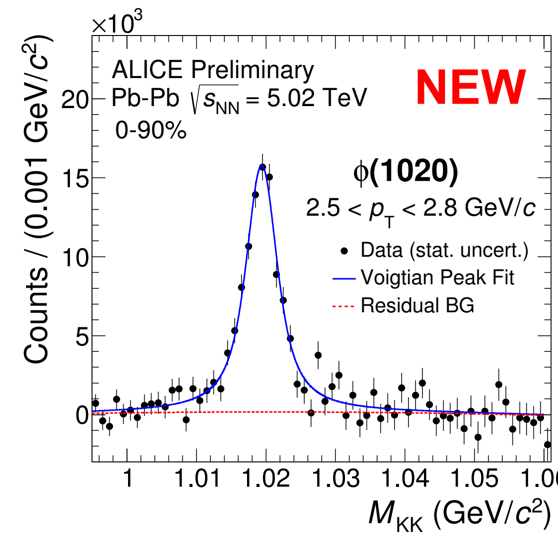
Summary

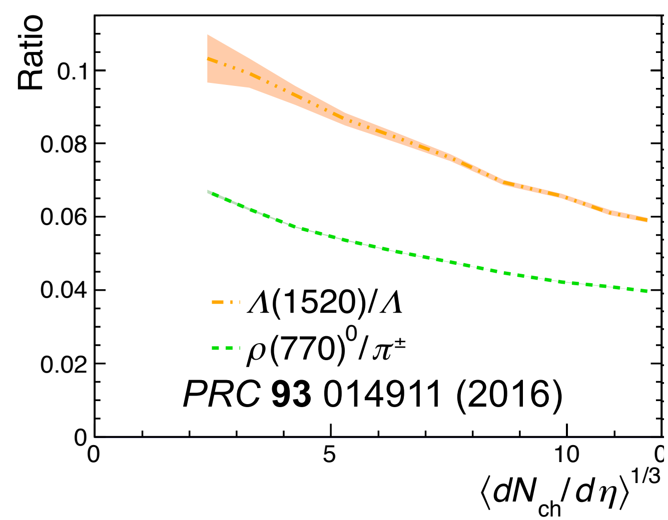
- Resonance Suppression:
  - Central Pb–Pb: ρ^0 & K^{*0} suppressed (re-scattering)
    - ϕ not suppressed (longer lifetime)
    - From K^{*0}/K^- ratio: lower limit on lifetime of hadronic phase: 2 fm/*c*
    - Described by EPOS (with UrQMD)
  - p–Pb: K^{*0}/K and ϕ/K ratios follow trend from pp to peripheral Pb–Pb
  - pp: K^{*0}/K suppressed at high multiplicity
- 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 in high-mult. p–Pb: possible onset of collective effects?
- Mean p_T:
  - $\langle p_T \rangle$ in pp and p–Pb and follow different trends w.r.t. Pb–Pb
  - 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?

Outlook

- Measurements in progress:
  - ρ^0 in p–Pb
  - K^{*0} & ϕ vs. multiplicity in pp collisions at 7 and 13 TeV
  - K^{*0} & ϕ in new Pb–Pb data (5.02 TeV)
  - Σ^0 in pp collisions at 7 TeV
  - $\Sigma^{*\pm}$ and Ξ^{*0} in Pb–Pb collisions at 2.76 TeV
  - $\Lambda(1520)$ in pp, p–Pb, and Pb–Pb collisions
    - EPOS predicts strong $\Lambda(1520)$ suppression (*cf.* ρ^0 and K^{*0})







Additional Material

Resonance Reconstruction

- Resonances measured in pp (0.9, 2.76, 7, 13 TeV) , p–Pb (5.02 TeV), and Pb–Pb (2.76, 5.02 TeV) collisions

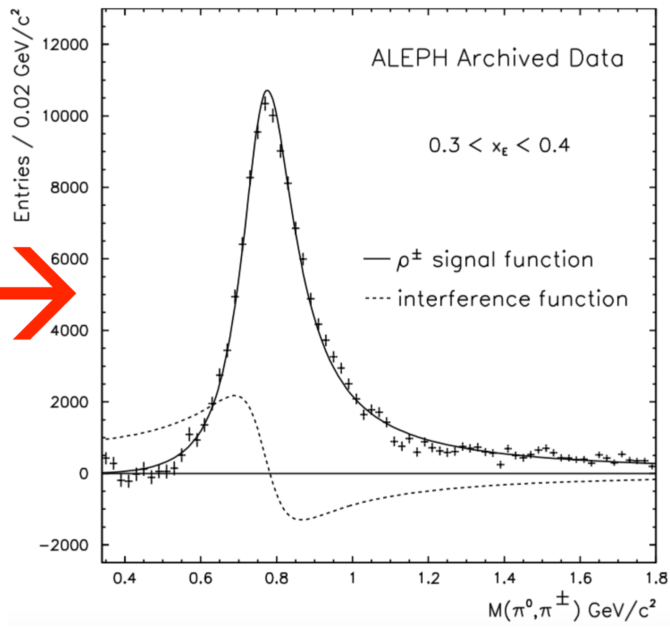
Particle	**Mass (MeV/c^2)**	**Width (MeV/c^2)**	**Decay**	**Branching Ratio (%)**
ρ^0	770	150	$\pi^-\pi^+$	100
K^{*0}	896	47.4	π^-K^+	66.7
ϕ	1019	4.27	K^-K^+	48.9
Σ^{*+}	1383	36.0	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	$\pi^-\Lambda$	87
$\Lambda(1520)$	1520	15.7	K^-p	22.5
Ξ^{*0}	1532	9.1	$\pi^+\Xi^-$	66.7

ρ^0: Söding Interference Term

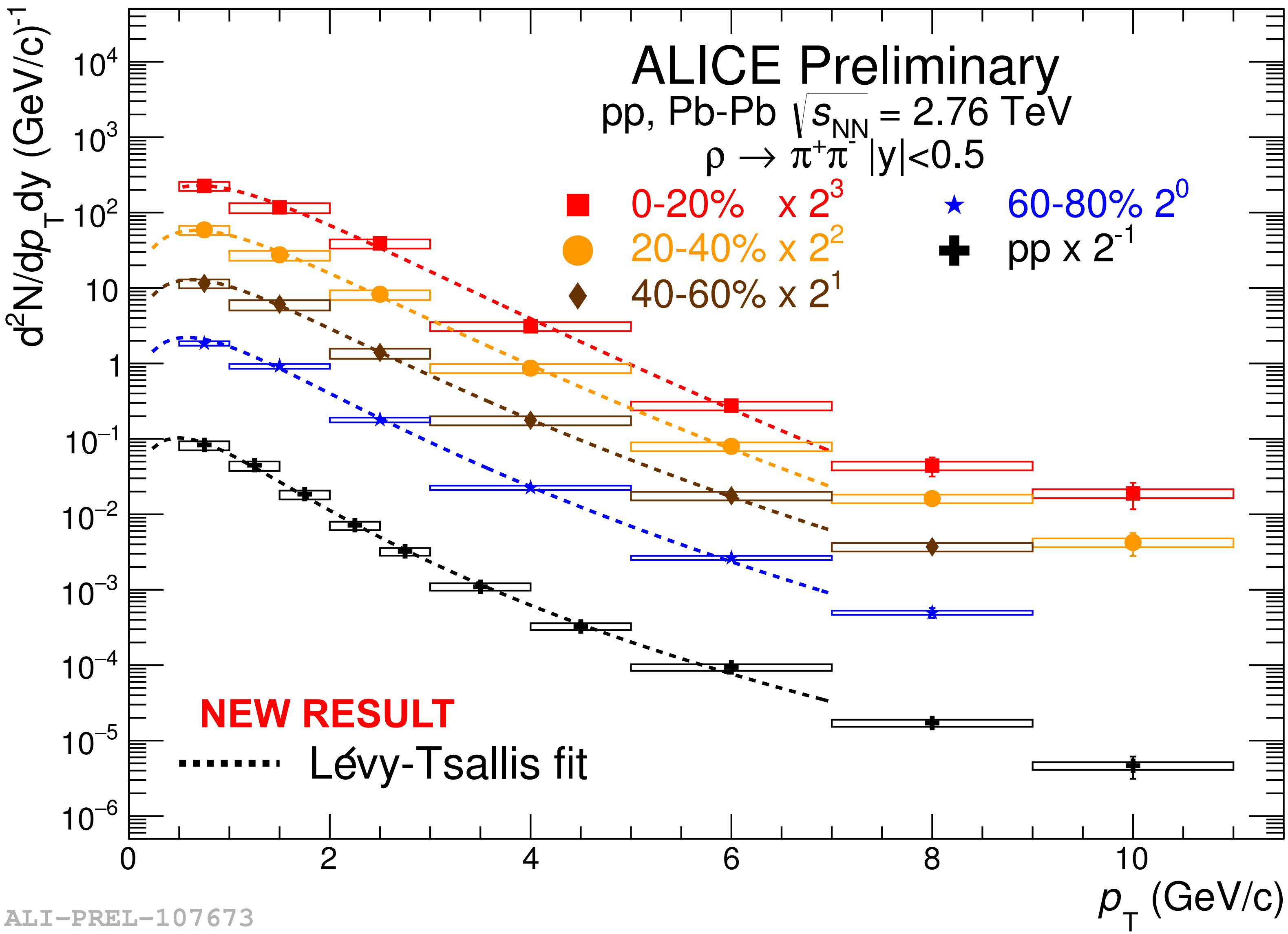
- Accounts for Bose-Einstein correlations between pions produced in ρ decays and other identical pions nearby in phase space

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

- Used for
  - ALICE for ρ^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)

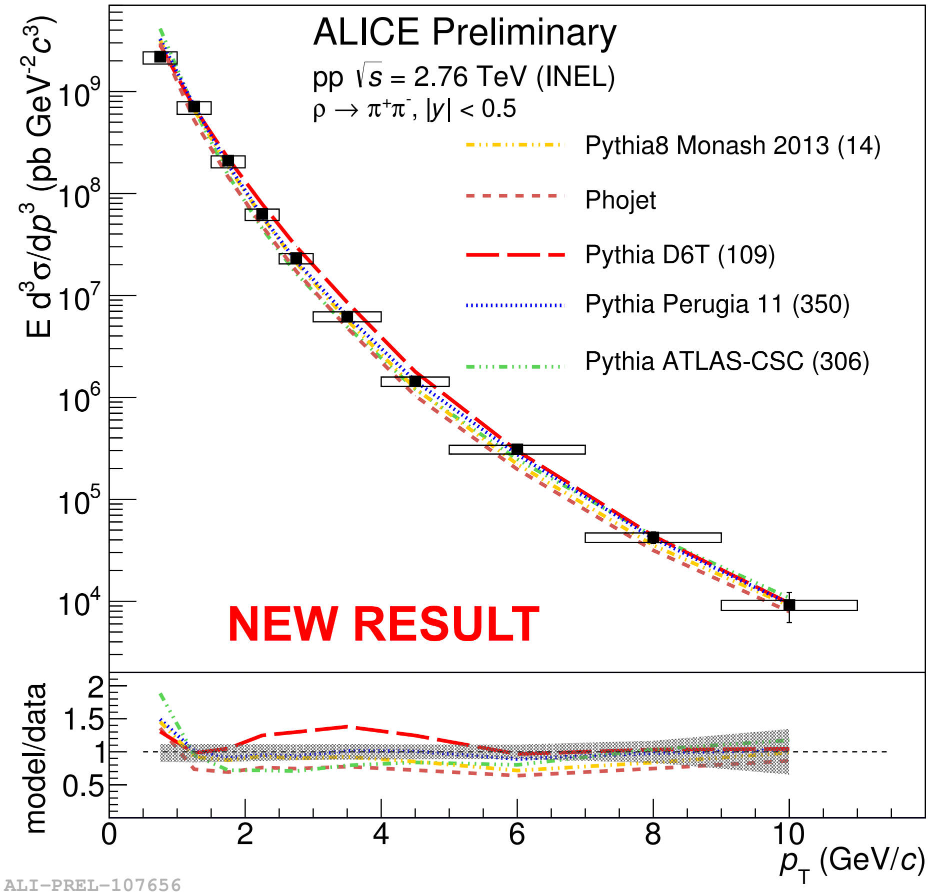


ρ^0 p_T Spectra



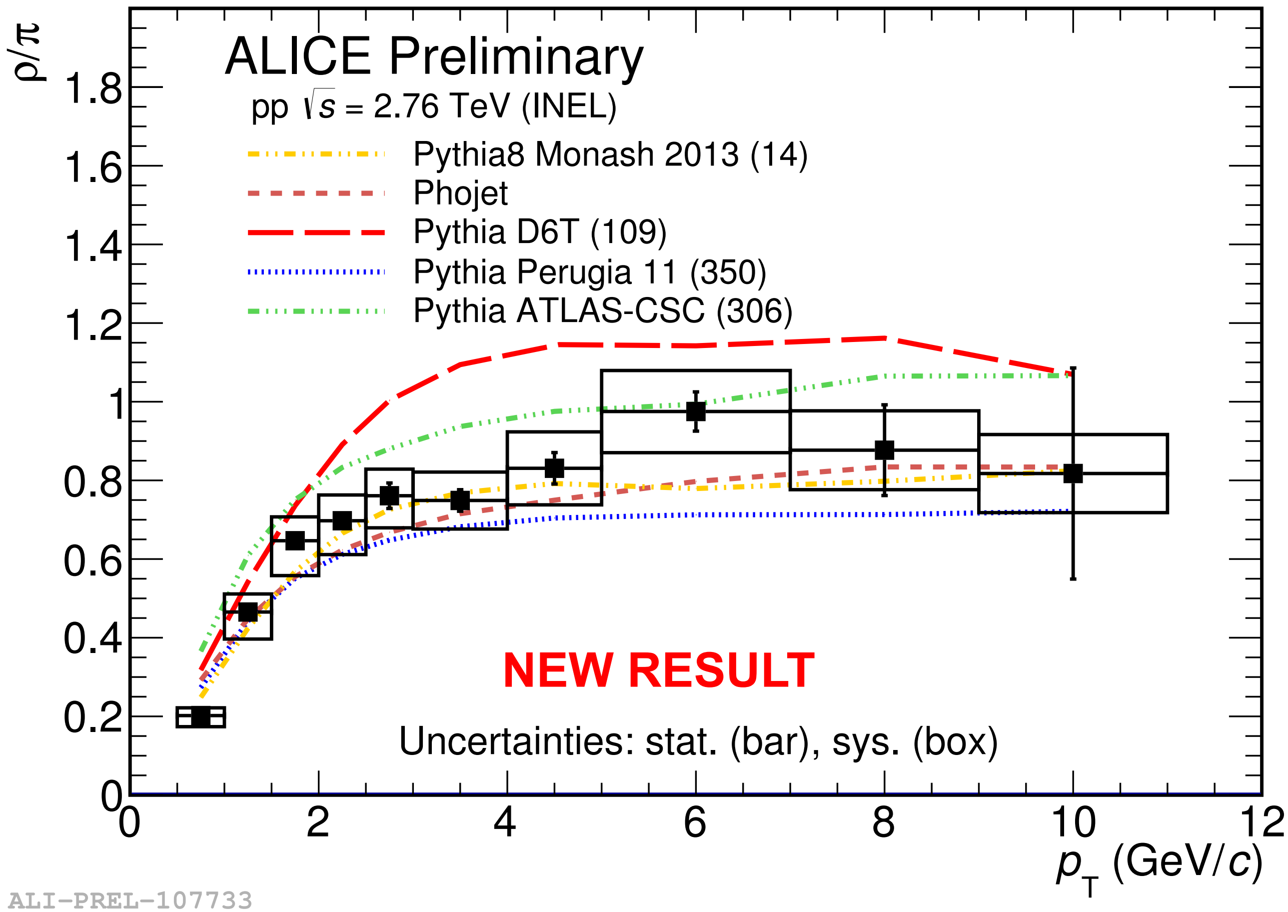
ρ^0 in pp: Model Comparisons

- ρ^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 $p_T > 1$ GeV/c
  - PYTHIA D6T over-predicts yield for $2 < p_T < 5$ GeV/c
  - PYTHIA Perugia 11 describes data within uncertainties for $p_T > 1$ GeV/c



ρ^0/π Ratio vs. p_T (pp)

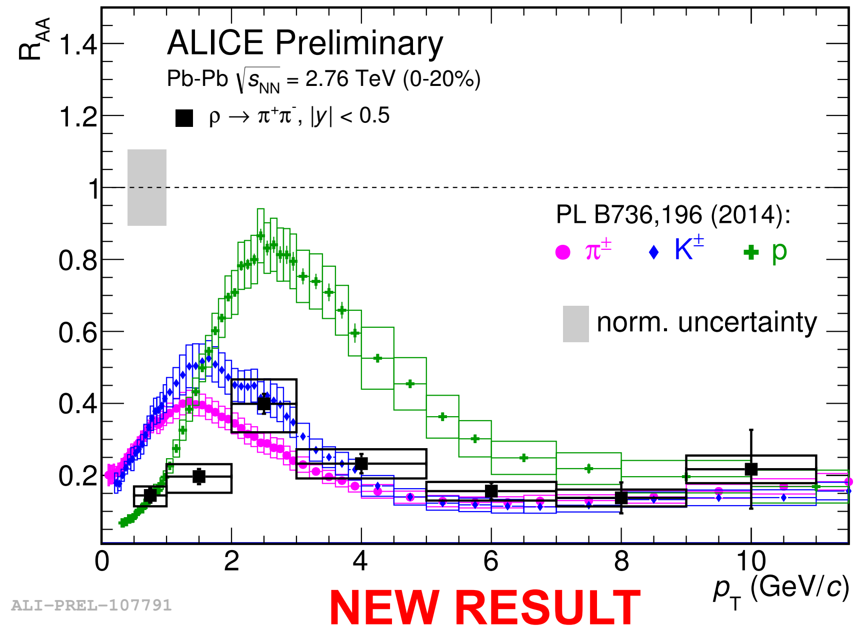
- Measured ρ^0/π ratio in pp collisions at 2.76 TeV compared to models:
  - PYTHIA D6T and ATLAS-CSC over-predict
  - PHOJET and PYTHIA Perugia 11 under-predict
  - Best Description by PYTHIA Monash 2013



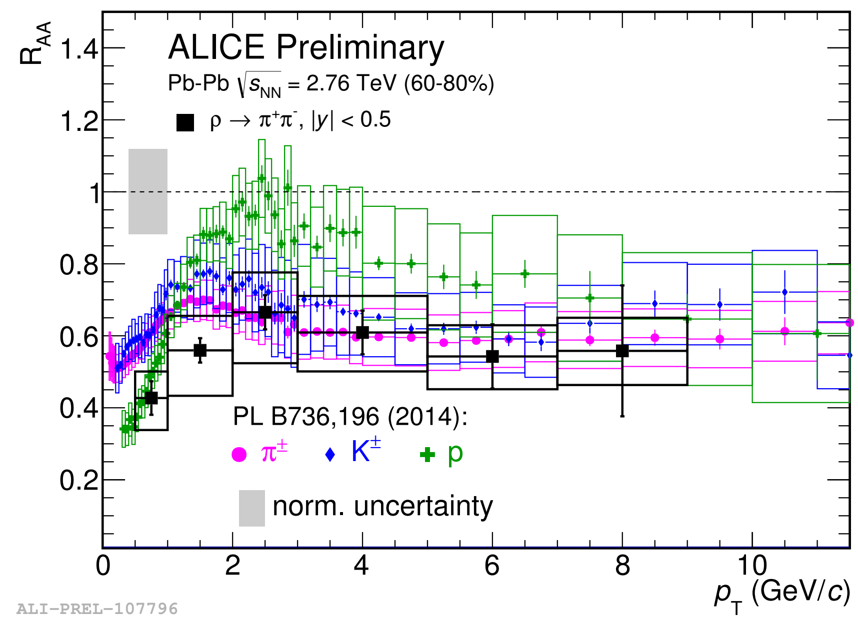
ρ^0 Nuclear Modification

- **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

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

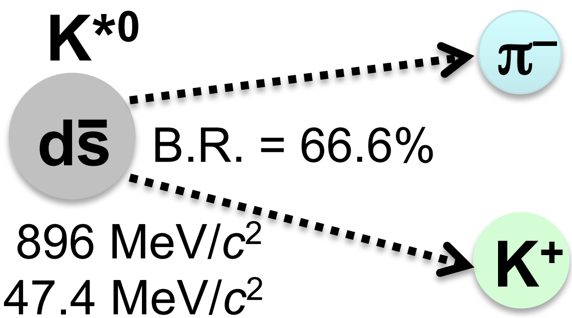


NEW RESULT

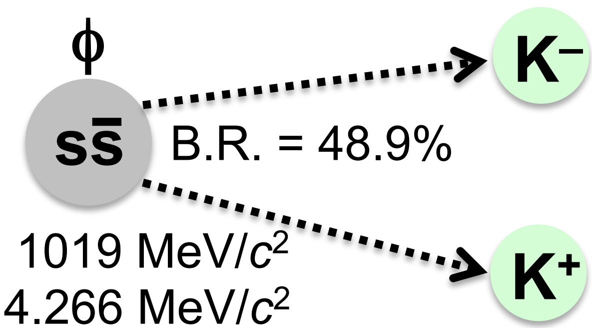


K*0 and ϕ Reconstruction

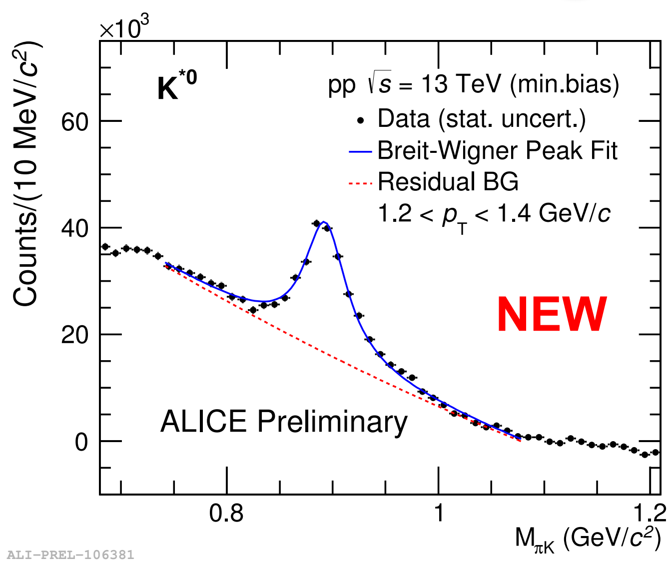
- Analyzed in pp collisions at 0.9, 7 (vs. multiplicity), 13 TeV; p–Pb collisions at 5.02 TeV; Pb–Pb collisions at 2.76 & 5.02 TeV
- Subtract mixed-event or like-charge combinatorial backgrounds
- Polynomial residual background
- Peaks: Breit-Wigner (K^{*0}) or Voigtian (ϕ)



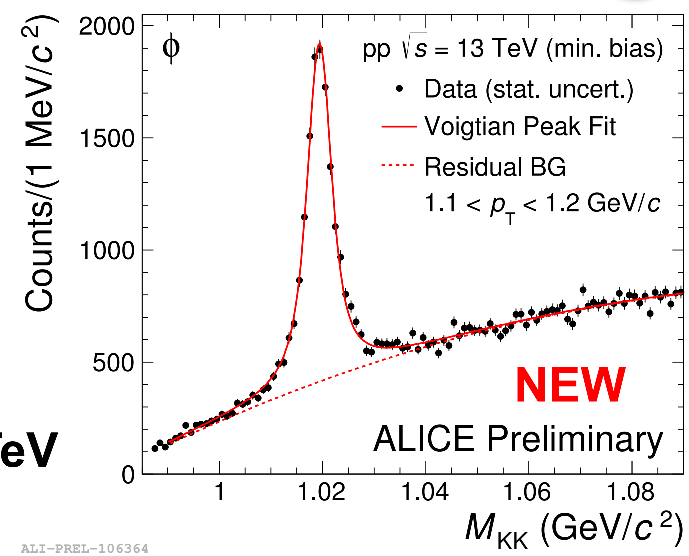
m = 896 MeV/c^2
Γ = 47.4 MeV/c^2



m = 1019 MeV/c^2
Γ = 4.266 MeV/c^2



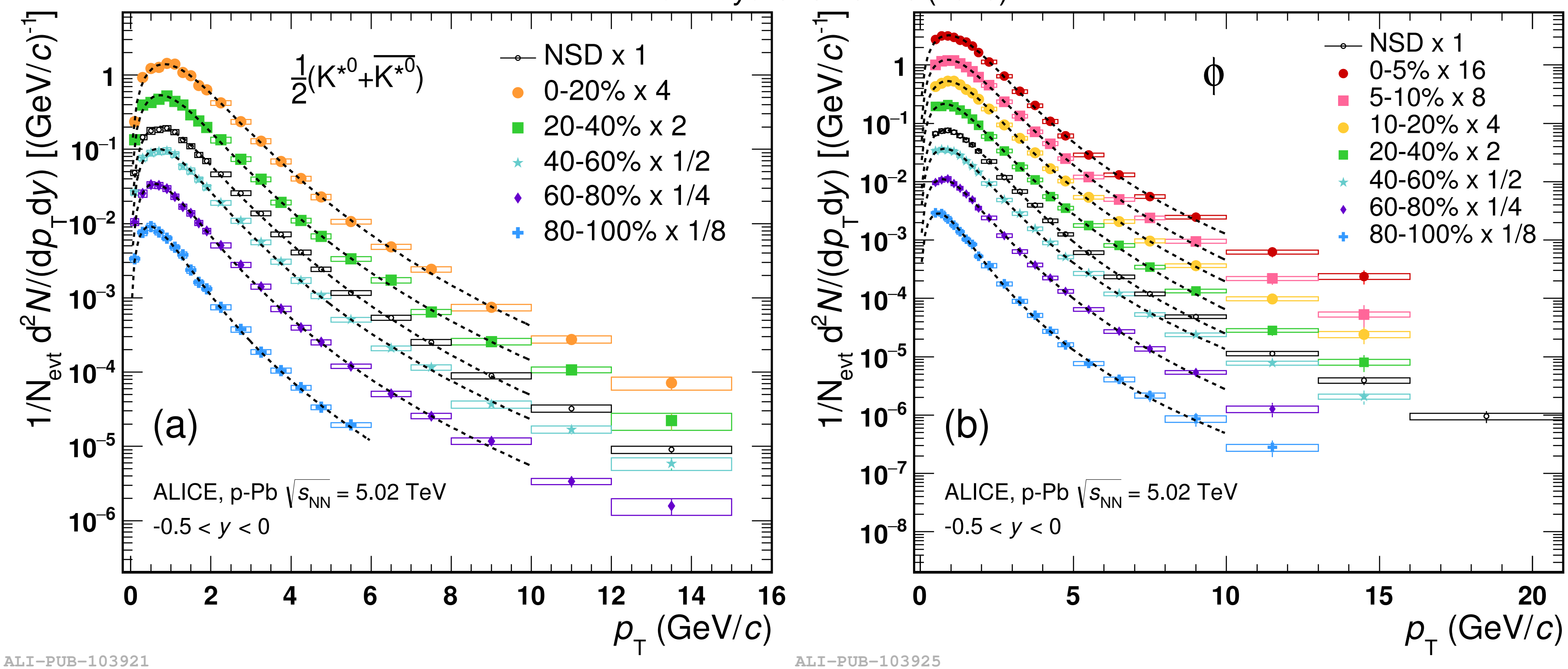
pp 13 TeV



K^{*0} and ϕ 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 (ϕ)

Eur. Phys. J. C **76** 245 (2016)

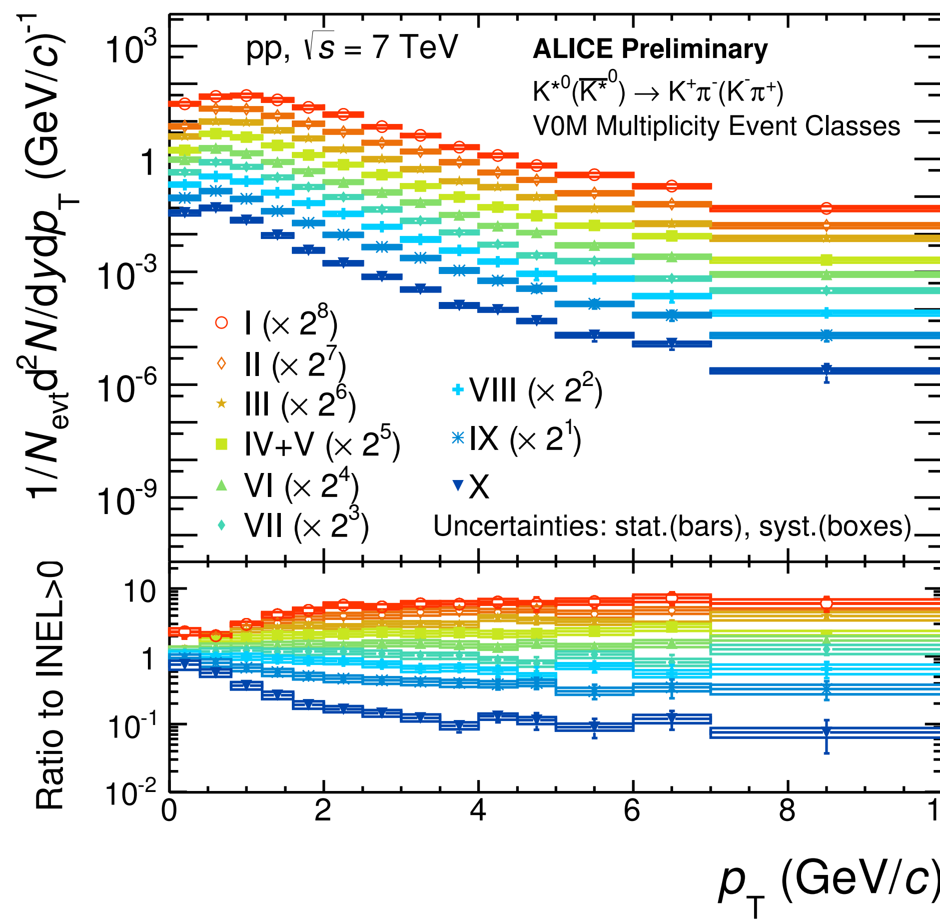


p–Pb 5.02 TeV

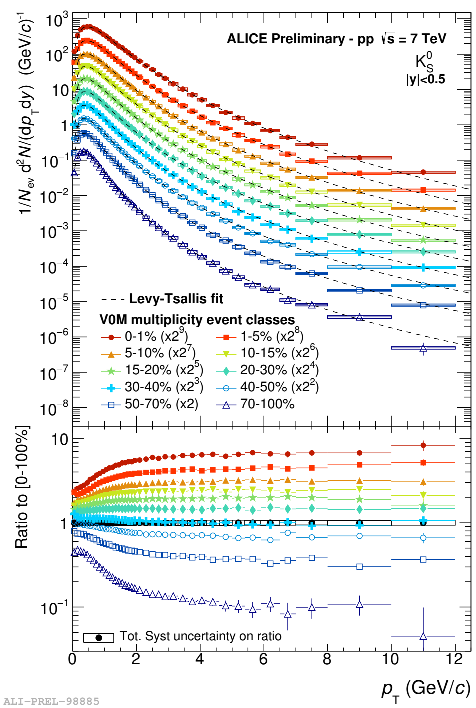
Multiplicity Dependence (K^{*0})

- K^{*0} measured in pp collisions at 7 TeV in 9 multiplicity bins
  - Multiplicity measured in ALICE V0: $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$
  - K^{*0} measured in $|y| < 0.5$
- Low → high multiplicity: spectra harden
- Same shapes for $p_T > 4$ GeV/c
- Similar behavior for other Hadrons: see also talk of R. Derradi de Souza, SQM 201

NEW RESULT



K^0_S



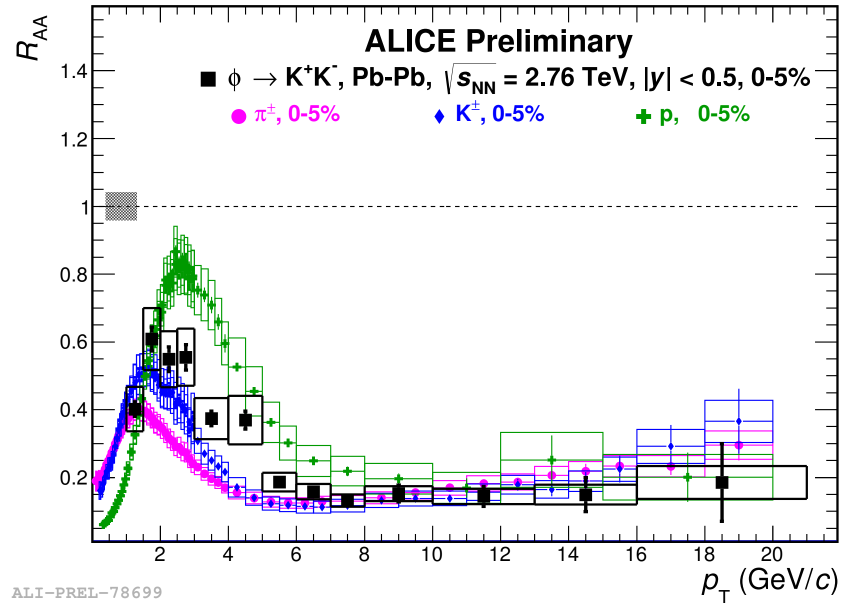
NEW RESULT

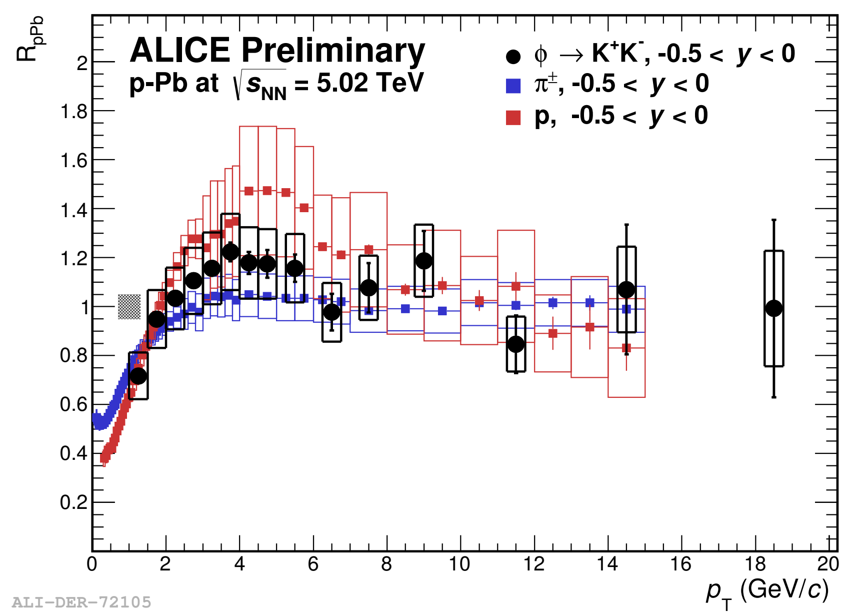
ϕ Nuclear Modification

- 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

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

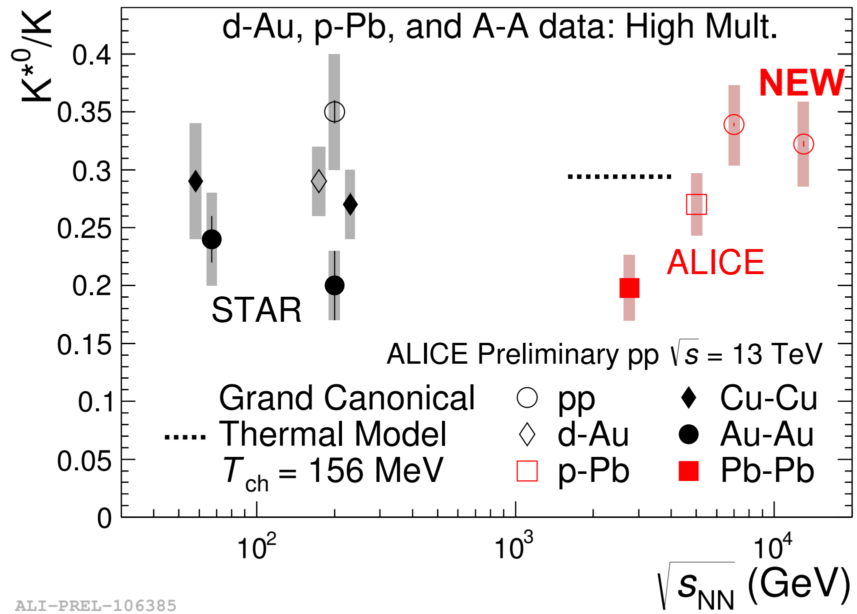
- In p–Pb:
  - No suppression of ϕ w.r.t. pp for p_T > 1.5 GeV/c
  - Intermediate p_T: Cronin peak for p, smaller peak for ϕ
  - Possible mass dependence or baryon/meson differences in R_{pPb}

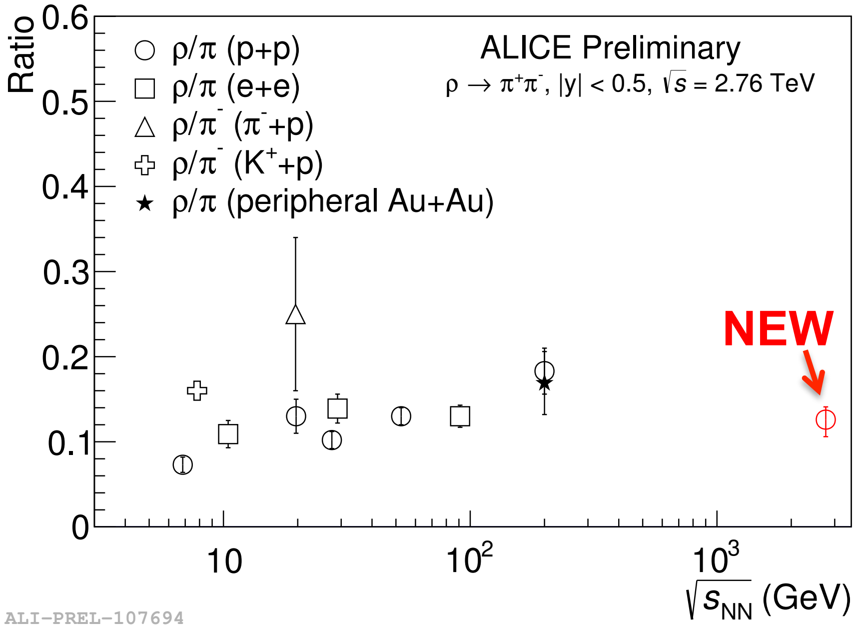


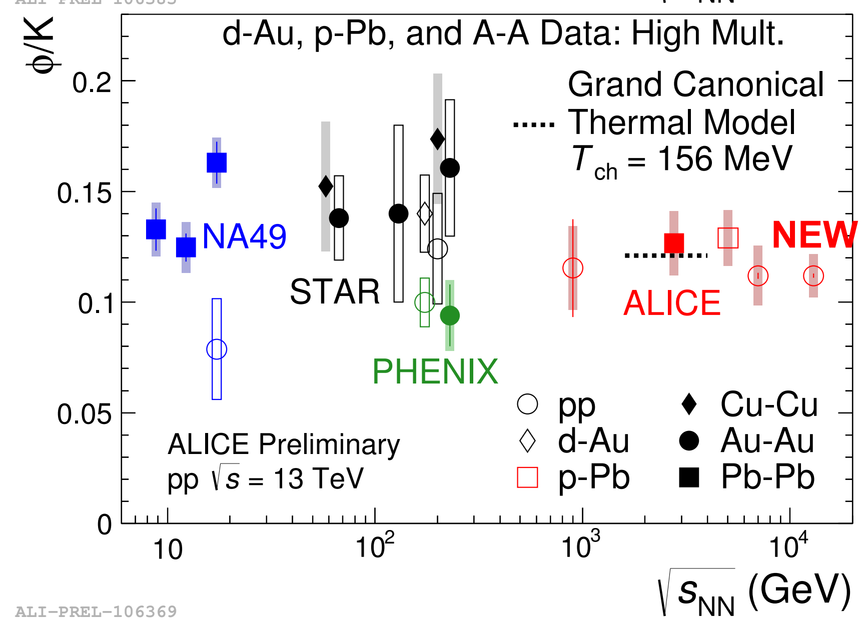


Ratios to Stable Hadrons

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

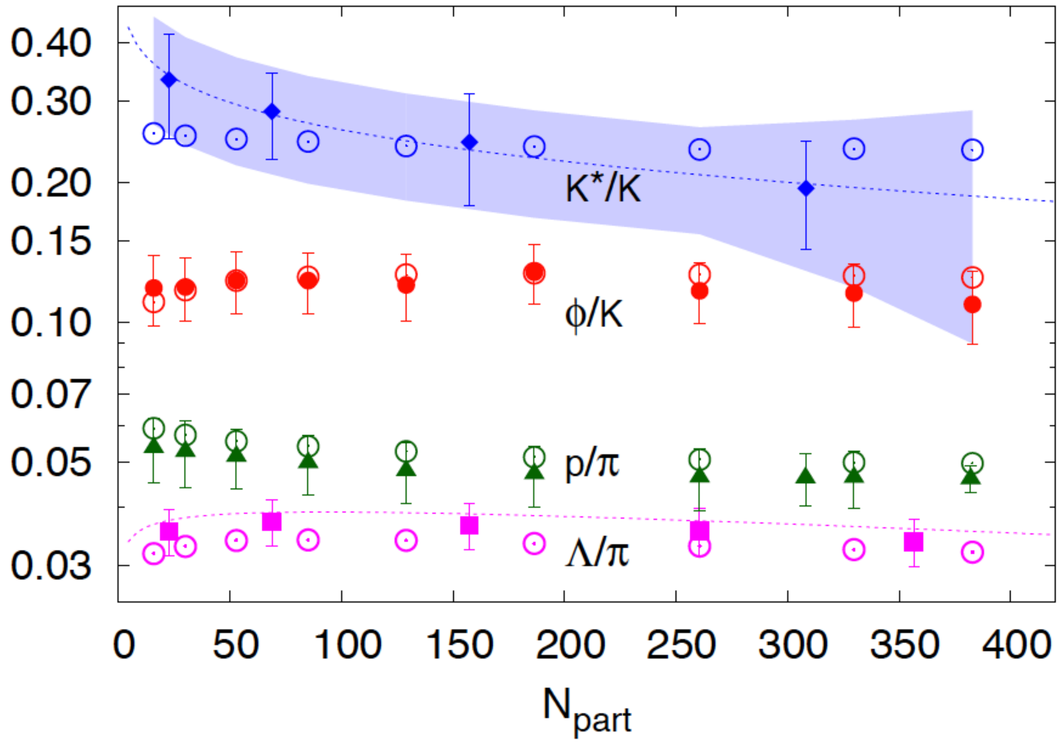






Non-equilibrium Model

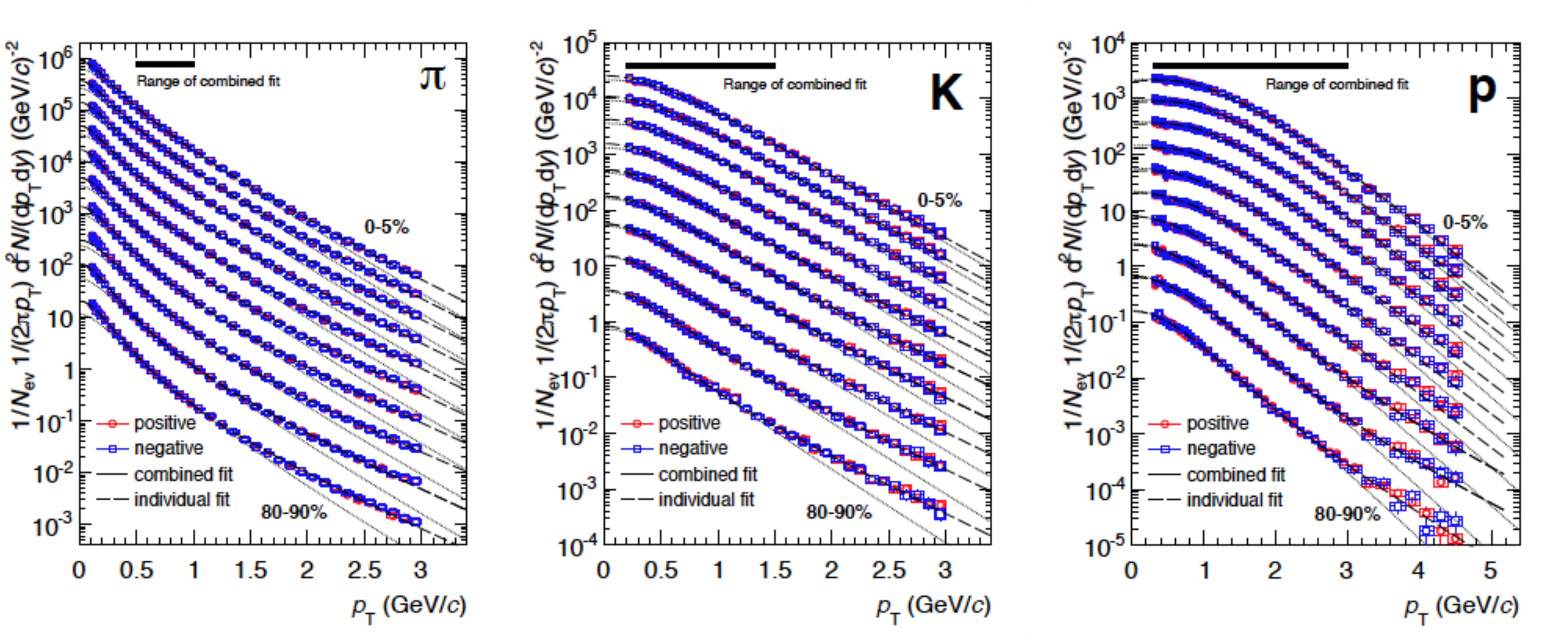
- Chemical non-equilibrium statistical hadronization model
  - *Phys. Rev. C* **88**, 034907 (2013)
- Factors $\gamma_q \neq 1$ and $\gamma_s \neq 1$ that modify u/d and s pair yields w.r.t. equilibrium values
  - $\gamma_q \neq 1$ when "source of hadrons disintegrates faster than the time necessary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



Uses preliminary ALICE K^{*0}/K, ϕ/K

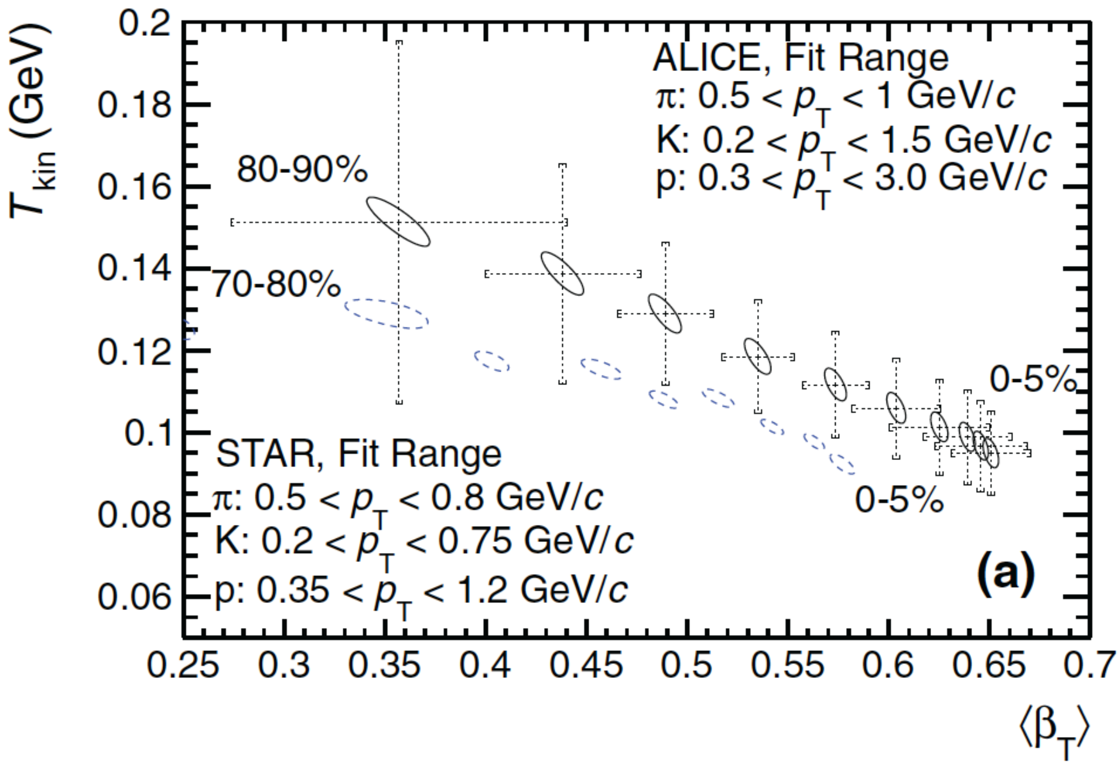
π/K/p Blast-Wave Fits

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



π/K/p Blast-Wave Fits

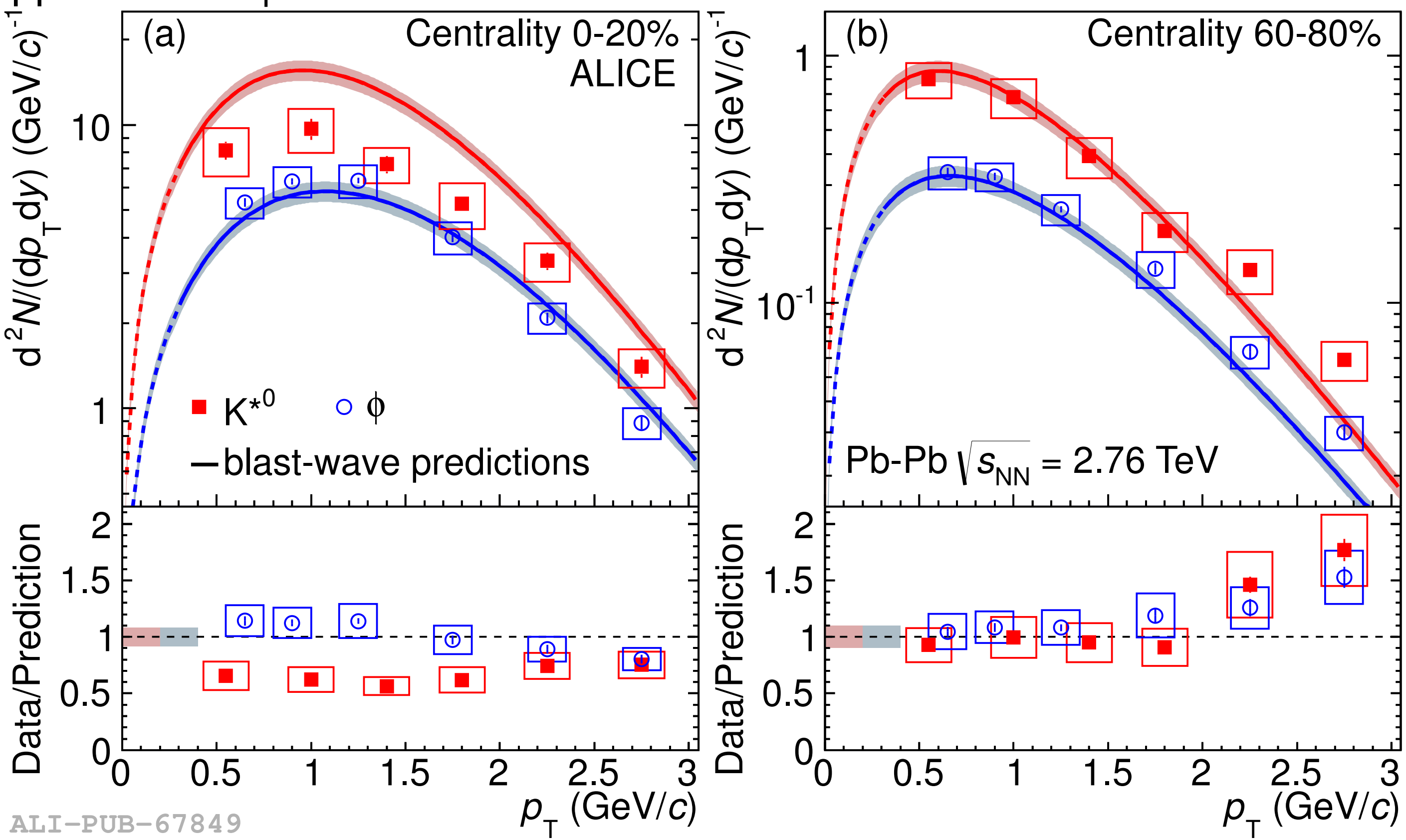
- Combined fits of $\pi^{\pm}$, $K^{\pm}$, and (anti)protons in Pb–Pb collisions
  - *Phys. Rev. C* **88** 044910 (2013)



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)



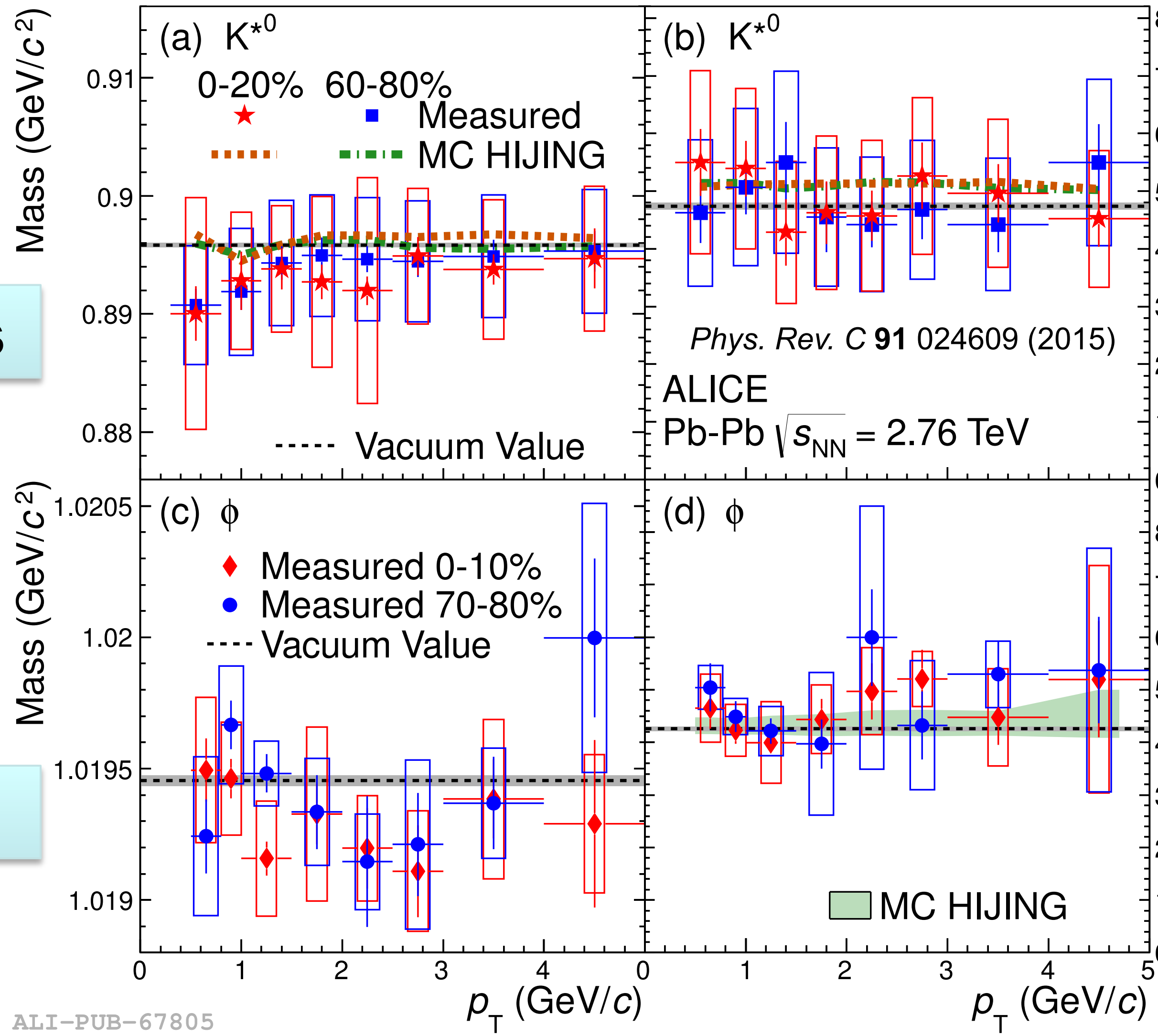
Mass and Width (Pb–Pb)

K*0 Mass

K*0 Width

ϕ Mass

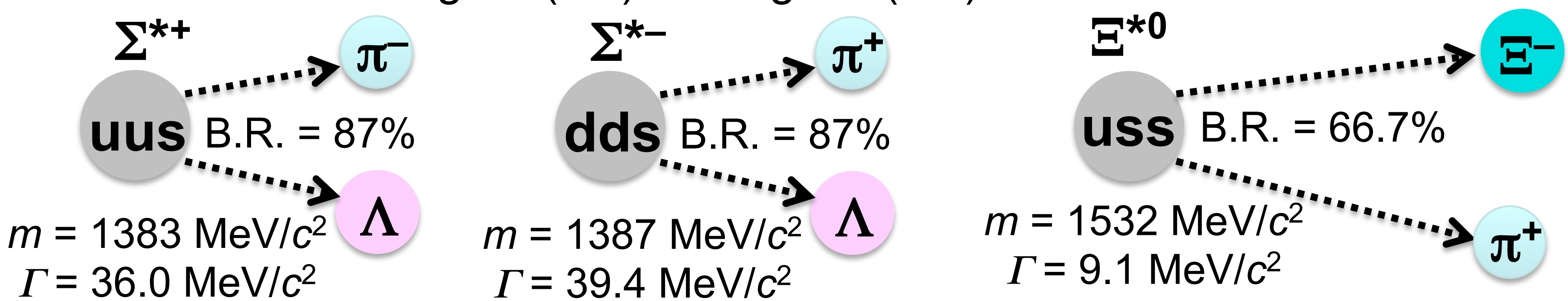
ϕ Width

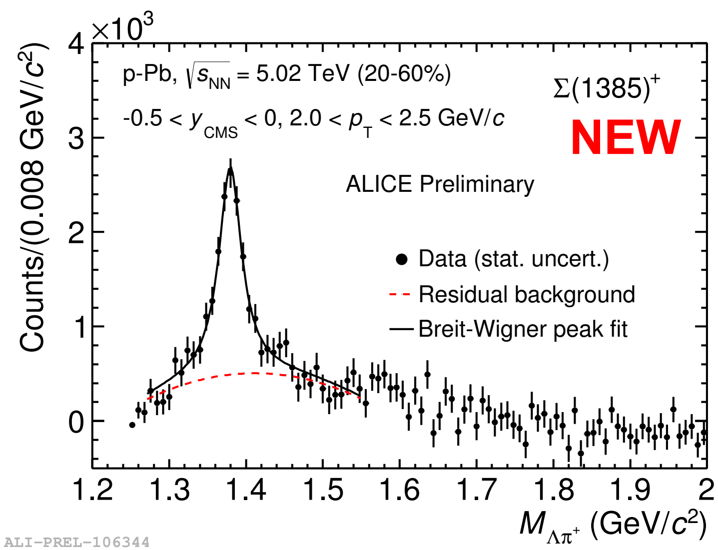


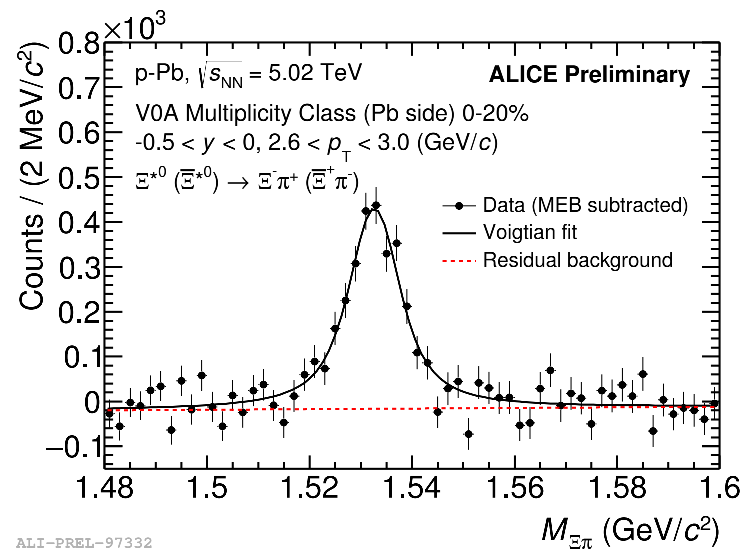
No significant mass or width shifts observed.
No centrality dependence of mass or width.

$\Sigma^{*\pm}$ and Ξ^{*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 (Ξ^{*0})



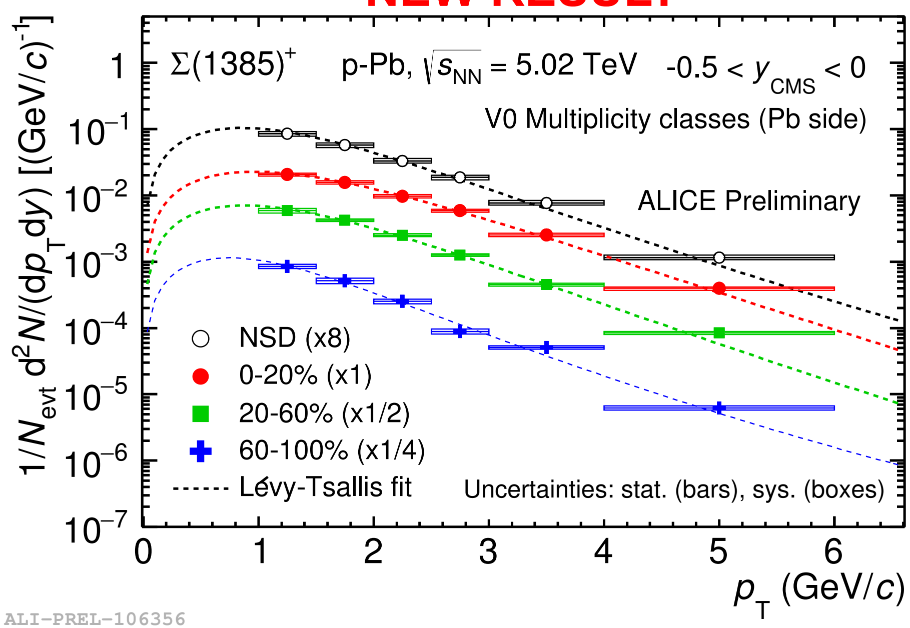


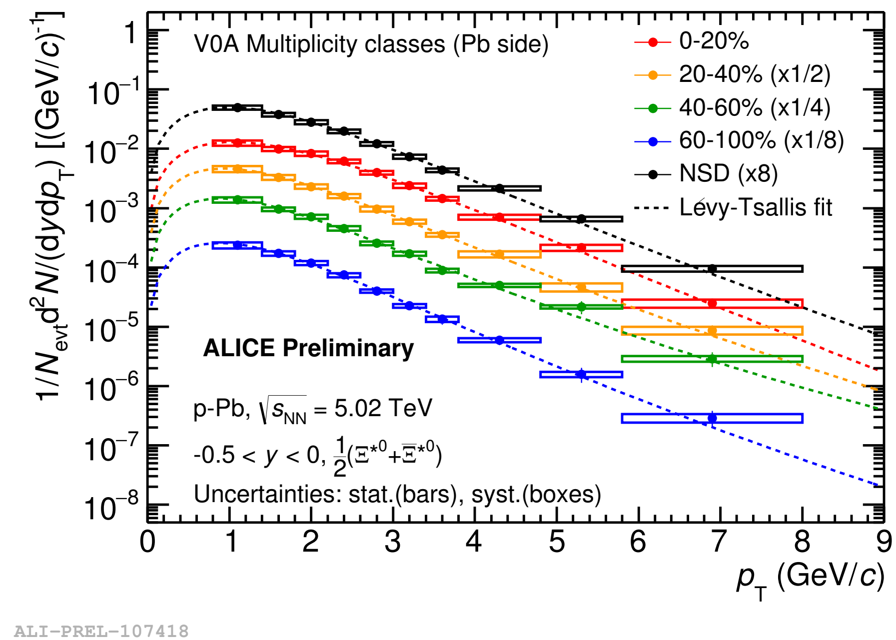


Σ*± and Ξ*0 Reconstruction

- 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 (Σ*±) or Voigtian (Ξ*0)

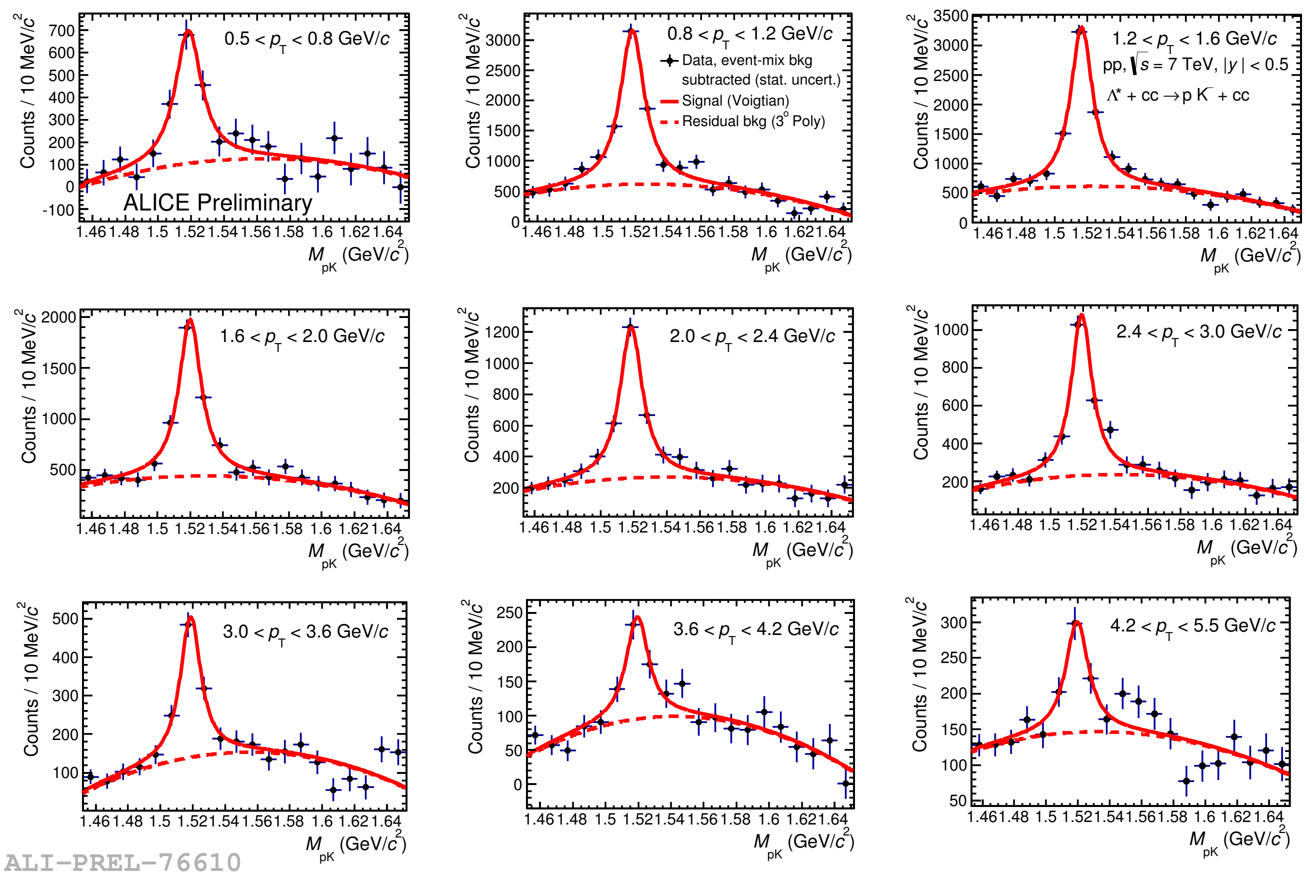
NEW RESULT





$\Lambda(1520)$

- Reconstruction in pp 2.76, 7, & 13 TeV; p–Pb 5.02 TeV, and Pb–Pb 2.76 TeV
- Decay channel: $\Lambda(1520) \rightarrow pK^-$
  - 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 in pp

- 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