Study of resonance production as a probe of heavy-ion collisions with the ALICE detector

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on behalf of the ALICE Collaboration

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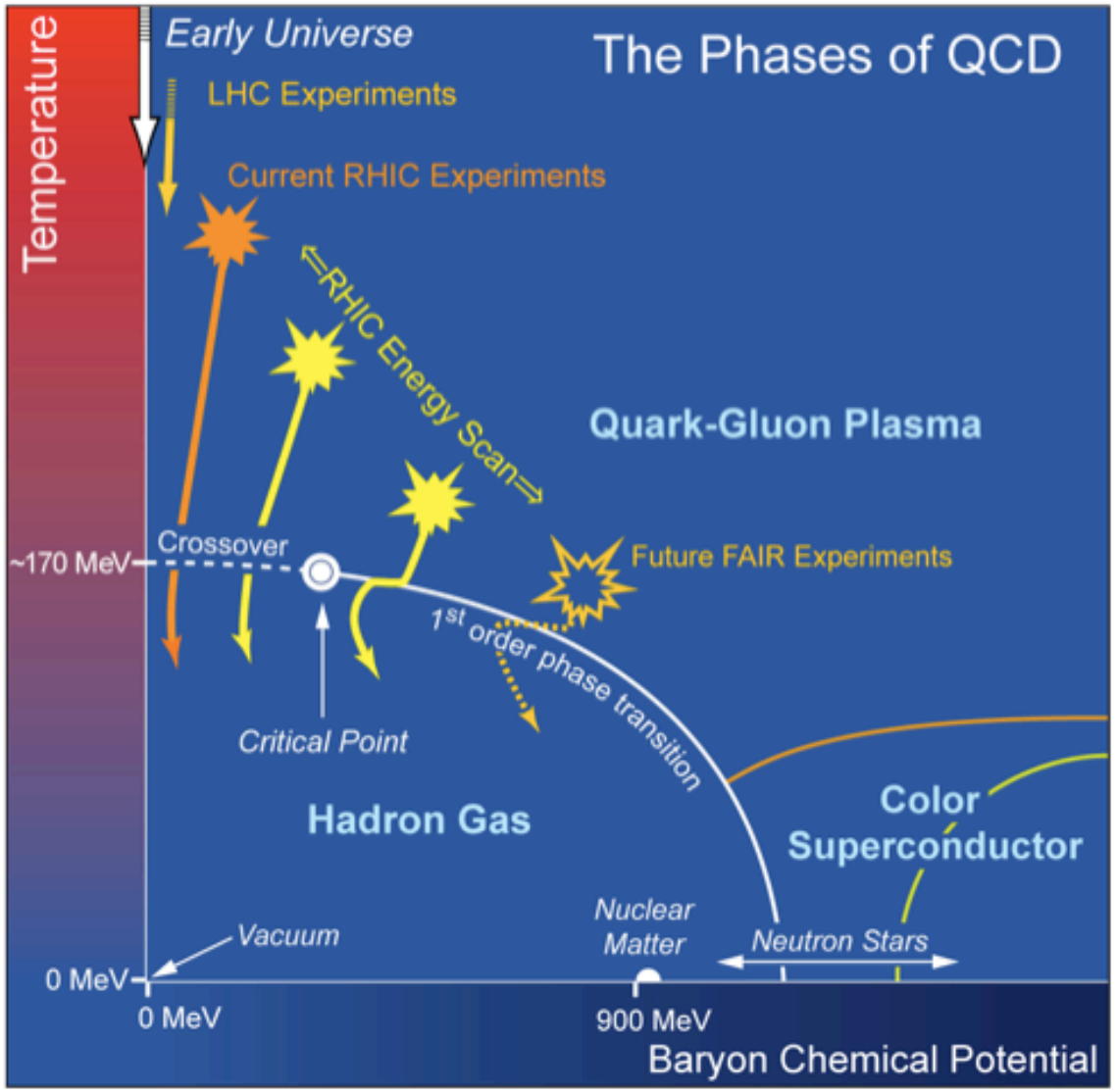
A Quick Introduction to Heavy-Ion Physics and ALICE

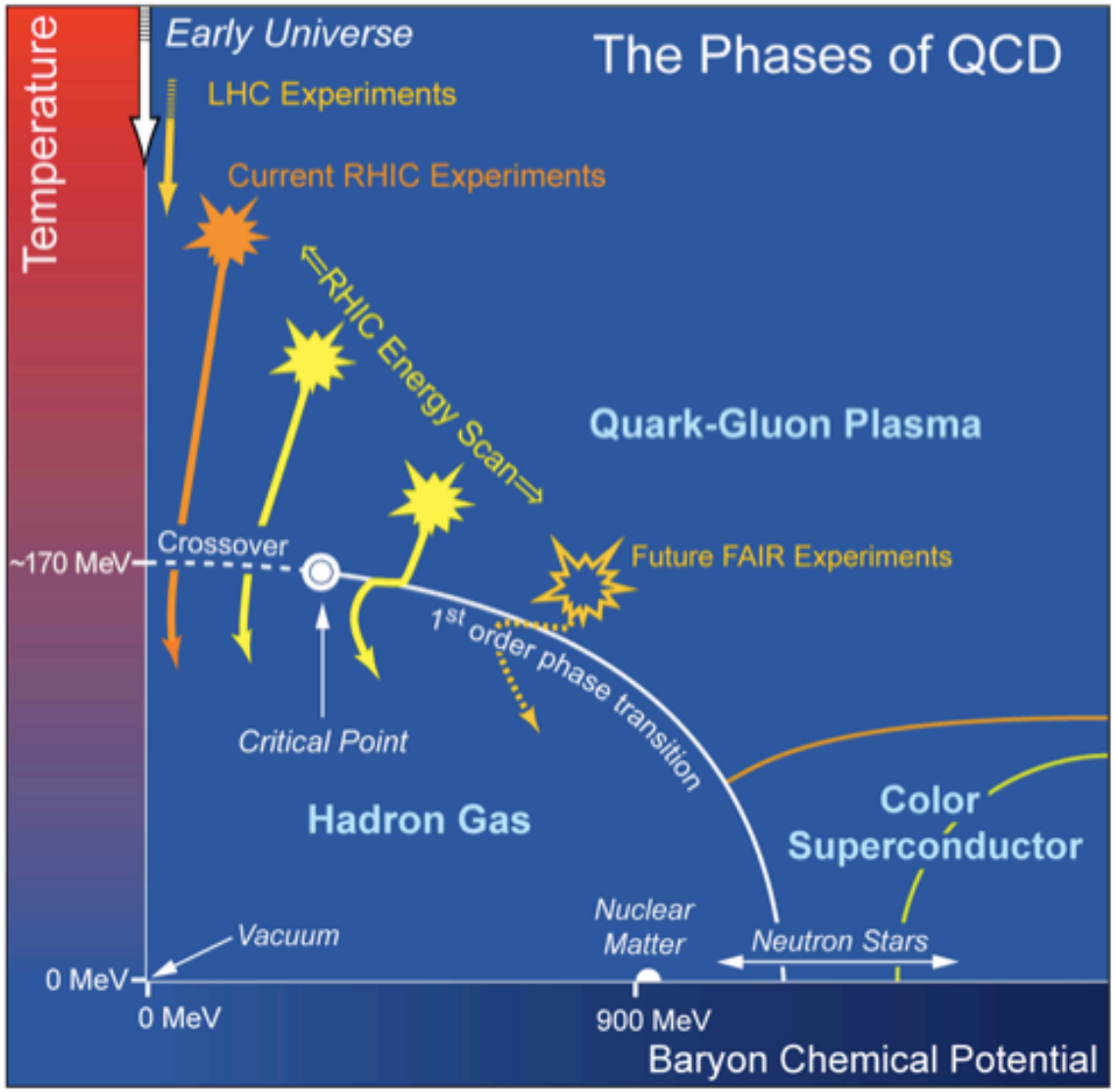
QCD Phase Diagram

- Schematic phase diagram of strongly interacting matter for temperature and baryon chemical potential
- At LHC energies: most particles produced during the collision → very low baryon chemical potential



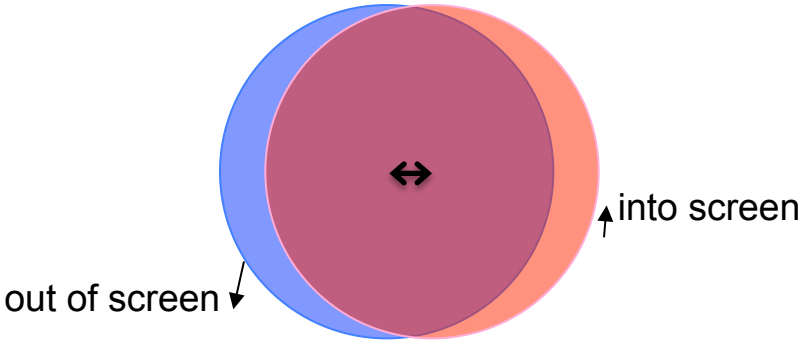
Quark-Gluon Plasma

- Quark-Gluon Plasma (QGP): phase of deconfined quarks and gluons
- QGP behaves as a perfect fluid
  - Well described by ideal hydrodynamics
  - Ratio of viscosity/ entropy density near quantum lower limit ($\eta/s > 1/4\pi$)
- Phase transition near 170 MeV
- Crossover or 1st-order phase transition between QGP and hadron gas
- Critical point?
  - RHIC Energy Scan

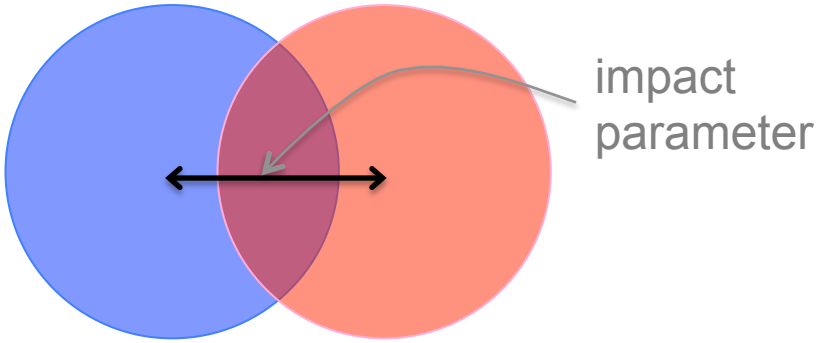


Collision Geometry

- Centrality: amount of overlap between nuclei
- Impact parameter: distance between centers of nuclei
- Cannot measured impact parameter directly; measure
  - Charged-particle multiplicity (mostly $\pi^{\pm}$, $K^{\pm}$, p, and $\bar{p}$)
    - Used as proxy for system size and horizontal axis for plots.
  - Number of spectator neutrons (unaffected by collision)
  - Use models to map these measurements into impact parameter

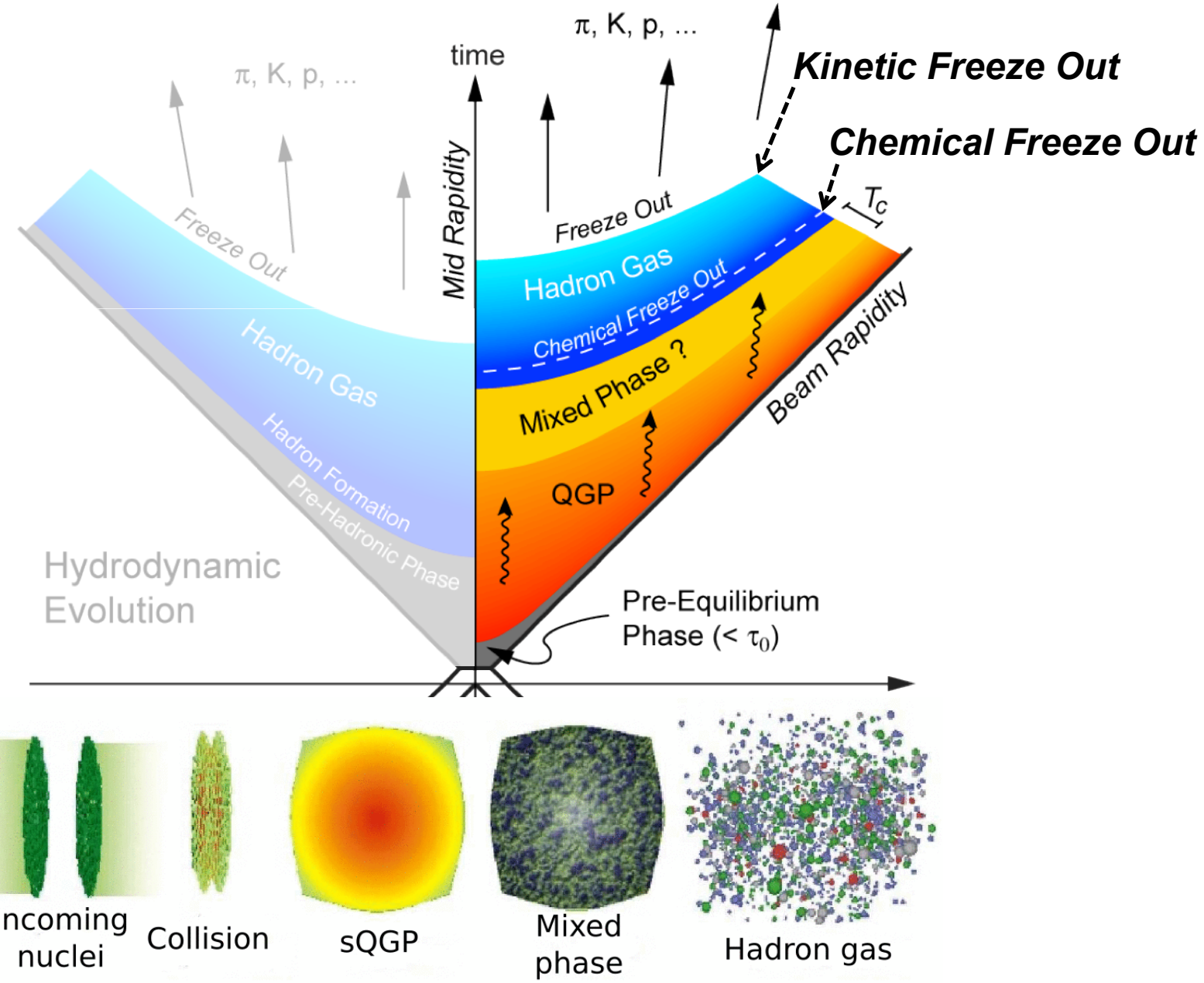


"Central"
Small impact parameter
Large system volume
Large charged-particle multiplicity

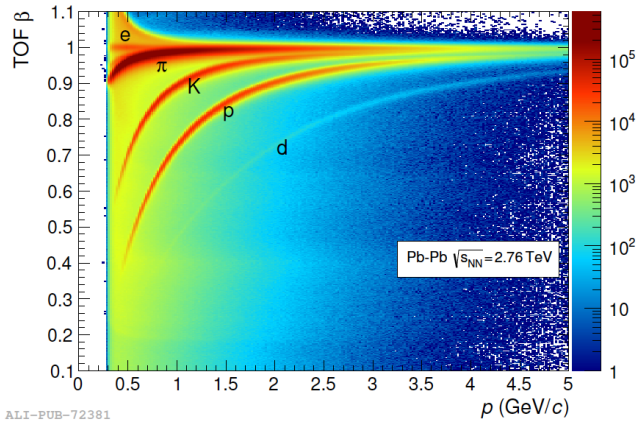


"Peripheral"
Large impact parameter
Small system volume
Small charged-particle multiplicity

Time Evolution



ALICE Detector

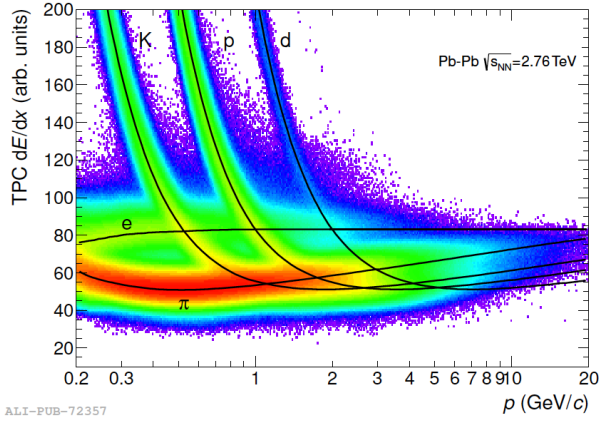


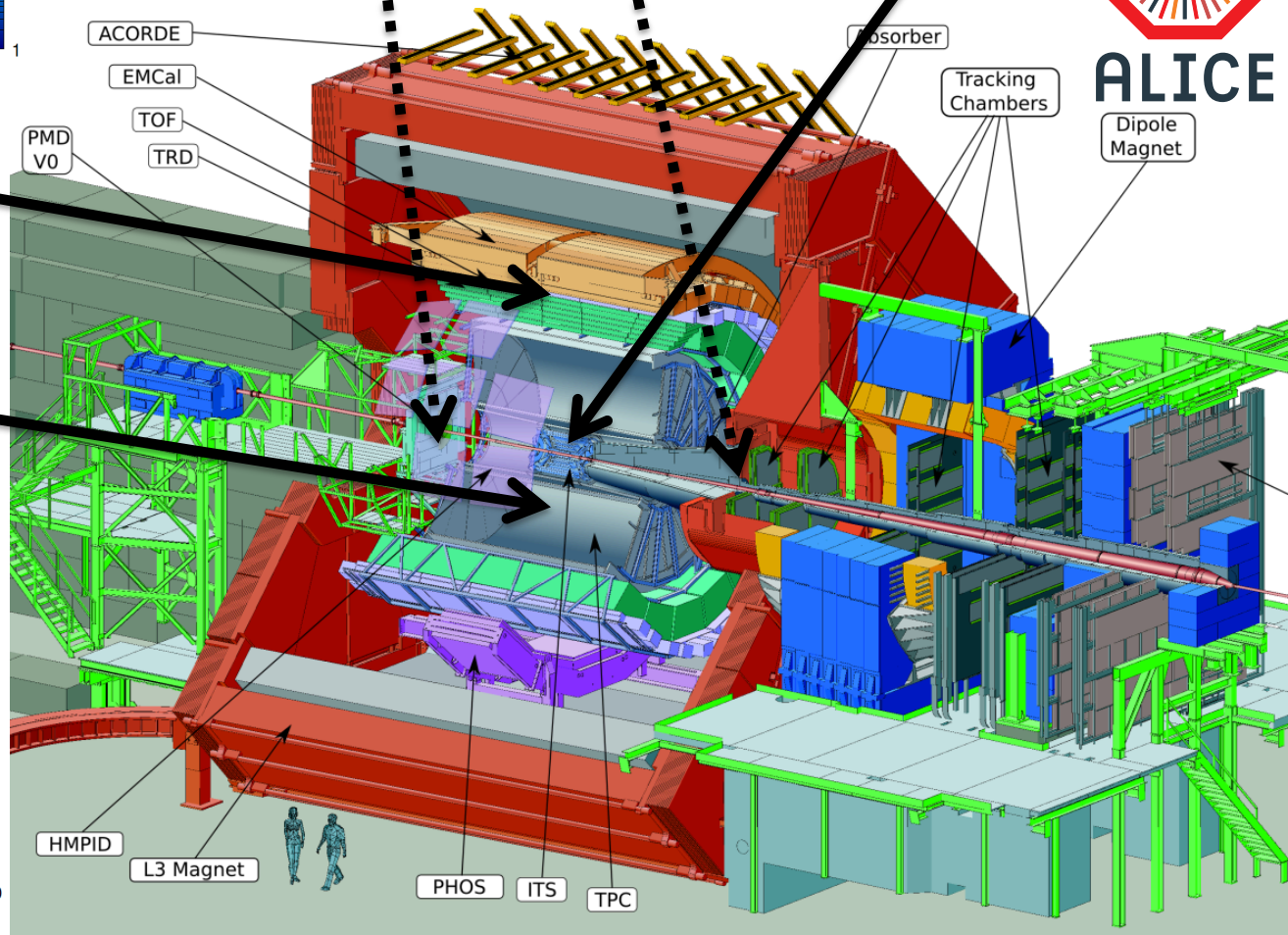
V0 (scintillators): centrality estimate through V0 multiplicity

ITS (silicon): Tracking and Vertexing

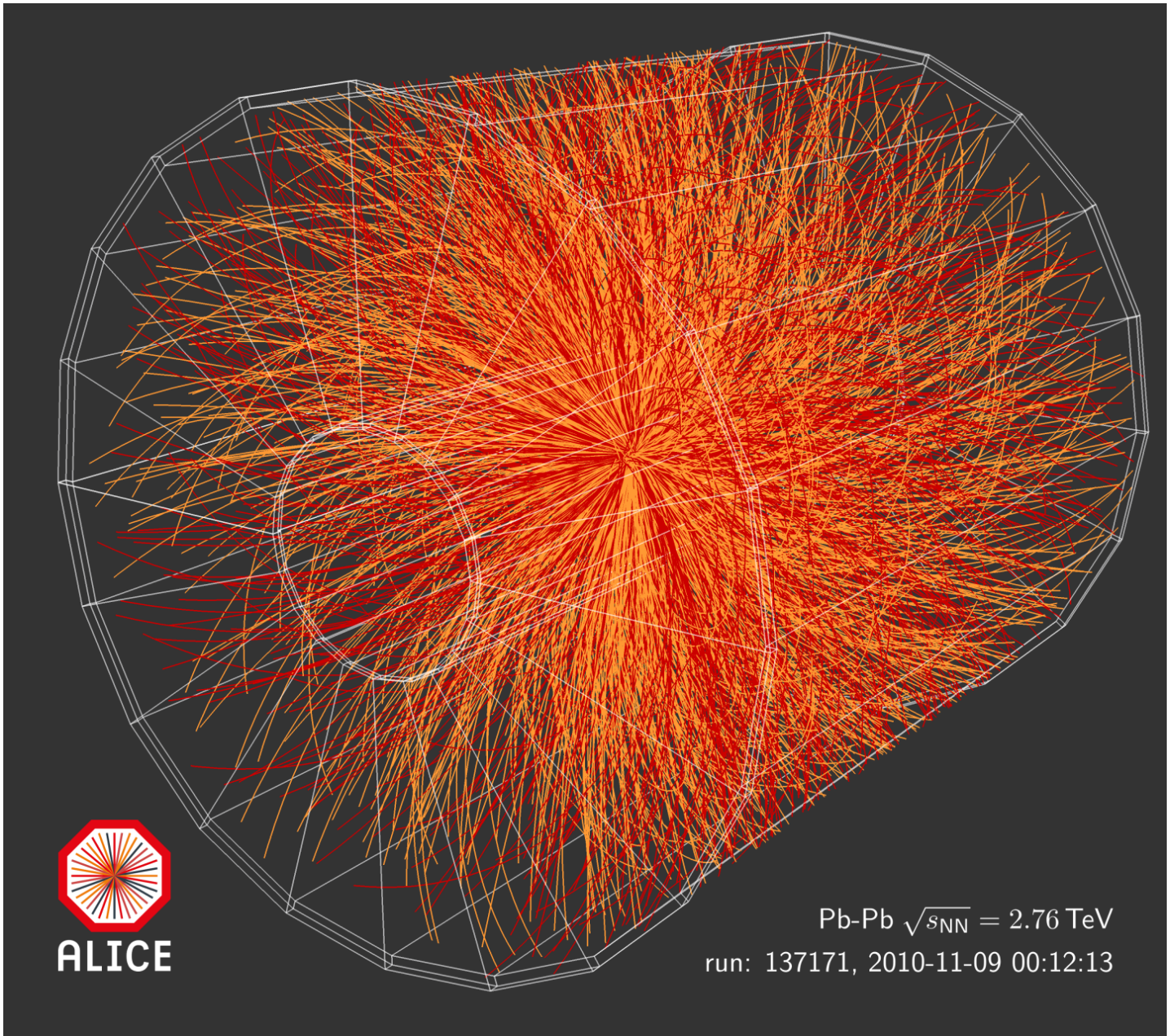
TOF: PID through particle time of flight

TPC: Tracking and PID through dE/dx





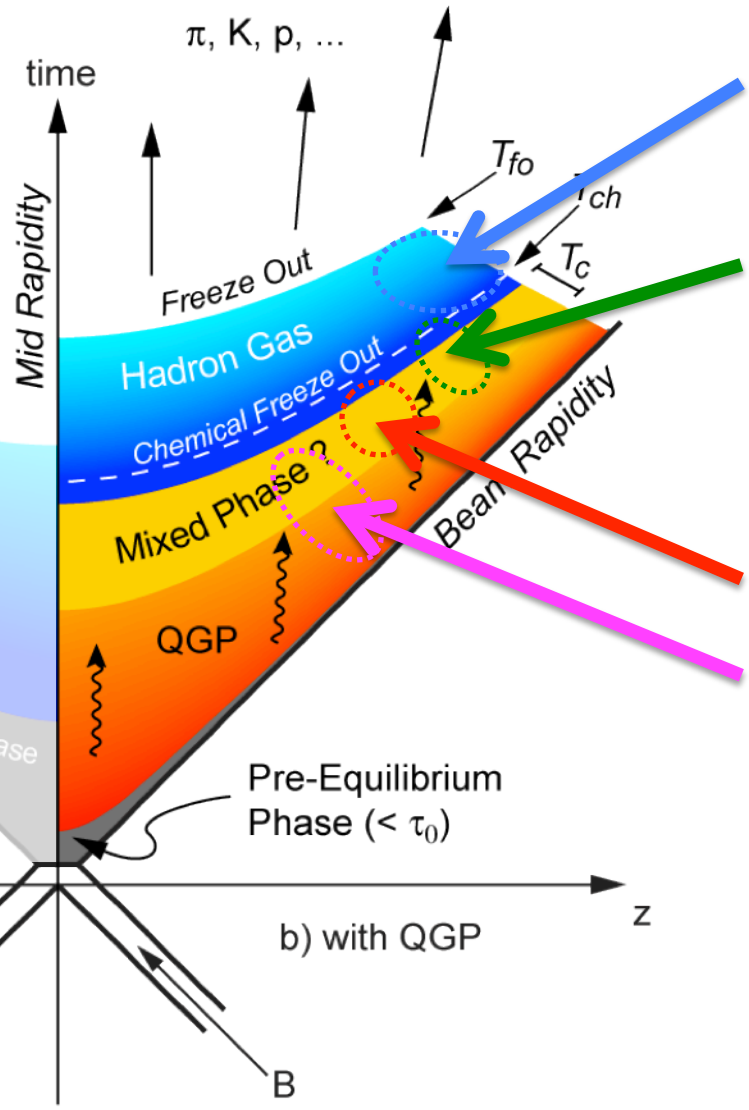
ALICE Pb–Pb Collision



Hadronic Resonances at ALICE

- Why do we study resonances?
- What resonances do we study?
- How do we study them?
- Important recent results

Motivation



Properties of hadronic phase

- Next slide…

What shapes particle p_T spectra?

- Hydrodynamics (particle mass is dominant factor)
- Recombination/Coalescence (quark content is important)

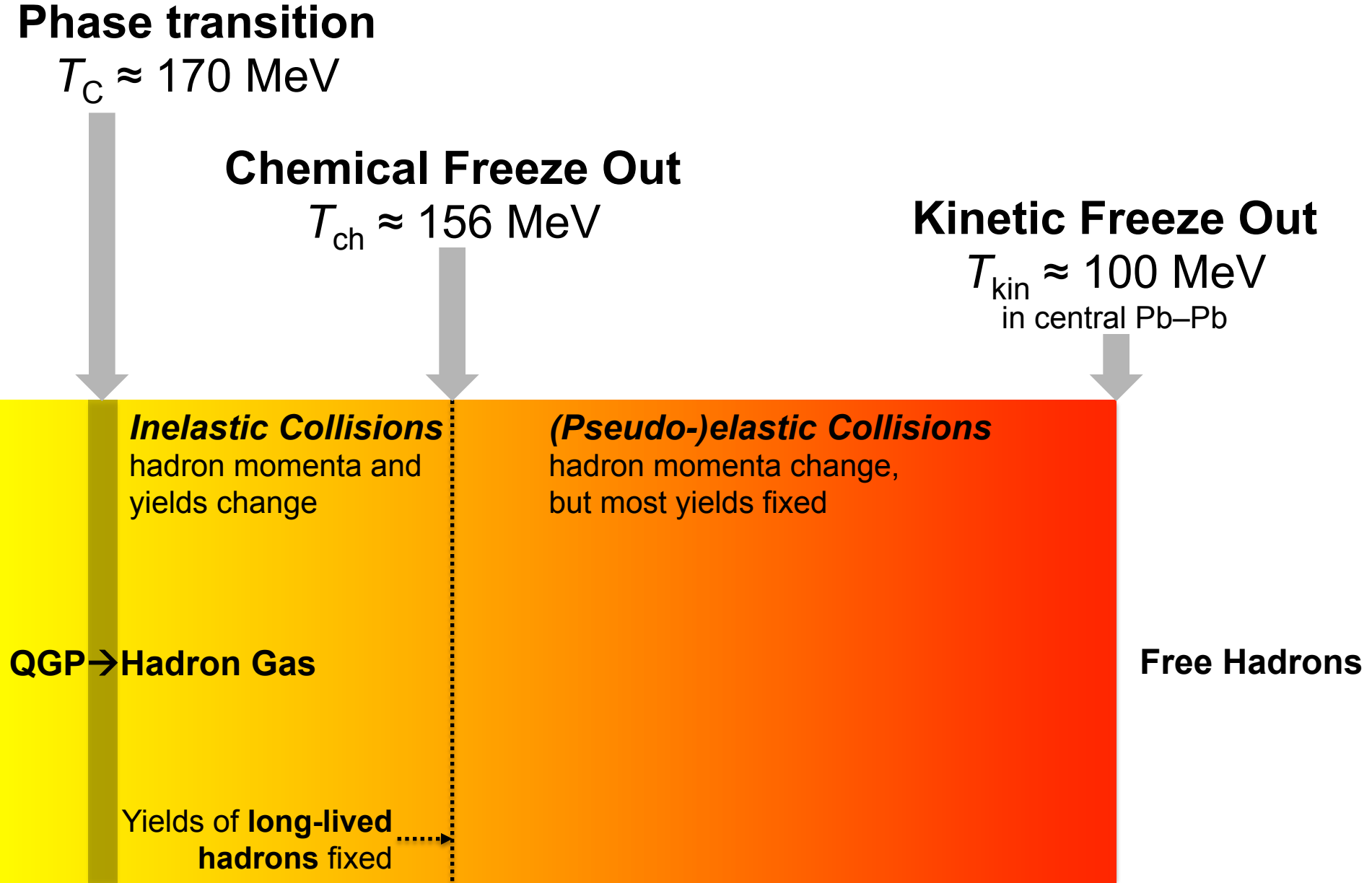
Chiral symmetry restoration

In-medium energy loss

Small Systems:

- pp and p–Pb
- Baselines for Pb–Pb
- Data to tune event generators
- Look for collective effects

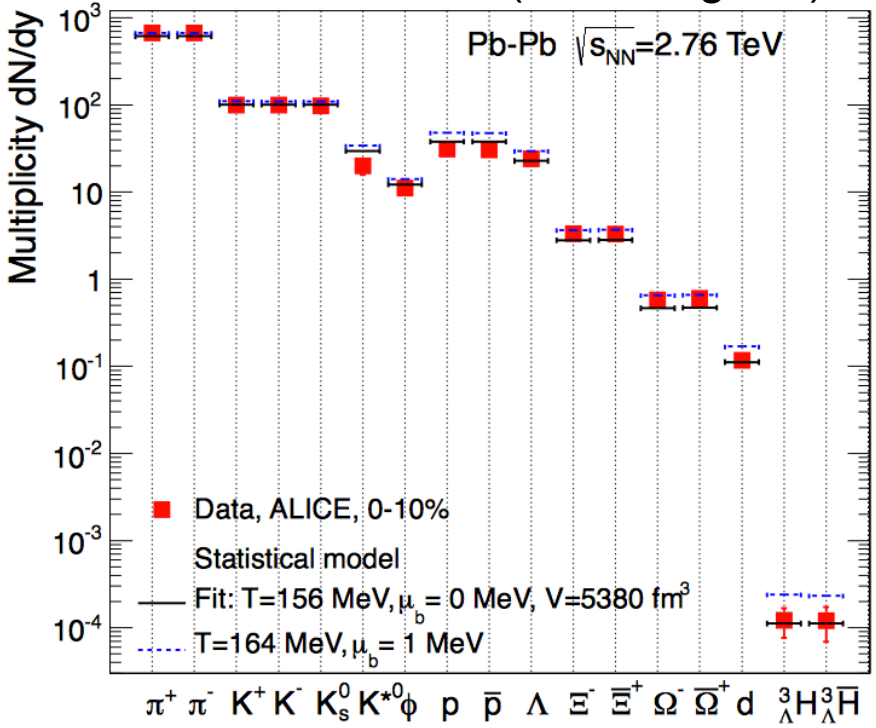
Hadronic Phase



Thermal Models

- Yields of particle species containing *u*, *d*, and *s* quarks can be described using a grand canonical thermal model
- Model parameters:
  - Chemical freeze out temperature (T_{ch})
  - Baryon chemical potential (μ_B)

Fit to ALICE data (excluding K^{*0})

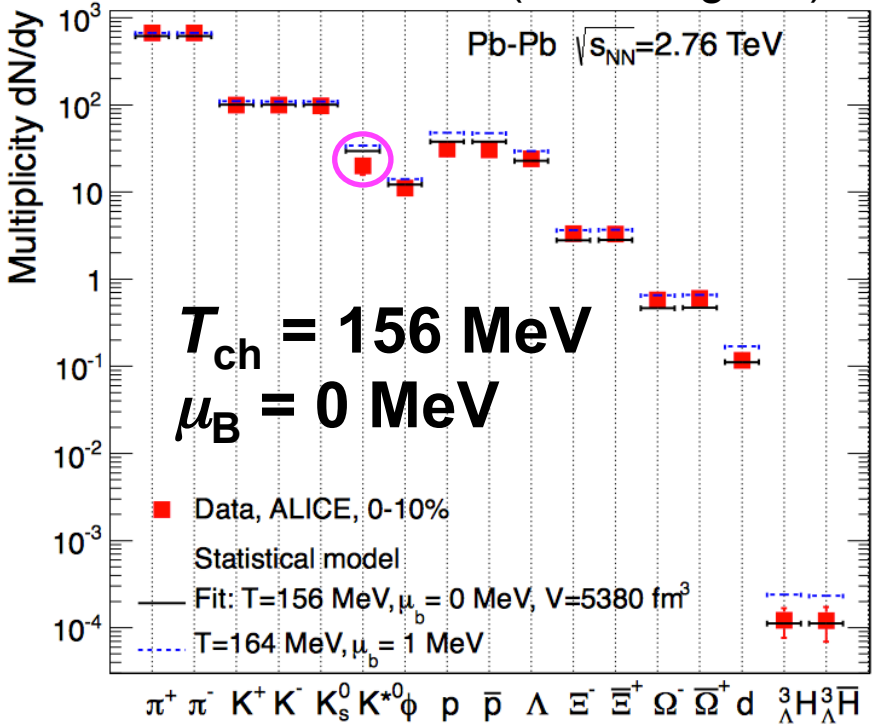


J. Phys.: Conf. Ser. **509** 012019 (2014)

Thermal Models

- T_{ch} = 150–180 MeV
- Small baryon chemical potentials: consistent with 0 at LHC, 20–50 MeV at RHIC
- One set of parameters can describe yields of mesons, baryons, and even light nuclei (d, $_{\Lambda}{}^{3}\mathrm{H}$) over several orders of magnitude
- But resonances (K^{*0}) not well described…

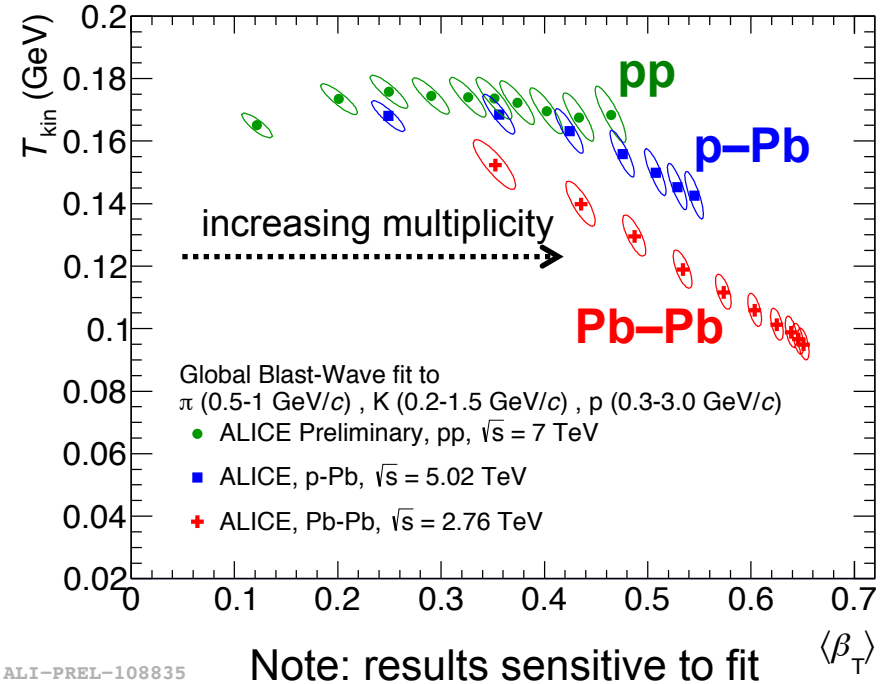
Fit to ALICE data (excluding K^{*0})



J. Phys.: Conf. Ser. **509** 012019 (2014)

Blast-Wave Model

- Hadrons have common kinetic freeze out temperature and velocity profile.
- Hadron p_T spectra parameterized with T_{kin}, n, and β (radial flow).
- Combined fits of $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$
- Increase centrality in Pb–Pb: T_{kin} decreases, $<\beta_T>$ increases



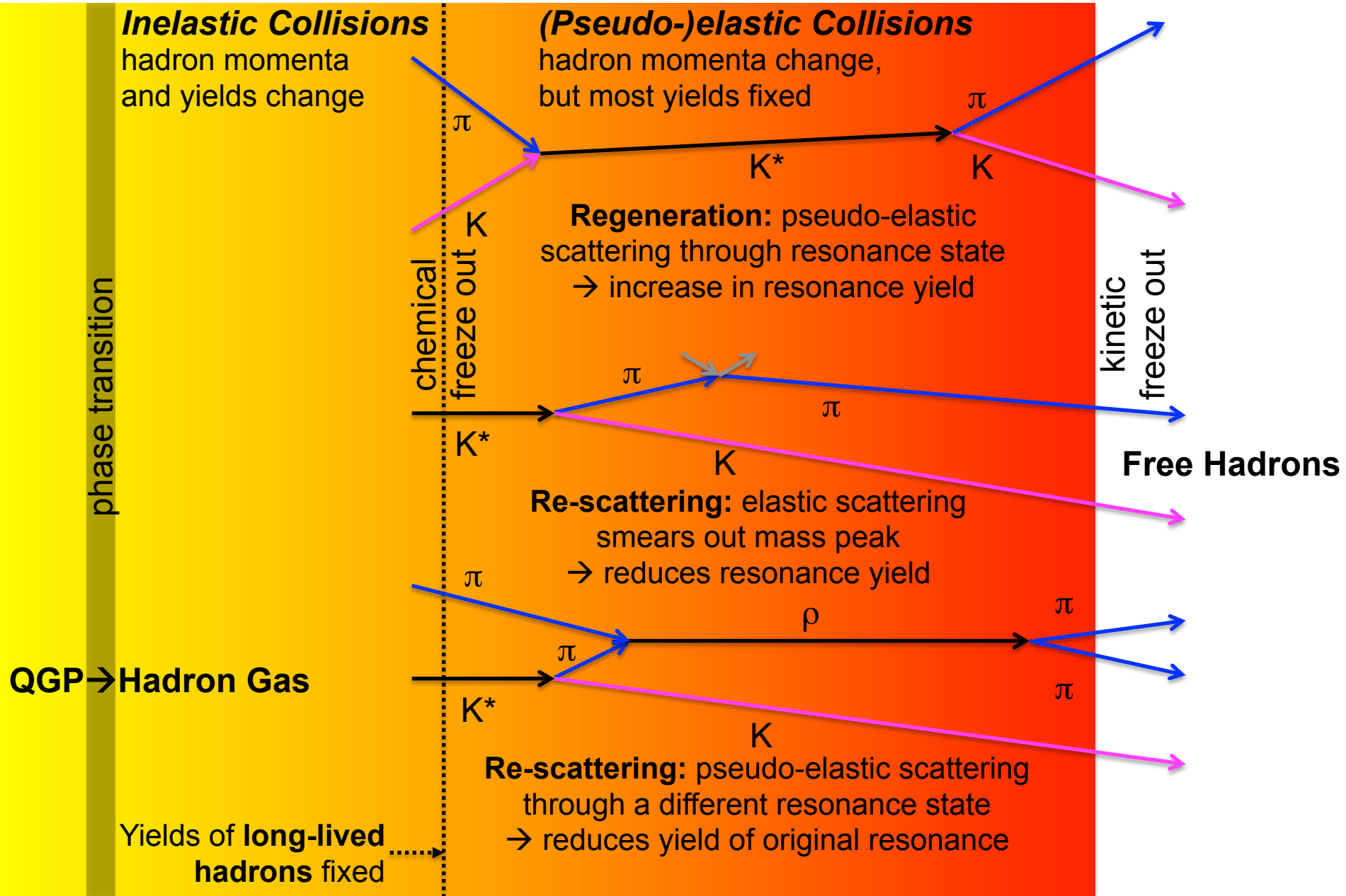
Note: results sensitive to fit range and particles included

$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r\,dr\, m_T\, I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right),$$

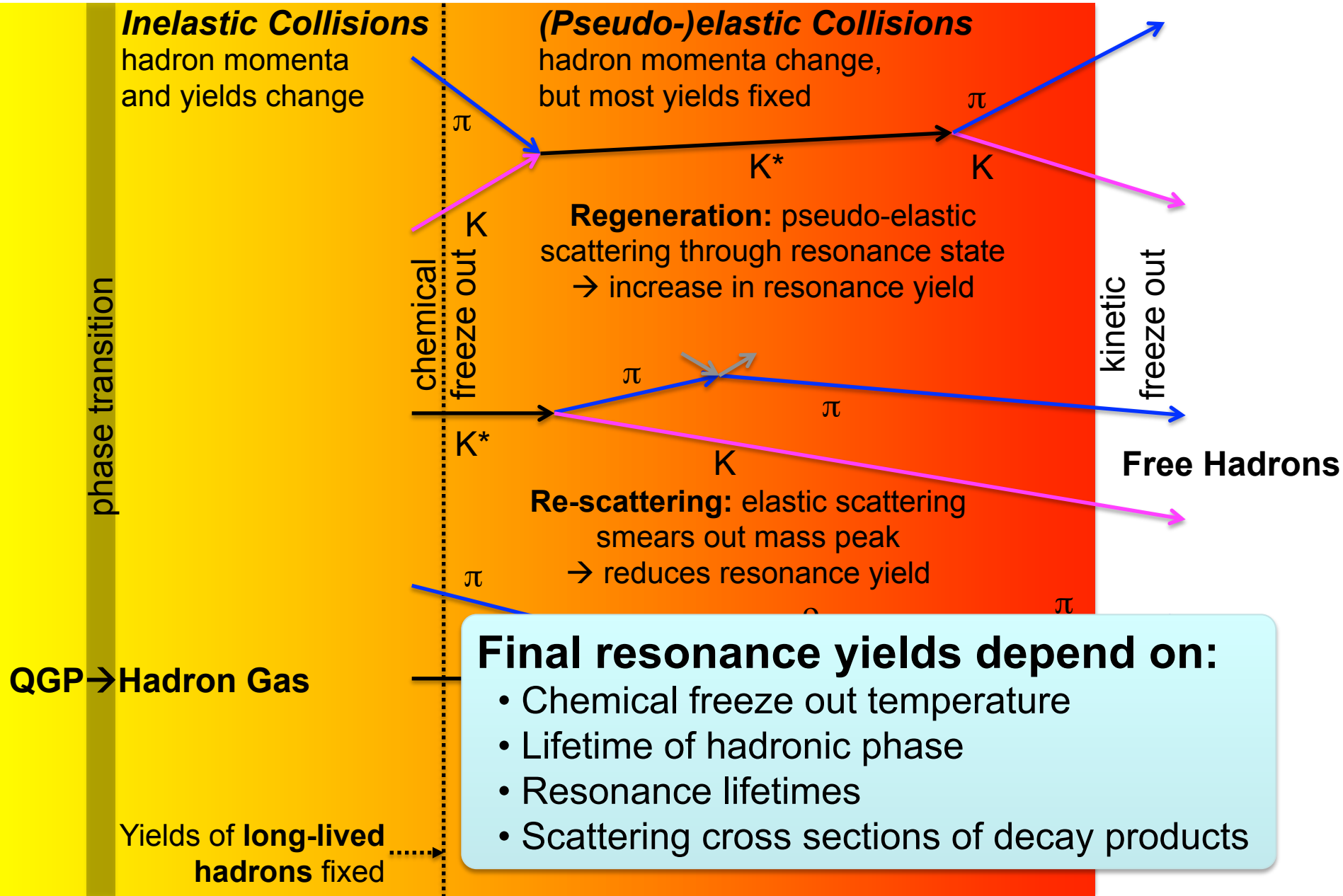
$$\rho = \tanh^{-1}\beta_T = \tanh^{-1}\left(\left(\frac{r}{R}\right)^n \beta_s\right)$$

Phys. Rev. C **48** 2462 (1993)

Hadronic Phase

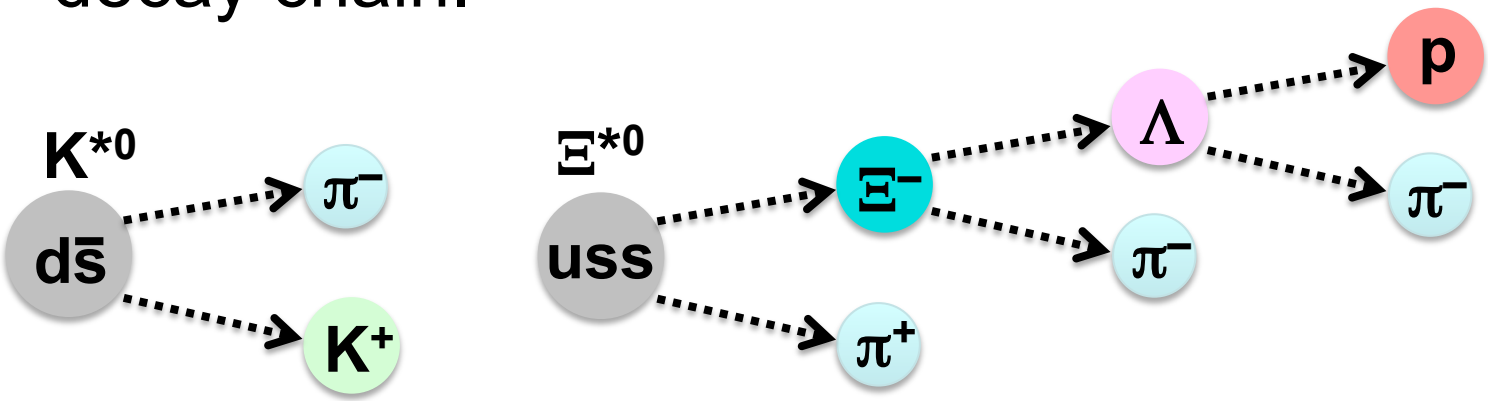


Hadronic Phase



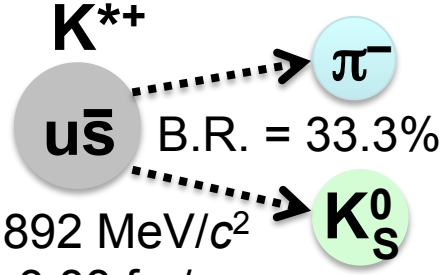
Resonances

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



Mesons

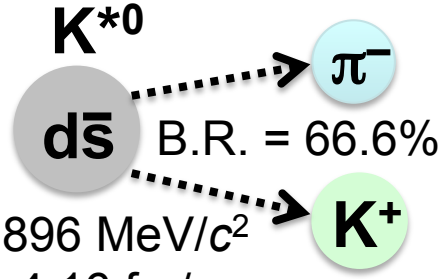
K*+



m = 892 MeV/c^2

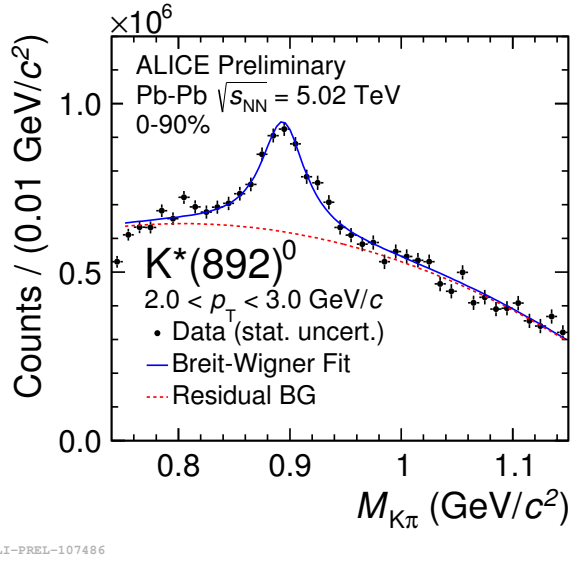
τ = 3.88 fm/c

K*0

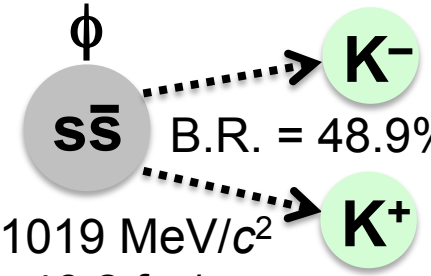


m = 896 MeV/c^2

τ = 4.16 fm/c

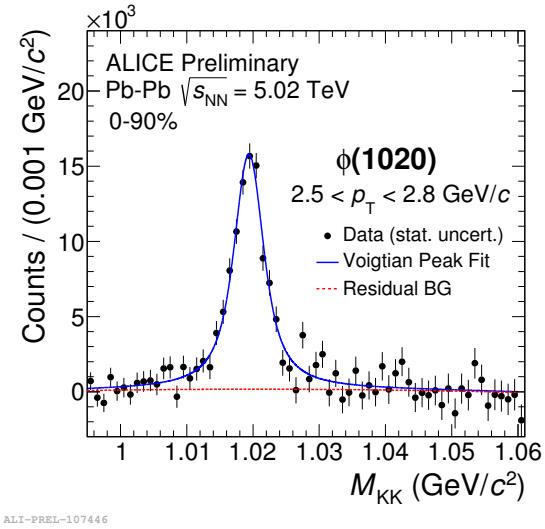


ϕ



m = 1019 MeV/c^2

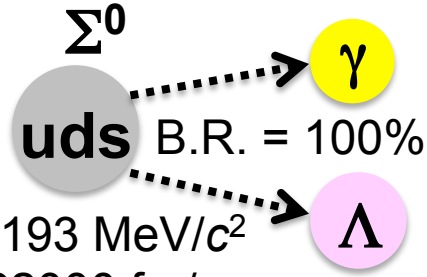
τ = 46.2 fm/c



And also ρ^0 (more information in 2 slides…)

Baryons

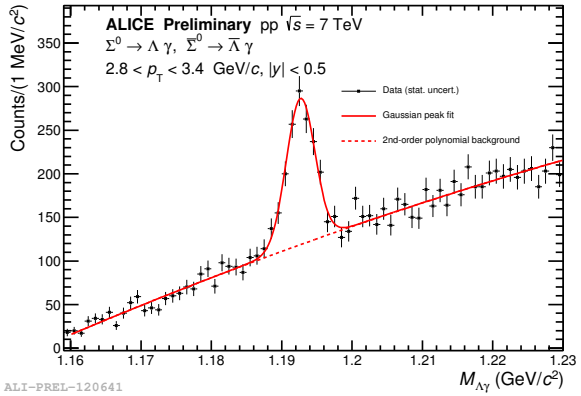
Σ^0



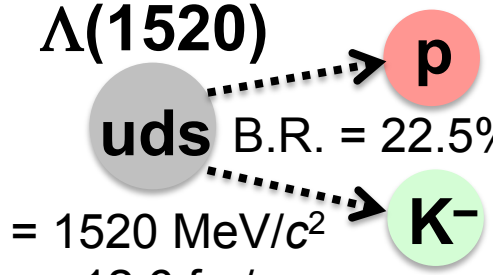
B.R. = 100%

m = 1193 MeV/c^2

τ = 22000 fm/c



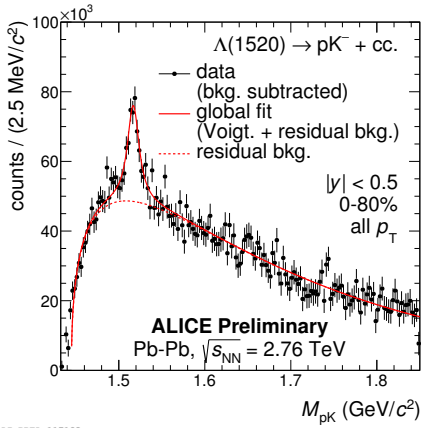
$\Lambda(1520)$



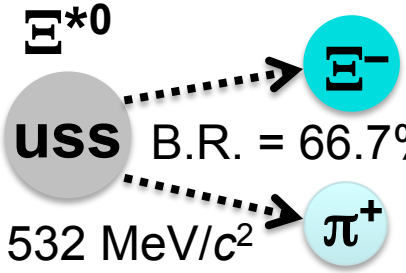
B.R. = 22.5%

m = 1520 MeV/c^2

τ = 12.6 fm/c



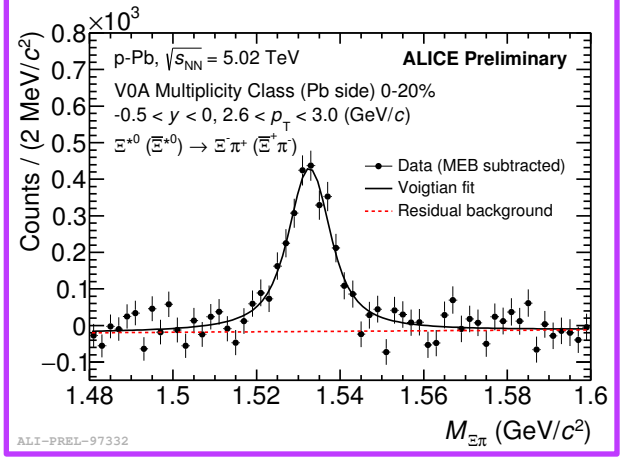
Ξ^{*0}



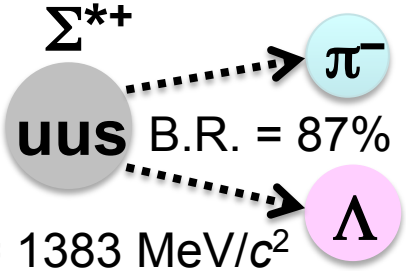
B.R. = 66.7%

m = 1532 MeV/c^2

τ = 21.7 fm/c



Σ^{*+}

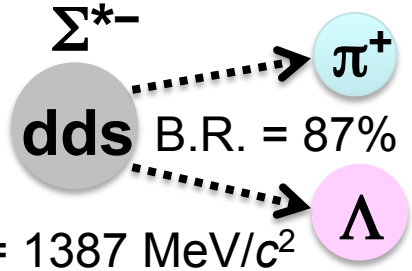


B.R. = 87%

m = 1383 MeV/c^2

τ = 5.5 fm/c

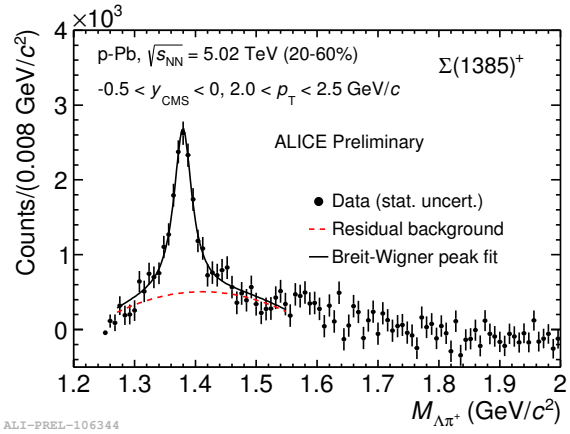
Σ^{*-}



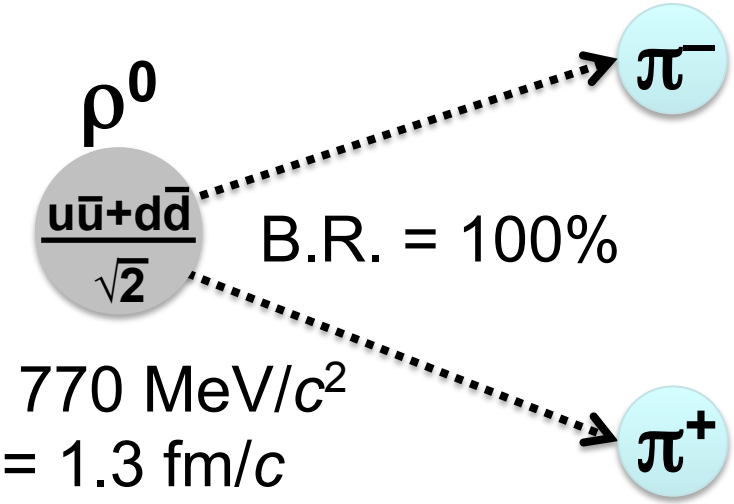
B.R. = 87%

m = 1387 MeV/c^2

τ = 5.0 fm/c



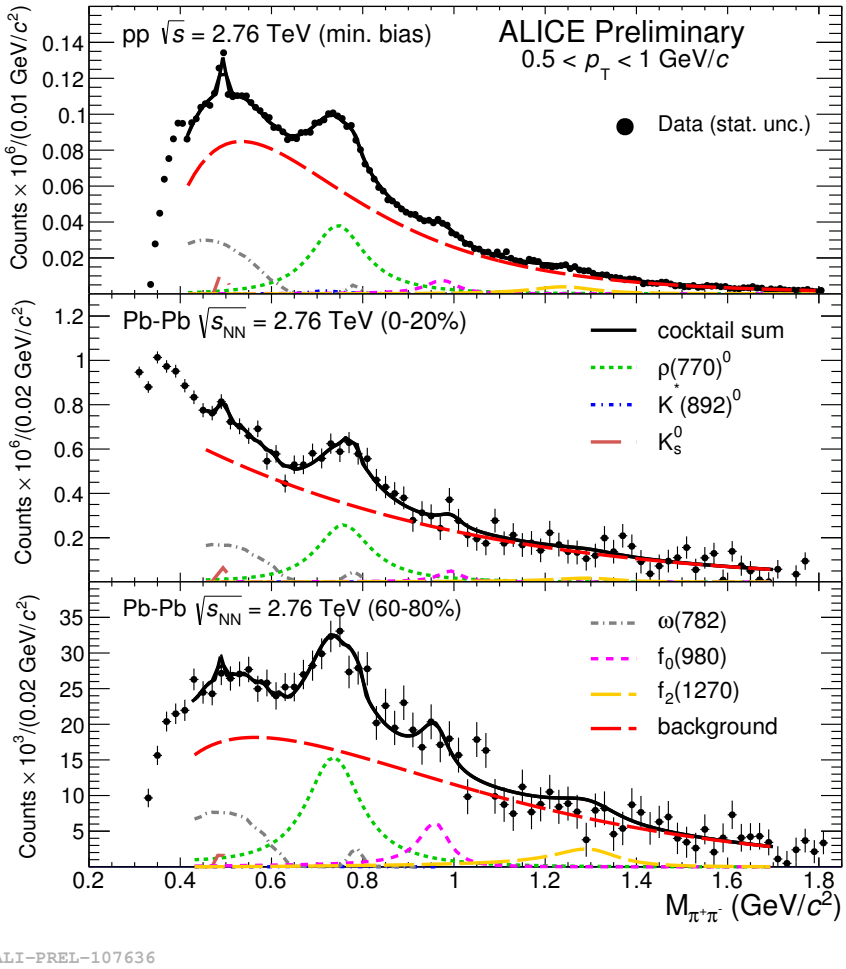
ρ^0 Reconstruction



m = 770 MeV/c^2

τ = 1.3 fm/c

NEW RESULT



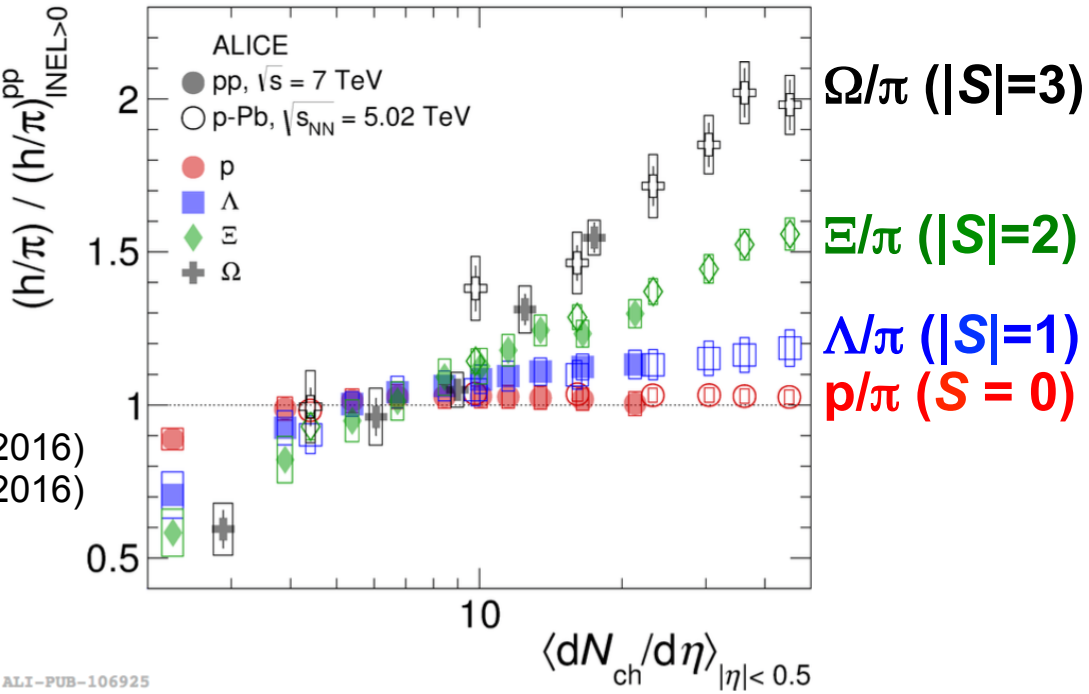
ALI-PREL-107636

- 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***

Strangeness Production

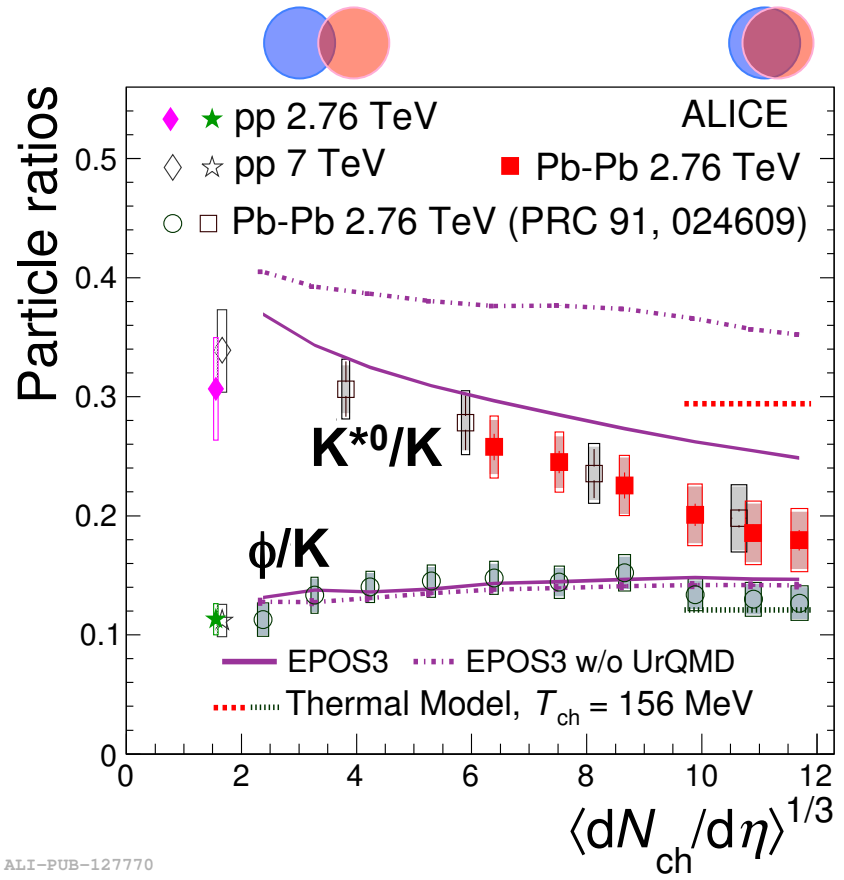
- Enhancement of strange hadron yields observed in Pb–Pb
  - Also seen in p–Pb and pp vs. multiplicity
  - Previously proposed as signature of QGP
- Double ratio: $[h/\pi]^{system}/[h/\pi]^{ppINEL}$: magnitude of enhancement increases with number of strange quarks
  - What causes it? Strangeness content? Mass? Baryon number?
- For resonances: plot ratio of resonance yields to ground-state particles with same strangeness content: cancel out strangeness enhancement



arXiv:1606.07424 (2016)
Phys. Lett. B **758** 389 (2016)

Particle Yield Ratios

- Ratios of p_T-integrated* yields
  - K^{*0}/K: divide by ground-state particle with same strangeness
- Suppression of K^{*0}/K in central Pb–Pb w.r.t. peripheral Pb–Pb, pp and thermal model
- No suppression of ϕ/K
  - Central Pb–Pb consistent with thermal model
- Suggests that re-scattering is dominant over regeneration
  - Lifetime of K^{*0} = 4.16 fm/c
  - Lifetime of ϕ = 46.2 fm/c
  - Lifetime of fireball ~10 fm/c (typical estimate)
  - Re-scattering not significant for ϕ



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

*integrated for all p_T (>0 GeV/c)

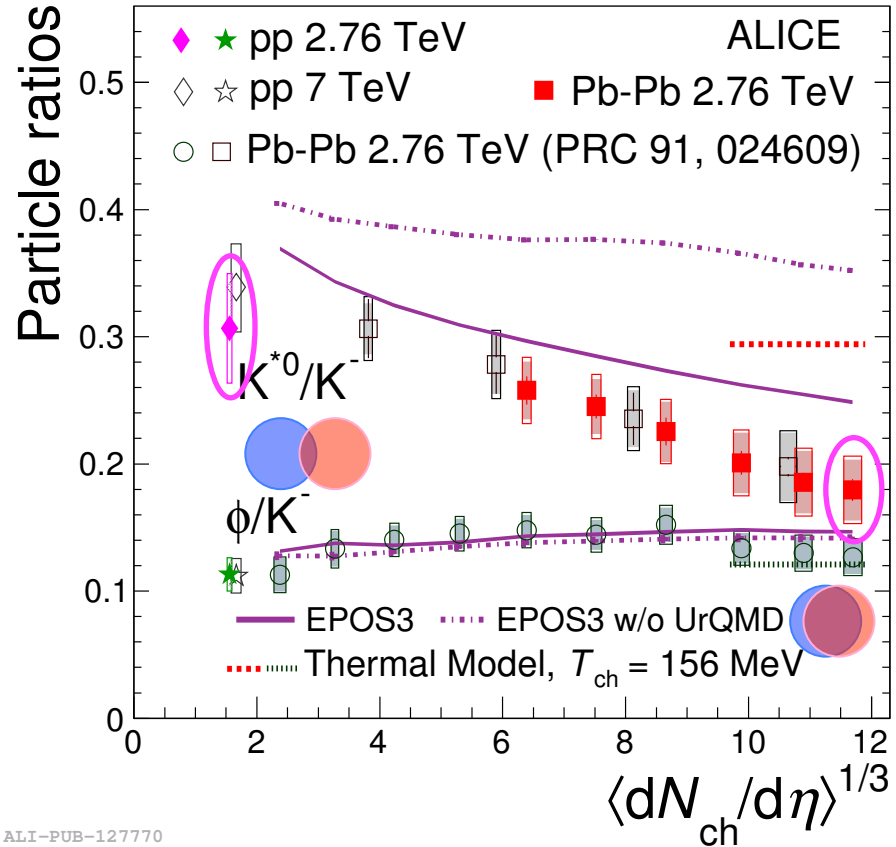
Phys. Rev. C **91** 024609 (2015)
arXiv:1702.00555 (2017)
EPOS: *Phys. Rev. C* **93** 014911 (2016)

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 (τ = 4.2 fm/c)

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

  - Use inelastic pp as initial value, central Pb–Pb as final value
    → lifetime of hadronic phase $\Delta t \geq 1$ fm/c



Hadronic Phase

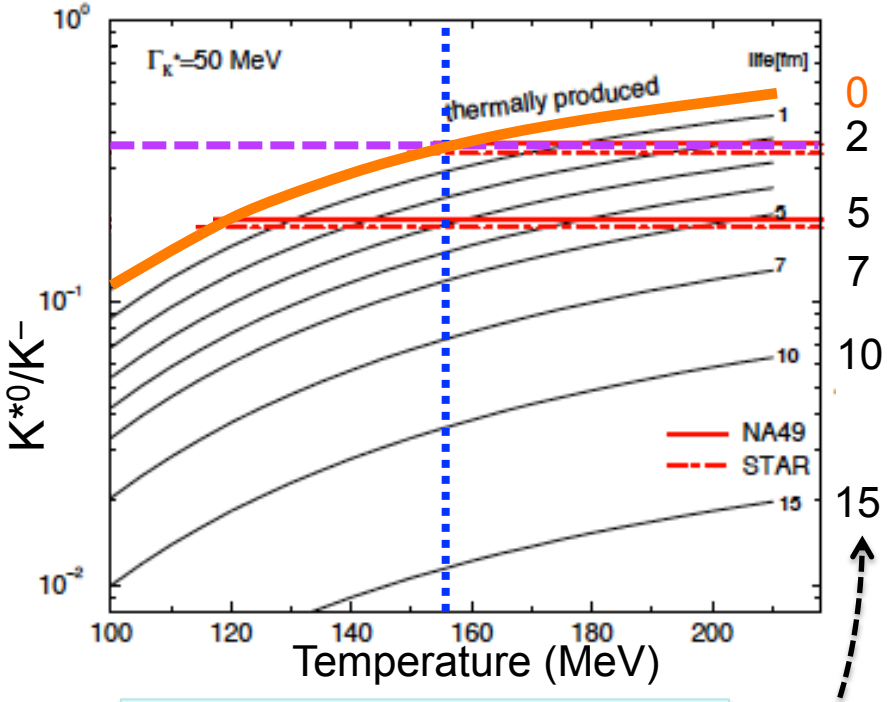
- Model of Torrieri, Rafelski, *et al.* predicts particle ratios as functions of chemical freeze-out temperature and lifetime of hadronic phase
- Model Predictions:

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

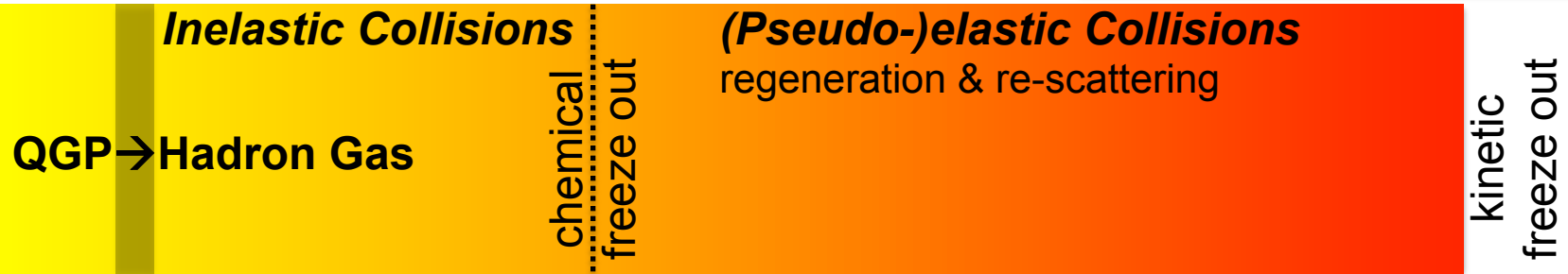
→ Prediction:
K^{*0}/K^{-} = 0.35

- T_{ch}: our assumption, based on thermal-model fits of ALICE data
- Prediction: consistent with pp value, much larger than measured Pb–Pb value: 0.180 ± 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*)



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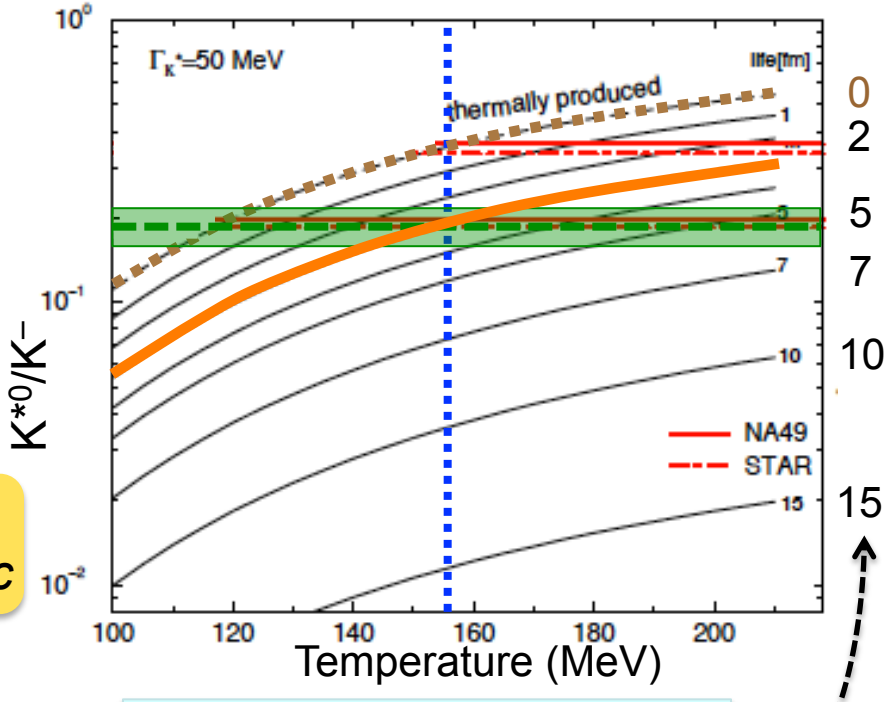
Torrieri/Rafelski [1-3]
no re-scattering
T_{ch} = 156 MeV

→ Prediction:
K^{*0}/K^{-} = 0.35

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

→ Prediction:
Lifetime ≥ 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)



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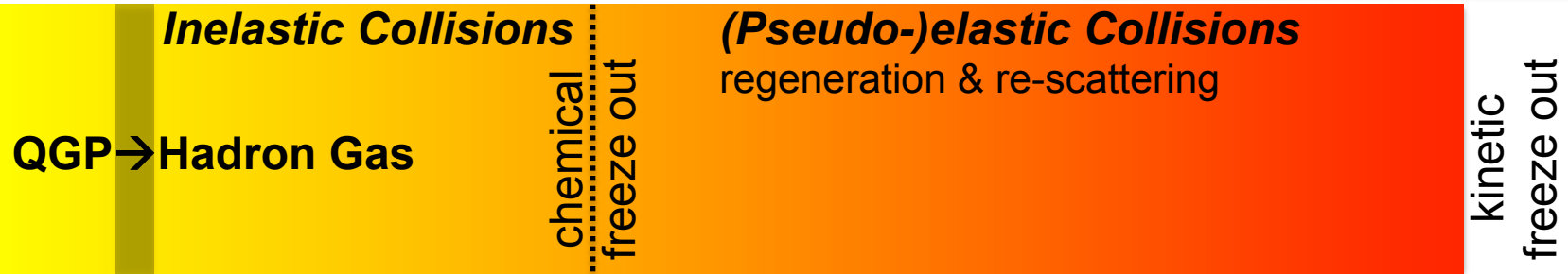
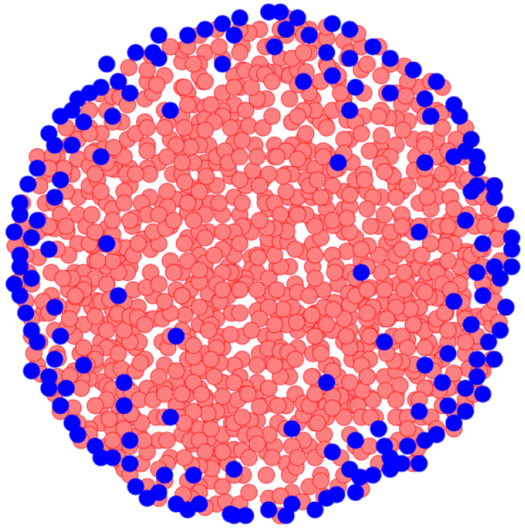
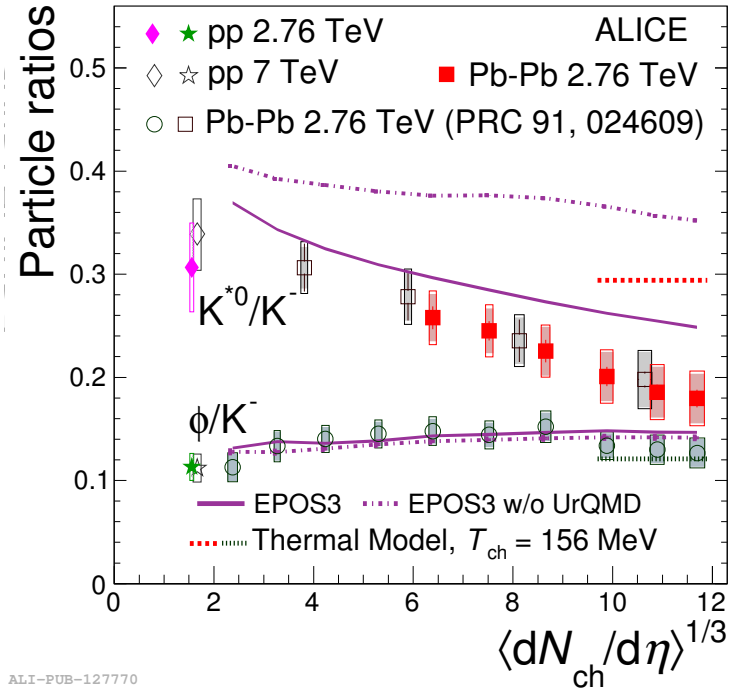


EPOS

- EPOS: describes pp, 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



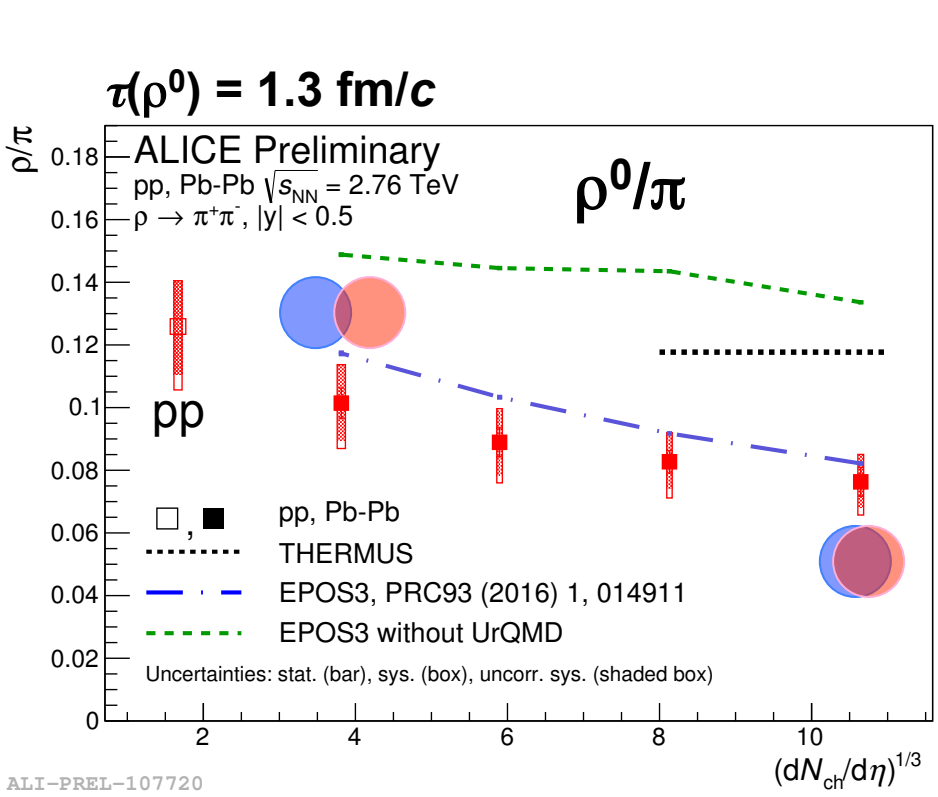


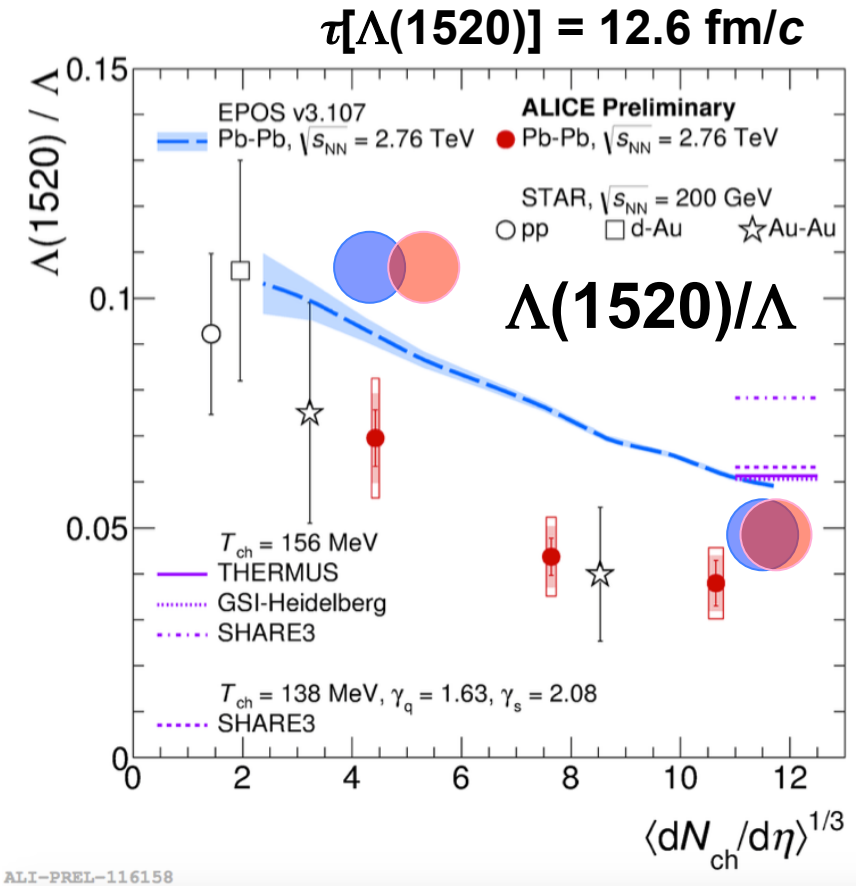
ALI-PUB-127770

EPOS: *Phys. Rev. C* **93** 014911 (2016)
UrQMD: *Prog. Part. Nucl. Phys.* **41** 255 (1998)
J. Phys. G **25** 1859 (1999)

Particle Yield Ratios

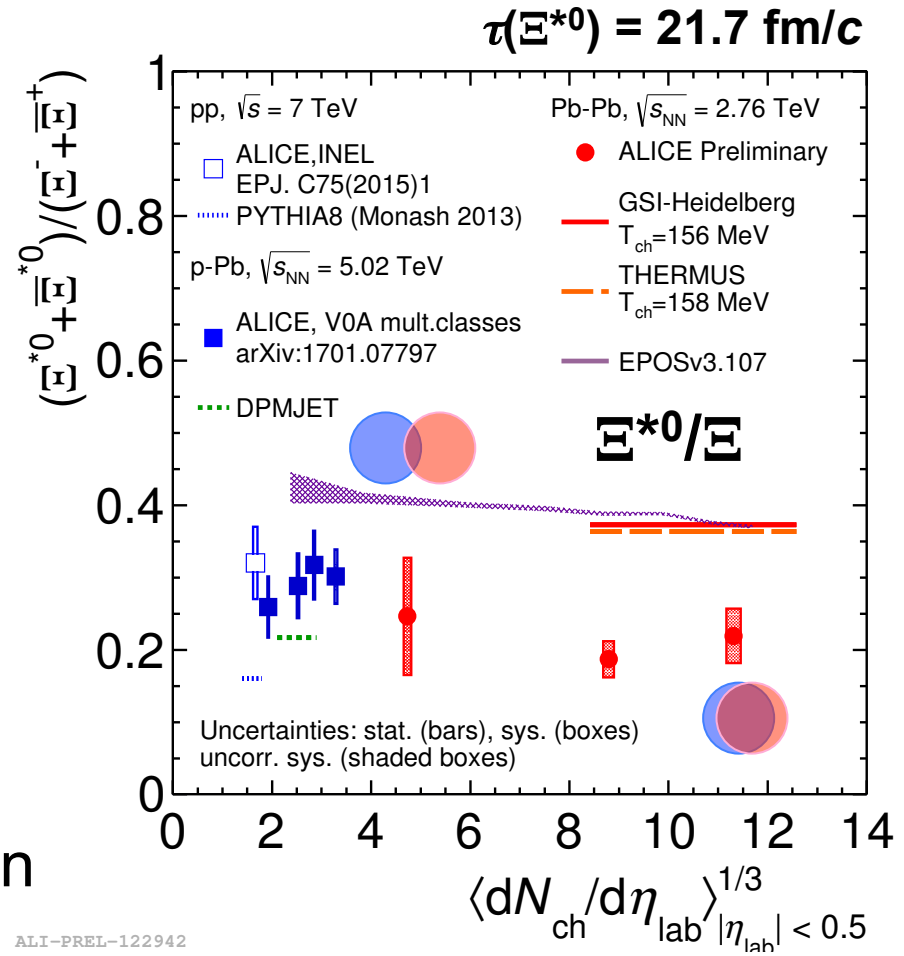
- Suppression of ρ^0/π and $\Lambda(1520)/\Lambda$ ratios also seen in central Pb–Pb w.r.t pp and thermal model
- Qualitatively described by EPOS with scattering effects, but not we turn off re-scattering (UrQMD)





Particle Yield Ratios

- Ξ^{*0}/Ξ ratio:
  - No significant centrality dependence in Pb–Pb
    - Qualitatively described by EPOS
  - Systematically lower in (mid-)central Pb–Pb than pp and p–Pb
  - Lower than thermal model values
  - Possible weak suppression



Particle Yield Ratios

- Pb–Pb summary:

Suppressed

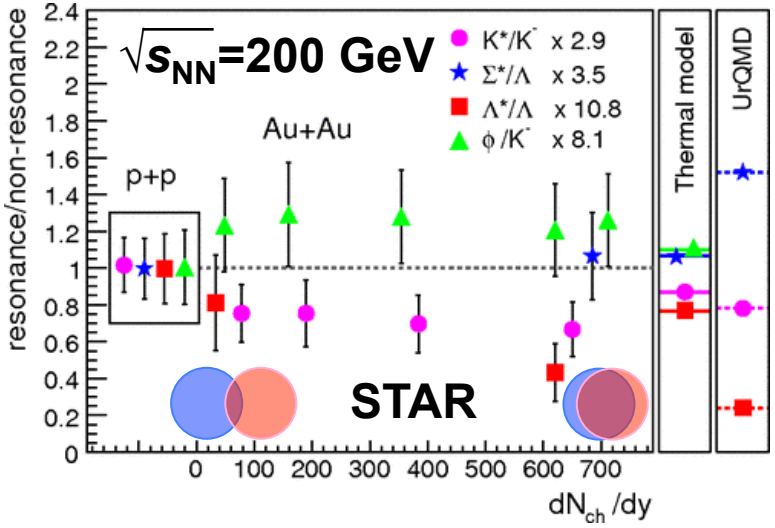
Not suppressed

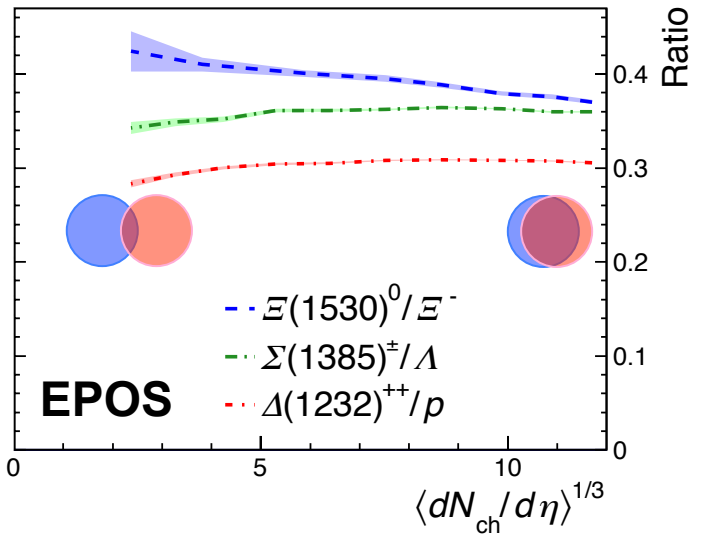
Resonance:	ρ^0	K^{*0}	$\Sigma^{*\pm}$	$\Lambda(1520)$	Ξ^{*0}	ϕ
Lifetime (fm/*c*):	1.3	4.16	5	12.6	21.7	46.2

Measurement in progress

Possible weak suppression

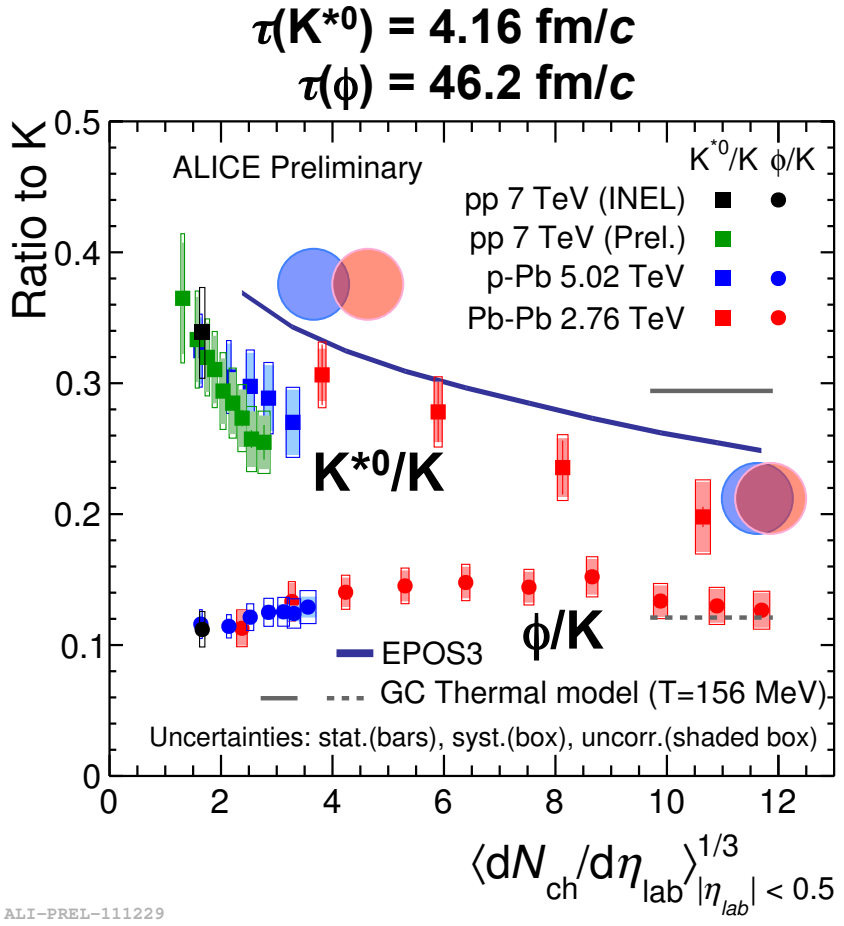
- Shorter-lived resonances suppressed, but lifetime is not the only factor: scattering cross sections also important
- STAR measured & EPOS predicts no $\Sigma^{*\pm}/\Lambda$ suppression





Small Systems

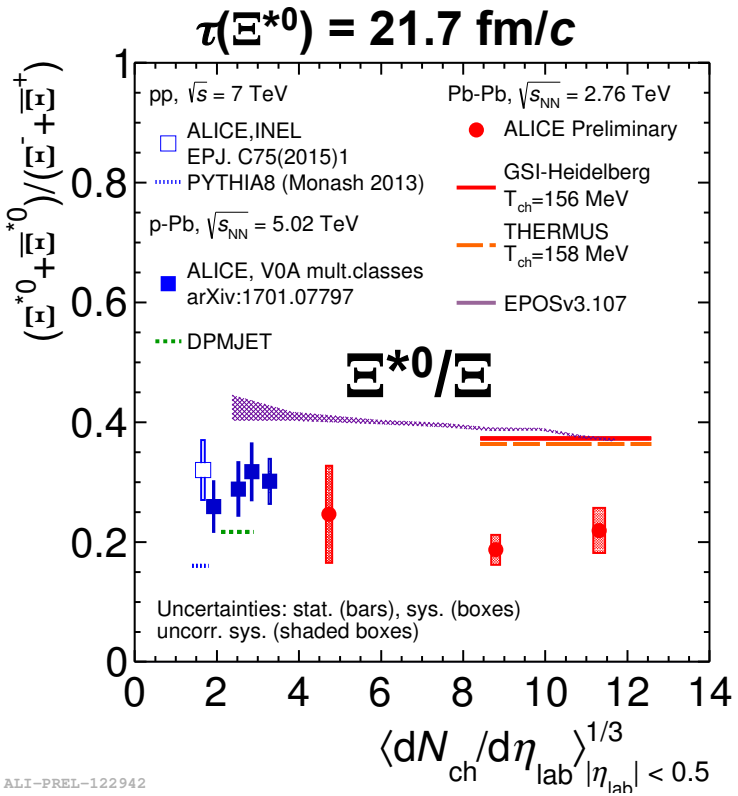
- Multiplicity-dependent suppression of K^{*0}/K in pp and p–Pb collisions
- p–Pb measurements of ϕ/K fill in trend from pp to peripheral Pb–Pb
- Is the same physics (re-scattering) responsible?

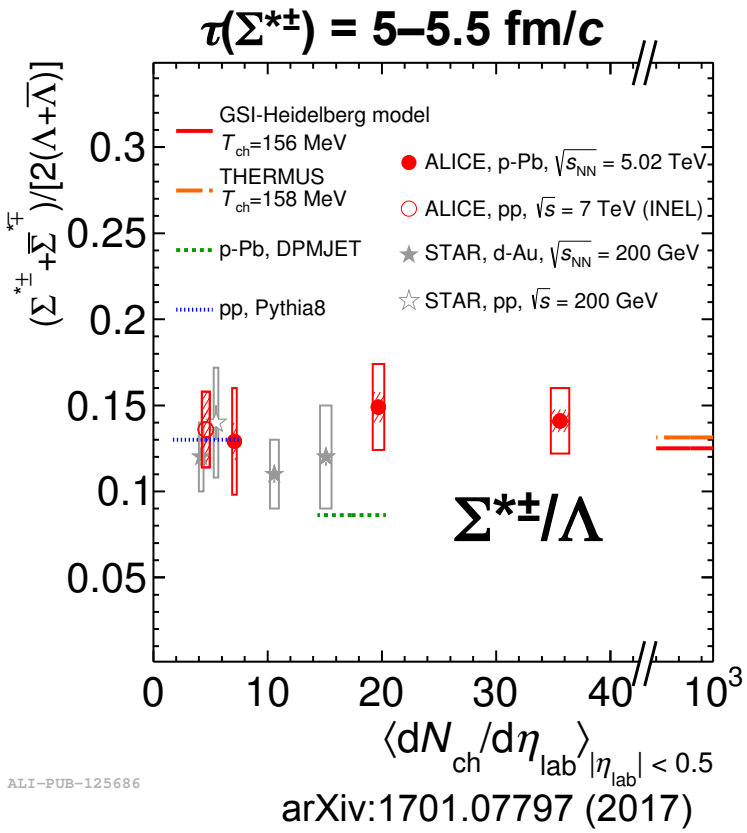


Phys. Rev. C **91** 024609 (2015)
Eur. Phys. J. C **76** 245 (2016)
arXiv:1702.00555 (2017)
EPOS: *Phys. Rev. C* **93** 014911 (2016)

Small Systems

- No multiplicity dependence of Ξ^{*0}/Ξ at LHC for pp and p–Pb
- No strong dependence of $\Sigma^{*\pm}/\Lambda$ on energy or multiplicity
  - Values consistent with thermal model and PYTHIA predictions



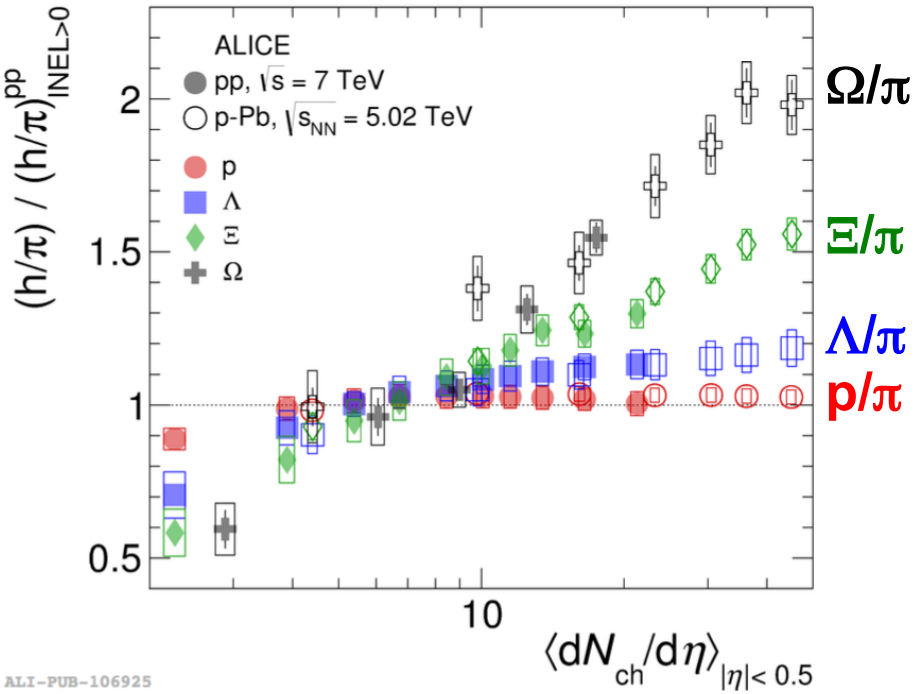


Strangeness Production

- What causes enhancement? Strangeness? Mass? Baryon number?
- p/π ratio is constant → enhancement not related to baryon number
- $\Sigma^{*\pm}$ and Ξ^{*0}: greater masses than ground-state counterparts
- $\Sigma^{*\pm}/\Lambda$ and Ξ^{*0}/Ξ constant in p–Pb
- Strangeness increase in p–Pb is due to strangeness content, not mass or baryon number.

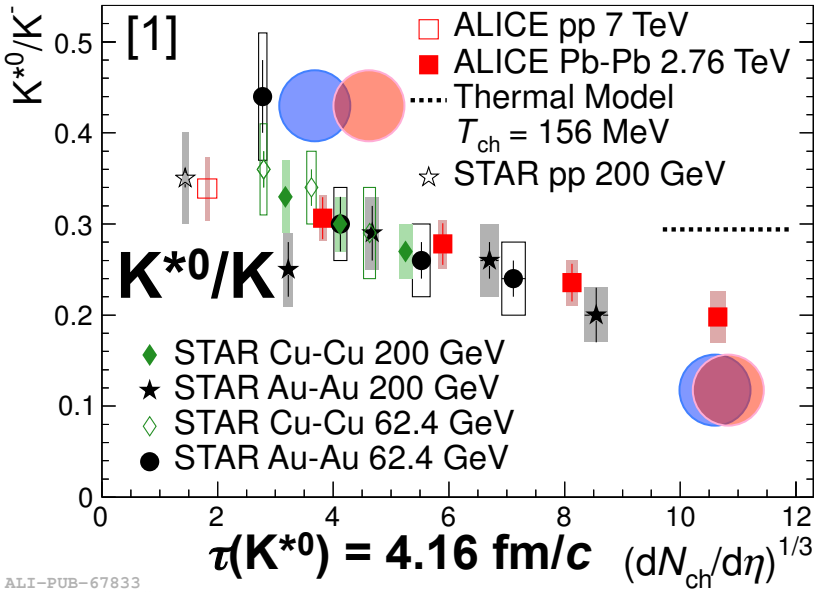
Baryon	Mass (MeV/c^2)	$\|S\|$
Ω	1672	3
Ξ^{*0}	1530	2
$\Sigma^{*\pm}$	1385	1
Ξ	1322	2
Λ	1116	1
p	938	0

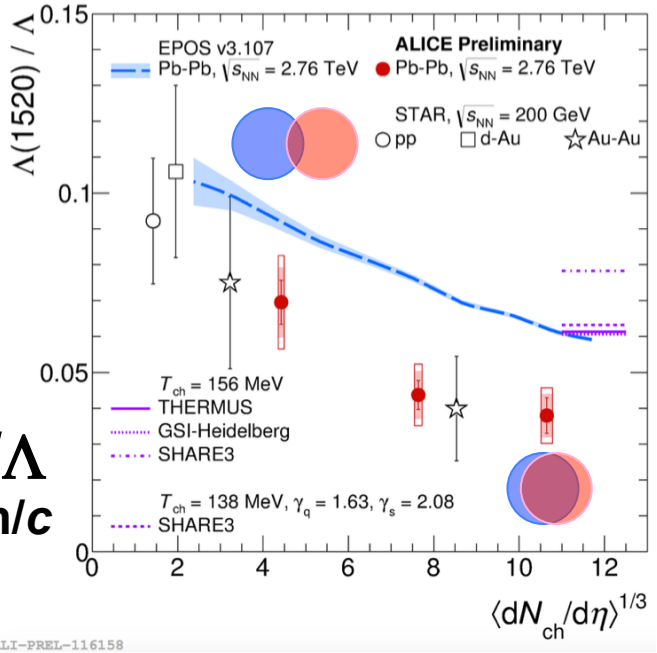
arXiv:1606.07424 (2016)
Phys. Lett. B **758** 389 (2016)



Comparison to RHIC

- RHIC: Lower energy heavy-ion collider at Brookhaven Lab, US
- No energy dependence in K^{*0} or $\Lambda(1520)$ suppression from RHIC to LHC
- No clear energy dependence of ϕ/K and $\Sigma^{*\pm}/\Lambda$ ratios (backup)
- For a given system size, observations are very similar from RHIC to LHC
  - Not much change in system lifetime expected from RHIC to LHC



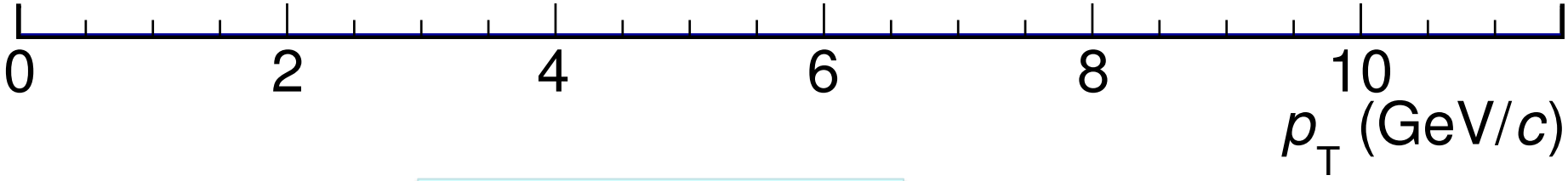


$\Lambda(1520)/\Lambda$

$\tau[\Lambda(1520)]$ = 12.6 fm/c

[1] *Phys. Rev. C* **91** 024609 (2015)

Hadron p_T Spectra



Regeneration and Re-scattering:
Predicted to be important at low p_T

Low p_T

Radial Flow (Hydrodynamics):
Hadrons move with common velocity profile → hadron mass determines p_T spectrum

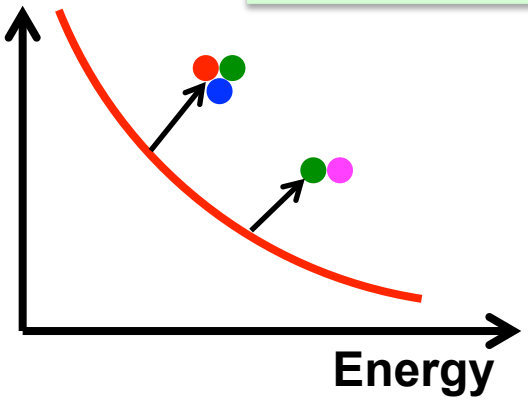
Low-Intermediate p_T

Fragmentation and In-Medium Energy Loss:
Quarks and gluons lose energy in QGP; hadrons formed from fragmentation of quarks/ gluons

High p_T

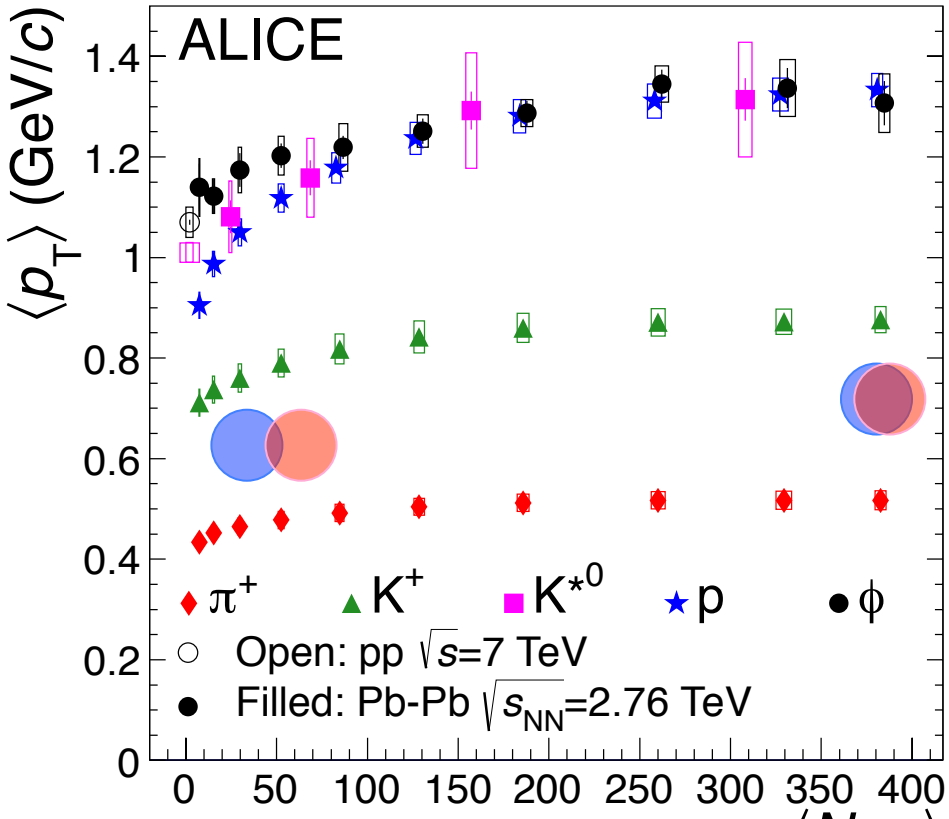
Recombination/ Coalescence:
Hadrons formed from pre-existing quarks in dense QCD matter → baryon/meson differences

Low-Intermediate p_T



Mean p_T

- Mass ordering of $\langle p_T \rangle$ in central Pb–Pb
- $\langle p_T \rangle$ for p and ϕ similar → expected from hydro
  - $M(p) = 938$ MeV/c^2
  - $M(\phi) = 1019$ MeV/c^2
- Mass ordering breaks down for smaller collision systems.



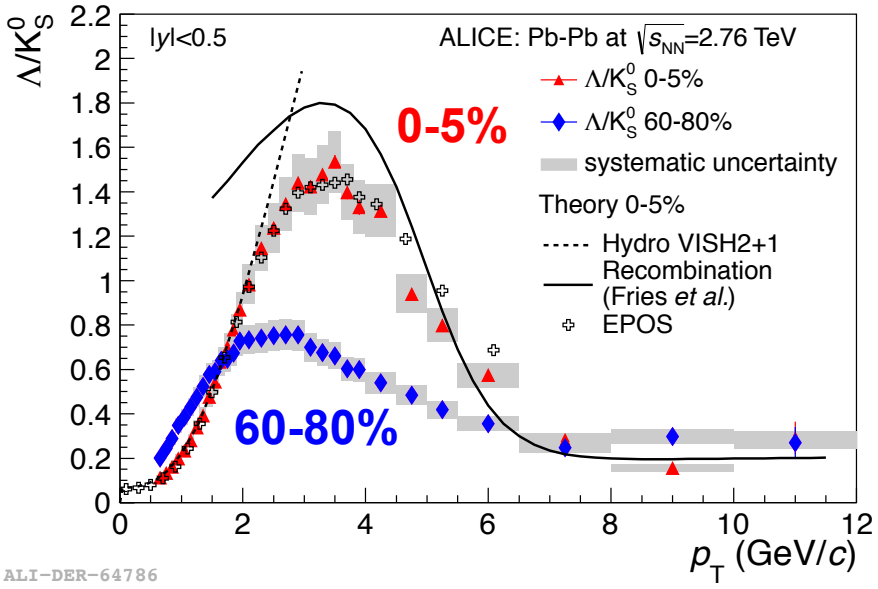
Average number of nucleons participating in A–A collisions

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

ALI-PUB-67873

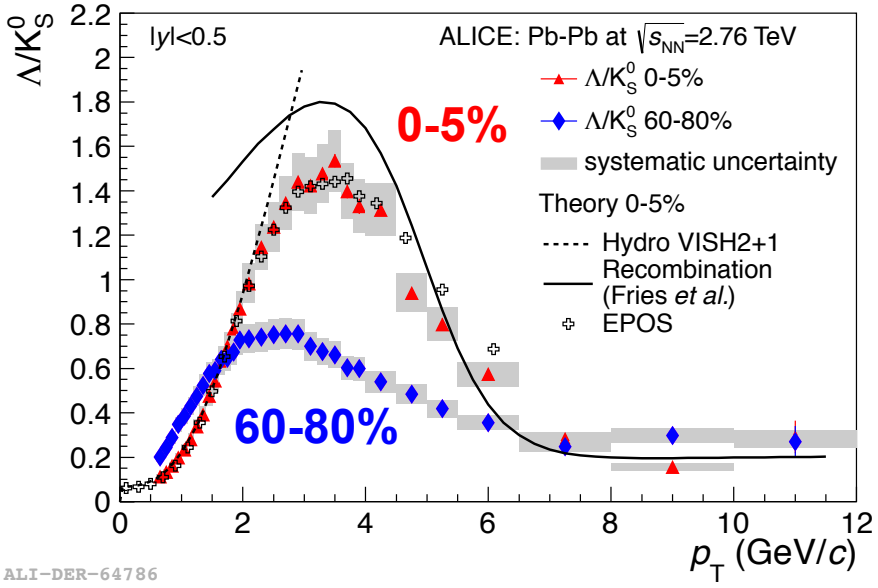
Baryon/Meson Ratios

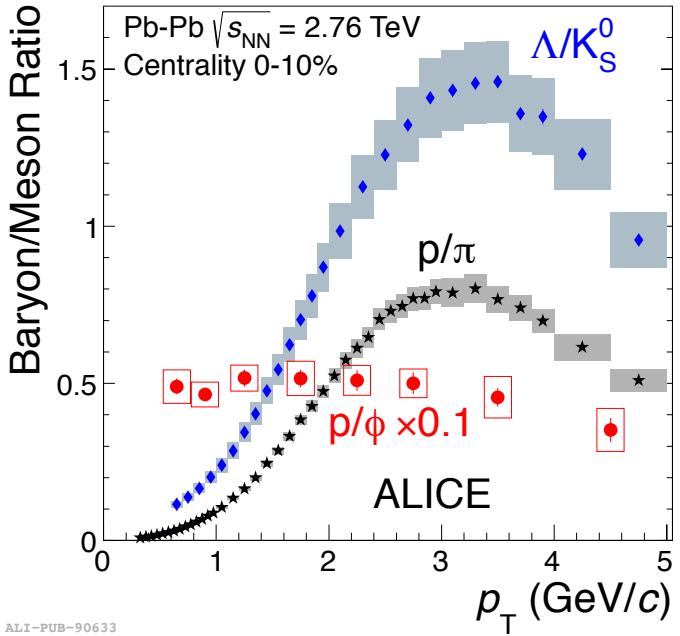
- Pb–Pb Λ/K^0_S ratio:
  - Low-p_T rise described by hydrodynamics (VISH 2+1)
  - Recombination qualitatively describes enhancement
  - EPOS consistent with measured enhancement → radial flow



Baryon/Meson Ratios

- Pb–Pb Λ/K^0_S ratio:
  - Low-p_T rise described by hydrodynamics (VISH 2+1)
  - Recombination qualitatively describes enhancement
  - EPOS consistent with measured enhancement → radial flow
- p/ϕ 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)



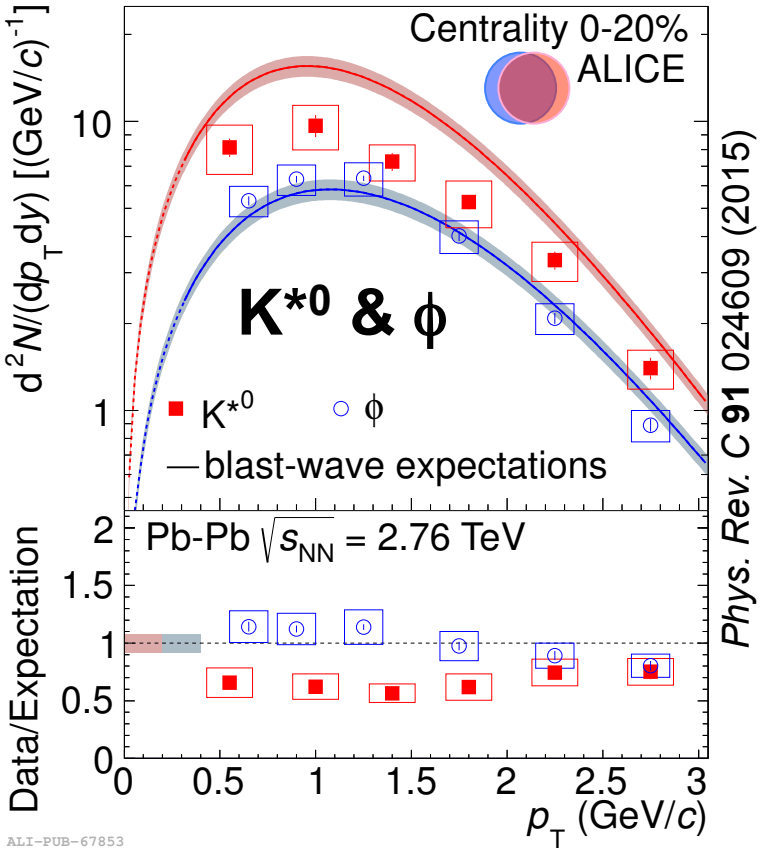


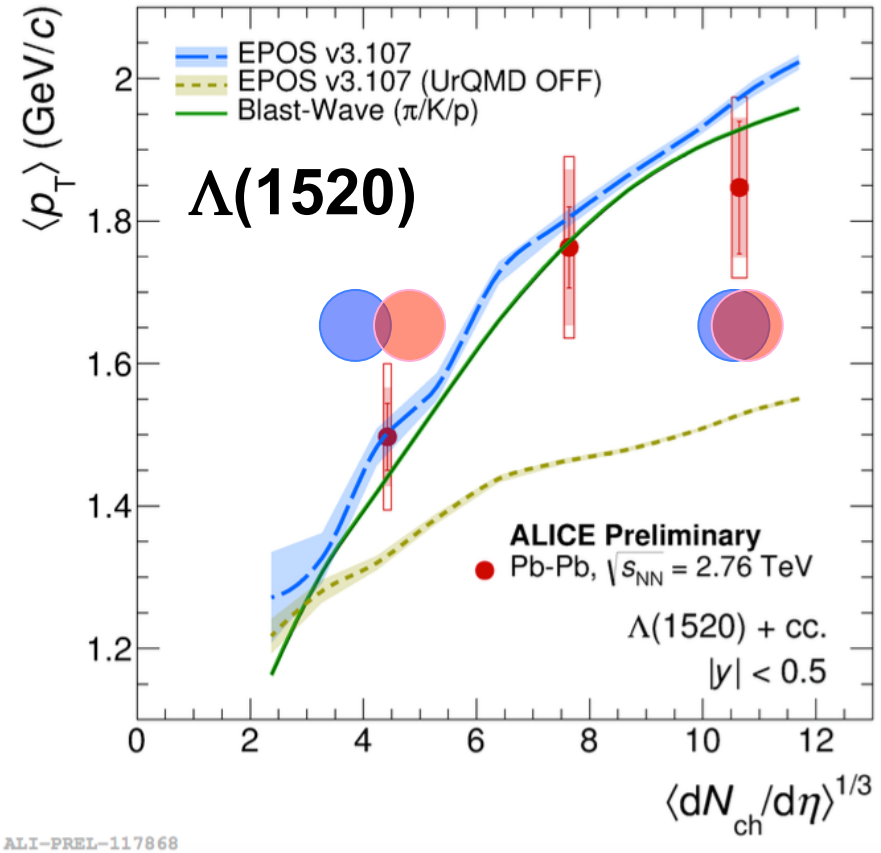
Suppression: p_T Dependence

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

Blast-Wave Model

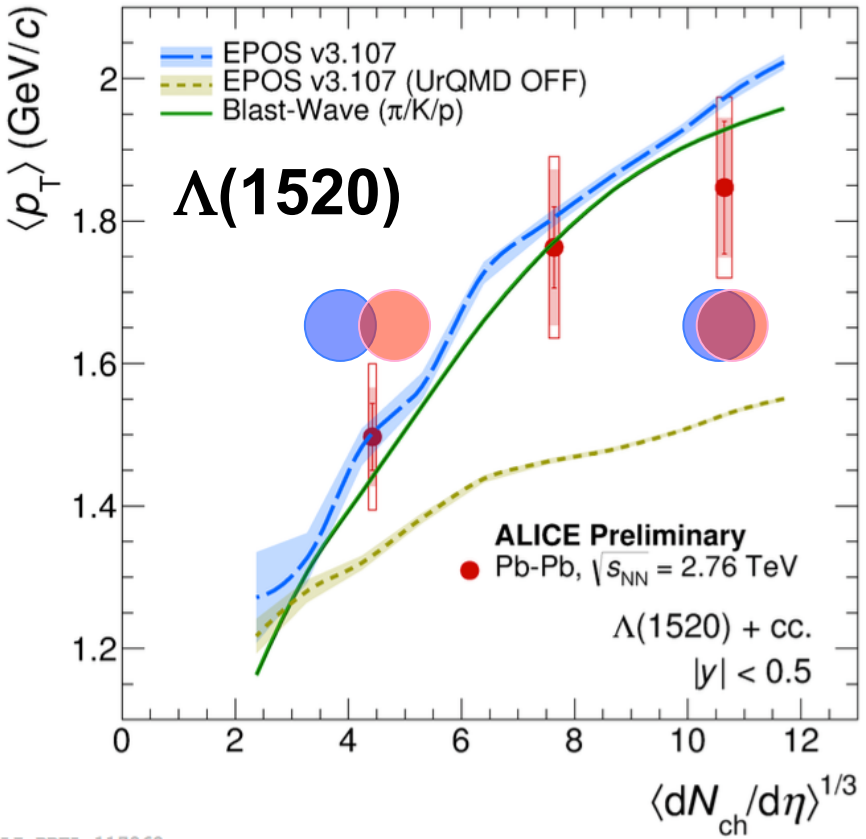
- Expected p_T distributions from blast-wave model using fits of π/K/p
- K^{*0} suppressed for p_T<3 GeV/c
- $\langle p_T \rangle$ of Λ(1520) well described
- Comparison to blast-wave model implies no strong p_T dependence of resonance suppression.





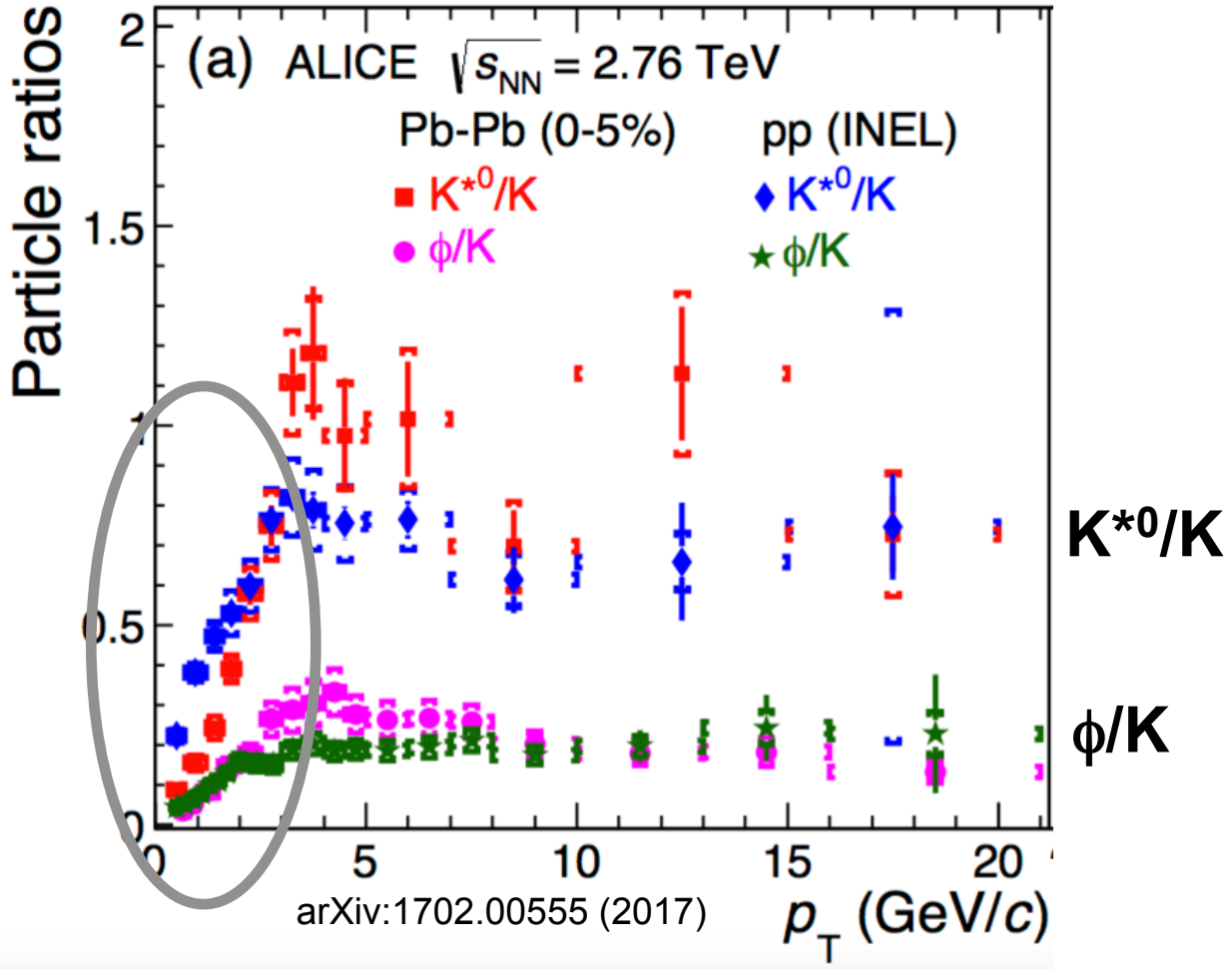
EPOS

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



Changing System Size

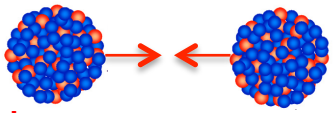
- Low-p_T K*^{0}/K decreases from pp to central Pb–Pb
- But ϕ/K does not decrease from pp to Pb–Pb
- Suggests short-lived resonance suppression at low p_T.



Nuclear Modification Factor

- How do we quantify particle suppression?

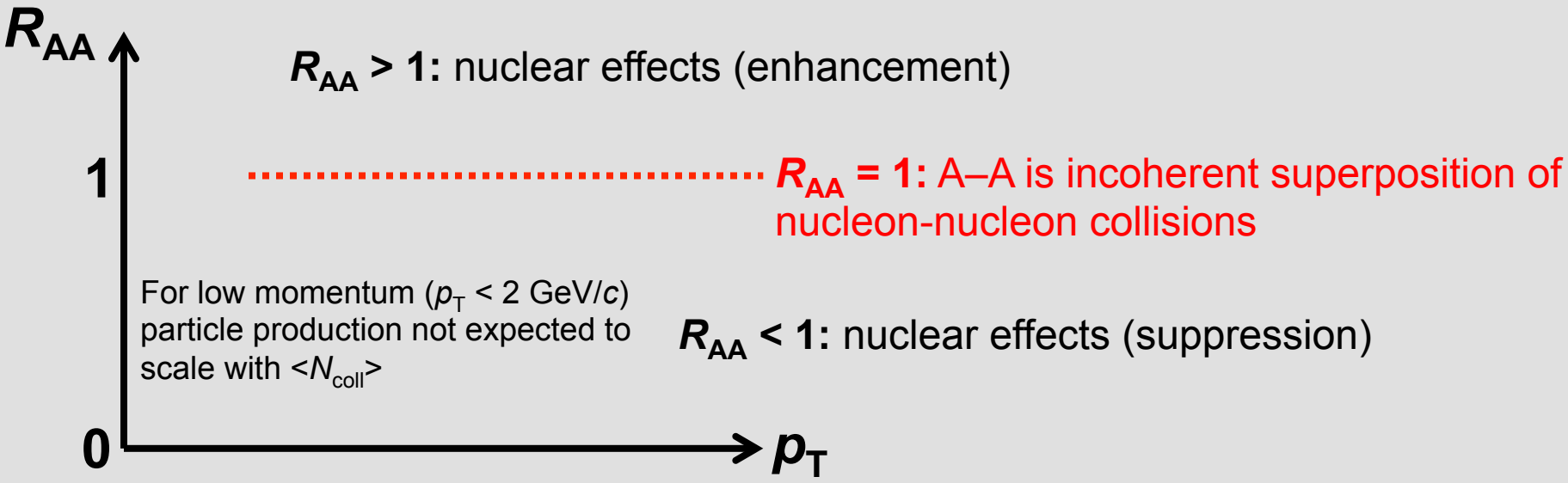
particle yield in nucleus-nucleus collisions



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

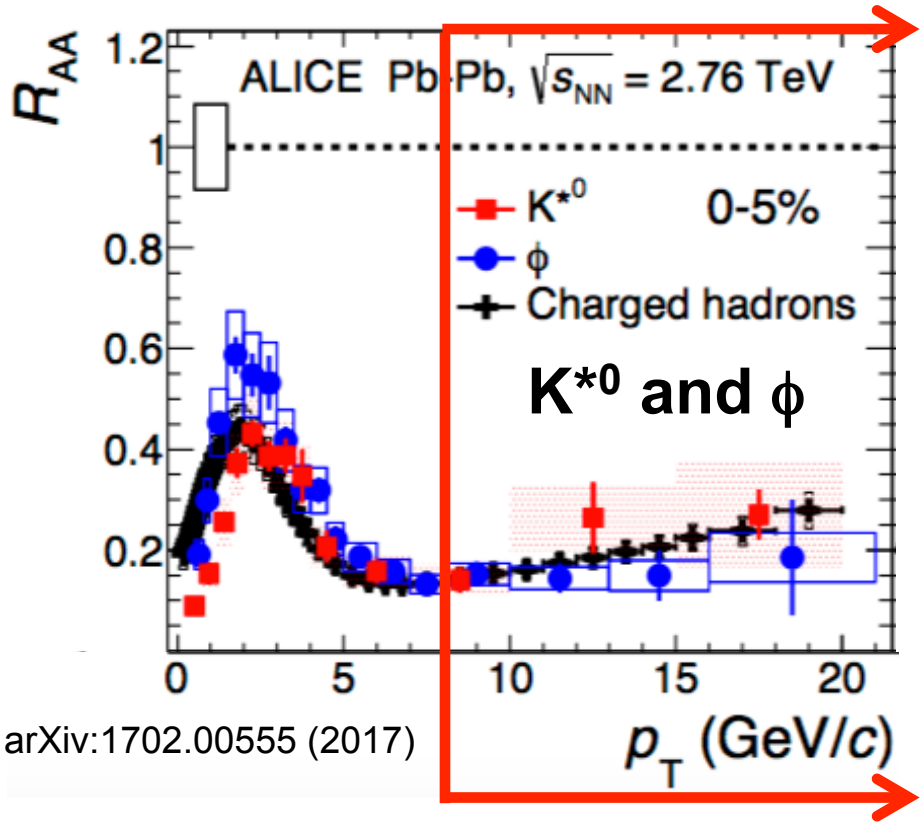
particle yield in proton-proton collisions (baseline)

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



Nuclear Modification Factor

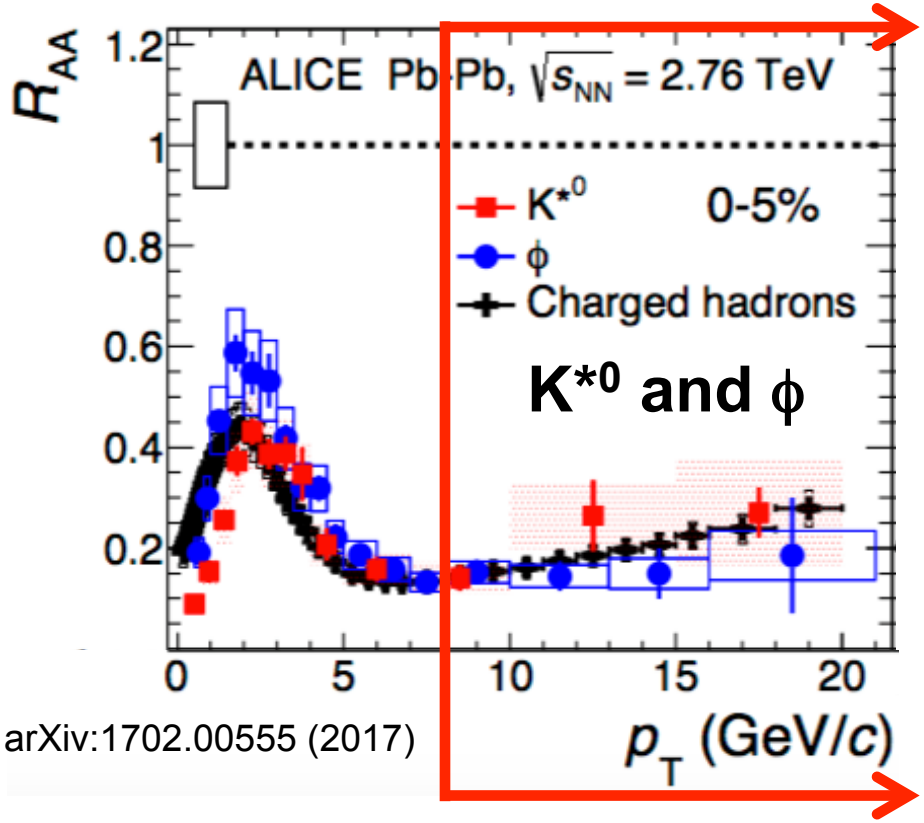
- High p_T (>8 GeV/c)
  - Charged hadrons ($\pi^{\pm}$+$K^{\pm}$+p) suppressed by factor of 4–5
  - As are K^{*0} and ϕ (and ρ^0)

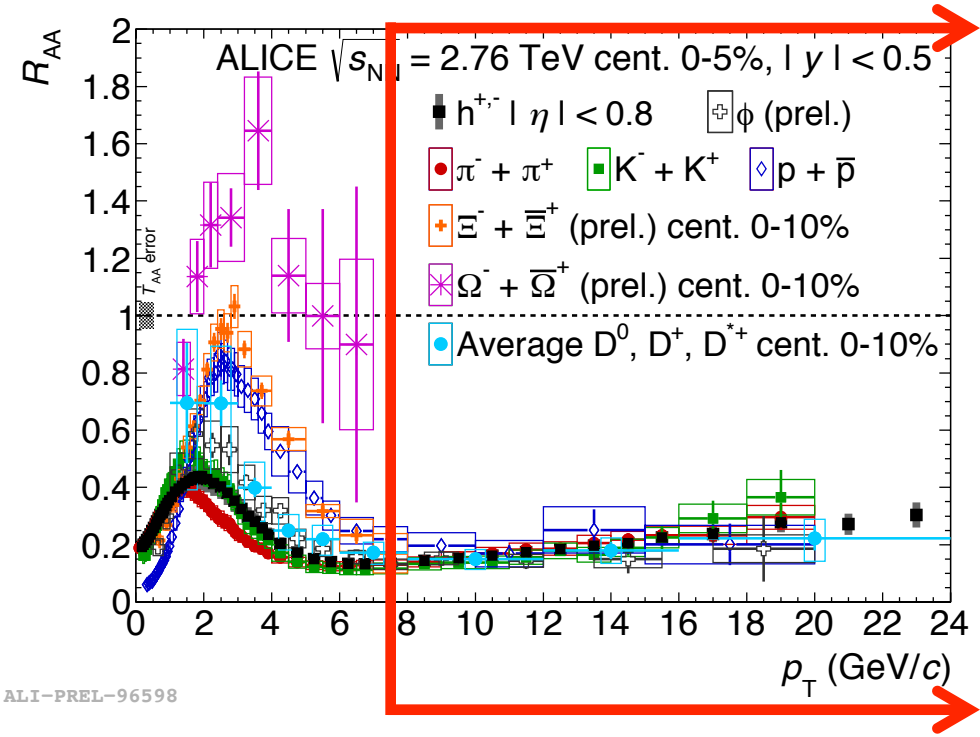


arXiv:1702.00555 (2017)

Nuclear Modification Factor

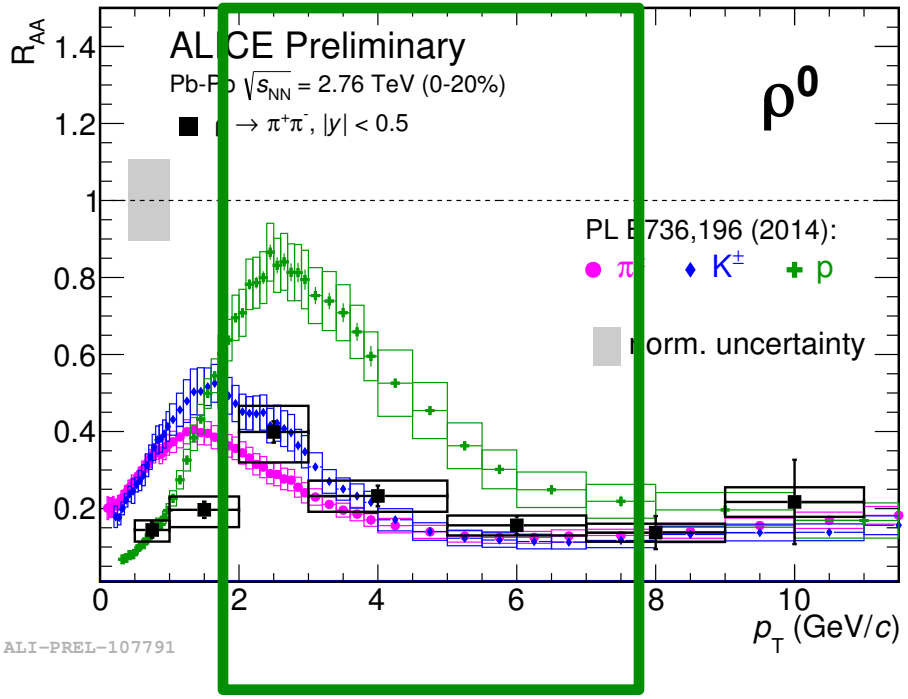
- High p_T (>8 GeV/c)
  - Charged hadrons ($\pi^{\pm}$+$K^{\pm}$+p) suppressed by factor of 4–5
  - As are K^{*0} and ϕ (and ρ^0) and most other hadron species.
  - Suppression not influenced by hadron properties (mass, baryon number, u/d/s/c quark content)

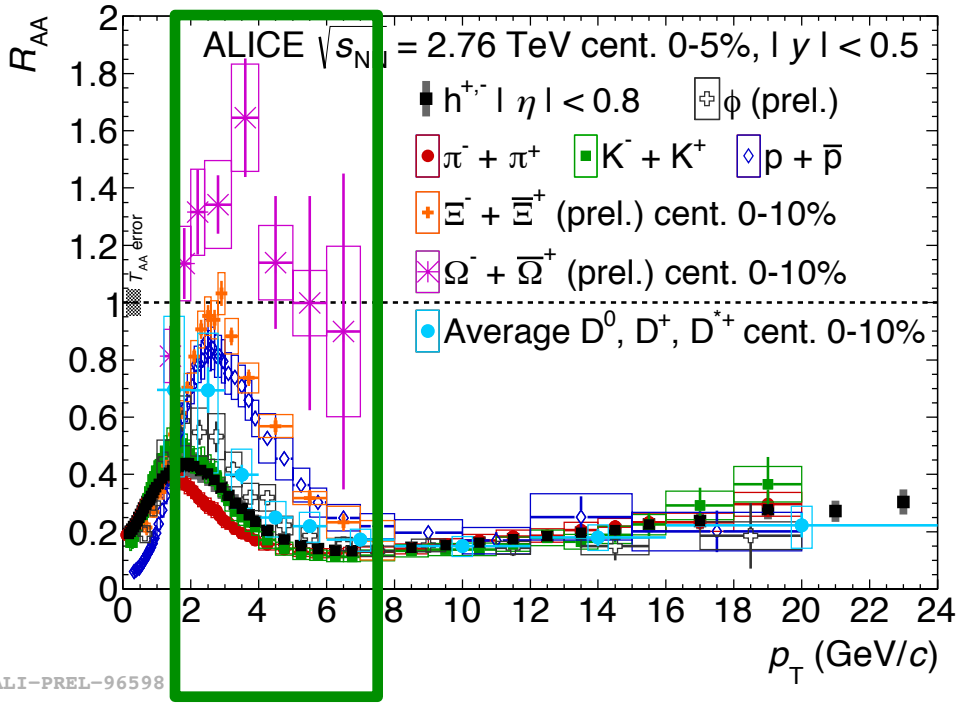




Nuclear Modification Factor

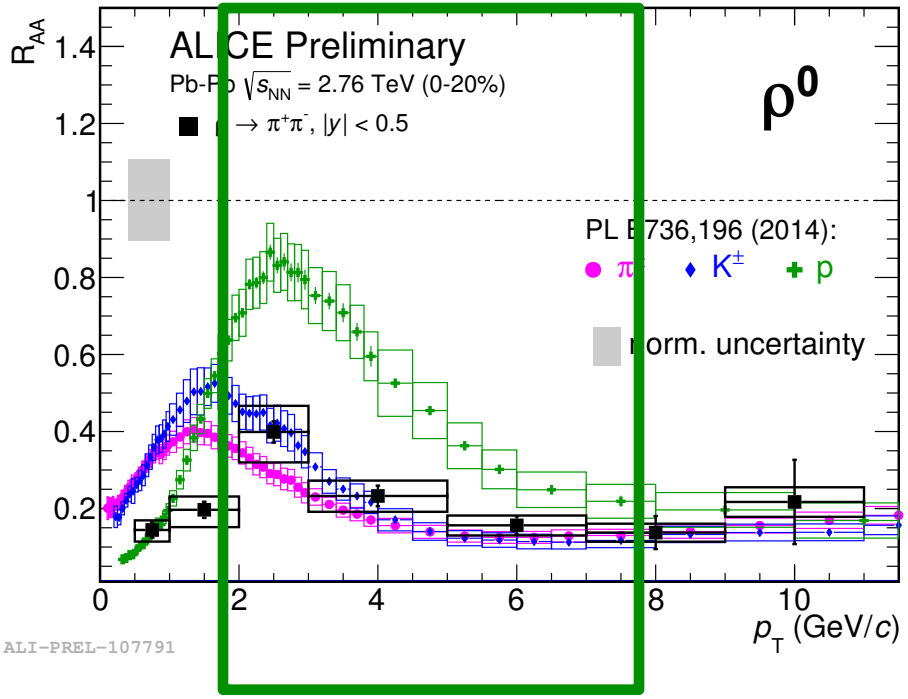
- Intermediate p_T ($2 < p_T < 8$ GeV/c)
  - Baryon-meson splitting: ρ^0, K^{*0}, ϕ, and even D are closer to other mesons than to baryons

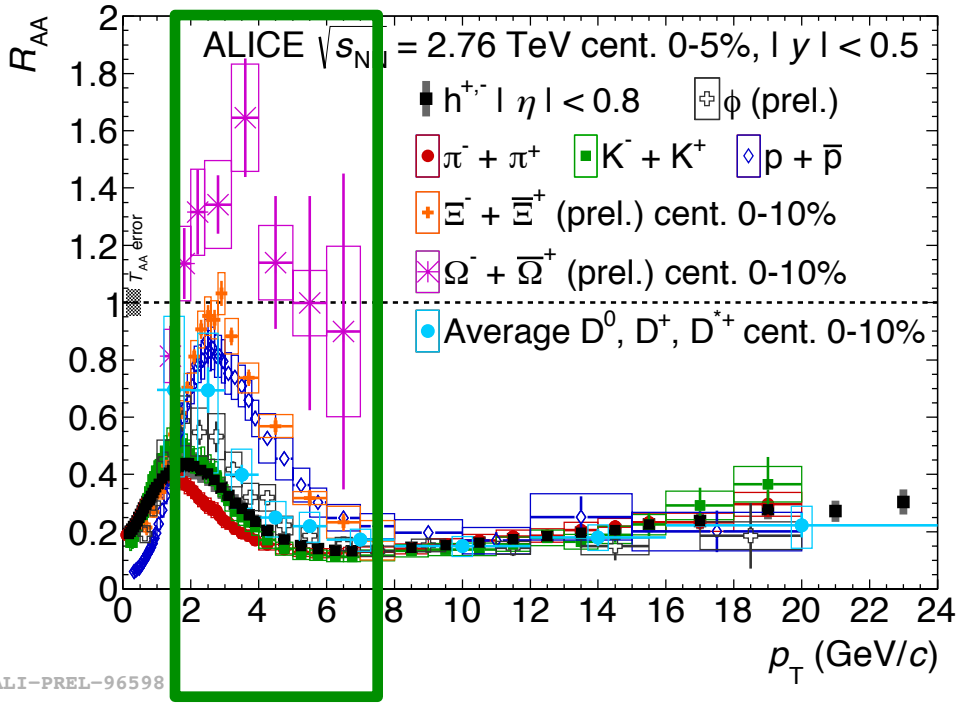




Nuclear Modification Factor

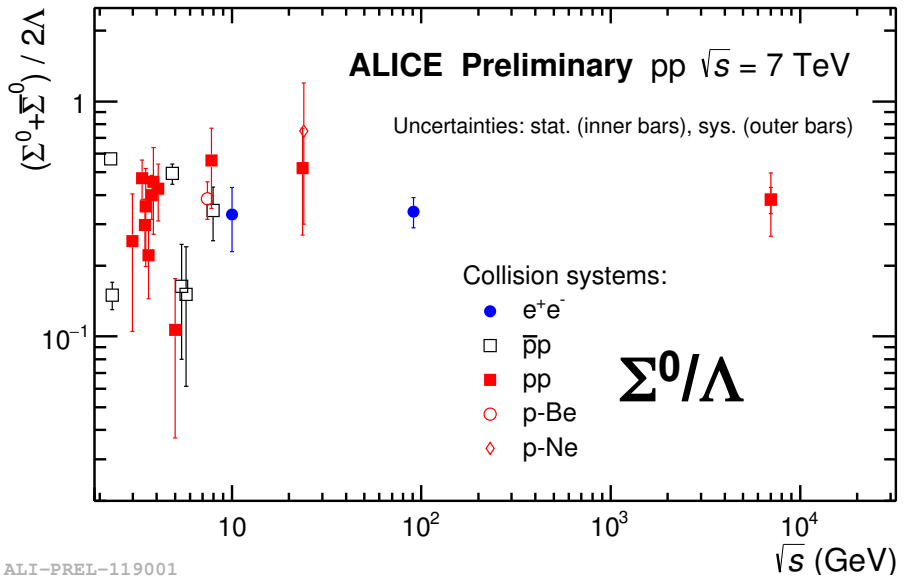
- Intermediate p_T ($2 < p_T < 8$ GeV/c)
  - Baryon-meson splitting: ρ^0, K^{*0}, ϕ, and even D are closer to other mesons than to baryons
  - Possible mass ordering among mesons
  - Differences between p and ϕ R_{AA} were taken as evidence for recombination in A–A → in fact, due to different pp baselines

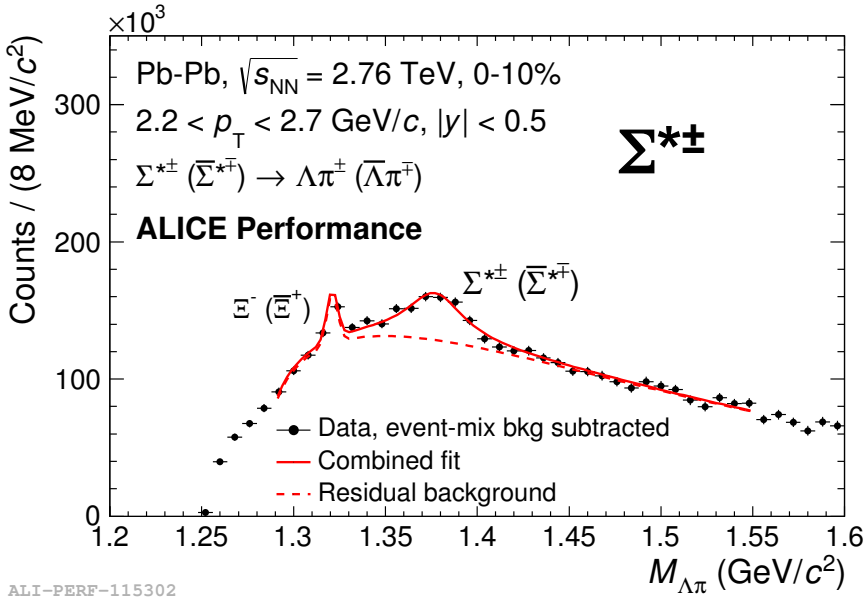




Looking Ahead

- Have measured Σ^0 at highest energy ever
- Forthcoming measurements of K*± (new for us) and $\Sigma^{*\pm}$ in Pb–Pb
- Run-2 Pb–Pb: push resonance suppression measurements to higher multiplicities
- Elliptic flow of K*0
- Spin alignment
- Search for additional resonances: states that are tentative in PDG or unobserved





Summary

- Short-lived resonances suppressed in central A–A collisions
  - Re-scattering of decay products dominant over regeneration
  - Trends described by EPOS with scattering effects
  - Multiplicity-dependent suppression in small collision systems
  - Some evidence for p_T-dependent suppression
- Enhancement of strange baryons in p–Pb is indeed due to strangeness content (not baryon number or mass)
- Constant p/ϕ ratio and mass ordering of $\langle p_T \rangle$ in central A–A: consistent with hydrodynamics
- High-p_T particle suppression in Pb–Pb (R_{AA}) does not depend on hadron properties (mass, baryon number, u/d/s/c quark content).

Additional Material

Light Flavor at ALICE

- Outline:
- Particle p_T Spectra and Ratios
  - Shapes: Blast-wave fits
  - Shapes: mass and multiplicity dependence of $\langle p_T \rangle$
  - Baryon/meson ratios vs. p_T
- Nuclear Modification Factors
  - R_{AA} and R_{pPb}
- Strangeness Production and Enhancement
- Hadronic Resonances

- Study **13 particle species** with various masses, quark contents, baryon numbers, and lifetimes (+ nuclei, other resonances…)

$\pi^{\pm}$ $u\bar{d}$ M=139 MeV/c^2

$K^{\pm}$ $u\bar{s}$ 494 MeV/c^2

K^0_S $(d\bar{s}+\bar{d}s)/\sqrt{2}$ 498 MeV/c^2

ρ^0 $(u\bar{u}-d\bar{d})/\sqrt{2}$ 770 MeV/c^2

K^{*0} $d\bar{s}$ 896 MeV/c^2

p uud 938 MeV/c^2

ϕ $s\bar{s}$ 1019 MeV/c^2

Λ uds 1116 MeV/c^2

Ξ^- dss 1322 MeV/c^2

Σ^{*+} uus 1383 MeV/c^2

Σ^{*-} dds 1387 MeV/c^2

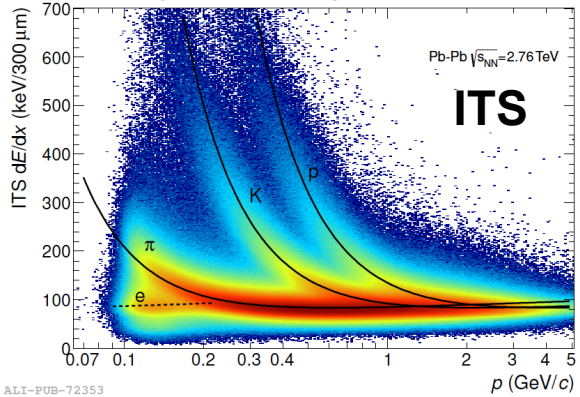
Ξ^{*0} uss 1532 MeV/c^2

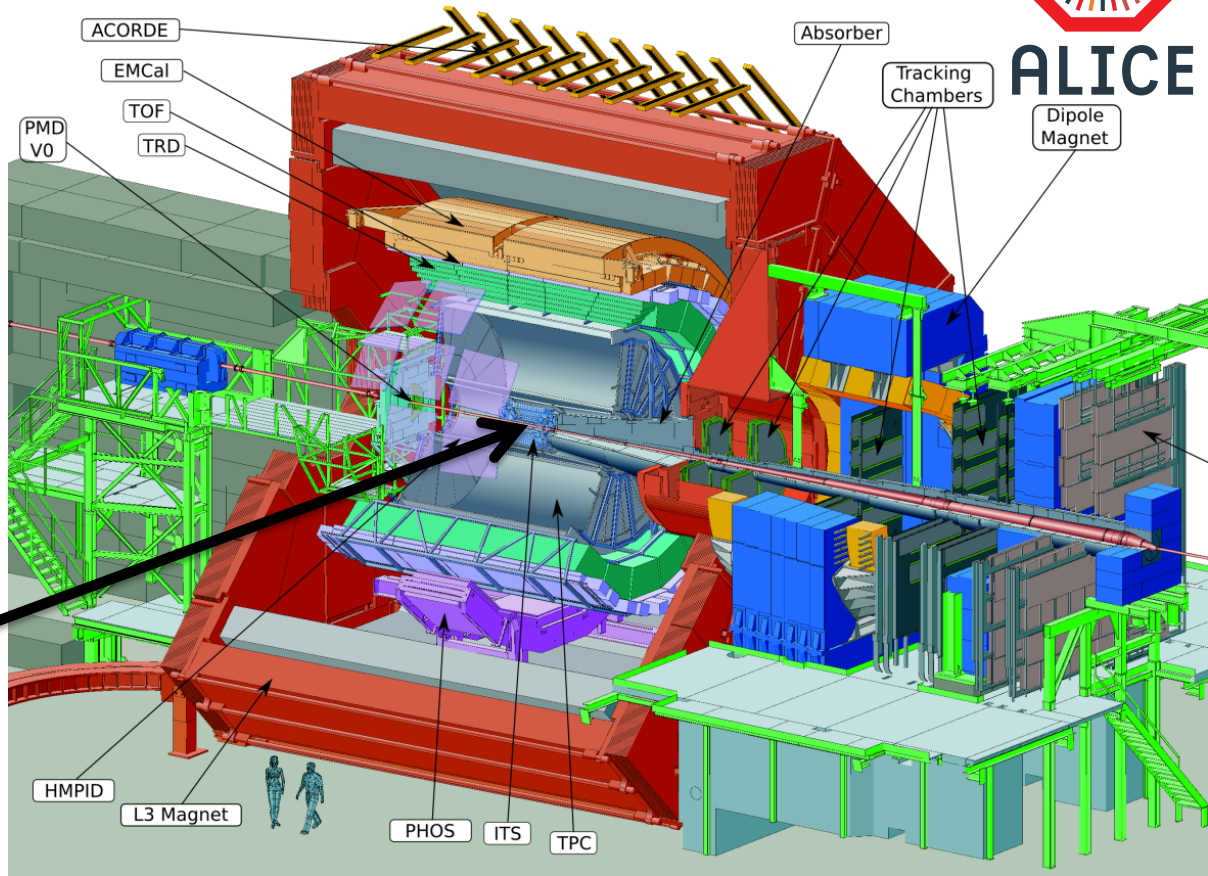
Ω sss 1672 MeV/c^2

ALICE Detector

Inner Tracking System:

Tracking, vertexing, PID (d*E*/d*x*)

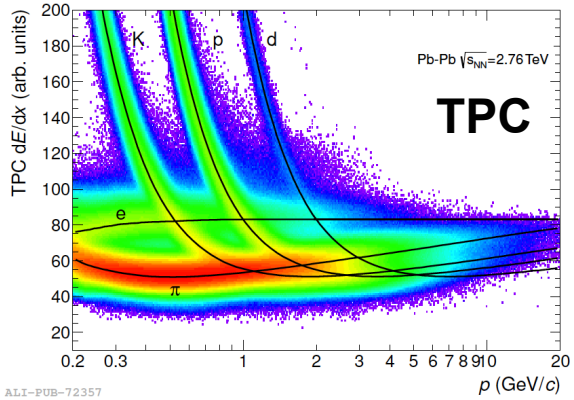


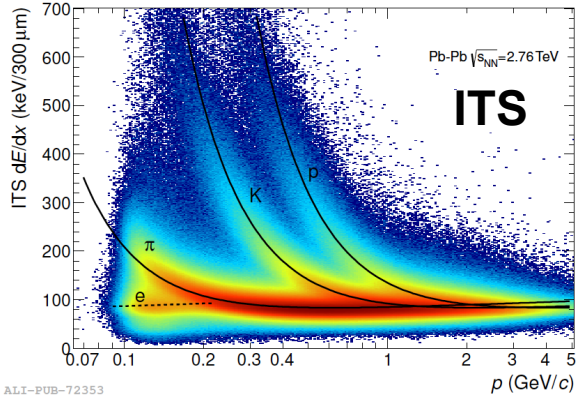


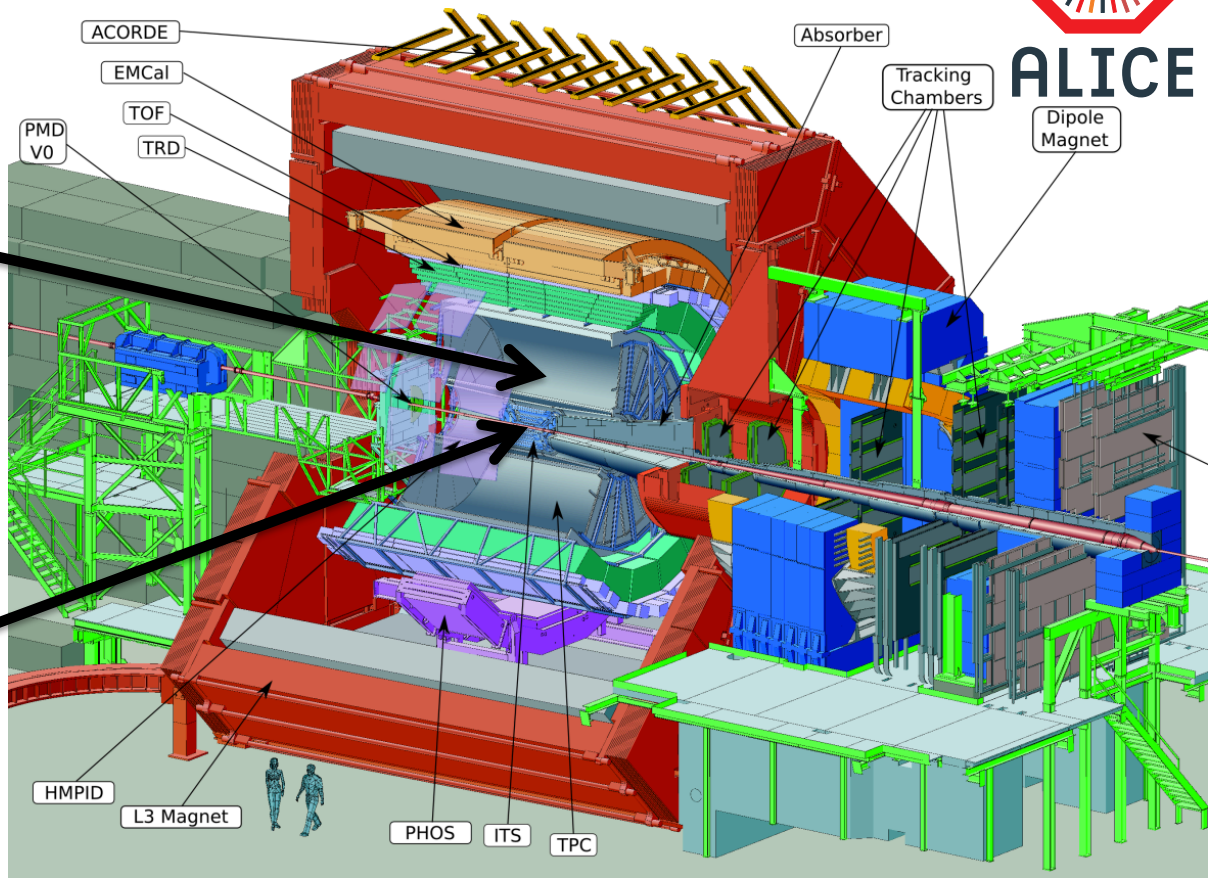
ALICE Detector

Time Projection Chamber:

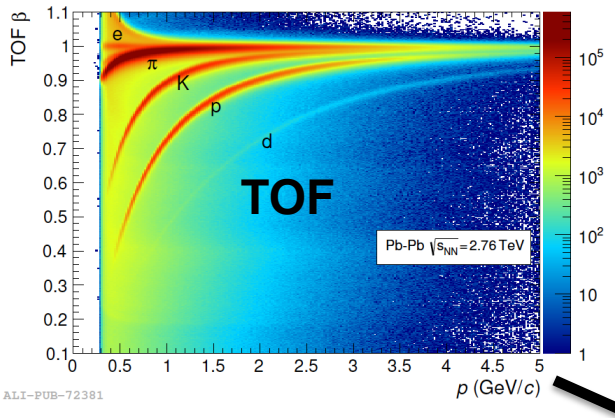
Tracking, PID (d*E*/d*x*)



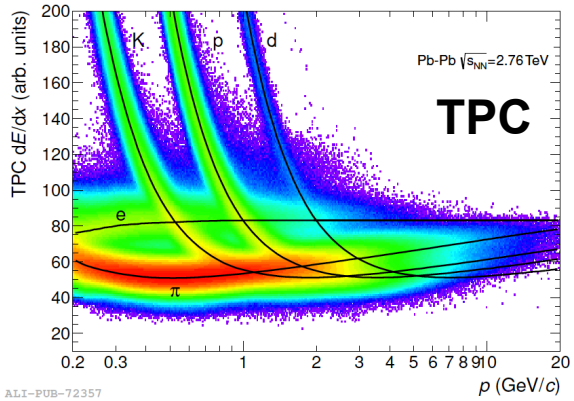


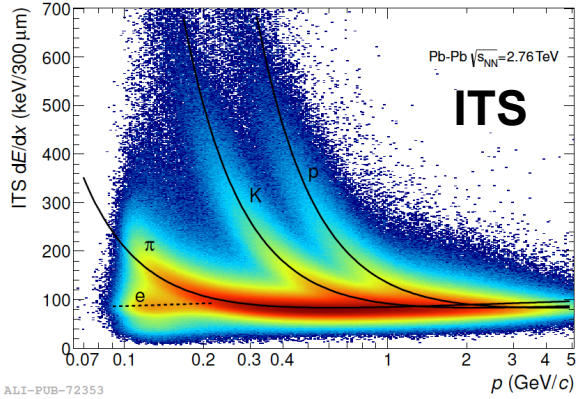


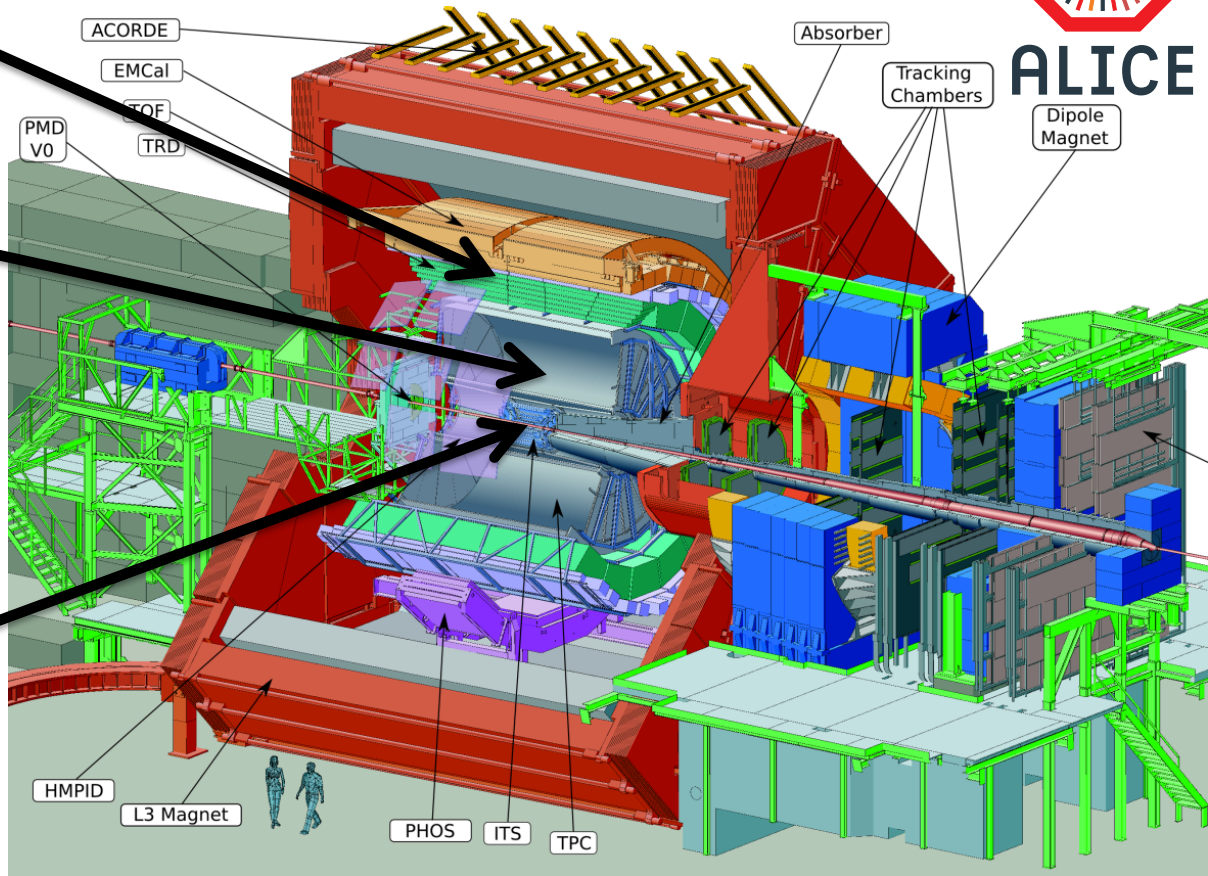
ALICE Detector



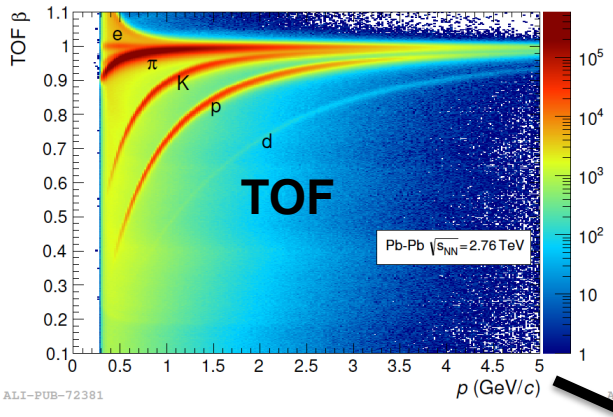
Time of Flight Detector:
PID (β)

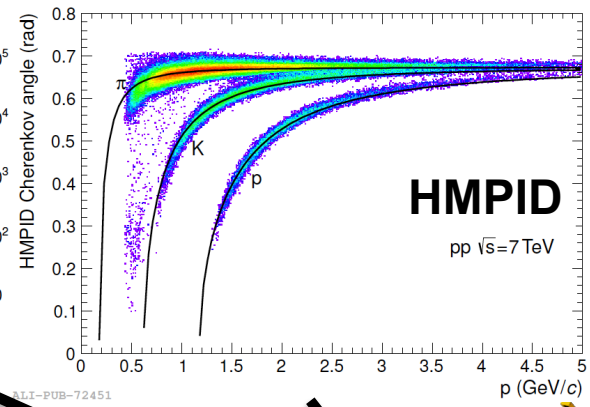




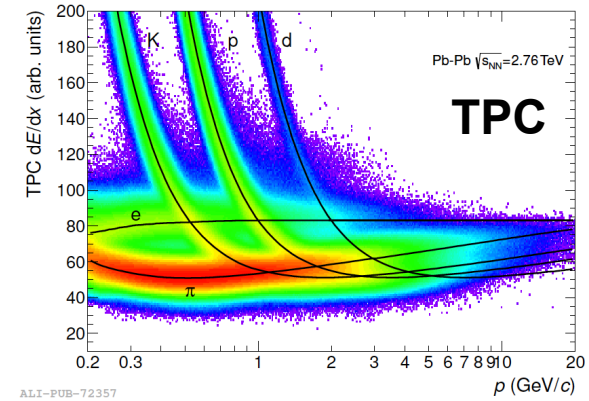


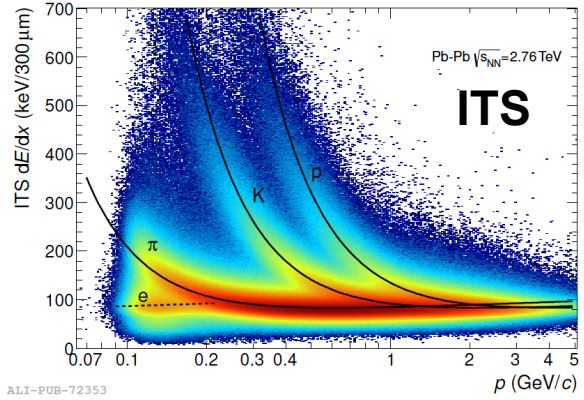
ALICE Detector

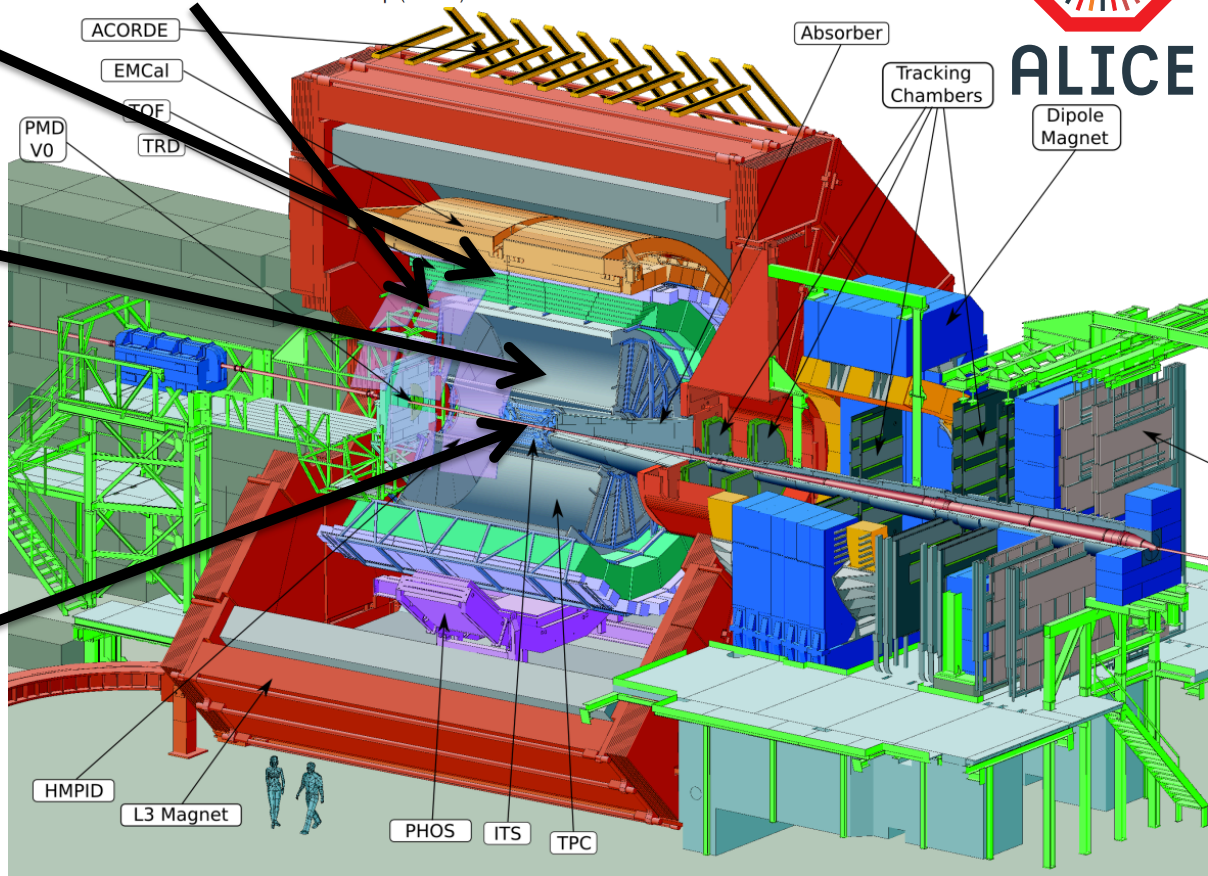




High Momentum PID:
PID (Cherenkov angle)

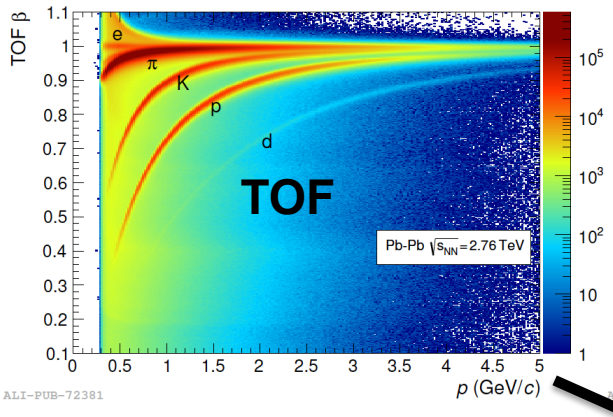


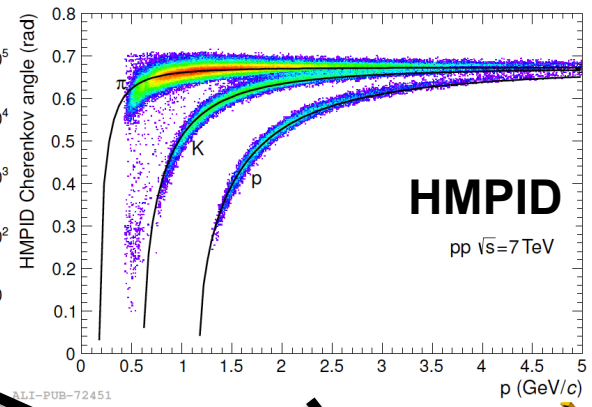




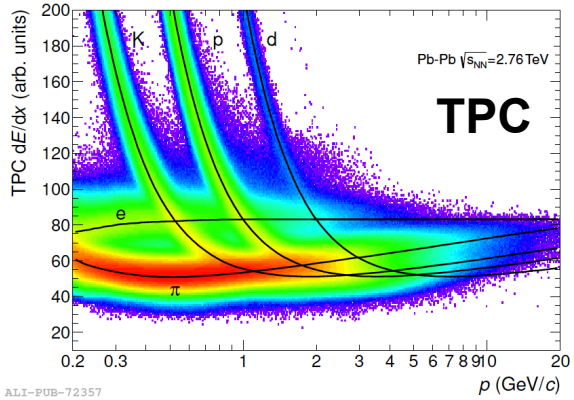
ALICE

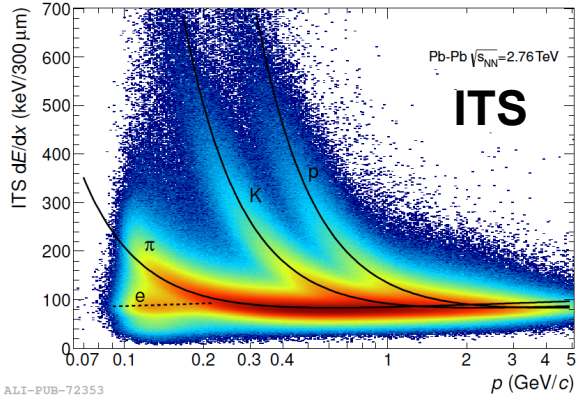
ALICE Detector

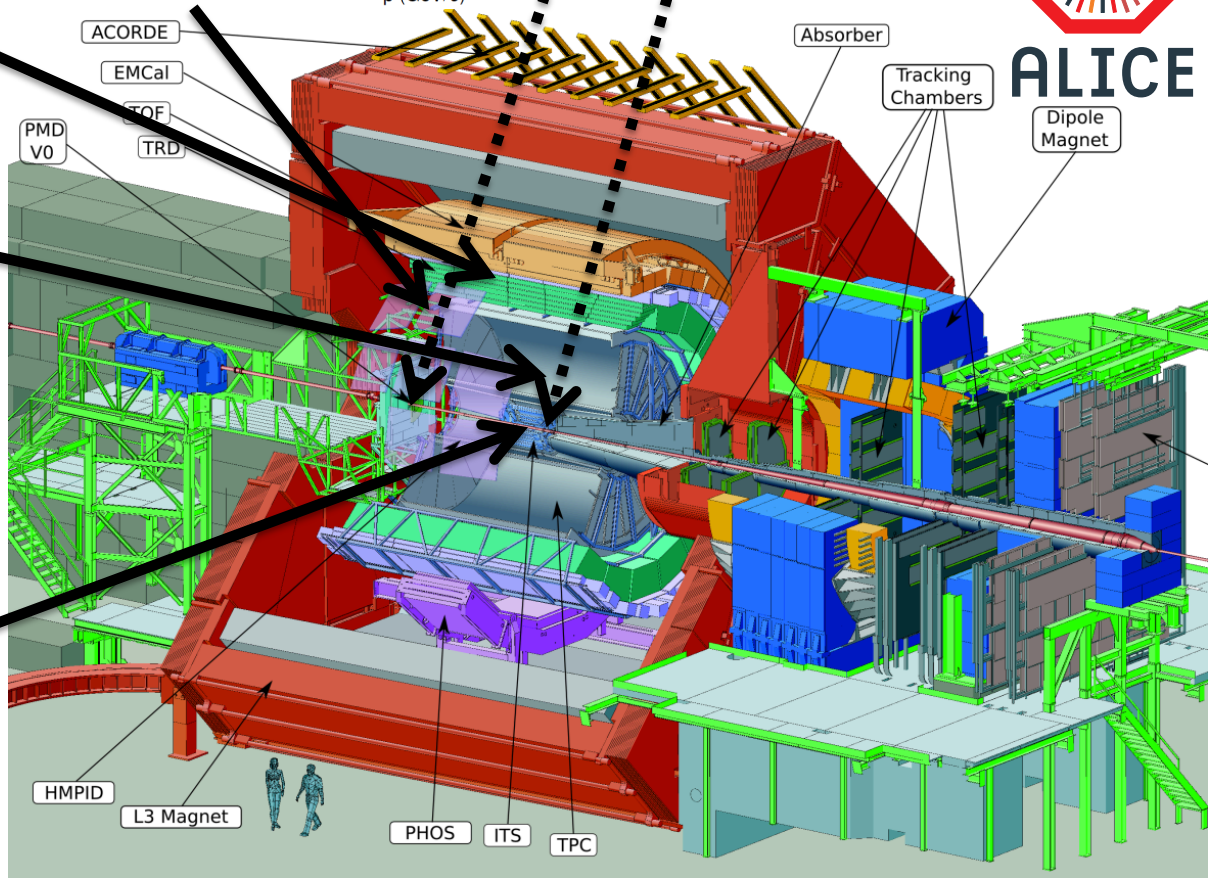




V0, other forward detectors:
Trigger, timing, multiplicity, centrality



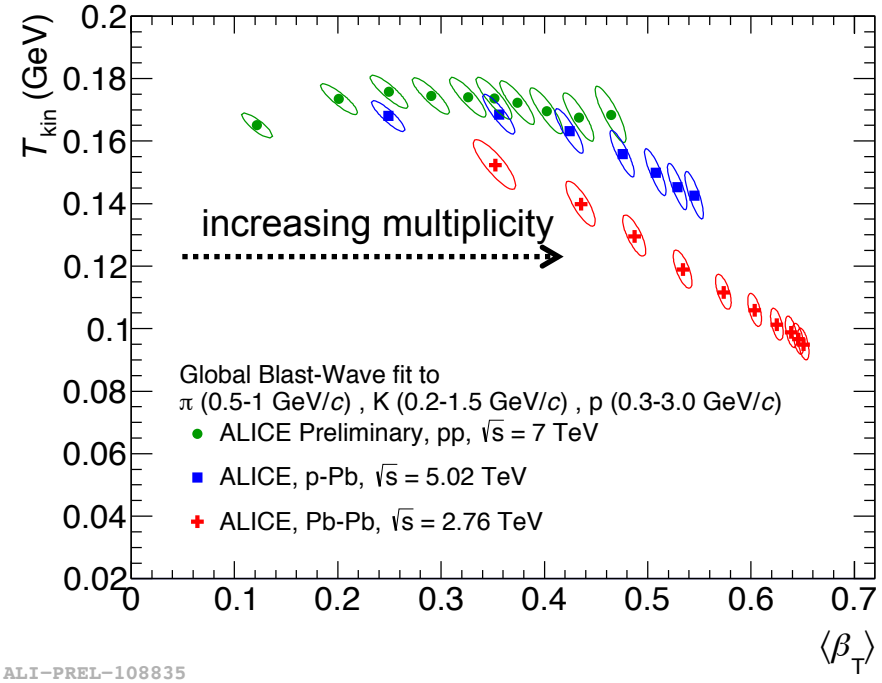




ALICE

Blast-Wave Fits

- Combined fits of $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$ in pp, p–Pb, and Pb–Pb
  - Note: results sensitive to fit range and particles included
- pp and p–Pb follow similar trends, different from Pb–Pb
- T_{kin} nearly constant for pp, small decrease in p–Pb
- Radial flow $\langle\beta_T\rangle$ increases with multiplicity/centrality



$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r dr\, m_T\, I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right),$$

$$\rho = \tanh^{-1}\beta_T = \tanh^{-1}\left(\left(\frac{r}{R}\right)^n \beta_s\right)$$

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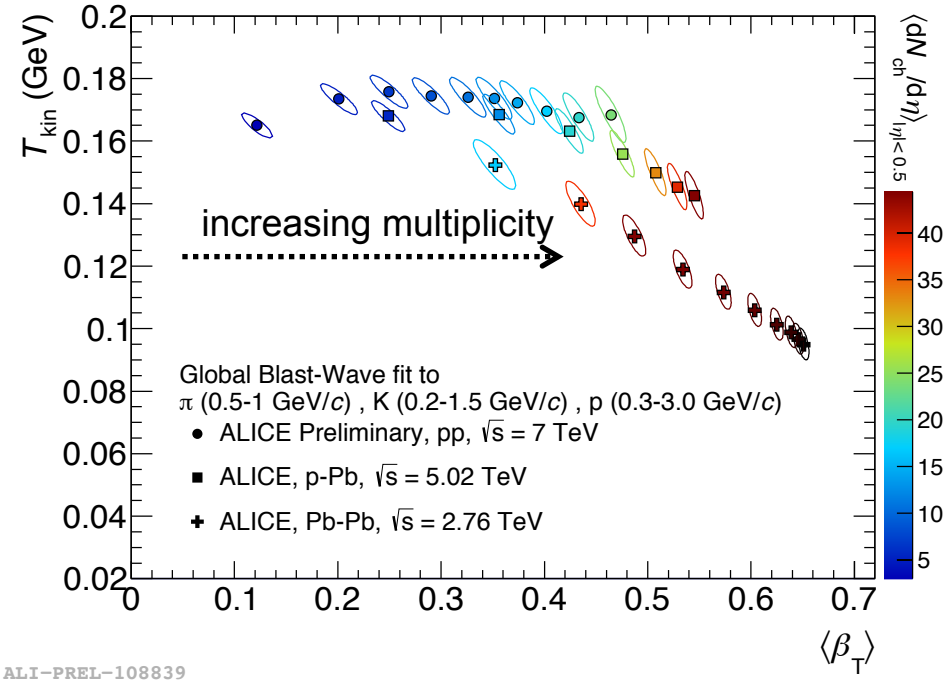
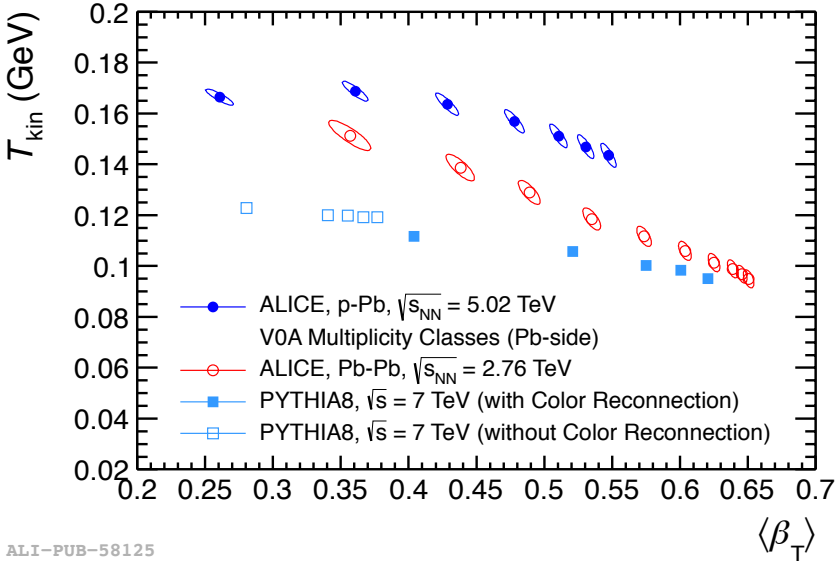
- pp and p–Pb follow similar trends, different from Pb–Pb
- T_{kin} nearly constant for pp, small decrease in p–Pb
- Radial flow $\langle\beta_T\rangle$ increases with multiplicity/centrality
- $\langle\beta_T\rangle$ stronger for smaller systems for similar multiplicity
- Color reconnection in pp models can mimic the increase in radial flow



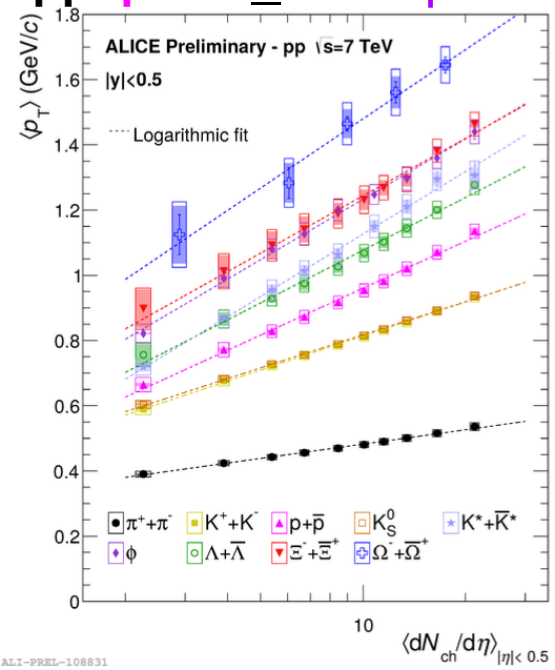


Mean p_T

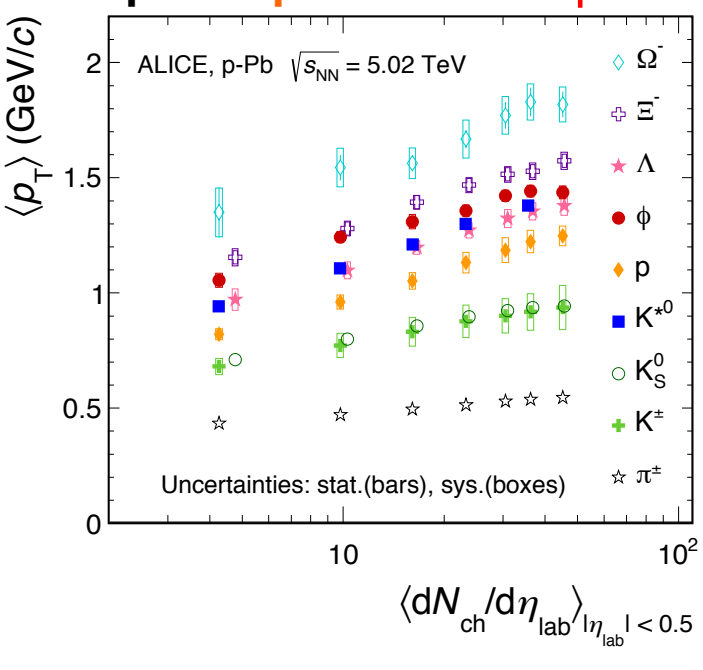
- Mass ordering of $\langle p_T \rangle$ in central Pb–Pb
  - $\langle p_T \rangle$ for K*0, p, and ϕ similar → expected from hydro (similar masses)
- Mass ordering only approximate for peripheral Pb–Pb, p–Pb, and pp
  - Resonances different from long-lived particles? Baryon/meson difference?

<pT> ordering:

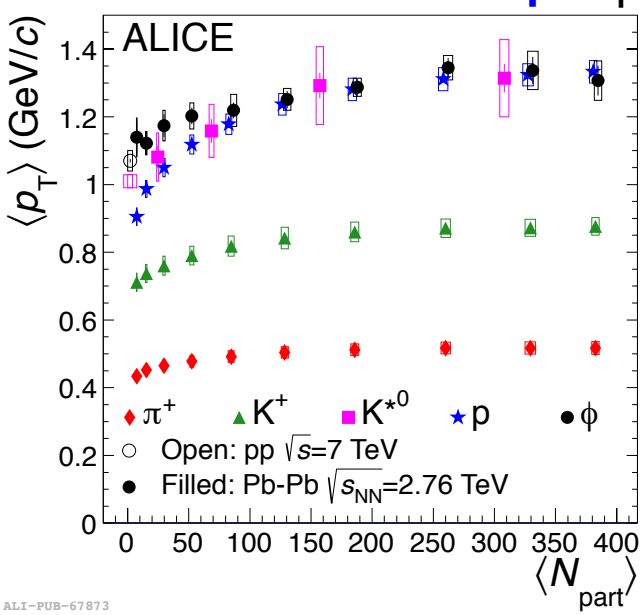
pp: p < Λ ≤ K*0 < ϕ ≈ Ξ⁻



p–Pb: p < Λ ≈ K*0 < ϕ < Ξ⁻



Central Pb–Pb: K*0 ≈ p ≈ ϕ



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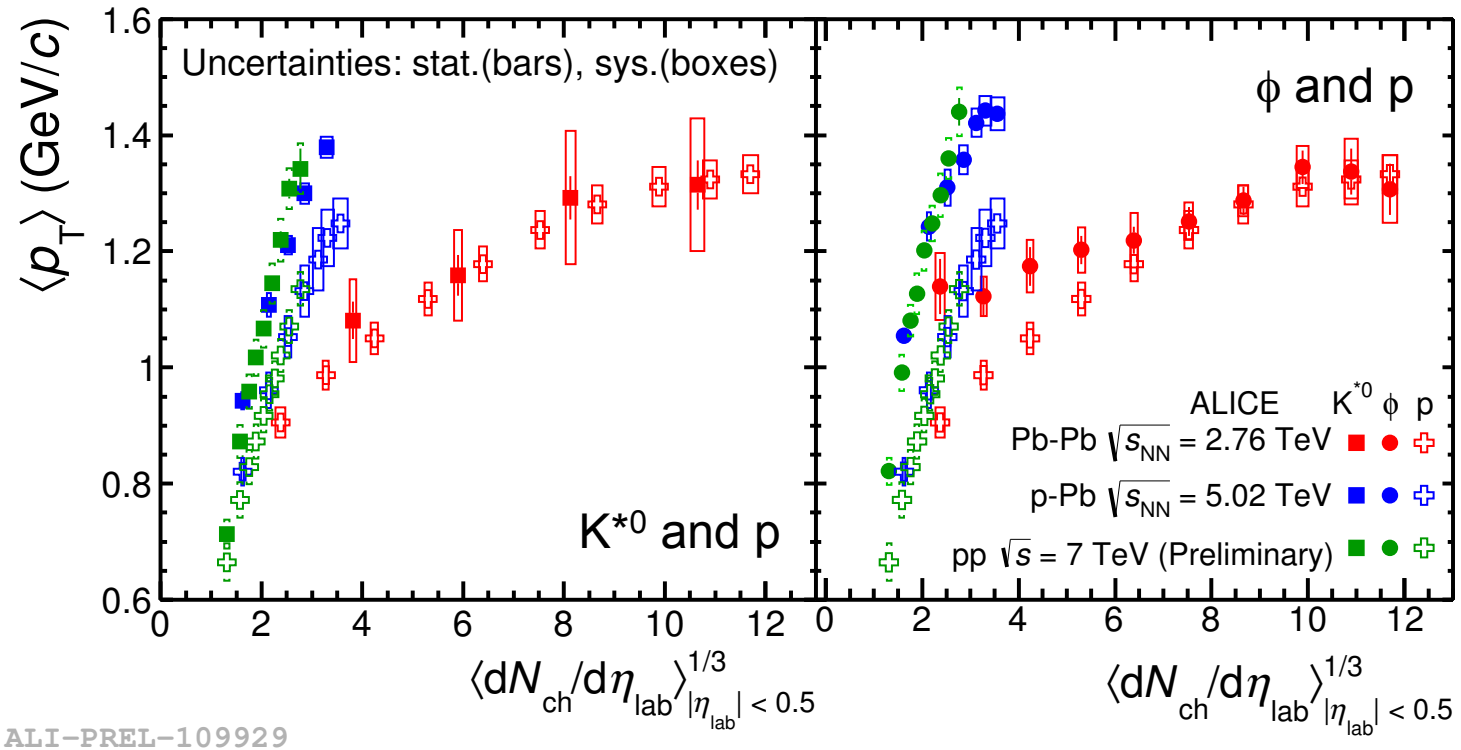
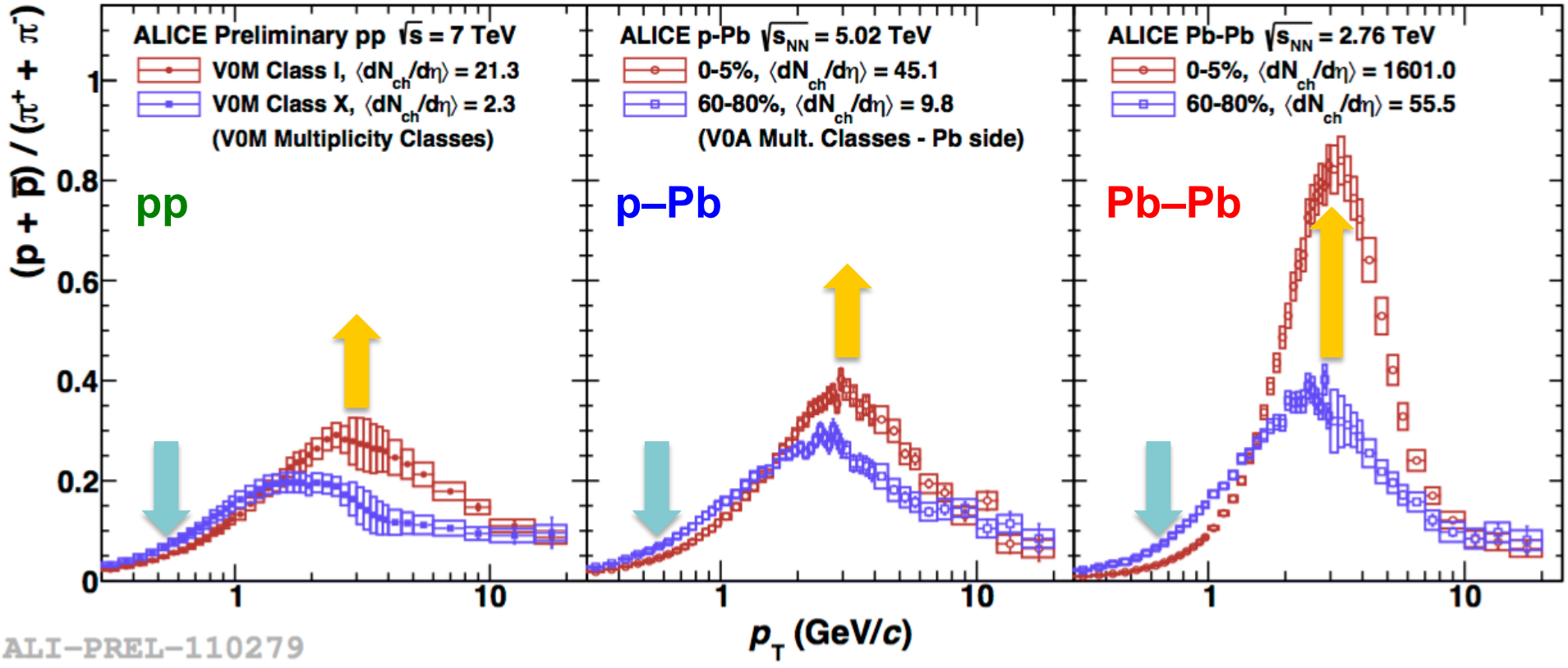
- Mass ordering only approximate for peripheral Pb–Pb, p–Pb, and pp
  - Resonances different from long-lived particles? Baryon/meson difference?
- $\langle p_T \rangle$ of of K*0, p, and ϕ:
  - pp and p–Pb follow same trends vs. multiplicity, different trend for Pb–Pb
  - Reach or exceed central Pb–Pb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



Baryon/Meson Ratios

- From low multiplicity (peripheral) to high multiplicity (central):
  - Baryon/Meson ratios depleted at low p_T
  - Enhanced at intermediate p_T
- Same behavior seen in pp and p–Pb, but with smaller magnitude than in Pb–Pb



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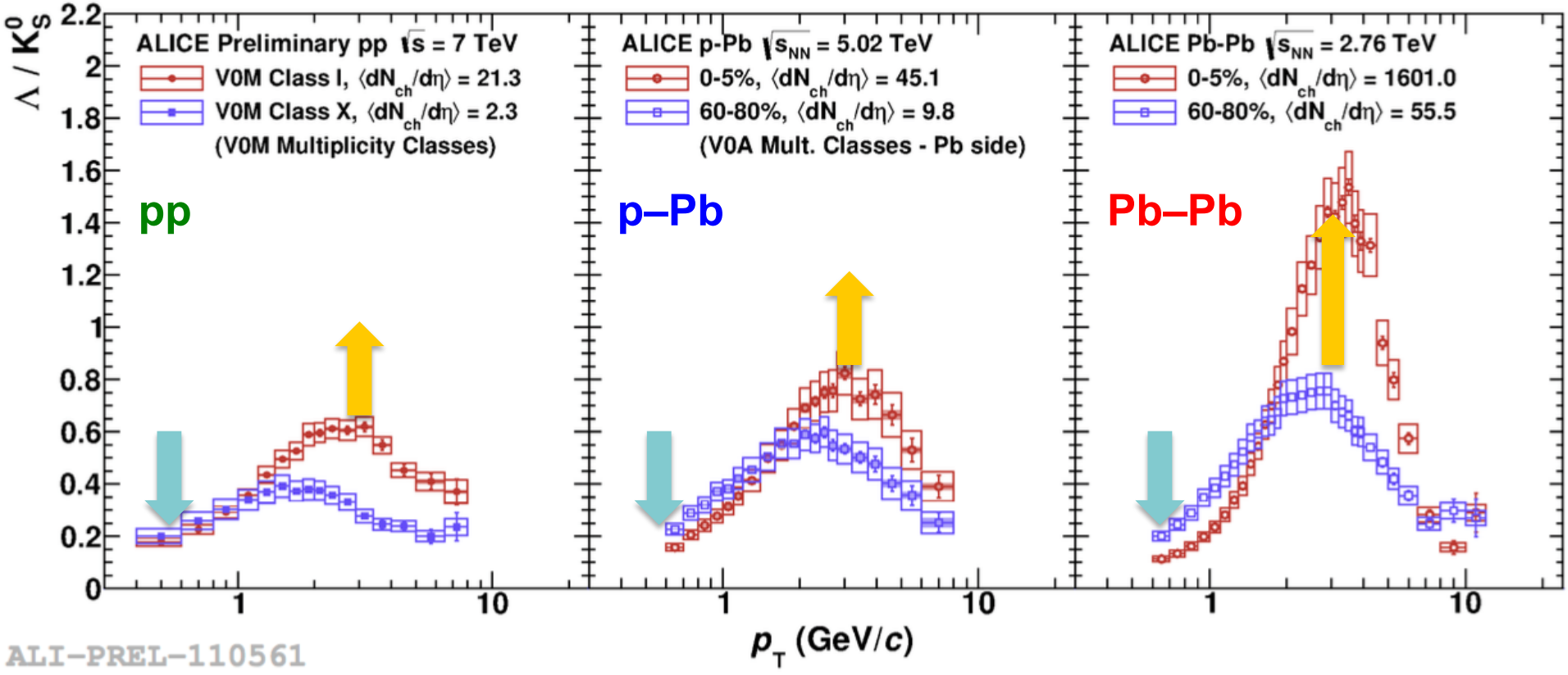
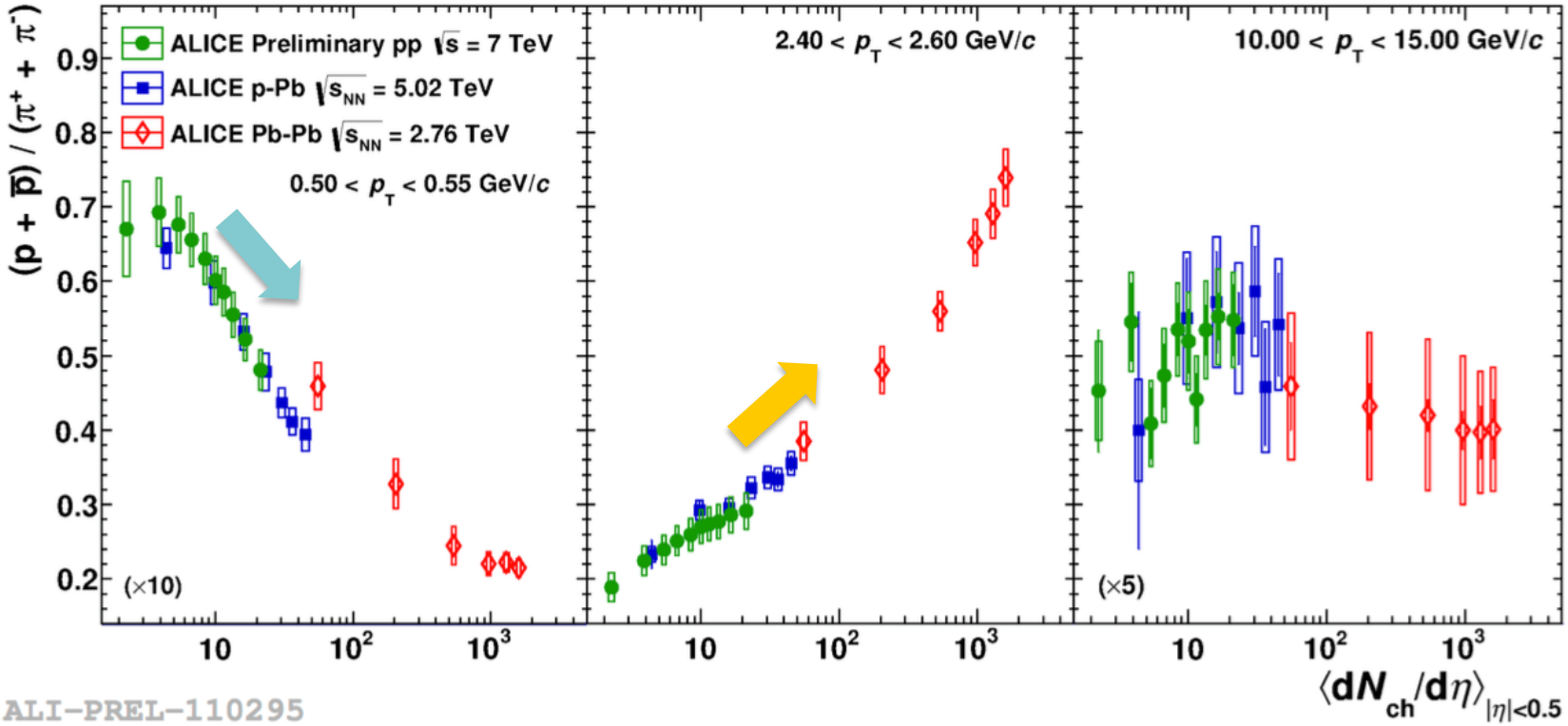


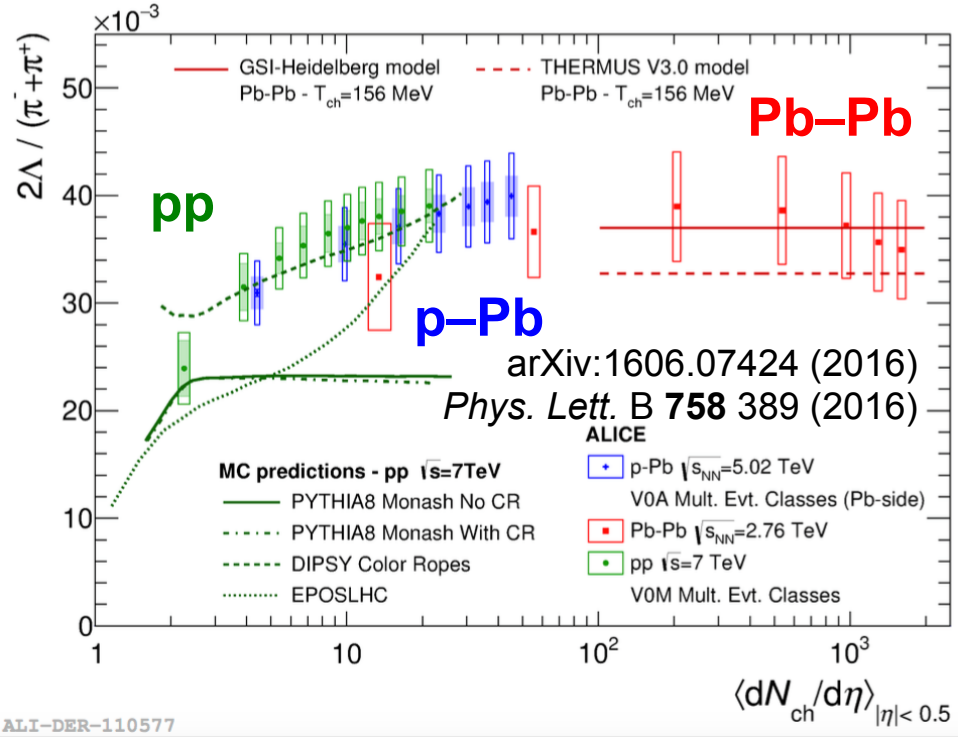
Baryon/Meson Ratios

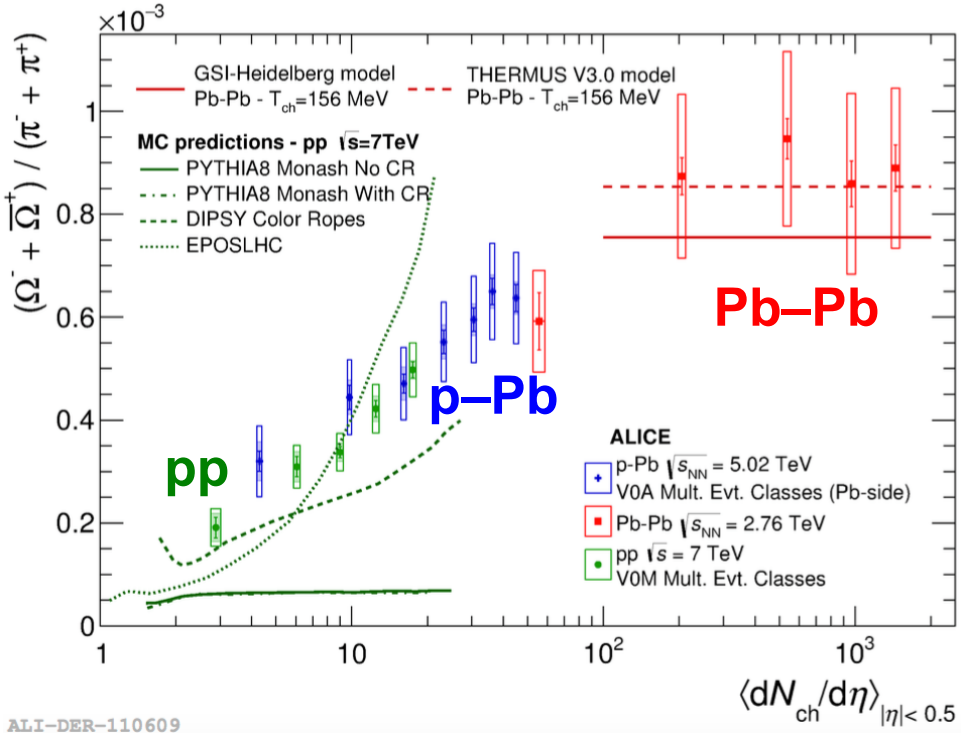
- p/π ratio in different p_T regions:
  - Low-p_T depletion and intermediate-p_T enhancement
  - Little change at high p_T → particle production via fragmentation?
- Very similar behavior for the three systems
- Trend in pp described qualitatively by color reconnection (PYTHIA) and color ropes (DIPSY); over-predicted by collective radial expansion in EPOS



Strangeness Production

- Pb–Pb: Λ/π, Ξ/π (not shown), and Ω/π reach Grand Canonical saturation value (thermal models)
- pp and p–Pb:
  - Follow similar trends as functions of multiplicity
    - Strong disagreement with PYTHIA predictions (even with color reconnection)
    - DIPSY (with color ropes) and EPOS LHC agree at least qualitatively
  - Approach (or reach) Pb–Pb values and GC saturation values
  - Lifting of canonical suppression in high-multiplicity pp and p–Pb?

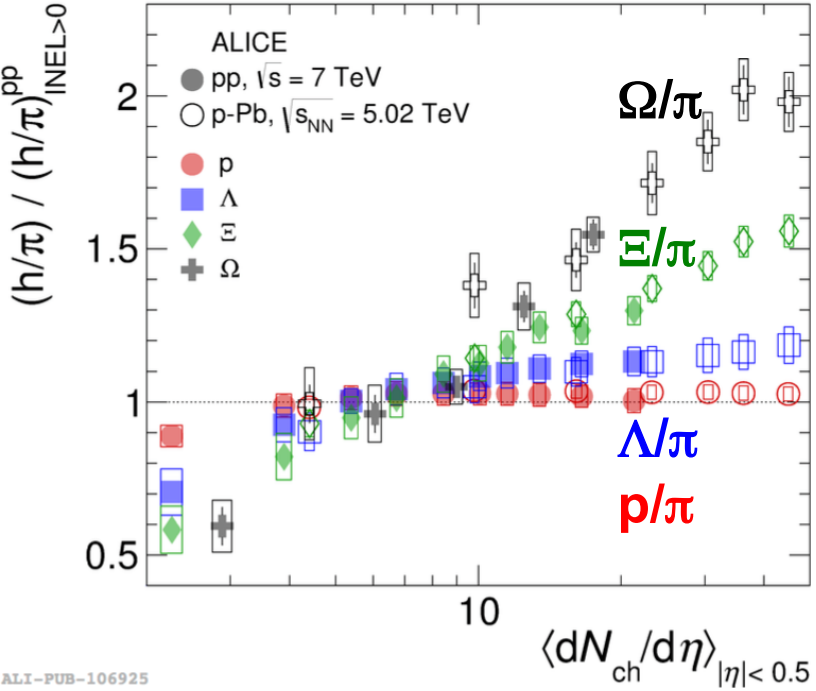


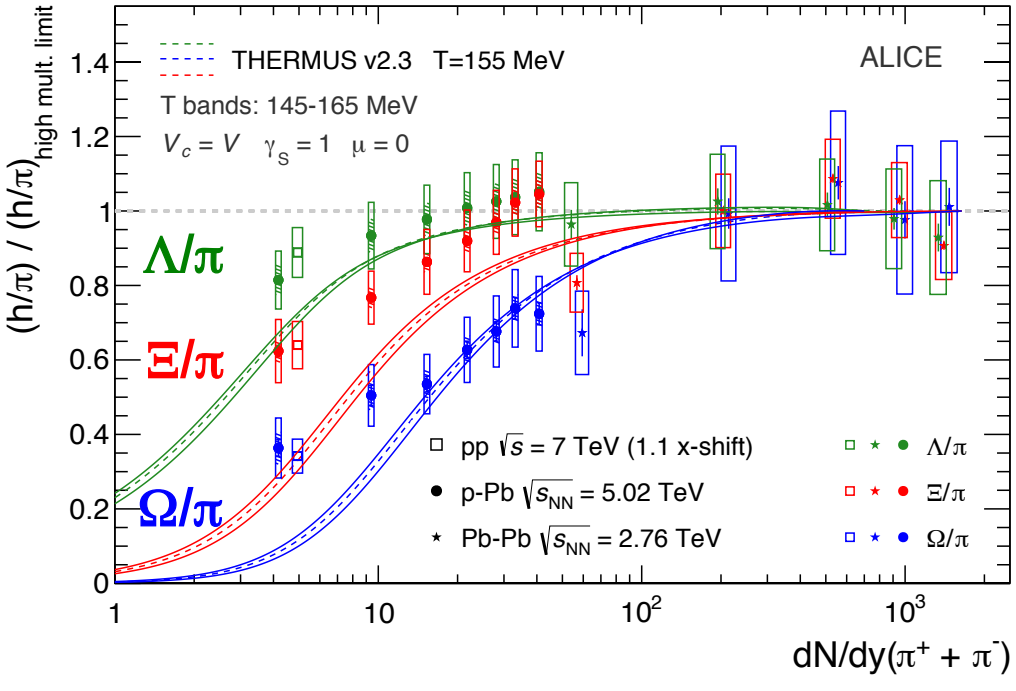


Strangeness Production

- Double ratio: $[h/\pi]^{system}/[h/\pi]^{ppINEL}$: magnitude of enhancement increases with number of strange quarks
- p/π ratio is constant → the effect is related to strangeness, not baryon number
- Decrease from high to low multiplicity is qualitatively described by models with canonical suppression

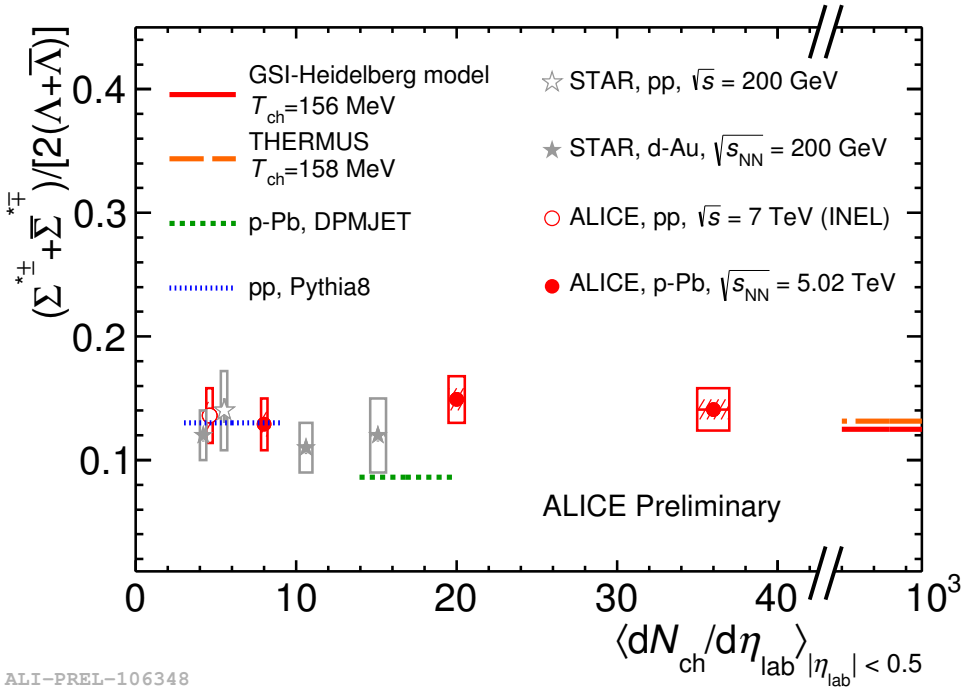
arXiv:1606.07424 (2016)
Phys. Lett. B **758** 389 (2016)

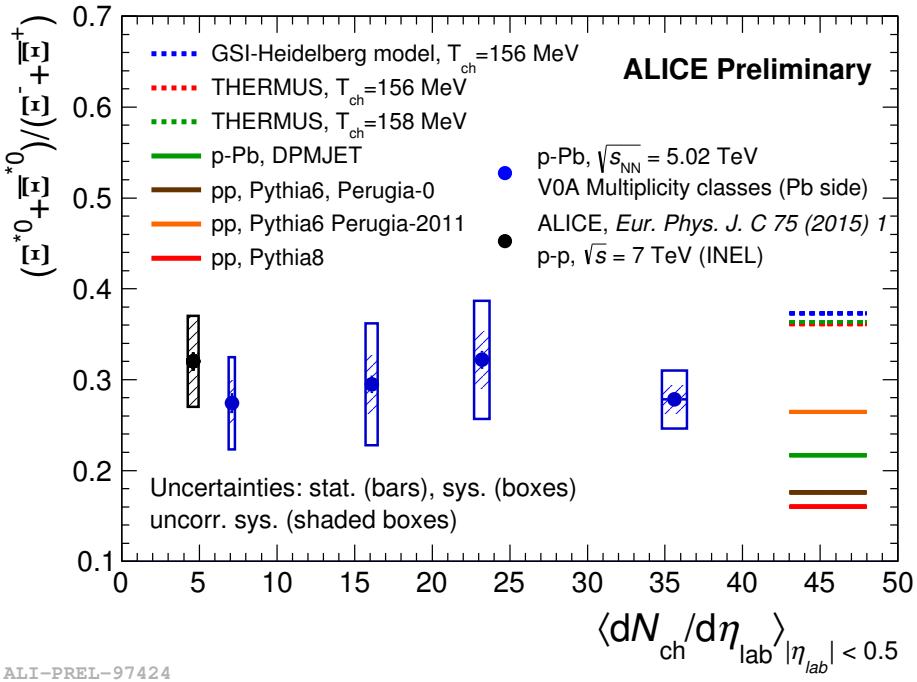




Strangeness Production

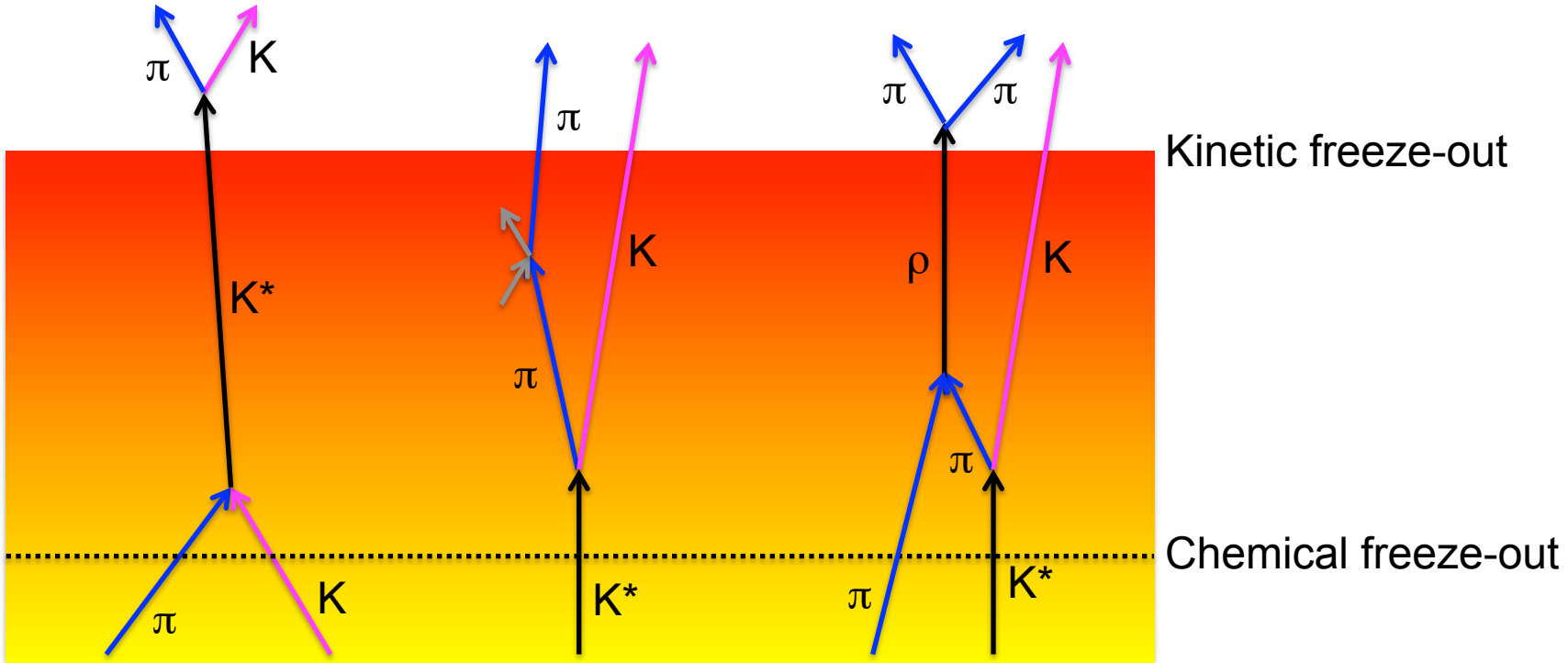
- New measurements of $\Sigma^{*\pm}$ and Ξ^{*0} in p–Pb collisions at 5.02 TeV
  - Measurements in progress for Pb–Pb collisions at 2.76 TeV
- No strong dependence of $\Sigma^{*\pm}/\Lambda$ on energy or system size
  - Values consistent with thermal model and PYTHIA predictions
- No system size dependence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





Hadronic Resonances

- Reconstructible resonance yields may be changed by hadronic scattering processes after chemical freeze-out:
  - **Regeneration:** pseudo-elastic scattering of hadrons
    - 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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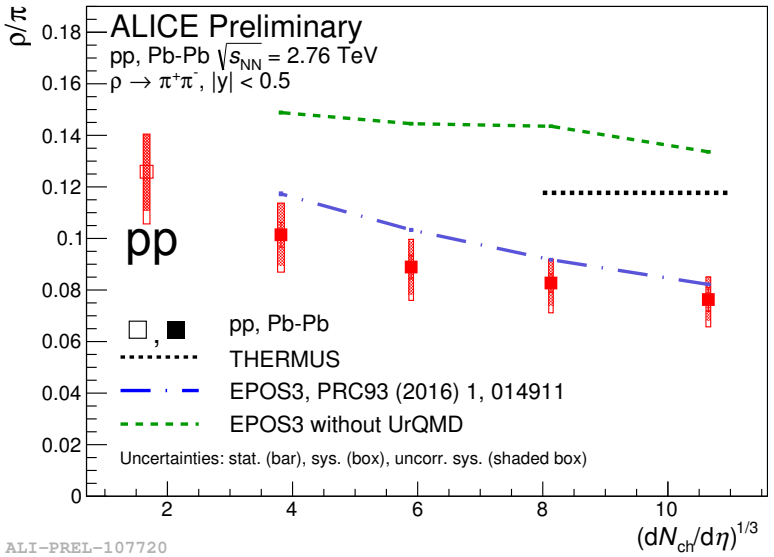
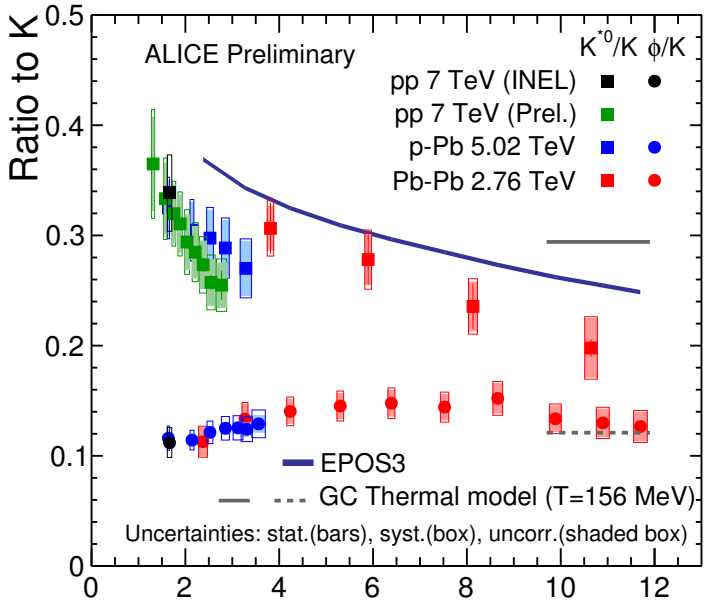
  - **Re-scattering:**
    - Resonance decay products undergo elastic scattering
    - Or pseudo-elastic scattering through a different resonance (e.g. ρ)
    - Resonance not reconstructed through invariant mass
- Final yields at kinetic freeze-out depend on
  - Initial Yields: chemical freeze-out temperature
  - 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)

Hadronic Resonances

- 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
  - Lifetime of ϕ ~10× longer than K^{*0}, ~35× longer than ρ^0 → re-scattering effects not significant





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

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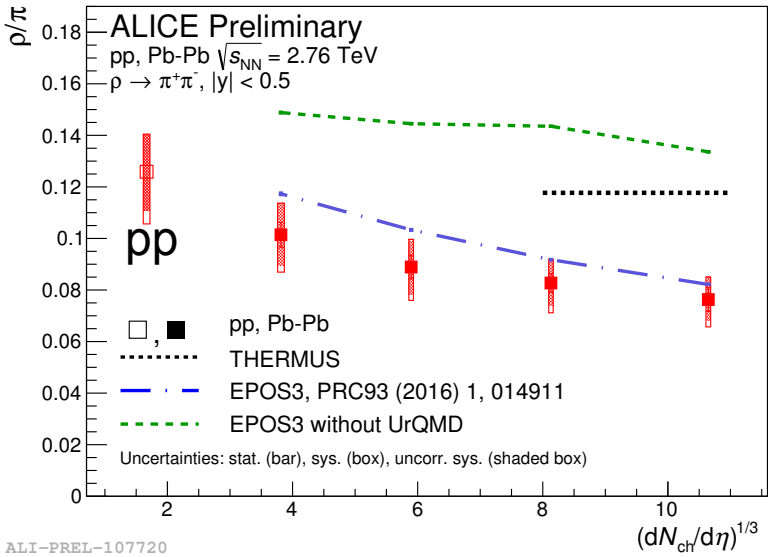
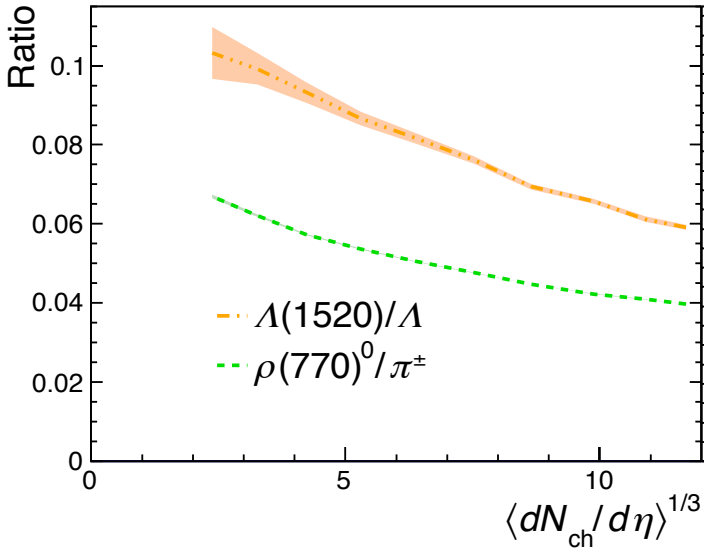
- Looking ahead: EPOS prediction for $\Lambda(1520)$ suppression, ALICE results to be presented at QM2017

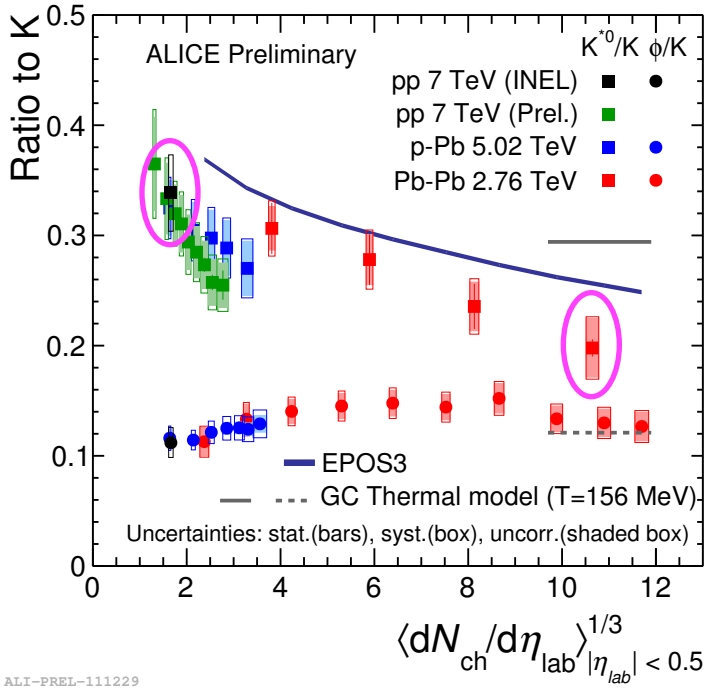


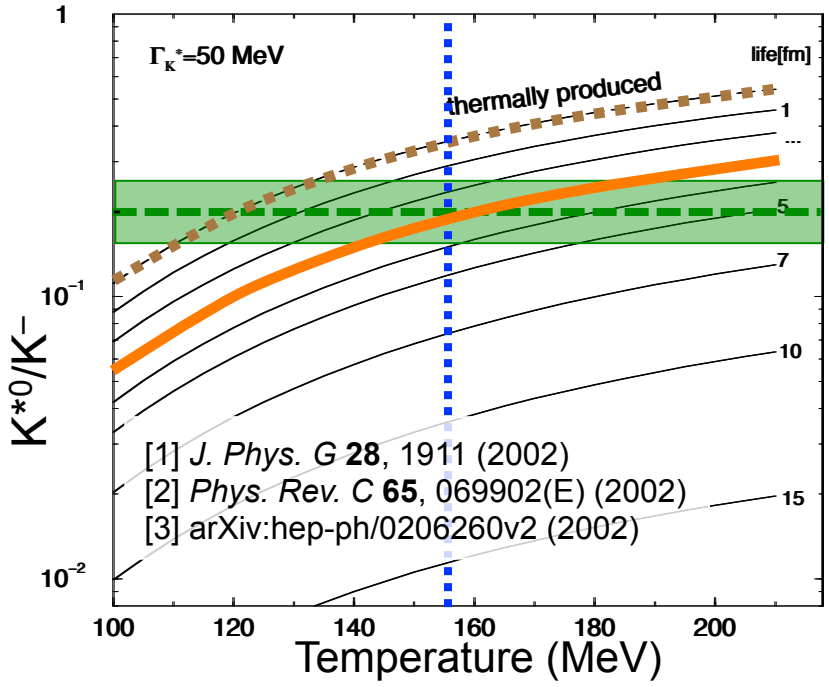


Phys. Rev. C **93** 014911 (2016)

Hadronic Resonances

- 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





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

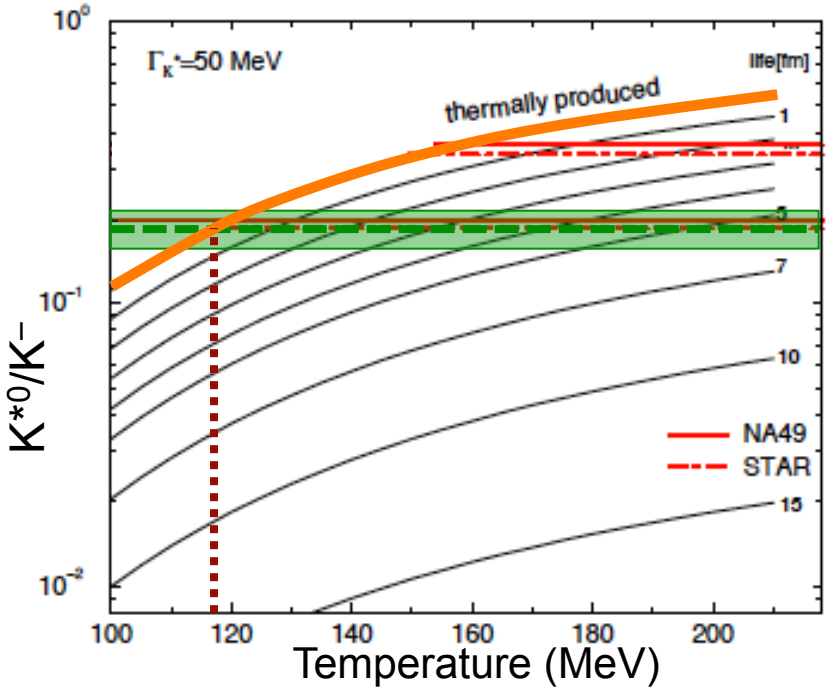
→ Prediction:
K^{*0}/K^{-} = 0.35

Torrieri/Rafelski [1-3]
no re-scattering
measured K^{*0}/K^{-}

→ Prediction:
T_{ch} = 117±6 MeV

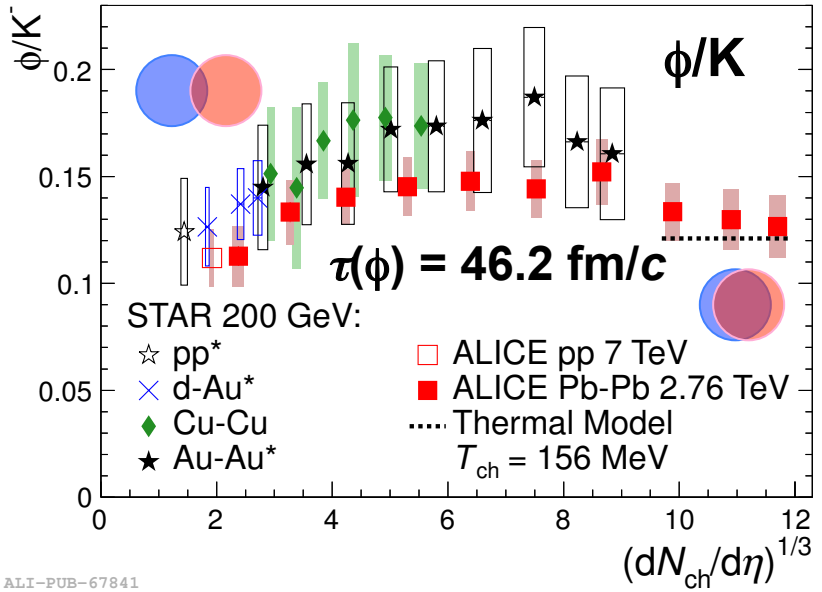
K^{*0}/K^{-} = 0.180 ± 0.027

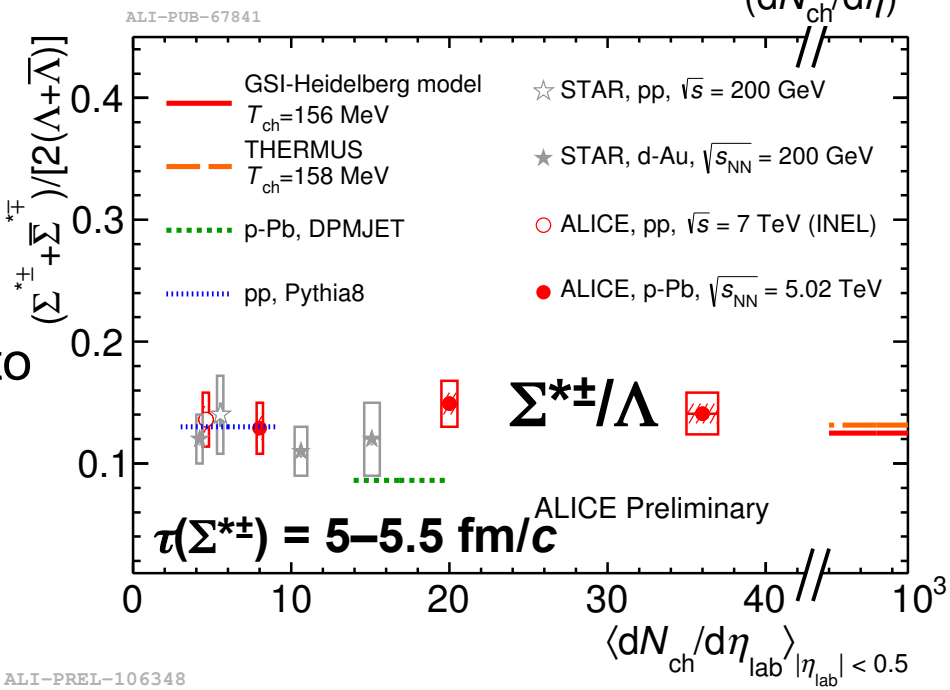
[1] *J. Phys. G* **28**, 1911 (2002)
[2] *Phys. Rev. C* **65**, 069902(E) (2002)
[3] arXiv:hep-ph/0206260v2 (2002)



Comparison to RHIC

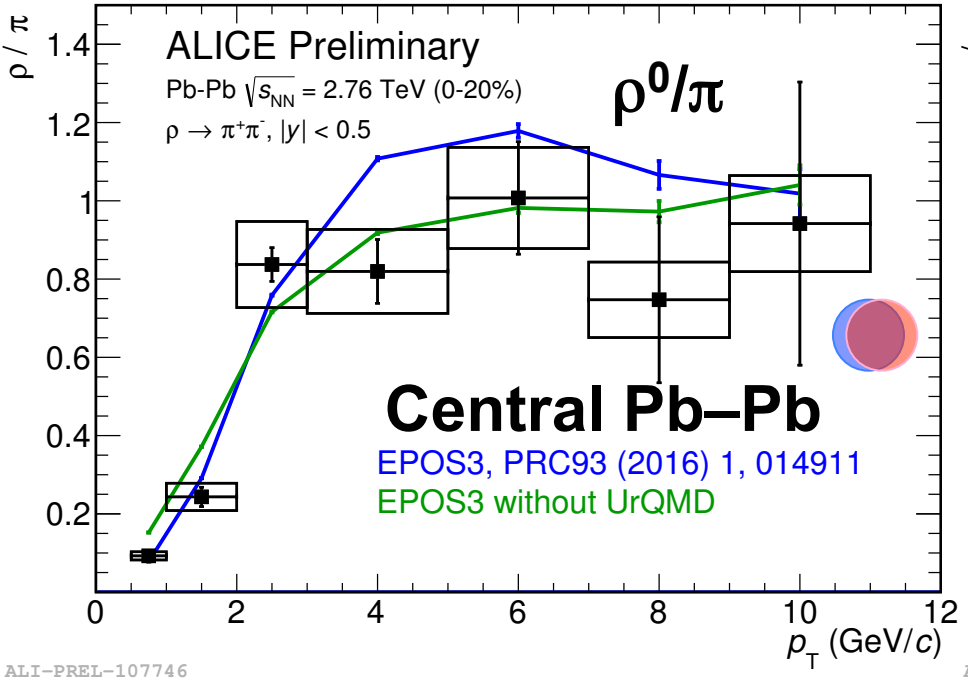
- RHIC: Lower energy heavy-ion collider at Brookhaven Lab, US
- No energy dependence in K^{*0} or $\Lambda(1520)$ suppression from RHIC to LHC
- No clear energy dependence of ϕ/K and $\Sigma^{*\pm}/\Lambda$ ratios
- For a given system size, observations are very similar from RHIC to LHC
  - Not much change in system lifetime expected from RHIC to LHC





Changing System Size

- Low-p_T ρ^0/π decreases from peripheral to central Pb–Pb



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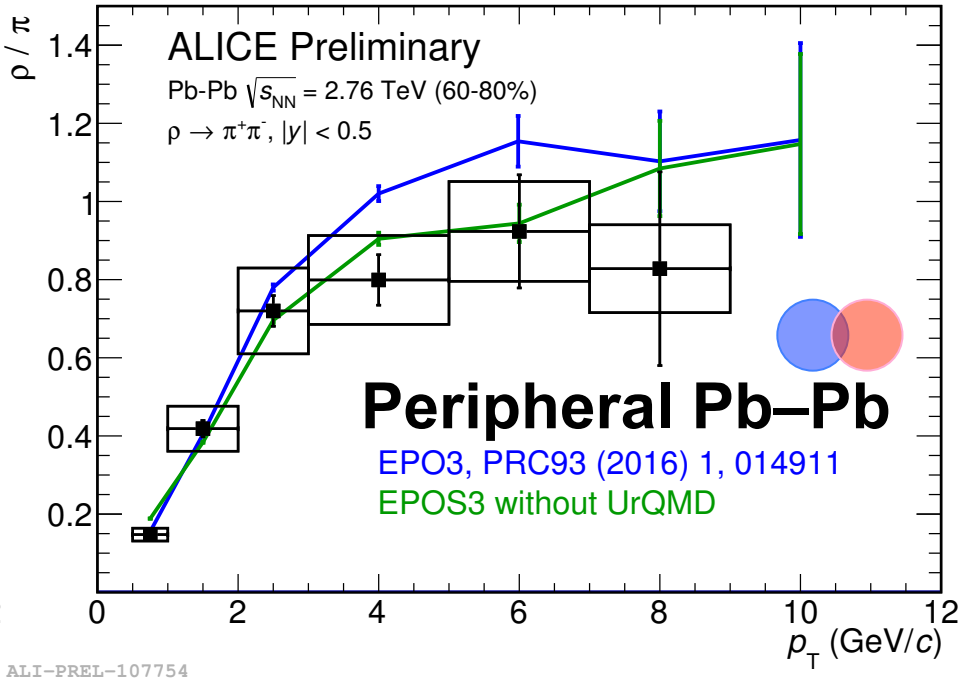
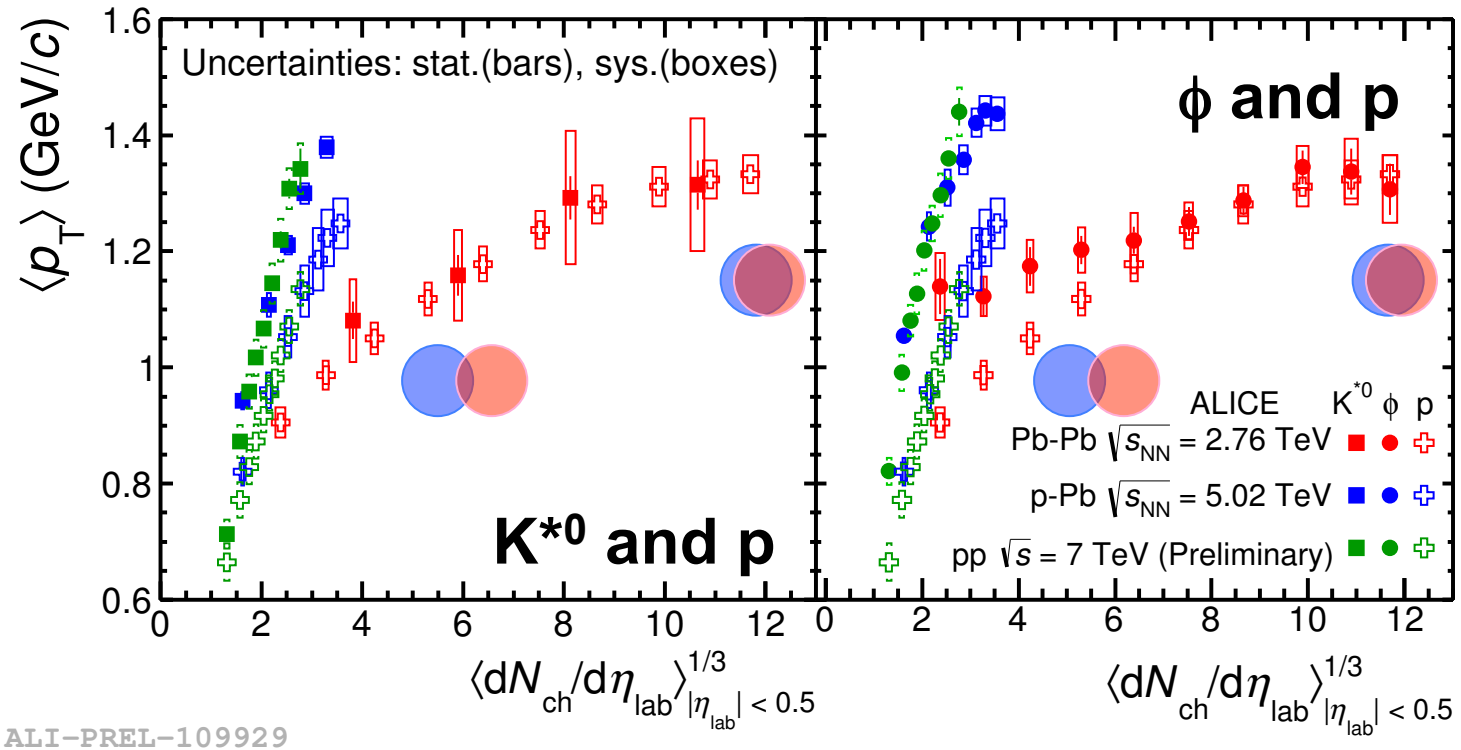


ALI-PREL-107754

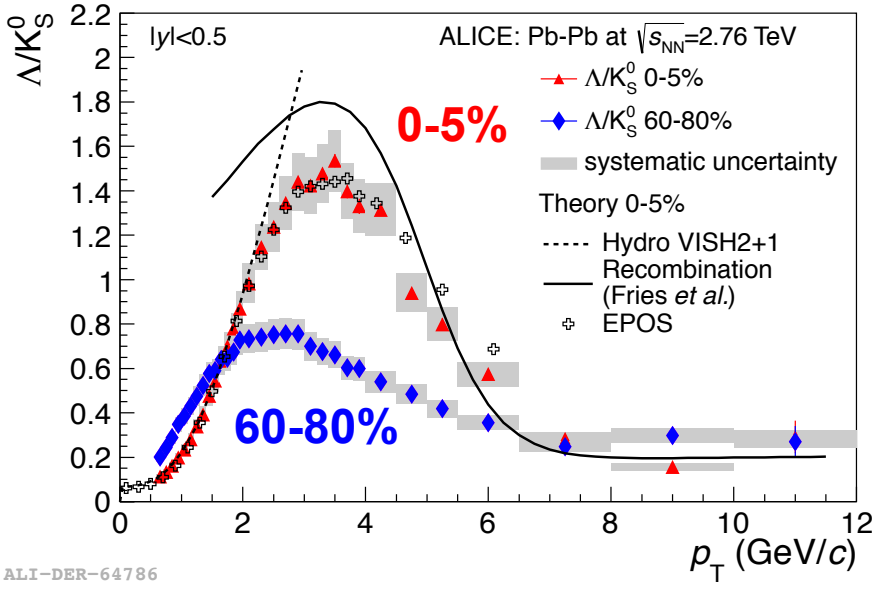
Mean p_T

- Mass ordering of $\langle p_T \rangle$ in central Pb–Pb
  - $\langle p_T \rangle$ for K*0, p, and ϕ 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 of K*0, p, and ϕ:
  - 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

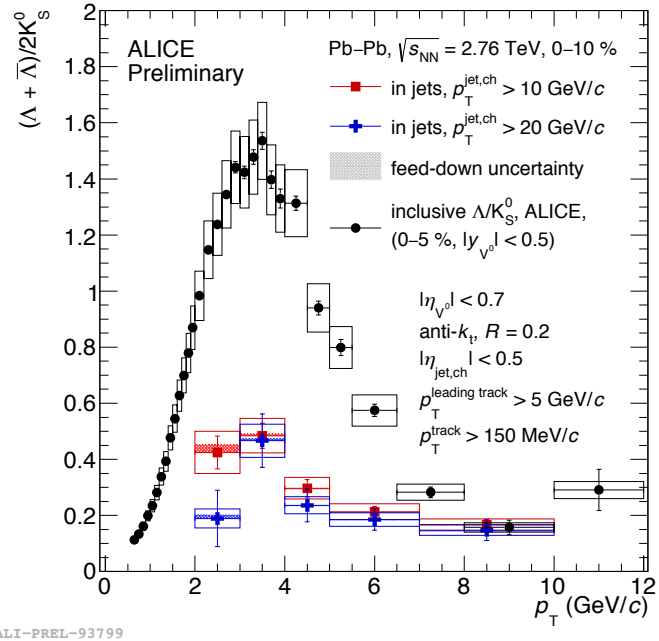


Baryon/Meson Ratios

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

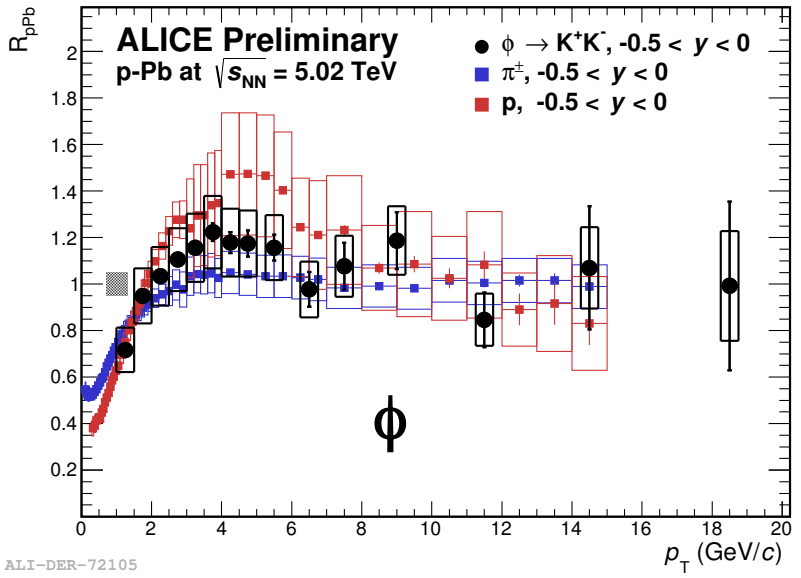


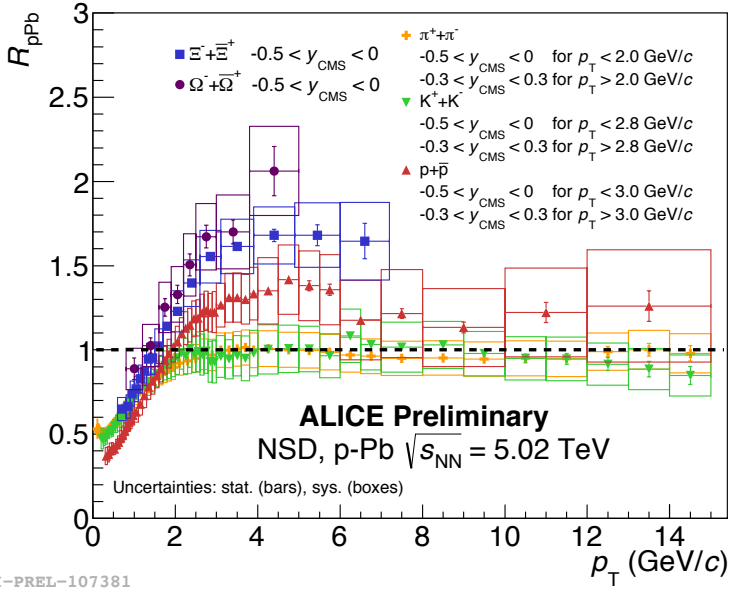
Not seen in jets → bulk effect



Nuclear Modification Factor

- p–Pb:
  - High p_T: no modification
  - Intermediate p_T: Cronin peak
  - D (not shown) and ϕ between π and p: possible baryon/meson differences?





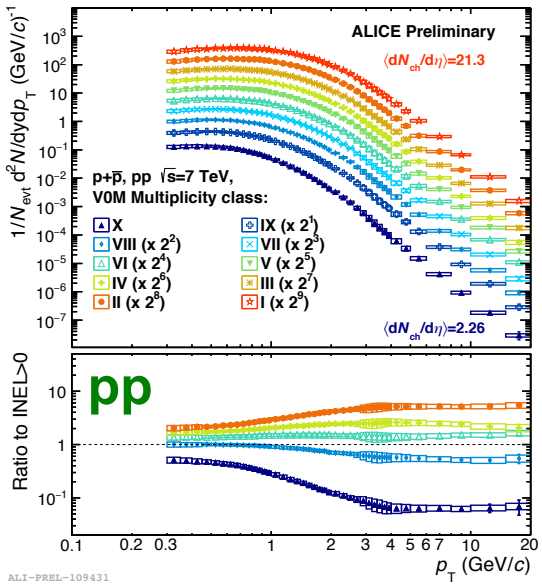
Summary

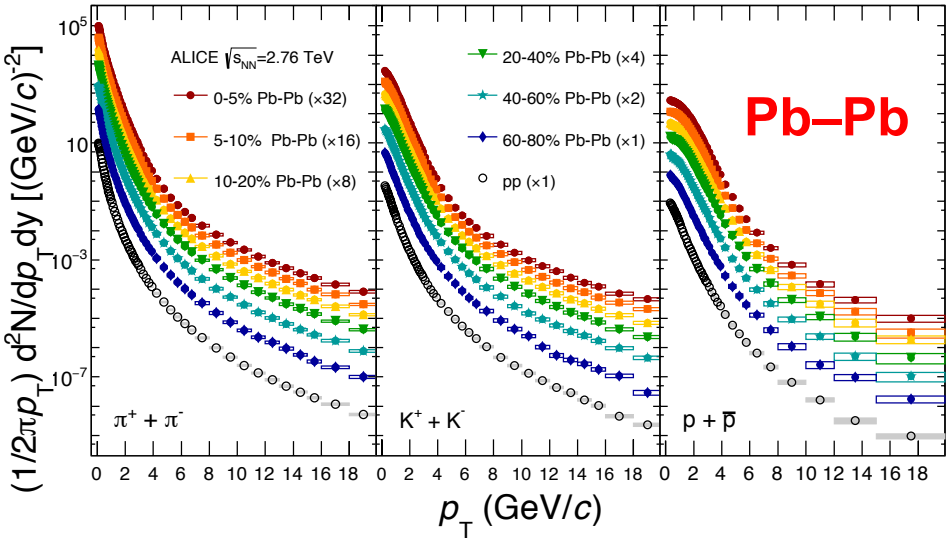
- Particle p_T Spectra and Ratios
  - $\langle p_T \rangle$ and $\langle \beta_T \rangle$ larger in small systems at similar multiplicities
    - Described by radial flow (Pb–Pb) or possibly color reconnection (pp)
  - Central Pb–Pb: $\langle p_T(K^{*0}) \rangle \approx \langle p_T(p) \rangle \approx \langle p_T(\phi) \rangle$: consistent with hydrodynamics
  - $\langle p_T \rangle$ mass ordering violated in small systems: baryon/meson differences?
  - Baryon/meson enhancement at intermediate p_T: increases with multiplicity
    - Described by recombination and EPOS; seen in bulk but not in jets
- Nuclear Modification Factors
  - Flavor-independent suppression at high p_T in central Pb–Pb
  - Baryon/meson differences at intermediate p_T?
- Strangeness Production
  - Fairly smooth rise with multiplicity across 3 systems to GC thermal values
  - Effect in pp may be described by DIPSY (color ropes) or EPOS-LHC
  - Strength of effect depends on strangeness content, not mass or baryon number
- Hadronic Resonances
  - Central Pb–Pb: ρ^0 & K^{*0} suppressed, ϕ not suppressed; described by EPOS
  - 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

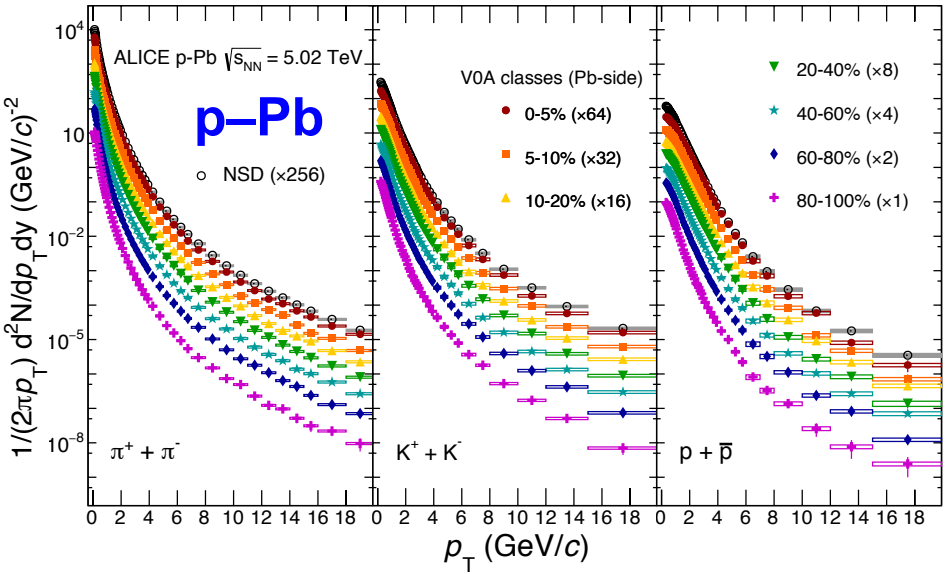
Supporting Plots

Particle p_T Spectra

- Pb–Pb: particle spectra in centrality bins
  - Low p_T (p_T<3 GeV/c): collective behavior (radial flow)
  - Intermediate p_T (3<p_T<8–10 GeV/c): study recombination, fragmentation
  - High p_T (p_T>8–10 GeV/c): jet quenching & energy loss
  - Spectra become harder in more central collisions
- p–Pb & pp: particle spectra in multiplicity bins
  - V0A mult. (2.8<η<5.1) for p–Pb
  - V0M mult. (2.8<η<5.1 AND –3.7<η<–1.7) for pp
  - Remarkable **qualitative similarities** between collision systems as functions of multiplicity/centrality

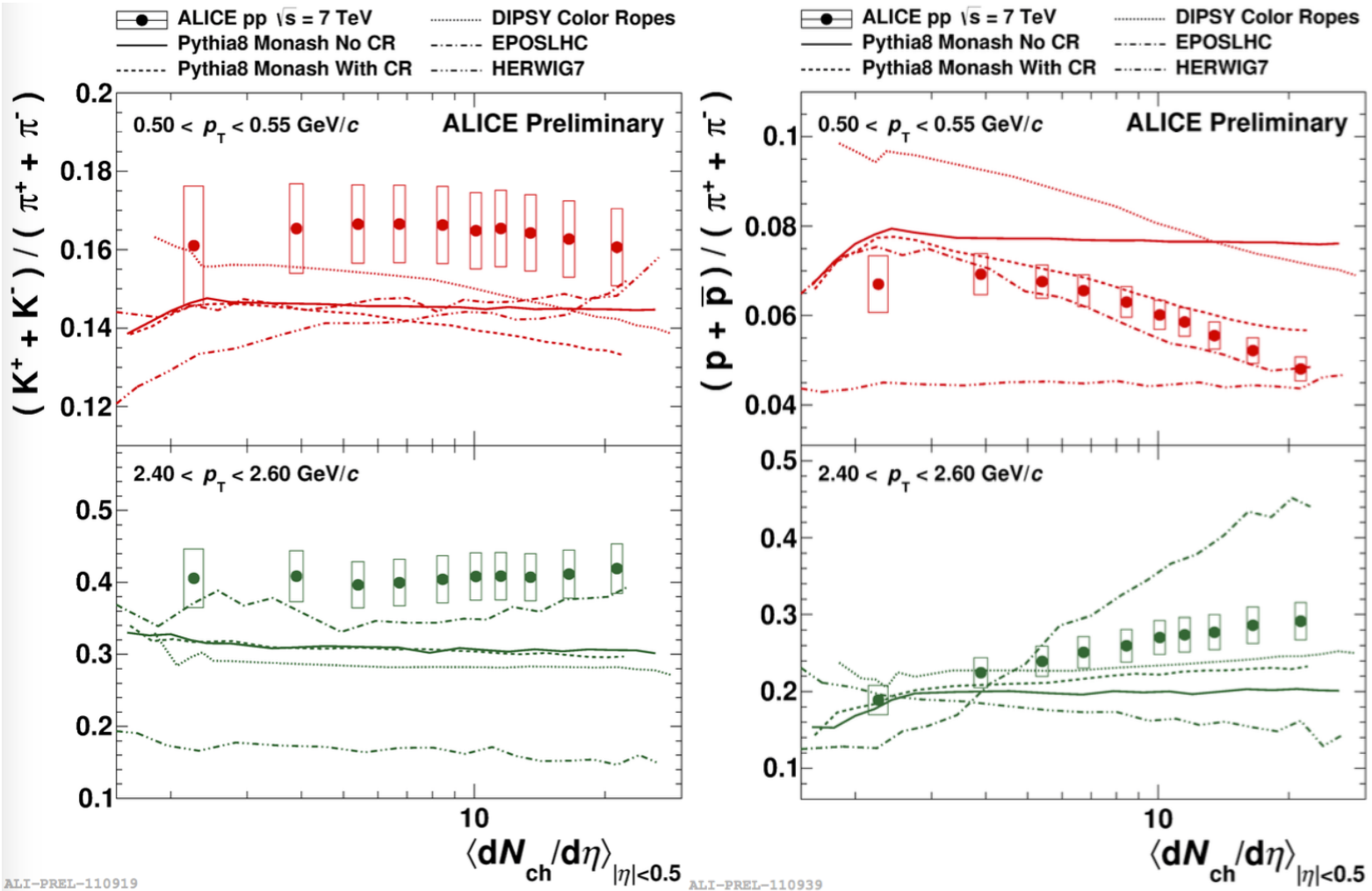




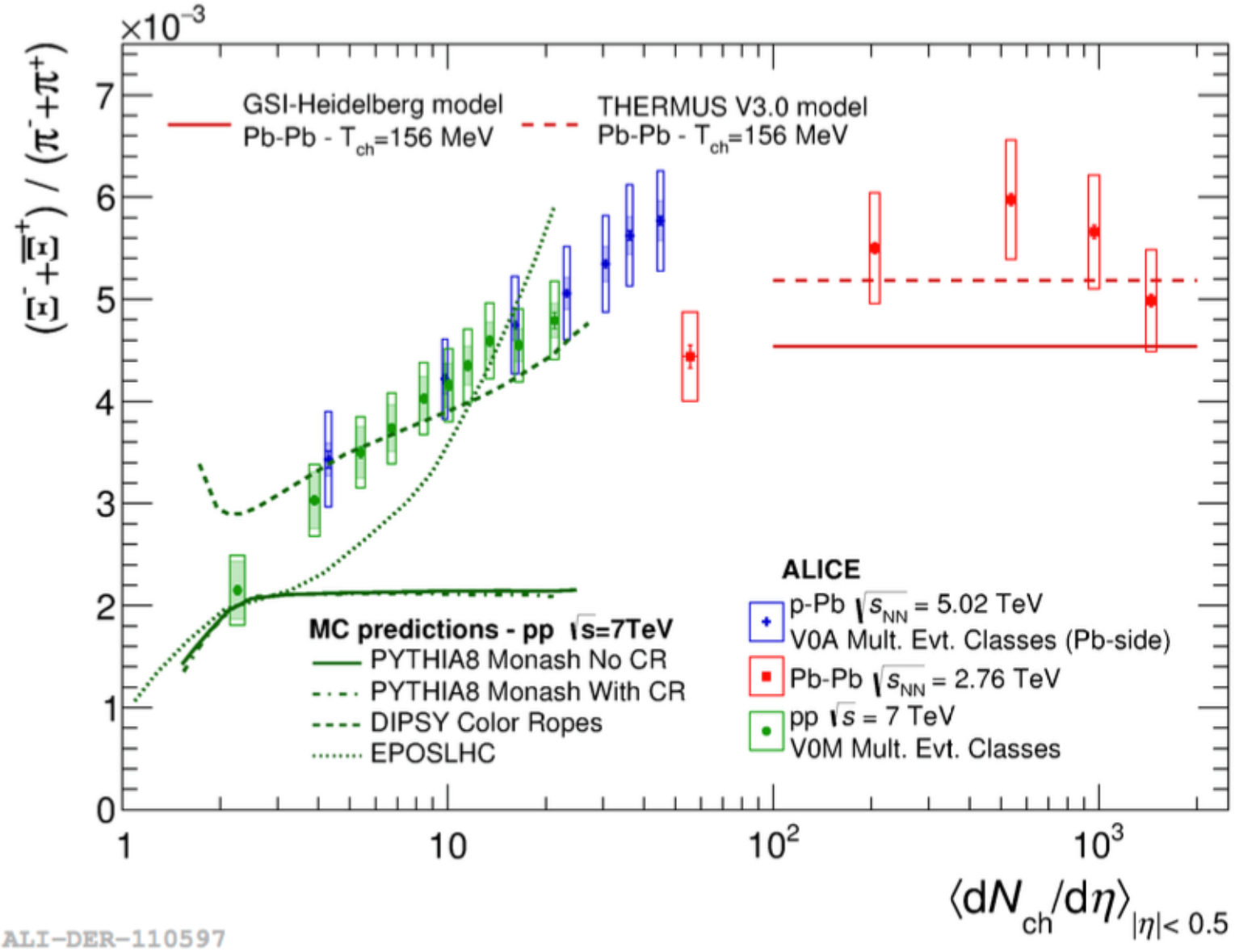


Baryon/Meson Ratios

- K/π and p/π ratios at low and intermediate p_T, compared with predictions

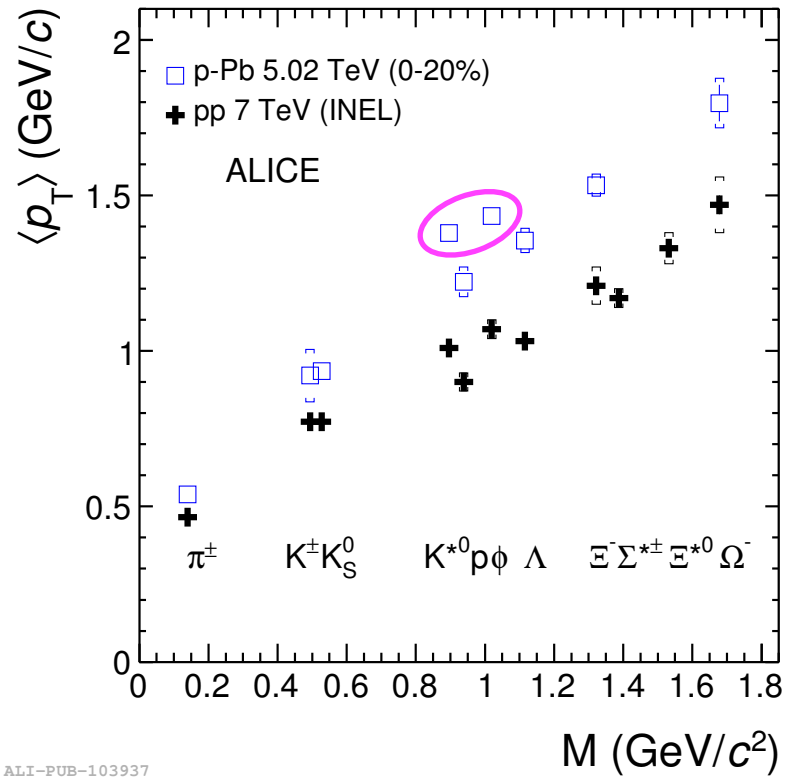


Ξ/π Ratio vs. Multiplicity

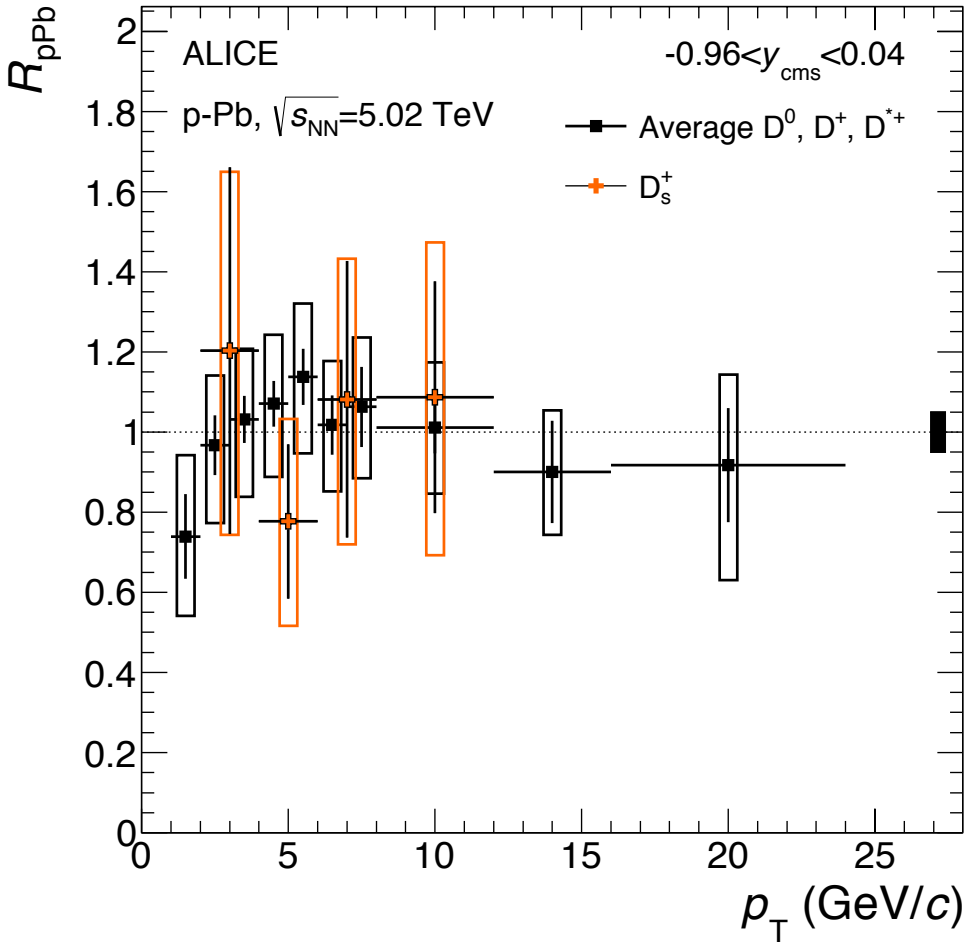


Mean p_T

- 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?

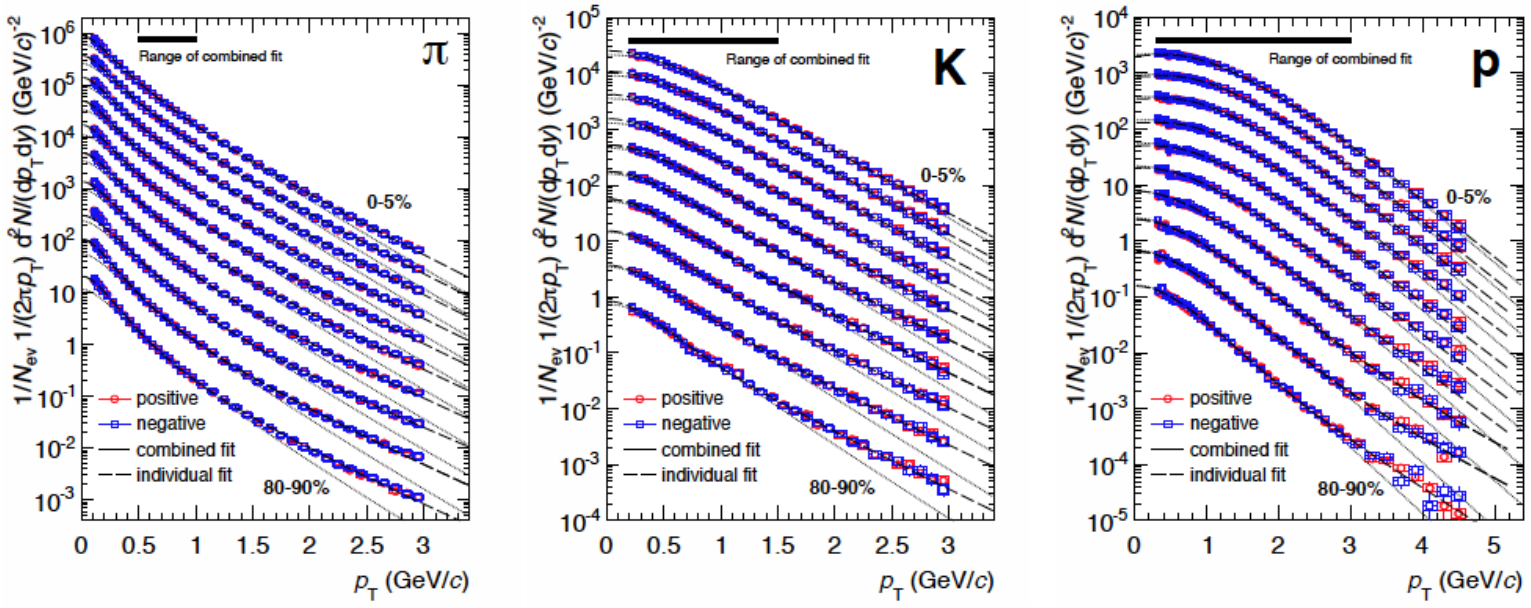


D R_{pPb}


R_{pPb}
ALICE
p-Pb, $\sqrt{s_{NN}}$=5.02 TeV
-0.96<y_{cms}<0.04
Average D^0, D^+, D^{*+}
D_s^+
p_T (GeV/c)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
5
10
15
20
25

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

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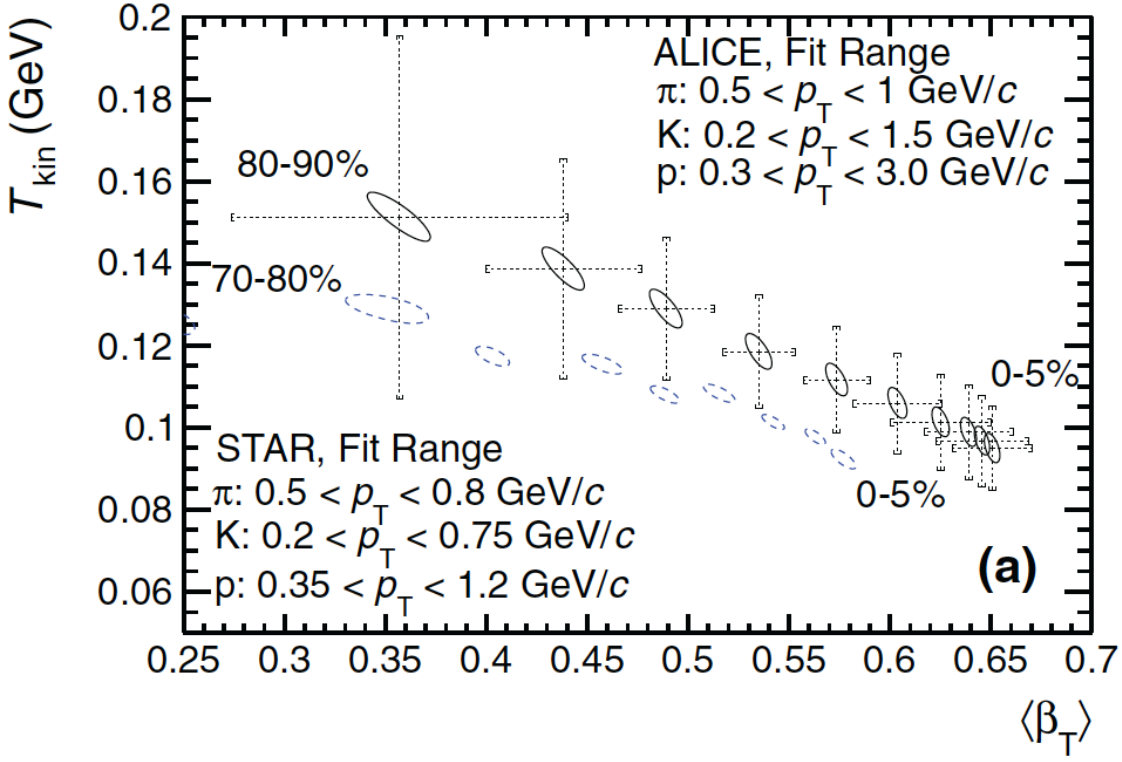


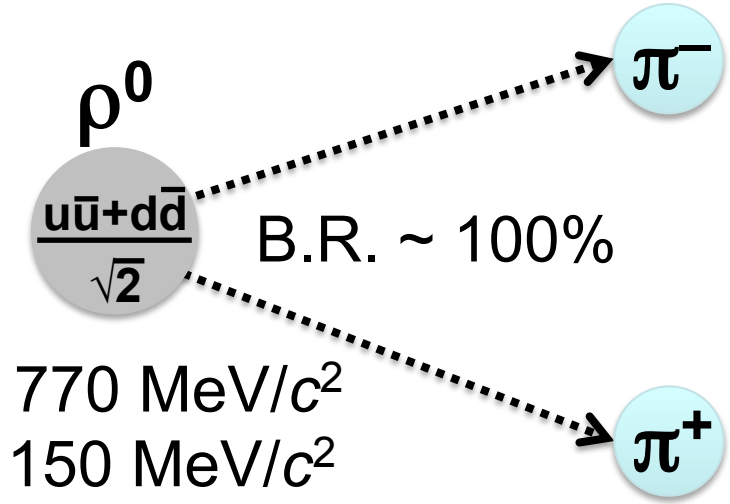
Resonances

Resonances

- 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)	Lifetime (fm/c)	Decay	Branching Ratio (%)
ρ^0	770	150	1.3	$\pi^-\pi^+$	100
K^{*0}	896	47.4	4.17	π^-K^+	66.7
ϕ	1019	4.27	46.2	K^-K^+	48.9
Σ^{*+}	1383	36.0	5.51	$\pi^+\Lambda$	87
Σ^{*-}	1387	39.4	5.01	$\pi^-\Lambda$	87
$\Lambda(1520)$	1520	15.7	12.6	K^-p	22.5
Ξ^{*0}	1532	9.1	21.7	$\pi^+\Xi^-$	66.7

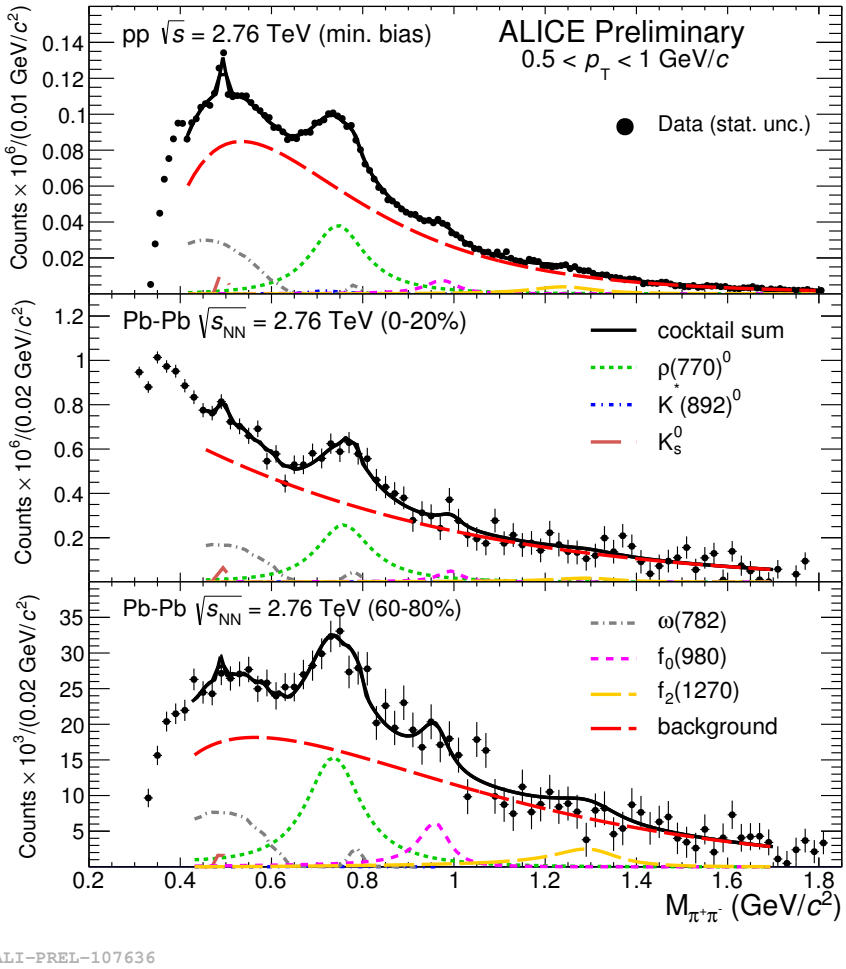
ρ^0 Reconstruction



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***

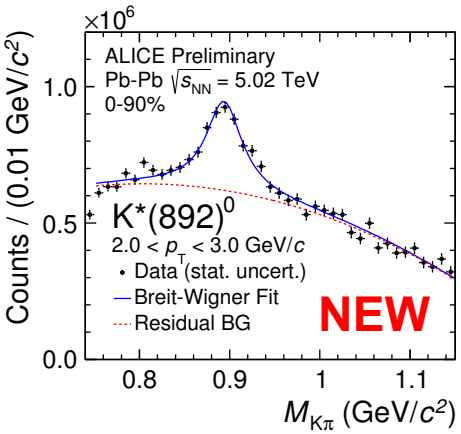
Other Resonances

K^{*0} → π^- + K^+ (B.R. = 66.6%)

$d\bar{s}$

m = 896 MeV/c^2

Γ = 47.4 MeV/c^2

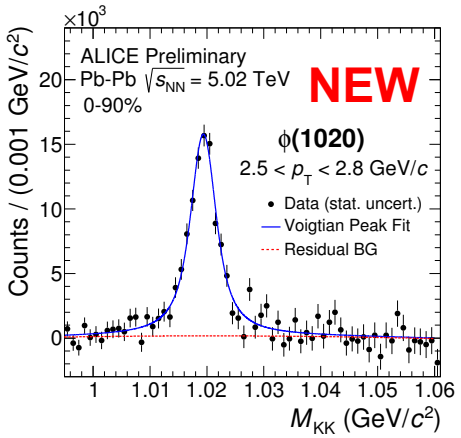


ϕ → K^- + K^+ (B.R. = 48.9%)

$s\bar{s}$

m = 1019 MeV/c^2

Γ = 4.266 MeV/c^2

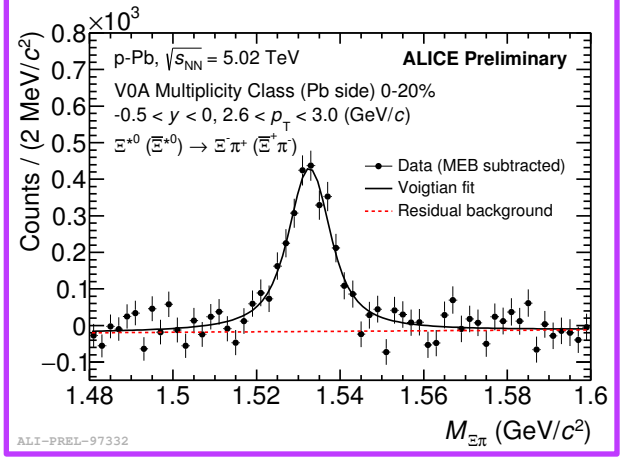


Ξ^{*0} → Ξ^- + π^+ (B.R. = 66.7%)

uss

m = 1532 MeV/c^2

Γ = 9.1 MeV/c^2



Σ^{*+} → π^- + Λ (B.R. = 87%)

uus

m = 1383 MeV/c^2

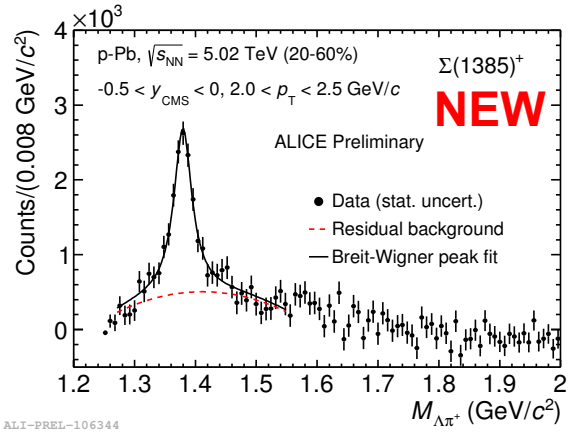
Γ = 36.0 MeV/c^2

Σ^{*-} → π^+ + Λ (B.R. = 87%)

dds

m = 1387 MeV/c^2

Γ = 39.4 MeV/c^2

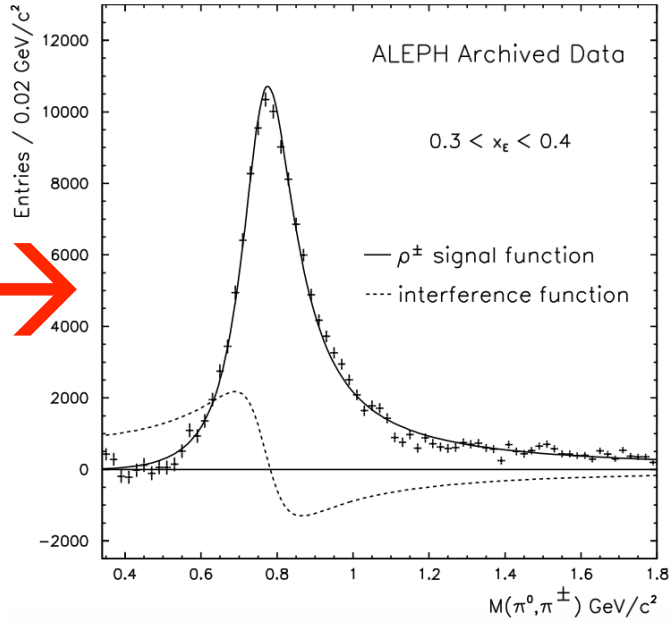


ρ^0: Söding Interference Term

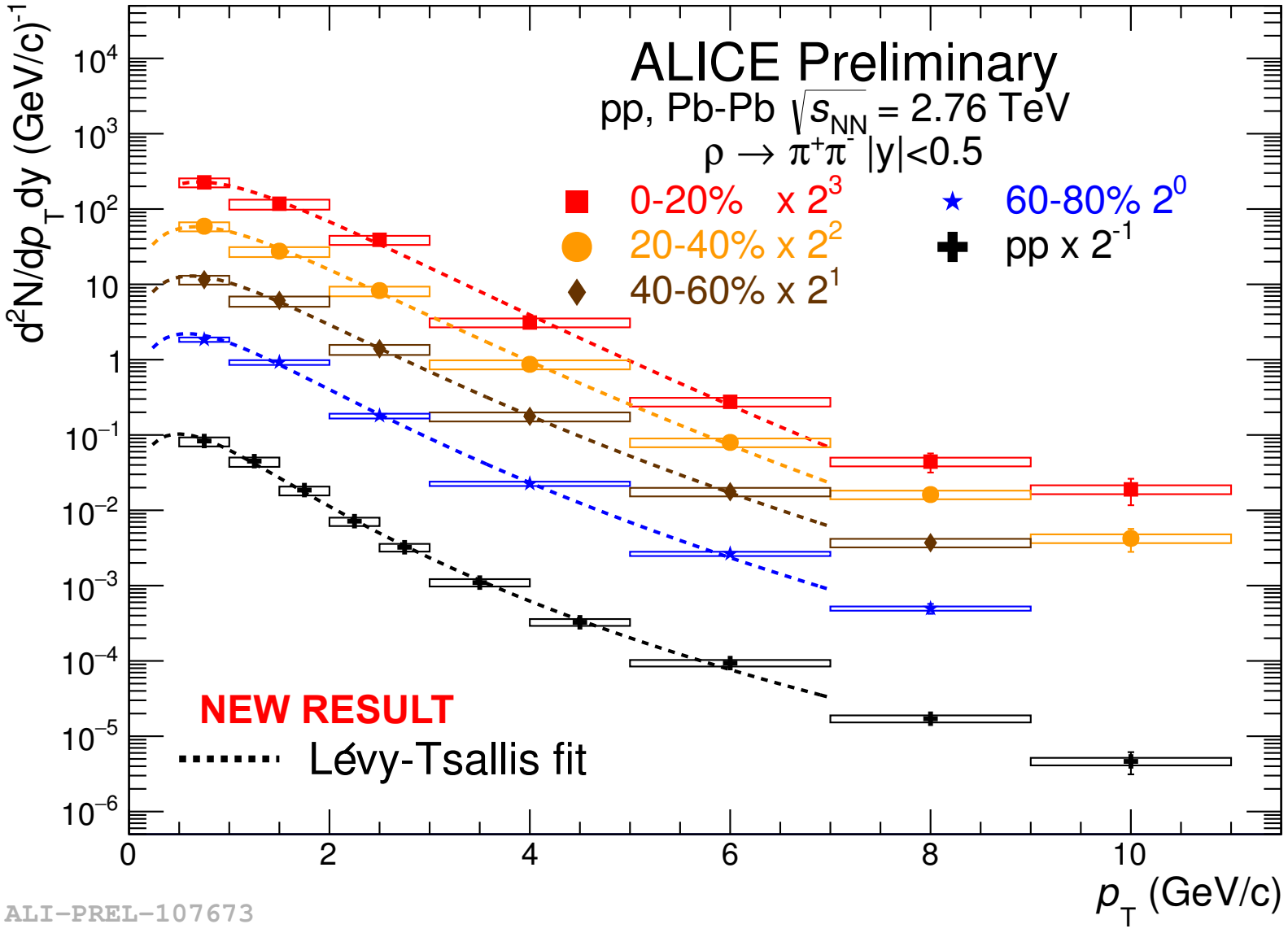
- Accounts for Bose-Einstein correlations between pions produced in ρ decays and other identical pions nearby in phase space

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

- 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)

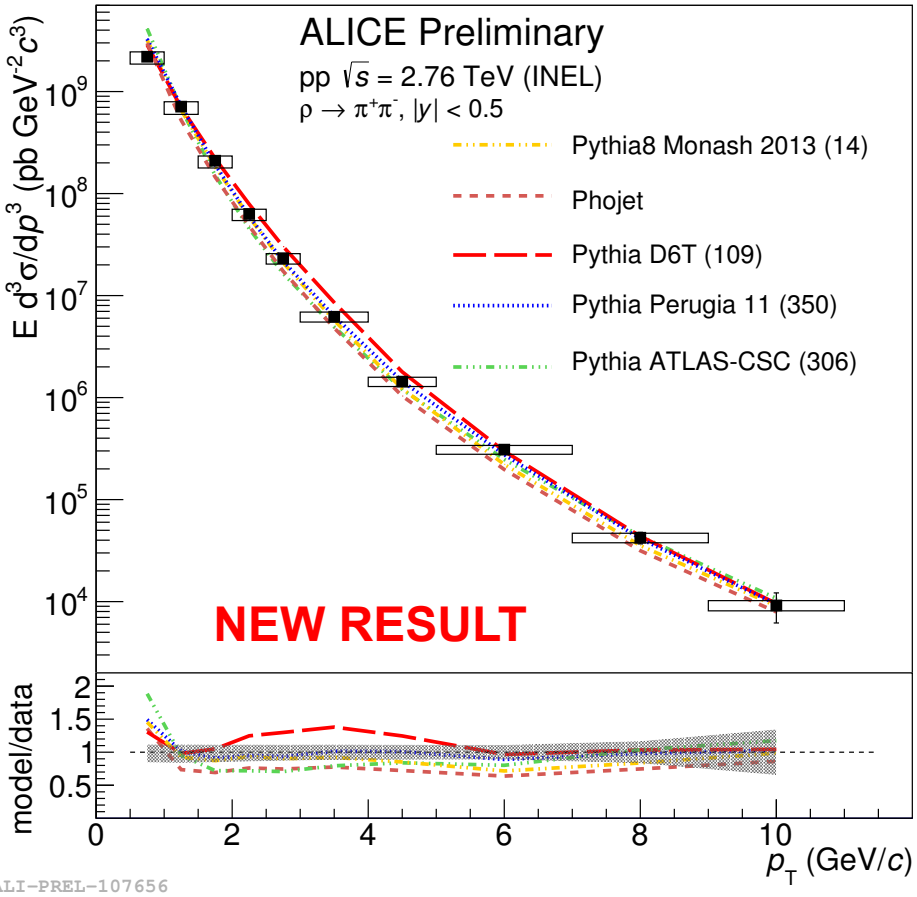


ρ^0 p_T Spectra



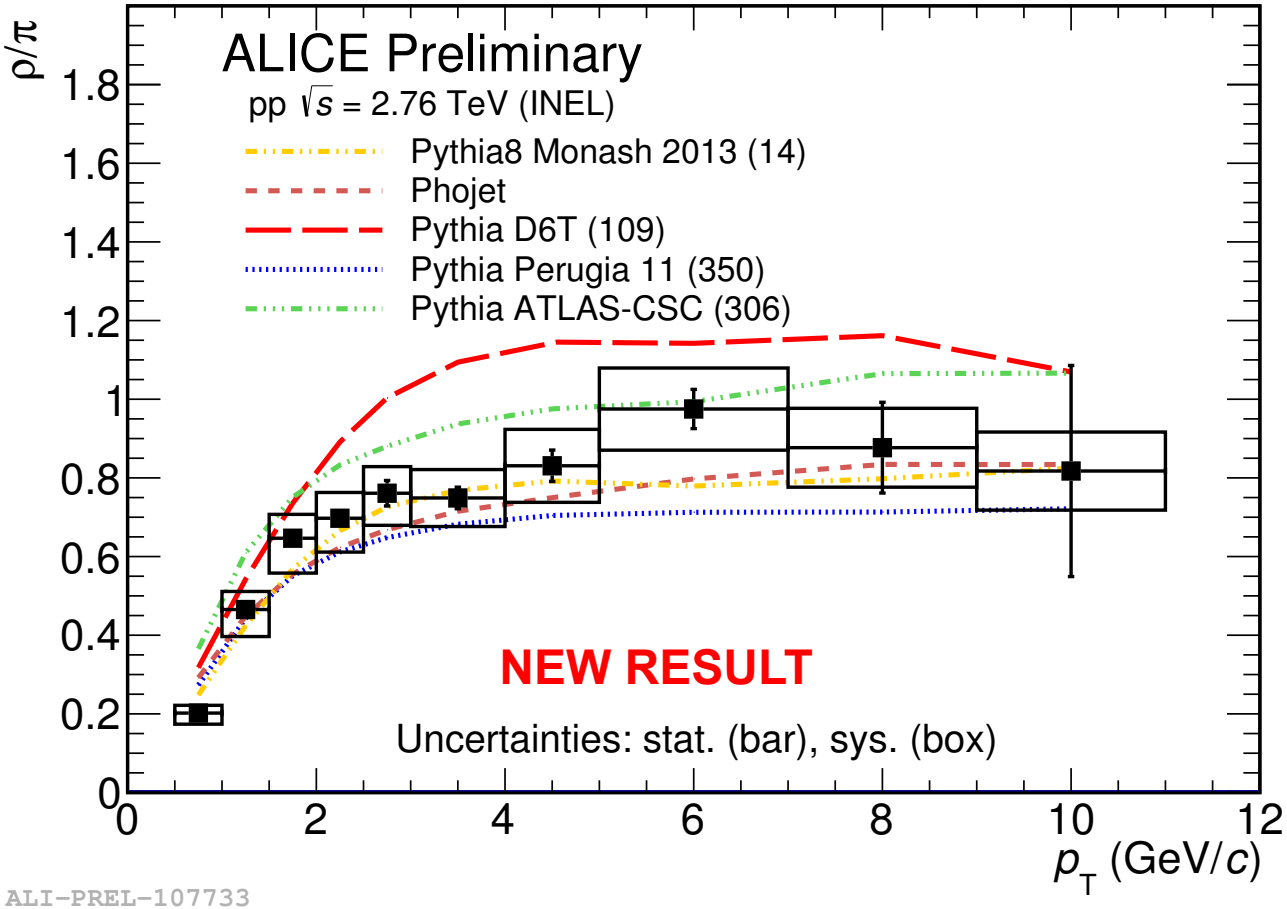
ρ^0 in pp: Model Comparisons

- 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)

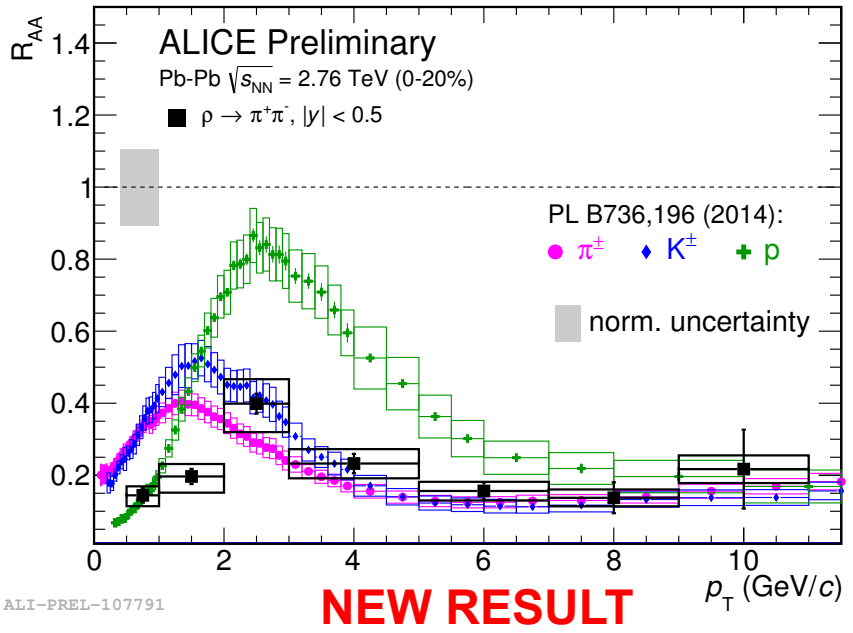
- Measured ρ^0/π ratio in pp collisions at 2.76 TeV compared to models:
  - PYTHIA D6T and ATLAS-CSC over-predict
  - PHOJET and PYTHIA Perugia 11 under-predict
  - Best Description by PYTHIA Monash 2013



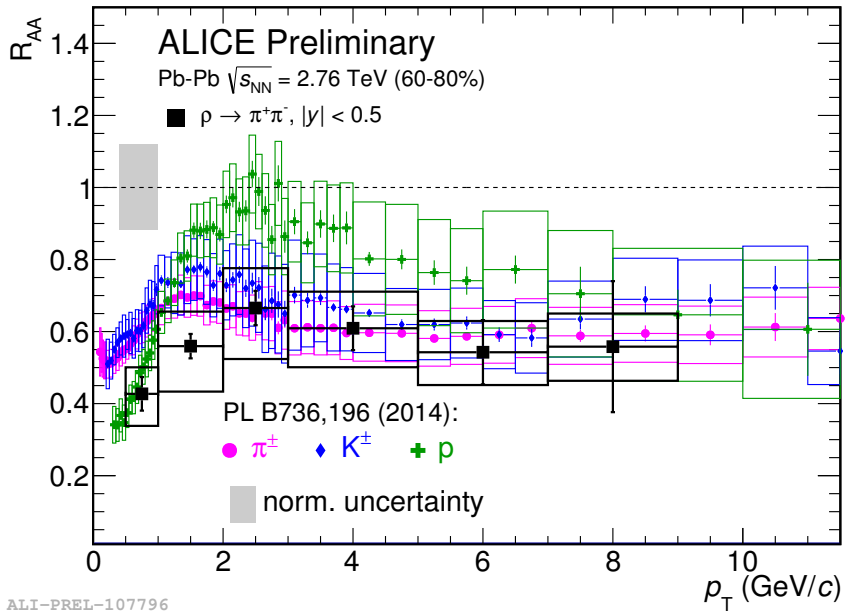
ρ^0 Nuclear Modification

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

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

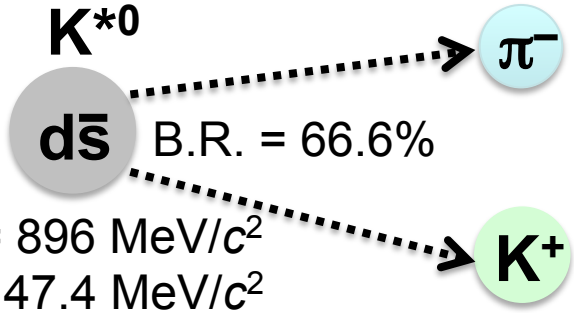


NEW RESULT

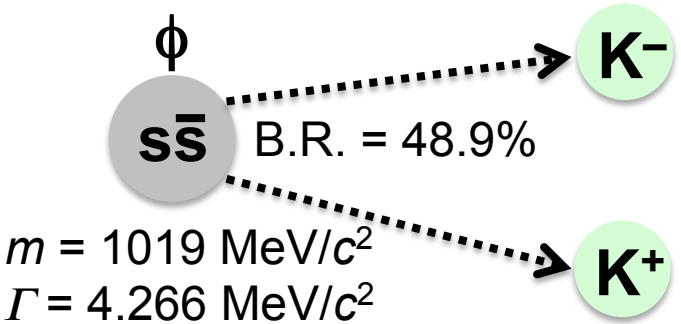


K^{*0} and ϕ Reconstruction

- 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



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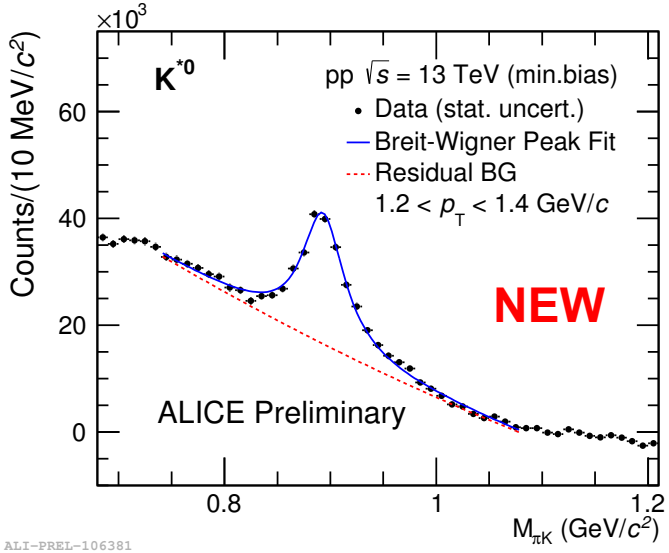
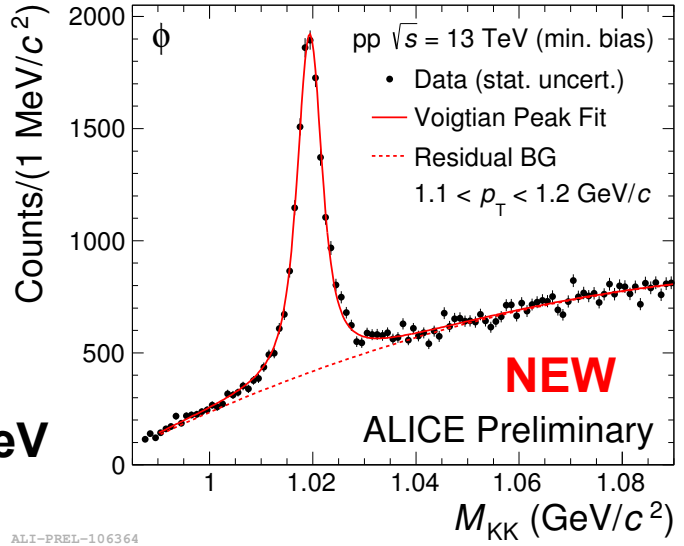


pp 13 TeV



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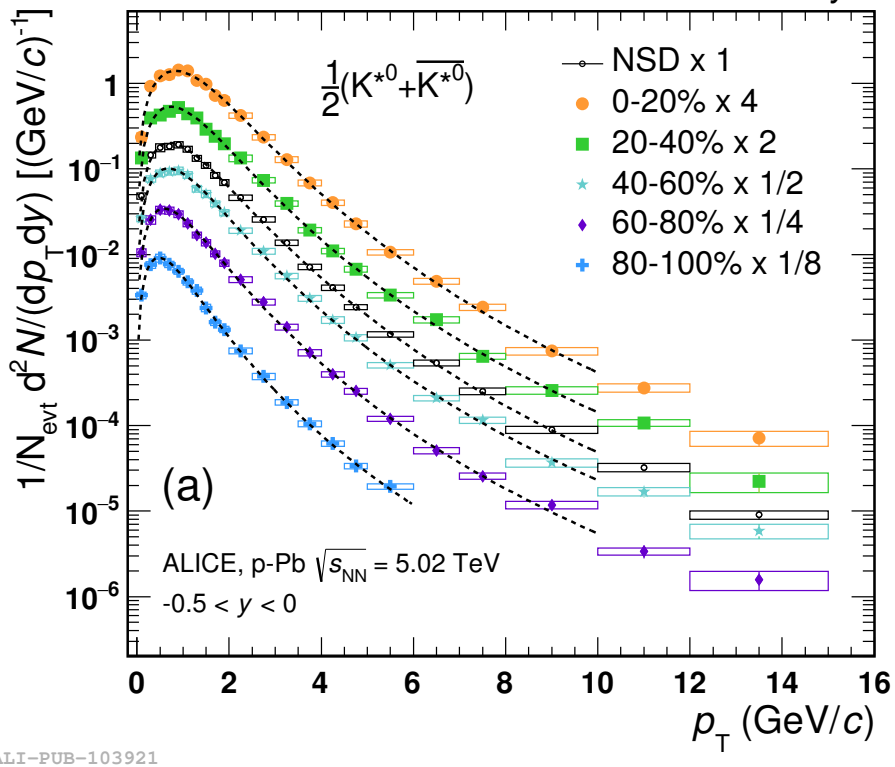

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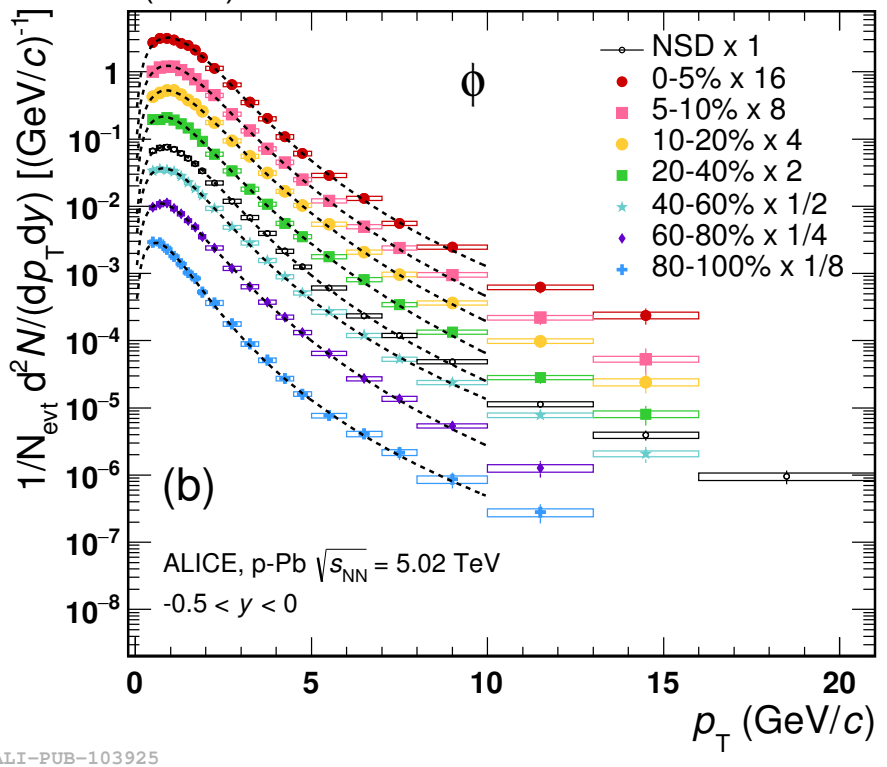
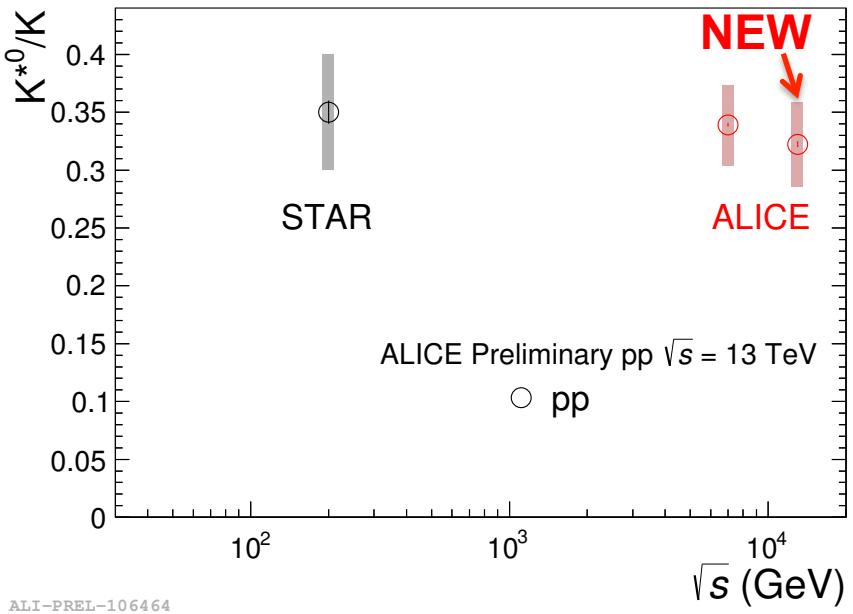


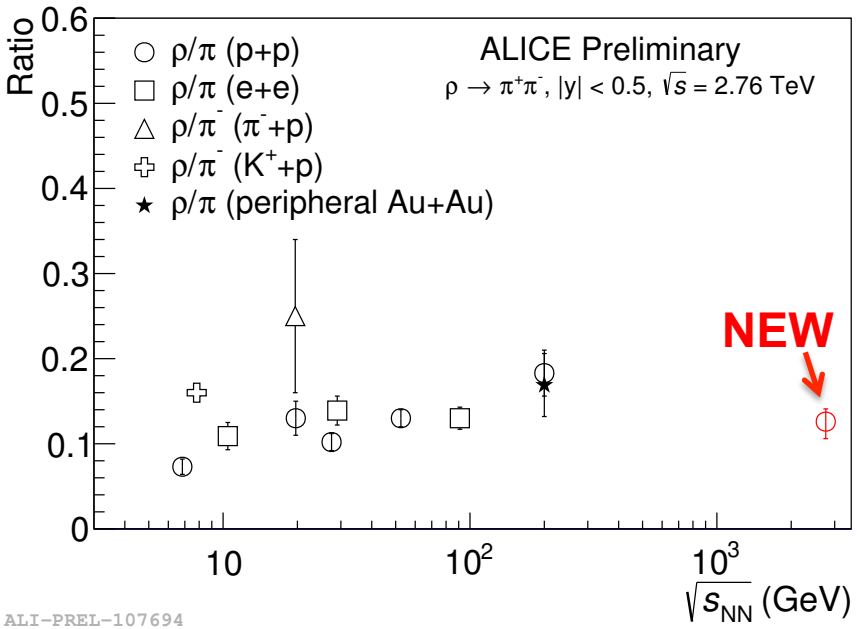
ALI-PUB-103925

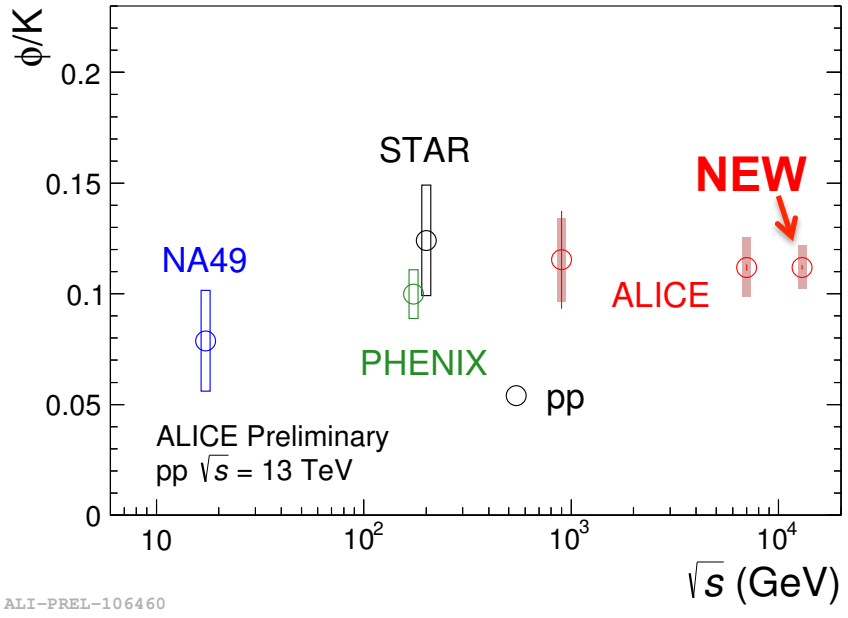
p–Pb 5.02 TeV

Ratios to Stable Hadrons (pp)

- 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

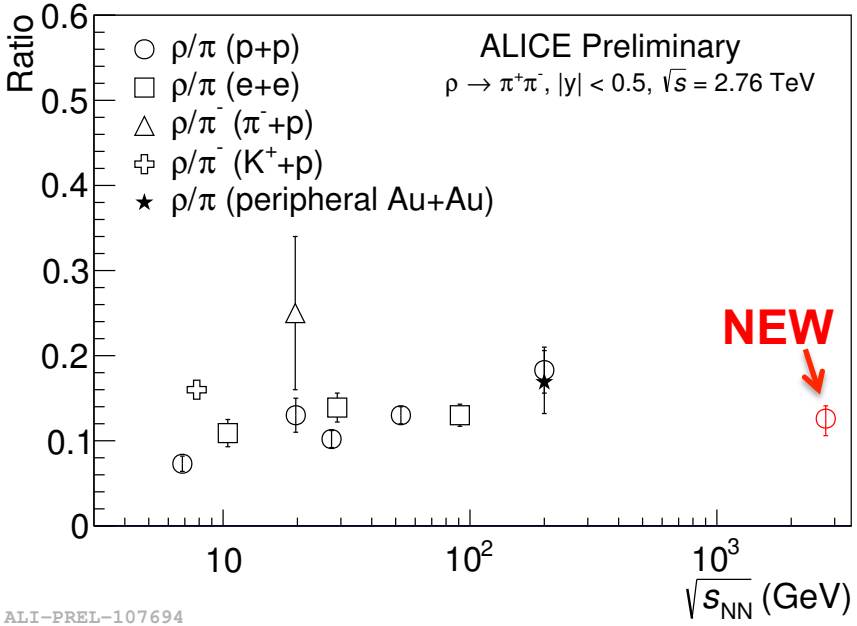


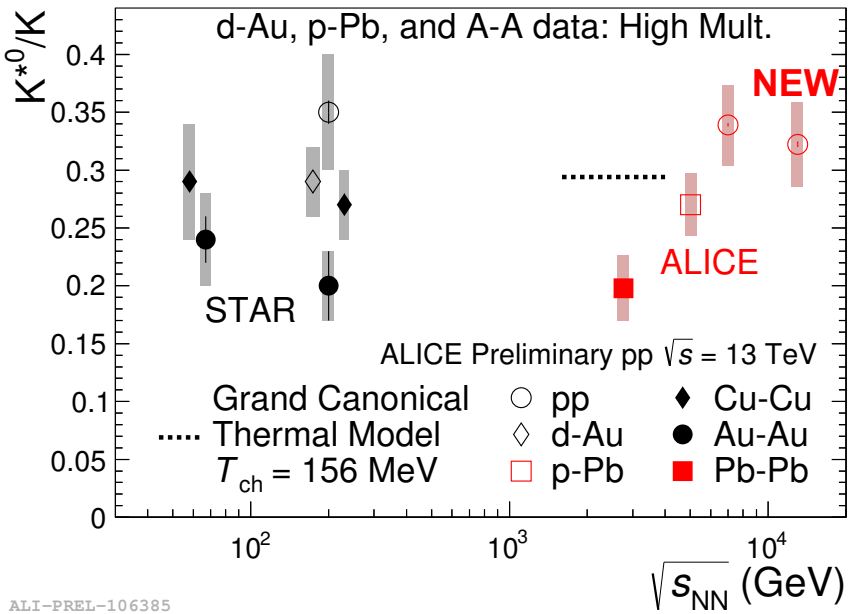


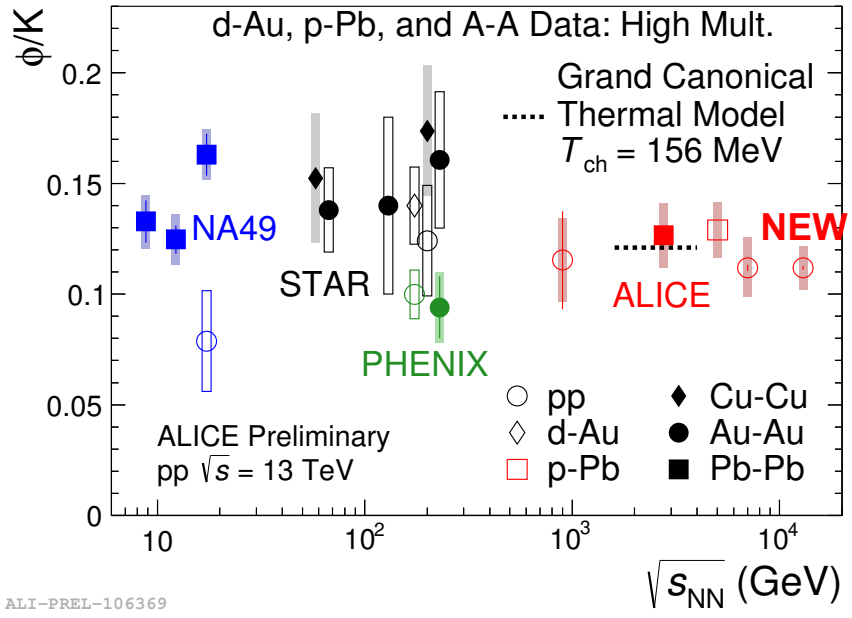


Ratios to Stable Hadrons

- 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…

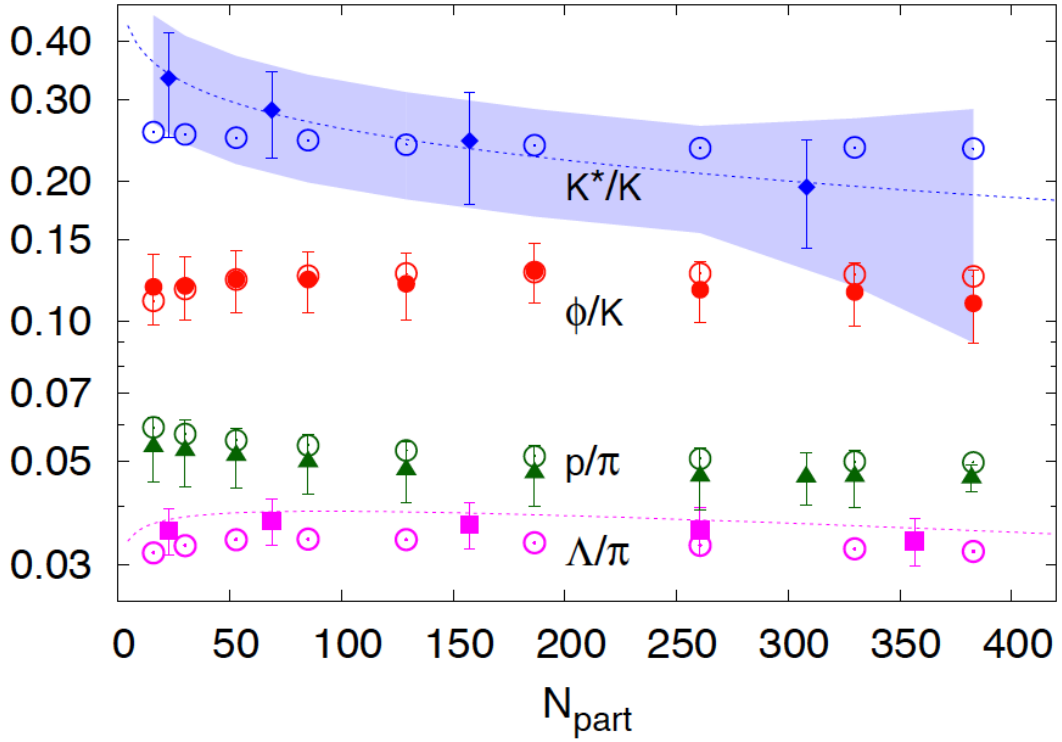






Non-equilibrium Model

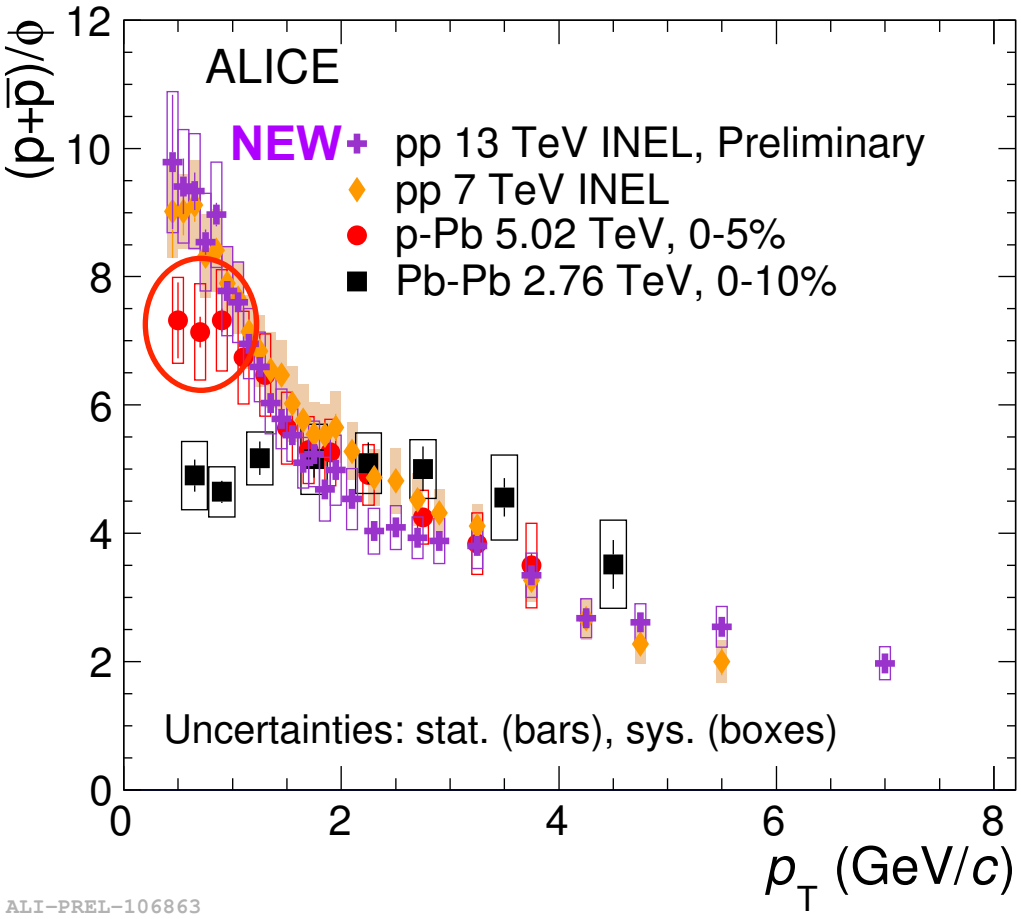
- Chemical non-equilibrium statistical hadronization model
  - *Phys. Rev. C* **88**, 034907 (2013)
- Factors $\gamma_q \neq 1$ and $\gamma_s \neq 1$ that modify u/d and s pair yields w.r.t. equilibrium values
  - $\gamma_q \neq 1$ when "source of hadrons disintegrates faster than the time necessary 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

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?



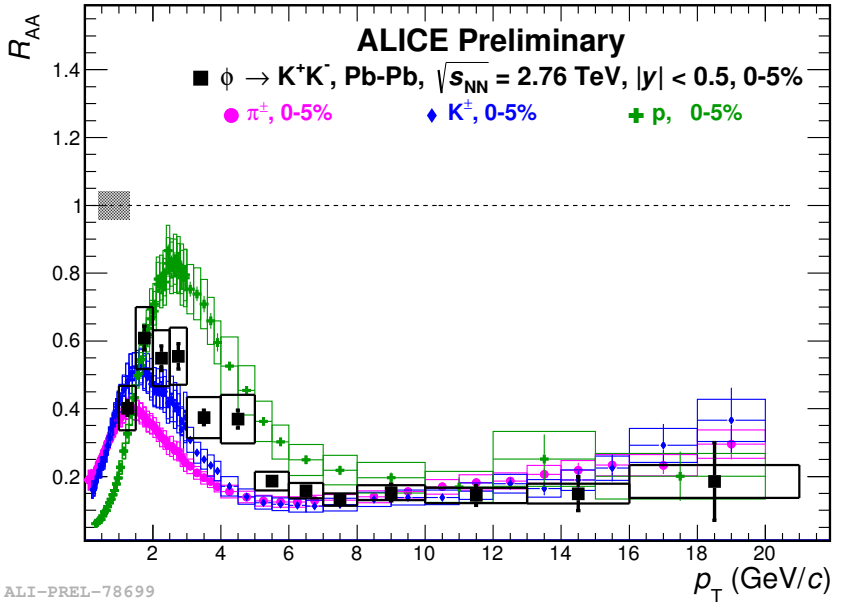
Phys. Rev. C **91** 024609 (2015)
Eur. Phys. J. C **76** 245 (2016)

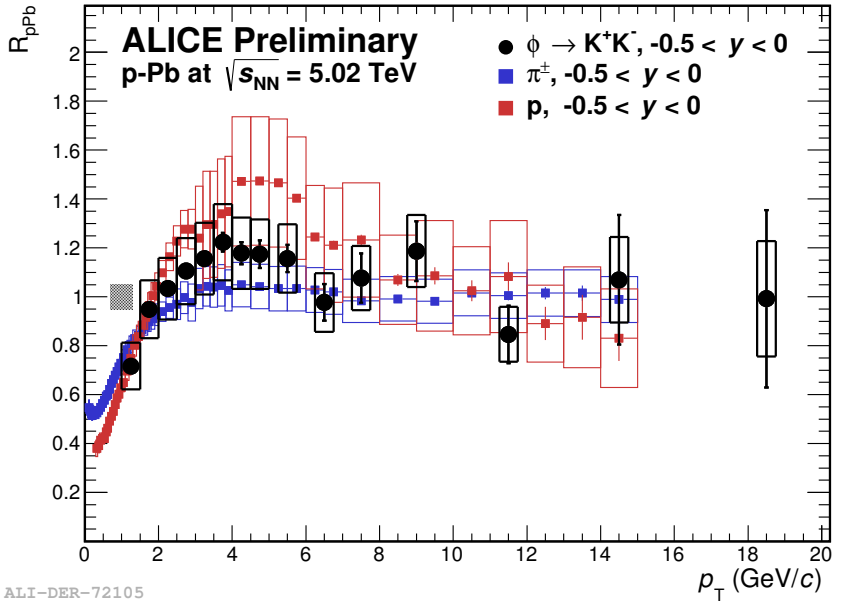
ϕ Nuclear Modification

- 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}

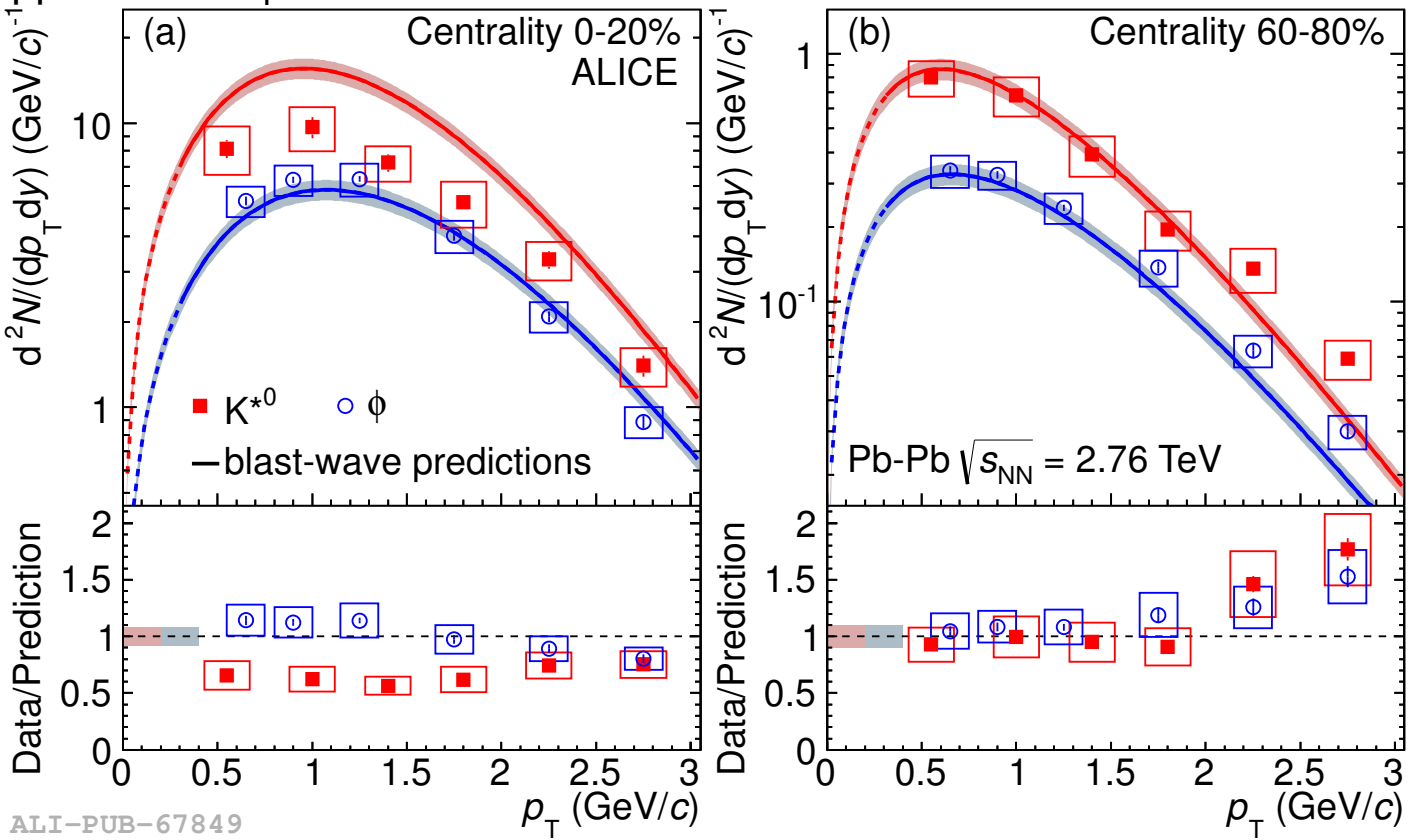




Resonance Suppression

- 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

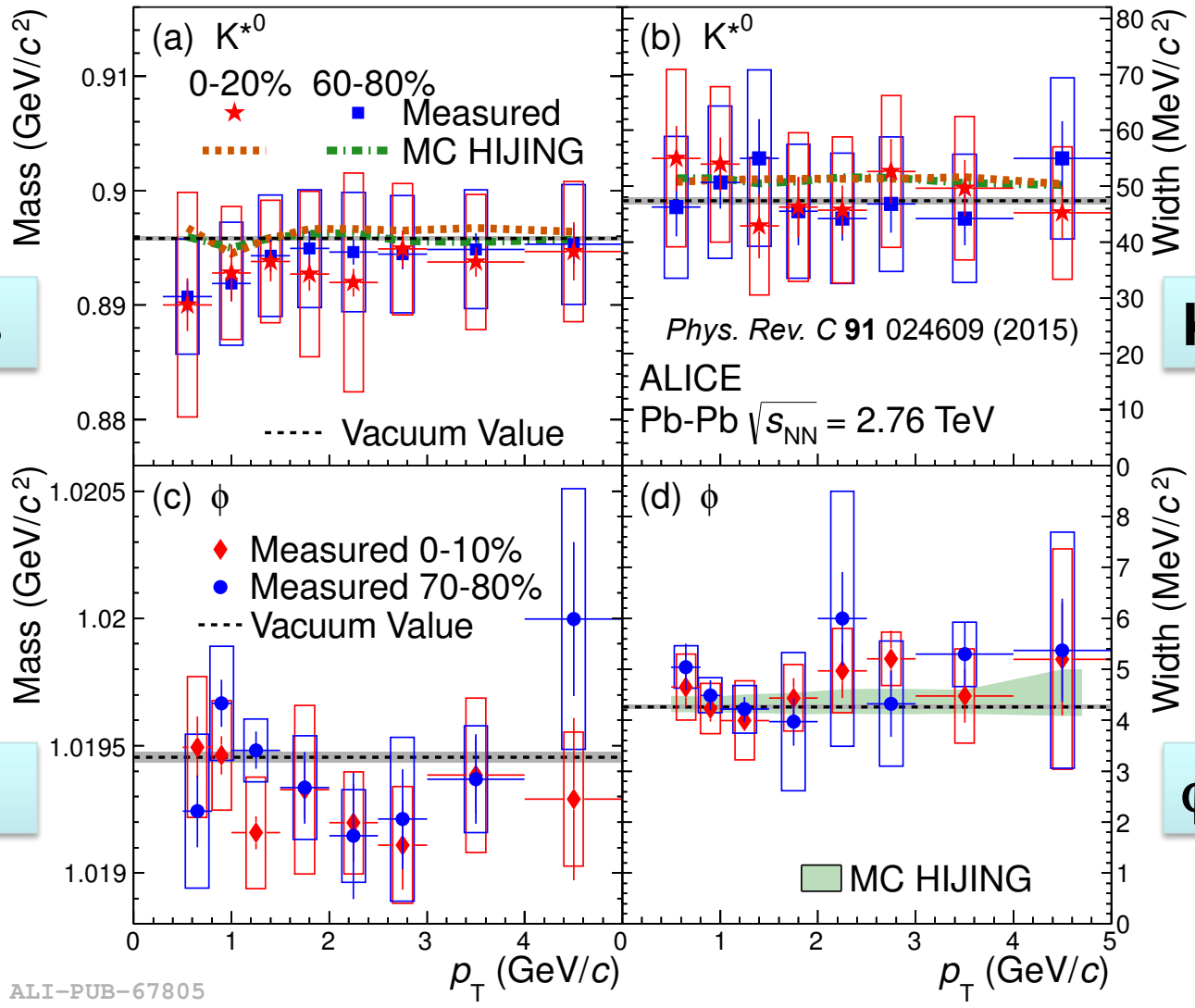
*PRC **88** 044910 (2013)



Mass and Width (Pb–Pb)

K*0 Mass

ϕ Mass



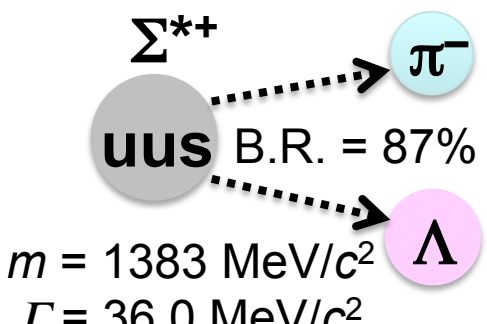
K*0 Width

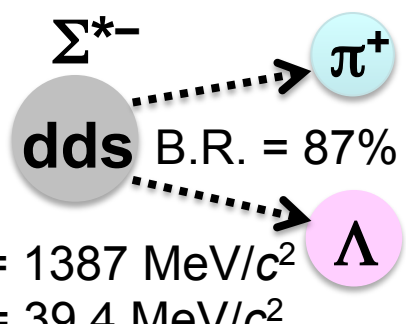
ϕ Width

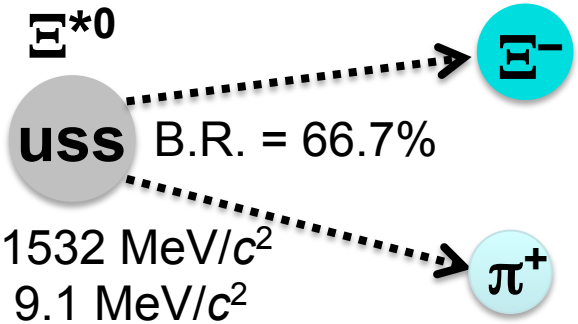
No significant mass or width shifts observed.
No centrality dependence of mass or width.

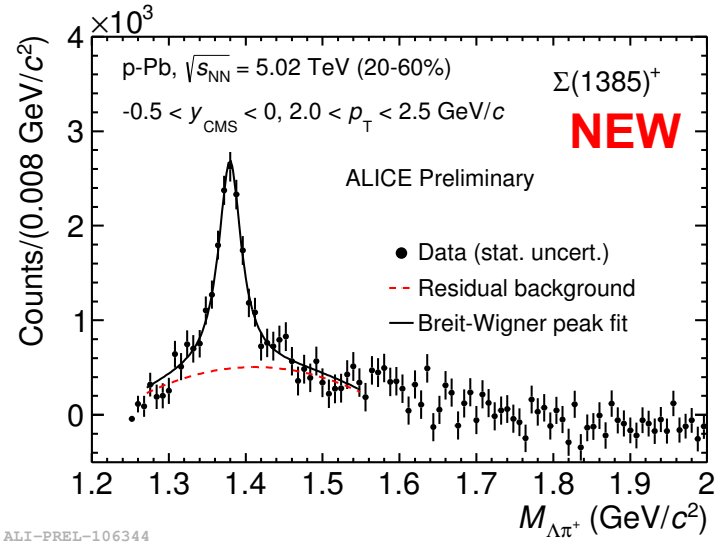
$\Sigma^{*\pm}$ and Ξ^{*0} Reconstruction

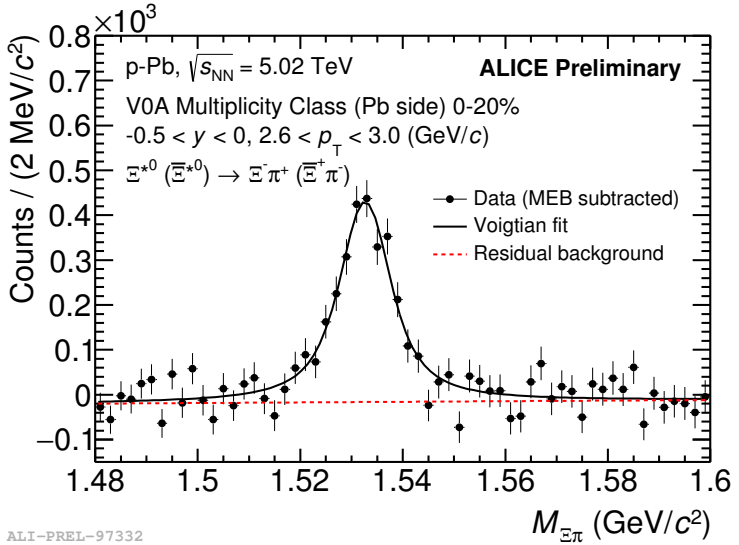
- Analyzed in pp collisions at 7 TeV & p–Pb collisions at 5.02 TeV (Pb–Pb collisions at 2.76 TeV in progress)
- Subtract mixed-event combinatorial background
- Polynomial residual background
- Peaks: Breit-Wigner ($\Sigma^{*\pm}$) or Voigtian (Ξ^{*0})







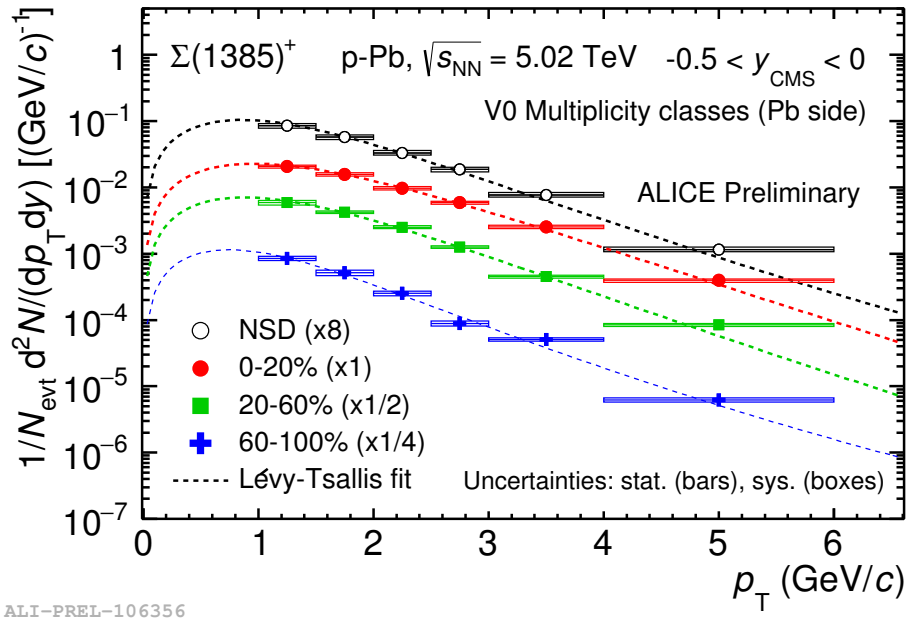




$\Sigma^{*\pm}$ and Ξ^{*0} Reconstruction

- 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})

NEW RESULT



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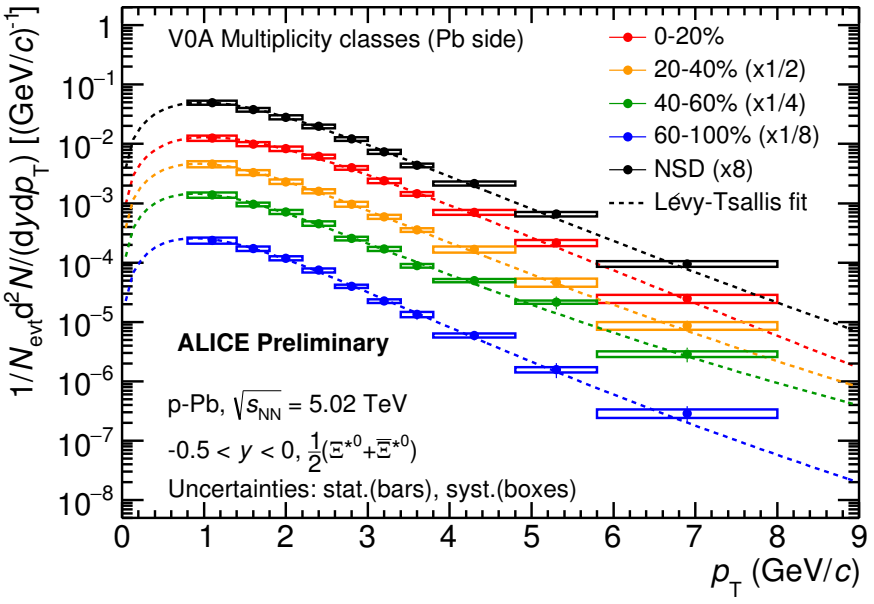

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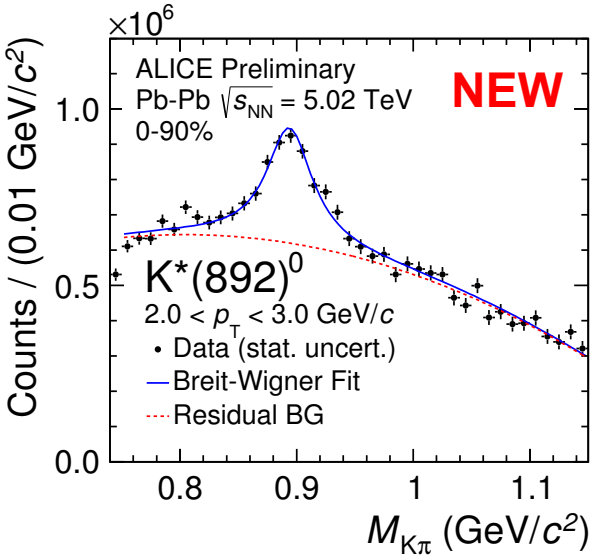
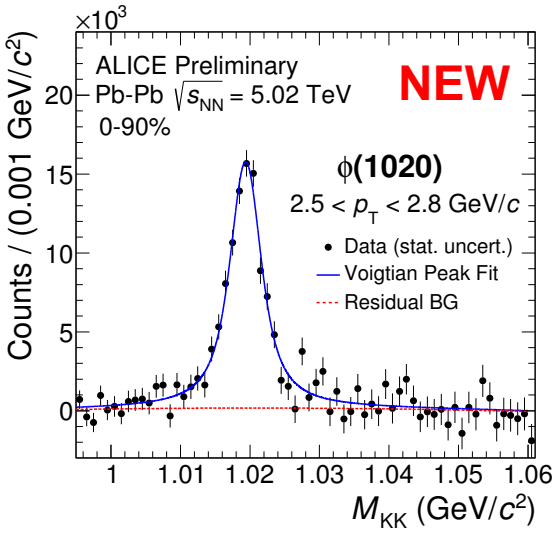
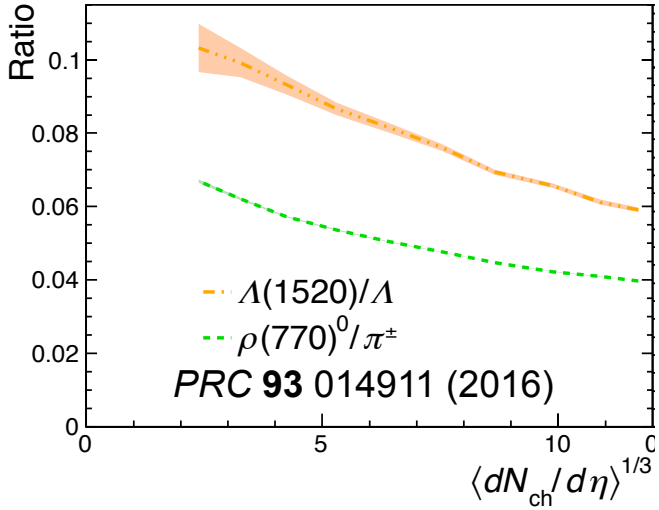
Outlook

- 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})







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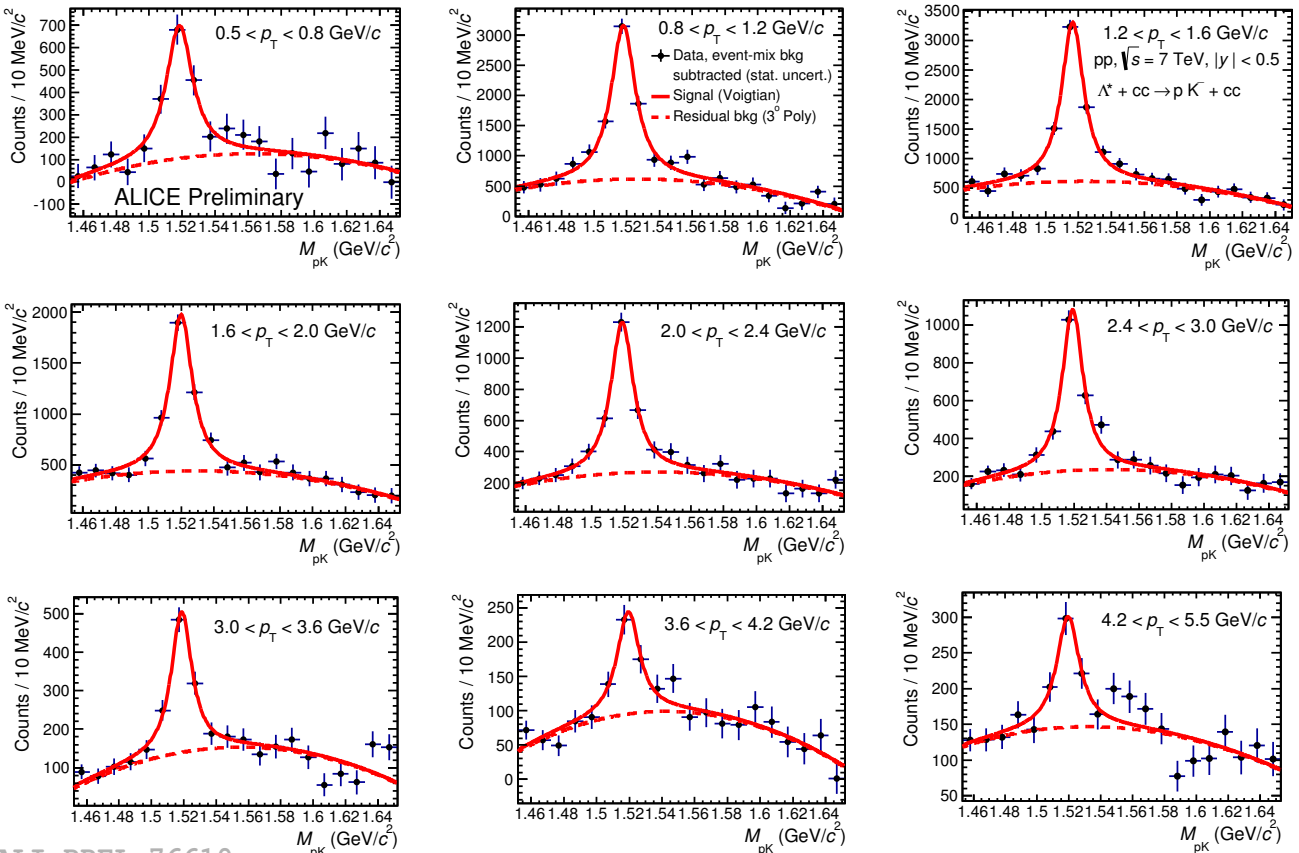
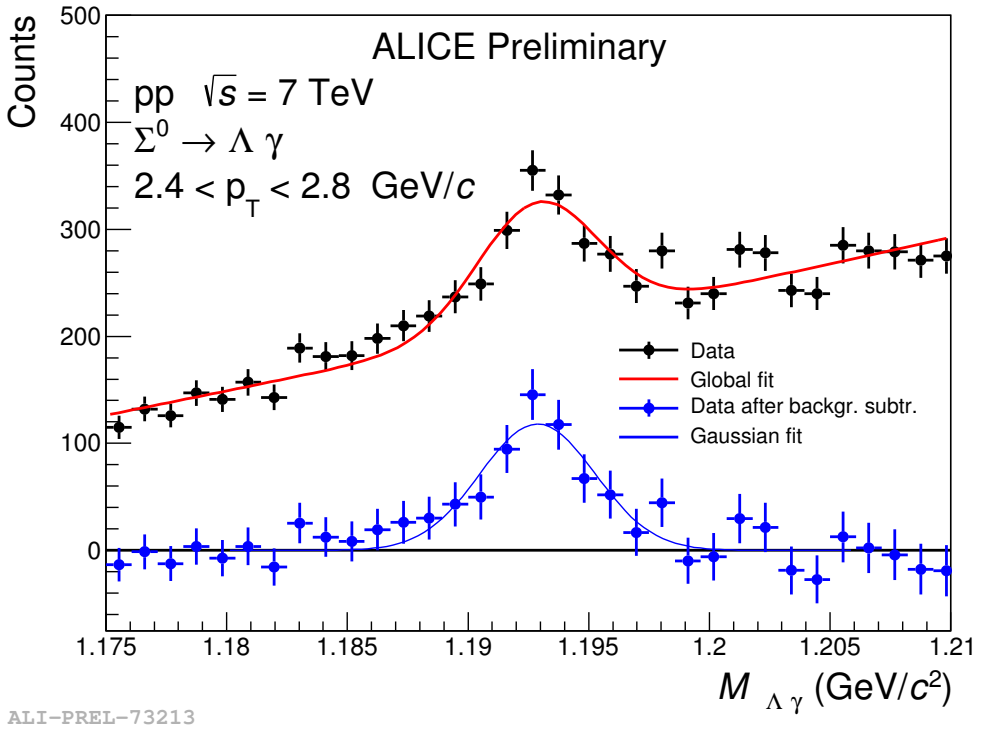
$\Lambda(1520)$

- 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