An Overview of Hadronic Resonance Measurements at ALICE

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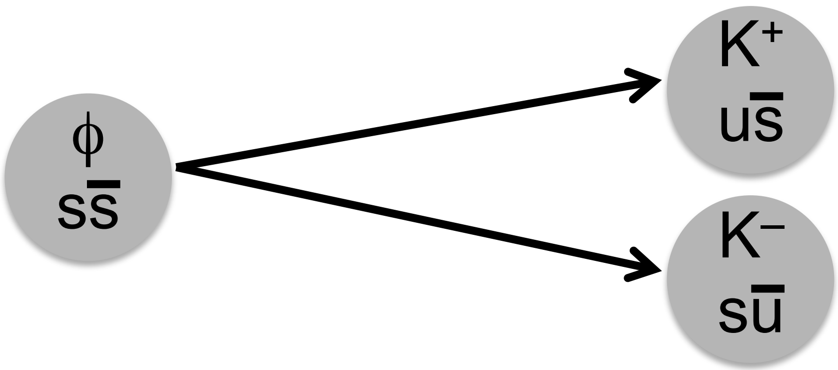
20 November 2014

Outline

- Resonances in ALICE:
  - What resonances do we study?
  - Why do we study resonances?
  - How do we study them?
  - Important recent results

Resonances

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



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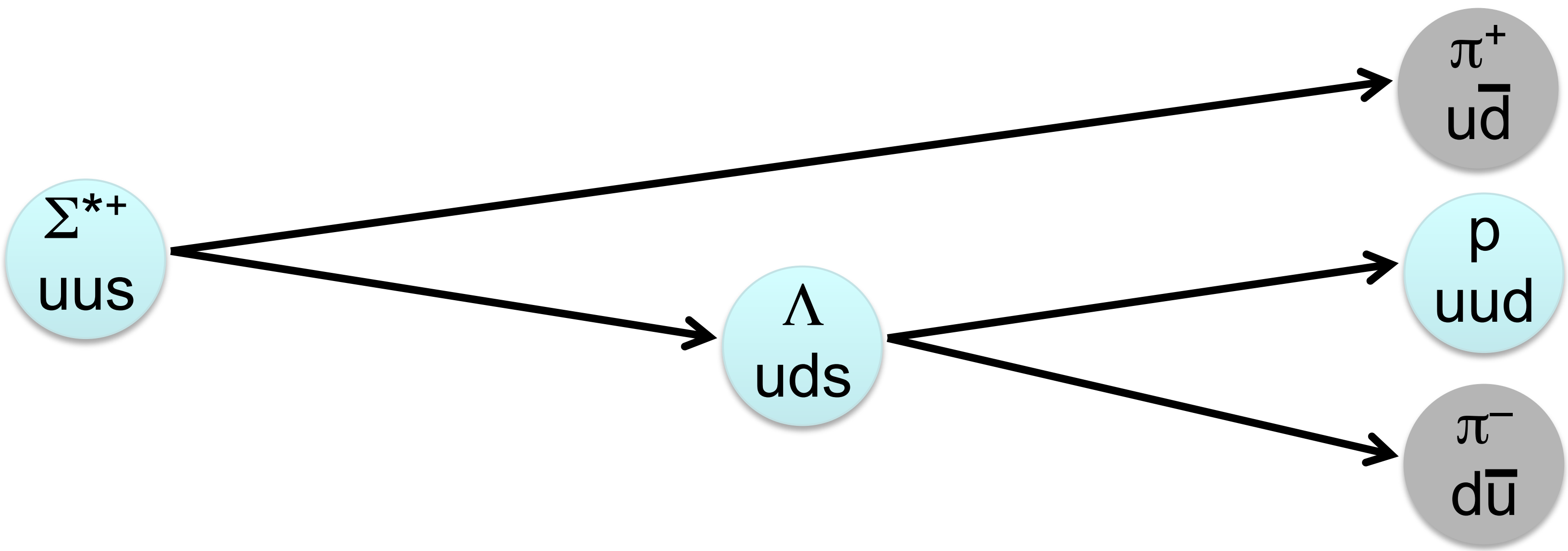


ALICE Resonance Program

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

- K^{*0}: $d\bar{s}$
- ϕ: $s\bar{s}$

Results for pp, initial studies for p–Pb

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

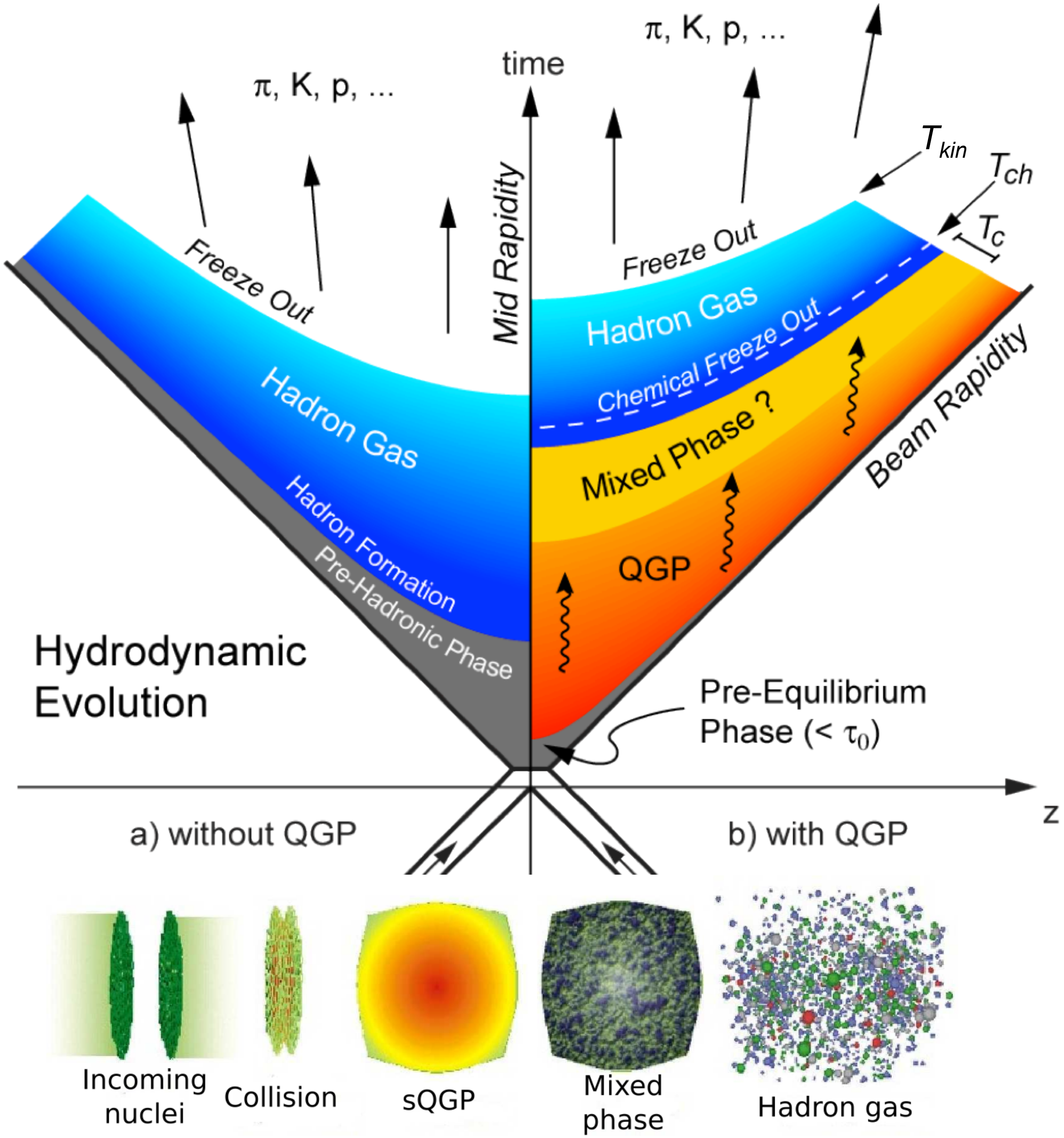
Initial studies (but I can only show you peaks)

- Σ^{0}: uds
- $\Lambda(1520)$: uds

Other Studies:

- ρ^{0}: $\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$
- Δ^{++}: uuu

Heavy-Ion Collisions



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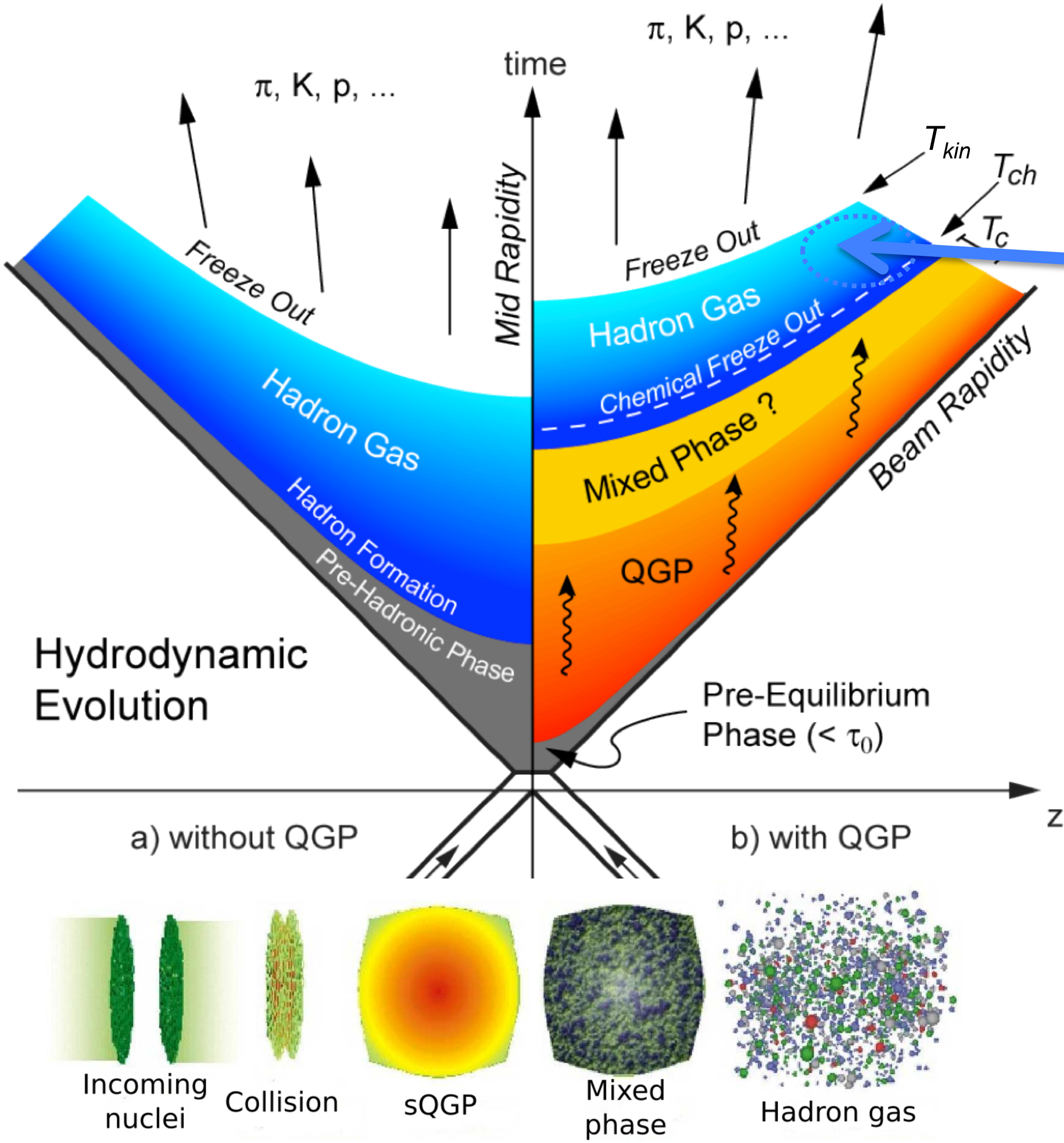
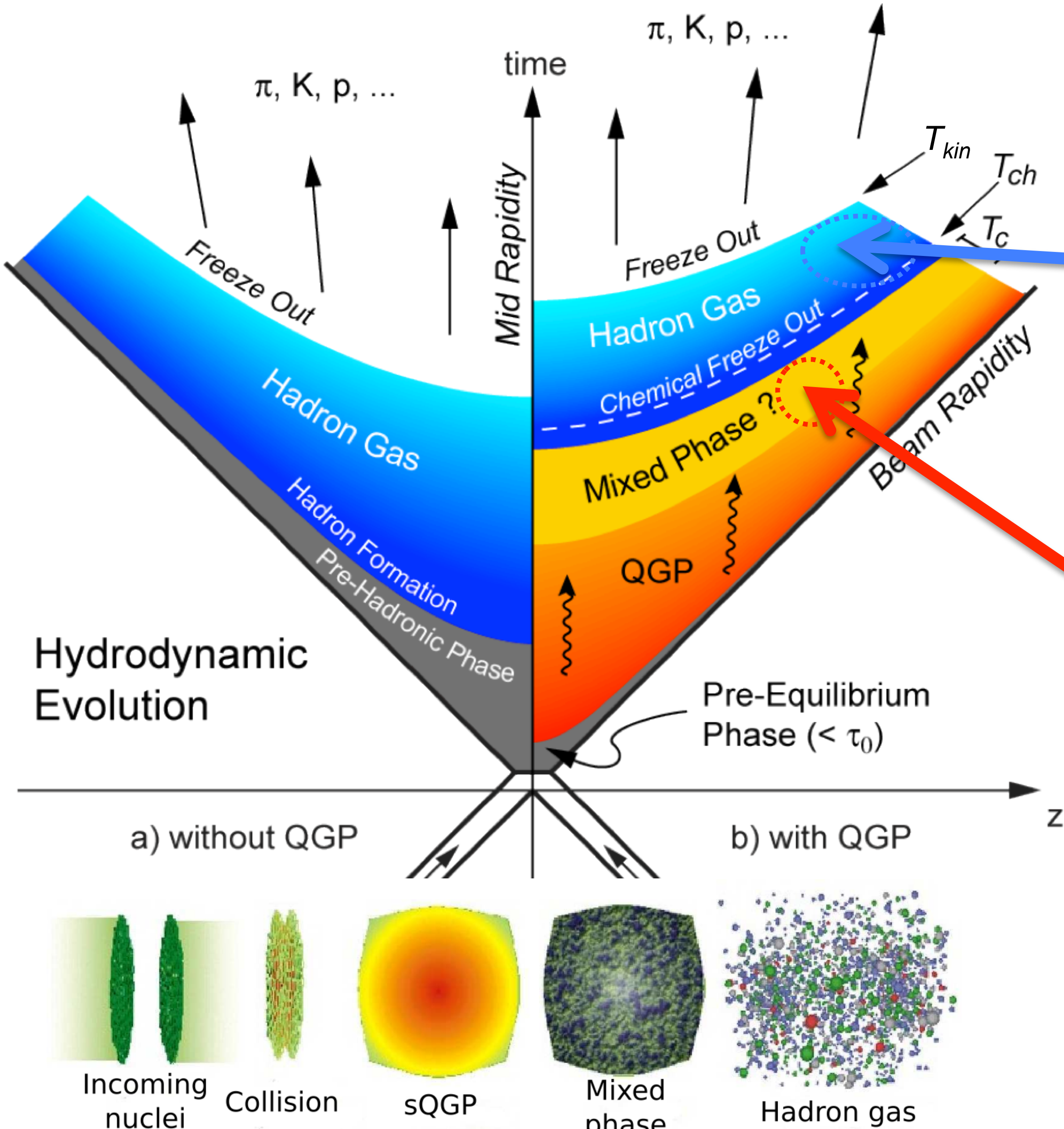


Properties of Hadronic Phase

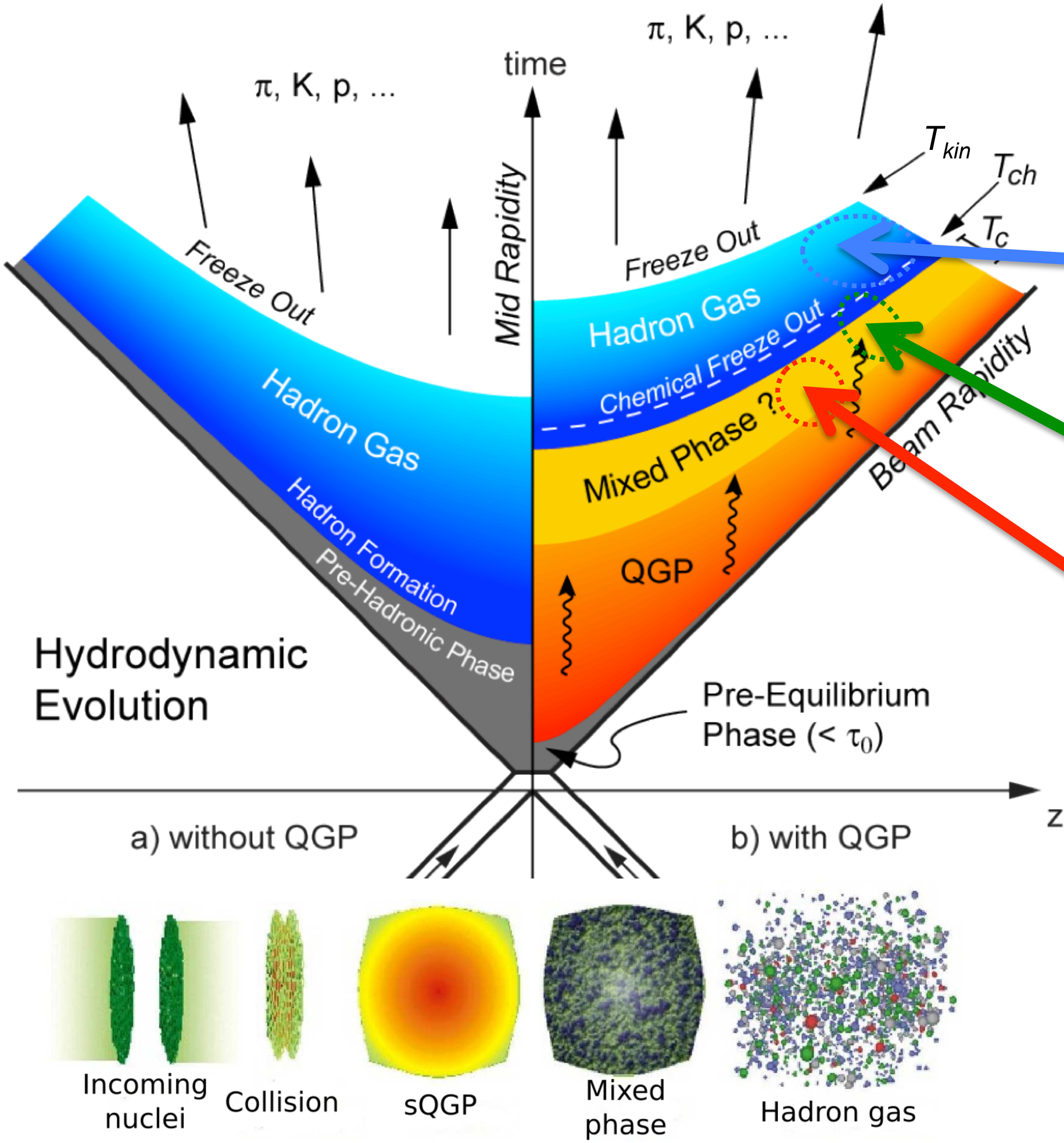
Heavy-Ion Collisions



Properties of Hadronic Phase

Chiral Symmetry Restoration

Heavy-Ion Collisions

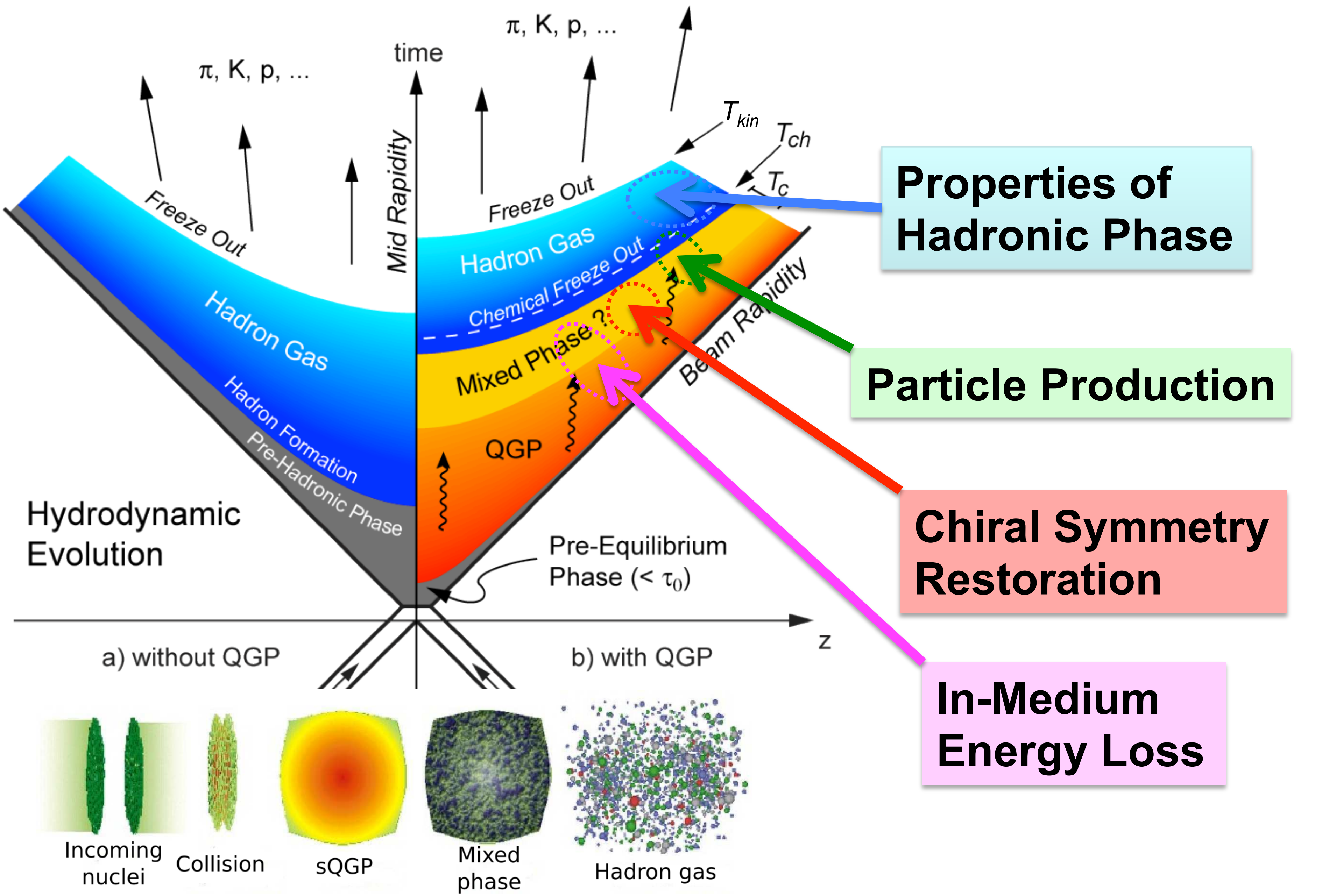


Properties of Hadronic Phase

Particle Production

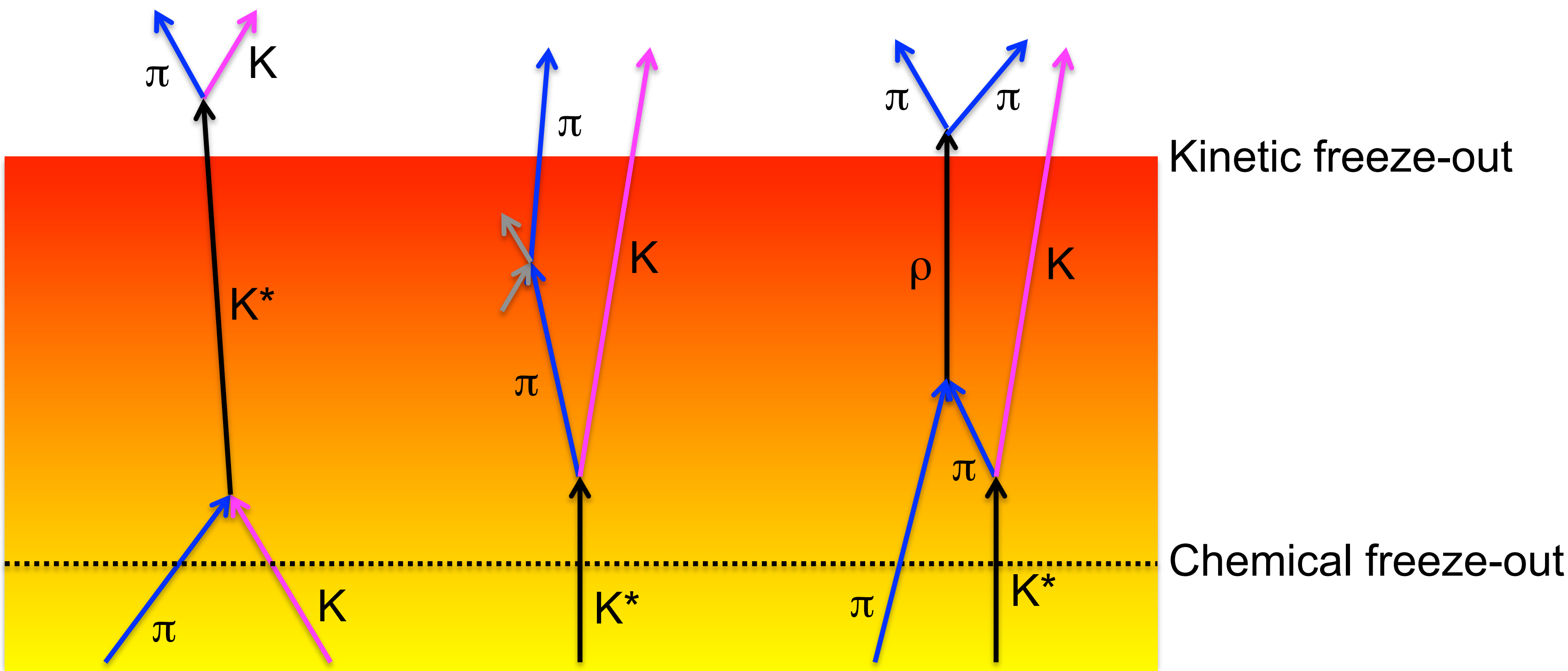
Chiral Symmetry Restoration

Heavy-Ion Collisions



Hadronic Phase

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



Hadronic Phase

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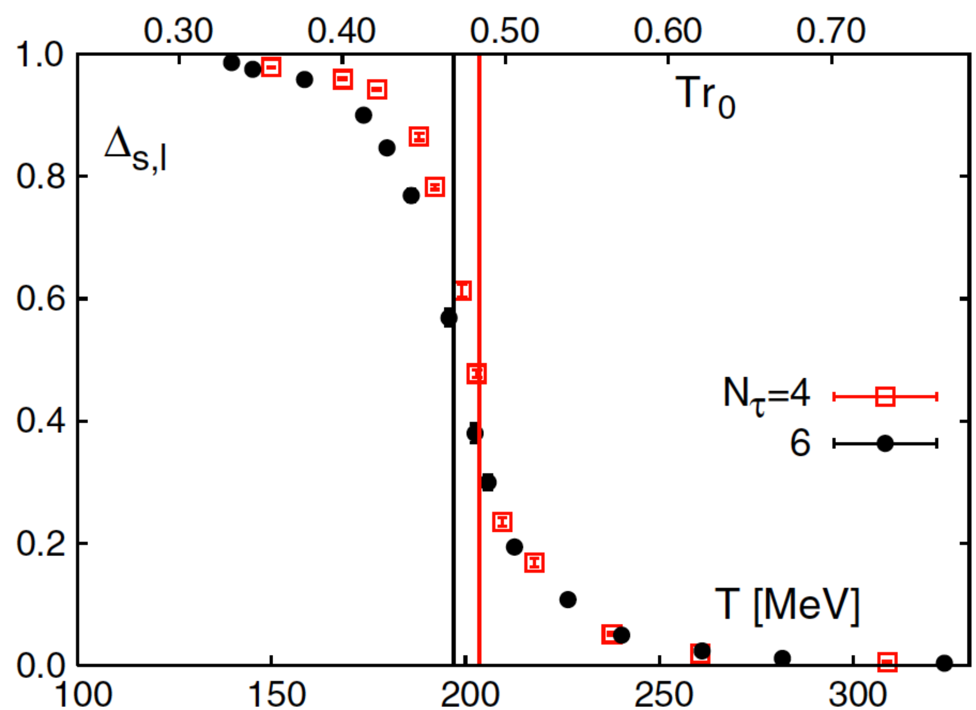
  - **Re-scattering:**
    - Resonance decay products undergo elastic scattering
    - Or pseudo-elastic scattering through a different resonance (e.g. ρ)
    - Resonance not reconstructed through invariant mass
- Final yields at kinetic freeze-out depend on
  - Chemical freeze-out temperature (T_{ch})
  - Time between chemical and kinetic freeze-out (Δt)
  - Resonance lifetime
  - Scattering cross sections
- Can use measured resonance yields to study these properties
- Re-scattering and regeneration expected to be most important for $p_T < 2$ GeV/c (UrQMD)

Chiral Symmetry Restoration

Chiral Symmetry ⇔ $\boldsymbol{m_q \rightarrow 0}$

- Quark condensate <0|q̄q|0> fills QCD vacuum
- Effective q masses related to value of condensate: $m_q^* \propto$ <0|q̄q|0>
- Lattice calculations indicate decrease in condensate around chiral phase transition temperature
  - Tends to be near deconfinement phase transition

$\Delta_{s,l}$ = normalized difference of light and strange quark chiral condensates



M. Cheng *et al.*, *Phys. Rev. D* **77** 014511 (2008)

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- Effective q masses related to value of condensate: $m_q^* \propto \langle 0|\bar{q}q|0\rangle$
- Lattice calculations indicate decrease in condensate around chiral phase transition temperature
  - Tends to be near deconfinement phase transition
- Particles that decay when chiral symmetry was at least partially restored expected to have mass shifts and/or width broadening
  - Need particles that decay early (*i.e.*, resonances) AND have decay products that pass through the hadronic phase without scattering

Particle Production

- ϕ meson has long enough lifetime that we may be able to treat it as a stable particle
  - No major modifications to spectrum or yields due to re-scattering or regeneration
- Compare ϕ to models (VISH, HKM, Kraków, …)

Hydrodynamics:
– Particle masses determine shapes of spectra

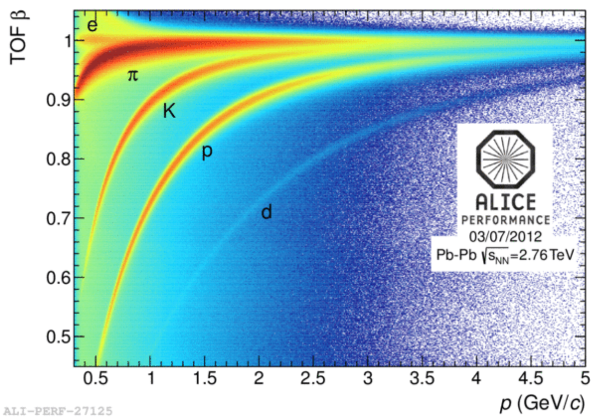
Quark Recombination:
– Number of quarks influences shapes of spectra
– Differences between baryons and mesons with similar masses

- Strangeness content
  - Strangeness enhancement
  - Is ϕ (hidden strangeness) enhanced similarly to Ξ (S=2)?

Resonances in pp and p–Pb

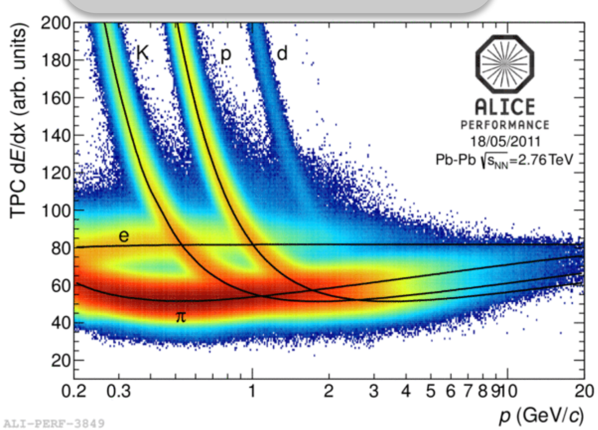
- Resonances in pp:
  - Baseline measurement to which heavy-ion measurements are compared:
    - Masses and widths
    - Yields and ratios to stable particles
    - Nuclear Modification Factor (R_{AA})
    - Comparison to peripheral Pb–Pb
    - Multiplicity-dependent measurements
  - Constrain QCD-inspired models
    - Particle spectra/ratios used to tune PYTHIA
- Resonances in p–Pb
  - Baseline measurement to control for cold nuclear matter effects

ALICE Detector



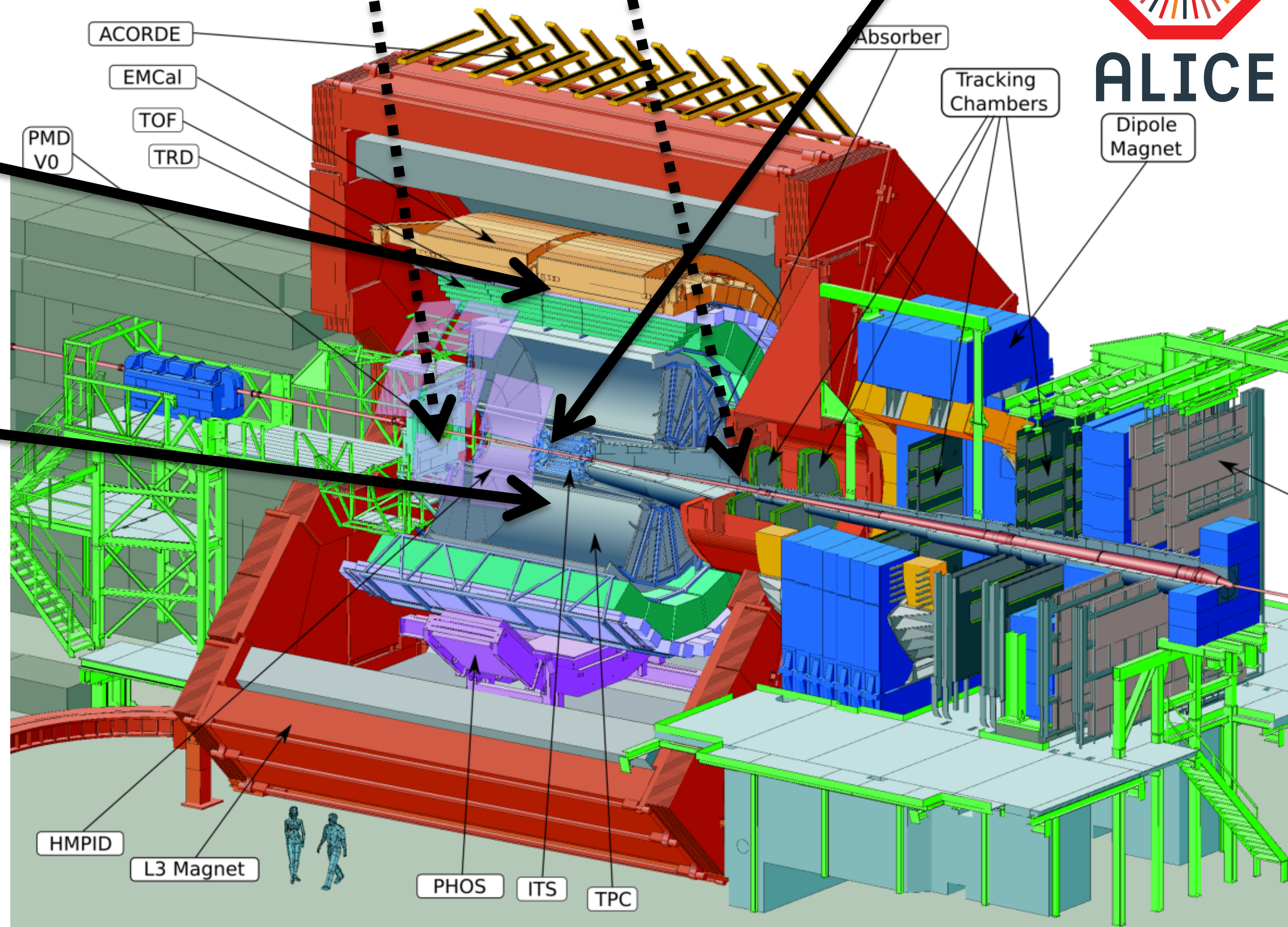
TOF: PID through particle velocity

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



VZERO (scintillators): multiplicity, centrality

ITS (silicon): Tracking and Vertexing



Finding Resonances

Find decay products

Find $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$:

-Track cuts:

 # TPC Clusters

track χ^2

DCA to primary vertex

others…

-Particle Identification

TPC energy loss ($n\sigma$)

Time of Flight ($n\sigma$)

Find intermediate decay products (*e.g.*, Λ):

-Cuts on decay topology

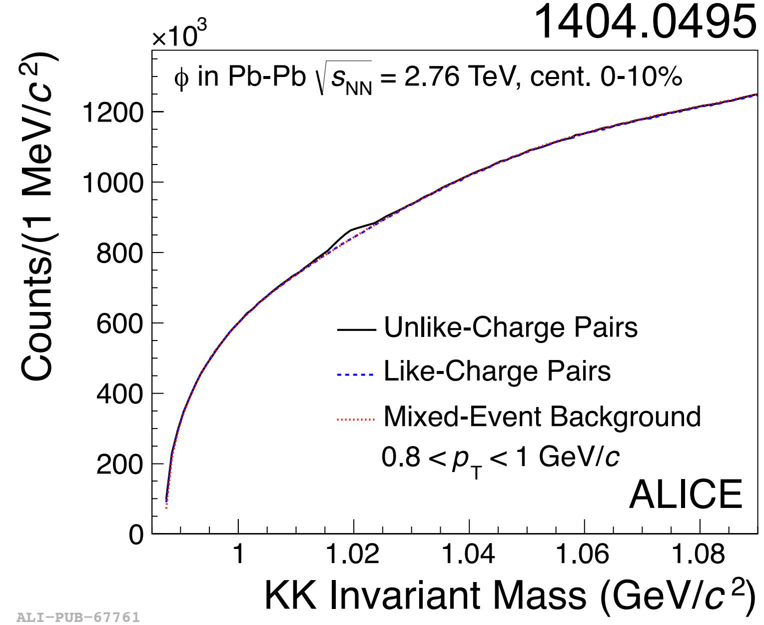
-Invariant mass

Finding Resonances

Find decay products

Construct invariant mass distributions

1404.0495

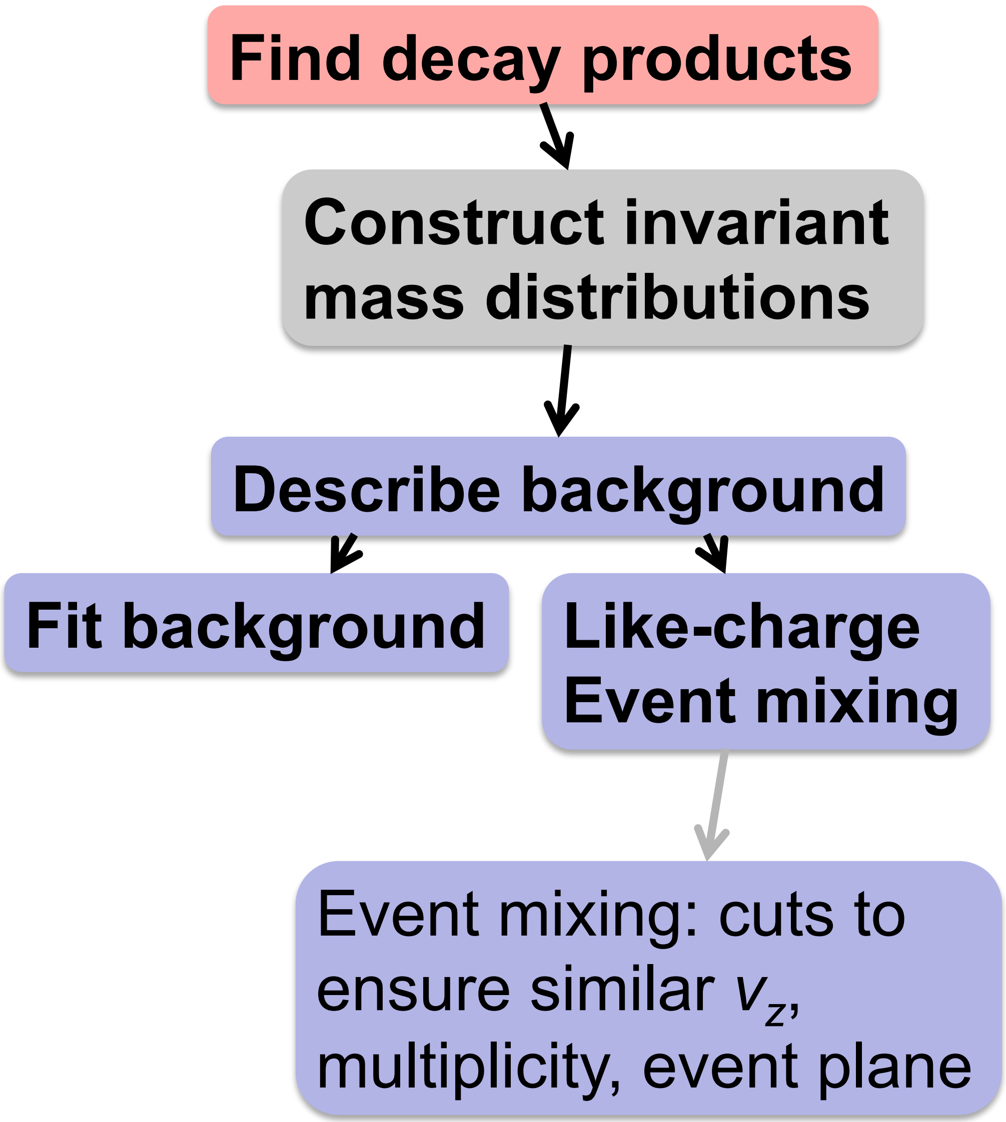


Example: Pb+Pb → Xϕ → K⁻K⁺

Compute invariant mass of decay-product pairs

$$M = \sqrt{m_1^2 + m_2^2 + 2E_1E_2 - 2p_1p_2\cos\alpha}$$

Finding Resonances



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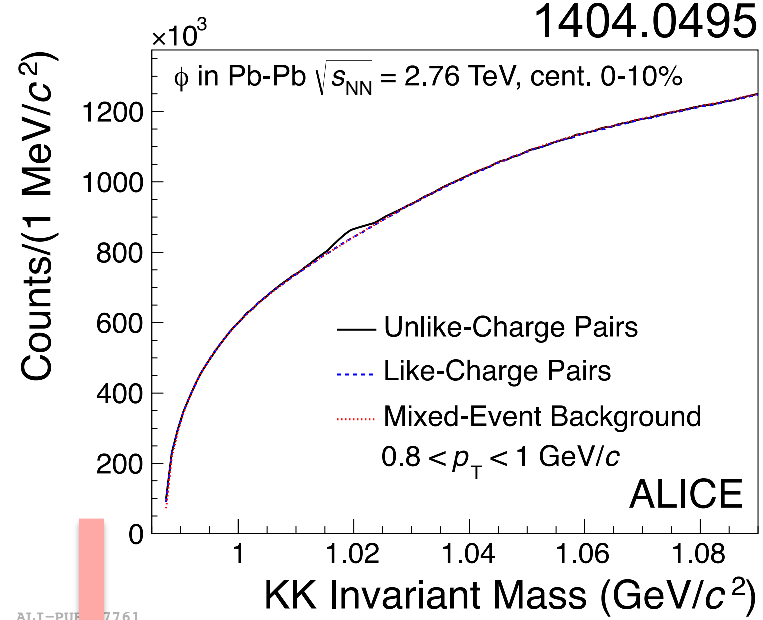
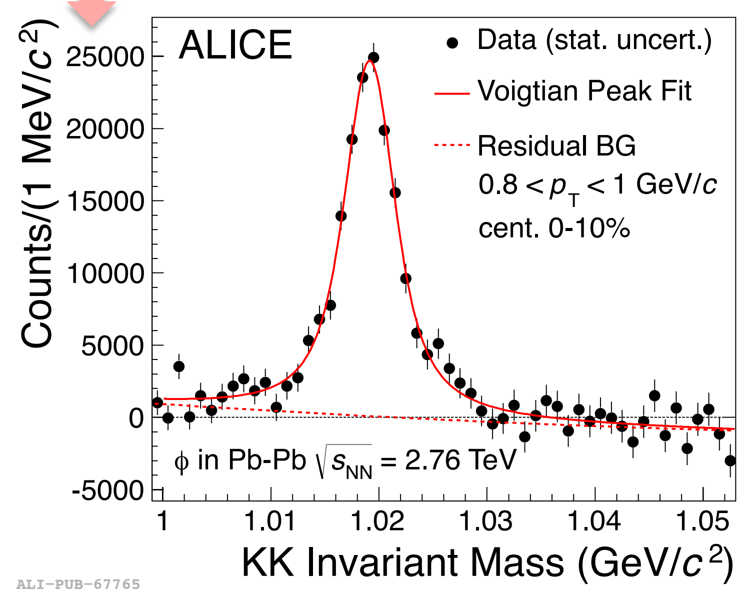


Background Subtraction



1404.0495

Finding Resonances

Find decay products

↓

Construct invariant mass distributions

↓

Describe background

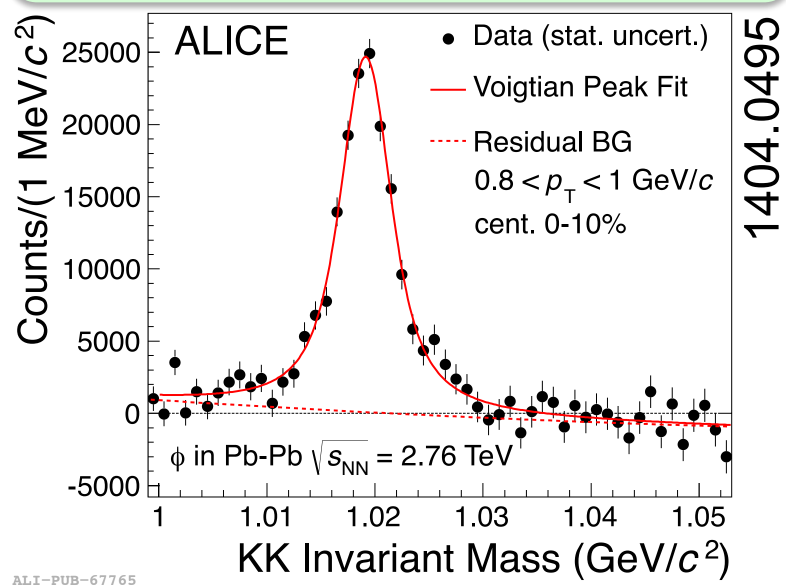
↓ **Fit background**

↓ **Like-charge Event mixing**

↓

Describe residual background

Fit residual background, usually with polynomial



Finding Resonances

Find decay products

↓

Construct invariant mass distributions

↓

Describe background

↓ **Fit background** ↓ **Like-charge Event mixing**

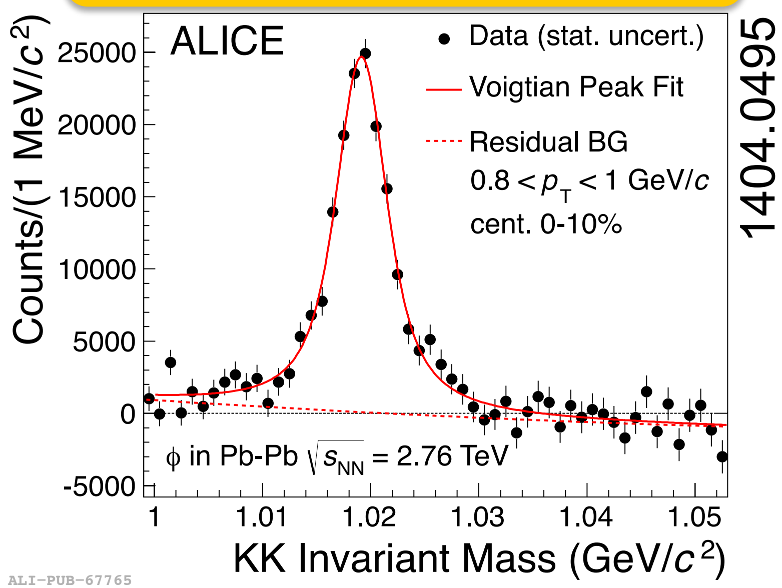
↓

Describe residual background

↓

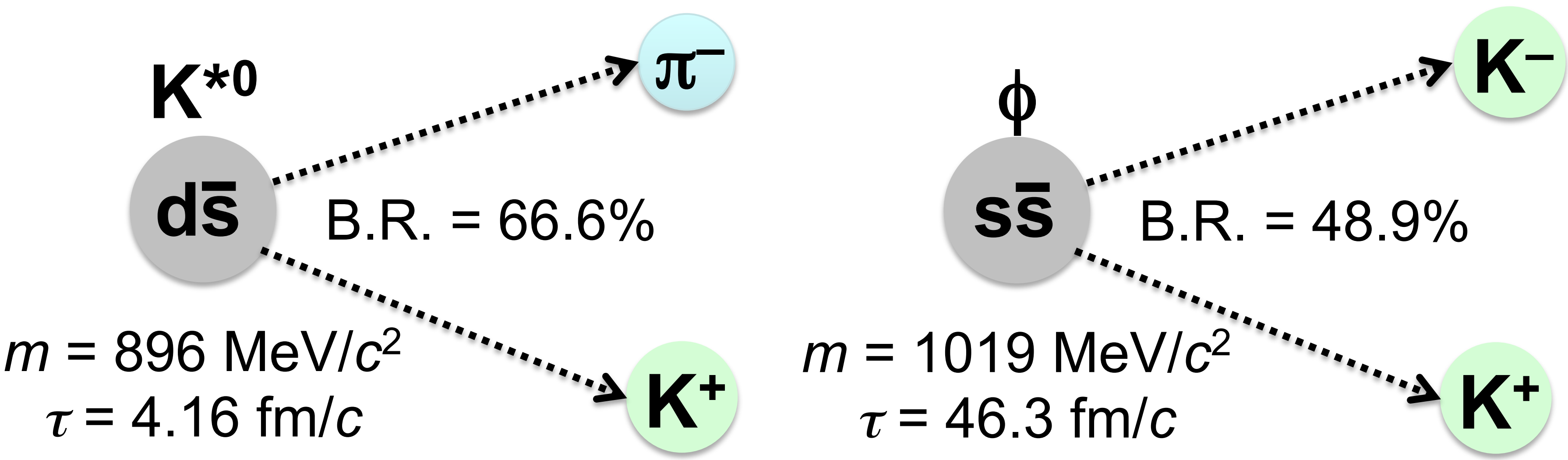
Fit peak → **Extract yield, mass, width**

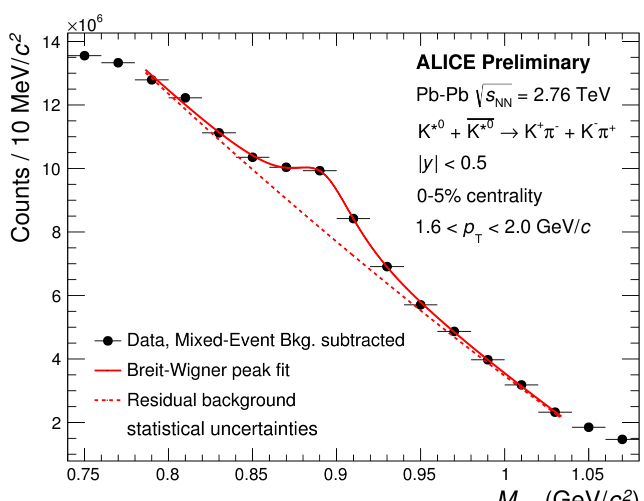
Fit peak with
- **-Breit-Wigner**
- **-Voigtian:** B-W convoluted with Gaussian to describe detector resolution (σ = 1-2 MeV/c^2)



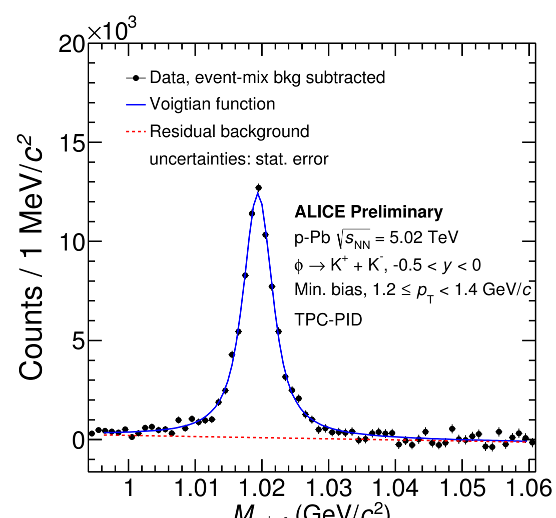
Resonance Reconstruction

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





ALI-PREL-69433



ALI-PREL-79042

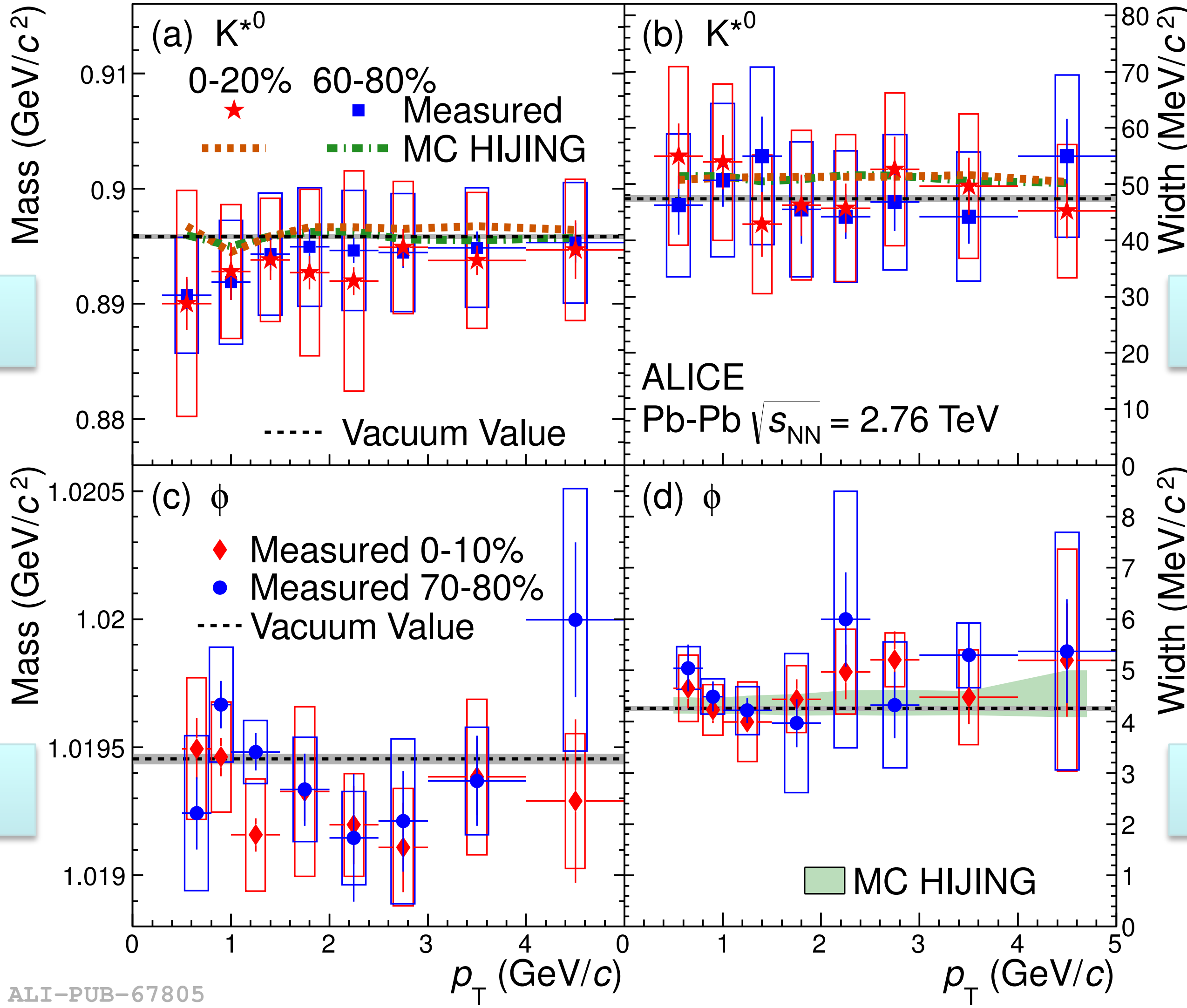
Mass and Width (Pb–Pb)

K*0 Mass

K*0 Width

ϕ Mass

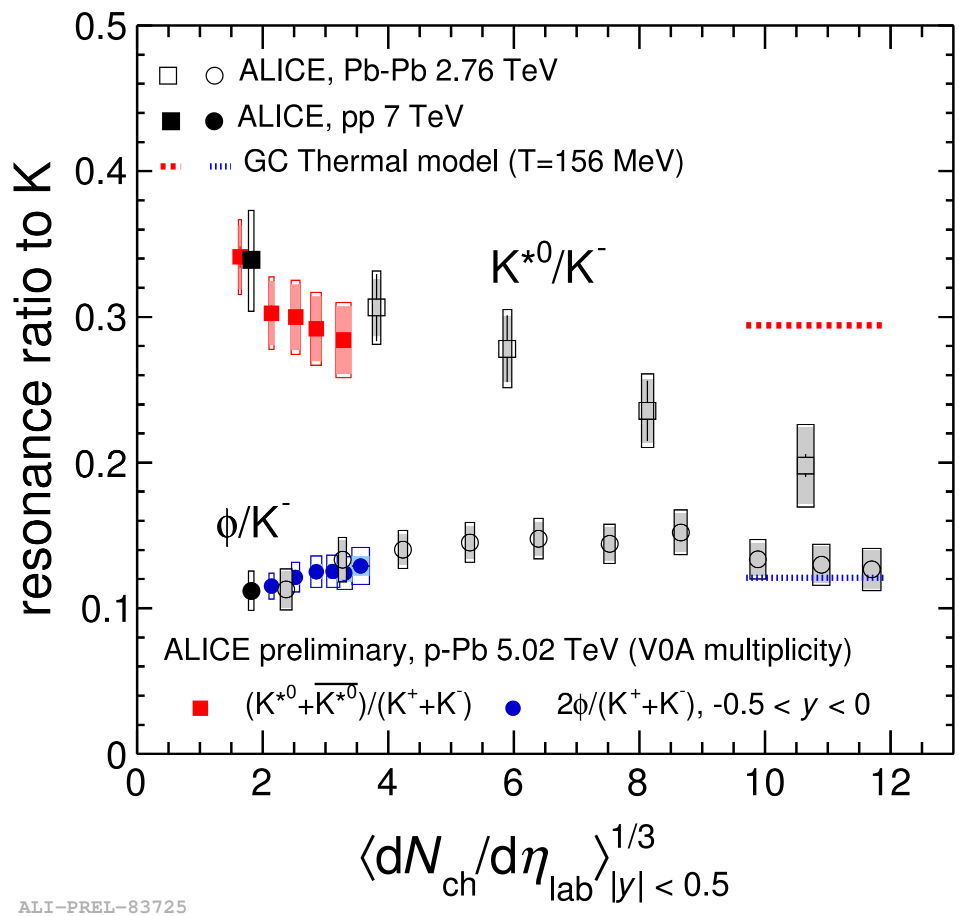
ϕ Width



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

Ratios of Yields

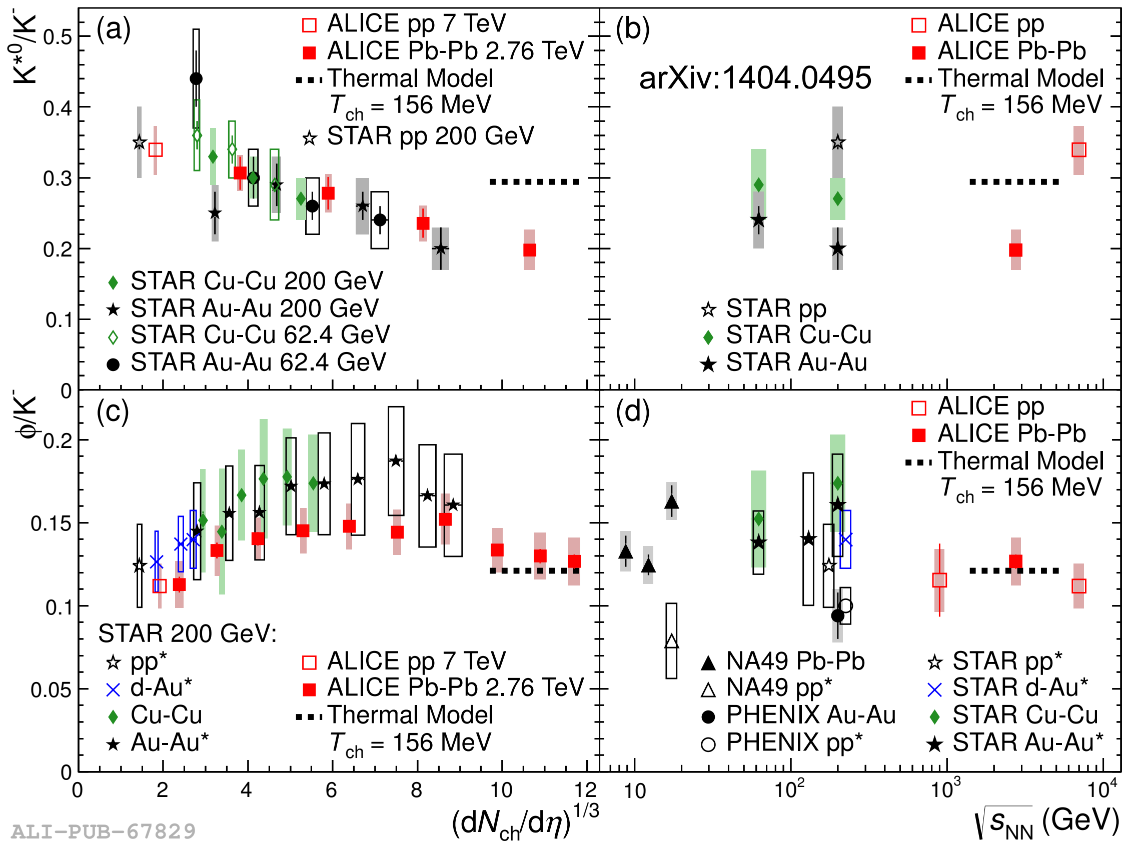
- K^{*0}/K
  - In Pb–Pb: strongly suppressed in central collisions w.r.t. peripheral, pp, p–Pb, or thermal model
  - Consistent with the hypothesis that re-scattering is dominant over regeneration
- ϕ/K
  - No strong dependence on centrality or collision system
  - ϕ lifetime ~10× longer than K^{*0},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



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

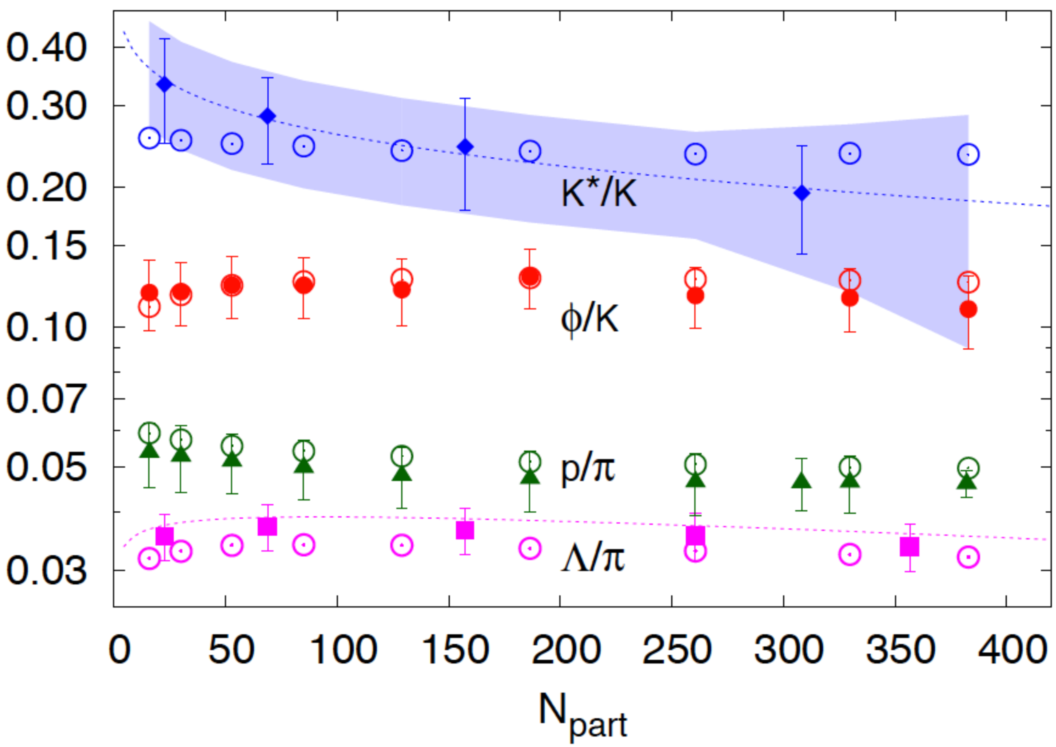
Ratios of Yields

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



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^{-}



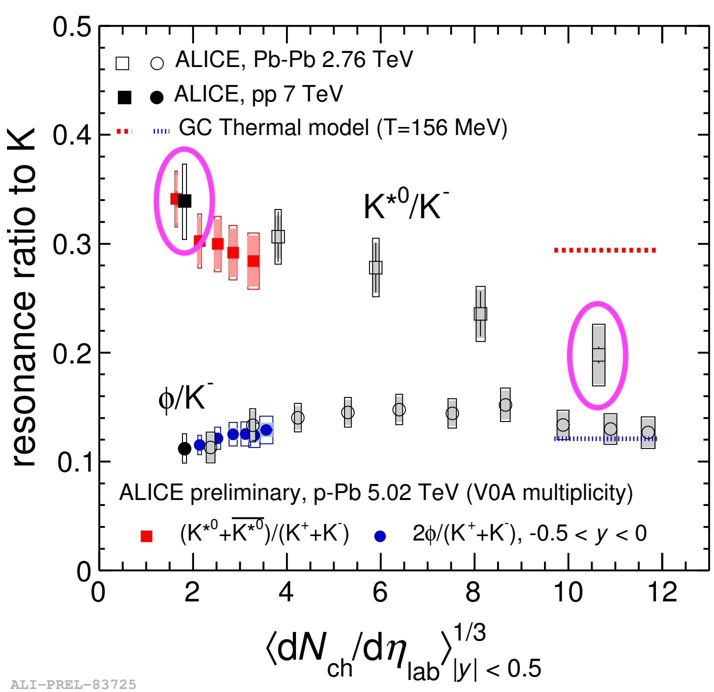
Uses preliminary ALICE K^{*0}/K, φ/K

Properties of Hadronic Phase

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

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

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



Properties of Hadronic Phase

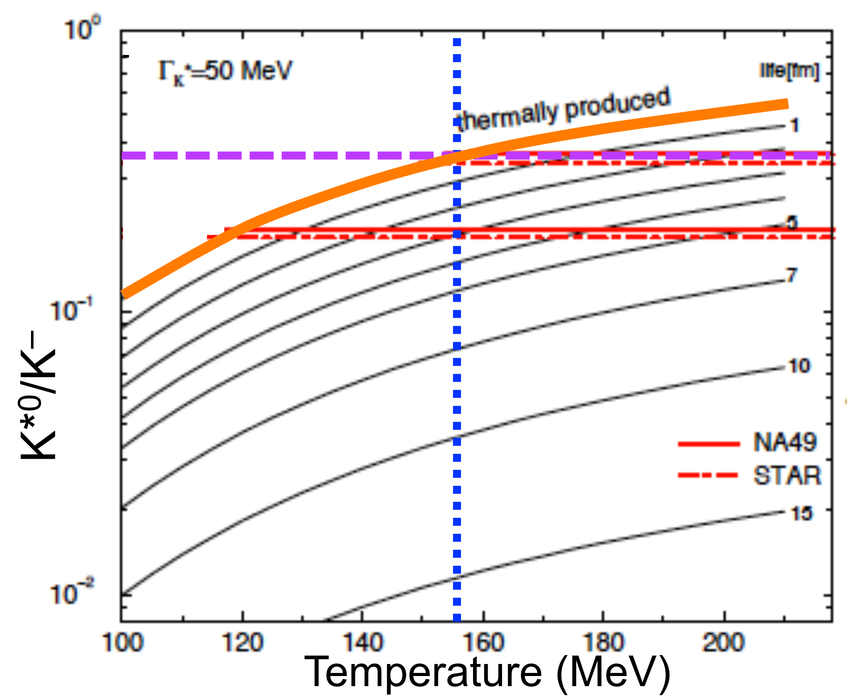
- Model of Torrieri, Rafelski, *et al.* predicts particle ratios as functions of chemical freeze-out temperature and lifetime of hadronic phase
- Model Predictions:

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

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

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

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



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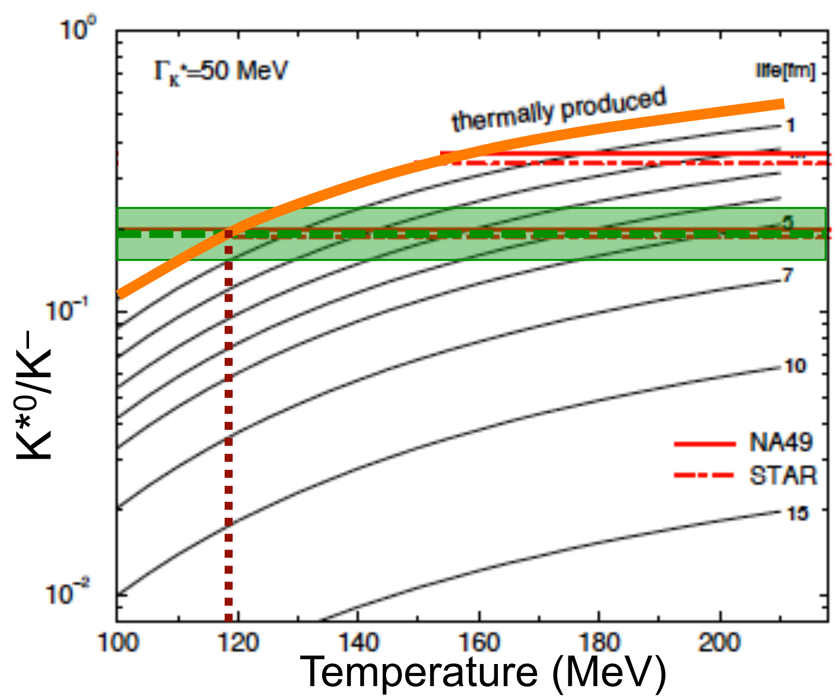
→ Prediction: K^{*0}/K^{-} = 0.35

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

→ Prediction: T_{ch} = 120±7 MeV

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



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→ Prediction: Lifetime ≥ 2 fm/c

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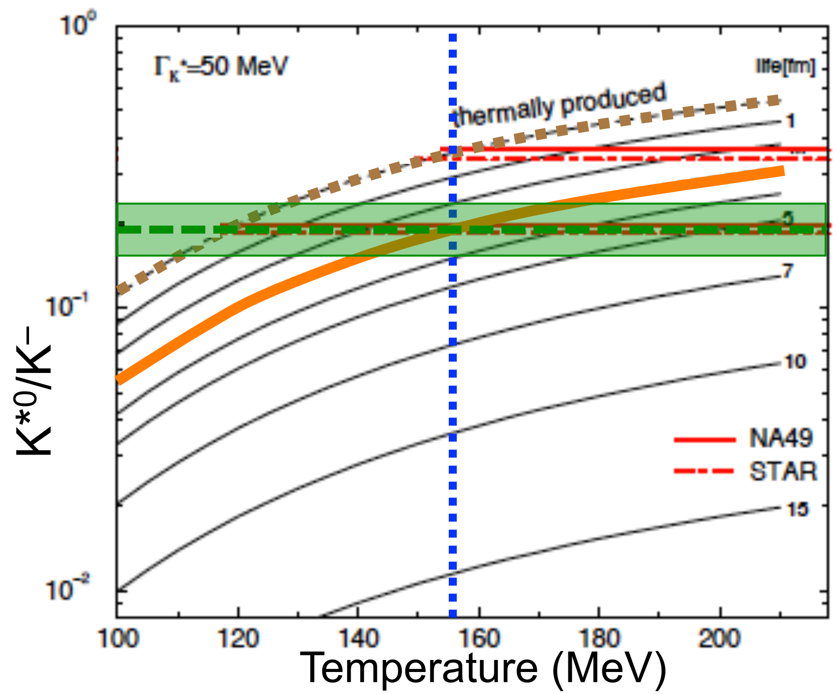
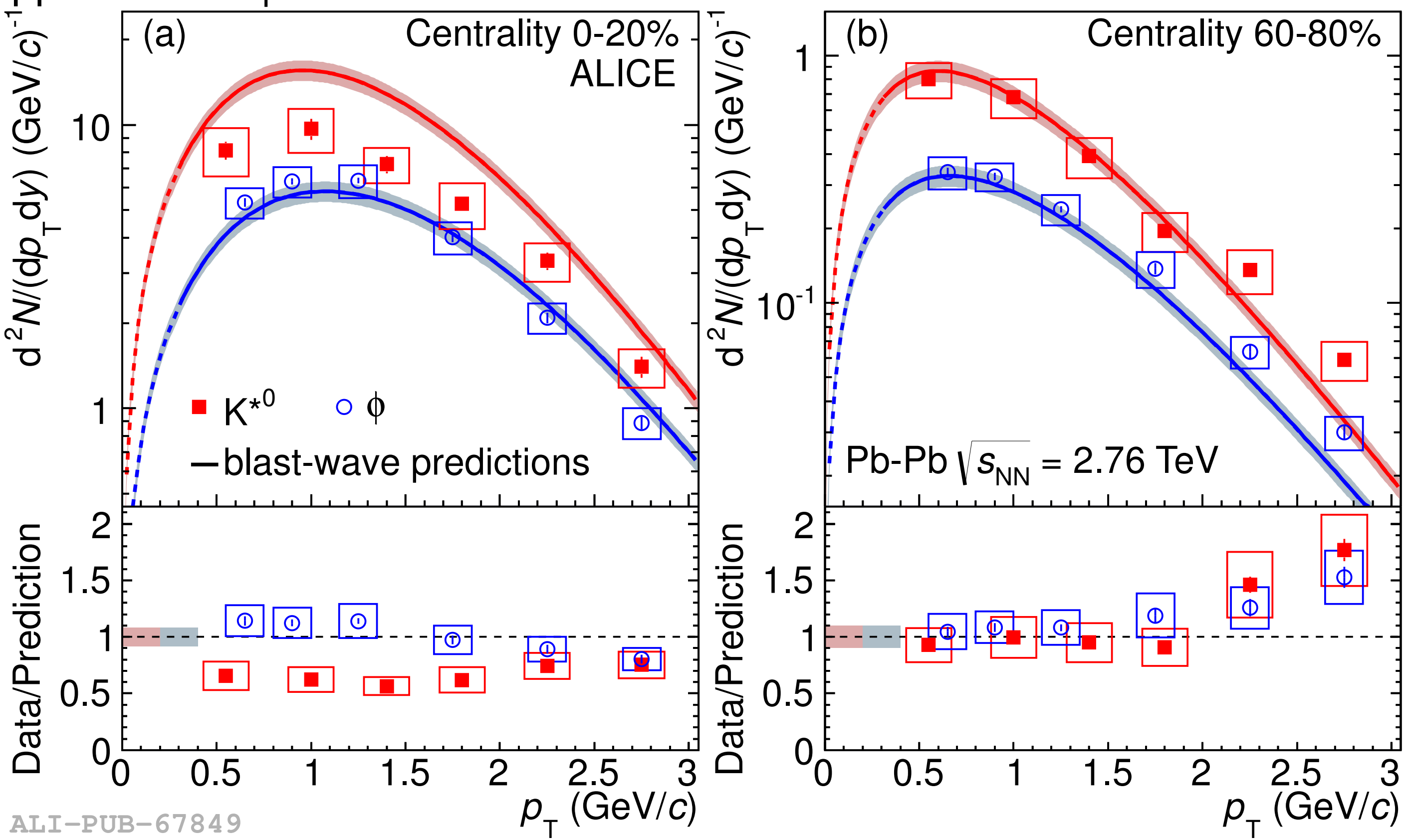


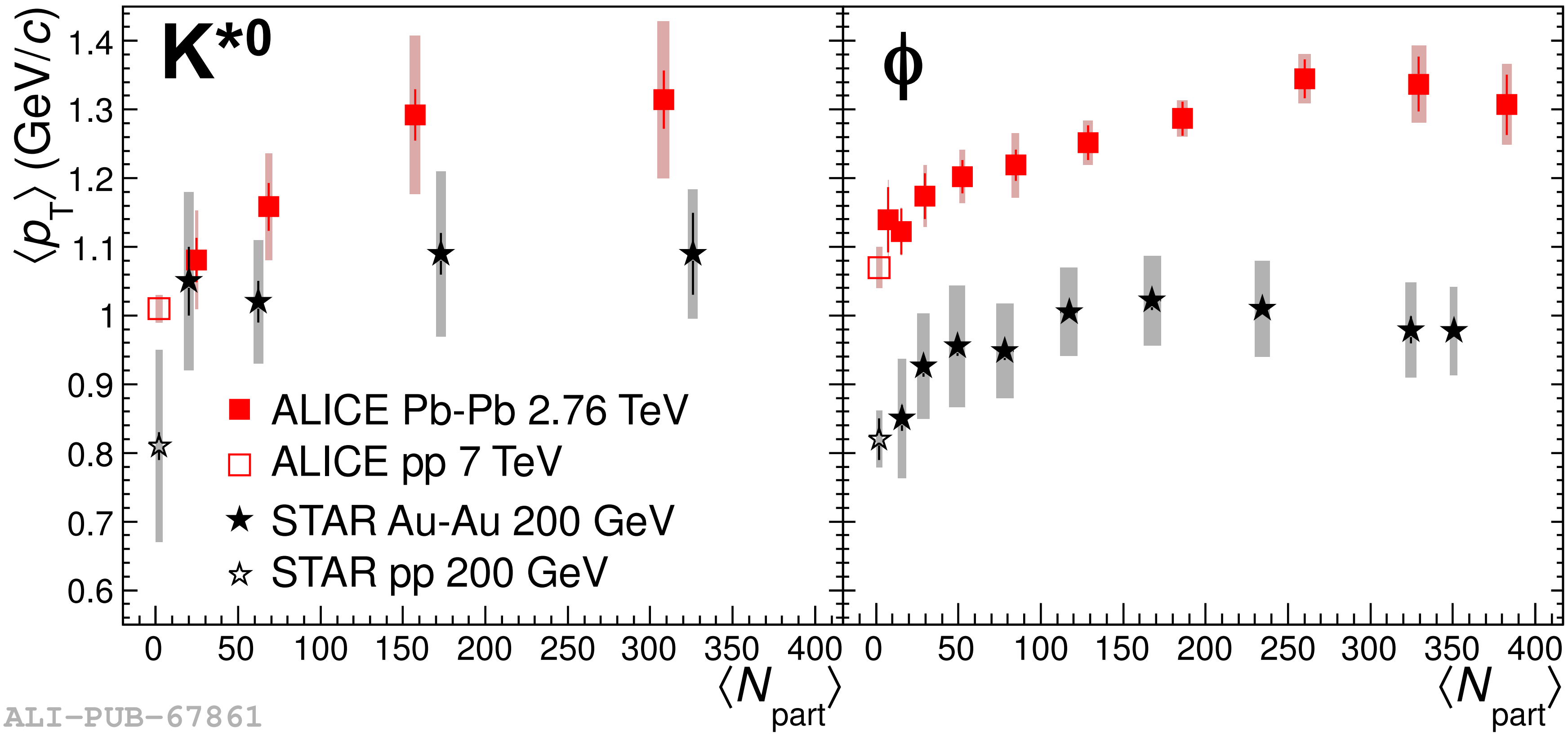
p_T Dependence

- 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



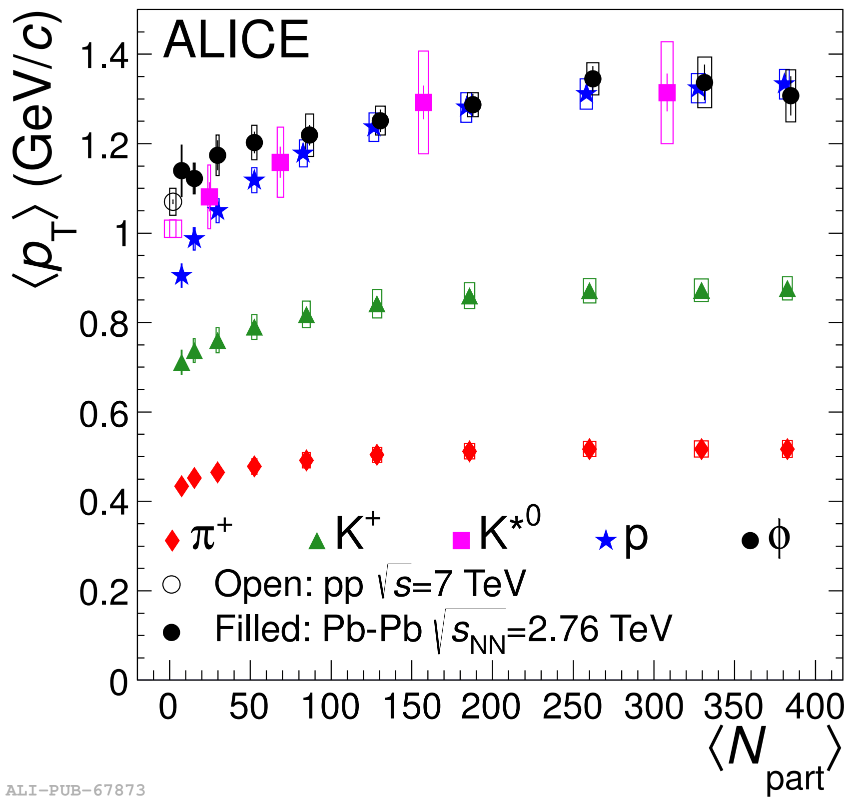
Mean p_T in A–A

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



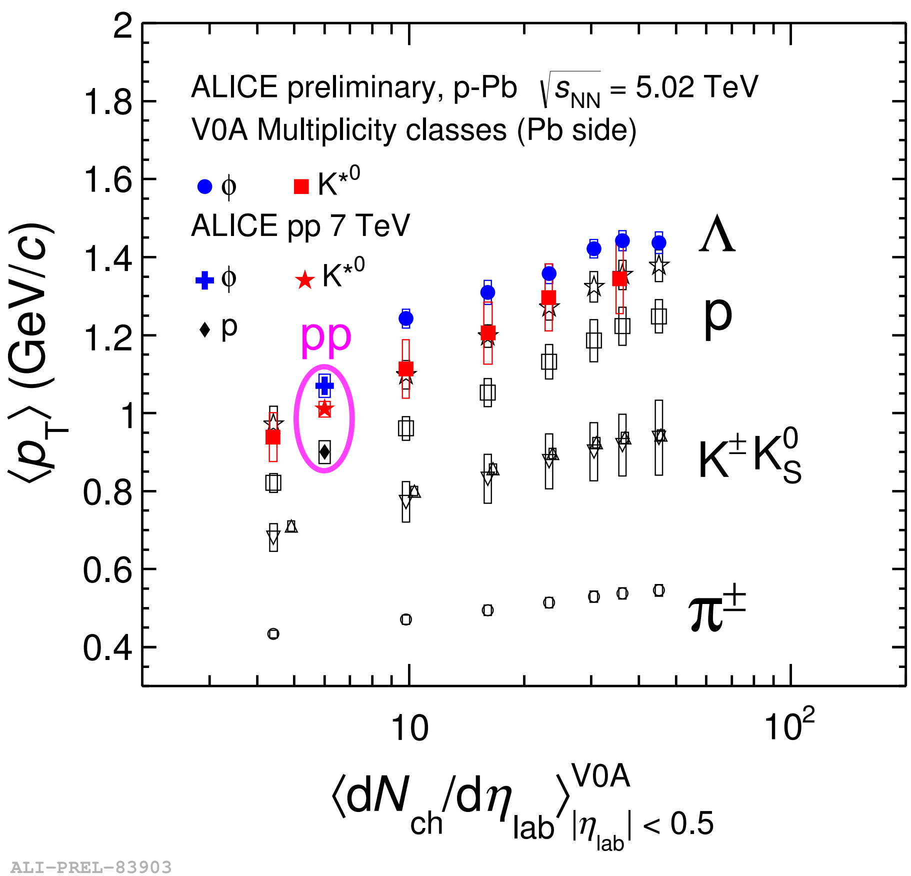
Mean p_T in Pb–Pb

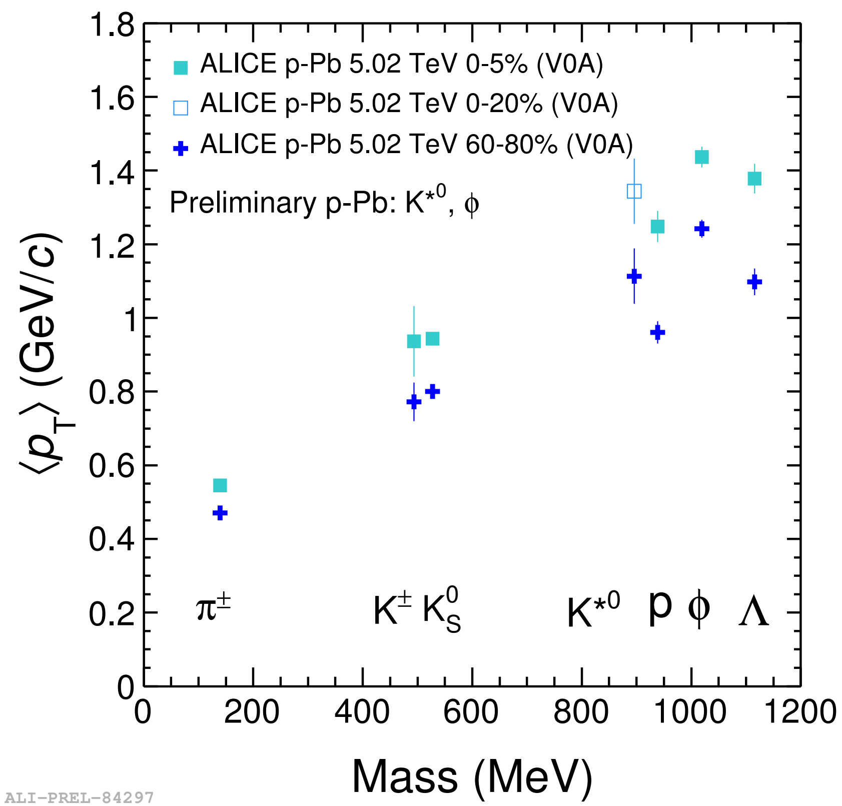
- Mass ordering of <p_T> observed
- <p_T> of K*0, p, and φ is similar for central Pb–Pb
  - Consistent with hydrodynamics
- <p_T> splitting between p and φ for peripheral Pb–Pb
- Increase in <p_T> from peripheral to central:
  - For $\pi^{\pm}$, $K^{\pm}$, K^{*0}, and φ: ~20% – For p: ~50%



Mean p_T in p–Pb

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





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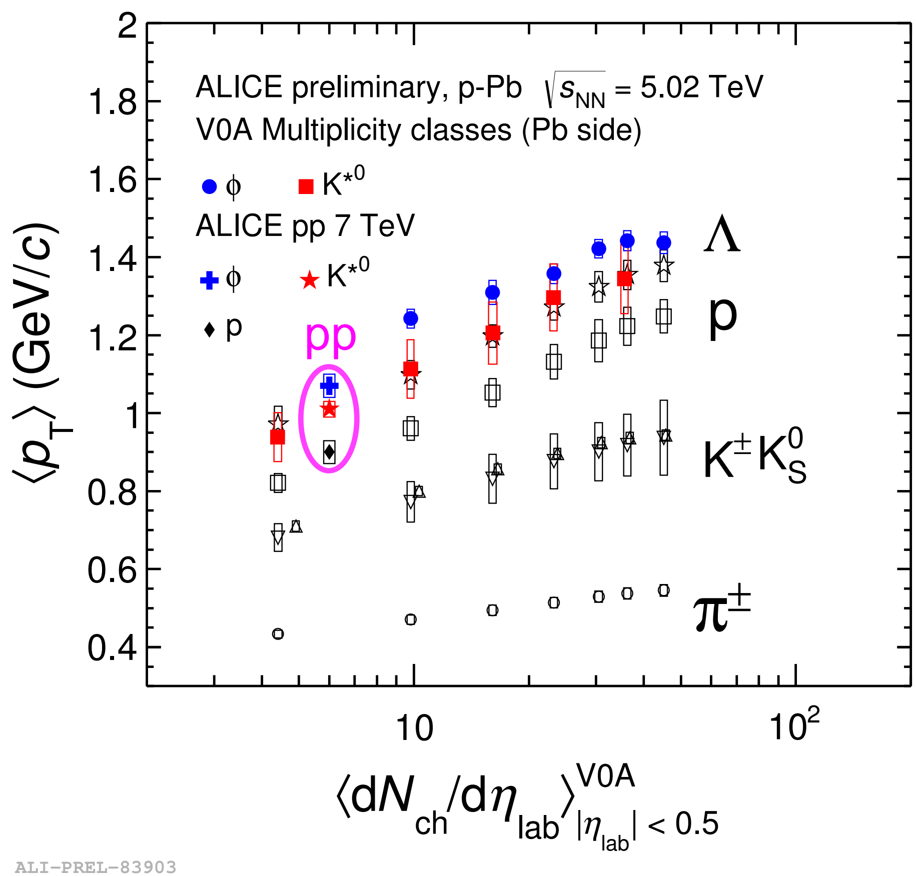

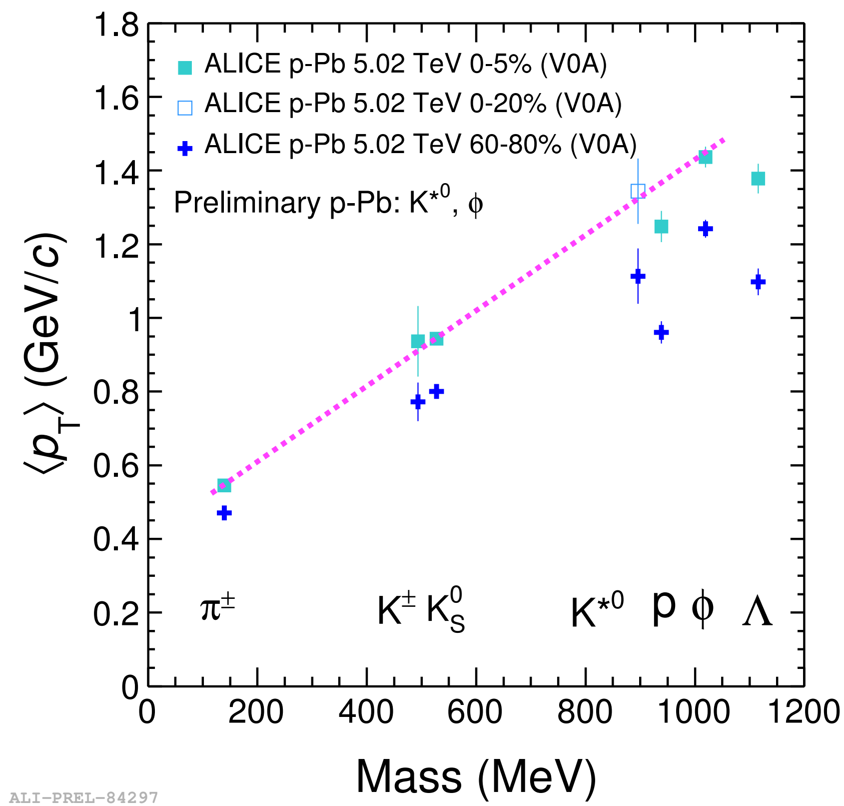

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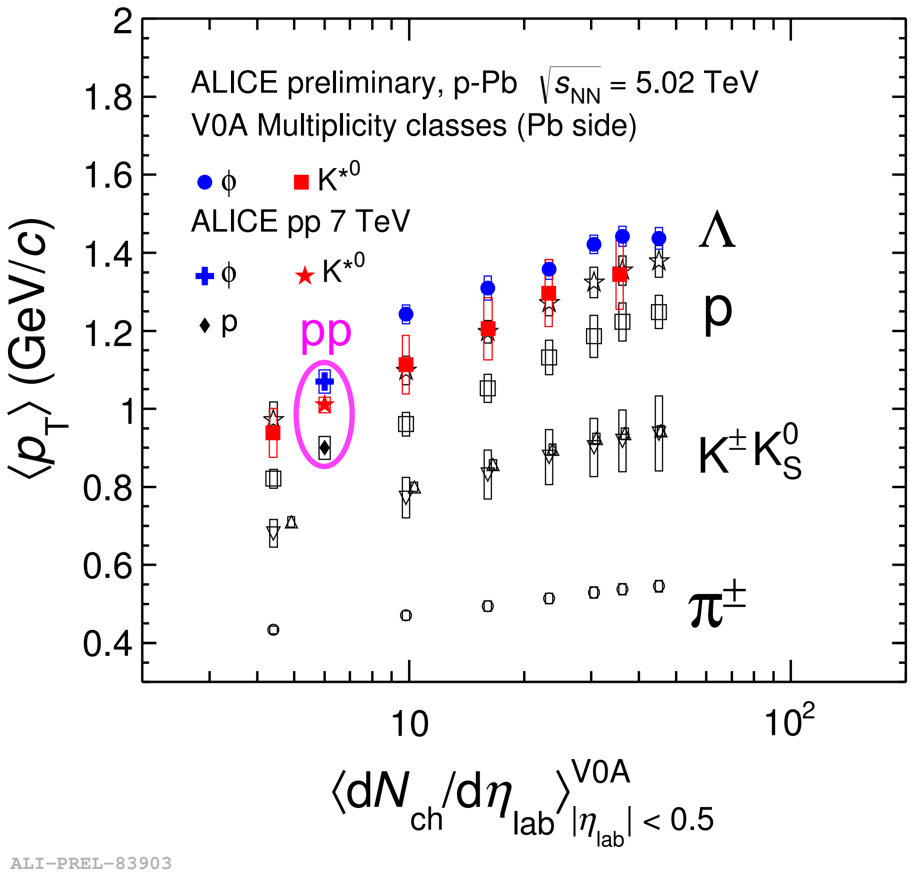
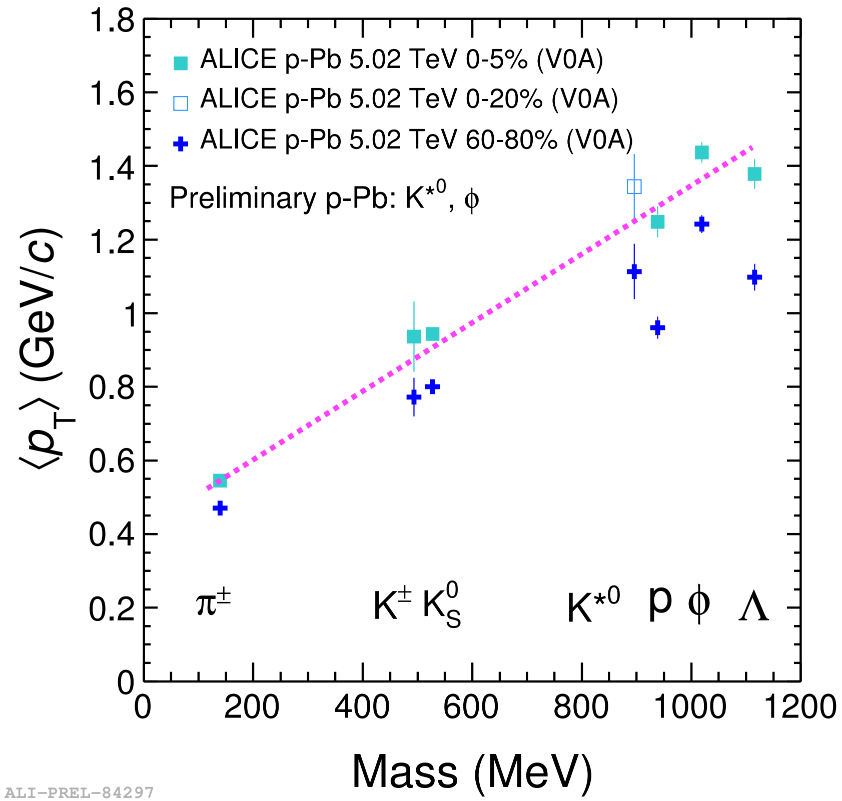
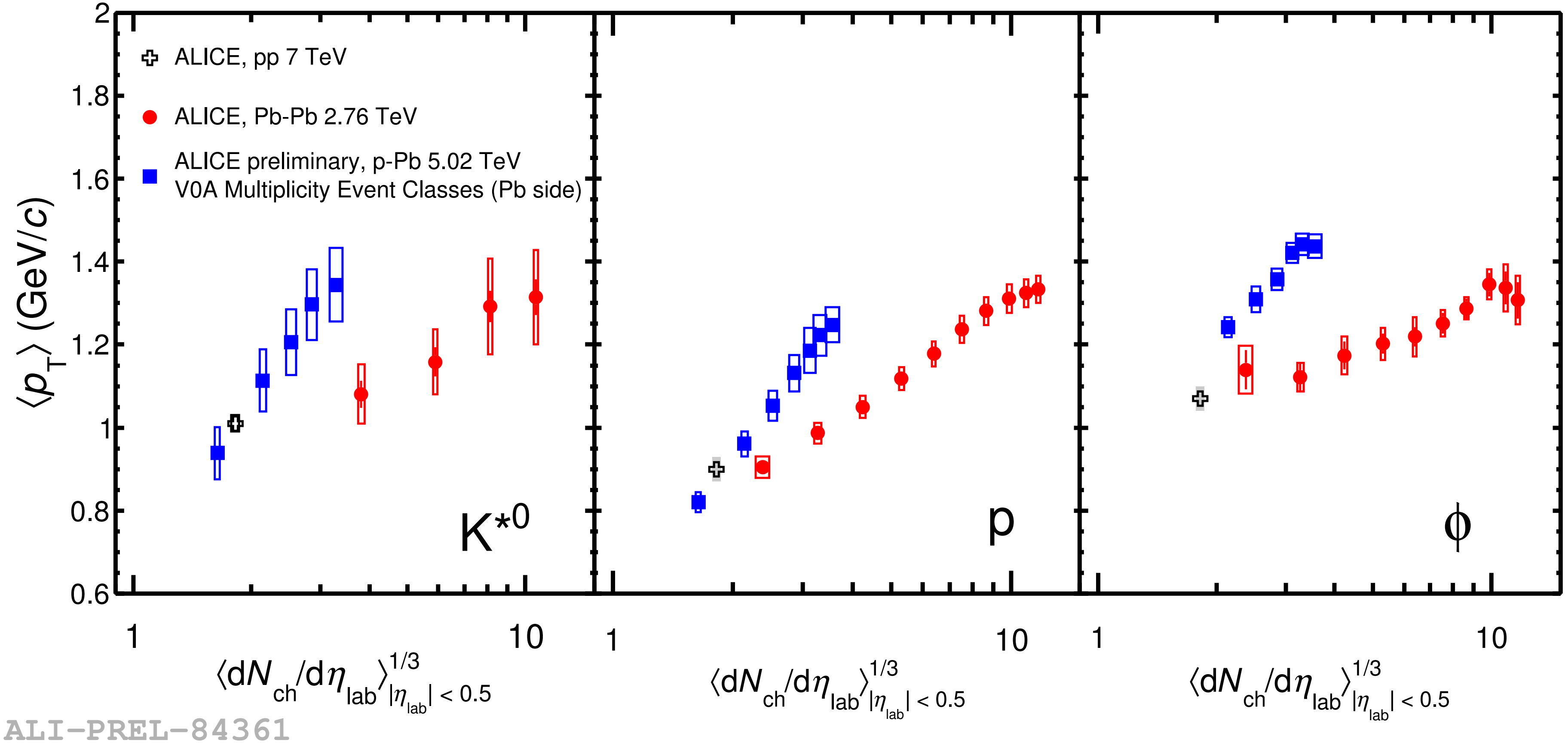




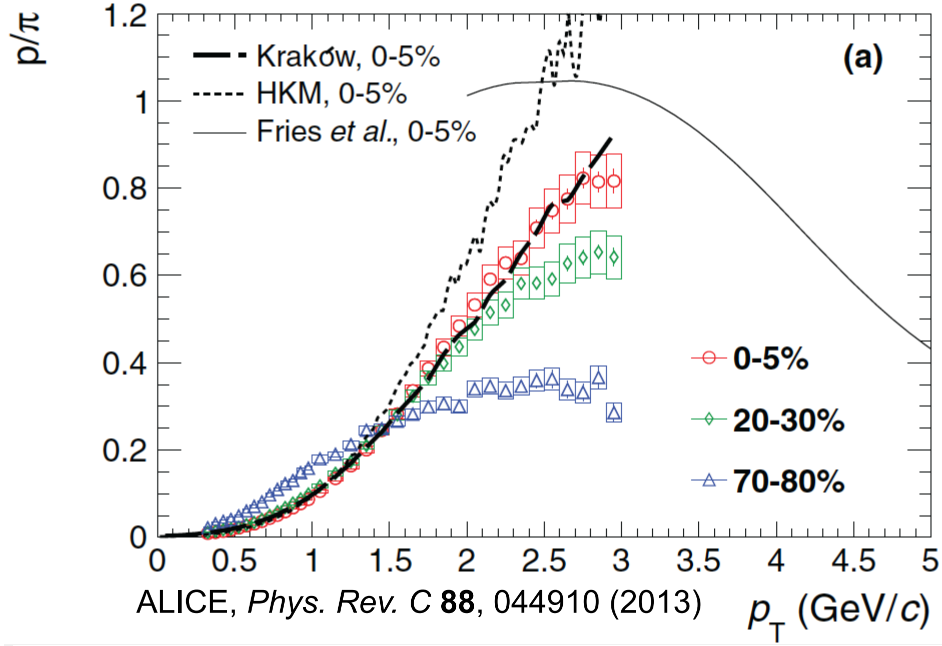
Mean p_T

- High-multiplicity p–Pb reaches similar $<p_T>$ values as central Pb–Pb
- $<p_T>$ in p–Pb increases more rapidly than Pb–Pb as a function of multiplicity
- Differences in $<p_T>$ due to difference in particle production mechanisms? Harder scattering in p–Pb?

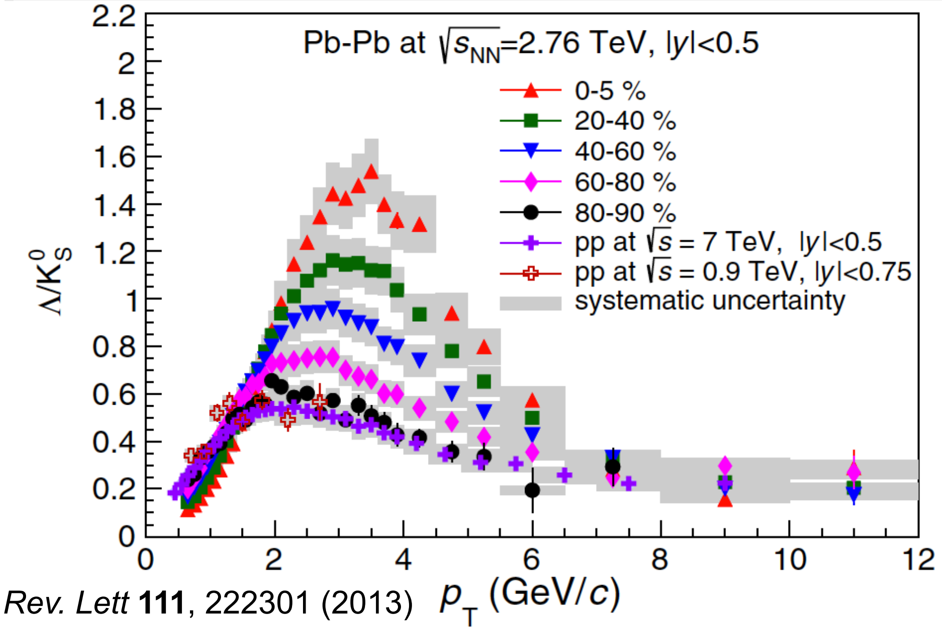


Particle Production

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



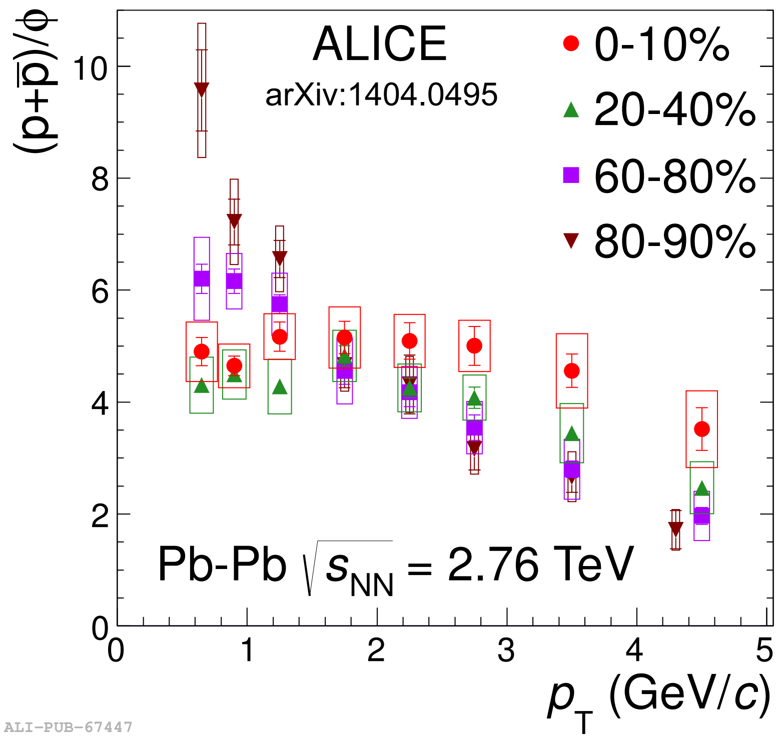
ALICE, *Phys. Rev. C* **88**, 044910 (2013)

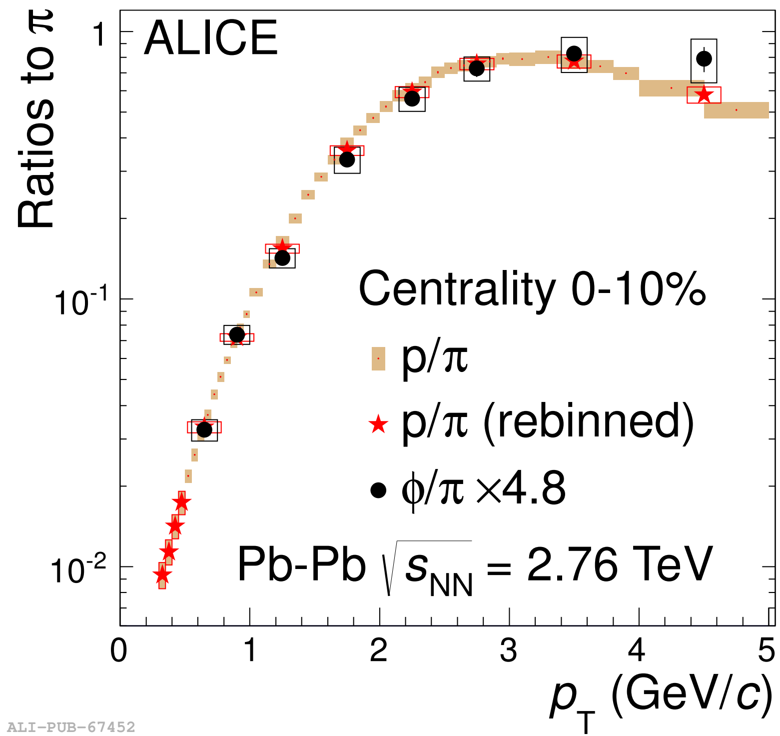


ALICE, *Phys. Rev. Lett* **111**, 222301 (2013)

p/ϕ vs. p_T in Pb–Pb

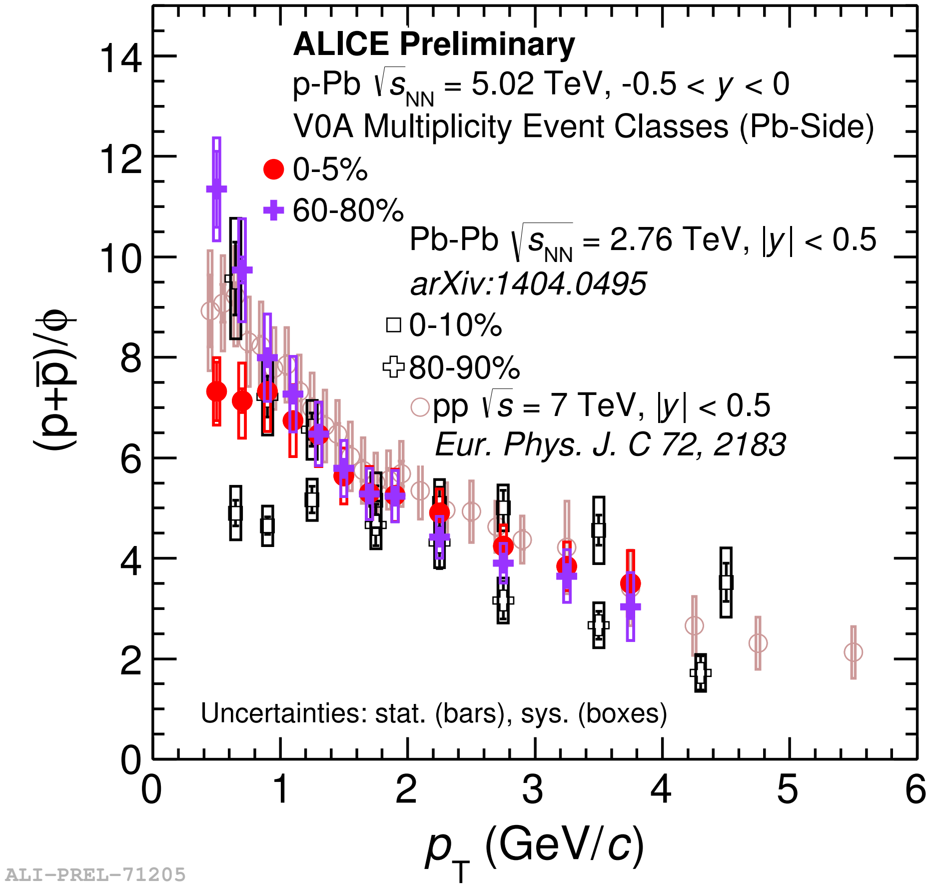
- p/ϕ flat for central collisions for p_T < 3-4 GeV/c
  - Baryon/meson difference goes away if the two particles have the same mass. Consistent with hydrodynamics
- Increasing slope for peripheral collisions
- Peripheral Pb–Pb similar to pp (7 TeV)
- Same trend seen in <p_T> (p and ϕ different for peripheral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





p/ϕ vs. p_T in p–Pb

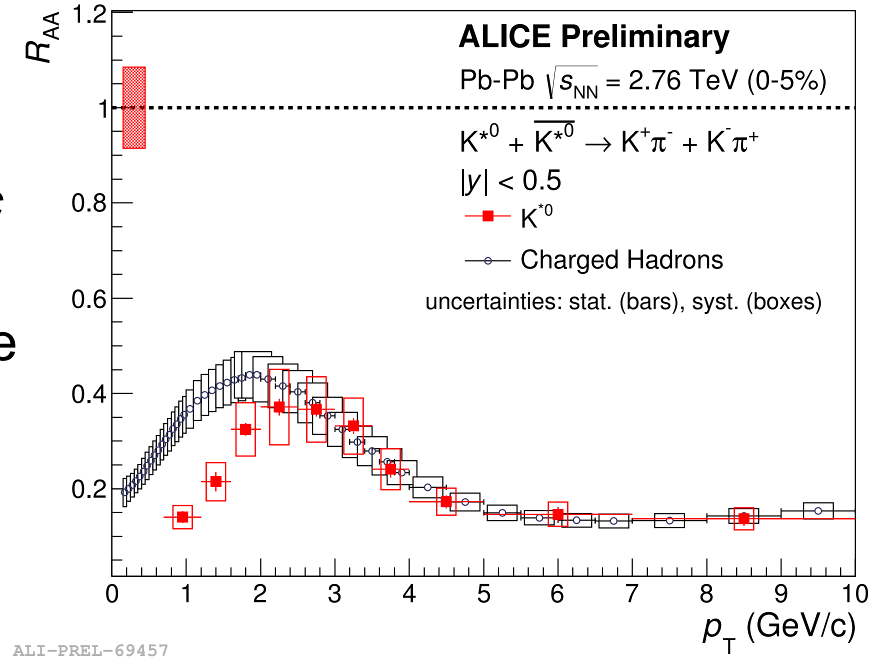
- p/ϕ in low-multiplicity p–Pb similar to peripheral Pb–Pb and pp
- For p_T > 1 GeV/c: no multiplicity dependence in p–Pb
- For p_T < 1 GeV/c: decrease of p/ϕ for high-multiplicity
  - Possible flattening of ratio: hint of onset of collective behavior in high-multiplicity p–Pb?

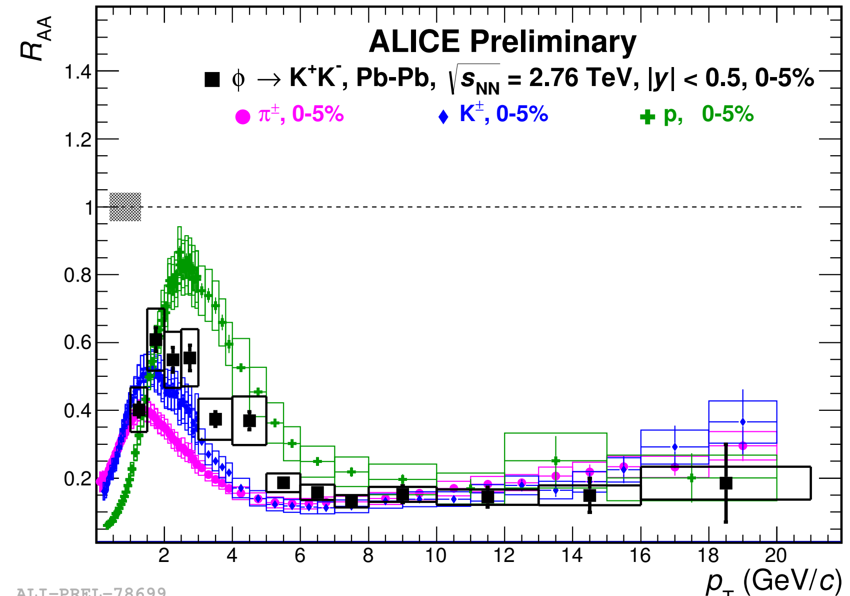


Nuclear Modification Factors

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

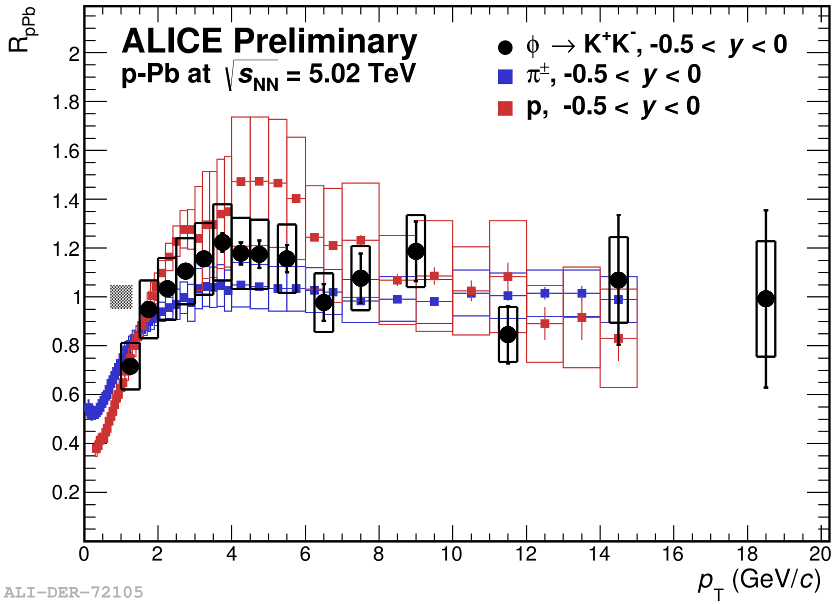
$$R_{AA}(p_T) = \frac{\text{Yield(A–A)}}{\text{Yield(pp)}\times\langle N_{coll}\rangle}$$





Nuclear Modification Factors

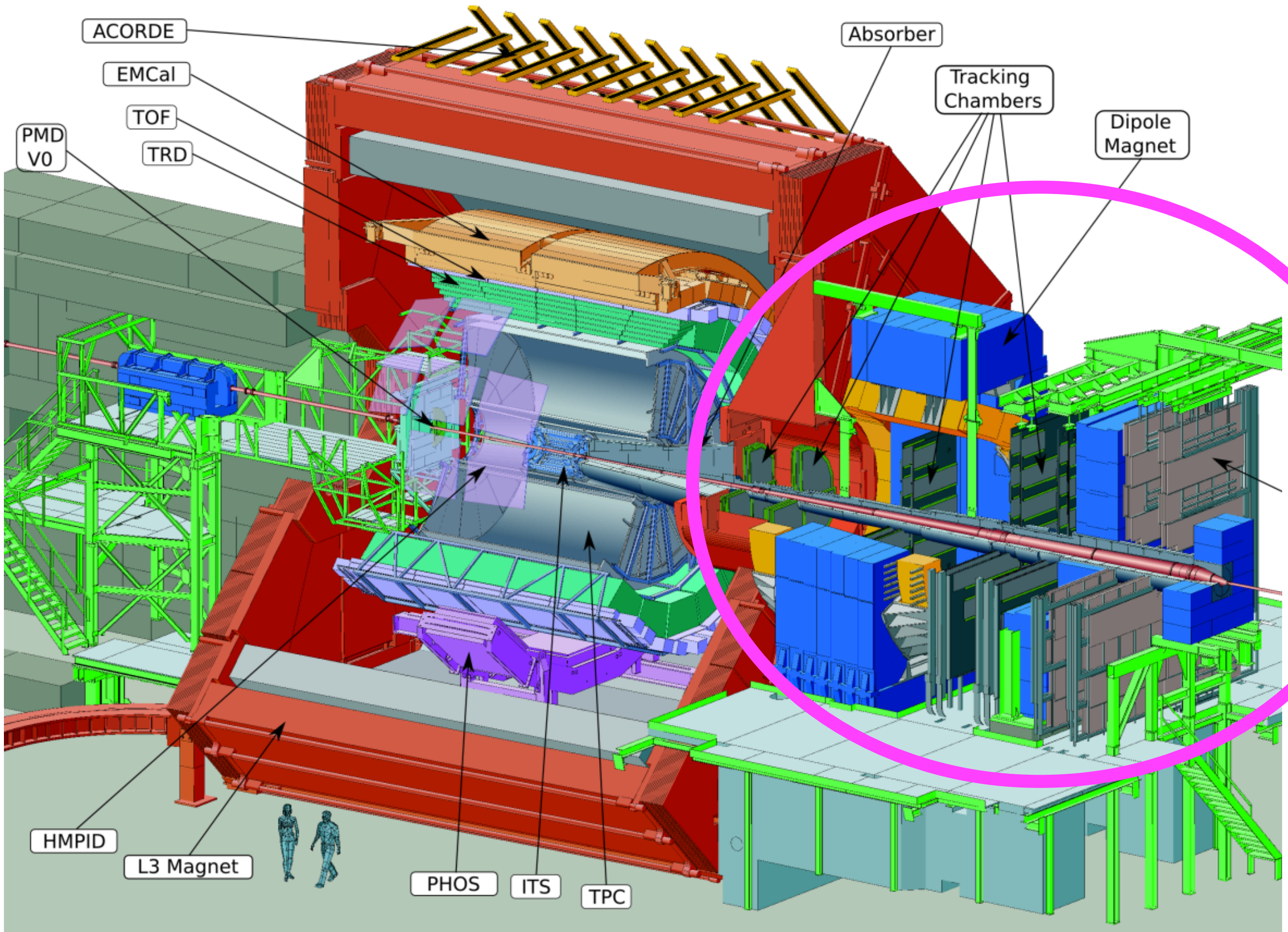
- In Pb–Pb:
  - More suppression of K^{*0} than of charged hadrons for p_T<2 GeV/c (consistent with re-scattering)
  - Differences between p and ϕ due to differences in reference (pp) spectra
  - Strong suppression of all hadrons at high p_T
- In p–Pb:
  - No suppression of ϕ w.r.t. pp for p_T > 1.5 GeV/c
  - Intermediate p_T: Cronin peak for p, smaller peak for ϕ
  - Possible mass dependence or baryon/meson differences in R_{pPb}



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

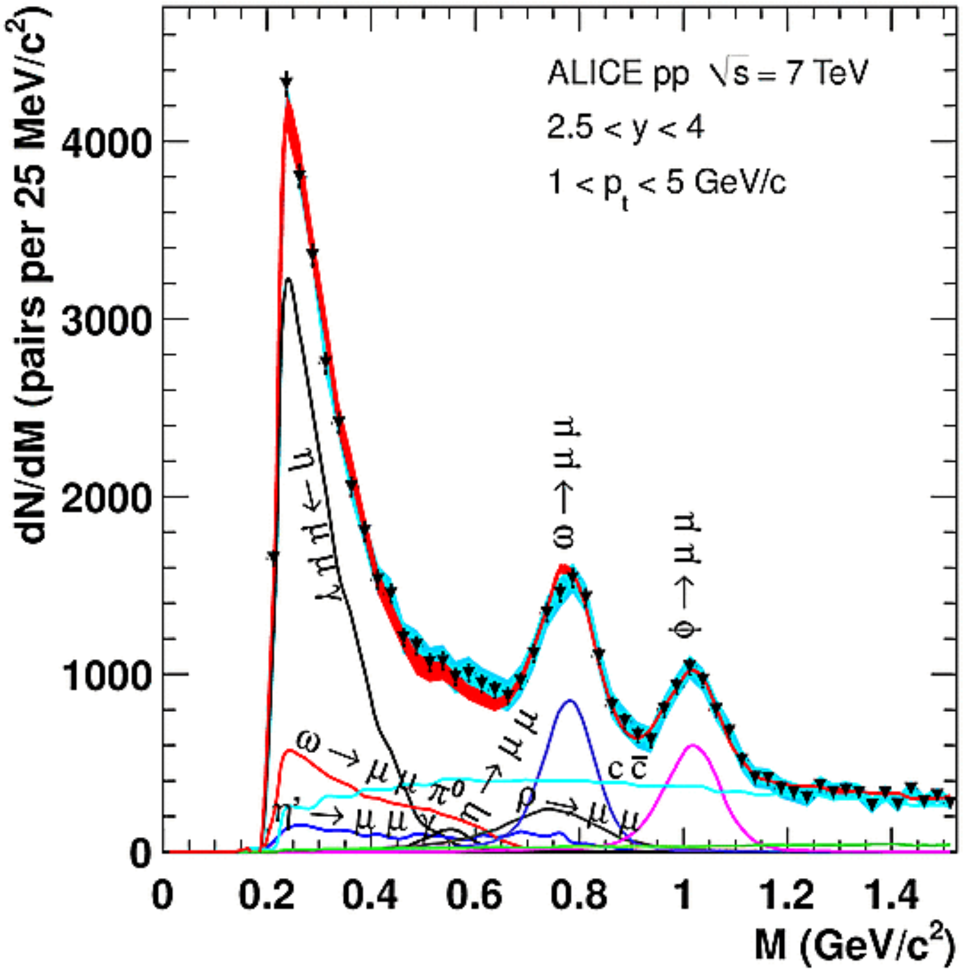
$\phi \rightarrow \mu^-\mu^+$

- Muon pairs from ϕ decays reconstructed in ALICE Muon Spectrometer:
  - Absorber, tracking chambers, dipole magnet at forward rapidity ($-4<\eta<-2.5$)



$\phi \rightarrow \mu^-\mu^+$

- Signal extracted by fitting dimuon invariant-mass distribution with hadronic cocktail:

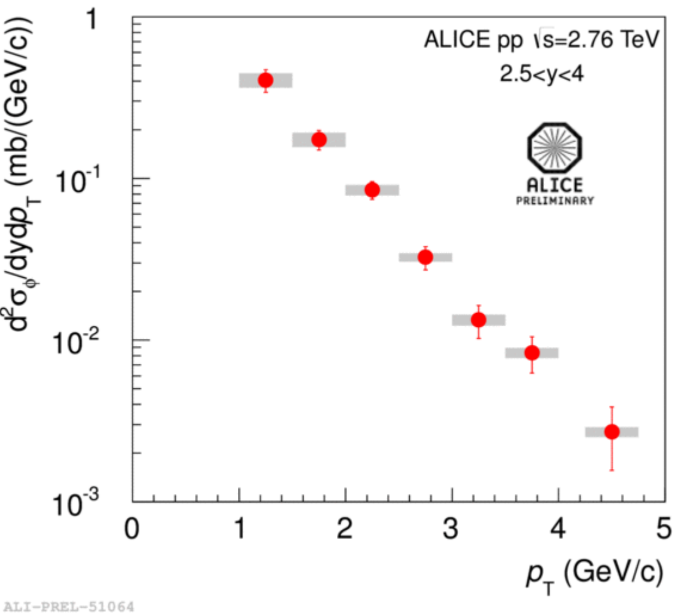


ALI-PUB-26621

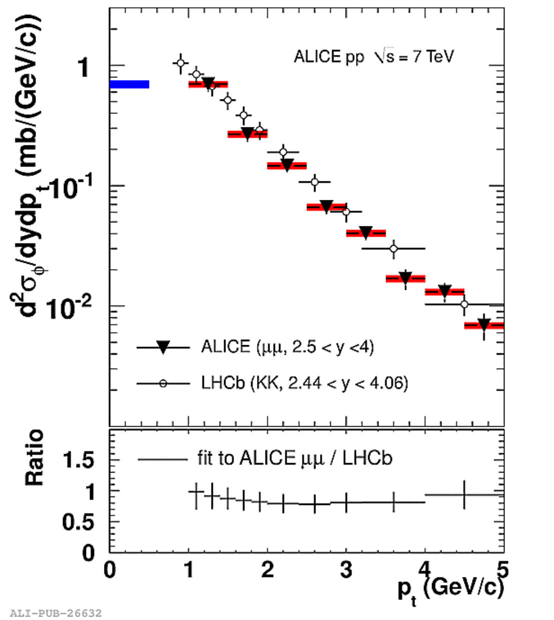
$\phi \rightarrow \mu^{-}\mu^{+}$

- Measured in pp collisions at 2.76 TeV and 7 TeV, Pb–Pb collisions

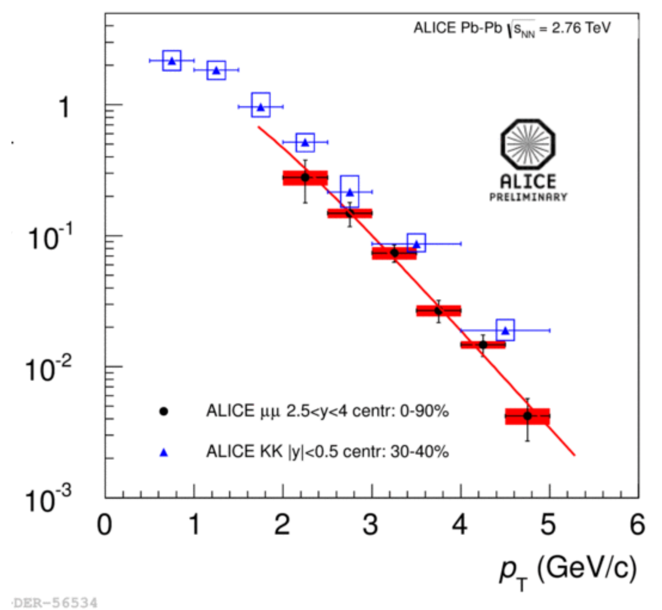
pp 2.76 TeV



pp 7 TeV

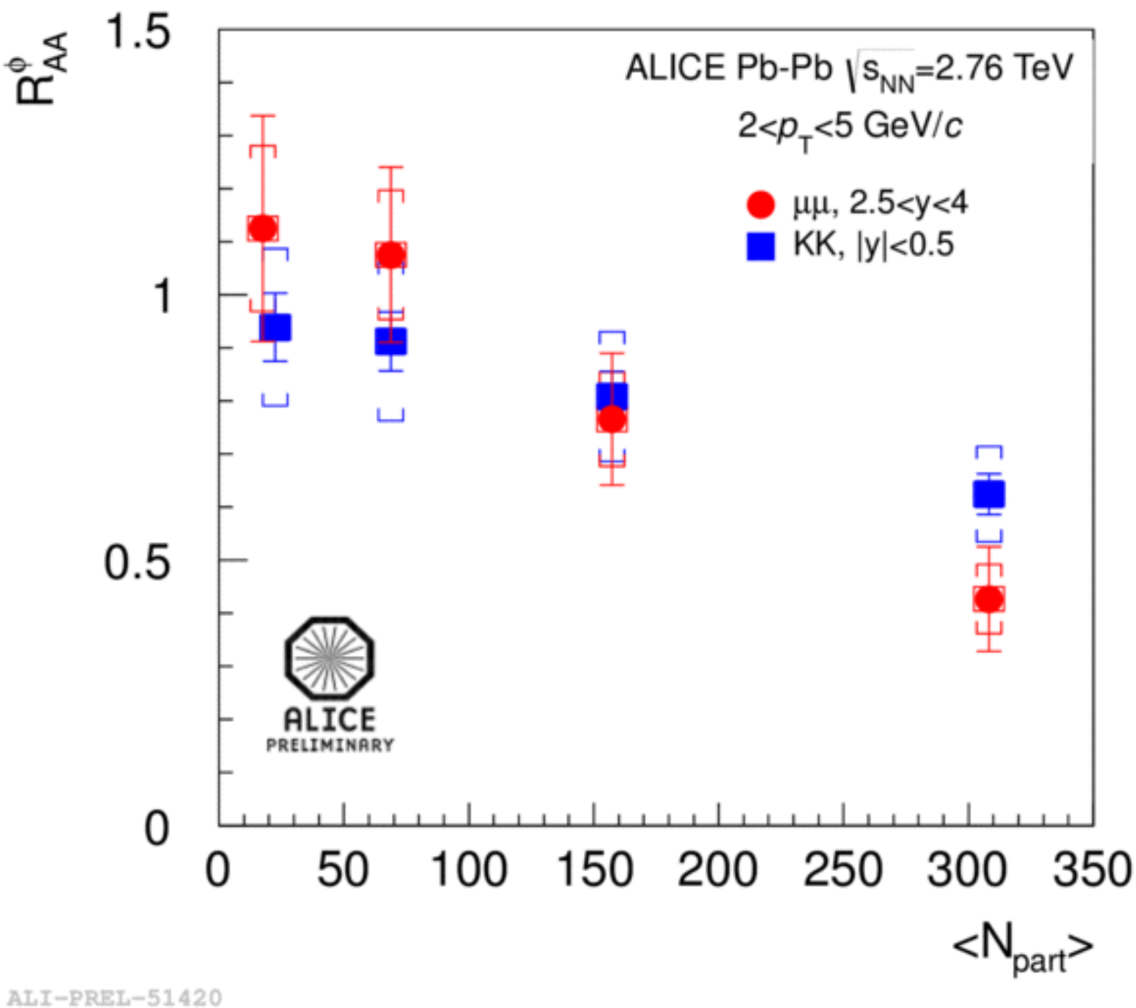


Pb–Pb 2.76 TeV



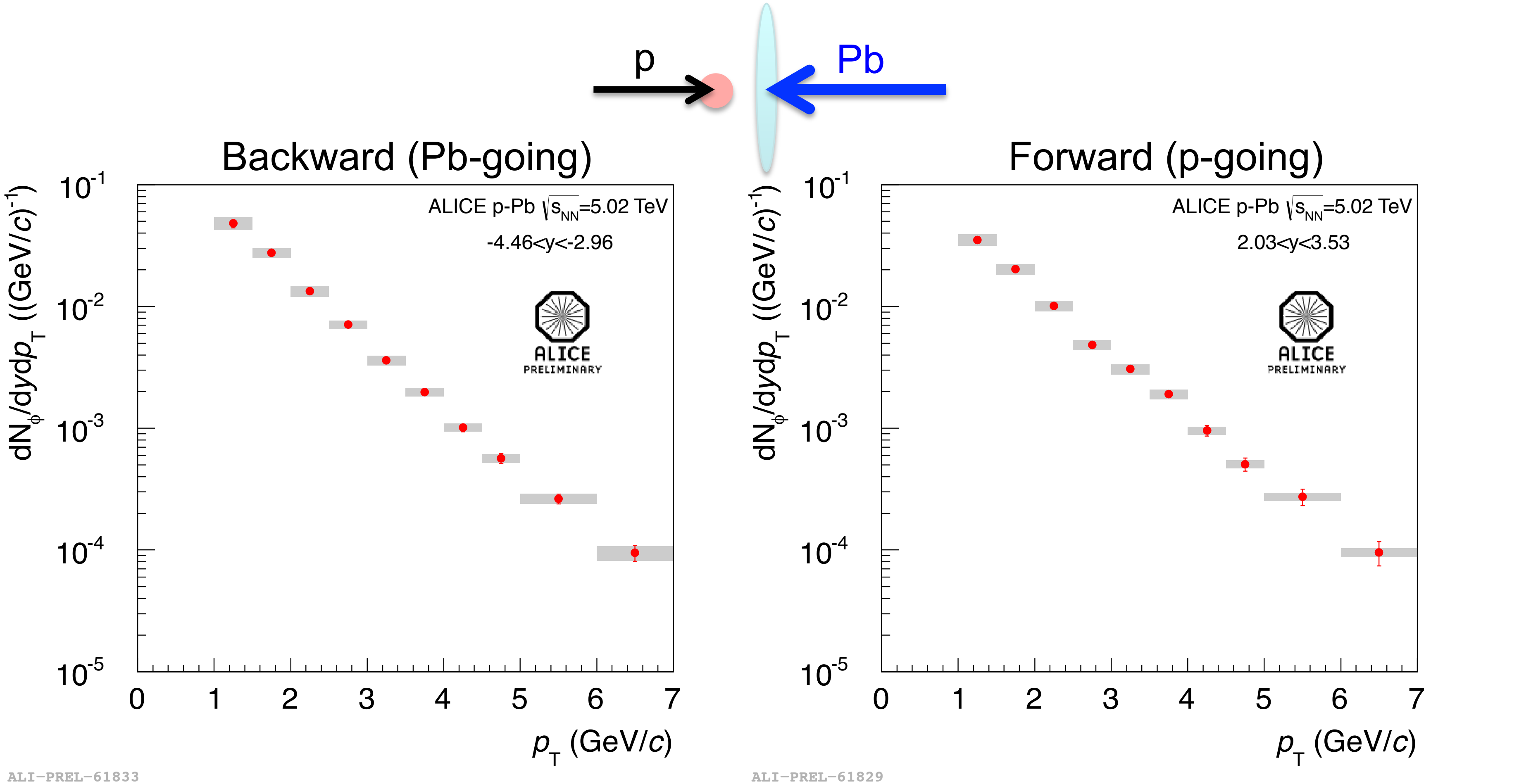
Nuclear Modification Factor

- R_{AA} for μμ channel at forward rapidity seems to follow different trend (greater slope) than KK channel at mid-rapidity
  - Different hydrodynamical push in the two rapidity ranges?



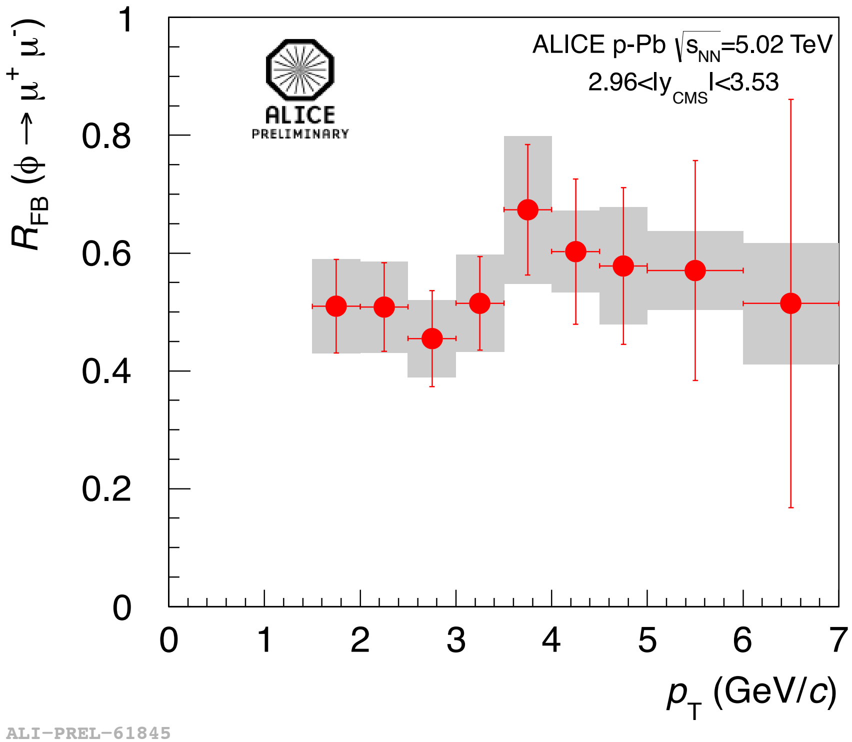
In p–Pb: Forward vs. Backward

- Yield in backward rapidity (Pb-going direction) greater than forward rapidity (p-going direction): asymmetry in particle production



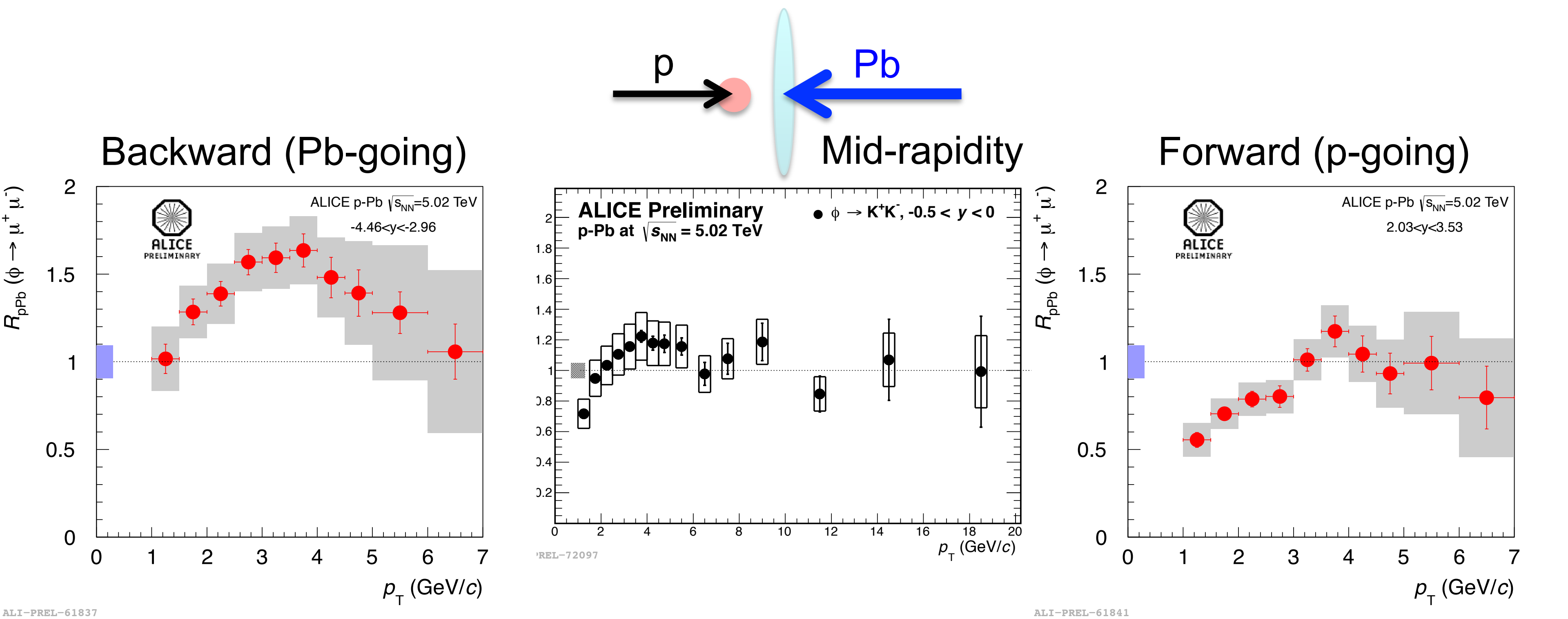
In p–Pb: Forward vs. Backward

- Yield in backward rapidity (Pb-going direction) greater than forward rapidity (p-going direction): asymmetry in particle production
- Forward/Backward ratio (in common *y* window)
  - Flat with p_T
  - Integrated value R_{FB} = 0.53 ± 0.03



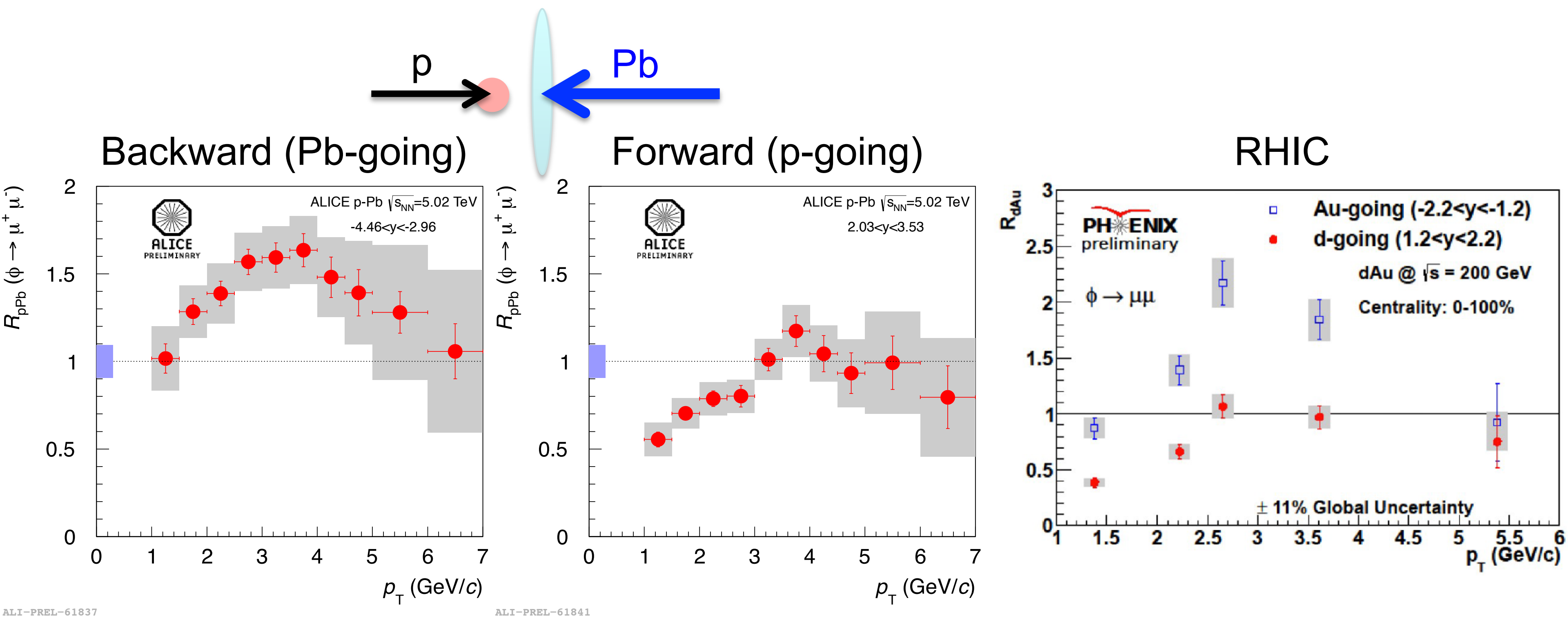
R_{pPb}

- Forward (p-going): increases with p_T, then saturates around 1 for p_T>3 GeV/*c*
- Backward (Pb-going): Cronin peak (bigger than at mid-rapidity)



R_{pPb}

- Forward (p-going): increases with p_T, then saturates around 1 for p_T>3 GeV/*c*
- Backward (Pb-going): Cronin peak (bigger than at mid-rapidity)
- Similar behavior observed in d–Au collisions (PHENIX)



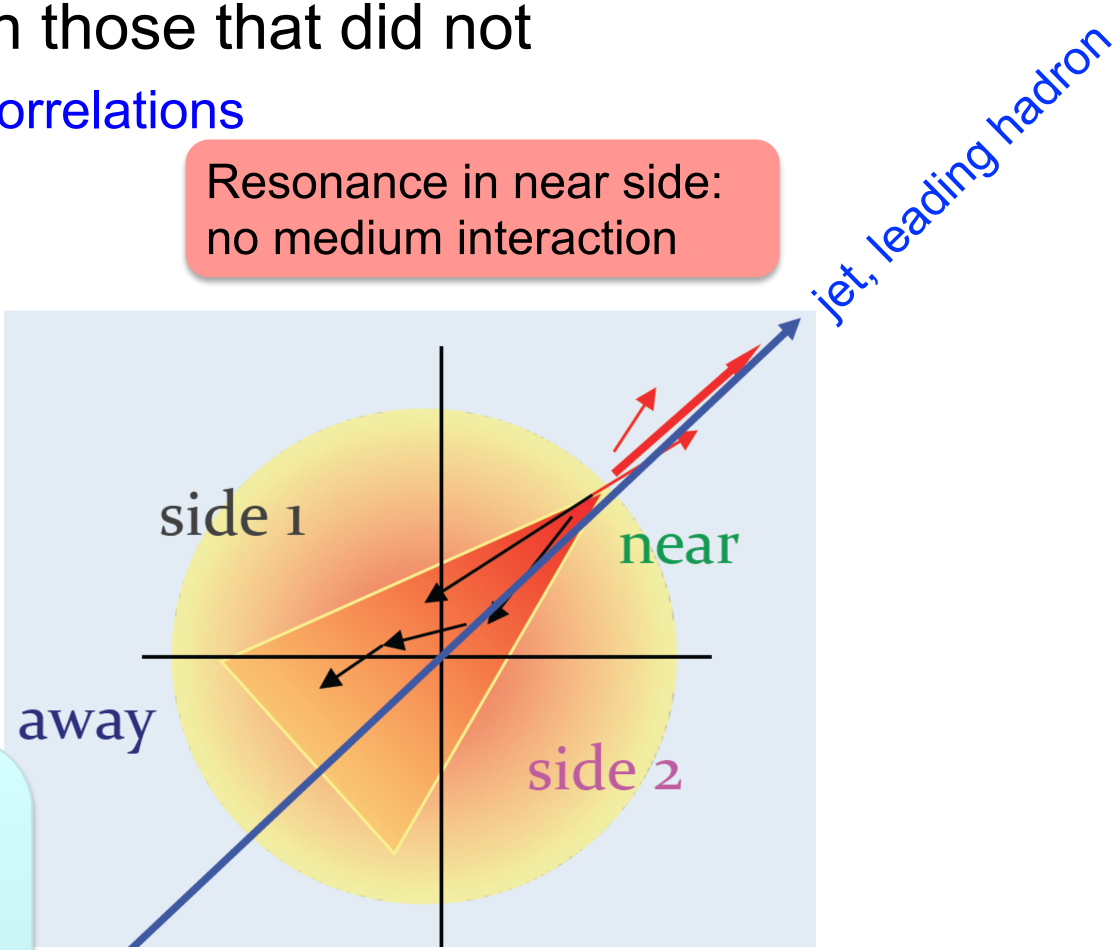
Hadron-Resonance Correlations

Hadron-Resonance Correlations

- To probe QGP: compare resonances that passed through medium with those that did not
  - Hadron-resonance correlations

Resonance in near side:
no medium interaction

Method proposed by:
C. Markert, R. Bellwied, I. Vitev,
Phys. Lett. B **669** 92-97 (2008)

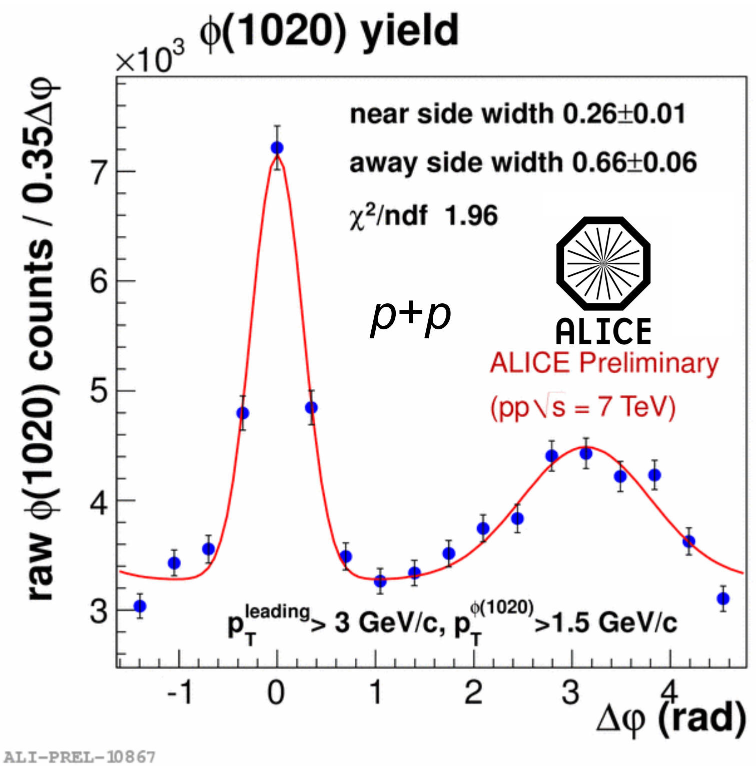


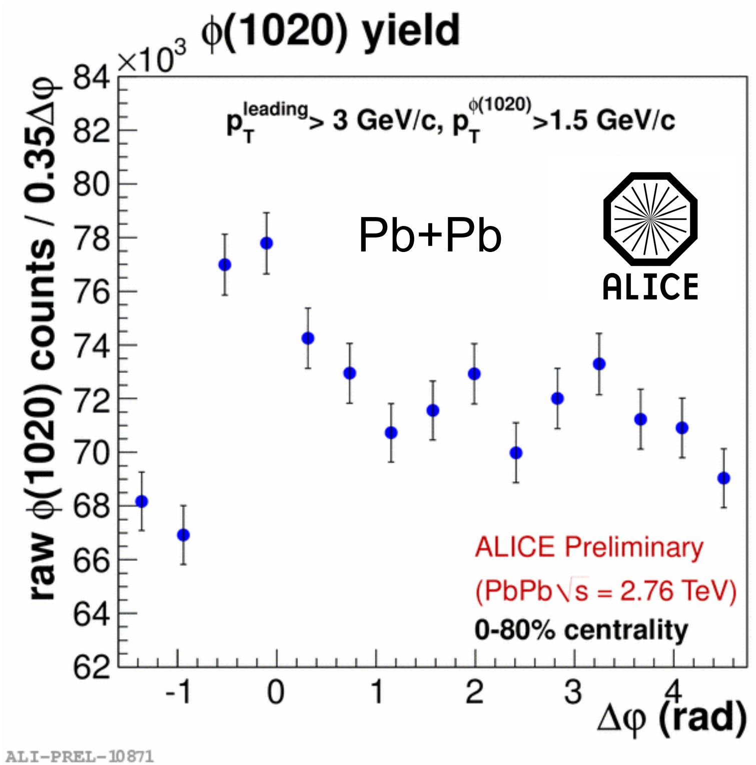
Resonance in away side:
Low p_T (below ~2 GeV/c):
dominated by interactions in hadronic medium
High p_T: dominated by interactions with early hadronic or partonic medium

Resonance transverse to jet:
Thermal production in hadronic medium

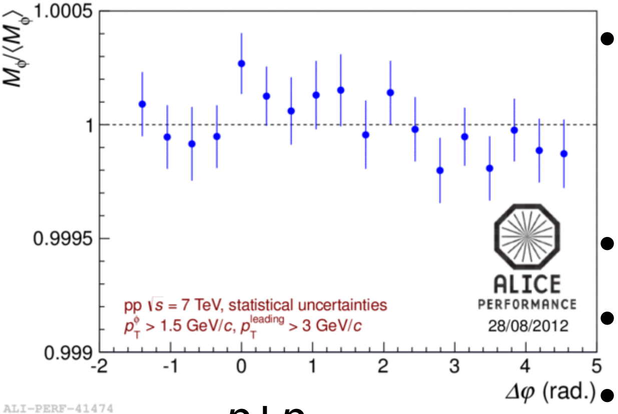
Angular Correlations

- Angular Correlation of trigger hadron with a ϕ meson
  - p_T(h)>3 GeV/*c*
  - $p_T(\phi)$>1.5 GeV/*c*





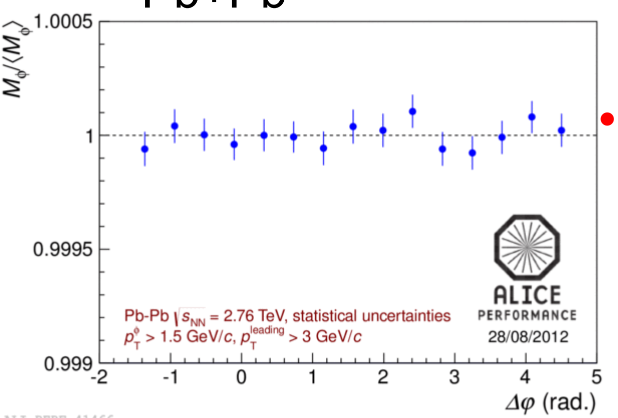
Mass and Width vs. $\Delta\varphi$



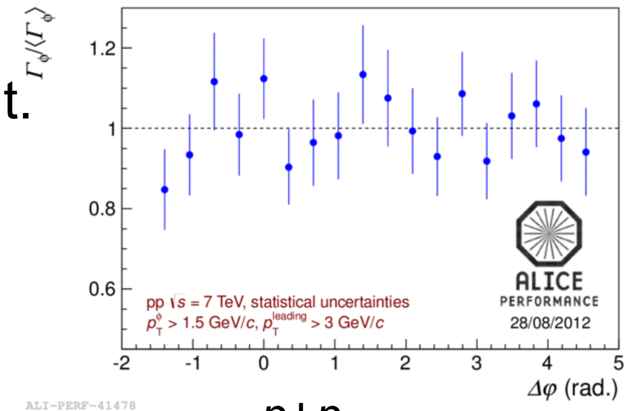
p+*p*

mass/average value

Pb+Pb



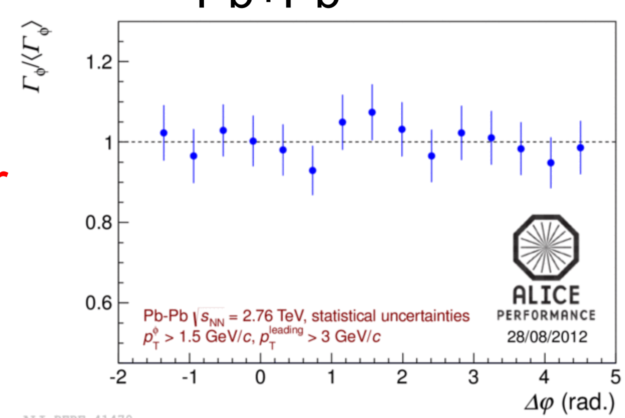
- ϕ mass and width as a function of angle ($\Delta\varphi$) w.r.t. leading hadron
- p_T(h)>3 GeV/c
- p_T(ϕ)>1.5 GeV/c
- Measured values divided by average value
- No clear difference in behavior between p+p and Pb+Pb
- In Pb+Pb: no mass shift or width broadening observed in away side
- However: ϕ signal may be dominated by non-jet ϕ for this p_T range



p+*p*

width/average value

Pb+Pb



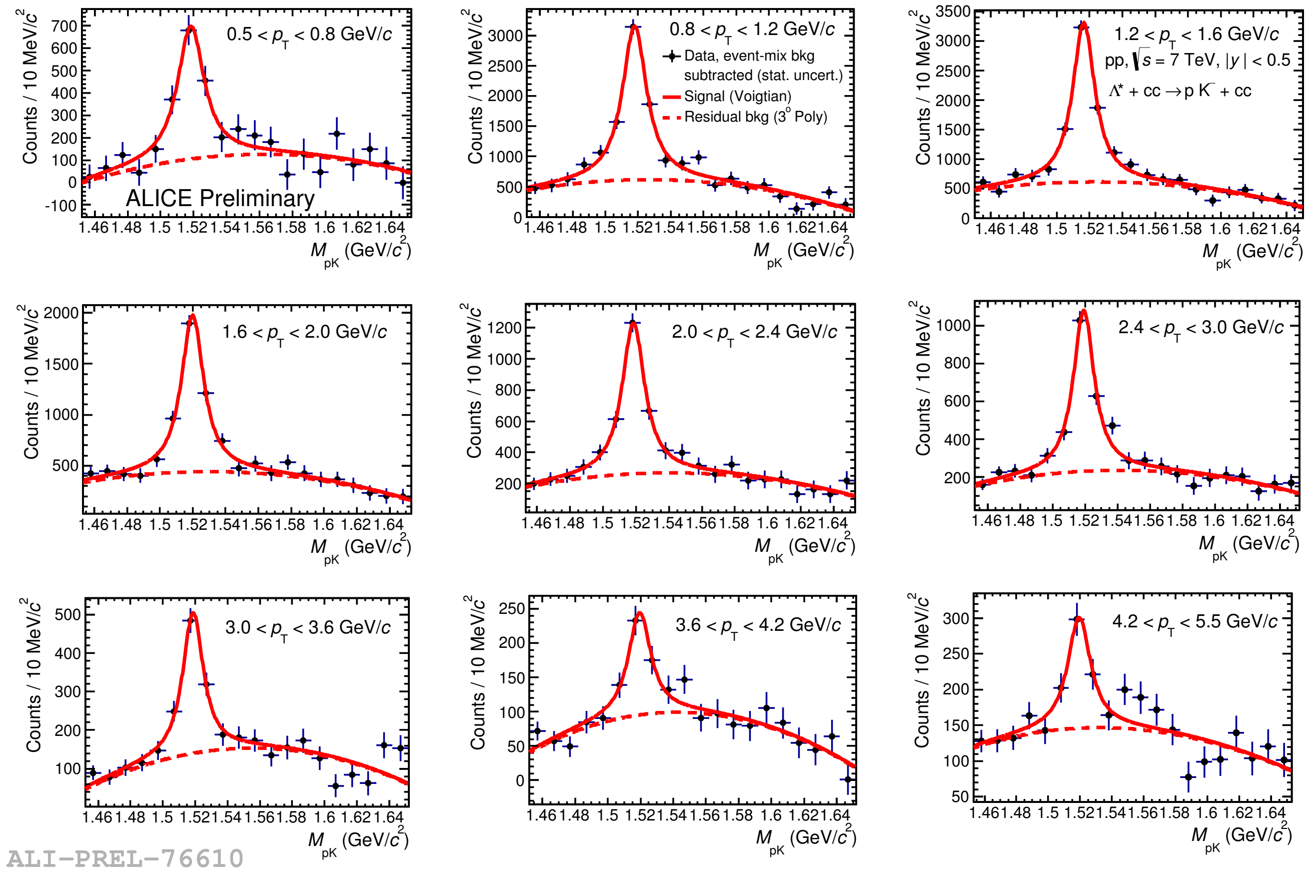
Conclusions

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

Backup Material

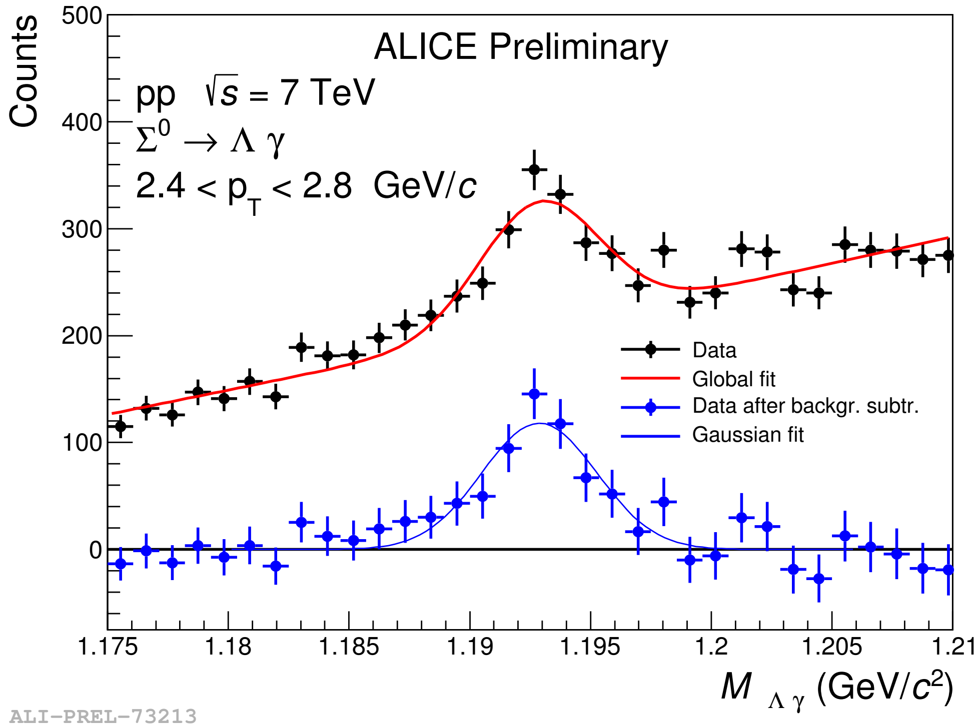
Λ(1520)

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



Σ^0

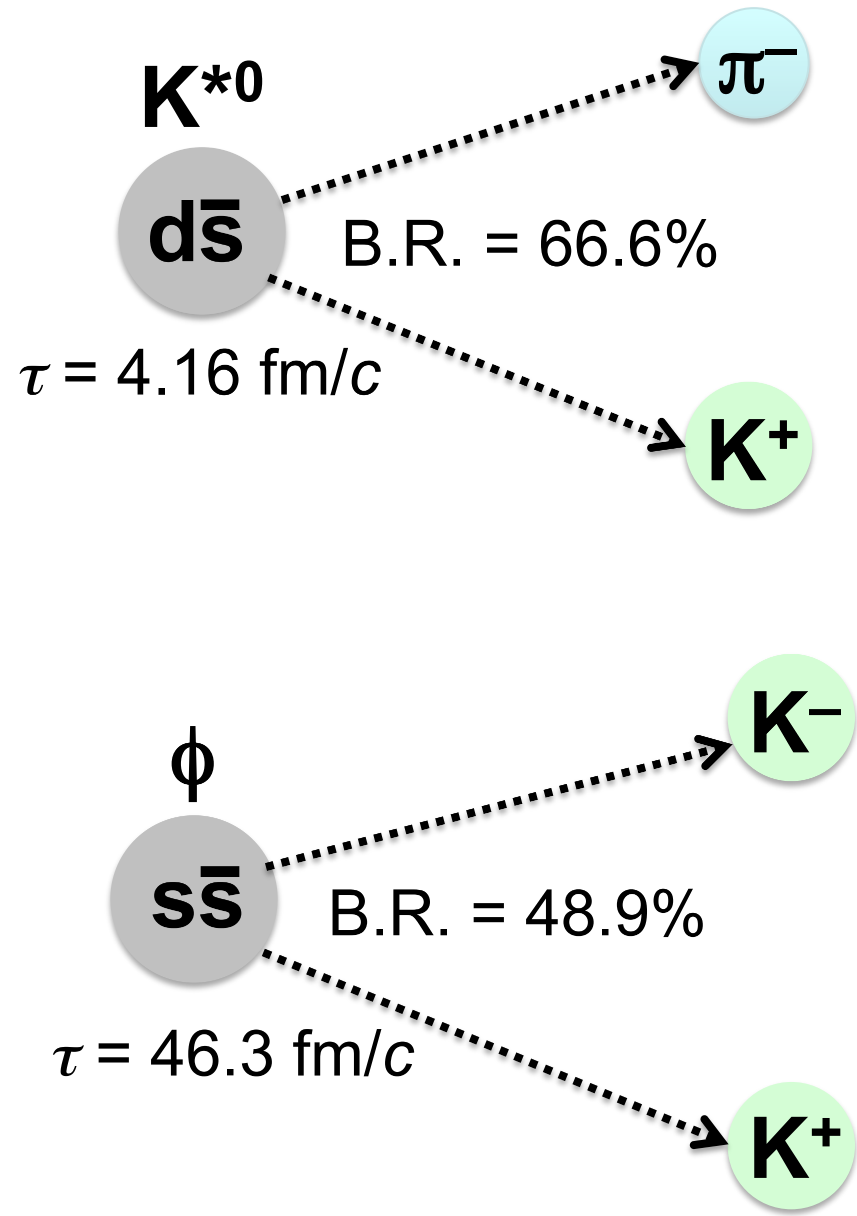
- Reconstruction in pp 7 TeV
- Decay channel: $\Sigma^0 \rightarrow \Lambda\gamma$
  - Photon identified through measurement of its conversion, and in PHOS (calorimeter)
- More information can be found in poster of A. Borissov at Quark Matter 2014: https://indico.cern.ch/event/219436/session/2/contribution/196/material/slides/0.pdf



Resonances in p+p Collisions

$K^*(892)^0$ and $\phi(1020)$

- Similar to Pb+Pb analyses:
- p+p 900 GeV: 250 k minimum-bias events
- p+p 7 TeV: 80 M (60 M) minimum-bias events for K^{*0} (ϕ)
- Use TPC for PID, plus TOF (if there is a signal)
- Mixed-event combinatorial BG
- Peak fits:
  - K^{*0}: Breit-Wigner
  - ϕ: Voigtian
- Published



K*(892)^0 and φ(1020)

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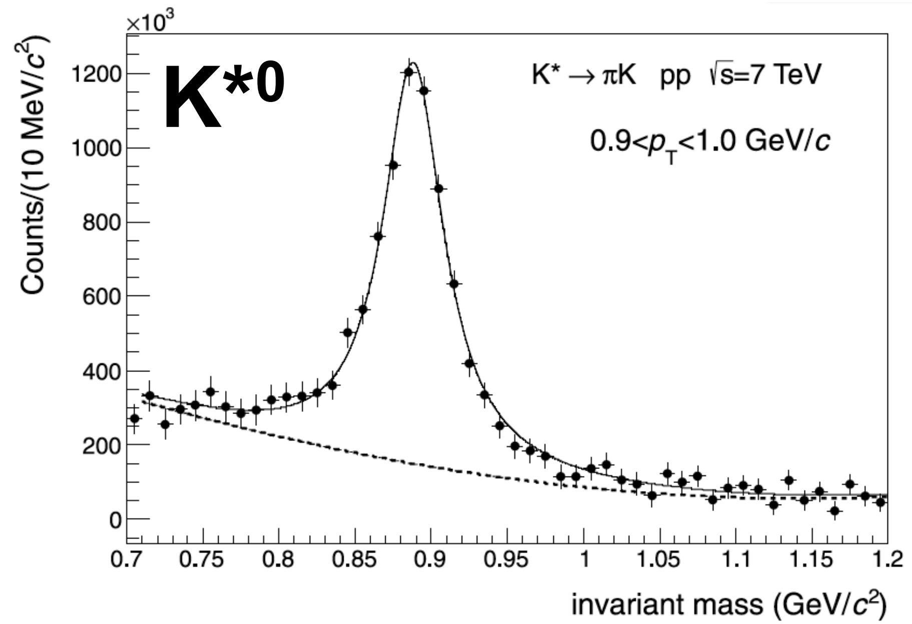
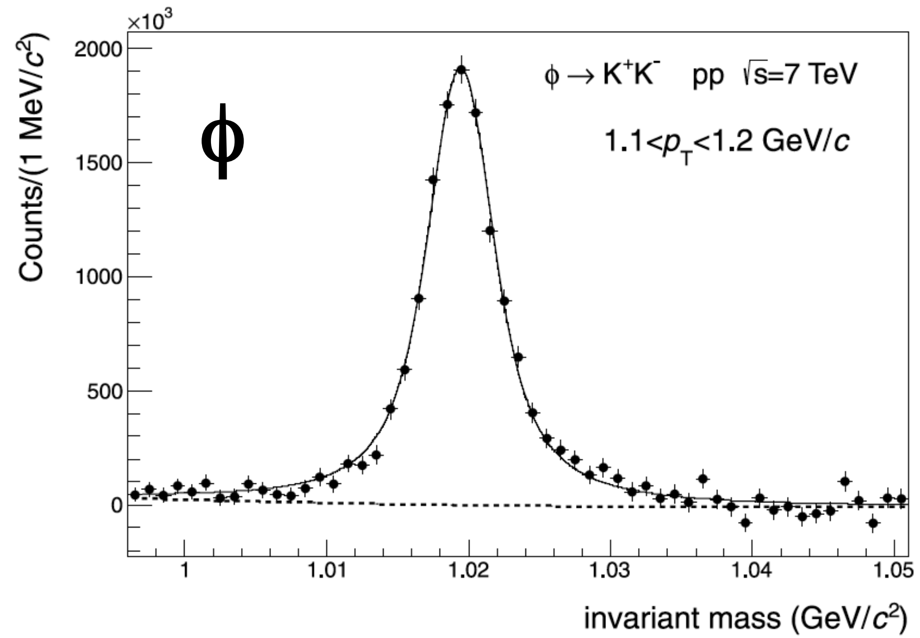
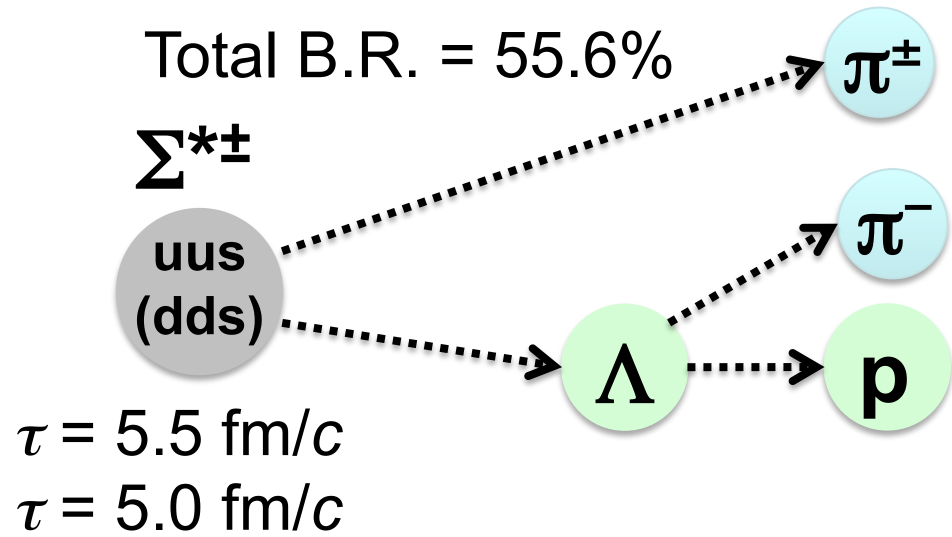
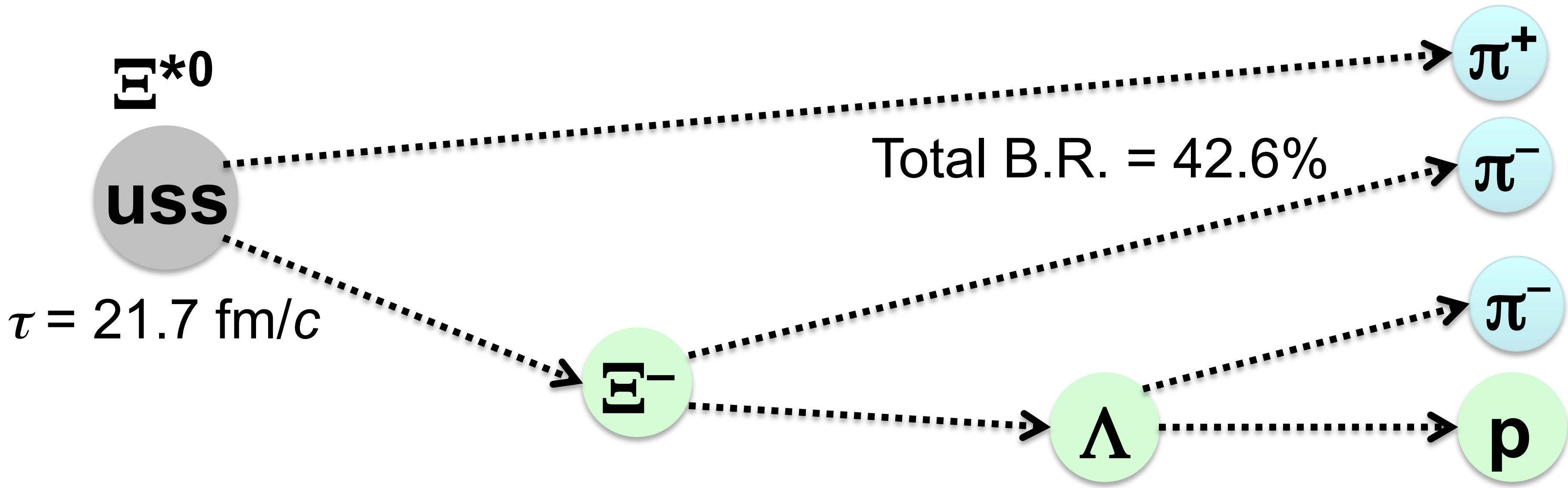




$\Sigma^*(1385)^{\pm}$ and $\Xi^*(1530)^0$

- 250 M p+p events (MB)
- TPC PID for $\Sigma^{*\pm}$ daughters
- Numerous topological cuts:
  - DCA
  - cos(pointing angle)
  - Fiducial volume
  - Invariant mass of Λ or Ξ^-





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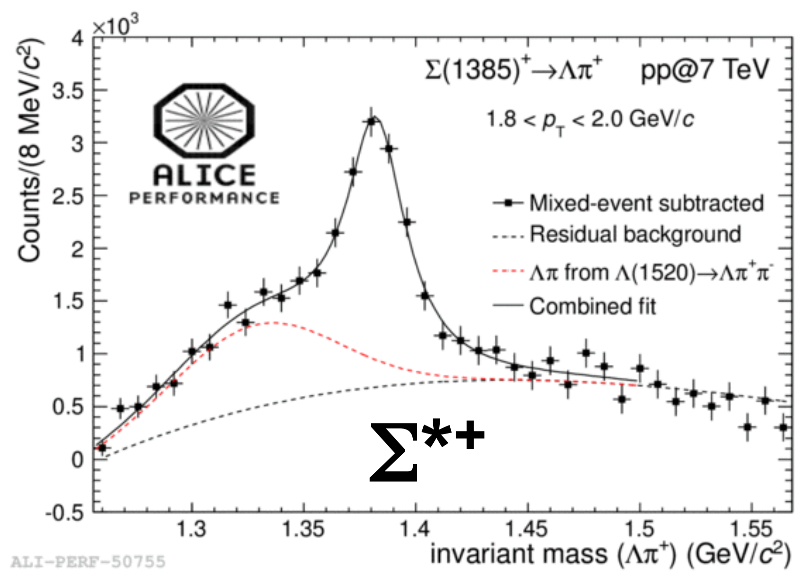
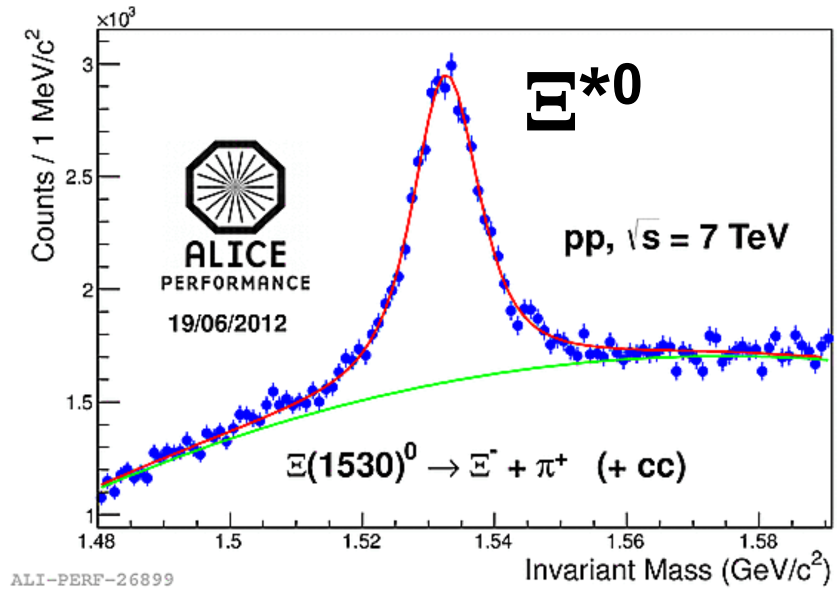
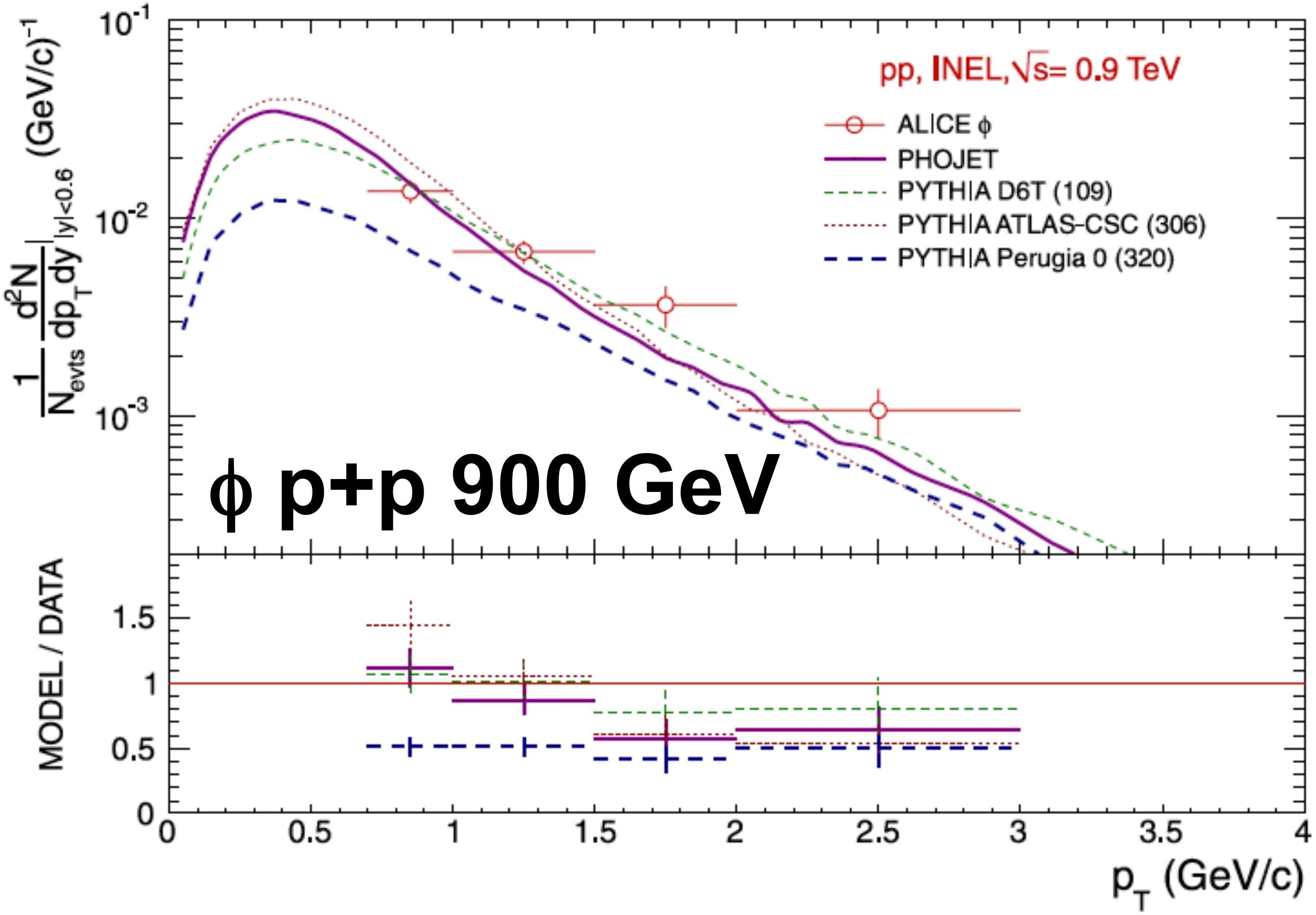
- Numerous topological cuts:
  - DCA
  - cos(pointing angle)
  - Fiducial volume
  - Invariant mass of Λ or Ξ^-
- Mixed-event combinatorial BG
- $\Sigma^{*\pm}$: complicated res. BG
  - Various sources of correlated $\Lambda\pi$ pairs (e.g., Ξ^- and Λ^* decays)
  - Shape of each contribution fit in MC, normalized using data
- For Ξ^{*0}: polynomial res. BG
- Paper in preparation



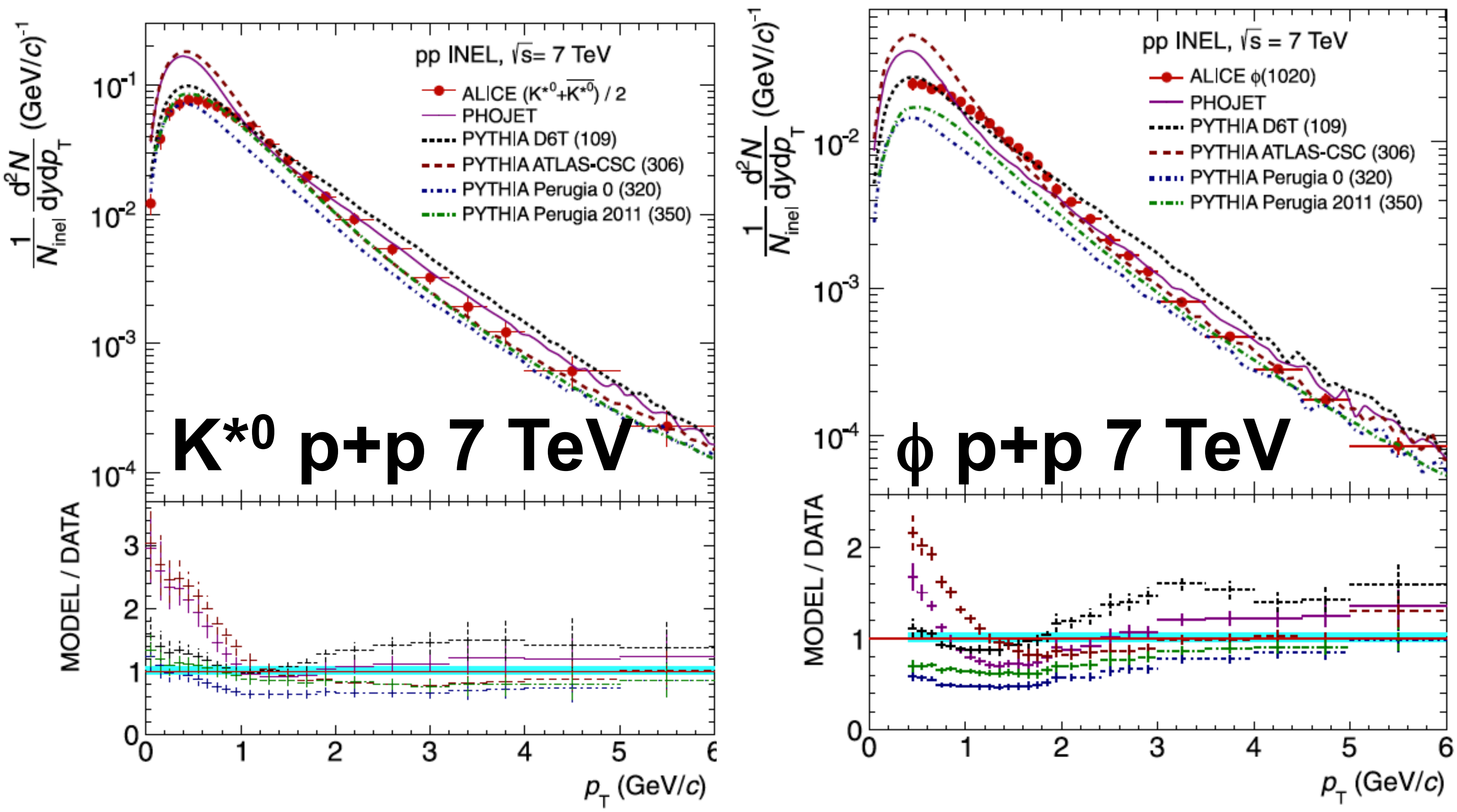


PYTHIA Comparisons



- PHOJET and PYTHIA ATLAS-CSC too soft
- PYTHIA D6T: reasonably good description
- PYTHIA Perugia 0: underestimates yield, but shape well reproduced

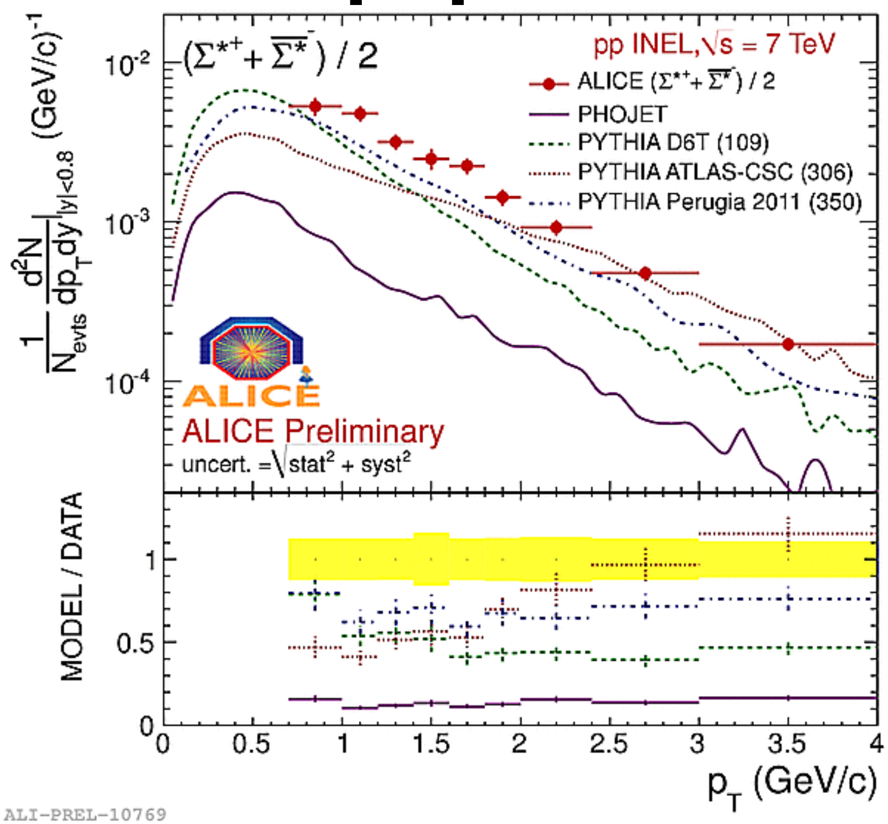
PYTHIA Comparisons



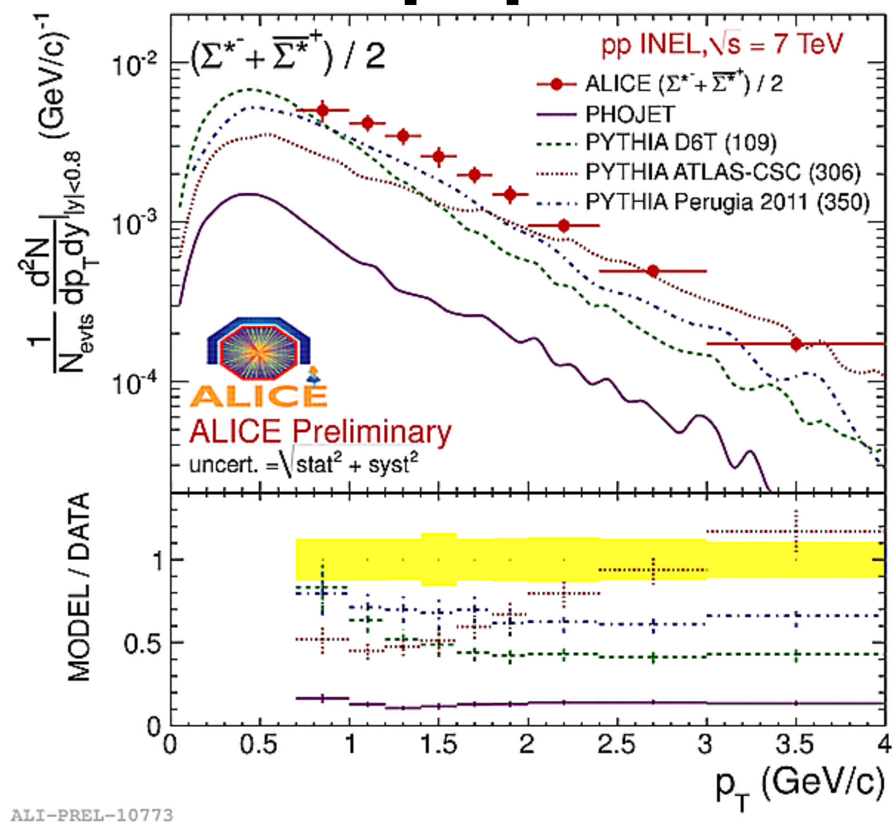
- PYTHIA Perugia 2011: reproduces K^{*0} and high-p_T ϕ well
- PHOJET and PYTHIA ATLAS-CSC overestimate spectra for p_T<1 GeV/c, describe high p_T well
- PYTHIA D6T: deviates at high p_T
- PYTHIA Perugia 0: underestimates spectra

PYTHIA Comparisons

Σ^{*+} p+p 7 TeV



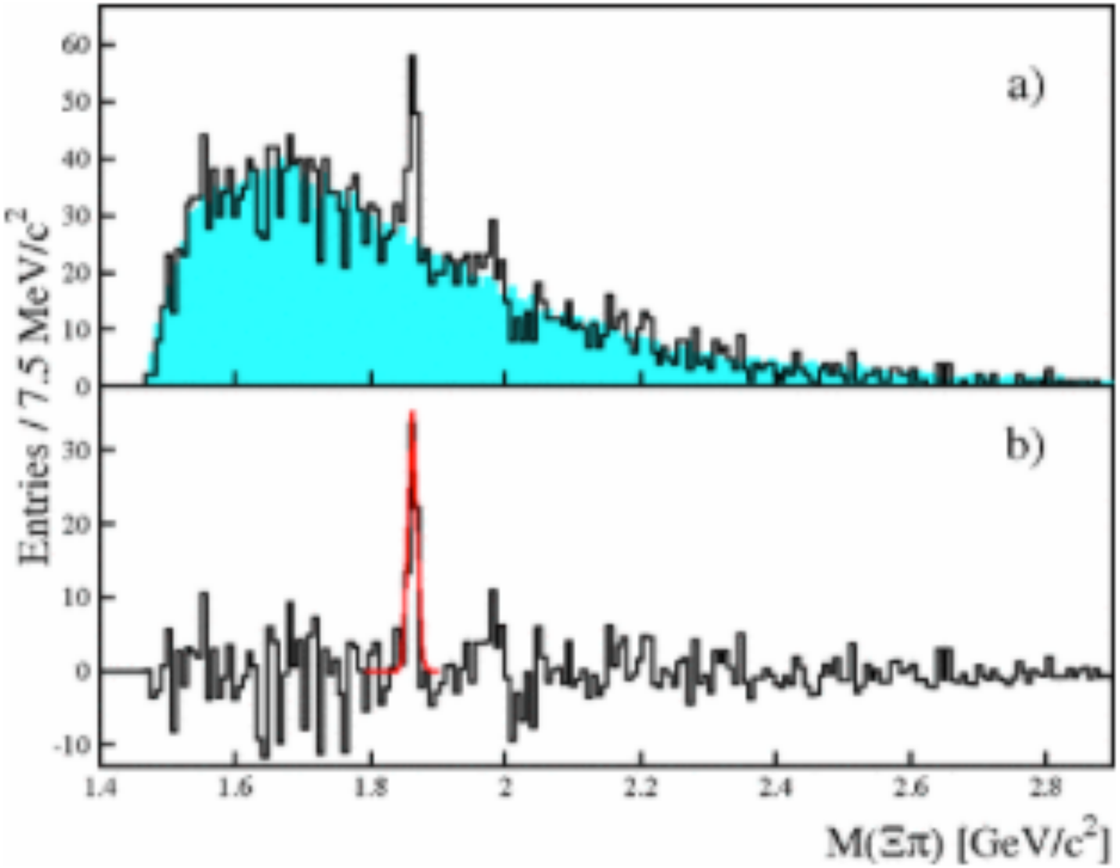
Σ^{*-} p+p 7 TeV



- PYTHIA ATLAS-CSC : good agreement for $p_T > 2$ GeV/c (too hard?)
- PHOJET and PYTHIA D6T under-predict spectra
- PYTHIA Perugia 2011: under-predicts yields, describes shapes

Pentaquarks

- $\Phi(1860)^{--}$ ($ddss\bar{u}$) and $\Phi(1860)^0$ ($udss\bar{d}$) would have $\Xi^-\pi^\pm$ decay channels, similar to Ξ^{*0}
- Observed by NA49
- ALICE sees no significant signal



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