Hadronic Resonances in Heavy-Ion Collisions

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Starting at the Beginning

Transition to hadronic matter:

Time ~ 10 μs

Temp. ~ 2×10^{12} K

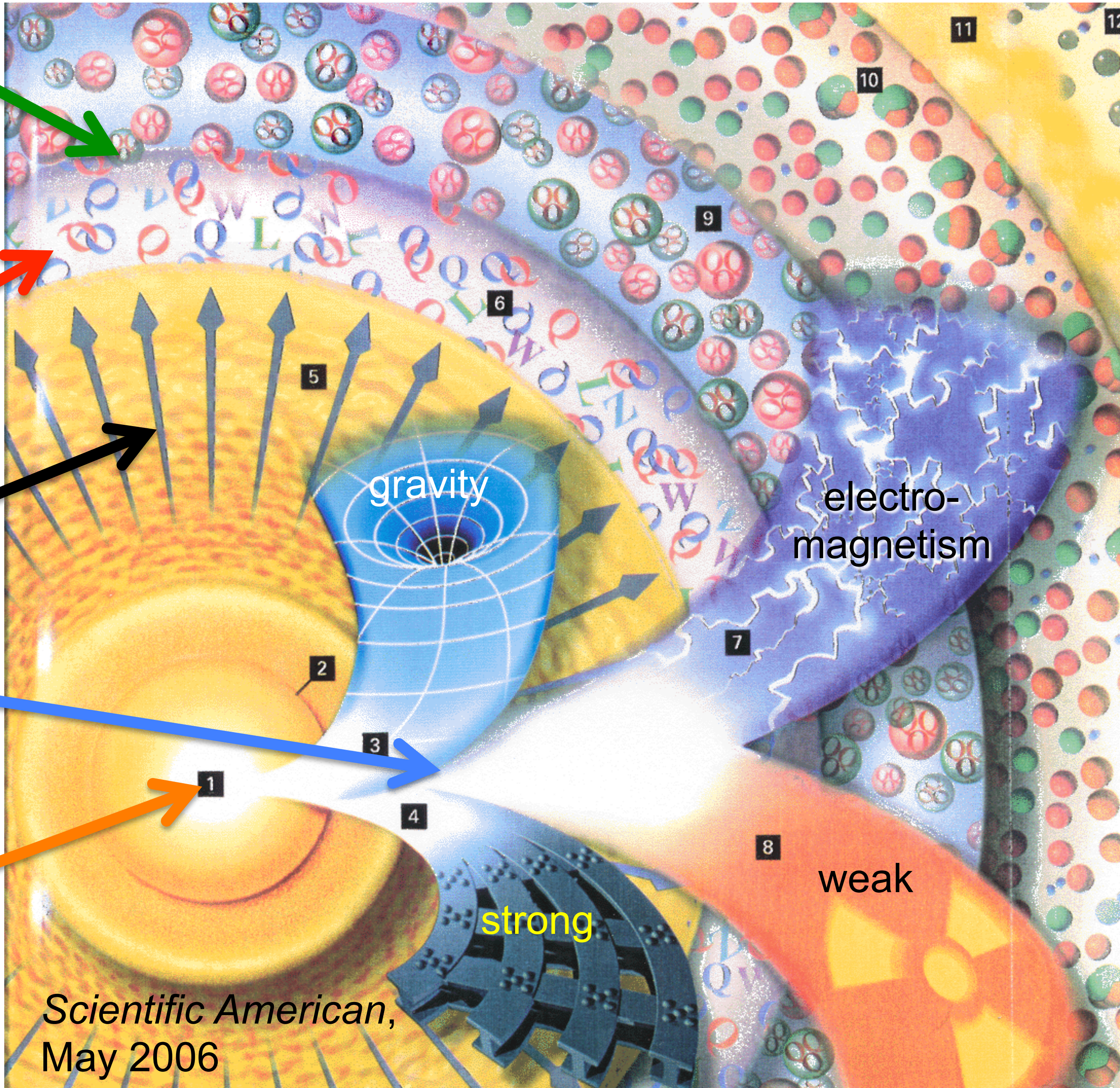
Quark-Gluon Plasma (QGP)

"soup" of deconfined quarks and gluons

inflation

fundamental forces separate

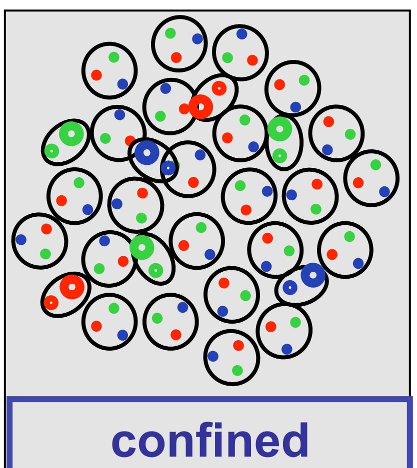
Big Bang

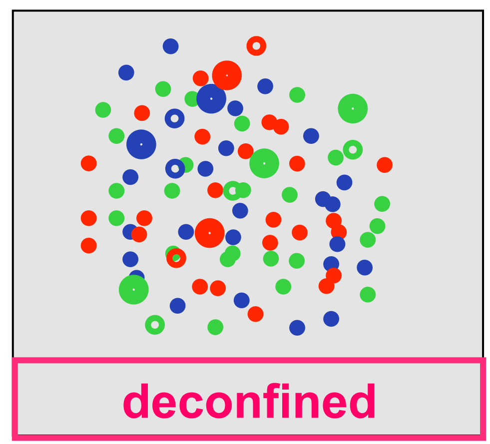


Scientific American, May 2006

(De)confinement

- Asymptotic freedom → confinement at large distances:
  - As interquark distance increases, it becomes energetically favorable to create a new $q\bar{q}$ pair.
- Asymptotic freedom → deconfinement for large energy densities:
  - Compress or heat hadronic matter to a sufficient energy density (0.3–1 $\mathrm{GeV/fm^3}$)
  - QCD vacuum “melts” and turns from color dielectric to color conductor
  - Leads to deconfined (but not isolated) quarks and gluons
  - A “soup” of quarks and gluons: the Quark-Gluon Plasma (QGP)





Asymptotic Freedom

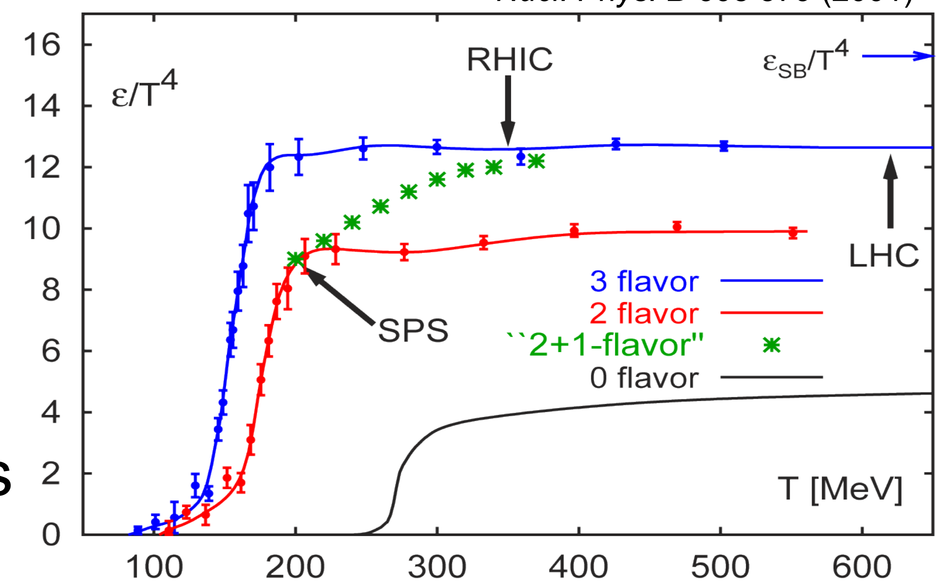
- 2004 Nobel Prize in Physics:
  - D. Gross, H. D. Politzer, and F. Wilczek
  - "for the discovery of asymptotic freedom in the theory of the strong interaction"

- "Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today…since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted…to form a quark-gluon plasma." – D. Gross, Nobel Lecture

Lattice QCD

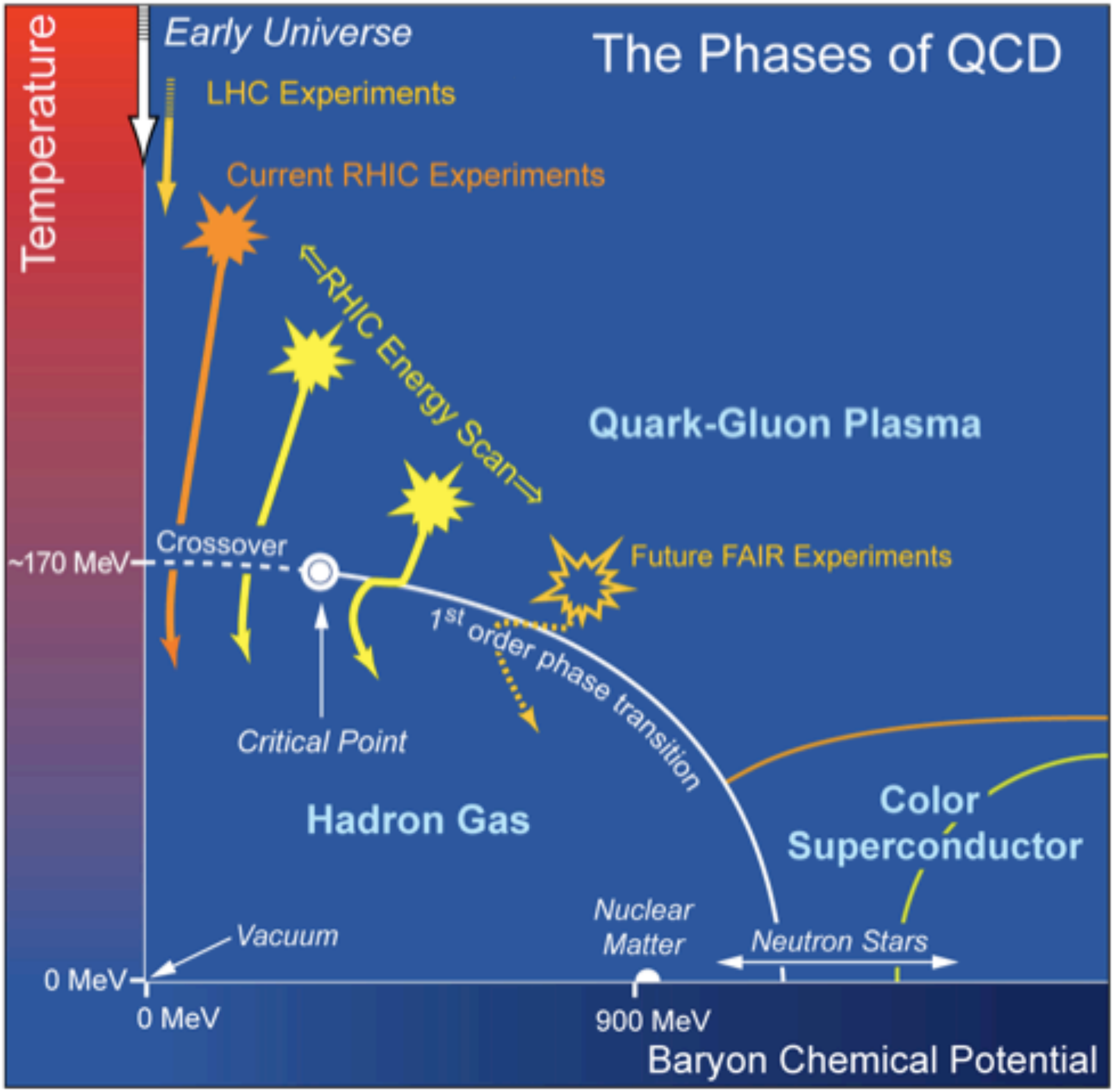
- Predictions of phase transition from Lattice QCD
- Calculation of ε/T^4 vs. Temperature
  - ε/T^4 ~ # degrees of freedom
- For T~150 MeV, sharp increase in degrees of freedom: hadrons → quarks and gluons
- Typical estimates: T_C = 150 – 180 MeV (10^5× hotter than the core of the sun)

Nucl. Phys. B **605** 579 (2001)



QCD Phase Diagram

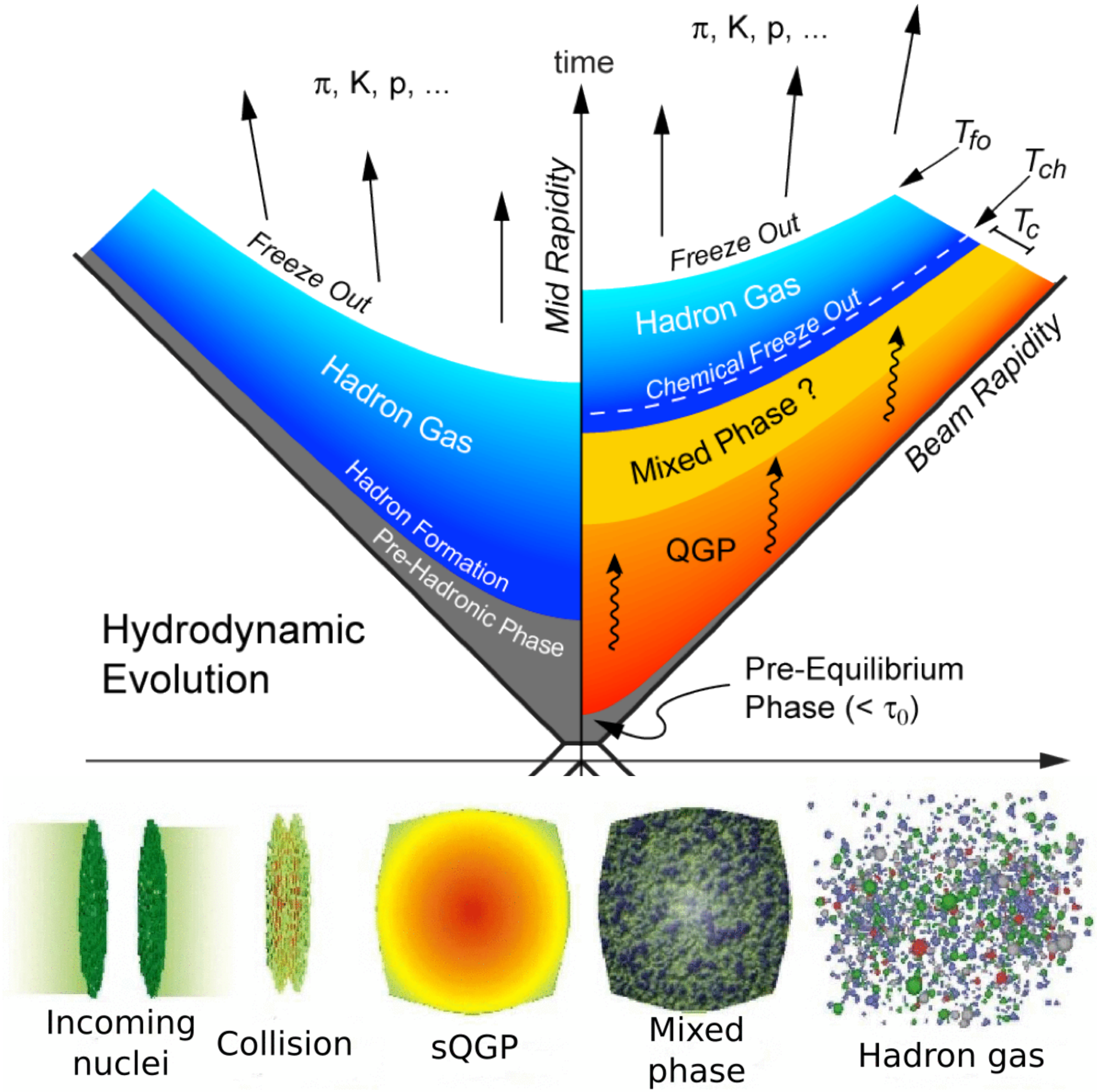
- Baryon chemical potential: related to matter-antimatter asymmetry
- In very high-energy collisions, most particles are produced in the collision itself → matter-antimatter symmetry
- Crossover or 1st-order phase transition between hadron gas and QGP
- Critical point?



How to Make QGP

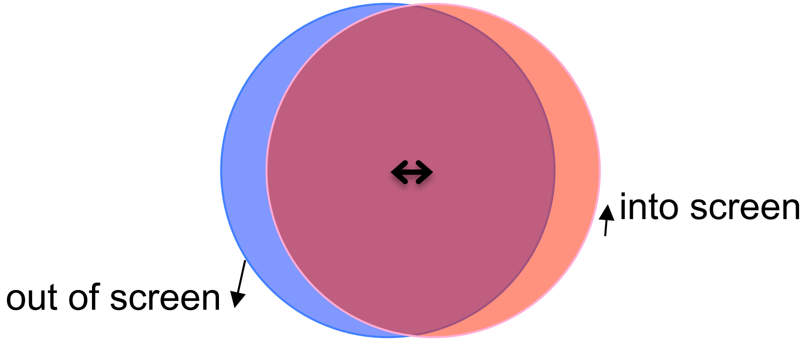
- Introduce large amount of energy into a space the size of an atomic nucleus.
  - Collide heavy ions: Au, Pb, U to produce large volume of QGP
- Baselines for heavy-ion measurements:
  - *p*+*p* collisions: no QGP
  - Asymmetric collisions: *d*+Au, *p*+Au, *p*+Pb
    - No QGP, but still large volumes of “cold” nuclear matter

Time Evolution

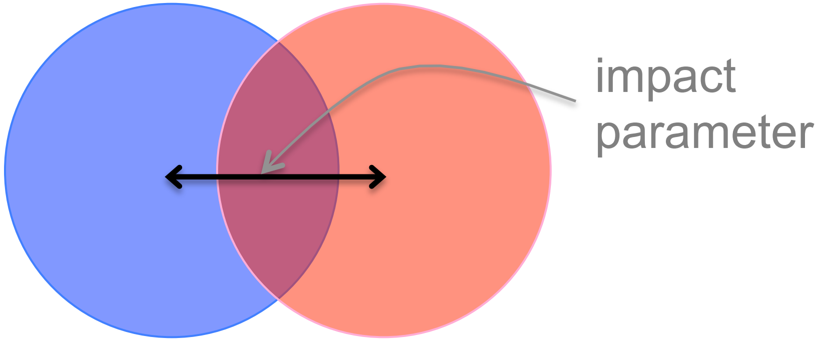


Collision Centrality

- 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 $\bar{p}$)
  - Number of spectator neutrons (pass through the collision unaffected)
  - Use models to map these measurements into impact parameter

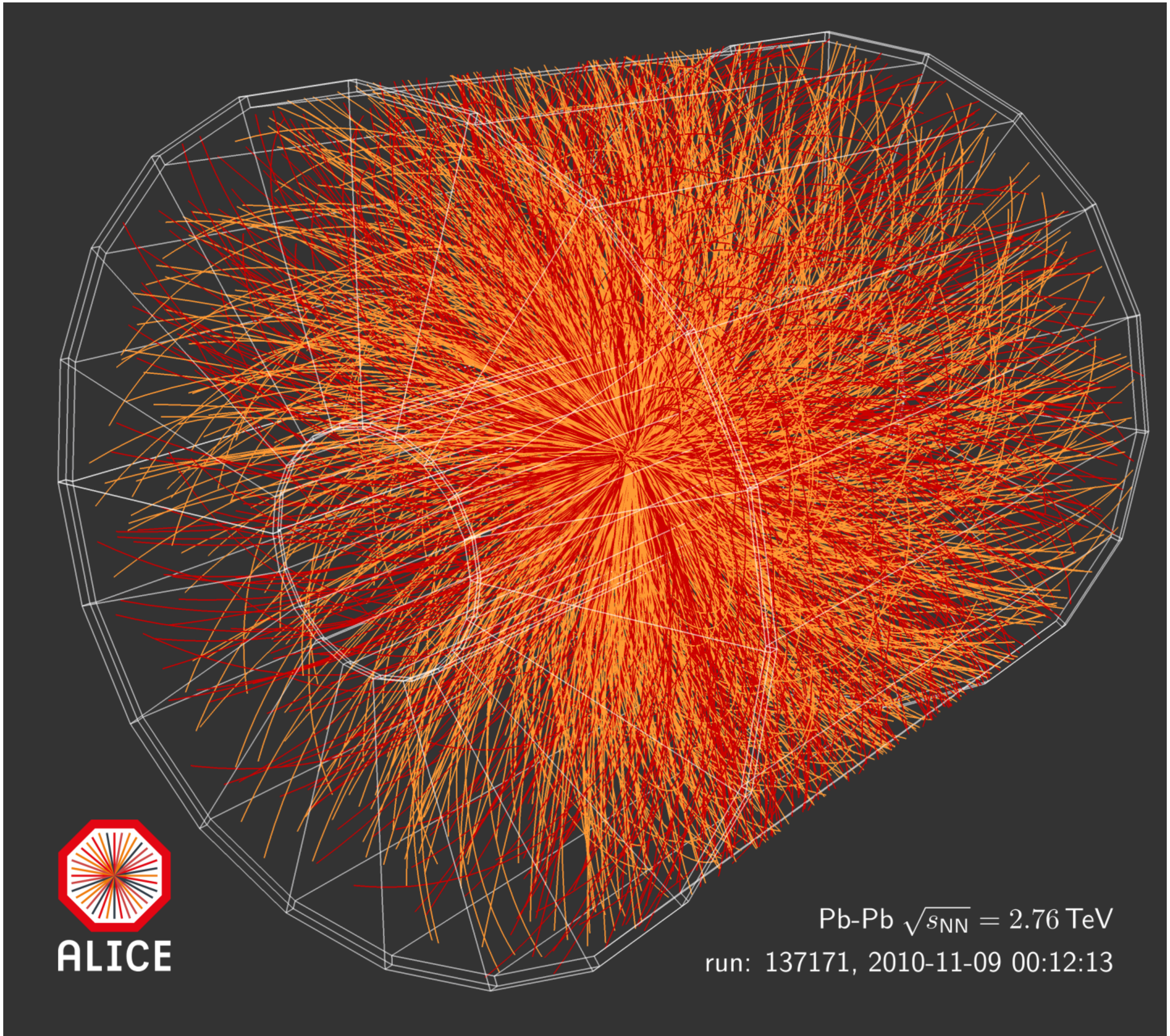


“Central”
Small impact parameter
Large volume of QGP



“Peripheral”
Large impact parameter
Small volume of QGP

ALICE Pb+Pb Collision



Heavy-Ion Physics

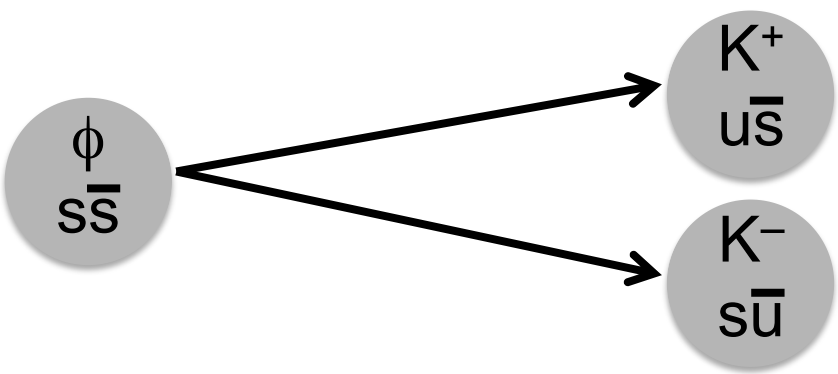
- Heavy-ion collisions are not simple superpostions of nucleon-nucleon collisions.
- Ultrarelativistic heavy-ion collisions produce a quark-gluon plasma: a strongly coupled “soup” of deconfined quarks and gluons.
- The QGP absorbs energy, leading to suppression of high-momentum hadrons and jets, but not of colorless probes (γ, $W^{\pm}$, Z).
  - Nuclear Modification Factor (R_{AA})…
- The QGP appears to be a thermalized “perfect liquid” with a viscosity near 0. Its behavior, including elliptic flow, is well described by ideal hydrodynamics.

Outline

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

Resonances

- What particles do we study?
  - Hadronic states with short lifetimes (~ lifetime of fireball)
  - For practical reasons, we prefer resonances with only charged particles at the end of the decay chain.



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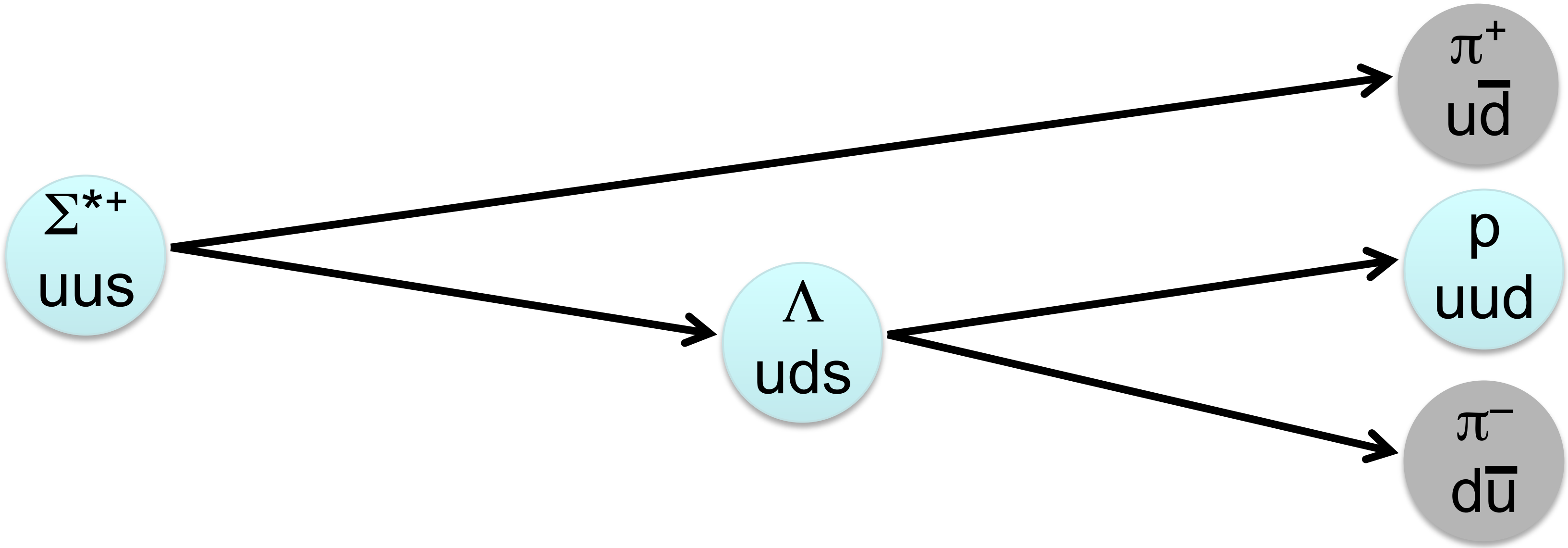


ALICE Resonance Program

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

K^{*0}	$d\bar{s}$
ϕ	$s\bar{s}$

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

Σ^{*-}	dds
Σ^{*+}	uus
Ξ^{*0}	uss

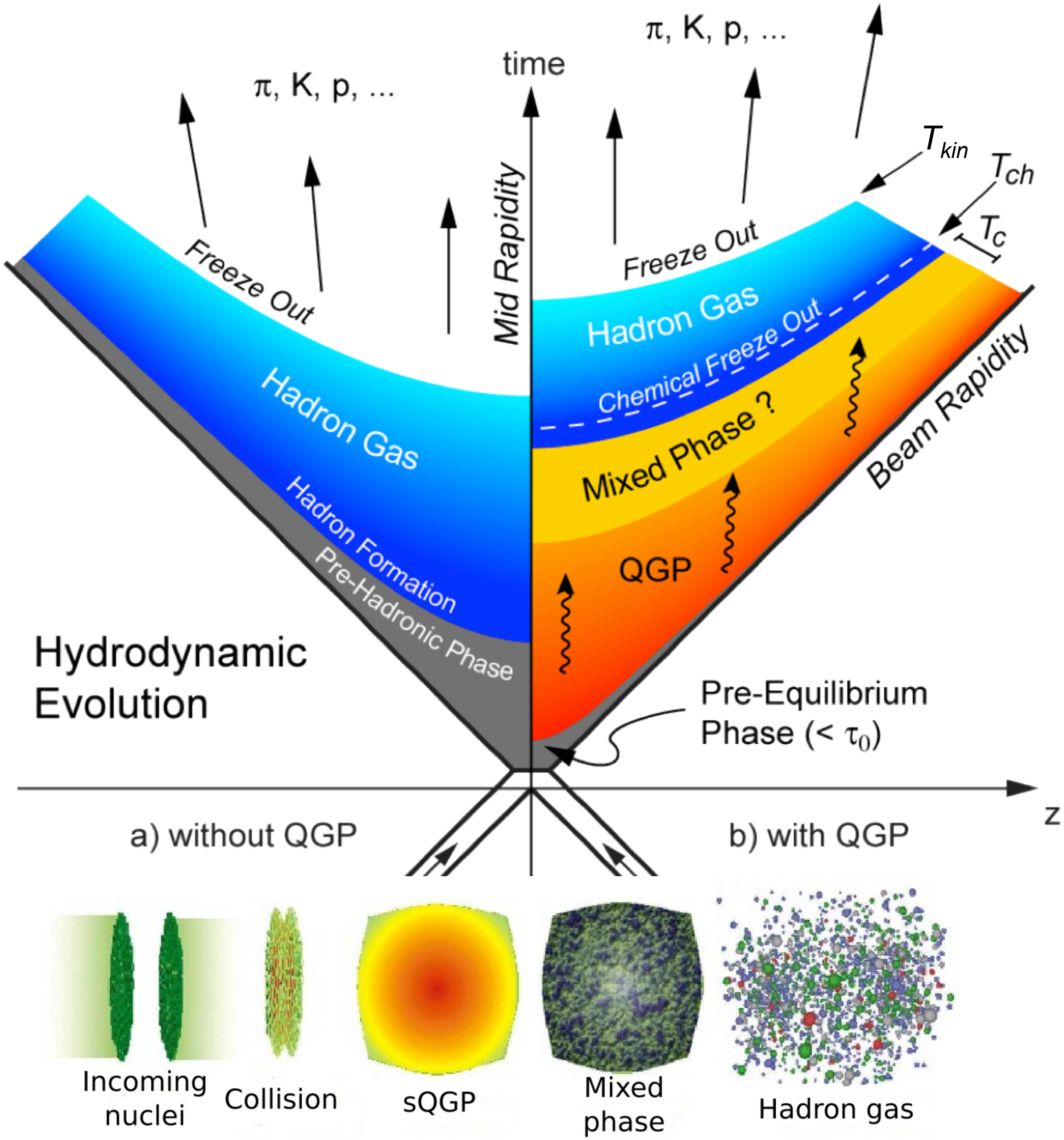
Advanced studies
(but few public results)

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

Other Studies:

K^{*+}	$u\bar{s}$
Δ^{++}	uuu

Heavy-Ion Collisions



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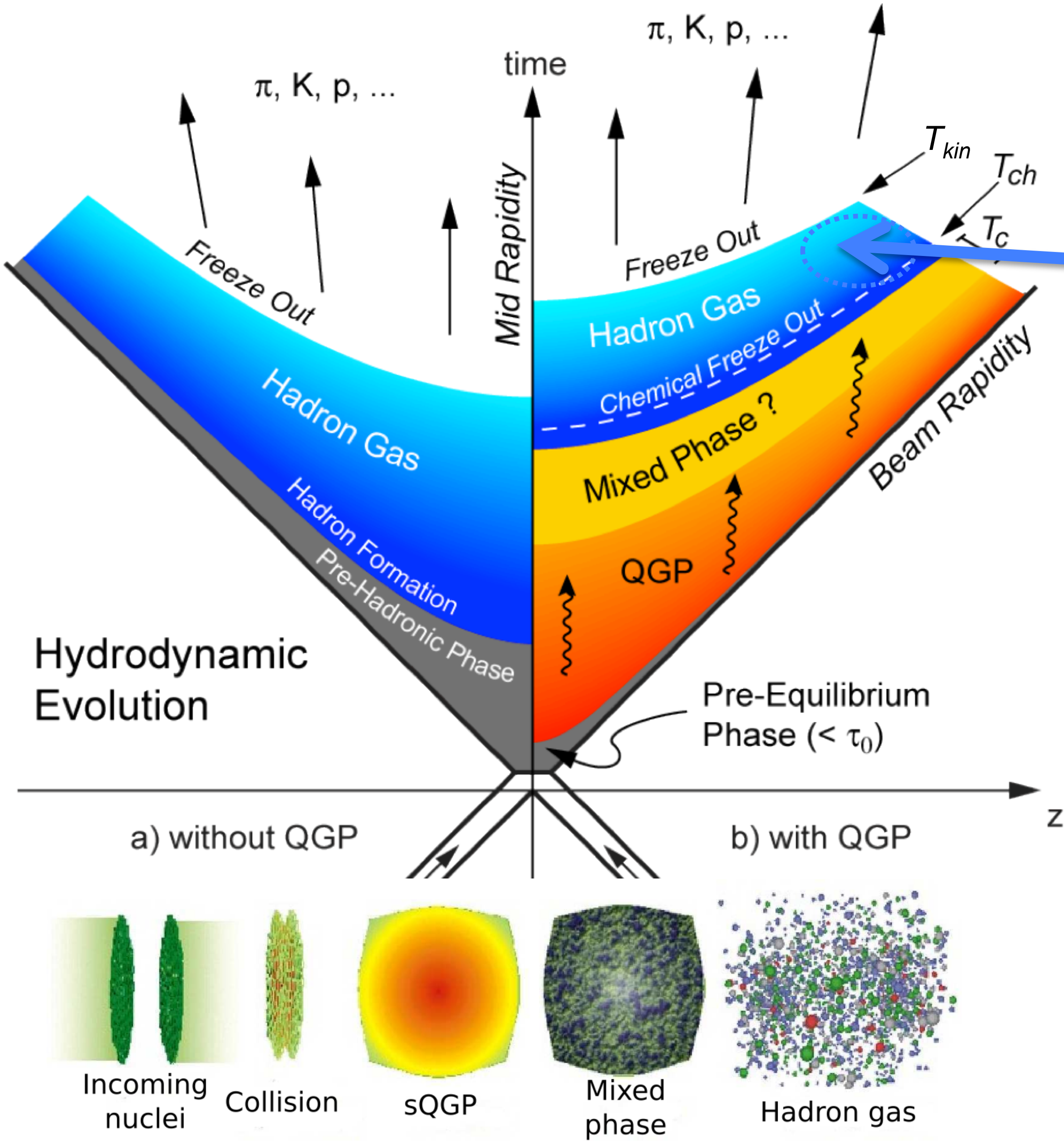
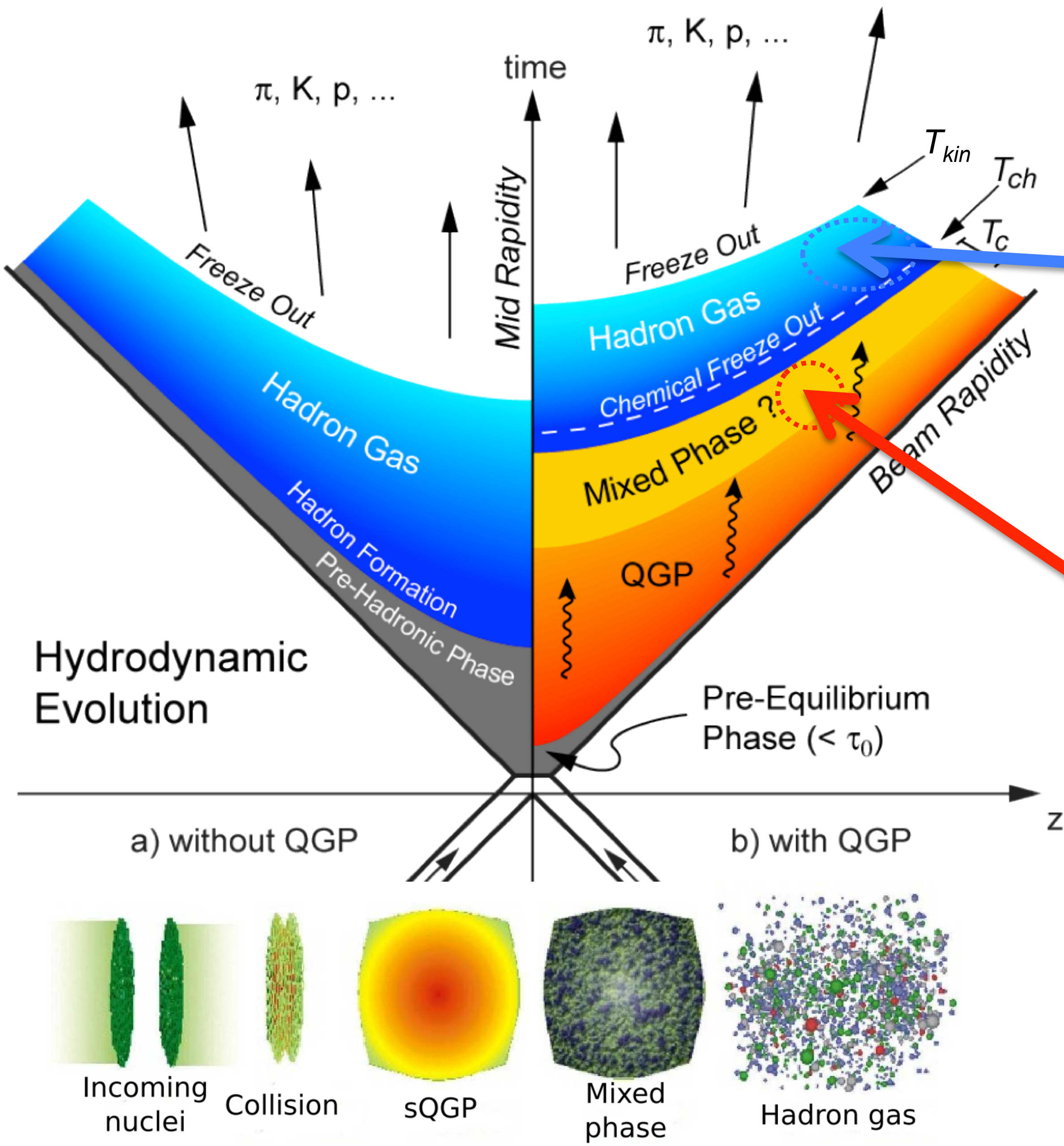


Properties of Hadronic Phase

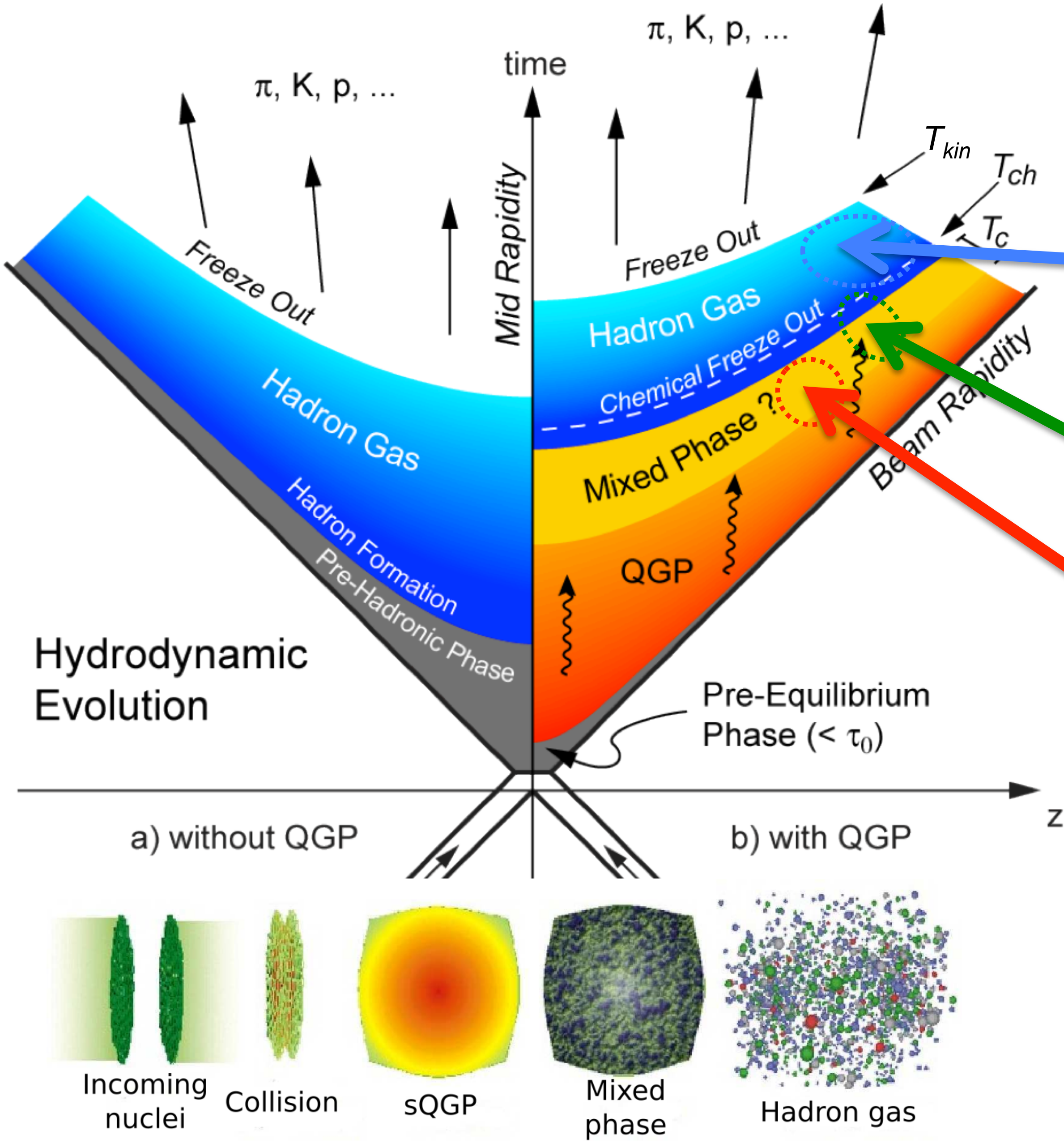
Heavy-Ion Collisions



Properties of Hadronic Phase

Chiral Symmetry Restoration

Heavy-Ion Collisions

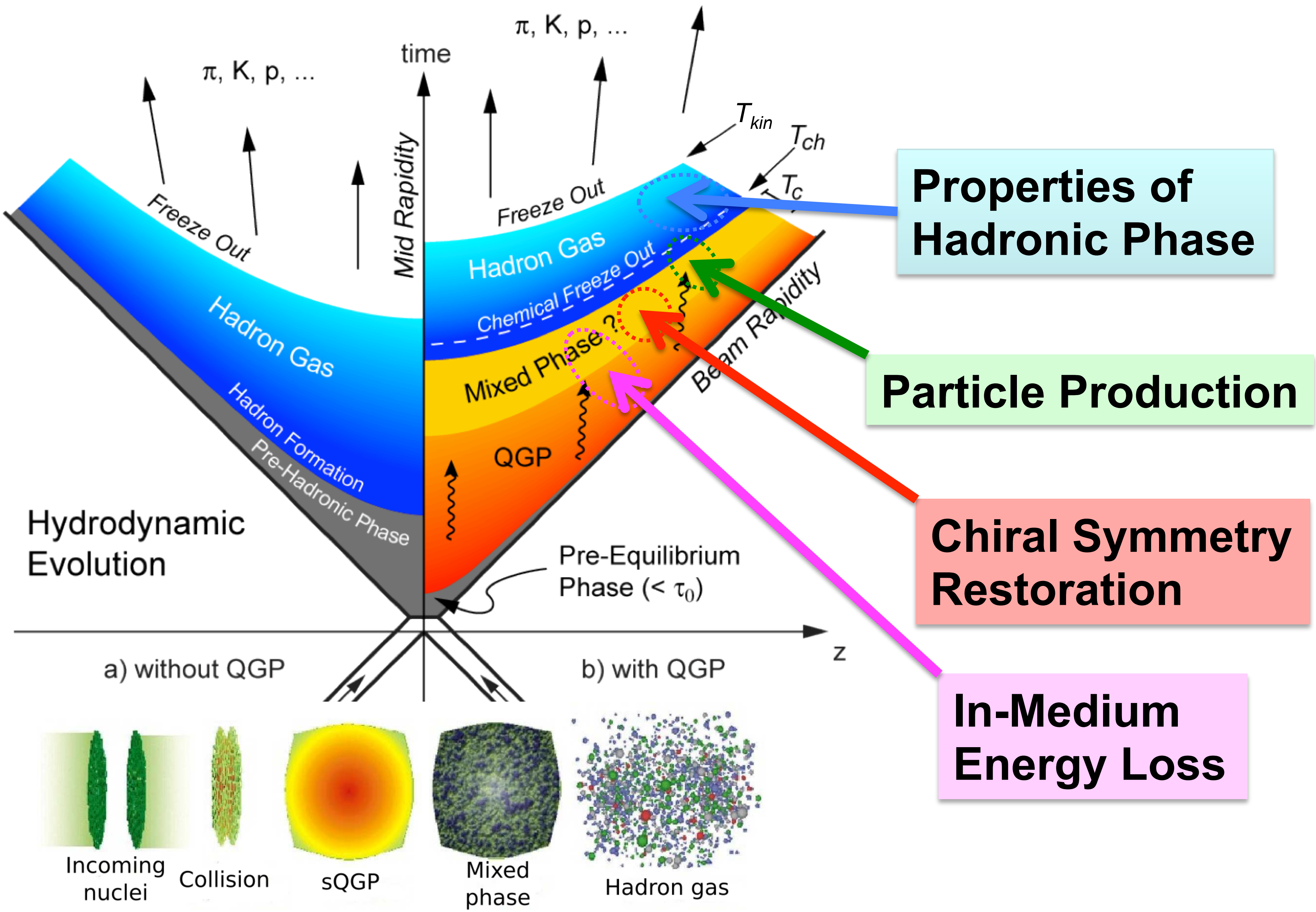


Properties of Hadronic Phase

Particle Production

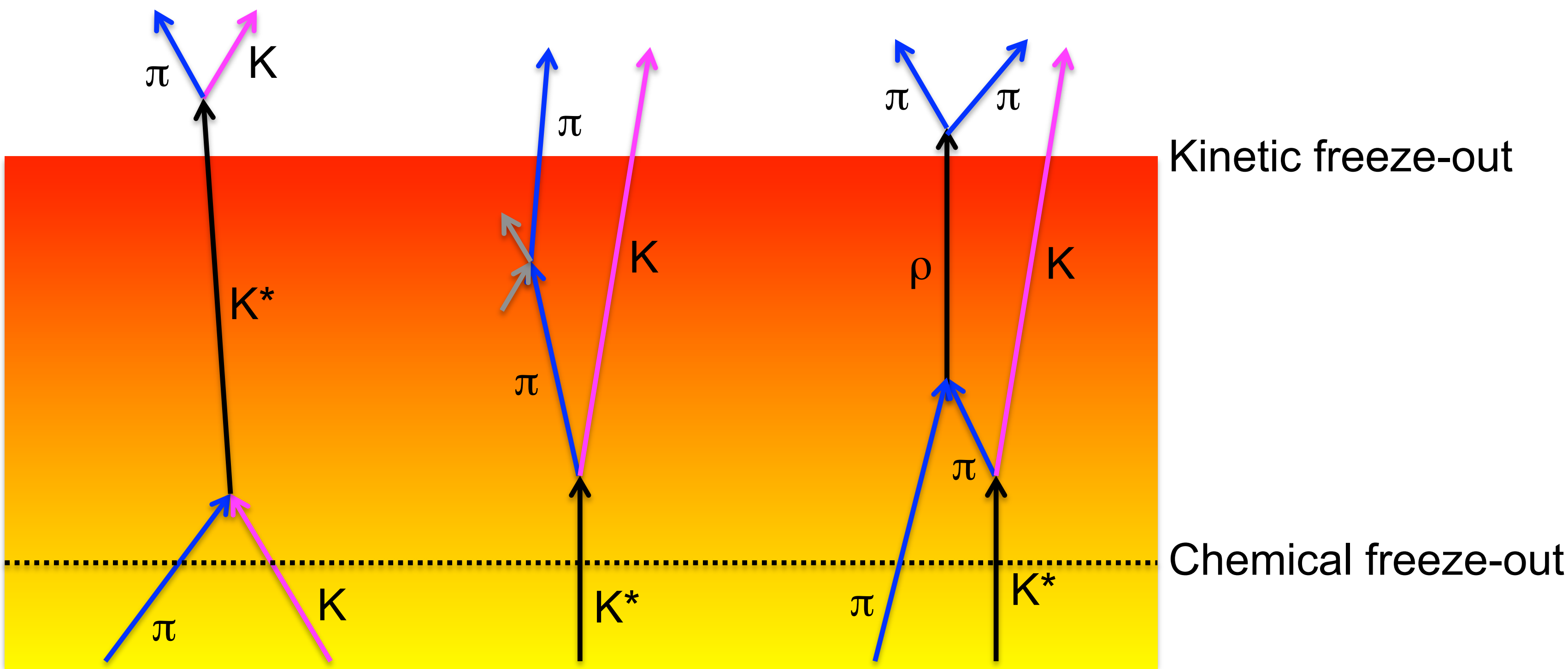
Chiral Symmetry Restoration

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

- Reconstructible resonance yields affected by hadronic processes after chemical freeze-out:
  - **Regeneration:** pseudo-elastic scattering of decay products
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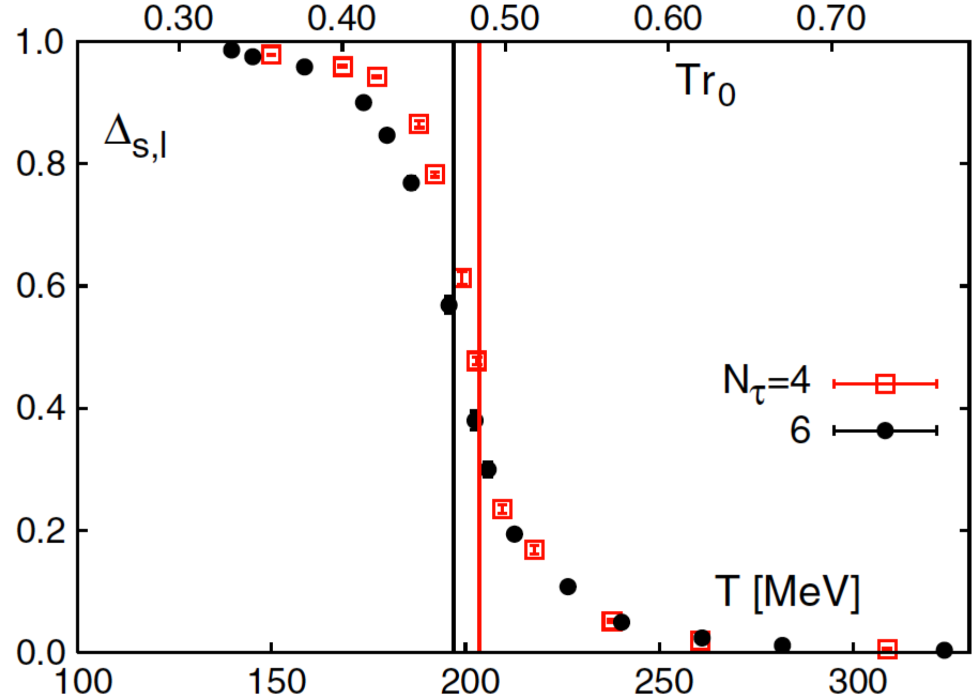
  - **Re-scattering:**
    - Resonance decay products undergo elastic scattering
    - Or pseudo-elastic scattering through a different resonance (e.g. ρ)
    - Resonance not reconstructed through invariant mass
- Final yields at kinetic freeze-out depend on
  - Chemical freeze-out temperature (T_{ch})
  - 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 ⇔ **$m_q \rightarrow 0$**

- Quark condensate <0|q̅q|0> fills QCD vacuum
- Effective q masses related to value of condensate: $m_q^* \propto$ <0|q̅q|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)

Chiral Symmetry Restoration

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

- Quark condensate $\langle 0|\bar{q}q|0\rangle$ fills QCD vacuum
- 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, EPOS, …)

Hydrodynamics:
– Particle masses determine shapes of spectra

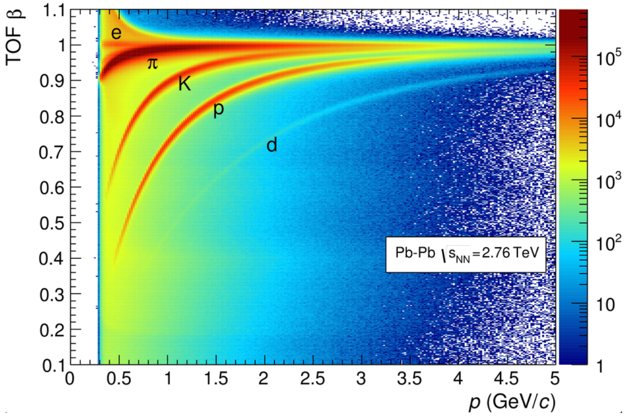
Quark Recombination:
– Number of quarks influences shapes of spectra
– Differences between baryons and mesons with similar masses

- 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
  - Probe parton distribution functions at low x
  - Searches for collective behavior

ALICE Detector

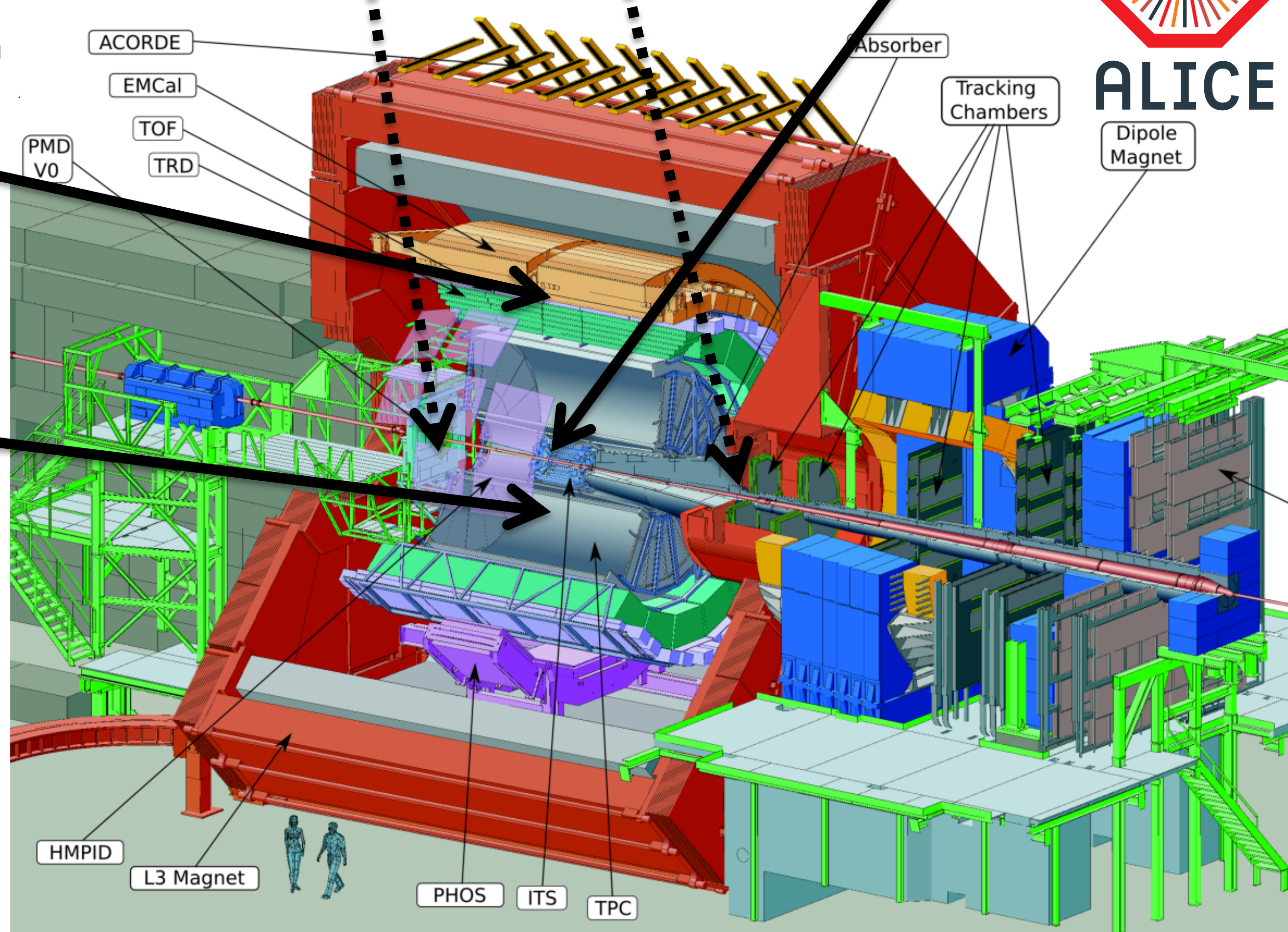


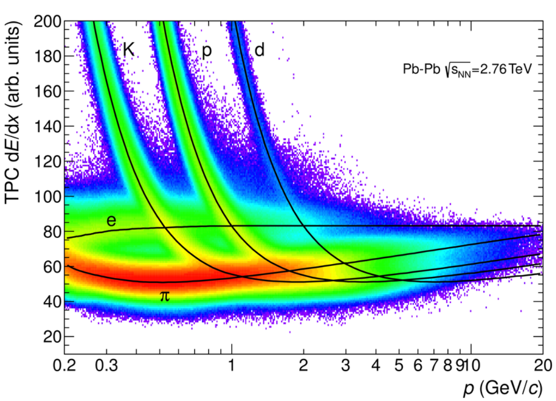
VZERO (scintillators): multiplicity, centrality

ITS (silicon): Tracking and Vertexing

TOF: PID through particle velocity

TPC: Tracking and PID through dE/dx





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 ($n\sigma$)**

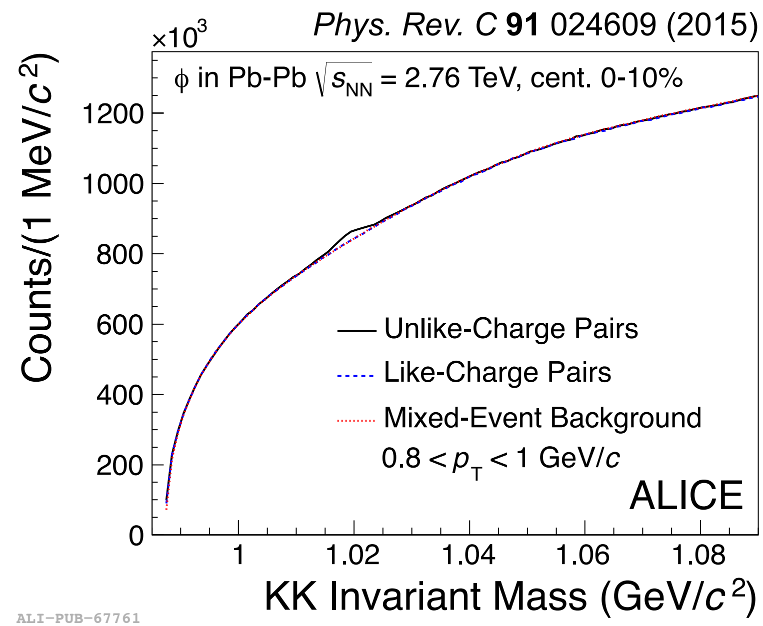
Find intermediate decay products (*e.g.*, Λ):

- **Cuts on decay topology**
- **Invariant mass**

Finding Resonances

Find decay products

Construct invariant mass distributions



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

Find decay products

↓

Construct invariant mass distributions

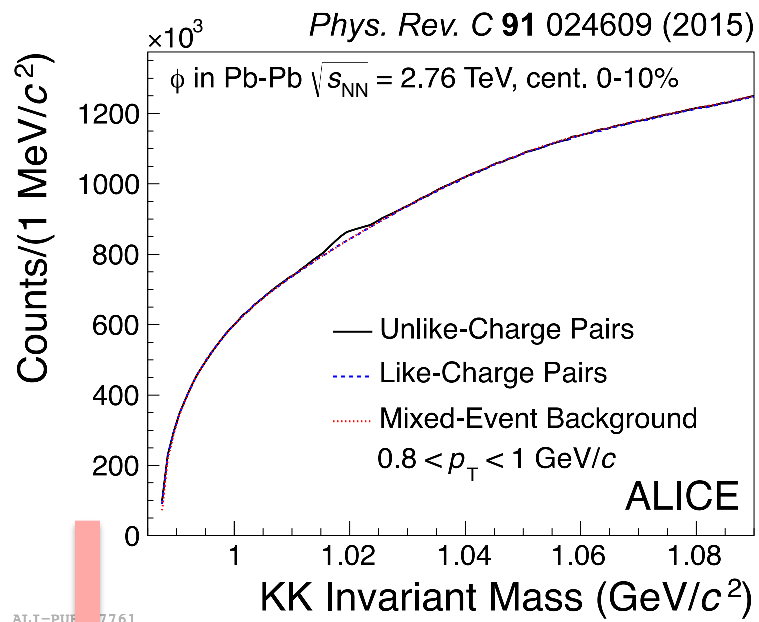
↓

Describe background

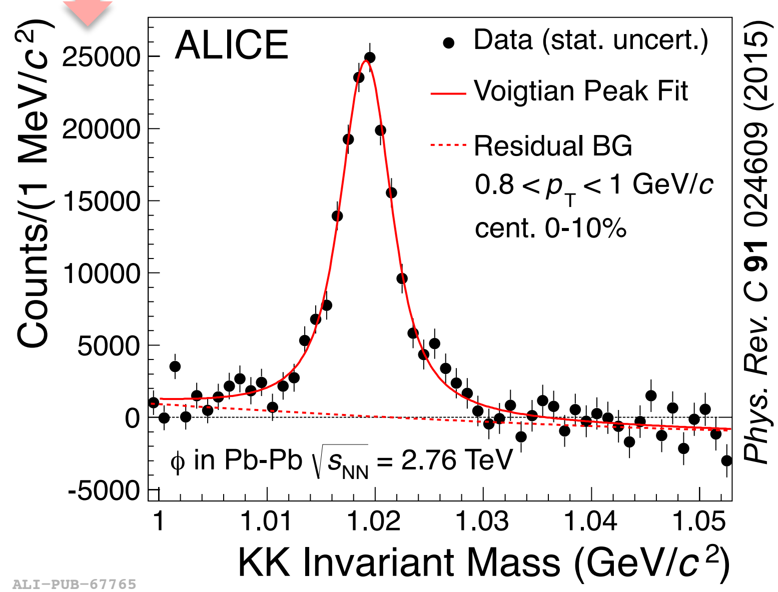
- **Fit background**
- **Like-charge Event mixing**

↓

Event mixing: cuts to ensure similar v_z, multiplicity, event plane



Background Subtraction



Finding Resonances

Find decay products

↓

Construct invariant mass distributions

↓

Describe background

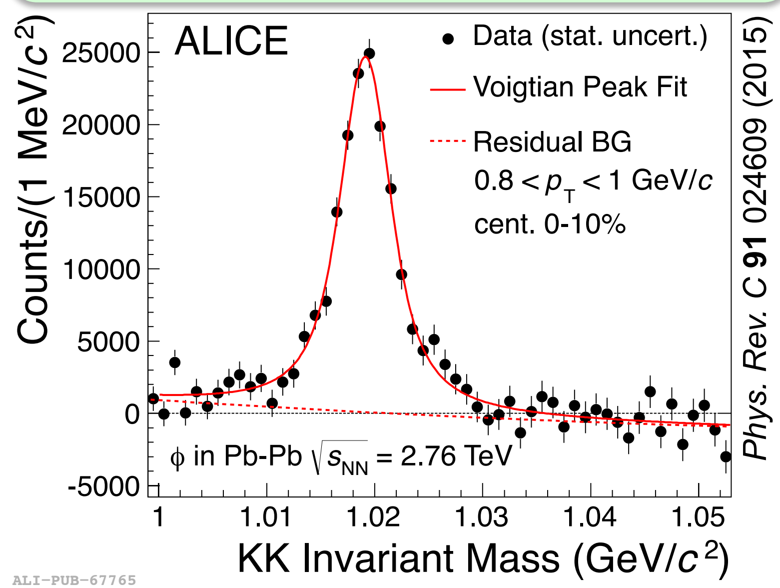
↓ **Fit background**

↓ **Like-charge Event mixing**

↓

Describe residual background

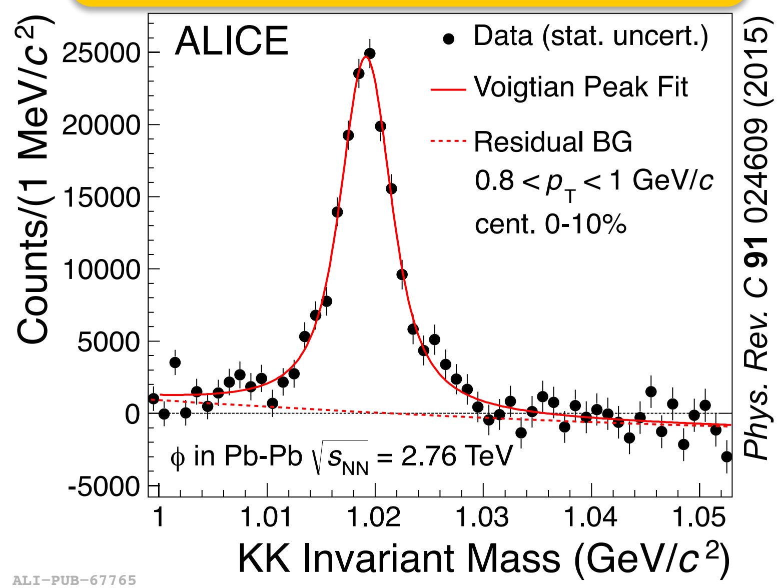
Fit residual background, usually with polynomial



Finding Resonances

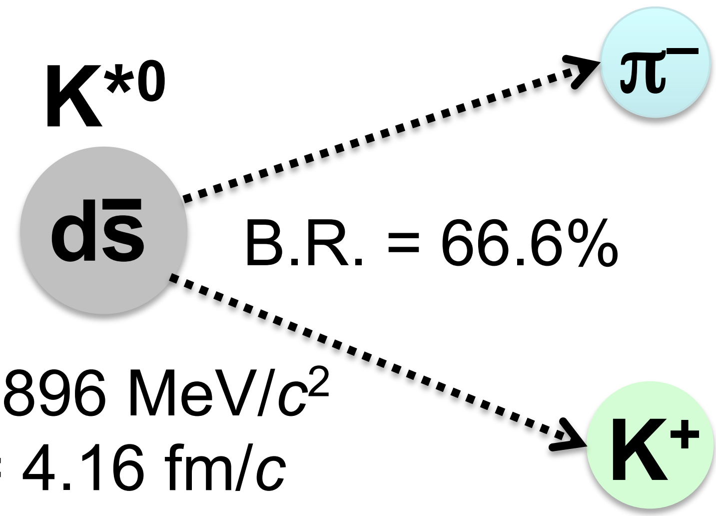
- **Find decay products**
- → **Construct invariant mass distributions**
- → **Describe background**
  - → **Fit background**
  - → **Like-charge Event mixing** → **Describe residual background**
- → **Fit peak** → **Extract yield, mass, width**

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

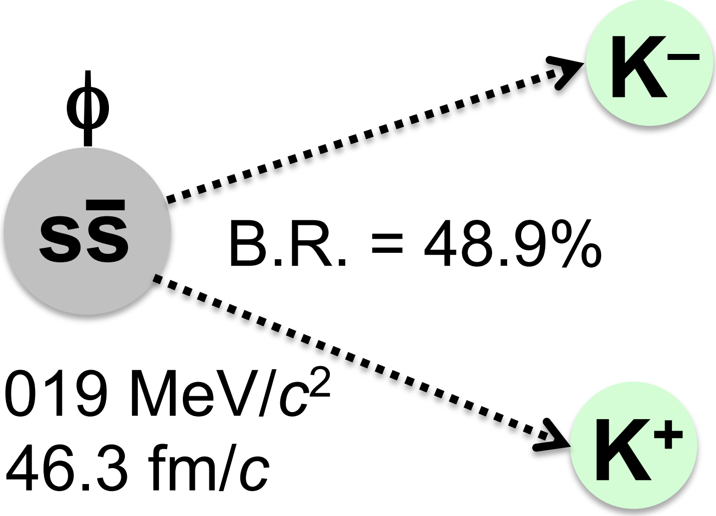


Resonance Reconstruction

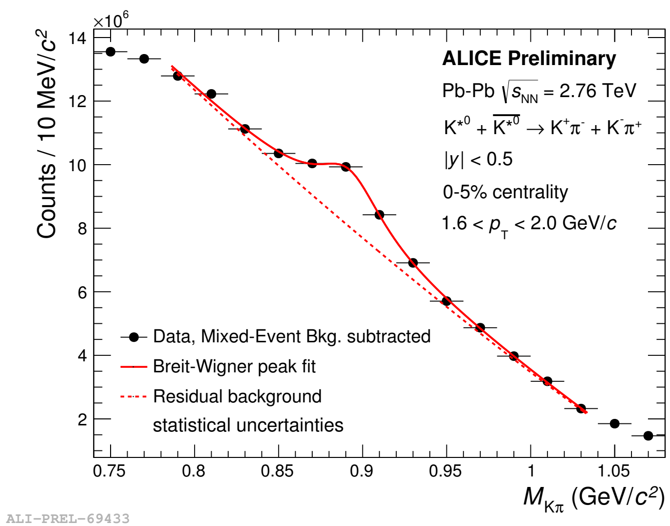
- Resonances measured in pp (0.9, 2.76, 5, 7, 13 TeV), p–Pb (5.02 TeV), and Pb–Pb (2.76, 5.02 TeV) collisions

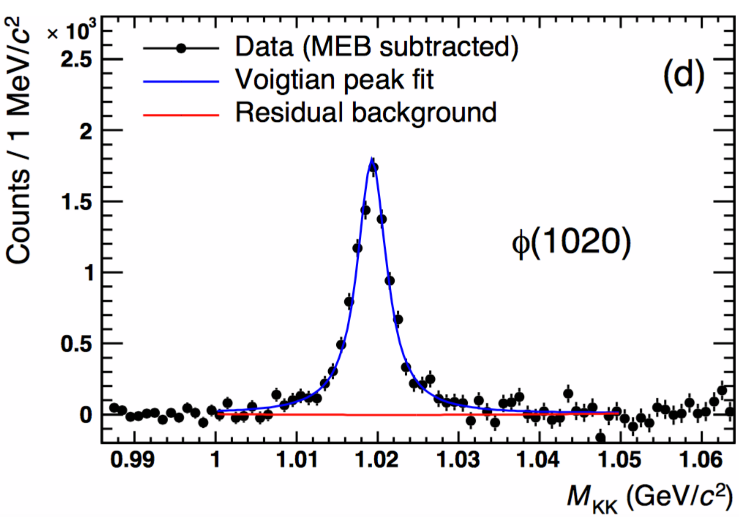


m = 896 MeV/c^2
τ = 4.16 fm/c



m = 1019 MeV/c^2
τ = 46.3 fm/c





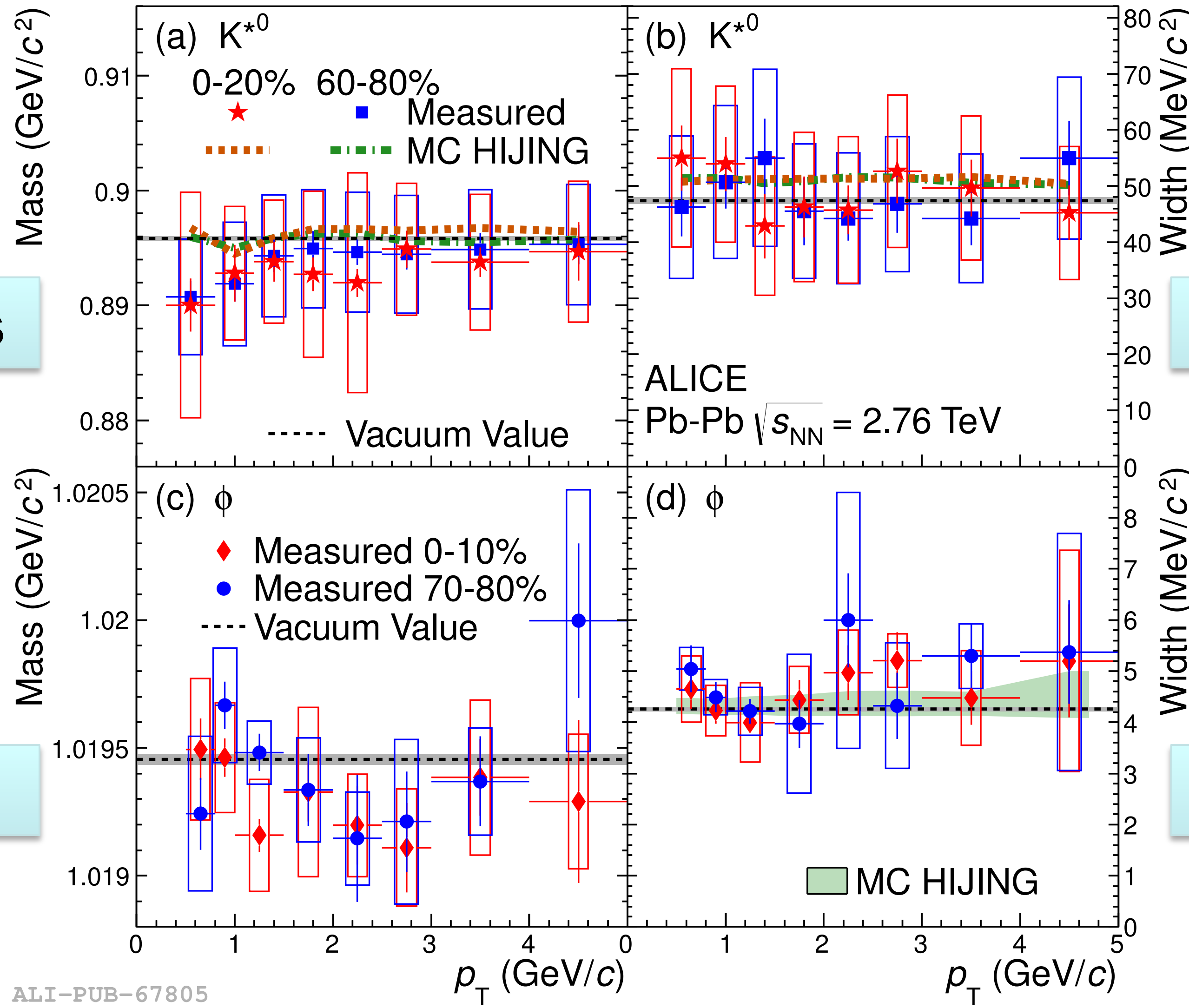
Mass and Width (Pb–Pb)

K*0 Mass

K*0 Width

ϕ Mass

ϕ Width

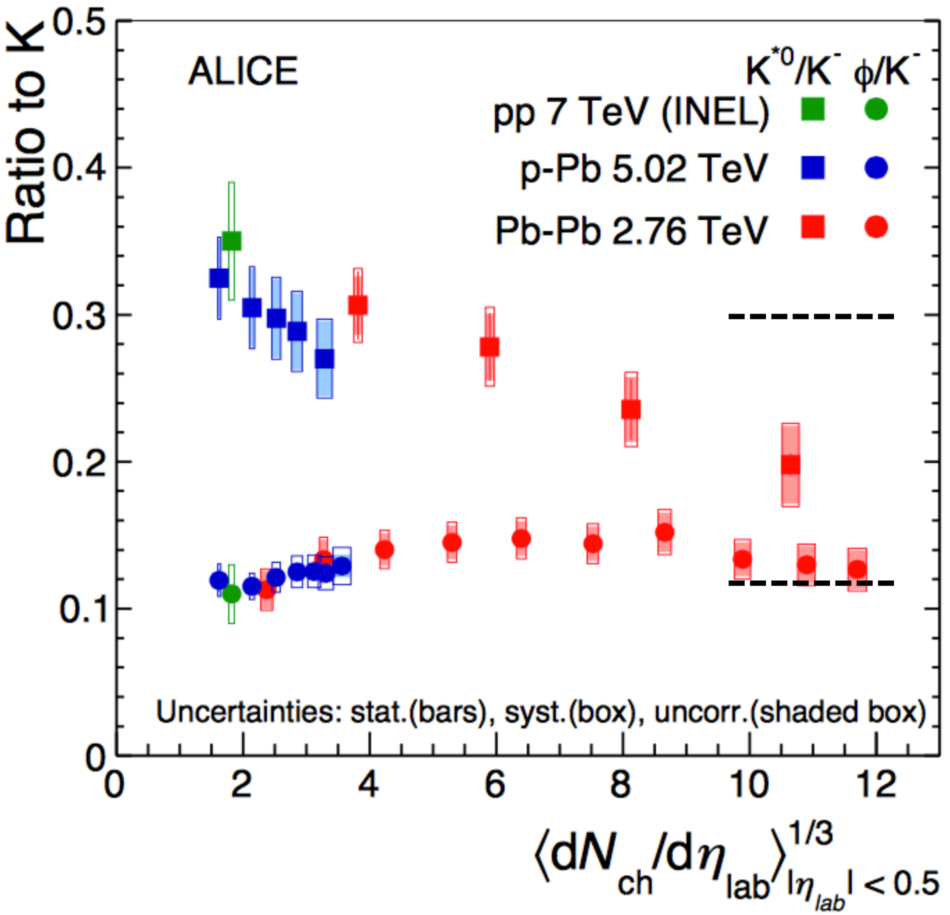


No significant mass or width shifts observed.
No centrality dependence of mass or width.

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

Ratios of Yields

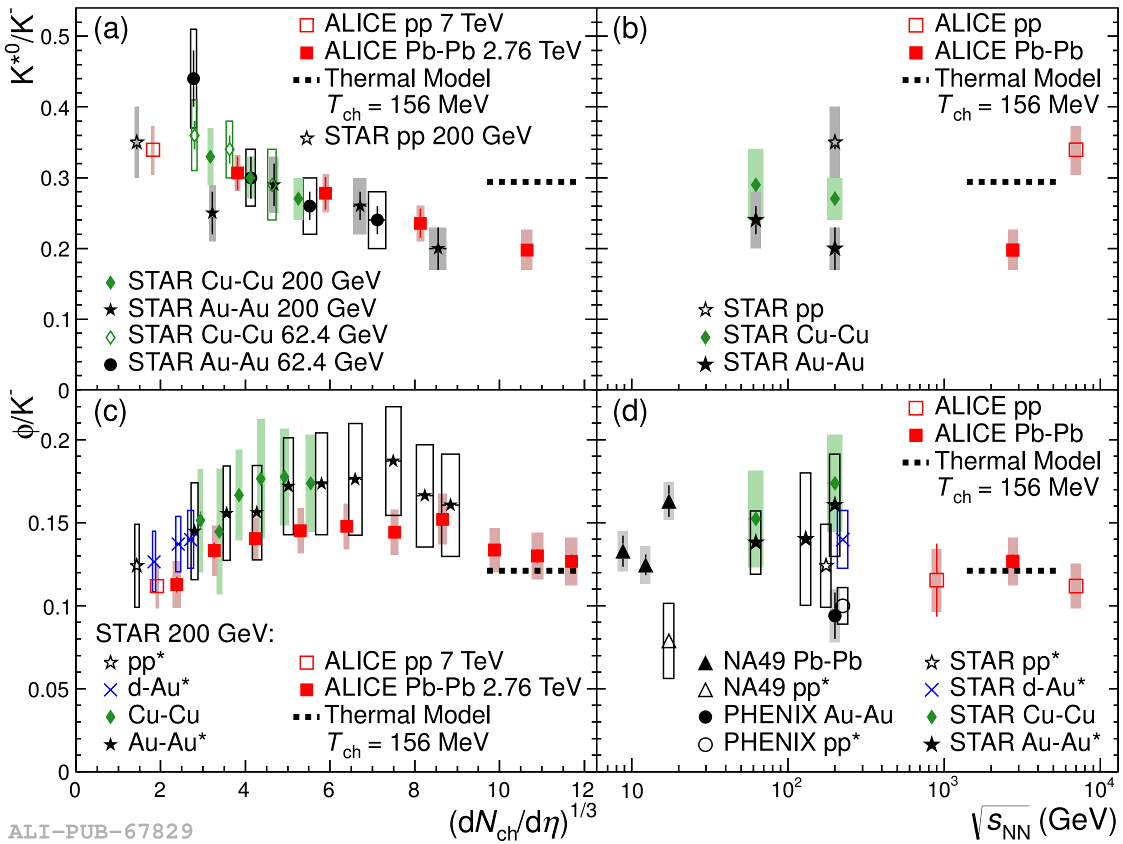
- K^{*0}/K
  - In Pb–Pb: strongly suppressed in central collisions w.r.t. peripheral, pp, p–Pb, or thermal model
  - Consistent with the hypothesis that re-scattering is dominant over regeneration
- ϕ/K
  - No strong dependence on centrality or collision system
  - ϕ lifetime ~10× longer than K^{*0}, 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
- p–Pb Results: New paper on arXiv: 1601.07868



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

Ratios of Yields

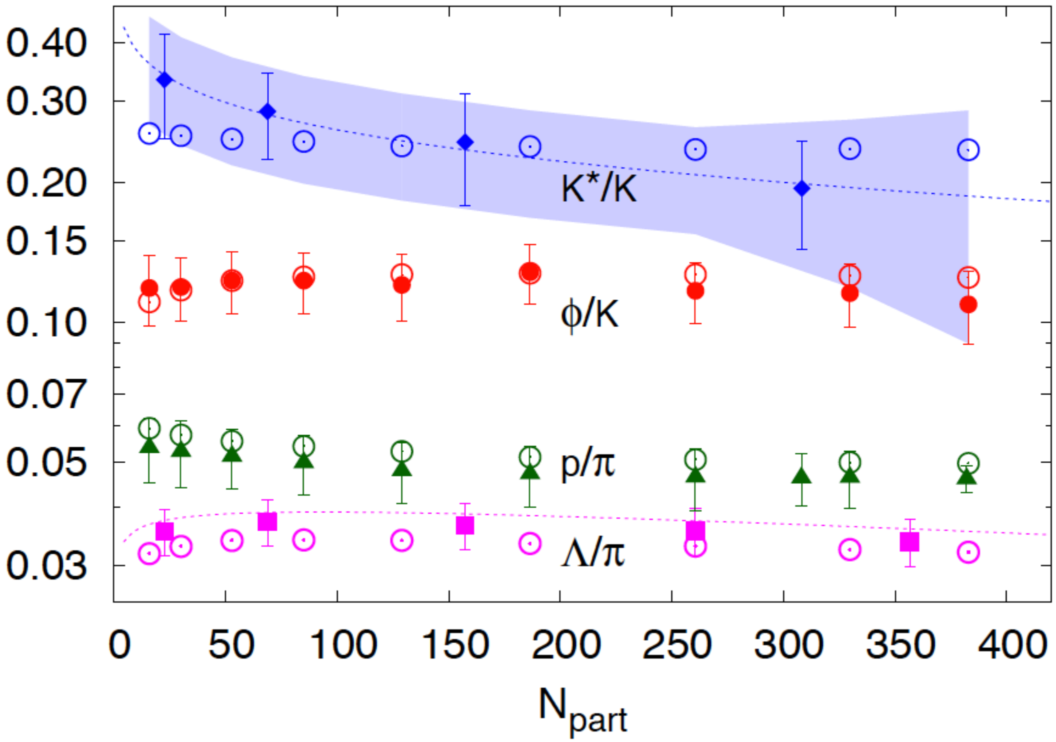
- K^{*0}/K
  - Values appear to follow same trend for both RHIC and LHC
  - Similar suppression of signal between pp and central A–A
- ϕ/K
  - Similar shapes in RHIC Au–Au and LHC Pb–Pb. Au–Au values tend to be larger than Pb–Pb, but consistent within uncertainties.
  - Ratio in d–Au fits into trend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



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

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

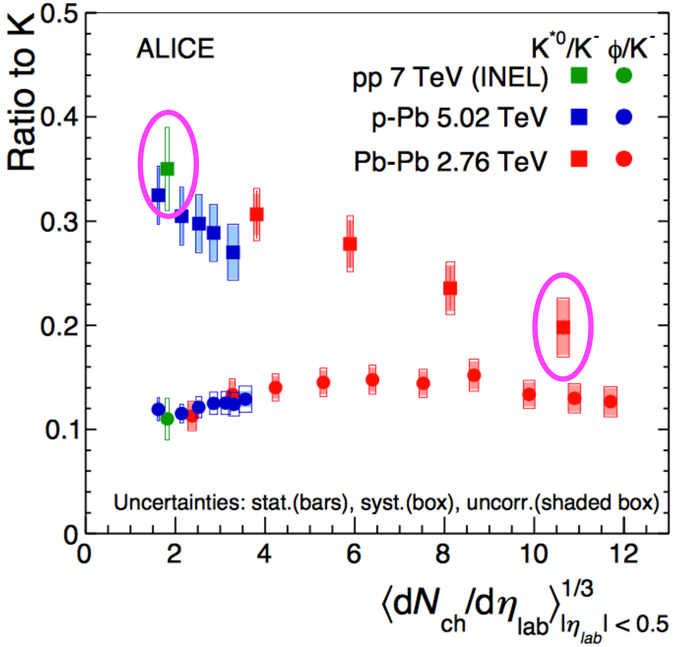
Properties of Hadronic Phase

Knospe

- 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

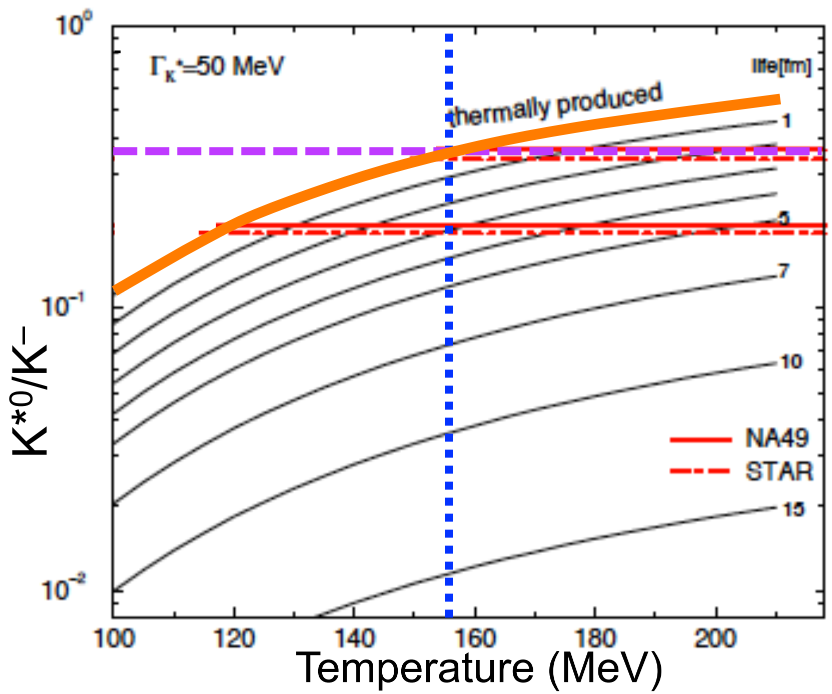
- Model of Torrieri, Rafelski, *et al.* predicts particle ratios as functions of chemical freeze-out temperature and lifetime of hadronic phase
- Model Predictions:

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

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



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Torrieri/Rafelski [1-3]
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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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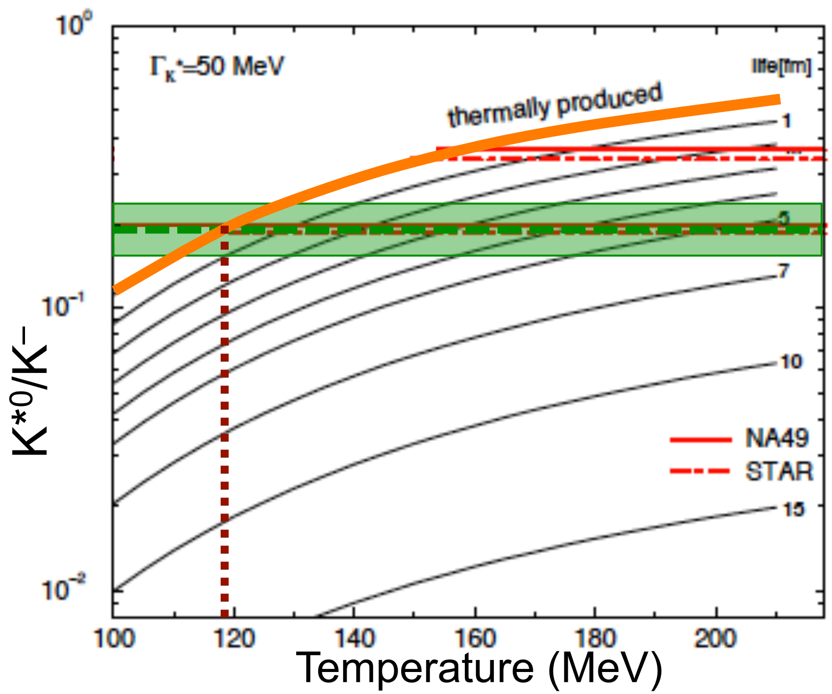

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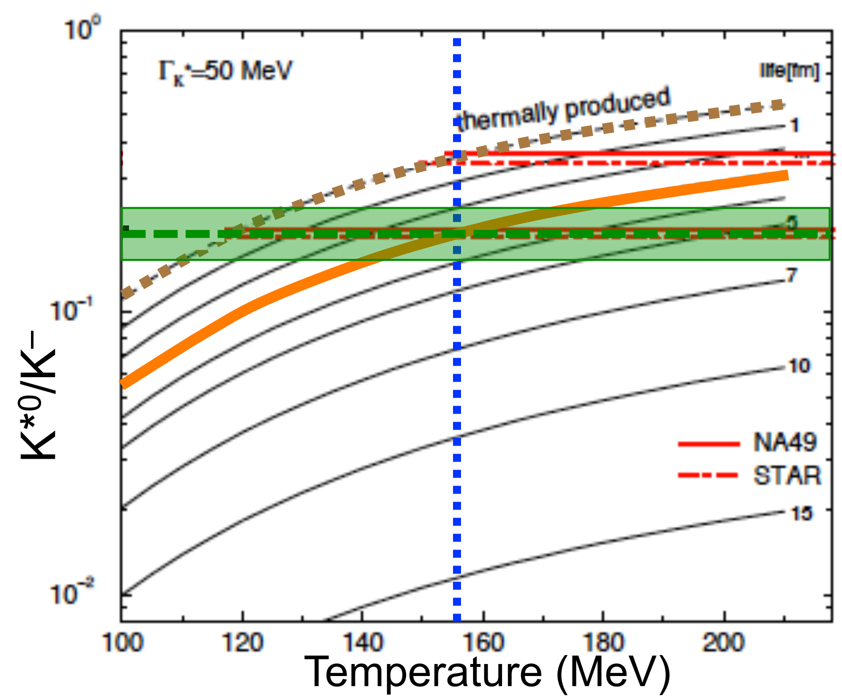
Torrieri/Rafelski [1-3] no re-scattering T_{ch} = 156 MeV → Prediction: K^{*0}/K^{-} = 0.35

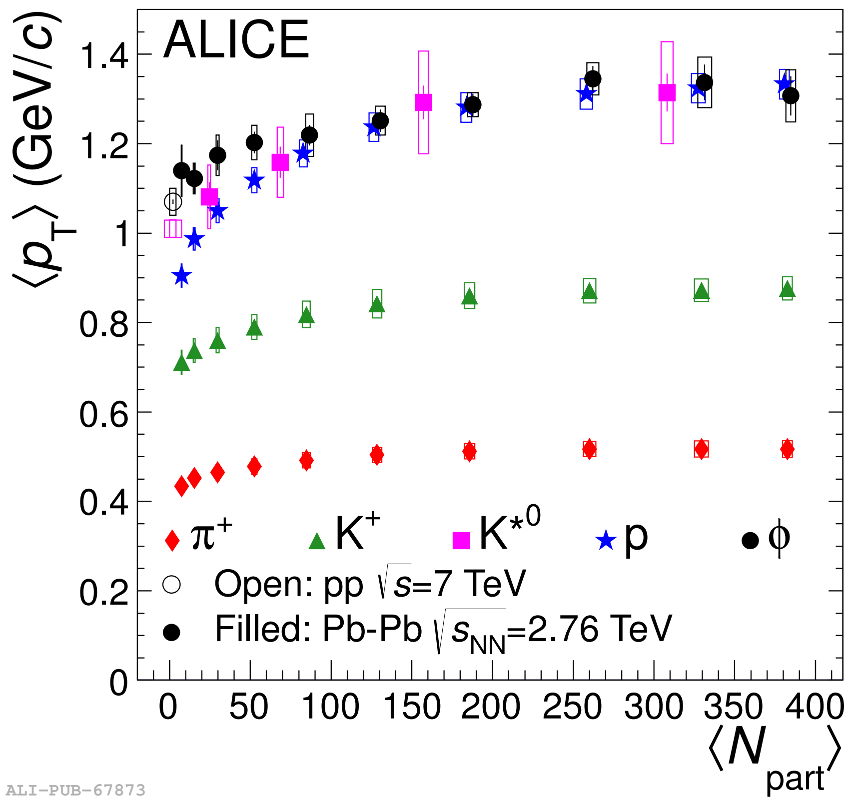
Torrieri/Rafelski [1-3] no re-scattering, measured K^{*0}/K^{-} → Prediction: T_{ch} = 120±7 MeV

Torrieri/Rafelski [1-3] measured K^{*0}/K^{-}, T_{ch} = 156 MeV → Prediction: Lifetime ≥ 2 fm/c



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%

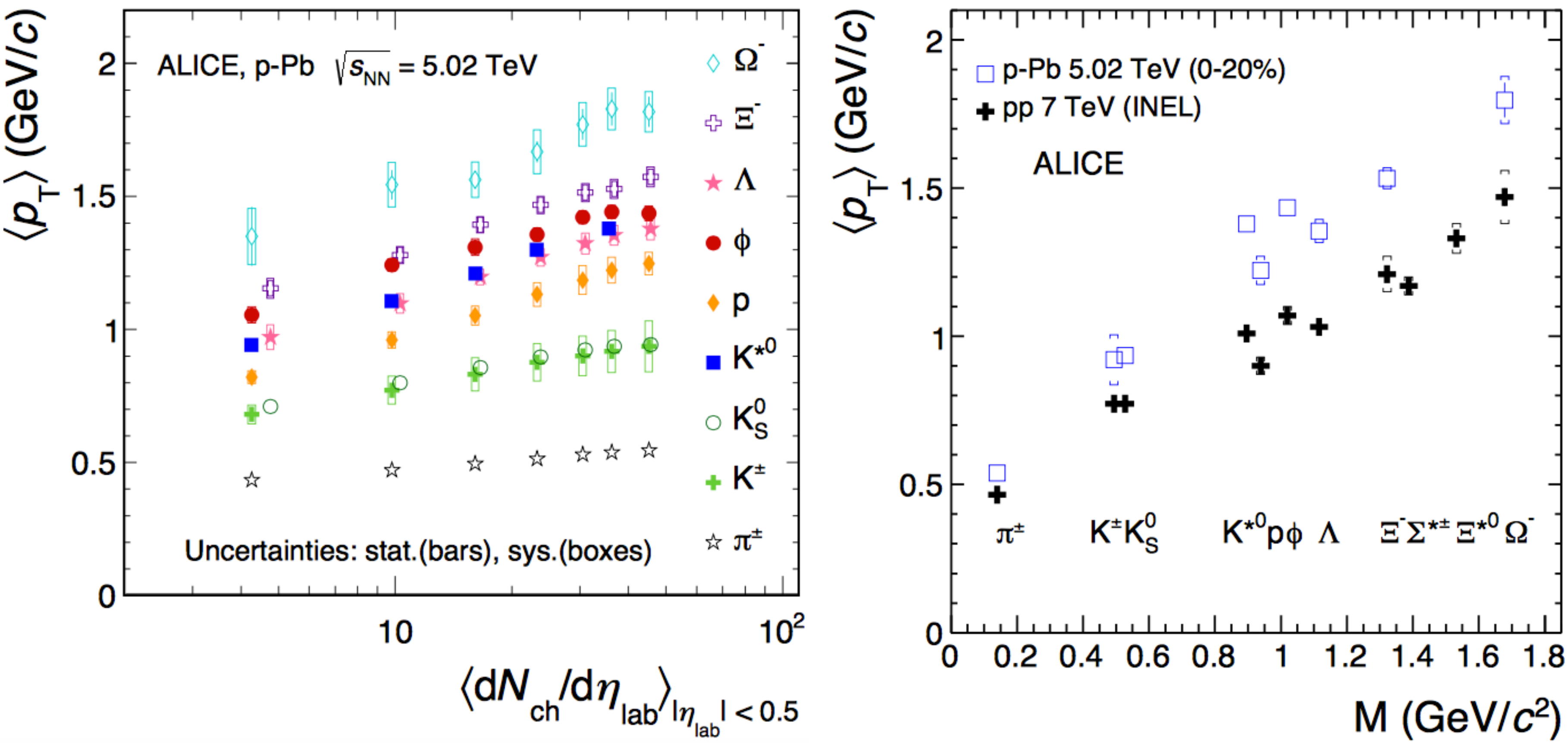


Phys. Rev. C **91** 024609 (2015)

Mean p_T in p–Pb

- Approximate mass ordering in $<p_T>$
  - But $<p_T>$ 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

arXiv:1601.07868



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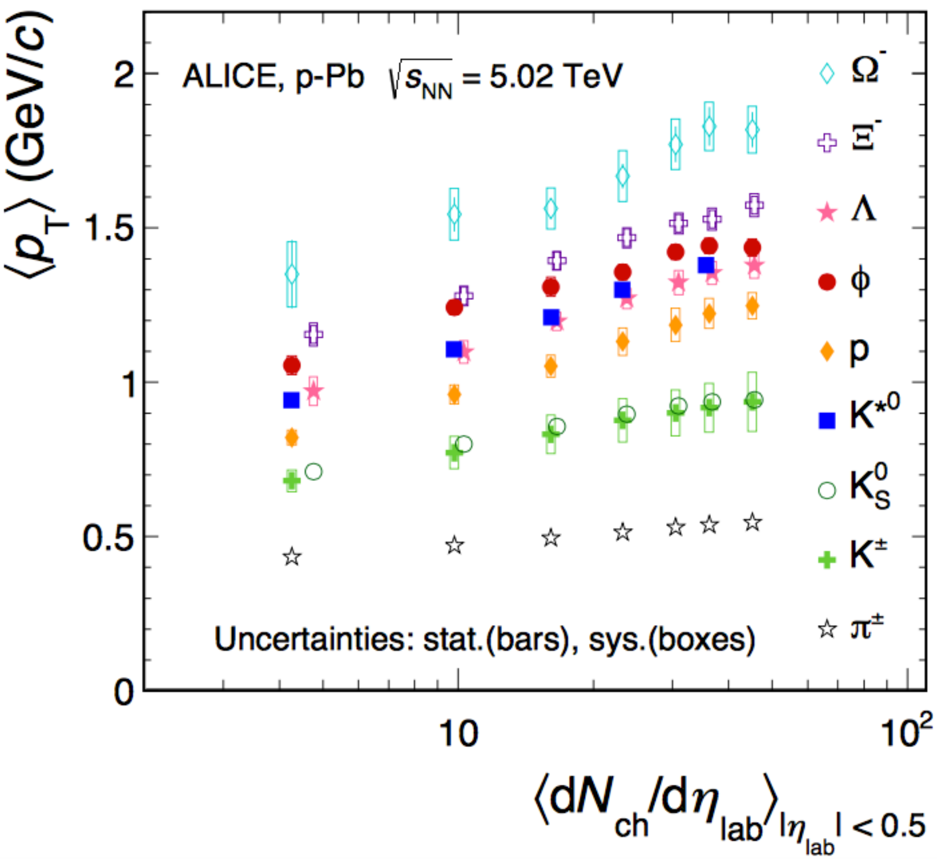

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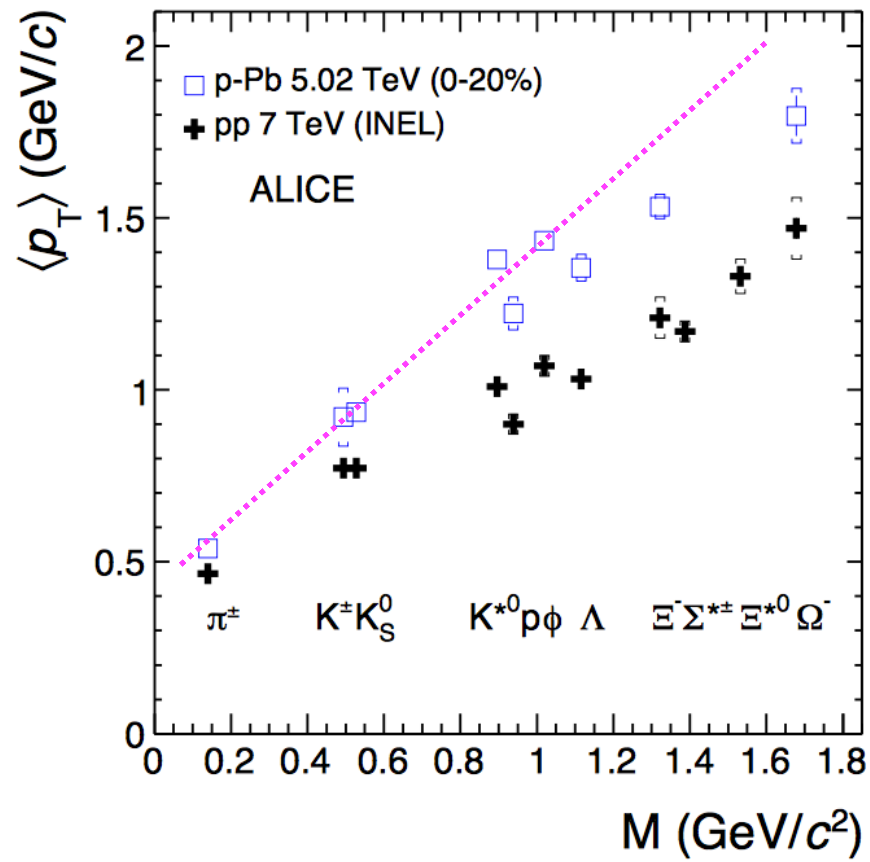

Mean p_T in p–Pb

- 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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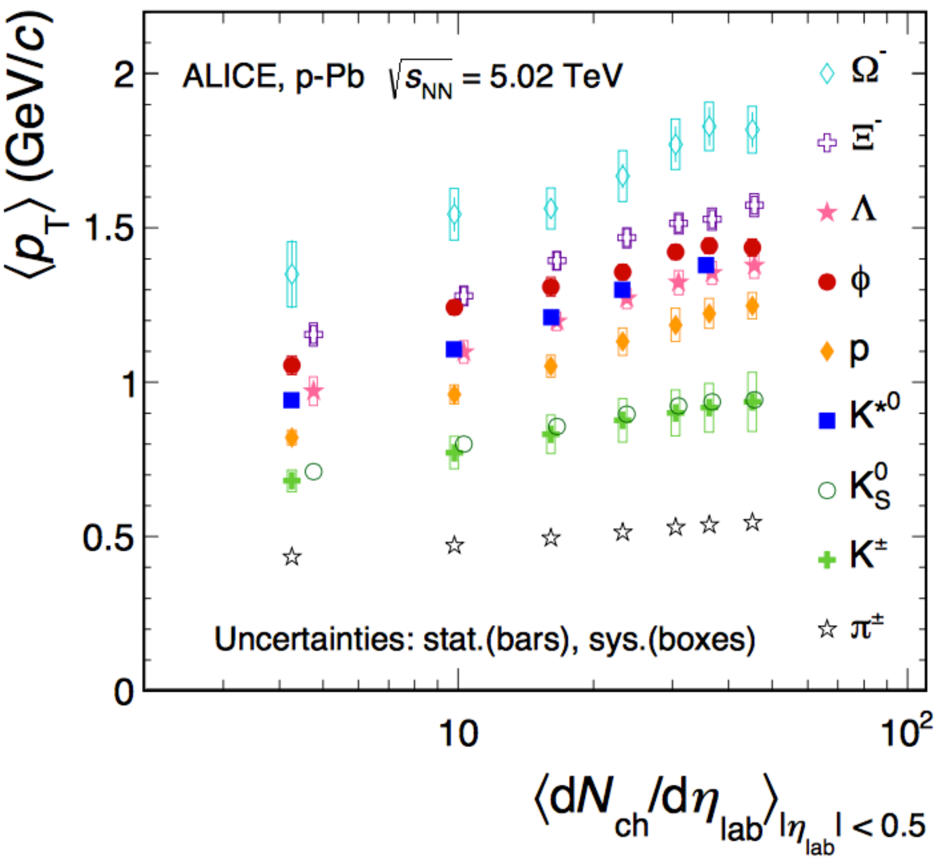
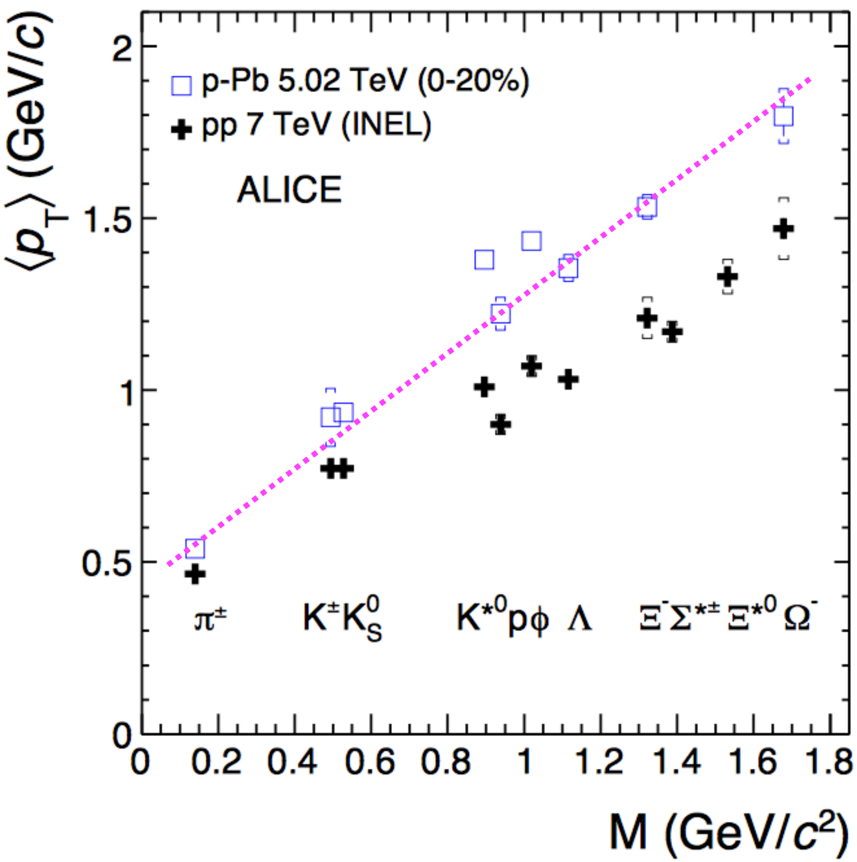
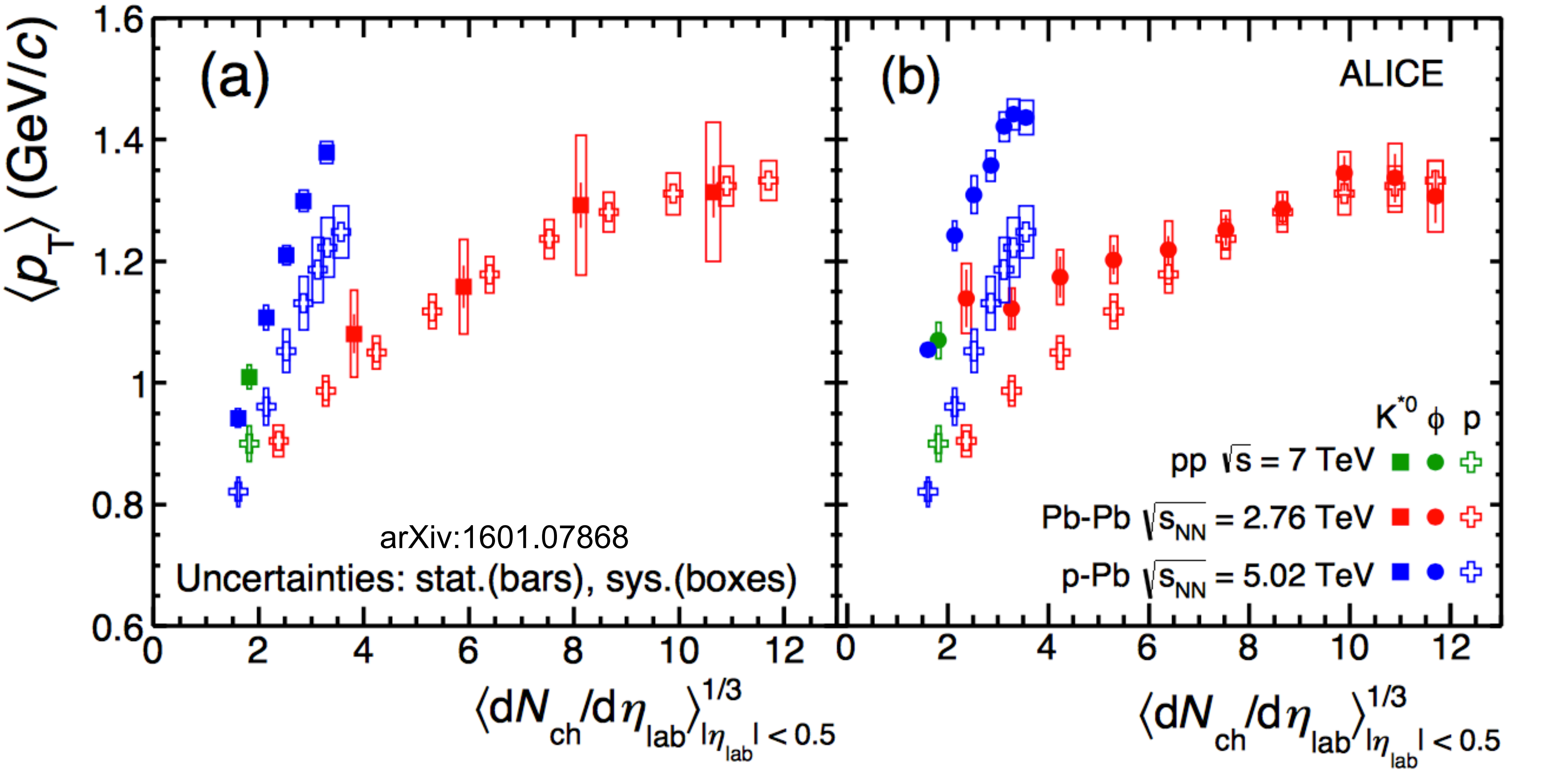




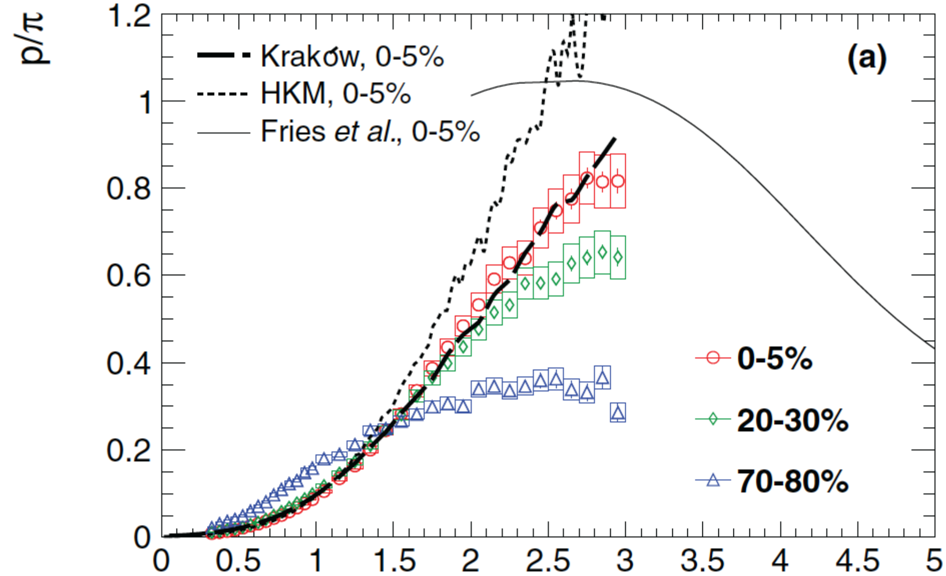
Mean p_T

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

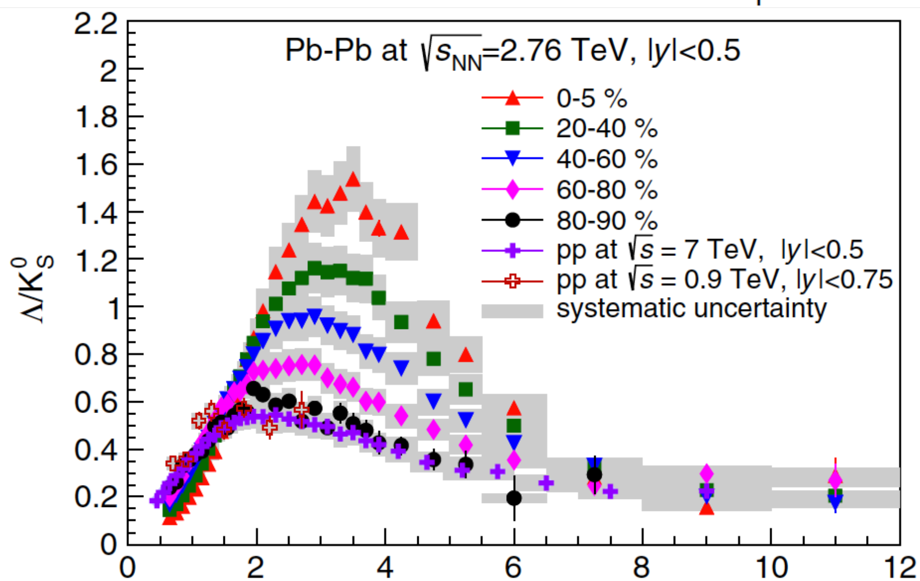


Particle Production

- 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



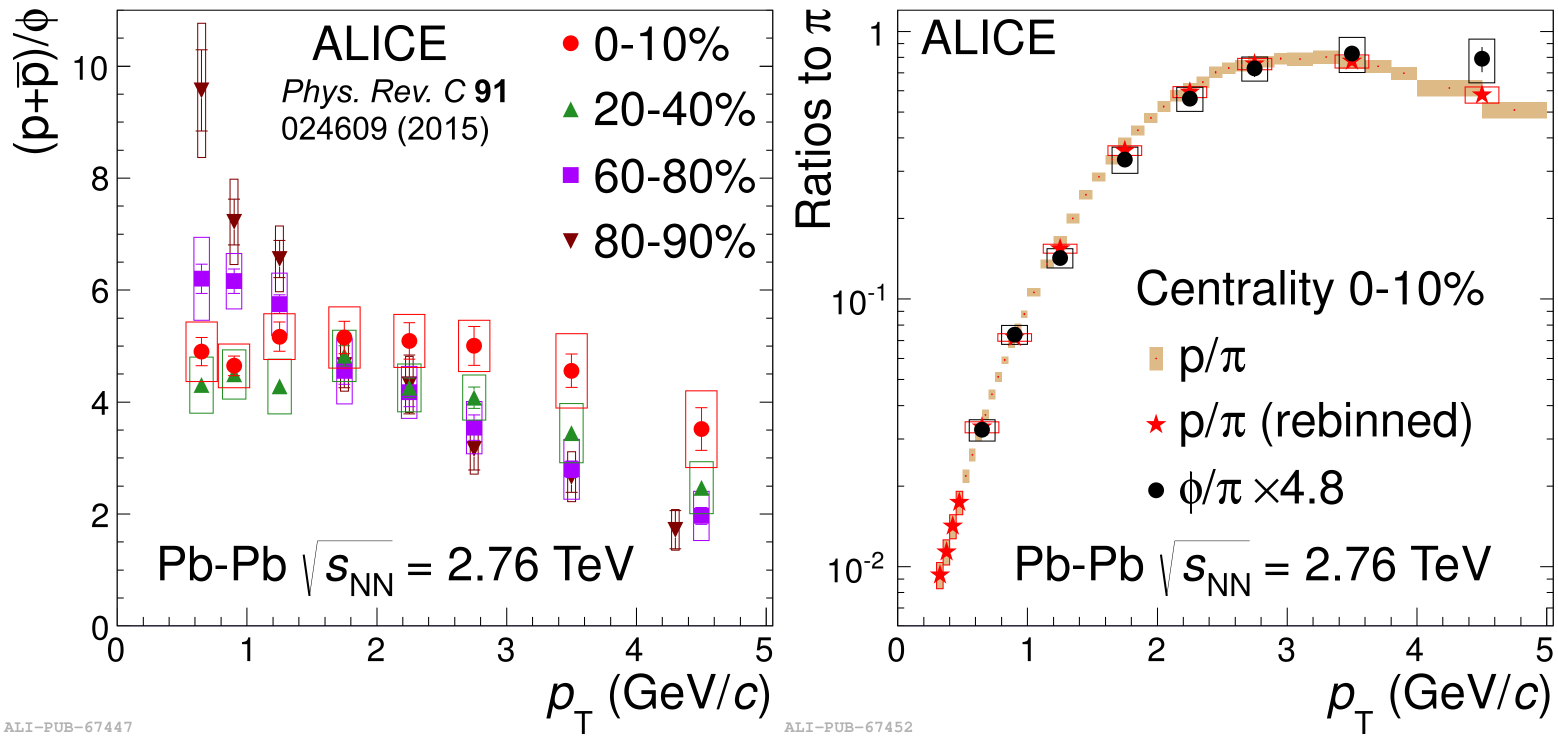
ALICE, *Phys. Rev. C* **88**, 044910 (2013)



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?



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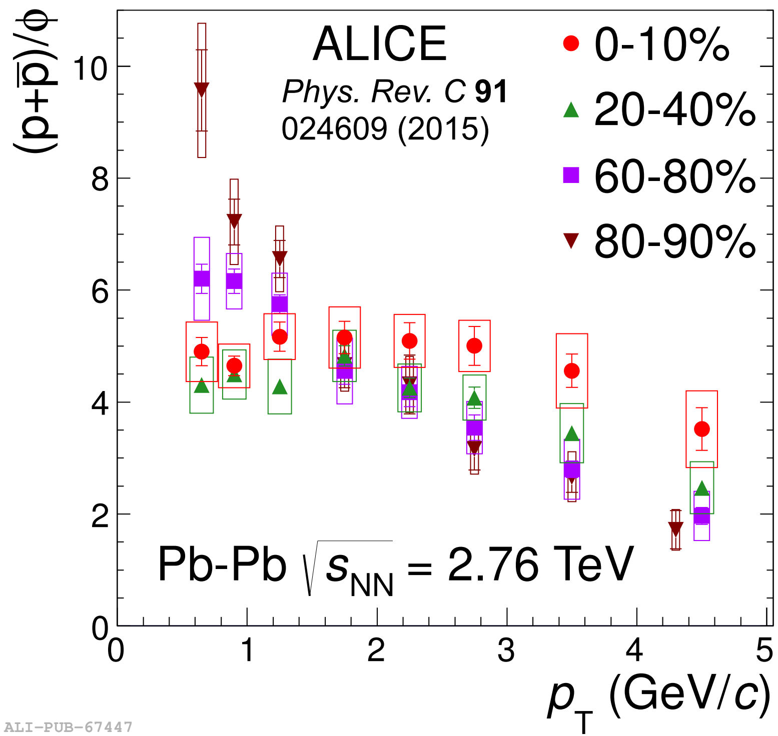
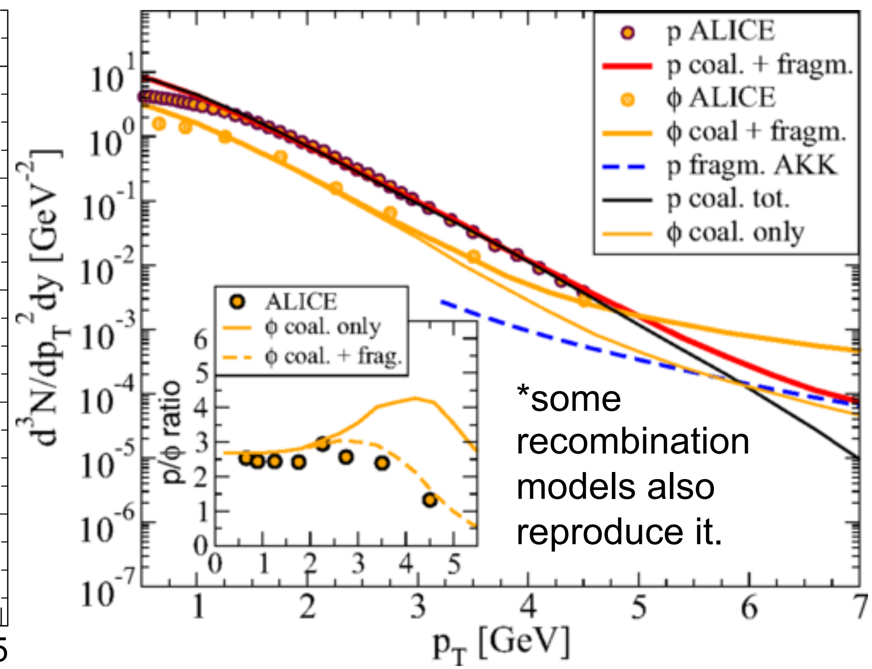


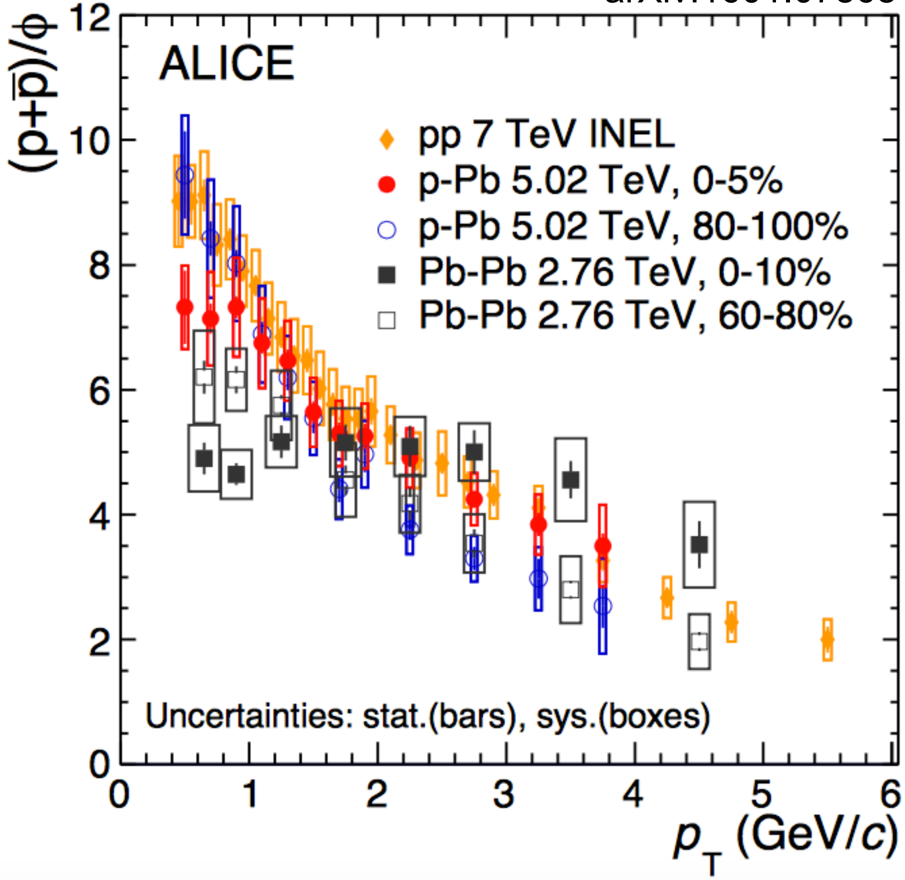


Phys. Rev. C **92** 054904 (2015)

p/ϕ vs. p_T in p–Pb

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

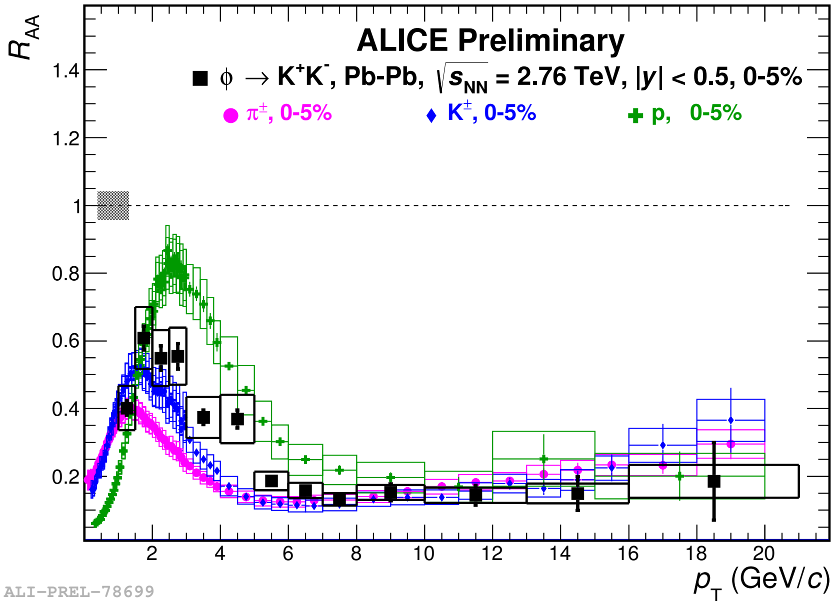
arXiv:1601.07868

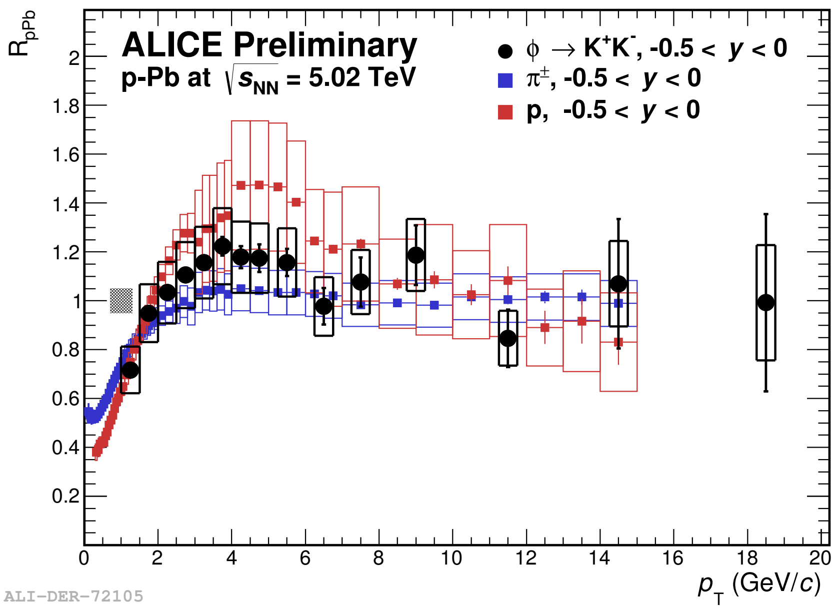


Nuclear Modification Factors

- In Pb–Pb:
  - 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}

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





Resonances in EPOS

EPOS

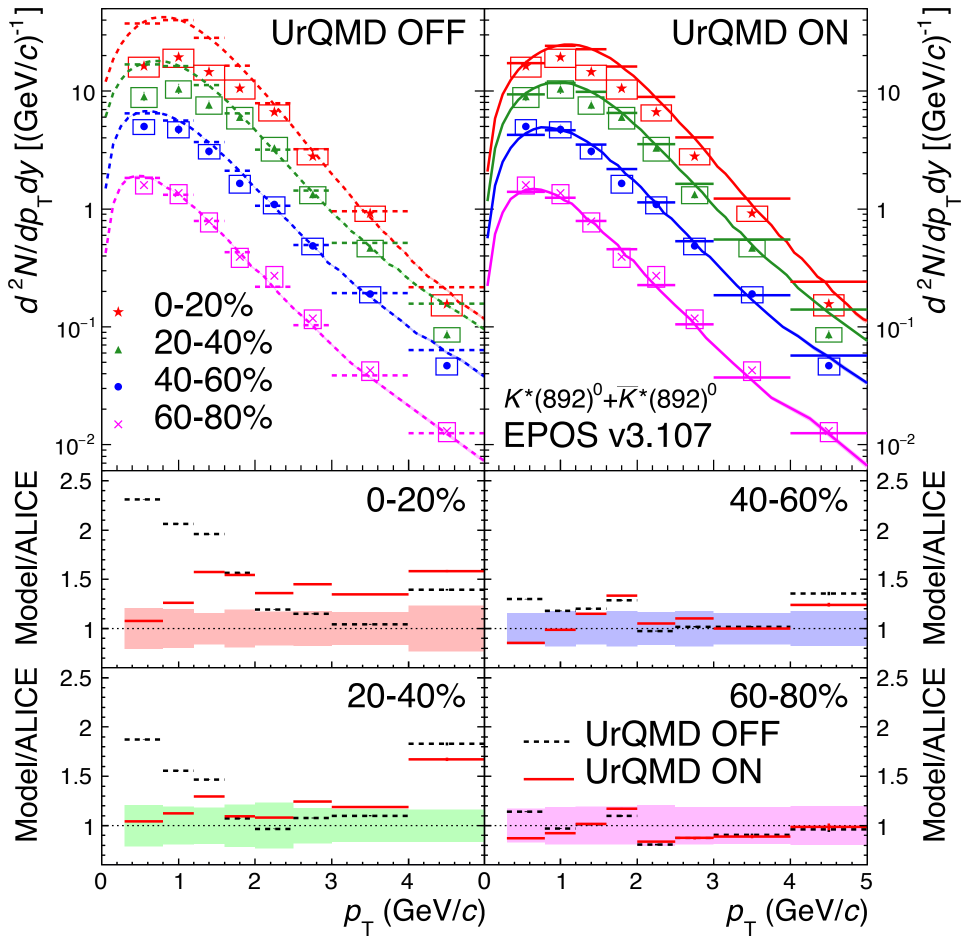
- EPOS: a universal approach: same framework for pp, p–A, and A–A collisions
- Initial conditions: flux tubes generated in Gribov-Regge multiple-scattering framework
  - Elementary object = Pomeron = parton ladder
  - Nonlinear effects: saturation scales $Q_s \propto N_{part} s^{\lambda}$
- Core/Corona:
  - String segments with high p_T escape → corona (jets)
  - Others form “core” of bulk matter → hydro initial condition
  - Depends on local string density
- 3+1D viscous hydro expansion, η/s=0.08
- Hadronization at 166 MeV (Cooper-Frye)
- Hadronic cascade: UrQMD

Resonances in EPOS

- New program unit
- Detect selected resonances (ρ, K*, ϕ, Δ, Σ*, Λ(1520), Ξ*)
- Identify their common hadronic decays
- Track the decay daughters, flag whether or not either decay product interacts
  - If neither decay product interacts, resonance flagged as reconstructible
- New Paper:
  - A. G. Knospe *et al.*, *Phys. Rev. C* **93** 014911 (2016)

EPOS: K*^{0} and ϕ

- EPOS (with UrQMD ON) provides good descriptions of K*^{0} and ϕ p_T spectra in Pb–Pb collisions
  - Agreement better for peripheral collisions
  - Turning UrQMD OFF → worse description for central K*^{0}, no major changes for peripheral and ϕ



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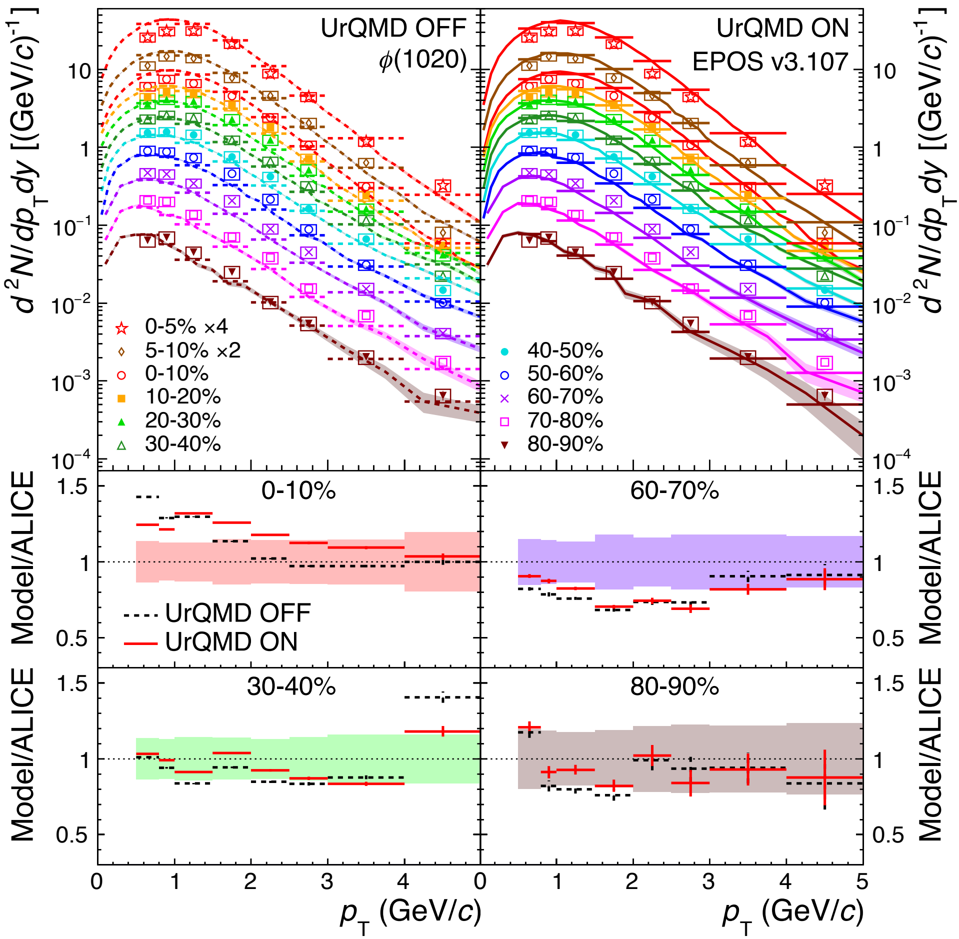
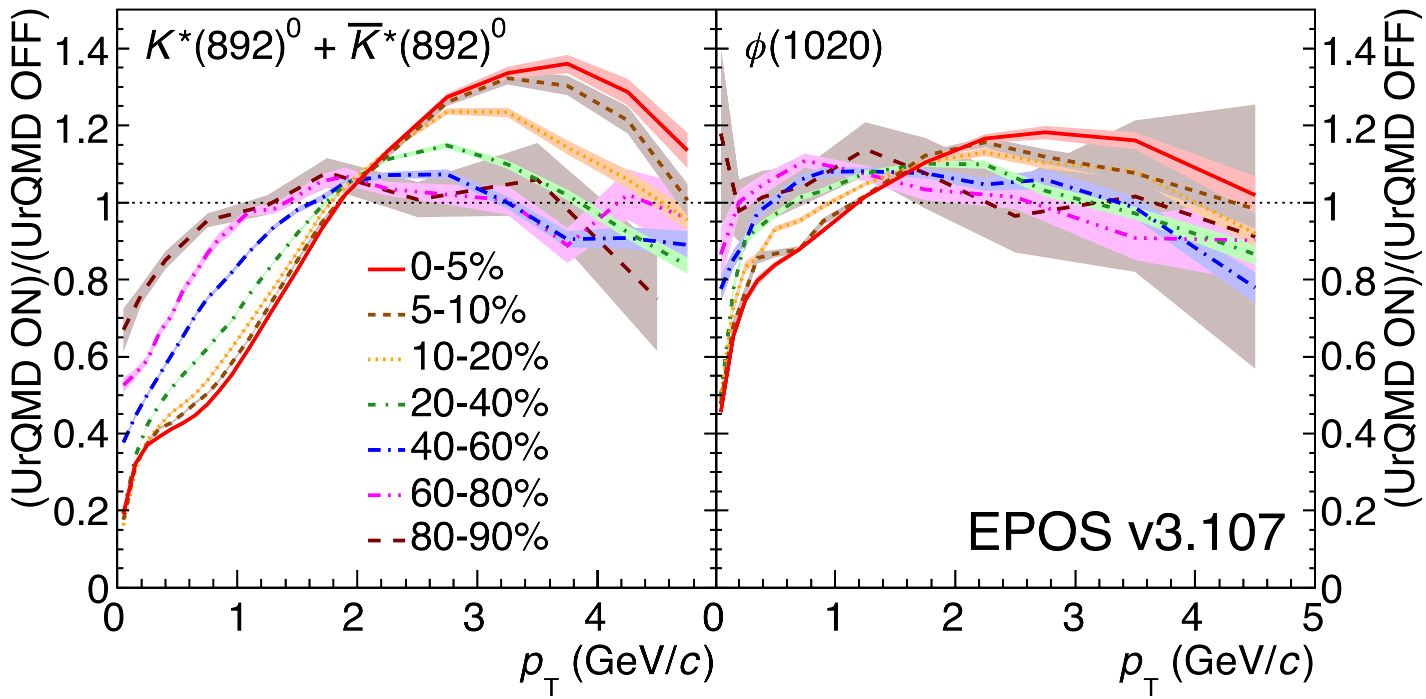


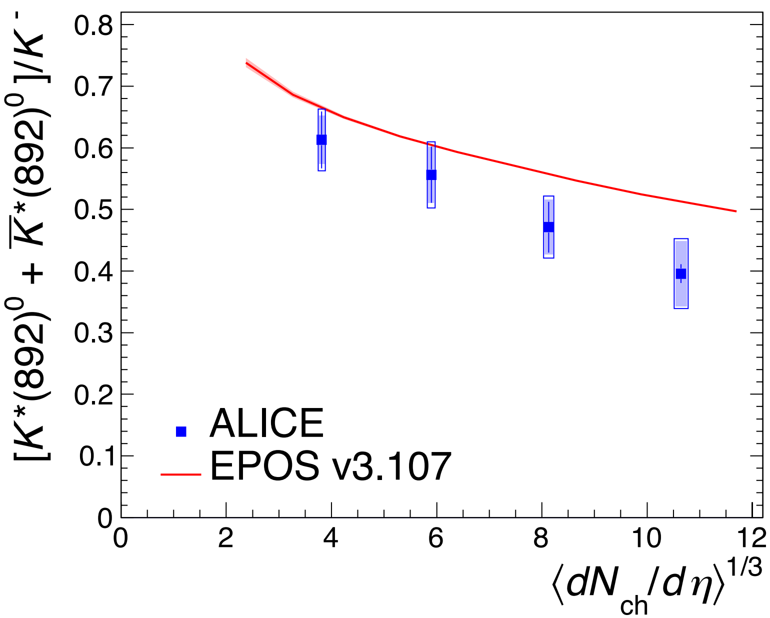
Effect of UrQMD

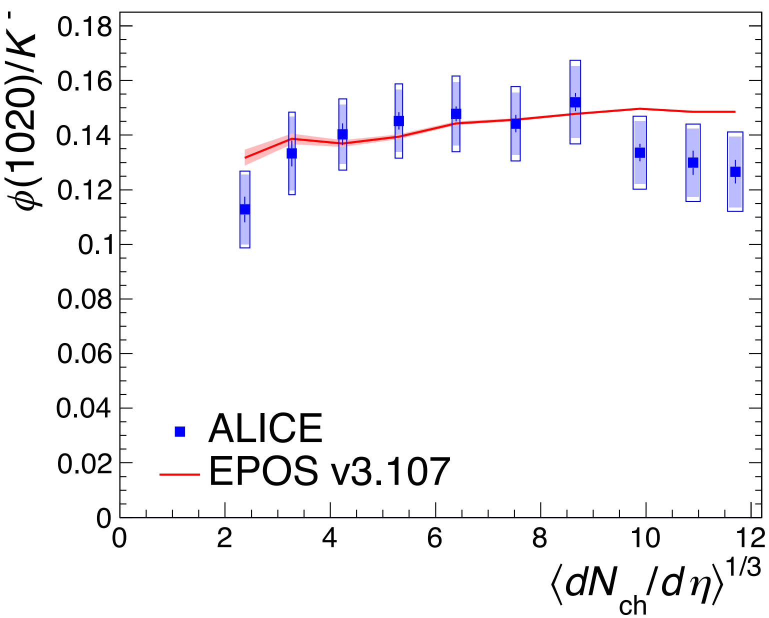
- Turning UrQMD (hadronic phase) on → low-p_T, centrality-dependent suppression of K^{*0} (re-scattering), less modification of ϕ



Particle Ratios in EPOS

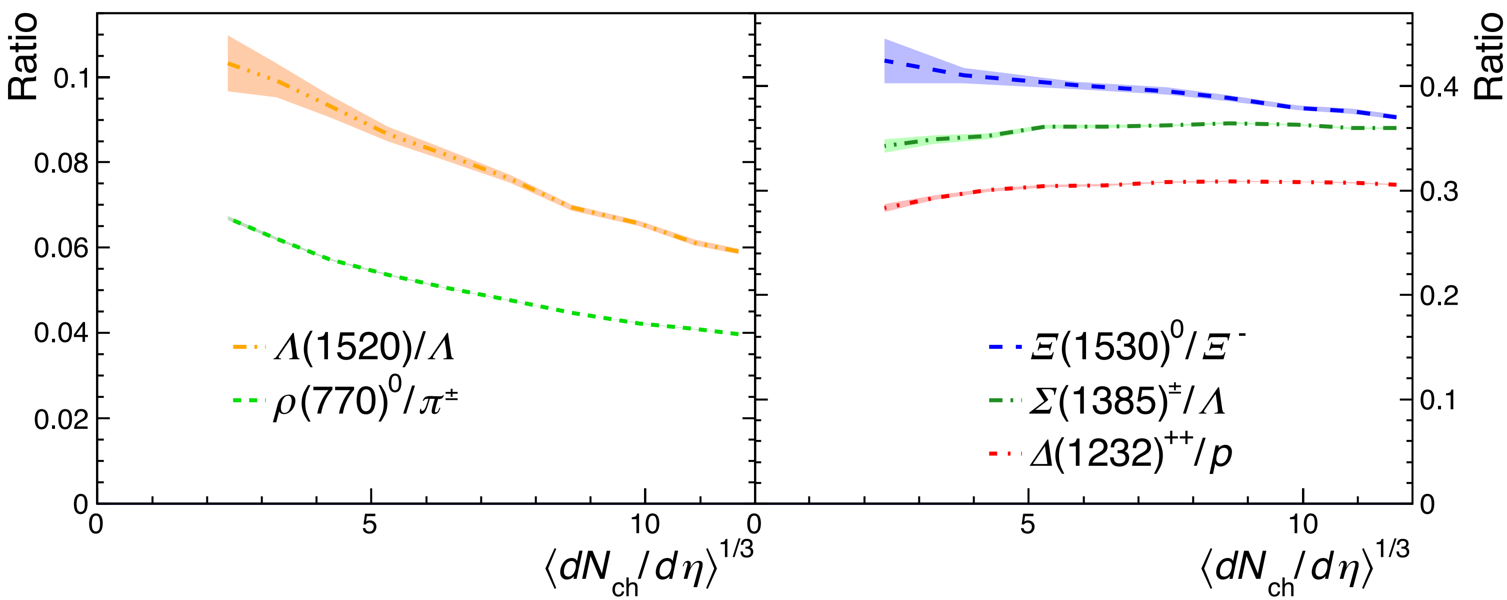
- Qualitatively describes centrality dependence of K^{*0}/K suppression (re-scattering)
  - Overestimates values
- Good description of ϕ/K





Particle Ratios in EPOS

- Strong centrality dependence for ρ/π and $\Lambda(1520)/\Lambda$
- Little modification of Ξ^{*0}/Ξ → long resonance lifetime and/or large regeneration cross section
- Little modification of Δ^{++}/p and $\Sigma^{*\pm}/\Lambda$ → large regeneration cross section
  - *Cf.* $\Sigma^{*\pm}/\Lambda$ ratio from RHIC: not suppressed in central Au–Au



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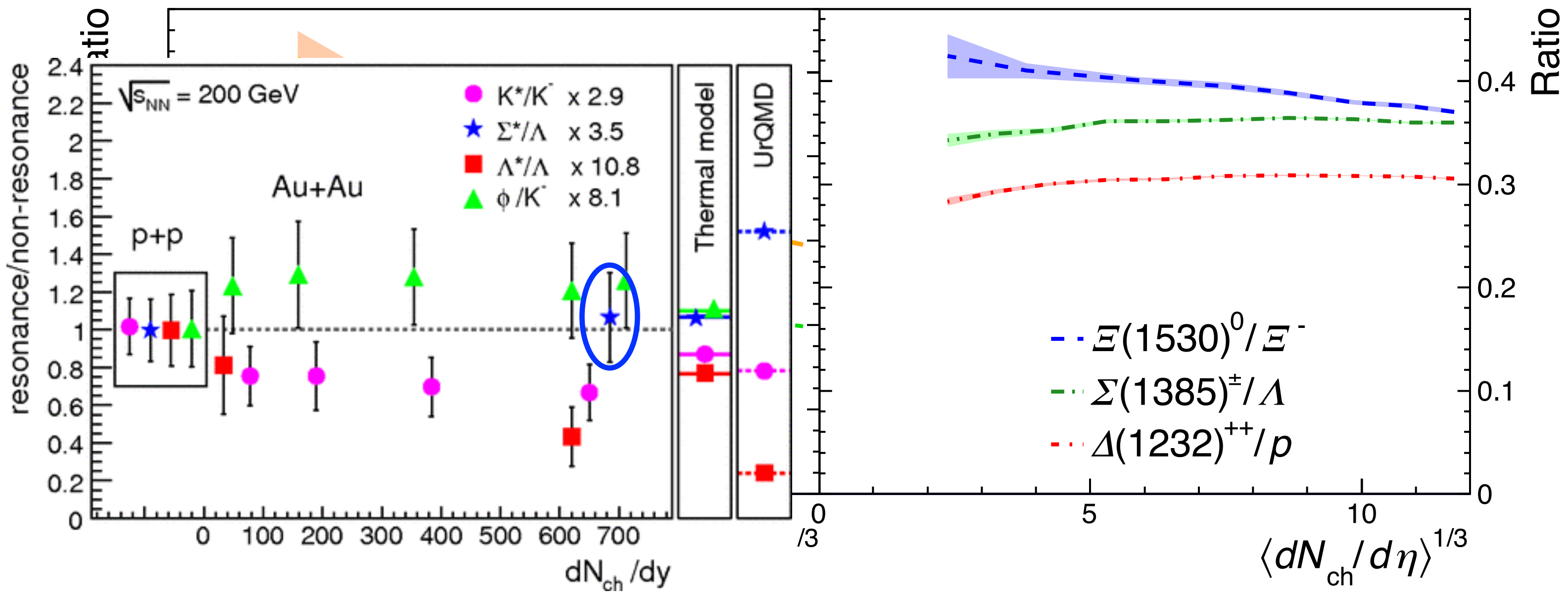


Conclusions

- 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
  - Possible onset of collective effects in p–Pb?
- Nuclear Modification Factors:
  - High-p_T suppression observed in central Pb–Pb (R_{AA}) but not in p–Pb
  - High-p_T behavior of ϕ similar to stable hadrons
  - Moderate ϕ Cronin peak (between π and p)
- New Results coming soon
  - Suppression of ρ^0 in Pb–Pb, baryonic resonances
  - Multiplicity dependent pp measurements
  - Run 2 data: pp 13 TeV and Pb–Pb 5.02 TeV

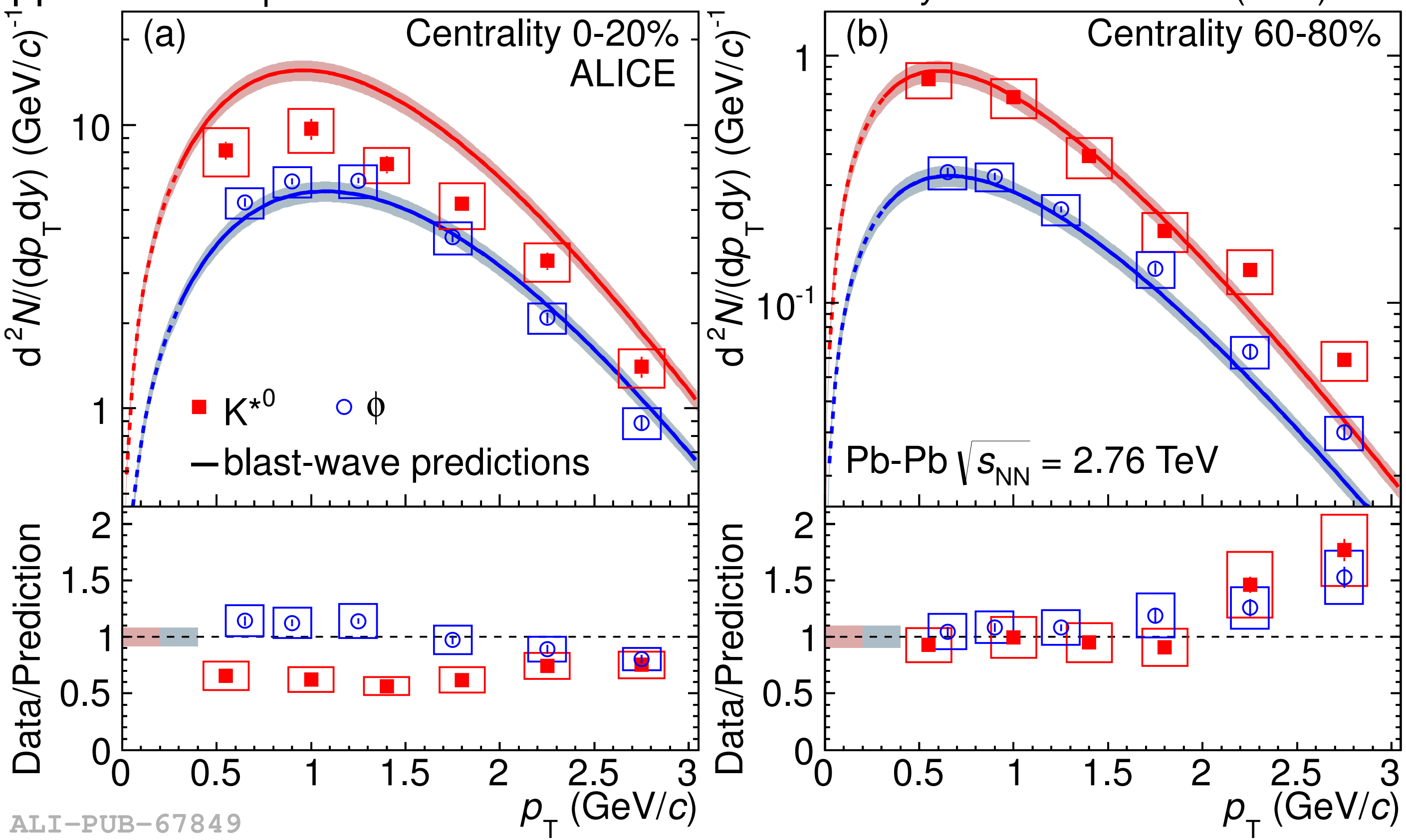
- Resonances in EPOS: new module flags reconstructible resonances
  - Re-scattering affects K^{*0} yields at low p_T, little effect for ϕ
  - Predictions of strong ρ/π and $\Lambda(1520)/\Lambda$ suppression, flat $\Sigma^{*\pm}/\Lambda$ to be tested…

Backup Material

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

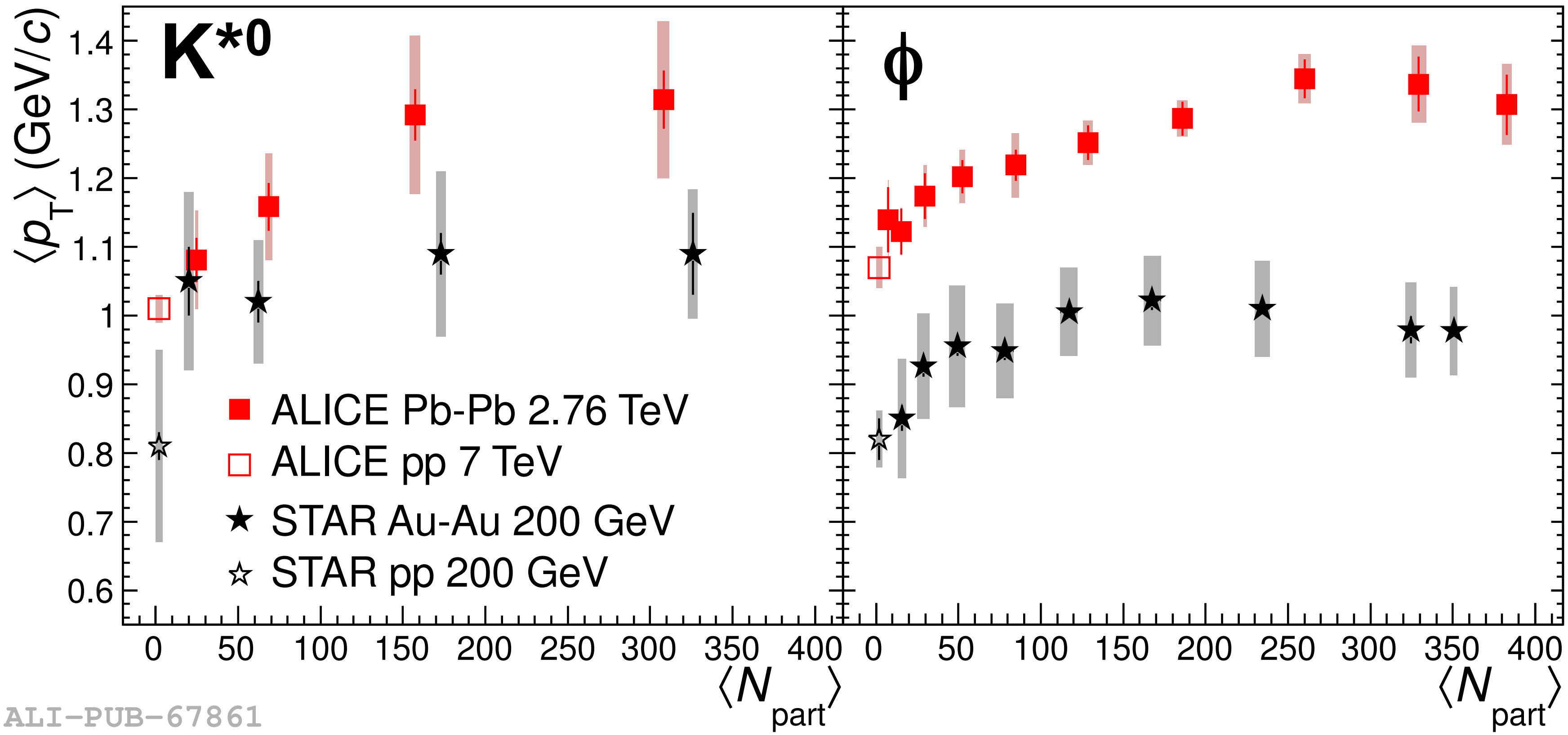
Phys. Rev. C **91** 024609 (2015)



Mean p_T in A–A

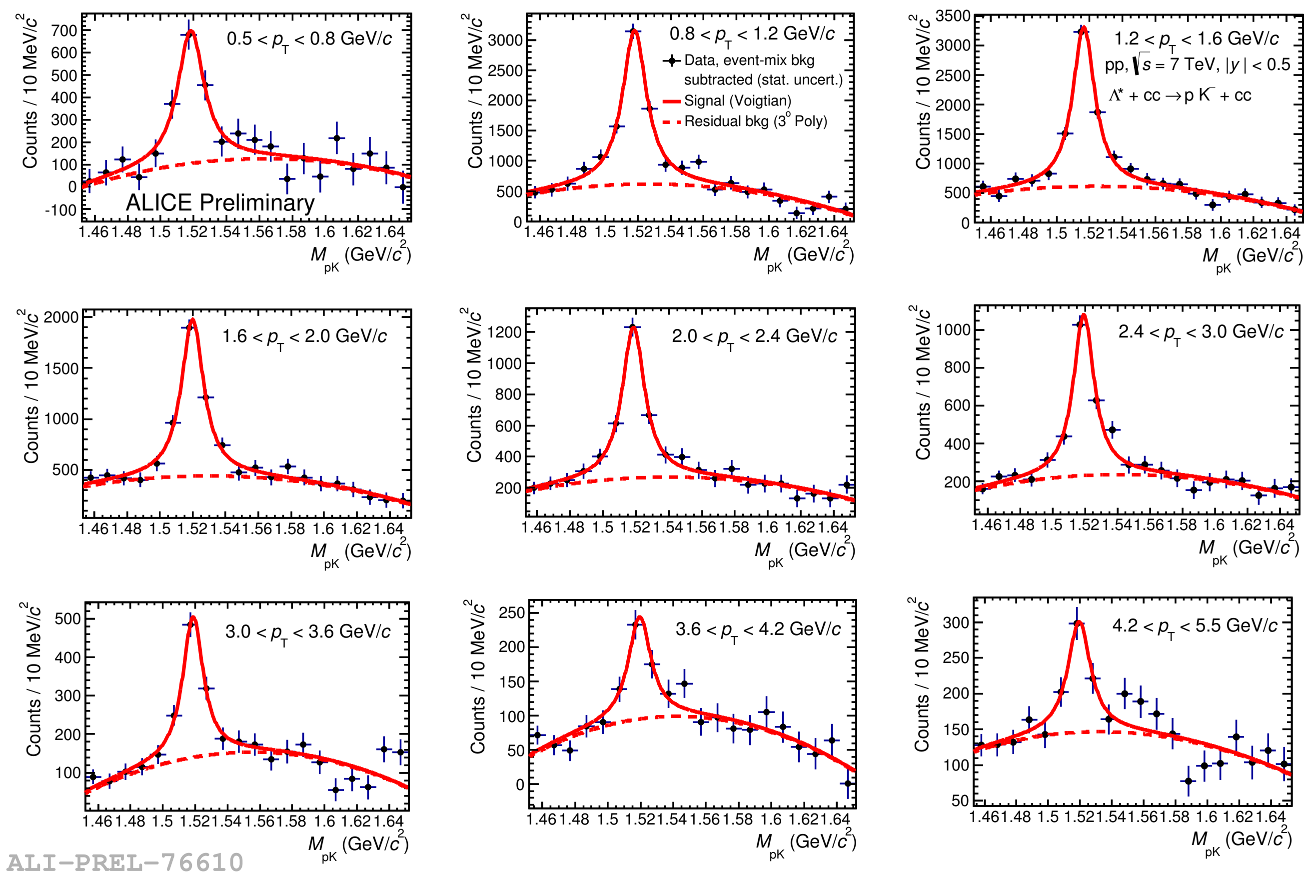
- $<p_T>$ appears to increase for more central Pb–Pb collisions w.r.t. peripheral and pp
- $<p_T>$ greater at LHC than RHIC
  - For K^{*0}: 20% larger   For ϕ: 30% larger
- ALICE π,K,p spectra: global blast-wave fit shows ~10% increase in radial flow w.r.t. RHIC

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



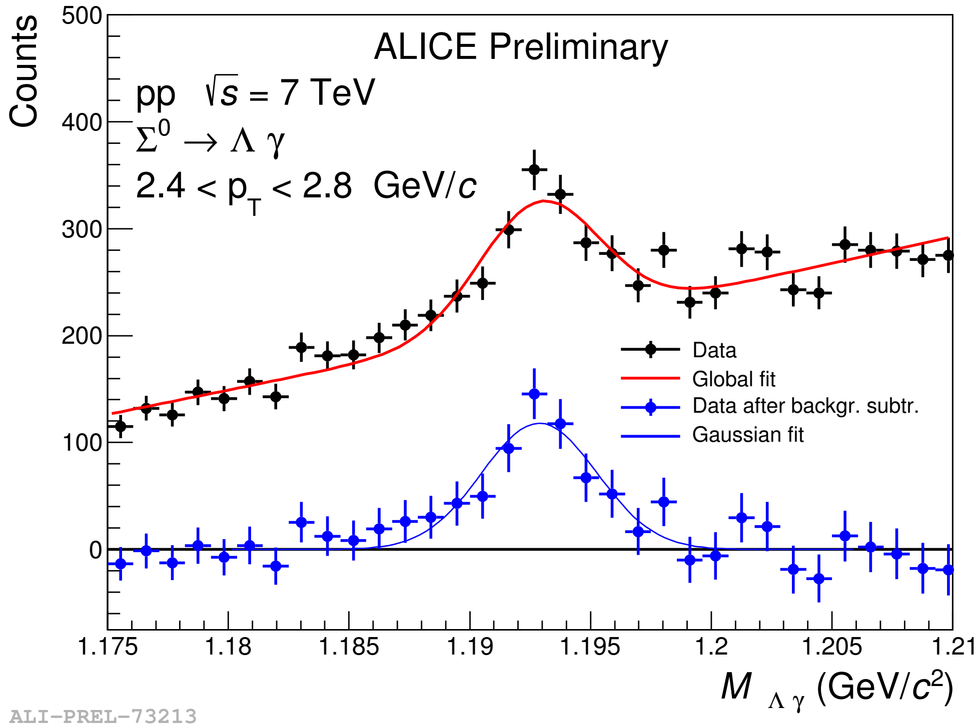
Λ(1520)

- Reconstruction in pp 2.76 TeV, pp 7 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 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

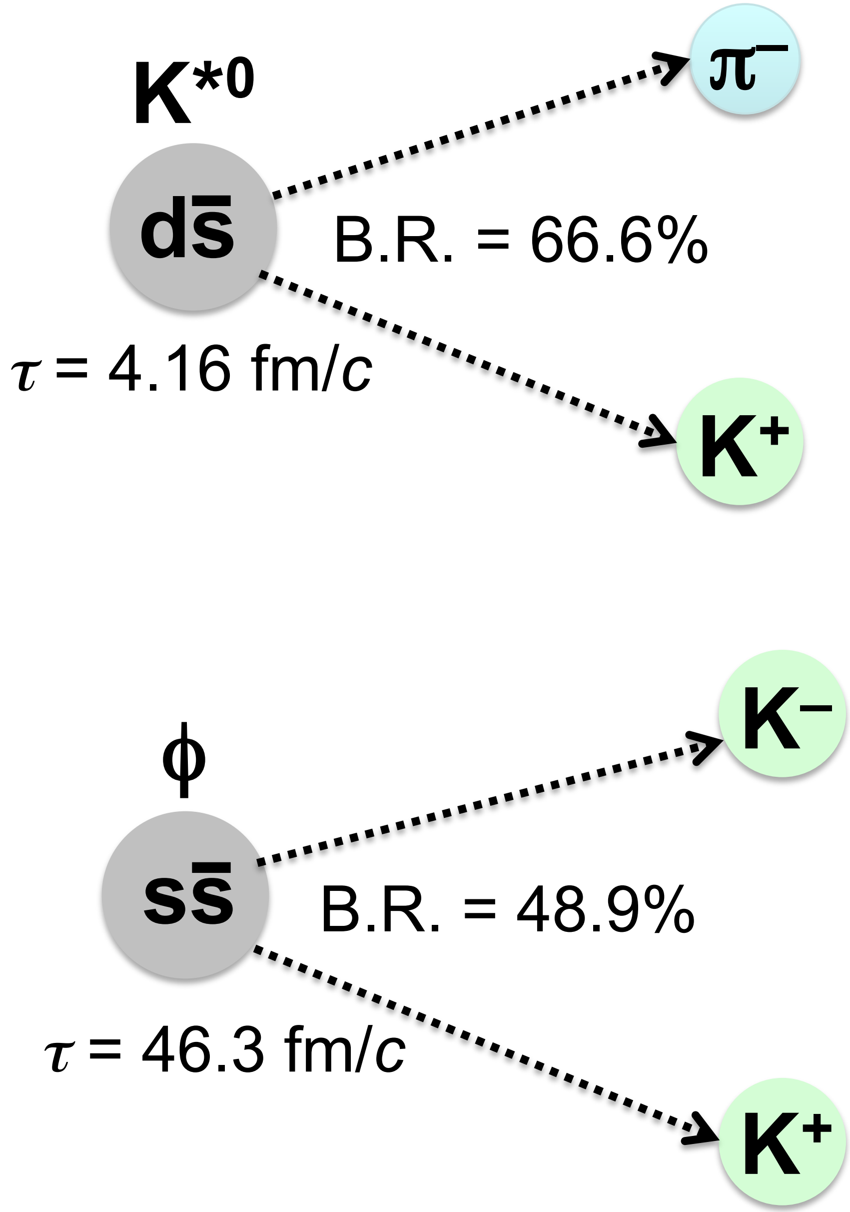
- Reconstruction in pp 7 TeV
- Decay channel: $\Sigma^0 \rightarrow \Lambda\gamma$
  - Photon identified through measurement of its conversion, and in PHOS (calorimeter)
- More information can be found in poster of A. Borissov at Quark Matter 2014: https://indico.cern.ch/event/219436/session/2/contribution/196/material/slides/0.pdf



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



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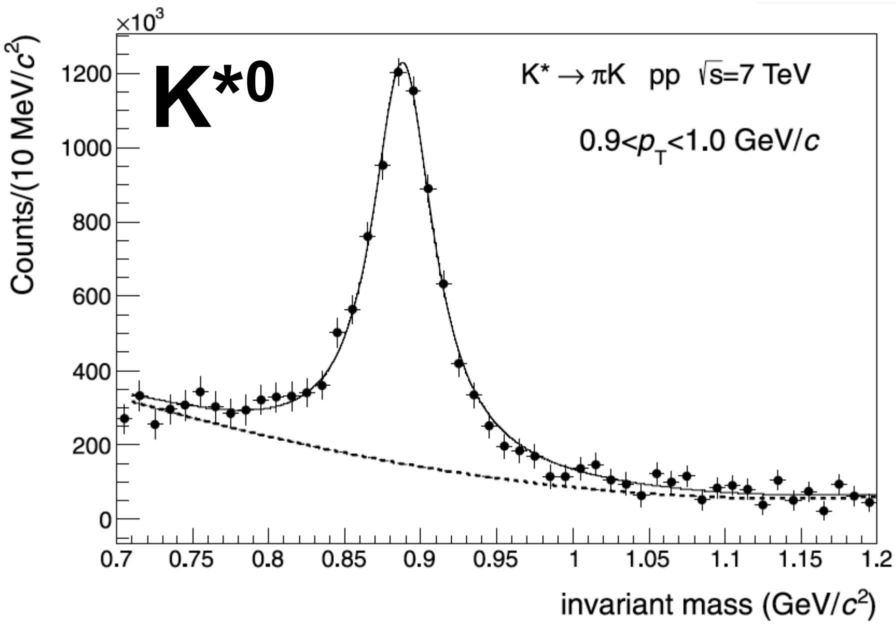
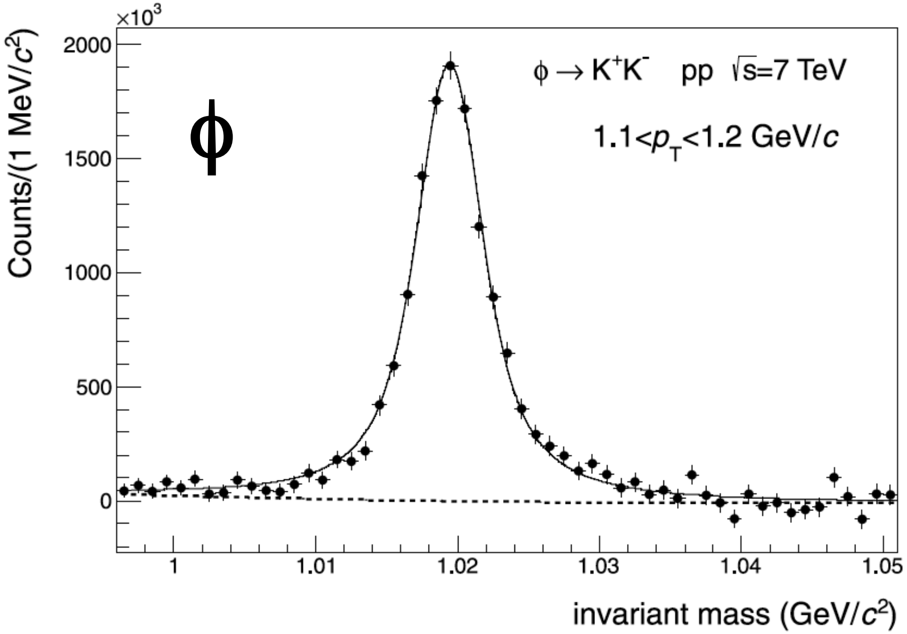
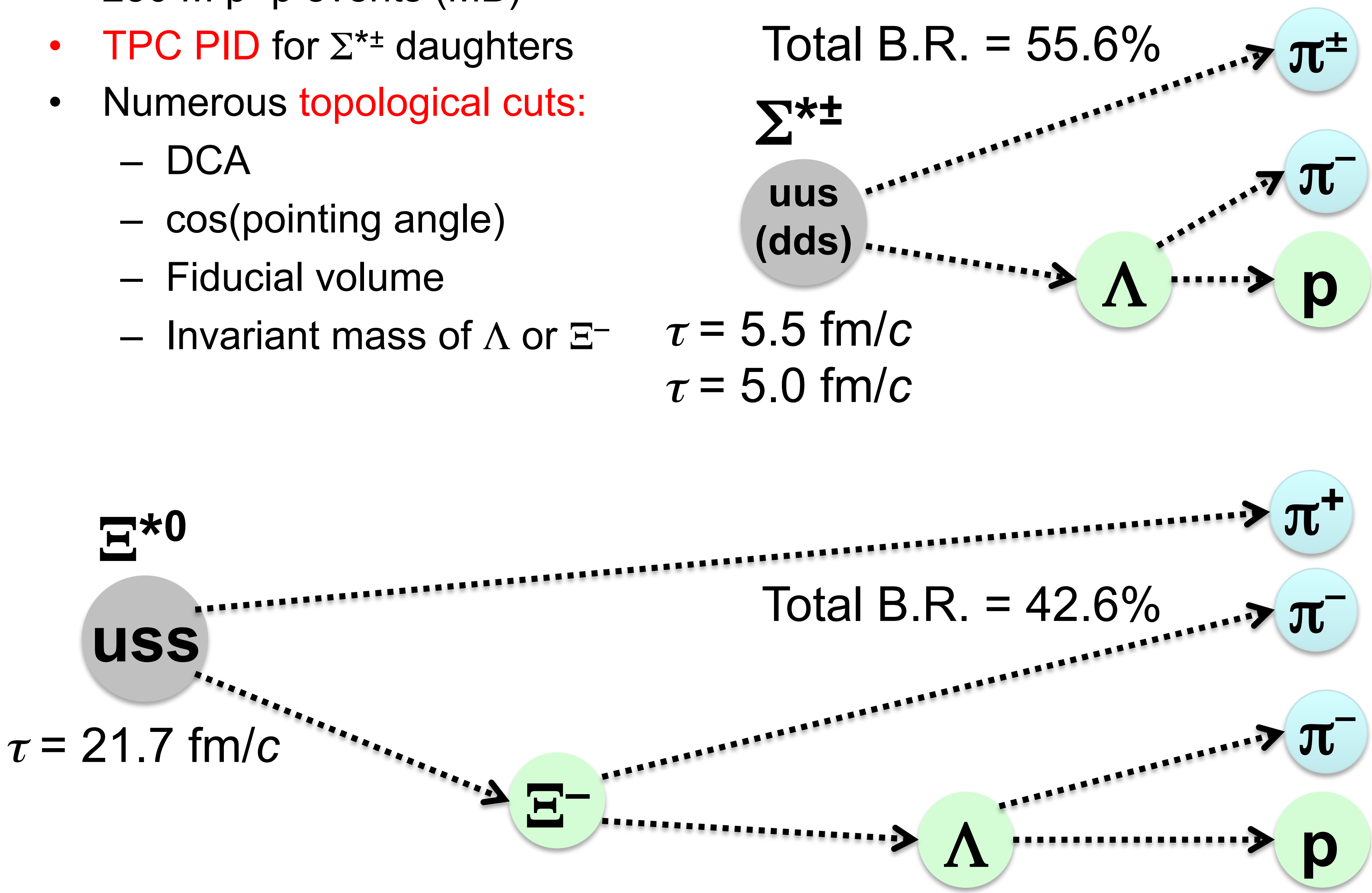




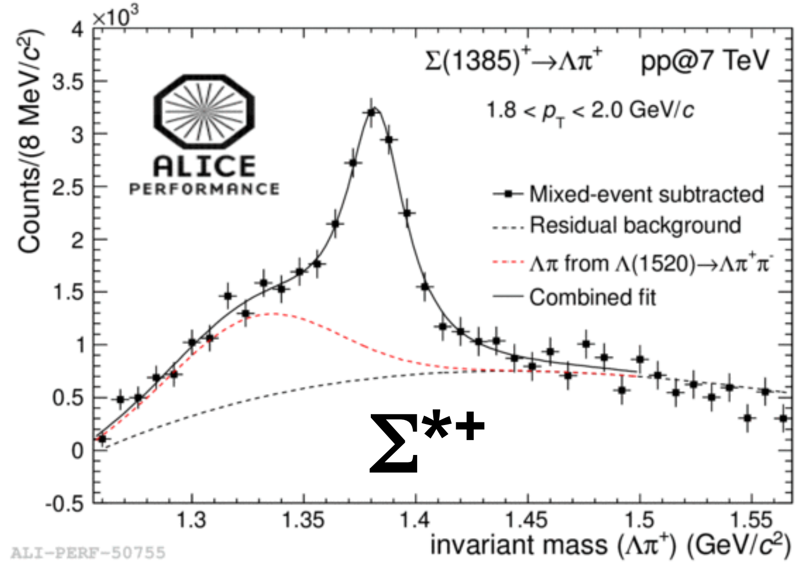
$\Sigma^*(1385)^\pm$ and $\Xi^*(1530)^0$

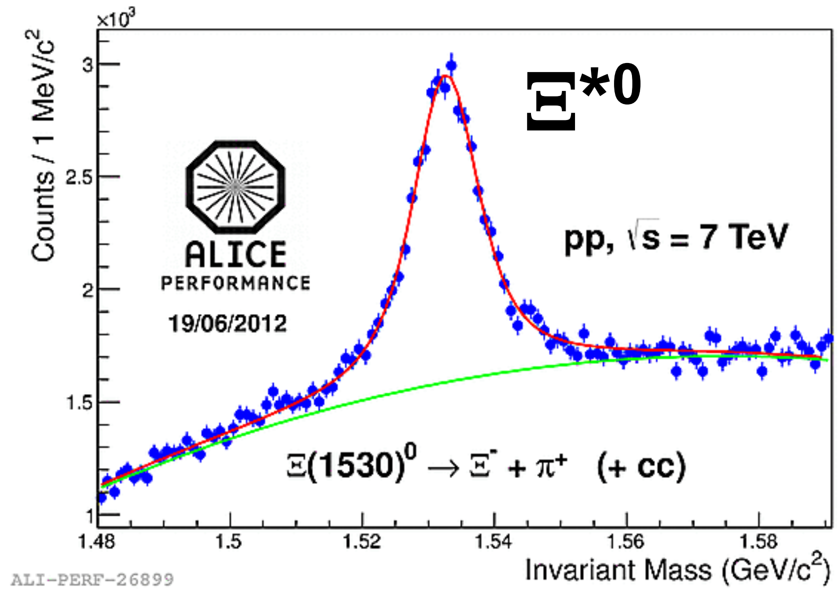
- 250 M p+p events (MB)
- TPC PID for $\Sigma^{*\pm}$ daughters
- Numerous topological cuts:
  - DCA
  - cos(pointing angle)
  - Fiducial volume
  - Invariant mass of Λ or Ξ^-



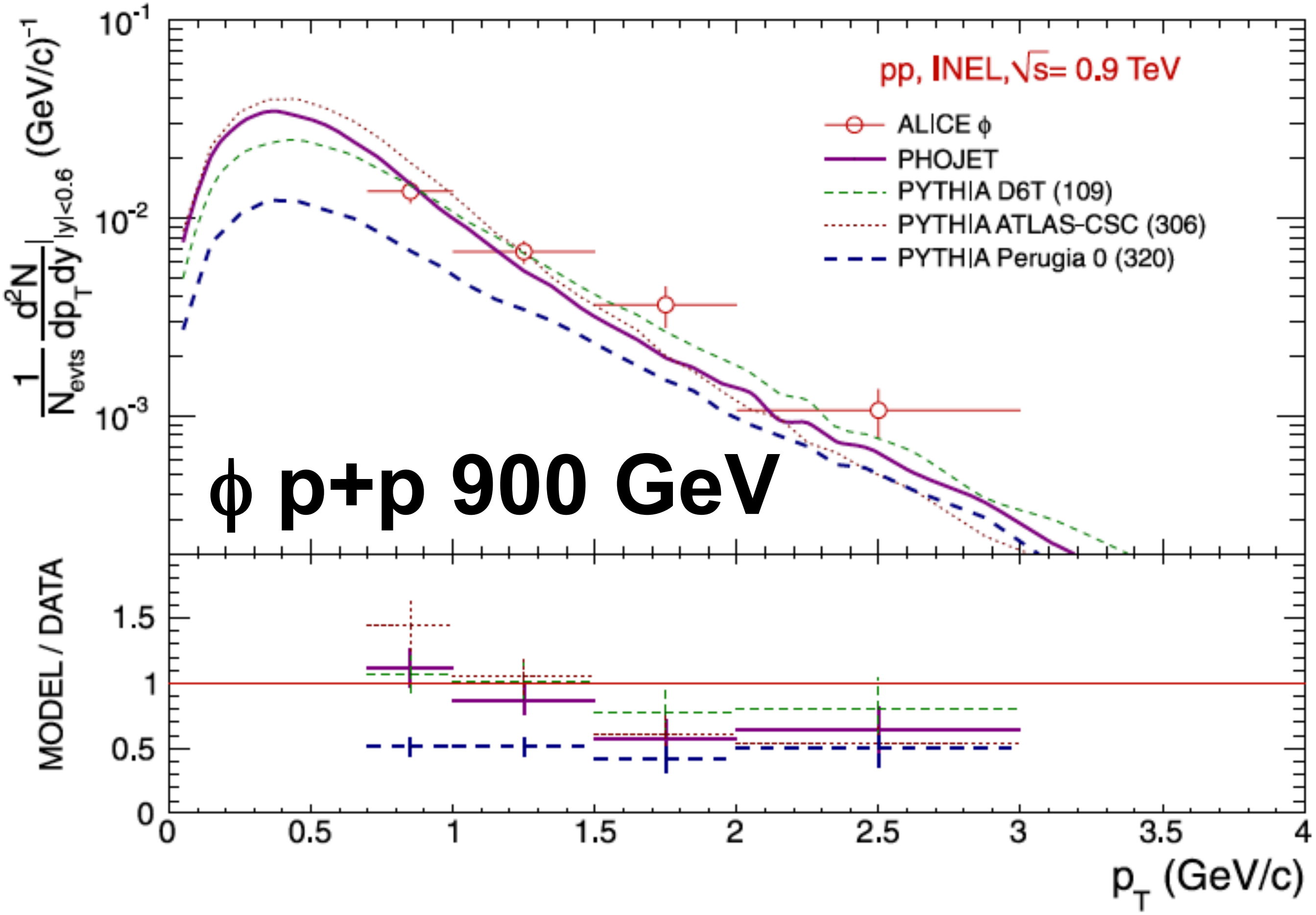
Σ*(1385)± and Ξ*(1530)⁰

- 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^-
- Mixed-event combinatorial BG
- $\Sigma^{*\pm}$: complicated res. BG
  - Various sources of correlated Λπ 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



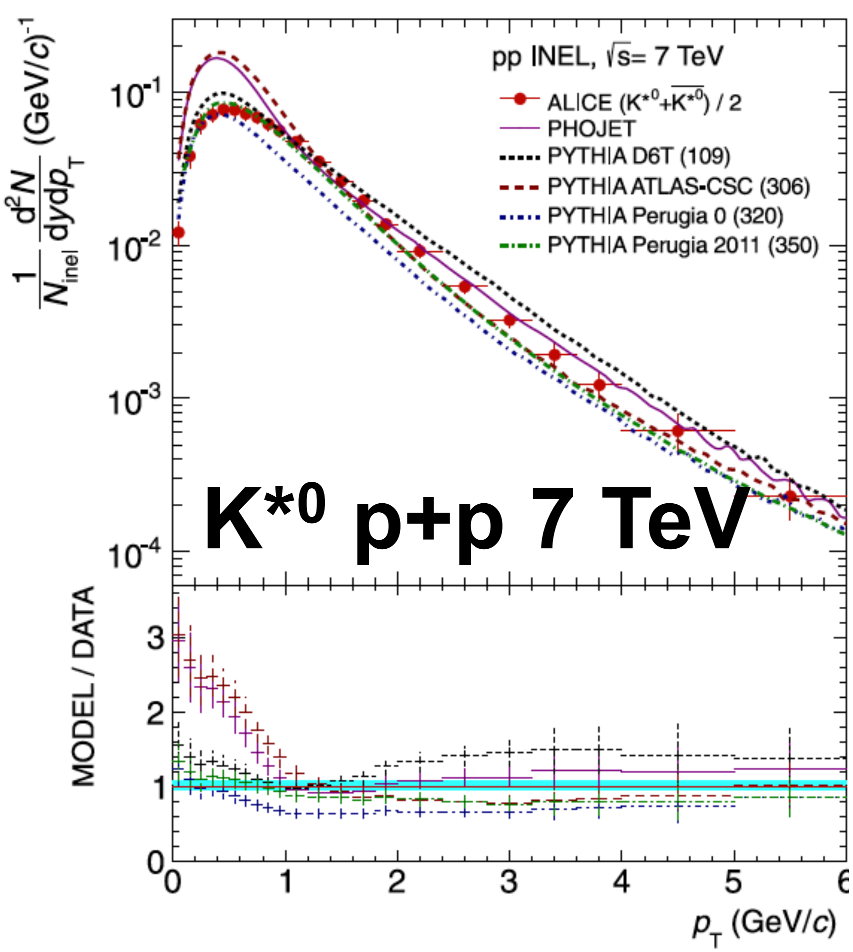


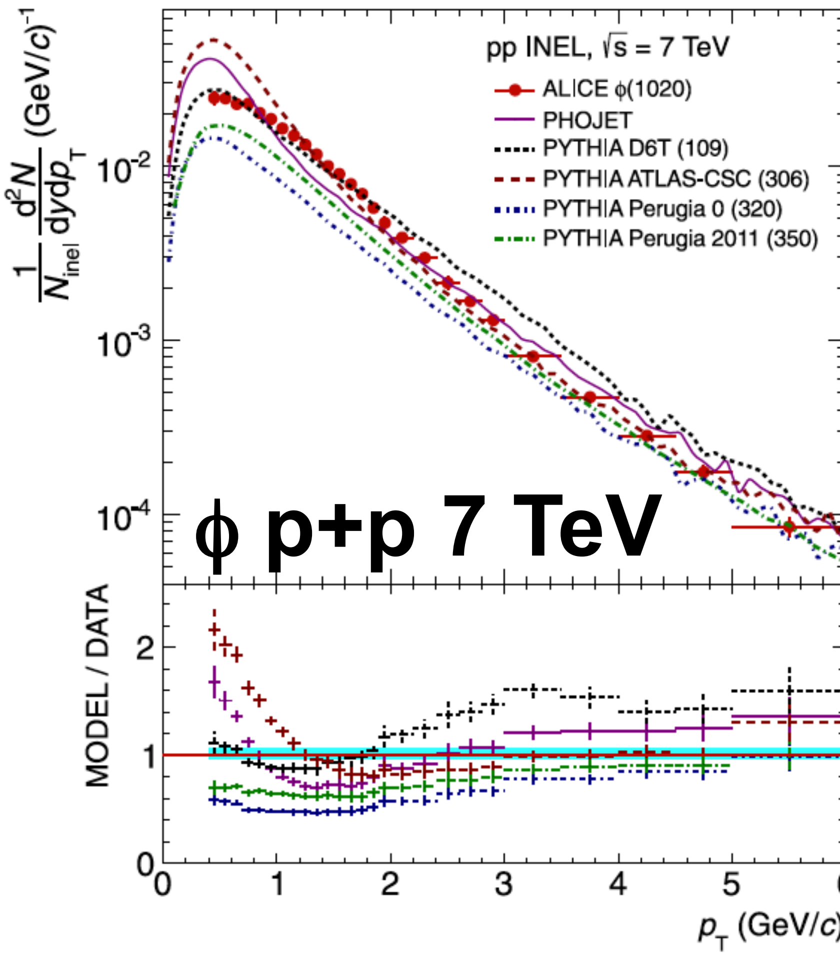
PYTHIA Comparisons



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

PYTHIA Comparisons

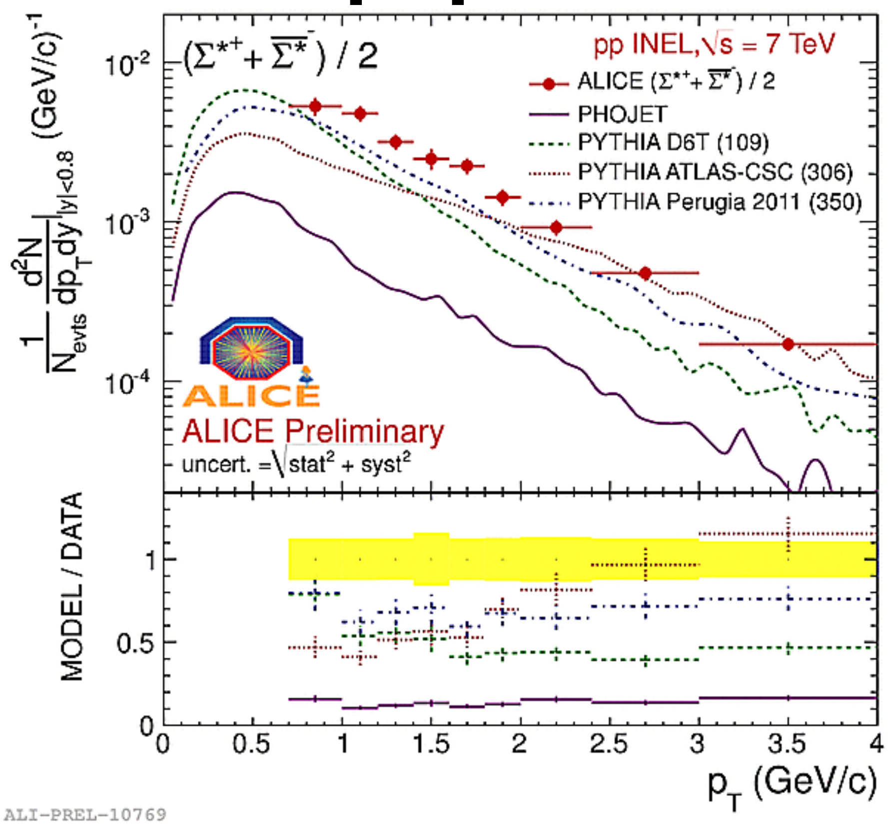




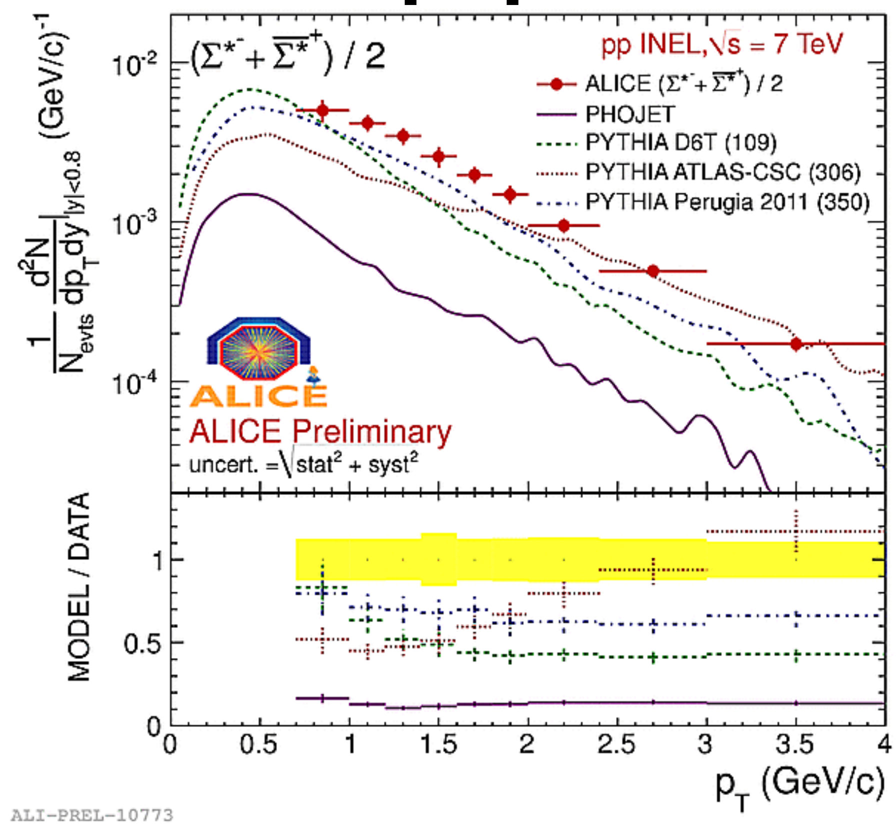
- PYTHIA Perugia 2011: reproduces K^{*0} and high-p_T ϕ well
- PHOJET and PYTHIA ATLAS-CSC overestimate spectra for p_T<1 GeV/c, describe high p_T well
- PYTHIA D6T: deviates at high p_T
- PYTHIA Perugia 0: underestimates spectra

PYTHIA Comparisons

Σ*+ p+p 7 TeV



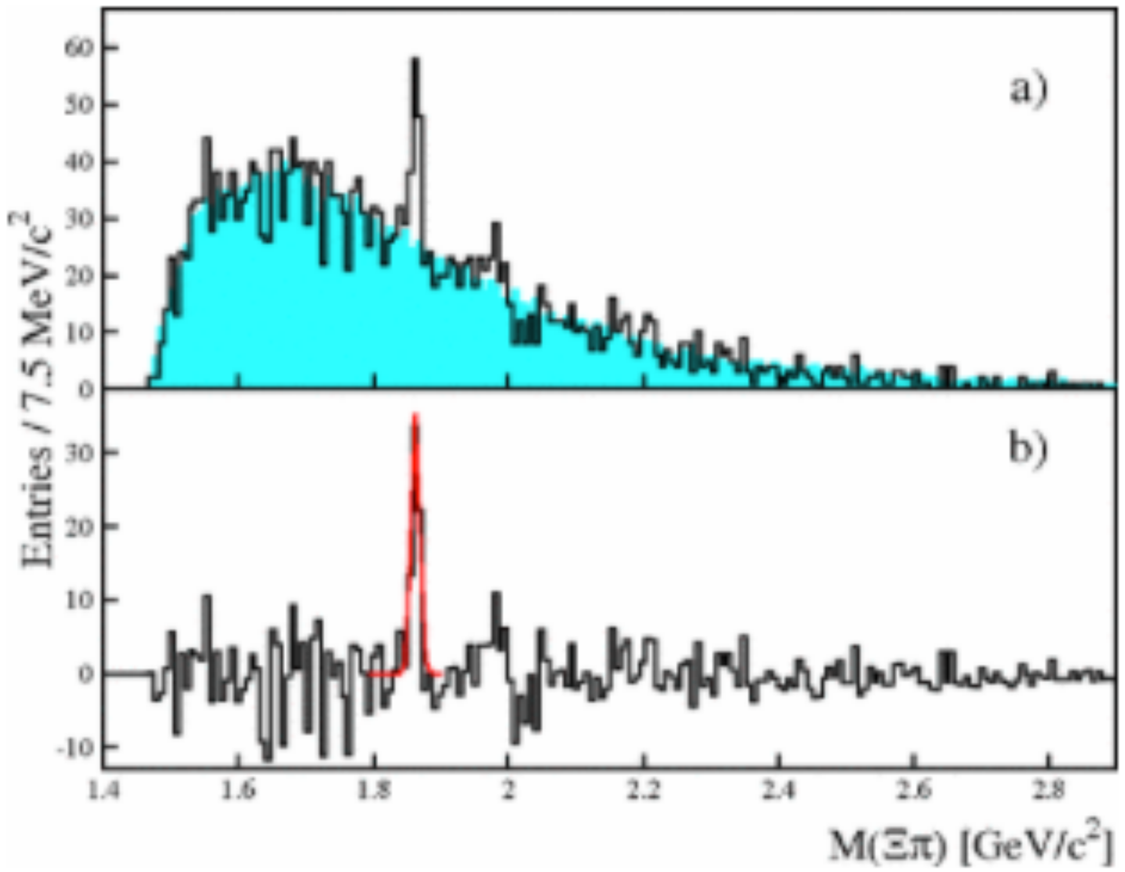
Σ*− p+p 7 TeV



- 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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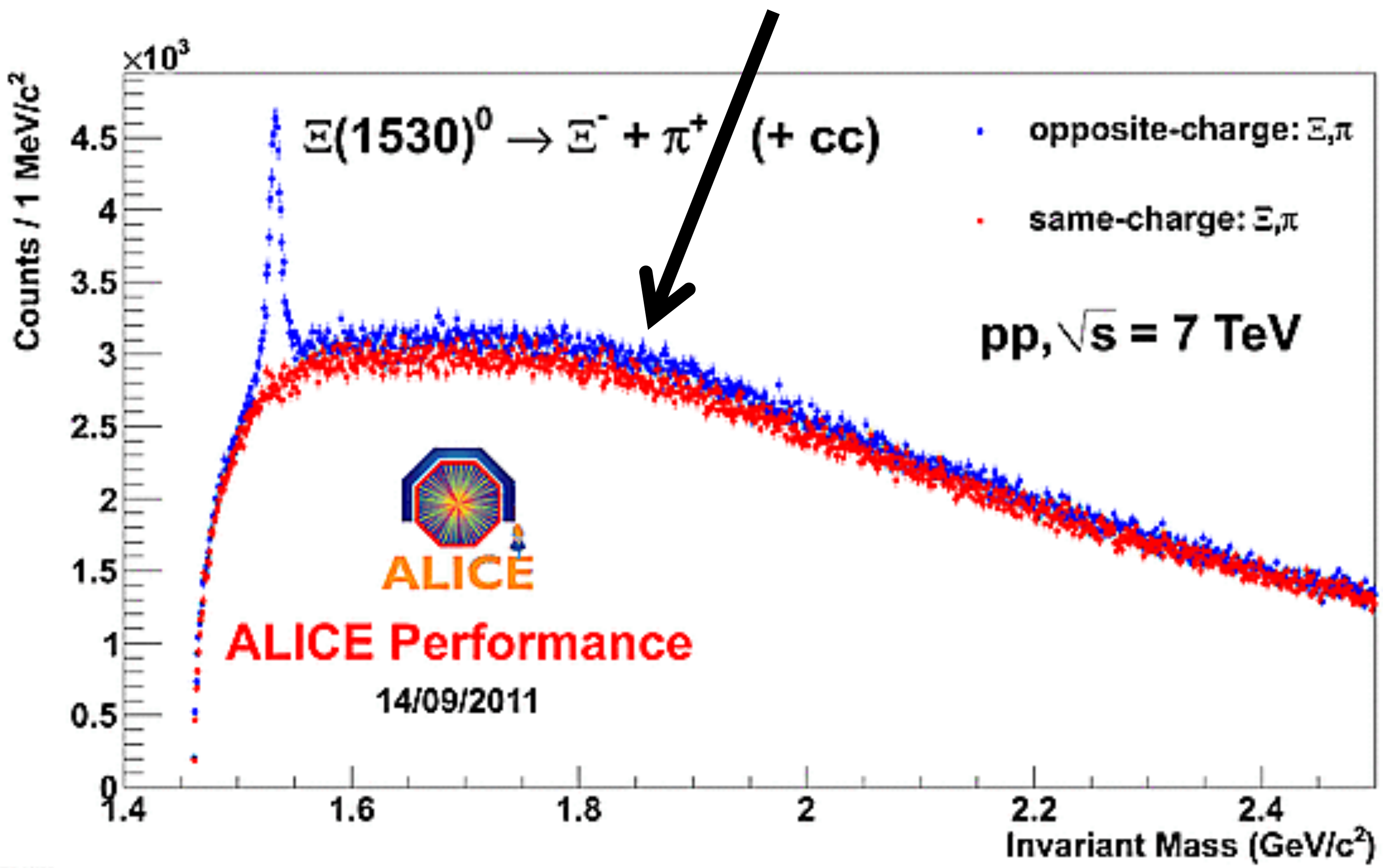

Hadron-Resonance Correlations

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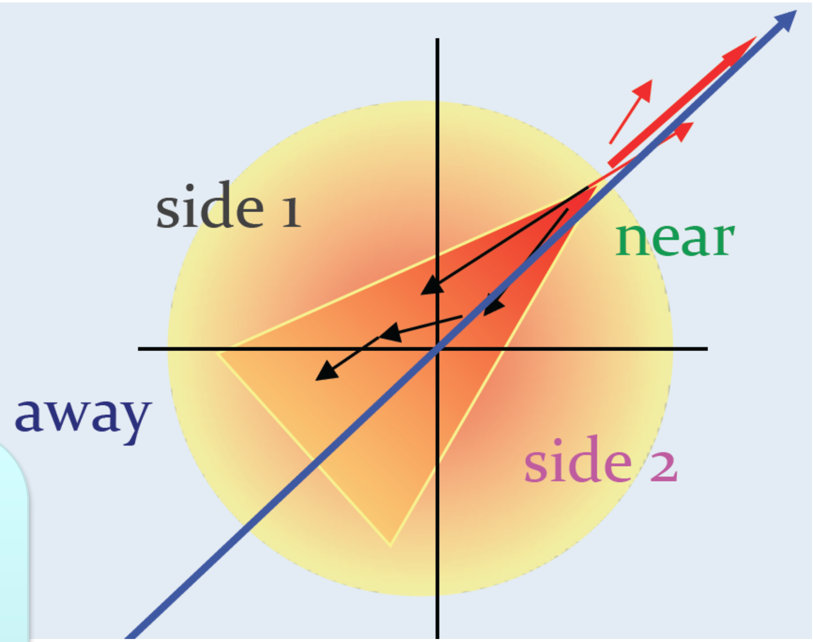
- To probe QGP: compare resonances that passed through medium with those that did not
  - Hadron-resonance correlations

Resonance in near side:
no medium interaction

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

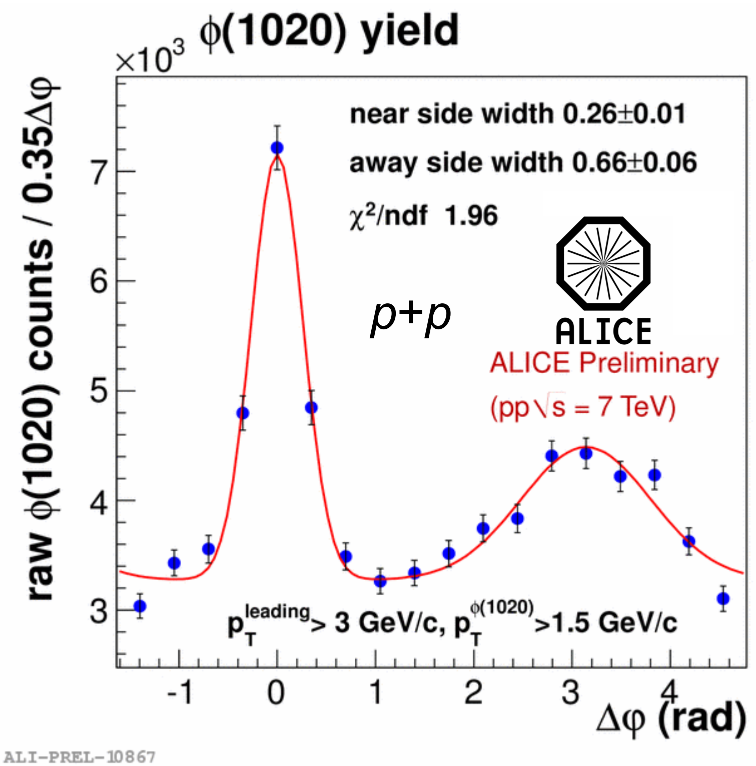


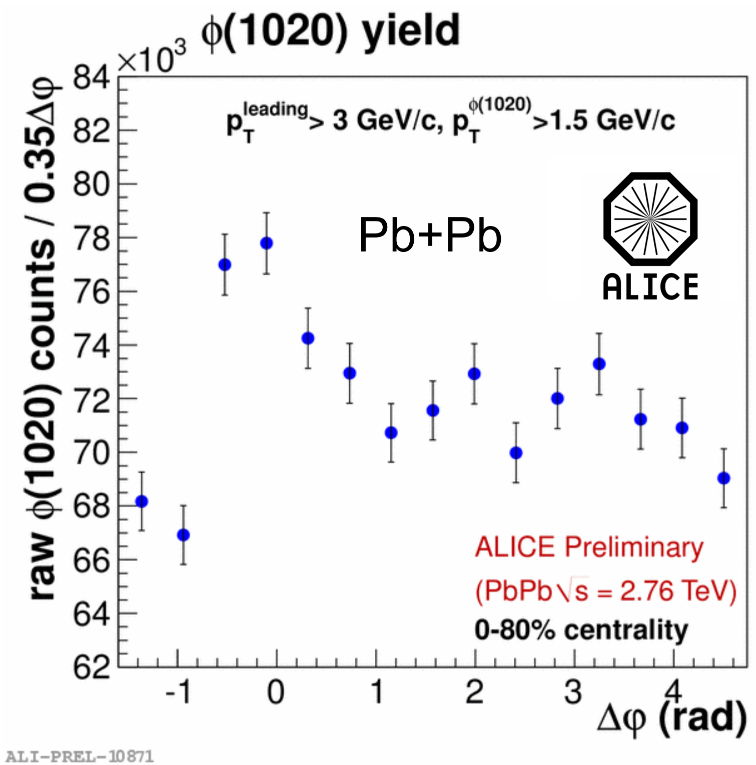
Resonance in away side:
Low p_T (below ~2 GeV/c):
dominated by interactions in hadronic medium
High p_T: dominated by interactions with early hadronic or partonic medium

Resonance transverse to jet:
Thermal production in hadronic medium

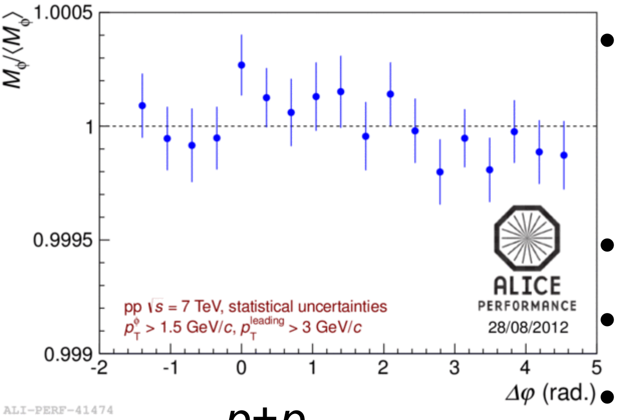
Angular Correlations

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



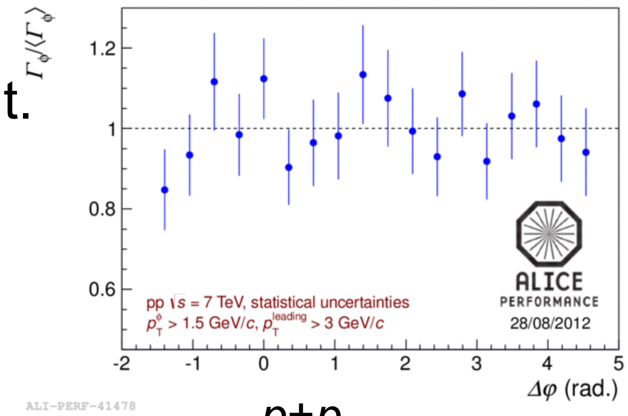


Mass and Width vs. $\Delta\varphi$



p+p

- 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

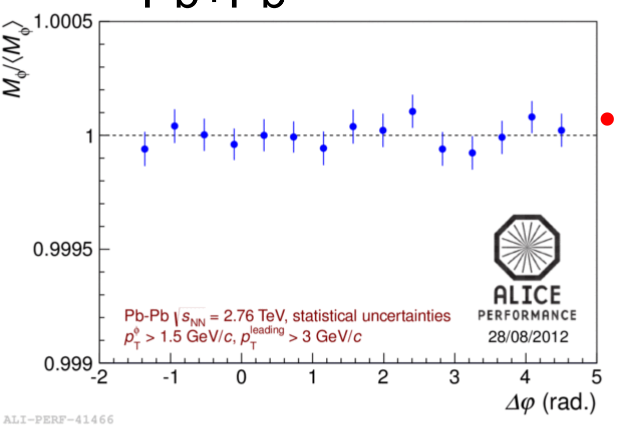


p+p

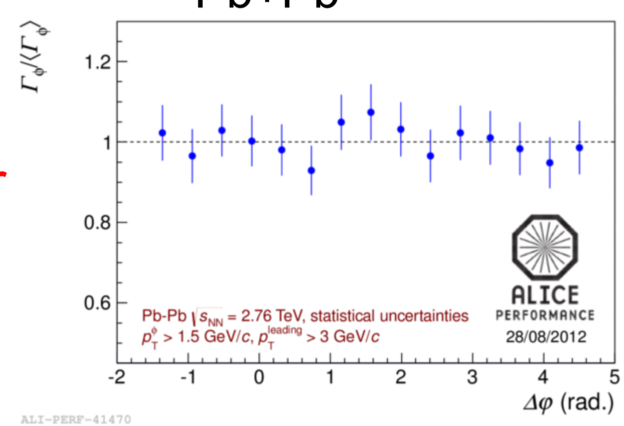
mass/average value

width/average value

Pb+Pb



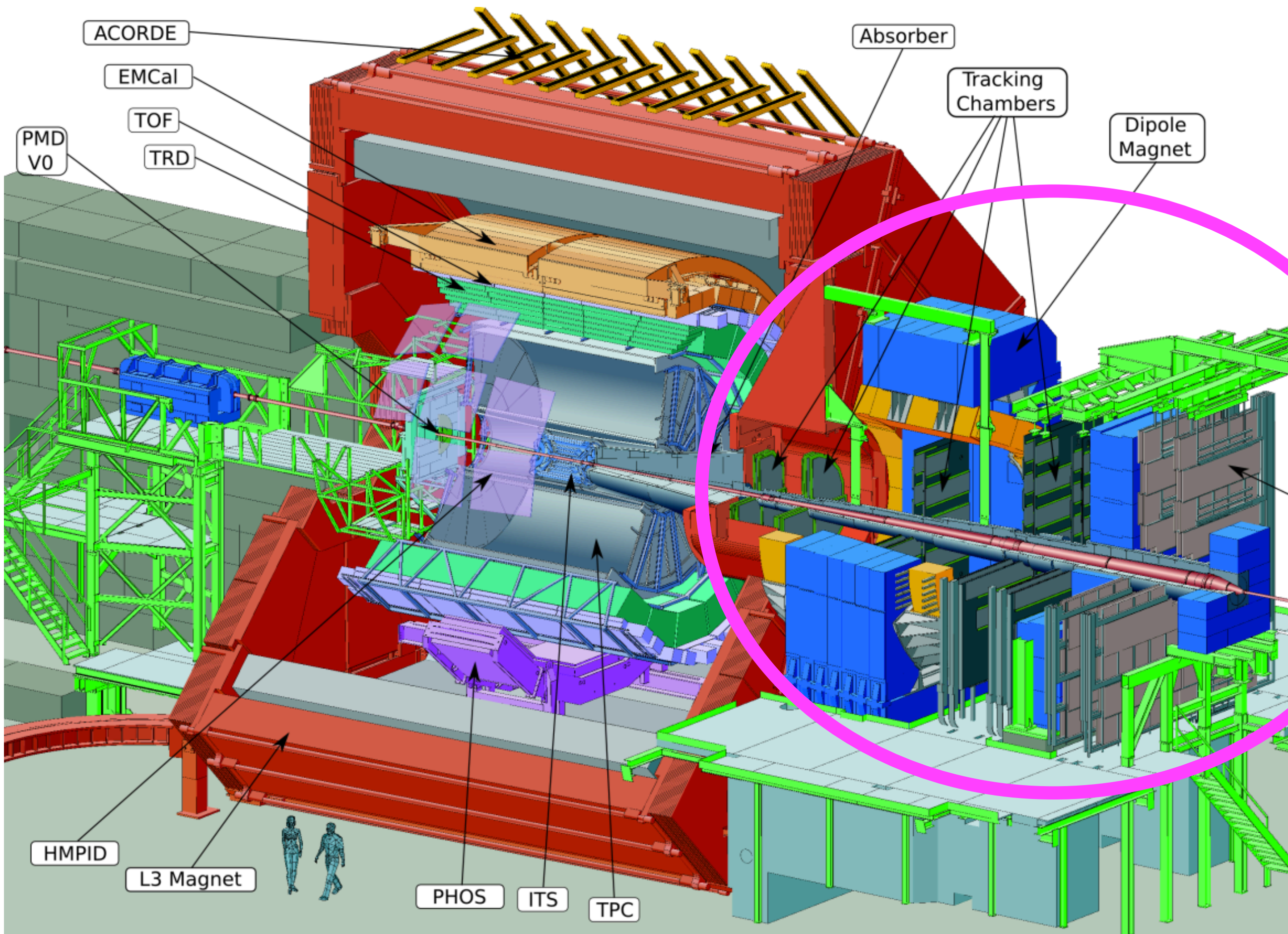
Pb+Pb



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

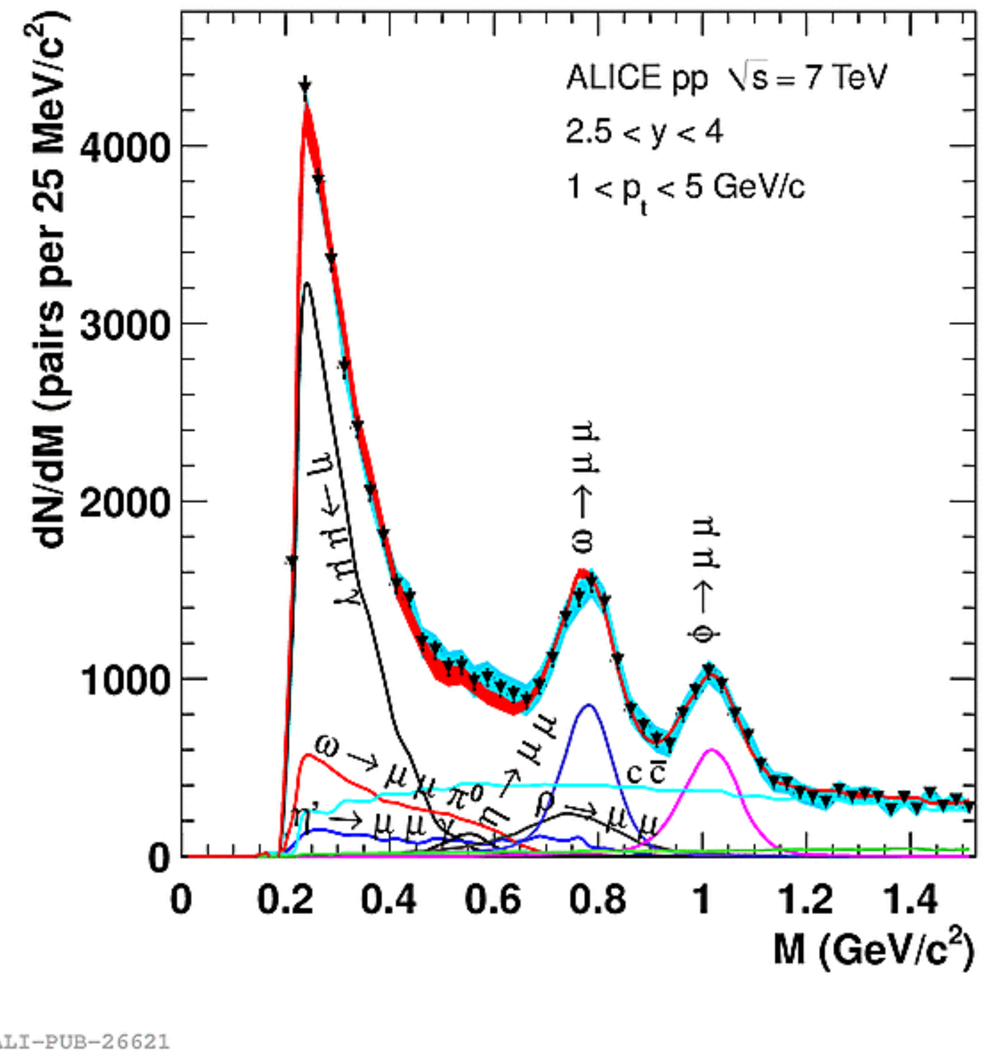
$\phi \rightarrow \mu^{-}\mu^{+}$

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



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

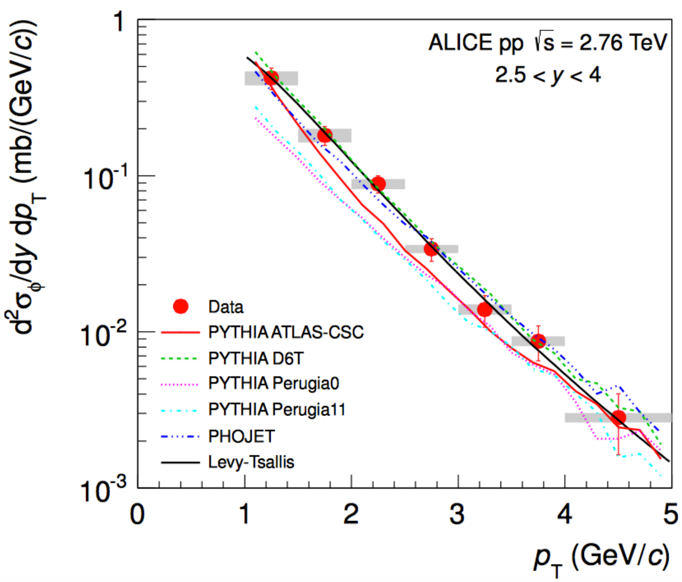
- Signal extracted by fitting dimuon invariant-mass distribution with hadronic cocktail:



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

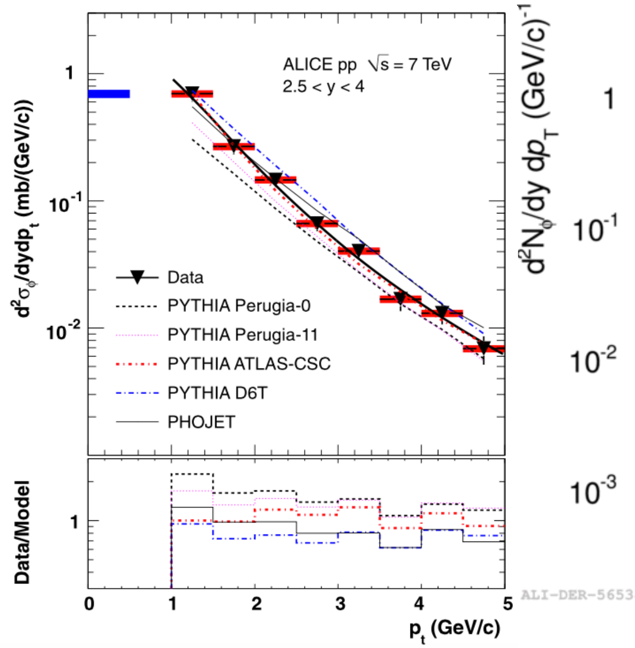
- Measured in pp collisions at 2.76 TeV and 7 TeV, Pb–Pb collisions

pp 2.76 TeV



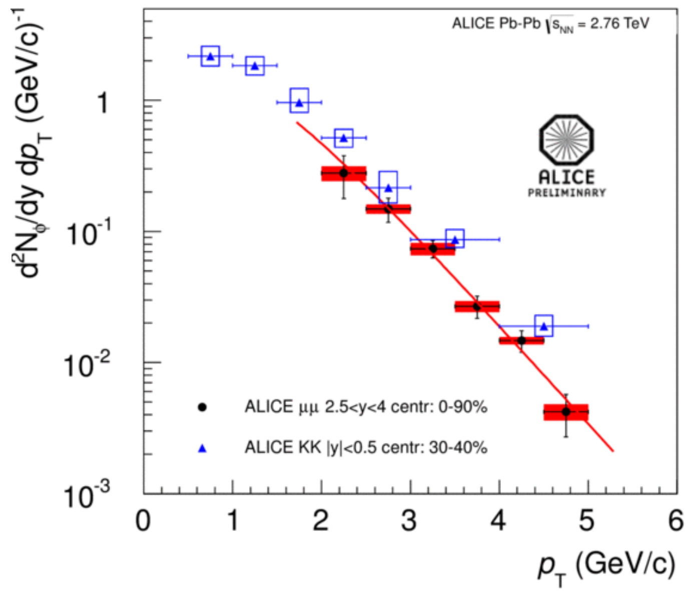
Best agreement with PHOJET and PYTHIA D6T

pp 7 TeV



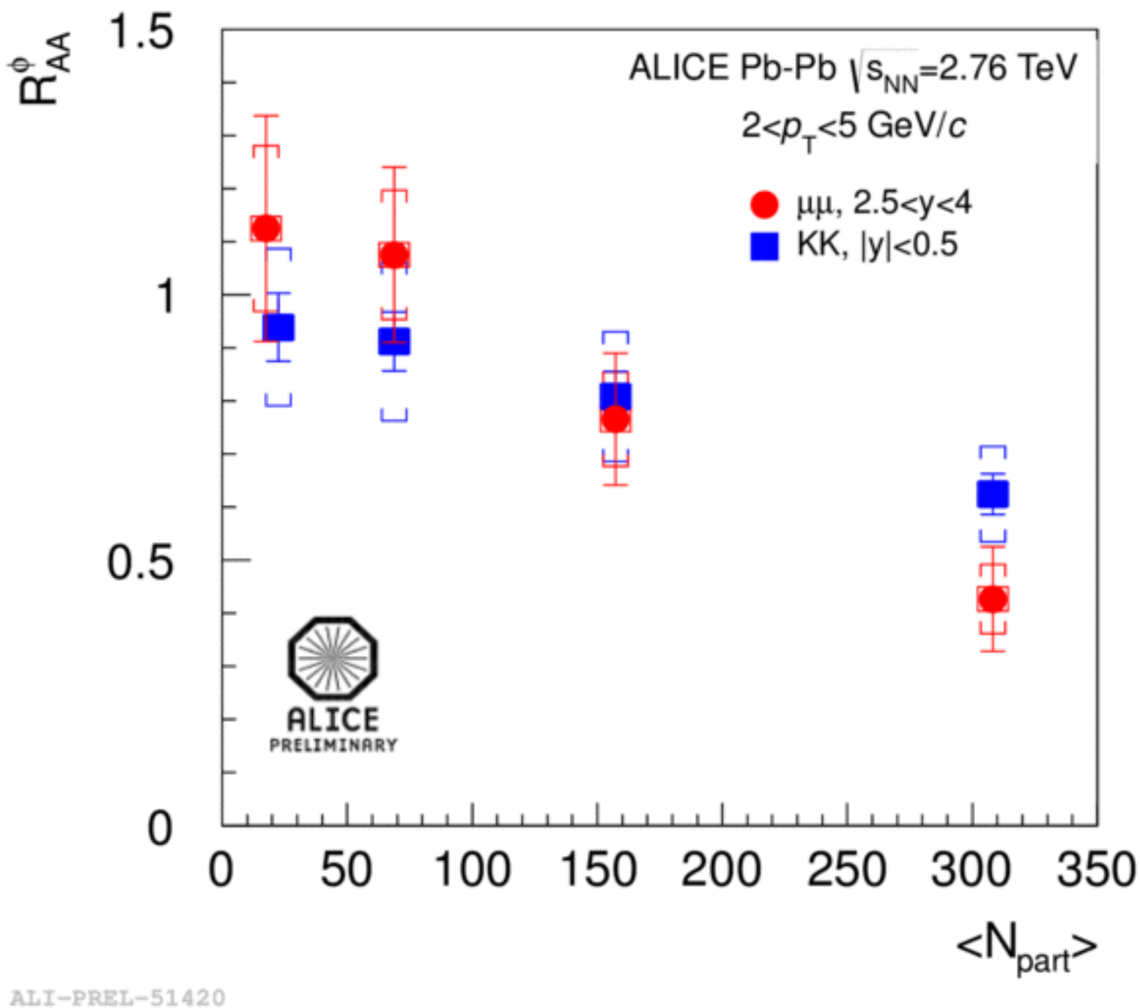
Best agreement with PHOJET, PYTHIA D6T and ATLAS-CSC

Pb–Pb 2.76 TeV



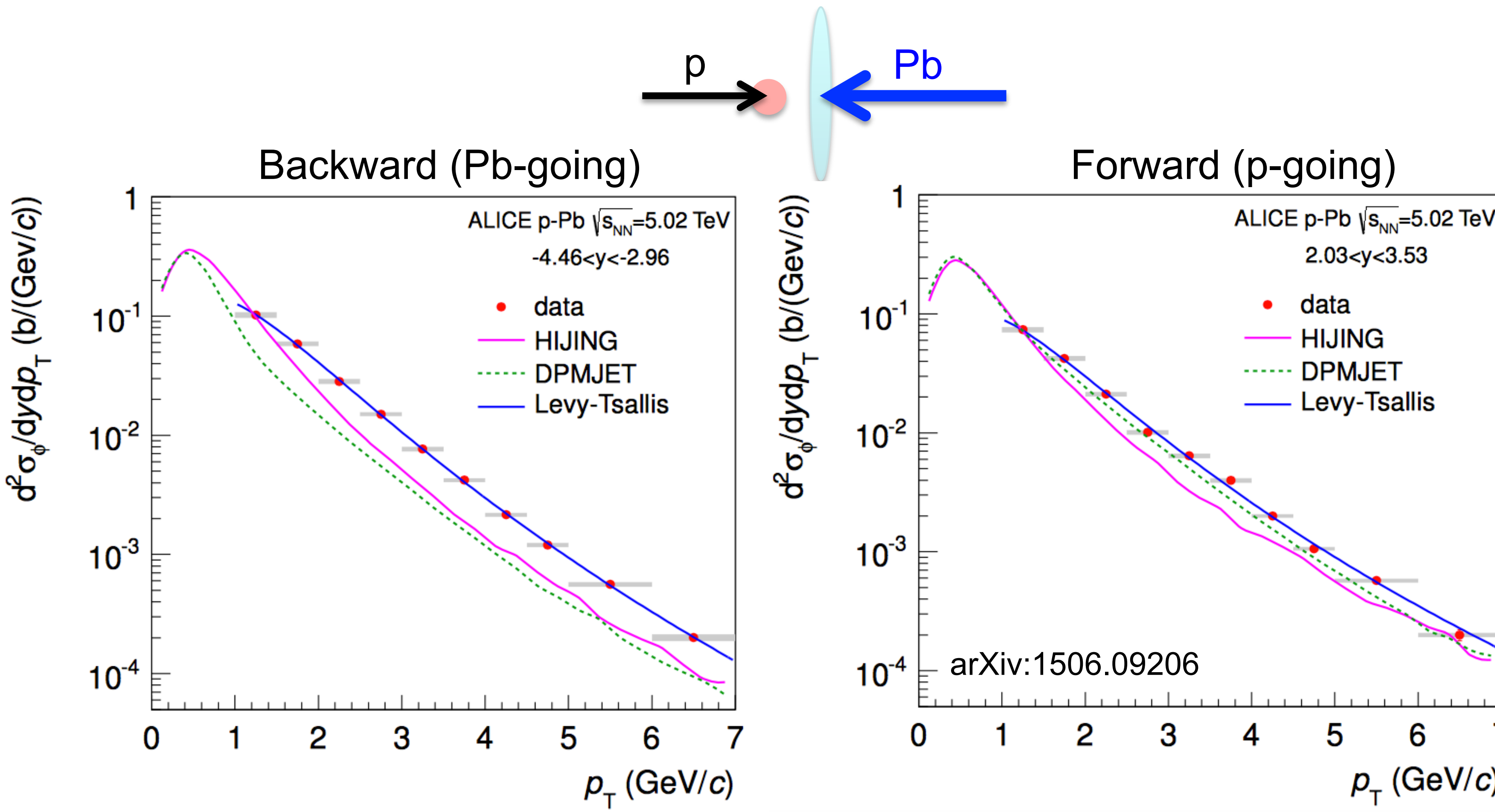
Nuclear Modification Factor

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



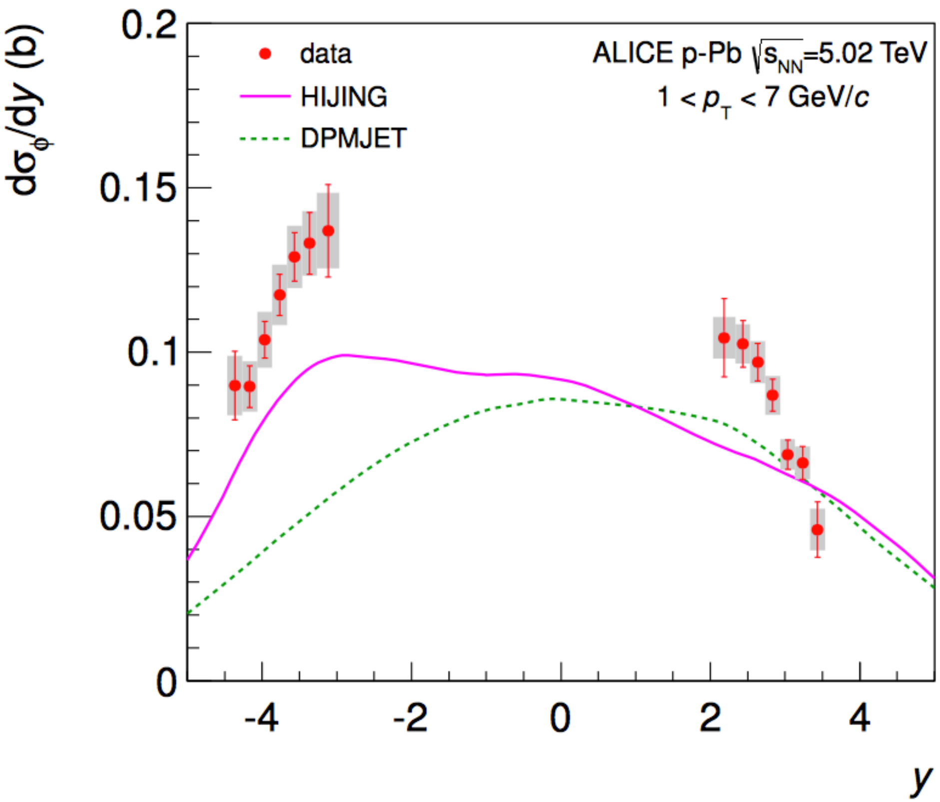
In p–Pb: Forward vs. Backward

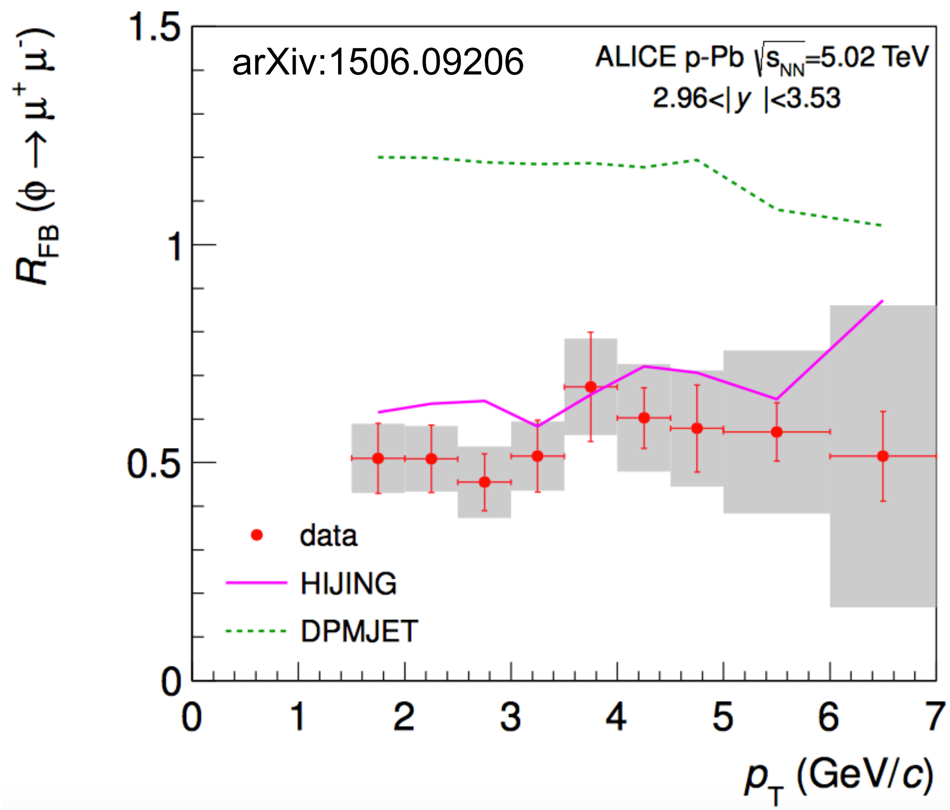
- Rapidity asymmetry in particle production
- HIJING and DPMJET describe charged-particle production well, but tend to underestimate ϕ.



In p–Pb: Forward vs. Backward

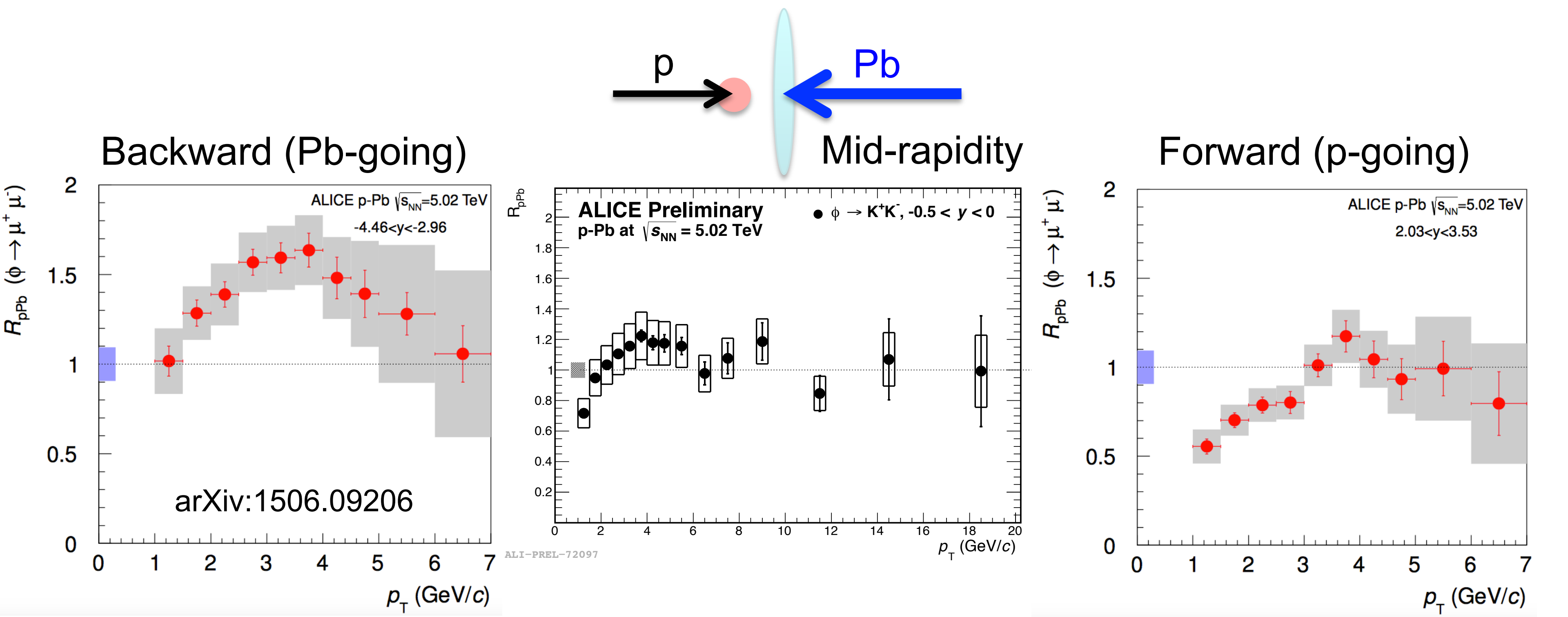
- Forward/Backward ratio (in common *y* window)
  - Flat (≈0.5) with p_T
- HIJING qualitatively describes rapidity asymmetry and describes R_{FB}





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) or final-state effect (radial flow)?



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) or final-state effect (radial flow)?
- Similar behavior observed in d–Au collisions (PHENIX)