Study of the hadron gas phase using short-lived resonances with ALICE

EPS-HEP 21/08/23 Hamburg

Johanna Lömker - Nikhef/Universiteit Utrecht

On behalf of the ALICE collaboration

Nikhef

Utrecht University

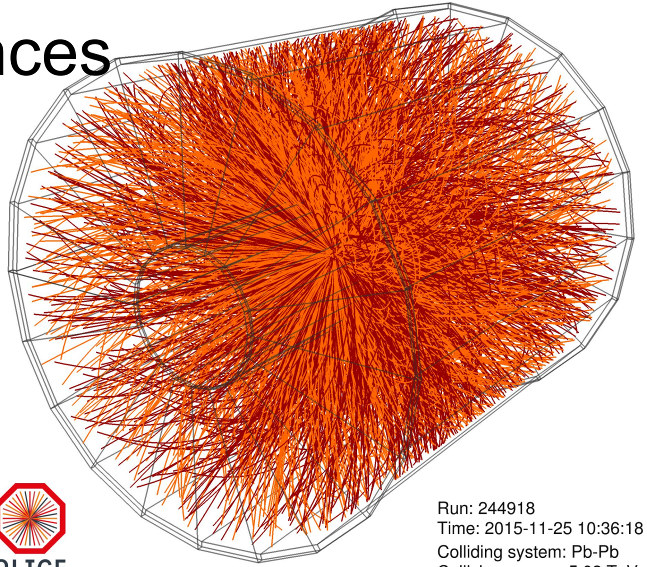
ALICE

https://www.uni-hamburg.de/uhh/profil/bilder.html - 11/08/23

Status of light-flavour hadronic resonances

Resonance	**K***(892)^0	**Λ**(1520)	**φ**(1020)
Quark composition	$d\bar{s}$, $\bar{d}s$	uds	$s\bar{s}$
τ (fm/*c*)	~4.1	~12.6	~46.3
Decay channel	**ππ**	**pK**	**KK**
B.R. (%)	~66.6	~22.5 PHYSICAL REVIEW C 99, 024905 (2019)	~49.2
Mass (MeV)	~891	~1519	~1019

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)



ALICE

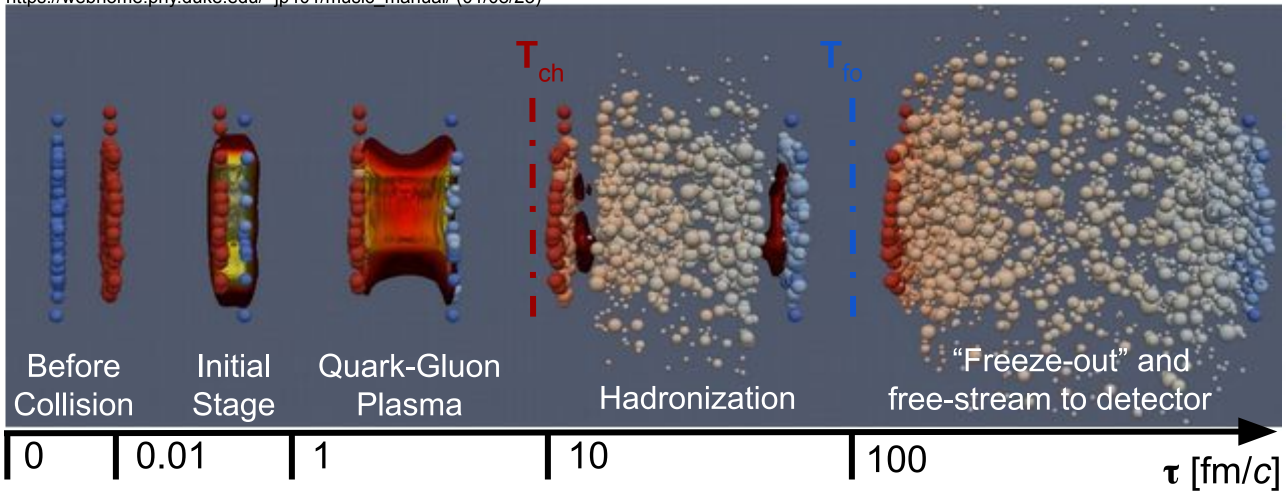
Run: 244918
Time: 2015-11-25 10:36:18
Colliding system: Pb-Pb
Collision energy: 5.02 TeV

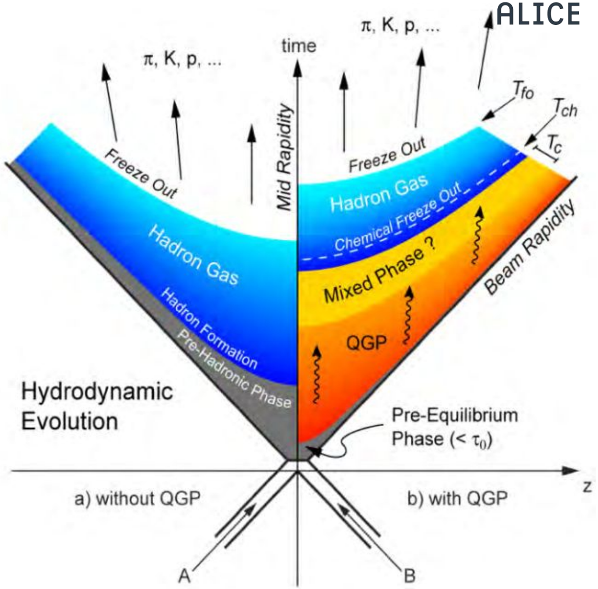
ALICE-PHO-GEN-2016-001-2

⇨**Short lifetimes** study the properties of the hadronic phase in heavy-ion collisions

Evolution of heavy-ion collisions

https://webhome.phy.duke.edu/~jp401/music_manual/ (01/08/23)





Doi: 10.22661/AAPPSbl.2019.29.4.16

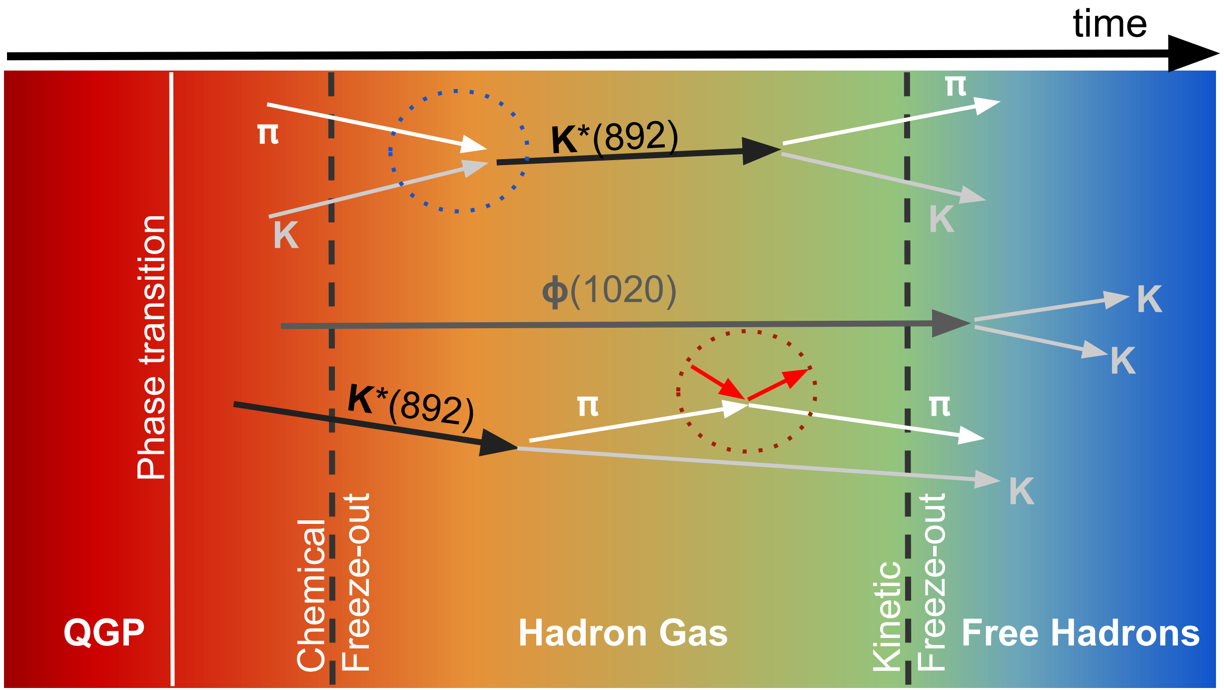
Hadronic-gas phase between chemical and kinetic freeze-out

➩Duration similar to lifetime of resonance (**ϕ**(1020) has longer lifetime)

➩In medium modifications (pp vs. AA)

➩Insights on QCD phase structure (**T_{ch}**, **T_{fo}**, **μ_B**)

Resonances in the hadronic gas phase



particle yields

spectral shape

I) Regeneration

Pseudo-elastic scattering of decay products

➩ Increases measured yield

II) Rescattering

Elastic scattering of decay products with other hadrons

➩ Smearing of mass peak (no more reconstruction from invariant mass)

➩ Decreases measured yield

➩**Total yields** of **K***(892) and **ϕ**(1020) are sensitive to rescattering and regeneration at low momenta (< 3 GeV/*c*)

➩**Ratios to stable particles** study relation of resonance production and lifetime as quark content cancels out

A Large Ion Collider Experiment

Multi-purpose detector with unique particle identification capabilities and tracking down to low momenta

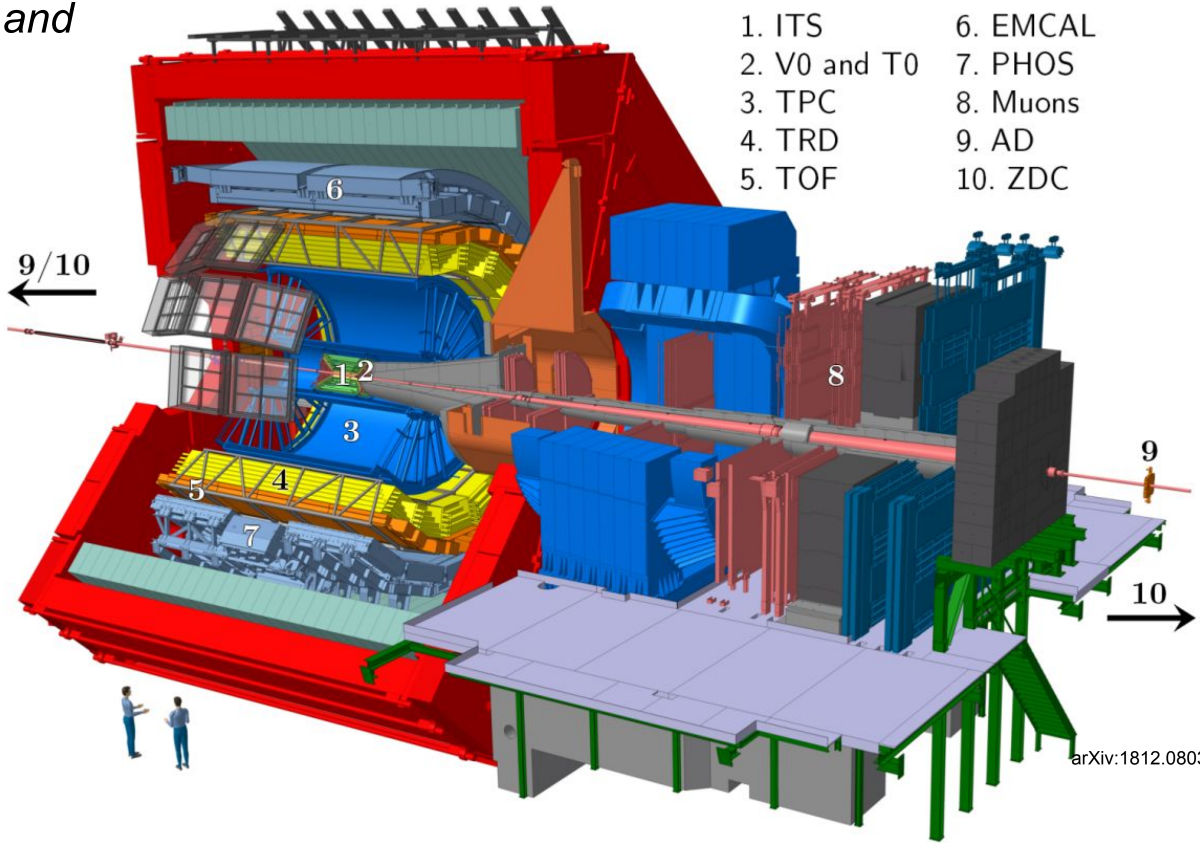
Central barrel detectors

ITS: Silicon detector for tracking and vertexing

TPC: Time Projection Chamber for PID and tracking

TOF: Time-of-flight for PID

V0: Scintillator detector for triggering and multiplicity estimation



arXiv:1812.08036v1

Example: Invariant mass reconstruction $\Lambda(1520) \rightarrow pK$

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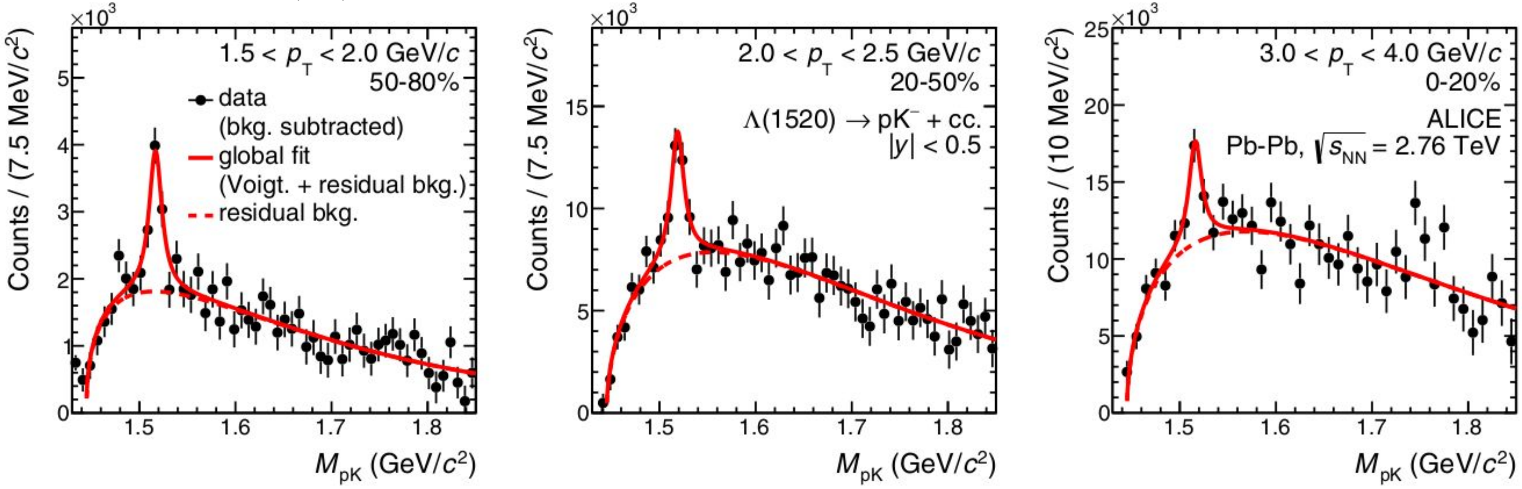

*Particle and anti-particle states are combined for larger statistics

1. <u>Mixed-event technique</u>: **rejection of combinatorial background**
   - Combining unlike-sign p and K tracks from different events with similar characteristics
   - Normalization and correction for mixing distortions through fit to mixed/same-event ratio of like-sign pairs
2. <u>Global Fit</u>:
   - **Signal** convolution of non-rel. Breit-Wigner function with Gaussian detector resolution
   - **Residual background ~** Maxwell-Boltzmann
3. <u>Corrections of raw yields</u>: HIJING MC simulations with additional $\Lambda(1520)$ and GEANT3 for transport
   - Decay branching fraction, detector acceptance, reconstruction efficiency, track selection, PID efficiency

Spectral shapes K*(892) and ϕ(1020) in pp

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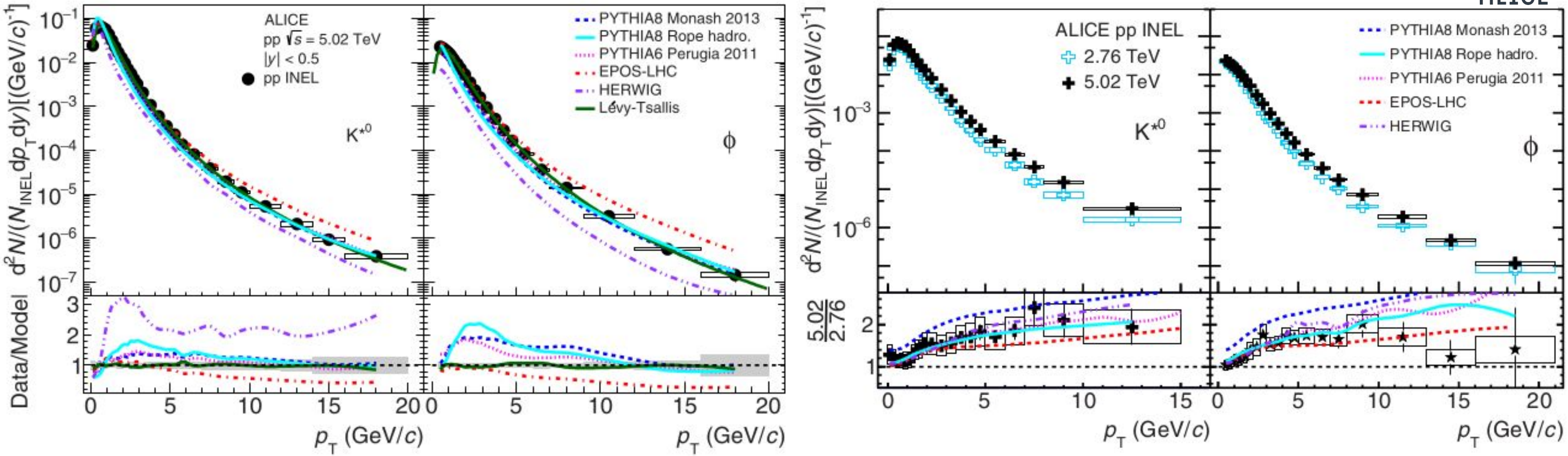

- **HERWIG** does not describe the data
- **EPOS-LHC** overestimates **ϕ** and **K**^{*0} for p_T > 5 GeV/c
- **PYTHIA** reasonable above 10 GeV/c
    - **K***(892)^0 overestimated/underestimated at low/intermediate p_T
    - **ϕ**(1020) overestimated at low and intermediate p_T

- **Resonance yield increase with collision energy**
- **Energy ratio increases with p_T** (saturation ?)
- **PYTHIA8 Monash 2013** overestimates yields
- **K**^{*0} described by models within uncertainties
- **ϕ**(1020) in agreement with models for for p_T < 8 GeV/c

Spectral shapes K*(892) and ϕ(1020) in pp

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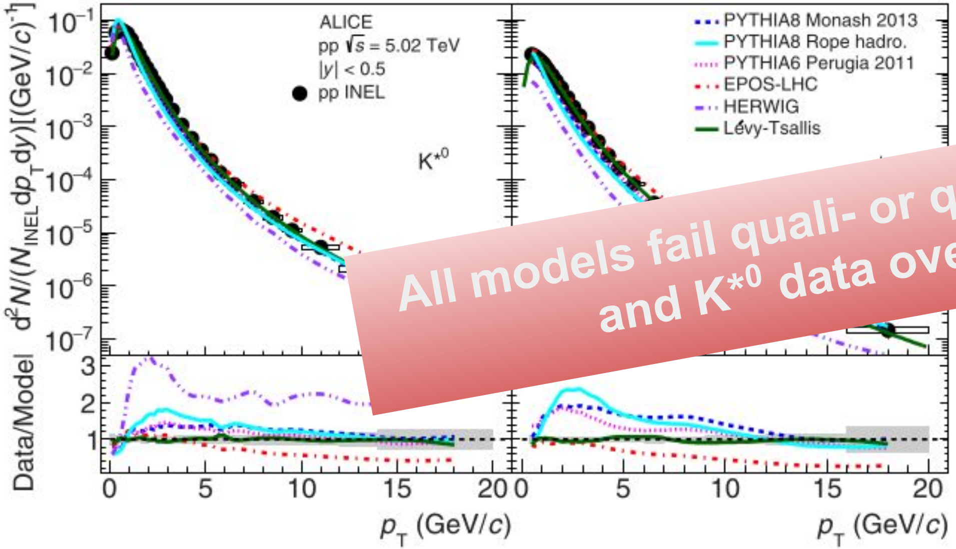

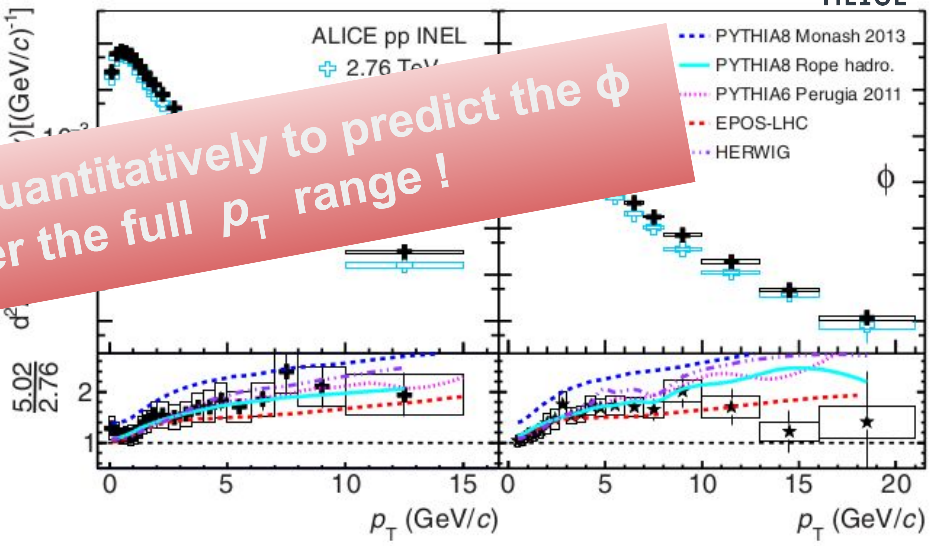

All models fail quali- or quantitatively to predict the ϕ and K*0 data over the full p_T range !

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Spectral shapes K*(892) and ϕ(1020) in Pb-Pb

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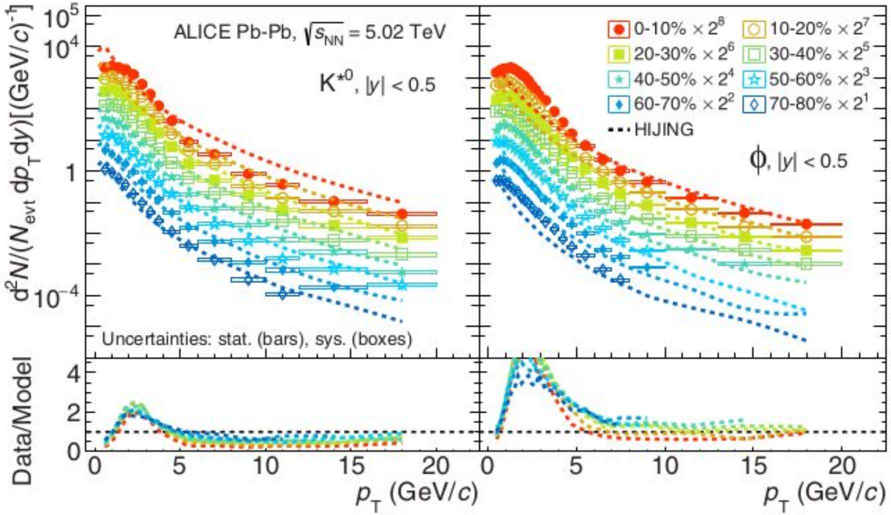

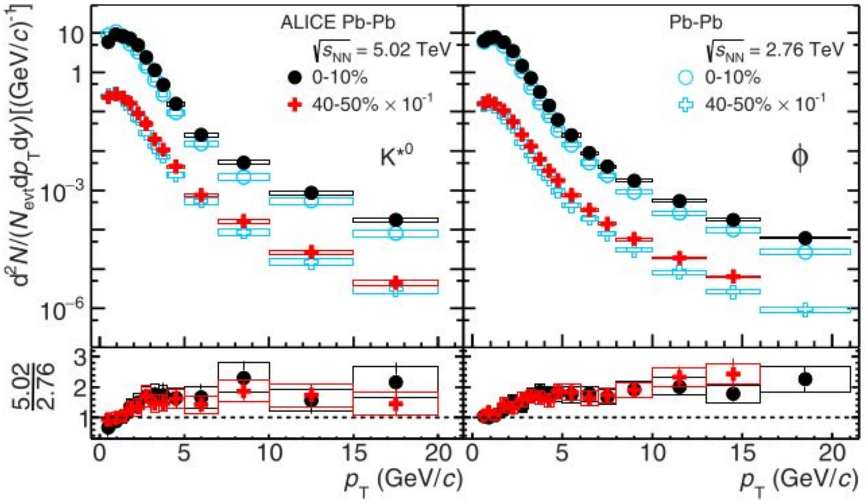

- **Increasing resonance yields with collision centrality** (increasing charged particle multiplicity)
- **HIJING** cannot describe the data over the full p_T range
  - **K**^{*0} better approximated in limited p_T range for mid-central to peripheral collisions
  - **ϕ**(1020) in agreement with predictions for mid-central collisions for p_T > 7 GeV/c

- **Resonance yield increase with collision energy**
- **Ratio increases with p**$_T$ (saturation !) for **central** and **peripheral** collisions
- **ϕ**(1020) yield at $\sqrt{s}$ = 5.02 TeV below **K**^{*0} for p_T < 3 GeV/c
- **K**^{*0} collision energy ratio below unity for p_T < 3 GeV/c

Spectral shapes **K*(892)** and **ϕ(1020)** in Pb-Pb

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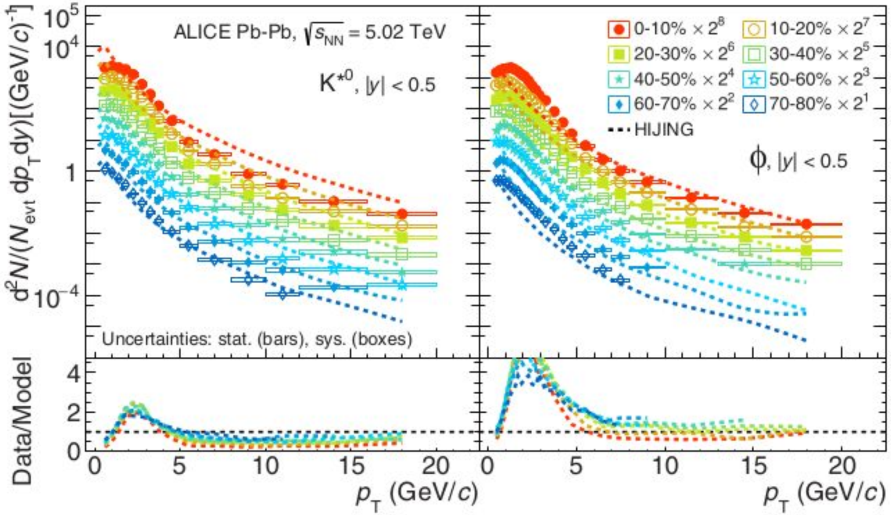

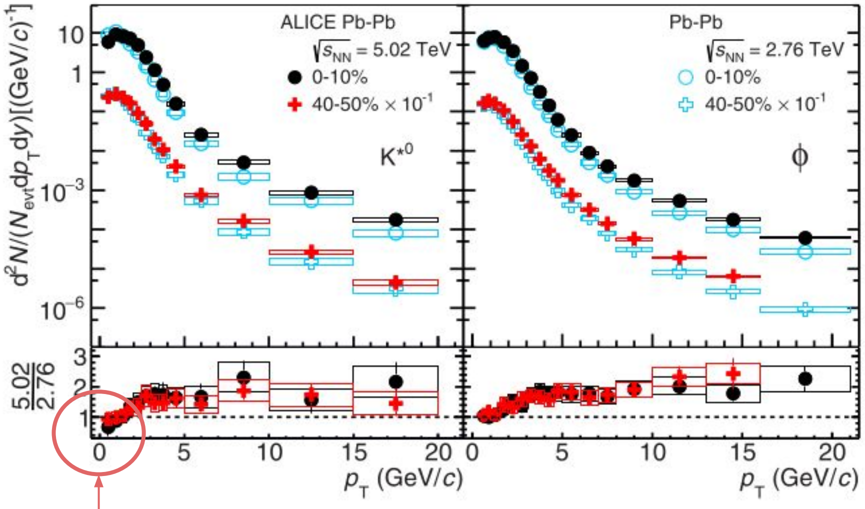

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Rescattering phenomena expected for K*0 with p_T < 3 GeV/c !

Mean p_T **K*(892) and ϕ(1020)**

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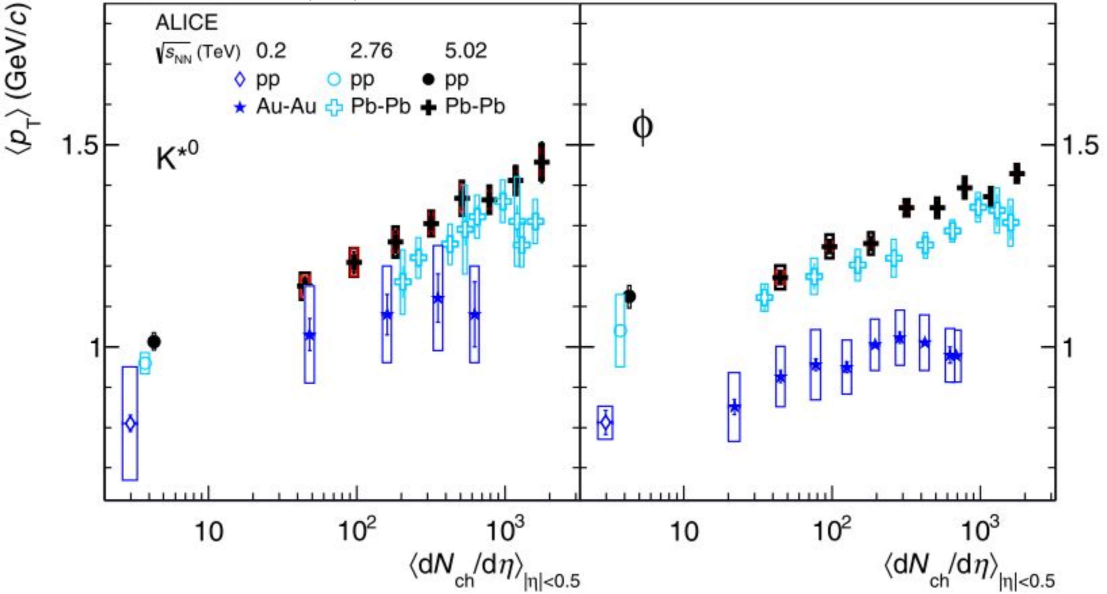

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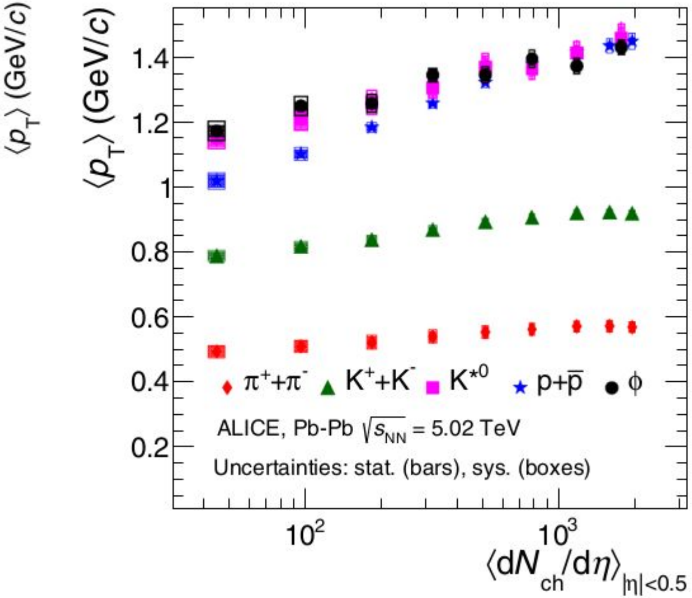

- **Increasing <p_T> with charged particle multiplicity and collision energy**
- **Similar masses** lead to similar <p_T> for **K*0** and **ϕ**(1020)

- **Steeper increase of <p_T>** with charged particle multiplicity for **heavier particles** (radial flow)
- **Breaking of mass ordering** for less central collisions **<dN_{ch}/dη>** < 300

Mean p_T K*(892) and ϕ(1020)

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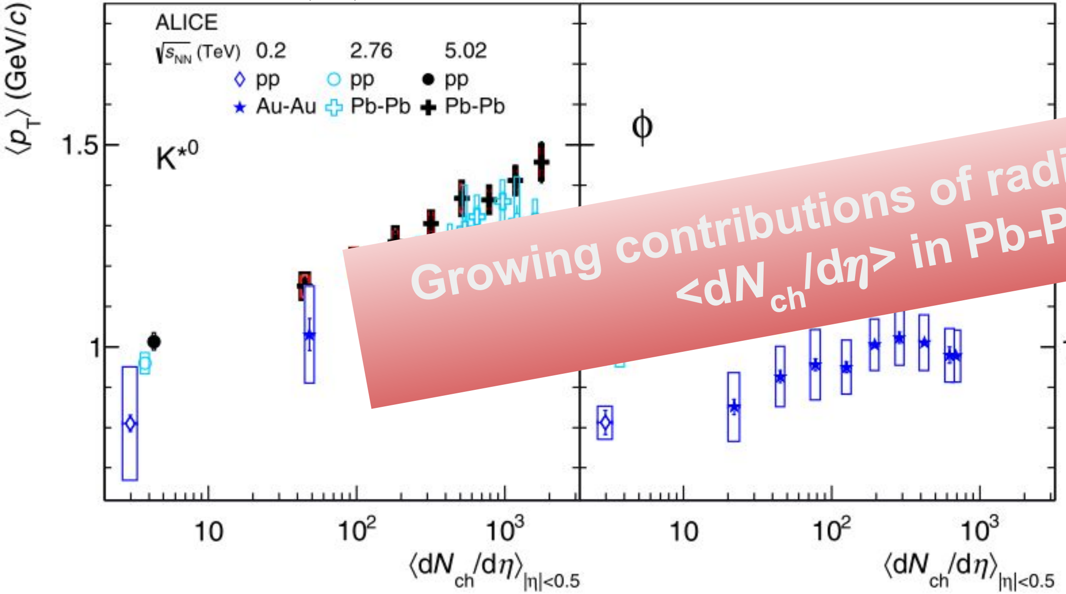

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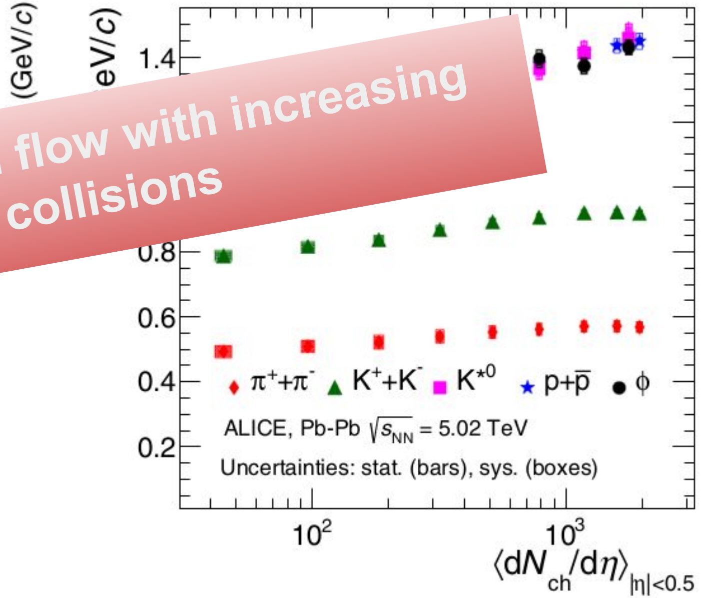

Growing contributions of radial flow with increasing $\langle dN_{ch}/d\eta \rangle$ in Pb-Pb collisions

- **Increasing $\langle p_T \rangle$ with charged particle multiplicity and collision energy**
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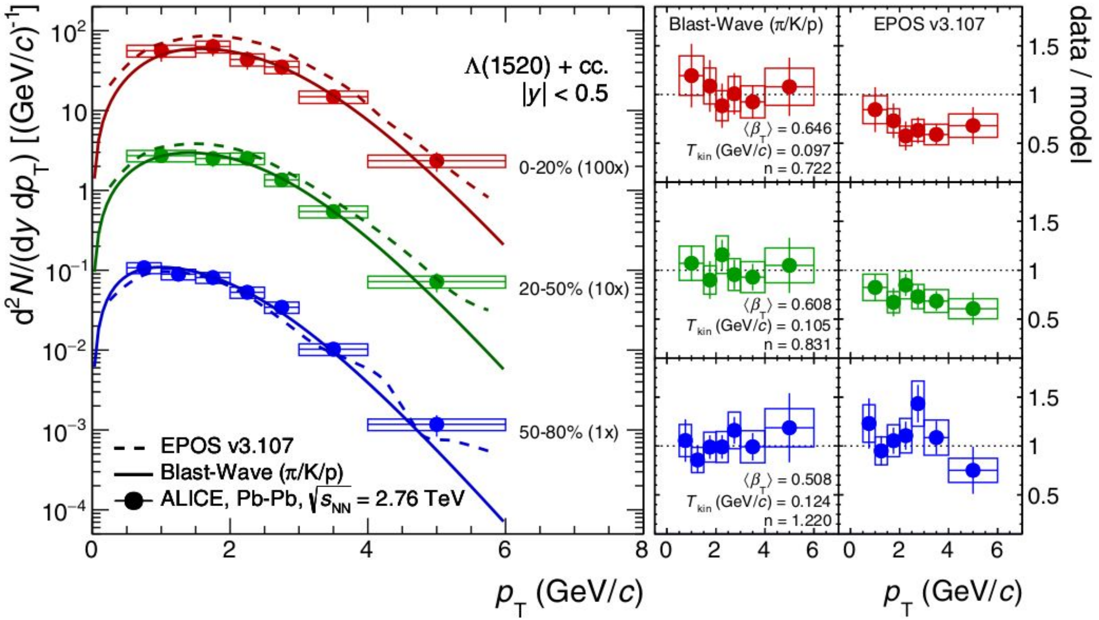
Spectral shapes and mean p_T $\Lambda(1520)$ in Pb-Pb

PHYSICAL REVIEW C 99, 024905 (2019)



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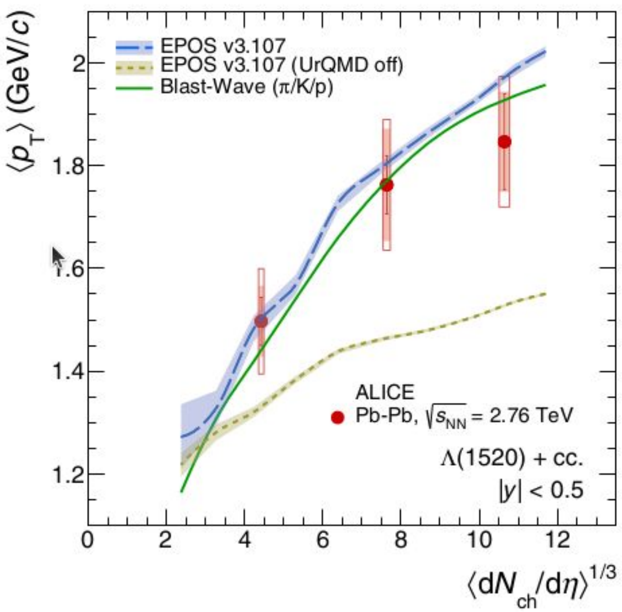

- **Blast-Wave model** ———
  - Reproduces spectral shapes
  - Hydrodynamic evolution with increasing $\langle\beta_T\rangle$ towards central collisions
- **EPOS v3.107** (with UrQMD) - - - - -
  - Reproduces spectral shapes qualitatively
  - Overestimates yield in **central** and **semi-central** collisions

- **Increasing $\langle p_T \rangle$ with system size** (and centrality)
- **Blast-Wave model**
  - In agreement with measurements
- **EPOS v3.107** (with UrQMD)
  - Describes evolution within uncertainties
- **EPOS v3.107** (without UrQMD)
  - Fails to approximate the data !

Spectral shapes and mean p_T $\Lambda(1520)$ in Pb-Pb

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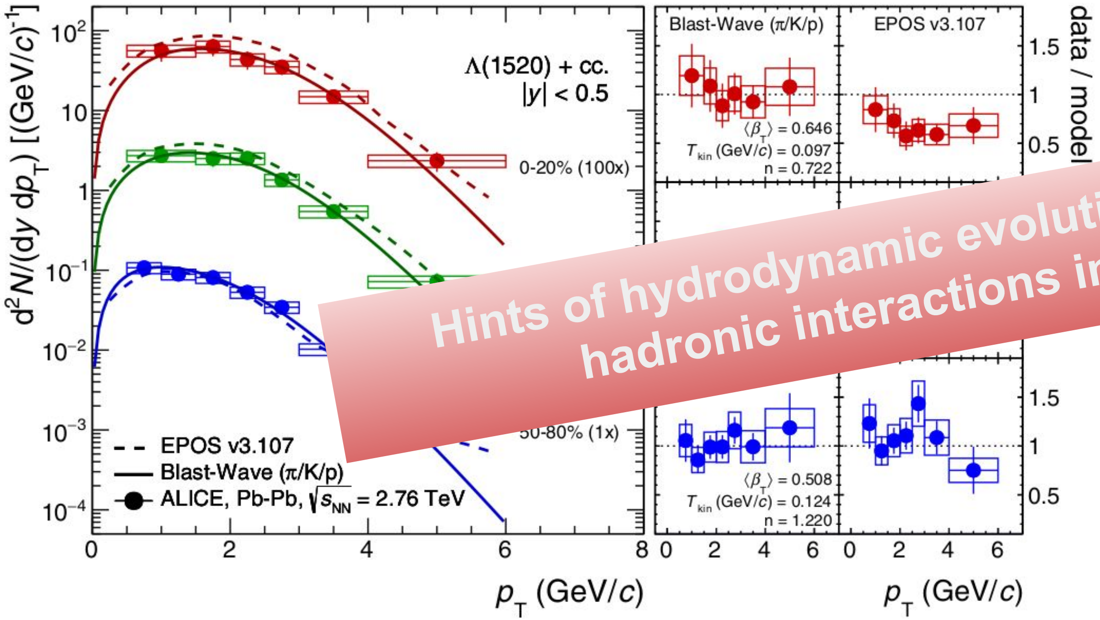

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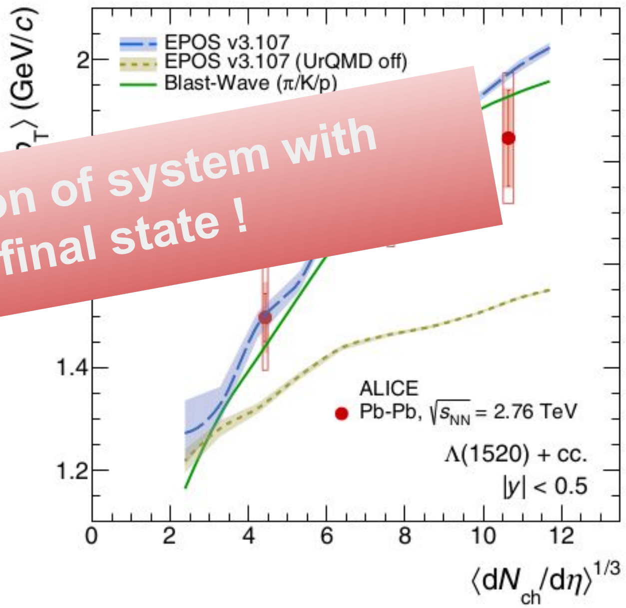

Hints of hydrodynamic evolution of system with hadronic interactions in final state !

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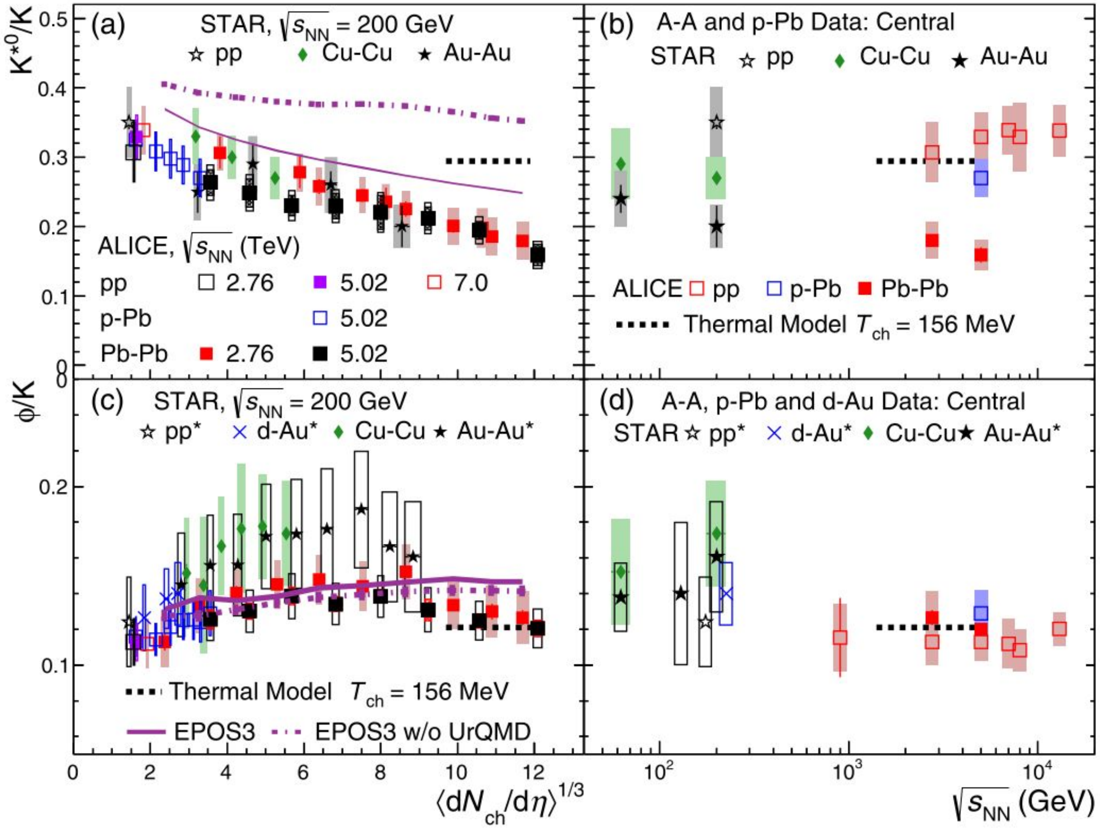
Ratios to stable particles (ϕ, K)

PHYSICAL REVIEW C 106, 034907 (2022)



- **K**^{*0} **/K** larger for pp wrt. Pb-Pb, Au-Au
- **K**^{*0} **/K suppression** (for larger system size)
- **ϕ**(1020)/**K** approximately constant as function of system size

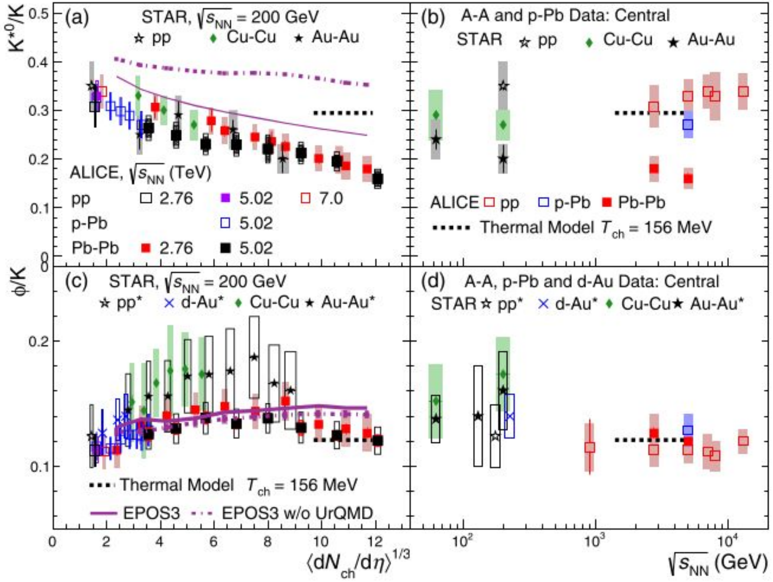
-- **Thermal model**
  - **K** ratio overestimated in central Pb-Pb collisions
  - **ϕ** ratio in good agreement
  - Fair description of energy dependence for both ratios

-- **EPOS3** (without UrQMD)
  - **Fails to reproduce K**^{*0}**/K suppression**

— **EPOS3** (with UrQMD)
  - **Good description for the trends of both ratio !**

Ratios to stable particles (ϕ, K, Λ)

PHYSICAL REVIEW C 106, 034907 (2022)



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- **EPOS3** (with UrQMD)
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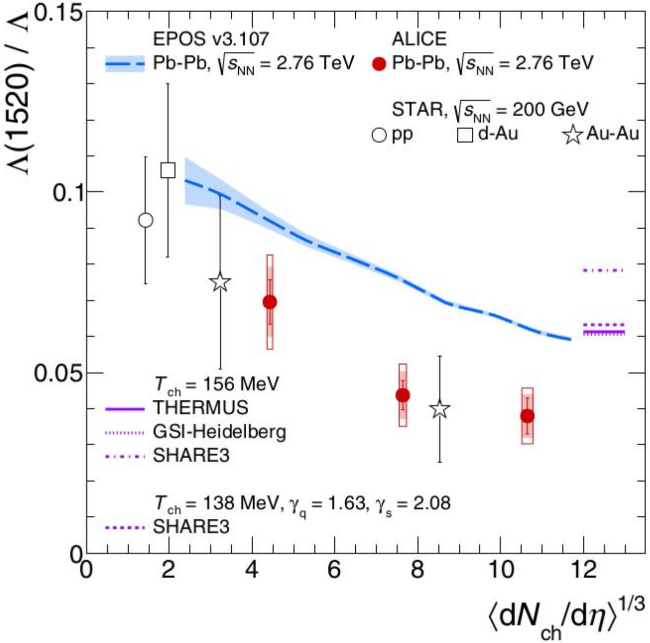

- **Λ(1520)/Λ suppression** (for larger system size)

Thermal models
- Poor approximation of ratio

EPOS3 (with UrQMD)
- Fair description of evolution with system size
- Overestimated yields

Ratios to stable particles (ϕ, K, Λ)

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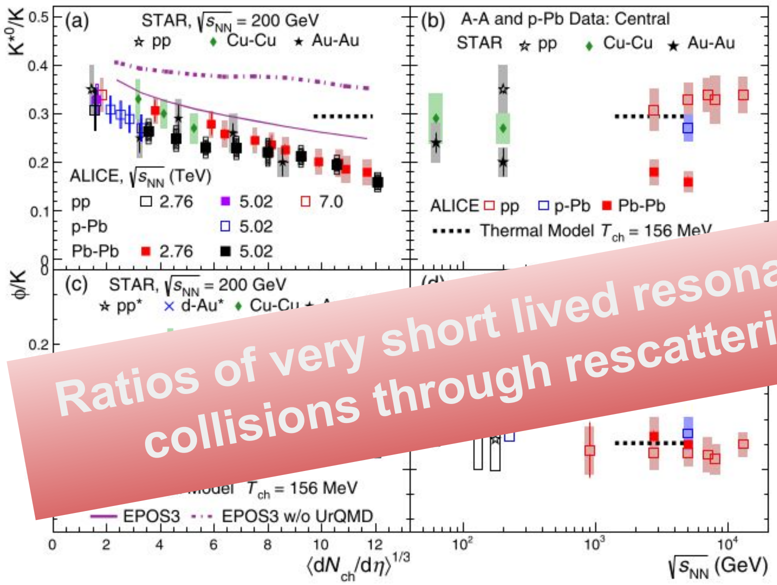

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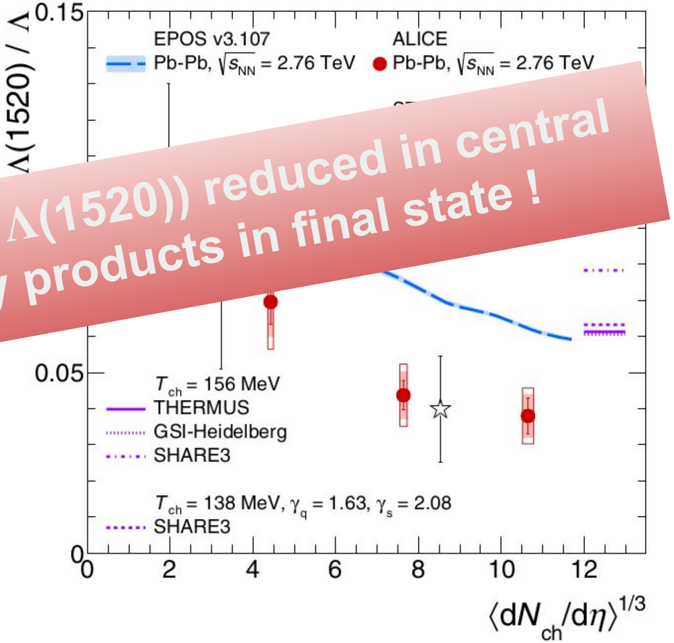


Ratios of very short lived resonances (K^{*0}, Λ(1520)) reduced in central collisions through rescattering of decay products in final state !

- **K^{*0} /K suppression** (for larger system size)

Thermal model fair description of energy dependence
- **K** ratio overrestimated in central Pb-Pb
- **ϕ** ratio in good agreement

EPOS3 (without UrQMD)
- **Fails to reproduce K^{*0}/K suppression**

EPOS3 (with UrQMD)
- **Good approximation for the trends of both ratio !**

- **Λ(1520)/Λ suppression** (for larger system size)

Thermal models
- Poor approximation of ratio

EPOS3 (with UrQMD)
- Fair description of evolution with system size
- Overestimated yields

Summary…

ALICE

- ★ **Resonance production is driven by the event multiplicity**, independent of the collision energy
  - Growing contributions of radial flow with increasing <dN_{ch}/dη> in Pb-Pb collisions
  - Ratios of very short lived resonances (**K**^{*0}, $\mathbf{\Lambda}$(1520)) suppressed in central collisions
  - Rescattering is a dominant effect for short-lived resonances at low momenta
- ★ **Presented models fail to predict the resonance production** over the full p_T range
  - Multiple indications of importance of hadronic interactions in the final state for the system created in heavy-ion collisions

Summary…

★ **Resonance production is driven by the event multiplicity**, independent of the collision energy

- Growing contributions of radial flow with increasing $\langle dN_{ch}/d\eta \rangle$ in Pb-Pb collisions
- Ratios of very short lived resonances ($\mathbf{K^{*0}}$, $\mathbf{\Lambda}$(1520)) suppressed in central collisions
- Rescattering is a dominant effect for short-lived resonances at low momenta

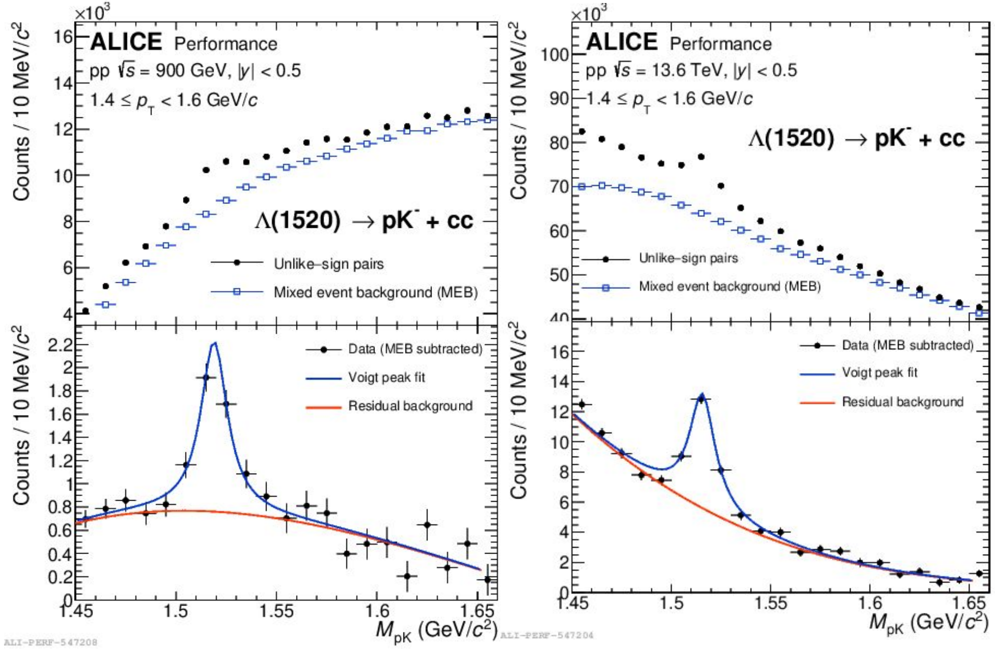
★ **Presented models fail to predict the resonance production** over the full p_T range

- Multiple indications of importance of hadronic interactions in the final state for the system created in heavy-ion collisions

…and Outlook

★ **Run3 studies of hadronic resonances**

- Increased statistics wrt. run2
- pp analysis at different collision energies



https://alice-figure.web.cern.ch/node/27568

Thank you !

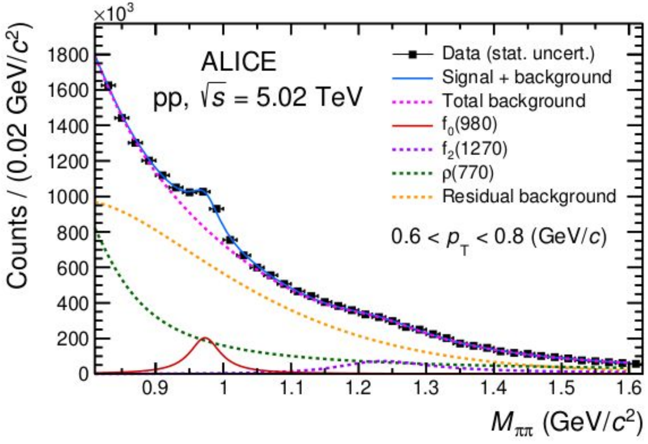
Backup

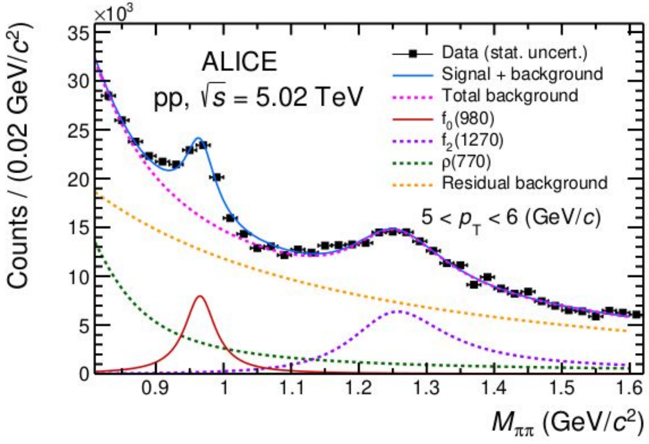
…

some more details and model summaries

Resonance reconstruction $f_0(980)$

arXiv:2206.06216v1 [nucl-ex] 13 Jun 2022





Like-sign method: rejection of combinatorial background from uncorrelated hadrons

- combining like-sign pion pairs from same event for like-sign invariant mass distribution as geometric mean of positive and negative pair distributions: $2\sqrt{(N^{++} N^{--})}$

Global Fit: width of (additional) signal(s) fixed to vev., masses and background parameter free !

Signal $f_0 \rightarrow \pi\pi$: Sum of three Breit-Wigner functions

Residual background ~ Maxwell-Boltzmann

Corrections of raw yields: PYTHIA8 MC simulations and GEANT3 for transport

- pp: detector acceptance, reconstruction efficiency, trigger efficiency, vertex reconstruction, signal loss

Model summaries for $K^*(892)$ and $\phi(1020)$

PHYSICAL REVIEW C 106, 034907 (2022)

PYTHIA tunes

- hadronization of light and heavy quarks through Lund string fragmentation model

Perugia tune of PYTHIA6

- revised set of fragmentation and flavor parameters for Tevatron; extrapolated to LHC data
- takes minimum bias and underlying events from LHC at 0.9 TeV and 7TeV into account

PYTHIA8 Monash 2013 (updated set of hadronization parameters wrt. PYTHIA6)

- independent string fragmentation
- good description for mesons, but poor for baryon yields at LHC

Rope Hadronization PYTHIA8

- no independent string fragmentation
- overlap of strings to form ropes in high multiplicity area
- large, dense collisions systems form color ropes that hadronize with larger string tension to enhance strangeness production with increasing multiplicity

HERWIG

- includes coherent parton showers from initial and final state QCD radiation
- eikonal multiple parton-parton interactions model for underlying event
- cluster hadronization model for formation of hadrons from quarks and gluons produced in parton shower

Thermal model

(SHM with $\mu_B \sim 0$ at T_{ch} = 156 MeV)

EPOS-LHC

- build on parton-based Gribov Regge Theory
- implements a type of radial flow for pp collisions where a very dense system is created in a small volume
- utilizes color exchange mechanism of string excitation and is tuned to LHC data

'Core':

High string or parton density that allow to create the QGP

Increasing strangeness production with multiplicity

'Corona':

Dilute region around core where fragmentation occurs as in the vacuum case

EPOS3 (w/o UrQMD)

- based on 3+1D viscous hydrodynamic evolution
- initial stage treated via multiple scattering approach based on pomerons and strings
- reaction volume is split into 'core'- and 'corona'-region
- hadrons from both regions fed into UrQMD where chemical and kinetic freeze-out occur (hadronic interactions are included in this approach)

'Core':

Dense region with initial conditions for QGP evolution

'Corona':

Dilute region composed of hadrons from string decays

Model summaries for $\Lambda(1520)$

PHYSICAL REVIEW C 99, 024905 (2019)

Blast-Wave model

- assumes particle production from thermal source which expands with a common transverse velocity
- parameters extracted from fir to stable counterparts

EPOS v3.107 (with UrQMD), **EPOS v3.107** (without UrQMD)

- MC generator that employs parton-based Gribov-Regge theory
- describes full evolution of heavy-ion collisions
- describes expansion of the bulk parton matter through viscous hydrodynamics
- incorporates UrQMD transport model for interactions among particles in the hadronic phase in a microscopic approach

Thermal models

- SHM variations with (μ_B ~ 0 at T_{ch} = 156 MeV)

SHARE3

- configuration without over/undersaturation parameter (μ_B ~ 0 at T_{ch} = 156 MeV)
- non equilibrium configuration with over/undersaturation parameter (μ_B ~ 0 at T_{ch} = 138 MeV, γ_s = 1.63 and γ_q= 2.08)

Model summaries for $\mathbf{f_0}$(980)

arXiv:2206.06216v1 [nucl-ex] 13 Jun 2022

ALICE

Herwig 7.2 (includes $\mathbf{f_0}$(980) generation by default)

- QCG inspired event generator that includes initial and final state QCD radiation
- description of underlying event via eikonal multiple parton-parton interaction model
- cluster hadronization model for formation of hadrons from quarks and gluons produced in the parton shower

Canonical statistical hadronization model CSM:

- hadrons formed from source in chemical equilibrium (μ_B ~ 0 at T_{ch} = 155 MeV)
- yields determined by partition function of the canonical ensemble
- multiplicity dependence driven by canonical suppression (exact conservation of baryon number, electrical charge and strangeness over the correlation volume)
- at high multiplicity: strangeness saturation in presence of the QGP

→**Incomplete equilibrium of strangeness through strangeness saturation factor γ_s**

γ_s-CSM (|S| = 2) double strangeness

γ_s-CSM (|S| = 0) no strangeness

Best fit to data with |S| = 1 - 2 !

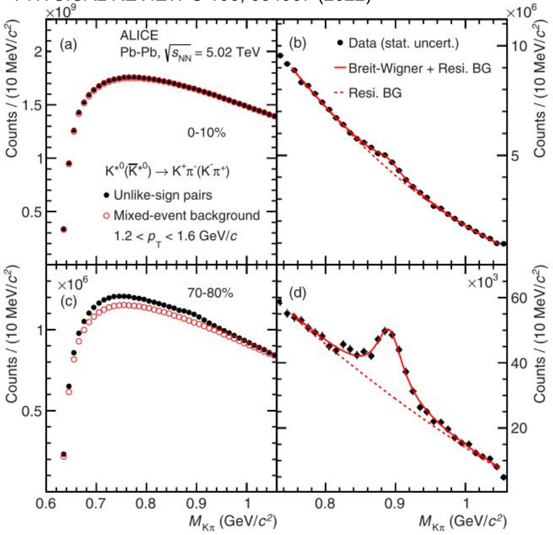
Coalescence calculations (that use AMPT)

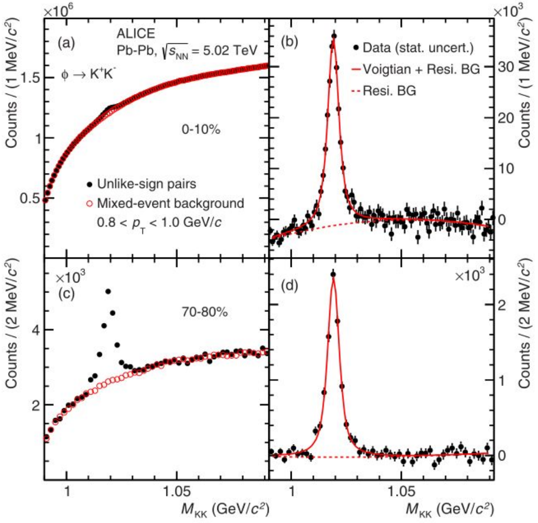
- multiphase transport model coupled with coalescence afterburner with Gaussian Wigner function to generate $\mathbf{f_0}$(980) in three configurations **AMPT** (ss-meson), **AMPT** (KK-molecule), **AMPT** (uuss-tetraquark)

1. initial conditions from HIJING model
2. partonic interactions from Zhang's parton cascade model (phase space information to implement quark coalescence with s anti-s and tetra-quark configuration)
3. conversion to hadronic matter
   - **default AMPT version:** conversion with Lund string fragmentation
   - **string melting:** quark coalescence used to combine partons into hadrons
   - generation of kaon phase-space information which goes into the afterburner for the molecular state
4. interactions amongst hadrons
   - based on a relativistic transport model (ART)

Resonance reconstruction **K***$(892)^0$ and **ϕ**(1020)

PHYSICAL REVIEW C 106, 034907 (2022)





<u>Mixed-event technique</u>: rejection of combinatorial background from uncorrelated hadrons

- combining unlike-sign pion and K tracks from different events with similar characteristics

  pairs required to have: |Δvtx|<1cm |Δn|<5

- mixing each event with 5 others to reduce stat. uncertainties
- normalization in region outside of mass peak

<u>Global Fit</u>: width of signals fixed to vev., sigma (detector resolution) and background parameter free !

Signal ϕ→KK: convolution of non. rel. Breit-Wigner function with Gaussian detector resolution

Signal K*→ ππ: Breit-Wigner function

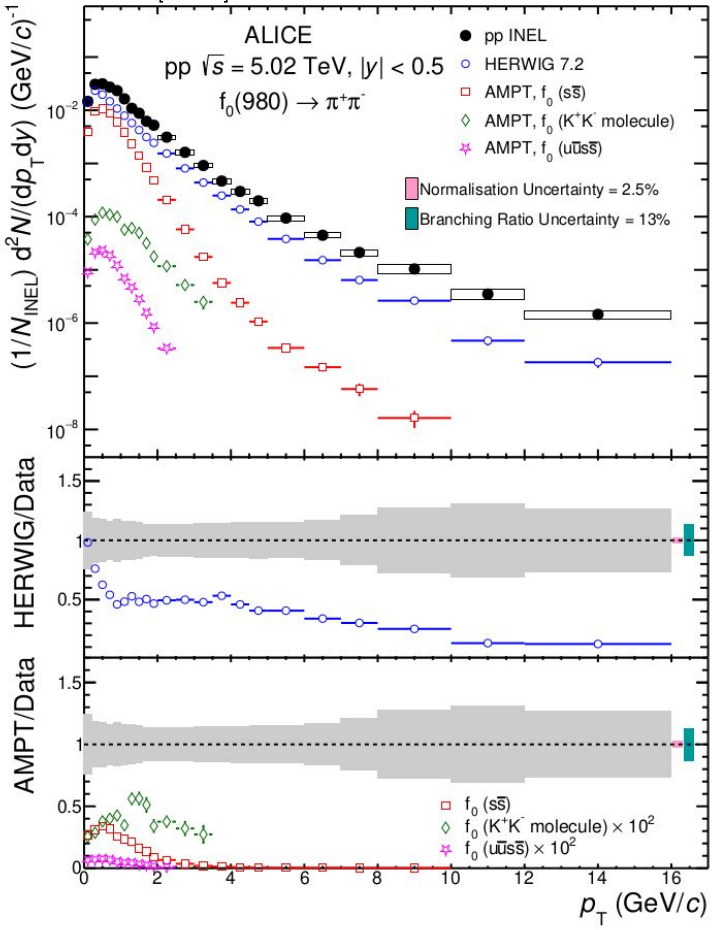
Residual background Second order polynomial (correlated pairs from real resonance decays where daughters are misidentified as K or pi)

<u>Corrections of raw yields</u>: HIJING (PbPb) and PYTHIA Monash2013 (pp) MC simulations and GEANT for transport

- pp: detector acceptance, reconstruction efficiency, trigger efficiency, vertex selection, decay branching fraction (signal loss)
- Pb-Pb: detector acceptance, reconstruction efficiency

Studying the quark composition of $\mathbf{f_0}$(980)

arXiv:2206.06216v1 [nucl-ex] 13 Jun 2022



Herwig 7.2 (includes $\mathbf{f_0}$(980) by default)

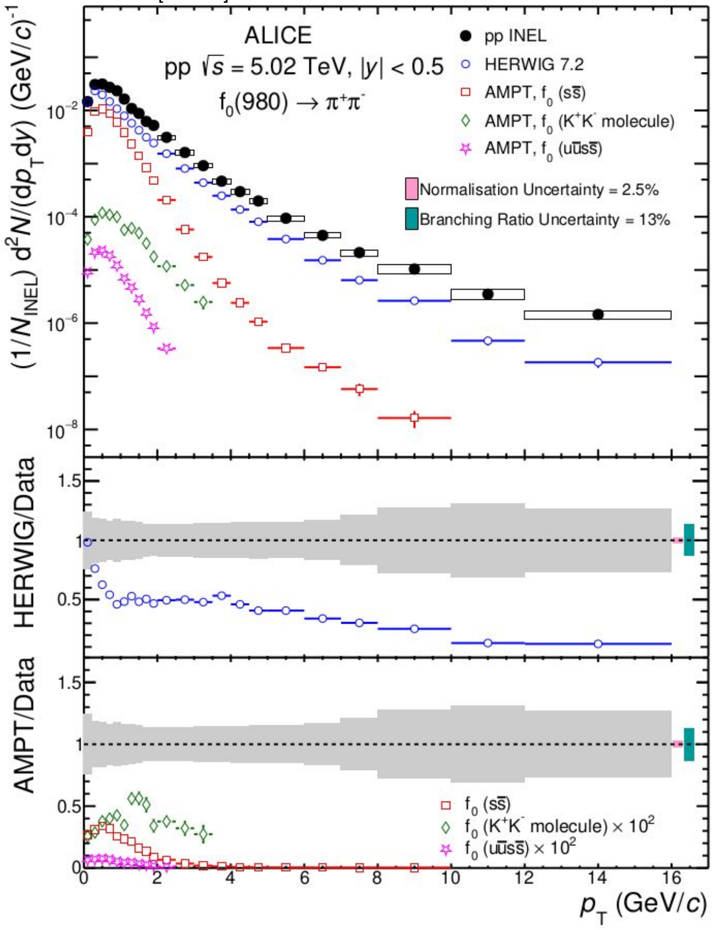
- reproduces spectral shape for p_T < 3 GeV/c
- underestimates the data by a factor of 2 (and more)

AMPT ($s\bar{s}$-meson), **AMPT** (KK-molecule), **AMPT** ($u\bar{u}s\bar{s}$-tetraquark)

- spectral shapes too steep
- underestimate the data by a factor > 2 (ratios rescaled !)

f_0(980) How strange can it be ?

arXiv:2206.06216v1 [nucl-ex] 13 Jun 2022



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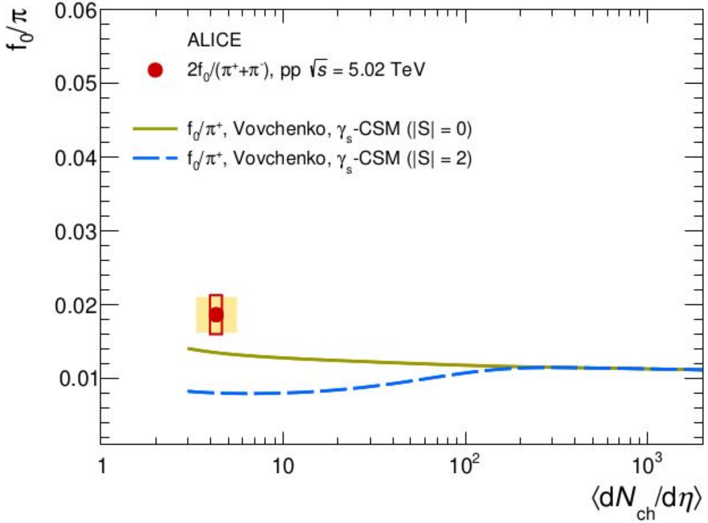
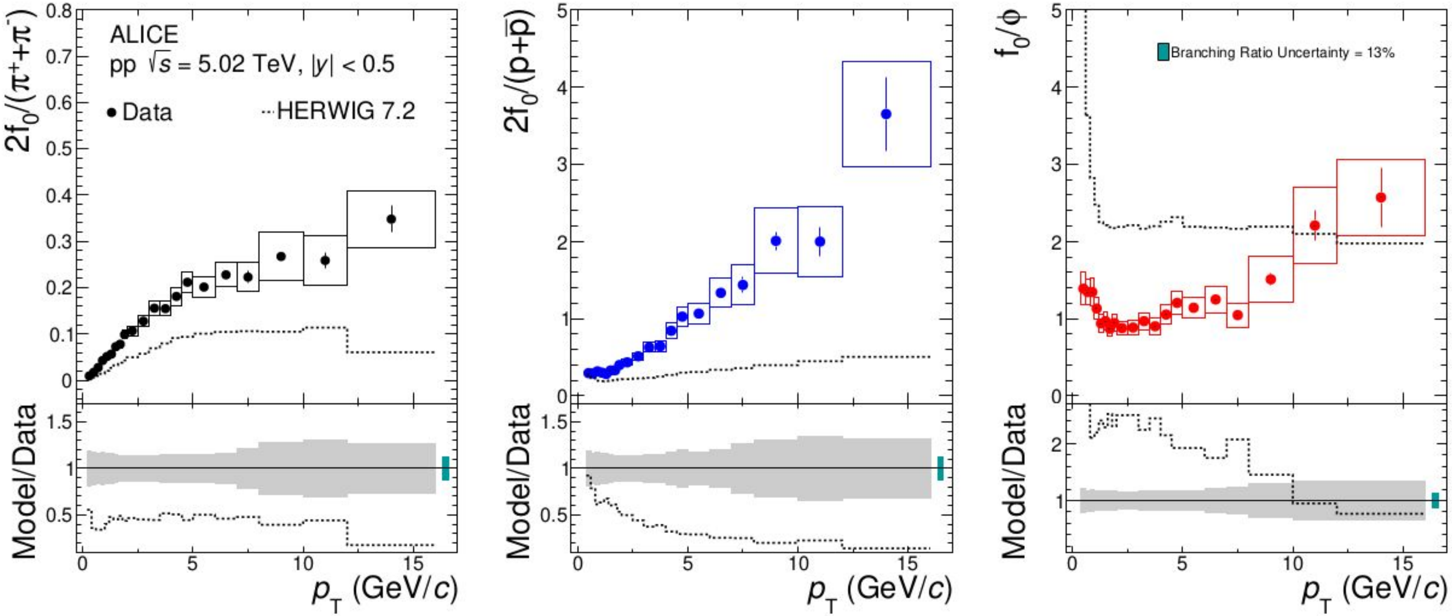


γ_s-CSM both configurations converge at grand canonical limit

- **γ_s-CSM (|S| = 0)** favored at low charged particle multiplicity

f_0(980) How strange can it be ?

arXiv:2206.06216v1 [nucl-ex] 13 Jun 2022



f_0(980)/π yield ratio

- shape **well** reproduced by HERWIG
- increasing trend as function of p_T with saturation above 5 GeV/*c*
- suppressed ratio at low p_T hints at **rescattering effects**

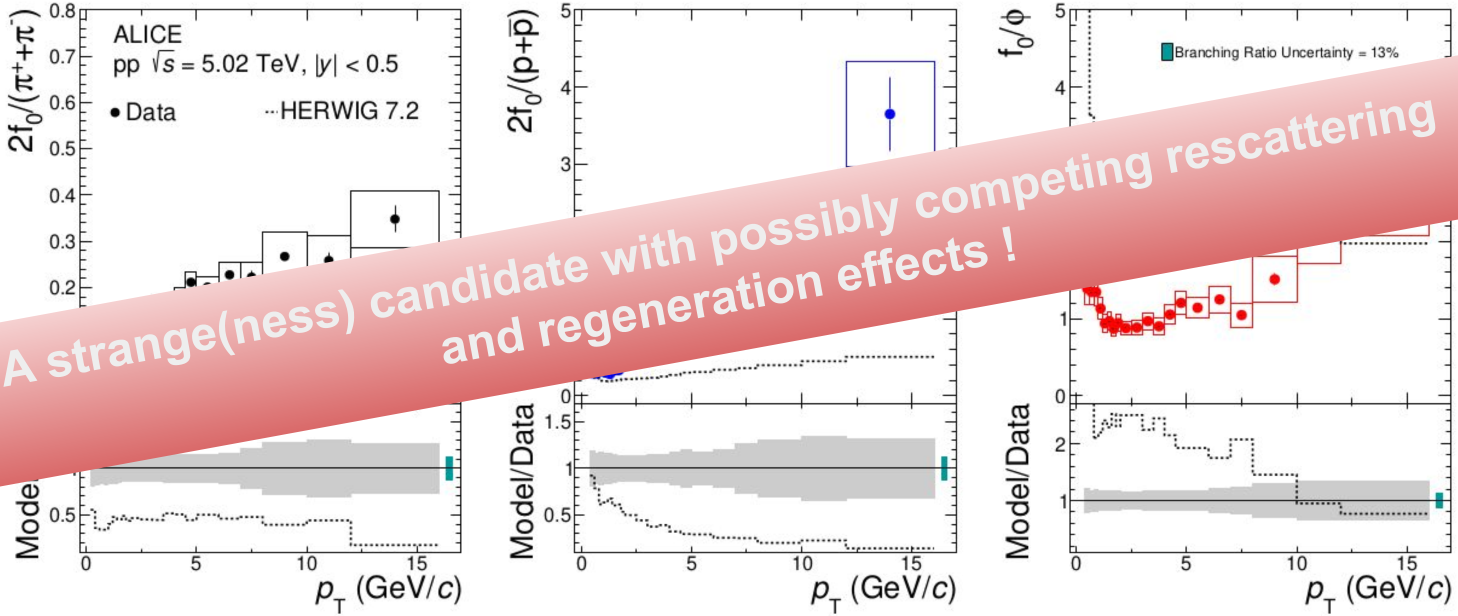
Yield ratios to particles of similar masses (p, ϕ)

- **proton ratio** increase as function of p_T is **not** reproduced by HERWIG
- **phi ratio** is **qualitatively** reproduced by HERWIG
- ppectral shapes rather determined by **strangeness content** than mass of the reference particle

f_0(980) How strange can it be ?

arXiv:2206.06216v1 [nucl-ex] 13 Jun 2022

ALICE



A strange(ness) candidate with possibly competing rescattering and regeneration effects !

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