Istituto Nazionale di Fisica Nucleare

Latest results on hadronic resonance production with ALICE at the LHC

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INFN - SEZIONE DI TRIESTE

on behalf of the ALICE collaboration

BARYONS 2022

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ALICE experiment and the resonance campaign

- ALICE has produced a large set of measurements on hadronic resonances for all collisions systems and energies provided by LHC during Run 1 and Run2

Resonance	$\rho(770)^0$	$K^*(892)^\pm$	$K^*(892)^0$	$f_0(980)$	$\Sigma(1385)^\pm$	$\Xi(1820)^\pm$	$\Lambda(1520)$	$\Xi(1530)^0$	$\phi(1020)$
Quark composition	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$u\bar{s}, \bar{u}s$	$d\bar{s}, \bar{d}s$	unknown	uus, dds	uss	uds	uss	$s\bar{s}$
τ(fm/c)	1.3	3.6	4.2	large unc.	5-5.5	8.1	12.6	21.7	46.4
Decay	$\pi\,\pi$	$K^0_s\,\pi$	$K\,\pi$	$\pi^+\pi^-$	$\Lambda\,\pi$	$\Lambda\,K$	$p\,K$	$\Xi\,\pi$	$K\,K$
B.R.(%)	100	33.3	66.6	46	87	unknown	22.5	66.7	48.9

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	75 μb^{-1} 800 μb^{-1}
Xe-Xe	2017	5.44	0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	15 nb^{-1} 3 nb^{-1}, 25 nb^{-1}
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	200 μb^{-1}, 100 nb^{-1} 1.5 pb^{-1}, 2.5 pb^{-1} 1.3 pb^{-1} 36 pb^{-1}

- 20 published articles out of 403 submitted by ALICE as of Oct. 2022

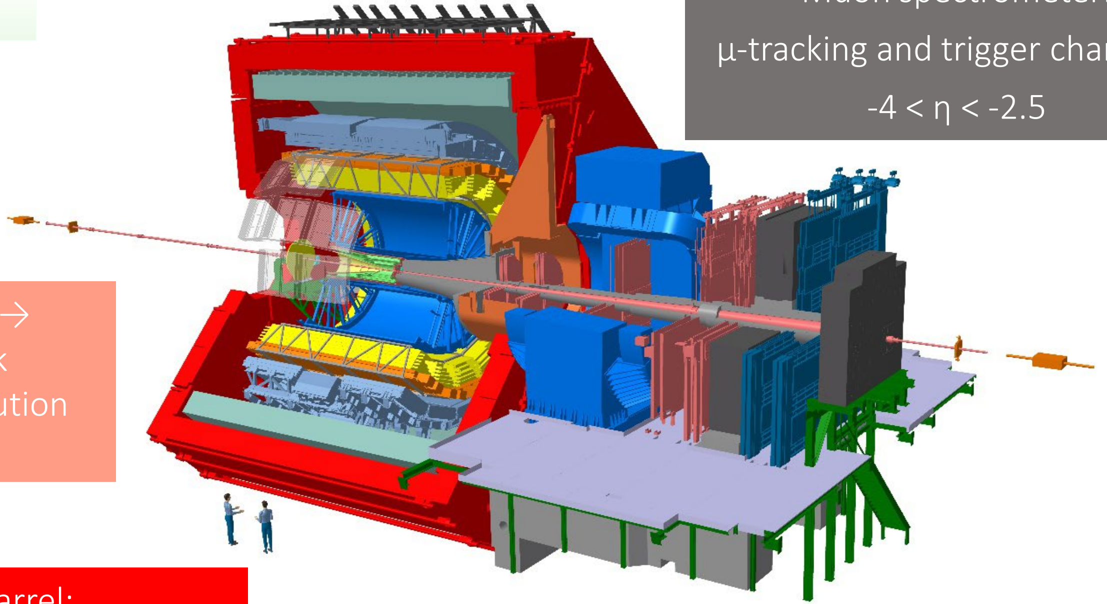
<u>Why we measure resonances</u>:

✓ Study the hadrochemistry of particle production

✓ Study the in-medium energy loss via R_{AA}

✓ **Study the hadron-gas phase of relativistic heavy-ion collisions**

Muon spectrometer:
μ-tracking and trigger chambers
-4 < η < -2.5

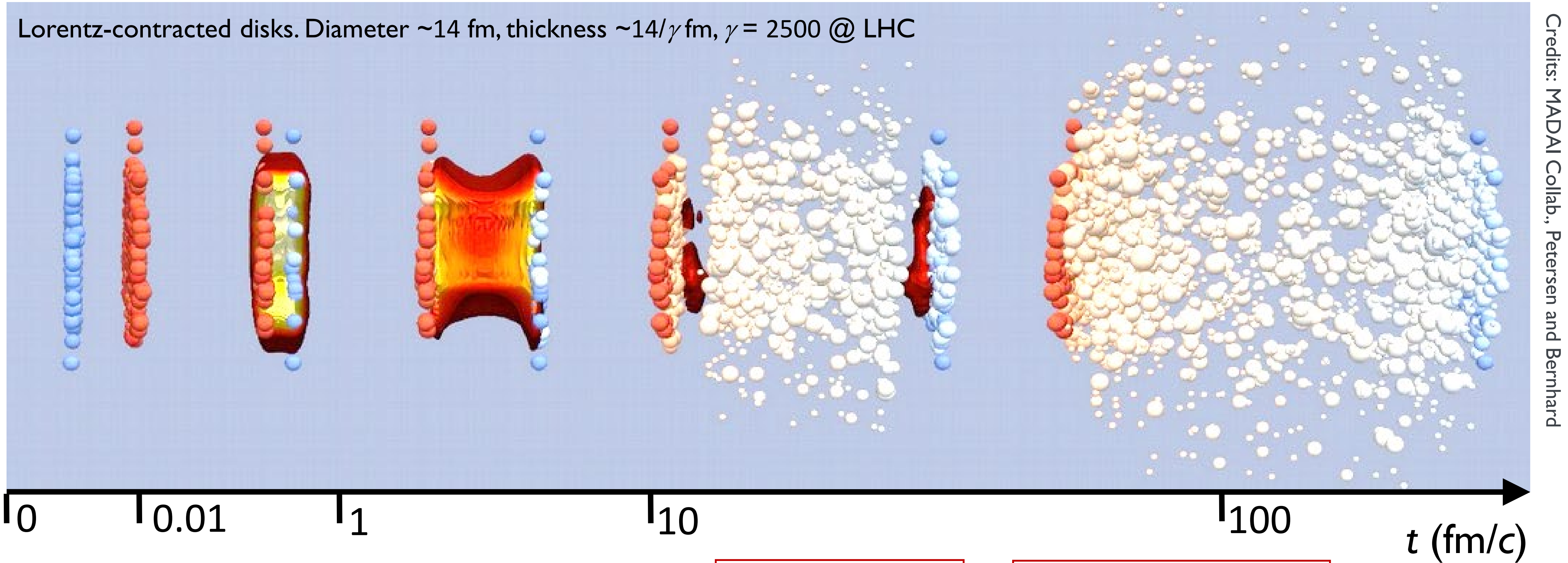


ALICE detector → excellent track momentum resolution and PID

Central barrel:
vertexing, tracking, PID, EM calos
|η| < 0.9

Forward detectors:
multiplicity, trigger, centrality, time zero

Final stage of the collision evolution: the hadron gas



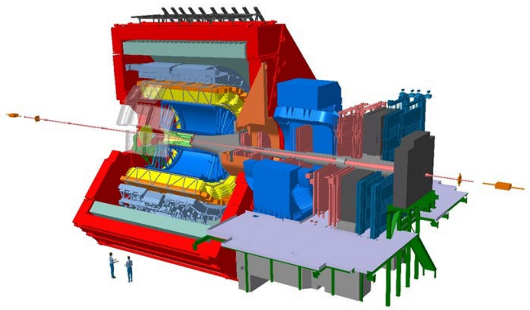
Initial stage nPDF, saturation, shadowing

Gluon and quark-pair creation
All heavy quarks created at this stage

QGP: deconfined nuclear matter expanding hydrodynamically

Hadronization and chemical freeze-out
Inelastic collisions cease

Kinetic freeze-out
Elastic collisions cease
Free streaming particles to the detectors



QGP phase

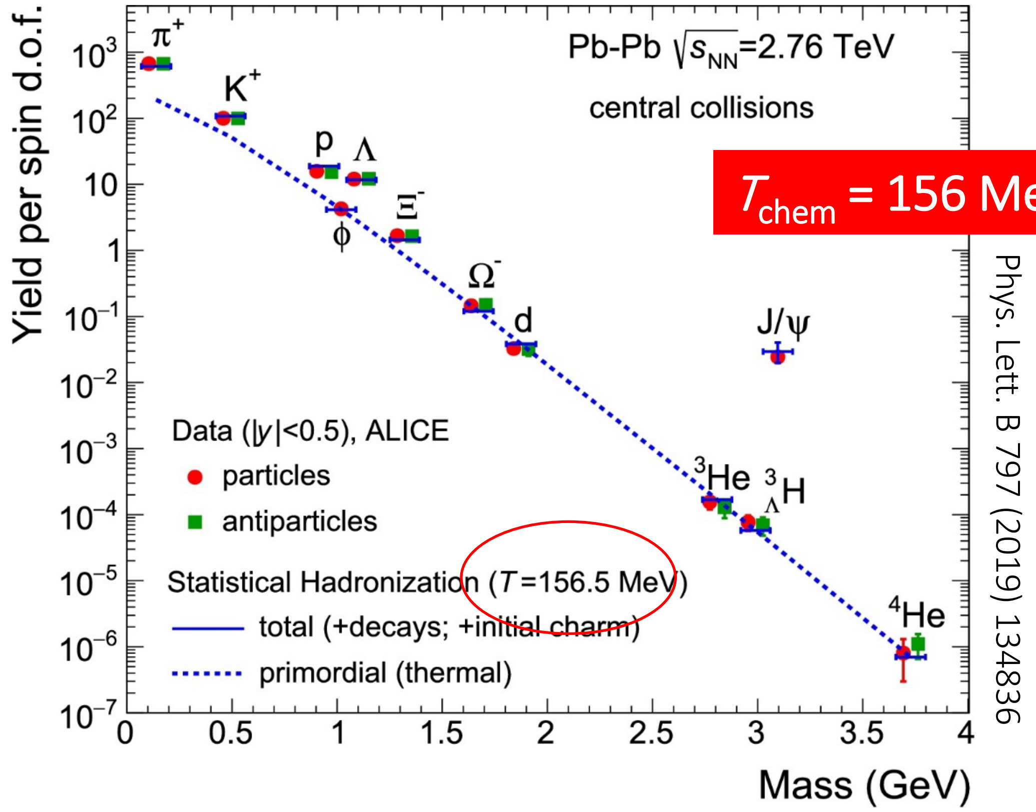
Hadron-gas phase

Duration of the same order as resonances lifetimes!

Temperature at chemical and kinetic freeze-outs

At hadronization the system is close to thermal equilibrium and a rapid hadrochemical freeze-out takes place at the phase boundary

Statistical Hadronization Model (SHM)

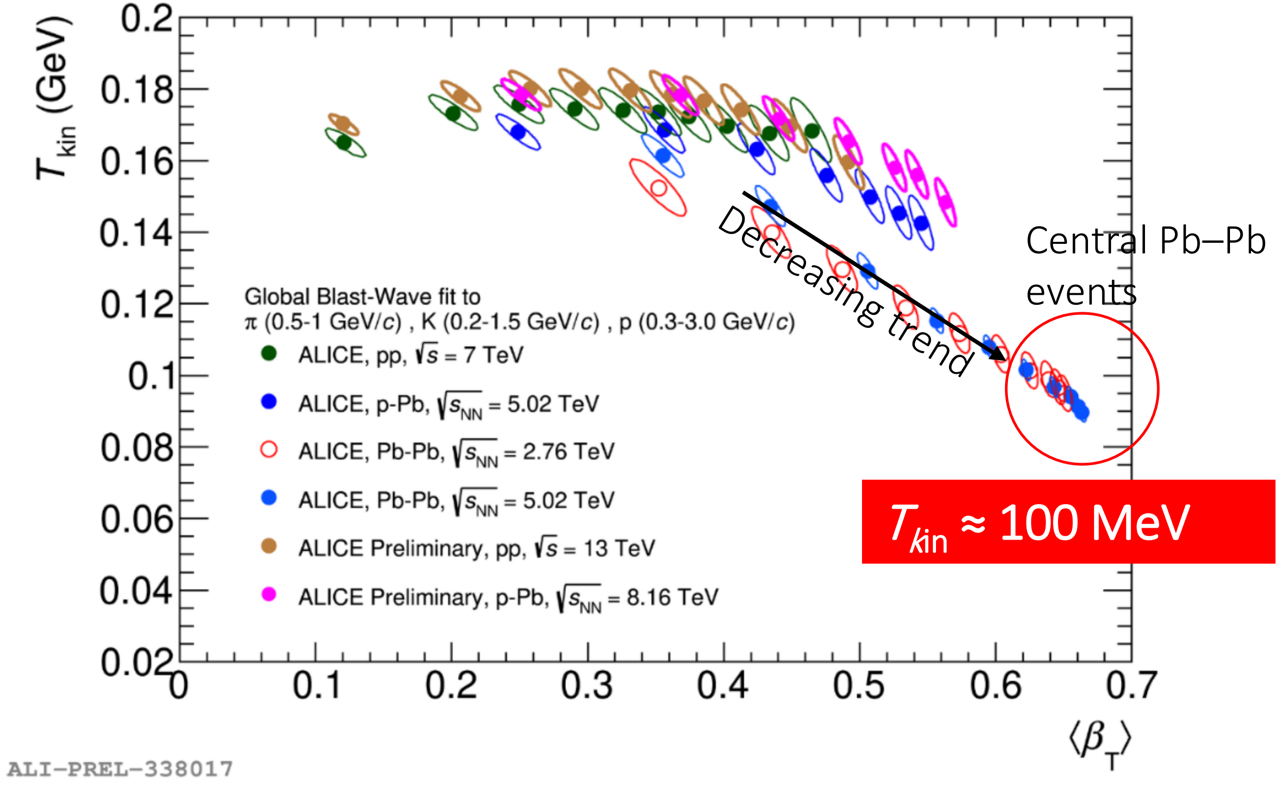


- Hadron abundances described by SHM over 9 orders of magnitude!
- Total yields include contributions from resonance decays!

Boltzmann-Gibbs Blast-Wave fits are used to determine parameters of the radial flow:

- T_{kin} – kinetic freeze-out temperature
- $<\beta_T>$ - transverse flow velocity

Fit parameters extracted from simultaneous fits to π, K, p spectra

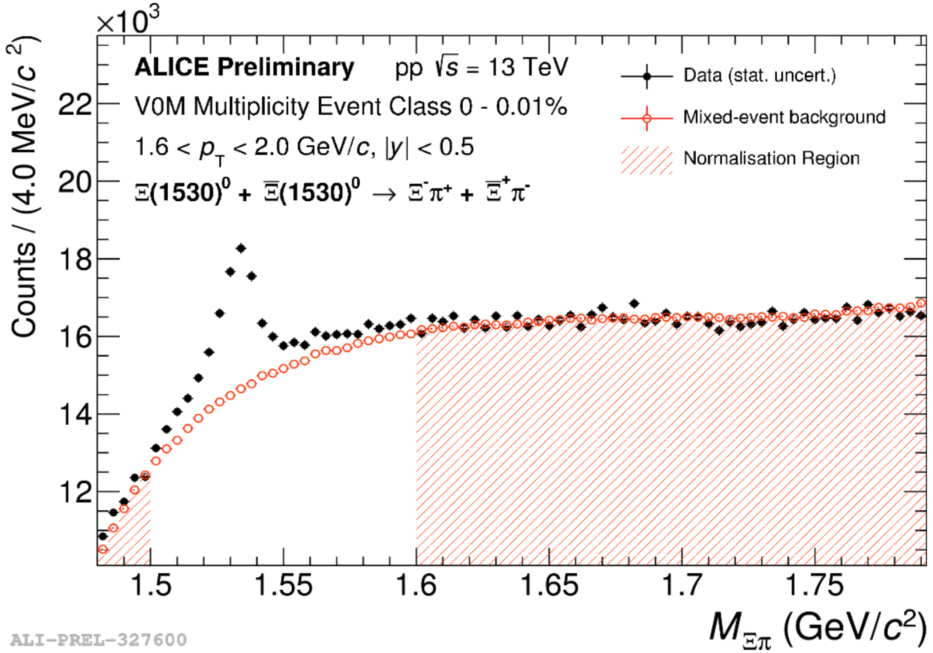


Resonance reconstruction: uncorrelated background

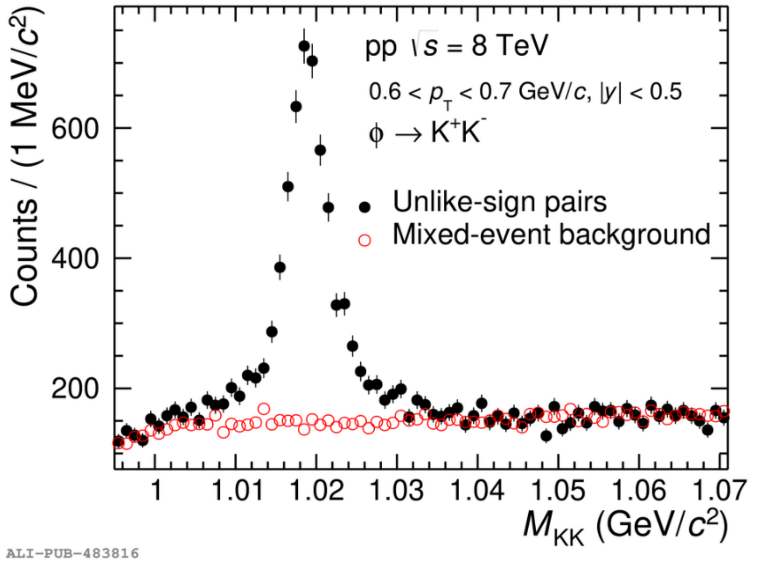
- Resonances are reconstructed from their decay daughters via the invariant mass technique:

$$M_{\text{inv}} = \sqrt{(E_1 + E_2)^2 - |\vec{p}_1 + \vec{p}_2|^2}$$

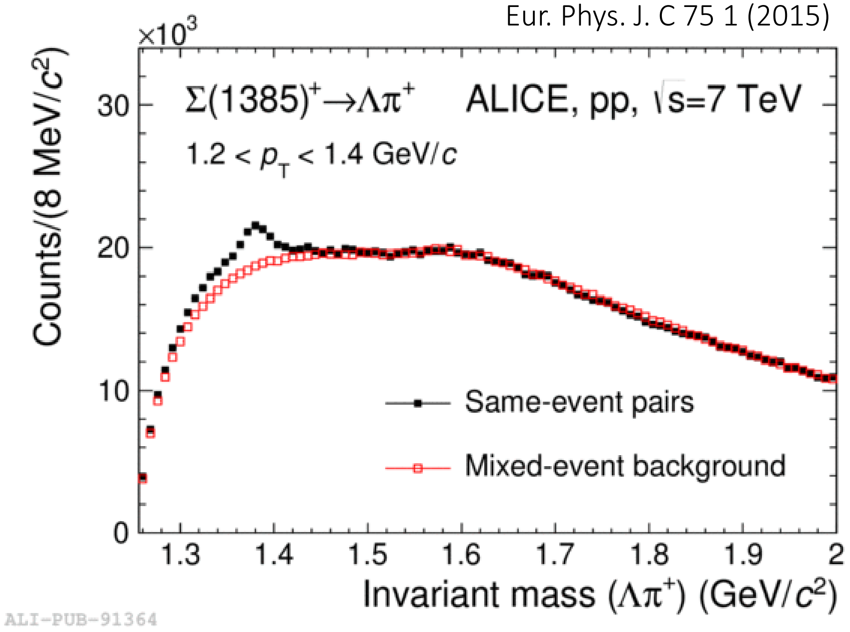
- **Large background due to uncorrelated pairs**
- Uncorrelated background is calculated via event mixing or like-sign techniques and normalized in a mass region far from the peak
- Uncorrelated background is subtracted from the invariant mass distribution

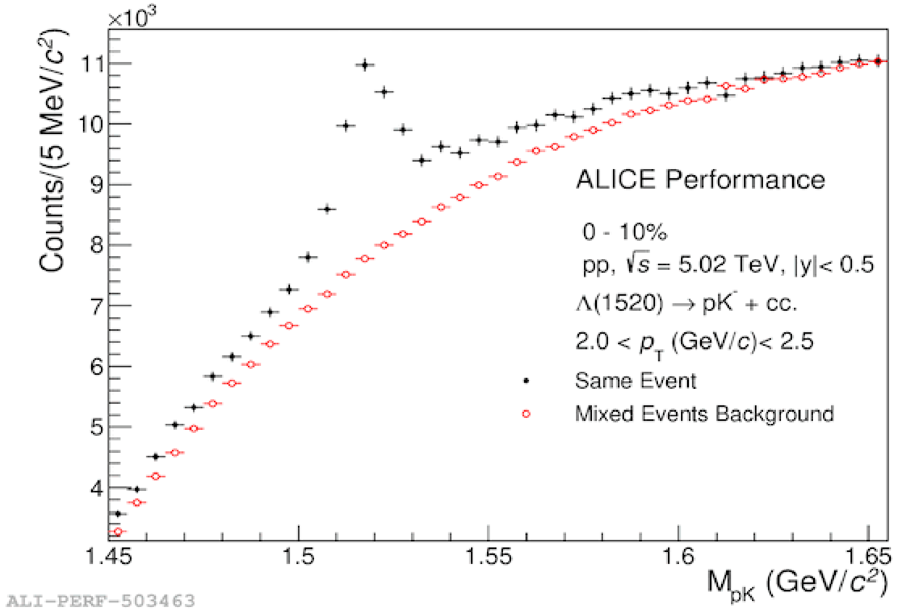


Phys. Rev. C 102 (2020) 024912



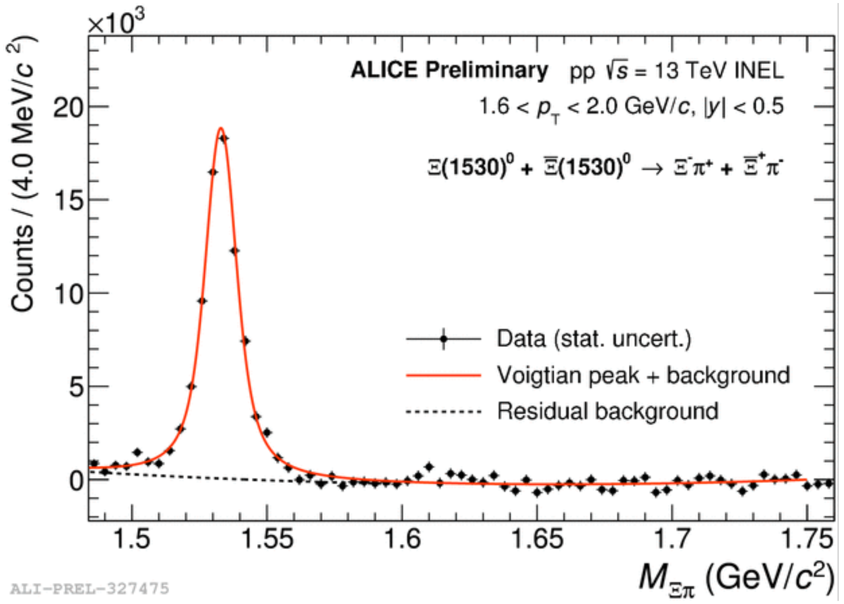
Eur. Phys. J. C 75 1 (2015)



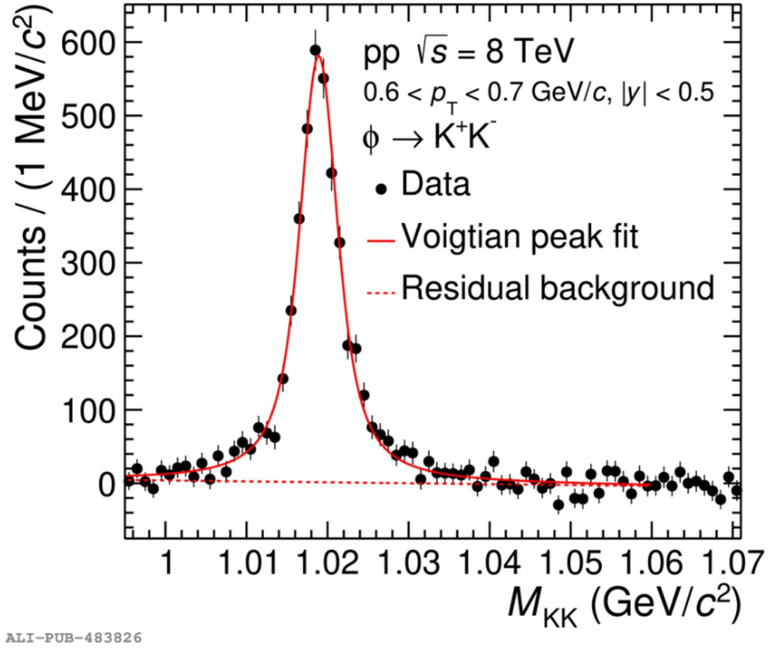


Resonance reconstruction: residual background (I)

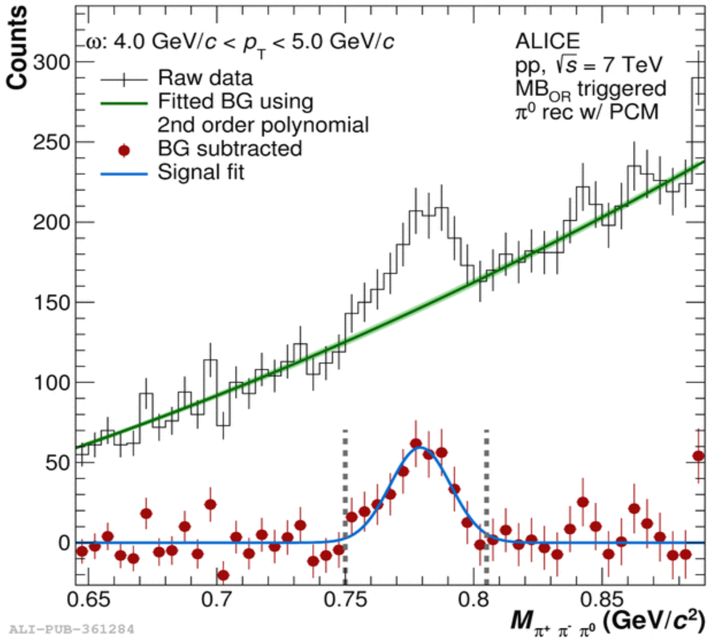
- After the subtraction of the uncorrelated background a residual background remains due to correlated pairs or misidentified decay products
- Residual background is usually modelled by a polynomial function
- Signal is fit with a Breit-Wigner or Voigtian function (convolution of a Breit-Wigner for the signal and a Gaussian to account for the resolution of the detector)

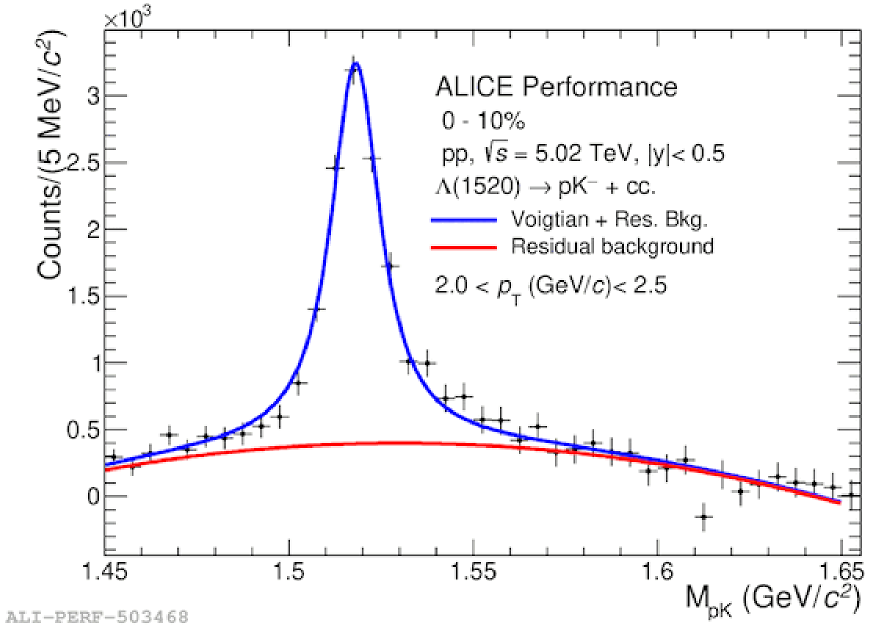


Phys. Rev. C 102 (2020) 024912



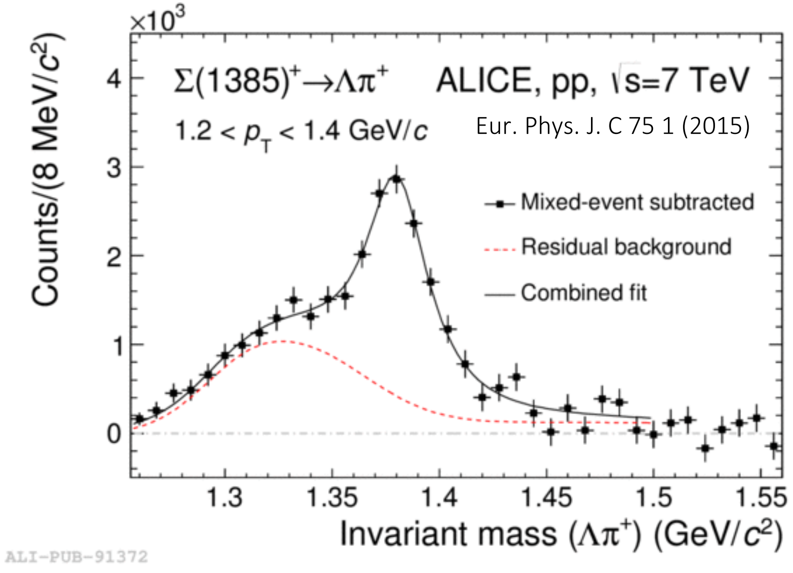
Eur. Phys. J. C 80 (2020) 1130

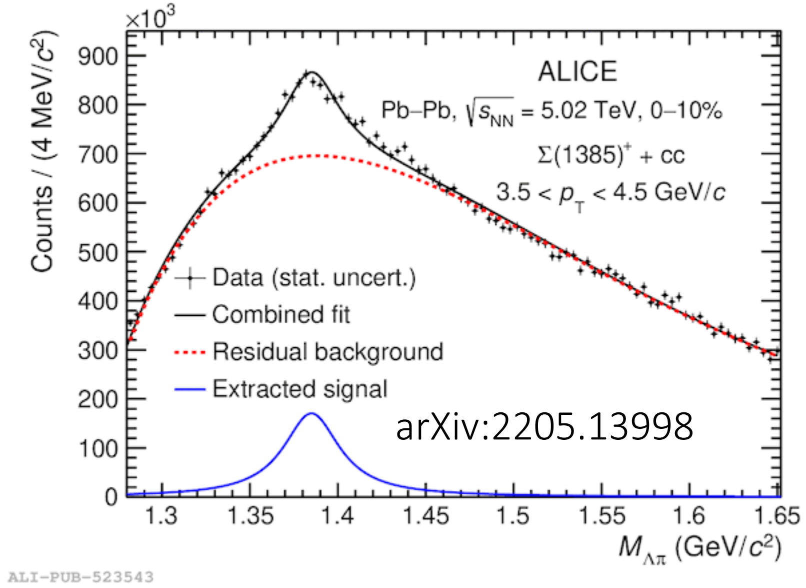


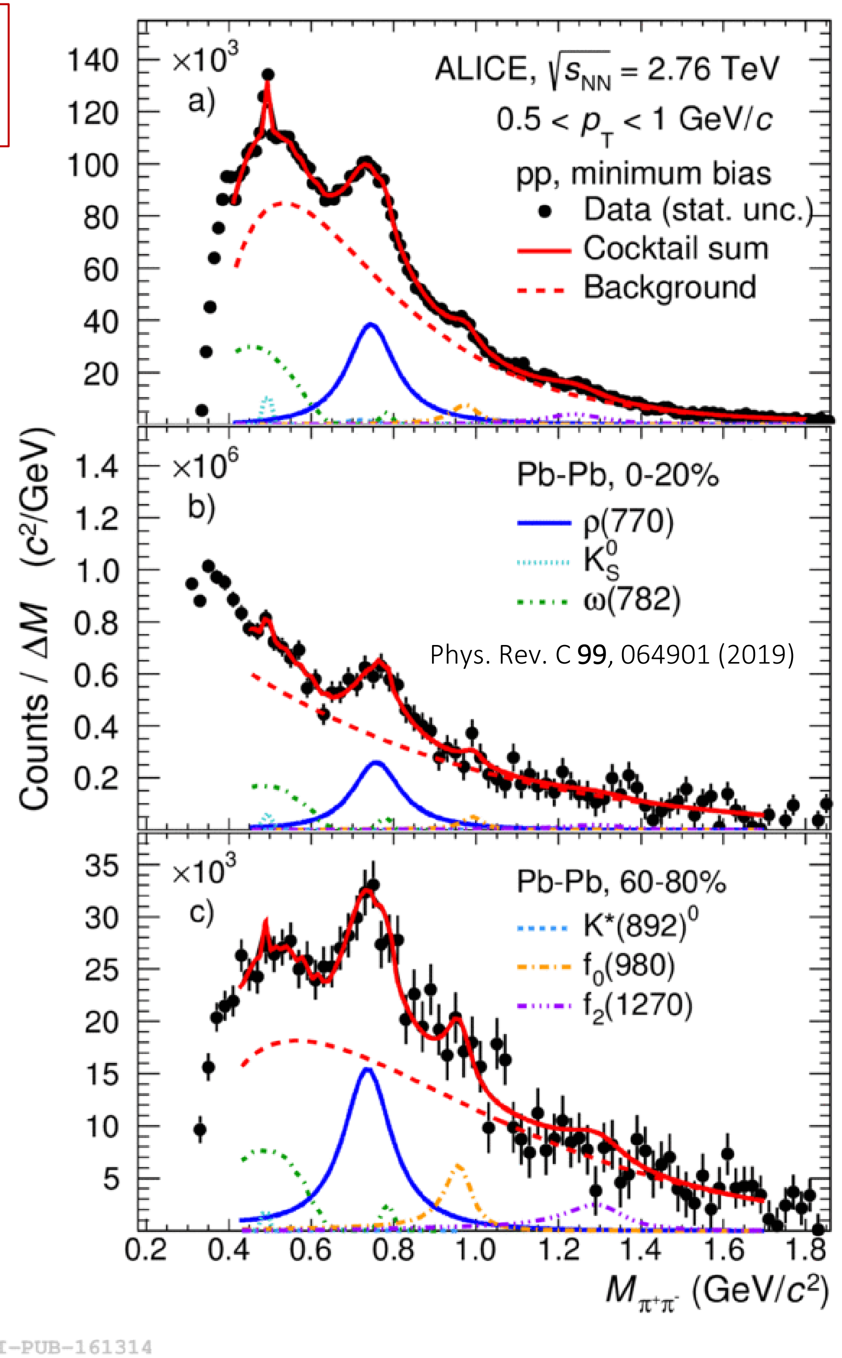


Resonance reconstruction: residual background (II)

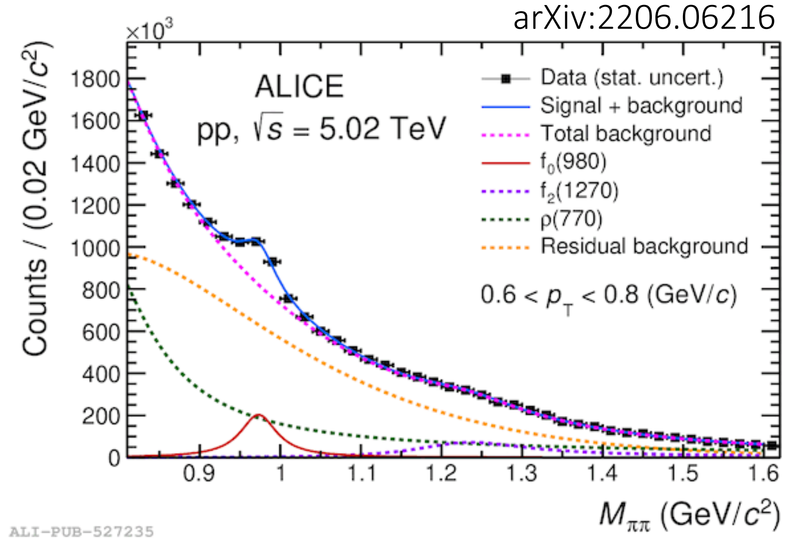
Residual background can be complicated and can require a more sophisticated modelling

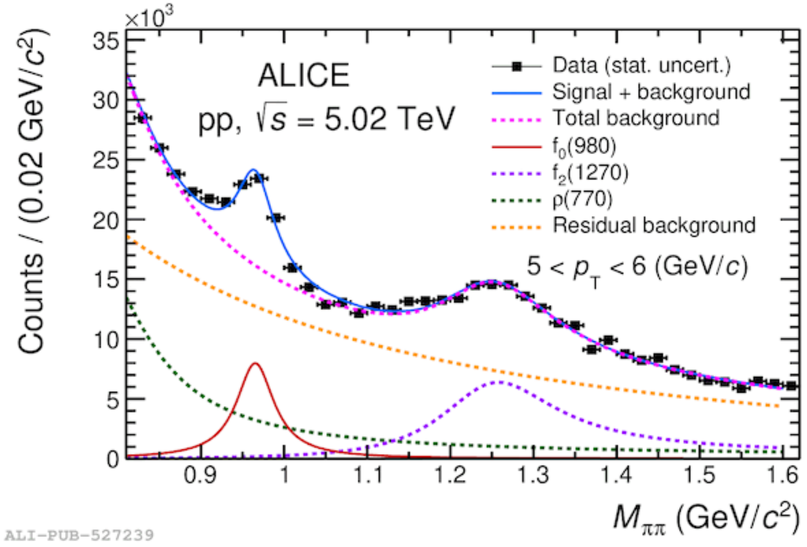






Background can include residual bkg. and peaks from other resonances

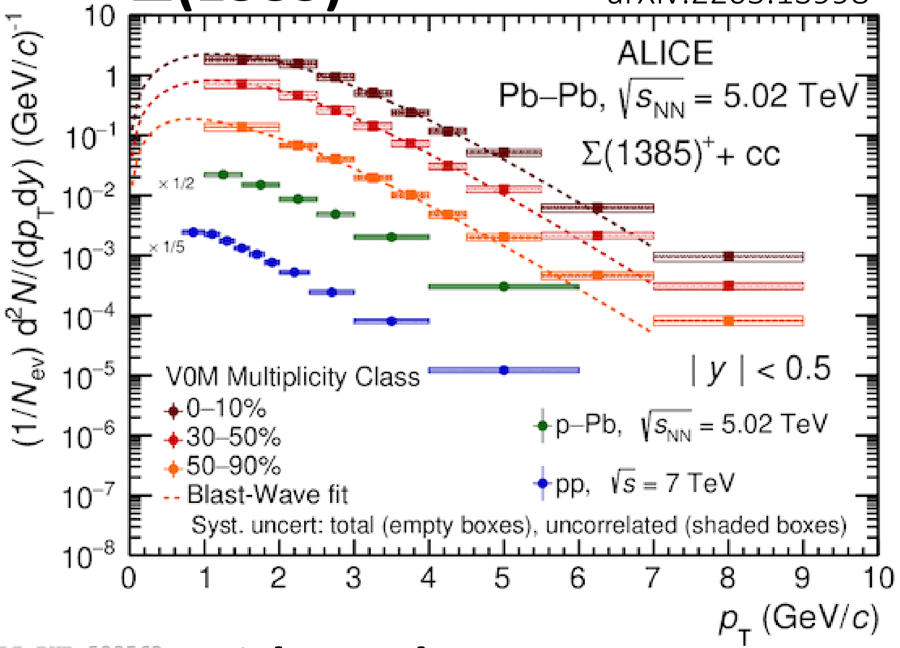




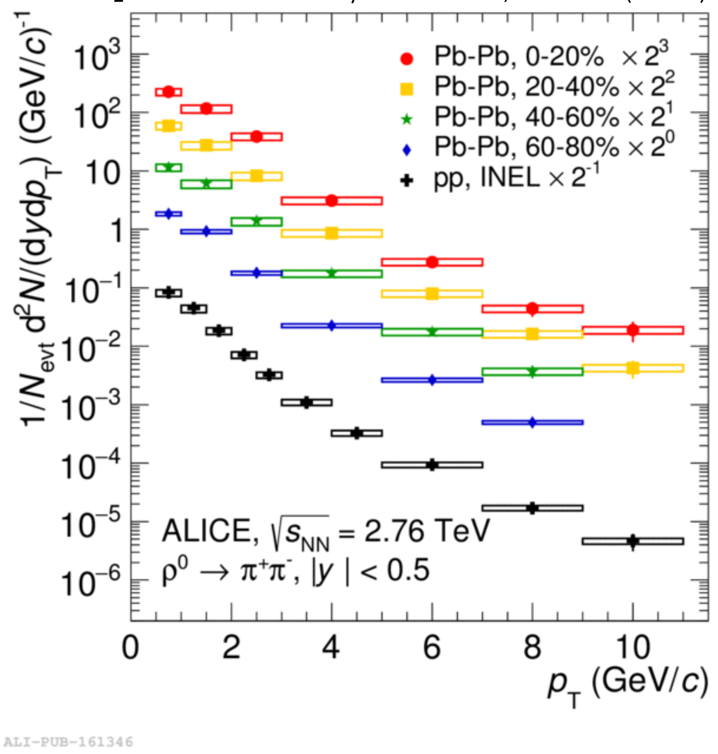
Transverse momentum spectra

- p_T spectra obtained for different multiplicity classes
- In Pb–Pb collisions multiplicity classes correspond to different centralities of the collision (with 0-10% the most central)

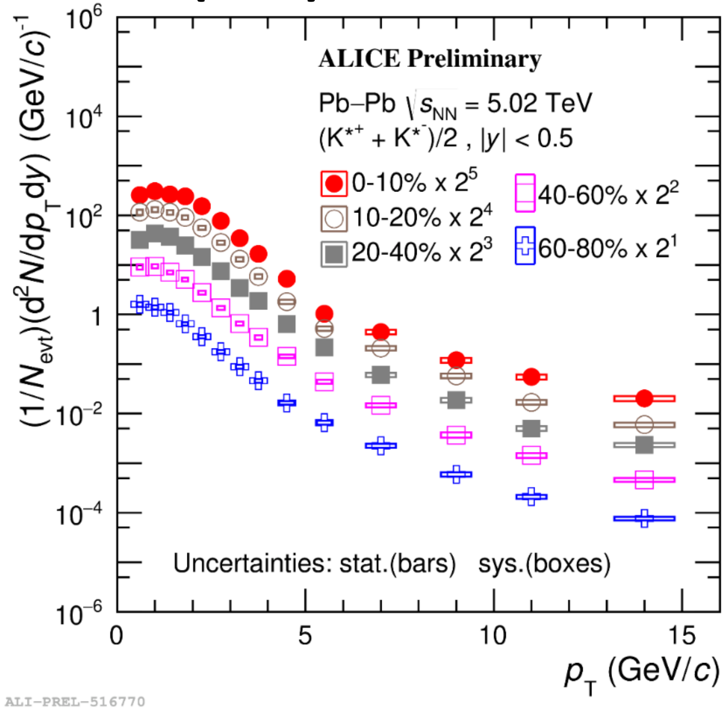
Σ(1385) arXiv:2205.13998



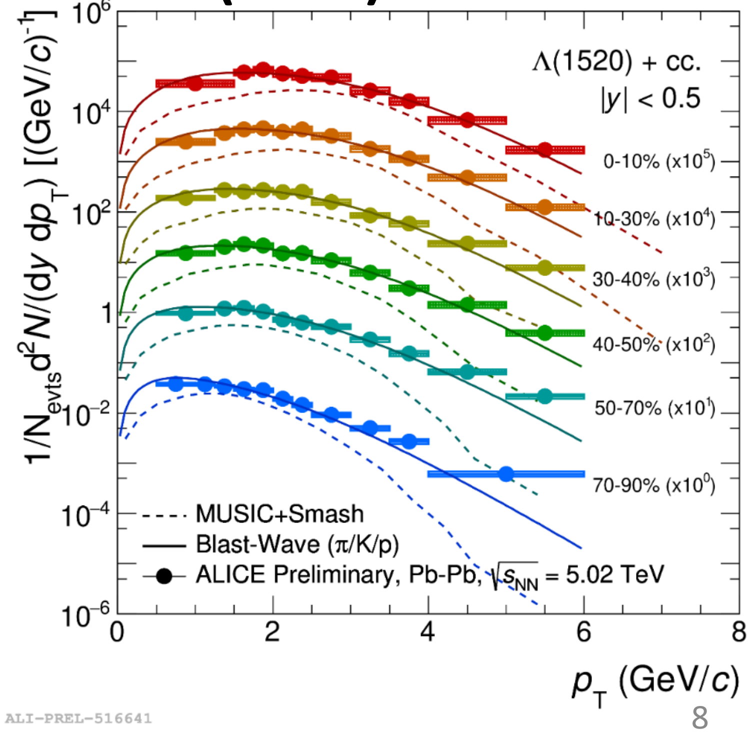
ρ(770) Phys. Rev. C **99**, 064901 (2019)



K*(892)



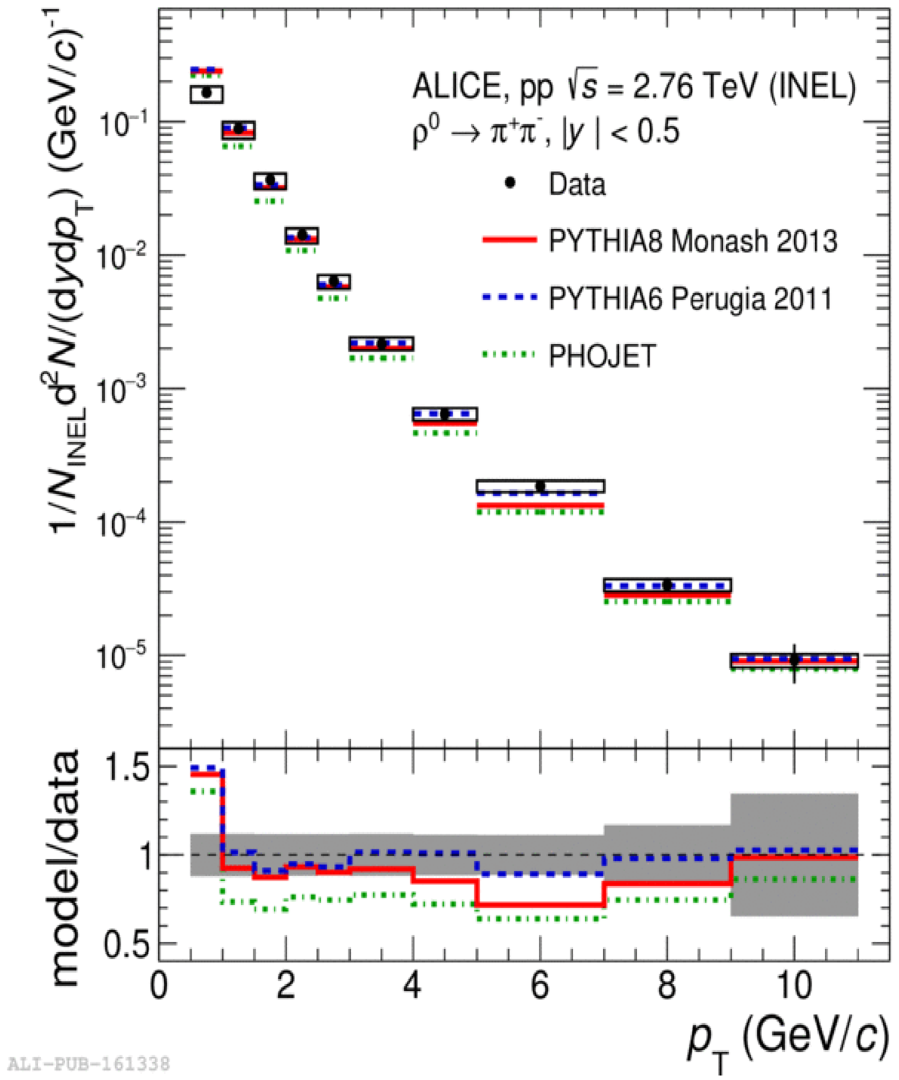
Λ(1520)



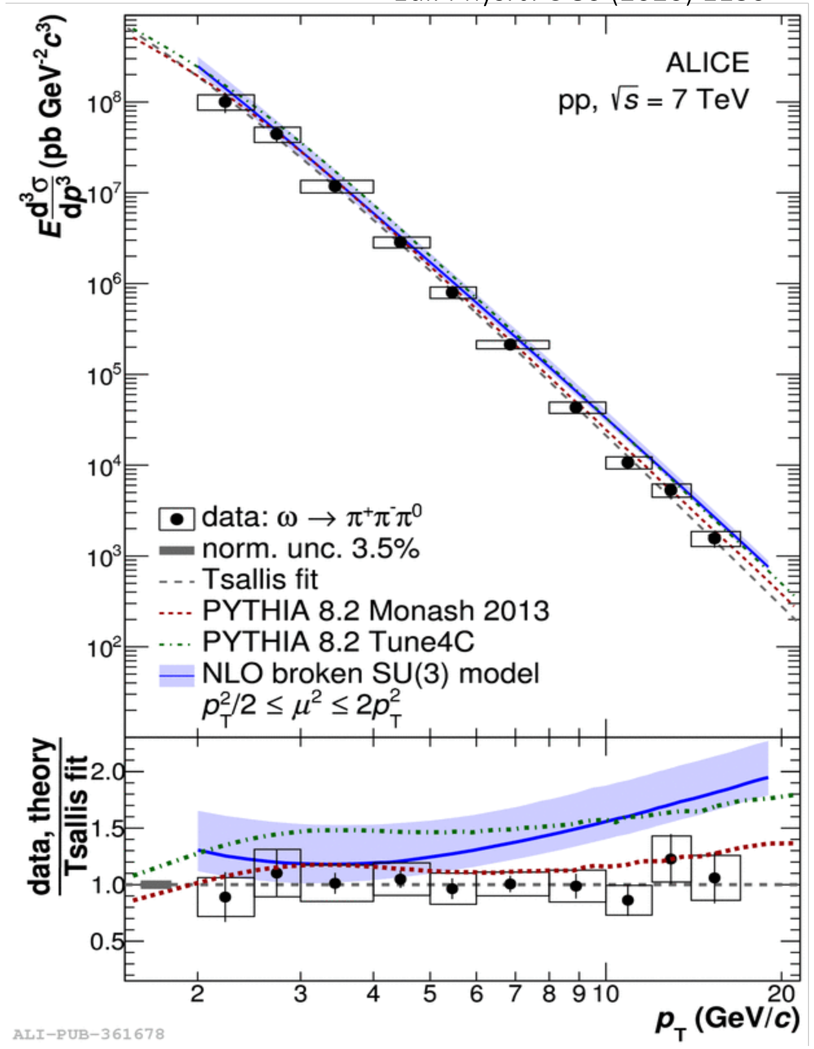
Comparison to models

- AMPT: Phys. Rev. C 72 (2005) 064901
- PYTHIA 6 Perugia 2011: Phys. Rev. D 82 (2010) 074018
- PYTHIA 8 Monash 2013: Eur. Phys. J. C 74 (2014) 3024
- PYTHIA 8.2: Comp. Phys. Comm. 191 (2015) 159
- HERWIG 7: Eur. Phys. J. C 76 (2016) no. 4, 196

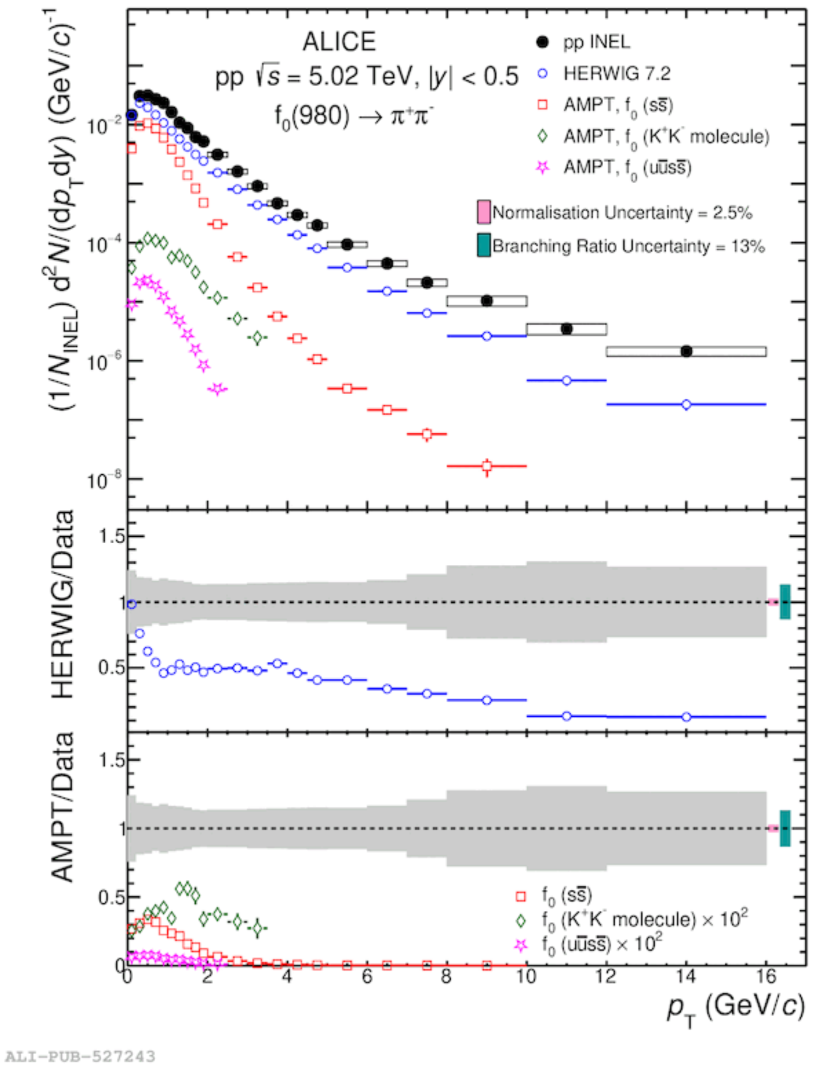
Phys. Rev. C **99**, 064901 (2019)



Eur. Phys. J. C 80 (2020) 1130



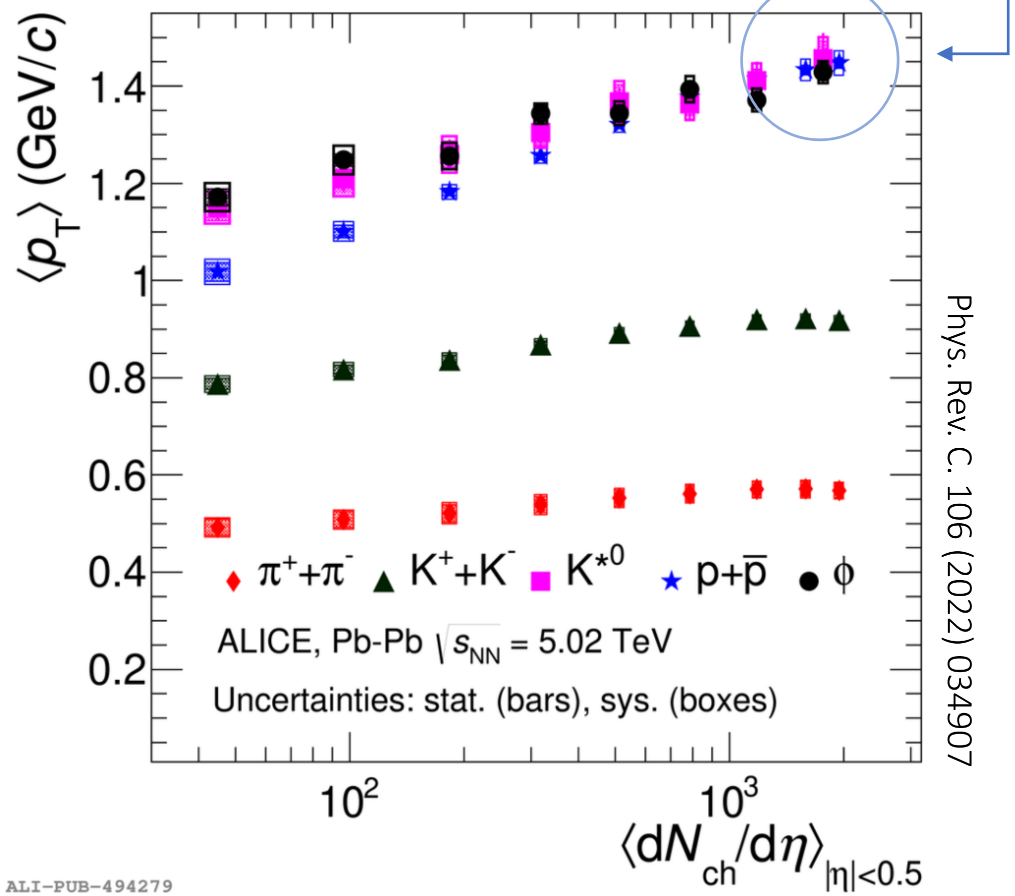
arXiv:2206.06216

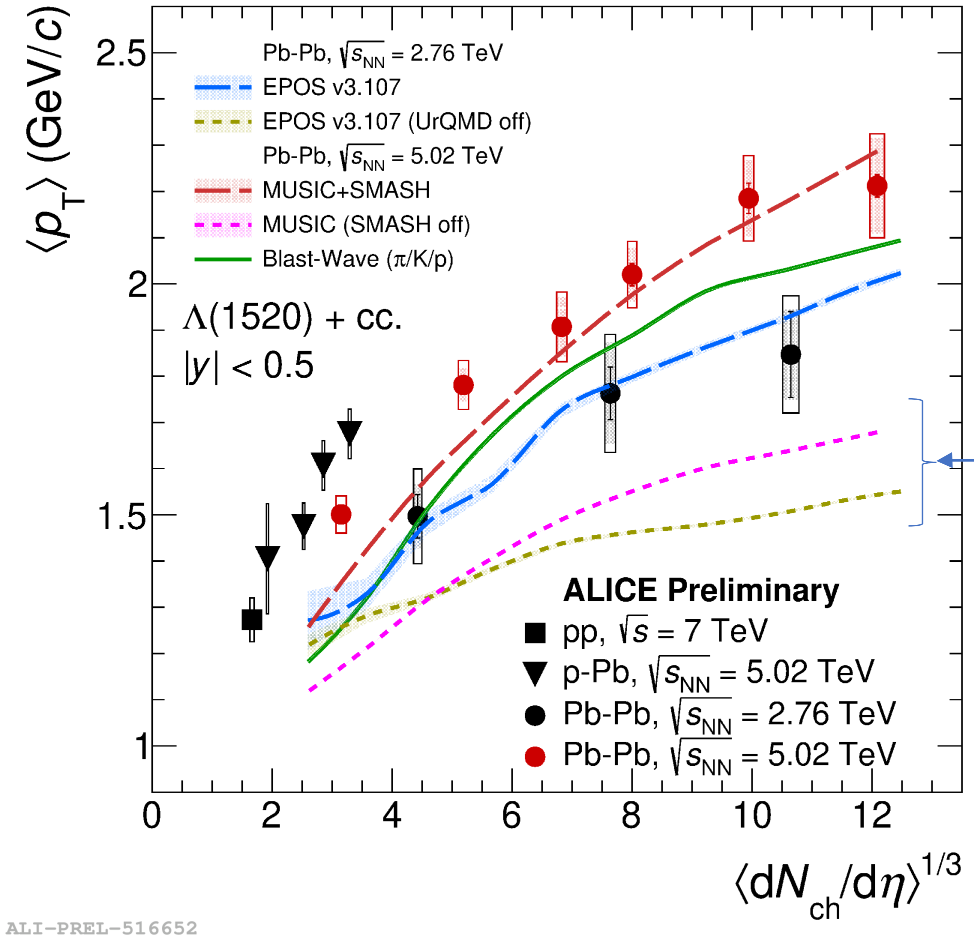


Several models on the market: need to tune them to data to obtain reasonable predictions!

Radial flow and hardening of p_T spectra

- Radial flow: predicted by hydrodynamics in AA due to the higher energy density
- Hardening of the spectra with increasing multiplicity
- Mass scaling observed in central collisions

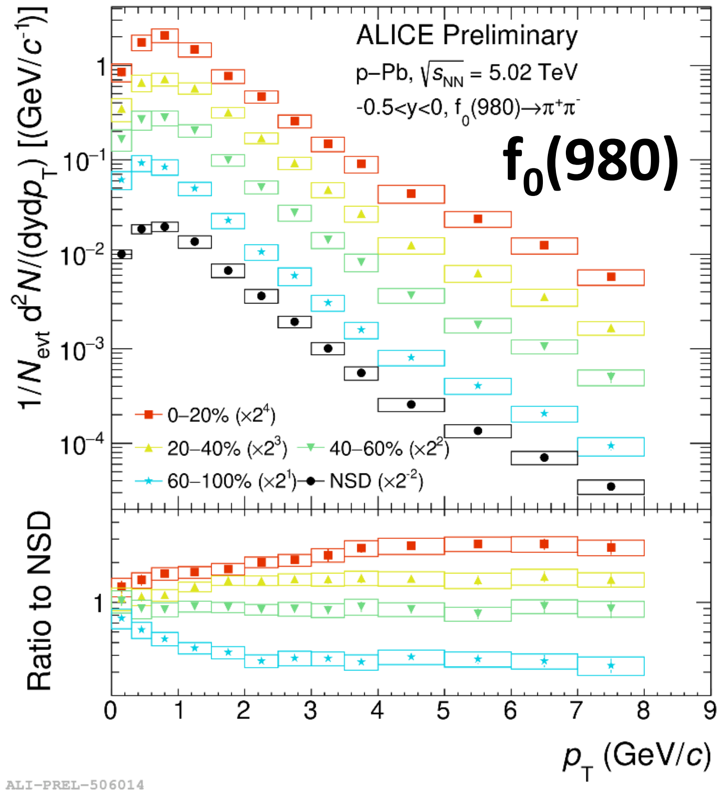


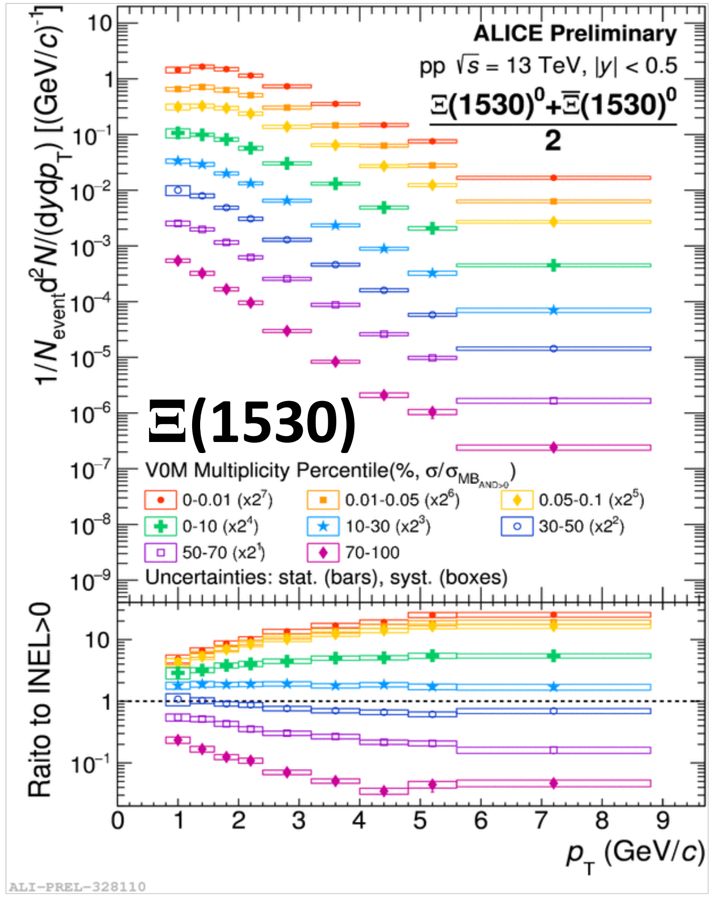


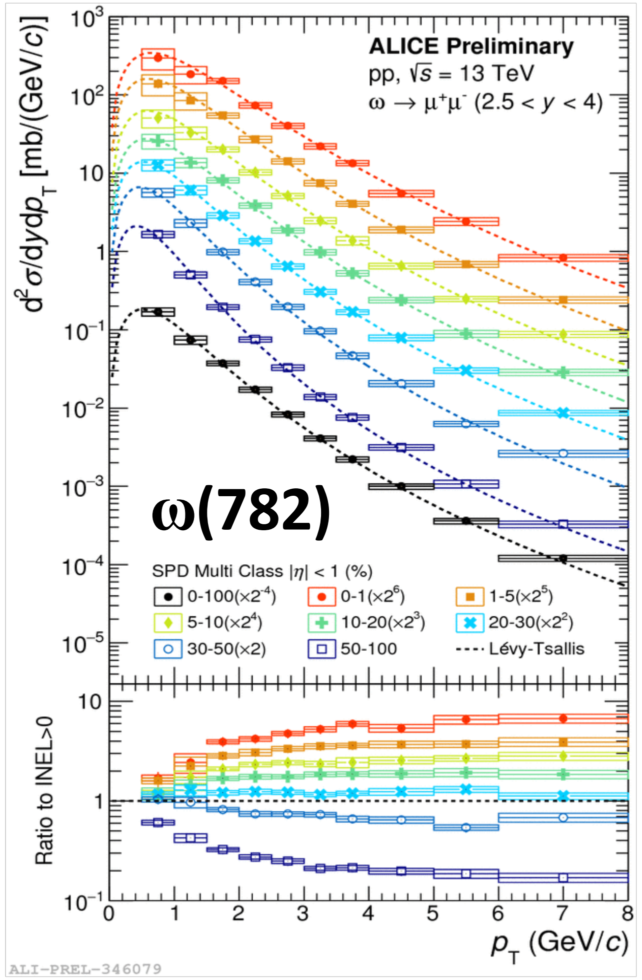
Models that do not include a hadronic afterburner do not reproduce the data

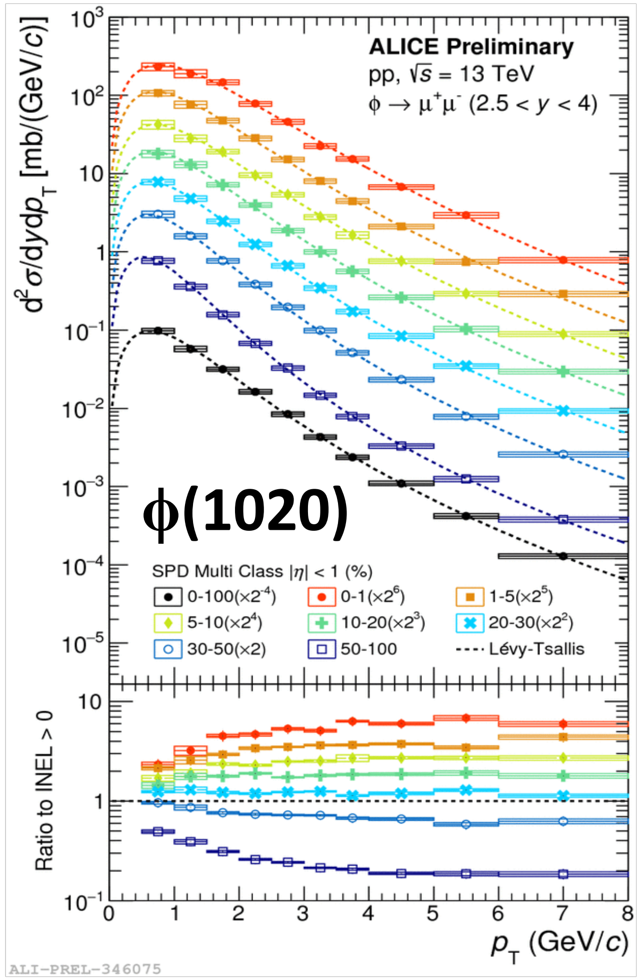
Hardening of p_T spectra in small systems (pp and p–Pb)

- Qualitatively similar observations as for heavy-ion collisions regarding the shapes → collective flow-like effects in small collision systems
- Effect observed also for other hadrons







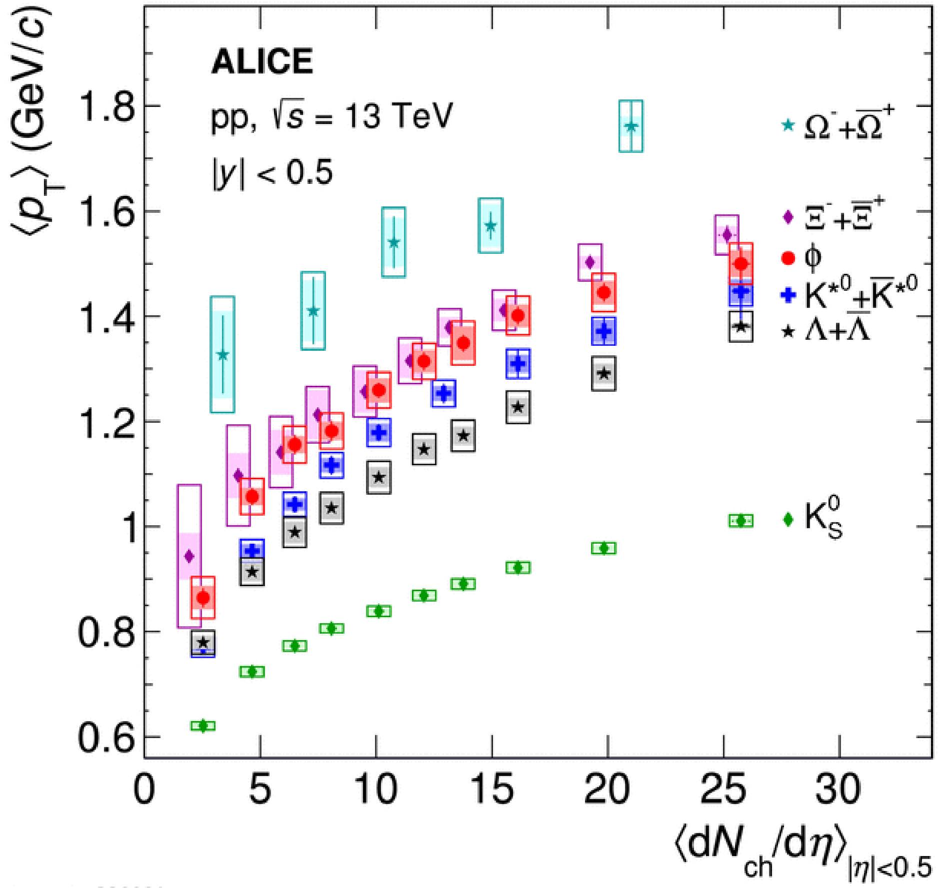


Effect observed both in p–Pb and pp collisions, for both mesons and baryons, and also for resonances reconstructed in the di-lepton channel

Hardening of p_T spectra in small systems (pp and p–Pb)

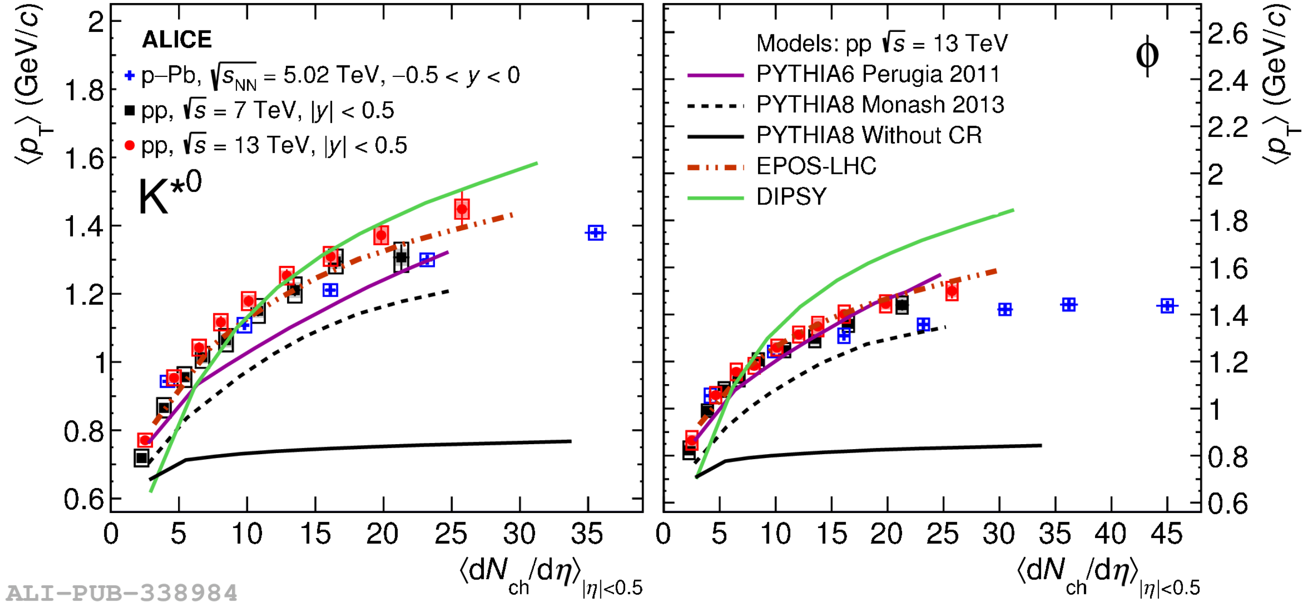
- Qualitatively similar observations as for heavy-ion collisions regarding the shapes → collective flow-like effects in small collision systems
- Effect observed also for other hadrons

Phys. Lett. B 807 (2020) 135501



ALI-PUB-339021

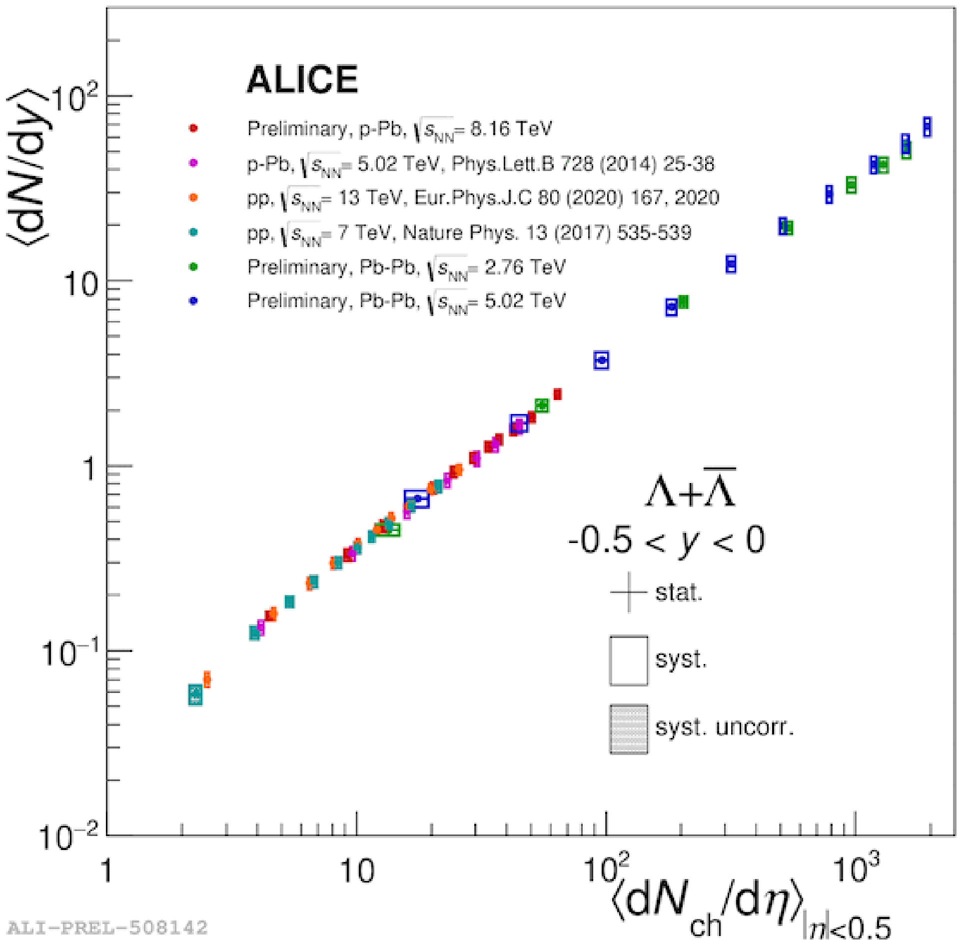
Phys. Lett. B 807 (2020) 135501



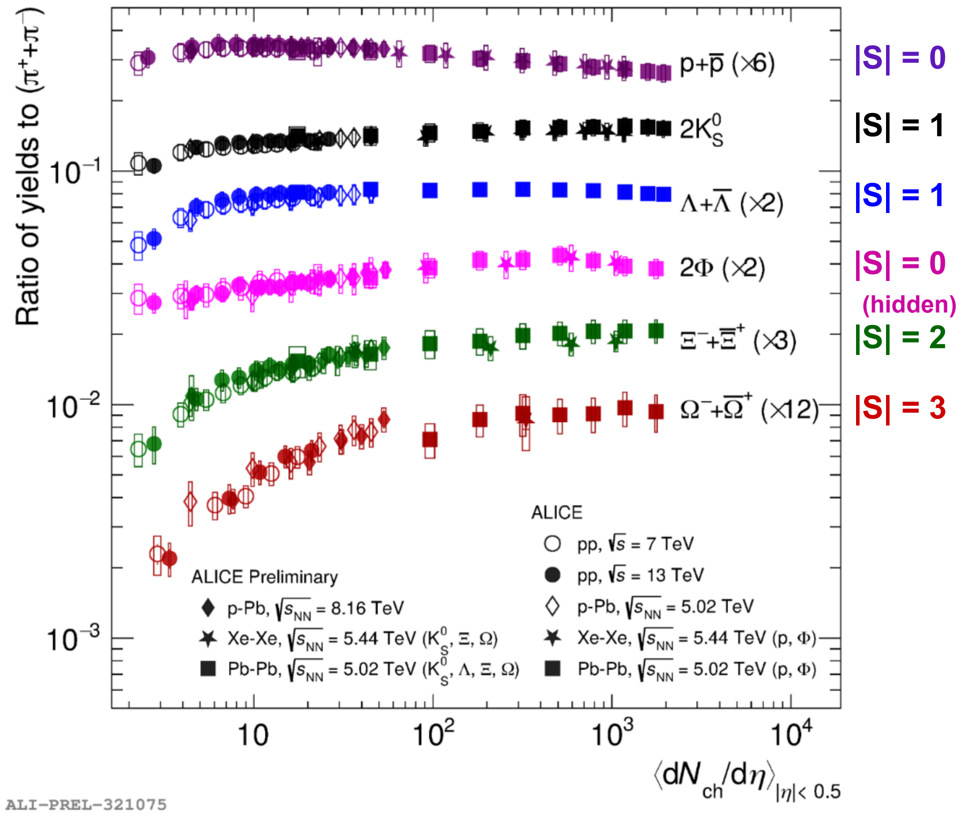
ALI-PUB-338984

- Models implementing Color Reconnection (CR) mechanisms are able to predict the hardening of spectra as function of multiplicity
- PYTHIA 8 w/o CR has a flat behaviour

Integrated yields and hadrochemistry



Nat. Phys **13,** 535–539 (2017)



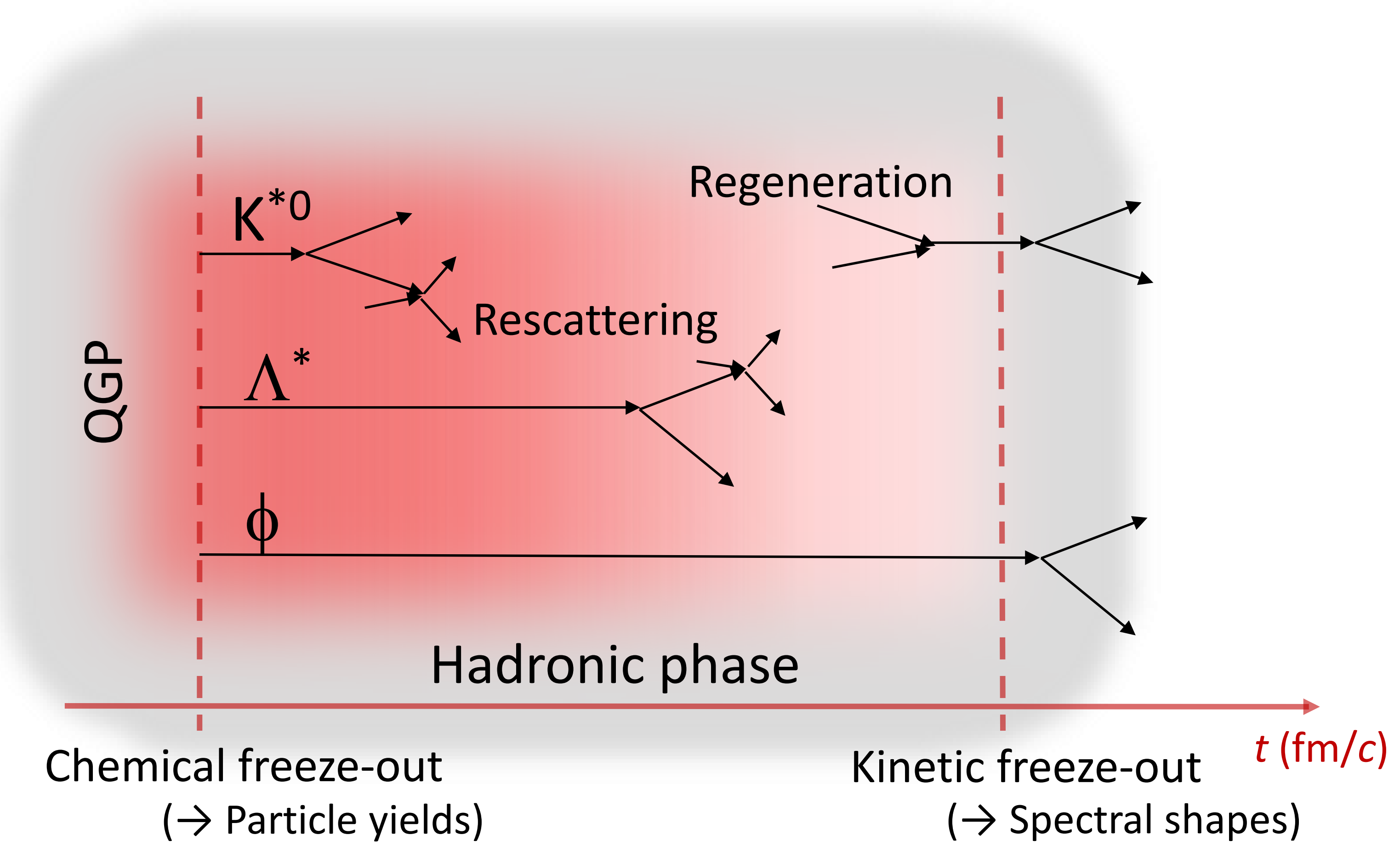
- Strangeness production increasing with multiplicity until saturation (grand-canonical plateau) is reached
- Steeper increase for particles with more strangeness content
- High-multiplicity pp: same hadrochemistry as larger (p–Pb, peripheral Pb–Pb) systems

Particle production is driven by the multiplicity and does not depend on the collision system or the centre-of-mass energy → Common particle production mechanism for all systems?

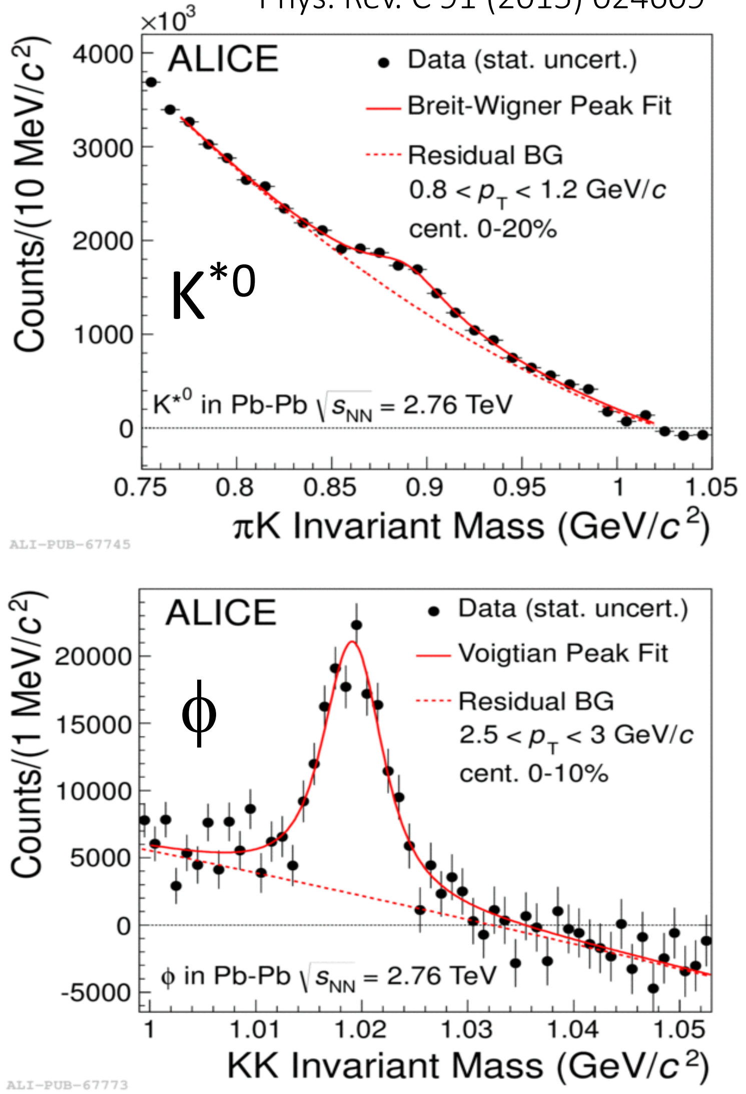
Expect flat behaviour as a function of multiplicity for the yield ratio of particles with the same strangeness content

Suppressed signal of resonances from the hadron gas

- Re-scattering and regeneration modify the yield of reconstructible resonances
- Effect more pronounced for central collisions where the duration is longer



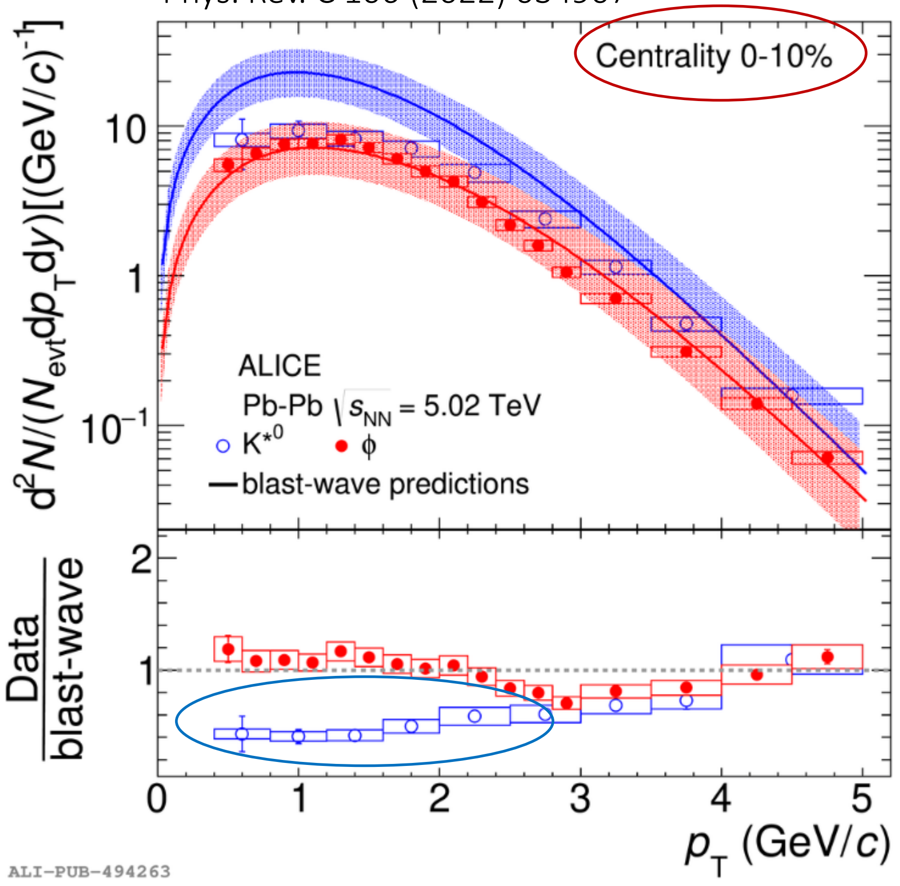
Phys. Rev. C 91 (2015) 024609

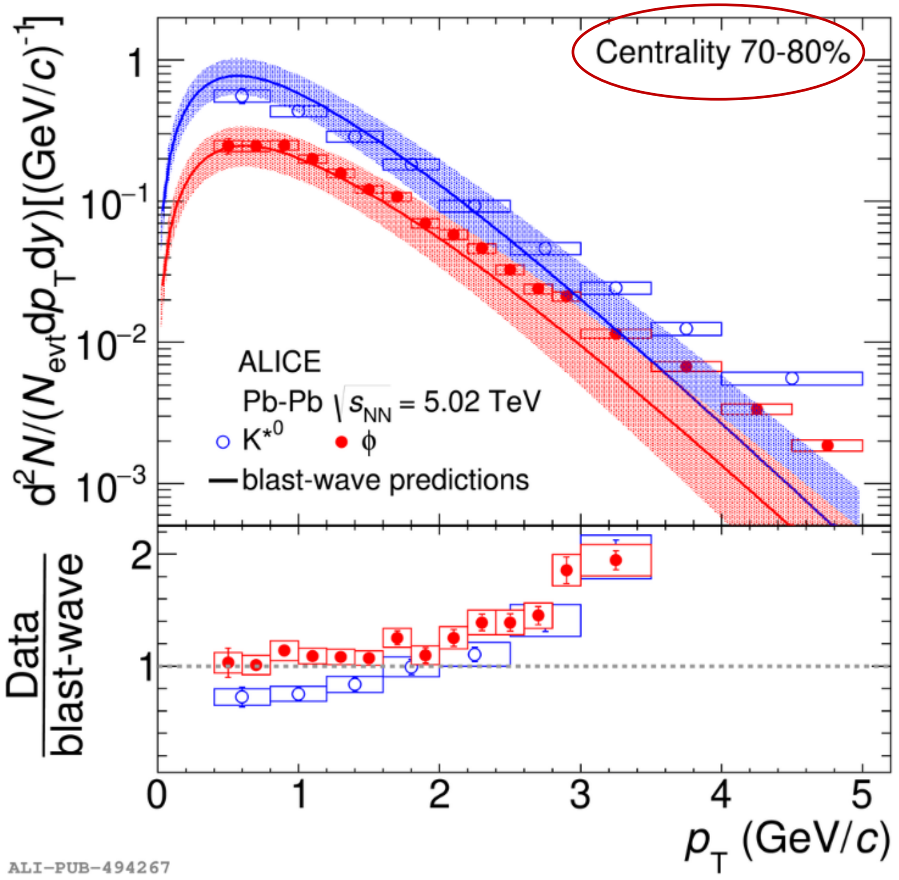


Suppressed signal of resonances from the hadron gas

- Re-scattering and regeneration modify the yield of reconstructible resonances
- Effect more pronounced for central collisions where the duration is longer
- Effect larger at low p_T

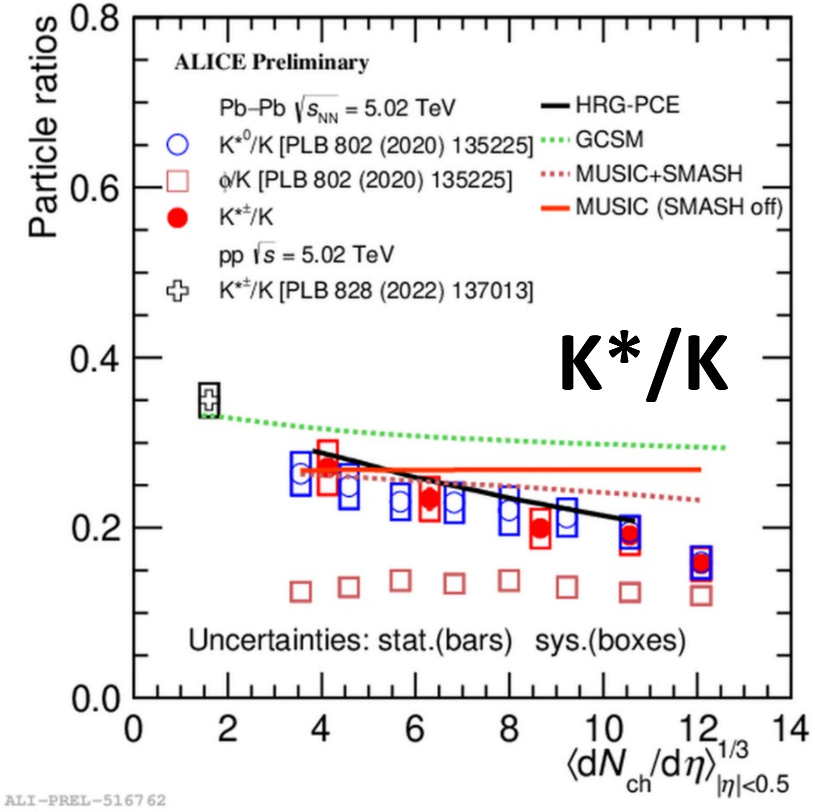
Phys. Rev. C 106 (2022) 034907





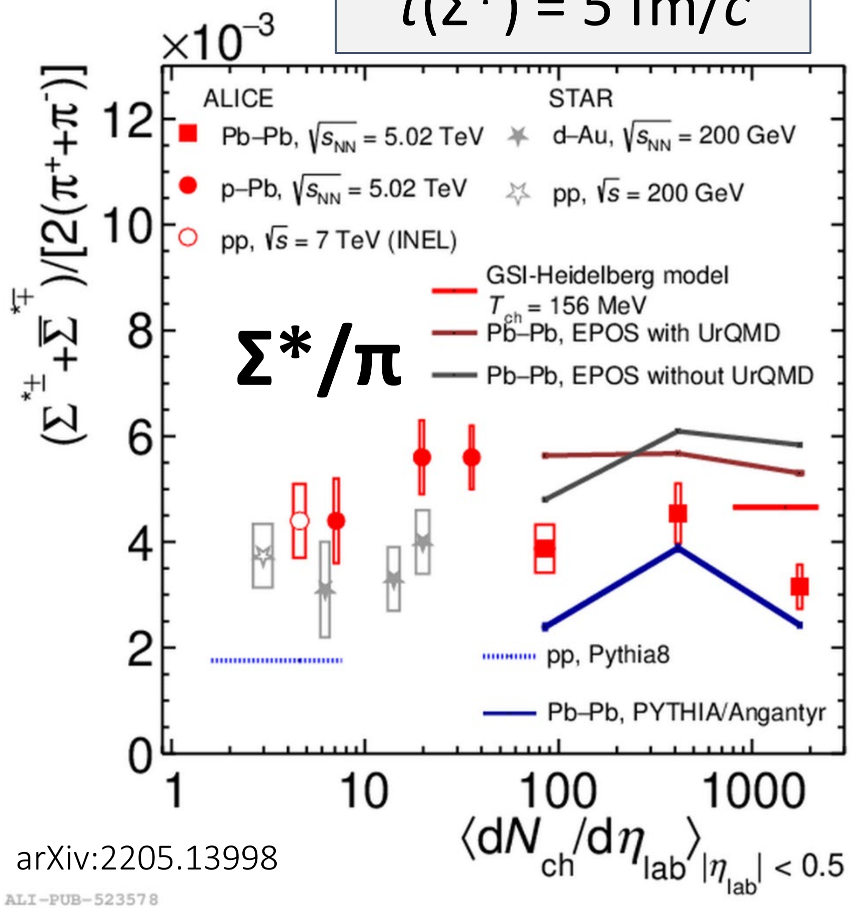
Resonance-to-long-lived-hadron yield ratios

$\tau(K^*) = 4.16$ fm/c



Suppression of ~55% from peripheral to most central Pb–Pb collisions → consistent with rescattering effects

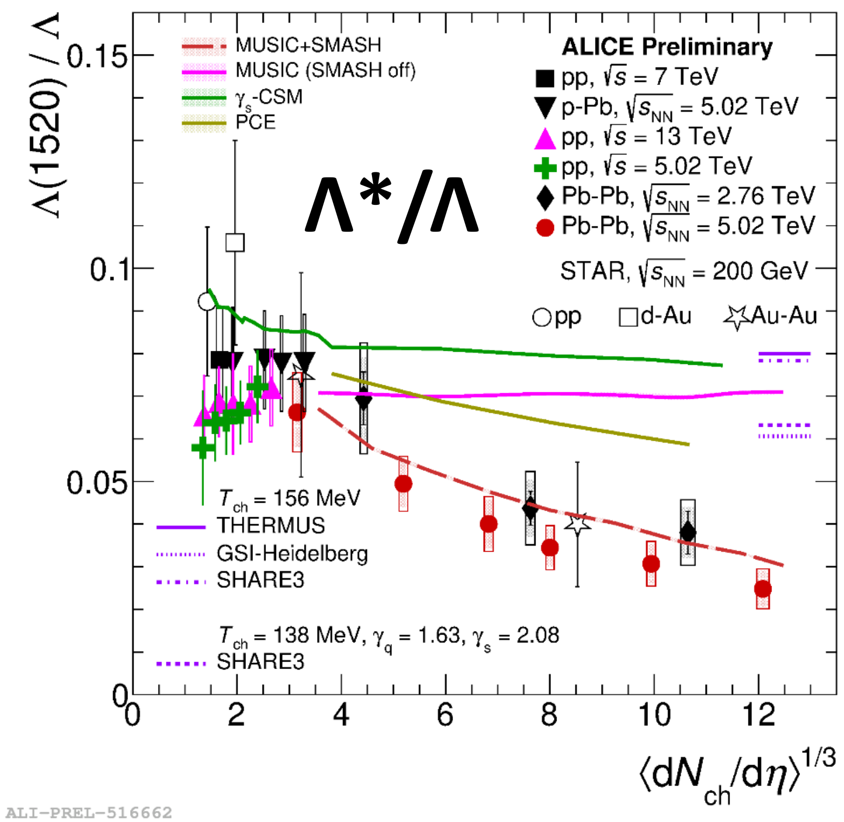
$\tau(\Sigma^*) = 5$ fm/c



arXiv:2205.13998

Suppression at a level of 3.6σ in 0-10% central Pb–Pb collisions with respect to statistical thermal model

$\tau(\Lambda^*) = 12$ fm/c



- Larger suppression (~70%) wrt. K* despite $\tau(\Lambda^*) = 3\,\tau(K^*)$
- **MUSIC+SMASH reproduces the multiplicity suppression trend**

- EPOS+UrQMD: Phys. Rev. C 93 (2016) 014911
- GCSM: Phys. Rev. C 100 (2019) 5, 054906
- PCE: Phys. Rev. C 102 (2020) 2, 024909
- MUSIC: arXiv:2105.07539

Simple model for the duration of the hadron-gas phase

Estimation of lower limit of the timespan between chemical and kinetic freeze-out by exponential law:

$$r_{kin} = r_{chem} \times \exp(-(\tau_{kin} - \tau_{chem})/\tau_{res})$$

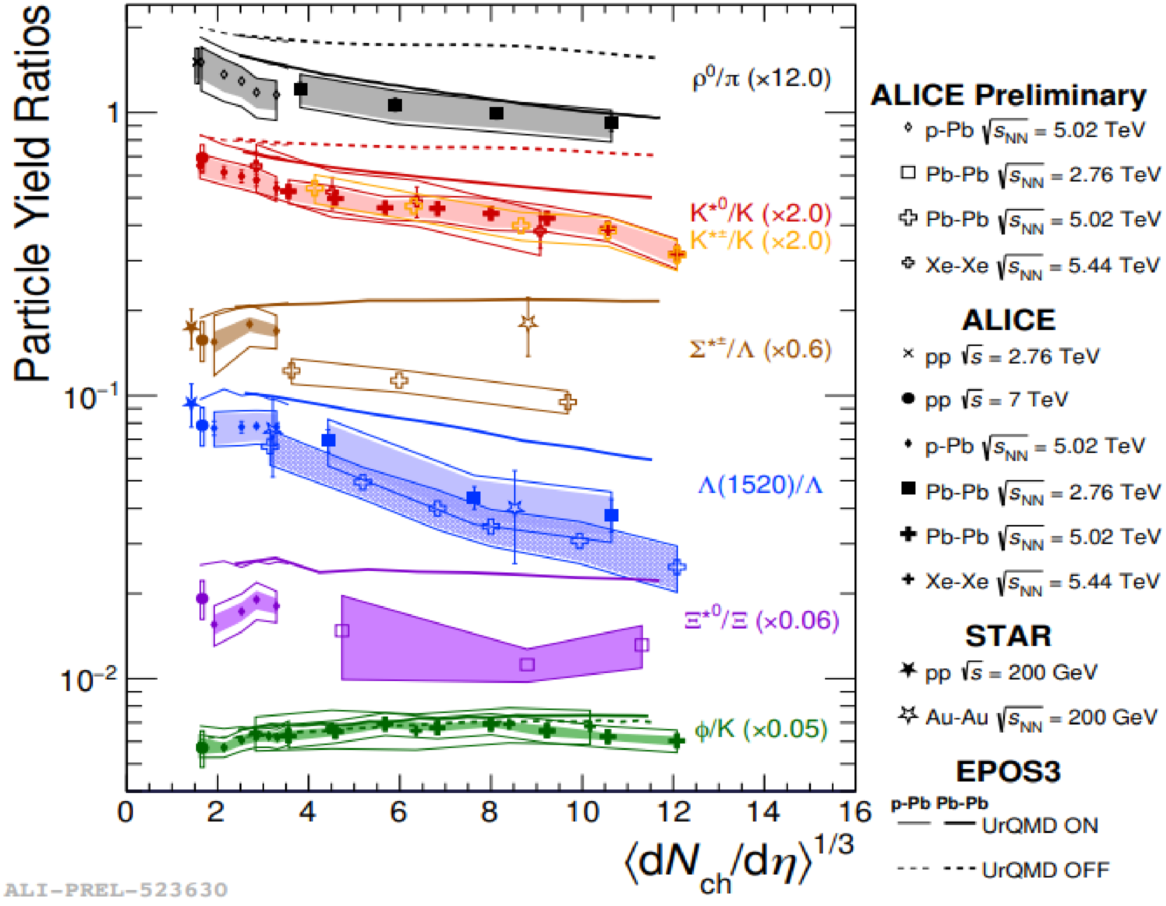
r_{kin} = measured yield ratios in Pb–Pb
r_{chem} = measured yield ratios in pp
τ_{res} = lifetime of resonance

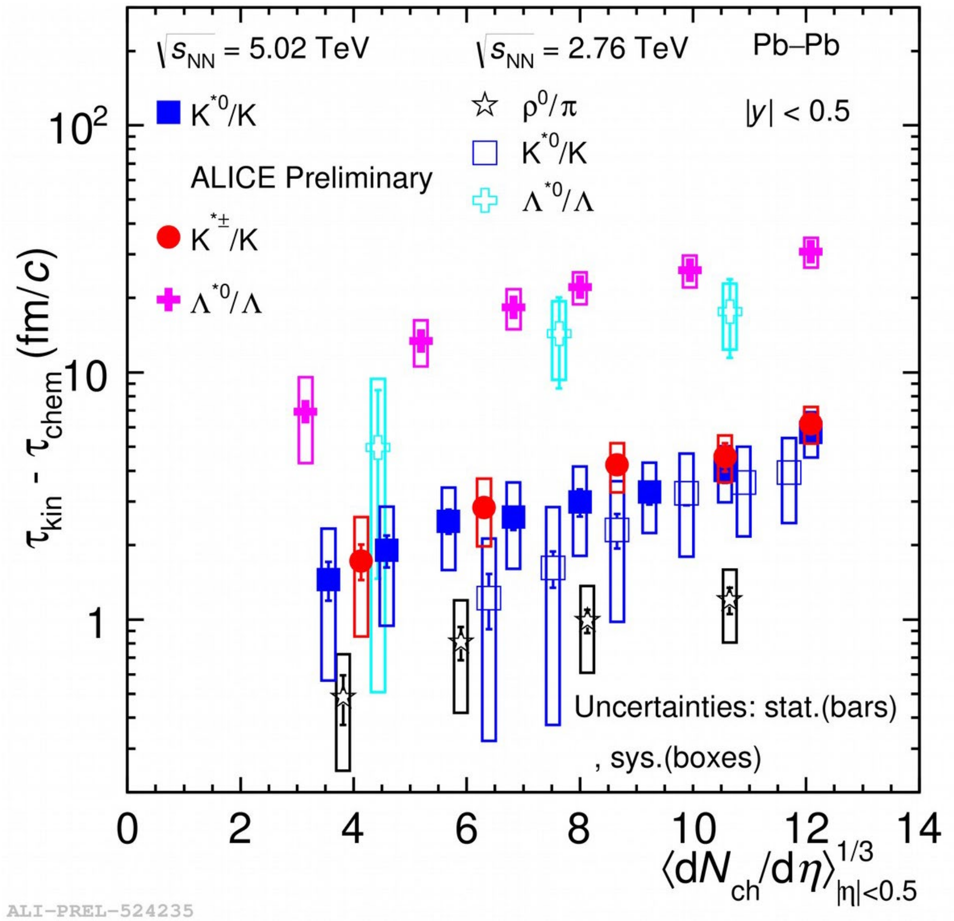
Assumptions:

i) Simultaneous freeze-out for all particles

ii) Negligible regeneration

	$c\tau_{res}$ (fm)
ρ	1.3
K*	4.2
Σ*	5.5
Λ*	12.6
Ξ*	21.7
ϕ	46.2





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Summary

- ✓ During Run 1 and Run 2 ALICE has measured a varied set of resonances with different lifetime, mass, quark content
- ✓ Resonances have proved to be a valuable probe to explore the hadron-gas phase at the end of the collision
- ✓ Precise measurements of resonances have allowed to study strangeness production and collective effects in large and small systems

- ✓ Future more precise data from Run 3 will allow multi-differential analyses, reconstruction of higher-mass resonances and a quantitative study of the hadron-gas phase via measurements of observables such as the flow of resonances