# Hadronic resonance production with ALICE at the LHC

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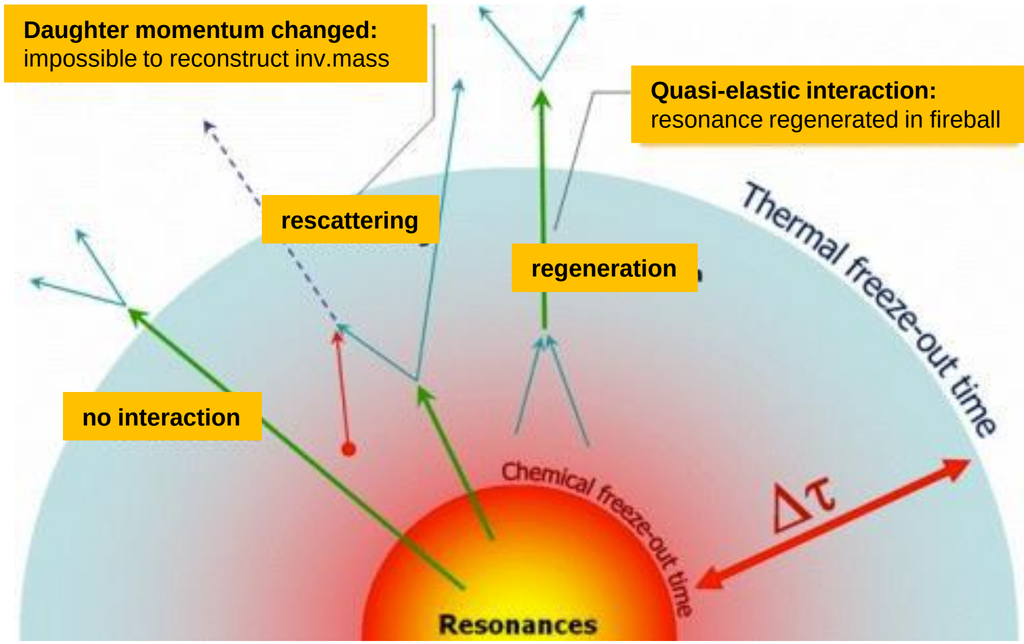
- Motivation
- ALICE detector
- Signal extraction
- Transverse momentum spectra
- Yields
- Mean transverse momentum
- Ratios to longer-lived hadrons
- Nuclear modification factors
- Summary

# Motivation

- **pp and p–Pb collisions:**
  - ✓ baseline for heavy-ion collisions
  - ✓ system size dependence
  - ✓ role of cold nuclear matter
  - ✓ study of collectivity in small collision systems
- **A–A collisions**:
  - ✓ in-medium energy loss
    - → nuclear modification factor for resonances
  - ✓ restoration of chiral symmetry
    - → modification of width, mass and branching ratio
  - ✓ regeneration and rescattering effects
    - → modification of measurable yield and ratios to longer-lived hadrons
    - → timescale between chemical and kinetic freeze-out

| Resonance | cτ (fm) | Decay | System @ energy (TeV) |
|---|---|---|---|
| $\rho(770)^0$ | 1.3 | $\pi\ \pi$ | pp/Pb–Pb @ 2.76 |
| $K^*(892)^0$ | 4.2 | $K\ \pi$ | pp/p–Pb/Pb–Pb/Xe–Xe @ all energies |
| $K^*(892)^\pm$ | 4.2 | $K_S^0\ \pi$ | pp @ 5.02/8/13 Pb–Pb @ 5.02 |
| $f_0$ (980) | ~ 5 | $\pi\ \pi$ | pp/p–Pb @ 5.02 |
| $\Sigma(1385)^\pm$ | 5-5.5 | $\Lambda\ \pi$ | pp@7/13 p–Pb /Pb–Pb @ 5.02 |
| $\Lambda(1520)$ | 12.6 | p K | pp @ 7 p–Pb @ 5.02 Pb–Pb@ 5.02 |
| $\Xi(1530)^0$ | 21.7 | $\Xi^-\ \pi$ | pp @ 7/13 p–Pb@ 5.02 |
| $\phi(1020)$ | 46.4 | K K | pp/p–Pb/Pb–Pb/Xe–Xe @ all energies |

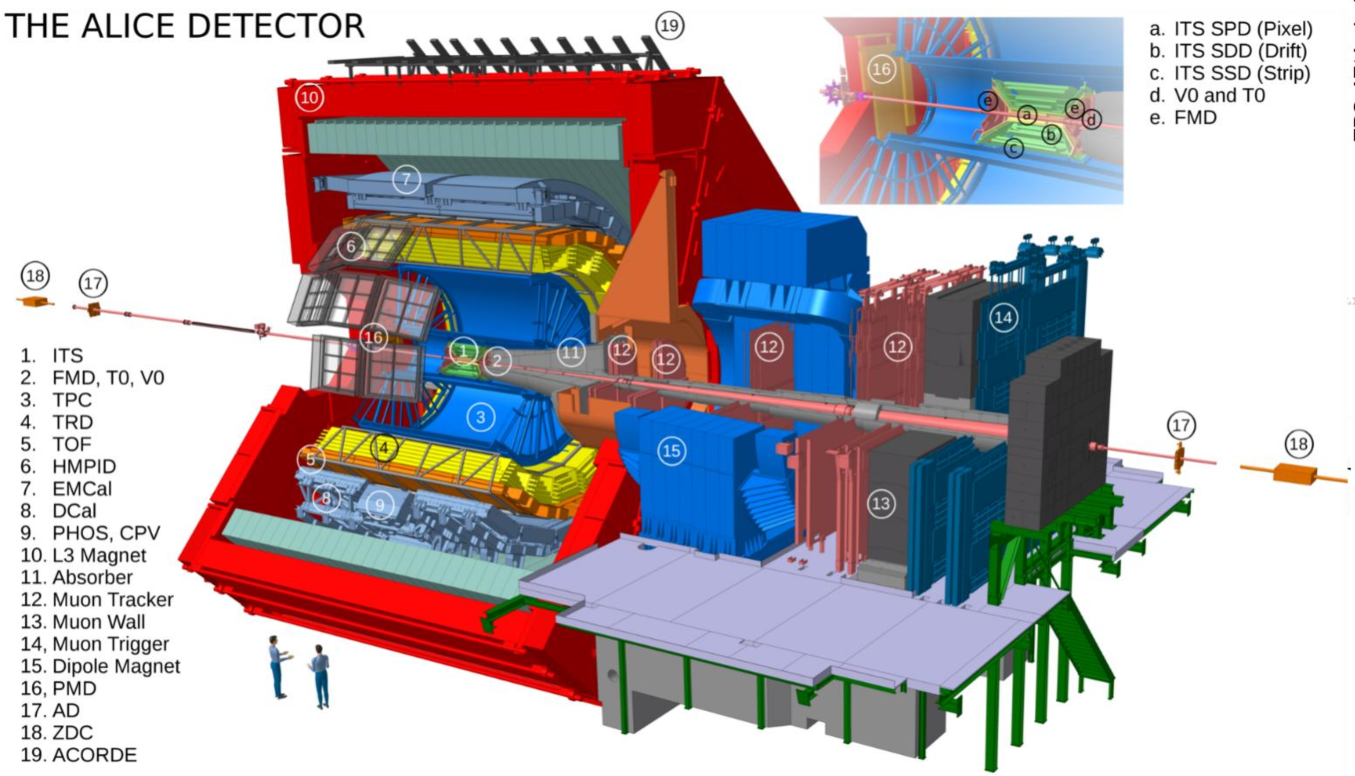


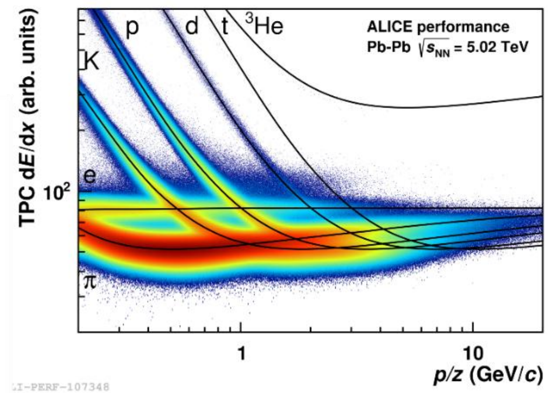
# ALICE detector

**V0**:
→ triggering minimum bias collisions
→ centrality/multiplicity estimator

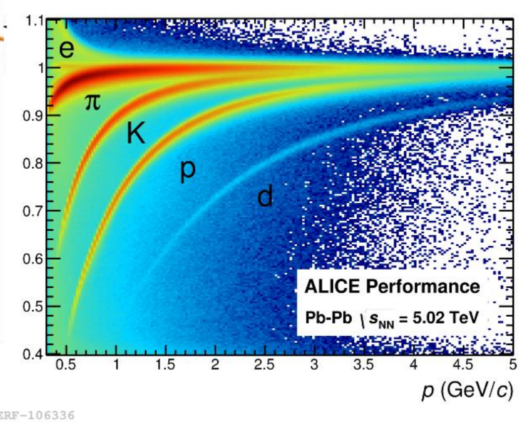
**ITS**: tracking and vertexing

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




**TOF**: PID through particle time of flight



# ALICE papers

## recent papers

1. in preparation (→ PLB)
Multiplicity dependence of K*(892)$^{\pm}$ production in pp collisions at $\sqrt{s}$ = 13 TeV
2. arXiv:2311.11786 (→ PLB)
Observation of abnormal suppression of $f_0$(980) production in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
3. arXiv:2308.16119 (→ PRC)
K*(892)± resonance production in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
4. arXiv:2308.16116 (→ JHEP)
Multiplicity-dependent production of Σ(1385)$^{\pm}$ and Ξ(1530)$^{0}$ in pp collisions at $\sqrt{s}$ = 13 TeV
5. PRC109(2024)014911
System size dependence of hadronic rescattering effect at LHC energies

## previous papers

**K*(892)$^0$, ϕ(1020)**

EPJC72(2012)2183
PRC91(2015)024609
EPJC76(2016)245
PRC95(2017)064606
PLB802(2020)135225
PLB807(2020)135501
PRC102(2020)024912
PRC106(2022)034907
PRC107(2023)055201
EPJC83(2023)540

**Σ(1385)$^{\pm}$, Ξ(1530)$^0$**

EPJC75(2015)1
EPJC77(2017)389
EPJC83(2023)351

**Λ(1520)**

PRC99(2019)024905
EPJC80(2020)160

**ρ(770)$^0$**

PRC99(2019)064901

**K*(892)$^{\pm}$**

PLB828(2022)137013

**$f_0$(980)**

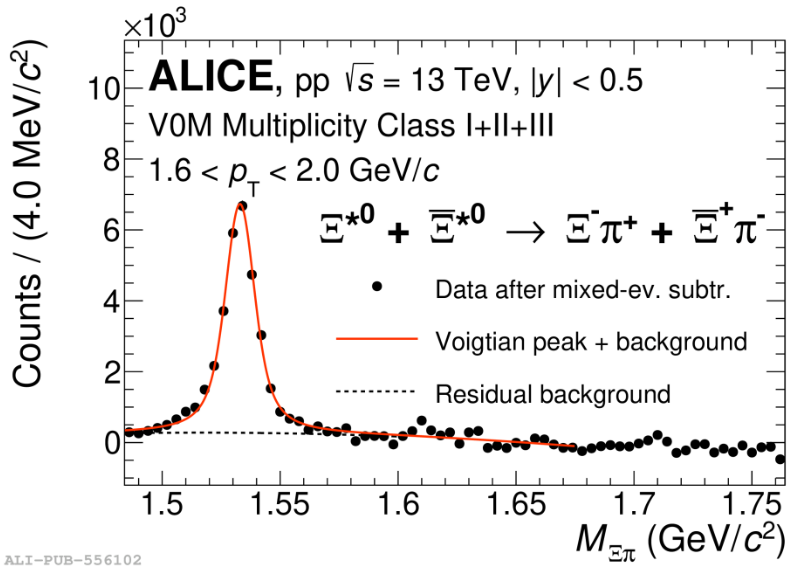
PLB846(2023)137644

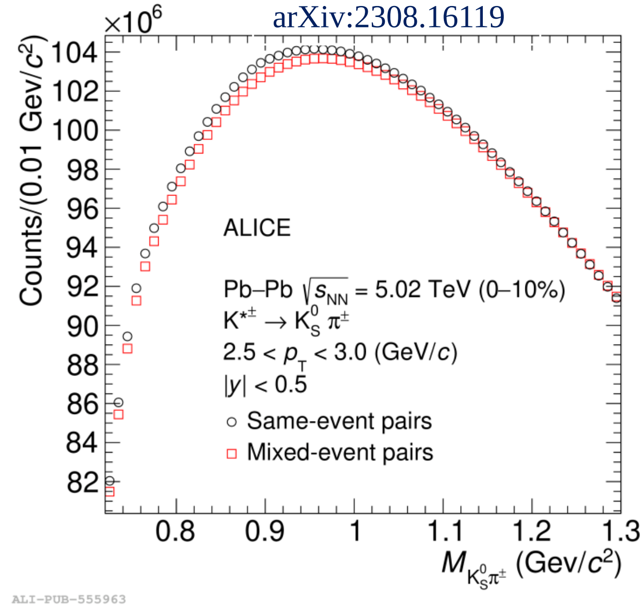
## pp@13 TeV $\Xi(1530)^0$

arXiv:2308.16116

# Signal extraction

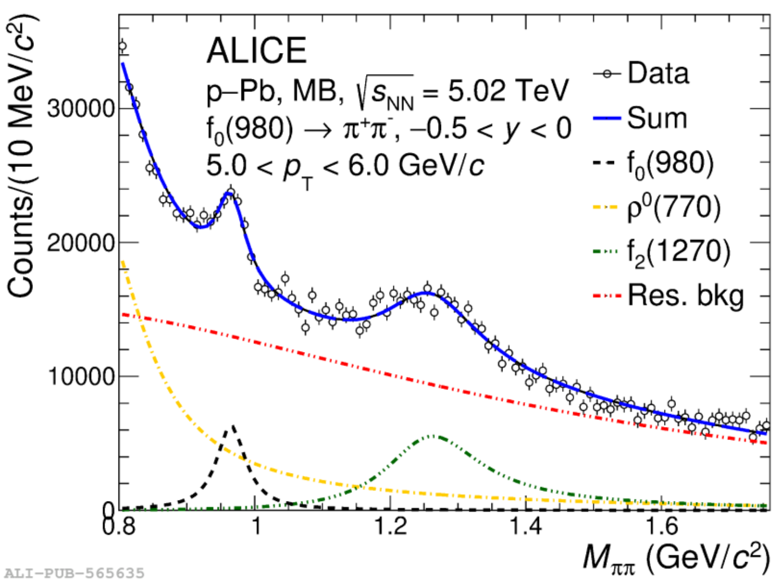
## Pb–Pb@5.02 TeV $K^*(892)^\pm$

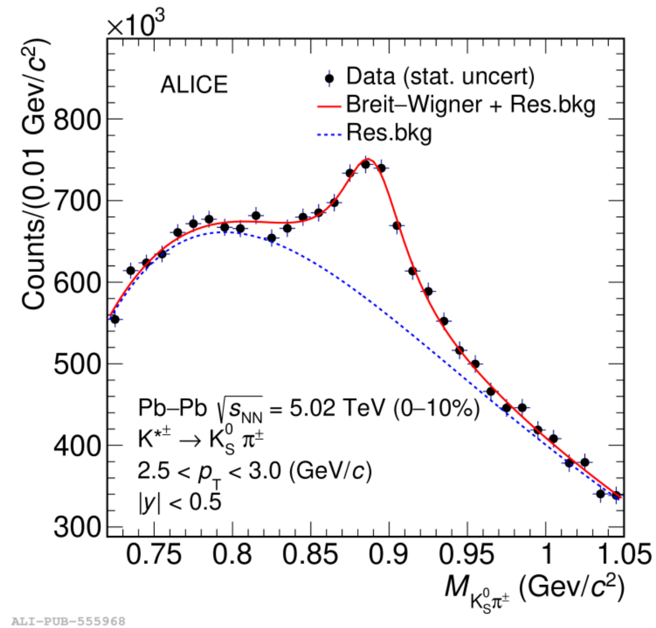



## p–Pb@5.02 TeV $f_0(980)$

arXiv:2311.11786

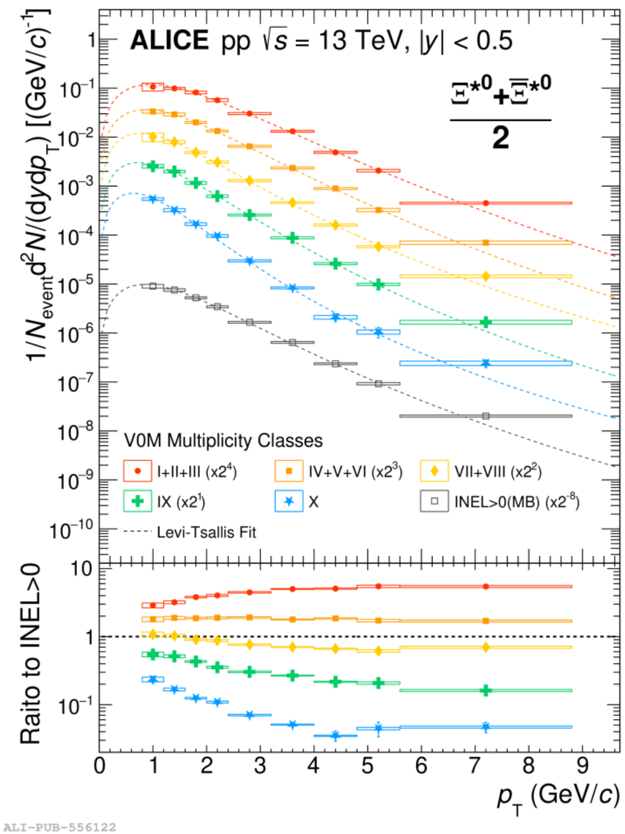


# Transverse momentum ($p_T$) spectra

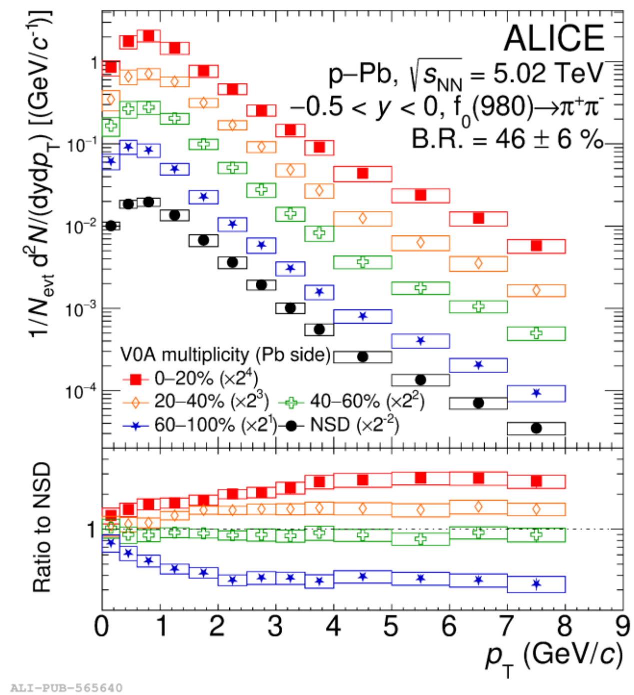
**pp@13 TeV Ξ(1530)$^0$**

arXiv:2308.16116



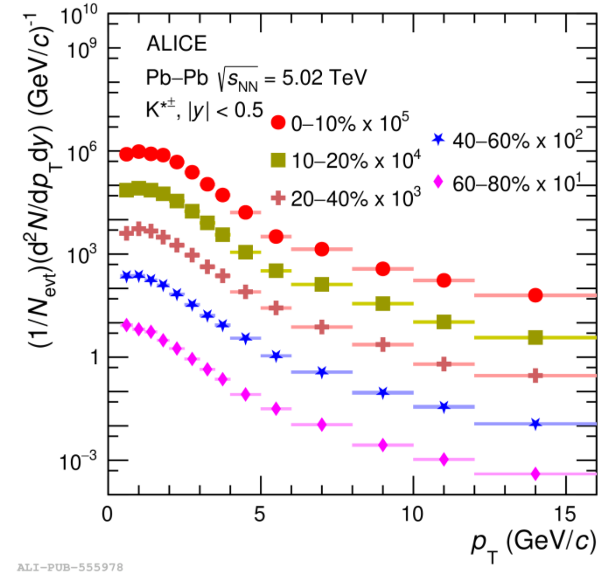

**p–Pb@5.02 TeV f$_0$(980)**

arXiv:2311.11786




**Pb–Pb@5.02 TeV K*(892)**

arXiv:2308.16119

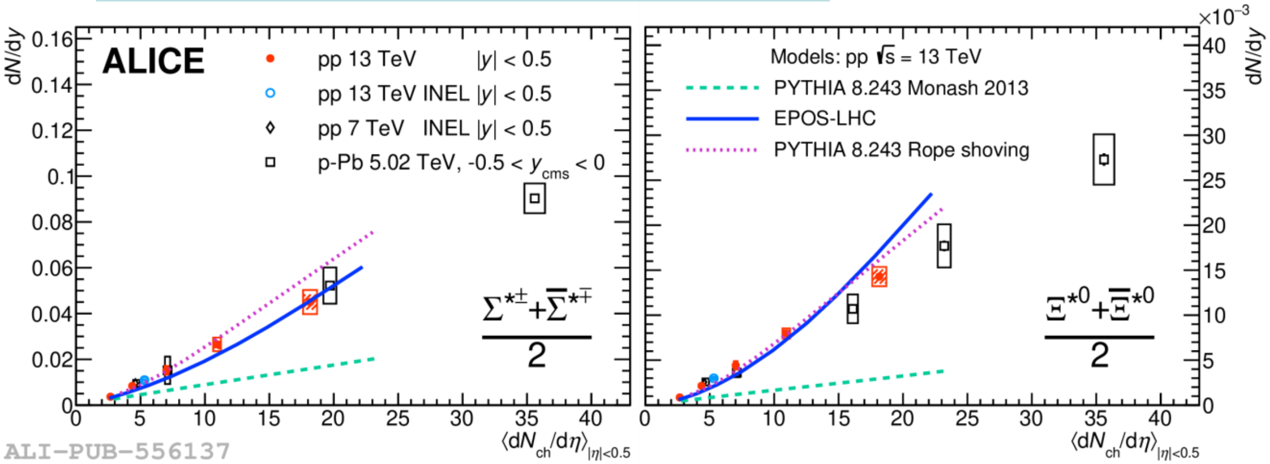



spectra become harder from low to high multiplicity collisions

# yields, ‹ $p_T$ › vs. d$N_{ch}$/d$\eta$

## pp@13 TeV Σ(1385)±, Ξ(1530)0

arXiv:2308.16116

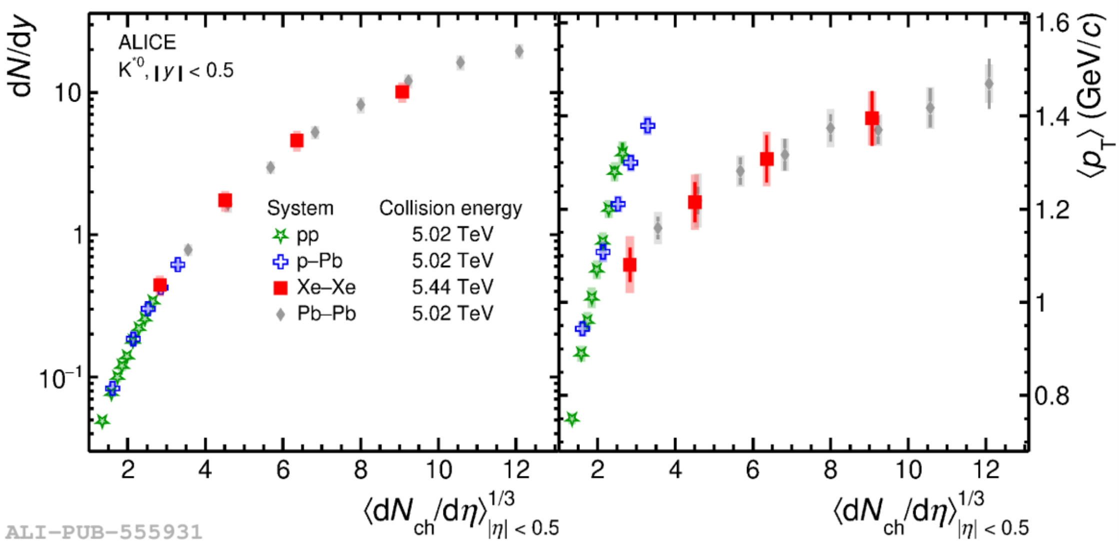



yields for a fixed multiplicity:

- independent of collision system and energy
- appear to be driven by event multiplicity
- EPOS-LHC and PYTHIA8 with Rope shoving describe within uncertainties

## Xe–Xe@5.44 TeV K*(892)0

PRC109(2024)014911



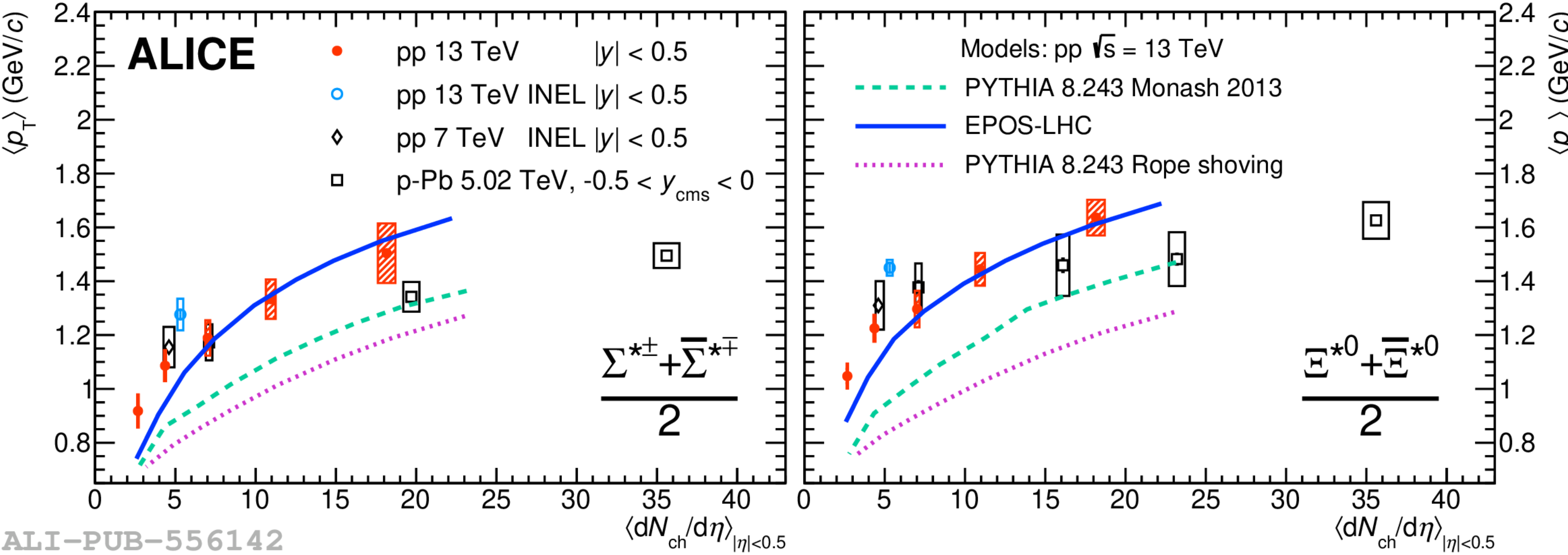

‹ $p_T$ ›:
pp, p–Pb vs. Xe–Xe, Pb–Pb

- larger at similar multiplicity
more rapid expansion
- steeper increase with multiplicity
can be understood as the effect of color reconnection between strings produced in multi-parton interactions, PL B727 (2013) 371

# ‹ $p_T$ › vs. models

**pp@13 TeV Σ(1385)$^{\pm}$, Ξ(1530)$^0$**

arXiv:2308.16116




- steeper increase with multiplicity in pp than in p–Pb
- well described by EPOS-LHC, underestimated by PYTHIA8

# $K^{*\pm}/K$ vs. $dN_{ch}/d\eta$

**τ(K*) = 4.2 fm/*c***

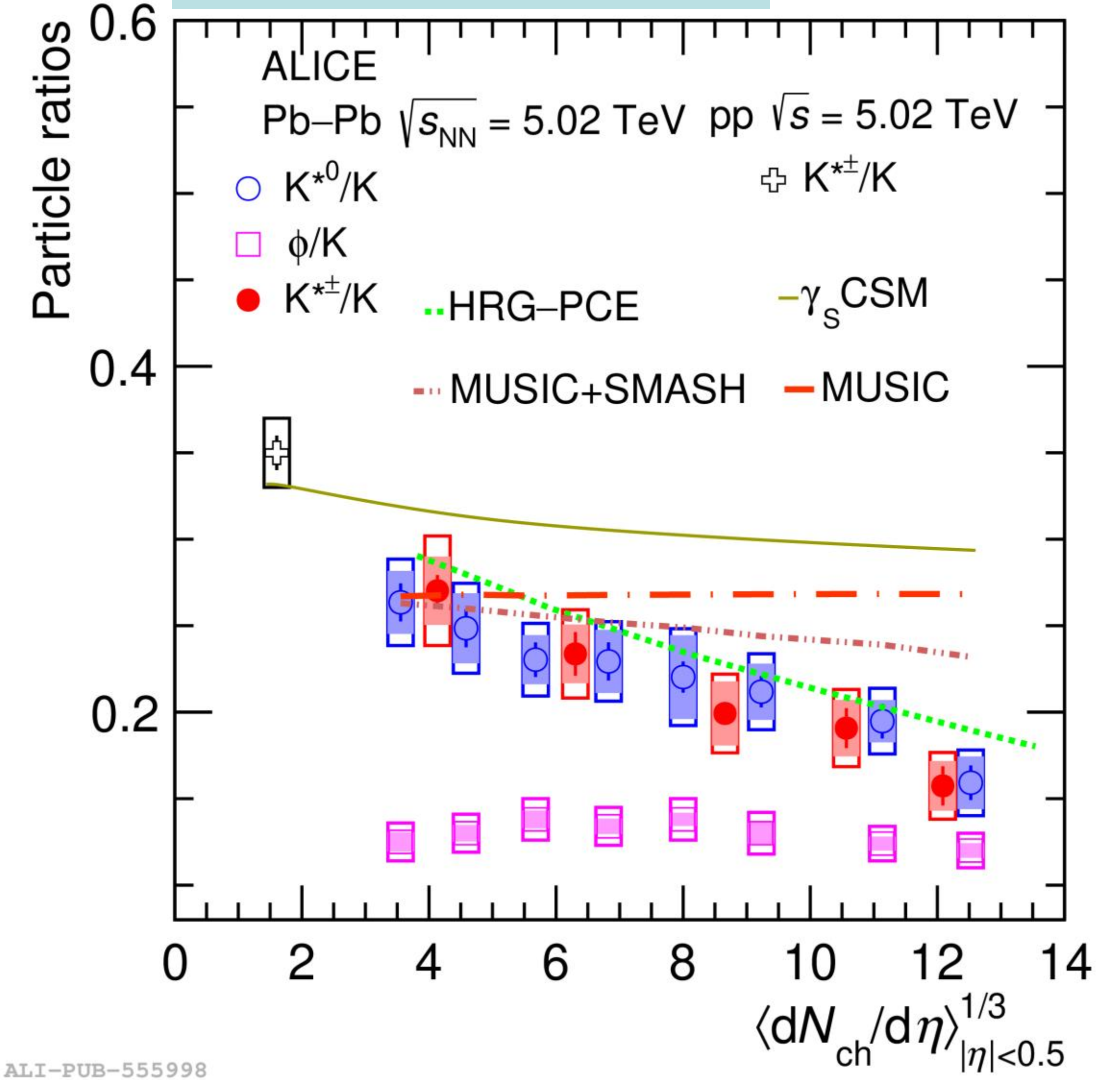
**$K^{*\pm}/K$** shows a suppression
- going from peripheral Pb–Pb collisions to most central Pb–Pb
→ consistent with the rescattering of the daughters as the dominant effect
- models with rescaterring effect (MUSIC+SMASH and HRG-PCE) qualitatively describe the data
- the thermal model $\gamma_s$CSM: a relatively flat ratio, overestimate

- $K^{*\pm}$ measurement is consistent with previous results for $K^{*0}$

- **φ/K** shows no suppression
  - almost constant behavior
  - rescattering is not significant for φ:
    **τ(φ) = 46.2 fm/c >> τ(K*⁰) = 4.2 fm/c**

**Pb–Pb@5.02 TeV K*(892)±**

arXiv:2308.16119

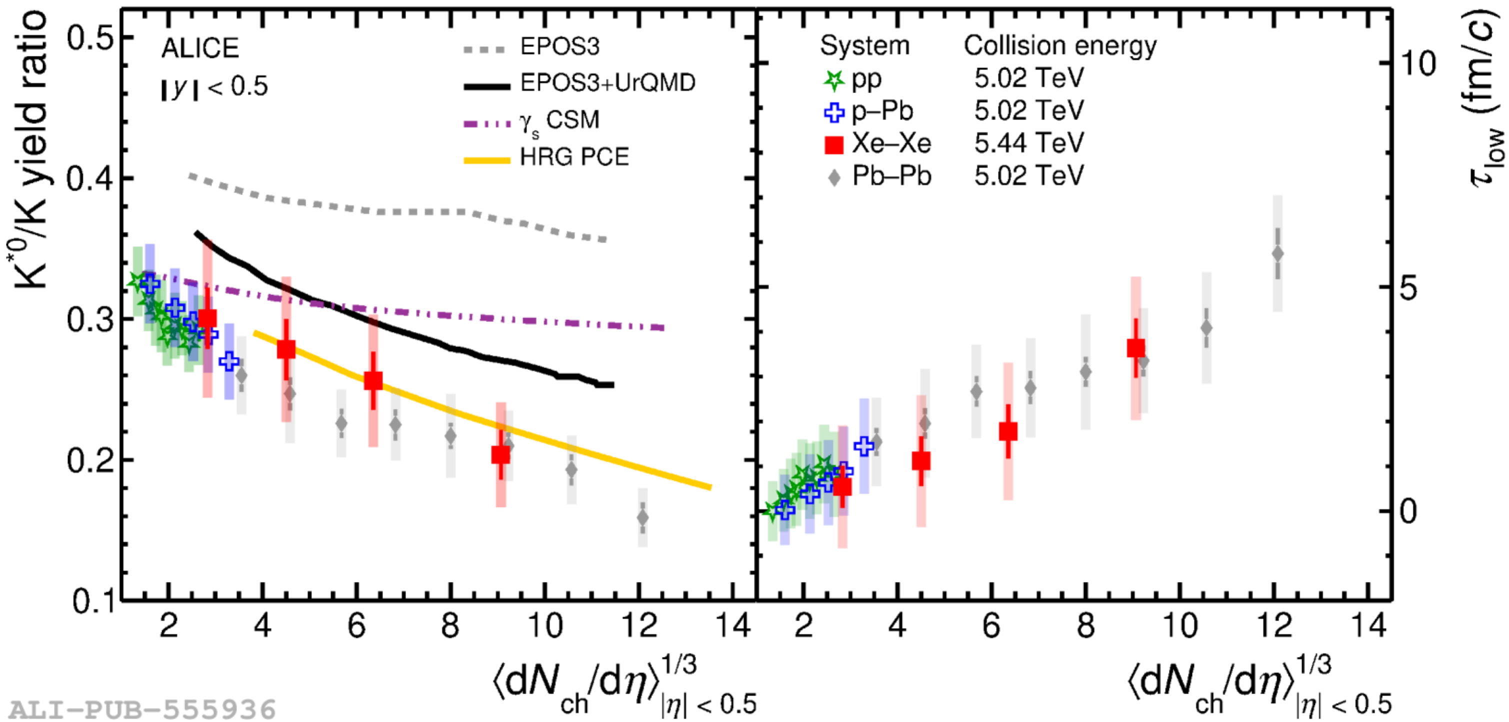


# $K^{*0}/K$ vs. $dN_{ch}/d\eta$: system size dependence

**$\tau(K^*) = 4.2$ fm/$c$**

**Xe–Xe@5.44 TeV $K^*(892)^0$**

PRC109(2024)014911




- results for Xe–Xe confirm the trend observed in Pb–Pb
- HRG-PCE gives the best agreement
- pp, p–Pb: hint of decrease

the lower bound of the hadronic phase lifetime $\tau_{low}$:

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

$r_{kin}$ – particle ratio at kinetic freeze-out (A–A)

$r_{chem}$ – particle ratio at chemical freeze-out (pp)

$\tau_{res}$ - lifetime of resonance

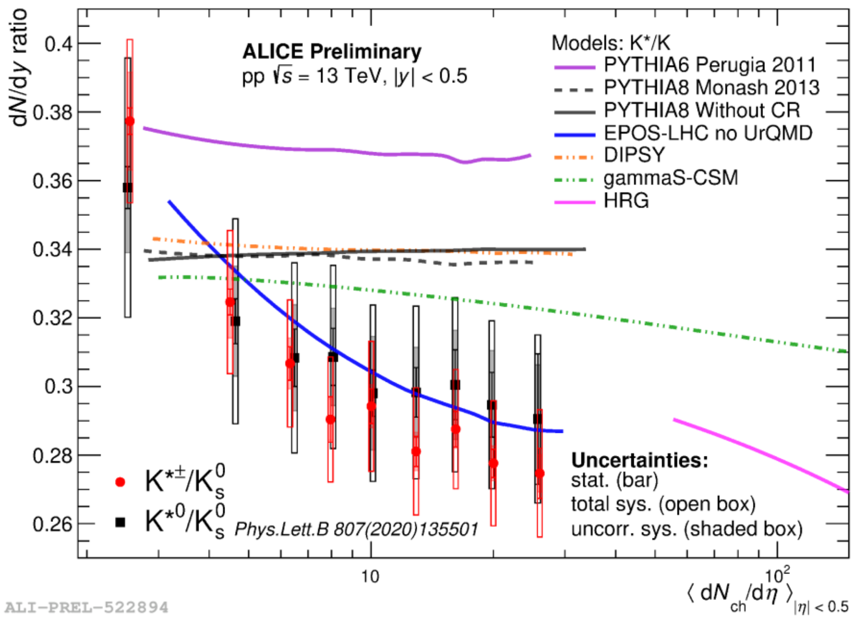
assuming no regeneration → lower bound

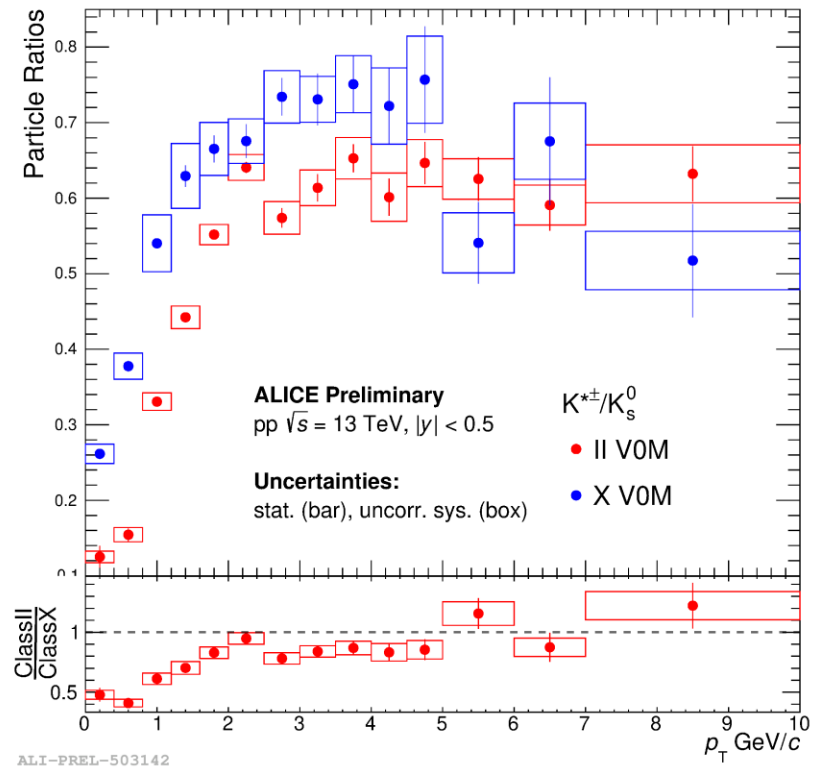
# K*/K: hadronic phase in pp?

**τ(K*) = 4.2 fm/*c***

**pp@13 TeV K*(892)$^{\pm}$**

paper in preparation




- suppression at a ~ 7σ level passing from low to high multiplicity pp collisions (taking into account the multiplicity-uncorrelated uncertainties)

a low $p_T$ dominant process

- suggest the presence of a finite lifetime hadronic phase
- but EPOS-LHC without a hadronic phase reproduces the decreasing trend

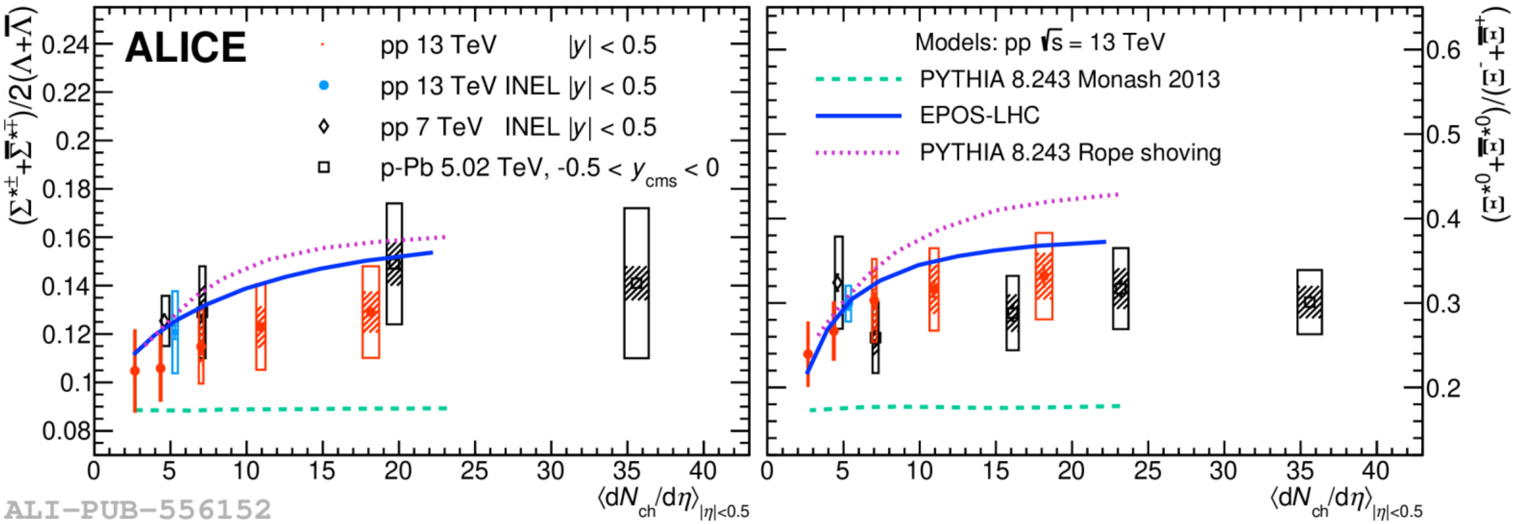
# $\Sigma^{*\pm}/\Lambda$ , $\Xi^{*0}/\Xi$: regeneration in pp?

**$\tau(\Sigma^*)$ = 5-5.5 fm/*c***

**$\tau(\Xi^*)$ = 21.7 fm/*c***

**pp@13 TeV $\Sigma(1385)^{\pm}$, $\Xi(1530)^{0}$**

arXiv:2308.16116




- a hint for an increase with multiplicity
- despite similar lifetimes, K* and $\Sigma^{*\pm}$ exhibit different trends
- $\Sigma^{*\pm} \rightarrow \Lambda\,\pi$ $\Xi^{*0} \rightarrow \Xi^{0}\,\pi$

  As long-lived, $\Lambda$ and $\Xi^{0}$ decay out of the hadronic phase

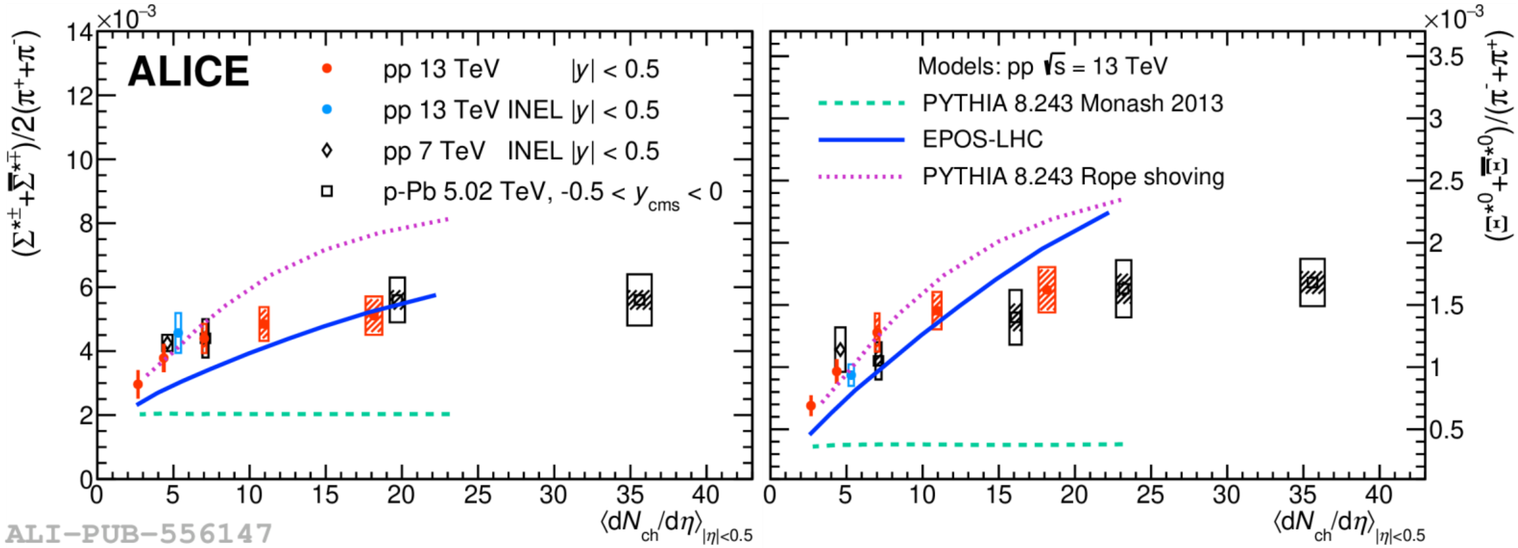
  only $\pi$ can be rescattered

  more pronounced regeneration effect: $\Lambda\,\pi \rightarrow \Sigma^{*\pm}$, $\Xi^{0}\,\pi \rightarrow \Xi^{*0}$
- EPOS-LHC and PYTHIA8 with Rope shoving predict a slight increase of the ratios

# $\Sigma^{*\pm}/\pi$ , $\Xi^{*0}/\pi$: increasing in pp

**pp@13 TeV $\Sigma(1385)^{\pm}$, $\Xi(1530)^{0}$**

arXiv:2308.16116




- increasing trend with multiplicity
- the enhancement is more pronounced for $\Xi^{*0}$ (S=2) than $\Sigma^{*\pm}$ (S=1)
- consistent with previous measurements of ground-state hyperons to pion ratios
- EPOS-LHC and PYTHIA8 with Rope shoving predict an increasing trend with multiplicity

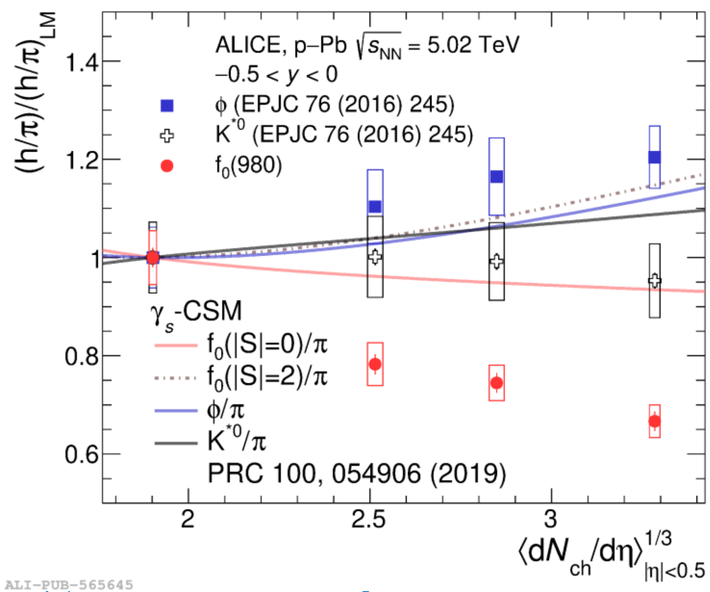
# $f_0/\pi$: hadronic phase in p–Pb?

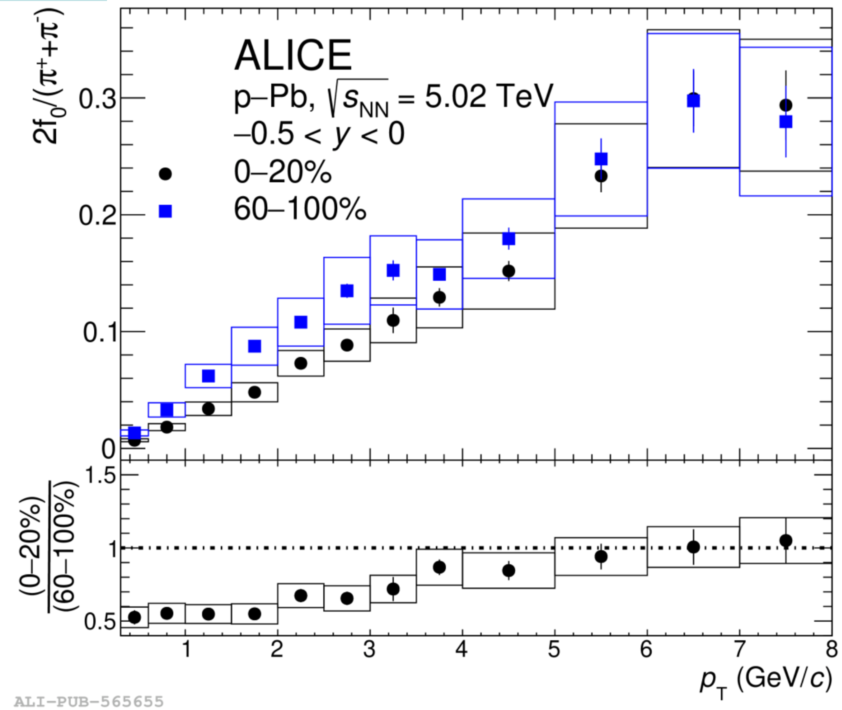
**$\tau(f_0)$ = ~5 fm/$c$**

quark structure of $f_0$ is still unknown
possible configurations: qqbar, (qq)(qbar qbar), hadronic molecules, …

**p–Pb@5.02 TeV $f_0$(980)**

arXiv:2311.11786




ϕ/π: strangeness enhancement
K*0/π: competition strangeness enhancement
and rescattering effect
$f_0/\pi$: rescattering is the dominant effect
exists at low $p_T$
$\gamma_s$-CSM (no rescattering effects): predictions with
zero hidden strangeness, |S|=0, are closer to the data

no enhancement at intermediate $p_T$
observed for baryon-to-meson ratio
→ a hint: $f_0$ composed of two quarks

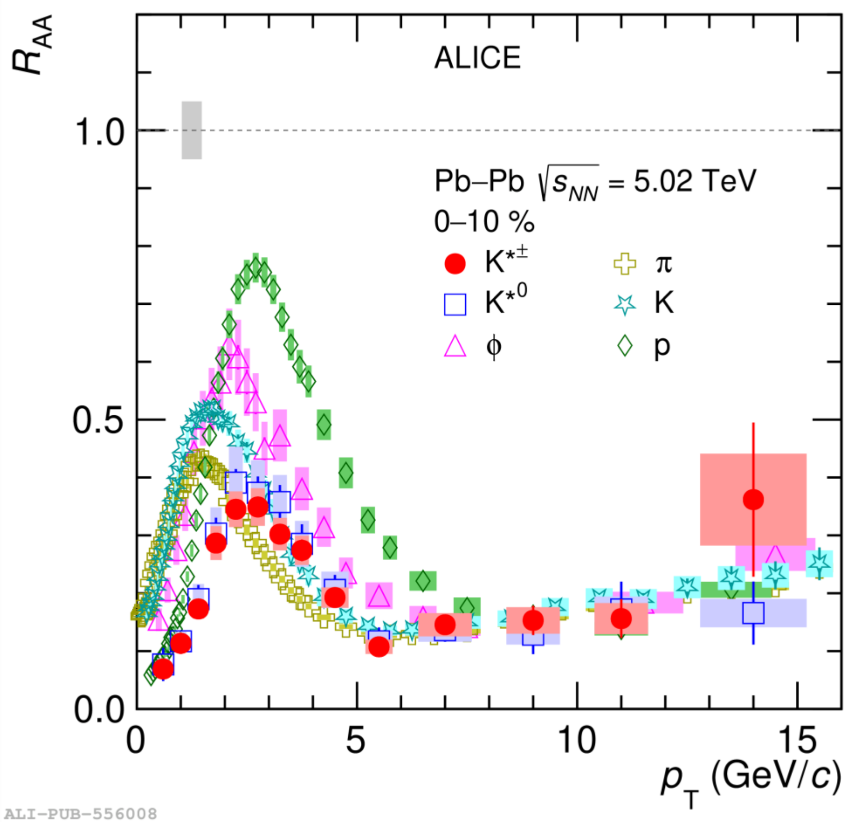
# Nuclear modification factor $R_{AA}$

$$R_{AA} = \frac{1}{\langle T_{AA}\rangle} \frac{d^2N^{AA}/(dy dp_T)}{d^2\sigma^{pp}/(dy dp_T)}$$

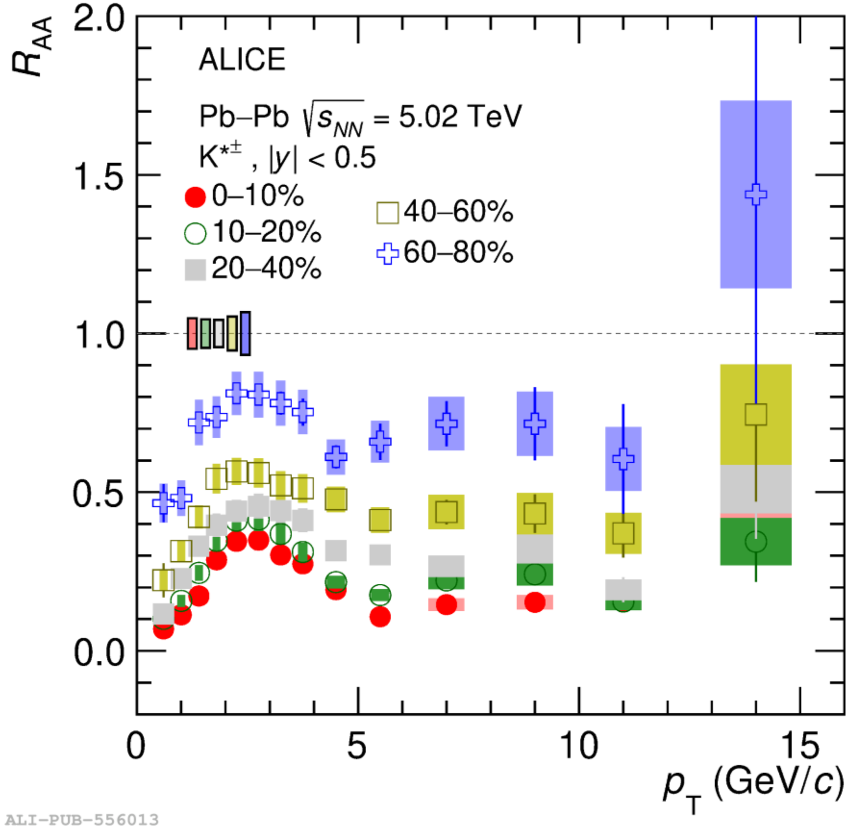
**Pb–Pb@5.02 TeV K*(892)$^{\pm}$**

arXiv:2308.16119

species dependence




centrality dependence




- consistent with light-flavoured hadrons at $p_T > 8$ GeV/$c$
  → suppression at high $p_T$ is not dependent on light quark content and mass
- K* affected by radial flow and suppression at lower $p_T$

the more central the collisions the larger the suppression

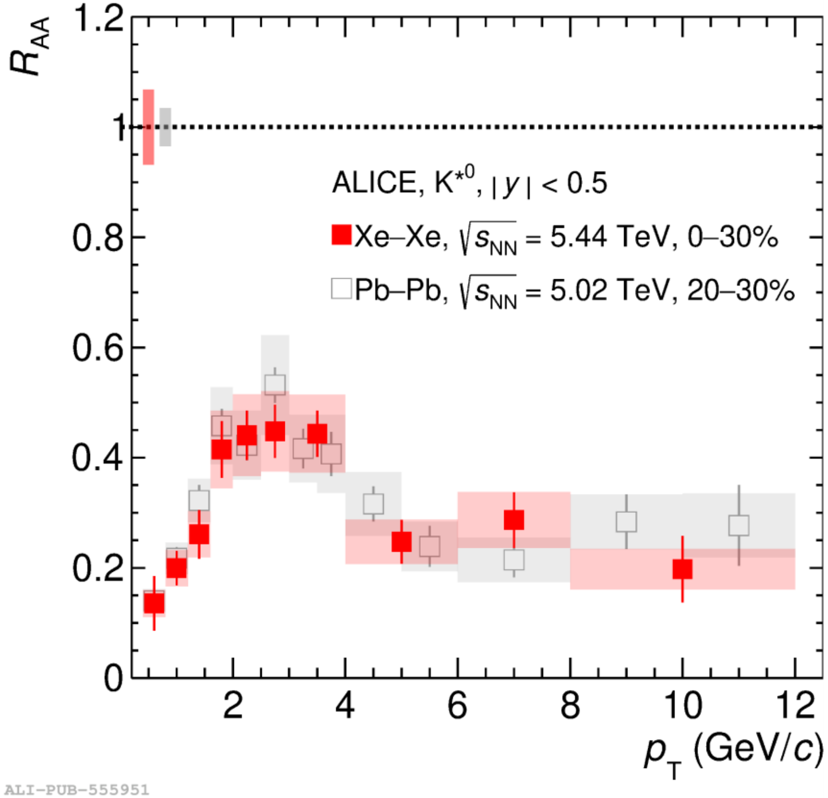
# Nuclear modification factor $R_{AA}$

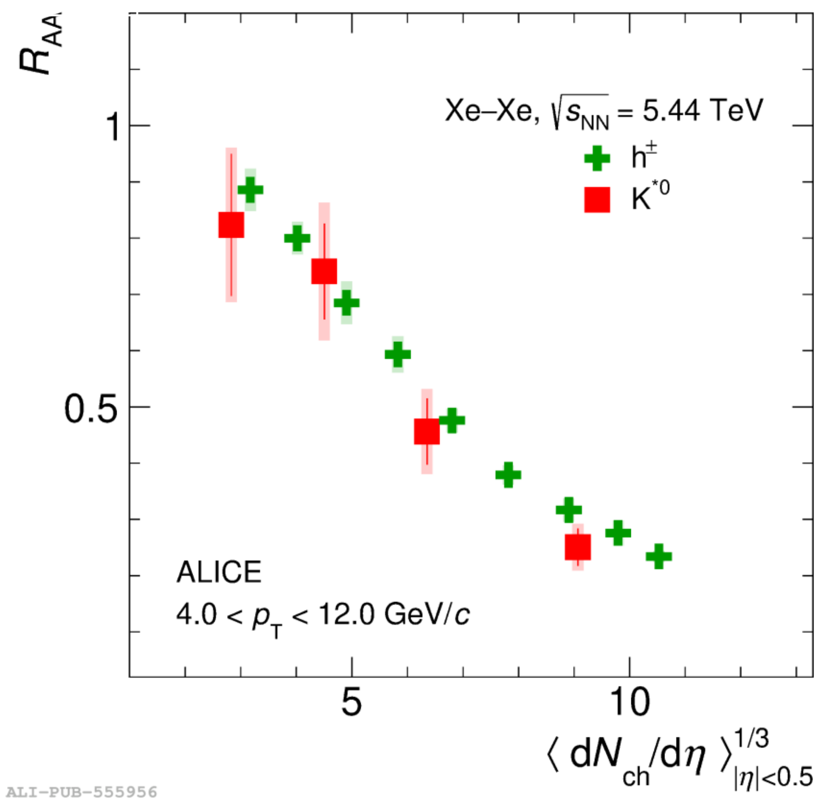
**Xe–Xe@5.44 TeV K*(892)$^0$**

system size dependence

centrality dependence

PRC109(2024)014911



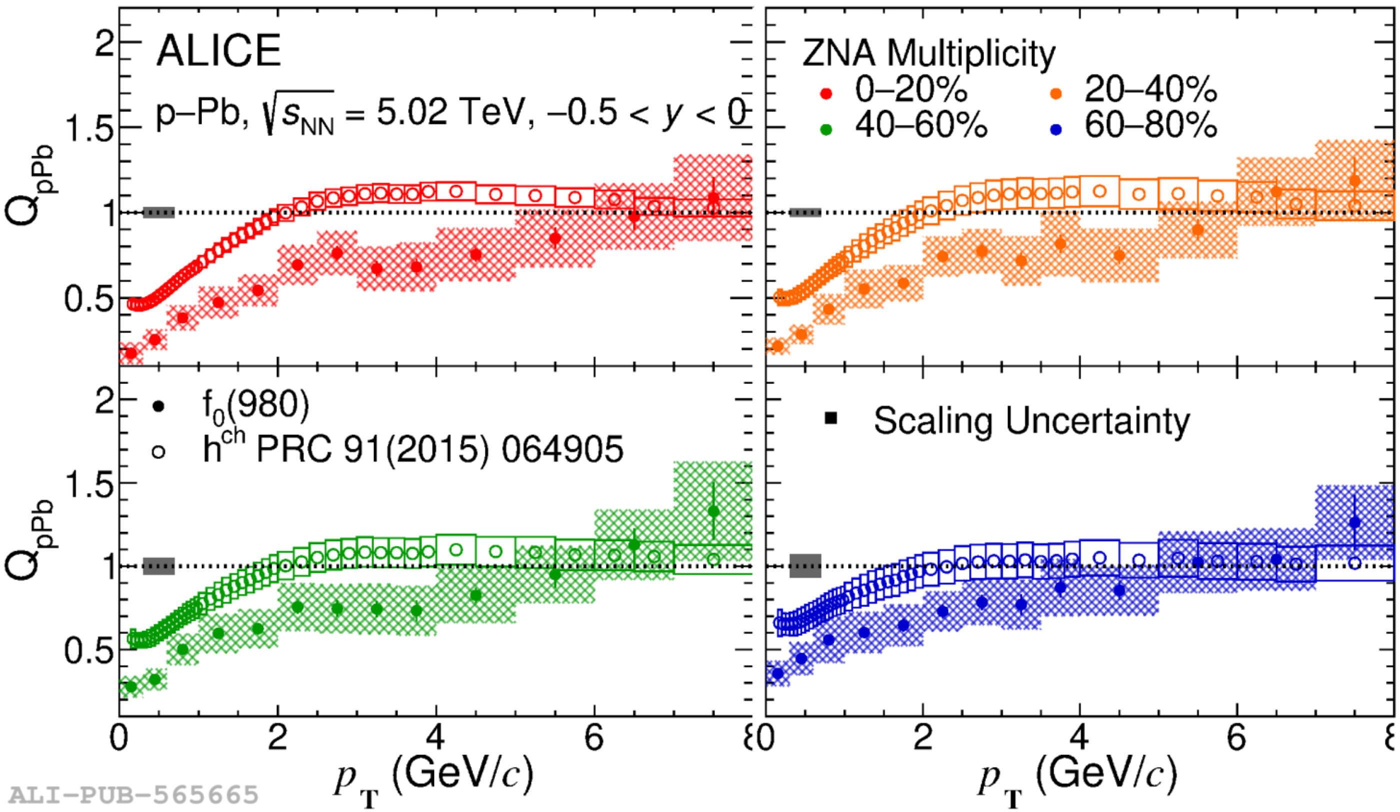

$R_{AA}$ in Xe–Xe and Pb–Pb are consistent
within uncertainties once compared
at the same multiplicity
(and not just centrality percentile)

# Nuclear modification factor $Q_{pPb}$

$$Q_{\mathrm{pPb}} = \frac{\mathrm{d}^2 N^{\mathrm{pPb}}_{\mathrm{f}_0(980)}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\langle T_{\mathrm{pPb}}\rangle \, \mathrm{d}^2\sigma^{\mathrm{pp}}_{\mathrm{f}_0(980)}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

**p–Pb@5.02 TeV $f_0$(980)**

arXiv:2311.11786




- no Cronin-like enhancement
  for baryons there is Cronin-like enhancement
  → $f_0$ composed of two quarks
- at low $p_T$ < 4 GeV/c: a suppression in p–Pb relative to pp
  more pronounced with increasing multiplicity
  → effects of rescattering and radial flow

# Summary

**Yields** for a fixed multiplicity:

independent of collision system and energy

appear to be driven by event multiplicity

**Mean $p_T$** for a fixed multiplicity:

$p_T$ (pp) > $p_T$(p–Pb) > $p_T$(Xe–Xe) ~ $p_T$(Pb–Pb)

**Particle yield ratios (with previous results):**

**to ground-state with the same strangeness content**

resonance suppression ( **yes** **?** **no** )

| resonance | $\rho^0$ | K* | $f_0$ | $\Sigma^{*\pm}$ | $\Lambda^*$ | $\Xi^{*0}$ | $\phi$ |
|---|---|---|---|---|---|---|---|
| lifetime (fm/*c*) | 1.3 | 4.2 | ~ 5 | 5-5.5 | 12.6 | 21.7 | 46.4 |
| **Pb–Pb, Xe–Xe** | **yes** | **yes** | **?** | **?** | **yes** | **?** | **no** |
| **pp, p–Pb** | **?** | **yes** | **yes** | **no** | **no** | **no** | **no** |

**Pb–Pb, Xe–Xe**:qualitatively described by models with rescattering

**pp, p–Pb:** a hint for an increase for $\Sigma^{*\pm}$ and $\Xi^{*0}$ (regeneration?)

estimation of the lower bound of the hadronic phase lifetime

**to $\pi$ in pp, p–Pb**

strangeness enhancement for $\Sigma^{*\pm}$ and $\Xi^{*0}$

**$R_{AA}$ : K*(892)$^{\pm}$ in Pb–Pb@ 5.02 TeV**

**K*(892)$^0$ in Xe–Xe@ 5.44 TeV :** at the same multiplicity $R_{AA}$ (Xe–Xe) ≈ $R_{AA}$ (Pb–Pb)

**$Q_{pPb}$:** no Cronin-like enhancement → $f_0$ composed of two quarks ?