# Overview of ALICE results on light flavor hadron production

Victor Riabov for the ALICE Collaboration

# Outline

- The ALICE detector
- Light flavor hadron production, integrated yields and ratios
- Short-lived hadronic resonances
- Strangeness production
- Light flavor hadrons at high transverse momenta

# ALICE experiment

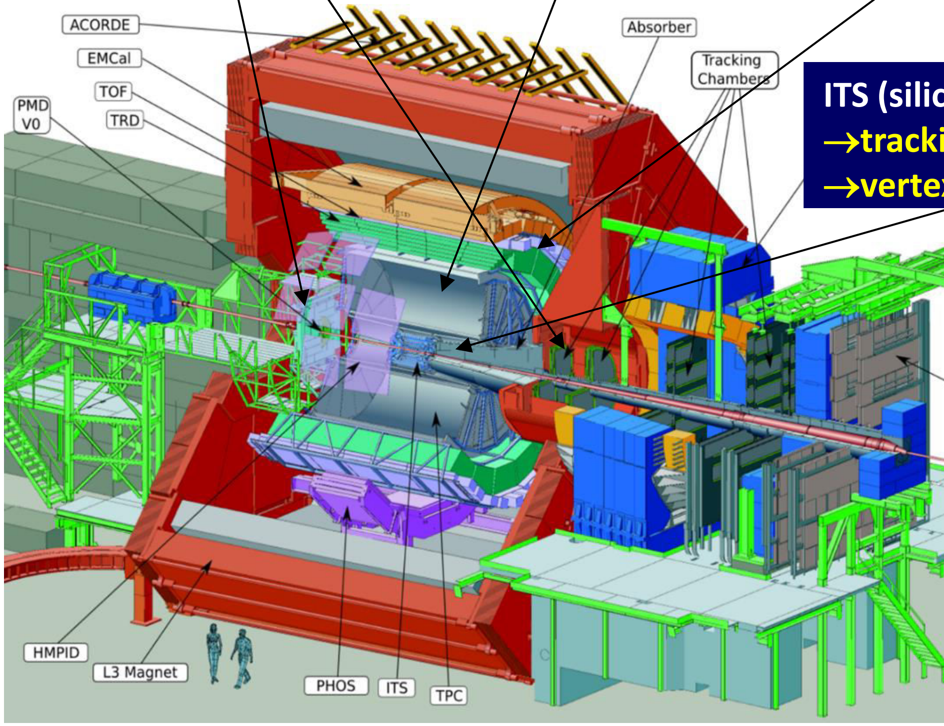
Int. J. Mod. Phys. A 29 1430044 (2014)

**VZERO scintillator detectors:**
→centrality determination in Pb-Pb
→multiplicity event classes in p-Pb

**TPC:**
→tracking
→PID through dE/dx

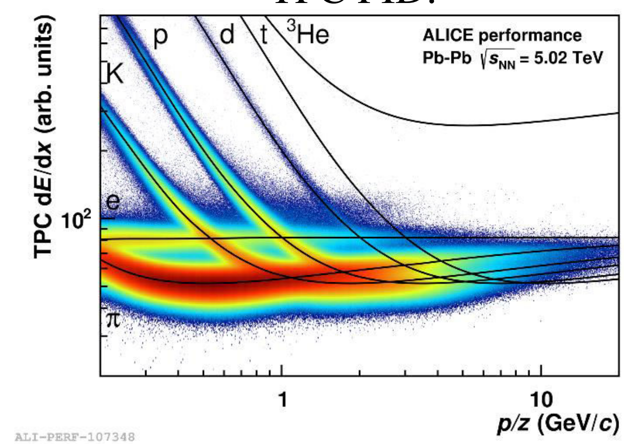
**TOF:**
→PID through momentum and ToF

**ITS (silicon):**
→tracking
→vertexing

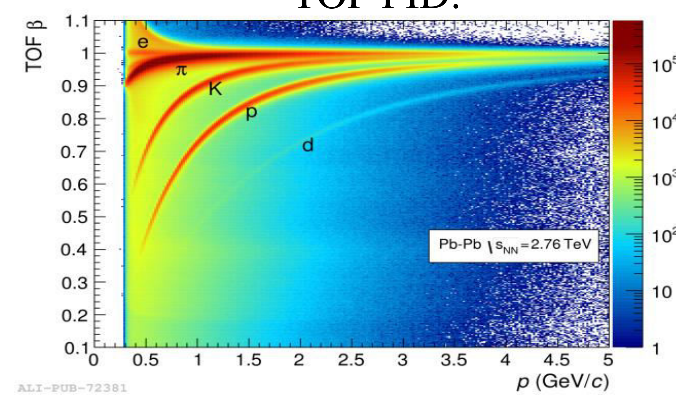



- Hadron identification in a wide $p_T$ range using complementary PID techniques (ITS, TPC, TOF, TRD. calorimetry):

TPC PID:

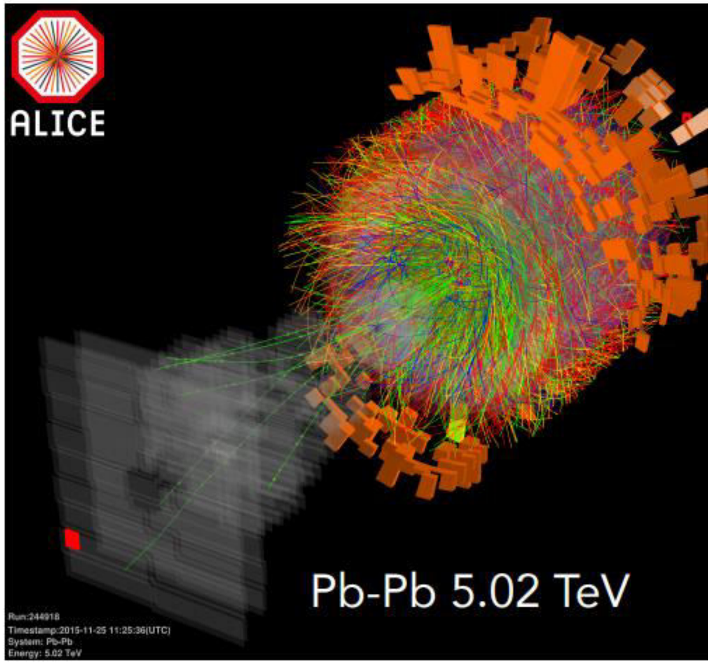



TOF PID:



# ALICE data taking since 2009

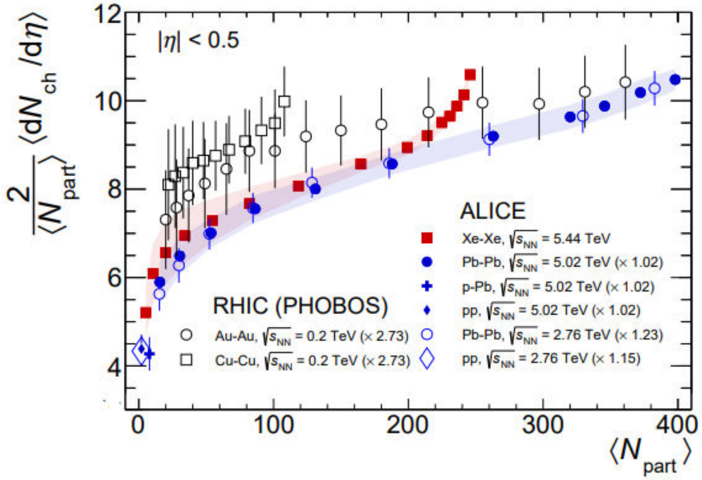
| System | Year(s) | $\sqrt{s_{NN}}$ (TeV) | $L_{int}$ |
|---|---|---|---|
| Pb-Pb | 2010-2011 | 2.76 | ~75 $\mu b^{-1}$ |
| | 2015 | 5.02 | ~250 $\mu b^{-1}$ |
| | *by end of 2018* | *5.02* | *~1 $nb^{-1}$* |
| Xe-Xe | 2017 | 5.44 | ~0.3 $\mu b^{-1}$ |
| p-Pb | 2013 | 5.02 | ~15 $nb^{-1}$ |
| | 2016 | 5.02, 8.16 | ~3 $nb^{-1}$, ~25 $nb^{-1}$ |
| pp | 2009-2013 | 0.9, 2.76, 7, 8 | ~200 $\mu b^{-1}$, ~100 $nb^{-1}$, ~1.5 $pb^{-1}$, ~2.5 $pb^{-1}$ |
| | 2015,2017 | 5.02 | ~1.3 $pb^{-1}$ |
| | 2015-2017 | 13 | ~25 $pb^{-1}$ |

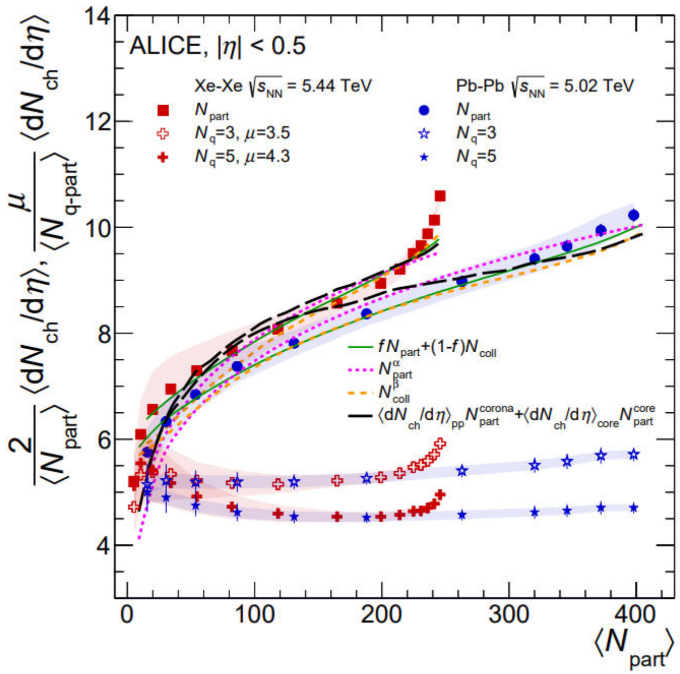



- Run-2 is ongoing
- Large data samples accumulated for pp, p-Pb and Pb-Pb collisions at different energies allow for precise study of energy and system size dependence of particle production

# Charged particle multiplicity

arXiv:1805.04432




❖ $N_{part}$ scaling is violated, now confirmed by new measurements in Xe-Xe

→ about a factor of two increase from peripheral to central collisions

→ reproduced by several models

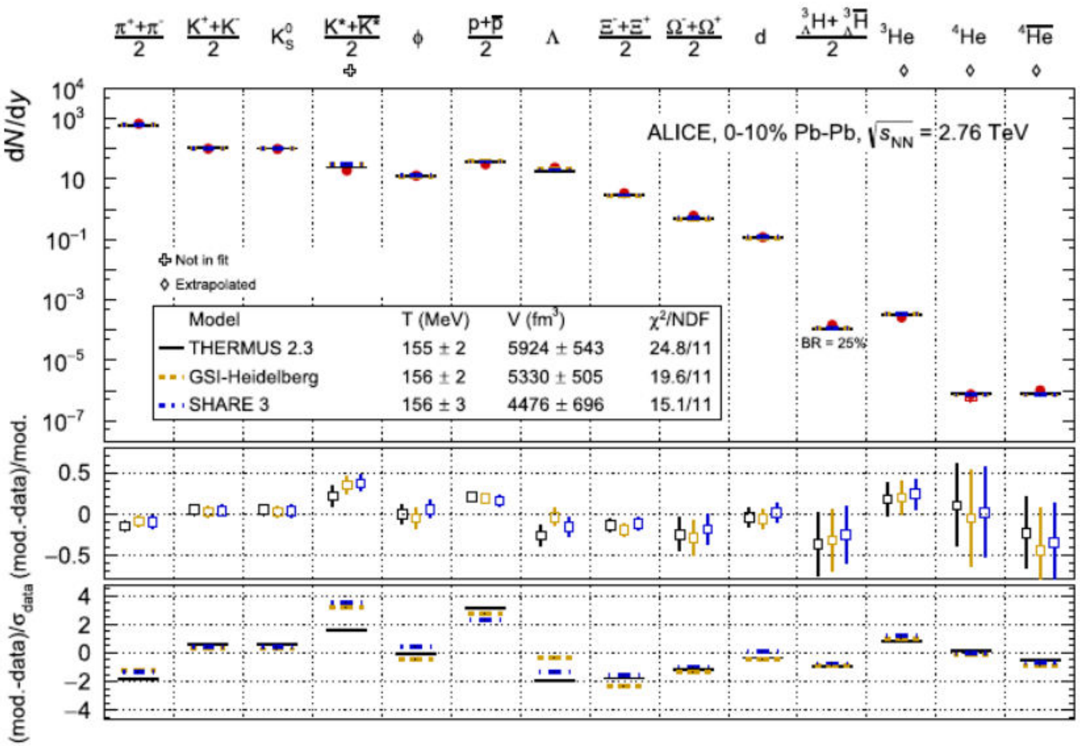
❖ Central collisions of Xe-Xe produce more particles per participant than semi-central collisions of Pb-Pb at similar $N_{part}$

→ not reproduced by models

→ hint of similar behavior in Cu+Cu/AuAu

# Thermal models vs. particle ratios: PbPb@2.76, 0-10%

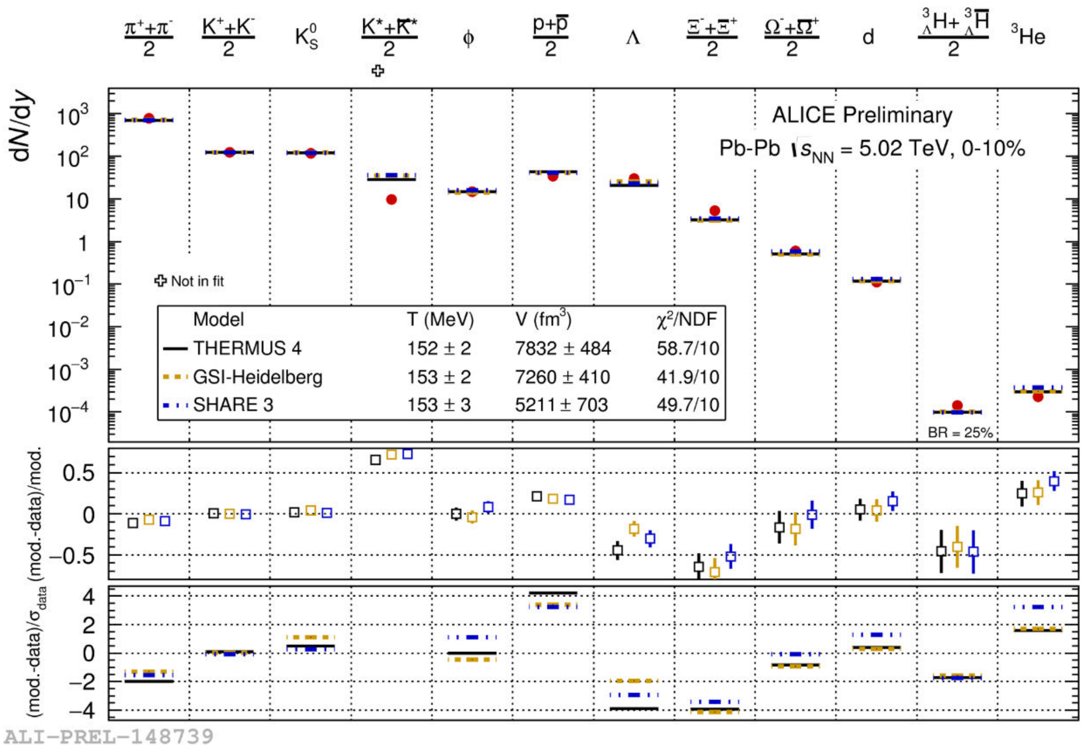
Nucl. Phys. A971 (2018) 1




THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142
SHARE: Petran et al, Comp. Phys. Commun. 195 (2014) 2056

- ❖ Models describe hadron production assuming chemical equilibrium
- ❖ Production of most hadrons, nuclei and hyper-nuclei is well reproduced with a chemical freeze-out temperature of T = 156 ± 3 MeV.
- ❖ $K^{*0}$ production is overestimated due to rescattering in the late hadronic phase, excluded from the fit
- ❖ Tensions for protons and multi-strange baryons: incomplete hadron spectrum, baryon annihilation in hadronic phase, interacting hadron gas, ...

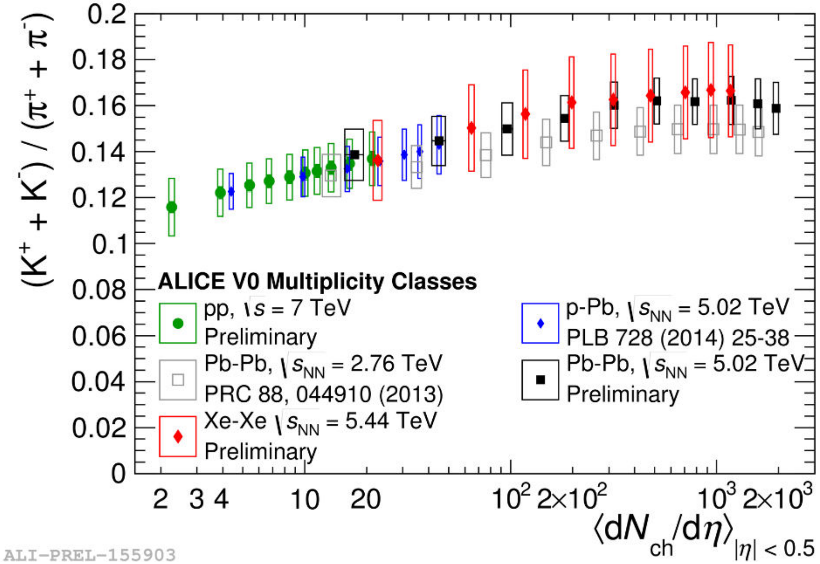
# Thermal models vs. particle ratios: PbPb@5.02, 0-10%

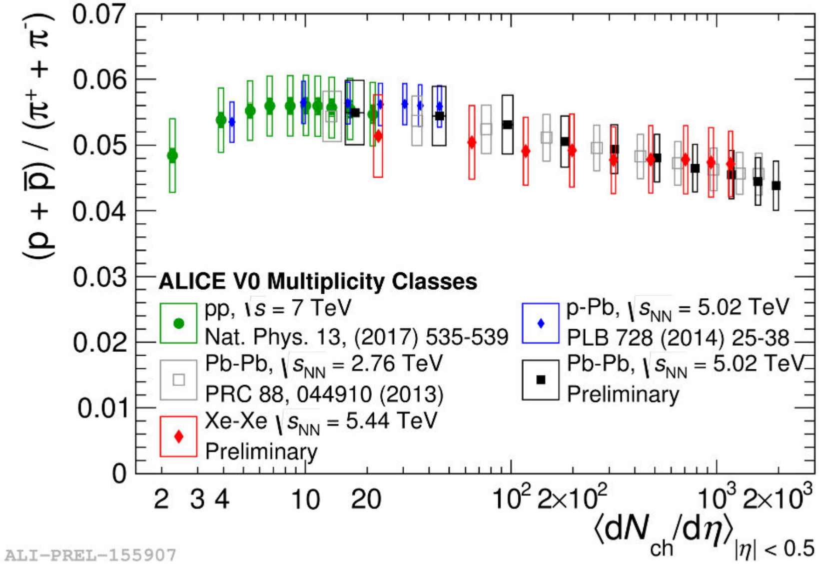



THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142
SHARE: Petran et al, Comp. Phys. Commun. 195 (2014) 2056

- ❖ Similar conclusions are valid for higher collision energy
- ❖ Fit at 5.02 TeV converges to slightly lower chemical freeze-out temperature of T = 153 ± 3 MeV due to proton yield

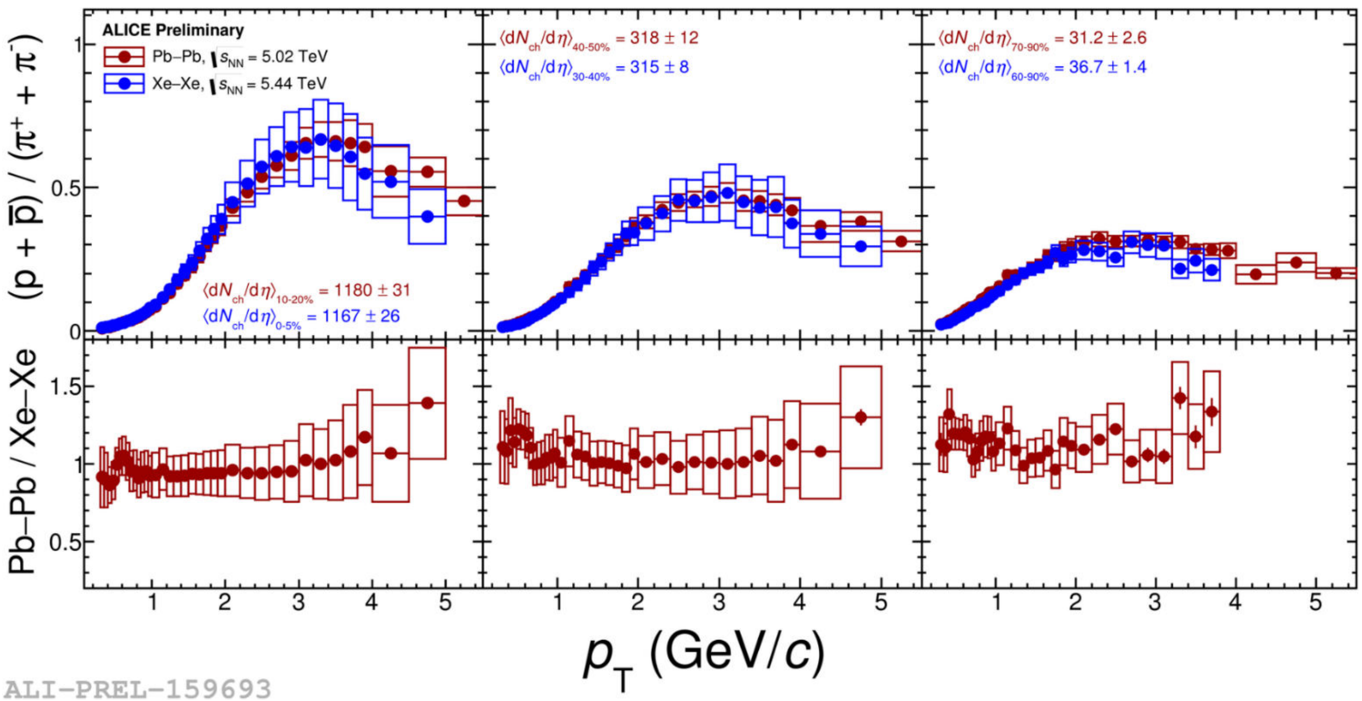
# Particle ratios: pp, p-Pb, Xe-Xe and Pb-Pb



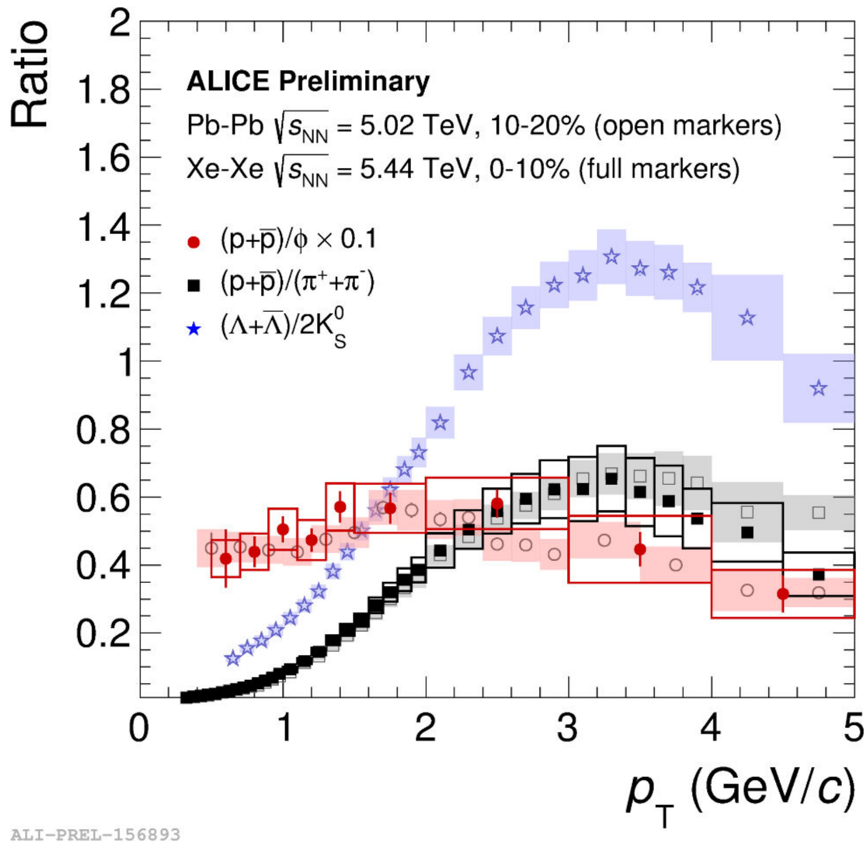

- Particle ratios (K/π, p/π etc.) are consistent for different collision systems at similar multiplicities
- No significant energy dependence of the ratios

# p/π ratio: Pb-Pb & Xe-Xe




- Enhanced p/π ratio in central collisions at intermediate momentum
  → hydrodynamic expansion, parton recombination
- Enhancement is consistent between Pb-Pb and Xe-Xe at similar multiplicities

# p/ϕ ratio: Pb-Pb & Xe-Xe




❖ Baryon-to-meson ratios for particles of similar masses ($m_\phi \approx m_p$) help to study the interplay between hydrodynamics and recombination mechanisms

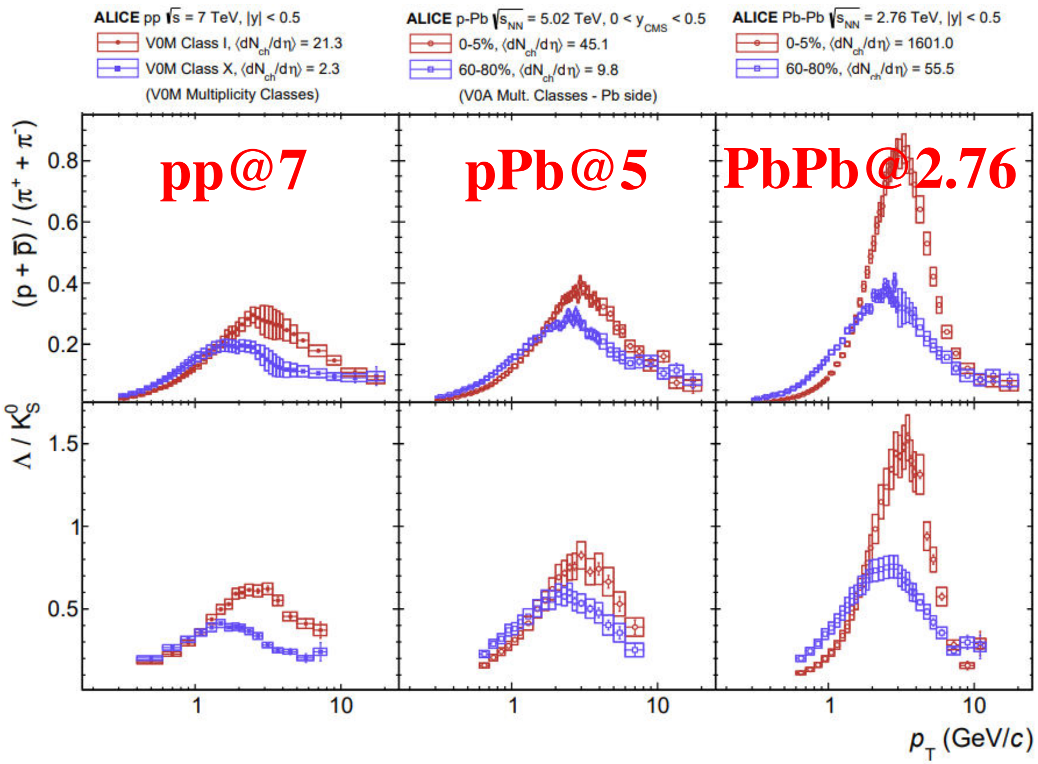
❖ p/ϕ ratio is flat vs. $p_T$ at intermediate momenta in Pb-Pb and Xe-Xe collisions

❖ Spectra shapes are driven by particle masses:
→ consistent with hydrodynamics
→ recombination models are not ruled-out*

* V. Greco et al, PRC 92 054904 (2015)

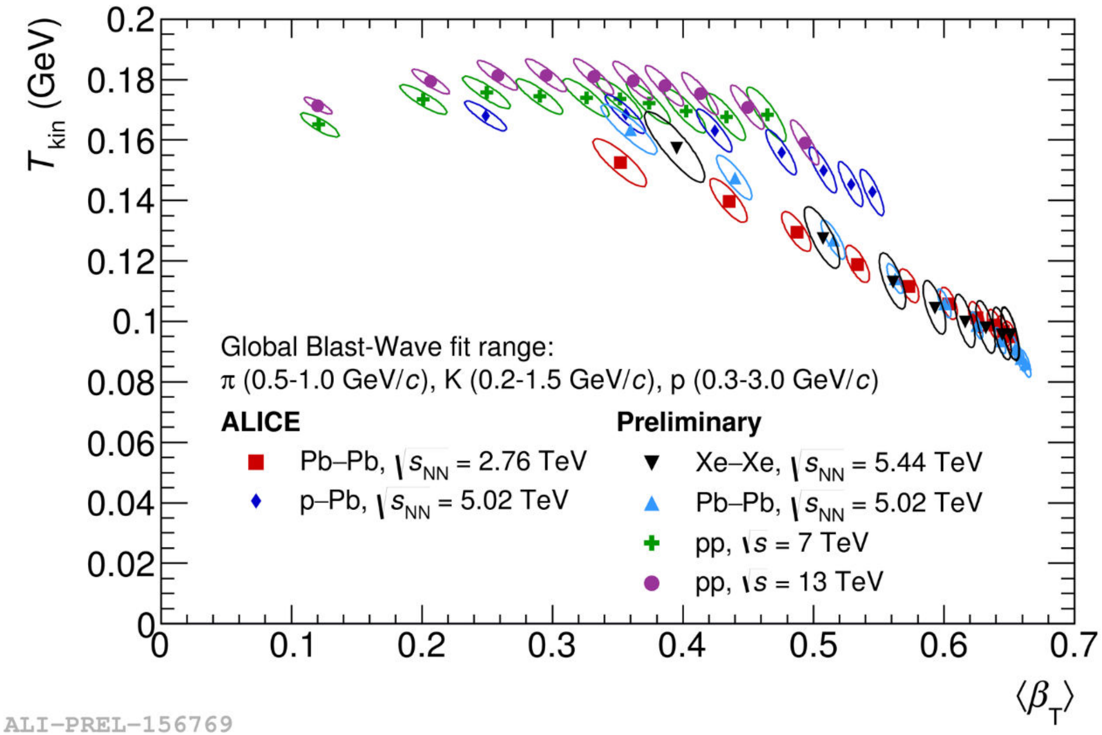
# p/π and Λ/K$_s$ ratios: pp, p-Pb and PbPb

arXiv:1807.11321




- Similar behavior for three systems, from peripheral to central collisions:
  - → depletion at low $p_T$
  - → enhancement at intermediate $p_T$
  - → consistent at high $p_T$
- No unique explanation for B/M ratios in small systems
- Pythia8 with color reconnection and DIPSY with color ropes qualitatively describe pp data

# Blast-Wave model fits to ALICE data

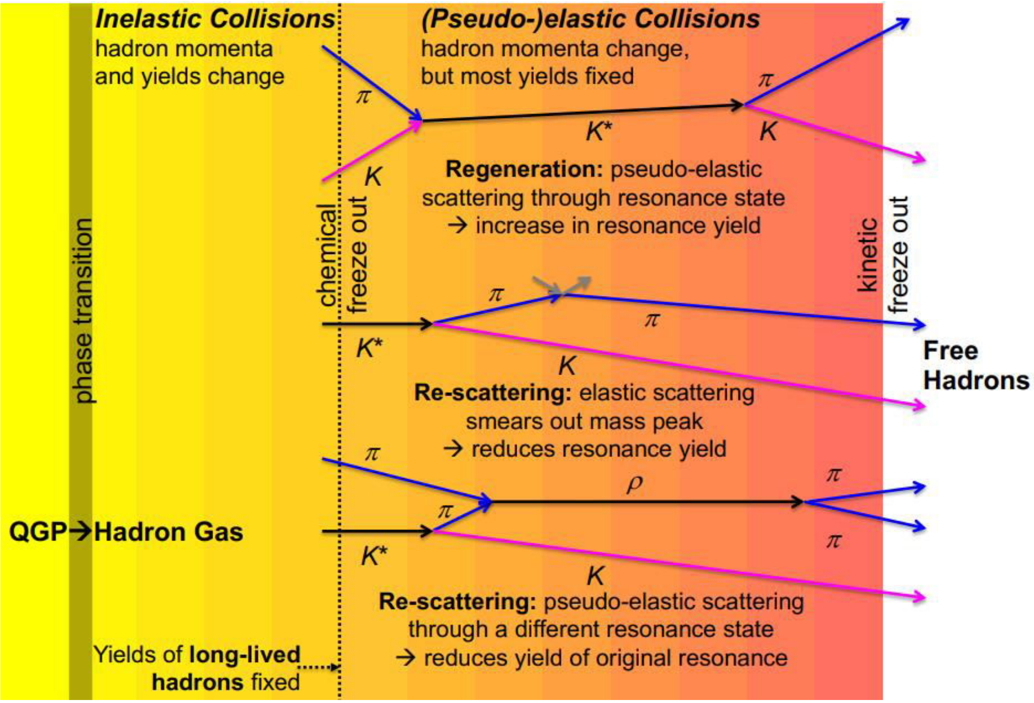



- Blast-wave is a simple hydrodynamic model to quantify the radial flow
- Fit parameters are obtained from a simultaneous fit to π K, p production spectra in a limited $p_T$ range, results are strongly dependent on the fitting range
- Kinetic freeze-out temperature decreases, transverse flow velocity increases with multiplicity
- Blast-wave fit parameters are consistent for Pb-Pb and Xe-Xe at similar multiplicities
- pp and p-Pb are also consistent but with larger values of $<\beta_T>$at similar multiplicities

# Short-lived resonances

increasing lifetime →

| | $\rho(770)$ | $K^*(892)$ | $\Lambda(1520)$ | $\Xi(1530)$ | $\phi(1020)$ |
|---|---|---|---|---|---|
| $c\tau$ (fm/c) | 1.3 | 4.2 | 12.7 | 21.7 | 46.2 |
| $\sigma_{rescatt}$ | $\sigma_\pi\sigma_\pi$ | $\sigma_\pi\sigma_K$ | $\sigma_K\sigma_p$ | $\sigma_\pi\sigma_\Xi$ | $\sigma_K\sigma_K$ |




❖ Final state yields of resonances depend on:

- ✓ resonance yields at chemical freeze-out
- ✓ lifetime of the resonance and the hadronic phase
- ✓ type and scattering cross sections of daughter particles

# Short-lived resonances

increasing lifetime →

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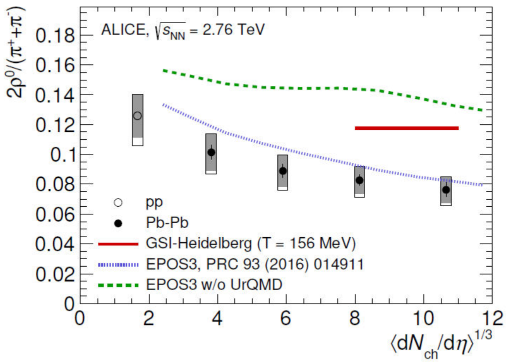
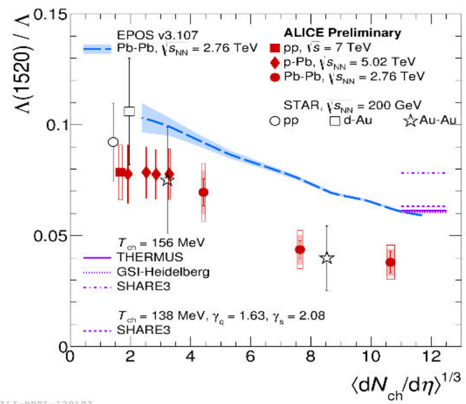
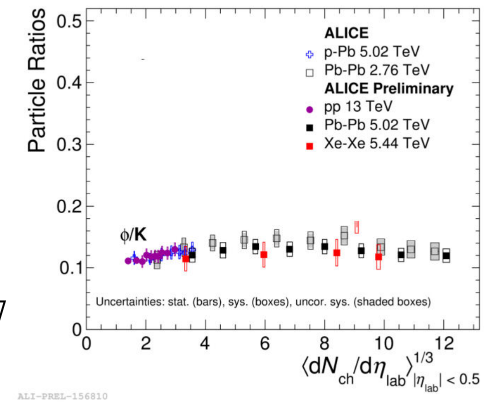
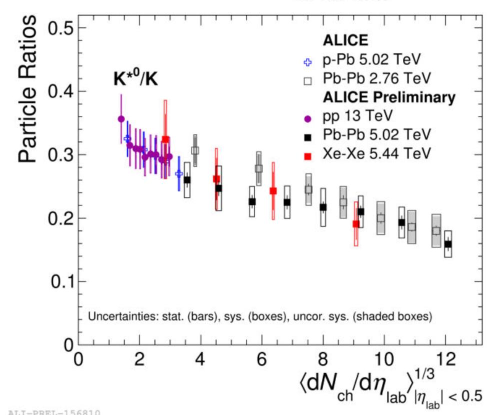
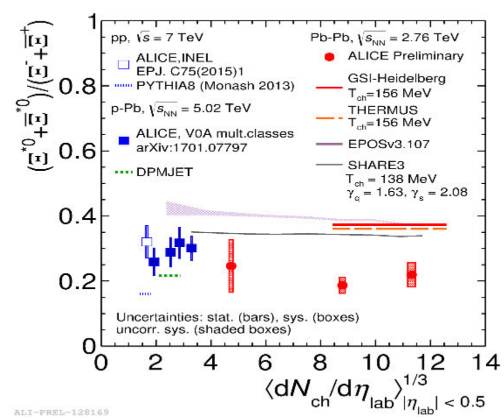
| $\sigma_{rescatt}$ | $\sigma_\pi\sigma_\pi$ | $\sigma_\pi\sigma_K$ | $\sigma_K\sigma_p$ | $\sigma_\pi\sigma_\Xi$ | $\sigma_K\sigma_K$ |



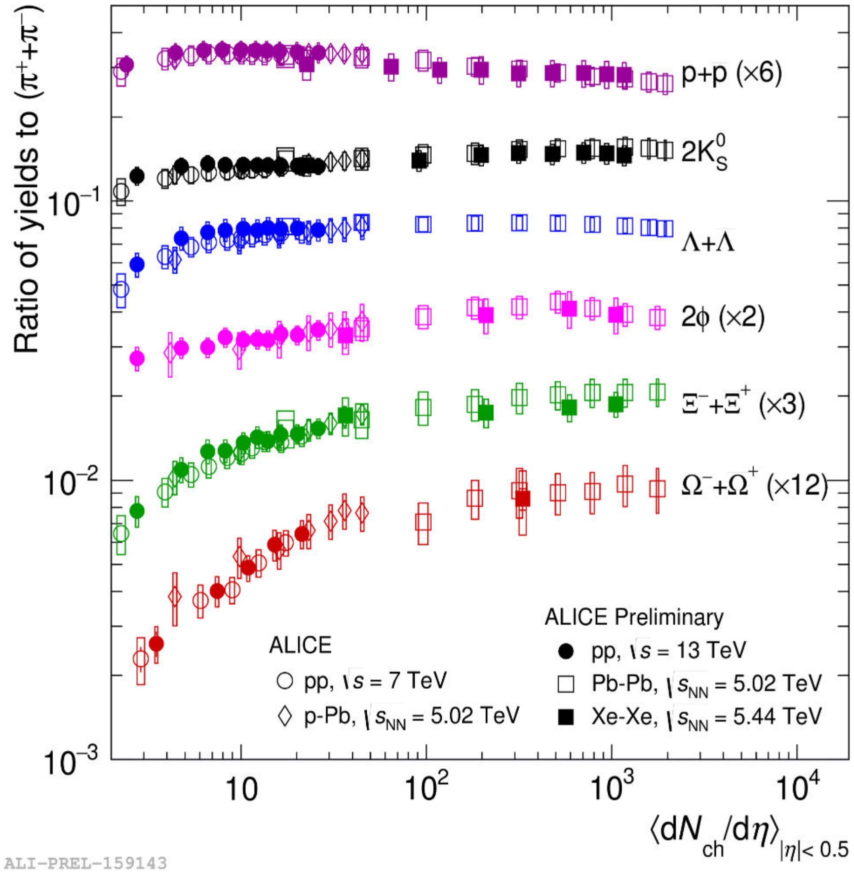




- ❖ Results support the existence of a hadronic phase that lives long enough to cause a significant reduction of the reconstructed yields of short lived resonances
- ❖ Lower limit for the lifetime of the hadronic phase, $\tau$ > 2 fm/c*

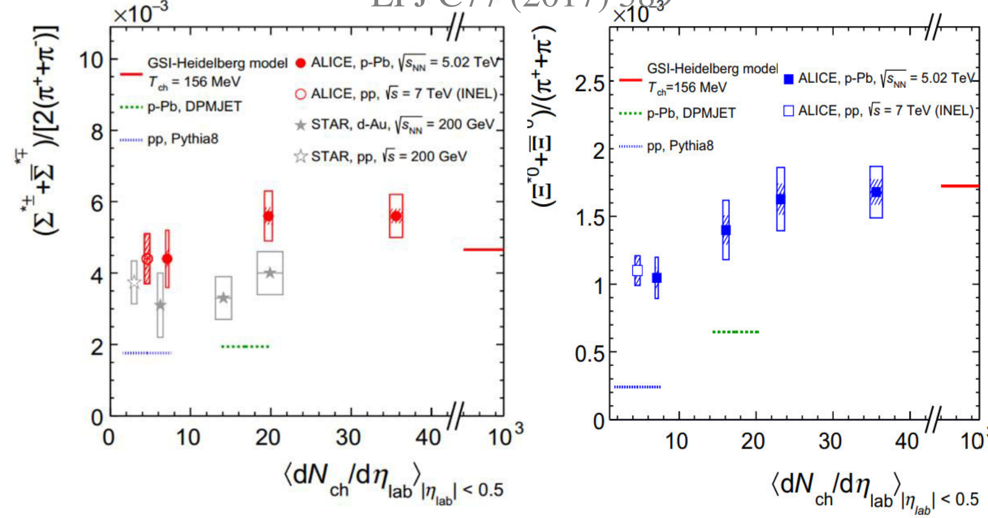
* G. Torrieri and J. Rafelski, J. Phys. G 28, 1911 (2002); C. Markert et al., arXiv:hep-ph/0206260v2 (2002)

# Strangeness production: pp, p-Pb, Xe-Xe and Pb-Pb

Nature Phys. 13 (2017) 535




EPJ C77 (2017) 389



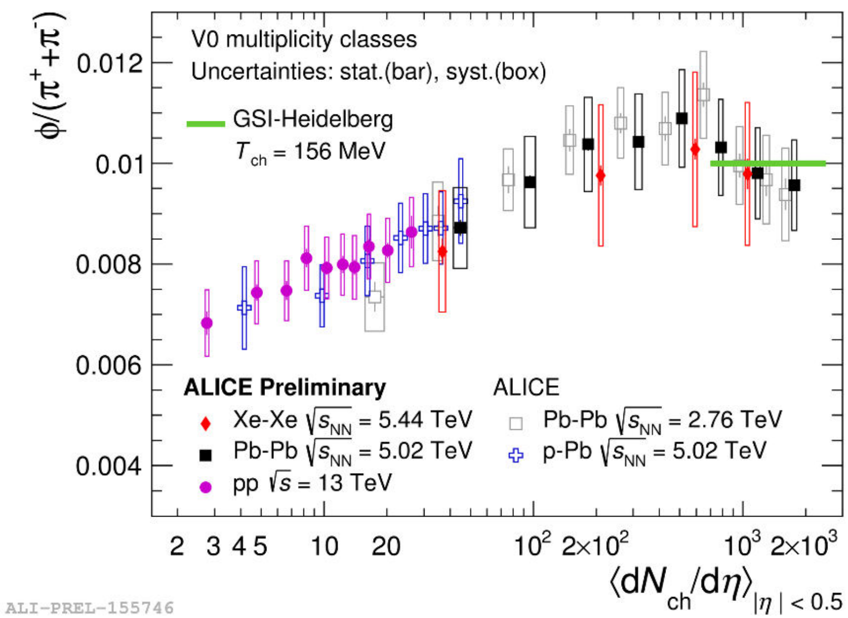

- ❖ Originally considered as a signature of QGP formation in heavy-ion collisions*
- ❖ Smooth evolution of the ratios vs. multiplicity for pp, p-Pb, Xe-Xe and Pb-Pb collisions at different energies

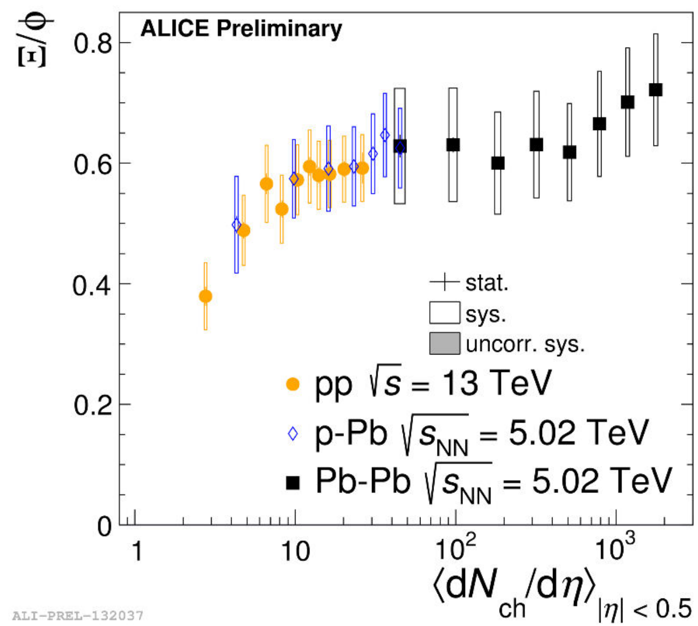
- ❖ Strangeness enhancement is seen in small/large systems, increases with strangeness content
- ❖ Strange resonances show increasing patterns depending on the strangeness content
  → consistent with observations for ground-state hadrons
- ❖ Thermal model predictions for Pb-Pb are consistent with the highest multiplicity results in p-Pb

* J. Rafelsky, B. Muller, Phys.Rev.Lett. 48 (1982) 1066, Erratum: Phys.Rev.Lett. 56 (1986) 2334

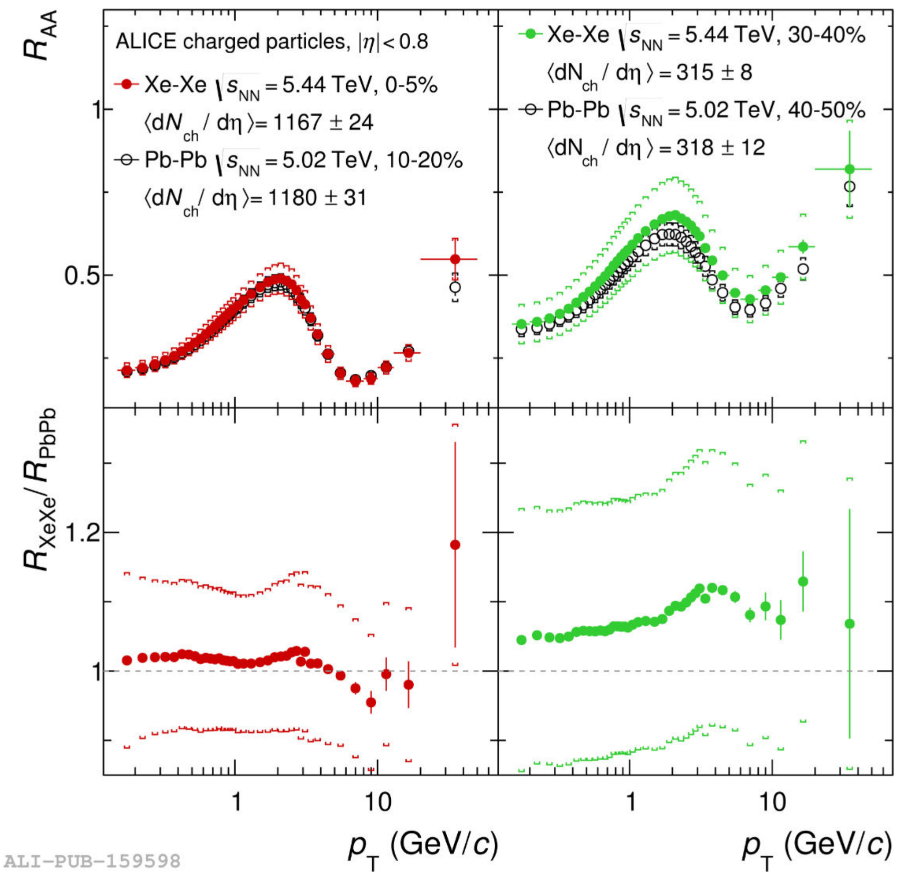
# Strangeness enhancement: $\phi$

- ❖ $\phi$ with a hidden strangeness is a key probe to study strangeness enhancement
  - ✓ $\phi/\pi$ increases with multiplicity in pp/ p-Pb → not expected for canonical suppression
  - ✓ $\phi/\pi$ is saturates in Pb-Pb and is consistent with thermal model predictions
- ❖ Non-equilibrium production ($\gamma_s$) ???
- ❖ Ratios $\phi$/K and $\Xi/\phi$ show weak dependence on multiplicity
  → $\phi$ has an effective strangeness of 1-2



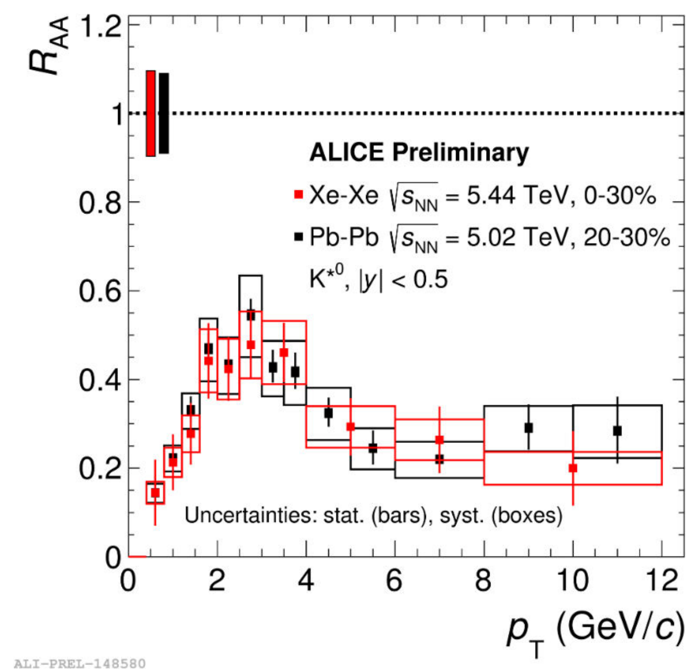



# Nuclear modification factors: Xe-Xe vs. Pb-Pb




- Nuclear modification factor:

$$R_{AA}(p_T) = \frac{Yield_{A-A}(p_T)}{Yield_{pp}(p_T) \cdot N_{coll}}$$




- $R_{AA}$ in Pb-Pb and Xe-Xe collisions are consistent at similar multiplicities
  → interplay of system geometry and path length dependence of the parton energy loss

# Summary

❖ Thermal models describe most of particle yields in Pb-Pb collisions

❖ Mass dependent hardening of particle production spectra

❖ Relative production of the light hadrons is independent of collision system and energy and is driven by event multiplicity

❖ Indication of collectivity in small systems

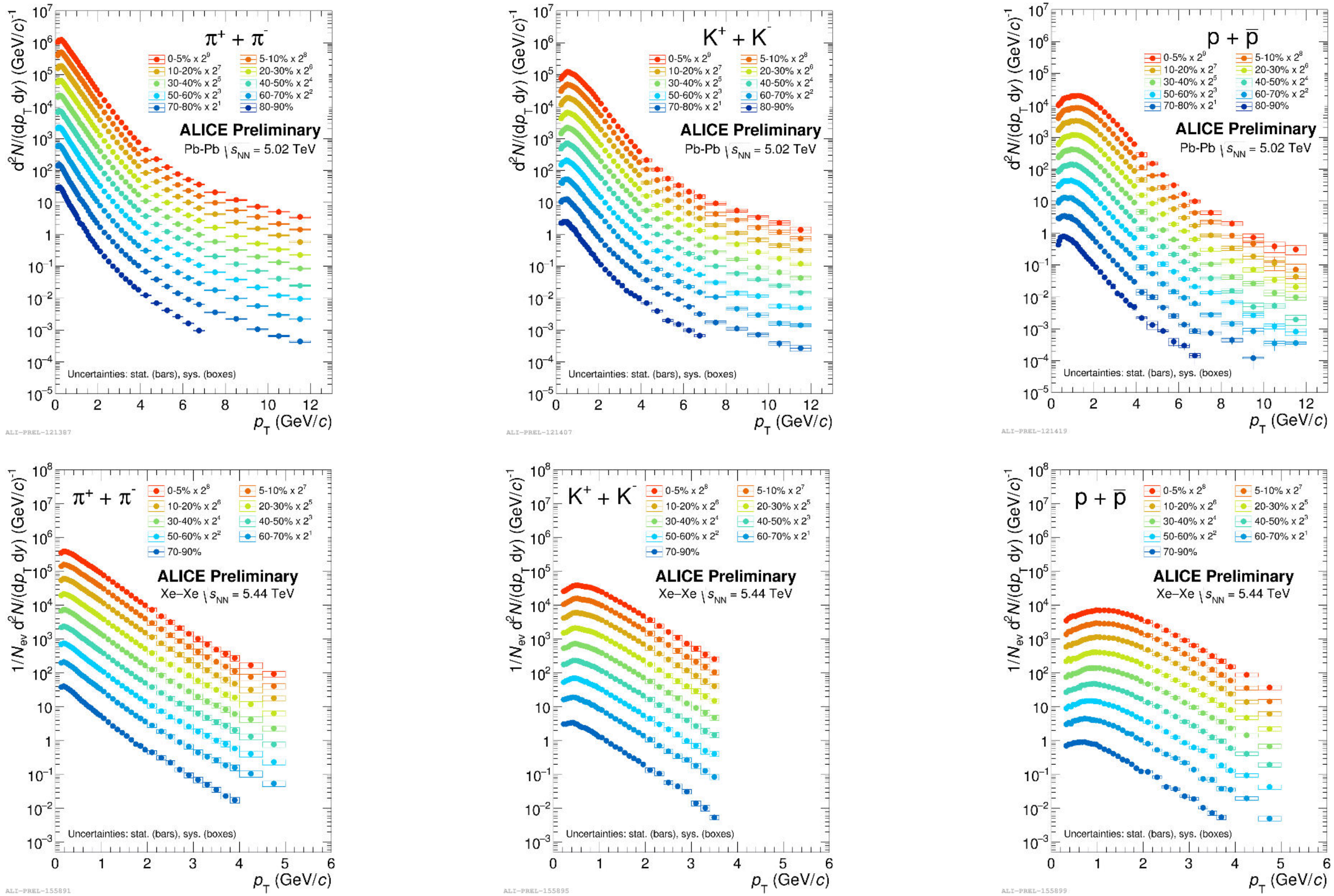
❖ Rescattering in the hadronic phase significantly reduces reconstructed yields of the short-lived resonances, hadronic phase lifetime $\tau > 2$ fm/c

❖ Strangeness enhancement is observed in small and large collision systems, it increases with multiplicity and strangeness content, no energy or collision system dependence, $\phi$ behaves as a particle with open strangeness

❖ Similar suppression of light hadrons at high $p_T$ in heavy-ion collisions, no significant energy dependence of suppression; Xe-Xe results are consistent with Pb-Pb at similar multiplicities

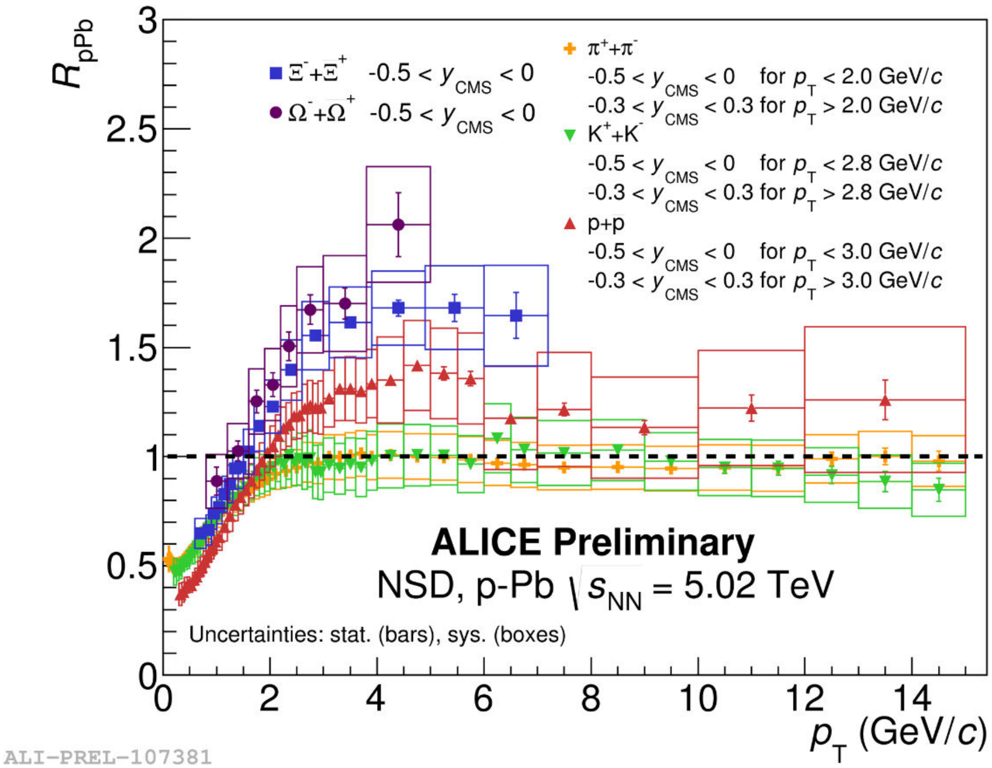
# BACKUP

# Transverse momentum spectra: Pb-Pb & Xe-Xe




- Mass dependent hardening of identified hadron spectra vs. centrality
  → common radial expansion

# Nuclear modification factors: p-Pb



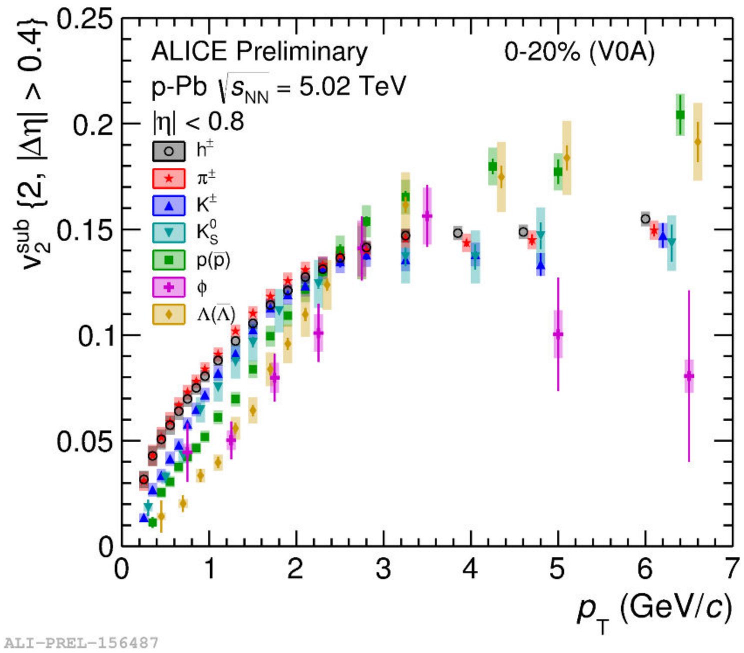

❖ Nuclear modification factor:

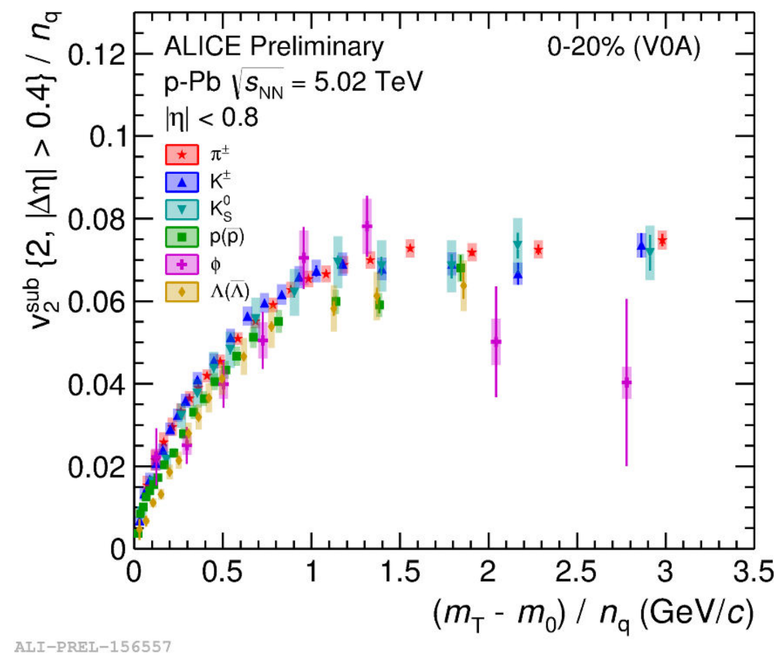
$$R_{AA}(p_T) = \frac{Yield_{A-A}(p_T)}{Yield_{pp}(p_T) \cdot N_{coll}}$$

❖ $R_{pPb}$ ~ 1 at high $p_T$ > 8 GeV/c → no jet modification, no evidence for suppression

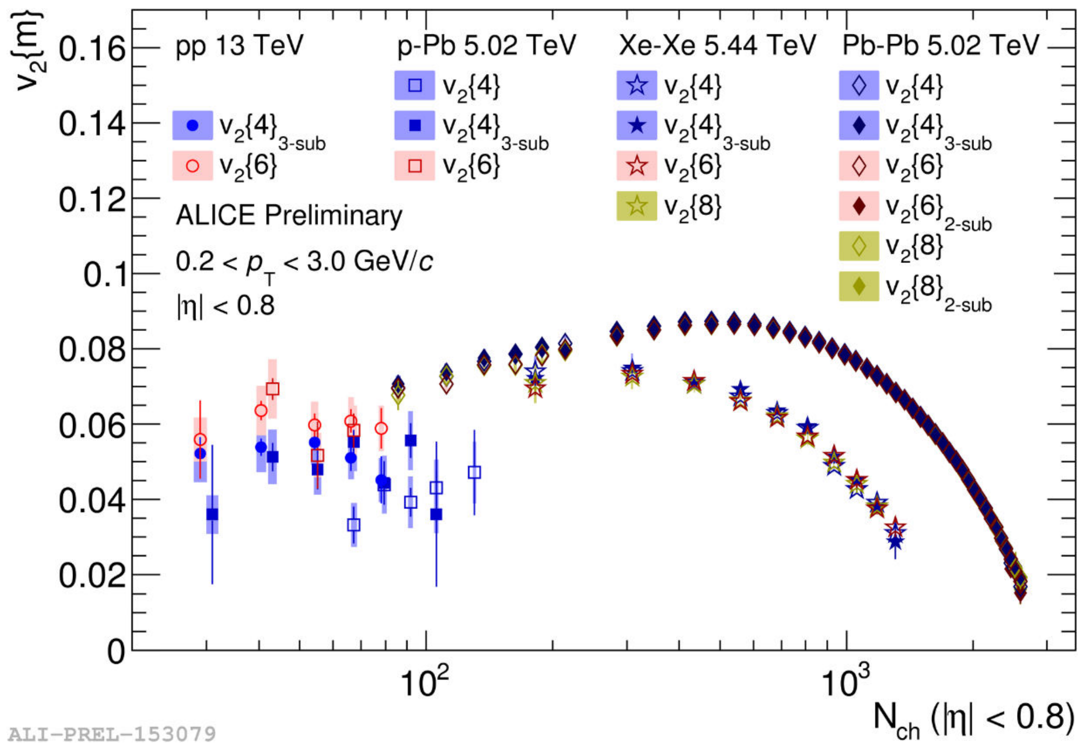
❖ Cronin enhancement at intermediate $p_T$
→ radial flow, color reconnection, soft multiple rescattering …
→ baryon/meson , mass effect?

# Elliptic flow: p-Pb

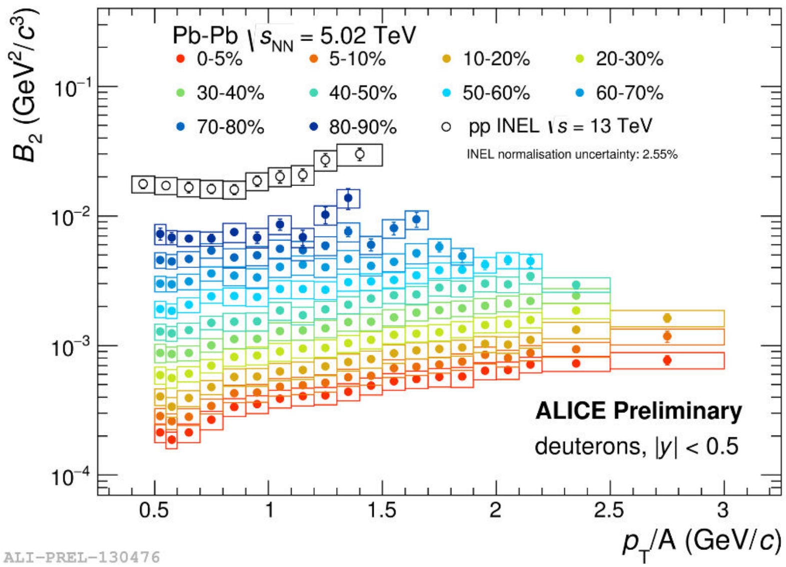


# Flow: pp, p-Pb, Xe-Xe and Pb-Pb



# Deuteron: pp, p-Pb, Xe-Xe and Pb-Pb

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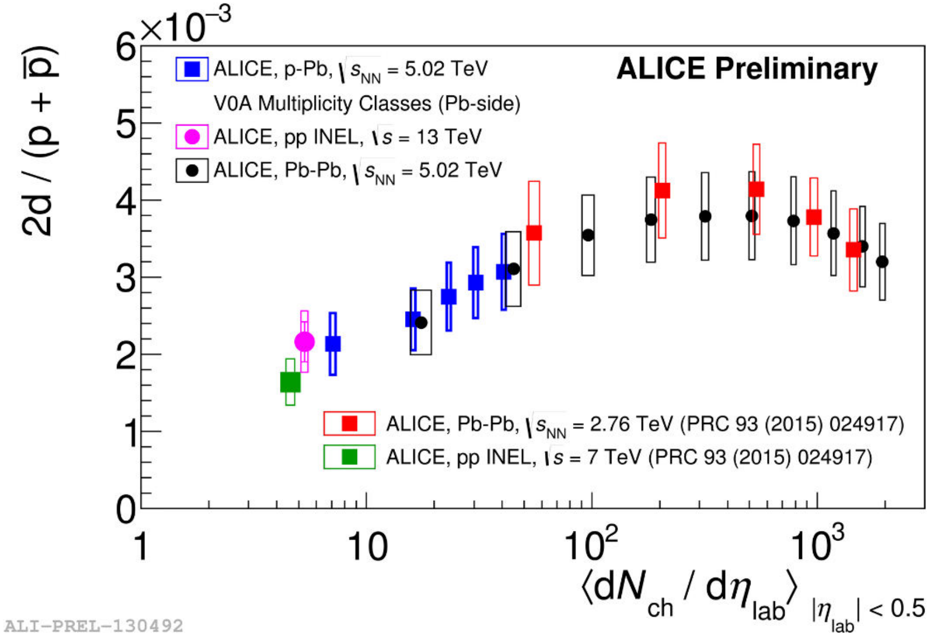


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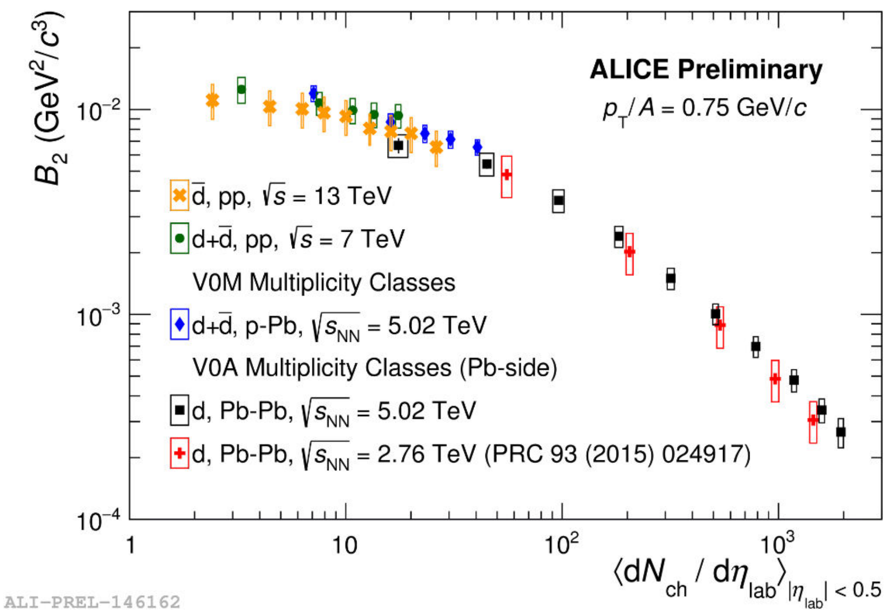
$$\frac{1}{2\pi p_T^A}\frac{d^2N^A}{dy\,dp_T^A} = B_A\left(\frac{1}{2\pi p_T^p}\frac{d^2N^p}{dy\,dp_T^p}\right)^A, \qquad p_T^p = p_T^A/A$$



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