# Proton annihilation: To be or not to be

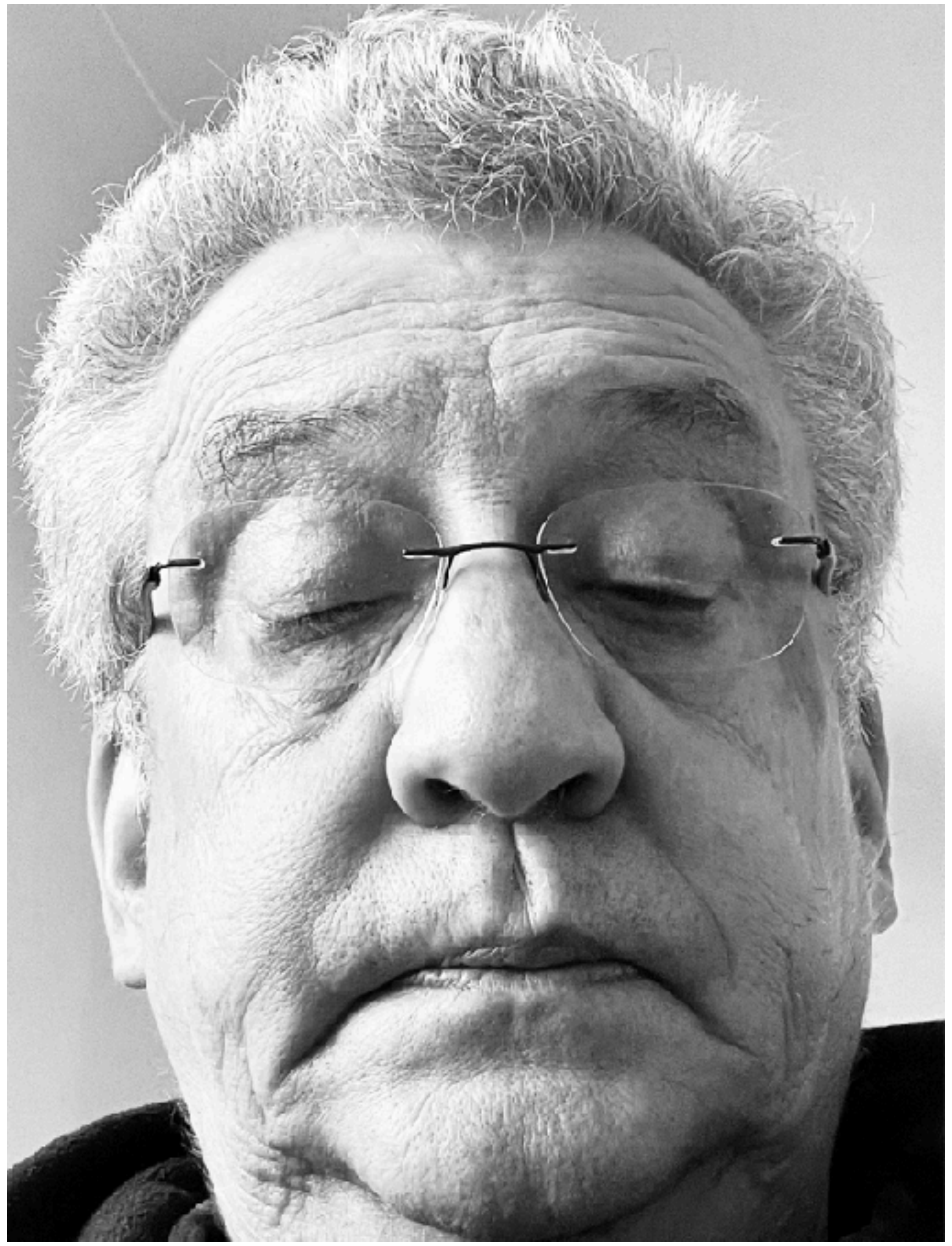
- Multiplicity dependence of $p/\pi$ and light nuclei ratio

  V. Vovchenko, V. K., Phys. Lett. B 835 (2022) 137577

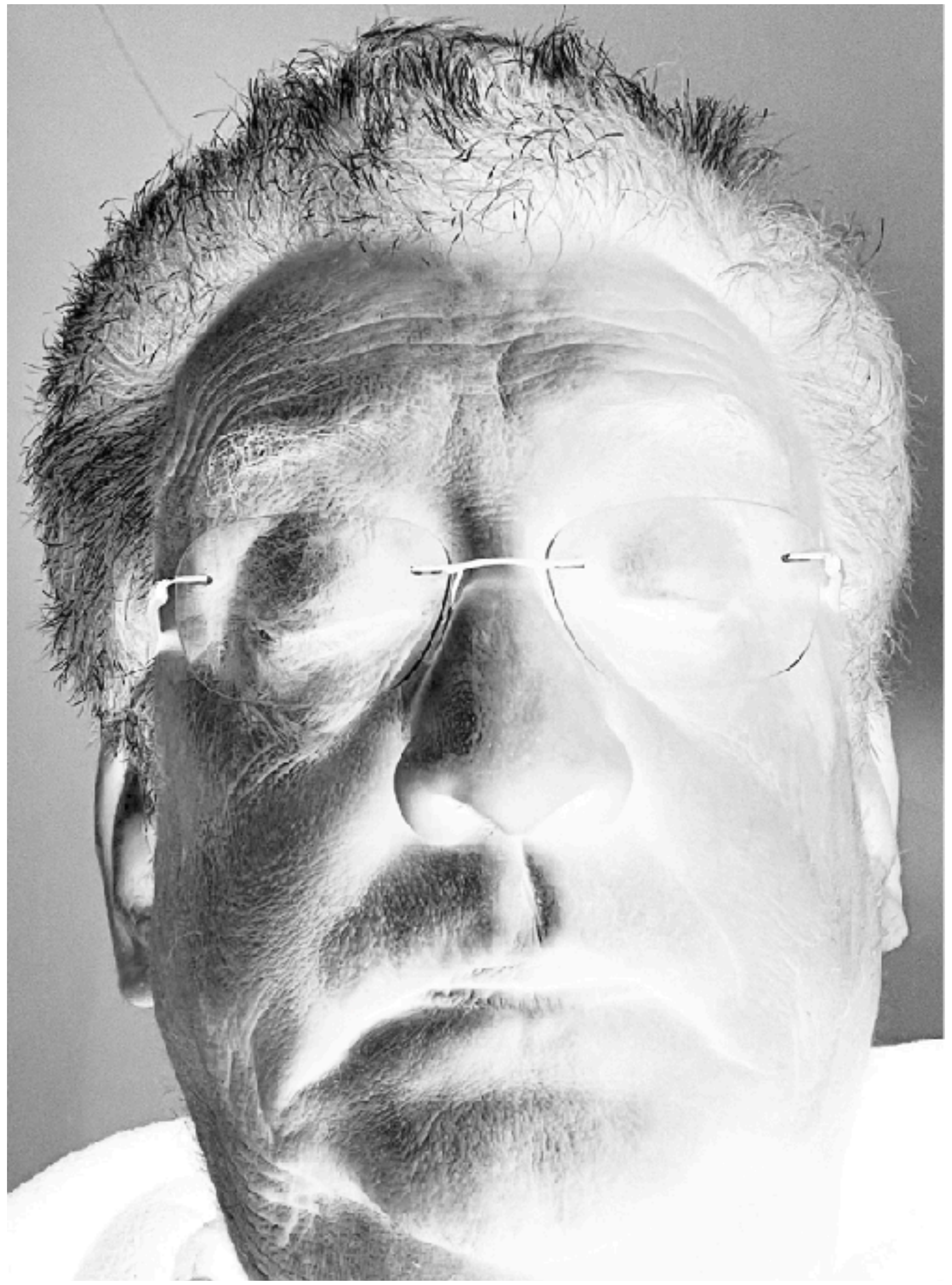
- Fluctuations of $p - \bar{p}$ and $p + \bar{p}$

  O. Savchuk, V. Vovchenko, J. Steinheimer et al., Phys. Lett. B 827 (2022) 136983

Me



$\overline{\text{Me}}$



# Why the discussion?

- Lifetime of hadronic phase is short
- pion number effectively conserved
  - $4\pi \Leftrightarrow 2\pi$ suppressed (chiral symmetry)
- $\Rightarrow$ finite $\mu_\pi$
- increased re-generation of anti-protons
  - $5\pi \Leftrightarrow p + \bar{p}$
- Most transport calculations violate
  detailed balance
  exceptions:
  E. Seifert, W. Cassing, PRC 97 (2018) 024913,
  O. Garcia-Montero et al, Phys. Rev. C 105 (2022) 064906

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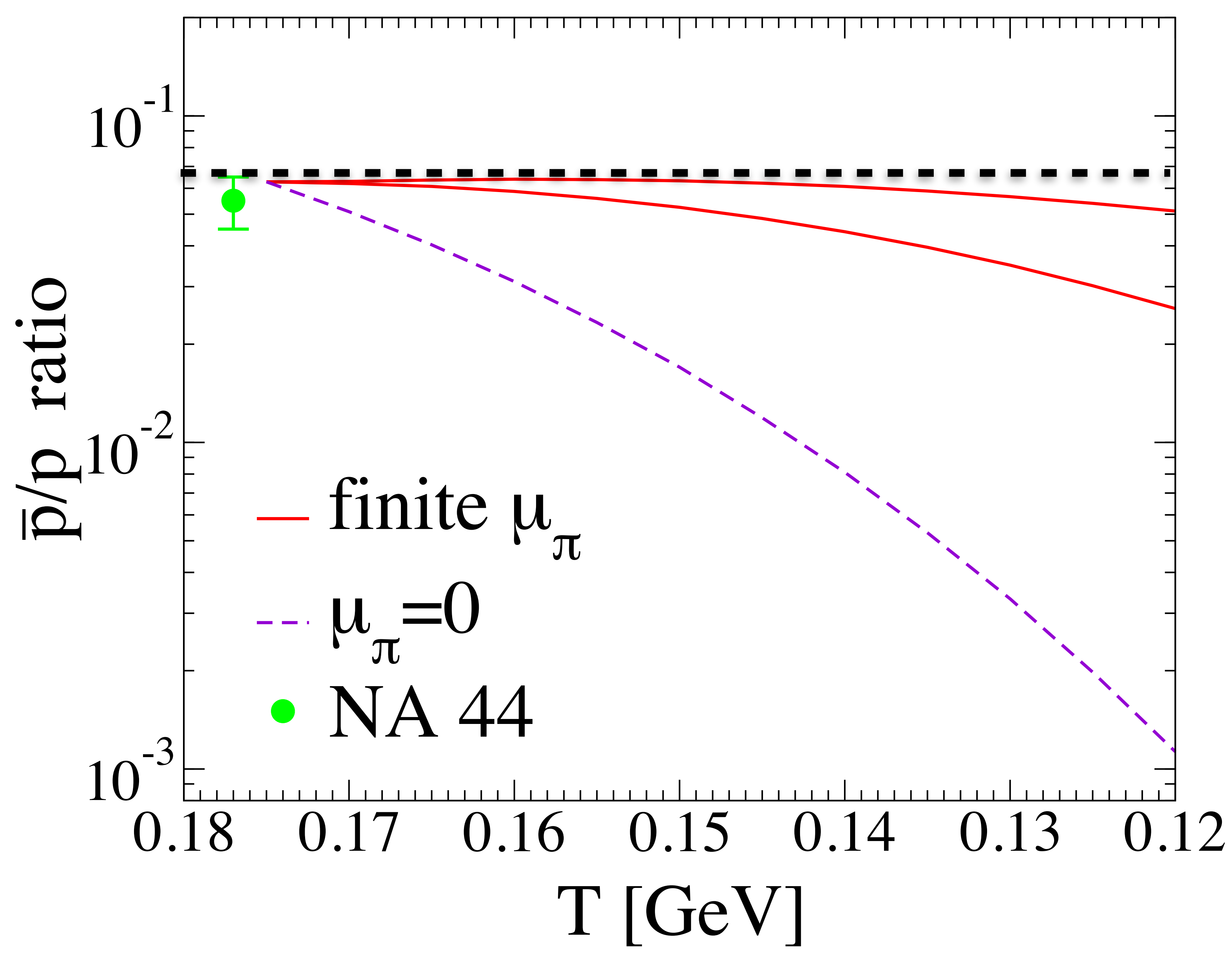
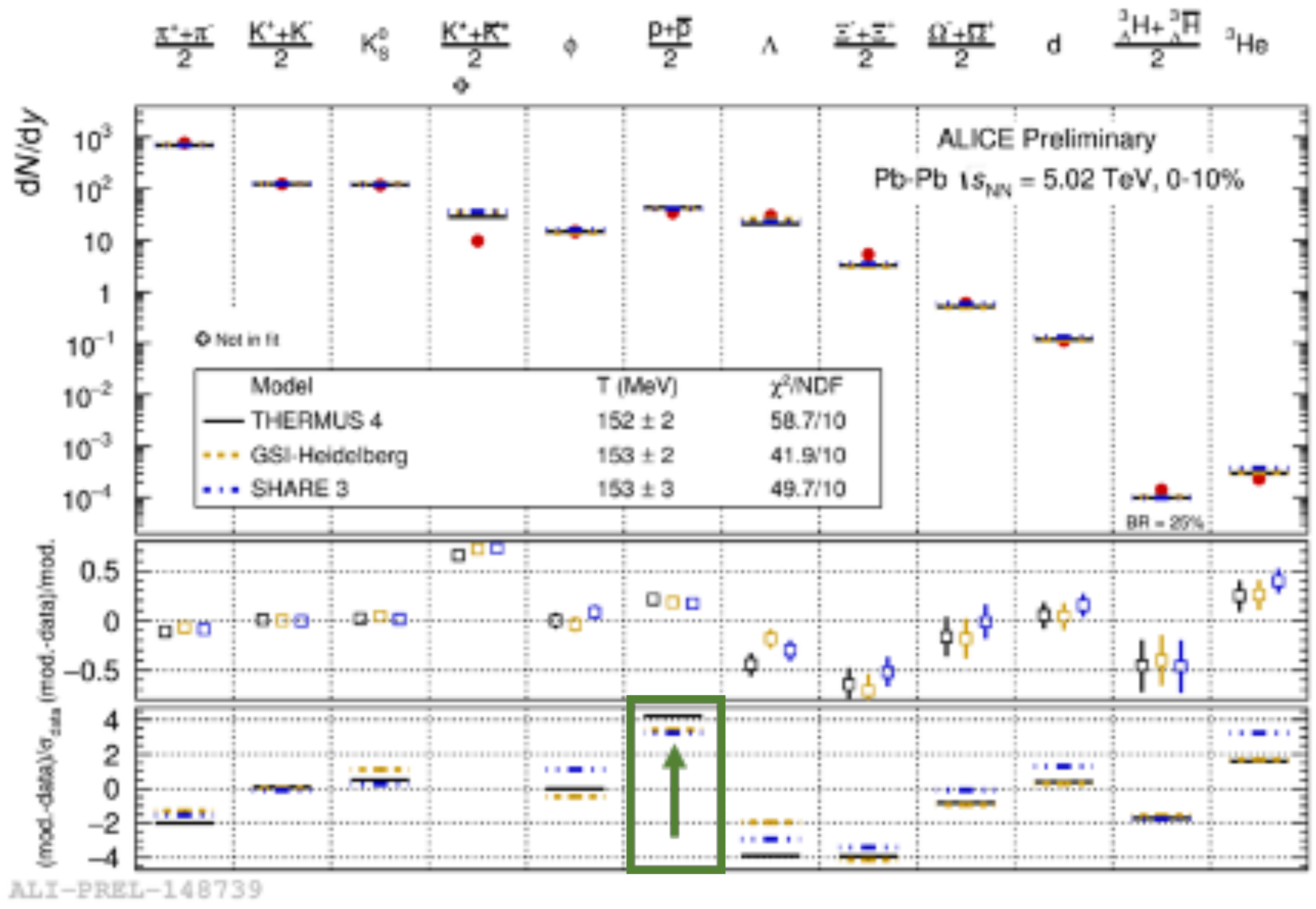
Rapp, Shuryak, PRL 86 (2001) 2980;



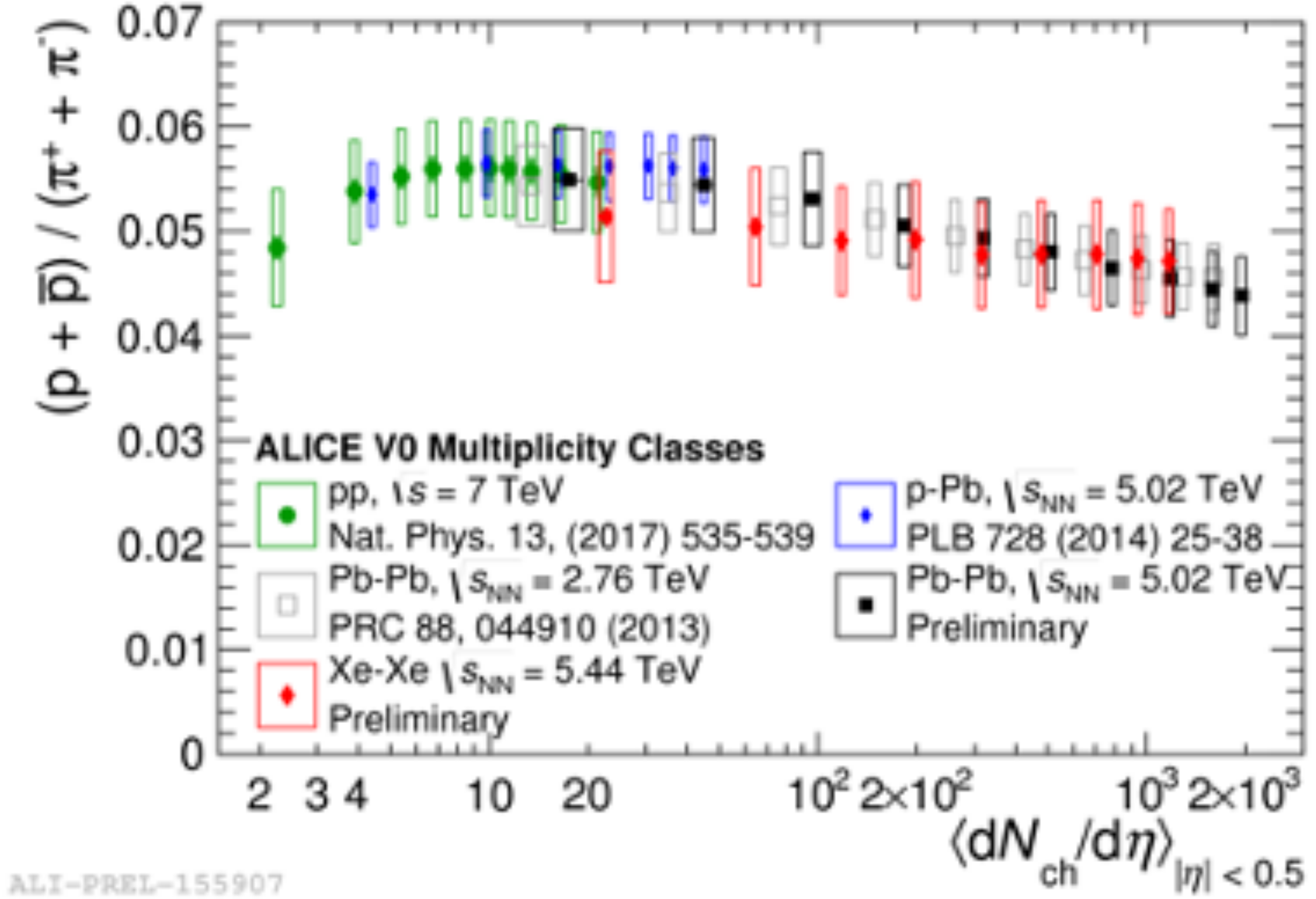

Need additional data to settle this issue

# Proton yield at LHC




Short hadronic phase

Long hadronic phase




- Yield overestimated in standard thermal models
  - However phase shift corrections seem to help
- Hints of annihilation in centrality dependence

# New data @ 5.02 TeV

ALICE Collaboration, Phys. Rev. C 101 (2020) 044907

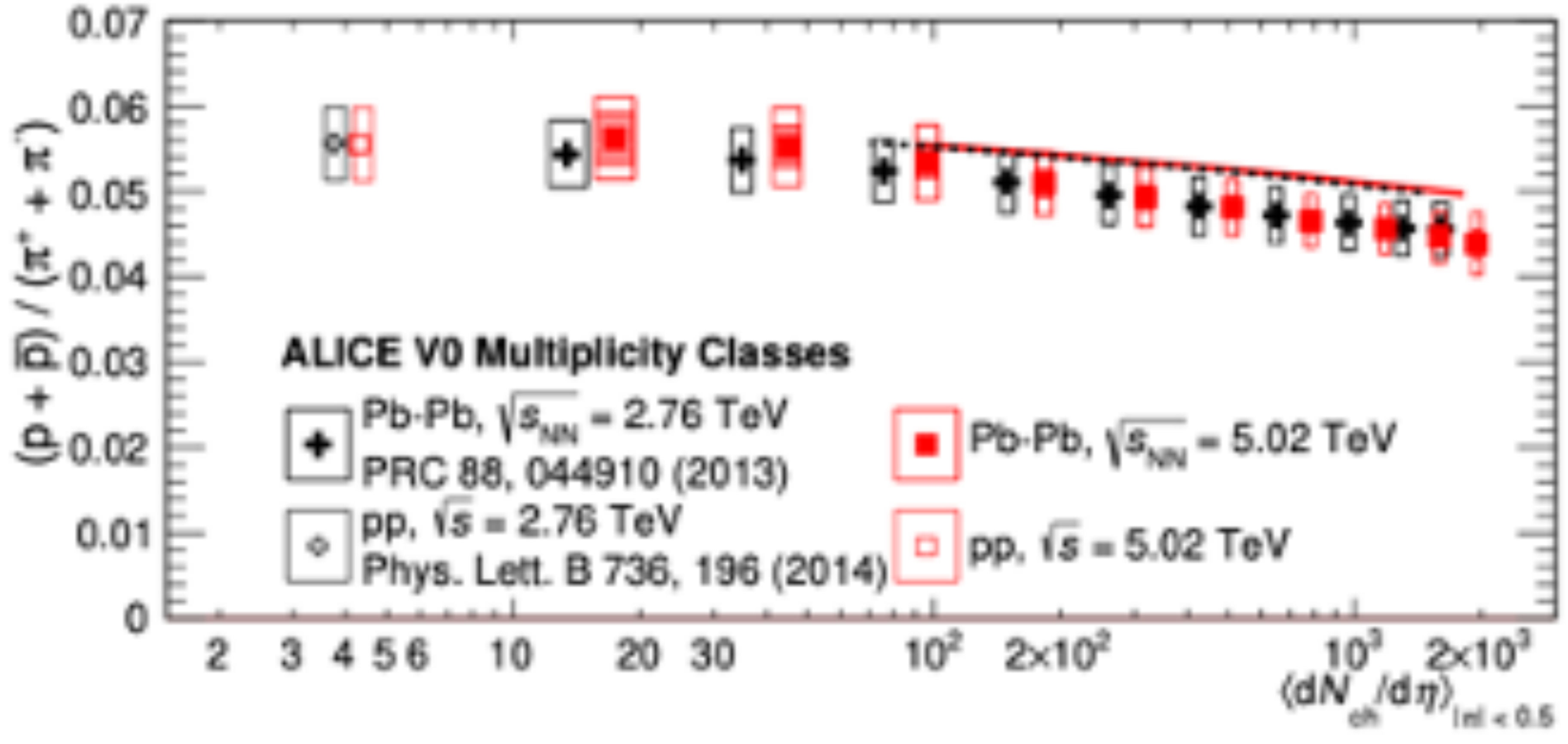
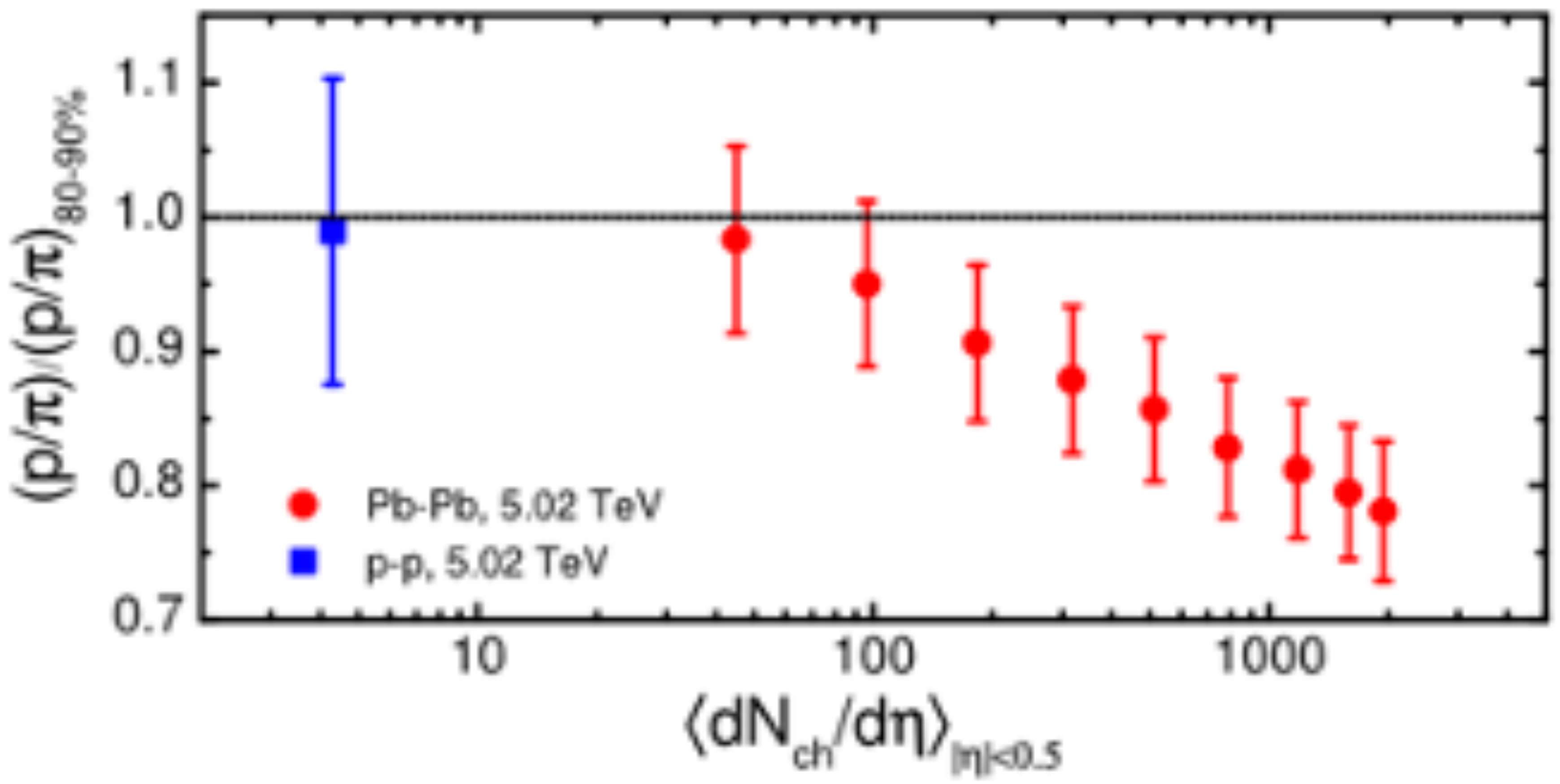



**Figure 7:** Transverse momentum integrated K/$\pi$ (top) and p/$\pi$ (bottom) ratios as a function of $\langle dN_{ch}/d\eta \rangle$ in Pb – Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared to Pb – Pb at 2.76 TeV [14]. The values in pp collisions at $\sqrt{s} = 5.02$ and 2.76 TeV are also shown. The empty boxes show the total systematic uncertainty; the shaded boxes indicate the contribution uncorrelated across centrality bins (not estimated in Pb – Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV).

Short hadronic phase

Long hadronic phase




- Evidence for suppression of $p/\pi$ ration in central collisions (~20%, >4$\sigma$ level)
- Due to hadronic phase?

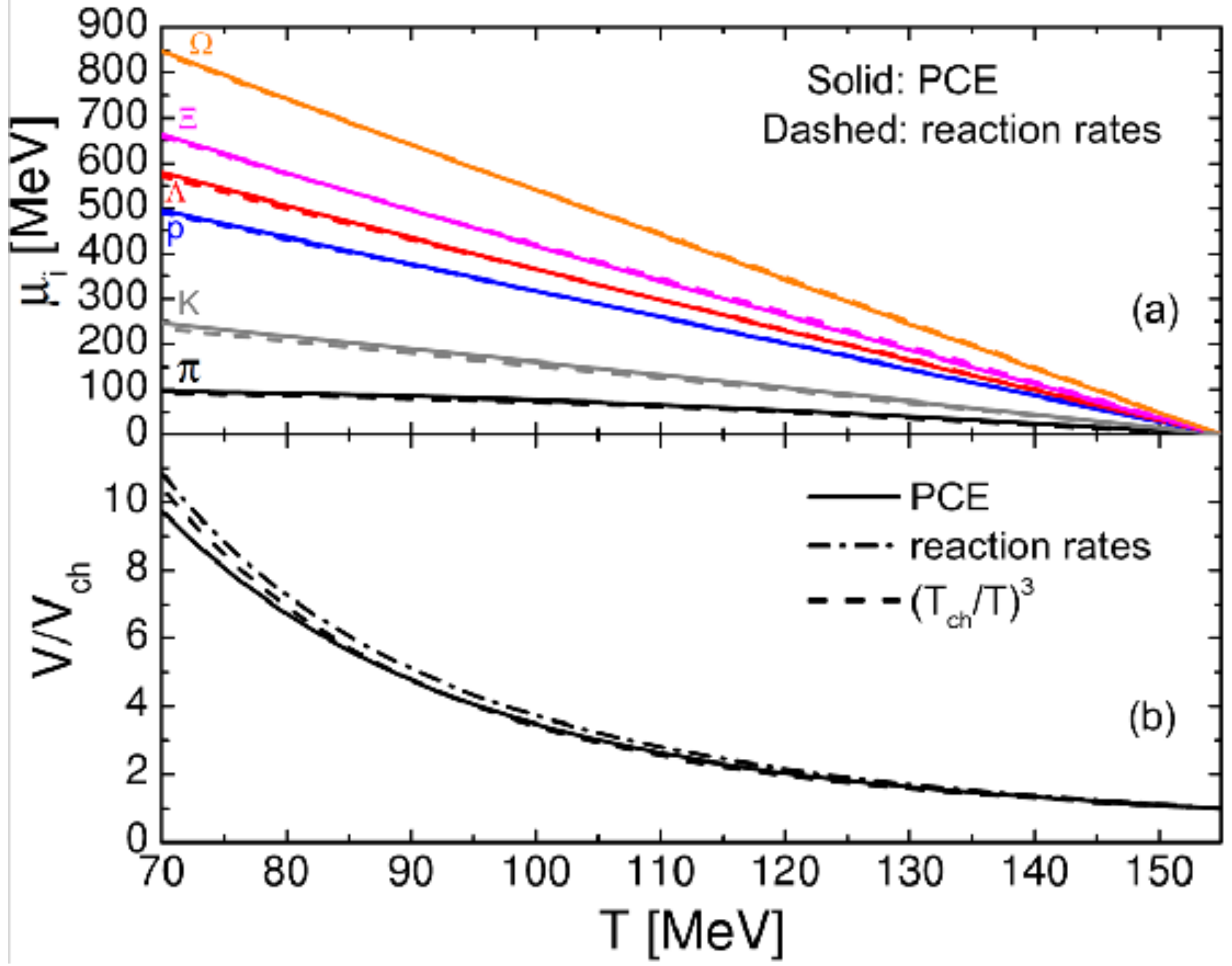
# Hadronic phase with partial chemical equilibrium (PCE)

Expansion of hadron resonance gas in partial chemical equilibrium at

$T < T_{ch}$ [H. Bebie, P. Gerber, J.L. Goity, H. Leutwyler, Nucl. Phys. B '92; C.M. Hung, E. Shuryak, PRC '98]

Chemical composition of stable hadrons is fixed, kinetic equilibrium maintained through pseudo-elastic resonance reactions $\pi\pi \leftrightarrow \rho, \;\; \pi K \leftrightarrow K^*, \; \pi N \leftrightarrow \Delta$ , etc.

E.g.: $\pi + 2\rho + 3\omega + \cdots = const, \quad K + K^* + \cdots = const, \quad N + \Delta + N^* + \cdots = const,$




**Effective chemical potentials:**

$$\tilde{\mu}_j = \sum_{i \in \text{stable}} \langle n_i \rangle_j \, \mu_i, \qquad \langle n_i \rangle_j \text{ – mean number of hadron } i \text{ from decays of hadron } j, \qquad j \in \text{HRG}$$

**Conservation laws:**

$$\sum_{j \in \text{hrg}} \langle n_i \rangle_j \, n_j(T, \tilde{\mu}_j) \, V = N_i(T_{\text{ch}}), \quad i \in \text{stable}$$

*numerical solution*

$$\sum_{j \in \text{hrg}} s_j(T, \tilde{\mu}_j) \, V = S(T_{\text{ch}}) \quad \Longrightarrow \quad \{\mu_i(T)\}, V(T)$$

Implementation within **Thermal-FIST** package (since v1.3)

[**VV**, H. Stoecker, *Comput. Phys. Commun.* ***244,*** *295 (2019)*] **open source:** https://github.com/vlvovch/Thermal-FIST

# Mechanisms affecting the proton yield

- Re-evaluating the chemical equilibrium proton abundance
  - Baryonic excluded volume [VV et al., PLB 775 (2017) 71]
  - Finite resonance widths [VV, Gorenstein, Stoecker, PRC 98 (2018) 034906]
  - S-matrix approach to $\pi N$ scattering [Andronic et al., PLB 792 (2019) 304]

  *centrality- independent*

- Multiple freeze-out scenario (strange vs light)

  e.g. Flor, Olinger, Bellwied, PLB 814, 136098 (2021)

  *centrality-independent*

- **Effects of the hadronic phase**
  - Baryon annihilation, $N\bar{N} \to 5\pi$ Steinheimer, Aichelin, Bleicher, PRL 110 (2013) 042501
  - No backreaction*, $5\pi \to N\bar{N}$. Some baryons will regenerate

  ***centrality-dependent***

  Rapp, Shuryak, PRL 86 (2001) 2980;
  Pan, Pratt, PRC 89 (2014) 044911

*Gradually being implemented [Garcia-Montero et al., PRC 105 (2022) 064906]

# Partial chemical equilibrium with baryon annihilation

Add nucleon annihilations $N\bar{N} \leftrightarrow 5\pi$ into the PCE framework

(Anti)nucleon and pions numbers no longer conserved, $N_N, N_{\bar{N}}, N_\pi \neq$ const. but

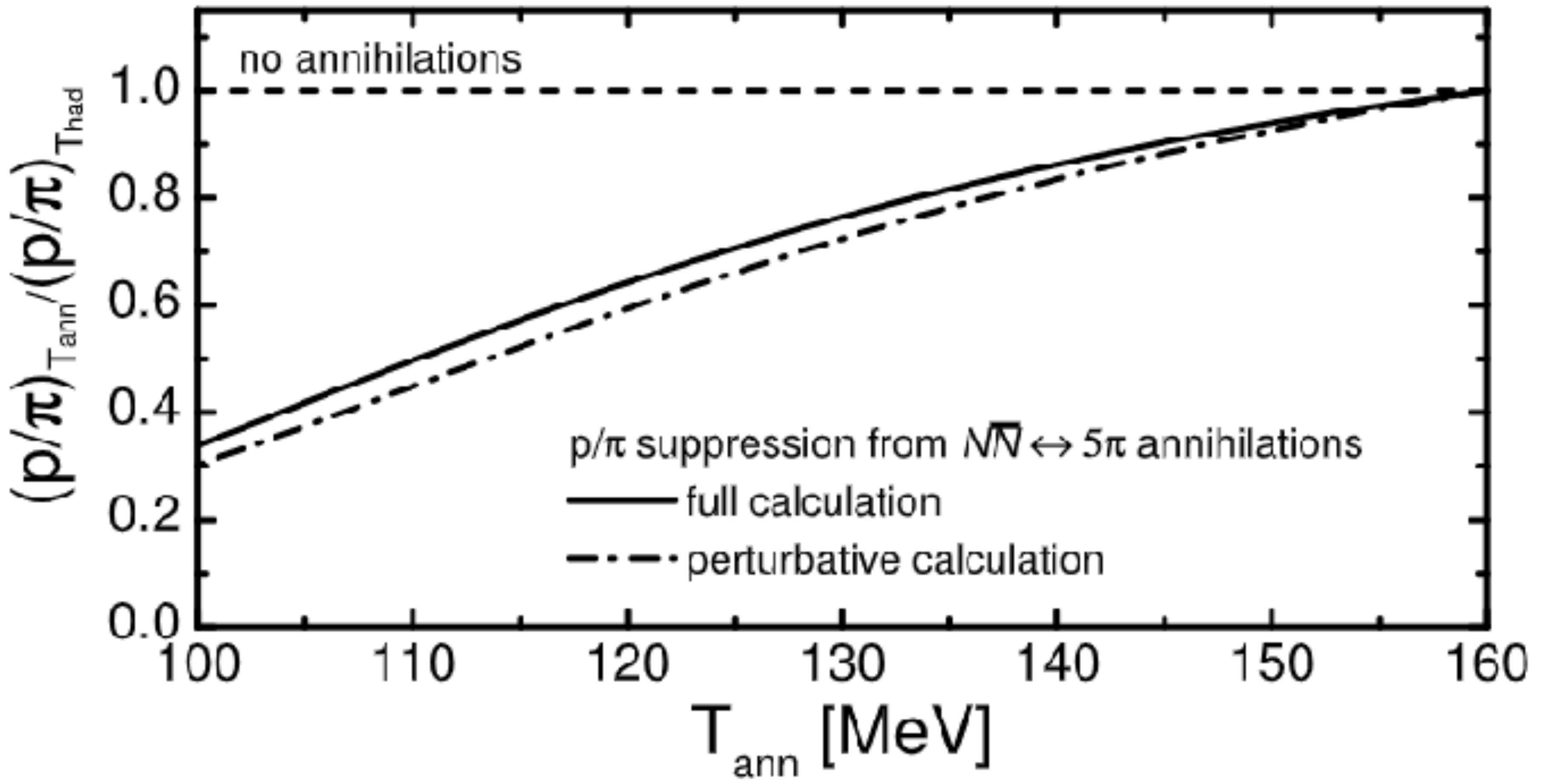
$$\frac{N_N + N_{\bar{N}}}{2} + \frac{N_\pi}{5} = \mathrm{const}$$

If $N\bar{N} \leftrightarrow 5\pi$ proceeds in relative equilibrium,

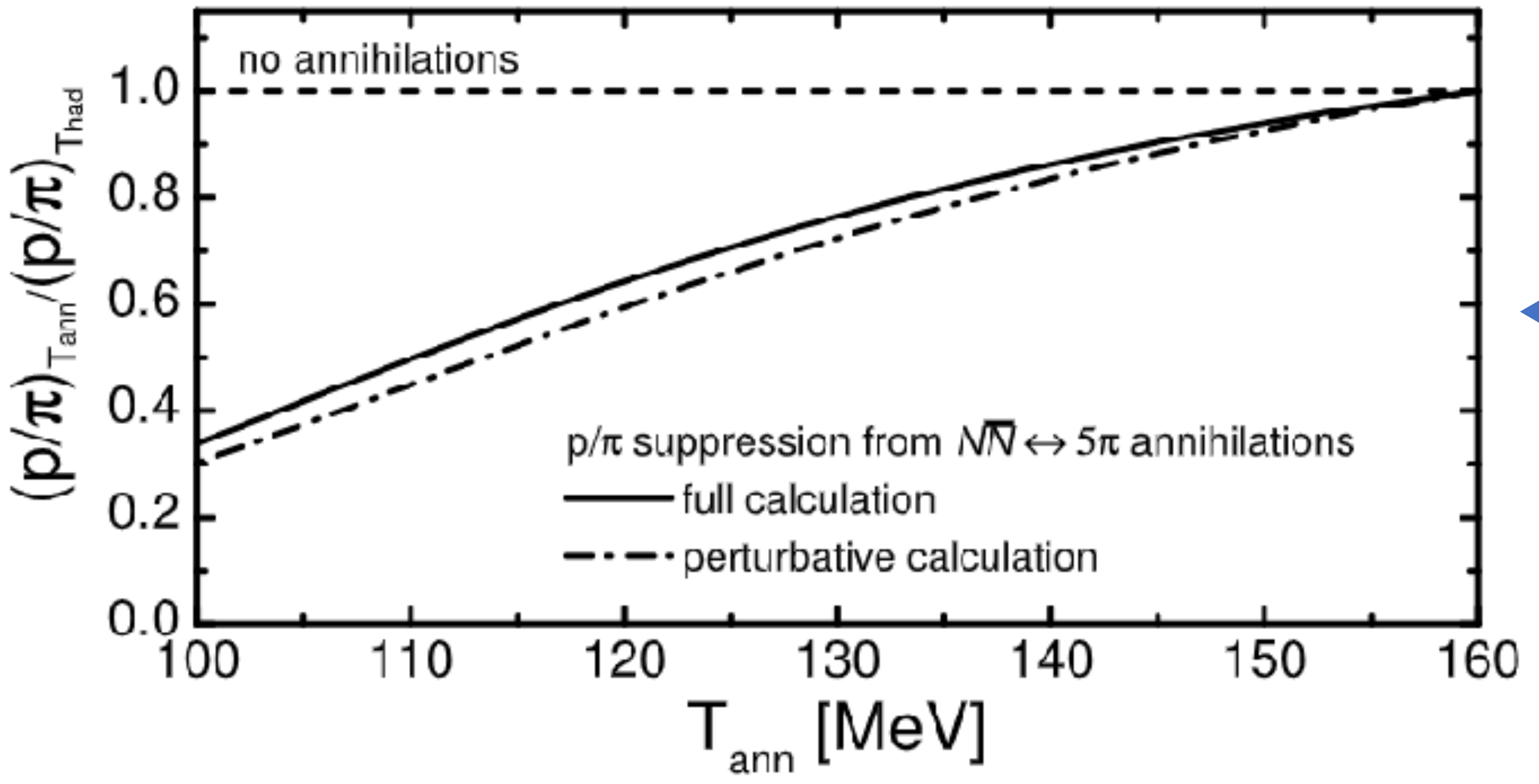
$$\mu_N = \mu_{\bar{N}} = \frac{5}{2}\mu_\pi$$

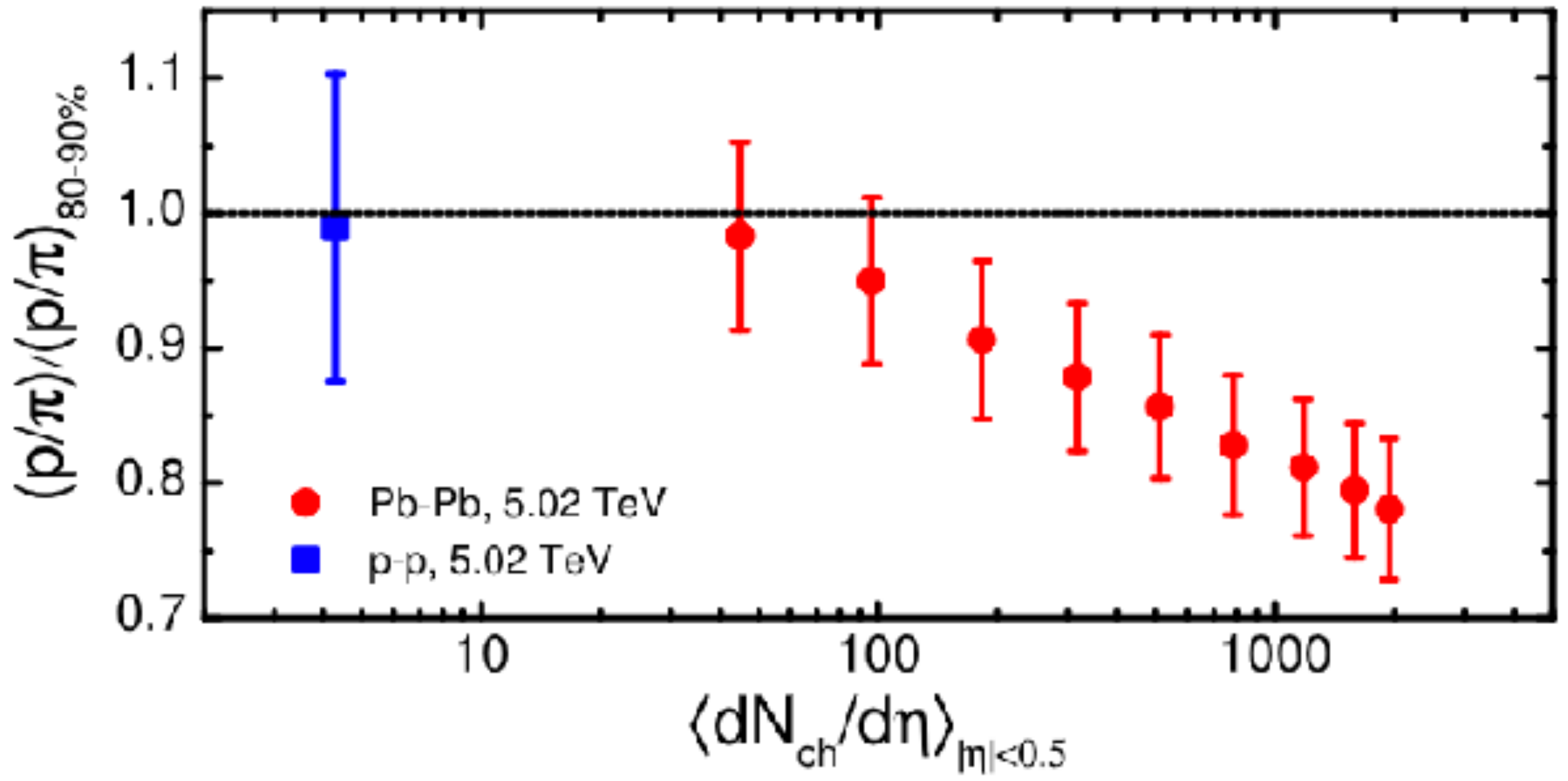
Also, $\pi N \leftrightarrow \Delta$ equilibrium implies $\Delta\bar{N} \leftrightarrow 6\pi$ and $\Delta\bar{\Delta} \leftrightarrow 7\pi$, *i.e. baryon resonances annihilate as well*

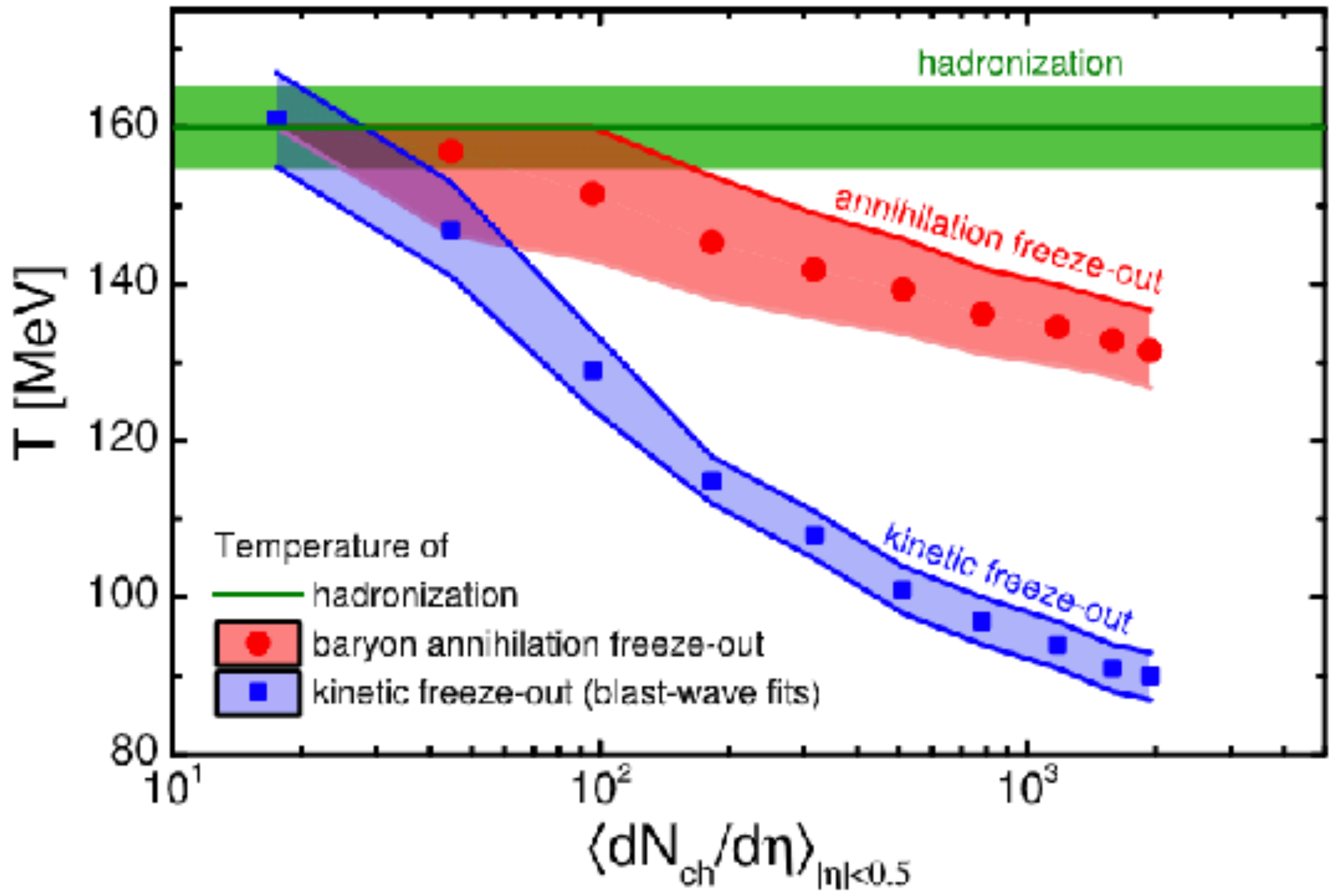
p/$\pi$ ratio is suppressed during the cooling in the hadronic phase



# Baryon annihilation freeze-out temperature




| Centrality | $\langle dN_{ch}/d\eta\rangle$ | $T_{ann}$ [MeV] |
|---|---|---|
| 0–5% | $1943 \pm 56$ | $132 \pm 5$ |
| 5–10% | $1587 \pm 47$ | $133 \pm 5$ |
| 10–20% | $1180 \pm 31$ | $135 \pm 5$ |
| 20–30% | $786 \pm 20$ | $136 \pm 6$ |
| 30–40% | $512 \pm 15$ | $139 \pm 6$ |
| 40–50% | $318 \pm 12$ | $142 \pm 7$ |
| 50–60% | $183 \pm 8$ | $145 \pm 8$ |
| 60–70% | $96.3 \pm 5.8$ | $152 \pm 8$ |
| 70–80% | $44.9 \pm 3.4$ | $157^{+3}_{-11}$ |
| 80–90% | $17.5 \pm 1.8$ | 160 |

Baryon annihilation remains relevant in the initial stage of the hadronic phase but freezes out earlier than (pseudo-)elastic hadron scatterings

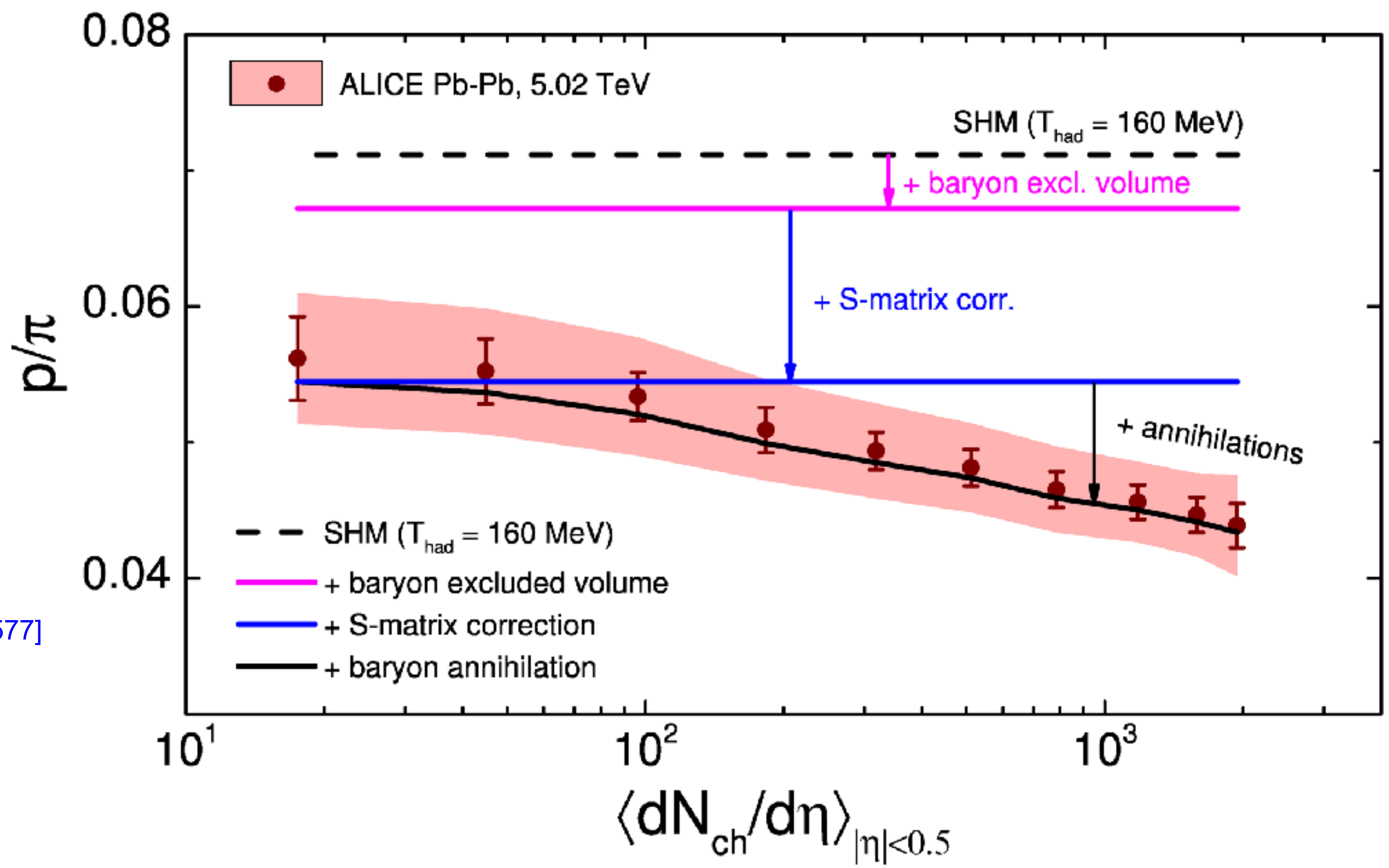
# Annihilation vs other mechanisms affecting the p/$\pi$ ratio

SHM: Thermal-FIST
[Vovchenko, Stoecker, Comput.Phys.Commun. 244 (2019) 295]

Baryon excl. volume
*(baryon-baryon int.)*
[Vovchenko et al., PLB 775 (2017) 71]

S-matrix correction
*(meson-baryon int.)*
[Andronic et al., PLB 792 (2019) 304]

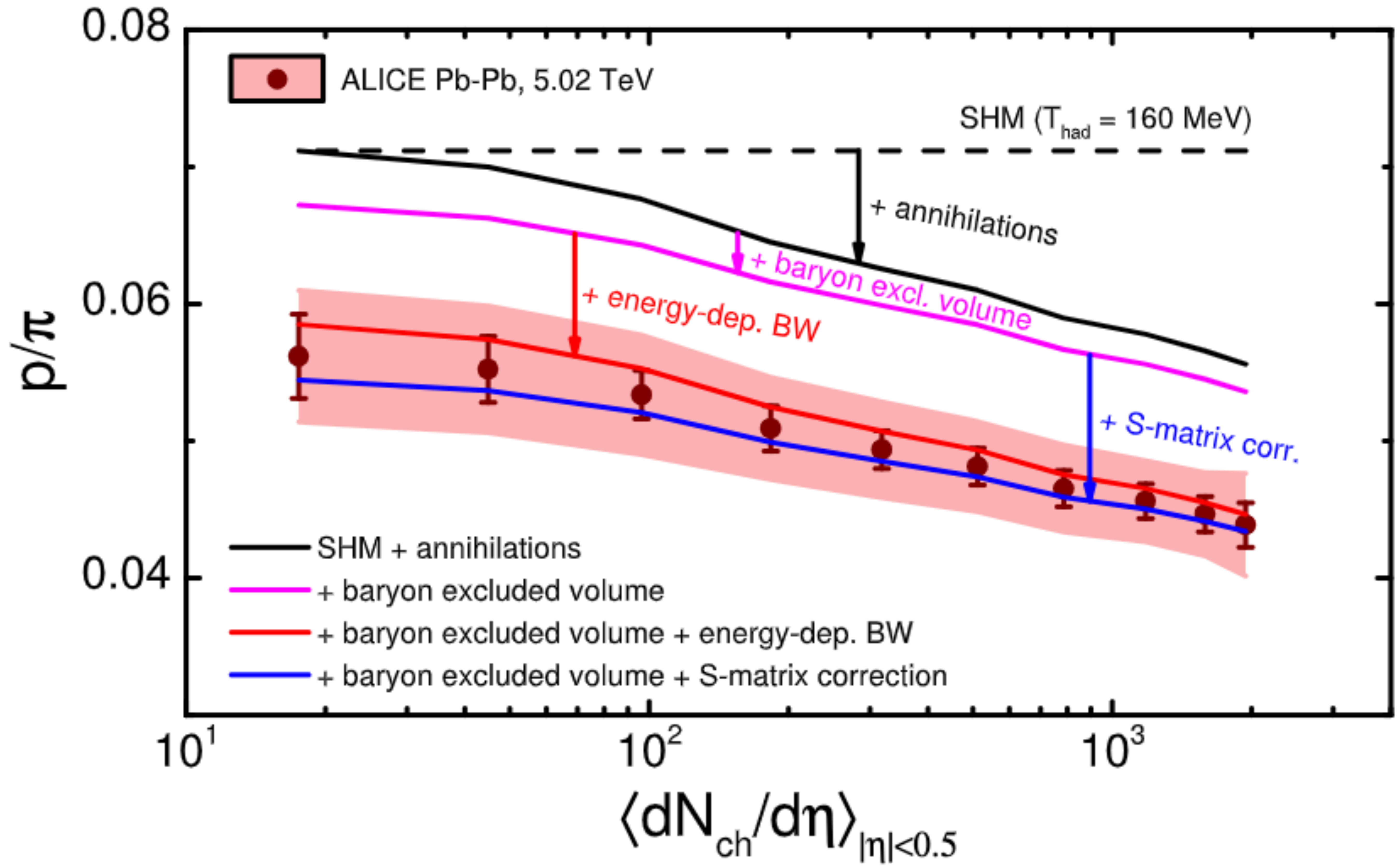
Baryon annihilation
*(baryon-antibaryon int.)*
[Vovchenko, VK, PLB 835 (2022) 137577]




*Baryon annihilation and other mechanisms are complementary*

# Another way to look at it

This is what is shown in the paper

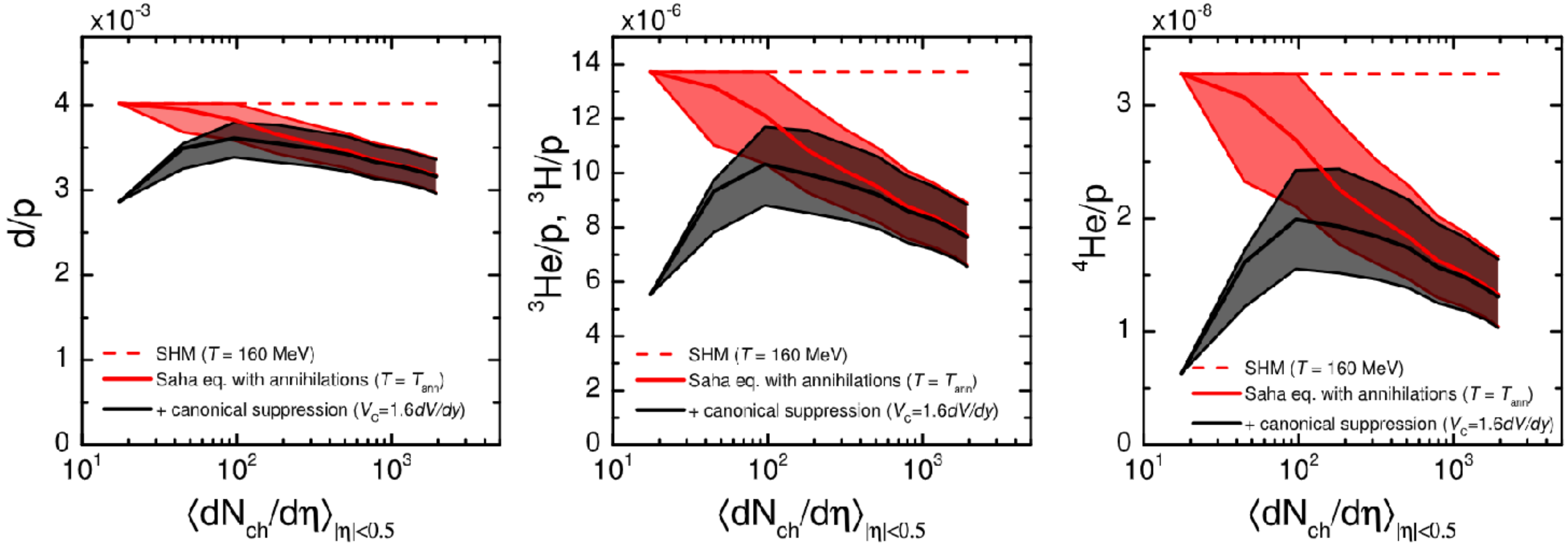



*Baryon annihilation and other mechanisms are complementary*

# Baryon annihilation and light nuclei

Naively, if nucleons are suppressed by $\gamma_N \sim 0.8$, then $\gamma_A \sim (\gamma_N)^A$ e.g. $\gamma_d \sim 0.64$

Quantitatively, use the Saha equation for nuclear abundances, $\mu_A = A\mu_N$ [Vovchenko et al, PLB 800 (2020) 135131]

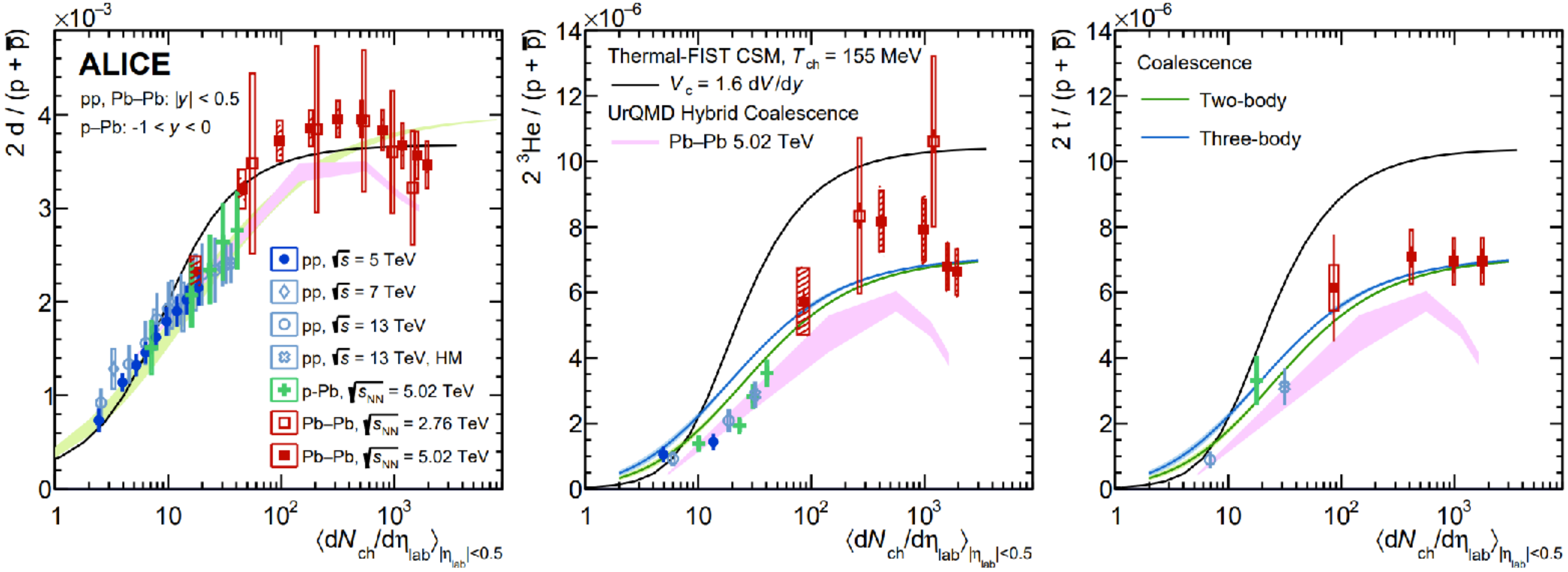



- Baryon annihilation causes ***suppression in central collisions***
- Possible *non-monotonic multiplicity dependence* due to (another) suppression in small systems

*Can be tested with precision measurements of the centrality dependence*

# Baryon annihilation and light nuclei

**New data:** ALICE Collaboration, arXiv:2211.14015



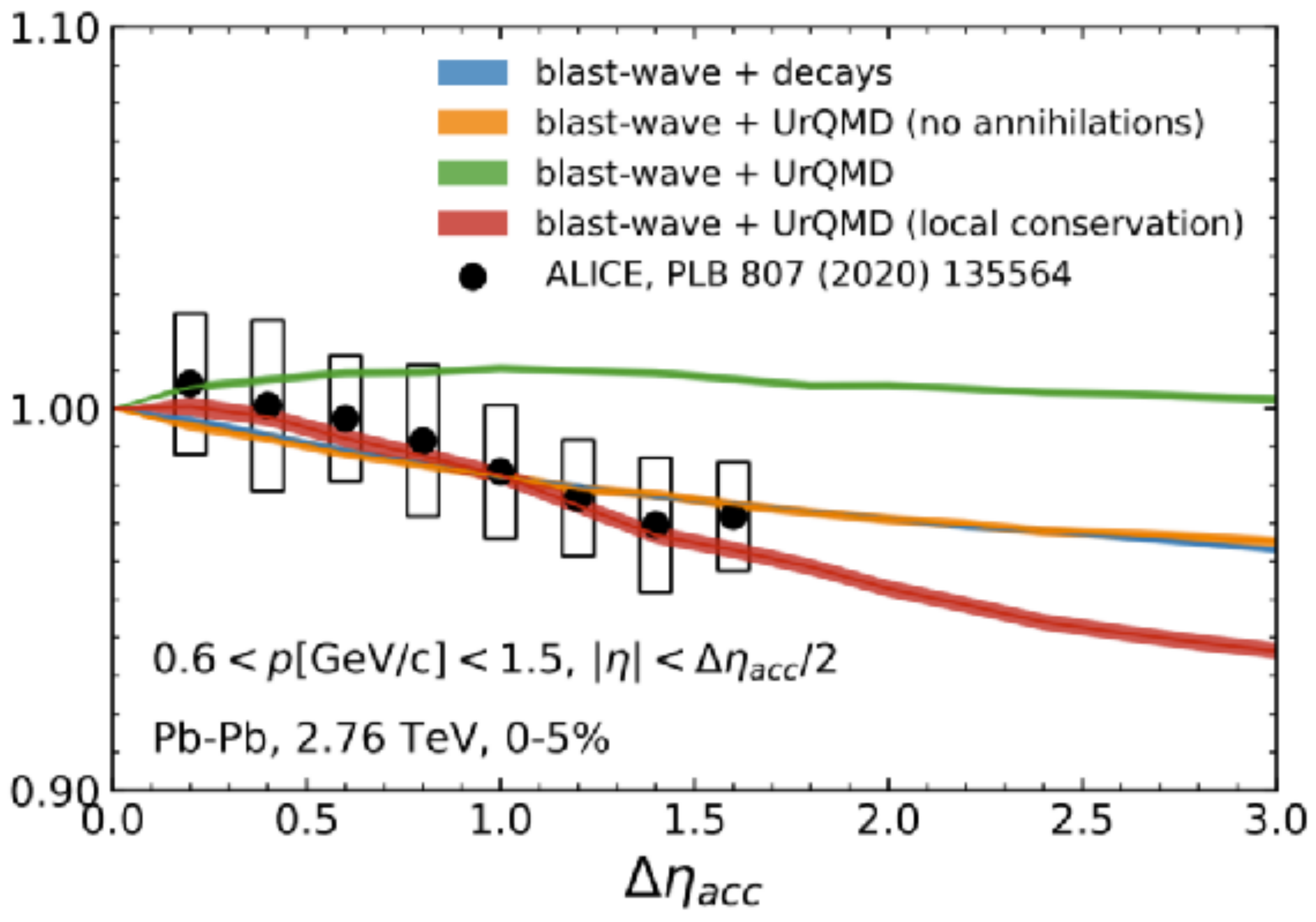

*Indications for non-monotonic multiplicity dependence of d/p and ³He/p*

# Baryon annihilation and fluctuations

Savchuk et al., PLB 827, 136983 (2022)

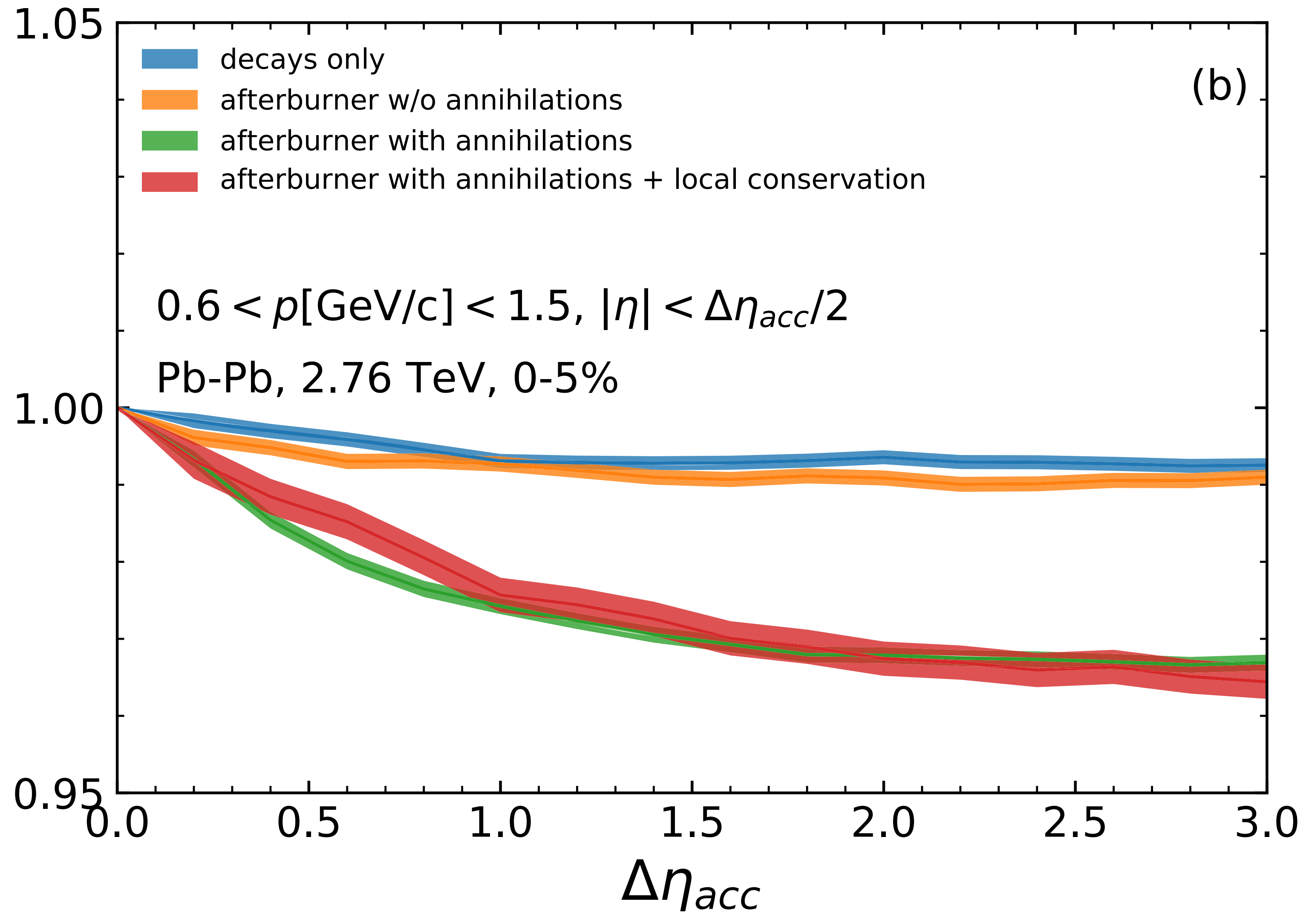
- $\kappa_2(p - \bar{p})$:
  - **Not** affected by annihilation
  - affected by baryon number conservation
- $\kappa_2(p + \bar{p})$:
  - affected by annihilation
  - **Not** affected by baryon number conservation

$$\frac{\kappa_2(p - \bar{p})}{\langle p + \bar{p} \rangle}$$




***N.B.:***
*In UrQMD annihilation has NO detailed balance*
$\rightarrow$*No reaction* $5\pi \rightarrow p + \bar{p}$
$\rightarrow$ *maximum effect*

$$\frac{\kappa_2(p + \bar{p})}{\langle p + \bar{p} \rangle}$$

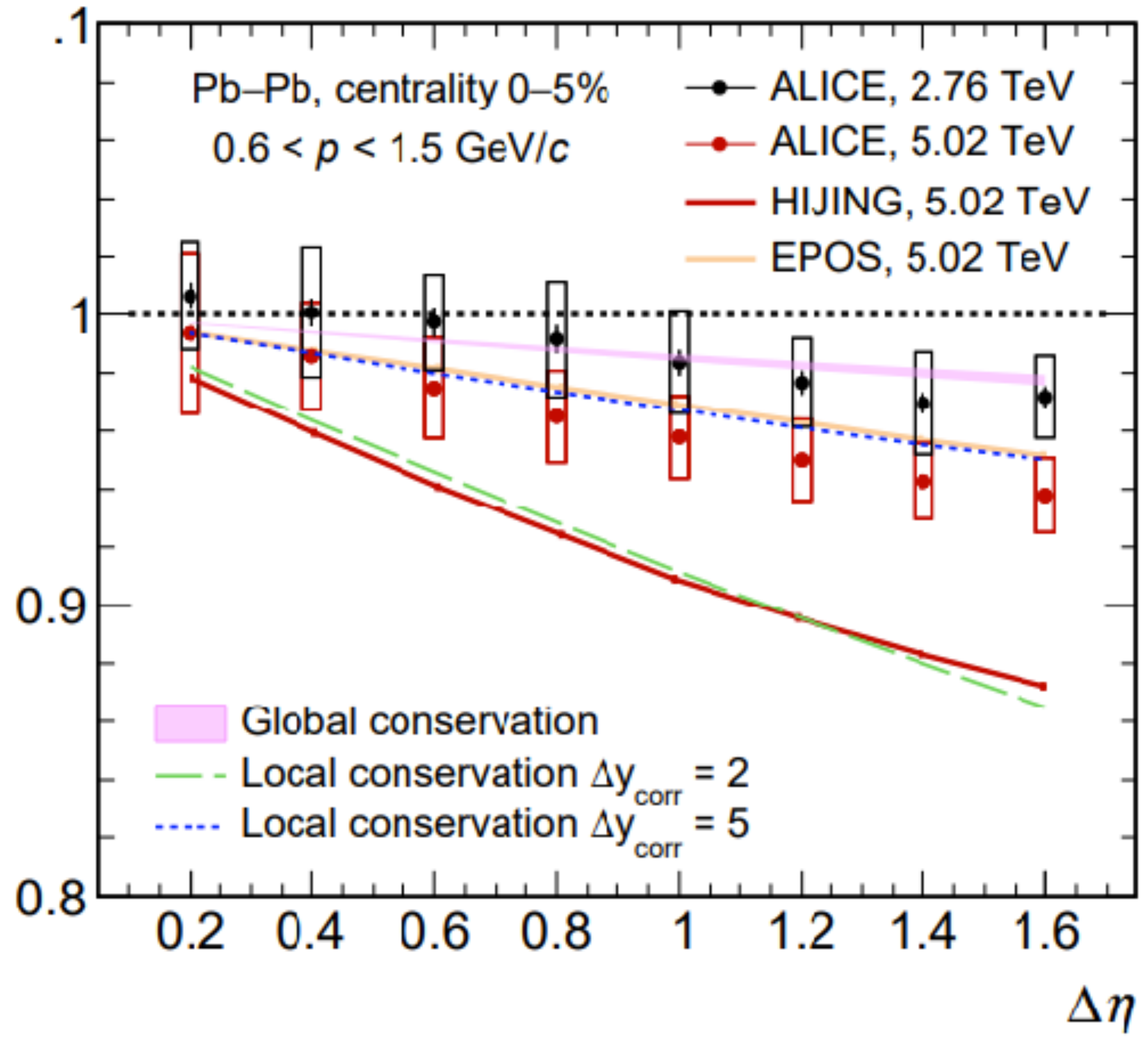



Measure $\kappa_2(p - \bar{p})$ AND $\kappa_2(p + \bar{p})$ to constrain both amount of annihilation AND baryon correlation length

# Baryon annihilation and fluctuations

ALICE Coll., arXiv:2206.03343

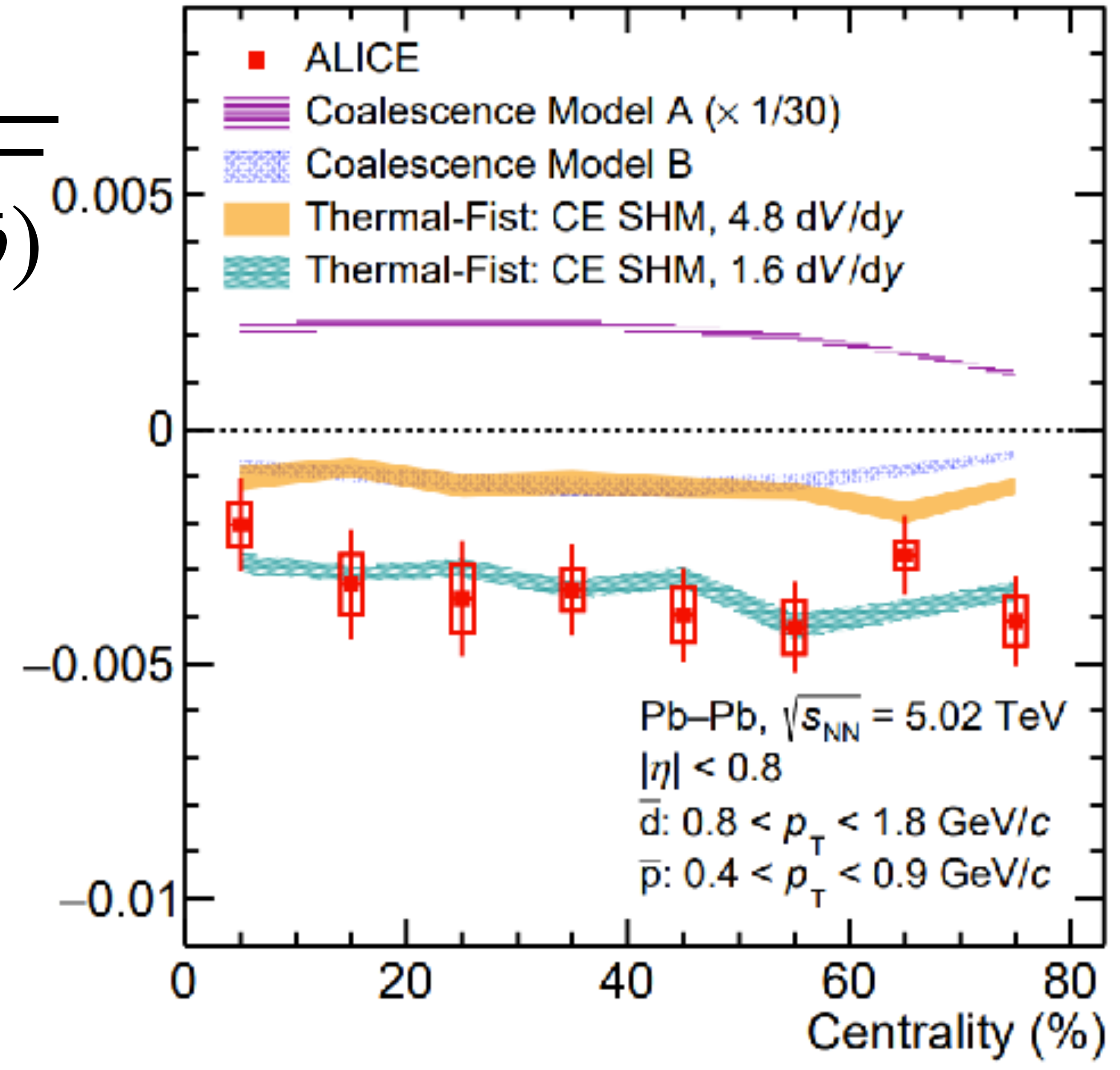
$$\frac{\kappa_2(p-\bar{p})}{\langle p+\bar{p}\rangle}$$




*No annihilation*

ALICE Coll., arXiv:2204.10166

$$\frac{\mathrm{cov}(\bar{\mathrm{d}},\bar{\mathrm{p}})}{\sqrt{\kappa_2(\bar{d})\kappa_2(\bar{p})}}$$




*No annihilation*

"wants" **long** range charge correlation

"wants" **short** range charge correlations

May resolve the tension between proton fluctuations that seem to prefer "global" baryon conservation vs light $\bar{d}$ - $\bar{p}$ correlations that prefer more "local" baryon conservation

# Summary

- Statistically significant suppression of p/pi in central collisions @LHC
- Can be attributed to baryon annihilation in the hadronic phase
    - Extract $T_{ann}$ from experimental data
    - Annihilations relevant but freeze-out earlier than hadron scatterings
    - PCE results are similar to hadronic afterburners
    - Testable suppression of light nuclei yields in central collisions
- Outlook
    - Effect on proton/light nuclei fluctuations and correlations
    - Hyperons (await exp. data on centrality dependence)
    - Modified thermal fits