Baryon annihilation and multiplicity dependence of p/π and light nuclei ratios

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- Centrality dependence of baryon annihilation freeze-out temperature
- Suppression of light nuclei in central collisions

Reference:

VV, V. Koch, Phys. Lett. B 835 (2022) 137577

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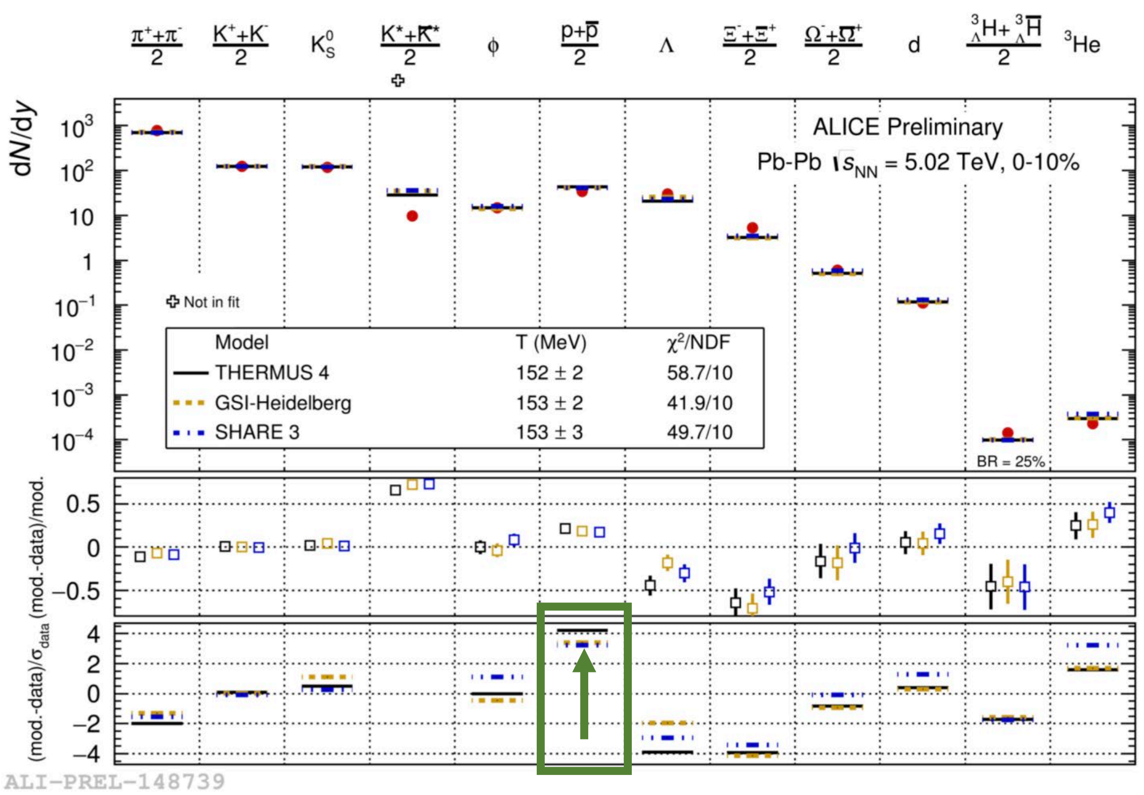
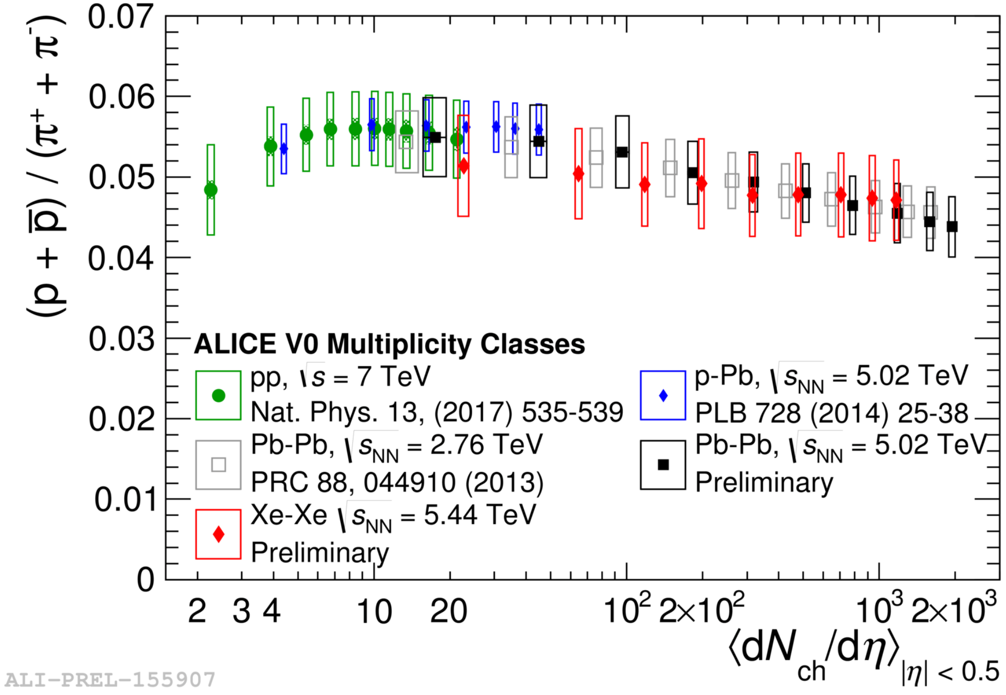
Proton yields at the LHC

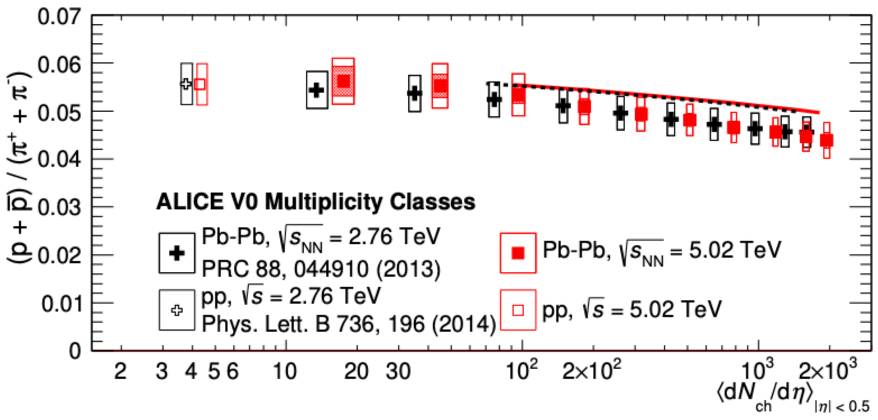




- Proton yield overestimated in standard thermal models
- The effect is larger in central collisions, hint of centrality dependence

Proton yields at the LHC: 5 TeV data

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



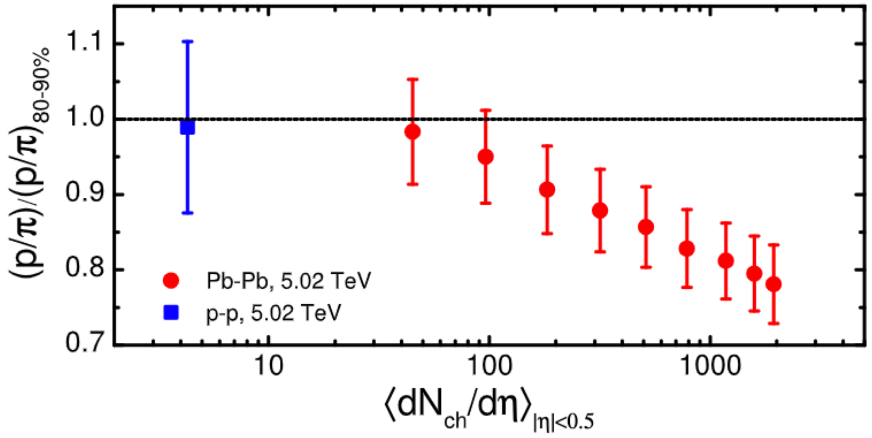


Figure 7: Transverse momentum integrated K/π (top) and p/π (bottom) ratios as a function of $\langle dN_{ch}/d\eta \rangle$ in Pb – Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared to Pb – Pb at 2.76 TeV [14]. The values in pp collisions at $\sqrt{s} = 5.02$ and 2.76 TeV are also shown. The empty 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).

- Evidence for suppression of p/pi ratio in central collisions ($\sim$20%, $>4\sigma$ level)
- Hadronic phase effect?

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 πN 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)

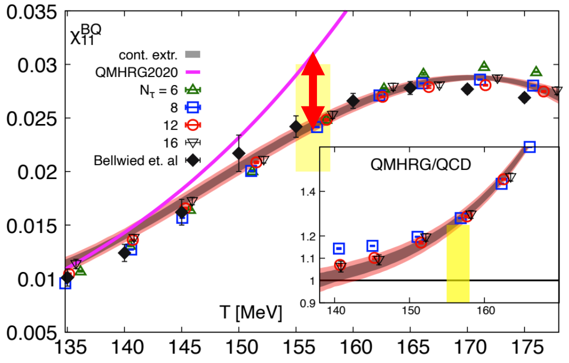
  centrality-independent

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

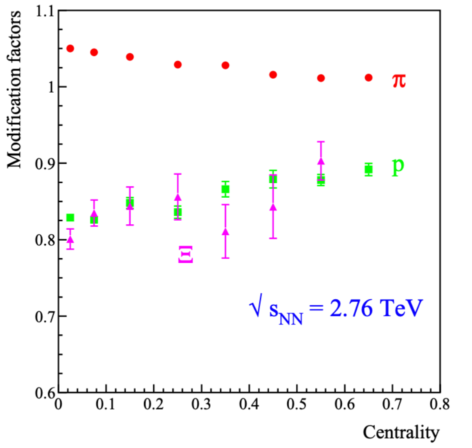
  centrality-dependent

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

Indications from lattice QCD



HotQCD Coll., PRD 104 (2021) 074512



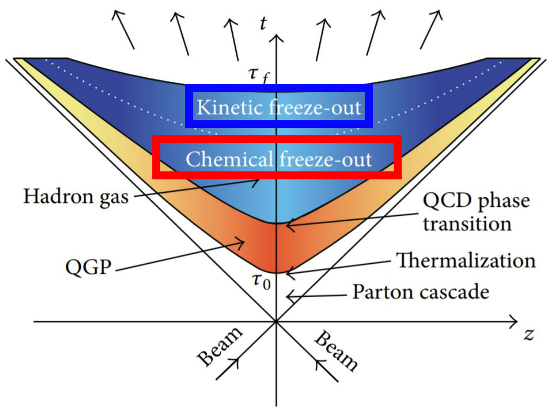
Becattini et al., PRC 90 (2014) 054907

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

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 maintaine through pseudo-elastic resonance reactions $\pi\pi \leftrightarrow \rho$, $\pi K \leftrightarrow K^*, \pi N \leftrightarrow \Delta$, etc.

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

Effective chemical potentials:

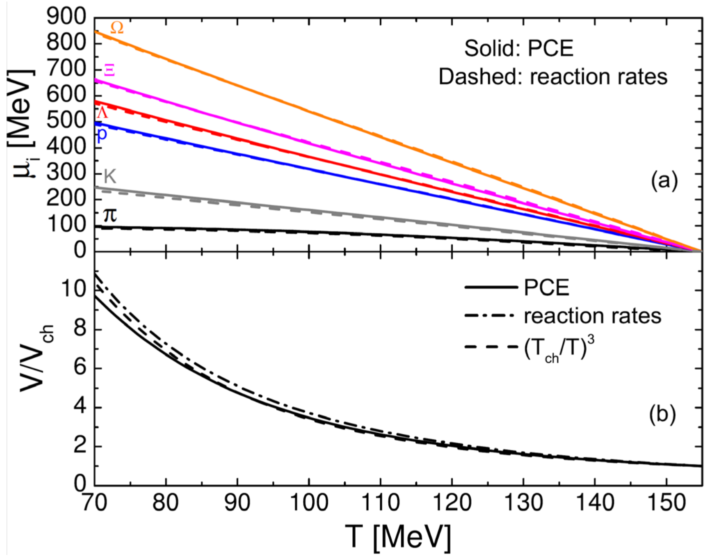
$$\tilde{\mu}_j = \sum_{i \in \text{stable}} \langle n_i \rangle_j \, \mu_i, \qquad \langle n_i \rangle_j \text{ – mean number of hadron } i \text{ from decays of hadron } j, \qquad j \in \text{HRG}$$

Conservation laws:

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

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

numerical solution → $\{\mu_i(T)\}, V(T)$



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

How to add baryon annihilation?

Partial chemical equilibrium with baryon annihilation

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

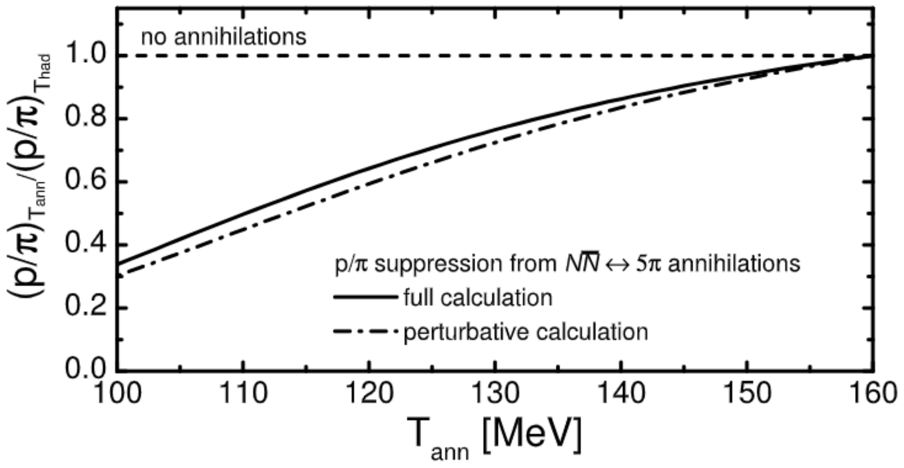
(Anti)nucleon and pions numbers no longer conserved, $N_N, N_{\bar{N}}, N_\pi \neq$ const. but

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

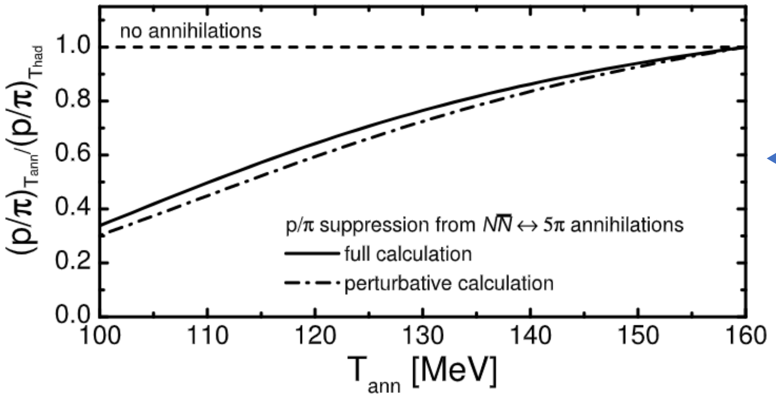
If $N\bar{N} \leftrightarrow 5\pi$ proceeds in relative equilibrium, $\mu_N = \mu_{\bar{N}} = \frac{5}{2}\mu_\pi$

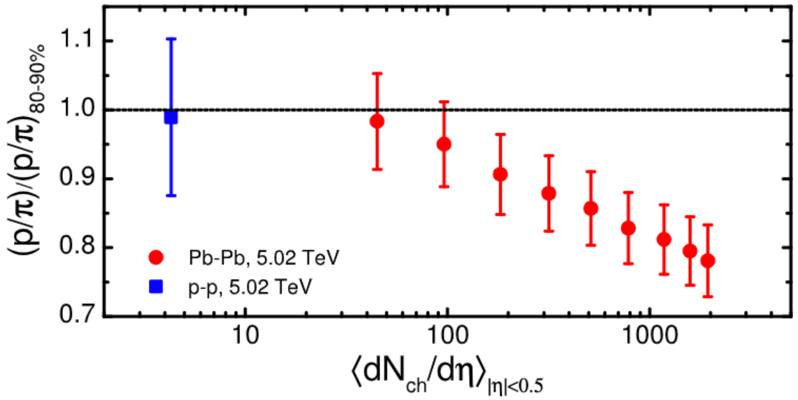
Also, $\pi N \leftrightarrow \Delta$ equilibrium implies $\Delta\bar{N} \leftrightarrow 6\pi$ and $\Delta\bar{\Delta} \leftrightarrow 7\pi$,
i.e. baryon resonances annihilate as well

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



Baryon annihilation freeze-out temperature





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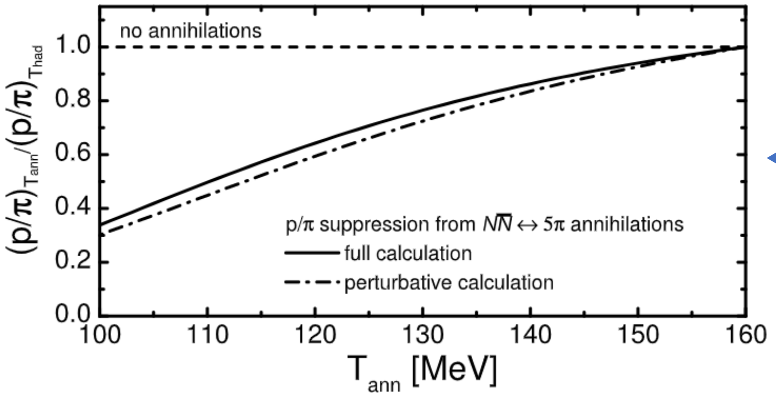
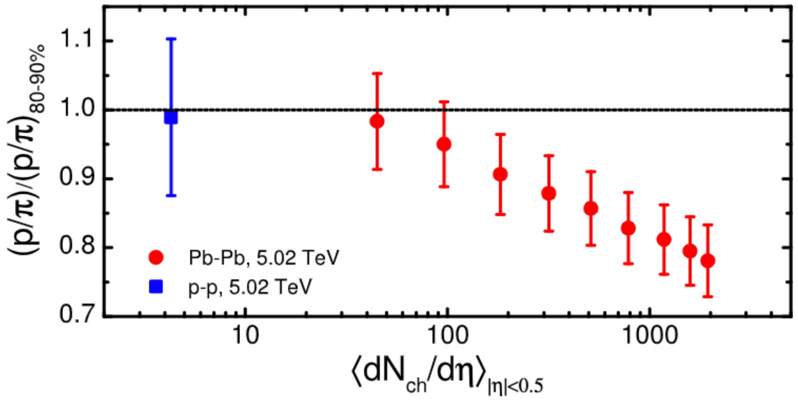
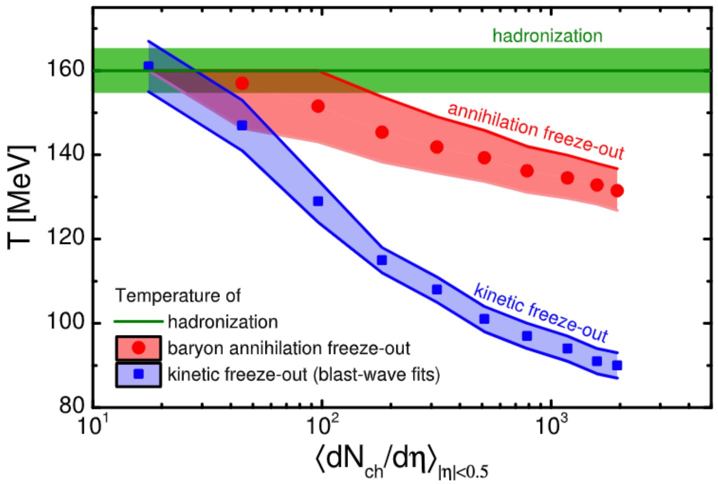




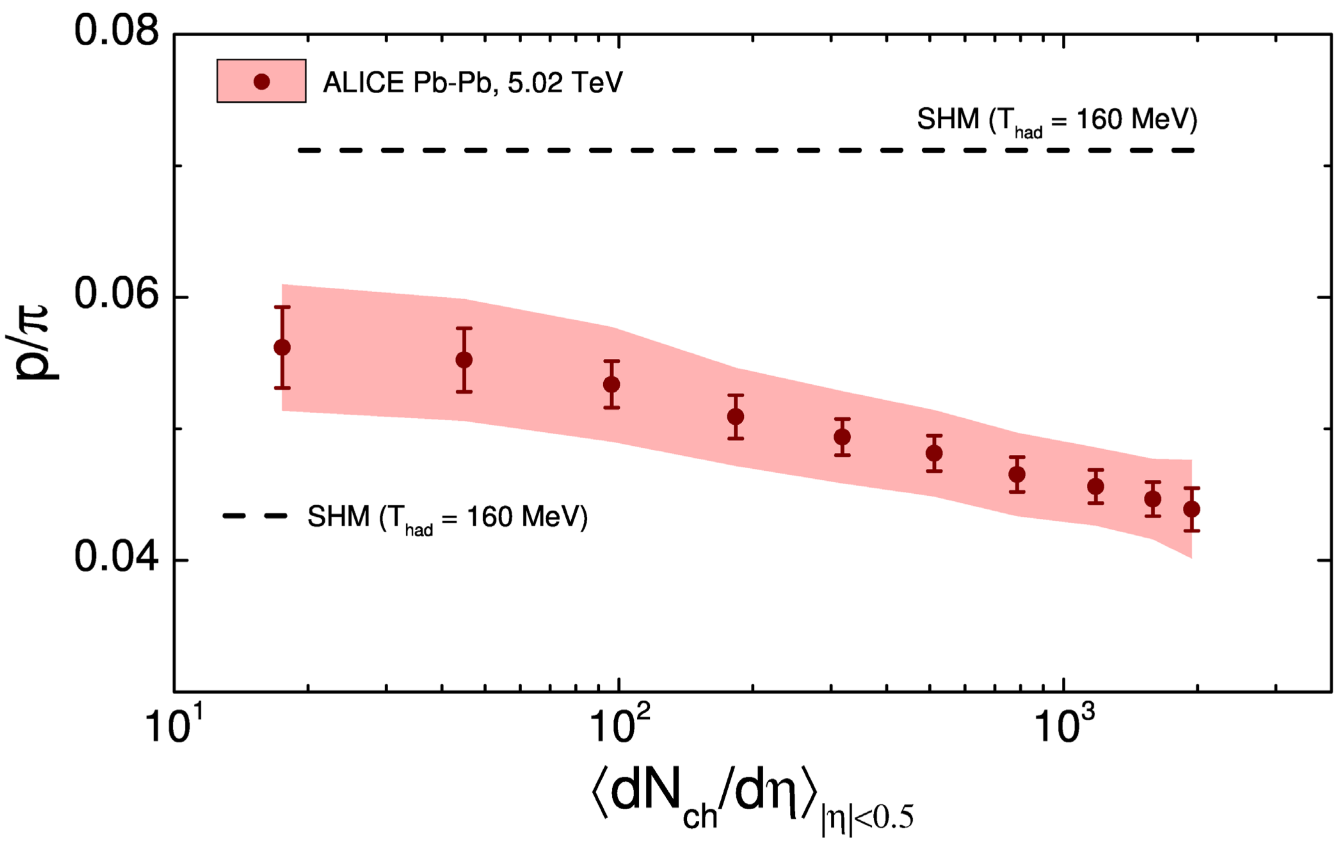


Centrality	$\langle dN_{ch}/d\eta \rangle$	T_{ann} [MeV]
0–5%	1943 ± 56	132 ± 5
5–10%	1587 ± 47	133 ± 5
10–20%	1180 ± 31	135 ± 5
20–30%	786 ± 20	136 ± 6
30–40%	512 ± 15	139 ± 6
40–50%	318 ± 12	142 ± 7
50–60%	183 ± 8	145 ± 8
60–70%	96.3 ± 5.8	152 ± 8
70–80%	44.9 ± 3.4	157^{+3}_{-11}
80–90%	17.5 ± 1.8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

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



Annihilation vs other mechanisms affecting the p/π ratio

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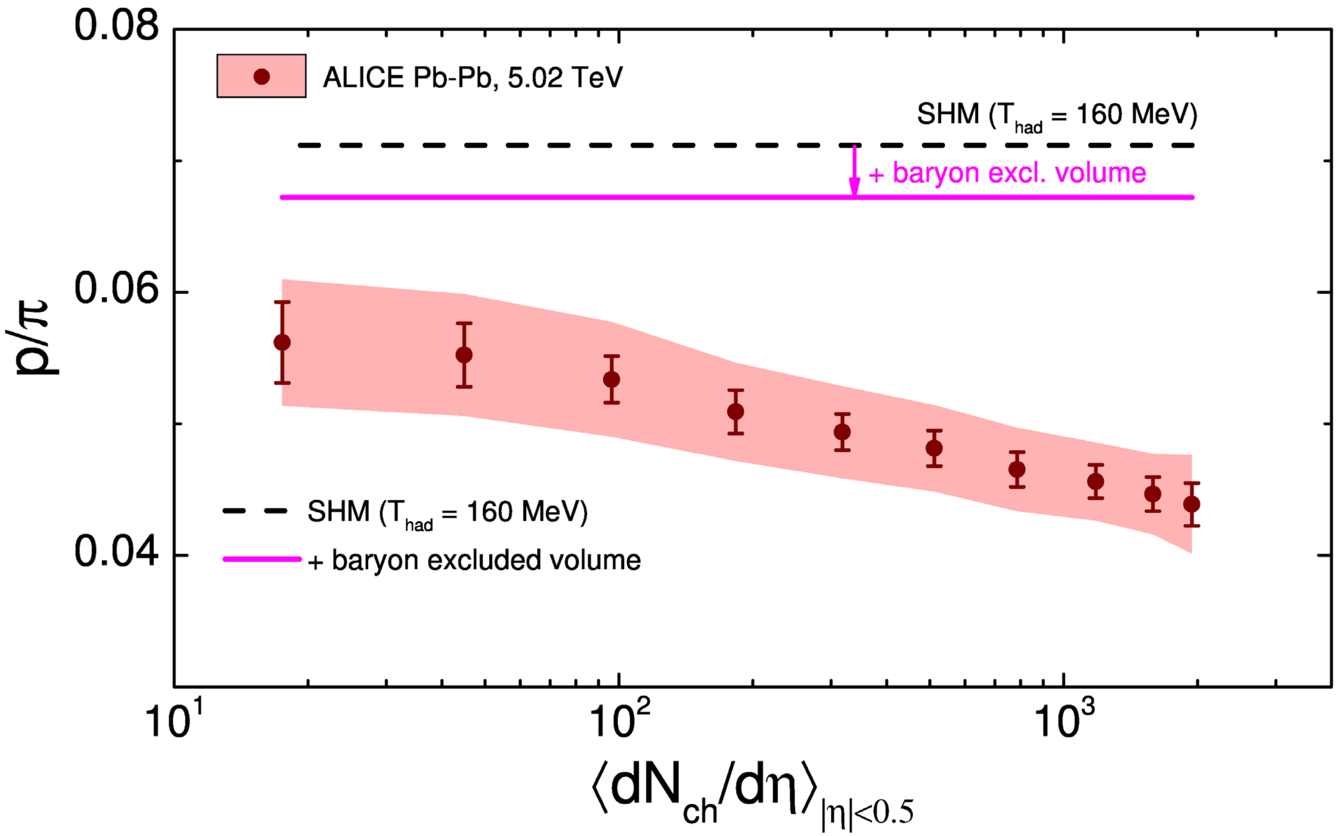
Baryon excl. volume
(baryon-baryon int.)
[VV et al., PLB 775 (2017) 71]



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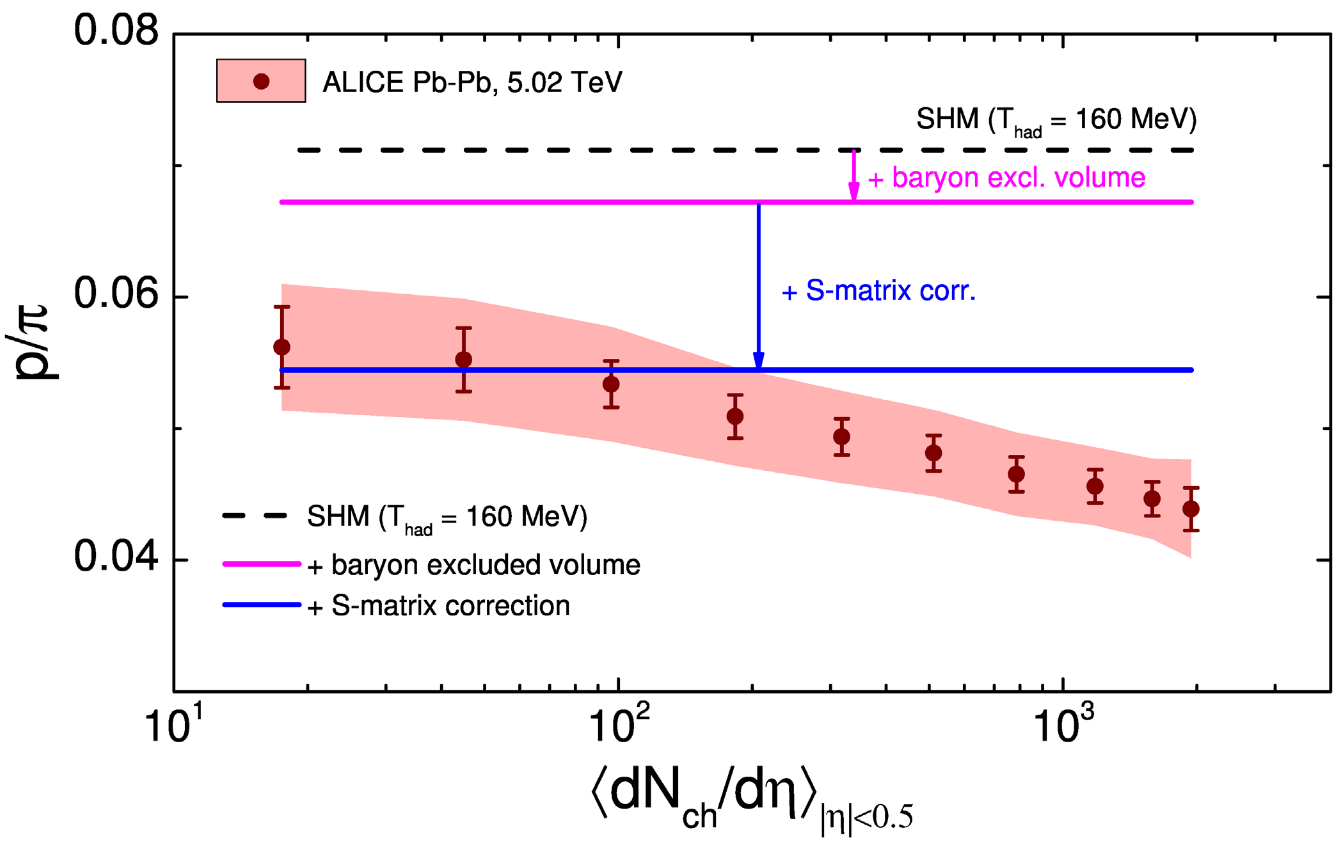
S-matrix correction
(meson-baryon int.)
[Andronic et al., PLB 792 (2019) 304]



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S-matrix correction
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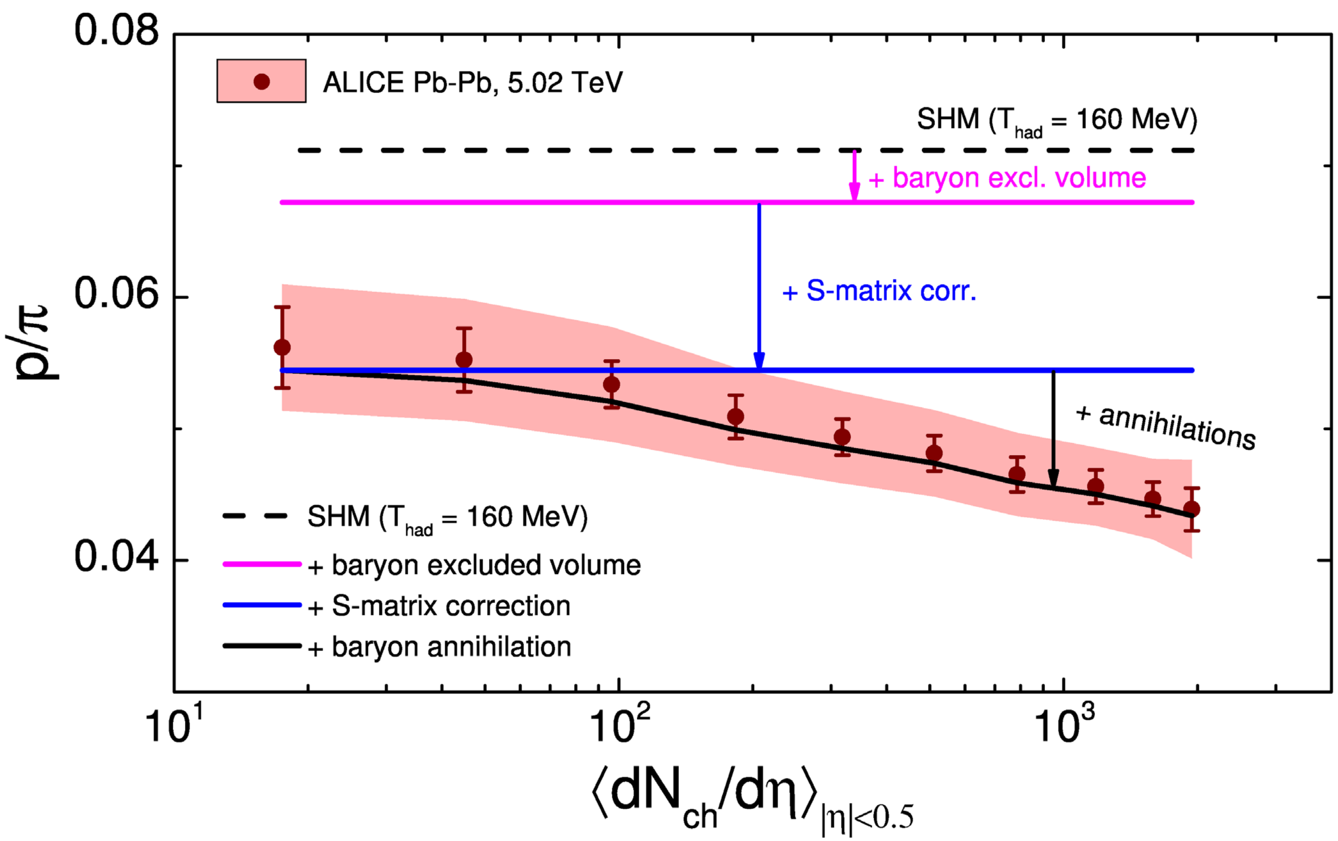
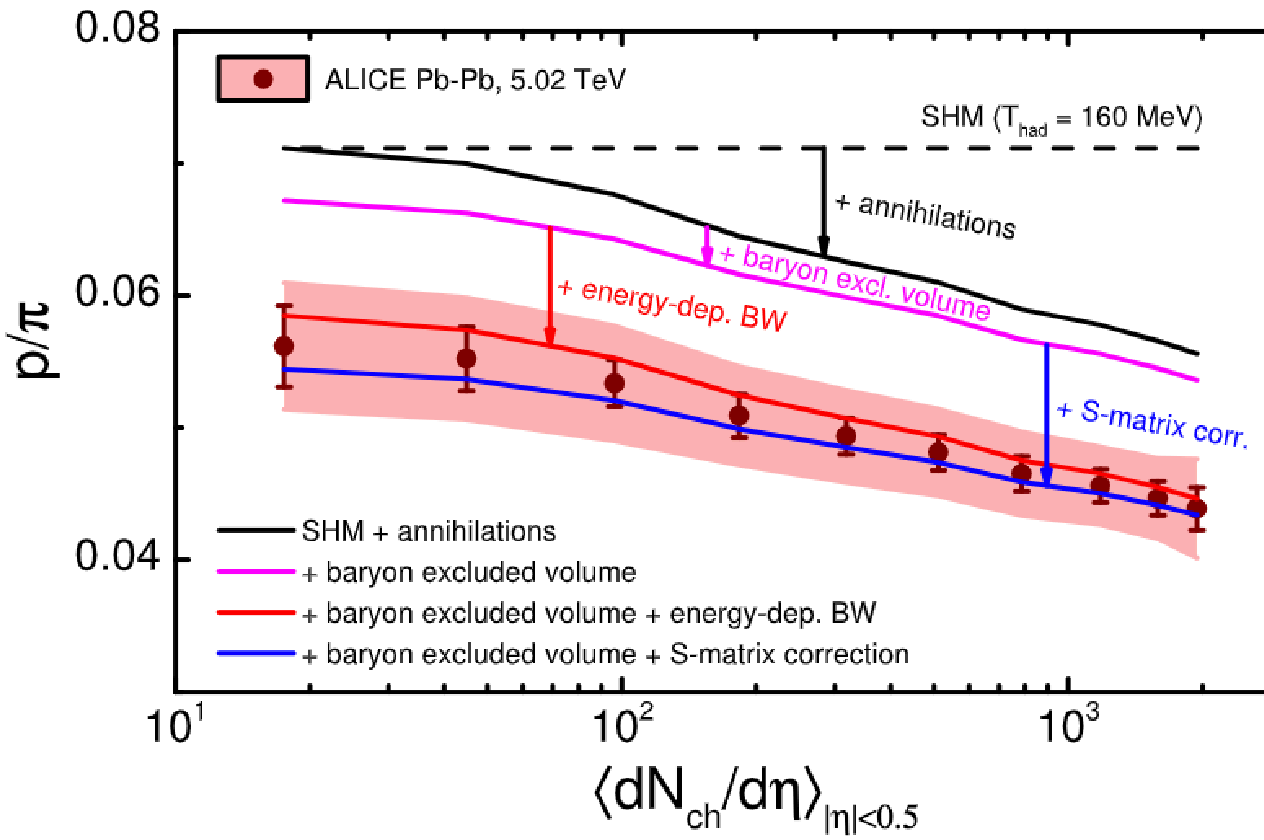
Baryon annihilation
(baryon-antibaryon int.)
[VV, Koch, PLB 835 (2022) 137577]



Baryon annihilation and other mechanisms are complementary

Another way to look at it

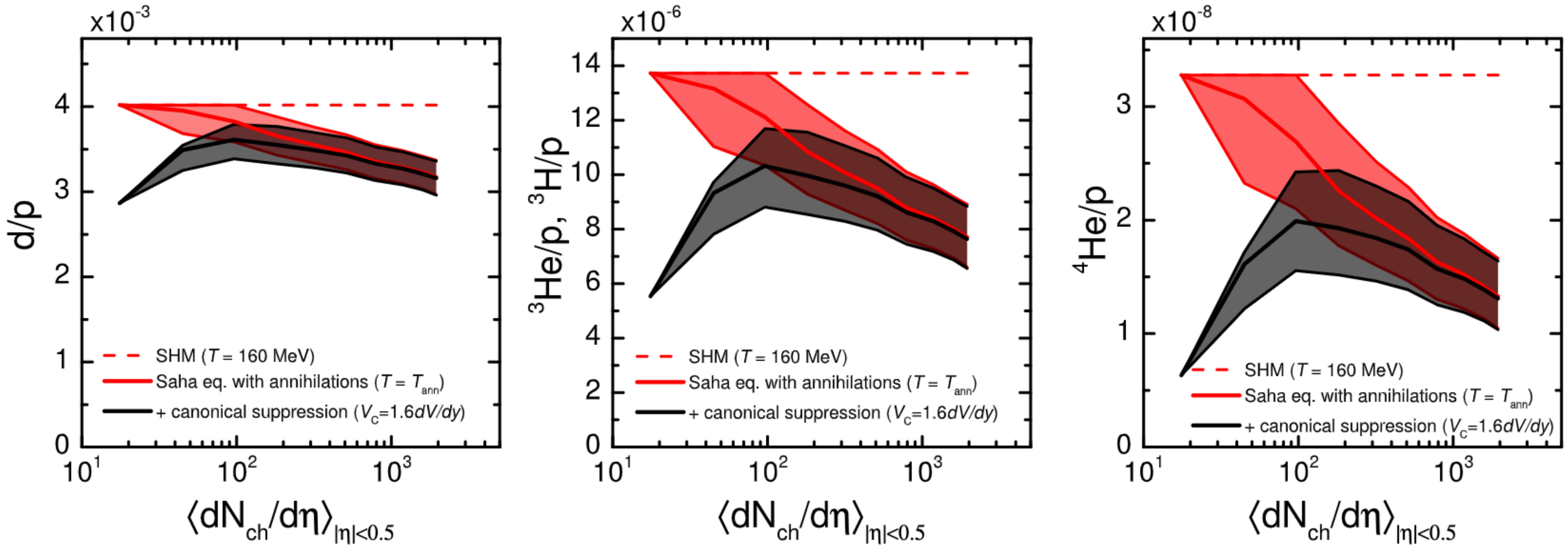


Baryon annihilation and other mechanisms are complementary

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, $\mu_A = A\mu_N$ [VV, Gallmeister, Schaffner-Bielich, Greiner, PLB 800 (2020) 135131]

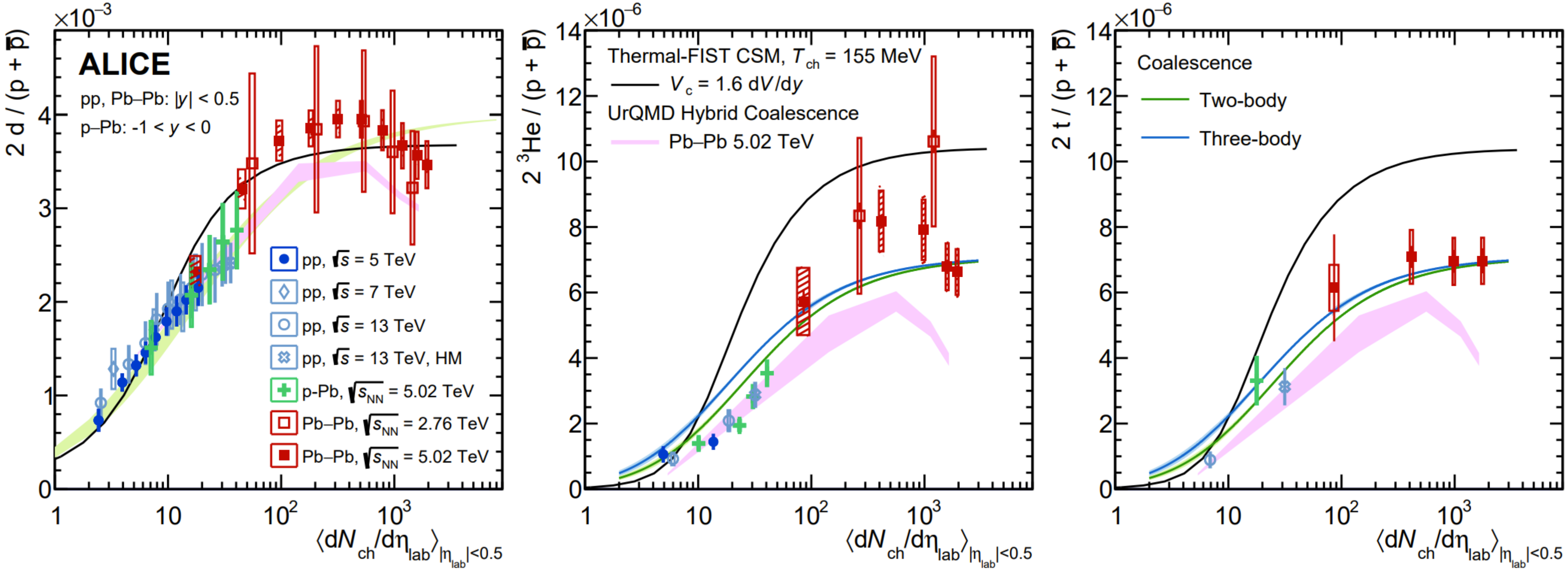


- Baryon annihilation causes ***suppression in central collisions***
- Possible *non-monotonic multiplicity dependence* due to (another) suppression in small systems

Can be tested with precision measurements of the centrality dependence

Baryon annihilation and light nuclei

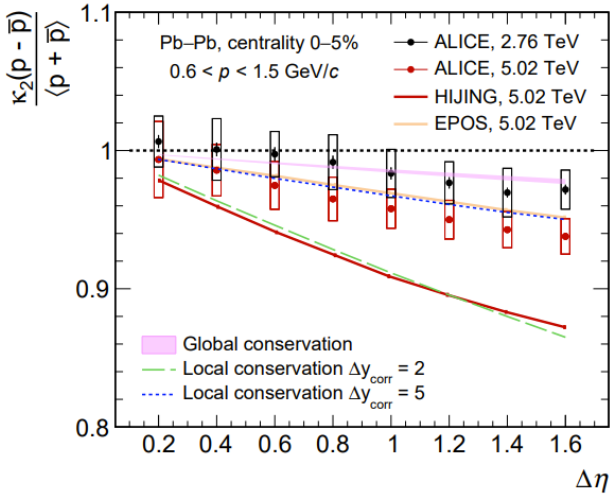
New data: ALICE Collaboration, arXiv:2211.14015



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

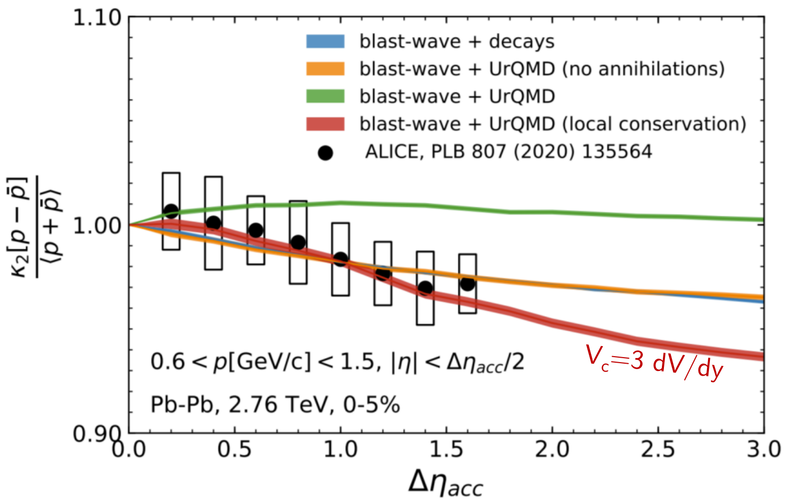
Baryon annihilation and e-by-e fluctuations and correlations

ALICE Coll., arXiv:2206.03343



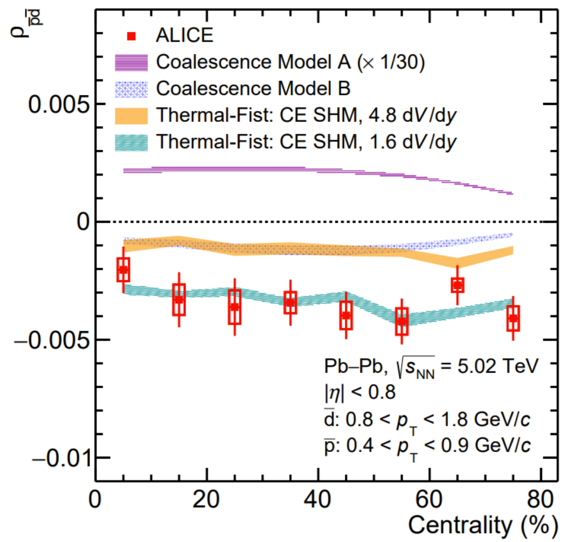
No annihilation

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



With UrQMD annihilation

ALICE Coll., arXiv:2204.10166



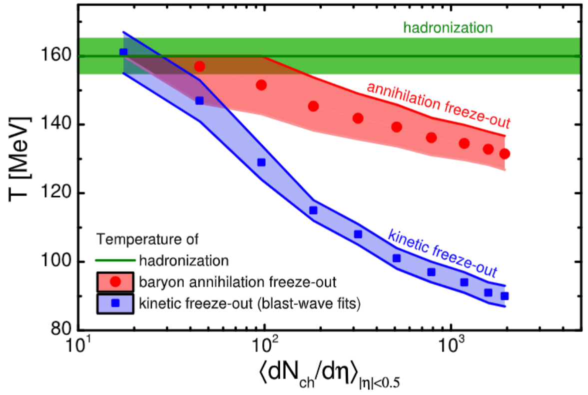
No annihilation

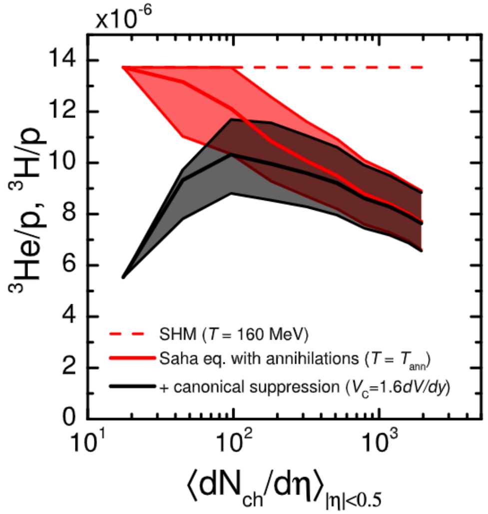
Baryon annihilation affects net-proton fluctuation measurements, making more "local" baryon conservation preferable

Can resolve the tension between proton fluctuations that seem to prefer "global" baryon conservation vs light nuclei data 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





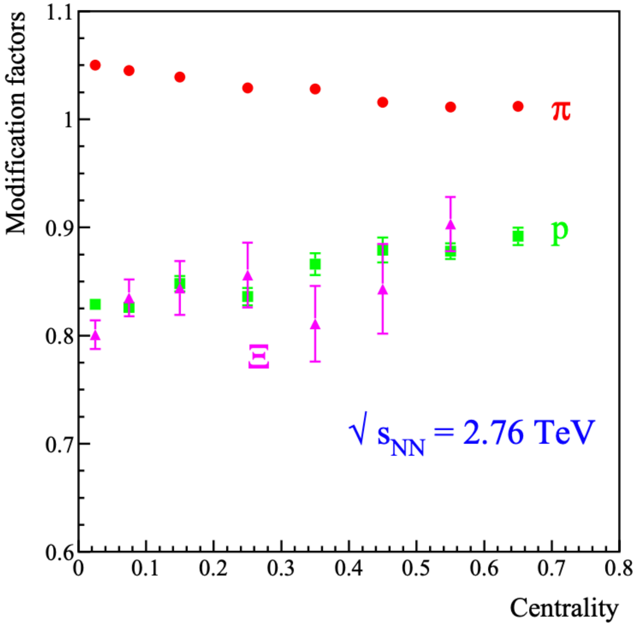
Thanks for your attention!

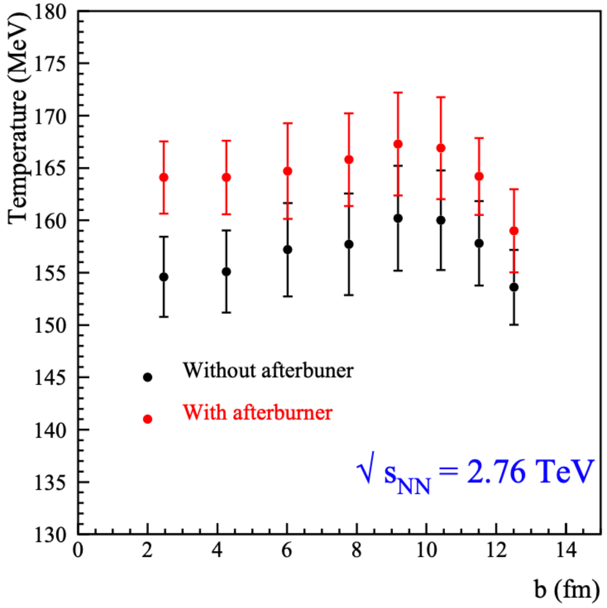
Backup slides

Hadronic afterburner

Model the hadronic phase with hadronic afterburner (UrQMD, SMASH)

Suppression of baryon abundances through baryon annihilation, e.g. $N\bar{N} \rightarrow 5\pi$





	T(MeV)	μ_B(MeV)	γ_S	χ^2/NDF
Pb-Pb 20% central $\sqrt{s_{\rm NN}} = 2.7$ TeV				
Std. fit	156 ± 5	1 ± 12	1.09 ± 0.07	26.5/9
Mod. fit	166 ± 3	2 ± 6	0.98 ± 0.04	11.5/9

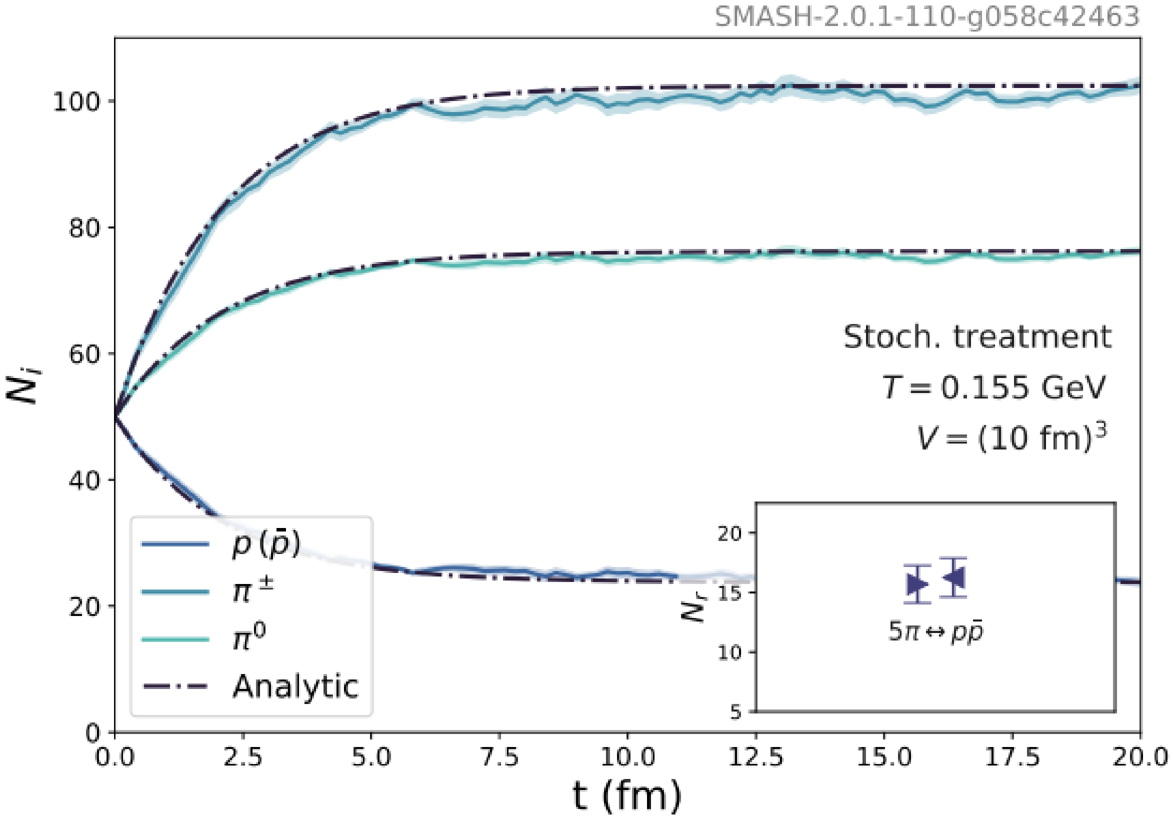
Issues:

- No backreaction*, $5\pi \rightarrow N\bar{N}$. Some baryons will regenerate [e.g. Rapp, Shuryak, PRL 86 (2001) 2980; Pan, Pratt, PRC 89 (2014) 044911]
- Global thermal fits may be affected by other theoretical uncertainties

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

Baryon annihilation in SMASH transport

Baryon annihilation in transport with stochastic rates



Garcia-Montero et al., PRC 105, 064906 (2022)