SMASH transport code and light nuclei production in heavy ion collisions

Dmytro (Dima) Oliinychenko

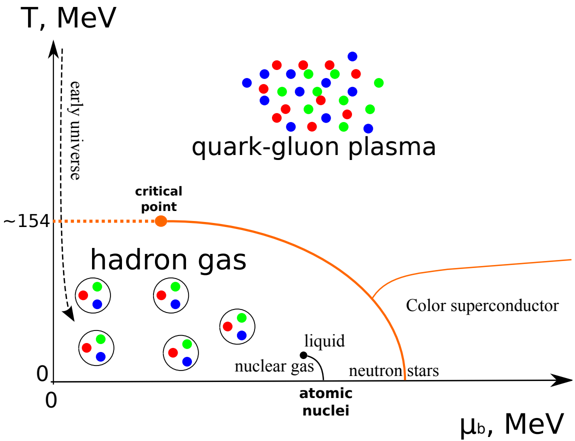
May 21, 2019

in collaboration with:
Volker Koch
LongGang Pang
Hannah (Petersen) Elfner

Phys.Rev. C99 (2019) no.4, 044907, arXiv:1809.03071
MDPI Proc. 10 (2019) no.1, 6, arXiv:1812.06225

BEST COLLABORATION

Where is phase transition/critical point?



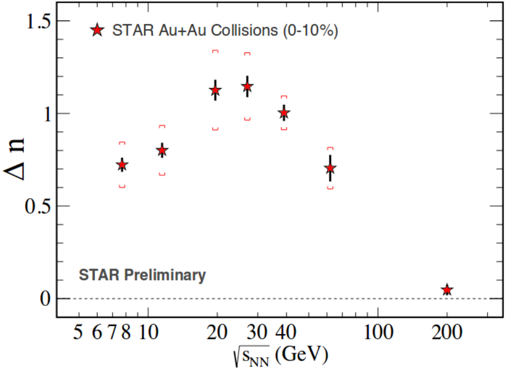
Generic critical point feature: fluctuations increase

Light nuclei production is related to nucleon density fluctuations in coordinate space

Kaijia Sun et al., Phys. Lett. B 774, 103 (2017)

$$\Delta n \equiv \frac{\langle(\delta n)^2\rangle}{\langle n\rangle^2},\ N_t \cdot N_p/N_d^2 \approx g(1+\Delta n),\ g \approx 0.29$$

derived using coalescence model



Dingwei Zhang, poster at Quark Matter 2018

Can one reproduce this without assuming critical point?

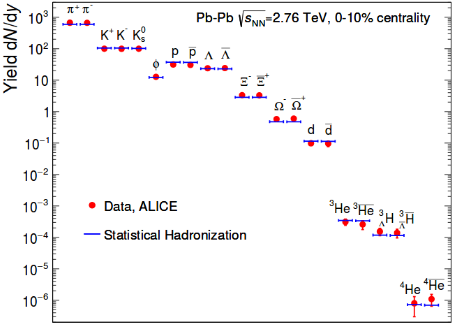
Coalescence models

- Nuclei are formed at late stages of collision, at kinetic freeze-out
- Nucleons bind into nuclei if they are close in phase space
  $E_A \frac{dN_A}{d^3P_A} = B_A \left(E_\mathrm{p} \frac{dN_\mathrm{p}}{d^3P_\mathrm{p}}\right)^Z \left(E_\mathrm{n} \frac{dN_\mathrm{n}}{d^3P_\mathrm{n}}\right)^N \Bigg|_{P_\mathrm{p}=P_\mathrm{n}=P_A/A}$
- In different types of coalescence models:
  $B_A \sim \left(\frac{4}{3}\pi p_0\right)^{A-1}$ or $B_A \sim V_{eff}^{-(A-1)}$
- $v_2^d(2p_T) = 2v_2^p(p_T)$

Thermal model

- Assumes rapid freeze-out of nuclei together with hadrons
- Deuteron yield in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV:
  $N_d = \frac{gV}{2\pi^2} T m^2 K_2(m/T)$, $T = 155$ MeV
- Deuteron: binding energy 2.2 MeV

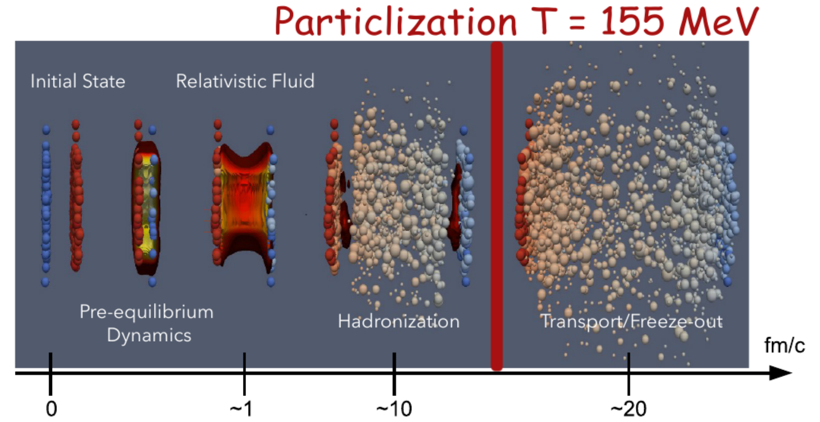
Snowballs in hell.



A. Andronic, et al., arXiv:1710.09425

Deuteron: rapid chemical freeze-out at 155 MeV, like hadrons?

Methodology: hybrid approach



- CLVisc hydro L. G. Pang, H. Petersen and X. N. Wang, arXiv:1802.04449 [nucl-th]
- SMASH hadronic afterburner J. Weil *et al.*, PRC 94, no. 5, 054905 (2016)
- Treat deuteron as a single particle
  - implement deuteron + X cross-sections explicitly

Most important deuteron production/disintegration reactions

Largest d + X disintegration rate $\rightarrow$ largest reverse production rate

Most important = largest $\sigma^{\rm inel}_{d+X} n_X$

X	$\sigma^{\rm inel}_{d+X}$ [mb] ($\sqrt{s} - \sqrt{s_{thr}} = [0.05, 0.25]$ GeV)	$\frac{dN^X}{dy}\|_{y=0}$
$\pi^{\pm}$	80 - 160	732
K^+	< 40	109
K^-	< 80	109
p	50 - 100	33
$\bar{p}$	80 - 200	33
γ	< 0.1	comparable to π?

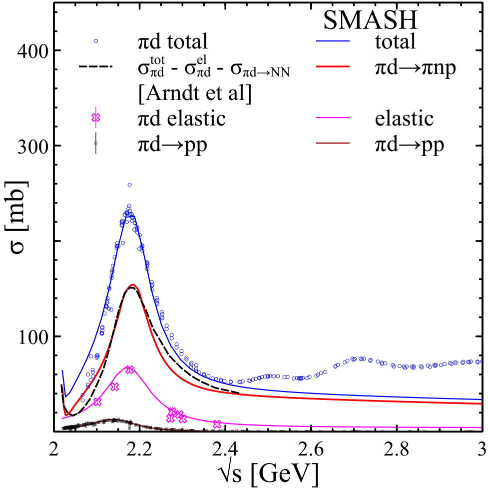
$\pi + d$ are the most important because of pion abundance

Reactions with deuteron implemented in SMASH

- $\pi d \leftrightarrow \pi np$, $\pi d \leftrightarrow np$, elastic $\pi d \leftrightarrow \pi d$
- $Nd \leftrightarrow Nnp$, elastic $Nd \leftrightarrow Nd$
- $\bar{N}d \leftrightarrow \bar{N}np$, elastic $\bar{N}d \leftrightarrow \bar{N}d$
- CPT conjugates of all above – reactions for anti-deuteron
- all are tested to obey detailed balance within 1% precision

$\pi d \leftrightarrow \pi np$ is the most important at high (LHC) energies
$Nd \leftrightarrow Nnp$ is the most important at low (AGS) energies

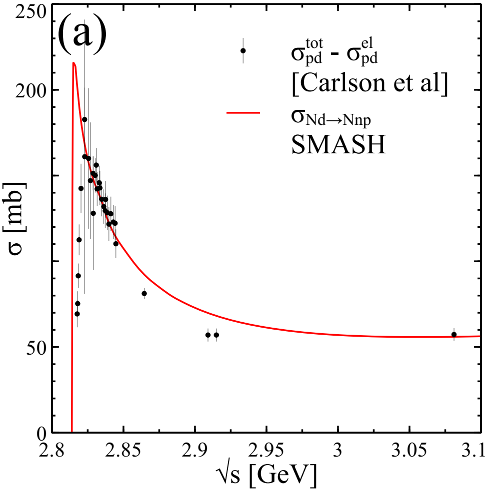
Reactions of deuteron with pions



$\pi d \leftrightarrow \pi np$ is the most important at LHC energies

$\sigma^{inel}_{\pi d} > \sigma^{el}_{\pi d}$, not like for hadrons

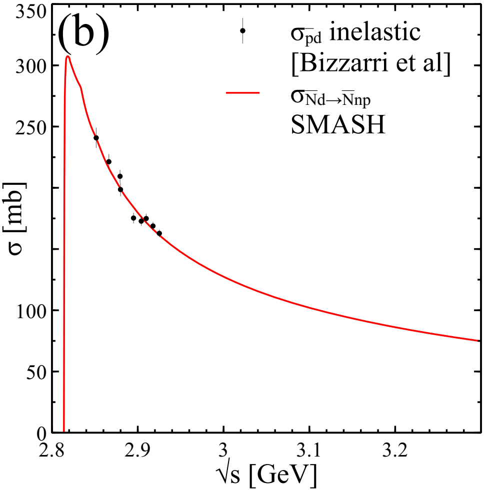
Reactions of deuteron with (anti-)nucleons



$Nd \leftrightarrow Nnp$, $\bar{N}d \leftrightarrow \bar{N}np$: large cross-sections

but not important at LHC energies, because N and $\bar{N}$ are sparse

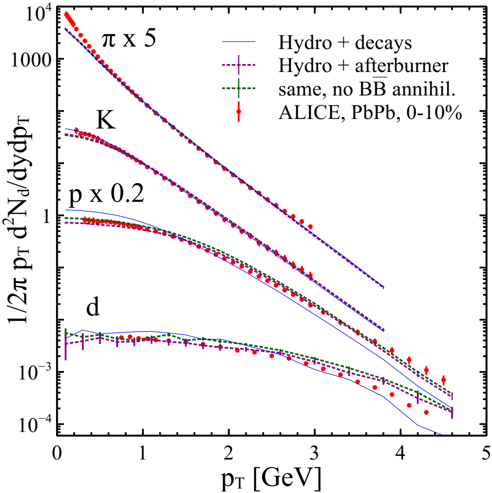
Reactions of deuteron with (anti-)nucleons



$Nd \leftrightarrow Nnp$, $\bar{N}d \leftrightarrow \bar{N}np$: large cross-sections

but not important at LHC energies, because N and $\bar{N}$ are sparse

Transverse momentum spectra

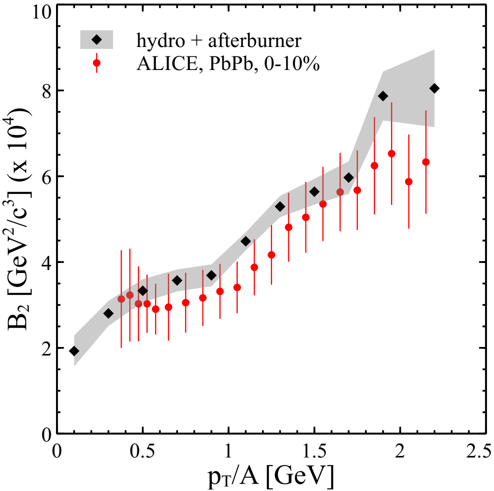


Pion and kaon spectra not affected by afterburner

Proton spectra: pion wind effect and $B\bar{B}$ annihilations ($\sim 10\%$)

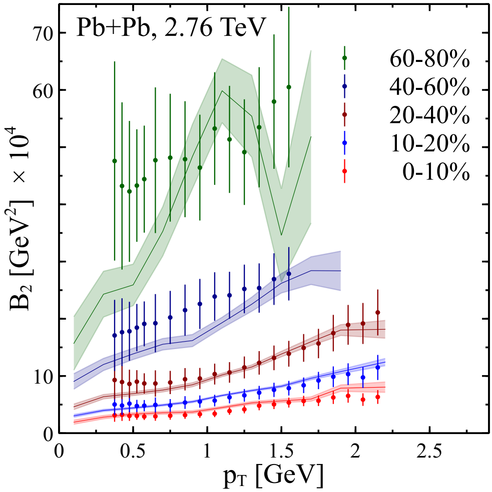
Obtaining $B_2(p_T)$ coalescence parameter

$$B_2(p_T) = \frac{\frac{1}{2\pi}\frac{d^2N_d}{p_T dp_T dy}\Big|_{p_T^d = 2p_T^p}}{\left(\frac{1}{2\pi}\frac{d^2N_p}{p_T dp_T dy}\right)^2}$$



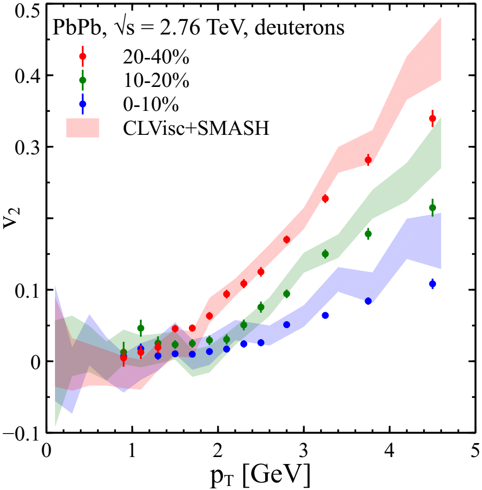
Reproducing B_2 without any free parameters

$B_2(p_T)$ for different centralities



Works well for all centralities

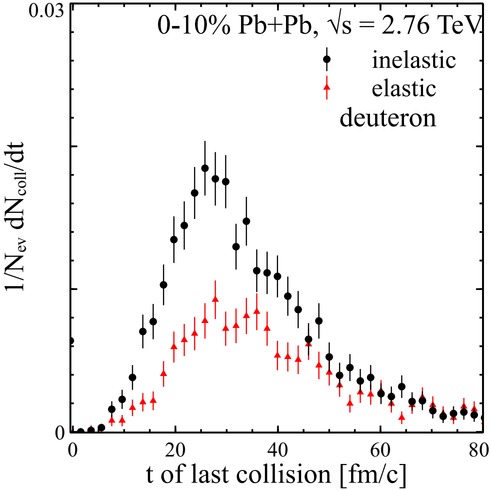
Deuteron v_2



PbPb, √s = 2.76 TeV, deuterons
20-40%
10-20%
0-10%
CLVisc+SMASH
0.5
0.4
0.3
0.1
0
−0.1
v_2
0
1
2
3
4
5
p_T [GeV]

Does deuteron freeze out at 155 MeV?

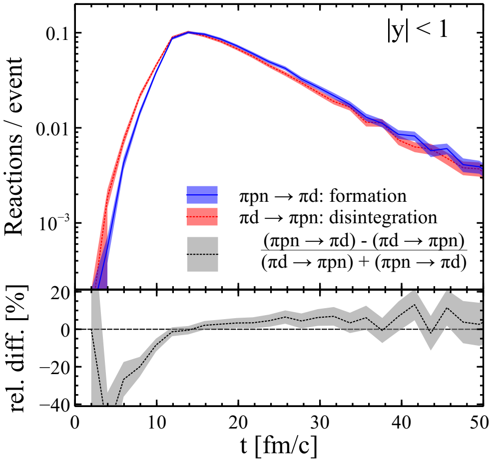
Only less than 1% of final deuterons original from hydrodynamics



Deuteron freezes out at late time

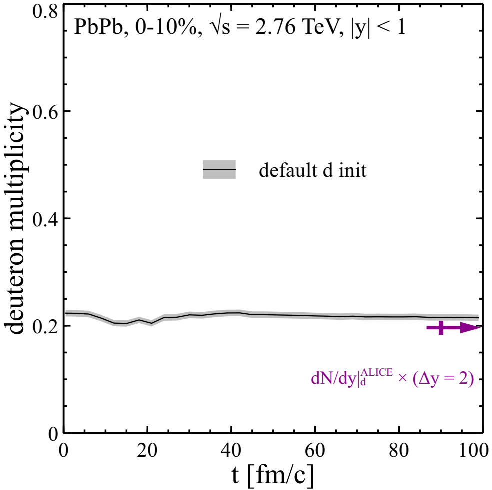
Its chemical and kinetic freeze-outs roughly coincide

Is $\pi d \leftrightarrow \pi np$ reaction equilibrated



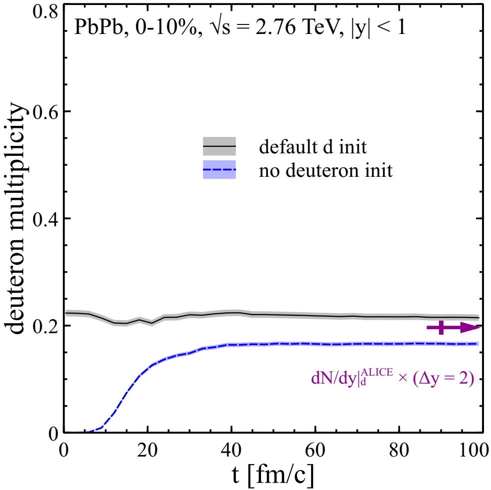
After about 12-15 fm/c within 5% $\pi d \leftrightarrow \pi np$ is equilibrated

Deuteron yield



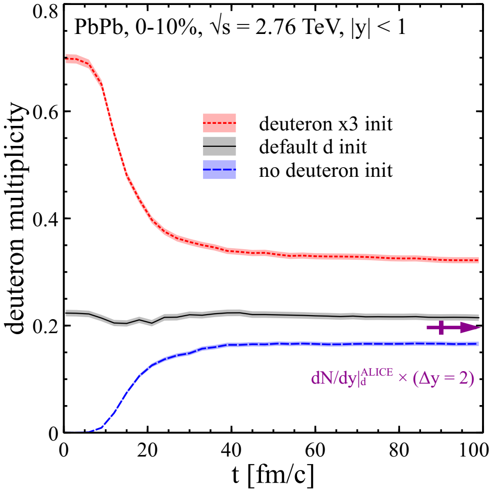
The yield is almost constant. Why? Does afterburner really play any role?

Deuteron yield



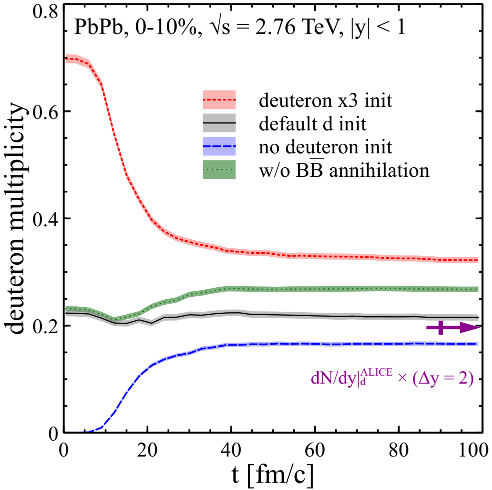
No deuterons at particlization: also possible. Here **all** deuterons are from afterburner.

Deuteron yield



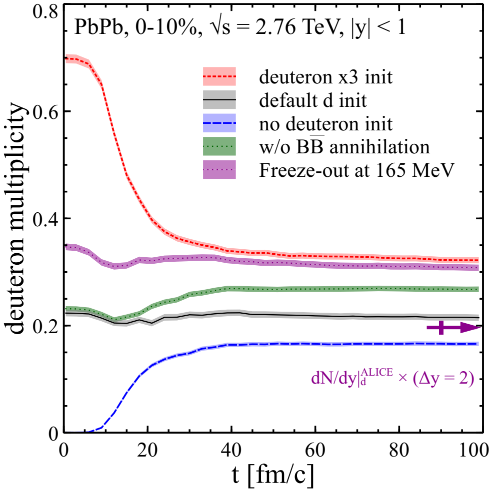
No deuterons at particlization: also possible. Here **all** deuterons are from afterburner.

Deuteron yield



Without $B\bar{B}$ annihilations yield coincidence is less impressive

Deuteron yield



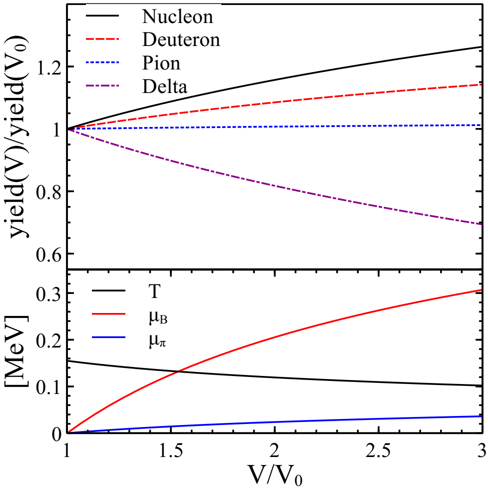
But it persists if T of particlization is changed to 165 MeV

Toy model of deuteron production: no annihilations

- only π, N, Δ, and d
- isoentropic expansion
- pion number conservation
- baryon (not net!) number conservation

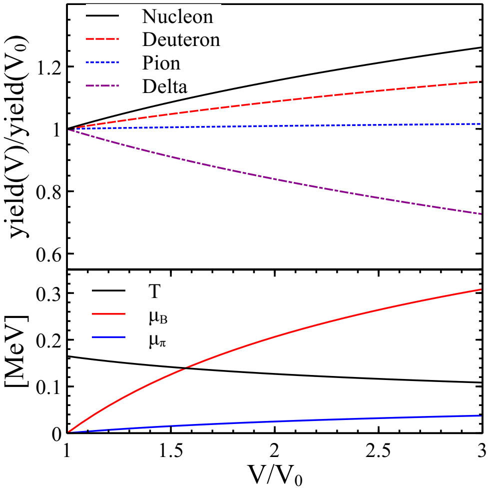
$$
\begin{aligned}
(s_\pi(T,\mu_\pi) + s_N(T,\mu_B) + +s_\Delta(T,\mu_B+\mu_\pi) + s_d(T,2\mu_B))V &= const \\
(\rho_\Delta(T,\mu_B+\mu_\pi) + \rho_\pi(T,\mu_\pi))V &= const \\
(\rho_N(T,\mu_B) + \rho_\Delta(T,\mu_B+\mu_\pi) + 2\rho_d(T,2\mu_B))V &= const
\end{aligned}
$$

Toy model of deuteron production: results



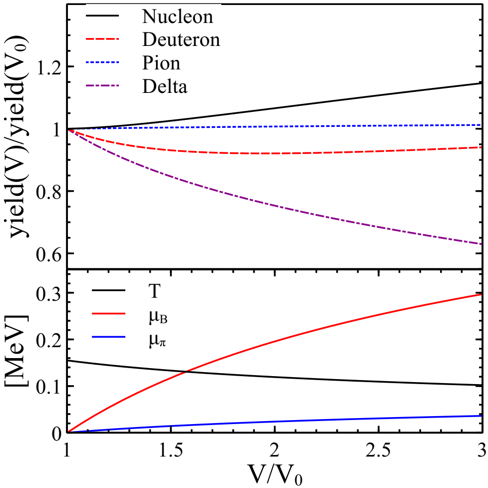
No annihilation: deuteron yield grows, like in simulation.

Toy model of deuteron production: results



$T_{\mathrm{particlization}} = 165$ MeV. Relative yields are similar, like in simulation.

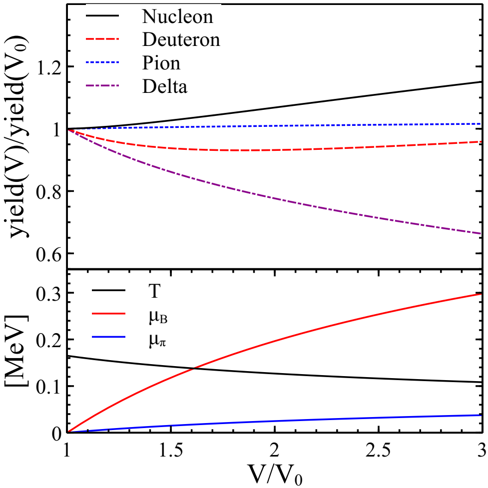
Toy model of deuteron production: results



Annihilation out of equilibrium: $\mu_B = \mu_B \frac{V/V_0}{a+V/V_0}$, $a = 0.1$

$T_{\rm particlization} = 155$ MeV.

Toy model of deuteron production: results



Annihilation out of equilibrium: $\mu_B = \mu_B \frac{V/V_0}{a+V/V_0}$, $a = 0.1$

$T_{\mathrm{particlization}} = 165$ MeV. Qualitatively similar to our simulation.

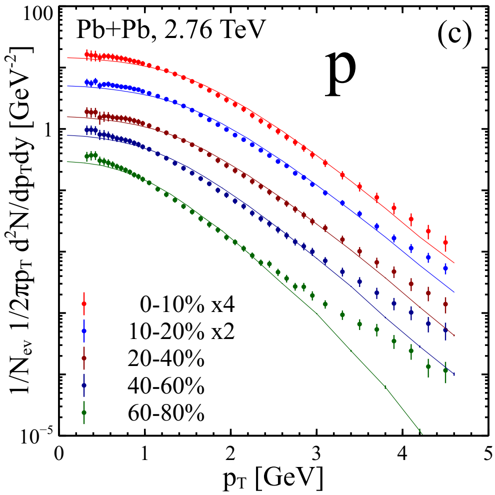
Summary

- $\pi d \leftrightarrow \pi pn$: most important deuteron producing / disintegrating reaction at LHC
- deuteron does not freeze-out at 155 MeV
- chemical and kinetic freeze-outs of deuteron roughly coincide
- deuteron yield stays constant after particlization, as thermal model assumes
  - reason: interplay of $\pi d \leftrightarrow \pi pn$ (d $\uparrow$) close to equilibrium and $B\bar{B}$ annihilations out of equilibrium (d $\downarrow$)

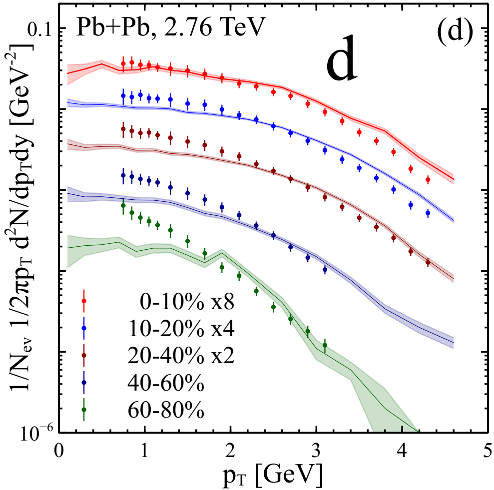
Outlook

- Deuteron: ongoing work on d production in pp
- d in AuAu at STAR BES, with SMASH / hydro + SMASH
- t and $^3\mathrm{He}$ via $dN\pi \leftrightarrow t\,\pi$, $dN\pi \leftrightarrow {}^3\mathrm{He}\,\pi$

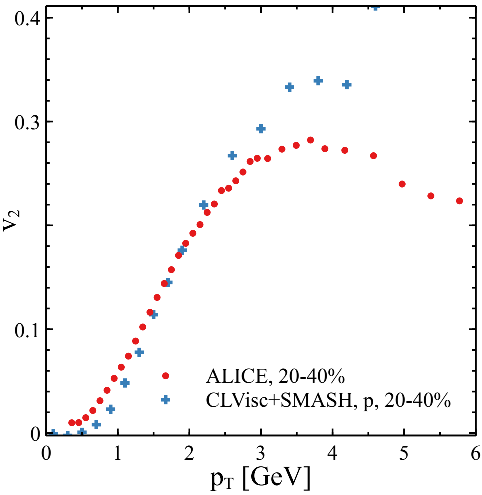
p_T-spectra for different centralities



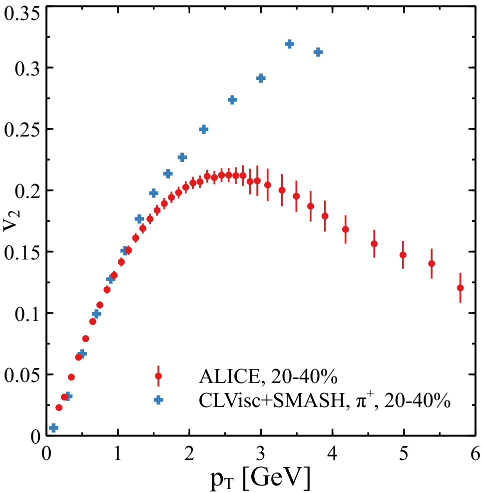
p_T-spectra for different centralities



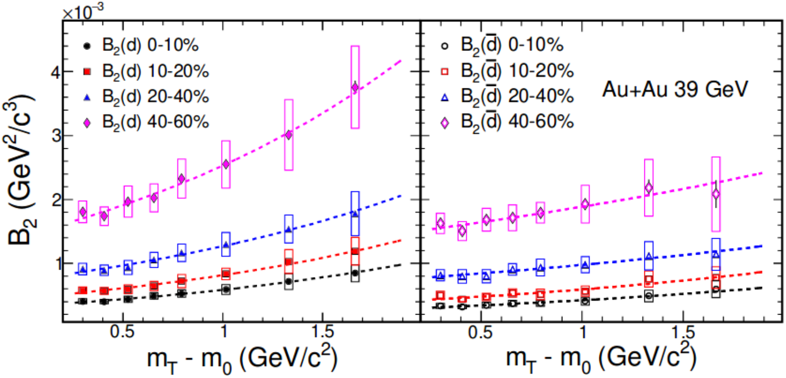
Proton and pion v_2



Proton and pion v_2



Dependencies of B_2

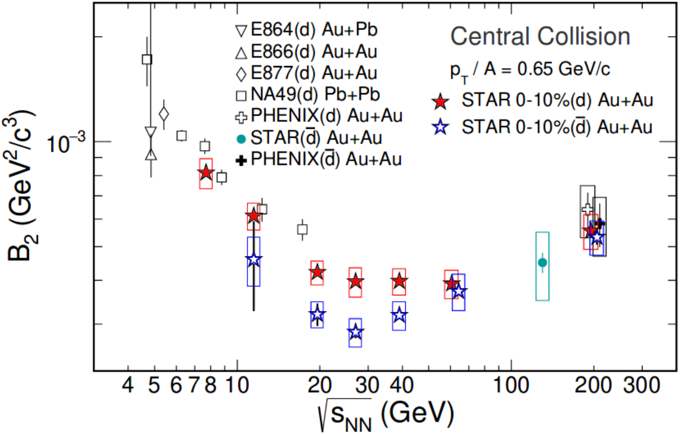


dependencies compatible with effective volume idea, $V_{eff} \sim V_{HBT}$

reliable extrapolations possible, but hard

R. Scheibl and U. W. Heinz, PRC **59**, 1585 (1999)

Dependencies of B_2

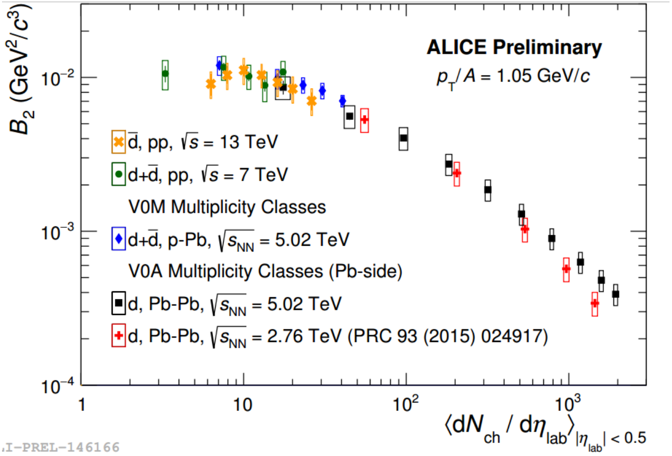


dependencies compatible with effective volume idea, $V_{eff} \sim V_{HBT}$

reliable extrapolations possible, but hard

R. Scheibl and U. W. Heinz, PRC **59**, 1585 (1999)

Dependencies of B_2



dependencies compatible with effective volume idea, $V_{eff} \sim V_{HBT}$

reliable extrapolations possible, but hard

R. Scheibl and U. W. Heinz, PRC **59**, 1585 (1999)

SMASH transport approach

Simulating
Multiple
Accelerated
Strongly-interacting
Hadrons

SMASH transport approach J. Weil et al., Phys.Rev. C94 (2016) no.5, 054905

- Monte-Carlo solver of relativistic Boltzmann equations

  BUU type approach, testparticles ansatz: $N \to N \cdot N_{test}$, $\sigma \to \sigma / N_{test}$

- Degrees of freedom
  - most of established hadrons from PDG up to mass 3 GeV
  - strings: do not propagate, only form and decay to hadrons

- Propagate from action to action (timesteps only for potentials)
  action $\equiv$ collision, decay, wall crossing

- Geometrical collision criterion: $d_{ij} \leq \sqrt{\sigma/\pi}$

- Interactions: $2 \leftrightarrow 2$ and $2 \to 1$ collisions, decays, potentials, string formation (soft - SMASH, hard - Pythia 8) and fragmentation via Pythia 8

SMASH: initialization

- "collider" - elementary or AA reactions, $E_{beam} \gtrsim 0.5\ A$ GeV
- "box" - infinite matter simulations

  detailed balance tests, computing transport coefficients, thermodynamics of hadron gas
  Rose et al., PRC 97 (2018) no.5, 055204
- "sphere" - expanding system

  comparison to analytical solution of Boltzmann equation,
  Tindall et al., Phys.Lett. B770 (2017) 532-538
- "list" - hadronic afterburner after hydrodynamics

SMASH: degrees of freedom

N	Δ	Λ	Σ	Ξ	Ω	Unflavored				Strange
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1189}	Ξ_{1321}	Ω^{-}_{1672}	π_{138}	$f_{0\,980}$	$f_{2\,1275}$	$\pi_{2\,1670}$	K_{494}
N_{1440}	Δ_{1620}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	Ω^{-}_{2250}	π_{1300}	$f_{0\,1370}$	$f'_{2\,1525}$		K^*_{892}
N_{1520}	Δ_{1700}	Λ_{1520}	Σ_{1660}	Ξ_{1690}		π_{1800}	$f_{0\,1500}$	$f_{2\,1950}$	$\rho_{3\,1690}$	$K_{1\,1270}$
N_{1535}	Δ_{1905}	Λ_{1600}	Σ_{1670}	Ξ_{1820}			$f_{0\,1710}$	$f_{2\,2010}$		$K_{1\,1400}$
N_{1650}	Δ_{1910}	Λ_{1670}	Σ_{1750}	Ξ_{1950}		η_{548}		$f_{2\,2300}$	$\phi_{3\,1850}$	K^*_{1410}
N_{1675}	Δ_{1920}	Λ_{1690}	Σ_{1775}	Ξ_{2030}		η'_{958}	$a_{0\,980}$	$f_{2\,2340}$		$K_0{}^*_{1430}$
N_{1680}	Δ_{1930}	Λ_{1800}	Σ_{1915}			η_{1295}	$a_{0\,1450}$		$a_{4\,2040}$	$K_2{}^*_{1430}$
N_{1700}	Δ_{1950}	Λ_{1810}	Σ_{1940}			η_{1405}		$f_{1\,1285}$		K^*_{1680}
N_{1710}		Λ_{1820}	Σ_{2030}			η_{1475}	ϕ_{1019}	$f_{1\,1420}$	$f_{4\,2050}$	$K_{2\,1770}$
N_{1720}		Λ_{1830}	Σ_{2250}				ϕ_{1680}			$K_3{}^*_{1780}$
N_{1875}		Λ_{1890}				σ_{800}		$a_{2\,1320}$		$K_{2\,1820}$
N_{1900}		Λ_{2100}					$h_{1\,1170}$			$K_4{}^*_{2045}$
N_{1990}		Λ_{2110}				ρ_{776}		$\pi_{1\,1400}$		
N_{2080}		Λ_{2350}				ρ_{1450}	$b_{1\,1235}$	$\pi_{1\,1600}$		
N_{2190}						ρ_{1700}				
N_{2220}							$a_{1\,1260}$	$\eta_{2\,1645}$		
N_{2250}						ω_{783}				
						ω_{1420}		$\omega_{3\,1670}$		
						ω_{1650}				

- Isospin symmetry
- Perturbative treatment of non-hadronic particles (photons, dileptons)

Hadrons and decay modes configurable via human-readable files

Interactions in SMASH

- Resonance formation and decay

  Ex. $\pi\pi \rightarrow \rho \rightarrow \pi\pi$, quasi-inlastic scattering
  $\pi\pi \rightarrow f_2 \rightarrow \rho\rho \rightarrow \pi\pi\pi\pi$

- (In)elastic $2 \rightarrow 2$ scattering

  parametrized cross-sections $\sigma(\sqrt{s}, t)$ or
  isospin-dependent matrix elements $|M|^2(\sqrt{s}, I)$

- String formation/fragmentation

  $2 \rightarrow n$ processes

- Potentials

  only change equations of motion

Interactions in SMASH

- Resonance formation and decay

  Ex. $\pi\pi \to \rho \to \pi\pi$, quasi-inlastic scattering
  $\pi\pi \to f_2 \to \rho\rho \to \pi\pi\pi\pi$

- (In)elastic $2 \to 2$ scattering

  parametrized cross-sections $\sigma(\sqrt{s}, t)$ or
  isospin-dependent matrix elements $|M|^2(\sqrt{s}, I)$

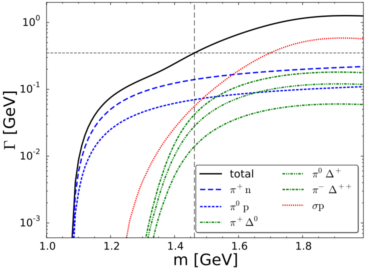
- String formation/fragmentation

  $2 \to n$ processes

- Potentials

  only change equations of motion

$N(1440)^+$



For every resonance:

- Breit-Wigner spectral function $\mathcal{A}(m) = \frac{2\mathcal{N}}{\pi} \frac{m^2\Gamma(m)}{(m^2 - M_0^2)^2 + m^2\Gamma(m)^2}$
- Mass dependent partial widths $\Gamma_i(m)$

  Manley formalism for off-shell width Manley and Saleski, Phys. Rev. D 45, 4002 (1992)
  Total width $\Gamma(m) = \sum_i \Gamma_i(m)$

Interactions in SMASH

- Resonance formation and decay

  Ex. $\pi\pi \rightarrow \rho \rightarrow \pi\pi$, quasi-inlastic scattering
  $\pi\pi \rightarrow f_2 \rightarrow \rho\rho \rightarrow \pi\pi\pi\pi$

- (In)elastic $2 \rightarrow 2$ scattering

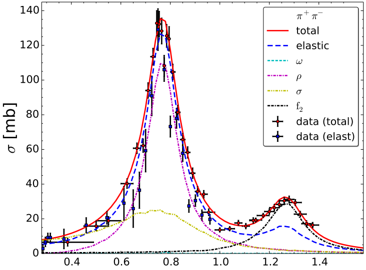
  parametrized cross-sections $\sigma(\sqrt{s}, t)$ or
  isospin-dependent matrix elements $|M|^2(\sqrt{s}, I)$

- String formation/fragmentation

  $2 \rightarrow n$ processes

- Potentials

  only change equations of motion



For every resonance:

- Breit-Wigner spectral function $\mathcal{A}(m) = \frac{2\mathcal{N}}{\pi} \frac{m^2\Gamma(m)}{(m^2 - M_0^2)^2 + m^2\Gamma(m)^2}$
- Mass dependent partial widths $\Gamma_i(m)$

  Manley formalism for off-shell width Manley and Saleski, Phys. Rev. D 45, 4002 (1992)
  Total width $\Gamma(m) = \sum_i \Gamma_i(m)$

- $2 \rightarrow 1$ cross-sections from detailed balance relations

Interactions in SMASH

- Resonance formation and decay

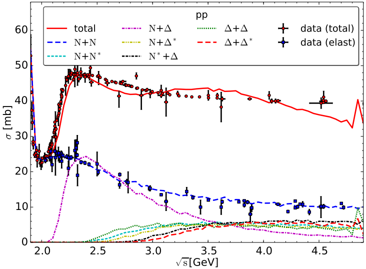
  Ex. $\pi\pi \to \rho \to \pi\pi$, quasi-inlastic scattering
  $\pi\pi \to f_2 \to \rho\rho \to \pi\pi\pi\pi$

- (In)elastic $2 \to 2$ scattering

  parametrized cross-sections $\sigma(\sqrt{s}, t)$ or
  isospin-dependent matrix elements $|M|^2(\sqrt{s}, I)$

- String formation/fragmentation

  $2 \to n$ processes



- Potentials

  only change equations of motion

- $NN \to NN^*$, $NN \to N\Delta^*$, $NN \to \Delta\Delta$, $NN \to \Delta N^*$, $NN \to \Delta\Delta^*$

  angular dependencies of $NN \to XX$ cross-sections implemented

- Strangeness exchange $KN \to K\Delta$, $KN \to \Lambda\pi$, $KN \to \Sigma\pi$

Interactions in SMASH

- Resonance formation and decay
  Ex. $\pi\pi \rightarrow \rho \rightarrow \pi\pi$, quasi-inlastic scattering
  $\pi\pi \rightarrow f_2 \rightarrow \rho\rho \rightarrow \pi\pi\pi\pi$
- (In)elastic $2 \rightarrow 2$ scattering
  parametrized cross-sections $\sigma(\sqrt{s}, t)$ or
  isospin-dependent matrix elements $|M|^2(\sqrt{s}, I)$
- String formation/fragmentation
  $2 \rightarrow n$ processes
- Potentials
  only change equations of motion

10 string model parameters
currently under tuning

- String (soft or hard) fragmentation: always via Pythia 8
- Hard scattering and string formation: Pythia
- Soft string formation: SMASH
  - single/double diffractive
  - $B\bar{B}$ annihilation
  - non-diffractive

Interactions in SMASH

- Resonance formation and decay

  Ex. $\pi\pi \to \rho \to \pi\pi$, quasi-inlastic scattering
  $\pi\pi \to f_2 \to \rho\rho \to \pi\pi\pi\pi$

- (In)elastic $2 \to 2$ scattering

  parametrized cross-sections $\sigma(\sqrt{s}, t)$ or
  isospin-dependent matrix elements $|M|^2(\sqrt{s}, I)$

- String formation/fragmentation

  $2 \to n$ processes

- Potentials

  only change equations of motion

  - Skyrme and symmetry potential
  - $U = a(\rho/\rho_0) + b(\rho/\rho_0)^\tau \pm 2S_{\text{pot}} \frac{\rho_{I3}}{\rho_0}$

    ρ - Eckart rest frame baryon density
    ρ_{I3} - Eckart rest frame density of I_3/I
    $a = -209.2$ MeV, $b = 156.4$ MeV, $\tau = 1.35$, $S_{\text{pot}} = 18$ MeV
    corresponds to incompressibility $K = 240$ MeV
    assures stability of a nucleus with Fermi motion

Transverse radius of Cu