

Deuterons at LHC: “snowballs in hell” via hydrodynamics and hadronic afterburner

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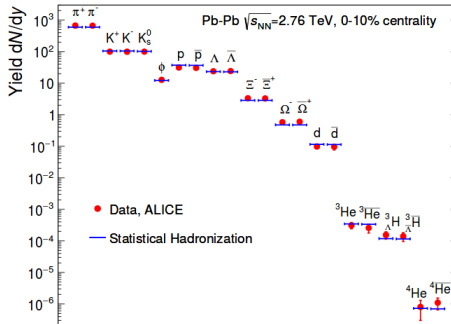


Deuteron in heavy ion collisions

- Bound state of proton and neutron, binding energy 2.2 MeV
- Deuteron yield in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV:

$$N_d = \frac{gV}{2\pi^2} T m^2 K_2(m/T), \quad T = 155 \text{ MeV}$$

Snowballs in hell.

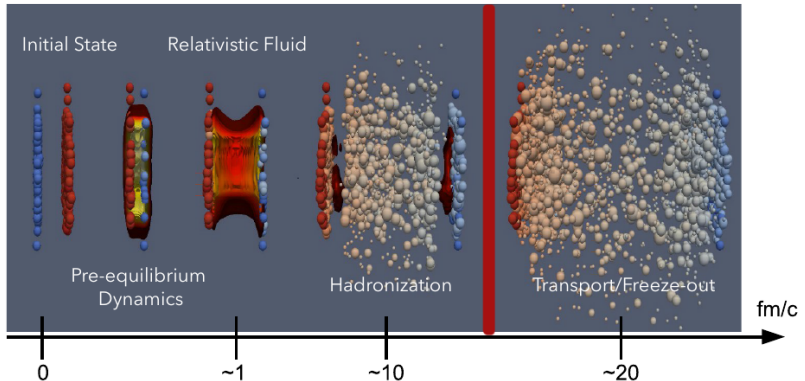


A. Andronic, et al., arXiv:1710.09425

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

Methodology: hybrid approach

Particlization $T = 155 \text{ MeV}$



- 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 $\sigma_{d+X}^{\text{inel}} n_X$

X	$\sigma_{d+X}^{\text{inel}}$ [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

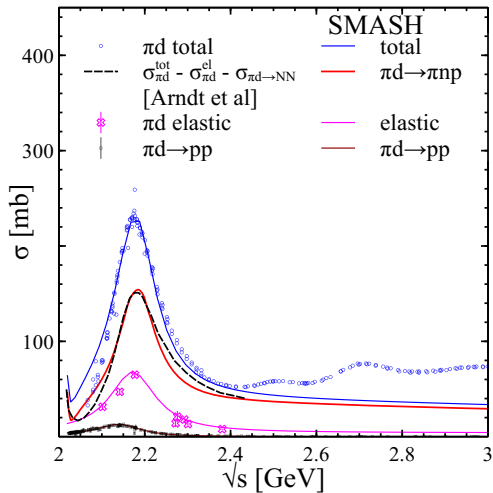
Reactions with deuteron implemented in SMASH

- $\pi d \leftrightarrow \pi np$, $\pi d \leftrightarrow np$, 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

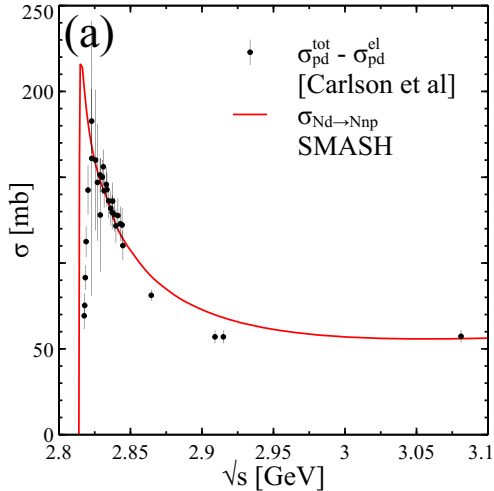
Reactions of deuteron with pions



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

$\sigma_{\pi d}^{\text{inel}} > \sigma_{\pi d}^{\text{el}}$, not like for hadrons

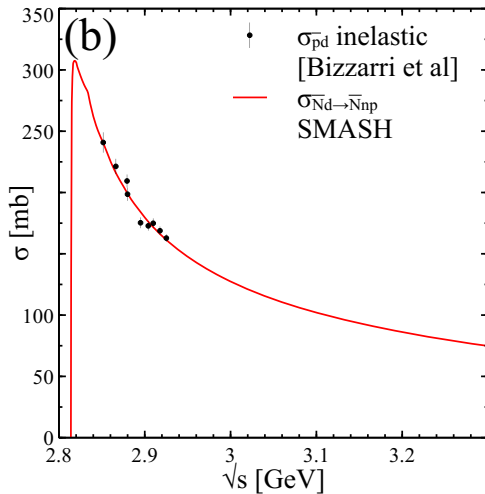
Reactions of deuteron with (anti-)nucleons



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

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

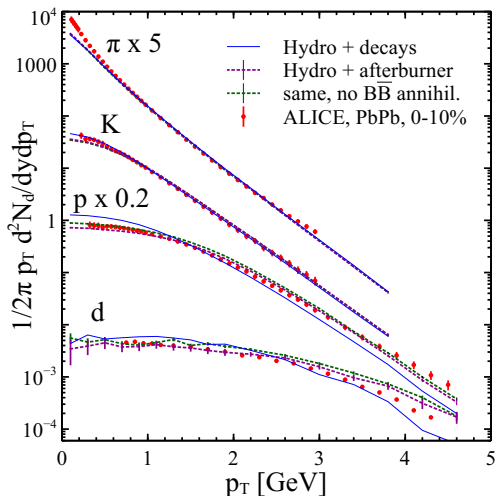
Reactions of deuteron with (anti-)nucleons



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Transverse momentum spectra

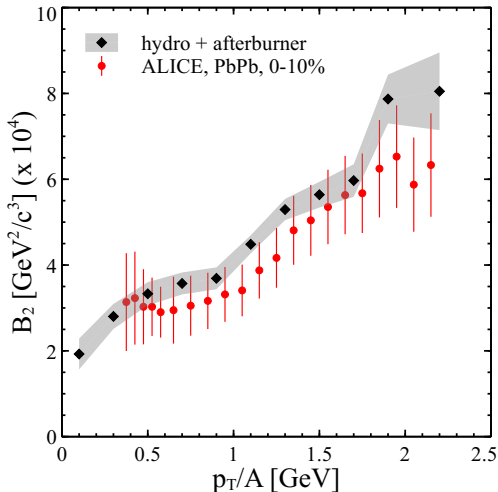


Pion and kaon spectra not affected by afterburner

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

Obtaining $B_2(p_T)$ coalescence parameter

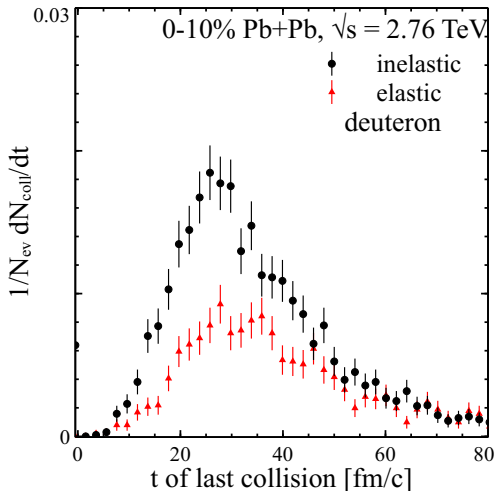
$$B_2(p_T) = \frac{\frac{1}{2\pi} \frac{d^2 N_d}{p_T dp_T dy} \big|_{p_T^d = 2p_T^p}}{\left(\frac{1}{2\pi} \frac{d^2 N_p}{p_T dp_T dy} \right)^2}$$



Reproducing B_2 without any free parameters

Does deuteron freeze out at 155 MeV?

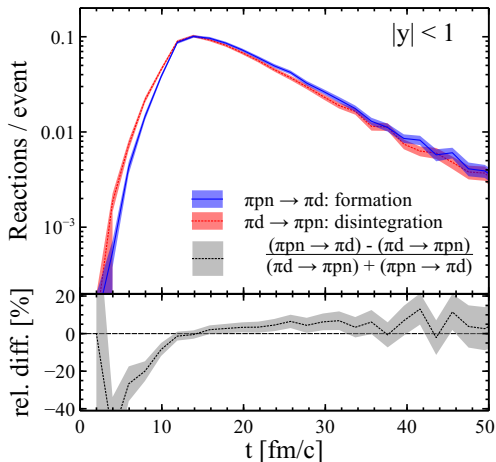
Only less than 1% of final deuterons original from hydrodynamics



Deuteron freezes out at late time

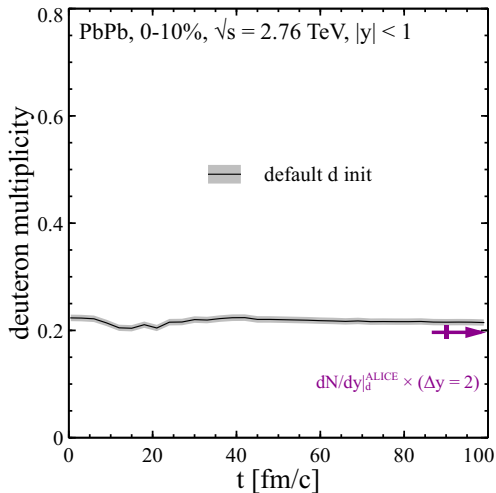
Its chemical and kinetic freeze-outs roughly coincide

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



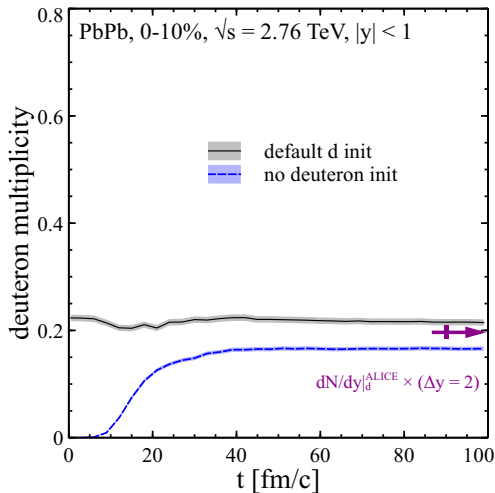
After about 12-15 fm/c within 5% $\pi d \leftrightarrow \pi np$ is equilibrated

Deuteron yield



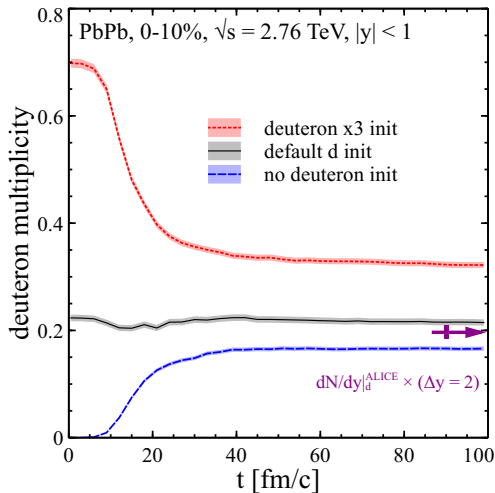
The yield is almost constant. Why? Does afterburner really play any role?

Deuteron yield



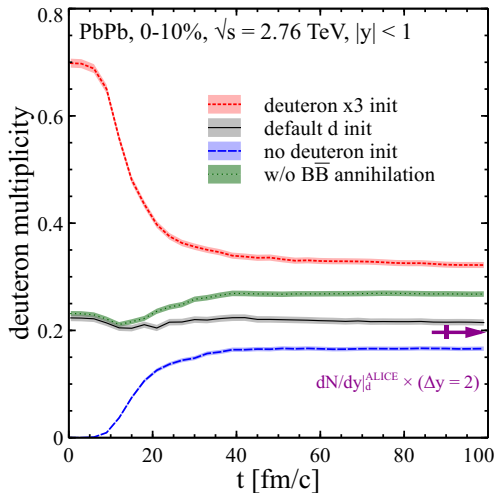
No deuterons at particlization: also possible. Here **all** deuterons are from afterburner.

Deuteron yield



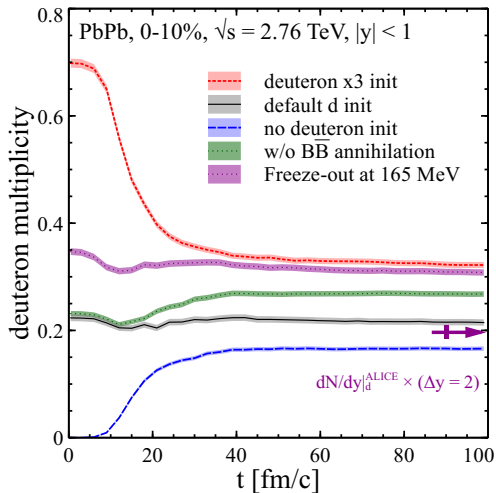
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Deuteron yield



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

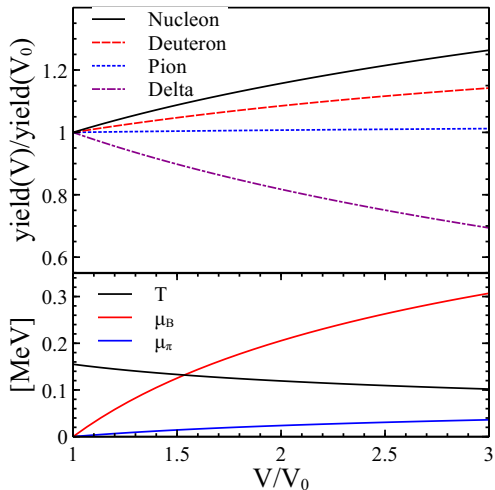
- only π , N , Δ , and d
- isoentropic expansion
- pion number conservation
- baryon (not net!) number conservation

$$(s_{\pi}(T, \mu_{\pi}) + s_N(T, \mu_B) + s_{\Delta}(T, \mu_B + \mu_{\pi}) + s_d(T, 2\mu_B))V = \text{const}$$

$$(\rho_{\Delta}(T, \mu_B + \mu_{\pi}) + \rho_{\pi}(T, \mu_{\pi}))V = \text{const}$$

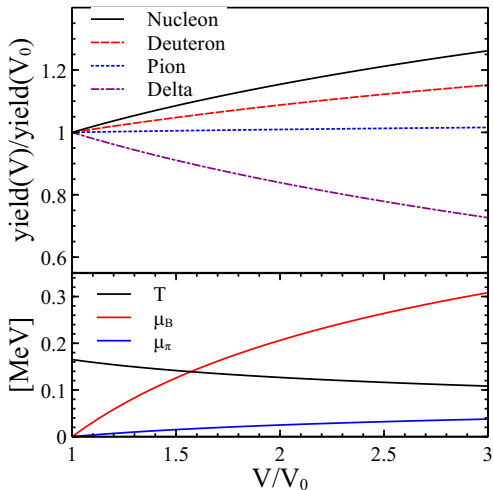
$$(\rho_N(T, \mu_B) + \rho_{\Delta}(T, \mu_B + \mu_{\pi}) + 2\rho_d(T, 2\mu_B))V = \text{const}$$

Toy model of deuteron production: results



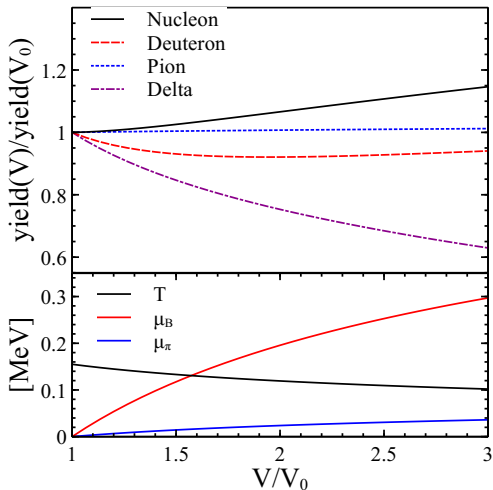
No annihilation: deuteron yield grows, like in simulation.

Toy model of deuteron production: results



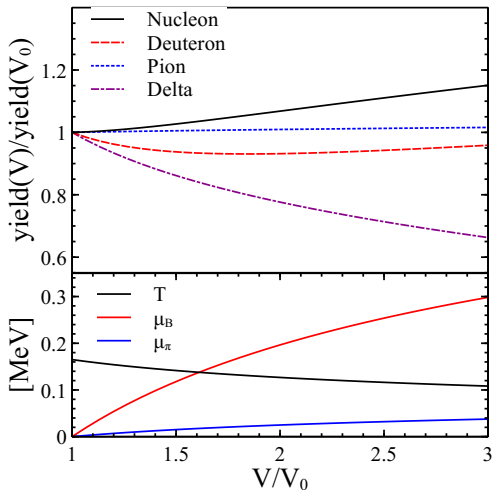
$T_{\text{particlization}} = 165 \text{ MeV}$. Relative yields are similar, like in simulation.

Toy model of deuteron production: results



Annihilation out of equilibrium: $\mu_B = \mu_B \frac{V/V_0}{a+V/V_0}$, $a = 0.1$
 $T_{\text{particization}} = 155 \text{ MeV}.$

Toy model of deuteron production: results



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

$T_{\text{particlization}} = 165 \text{ MeV}$. 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 ($d \downarrow$)

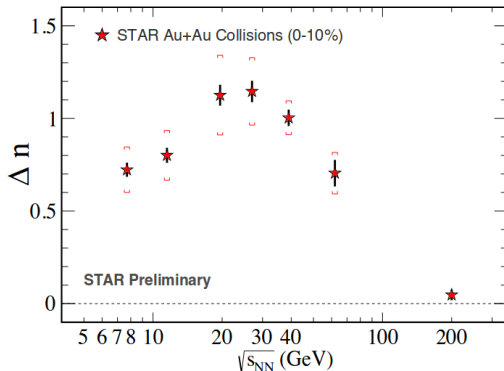
Outlook

- Deuteron: lower energies / smaller systems / other centralities
- Relation to proton density fluctuations and critical point

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

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

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



Dingwei Zhang, poster at Quark Matter 2018

Can one reproduce this with pure cascade?

Explanation of Siemens and Kapusta

Phys. Rev. Lett. 43, 1486 (1979)

- Originally applied at collision energy $E_{lab} < 1$ GeV
- Assume equilibrated $Nd \leftrightarrow Nnp$ reactions
- $f_d(x, p, S_z) = f_n(x, p/2, S_z - s_z) f_p(x, p/2, s_z)$
- $(2S_d + 1)N_d = 8(2S_N + 1) \int d^3p d^3x f_p^2(x, p)$
- Average nucleon phase-space density $\bar{f}_N \sim N_d/N_p$
- Entropy of nucleons per nucleon: $S_N = \frac{5}{2} - \log(2^{3/2} \bar{f})$

$$S_N \approx 3.95 - \log(N_d/N_p)$$

Low energies: $\approx$ all baryon number and entropy carried by nucleons

Hydrodynamic expansion: $S_N = \text{const} \rightarrow N_d/N_p = \text{const}$

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$$S_N \approx 3.95 - \log(N_d/N_p)$$

At LHC energies neither net baryon number nor total entropy are carried mostly by nucleons. Resonances? $B\bar{B}$ annihilations?

SMASH transport approach

Simulating

Multiple

Accelerated

Strongly-interacting

Hadrons

- Monte-Carlo solver of relativistic Boltzmann equations

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

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

SMASH: initialization

- “collider” - elementary or AA reactions, $E_{beam} \gtrsim 0.5 A \text{ GeV}$
- “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-inelastic 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

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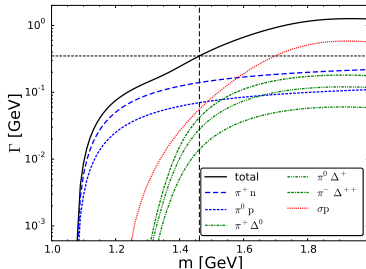
For every resonance:

- 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 $\Gamma(m) = \sum_i \Gamma_i(m)$

$N(1440)^+$



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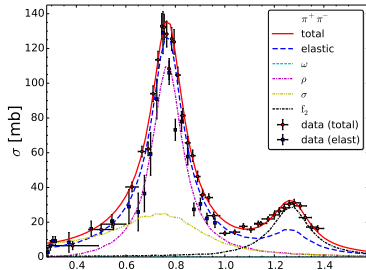
isospin-dependent matrix elements $|M|^2(\sqrt{s}, t)$

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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. $\pi\pi \rightarrow \rho \rightarrow \pi\pi$, quasi-inelastic scattering

$$\pi\pi \rightarrow f_2 \rightarrow \rho\rho \rightarrow \pi\pi\pi\pi$$

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

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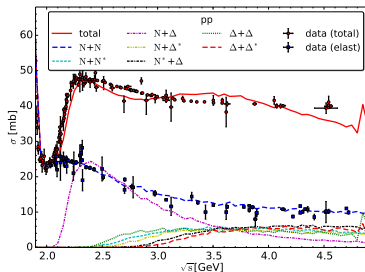
- Potentials

only change equations of motion

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

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

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



Interactions in SMASH

- Resonance formation and decay

Ex. $\pi\pi \rightarrow \rho \rightarrow \pi\pi$, quasi-inelastic scattering

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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

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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

