Threebody reactions in AA collsions

Eduard Seifert

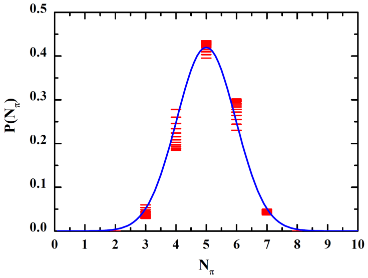
for the PHSD group

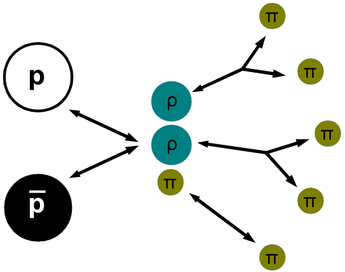
Institut für Theoretische Physik, Gießen

Lunchclub Seminar, 22.11.2017

Motivation

- In heavy-ion collisions the antibaryons formed inside baryonic matter annihilate depending on the energy to a couple of mesons and/or another baryon-antibaryon pair
- A possible description of such a reaction is the rearrangement of the quark content to 3 mesons $(0^-, 1^-, \ldots)$ $\longrightarrow$ decay to many pions and kaons in vacuum





[W. Cassing, NPA700(2002)618]

- $\langle N_\pi \rangle = 5$ realized through initial $\rho\rho\pi$ - with each ρ meson decaying to 2 pions
- For a physically correct description the backward reactions have to be implemented in transport
- Impact of these many-body reactions in heavy-ion collisions has to be checked
- Relative importance for different energy regions from FAIR/NICA to RHIC and LHC energies has to be investigated

Overview

1. Theory for multi-particle interactions
2. Test of n-particle detailed balance
3. Parton Hadron String Dynamics (PHSD)
4. PHSD simulations with extended many-body reactions
5. Summary

Theory for multi-particle interactions

- Covariant on-shell reaction rate inside a volume element $\mathrm{d}V$ and time interval $\mathrm{d}t$ for general particle number changing process [W. Cassing, NPA700(2002)618]

$$\frac{\mathrm{d}N_{\mathrm{coll}}[n \to m]}{\mathrm{d}t\mathrm{d}V} = \sum_{\nu}\sum_{\lambda}\int \prod_{j=1}^{n}\left(\frac{\mathrm{d}^3 p_j}{(2\pi)^3 2E_j}\right)\prod_{k=1}^{m}\left(\frac{\mathrm{d}^3 p_k}{(2\pi)^3 2E_k}\right)$$
$$\times\, W_{n,m}(p_j;\nu|p_k;\lambda)(2\pi)^4\delta^4\Big(\sum_{j=1}^{n} p_j^{\mu} - \sum_{k=1}^{m} p_k^{\mu}\Big)\prod_{j=1}^{n}(f_j(x,p_j))\prod_{k=1}^{m}(\tilde{f}_k(x,p_k))$$

$W_{n,m}$=Transition matrix element squared
f= phase-space distribution function
$\tilde{f} = 1 \pm f$ accounting for quantum statistics

- m-body phase-space, incorporates dynamics of the system in case of constant transition matrix element

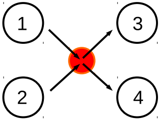
$$R_m(P^{\mu}; M_1, \dots, M_m) = \left(\frac{1}{(2\pi)^3}\right)^m \int \prod_{k=1}^{m}\frac{\mathrm{d}^3 p_k}{2E_k}\,(2\pi)^4\delta^4\left(P^{\mu} - \sum_{j=1}^{m} p_j^{\mu}\right)$$

- Relation for a $2 \to m$ reaction to the cross section for a pair with quantum numbers i, j

$$\sum_{m}\sum_{\lambda_m} W_{2,m}(P^{\mu} = p_1^{\mu} + p_2^{\mu}; i, j; \lambda_m) R_m(P^{\mu}; M_3, \dots, M_{m+1}) = 4E_1 E_2 v_{\mathrm{rel}}\sigma_{i,j}(\sqrt{s})$$

[E. Byckling, K. Kajantie, *Particle Kinematics*]

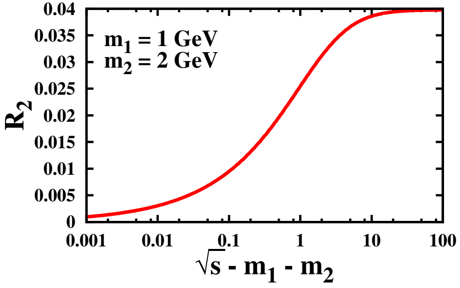
Covariant transition rate for 2→2



$$\frac{\mathrm{d}N_{\mathrm{coll}}[2 \to 2]}{\mathrm{d}t\mathrm{d}V} = \frac{1}{16(2\pi)^{12}} \sum_{i,j} \sum_{k,l} \int \left(\frac{\mathrm{d}^3 p_1 \mathrm{d}^3 p_2 \mathrm{d}^3 p_3 \mathrm{d}^3 p_4}{E_1 E_2 E_3 E_4} \right)$$
$$\times\, W_{2,2}(p_1, p_2; i, j | p_3, p_3; j, k)(2\pi)^4 \delta^4(p_1^\mu + p_2^\mu - p_3^\mu - p_4^\mu)$$
$$\times\, f_1(x_1, p_1) f_2(x_2, p_2) \tilde{f}_3(x_3, p_3) \tilde{f}_4(x_4, p_4)$$

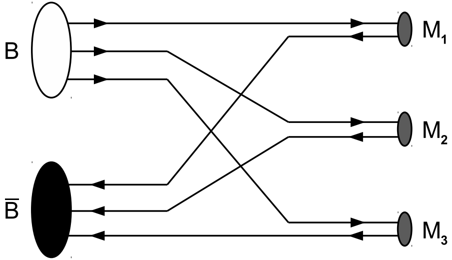
- two-body phase space can be solved analytically

$$R_2(\sqrt{s}; M_1, M_2) = \frac{\sqrt{\lambda(s, m_1^2, m_2^2)}}{8\pi s}$$
$$\lambda(a, b, c) = (a - b - c)^2 - 4bc$$



Quark Rearrangement Model

- $B, \bar{B}$: baryons and antibaryons from the baryon octet and decuplet plus N(1440) and N(1535) $M_1, M2, M3$: arbitrary mesons under conservation of the total quantum numbers (here 0^- and 1^- nonets)



- Reshuffle quark content from the baryon + antibaryon pair into 3 mesons or backwards
- Conserve quantum numbers in any combination of channels

Transition probability

- $B\bar{B} \rightarrow$3 mesons

$$\frac{\mathrm{d}N_{\mathrm{coll}}[B\bar{B} \rightarrow 3 \text{ mesons}]}{\mathrm{d}t\mathrm{d}V} =$$

$$\sum_c \sum_{c'} \frac{1}{(2\pi)^6} \int \frac{\mathrm{d}^3 p_1}{2E_1} \frac{\mathrm{d}^3 p_2}{2E_2} \; W_{2,3}\big(\sqrt{s}; c' = (M_1, M_2; i, j), c = (M_3, M_4, M_5; k, l, m)\big)$$

$$\times R_3(p_1^\mu + p_2^\mu; c) N_{\mathrm{fin}}^c f_i(x, p_1) f_j(x, p_2)$$

$$N_{\mathrm{fin}}^c = (2s_3 + 1)(2s_4 + 1)(2s_5 + 1) \frac{F_{\mathrm{iso}}}{N_{\mathrm{id}}!}$$

N_{fin}^c: Multiplicity of final state in channel c
F_{iso}: Number of isospin projections compatible with charge conservation
s: spin of respective meson

Transition probability

- $B\bar{B} \rightarrow$3 mesons

$$\frac{\mathrm{d}N_{\mathrm{coll}}[B\bar{B} \rightarrow 3\ \mathrm{mesons}]}{\mathrm{d}t\mathrm{d}V} =$$

$$\sum_c \sum_{c'} \frac{1}{(2\pi)^6} \int \frac{\mathrm{d}^3 p_1}{2E_1} \frac{\mathrm{d}^3 p_2}{2E_2}\ W_{2,3}(\sqrt{s}; c' = (M_1, M_2; i, j), c = (M_3, M_4, M_5; k, l, m))$$

$$\times R_3(p_1^\mu + p_2^\mu; c) N^c_{\mathrm{fin}} f_i(x, p_1) f_j(x, p_2)$$

$$N^c_{\mathrm{fin}} = (2s_3 + 1)(2s_4 + 1)(2s_5 + 1)\frac{F_{\mathrm{iso}}}{N_{\mathrm{id}}!}$$

N^c_{fin}: Multiplicity of final state in channel c
F_{iso}: Number of isospin projections compatible with charge conservation
s: spin of respective meson

- Assume W das not depend significantly on final momenta, only on $\sqrt{s}$
- Probability for the reaction to happen:

$$P^{2,3}_{cc'} = \frac{1}{4E_1E_2} W_{2,3}(\sqrt{s}, c, c') R_3(\sqrt{s}, c) N^c_{\mathrm{fin}}, \qquad \sum_c P^{2,3}_{cc'}(\sqrt{s}) = v_{\mathrm{rel}} \sigma^{c'}_{\mathrm{ann}}(\sqrt{s})$$

$$\tilde{P}^c(\sqrt{s}) = N_3(\sqrt{s}, c') R_3(\sqrt{s}, c) N^c_{\mathrm{fin}}, \qquad N_3^{-1}(\sqrt{s}, c') = \sum_c R_3(\sqrt{s}, c) N^c_{\mathrm{fin}}$$

Transition probability

- 3 mesons $\rightarrow B\bar{B}$ (inverse channel)

$$\frac{\mathrm{d}N_{\mathrm{coll}}[3\ mesons \rightarrow B\bar{B}]}{\mathrm{d}t\mathrm{d}V} = \sum_{c}\sum_{c'}\int \frac{\mathrm{d}^3 p_3}{(2\pi)^3 2E_3}\frac{\mathrm{d}^3 p_4}{(2\pi)^3 2E_4}\frac{\mathrm{d}^3 p_5}{(2\pi)^3 2E_5}$$

$$\times W_{3,2}(\sqrt{s})R_2(\sqrt{s},c')N_B^{c'} f_k(x,p_3)f_l(x,p_4)f_m(x,p_5)$$

$$N_B^{c'} = (2s_1+1)(2s_2+1)$$

- Probability for the reaction to happen:

$$P_{c'c}^{3,2} = \frac{1}{8E_3E_4E_5} W_{2,3}(\sqrt{s},c',c)R_2(\sqrt{s},c')N_B^{c'}$$

Transition probability

- 3 mesons $\rightarrow B\bar{B}$ (inverse channel)

$$\frac{\mathrm{d}N_{\mathrm{coll}}[3\ mesons \rightarrow B\bar{B}]}{\mathrm{d}t\mathrm{d}V} = \sum_{c}\sum_{c'}\int \frac{\mathrm{d}^3 p_3}{(2\pi)^3 2E_3}\frac{\mathrm{d}^3 p_4}{(2\pi)^3 2E_4}\frac{\mathrm{d}^3 p_5}{(2\pi)^3 2E_5}$$

$$\times W_{3,2}(\sqrt{s})R_2(\sqrt{s},c')N_B^{c'} f_k(x,p_3)f_l(x,p_4)f_m(x,p_5)$$

$$N_B^{c'} = (2s_1+1)(2s_2+1)$$

- Probability for the reaction to happen:

$$P^{3,2}_{c'c} = \frac{1}{8E_3E_4E_5}W_{2,3}(\sqrt{s},c',c)R_2(\sqrt{s},c')N_B^{c'}$$

- Connection to the annihilation cross section of respective baryon-antibaryon pair c' for $W_{2,3}$ independent of c

$$v_{\mathrm{rel}}\sigma^{c'}_{\mathrm{ann}}(\sqrt{s}) = \sum_{c}\frac{1}{4E_1E_2}W_{2,3}(\sqrt{s},c')R_3(\sqrt{s},c)N^{c}_{\mathrm{fin}}$$

$$= \frac{1}{4E_1E_2}W_{2,3}(\sqrt{s},c')N_3^{-1}(\sqrt{s},c')$$

Transition probability

- 3 mesons $\rightarrow B\bar{B}$ (inverse channel)

$$\frac{\mathrm{d}N_{\mathrm{coll}}[3\ mesons \rightarrow B\bar{B}]}{\mathrm{d}t\mathrm{d}V} = \sum_c \sum_{c'} \int \frac{\mathrm{d}^3 p_3}{(2\pi)^3 2E_3} \frac{\mathrm{d}^3 p_4}{(2\pi)^3 2E_4} \frac{\mathrm{d}^3 p_5}{(2\pi)^3 2E_5}$$
$$\times W_{3,2}(\sqrt{s}) R_2(\sqrt{s}, c') N_B^{c'} f_k(x, p_3) f_l(x, p_4) f_m(x, p_5)$$
$$N_B^{c'} = (2s_1 + 1)(2s_2 + 1)$$

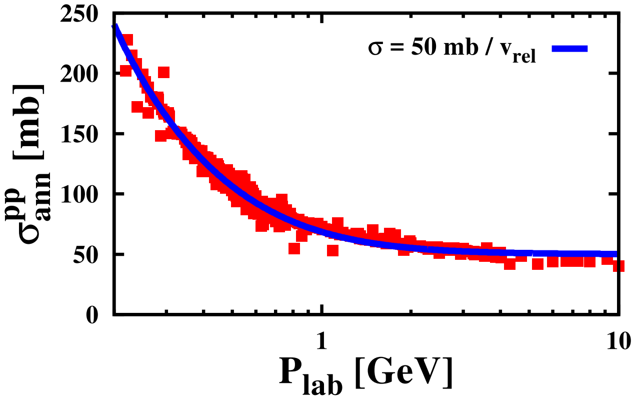
- Probability for the reaction to happen:

$$P_{c'c}^{3,2} = \frac{1}{8E_3 E_4 E_5} W_{2,3}(\sqrt{s}, c', c) R_2(\sqrt{s}, c') N_B^{c'}$$

- Connection to the annihilation cross section of respective baryon-antibaryon pair c' for $W_{2,3}$ independent of c

$$v_{\mathrm{rel}} \sigma_{\mathrm{ann}}^{c'}(\sqrt{s}) = \sum_c \frac{1}{4E_1 E_2} W_{2,3}(\sqrt{s}, c') R_3(\sqrt{s}, c) N_{\mathrm{fin}}^c$$
$$= \frac{1}{4E_1 E_2} W_{2,3}(\sqrt{s}, c') N_3^{-1}(\sqrt{s}, c')$$
$$\Rightarrow P_{c'c}^{3,2} = \frac{4E_1 E_2}{8E_3 E_4 E_5} \sigma_{\mathrm{ann}}^{c'}(\sqrt{s}) v_{\mathrm{rel}} N_3(\sqrt{s}, c') R_2(\sqrt{s}, c') N_B^{c'}$$

$p\bar{p}$ annihilation cross section



- Good fit with $\sigma_{p\bar{p}} = 50\,\mathrm{mb}/v_{\mathrm{rel}}$
- Consistent with constant matrix element ($\sigma_{p\bar{p}} v_{\mathrm{rel}} = const.$)

[http://pdg.lbl.gov/2015/hadronic-xsections/]

Tests of n-particle detailed balance

Consider the light and strangeness sector:

- Baryon octet and decuplet: N,Δ(1232),N(1440),N(1535),Λ,Σ,Σ^*,Ξ,Ξ^*,Ω
- Meson 0^- and 1^- nonets: π,η,η',K,K^*,ρ,ω,Φ,a_1
- Hidden strangeness of η is taken into account as 50% $s\bar{s}$ content and the ϕ meson is assumed to have 83.1% $s\bar{s}$

  $\Rightarrow$ 2546 possible mass channels

Tests of n-particle detailed balance

Consider the light and strangeness sector:

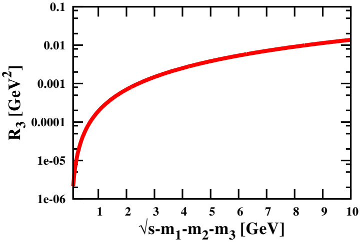
- Baryon octet and decuplet: N,Δ(1232),N(1440),N(1535),Λ,Σ,Σ*,Ξ,Ξ*,Ω
- Meson 0^- and 1^- nonets: π,η,η',K,K^*,ρ,ω,Φ,a_1
- Hidden strangeness of η is taken into account as 50% $s\bar{s}$ content and the ϕ meson is assumed to have 83.1% $s\bar{s}$
  $\Rightarrow$ 2546 possible mass channels

Strategy for actual calculations:

- Fit 3-body phase-space

$$R_3(t) = a_1\, t^{a_2} \left(1 - \frac{1}{a_3\, t + 1 + a_4}\right)$$

with $t = \sqrt{s} - m_1 - m_2 - m_3$ for 165 meson mass combinations



- Store multiplicities and possible final states for each combination of particles

Tests of n-particle detailed balance

Consider the light and strangeness sector:

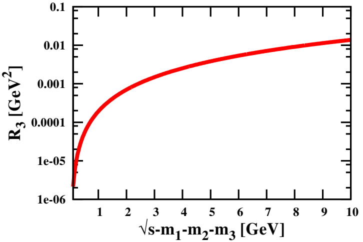
- Baryon octet and decuplet: N,Δ(1232),N(1440),N(1535),Λ,Σ,Σ^*,Ξ,Ξ^*,Ω
- Meson 0^- and 1^- nonets: π,η,η',K,K^*,ρ,ω,Φ,a_1
- Hidden strangeness of η is taken into account as 50% $s\bar{s}$ content and the ϕ meson is assumed to have 83.1% $s\bar{s}$
  $\Rightarrow$ 2546 possible mass channels

Strategy for actual calculations:

- Fit 3-body phase-space

$$R_3(t) = a_1\, t^{a_2} \left(1 - \frac{1}{a_3\, t + 1 + a_4}\right)$$

with $t = \sqrt{s} - m_1 - m_2 - m_3$ for 165 meson mass combinations



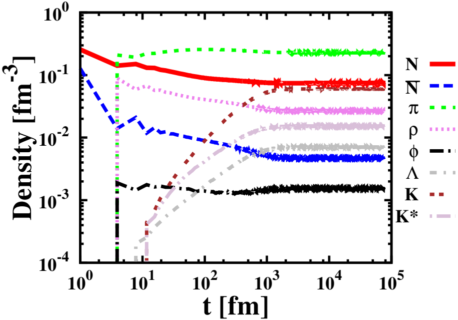
- Store multiplicities and possible final states for each combination of particles

Actual calculation:

- Divide space-time into 4-dimensional cells: $\Delta x, \Delta y, \Delta z, \Delta t$
- Particles inside the same cell may interact with each other
- Calculate transition probabilities and select via Monte Carlo the partners and final states

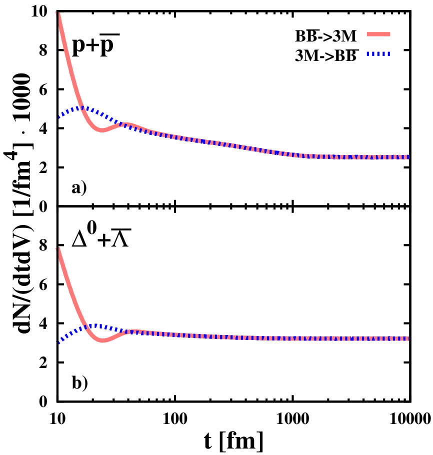
Test of n-particle detailed balance

- Box simulations with volumes around $V = 18000\,\mathrm{fm}^3$
- Periodic boundary condition
- Initialization with only one type of baryon and antibaryon: N,Δ(1232),N(1440),N(1535),Λ,Σ,Σ*,Ξ,Ξ*,Ω
- Energy density $\epsilon = 0.4\,\mathrm{GeV\ fm}^{-3}$, with 10% being kinetic energy
- Ratio baryon/antibaryon set to 2:1 $\longrightarrow$ baryon density ρ_B lies around $0.2\,\mathrm{fm}^{-3}$
- Boltzmann-like initial momentum distribution
- No decays of resonances and no elastic scattering; only $B\bar{B} \leftrightarrow 3M$



Total Reaction Rates

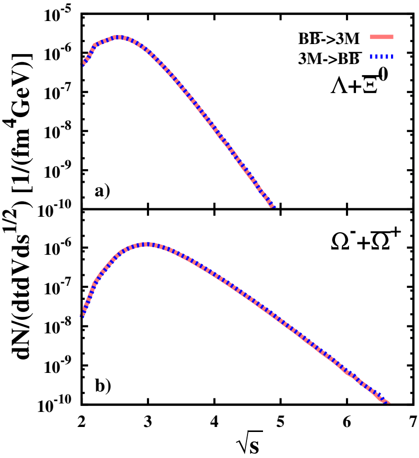
Total reaction rates as a function of time *t* in forward and backward-direction



- Detailed balance is fulfilled after ≈ 100 fm/c
- Equilibrium is reached the latest after 2000 fm/c

Total Reaction Rates

Total reaction rates as a function of invariant mass $\sqrt{s}$ in foward and backward direction



⇒ Detailed balance is fulfilled also differentially for the total system in equilibrium

Deviation from Detailed Balance

Deviation from Detailed Balance on a channel by channel basis

$$\delta = \left| \frac{\frac{\mathrm{d}N}{\mathrm{d}t}(B\bar{B} \to 3M)}{\frac{\mathrm{d}N}{\mathrm{d}t}(3M \to B\bar{B})} - 1 \right|$$

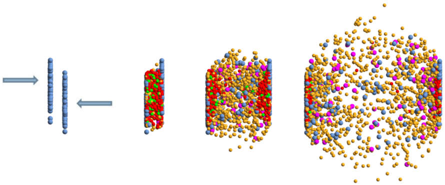
rank	$p + \bar{p}$		$\Delta^0 + \bar{\Lambda}$		$\Lambda + \bar{\Xi}^0$		$\langle\delta\rangle$ [%]
	channel	δ [%]	channel	δ [%]	channel	δ [%]	
1	$N\bar{N} \leftrightarrow \pi\pi\rho$	0.17	$N\bar{\Xi} \leftrightarrow \pi K K^*$	1.45	$N\bar{N} \leftrightarrow \pi\pi\rho$	0.13	1.24
2	$N\bar{N} \leftrightarrow \pi\rho\rho$	3.06	$N\bar{\Omega} \leftrightarrow K K^* K^*$	3.59	$N\bar{\Delta} \leftrightarrow \pi\rho\rho$	1.70	1.82
3	$N\bar{\Delta} \leftrightarrow \pi\pi\rho$	1.58	$\Delta\bar{\Xi} \leftrightarrow \pi K K^*$	1.32	$N\bar{\Delta} \leftrightarrow \pi\pi\rho$	2.04	1.70
4	$N\bar{\Delta} \leftrightarrow \pi\rho\rho$	0.84	$\Delta\bar{\Xi} \leftrightarrow K K^* \rho$	0.64	$N\bar{N} \leftrightarrow \pi\rho\rho$	3.31	1.54
5	$\Delta\bar{N} \leftrightarrow \pi\pi\rho$	2.43	$\Delta\bar{\Omega} \leftrightarrow K K^* K^*$	1.08	$\Delta\bar{N} \leftrightarrow \pi\rho\rho$	1.33	1.49
6	$\Delta\bar{N} \leftrightarrow \pi\rho\rho$	0.73	$N\bar{\Sigma} \leftrightarrow \pi K^* \rho$	3.58	$\Delta\bar{N} \leftrightarrow \pi\pi\rho$	2.71	1.97
7	$N\bar{N} \leftrightarrow \pi\pi a_1$	6.52	$\Delta\bar{\Sigma} \leftrightarrow \pi K^* \rho$	2.00	$\Delta\bar{\Delta} \leftrightarrow \pi\pi\rho$	2.69	2.04
8	$N\bar{N} \leftrightarrow \pi\pi\pi$	5.10	$N\bar{N} \leftrightarrow \pi\pi\rho$	0.23	$N\bar{\Sigma} \leftrightarrow \pi K^* \rho$	2.04	2.03
9	$N\bar{\Sigma} \leftrightarrow \pi K \rho$	0.31	$N\bar{\Sigma} \leftrightarrow \pi K \rho$	0.42	$\Delta\bar{\Delta} \leftrightarrow \pi\pi\rho$	2.12	2.11
10	$N\bar{\Sigma} \leftrightarrow \pi K^* \rho$	0.96	$N\bar{\Omega} \leftrightarrow K K K$	0.35	$N\bar{\Sigma} \leftrightarrow \pi K \rho$	0.35	2.11

Ranked by interaction rate and averaged over 100 system combinations

$\Rightarrow$ Detailed balance is fulfilled on a channel by channel basis in equilibrium better than 98%

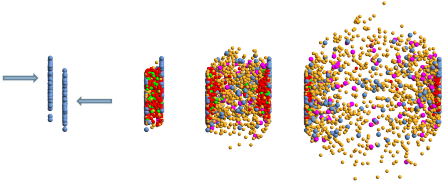
Parton Hadron String Dynamics (PHSD)

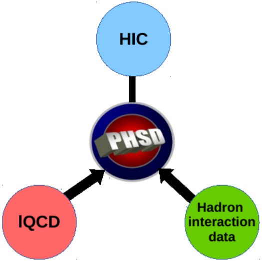
- Dynamical many-body transport approach.
- Consistently describes the full time evolution of a heavy-ion collision.
- Explicit parton-parton interactions, explicit phase transition from hadronic to partonic degrees of freedom.



Parton Hadron String Dynamics (PHSD)

- Dynamical many-body transport approach.
- Consistently describes the full time evolution of a heavy-ion collision.
- Explicit parton-parton interactions, explicit phase transition from hadronic to partonic degrees of freedom.





- Model applicable out-of equilibrium and in agreement with the lattice results in equilibrium as well as with the nuclear physics input.
- Transport theory: off-shell transport equations in phase-space representation based on Kadanoff-Baym equations for the partonic and hadronic phase.

W.Cassing, E.Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W.Cassing, EPJ ST 168 (2009) 3.

Solve generalized transport equations with extended test-particle ansatz

$$F_{XP} = iG^{<}(X,P) \sim \sum_{i=1}^{N} \delta^{(3)}(\mathbf{X} - \mathbf{X}_i(t))\delta^{(3)}(\mathbf{P} - \mathbf{P}_i(t))\delta(P_0 - \epsilon_i(t))$$

The equations of motion extracted from Kadanoff-Baym equations in first order gradient expansion in phase space read:

$$\frac{d\mathbf{X}_i}{dt} = \frac{1}{2\epsilon_i}\left[2\mathbf{P}_i + \nabla_{P_i}\mathrm{Re}\mathbf{\Sigma}^{ret}_{(i)} + \frac{\epsilon_i^2 - \mathbf{P}_i^2 - M_0^2 - \mathrm{Re}\mathbf{\Sigma}^{ret}_{(i)}}{\Gamma_{(i)}}\nabla_{P_i}\Gamma_{(i)}\right]$$

$$\frac{d\mathbf{P}_i}{dt} = -\frac{1}{2\epsilon_i}\left[\nabla_{X_i}\mathrm{Re}\mathbf{\Sigma}^{ret}_{(i)} + \frac{\epsilon_i^2 - \mathbf{P}_i^2 - M_0^2 - \mathrm{Re}\mathbf{\Sigma}^{ret}_{(i)}}{\Gamma_{(i)}}\nabla_{X_i}\Gamma_{(i)}\right]$$

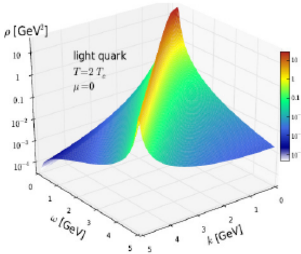
$$\frac{d\epsilon_i}{dt} = \frac{1}{2\epsilon_i}\left[\frac{\partial\mathrm{Re}\mathbf{\Sigma}^{ret}_{(i)}}{\partial t} + \frac{\epsilon_i^2 - \mathbf{P}_i^2 - M_0^2 - \mathrm{Re}\mathbf{\Sigma}^{ret}_{(i)}}{\Gamma_{(i)}}\frac{\partial\Gamma_{(i)}}{\partial t}\right]$$

Σ^{ret}: retarded self-energy
$\Gamma = \mathrm{Im}\Sigma^{ret}/2\epsilon$: effective width

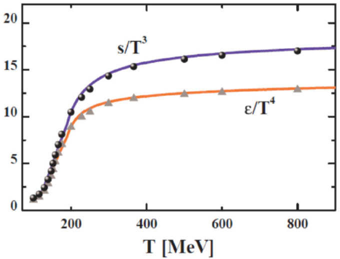
Dynamical Quasi-Particle Model (DQPM)

The QGP phase is described in terms of interacting quasi-particles with Lorentzian spectral functions:

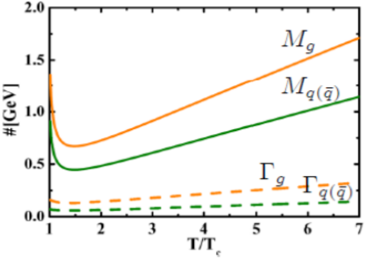
$$\rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{(\omega^2 - \mathbf{p}^2 - M_i^2(T))^2 + 4\omega^2\Gamma_i^2(T)}, \quad (i = q, \bar{q}, g).$$



Properties of quasi-particles are fitted to the lattice QCD results:

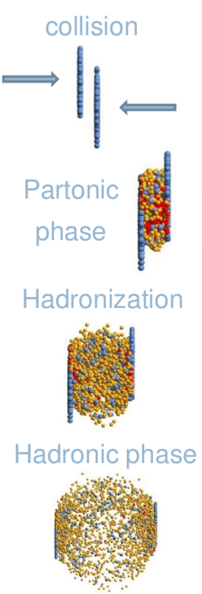


Masses and widths of partons depend on the temperature T and chemical potential μ_q of the medium:

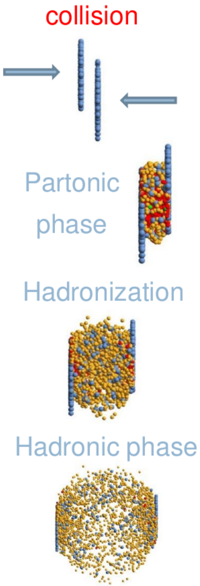


Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007) .

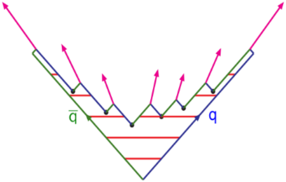
Stages of a heavy-ion collision in PHSD



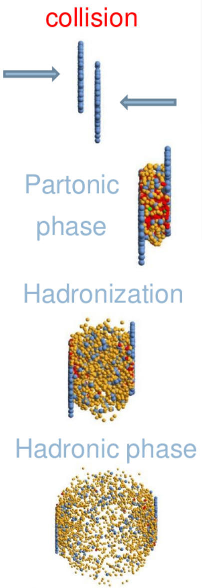
Stages of a heavy-ion collision in PHSD



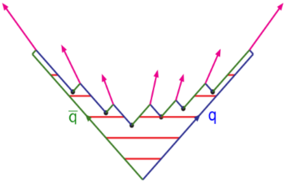
- **String formation** in primary NN Collisions.
- **String decays** to pre-hadrons(baryons and mesons).



Stages of a heavy-ion collision in PHSD



- **String formation** in primary NN Collisions.
- **String decays** to pre-hadrons(baryons and mesons).



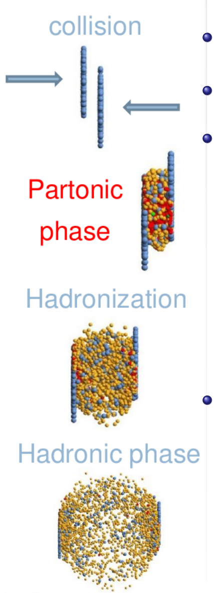
- Formation of a **QGP state** if the energy density $\epsilon > \epsilon_C \approx 0.5\ GeV\ fm^{-3}$.
- Dissolution of newly produced secondary hadrons into **massive colored quarks/antiquarks** and **mean-field energy** U_q:

$$B \to qqq\,(\bar{q}\bar{q}\bar{q}) \qquad M \to q\bar{q} \qquad + \quad U_q .$$

- **DQPM** defines the properties (masses and widths) of partons and mean-field potential at a given local energy density ϵ:

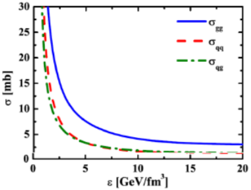
$$m_q(\epsilon) \qquad \Gamma_q(\epsilon) \qquad U_q(\epsilon).$$

Stages of a heavy-ion collision in PHSD



- Propagation of partons, considered as dynamical quasi-particles, in the self-generated mean-field potential from the DQPM.
- EoS of partonic phase: crossover from Lattice QCD fitted by DQPM.
- (Quasi-)elastic collisions:

$$
\begin{aligned}
q+q &\Rightarrow q+q \qquad & g+q &\Rightarrow g+q \\
q+\bar{q} &\Rightarrow q+\bar{q} \qquad & g+\bar{q} &\Rightarrow g+\bar{q} \\
\bar{q}+\bar{q} &\Rightarrow \bar{q}+\bar{q} \qquad & g+g &\Rightarrow g+g
\end{aligned}
$$



- Inelastic collisions:

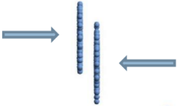
$$
\begin{aligned}
q+\bar{q} &\Rightarrow g \\
g &\Rightarrow q+\bar{q}
\end{aligned}
$$

~~$q+\bar{q} \Rightarrow g+g$~~
~~$g \Rightarrow g+g$~~

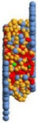
} Suppressed due to the large gluon mass.

Stages of a heavy-ion collision in PHSD

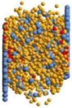
collision



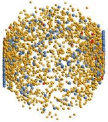
Partonic phase



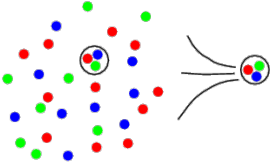
Hadronization



Hadronic phase



- Massive and off-shell (anti-)quarks hadronize to colorless off-shell mesons and baryons:

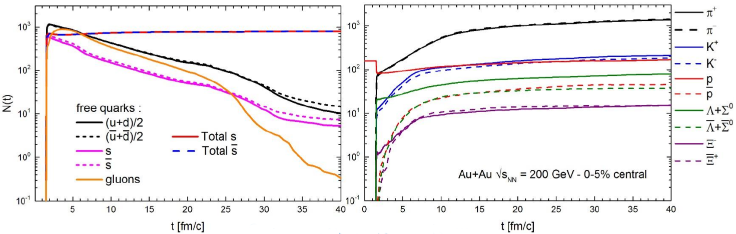


$$g \Rightarrow q + \bar{q}$$
$$q + \bar{q} \Rightarrow \text{meson ('string')}$$
$$q + q + q \Rightarrow \text{baryon ('string')}$$

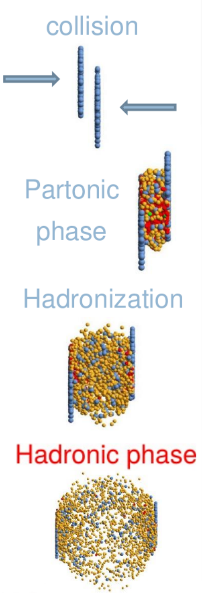
- Local covariant off-shell transition rate.
- Strict 4-momentum and quantum number conservation.

parton number

hadron number

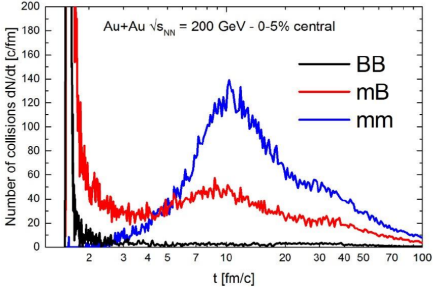


Stages of a heavy-ion collision in PHSD



- Hadron-string interactions – **off-shell HSD (Hadron String Dynamics)**.
- Elastic and inelastic collisions between baryons (B), mesons (m).

Distribution of hadron collisions as a function of time:

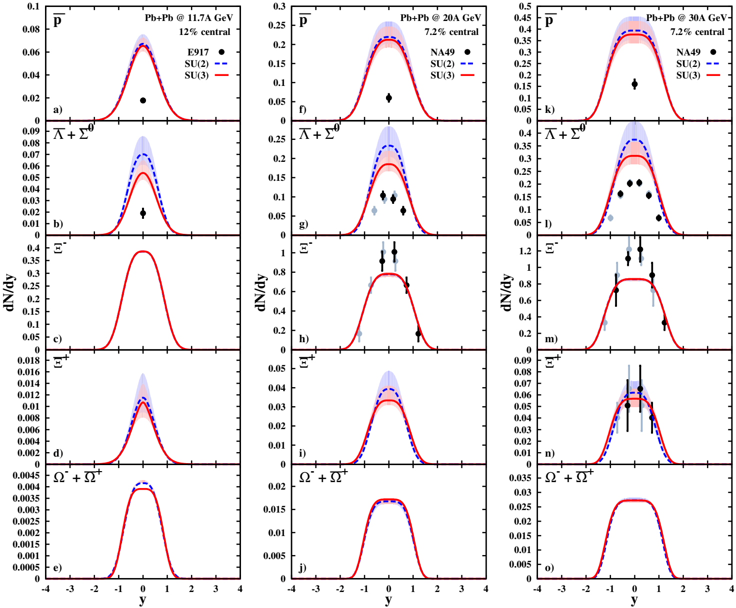


- Large amount of mm and mB collisions at times > 10 fm/c

PHSD simulations with extended many-body reactions

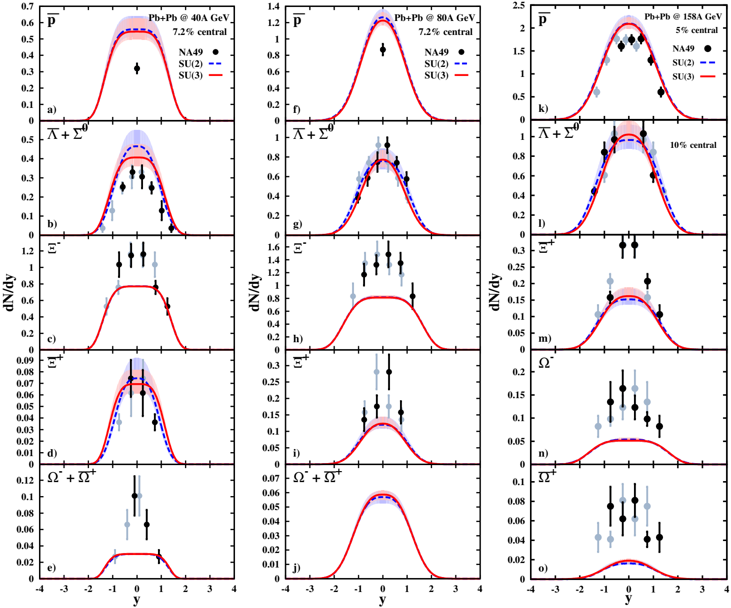
- The introduced many-body reactions have been implemented in PHSD in the light sector
- Now also the strangeness sector is implemented
- Check for sensitive observables in heavy-ion collisions
- Scan complete energy range from AGS to LHC ($\sqrt{s_{NN}} = 2 - 2760\,\mathrm{GeV}$)

AGS to SPS



- No visible change in baryons and mesons
- Strangeness sector has weak influence on $\bar{p}$
- Pushes PHSD results closer to experiment

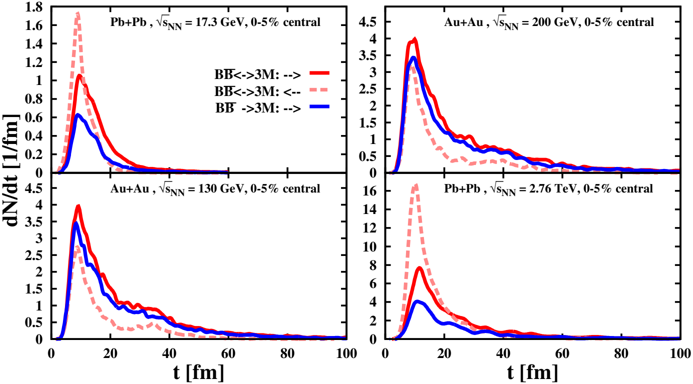
AGS to SPS



- With rising energy up to 158*A* GeV the sensitivity to the strangeness sector diminishes

Reaction rates

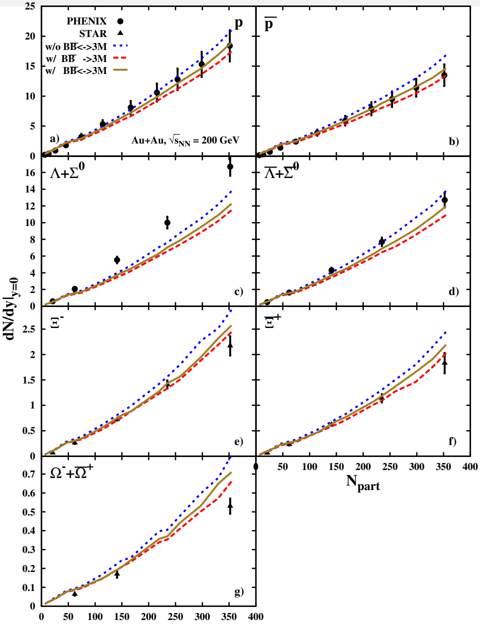
- Simulations with energies above $\sqrt{s_{NN}}$ =20.4 GeV do not use $B\bar{B} \leftrightarrow 3M$ reactions in standard PHSD



Looking at the total $B\bar{B} \leftrightarrow 3M$ reaction rates we find:

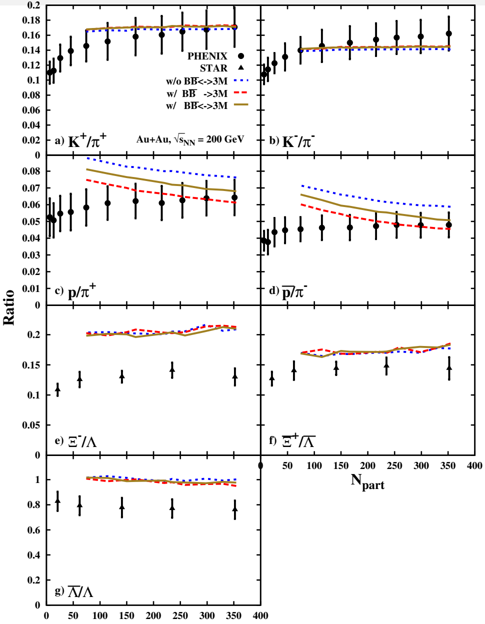
- Below 130 GeV almost balance of annihilation and reproduction
- At RHIC energies net annihilation
- For energies higher than RHIC net reproduction
- Annihilation rates without reproduction are always below the full dynamics

RHIC



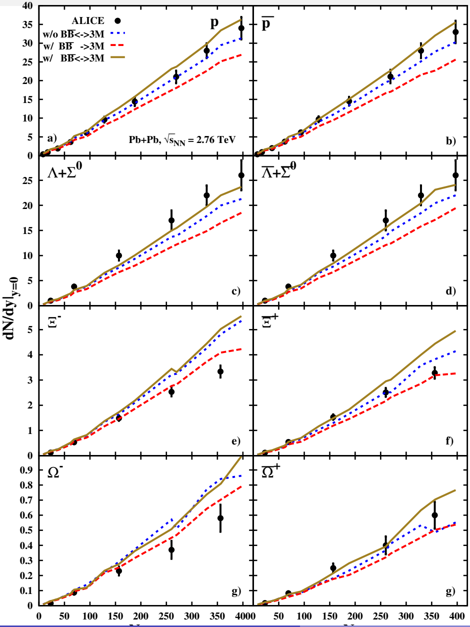
- Comparison of calculations without $B\bar{B} \leftrightarrow 3M$ (blue dotted), with only annihilation (red dashed) and annihilation and recreation (olive solid)
- Au+Au, $\sqrt{s_{NN}} = 200\,\text{GeV}$
- Centrality dependence of central rapidity density is generally reproduced well
- Full $B\bar{B} \leftrightarrow 3M$ calculations lie always between the results of only annihlation and no such reactions considered
- Better agreement with recreation than without

RHIC



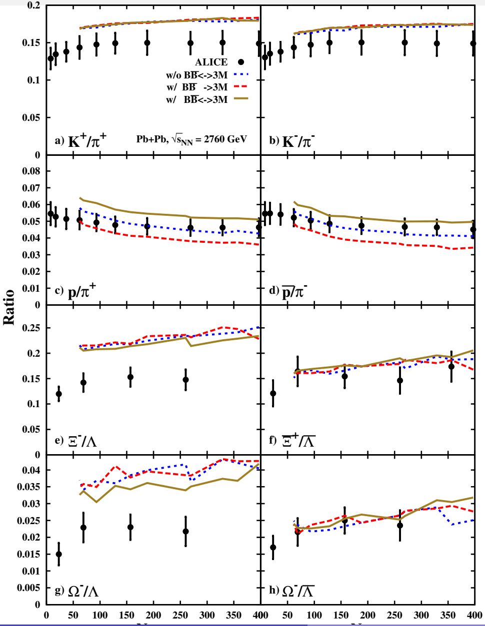
- Particle ratios are close to data for all versions
- Only p/π^+ and $\bar{p}/\pi^-$ are sensitive to different versions

LHC

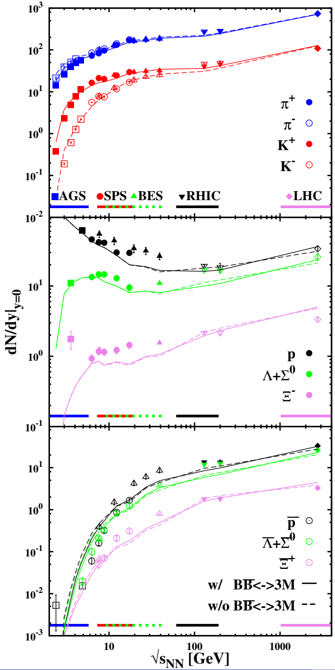


- Pb+Pb, $\sqrt{s_{NN}} = 2.76\,\text{TeV}$
- Full $B\bar{B} \leftrightarrow 3M$ lie now always above the calculations without these reactions and only annihilation considered
- Description of Ξ's and Ω^- is a little off

LHC



- Again only ratios p/π^+ and $\bar{p}/\pi^-$ are sensitive to different calculations
- Particle ratios lie very close to experimental data



From AGS to LHC:

- Calculations are done using full $B\bar{B} \leftrightarrow 3M$ reactions (solid) and no $B\bar{B} \leftrightarrow 3M$ reactions (dashed)
- AGS: Au+Au, SPS: Pb+Pb, BES: Au+Au, RHIC: Au+Au, LHC: Pb+Pb
- Centrality classes for each point are chosen to be in line with experimental analysis
- In SPS/BES overlap region the parameters match SPS

- Overall good agreement with data
- $\Lambda + \Sigma^0$ and $\bar{\Lambda} + \bar{\Sigma}^0$ are slightly too low at RHIC energies
- Ξ^- and $\bar{\Xi}^+$ are overshot at LHC and slightly too low at SPS/BES
- possible reason: a single universal matrix element taken from $p + \bar{p}$ annihilation

Summary

Summary

- We described $B\bar{B} \leftrightarrow 3M$ reactions as a rearrangement of the quark content
- Implementation is proven to fulfil detailed balance relation using box simulations
- Strangeness sector affects mostly anti-hyperons and pushes results closer to data
- At low energies we find initially a balance between annihilation and recreation
- With rising energy we see at first a net annihilation at RHIC energies
- With even higher energies we find a strong net reformation at LHC energies
- Investigation of the central rapidity density as a function of centrality shows that the recreation of $B\bar{B}$ pairs through 3 meson fusion is needed to reproduce most of the data
- Particle ratios other than p/π^+ and $\bar{p}/\pi^-$ are not sensitive to the difference of the three versions investigated: only annihilation, annihilation+recreation reactions and no $B\bar{B} \leftrightarrow 3M$
- The excitation functions show that PHSD with the $B\bar{B} \leftrightarrow 3M$ including the strangeness sector are in good agreement with experimental data
- Deviations are only seen in Ξ^-, $\Lambda + \Sigma^0$ and $\bar{\Lambda} + \bar{\Sigma}^0$ at some energies

Thank you for your attention!

Backup-Slides

Reactionrate

$$\frac{\mathrm{d}N_{\mathrm{coll}}[n \to m]}{\mathrm{d}t\mathrm{d}V} = \sum_{\nu}\sum_{\lambda}\int \prod_{j=1}^{n}\left(\frac{\mathrm{d}^3 p_j}{(2\pi)^3 2E_j}\right)\prod_{k=1}^{m}\left(\frac{\mathrm{d}^3 p_k}{(2\pi)^3 2E_k}\right)$$

$$\times W_{n,m}(p_j;\nu|p_k;\lambda)(2\pi)^4\delta^4(\sum_{j=1}^{n} p_j^{\mu} - \sum_{k=1}^{m} p_k^{\mu})\prod_{j=1}^{n}(f_j(x,p_j))\prod_{k=1}^{m}(\tilde{f}_k(x,p_k))$$

Annihilation cross section

$$\sum_{m}\sum_{\lambda_m} W_{2,m}(P^{\mu} = p_1^{\mu} + p_2^{\mu}; i,j;\lambda_m)R_m(P^{\mu}; M_3,\ldots,M_{m+1}) = 2\sqrt{\lambda(s, M_1^2, M_2^2)}\sigma_{i,j}(\sqrt{s}) = 4E_1E_2 v_{\mathrm{rel}}\sigma_{i,j}(\sqrt{s})$$

$$R_m(P^{\mu}; M_1,\ldots,M_m) = \left(\frac{1}{(2\pi)^3}\right)^m \int \prod_{k=1}^{m}\frac{\mathrm{d}^3 p_k}{2E_k}(2\pi)^4\delta^4\left(P^{\mu} - \sum_{j=1}^{m} p_j^{\mu}\right)$$

$$\lambda(a,b,c) = (a-b-c)^2 - 4bc$$

$$v_{\mathrm{rel}} = \frac{\sqrt{\lambda(s, M_1^2, M_2^2)}}{2E_1E_2}$$

$B\bar{B} \to 3$ mesons

$$\frac{\mathrm{d}N_{\mathrm{coll}}[B\bar{B} \to 3 \text{ mesons}]}{\mathrm{d}t\mathrm{d}V} = \sum_c \sum_{c'} \frac{1}{(2\pi)^6} \int \frac{\mathrm{d}^3 p_1}{2E_1} \frac{\mathrm{d}^3 p_2}{2E_2} W_{2,3}(\sqrt{s}; c' = (M_1, M_2; i, j), c = (M_3, M_4, M_5; k, l, m))$$
$$\times R_3(p_1^\mu + p_2^\mu; c) N_{\mathrm{fin}}^c f_i(x, p_1) f_j(x, p_2)$$
$$N_{\mathrm{fin}}^c = (2s_3 + 1)(2s_4 + 1)(2s_5 + 1) \frac{F_{\mathrm{iso}}}{N_{\mathrm{id}}!}$$

Probability $B\bar{B} \to 3$ mesons

$$P_{cc'}^{2,3} = \frac{1}{4E_1 E_2} W_{2,3}(\sqrt{s}, c, c') R_3(\sqrt{s}, c) N_{\mathrm{fin}}^c$$
$$\sum_c P_{cc'}^{2,3}(\sqrt{s}) = v_{\mathrm{rel}} \sigma_{\mathrm{ann}}^{c'}(\sqrt{s})$$
$$\tilde{P}^c(\sqrt{s}) = N_3(\sqrt{s}, c') R_3(\sqrt{s}, c) N_{\mathrm{fin}}^c$$
$$N_3^{-1}(\sqrt{s}, c') = \sum_c R_3(\sqrt{s}, c) N_{\mathrm{fin}}^c$$

3 mesons $\to B\bar{B}$

$$\frac{\mathrm{d}N_{\mathrm{coll}}[3 \text{ mesons } \to B\bar{B}]}{\mathrm{d}t\mathrm{d}V} = \sum_c \sum_{c'} \int \frac{\mathrm{d}^3 p_3}{(2\pi)^3 2E_3} \frac{\mathrm{d}^3 p_4}{(2\pi)^3 2E_4} \frac{\mathrm{d}^3 p_5}{(2\pi)^3 2E_5} W_{3,2}(\sqrt{s}) R_2(\sqrt{s}, c') N_B^{c'} f_k(x, p_3) f_l(x, p_4) f_m(x, p_5)$$

Probability 3 mesons $\to B\bar{B}$

$$P^{3,2}_{c'c} = \frac{1}{8E_3 E_4 E_5} W_{2,3}(\sqrt{s}, c', c) R_2(\sqrt{s}, c') N_B^{c'}$$

$$v_{\mathrm{rel}} \sigma^{c'}_{\mathrm{ann}}(\sqrt{s}) = \sum_c \frac{1}{4E_1 E_2} W_{2,3}(\sqrt{s}, c', c) R_3(\sqrt{s}, c) N^c_{\mathrm{fin}}$$

$$= \frac{1}{4E_1 E_2} W_{2,3}(\sqrt{s}, c', c) N_3^{-1}(\sqrt{s}, c')$$

$$\Rightarrow P^{3,2}_{c'c} = \frac{4E_1 E_2}{8E_3 E_4 E_5} \sigma^{c'}_{\mathrm{ann}}(\sqrt{s}) v_{\mathrm{rel}} N_3(\sqrt{s}, c') R_2(\sqrt{s}, c') N_B^{c'}$$

Dimensionless probabilities

$$\tilde{P}^{2,3}_{\mathrm{tot}} = \sum_c P^{2,3}_{cc'} = \sigma^{c'}_{\mathrm{ann}} v_{\mathrm{rel}} \frac{\mathrm{d}t}{\mathrm{d}V}$$

$$\tilde{P}^{3,2}_{c'c} = \frac{1}{4E_3 E_4 E_5} \sigma^{c'}_{\mathrm{ann}}(\sqrt{s}) N_3(\sqrt{s}, c') \frac{\lambda(s, M_1^2, M_2^2)}{8\pi s} N_B^{c'} (\hbar c)^3 \frac{\mathrm{d}t}{\mathrm{d}V^2}$$