Nucleus- and particle-nucleus collisions in the Giessen Boltzmann-Uehling-Uhlenbeck model (GiBUU)

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JINR Dubna, 25.12.2018

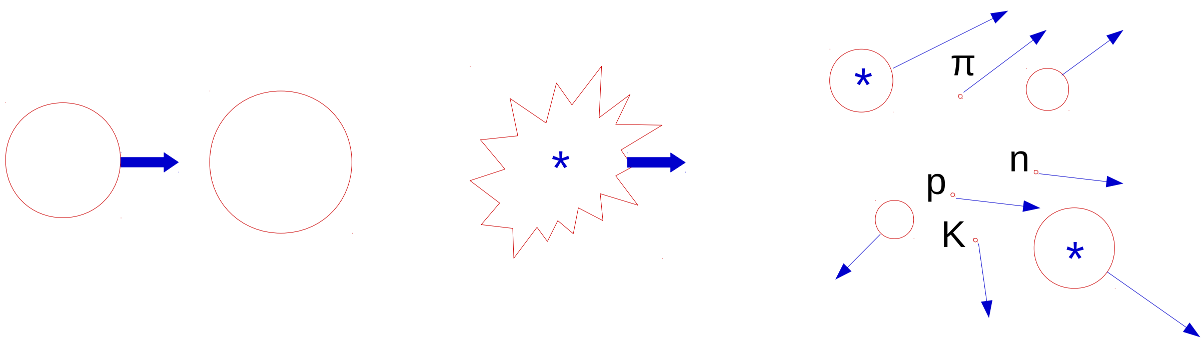
Plan:

- Motivation.
- BUU equation: main approximations, structure, static solution, test-particle method.
- GiBUU model: relativistic mean field, degrees of freedom, collision term.
- Heavy ion collísions: influence of three-body collisions on particle production.
- Antiproton-nucleus reactions: strangeness production.
- High-energy virtual-photon-nucleus reactions: hadron formation, neutron production.
- Possible new directions of studies in NICA regime.
- Conclusions.

Motivation

- In a large number of experiments with nuclear targets the quantum states of the outgoing particles (spin degrees of freedom, shell structures of the nuclear fragments etc.) are not resolved or not resolved completely.

Examples are heavy-ion collisions at AGS, SPS, RHIC, LHC, GSI, FAIR, NICA:



Hadron (p, $\bar{p}$, π^-, $K^{\pm}$)-nucleus collisions at J-PARC, FAIR, NICA and virtual-photon-nucleus collisions at TJNAF:

- extremely complex dynamics

- In general, one has to solve the many-body quantum problem and then perform proper summation and/or averaging over quantum states. However, it is possible **to simplify the dynamical description with a help of kinetic theory.**

BUU equation

Schroedinger equation for N-body wave function:

$$i\partial_t \psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_N; t) = \left[\sum_{i=1}^{N} \sqrt{m^2 - \nabla_i^2} + V(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_N) \right] \psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_N; t) \ .$$

- Reduce time evolution of N-body wave function to the time evolution of spin-averaged single-particle Wigner density

$$f(\mathbf{r}, \mathbf{p}, t) = \frac{N}{g_s} \mathrm{Tr} \int d^3r' d^3r_2 \ldots d^3r_N \psi^* \left(\mathbf{r} + \frac{\mathbf{r}'}{2}, \mathbf{r}_2, \ldots, \mathbf{r}_N; t \right) \psi \left(\mathbf{r} - \frac{\mathbf{r}'}{2}, \mathbf{r}_2, \ldots, \mathbf{r}_N; t \right) \mathrm{e}^{i\mathbf{p}\mathbf{r}'} \ ,$$

$g_s = 2J + 1$ - particle spin degeneracy.

- Cut the BBGKY hierarchy of equations for many-body Wigner functions ($\Leftrightarrow$ neglecting correlations between subsequent particle-particle collisions).

- Semiclassical approximation.

Boltzmann-Uehling-Uhlenbeck (BUU) equation for one-component system of fermions or bosons:

$$(\partial_t + \nabla_{\mathbf{p}}\varepsilon\nabla_{\mathbf{r}} - \nabla_{\mathbf{r}}\varepsilon\nabla_{\mathbf{p}})f(\mathbf{r},\mathbf{p},t) =$$
$$= \int \frac{g_s d^3p_2}{(2\pi)^3}\, v_{12} \int d\Omega\, \frac{d\sigma_{12\to 34}}{d\Omega}\, (f_3 f_4 \bar{f}_1 \bar{f}_2 - f_1 f_2 \bar{f}_3 \bar{f}_4)\ ,$$

$d\sigma_{12\to 34}/d\Omega$ - angular differential cross-section of elastic scattering,

$v_{12} = \sqrt{(p_1 p_2)^2 - (m_1 m_2)^2}/E_1 E_2$ - relative velocity of colliding particles,

$f_i \equiv f(\mathbf{r},\mathbf{p}_i,t)\ (i=1,2,3,4),\ \mathbf{p}_1 \equiv \mathbf{p},$

$\bar{f}_i \equiv 1 \mp f_i$ (upper sign: fermions; lower sign: bosons)

$\varepsilon(\mathbf{r},\mathbf{p},t)$ - single-particle energy,

Usual nonrelativistic Boltzmann equation if $\bar{f}_i = 1,\ \varepsilon = p^2/2m.$

With properly defined single-particle energies the BUU equation is Lorentz-invariant !

Number of particles: $$N = \int \underbrace{\frac{g_s d^3r d^3p}{(2\pi)^3}}_{\text{Lorentz invariant}} \underbrace{f(\mathbf{r},\mathbf{p},t)}_{\text{Lorentz invariant}}$$

Static solution of BUU equation: $$f_0(\mathbf{r},\mathbf{p}) = \frac{1}{\mathrm{e}^{(\varepsilon_0(\mathbf{r},\mathbf{p})-\mu)/T} \pm 1}$$

(+) fermions, (-) bosons

Fermi distribution at T=0 can be used for the initialization of the nucleus (Thomas-Fermi approximation)

Lorentz boosted thermal distribution is also the solution of BUU equation:

$$f(\mathbf{r},\mathbf{p},t) = \frac{1}{\mathrm{e}^{(pu-\mu)/T} \pm 1} \ ,$$

$$p = (p^0, \mathbf{p}) \ , \quad u = (\gamma, \gamma\boldsymbol{\beta}) \ , \quad \gamma = \frac{1}{\sqrt{1-\beta^2}} \ , \quad \boldsymbol{\beta} - \text{boost velocity}$$

$$p^0 \equiv \varepsilon(\tilde{\mathbf{r}},\mathbf{p}) \ , \quad \tilde{\mathbf{r}} = \gamma(\mathbf{r} - \boldsymbol{\beta}t)$$

includes moving Lorentz-contracted potential well, e.g. pure scalar: $\varepsilon(\tilde{\mathbf{r}},\mathbf{p}) = \sqrt{(m+s(\tilde{\mathbf{r}}))^2 + \mathbf{p}^2}$

- can be used for the Lorentz boost of the ground state nucleus and for coupling with hydro

Most numerical models apply the test particle method to solve BUU equation:

G.F. Bertsch, S. Das Gupta, Phys. Rep. 160, 189 (1988)

$$f(\boldsymbol{r},\boldsymbol{p},t) = \frac{(2\pi)^3}{g_s N_{\text{test}}} \sum_{n=1}^{N\cdot N_{\text{test}}} \delta(\boldsymbol{r}-\boldsymbol{r_n}(t))\delta(\boldsymbol{p}-\boldsymbol{p_n}(t)) \ ,$$

N_{test} - number of test particles per nucleon (typically ~200-1000 for uniform coverage of phase space)

Hamiltonian equations of motion for centroids:

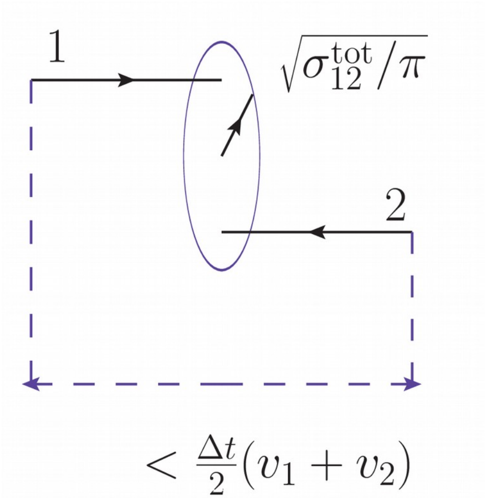
Formally solving Vlasov equation

$$(\partial_t + \nabla_{\mathbf{p}}\varepsilon\nabla_{\mathbf{r}} - \nabla_{\mathbf{r}}\varepsilon\nabla_{\mathbf{p}}) f(\mathbf{r},\mathbf{p},t) = 0$$

$$\begin{cases} \dfrac{d\boldsymbol{r_n}}{dt} = \dfrac{\partial\varepsilon(\boldsymbol{r_n},\boldsymbol{p_n},t)}{\partial\boldsymbol{p_n}} \ , \\ \dfrac{d\boldsymbol{p_n}}{dt} = -\dfrac{\partial\varepsilon(\boldsymbol{r_n},\boldsymbol{p_n},t)}{\partial\boldsymbol{r_n}} \ . \end{cases}$$

Collision term is modeled within the geometrical minimum distance criterion:

c.m.s. of 1 and 2



Drawback: collision ordering depends on the frame.

In modern transport codes (incl. GiBUU) done better with Kodama recepie, which approximately restores Lorentz invariance

T. Kodama et al., PRC 29, 2146 (1984)

- If particles 1 and 2 collide, the final state "f" is sampled by Monte-Carlo:

$$P_f = \frac{\sigma_f}{\sigma_{12}^{\mathrm{tot}}} \ , \quad \sum_f \sigma_f = \sigma_{12}^{\mathrm{tot}}$$

- Empirical or theoretical c.m. angular distributions for elastic and inelastic scattering $NN \to NN$, $NN \leftrightarrow N\Delta$ etc.

- Resonance production and decay, e.g. $\pi N \to \Delta, \ \Delta \to \pi N$

isospin dependent partial decay width

total width

$$\sigma_{\pi N \to \Delta}(\sqrt{s}) = \frac{4\pi}{q^2(\sqrt{s})} \frac{2s\Gamma_{\Delta \to \pi N}(\sqrt{s})\Gamma_{\Delta}(\sqrt{s})}{(s - m_{\Delta}^2)^2 + s\Gamma_{\Delta}^2(\sqrt{s})} \ , \quad q(\sqrt{s}) = \sqrt{(s + m_{\pi}^2 - m_N^2)^2/4s - m_{\pi}^2}$$

c.m. momentum of pion and nucleon

$$P_{\mathrm{decay}} = 1 - \mathrm{e}^{-\Gamma_{\Delta}\Delta t/\gamma}$$

- Collision or decay is accepted with probability

$$P = \prod_{i=1}^{n_{\mathrm{nucl}}} [1 - f_i(\boldsymbol{r}, \boldsymbol{p}_i, t)]$$

n_{nucl} - number of outgoing nucleons

GiBUU model

- solves the coupled system of kinetic equations for the baryons (N,N*,Δ,Λ,Σ,…), corresponding antibaryons ($\bar{N}$,$\bar{N}$*,$\bar{\Delta}$,$\bar{\Lambda}$,$\bar{\Sigma}$,…), and mesons (π,K,...)

- initializations for the lepton-, photon-, hadron-, and heavy-ion-induced reactions on nuclei

Open source code in Fortran 2003 downloadable from:

https://gibuu.hepforge.org/trac/wiki

Details of GiBUU: ***O. Buss et al., Phys. Rep. 512, 1 (2012).***

Kinetic equation with relativistic mean fields:

Distribution function in phase space (***r***,***p****)

Number of sort "j" particles = $\int \frac{g_s^j d^3r d^3p^*}{(2\pi)^3} f_j^*(x,\mathbf{p}^*)$

$$(p_0^*)^{-1}\left[p_\mu^*\partial^\mu + (p_\mu^*\mathcal{F}_j^{\alpha\mu} + m_j^*\partial^\alpha m_j^*)\frac{\partial}{\partial p^{*\alpha}}\right] f_j^*(x,\mathbf{p}^*) = I_j[\{f^*\}] \ , \qquad (*)$$

Collision term

$\mu = 0,1,2,3, \quad \alpha = 1,2,3, \quad j = N, \bar{N}, \Delta, \bar{\Delta}, \Lambda, \bar{\Lambda}, \pi, K, \ldots \qquad x \equiv (t,\mathbf{r})$

$m_j^* = m_j + S_j$ - effective mass, $S_j = g_{\sigma j}\sigma$ - scalar field,

$p^{*\mu} = p^\mu - V_j^\mu$ - kinetic four-momentum with effective mass shell constraint $p^{*\mu}p_\mu^* = m_j^{*2}$,

$V_j^\mu = g_{\omega j}\omega^\mu + g_{\rho j}\tau_j^3\rho^{3\mu} + q_j A^\mu$ - vector field, $\qquad \tau_j^3 = +(-)1 \text{ for } j = p, \bar{n} \ (\bar{p}, n)$,

$\mathcal{F}_j^{\mu\nu} = \partial^\mu V_j^\nu - \partial^\nu V_j^\mu$ - field tensor.

- For momentum-independent fields Eq.(*) is equavalent to the BUU equation

$$(\partial_t + \nabla_\mathbf{p}\varepsilon_j\nabla_\mathbf{r} - \nabla_\mathbf{r}\varepsilon_j\nabla_\mathbf{p})f_j(x,\mathbf{p}) = I_j[\{f\}]$$

$$\varepsilon_j(x,\mathbf{p}) = V_j^0 + \sqrt{m_j^{*2} + \mathbf{p}_j^{*2}} \ , \quad f_j(x,\mathbf{p}) = f_j^*(x,\mathbf{p}^*) \ .$$

Direct derivations of relativistic kinetic equation:

Yu.B. Ivanov, NPA 474, 669 (1987);
B. Blättel, V. Koch, U. Mosel, Rept. Prog. Phys. 56, 1 (1993).

Lagrangian density:

$$\mathcal{L} = \sum_{j=N,\bar{N}} \bar{\psi}_j[\gamma_\mu(i\partial^\mu - g_{\omega j}\omega^\mu - g_{\rho j}\boldsymbol{\tau}\boldsymbol{\rho}^\mu - \frac{e}{2}(B_j + \tau^3)A^\mu) - m_N - g_{\sigma j}\sigma]\psi_j$$

$$+ \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^2 - \frac{1}{4}\boldsymbol{R}_{\mu\nu}\boldsymbol{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}^2 - \frac{1}{16\pi}F_{\mu\nu}F^{\mu\nu} ,$$

$$B_N = 1,\ B_{\bar{N}} = -1, \quad \Omega_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu ,\ \boldsymbol{R}_{\mu\nu} = \partial_\mu\boldsymbol{\rho}_\nu - \partial_\nu\boldsymbol{\rho}_\mu ,\ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu ,$$

$$U(\sigma) = \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4 .$$

G-parity (Walecka model): $g_{\sigma\bar{N}} = g_{\sigma N}, \quad g_{\omega\bar{N}} = -g_{\omega N}, \quad g_{\rho\bar{N}} = g_{\rho N}$.

Phenomenological couplings: $g_{\sigma\bar{N}} = \xi g_{\sigma N}, \quad g_{\omega\bar{N}} = -\xi g_{\omega N}, \quad g_{\rho\bar{N}} = \xi g_{\rho N}, \quad 0 < \xi \leq 1.$

Lagrange equations of motion for meson fields:

$$\left\{ \begin{aligned} &(\partial_\mu\partial^\mu + m_\sigma^2)\sigma(x) + g_2\sigma^2 + g_3\sigma^3 = -\sum_{j=N,\bar{N}} g_{\sigma j}\,\rho_{Sj}(x) , \\ &(\partial_\nu\partial^\nu + m_\omega^2)\,\omega^\mu(x) = \sum_{j=N,\bar{N}} g_{\omega j}\,J^\mu_{Bj}(x) , \\ &(\partial_\nu\partial^\nu + m_\rho^2)\,\rho^{3\,\mu}(x) = \sum_{j=N,\bar{N}} g_{\rho j}\,J^\mu_{Ij}(x) , \\ &\partial_\nu\partial^\nu A^\mu(x) = 4\pi \sum_{j=N,\bar{N}} J^\mu_{Qj}(x) . \end{aligned} \right.$$

$$\rho_{Sj}(x) =< \bar{\psi}_j(x)\psi_j(x) >= \frac{2}{(2\pi)^3}\int \frac{d^3p^*}{p^{*0}} m_j^* f_j(x,\boldsymbol{p}^*) ,$$

$$J^\mu_{aj}(x) =< \bar{\psi}_j(x)\gamma^\mu O_a\psi_j(x) >= \frac{2}{(2\pi)^3}\int \frac{d^3p^*}{p^{*0}} p^{*\mu} O_a f_j(x,\boldsymbol{p}^*) , \quad O_B = 1, \ \ O_I = \tau^3, \ \ O_Q = \frac{e}{2}(B_j + \tau^3) \equiv q_j .$$

Mesons

Name	ID	Mass	Width	Spin	Isospin	Strange	Charm	Stability	min.Mass
π	101	0.1380	0.0000	0.0	1.0	0	0	0	0.000
η	102	0.5478	0.0000	0.0	0.0	0	0	3	0.000
ρ	103	0.7755	0.1491	1.0	1.0	0	0	3	0.276
σ	104	0.8000	0.5000	0.0	0.0	0	0	3	0.276
ω	105	0.7826	0.0085	1.0	0.0	0	0	3	0.138
η'	106	0.9578	0.0002	0.0	0.0	0	0	3	0.000
ϕ	107	1.0194	0.0043	1.0	0.0	0	0	3	0.414
η_c	108	2.9800	0.0280	0.0	0.0	0	0	3	0.000
J/ψ	109	3.0969	0.0000	1.0	0.0	0	0	0	0.000
K	110	0.4960	0.0000	0.0	0.5	1	0	0	0.496
$\overline{K}$	111	0.4960	0.0000	0.0	0.5	-1	0	0	0.496
K^*	112	0.8920	0.0500	1.0	0.5	1	0	3	0.634
$\overline{K}^*$	113	0.8920	0.0500	1.0	0.5	-1	0	3	0.634
D	114	1.8670	0.0000	0.0	0.5	0	1	0	1.500
$\overline{D}$	115	1.8670	0.0000	0.0	0.5	0	-1	0	1.500
D^*	116	2.0070	0.0020	1.0	0.5	0	1	3	1.500
$\overline{D}^*$	117	2.0070	0.0020	1.0	0.5	0	-1	3	1.500
D_s^+	118	1.9690	0.0000	0.0	0.0	1	1	0	1.500
D_s^-	119	1.9690	0.0000	0.0	0.0	-1	-1	0	1.500
D_s^{*+}	120	2.1120	0.0010	1.0	0.0	1	1	3	1.500
D_s^{*-}	121	2.1120	0.0010	1.0	0.0	-1	-1	3	1.500
$f_2(1270)$	122	1.2754	0.1852	2.0	0.0	0	0	3	0.276

By default, all resonances are propagated
while for cross sections are used all resonances except those with I=1/2 and one-star.

Nonstrange baryons

Name	ID	Mass	Width	Spin	Rating	Isospin	Strange	Charm	Stability	min.Mass
N	1	0.938	0.000	0.5	****	0.5	0	0	0	0.700
Δ	2	1.232	0.118	1.5	****	1.5	0	0	3	1.076
$P_{11}(1440)$	3	1.462	0.391	0.5	****	0.5	0	0	3	1.076
$S_{11}(1535)$	4	1.534	0.151	0.5	***	0.5	0	0	3	1.076
$S_{11}(1650)$	5	1.659	0.173	0.5	****	0.5	0	0	3	1.076
$S_{11}(2090)$	6	1.928	0.414	0.5	*	0.5	0	0	3	1.076
$D_{13}(1520)$	7	1.524	0.124	1.5	****	0.5	0	0	3	1.076
$D_{13}(1700)$	8	1.737	0.249	1.5	*	0.5	0	0	3	1.076
$D_{13}(2080)$	9	1.804	0.447	1.5	*	0.5	0	0	3	1.076
$D_{15}(1675)$	10	1.676	0.159	2.5	****	0.5	0	0	3	1.076
$G_{17}(2190)$	11	2.127	0.547	3.5	****	0.5	0	0	3	1.076
$P_{11}(1710)$	12	1.717	0.478	0.5	*	0.5	0	0	3	1.076
$P_{11}(2100)$	13	1.885	0.113	0.5	*	0.5	0	0	3	1.076
$P_{13}(1720)$	14	1.717	0.383	1.5	*	0.5	0	0	3	1.076
$P_{13}(1900)$	15	1.879	0.498	1.5	***	0.5	0	0	3	1.076
$F_{15}(1680)$	16	1.684	0.139	2.5	****	0.5	0	0	3	1.076
$F_{15}(2000)$	17	1.903	0.494	2.5	*	0.5	0	0	3	1.076
$F_{17}(1990)$	18	2.086	0.535	3.5	**	0.5	0	0	3	1.076
$S_{31}(1620)$	19	1.672	0.154	0.5	**	1.5	0	0	3	1.076
$S_{31}(1900)$	20	1.920	0.263	0.5	***	1.5	0	0	3	1.076
$D_{33}(1700)$	21	1.762	0.599	1.5	*	1.5	0	0	3	1.076
$D_{33}(1940)$	22	2.057	0.460	1.5	*	1.5	0	0	3	1.076
$D_{35}(1930)$	23	1.956	0.526	2.5	**	1.5	0	0	3	1.076
$D_{35}(2350)$	24	2.171	0.264	2.5	**	1.5	0	0	3	1.076
$P_{31}(1750)$	25	1.744	0.299	0.5	*	1.5	0	0	3	1.076
$P_{31}(1910)$	26	1.882	0.239	0.5	****	1.5	0	0	3	1.076
$P_{33}(1600)$	27	1.706	0.430	1.5	***	1.5	0	0	3	1.076
$P_{33}(1920)$	28	2.014	0.152	1.5	*	1.5	0	0	3	1.076
$F_{35}(1750)$	29	1.752	0.251	2.5	*	1.5	0	0	3	1.076
$F_{35}(1905)$	30	1.881	0.327	2.5	***	1.5	0	0	3	1.076
$F_{37}(1950)$	31	1.945	0.300	3.5	****	1.5	0	0	3	1.076

Strange baryons

Name	ID	Mass	Width	Spin	Rating	Isospin	Strange	Charm	Stability	min.Mass
Λ	32	1.116	0.000	0.5	****	0.0	-1	0	0	1.076
Σ	33	1.189	0.000	0.5	****	1.0	-1	0	0	1.076
$\Sigma(1385)$	34	1.385	0.036	1.5	****	1.0	-1	0	3	1.254
$\Lambda(1405)$	35	1.405	0.050	0.5	****	0.0	-1	0	3	1.254
$\Lambda(1520)$	36	1.520	0.016	1.5	****	0.0	-1	0	3	1.254
$\Lambda(1600)$	37	1.600	0.150	0.5	***	0.0	-1	0	3	1.254
$\Lambda(1670)$	38	1.670	0.035	0.5	****	0.0	-1	0	3	1.254
$\Lambda(1690)$	39	1.690	0.060	1.5	****	0.0	-1	0	3	1.254
$\Lambda(1810)$	40	1.810	0.150	0.5	***	0.0	-1	0	3	1.254
$\Lambda(1820)$	41	1.820	0.080	2.5	****	0.0	-1	0	3	1.254
$\Lambda(1830)$	42	1.830	0.095	2.5	****	0.0	-1	0	3	1.254
$\Sigma(1670)$	43	1.670	0.060	1.5	****	1.0	-1	0	3	1.254
$\Sigma(1775)$	44	1.775	0.120	2.5	****	1.0	-1	0	3	1.254
$\Sigma(2030)$	45	2.030	0.180	3.5	****	1.0	-1	0	3	1.254
$\Lambda(1800)$	46	1.800	0.300	0.5	***	0.0	-1	0	3	1.254
$\Lambda(1890)$	47	1.890	0.100	1.5	****	0.0	-1	0	3	1.254
$\Lambda(2100)$	48	2.100	0.200	3.5	****	0.0	-1	0	3	1.254
$\Lambda(2110)$	49	2.110	0.200	2.5	***	0.0	-1	0	3	1.254
$\Sigma(1660)$	50	1.660	0.100	0.5	***	1.0	-1	0	3	1.254
$\Sigma(1750)$	51	1.750	0.090	0.5	***	1.0	-1	0	3	1.254
$\Sigma(1915)$	52	1.915	0.120	2.5	****	1.0	-1	0	3	1.254
Ξ	53	1.315	0.000	0.5	****	0.5	-2	0	0	1.254
Ξ^*	54	1.530	0.009	1.5	****	0.5	-2	0	3	1.254
Ω	55	1.672	0.000	1.5	****	0.0	-3	0	0	1.254

Charmed baryons

Name	ID	Mass	Width	Spin	Rating	Isospin	Strange	Charm	Stability	min.Mass
Λ_c	56	2.285	0.000	0.5	****	0.0	0	1	0	1.076
Σ_c	57	2.452	0.000	0.5	****	1.0	0	1	0	1.076
Σ_c^*	58	2.520	0.015	1.5	****	1.0	0	1	3	2.423
Ξ_c	59	2.466	0.000	0.5	***	0.5	-1	1	0	2.423
Ξ_c^*	60	2.645	0.004	1.5	***	0.5	-1	1	3	2.423
Ω_c	61	2.697	0.000	0.5	***	0.0	-2	1	0	2.423

Collision term of the GiBUU model

- includes 2→2, 2↔3 and 2→4 transitions at low energies, and 2→N transitions at high energies (via PYTHIA and FRITIOF models) and for baryon-antibaryon annihilation (via statistical annihilation model);

- cross sections of the time-reversed processes (e.g. ΛK→Nπ) – by the detailed balance relation:

$$\sigma_{cd\to ab} = \sigma_{ab\to cd} \left(\frac{q_{ab}}{q_{cd}}\right)^2 \frac{(2J_a+1)(2J_b+1)}{(2J_c+1)(2J_d+1)} \frac{\mathcal{S}_{ab}}{\mathcal{S}_{cd}} ,$$

$q_{ab},\ q_{cd}$ - c.m. momenta,

$J_a,\ J_b$ - spins,

$$\mathcal{S}_{ab} = \begin{cases} 1 & \text{if a,b not identical} \\ \frac{1}{2} & \text{if a,b identical} \end{cases} .$$

Baryon-baryon collisions:

For $\sqrt{s} < 3.4$ GeV: $BB \to BB$ (elastic & inelastic), $NN \to NNM$ $(M = \pi,\ \omega,\ \phi)$, $np \to d\eta$, $BB \to BYK$, $BB \to NNK\bar{K}$ $(B = N,\ R)$.

For $\sqrt{s} > 3.4$ GeV: $BB \to X$ (PYTHIA v 6.419).

Meson-baryon collisions:

For $\sqrt{s} < 2.2$ GeV: $\pi N \to R,\ MN\ (M = \pi, \omega, \phi, \rho, \sigma, \eta),\ M\Delta\ (M = \pi, \eta, \rho)$,
$\pi N^*(1440),\ K\Lambda,\ K\Sigma,\ \omega\pi N,\ \phi\pi N,\ K\bar{K}N,\ \Lambda K\pi,\ \Sigma K\pi,\ \pi\pi N,\ \pi\pi\pi N$;
$\omega N \to R,\ \pi N,\ \omega N,\ \pi\pi N,\ \Lambda K,\ \Sigma K$;
$\rho N \to R,\ \pi N,\ \Lambda K,\ \Sigma K$;
$\sigma N \to R,\ \pi N,\ \sigma N$;
$\eta N \to R,\ \pi N,\ \Lambda K,\ \Sigma K$;
$\phi N \to \phi N,\ \pi N,\ \pi\pi N$;
$KN \to KN,\ KN\pi$;
$\bar{K}N \to Y^*,\ \bar{K}N,\ Y\pi,\ Y^*\pi,\ \Xi K,\ \Xi K\pi$;
$J/\psi N \to J/\psi N,\ \Lambda_c\bar{D},\ \Lambda_c\bar{D}^*,\ ND\bar{D}$;
$\pi\Delta \to R,\ K\Lambda,\ \Sigma\Lambda$;
$\rho\Delta \to R$;
$\eta\Delta \to \pi N$;
$\pi N^*(1440) \to R$;
$\pi Y(Y^*) \to Y^*,\ \bar{K}N$;
$\eta\Lambda \to \Lambda^*$;
$K\Lambda \to R,\ \pi N,\ \pi\Delta$;

For $\sqrt{s} > 2.2$ GeV: $MB \to X$ (PYTHIA v 6.419 and JETSET)

Meson-meson collisions:
$MM \to R,\ K\bar{K},\ K^*\bar{K},\ K\bar{K}^*\ (M = \pi, \eta, \eta', \sigma, \rho, \omega)$.

Baryon-antibaryon collisions:
$\bar{B}B \to$ mesons by statistical annihilation model (I.A. Pshenichnov et al., 1992)
or by string model (if $|Z_{\rm tot}| > 1$ or total charm$\neq 0$ or total strangeness$\neq 0$),
$\bar{B}B \to \bar{B}B$ (EL and CEX), $\bar{N}N \leftrightarrow \bar{\Delta}N(\bar{N}\Delta)$ (for $\sqrt{s} < 2.38$ GeV)
or $\bar{B}B \to \bar{B}B +$ mesons by FRITIOF (for $\sqrt{s} > 2.38$ GeV),
$\bar{N}N \to \bar{\Lambda}\Lambda$, $\bar{N}(\bar{\Delta})N(\Delta) \to \bar{\Lambda}\Sigma(\bar{\Sigma}\Lambda)$, $\bar{N}(\bar{\Delta})N(\Delta) \to \bar{\Xi}\Xi$, $\bar{N}N \to \bar{\Omega}\Omega$,
$\bar{N}N \to J/\psi$.

$3 \to 2$ collisions: $NN\pi \to NN$.

$3 \to 3$ collisions: $NN\Delta \to NNN$.

$3 \to N$ collisions: see below.

Heavy ion collisions

A.L., O. Buss, K. Gallmeister, and U. Mosel, PRC 76, 044909 (2007)

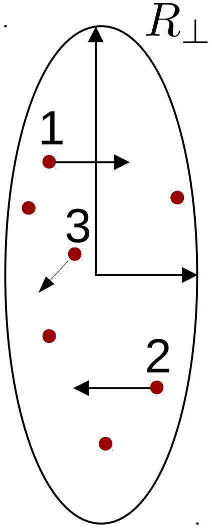
Gas parameter at $\rho_B \simeq 10\rho_0$ (maximal baryon density reached in a central Au+Au collision at 20 A GeV):

$$\left(\frac{\text{interaction radius}}{\text{interparticle distance}}\right)^3 = (\sigma/\pi)^{3/2}\rho_B \simeq 2 > 1 \ ,$$

where σ=40 mb — asymptotic high-energy pp cross section.

➡ Many-body collisions are important
(St. Mrówczynski, Phys.Rev. C32 (1985) 1784-1785)

Three-body collisions: method from G. Batko, J. Randrup, T. Vetter, 1992, modified for relativistic effects



$$R_\perp = \sqrt{\sigma_{\rm tot}/\pi}$$

$$R_{||} = \gamma_{12}^{-1}\sqrt{\sigma_{\rm tot}/\pi}$$

$$\gamma_{12} = \frac{\gamma_1 + \gamma_2}{2}$$

- define the interaction volume of colliding particles 1 and 2 in their c.m.s.

- find the particle 3, which is the closest to the c.m. of 1 and 2 inside the interaction volume

- redistribute the kinetic momenta of 1,2 and 3 microcanonically

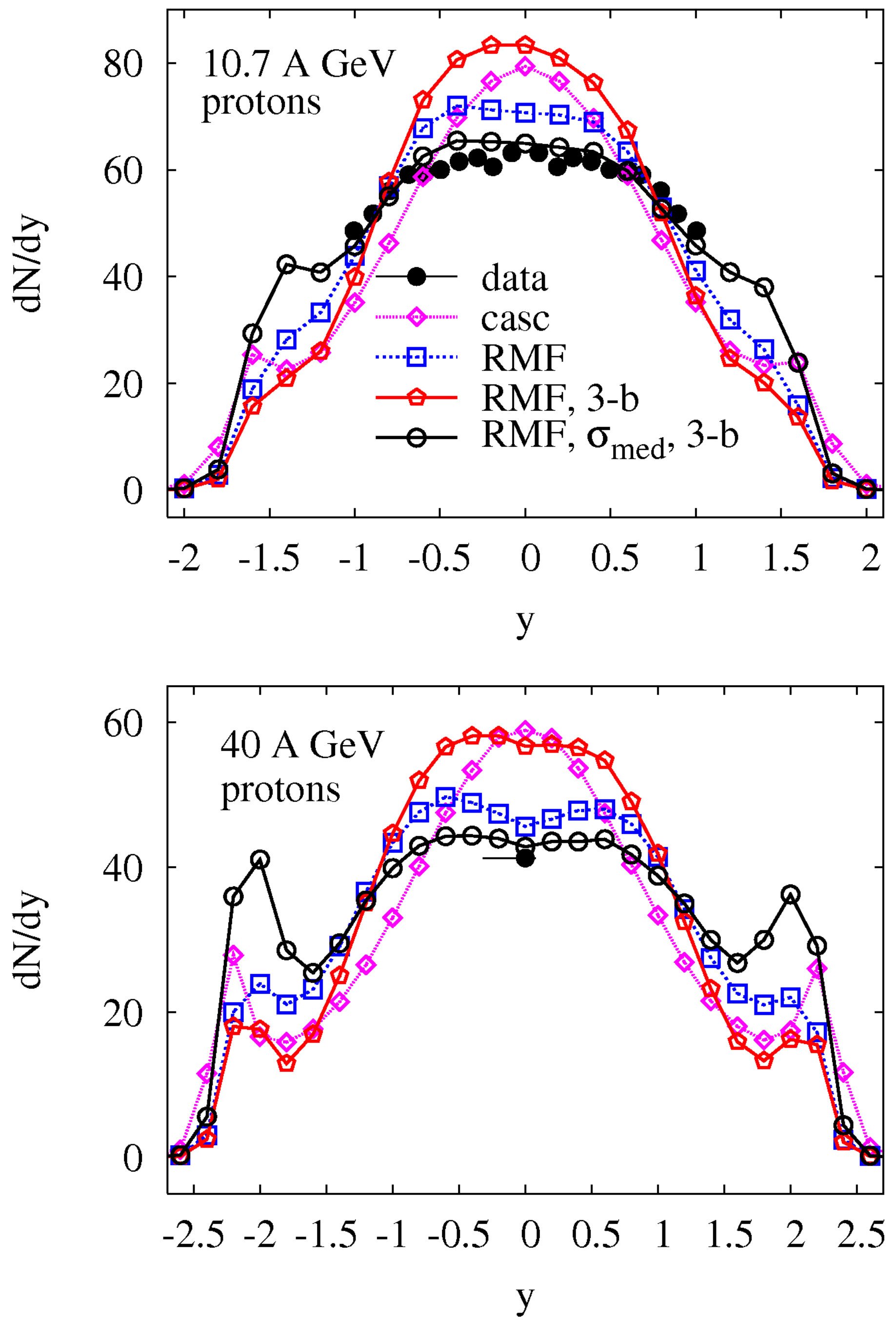
$$dP \propto \delta^{(4)}(p_1^* + p_2^* + p_3^* - p_{1'}^* - p_{2'}^* - p_{3'}^*)\frac{d^3p_{1'}^*}{(2\pi)^3 2p_{1'}^{*0}}\frac{d^3p_{2'}^*}{(2\pi)^3 2p_{2'}^{*0}}\frac{d^3p_{3'}^*}{(2\pi)^3 2p_{3'}^{*0}}$$

Dirac mass shell conditions: $(p_{i'}^*)^2 = (p_i^*)^2 = (m_i^*)^2\ , \quad i = 1,2,3$

- simulate the two-body collision of 1 and 2 with their new four-momenta $p_{1'}^*,\ p_{2'}^*$

Proton rapidity distributions

Data: Au+Au at 10.7 A GeV, 5% centrality,
B.B. Back et al., PRC **66**, 054901 (2002);
Pb+Pb at 40 A GeV, 7% centrality,
T. Anticic et al., PRC **69**, 024902 (2004).



Cascade gives too much stopping

RMF reduces stopping: less collisions due to repulsive ω_0 field

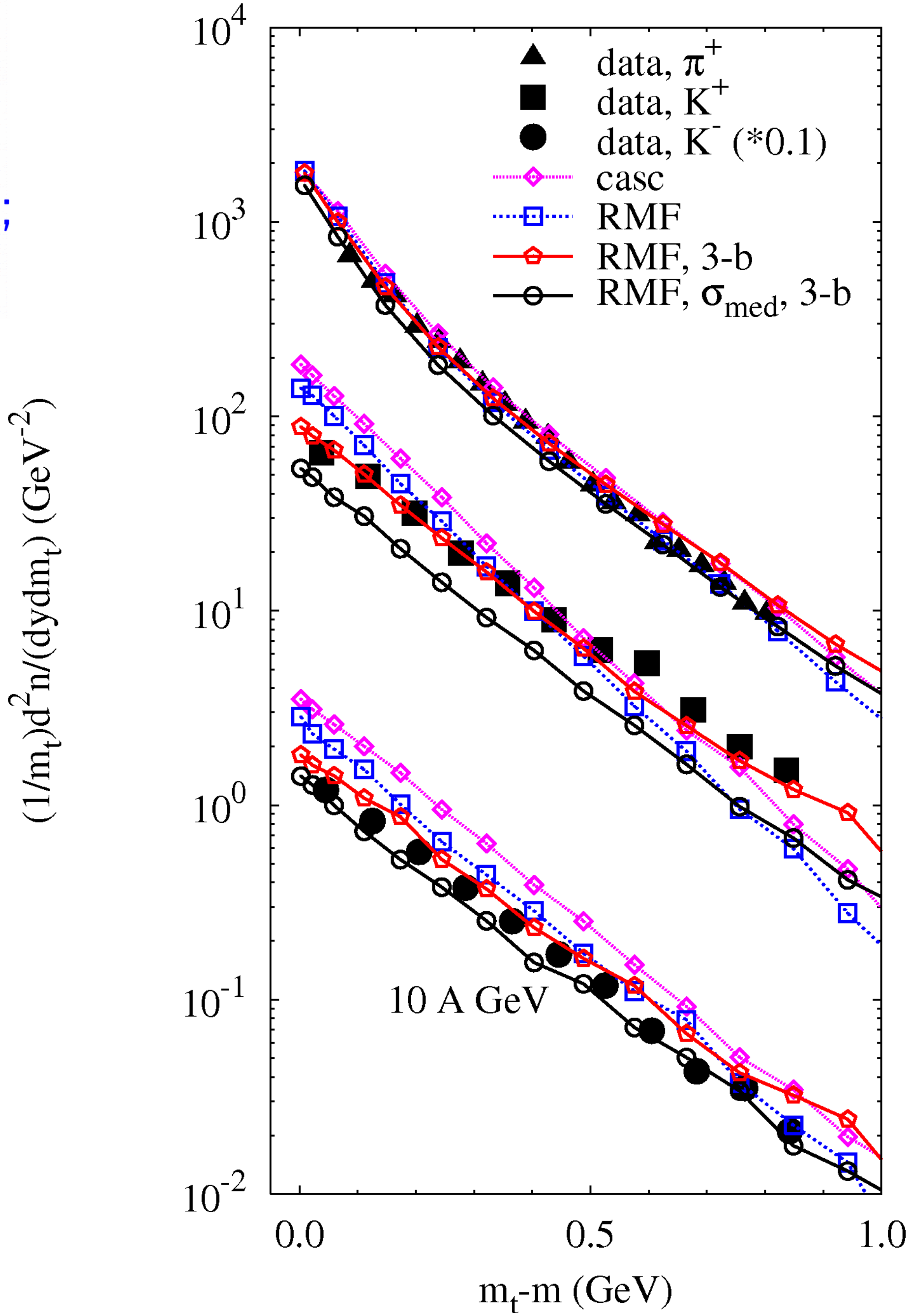
Three-body collisions increase thermalization → more stopping

In-medium reduced cross sections

again reduce stopping

π^+, K^+ and K^- transverse mass spectra at midrapidity from central Au+Au collisions at 10.7 A GeV

Data: L. Ahle et al., PLB **476**, 1 (2000); PLB **490**, 53 (2000).



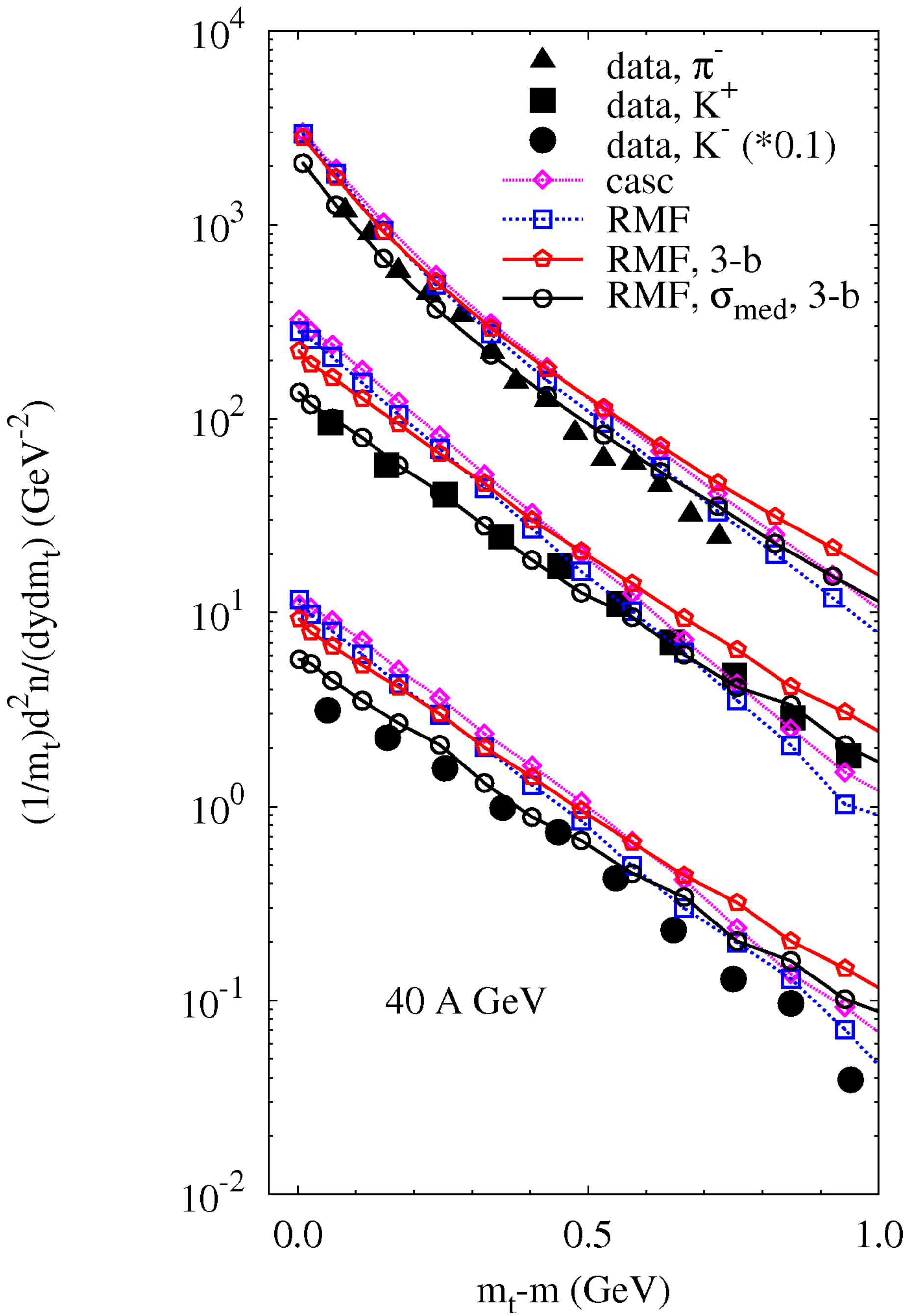
π^-, K^+ and K^- transverse mass spectra at midrapidity from central Pb+Pb collisions at 40 A GeV.

Data: S. Afanasiev et al., PRC **66**, 054902 (2002).

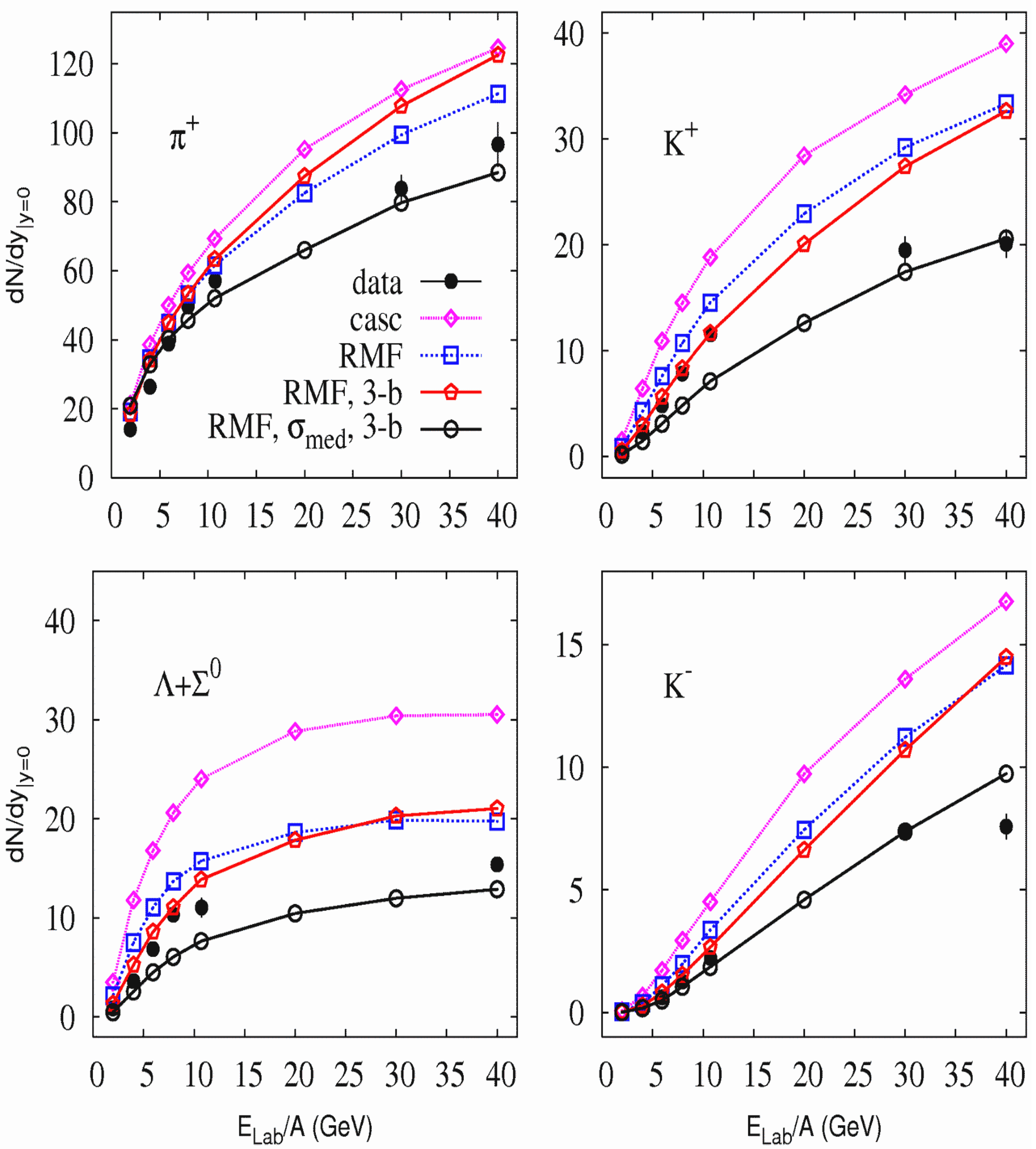
Cascade and RMF calculations w/o three-body collisions produce too soft m_t-spectra of K^+ and K^-.

Three-body collisions reduce slope → better agreement with data.

Pion m_t-spectra are not much influenced by three-body collisions.



The midrapidity yields of π^+, K^+, $(\Lambda + \Sigma^0)$ and K^- vs the beam energy for central collisions of Au+Au at $E_{lab} \leq$ 20 A GeV and Pb+Pb at $E_{lab} = $ 30 and 40 A GeV.

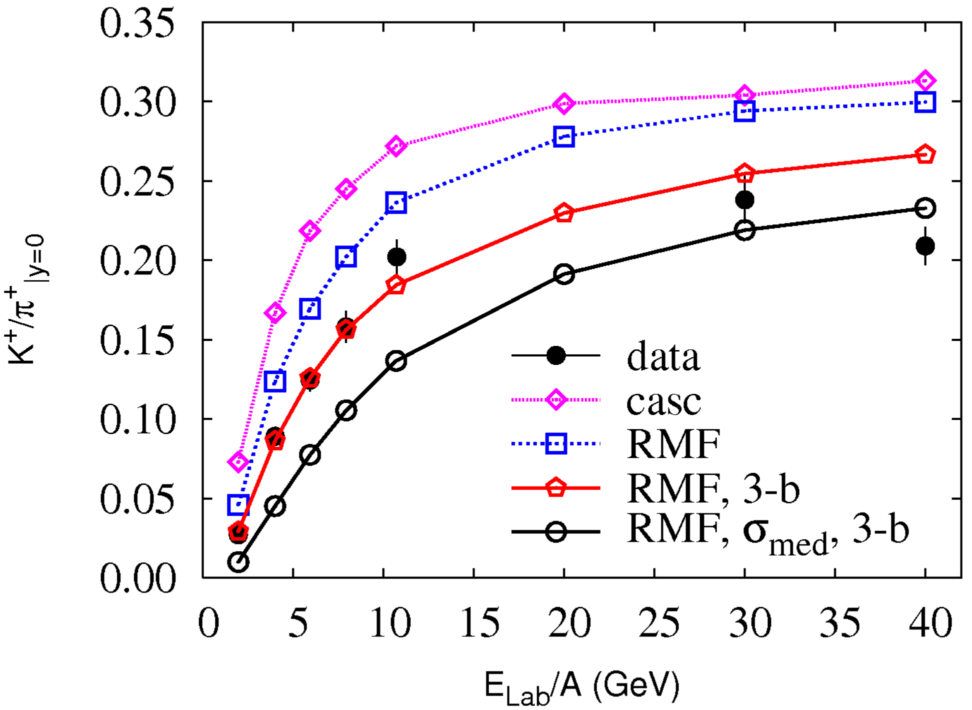


RMF strongly reduces the hyperon yield at midrapidity.

In-medium cross sections reduce meson production.

The ratio of midrapidity yields K^+/π^+ for central Au+Au and Pb+Pb collisions.

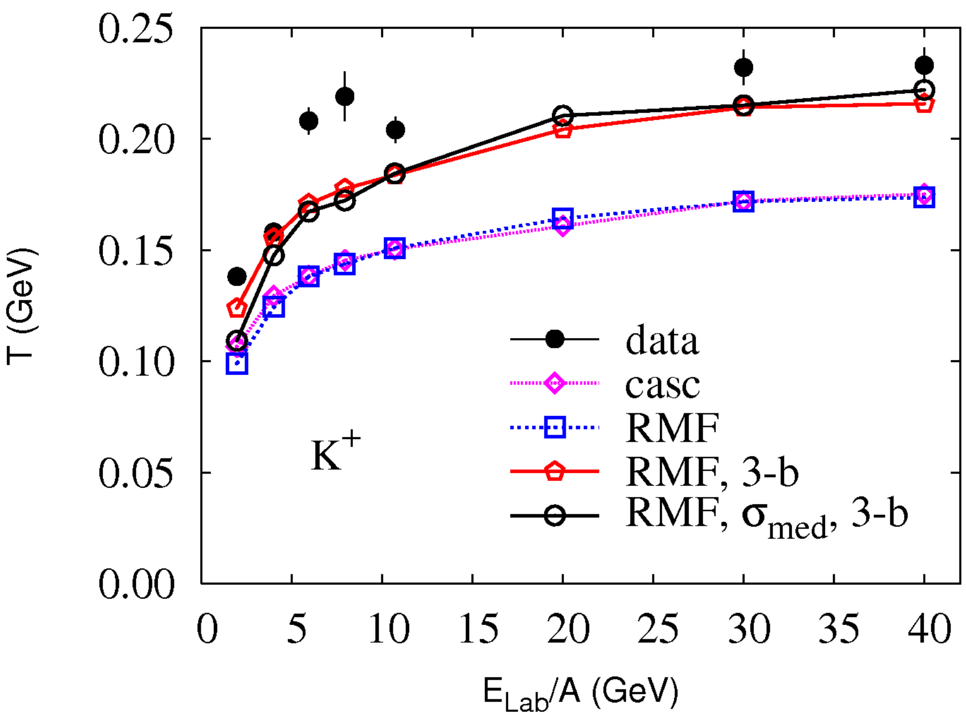
Data: L. Ahle et al., PLB **476**, 1 (2000); S. Afanasiev et al., PRC **66**, 054902 (2002); V. Friese, J. Phys. G **30**, 119 (2004).



Problem to describe the reduction of K^+/π^+ above 30 A GeV.

Inverse slope parameter T of the K^+ transverse mass spectrum at midrapidity obtained by a fit $\frac{d^2n}{m_\perp dm_\perp dy} = a\exp\{-m_\perp/T\}$ for central collisions of Au+Au and Pb+Pb as a function of the beam energy.

Data: L. Ahle et al., PLB **490**, 53 (2000); S. Afanasiev et al., PRC **66**, 054902 (2002); V. Friese, J. Phys. G **30**, 119 (2004).



Three-body collisions raise T by ~30% at large E_{lab}.

Agreement with three-fluid hydrodinamical model results

Yu.B. Ivanov, V.N. Russkikh, Eur. Phys. J. A37, 139 (2008), nucl-th/0607070

Antiproton-nucleus reactions

~5 % of $\bar{p}p$ annihilations at rest produce a $\bar{K}K$ pair – rate comparable to the YK production rate in Au+Au collisions at E_{lab}=1.5 GeV/nucleon.

Hyperon production: $\bar{p}A$: $\bar{K}N \longrightarrow Y\pi$

AA: $BB \longrightarrow BYK$

Experiments on strangeness production in $\bar{p}$-nucleus reactions:

BNL (G.T. Condo et al, 1984): Λ from $\bar{p}$(0-450 MeV/c)^{12}C,^{48}Ti,^{181}Ta,^{208}Pb

LEAR (F. Balestra et al, 1987): K^0_S, Λ from $\bar{p}$(607 MeV/c)^{20}Ne

KEK (K. Miyano et al, 1988): K^0_S, Λ, $\bar{\Lambda}$ from $\bar{p}$(4 GeV/c)^{181}Ta

LEAR (A. Panzarasa et al, 2005, G. Bendiscioli et al, 2009):

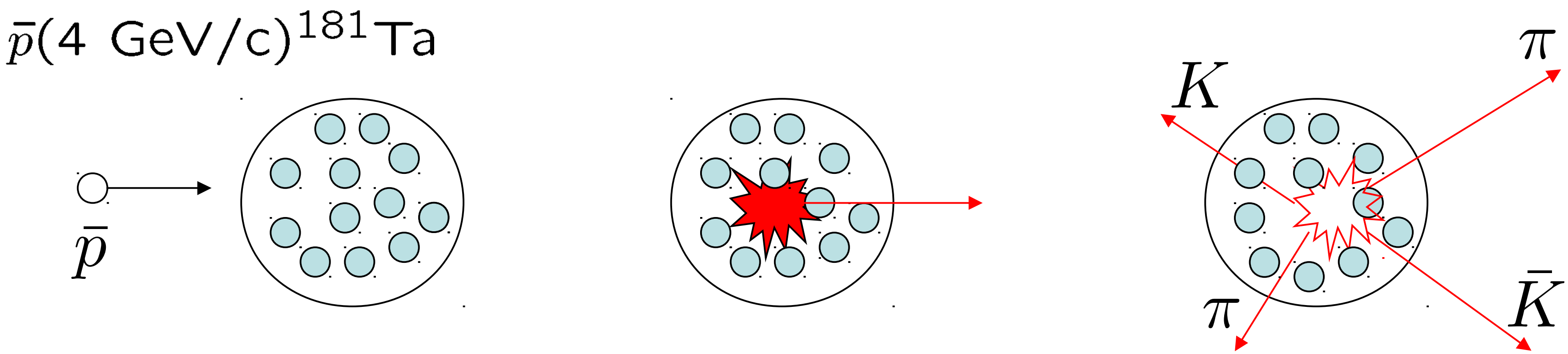
$K^{\pm}$ from $\bar{p}$(at rest)$p, d,^{3}$He,^{4}He

- Large ratio $\Lambda/K^0_S = 2-3$ both for light (^{20}Ne) and heavy (^{181}Ta) targets.

- Λ rapidity spectrum is peaked close to y=0 in lab. frame even for energetic collisions $\bar{p}$(4 GeV/c)^{181}Ta.

- Enhanced strangeness production for B>0 annihilations at rest.

***Exotic scenario (J. Rafelski, 1988)*: propagating annihilation fireball with baryon number B > 0 due to absorption of nucleons**



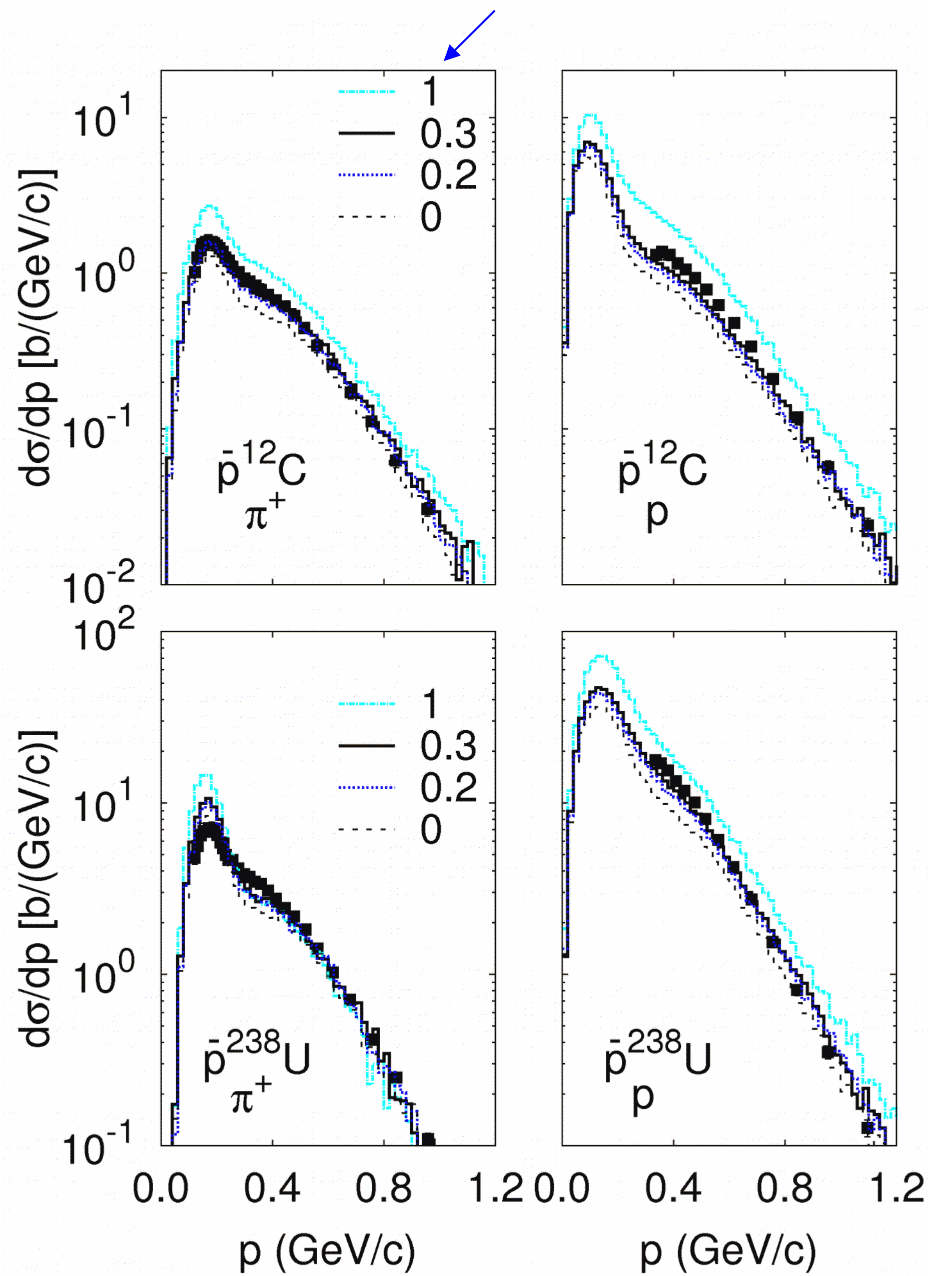
-Large energy deposition ~2m_N in a small volume of nuclear matter. Supercooled QGP might be formed if more than one nucleon participate in annihilation.

-Strangeness production in a QGP should be enhanced.

Momentum spectra of protons and pions for p_{lab}=608 MeV/c.

Data (LEAR): P.L. McGaughey et al., PRL 56, 2156 (1986).

Antiproton mean field scaling factor ξ
(G-parity transformation → ξ=1)



A weak sensitivity to the $\bar{p}$ mean field: best agreement for ξ≈0.3, or Re(V_{opt})=-(220±70) MeV

A.L., I.A. Pshenichnov, I.N. Mishustin, W. Greiner, PRC 80, 021601(R) (2009)

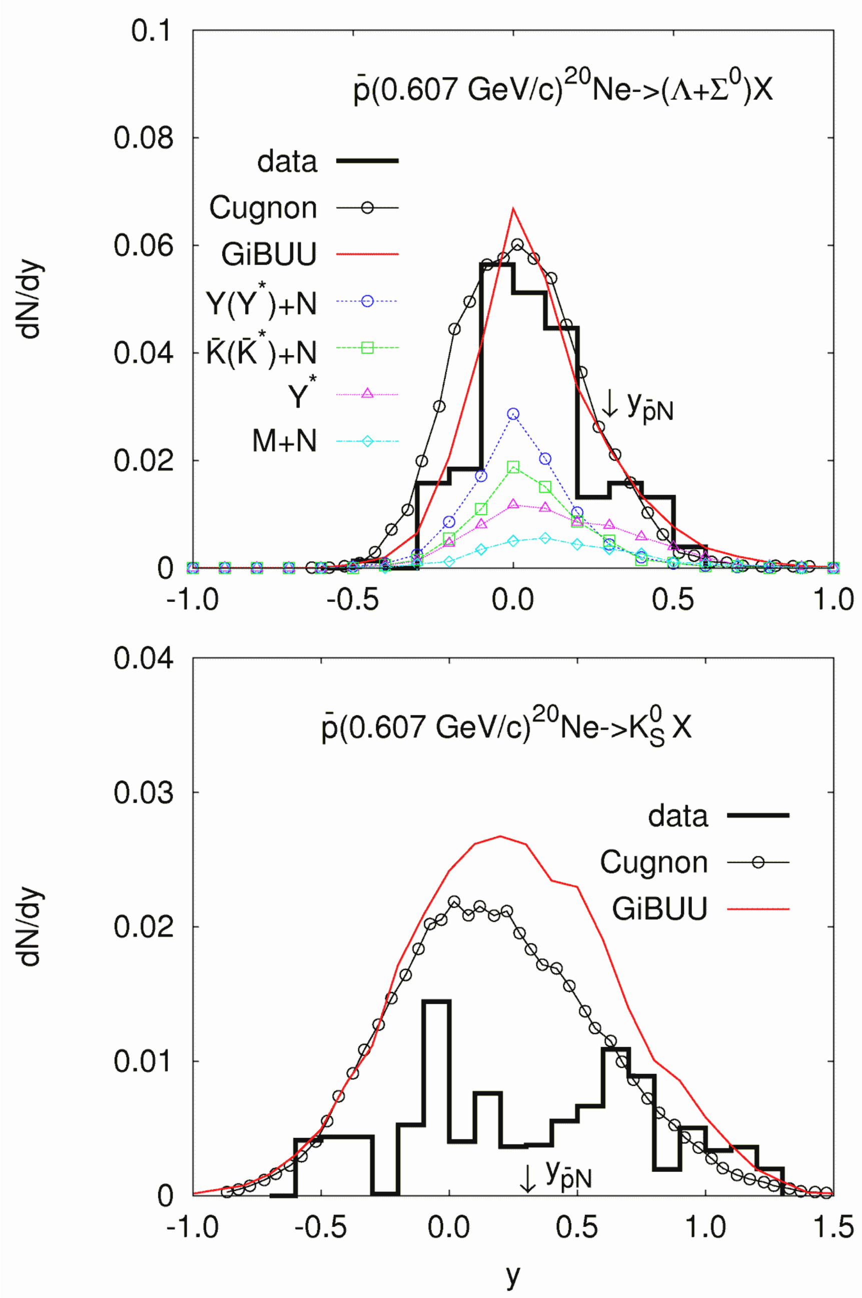
Rapidity distributions of Λ and K_S^0 from $\bar{p}(607\ MeV/c)^{20}$Ne.

Data (LEAR): F. Balestra et al., PLB 194, 192 (1987).

Comparison of the GiBUU and cascade calculations by J. Cugnon et al., PRC 41, 1701 (1990).

Hyperons are mostly produced in $\bar{K}(\bar{K}^*)N$ collisions. Hyperon rescattering with flavour/charge exchange very important (e.g. $\Sigma^+ n \to \Lambda p$).

Good agreement with data on Λ production. The yield of K_S^0 is overestimated.



A.L., T. Gaitanos, U. Mosel, Phys.Rev. C85, 024614 (2012)

Rapidity distributions of Λ and K_S^0 from $\bar{p}(4\ GeV/c)^{181}$Ta with partial contributions from different reaction channels

$B \equiv N,\ \Delta,\ N^* \dots$

– nonstrange baryons,

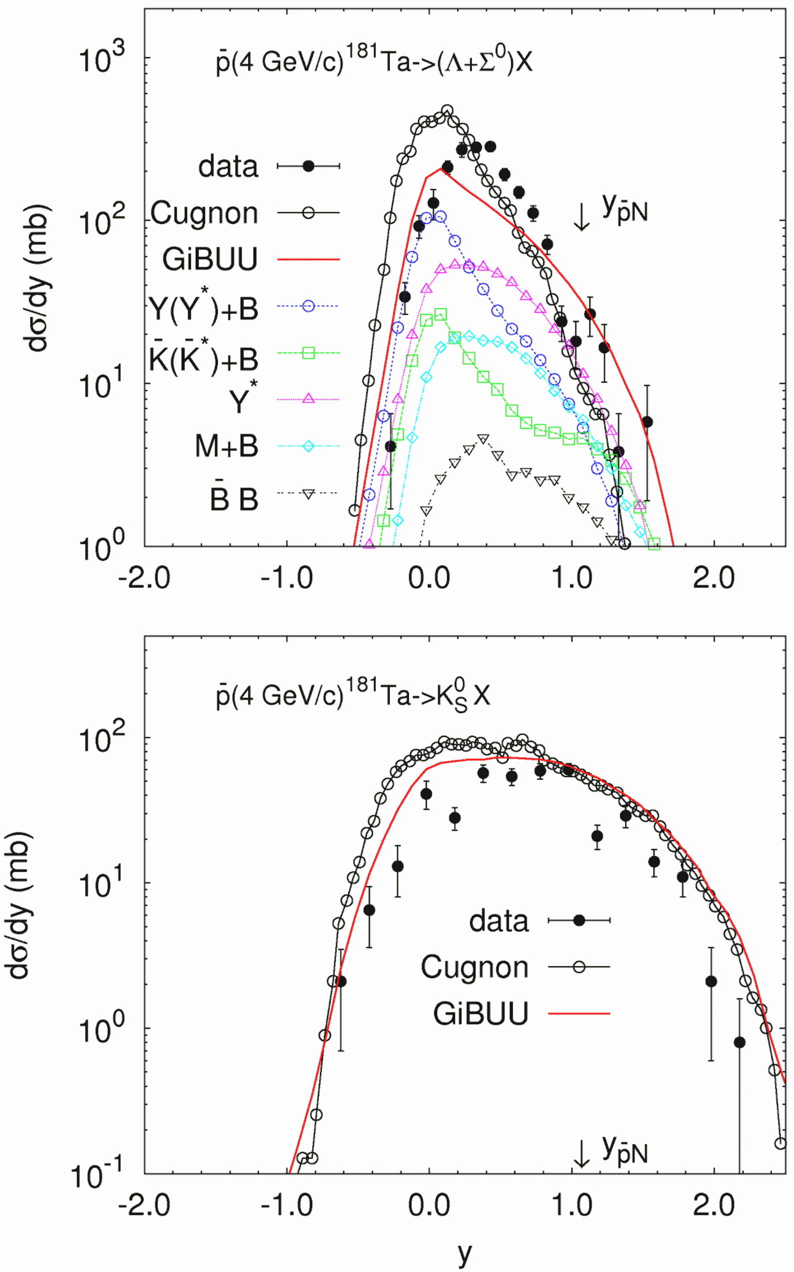
$M \equiv \pi,\ \eta,\ \rho,\ \sigma,\ \omega,\ \eta'$

– nonstrange mesons

Data (KEK): K. Miyano et al., PRC 38, 2788 (1988).

~70-80% of the Y(Y*) production rate is due to antikaon absorption

$\bar{K}B \to YX,\ \bar{K}B \to Y^*,\ \bar{K}B \to Y^*\pi$

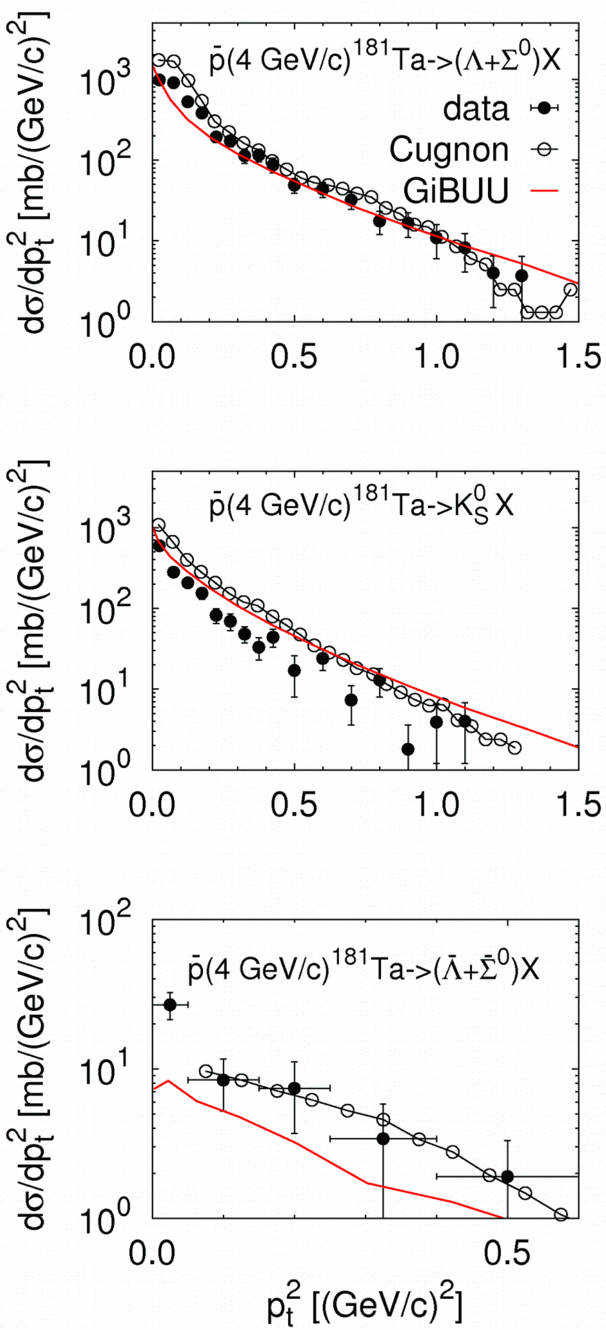


A.L., T. Gaitanos, U. Mosel, Phys.Rev. C85, 024614 (2012)

Transverse momentum distributions of Λ, K_S, and $\overline{\Lambda}$ from $\bar{p}(4\ GeV/c)^{181}$Ta

Data (KEK): K. Miyano et al., PRC 38, 2788 (1988).

Comparison of the GiBUU and cascade calculations by J. Cugnon et al., PRC 41, 1701 (1990).



Spectral shapes well described.
K_S yield overestimated by both models.
$\overline{\Lambda}$ yield underestimated by GiBUU.

A.L., T. Gaitanos, U. Mosel, Phys.Rev. C85, 024614 (2012)

Rapidity spectra of strange particles.

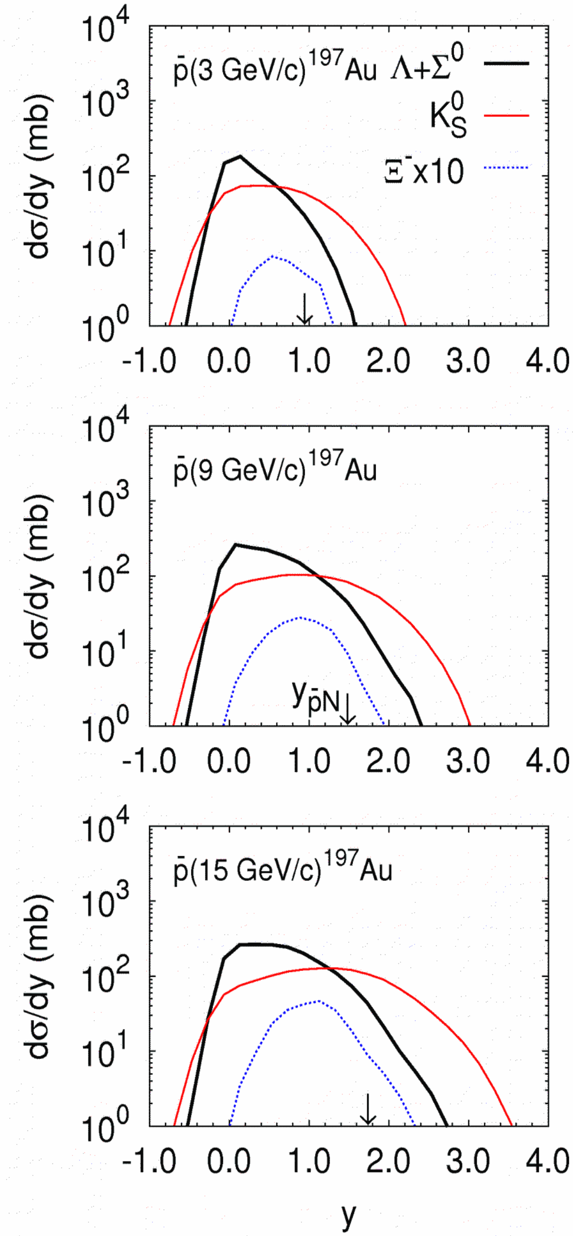
Λ spectra always peak at y≈0 due to exothermic reactions $\bar{K}N \to Y\pi$ with slow $\overline{\mathrm{K}}$

Spectra for Ξ^- are shifted to forward rapidities due to endothermic reactions $\bar{K}N \to \Xi K$

$(p_{\mathrm{lab}}^{\mathrm{thr}} = 1.048\ \mathrm{GeV/c},\ y_{\bar{K}N}^{\mathrm{thr}} = 0.55)$

In the fireball scenario the rapidity spectra of all strange particles would be peaked at the same rapidity !

Can be tested at PANDA@FAIR



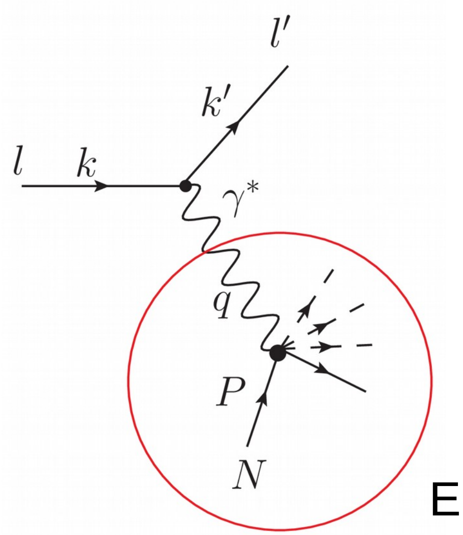
A.L., T. Gaitanos, U. Mosel, Phys.Rev. C85, 024614 (2012)

High-energy virtual-photon-nucleus reactions

$$q = k - k' \ , \quad Q^2 = -q^2$$

Deep inelastic scattering (DIS)

$$W^2 = (P+q)^2 = m_N^2 - Q^2 + 2Pq = m_N^2 - Q^2 + 2m_N\nu$$



HERMES at HERA:

(A. Airapetian et al., 2003)

$E_{e^+} = 27.6$ GeV, D, N, Kr targets
$Q^2 > 1$ GeV^2, $W > 2$ GeV
$\pi^\pm$, π^0, $K^\pm$, p, $\bar{p}$ production.

EMC at CERN SPS:

(J. Ashman et al., 1991)

$E_{\mu^-} = 100,\ 120,\ 200,\ 280$ GeV, D, C, Cu, Sn targets
$Q^2 > 2-5$ GeV^2, $\nu > 10-50$ GeV
charge hadron production.

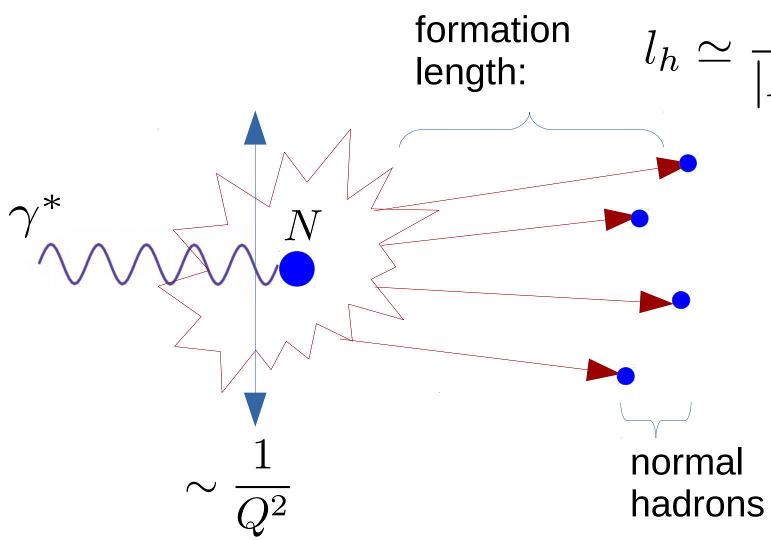
Analysis (GiBUU model) in: K. Gallmeister, U. Mosel, NPA 801, 68 (2008)

→ Differential multiplicity ratious

$$R_M^h(\nu, Q^2, z_h, p_T^2, \dots) = \frac{\left[N_h(\nu, Q^2, z_h, p_T^2, \dots)/N_e(\nu, Q^2)\right]_A}{\left[N_h(\nu, Q^2, z_h, p_T^2, \dots)/N_e(\nu, Q^2)\right]_{\rm D}}, \quad z_h = E_h/\nu,$$

are sensitive to the model for hadronization.

The space-time scale of hadronization:



$$l_h \simeq \frac{2p_h}{|M_h^2 - M_{h'}^2|} \sim 0.4 - 0.6(\mathrm{fm/GeV}) \cdot p[\mathrm{GeV}]$$

During formation stage the “prehadrons” interact with nucleons with reduced strength.

E665 at Fermilab:

(M.R. Adams et al., 1995)

$E_{\mu^-} = 470$ GeV, H, D, C, Ca, Pb targets
$Q^2 > 0.8$ GeV^2, $\nu > 20$ GeV
low-energy neutrons ($E < 10$ MeV)

- Nucleus may serve as a “microcalorimeter” for high-energy hadrons : the excitation energy of the residual nucleus grows with the number of holes (wunded nucleons) and can be measured by the number of emitted low-energy neutrons

Theoretical analyses: M. Strikman, M.G. Tverskoy, M.B. Zhalov, PLB 459, 37 (1999); A.L., M. Strikman, arXiv:1812.08231

Models (prescriptions) for the prehadron-nucleon interaction cross section:

(I) Based on JETSET-production-formation points (GiBUU default):

K. Gallmeister, T. Falter, PLB 630, 40 (2005);
K. Gallmeister, U. Mosel, NPA 801, 68 (2008)

$$\sigma_{\rm eff}(t)/\sigma_0 = X_0 + (1-X_0)\frac{t-t_{\rm prod}}{t_{\rm form}-t_{\rm prod}} \ ,$$

$$X_0 = r_{\rm lead}a/Q^2, \ a = 1 \ {\rm GeV}^2,$$

$r_{\rm lead}$ - the ratio (#of leading quarks)/(total # of quarks) in the prehadron,

(II) Quantum diffusion model (QDM):

G.R. Farrar, H. Liu, L.L. Frankfurt, M.I. Strikman, PRL 61, 686 (1988)

$$\sigma_{\rm eff}(t)/\sigma_0 = X_0 + (1-X_0)\frac{c(t-t_{\rm hard})}{l_h} \ ,$$

No direct way to derive X_0 for DIS (this is not exclusive process).
Thus we set X_0=0 for simplicity.

(III) Cutoff:

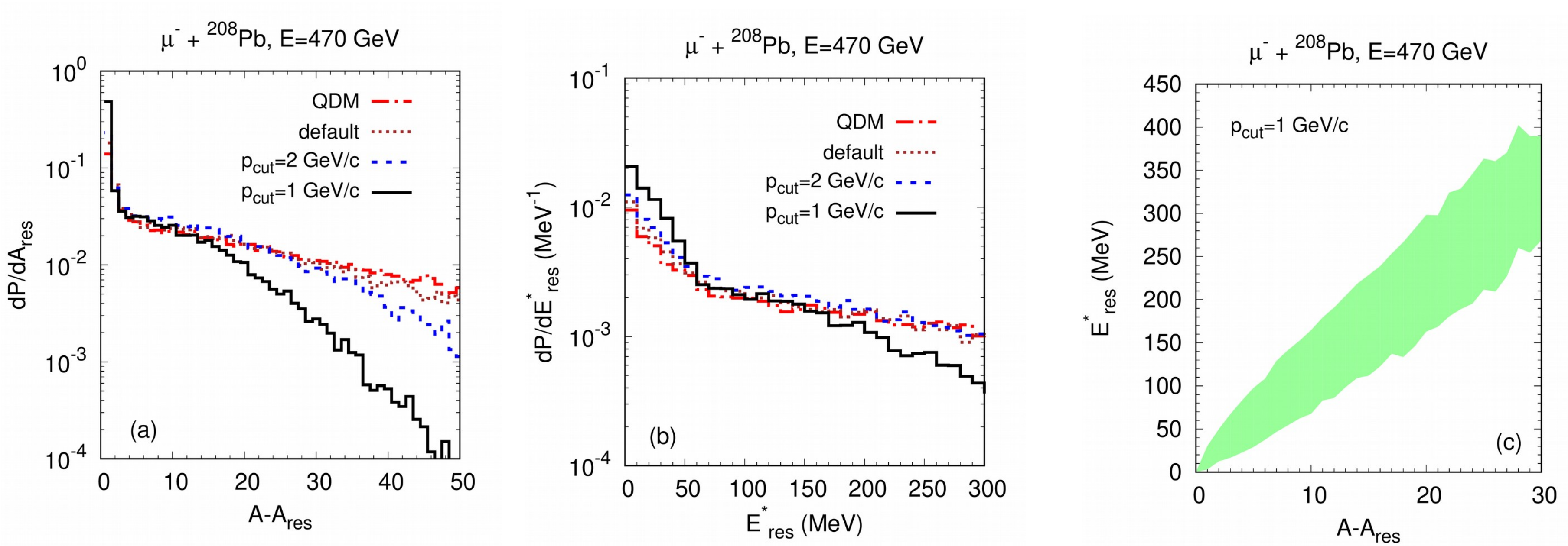
$$\sigma_{\rm eff}/\sigma_0 = \Theta(p_{\rm cut}-p) \ , \quad p_{\rm cut} \sim 1-2 \ {\rm GeV/c}.$$

A.L., M. Strikman, arXiv:1812.08231

The neutron spectrum contains both the preequlibrium part (cascade particles) and the equilibrium part from the decay of the excited residual nucleus.

Characteristics of the residual nucleus obtained by counting hole excitations in GiBUU time-evolution (corresponds to wounded nucleons in Glauber model):

$$\begin{cases} A_{\rm res} = A - n_{\rm h} \ , \\ Z_{\rm res} = Z - \sum_{i=1}^{n_{\rm h}} Q_i \ , \\ E^*_{\rm res} = \sum_{i=1}^{n_{\rm h}} (E_{F,i} - E_i) \ , \\ \boldsymbol{p}_{\rm res} = -\sum_{i=1}^{n_{\rm h}} \boldsymbol{p}_i \ . \end{cases}$$



Stronger restriction on FSI of the hadrons results in smaller mass loss and smaller excitation energy.

$$\langle E^*_{\rm res} \rangle \simeq 10 \ {\rm MeV} (A - A_{\rm res}),$$

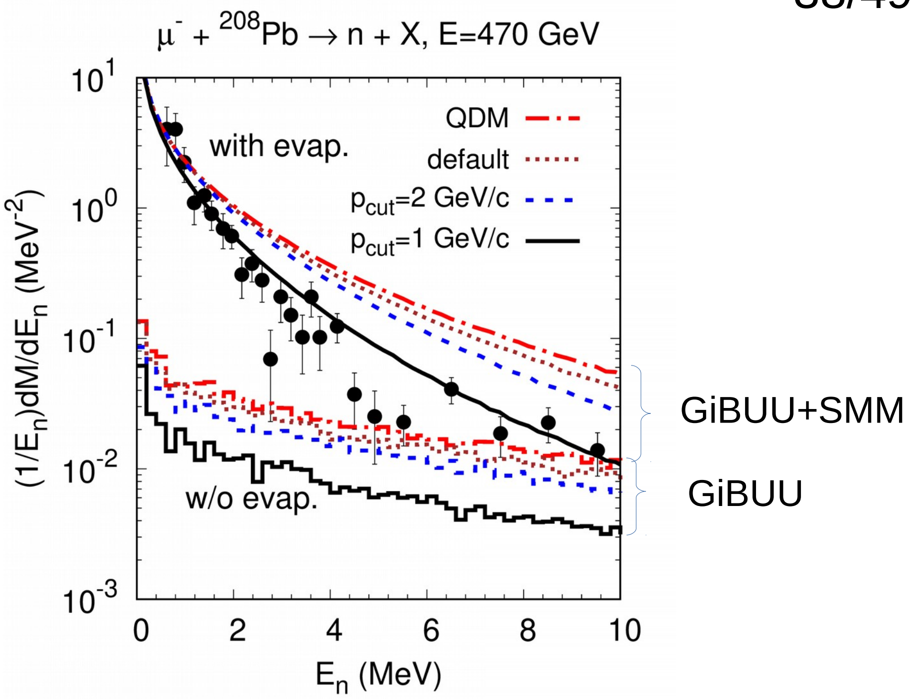
the spread is due to Fermi motion.

A.L., M. Strikman, arXiv:1812.08231

Source parameters $A_{\rm res},\ Z_{\rm res},\ E^*_{\rm res},\ \mathbf{p}_{\rm res}$ were determined from GiBUU at t_{max}=100 fm/c and used as input for statistical multifragmentation model (SMM) in evaporation mode (multifragmentation turned-off).

SMM: J.P. Bondorf, A.S. Botvina, A.S. Iljinov, I.N. Mishustin, K. Sneppen, Phys. Rept. 257, 133 (1995)

SMM code provided by Dr. Alexander S. Botvina



E665 data from M.R. Adams et al., PRL 74, 5198 (1995)

- almost all neutrons below 1 MeV are statistically evaporated;

- sensitivity to the model of hadron formation for E_n > 5 MeV;

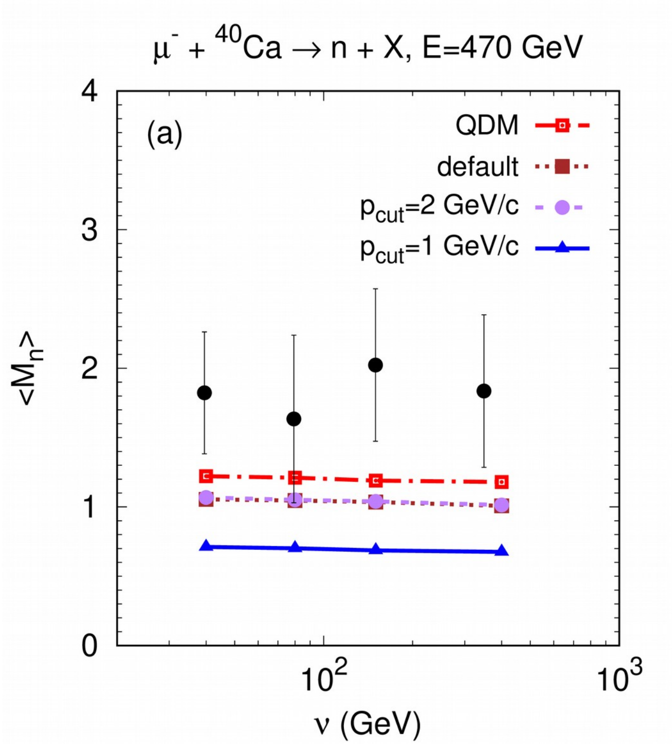
- E665 data for lead target can be only described with very strong restriction on the FSI of hadrons (p_{cut}=1 GeV/c) in agreement with earlier calculations

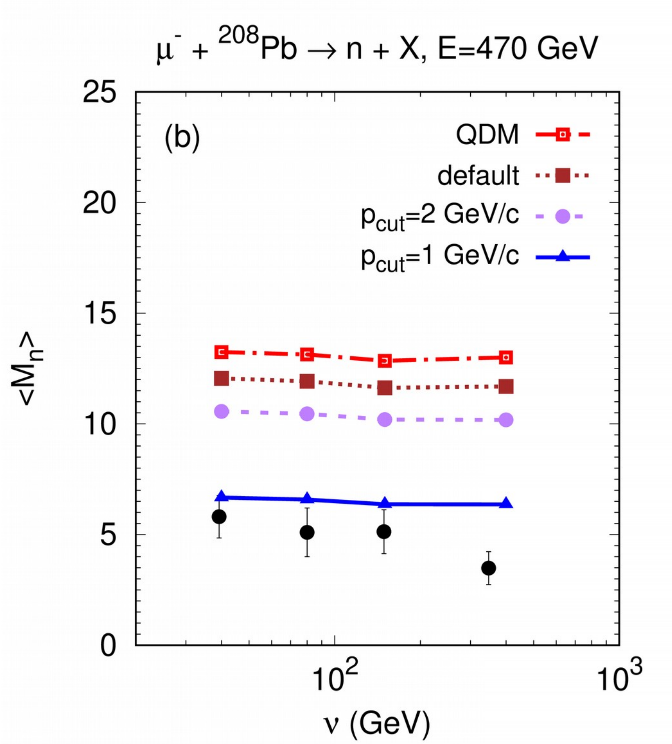
M. Strikman, M.G. Tverskoy, M.B. Zhalov, PLB 459, 37 (1999)

Cuts:
$\nu > 20$ GeV,
$Q^2 > 0.8$ GeV^2.

A.L., M. Strikman, arXiv:1812.08231

Average multiplicity of neutrons with energy below 10 MeV
as a function of virtual photon energy





E665 data from
M.R. Adams et al.,
PRL 74, 5198 (1995)

- no way to describe the E665 data for calcium target with any reasonable model parameters

A.L., M. Strikman, arXiv:1812.08231

Various scenaria for hadron formation can be tested
in Ultraperipheral Collisions (UPCs) of heavy ions at LHC and RHIC.

Quasireal photons are emitted coherently by the entire nuclei.

Minimal wavelength should match the radius
of the Lorentz-contracted emitting nucleus.

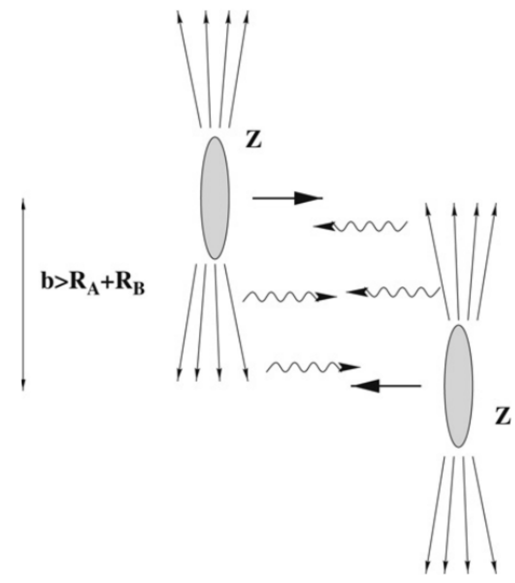


Figure from A.J. Baltz et al., Phys. Rept. 458, 1 (2008)

Maximal longitudinal momentum
of the photon in the c.m. frame
of colliding nuclei (collider lab. frame):

$$k_L^{\max} \simeq \frac{\gamma_L}{R_A}$$

For symmetric colliding system
in the rest frame of the target nucleus:

$$k^{\max} = \gamma_L 2 k_L^{\max} \simeq \frac{2\gamma_L^2}{R_A}$$

Table 1: Parameters of UPCs Au+Au at RHIC and Pb+Pb at LHC.

	$\sqrt{s_{NN}}$ (TeV)	γ_L	$k^{\max}$ (TeV/c)	W (GeV)
RHIC	0.2	106	0.642	34.7
LHC	5.5	2931	477	946

Transverse momentum spectra of neutrons in quasireal-photon-nucleus collisions

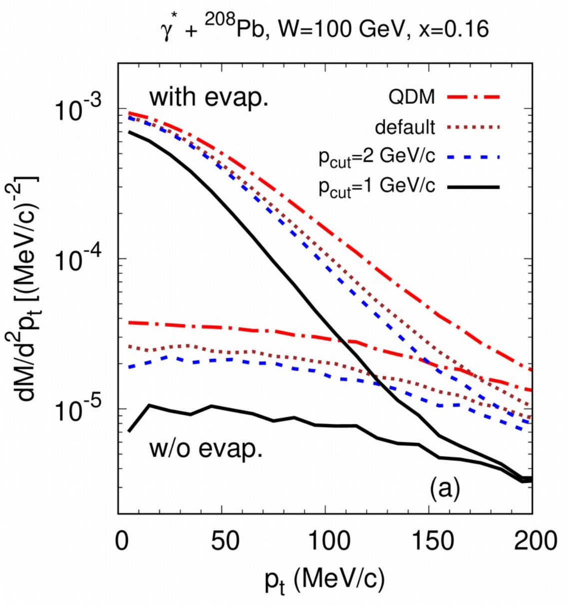
The value of Bjorken x is set from matchning x_{parton} in inclusive set of PYTHIA events to x_g for $\gamma g \to 2\mathrm{jets}$ using condition:

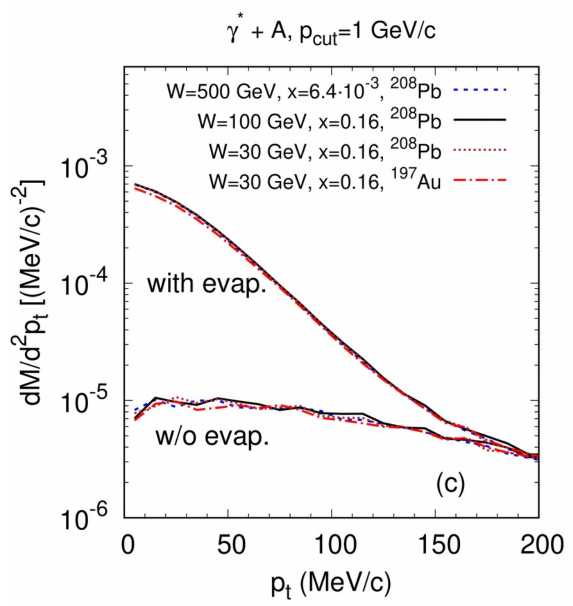
$$x = \frac{(40\ \mathrm{GeV})^2}{W^2}$$

The dijet invariant mass of 40 GeV is the low cut at LHC – guaranties the smallness of the photon shadowing effect which we neglected in calculations.

- strong sensitivity to the hadron formation model at moderate p_t

- no influence of photon kinematics (thus folding with photon flux not important)





A.L., M. Strikman, arXiv:1812.08231

Possible new directions of studies in NICA regime

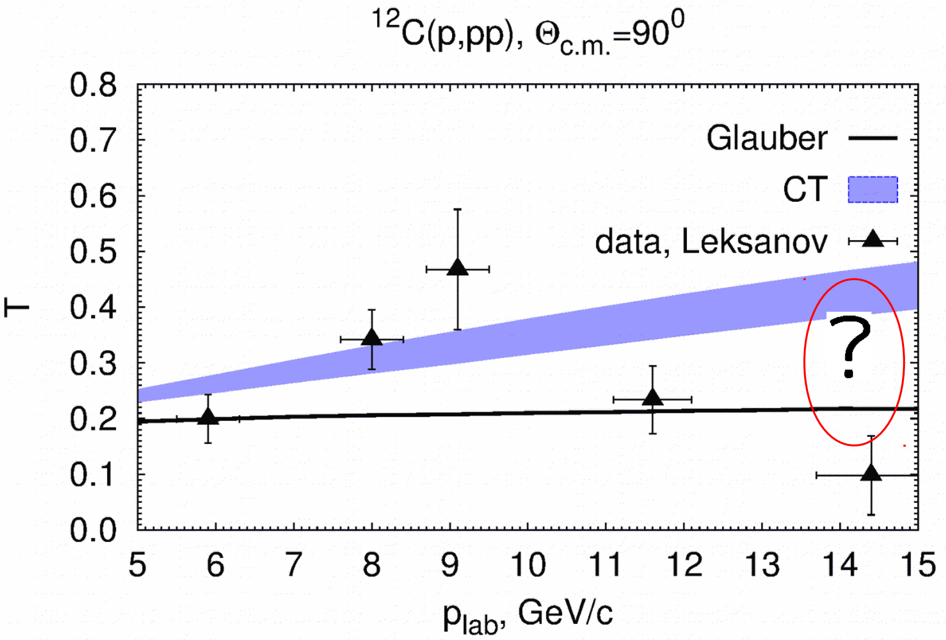
- Influence of color transparency (CT) on A(p,pp) semiexclusive process.

Nuclear transparency for target proton at rest:

$$T = \frac{d\sigma/dt}{d\sigma^{\rm IA}/dt}$$

Data: EVA at AGS,
A. Leksanov et al.,
PRL 87, 212301 (2001).

Calculations:
A.L., M. Strikman,
work in progress



Decrease of T at high p_{lab} is not understood:

- could be due to stronger absorption of the large-size quark configurations produced by Landshoff mechanism, J.P. Ralston, B. Pire, PRL 61, 1823 (1988);
- or due to intermediate (very broad, Γ~ 1 GeV) 6q$c\bar{c}$ resonance formation with mass ~ 5 GeV, S.J. Brodsky, G.F. de Teramond, PRL 60, 1924 (1988).

- In the case of central AA collisions the hadron formation dynamics (CT) should influence the nuclear stopping power (hadron rapidity distributions).

- Short-range NN correlations (SRC) in nuclei can be explored in exclusive binary and triple reactions with $|t|,|u| \approx 1\text{-}2$ GeV^2 at p_{lab}=4-20 GeV :

$$A(p,pp),\;\; A(p,pn),\;\; A(p,ppn),\;\; A(p,ppp),\;\; A(p,pnn)$$

SRCs are responsible for high-momentum tails of nucleon momentum distributions in nuclei:

Solid line – full momentum distribution with NN correlations,
Dashed line – contribution from occupied levels with $\varepsilon < \varepsilon_F$.
Open squares – from y-scaling analysis of (e,e´) data.

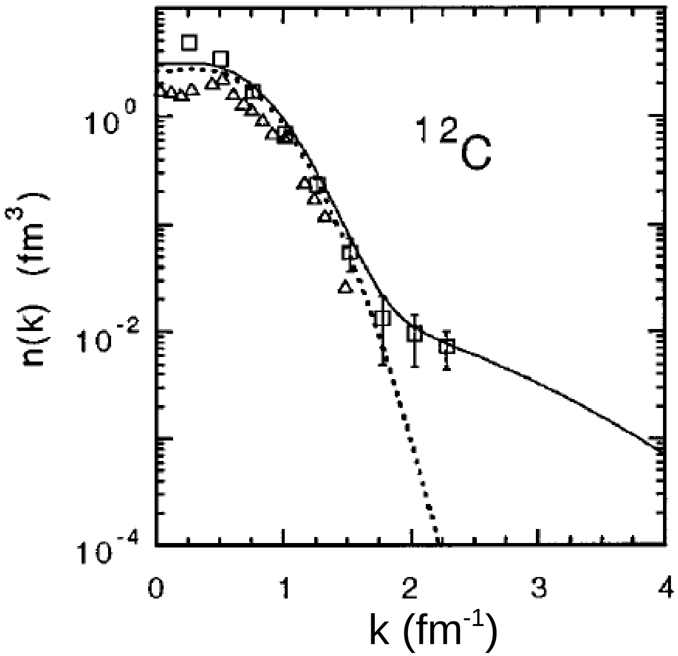


Figure from C. Ciofi degli Atti, S. Simula, PRC 53, 1689 (1996)

- Charmonia and open charm production and dynamics.

J/Ψ production in AA collisions may help to clarify whether the QGP formed or not. However, for this one has to know all possible hadronic channels of the J/Ψ absorption in collisions with nucleons and mesons.

E.g. $\sigma_{J/\psi N} = 3 - 6\ \mathrm{mb}$ as known presently.

The dedicated study of $\sigma_{J/\psi N}$ using production channel $A(\bar{p}, J/\psi)$ is planned in PANDA experiment at FAIR. See, e.g. ***AL, M. Bleicher, A. Gillitzer, M. Strikman, PRC 87, 054608 (2013)***

At NICA it is possible to measure the J/ψ production cross section in the pp →p+p+J/ψ channel starting from threshold.

This cross section would be possible to include in transport codes (e.g. GiBUU) for predictions on J/ψ production in AA collisions within hadronic scenario.

Comparison with NICA measurements of J/ψ production in AA collisions will allow then to make conclusions on the existence of “exotic” channels of J/ψ absorption (e.g. melting in the QGP).

Conclusions

- GiBUU is a versatile microscopic transport model capable to describe practically all presently known types of intermediate- and high-energy inclusive and seminclusive (where the quantum states of the outgoing nuclei are not resolved) reactions on nuclei.

- The model can be applied to simulate the pA and AA collisions in NICA regime (presently tested until $\sqrt{s_{NN}} = 8.9$ GeV, $E_{\rm lab} = 40$ A GeV fixed target, symmetric nuclei).

- Qualitative agreement of GiBUU + three-body-collisions with 3-fluid hydrodynamical model.

Open problems:

- K^+/π^+ ratio vs E_{lab} (strange horn);

- Underestimated Λ/K^0_S ratio in $\bar{p}$A collisions: not enough $\bar{K}$ absorption ?

- Correlated ground state: quasideuteron pn correlations.

- Subthreshold charm production dynamics: Fermi motion vs off-shell nucleons.

- Momentum Dependent Interaction (MDI) effects in relativistic mean field.

- Detailed balance: missed N $\rightarrow$2 and N$\rightarrow$3 (N≥3) transitions.

Backup

In-medium cross sections: $B_1B_2 \to B_3B_4M_5M_6...M_N$.

$$\sigma^{med}(\sqrt{s^*}) = F\sigma^{vac}(\sqrt{s_{\rm corr}})\ ,$$

where

$$s^* = (p_1^* + p_2^*)^2\ , \qquad \sqrt{s_{\rm corr}} = \sqrt{s^*} - (m_1^* - m_1) - (m_2^* - m_2)\ .$$

The modification factor:

$$F \equiv \frac{m_1^* m_2^* m_3^* m_4^*}{m_1 m_2 m_3 m_4} \frac{I}{I^*} \frac{\Phi_{N-2}(\sqrt{s^*}; m_3^*, m_4^*, ..., m_N^*)}{\Phi_{N-2}(\sqrt{s_{\rm corr}}; m_3, m_4, ..., m_N)}\ ,$$

where

$$\Phi_n(M; m_1, m_2, ..., m_n) = \int \frac{d^3p_1}{(2\pi)^3 2p_1^0} \int \frac{d^3p_2}{(2\pi)^3 2p_2^0} \cdots \int \frac{d^3p_n}{(2\pi)^3 2p_n^0} \delta^{(4)}(\mathcal{P} - p_1 - p_2 - ... - p_n)$$

— n-body phase space volume, $m_i^2 = p_i^2$ $(i = 1, 2, ..., n)$, $M^2 = \mathcal{P}^2$.

$$
\begin{aligned}
I &= q(\sqrt{s_{\mathrm{corr}}}, m_1, m_2)\sqrt{s_{\mathrm{corr}}} \ , \\
I^* &= q(\sqrt{s^*}, m_1^*, m_2^*)\sqrt{s^*}
\end{aligned}
$$

— vacuum and in-medium flux factors,

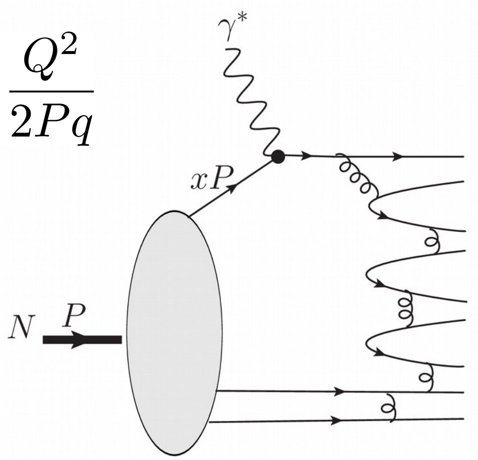
$$
q(\sqrt{s}, m_1, m_2) = \sqrt{(s + m_1^2 - m_2^2)^2/(4s) - m_1^2}
$$

— center-of-mass (c.m.) momentum.

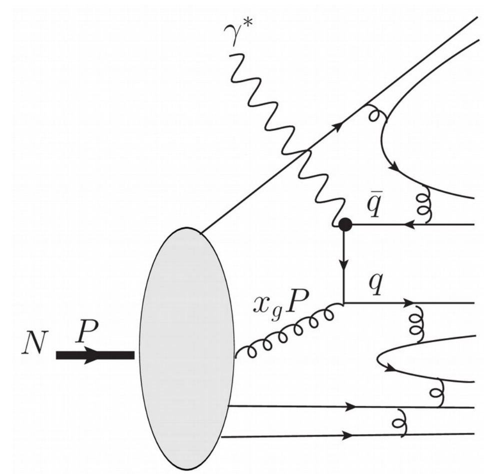
⇒ In-medium reduction, since $m^*/m < 1$.

1 jet: QCD Compton scattering (high Q^2)

$$x = \frac{Q^2}{2Pq}$$

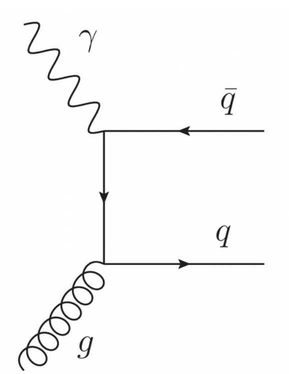


2 jets: Boson-gluon fusion (low Q^2)



$$x_g = \frac{Q^2 + M_{q\bar{q}}^2}{2Pq} \simeq x + \frac{M_{q\bar{q}}^2}{W^2}$$

In PYTHIA model only virtual photons can be initialized via e→e'γ*. Thus the Bjorken x in inclusive PYTHIA simulation is set equal to minimal x_g for real photon+gluon →2 jets transition:



$$x_g = \frac{M_{\bar{q}q}^2}{W^2}\ , \quad M_{\bar{q}q} \simeq |p_t(\mathrm{jet}_1)| + |p_t(\mathrm{jet}_2)| \geq 40\ \mathrm{GeV}$$

typical setting at LHC for dijets