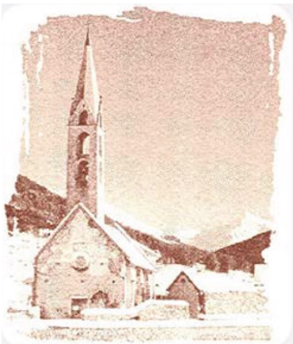
Hadron production in p-Pb collisions at the LHC

Georg Wolschin



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Topics

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2. Thermalization and stopping in heavy-ion collisions

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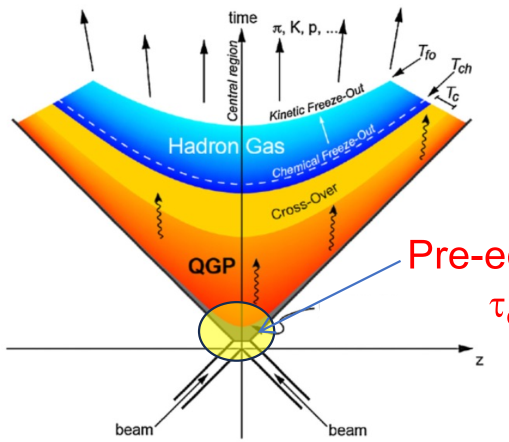
4. Summary and Conclusion

1. Introduction: Stages of relativistic heavy-ion collisions

- Baryon “stopping“ (≡ slowing down, or net-baryon transport) in RHI collisions occurs on a short timescale of ≈ 1 fm/*c*, similar to the
- Local kinetic equilibration (thermalization) that occurs on a typical timescale
  Gluons $\tau_{eq}^{g} \approx 0.1$ fm/*c* *(C_F=3; bosons)*
  Quarks $\tau_{eq}^{q} \approx 1$ fm/*c*. *(C_F=4/3; Pauli‘s principle)*



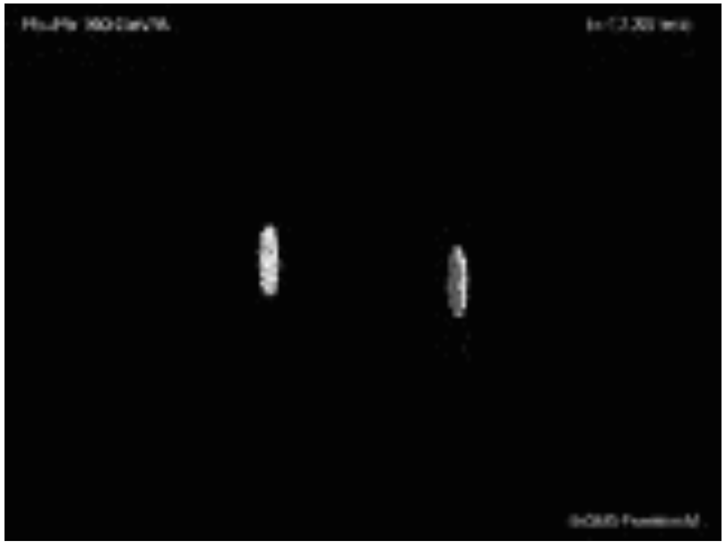
Pre-equilibrium phase, τ_{eq}< 1 fm/c

Local thermalization is a sufficient precondition for the subsequent hydrodynamic treatment of expansion and cooling

Start of the hydrodynamic expansion
$\tau_i \approx 0.1 - 0.2$ fm/*c*

Interaction (freezeout) time:
$\tau_{int} \approx 5 - 8$ fm/*c* in central Pb-Pb @ LHC energies

Most of the light hadrons ($\pi^{\pm}$, $K^{\pm}$,..) are produced at the phase boundary, but heavy quarks and quarkonia emerge in the initial stages



2. Thermalization and stopping in heavy-ion collisions

2.1 An analytical nonlinear diffusion model for local thermalization

Local thermalization of the single-particle distribution functions for gluons (+) and quarks (-)

$$n^{\pm} \equiv n^{\pm}(\epsilon, t) \equiv n$$

is accounted for by the nonlinear diffusion equation as derived * from the quantum Boltzmann equation

$$\frac{\partial n^{\pm}}{\partial t} = -\frac{\partial}{\partial \epsilon}\left[v\, n\,(1 \pm n) + n \frac{\partial D}{\partial \epsilon}\right] + \frac{\partial^2}{\partial \epsilon^2}\left[D\, n\right].$$

Dissipative effects are expressed through the drift term $v(\epsilon, t)$, diffusive effects through the diffusion term $D(\epsilon, t)$. The stationary solutions are given by the Fermi-Dirac / Bose-Einstein distributions

$$n_{\mathrm{eq}}^{\pm}(\epsilon) = \frac{1}{e^{(\epsilon - \mu^{\pm})/T} \mp 1}$$

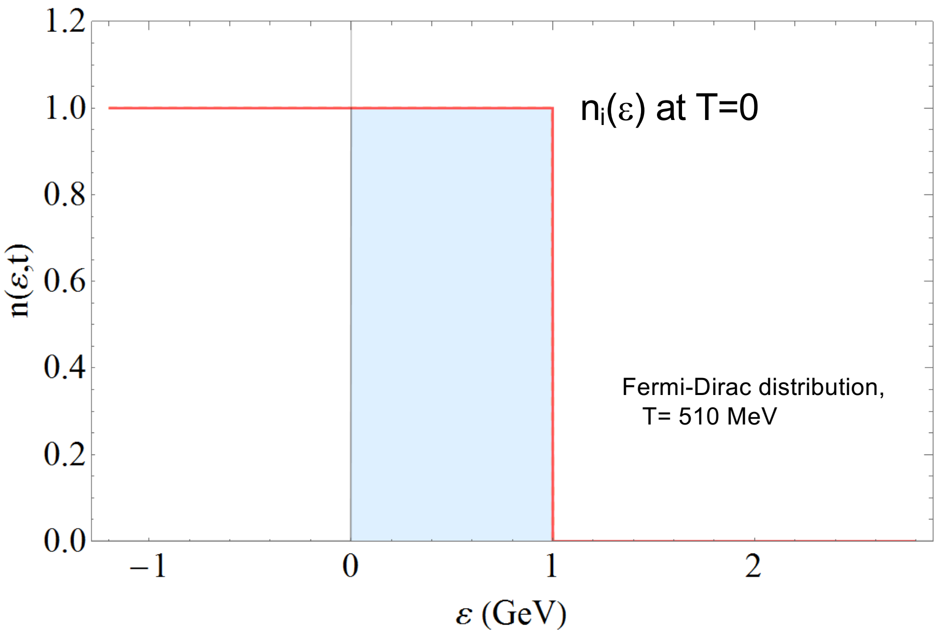
with the temperature T obtained from $\lim_{t\to\infty}[-v\,(\epsilon, t)/D\,(\epsilon, t)] \equiv 1/T$

In the limit of constant transport coefficients, the nonlinear diffusion equation for the occupation-number distribution of bosons/ fermions with the temperature T= - D/v can be solved analytically through a nonlinear transformation.

* GW, Physica A 499, 1 (2018); A 597, 127299 (2022)

Local thermalization: Analytical solutions of the nonlinear diffusion equation

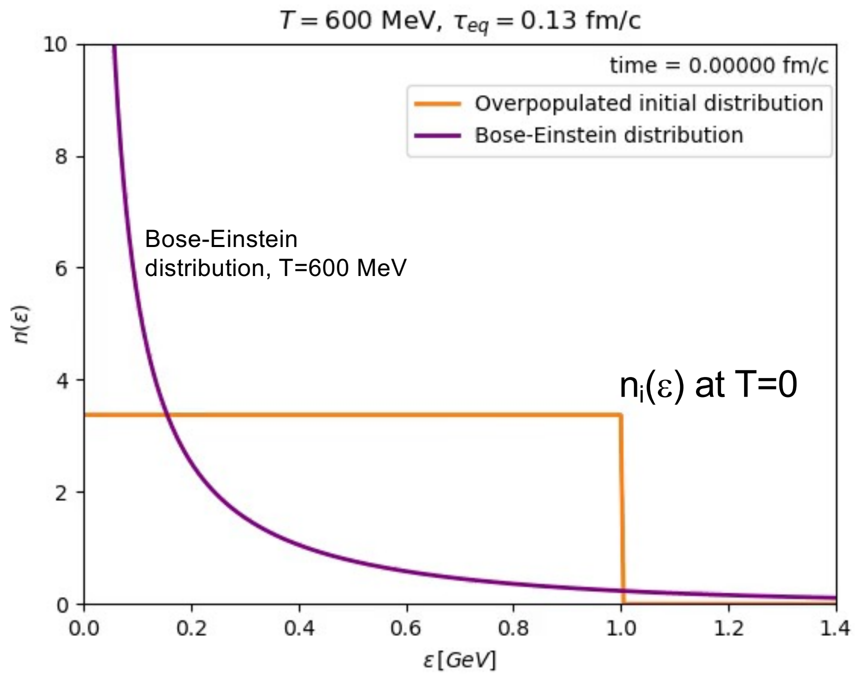
Thermalization of quarks



The total particle number (particles + antiparticles) is conserved

T. Bartsch and GW, Ann. Phys. 400, 21 (2019)
Based on GW, PRL 48, 1004 (1982)

Thermalization of gluons (ε=p, massless)



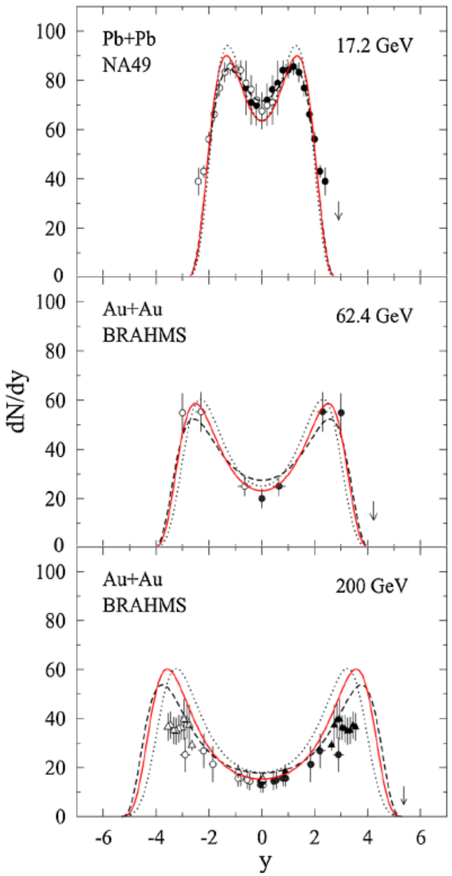
G. Wolschin, EPL 140, 40002 (2022); Physica A 597, 127299 (2022)

Local thermalization of partons does not imply global thermalization of macroscopic variables:
Net-baryon rapidity distributions are not thermalized

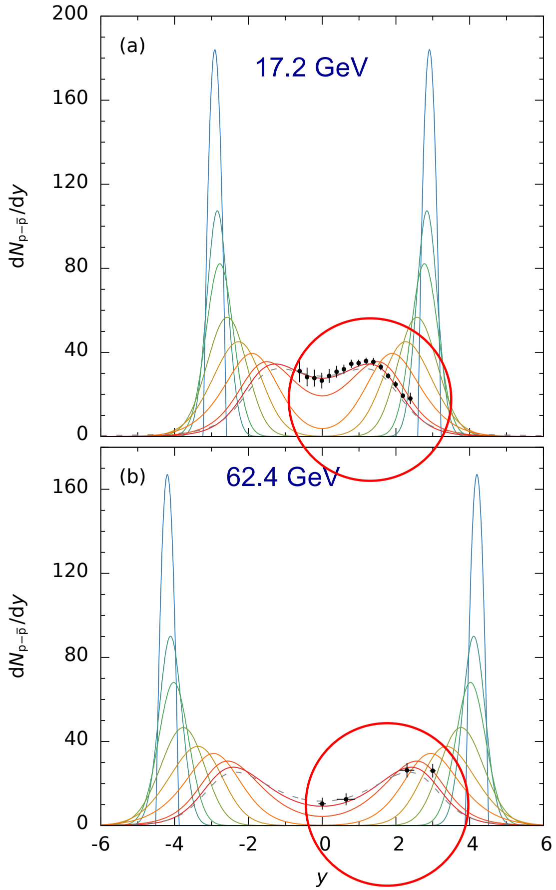
Energy and time dependence of baryon transport

Stationary CGC-results (baryons-antibaryons)

Stopping due to the interaction of valence quarks with low-x gluons in the other nucleus



Y. Mehtar-Tani, GW, PRL 102, 182301 (2009)



Time-dependent results (protons-antiprotons)

Stationary distributions agree with the CGC-results, see left

The initial distribution is evolved in time according to a linear Fokker-Planck equation, as derived from a relativistic stochastic theory*

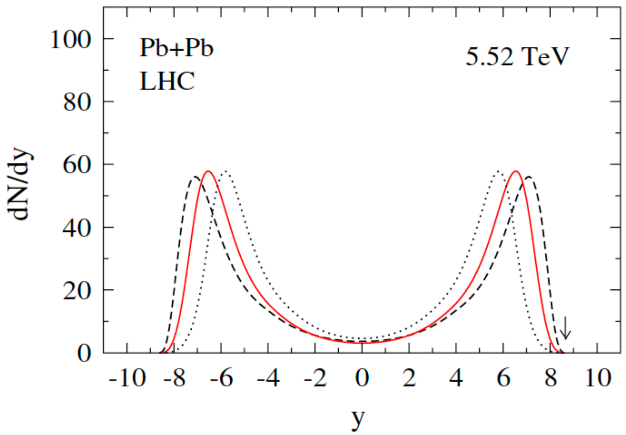
$$\partial_t \psi(t;y) = -\partial_y[\mu(y)\psi(t;y)] + D\partial_y^2 \psi(t;y)$$

J. Hoelck, G. Wolschin, Phys.Rev. Research 2, 033409 (2020);
*Ann. Physik 536, 2300307 (2024)

“Stopping” in Pb-Pb and p-Pb at LHC energies

No y-dependent stopping data yet at LHC.
Theoretical results:

central 5.52 TeV Pb-Pb:



Y. Mehtar-Tani, G. Wolschin, PRL 102, 182301 (2009)

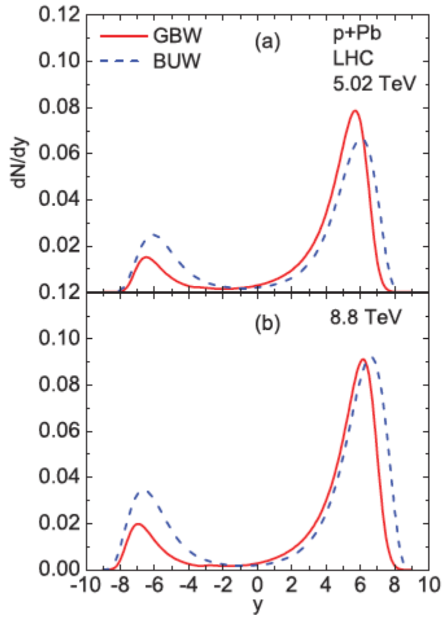
$N \equiv N_B - N_{\bar{B}}$

Q_0^2 = 0.08 GeV^2, $\lambda = 0$ – –
0.07 GeV^2 1.5 —
0.06 GeV^2 3.0 ·····

$$Q_s^2 = Q_0^2 A^{1/3} x^{-\lambda}$$

Gluon saturation momentum

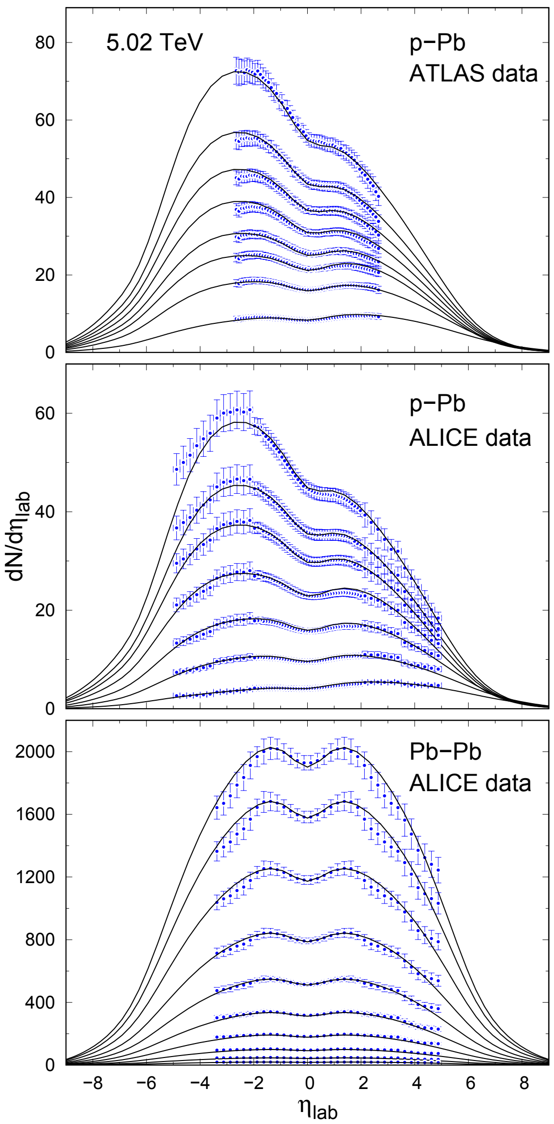
central 5.02/8.8 TeV p-Pb:



- - Golec-Biernat, Wüsthoff
–– Boer, Utermann, Wessels PRD (2008)

← p-going Pb-going →

F.O. Duraes et al., PRC 89, 035205 (2014)



ALICE data: PLB 845, 137730 (2023)

P. Schulz, G. Wolschin, Phys. Rev. C110, 044910 (2024)

3. Charged-hadron production:

Pseudorapidity distributions for p-Pb and Pb-Pb @ 5.02 TeV

- Three-sources Relativistic diffusion model with color-glass (CGC) initial conditions

- Gluon-gluon source (k_T-factorization)

$$\frac{d^3N^h_{gg}}{dy\,dp_T^2} = \frac{2}{C_F}\frac{\alpha_s(m_T^2)}{m_T^2} \times \int_0^{p_T} dk_T^2 \left[N_1\varphi_1(x_1,k_T^2)\varphi_2(x_2,|\mathbf{p}_T-\mathbf{k}_T|^2) + N_2\varphi_2(x_2,k_T^2)\varphi_1(x_1,|\mathbf{p}_T-\mathbf{k}_T|^2)\right]$$

- Quark-gluon ("fragmentation") sources

$$\frac{d^3N^h_{qg}}{dy\,d^2p_T} = \frac{K}{(2\pi)^2}\frac{1}{m_T^2}\int_{x_F}^{1}\frac{dz}{z^2}D_{h/q}(z,\mu_f^2) \times x_1 f_{q/p}(x_1,Q_f^2)\varphi(x_2,q_T^2),$$

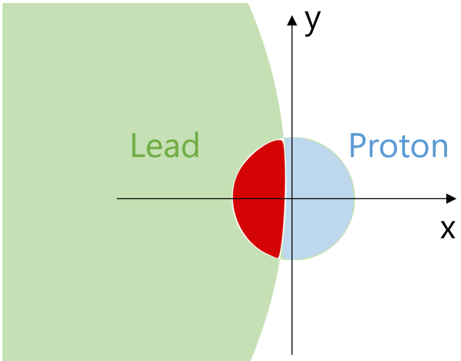
- Time evolution of the fragmentation sources towards partial equilibrium is modelled by a linear Fokker-Planck equation (with p_T integrated out)

$$\frac{\partial}{\partial t}R(y,t) = -\frac{\partial}{\partial y}\left[J(y)R(y,t)\right] + D_y\frac{\partial^2}{\partial y^2}R(y,t).$$

$$J(y) = -\frac{m_T D}{T}\sinh(y)$$

- Use an effective Jacobian transformation y->η with an average mass <m>, <p_T>

Overlap of the thickness functions in the transverse plane for p-Pb



Thickness functions

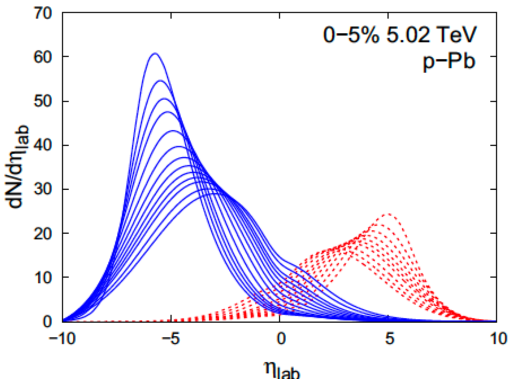
$$\theta_{\rm p}(b;x^1,x^2) = \int \mathrm{d}x^3 \rho_{\rm p}(|b\vec{e}_1 - \vec{x}|)\,,$$

$$\theta_{\rm Pb}(b;x^1,x^2) = \int \mathrm{d}x^3 \rho_{\rm Pb}(|\vec{x}|)\,,$$

Overlap function

$$\theta_{\rm pPb}(b;x^1,x^2) = \theta_{\rm p}(b;x^1,x^2) \times \theta_{\rm Pb}(b;x^1,x^2)$$

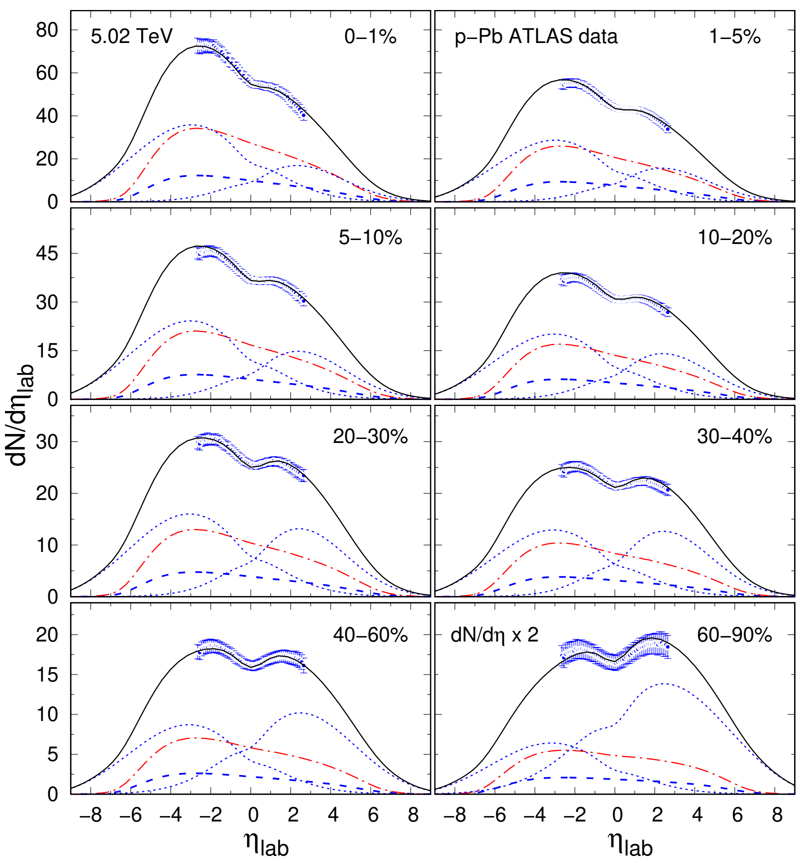
Drift and diffusion of the fragmentation sources

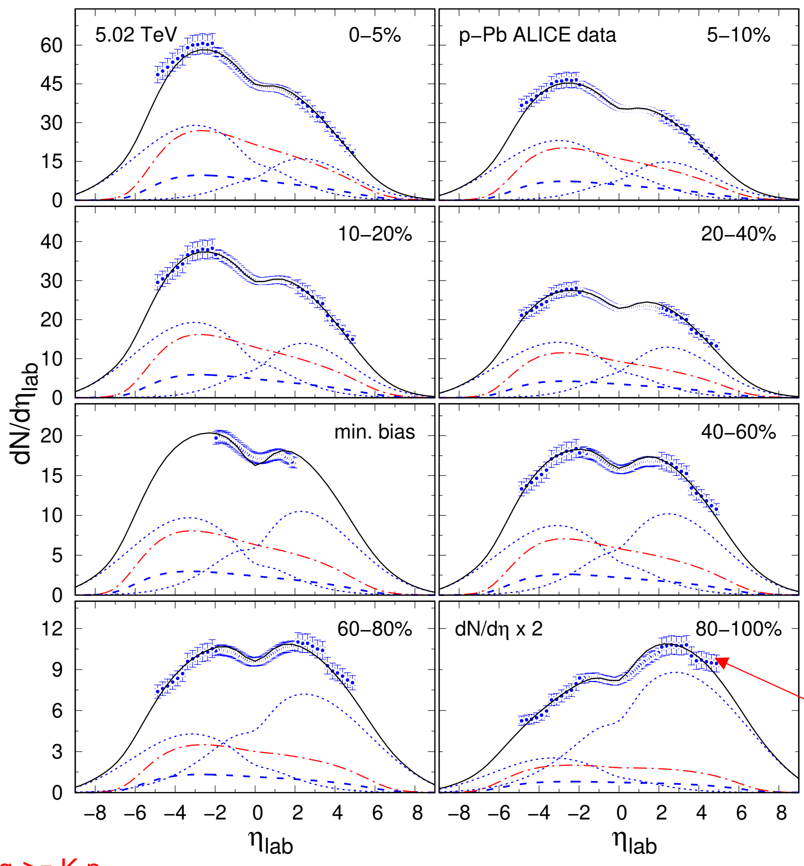


Most of the system remains ‘cold‘: $T \ll T_H$, but the temperature in the overlap zone in central 8.16 TeV p-Pb is T≈ 460 MeV, from Υ suppression analysis in p-Pb @ 8.16 GeV, see

Heidelberg model:
J. Hoelck, F. Nendzig, GW, Phys.Rev.C 95, 024905 (2017)
V.H. Dinh, J. Hoelck, GW, Phys. Rev. C 100, 024906 (2019)
G. Wolschin, Int. J. Mod. Phys. A35, 2030016 (2020); Universe 6, 61 (2020)

Centrality dependence of RDM results in p-Pb at 5.02 TeV





Enhancement of the p-going source in peripheral collisions

← Pb-going

p-going →

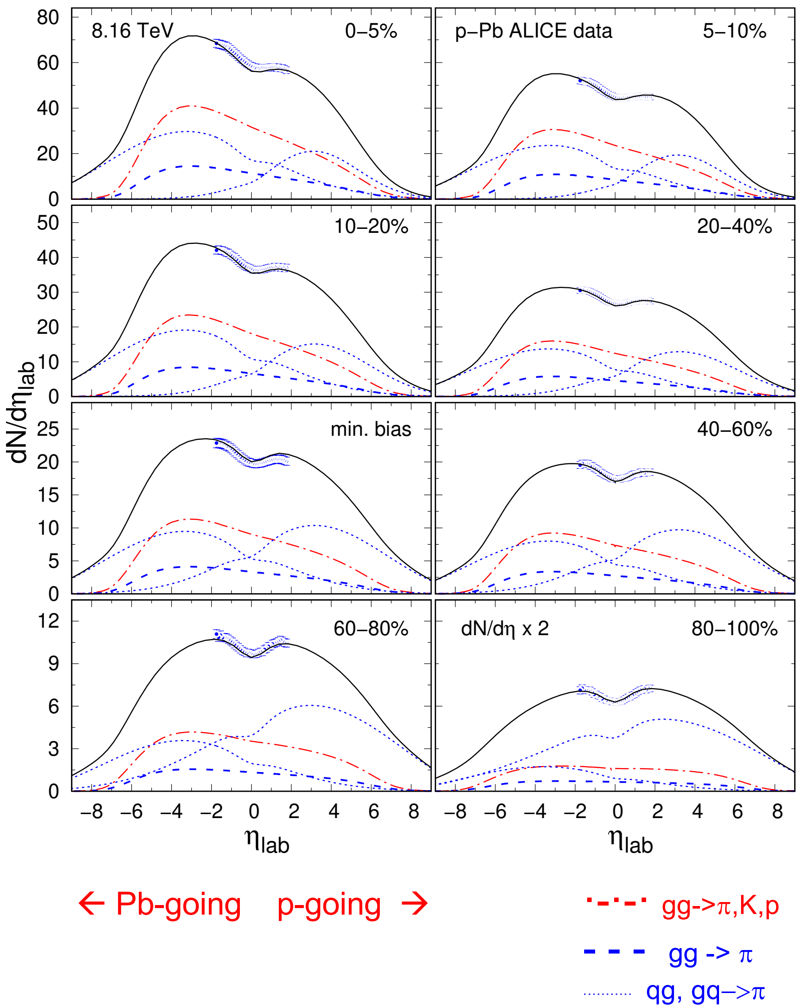
gg->π,K,p

gg -> π

qg, gq->π

P. Schulz, G. Wolschin, Phys. Rev. C110, 044910 (2024)

Centrality dependence of RDM results in p-Pb at 8.16 TeV



Calculated produced charged hadrons N_{ch}

cent.(%)	N_{ch}	N_{ch}^{gg}	N_{π}^{gg}	N_{K}^{gg}	N_{p}^{gg}	$N_{\pi,Pb}^{qg}$	$N_{\pi,p}^{qg}$	R_{p}^{Pb}	R_{qg}^{gg}
0-5	723	342	123	115.3	104.0	268.2	120.3	2.2	0.9
5-10	576	259	93.6	87.3	78.0	212.5	110.7	1.9	0.8
10-20	469	201	73.2	67.8	60.0	171.7	101.7	1.7	0.7
20-40	350	140	51.3	47.1	41.3	122.8	92.2	1.3	0.6
m.b.	267	102	37.3	34.3	30.0	84.8	86.2	1.0	0.6
40-60	232	83.7	31.0	28.2	24.5	71.5	80.7	0.9	0.5
60-80	131	40.7	15.3	13.7	11.7	31.8	60.5	0.5	0.4
80-100	45	10.0	4.0	3.3	2.6	7.6	28.8	0.3	0.3

Relativistic diffusion model parameters

cent.(%)	$\langle N_{\rm part}^{Pb} \rangle$	$Q_0^2\,(\mathrm{GeV}^2)$	$D^p \tau_y$	$\chi^2/N_{\rm dof}$
0-5	16.00	0.058	7.0	0.896
5-10	14.00	0.049	7.0	0.373
10-20	12.40	0.042	11.0	0.532
20-40	9.90	0.035	13.0	0.268
m.b.	7.09	0.033	20.0	0.554
40-60	6.47	0.029	20.0	0.143
60-80	3.53	0.021	36.0	0.452
80-100	1.76	0.007	48.0	0.080

High-η data not yet available at 8.16 TeV

P. Schulz, G. Wolschin, Phys. Rev. C110, 044910 (2024)

4. Summary and Conclusion

- Local thermalization of quarks (τ_{eq}^{q}<1 fm/c) and gluons (τ_{eq}^{g}<0.1 fm/c) is accounted for analytically in a nonlinear diffusion model
- A nonequilibrium-statistical model for net-baryon transport (“stopping“) through the interaction of valence quarks with gluons agrees with SPS and RHIC data
- Charged-hadron production is accounted for in a three-sources relativistic diffusion model. Comparisons with d-Au, Au-Au, p-Pb and Pb-Pb data from RHIC and LHC are presented
- For very peripheral asymmetric collisions (p-Pb @ 5.02 TeV), the yield in the p-going direction becomes larger than the one in the Pb-going direction due to the strong gluon field in the heavy nucleus

Thank you for your attention,

and for the delightful and constructive Bormio winter meeting 2025 !