

Predictions for charged-hadron production in p - O collisions at LHC energies

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Topics

1. Introduction

2. “Stopping” in heavy-ion collisions

2.1 Stopping model: Interaction of valence quarks with soft gluons; SPS and RHIC data

2.2 Predictions for stopping in Pb-Pb and p-Pb at LHC energies

3. Charged-hadron production

3.1 Three-sources relativistic diffusion model for asymmetric systems

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

3.3. Predictions for p-O @ 9.62 TeV, with L. Konrad and P. Schulz

4. Summary and Conclusion

1. Introduction: Stages of relativistic heavy-ion collisions

- **Baryon “stopping”** (\equiv 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)** 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)

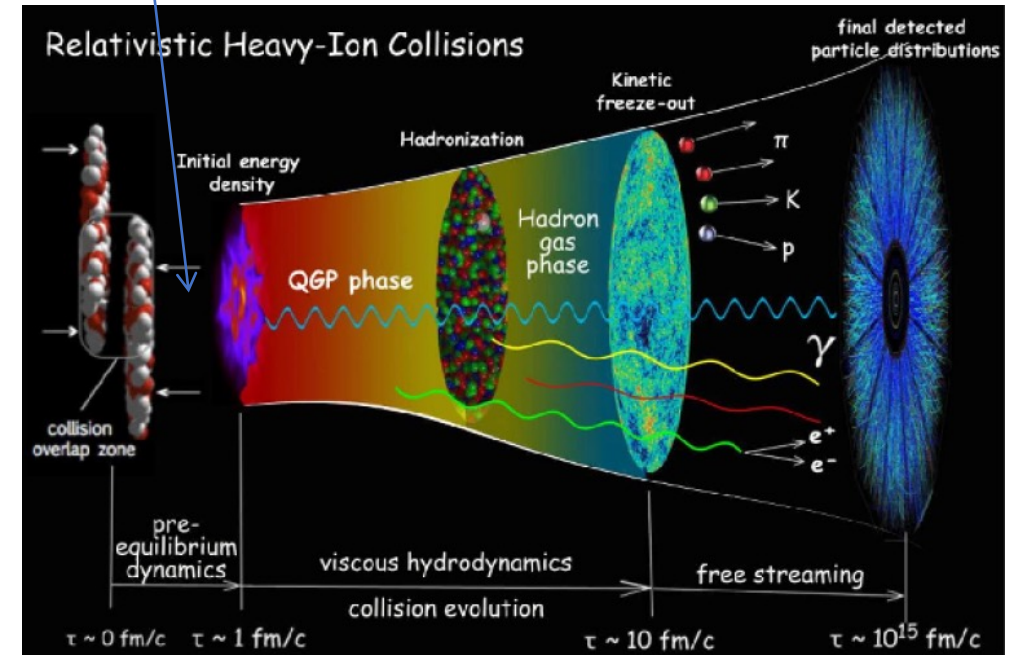
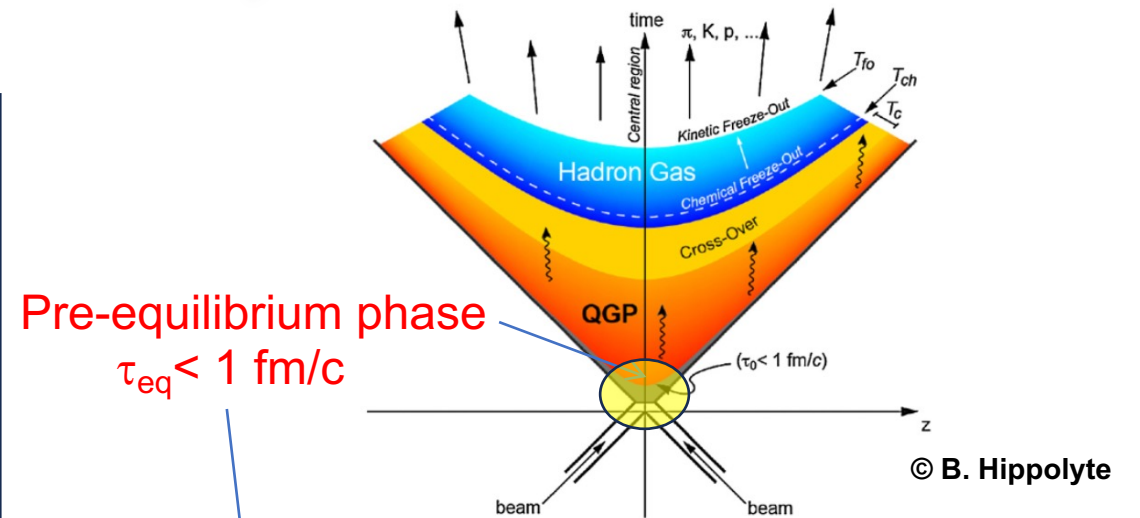
Local thermalization is a sufficient precondition for the subsequent hydrodynamic or diffusion-model treatment of expansion and cooling

Start of the hydrodynamic expansion

$$\tau_i \approx 0.1 - 0.2 \text{ fm/c}$$

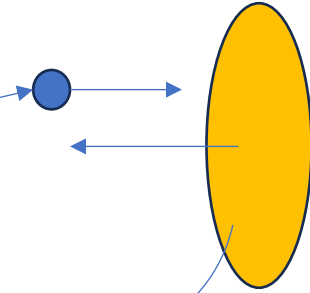
Interaction (freezeout) time:

$$\tau_{int} \approx 5 - 8 \text{ fm/c in central Pb-Pb @ LHC energies}$$



2.1 Stopping model: Interaction of valence quarks with soft gluons

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



m_T : transverse mass of the produced hadron h

$x_1 = (m_T/\sqrt{s_{NN}}) e^y$: Bjorken- x of the valence quark, y = rapidity

$x_2 = (m_T/\sqrt{s_{NN}}) e^{-y}$: Bjorken- x of the soft gluon in the other nucleus

$f_{q/p}(x_1, Q_f^2)$: Quark distribution function

$\phi(x_2, q_T^2)$: Gluon distribution function (MSTW parametrization)

$x_F = xp_T/k_T$: Feynman- x , transverse momentum of the hadron p_T /parton k_T

$z = x_F/x$: fraction of the quark energy carried by the hadron

$D_{h/q}(z, \mu_f^2)$: fragmentation function for fragmenting a parton into a hadron

p-A; scale with N_{part}
for A-A

Integrate over p_T to obtain dN/dy

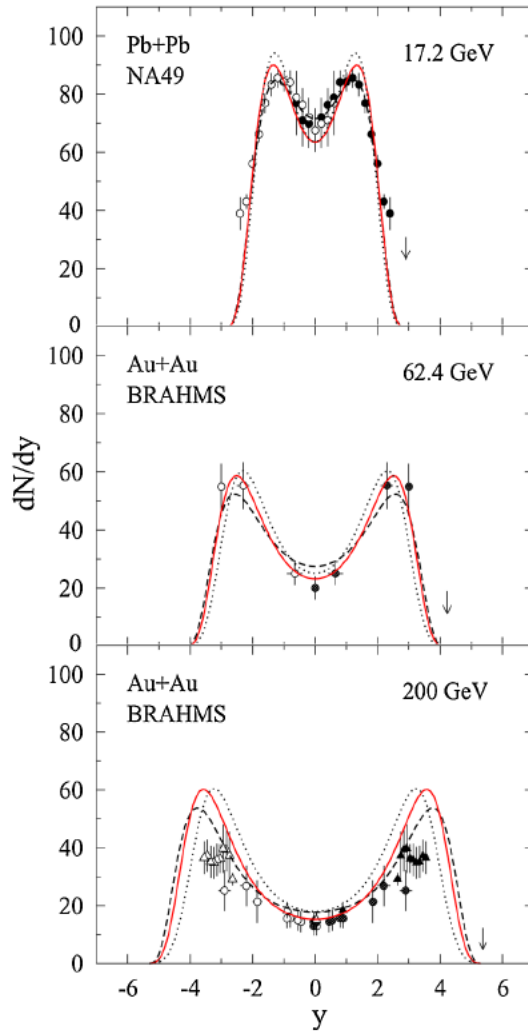
Hybrid factorization, “DHJ-formula”, Dumitru, Hayashigaki, Jalilian-Marian

Stopping model: Energy- and time-dependence of baryon transport

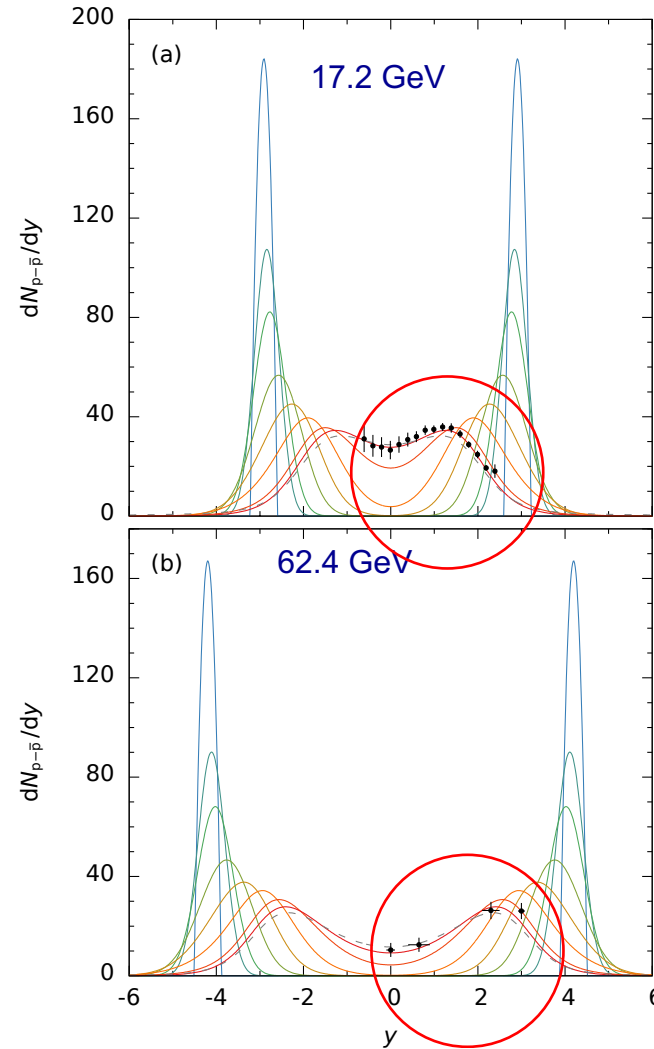
Stationary CGC-
results
(baryons-antibaryons)

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

rapidity
 $y = \ln[(E+p_{||})/(E-p_{||})]/2$



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*

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

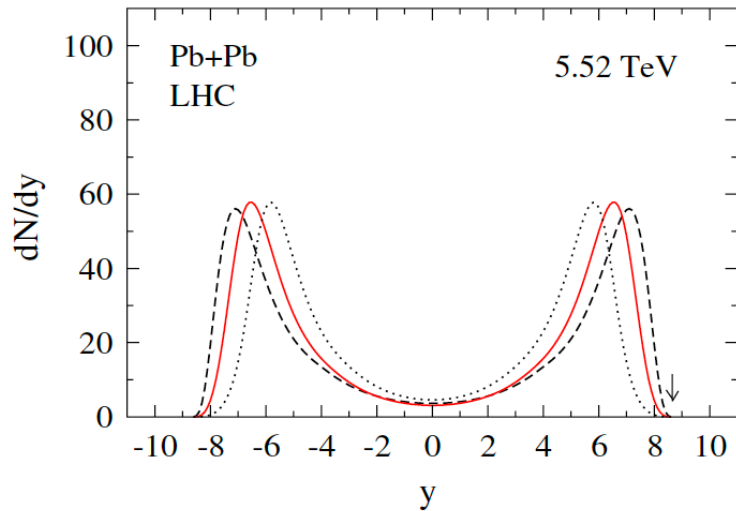
J. Hoelck, G. Wolschin, Phys.Rev. Research 2, 033409 (2020);
*Ann. Physik 536, 2300307 (2024)

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

No y -dependent stopping data yet at LHC: A forward detector is needed

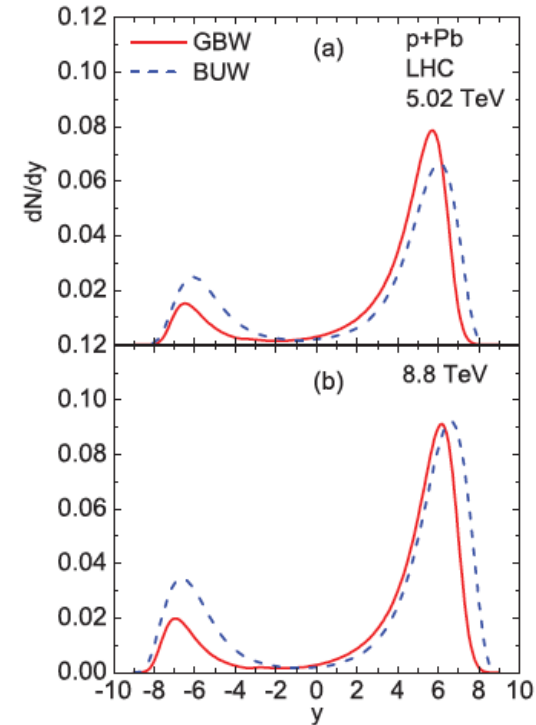
Theoretical results:

central 5.52 TeV Pb-Pb



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

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)

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

$$Q_0^2 = 0.08 \text{ GeV}^2, \lambda = 0 \text{ ---}$$

$$0.07 \text{ GeV}^2 \quad 1.5 \text{ ---}$$

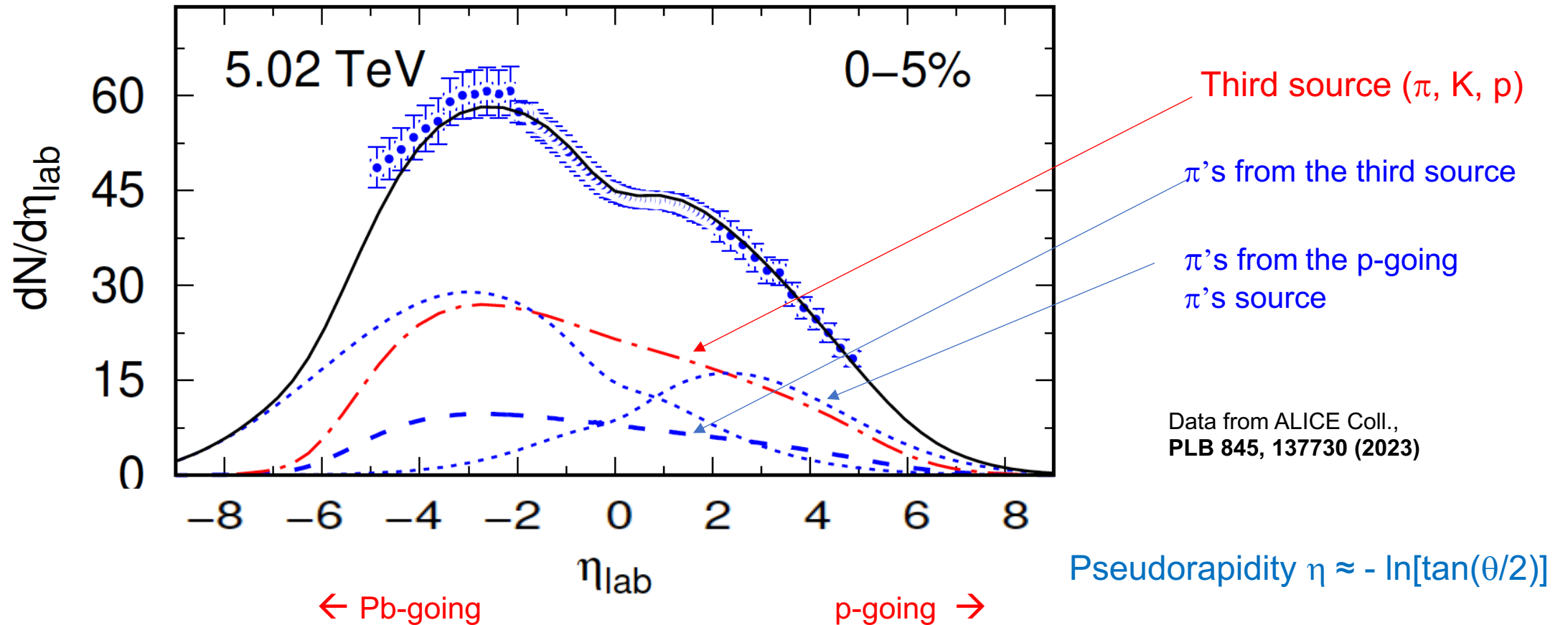
$$0.06 \text{ GeV}^2 \quad 3.0 \text{}$$

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

3.1 Charged-hadron production: Three-sources momentum-space model

In addition to the two sources relevant in stopping, charged-hadron production has a third source arising mainly from gluon-gluon collisions in the hot fireball

Central p-Pb @ $\sqrt{s_{NN}}=5.02$ TeV



Relativistic diffusion model for the fragmentation sources

The calculated stopping distributions dN/dy are taken as initial conditions for the subsequent partial thermalization and time-dependent particle production in a diffusion process that is accounted for by a linear Fokker-Planck equation (FPE)

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

D_y diffusion coefficient

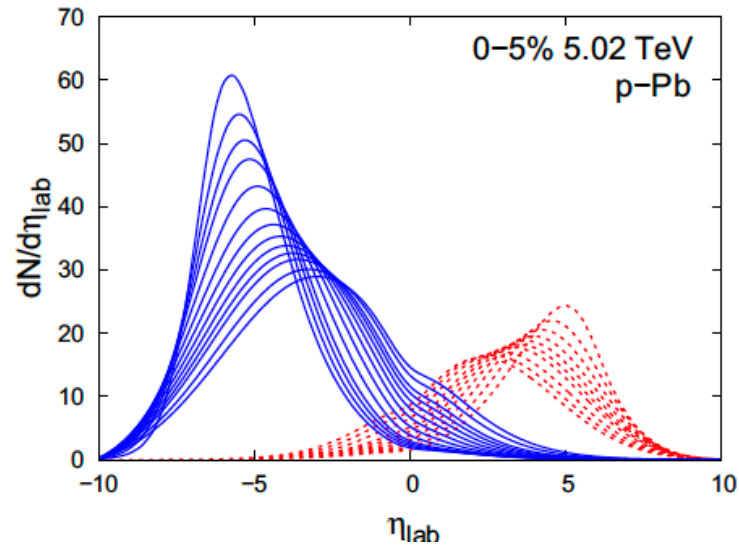
$J(y) = -(m_T D_y / T) \sinh(y) \approx (y_{\text{eq}} - y) / \tau_y$ drift coefficient (fluctuation-dissipation relation), T equilibrium temperature; linear approximation with rapidity relaxation time τ_y and the equilibrium value of the rapidity

$$y_{\text{eq}}(b) = \frac{1}{2} \ln \left(\frac{\langle m_T^{(2)}(b) \rangle}{\langle m_T^{(1)}(b) \rangle} \right)$$

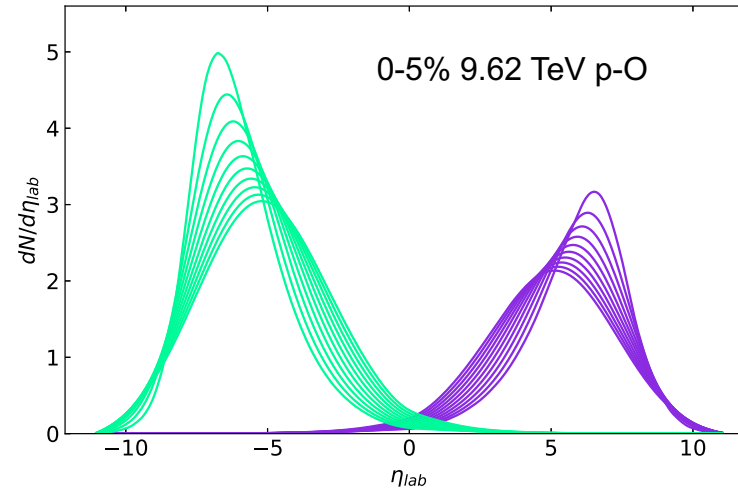
with the centrality-dependent average transverse masses $\langle m_T^{(1,2)}(b) \rangle$ at impact parameter b

➤ The FPE is solved numerically with the CGC stopping distributions as initial conditions, $R(y, t=0) = \psi_{\text{CGC}}(y)$

Drift and diffusion of the fragmentation sources



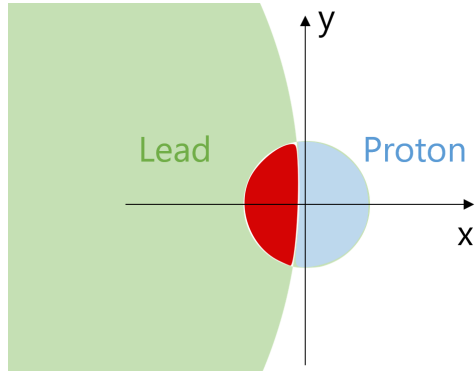
← Pb-going p-going →



← O-going p-going →

Shift of the distribution functions towards the equilibrium value $y=y_{eq}$ according to the drift coefficient $J(y)$,
Broadening through particle creations and scatterings according to the diffusion coefficient D

CGC distribution function for the central source



Thickness functions

$$\theta_P(b; x^1, x^2) = \int dx^3 \rho_P(|b\vec{e}_1 - \vec{x}|),$$

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

Overlap function

$$\theta_{PPb}(b; x^1, x^2) = \theta_P(b; x^1, x^2) \times \theta_{Pb}(b; x^1, x^2)$$

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 $T \approx 460$ MeV, from Y suppression analysis in p-Pb @ 8.16 GeV

(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))

- Gluon-gluon source (k_T -factorization)

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

- Integrate this distribution function over p_T in each centrality bin $\rightarrow R_{gg}(y)$

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

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

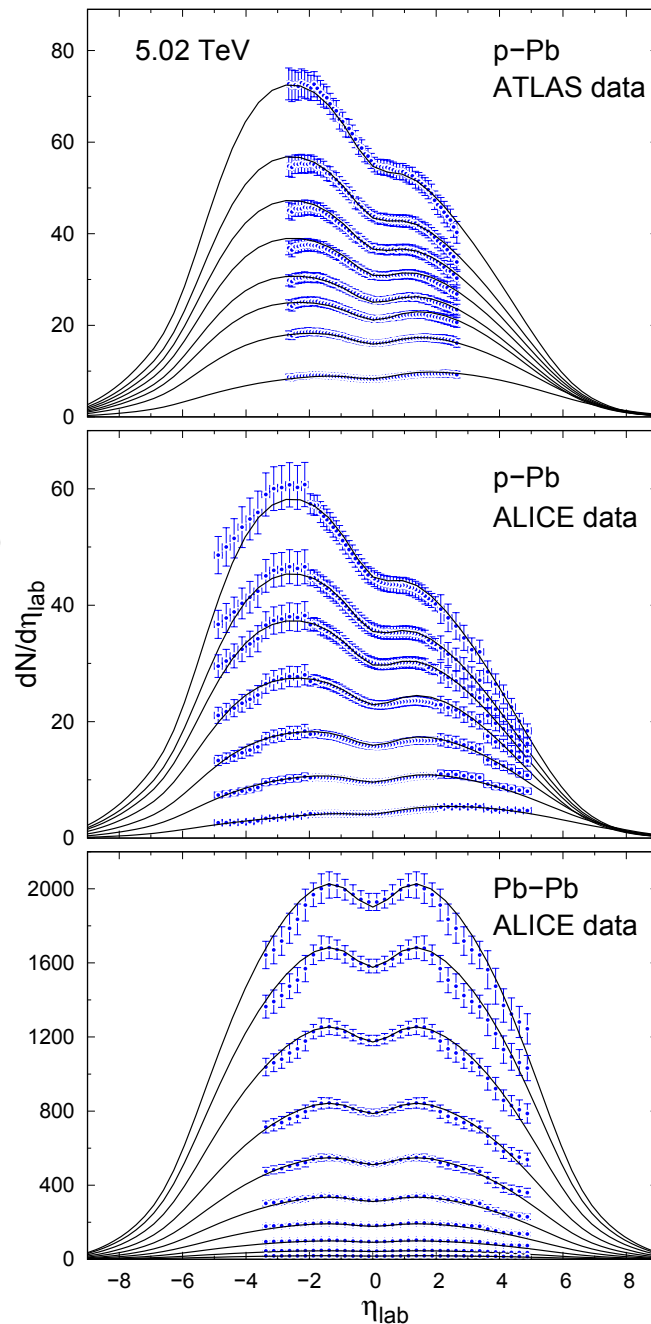
- Add the quark-gluon (“fragmentation”) sources R_1 , R_2 from the relativistic diffusion model to the gluon-gluon source (k_T -factorization) incoherently

$$\frac{dN_{\text{ch}}}{dy}(\tau_{\text{int}}) = N_{\text{ch}}^1 R_1(y, \tau_{\text{int}}) + N_{\text{ch}}^2 R_2(y, \tau_{\text{int}}) + N_{\text{ch}}^{\text{gg}} R_{\text{gg}}(y)$$

Observables are FWHM (τ_{int}/τ_y) and shifts of the maxima from y_{beam} towards y_{eq}

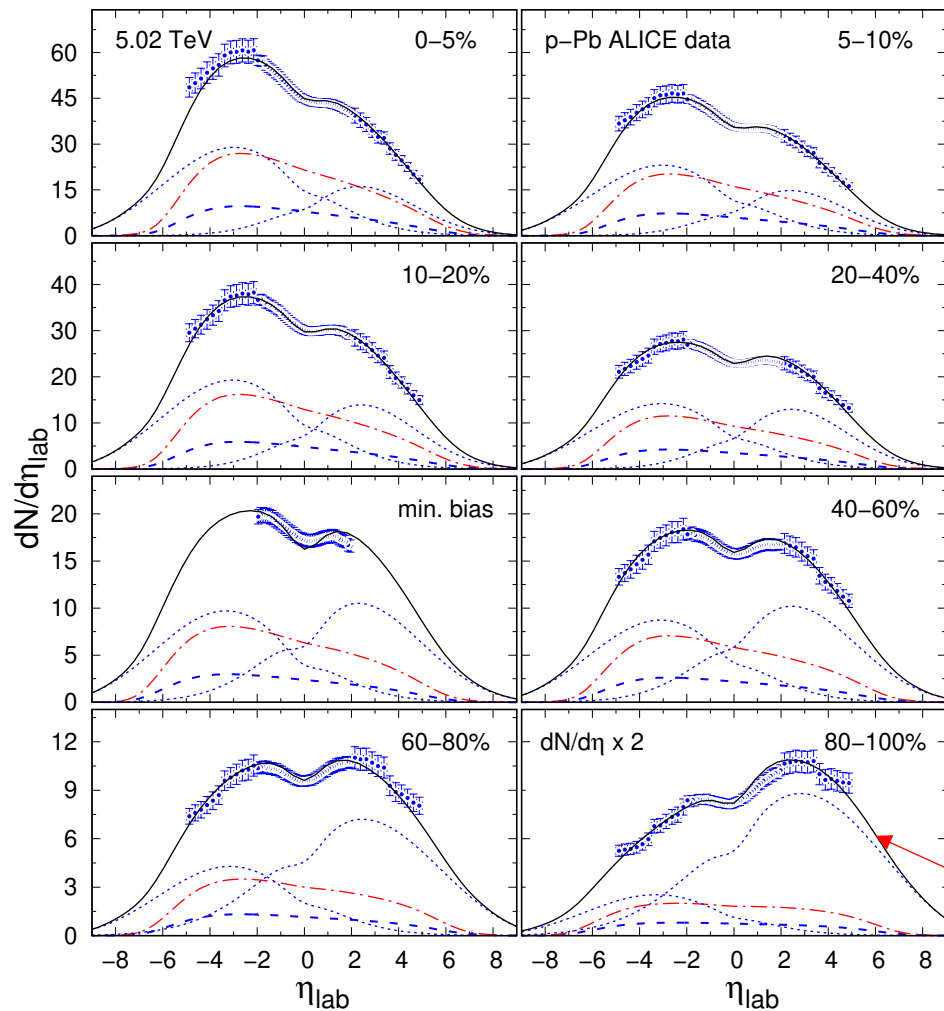
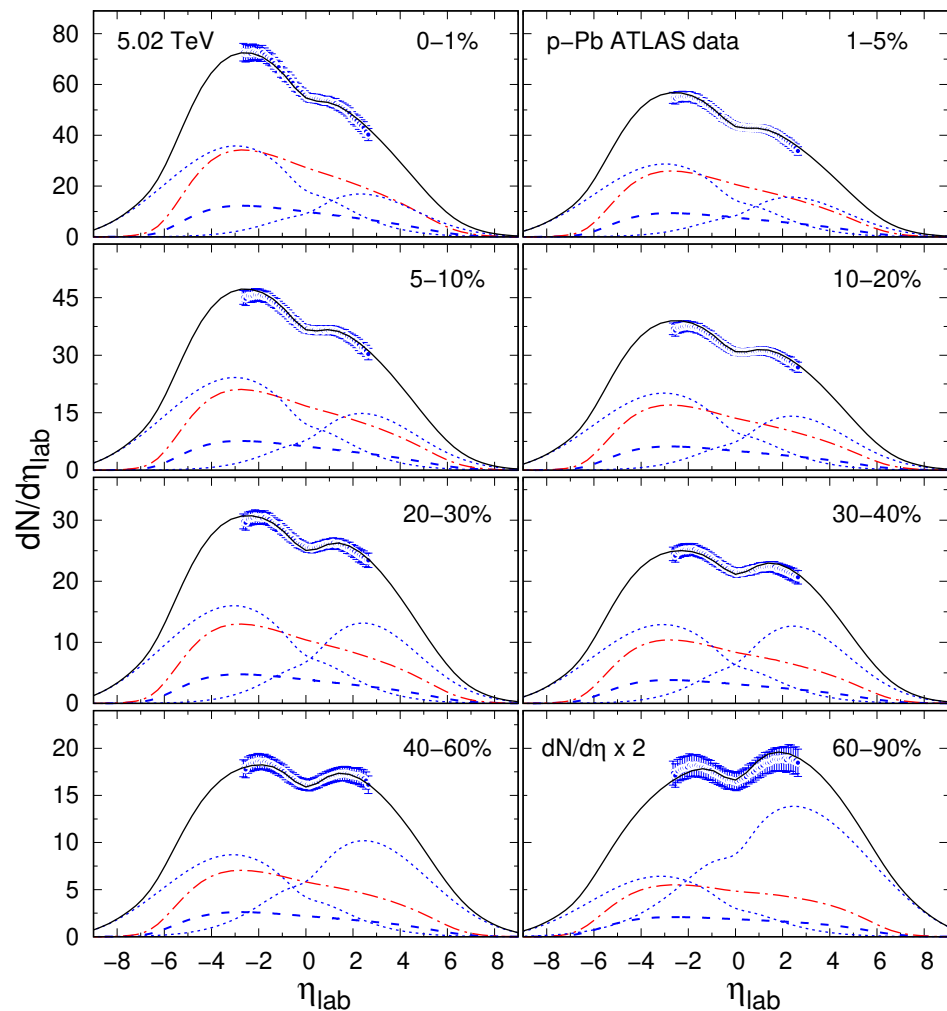
- Convert the distribution function from rapidity to pseudorapidity space using a Jacobian transformation with an average mass $\langle m \rangle$ and average transverse momentum $\langle p_T \rangle$
- Compare to ATLAS and ALICE $dN/d\eta$ centrality-dependent data

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



ALICE data:
PLB 845,
137730 (2023)

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



Enhancement of the p-going source in peripheral collisions

← Pb-going

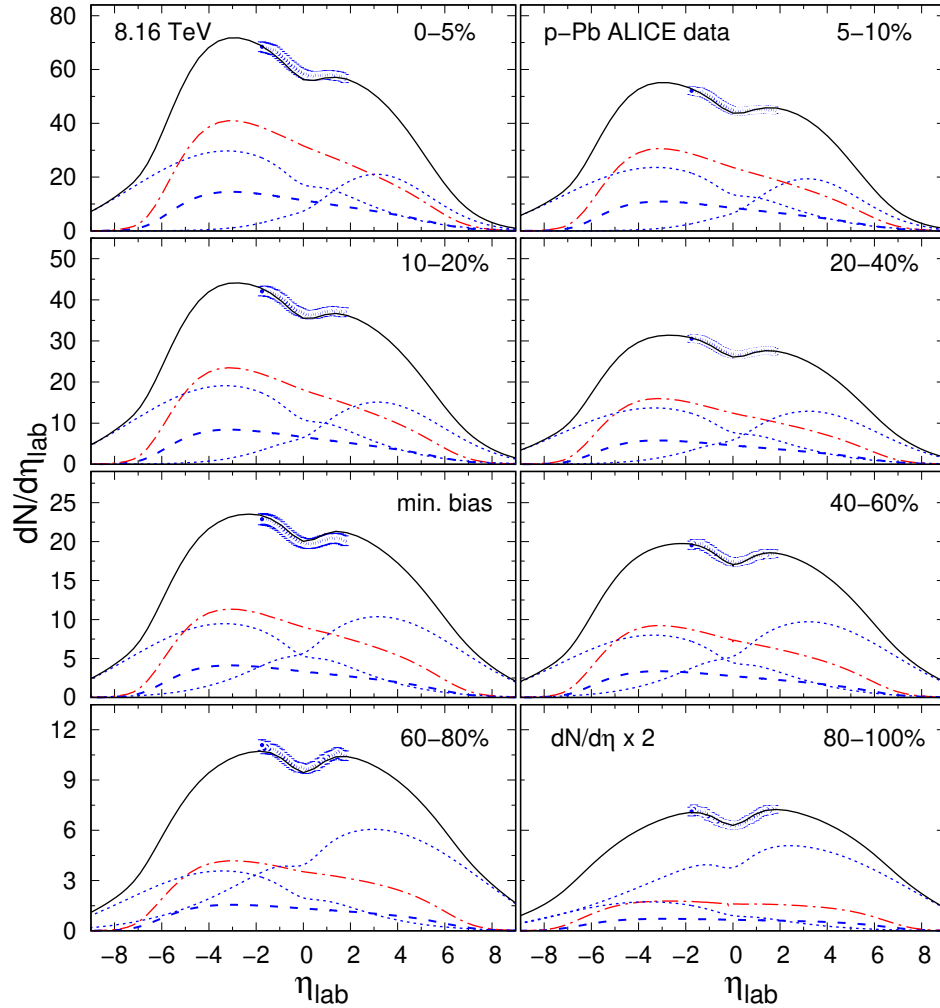
p-going →

← Pb-going

p-going →

- · - · - · $gg \rightarrow \pi, K, p$
- - - $gg \rightarrow \pi$
- · · · · $qg, gq \rightarrow \pi$

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



← Pb-going p-going →

·-·-· gg→π,K,p

- - - gg → π

····· qq, qg→π

Calculated produced charged hadrons N_{ch}

cent.(%)	N_{ch}	N_{ch}^{gg}	N_{π}^{gg}	N_K^{gg}	N_p^{gg}	$N_{\pi,Pb}^{qq}$	$N_{\pi,p}^{qq}$	R_p^{Pb}	R_{qq}^{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

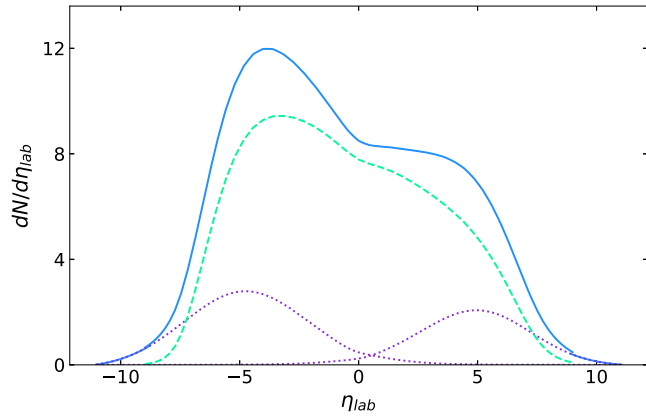
Relativistic diffusion model parameters

cent.(%)	$\langle N_{part}^{Pb} \rangle$	Q_0^2 (GeV ²)	$D^p \tau_y$	χ^2/N_{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

3.3. Predictions for p-O @ 9.62 TeV

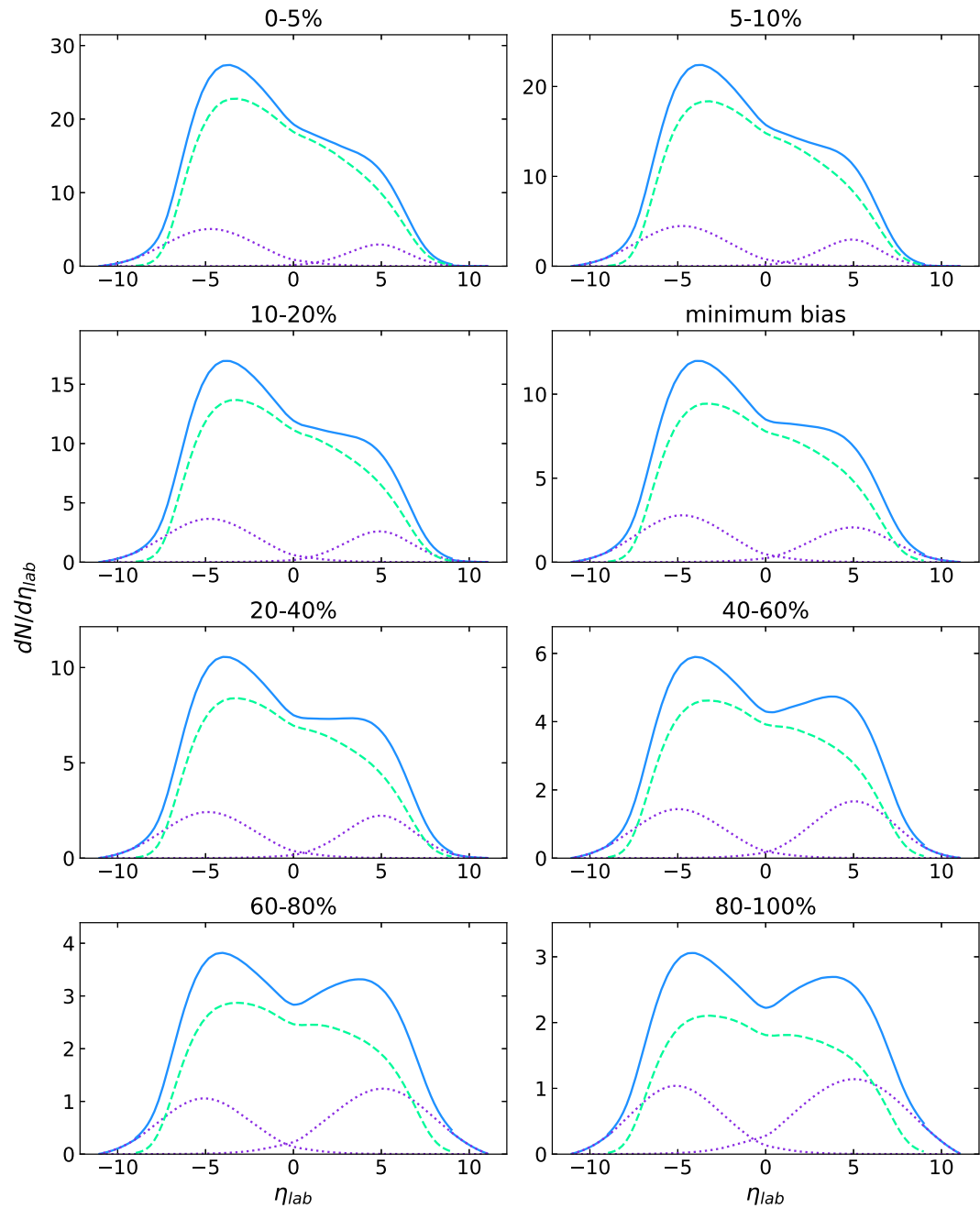
Minimum bias (0-100%)



Centrality dependence of RDM pseudorapidity distributions in p-O collisions at 9.62 TeV

--- gg → π, K, π
 qg, gq → π

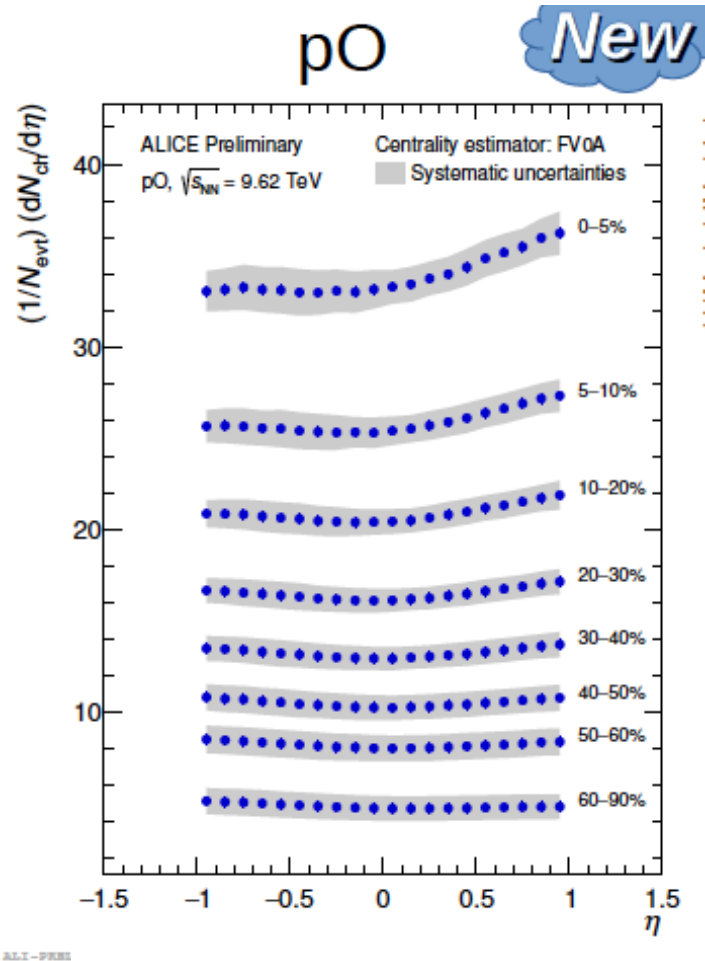
L. Konrad, P. Schulz, G. Wolschin,
 Phys. Lett. B 871, 140003 (2025)



← O-going

p-going →

Centrality dependence of measured (prel). pseudorapidity distributions in p-O collisions at 9.62 TeV from ALICE



Prel. data still confined to $|\eta| < 1$, no data in the region of the fragmentation sources $1 < |\eta| < 8$

Once the full data set $|\eta| < 5$ is available, the diffusion-model and CGC parameters will be adapted in χ^2 minimizations with respect to the data

From: ALI-Prel-610023 (2025), shown at Initial Stages 2025, Taiwan

← p-going O-going →

4. Summary and Conclusion

- 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 centrality-dependent p-Pb and Pb-Pb data from 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
- Centrality-dependent charged-hadron production in p-O at 9.62 TeV is predicted. The diffusion-model parameters will be determined in χ^2 -minimizations once the full data set is available

Thank you for your attention,
and for the delightful and constructive Bormio winter meeting 2026 !

