Particle production sources in *p*Pb and PbPb at the LHC

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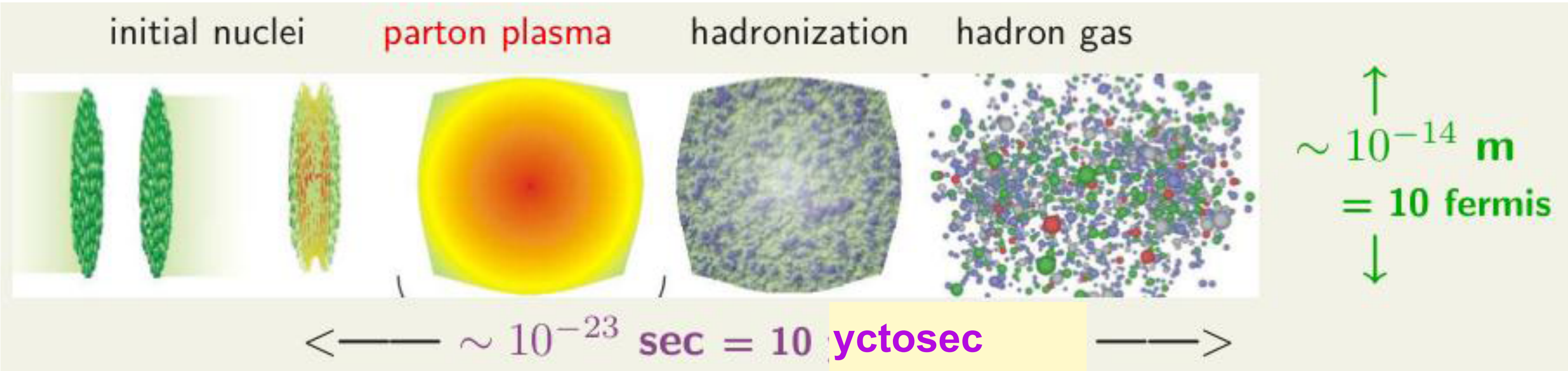
Topics

1. Introduction: Relativistic heavy ions @ LHC; Stopping
2. Particle production: Relativistic Diffusion Model (RDM)
3. Particle production sources in *p*Pb at 5.02 TeV
4. Conclusion

1. Stopping: Net protons/baryons and gluon saturation

Stopping occurs mainly through the interaction of valence quarks with gluons

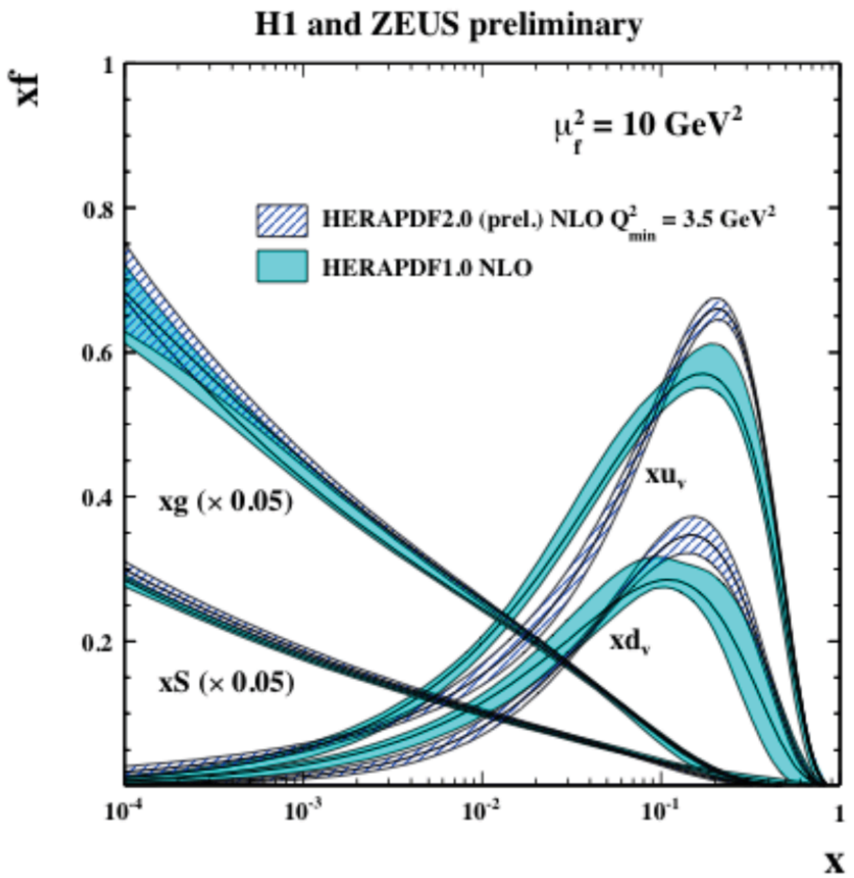


Artwork: Nikhef/S.Bass

At RHIC (≤ 0.2 TeV) and LHC (≤ 5.52 TeV) energies, initially a state of very high gluon density is formed, which transforms into a strongly coupled quark-gluon plasma, and then hadronizes after ≈10^{-23} s into mesons and baryons.

Search for signatures of the QGP, and the initial Gluon Condensate in net-baryon (proton) distribution functions.

QCD



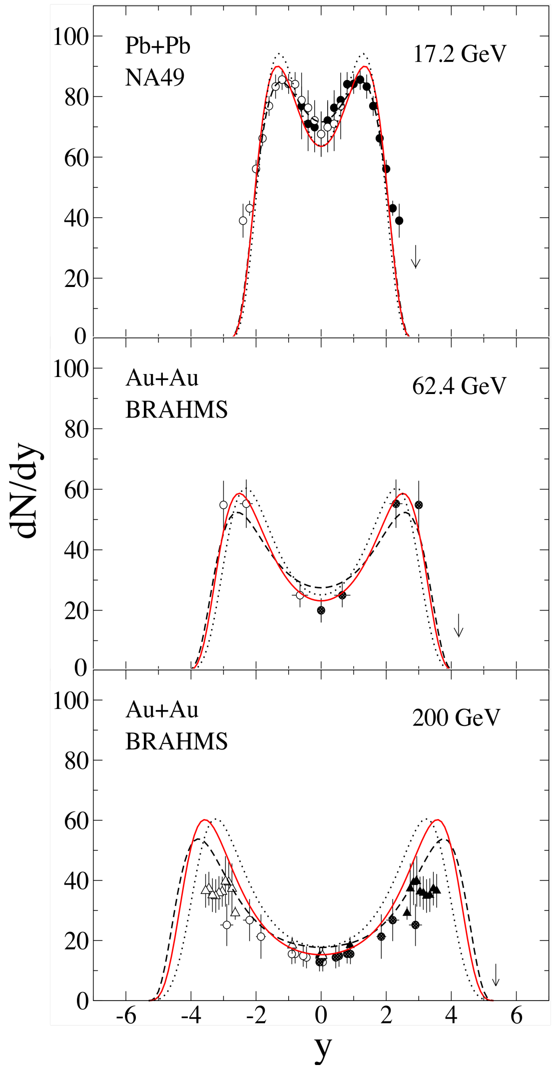
Structure functions (pdfs) from e + p deep inelastic scattering (DIS) at HERA (DESY) (from H. Abramowicz, ICNFP2014)

- Gluon structure functions grow with increasing Q^2 and 1/x
- At small x and high energy, gluons dominate the dynamics.
- The gluon distribution should saturate at very small x. The saturation scale is $Q_s^2(x) \sim A^{1/3} x^{-\lambda}, \lambda \sim 0.3$

→ Saturation effects expected to be more pronounced in nuclei

Stopping: Net-baryon rapidity distributions at SPS, RHIC, and LHC

$Q_s^2(x) \sim A^{1/3} x^{-\lambda}, \lambda \sim 0.3$



- Central (0-5%) Pb+Pb (SPS) and Au+Au (RHIC) Collisions

- Dashed black curves: Q_0^2 = 0.08 GeV^2 , λ=0
  Solid red curves: Q_0^2 = 0.07 GeV^2, λ=0.15
  Dotted black curves: Q_0^2 = 0.06 GeV^2, λ=0.3

- A larger gluon saturation scale produces more baryon stopping, as does a larger value of A.

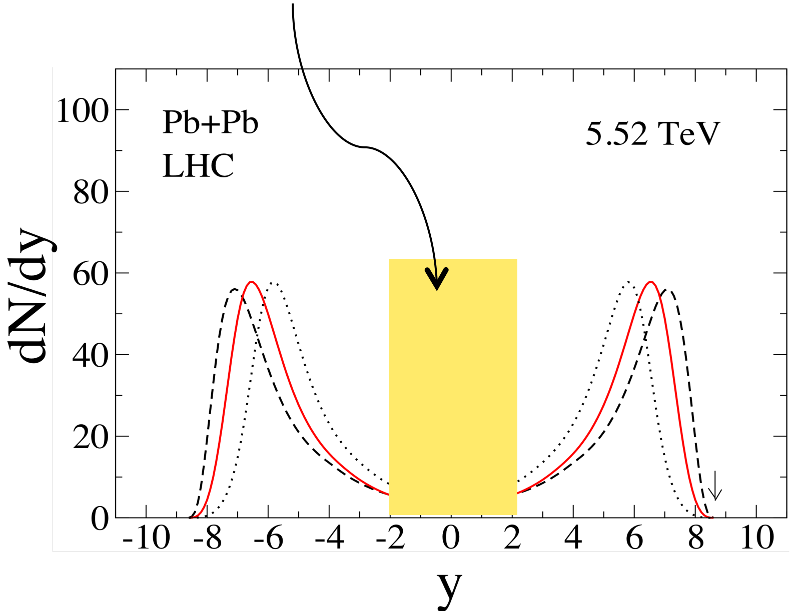
- The saturation scale is $Q_s^2(x) = A^{1/3} Q_0^2 x^{-\lambda}$

Calculations are in a QCD-inspired model first published as

Y. Mehtar-Tani and GW, Phys. Rev. Lett. 102,182301 (2009).

Net-baryon rapidity distributions at LHC: prediction

Particle identification region in ALICE



Y. Mehtar-Tani and GW
Phys. Rev. Lett. 102,182301 (2009)

Fragmentation peaks seen in stopping are also relevant for particle production

- Central (0-5%) Pb+Pb collisions, $y_{beam} = 8.68$
- Dashed black curve: λ= 0
  Solid red curve: λ = 0.15
  Dotted black curve: λ= 0.3
- **A larger gluon saturation scale produces more baryon stopping; the fragmentation peak position is sensitive to λ**
- The midrapidity value of the net-baryon distribution is small, but finite:
  dN/dy (y = 0) ≈ 4. The **total yield** is normalized to the number of baryon participants, $N_B \approx 357$.

Measurements with particle identification will be confined to the yellow region for the next years

2. Particle production: Relativistic Diffusion Model (RDM)

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

R (y,t) Rapidity distribution function. The standard linear Fokker-Planck equation corresponds to q = 1, and a linear drift function. For the three components k = 1,2,3 of the rapidity distribution,

$$\boxed{\frac{\partial}{\partial t}R_k(y,t) = -\frac{1}{\tau_y}\frac{\partial}{\partial y}\left[(y_{eq}-y)\cdot R_k(y,t)\right] + D_y^k\frac{\partial^2}{\partial y^2}R_k(y,t)}$$

Linear drift term with relaxation time τ_y Diffusion term, D_y=const.

Relaxation time and diffusion coefficient are related through a dissipation-fluctuation theorem. The broadening is enhanced due to collective expansion.

$$< y_{1,2}(t) >= y_{eq}[1-\exp(-t/\tau_y)] \mp y_{max}\exp(-t/\tau_y)$$ mean value

$$\sigma^2_{1,2,eq}(t) = D_y^{1,2,eq}\tau_y[1-\exp(-2t/\tau_y)]$$ variance

Linear Model: G. Wolschin, Eur. Phys. J. A5, 85 (1999); with 3 sources: Phys. Lett. B 569, 67 (2003); PLB 698, 411 (2011); M. Biyajima, M. Ide, M. Kaneyama, T. Mizoguchi, and N. Suzuki, Prog. Theor. Phys. Suppl. 153, 344 (2004)

Equilibrium value of the rapidity determined from
energy and momentum conservation as

$$y_{eq}(b) = -0.5 \cdot \ln \frac{\langle m_1^T(b)\rangle \exp(y_{max}) + \langle m_2^T(b)\rangle \exp(-y_{max})}{\langle m_2^T(b)\rangle \exp(y_{max}) + \langle m_1^T(b)\rangle \exp(-y_{max})}$$

with transverse masses

$$\langle m_{1,2}^T(b)\rangle = \sqrt{m_{1,2}^2(b) + \langle p_T\rangle^2}$$

For large beam rapidities (LHC) this reduces to

$$y_{eq}(b) \simeq 0.5 \cdot \ln \frac{\langle m_2^T(b)\rangle}{\langle m_1^T(b)\rangle}$$

And the impact-parameter dependent numbers of participants can be determined from the geometric overlap, or the Glauber model.

Diffusion of produced particles in η-space

Pseudorapidity distributions of produced particles are obtained through the Jacobian transformation

$$\frac{dN}{d\eta} = \frac{dN}{dy}\frac{dy}{d\eta} = \frac{p}{E}\frac{dN}{dy} \simeq J(\eta, \langle m\rangle/\langle p_T\rangle)\frac{dN}{dy}$$

$$J(\eta, \langle m\rangle/\langle p_T\rangle) = \cosh(\eta)\cdot$$
$$[1 + (\langle m\rangle/\langle p_T\rangle)^2 + \sinh^2(\eta)]^{-1/2}.$$

GW, J.Phys. G40, 045104 (2013)
D. Roehrscheid, GW, Phys. Rev. C86, 024902 (2012)

with the rapidity distribution in the three-sources model

$$\frac{dN_{ch}(y, t = \tau_{int})}{dy} = N^1_{ch} R_1(y, \tau_{int}) + N^2_{ch} R_2(y, \tau_{int}) + N^{eq}_{ch} R_{eq}(y, \tau_{int}).$$

and the rapidity

$$y = 0.5 \cdot \ln((E + p)/(E - p))$$

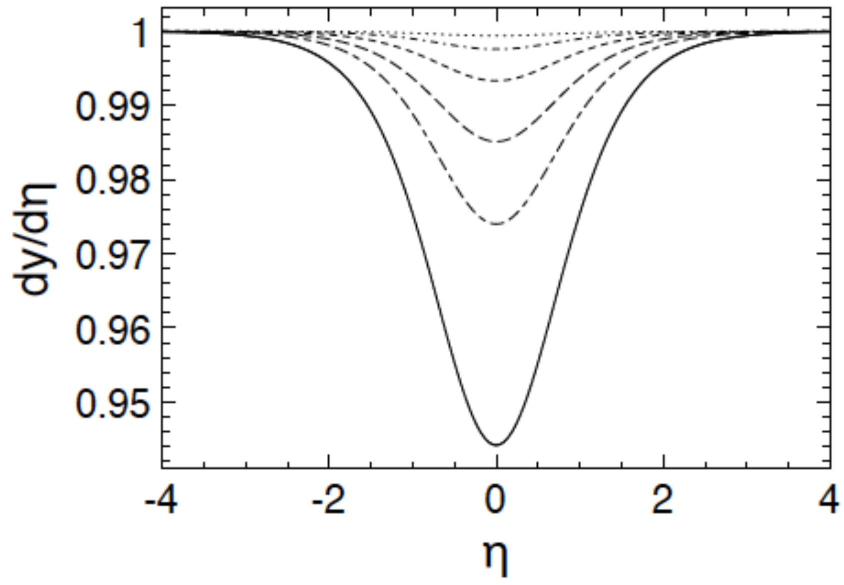
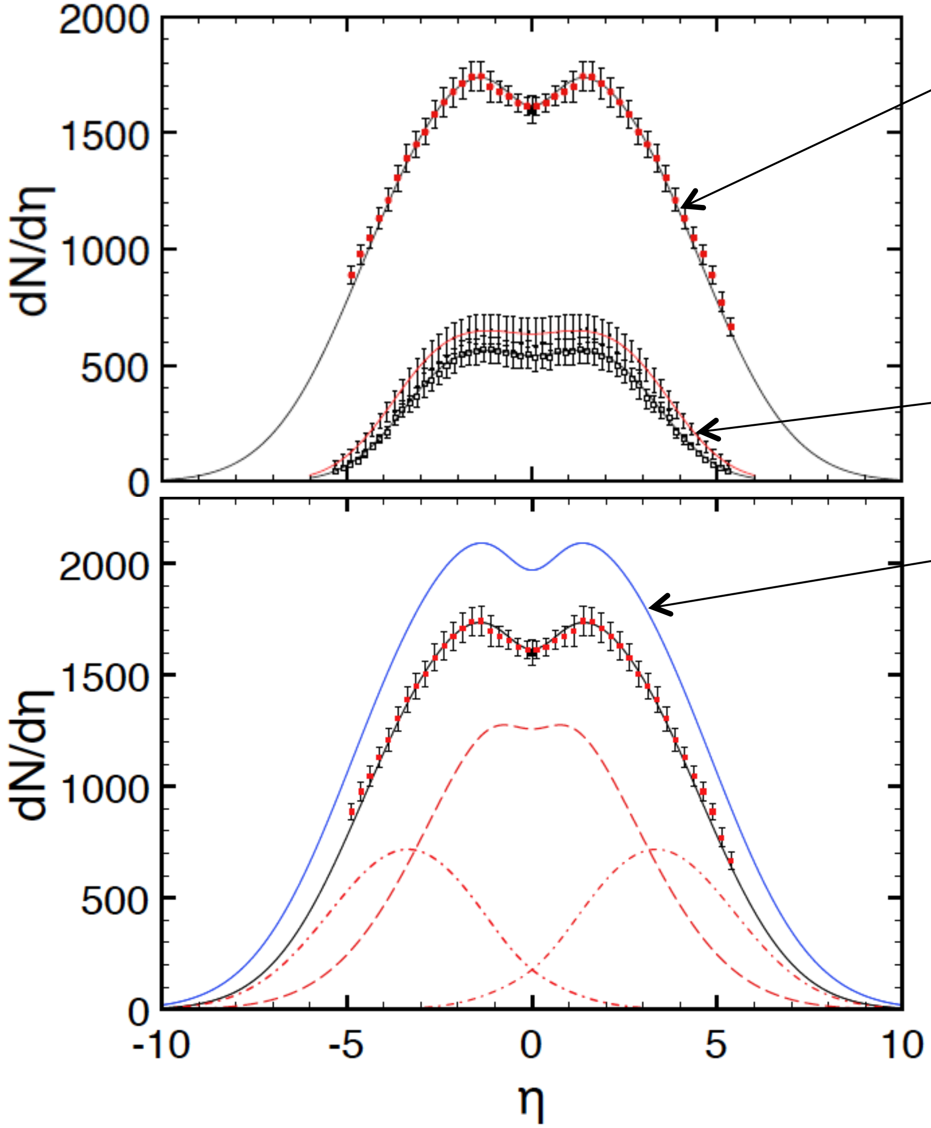


Figure 1: The Jacobian $dy/d\eta$ for $< m >= m_\pi$ and average transverse momenta (bottom to top) $< p_T >= 0.4, 0.6, 0.8, 1.2, 2$ and 4 GeV/c.

Comparing data with the RDM calculation for produced charged hadrons



Central PbPb @ 2.76 TeV
(ALICE data; RDM calc.)

RHIC data
(PHOBOS)
130 and 200 GeV

Prediction at 5.52 TeV

3 sources: 2 symmetric fragmentation sources
1 midrapidity gluon-gluon source, modified by the Jacobian.

RDM parameters determined in χ^2 minimizations

GW, J. Phys. G40, 045104 (2013)

[1] ALICE collab., PRL 105, 252301 (2010)
[2] ALICE collab., PRL 106, 032301 (2011)
[3] B.B. Back et al.,PHOBOS coll., PRL 87, 102303 (2001); PRL 91, 052303 (2003); PRC 83, 024913 (2011)

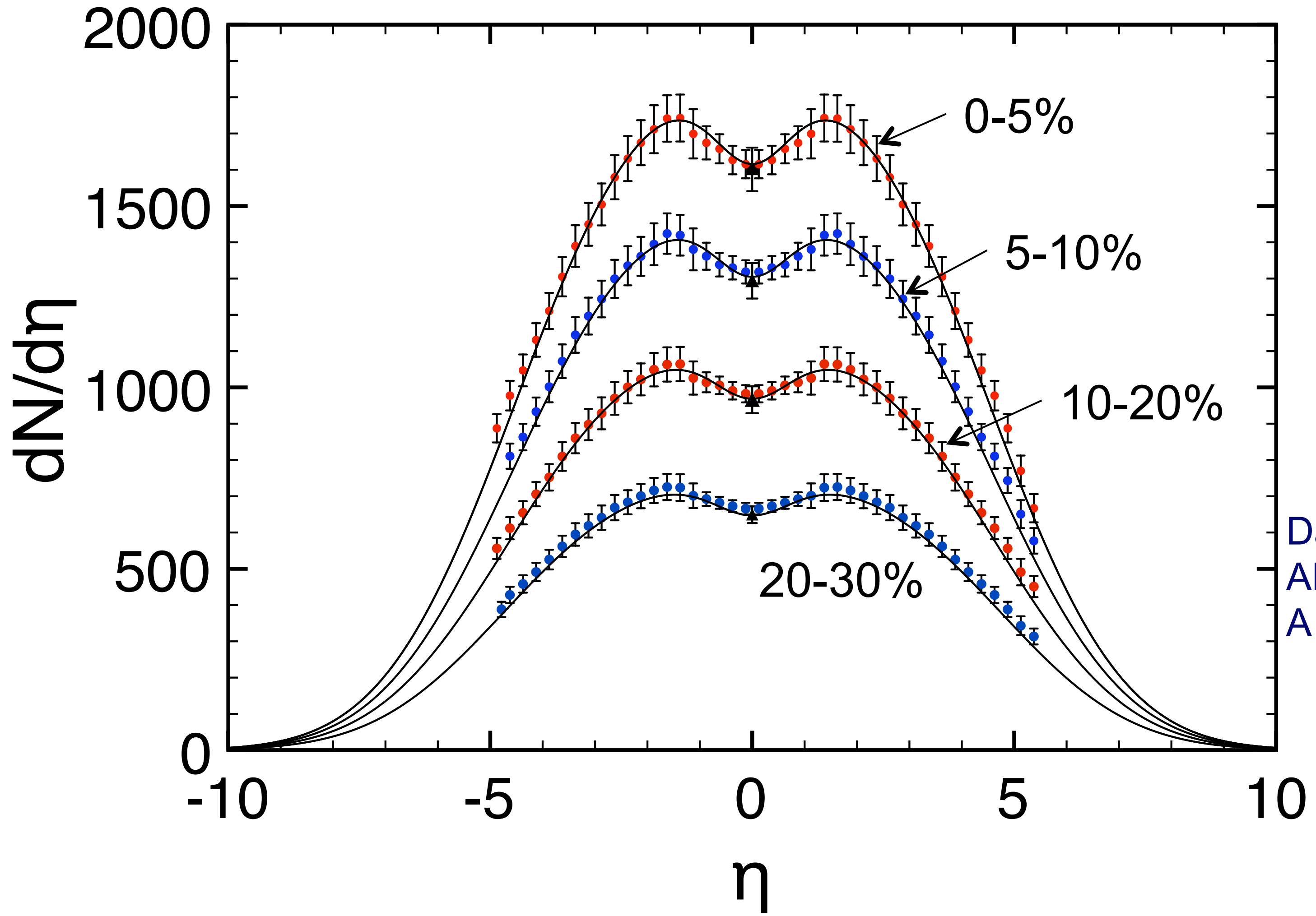
Parameters of the 3-sources RDM at RHIC and LHC energies

Table 1. Three-sources RDM-parameters $\tau_{\rm int}/\tau_y$, $\Gamma_{1,2}$, Γ_{gg}, and N_{gg}. $N_{\rm ch}^{1+2}$ is the total charged-particle number in the fragmentation sources, N_{gg} the number of charged particles produced in the central source. Results for $\langle y_{1,2}\rangle$ are calculated from $y_{\rm beam}$ and $\tau_{\rm int}/\tau_y$. Values are shown for 0–5% PbPb at LHC energies of 2.76 and 5.52 TeV in the lower two lines, with results at 2.76 TeV from a χ^2-minimization with respect to the preliminary ALICE data [2], and using limited fragmentation as constraint. Corresponding parameters for 0–6% AuAu at RHIC energies are given for comparison in the upper four lines based on PHOBOS results [1]. Parameters at 5.52 TeV denoted by * are extrapolated. Experimental midrapidity values (last column) are from PHOBOS [1] for $|\eta| < 1$, 0–6% at RHIC energies and from ALICE [13] for $|\eta| < 0.5$, 0–5% at 2.76 TeV.

$\sqrt{s_{NN}}$ (TeV)	$y_{\rm beam}$	$\tau_{\rm int}/\tau_y$	$\langle y_{1,2}\rangle$	$\Gamma_{1,2}$	Γ_{gg}	$N_{\rm ch}^{1+2}$	N_{gg}	$\frac{dN}{d\eta}\vert_{\eta\simeq 0}$
0.019	$\mp$3.04	0.97	$\mp$1.16	2.83	0	1704	–	314 ± 23 [1]
0.062	$\mp$4.20	0.89	$\mp$1.72	3.24	2.05	2793	210	463 ± 34 [1]
0.13	$\mp$4.93	0.89	$\mp$2.02	3.43	2.46	3826	572	579 ± 23 [1]
0.20	$\mp$5.36	0.82	$\mp$2.40	3.48	3.28	3933	1382	655 ± 49 [1]
2.76	$\mp$7.99	0.87	$\mp$3.34	4.99	6.24	7624	9703	1601 ± 60 [13]
5.52	$\mp$8.68	0.85*	$\mp$3.70	5.16*	7.21*	8889*	13903*	1940*

RDM χ^2 fits to LHC/ALICE results for 2.76 TeV PbPb

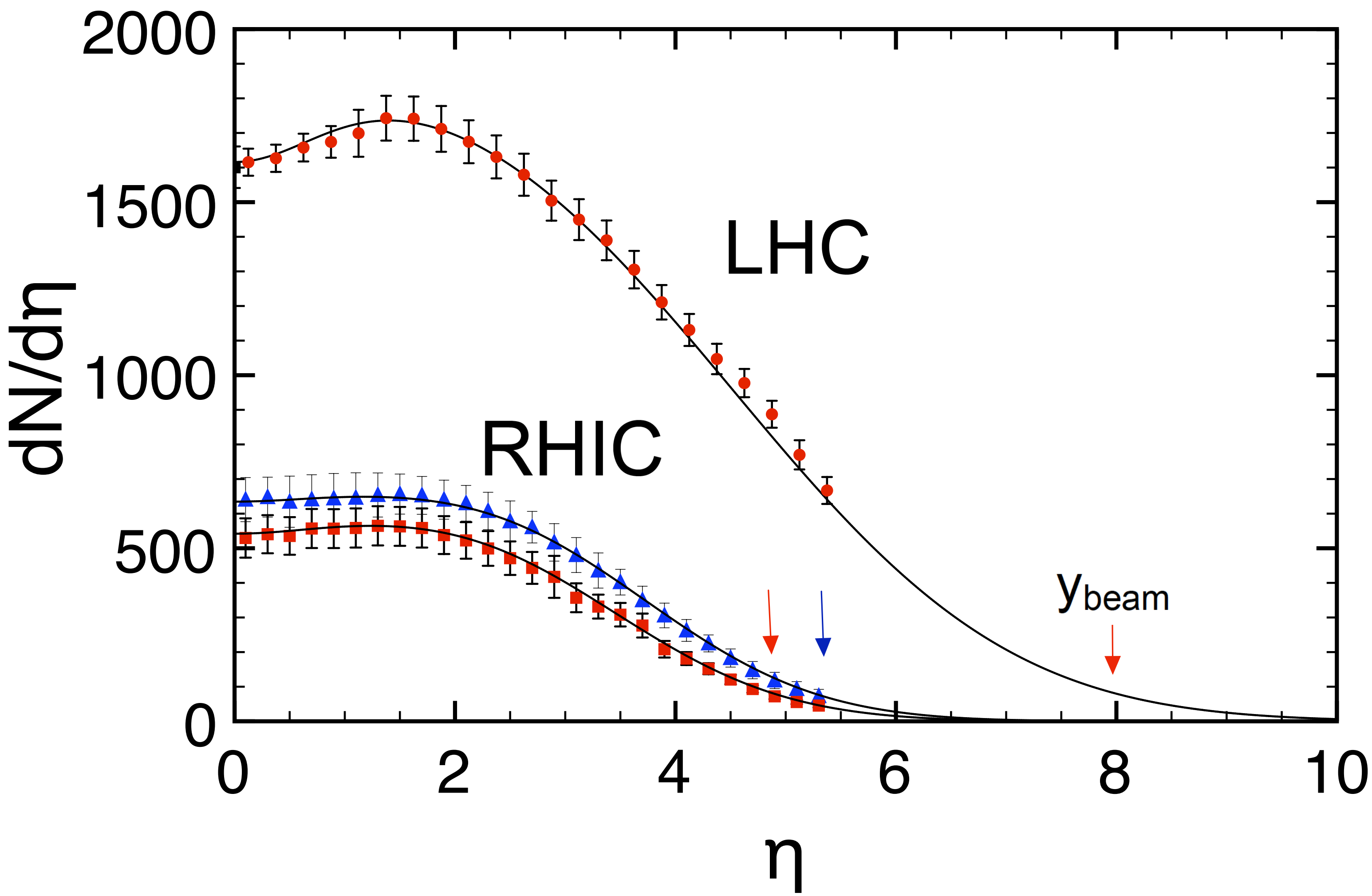
GW, J. Phys. G40, 045104 (2013)



Data: M. Guilbaud et al., ALICE Coll., Nucl. Phys. A 904-905, 381c (2013)

Cross section contributions beyond the beam rapidity

Charged hadrons

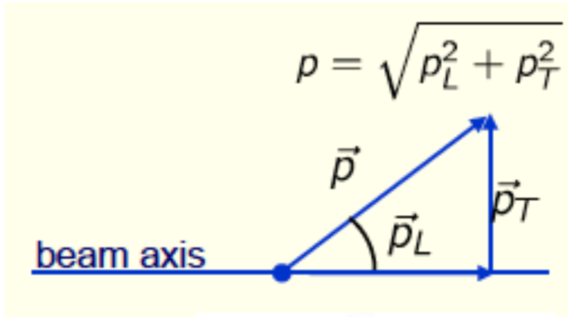


Cross section contributions beyond the beam rapidity

The relation between rapidity $y = \frac{1}{2}\ln\frac{1+\beta_{||}}{1-\beta_{||}}$

and pseudorapidity $\eta = -\ln\left(\tan(\theta/2)\right)$

is given by $y = \frac{1}{2}\ln\frac{\sqrt{(m/p_T)^2+\cosh^2 y}+\sinh\eta}{\sqrt{(m/p_T)^2+\cosh^2 y}-\sinh\eta}$



$$\beta_{||} = \frac{\exp(2y) - 1}{\exp(2y) + 1}$$

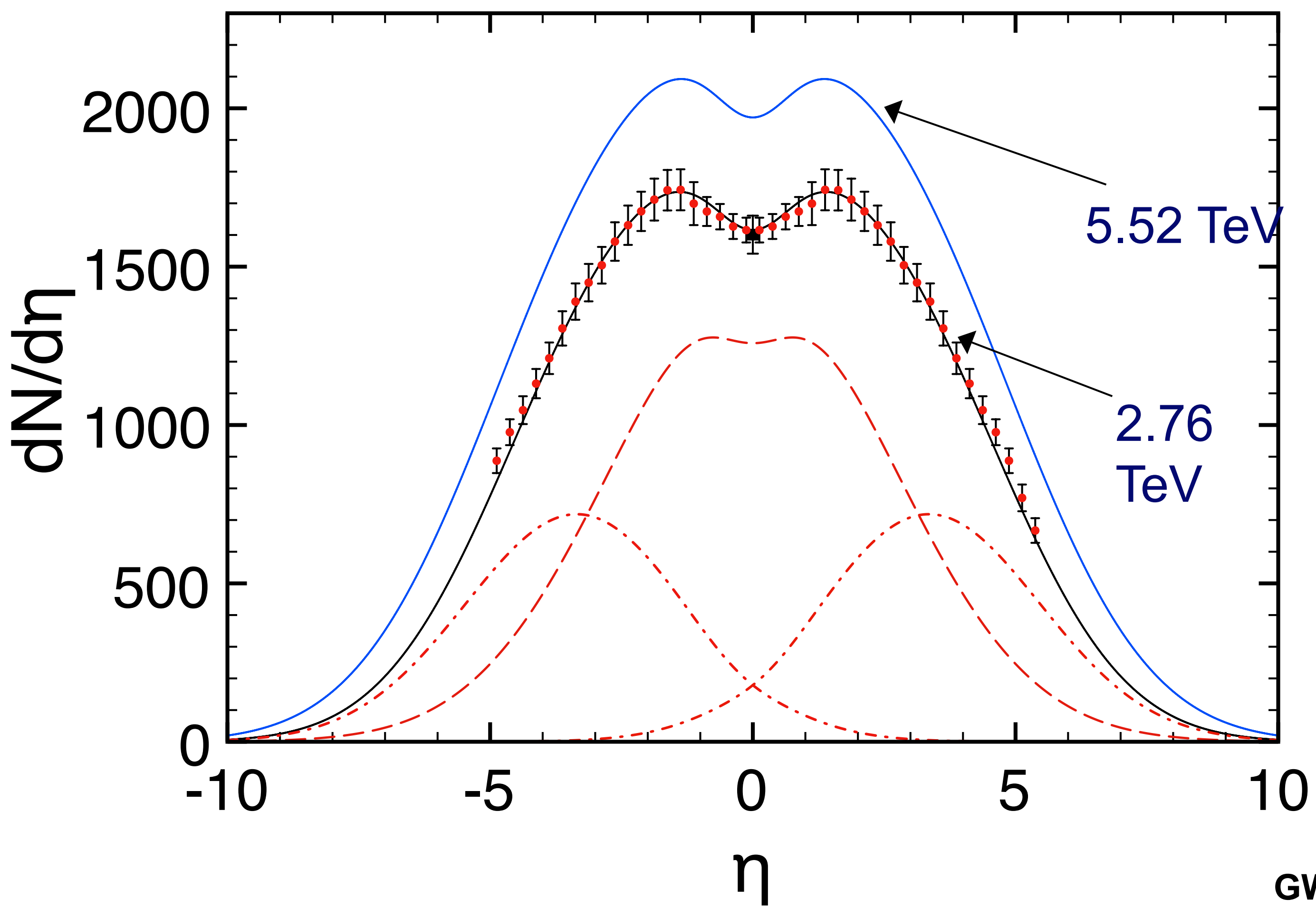
which has the limits (1st order expansion)

$$y \to \eta - \ln(m/p_T) \text{ for } m << p_T$$

$$y \to \eta \text{ for } p_T << m$$

About 83% of produced charged hadrons at LHC energies are pions, and for pions the limit $\eta \approx y$ is reached at larger values of η than for protons.

3 sources, and prediction for 5.52 TeV PbPb

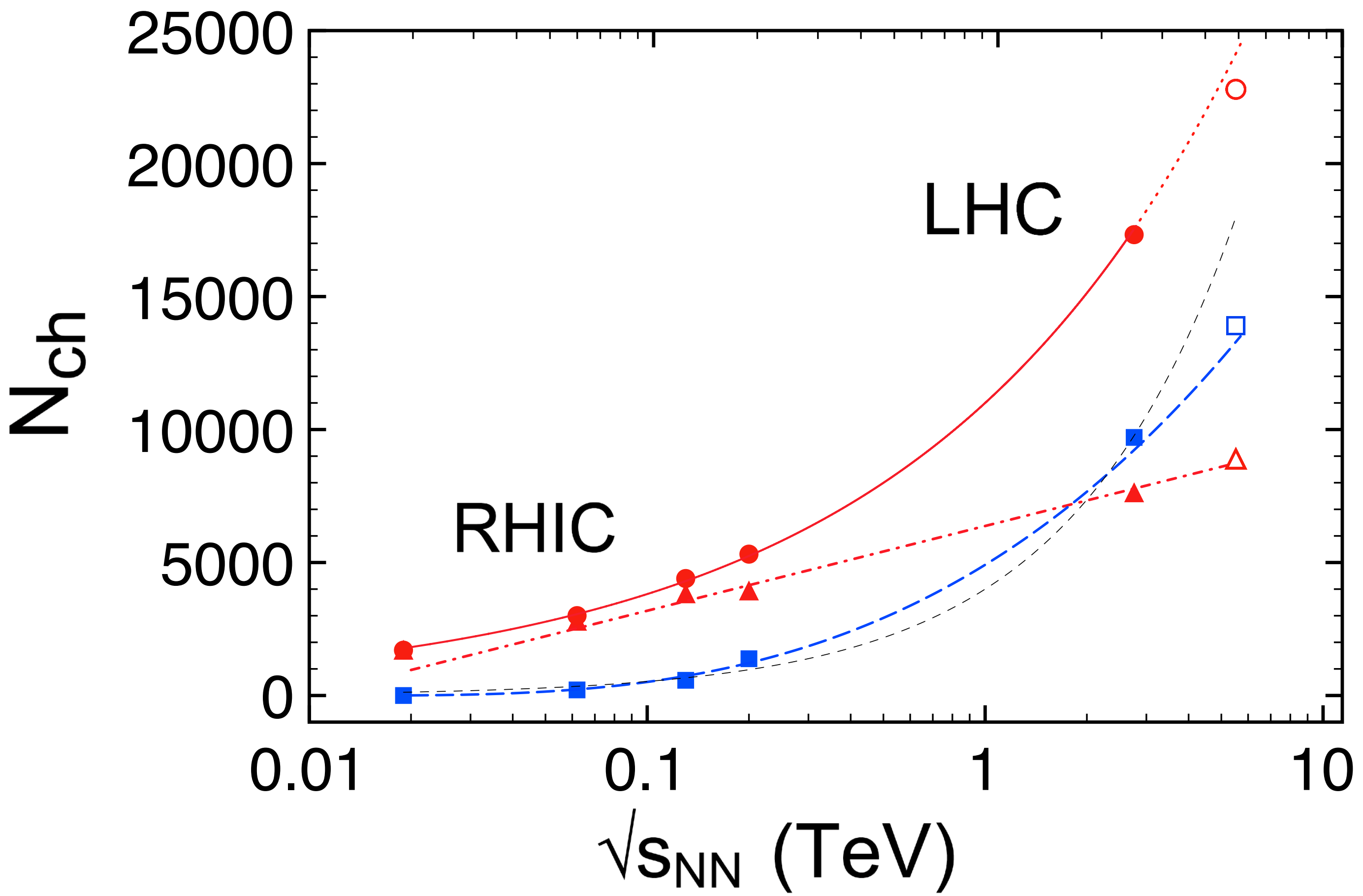


Centrality 0-5%

ALICE data

GW, J. Phys. G40, 045104 (2013)

Content of the sources as function of energy



Centrality 0-5%

(RHIC 0-6%)

Fragmentation sources $\propto \ln(s_{NN}/s_0)$

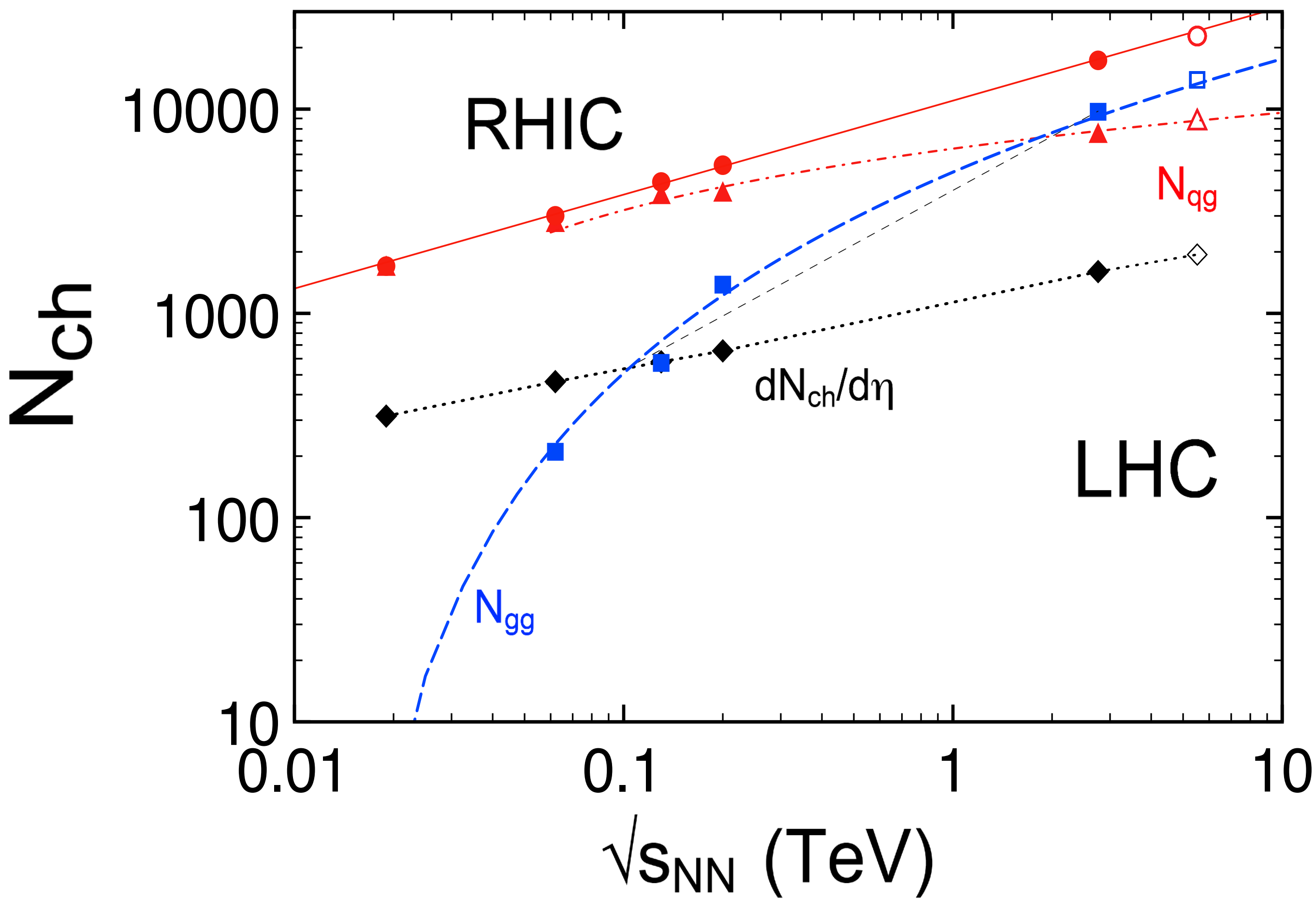
Central source $\propto \ln^3(s_{NN}/s_0)$

$\ln^3$: courtesy T. Trainor

[power law: ≈ $(s_{NN}/s_0)^{0.44}$]

GW, J. Phys. G40, 045104 (2013)

Content of the sources as function of energy



Centrality 0-5%

(RHIC 0-6%)

Fragmentation sources

$\propto \ln(s_{NN}/s_0)$

Central source

$\propto \ln^3(s_{NN}/s_0)$

T. Trainor and GW

Content of the central source as function of energy

Rise of the cross section with energy in the central distribution is driven by the growth of the gluon density at small *x*, but is "..suppressed by the quantum-classical interaction from the dense medium"

$$\frac{dN}{d\eta}|^{gg}_{\eta\simeq 0} \propto \ln^2(s_{NN}/s_0)$$

cf. M.F. Cheung and C.B. Chiu, arXiv:1111.6957; analogous to Froissart bound of the total cross section (approximate solution to leading order)

Total particle content in the *gg*-source by integrating over η:

$$\int_{-y_{\rm beam}}^{y_{\rm beam}} \frac{dN}{d\eta}|^{gg}_{\eta\simeq 0} d\eta \propto \ln^3(s_{NN}/s_0)$$

since

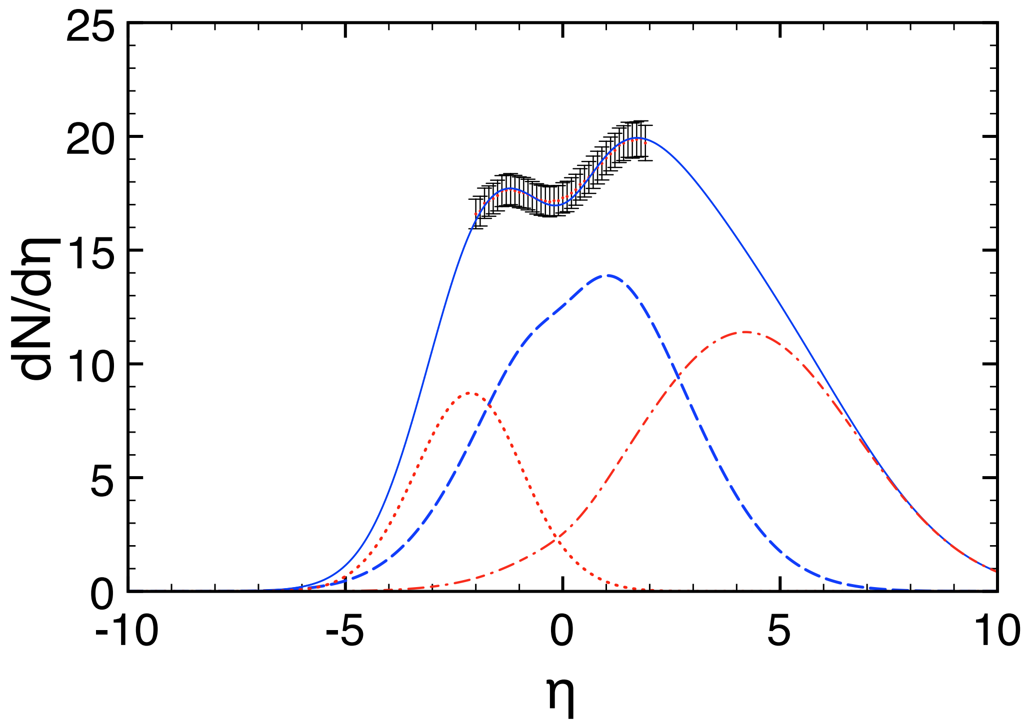
$$y_{\rm beam} = \ln(\sqrt{s_{NN}}/m_p)$$

$$\rightarrow N^{gg}_{tot} \propto \ln^3(s_{NN}/s_0)$$

as inferred from the phenomenological analysis: Room for further theoretical development.

3. Asymmetric system: *p*Pb @ 5.02 TeV

Min. bias 5.02 TeV pPb @ LHC



- Asymmetric central and fragmentation sources for particle production

p_p= 4 TeV/c

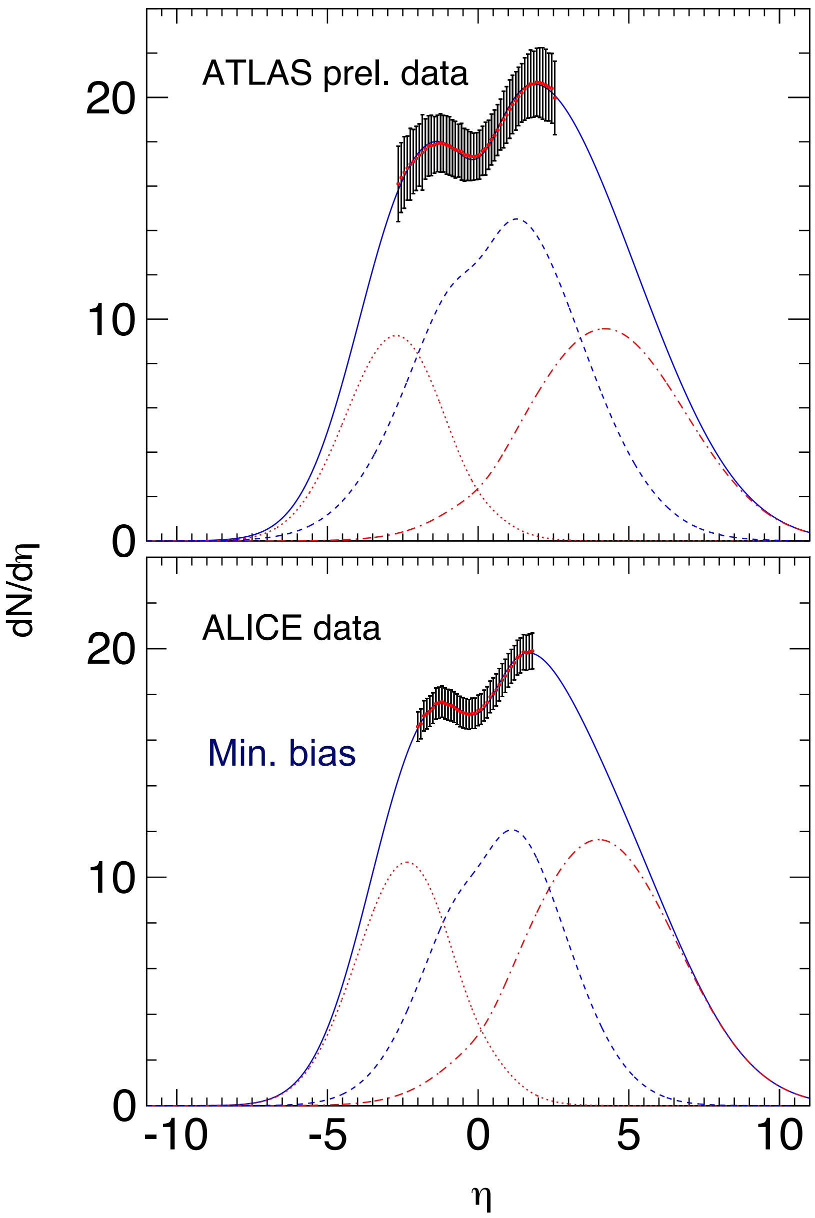
$$\sqrt{s_{NN}} = \sqrt{\frac{Z_1 * Z_2}{(A_1 * A_2)}} * 2p_p = 5.02\text{TeV}$$

$$y_{\text{beam}}^{cm} = \mp \ln(\sqrt{s_{NN}}/m_0) = \mp 8.586$$

Calculation: GW, J. Phys. G40, 045104 (2013)

Midrap. data: ALICE collab., PRL 110, 032301 (2013)

3-sources model (RDM): *p*Pb @ 5.02 TeV

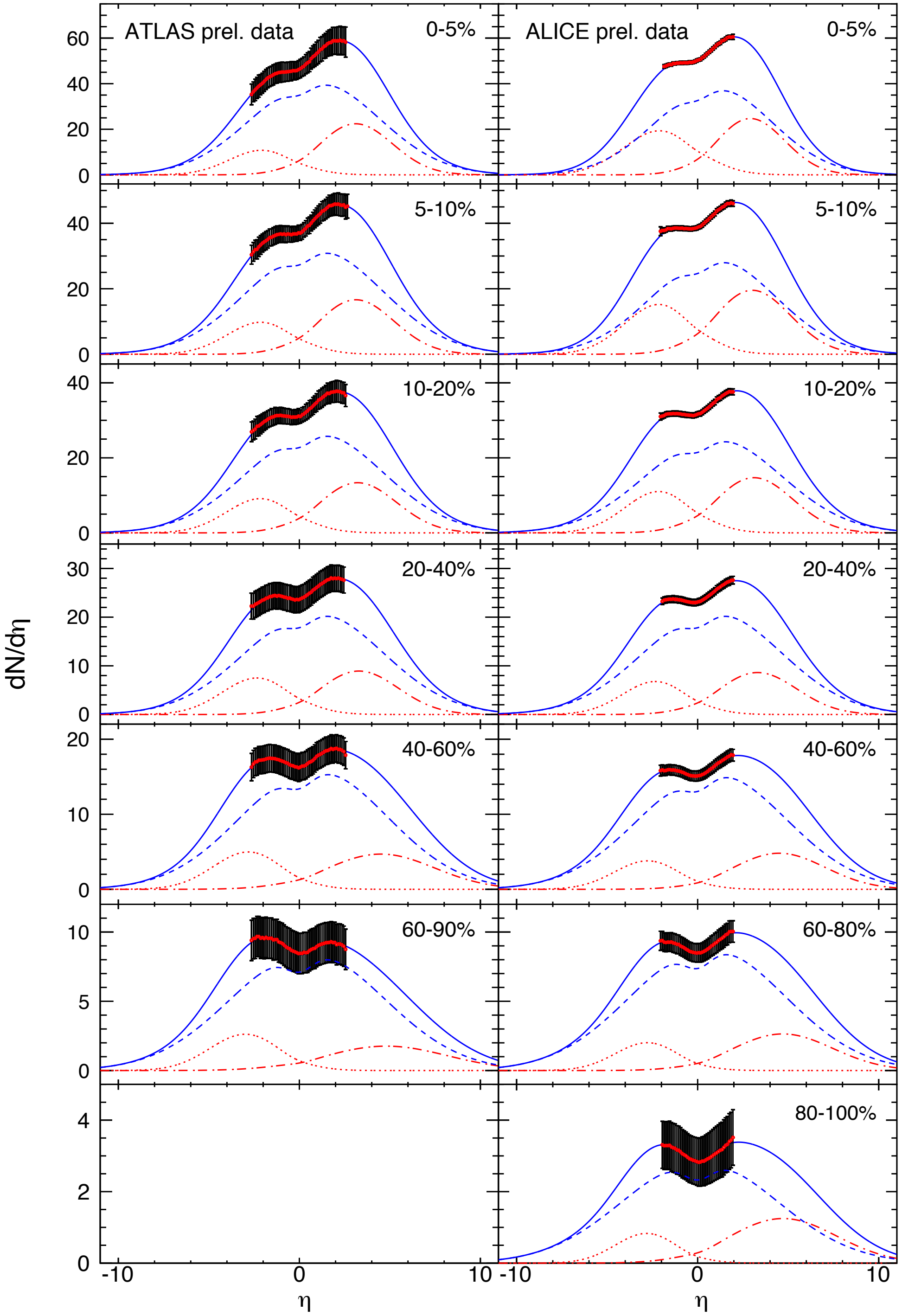


Minimum bias charged hadrons in pPb

- ALICE 0-100% min. bias data and preliminary ATLAS 0-90% data are fully consistent once the latter are rescaled with the cross section ratio σ(0-90%)/σ(0-100%) = 0.898.
- The ≈ midrapidity gluon-gluon source is the largest particle production source. It is significantly modified by the Jacobian, whereas the fragmentation sources are almost gaussian.
- Data at larger values of η needed to determine the particle content more precisely

Midrap. data: ALICE collab., PRL 110, 032301 (2013); 0-100% centrality

ATLAS prelim. data 0-90% scaled with the cross section ratio (90%/100%): ATLAS-CONF-2013-096 (2013)



Centrality dependence *p*Pb @ 5.02 TeV

- Good agreement of preliminary ATLAS and prel. ALICE results for most centralities
- The midrapidity gluon-gluon source remains the largest hadron production source at all centralities, the *p*-like source the smallest
- (dN/dη)_max decreases from ≈ 60 at 0-5 % to ≈ 3 at 80-100 %

Calculations: P. Schulz and GW (2014)
χ^2- minimizations with respect to the prel. data.

Preliminary data: A. Toia (ALICE collab./ CL1), Quark Matter Conf., Darmstadt (2014); ATLAS-CONF-2013-096 (2013).

Centrality dependence of the RDM-parameters in *p*Pb @ 5.02 TeV

Table 1: RDM parameters for centrality-dependent pPb collisions at 5.02 TeV from a χ^2-optimization based on preliminary ALICE data [5], and equilibrium values y_{eq} of the mid-rapidity source. The mean transverse momenta $\langle p_T \rangle$ are taken from [9]. The beam rapidity is $y_{beam} = \mp y_{max} = \mp 8.586$.

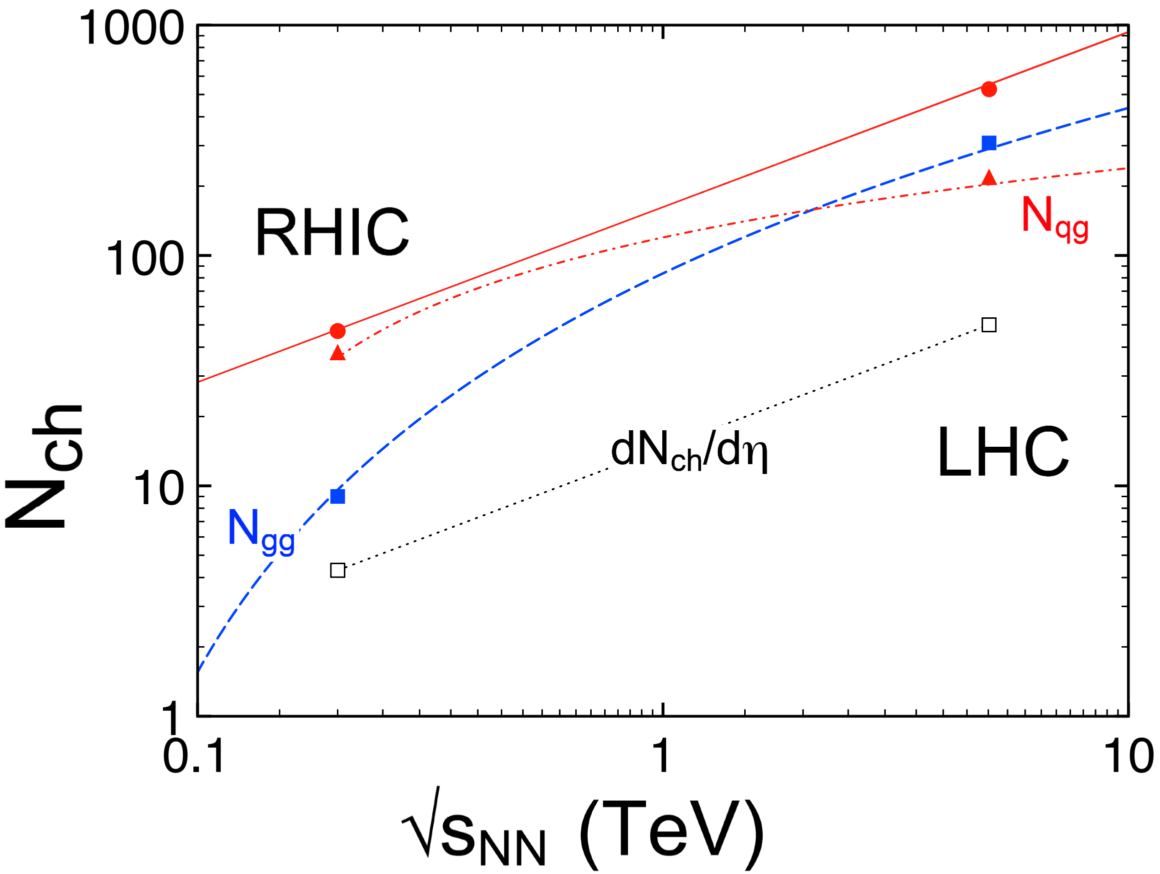
centrality(%)	$\langle p_T \rangle$ GeV/c	y_{eq}	$\langle y_1 \rangle$	$\langle y_2 \rangle$	Γ_1	Γ_2	Γ_{gg}	N_1	N_2	N_{gg}
0–5	0.800	0.887	-2.050	2.900	4.819	4.500	7.500	100	119	308
5–10	0.779	0.886	-2.090	3.005	4.591	5.000	7.994	75	104	248
10–20	0.767	0.876	-2.100	3.100	4.500	5.100	8.750	53	80	236
20–40	0.743	0.818	-2.300	3.300	4.353	5.150	8.900	32	47	200
40–60	0.713	0.817	-2.750	4.500	4.350	6.000	9.500	18	31	157
60–80	0.660	0.563	-2.760	4.700	4.200	6.500	10.000	9	18	95
80–100	0.608	0.129	-2.800	4.710	4.101	6.998	10.050	4	9	31

- The midrapidity gluon-gluon source is the largest hadron production source at all centralities, the *p*-like source the smallest
- The width Γ_{gg} increases towards more peripheral collisions

Calculations: P. Schulz and GW (2014)
From χ^2- minimizations with respect to the prel. ALICE data.

Preliminary data: A. Toia (ALICE collab./ CL1), Quark Matter Conf., Darmstadt (2014);

Content of the sources in dAu and *p*Pb as function of c.m. energy



(RHIC: 200 GeV dAu
PHOBOS data)

Centrality 0-5%

Fragmentation sources

$$\propto \ln(s_{NN}/s_0)$$

Central source

$$\propto \ln^3(s_{NN}/s_0)$$

4. Conclusion

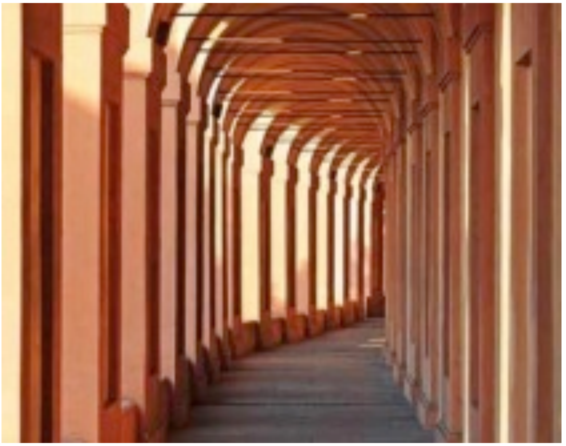
- Charged-hadron production at RHIC and LHC energies has been investigated in a Relativistic Diffusion Model (RDM).

- Predictions of pseudorapidity distributions $dN/d\eta$ of produced charged hadrons in the 3-sources RDM at LHC energies, and comparisons with ALICE data have been performed.

- The contribution of the fragmentation sources from quark-gluon collisions at LHC energies is substantial at larger values of pseudorapidity η.

- Between RHIC and LHC energies, the midrapidity gluon-gluon source becomes more important than the fragmentation sources. The total particle content in this source rises with $\ln^3(\sqrt{s_{NN}})$.

- Charged-hadron production in pPb @ 5.02 TeV and its centrality dependence is well reproduced. The midrapidity source dominates at all centralities.



Thank you for your attention,
and for setting up ISMD2014
in Bologna !