On the rapidity dependence of the average transverse momentum in hadronic collisions

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based on work done with
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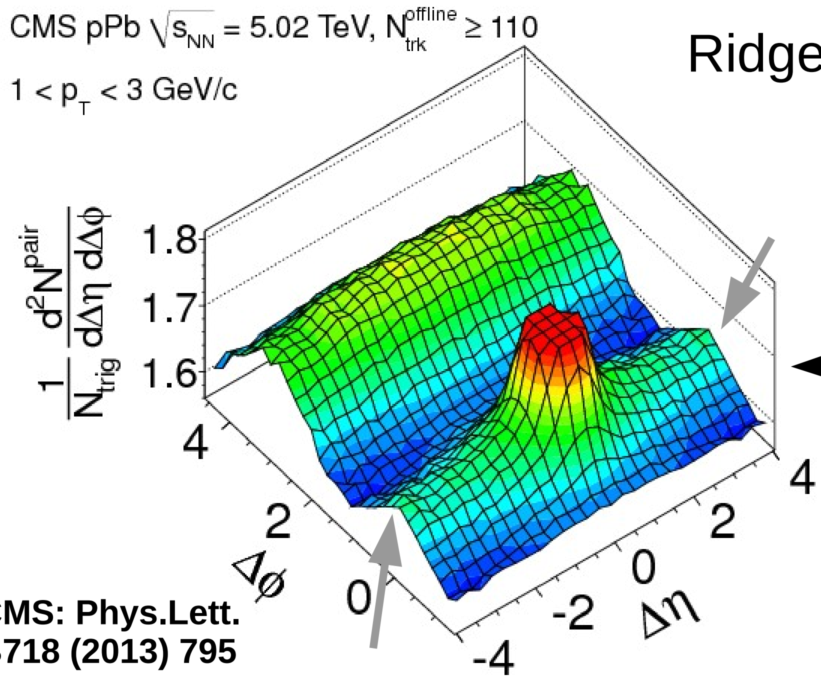
Outline:

- Motivation: CGC and hydrodynamics
- CGC calculation: the hybrid formalism
- Dipole models
- Results for $\frac{dN_h}{d^2p_T d\eta}$ vs p_T: from LHC to RHIC
- Results for $R = \langle p_T(\sqrt{s}, y)\rangle / \langle p_T(\sqrt{s}, y=0)\rangle$
- Results for $R_{pp}(\sqrt{s}, y)/R_{pPb}(\sqrt{s}, y)$
- Conclusions

Motivation: CGC and hydro entangled?



CMS: Phys.Lett. B718 (2013) 795

Ridge effect → long range correlations in the $(\Delta\phi, \Delta\eta)$ plane

High multiplicity p+Pb collisions @ LHC...

but this structure is also seen in d+Au @ RHIC, Pb+Pb @ LHC and even in p+p @ LHC!!

JHEP 1009 (2010) 091; Phys.Lett. B 719 (2013) 29; Phys. Rev. Lett. 110, 182302 (2013); Phys. Lett. B 718, 795 (2013); Phys. Lett. B 743, 333 (2015); Phys. Lett. B 724, 213 (2013), and several other works...

After some years of theoretical (and experimental) work two main lines are currently under investigation → the "initial state" or "final state" models!

Color Glass Condensate: initial state anisotropies which are present at the earliest stages of the collision (during the particle production; proper time ~ 0)

Hydrodynamics: anisotropies emerging as a final state feature due an anisotropic expanding medium, the so called "hydrodynamical flow"

Motivation: CGC and hydro entangled?

Both approaches are able to describe (at least at a qualitative level!) the same set of data on the ridge effect...

For a hydro description see e.g.

B. Alver and G. Roland, Phys. Rev.C81, 054905 (2010), erratum-ibid.C82, 039903 (2010), 1003.0194.
L. Adamczyket al.(STAR Collaboration), Phys. Rev.C88, 014904 (2013), 1301.2187.
P. Bozek, Eur. Phys. J.C71, 1530 (2011), 1010.0405; Phys. Rev.C88, 014903 (2013);.
P. Bozek and W. Broniowski, Phys.Lett.B718, 1557 (2013), 1211.0845.
P. Bozek, W. Broniowski and G. Torrieri, Phys. Rev. Lett.111, 172303 (2013).
E. Shuryak and I. Zahed, Phys. Rev. C88, 044915 (2013).
K. Werner, M. Bleicher, B. Guiot, I. Karpenkoand T. Pierog, Phys. Rev. Lett.112, 232301 (2014).

For a CGC description see e.g.

A. Dumitru, F. Gelis, L. McLerran, and R. Venugopalan, Nucl. Phys.A810, 91 (2008).
S. Gavin, L.McLerran, and G. Moschelli, Phys. Rev.C79, 051902 (2009).
A. Dumitru, K. Dusling, F. Gelis, J. Jalilian-Marian, T. Lappi and Venugopalan, Phys. Lett.B697, 21 (2011).
A. Dumitru and J. Jalilian-Marian, Phys. Rev.D81, 094015 (2010).
A. Kovner and M. Lublinsky, Phys. Rev.D83, 034017 (2011); Phys. Rev.D84, 094011 (2011).
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E. Iancu and D. Triantafyllopoulos, JHEP1111105 (2011).
K. Dusling and R. Venugopalan, Phys. Rev.D87, 094034 (2013);D87, 054014 (2013).
Y. V. Kovchegov and D. E. Wertepny, Nucl.Phys.A925, 254 (2014).
R. L. Ray, Phys. Rev.D84, 034020 (2011); Phys. Rev.D90, 5, 054013 (2014).
A. Kovner and M. Lublinsky, Int. J. Mod.Phys.E22, 1330001 (2013)

Motivation: CGC and hydro entangled?

Similar situation regarding the azimuthal asymmetries observed in the p+Pb collisions @ LHC

For hydro, see e.g.

P. Bozek, Eur. Phys. J. C71, 1530 (2011); Phys. Rev. C85, 014911 (2012).

P. Bozek and W. Broniowski, Phys. Lett. B718, 1557 (2013); Phys. Rev. C88, 014903 (2013).

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A. Bzdak, B. Schenke, P. Tribedy and R. Venugopalan, Phys. Rev. C87,064906 (2013).

E. Shuryak and I. Zahed, Phys. Rev. C88, 044915 (2013).

K. Werner, M. Bleicher, B. Guiot, I. Karpenkoand T. Pierog, Phys. Rev. Lett.112, 232301 (2014).

B. Schenke and R. Venugopalan, arXiv:1405.3605

For CGC, see e.g.

A. Dumitru and A. V. G., Nucl. Phys. A933, 212 (2014).

A. Dumitru, L. McLerran and V. Skokov, arXiv:1410.4844.

T. Lappi, Phys. Lett. B744, 315 (2015).

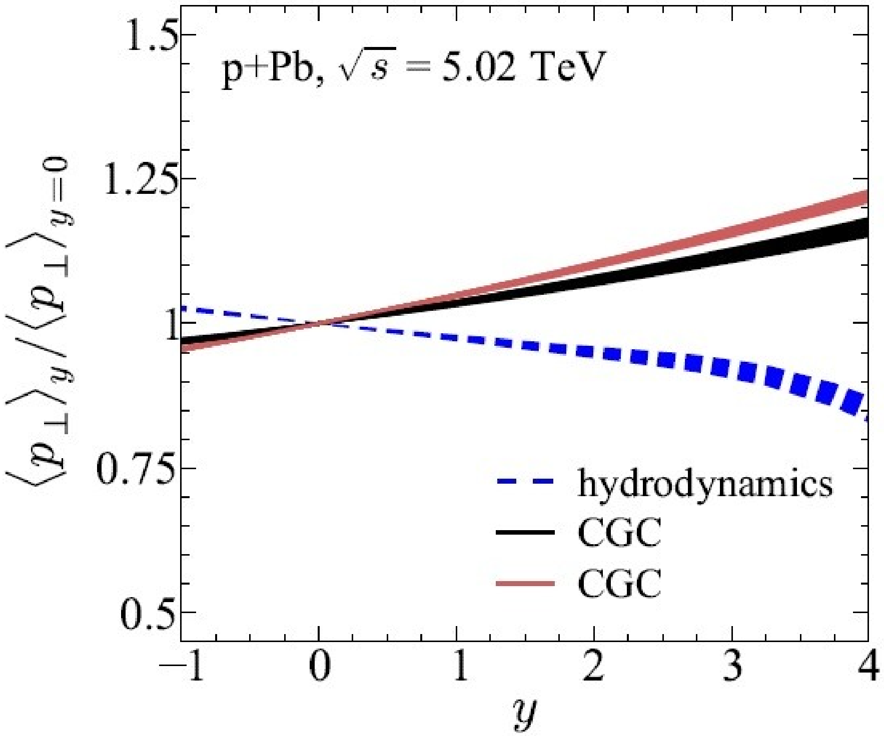
B. Schenke,S. Schlichting and R. Venugopalan, Phys. Lett. B747, 76 (2015).

A. Dumitru, A. V. G. and V. Skokov, arXiv:1503.03897 [hep-ph].

T. Lappi, B. Schenke, S. Schlichting and R. Venugopalan, arXiv:1509.03499 [hep-ph].

Motivation: CGC and hydro disentangled?

But then, it has been proposed that the rapidity dependence of the average transverse momentum would be able to discriminate both scenarios!



P. Bozek, A. Bzdak and V. Skokov, Phys. Lett. B728, 662 (2014).

Striking difference between CGC and hydro!

(Very) Naively, in the CGC:

$$\langle p_T \rangle \sim Q_s \sim Q_0 N_{part}^{Pb} e^{\lambda y/2}$$

but for hydro it decreases due to less particles being produced in the forward region

However, these CGC results were obtained with:

- kt factorization (good for mid rapidity; questionable for forward region)
- Analytical approx. of the unintegrated gluon distrib. not describing the exp. data
- No phase space restrictions at large rapidities (the CGC curves grow forever as y → infinity)

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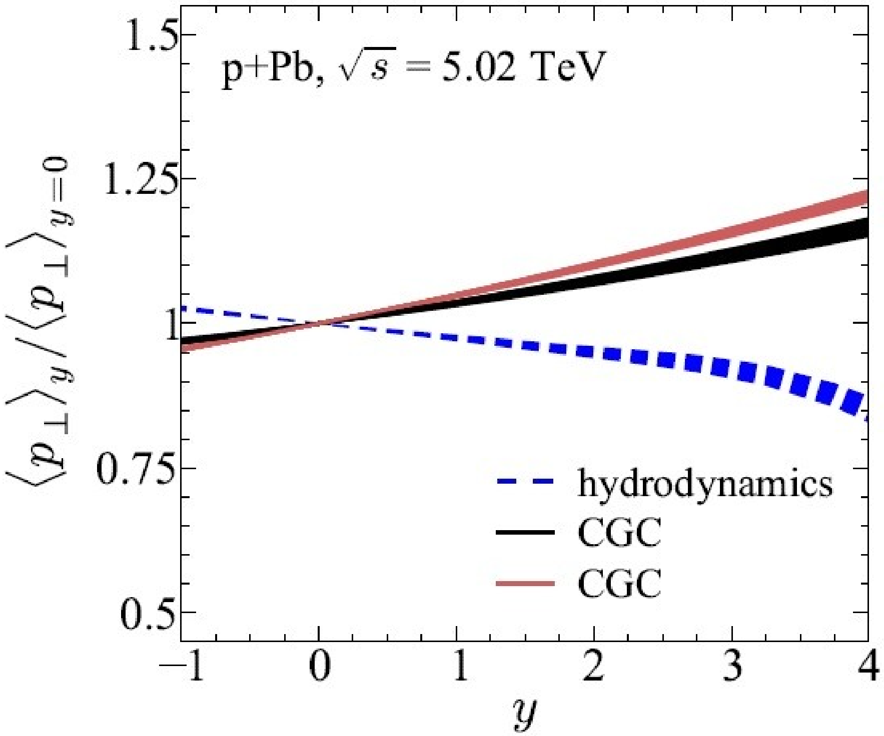

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Are these CGC curves a too qualitative result?

What happens when one does a more complete calculation employing better ingredients, taking into account effects from the fragmentation process and worrying about the exp. data and phase space restrictions left aside?

Color Glass Condensate: the Hybrid Formalism

Dumitru, Hayashigaki and Jalilian-Marian, NPA 765, 464 (2006); NPA 770, 57 (2006)

The min. bias invariant yield for single-inclusive hadron production

$$\frac{dN_h}{dy d^2 p_T} = \frac{K(y)}{(2\pi)^2} \int_{x_F}^{1} dx_1 \frac{x_1}{x_F} \left[f_{q/p}(x_1,\mu^2) \tilde{N}_F\left(\frac{x_1}{x_F} p_T, x_2\right) D_{h/q}\left(\frac{x_F}{x_1},\mu^2\right) + f_{g/p}(x_1,\mu^2) \tilde{N}_A\left(\frac{x_1}{x_F} p_T, x_2\right) D_{h/g}\left(\frac{x_F}{x_1},\mu^2\right) \right]$$

$x_F = \frac{m_T}{\sqrt{s}} e^y$ Feynman-x;

$q_T = \frac{x_1}{x_F} p_T$ parton momentum;

$x_2 = x_1 e^{-2y}$ momentum fraction of the target partons

$z = x_F / x_1$ momentum fraction of the produced hadron

$x_1 f(x_1,\mu^2)$ projectile Parton Dist. Function → CTEQ5L

$D_{\mathrm{h/parton}}(z,\mu^2)$ Frag. Function → KKP

$$\boxed{\tilde{N}_{A,F}(x,p_T) = \int d^2 r \, e^{i\vec{p}_T \cdot \vec{r}} \left[1 - \mathcal{N}_{A,\mathcal{F}}(x,r)\right]}$$

Unintegrated Gluon Distribution → encodes the nonlinear effects at small-x

A = Adjoint rep. → quark dipole ; F = Fundamental rep.→ gluon dipole

Dipole models

anomalous dimension

$$\mathcal{N}(x, r_T) = 1 - \exp\left[-\frac{1}{4}(r_T^2 Q_s^2)^{\gamma(x, r_T^2)}\right]$$

$$\boxed{\begin{aligned} Q_s^2 &= A^{1/3}\left(\frac{x_0}{x}\right)^{\lambda} \\ x_0 &= 3 \times 10^{-4} \\ \lambda &= 0.288 \end{aligned}}$$

Dumitru, Hayashigaki and Jalilian-Marian, NPA 765, 464 (2006); NPA 770, 57 (2006)

$$\gamma(x, r_T)_{DHJ} = \gamma_s + (1 - \gamma_s)\frac{|\log(1/r_T^2 Q_s^2)|}{\underline{\lambda y} + \underline{d\sqrt{y}} + |\log(1/r_T^2 Q_s^2)|}$$

violates geometric scaling!

$$\left\{ \begin{aligned} d &= 1.2 \\ \gamma_s &= 0.628 \end{aligned} \right.$$

fit of the pt-spectra from forward d+Au collisions at RHIC

Boer, Utermann and Wessels, Phys. Rev. D77, 054014 (2008)

$$\gamma(\omega = q_T/Q_s)_{BUW} = \gamma_s + (1 - \gamma_s)\frac{(\omega^a - 1)}{(\omega^a - 1) + b}$$

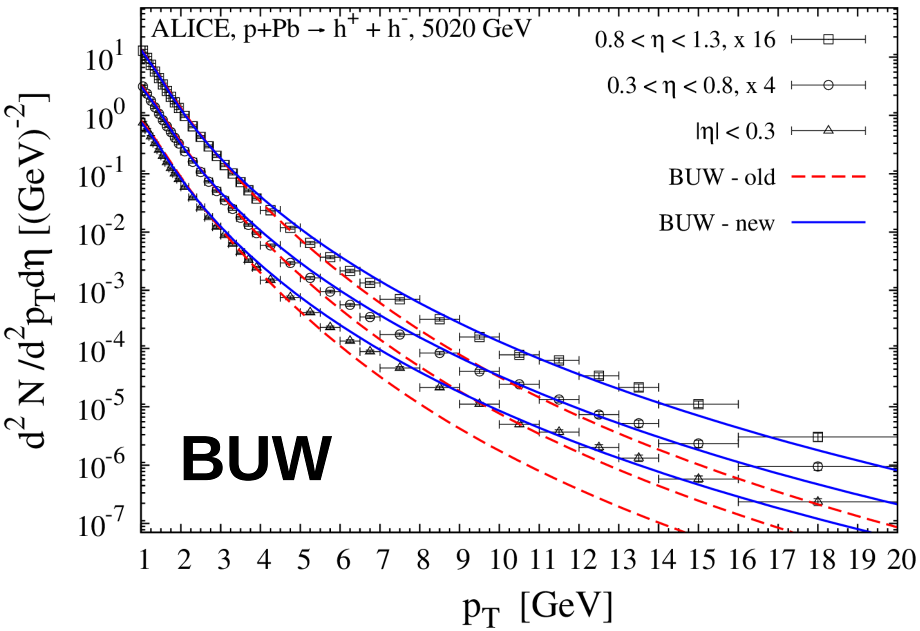
satisfies geometric scaling!

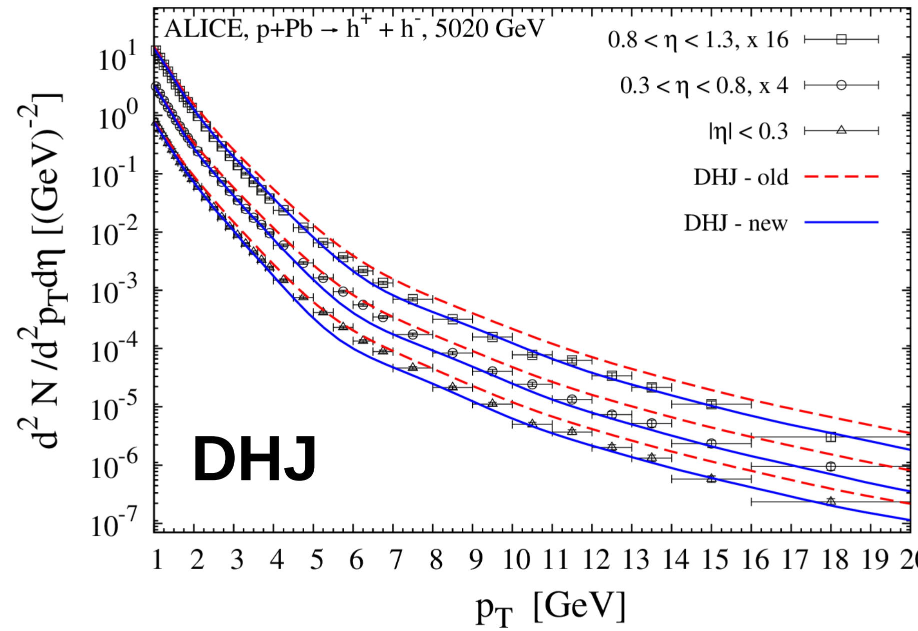
$$\left\{ \begin{aligned} a &= 2.82 \\ b &= 168 \\ \gamma_s &= 0.628 \end{aligned} \right.$$

fit the same data; also works for p+p and it is consistent with the HERA data for the total $\sigma^{\gamma^* p}$ x-section (x < 0.01)

Results for $\frac{dN_h}{d^2p_T d\eta}$: from LHC to RHIC

p+Pb→ch. Particles @ LHC (5.02 TeV)





old parameters, fitting the RHIC data

new parameters, fitting the LHC data

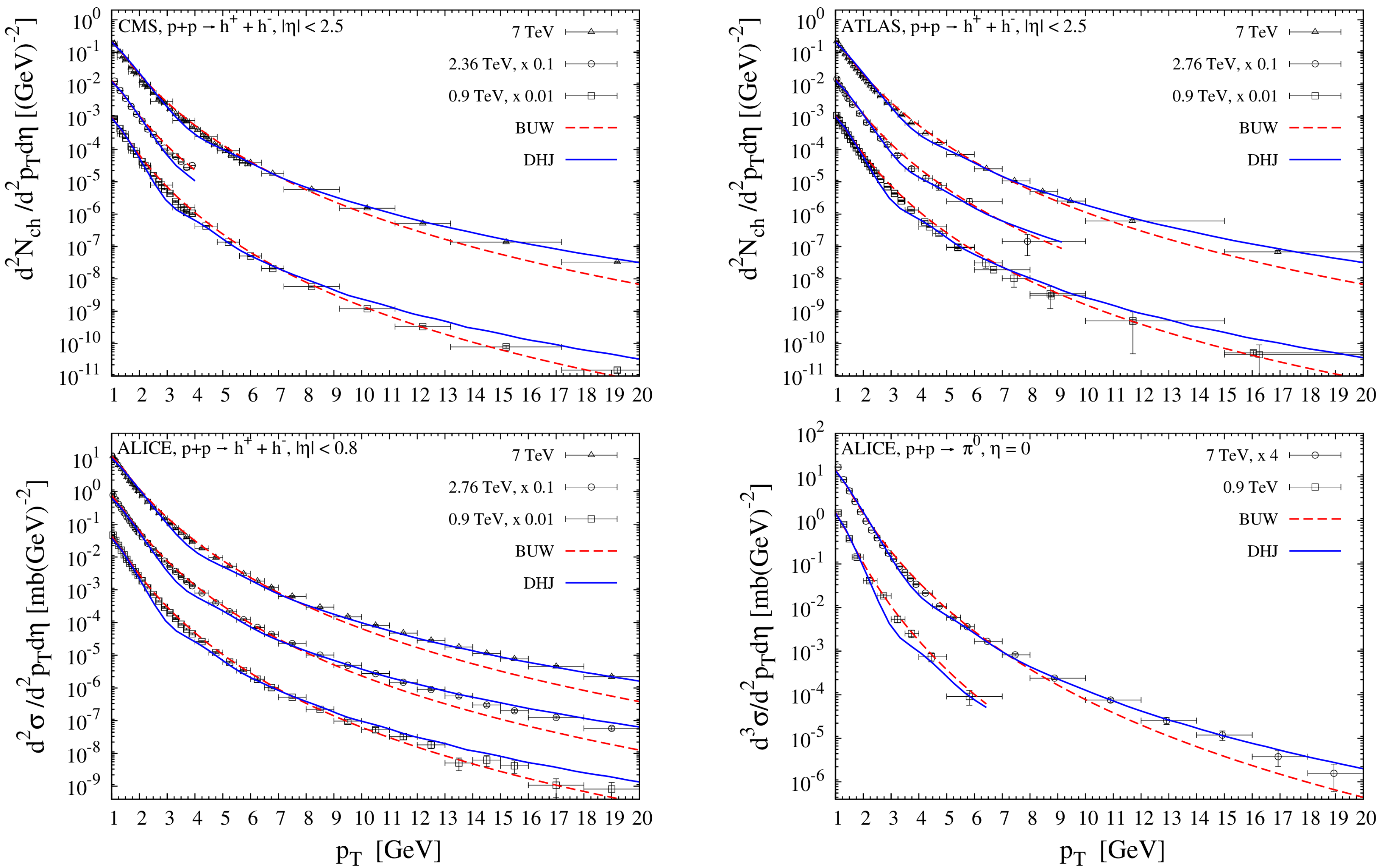
BUW $\begin{cases} a = 2.0 \\ b = 125 \\ \gamma_s = 0.74 \end{cases}$

DHJ $\begin{cases} d = 1.0 \\ \gamma_s = 0.7 \end{cases}$

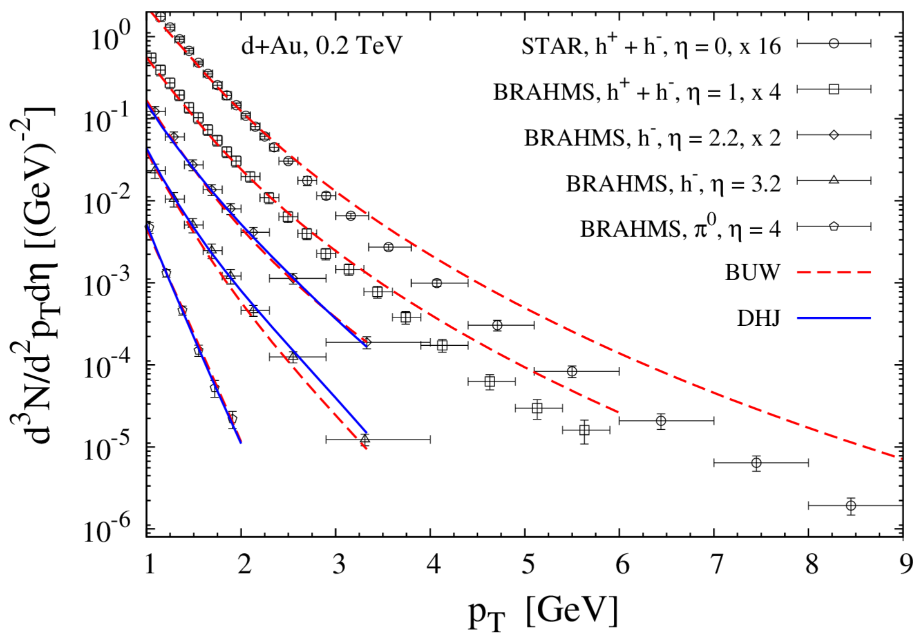
$\gamma_s \geq 0.7$ is consistent with the results obtained using the renormalization group improved BFKL kernels at NLO order and fixed running coupling

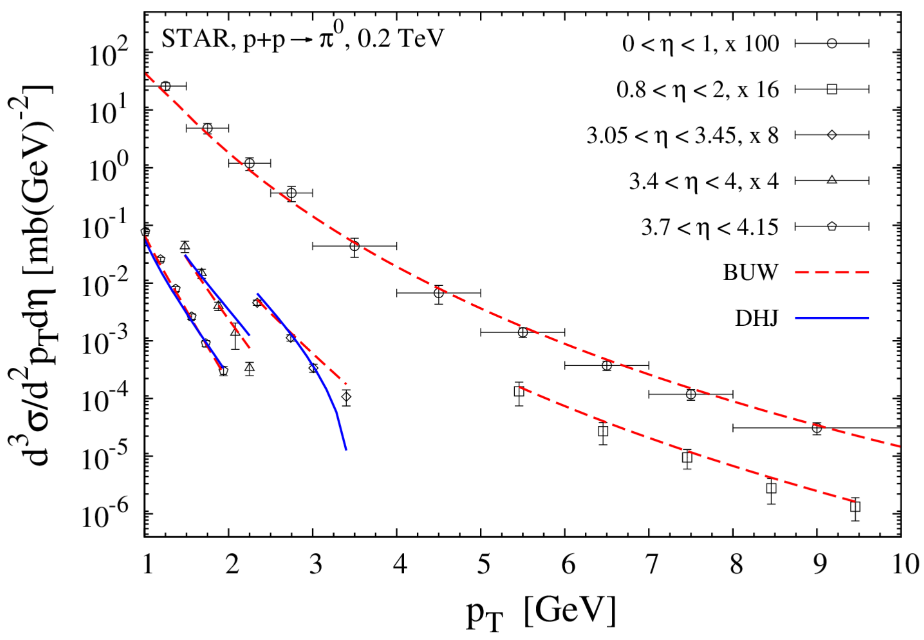
see JHEP 9807, 019 (1998); PRD 60, 114036 (1999)

p+p→ch. particles and neutral pions @ LHC (0.9 – 7 TeV)



d+Au and p+p @ RHIC (0.2 TeV)





No DHJ model in the central region due to heavy oscillations in the pt-spectra

Low energy collision + formalism suitable for the forward region

We should not expect be able to describe the data in the central region!

Now let's check the rapidity dependence of the average pt...

Results for $\langle p_T(\sqrt{s}, y)\rangle / \langle p_T(\sqrt{s}, y=0)\rangle$

$$\langle p_T(\sqrt{s}, y)\rangle = \frac{\int_{p_{T\,\mathrm{min}}} d^2p_T \, p_T \, \frac{dN_h}{dy d^2 p_T}}{\int_{p_{T\,\mathrm{min}}} d^2p_T \, \frac{dN_h}{dy d^2 p_T}}$$

How does it depend on the lower cutoff ?

Results for $\langle p_T(\sqrt{s},y)\rangle / \langle p_T(\sqrt{s},y=0)\rangle$

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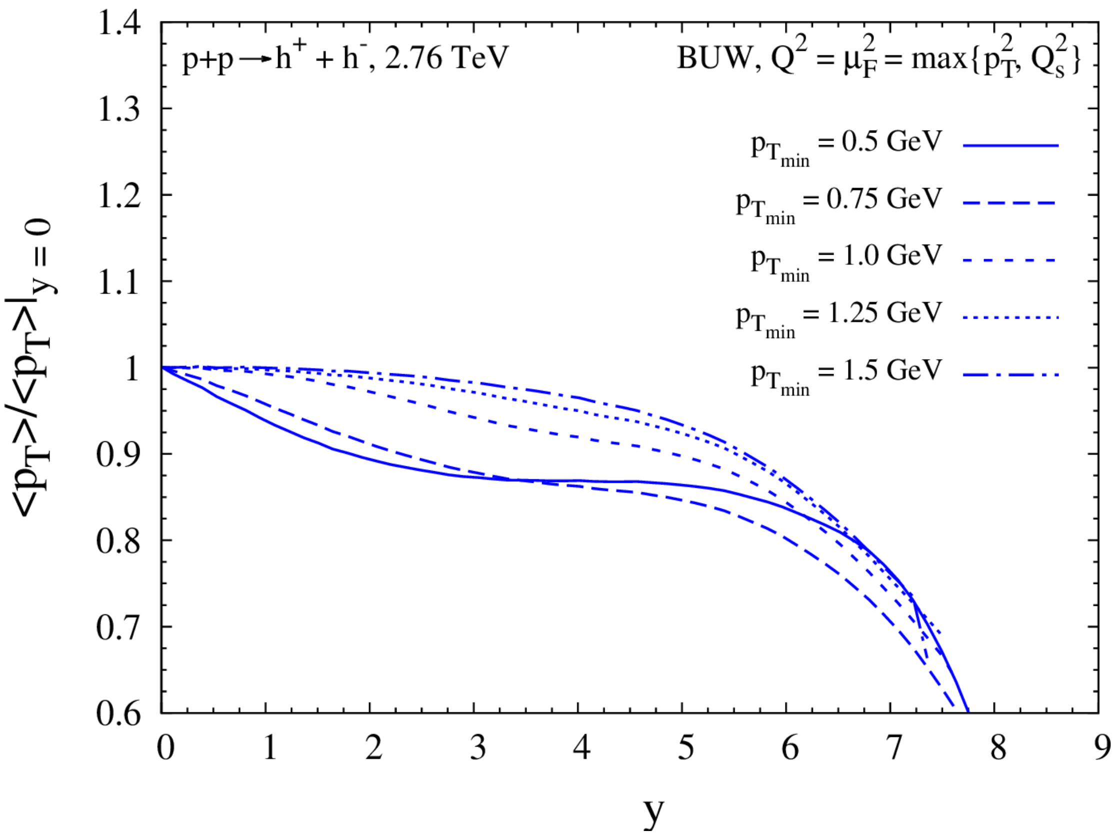
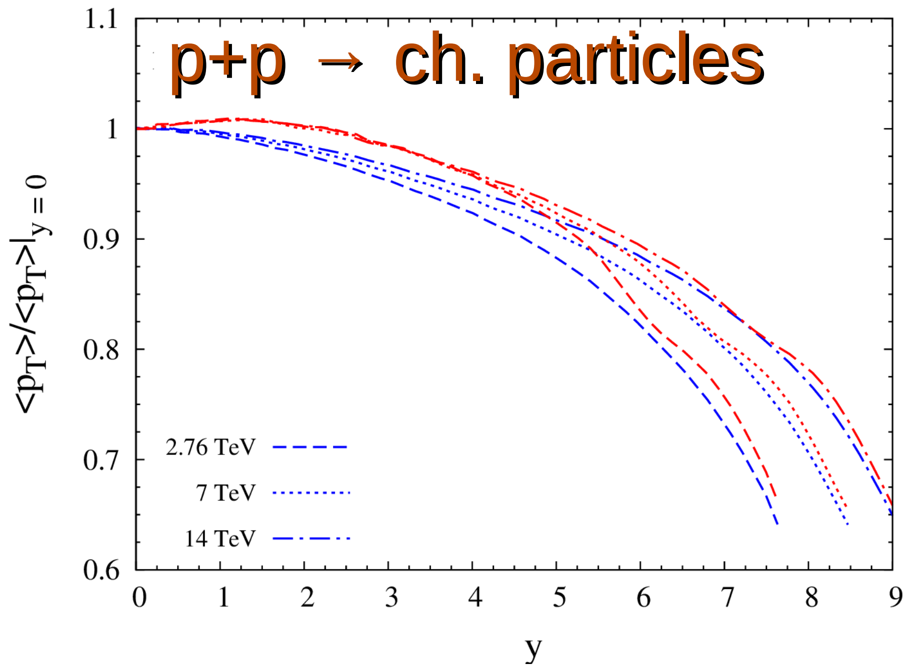
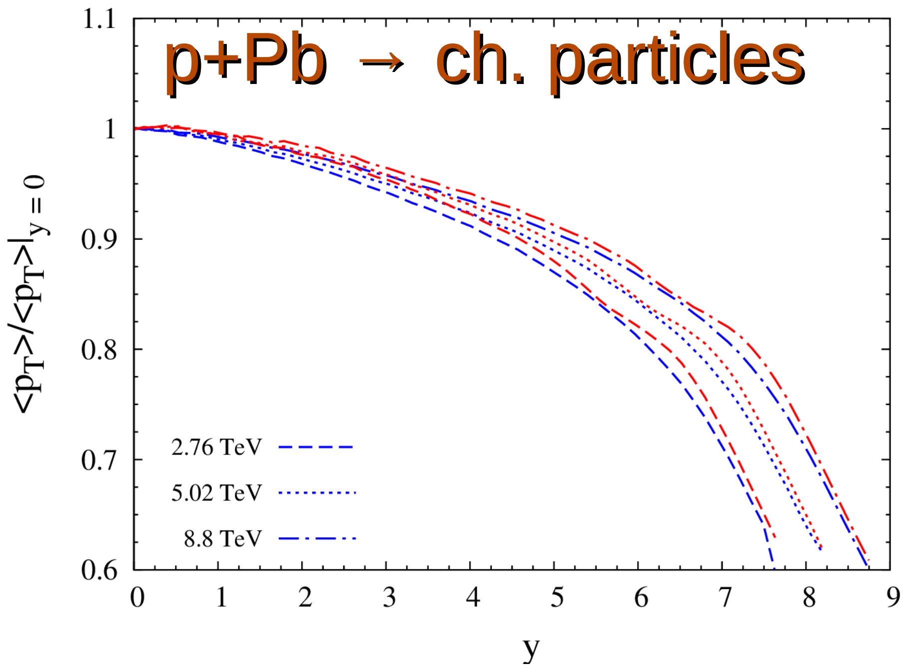


- $\langle p_T(\sqrt{s},y)\rangle / \langle p_T(\sqrt{s},y=0)\rangle$ is not strongly modified by $p_{T\,min}$
- Similar results for p+Pb
- Similar results for $Q^2 = \mu^2 = p_T^2$
- Similar results for DHJ model
- Let's assume $p_{T\,min} = 1\,\mathrm{GeV}$

Results for $\langle p_T(\sqrt{s}, y)\rangle / \langle p_T(\sqrt{s}, y=0)\rangle$





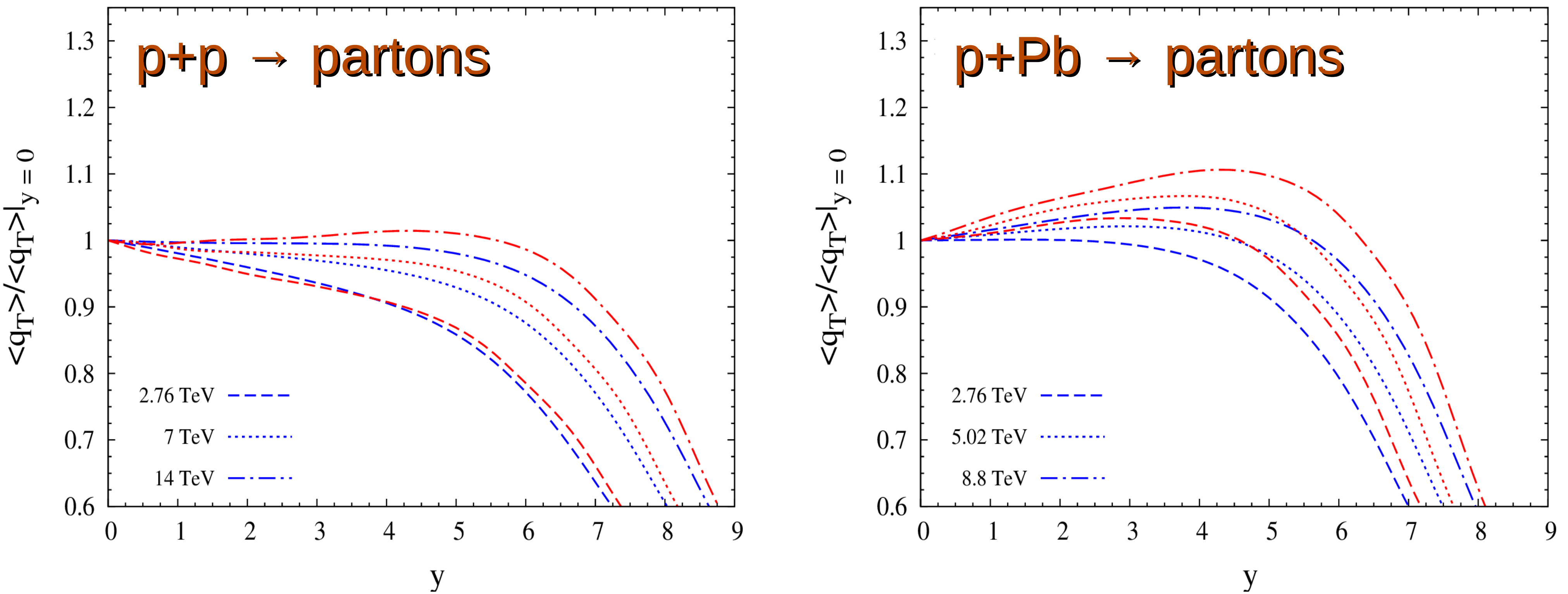
Similar behavior for both models, with **DHJ** being slightly larger than **BUW**

The ratio **increases** with the energy as the phase space opens up...
… but it **decreases** with the rapidity of the produced particles

a behavior **similar** to that obtained using a **hydrodynamical approach!**

$$\langle p_T(\sqrt{s}, y)\rangle / \langle p_T(\sqrt{s}, y=0)\rangle$$ from partons

This means no fragmentation $\boxed{D_{\mathrm{h/parton}}(z,\mu^2) = \delta(1-z)}$

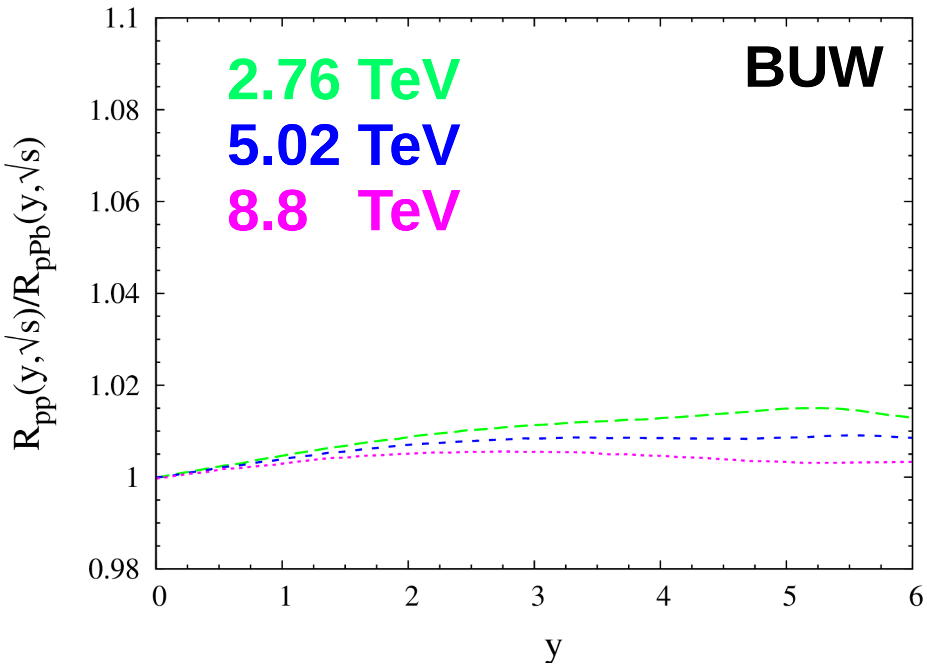


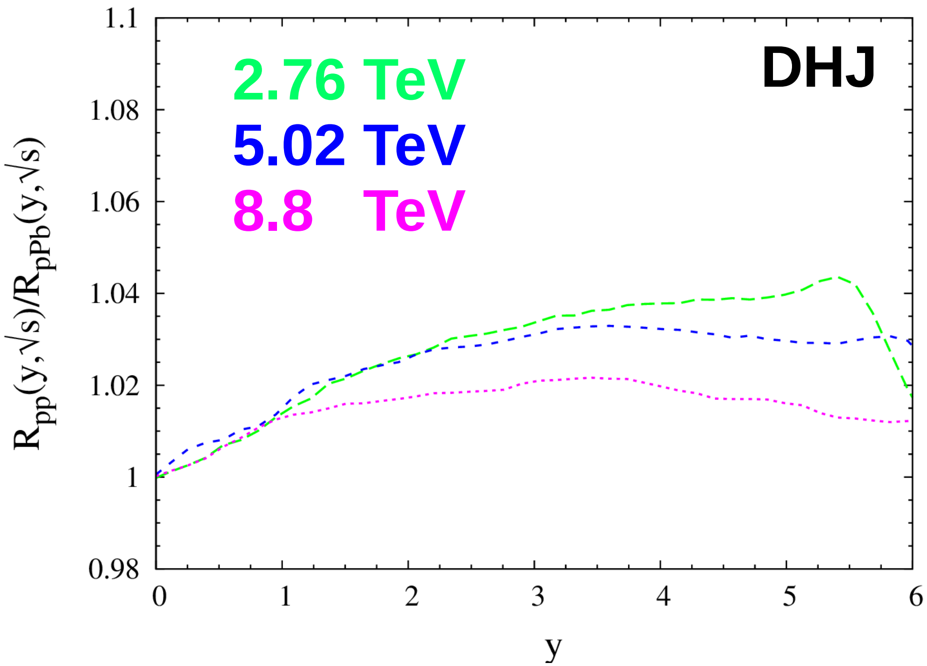
We see some tiny increase in the pPb case but, due to phase space restrictions, it also decreases at forward rapidities!

Results for $R_{pp}(\sqrt{s},y)/R_{pPb}(\sqrt{s},y)$

Back to the hadronic case...

$$R = \langle p_T(\sqrt{s},y)\rangle / \langle p_T(\sqrt{s},y=0)\rangle$$





$R_{pp}(\sqrt{s},y) = R_{pPb}(\sqrt{s},y)$ at large energies in the hybrid formalism of the CGC

This will be an important test for the hybrid formalism!

Conclusions

Using the hybrid formalism of the CGC we...

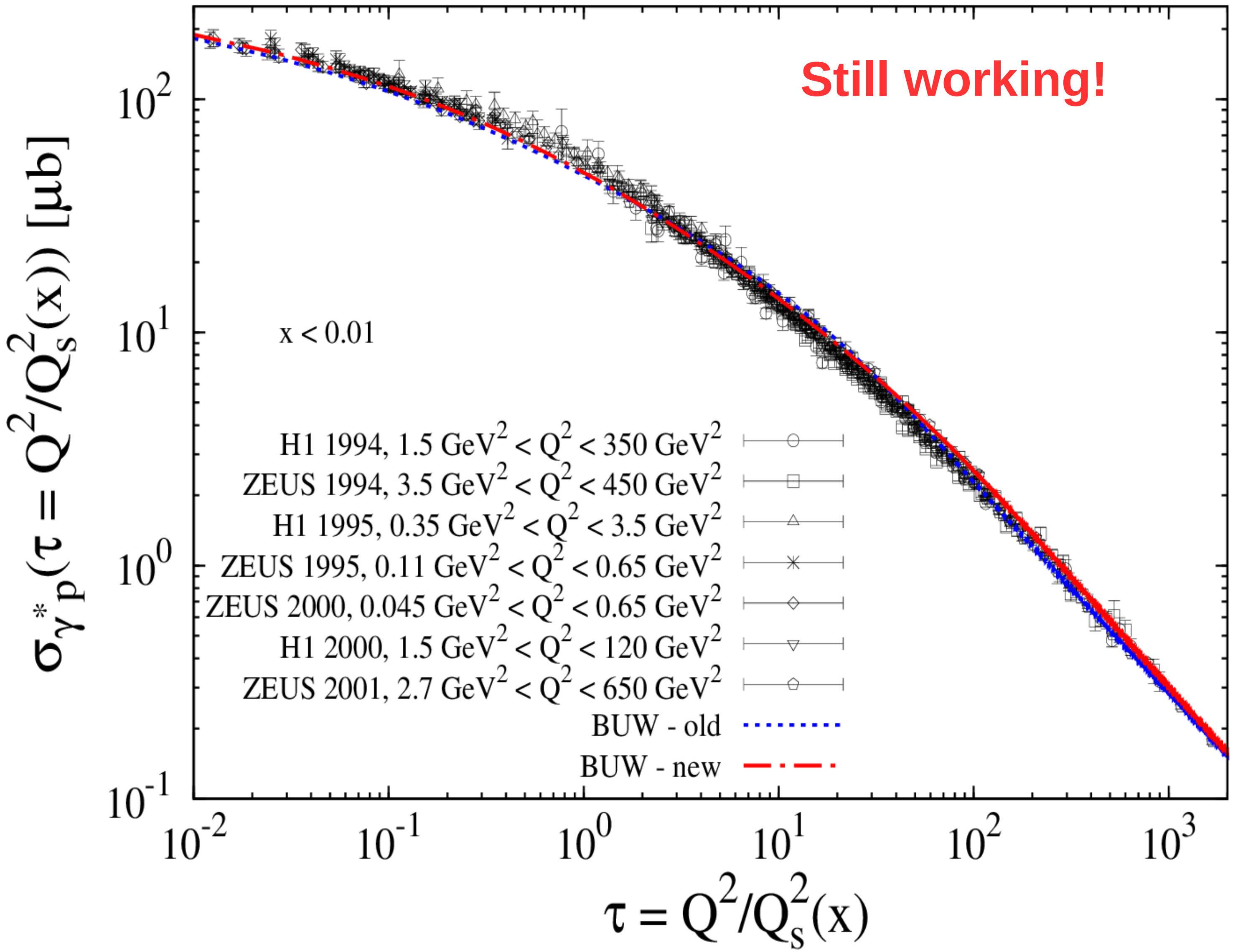
- updated previous phenomenological models for the forward scattering amplitude through the p+Pb @ LHC data
- showed they are able to describe the pt-spectra of charged particles and neutral pions from: i) p+p collisions @ LHC; ii) d+Au and p+p @ RHIC in the forward region
- calculated $\langle p_T(\sqrt{s},y)\rangle$ in p+p and p+Pb collisions and estimated the energy and rapidity dependencies of

$$R = \frac{\langle p_T(\sqrt{s},y)\rangle}{\langle p_T(\sqrt{s},0)\rangle}$$

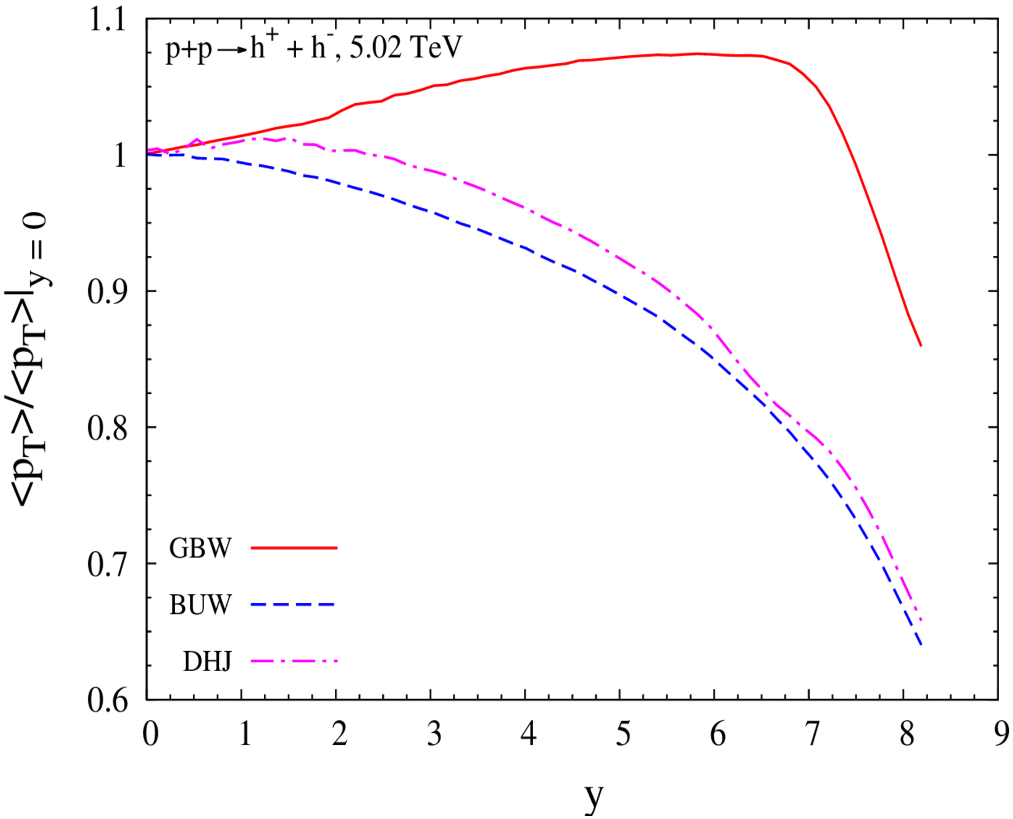
- showed that R(s,y) increases with energy for fixed rapidity and decreases with rapidity for fixed energy having a behaviour similar to that predicted by hydrodynamical approaches
- Finally, this behaviour is almost independent of the model used for $\mathcal{N}(x,r_T)$ in p+p and p+Pb collisions

Backup slides

Geometric Scaling: BUW model



$\langle p_T(\sqrt{s}, y)\rangle / \langle p_T(\sqrt{s}, y=0)\rangle$ with GBW model

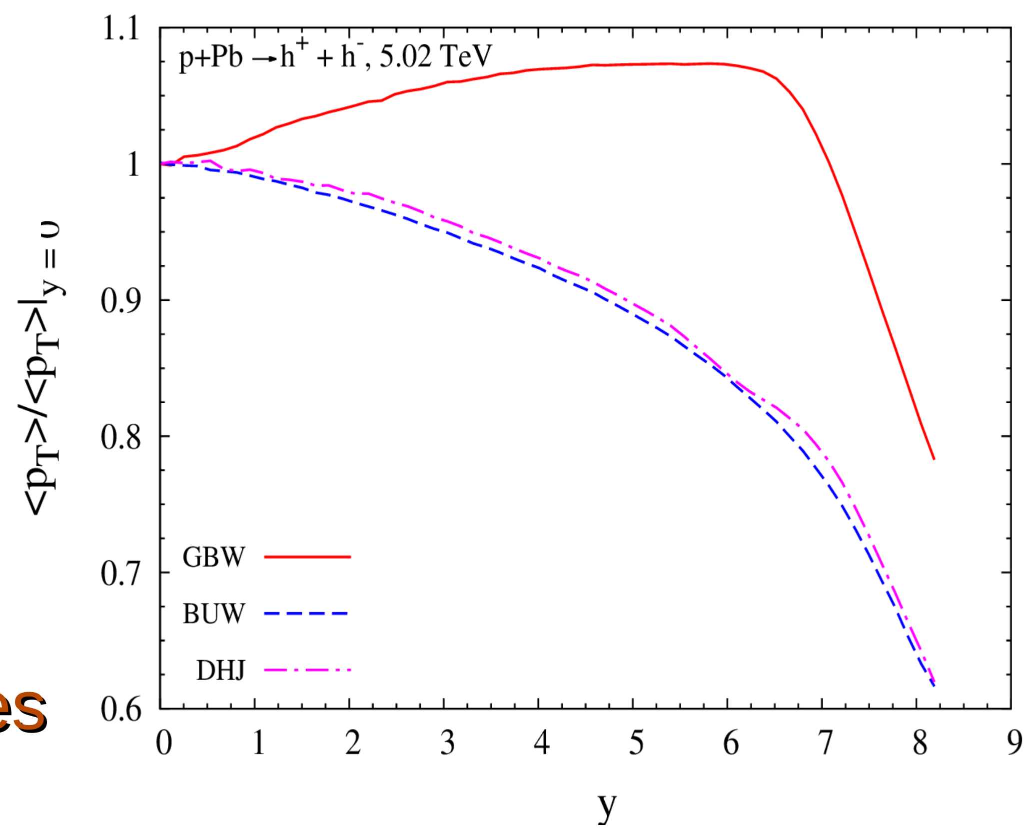


p+p → ch. particles

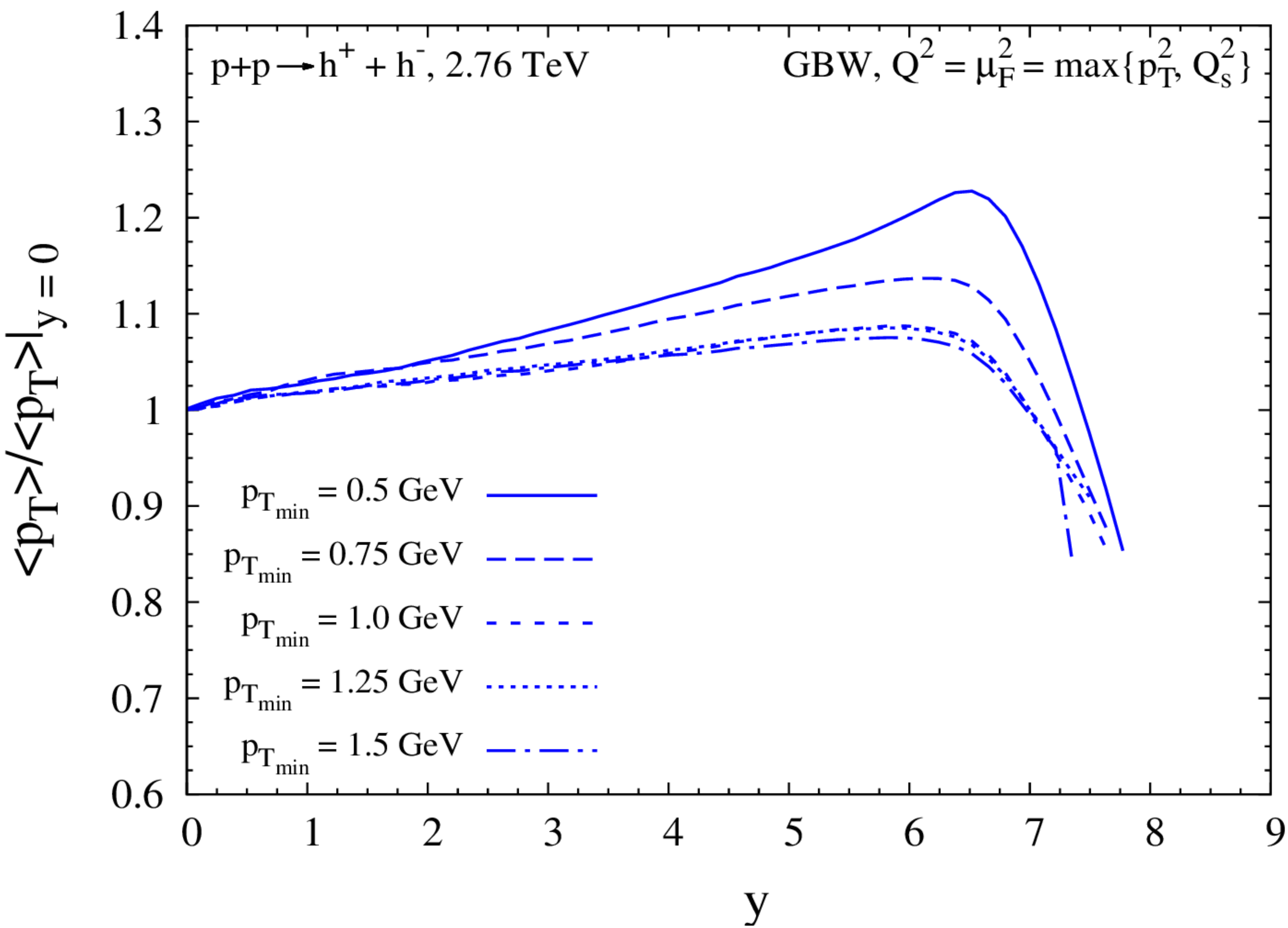
The GBW model ($\gamma(x, r_T^2) = 1$)

* does not * describe the pt-spectra data!

p+Pb → ch. particles



$\langle p_T(\sqrt{s}, y)\rangle / \langle p_T(\sqrt{s}, y=0)\rangle$ with GBW model



The GBW model – $\gamma(x, r_T^2) = 1$ – * does not * describe the pt-spectra data!