Baryon production mechanisms and jet energy loss in heavy ion collisions at RHIC and LHC energies

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EPS HEP 2013, Stockholm, 19 July 2013

Contents

1. Proton production at RHIC energies
    --- experimental data
    (STAR'09, PHENIX'11, ALICE'13)
    --- theoretical results with pQCD

2. New channel: diquark from strong field
    --- Wigner function and kinetic equation

3. Baryon yield from diquark channels
    and modifications in R_{AA}

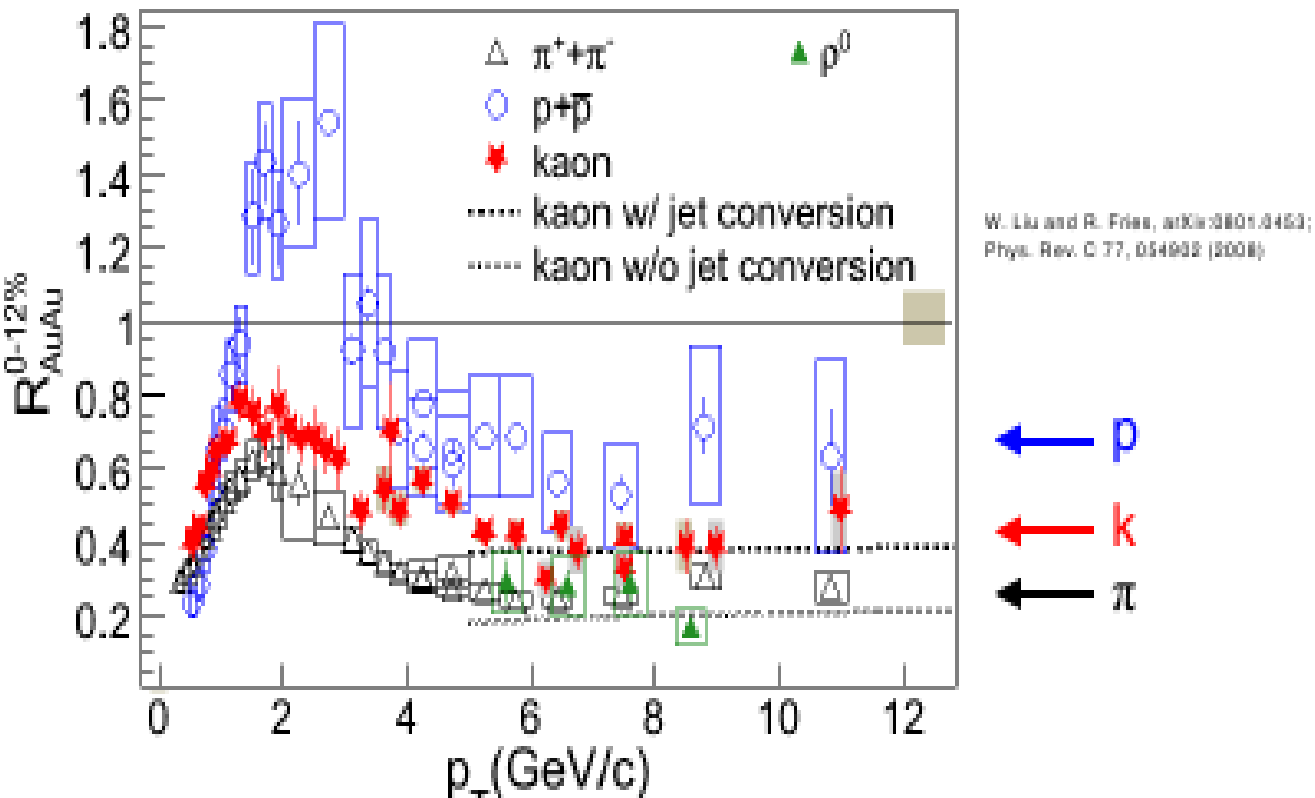
4. LHC results and their interpretation

RHIC: R_{AA} for identified hadrons in AuAu at 200 AGeV --- STAR

2009 Quark Matter Conference, Knoxville,

J. Putschke, Nucl. Phys. A830 (2009) 58c.

Y. Xu, Nucl. Phys. A830 (2009) 701c.



Suggestion: q/g jet conversion W. Liu, R.L. Fries, PRC77, 054902 (2008)

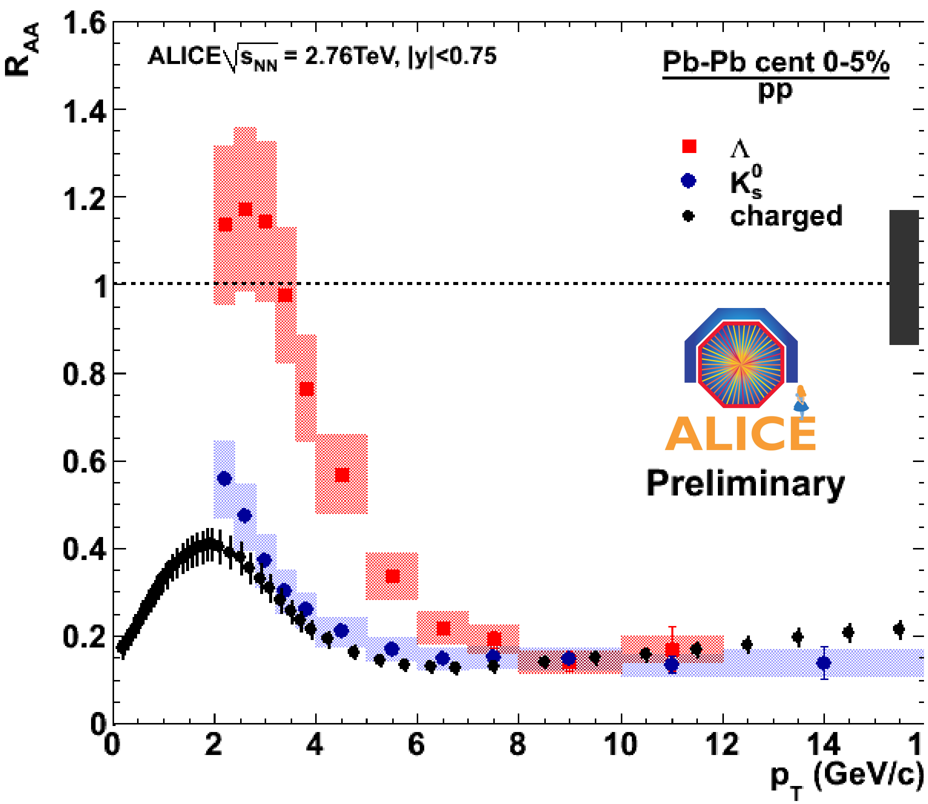
W. Liu, C.M. Ko, .., PRC75, 051901 (2007)

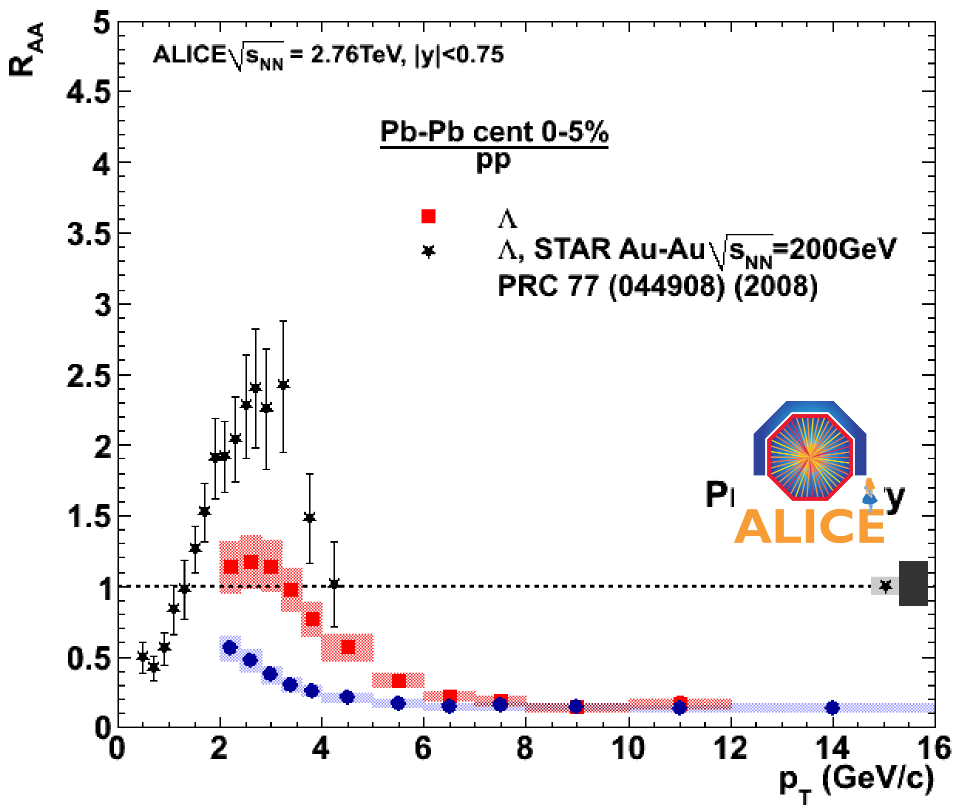
Problem: maybe it is not large enough, explains kaon, but not proton R_{AA}

➻ Medium modified jets + FF: S. Sapeta, U. Wiedemann, EPJ C55, 293 (2008)

Latest result on strange hadron R_{AA} in Pb+Pb at 2.76 ATeV

ALICE (H. Appelshauser) vs. RHIC results on QM 2011/12



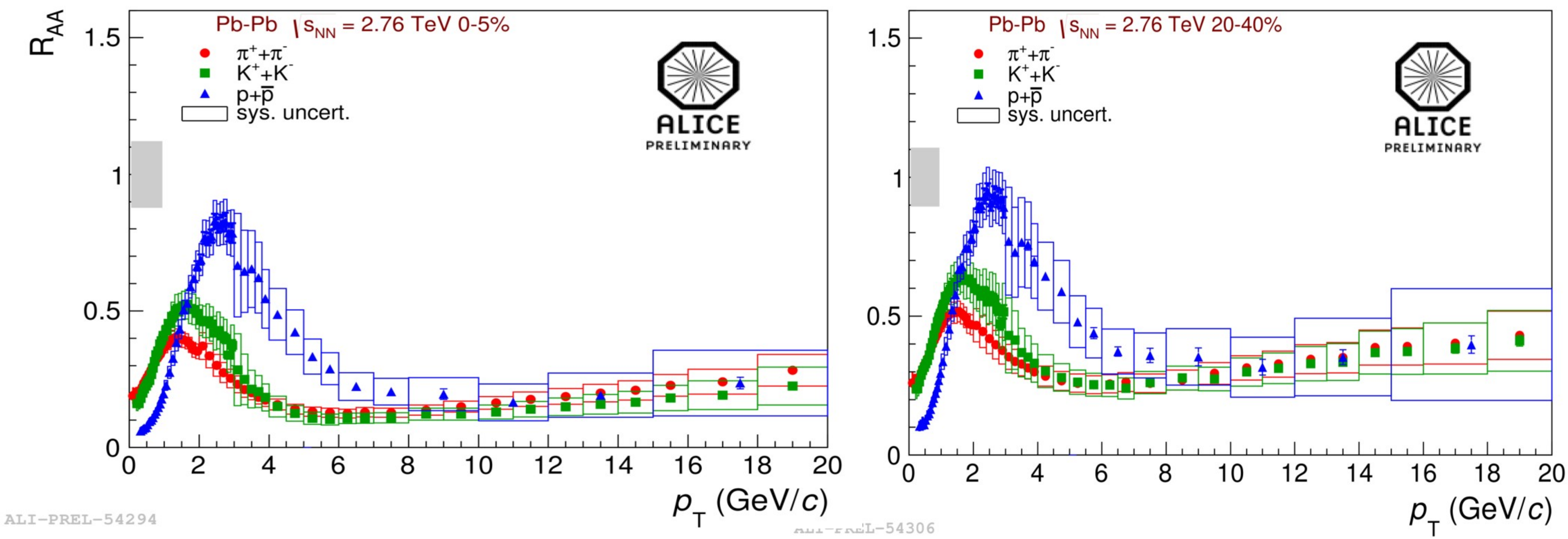


ALICE result at LHC: Λ^0 and K^0_S have the same suppression for p_T > 8 GeV/c

$R_{AA}(\Lambda^0)$ is enhanced over $R_{AA}(K^0_S)$ for p_T < 8 GeV/c

LHC: R_{AA} for identified hadrons in PbPb at 2.76 ATeV --- ALICE

2013 EPS HEP, ALICE talk of Peter Christiansen



Latest ALICE results (2013, Preliminary):

p_T < 10 GeV/c: R_{AA} for protons > R_{AA} for kaons and pions

p_T > 10 GeV/c: R_{AA} for protons ≃ R_{AA} for kaons and pions

➣ Modifications for protons (baryons) are acting under 10 GeV/c !!! (??)

What can we find in a "usual" pQCD based description?

1. Let see charged particle production at LHC energies

PDF + pQCD + FF --> hadron production in pp coll.

2. + Shadowing
+ Multiscattering
+ QUENCHING --> hadron production in AA coll.

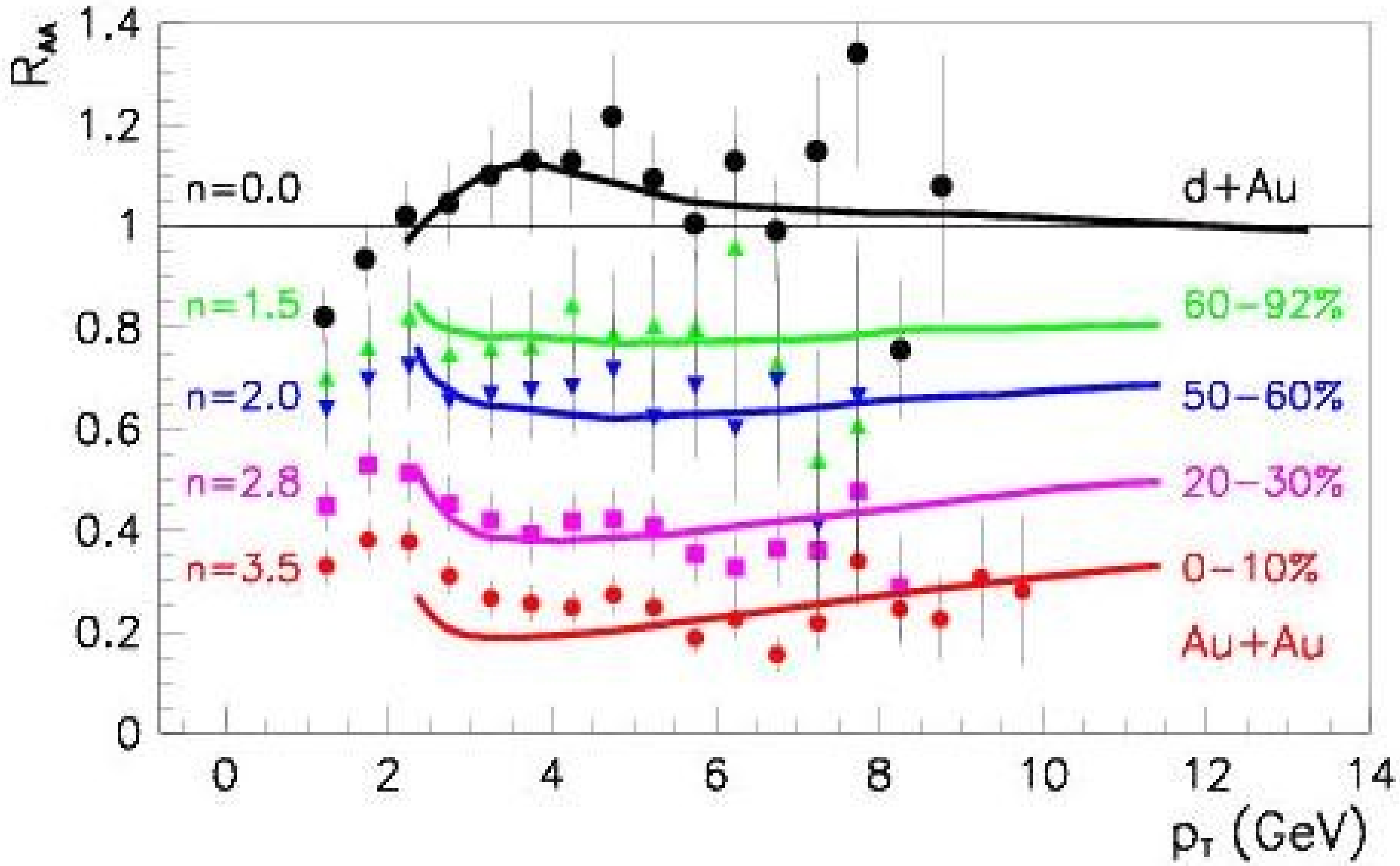
How large is R_{AA}(charged hadrons) in this model ???

Hard physics: pion production in AA collision at high-p_T

Perturbative QCD calculations in NLO for heavy ion collisions:

geometrical overlap + shadowing, multiscattring, jet-quenching, ...

$$E_\pi \frac{d\sigma^{AB}}{d^3 p_\pi} = \int d^2b\, d^2r\;\; t_A(\vec{r})\, t_B(|\vec{b}-\vec{r}|)\;\; E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} \otimes S(\ldots) \otimes M(\ldots) \otimes Q(\ldots)$$



RHIC
200 GeV/N

d+Au

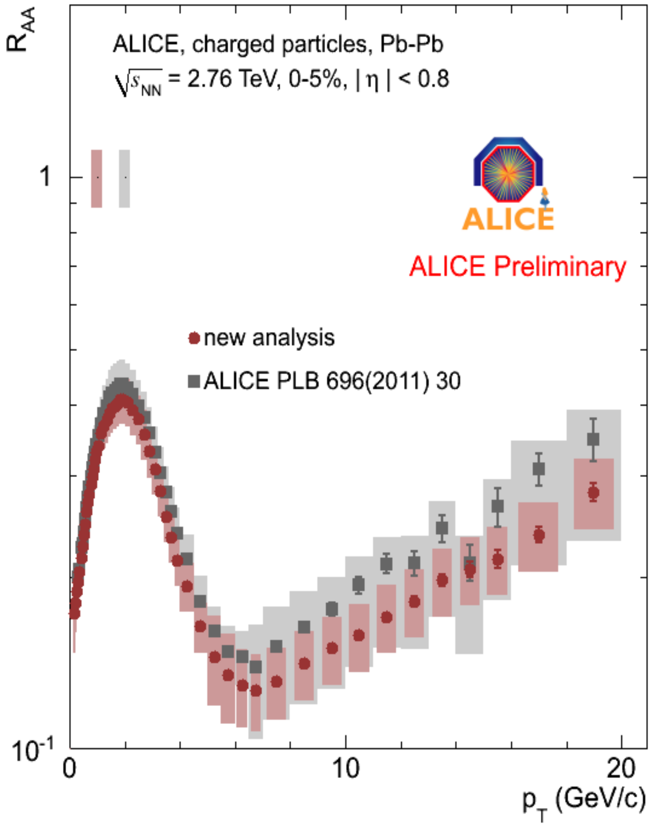
Au+Au

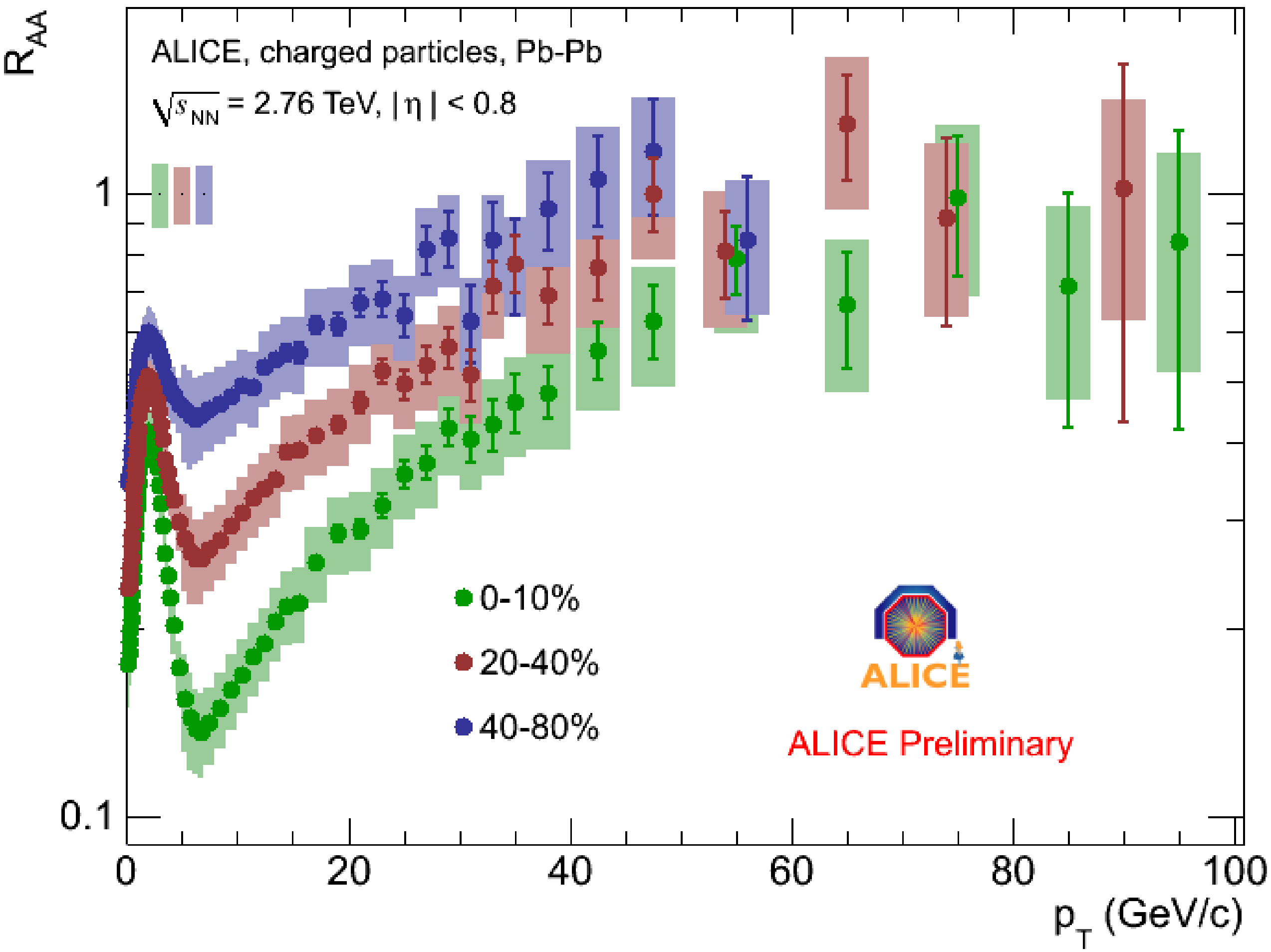
$\eta = 0$

G.G. Barnaföldi, P. Lévai, G. Papp, G. Fai, EPJ C33, S609 (2004)

ALICE: Latest result on charged hadron R_{AA} in Pb+Pb at 2.76 ATeV

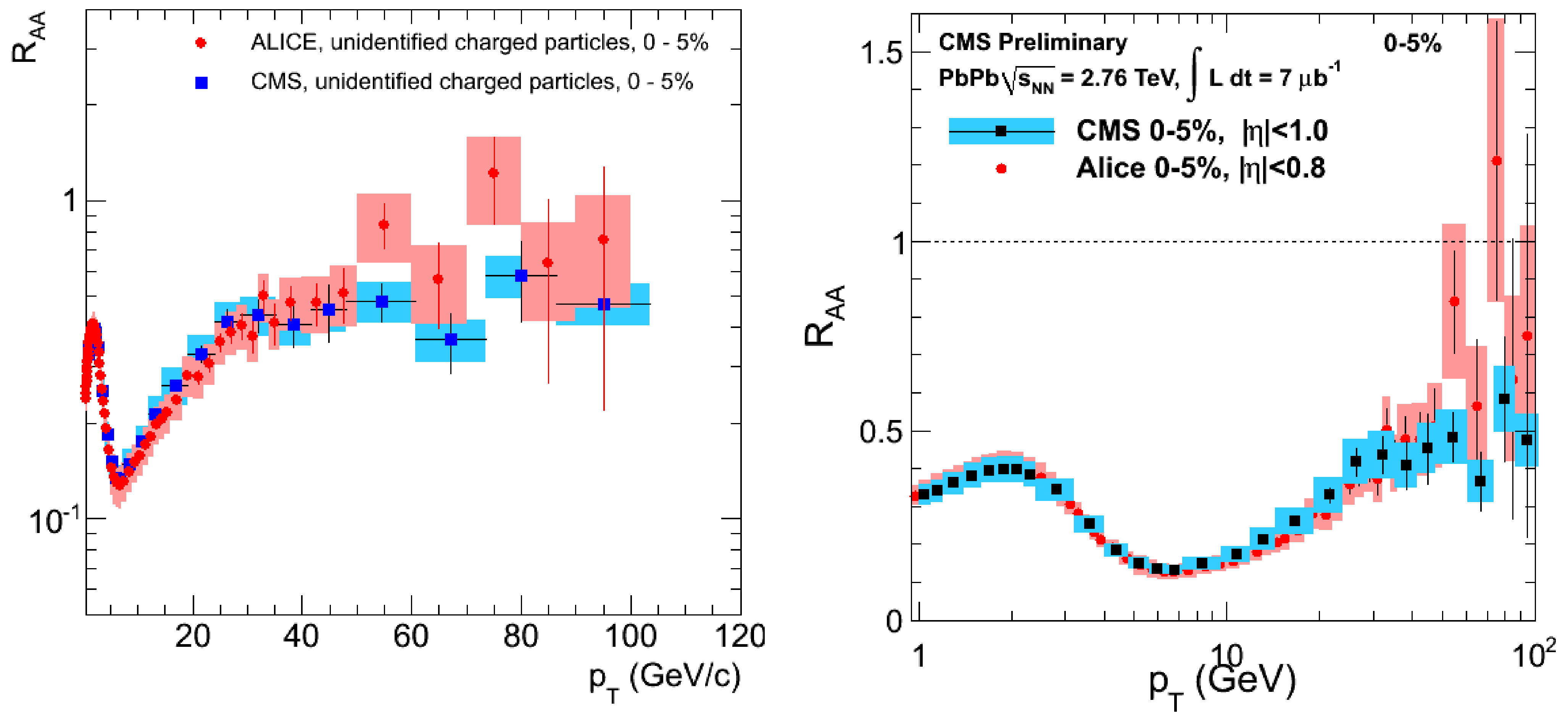
Phys. Lett. B696 (2011) 30.   + H. Appelshauser on QM 2011/12





Latest result on charged hadron R_{AA} in Pb+Pb at 2.76 ATeV

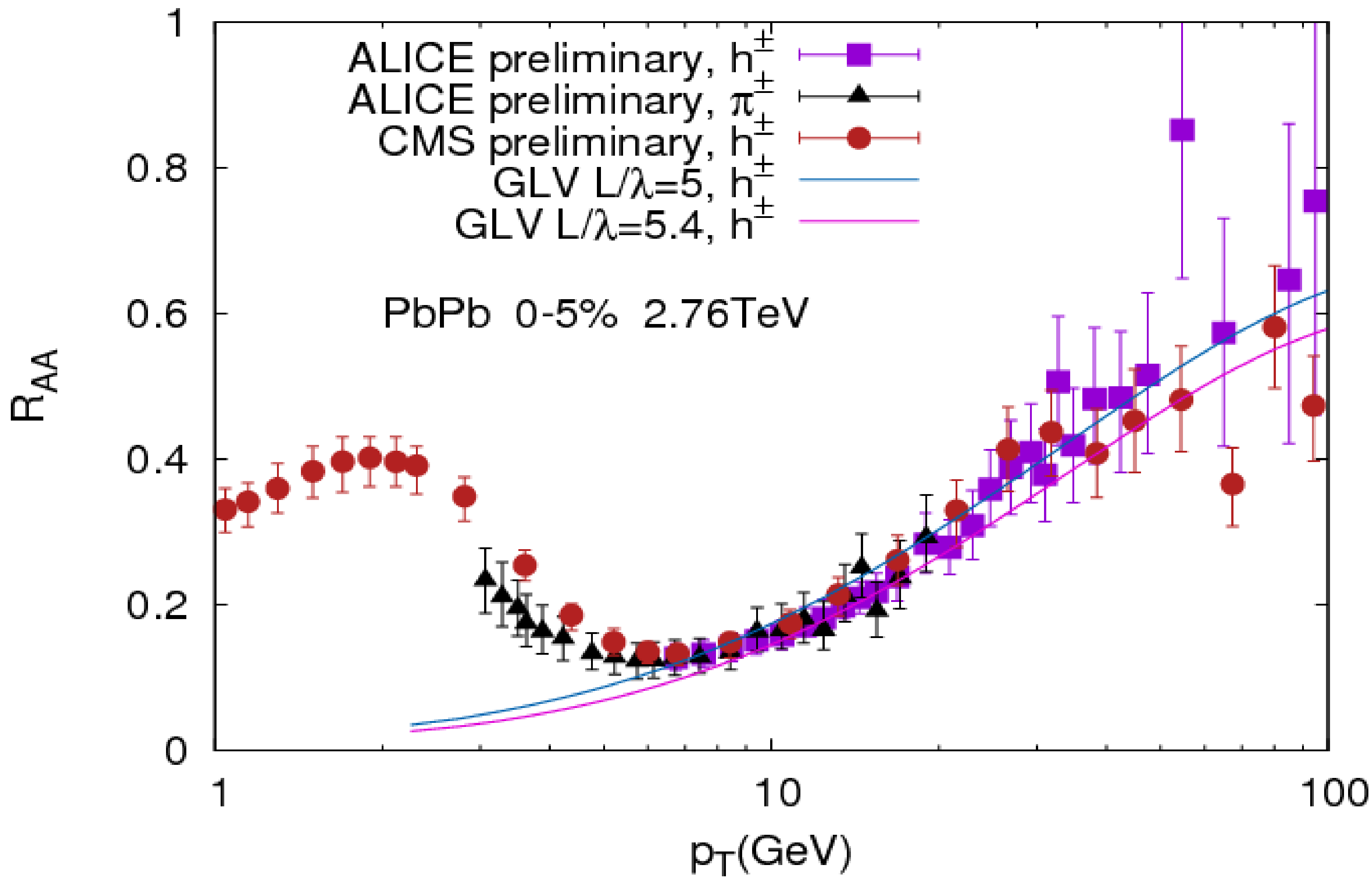
ALICE (H. Appelshauser) & CMS (Y.J. Lee) on QM 2011/2012



Latest calculations on charged hadron R_{AA} in Pb+Pb at 2.76 ATeV

pQCD + Quenching (only)   P. Levai, Nucl. Phys. A862 (2011) 146

D. Berenyi, A. Pasztor, V. Skokov, P. Levai, ArXiv: 1208.0448 [hep-ph]



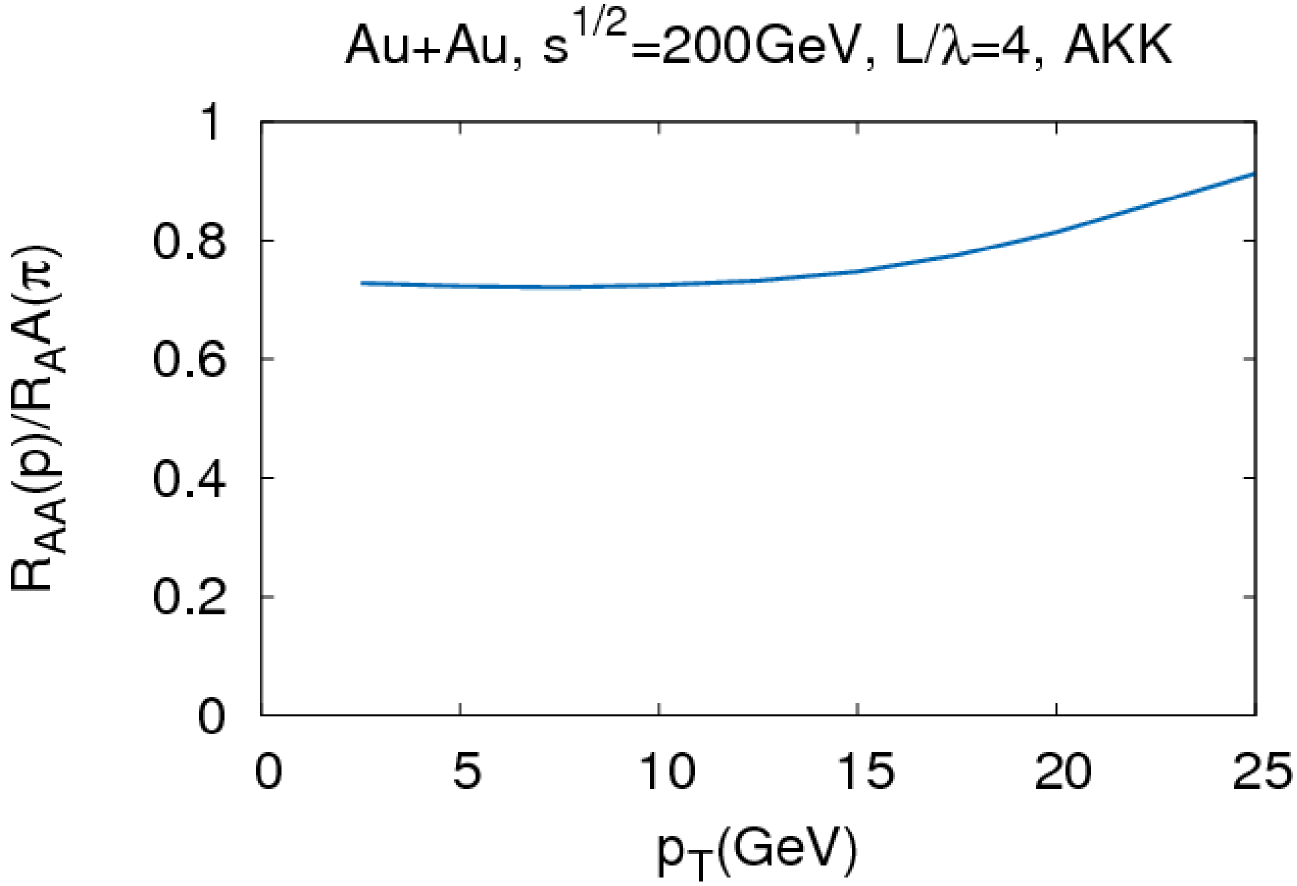
What can we find in a "usual" pQCD based description?

1. PDF + pQCD + FF --> proton production in pp coll.

2. + Shadowing
+ Multiscattering
+ QUENCHING --> proton production in AA coll.

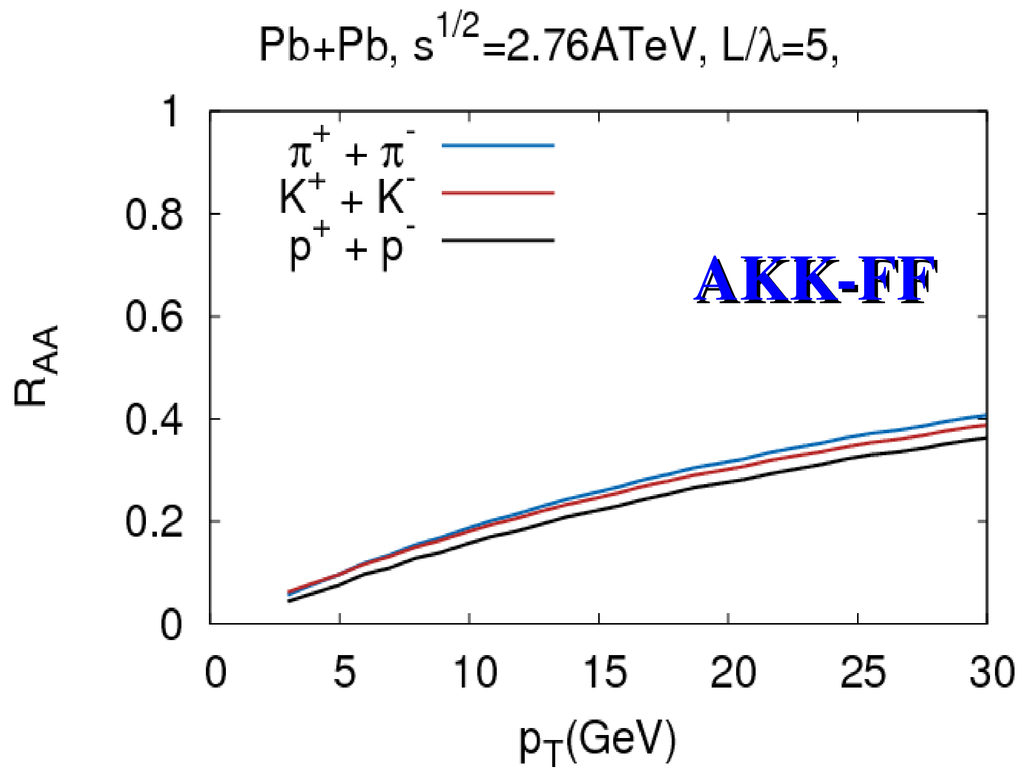
How large is R_{AA}(pion) and R_{AA}(proton) in this model ???

How large is the R_{AA} nuclear modification factor for pion and proton ? What is the difference at RHIC?



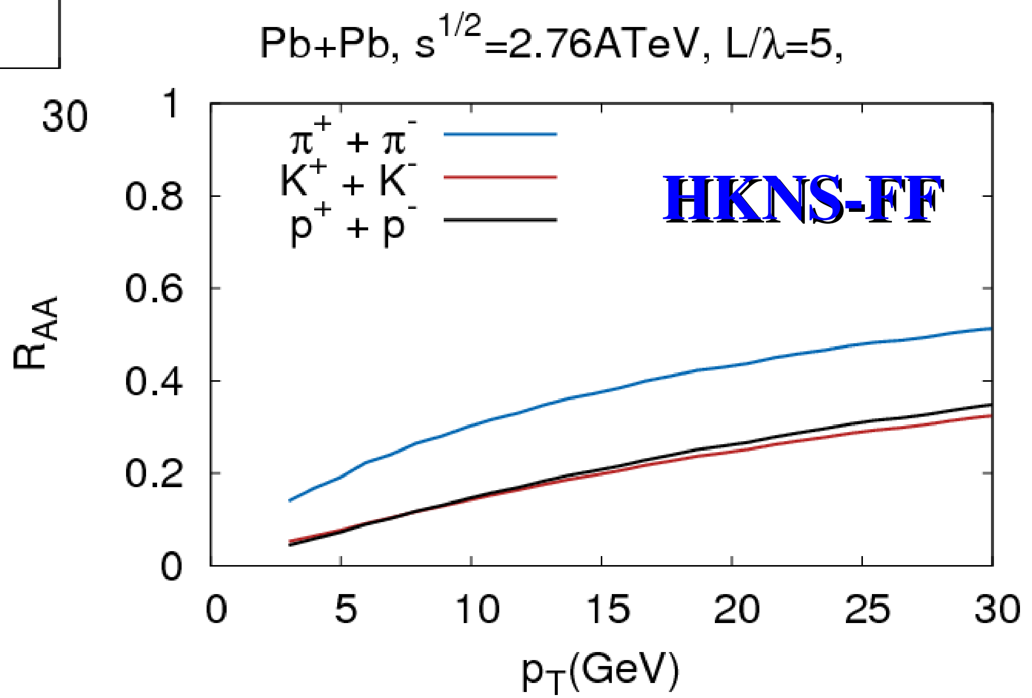
Jet quenching scenario: R_{AA}(pion) > R_{AA} (proton)

Preliminary RHIC data displays just the opposite !!!!



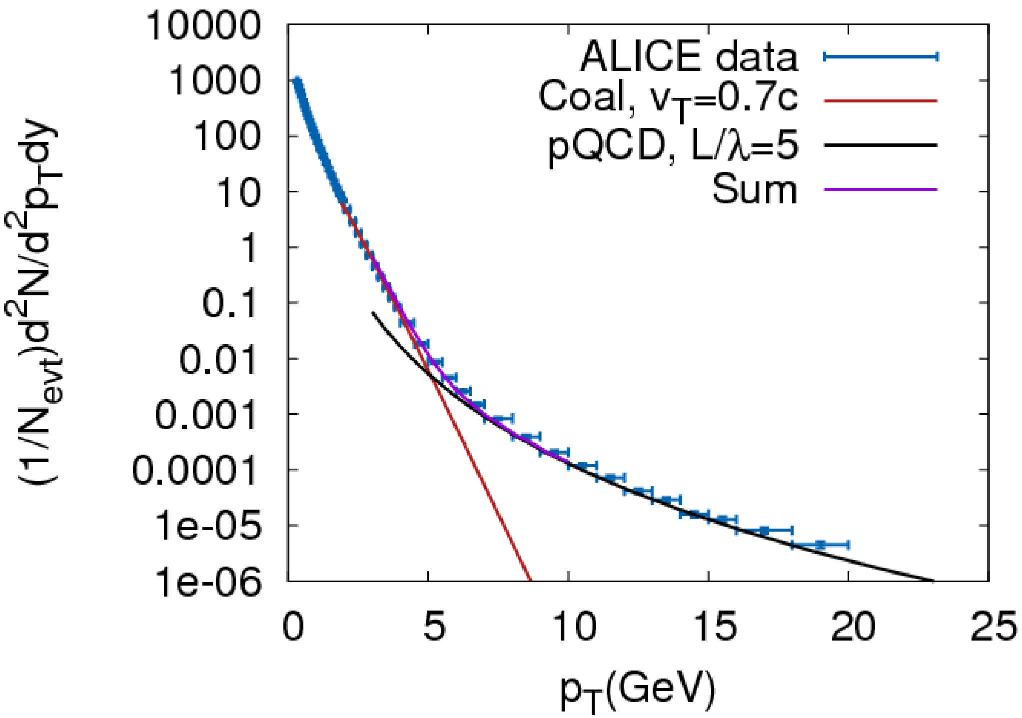
What is the difference at LHC at 2.76 ATeV?

What is the dependence on the hadron flavour with different FF ?



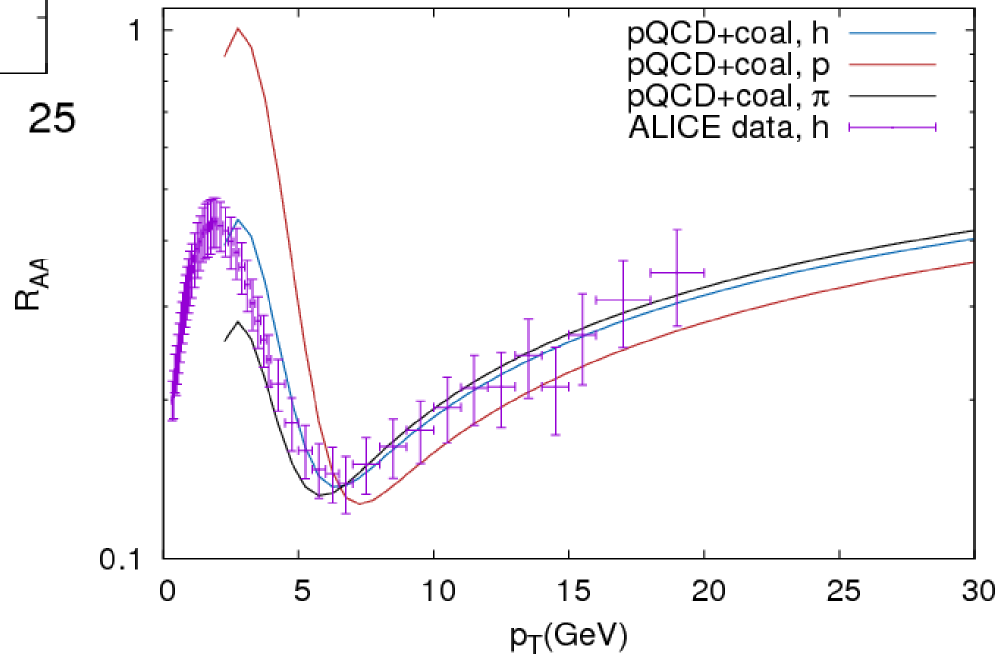
Same situation at LHC !

Results of our study at LHC:



ALICE data on charged hadrons at 2.76 AGeV , PLB696(2011)30 :

Coalescence of thermal quarks
+
pQCD with quenching



OK: Low-p_T and

Intermediate-p_T region

Question: Proton R_{AA} ?!

D. Berenyi, A. Pasztor, V. Skokov, P. Levai, ArXiv: 1208.0448 [hep-ph]

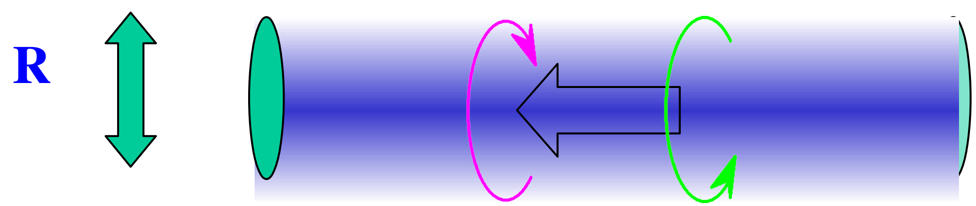
Suggestion: Diquark channel from time dependent strong field

New channel, open for extra proton production.

<u>Non-perturbative,</u> non-asymptotic color transport:

"confined flux tube formation and breaking"

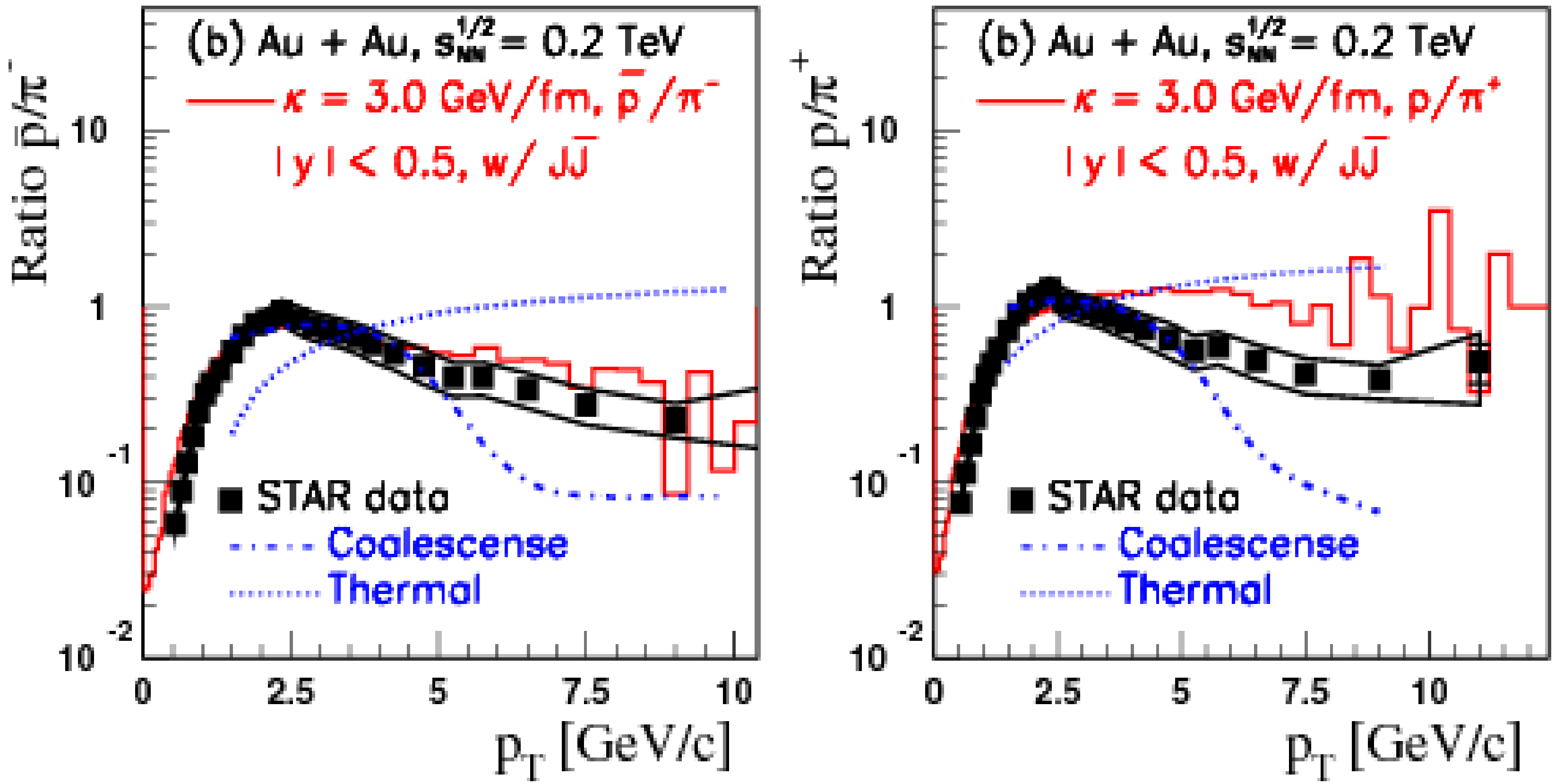
--- phenomenological approximations are known (string, rope)
--- phenomenology is applied successfully in string-based codes
--- FRITIOF, PYTHIA, HIJING 1.0/2.0 are using strings
--- URQMD, HIJING BB is using ropes (melted strings)
--- good agreement with data at different energies



--- formal QCD-based equations are known (Heinz, Mrowczynski)
--- YM-field evolution in 3+1 dim, collision (Poschl, Müller)
--- lattice-QCD calculations have been started (Krasnitz, Lappi)
--- HIJING BB – ropes with large string constants (Topor Pop, Gyullasy)
--- time-dependent strong fields, color kinetic eq. (Skokov, PL)

Description of non-perturbative proton production from ropes:

The string constant is increased: σ = 3 GeV/fm



HIJING BB with strong long. field : V. Topor Pop, M. Gyulassy, ...,
Phys. Rev. C83 (2010) 024902
ArXiv: 1105.3940 [hep-ph]

Description of non-perturbative particle production:

Non-perturbative, non-asymptotic color transport:

"pair-creation in strong fields"

--- strong (Abelian) static E field: Schwinger mechanism

probability of pair-creation:

$$P(p_T)\,d^2 p_T = -\frac{eE}{4\pi^3}\ln\left(1-\exp\left[-\pi\frac{m^2+p_T^2}{eE}\right]\right)d^2 p_T$$

integrated probability at mass m:

$$P_m = \frac{(eE)^2}{4\pi^3}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-\pi\frac{n\,m^2}{eE}\right]$$

ratio of production rates (e.g. strange to light)

$$\gamma_s = \frac{P(s\bar{s})}{P(q\bar{q})} = \exp\left[-\pi\frac{m_s^2-m_q^2}{eE}\right]$$

$$eE = 0.9\,GeV/fm$$

--- strong time dependent SU(N) color fields:

Kinetic Equation for the color Wigner function

A.V. Prozokevich, S.A. Smolyansky, S.V. Ilyin, hep-ph/0301169.

Kinetic equation for fermion pair production:

Wigner function: $W(k_1, k_2, k_3)$

Color decomposition: $W = W^s + W^a t^a, \quad where \quad a = 1, 2, \ldots, N_c^2 - 1$

Spinor decomposition: $W^{s;a} = a^{s;a} + b_\mu^{s;a} \gamma^\mu + c_{\mu\nu}^{s;a} \sigma^{\mu\nu} + d_\mu^{s;a} \gamma^\mu \gamma^5 + i e^{s;a} \gamma^5$

Color vector field (longit.): $A_\mu^a = (0, -\vec{A}) = (0, 0, 0, A_3^a)$

Kinetic equation for Wigner function:

$$\partial_t W + \frac{g}{8} \frac{\partial}{\partial k_i} \left(4\{W, F_{0,i}\} + 2\{F_{i\nu}, [W, \gamma^0 \gamma^\nu]\} - [F_{i\nu}, \{W, \gamma^0 \gamma^\nu\}] \right) =$$

$$= i k_i \{\gamma^0 \gamma^i, W\} - i m [\gamma^0, W] + i g \left[A_i, [\gamma^0 \gamma^i, W] \right].$$

for details see V.V. Skokov, P. Levai: PRD71 (2005) 094010 for U(1)
PRD78 (2008) 054004 for SU(2)
PRD82 (2010) 074014

Distribution function for fermions with mass m:

$$f_f(\vec{k}, t) = \frac{m a^s(\vec{k}, t) + \vec{k} \vec{b}^s(\vec{k}, t)}{\omega(\vec{k})} + \frac{1}{2}$$

Time dependent external field, E(t) and neglected mass, m=0:

A, Pulse field (dotted):

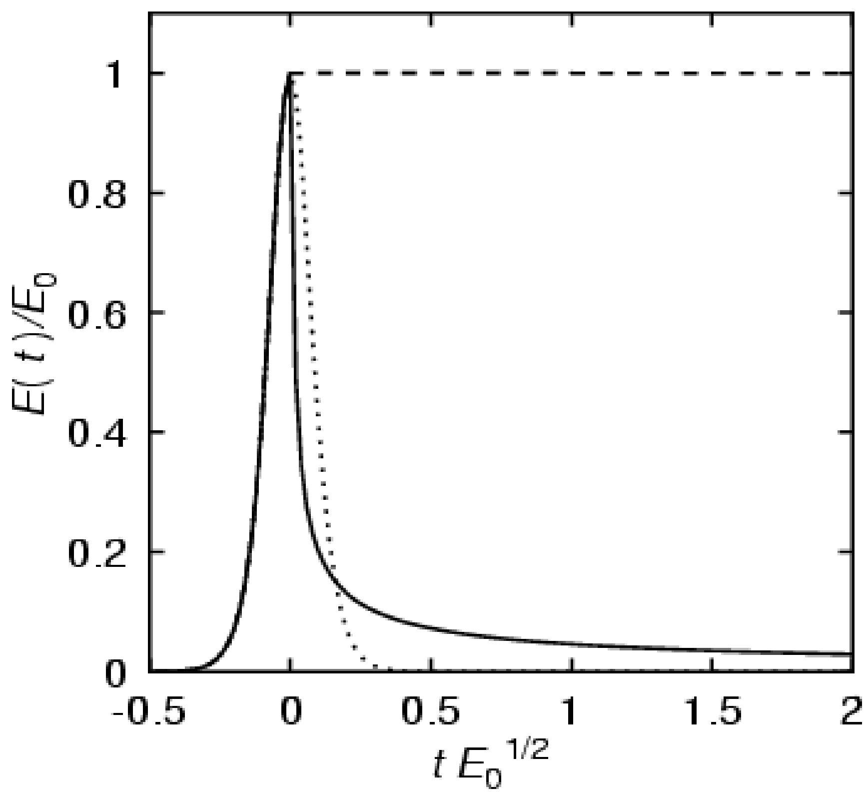
$$E_{pulse}(t) = E_0\left[1 - \tanh^2(t/\delta)\right]$$

B, Constant field (dashed):

$$E_{const}(t) = E_{pulse}(t) \quad at \quad t < 0$$
$$E_{const}(t) = E_0 \quad at \quad t > 0$$

C, Scaled field (solid):

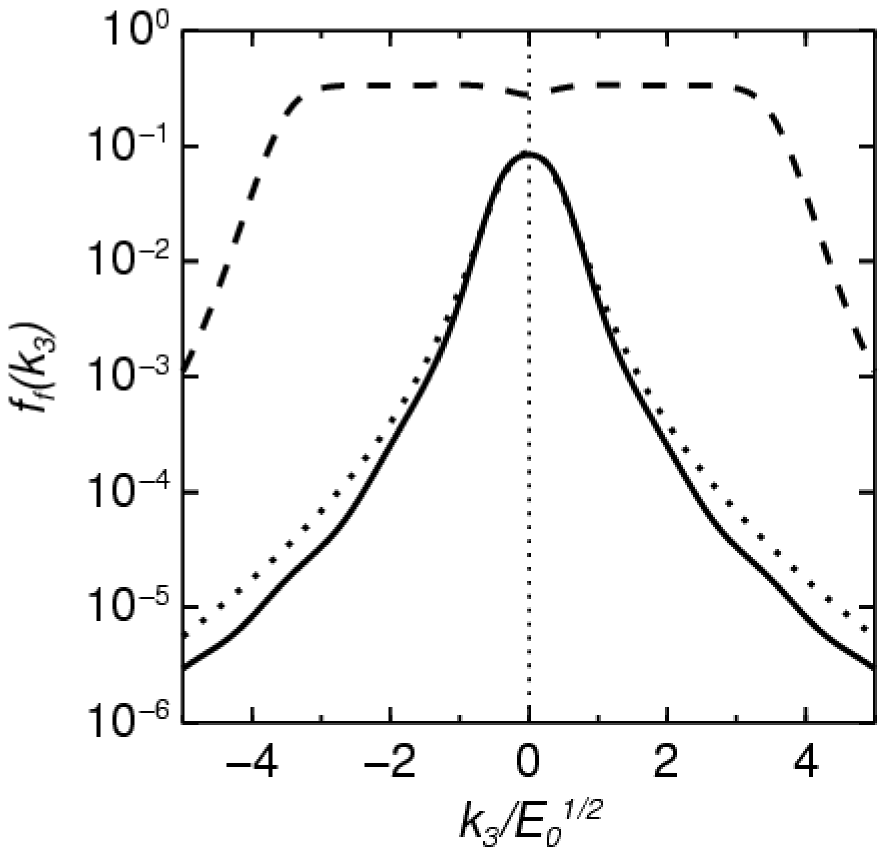
$$E_{scaled}(t) = E_{pulse}(t) \quad at \quad t < 0$$
$$E_{scaled}(t) = \frac{E_0}{(1 + t/t_0)^{\kappa}} \quad at \quad t > 0$$

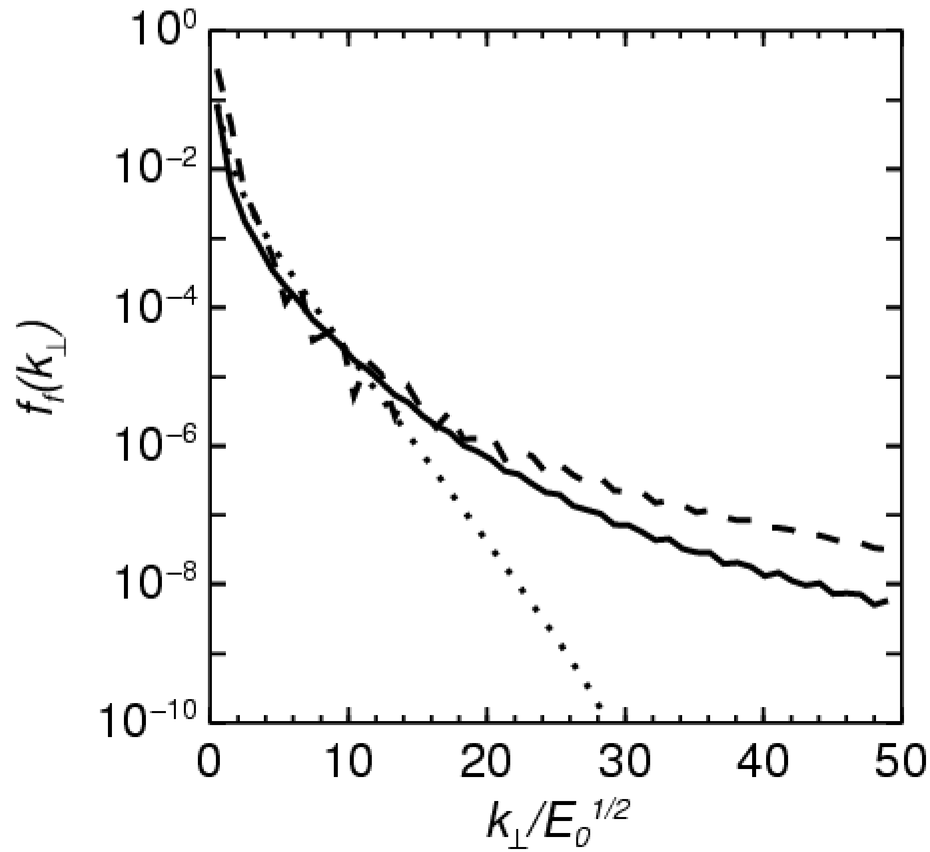


$$\delta = 0.1/E_0^{1/2} \quad at\ RHIC\ energy$$

$$\kappa = 2/3 \quad for\ scaled\ Bjorken\ expans.$$
$$with \quad t_0 = 0.01/E_0^{1/2}$$

Numerical results for fermion distributions at $t = 2/\sqrt{E_0}$ in SU(2):





$f_f(k_3)$: longitudinal mom. distr.

$f_f(k_T)$: transv. mom. distr.

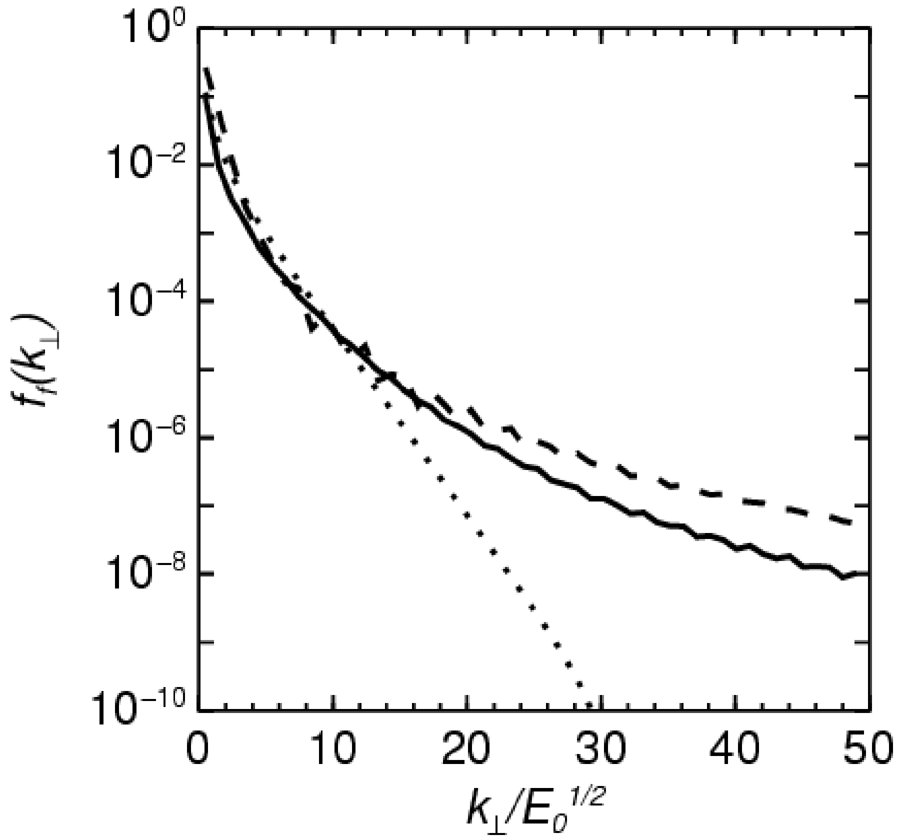
$k_T/\sqrt{E_0} = 0.5$

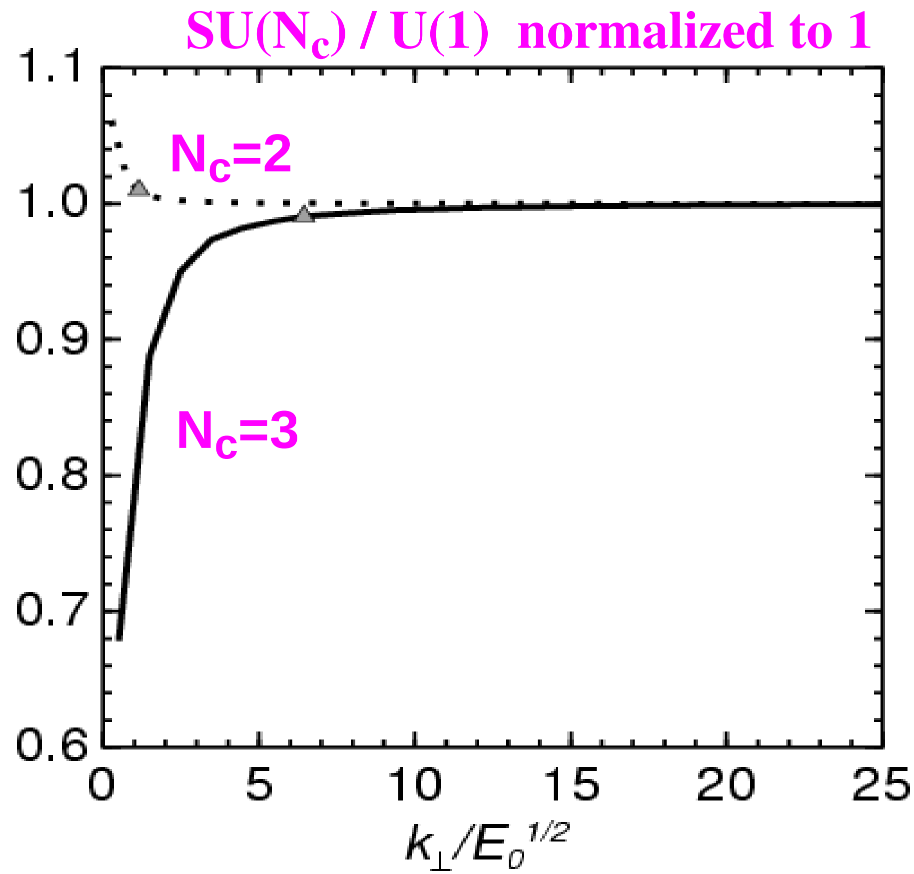
$k_3 = 0$

⇒ exponential (pulse)

⇒ polinomial (scaled)

Transverse momentum distr: scaling in SU(3) at high-pT (m=0)





$f_f(k_T)$: transv. mom. distr.

in SU(3)

3 cases of E(t)

[similar to SU(2)]

Ratios (scaled time evol.):

SU(2) / U(1) ⇒ 3/4

SU(3) / U(1) ⇒ 4/3

(scaling in the Kinetic Eq.)

Quark-pair production in strong coherent field

+

Diquark/antidiquark production in strong coherent field

=

Extra (anti)baryon production from (anti)diquarks

Key point:

the time evolution of the strong field

$$E_{scaled}(t) = \frac{E_0}{(1 + t/t_0)^{\kappa}} \quad at \quad t > 0$$

Scaled time evol. ↣ polinomial spectra for quark/diquark different from pQCD calculations

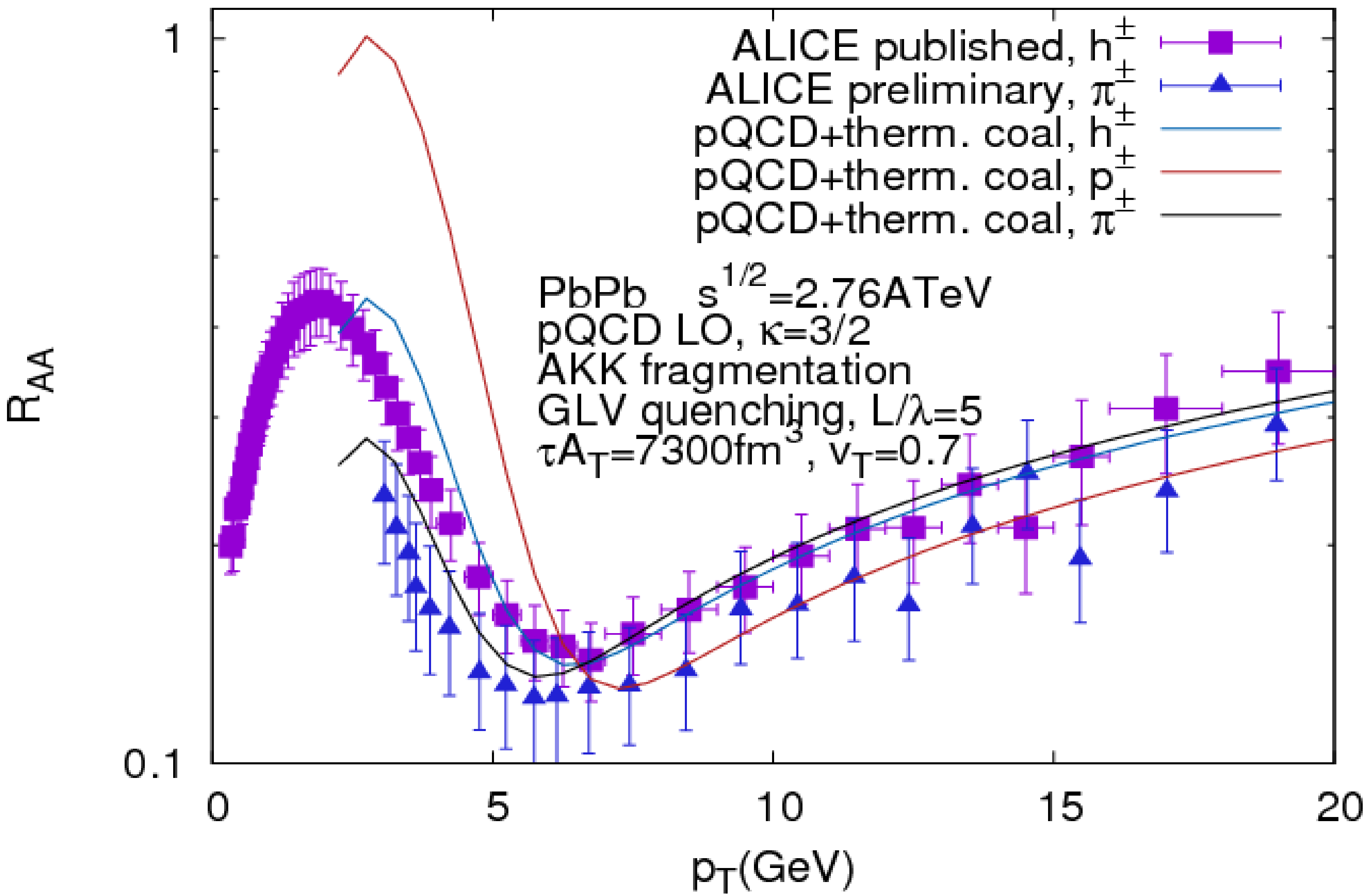
Phys. Rev. D82 (2010) 074014

further details under publications

What can we conclude from the latest data at LHC energies?

Latest calculations on charged hadron R_{AA} in Pb+Pb at 2.76 ATeV

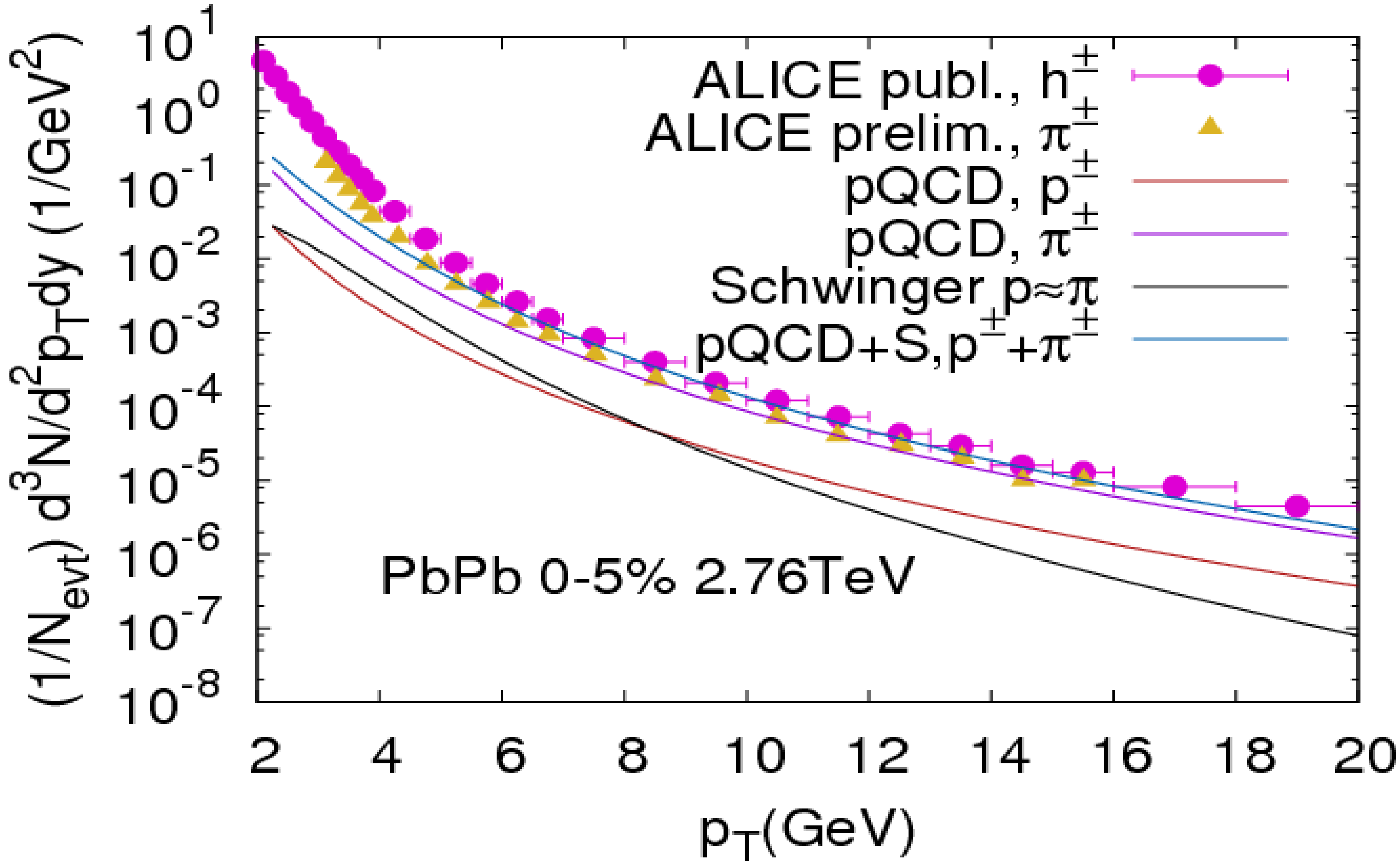
pQCD + Quenching + Thermal coalesc. D. Berenyi, 1208.0448 [hep-ph]



Latest calculations on charged hadron R_{AA} in Pb+Pb at 2.76 ATeV

pQCD + Quenching + Schwinger diquark coalesc.

D. Berenyi, A. Pasztor, V.V. Skokov, P. Levai, 1208.0448 [hep-ph]

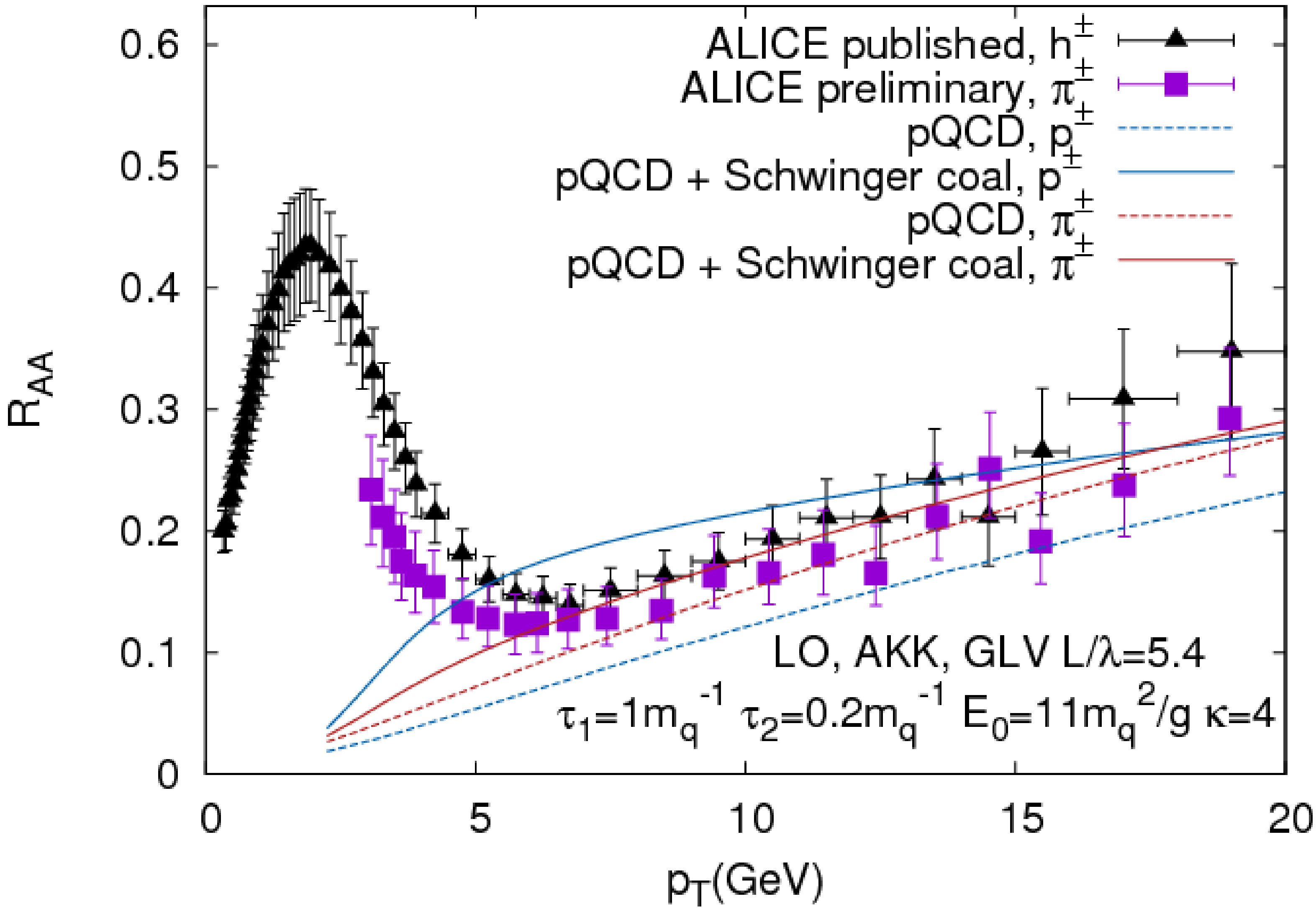


Extra proton yield from coalescence of Schwinger-diquarks in the window of 2 GeV/c < pT < 8 GeV/c !!!

Latest calculations on charged hadron R_{AA} in Pb+Pb at 2.76 ATeV

pQCD + Quenching + Schwinger diquark coalesc.

D. Berenyi, A. Pasztor, V.V. Skokov, P. Levai, 1208.0448 [hep-ph]



Latest calculations on charged hadron R_{AA} in Pb+Pb at 2.76 ATeV

pQCD + Quenching + (Thermal + Schwinger diquark) coalesc.

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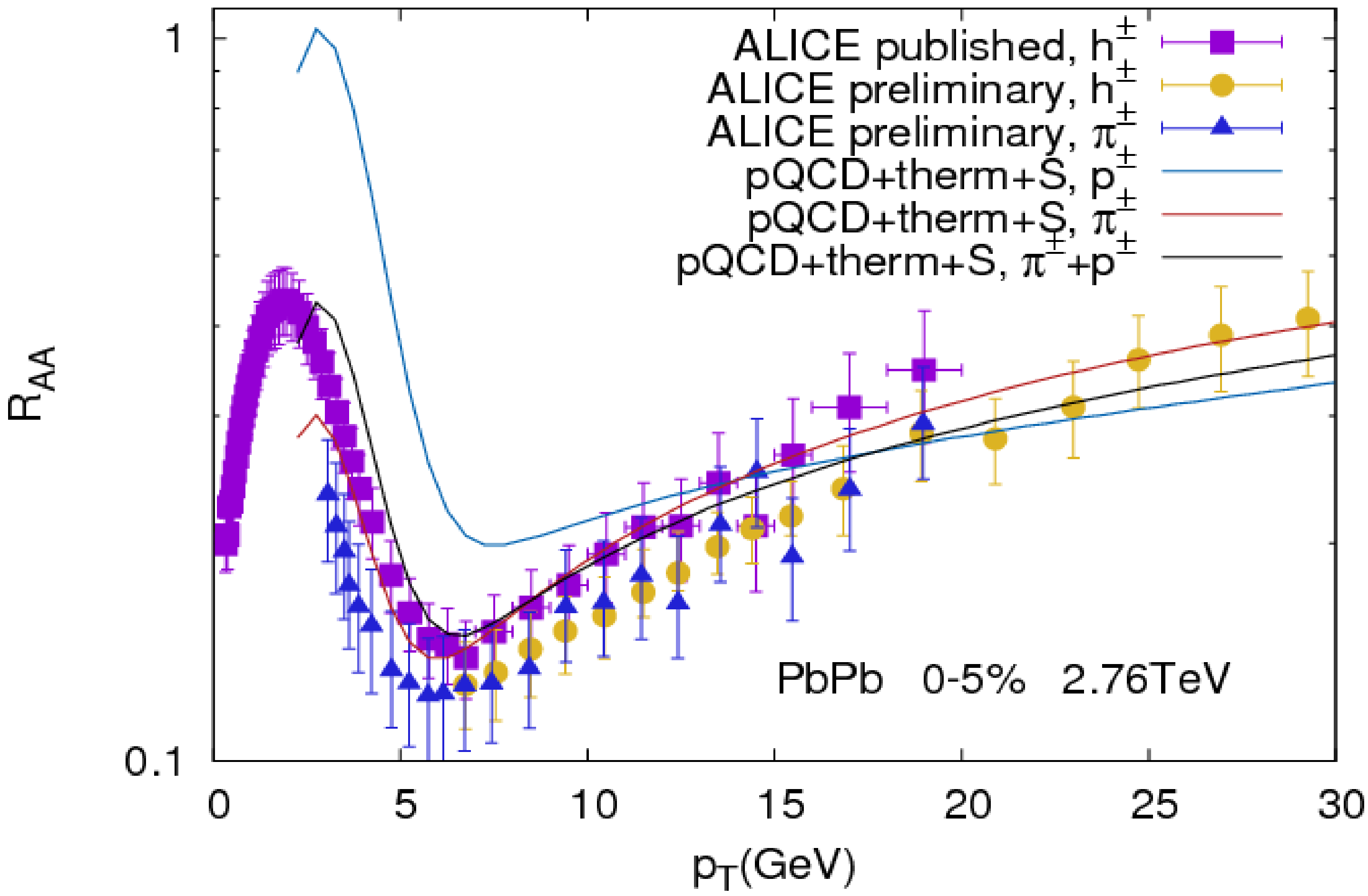
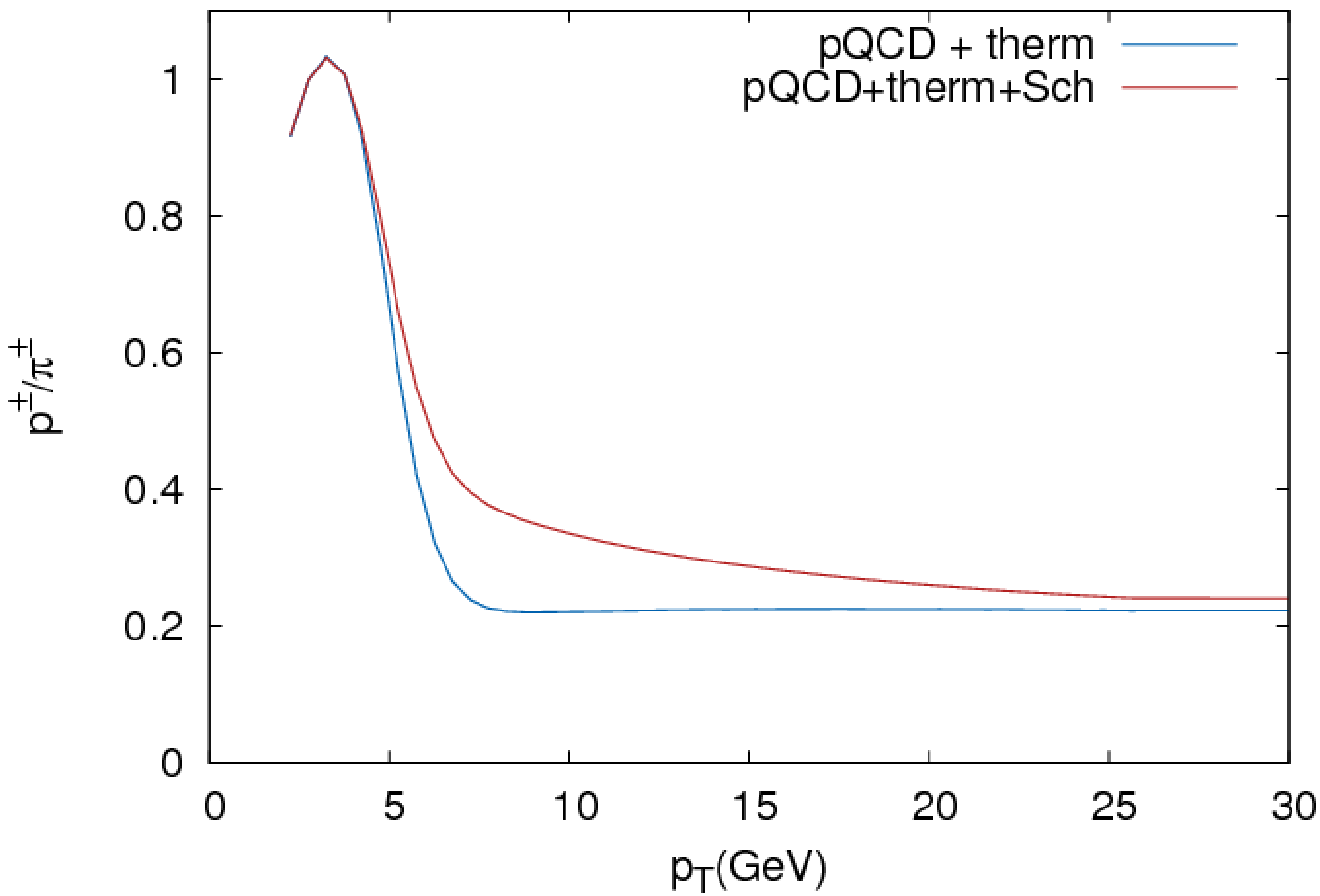


$R_{AA}(p) > R_{AA}(pion)$ for $2 < p_T < 15$ GeV/c

Latest calculations on proton/pion ratio in Pb+Pb at 2.76 ATeV

pQCD + Quenching + (Thermal + Schwinger diquark) coalesc.

D. Berenyi, A. Pasztor, V.V. Skokov, P. Levai, 1208.0448 [hep-ph]



Extra proton yield at intermediate-p_T and high-p_T

Strongly depends on details of diquark pair-production

Complicated model with many channels (many parameters):

pQCD
+ Quenching
+ thermal coalescence
+ Schwinger production + diquark coalescence

Control:

pp data
high-pT AA data (only pQCD + quenching)
data on pions and protons
data on kaons and lambdas
data on further non-strange and strange hadrons, e.g. $R_{AA}(\Omega)$
data on ...

Conclusions:

1. Baryon production mechanisms are not fully explored in non-perturbative cases, especially in case of strong fields.

2. If the overlap of heavy ions is very short, and the time scale of the initial phase is also short, then quark-pair and diquark-pair production is expected.

3. Diquarks increase the baryon yields, but not mesons.

4. LHC data with PID are extremely interesting, detailed studies are in progress.

5. What happened with the RHIC results which display the interesting R_{AA}(proton) > R_{AA}(pion) data ???