NLO improved pQCD initial state + saturation + hydrodynamics model for $A+A$ collisions

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IS2013, Spain

13 September, 2013

Intro

This work:

- Rigorous NLO pQCD calculation for E_T production from minijets

- Saturation for E_T production

Compute IC for fluid dynamics in $A+A$

Roots in the old EKRT model [Nucl. Phys. B 570, 379 (2000)]

- Apply viscous hydrodynamics

$\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}$, $\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}p_T\mathrm{d}\eta}$ and $v_2(p_T)$ simultaneously at LHC and RHIC

[Paatelainen, et al, Phys Rev C 87 044904 (2012)]
[Paatelainen, Niemi, Eskola and Tuominen, work in progress]

Minijet E_T production: pQCD calculation

We compute the minijet E_T production in $A+A$ and Δy

$$E_T(p_0, \sqrt{s}, \Delta y, \mathbf{s}, \mathbf{b}) = \int \mathrm{d}^2\mathbf{s}\ T_A(\mathbf{s}+\mathbf{b}/2)T_A(\mathbf{s}-\mathbf{b}/2)\sigma\langle E_T\rangle_{p_0,\Delta y}$$

$\mathbf{s}$ = transverse position, $\mathbf{b}$ = impact parameter

Ingredients:

- Nucleon thickness functions $T_A T_A$ account for the nuclear collision geometry (Optical Glauber, Woods-Saxon profile)
- LO pQCD (collinear factorization)

$$\sigma\langle E_T\rangle \propto \int_{p_0^2} \mathrm{d}p_T^2 p_T \int_{\Delta y} \mathrm{d}y_1 \mathrm{d}y_2 \sum_{ijk\ell} x_1 f_{i/A} \otimes x_2 f_{j/A} \otimes \frac{\mathrm{d}\sigma^{ijk\ell}}{\mathrm{d}t}$$

Rigorous NLO pQCD computation of $\sigma\langle E_T\rangle$

$$\sigma\langle E_T\rangle = \frac{1}{2!}\int [\mathrm{DPS}]_2 \frac{\mathrm{d}\sigma^{2\to 2}}{[\mathrm{DPS}]_2} \tilde{S}_2(p_1,p_2) + \frac{1}{3!}\int [\mathrm{DPS}]_3 \frac{\mathrm{d}\sigma^{2\to 3}}{[\mathrm{DPS}]_3} \tilde{S}_3(p_1,p_2,p_3)$$

- Partonic $2\to 2$ and $2\to 3$ processes for LO & NLO corrections
  - UV renormalized $|M|^2$ in $4-2\epsilon$ dimensions (R.K Ellis & Sexton; My PhD thesis)
  - IR/CL divergencies handled with NLO def. of PDFs & Ellis-Kunszt-Soper subtraction method
- The measurement functions $\tilde{S}_2$ and $\tilde{S}_3$ fulfil the IR/CL criteria $\to$ $\sigma\langle E_T\rangle$ is a well defined IR/CL safe quantity

$$\tilde{S}_2 = \{\epsilon(y_1) + \epsilon(y_2)\} p_{T2}\ \Theta(p_{T2} \geq p_0)$$

$$\tilde{S}_3 = \{\epsilon(y_1) p_{T1} + \epsilon(y_2) p_{T2} + \epsilon(y_3) p_{T3}\} \Theta(p_{T1} + p_{T2} + p_{T3} \geq 2p_0)\ \Theta(E_T \geq \beta \times p_0)$$

where $\epsilon(y_i) = 1$ if $y_i \in \Delta y$ otherwise $\epsilon(y_i) = 0$

$$
\begin{aligned}
\tilde{S}_2 &= \{\epsilon(y_1) + \epsilon(y_2)\} p_{T2}\ \Theta(p_{T2} \geq p_0) \\
\tilde{S}_3 &= \{\epsilon(y_1) p_{T1} + \epsilon(y_2) p_{T2} + \epsilon(y_3) p_{T3}\} \\
&\quad \Theta(p_{T1} + p_{T2} + p_{T3} \geq 2p_0)\ \Theta(E_T \geq \beta \times p_0)
\end{aligned}
$$

where $\epsilon(y_i) = 1$ if $y_i \in \Delta y$ otherwise $\epsilon(y_i) = 0$

- $\tilde{S}_3 \to \tilde{S}_2$ at IR/CL limits

$$\tilde{S}_2 = \{\epsilon(y_1) + \epsilon(y_2)\} p_{T2} \; \Theta(p_{T2} \geq p_0)$$

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- $\tilde{S}_3 \to \tilde{S}_2$ at IR/CL limits
- Def. E_T in Δy and $\Theta(\dots)$ hard scattering of partons

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- $\tilde{S}_3 \to \tilde{S}_2$ at IR/CL limits
- Def. E_T in Δy and $\Theta(\ldots)$ hard scattering of partons
- $0 \leq \beta \leq 1$ defines the minimum amount of E_T in Δy
- Any $\beta \in [0, 1]$ is IR/CL safe, thus equally good – leave β free

Nuclear PDFs $f_{i/A}(x, Q^2, \mathbf{s})$ for each parton flavor i

$$f_{i/A}(x, Q^2, \mathbf{s}) \equiv R_i^A(x, Q^2, \mathbf{s}) f_i^p(x, Q^2)$$

R_i^A denotes the nuclear modification to the free proton PDF f_i^p

- f_i^p: CTEQ6 NLO parton densities
- R_i^A: EPS09s (spatially dependent) NLO nuclear modifications

EPS09s [Helenius, Eskola, Honkanen and Salgado JHEP (2012) 073]

Saturation criterion for E_T

Determine $p_0(\mathbf{s}) = p_{sat}(\mathbf{s})$ from local saturation criterion of E_T:

$$\frac{dE_T}{\mathrm{d}^2\mathbf{s}\mathrm{d}y}(2 \to 2) \sim \frac{dE_T}{\mathrm{d}^2\mathbf{s}\mathrm{d}y}(3 \to 2)$$

$$(T_A g_A)^2 \frac{\alpha_s^2}{p_0} \sim (T_A g_A)^3 \left(\frac{\alpha_s}{p_0}\right)^3 \quad \Rightarrow \quad T_A g_A \sim \frac{p_{sat}^2}{\alpha_s} \quad \Rightarrow \quad \frac{dE_T}{\mathrm{d}^2\mathbf{s}\mathrm{d}y} \sim p_0^3$$

$$\frac{\mathrm{d}E_T}{\mathrm{d}^2\mathbf{s}}(p_0, \sqrt{s}, \Delta y, \mathbf{b}, \mathbf{s}, \beta) = \Delta y \left(\frac{K_{sat}}{\pi}\right) p_0^3$$

$$\Rightarrow \quad p_0 = p_{\mathrm{sat}}(\sqrt{s}, \mathbf{b}, \mathbf{s}; \beta, K_{\mathrm{sat}})$$

Analogy to old EKRT saturation, but now for IR/CL safe E_T

1. Simplest case: pQCD + non-local saturation ($\mathbf{b} = 0$) + ideal hydro

Integrate over the transverse plane $\mathrm{d}^2\mathbf{s} \longrightarrow$

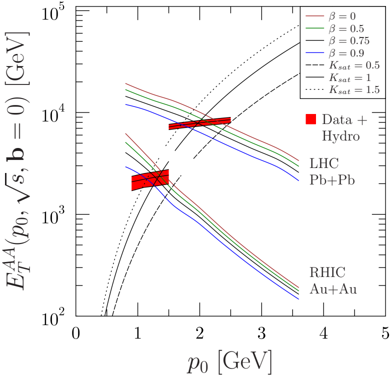
$$E_T(p_0, \sqrt{s}, \Delta y, \mathbf{b} = 0, \beta) = K_{\rm sat} R_A^2 p_0^3 \Delta y$$
$$\Rightarrow \;\; p_0 = p_{\rm sat}(\sqrt{s}; \beta, K_{\rm sat})$$

- start hydro at $\tau_0 = 1/p_{\rm sat}$ with the computed $E_T(p_{\rm sat})$
- assume BC (or WN) profile for energy density

$$e(\tau_0) = \frac{\mathrm{d}E_T}{\mathrm{d}^2\mathbf{s}} \frac{1}{\tau_0 \Delta y}$$

Results from Phys Rev C 87 044904 (2012) (central $A{+}A$ case).

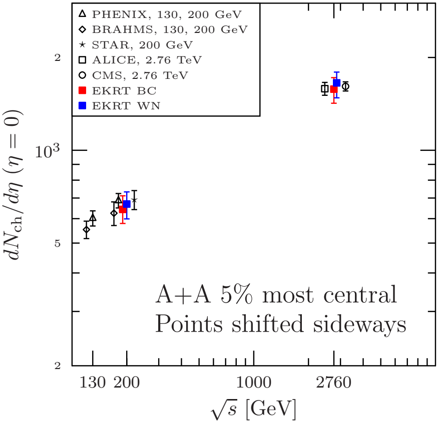
- Understanding $(K_{\rm sat}, \beta)$ systematics at LHC and RHIC; possible saturation solutions at the curve crossings



- Red bands tell how much initial $E_T(p_{\rm sat})$ we need to reproduce the measured multiplicities
- Multiple $(\beta, K_{\rm sat})$ pairs reproduce both LHC and RHIC multiplicity

Result for central collisions: Multiplicity and Identified particle p_T-spectra

- Ex. with $\beta = 0.75$ and $K_{\rm sat} = 1$



[Phys Rev C 87 044904 (2012)]

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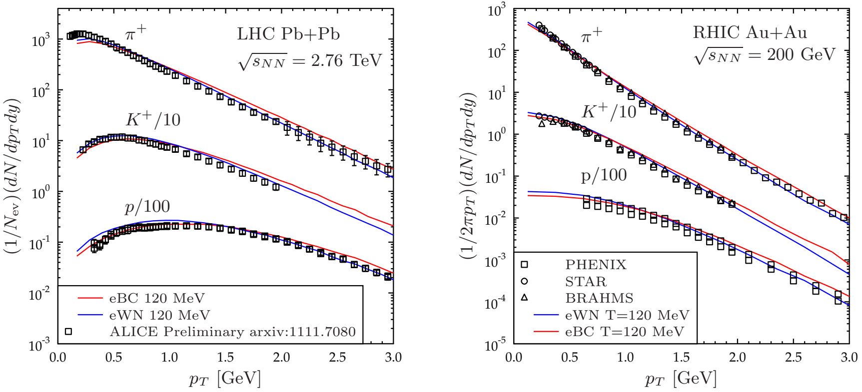

[Phys Rev C 87 044904 (2012)]

2. pQCD + local saturation ($\mathbf{b} \neq 0$) + viscous hydro

Now we calculate the transverse profiles....

LOCAL SATURATION

- Solve saturation equation for $p_0(\mathbf{b},\mathbf{s}) = p_{\rm sat}(\mathbf{b},\mathbf{s})$ at different $\mathbf{b}$
- Observation $p_{\rm sat}(\mathbf{b},\mathbf{s}) \propto [T_A(\mathbf{s}+\mathbf{b}/2)T_A(\mathbf{s}-\mathbf{b}/2)]^n$

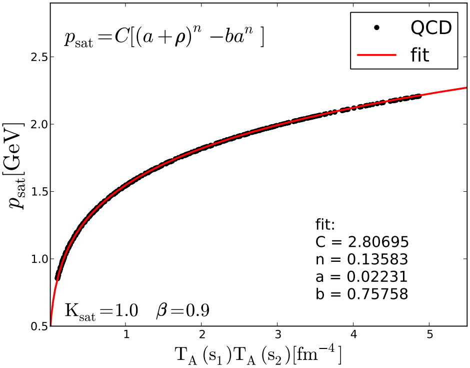

Fig: $p_{\rm sat}(\mathbf{b},\mathbf{s})$ at LHC for $\mathbf{b} = 0, 2.35, 7.87$ and 10.6 fm

FLUID DYNAMICS: 3 steps to initialize Hydro

STEP 1: Solving the saturation equation we can write energy density e at time $\tau_{\rm sat} = 1/p_{\rm sat}(\mathbf{s})$

$$e(\mathbf{s}, \tau_{\rm sat} = 1/p_{\rm sat}(\mathbf{s})) = \frac{K_{\rm sat}}{\pi} p_{\rm sat}(\mathbf{s})^4$$

At this level two unknown parameters:

- $K_{\rm sat}$ in the saturation condition
- $\beta \in [0, 1]$ in the def. of E_T measurement functions

STEP 2: For fluid dynamics we need e at fixed proper time τ_0

- Need to evolve the energy density $e(\mathbf{s})$ to a same time τ_0
- Largest time given by $\tau_{\max} = 1/p_{\rm sat}^{\rm min}$, where $p_{\rm sat}^{\rm min} \sim 1$ GeV, the smallest scale we can still trust the pQCD calculation; $\tau_0 = \tau_{\max}$

We consider two limits:

STEP 2: For fluid dynamics we need e at fixed proper time τ_0

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We consider two limits:

- Free streaming (conserves E_T)

$$e(\tau_0) = e(\tau_{\rm sat} = 1/p_{\rm sat}) \left(\frac{\tau_{\rm sat}}{\tau_0}\right)$$

STEP 2: For fluid dynamics we need e at fixed proper time τ_0

- Need to evolve the energy density $e(\mathbf{s})$ to a same time τ_0
- Largest time given by $\tau_{\max} = 1/p_{\rm sat}^{\min}$, where $p_{\rm sat}^{\min} \sim 1$ GeV, the smallest scale we can still trust the pQCD calculation; $\tau_0 = \tau_{\max}$

We consider two limits:

- Free streaming (conserves E_T)

$$e(\tau_0) = e(\tau_{\rm sat} = 1/p_{\rm sat}) \left(\frac{\tau_{\rm sat}}{\tau_0}\right)$$

- Bjorken scaling (conserves entropy)

$$e(\tau_0) = e(\tau_{\rm sat} = 1/p_{\rm sat}) \left(\frac{\tau_{\rm sat}}{\tau_0}\right)^{4/3}$$

Saturation calculation extends only to $e_{\min} = \left(\frac{K_{\rm sat}}{\pi}\right) p_{\rm sat}^{\min}(\mathbf{s})^4$

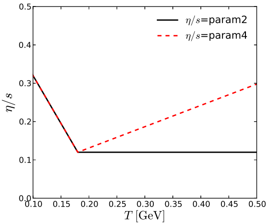
STEP 3: Continuation of $e(\tau_0)$ below $e_{\min}$

- Smoothly connect the computed e-profile to $e \propto \rho_{\rm bin}$
- small uncertainty at LHC central collisions, more effect in peripheral collisions and at RHIC

FLUID DYNAMICS: Hydro Evolution (H. Niemi)

2+1D viscous hydro, eqs. from Denicol et al, Phys. Rev. D85 (2012) 114047, Molnar et al, arXiv:1308.0785 [nucl-th]:

- Equation of state
  - Lattice parametrization by Petreczky/Huovinen and (partial) chemical freeze-out at $T_{\rm chem} = 175$ MeV (s95p-PCE175-v1)
  - Hadron Resonance Gas (HRG) up to $m \sim 2\text{GeV}$
- Temperature dependent η/s



motivation from [H. Niemi et al Phys Rev C 86 014909 (2012)]

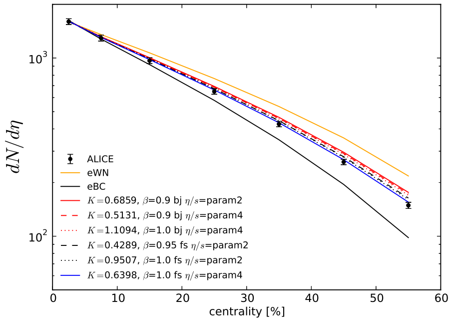
- Decoupling temperature $T_f = 100$ MeV

RESULTS (preliminary)

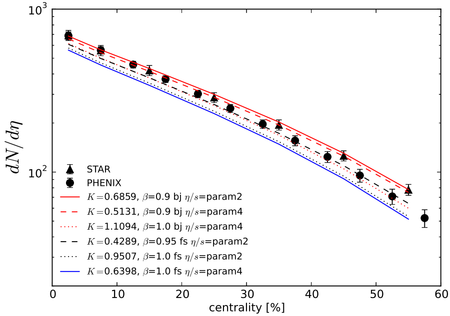
Centrality dependence of multiplicity at the LHC $\sqrt{s} = 2.76$ TeV and RHIC $\sqrt{s} = 200$ GeV

- Choose parameters $(K_{\rm sat}, \beta, {\rm fs/bj}, \eta/s)$ such that the most central LHC multiplicity is reproduced
- LHC centrality dependence favors $\beta \in [0.9, 1]$ and fs-to-τ_0 scenario

LHC



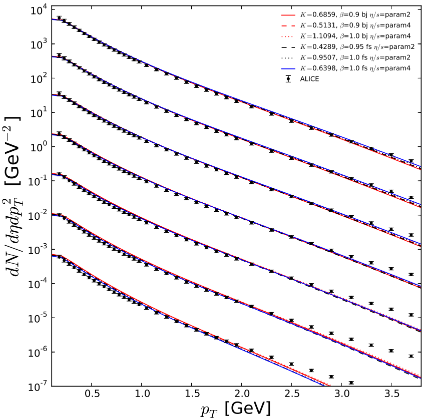
RHIC



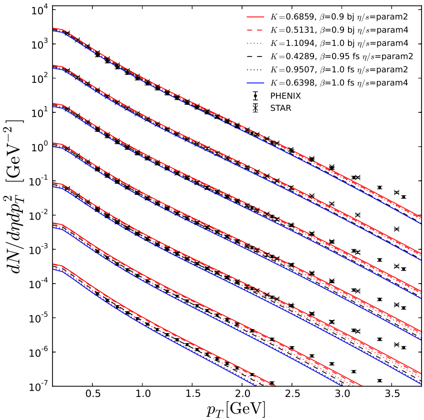
Charged particle p_T spectra VS Data at the LHC and RHIC

- T_{chem} determines the low p_T shape of the spectra (better shape with PCE 175 MeV than 150 MeV)

LHC



RHIC

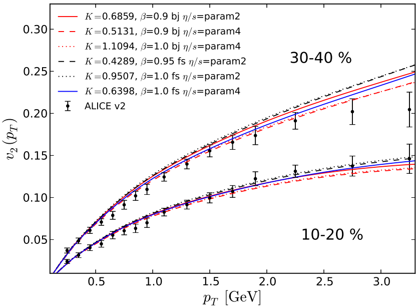


Elliptic flow $v_2(p_T)$ VS Data at the LHC and RHIC

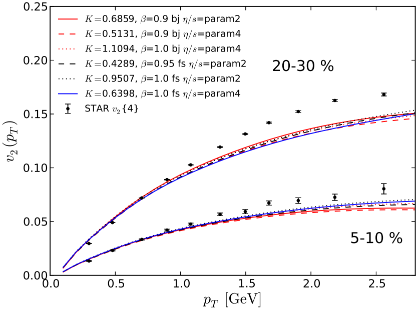
For $\eta/s(T)$ studied so far:

- Good low-p_T agreement with the data at both LHC and RHIC
- Note: $\eta/s(T)$ same at RHIC and LHC

LHC



RHIC



→ Ongoing: can we finetune $\eta/s(T)$ further ?

Summary and outlook

- Rigorous NLO pQCD computation for $E_T(p_0, \beta, \mathbf{b}, \dots)$
- E_T saturation
- Computation of the initial e-profiles at LHC and RHIC
- Viscous hydro evolution

Results for the centrality dependence of the multiplicity, p_T-spectra and $v_2(p_T)$ look promising; finetuning of $\eta/s(T)$ ongoing

Further studies:

- Geometrical fluctuations from Event-By-Event simulation
  - $\rightarrow$ Study v_n's

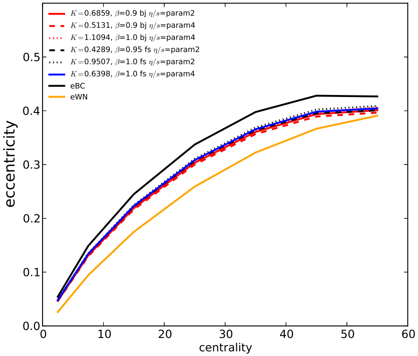
BACKUP SLIDES

- Profile eccentricity VS centrality

- Effect from the edge

Profile eccentricity VS centrality at the LHC and RHIC

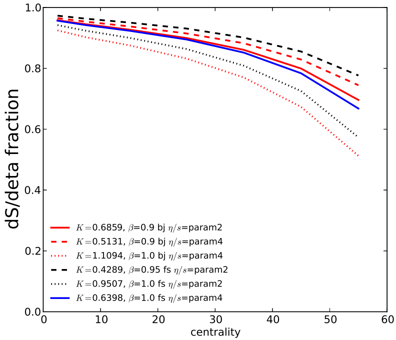
- Computed profiles (LHC) are between the usual BC and WN profiles



Effect from the edge at the LHC and RHIC

- fraction of the total entropy computed from pQCD at LHC and RHIC

LHC



RHIC