NLO updates of the EKRT model for central *AA* collisions at RHIC and LHC

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Outline

- Introduction: "Old" EKRT final-state saturation model
- NLO pQCD updated new EKRT setup
- Hydrodynamical evolution with EKRT initial state
- Results: multiplicities and identified hadron p_T spectra for RHIC & LHC
- Summary and Outlook

The old EKRT model

EKRT = Eskola, Kajantie, Ruuskanen, Tuominen Nucl. Phys. B750 (2000) 379

- model combines pQCD minijet production with the saturation of gluons and (ideal) hydrodynamics
- one can Compute the initial conditions for hydrodynamical evolution from pQCD
- predictions for multiplicity scaling $N_{ch} \propto A^{0.92}(\sqrt{s})^{0.40}$

EKRT pQCD + Saturation + Hydrodynamics

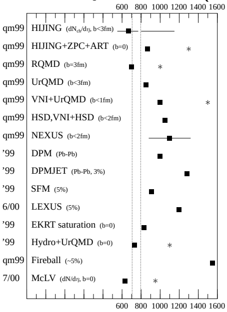
- Low-p_T parton production is controlled by saturation among the produced gluons
- Saturation; Based on the geometric estimate, saturation sets in when produced gluons with $p_T > p_0$ and transverse area π/p_0^2 fill the whole transverse overlap area πR_A^2 of the colliding nuclei

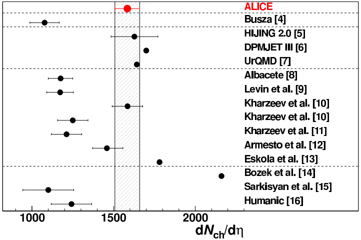
$$\Rightarrow K_{QCD} \underbrace{N_{AA}(p_0, \sqrt{s}, \Delta y, \mathbf{b} = \mathbf{0})}_{\#\text{of produced gluons with } p_T > p_0} \frac{\pi}{p_0^2} = K_{sat}(\pi R_A^2)$$

- Solution gives saturation scale $p_0 = p_{sat}$ for any central ($\mathbf{b} = \mathbf{0}$) AA collision. ($K_{sat} \propto 1$ uncertainty constant)
- If $p_{sat} >> \Lambda_{QCD}$, pQCD particles (q,g)'s with $p_T > p_{sat}$ can give a good estimate of the # of partons and transverse energy E_T produced to midrapidity interval Δy

Old EKRT model results: pQCD + Saturation + Hydro in good agreement with data

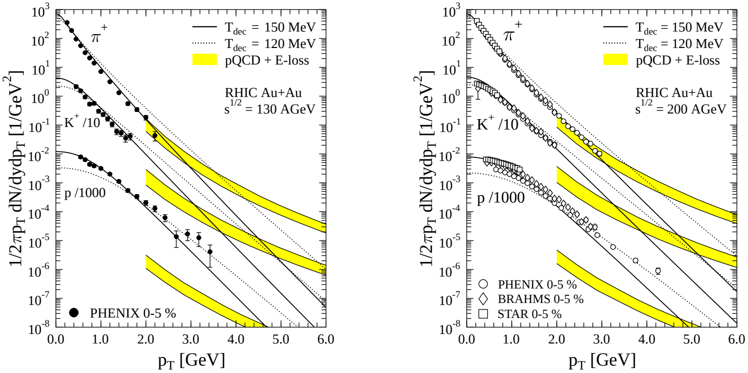
- Multiplicity predictions for RHIC $\sqrt{s} = 200$ GeV and LHC $\sqrt{s} = 2760, 5500$ GeV (10 years before LHC data! [ref. Eskola et al Nucl.Phys. A696 (2001)])





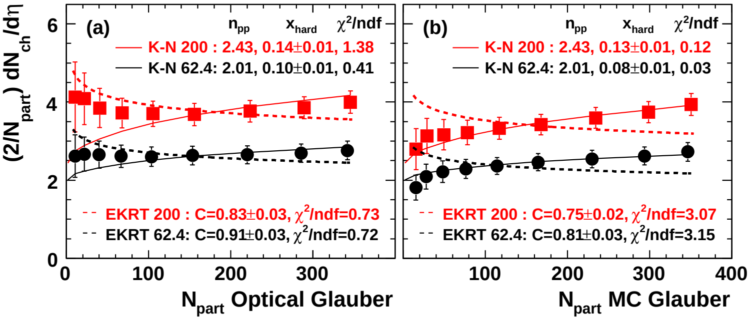
- ALICE LHC figure [ref. PRL 105 (2010) 252301]

- the p_T spectra of charged particles for 5% most central AuAu collisions at RHIC



- [ref. Eskola et al Phys.Rev. C72 (2005)]

- Charged-particle multiplicity vs participants



- EKRT model (which uses optical Glauber) [ref. Eskola et al Phys.Lett. B497 (2001)] agrees with the data if N_{part}^{exp} is estimated with an optical calculation!! [ref. STAR figure Phys.Rev. C79 (2009) 034909]

EKRT pQCD Modeling Problems

Saturation:

$$K_{QCD} \underbrace{N_{AA}(p_0, \sqrt{s}, \Delta y, \mathbf{b}=\mathbf{0})}_{\#\text{of produced gluons with } p_T > p_0} \frac{\pi}{p_0^2} = K_{sat}(\pi R_A^2)$$

$$dN_{AA} = \int d^2s \sum_{ij} T_A(s) f_i^A(Q^2) \otimes T_A(s) f_j^A(Q^2) \otimes d\hat{\sigma}_{ij}^{pQCD}$$

- Extension to NLO pQCD? $K_{QCD} = NLO/LO$ rigorously defined only for E_T, which is infrared and collinear safe (ICS) quantity!!
- Δy and α_s dependence in the saturation criterion ?
- Before now, insufficient control over the uncertainties of the NLO nPDFs (NLO evolution of gluon shadowing, etc..)

Can we fix these problems ?? YES we can!!

NLO pQCD updated new EKRT setup

New EKRT saturation

$$\frac{dE_T}{d^2 s dy}(2 \to 2) \sim \frac{dE_T}{d^2 s dy}(3 \to 2)$$

$$\Rightarrow (T_A g_A)^2 \frac{\alpha_s^2}{p_0} \sim (T_A g_A)^3 \left(\frac{\alpha_s}{p_0}\right)^3 \Rightarrow T_A g_A \sim \frac{p_{sat}^2}{\alpha_s} \Rightarrow \frac{dE_T}{dy} \sim R_A^2 p_{sat}^3$$

Thus a new saturation criterion for E_T in a region $\Delta y = 1$

$$E_T(p_0, \sqrt{s}, \Delta y = 1, \mathbf{b} = \mathbf{0}) = T_{AA}(\mathbf{0}) \sigma_{QCD} \langle E_T \rangle_{\Delta y, p_0} = K_{sat}(R_A^2 p_0^3)$$

- No explicit α_s appears!
- Standard nuclear overlap function $T_{AA}(\mathbf{0})$ accounts for the nuclear collision geometry (Woods-Saxon profile).
- $\sigma_{QCD} \langle E_T \rangle_{\Delta y, p_0}$ is the first moment of the minijet E_T distribution in NN.
- We perform a rigourous NLO pQCD computation of $\sigma_{QCD} \langle E_T \rangle$: no K_{QCD} factors anymore!

$$\sigma_{QCD}\langle E_T\rangle_{p_0,\Delta y} = \sigma_{QCD}\langle E_T\rangle^{2\to 2}_{p_0,\Delta y} + \sigma_{QCD}\langle E_T\rangle^{2\to 3}_{p_0,\Delta y}$$

where

$$\sigma_{QCD}\langle E_T\rangle^{2\to 2}_{p_0,\Delta y} = \frac{1}{2!}\int [DPS]_2 \frac{d\sigma^{2\to 2}}{[DPS]_2}\tilde{S}_2(p_1,p_2)$$

$$\sigma_{QCD}\langle E_T\rangle^{2\to 3}_{p_0,\Delta y} = \frac{1}{3!}\int [DPS]_3 \frac{d\sigma^{2\to 3}}{[DPS]_3}\tilde{S}_3(p_1,p_2,p_3)$$

- Partonic $2\to 2$ $\quad(gg\to gg$, etc...) processes for LO & NLO corrections (1-loop level)
- $2\to 3$ $\quad(gg\to ggg$, etc...) processes - only NLO corrections
- UV renormalized $|M|^2$ in $4-2\epsilon$ dimensions (R.K Ellis at all)
- IR/CL divergencies handled with NLO def. of PDFs & EKS subtraction method

The measurement functions $\tilde{S}_2$ and $\tilde{S}_3$ fulfil the IR/CL criteria, which ensure that $\sigma_{QCD}\langle E_T\rangle$ is a well defined IR/CL safe quantity

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

$$\tilde{S}_3 = E_T\Theta(p_{T1} + p_{T2} + p_{T3} \geq 2p_0)\Theta(E_T \geq C \times p_0)$$

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
- We introduce a new set of measurement functions, $0 \leq C \leq 1$ which control the amount of E_T in Δy carried by the partons
- New: any C between 0&1 is equally good and IR/CL safe!

Bound proton PDFs $f_{i/A}(x, Q^2)$ for each parton flavor i

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

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

- Old EKRT setup
  - GRV94 LO parton densities with nuclear effects from the EKS98 [ref. Eskola et al Eur.Phys.J. C9 (1999)] LO parametrization
  - K_{QCD} NLO factor - GRV94 and CTEQ5 (LO& NLO) and LO EKS98: NO full NLO evolution
- New EKRT setup
  - CTEQ6 NLO parton densities with EPS09 [ref. JHEP 0904 (2009) 065] NLO parametrization
  - Study also the propagation of nPDF uncertainties with the 30 error sets in EPS09

Hydrodynamical evolution; Based on the 1+1 ideal hydrodynamics (H. Holopainen)

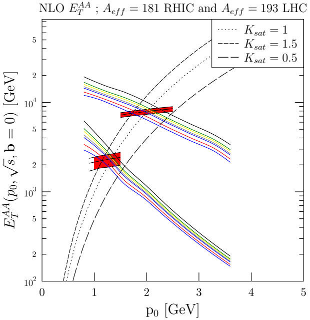
- Impact parameter $\mathbf{b} = \mathbf{0}$ fm
- Boost invariance in z-direction
- Initial time $\tau_0 = 1/p_{sat}$
- Initial $\epsilon(\tau_0)$ from $\{E_T(p_{sat}), \tau_0\}$ and eBC/eWN profiles
- EoS: s95p-PCE from P. Huovinen and P. Petreczky [ref. Nucl. Phys. A837 (2010)]
- Freeze-out temperature $T_f = 120$ MeV

$\Rightarrow$ Calculate particle multiplicities, p_T spectra for central Au+Au $\sqrt{s} = 200$ GeV at RHIC, and Pb+Pb $\sqrt{s} = 2760$ GeV at LHC (see Results)

New EKRT model Results (preliminary)

Study the $E_T \leftrightarrow N_{ch}$ systematics of the new EKRT model from RHIC to LHC (central collisions):

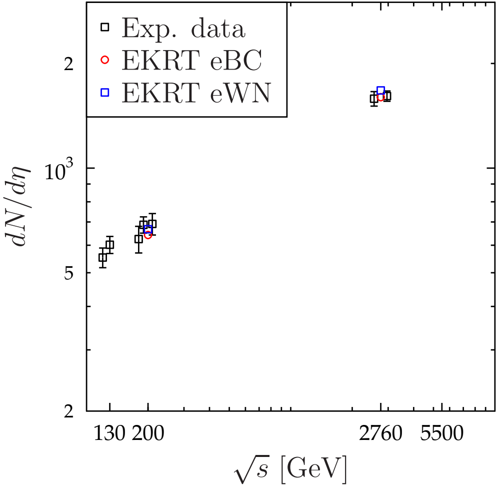
- effects of choosing C
- effects of K_{sat}
- map with Hydro (red bands): Hydro curves calculated by fixing multiplicity to the LHC and RHIC measurements



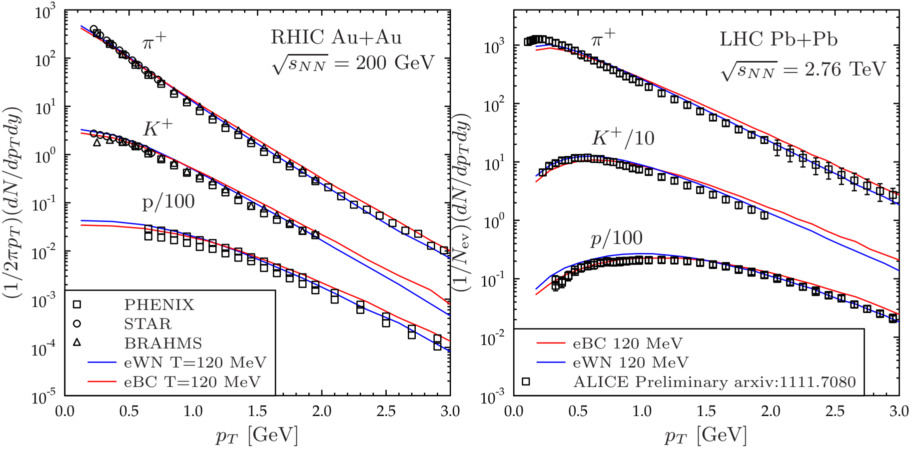
E_T saturation for C= 0.75

$\sqrt{s}$ GeV	p_{sat}	τ_0
RHIC 200	1.31 GeV	0.15 fm
LHC 2760	1.97 GeV	0.10 fm

- Good agreement with the multiplicity data with $C = 0.75$, both for LHC and RHIC!



p_T spectra (ALICE preliminary data ref. arxiv:1111.7080)



Improvements over the old EKRT

- new saturation criterion for IR/CL safe E_T, no K_{QCD} needed
- NLO nPDFs (CTEQ6 & EPS09)
- rigorous NLO pQCD computation for E_T
- new measurement functions with $0 \leq C \leq 1$

RHIC-LHC systematics of the new EKRT setup looks good!

Next

- Centrality dependence: local saturation with impact parameter dependent nPDFs (EPS09s [ref. arXiv:1205.5359])
- Viscous hydrodynamics