Monte Carlo EKRT event generator for initializing 3+1 D fluid dynamics in high energy nuclear collisions

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with

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H. Hirvonen, M. Kuha, J. Auvinen, K. J. Eskola, Y. Kanakubo, H. Niemi, Phys.Rev.C 110 (2024) 3, 034911
M. Kuha, J. Auvinen, K. J. Eskola, H. Hirvonen, Y. Kanakubo and H. Niemi, Phys.Rev.C 111 (2025) 5, 054914

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MC-EKRT ingredients

- Based on LO collinearly factorized perturbative QCD

$$\sigma^{ab}_{\text{jet}} = K \int dp_T^2 dy_1 dy_2 \sum_{ij\langle kl\rangle} \frac{1}{1+\delta_{kl}} x_1 f_i^{a/A}(x_1, Q^2)\, x_2 f_j^{b/B}(x_2, Q^2) \frac{\mathrm{d}\hat{\sigma}^{ij\to kl}}{\mathrm{d}\hat{t}}(\hat{s}, \hat{t}, \hat{u})$$

- LO partonic $2 \to 2$ cross sections $\frac{\mathrm{d}\hat{\sigma}^{ij\to kl}}{\mathrm{d}\hat{t}}(\hat{s}, \hat{t}, \hat{u})$
- Nuclear parton distribution functions (nPDF): $f_i^{a/A}(x, Q^2)$
- Saturation to control low-p_T particle production

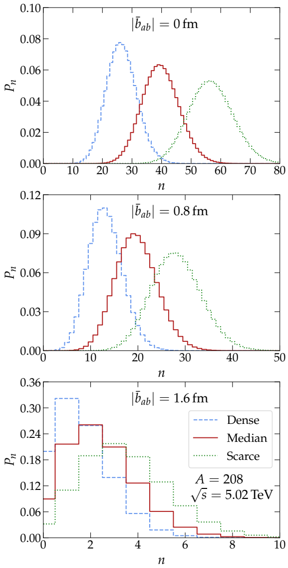
New features compared to EbyE-EKRT model

- Local energy/momentum conservation
- Dynamical fluctuations in minijet production and saturation
- Full 3D initial conditions with rapidity dependence

Steps in MC-EKRT

1. Sample nucleon configuration from Woods-Saxon + trigger condition for inelastic AA collisions
2. Poissonian generation of candidate pQCD dijets with $p_{T,\mathrm{min}} = 1$ GeV
3. Saturation: Filter smaller p_T dijets away if process overlaps with a higher-p_T one
4. Filter remaining low-p_T dijets away if per-nucleon energy is violated
5. Propagate surviving dijets to $\tau = 1/p_{T,\mathrm{min}} \sim 0.2$ fm surface and compute energy density with Gaussian smearing
6. 3+1D hydrodynamical evolution

The Poissonian sampling of candidate dijets



- Number of $2 \to 2$ processes, with $p_{T,\min} = 1$ GeV, sampled from Poissonian distribution for each NN pair

$$P_n = \frac{(T_{\rm nn}(b)\sigma_{\rm jet})^n}{n!} e^{-T_{\rm nn}(b)\sigma_{\rm jet}}$$

- $T_{\rm nn}(b)$ is nucleon-nucleon overlap function
- Nuclear effects through EbyE fluctuationg nPDF's
- Gives back the correct LO pQCD jet cross section
- Sample $2 \to 2$ kinematics
- NLO contributions accounted with K-factor
- Distribute dijets to (x, y)-plane sampling $T_n^a T_n^b$

$$\frac{d\sigma^{ab}_{\rm jet}(\{\bar{s}_a\},\{\bar{s}_b\})}{dp_T^2 dy_1 dy_2} = K \sum_{ij\langle kl\rangle} x_1 f_i^{a/A}(\{\bar{s}_a\}, x_1, Q^2)\, x_2 f_j^{b/B}(\{\bar{s}_b\}, x_2, Q^2)\, \frac{d\hat{\sigma}^{ij\to kl}}{d\hat{t}}(\hat{s}, \hat{t}, \hat{u})$$

EbyE fluctuating nuclear PDFs

- Idea: Parametrize nuclear effects as function of nuclear thickness function T_A, e.g. EPS09s: I. Helenius, K. J. Eskola, H. Honkanen and C. A. Salgado, JHEP 07, 073 (2012)
- EPS09s only valid up to maximum of Wood-Saxon T_A: fluctuations result in much larger values $\Longrightarrow$ need to be generalized
- Introduce nuclear modification factors $r_i^{a/A}(\{\bar{s}_a\}, x, Q^2)$

$$f_i^{a/A}(\{\bar{s}_a\}, x, Q^2) = f_i^a(x, Q^2) r_i^{a/A}(\{\bar{s}_a\}, x, Q^2)$$

- Spatial dependence and EbyE fluctuations through $T_A(\{\bar{s}_a\})$

$$r_i^{a/A}(\{\bar{s}_a\}, x, Q^2) = \begin{cases} 1 + \log\left[1 + c_A^i(x, Q^2)\,\hat{T}_A^a\right], & \text{anti-shadowing } c_A^i > 0 \\ 1/\left[1 - c_A^i(x, Q^2)\,\hat{T}_A^a\right] & \text{shadowing } c_A^i < 0 \end{cases}$$

- c_A^i fixed by requiring that average nuclear modification reduces back to EPS09
- Effective parton density $T_A f(x, Q^2)$ increases monotonically with T_A
- Per-nucleon momentum sum rule still holds

EKRT saturation conjecture

- Saturation sets in when $3 \to 2, 4 \to 2, \ldots$ start to dominate over $2 \to 2$ processes. Using Feynman rules and dimensional analysis one can write:

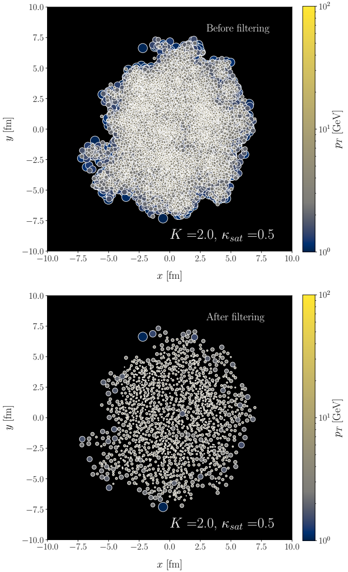
$$\frac{dN_{AA}^{2\to2}}{d^2\bar{s}} \sim (T_A xg) \times (T_A xg) \times \left(\frac{\alpha_s^2}{p_0^2}\right), \qquad \frac{dN_{AA}^{3\to2}}{d^2\mathbf{s}} \sim (T_A xg)^2 \times T_A xg \times \frac{\alpha_s}{p_0^2}\left(\frac{\alpha_s^2}{p_0^2}\right)$$

$$\frac{dN_{AA}^{3\to2}}{d^2\bar{s}} \sim \frac{dN_{AA}^{2\to2}}{d^2\bar{s}} \implies T_A xg \sim \frac{p_0^2}{\alpha_s}$$

$$N_{AA}^{2\to2}\frac{\pi}{p_0^2} \sim \pi R_A^2 \quad \text{with } p_0 = p_{\rm sat}$$

- Can interpret this geometrically: Saturation sets in when partonic processes with transverse formation-area $\pi/p_{\rm sat}^2$ fill the whole available transverse plane

Saturation and E/M conservation



- Go through the list of candidate dijets. Start from the highest-p_T
- Reject candidate dijet if it overlaps with any already accepted dijet (transverse area $= \pi/p_T^2$)

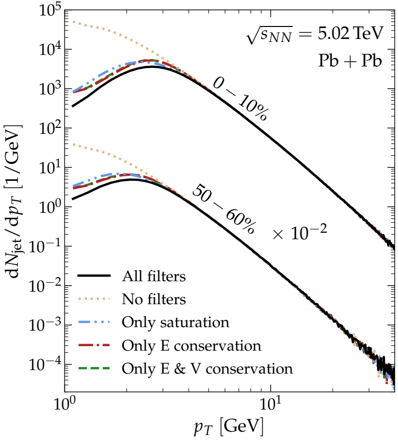
$$|\bar{s} - \bar{s}^{\text{cand}}| < \frac{1}{\kappa_{\text{sat}}}\left(\frac{1}{p_T} + \frac{1}{p_T^{\text{cand}}}\right)$$

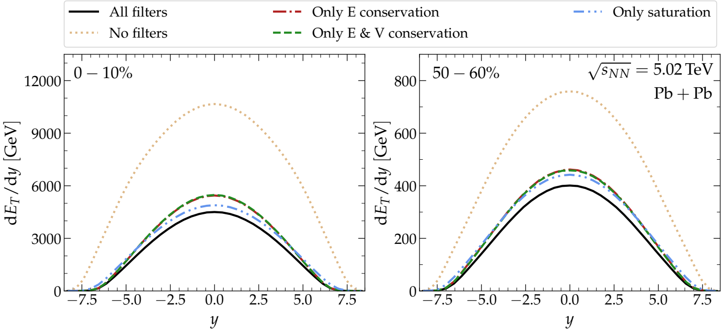
- Packing factor κ_{sat} free parameter
- Go through the accepted list again in p_T order and reject the remaining (low-p_T) partons if for any nucleon

$$x^{\text{cand}} + \sum_{i=1}^{n} x^{(i)} > 1$$

- Valence quarks statistically determined, their conservation imposed

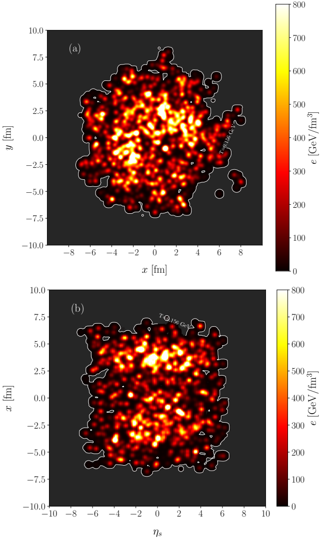
Effects of filtering





- Factorization holds for high-p_T dijets
- After saturation E/M conservation relatively small effect

Initial conditions for 3+1D hydrodynamics



- Propagate partons as free particles to $\tau = 1/p_{T,\mathrm{min}} \approx 0.2$ fm surface
- Compute energy density with Gaussian smearing as:

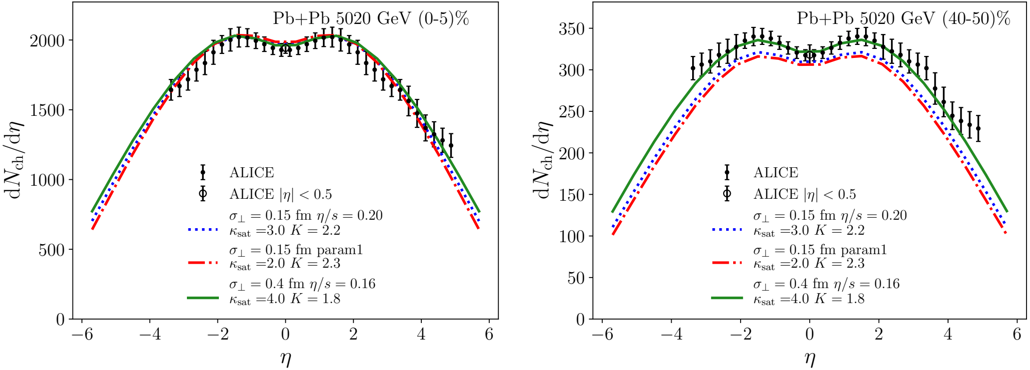
$$T^{\tau\tau}(\tau_0, \mathbf{x}_\perp, \eta_s) = \frac{1}{\tau_0} \sum_i p_{Ti} g_\perp(\mathbf{x}_\perp; \mathbf{x}_{\perp i}) g_{||}(\eta_s; \eta_{s,i})$$

- Gaussian functions $g_\perp$ and $g_{||}$ with widths $\sigma_\perp$ and $\sigma_{||}$ as free parameters

Hydrodynamical evolution and event-averages

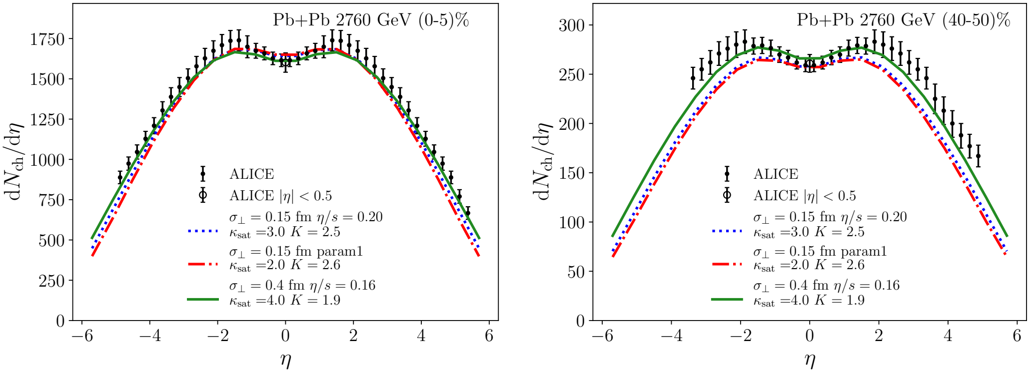
- Here we compute 3+1D hydrodynamical evolution for centrality-class averaged initial conditions
- Mimic the EbyE multiplicity distribution: average initial entropy densities
- 3+1D Israel-Stewart hydrodynamics with only shear viscosity
- Equation of state: s95p-PCE-v1: partial chemical equilibrium with chemical freeze-out at $T_{\rm chem} = 150$ MeV
  P. Huovinen and P. Petreczky, NPA 837, 26 (2010), P. Huovinen, Eur. Phys. J. A 37, 121-128 (2008)
- Kinetic decoupling at $T_{\rm dec} = 130$ MeV

Charged hadron multiplicity: 5.02 TeV Pb+Pb



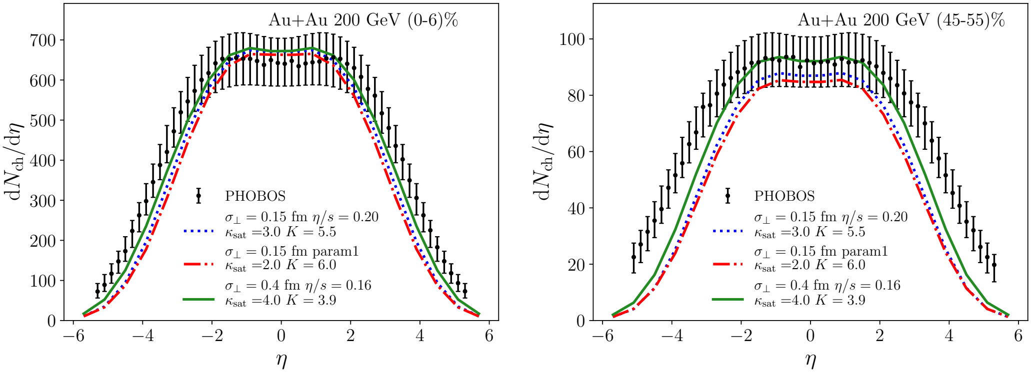
- $\sigma_\perp, \kappa_{sat}$, and K tuned to approximately reproduce the centrality dependence of mid-rapidity multiplicity (fixed $\sigma_\parallel = 0.15$)

Charged hadron multiplicity: 2.76 TeV Pb+Pb



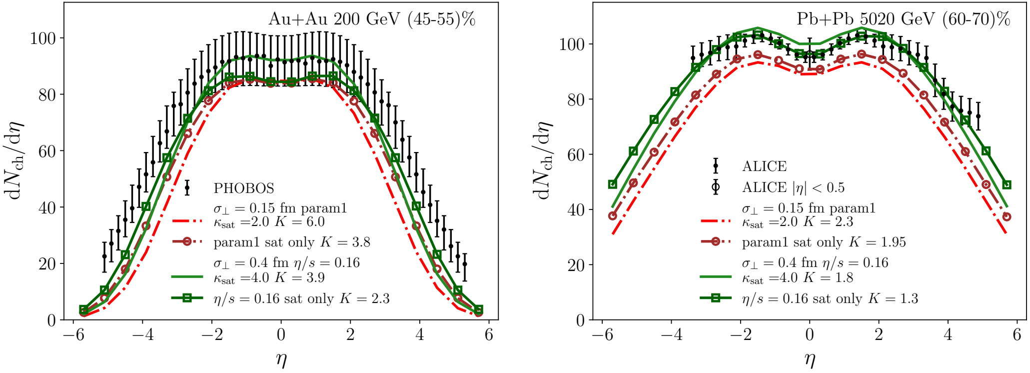
- $\sigma_\perp, \kappa_{sat}$ fixed, K tuned to give mid-rapidity multiplicity

Charged hadron multiplicity: 200 GeV Au+Au



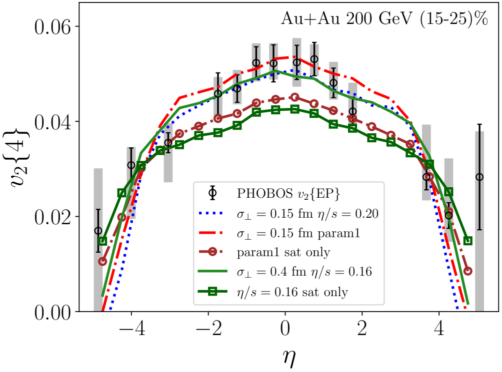
- $\sigma_\perp, \kappa_{sat}$ fixed, K tuned to give mid-rapidity multiplicity

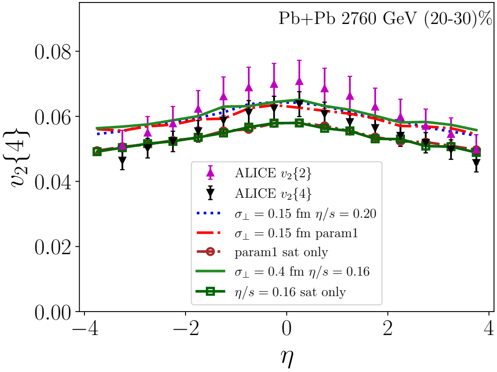
Saturation only: Nucleon level energy conservation?



- If we neglect the per-nucleon energy conservation even peripheral collisions are quite well described
- In peripheral collisions total energy (in participating nucleons) is not violated. Per-nucleon energy conservation too restrictive?

Elliptic flow: 2.76 TeV Pb+Pb and 200 GeV Au+Au





- Rapidity dependence of elliptic flow well described both at the LHC and RHIC
- Note: Viscosity in saturation-only results is not yet tuned to data

Summary

- We introduce new 3+1D Monte-Carlo implementation of the EKRT model (MC-EKRT)
- Dynamical fluctuations in minijet production and saturation
- New EbyE fluctuating nPDFs
- Full 3D initial conditions with rapidity dependence
- First tests: Promising agreement with measured pseudorapidity distributions of multiplicity at LHC and RHIC