Rapidity-dependent fluctuations in the TRENTo initial state model

Govert Nijs

March 28, 2023

Based on:

- Giacalone, GN, van der Schee, to appear

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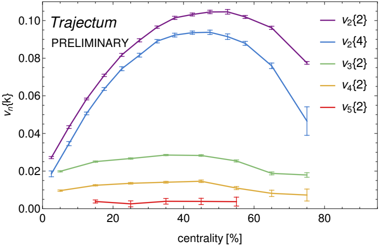
Trajectum

- New heavy ion code developed in Utrecht/MIT/CERN.
- Contains initial stage, hydrodynamics and freeze-out, as well as an analysis suite.
- Easy to use, example parameter files distributed alongside the source code.
- Fast, fully parallelized.
  - Figure (20k oversampled PbPb events at 2.76 TeV) computes on a laptop in 21h.
  - Bayesian analysis requires $\mathcal{O}(1000)$ similar calculations to this one.
- Publicly available at sites.google.com/view/govertnijs/trajectum/.



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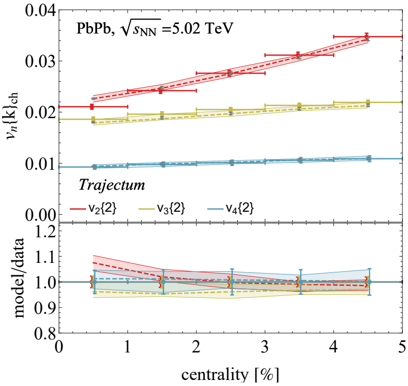
The ultracentral puzzle

- It is difficult to simultaneously describe v_2 and v_3 in the 0–1% centrality bin.
  - Caveat: newer fits give worse agreement.
- Description gets much better when fitting to $\delta p_T / \langle p_T \rangle$, ensuring the right amount of fluctuations in the initial state.
- Weighted runs allow us to make predictions down to 0.001% centrality.



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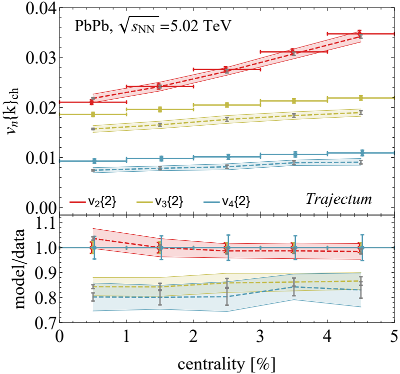

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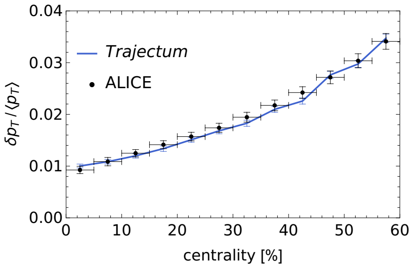

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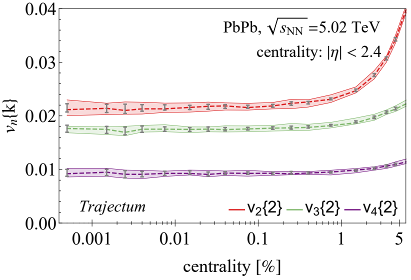
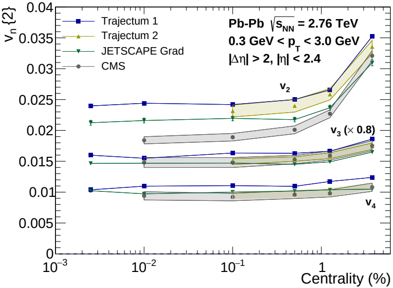


A comparison to CMS data

- No $v_n\{k\}$ measurements by ALICE more central than 0–1% exist yet.
- Comparing to available CMS data reveals discrepancies.
- Works use the same parameters, so why such different agreement?

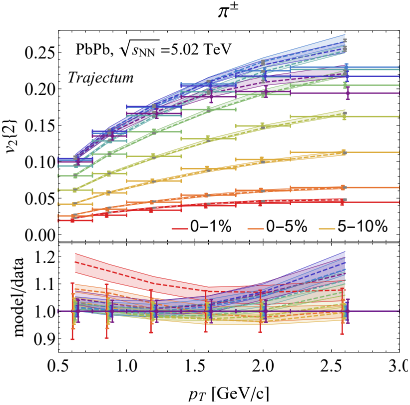


Dependence on kinematic cuts

- Parameters used were fitted to ALICE using boost invariant hydro.
- Cuts for ALICE and CMS are different:

	ALICE	CMS
$p_T\,[GeV]$	0.2–3	0.3–3
$\lvert\eta\rvert$	0.5–0.8	1–2.4

  - Boost invariant model cannot capture the difference in η cut.
  - Previous 3+1D Bayesian analysis by the Duke group gets $v_2(\eta)$ right for higher centrality, but not for central collisions.
- Maybe an updated 3+1D analysis can resolve the issue?



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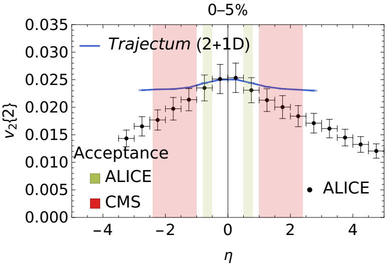

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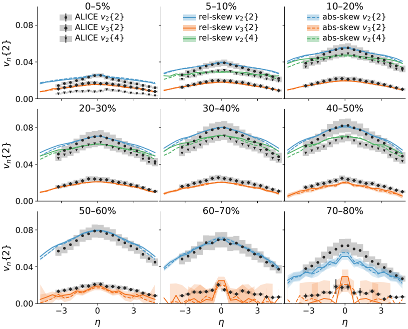


The original 3D TRENTo

- Wounded nuclei contribute to thickness functions $\mathcal{T}_{A/B}$:

$$\mathcal{T}_{A/B} = \sum_{\text{wounded}} \gamma \exp\left(-|\mathbf{x} - \mathbf{x}_i|^2/2w^2\right),$$

with γ drawn from a Gamma distribution with mean 1 and standard deviation σ_{fluct}.

- $\mathcal{T}_A$ and $\mathcal{T}_B$ are combined to form:

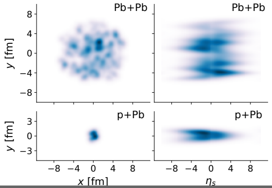
$$\mu = \frac{1}{2}\mu_0 \log(\mathcal{T}_A/\mathcal{T}_B),$$
$$\gamma = \gamma_0 \frac{\mathcal{T}_A - \mathcal{T}_B}{\mathcal{T}_A + \mathcal{T}_B}.$$

- The entropy density becomes:

$$s(\eta_s) = \left(\frac{\mathcal{T}_A^p + \mathcal{T}_B^p}{2}\right)^{1/p} g(\mu, \sigma_0, \gamma; \eta_s)\frac{dy}{d\eta},$$

with $g(\mu, \sigma_0, \gamma; \eta_s)$ a distribution with mean μ, standard deviation σ_0 and skewness γ, and

$$\frac{dy}{d\eta} = \frac{J \cosh \eta}{\sqrt{1 + J^2 \sinh^2 \eta}}.$$



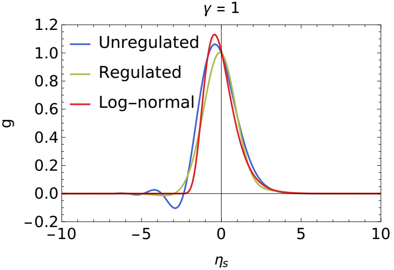
Modified skewness of longitudinal distribution

- g is given by an inverse Fourier transform:

$$g(\mu, \sigma, \gamma; \eta_s) = \mathcal{F}^{-1}(\tilde{g}(\mu, \sigma, \gamma; k)),$$

$$\log \tilde{g} = i\mu k - \frac{1}{2}\sigma^2 k^2 - \frac{1}{6} i\gamma\sigma^3 k^3.$$

- Moments are correct, but g is negative for large enough γ.
  - Regulating $\gamma \to \gamma \exp(-\frac{1}{2}\sigma^2 k^2)$ alleviates this problem, but modifies the moments.
  - A log-normal distribution is positive for any γ.



$$g_{\text{log-normal}}(\mu, \sigma, \gamma; \eta_s) = \frac{1}{\sqrt{2\pi}\tilde{\sigma}\eta_s} \exp\left(-\frac{(\log \eta_s - \tilde{\mu})^2}{2\tilde{\sigma}^2}\right).$$

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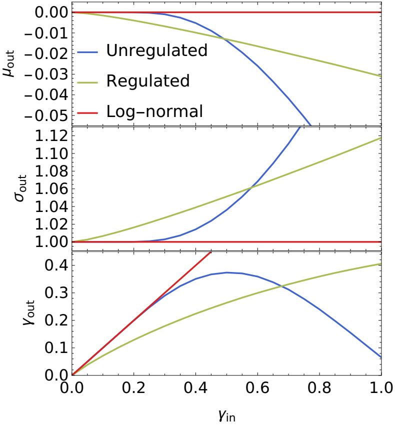

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Rapidity dependent fluctuations

- Recall:

$$\mathcal{T}_{A/B} = \sum_{\text{wounded}} \gamma \exp\left(-|\mathbf{x} - \mathbf{x}_i|^2/2w^2\right),$$

  with γ drawn from a Gamma distribution.

- We replace γ by $\gamma(\eta_s)$:
  - For any η_s follows a Gamma distribution with mean 1 and standard deviation σ_{fluct}.
  - The Pearson correlation coefficient between $\gamma(\eta_s^A)$ and $\gamma(\eta_s^B)$ equals $\exp(-|\eta_s^A - \eta_s^B|/\eta_{\text{corr}})$.

- μ and γ are computed from

$$\mu = \frac{1}{2}\mu_0 \log(\tilde{\mathcal{T}}_A/\tilde{\mathcal{T}}_B),$$

$$\gamma = \gamma_0 \frac{\tilde{\mathcal{T}}_A - \tilde{\mathcal{T}}_B}{\tilde{\mathcal{T}}_A + \tilde{\mathcal{T}}_B},$$

  with

$$\tilde{\mathcal{T}}_{A/B} = \int e^{-\eta_s^2/2\sigma_0^2} \mathcal{T}_{A/B}(\eta_s)\, d\eta_s.$$

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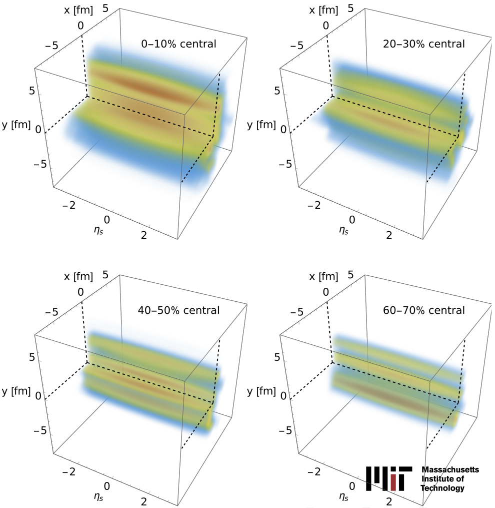
Initial state profiles

- We show initial state profiles with the following parameters:

μ_0	0
σ_0	4
γ_0	0

  with η_{corr} either ∞, 4 or 0.
- Fluctuations can be seen to be more correlated as a function of η_s in the $\eta_{corr} = 4$ case.
- This is also reflected in the initial state eccentricity ϵ_2 for different η_s.



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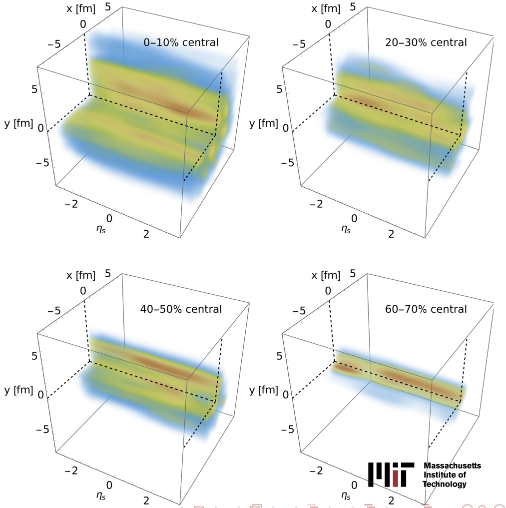

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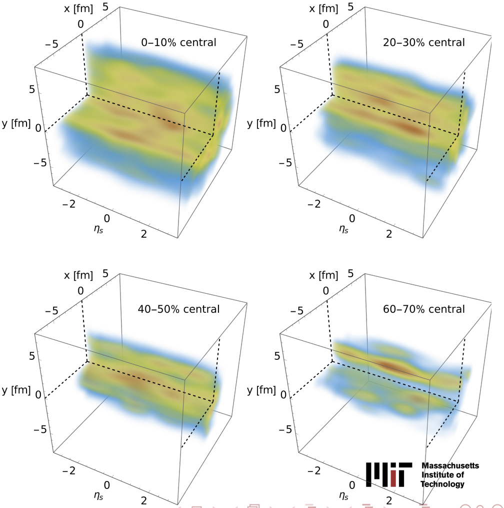

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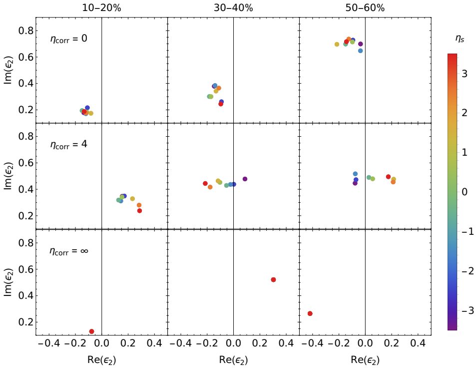
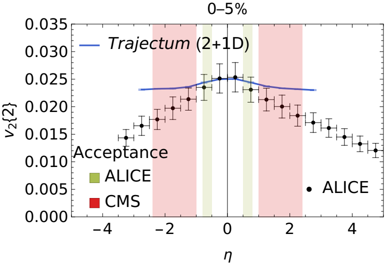


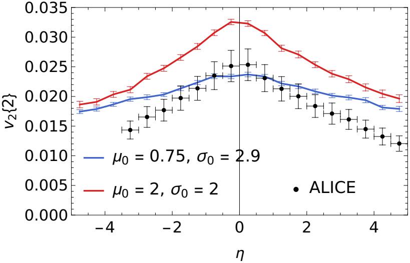
Tuning the parameters

- To compare to both ALICE and CMS at the same time, we must match the η-dependence of v_2.
- We eventually want to do a Bayesian analysis, but will first hand-tune the parameters to see if we can make the slope of $v_2(\eta)$ steeper.
    - Important to try this out first. Bayesian analysis is expensive, and if we do not have a parameter that can change the slope Bayesian analysis will not be useful.



We can get the slope right...

- Decreasing σ_0 makes the slope of $v_2(\eta)$ steeper.
  - This decreases the η_s extent of energy deposition in the initial state, making the ϵ_2 of different η_s less correlated.
  - $r_2(\eta^a, \eta^b)$ is too steep as a consequence.
- We need to increase μ_0 to keep the shape of dN/dy correct.
- Note that we undershoot integrated particle production, and overshoot integrated v_2.
  - Cannot expect to fit perfectly when tuning by hand.
  - Full Bayesian analysis should get everything right simultaneously.



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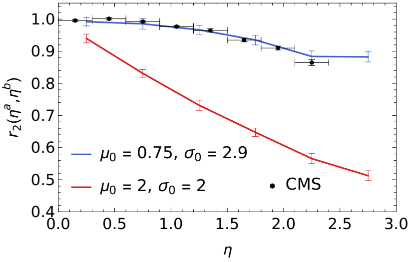

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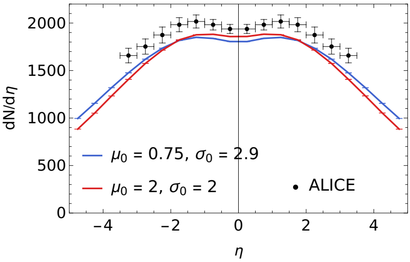

. . . but other observables also change.

- For non-central collisions v_2 is much too high for the settings which produce the correct slope.
- $\delta p_T / \langle p_T \rangle$ is also too high.
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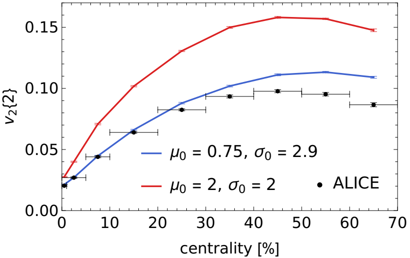

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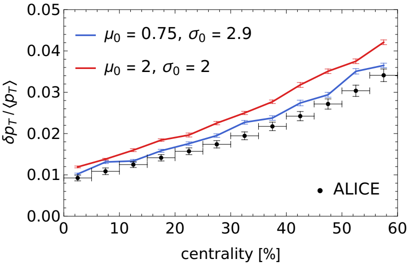

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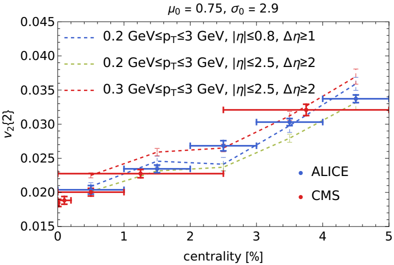
Kinematic cut dependence

- Comparing ALICE to CMS cuts depends on competing effects.
  - CMS p_T cut increases v_2 compared to ALICE.
  - CMS $|\eta|$ and $\Delta\eta$ cuts decrease v_2 compared to ALICE.
- Focus on the 0–1% bin (the only one ALICE and CMS share).
  - In experiment, $v_{2,ALICE} > v_{2,CMS}$.
  - In the model, this happens for the settings which reproduce a high slope of $v_2(\eta)$.



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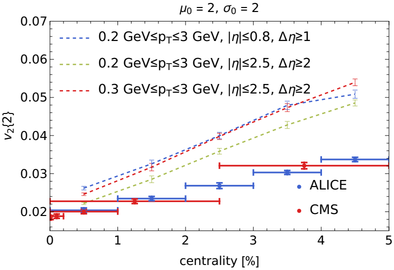
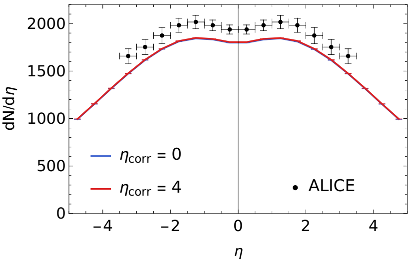


The (non)effect of η_{corr}

- η_{corr} seems to have a very mild effect on observables.
- A potential exception is $r_2(\eta^a, \eta^b)$, but this not clear with current statistics.
- The smallness of the effect of η_{corr} is surprising given the substantial effect on the initial state.



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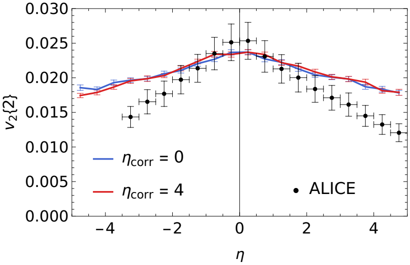

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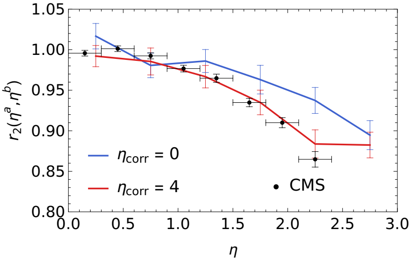

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Conclusions & Outlook

Conclusions:

- Comparing model to data for ultracentral collisions depends sensitively on the kinematic cuts.
- 3+1D model simulations have the potential to describe both ALICE and CMS data simultaneously.
  - Should however understand the interplay of parameters to describe all observables simultaneously.

Outlook:

- We will perform a full Bayesian analysis in the future.