Constraining the nuclear shape of Uranium-238 in heavy-ion collisions with Bayesian inference

Jenni Marjomaa[1] M. Virta[2] D.J. Kim[3]

[1] Aalto University
[2] Aarhus University, Denmark
[3] University of Jyväskylä & HIP

Particle Physics Day 2026
November 11, Tieteiden talo, Helsinki

Aalto-yliopisto
Aalto-universitetet
Aalto University

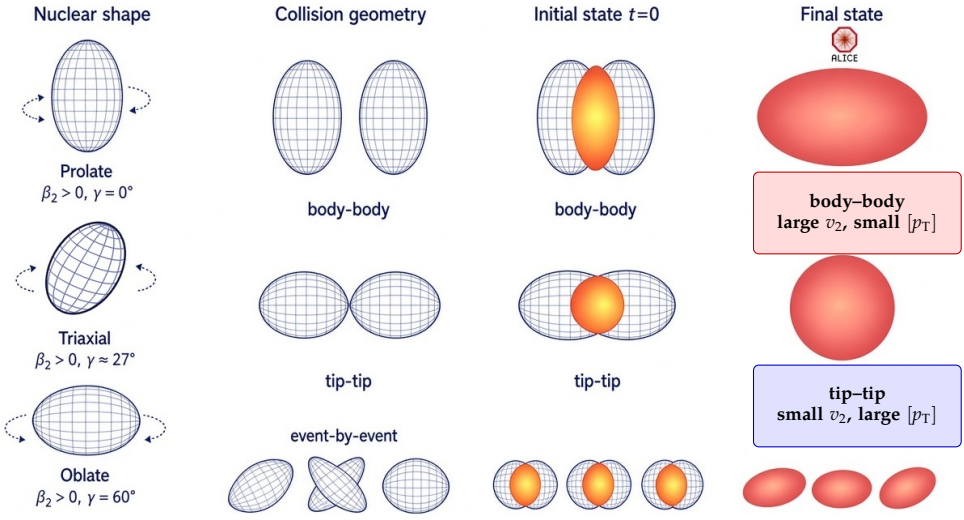
AARHUS UNIVERSITY

UNIVERSITY OF JYVÄSKYLÄ

HELSINKI INSTITUTE OF PHYSICS

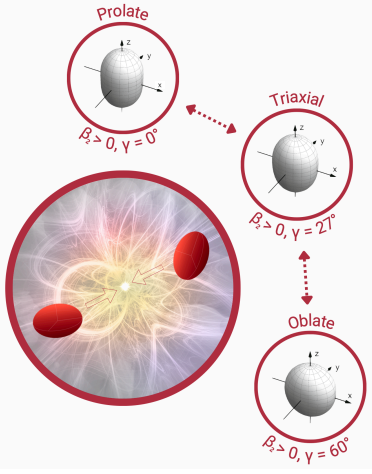
Centre of Excellence in Quark Matter

Imaging nuclear shapes with heavy-ion collisions



Courtesy of D.J. Kim

Nuclear deformation → final-state correlations



Courtesy of E.G. Nielsen

Nuclear structure

$$R(\theta, \phi) = R_0 \Big[1 + \beta_2 \big(\cos\gamma \, Y_{2,0} + \sin\gamma \, Y_{2,2} \big) \Big]$$

Sensitive observables

Flow and $[p_T]$: their moments scale with the shape parameters

- $\langle v_2^2 \rangle \simeq a_1 + b_1 \, {\beta_2}^2$
- $\langle (\delta[p_T])^2 \rangle \simeq a_2 + b_2 \, {\beta_2}^2$
- $\langle v_2^2 \, \delta[p_T] \rangle \simeq a_3 - b_3 \cos(3\gamma) \, {\beta_2}^3$

$$\rho(v_2^2, [p_T]) = \frac{\mathrm{cov}(v_2^2, [p_T])}{\sqrt{\mathrm{Var}(v_2^2)\,\mathrm{Var}([p_T])}}$$

G. Giacalone, J. Jia, C. Zhang, PRL 127, 242301 (2021); J. Jia, PRC 105, 014905 (2022)

JYU–ALICE:

- Multiparticle flow in Xe–Xe/Pb–Pb ⇒ β_2, a_0 of ^{129}Xe [PLB 869 (2025) 139855]
- Xe–Xe/Pb–Pb + **Bayesian** ⇒ β_2-, γ-soft ^{129}Xe [to be submitted to Rep. Prog. Phys.]

From ^{129}Xe to ^{238}U

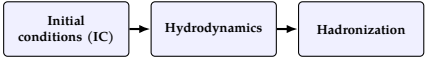
- Same shape → flow/$[p_T]$ mapping as in the intro (Xe–Xe/Pb–Pb at the LHC → U+U/Au+Au at RHIC).
- ^{238}U: strongly deformed, **prolate**.
- ^{197}Au: nearly **spherical** — like ^{208}Pb at the LHC — so Au+Au is the undeformed reference.
- Absolute $\langle\mathcal{O}\rangle$ depend on hydrodynamic response; the ratio and difference

$$R_{\mathcal{O}} = \frac{\langle\mathcal{O}\rangle_{\mathrm{U+U}}}{\langle\mathcal{O}\rangle_{\mathrm{Au+Au}}}, \qquad D_{\mathcal{O}} = \langle\mathcal{O}\rangle_{\mathrm{U+U}} - \langle\mathcal{O}\rangle_{\mathrm{Au+Au}}$$

are less sensitive to hydrodynamic response.

STAR, Nature 635, 67 (2024)

Model



STAR (few parameters from $R_{\mathcal{O}}$)

- Observables: mainly $R_{\langle(\delta[p_T])^2\rangle}$, $R_{\langle v_2^2\delta[p_T]\rangle}$ (plus $R_{\langle v_2^2\rangle}$ as a cross-check)
- Fit only nuclear shape: β_2, γ

IC: IP-Glasma. Phys. Rev. C 102, 034905 (2020)

This work (Bayesian)

{UU193}	absolute U+U
{UU193, AuAu200, $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}	U+U + Au+Au + $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$
{$R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}	$R_{\mathcal{O}}$ & $D_{\mathcal{O}}$ only

IC: TRENTo + free streaming. Phys. Rev. C 111, 044903 (2025)

Hydrodynamics ($\eta/s(T)$, $\zeta/s(T)$) + hadronization held fixed

STAR	MUSIC + hadronic transport
This work	VISH(2+1) + UrQMD

Method: Bayesian parameter estimation

Infer nuclear shape from the deformation-sensitive observables:

$$P(\vec{x} \,|\, \vec{y}) = \frac{P(\vec{y} \,|\, \vec{x})\, P(\vec{x})}{P(\vec{y})}$$

- $\vec{x}$: model parameters, including uranium β_2 and γ.
- $\vec{y}$: STAR flow and $[p_T]$ moments in the data combinations below.
- $P(\vec{x} \,|\, \vec{y})$: **posterior** on the ^{238}U ground-state shape.

Likelihoods for {UU193}; {UU193, AuAu200, $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}; {$R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}.

QA checklist

- ✓ Centrality calibrations per design point
- ✓ Emulator performance / validation
- ✓ Number of principal components (NPC)
- ✓ Prior predictive checks
- ✓ **Sensitivity analysis**
- ✓ **Observable-selection tests**

Shape-sensitive observables → likelihoods

STAR HEPData (U+U, Au+Au): $0.2 < p_T < 3\,\mathrm{GeV}/c$, $|\eta| < 0.5$; centrality 0–2, …, 25–30%.

Absolute $\langle\mathcal{O}\rangle$ — {UU193}, {AuAu200}

$dN_{ch}/d\eta$	Charged-particle multiplicity / geometry baseline	
$\langle v_n^2\rangle$	Two-particle flow cumulants ($n = 2, 3$); $\langle v_2^2\rangle \propto \beta_2^2$	†
$\langle(\delta[p_T])^2\rangle$	Variance of event-by-event $[p_T]$; scales with β_2^2	⋆
$\langle v_2^2\,\delta[p_T]\rangle$	Flow–momentum correlation; γ-sensitive	⋆
$\rho(v_2^2, [p_T])$	Normalized flow–momentum correlation	

⋆ STAR shape from $R_{\mathcal{O}}$; † STAR $R_{\langle v_2^2\rangle}$ as lower-limit cross-check (not in final fit)

$\{R_{\mathcal{O}}\ \&\ D_{\mathcal{O}}\}$ — $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$ only

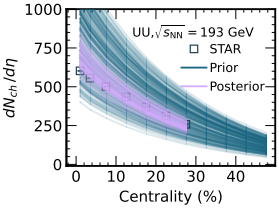
$R_{\mathcal{O}} = \dfrac{\langle\mathcal{O}\rangle_{U+U}}{\langle\mathcal{O}\rangle_{Au+Au}}$, $D_{\mathcal{O}} = \langle\mathcal{O}\rangle_{U+U} - \langle\mathcal{O}\rangle_{Au+Au}$ — less sensitive to hydrodynamic response.

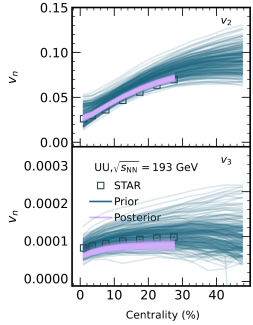
STAR: mainly $R_{\langle(\delta[p_T])^2\rangle}$, $R_{\langle v_2^2\delta[p_T]\rangle} \Rightarrow \beta_2, \gamma$.

This work: $R_{\mathcal{O}}$ for $\langle v_2^2\rangle$, $\langle v_3^2\rangle$, $\langle(\delta[p_T])^2\rangle$; $D_{\mathcal{O}}$ for $\rho(v_2^2, [p_T])$, $\langle v_2^2\delta[p_T]\rangle$.

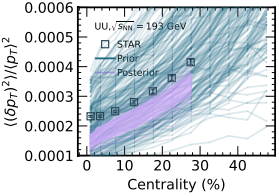
Likelihoods: {UU193}; {UU193, AuAu200, $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}; $\{R_{\mathcal{O}}\ \&\ D_{\mathcal{O}}\}$

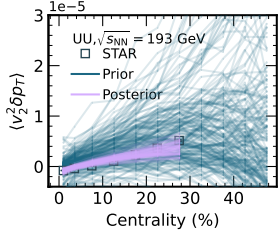
Posterior check: {UU193}

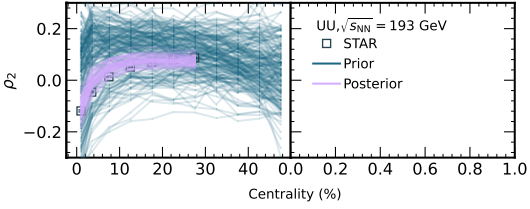




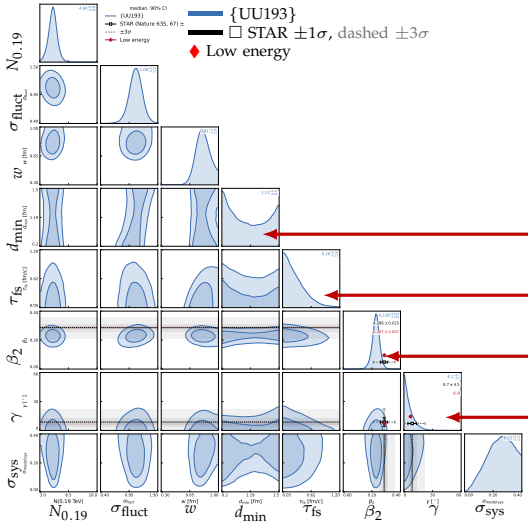
Posterior validation
Multiplicity, v_n, $\langle v_2^2 \delta p_T \rangle$, and ρ_2 are **well described**.
$\langle (\delta p_T)^2 \rangle$ is slightly underestimated.





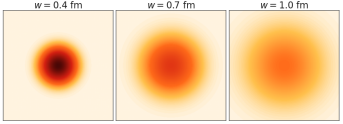


Result: Posterior for {UU193}



TRENTo IC

$N_{0.19}$: normalization (193 GeV)
$\sigma_{\rm fluct}$: nucleon mult. fluct.
w: nucleon width
$d_{\rm min}$: min. nucleon distance
p fixed; w changes the profile



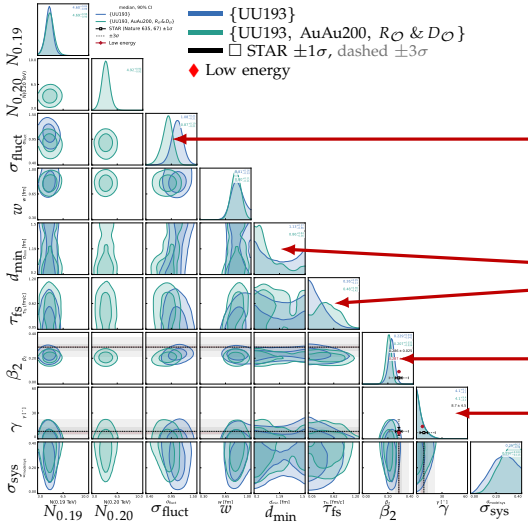
$d_{\rm min}$: weakly constrained (both prior edges)

$\tau_{\rm fs}$: free streaming before hydro prefers small values

$\beta_2 = 0.229^{+0.041}_{-0.042}$
STAR 0.286 ± 0.025 at upper edge

$\gamma = 4.1^{+9.1}_{-4.1}\,^{\circ}$
near-axial ($\gamma \to 0$)
STAR $8.7 \pm 4.5^{\circ}$ closer upper edge

Result: Posterior for {UU193} vs. {UU193, AuAu200, $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}



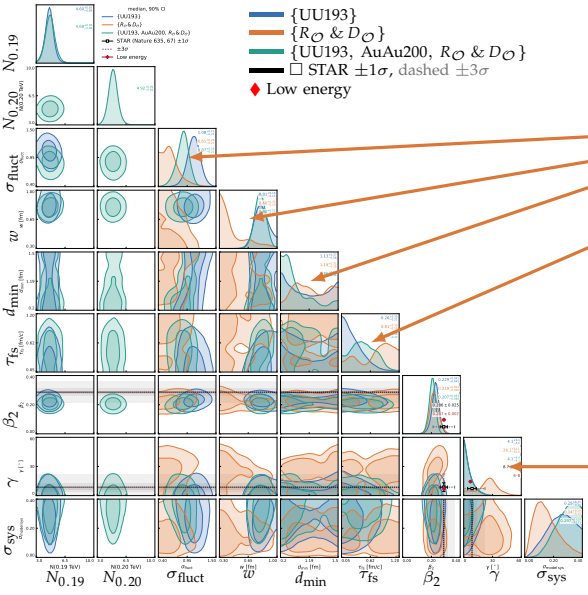
σ_{fluct}: shifted

d_{min}, τ_{fs}: better converged

Adding Au+Au+$R_{\mathcal{O}}$ & $D_{\mathcal{O}}$ narrows β_2: 0.229→0.207
STAR still at upper edge

γ unchanged: both small triaxiality ($\gamma \lesssim 14°$, 90% CI)

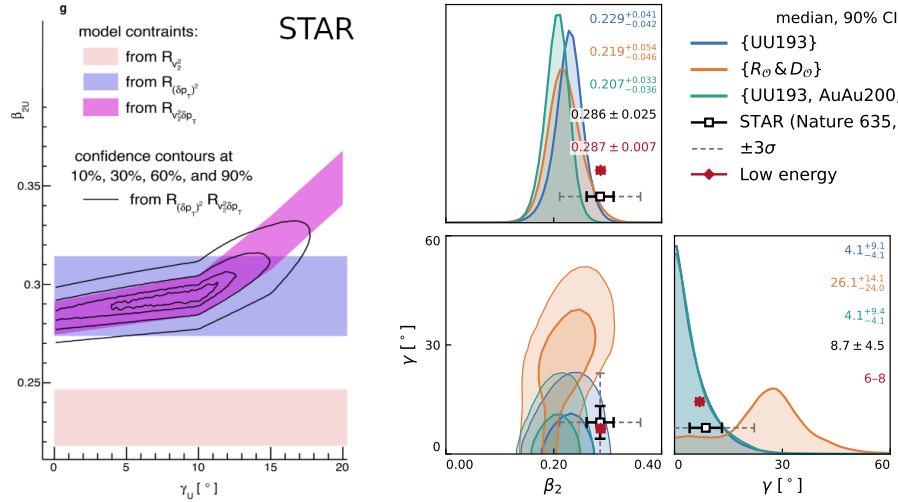
Result: Posterior for {UU193}; {UU193, AuAu200, $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}; {$R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}



{$R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}: σ_{fluct}, w, d_{min}, and τ_{fs} not constrained.

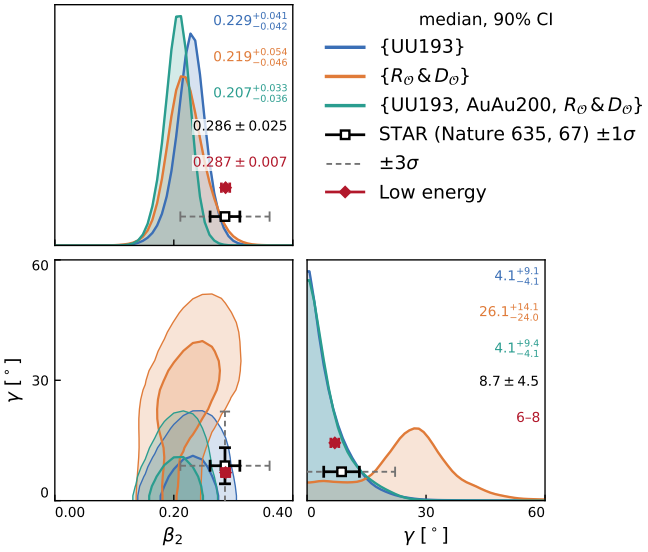
{$R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}: γ pulled **larger** (STAR marker: ±1σ solid, ±3σ dashed)

Result: β_2–γ constraint vs. STAR



- {UU193} and {UU193, AuAu200, $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}: prefer small γ, still compatible with STAR's large uncertainty on γ.
- {$R_{\mathcal{O}}$ & $D_{\mathcal{O}}$} alone: less sensitive to hydrodynamic response, but pulls γ **larger** — less aligned with STAR's near-axial preference.
- ♦ Low energy: $\beta_{2,\mathrm{U}} = 0.287 \pm 0.007$ (ADNDT 107, 1 (2016)), $\gamma_{\mathrm{U}} = 6^\circ$–$8^\circ$ (PRC 54, 2356 (1996)).

Best choice: {UU193, AuAu200, $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}?



- STAR: tuned IP-Glasma, but disagreements on some observables.
- Using only $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$ biases our extraction: TRENTo is too flexible, so we use both systems and $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$.
- {UU193, AuAu200, $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$} **might be the best choice.**

Two questions remain

1. Uncertainty from different initial-condition models.
2. If $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$ does not cancel the QGP parameters, how is their uncertainty quantified?

Summary

- Nuclear deformation maps onto final-state flow and $[p_{\mathrm{T}}]$ correlations.
- Bayesian inference with {UU193}, {UU193, AuAu200, $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}, and {$R_{\mathcal{O}}$ & $D_{\mathcal{O}}$}. {UU193} and {UU193, AuAu200, $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$} favour small γ; {$R_{\mathcal{O}}$ & $D_{\mathcal{O}}$} pulls γ larger.
- STAR: tuned IP-Glasma, but disagreements on some observables.
- Using only $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$ biases our extraction: TRENTo is too flexible, so we use both systems and $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$.
- {UU193, AuAu200, $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$} **might be the best choice.**

Two questions remain

Initial-condition models, and QGP parameters if $R_{\mathcal{O}}$ & $D_{\mathcal{O}}$ does not cancel them.

Thank you!

Backup

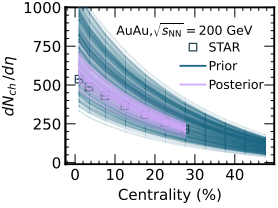
Posterior check: {AuAu200}

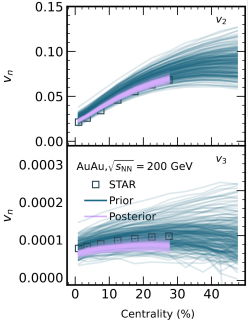
Posterior validation

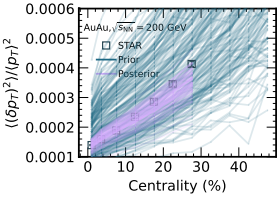
Multiplicity, v_2, $\langle(\delta p_T)^2\rangle$, and $\langle v_2^2 \delta p_T\rangle$ are **well described**.

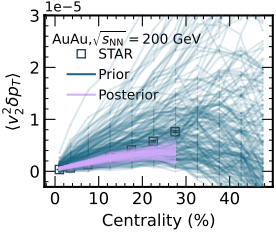
ρ_2 is overestimated in ultra-central collisions, but in the late central collisions it is underestimated.

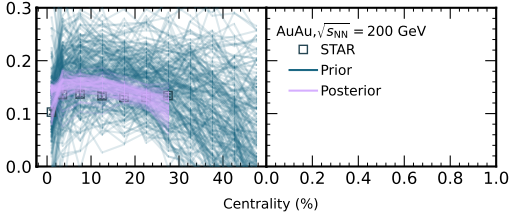
v_3 is **slightly underestimated**.











Posterior check: $\{R_{\mathcal{O}}\ \&\ D_{\mathcal{O}}\}$

Posterior validation

v_2, ρ_2, and $\langle v_2^2 \delta p_{\mathrm{T}} \rangle$ corr. are **well described**.

$\langle (\delta p_{\mathrm{T}})^2 \rangle$ is **sensitive**, but **not well described**: the prior reaches STAR, the posterior stays near 1.

v_3 is more sensitive to granularity, (w smaller for system $\{R_{\mathcal{O}}\ \&\ D_{\mathcal{O}}\}$) and for large free streaming time (τ_{fs}).

