System size dependence of collective phenomena: Theoretical developments

by

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OUTLINE

- 1. Fluid (or non-fluid) dynamics and system size.

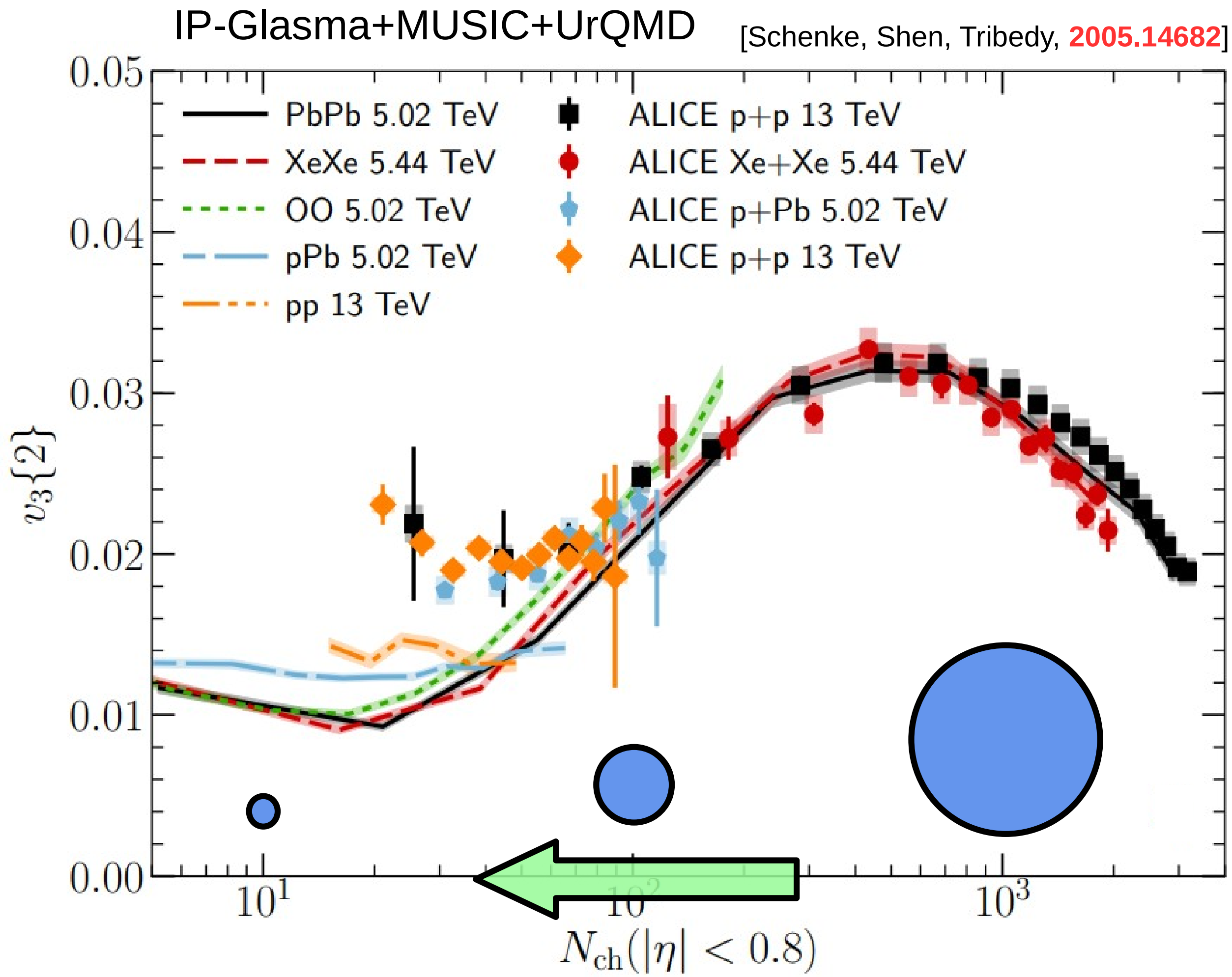
- 2. Initial conditions from large to small systems.

  → Energy deposition.

  → Sub-nucleonic structures.

Hydrodynamic setup works well.

What do we learn by changing system size?



Within a fluid picture (1/2): changing system size is the way to go.

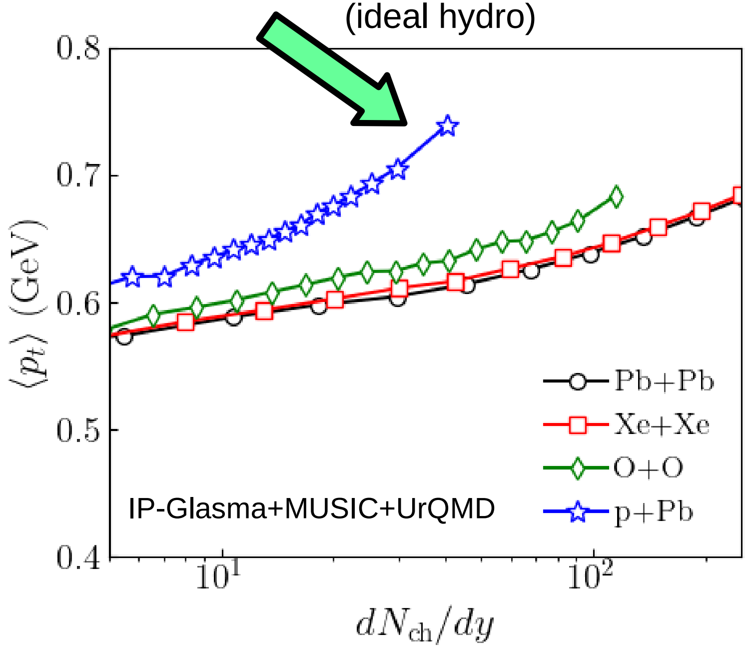
$$F = -\nabla P$$ + more gradients

(1/system size)^n

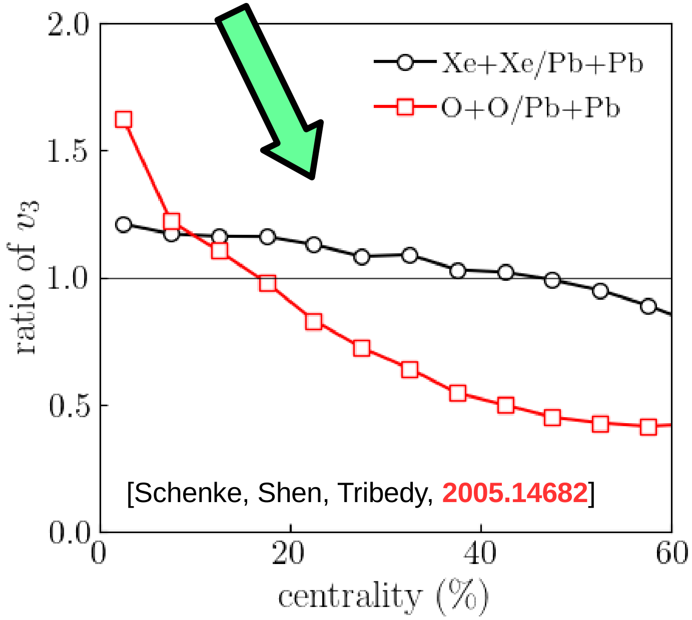
$$Re^{-1} = \frac{\eta}{\rho u L} \qquad Kn = \frac{l_{mfp}}{L}$$

[e.g. Schäfer, 1403.0653]

breaking of scale invariance (ideal hydro)



viscous damping



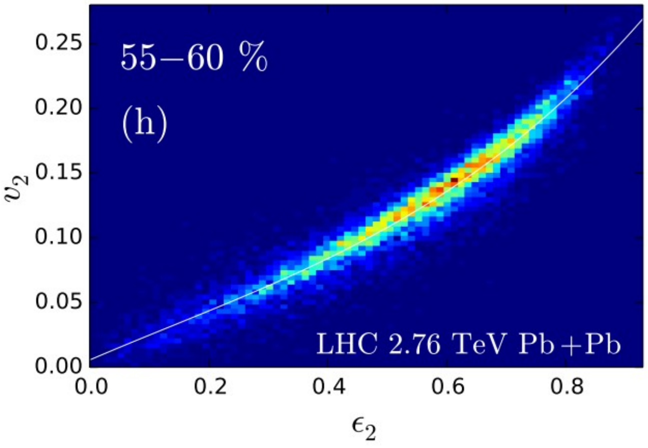
Good potential of future combined analysis of O-O and Pb-Pb data.

Within a fluid picture (2/2): reducing system size to study non-linear dynamics.

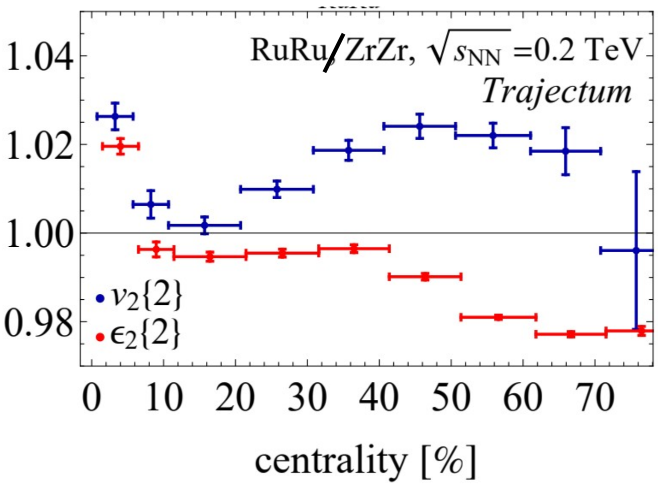
$$V_n = \sum_{m=n}^{\infty} \kappa_{n,m}\mathcal{E}_{n,m} \quad + \quad \text{higher orders}$$

(1/system size)^m

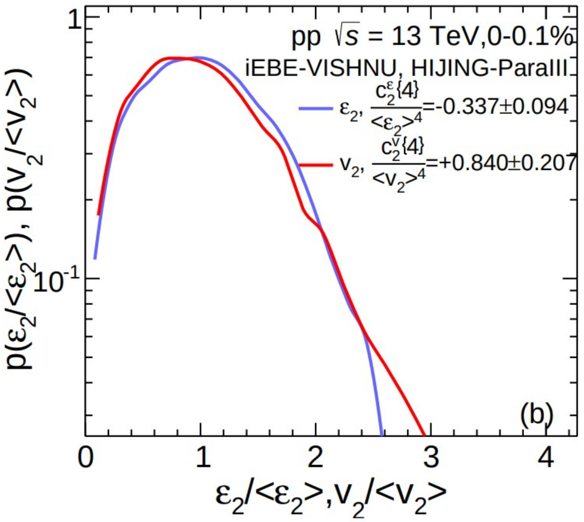
[Noronha-Hostler, Yan, Gardim, Ollitrault, 1511.03896]
[Niemi, Eskola, Paatelainen, 1505.02677]



[Jia, Zhang, 2111.15559]
[Nijs, van der Schee, 2112.13771]



[Taghavi, 1907.12140]
[Zhao, Zhou, Murase, Song, 2001.06742]



But are we within a fluid picture? First-order correction:

$$\frac{\eta}{e+\mathcal{P}}\frac{1}{\tau} \ll 1$$

[Teaney, 0905.2433]

In practice:

$$\underbrace{\frac{\eta}{s}}_{\text{medium parameter}} \times \underbrace{\frac{1}{\tau T}}_{\text{experimental parameter}} \ll 1$$

Phenomenological values:

$$\to \underline{0.2}\left(\frac{\eta/s}{0.3}\right)\left(\frac{1\,\mathrm{fm}}{\tau_o}\right)\left(\frac{300\,\mathrm{MeV}}{T_o}\right) \ll 1$$

Border line… and it only gets worse at small system size.

Experimental observations in small systems have no straightforward interpretation.

Elucidating the non-fluid dynamics: the medium response as a function of system size.

Question revamped by small system collisions.
Unified picture?

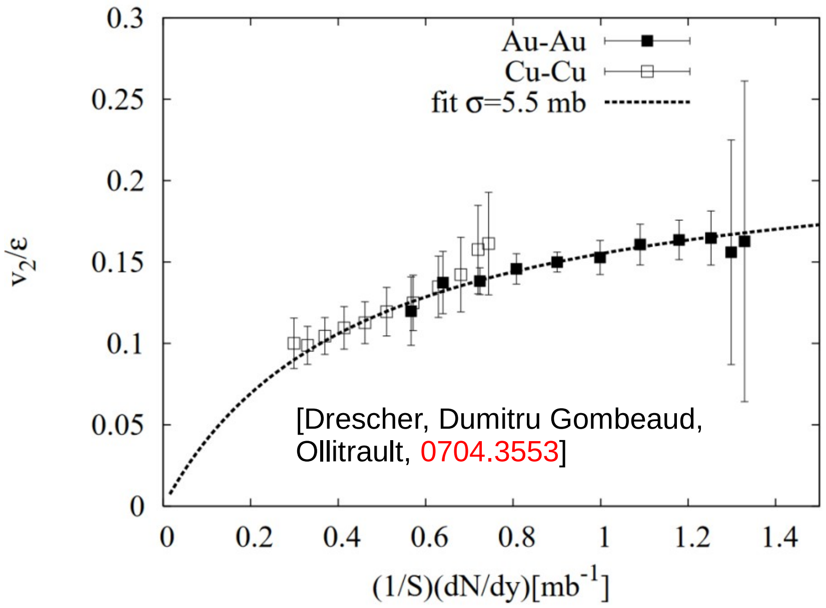
v_2/ε_2 [Voloshin, Poskanzer, nucl-th/9906075]

Approach: kinetic theory. New opacity variable.

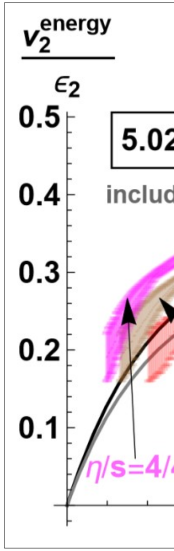
[Kurkela, Wiedemann, Wu, 1803.02072]

$$\hat{\gamma} = R^{3/4}\gamma(\varepsilon_0\tau_0)^{1/4}$$

- min. bias pp: $\hat{\gamma} \approx 0.88 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{0.4\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{5\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{40}\right)^{-1/4}$
- central PbPb: $\hat{\gamma} \approx 9.2 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{6\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{4000\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{40}\right)^{-1/4}$



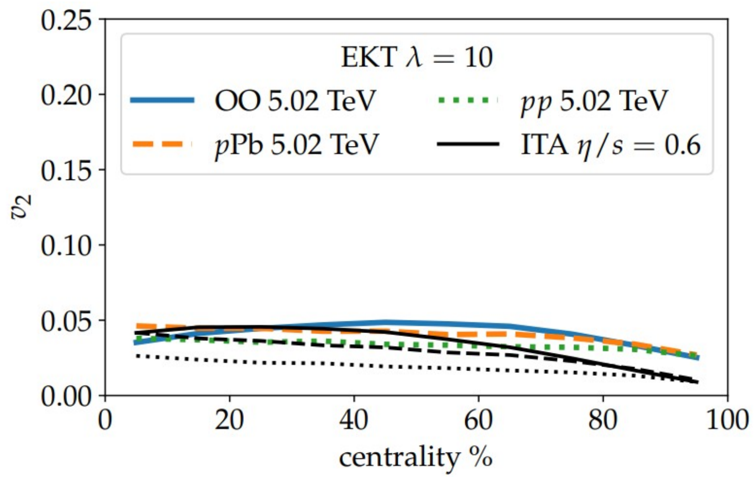
[Drescher, Dumitru Gombeaud, Ollitrault, 0704.3553]



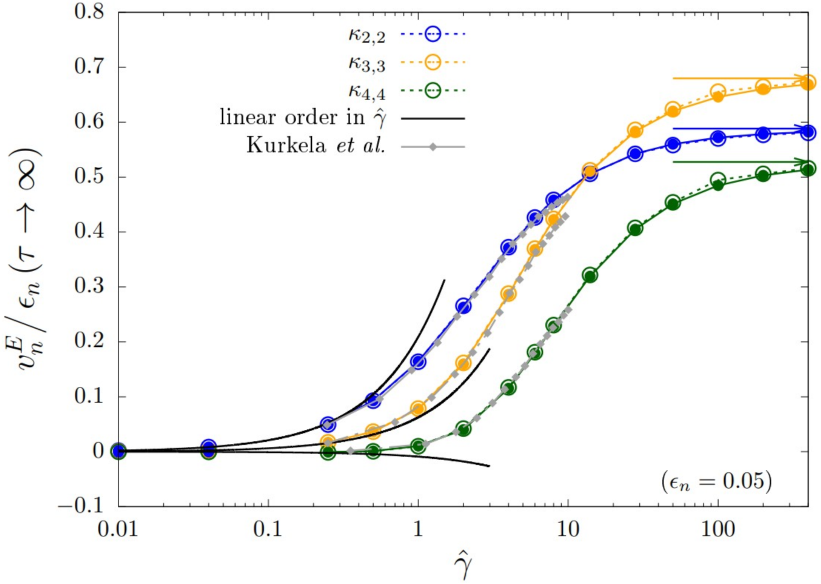
[Kurkela, Wiedemann, Wu, 1905.05139]

Lots of tools being developed. Great program ahead.

- New billiard ball Monte Carlo calculations and analytical methods. [Borghini,Roch, 2012.02138] [Borrell, Borghini, 2109.15218] [Borghini, Borrell, Roch, 2201.13294]
- QCD effective kinetic theory (EKT) kernel implemented in single-hit approximation. [Kurkela, Mazeliauskas, Törnkvist, 2104.08179]
- Kinetic theory solved at all opacities with detailed transverse dynamics. [Kurkela, Taghavi, Wiedemann, Wu, 2007.06851] [Ambrus, Schlichting, Werthmann, 2109.03290]



TALK BY CLEMENS WERTHMANN



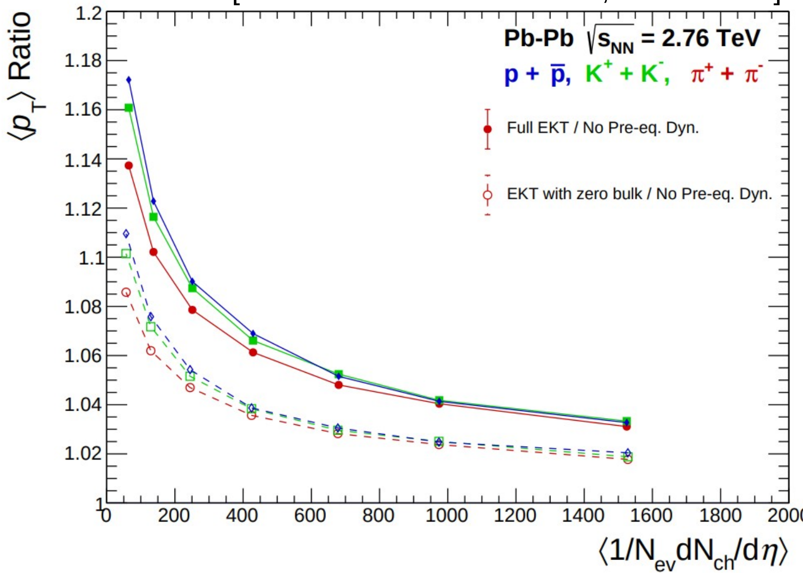
IMPORTANT – Question of conformal symmetry: matching to QCD EOS?

$$\Pi + p(e) = \frac{e}{3}$$

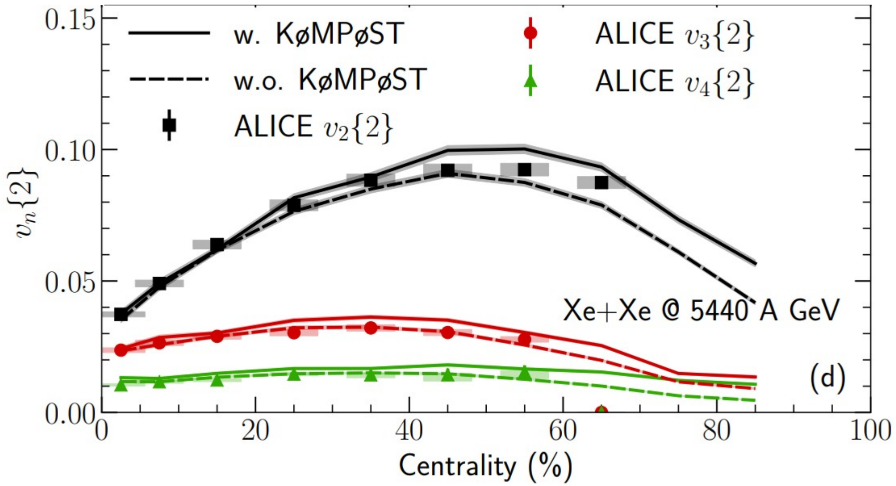
Effect of pre-hydrodynamic phase seem more important towards small systems.

How much of that is an artifact?

[The ExTrEMe Collaboration, 2006.02324]



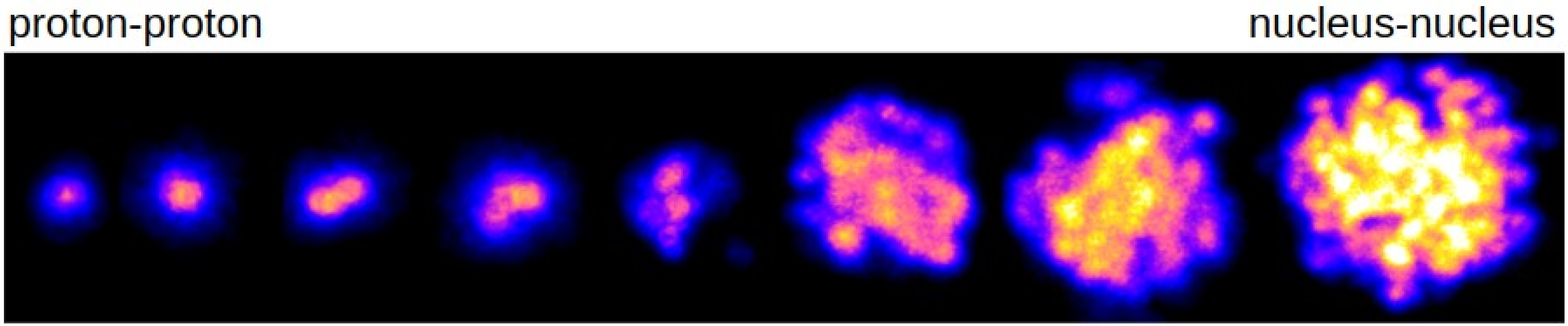
[Gale, Paquet, Schenke, Shen, 2106.11216]



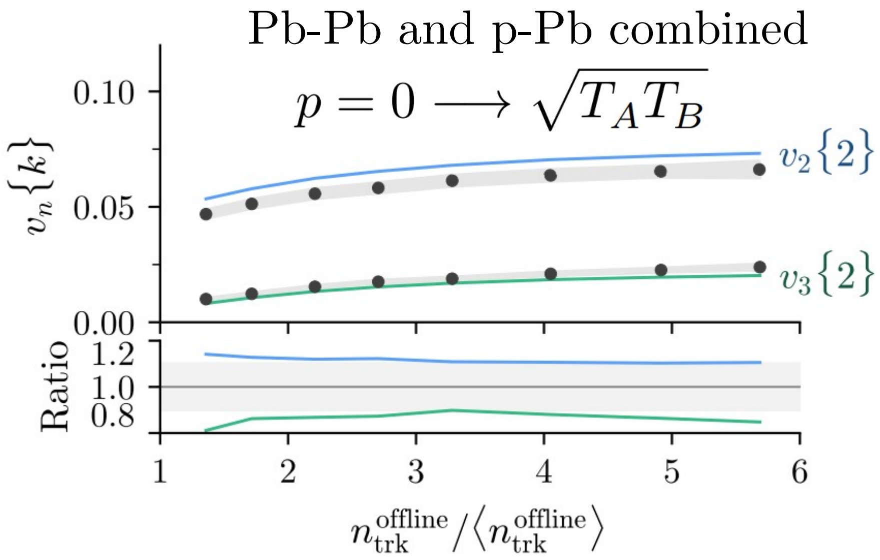
Besides the dynamics, we need to know the initial conditions.

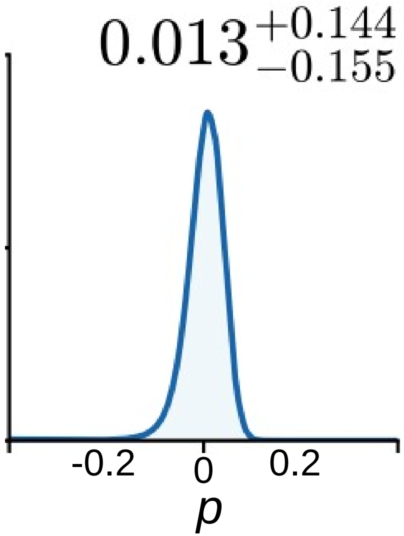
From large to small systems?

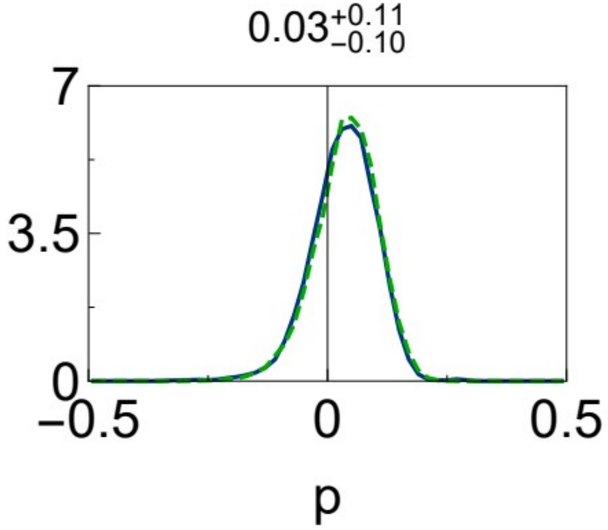
Potentially, obtaining information from data is a simpler task.



Status: data-driven consistency between p-Pb and Pb-Pb.







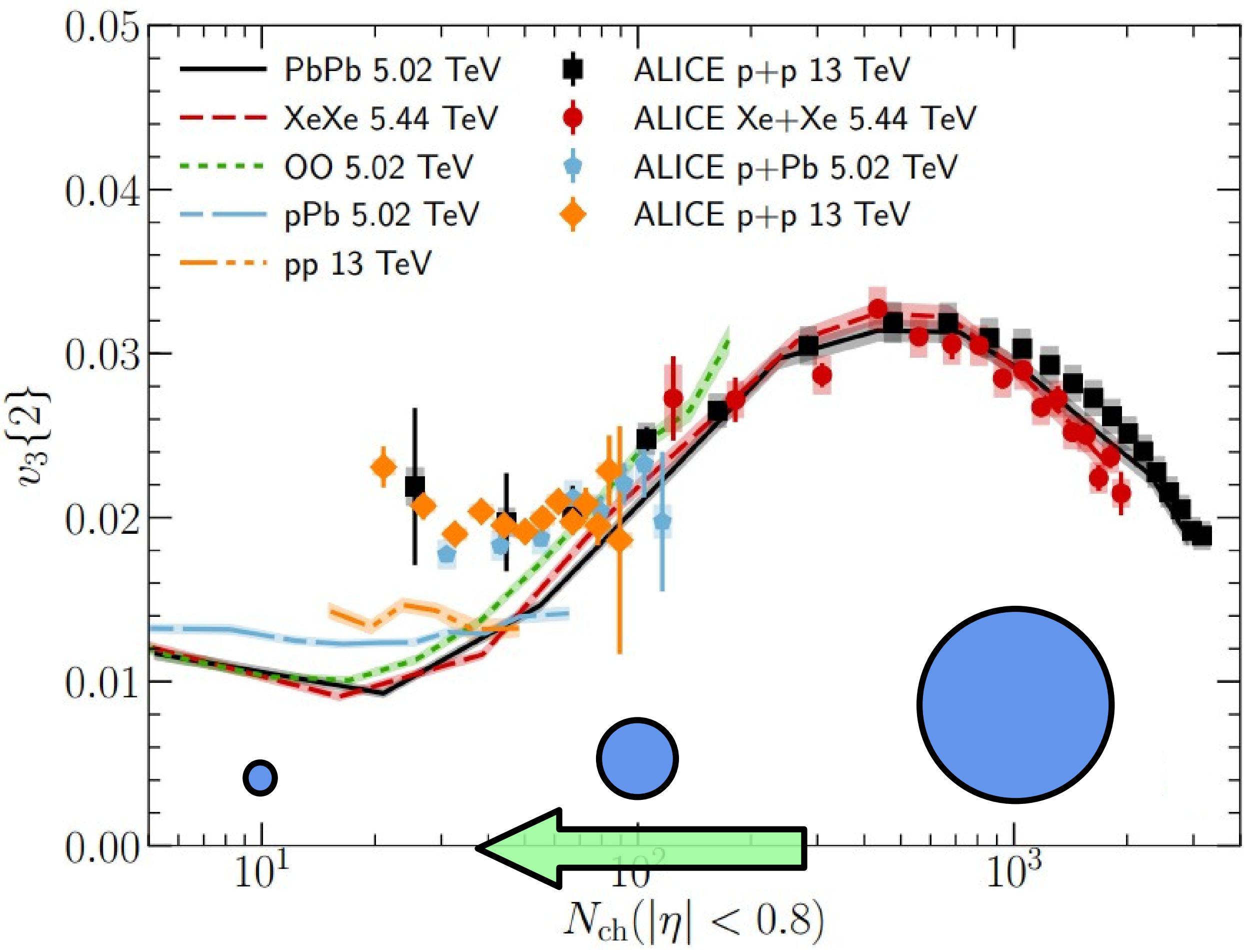
[Bass, Bernhard, Moreland 1808.02106]
[Nijs, van der Schee, Gürsoy, Snellings 2010.15130, 2010.15134]

CURRENT PARADIGM:

CGC-like energy deposition + sub-nucleonic structure. **NB:** p=1 (wounded nucleons) excluded.

Constraining the initial state.

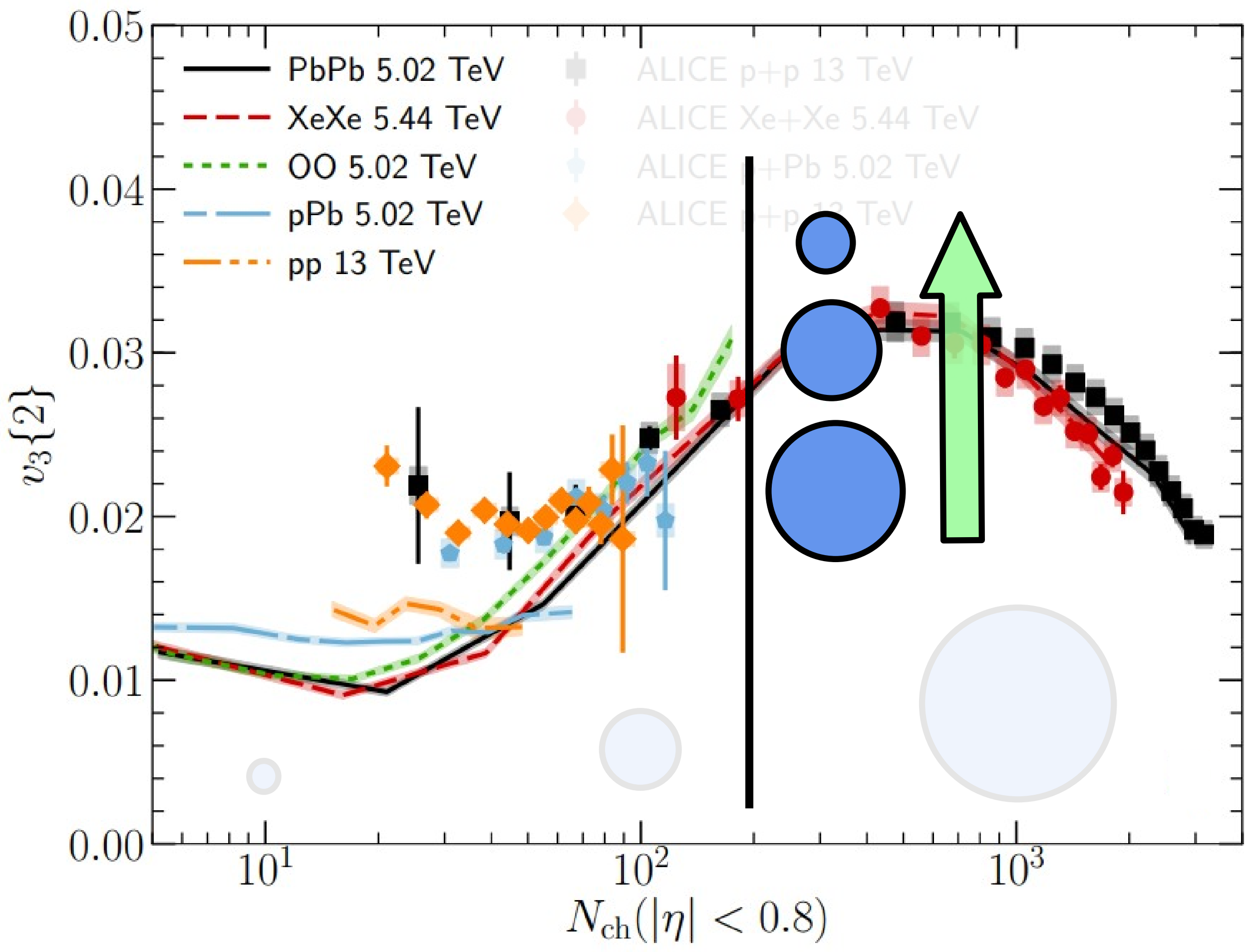
What else can we do?



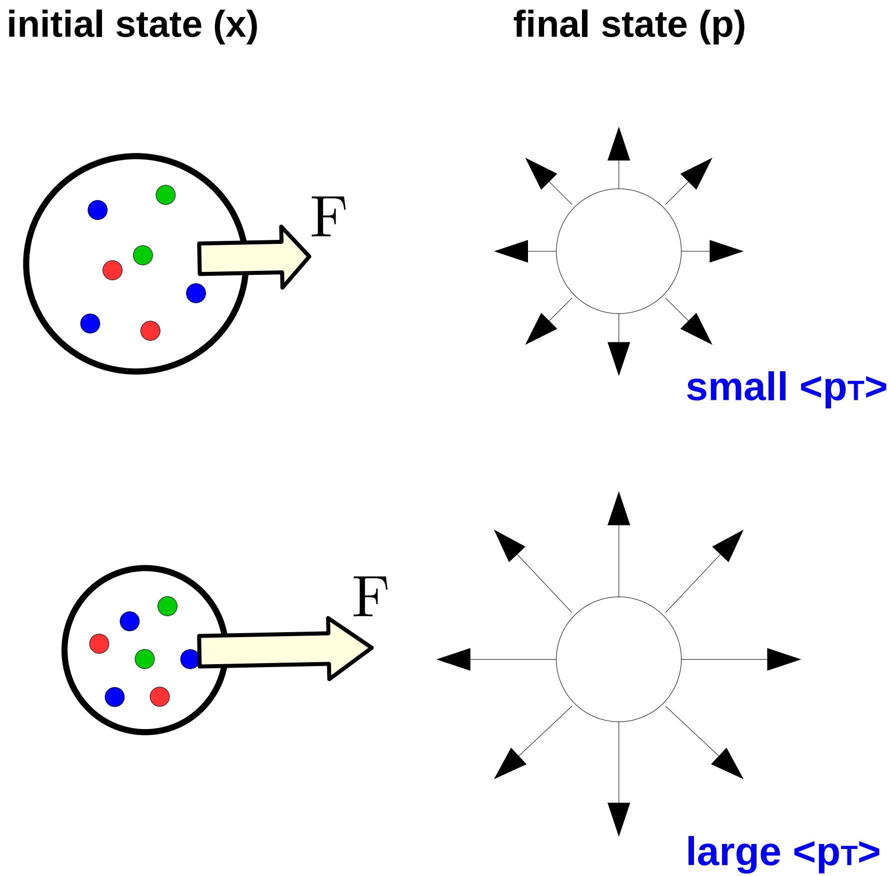
Constraining the initial state.

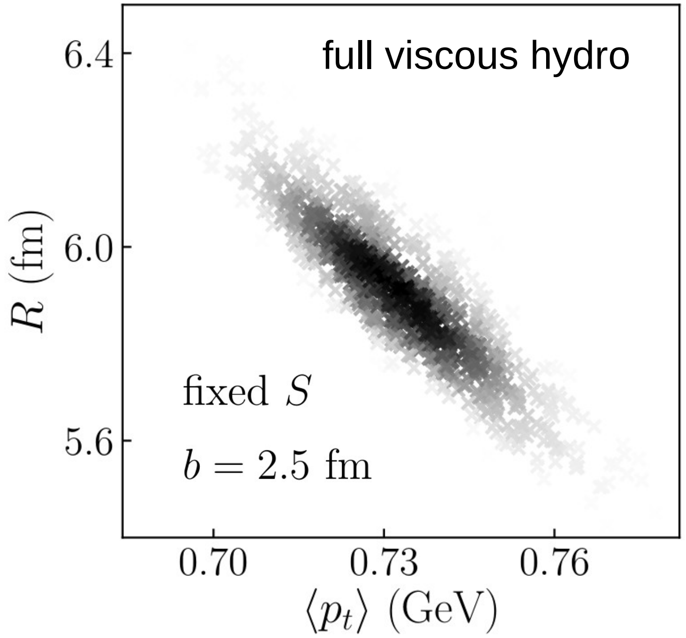
How about this?

System size dependence @ fixed multiplicity.



How? Answer from Krakow: with the mean transverse momentum.

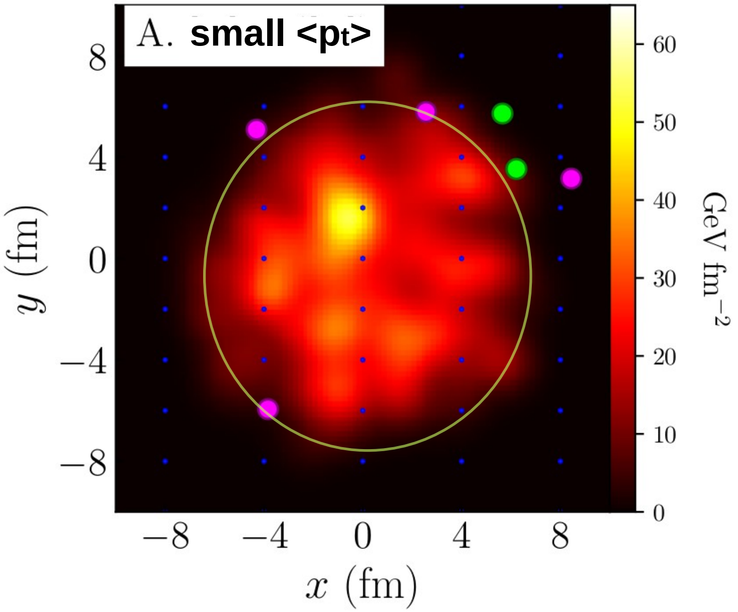




[Broniowski, Chojnacki, Obara, 0907.3216]
[Bozek, Broniowski, 1203.1810]
[Bozek, Broniowski, 1701.09105]

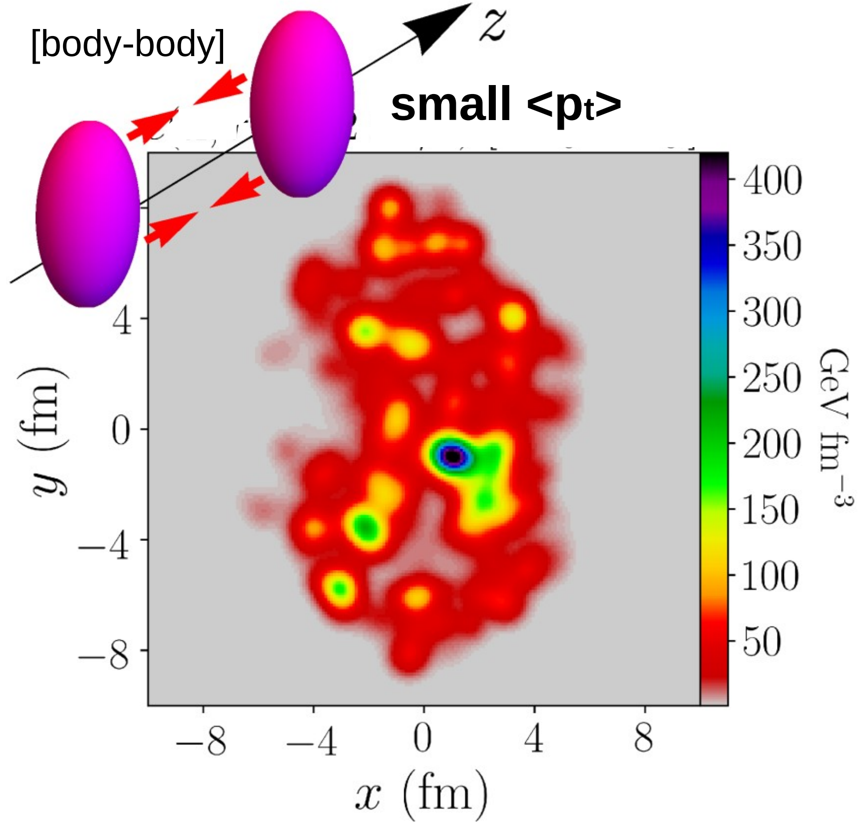
Playing with the QGP.

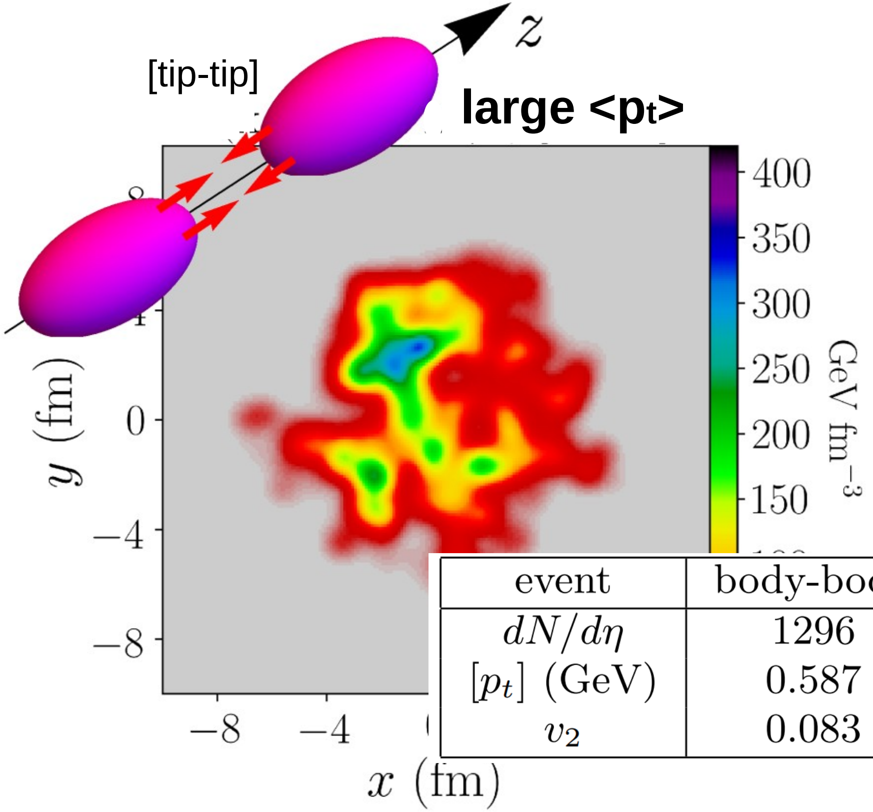
System size dependence of collective properties.



event	A	B
$N_{\rm ch}$	2813	2791
b (fm)	0.49	4.41
N_s	6	72
$[p_t]/\langle[p_t]\rangle$	0.976	1.028
$\langle B_y\rangle/m_\pi^2$	0.013	0.151
R (fm)	4.53	4.03
ε_2	0.073	0.153

IMPORTANT – Playing with the QGP and the shape of nuclei in central collisions.





event	body-body	tip-tip
$dN/d\eta$	1296	1280
$[p_t]$ (GeV)	0.587	0.651
v_2	0.083	0.027

New tool to access nuclear shapes experimentally.

TALK BY SOMADUTTA BHATTA

In practice: correlate observables, e.g. v_n, with the mean p_t.

$$\langle v_n^2 \delta[p_t] \rangle \equiv \left\langle \frac{\int_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3} (p_1 - \langle\langle p \rangle\rangle) e^{in(\phi_2-\phi_3)} \frac{dN}{d^2\mathbf{p}_1 d^2\mathbf{p}_2 d^2\mathbf{p}_3}}{\int_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3} \frac{dN}{d^2\mathbf{p}_1 d^2\mathbf{p}_2 d^2\mathbf{p}_3}} \right\rangle$$

First mention in a principal component analysis. [Mazeliauskas, Teaney, 1509.07492]

Bożek's formulation as a Pearson correlation coefficient:

$$\rho(v_n^2, [p_t]) = \frac{\langle \delta v_n^2 \delta[p_t] \rangle}{\sqrt{\langle (\delta v_n^2)^2 \rangle \langle (\delta[p_t])^2 \rangle}}$$

[Bożek, 1601.04513]

With $\delta o = o - \langle o \rangle$ at fixed multiplicity (entropy).

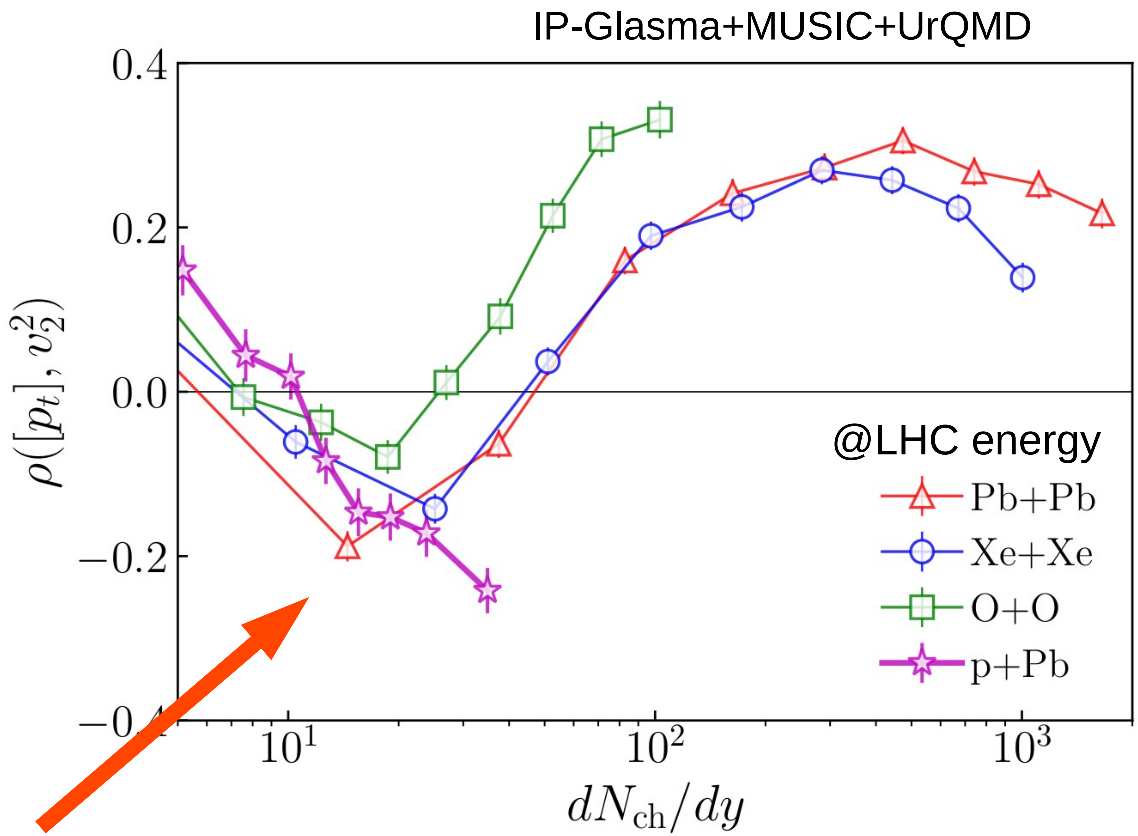
Event-by-event techniques may also be viable.

[Beattie, Nijs, Sas, van der Schee, 2203.13265]

Positive correlation in ‘large systems’.

What happens towards low Nch?

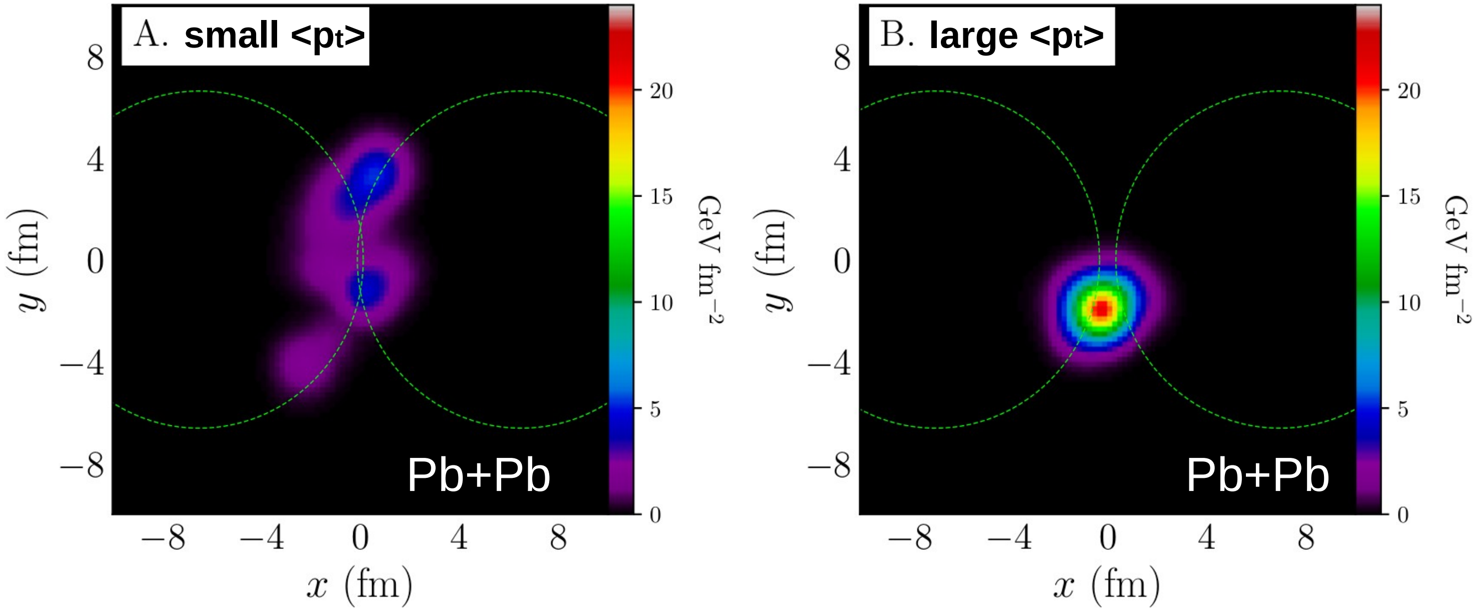
What do we learn?



Goes to negative values.
Universal feature.

Manipulating the collision geometry in small systems.
At large mean pt, hot spots are clustered around one point.

[Schenke, Shen, Teaney, 2004.00690]



event	A	B
N_{ch}	134	134
b (fm)	13.0	13.9
$[p_t]/\langle[p_t]\rangle$	0.907	1.143
R (fm)	2.97	1.34
ε_2	0.675	0.133
ε_3	0.229	0.067

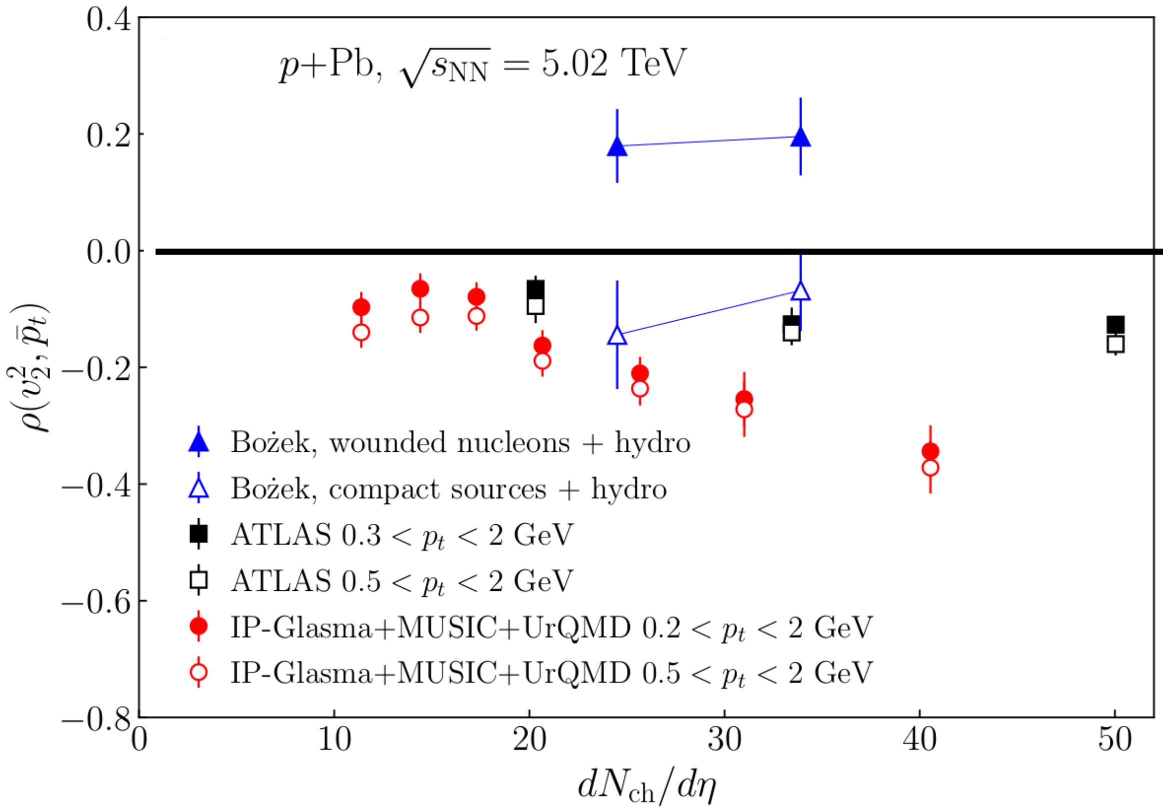
Predicts negative correlation between anisotropy and system size.

$$\rho(v_n^2, [p_t]) < 0$$

QM22: The picture is verified in ATLAS and CMS data.

[Bozek, 1601.04513]
[ATLAS Collaboration, 1907.05176]
[Bożek, Mehrabpour, 2002.08832]
[Schenke, Shen, Teaney, 2004.00690]

TALK BY SHENGQUAN TUO



wounded nucleons

$$(T_A + T_B)$$

CGC- or TRENTo-like

$$\left(T_A(\mathbf{x})T_B(\mathbf{x})\right)^q$$

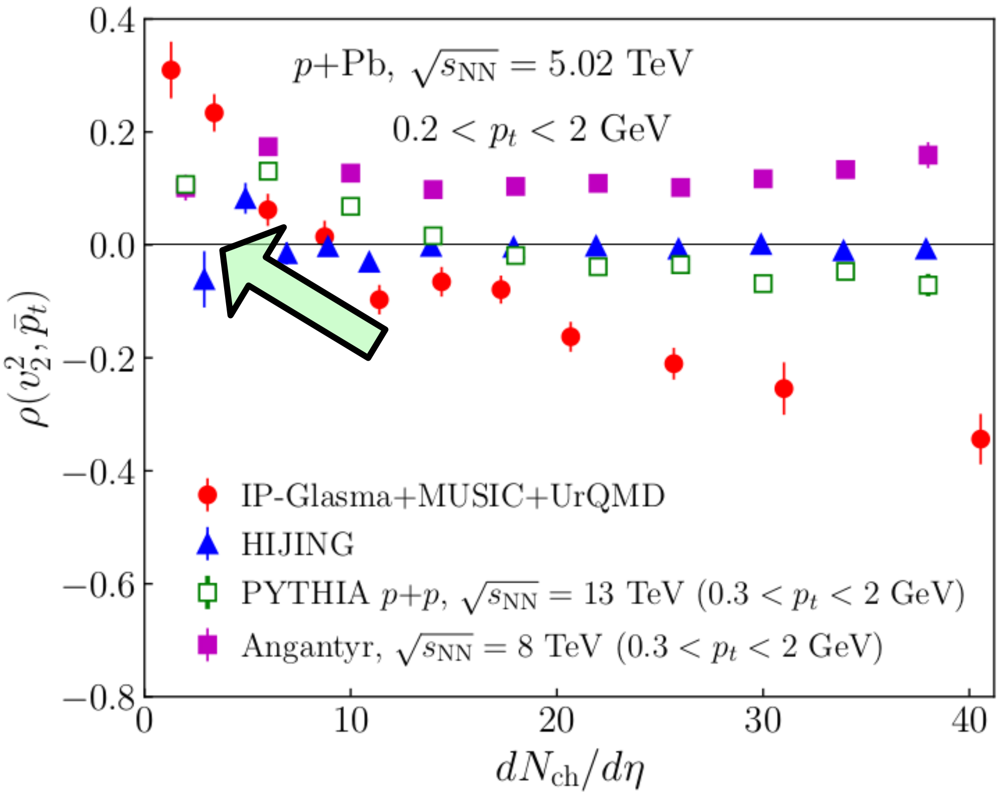
Constrains the energy deposition in pA collisions (independent of AA)!

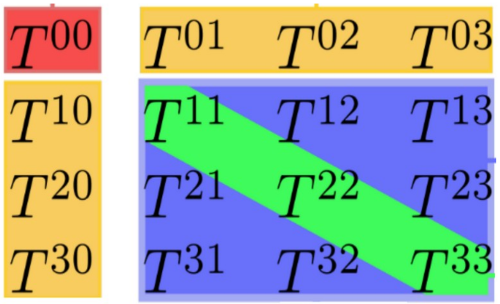
Independent proof of paradigm where flow emerges from sub-nucleonic structure.

IMPORTANT – initial state in the smallest systems (1/2)

Going beyond the response to the geometry?

[Giacalone, Schenke, Shen **2006.15721**]





"MOMENTUM" ANISOTROPY

$$\mathcal{E}_{2p} \propto \langle T^{xx} - T^{yy} + 2iT^{xy} \rangle$$

Comprehensive analyses in non-flow models.

[Behera, Bhatta, Jia, Zhang, **2102.05200**]

[Lim, Nagle, **2103.01348**]

No sign change in CMS data with large η gap.

TALK BY SHENGQUAN TUO

Initial momentum anisotropy is short-range.

[Schenke, Schlichting, Singh, **2201.08864**]

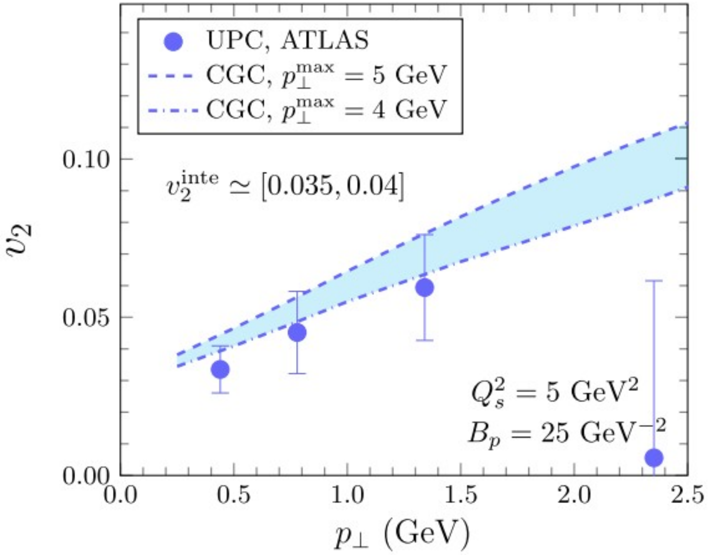
TALK BY PRAGYA SINGH

IMPORTANT – initial state in the smallest systems (2/2)

TALK BY DENNIS PEREPELITSA

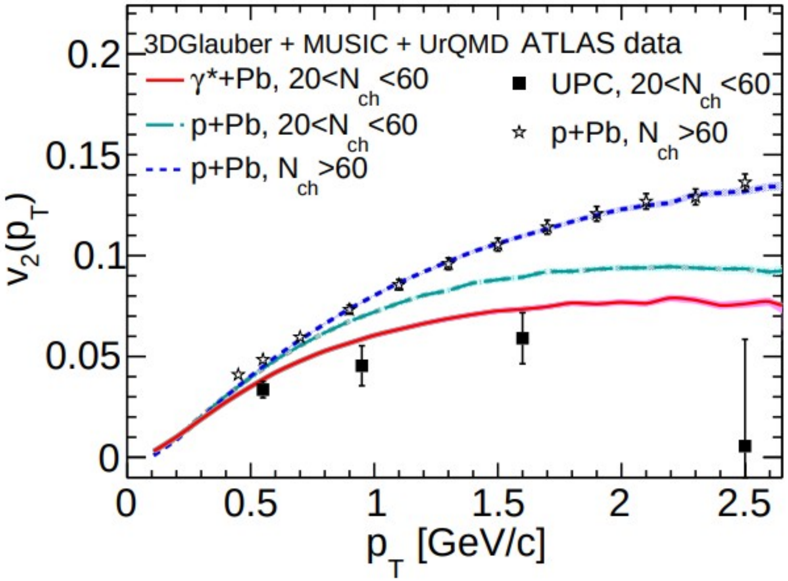
Collective flow observed in EIC-like gamma-A collisions (UPC). Origin?

initial-state-only



[Shi, Wang, Wei, Xiao, Zheng, 2008.03569]

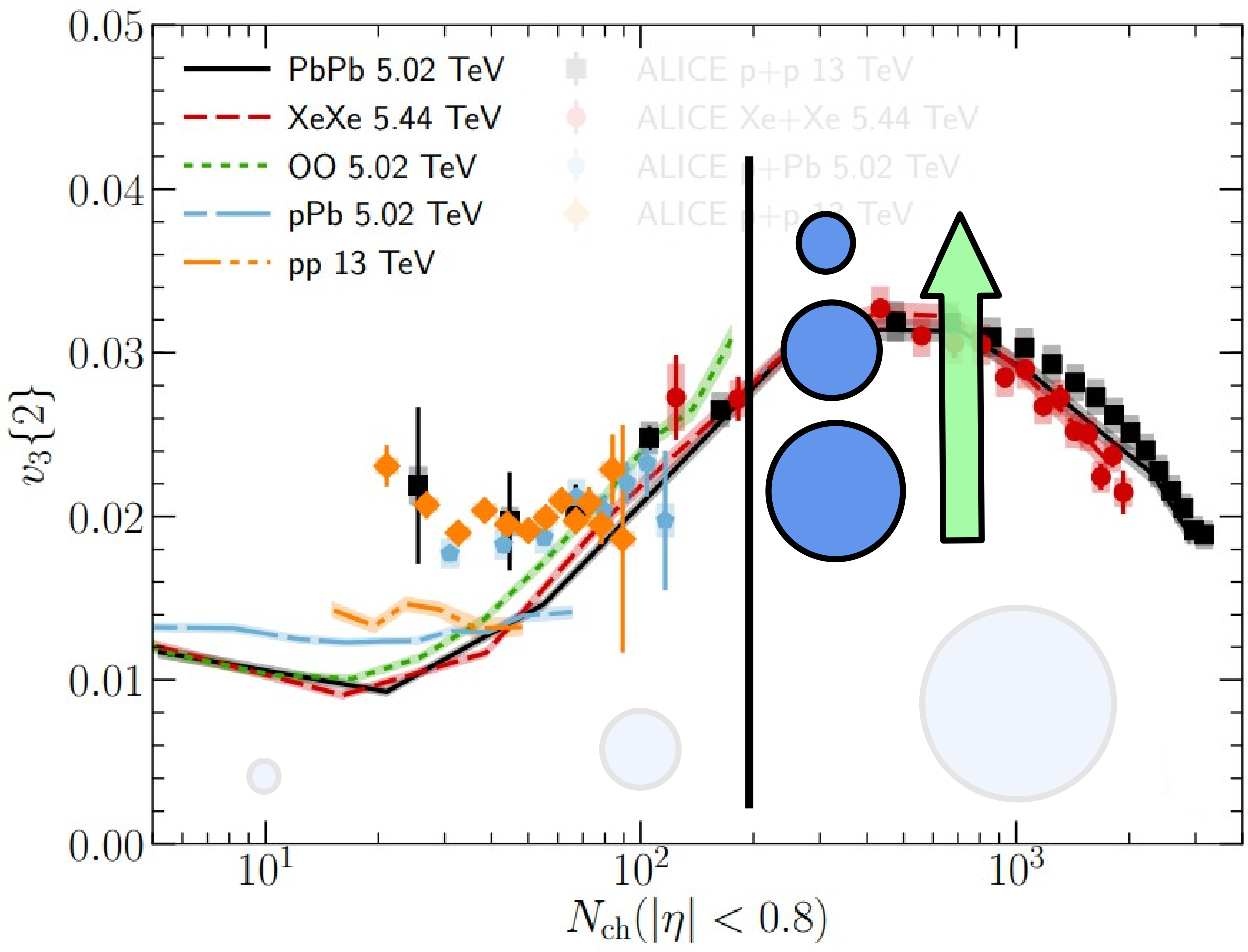
final-state-only



[Zhao, Shen, Schenke, 2203.06094]

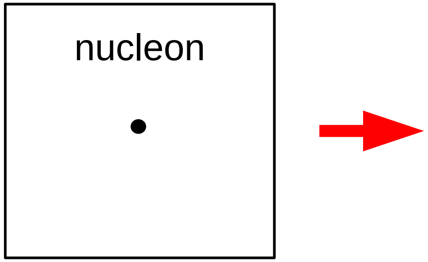
Flow-mean pt correlation to disentangle the effects?

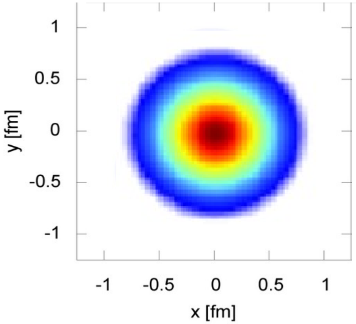
Constraining the initial state.



Sensitive to nucleon structure?

Nucleon structure at high energy? Discussed mostly in small systems (e+p).





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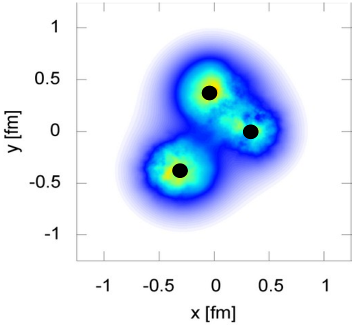


- 2-gluon radius from diffractive J/ψ photoproduction at HERA. **Scale ~ 0.4 fm.**

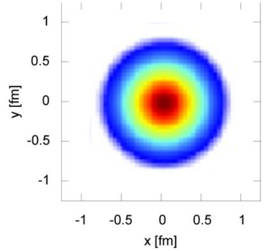
PHYSICAL REVIEW C **81**, 025203 (2010)

Investigating the gluonic structure of nuclei via J/ψ scattering

A. Caldwell[1] and H. Kowalski[2,*]

The corresponding proton Gaussian width is $B_G = 3.18 \pm 0.4\ \mathrm{GeV}^{-2}$, where we added the theoretical and experimental errors in quadrature. The transverse proton radius is then

$$\sqrt{\langle b^2\rangle} = \sqrt{\int d^2\vec{b}\, b^2 T_G(b)} = \sqrt{2\cdot B_G} = 0.50 \pm 0.03\ \mathrm{fm}.$$

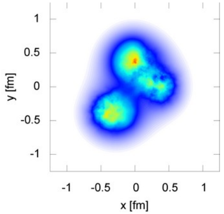


- Fluctuating protons from incoherent J/ψ photoproduction at HERA. **Parton scale ~ 0.1fm.**

[Mäntysaari, Schenke **1603.04349**, **1607.01711**]

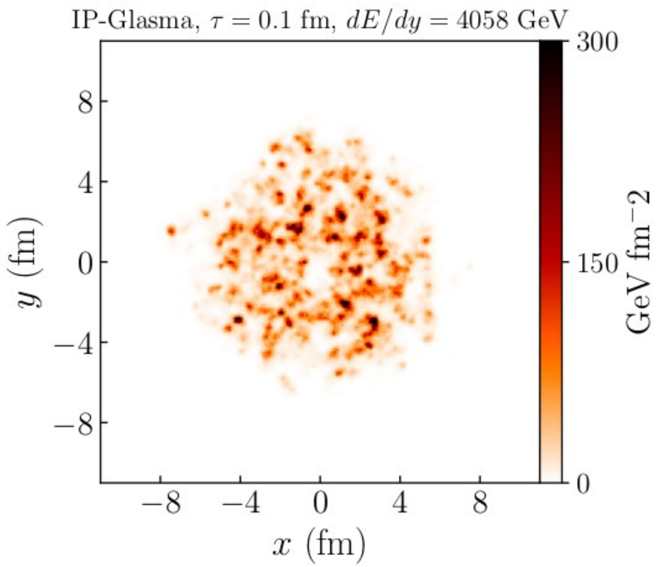
Number of constituents poorly constrained (may be higher).

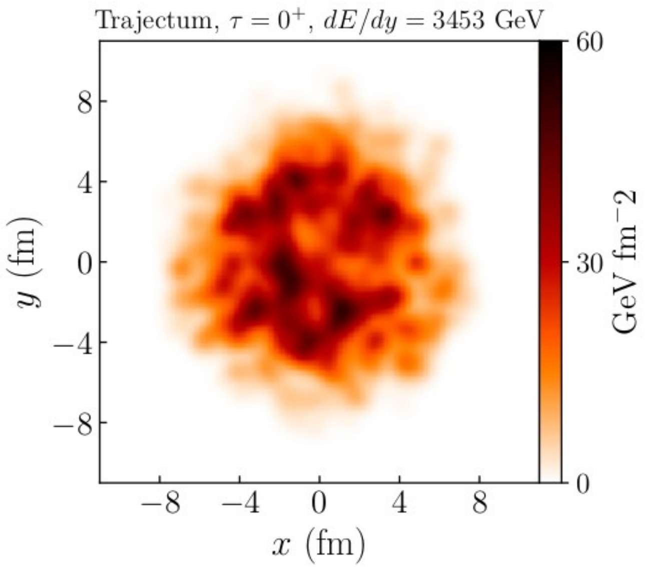
[Mäntysaari, Schenke, Shen, Zhao **2202.01998**]

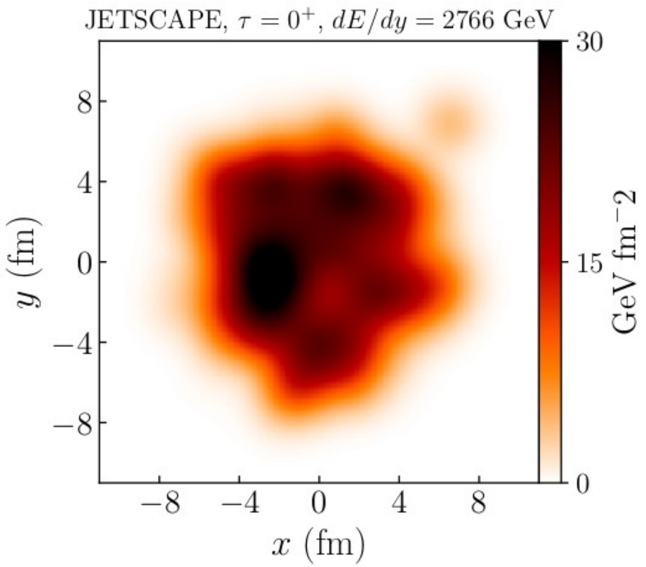


TALK BY HEIKKI MÄNTYSAARI

STATE-OF-THE-ART MODELS







[Schenke, Shen, Tribedy 2005.14682]

[Nijs, van der Schee, Gürsoy, Snellings 2010.15130, 2010.15134]

[Nijs, van der Schee 2110.13153,2112.13771]

[Bass, Bernhard, Moreland 1808.02106]

[Parkkila, Onnerstad, Taghavi, Mordasini, Bilandzic 2111.08145]

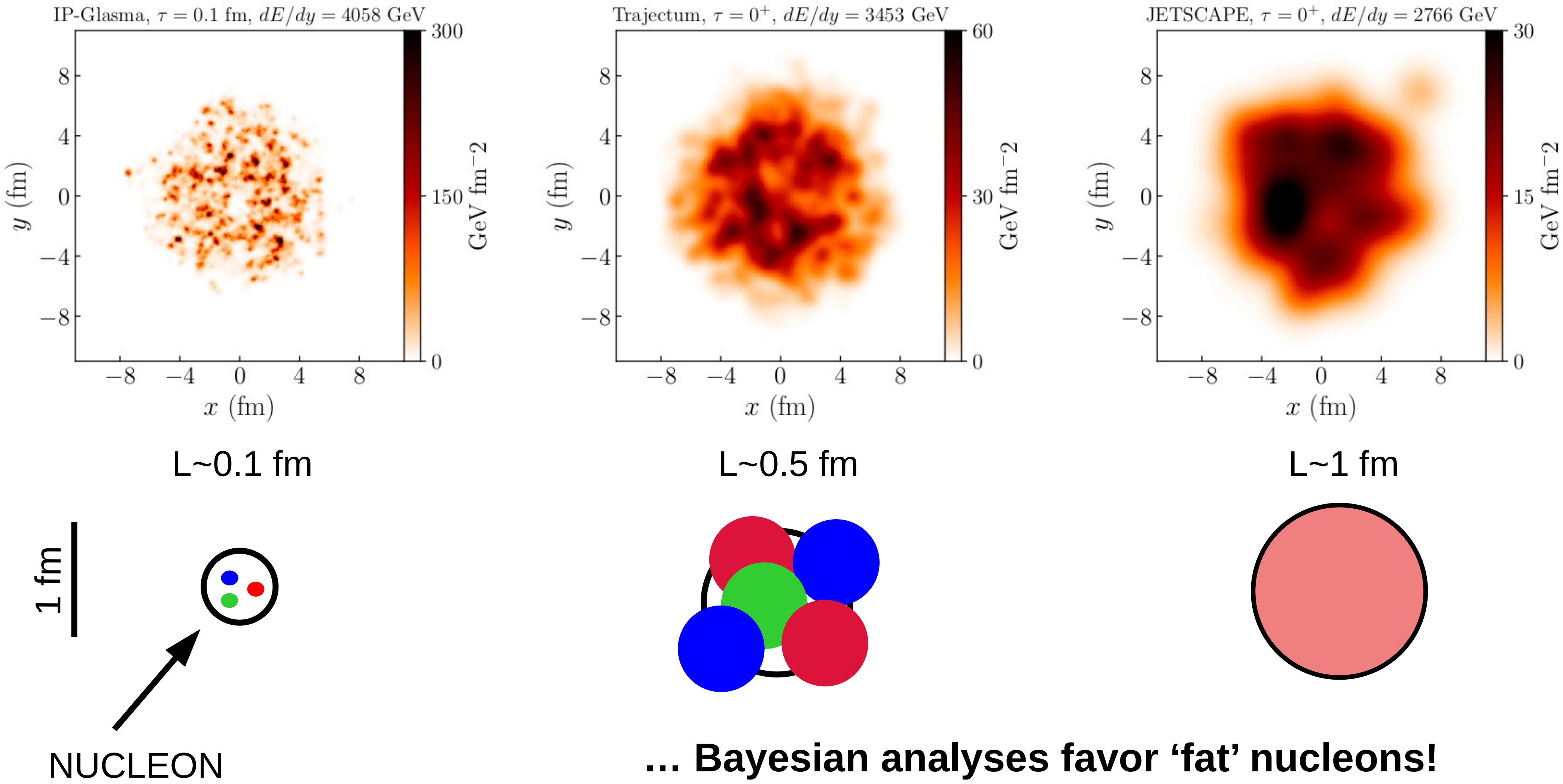
[Parkkila, Onnerstad, Kim 2106.05019]

[JETSCAPE Collaboration 2011.01430, 2010.03928]

[Bass, Bernhard, Moreland Nature Phys. 15 (2019)]

… WHY SO DIFFERENT?

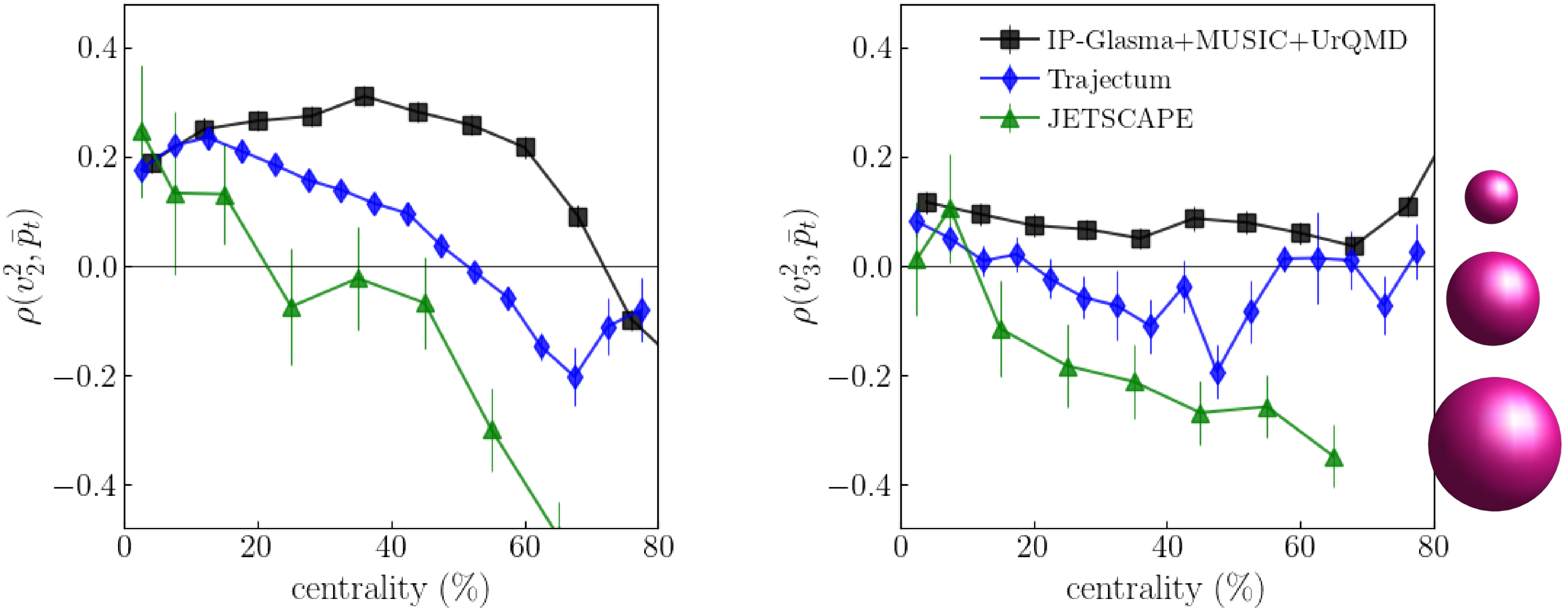
STATE-OF-THE-ART MODELS



… Bayesian analyses favor ‘fat’ nucleons!

Can we discern different models? Highlight from 2021.

TALK BY VYTAUTAS VISLAVICIUS



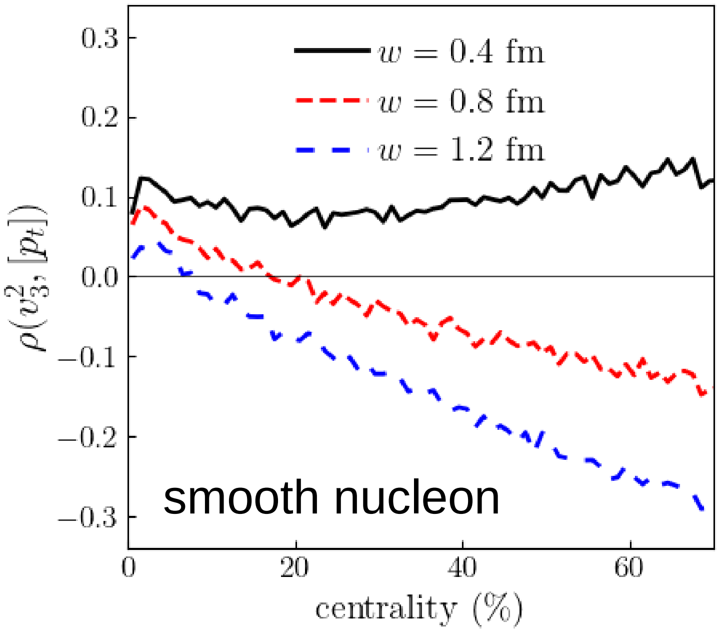
Qualitatively different results largely driven by the nucleon size.

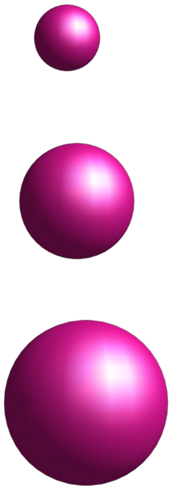
Exp. data favors small width. Bayesian analyses not comprehensive enough.

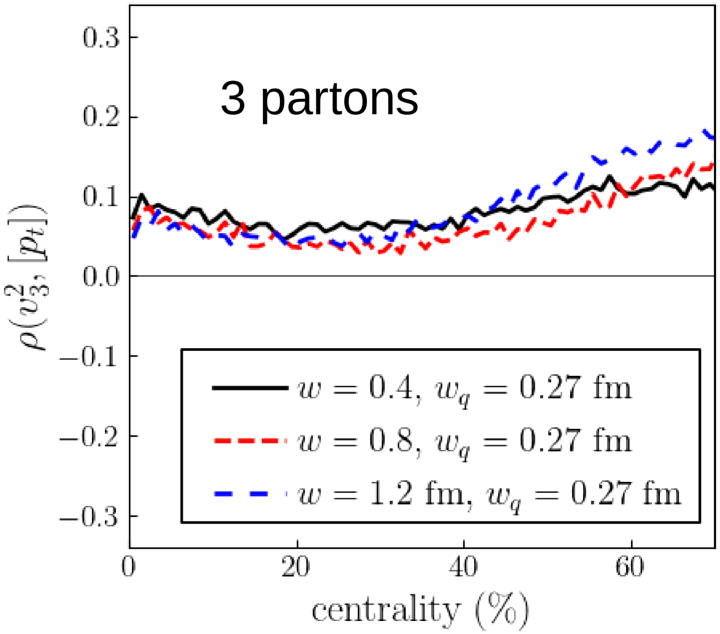
The relevant length scale?

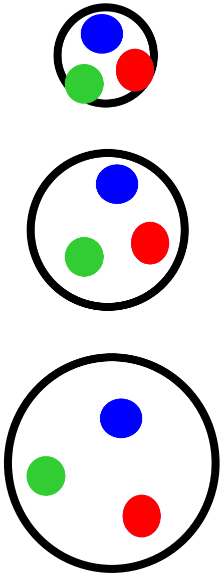
[Giacalone, Schenke, Shen 2111.02908]

TRENTo estimates in Pb+Pb









Constraints on sub-nucleon scales from large systems!
IMPORTANT: goes beyond the nucleon size constraint from AA cross section.

TALK BY GOVERT NIJS

RECAP

- Changing system size leads to unique information about the dynamics, both in fluid and non-fluid regimes.

  Prospect: Combining O-O and Pb-Pb data. Rich program of QCD kinetic theories ahead.

- Changing system size at fixed particle number leads to unique information about the initial geometry.

  Prospect: Pinning down the energy deposition. We access sub-nucleonic scales with AA collisions, we need more comprehensive Bayesian analyses.

THANK YOU!

ExtreMe Matter Institute EMMI

EMMI Rapid Reaction Task Force

Nuclear Physics Confronts
Relativistic Collisions of Isobars

Heidelberg University, Germany, May 30 – June 3 & October 12-14 2022

Organizers:
Giuliano Giacalone
Jiangyong Jia
Vittorio Somà
You Zhou

Deciphering nuclear phenomenology across energy scales

https://esnt.cea.fr/Phocea/Page/index.php?id=107 **Sep 20th - Sep 23rd 2022**

Organizers:
Giuliano Giacalone (ITP Heidelberg)
Jean-Yves Ollitrault (IPhT Saclay)
You Zhou (Niels Bohr Institute)

Intersection of nuclear structure and high-energy nuclear collisions

Organizers:
Jiangyong Jia (Stony Brook & BNL)
Giuliano Giacalone (ITP Heidelberg)
Jacquelyn Noronha-Hostler (Urbana-Champaign)
Dean Lee (Michigan State & FRIB)
Matt Luzum (São Paulo)
Fuqiang Wang (Purdue)

Jan 23rd - Feb 24th 2023