U.S. DEPARTMENT OF ENERGY | Office of Science

Brookhaven National Laboratory

EFFECTS OF (SUB)NUCLEON STRUCTURE IN SMALL AND LARGE COLLISION SYSTEMS

BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

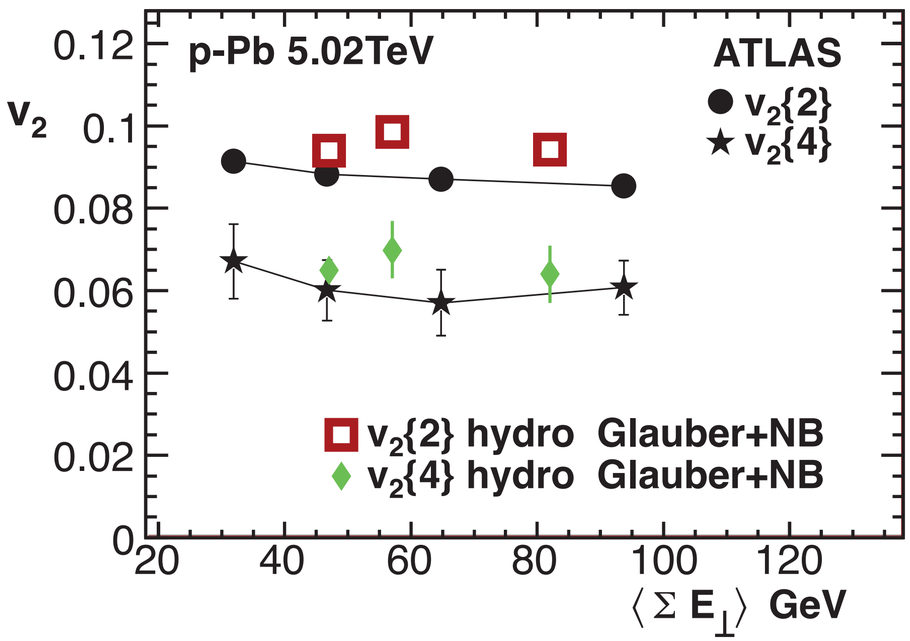
DECEMBER 6 2021

21ST ZIMÁNYI SCHOOL WINTER WORKSHOP ON HEAVY ION PHYSICS

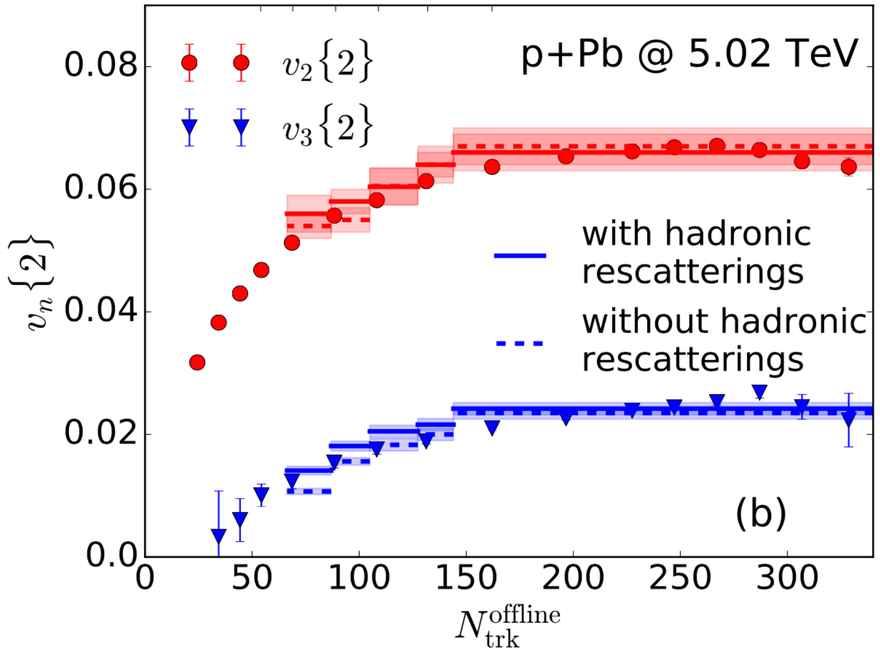
SMALL SYSTEM ANISOTROPIC FLOW

MC-Glauber (-like) models describe v_n without the need for subnucleon structure

ATLAS Coll. PLB725 (2013) 60-78



CMS Coll. PLB724, 213-240 (2013)



Bozek, Broniowski, PRC88 (2013) 014903

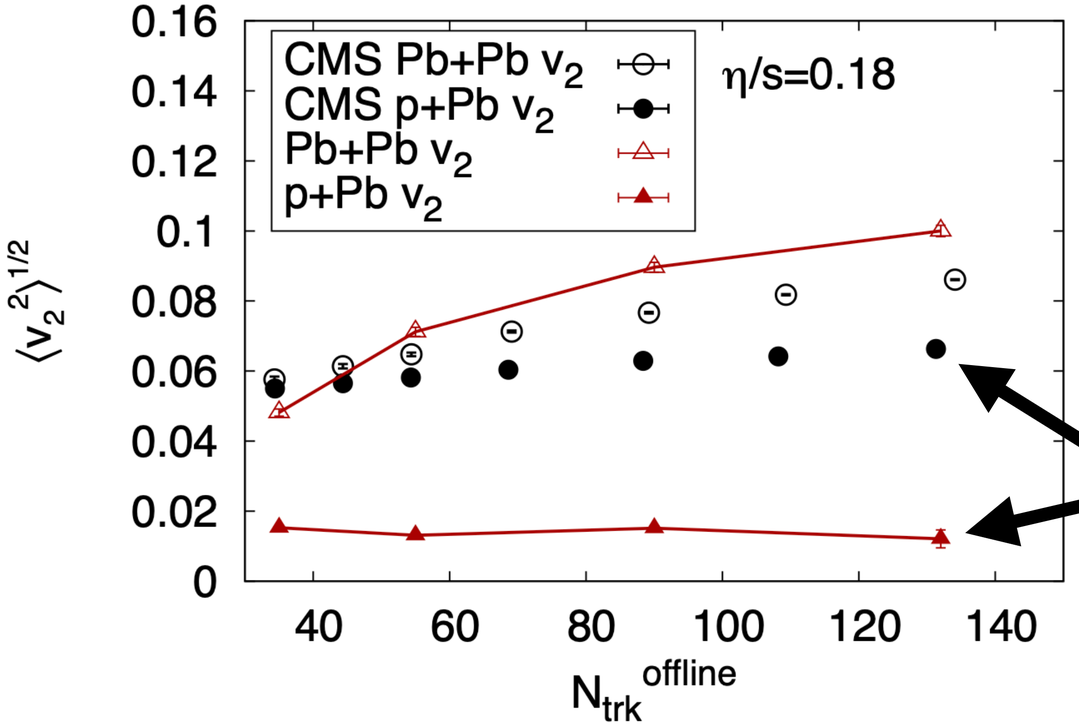
Shen, Paquet, Denicol, Jeon, Gale, PRC95 (2017) 014906

Also see: Kozlov, Luzum, Denicol, Jeon, Gale; Werner, Beicher, Guiot, Karpenko, Pierog; Romatschke; Kalaydzhyan, Shuryak, Zahed; Ghosh, Muhuri, Nayak, Varma; Qin, Mueller; Bozek, Broniowski, Torrieri; Habich, Miller, Romatschke, Xiang; T. Hirano, K. Kawaguchi, K. Murase; …

SMALL SYSTEM ANISOTROPIC FLOW

IP-Glasma + Hydrodynamics underestimated the v_n in p+Pb collisions

CMS Coll. PLB724, 213-240 (2013)



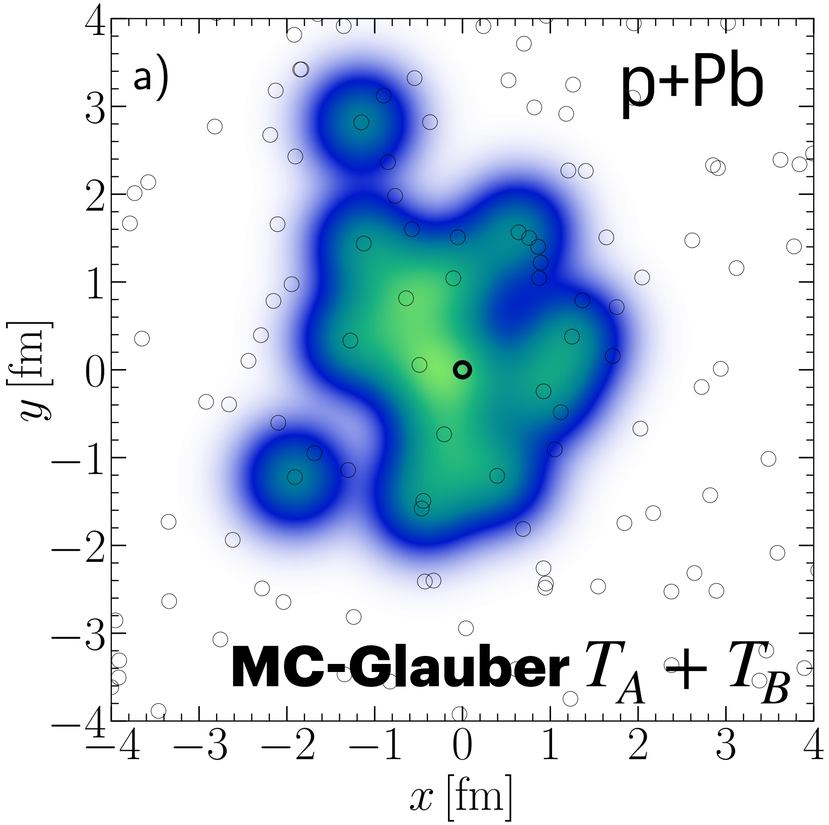
Large (factor ~5) difference between model and experimental data

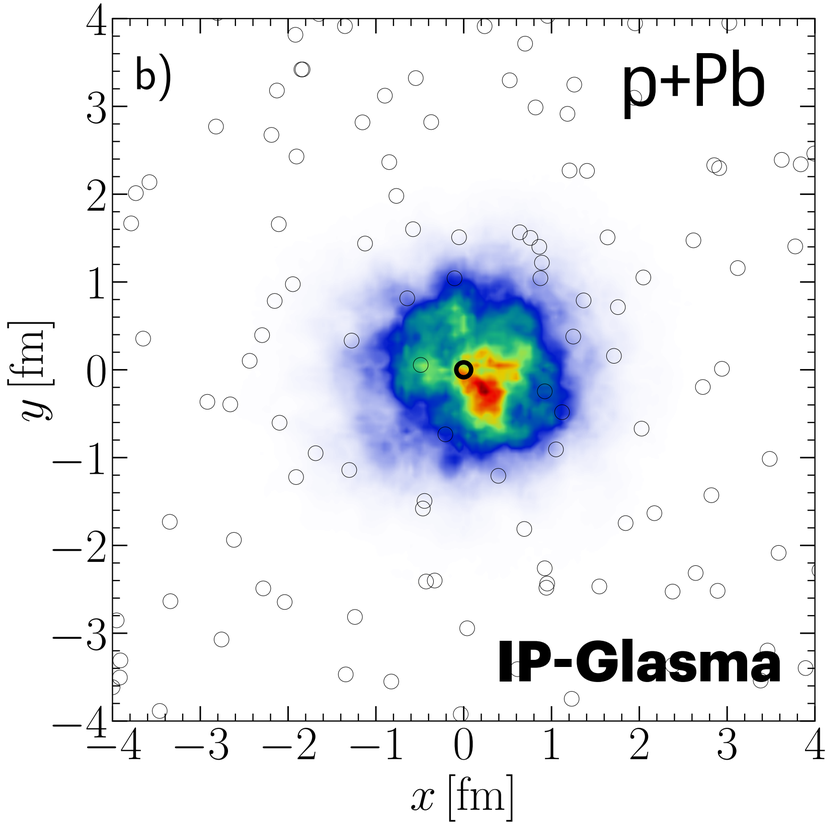
B. Schenke, R. Venugopalan, Phys.Rev.Lett. 113 (2014) 102301

ENERGY DEPOSITION MATTERS

Compare MC-Glauber $T_A + T_B$ to IP-Glasma with round nucleon ($\sim T_A T_B$)

B. Schenke, Rep. Prog. Phys. 84 082301 (2021)





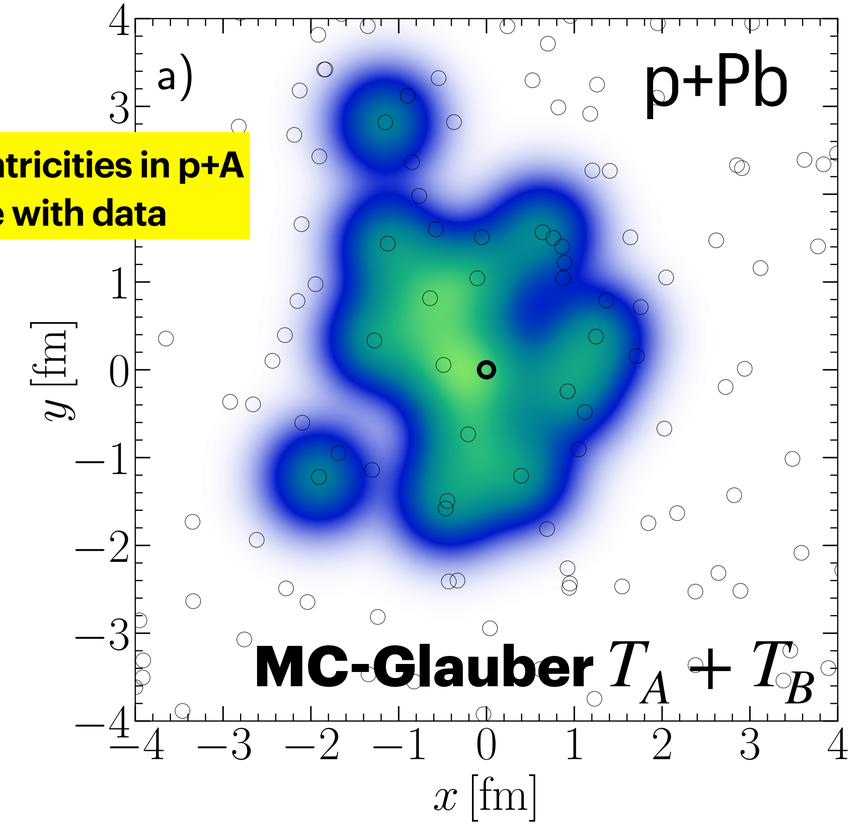
Proton position: thick circle; Nucleon positions in Pb: thin circles

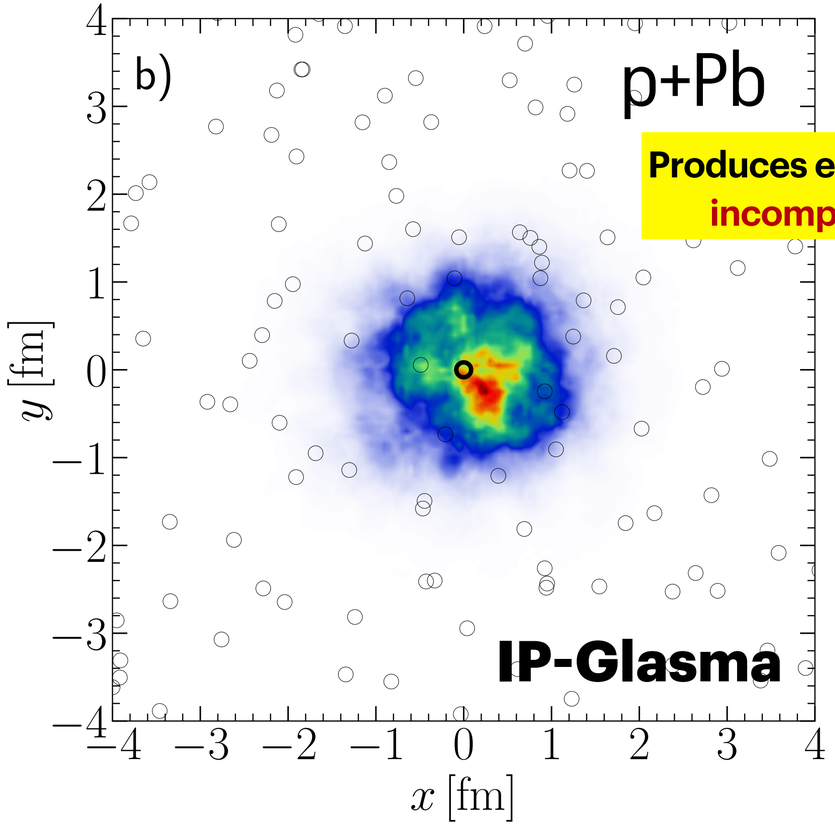
ENERGY DEPOSITION MATTERS

Compare MC-Glauber $T_A + T_B$ to IP-Glasma with round nucleon ($\sim T_A T_B$)

B. Schenke, Rep. Prog. Phys. 84 082301 (2021)

Produces eccentricities in p+A compatible with data





Produces eccentricities in p+A incompatible with data

Proton position: thick circle; Nucleon positions in Pb: thin circles

HOW SHOULD THE ENERGY DEPOSITION GO?

Energy (or entropy) deposition $\sim (T_A T_B)^q$ is preferred:

- **Bayesian analysis: Trento model prefers initial transverse entropy density to behave as $\sim \sqrt{T_A T_B}$ and also prefers a nucleon substructure**
  J.S. Moreland, J.E. Bernhard, and S.A. Bass, Phys. Rev. C 92 (2015) 011901
  G. Nijs, W. van der Schee, U. Gürsoy, R. Snellings, Phys.Rev.Lett. 126 (2021), Phys.Rev.C 103 (2021) 5, 054909
  JETSCAPE Collaboration, Phys.Rev.C 103 (2021) 5, 054904
- **AdS/CFT based calculations also result in such a relation**
  P. Romatschke, J.D. Hogg, JHEP 04 (2013) 048
- **IP-Glasma results in the initial energy density $\sim T_A T_B$**
- **$T_A + T_B$ disfavored by centrality dependence of v_2 in A+A** G. Giacalone, J. Noronha-Hostler, J.-Y. Ollitrault, Phys. Rev. C 95, 054910 (2017)

So, $T_A + T_B$ prescription with nucleons, that works for v_n in p+A, is generally disfavored

$\sim T_A T_B$ for round proton leads to too small fluctuations (eccentricities)

$\rightarrow$ subnucleon fluctuations required

CONSTRAINING NUCLEON SUBSTRUCTURE

Introduce a model for the nucleon substructure within IP-Glasma

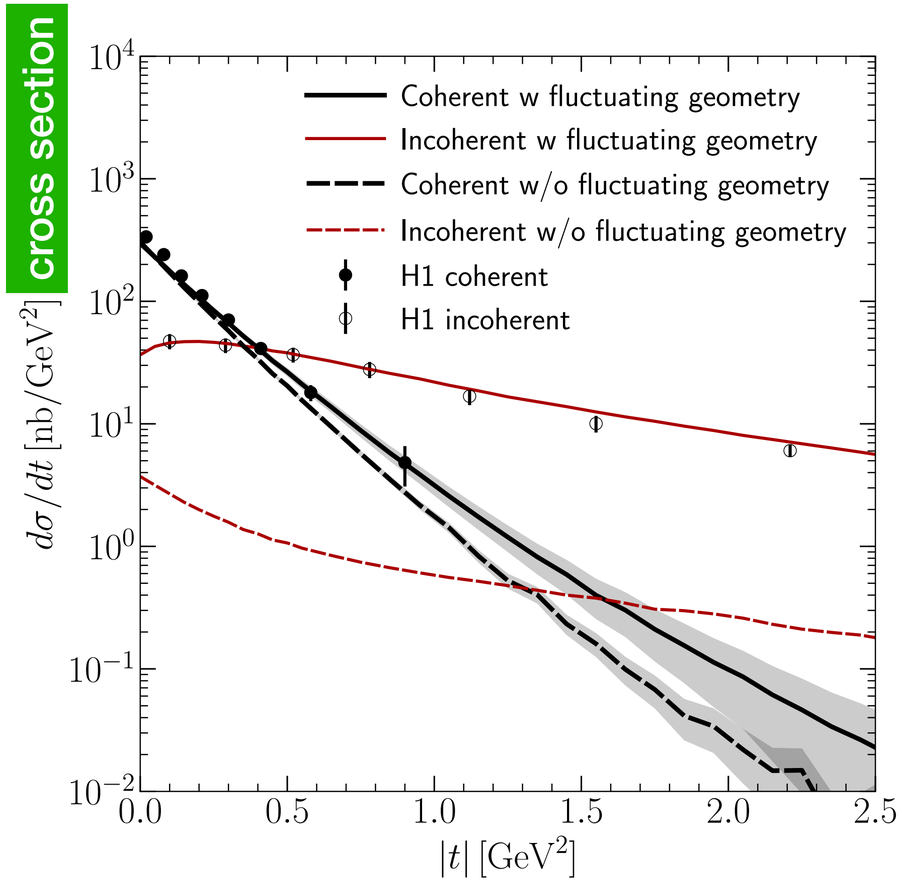
$$T_p(\vec{b}_\perp) = \sum_{i=1}^{N_q} T_q(\vec{b}_\perp - \vec{b}^{\,i}_\perp) \qquad T_q(\vec{b}_\perp) = \frac{1}{2\pi B_q} e^{-\vec{b}_\perp^{\,2}/(2B_q)}$$

with $\vec{b}^{\,i}_\perp$ sampled from a Gaussian with parameter B_{qc}

Constrain parameters B_{qc} and B_q with HERA data

Exclusive diffractive J/Ψ production in e+p: Incoherent x-sec sensitive to fluctuations

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301
Phys.Rev. D94 (2016) 034042
also see:
S. Schlichting, B. Schenke, Phys.Lett. B739 (2014) 313-319
H. Mäntysaari, Rep. Prog. Phys. 83 082201 (2020)
B. Schenke, Rep. Prog. Phys. 84 082301 (2021)

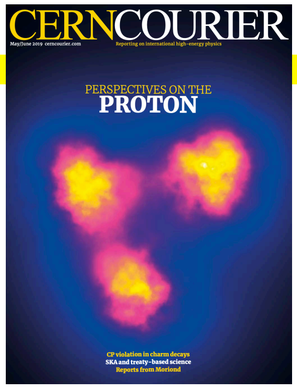


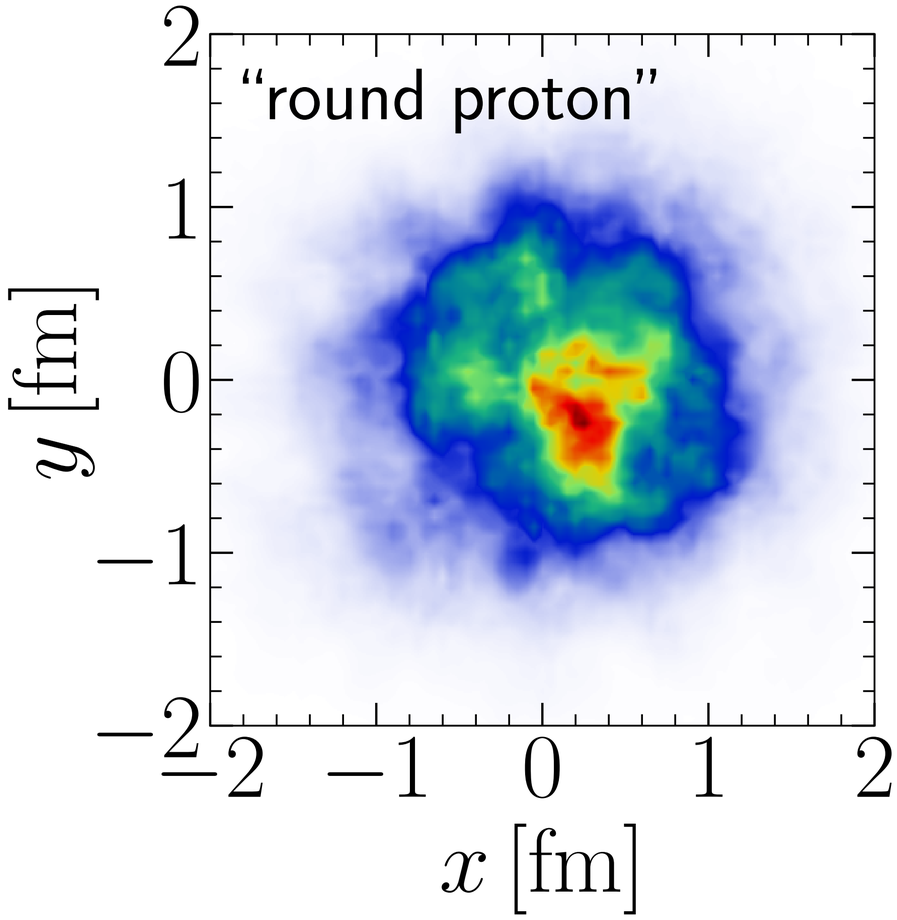
(transverse momentum transfer)^2

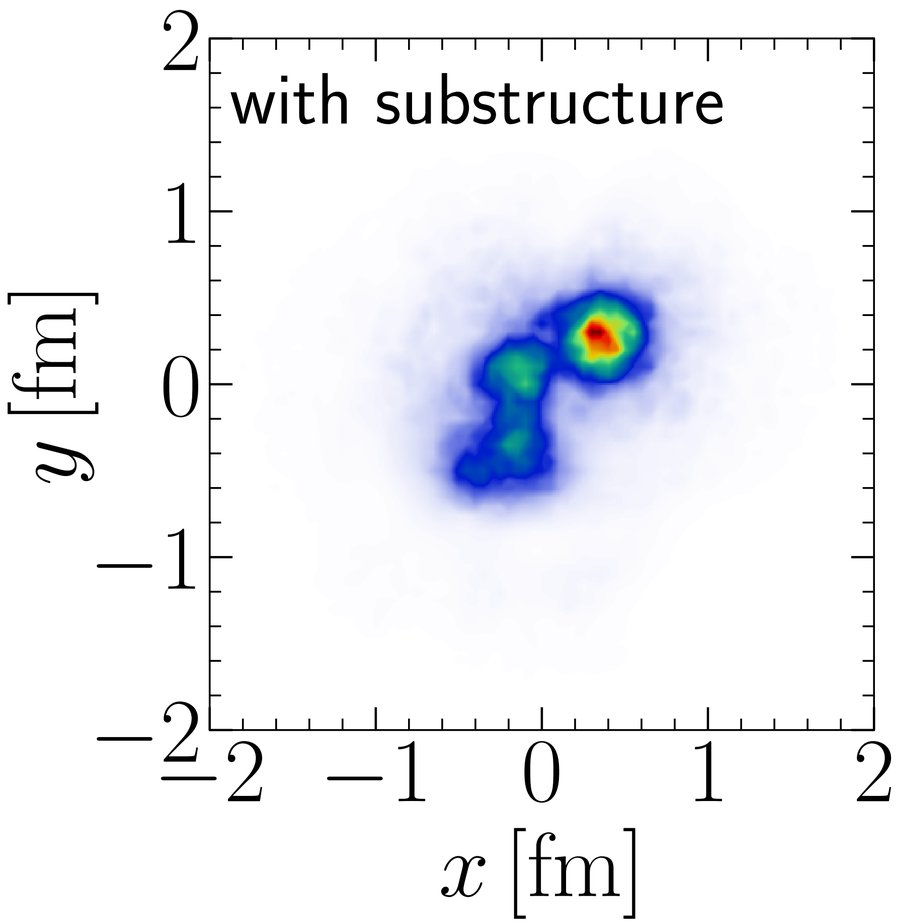
H1 Collaboration, Eur. Phys. J. C73 (2013) no. 6 2466

EFFECT OF SUBSTRUCTURE

B. Schenke, Rep. Prog. Phys. 84 082301 (2021)

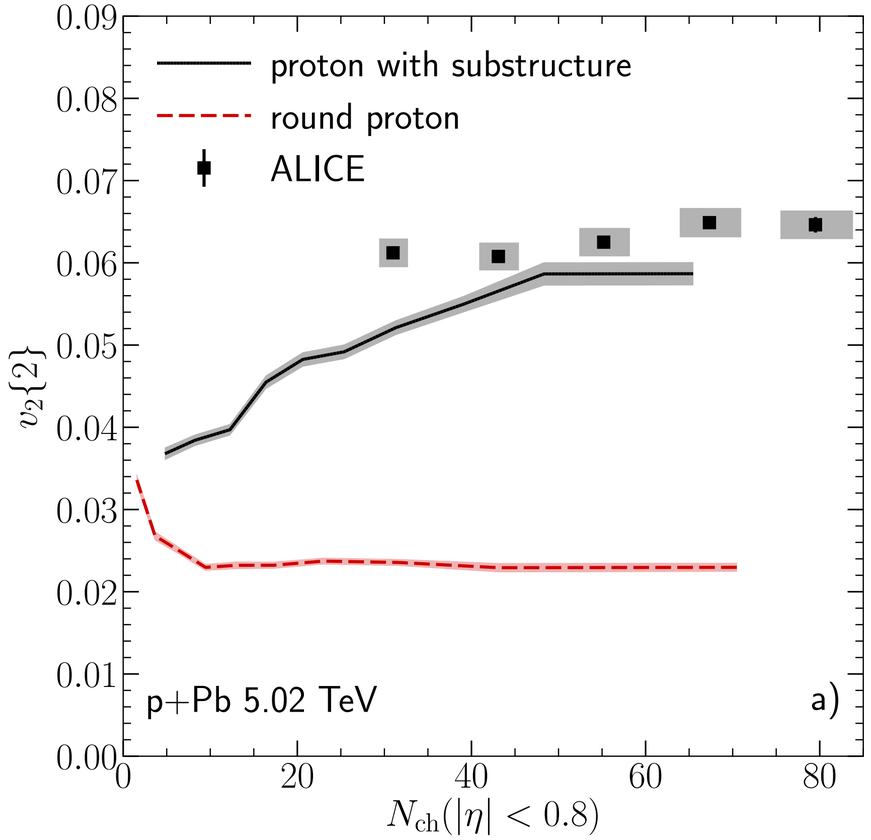


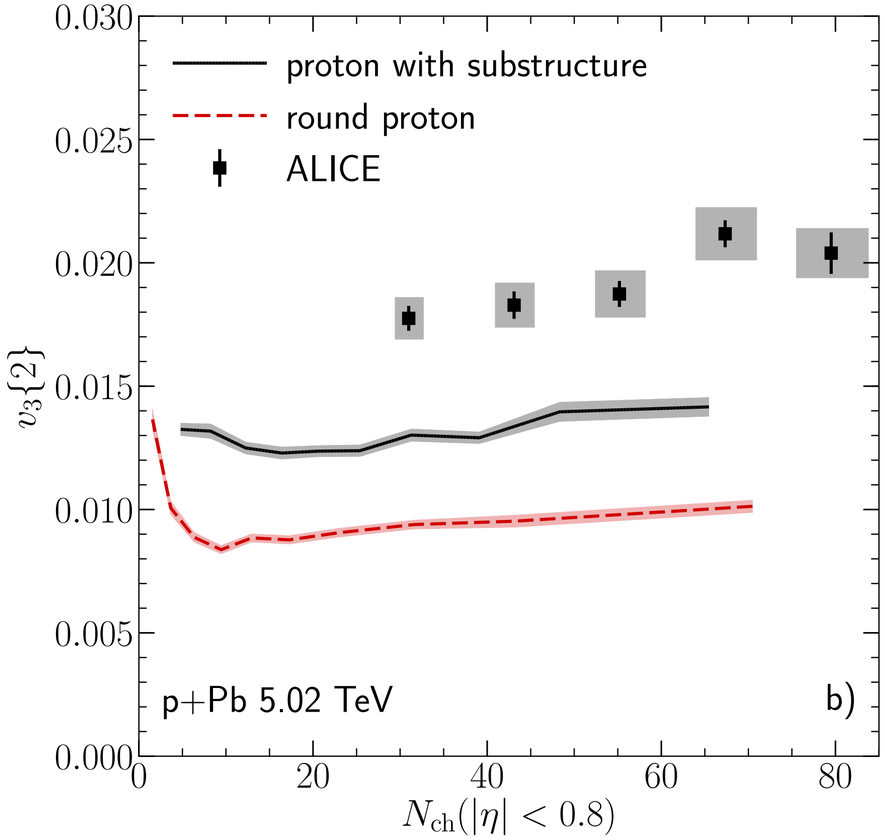


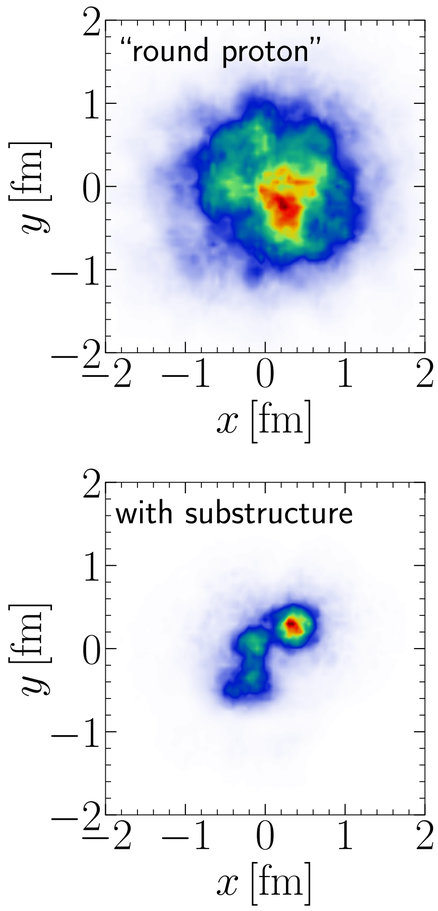


EFFECT OF SUBSTRUCTURE

Substructure improves the description of anisotropic flow in p+A collisions with IP-Glasma





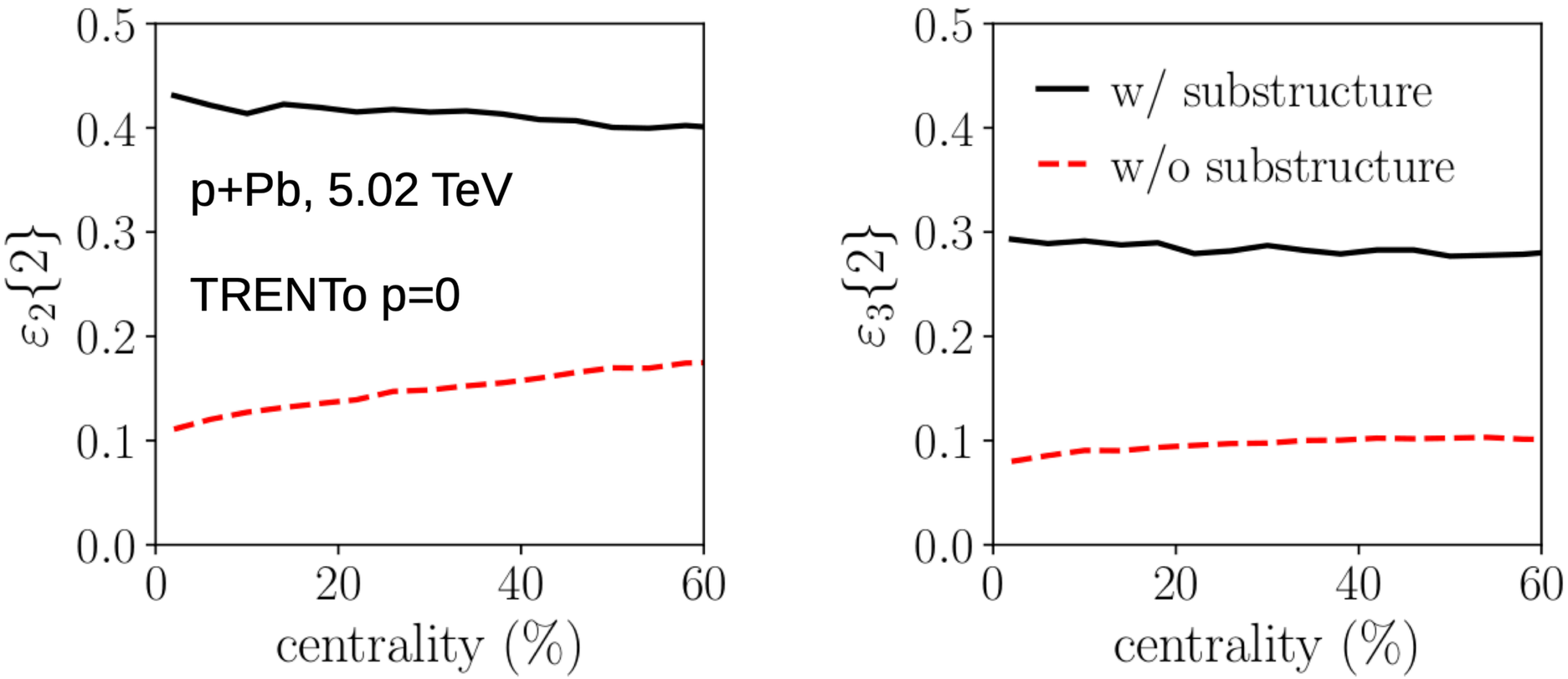


B. Schenke, Rep. Prog. Phys. 84 082301 (2021)

TRENTO ALSO NEEDS SUBSTRUCTURE

The same holds true in Trento p=0 ($\sim (T_A T_B)^{1/2}$)

Figure from G. Giacalone



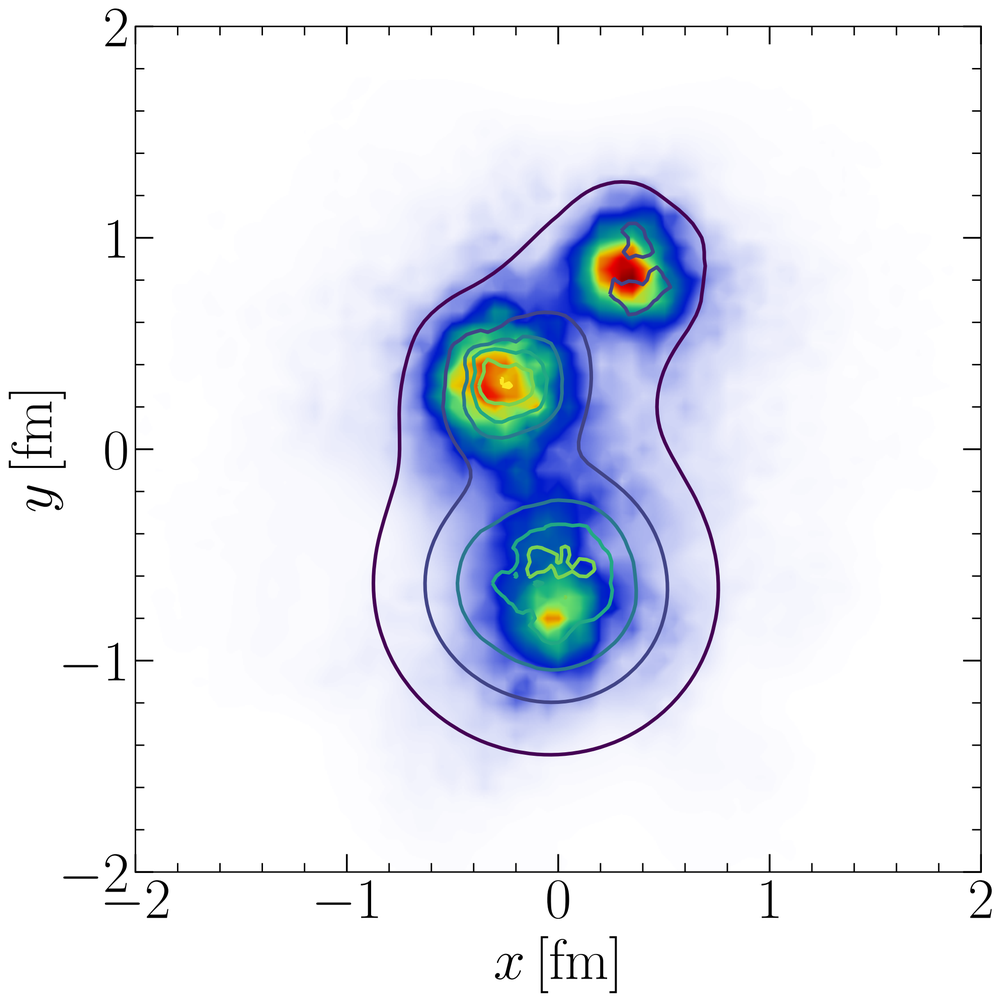
FIREBALL SHAPE ~ PROTON SHAPE

The shape of the overlap region in p+A collisions resembles the proton's shape

Color map: Energy density distribution (arbitrary units)

Contour lines: Shape of the projectile proton (quantified using a measure of the gluon density in the proton)

B. Schenke, Rep. Prog. Phys. 84 082301 (2021)



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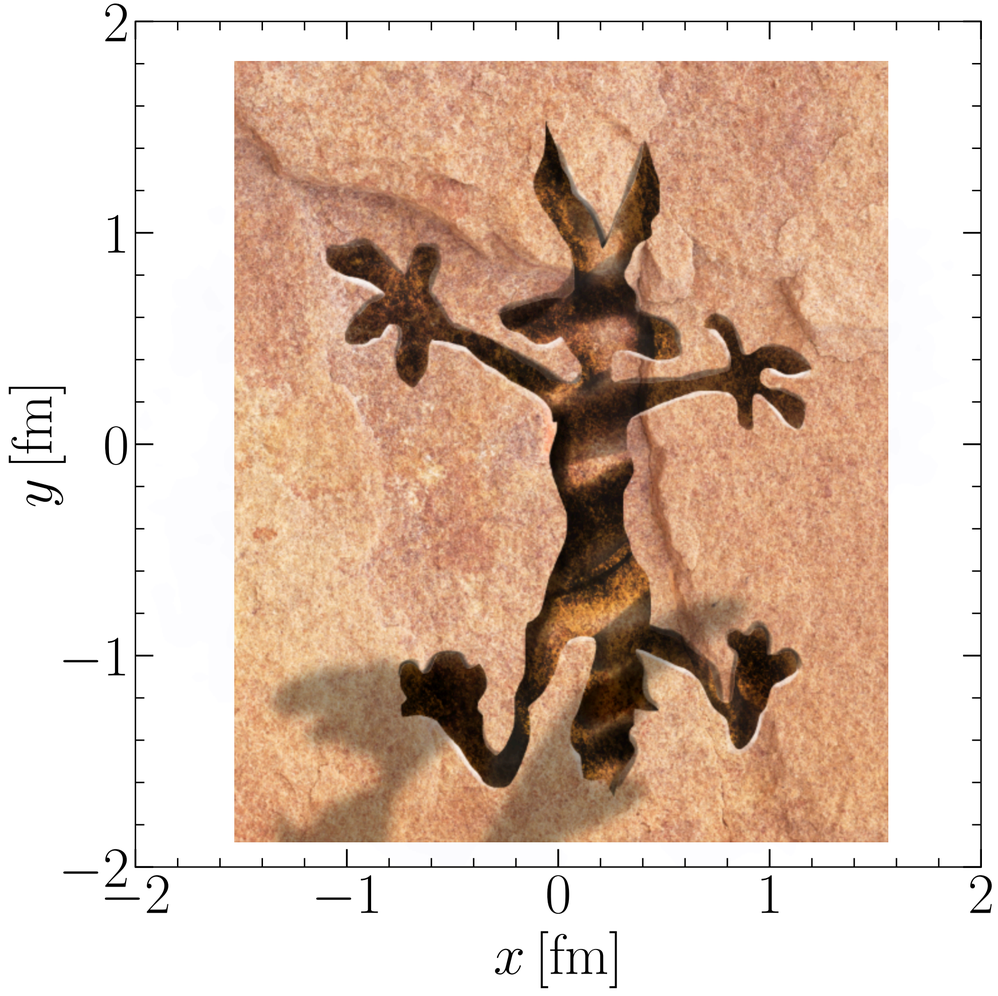
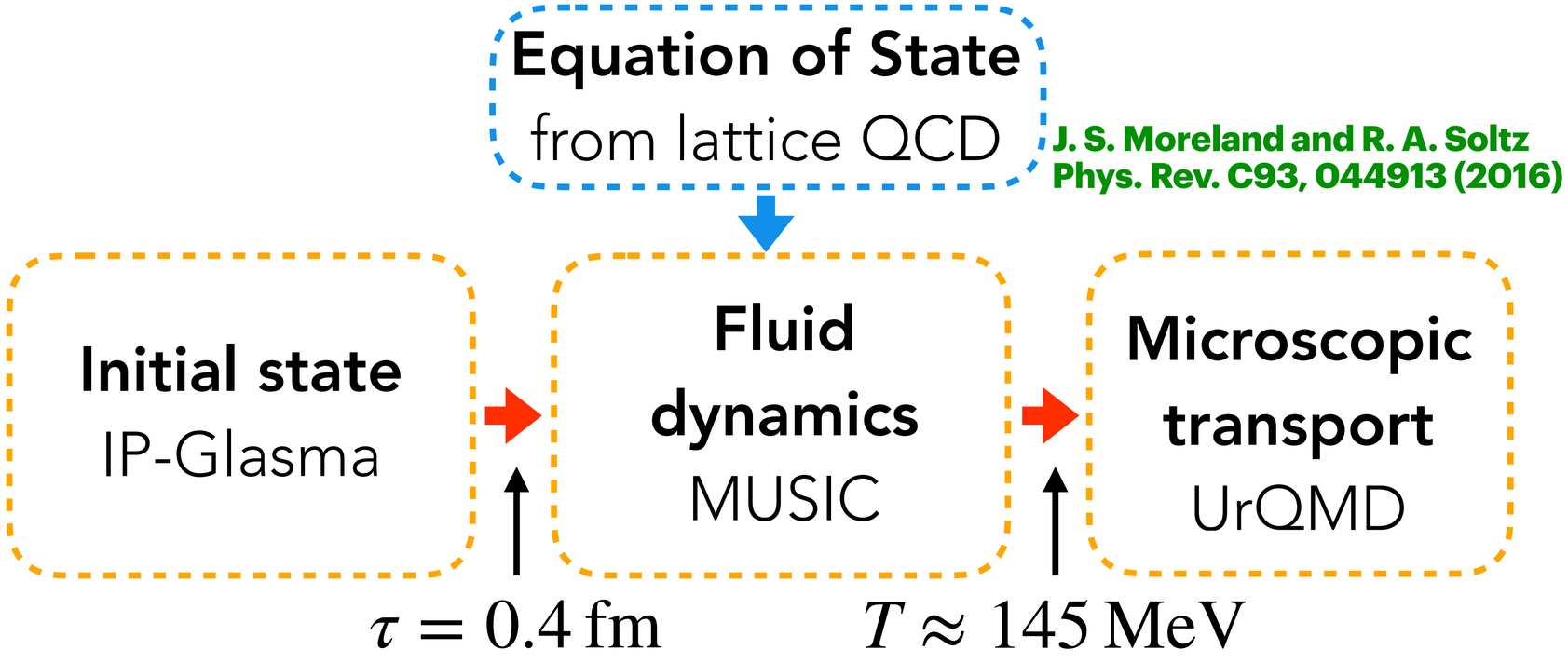


THE HYBRID FRAMEWORK



Described in detail in

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

"Running the gamut of high energy nuclear collisions"

The term gamut was adopted from the field of **music**, where in middle age Latin "gamut" meant the entire range of musical notes of which musical melodies are composed

- **Exactly match $T^{\mu\nu}$ when switching from one part to the next**

B. Schenke, P. Tribedy, and R. Venugopalan, Phys. Rev. Lett. 108, 252301 (2012)
B. Schenke, S. Jeon, and C. Gale, Phys. Rev. Lett. 106, 042301 (2011)
S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998); M. Bleicher et al., J. Phys. G25, 1859 (1999)

TRANSPORT COEFFICIENTS

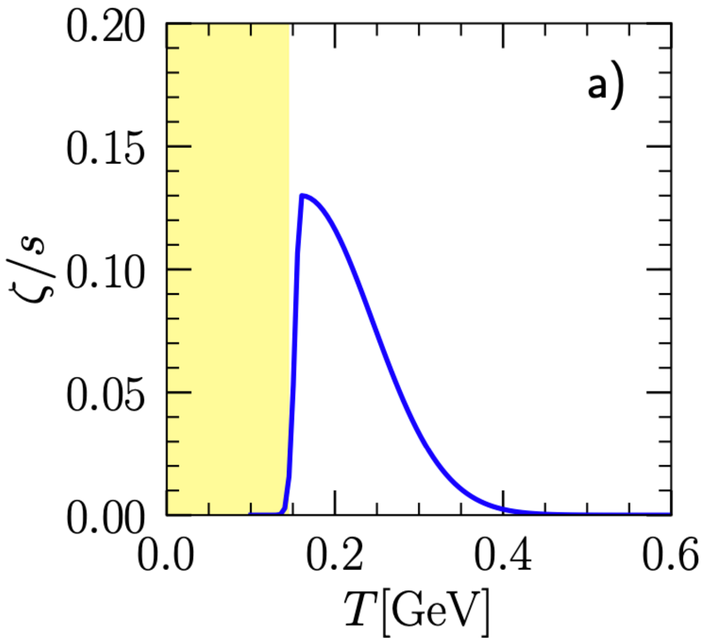
B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905

Transport coefficients:

Shear viscosity:

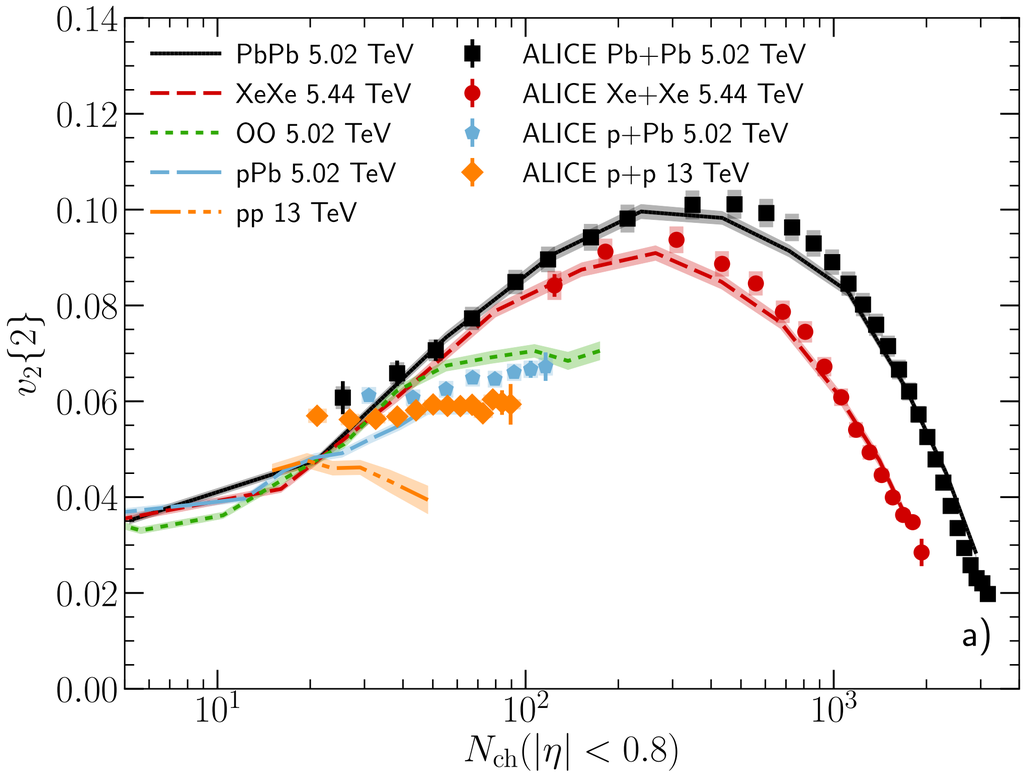
$$\eta/s = 0.12$$

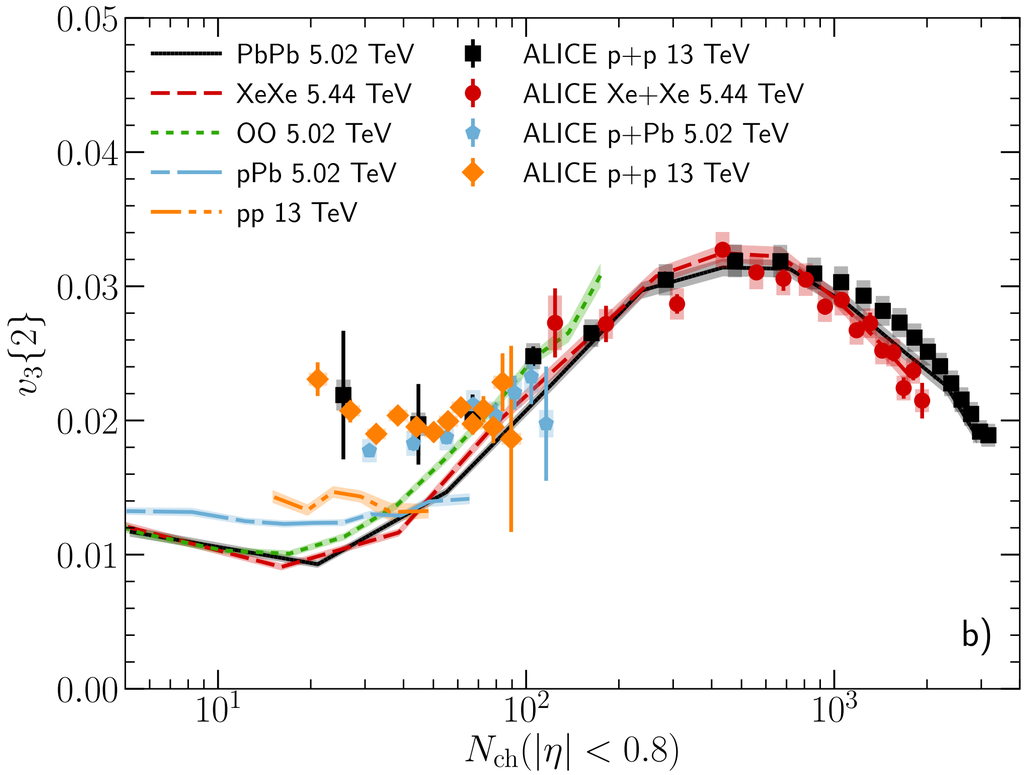
Bulk viscosity:



SOME HYBRID MODEL RESULTS

B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905





Parameters constrained only by HERA data (proton shape) and Au+Au data at RHIC

Underestimate v_n in p+p and v_3 in p+Pb

DO WE AGREE ON THE NUCLEON SIZE?

We constrained the nucleon and hot spot size from e+p collisions at HERA.

We assumed a 2D Gaussian:

$$\frac{1}{2\pi w^2} e^{-\frac{x^2+y^2}{2w^2}}$$

$$w = \sqrt{B_{qc}}$$
$$w_q = \sqrt{B_q}$$

We found a width $w = 0.4\,\mathrm{fm}$ **(we also use subnucleon hot spots with width** $w_q = 0.11\,\mathrm{fm}$**)**

Similar values for w **used in the past to describe heavy ion collisions**

see e.g. B. Schenke, S. Jeon, C. Gale, Phys.Rev.C 85 (2012) 024901

J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu and U. Heinz, Phys. Rev. C 94, no.2, 024907 (2016)

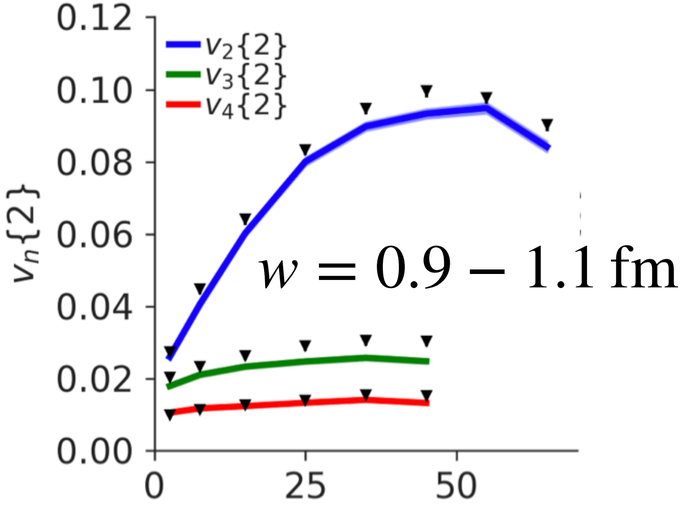
But some newer Bayesian analyses of heavy ion data find much larger values

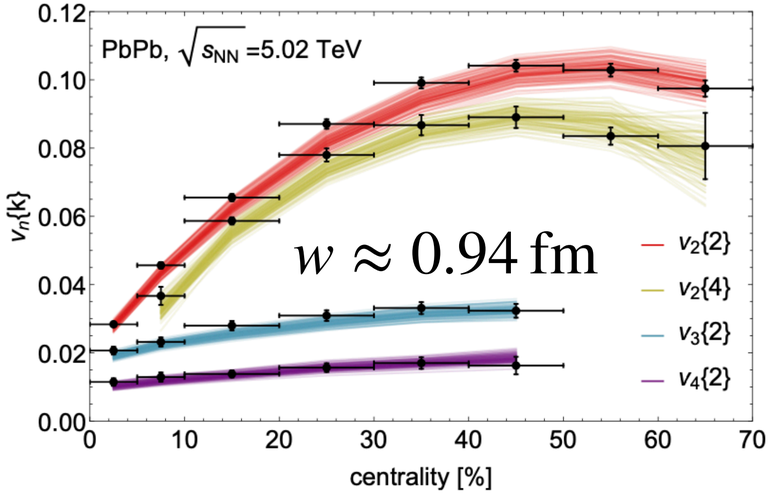
J. E. Bernhard, J. S. Moreland and S. A. Bass, Nature Phys. 15, no.11, 1113-1117 (2019) $w = 0.96\,\mathrm{fm}$

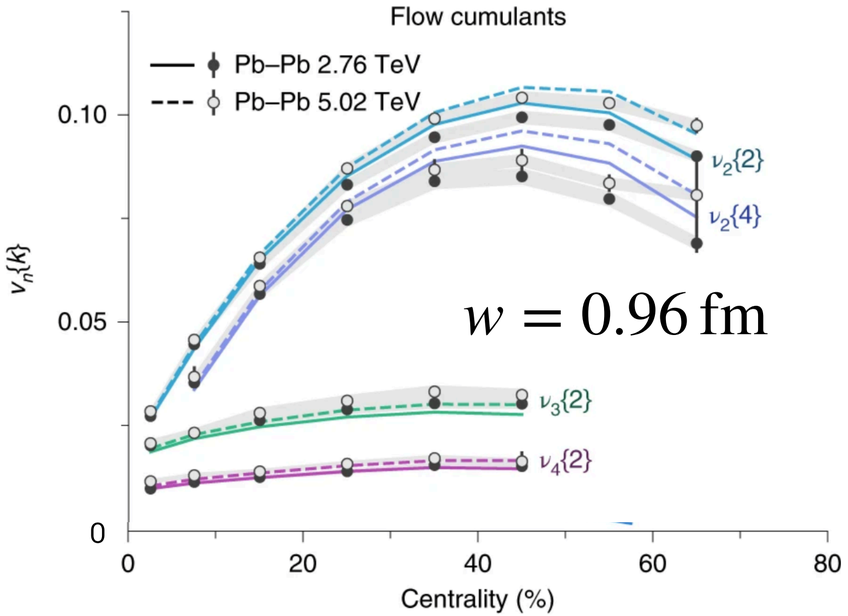
D. Everett et al. [JETSCAPE], Phys. Rev. Lett. 126, no.24, 242301 (2021) $w = 0.9 - 1.1\,\mathrm{fm}$

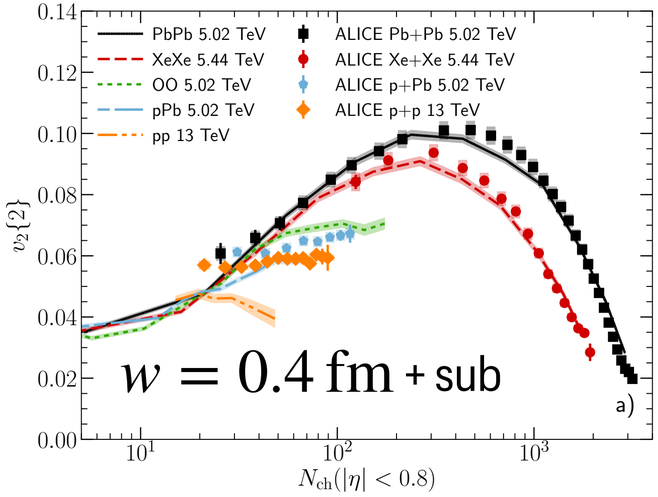
G. Nijs, W. van der Schee, U. Gürsoy, R. Snellings, Phys.Rev.Lett. 126 (2021) 20, 202301 $w \approx 0.94\,\mathrm{fm}$

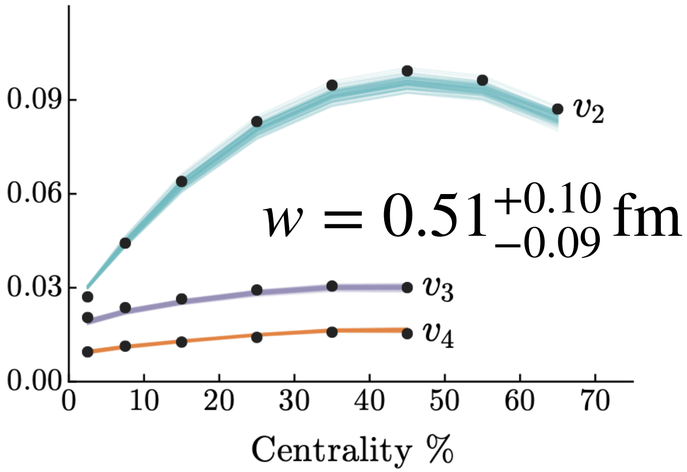
DIFFERENT w BUT DATA IS WELL DESCRIBED





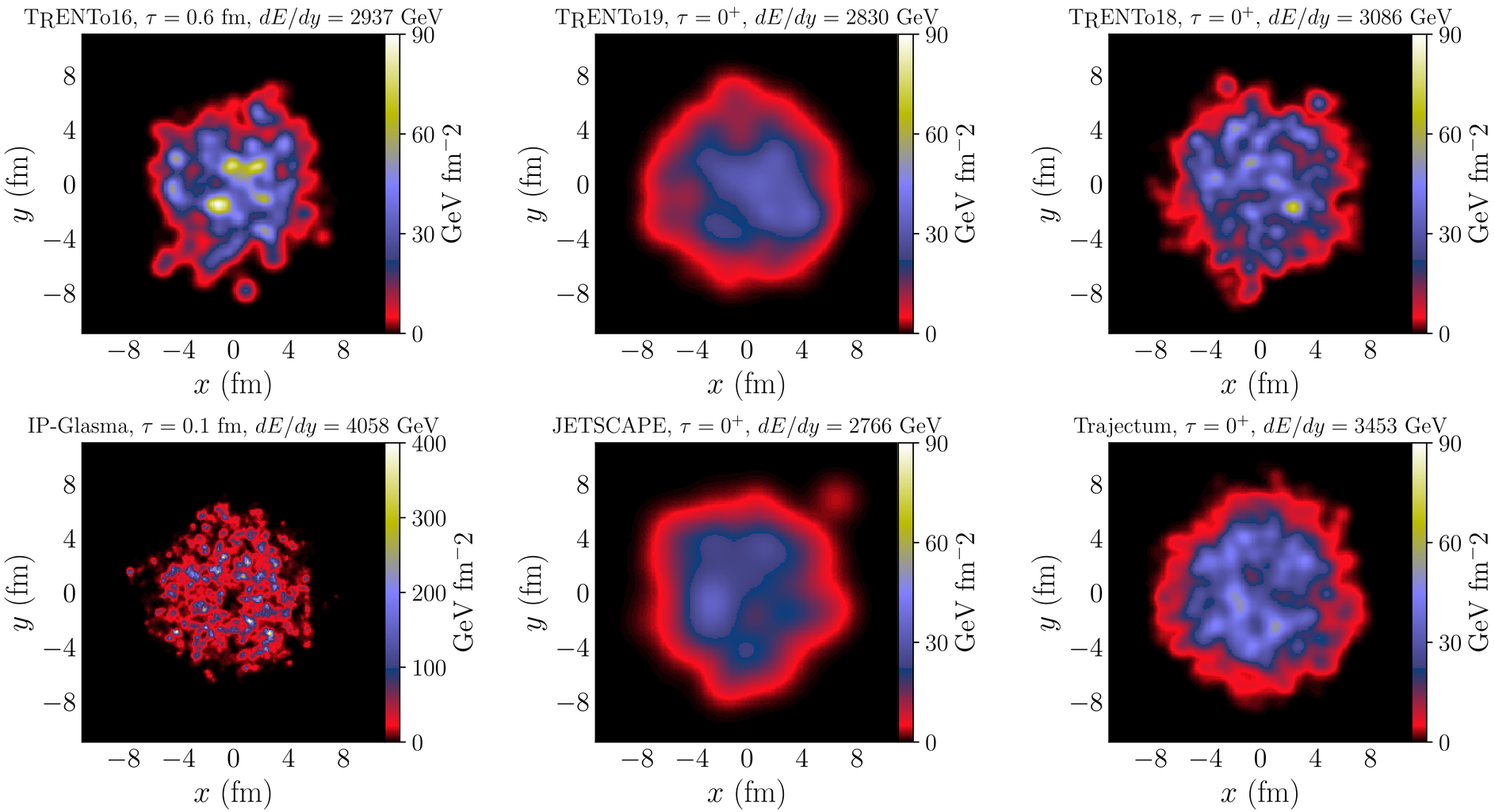






D. Everett et al. [JETSCAPE], Phys. Rev. Lett. 126, no.24, 242301 (2021)
G. Nijs, W. van der Schee, U. Gürsoy, R. Snellings, Phys.Rev.Lett. 126 (2021) 20, 202301
J. E. Bernhard, J. S. Moreland and S. A. Bass, Nature Phys. 15, no.11, 1113-1117 (2019)
B. Schenke, C. Shen, P. Tribedy, Phys. Rev. C 102 (2020) 4, 044905
J. E. Bernhard, J. S. Moreland and S. A. Bass, J. Liu, U. Heinz, Phys.Rev.C 94 (2016) 2, 024907

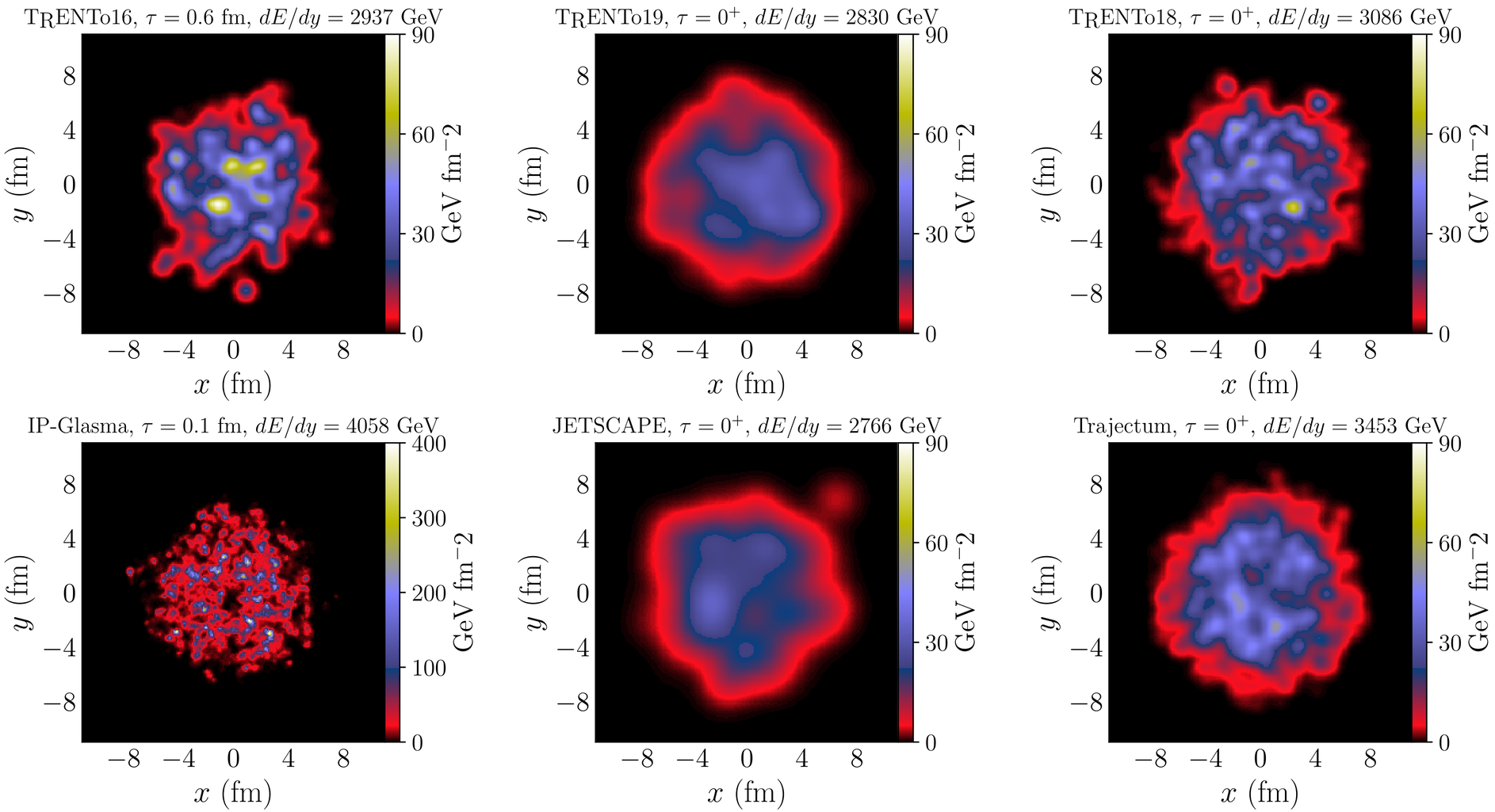
DO WE AGREE ON THE NUCLEON SIZE? NO



Trento16
[Bass, Bernhard, Moreland 1605.03954]
Trento18
[Bass, Bernhard, Moreland 1808.02106]
Trento19
[Bass, Bernhard, Moreland Nature Phys. 15 (2019)]
IP-Glasma
[Schenke, Shen, Tribedy 2005.14682]
JETSCAPE
[JETSCAPE Collaboration 2011.01430, 2010.03928]
Trajectum
[Nijs, van der Schee, Gürsoy, Snellings 2010.15130, 2010.15134]

Figure by G. Giacalone

DO WE AGREE ON THE NUCLEON SIZE? NO



The fits trade a large w for smaller viscosities (especially bulk)

Can we pin down w and viscosities individually?

Figure by G. Giacalone

CORRELATION OF $[p_T]$ WITH v_2

P. Bozek, Phys. Rev. C 93, 044908 (2016); B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)

The correlation of $[p_T]$ and v_n fluctuations can help!

Define $$\hat{\rho}(v_n^2, [p_T]) = \frac{\langle \hat{\delta} v_n^2 \, \hat{\delta}[p_T] \rangle}{\langle (\hat{\delta} v_n^2)^2 \rangle \langle (\hat{\delta}[p_T])^2 \rangle}$$

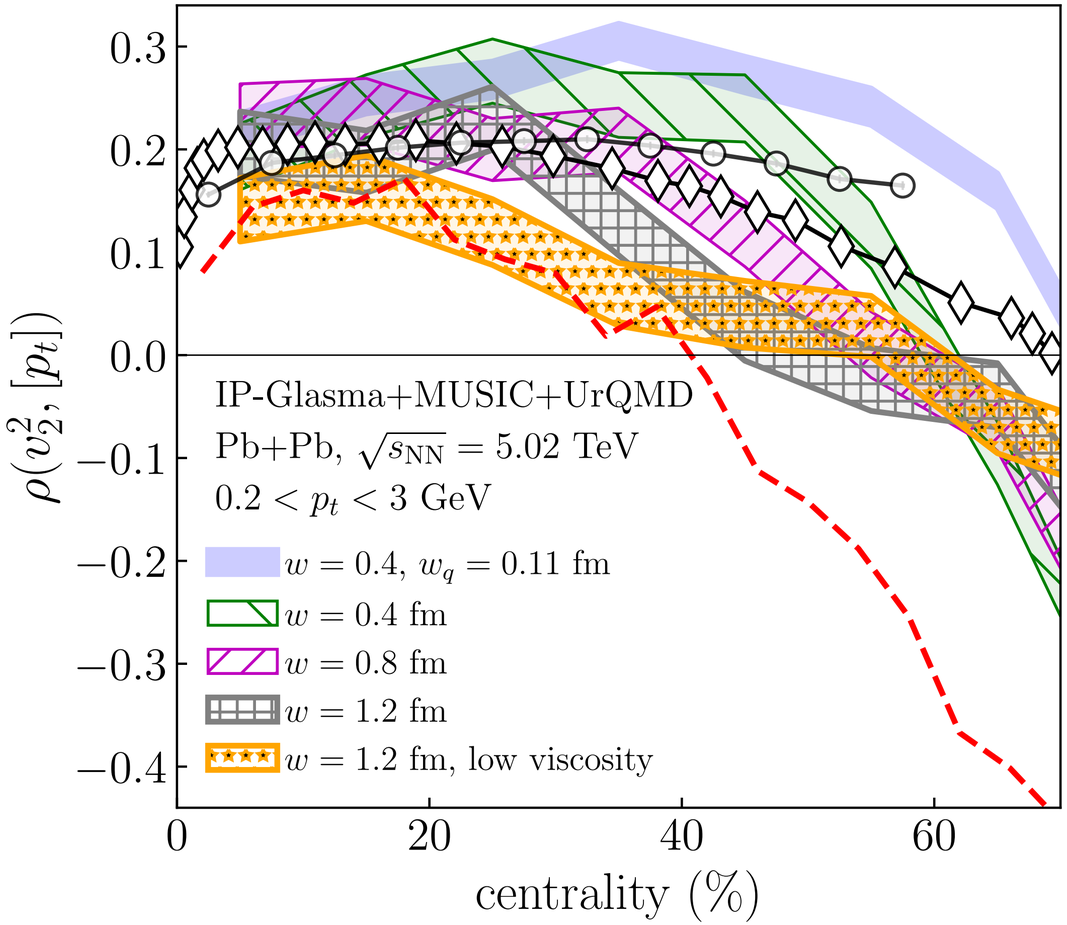
$$\delta O \equiv O - \langle O \rangle$$

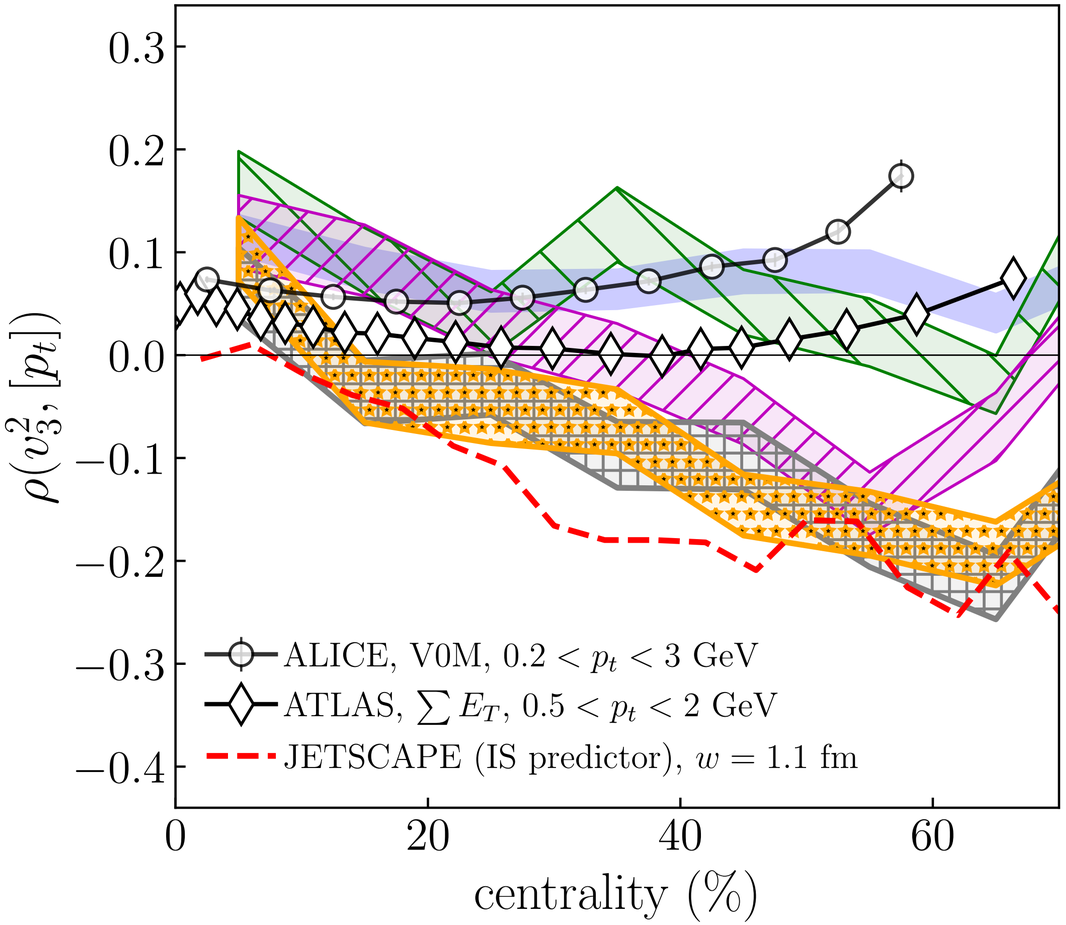
$$\hat{\delta} O \equiv \delta O - \frac{\langle \delta O \delta N \rangle}{\sigma_N^2} \delta N$$ **is the variation of O at fixed multiplicity**

A. Olszewski, W. Broniowski, Phys. Rev. C96, 054903 (2017)

DEPENDENCE OF ρ CORRELATOR ON w

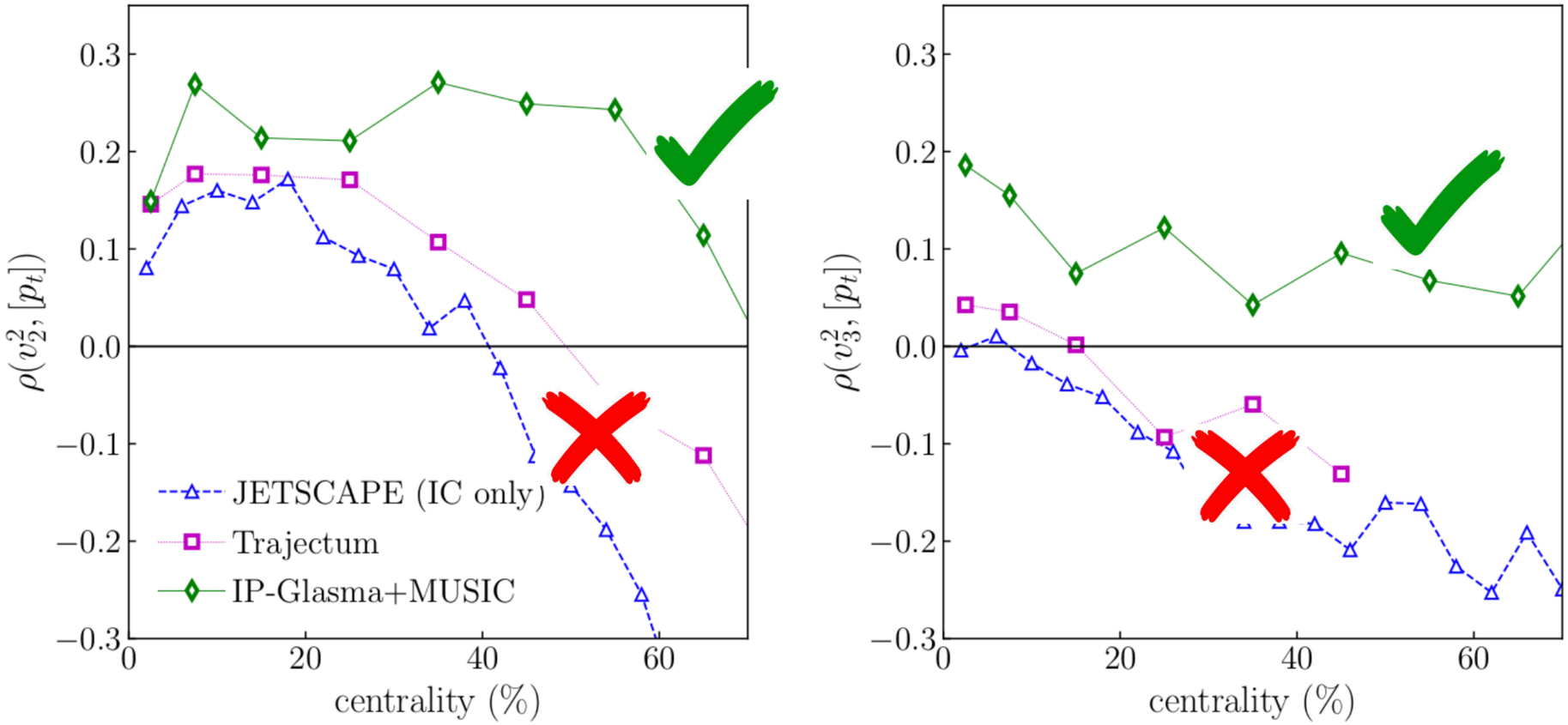
G. Giacalone, B. Schenke, C. Shen, arXiv:2111.02908; ALICE Collaboration, arXiv:2111.06106
ATLAS-CONF-2021- 001. https://cds.cern.ch/record/2748818?ln=en





DEPENDENCE OF ρ CORRELATOR ON w

G. Giacalone, B. Schenke, C. Shen, arXiv:2111.02908



[JETSCAPE Collaboration 2011.01430, 2010.03928]

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

[Giacalone, Schenke, Shen 2005.14682]

SUMMARY

- Energy deposition $(T_A T_B)^q$ is preferred (by data and theoretical consideration)
- With such energy deposition subnucleon fluctuations are needed to describe v_n in p+A
- Models disagree on nucleon size in A+A collisions
- The correlation of mean transverse momentum and elliptic flow can distinguish the models
- This observable should be included in future Bayesian analyses

CODES - ALL PUBLIC

- The iEBE-MUSIC framework integrates individual physical models which describe different stages of relativistic heavy-ion collisions. This work uses v1.0 of this framework, which can be downloaded from
https://github.com/chunshen1987/iEBE-MUSIC/releases

- The official code repository of the IP-Glasma initial conditions is
https://github.com/schenke/ipglasma . Here we used v1.0:
https://github.com/schenke/ipglasma/releases

- MUSIC is the numerical implementation of (3+1)D relativistic viscous hydrodynamic simulations for high energy heavy-ion collisions. Its official website is
http://www.physics.mcgill.ca/music . This work uses the version 3.0 of MUSIC, which can be downloaded from
https://github.com/MUSIC-fluid/MUSIC/releases

- The iSS code package is an open-source particle sampler based on the Cooper-Frye freeze-out prescription. It converts fluid cells to particle samples. This work uses v1.0 of the iSS, which can be downloaded from
https://github.com/chunshen1987/iSS/releases

- We use the official UrQMD v3.4 and set it up to run as the afterburner mode
https://bitbucket.org/Chunshen1987/urqmd_afterburner/src/master/

- The hadronic afterburner toolkit is a code package which performs analysis of particle spectra, flow observables, and their correlations using the outputs from hadronic transport models. This work uses v1.0 of the code which can be downloaded from
https://github.com/chunshen1987/hadronic_afterburner_toolkit/releases

- The NEOS equation of state v0.11:
https://sites.google.com/view/qcdneos/