Measuring nuclei radii in heavy-ion collisions

Interfacing nuclear structure with high-energy nuclear collisions

Giuliano Giacalone

Institut für Theoretische Physik – Universität Heidelberg

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SQM2024

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3-7 June 2024, Strasbourg, France

3–7 Jun 2024
Université de Strasbourg / Palais de la Musique et des Congrès
Europe/Paris timezone

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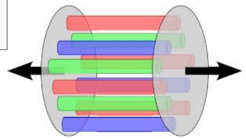
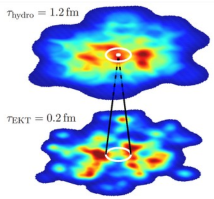
2 Effective theory of highly coherent gluon states: “***Glasma***”



$$\langle T^{00}\rangle \propto Q_A^2(\mathbf{x})Q_B^2(\mathbf{x})$$

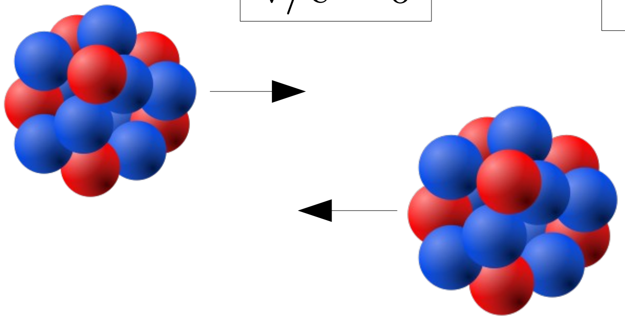
3 Effective QCD kinetic theory

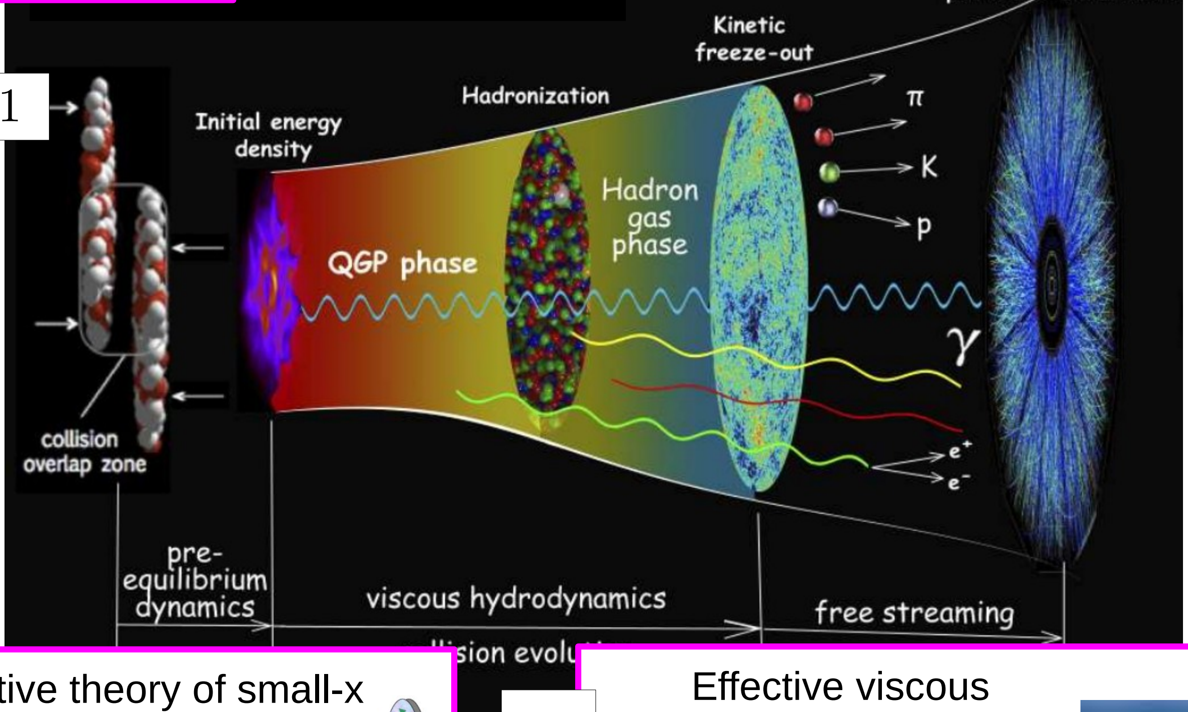
$$\partial_\tau f_{\mathbf{x},\mathbf{p}} + \frac{\mathbf{p}}{|\mathbf{p}|}\cdot\nabla_{\mathbf{x}} f_{\mathbf{x},\mathbf{p}} - \frac{p^z}{\tau}\partial_{p^z} f_{\mathbf{x},\mathbf{p}} = -\mathcal{C}_{2\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}] - \mathcal{C}_{1\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}]$$



$v/c \sim 0$

$v/c = 1$

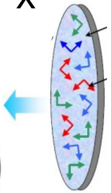




HEAVY-ION COLLISIONS
=
A TOWER OF EFFECTIVE THEORIES

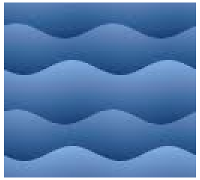
1 Effective theory of small-x degrees of freedom
CGC

$$A^\mu_{1,2}(x) \qquad Q_s^2(\mathbf{x})$$



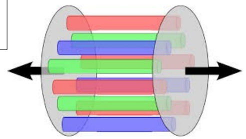
4 Effective viscous hydrodynamic description
QGP

$$\vec{F} = -\vec{\nabla} P \qquad \eta/s$$



2

Effective theory of highly coherent gluon states: “***Glasma***”

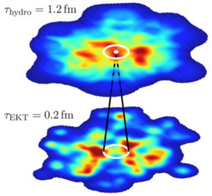


$$\langle T^{00} \rangle \propto Q_A^2(\mathbf{x}) Q_B^2(\mathbf{x})$$

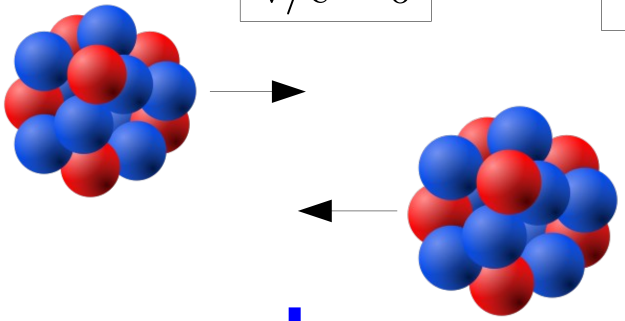
3

Effective QCD kinetic theory

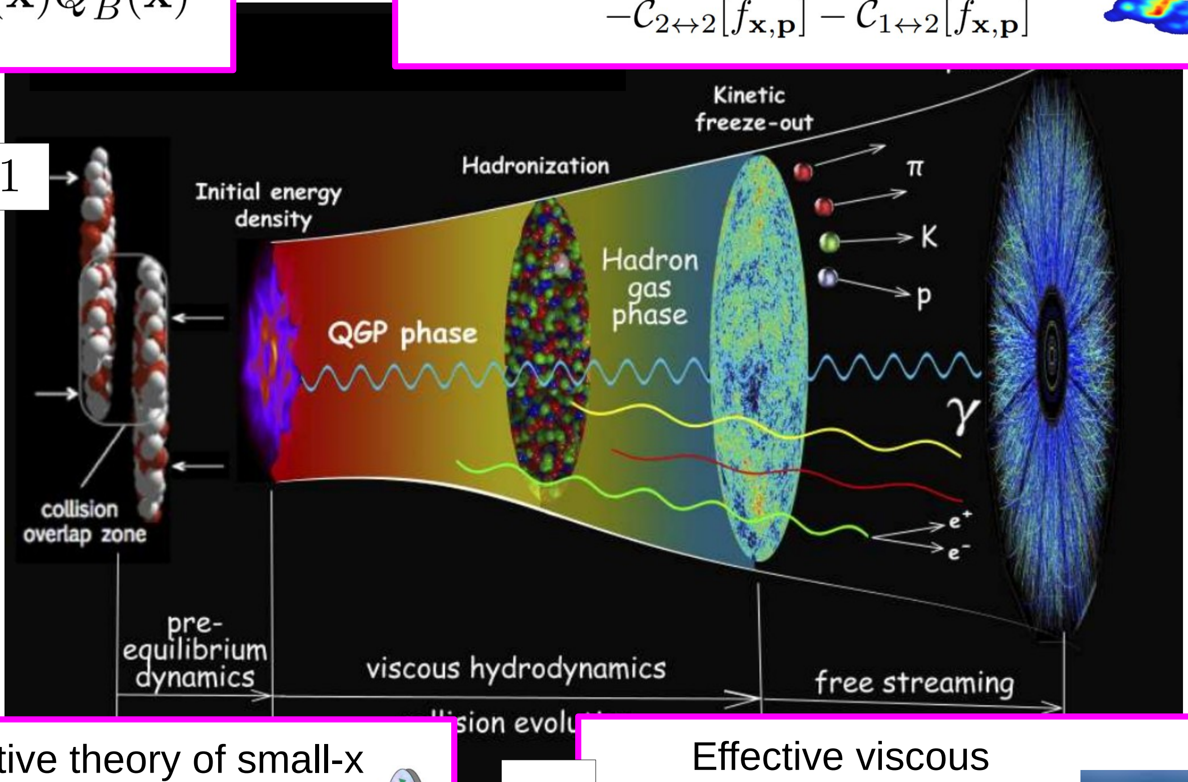
$$\partial_\tau f_{\mathbf{x},\mathbf{p}} + \frac{\mathbf{p}}{|\mathbf{p}|} \cdot \nabla_{\mathbf{x}} f_{\mathbf{x},\mathbf{p}} - \frac{p^z}{\tau} \partial_{p^z} f_{\mathbf{x},\mathbf{p}} = -\mathcal{C}_{2\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}] - \mathcal{C}_{1\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}]$$



$v/c \sim 0$



$v/c = 1$

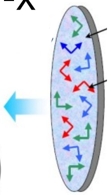


0

THIS TALK

1

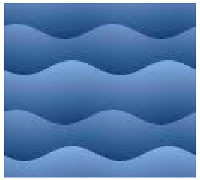
Effective theory of small-x degrees of freedom
CGC



$$A^{\mu}_{1,2}(x) \qquad Q_s^2(\mathbf{x})$$

4

Effective viscous hydrodynamic description
QGP

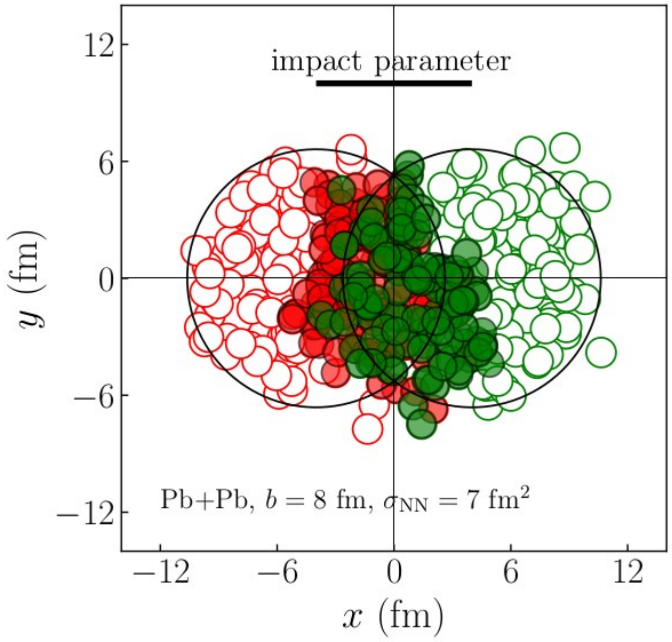


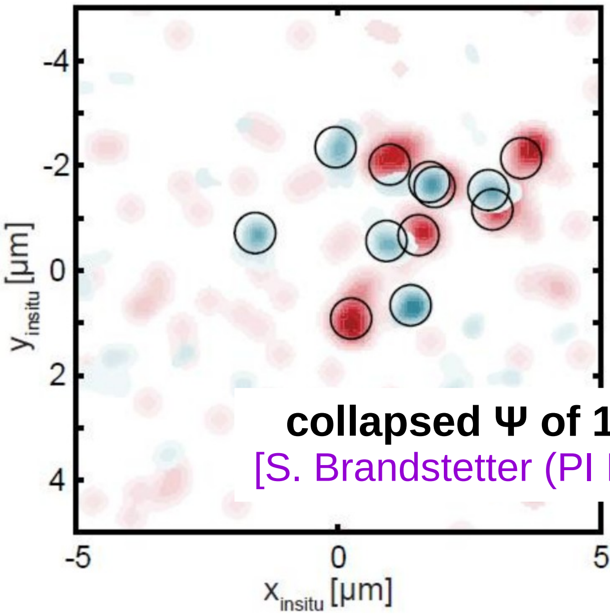
$$\vec{F} = -\vec{\nabla} P \qquad \eta/s$$

PART I – BREAKING THE BARRIER

The paradigm

[Miller *et al.*, Ann.Rev.Nucl.Part.Sci. **57** (2007) 205-243]
[PHOBOS Collaboration, PRL **98** (2007) 242302]
[Alver, Roland, PRC **81** (2010) 054905]





collapsed Ψ of 10 Li atoms
[S. Brandstetter (PI Heidelberg)]

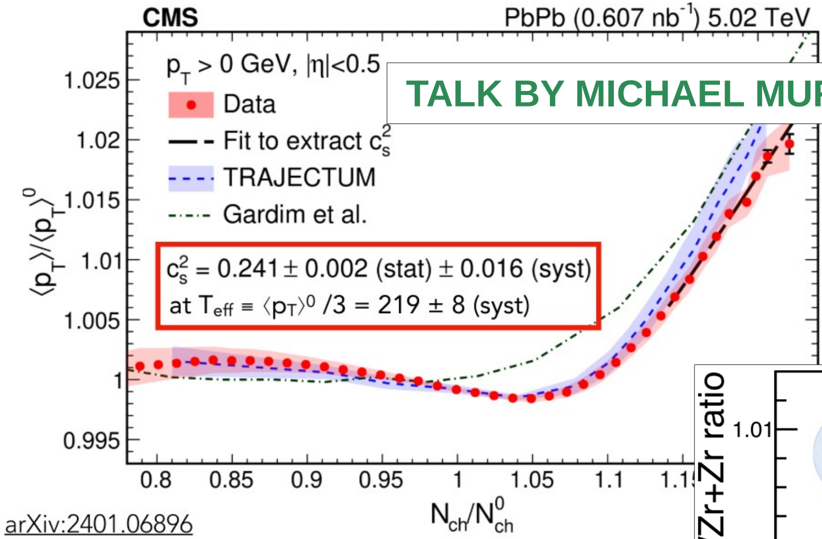
Snapshot of many-body ground state $\left|\Psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A)\right|^2$

KNOWLEDGE OF THIS OBJECT IS IMPORTANT

NB: same paradigm (nucleons) also at low beam energy / fixed-target

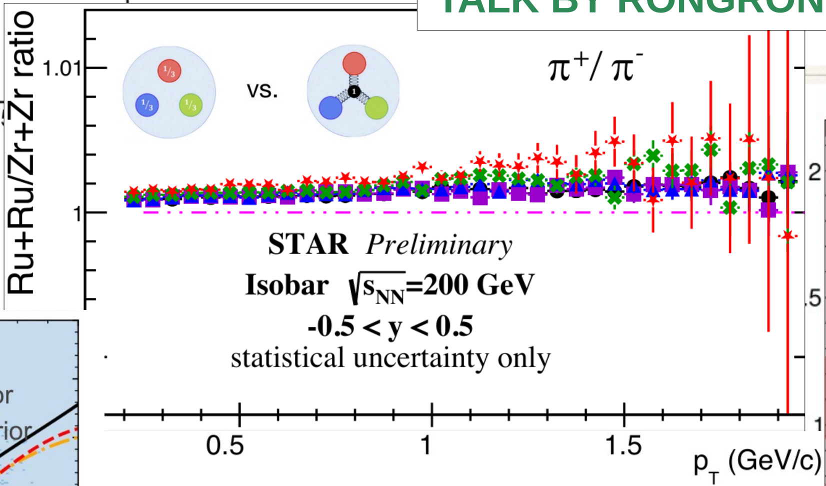
Motivation # 1

Quantitative studies in the soft sector

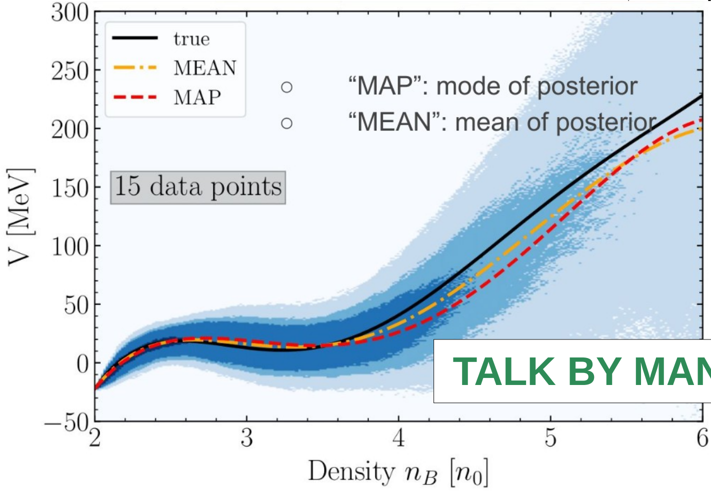


TALK BY MICHAEL MURRAY

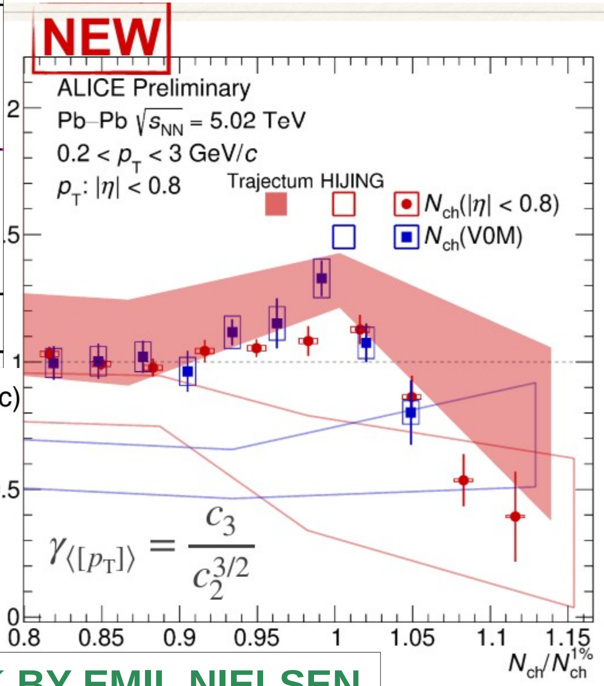
arXiv:2401.06896



TALK BY RONGRONG MA



TALK BY MANJUNATH O. KUTTAN

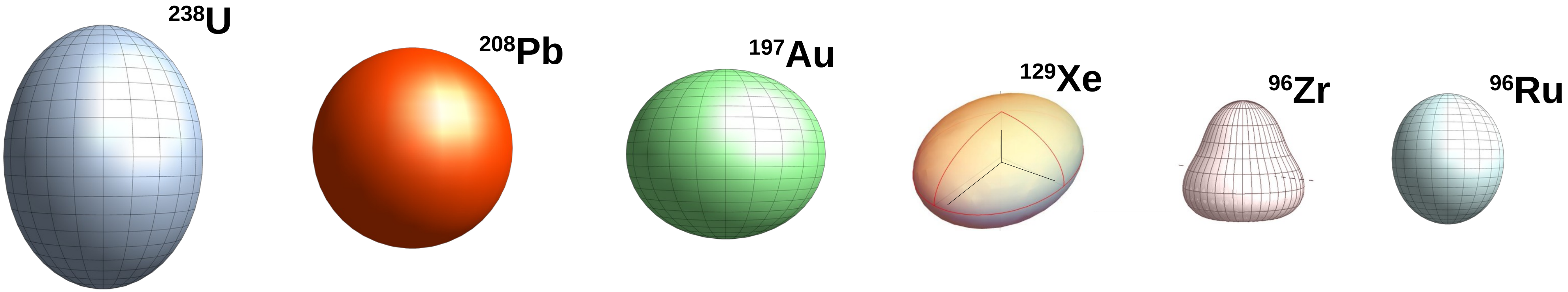


TALK BY EMIL NIELSEN

Motivation # 2 – Many different species available

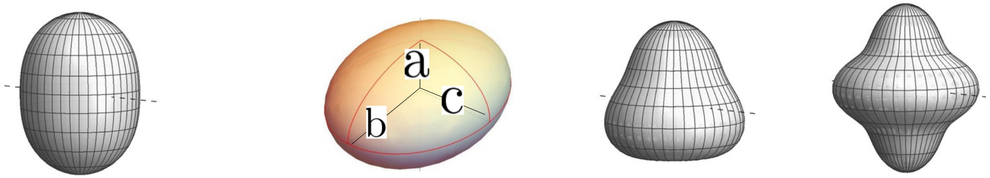
$$\left|\Psi(\mathbf{r_1}, \mathbf{r_2}, \ldots, \mathbf{r_A})\right|^2$$

NUCLEAR SHAPES TO CAPTURE MANY-BODY CORRELATIONS



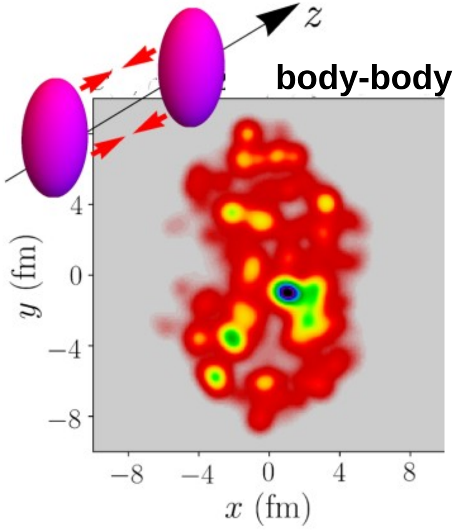
Highly nontrivial parametrizations for nucleon distributions from low-energy physics

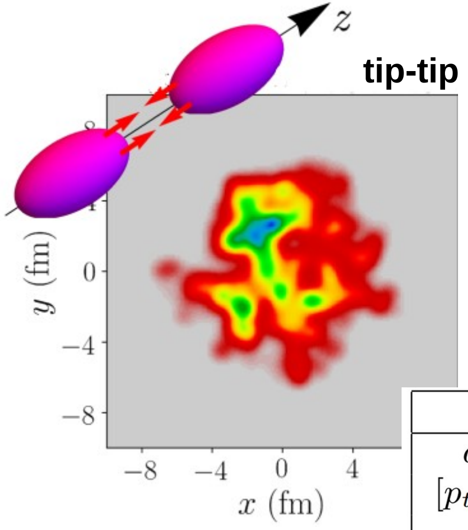
$$\rho(r,\theta,\phi) \propto \frac{1}{1+\exp\left(\left[r-R(\theta,\phi)\right]/a\right)} \quad , \quad R(\theta,\phi) = R_0\left[1+\underline{\beta_2}\left(\cos\underline{\gamma} Y_{20}(\theta)+\sin\gamma Y_{22}(\theta,\phi)\right)+\underline{\beta_3}Y_{30}(\theta)+\underline{\beta_4}Y_{40}(\theta)\right]$$



[Bally *et al.*, PRL **128** (2022) 8, 082301]
[Ryssens *et al.*, PRL **130** (2023) 21, 212302]

Unambiguous signatures of the shape

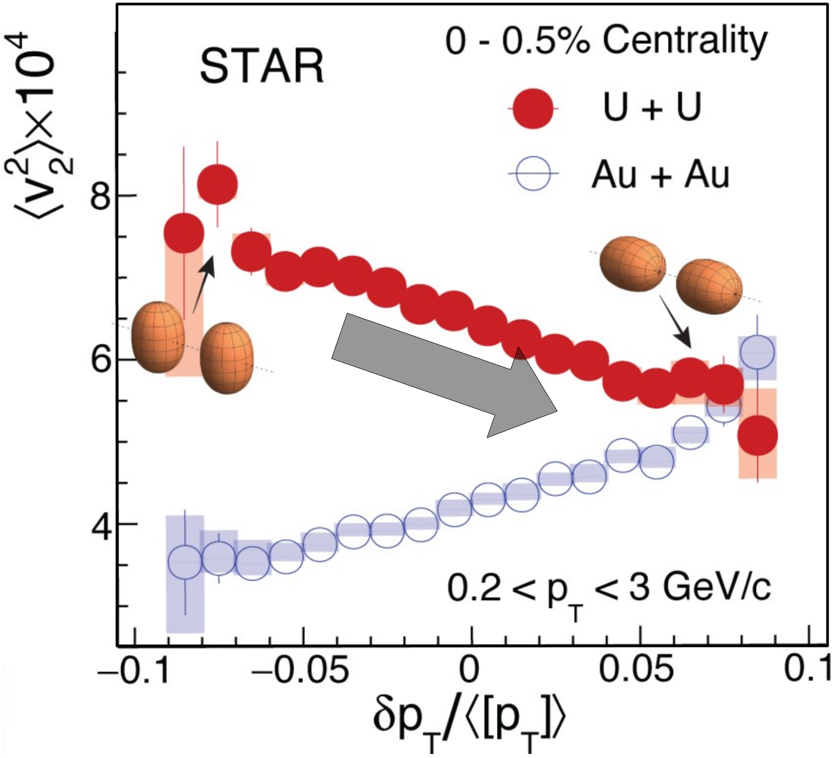




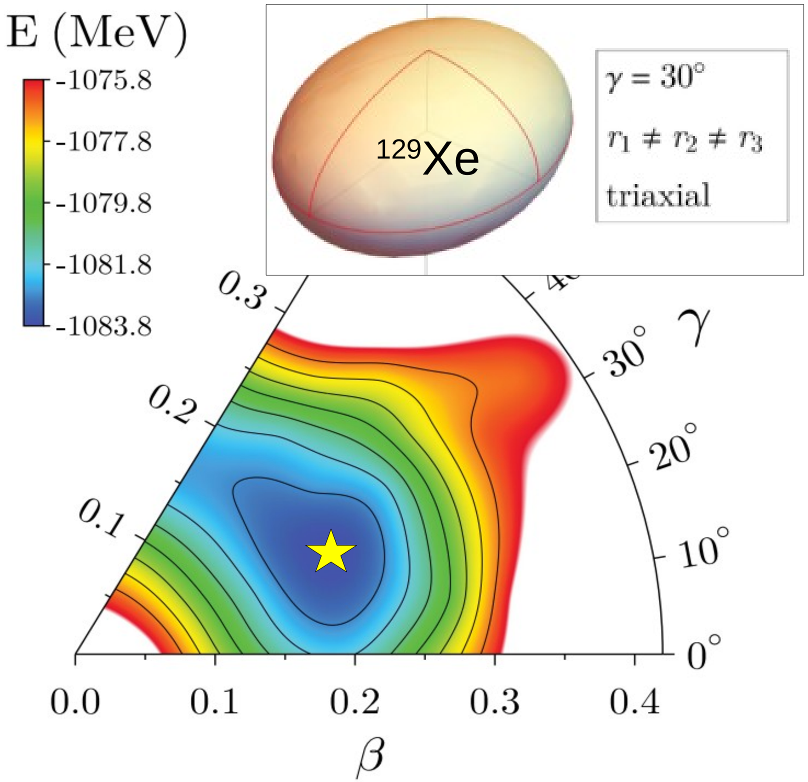
[Giacalone, PRL **124** (2020) 20, 202301
PRC **102** (2020) 2, 024901]

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

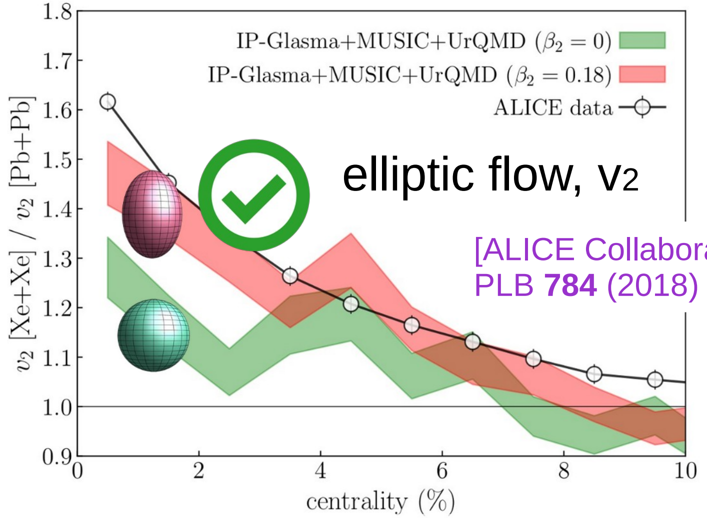
[STAR collaboration, arXiv:2401.06625]



A (seemingly) success story – Understanding Xe-Xe data

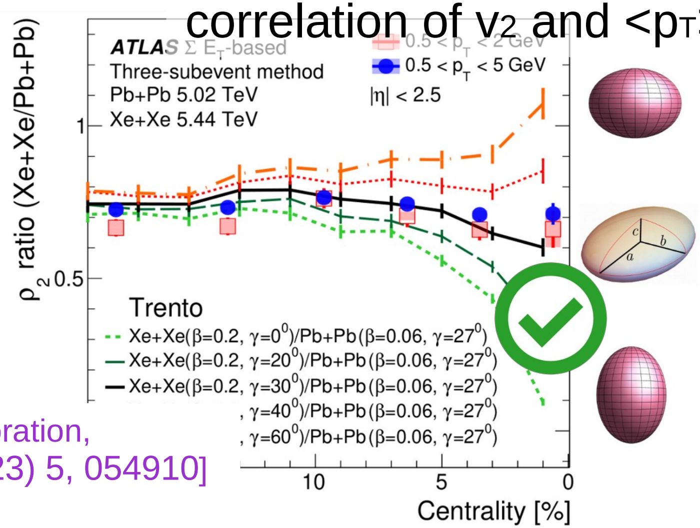


[Bally *et al.*, PRL **128** (2022) 8, 082301]
[Bally, Giacalone, Bender, EPJA **58** (2022) 9, 187]



[ALICE Collaboration, PLB **784** (2018) 82-95]

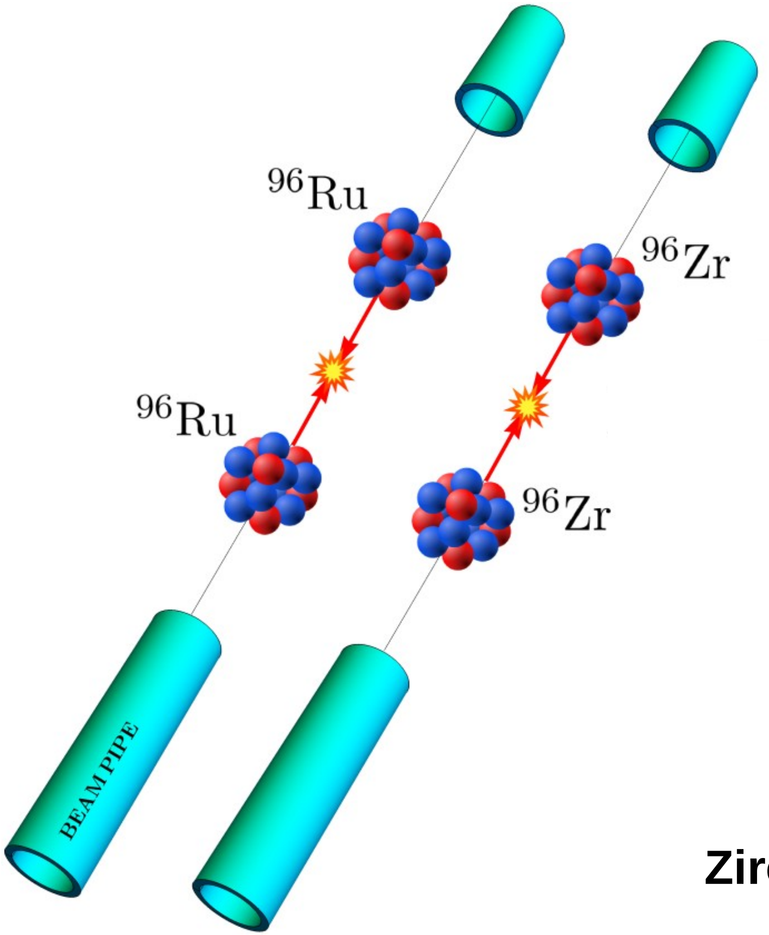
correlation of v_2 and <p_T>



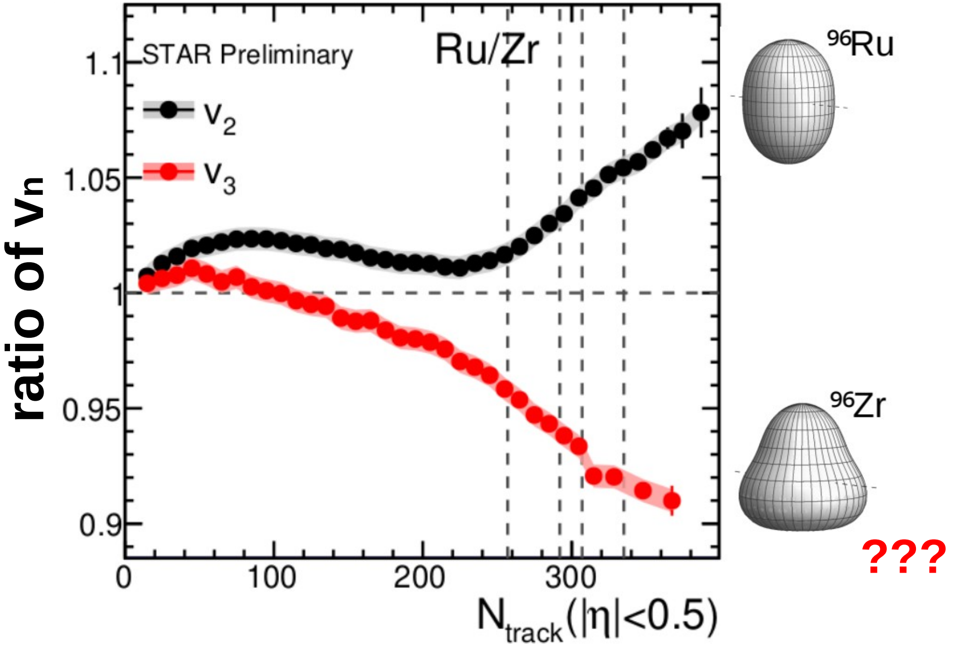
[ATLAS Collaboration, PRC **107** (2023) 5, 054910]

So far so good … until 2021 and data from “isobar collisions”

[STAR collaboration, PRC **105** (2022) 1, 014901]



[courtesy Chunjian Zhang]



Zirconium-96 must have an octupole deformation

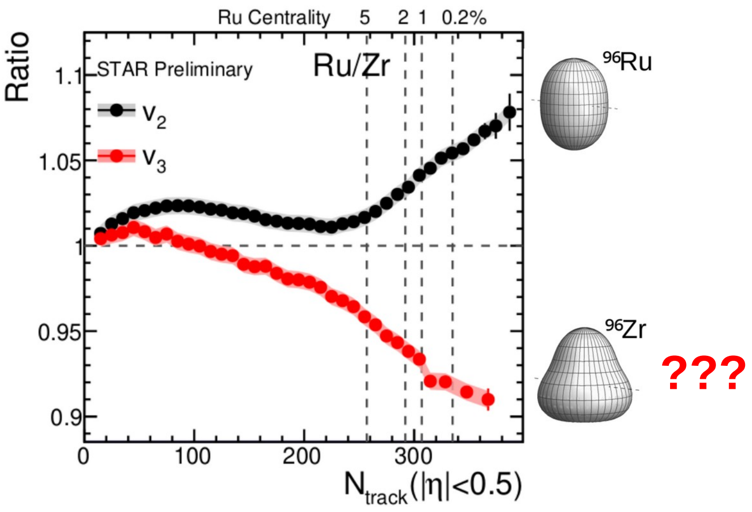
[Zhang, Jia, PRL **128** (2022) 2, 022301]
[Nijs, van der Schee, SciPost Phys. **15** (2023) 041]

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



– **Low-energy experiments:** A~100 is away from double shell closure. “Difficult” isotopes Ru and Zr have completely different spectra/structures

– **Low-energy theory:** Some indications of octupole deformation in Zr. Little known about Ru
No solid understanding of these nuclei

Possibly the worst choice of nuclei for precision high-energy studies

Precision STAR data is a breakthrough, albeit in a different direction

Starting from scratch – Nuclei directly from high-energy data

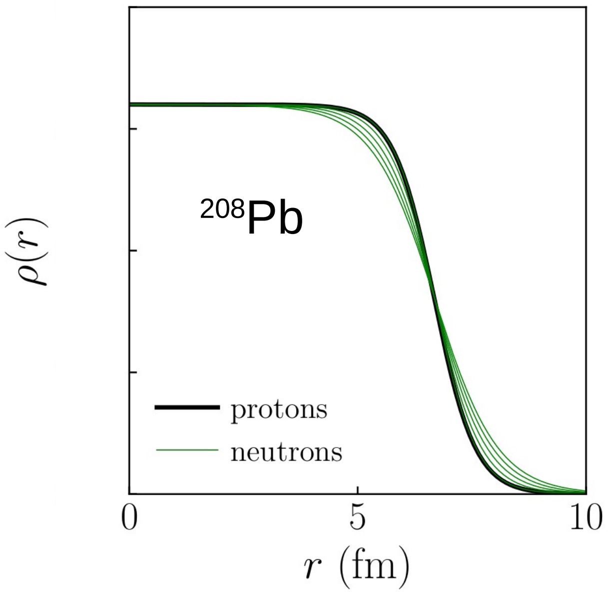
BAYESIAN ANALYSIS

$$\Pr(p\,\&D) = \Pr(p) \times \Pr(D|p) = \Pr(D) \times \Pr(p|D)$$
$$\text{prior} \times \text{likelihood} = \text{evidence} \times \text{posterior}$$

[e.g. Paquet, arXiv:2310.17618]

Beautiful example and opportunity: The neutron distribution of ^{208}Pb is poorly known

$$\rho(r) \propto \frac{1}{1+e^{(r-R)/\underline{a}}}$$



Protons: density from low-energy scattering

[Zenihiro *et al.*, PRC **82** (2010) 044611]

Neutrons: same R as protons, infer a from LHC data

Measuring the total radius of ^{208}Pb

$$R_{\mathrm{Pb}}^2 = \frac{1}{208}\left(126\langle r_n^2\rangle + 82\langle r_p^2\rangle\right)$$

LHC data **low-energy data**

- 18 tuned EDF Brussels-Skyrme results

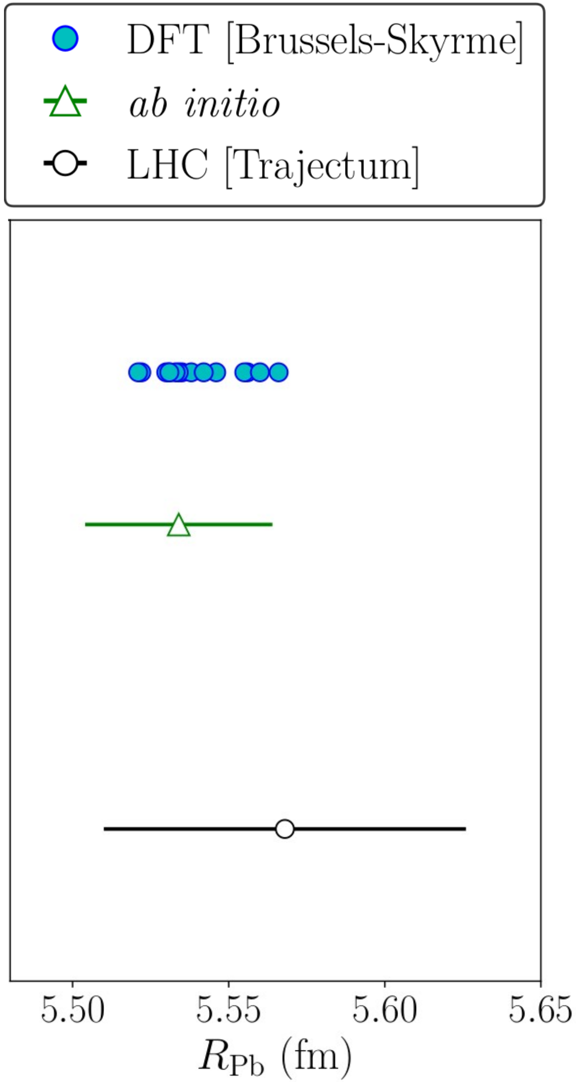
  [BSkG2 functional by W. Ryssens]

- $R_{\mathrm{Pb}}(ab\ initio) = 5.534 \pm 0.030\ \mathrm{fm}$

  [Hu *et al.*, Nature Phys. **18** (2022) 10, 1196-1200]

- $R_{\mathrm{Pb}}(\mathrm{LHC}) = 5.568 \pm 0.058\ \mathrm{fm}$

  [Giacalone, Nijs, van der Schee, PRL **131** (2023) 20, 20]



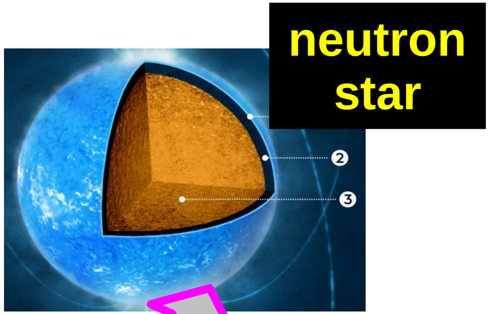
First implication – Independent determination of neutron skin of ^{208}Pb

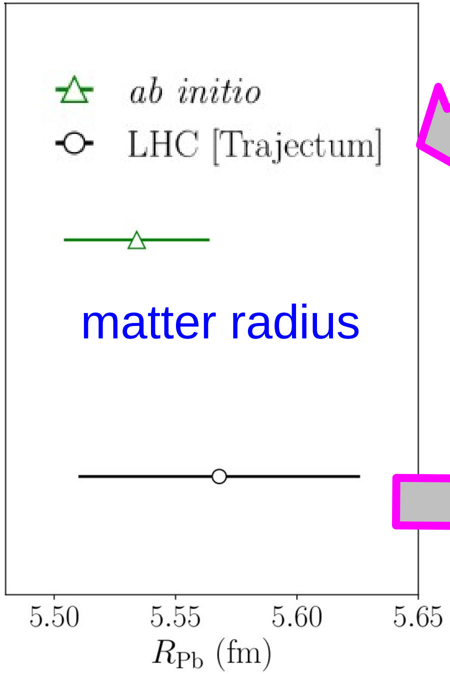
– **Dedicated PREX II experiment at JLAB**

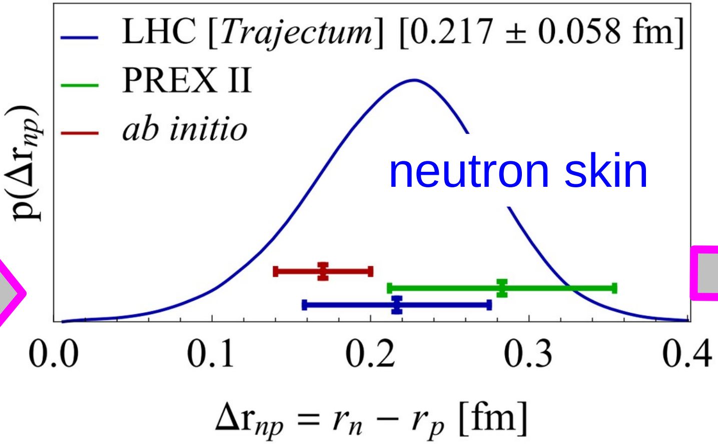
[PREX Collaboration, PRL **126** (2021) 17, 172502]

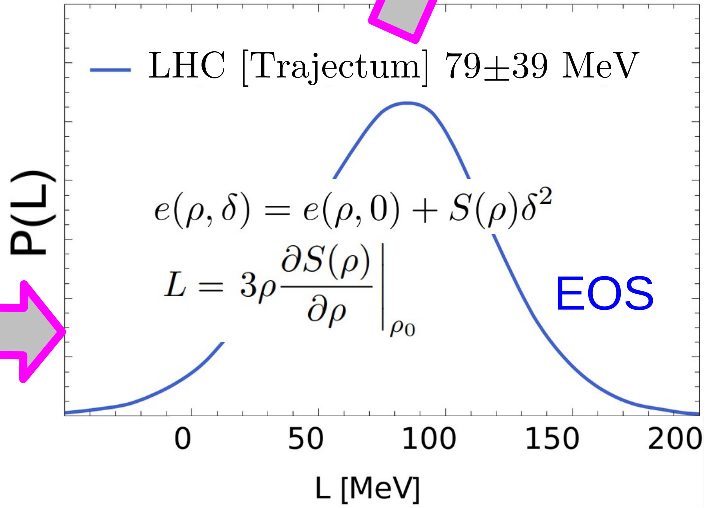
– **Determination in the context of *ab initio* nuclear theory**

[Hu *et al.*, Nature Phys. 18 (2022) 10, 1196-1200]



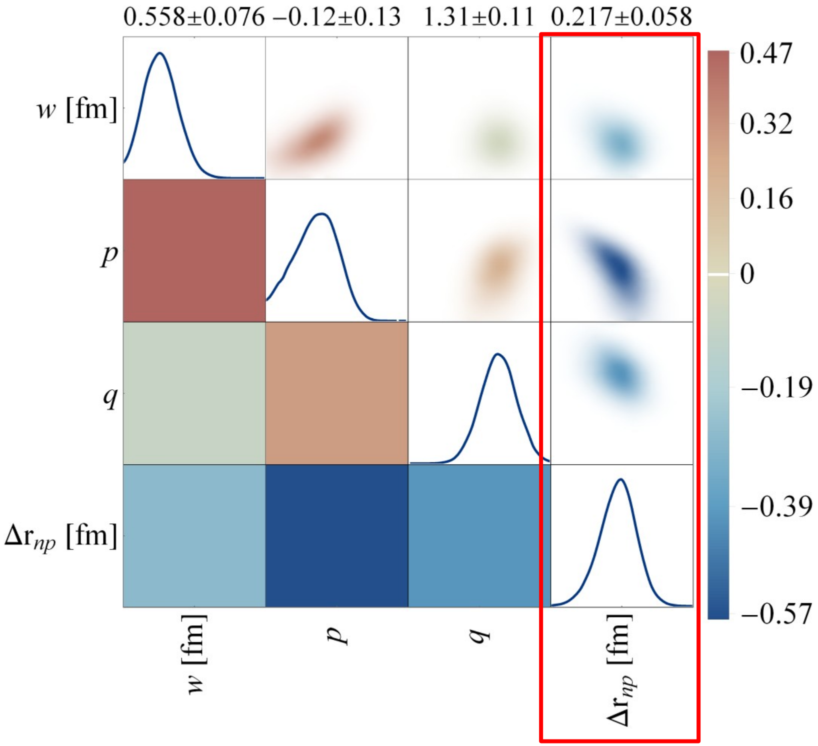






Second implication – The barrier is broken in a unified picture

[Giacalone, Nijs, van der Schee, PRL **131** (2023) 20, 20]



ENERGY DEPOSITION

$$e(x_\perp) \propto \left(\frac{\mathcal{T}_L(x_\perp - b/2)^p + \mathcal{T}_R(x_\perp + b/2)^p}{2} \right)^{q/p}$$

NUCLEON STRUCTURE

w [fm] "gluon size" of the nucleon

Generalize to other parameters (e.g. deformation of 129Xe) – Improve uncertainties

… HOW TO DO THAT SYSTEMATICALLY?

PART II – TOWARDS A UNIFIED MODEL

Modern nuclear structure theory

[Weinberg, PLB **251** (1990) 288-292,
NPB **363** (1991) 3-18]

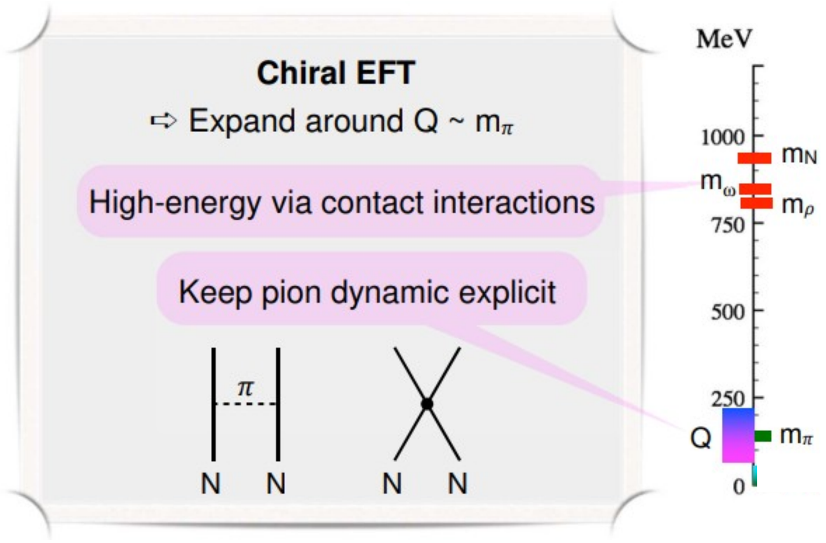
Effective field theory of low-energy QCD

$$\mathcal{H} = \sum_i \mathcal{T}_i + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \cdots$$

– theory of nucleons and pions

– consistent with symmetries of QCD

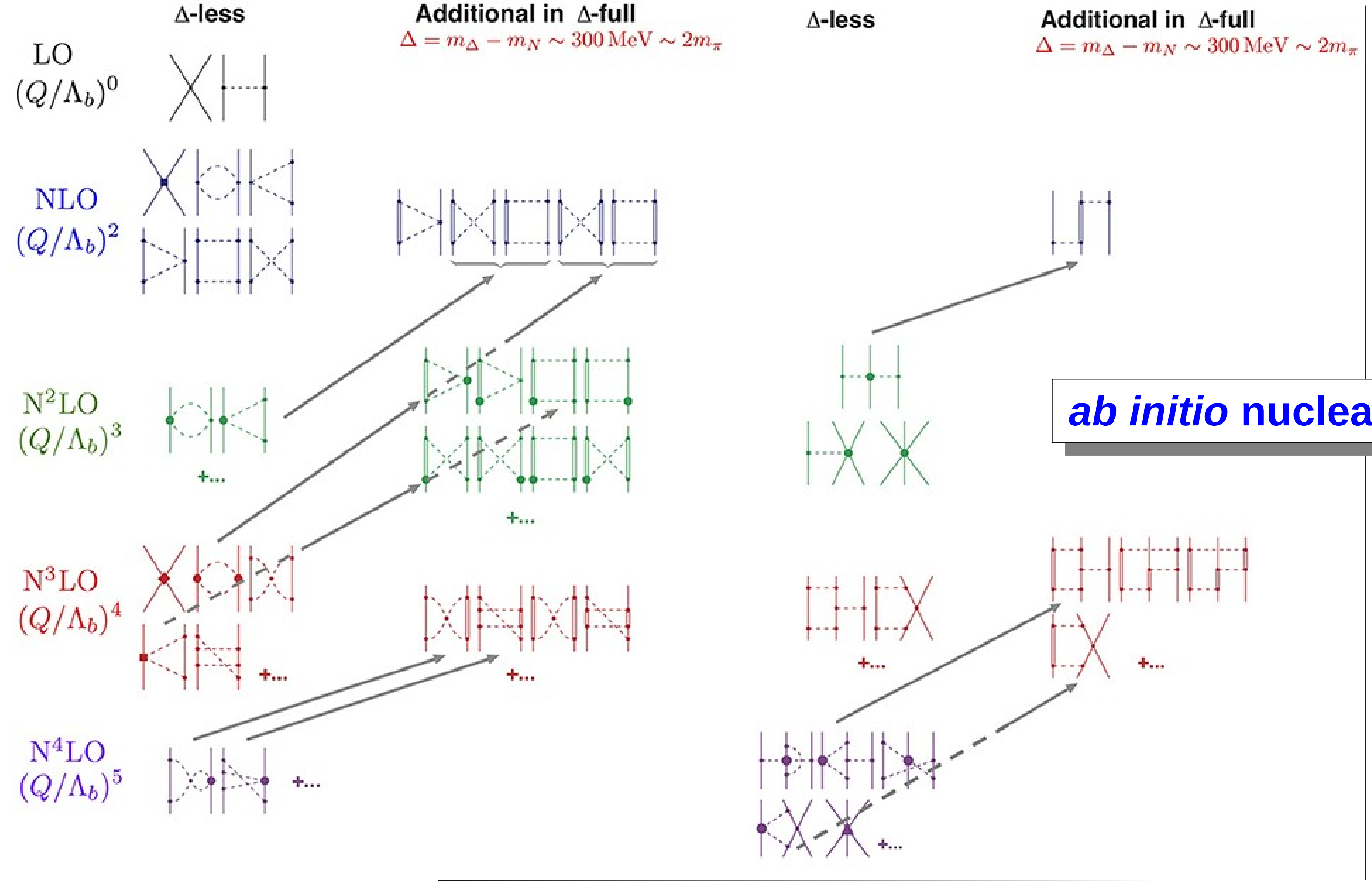
– nucleon-nucleon contact interaction proportional to low-energy constants (EFT parameters, from lattice QCD or exp. data)



Power counting enabled by scale separation

$$m_\pi / m_{\mathrm{QCD}} \ll 1$$

[Hammer, König, van Kolck, RMP **92** (2020) 2, 025004]
[Piarulli, Tews, Front.in Phys. **7** (2020) 245]
[Epelbaum, Hammer, Meissner, RMP **81** (2009) 1773-1825]



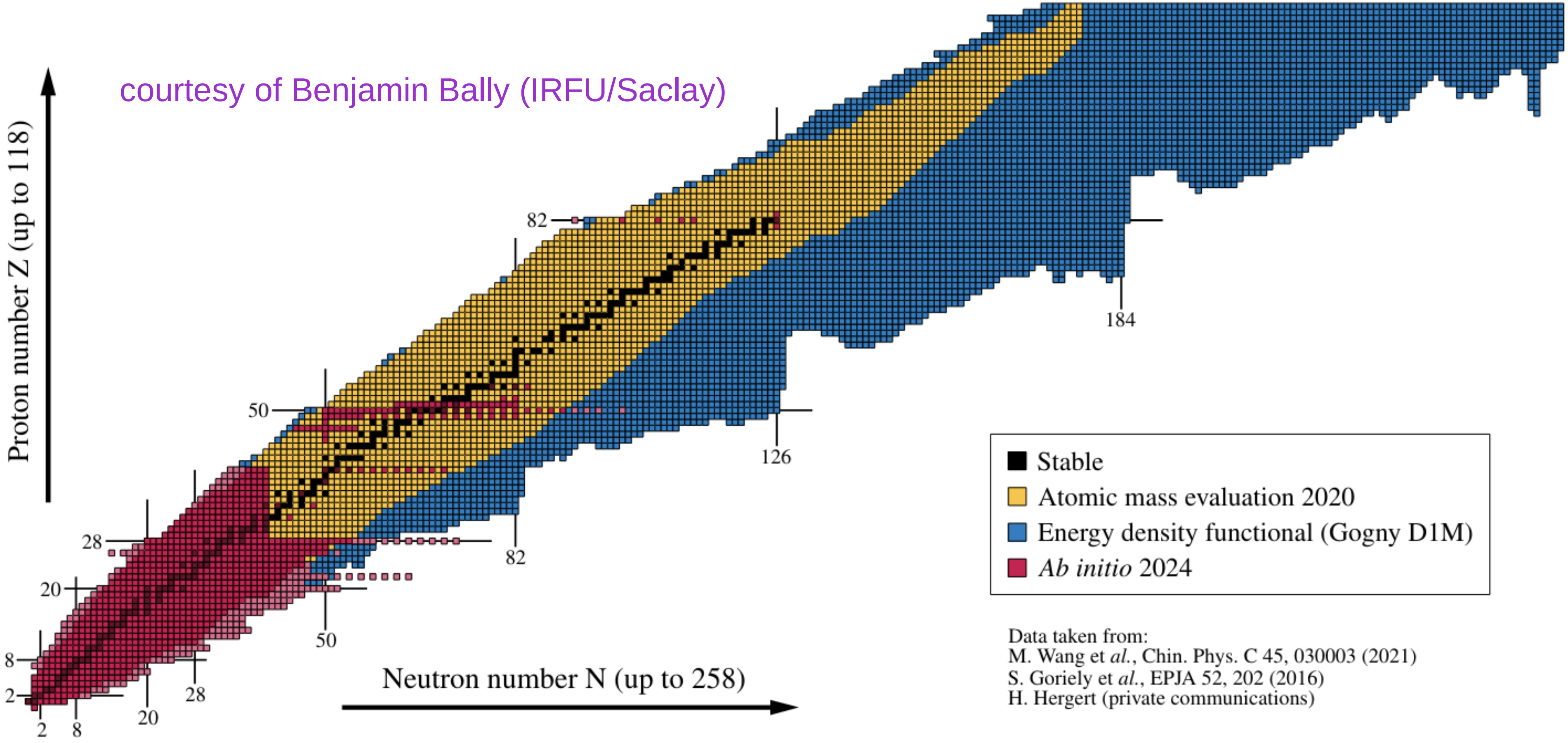
***ab initio* nuclear theory**

… many-body methods to solve the Schrödinger equation $H|\Psi_k^A\rangle = E_k^A|\Psi_k^A\rangle$

Outstanding effort in low-energy community to reach higher masses / deformed systems

Nuclei relevant for heavy-ion collisions fully within reach in next decade

courtesy of Benjamin Bally (IRFU/Saclay)



Data taken from:
M. Wang et *al.*, Chin. Phys. C 45, 030003 (2021)
S. Goriely et *al.*, EPJA 52, 202 (2016)
H. Hergert (private communications)

CURRENT COLLABORATIONS

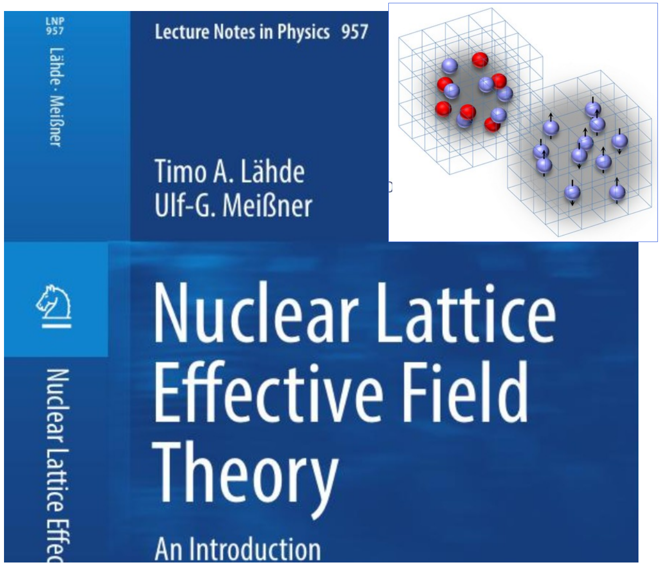
– Nuclear Lattice Effective Field Theory (NLEFT)

MC solution of Schrödinger equation on a lattice

≈ 15 000 ground-state configurations available

[Lu *et al.*, PLB **797** (2019) 134863]
[Summerfield *et al.*, PRC **104** (2021) 4, L041901]

Nucleons sampled directly from A-body wave function!



– *ab initio* Projected Generator Coordinate Method (PGCM)

Wave function from variational calculation
(as in energy density functional theory)

$$\delta \frac{\langle \Psi | H | \Psi \rangle}{\langle \Psi | \Psi \rangle} = 0$$

[Frosini *et al.*, EPJA **58** (2022) 4, 62
EPJA **58** (2022) 4, 63
EPJA **58** (2022) 4, 64]

Provides a deformed density motivated by chiral EFT

CERN-TH-2024-021

arXiv:2402.05995

The unexpected uses of a bowling pin: exploiting ^{20}Ne isotopes for precision characterizations of collectivity in small systems

Giuliano Giacalone,[1,*] Benjamin Bally,[2] Govert Nijs,[3] Shihang Shen,[4] Thomas Duguet,[5,6] Jean-Paul Ebran,[7,8] Serdar Elhatisari,[9,10] Mikael Frosini,[11] Timo A. Lähde,[12,13] Dean Lee,[14] Bing-Nan Lu,[15] Yuan-Zhuo Ma,[14] Ulf-G. Meißner,[10,16,17] Jacquelyn Noronha-Hostler,[18] Christopher Plumberg,[19] Tomás R. Rodríguez,[20] Robert Roth,[21,22] Wilke van der Schee,[3,23,24] and Vittorio Somà[5]

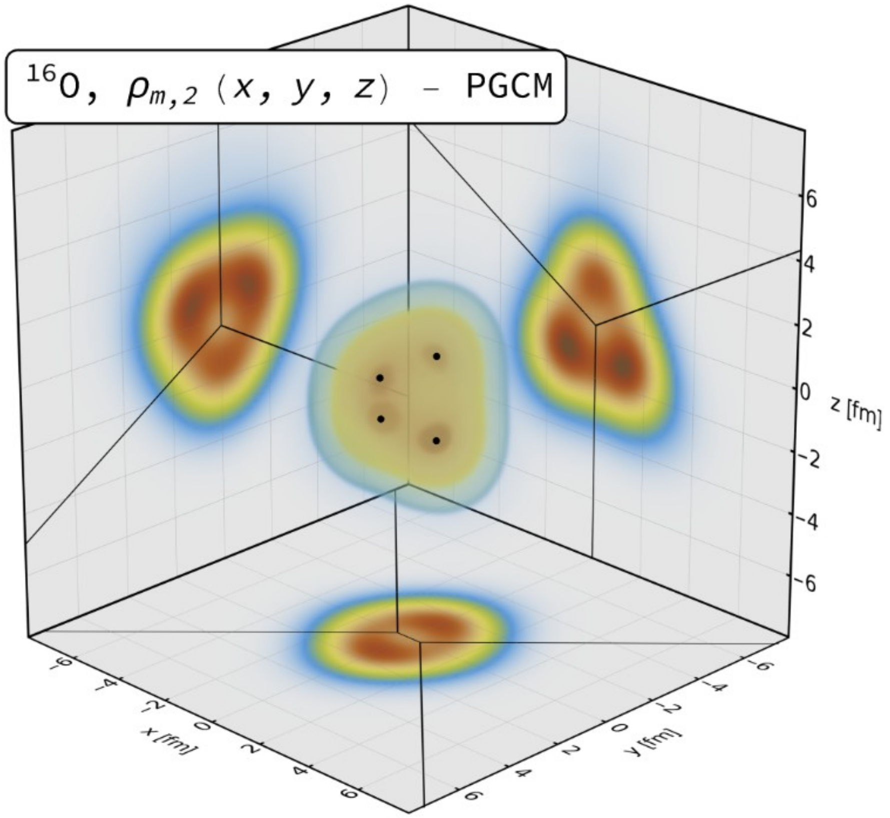
HEAVY IONS — PGCM — NLEFT

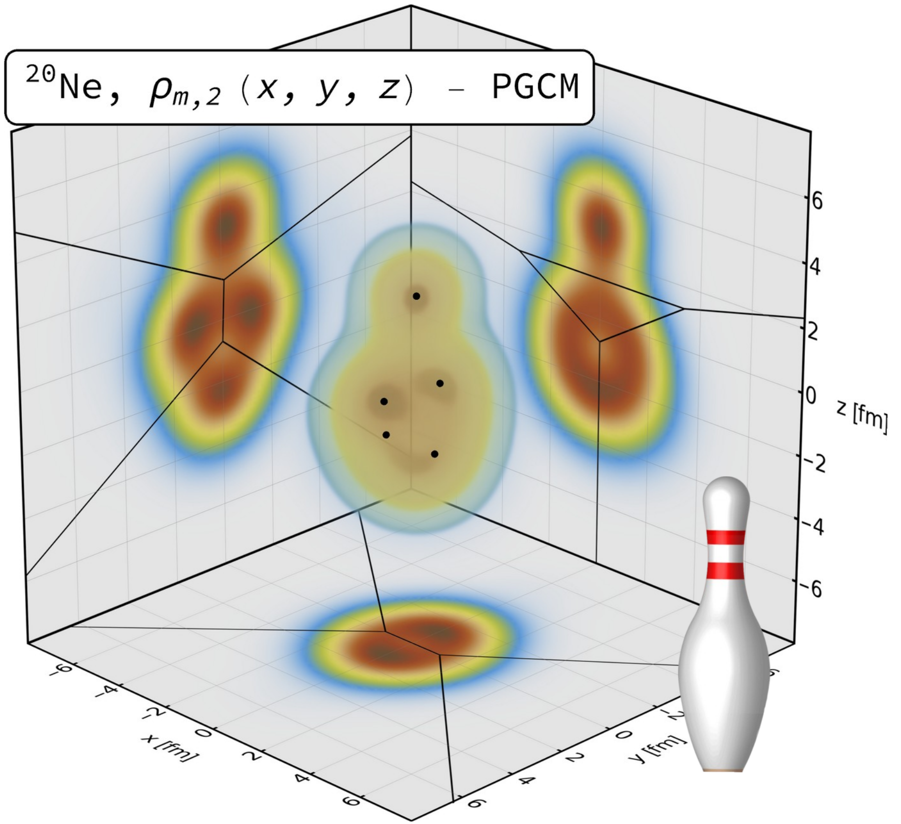
CERN-TH-2024-074

arXiv:2405.20210

The unexpected uses of a bowling pin: anisotropic flow in fixed-target ^{208}Pb+^{20}Ne collisions as a probe of quark-gluon plasma

Giuliano Giacalone,[1,*] Wenbin Zhao,[2,3,†] Benjamin Bally,[4] Shihang Shen,[5] Thomas Duguet,[6,7] Jean-Paul Ebran,[8,9] Serdar Elhatisari,[10] Mikael Frosini,[11] Timo A. Lähde,[12,13] Dean Lee,[14] Bing-Nan Lu,[15] Yuan-Zhuo Ma,[14] Ulf-G. Meißner,[16,17,5] Govert Nijs,[18] Jacquelyn Noronha-Hostler,[19] Christopher Plumberg,[20] Tomás R. Rodríguez,[21] Robert Roth,[22,23] Wilke van der Schee,[18,24,25] Björn Schenke,[26,‡] Chun Shen,[27,28,§] and Vittorio Somà[6]





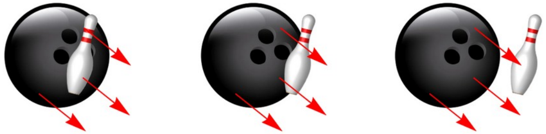
Ancillary files (details):

- NLEFT_dmin_0.5fm_negativeweights_Ne.h5
- NLEFT_dmin_0.5fm_negativeweights_O.h5
- NLEFT_dmin_0.5fm_positiveweights_Ne.h5
- NLEFT_dmin_0.5fm_positiveweights_O.h5
- PGCM_clustered_dmin0_Ne.h5
- PGCM_clustered_dmin0_O.h5
- PGCM_uniform_dmin0_Ne.h5
- PGCM_uniform_dmin0_O.h5

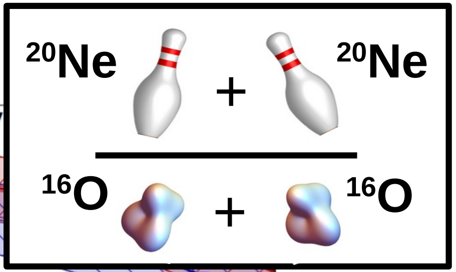
arXiv:2402.05995

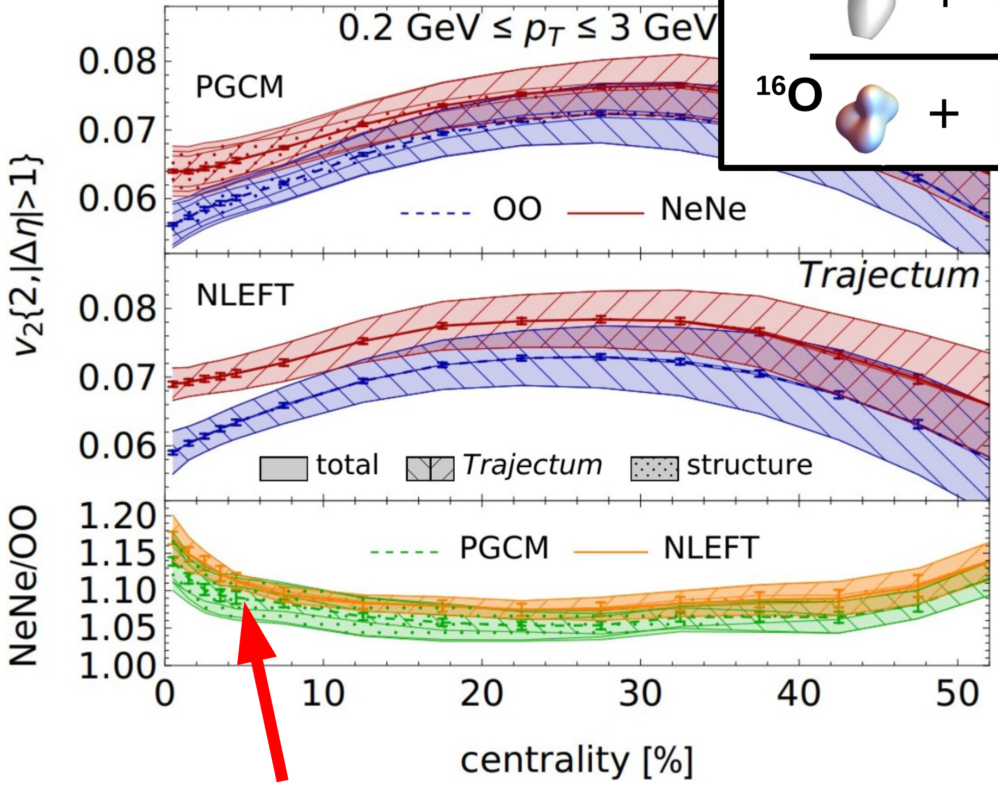
Ne+Ne for precision studies of small-system collectivity

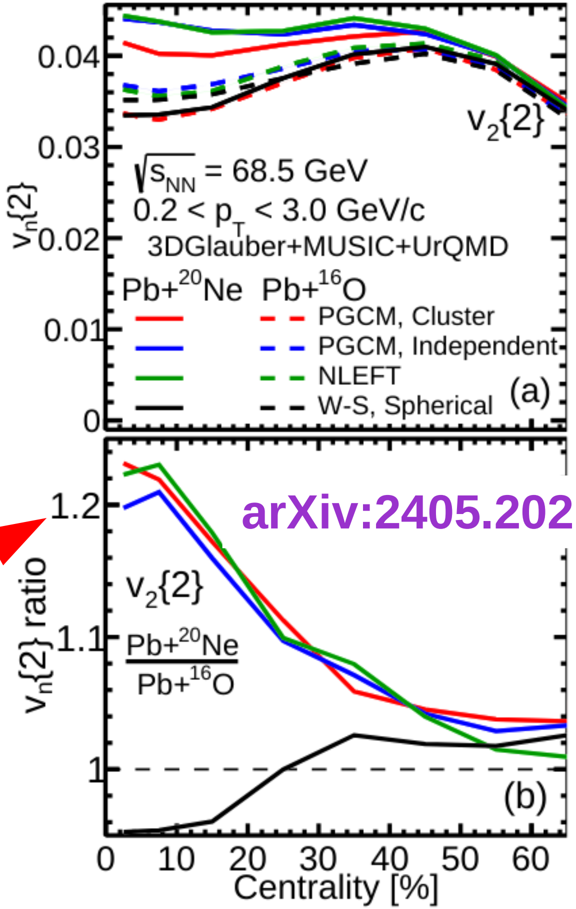
Playing bowling at LHCb



arXiv:2402.05995







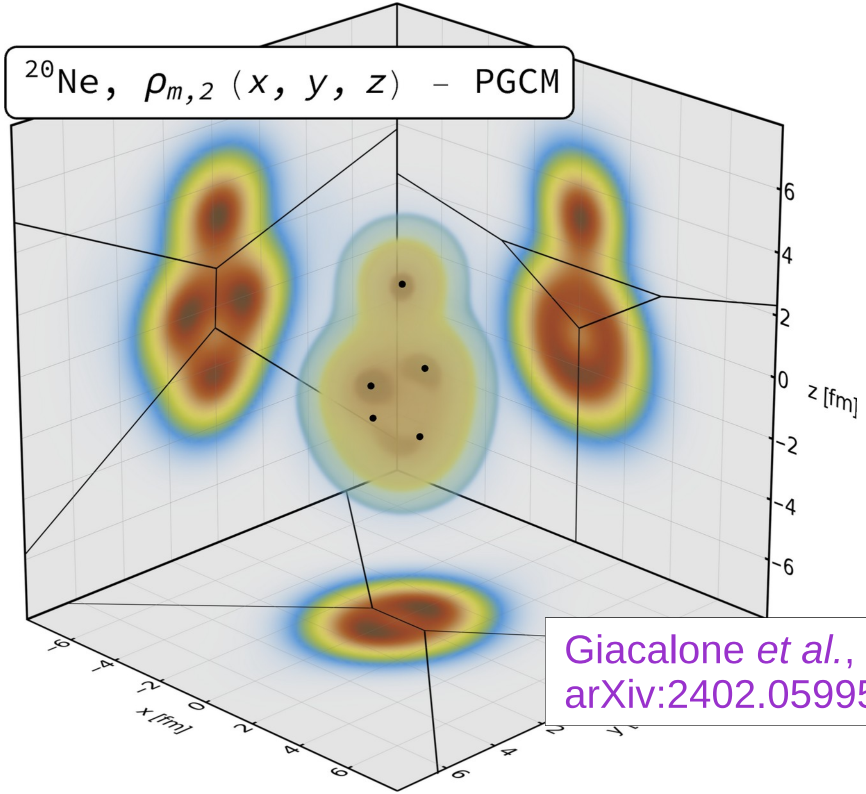
arXiv:2405.20210

huge signal from SMOG2

%-level theoretical systematics in small system

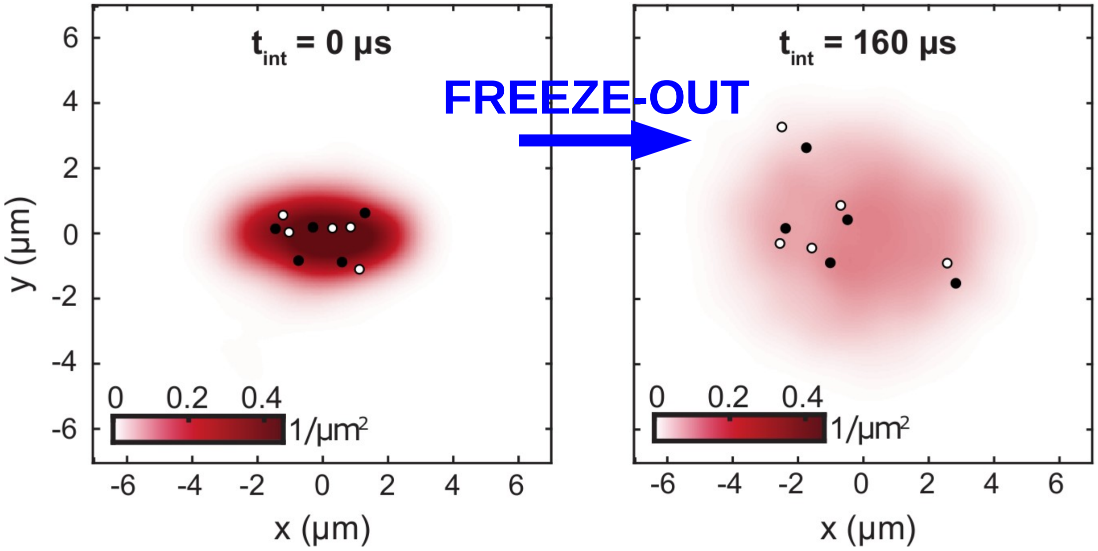
SIDE NOTE – STRONGLY CORRELATED *MESOSCOPIC* QUANTUM SYSTEMS

5 "α-clusters" (2p+2n) in neon-20



Giacalone *et al.*,
arXiv:2402.05995

5 clusters in 5(↑)+5(↓) cold fermions



[Brandstetter, Lunt, Heintze, Giacalone *et al.*,
arXiv:2308.09699, to appear in Nature Physics]

TALK BY LARS HEYEN

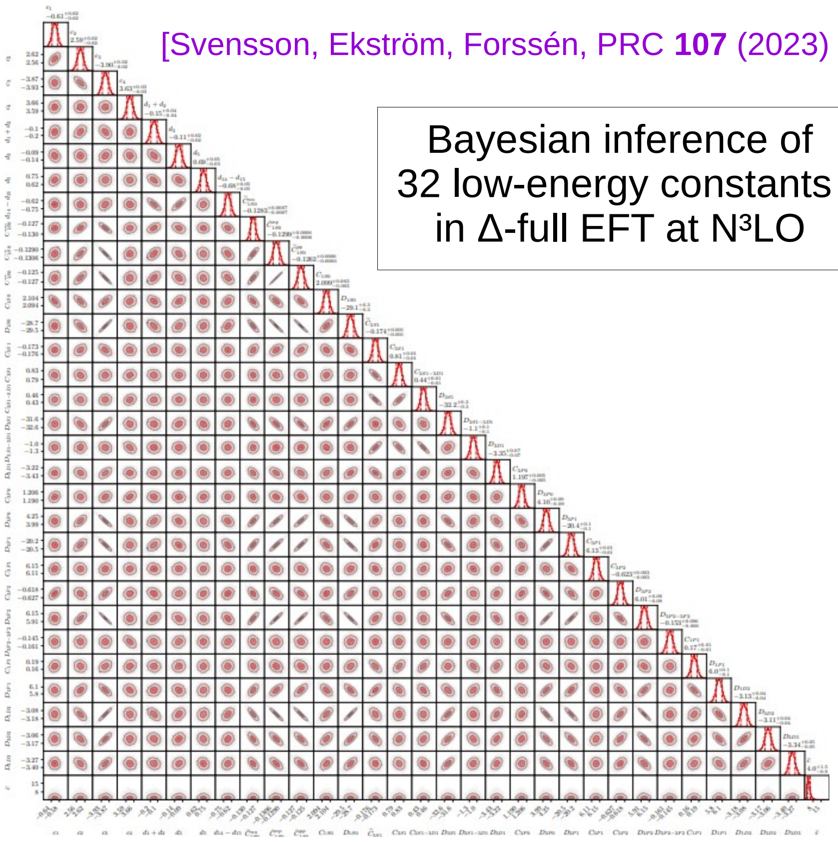
NB: We probe clusters in high-energy OO collisions
Unique experimental opportunity

[Yuan *et al.*, PRC **109** (2024) 5, L051904
[Zhao *et al.*, arXiv:2404.09780]
[Zhang *et al.*, arXiv:2404.08385]

Long term goals? Coupling chiral EFT to hydrodynamics

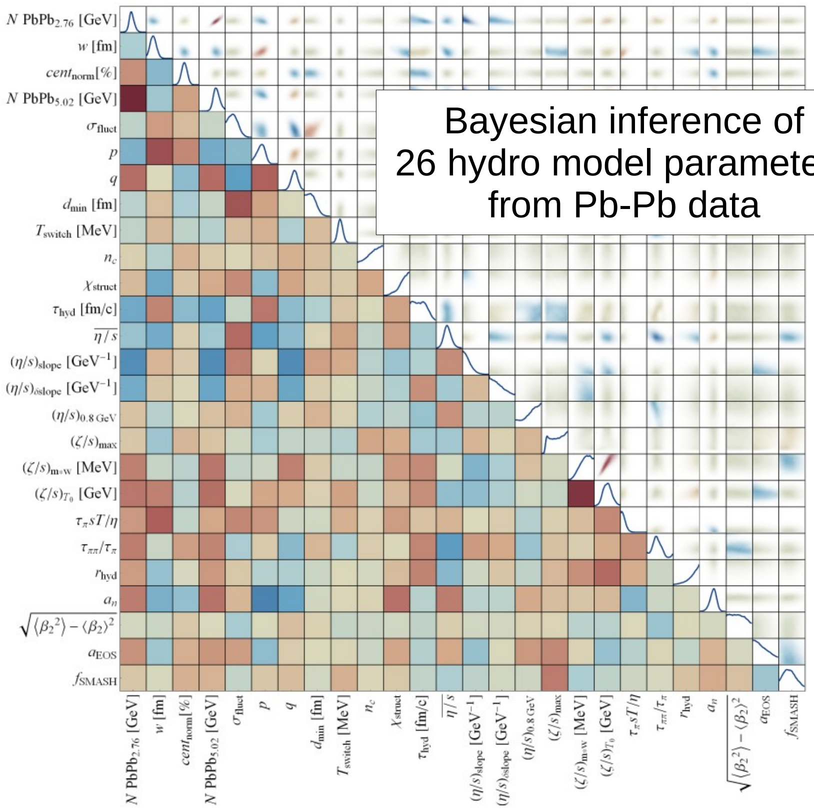
Essential for proper uncertainty quantification

[Svensson, Ekström, Forssén, PRC **107** (2023) 1, 014001]



Bayesian inference of
32 low-energy constants
in Δ-full EFT at N³LO

[Giacalone, Nijs, van der Schee, PRL **131** (2023) 20, 20]



Bayesian inference of
26 hydro model parameters
from Pb-Pb data

Near future? "Minimal" interaction (pion-less SU(4)-symmetric) in NLEFT

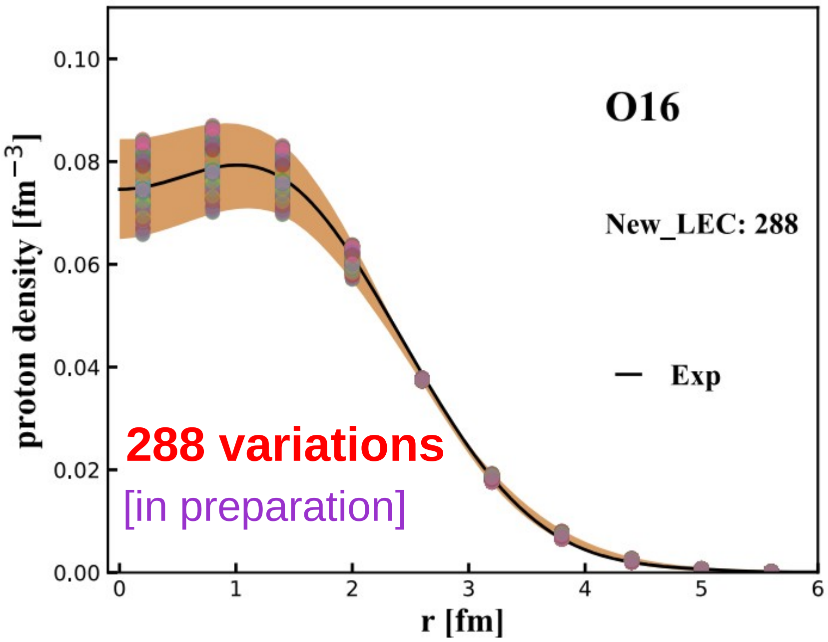
[Lu *et al.*, PLB **797** (2019) 134863]

$$H_{\mathrm{SU}(4)} = H_{\mathrm{free}} + \frac{1}{2!} C_2 \sum_{\mathbf{n}} \tilde{\rho}(\mathbf{n})^2 + \frac{1}{3!} C_3 \sum_{\mathbf{n}} \tilde{\rho}(\mathbf{n})^3$$

$$\tilde{\rho}(\mathbf{n}) = \sum_i \tilde{a}_i^\dagger(\mathbf{n}) \tilde{a}_i(\mathbf{n}) + s_L \sum_{|\mathbf{n}'-\mathbf{n}|=1} \sum_i \tilde{a}_i^\dagger(\mathbf{n}') \tilde{a}_i(\mathbf{n}')$$

$$\tilde{a}_i(\mathbf{n}) = a_i(\mathbf{n}) + s_{NL} \sum_{|\mathbf{n}'-\mathbf{n}|=1} a_i(\mathbf{n}')$$

lattice coordinates $\boldsymbol{n} = (n_x, n_y, n_z)$

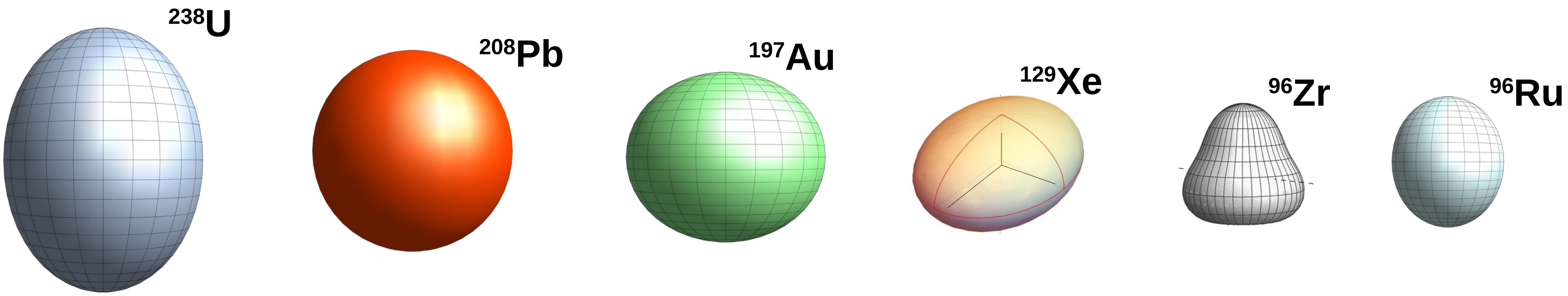


Replacing the Woods-Saxon with a nuclear force inferred from ^{16}O collisions

Akin to femtoscopy studies. Consistency with low-energy physics?

[ALICE collaboration, Nature **588** (2020) 232-238]

Program is feasible – Fully exploiting Run 3+4 data



Planned LHC experiments with novel species:


^{16}O

(**Pb+O** fixed-target @ 70 GeV,
O+O both collider and fixed-target)


^{20}Ne

(**Pb+Ne** fixed-target, possibly collider?)

Huge opportunities from LHCb and small systems:

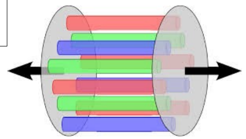
Pb+N, **Pb+Ar**, **Pb+Kr**, **Pb+Xe** (fixed-target) **B+B**, **Mg+Mg** (will run in SPS, short LHC run?)

Schedule for Run 5+6? Choice of nuclei?

CONCLUSION

COMPLETING THE PICTURE

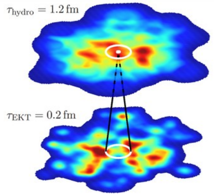
2 Effective theory of highly coherent gluon states: *"Glasma"*



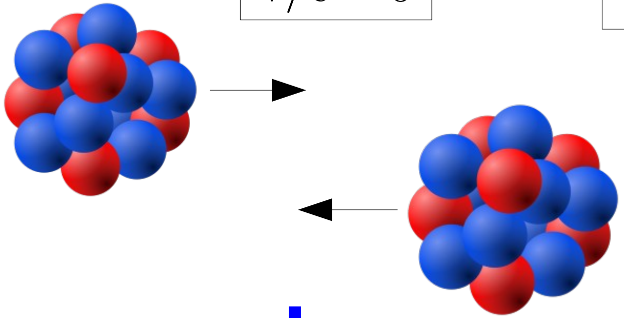
$$\langle T^{00}\rangle \propto Q_A^2(\mathbf{x})Q_B^2(\mathbf{x})$$

3 Effective QCD kinetic theory

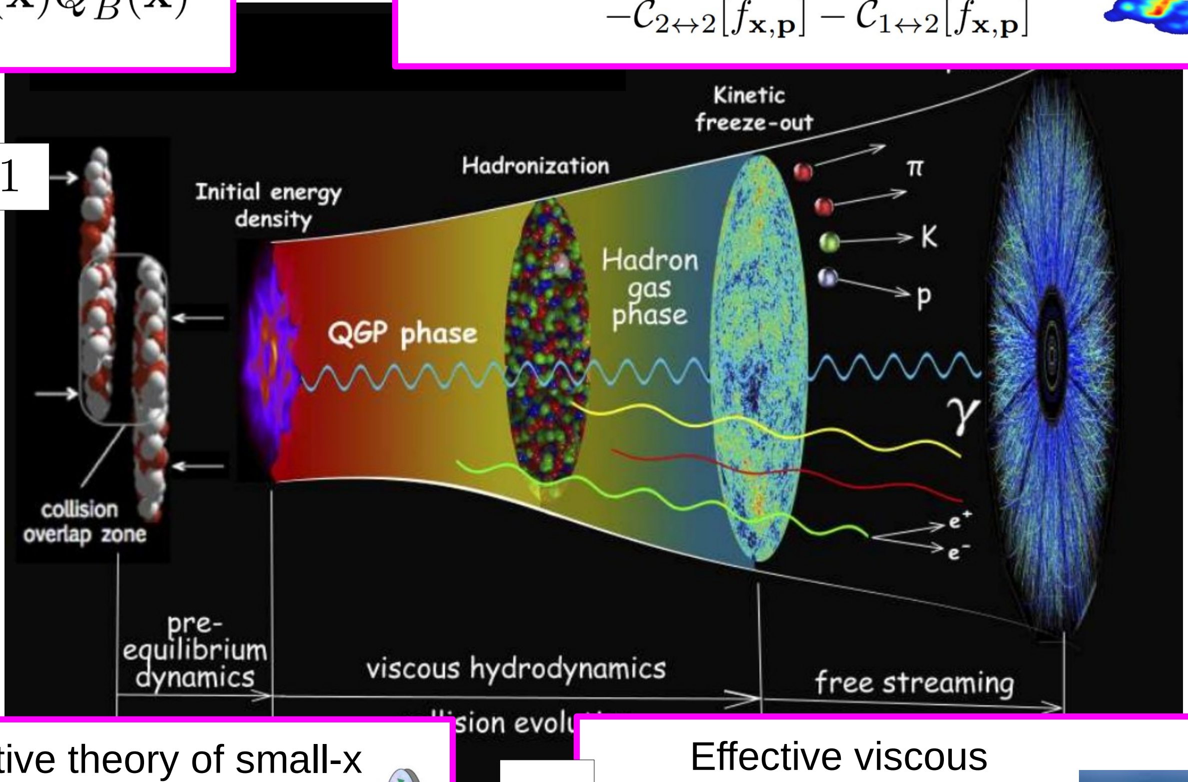
$$\partial_\tau f_{\mathbf{x},\mathbf{p}} + \frac{\mathbf{p}}{|\mathbf{p}|}\cdot\nabla_{\mathbf{x}} f_{\mathbf{x},\mathbf{p}} - \frac{p^z}{\tau}\partial_{p^z} f_{\mathbf{x},\mathbf{p}} = -\mathcal{C}_{2\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}] - \mathcal{C}_{1\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}]$$



$v/c \sim 0$



$v/c = 1$



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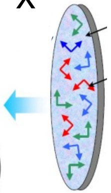
Effective theories of low-energy QCD for spatial distribution of large-x partons

cross-disciplinary research

1 Effective theory of small-x degrees of freedom

CGC

$$A^\mu_{1,2}(x) \qquad Q_s^2(\mathbf{x})$$



4 Effective viscous hydrodynamic description

$$\vec{F} = -\vec{\nabla}P \qquad \eta/s$$