The XXXth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions (Quark Matter 2023), Houston, USA

SUOMEN AKATEMIA
FINLANDS AKADEMI
ACADEMY OF FINLAND

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Collective Dynamics – theoretical overview

Yuuka Kanakubo

University of Jyväskylä, Centre of Excellence in Quark Matter

v_n Correlation of particles in momentum space

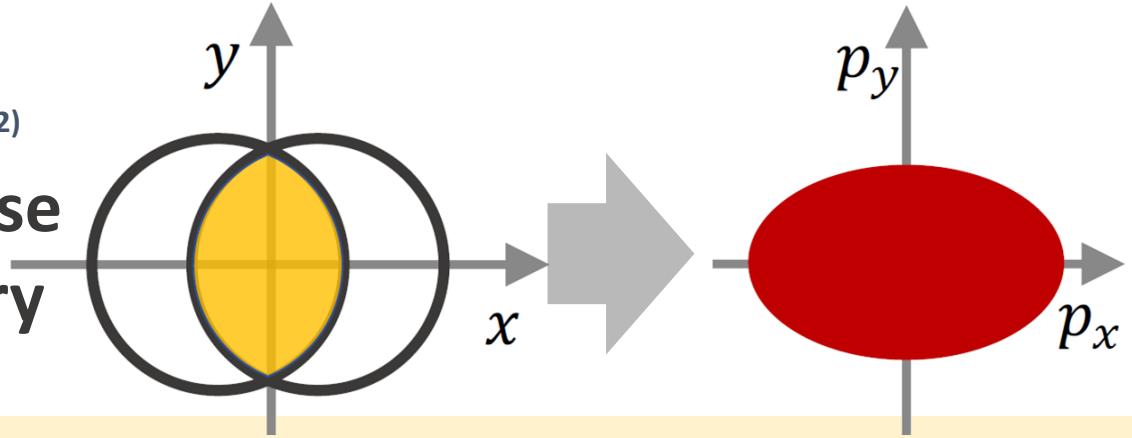
Collectivity in early 2000s

v_n Correlation of particles in momentum space

Initial state

Evolution of QGP + hadron gas

Elliptic flow… J. Y. Ollitrault (1992)
Hydrodynamic response against initial geometry



➔ Hydrodynamic behaviour of QGP
D. Molnar and M. Gyulassy (2002), P. F. Kolb and U. Heinz (2003)…

Collectivity: purely born in hydrodynamic expansion

Collectivity in small systems

J. Sun (Thu, plenary)

In high-multiplicity small systems…

Hydro-like collectivity

Reviews: B. Schenke (2021); J. L. Nagle and W. A. Zajc (2018); K. Dusling *et al.* (2016)…

QGP formation or not?

Workshop series: QCD challenges from pp to AA

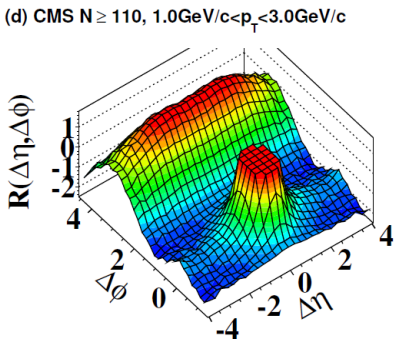
J. Adolfsson *et al.* (2020)

Taxco 2016, Puebla 2017, Lund 2019, Padova 2023

Other possible sources of collectivity?

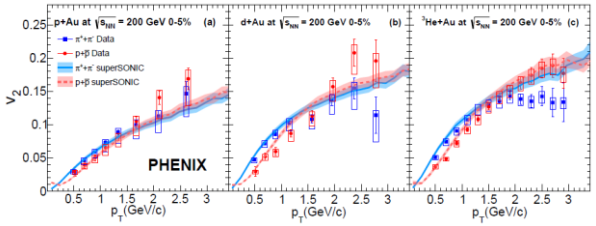
Momentum anisotropy in CGC?

Underlying event (e.g. MPI)? etc.



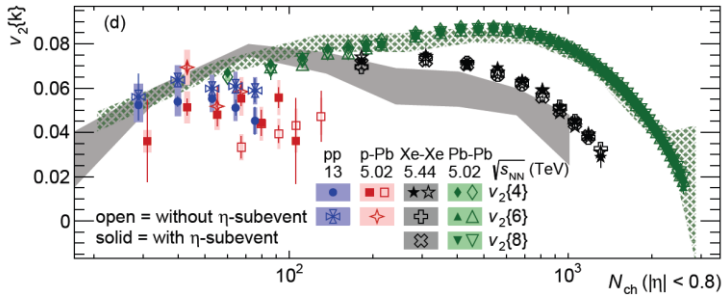
Long range correlation

CMS Collaboration, JHEP 09 091 (2010)



Flow from three distinct geometries

PHENIX Collaboration, Phys. Rev. C 97, 064904 (2018), Nature Phys. 15 (2019) 3, 214-220

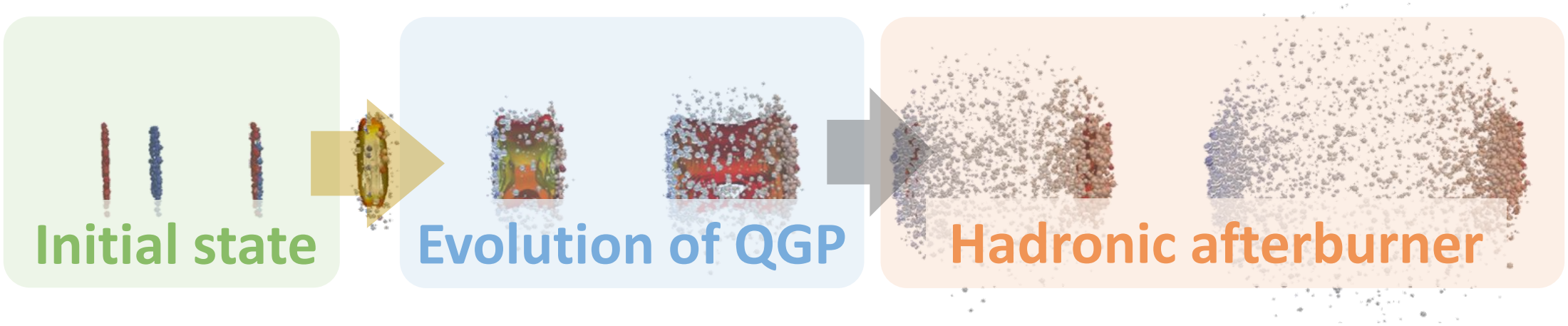


Multiparticle azimuthal correlations

ALICE Collaboration, Phys. Rev. Lett. 123 (2019) 14, 142301

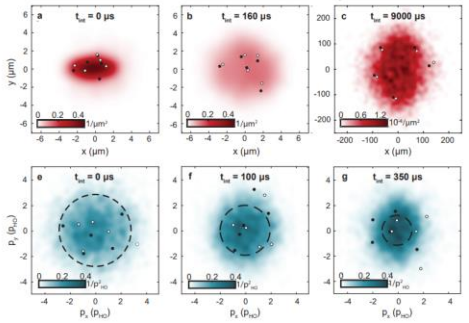
Collectivity in 2023

v_n Correlation of particles in momentum space

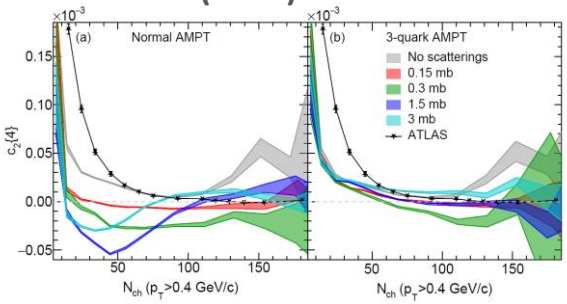


Collectivity in 2023

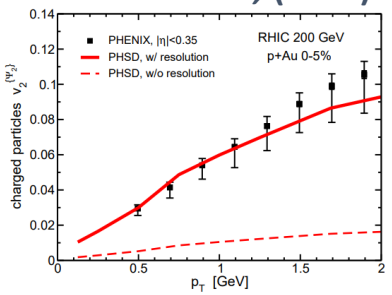
G. Giacalone 2308.09699

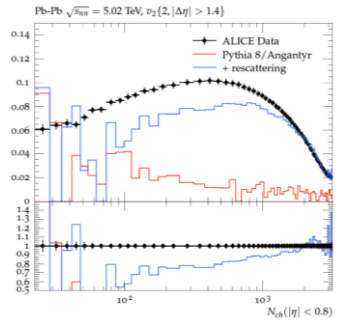


X. Zhao *et al.* (2023)



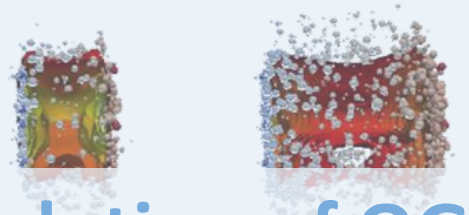
L. Oliva *et al.*, (2020)





C. Bierlich *et al.* (2021)

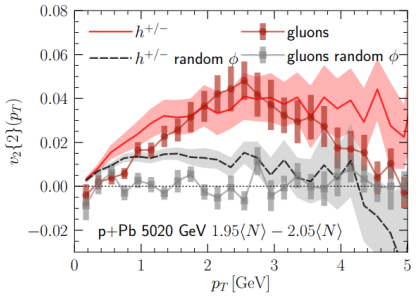
Initial state



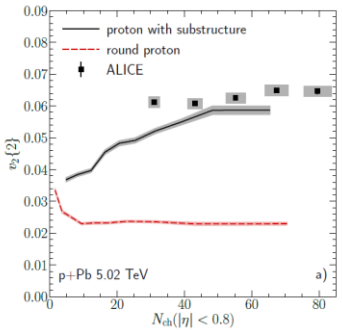
Evolution of QGP

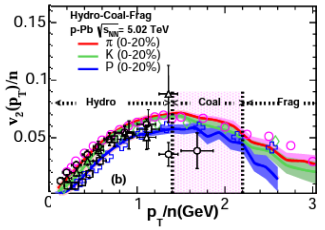
Hadronic afterburner

M. Greif *et al.* (2021)



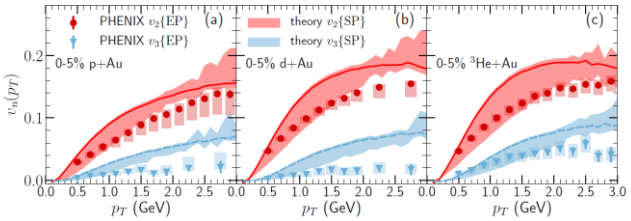
B. Schenke (2021)

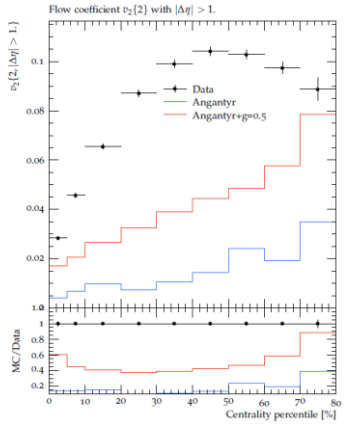




W. Zhao *et al.* (2020)

B. Schenke *et al.*, (2020)





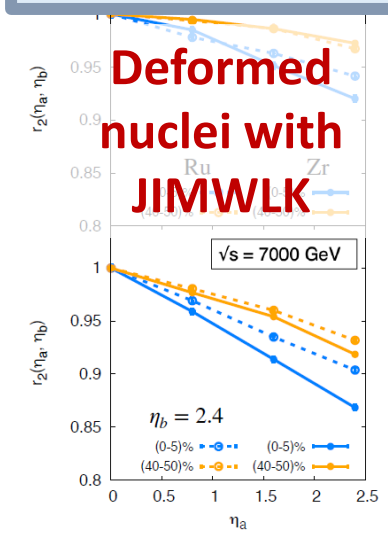
C. Bierlich *et al.* (2021)

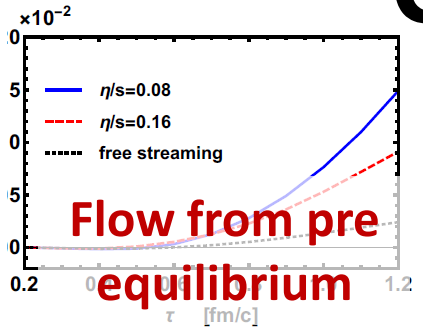
etc.

Collectivity in 2023

P. Singh (Wed, parallel)

Deformed nuclei with JIMWLK

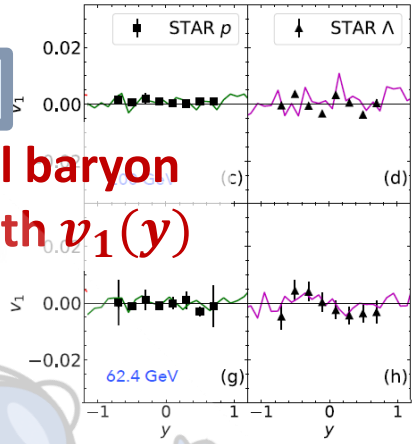




Flow from pre equilibrium

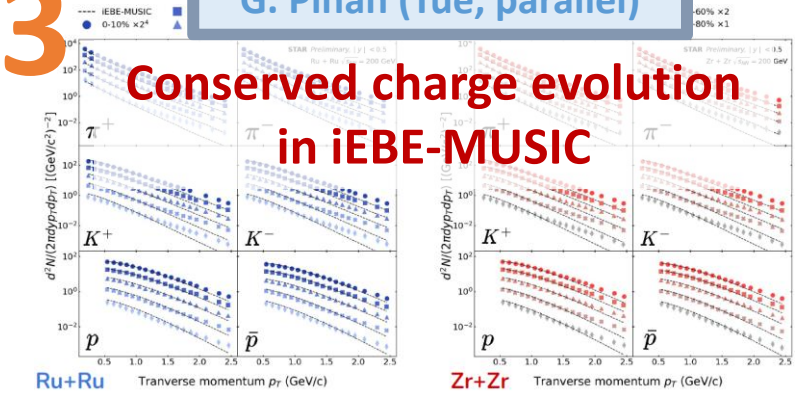
L. Du (Tue, parallel)

Probing initial baryon production with $v_1(y)$



G. Pihan (Tue, parallel)

Conserved charge evolution in iEBE-MUSIC



P. Bozek (Tue, parallel)

Initial state

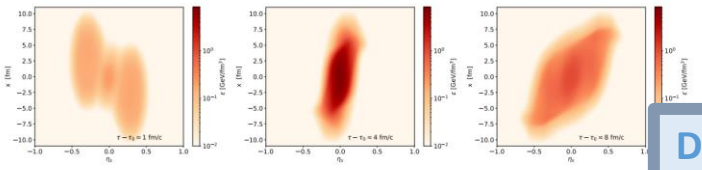
Evolution of QGP

Hadronic afterburner

I. Karpenko (Wed, parallel), B. Tomasik (Wed, parallel)

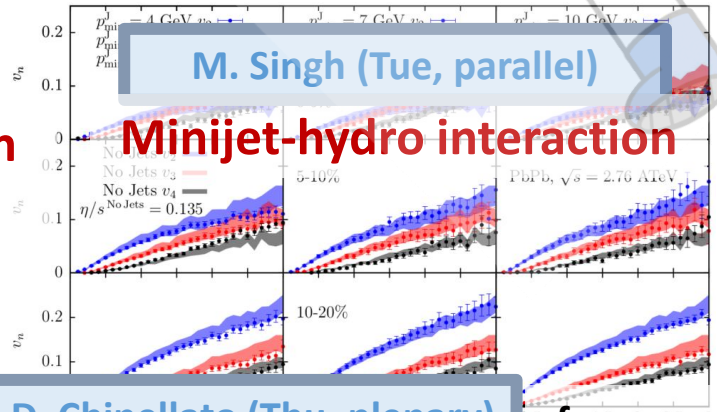
MUFFIN: MUlti Fluid simulation for Fast IoN collisions

J. Cimerman et al., (2023)



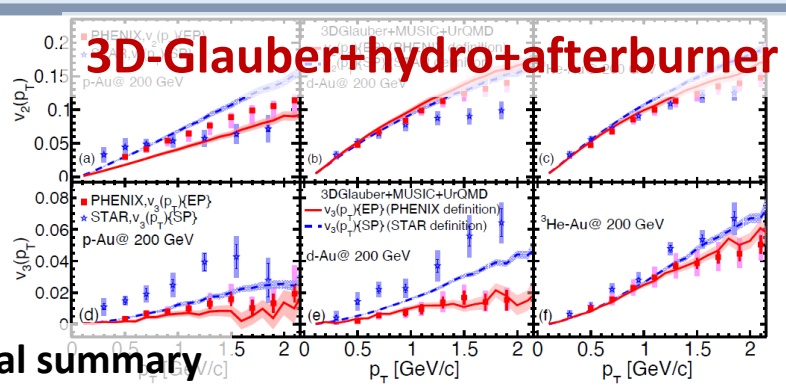
M. Singh (Tue, parallel)

Minijet-hydro interaction



C. Shen (Tue, parallel), B. Schenke (Tue, parallel)

3D-Glauber+hydro+afterburner



W. Zhao *et al.* (2023)

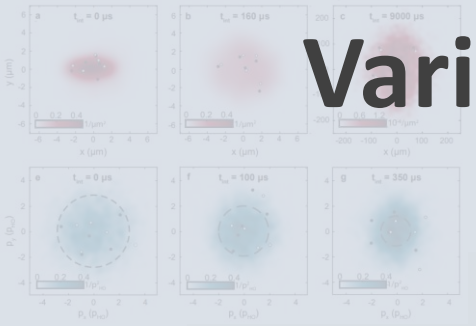
D. D. Chinellato (Thu, plenary)

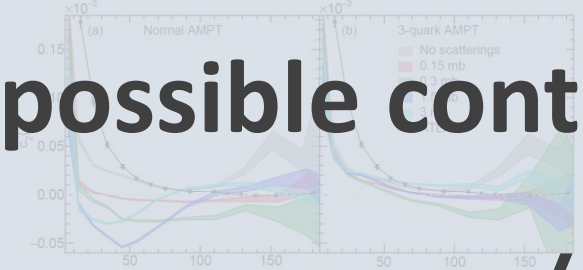
for experimental summary

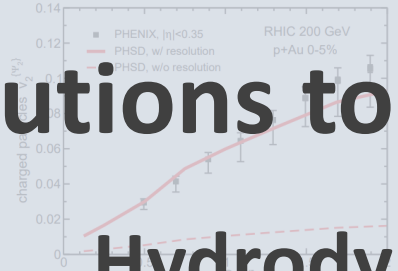
etc.

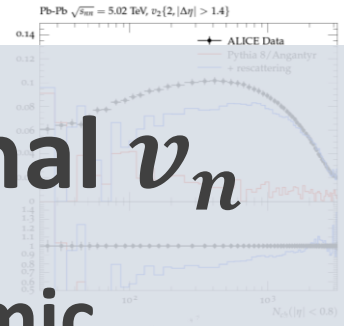
Collectivity in 2023

Various possible contributions to final v_n









C. Bierlich *et al.* (2021)

Collectivity $\not\Rightarrow$ **Hydrodynamic behavior of QGP**

Good

Opportunities to study…

Nuclear structure, feature of CGC, properties of QGP etc.

Bad

Large theoretical uncertainty

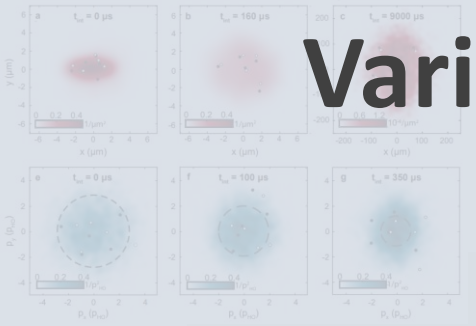
Which physics? How much?

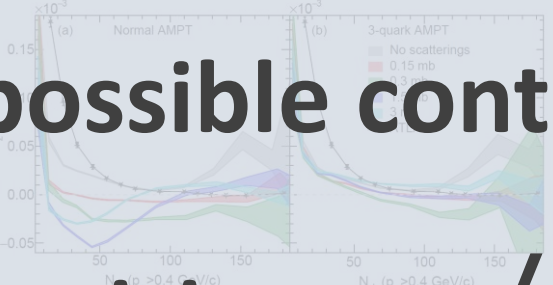
Collectivity is from everywhere

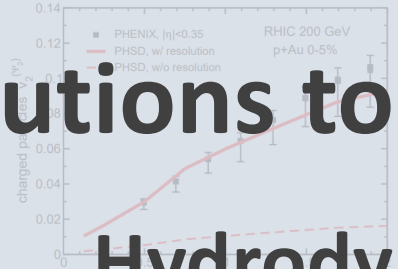
etc.

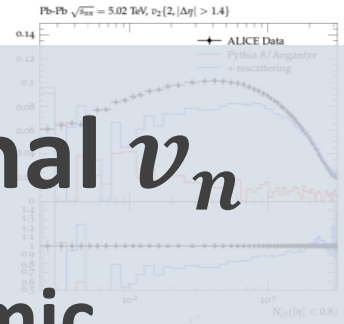
Collectivity in 2023

Various possible contributions to final v_n









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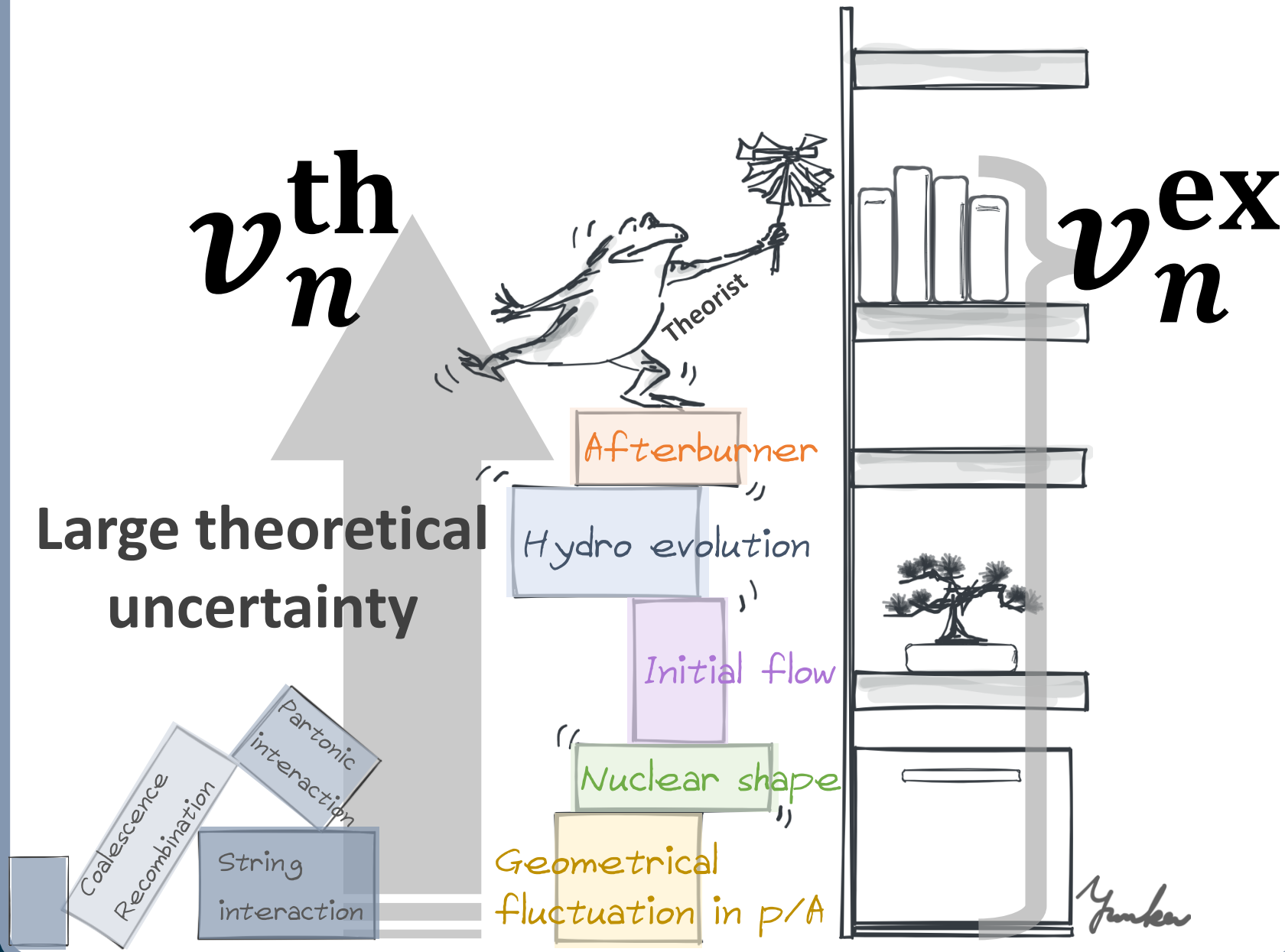


In this talk...

How to disentangle each contribution qualitatively and quantitatively

HIC is now precision science.

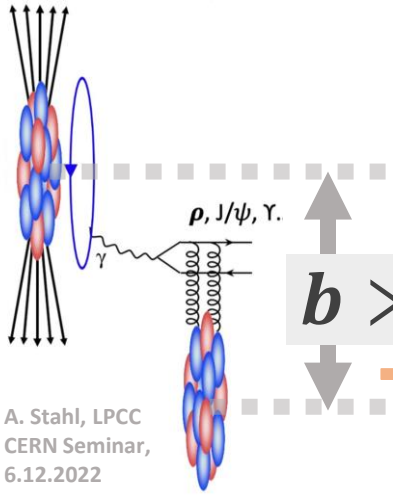
Towards next generation...

Hydro Monte-Carlo Event Generators

+ Statistical tools

Highlights on recent results

Ultra Peripheral Collisions (UPC)



$b \gg R_A + R_B$

➔ Ultra Peripheral!

A. Stahl, LPCC CERN Seminar, 6.12.2022

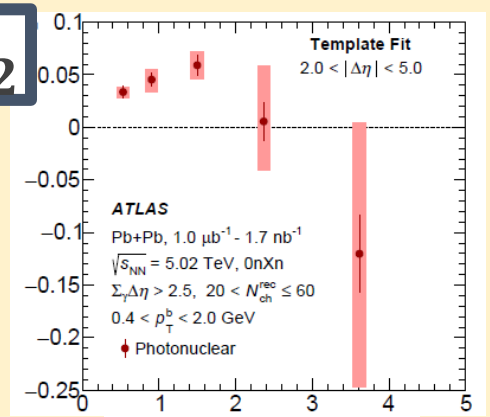
~~AA~~ ~~pA~~ Go smaller…

γA

Photon-nucleus

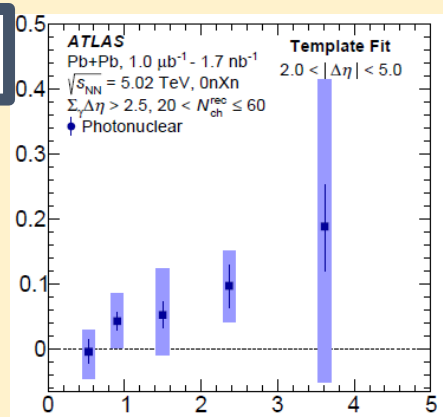
Study on partonic structure of nucleus

v_2



p_T [GeV]

v_3



p_T [GeV]

Collectivity in high multiplicity UPC

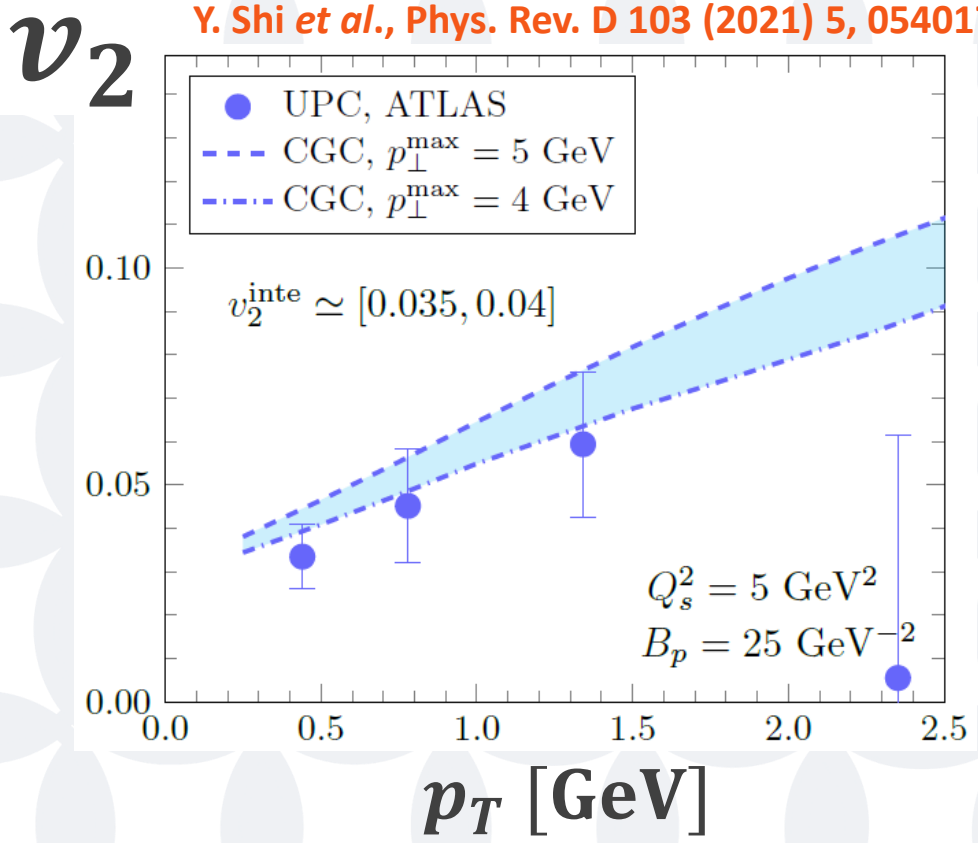
ATLAS collaboration: Phys. Rev. C 104 (2021) 1, 014903

Is it possible to understand with existing theoretical models?

Ultra Peripheral Collisions (UPC)

CGC

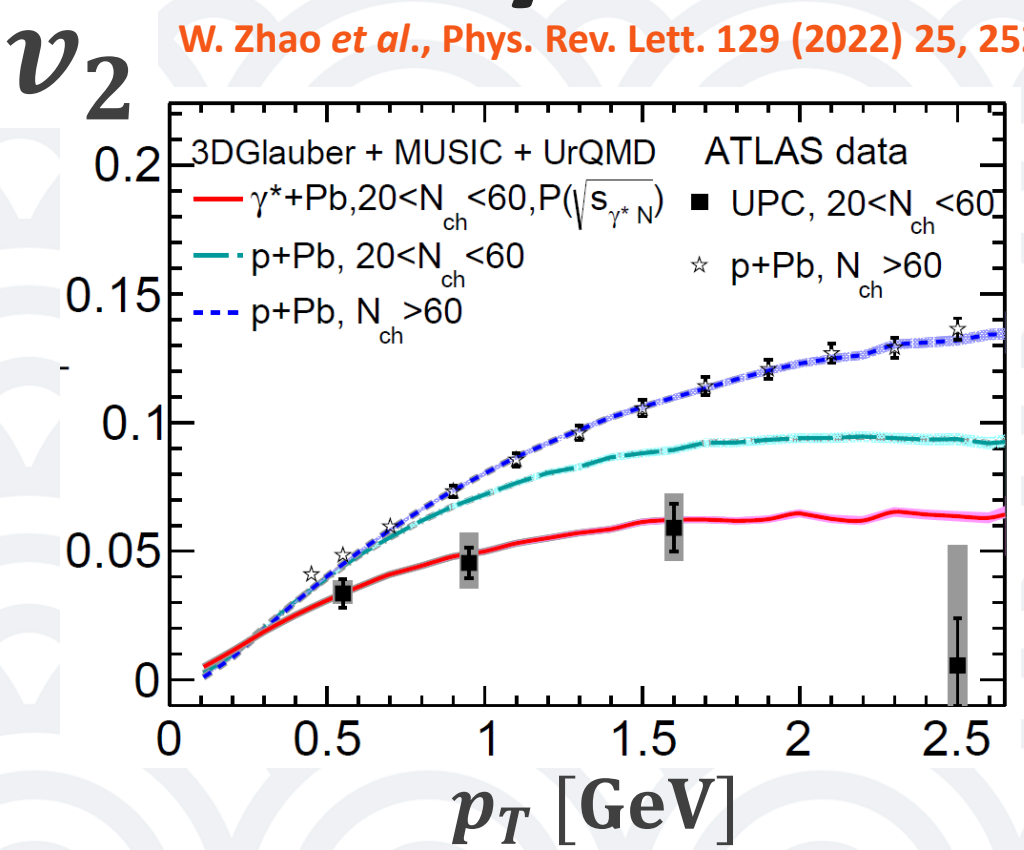
Y. Shi *et al.*, Phys. Rev. D 103 (2021) 5, 054017



B. Schenke (Tue, parallel)

Hydro

W. Zhao *et al.*, Phys. Rev. Lett. 129 (2022) 25, 252302



Ultra Peripheral Collisions (UPC)

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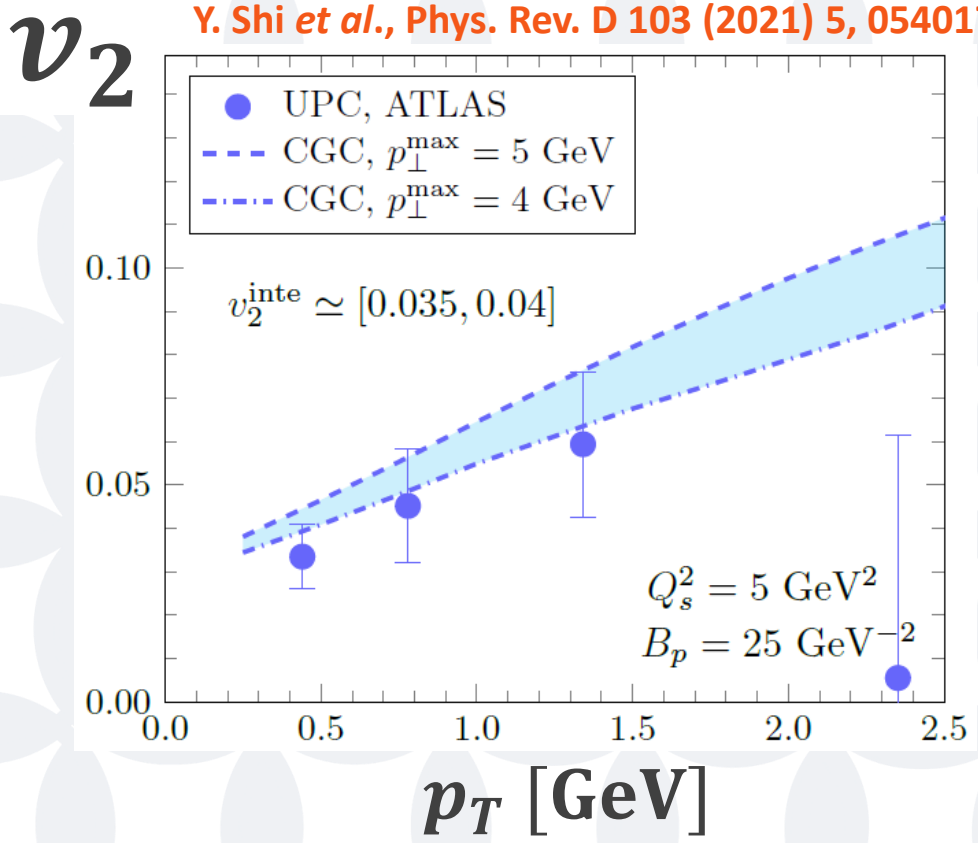

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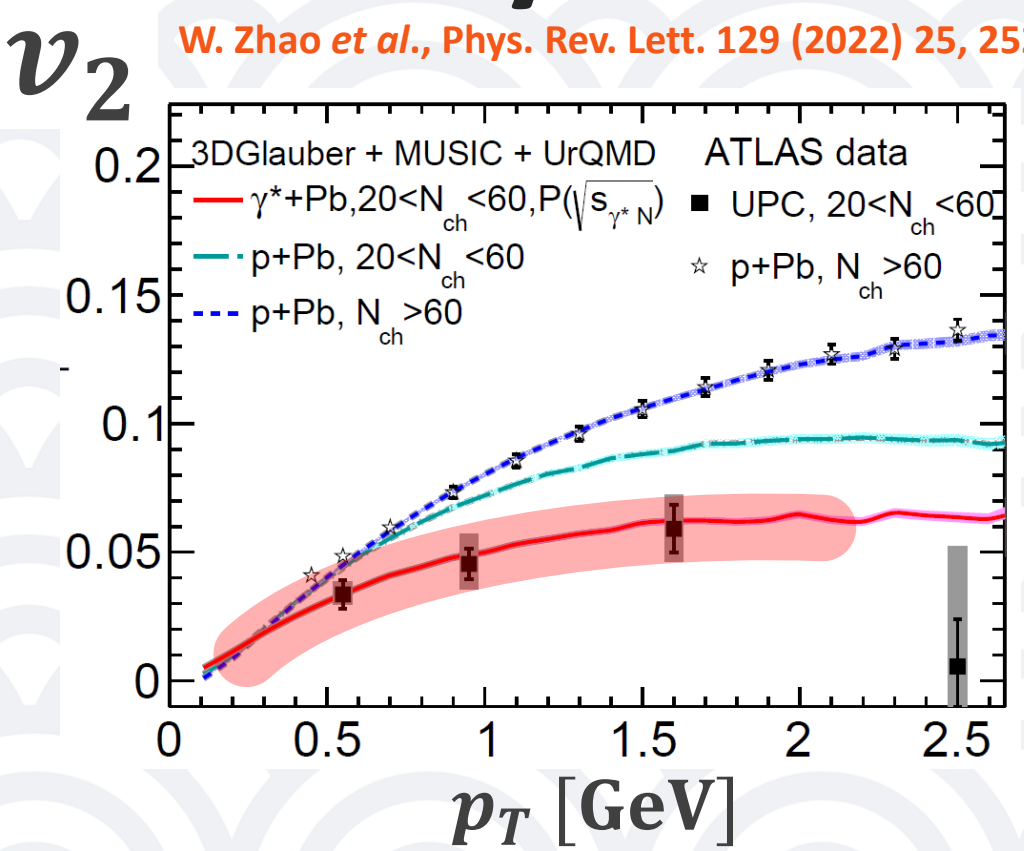
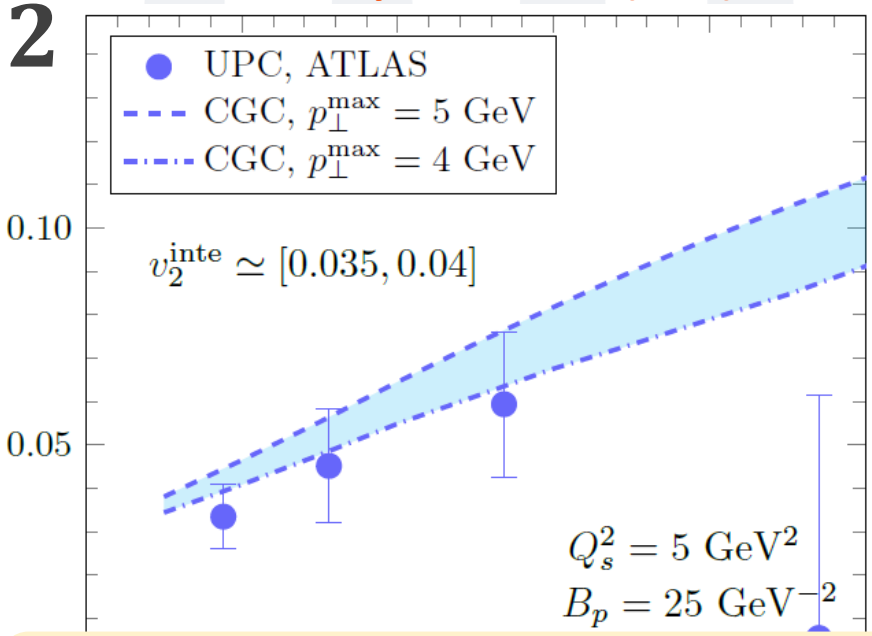


Ultra Peripheral Collisions (UPC)

CGC

Y. Shi *et al.*, Phys. Rev. D 103 (2021) 5, 054017

v_2



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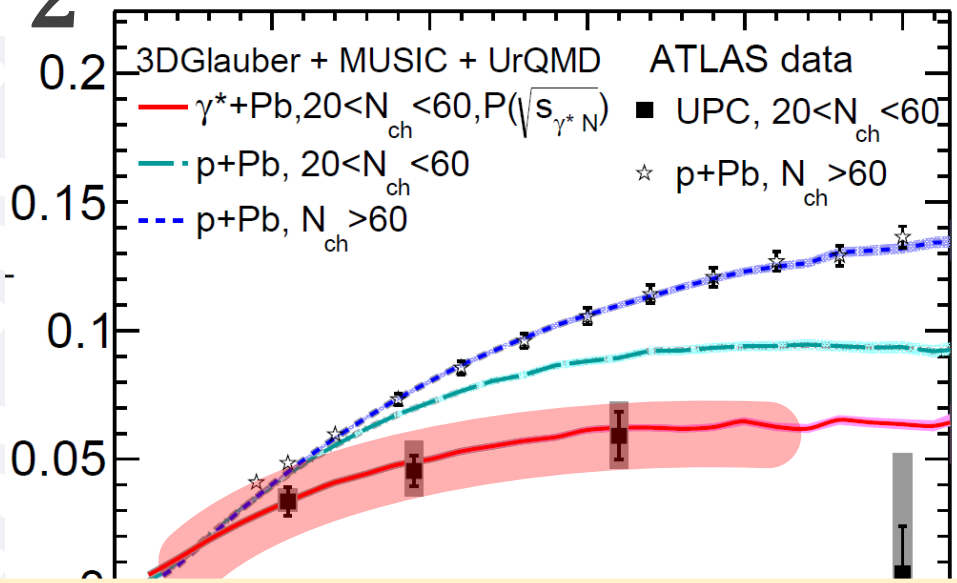
W. Zhao *et al.*, Phys. Rev. Lett. 129 (2022) 25, 252302

v_2



Both CGC and hydro give reasonable description

➔ Initial state or/and final state?

P. Bozek (2016); G. Giacalone *et al.* (2020); S. H. Lim *et al.* (2021).

J. L. Nagle (Tue, poster)

Origin of collectivity in IP-Glasma

B. Schenke *et al.*, Phys. Rev. D 105 (2022) 9, 094023

Momentum anisotropy

Correlated gluons from each colour field domain in **initial state**

T. Lappi *et al.*, (2016)

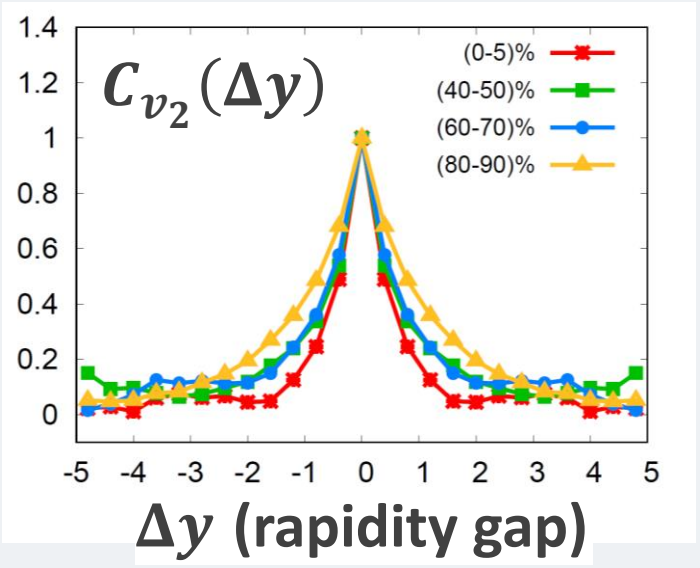
Which physics?

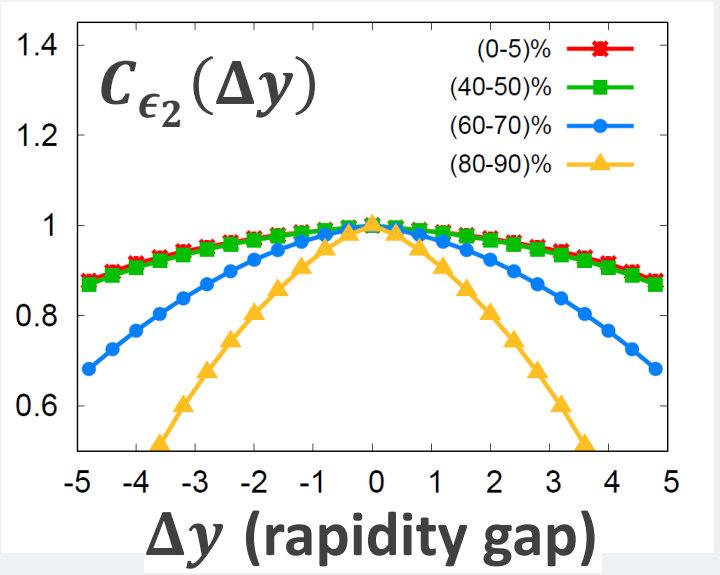
Geometrical anisotropy

Seeds for momentum anisotropy in **final state** evolution

H. Mäntysaari and B. Schenke, (2016)

➔ **disentangle with full 3D glasma in pPb**





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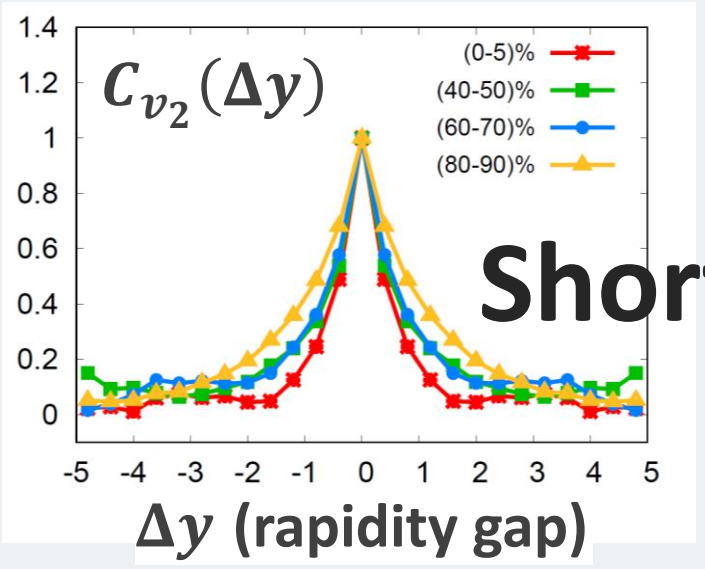
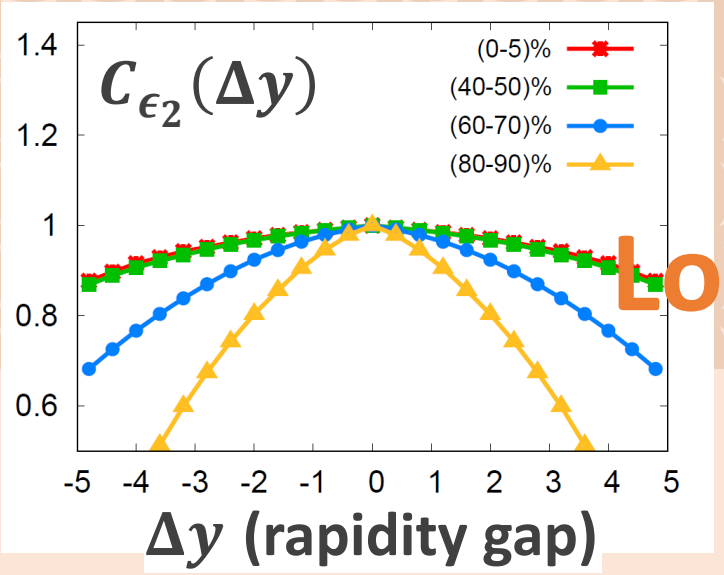


Short



Long

Origin of collectivity in IP-Glasma

B. Schenke *et al.*, Phys. Rev. D 105 (2022) 9, 094023

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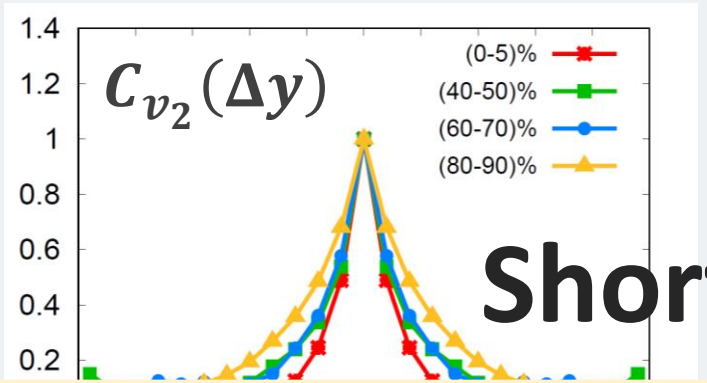

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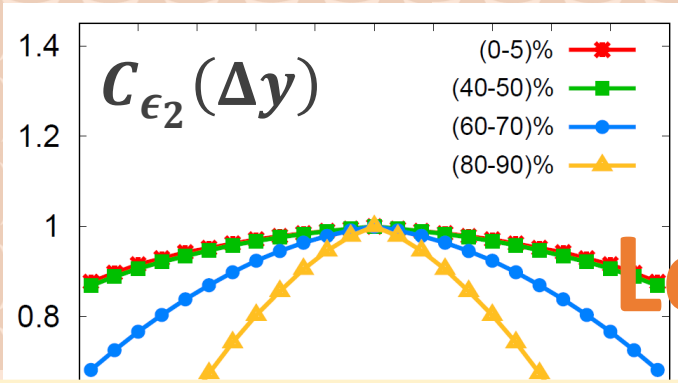


Long

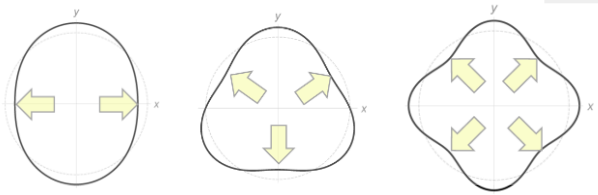
Long-range correlation in IP-Glasma: Geometrical anisotropy

Sign change of $\rho(v_2^2, [p_T])$: re-investigation needed

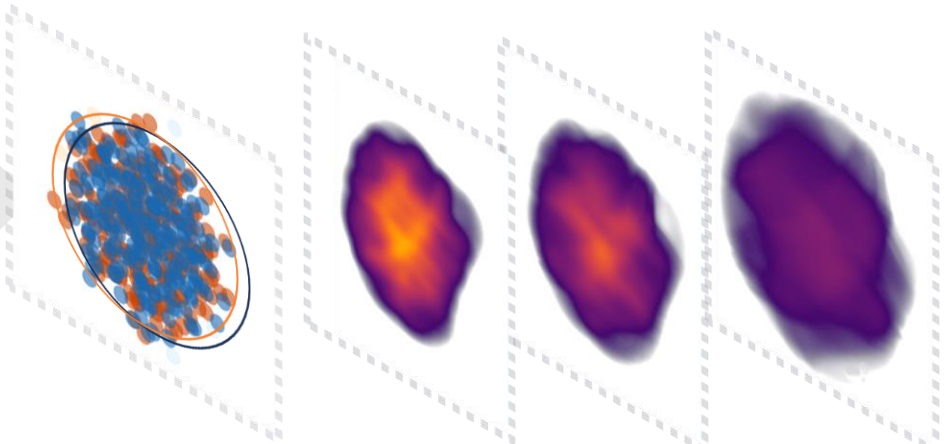
Nuclear imaging

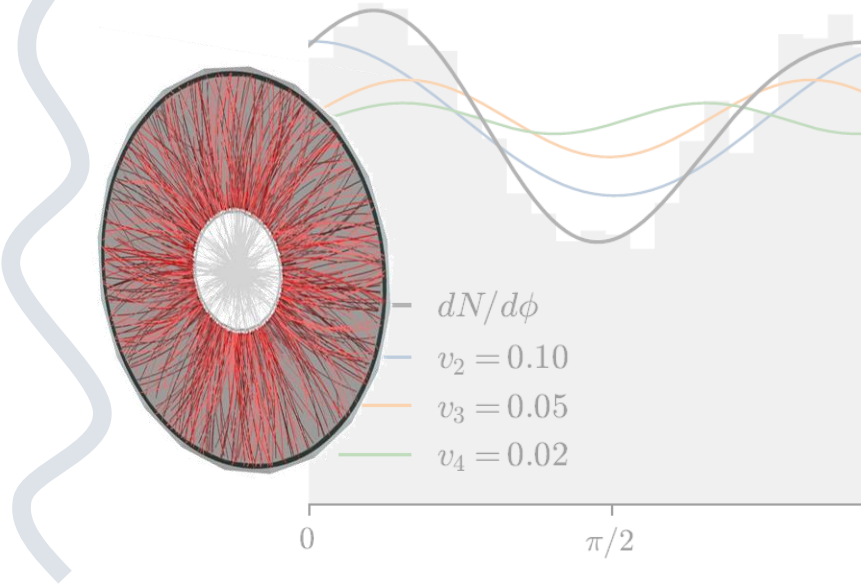
Figs modified from J. E. Bernhard, 1804.06469

$$\rho^{\mathrm{WS}}(\mathbf{r}) = \frac{\rho_0}{1 + \exp\left([r - R(\theta, \phi)]/a\right)}$$



J. Jia, Phys. Rev. C 105 (2022) 1, 014905





Nuclear imaging

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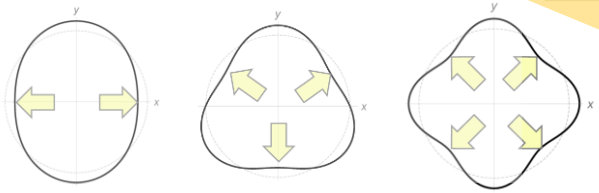
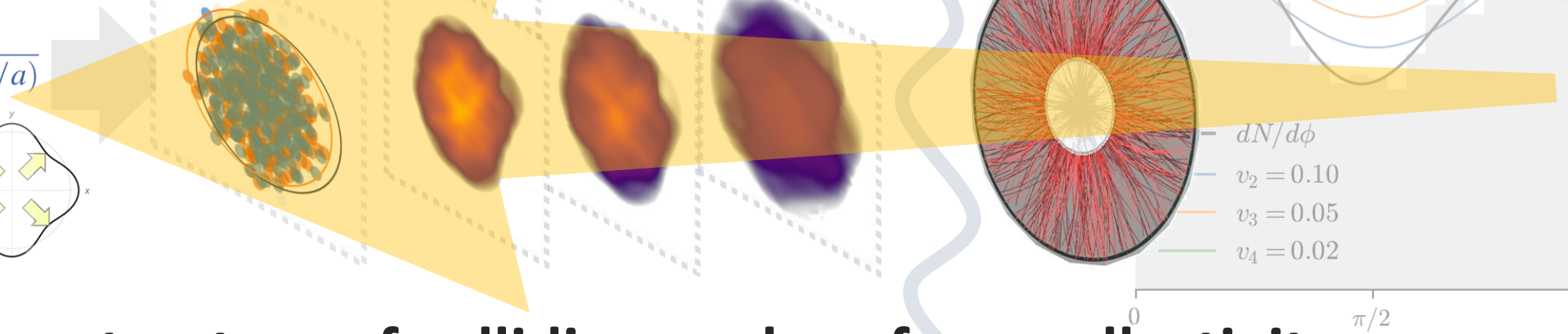


J. Jia, Phys. Rev. C 105 (2022) 1, 014905



Accessing structure of colliding nucleus from collectivity

Nuclear imaging

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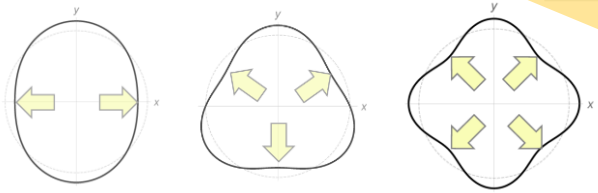

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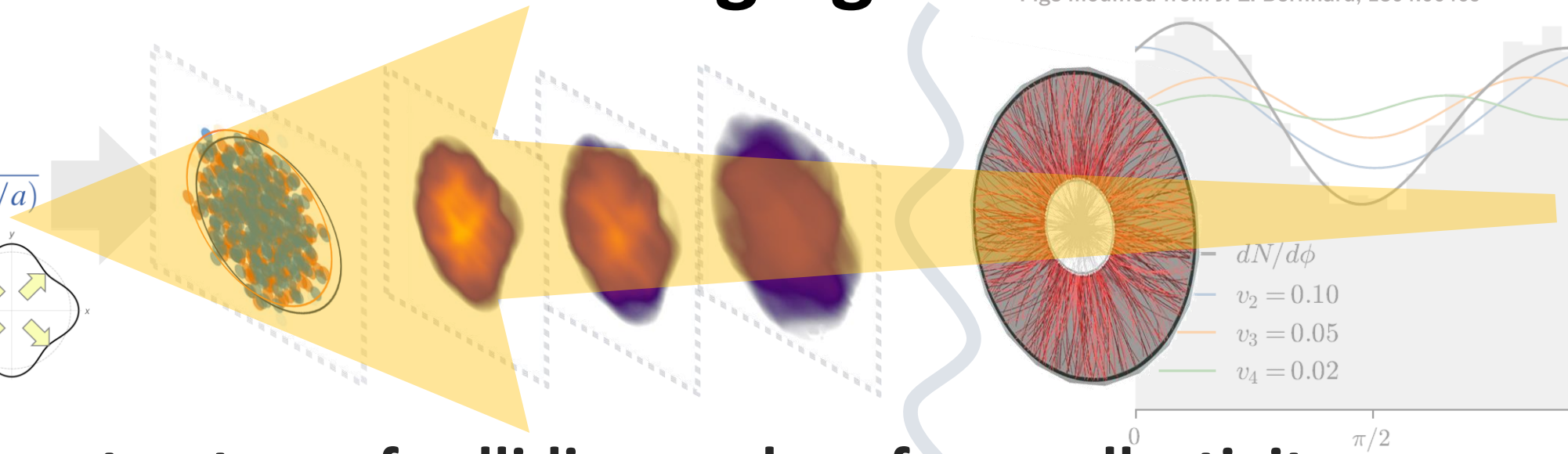


Accessing structure of colliding nucleus from collectivity

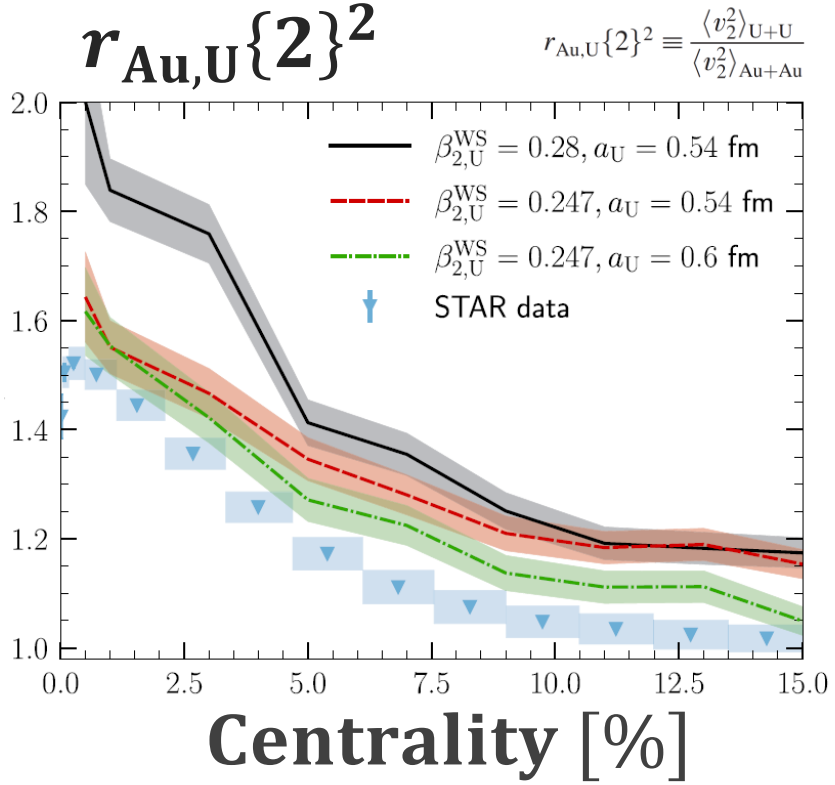
- Neutron skin of ^{208}Pb
  - G. Giacalone et al., 2305.00015
  - G. Nijs (Wed, parallel)
- Quadrupole & octupole moment deformation in isobar collisions ^{96}Ru+^{96}Zr
  - J. Jia (2022)
  - J. Jia et al., (2023)
  - J. Jia (Tue, parallel)
- Nuclear structure from $\gamma + U \rightarrow J/\Psi + U^*$
  - H. Mäntysaari *et al.*(2023)
  - W. Zhao (Wed, parallel) , H. Mäntysaari (Fri, plenary)
- Energy scale dependence of nuclear structure with JIMWLK
  - P. Singh (Wed, parallel)
- Method for systematic study on nuclear structure
  - M. Luzum *et al.* (2023)
  - M. W. Luzum (Tue, parallel)

See also INT PROGRAM INT-23-1A Jan-Feb 2023: Giacalone, Jia, Lee, Noronha-Hostler

Woods-Saxon parameters from microscopics

W. Ryssens *et al.*, Phys. Rev. Lett. 130 (2023) 21, 212302

Parameters in $\rho^{\mathrm{WS}}(r)$:



nuclear radius R_0
skin depth a

deformation β_l^{WS}

From different types of nuclear experiments

Q. Y. Shou et al. (2015)

➔ **R_0 and a: obtained integrated over rotation**

➔ **With simple theoretical models**

Idea: **Fit all WS parameters with $\rho(r)$** from Energy Density Functional (EDF)

Woods-Saxon parameters from microscopics

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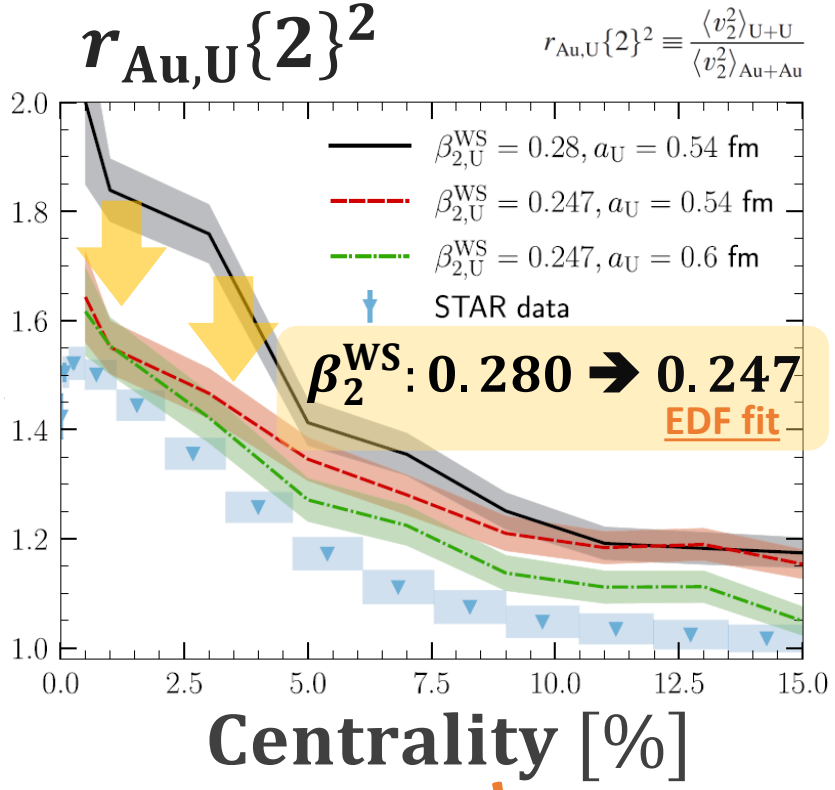

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→ **R_0 and a: obtained integrated over rotation**

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Precision science!

Woods-Saxon to the next level

Opened up opportunity to connect two different fields, nuclear structure & HIC

Statistical Analysis on collectivity

- Towards quantitative investigation -

Model-data comparisons with Bayesian analysis

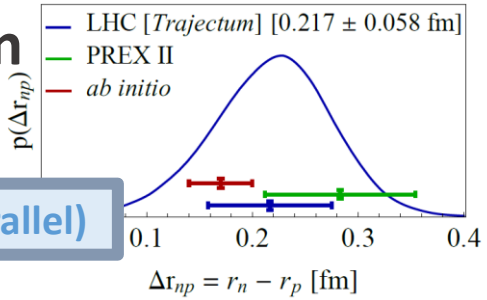
Most quantitative method
to disentangle each contribution to final v_n

Model-data comparisons with Bayesian analysis

Most quantitative method
to disentangle each contribution to final v_n

Neutron skin

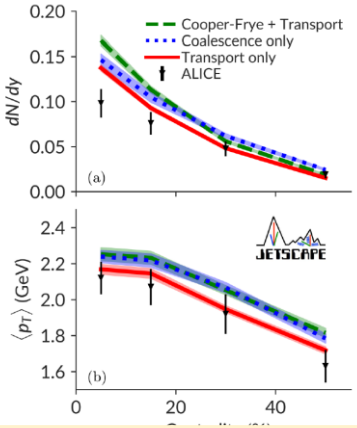
G. Giacalone et al., 2305.00015



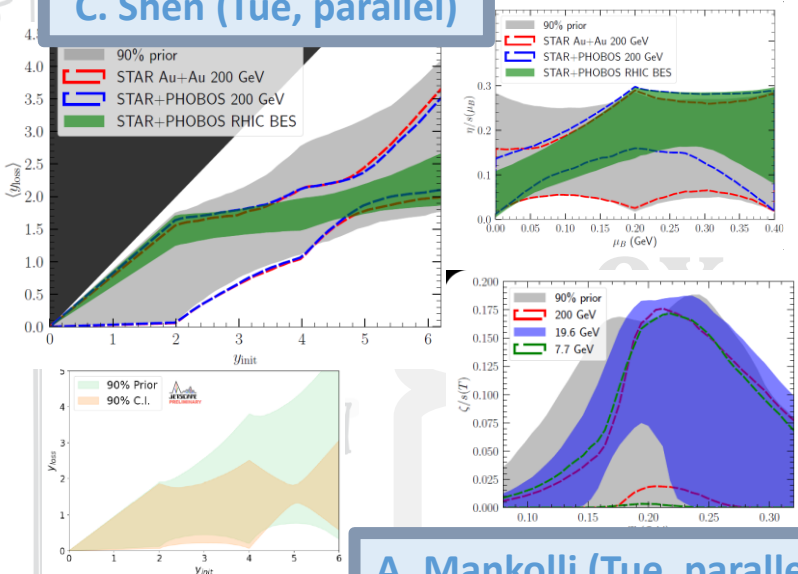
G. Nijs (Wed, parallel)

Deuteron production mechanism

D. Everett et al. (JETSCAPE), (2022)



C. Shen (Tue, parallel)

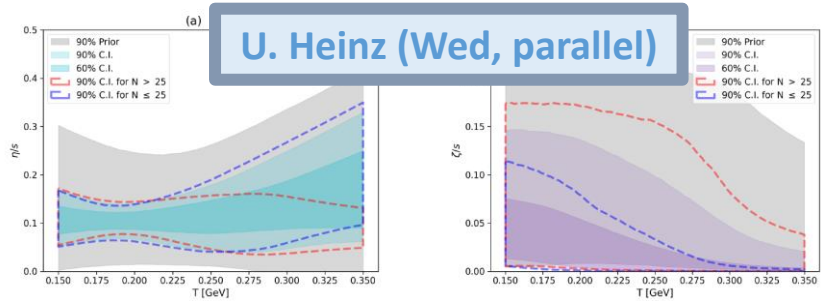


A. Mankolli (Tue, parallel)

η/s and ζ/s at high T with anisotropic hydro

D. Liyanage et al., 2302.14184

U. Heinz (Wed, parallel)



3D-Glauber with string deceleration
➔ Constraint with energy scan!

See also

J. Mulligan (Mon, plenary)

Lead by pioneering works…
Bernhard et al. (2016), Bass et al. (2017), Bernhard et al. (2019)...

HIC has entered the era of precision science.

Caveat on Bayesian results

G. Nijs (Wed, parallel)

G. Nijs and W. van. der. Schee, Phys. Rev. Lett. 129 (2022) 23, 232301

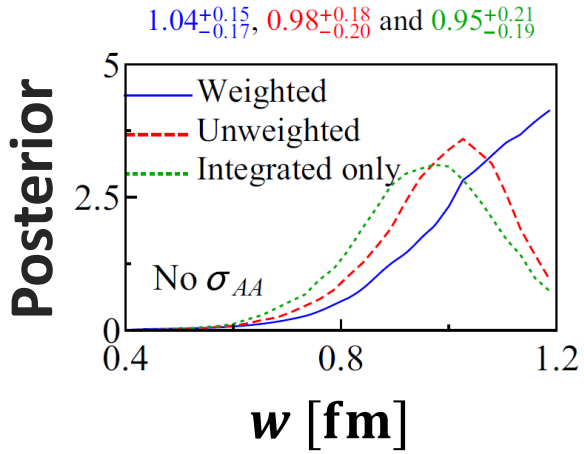
Problem: Quite "large" nucleon width w (~ 0.8-1.0 fm) from Bayesian

Idea: include σ_{AA} as input observable

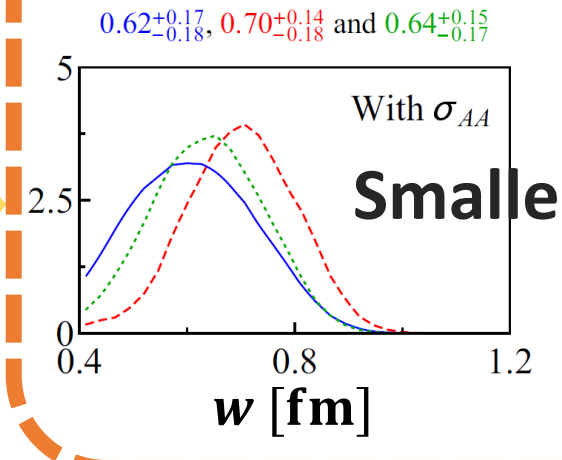
ALICE Collaboration 2204.10148

$-$ σ_{AA} is expected to be sensitive only on nuclear profile

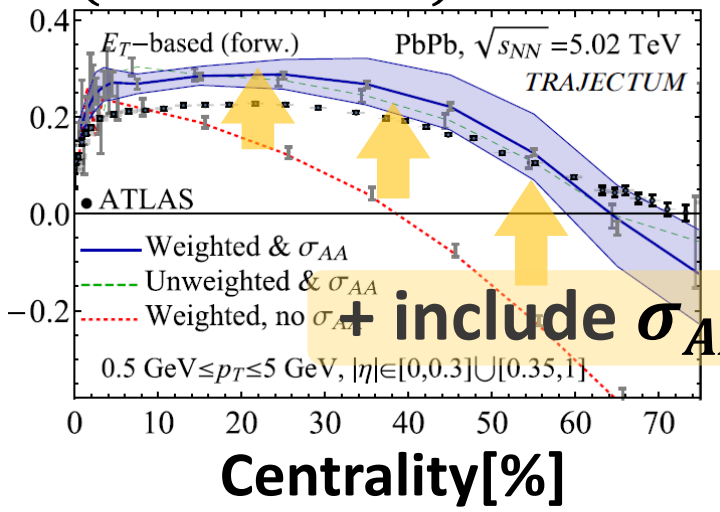
Without σ_{AA}



With σ_{AA}



$\rho\left(v_2\{2\}^2, \langle p_T \rangle\right)$



+ include σ_{AA}

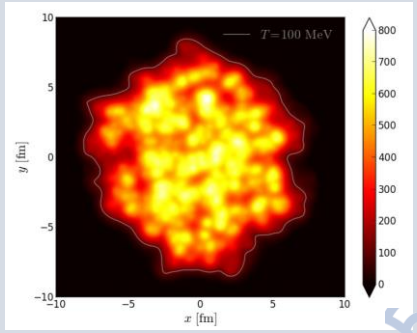
Potential uncertainties in selection of data and theoretical models

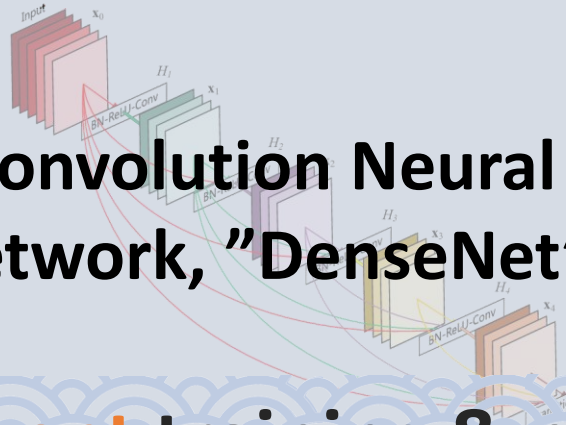
H. Hirvonen (Tue, poster)

“Skipping” hydro simulation with Deep Learning

H. Hirvonen *et al.*, 2303.04517

$e(x, y)$ from EKRT





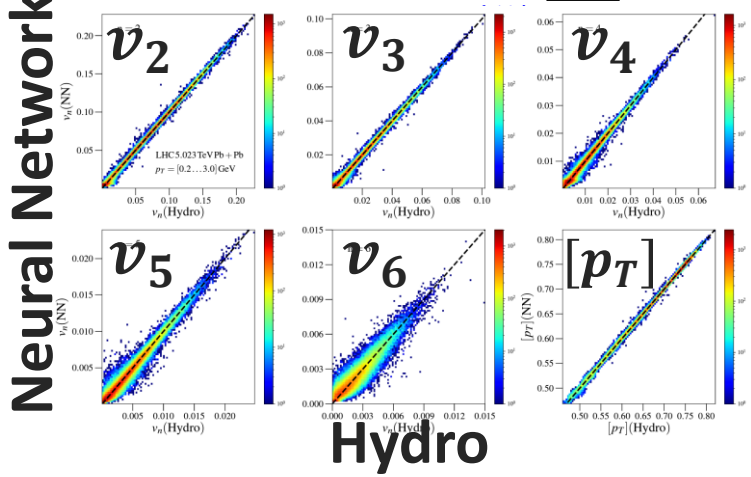
Convolution Neural Network, ”DenseNet”

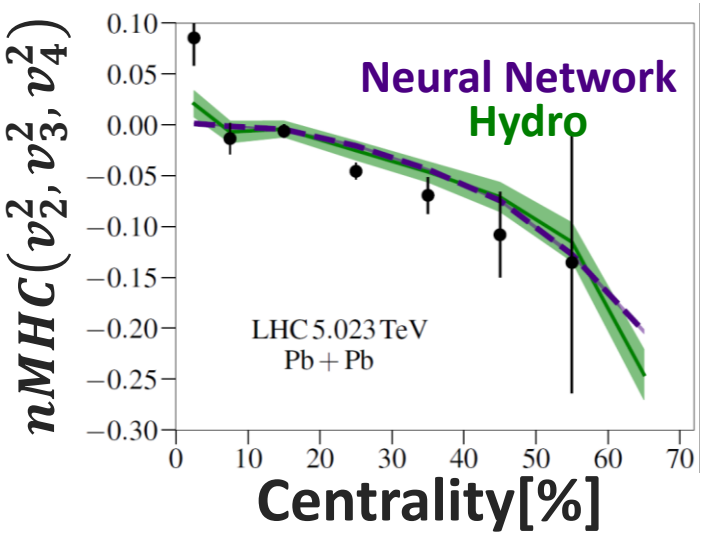
Observables

$v_n, [p_T], dN/d\eta$

Event-by-event training & prediction

Validation ☑

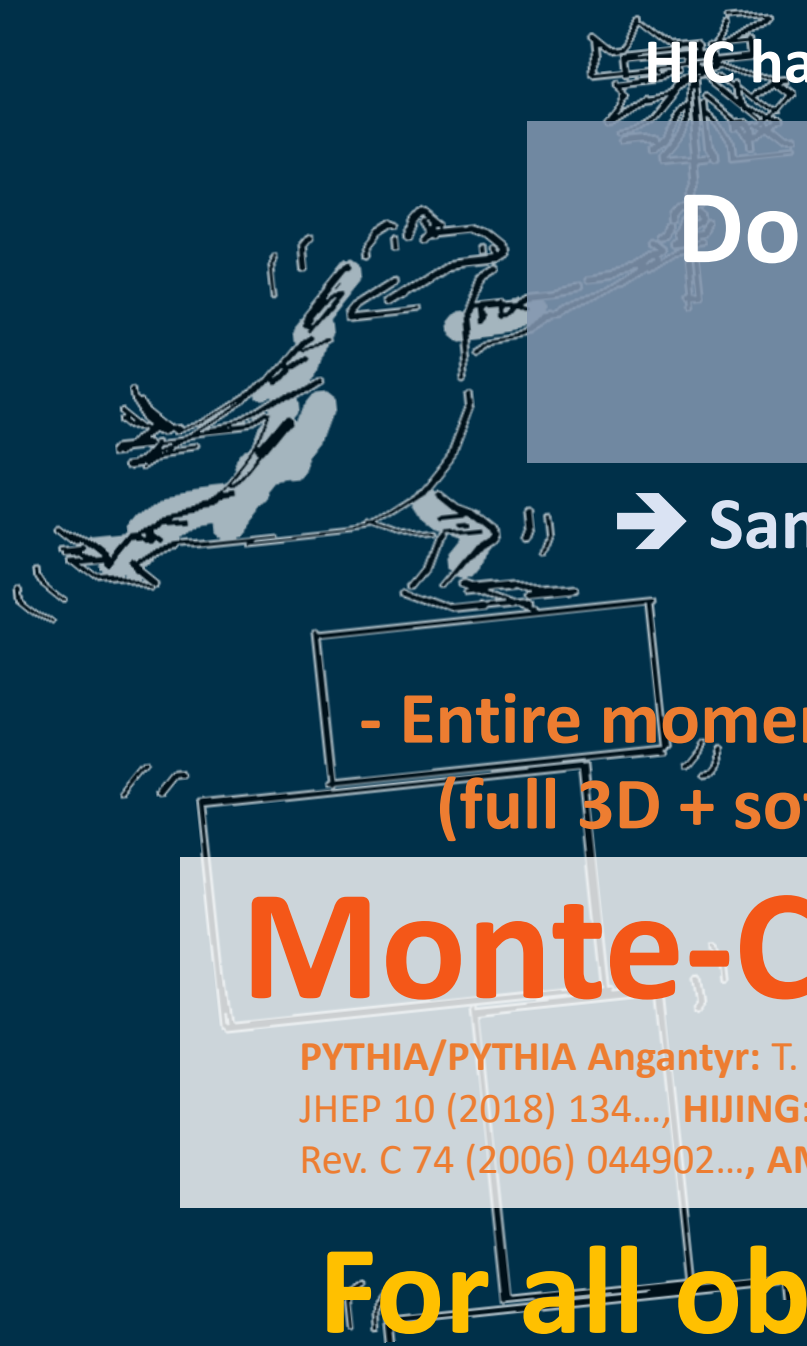




Works for ‘difficult’ observables

Sophistication of observables on collectivity

➔ Cut computational cost & Gain statistics for precisions!



HIC has entered the era of precision science, but

Do dynamical models have such precision?

➔ Same analysis method as experiments should be applied

- Entire momentum space (full 3D + soft to hard)

- Event by event energy-momentum conservation

Monte-Carlo Event Generators

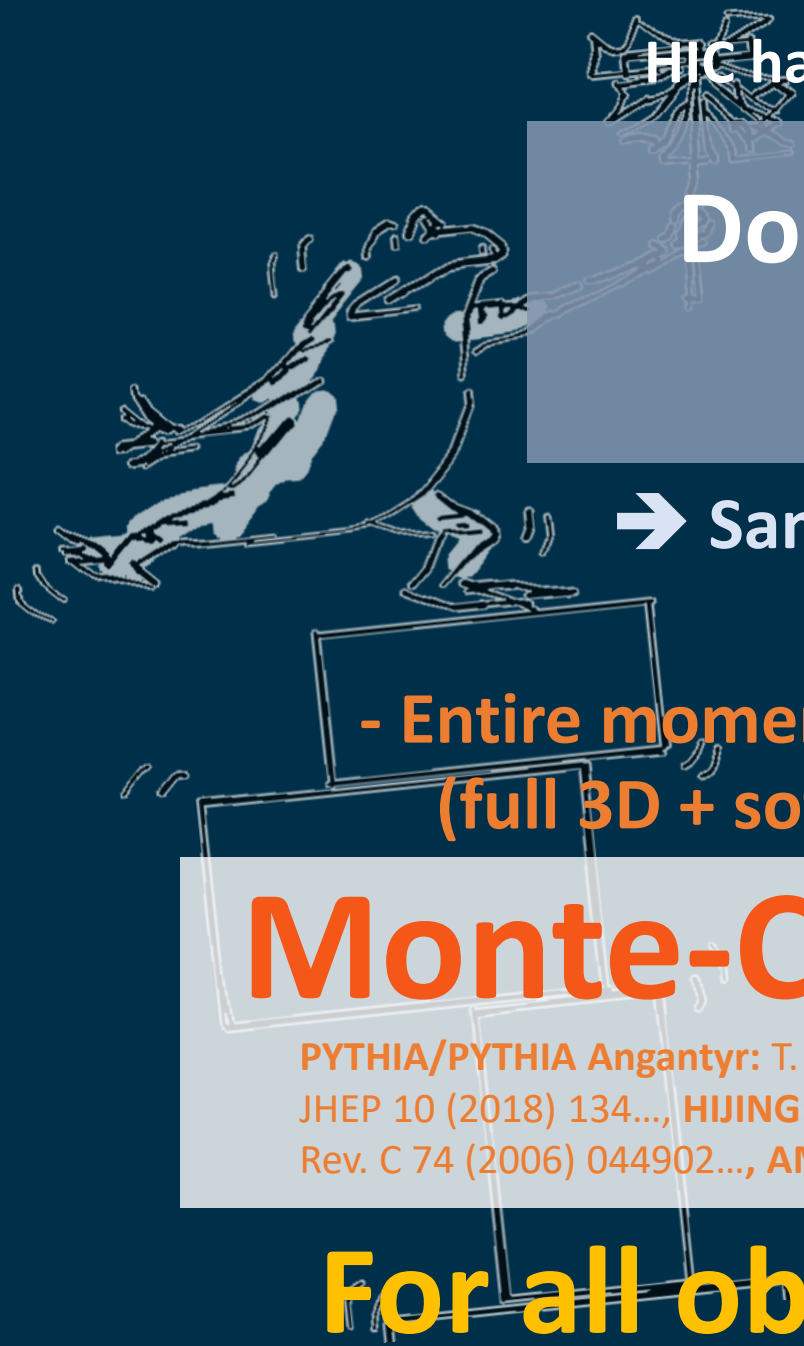
A. Buckley *et al.*, Phys. Rept. 504 (2011) 145-233

PYTHIA/PYTHIA Angantyr: T. Sjöstrand *et al.*, Comput. Phys. Commun. 178, 852 (2008), C. Bierlich *et al.*, JHEP 10 (2018) 134…, **HIJING:** X. N. Wang *et al.*, Phys. Rev. D 44 (1991) 3501-3516…, **EPOS:** K. Werner *et al*, Phys. Rev. C 74 (2006) 044902…, **AMPT:** Z. W. Lin *et al.*, Phys. Rev. C 72 (2005) 064901…

+ Statistical tools

For all observables

➔ Which physics? How much?



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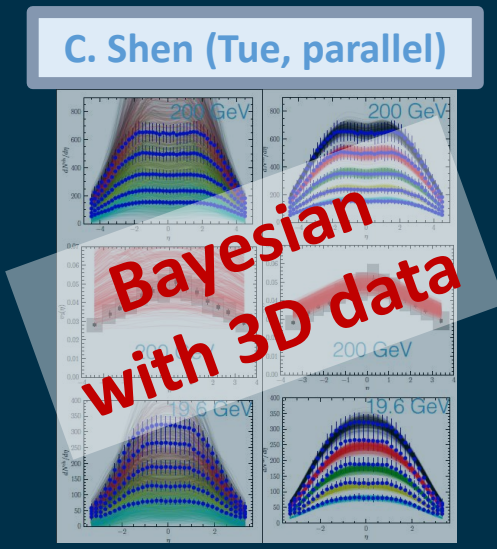
C. Shen (Tue, parallel)



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+ Statistical tools

For all observables

➔ Which physics? How much?

Two component picture: hydro and strings

EPOS4 K. Werner, 2301.12517; 2306.10277; 2306.02396

allows (for the first time!) to accommodate simultaneously

Energy conservation + **P**arallel scattering + fact**O**rization + **S**aturation

Now we can do in one single ("general purpose") approach "multi-observable analysis" concerning

Core-corona picture

in equilibrium: **QGP hydro (core)**, out-of equilibrium: **strings (corona)**

- Initial: factorization/binary scaling at high p_T + saturation at low p_T

➔ Entire p_T range (soft to hard)

- Microcanonical sampling from hydro via Markov chains

➔ Event-by-event energy-momentum & charge conservation

From ee to AA within a single framework

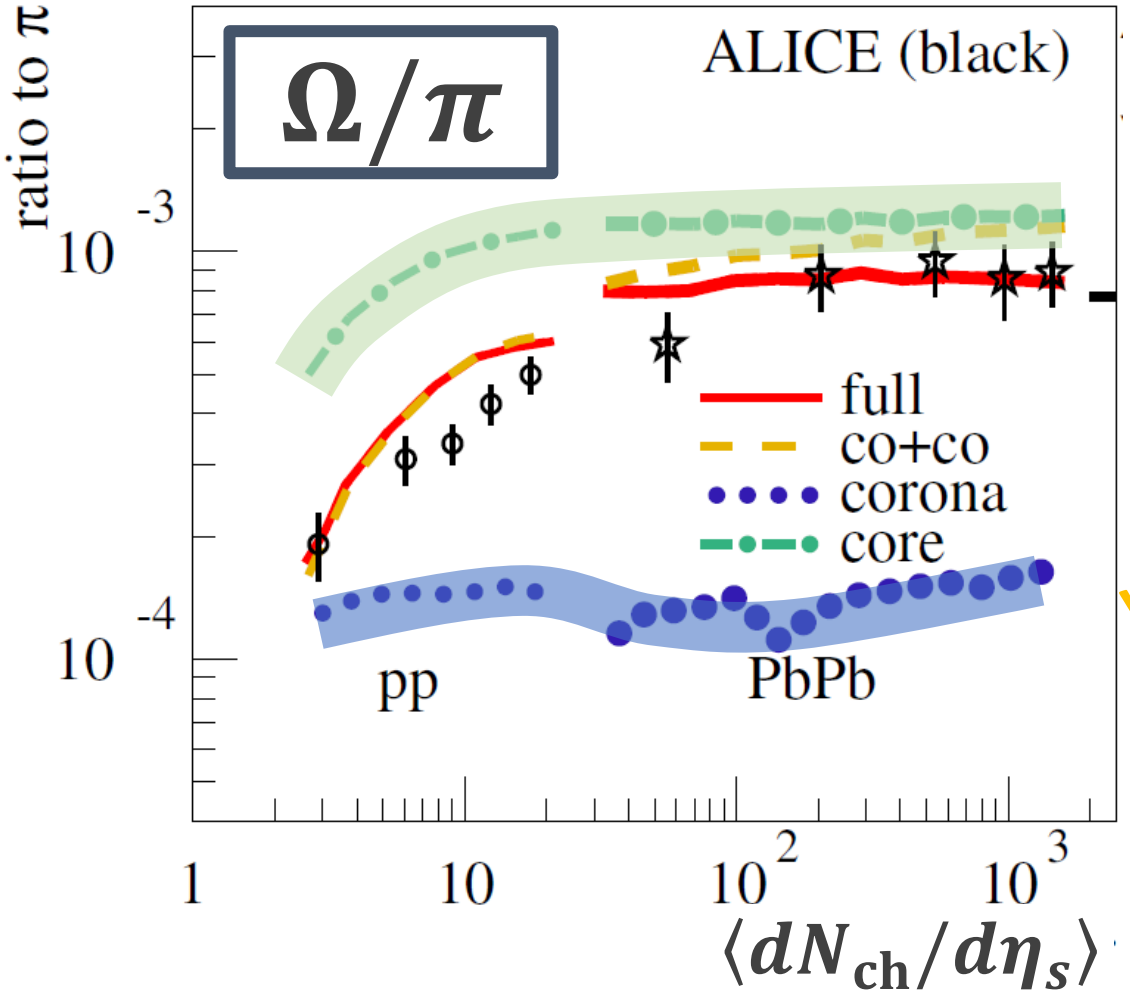
For all observable

Hydro Monte-Carlo Event Generators

Figs: Talk by K. Werner at QCD challenges from pp to AA collisions 2023

Multi-strange hadron yield ratios from EPOS

K. Werner, 2301.12517



Competition between

QGP hydro (core) & strings (corona)

➔ **Multiplicity dependence of Ω/π** ☑

Which physics?

Both in and out-of equilibrium

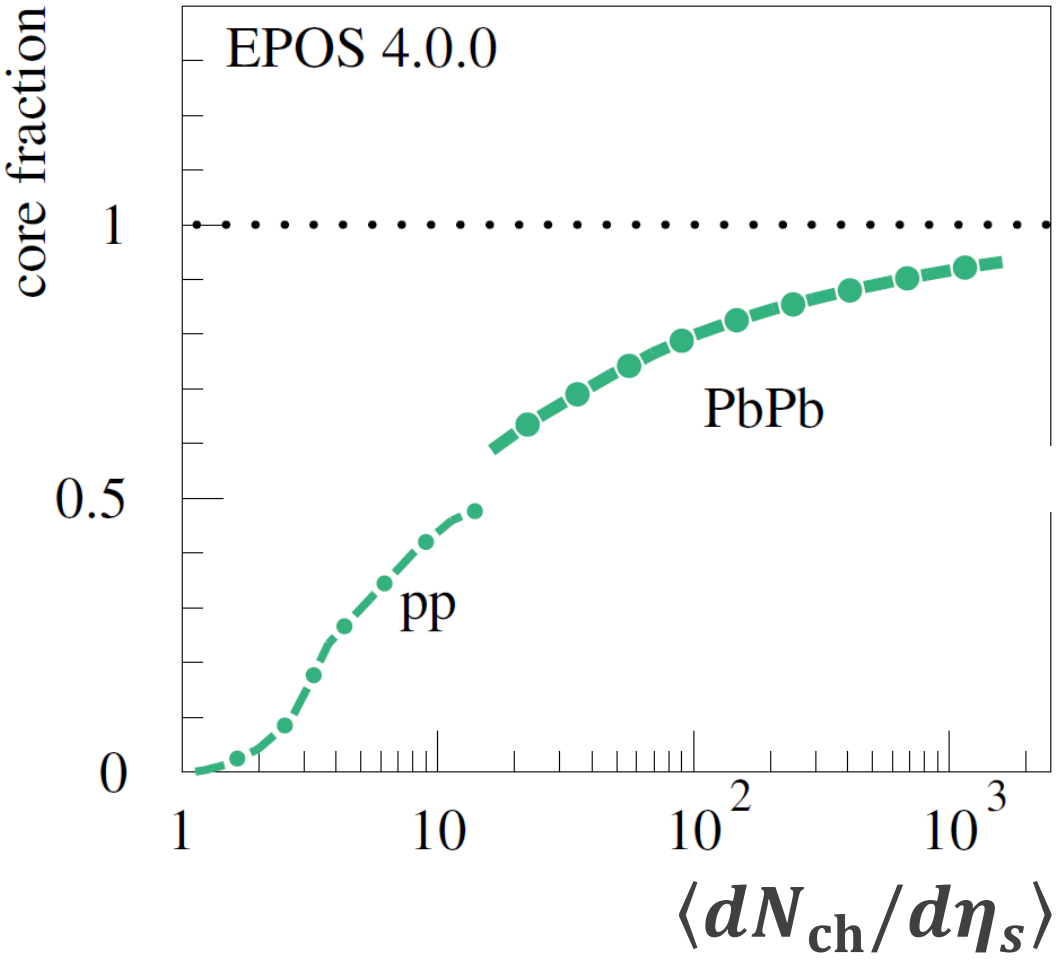
Global description of all observables!

Not only collectivity but also hadron chemistry

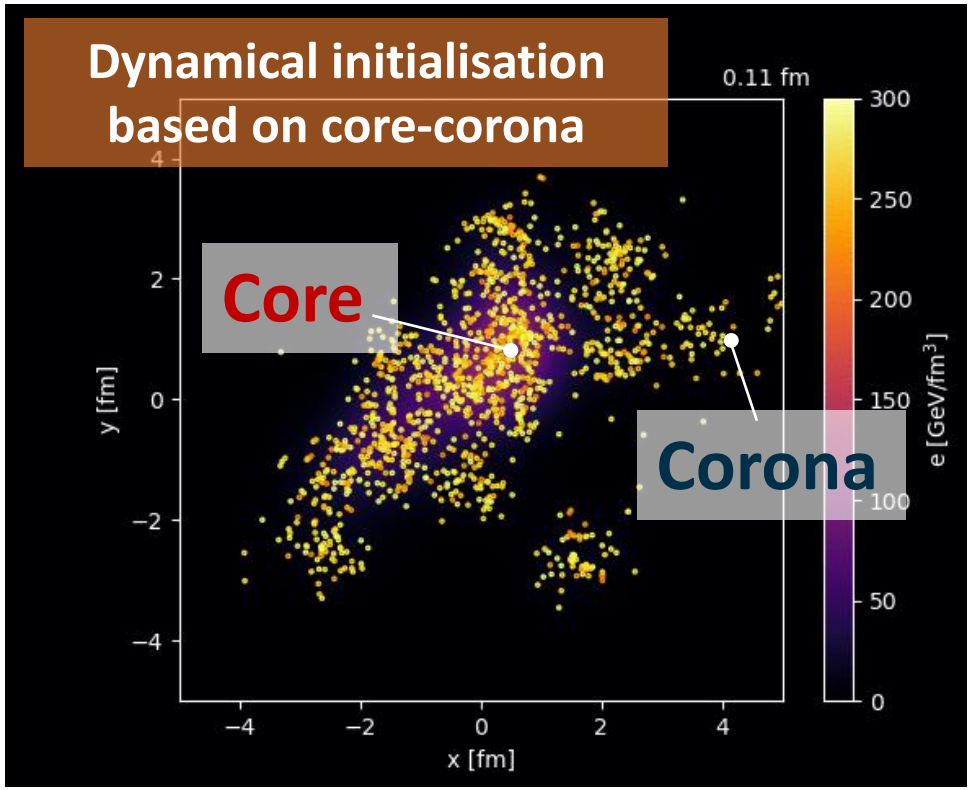
How much?

Fraction of production from QGP

EPOS4 K. Werner, 2301.12517



DCCI2 Y. Kanakubo *et al.*, Phys. Rev. C 105 (2022) 2, 024905



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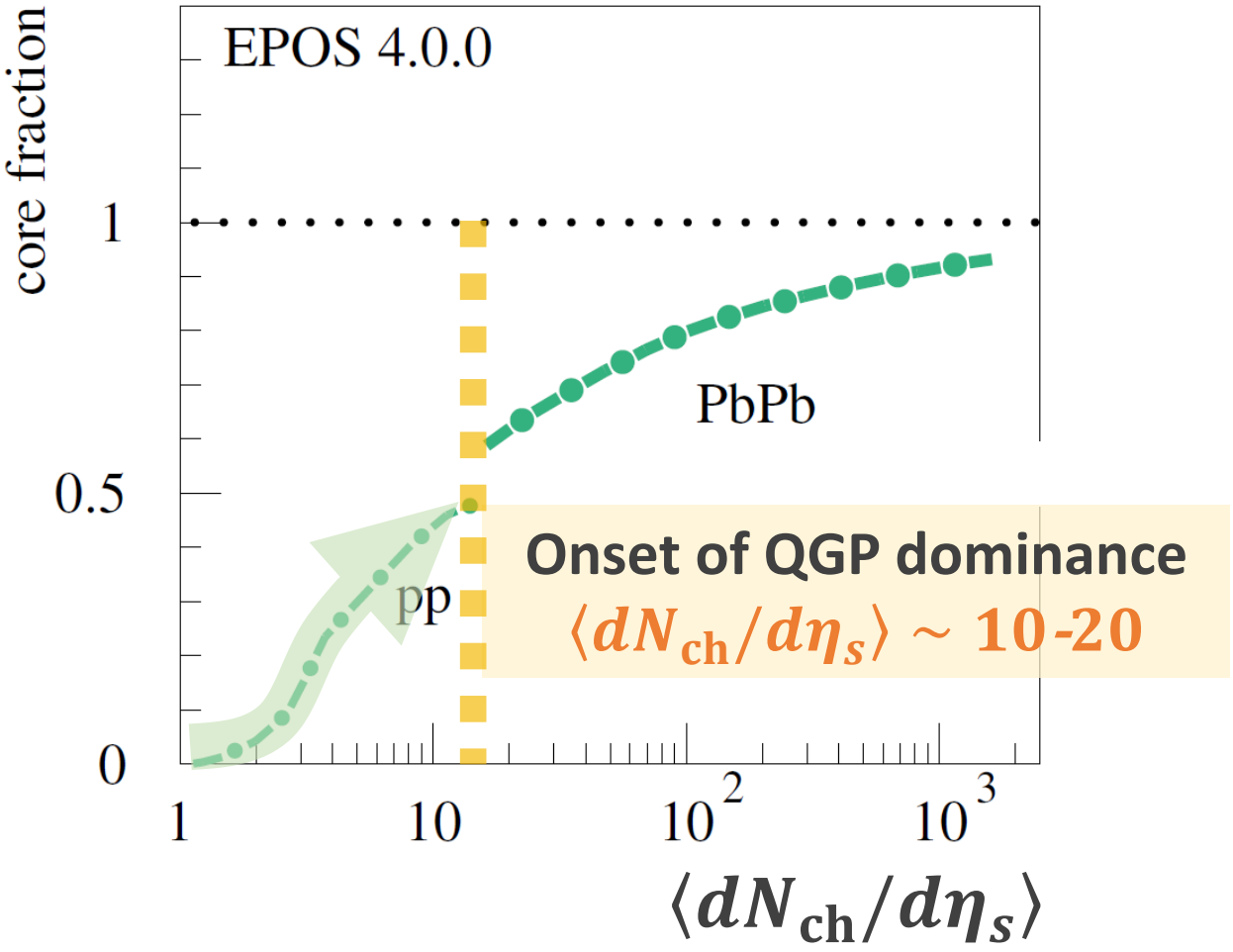
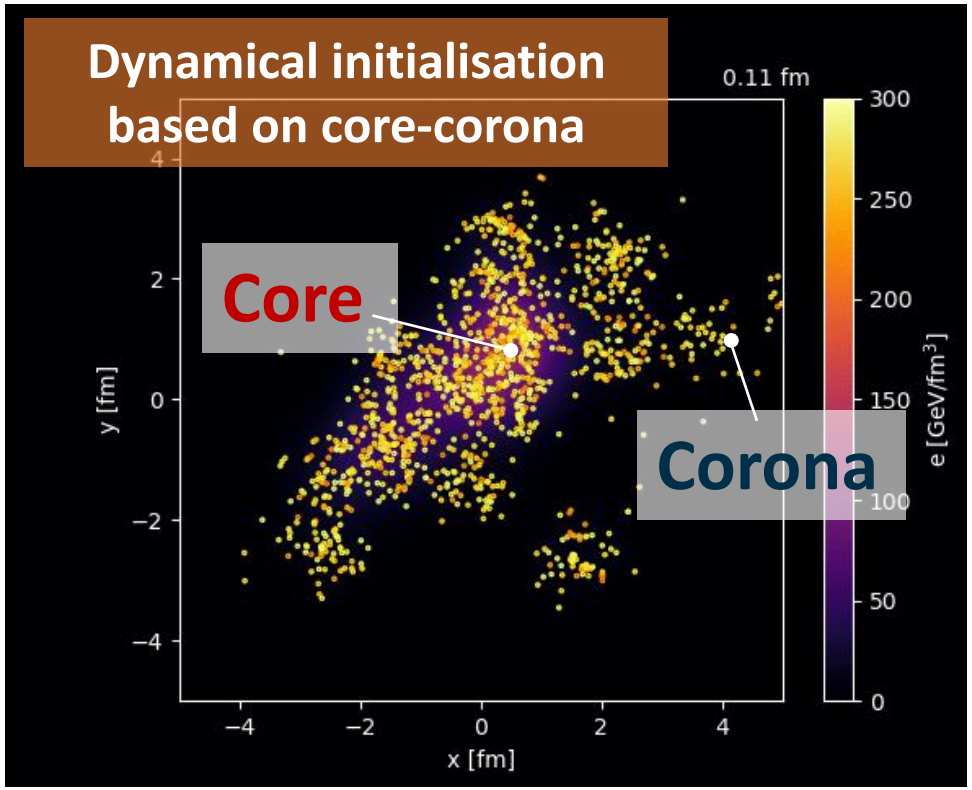


Onset of QGP dominance
$\langle dN_{\rm ch}/d\eta_s \rangle \sim$ 10-20

DCCI2 Y. Kanakubo *et al.*, Phys. Rev. C 105 (2022) 2, 024905



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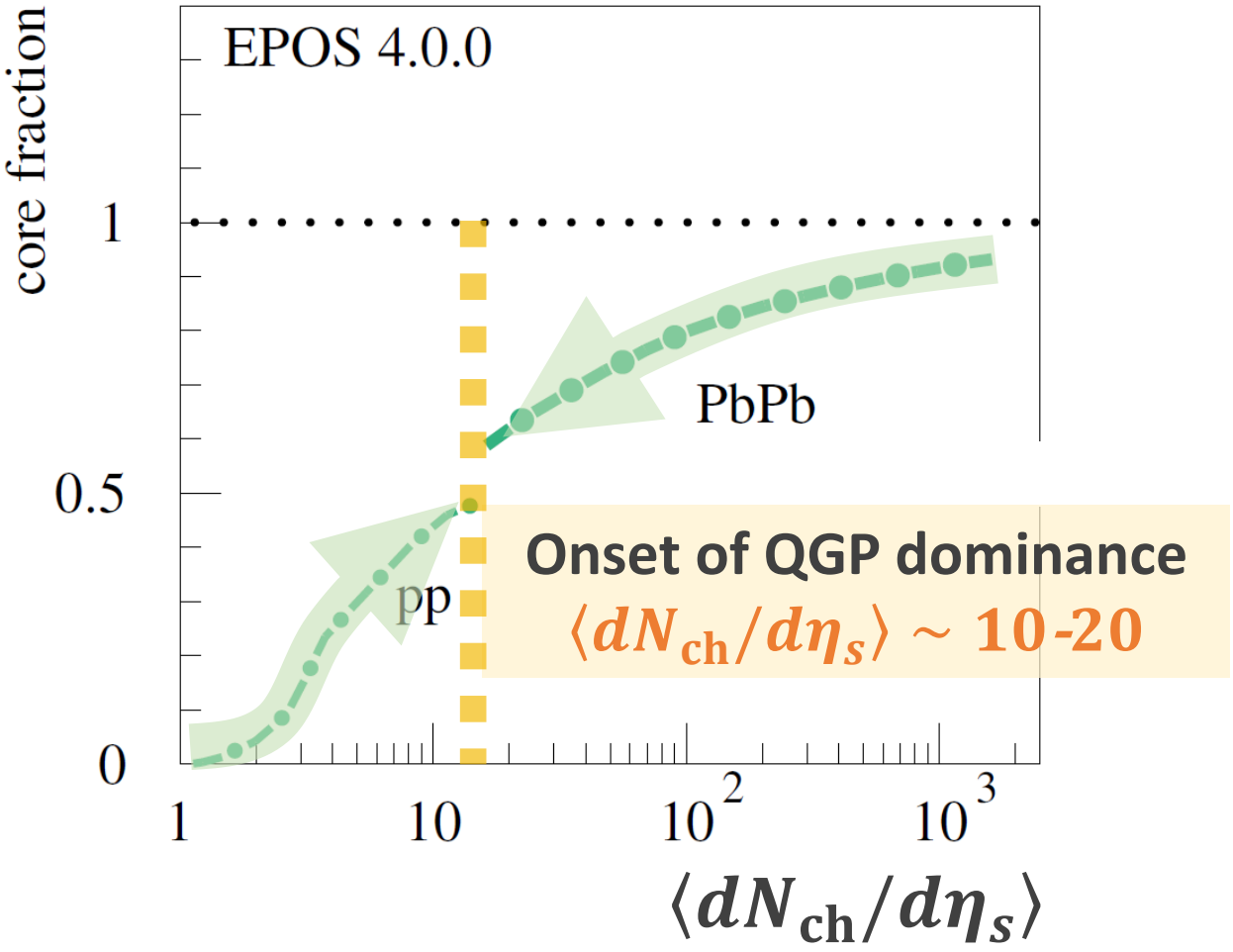
EPOS4 K. Werner, 2301.12517



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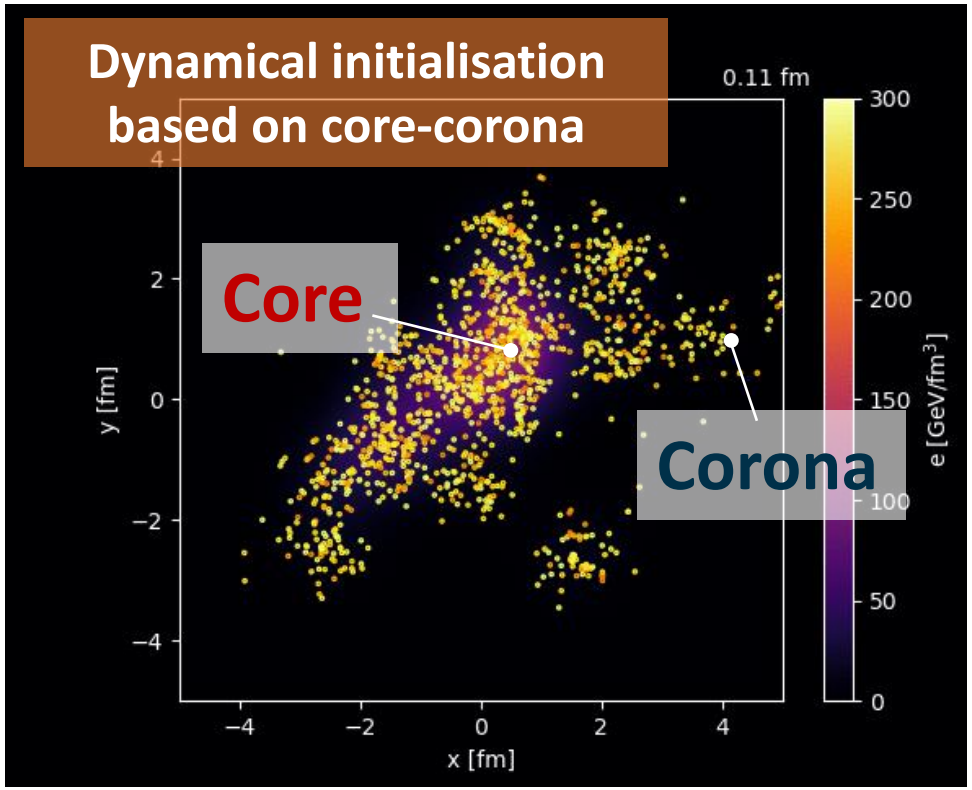

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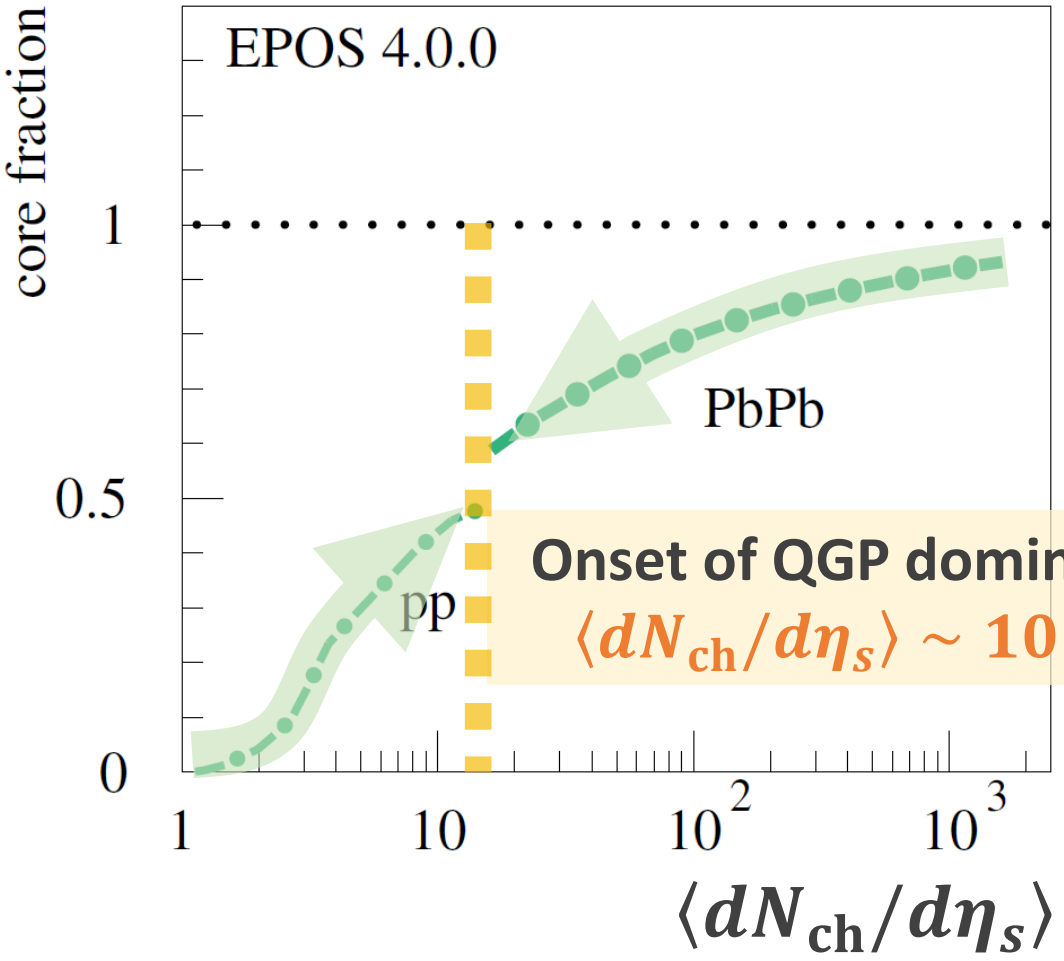

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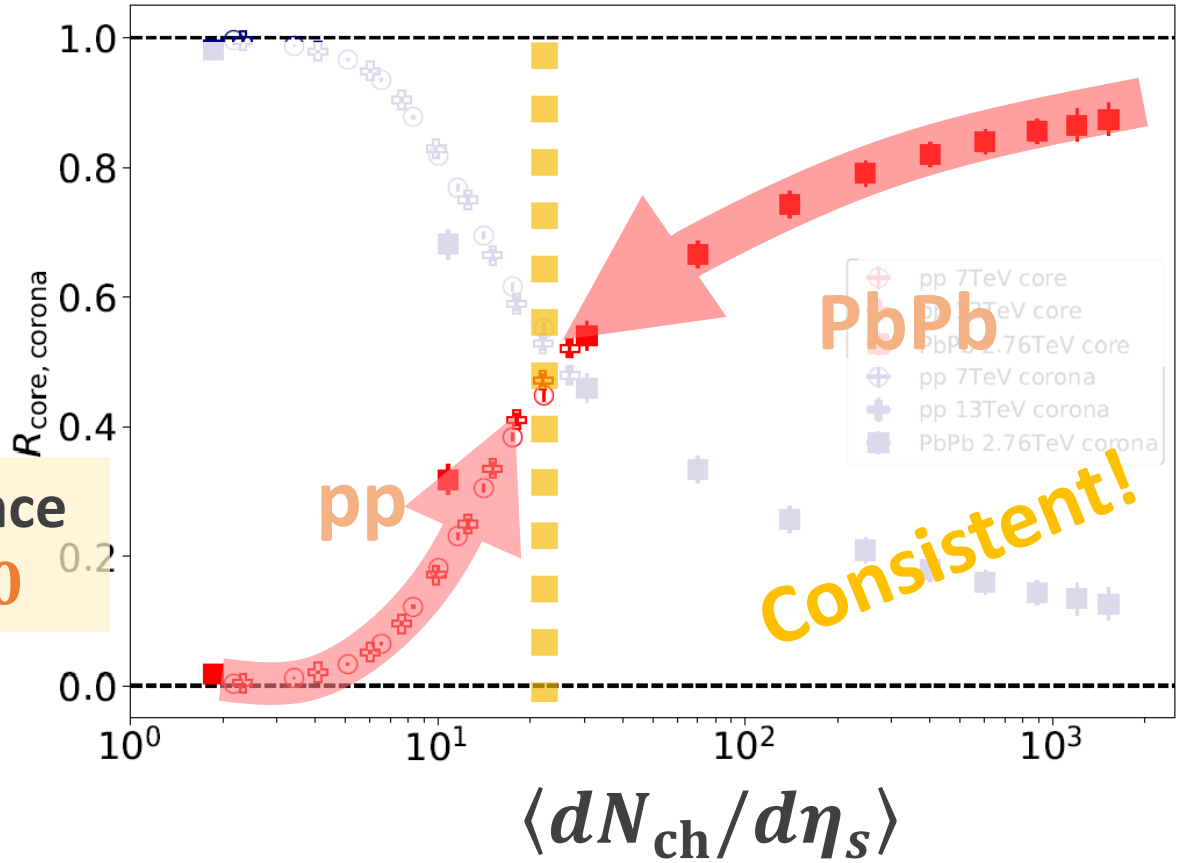

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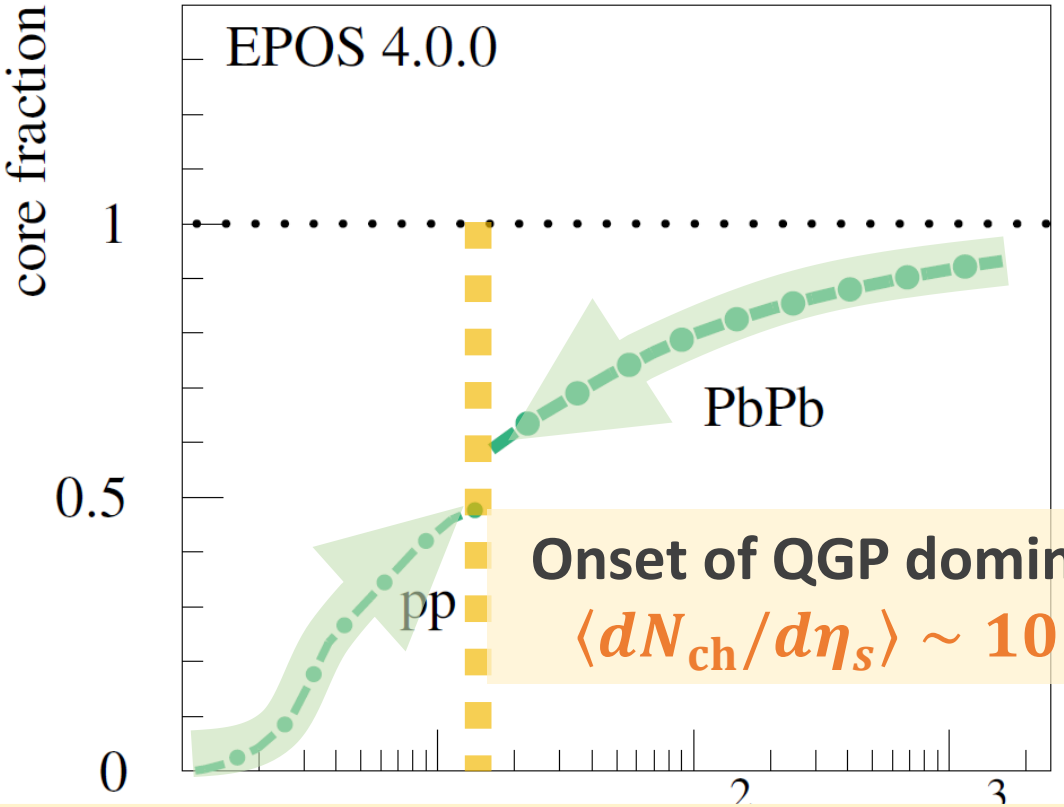
EPOS4 K. Werner, 2301.12517



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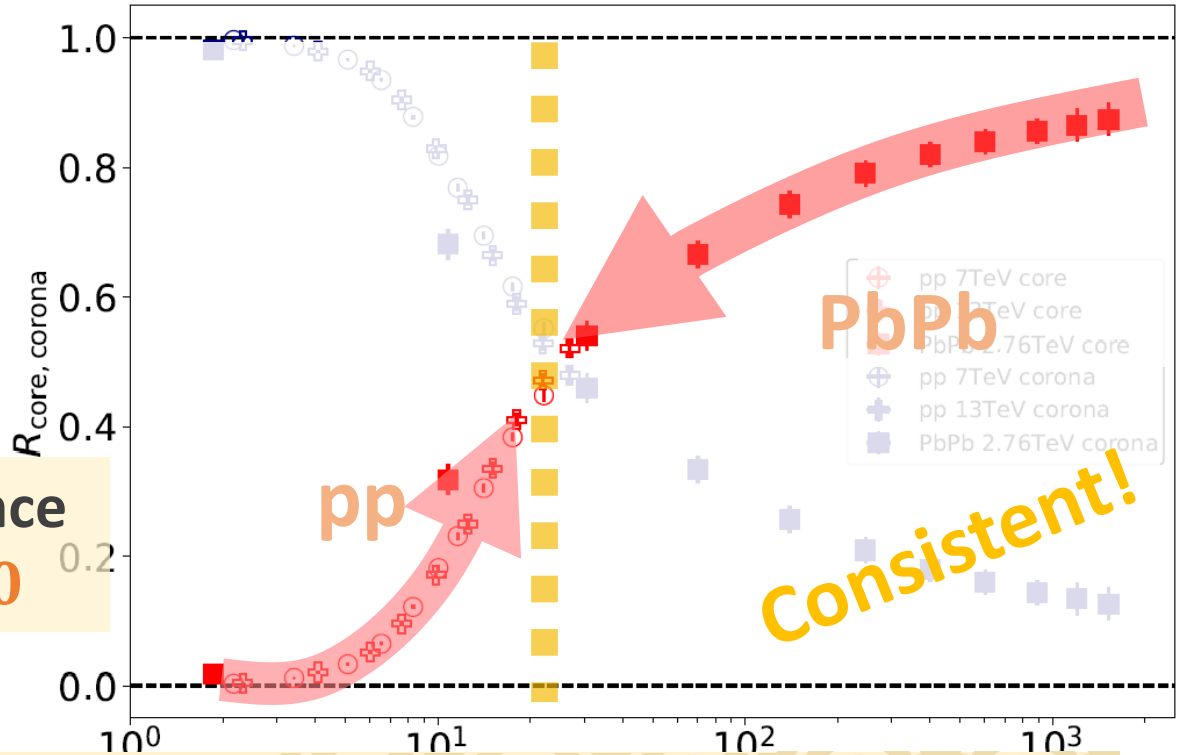
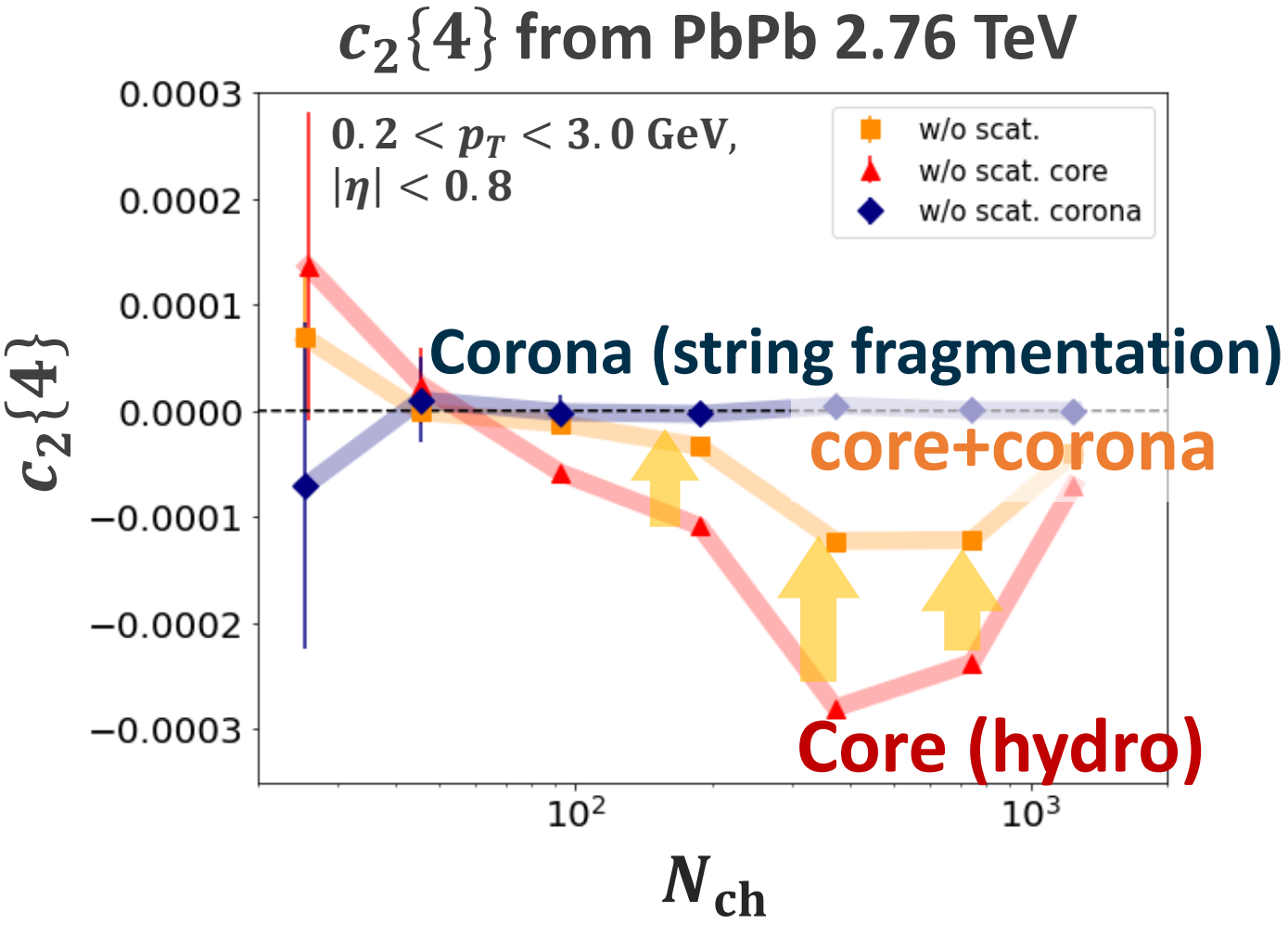


Hadron chemistry (Ω/π , Ξ/π…): strong candidates for global analysis

Both equilibrated and non-equilibrated not only in pp but also in AA

Non-equilibrium contribution to collectivity in AA

Y. Kanakubo *et al.*, Phys. Rev. C 106 (2022) 5, 054908



$c_2\{4\}_{\mathrm{core}} \neq c_2\{4\}_{\mathrm{tot}}$

Collectivity is diluted by corona

Caution on $\eta/s, \zeta/s$… from model-data comparison

Event generator-lisation of hydro model

➔ Interplay of soft and hard

See also M. Singh (Tue, parallel)

Towards hydro MC event generator

Main problems to consider

Event-by-event energy-momentum conservation

Description of entire momentum space (from soft to hard)

Works towards this direction….

M. Kuha (Tue, poster)

Full 3D MC EKRT M. Kuha *et al.*, in progress

pQCD (mini)jet production + saturation
+ energy-momentum conservation

➔ Initial condition with both soft and hard

Microcanonical Sampling

D. Oliinychenko *et al.* (2019) (2020), K. Werner 2306.10277

Exact energy-momentum and charge conservation
in hadronic sampling event-by-event

Core-corona K. Werner (2006), 2301.12517; Y. Kanakubo *et al.* (2022)

Soft and hard productions from a single framework

* For hydro works with extension to low energy

L. Du (Tue, parallel), C. Shen (Tue, parallel), D. Almaalol (Wed, parallel), I. Karpenko (Wed, parallel), B. Tomasik (Wed, parallel)

More to come…!

Summary

Summary

Collectivity in relativistic nuclear collisions v_n

pp, pAl, pAu, dAu, pO, pPb, HeAu, RuRu, ZrZr, OO, CuCu, CuAu, AuAu, UU, XeXe, PbPb…

Which physics? **How much?**

Next generation dynamical models!

- Event by event energy-momentum conservation

- Entire momentum space (full 3D + soft to hard)

For "all" observables

Powerful statistical tools (Bayesian analysis, Deep Learning etc.)

Extraction of nuclear structure, initial state dynamics etc.

…and QCD matter properties

Future experiments are awaiting! Theoretical models need to be ready.

System size scan ➔ see e.g. OO, pO: Brewer et al. 2103.01939 sPHENIX: Belmont et al. 2305.15491 etc.

2023 Yagi Award

https://ithems.riken.jp/en/about/yagi-award

"Kohsuke Yagi Quark Matter Award" (Yagi Award) is based on the donation to iTHEMS from bereaved family of late Professor Kohsuke Yagi who was a renowned Japanese nuclear physicist. Responding to the family request, the award aims to support early career scientists with Japanese nationality, to promote and expand country's nuclear physics research field. It will be awarded to **junior Japanese physicists under age of 40 who give plenary talk at the "Quark Matter**: International Conference on Ultra-relativistic Nucleus-Nucleus Collisions" held in every 1.5 years.

Prof. Kohsuke Yagi (1934-2014)
Quark Matter 1997, Chair

Special thanks for discussions on results

Giuliano Giacalone, Henry Hirvonen, Mikko Kuha, Heikki Mäntysaari, Govert Njis, Wouter Ryssens, Wilke van der Schee, Pragya Singh

and all members of

Centre of Excellence in Quark Matter

in Jyväskylä

CoE QM

@coequarkmatter

Thank you!