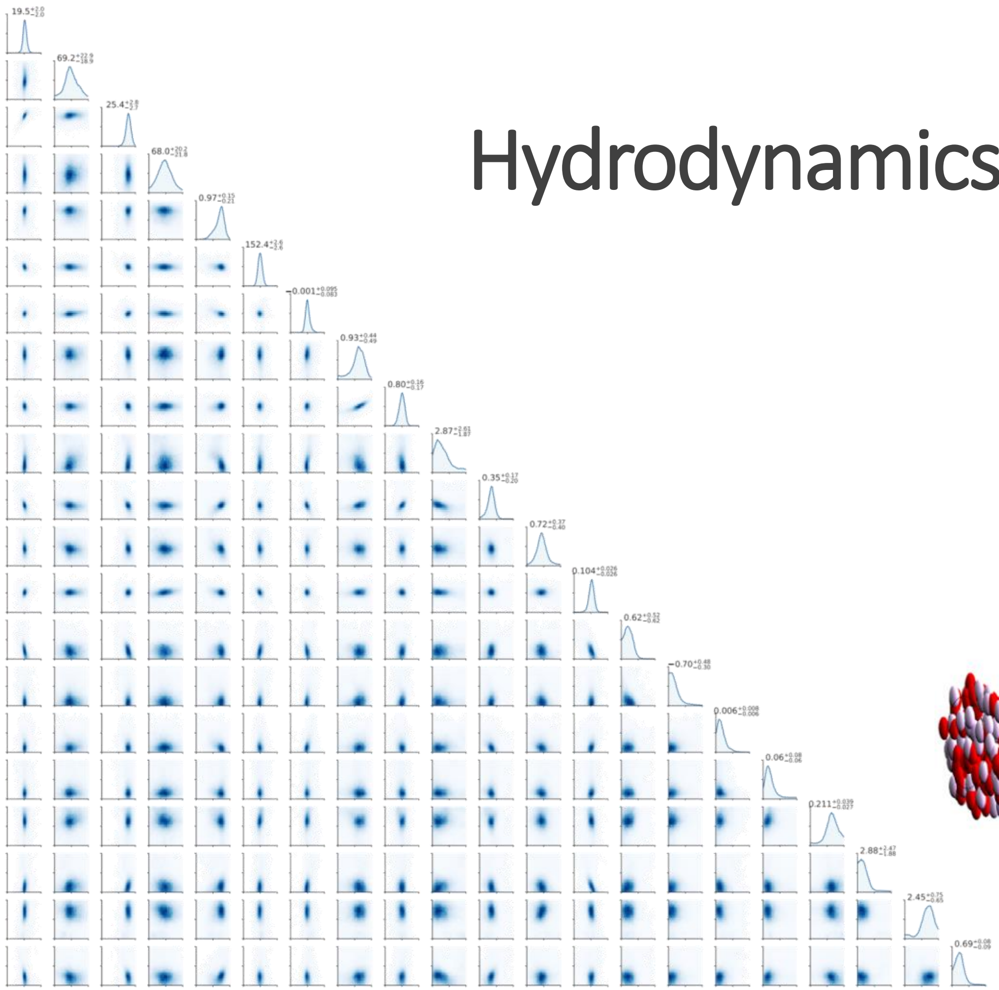
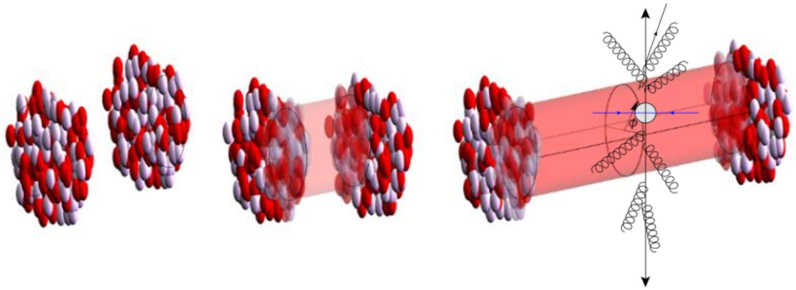


Hydrodynamics and Bayesian Inferences in isobar collisions

Latest *Trajectum* results on Isobar collisions

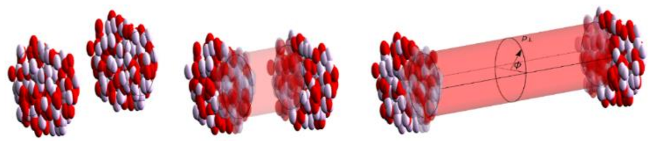
Based on 2112.13771 with Govert Nijs

Thanks to STAR for sharing their data at an early stage



Wilke van der Schee
ESNT, Paris
21 September 2022

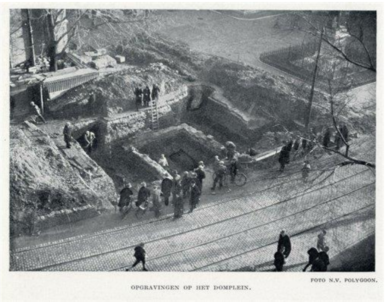
Standard model of heavy ion collisions



(# parameters)

Trajectum

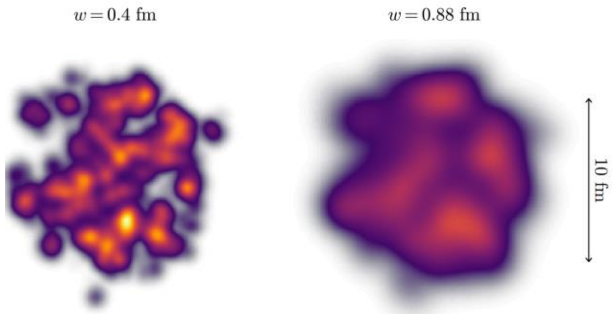
- New public heavy ion code
- Originally Utrecht (now MIT/CERN)
- Fast
- Precise (all cuts equal to experiment)
- Scalable



Roman excavations in Utrecht in 1929

Initial stage (9)

Subnucleonic structure? (7)

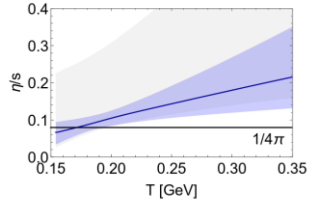


Non-thermal flow? (2)
with varying speed (***new***)

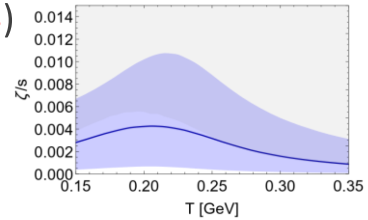
Fluctuations? (1)

Viscous hydrodynamics (9)

Shear viscosity (3)

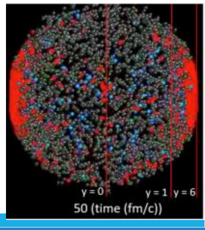


Bulk viscosity (3)

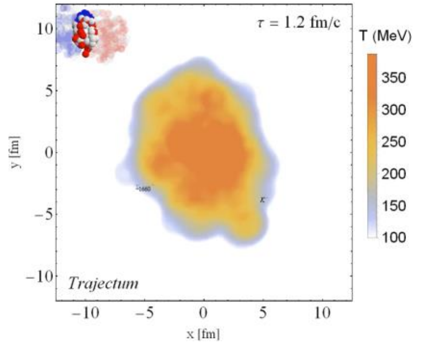


Second order transports: 3 (***new***)

Cascade of hadrons (1)

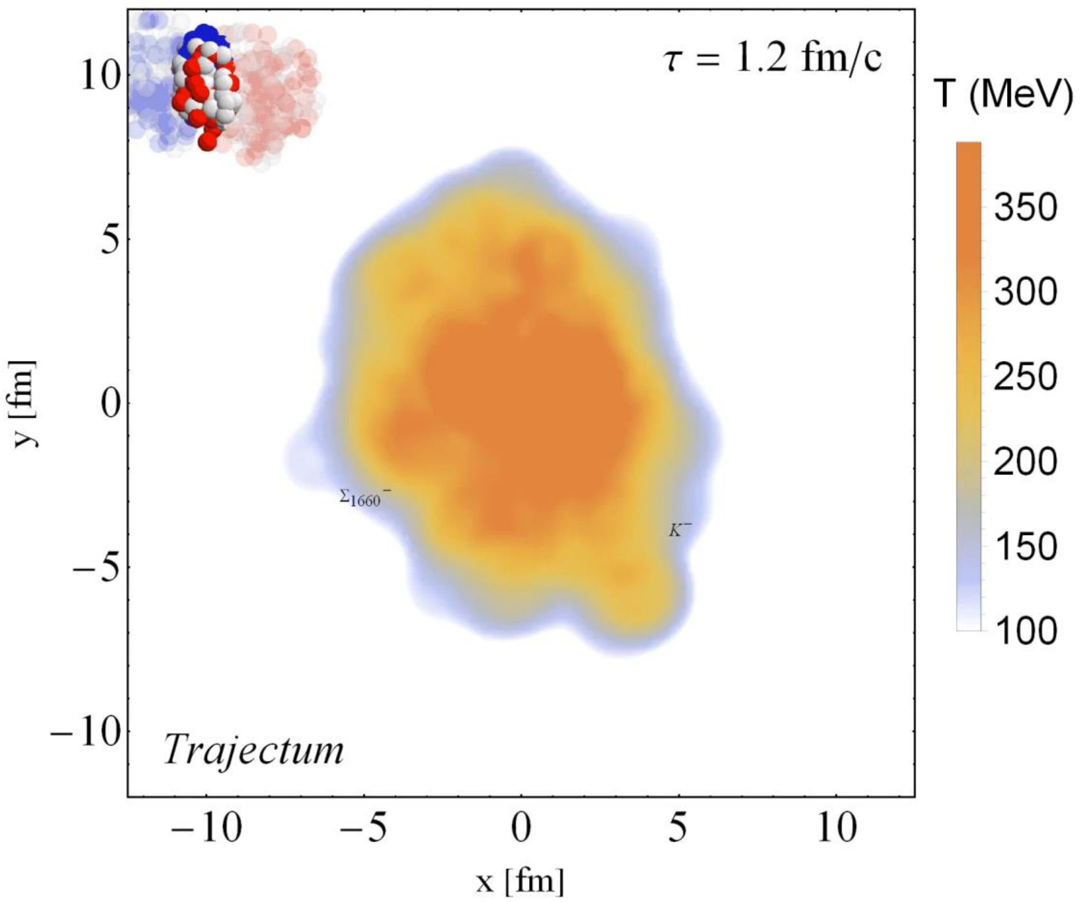


Jonah Bernhard, Scott Moreland and Steffen Bass, Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma (2019)
Govert Nijs, WS, Umut Gursoy and Raimond Snellings, A Bayesian analysis of Heavy Ion Collisions with Trajectum (2020)



Trajectum

1. Quite straightforward to use (see param file, right)
2. Includes analyse routine
    - Parallelised: can analyse unlimited number of events

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    format=smash
    f0500=false
    numevents=1
    seed=7398984.747399307
    debugoutput=true
    numthreads=2
}

entropyacceptanceprobability{
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    24:0.0
    24.5:0.05
    25.5:0.05
    26:0.0
    100:0.0
}

trentosubstructurePbPb{
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    w=0.701919
    sigmann=70.0
    sigmafluct=0.73579
    p=0.14388
    q=1.0
    Eref=0.2
    norm=23.507
    freestreamingreferencetime=1.17085
    freestreamingvelocity=0.62672
    weaktostrong=0.0
    nref=20
    alpha=0
    nc=3.2747
    voverw=0.4892041602706295
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    bulkrelaxationtime=0.0687
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    phi7overpressure=0.128571
    taupipiovertaupi=1.61033
    lambdapiPiovertaupi=1.2
    deltaPiPiovertauPi=0.6666666666666
    lambdaPipiovertauPi=1.6
    phi1overpressure=0
    phi3overpressure=0
    phi6overpressure=0
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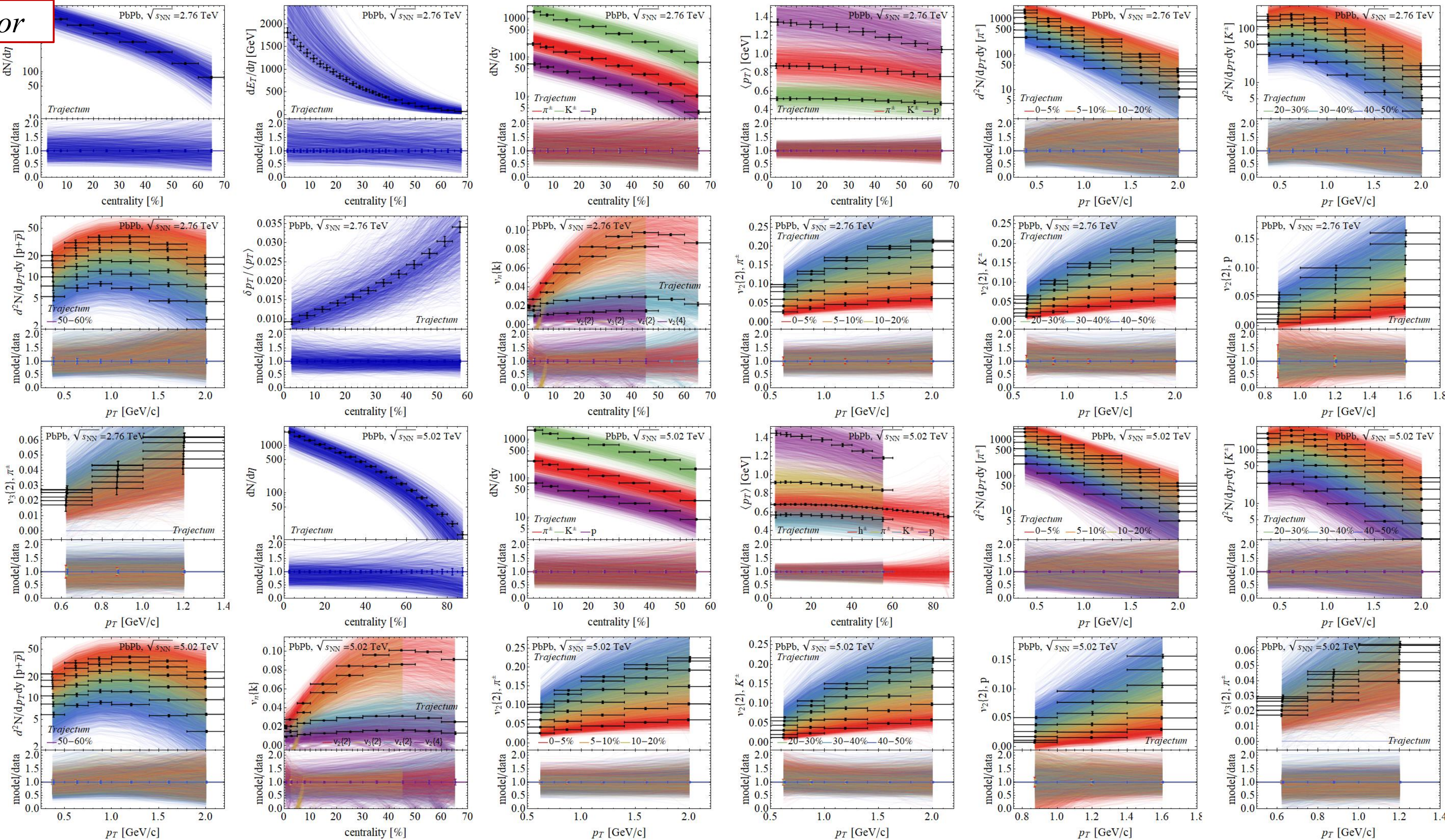
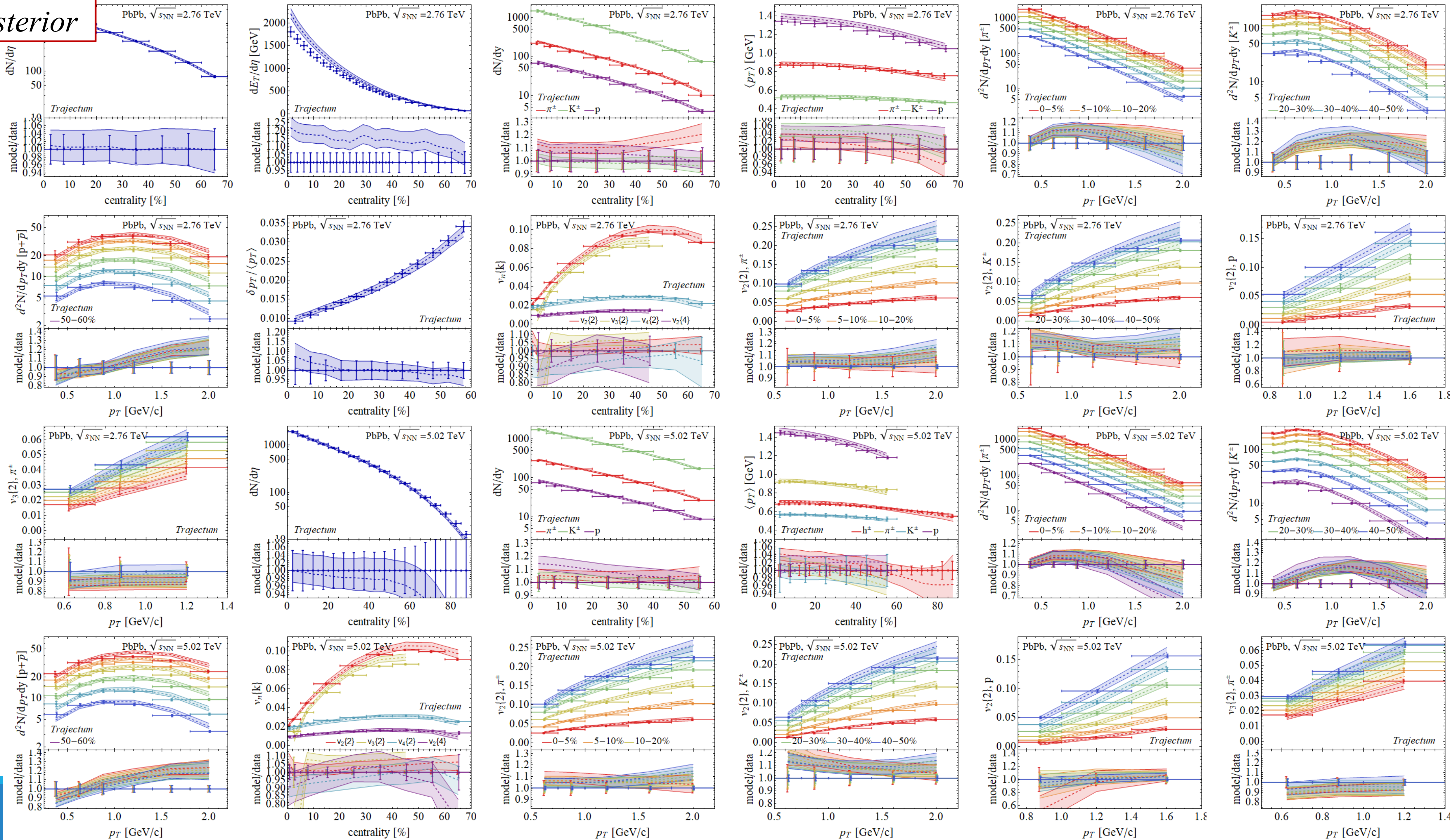
Prior



PbPb, $\sqrt{s_{NN}}$ =2.76 TeV
PbPb, $\sqrt{s_{NN}}$ =5.02 TeV
Trajectum
dN/dη
$dE_T/d\eta$ [GeV]
dN/dy
$\langle p_T \rangle$ [GeV]
$d^2N/dp_T dy$ [$\pi^\pm$]
$d^2N/dp_T dy$ [$K^\pm$]
$d^2N/dp_T dy$ [p+$\bar{p}$]
$\delta p_T / \langle p_T \rangle$
$v_n\{k\}$
$v_2\{2\}$, $\pi^\pm$
$v_2\{2\}$, $K^\pm$
$v_2\{2\}$, p
$v_3\{2\}$, $\pi^\pm$
model/data
centrality [%]
p_T [GeV/c]
$\pi^\pm$ $K^\pm$ p
$h^\pm$ $\pi^\pm$ $K^\pm$ p
0–5% 5–10% 10–20%
20–30% 30–40% 40–50%
50–60%
$v_2\{2\}$ $v_3\{2\}$ $v_4\{2\}$ $v_2\{4\}$

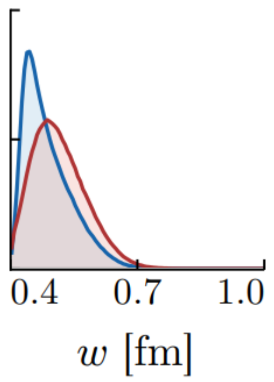
Posterior


PbPb, $\sqrt{s_{NN}}$ =2.76 TeV
PbPb, $\sqrt{s_{NN}}$ =5.02 TeV
Trajectum
dN/dη
$dE_T/d\eta$ [GeV]
dN/dy
$\langle p_T \rangle$ [GeV]
$d^2N/dp_T dy$ [$\pi^\pm$]
$d^2N/dp_T dy$ [$K^\pm$]
$d^2N/dp_T dy$ [$p+\bar{p}$]
$\delta p_T / \langle p_T \rangle$
$v_n\{k\}$
$v_2\{2\}, \pi^\pm$
$v_2\{2\}, K^\pm$
$v_2\{2\}$, p
$v_3\{2\}, \pi^\pm$
model/data
centrality [%]
p_T [GeV/c]
$\pi^\pm$ — $K^\pm$ — p
$h^\pm$ — $\pi^\pm$ — $K^\pm$ — p
0–5% 5–10% 10–20%
20–30% 30–40% 40–50%
50–60%
$v_2\{2\}$ — $v_3\{2\}$ — $v_4\{2\}$ — $v_2\{4\}$

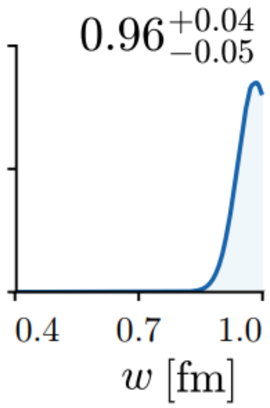
The nucleon width from Bayesian scans

Nucleons grow with collision energy, but by how much?

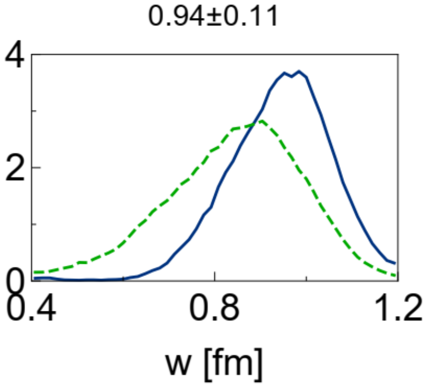
Duke + OSU, 2016



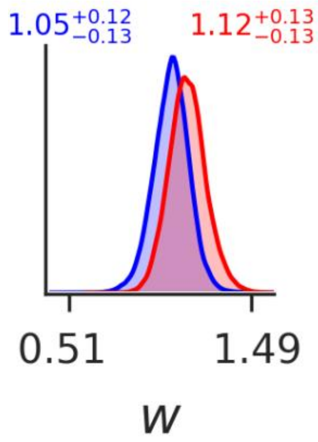
Duke nature physics, 2018



Trajectum, 2020



JETSCAPE, 2020



Nucleon width increased in 2018 (very significantly)

- Includes initial stage (free streaming)
- Switched Trento from entropy to energy
- Realistic bulk viscous corrections at particlisation

- Initial stage gives more radial flow, which is countered by larger width
- w is Gaussian width: nucleons would have ~5 fm diameter
- Such large nucleons are unlikely: cut off prior at 1 fm

PhD thesis Jonah Bernhard (p157)

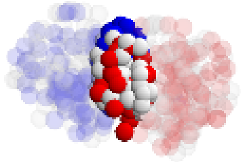
Jonah Bernhard, Scott Moreland, Steffen Bass, Jia Liu and Ulrich Heinz, Applying Bayesian parameter estimation to RHIC (2016)
Jonah Bernhard, Scott Moreland and Steffen Bass, Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma (2019)
Govert Nijs, WS, Umut Gursoy and Raimond Snellings, A Bayesian analysis of Heavy Ion Collisions with Trajectum (2020)
D. Everett, W. Ke, J.-F. Paquet, G. Vujanovic et al, Multi-system Bayesian constraints on the transport coefficients of QCD matter (2020)

The nucleon width and the total PbPb hadronic cross section

What is easier to measure the width by simply measuring the size?

Trento is basically MC Glauber with

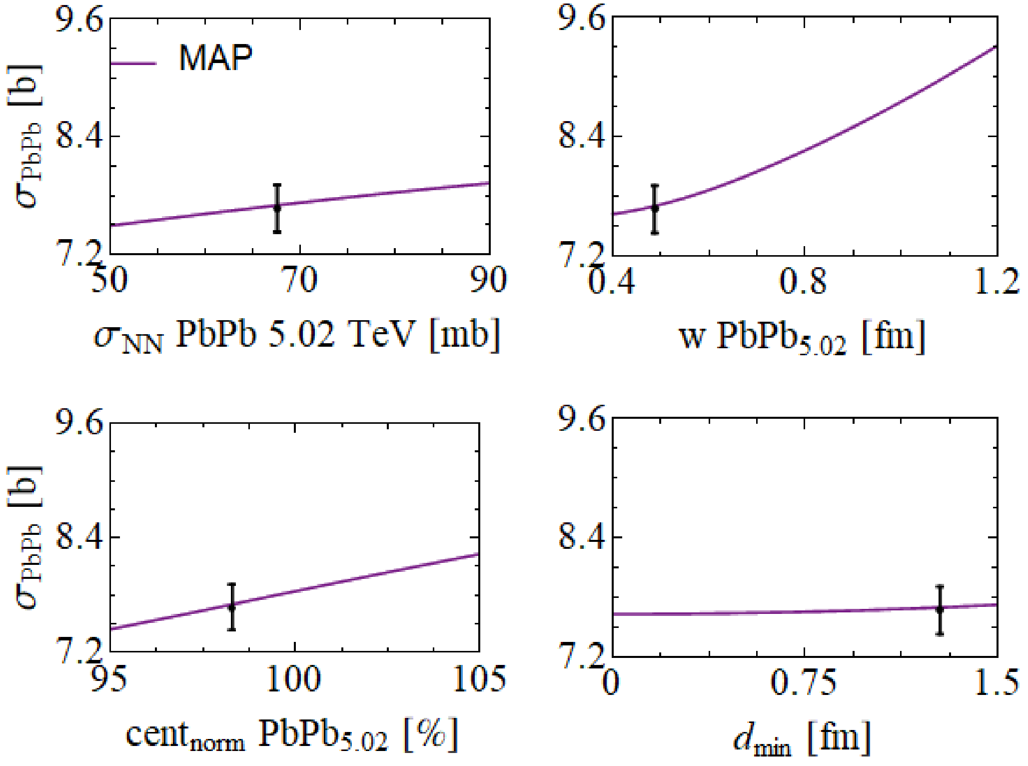
$$P_{\mathrm{coll}} = 1 - \exp\left[-\sigma_{gg} \int dx\, dy \int dz\, \rho_A \int dz\, \rho_B\right]$$



e.g. collision probability tuned to σ_{NN} for Gaussian profile ρ

Theoretically, cross section only depends on

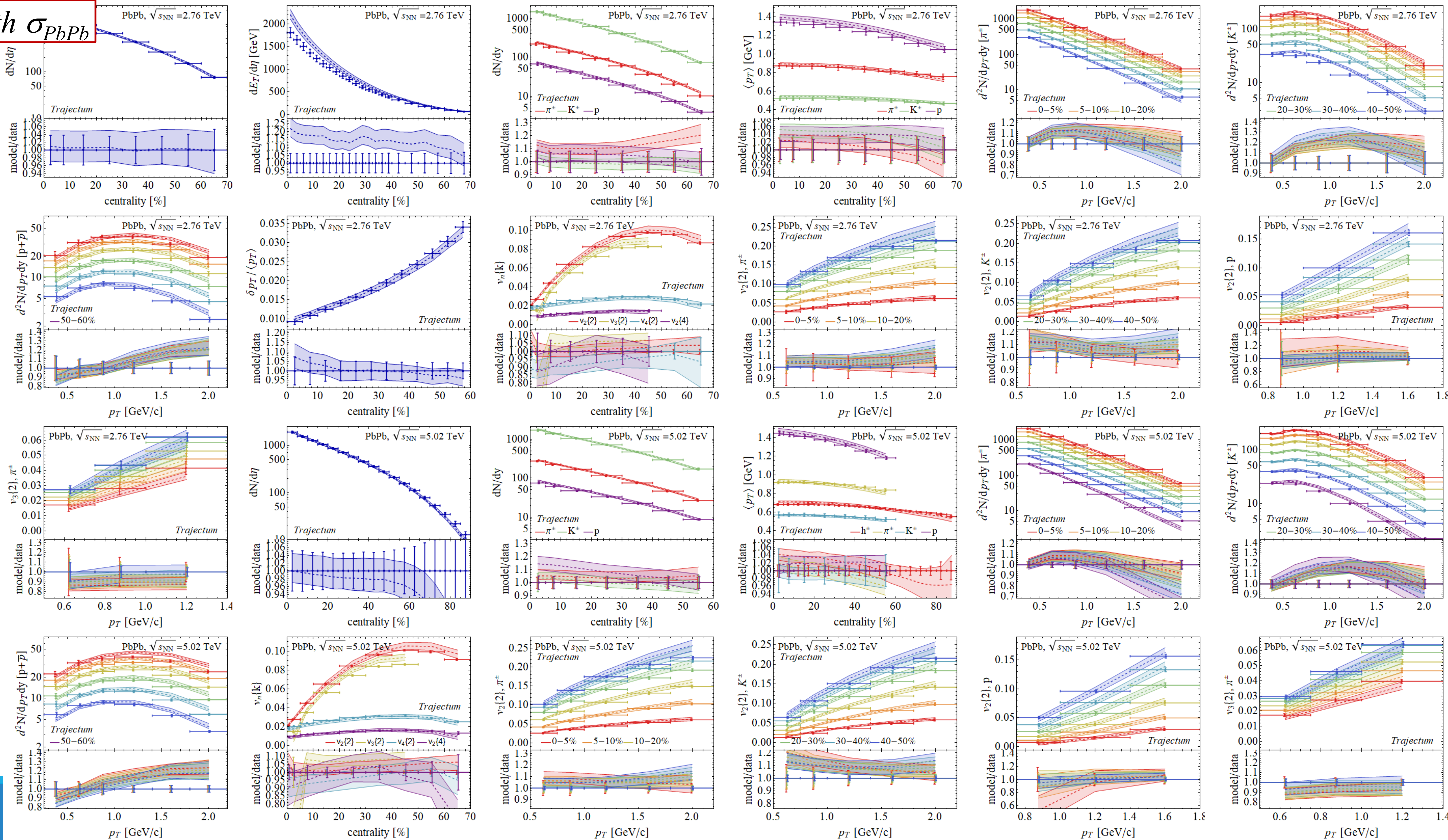
- Nucleon-nucleon cross section
- Nucleon Gaussian width (dominant)
- Centrality normalisation
- Minimum inter-nucleon spacing



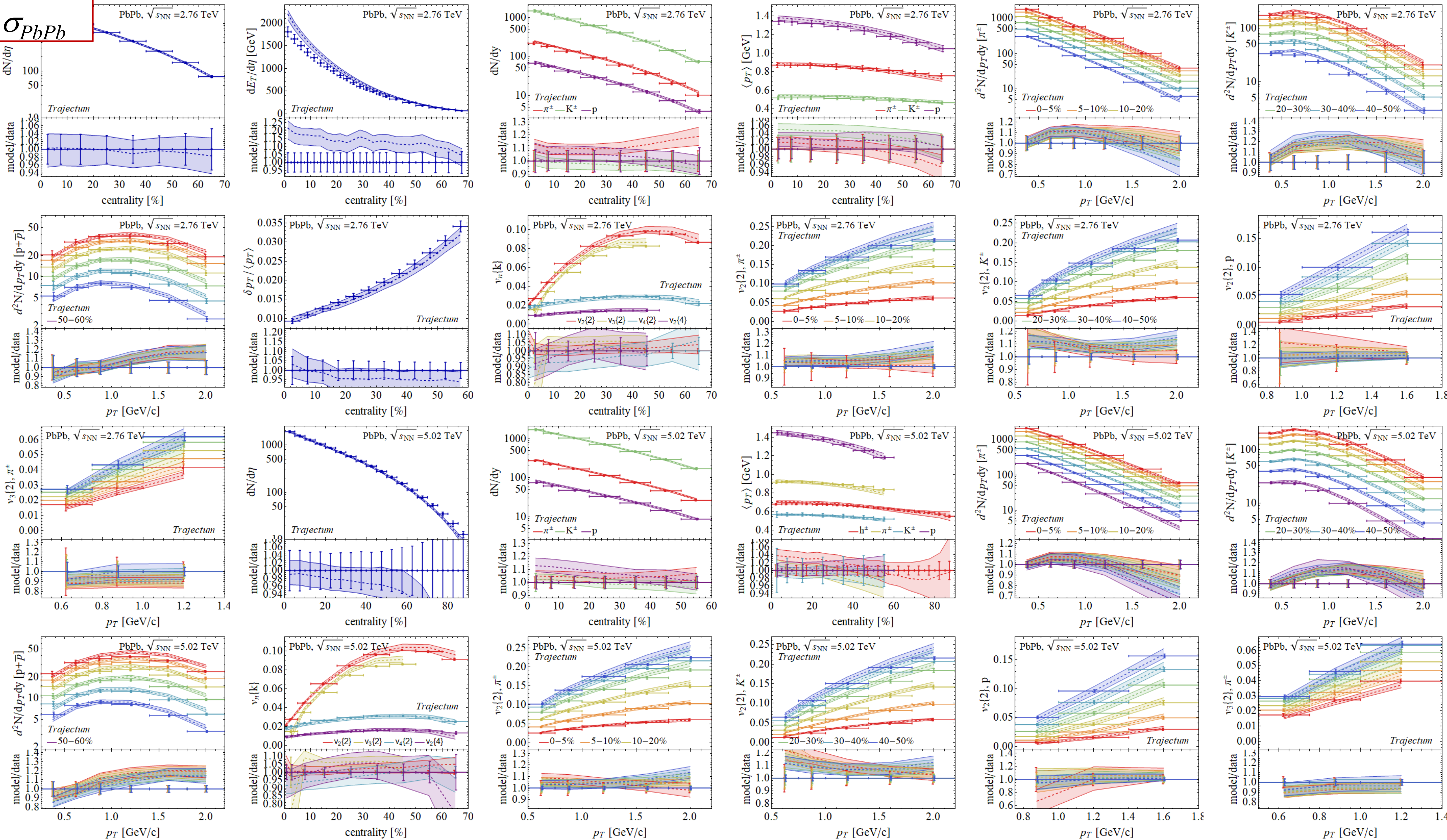
Makes the cross section a robust observable

- Basically implying every model needs to get this right
- Basically implying the nucleon width should be small

With σ_{PbPb}



No σ_{PbPb}



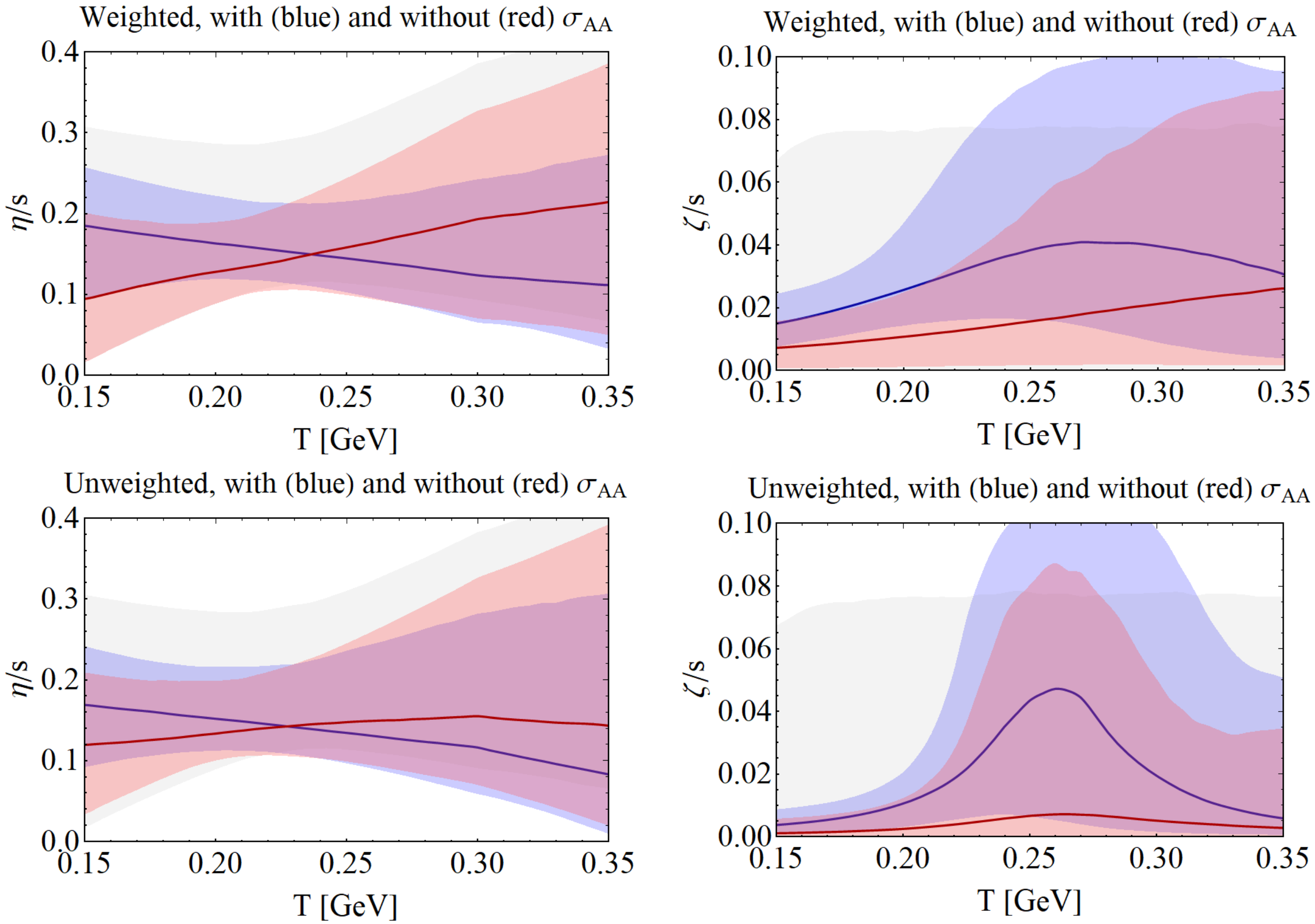
Effect on the viscosities

Smaller width:

- Increased bulk viscosity to counter radial flow
- Hint of increase in η/s at low temperature

Weighing data:

- Increases size bulk viscosity (consistent with width)
- Larger uncertainty bulk, especially at low T
- Shear viscosity almost unperturbed

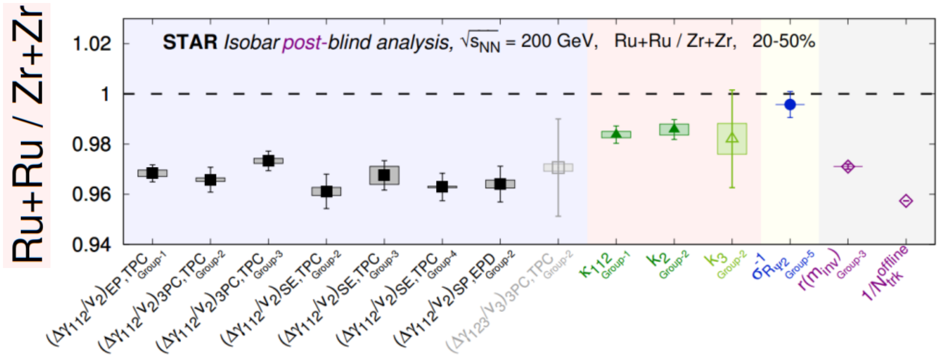


Isobar collisions at STAR

Varying the magnetic field

Idea: similar nuclei (same # of baryons), different charge

- Ruthenium generates a 10% larger magnetic field
- Ideal set-up to suppress background and detect Chiral Magnetic Effect (CME)
- Very precise blinded analysis by STAR:

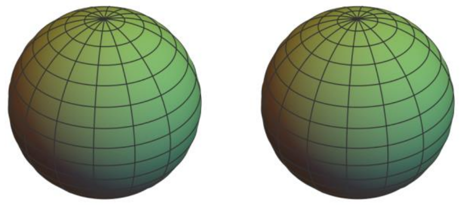


CME-like

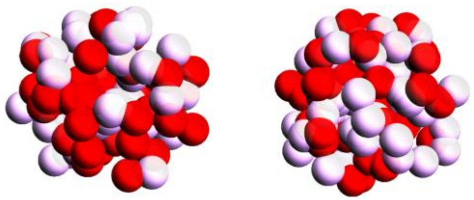
No CME

Unfortunately (?), no CME detected

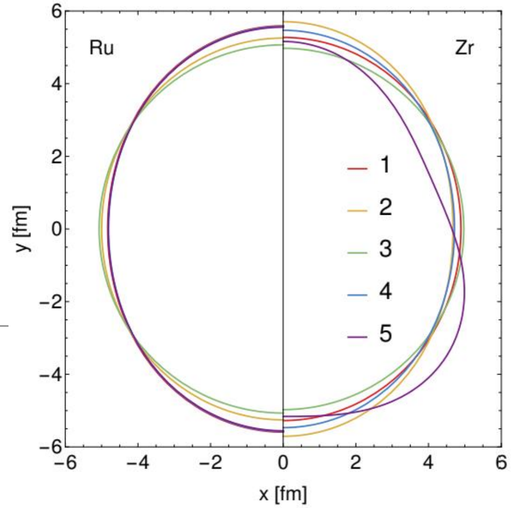
$^{96}_{44}\mathrm{Ru}^{44+}$ $^{96}_{40}\mathrm{Zr}^{40+}$

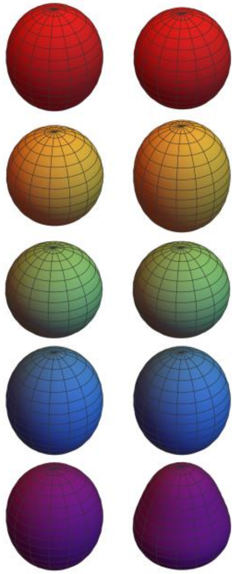


Averaged



Fluctuating (realistic)





Isobar collisions at STAR

Five different cases simulated:

nucleus	R_p [fm]	σ_p [fm]	R_n [fm]	σ_n [fm]	β_2	β_3	σ_{AA} [b]
$^{96}_{44}$Ru(1)	5.085	0.46	5.085	0.46	0.158	0	4.628
$^{96}_{40}$Zr(1)	5.02	0.46	5.02	0.46	0.08	0	4.540
$^{96}_{44}$Ru(2)	5.085	0.46	5.085	0.46	0.053	0	4.605
$^{96}_{40}$Zr(2)	5.02	0.46	5.02	0.46	0.217	0	4.579
$^{96}_{44}$Ru(3)	5.06	0.493	5.075	0.505	0	0	4.734
$^{96}_{40}$Zr(3)	4.915	0.521	5.015	0.574	0	0	4.860
$^{96}_{44}$Ru(4)	5.053	0.48	5.073	0.49	0.16	0	4.701
$^{96}_{40}$Zr(4)	4.912	0.508	5.007	0.564	0.16	0	4.829
$^{96}_{44}$Ru(5)	5.053	0.48	5.073	0.49	0.154	0	4.699
$^{96}_{40}$Zr(5)	4.912	0.508	5.007	0.564	0.062	0.202	4.871

1. e-A scattering experiments(STAR case 1)
2. Theory (finite-range liquid drop model, STAR 2)
3. DFT with neutron skin (spherical) [1]
4. DFT with neutron skin (deformed, β_2 = 0.16) [1]
5. As 4, but with β_2 from electric transition probability and β_3 from comparing AMPT with STAR [2]

[1] Hao-jie Xua, Hanlin Lib, Xiaobao Wanga, Caiwan Shena and Fuqiang Wang, Determine the neutron skin type by relativistic isobaric collisions (2021)
[2] Chunjian Zhang and Jiangyong Jia, Evidence of quadrupole and octupole deformations in 96Zr+96Zr and 96Ru+96Ru collisions at ultra-relativistic energies (2021)

For each case we run 0.5M collisions except for case 5 (5M), 14M in total.

Wilke van der Schee, CERN

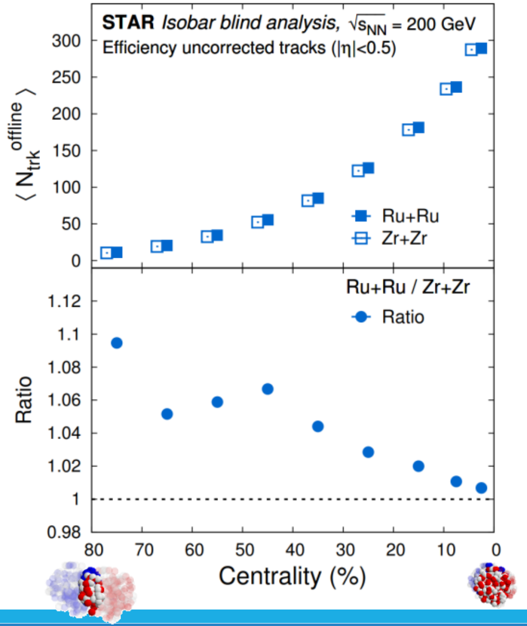
Isobar collisions at STAR - Multiplicity

Precision and non-conventional definition of centrality

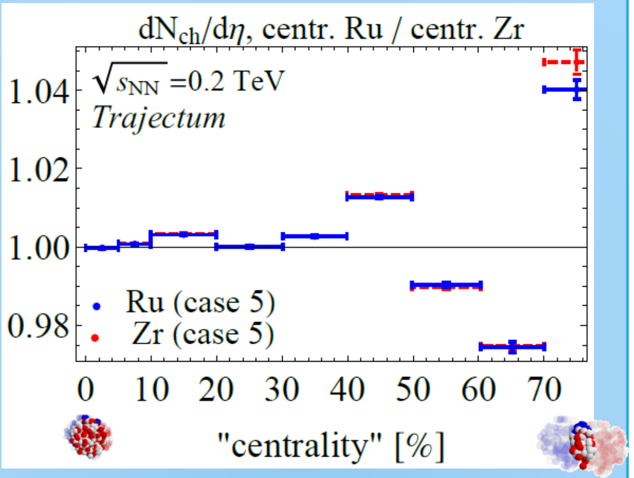
Subtlety in STAR data: "centrality label" is different for Ru and Zr

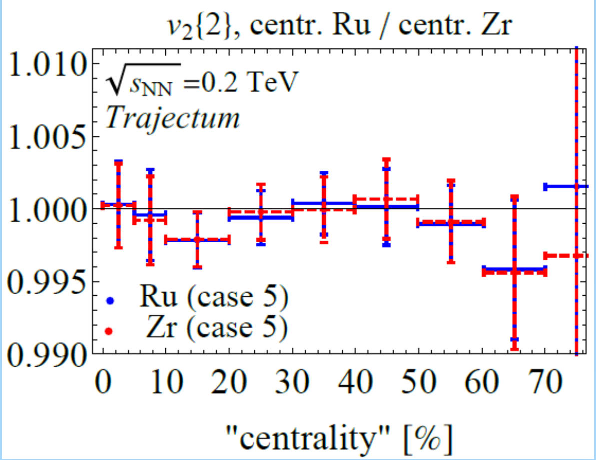
- Especially important for multiplicity (~7% effect)
- Hardly significant for other observables (<0.5% for v_2)

Centrality label (%)	Ru+Ru Centrality(%)	Ru+Ru $N_{trk}^{offline}$	Ru+Ru $\langle N_{trk}^{offline} \rangle$	Zr+Zr Centrality(%)	Zr+Zr $N_{trk}^{offline}$	Zr+Zr $\langle N_{trk}^{offline} \rangle$
0–5	0–5.01	258.–500.	289.32	0–5.00	256.–500.	287.36
5–10	5.01–9.94	216.–258.	236.30	5.00–9.99	213.–256.	233.79
10–20	9.94–19.96	151.–216.	181.76	9.99–20.08	147.–213.	178.19
20–30	19.96–30.08	103.–151.	125.84	20.08–29.95	100.–147.	122.35
30–40	30.08–39.89	69.–103.	85.22	29.95–40.16	65.–100.	81.62
40–50	39.89–49.86	44.–69.	55.91	40.16–50.07	41.–65.	52.41
50–60	49.86–60.29	26.–44.	34.58	50.07–59.72	25.–41.	32.66
60–70	60.29–70.04	15.–26.	20.34	59.72–70.00	14.–25.	19.34
70–80	70.04–79.93	8.–15.	11.47	70.00–80.88	7.–14.	10.48
20–50	19.96–49.86	44.–151.	89.50	20.08–50.07	41.–147.	85.68



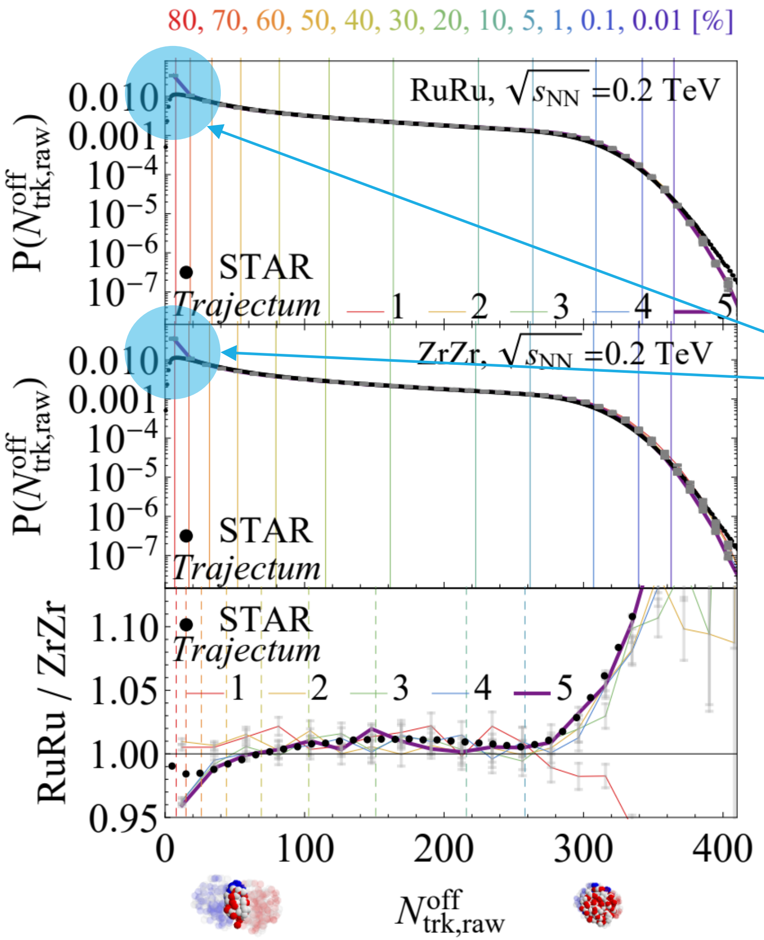
Theory: only change centrality bounds





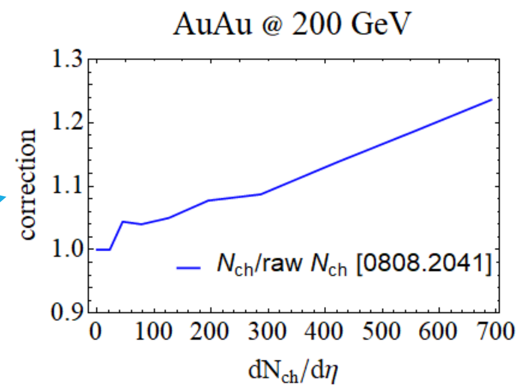
Wilke van der Schee, CERN

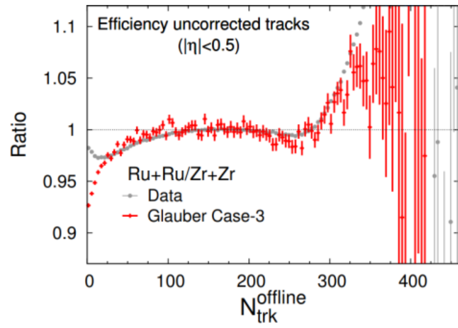
Isobar collisions at STAR - Multiplicity



Better to directly look at (raw) data

- Experimental subtlety: crucial to correct for detector efficiency
- *Trajectum* subtlety: norm not fitted to RHIC energy: multiply mult by 1.21
- Experiment misses (many) very peripheral collisions: multiply P(N) by 1.31 to correct for this (not for ratio)
- Ratio experiment: normalise both and divide
  Subtle: experiment unreliable for N_{trk} < 50
  Ratio theory: integrate **Ru+Zr experiment and Ru+Zr theory** for N_{trk} > 50 and require ratio to match
  Exp-theory comparison only depends on N_{trk} > 50



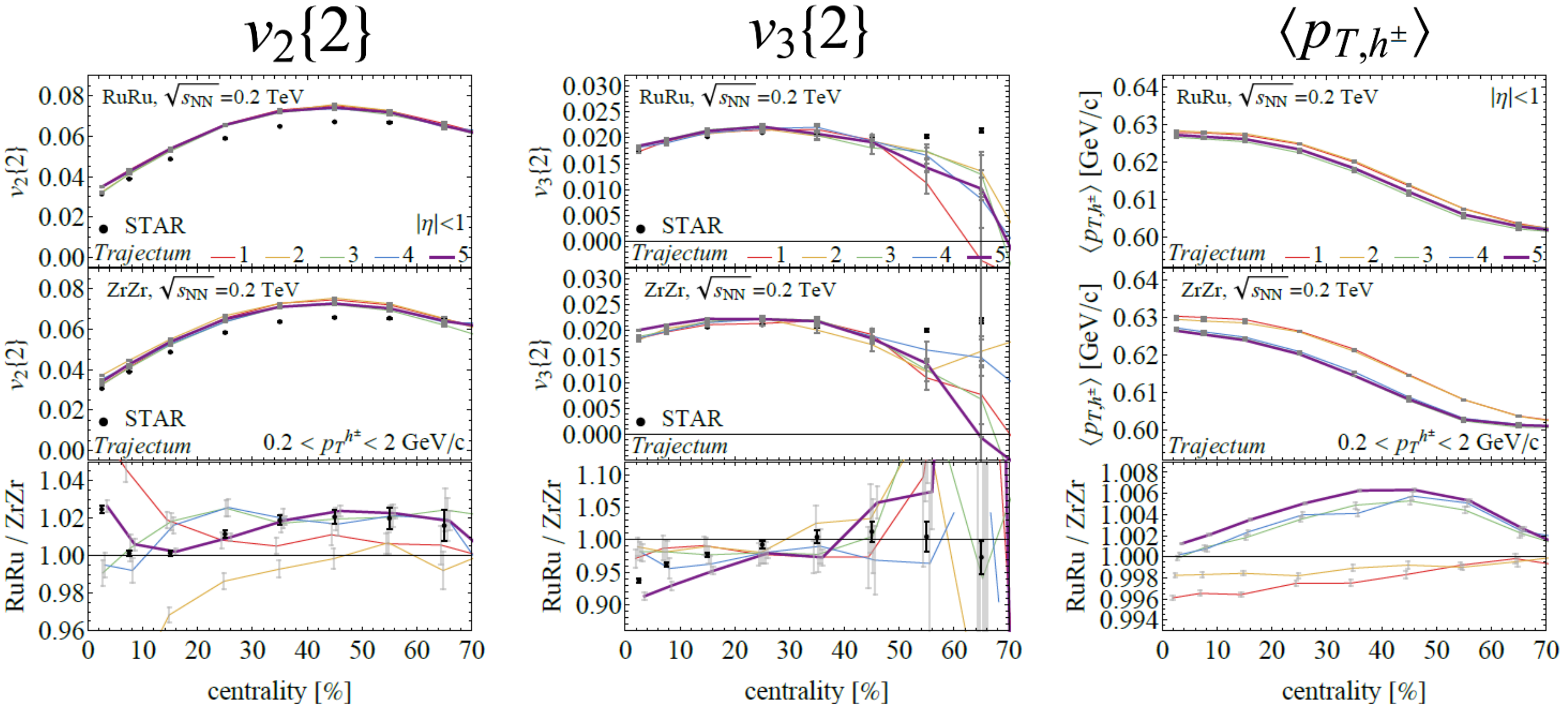


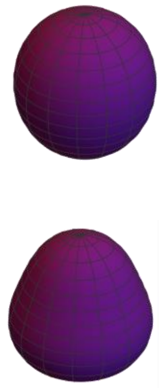
Only case 3, 4 and 5 match well over entire range (neutron-skin)

Isobar collisions at STAR – Flow and mean p_T

RuRu

ZrZr





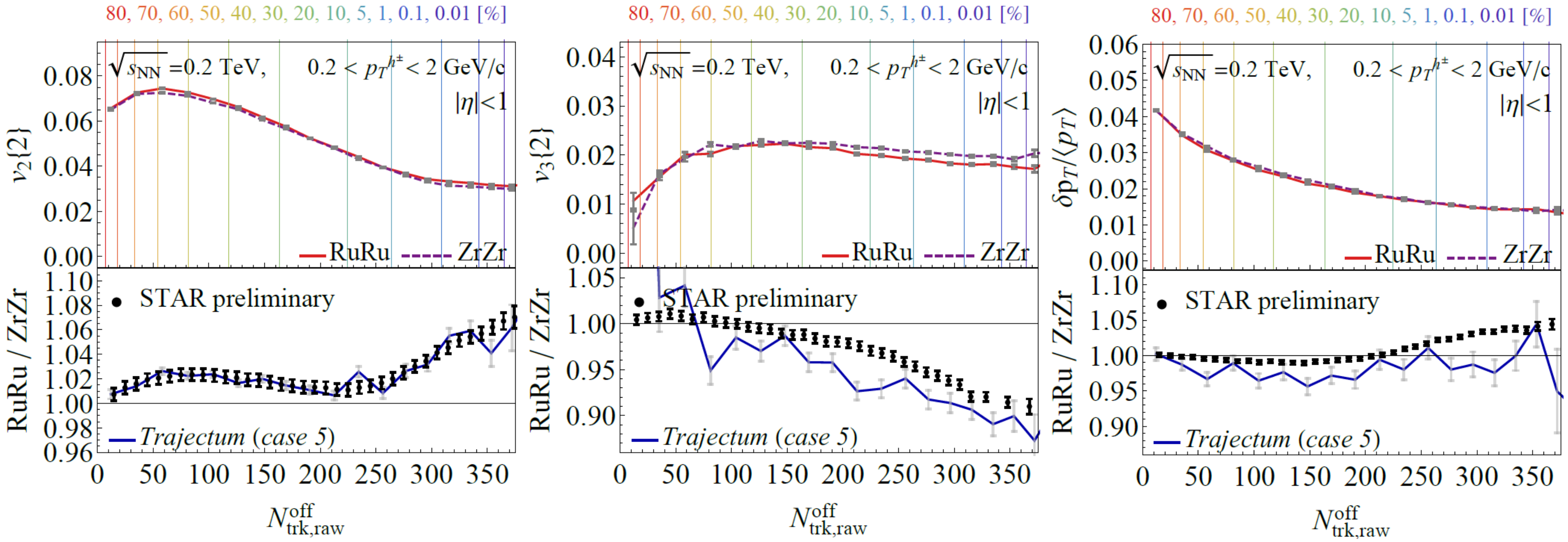
Statistics better for best case (5, with 5M collisions)

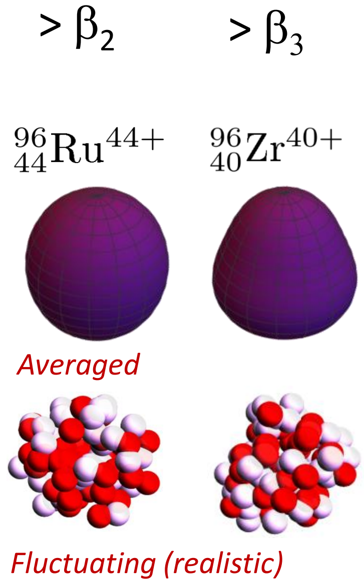
- Excellent fit, especially for v2 ratio, v3 ratio overestimated at central
- Note that *Trajectum* is not fitted to RHIC energies, no absolute agreement
- Mean transverse momentum is a prediction

Extremely ultracentral collisions

Going to 0.01% centrality (we sample from 250M Trento events)

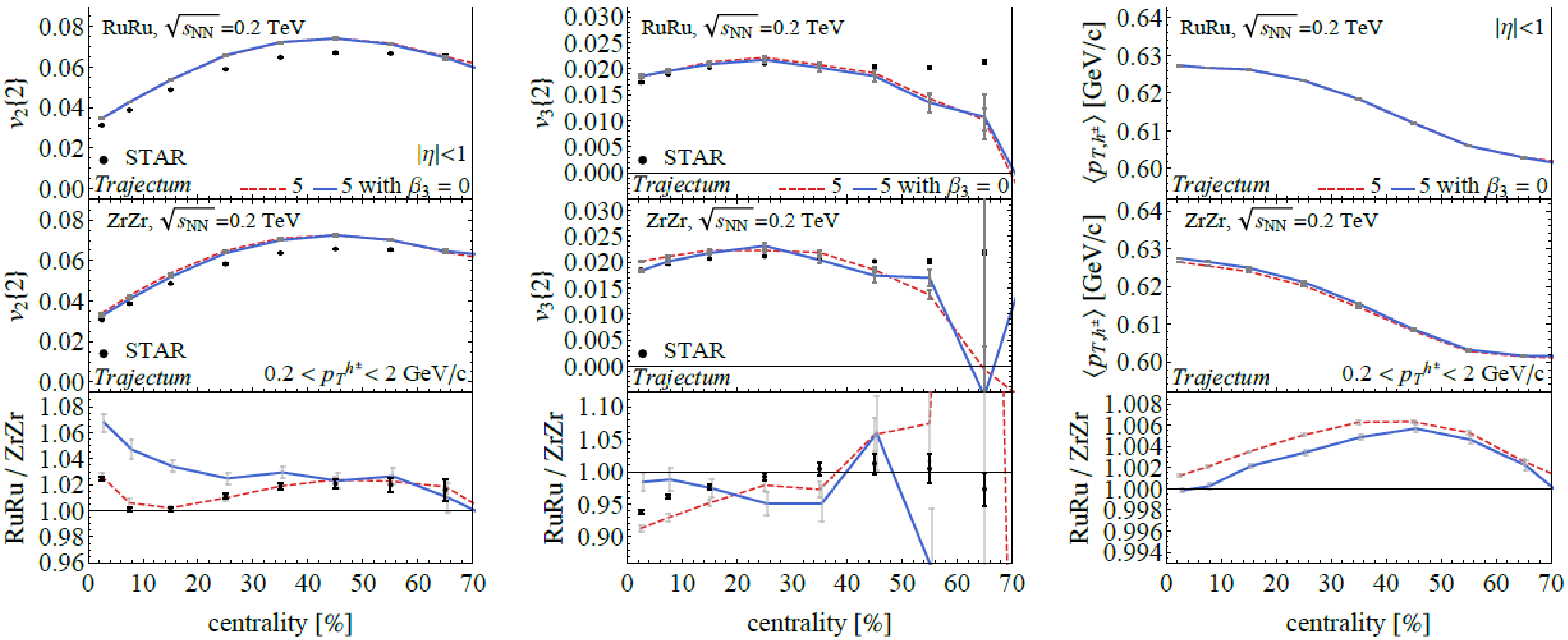
- Excellent match v2, v3 en pt fluct somewhat overpredicted
- Extremely ultracentral is ideal regime to probe nuclear structure

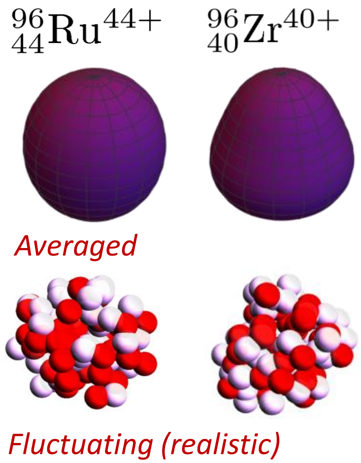




Effect of β_3 on observables

Clear effect on v_3, but also on v_2. Need a (Bayesian) refit of β_2 as well to fit v_2 and v_3?





Initial state predictors

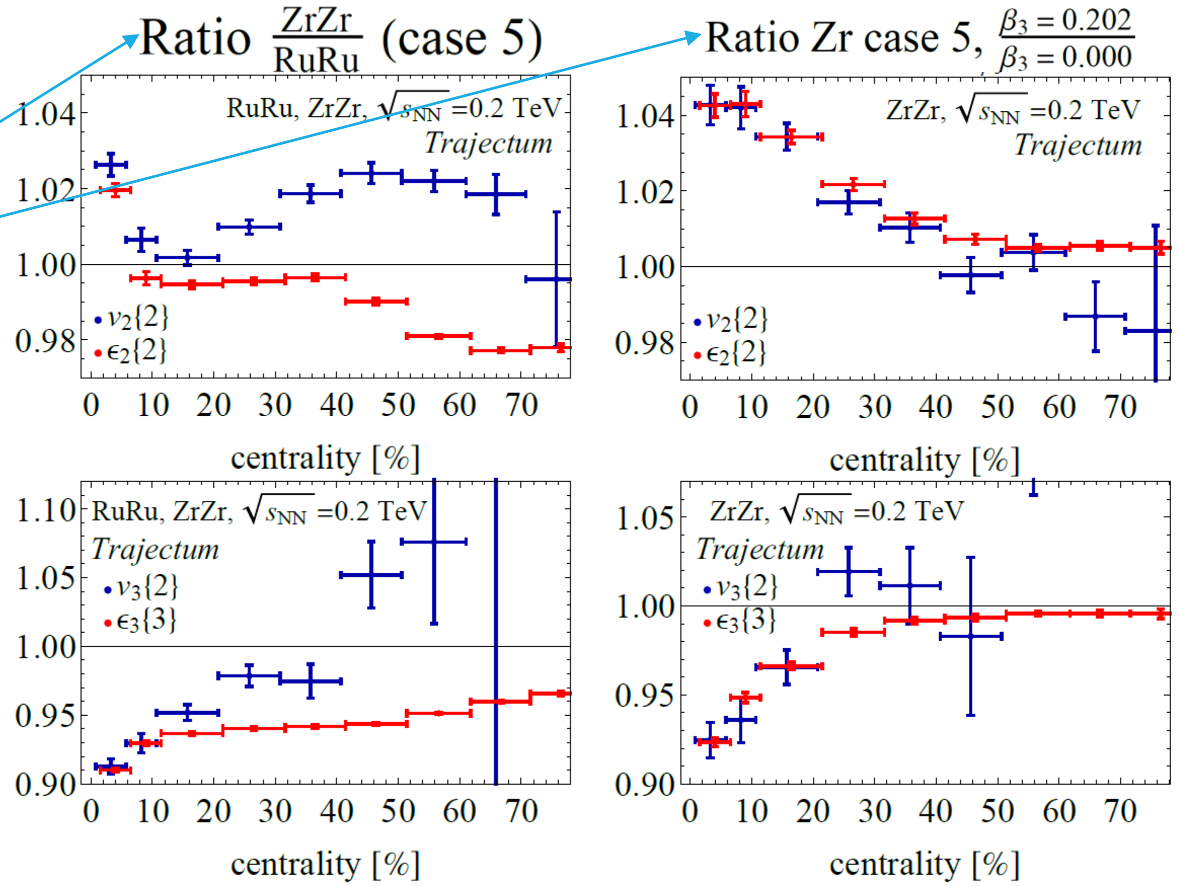
With large sample we can verify the relation

$$v_n\{2\} = \kappa \epsilon_n\{2\}$$

All else being equal this works, e.g. within Zr as in right plots

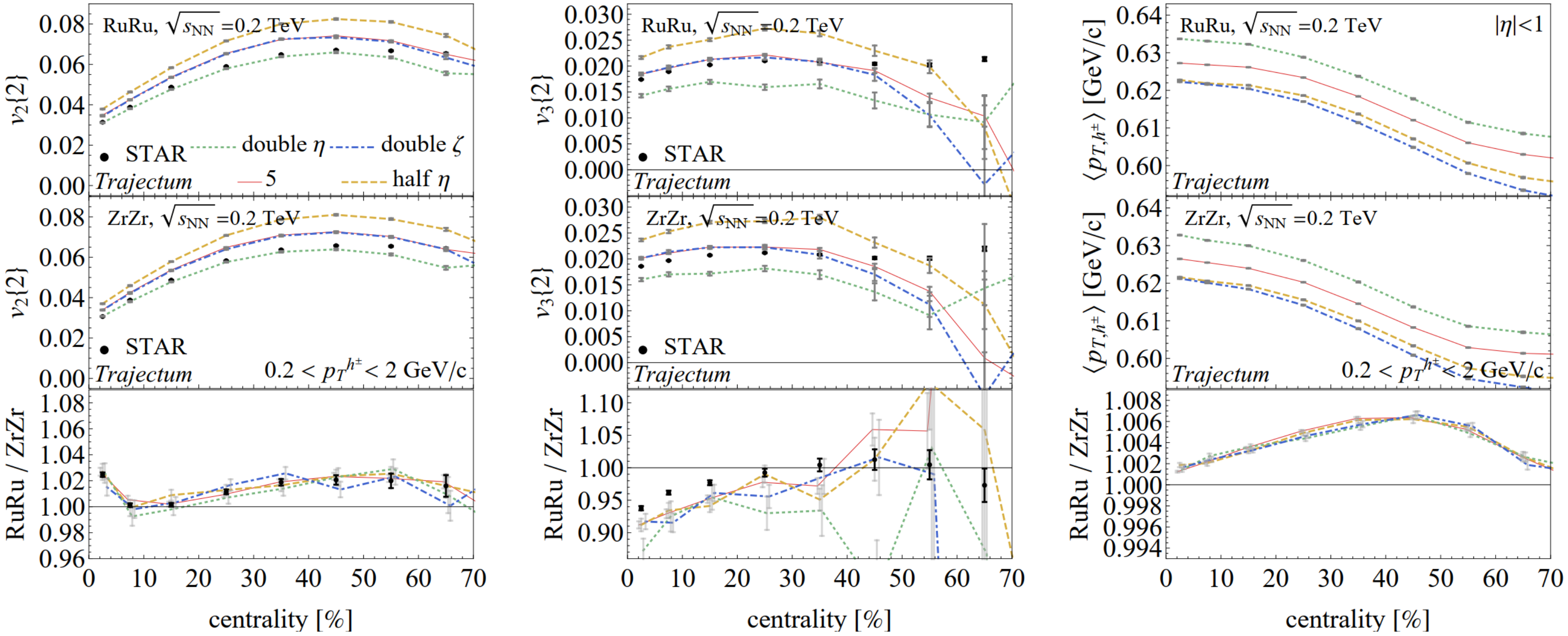
If also size changes etc (Zr vs Ru), it can affect κ and the initial geometry cannot be used

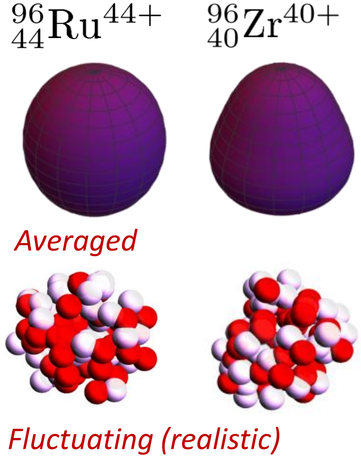
Unfortunate: hydro is expensive…

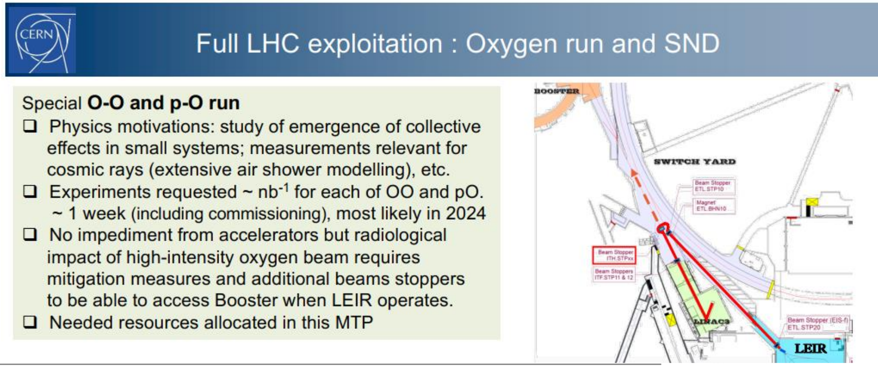


Effect of viscosity on observables

Significant effects, but cancel in the ratio

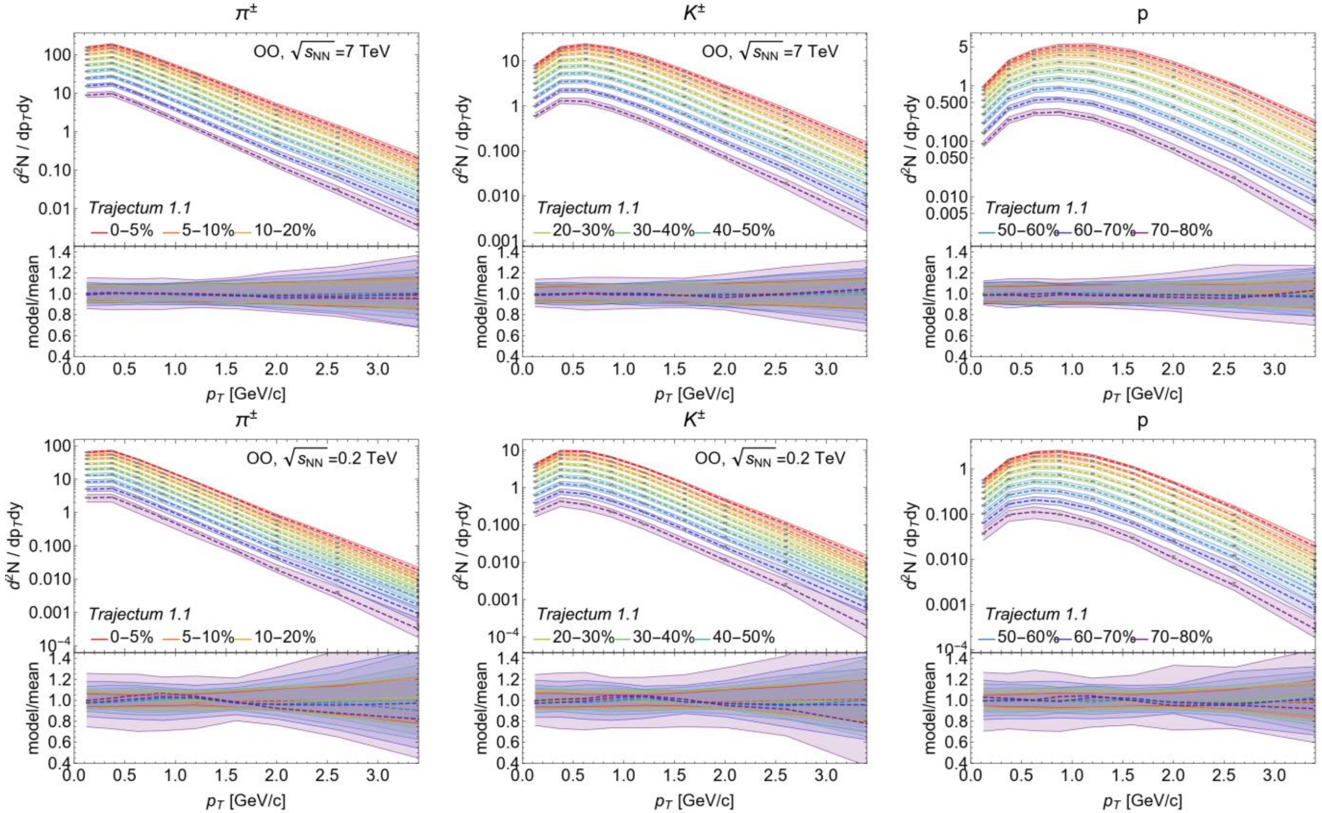


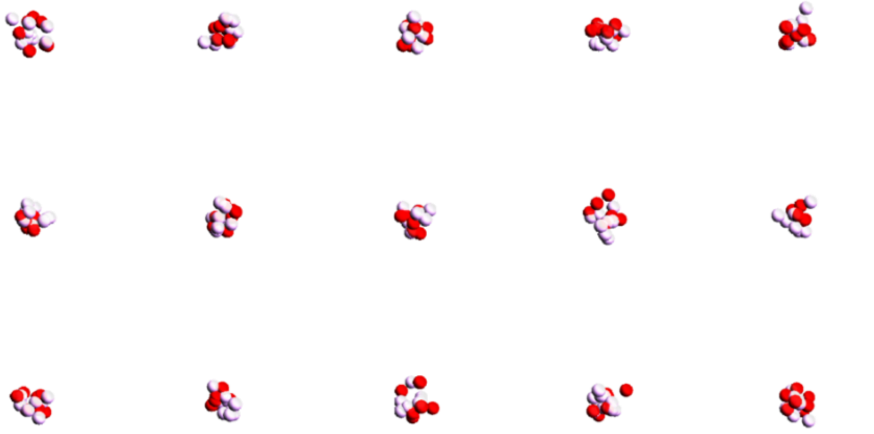




Exciting: oxygen-oxygen special run in 2024!

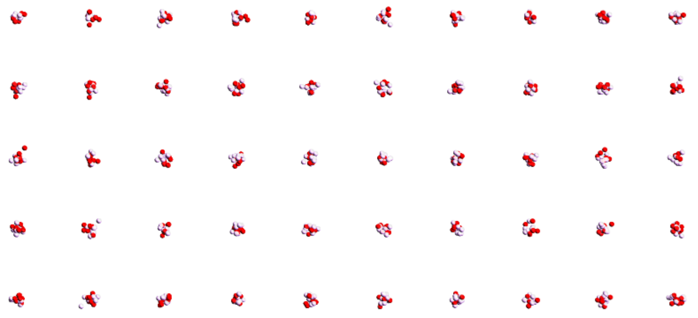
1. Predictions for oxygen at RHIC (run already performed) and LHC
   - Perhaps surprisingly narrow predictions, only fitted on PbPb data



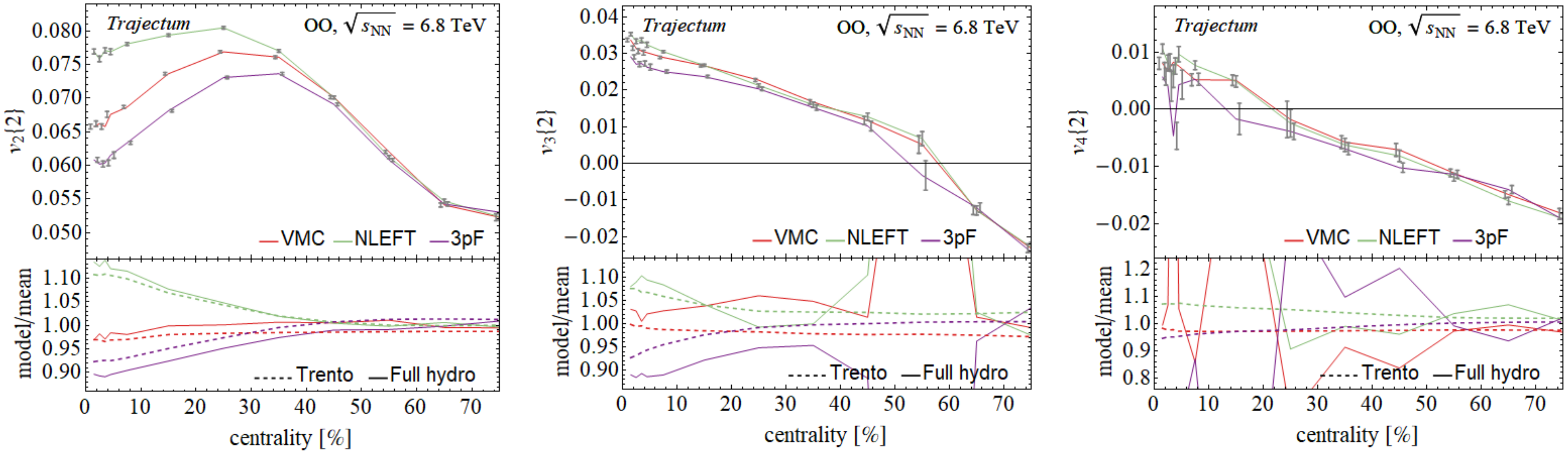


Jasmine Brewer, Aleksas Mazeliauskas and WS: http://cern.ch/ooatlhc or https://arxiv.org/abs/2103.01939
Govert Nijs and WS, Predictions and postdictions for relativistic lead and oxygen collisions with Trajectum (2021)

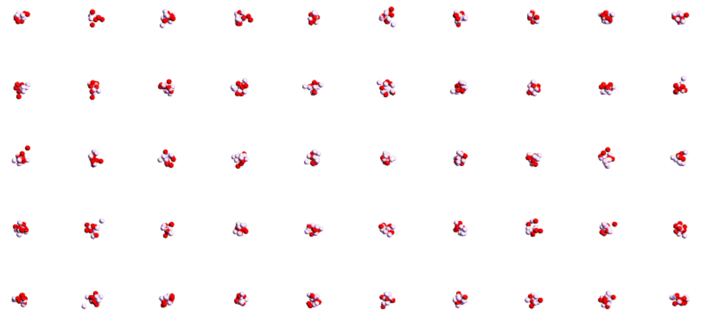
Oxygen nuclear structure



1. Comparing two state-of-the-art microscopics with old profile (MAP run with 1M hydro events per run)
   - 3pF: 3 parameter Wood-Saxon Fermi fit from 1976 with d_{min}
   - VMC: Variational Monte Carlo to sample wave function with advanced nucleon interaction
   - NLEFT: Nuclear Lattice Effective Field Theory, ground state with `pin holes‘ (no repulsive interaction implemented)



   - Trento works quite well for v_2, are the sizes similar? Dissimilar for isobars.



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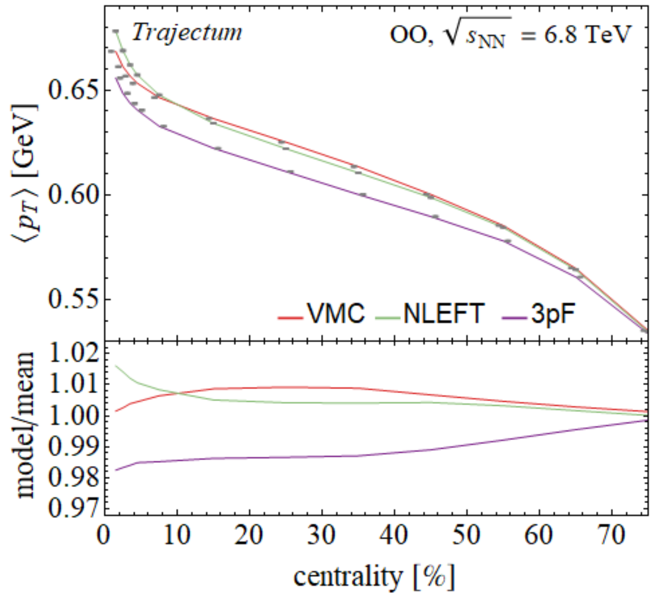
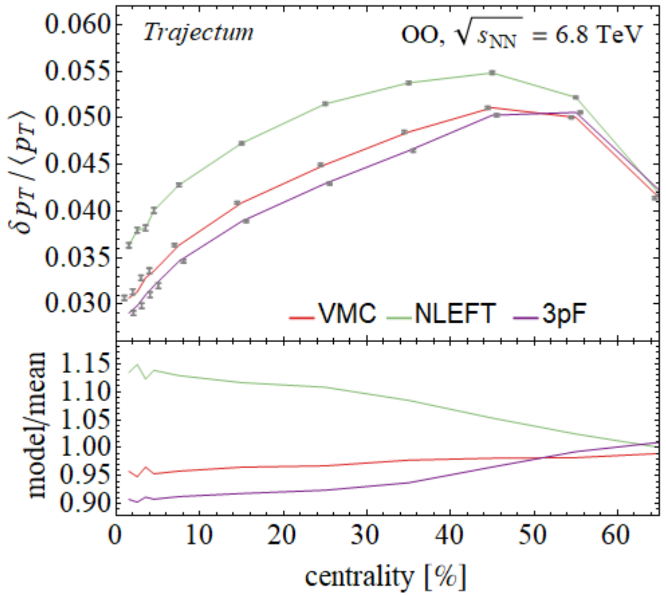
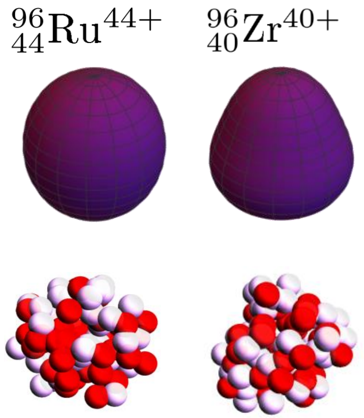
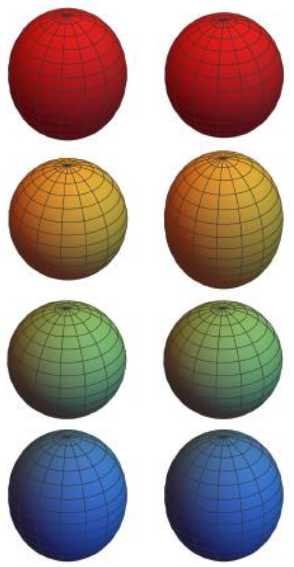




Discussion





Isobar collisions: an opportunity at unprecedented precision
- So many systematics cancel, both experimentally and in theory
- Implies a need for statistics… of order 1M events at least to be competitive

A Bayesian point of view
- So far only performed a scan of several Wood-Saxon parameters (see also [1, 2])
- Global analysis would be preferred, but statistically hard to pull off
- Initial state predictor would be ideal, but first tests are not encouraging

Towards nuclear structure
- Oxygen different from isobars: can collide only the `true’ oxygen
- In that sense isobars are ideal: much control over initial state
- Still to be shown that this is the dealbreaker for QGP properties

Oxygen: exciting interplay between STAR isobars, RHIC and the LHC. Opportunities for predictions.

[1] Hao-jie Xua, Hanlin Lib, Xiaobao Wanga, Caiwan Shena and Fuqiang Wang, Determine the neutron skin type by relativistic isobaric collisions (2021)
[2] Chunjian Zhang and Jiangyong Jia, Evidence of quadrupole and octupole deformations in 96Zr+96Zr and 96Ru+96Ru collisions at ultra-relativistic energies (2021)