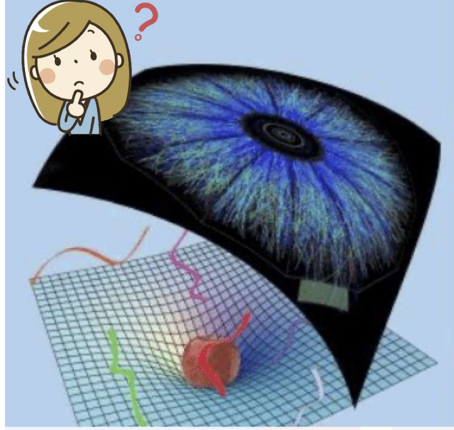
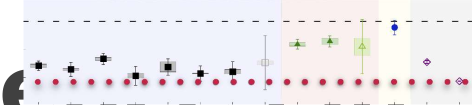


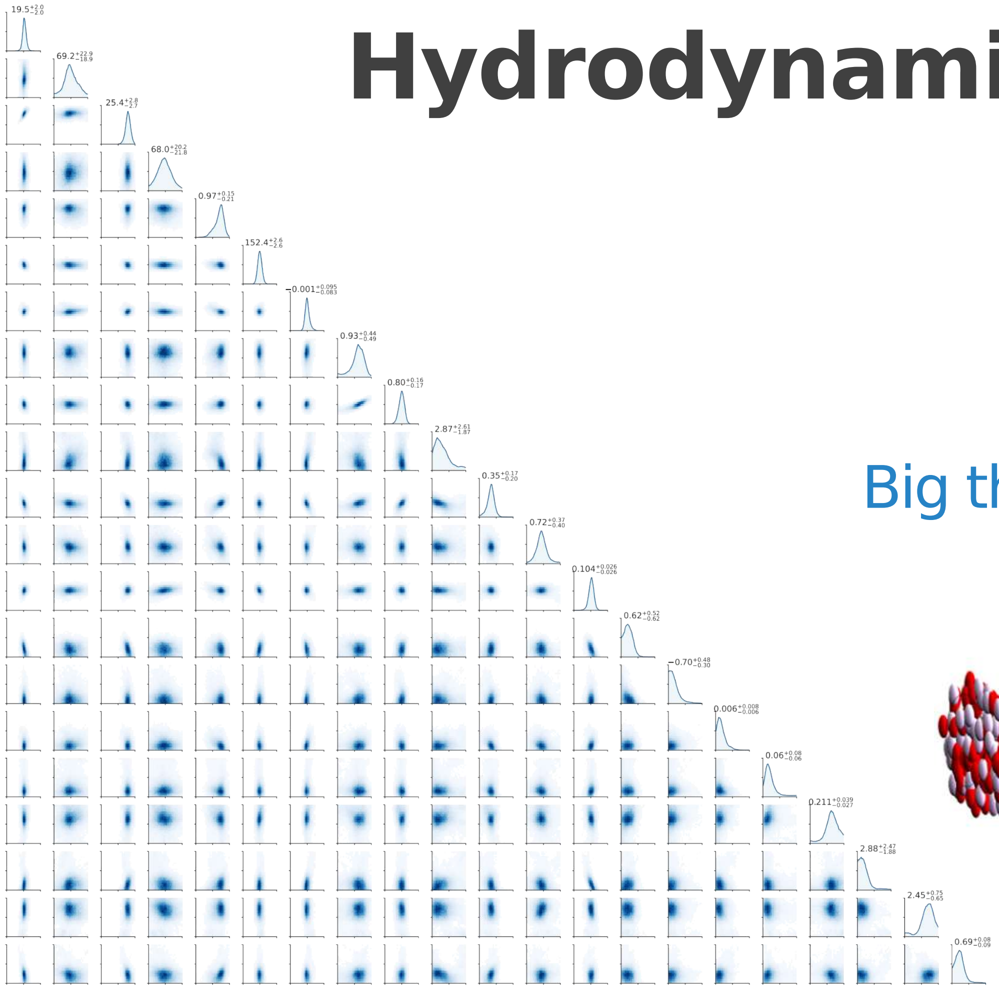


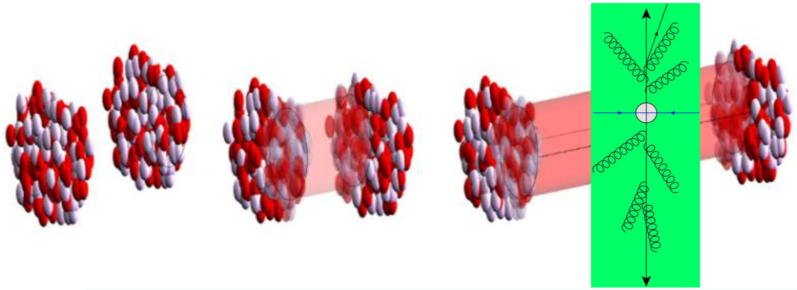
Hydrodynamics and Bayesian Inferences in isobar collisions

Latest *Trajectum* results on Isobar collisions

Based on 2112.13771 with Govert Nijs

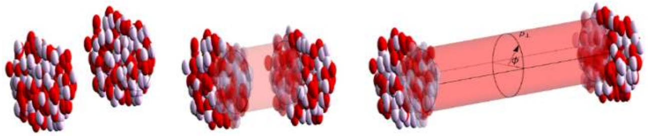
Big thanks to STAR for sharing their data at very early stage





Wilke van der Schee
AdS4CME@HIC, Madrid
15 Mach 2022

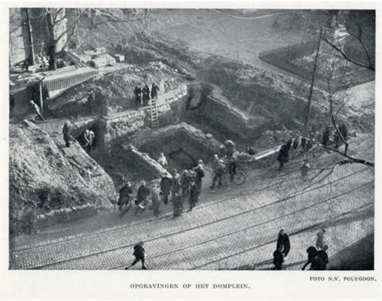
Standard model of heavy ion collisions



(# parameters)

Trajectum

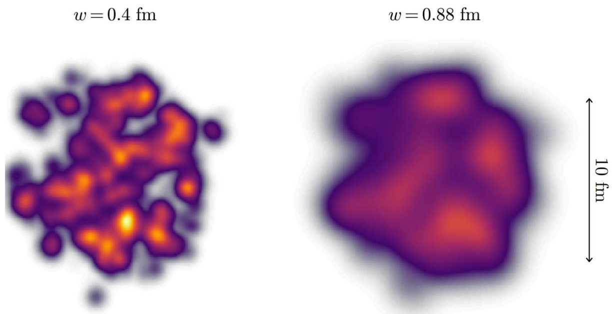
- New public heavy ion code
- Originally Utrecht (now MIT/CERN)
- Fast
- Precise (all cuts equal to experiment)
- Scalable



Roman excavations in **Utrecht** in 1929

Initial stage (9)

Subnucleonic structure? (7)

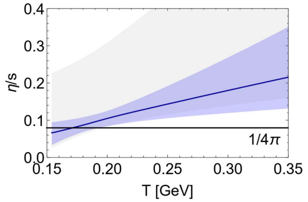


Non-thermal flow? (2)
with varying speed (***new***)

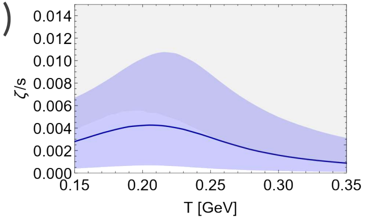
Fluctuations? (1)

Viscous hydrodynamics (9)

Shear viscosity (3)

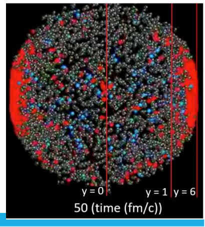


Bulk viscosity (3)



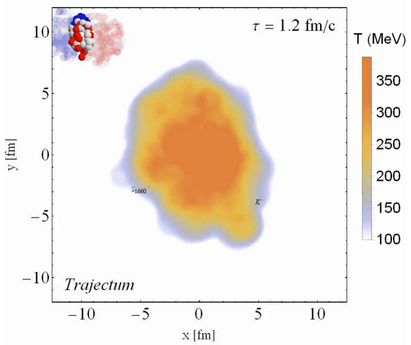
Second order transports: 3 (***new***)

Cascade of hadrons (1)

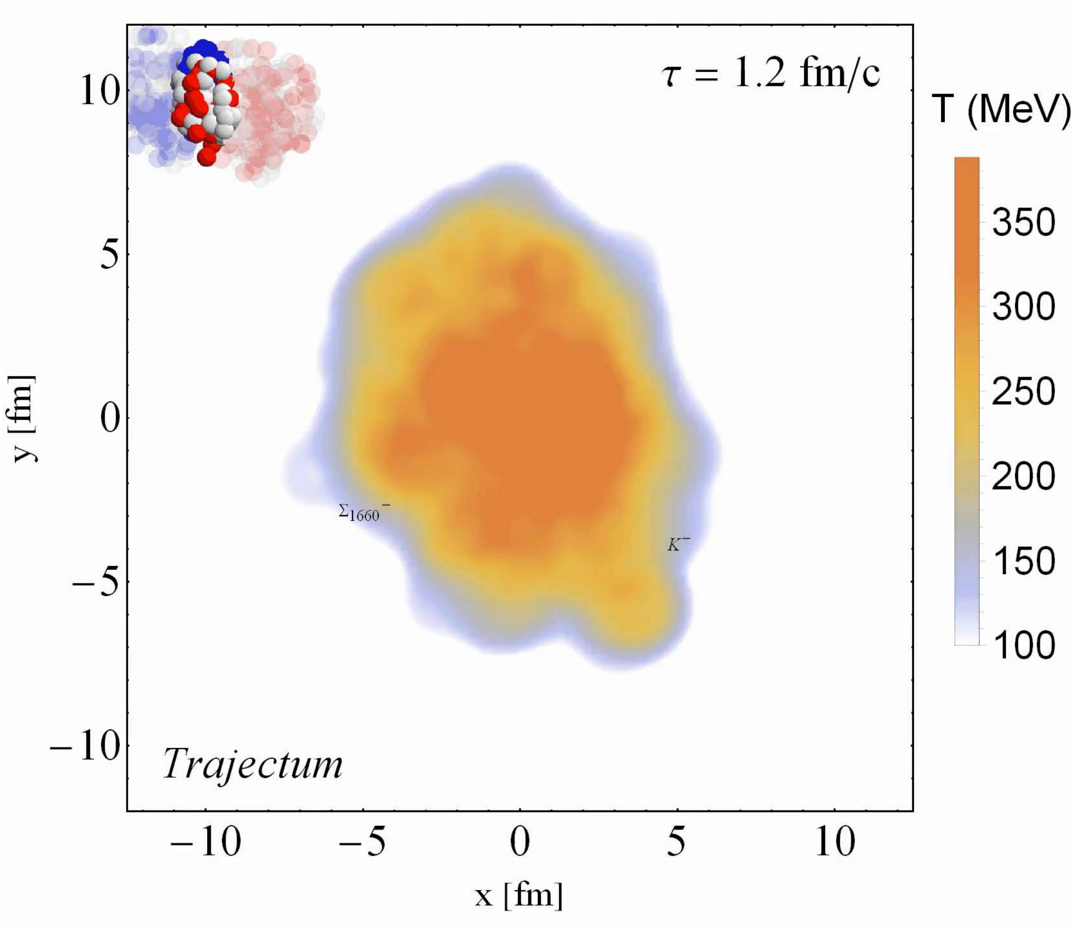


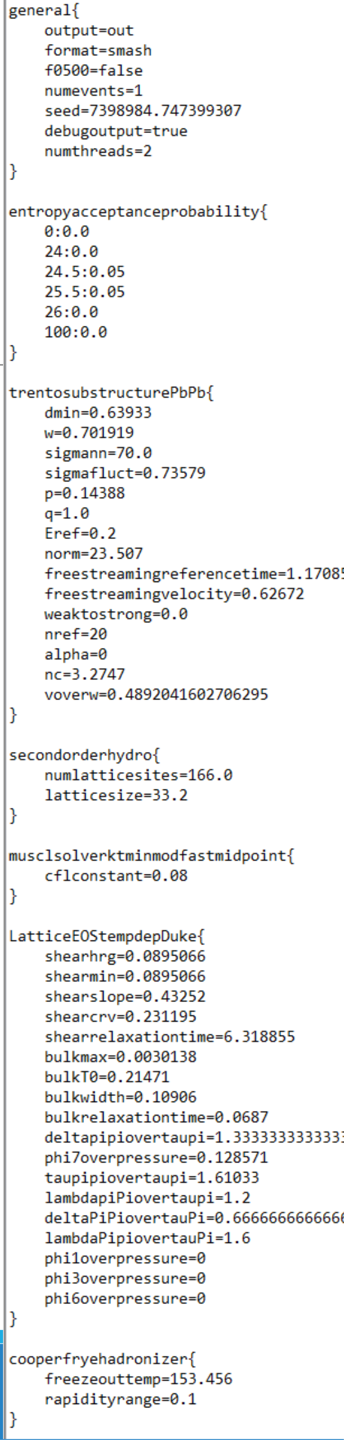
Jonah Bernhard, Scott Moreland and Steffen Bass, Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma (2019)

Trajectum



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





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

entropyacceptanceprobability{
    0:0.0
    24:0.0
    24.5:0.05
    25.5:0.05
    26:0.0
    100:0.0
}

trentosubstructurePbPb{
    dmin=0.63933
    w=0.701919
    sigmann=70.0
    sigmafluct=0.73579
    p=0.14388
    q=1.0
    Eref=0.2
    norm=23.507
    freestreamingreferencetime=1.1708
    freestreamingvelocity=0.62672
    weaktostrong=0.0
    nref=20
    alpha=0
    nc=3.2747
    voverw=0.4892041602706295
}

secondorderhydro{
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    latticesize=33.2
}

musclsolverktminmodfastmidpoint{
    cflconstant=0.08
}

LatticeEOStempdepDuke{
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    shearmin=0.0895066
    shearslope=0.43252
    shearcrv=0.231195
    shearrelaxationtime=6.318855
    bulkmax=0.0030138
    bulkT0=0.21471
    bulkwidth=0.10906
    bulkrelaxationtime=0.0687
    deltapipiovertaupi=1.333333333333
    phi7overpressure=0.128571
    taupipiovertaupi=1.61033
    lambdapiPiovertaupi=1.2
    deltaPiPiovertauPi=0.66666666666
    lambdaPipiovertauPi=1.6
    phi1overpressure=0
    phi3overpressure=0
    phi6overpressure=0
}

cooperfryehadronizer{
    freezeouttemp=153.456
    rapidityrange=0.1
}
```
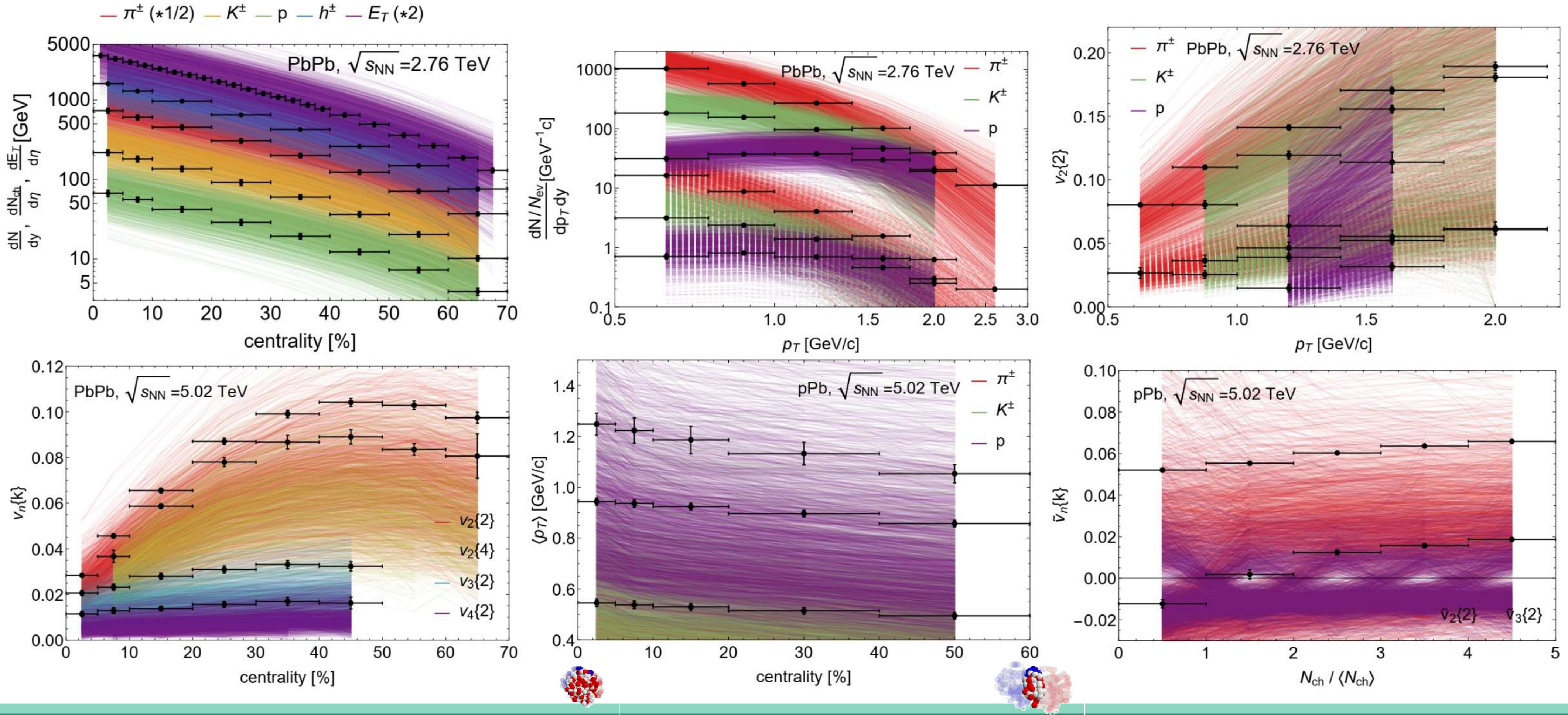

http://sites.google.com/view/govertnijs/trajectum
http://wilkevanderschee.nl/trajectum

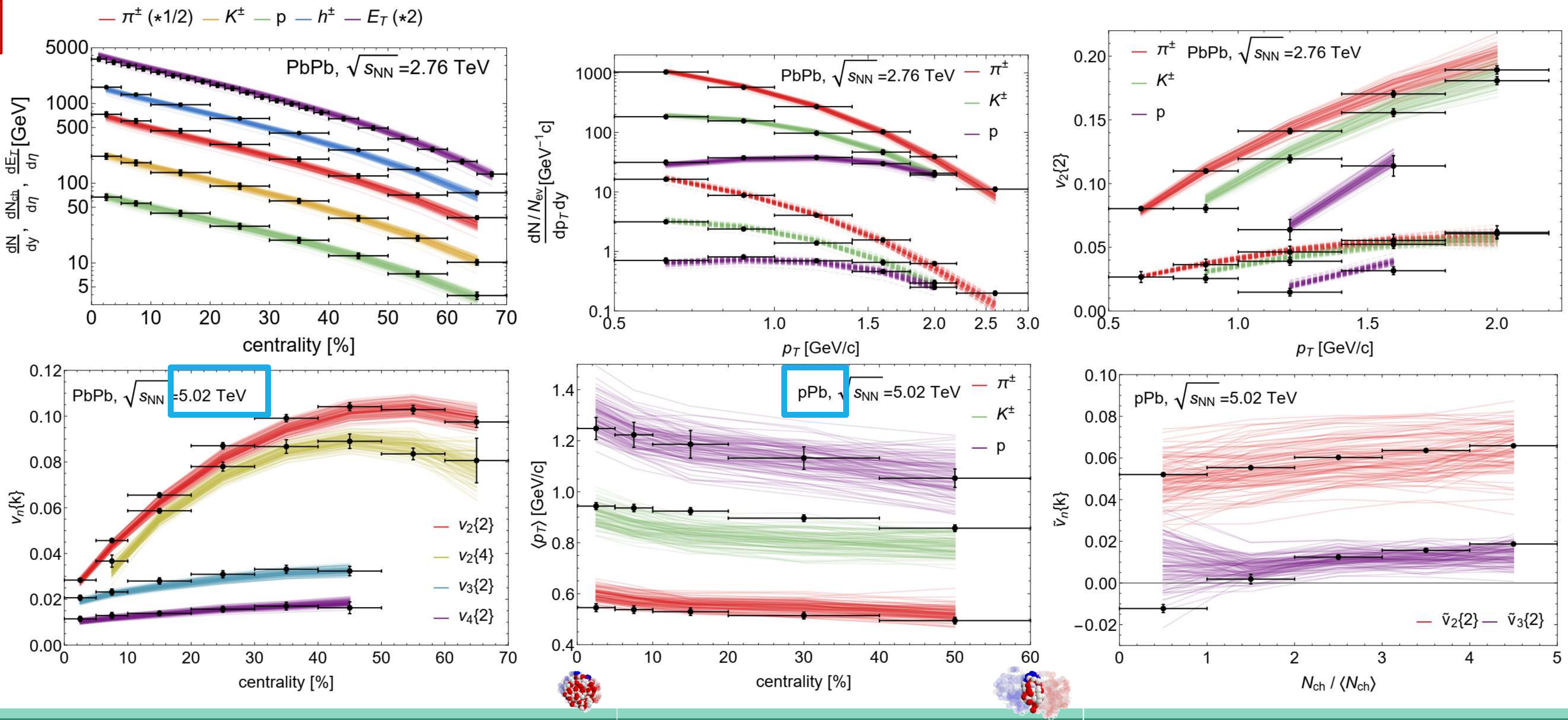
Prior



Experimental observables: *a wealth of data*

1. Yields, spectra, identified $v_n\{2\}$ versus p_T, *p*Pb and PbPb (514 datapoints)
2. First study with a comprehensive analysis including **p_T-differential observables**

Posterior



Experimental observables: *a wealth of data*

1. Yields, spectra, identified $v_n\{2\}$ versus p_T, *p*Pb and PbPb (514 datapoints)
2. First study with a comprehensive analysis including **p_T-differential observables**

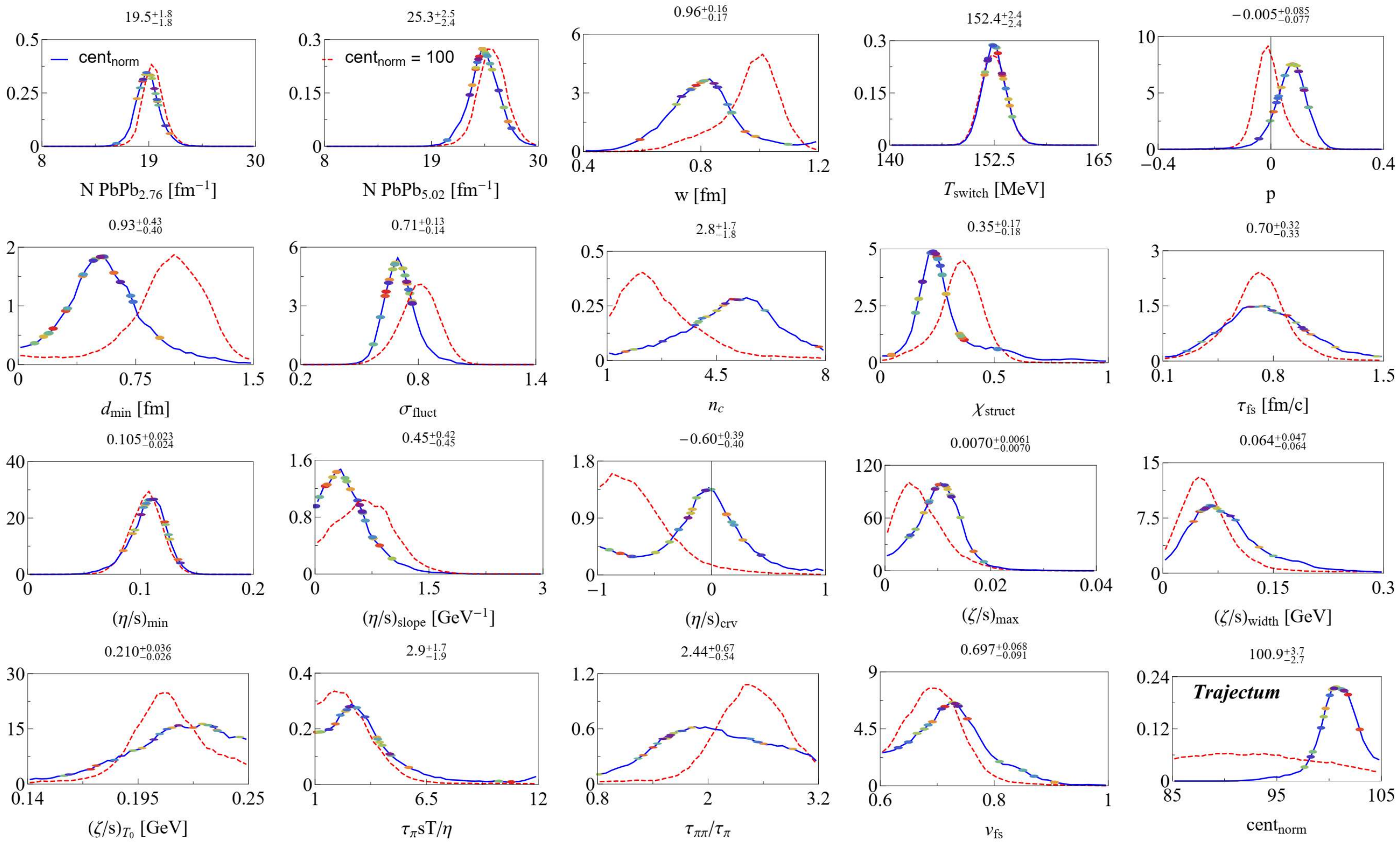
Posterior distributions

1. Dashed: standard *cent*$_{\text{norm}}$
   - Emulation effects for *cent*$_{\text{norm}}$ itself
2. Solid: posterior distributions
   - More accurate than previously

Also indicated: 20 randomly drawn points

-> allows for systematic uncertainties

3. This work: take MAP



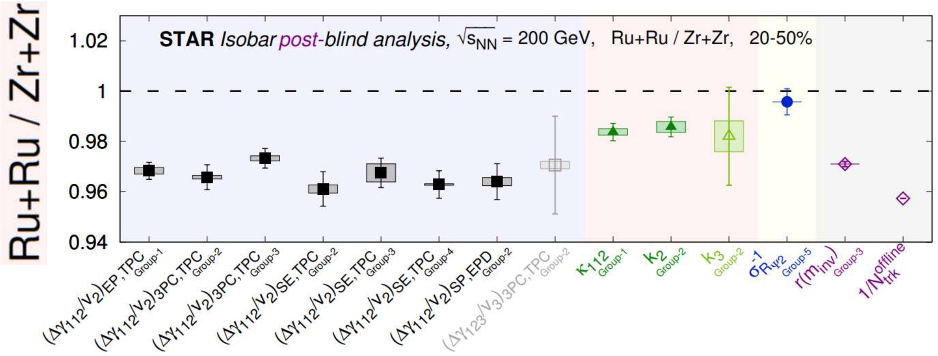
Govert Nijs, WS, Predictions and postdictions for relativistic lead and oxygen collisions with Trajectum (2021)

Isobar collisions at STAR

Varying the magnetic field

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

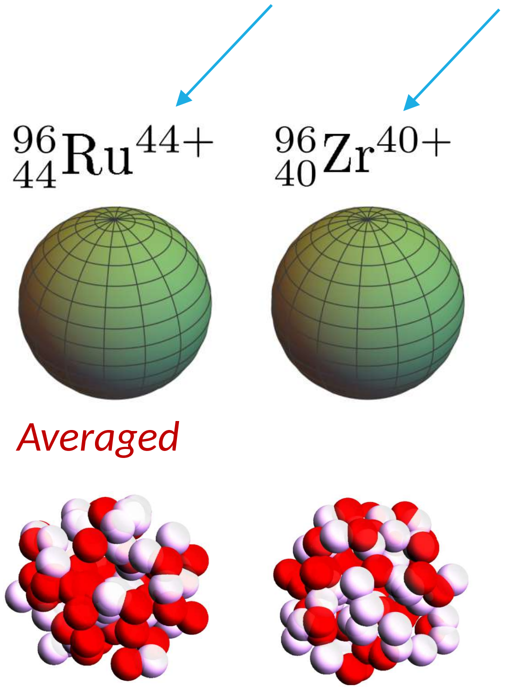
- Ruthenium generates a 10% larger magnetic field
- Ideal set-up to suppress background and detect Chiral Magnetic Effect (CME)
- Very precise blinded analysis by STAR:



CME-like

No CME

Unfortunately (?), no CME detected

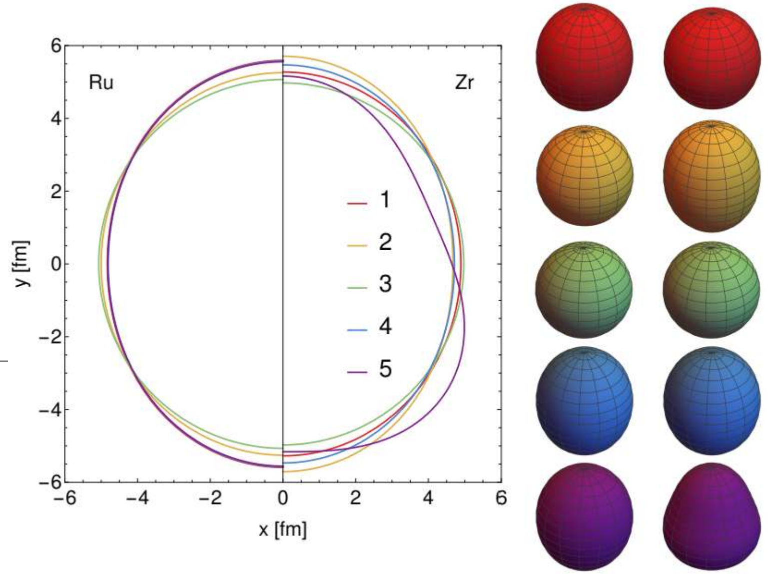


Averaged

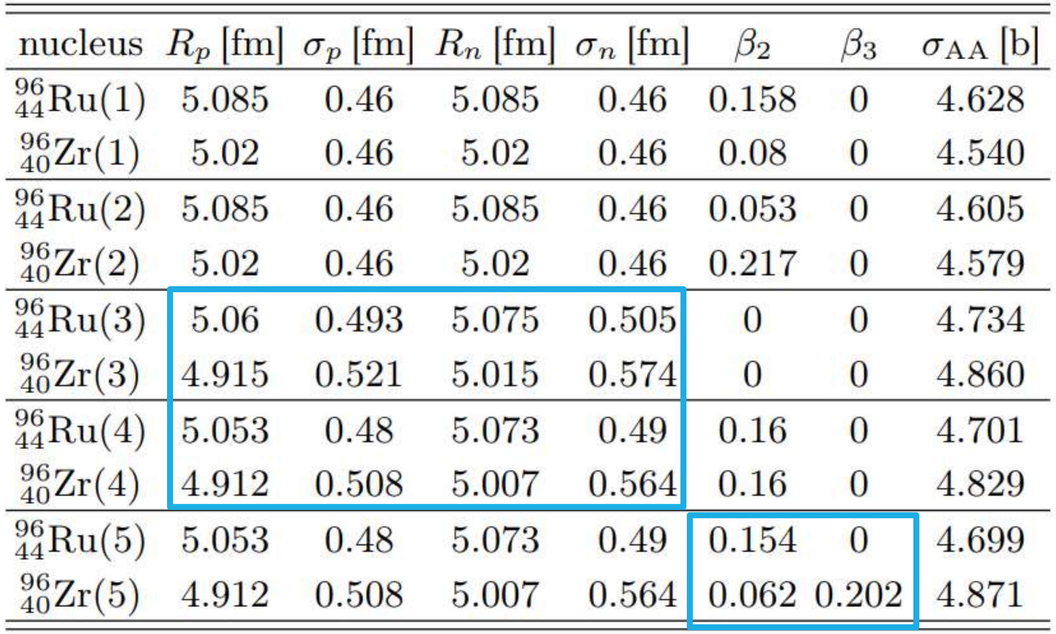
Fluctuating (realistic)

STAR, Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR Collaboration at RHIC

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)

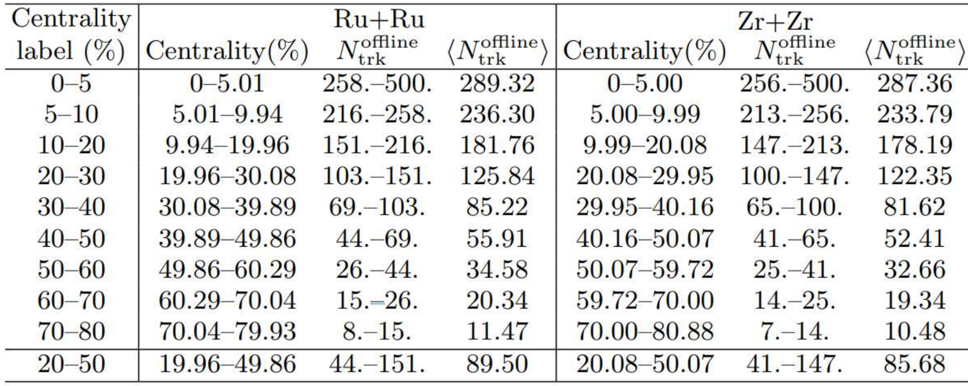
For each case we run 0.5M collisions except for case 5 (5M), 14M in total.

Isobar collisions at STAR - Multiplicity

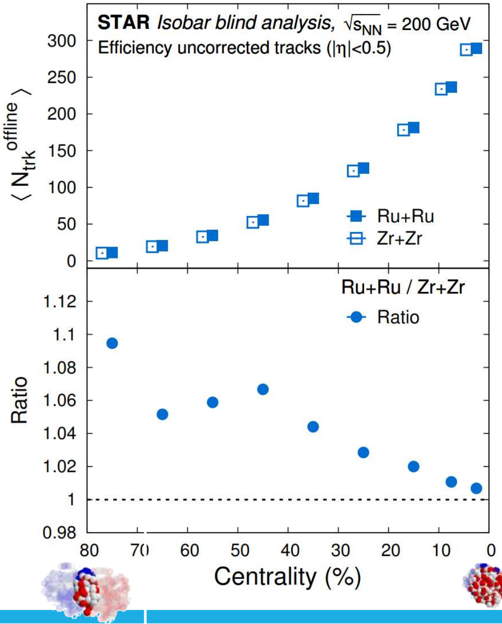
Precision and non-conventional definition of centrality

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

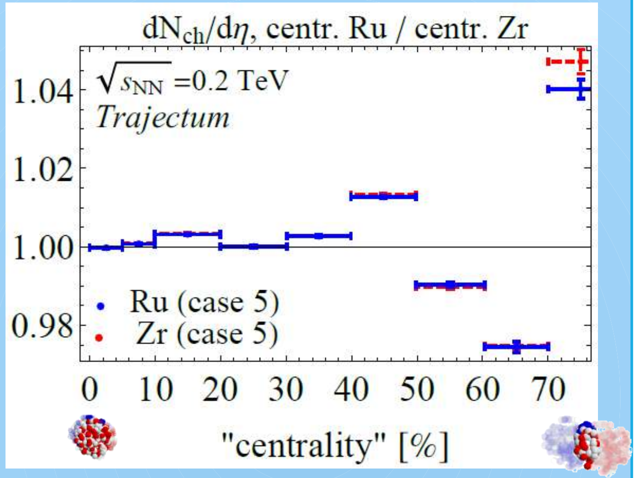
- Especially important for multiplicity (~7% effect)
- Hardly significant for other observables (<0.5% for v_2)

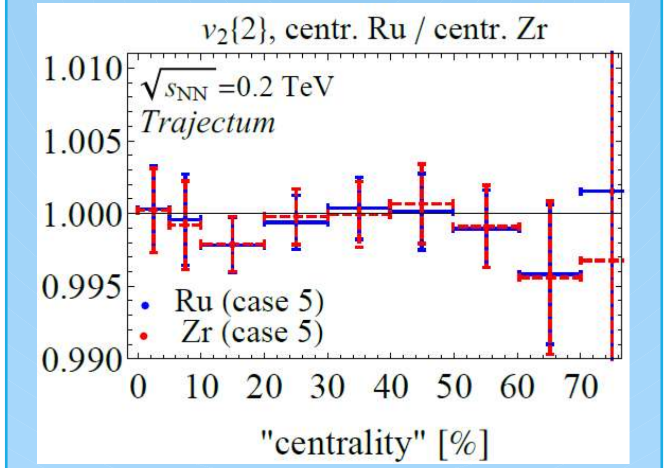


Centrality label (%)	Ru+Ru Centrality(%)	Ru+Ru $N_{\mathrm{trk}}^{\mathrm{offline}}$	Ru+Ru $\langle N_{\mathrm{trk}}^{\mathrm{offline}} \rangle$	Zr+Zr Centrality(%)	Zr+Zr $N_{\mathrm{trk}}^{\mathrm{offline}}$	Zr+Zr $\langle N_{\mathrm{trk}}^{\mathrm{offline}} \rangle$
0–5	0–5.01	258.–500.	289.32	0–5.00	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



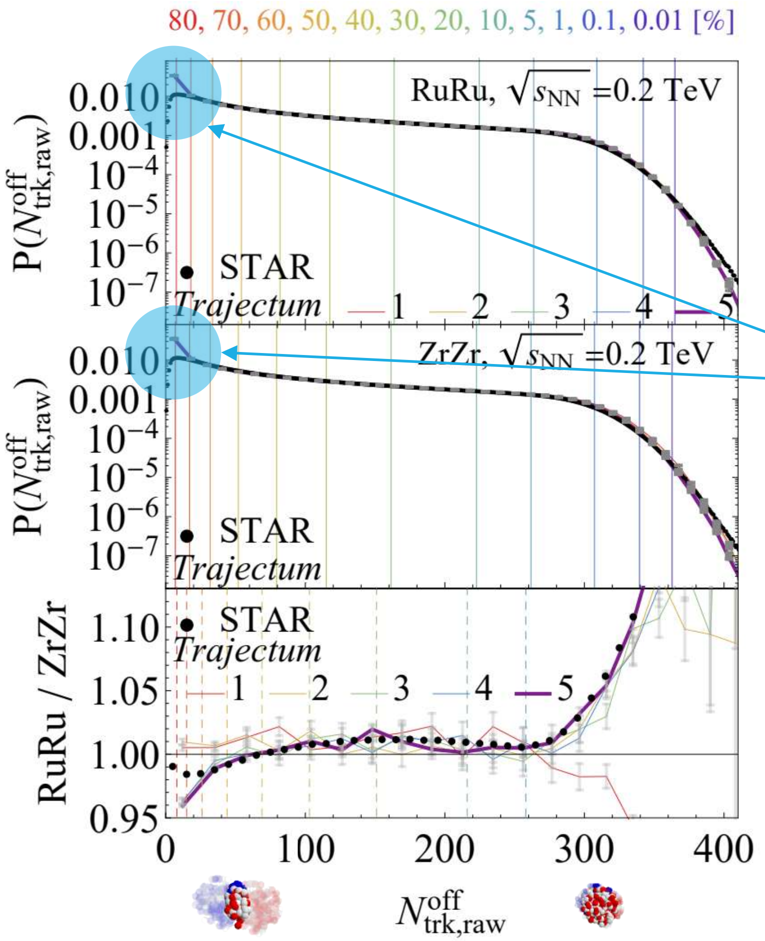
Theory: only change centrality bounds





STAR, Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR Collaboration at RHIC (sept 2021)

Isobar collisions at STAR - Multiplicity



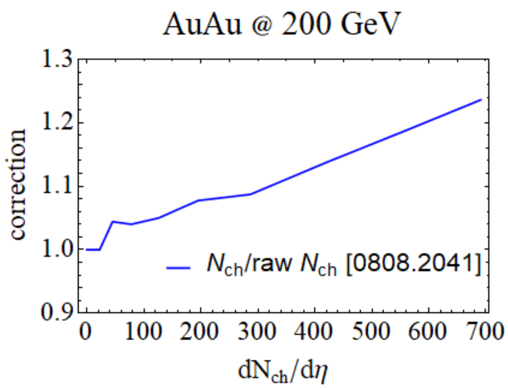
Better to directly look at (raw) data

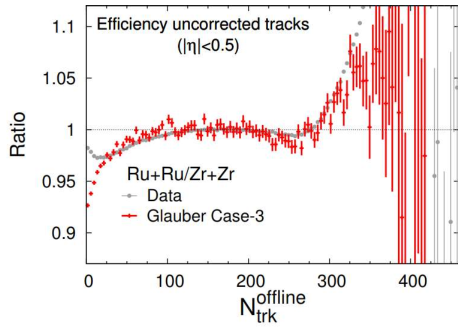
- Experimental subtlety: crucial to correct for detector efficiency
- *Trajectum* subtlety: norm not fitted to RHIC energy: multiply mult by 1.21
- Experiment misses (many) very peripheral collisions: multiply P(N) by 1.31 to correct for this (not for ratio)
- Ratio experiment: normalise both and divide

  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

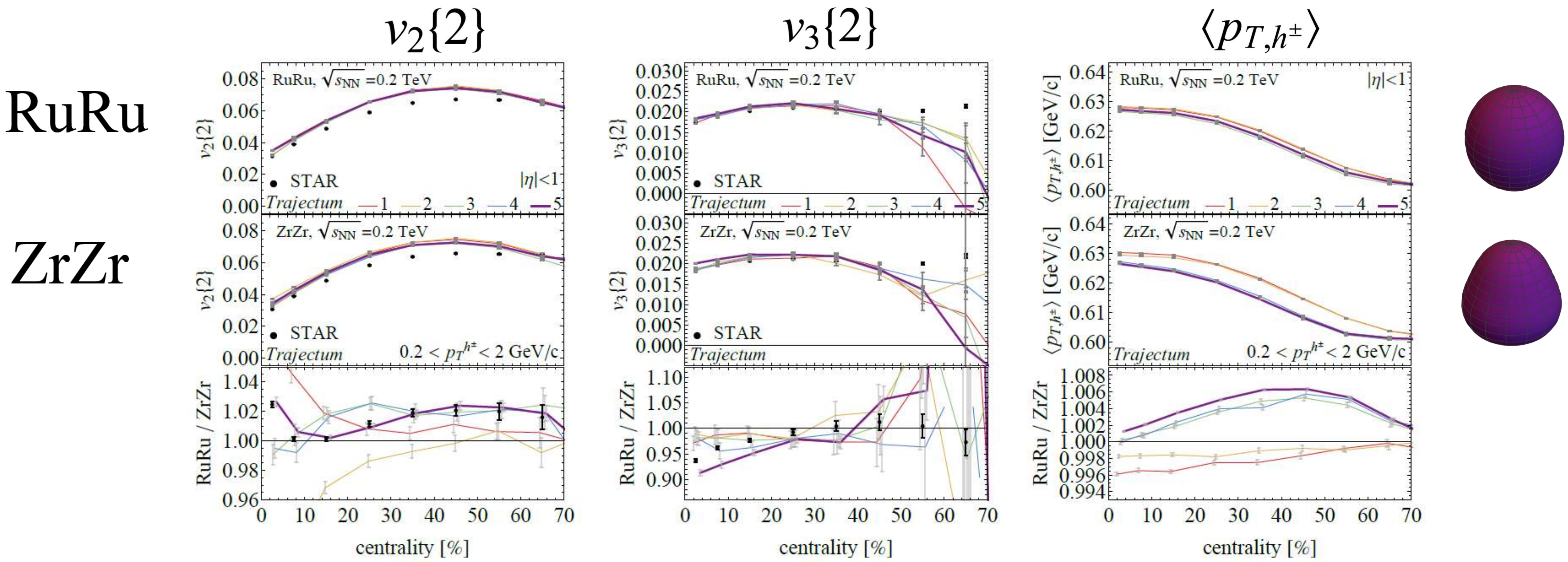




Only case 3, 4 and 5 match well over entire range (neutron-skin)

STAR, Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR Collaboration at RHIC (sept 2021)

Isobar collisions at STAR – Flow and mean p_T



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

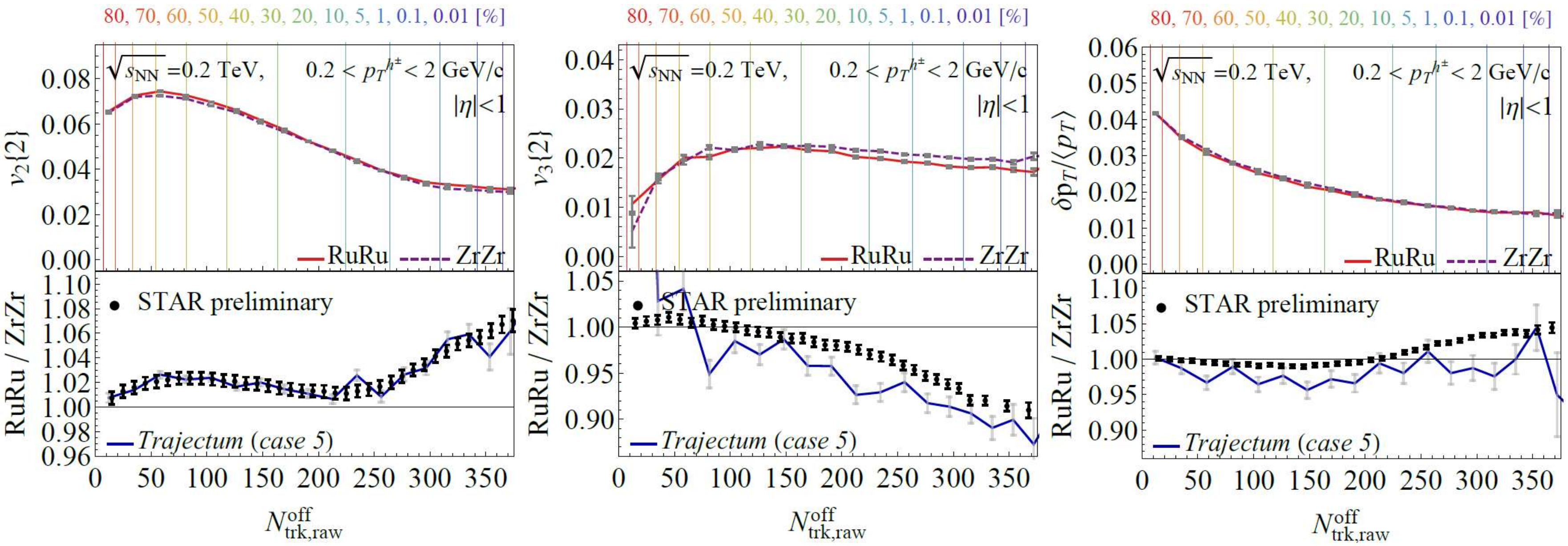
- Excellent fit, especially for v2 ratio, v3 ratio overestimated at central
- Note that *Trajectum* is not fitted to RHIC energies, no absolute agreement
- Mean transverse momentum is a prediction

STAR, Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR Collaboration at RHIC (sept 2021)

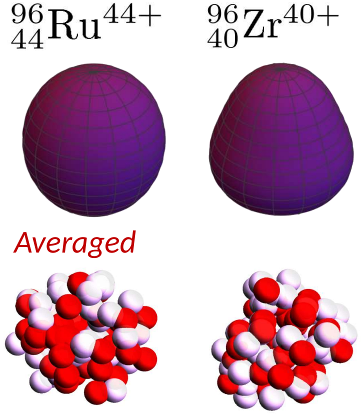
Extremely ultracentral collisions

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



$> \beta_2$ $> \beta_3$



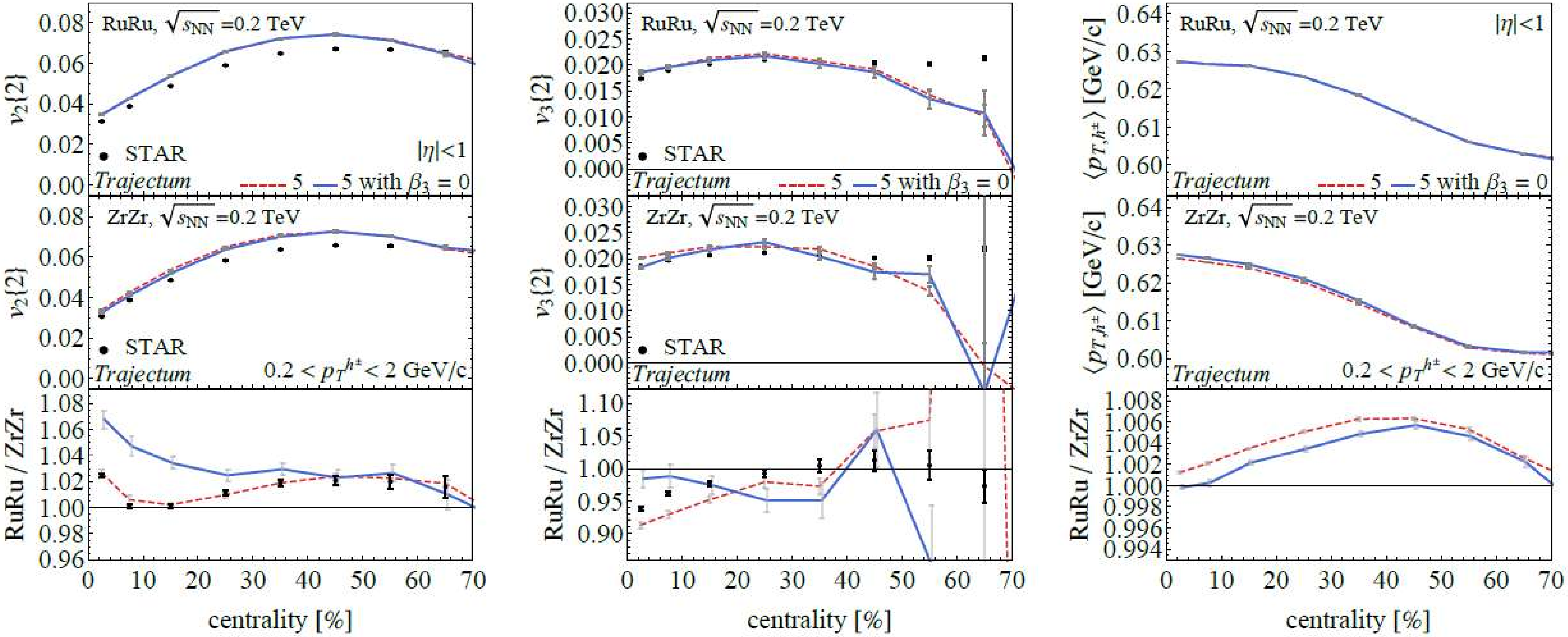
Averaged

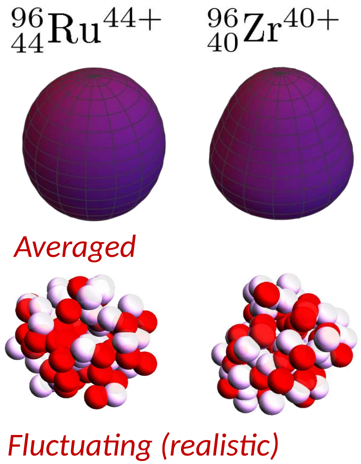
Fluctuating (realistic)

ATHIC2021 talk Chunjian Zhang, https://drupal.star.bnl.gov/STAR/files/ATHIC_Nov_STAR_SBU_ChunjianZhang.pdf

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

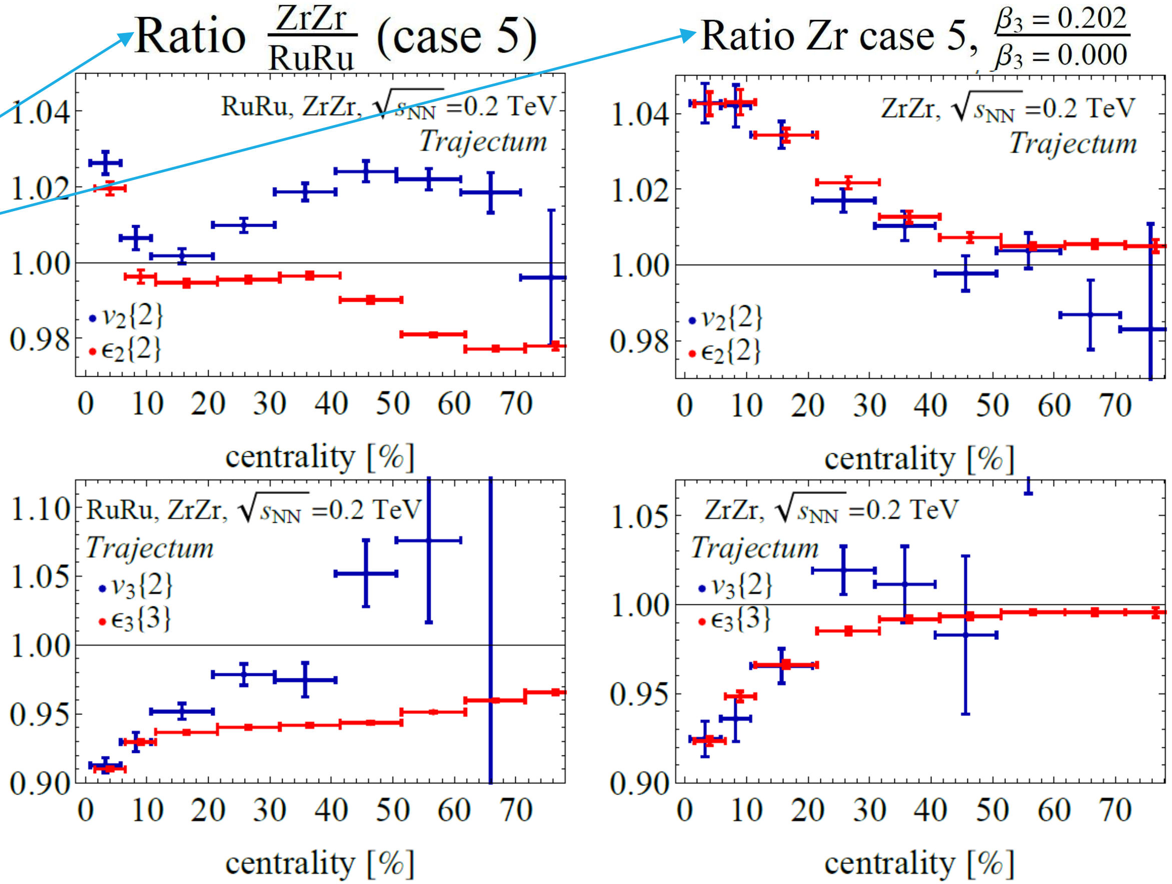
With large sample we can verify the relation

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

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

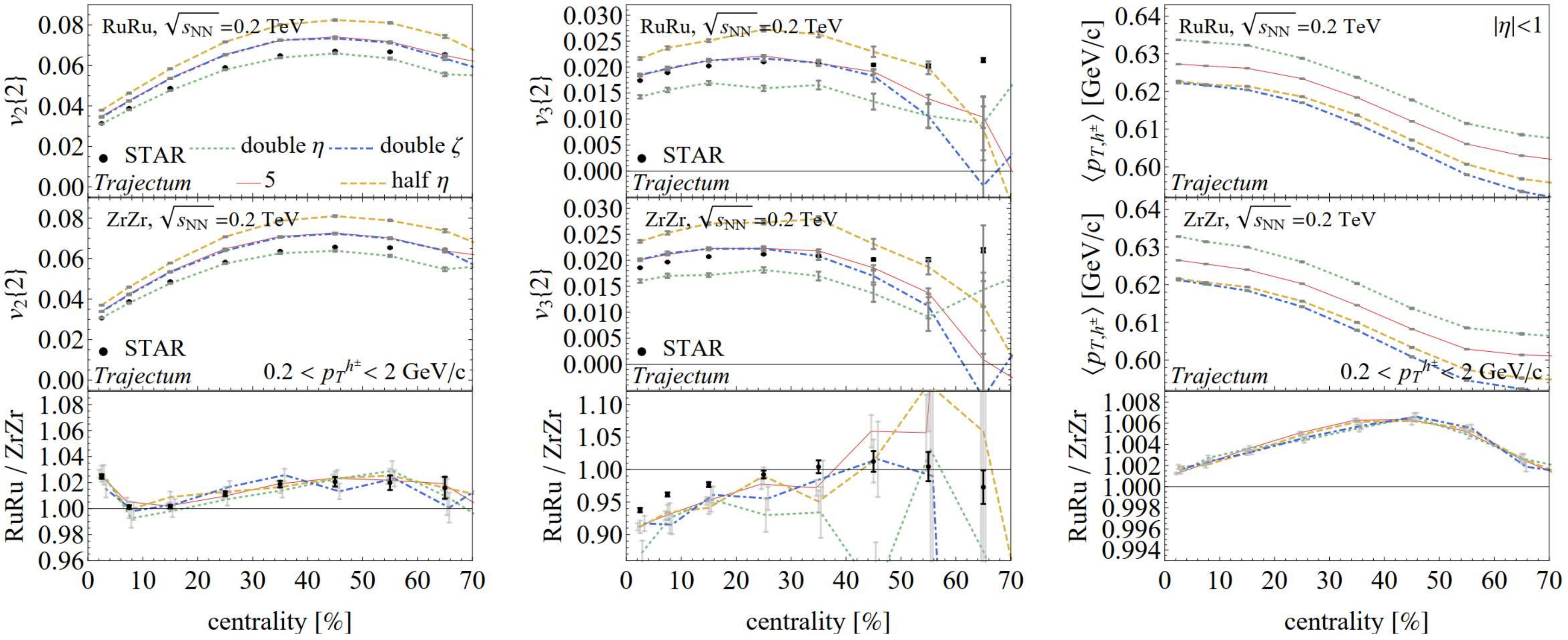
If also size changes etc (Zr vs Ru), it can affect κ and the initial geometry cannot be used

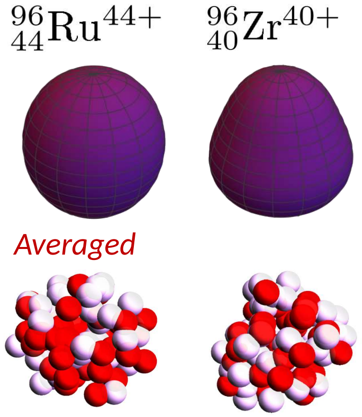
Unfortunate: hydro is expensive…



Effect of viscosity on observables

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?

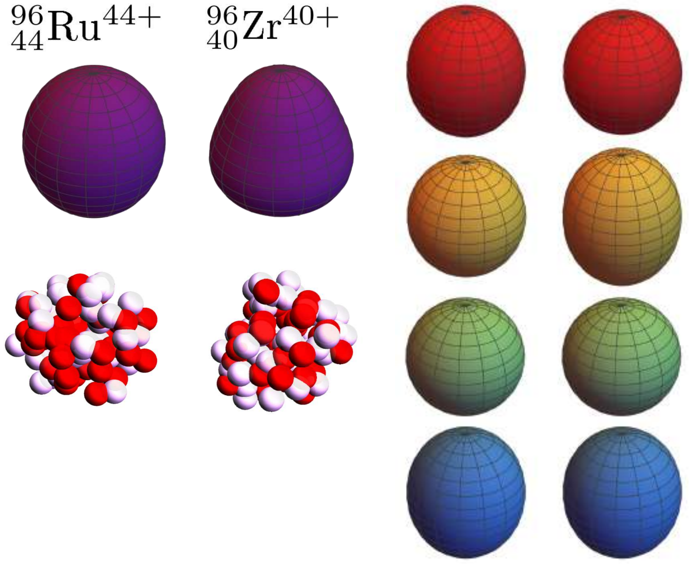




Averaged

Fluctuating (realistic)

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 magnetic effects

- First things first: understanding nuclear structure. Interesting in itself (!), see also neutron stars
- Trajectum done without 3+1D or baryon number…
- Isobars still ideal setting to probe magnetic effect, but will take time to have theory at required precision

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[1] Hao-jie Xua, Hanlin Lib, Xiaobao Wanga, Caiwan Shena and Fuqiang Wang, Determine the neutron skin type by relativistic isobaric collisions (2021)