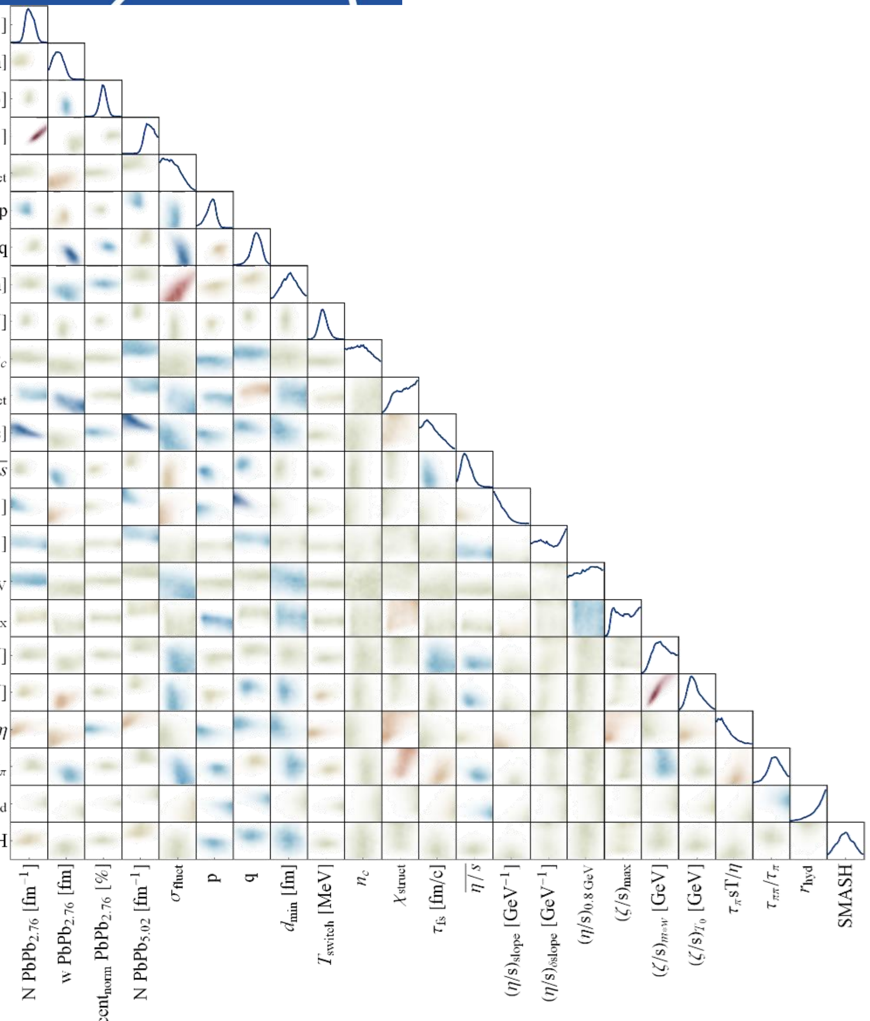
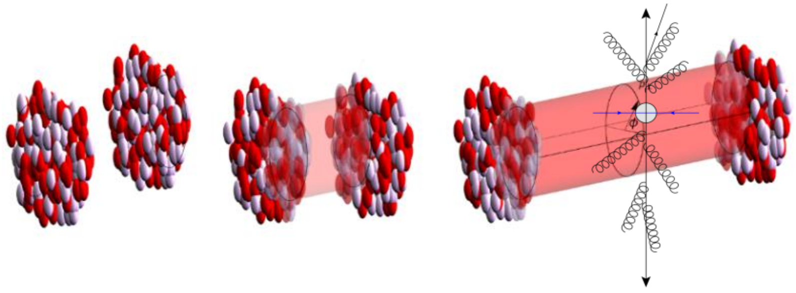


Nuclear structure imaging via hydrodynamics

Towards precision physics with global analyses

2112.13771, 2206.13522 (PRL) and to appear with Govert Nijs and Giuliano Giacalone



Wilke van der Schee
INT, Seattle

6 February 2023

Outline

Heavy ion collisions, hydrodynamics and nuclear structure

- Shape of nuclei and nucleons is important (!)
- Often subtle effects: bringing heavy ion collision to *percent level science*

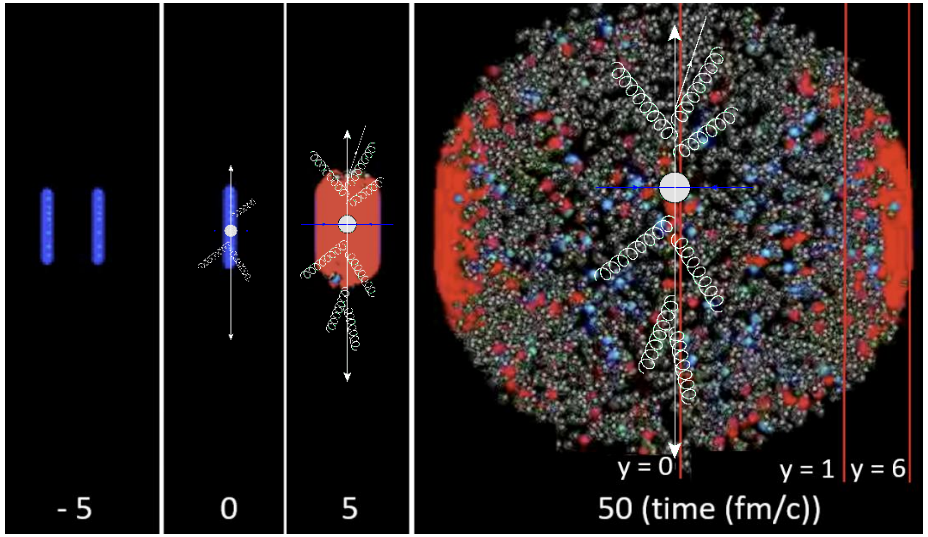
Three parts:

1. Exciting results from STAR isobar run: ^{96}Zr and ^{96}Ru
2. New results on the neutron skin of ^{208}Pb
3. New results on comparing ^{20}Ne and ^{16}Oat LHC energies

CERN accelerator complex

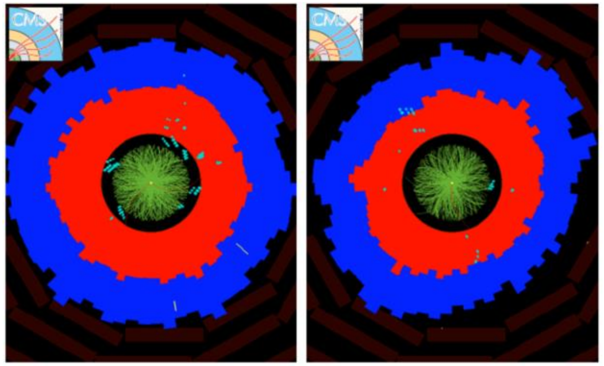
Quark-gluon plasma is strongly coupled

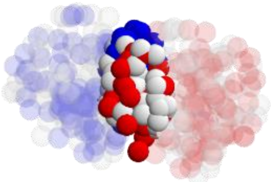
1. Initial stage - QGP - hadronic phase

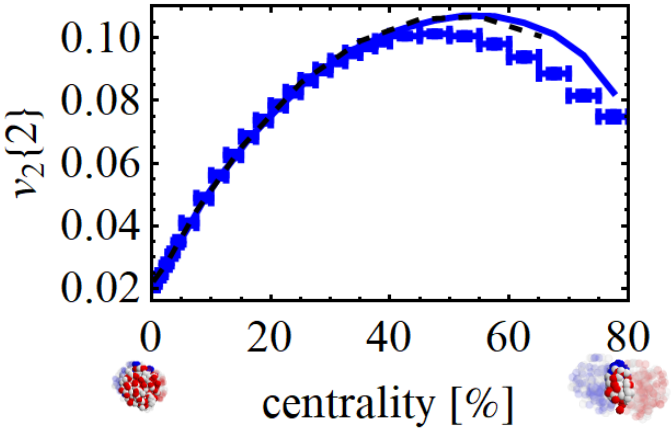


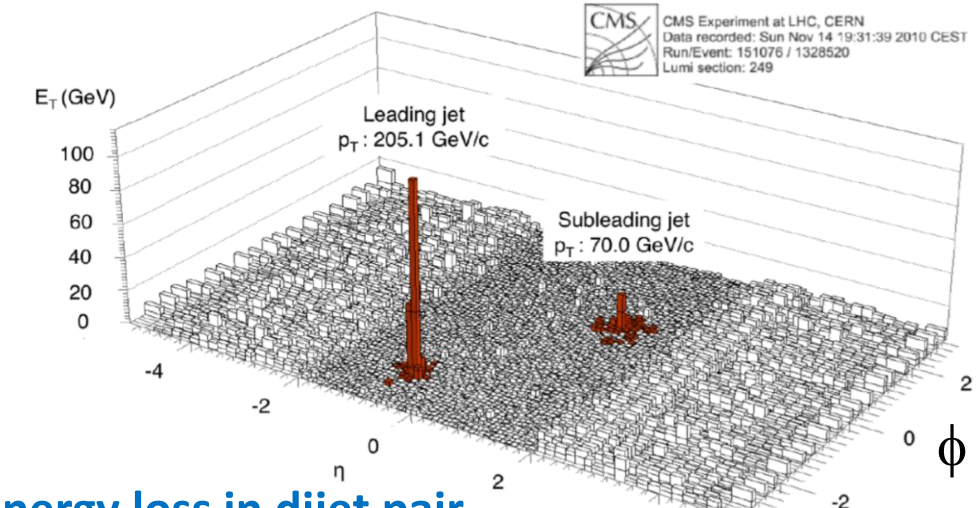
2. Anisotropic/elliptic flow (v_2)

Small viscosity: strong coupling



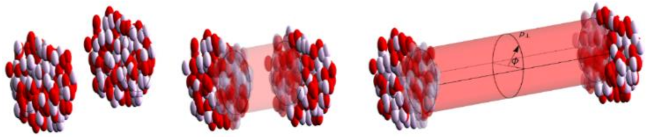






3. Jet energy loss in dijet pair

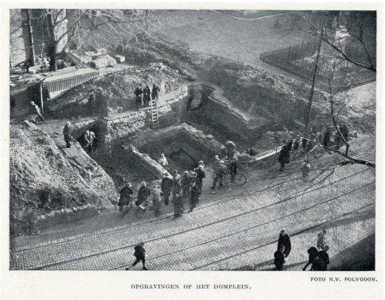
Standard model of heavy ion collisions



(# parameters)

Trajectum

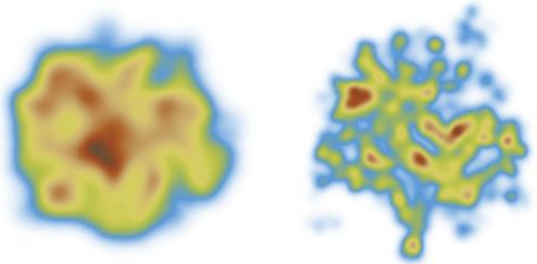
- New public heavy ion code
- Originally Utrecht (now MIT/CERN)
- Fast
- Precise (all cuts equal to experiment)
- Scalable



Roman excavations in **Utrecht** in 1929

Initial stage (11)

Subnucleonic structure? (8)

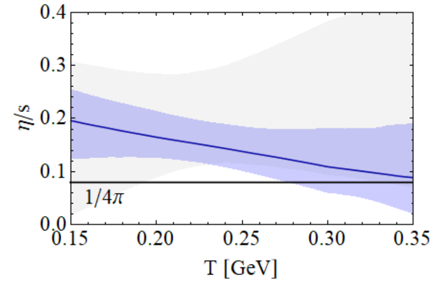


Non-thermal flow? (2)
with hydrodynamised initial stage

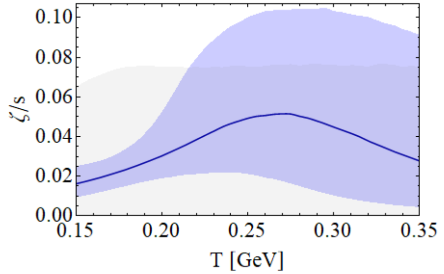
Fluctuations? (1)

Viscous hydrodynamics (9)

Shear viscosity (4)

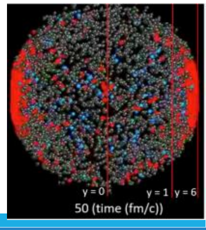


Bulk viscosity (3)



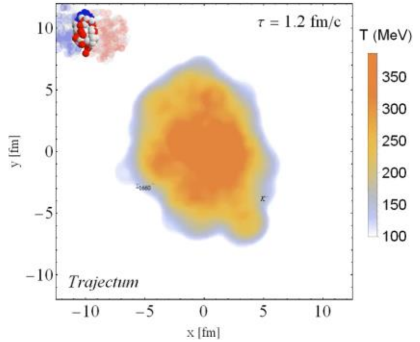
Second order transports: 2

Cascade of hadrons (1)



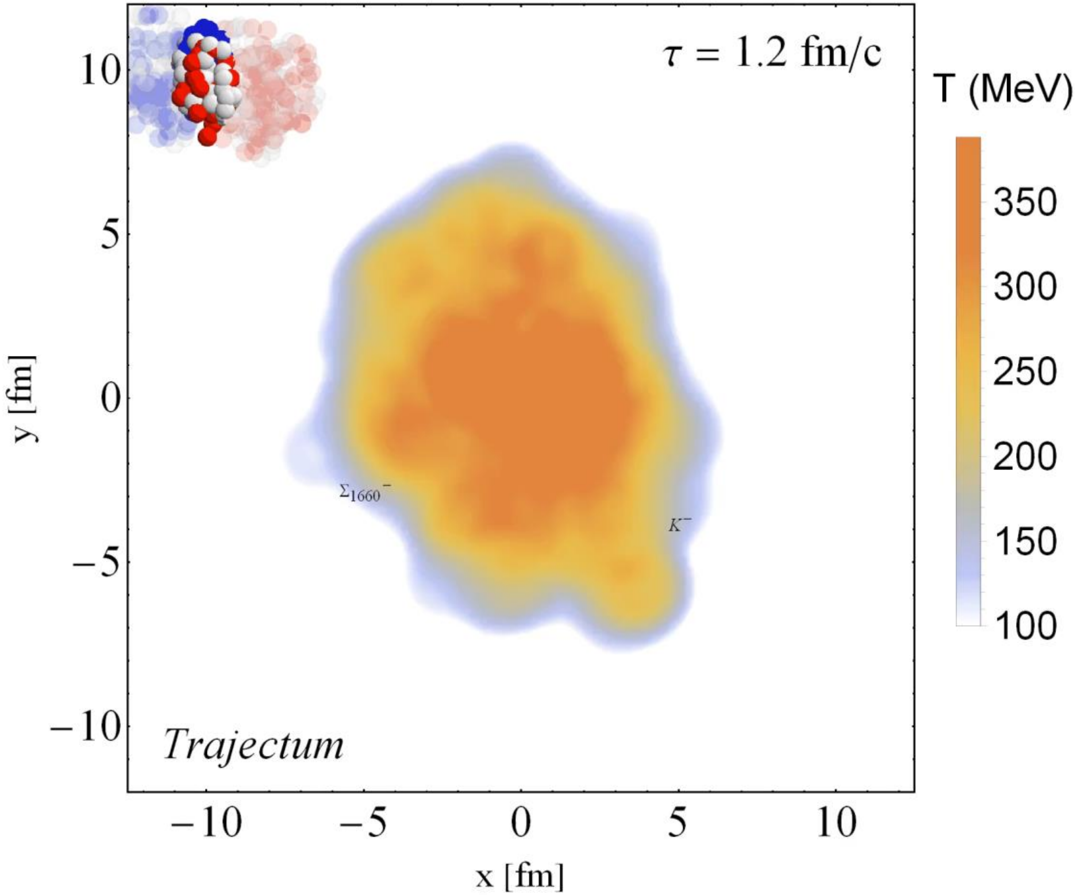
Jonah Bernhard, Scott Moreland and Steffen Bass, Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma (2019)
Govert Nijs, WS, Umut Gursoy and Raimond Snellings, A Bayesian analysis of Heavy Ion Collisions with Trajectum (2020)

Trajectum



1. Quite straightforward to use (see param file, right)

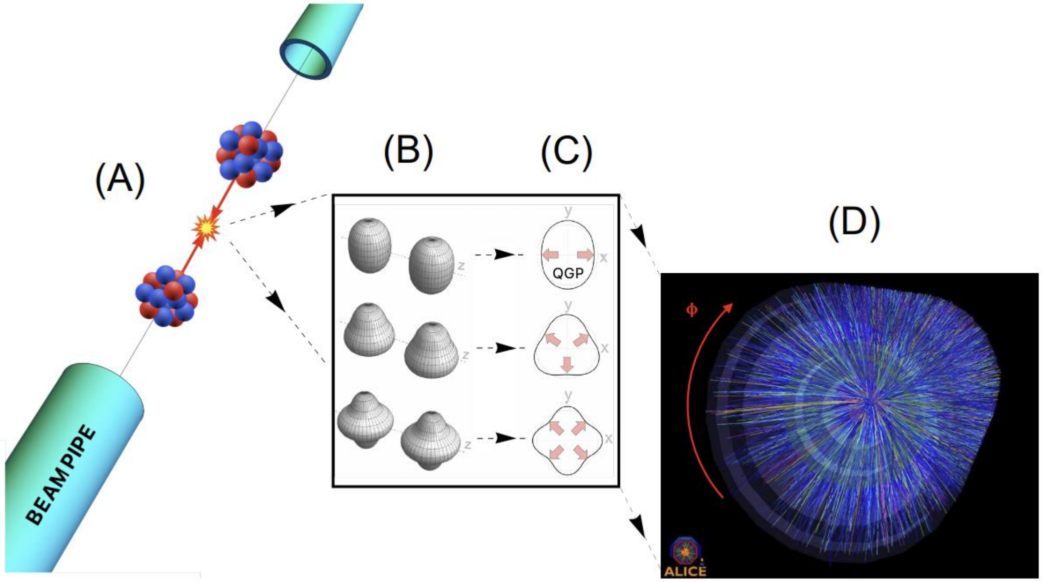
2. Includes analyse routine
   - Parallelised: can analyse unlimited number of events




```
general{
    output=out
    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{
    numlatticesites=166.0
    latticesize=33.2
}

musclsolverktminmodfastmidpoint{
    cflconstant=0.08
}

LatticeEOStempdepDuke{
    shearhrg=0.0895066
    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=1.3333333333333
    phi7overpressure=0.128571
    taupipiovertaupi=1.61033
    lambdapiPiovertaupi=1.2
    deltaPiPiovertauPi=0.6666666666666
    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

The shape of nuclei



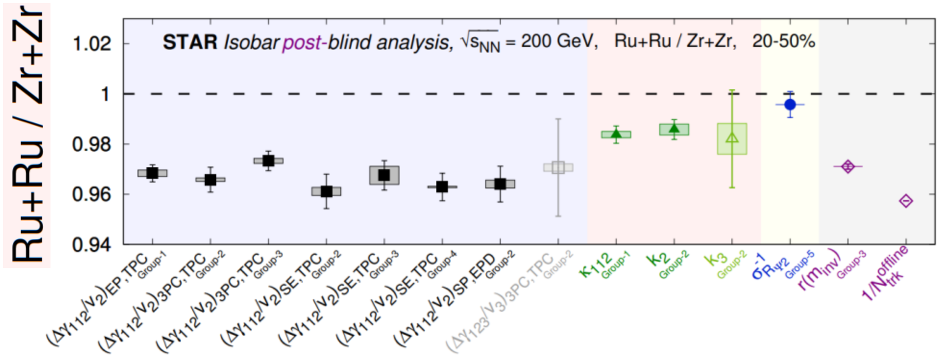
Benjamin Bally, James Daniel Brandenburg, Giuliano Giacalone, Ulrich Heinz, Shengli Huang, Jiangoyng Jia, Dean Lee, Yen-Jie Lee, Wei Li, Constantin Loizides, Matthew Luzum, Govert Nijs, Jacquelyn Noronha-Hostler, Mateusz Ploskon, WS, Bjoern Schenke, Chun Shen, Vittorio Somà, Anthony Timmins, Zhangbu Xu and You Zhou
Imaging the initial condition of heavy-ion collisions and nuclear structure across the nuclide chart (2022)

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:

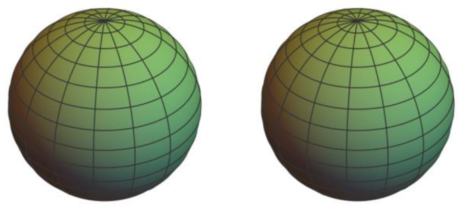


CME-like

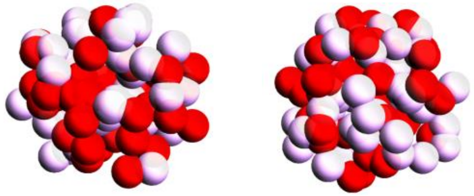
No CME

Unfortunately (?), no CME detected

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



Averaged

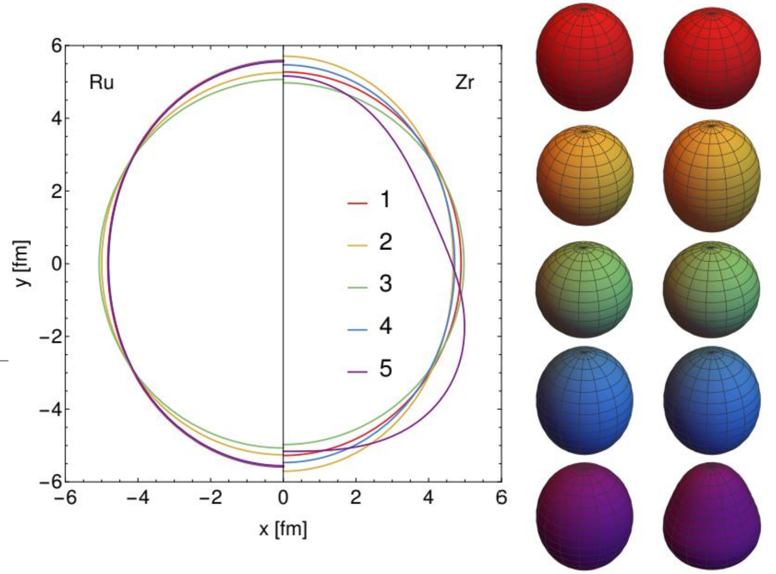


Fluctuating (realistic)

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

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)

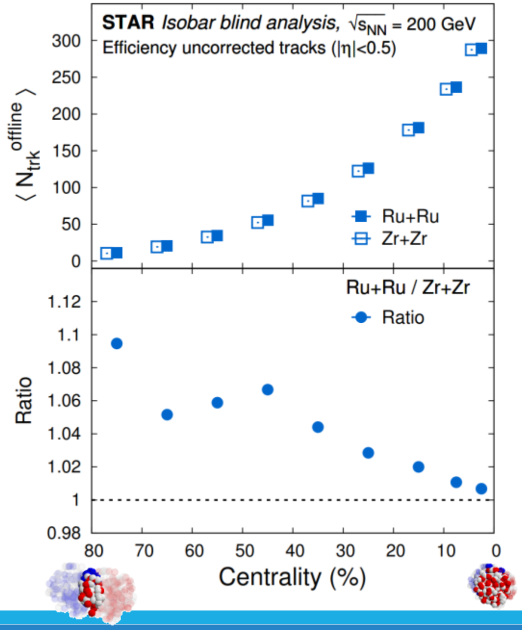
Isobar collisions at STAR - Multiplicity

Precision and non-conventional definition of centrality

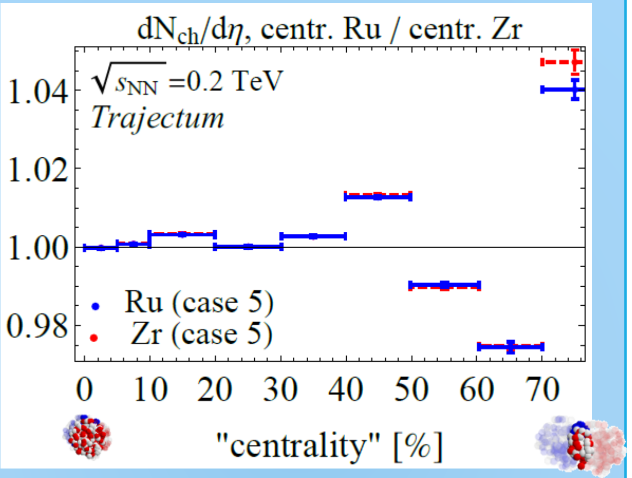
Subtlety in STAR data: "centrality label" is different for Ru and Zr

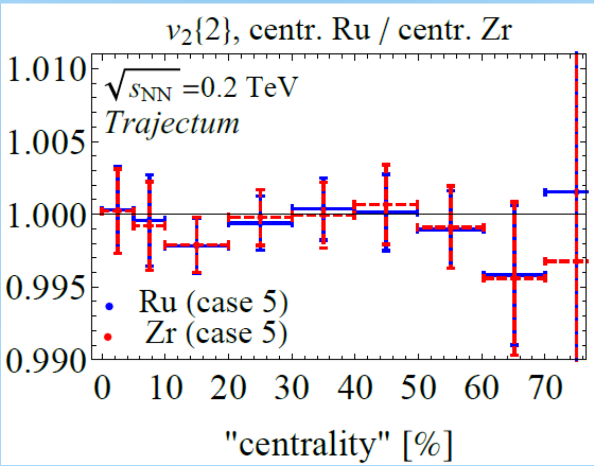
- Especially important for multiplicity (~7% effect)
- Hardly significant for other observables (<0.5% for v_2)

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

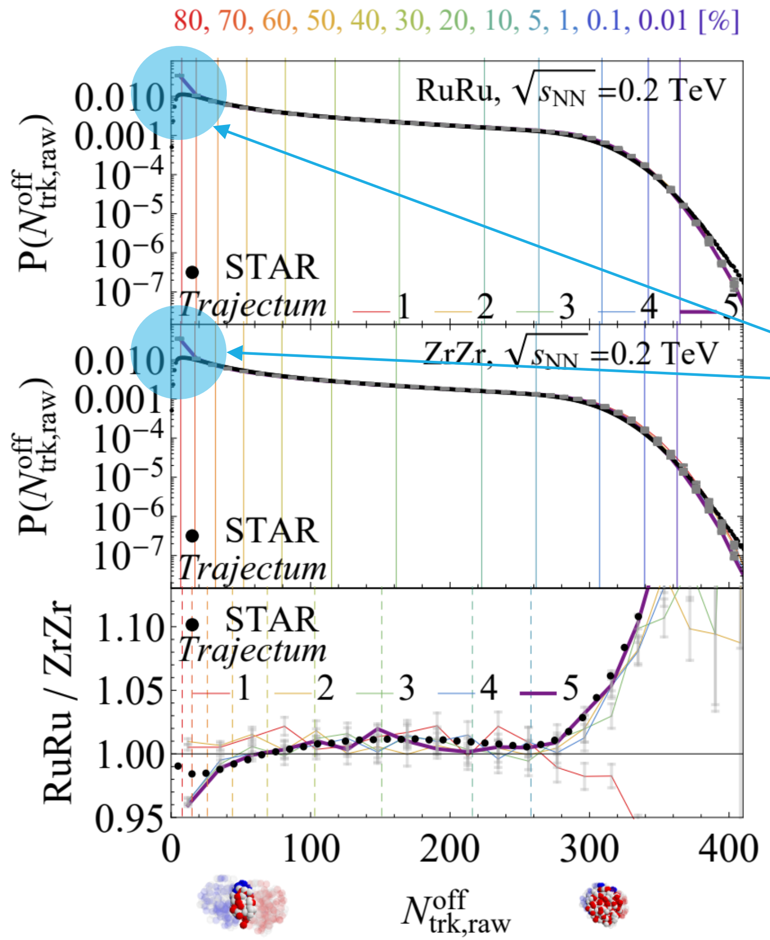


Theory: only change centrality bounds



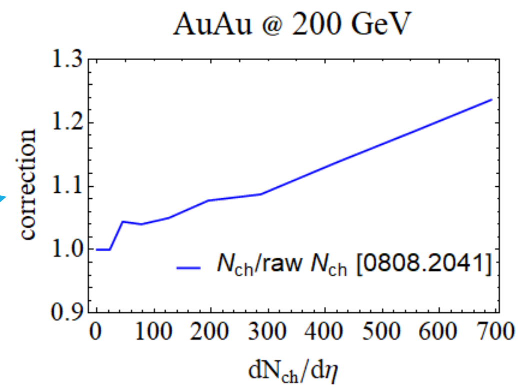


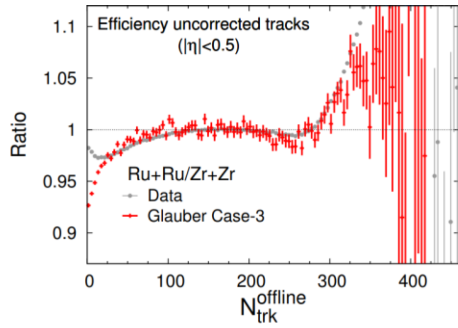
Isobar collisions at STAR - Multiplicity



Better to directly look at (raw) data

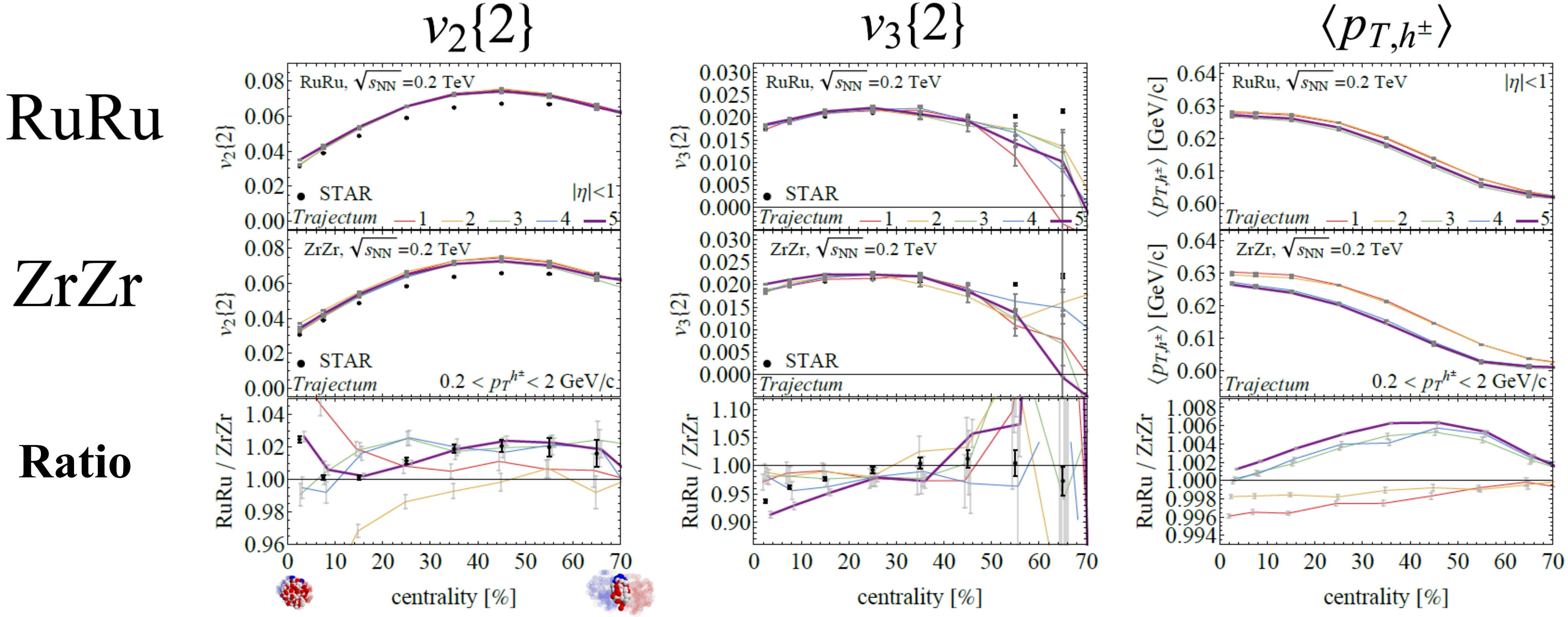
- Experimental subtlety: crucial to correct for detector efficiency
- *Trajectum* subtlety: norm not fitted to RHIC energy: multiply mult by 1.21
- Experiment misses (many) very peripheral collisions: multiply P(N) by 1.31 to correct for this (not for ratio)
- Ratio experiment: normalise both and divide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

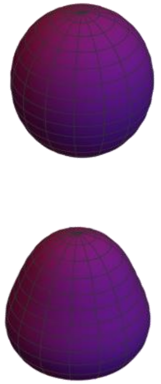




Only case 3, 4 and 5 match well over entire range (neutron-skin)

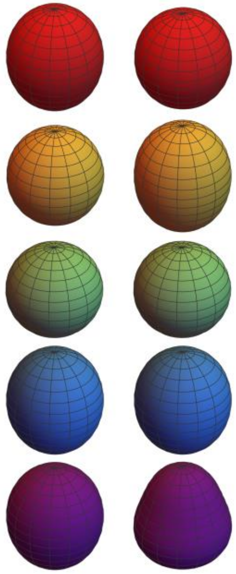
Isobar collisions at STAR – Flow and mean p_T





$^{96}_{44}Ru^{44+}$

$^{96}_{40}Zr^{40+}$



Original motivation was to study Chiral Magnetic Effect (CME, not found…)

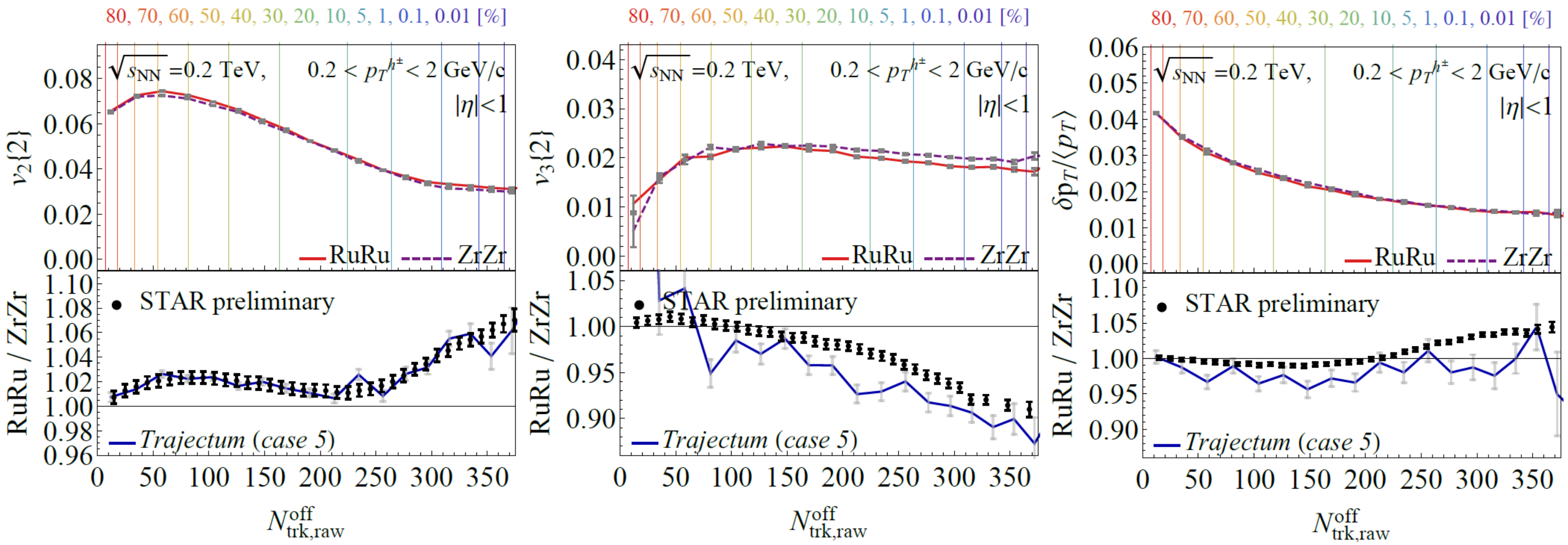
- Turns out that the background is significant, can be studied with **hydro** only
- Note that *Trajectum* is not fitted to RHIC energies, no absolute agreement
- Requires many events, percent level accuracy

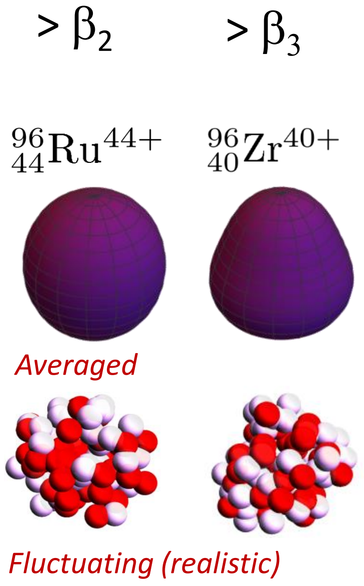
STAR, Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR Collaboration at RHIC (sept 2021)
Govert Nijs and WS, Inferring nuclear structure from heavy isobar collisions using Trajectum (2021)

Extremely ultracentral collisions

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

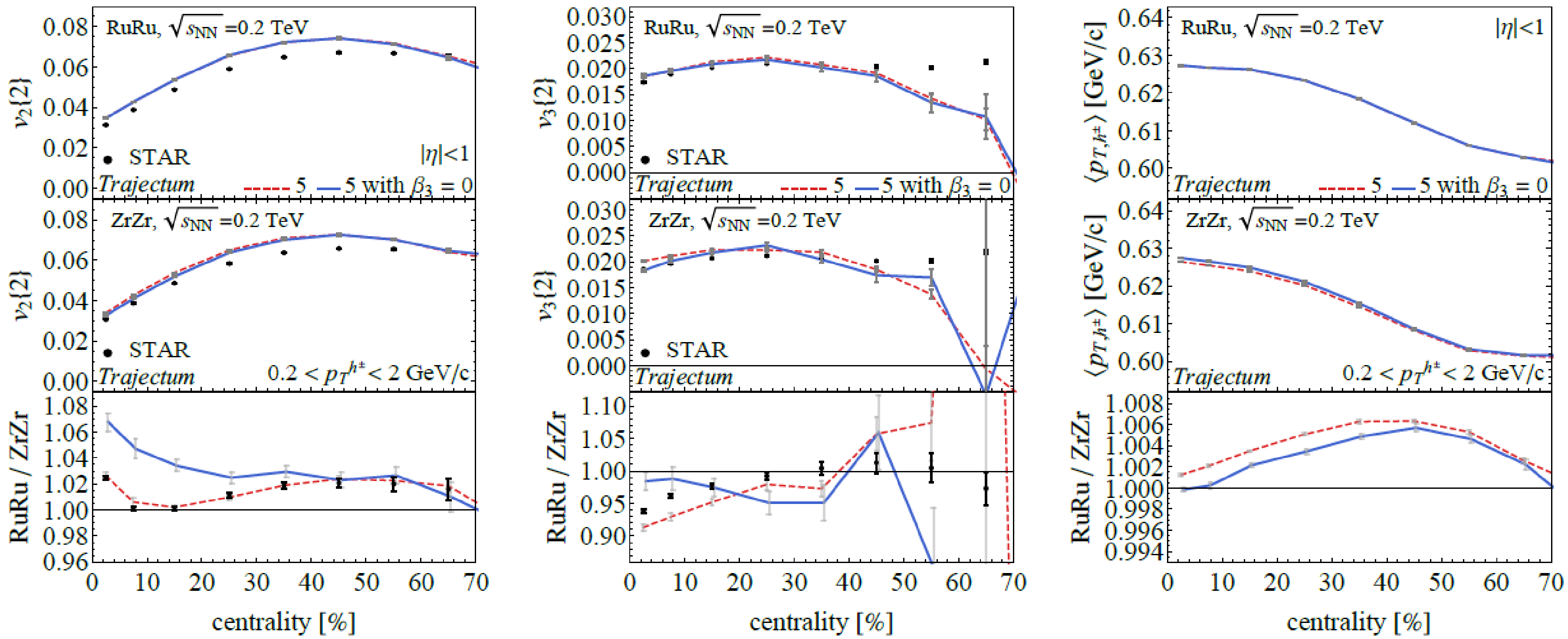
- Excellent match v2, v3 en pt fluct somewhat overpredicted
- Extremely ultracentral is ideal regime to probe nuclear structure (also: better hydro!)



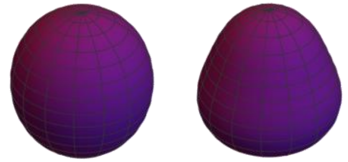


Effect of β_3 on observables

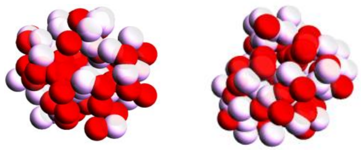
Clear effect on v_3, but also on v_2. Need a (Bayesian) refit of β_2 as well to fit v_2 and v_3?



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



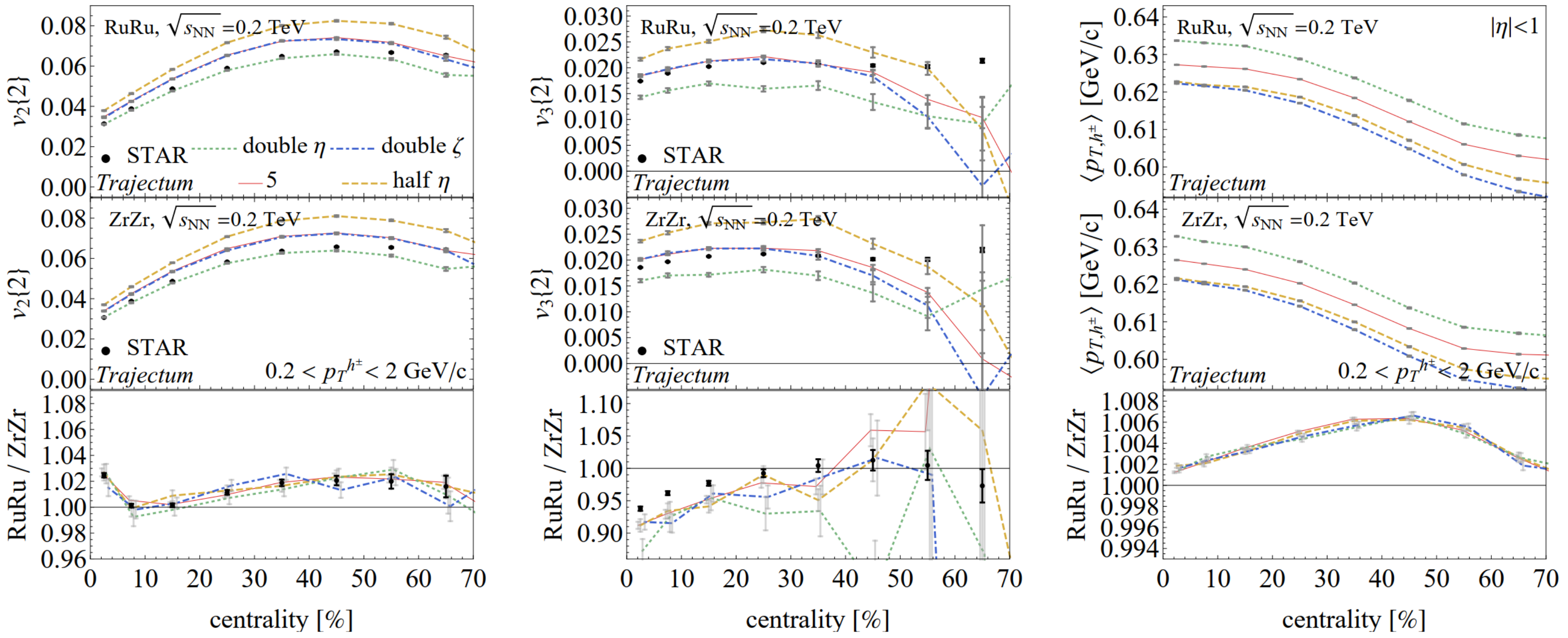
Averaged

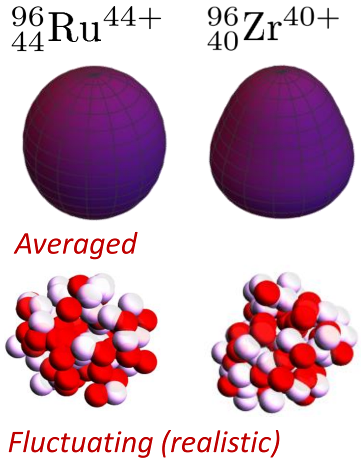


Fluctuating (realistic)

Effect of viscosity on observables

Significant effects, but cancel in the ratio





Initial state predictors

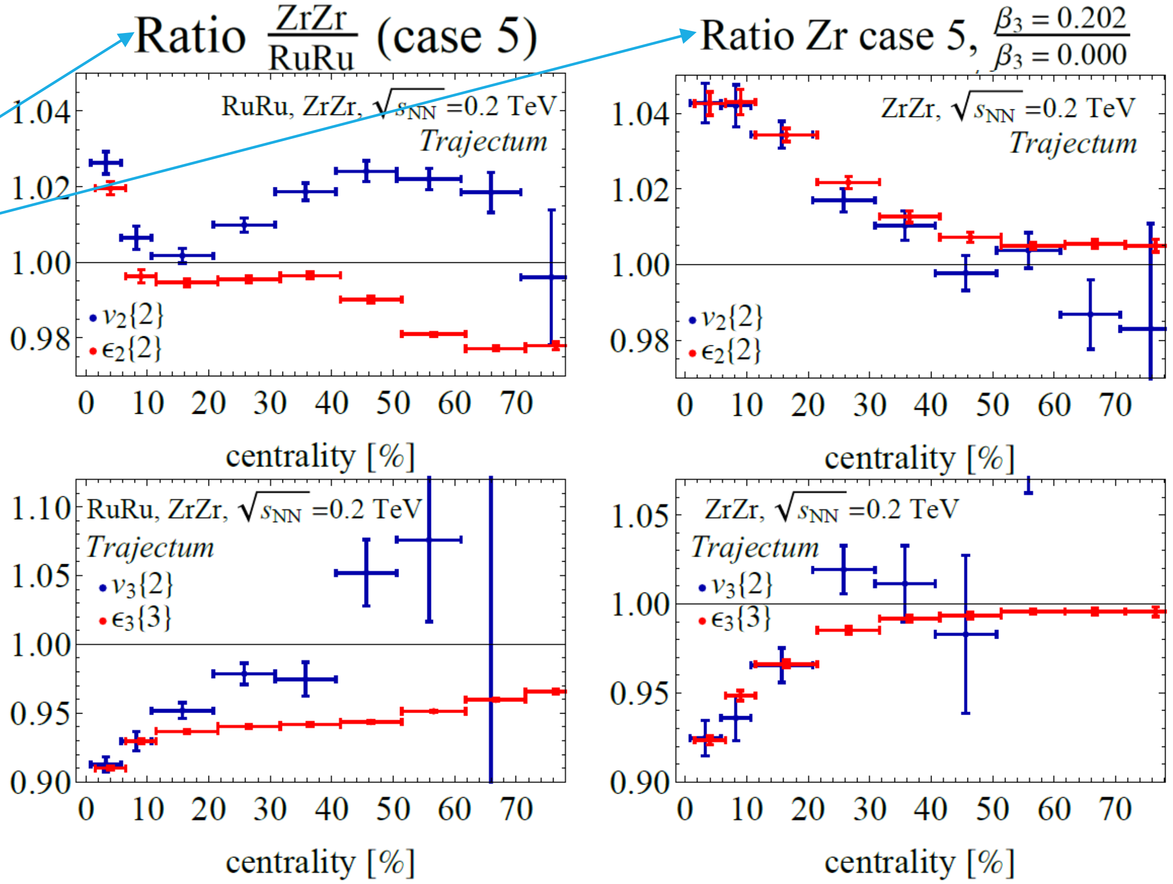
With large sample we can verify the relation

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

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

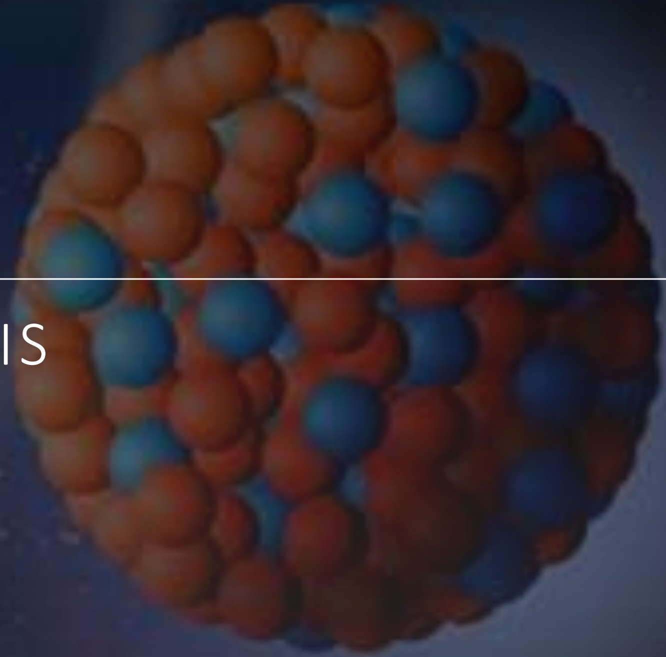
If also size changes etc (Zr vs Ru), it can affect κ and the initial geometry cannot be used

Unfortunate: hydro is expensive…



Neutron skin

WITH A SHORT INTRO ON BAYESIAN ANALYSIS



Bayes theorem:

$$\mathcal{P}(\boldsymbol{x}|\mathbf{y}_{\text{exp}}) = \frac{e^{-\Delta^2/2}}{\sqrt{(2\pi)^n \det(\Sigma(\boldsymbol{x}))}} \mathcal{P}(\boldsymbol{x})$$

$$\text{with} \quad \Delta^2 = (\mathbf{y}(\boldsymbol{x}) - \mathbf{y}_{\text{exp}}) \cdot \Sigma(\boldsymbol{x})^{-1} \cdot (\mathbf{y}(\boldsymbol{x}) - \mathbf{y}_{\text{exp}})$$

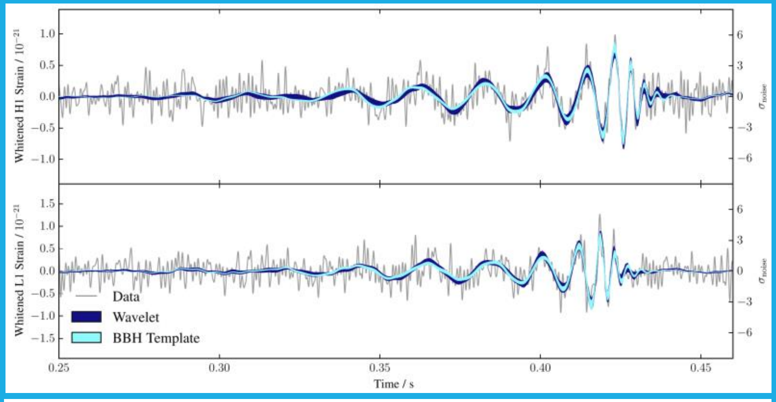
Performing a global analysis

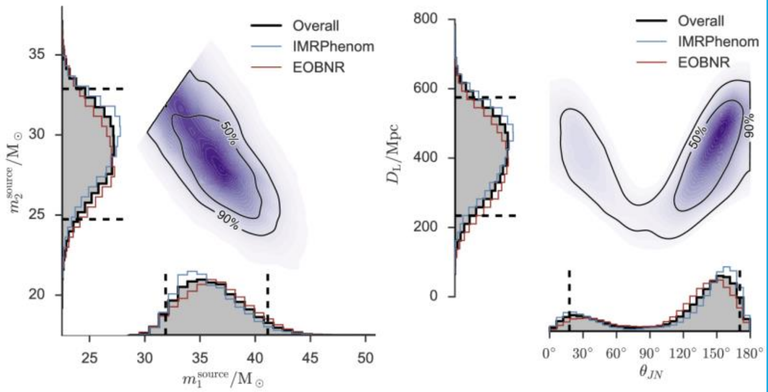
Model depends on parameters non-linearly
- Run model on 1200 `design' points
- Use an emulator for any point in parameter space (**GP**)

Markov Chain Monte Carlo
- 653 data points
- Obtain posterior probability density of parameters

Compare posterior with data
- Can include high statistics run

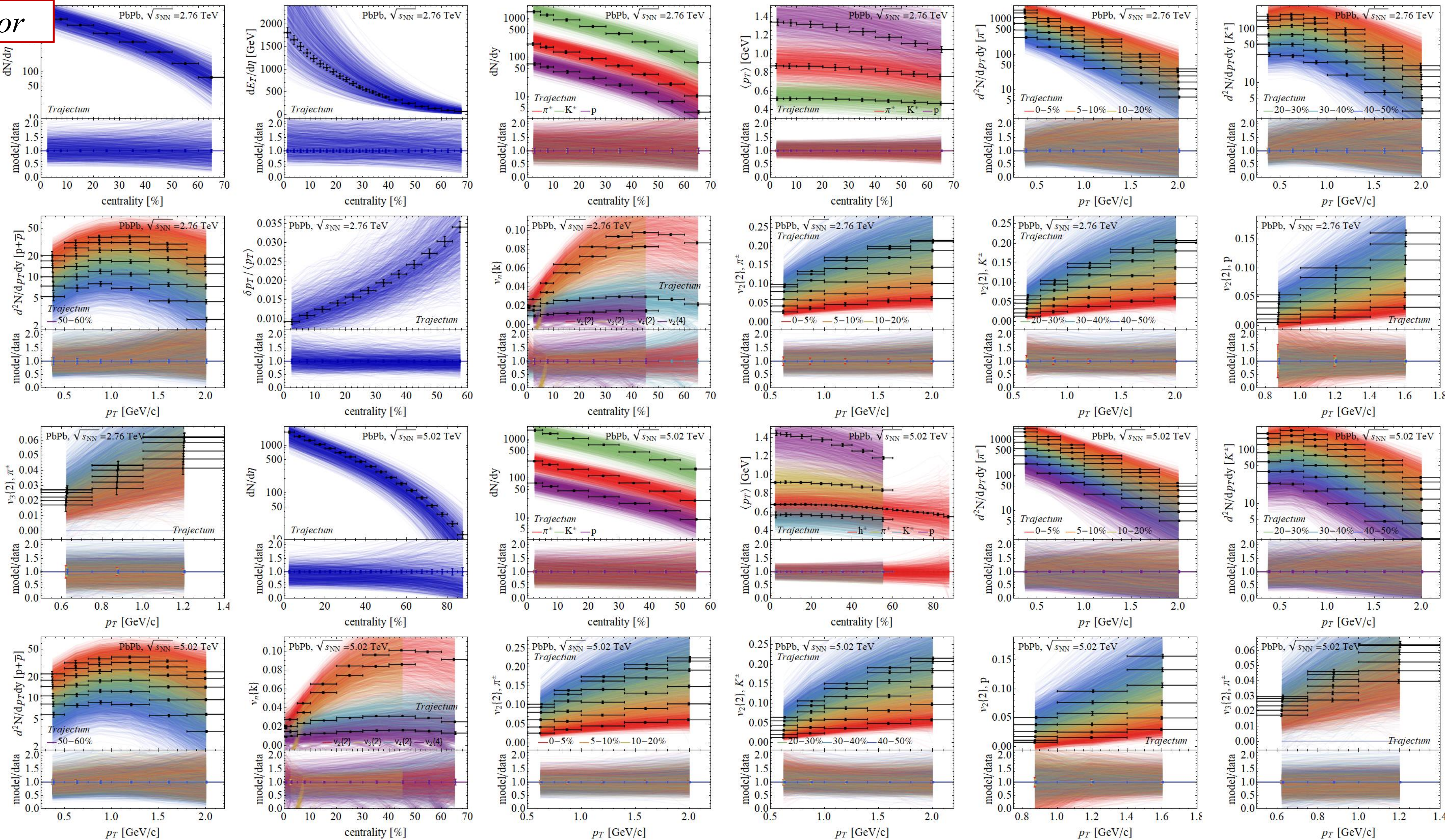
Same technique: gravitational waves





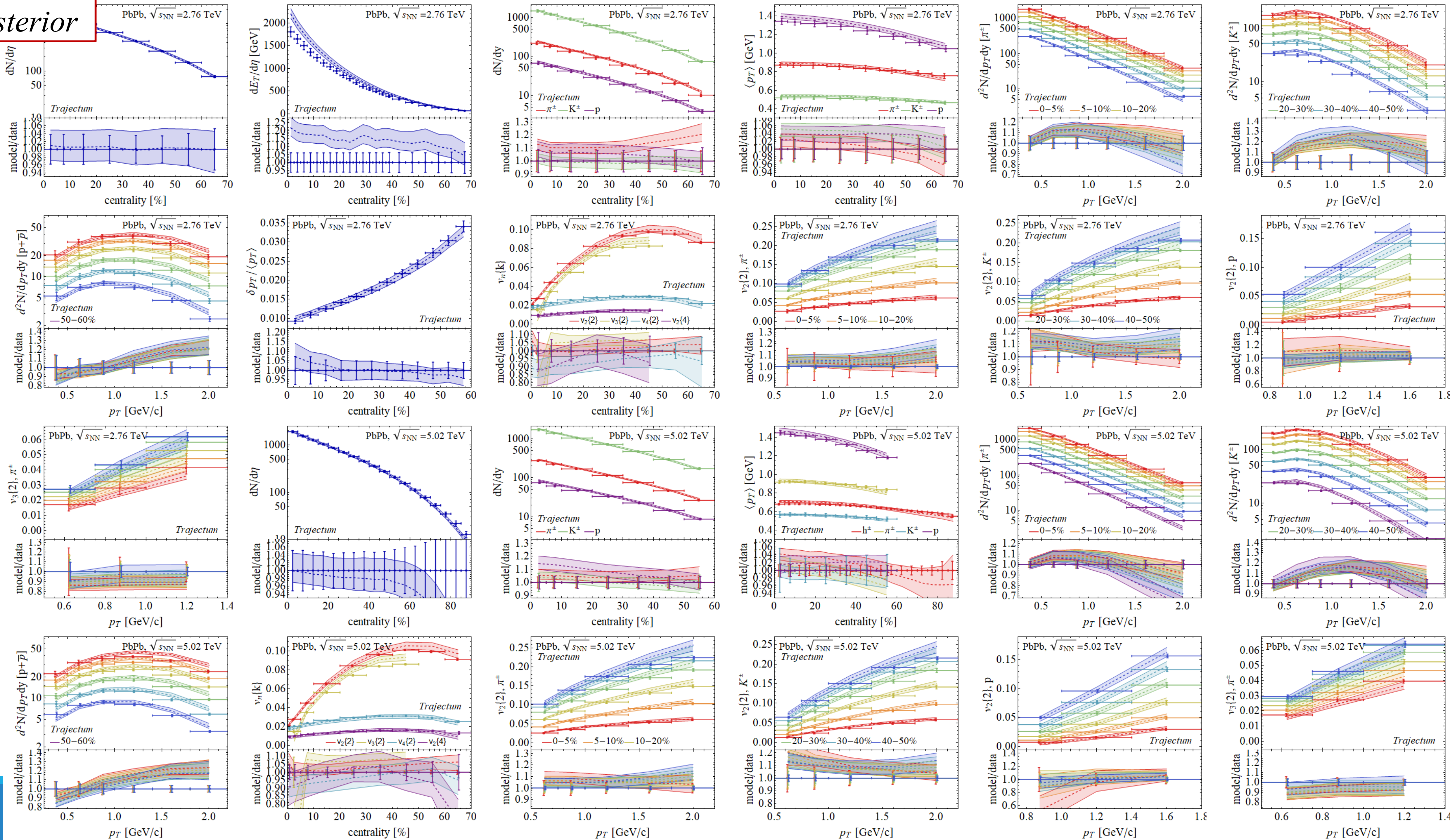
LIGO, Properties of the Binary Black Hole Merger GW150914 (2016)

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

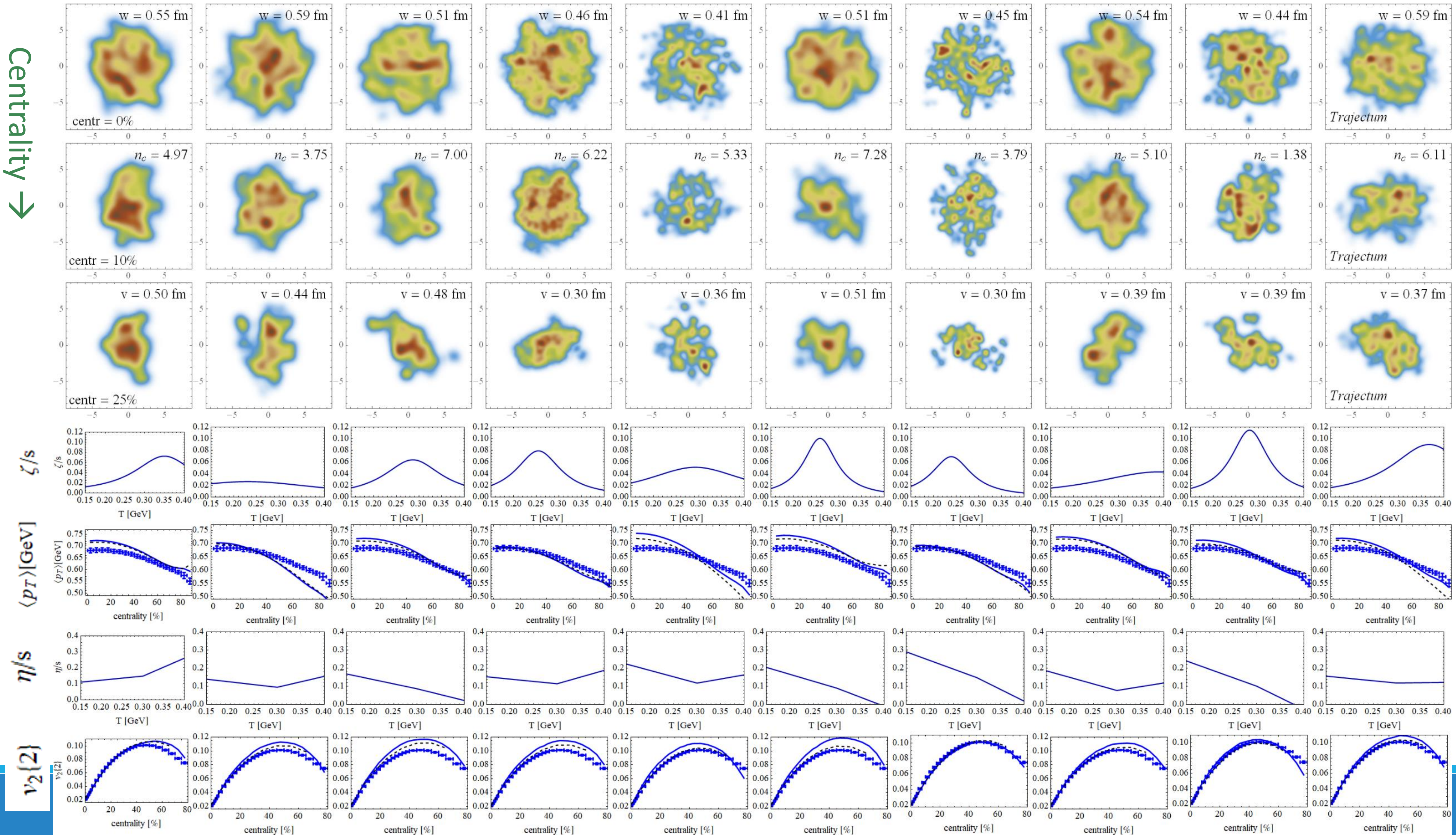


PbPb, $\sqrt{s_{NN}}$ =2.76 TeV
PbPb, $\sqrt{s_{NN}}$ =5.02 TeV
Trajectum
dN/dη
$dE_T/d\eta$ [GeV]
dN/dy
$\langle p_T \rangle$ [GeV]
d^2N/dp_Tdy [$\pi^\pm$]
d^2N/dp_Tdy [$K^\pm$]
d^2N/dp_Tdy [$p+\bar{p}$]
$\delta p_T / \langle p_T \rangle$
$v_n\{k\}$
$v_2\{2\}, \pi^\pm$
$v_2\{2\}, K^\pm$
$v_2\{2\}$, 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%
$v_2\{2\}$ — $v_3\{2\}$ — $v_4\{2\}$ — $v_2\{4\}$

Energy + viscosities + experiment

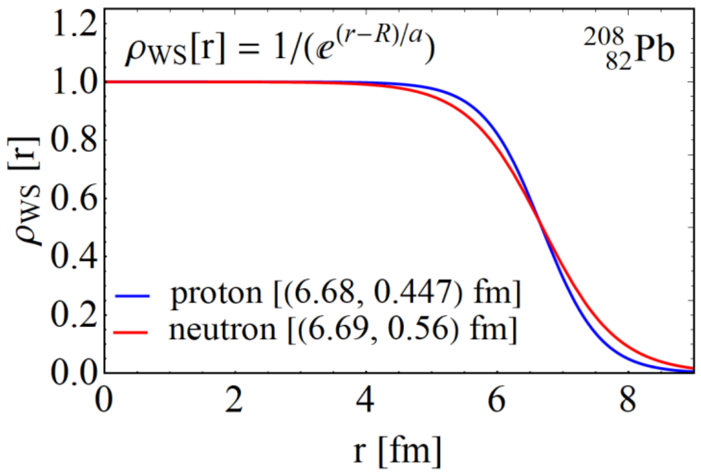
Ten different probable parameter settings →

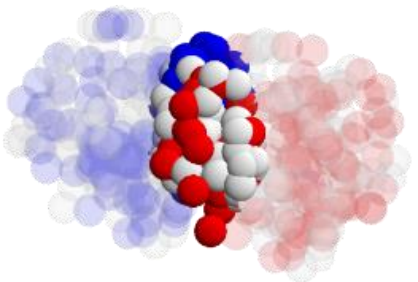
Centrality →



The neutron skin

1. Nucleus charge profile can be measured very accurately
   - Much more uncertainty in the profile of the neutrons
   - Relevant to understand cold QCD: EOS for neutron stars
2. Can we make progress using heavy ion collisions?
   - Isospin symmetry makes distinction neutron/proton difficult
   - Leverage accurate proton knowledge and obtain profile of nucleus?
3. How to obtain the profile of a nucleus?
   - Wood-Saxon + MC-Glauber + (model like Trento) → dynamics
   - Currently from state-of-the-art …
4. Profile influences many observables
   - Interplay with bulk viscosity, Trento model etc
   - Likely need a full global analysis



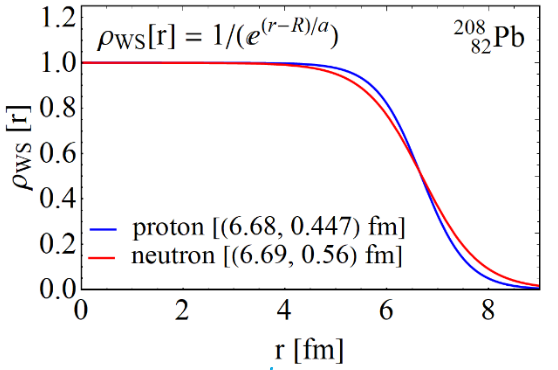


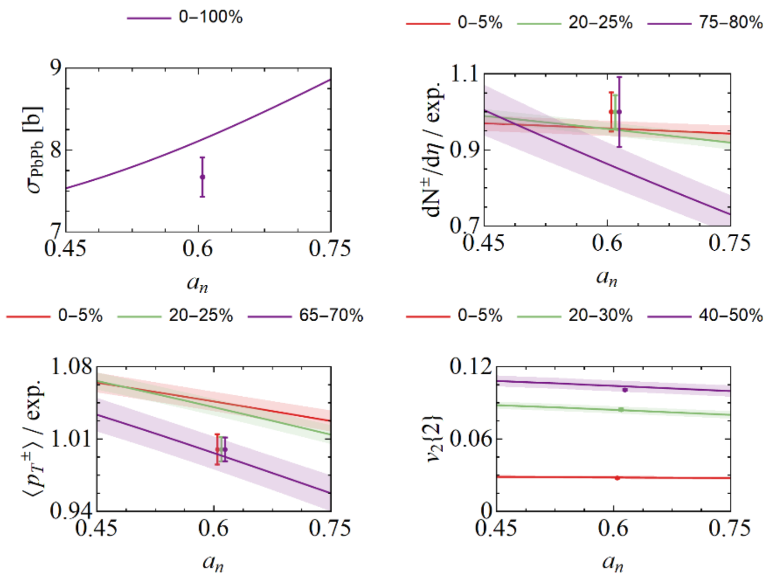
Constantin Loizides, Jason Kamin and David d'Enterria, Improved Monte Carlo Glauber predictions at present and future nuclear colliders (2017)

The neutron skin - emulator

1. Plan is to vary a for neutrons and see if HIC can constrain it
   - a determines the neutron radius (approx. linear for RMS radius)

2. First step: what does the emulator say?
   - Using a precise global analysis (26 parameters, 3000 design points)

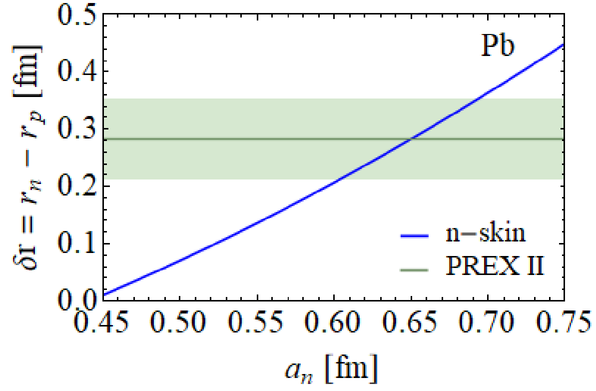




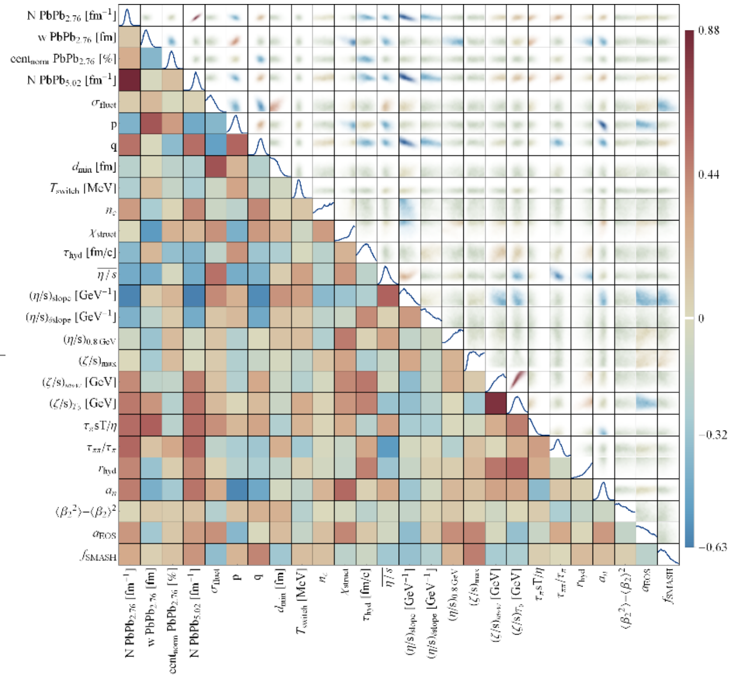
1. Main change: cross section
   - Measures 'size' of nucleus

2. Both multiplicity and mean pT change
   - Mainly for peripheral ('skin effect')

3. Small changes for other observables

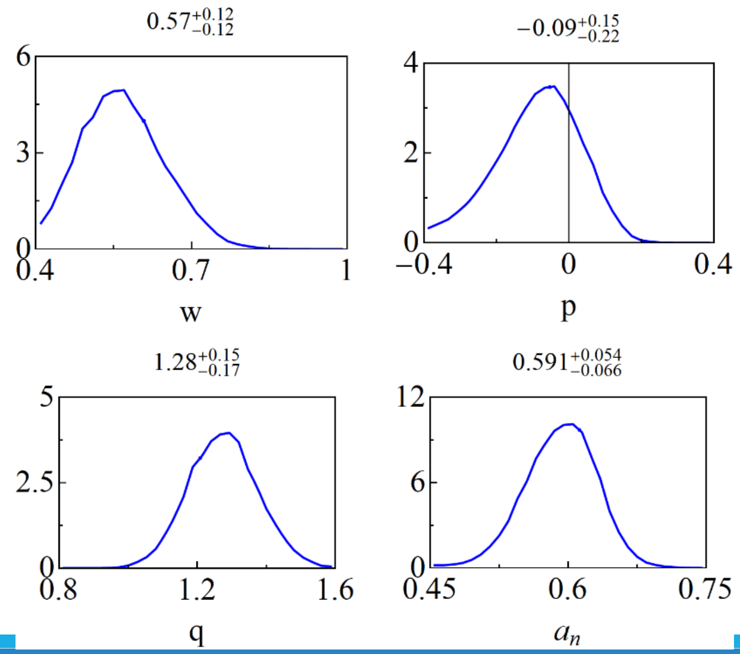


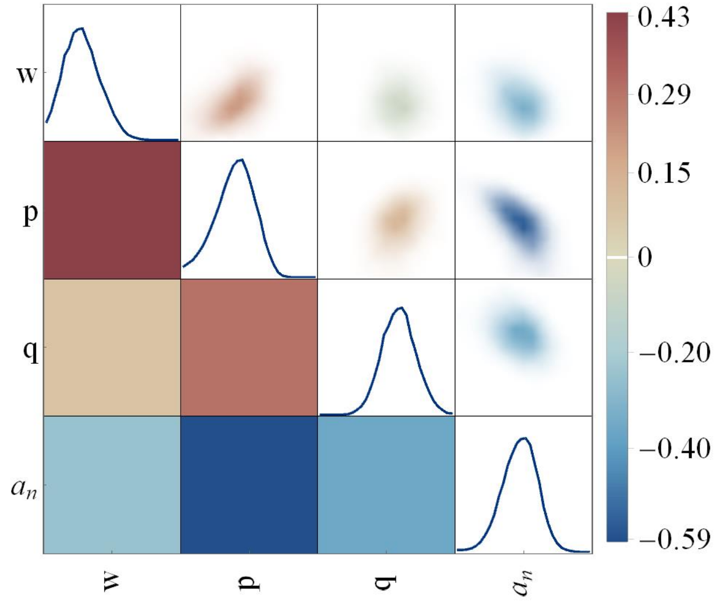
$$\mathcal{E} \propto \left(\tfrac{1}{2}T_A^p + \tfrac{1}{2}T_B^p\right)^{q/p} = \left(T_A T_B\right)^{q/2} |_{p=0}$$

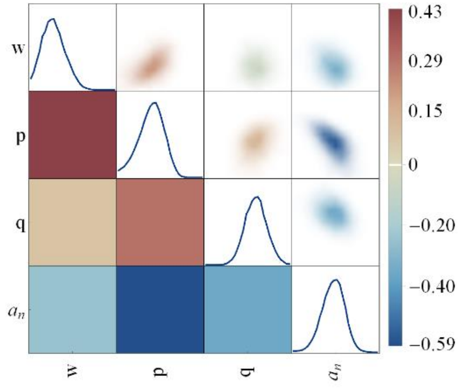


The neutron skin - posterior

1. Three parameters are most sensitive to the neutron skin:
   - The nucleon width and the Trento parameters p and q
   - Small correlation with width (cross section is highly sensitive to w)
   - Very strong anticorrelation with p; centrality dependence is crucial



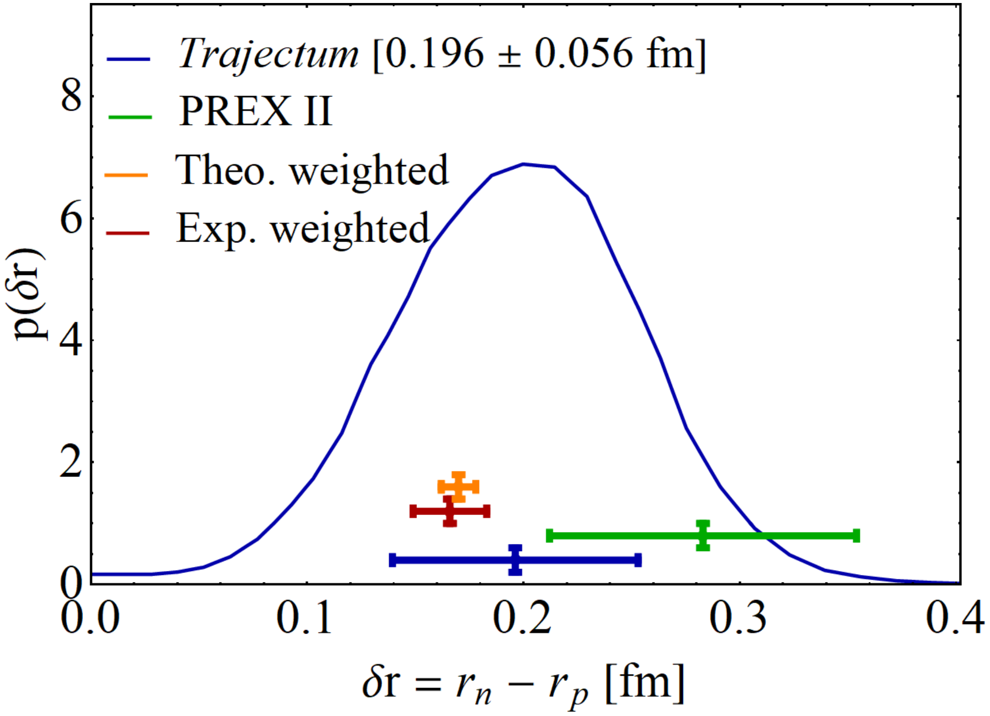


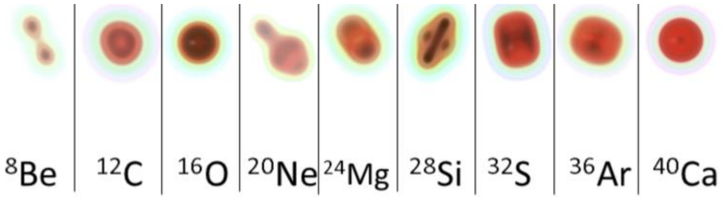


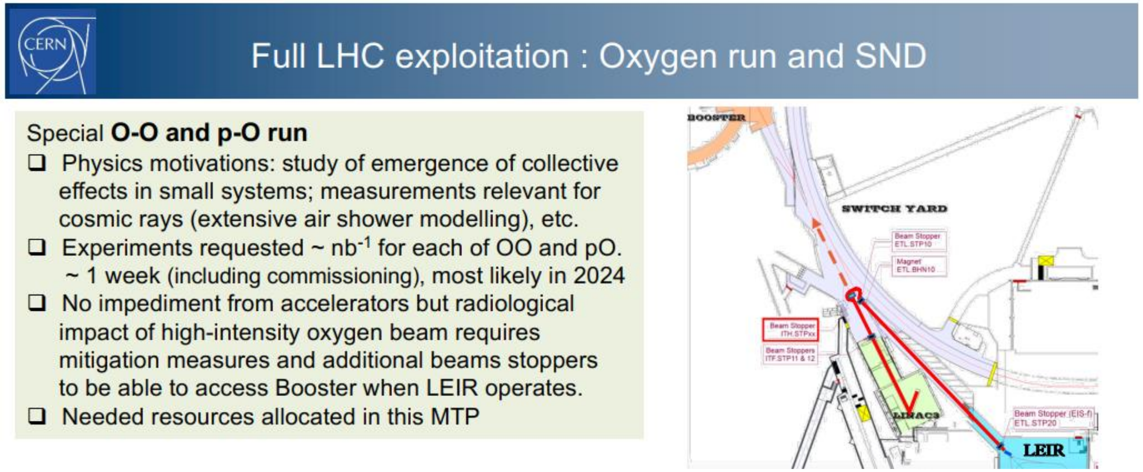
The neutron skin – final result

1. Transform to neutron radius minus proton radius
2. Final result consistent but smaller than PREX II
3. Uncertainty is about 20% smaller than PREX II
4. Cross section is crucially important, but also centrality dependence
   - Important to vary Trento parameters in particular

Not competitive with weighted averages (from 14 different methods), but adds unique experimental determination of neutron skin

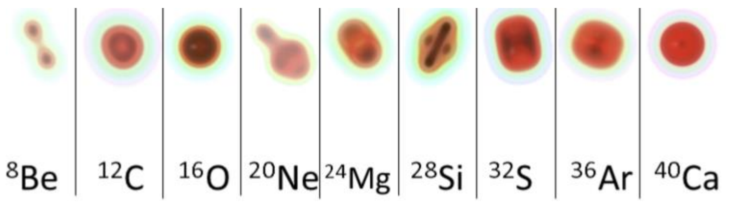






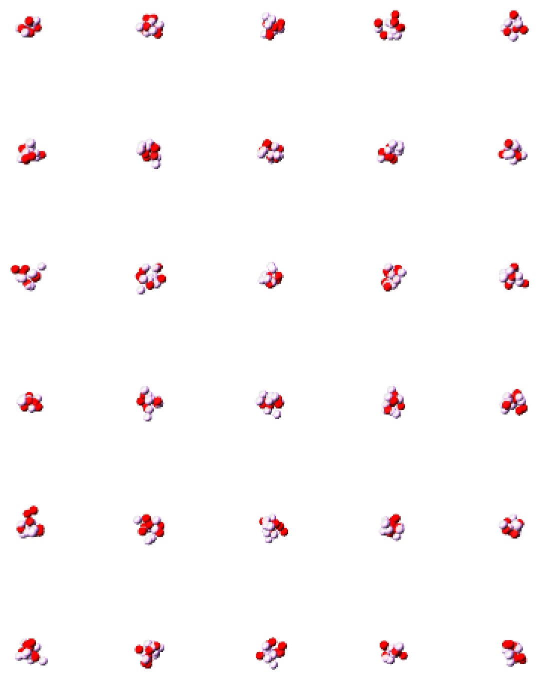
Oxygen and Neon (??) collisions at the LHC

Nuclear structure and heavy ion collisions



Isobar collisions raise several questions:

- Are HIC sensitive to nuclear structure? Yes, but at percent level accuracy
- Are HIC understood at percent level? Historically likely not…



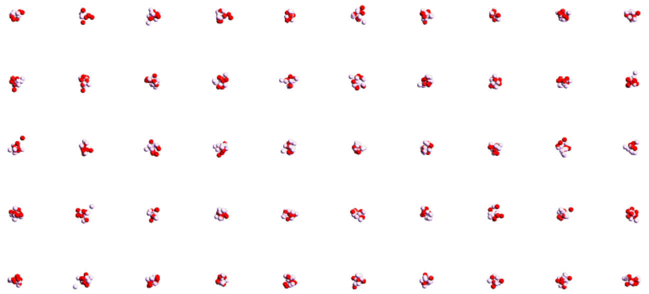
A more systematic approach

- Vary several approaches to nuclear structure
- Vary parameter settings within current posterior distribution
- Do we need an (isobar) ratio to make progress?

Oxygen (and Neon?) at CERN

- Independently interesting: the smallest droplet of QGP, cosmic rays (p-O collisions)
- Oxygen (Neon) specifically interesting: can we see 4 (5) clusters of alpha-particles?
- Neon – Lead beam gas collisions foreseen at LHCb fixed target mode

Jasmine Brewer, Aleksas Mazeliauskas and WS: http://cern.ch/ooatlhc or https://arxiv.org/abs/2103.01939
J.-P. Ebran, E. Khan, T. Niksic and D. Vretenar, Density Functional Theory studies of cluster states in nuclei (2014)

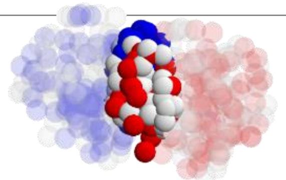


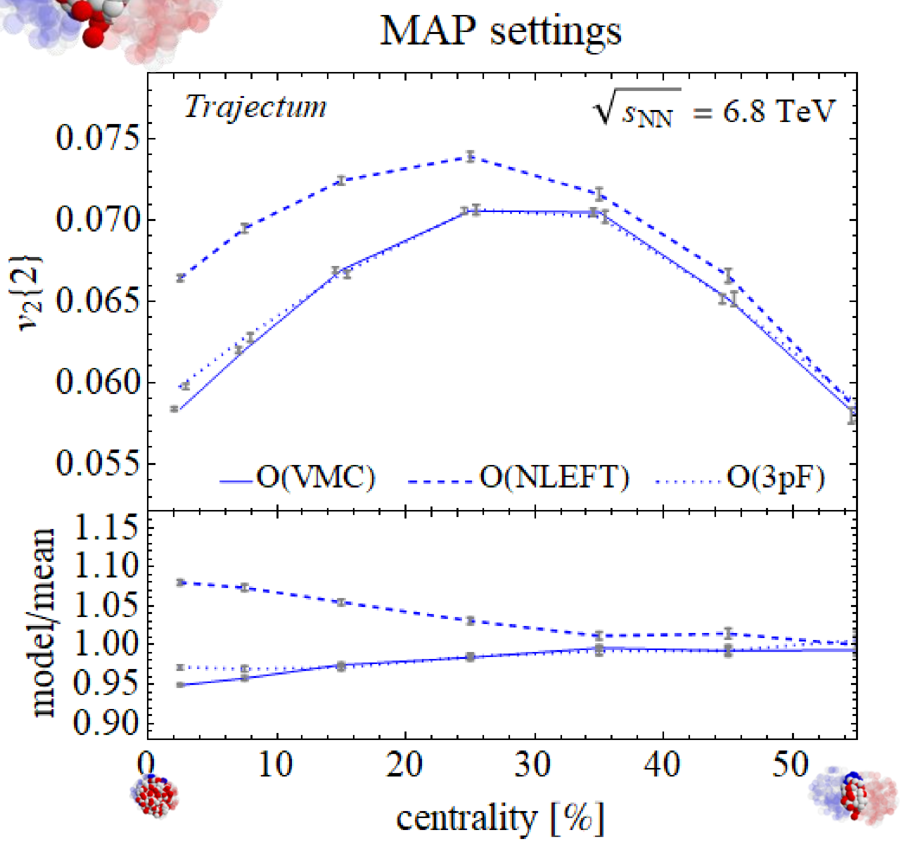
Oxygen nuclear structure

1. Comparing two state-of-the-art microscopics with old profile (MAP run with 100M 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)

2. Elliptic flow does not distinguish VMC/3pF
   - Other observables can (e.g. mean transverse momentum)

3. Significant differences for central collisions

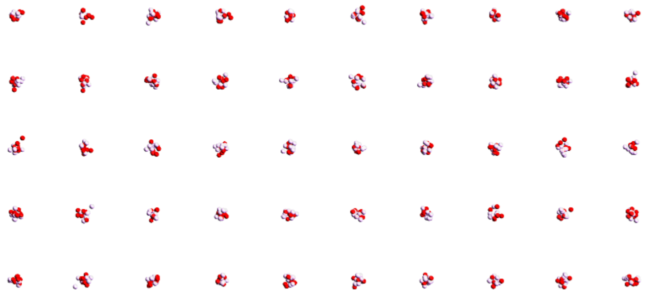


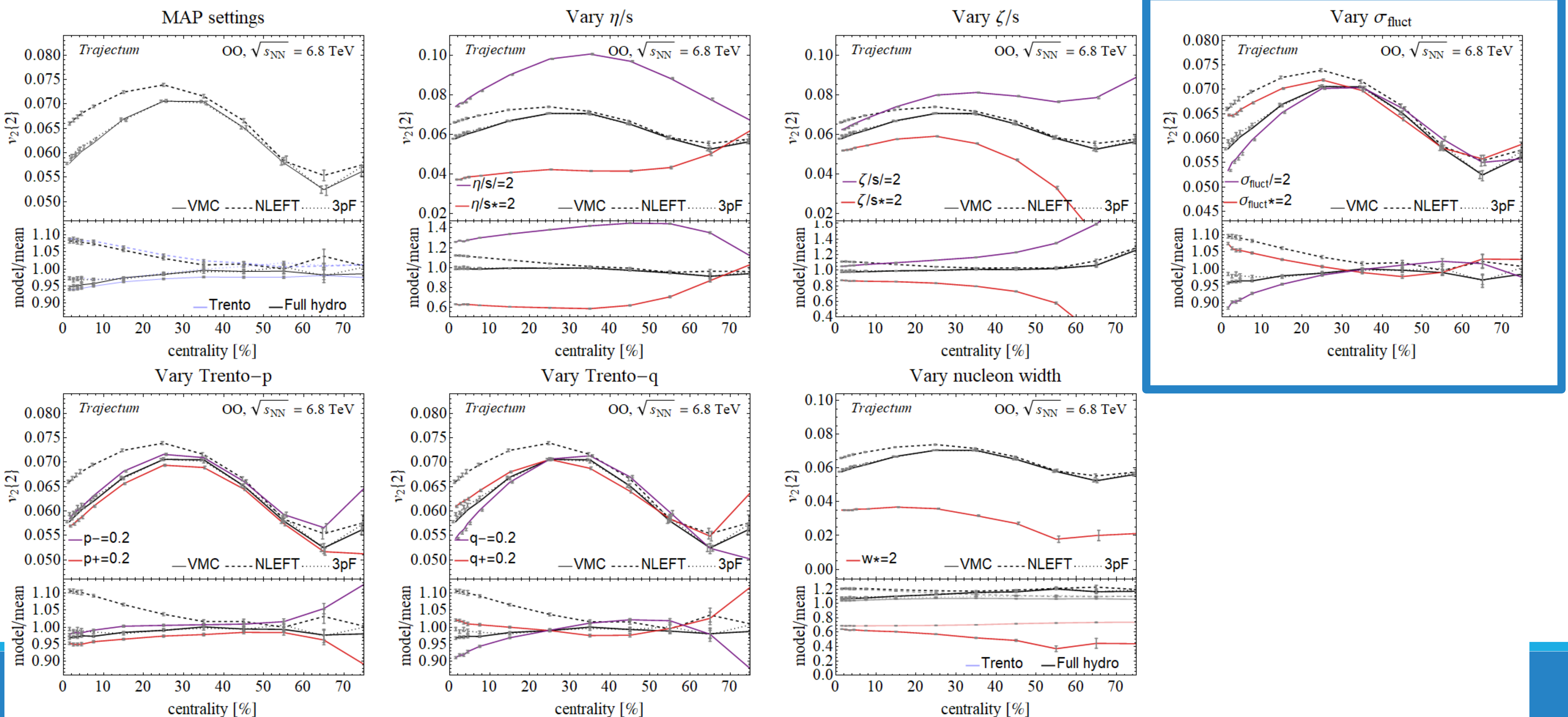


Oxygen nuclear structure

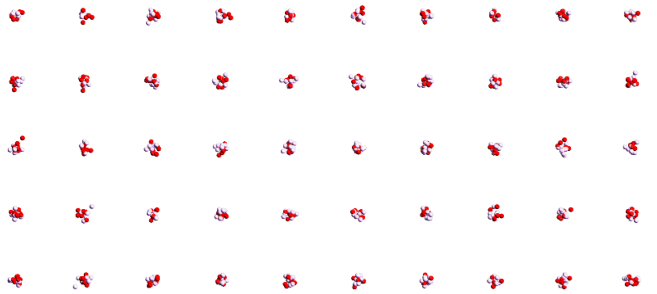
Are results robust when varying parameter?

- Not really… nuclear structure similar to fluctuations





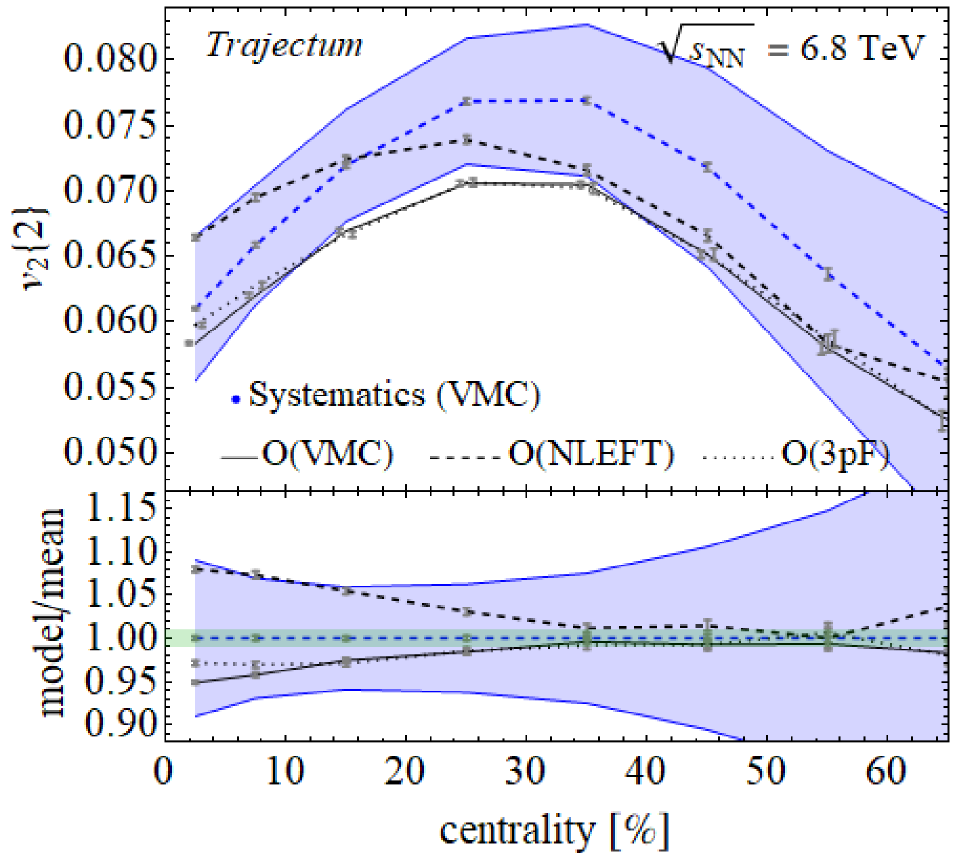
Oxygen nuclear structure



Can we do this more systematically?

- Parameters such as viscosities are highly correlated
- Take random sample of `probable’ parameter settings
- Compute one standard deviation systematic uncertainty

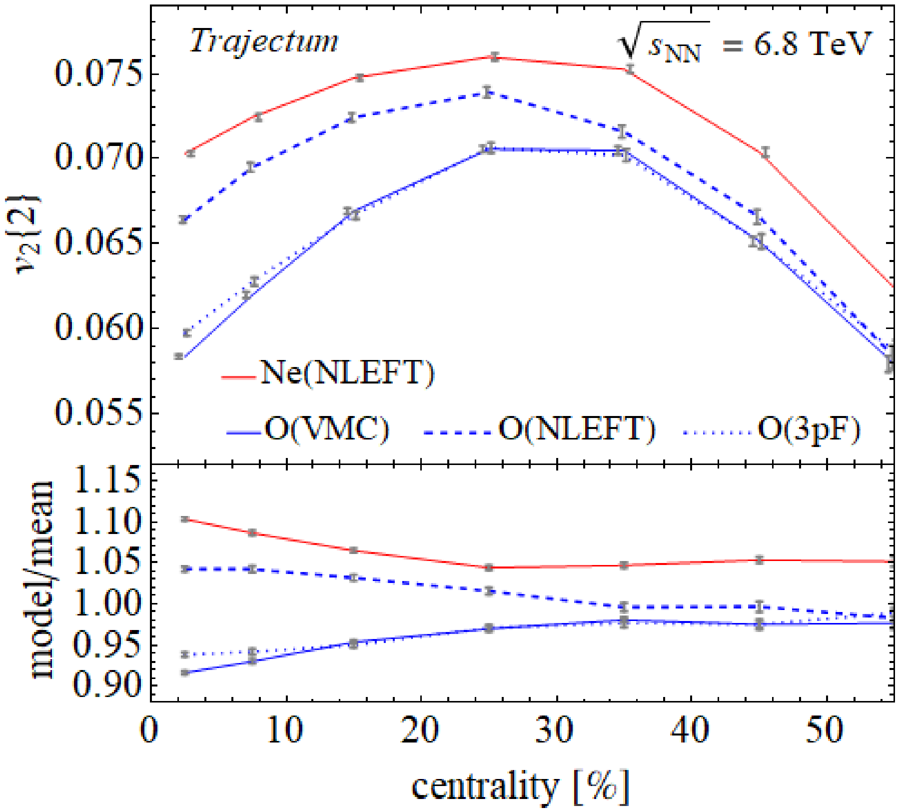
Systematic uncertainty comparable to differences due to nuclear structure

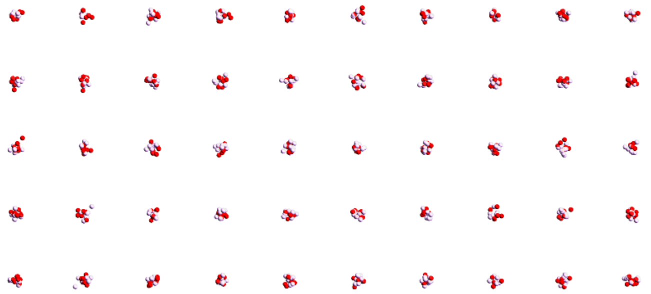


^{16}Oxygen and ^{20}Neon nuclear structure

Can we do better?

- Compare (almost) isobars: *Oxygen and Neon*
- No apples-to-apples nuclear structure available (yet)
- Neon has significantly more elliptic flow

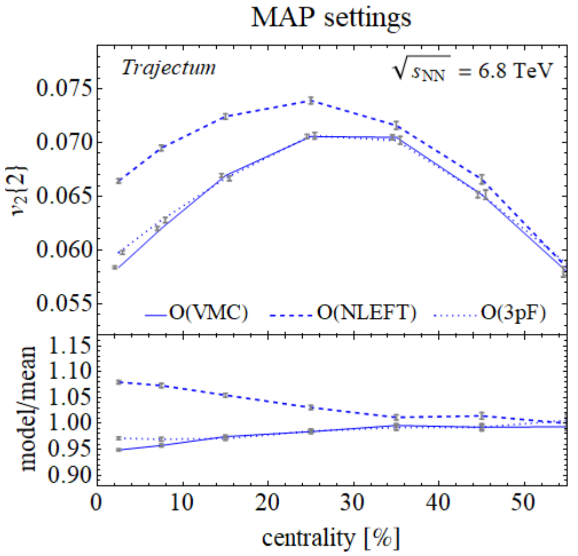


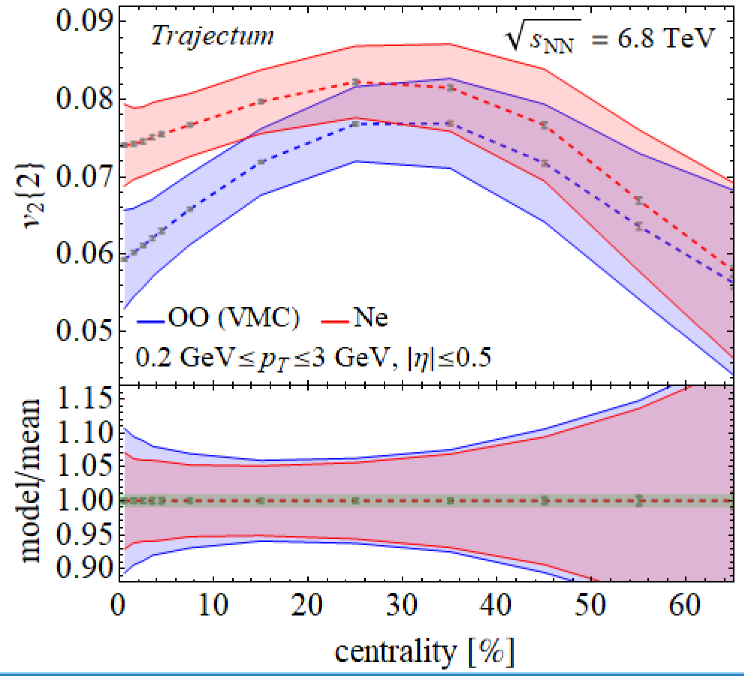


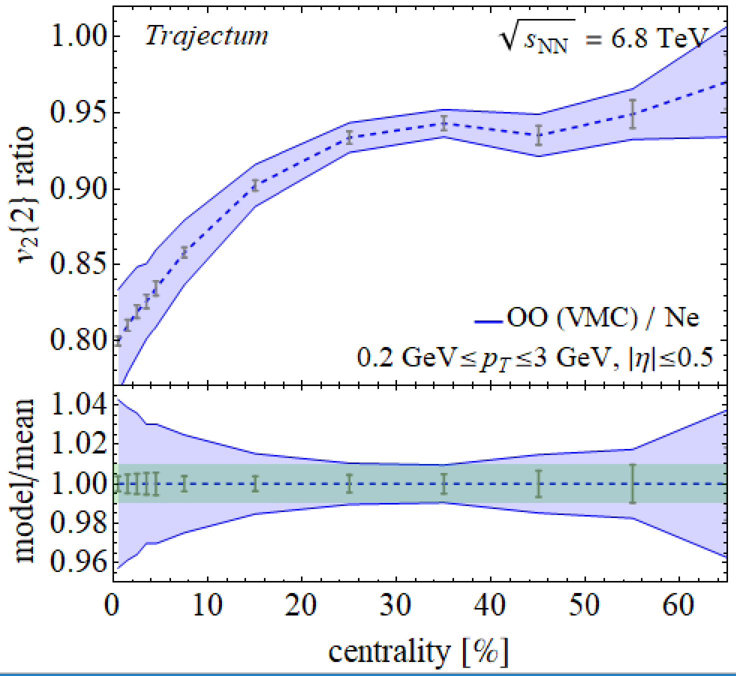
^{16}Oxygen and ^{20}Neon nuclear structure

What about the systematics?

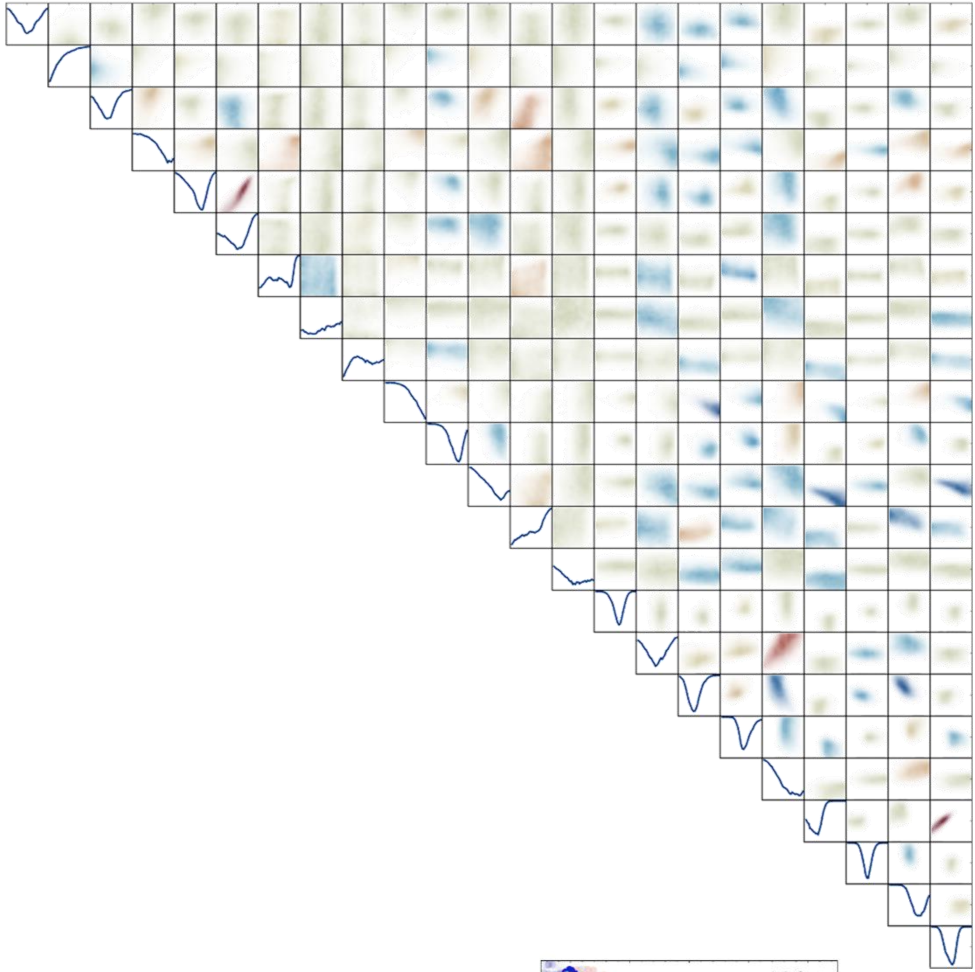
- Barely significant difference between Oxygen and Neon elliptic flow within systematics
- **The ratio**, however, is accurate at percent level (!). Sweet spot at ~25% centrality
- Could be an expensive fact …







Discussion

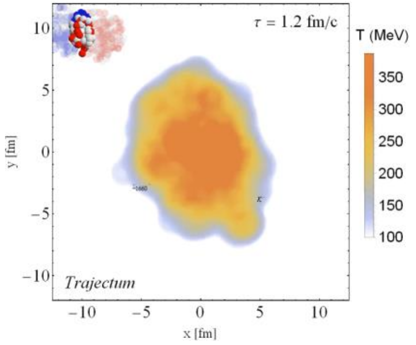


Exciting progress using isobars and nuclear structure

- Heavy ion collisions towards percent level precision
- Will feature also as improved understanding of QGP properties
- Oxygen collisions to be performed at the LHC summer 2024!

Skipped many related topics:

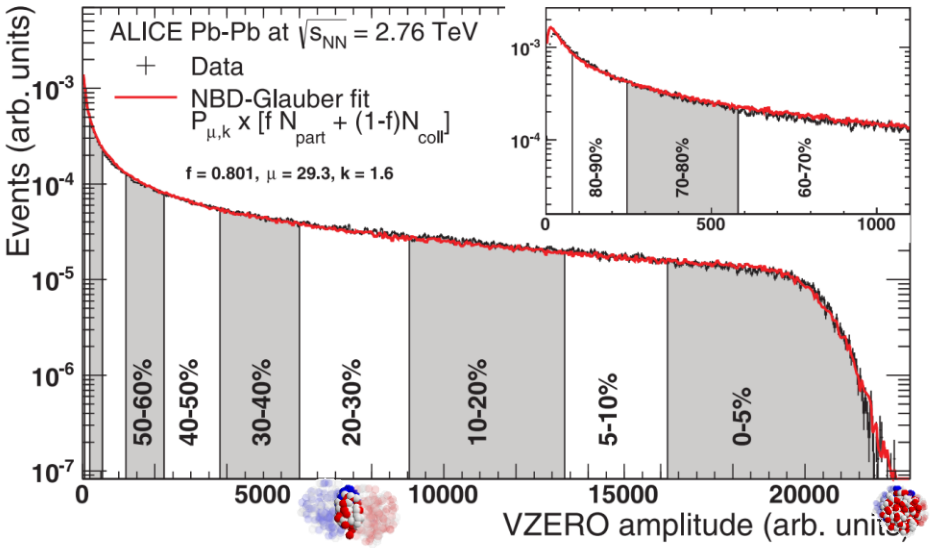
- Nucleon width (see Govert's talk), subtleties in Bayesian scans/emulator etc, more interesting/discriminatory observables (ρ_2?) etc..



Back-up

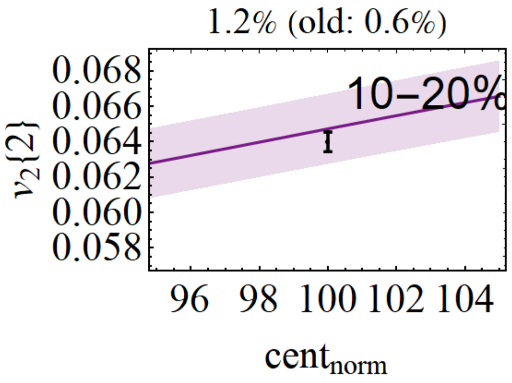
The PbPb cross section and the centrality normalisation

Cross section follows from
- Luminosity (van der Meer scan, dominates uncertainty)
- The number of collisions
- First measured in April 2022 (!)



ALICE can accurately measure collisions in 0-90% region
- 90-100% is estimated from NBD Glauber fit

Trajectum defines 100% by having at least one nucleon-nucleon interaction
- Now also a parameter, perhaps as a check, or to address experimental uncertainty
- We take a Gaussian prior of width 1%



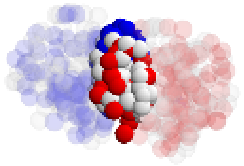
Centrality normalisation trivially correlates **all** observables by shifting classes
- Probably best to marginalise over in MCMC Bayesian analysis
- Means ALICE should quote this uncertainty separately
- Important even for some central observables ($v_2\{2\}$)

The nucleon width and the total PbPb hadronic cross section

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

Fix nucleon-nucleon cross section:

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



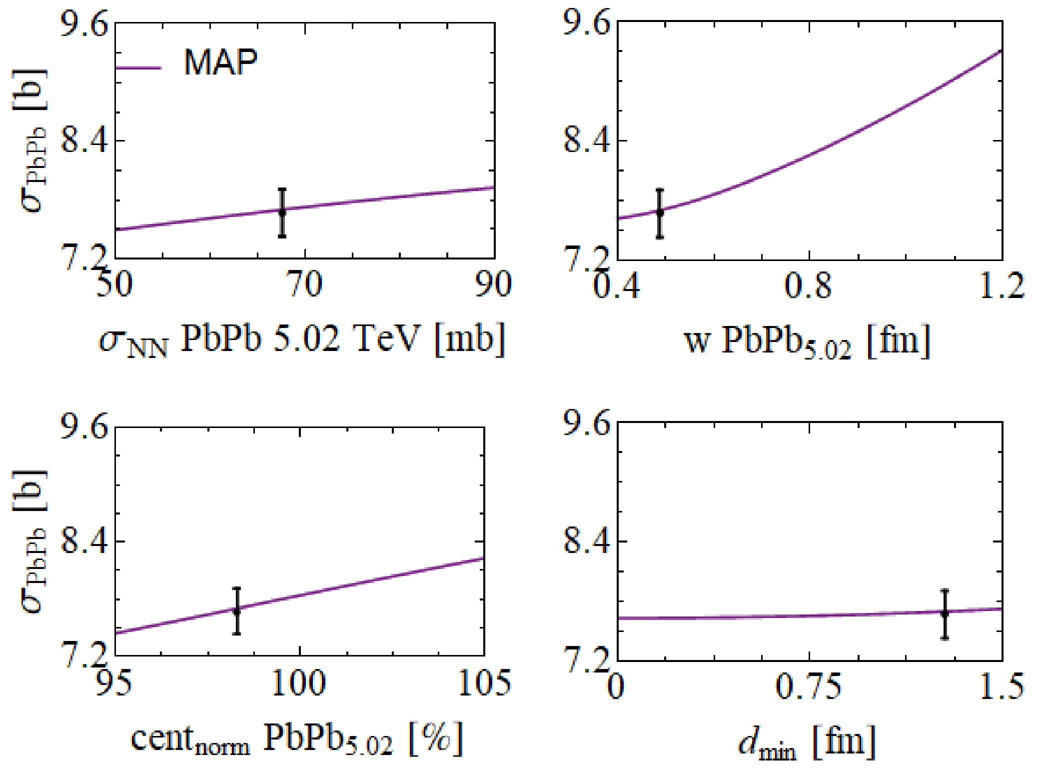
e.g. collision probability tuned to σ_{NN} for Gaussian profile ρ

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

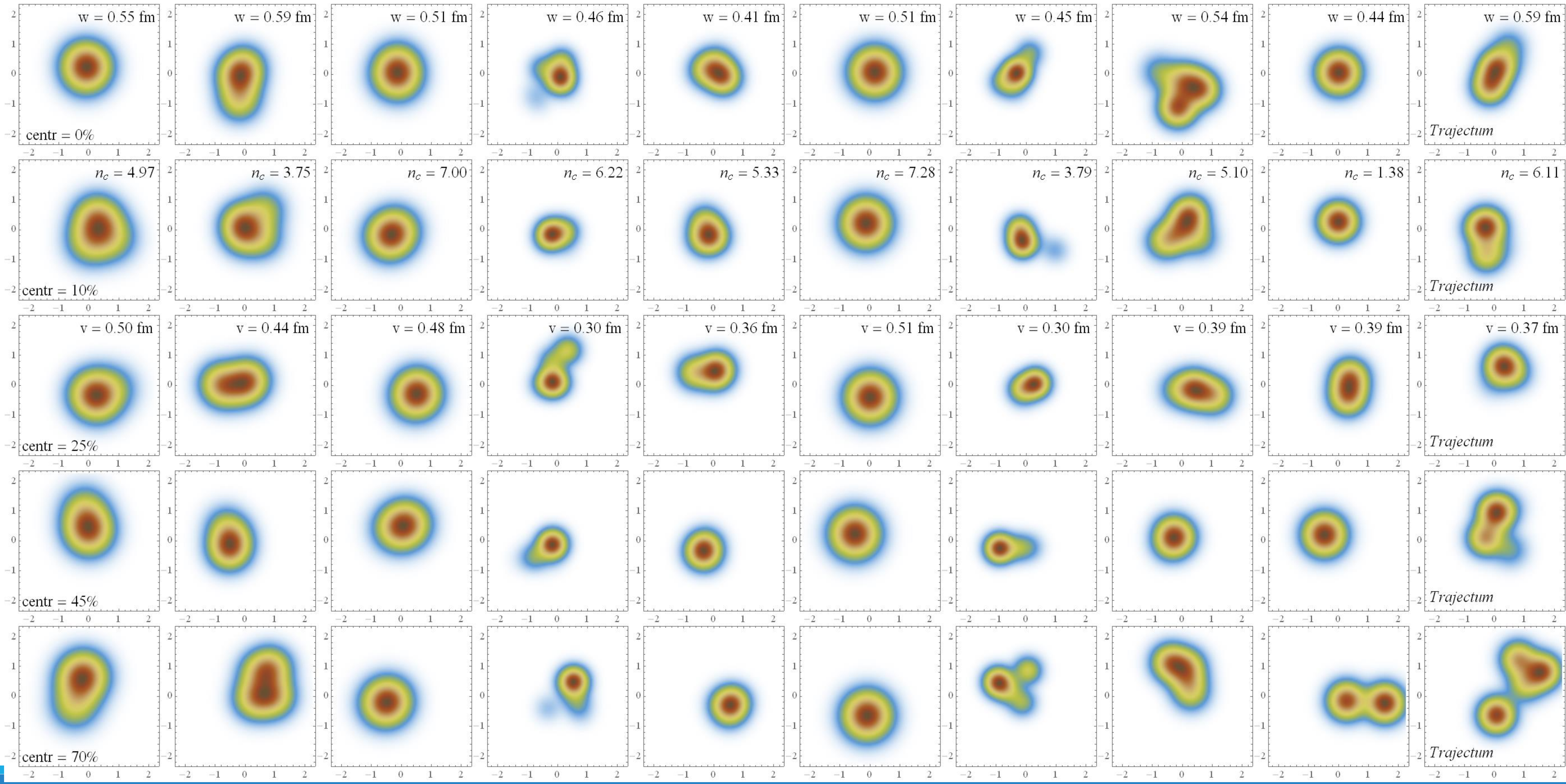
- Basically implying every model needs to get this right
- Basically implying the nucleon width should be small



Thickness function nucleon

Ten different probable parameter settings →

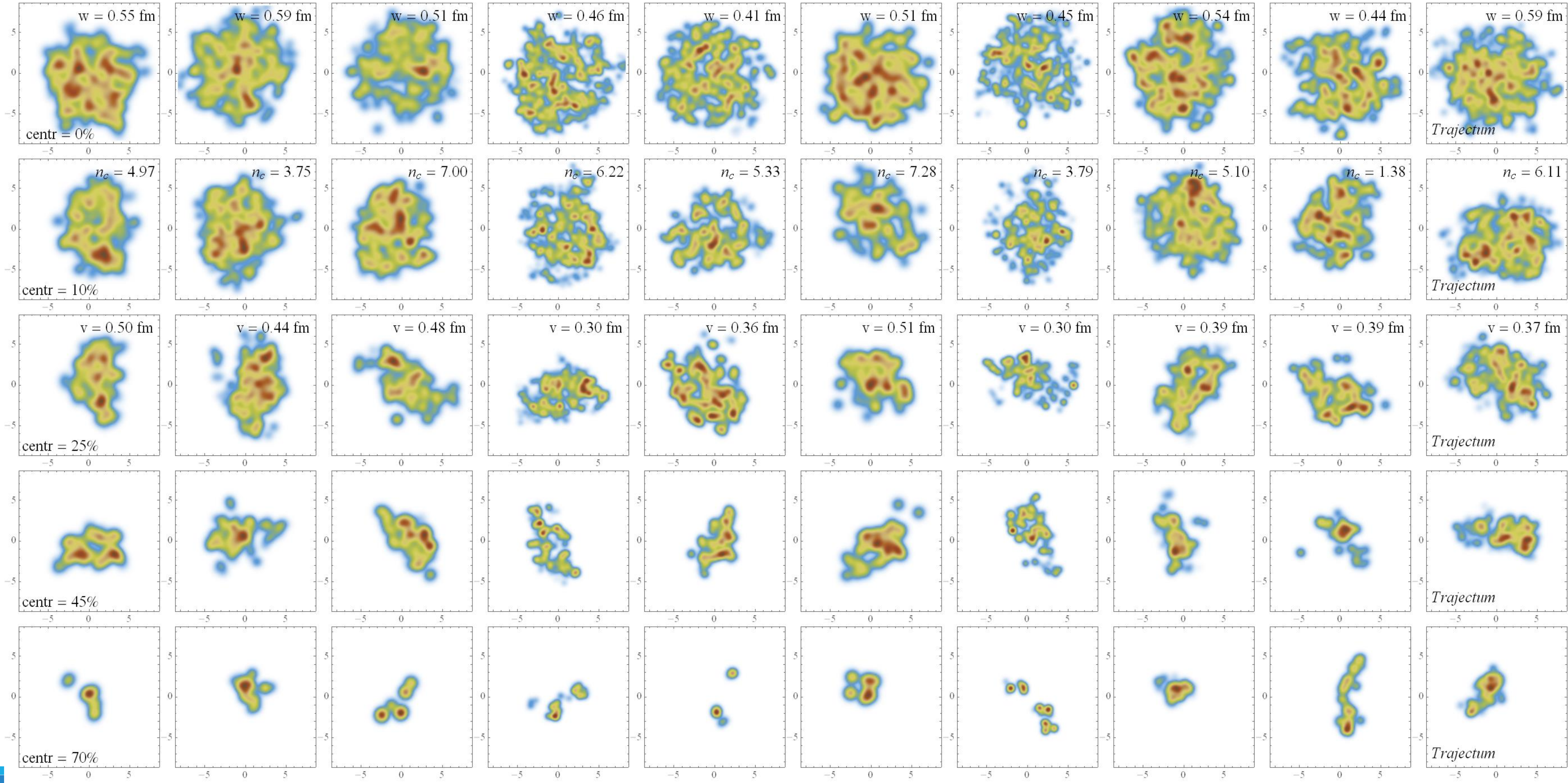
Configurations →



Thickness function Pb

Ten different probable parameter settings →

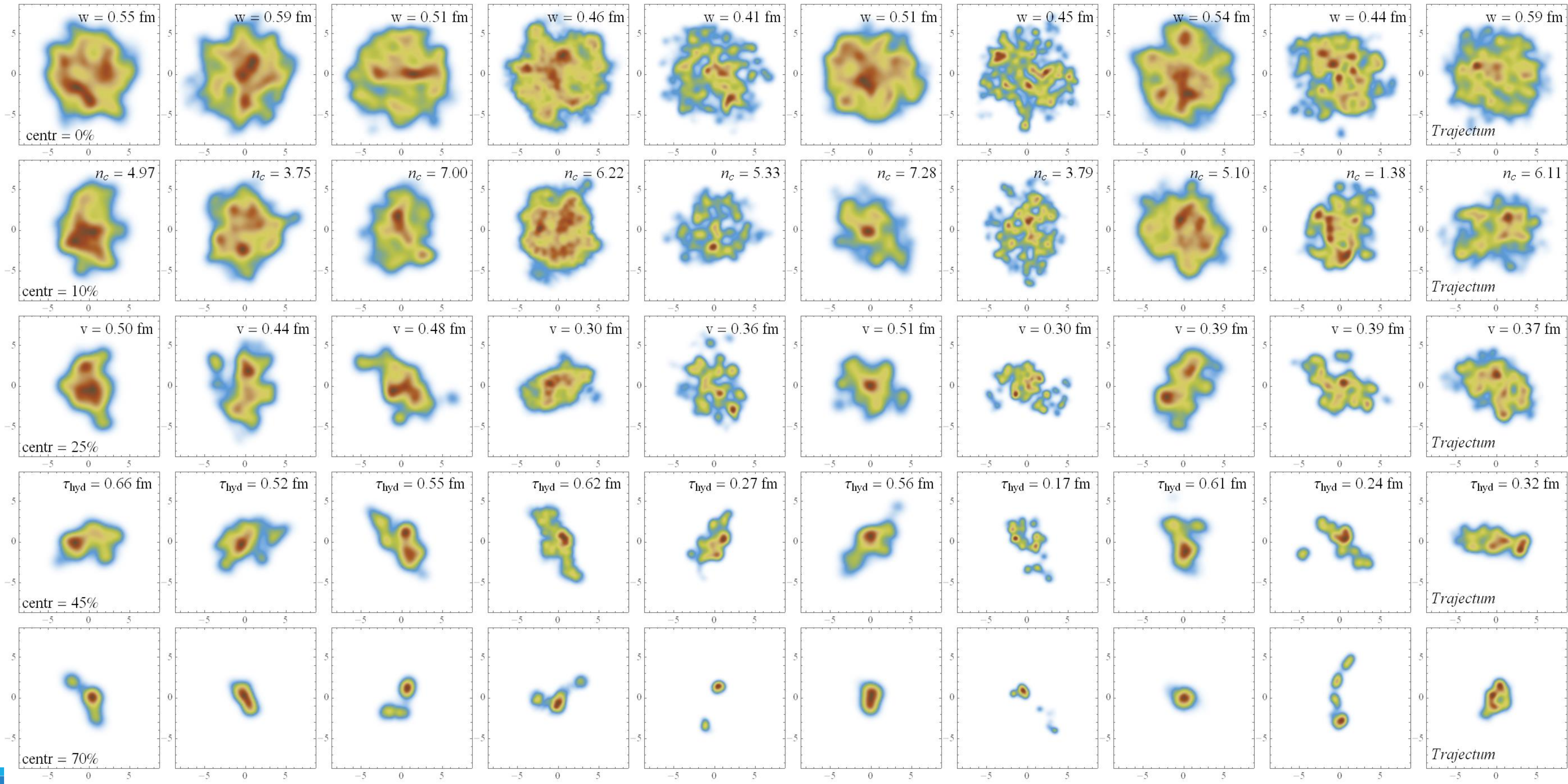
Centrality →



Energy density function Pb

Ten different probable parameter settings →

Centrality →

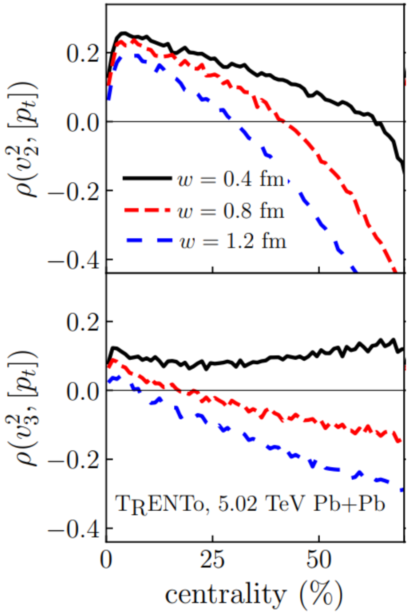


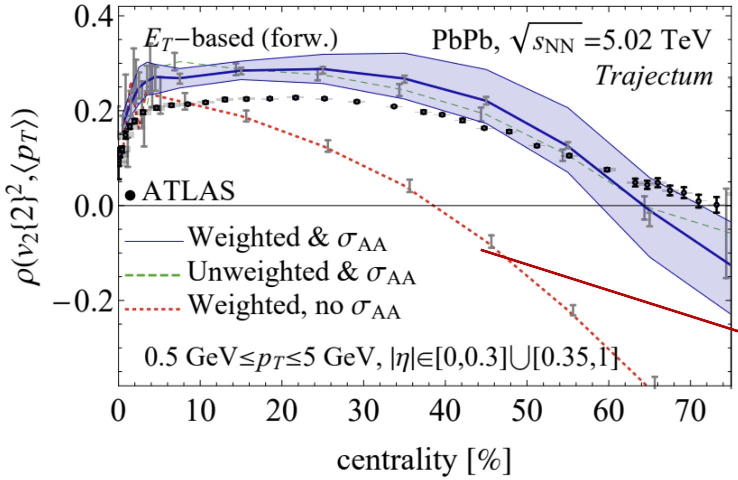
Bonus: mean p_T and v_2 or v_3 correlations

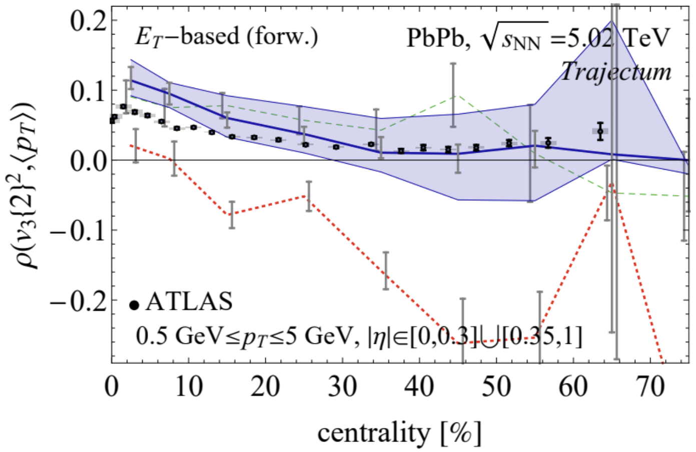
A Bayesian MAP check: unfitted data:

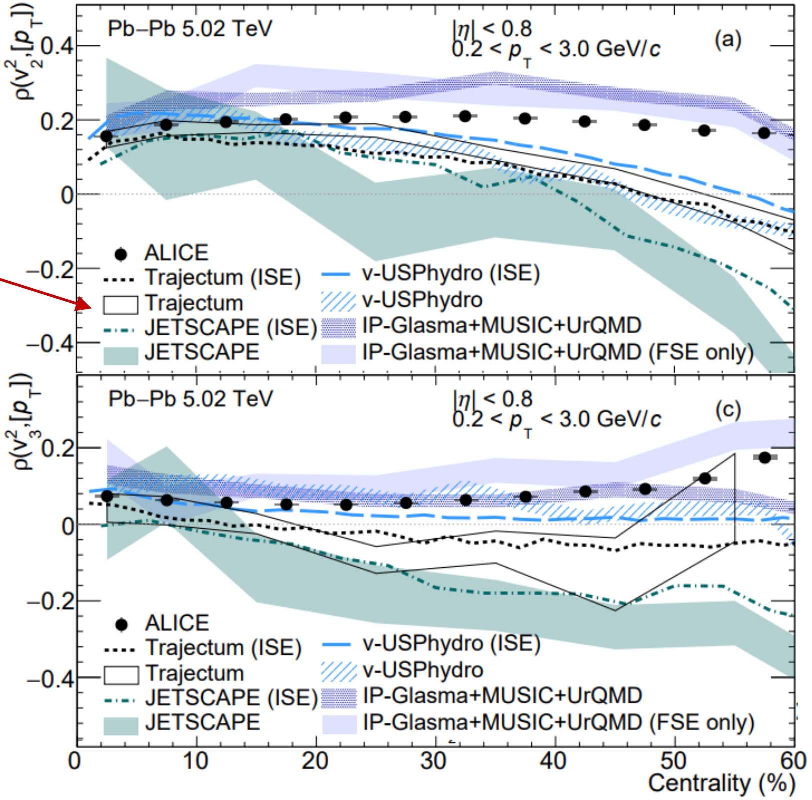
- Triple differential observables:
- Correlation p_T and v_n

Anticipated by (simpler) Trento analysis:



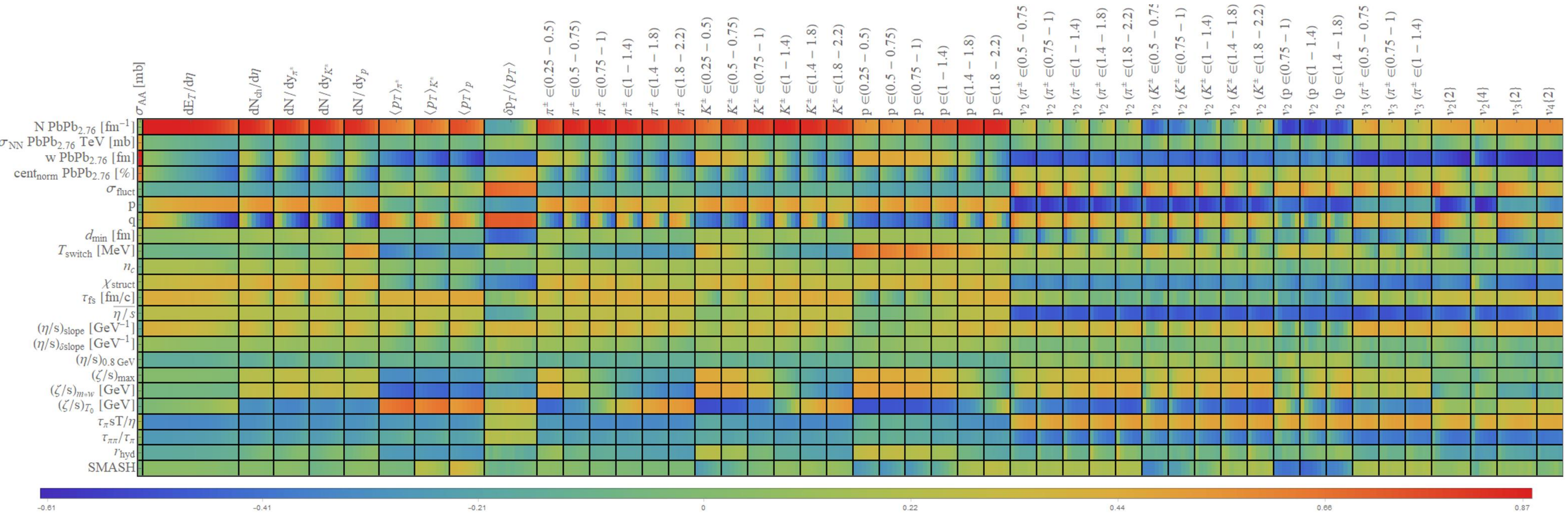






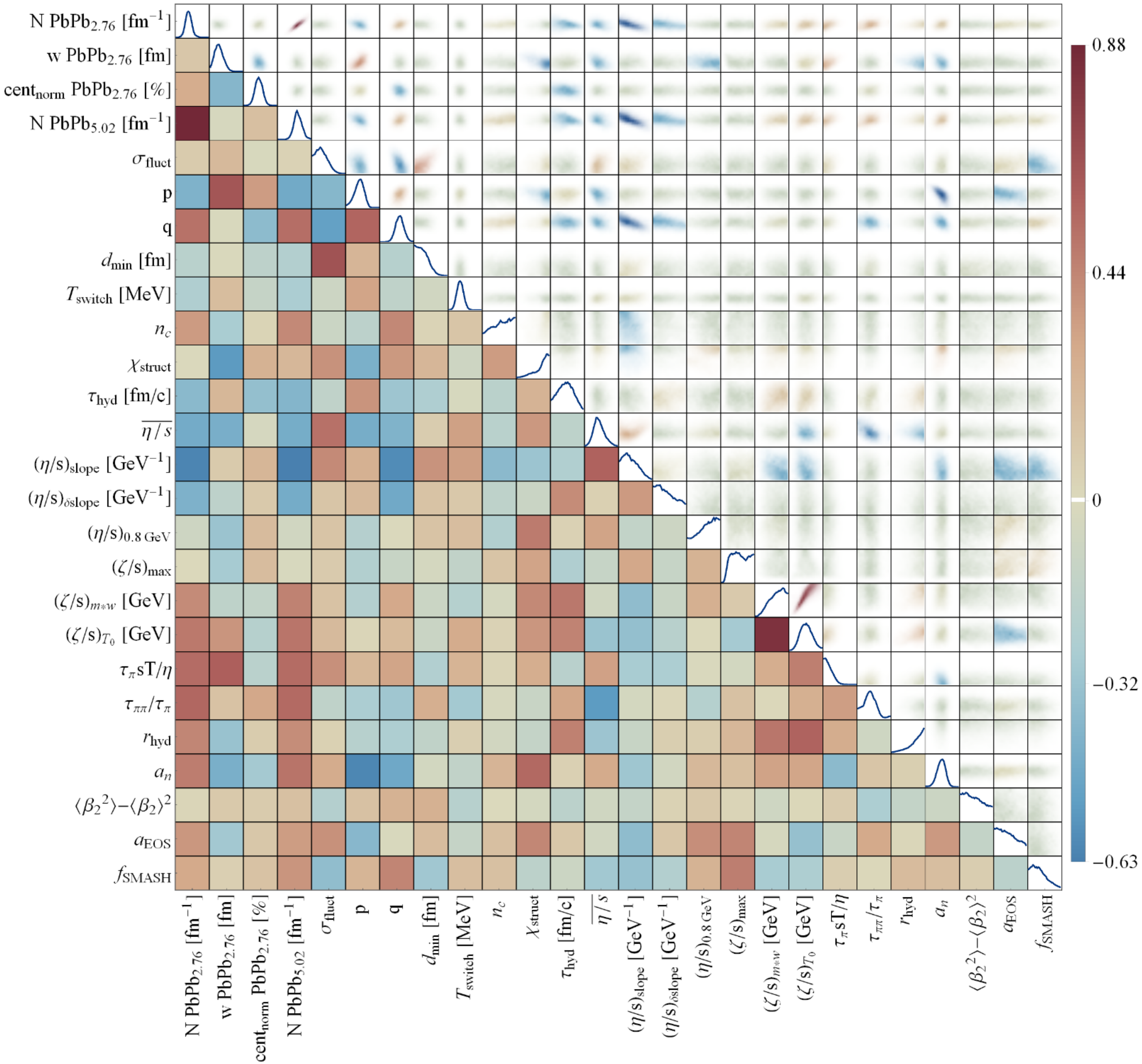
Giuliano Giacalone, Bjorn Schenke and Chun Shen, Constraining the nucleon size with relativistic nuclear collisions (2021)
ALICE, Characterizing the initial conditions of heavy-ion collisions at the LHC with mean transverse momentum and anisotropic flow correlations (2021)

Design parameter-observable correlations:

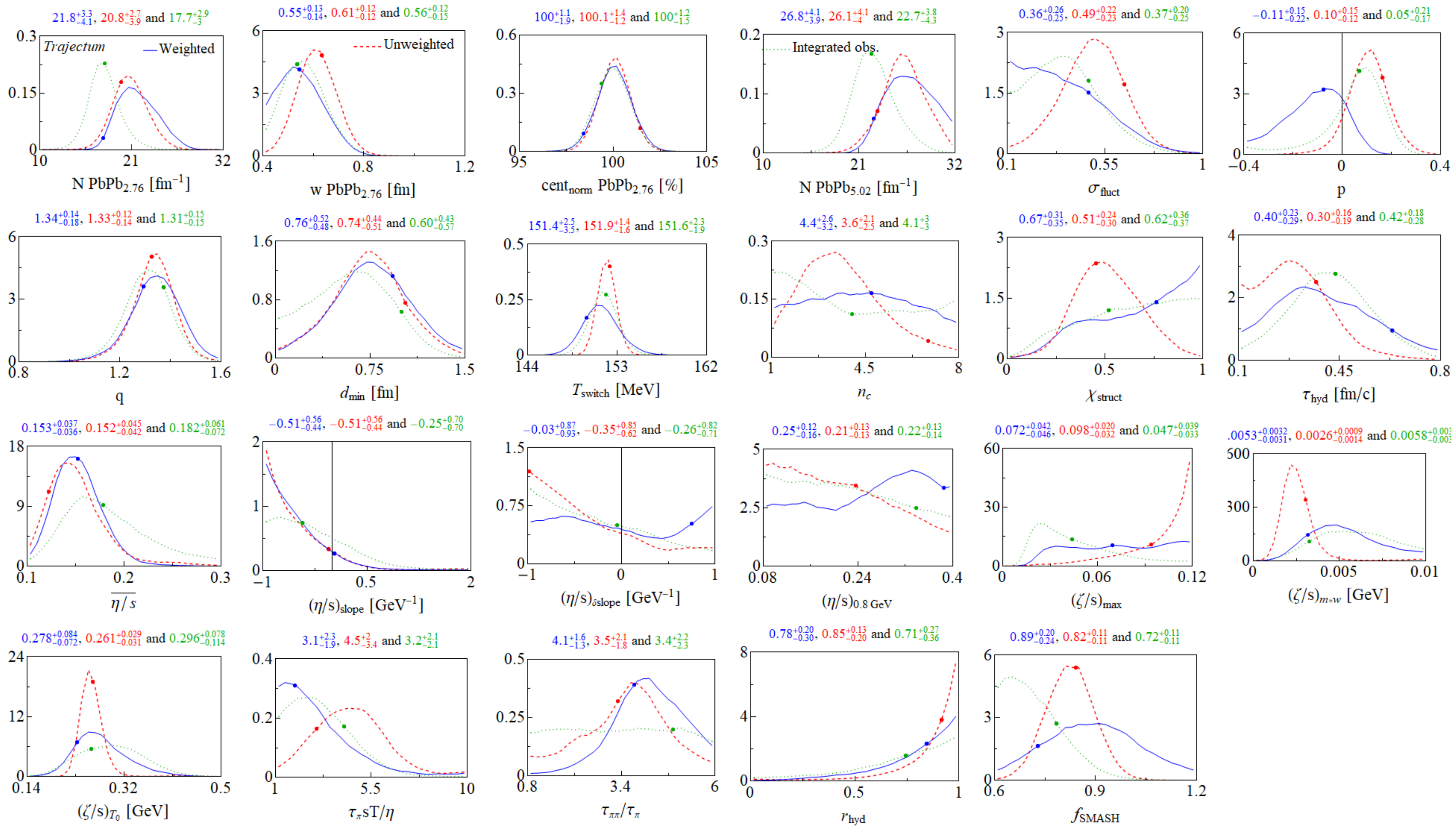


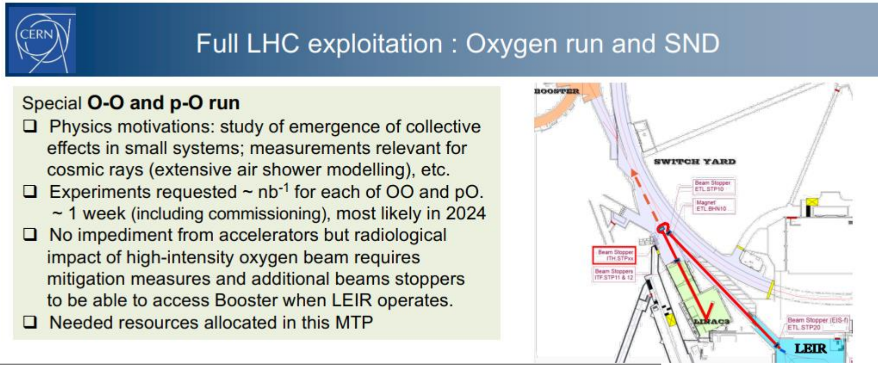
Full posterior distributions

1. Some parameters better constrained than others
   - Correlations add important information, e.g. width constrained much more accurately if *q* parameter is known



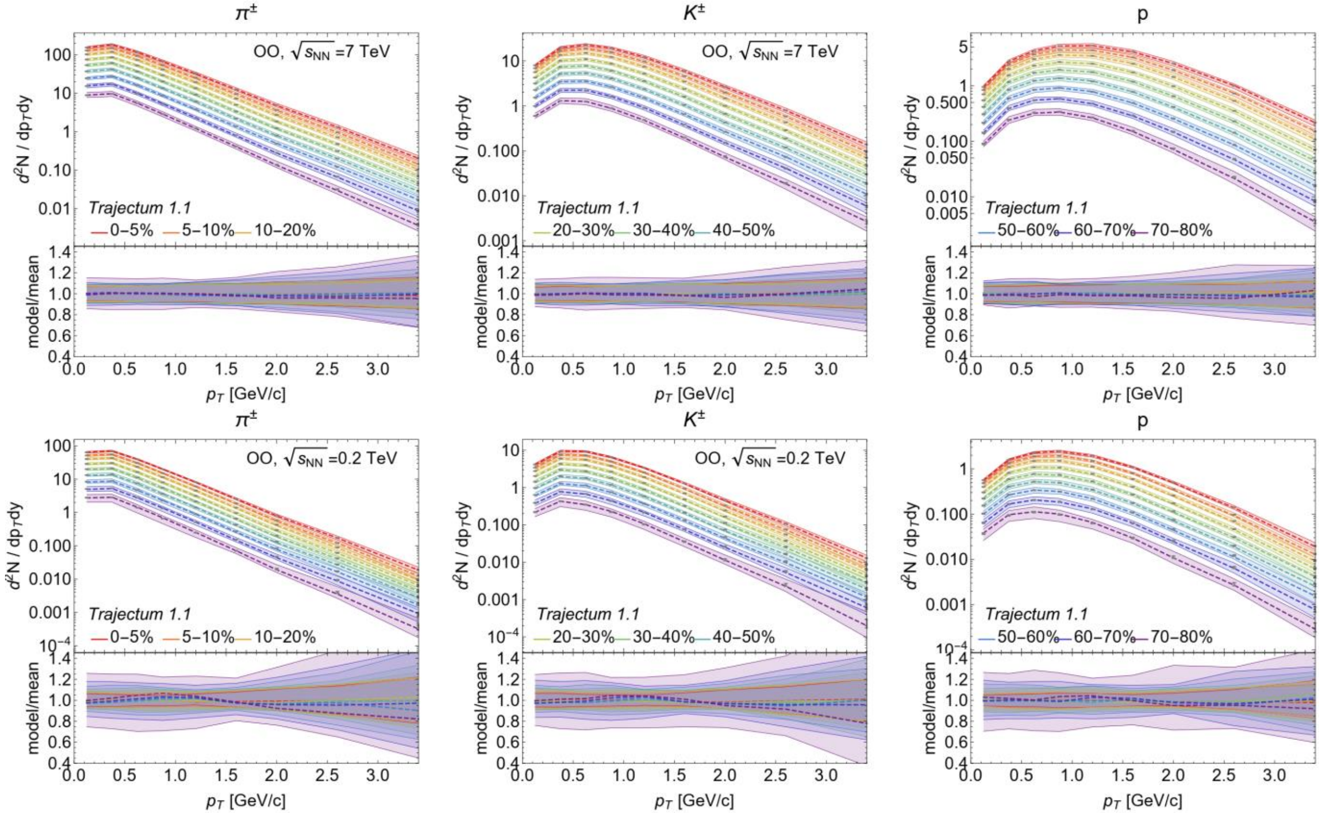
Full posterior distributions

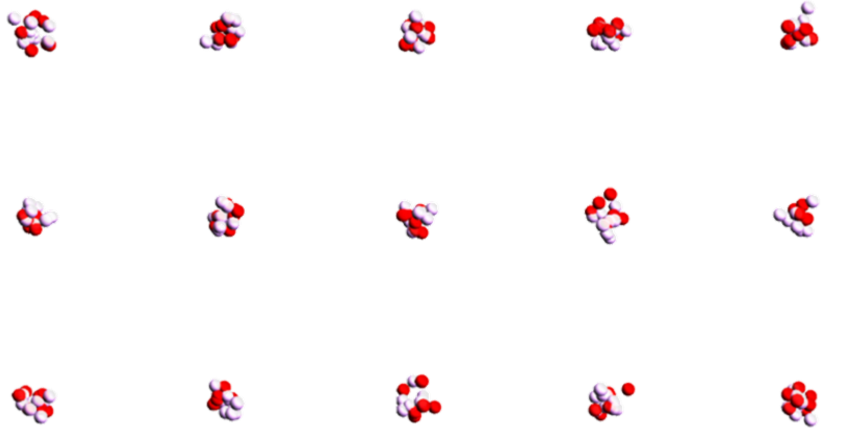




Exciting: oxygen-oxygen special run in 2024!

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

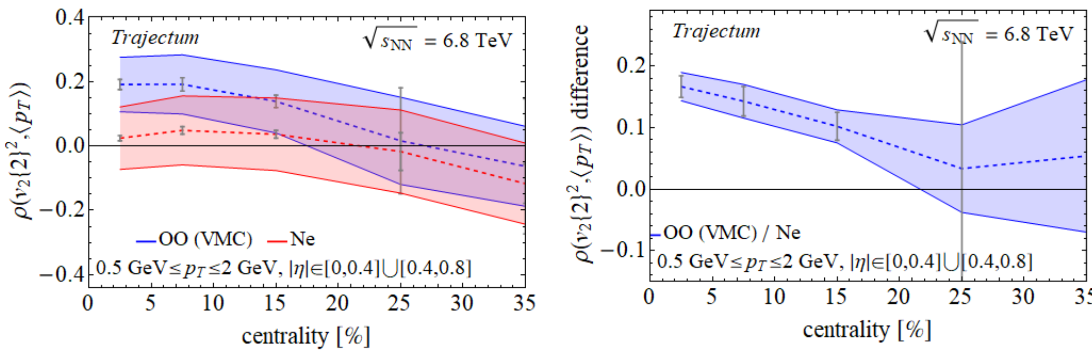


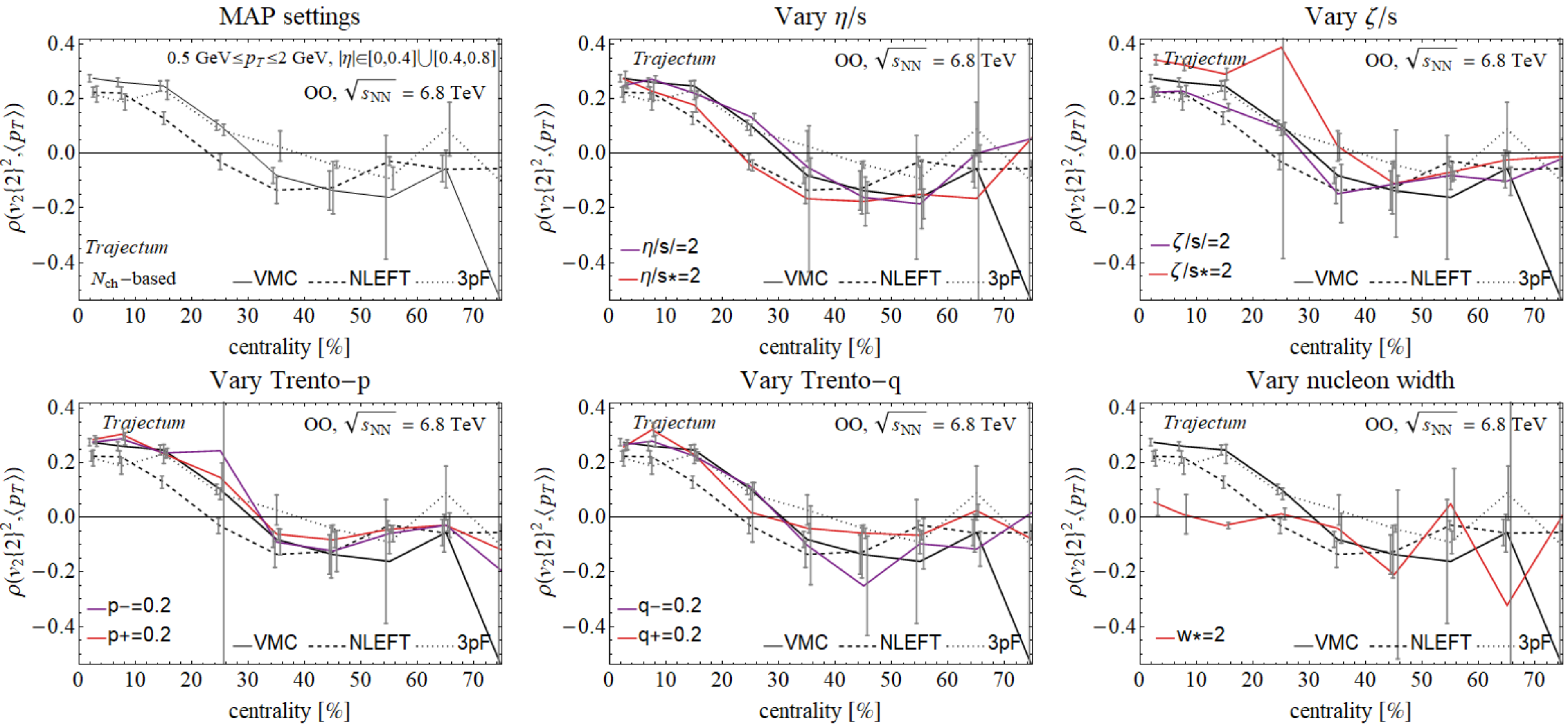


Jasmine Brewer, Aleksas Mazeliauskas and WS: http://cern.ch/ooatlhc or https://arxiv.org/abs/2103.01939
Govert Nijs and WS, Predictions and postdictions for relativistic lead and oxygen collisions with Trajectum (2021)

Correlation between v_2 and mean p_T

Vary some model parameters (for VMC only)





Conjectured to be a good observable. But must be careful with width and viscosities.