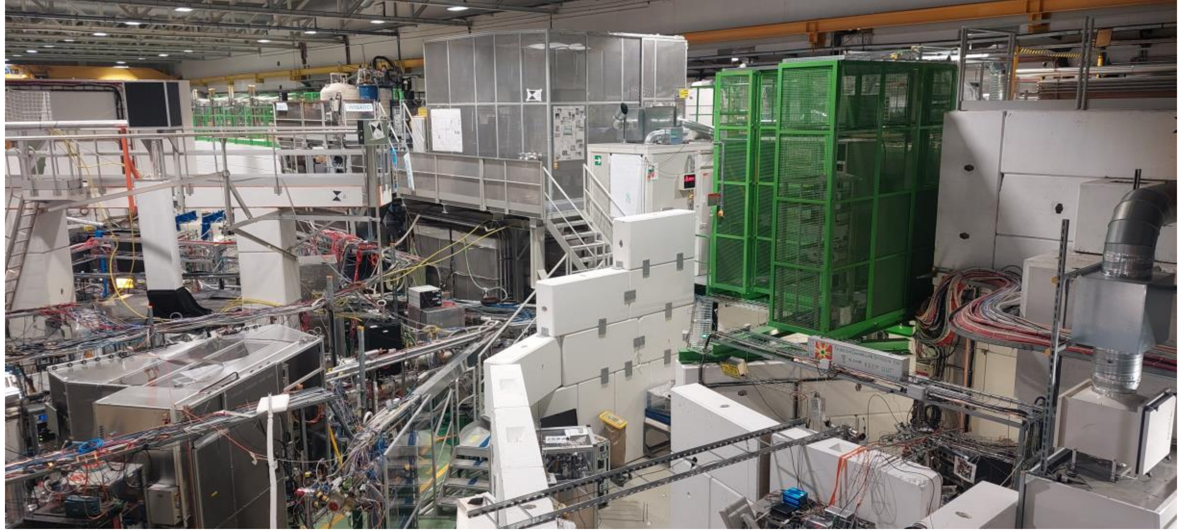
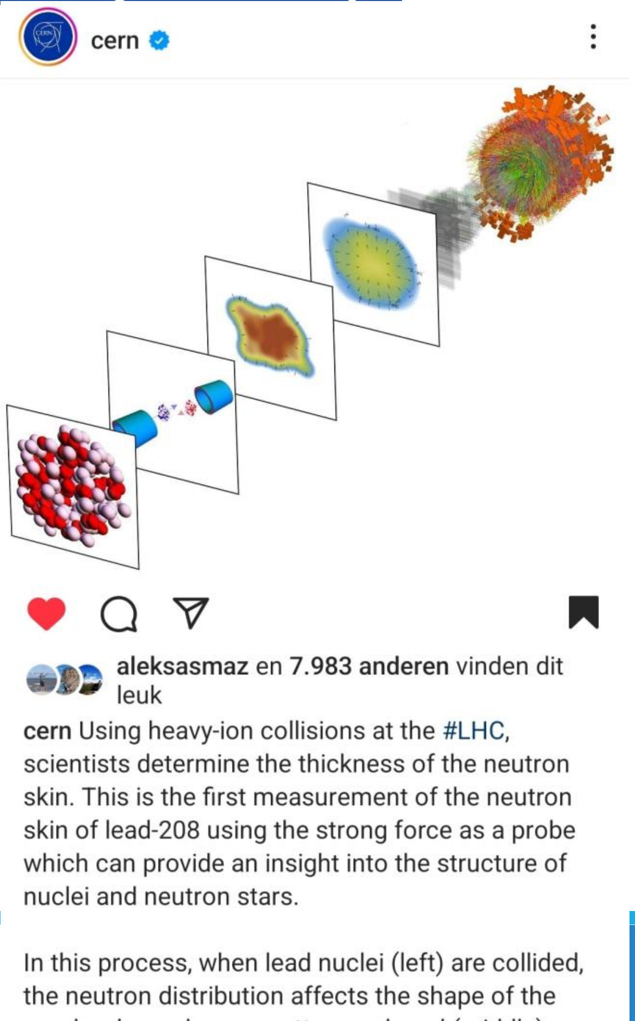
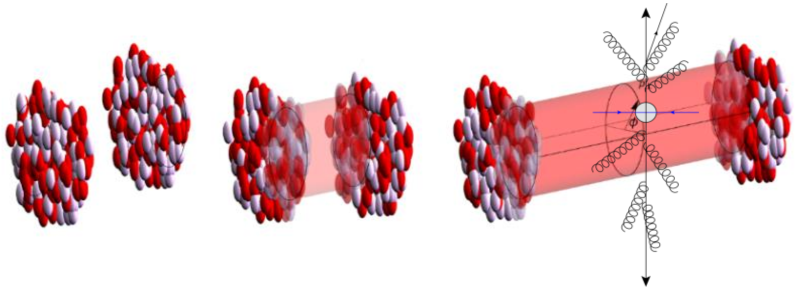




Determination of the neutron skin of ^{208}Pb from ultrarelativistic nuclear collisions

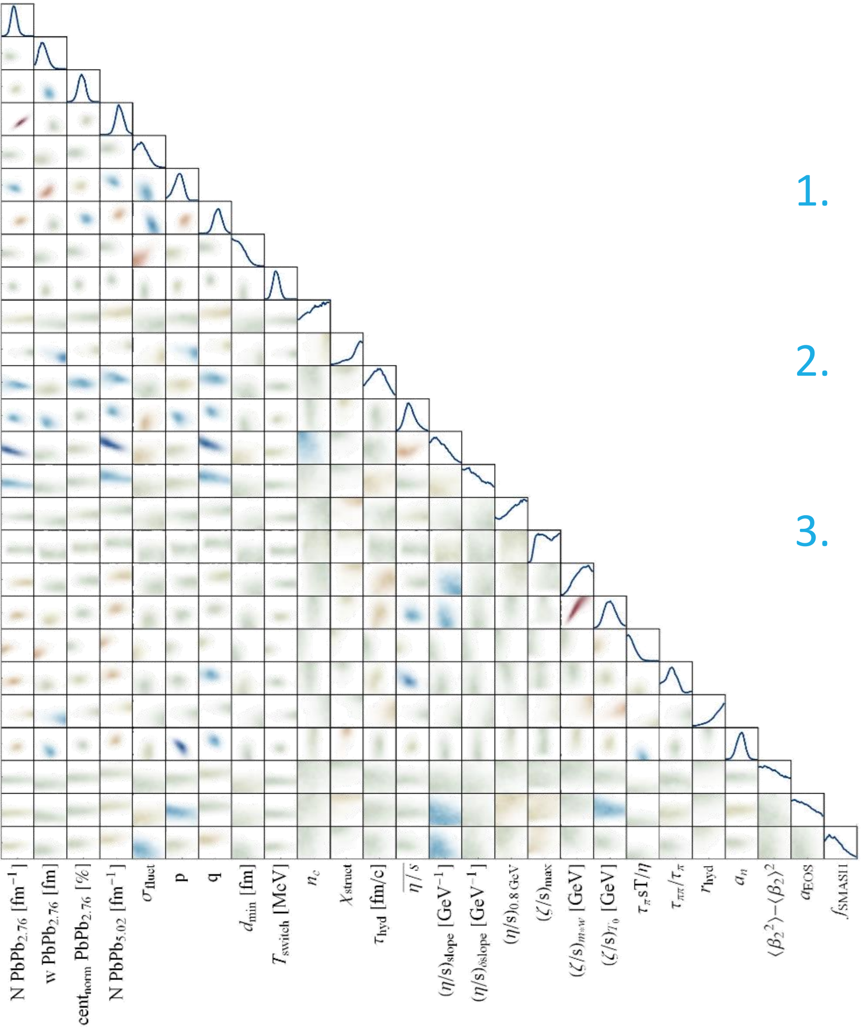
From nuclear structure from quark-gluon plasma

2305.00015 (PRL) with Govert Nijs and Giuliano Giacalone



Wilke van der Schee
Isolde Workshop, CERN
30 November 2023

Outline

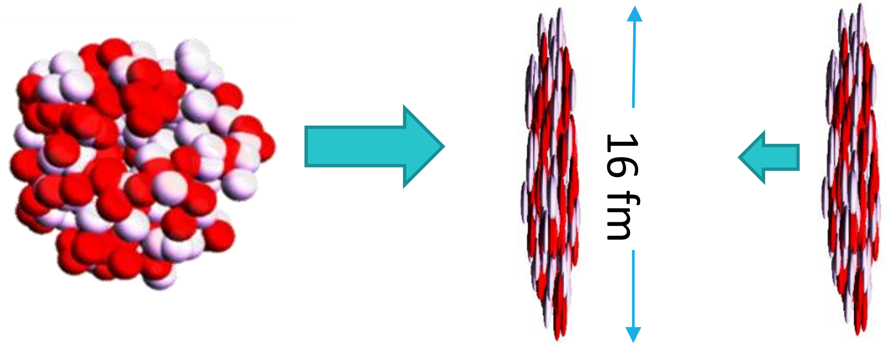


1. Brief introduction on relativistic heavy ion collisions
2. Neutron skin, also as an illustration of Bayesian analyses
3. The shape of nuclei and preparing for oxygen collisions

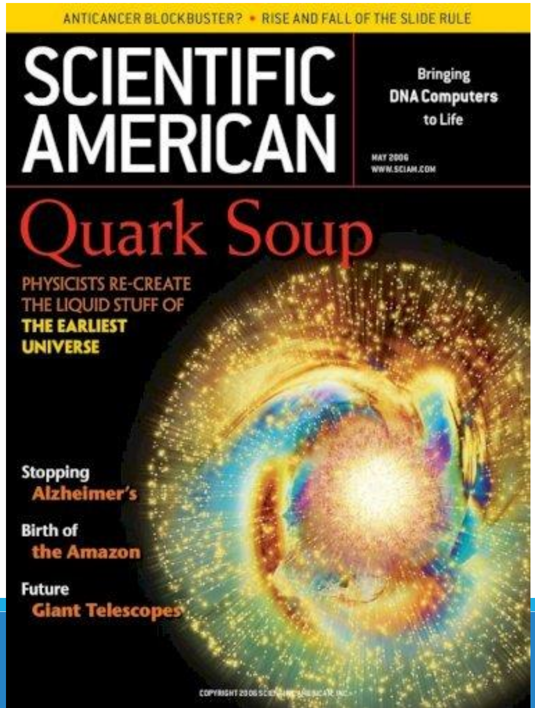
How to create QGP

Colliding heavy nuclei (Pb) at high energies

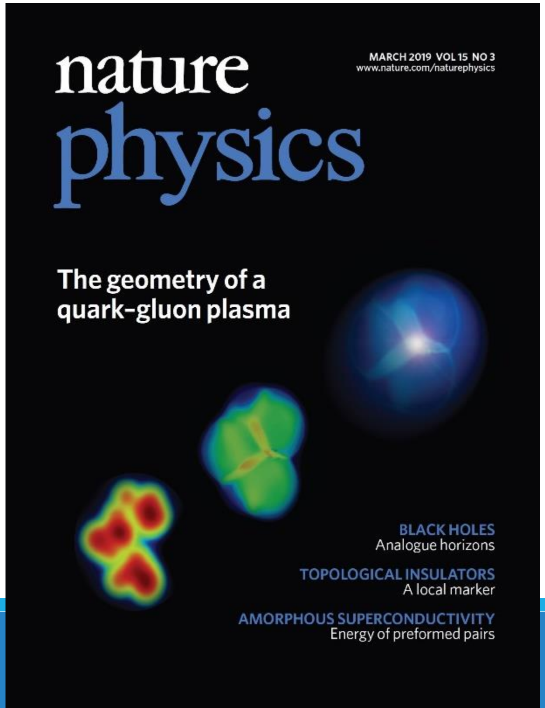
Lorentz gamma factor up to 2500



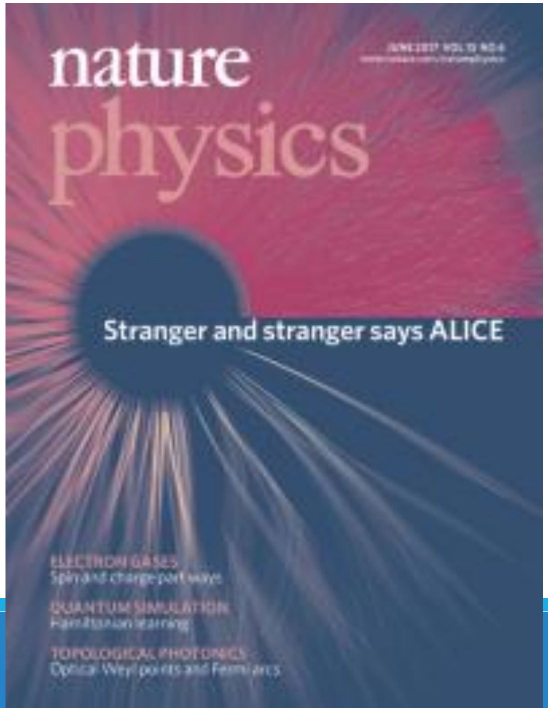
Hottest fluid:
10^{12} K



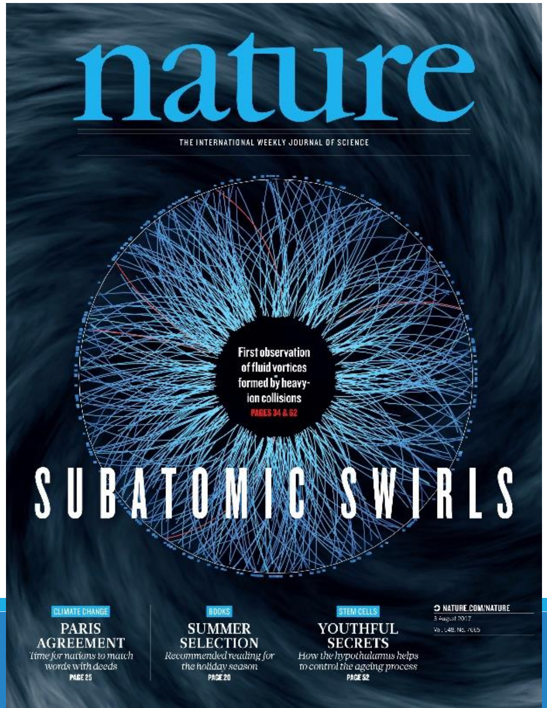
Smallest fluid:
~ 2 fm living 10^{-23} s



Most perfect/strange:
η/s ~ 0.08

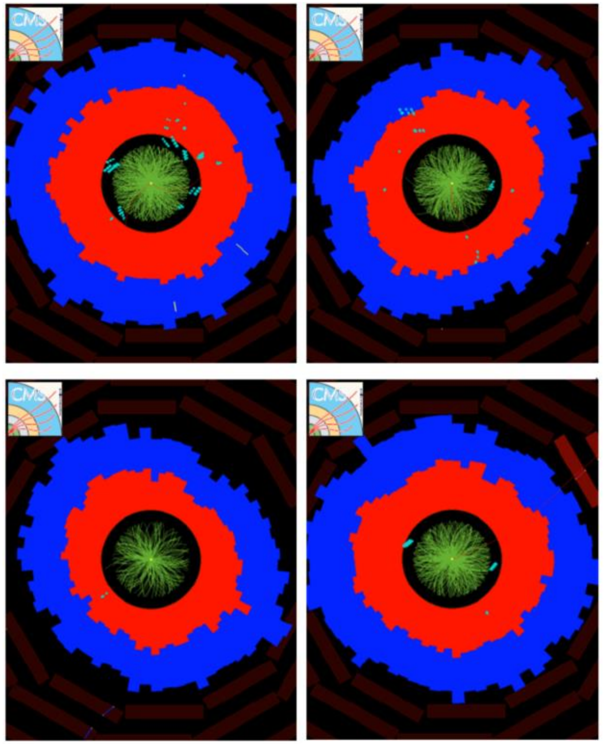


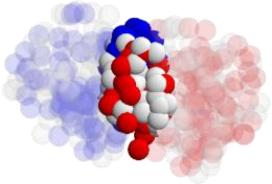
Most vortical fluid:
ω ~ 10^{22}/s



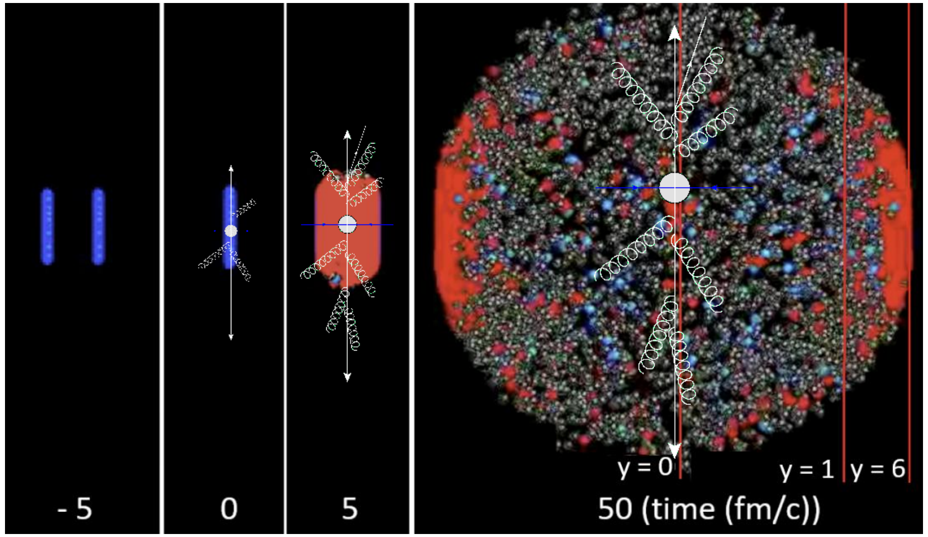
Quark-gluon plasma is strongly coupled

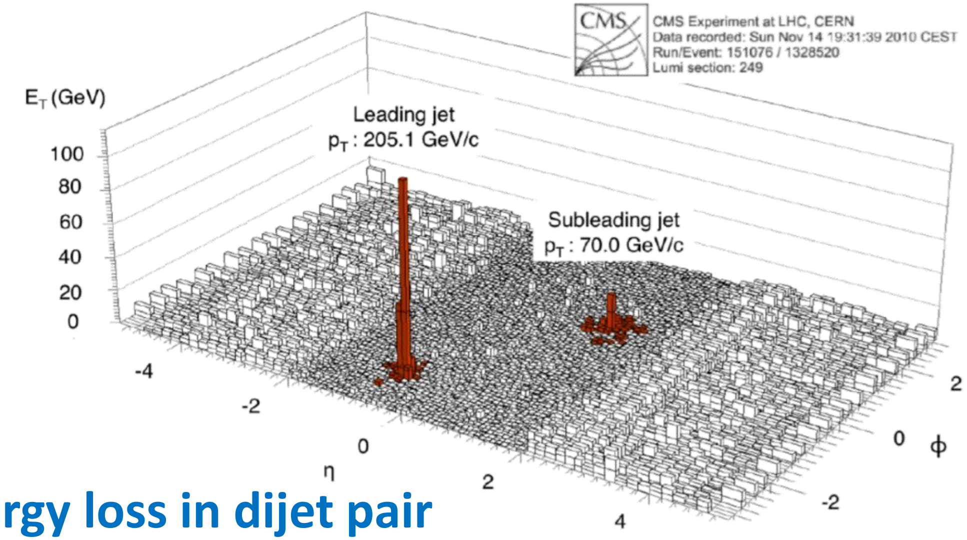
Anisotropic flow (small viscosity)





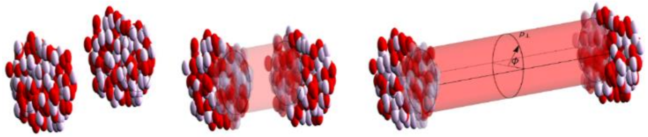
Initial stage - QGP - hadronic phase





Jet energy loss in dijet pair

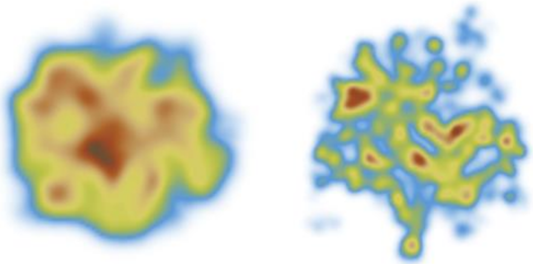
Standard model of heavy ion collisions



(# parameters)

Initial stage (13)

Subnucleonic structure? (8)



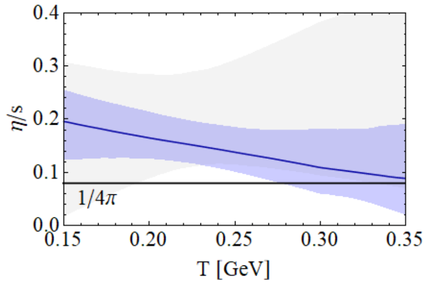
Non-thermal flow? (2)
with hydrodynamised initial stage

Fluctuations? (1)

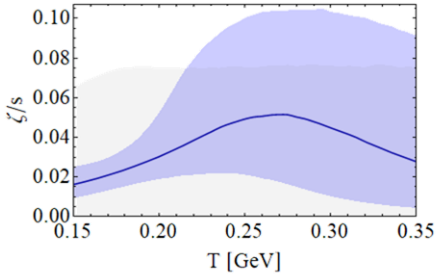
Shape (2)

Viscous hydrodynamics (10)

Shear viscosity (4)



Bulk viscosity (3)

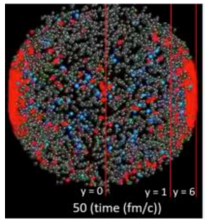


Second order transports: 2

EOS: 1

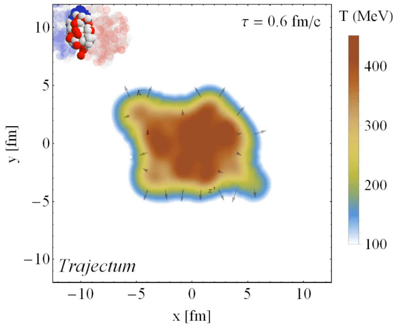
Cascade of hadrons (2)

SMASH



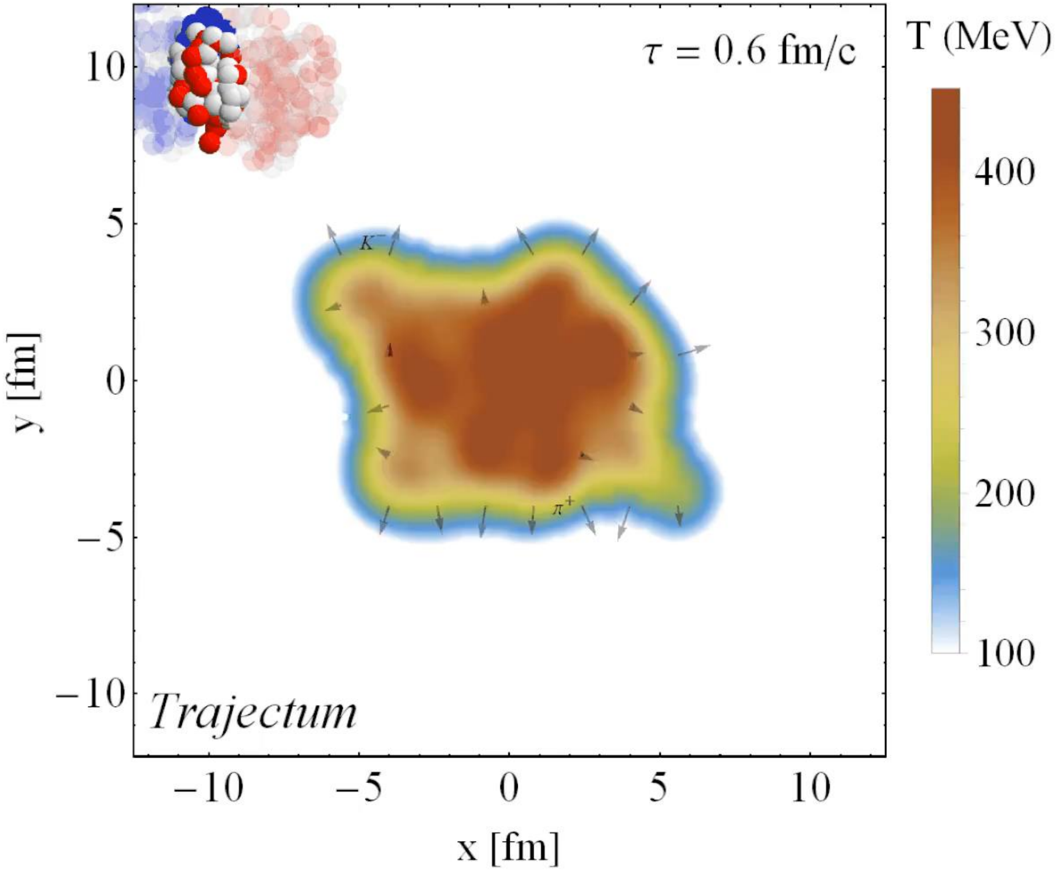
Jonah Bernhard, Scott Moreland and Steffen Bass, Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma (2019)
Govert Nijs, WS, Umut Gursoy and Raimond Snellings, A Bayesian analysis of Heavy Ion Collisions with Trajectum (2020)

Trajectum



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

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

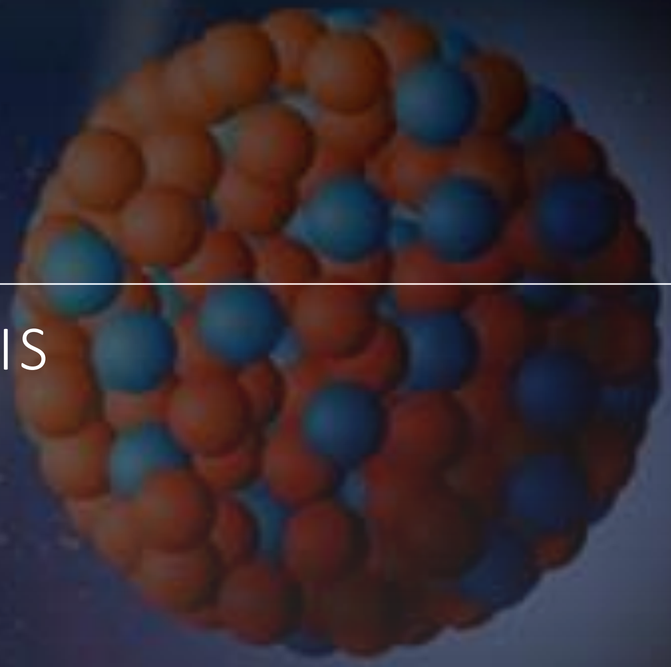



```
general{
    output=out
    format=smash
    f0500=false
    numevents=1
    seed=7398984.747399307
    debugoutput=true
    numthreads=2
}

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=0.666666666666
    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

Neutron skin

WITH A SHORT INTRO ON BAYESIAN ANALYSIS



Bayes theorem:

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

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

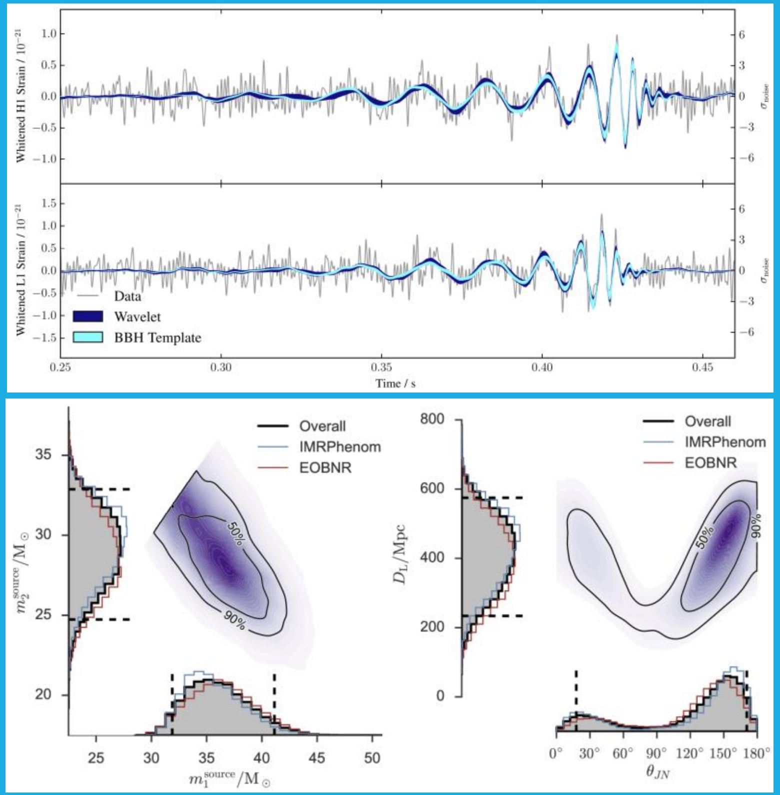
Performing a global analysis

Model depends on parameters non-linearly
- Run model on 3000 `design' points
- Use an emulator for any point in parameter space (**GP**)

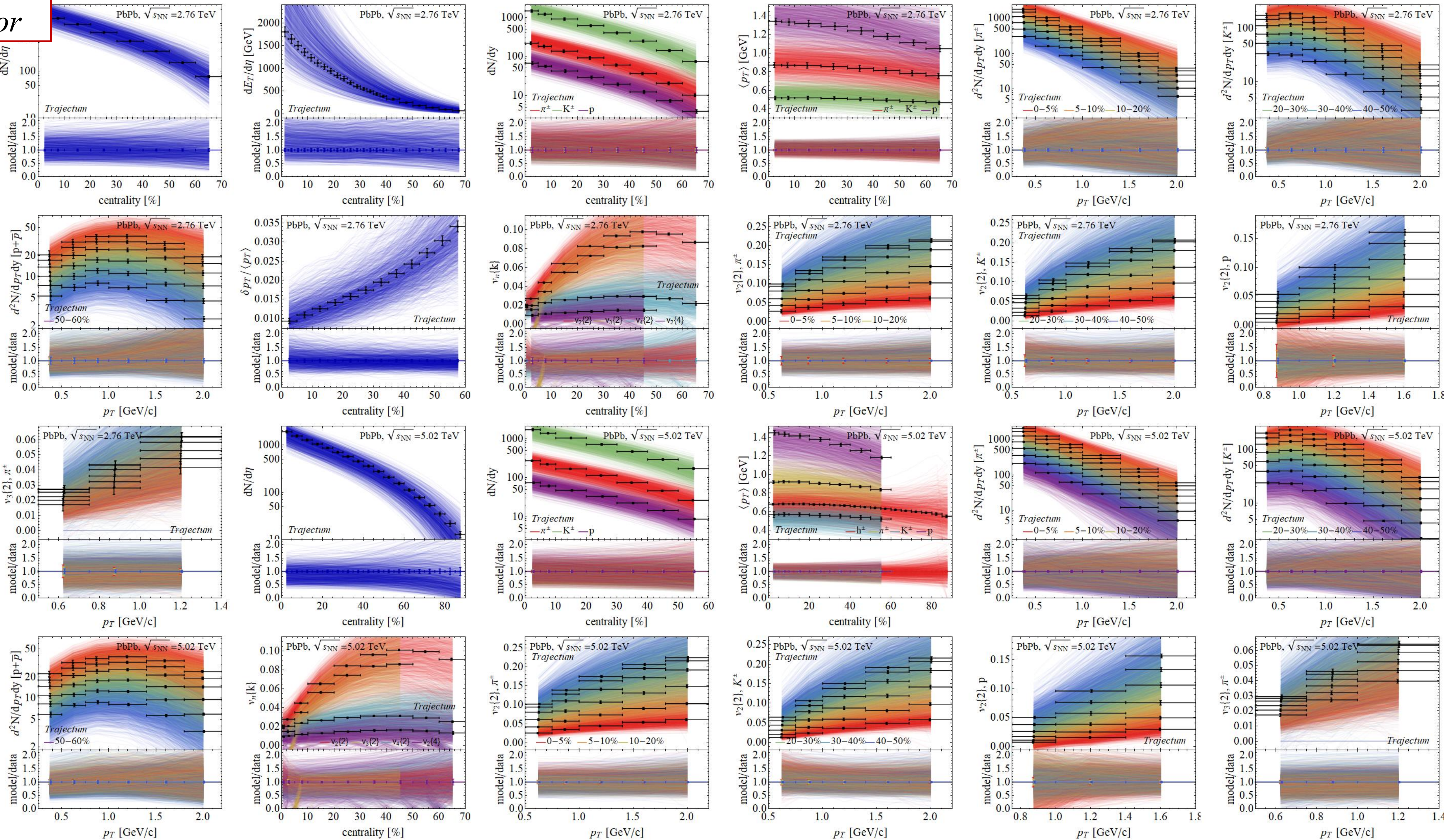
Markov Chain Monte Carlo
- 653 data points
- Obtain posterior probability density of parameters

Compare posterior with data
- Can include high statistics run

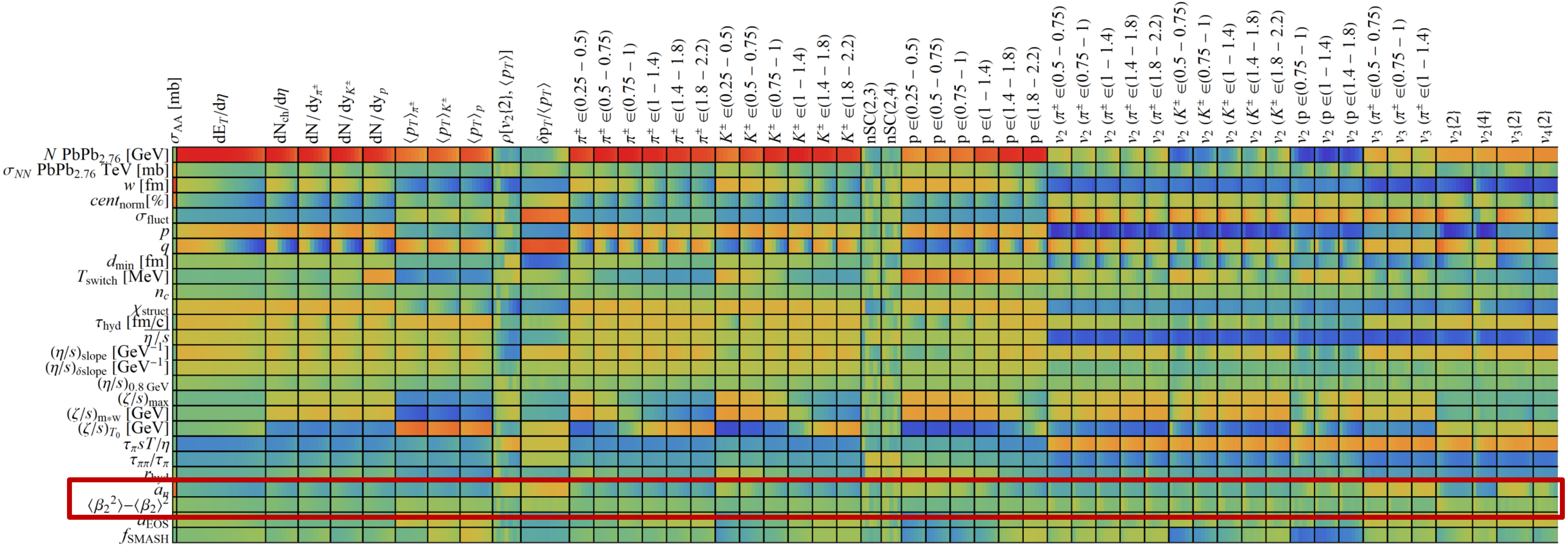
Same technique: gravitational waves



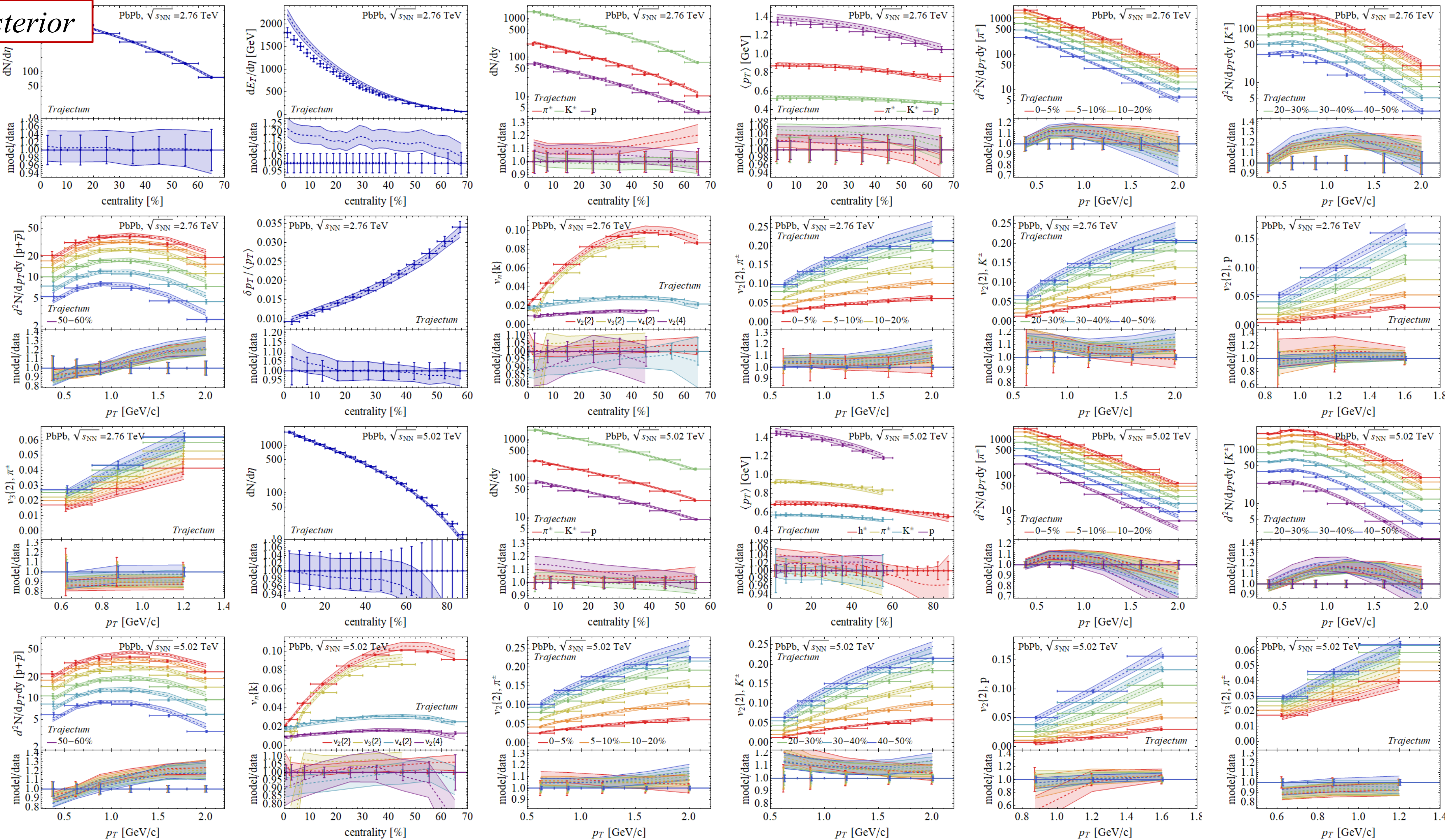
Prior


PbPb, $\sqrt{s_{NN}}$ =2.76 TeV
PbPb, $\sqrt{s_{NN}}$ =5.02 TeV
Trajectum
dN/dη
dE_T/dη [GeV]
dN/dy
⟨p_T⟩ [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%
$v_2\{2\}$ $v_3\{2\}$ $v_4\{2\}$ $v_2\{4\}$

Design parameter-observable correlations:

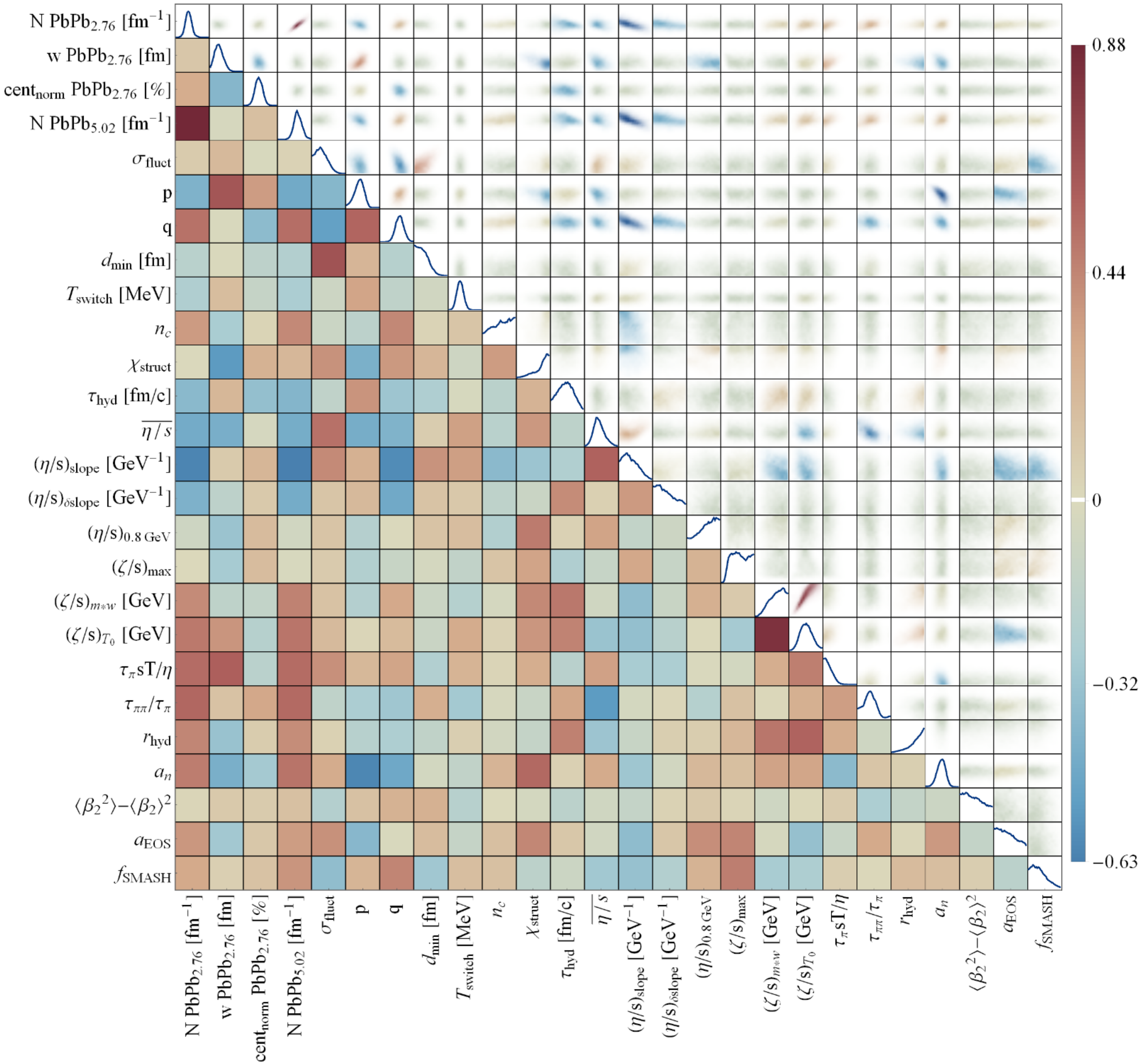


Posterior


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%
$v_2\{2\}$ — $v_3\{2\}$ — $v_4\{2\}$ — $v_2\{4\}$

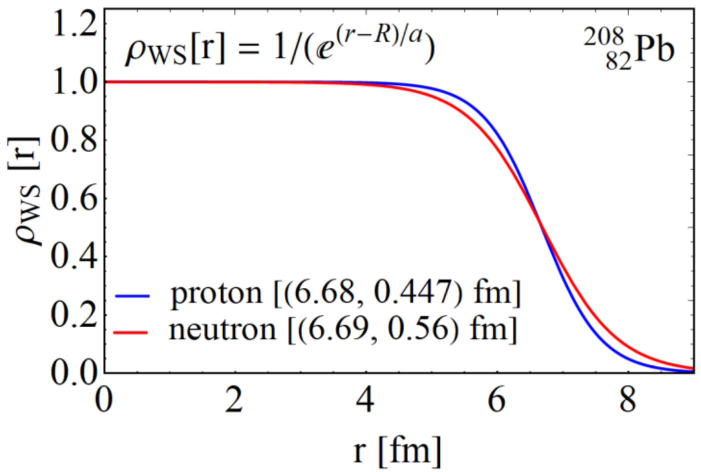
Full posterior distributions

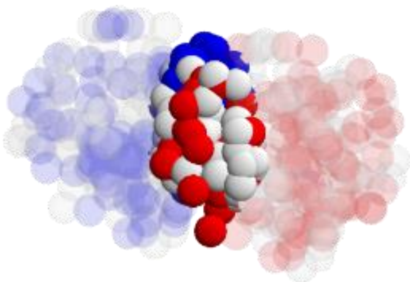
1. Some parameters better constrained than others
    - Correlations add important information, e.g. width constrained much more accurately if *q* parameter is known



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 state-of-the-art …
4. Profile influences many observables
   - Interplay with bulk viscosity, Trento model etc
   - Likely need a full global analysis



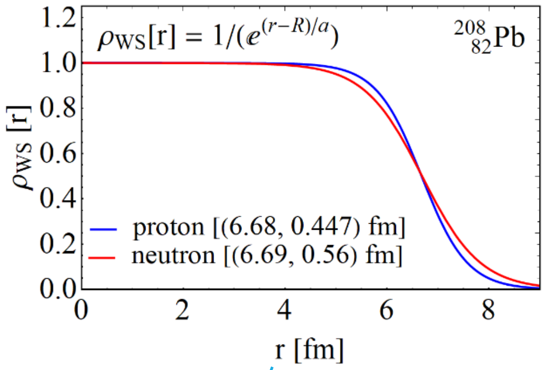


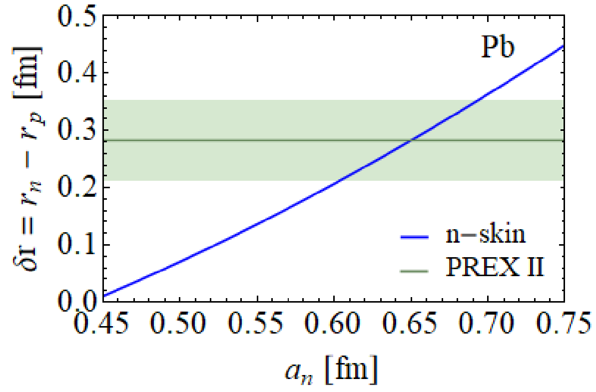
Constantin Loizides, Jason Kamin and David d'Enterria, Improved Monte Carlo Glauber predictions at present and future nuclear colliders (2017)

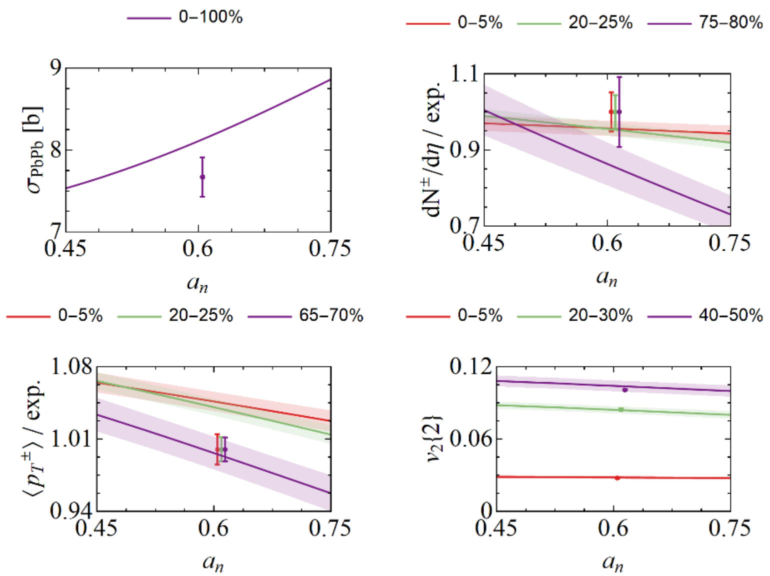
The neutron skin - emulator

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)

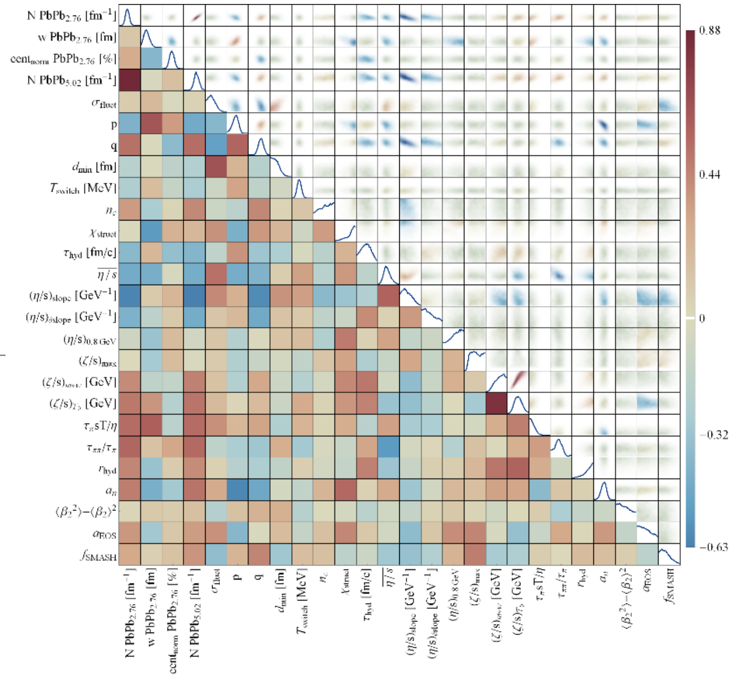






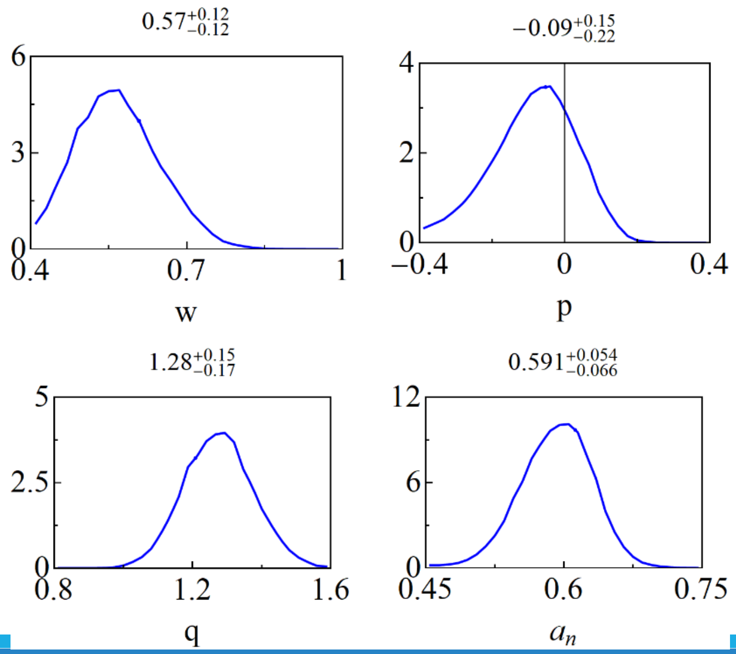
1. Main change: cross section
   - Measures 'size' of nucleus
2. Both multiplicity and mean pT change
   - Mainly for peripheral ('skin effect')
3. Small changes for other observables

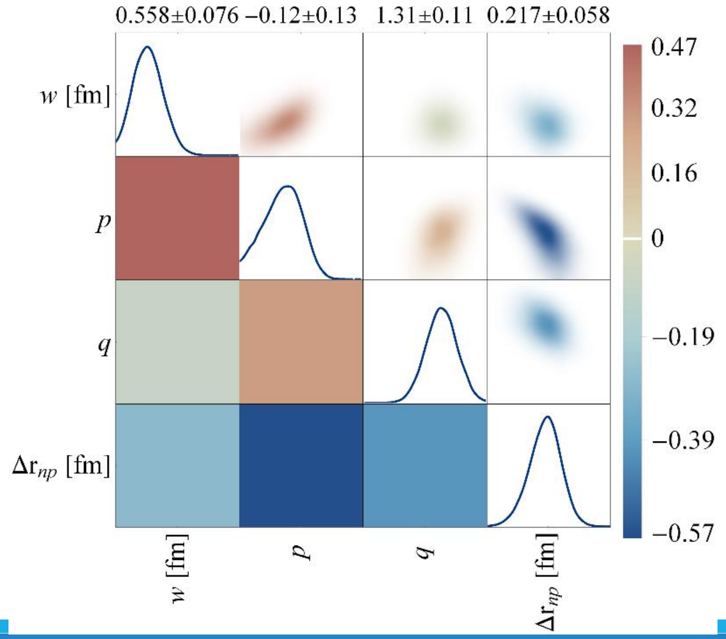
$$\mathcal{E} \propto \left(\tfrac{1}{2}T_A^p + \tfrac{1}{2}T_B^p\right)^{q/p} = (T_A T_B)^{q/2}\,|_{p=0}$$

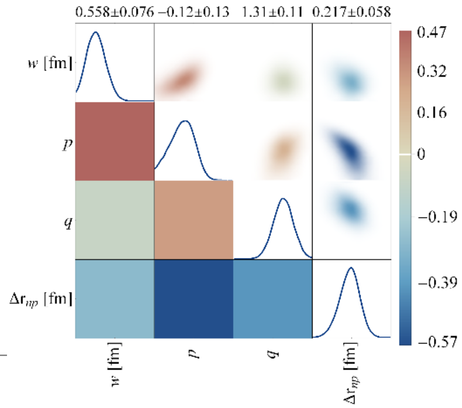


The neutron skin - posterior

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 important

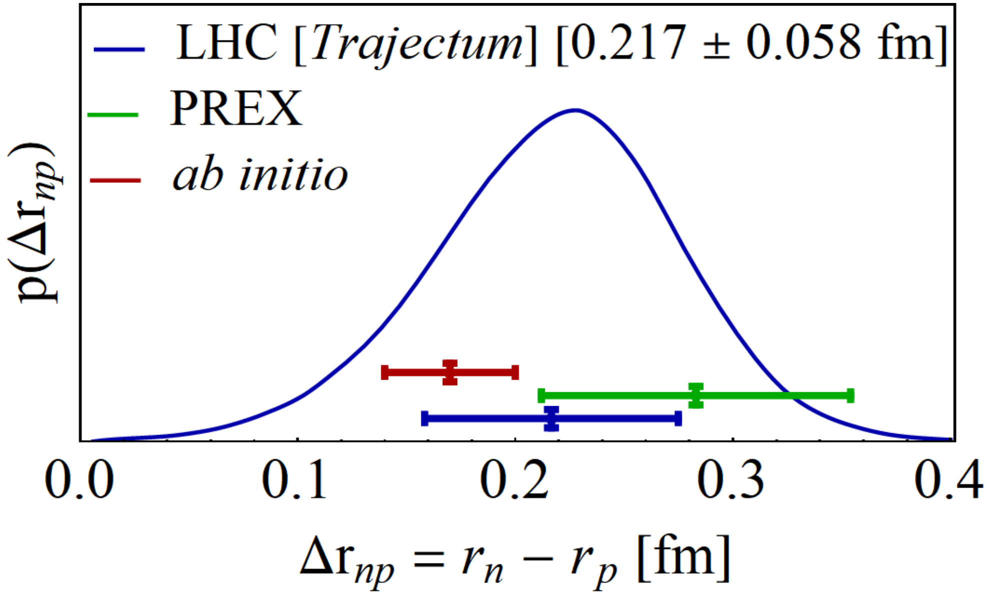




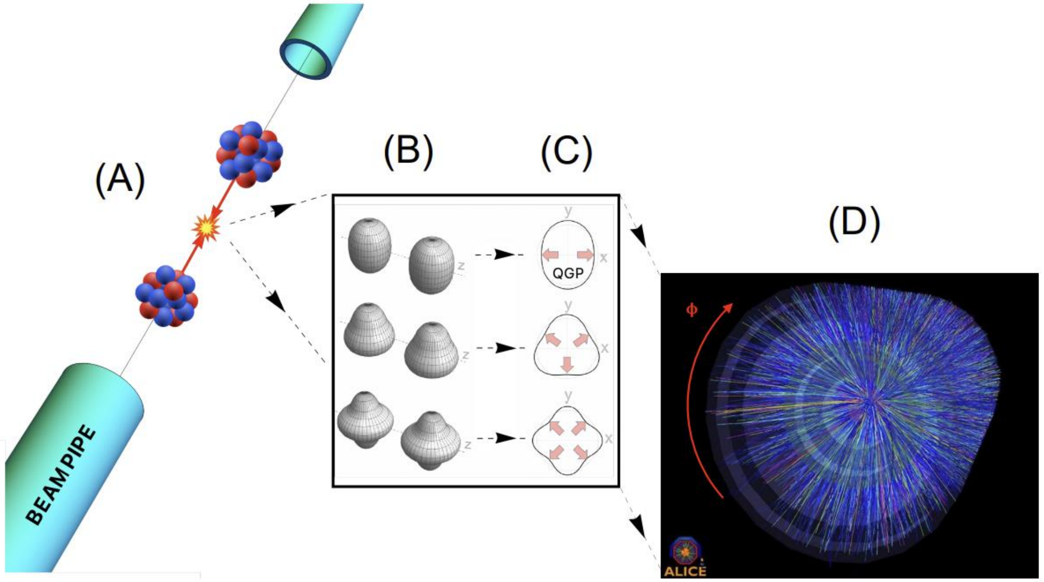


The neutron skin – final result

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



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)

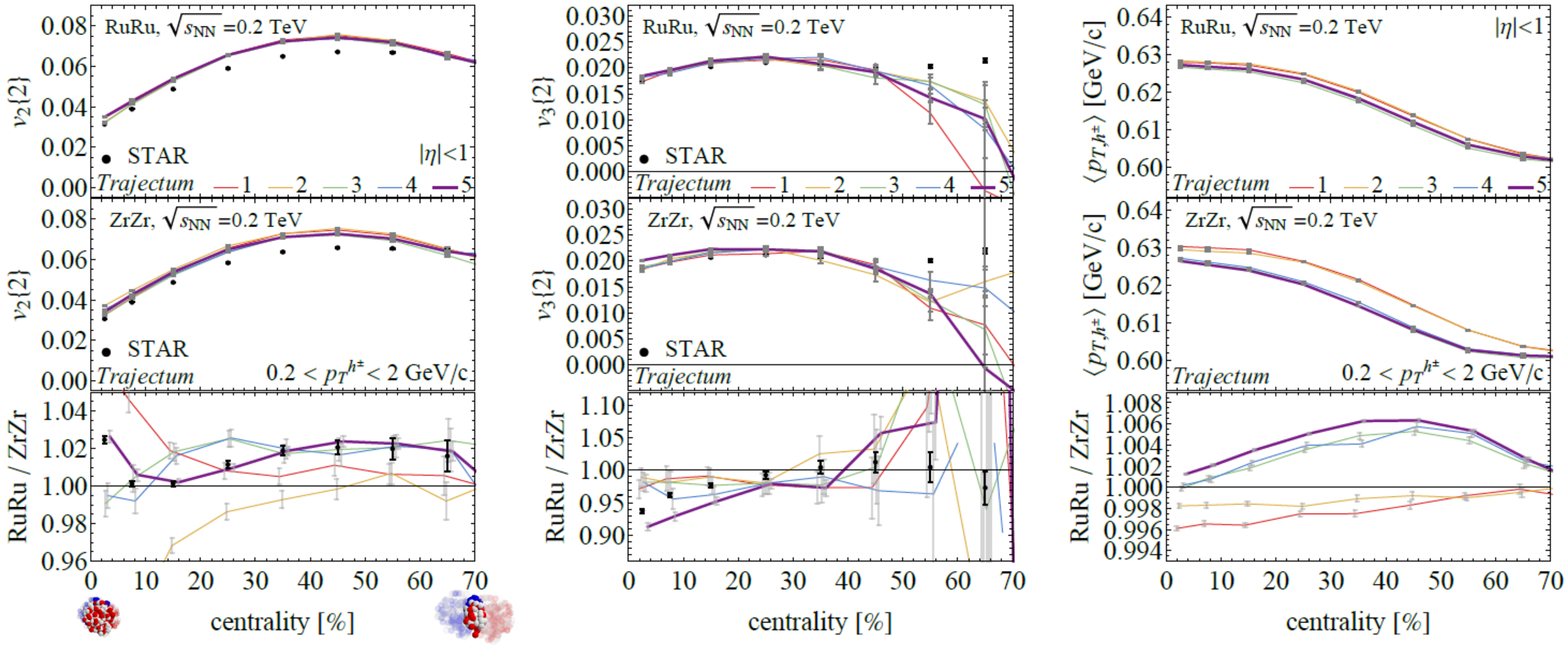
Isobar collisions at STAR – Flow and mean p_T

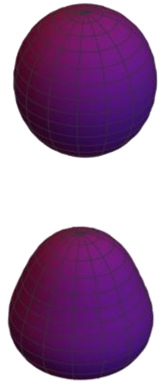
RuRu

ZrZr

Ratio

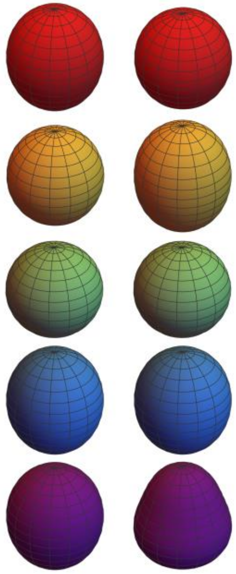
$v_2\{2\}$ $v_3\{2\}$ $\langle p_{T,h^\pm} \rangle$





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

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

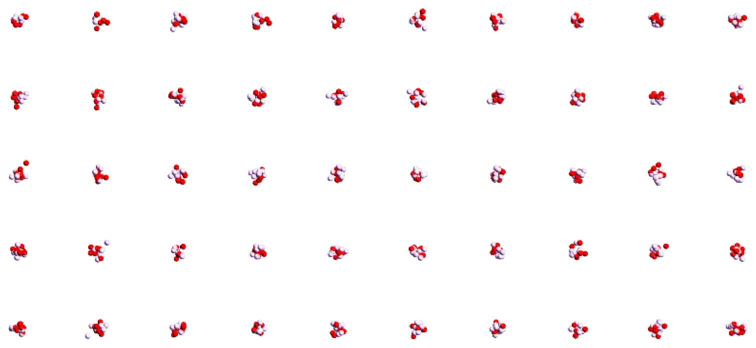


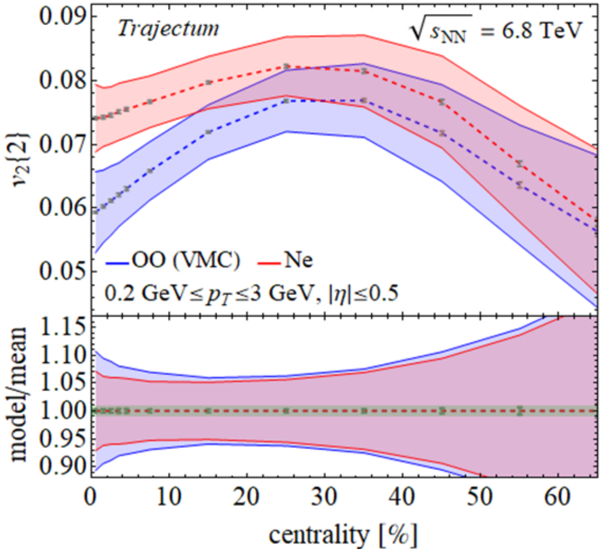
Original motivation was to study Chiral Magnetic Effect (CME, not found…)

- 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)

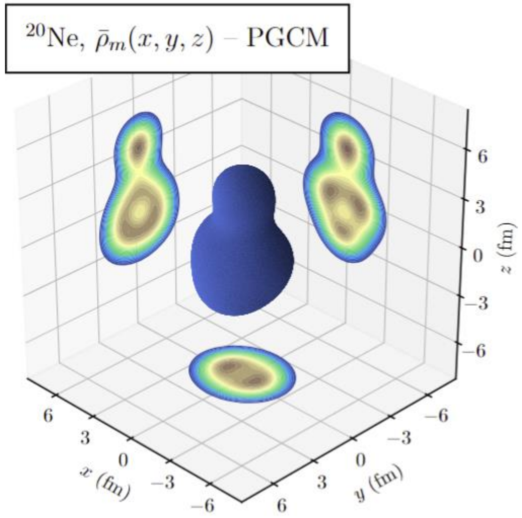
^{16}Oxygen and ^{20}Neon nuclear structure

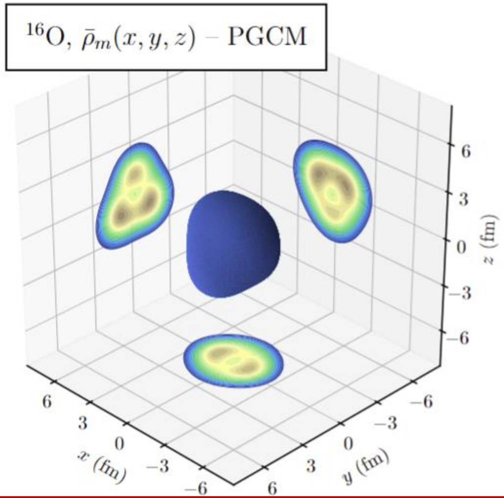


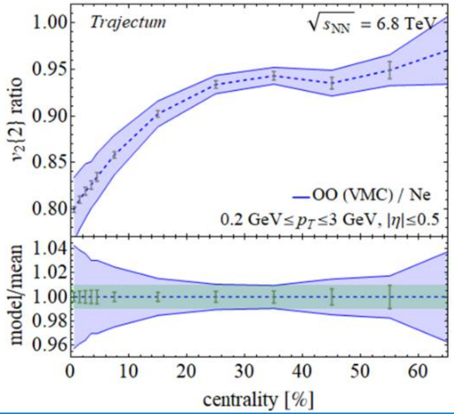


Do we understand and/or need to understand the shape of O and Ne?

- Naively it seems so: large uncertainty
- Interesting by itself: combination of 4 or 5 alpha particles
- State-of-the-art Projected Generator Coordinate Method (PGCM) and NLEFT results:







Work in process with B. Bally, D. Lee et al

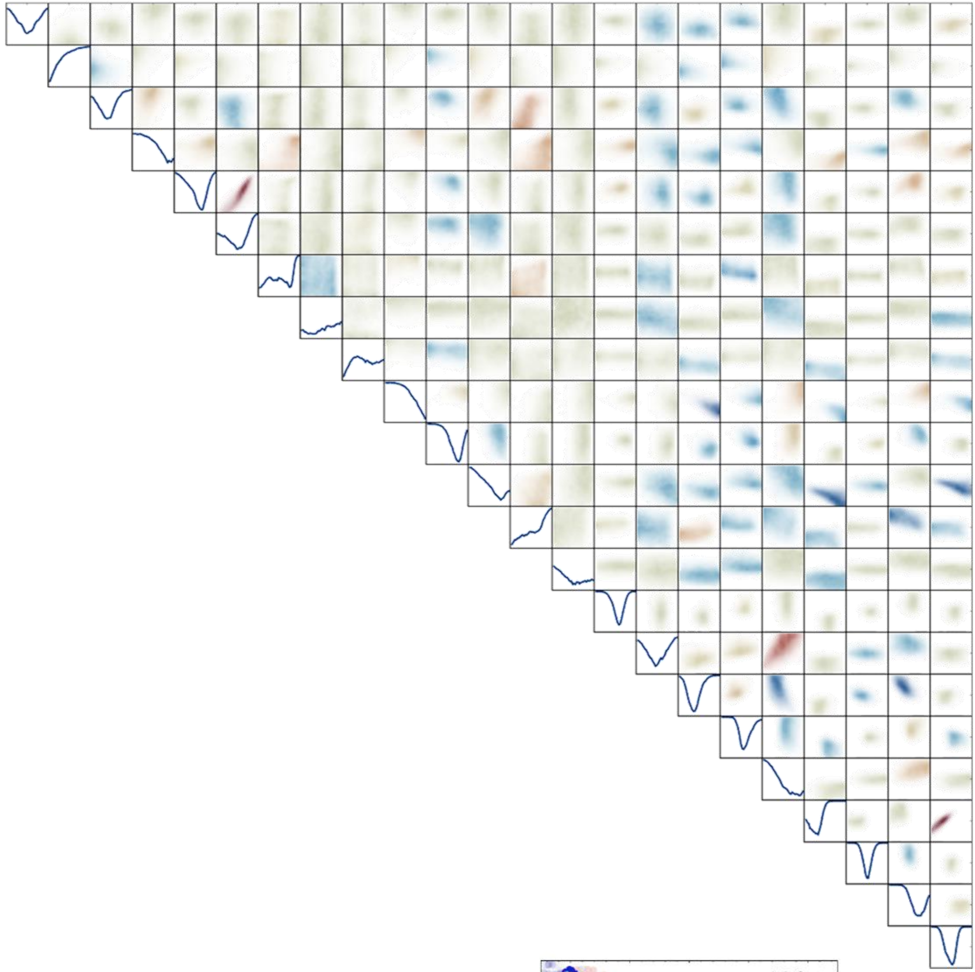
Discussion

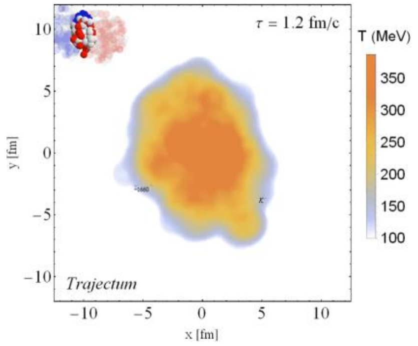
Exciting progress using global analyses

- Heavy ion collisions towards percent level precision
- Nuclear structure becoming relevant and interesting

First study for neutron skin, many improvements possible

Oxygen collisions to be performed at the LHC summer 2024!



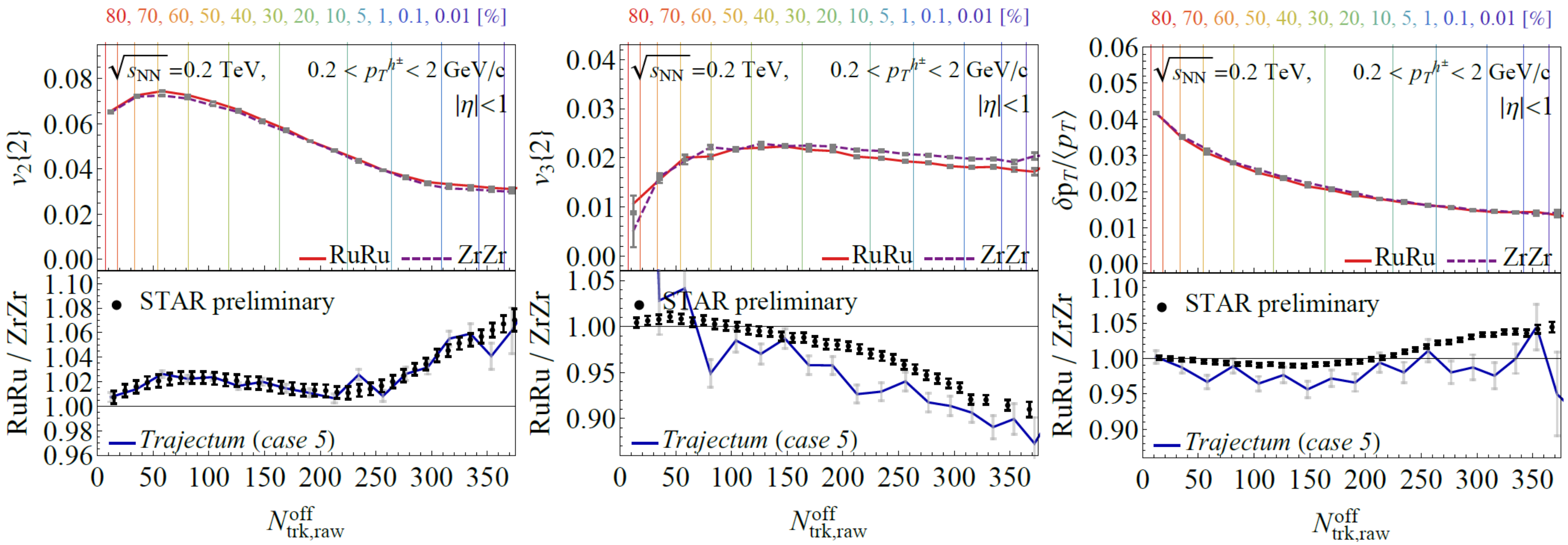


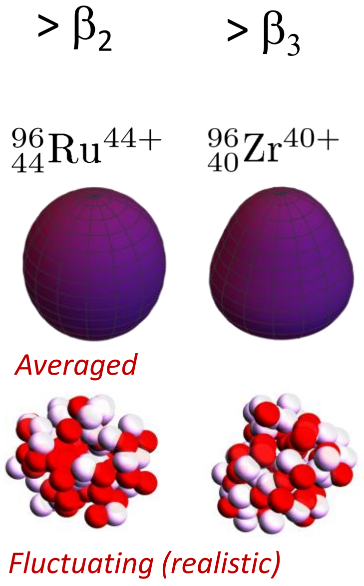
Back-up

Extremely ultracentral collisions

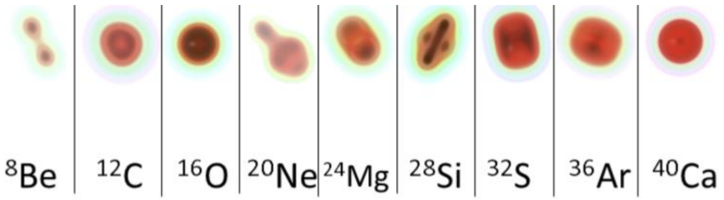
Going to 0.01% centrality (we sample from 250M Trento events)

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

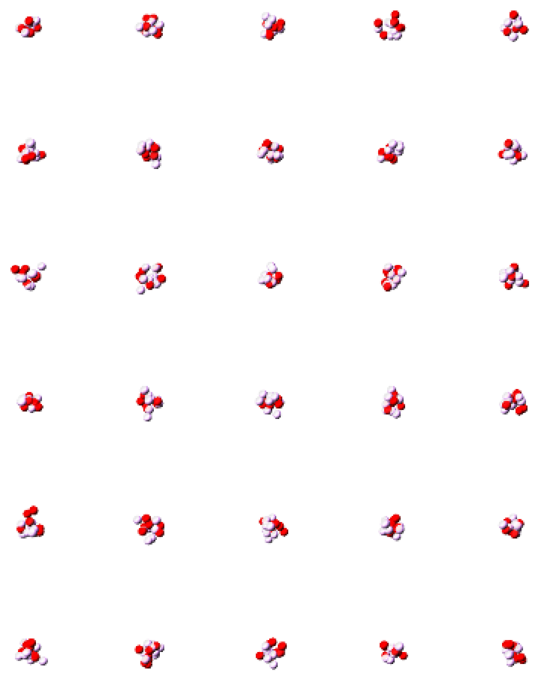




ATHIC2021 talk Chunjian Zhang, https://drupal.star.bnl.gov/STAR/files/ATHIC_Nov_STAR_SBU_ChunjianZhang.pdf



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)