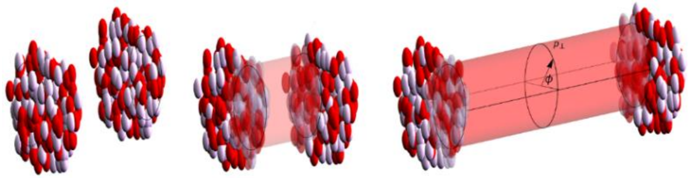
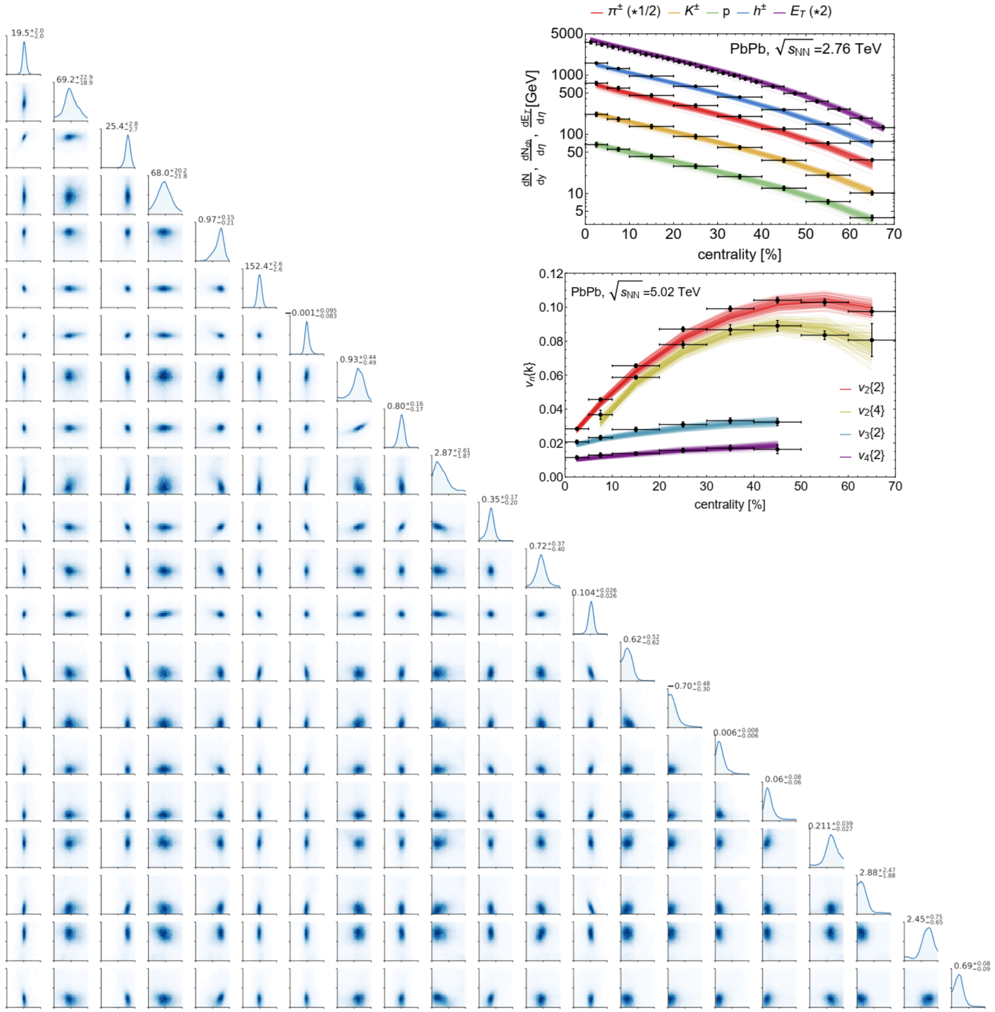
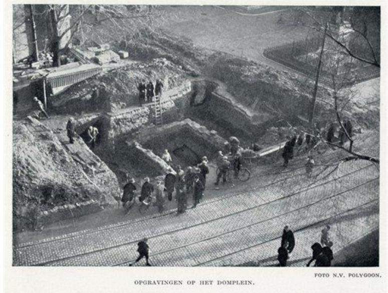


Theory of heavy ions in the LHC era

Towards a precision analysis of heavy ion collisions

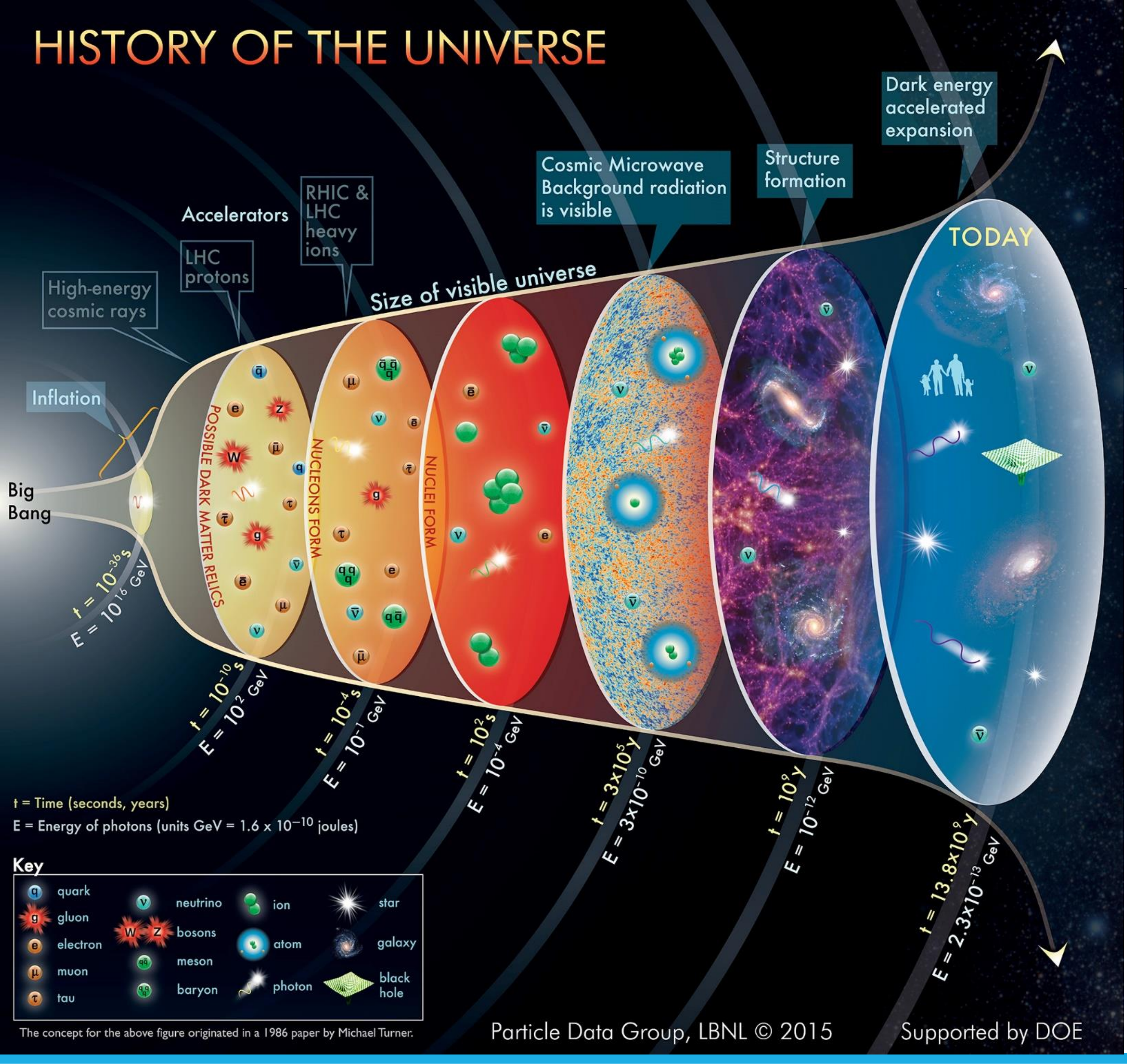
Based on *Trajectum* with Govert Nijs
2010.15130, 2010.15134 with Govert Nijs, Umut Gursoy and Raimond Snellings





Roman excavations in Utrecht (from Trajectum, or bridge) in 1929

Wilke van der Schee
NIKHEF colloquium, Amsterdam
5 March 2021



The concept for the above figure originated in a 1986 paper by Michael Turner.

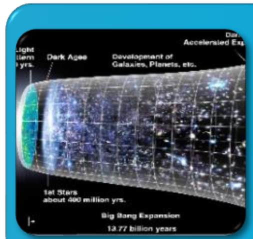
Particle Data Group, LBNL © 2015

Supported by DOE

Quark-gluon plasma (QGP)

Quantum-Chromodynamics (QCD)

A fundamental force of nature



Recreating the big bang

At age 1 µs the entire universe was QGP!

QGP turns out interesting

Strongly coupled quantum matter

The QCD phase diagram

Strong coupling: first principle only from lattice QCD

- Smooth cross-over from confined hadron gas to deconfined QGP

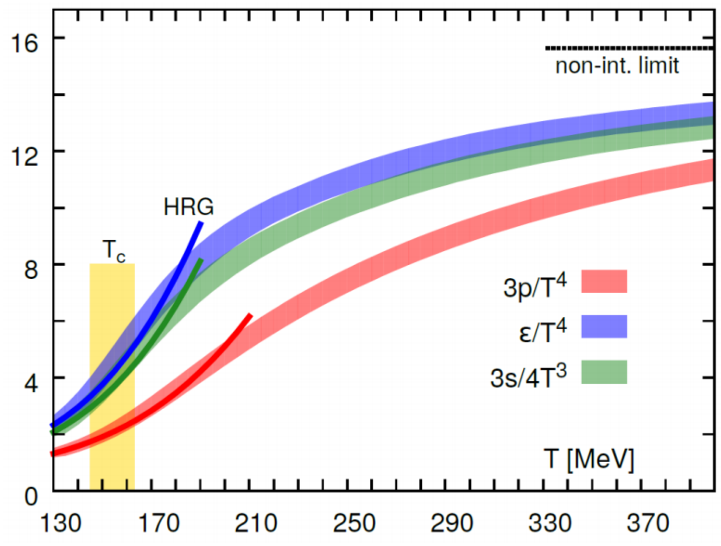
Sign problem: only Euclidean

- Problematic to study baryon chemical potential (neutron stars)
- Problematic to study real-time dynamics (shear viscosity)

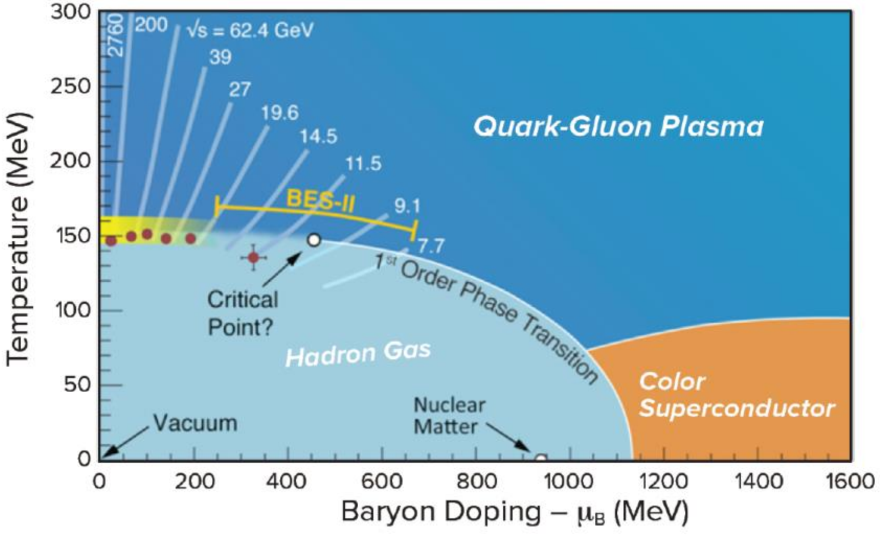
A conjectured critical point in reach of RHIC energies?

- LHC does not reach high enough baryon number densities

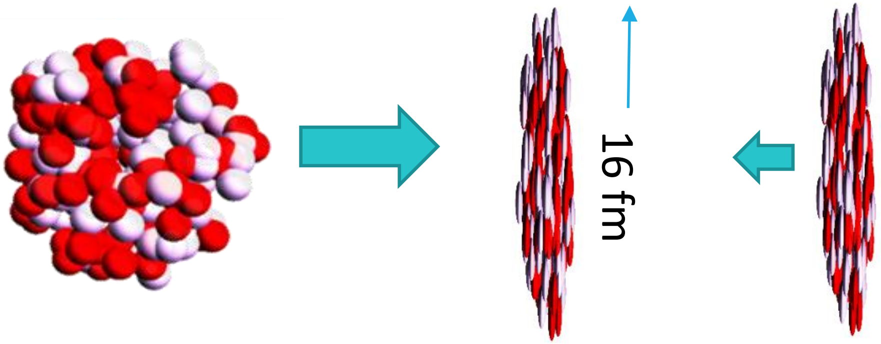
Lattice equation of state



Phase diagram



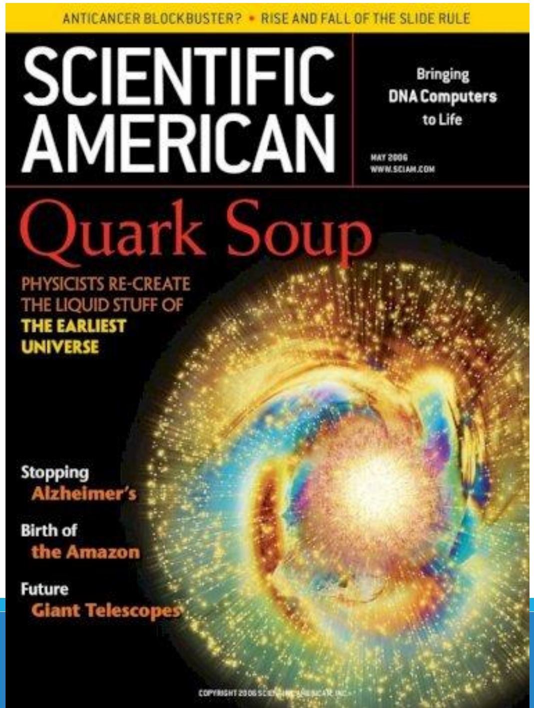
How to create QGP



Colliding heavy nuclei (Pb, Au) at high energies

Lorentz gamma factor up to 2500 (LHC) or 100 (RHIC)

Hottest fluid:
10^{12} K



ANTICANCER BLOCKBUSTER? • RISE AND FALL OF THE SLIDE RULE

SCIENTIFIC AMERICAN

Bringing DNA Computers to Life

MAY 2006
WWW.SCIAM.COM

Quark Soup

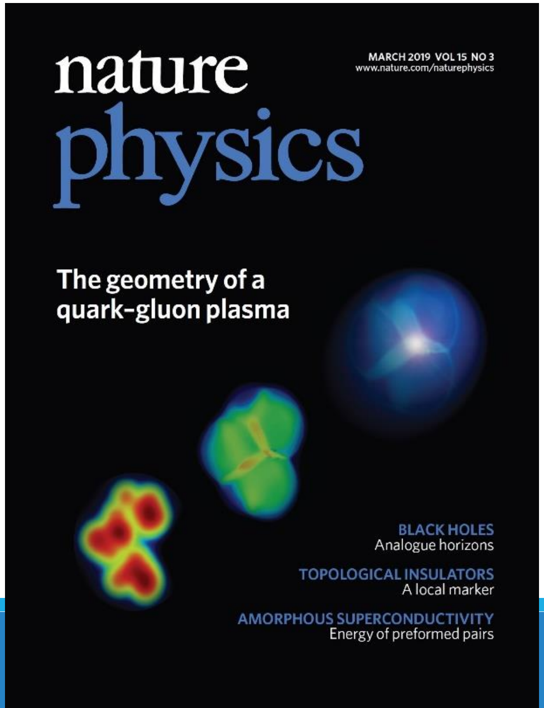
PHYSICISTS RE-CREATE THE LIQUID STUFF OF THE EARLIEST UNIVERSE

Stopping Alzheimer's

Birth of the Amazon

Future Giant Telescopes

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



nature physics

MARCH 2019 VOL 15 NO 3
www.nature.com/naturephysics

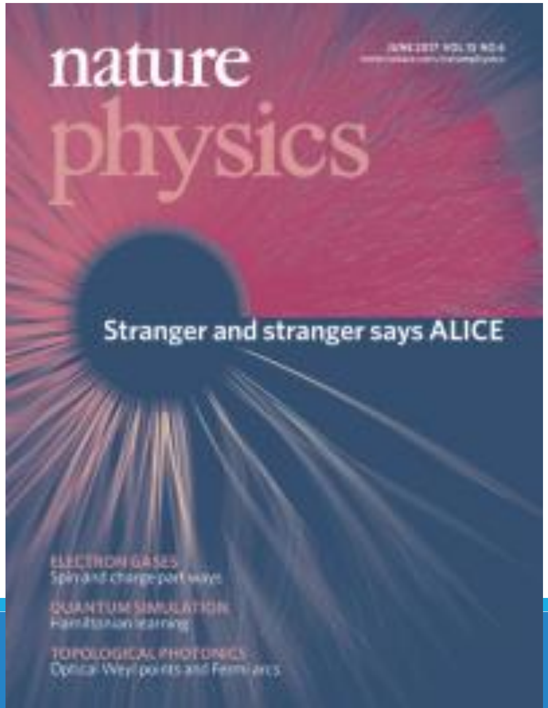
The geometry of a quark-gluon plasma

BLACK HOLES
Analogue horizons

TOPOLOGICAL INSULATORS
A local marker

AMORPHOUS SUPERCONDUCTIVITY
Energy of preformed pairs

Most perfect/strange:
η/s ~ 0.08



nature physics

Stranger and stranger says ALICE

ELECTRON GASES
Spin and charge part ways

QUANTUM SIMULATION
Hamiltonian learning

TOPOLOGICAL PHOTONICS
Optical Weyl points and Fermi arcs

Most vortical fluid:
ω ~ 10^{22}/s

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

First observation of fluid vortices formed by heavy-ion collisions
PAGES 34 & 62

SUBATOMIC SWIRLS

CLIMATE CHANGE
PARIS AGREEMENT
Time for nations to match words with deeds
PAGE 25

BOOKS
SUMMER SELECTION
Recommended reading for the holiday season
PAGE 20

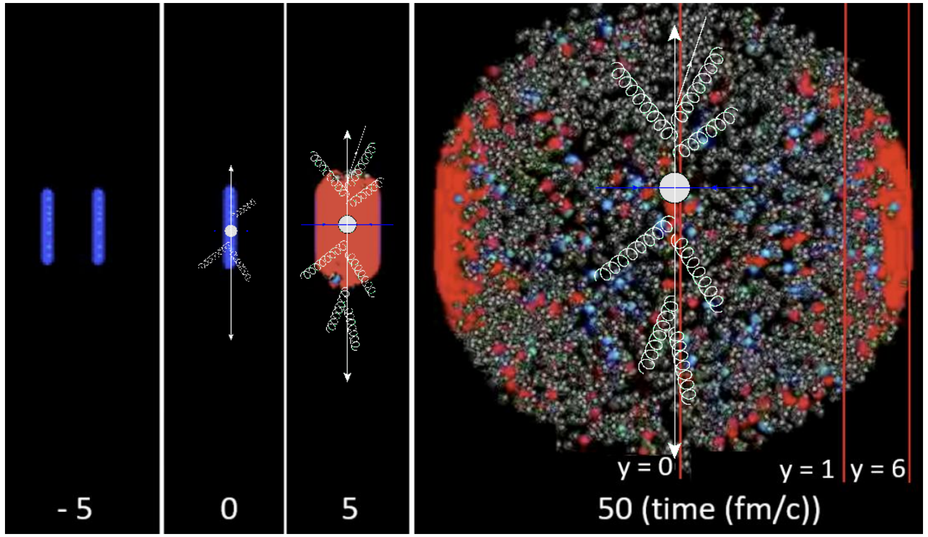
STEM CELLS
YOUTHFUL SECRETS
How the hypothalamus helps to control the ageing process
PAGE 52

NATURE.COM/NATURE
3 August 2017
Vol. 548, No. 7665

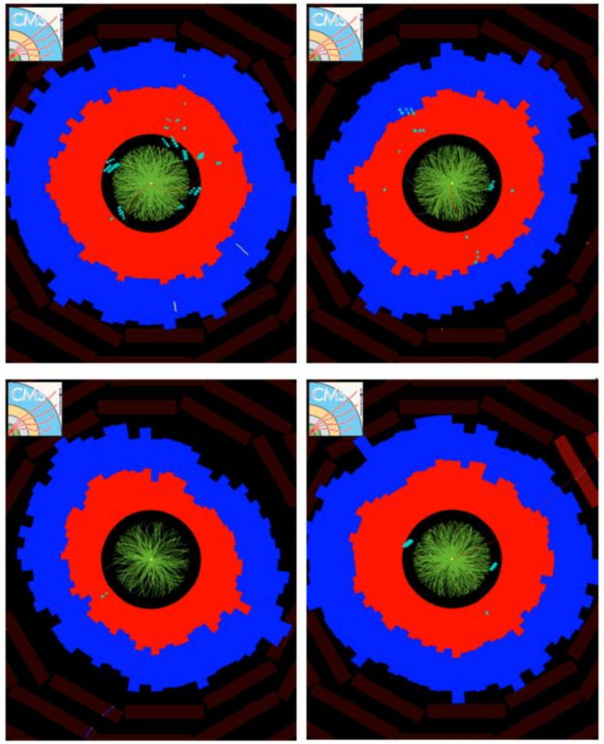
CERN accelerator complex

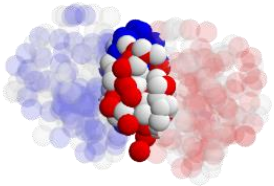
Quark-gluon plasma is strongly coupled

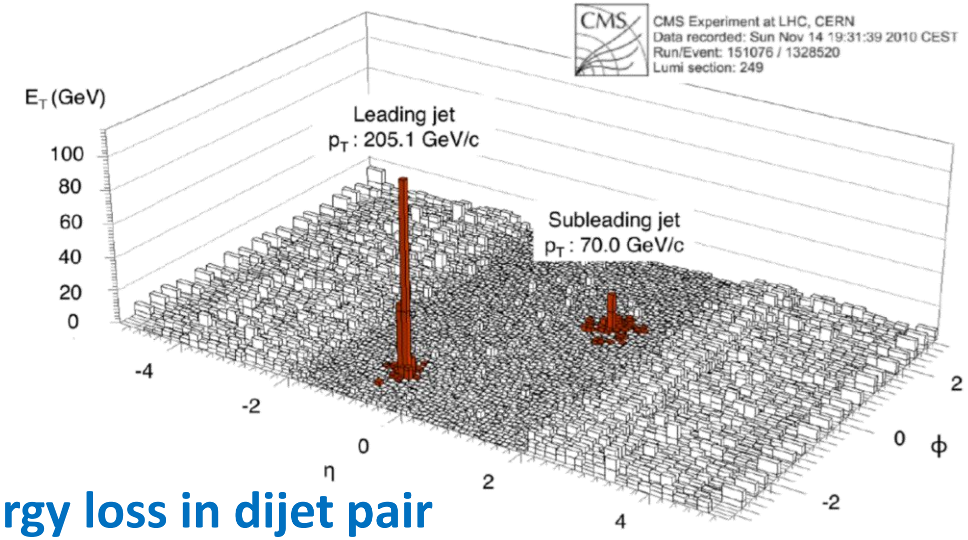
Initial stage - QGP - hadronic phase



Anisotropic flow (small viscosity)







Jet energy loss in dijet pair

Wit Busza, Krishna Rajagopal and WS, Heavy Ion Collisions: The Big Picture, and the Big Questions (2018)

Strangeness: from pQCD to thermal

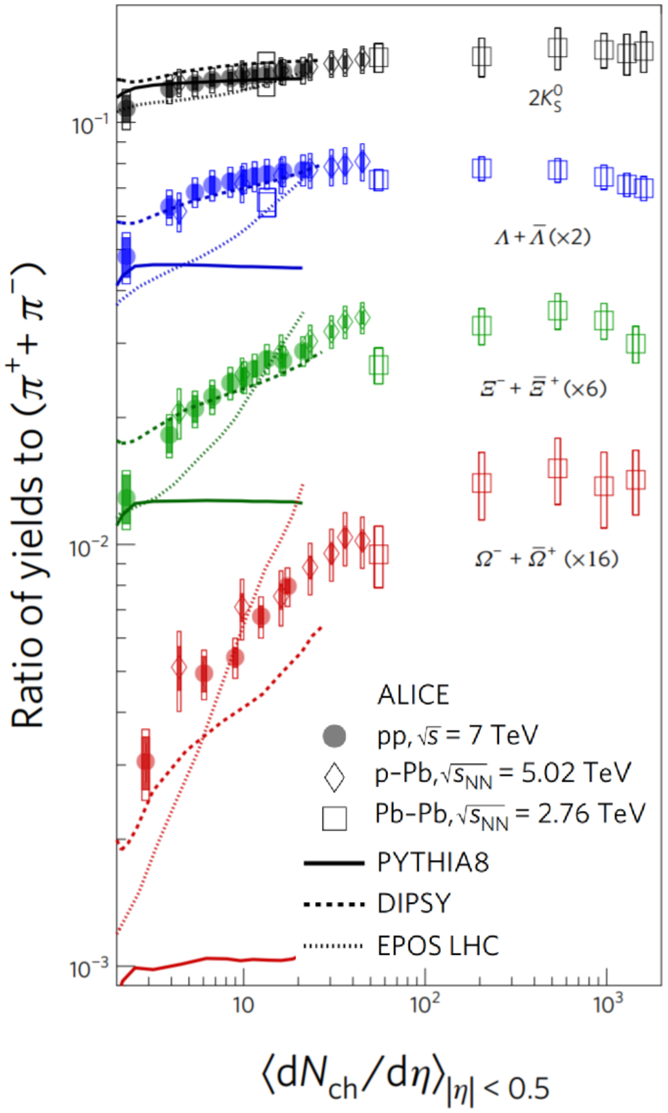
1. Ratio of strange baryons versus pions
   - Pythia fits low multiplicity
     - But constant towards higher multiplicity (!)

Thermodynamical string fragmentation

Nadine Fischer^{a,b} **and Torbjörn Sjöstrand**^{a} *January 31, 2017*

ABSTRACT: The observation of heavy-ion-like behaviour in pp collisions at the LHC suggests that more physics mechanisms are at play than traditionally assumed.

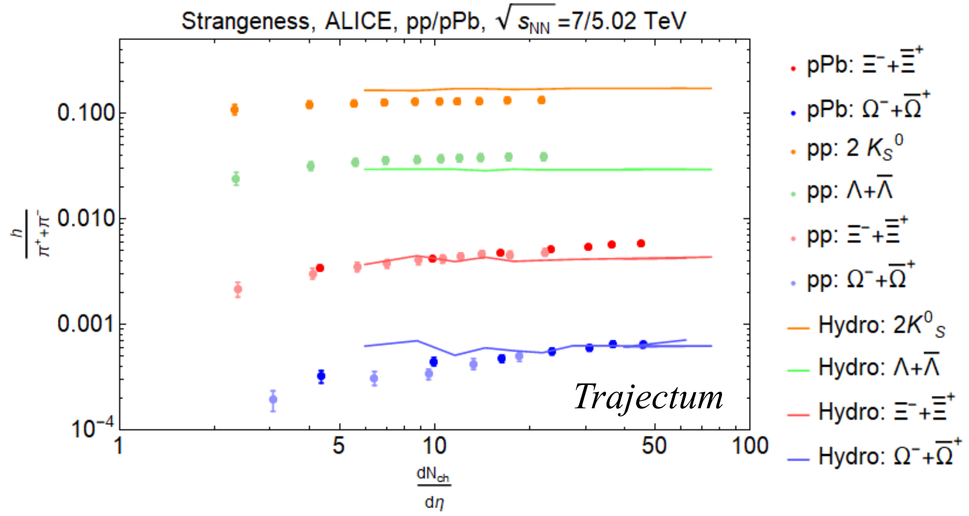
2. Saturates for high multiplicity pPb / PbPb
   - Interpretation: thermal strangeness production

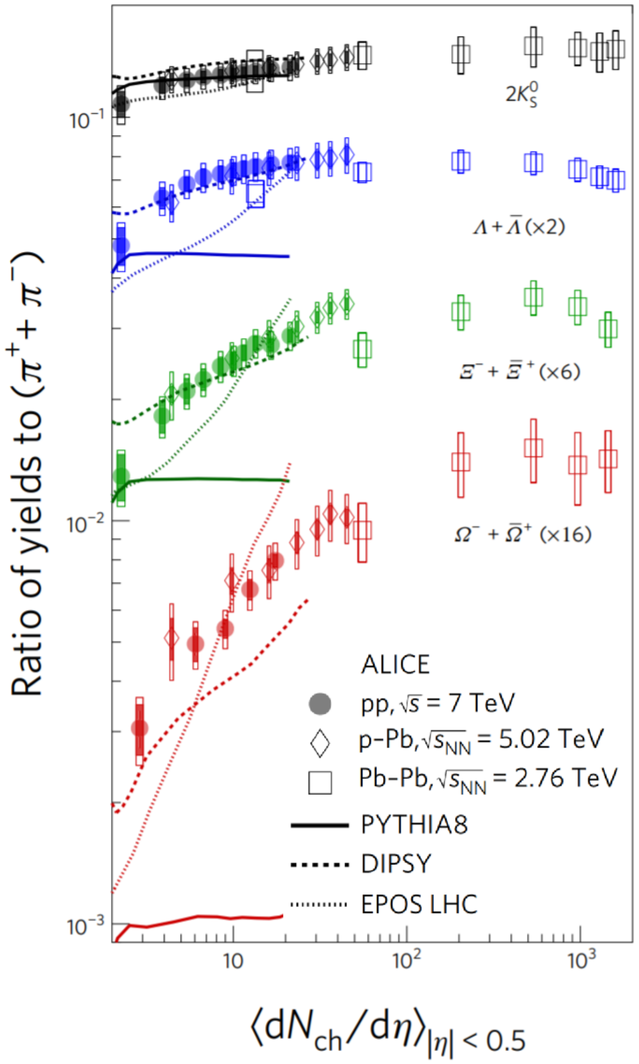


ALICE, Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions (Nature Physics, 2017)

Strangeness: from pQCD to thermal

1. Hydro+hadronic cascade, one parameter ($T_{\text{particl.}}$):





2. Hydro has only small dependence on N_{ch}
   - Approximately fits thermal model

ALICE, Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions (Nature Physics, 2017)

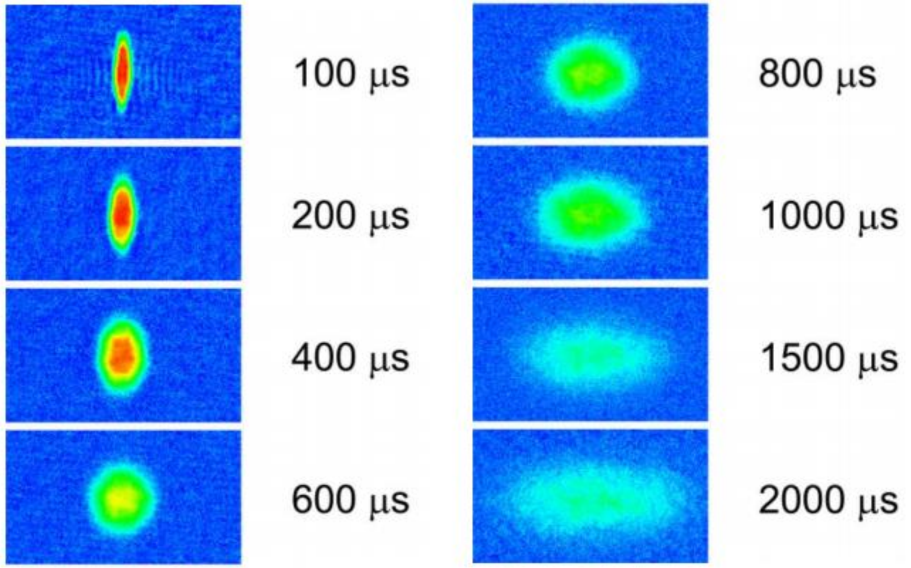
The most perfect liquid?

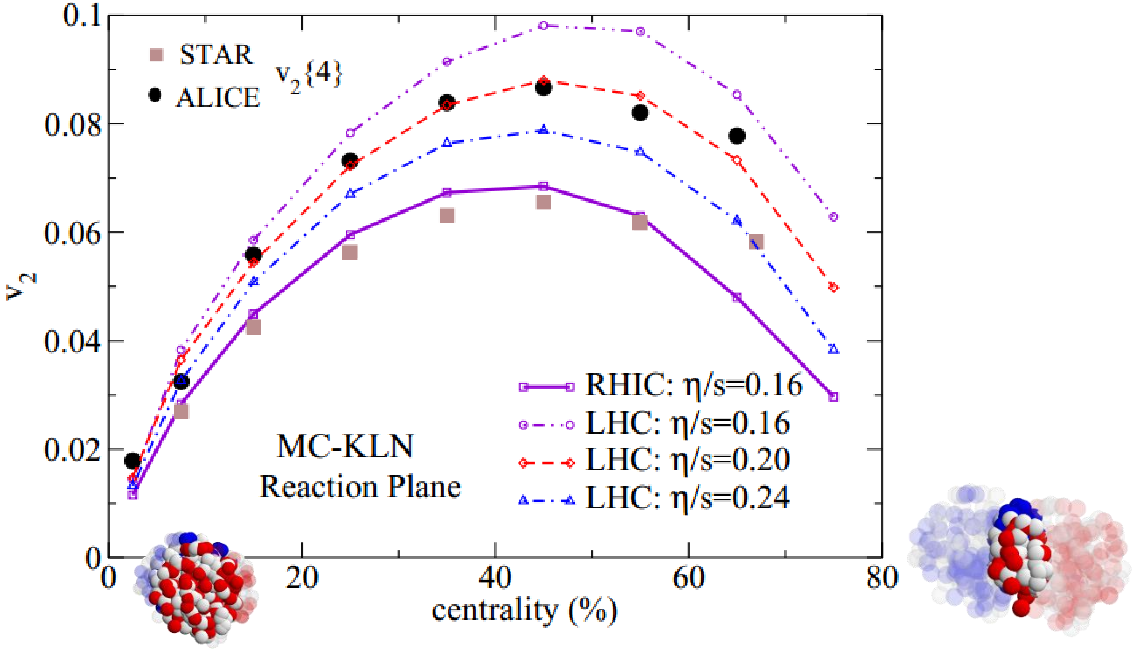
$$\frac{d\bar{N}}{d\varphi} = \frac{\bar{N}}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} \boxed{\bar{v}_n} \cos(n(\varphi - \bar{\Psi}_n))\right)$$

Famous viscosity, AdS/CFT or **holography**: $\frac{\eta}{s} = \frac{1}{4\pi} \approx 0.08$

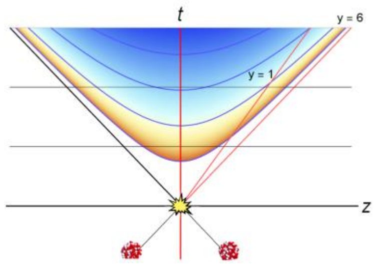
Fermions at unitarity (cold ☺)

Quark-gluon plasma (hot ☺)



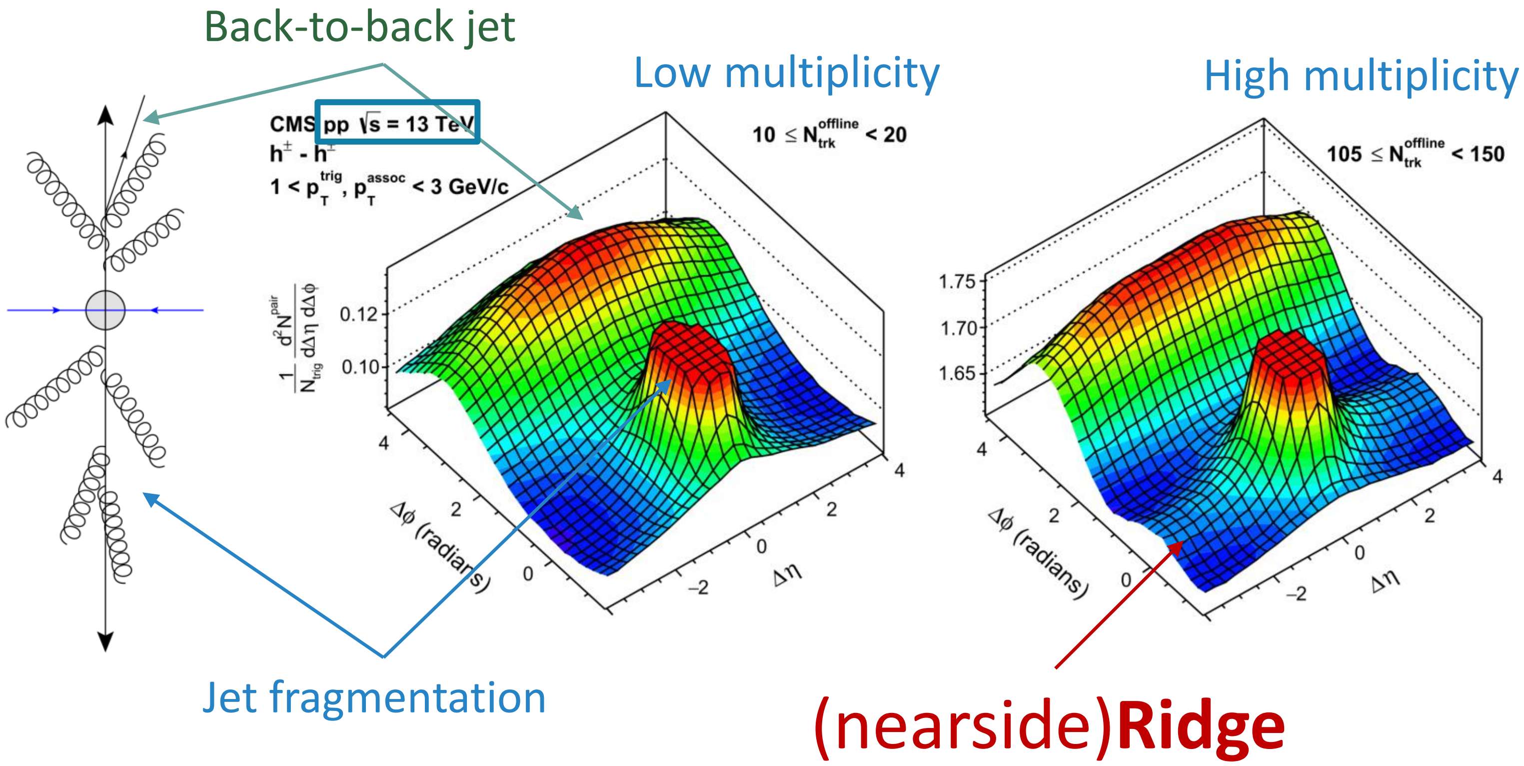


K. O'Hara, S. Hemmer, M. Gehm, S. Granade and J. Thomas, Observation of a Strongly-Interacting Degenerate Fermi Gas of Atoms, 2002
U. Heinz, C. Shen and H. Song, The Viscosity of Quark-Gluon Plasma at RHIC and the LHC, 2011



Ridges everywhere: *panta rei*

1. Ridge at Δϕ=0 and **large Δη**: *an initial or geometric effect*

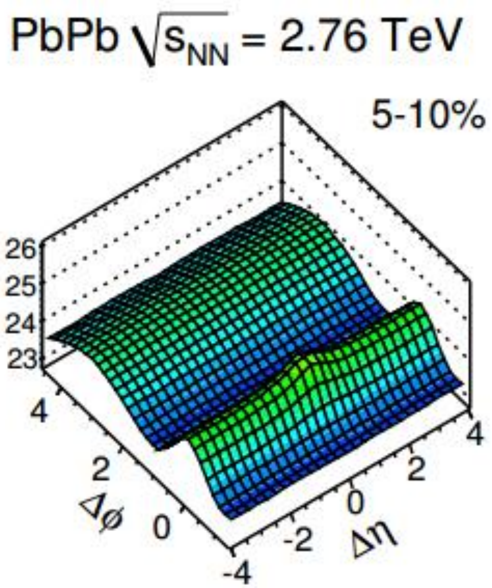

Back-to-back jet

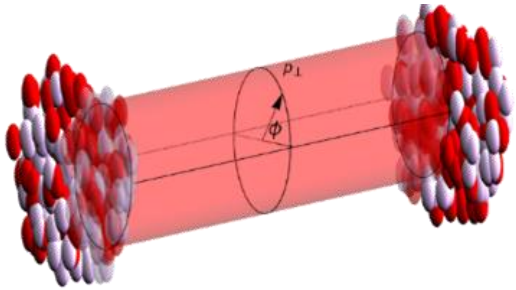
Low multiplicity

High multiplicity

Jet fragmentation

(nearside)**Ridge**

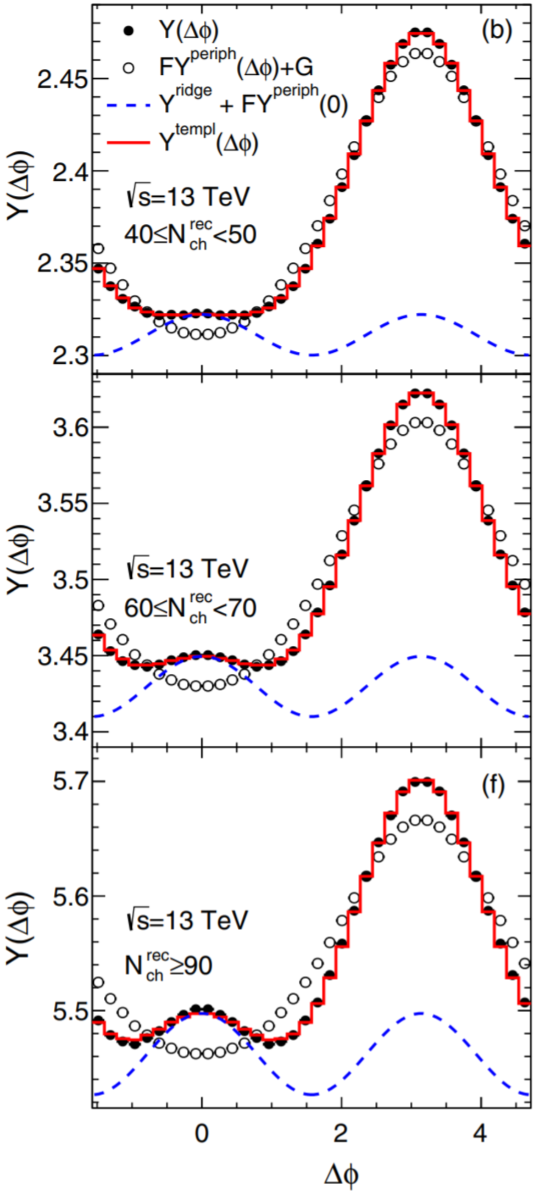


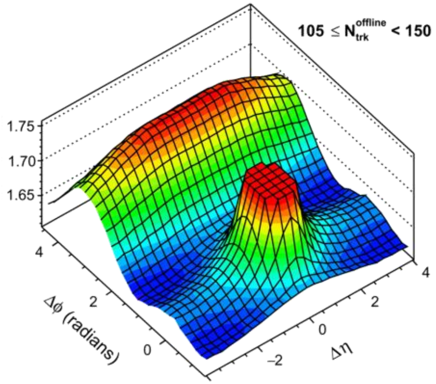


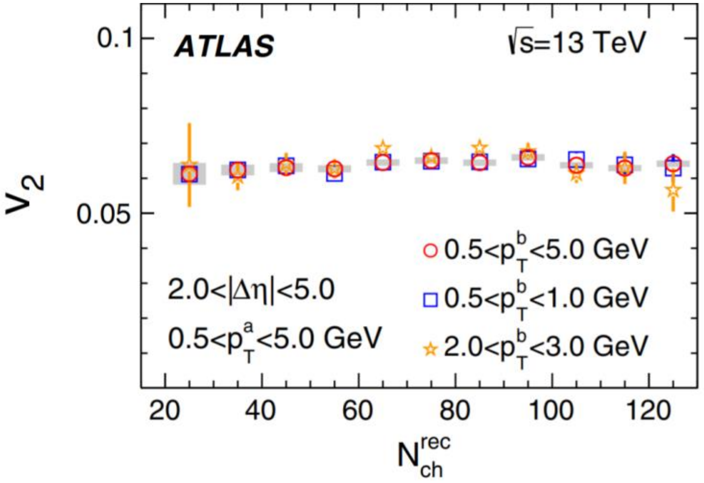
CMS, Evidence for collectivity in pp collisions at the LHC (2016)

Extract Fourier harmonics of the ridge

1. Essential to split ridge in `hard' and `soft' part
2. Template fit allows extrapolation down to N^{rec} <20
3. Soft v_2 essentially constant versus multiplicity:
   - QGP-like physics in *pp* collisions?





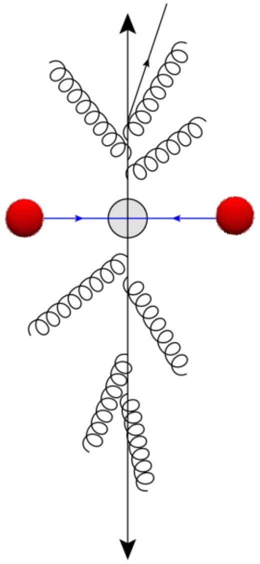


$$Y^{\mathrm{templ}}(\Delta\phi) = FY^{\mathrm{periph}}(\Delta\phi) + Y^{\mathrm{ridge}}(\Delta\phi)$$

$$Y^{\mathrm{ridge}}(\Delta\phi) = G[1 + 2v_{2,2}\cos(2\Delta\phi)]$$

ATLAS, Observation of Long-Range Elliptic Azimuthal Anisotropies in √s=13 and 2.76 TeV pp Collisions with the ATLAS Detector (2015)

(high energy) ¿HEP versus HIP? (heavy ion)



Low multiplicity

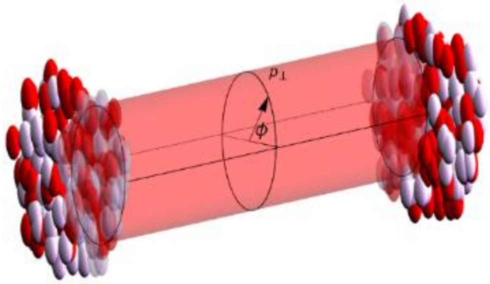
Jet-like particle shower

No equilibration

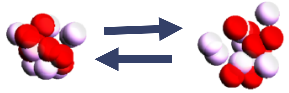
High multiplicity

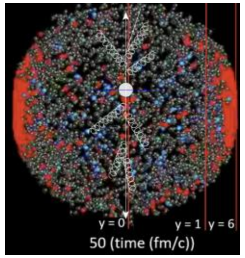
Relatively few jets

Equilibration: QGP

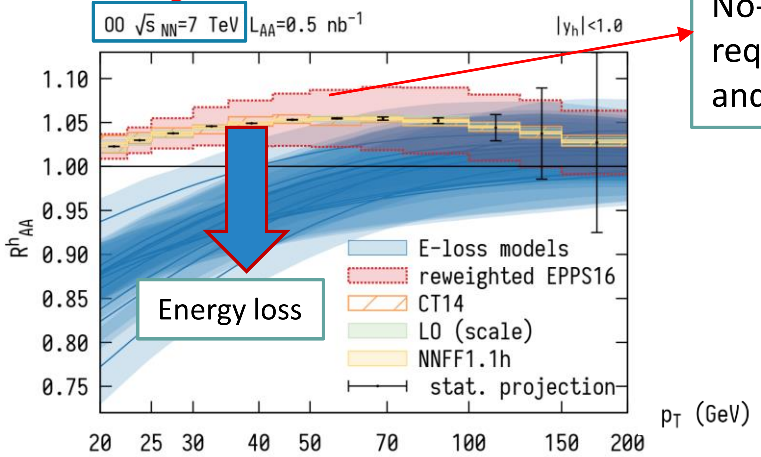


Jets important in heavy ion/small systems
Often intermediate multiplicity
QGP-type physics part of *pp* collisions





OO collisions as an example:
Nuclear modification factor: hadron R_{AA}
More energy loss → fewer hadrons
Interplay from HEP and HIP



No-energy-loss baseline: requires accurate pQCD and nuclear physics

A. Huss, A. Kurkela, A. Mazeliauskas, R. Paatelainen, WS and U. Wiedemann, Discovering partonic rescattering in light nucleus collisions (2020)

Can heavy ions be understood from a non-Abelian gauge theory?

1. For low p_T particles: is QGP just sensitive to the thermal sector of QCD?
   - And can we compute **and** measure its **fundamentals**? EOS & viscosities?
2. Towards high p_T and smaller systems:
   - Significant jet-like correlations: non-flow
   - Either suppress (large $\Delta\eta$) or use as a probe (hard probes)
3. Precise questions to *unravel the fundamentals of QCD*
   - T-dependent shear viscosity, bulk viscosity, second order transport
   - Fast thermalisation? 0.1 fm/c or 1.5 fm/c?
   - Particle ratios: (sizeable) deviations from thermal equilibrium
   - Initial shape: how to convert colliding nucleons to energy density, structure of a proton

Is QGP strongly coupled?
At which energy scale?
Non-conformal?

Hydro at large gradients

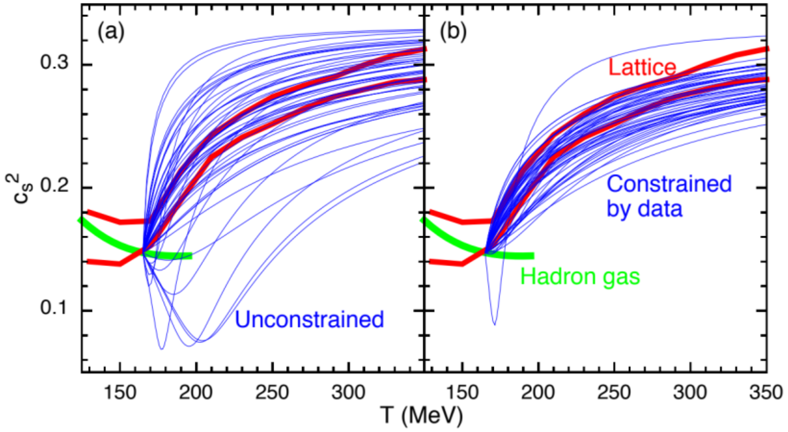
What are the d.o.f.?
Partons? Glasma?

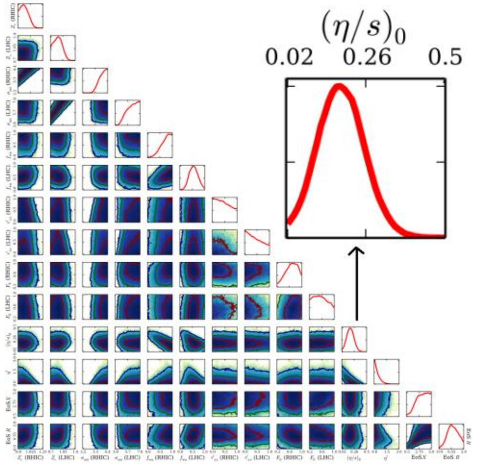
First global analyses

Precise questions require precise understanding of interplay of rich physics in heavy ion collisions

Constraining EOS (Jan 2015)

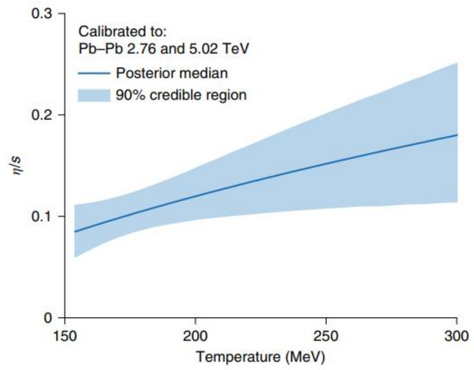
Prior Posterior (data)

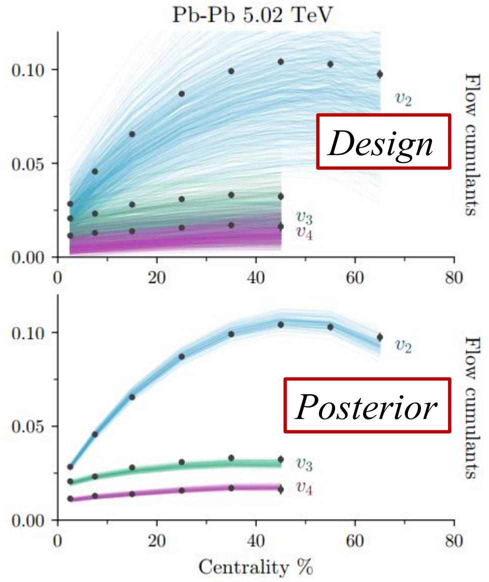




Constraining η/s (2019, Nature Physics)

η/s versus temperature Posterior (**η/s+slope**)



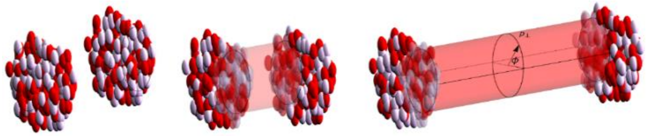


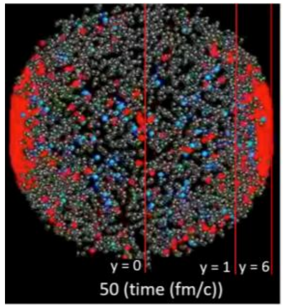
Jonah E. Bernhard, J. Scott Moreland and Steffen A. Bass
Bayesian estimation of the specific shear and bulk viscosity of QGP

Important: pioneering studies that only included p_T-integrated observables

S. Pratt, E. Sangaline, P. Sorensen and H. Wang, Constraining the Eq. of State of Super-Hadronic Matter from Heavy-Ion Collisions (2015)
Evan Sangaline and Scott Pratt, Towards a Deeper Understanding of How Experiments Constrain the Underlying Physics of Heavy-Ion Collisions (2015)

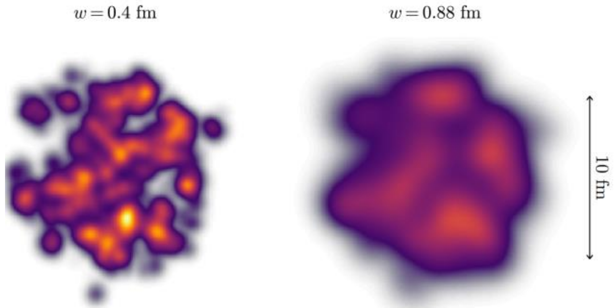
Standard model of heavy ion collisions





Initial stage (9)

Subnucleonic structure? (7)

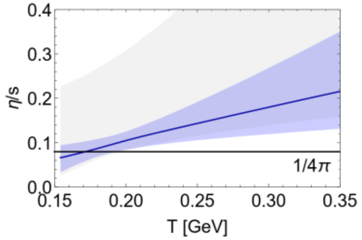


Non-thermal flow? (2)
for time τ with varying speed (***new***)

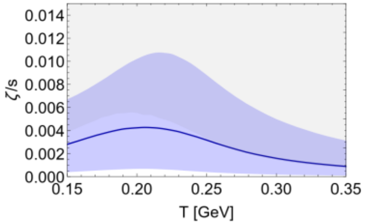
Fluctuations? (1)

Viscous hydrodynamics (9)

Shear viscosity (3)



Bulk viscosity (3)



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

Cascade of hadrons (1)

Convert quark-gluon plasma at T_{switch} to particles following Boltzmann distribution (particlization, 1)

Subtle: viscous corrections

Evolve particles with hadronic code: 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)

Hydrodynamics: first and second order

1. Constitutive relations for the stress tensor, with p(ρ) EOS from HotQCD

$$T^{\mu\nu} = \rho u^\mu u^\nu - (p+\Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}, \quad \Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

With shear and bulk tensors:

$$D\Pi = -\frac{1}{\tau_\Pi}\left[\Pi + \zeta\nabla\cdot u + \delta_{\Pi\Pi}\nabla\cdot u\Pi - \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}\right],$$

$$\Delta^\mu_\alpha\Delta^\nu_\beta D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}\Big[\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu} + \delta_{\pi\pi}\pi^{\mu\nu}\nabla\cdot u - \phi_7\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} + \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} - \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}\Big].$$

2. We vary the green coefficients, η and ζ as a function of temperature,

2nd order according to $\frac{\tau_\Pi s T \delta^2}{\zeta}$, $\frac{\tau_\pi s T}{\eta}$ and $\frac{\tau_{\pi\pi}}{\tau_\pi}$

Performing a global analysis

Bayes theorem:

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

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

We have a 20-dimensional parameter space and 514 datapoints

- Run model on 1000 `design’ points, spaced on a latin hypercube
- `Interpolate’ results by training a *Gaussian Process Emulator*

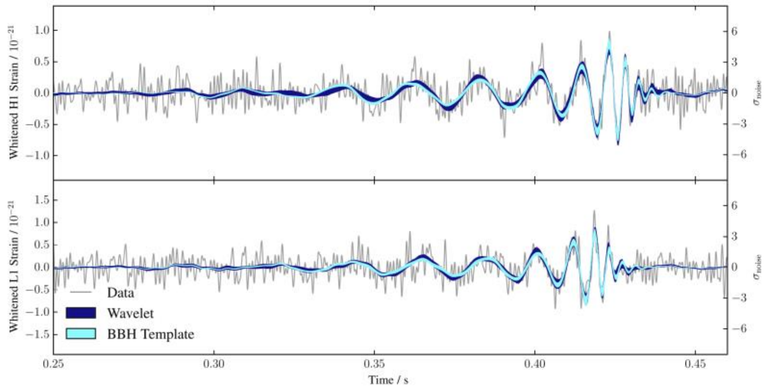
Markov Chain Monte Carlo (emcee2.2)

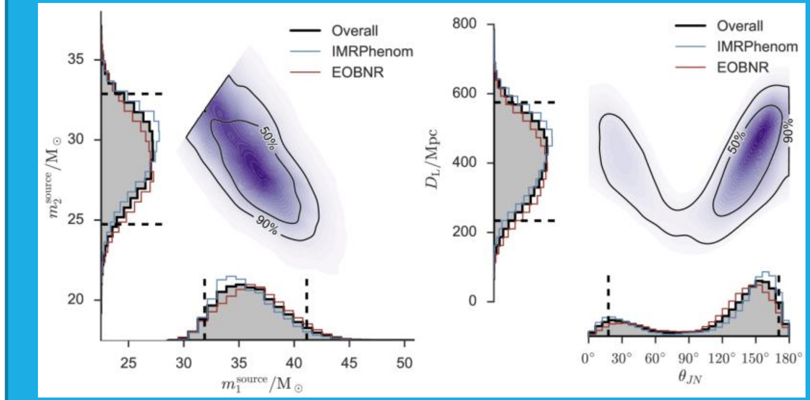
- Obtain sample of 10^6 likely values

Compare posterior with data

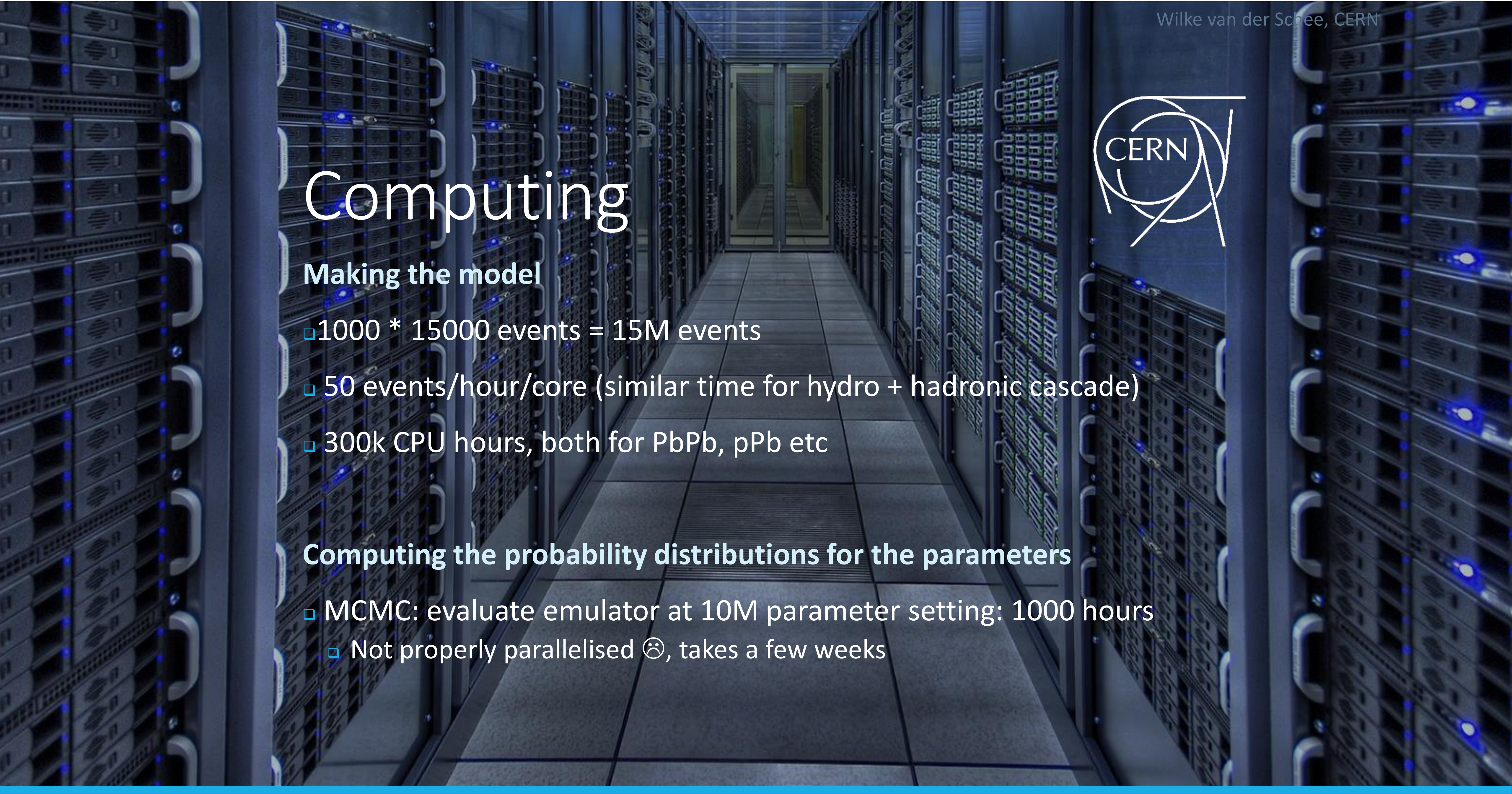
- From emulator (emulator has its own uncertainty estimate)
- A high statistics run at the optimal value (MAP, maximum a posteriori)

Example: gravitational waves





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



Computing

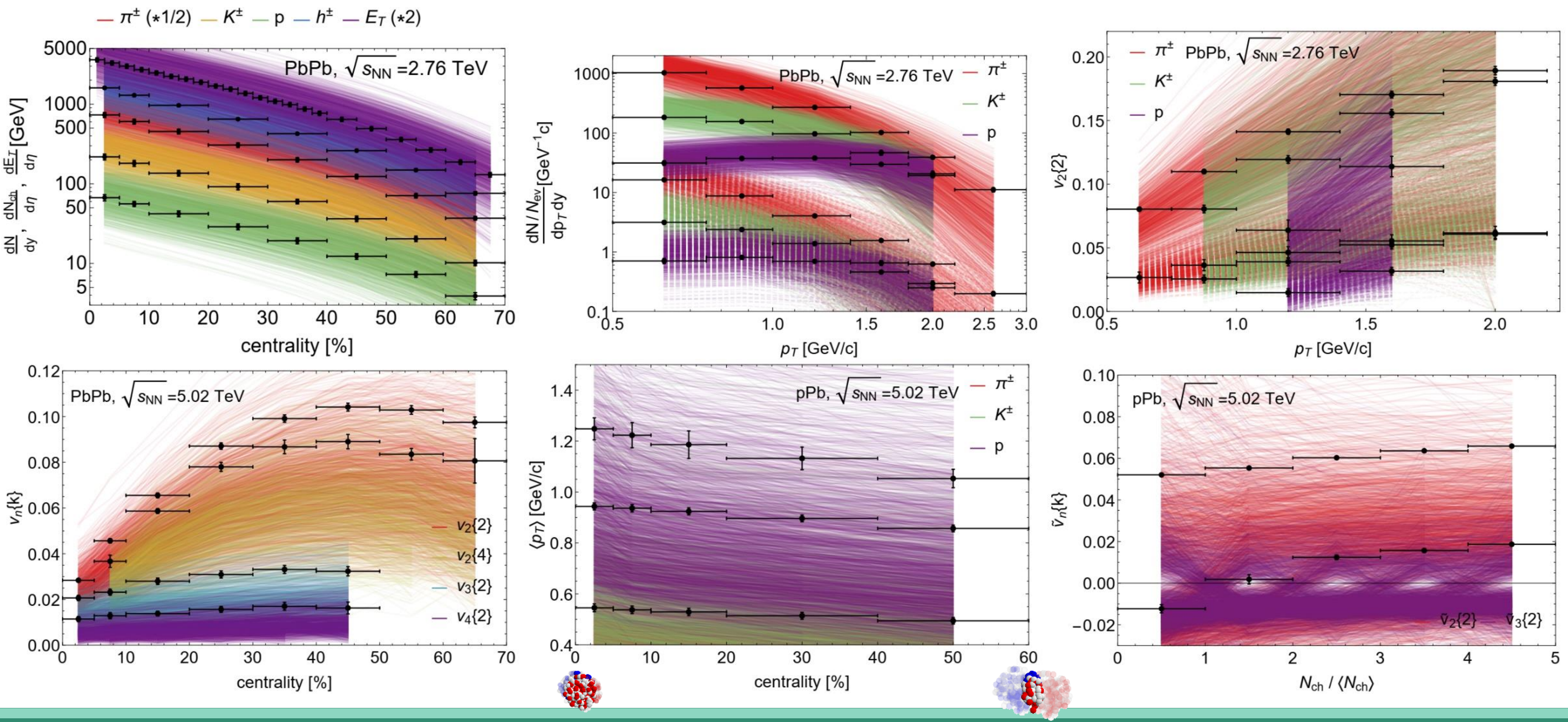
Making the model

- 1000 * 15000 events = 15M events
- 50 events/hour/core (similar time for hydro + hadronic cascade)
- 300k CPU hours, both for PbPb, pPb etc

Computing the probability distributions for the parameters

- MCMC: evaluate emulator at 10M parameter setting: 1000 hours
  - Not properly parallelised ☹, takes a few weeks

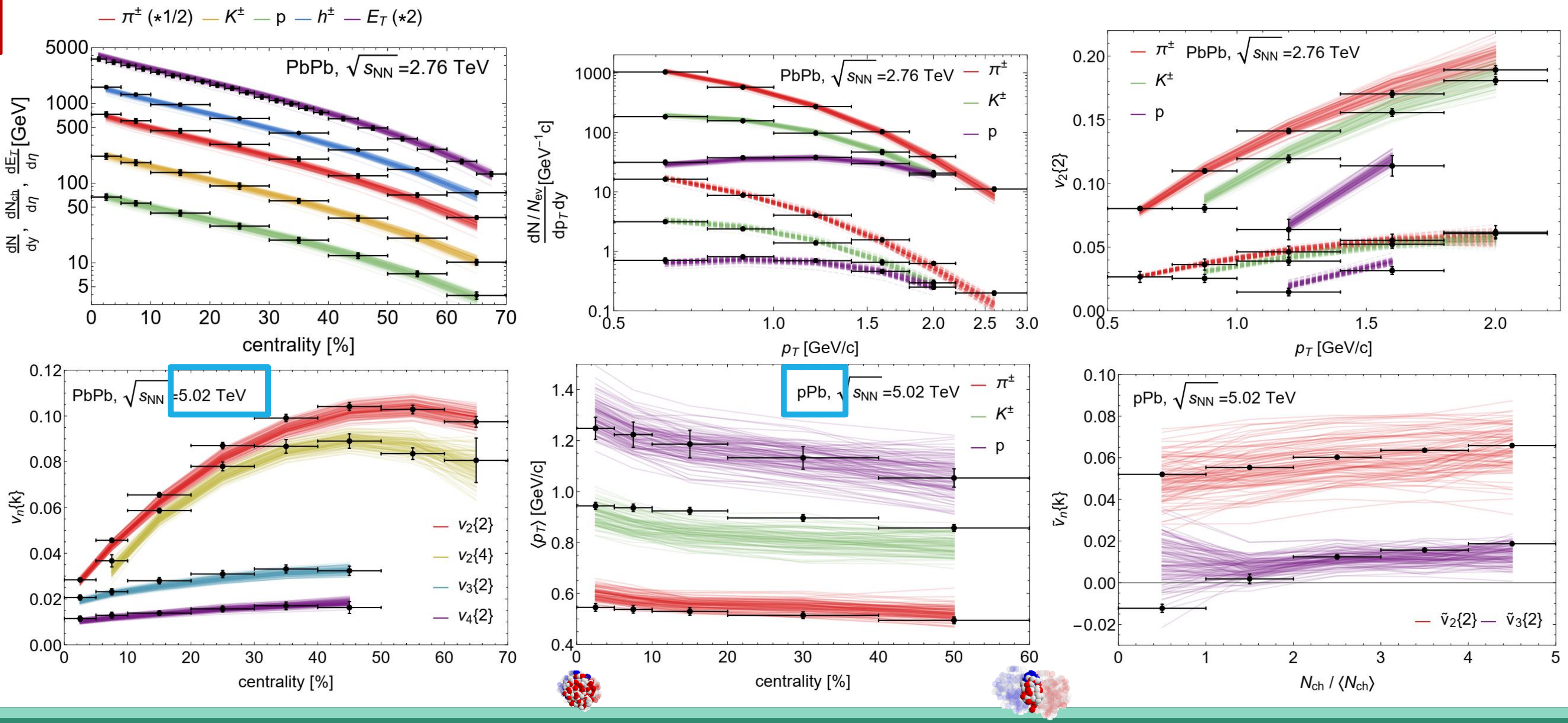
Design



Experimental observables: *a wealth of data*

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

Posterior

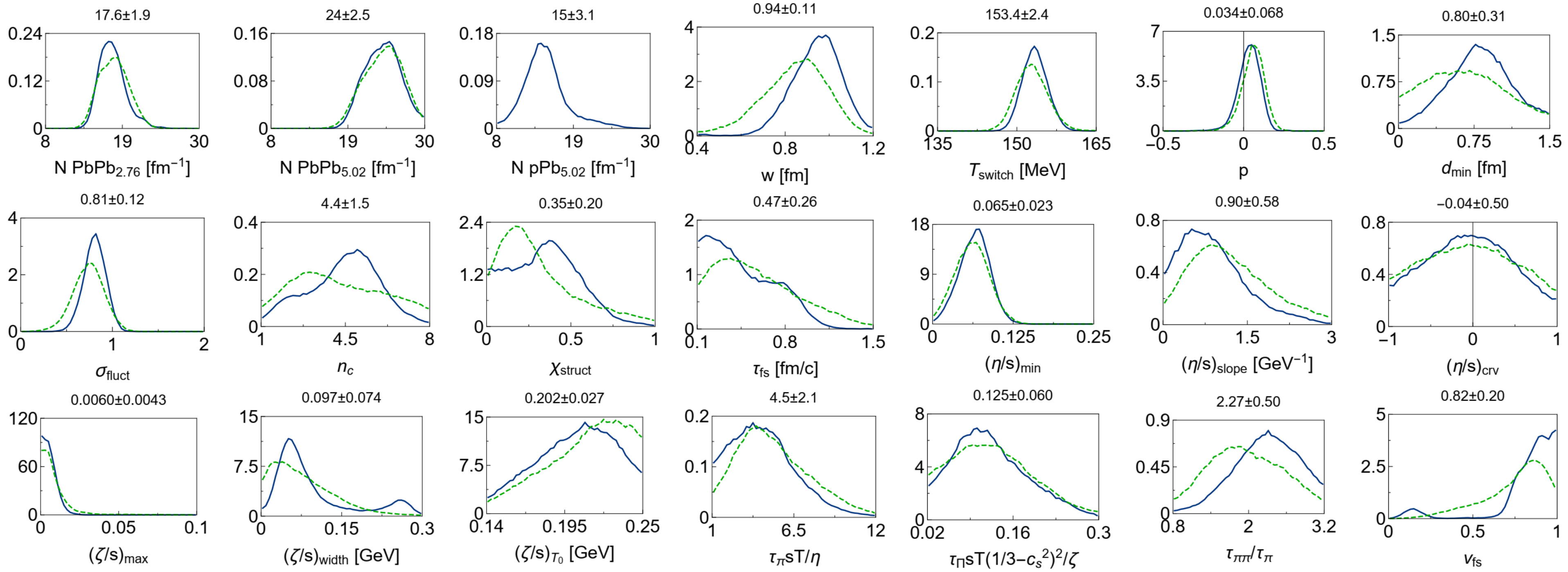


Experimental observables: *a wealth of data*

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**

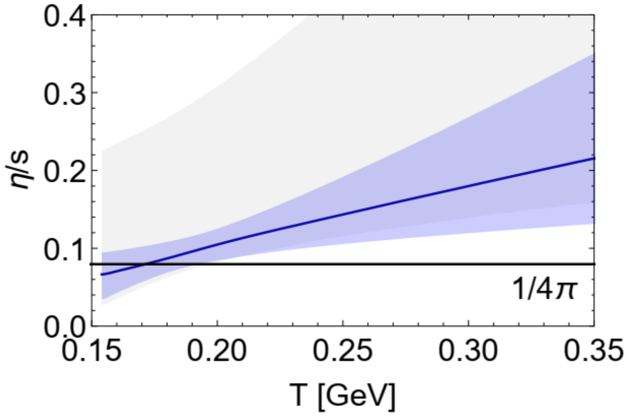
Posterior distributions

1. Dashed: without *p*Pb: indeed much flatter for e.g. n_c
2. Strong constraint on nucleon-nucleon fluctuations (also found at Duke)

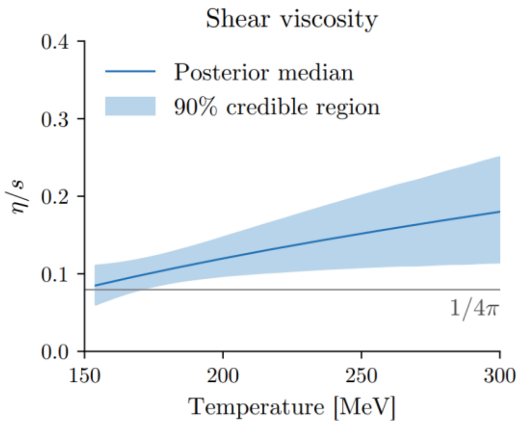


Posterior distributions – shear viscosity

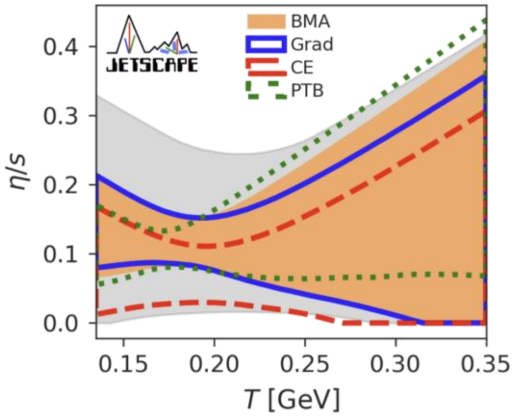
1. Shear viscosity consistent with previous work
    - More data, but also enlarged model → similar constraint on η/s
    - New JETSCAPE slightly broader band (larger priors, single PbPb energy but including RHIC)
    - Consistent with state-of-the-art pQCD computations



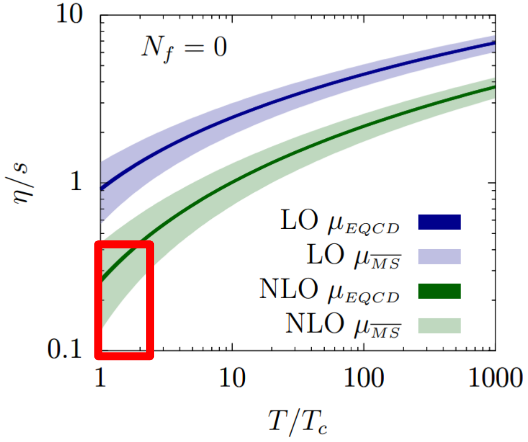
Current work (2020)



J. Bernhard, S. Moreland and S. Bass, Nature Physics (2019)



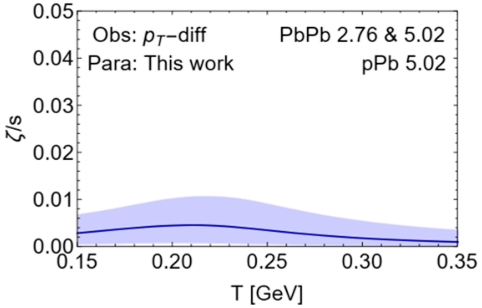
JETSCAPE (2020)

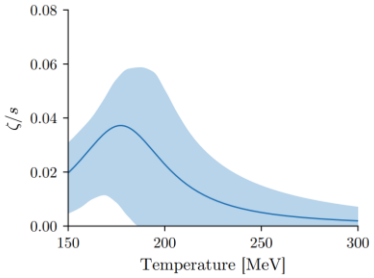


Jacopo Ghiglieri, Guy Moore and Derek Teaney **QCD Shear Viscosity at (almost) NLO** (2018)

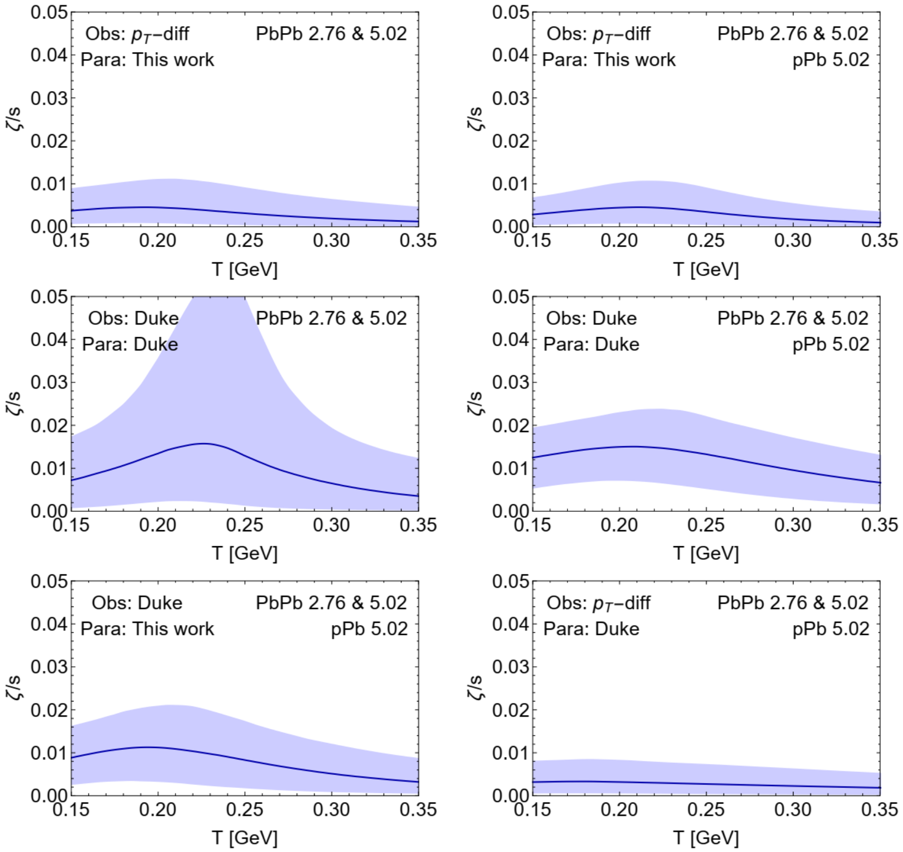
Posterior distributions – bulk viscosity:

Much smaller, even consistent with zero





J. Bernhard, S. Moreland and S. Bass,
Nature Physics (2019)



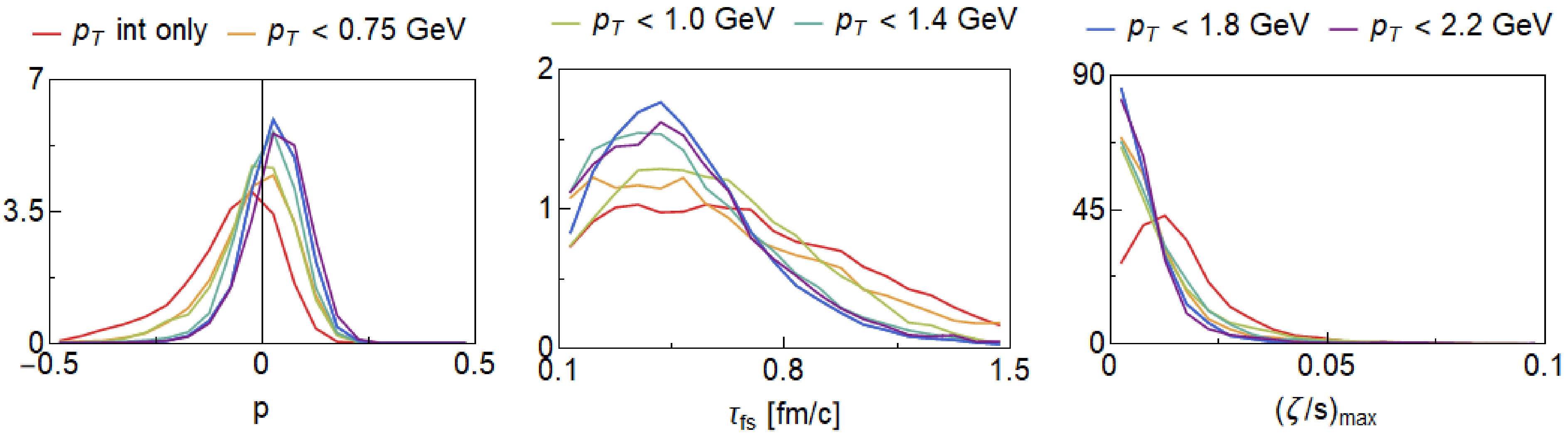
Bulk viscosity, varied several aspects:

- More limited parameter set
  - All versus only `Duke’
- Include or not include p-Pb collisions
- **Include p_T-differential observables**

Sensitivity to p_T-differential observables

Vary maximum p_T of observables to identify their constraining power

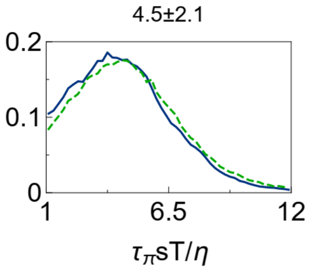
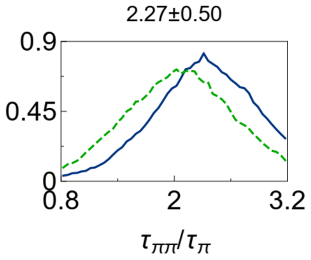
- First two bins till 1 GeV give strongest constraints (if at all, selection shown)
  - Also due to tougher statistics at higher p_T: emulator error
- Viscous corrections at freeze-out very uncertain at large p_T
  - Encouraging that results are quite insensitive to high p_T bins



Posterior distributions – 2nd order transport

τ_π and $\tau_{\pi\pi}$ can be compared to strong and weak coupling values

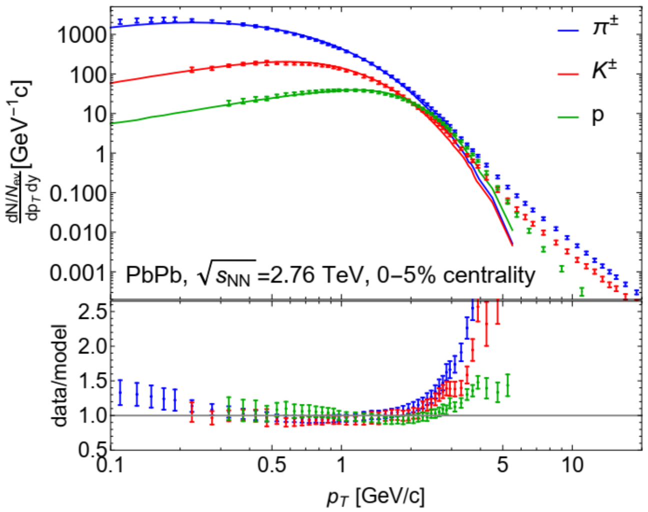
- Both consistent, AdS/CFT slightly favoured for $\tau_{\pi\pi}$

	this work	AdS/CFT	kinetic theory
$\frac{\tau_\pi sT}{\eta}$	 4.5±2.1	$4-\log(4)\approx 2.61$	5
$\frac{\tau_{\pi\pi}}{\tau_\pi}$	 2.27±0.50	$\frac{88}{35(2-\log 2)}\approx 1.92$	$\frac{10}{7}\approx 1.43$

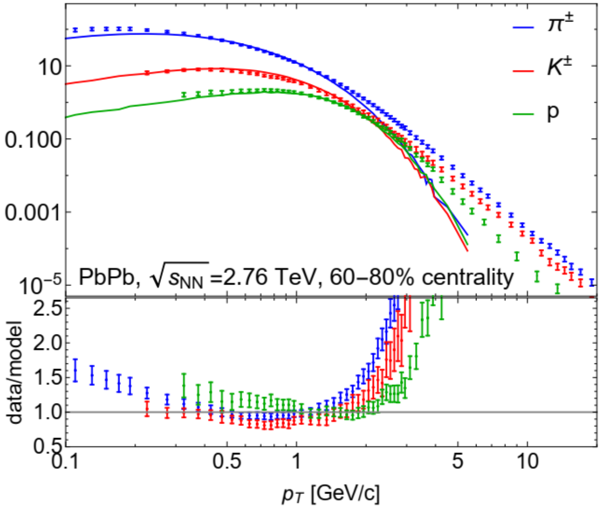
MAP: maximum a posteriori: spectra

1. High statistics run at (almost) optimal parameters, compared with ALICE data
    - 400k events (PbPb) and 4M events (pPb)

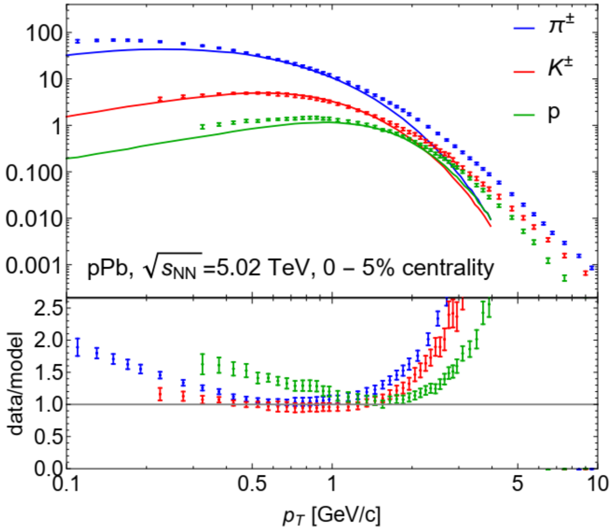
Central PbPb



Very peripheral PbPb



Central *p*Pb

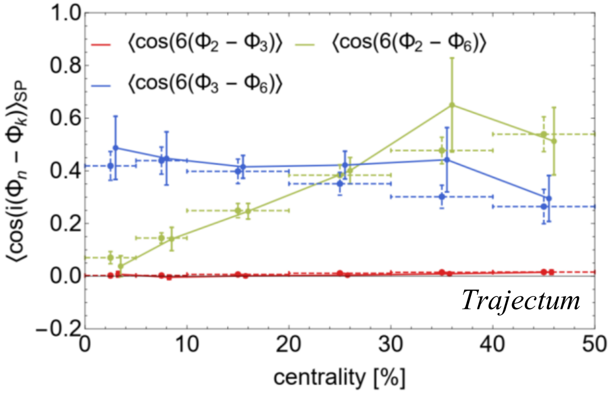


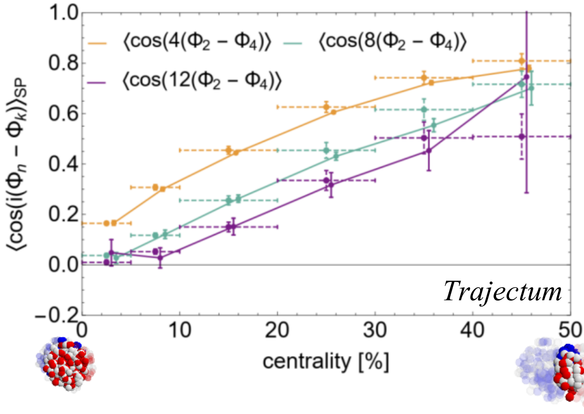
$$\frac{d\bar{N}}{d\varphi} = \frac{\bar{N}}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} \bar{v}_n \cos(n(\varphi - \boxed{\bar{\Psi}_n}))\right)$$

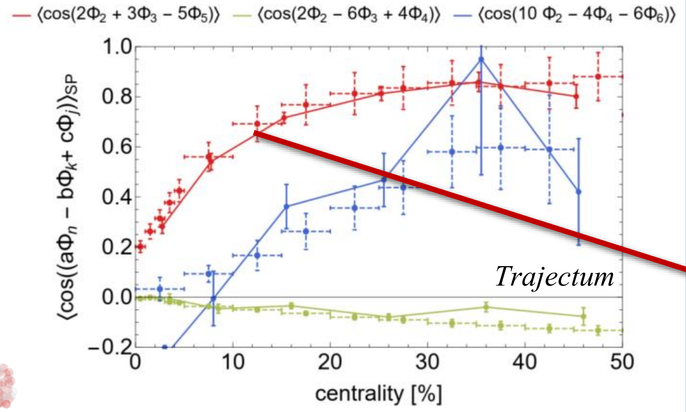
MAP: PbPb event plane angles

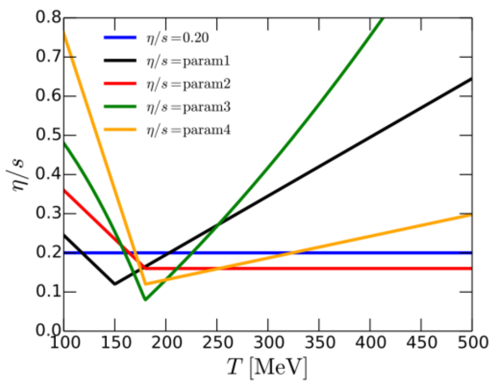
1. A non-trivial check: the event-plane angle correlations (not used in Bayesian)
2. Non-trivial agreement: needs a very specific η/s(T) (even when fitting v_n)

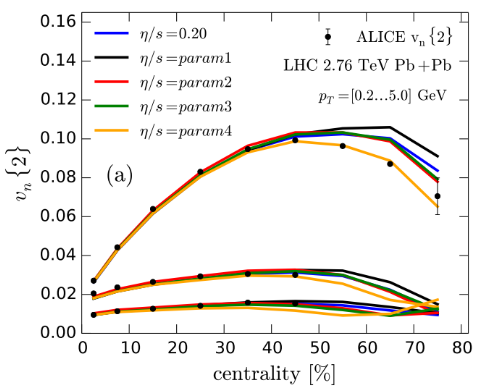
Data by ***ATLAS***

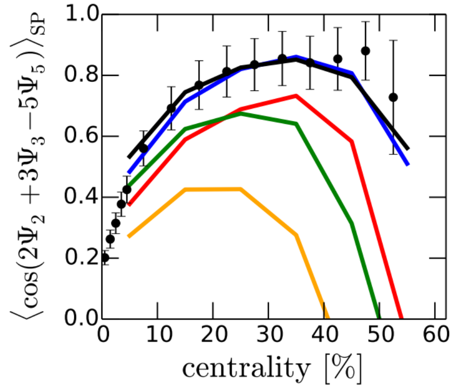








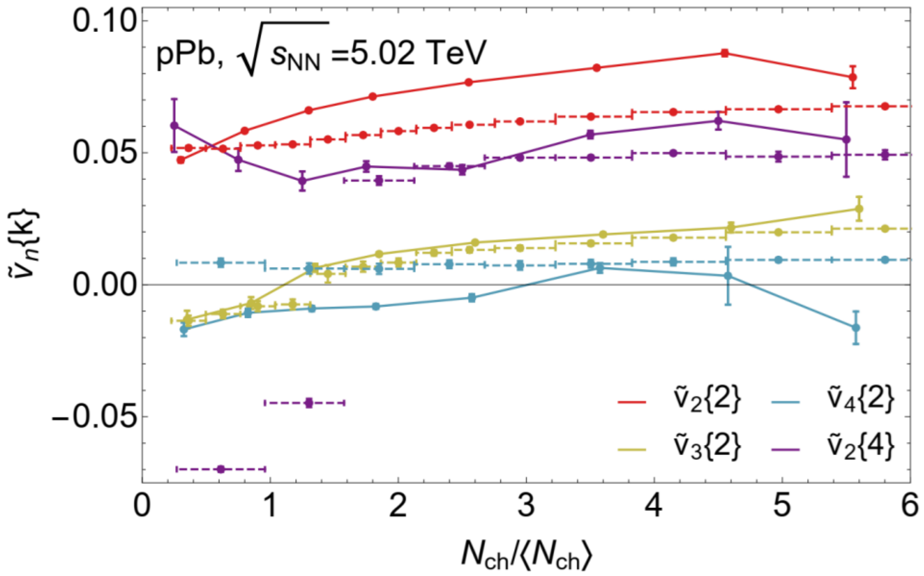




ATLAS, Measurement of event-plane correlations in $\sqrt{s_{NN}}$=2.76 TeV lead-lead collisions with the ATLAS detector (2014)
H. Niemi, K. J. Eskola and R. Paatelainen, EbE fluctuations in pQCD + saturation + hydro model: pinning down QCD matter shear viscosity in HIC (2015)

MAP: *p*Pb anisotropic flow

1. Emulator and MCMC are less precise for *p*Pb: uncertainty is statistical only
2. Shows potential to obtain imaginary $v_n\{2\}$ (= negative $\tilde{v}_n\{k\}$),
   in agreement with ATLAS low multiplicity result
3. Sheds new light on discussion of hydro versus sign of $\langle\langle 2\rangle\rangle_n$



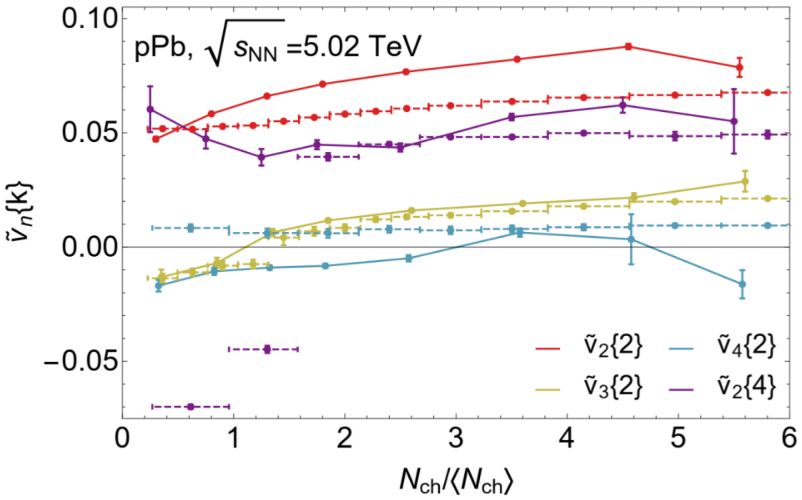
$$Q_n = \sum_{i=1}^{M} e^{in\phi_i}$$

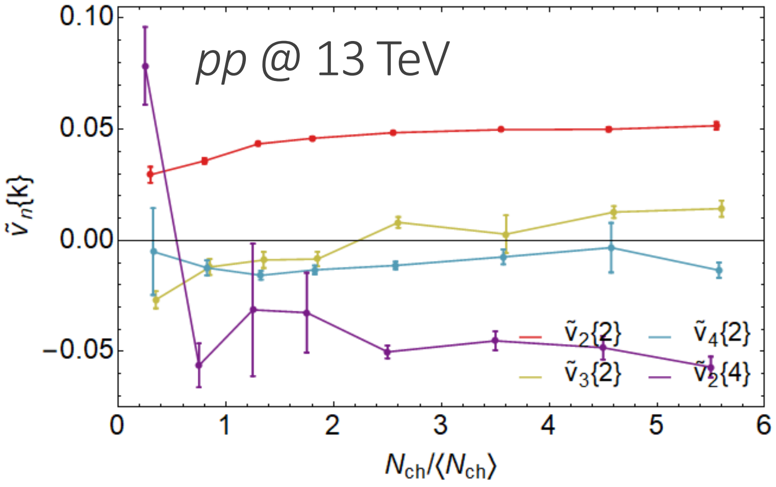
$$\langle 2\rangle_n = \frac{|Q_n|^2 - M}{M(M-1)}$$

$$v_n\{2\} = \sqrt{\langle\langle 2\rangle\rangle_n}$$

MAP: *pp* anisotropic flow

1. Preliminary results for *pp*; different sign for $v_2\{4\}^2$ (?)

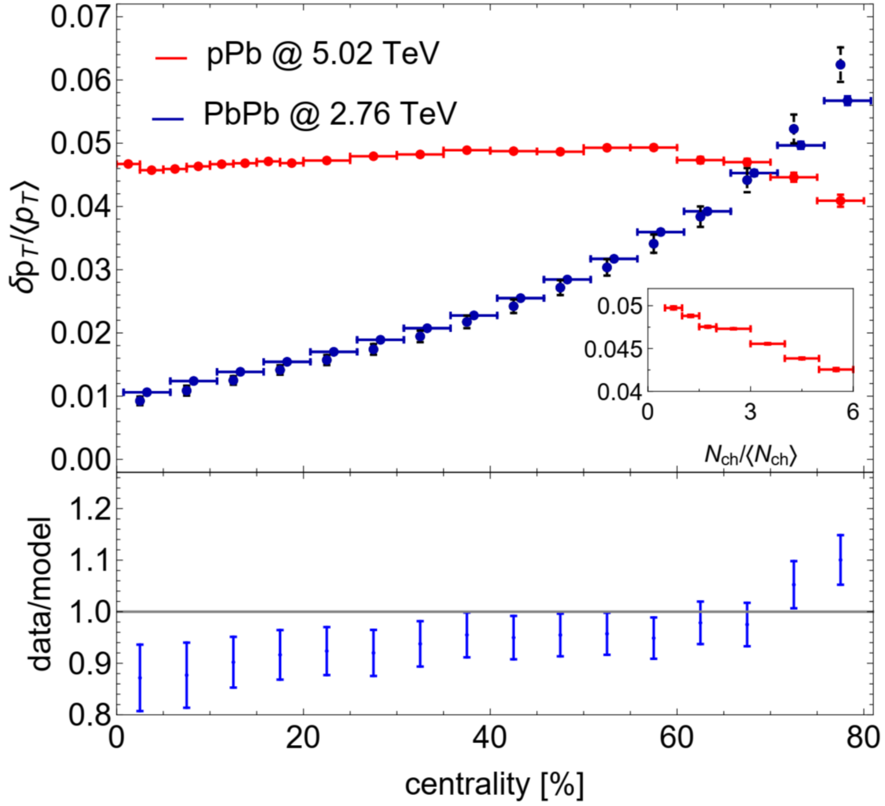


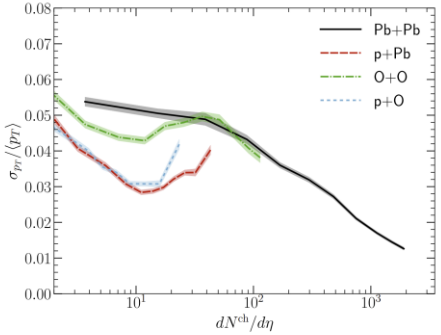


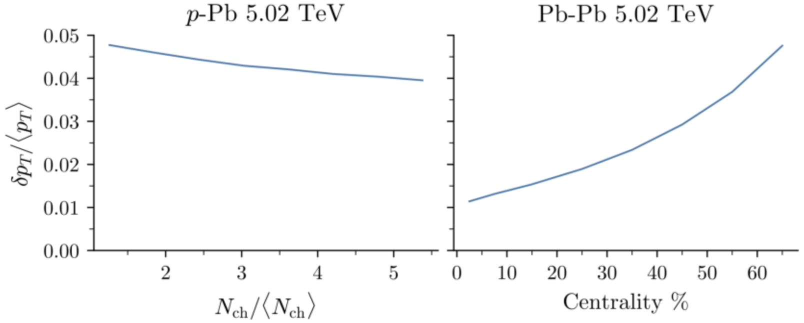
$$\delta p_T^2 = \left\langle\!\left\langle (p_{T,i} - \langle p_T \rangle)(p_{T,j} - \langle p_T \rangle) \right\rangle\!\right\rangle$$

A prediction for *p*Pb: momentum fluctuations

1. Rather hard to find observables that have not been measured
2. Typically hard to match to data
3. Roughly comparable to results by Moreland et al, higher than Shen et al:



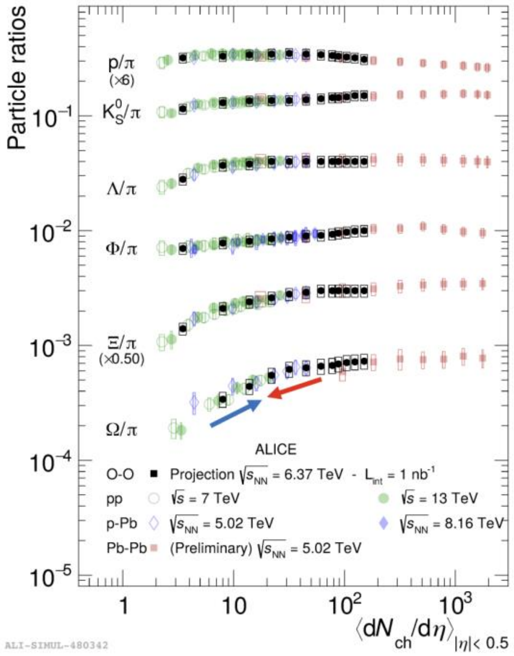


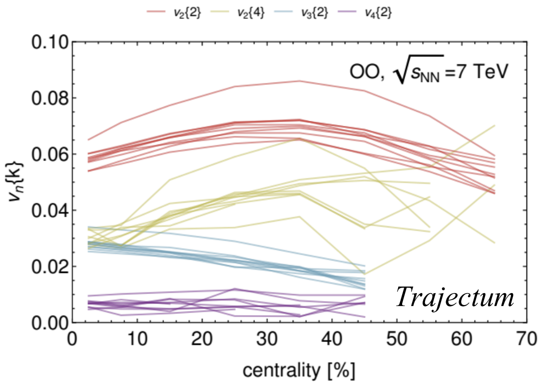


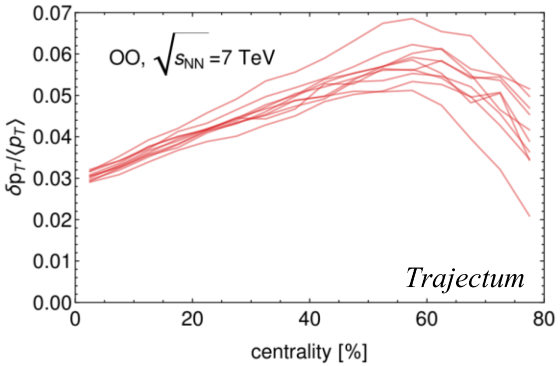
Chun Shen, workshop OppOrtunities at the LHC (2021)
Scott Moreland, Initial conditions of bulk matter in ultrarelativistic nuclear collisions (PhD thesis, 2019)

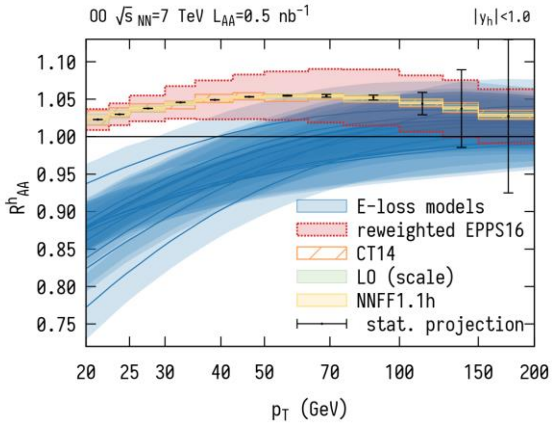
Oxygen & small systems: LHC as a light ion collider

1. Will help resolving the `flow in small systems' puzzle
2. A well-controlled environment to discover *jet quenching* in small systems
3. Bridges the gap between pPb and PbPb for strangeness enhancement
4. pO: of crucial interest in modelling cosmic ray showers (LHCf)



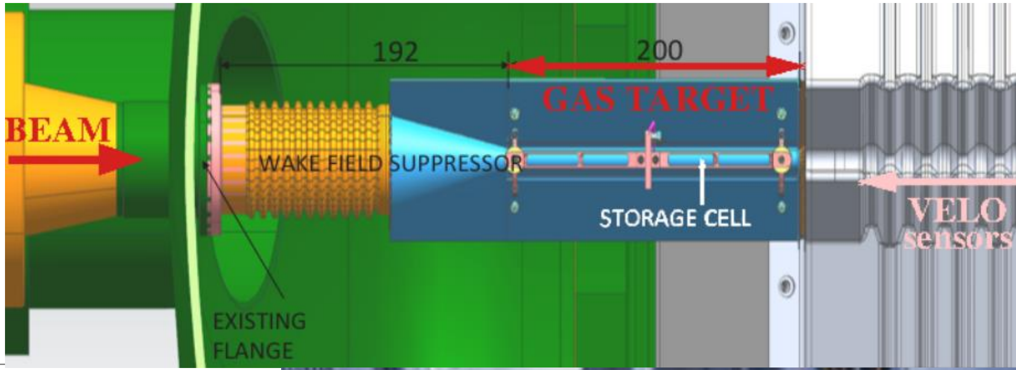


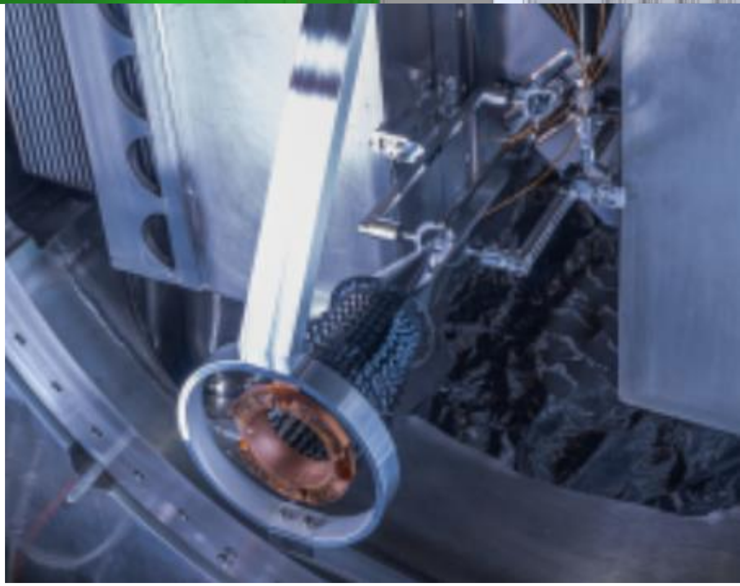




Workshop Opportunities of OO and pO collisions at the LHC, organised together with Jasmine Brewer and Aleksas Mazeliauskas, cern.ch/OppOatLHC (Feb 2021)
Alexander Huss, Aleksi Kurkela, Aleksas Mazeliauskas, Risto Paatelainen, WS and Urs Achim Wiedemann, Discovering partonic rescattering in light nucleus collisions (2020)

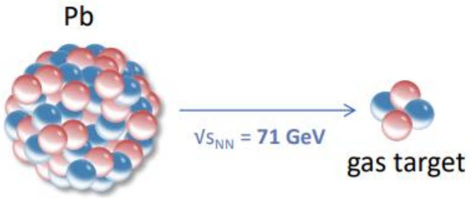
Light ions and SMOG2
LHCb at fixed target





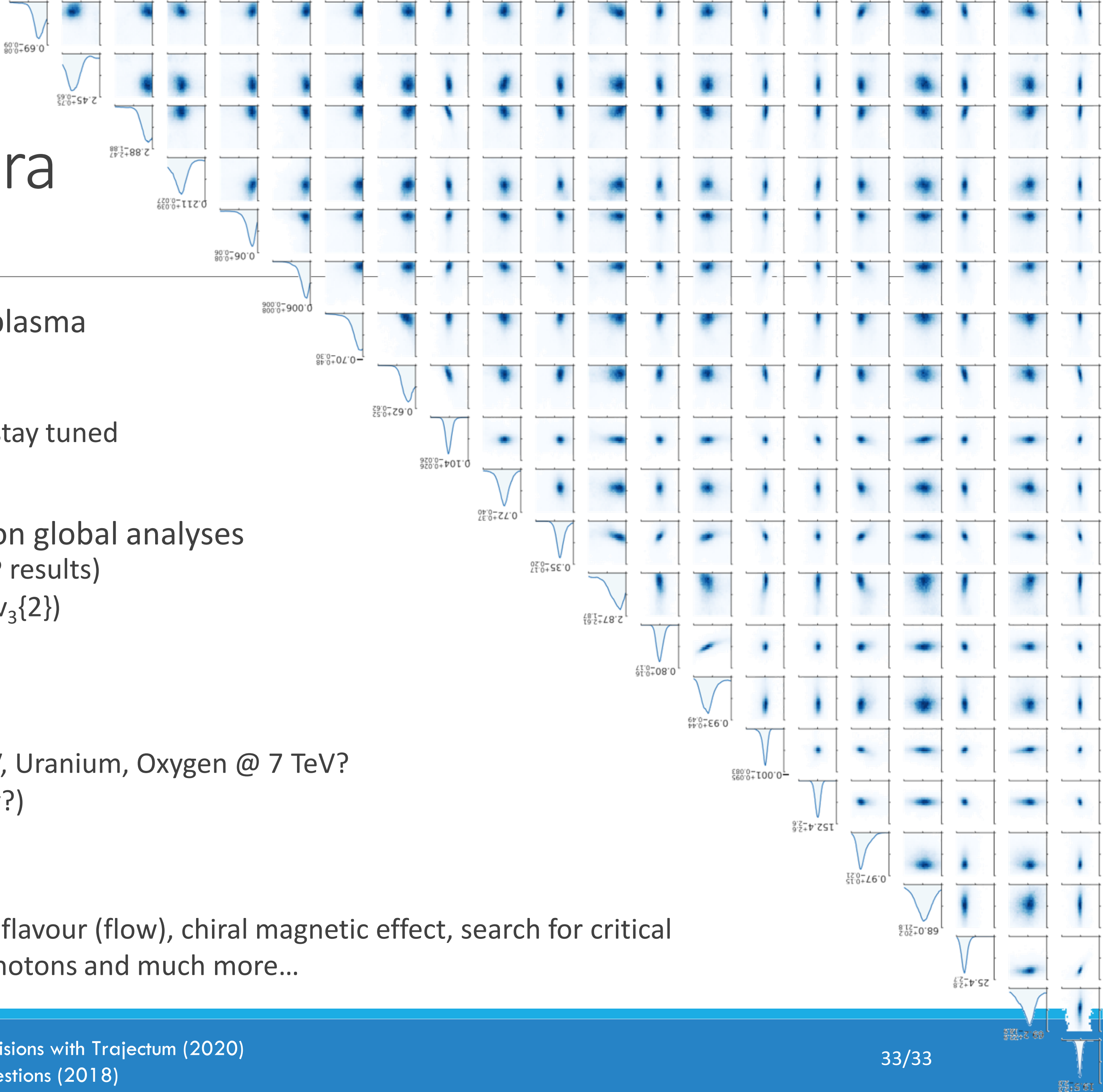
1. Interesting idea: ‘contaminate’ beam with gas (only at LHCb)
2. Fixed target (gas is at rest); options: H, He, N, O, Ar, Ne, Kr, Xe, …
3. Lower energy ($\sqrt{s_{NN}} \simeq 110\,\mathrm{GeV}$): complementary to colliding set-up
4. Possible with *p*, Pb and O in the beam
5. Data taking simultaneous: sizeable integrated lumi: 100 pb^{-1}

Global analysis perspective: need for a wide variety of colliding systems and energies



Giacomo Graziani, Oxygen beams and LHCb: prospects of collisions with fixed-targets (http://cern.ch/OppOatLHC/contributions/4172213/)

Theory of HIC in the LHC era



1. A road to precision analysis of the quark-gluon plasma
   - Measuring transport and initial stage `beyond η/s’,
   - **Revisited bulk viscosity: surprisingly small**
   - Hint towards second order transport coefficients: stay tuned

2. p_T-differential anisotropic flow sheds new light on global analyses
   - An excellent fit, including event-plane angles (MAP results)
   - Interesting MAP results on flow in *p*Pb (imaginary $v_3\{2\}$)
   - Initial stage and degrees of freedom: stay tuned

3. Only our first study
   - Include more systems and energies: Au @ 200 GeV, Uranium, Oxygen @ 7 TeV?
   - Finer observables (but sometimes statistics hungry?)

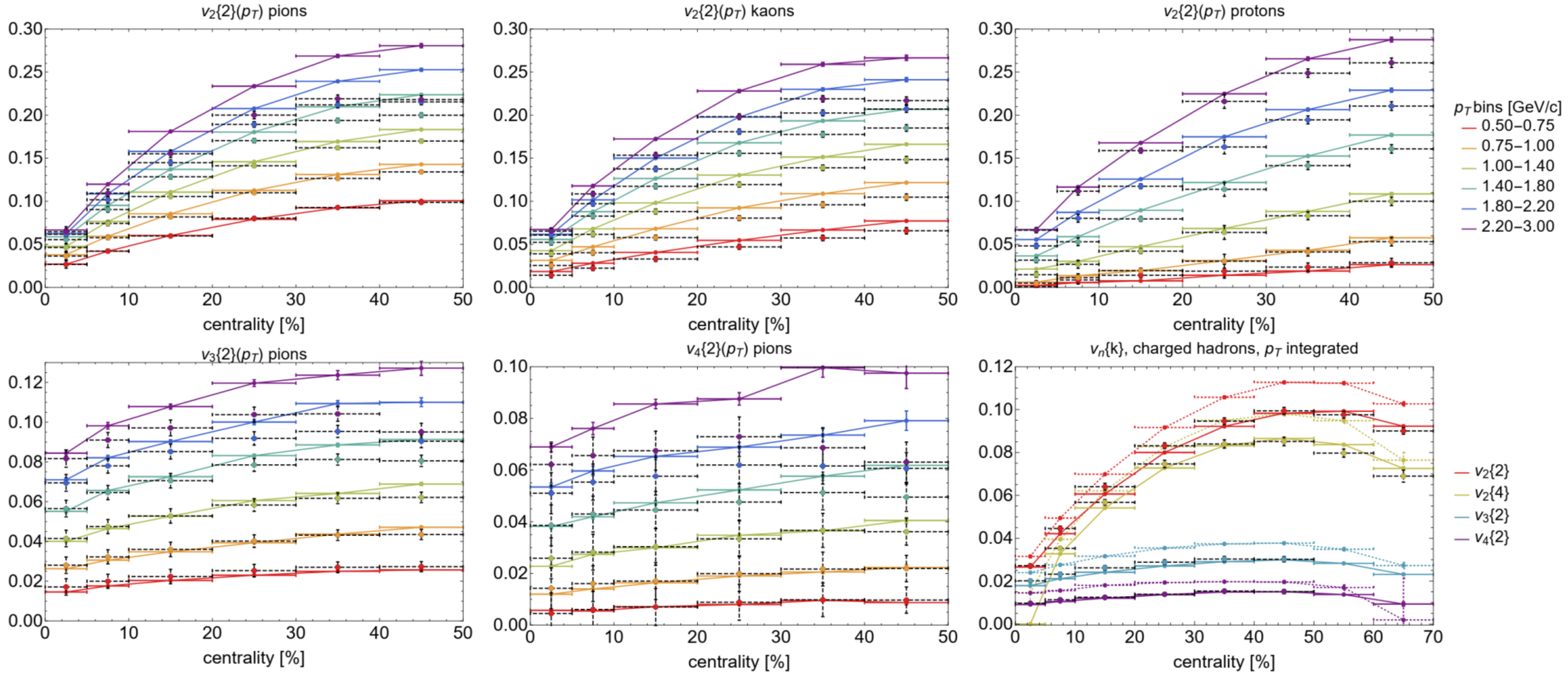
4. Did I skip anything?
   - progress in jet (substructure) modifications, heavy flavour (flow), chiral magnetic effect, search for critical point, rapidity dependence, bound quark states, photons and much more…

Govert Nijs, WS, Umut Gursoy and Raimond Snellings, A Bayesian analysis of Heavy Ion Collisions with Trajectum (2020)
Wit Busza, Krishna Rajagopal and WS, Heavy Ion Collisions: The Big Picture, and the Big Questions (2018)

Back up

MAP: PbPb anisotropic flow

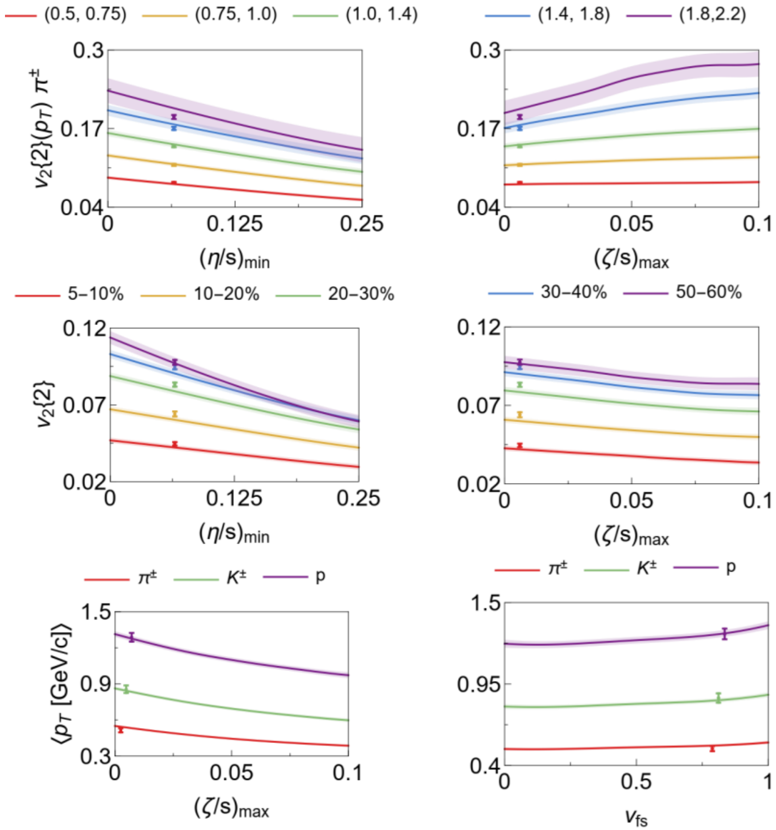
1. Anisotropic flow matches well, except for a few high p_T bins



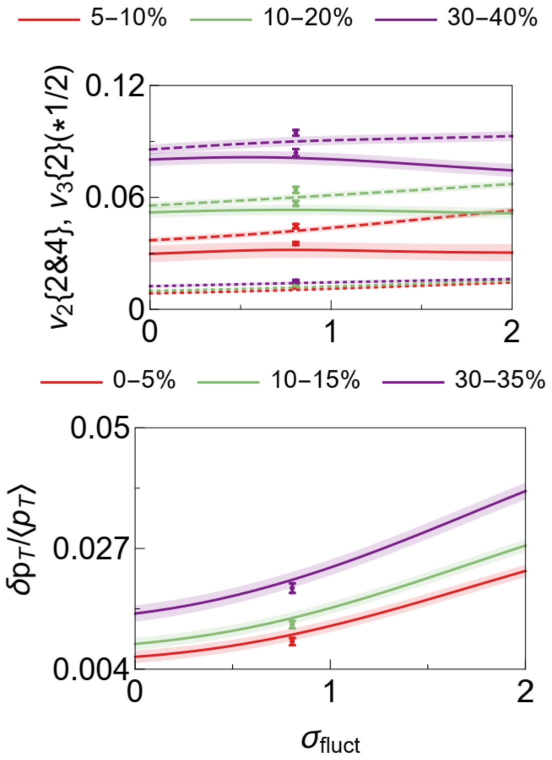
The emulator: Viscosities and fluctuations

also note: emulator uncertainty (50-60%, or $v_2\{4\}$)

v_2 increases in every p_T bin, but decreases on average for ζ.



$v_2\{2\}$ - $v_2\{4\}$ increases when increasing fluctuations

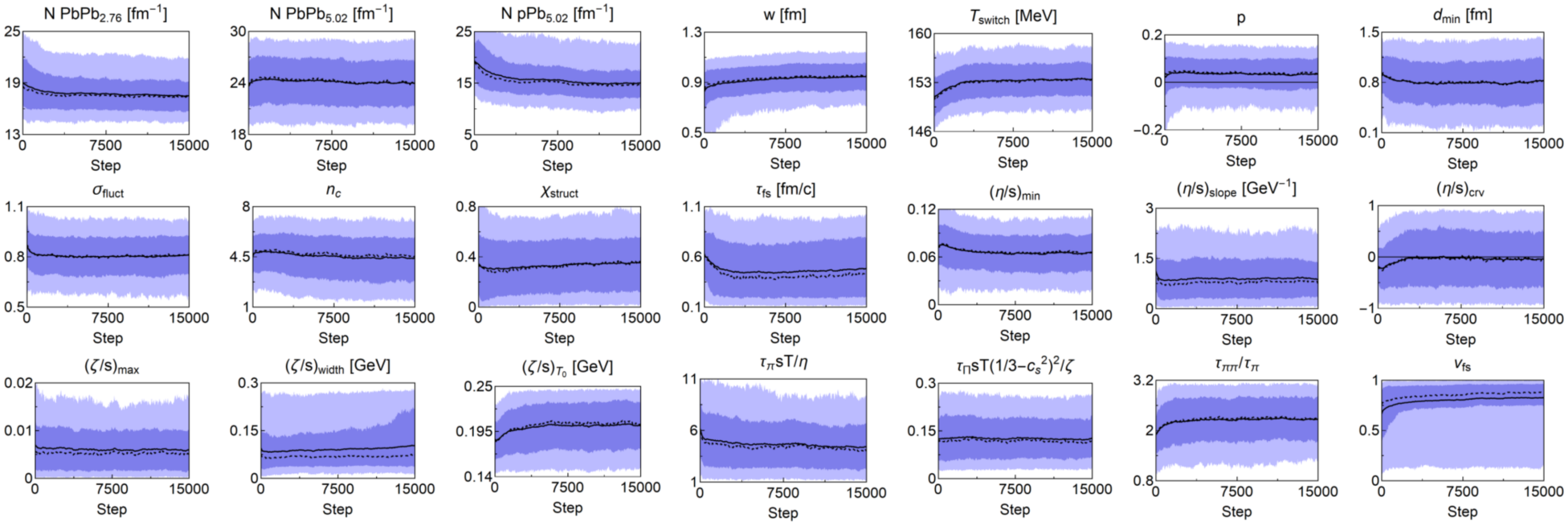


Making the chain: (pt)emcee

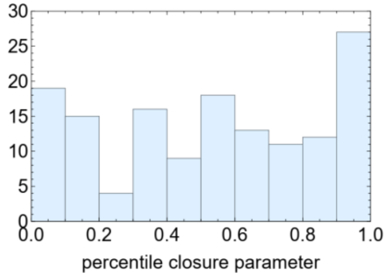
1. Constructing a chain of posteriors (MCMC); we use emcee

---

2. Necessary to verify convergence:

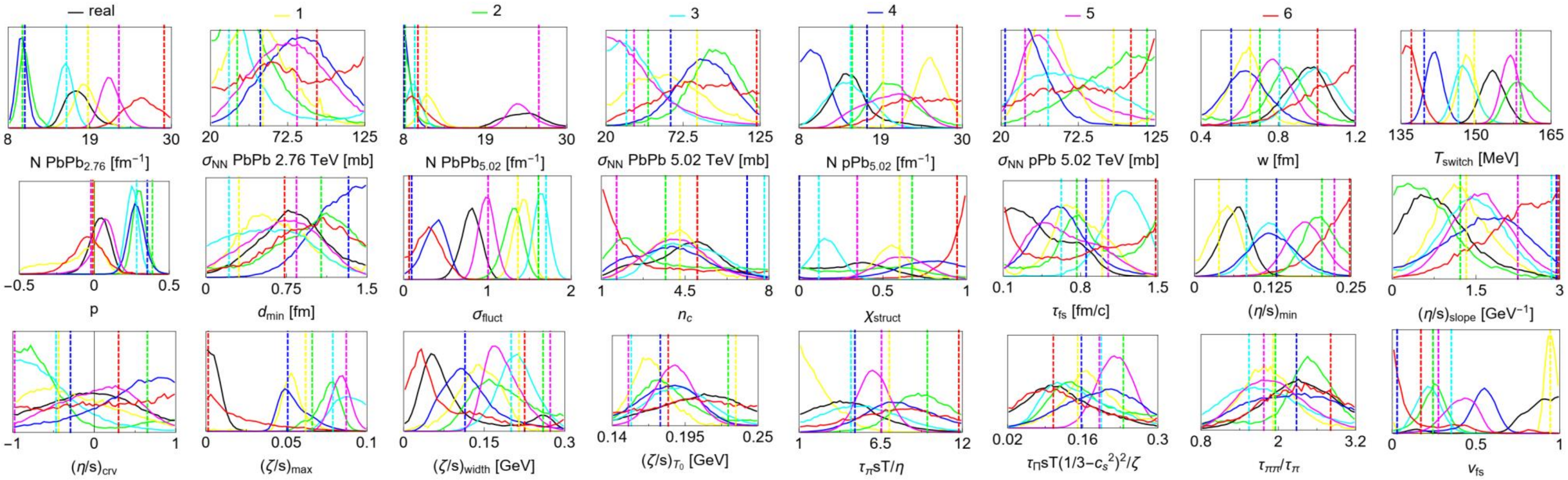


3. Still quite expensive to emulate:
600 walkers * 15000 steps * 10% acceptance with 2000 points = 3 weeks



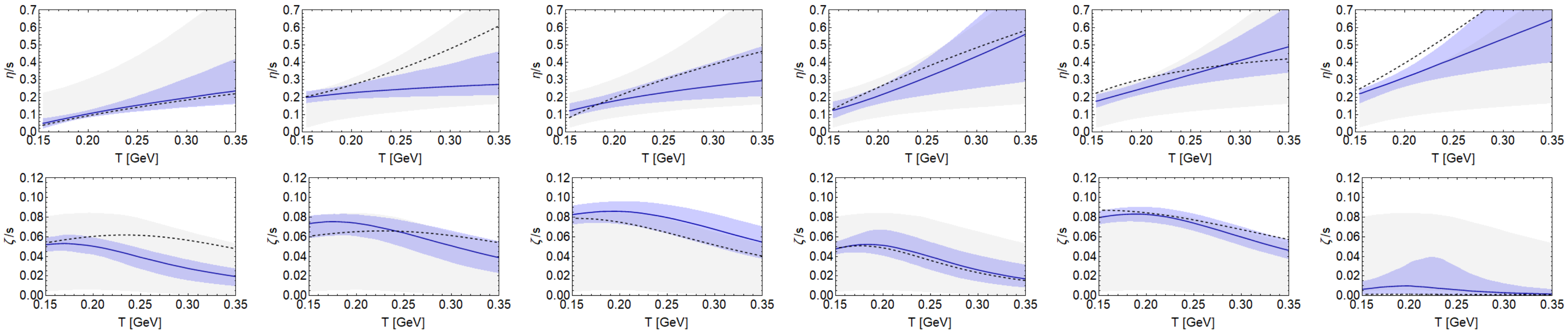
Selected results: closure test

1. We chose six random parameter points (sometimes at edge of prior)
   - Try to extract parameters from model-generated `experimental’ data
2. Verifies model + shows sensitivity data on parameter
   - Output indeed consistent with input
   - Sensitive to viscosities, less so for second order

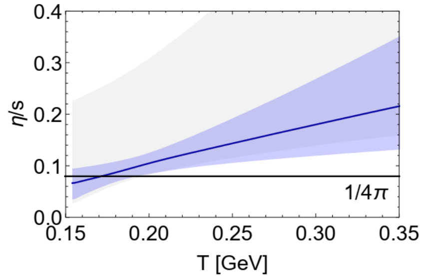


Closure test: viscosities

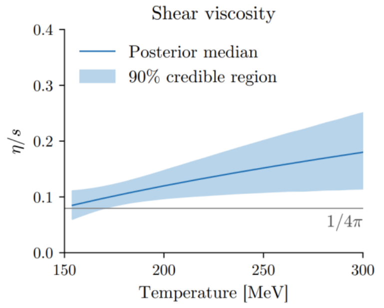
1. Closure test works well for both viscosities
2. Most sensitive to low-T region



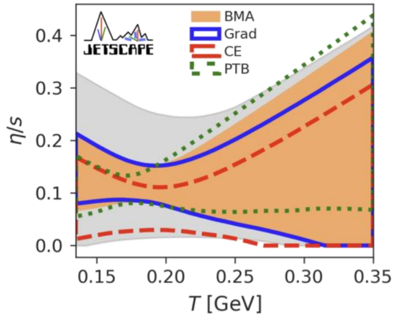
Posterior distributions – shear viscosity



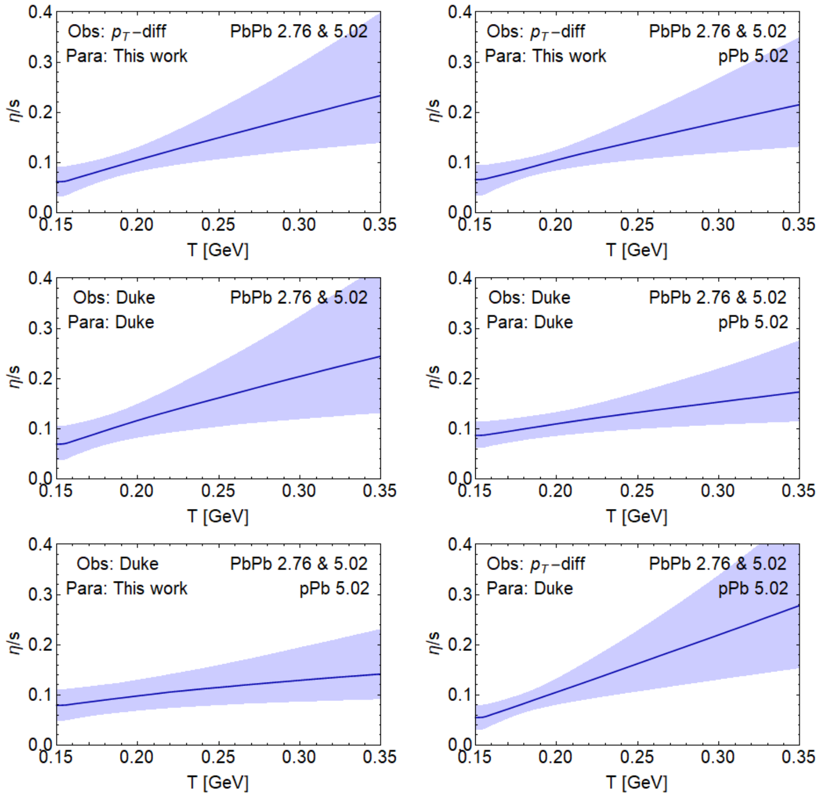
Current work (2020)



J. Bernhard, S. Moreland and S. Bass, Nature Physics (2019)



JETSCAPE (2020)



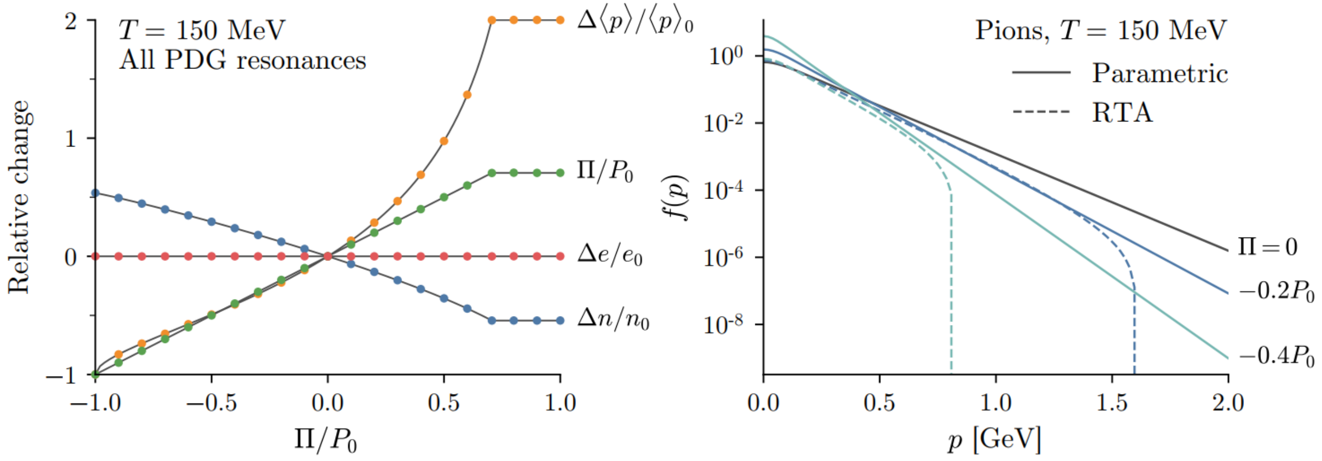
Particlization: viscous corrections

$$T^{\mu\nu} = \sum_{\rm sp} g \int \frac{d^3p}{(2\pi)^3}\frac{p^\mu p^\nu}{E} f(p),$$

1. Particles in fluid restframe cannot be in thermal equilibrium
2. Several methods that (only/mostly) agree for small deviations

$f(p) \to z_{\rm bulk} f(p+\lambda_{\rm bulk} p)$ parametric, rescale p: fix z and λ such that e and P match

$\delta f = f_0(1 \pm f_0)\frac{\tau}{ET}\left[\frac{1}{2\eta}p^i p^j \pi_{ij} + \frac{1}{\zeta}\left(\frac{p^2}{3} - c_s^2 E^2\right)\Pi\right]$ change *f(p)* directly, motivated by RTA



\`Parametric' clearly better at high p_T, but somewhat ad-hoc and species independent

Jonah Bernhard, Bayesian parameter estimation for relativistic heavy-ion collisions (2018)

Comparison with JETSCAPE

Results seem to be in relatively good agreement. Data is quite consistent without a sizeable bulk viscosity.

Energy Normalization
15.80
10.00 20.00

TRENTo Reduced Thickness
-0.04
-0.70 0.70

Multiplicity Fluctuation
0.74
0.30 2.00

Nucleon width [fm]
0.99
0.50 1.50

Min. Distance btw. nucleons cubed [fm^3]
0.88
0.00 4.91

Free-streaming time scale [fm/c]
0.52
0.30 2.00

Free-streaming energy dep.
0.00
-0.30 0.30

Temperature of shear kink [GeV]
0.16
0.13 0.30

Low-temp. shear slope [GeV^-1]
0.01
-2.00 1.00

High-temp shear slope [GeV^-1]
0.68
-1.00 2.00

Shear viscosity at kink
0.08
0.01 0.20

Bulk viscosity max.
0.03
0.01 0.20

Temperature of max. bulk viscosity [GeV]
0.19
0.12 0.30

Width of bulk viscosity [GeV]

The experimentally measured observables by the ALICE collaboration are shown as black dots.

The last row displays the temperature dependence of the specific shear and bulk viscosities (red lines), as determined by different parameters on the left sidebar.

By default, these parameters are assigned the values that fit the experimental data *best* (maximize the likelihood).

An important modelling ingredient is the particlization model used to convert hydrodynamic fields into individual hadrons. Three different viscous correction models can be selected by clicking the "Particlization model" button below.

Particlization model

Pratt-Torrieri-Bernhard

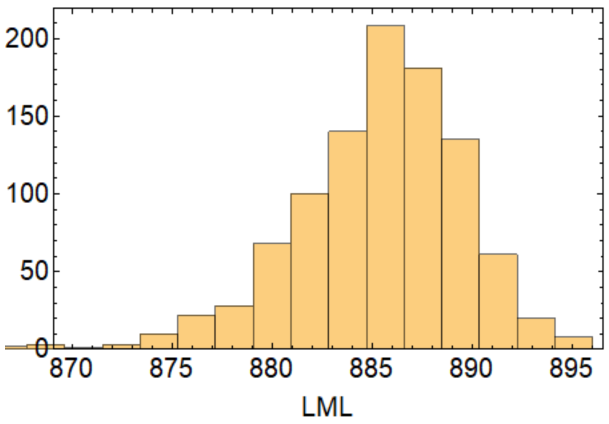
Reset

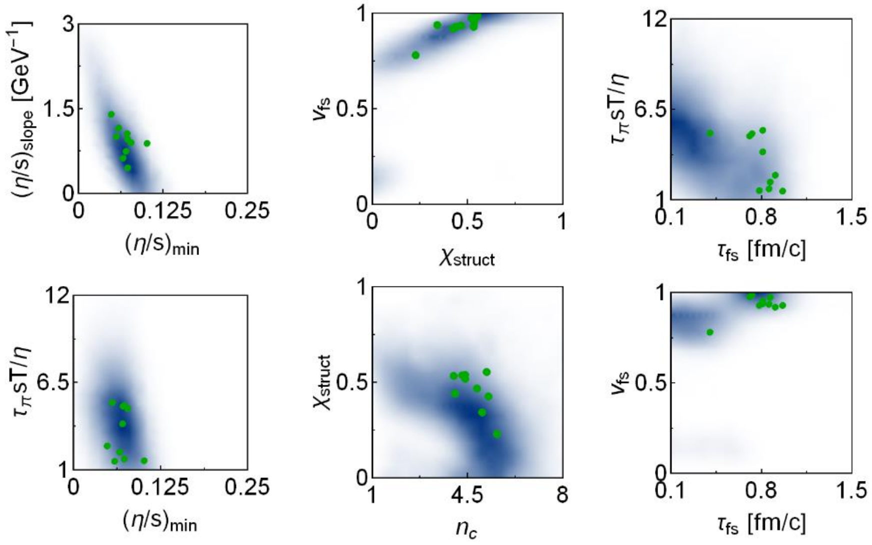
MAP: maximum a posteriori

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

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

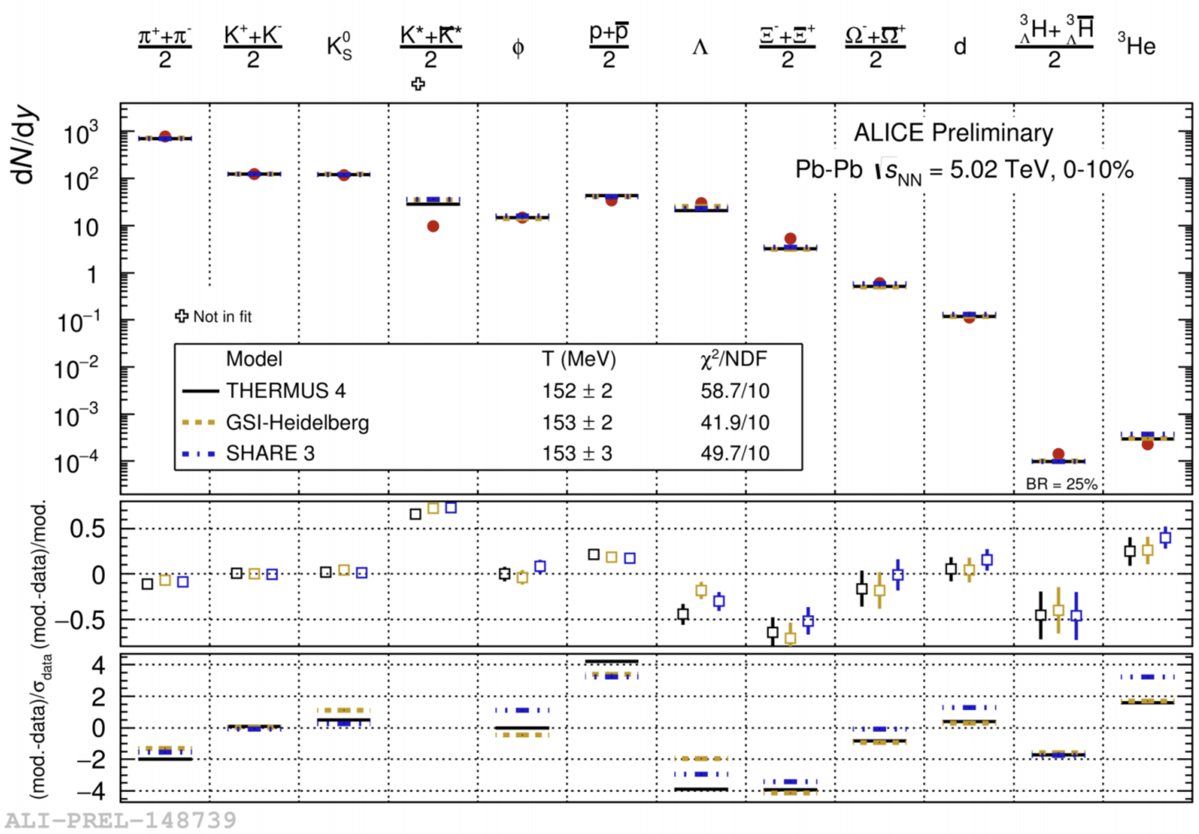
1. Subtle to find the `true' maximum of the LML:
2. take 3000 points from the posterior chain, plot highest 10 LMLs (LML > 893):





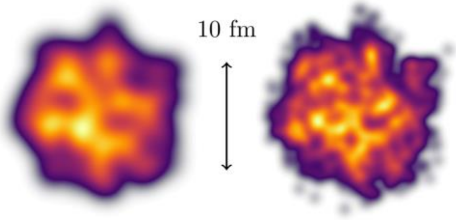
3. We decided to use expectation value of each param as `MAP' (LML = 884)

Strangeness and thermal fits: close but not perfect



ALICE, Testing the system size dependence of hydrodynamical expansion and thermal particle production with π, K, p, and ϕ in Xe–Xe and Pb–Pb collisions with ALICE (2018)

Initial geometry: two (three?) uncertainties



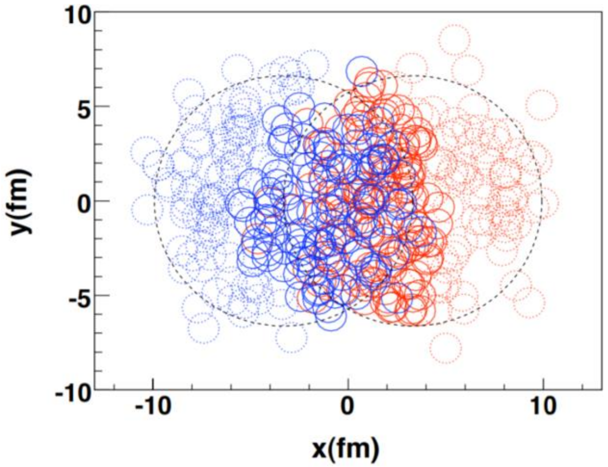
1. The structure of nucleons
    - n_c constituents of Gaussian subwidth *v* within a nucleon of width *w*
    - Nucleons placed according to MC Glauber
2. How do colliding (sub)nucleons deposit their energy? $\mathcal{T} = \left(\frac{\mathcal{T}_A^p + \mathcal{T}_B^p}{2}\right)^{1/p}$
    - For $p = 0$ we get $\mathcal{T} = \sqrt{\mathcal{T}_A \mathcal{T}_B}$: close to EKRT or Holography ($\mathcal{T} \approx (\mathcal{T}_A \mathcal{T}_B)^{4/9}$)
    - Does not quite allow binary scaling?
3. (Quantum) fluctuations in the above: Gamma-distribution:
    - Goes beyond MC Glauber fluctuations $p(T) = \frac{1}{\Gamma(1/\sigma)\sigma^{1/\sigma}} T^{(1-\sigma)/\sigma} e^{-T/\sigma}$

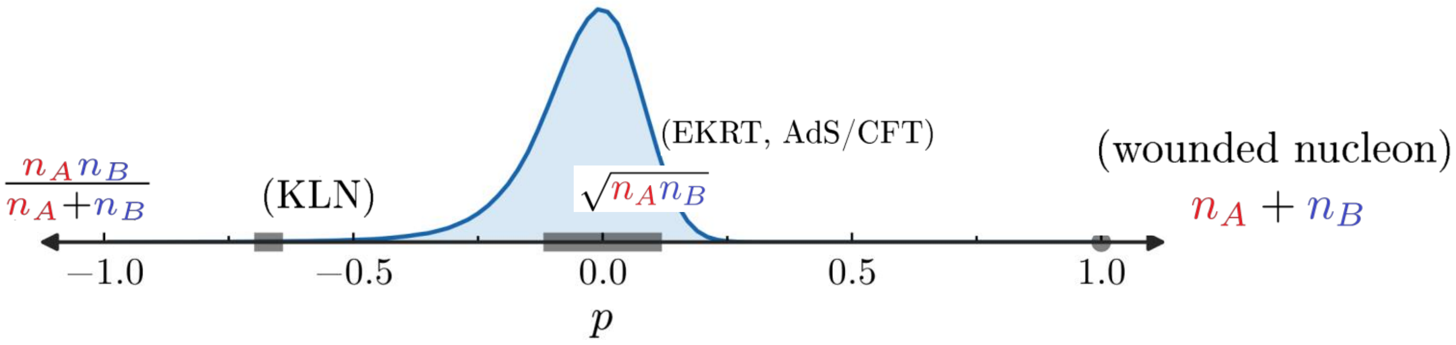
Scott Moreland, Jonah Bernhard and Steffen Bass, Estimating nucleon substructure properties in a unified model of p-Pb and Pb-Pb collisions (2018)
WS and Bjoern Schenke, Rapidity dependence in holographic heavy ion collisions (2015)

Constraints on initial conditions

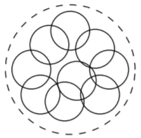
Trento parametrization allows for many models:

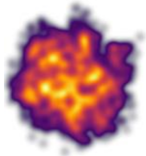
- Distinguishes KLN, EKRT or AdS/CFT, wounded nucleons
- Data clearly rules out KLN and wounded nucleons



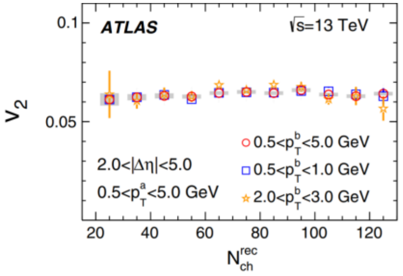


Jonah E. Bernhard, Bayesian parameter estimation for relativistic heavy-ion collisions (PhD thesis, 2018)
J. Bernhard, S. Moreland and S. Bass, Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma (Nature Physics, 2019)

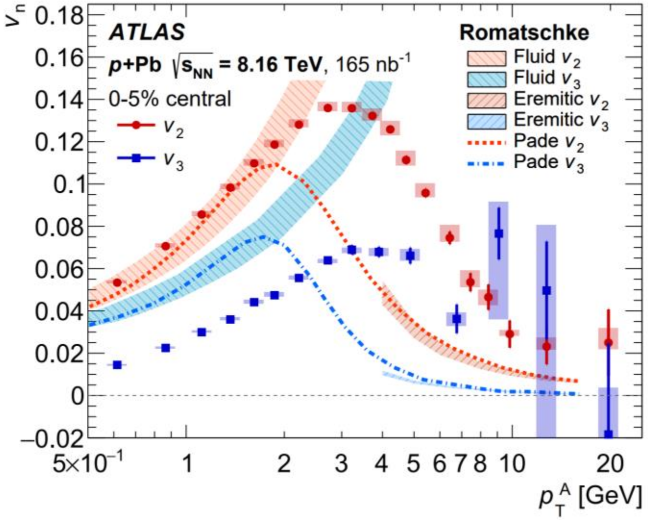


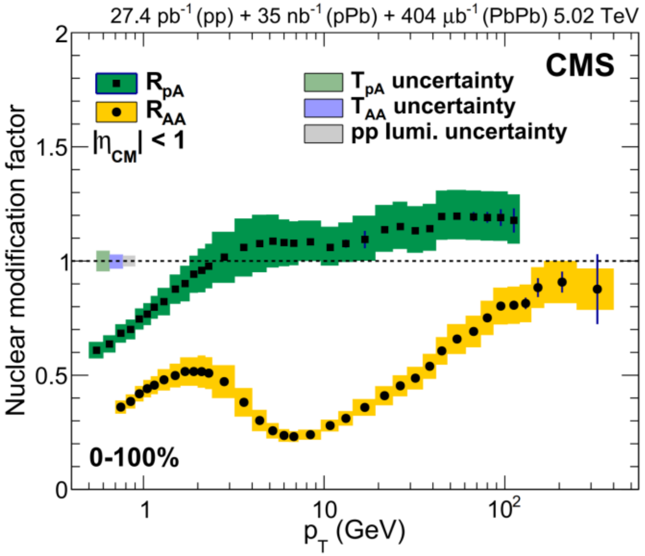


A puzzle: flow in pPb or pp collisions?



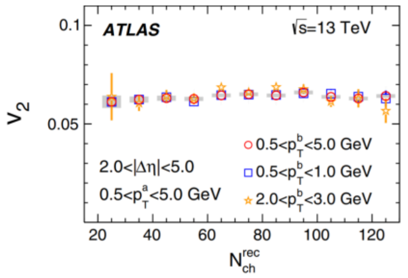
1. There seems to be flow
   - Quite some modeling, but everything consistent with hydro (does not proof hydro!)
2. But: nuclear modification > 1: **no jet energy loss**, but nuclear effects dominate



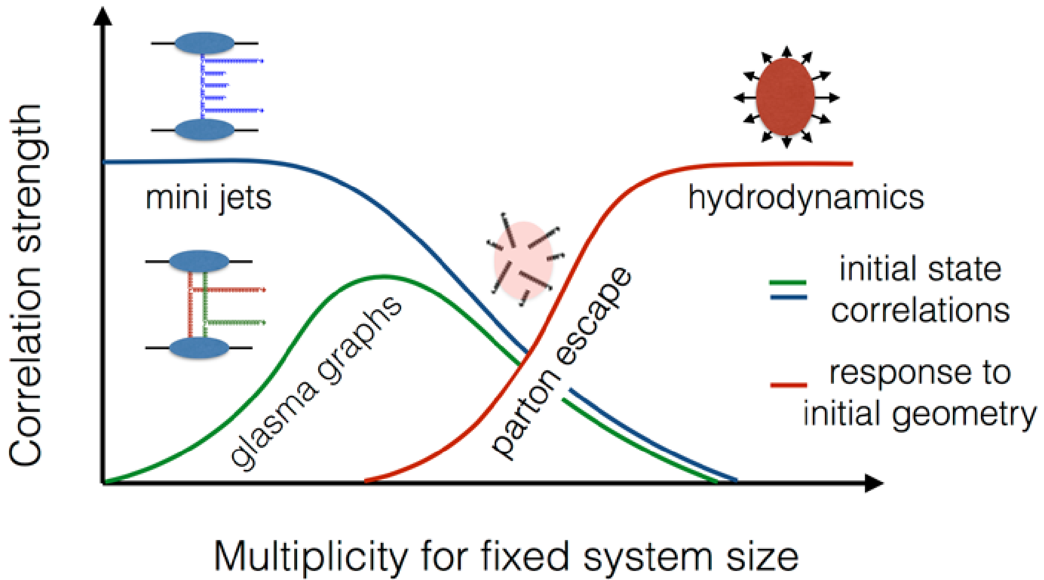


S. Moreland, J. Bernhard, and S. Bass, Estimating initial state and QGP medium properties using … p-Pb and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (2018)
CMS, Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}}$= 5.02 TeV (2016)

A puzzle: flow in pPb or pp collisions?



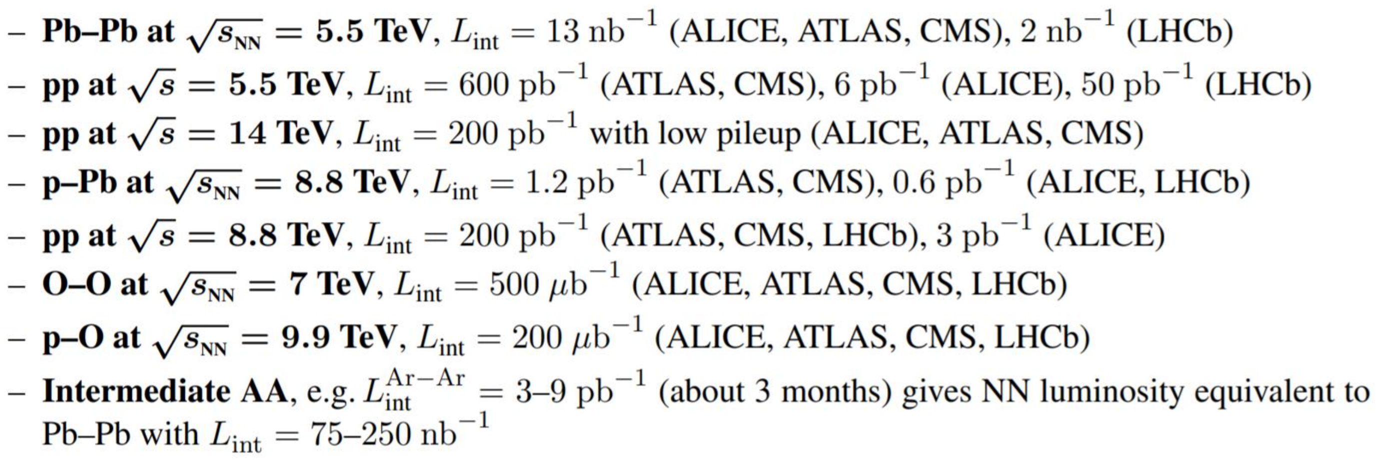
1. It should be possible to `turn off' hydro (small system)
2. Tantalising option: Combination of mini-jets/glasma connecting to hydro
   - Challenge: hard to explain constant v2; spectra not necessarily thermal
   - Quenching versus flow is challenging for any model



S. Schlichting, Initial state and pre-equilibrium effects in small systems (2016)

The future

1. Comprehensive (Bayesian) analysis, with more complete dataset
2. For small systems: runs with light or intermediate ions:

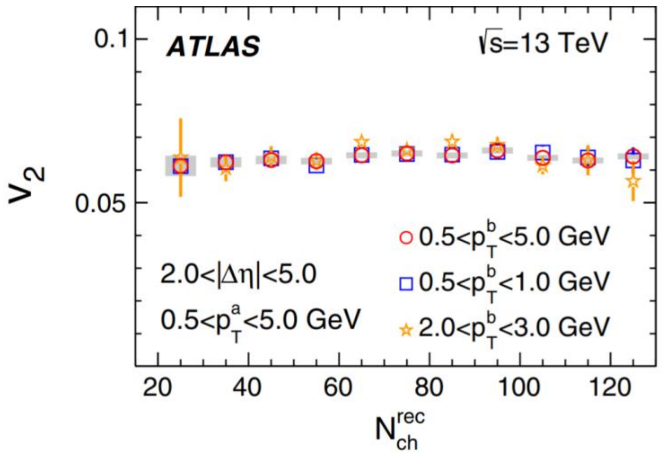


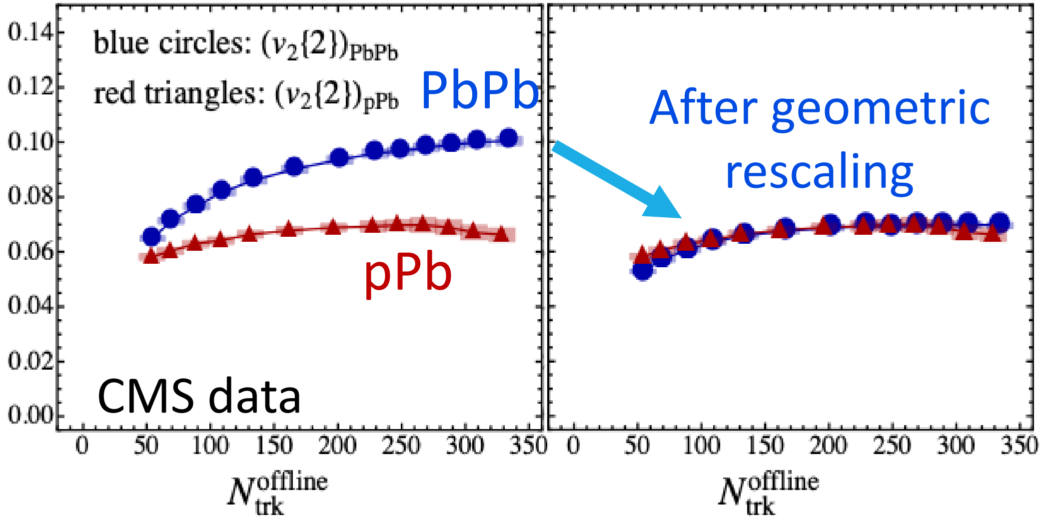
- **Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV**, $L_{\mathrm{int}} = 13\ \mathrm{nb}^{-1}$ (ALICE, ATLAS, CMS), $2\ \mathrm{nb}^{-1}$ (LHCb)
- **pp at $\sqrt{s} = 5.5$ TeV**, $L_{\mathrm{int}} = 600\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $6\ \mathrm{pb}^{-1}$ (ALICE), $50\ \mathrm{pb}^{-1}$ (LHCb)
- **pp at $\sqrt{s} = 14$ TeV**, $L_{\mathrm{int}} = 200\ \mathrm{pb}^{-1}$ with low pileup (ALICE, ATLAS, CMS)
- **p–Pb at $\sqrt{s_{\mathrm{NN}}} = 8.8$ TeV**, $L_{\mathrm{int}} = 1.2\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $0.6\ \mathrm{pb}^{-1}$ (ALICE, LHCb)
- **pp at $\sqrt{s} = 8.8$ TeV**, $L_{\mathrm{int}} = 200\ \mathrm{pb}^{-1}$ (ATLAS, CMS, LHCb), $3\ \mathrm{pb}^{-1}$ (ALICE)
- **O–O at $\sqrt{s_{\mathrm{NN}}} = 7$ TeV**, $L_{\mathrm{int}} = 500\ \mu\mathrm{b}^{-1}$ (ALICE, ATLAS, CMS, LHCb)
- **p–O at $\sqrt{s_{\mathrm{NN}}} = 9.9$ TeV**, $L_{\mathrm{int}} = 200\ \mu\mathrm{b}^{-1}$ (ALICE, ATLAS, CMS, LHCb)
- **Intermediate AA**, e.g. $L_{\mathrm{int}}^{\mathrm{Ar-Ar}} = 3$–$9\ \mathrm{pb}^{-1}$ (about 3 months) gives NN luminosity equivalent to Pb–Pb with $L_{\mathrm{int}} = 75$–$250\ \mathrm{nb}^{-1}$

Working Group 5 of HL-LHC, Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams (2018)

Similar in pPb or PbPb

1. pPb geometry intrinsically more spherical → lower v_2





Gokce Basar and Derek Teaney, A scaling relation between pA and AA collisions (2013)