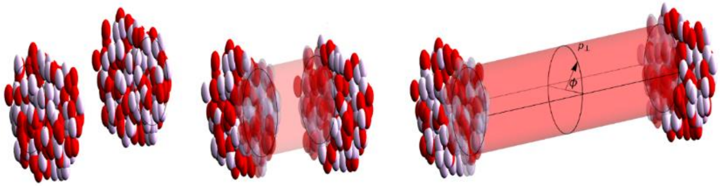
Theory of heavy ions in the LHC era

Towards a precision analysis of heavy ion collisions

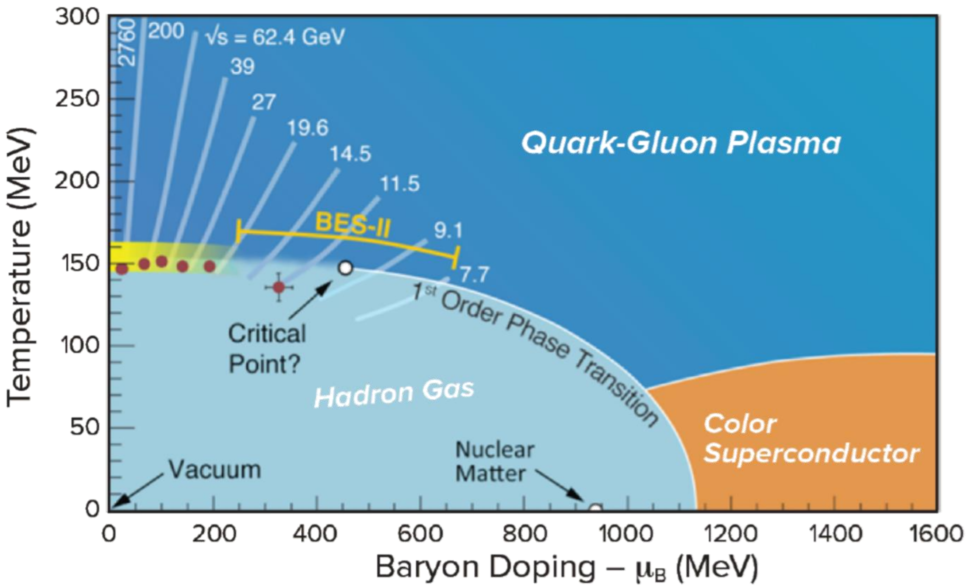


Wilke van der Schee
LHCP, Paris
27 May 2020

Why do we study heavy ion collisions?

1. Fundamental force of nature

2. Perhaps the simplest form of complex matter
   - Confinement: hadron gas in IR
   - Cross-over to quark-gluon plasma
   - QGP: strongly coupled
   - A critical point?



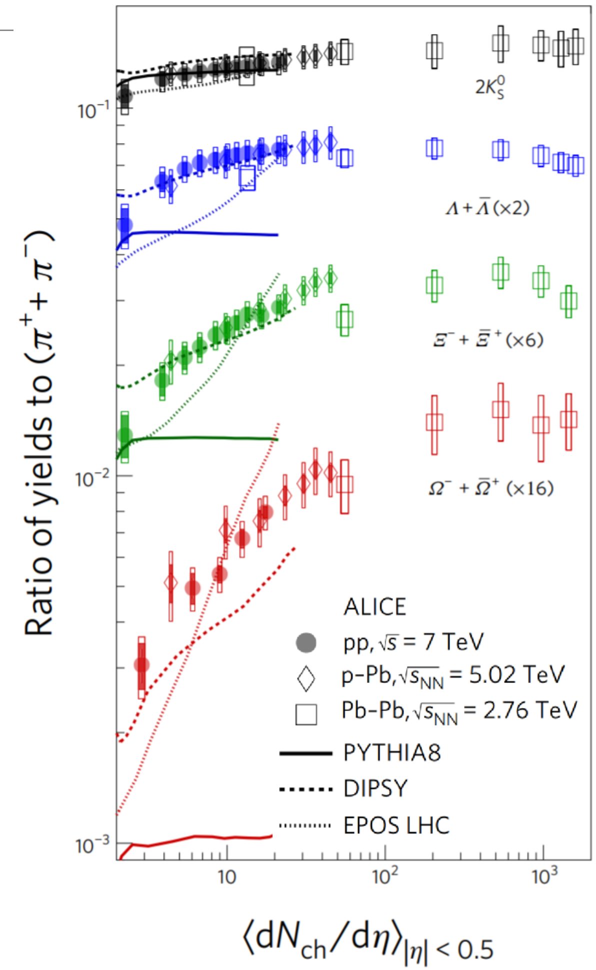
Strangeness: from pQCD to thermal

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

Thermodynamical string fragmentation JHEP

Nadine Fischer[a,b] and Torbjörn Sjöstrand[a] *January 31, 2017*

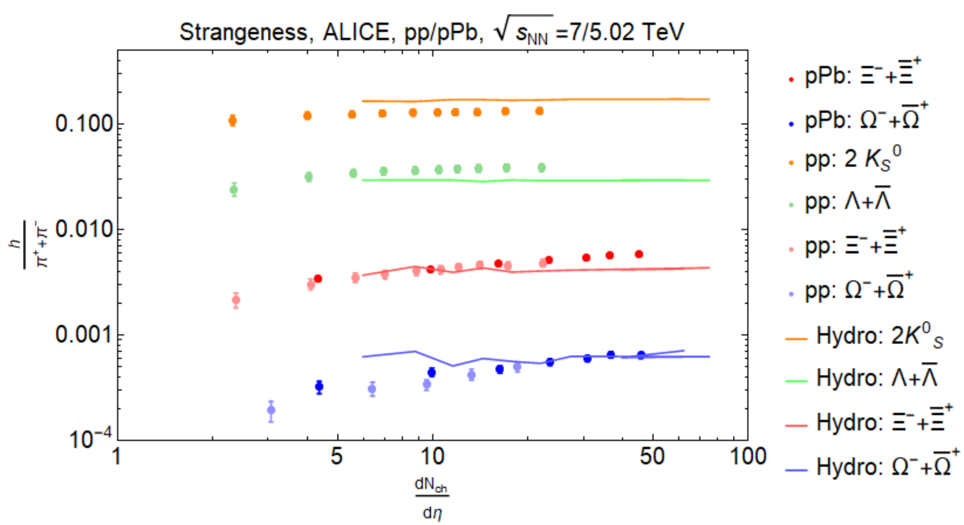
ABSTRACT: The observation of heavy-ion-like behaviour in pp collisions at the LHC suggests that more physics mechanisms are at play than traditionally assumed.

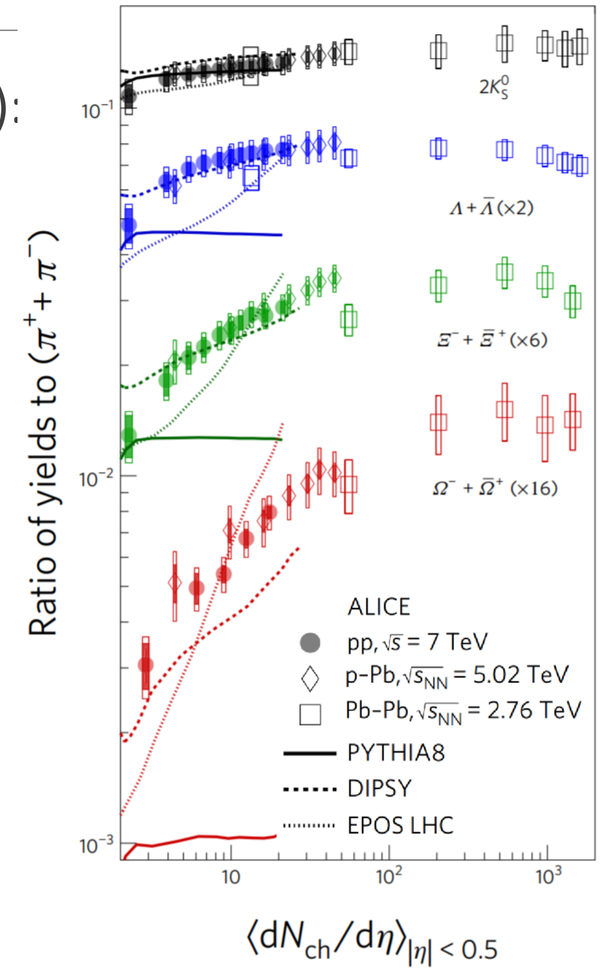


2. Saturates for high multiplicity pPb / PbPb
   - Interpretation: thermal strangeness production

Strangeness: from pQCD to thermal

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

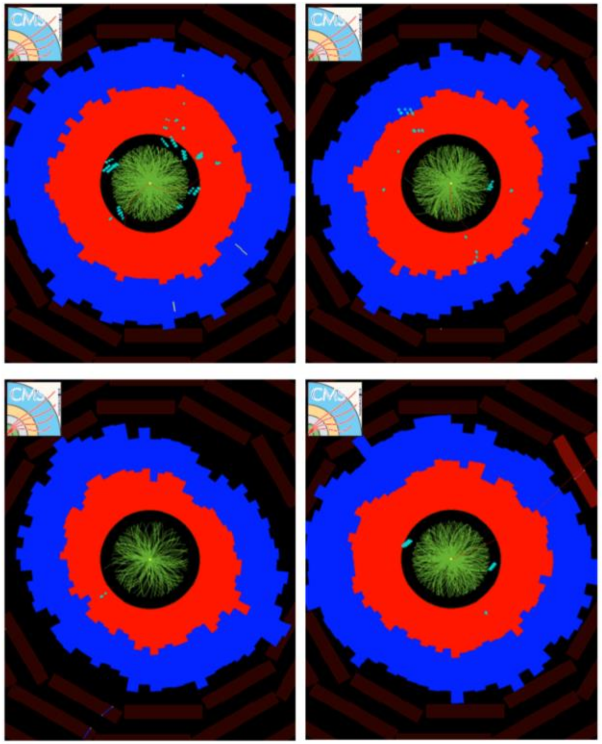


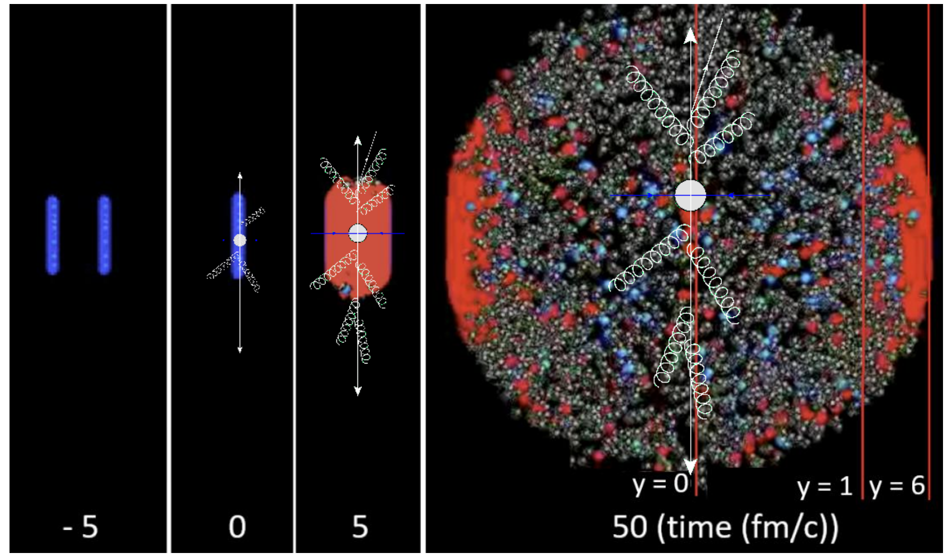


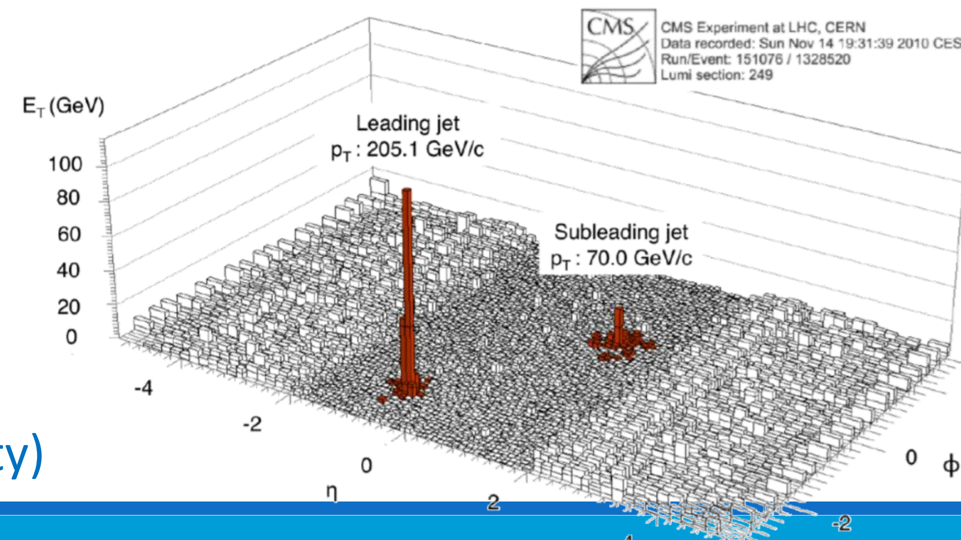
2. Hydro has only small dependence on N_{ch}
   - Approximately fits thermal model

See also: Volodymyr Vovchenko, Benjamin Donigus and Horst Stoecker, Canonical statistical model analysis of pp, pPb, and PbPb collisions at the LHC (2019)

Quark-gluon plasma is strongly coupled

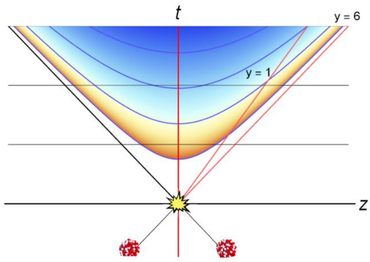






Studying the most perfect liquid

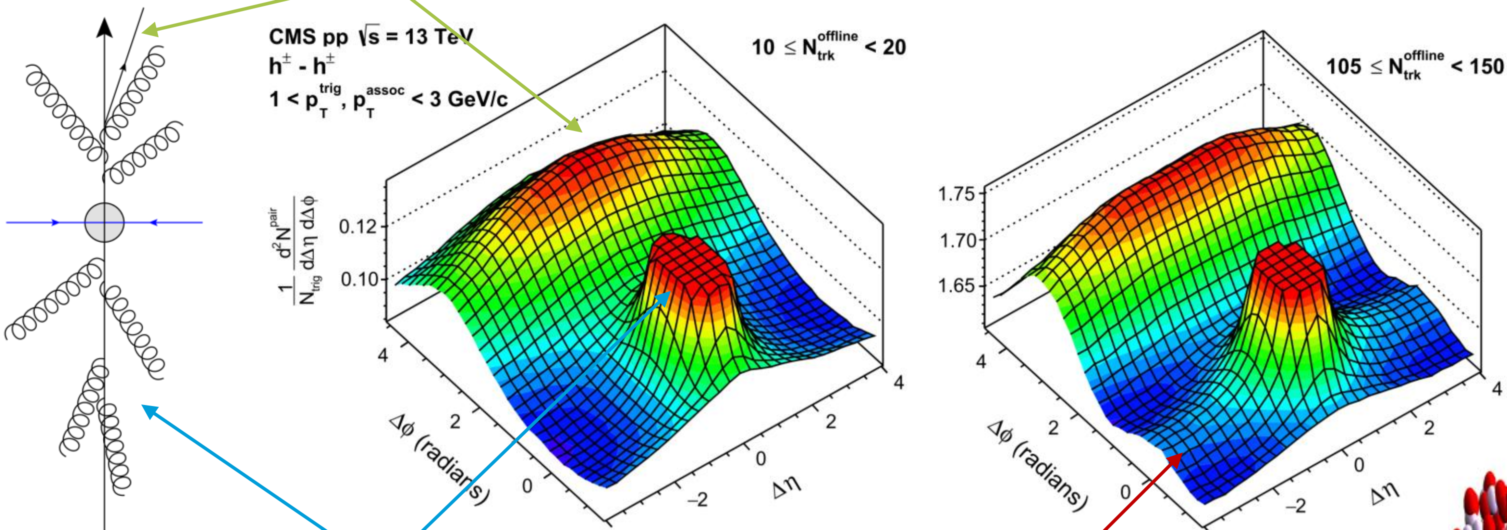
- Jet energy loss in dijet pair
- Anisotropic flow (small viscosity)

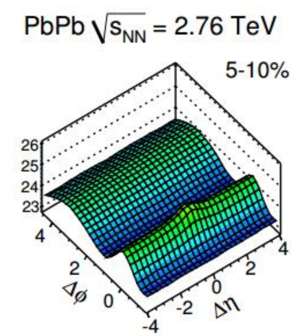


A puzzling ridge in *pp* collisions

1. Ridge at $\Delta\phi$=0 and large $\Delta\eta$: *an initial or geometric effect*

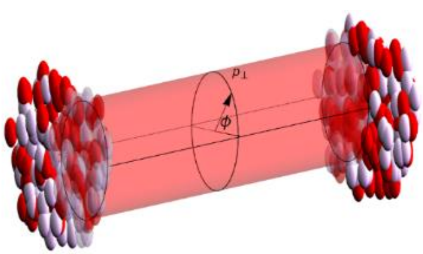
Back-to-back jet





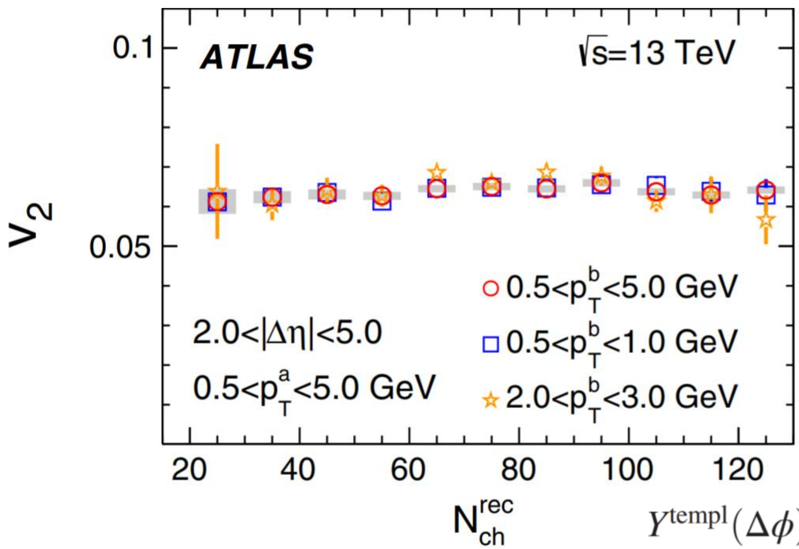
Jet fragmentation

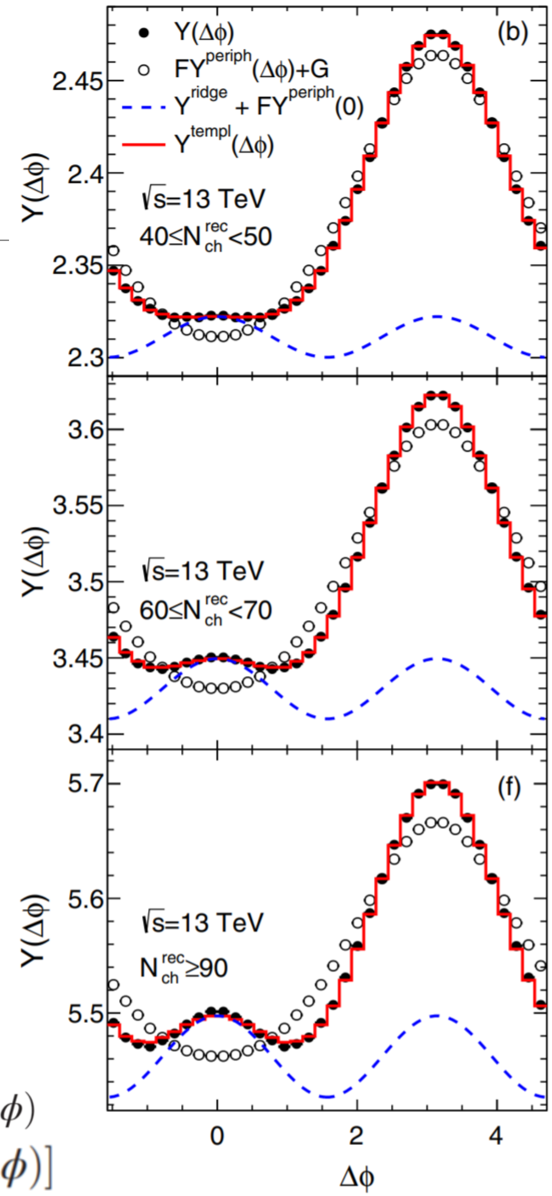
(nearside)**Ridge**



Extract spherical 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





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

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

One fluid to rule them all …

1. pp, pPb & PbPb: all have thermal identified particle spectra

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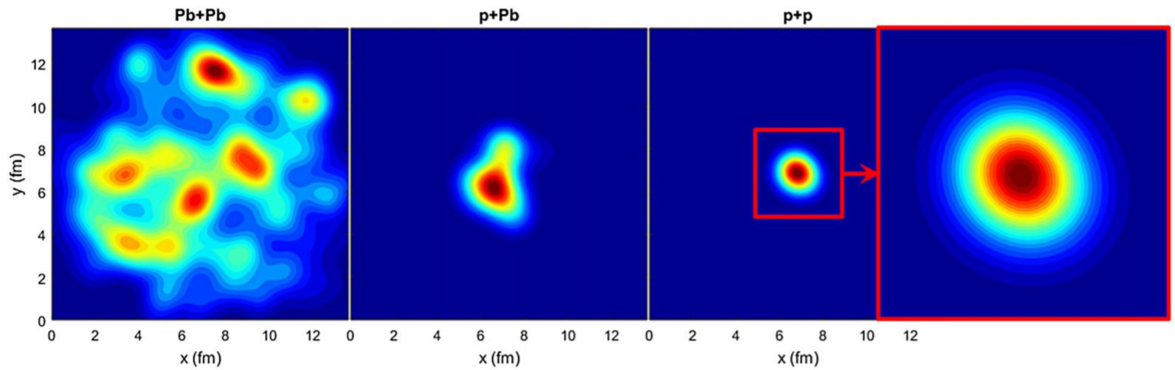
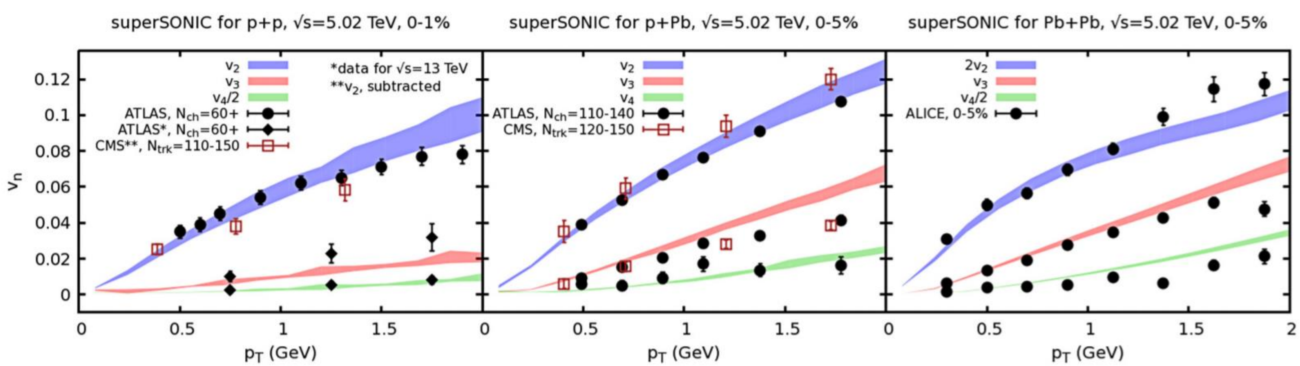
2. SuperSONIC: AdS/CFT evolution smoothly matched to hydro
   - Includes sizeable `pre-flow’; reasonable match to experiment for PbPb, pPb and pp





Raises question:
If and how a hydrodynamic fluid arises?

1. Expectation: hydro can be `turned off' by going to smaller systems

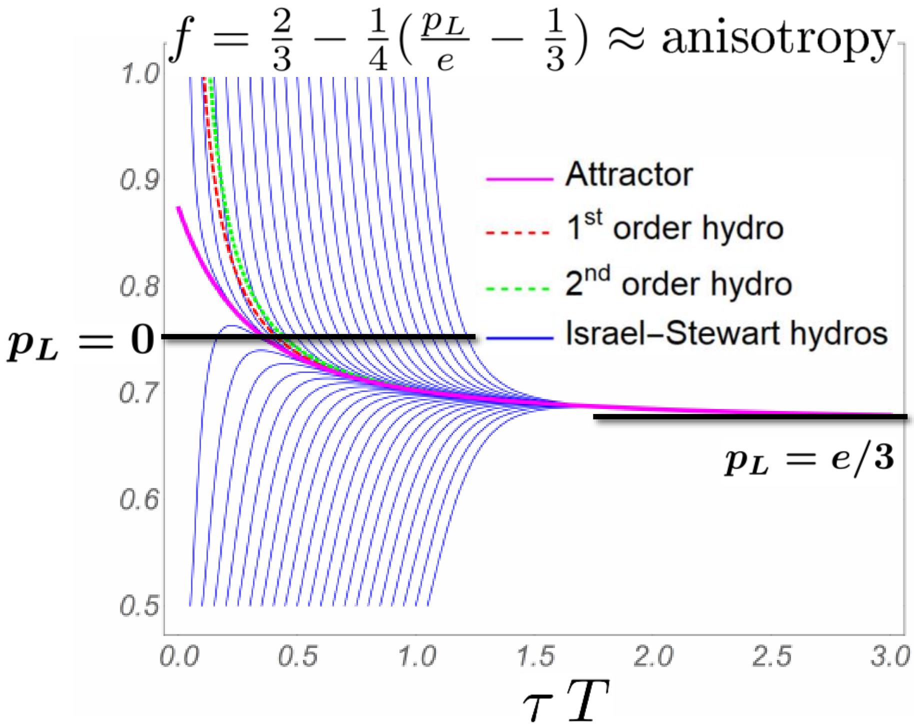
2. A need to explore hydrodynamics with high precision

3. Rest of the talk:
   - The approach to (viscous) hydrodynamics
   - Modelling: initial conditions, hydro → particles etc: many parameters
   - A comprehensive (Bayesian) analysis

New development: hydrodynamic attractor

Resummed hydrodynamics

1. \`UV completed' hydro evolutions
   - All curves approach attractor
   - More accurate than 1st or 2nd order
2. Hydrodynamises in time 1/T
   - Simulation where $\eta/s=1/4\pi$
   - Anistropy still large at time 1/T
3. Caveat: \`resummation' is in general ambiguous
   - In this case unique: $f(\tau \to 0)$ is finite

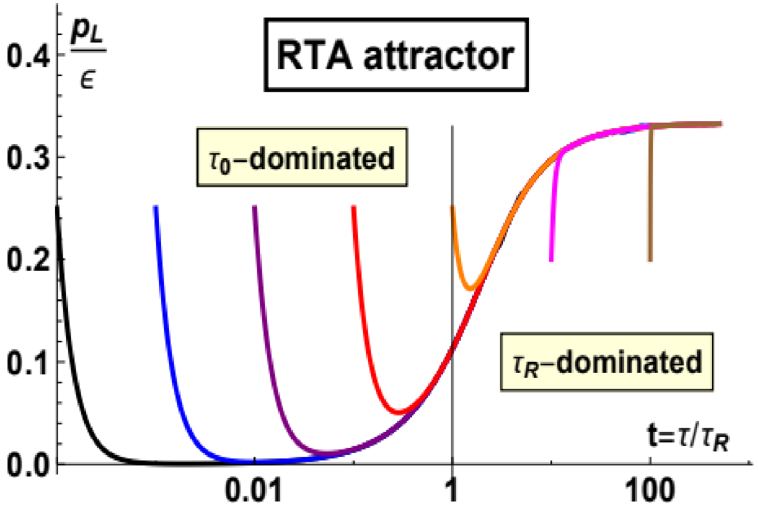


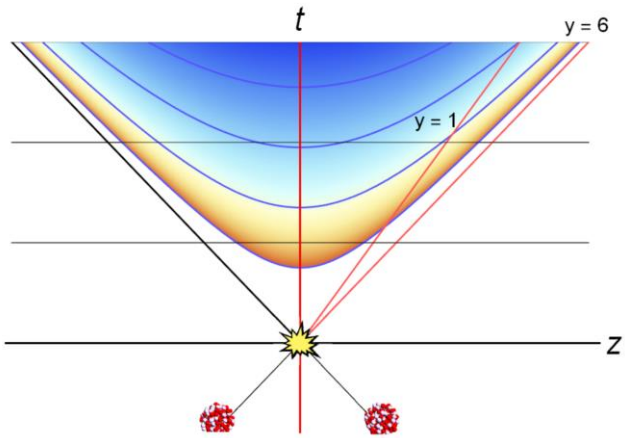
Michal P. Heller and Michał Spaliński, Hydrodynamics Beyond the Gradient Expansion: Resurgence and Resummation (2015)
Paul Romatschke, Relativistic Fluid Dynamics Far From Local Equilibrium (2018)

Attractor at weak coupling

Attractor in kinetic theory with relaxation time approximation (RTA)

- Decay to attractor on time scale of initialization time: τ_0
- RTA: expansion dominated: free streaming ($p_L = 0$, $p_T = e/2$)
  - Expansion is selection mechanism of particles without longitudinal momentum
- Hydrodynamises when interactions take over: relaxation time: $\tau_R = \frac{\eta/s}{1/4\pi}\frac{1}{T}$

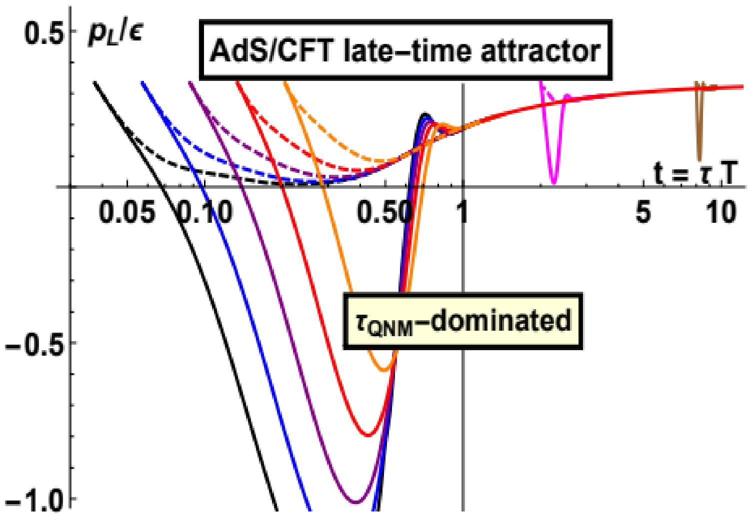


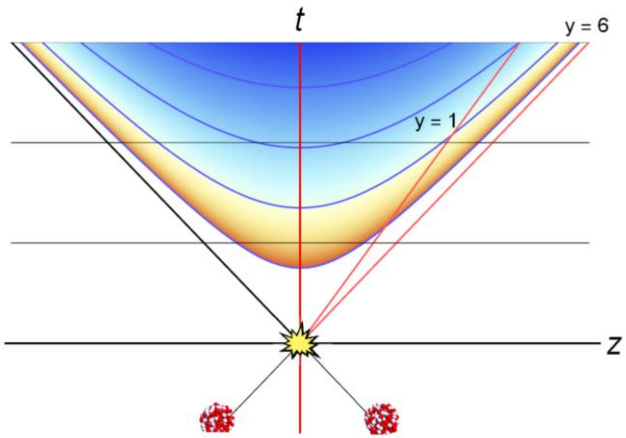


Attractor at strong coupling

Attractor in AdS/CFT (QFT in infinite coupling and large N_c limit)

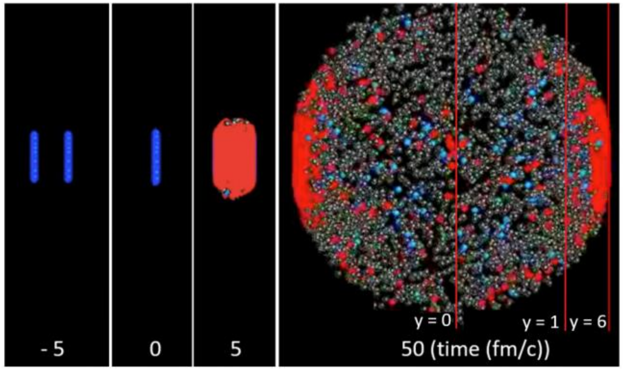
- Initial dynamics determined by initial condition (IC)
  - `UV' profile converges faster (dashed), interesting role higher-point correlators
- Hydrodynamises when interactions take over: relaxation time: $\tau_R = \frac{\eta/s}{1/4\pi}\frac{1}{T}$

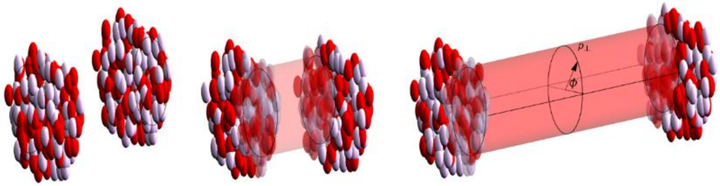




Standard model of heavy ion collisions

1. Initial stage (6)
   - Initial energy deposition
   - Pre-hydro stage; attractor/free streaming? Model for shear viscous pressures?
2. At switch time: Hydro (7)
   - Transport coefficients, EOS (from lattice)
   - Transport can be higher order; can depend on T
3. Freeze-out and hadronic gas phase (1)
   - Cooper-Frye freeze-out
   - UrQMD hadronic cascade afterburner
4. Compare with experiment

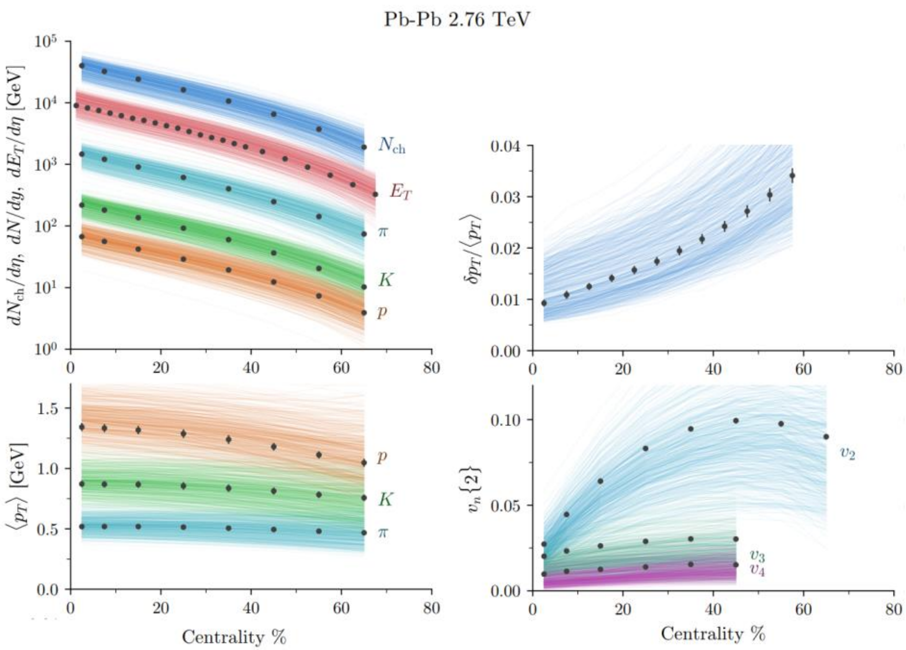




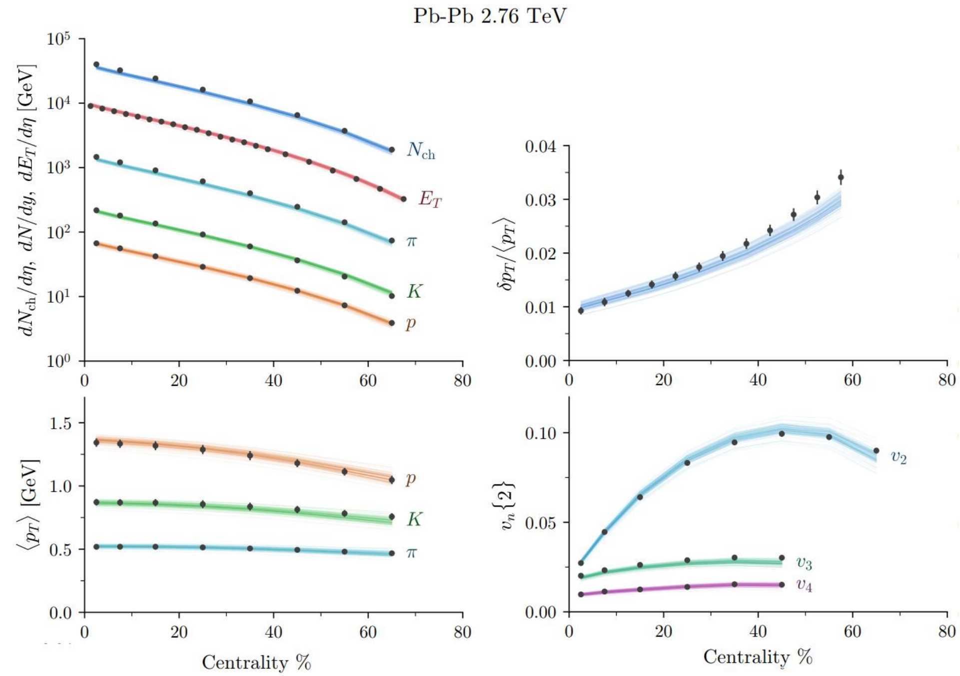
Bayesian analysis

1. Many stages, many (non-linear) parameters: comprehensive scan
   - Similar to what is done in cosmology (CMB analysis, structure formation)
   - Need high statistics at many `design’ parameter points (O(500) with 10k events)

Design/prior (data from ALICE)

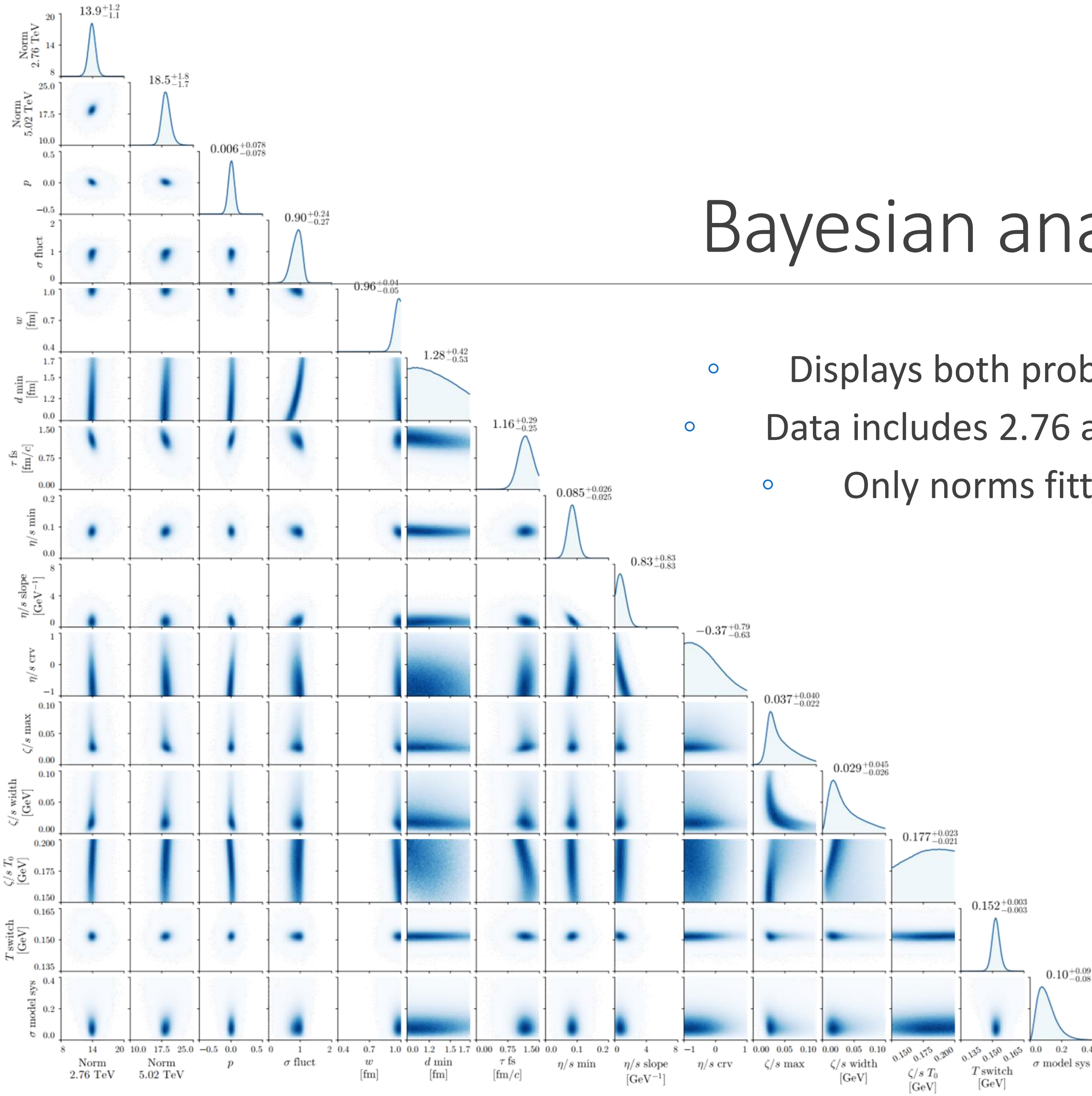


posterior



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)

Bayesian analysis



- Displays both probability as well as correlations
- Data includes 2.76 and 5.02 TeV (+200 GeV+pPb)
- Only norms fitted independently per energy

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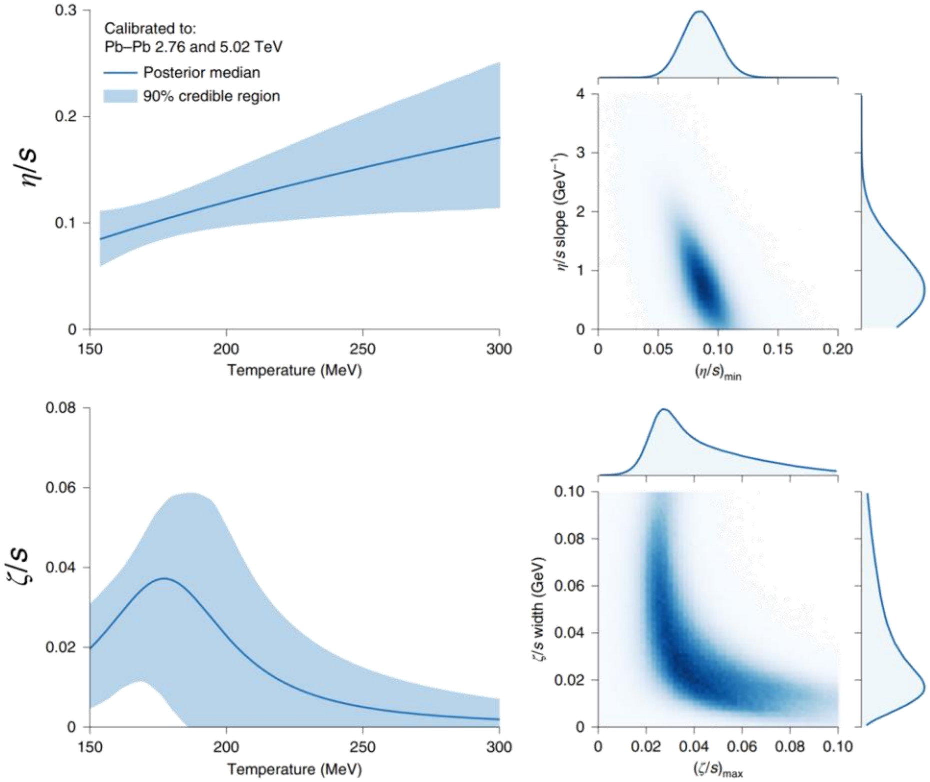
The viscosities

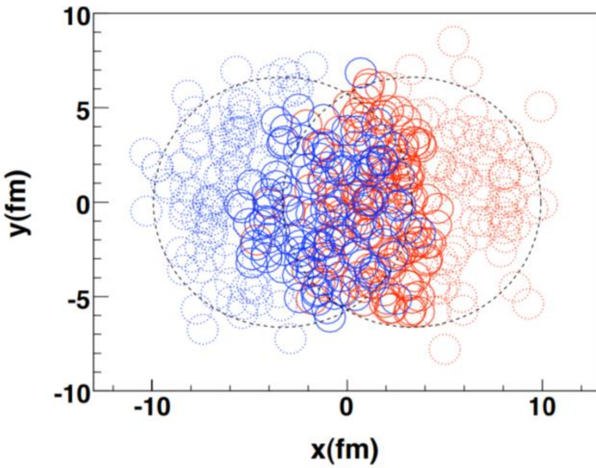
1. Specific shear viscosity: 0.07 – 0.25
   - Higher at high T (weaker coupling)
   - Close to string theory $1/4\pi$ (0.08)
2. Bulk viscosity:
   - Either large and narrow in T
   - Or small and wide in T
3. Still uncertainty on viscosity and `particlisation':
   pressures not isotropic (thermal)
   work in progress

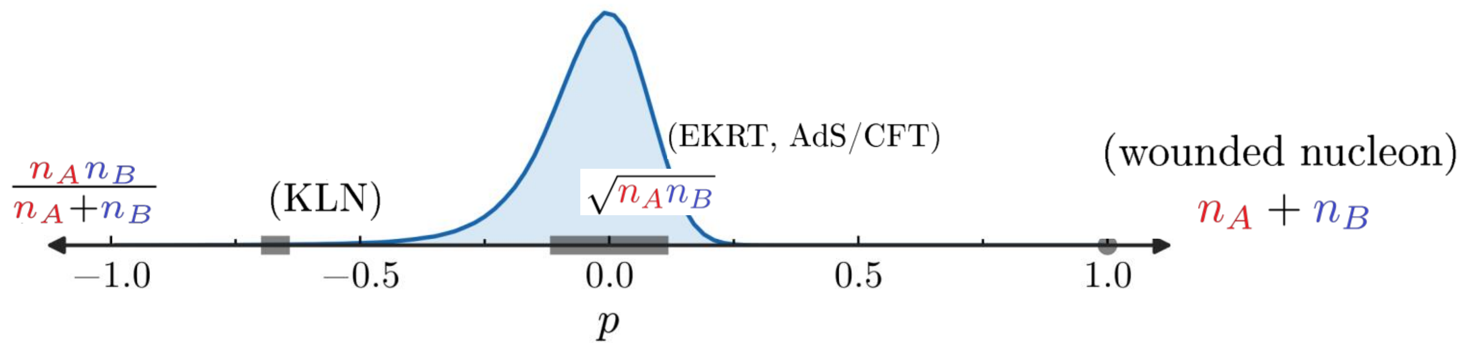


Constraints on initial conditions

Trento parametrization allows for many models:

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





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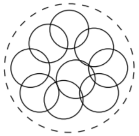
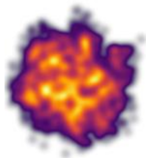
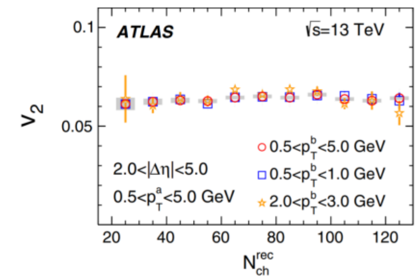
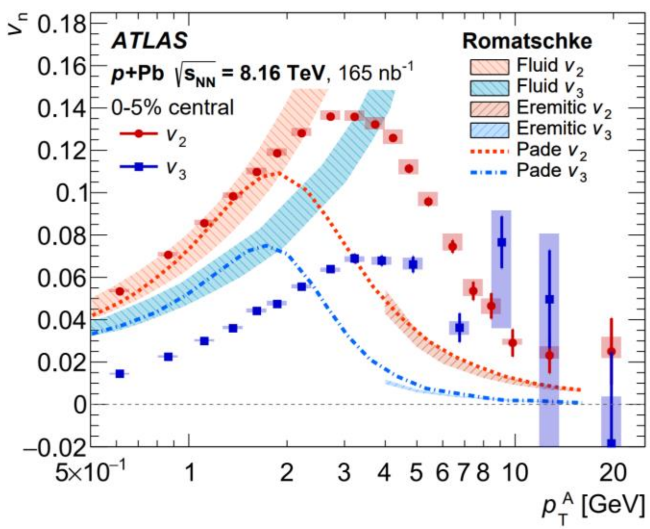


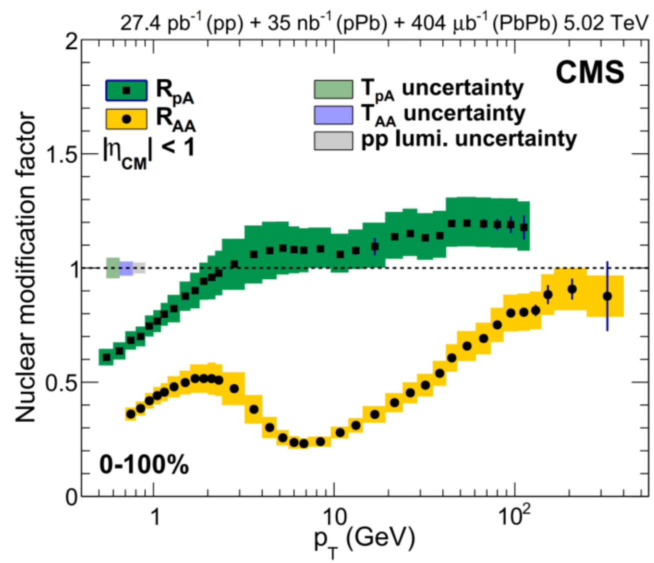


A puzzle: flow in pPb or pp collisions?



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

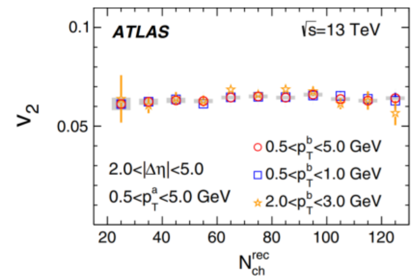




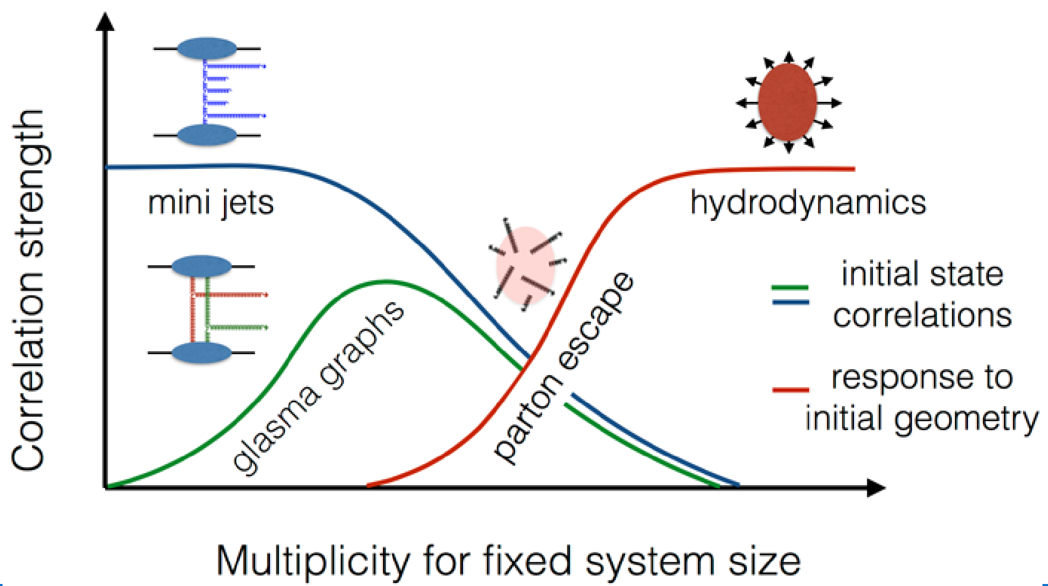
See also: Aleksas Mazeliauskas, Thu 14:45 CET

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



The future

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

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

Theory of HIC in the LHC era

1. Heavy ions: within 1 fm/c a droplet of QGP forms with very small η/s
   - Plasma is strongly coupled and partons have significant quenching
   - Picture seems to apply in pPb and even (some) pp collisions

2. How does the QGP form and hydrodynamise?
   - Showed recent progress with hydrodynamic attractors

3. What are the limits of the applicability of hydrodynamics?
   - Puzzling: flow persists at low multiplicity
   - But no jet quenching

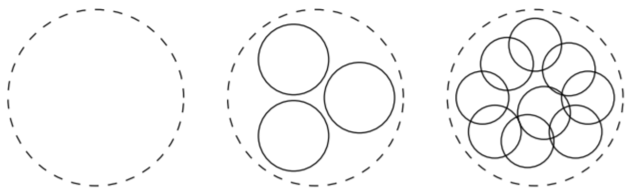
Skipped: interesting progress in jet (substructure) modifications, heavy flavour (flow), chiral magnetic effect, search for critical point

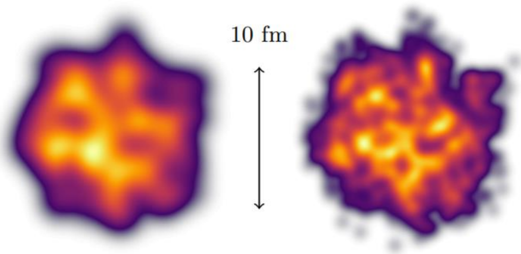
Wit Busza, Krishna Rajagopal and WS, Heavy Ion Collisions: The Big Picture, and the Big Questions (2018)

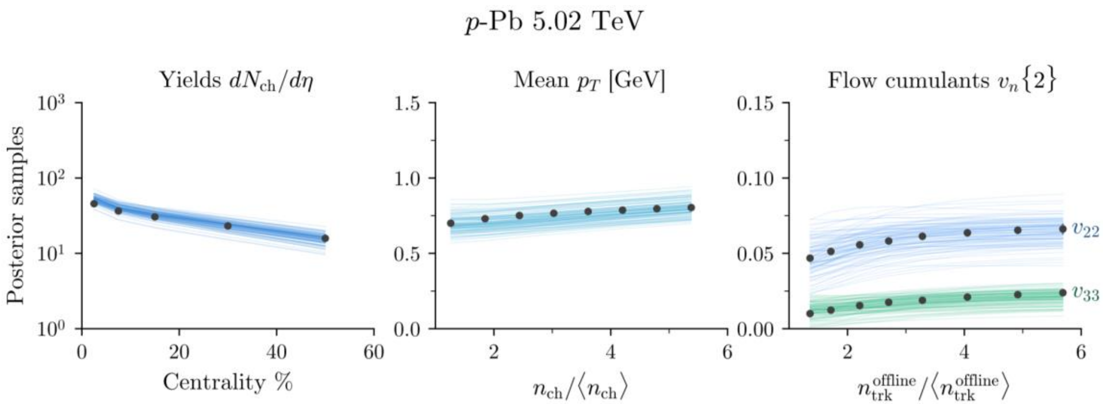
Back-up

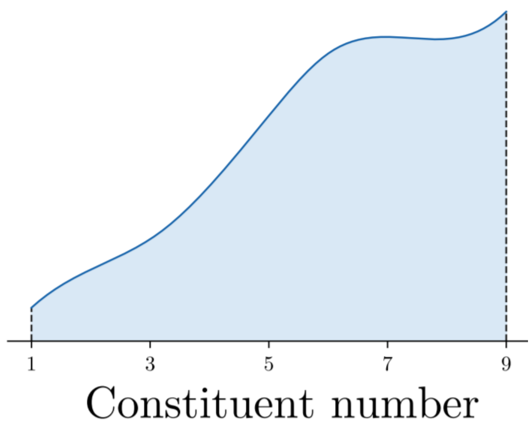
Hydro in pPb or pp collisions?

1. Try hydrodynamics with proton substructure









J. Scott Moreland, Jonah E. Bernhard, and Steffen A. Bass, Estimating initial state and quark-gluon plasma medium properties using a hybrid model with nucleon substructure calibrated to p-Pb and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (2018)

Similar in pPb or PbPb

1. pPb geometry intrinsically more spherical → lower v_2