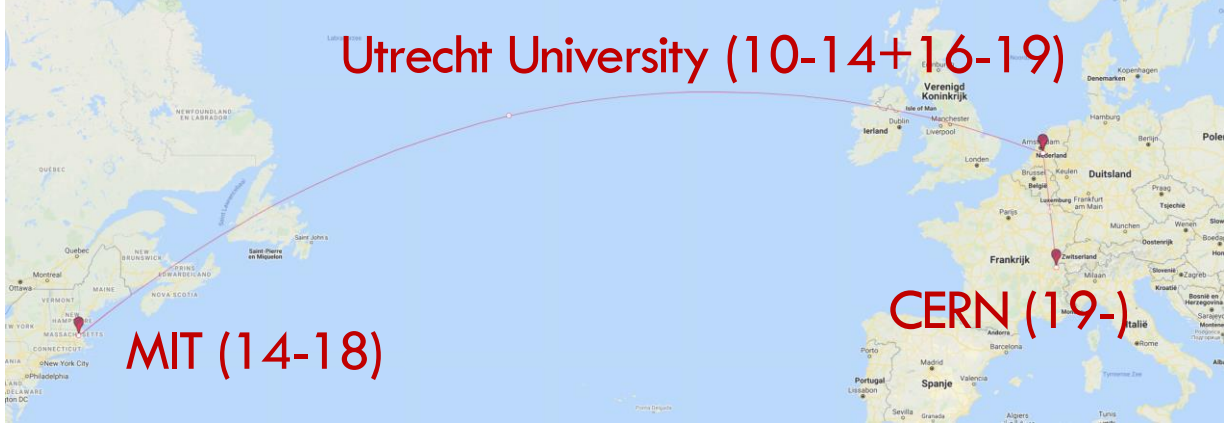
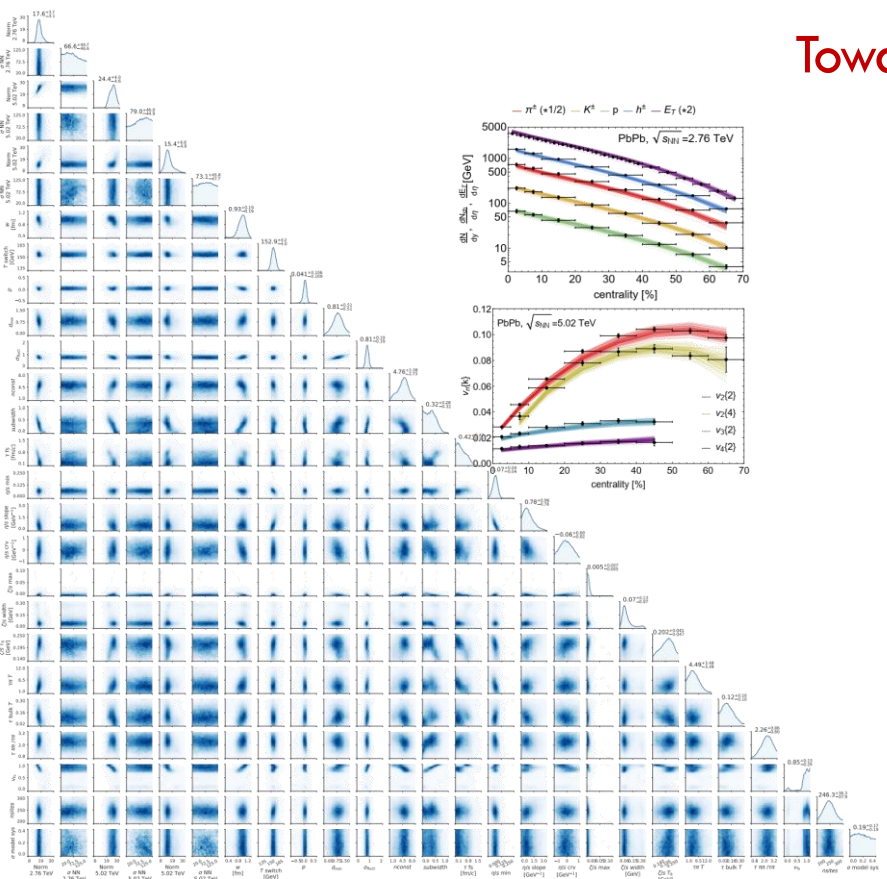
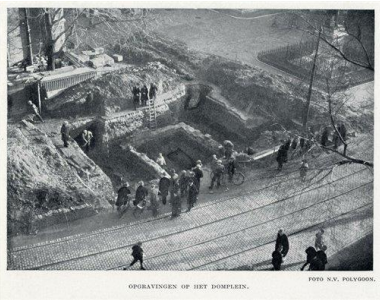


Quark-gluon plasma and a bit of entanglement



Towards a precision analysis of heavy ion collisions

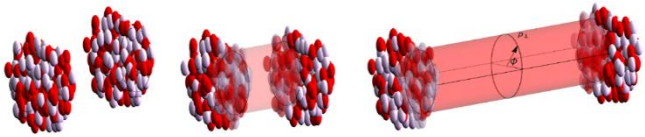
Based on *Trajectum* with Govert Nijs

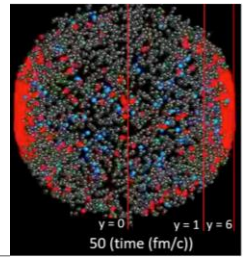


Roman excavations in Utrecht (from Trajectum, or bridge) in 1929

Wilke van der Schee
CERN TH retreat
5 November 2020

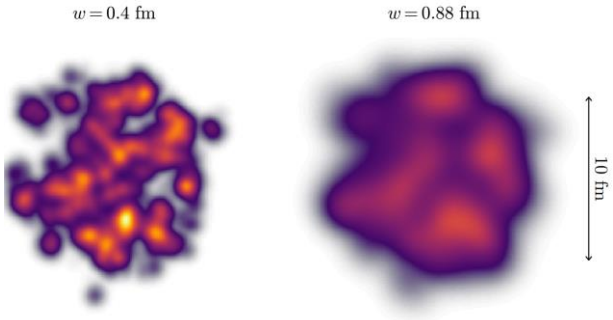
Standard model of heavy ion collisions





Initial stage (9)

Subnucleonic structure? (7)



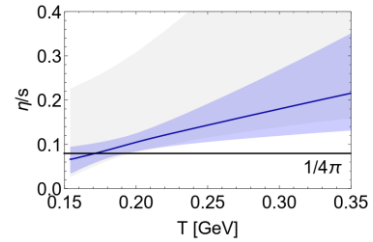
Non-thermal flow? (2)
Yes: for time τ with varying speed

Fluctuations? (1)
Yes: from Gamma distribution:

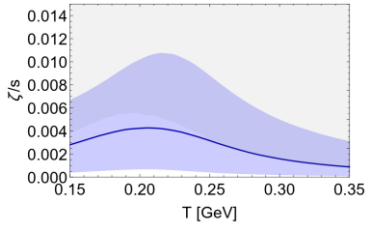
$$p(T) = \frac{1}{\Gamma(1/\sigma)\sigma^{1/\sigma}} T^{(1-\sigma)/\sigma} e^{-T/\sigma}$$

Viscous hydrodynamics (9)

Shear viscosity (3)



Bulk viscosity (3)



Second order transports: 3
Yes: from Gamma distribution:

Cascade of hadrons (1)

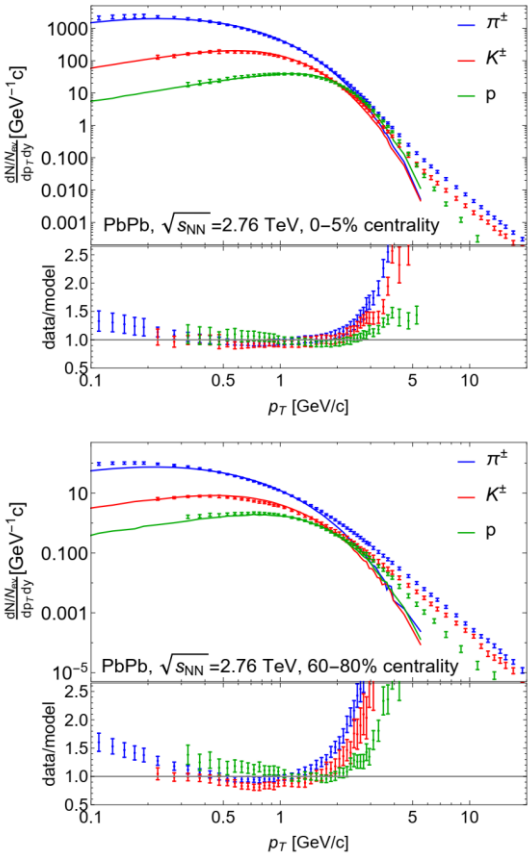
Convert quark-gluon plasma at T_{switch} to particles following Boltzmann distribution (particlization, 1)

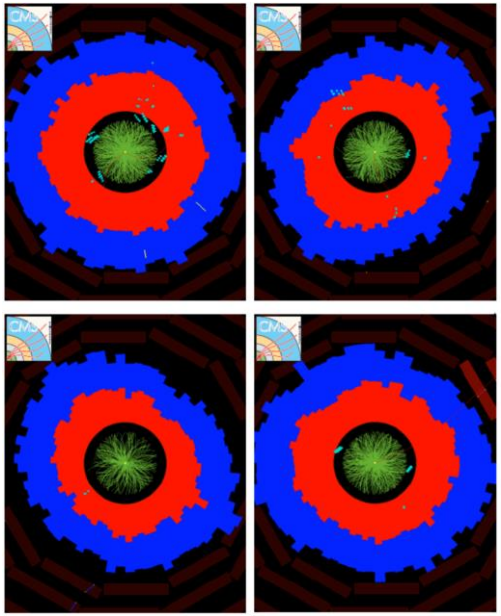
Subtle: viscous corrections

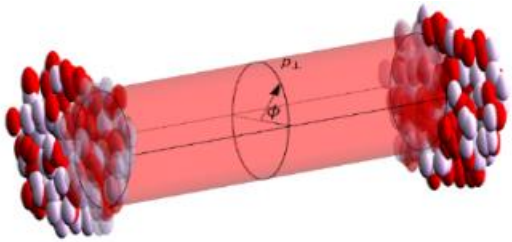
Evolve particles with hadronic code: SMASH

A wealth of experimental data

Spectra for pions, kaons and protons



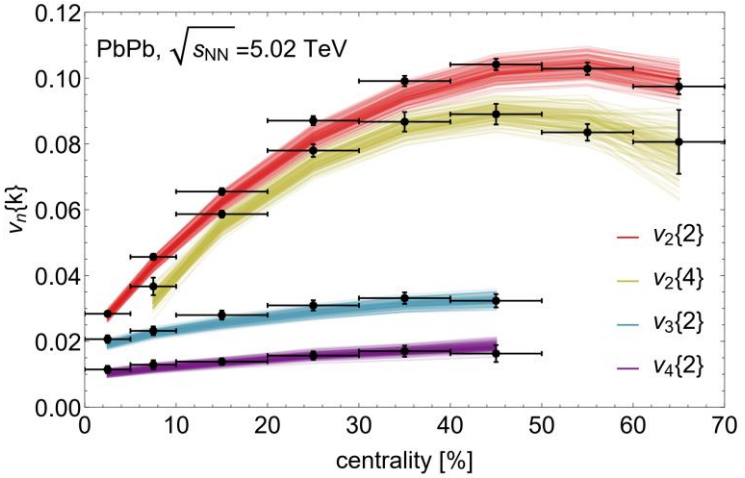




Quantify anisotropic flow:

Fourier coefficients:

- v_2 : elliptic flow
- v_3 : triangular flow, etc



Performing a global analysis

Bayes theorem:

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

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

We have a 20-dimensional parameter space and 514 datapoints

- Run model on 1000 `design' points, spaced on a latin hypercube (lxplus ☺)
- `Interpolate' results by training a Gaussian Process Emulator

Markov Chain Monte Carlo (emcee2.2)

- Obtain sample of 10^6 likely values

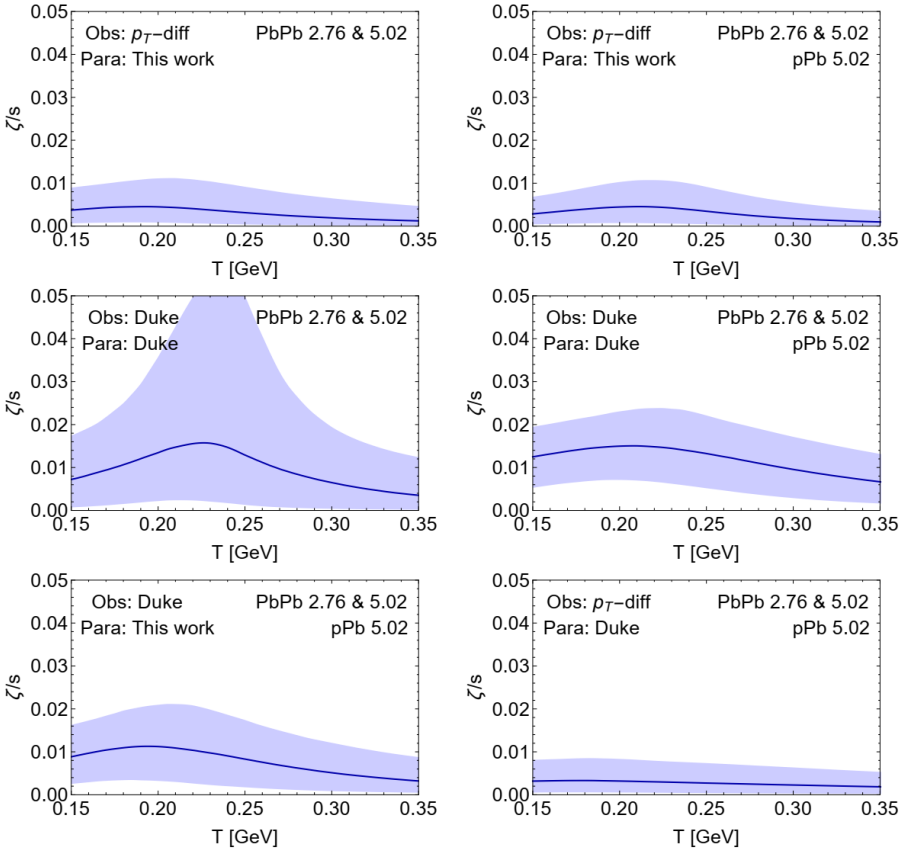
Compare posterior with data

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

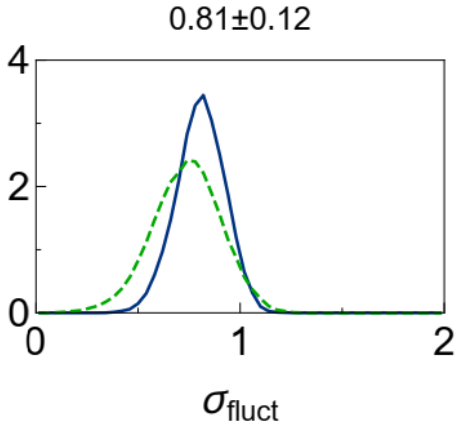
Very tiny overview of results

Bulk viscosity, varied several aspects:

- More limited parameter set
- Include or not include p-Pb collisions
- **Include p_T-differential observables**



Fluctuations:



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

An advertisement for entanglement in de Sitter

Upcoming with Jorge Casalderrey, Christian Ecker and David Mateos

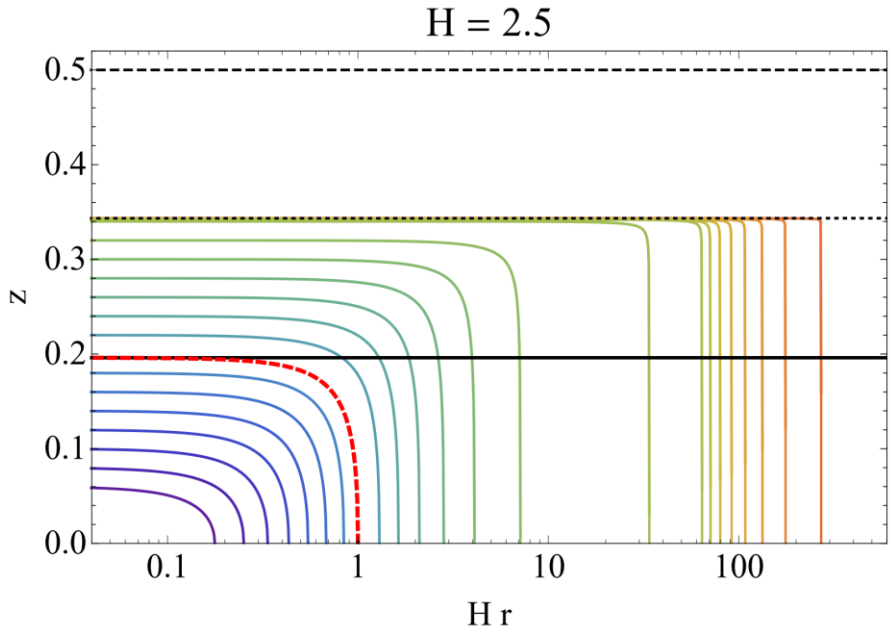
Simple **holographic** non-conformal Einstein-scalar model, with **de Sitter$_4$ as boundary metric**

- Unique late-time state, three horizons with temperature T

Hubble constant: H

- Extremal surfaces:

note that entangling region with r=1/H is cosmological horizon



Cosmological horizon

Apparent horizon: $T = -\frac{H}{2\pi}$

Entanglement horizon: $T = 0$

Event horizon: $T = \frac{H}{2\pi}$