LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

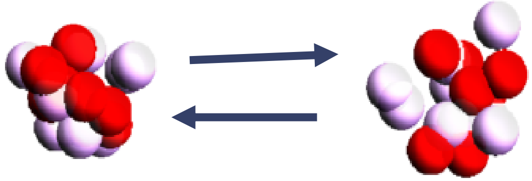
Opportunities of light ion collisions at the LHC

Towards smaller and smaller QGPs

Based on workshop OppOrtunities at the LHC, with Jasmine Brewer and Aleksas Mazeliauskas (2103.01939)

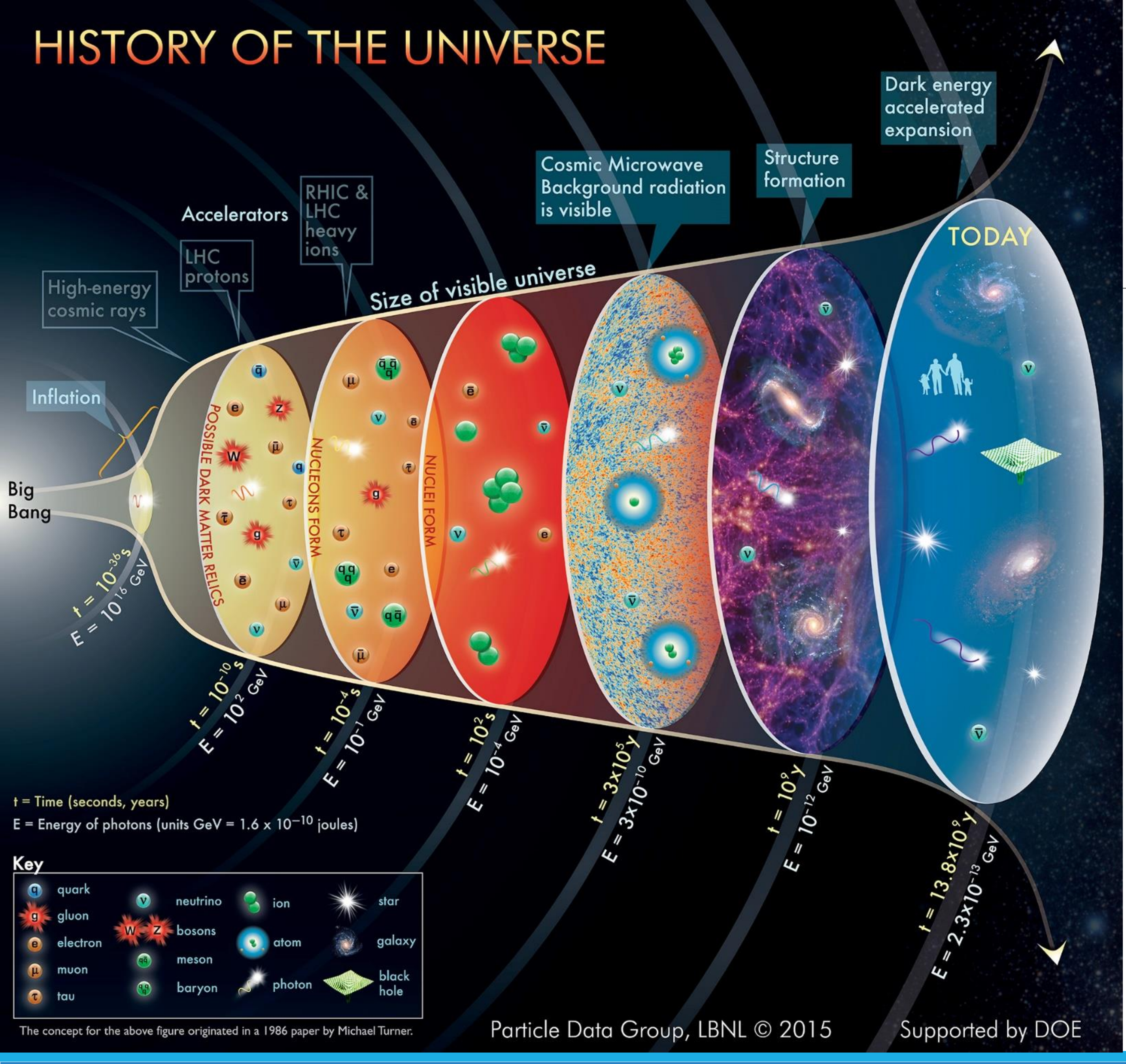
Parton energy loss based on (2007.13754 (PRL) and 2007.13758 (PRC))
with Alexander Huss, Aleksi Kurkela, Aleksas Mazeliauskas, Risto Paatelainen and Urs Wiedemann

Trajectum results to appear with Govert Nijs



Wilke van der Schee
LIP Seminar, Lisbon
20 May 2021

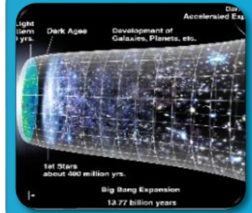
Wilke van der Schee, CERN



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

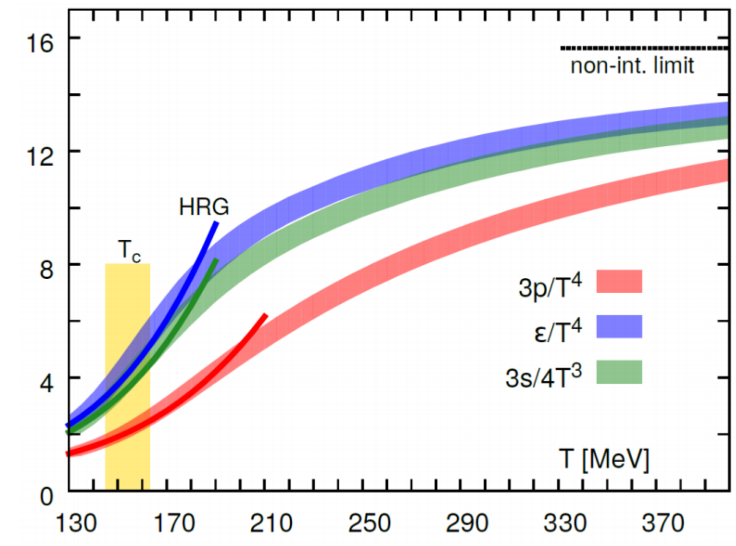
Sign problem: only Euclidean

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

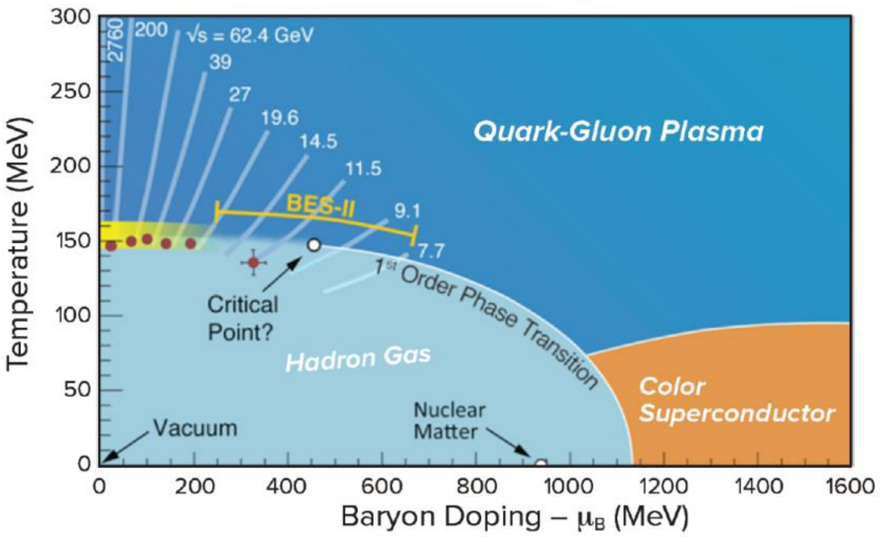
A conjectured critical point in reach of RHIC energies?

- LHC does not reach high enough baryon number densities

Lattice equation of state



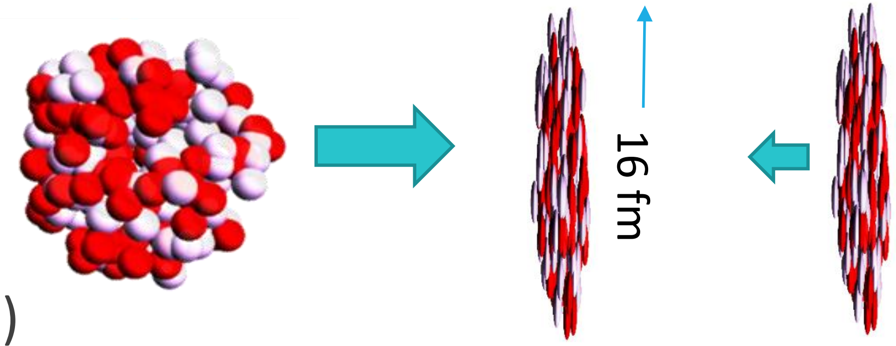
Phase diagram



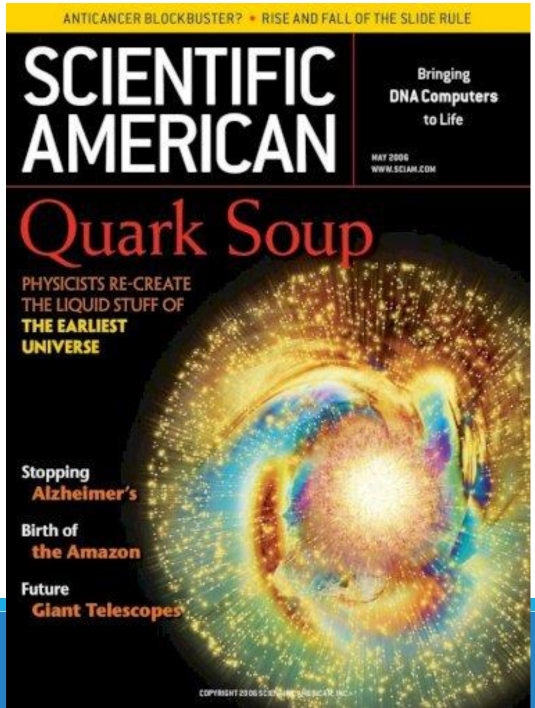
How to create QGP

Colliding heavy nuclei (Pb, Au) at high energies

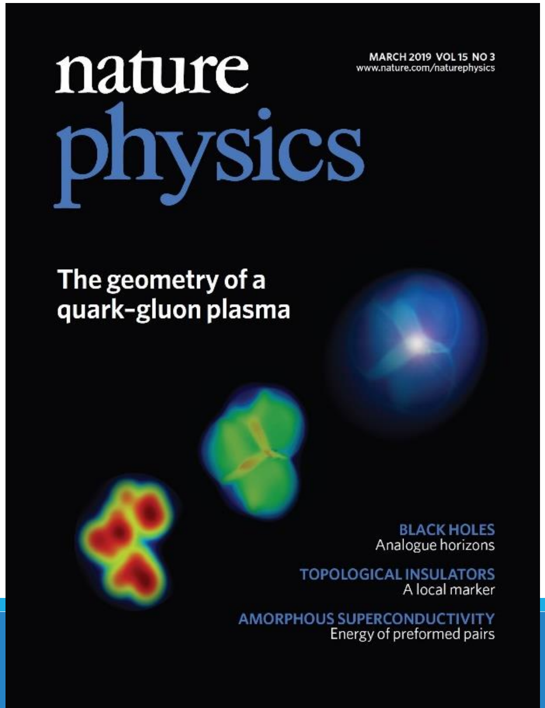
Lorentz gamma factor up to 2500 (LHC) or 100 (RHIC)



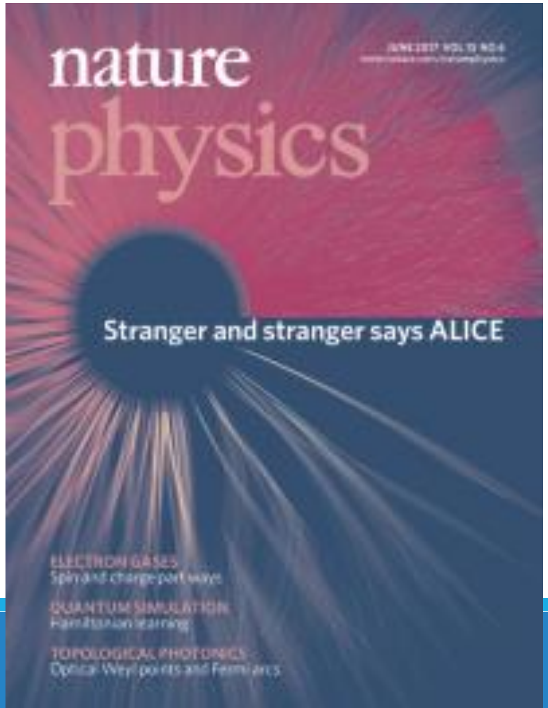
Hottest fluid:
10^{12} K



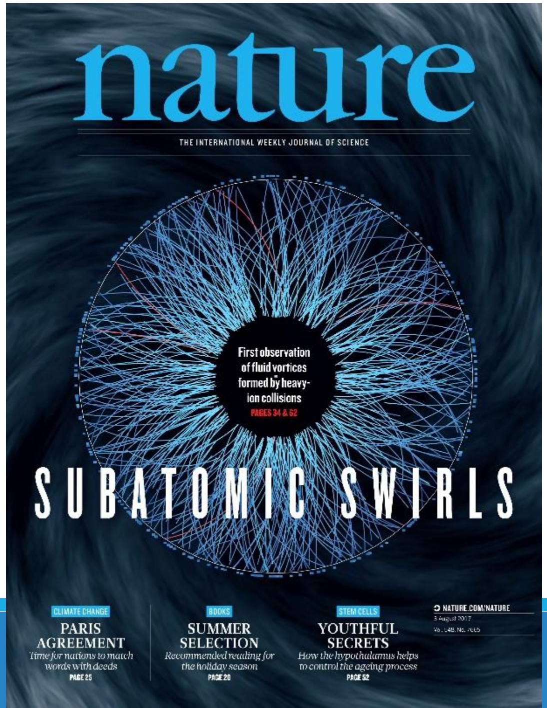
Smallest fluid:
~ 2 fm living 10^{-23} s



Most perfect/strange:
$\eta/s \sim 0.08$



Most vortical fluid:
$\omega \sim 10^{22}$/s



Wilke van der Schee, CERN

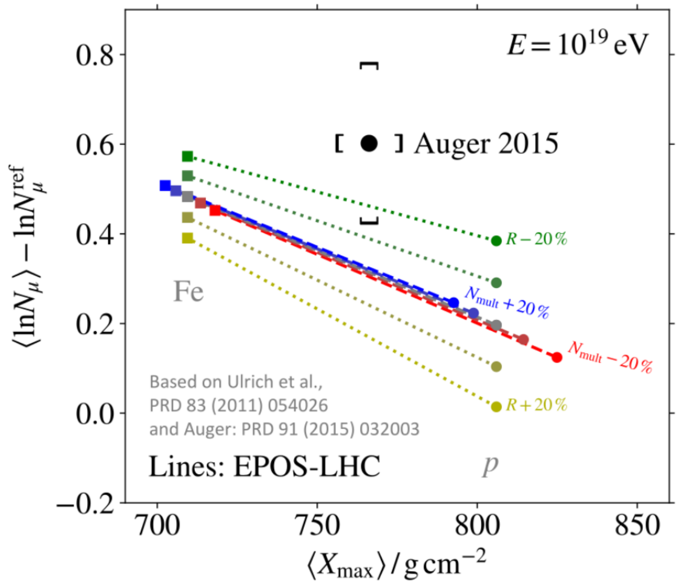
CERN accelerator complex

A brief cosmic-ray perspective

Muon puzzle in cosmic air showers

- Cascade of energetic collisions, producing muons and photons
- Difficult to *simultaneously* predict
  - Number of muons
  - Depth of air shower (in air density units)

- Relies crucially on ratio π_0: $R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$

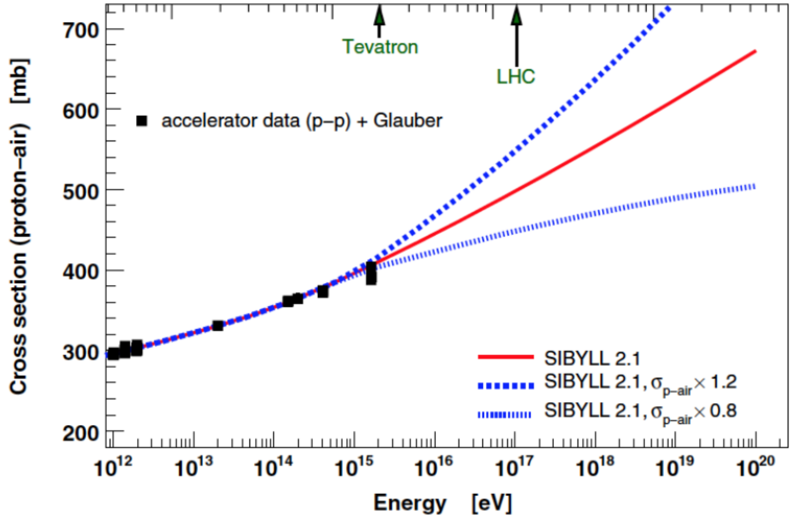


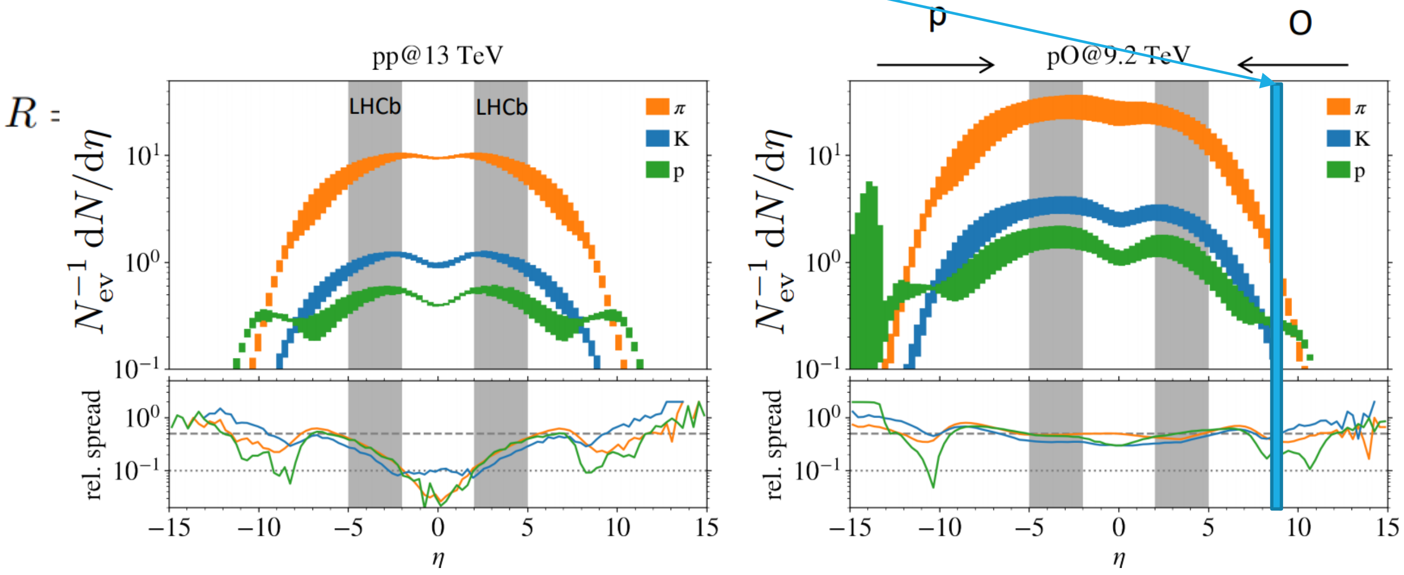
A brief cosmic-ray perspective

LHC contribution

- Proton-oxygen cross section: large uncertainty
- Spectrum at very forward rapidities
- Help with π_0 ratio? Strangeness? QGP?

LHCf: this is were most of the energy is deposited (ends after run 3)

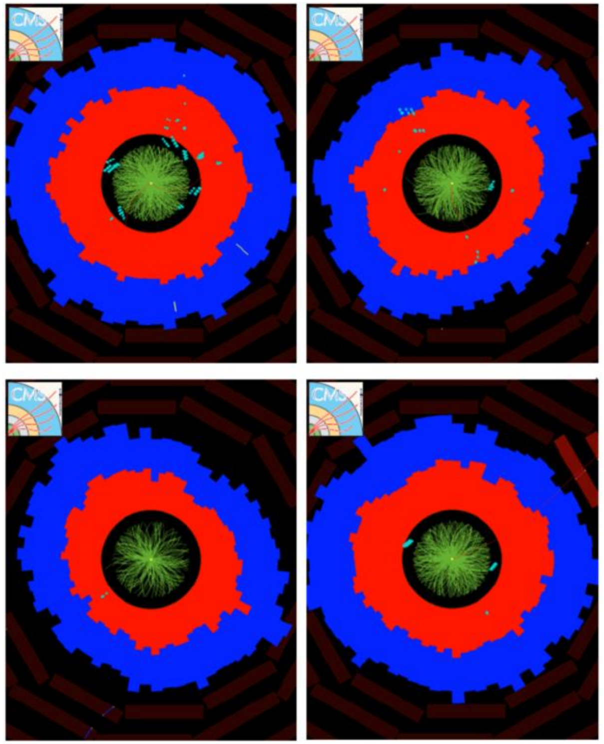


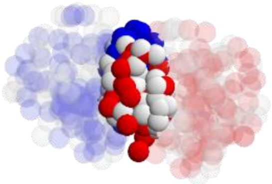


Ralf Ulrich, Ralph Engel and Michael Unger, Hadronic multiparticle production at ultrahigh energies and extensive air showers (2011)
Hans Dembinski, Oxygen beams and LHCb: prospects of pO and OO collisions for nuclear and astroparticle physics: cern.ch/oppoatlhc/contributions/4172211/

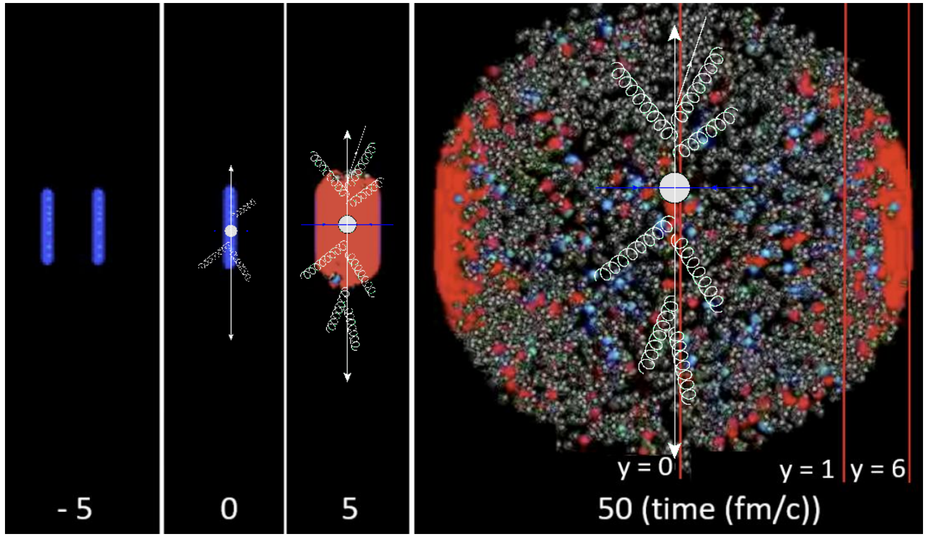
Quark-gluon plasma is strongly coupled

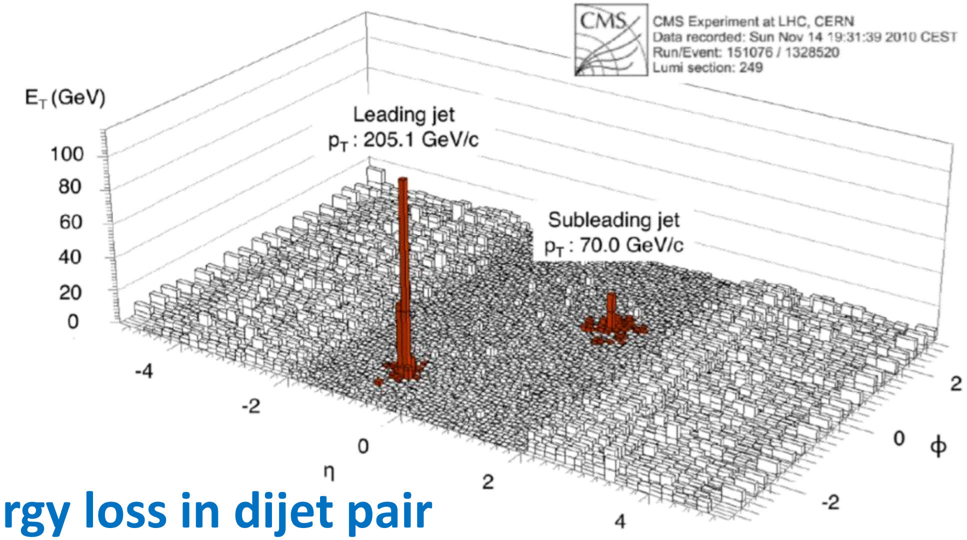
Anisotropic flow (small viscosity)





Initial stage - QGP - hadronic phase





Jet energy loss in dijet pair

Strangeness: from pQCD to thermal

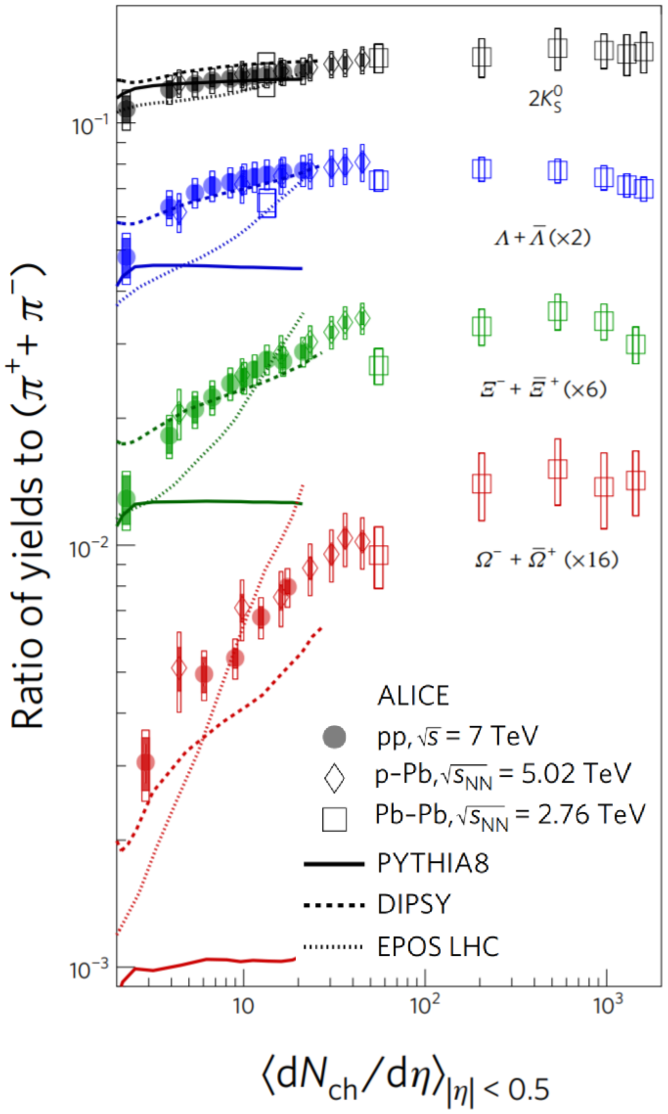
1. Ratio of strange baryons versus pions
   - Pythia fits low multiplicity
     - But constant towards higher multiplicity (!)

Thermodynamical string fragmentation JHEP

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

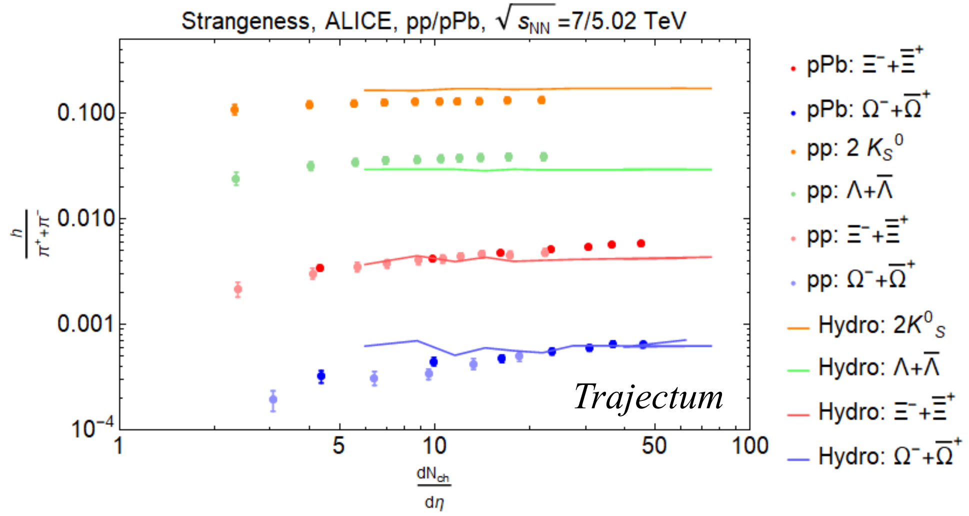
ABSTRACT: The observation of heavy-ion-like behaviour in pp collisions at the LHC suggests that more physics mechanisms are at play than traditionally assumed.

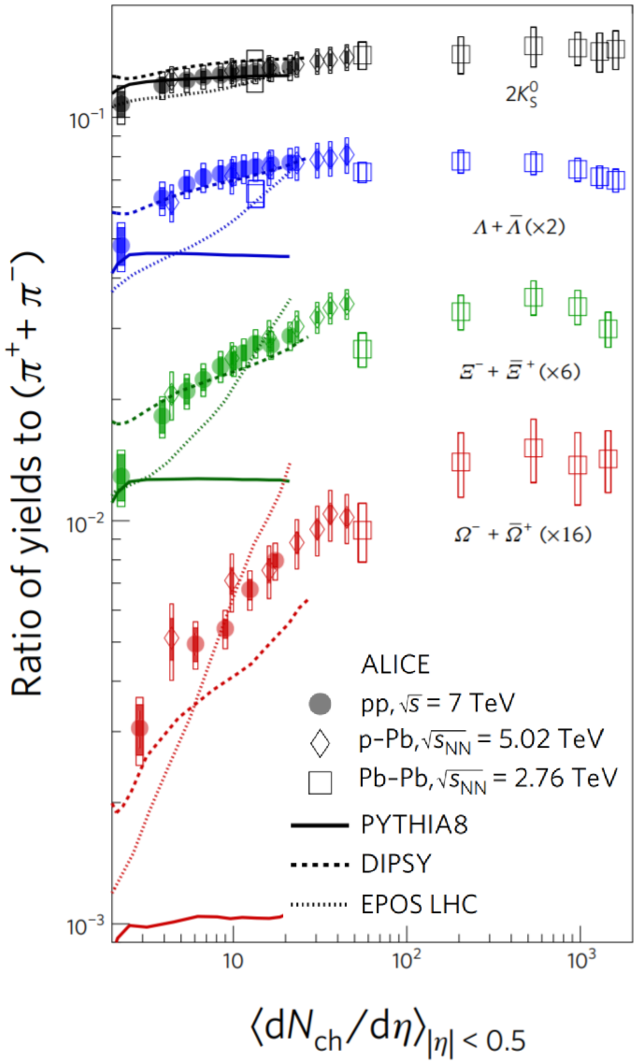
2. Saturates for high multiplicity pPb / PbPb
   - Interpretation: thermal strangeness production



Strangeness: from pQCD to thermal

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

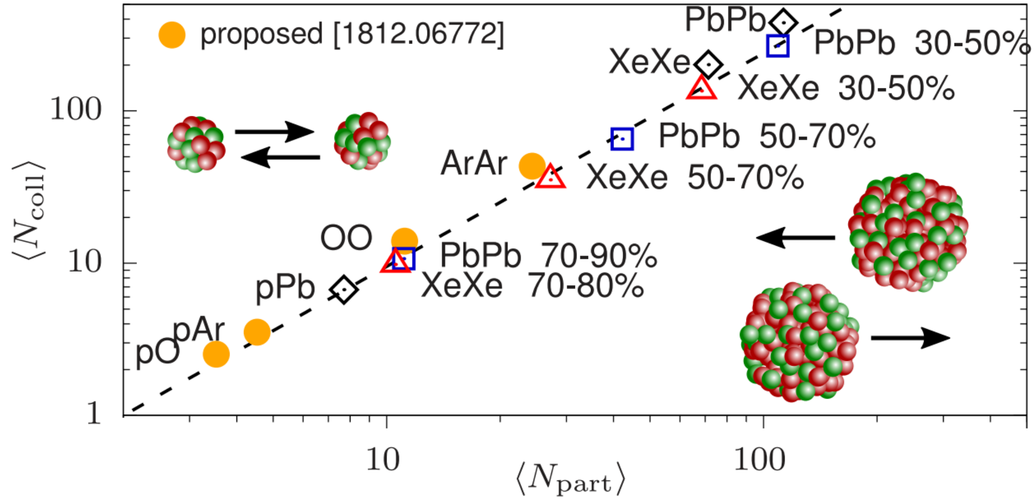




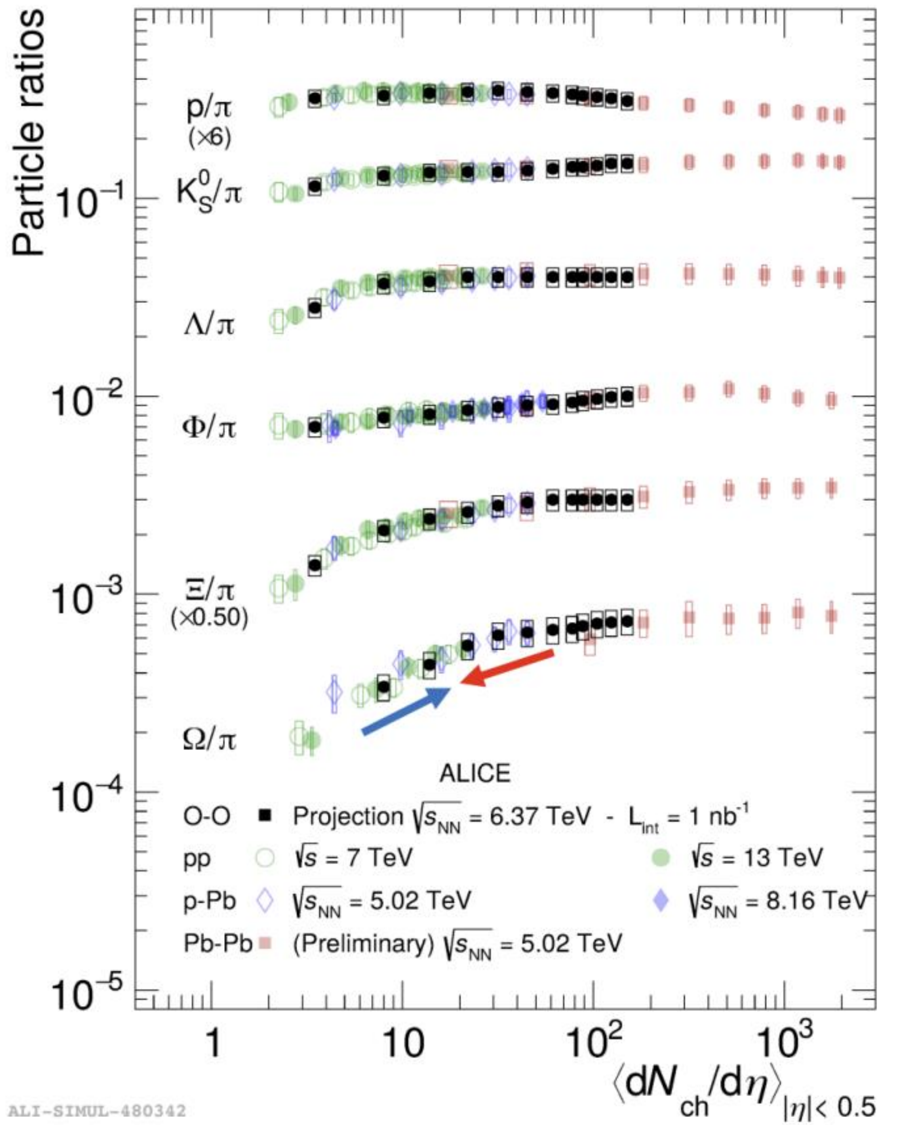
2. Hydro has only small dependence on N_{ch}
   - Approximately fits thermal model

Strangeness: OO fills the gap

1. Oxygen collisions would provide unique opportunity to smoothly connect pPb and PbPb



2. Caveat: large statistics pPb and PbPb could extend curves
   - But at the price of selecting 'atypical' events

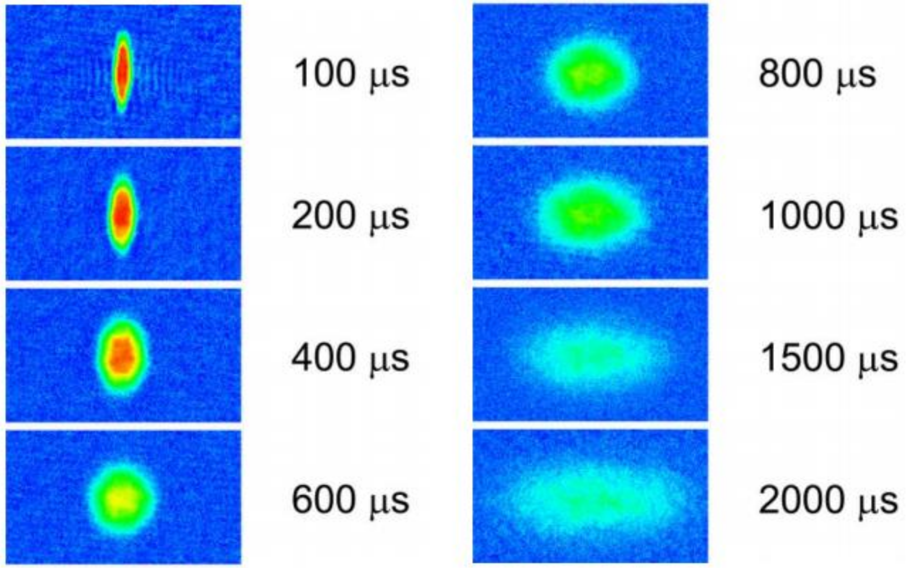


The most perfect liquid?

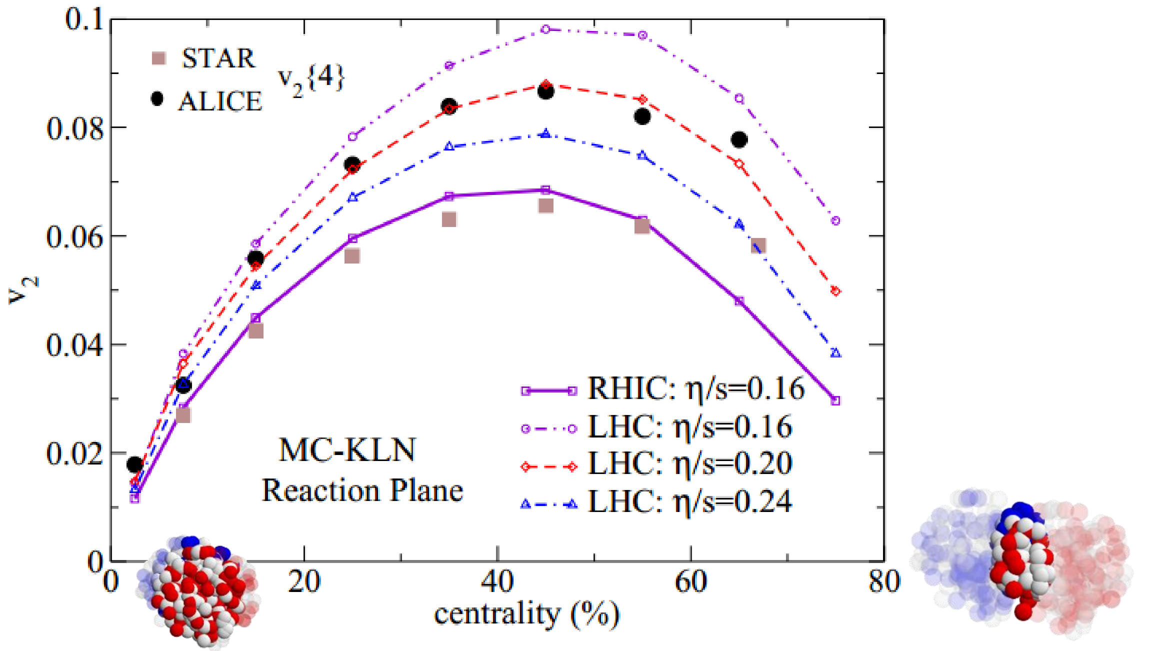
$$\frac{d\bar{N}}{d\varphi} = \frac{\bar{N}}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} \boxed{\bar{v}_n} \cos(n(\varphi - \bar{\Psi}_n))\right)$$

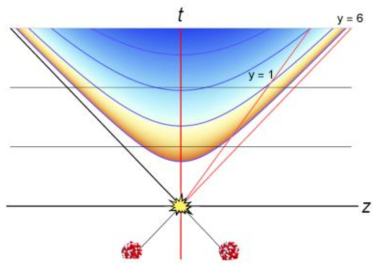
Famous viscosity, AdS/CFT or **holography**: $\frac{\eta}{s} = \frac{1}{4\pi} \approx 0.08$

Fermions at unitarity (cold ☺)



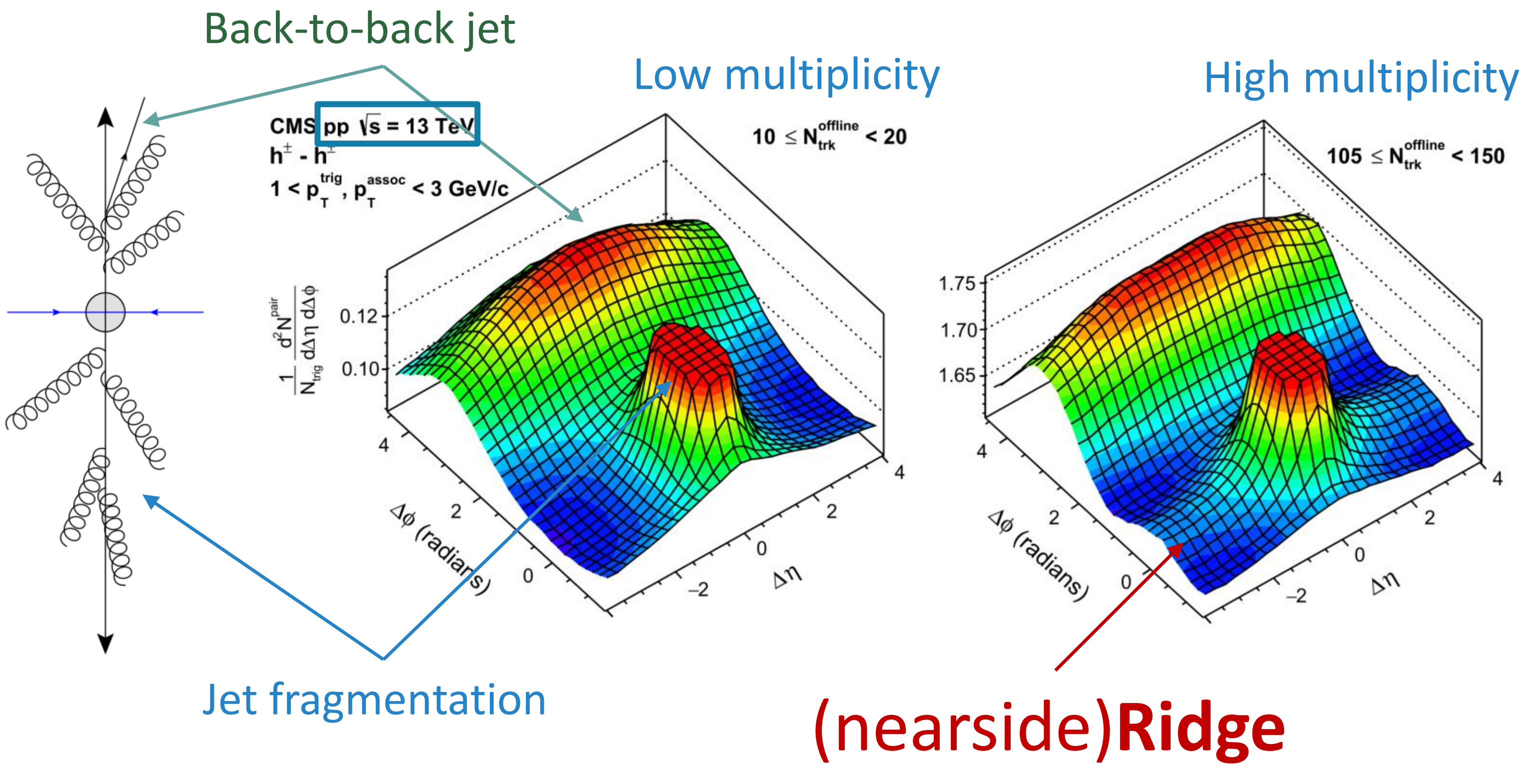
Quark-gluon plasma (hot ☺)

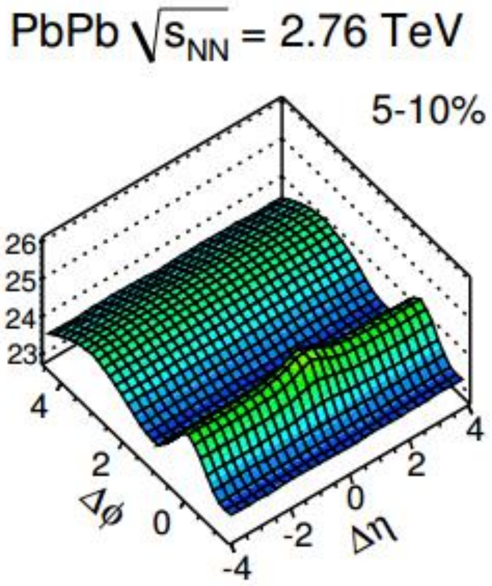


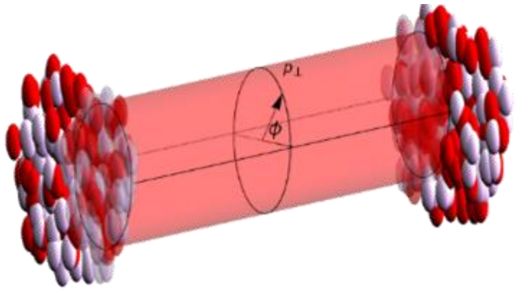


Ridges everywhere: *panta rei*

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

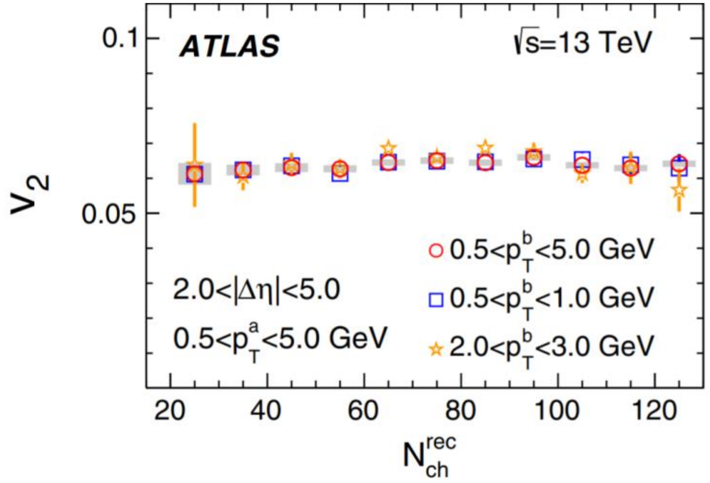


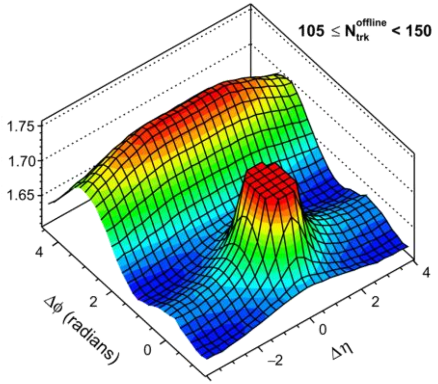




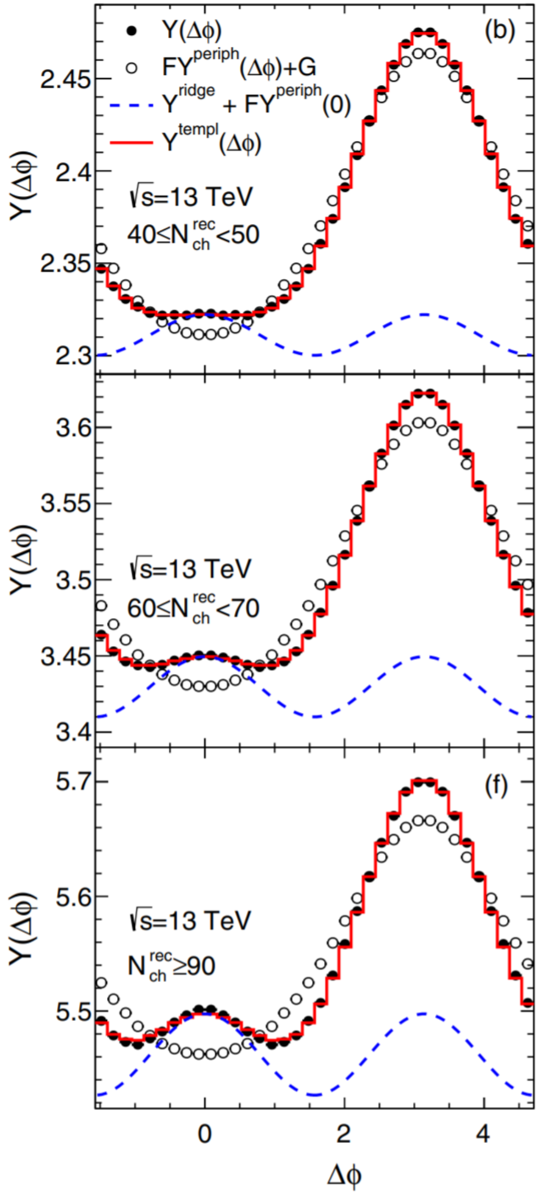
Extract Fourier harmonics of the ridge

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?

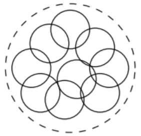


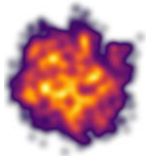


$$Y^{\text{templ}}(\Delta\phi) = FY^{\text{periph}}(\Delta\phi) + Y^{\text{ridge}}(\Delta\phi)$$
$$Y^{\text{ridge}}(\Delta\phi) = G[1 + 2v_{2,2}\cos(2\Delta\phi)]$$

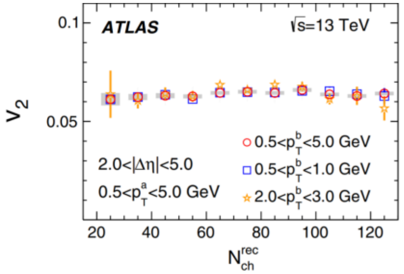


ATLAS, Observation of Long-Range Elliptic Azimuthal Anisotropies in √s=13 and 2.76 TeV pp Collisions with the ATLAS Detector (2015)

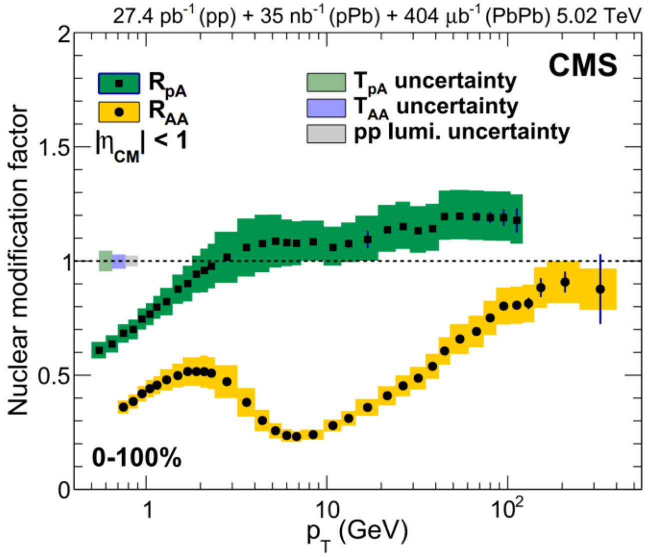




A puzzle: flow in pPb or pp collisions?

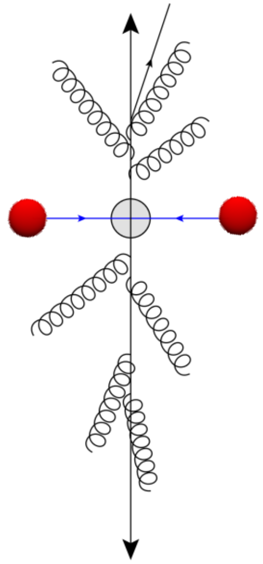


1. There seems to be flow
   - Quite some modeling, but everything consistent with hydro (does not prove hydro!)
2. But: nuclear modification > 1: **no (naive) jet/hadron energy loss**

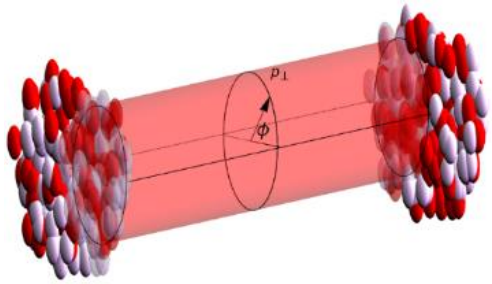


S. Moreland, J. Bernhard, and S. Bass, Estimating initial state and QGP medium properties using … p-Pb and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (2018)
CMS, Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}}$= 5.02 TeV (2016)

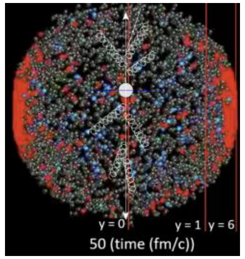
(high energy) ¿HEP versus HIP? (heavy ion)



Low multiplicity	High multiplicity
Jet-like particle shower	Relatively few jets
No equilibration	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 than pPb
Interplay from HEP and HIP

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

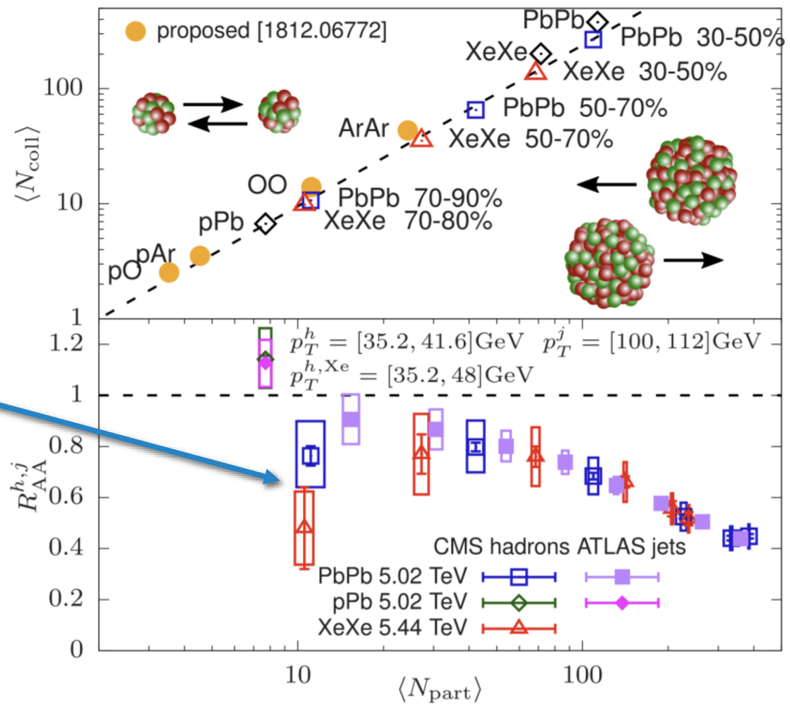
Nuclear modification factor – centrality cuts

1. Compare hadrons/jets with expected number, *assuming no nuclear physics:*

$$R^{h,j}_{\mathrm{AA}}(p_T, y) = \frac{1}{\langle T_{\mathrm{AA}}\rangle} \frac{(1/N_{\mathrm{ev}})\ dN^{h,j}_{\mathrm{AA}}/dp_T dy}{d\sigma^{h,j}_{pp}/dp_T dy}$$

2. **Centrality cuts**: $\langle N_{\mathrm{coll}}\rangle = \sigma^{\mathrm{inel}}_{pp}\langle T_{\mathrm{AA}}\rangle$

   - Peripheral has smaller modification; R_{AA} consistent with 1, but
   - **Modelling** error (in MC Glauber) increases boxes: dominated by T_{AA} uncertainty



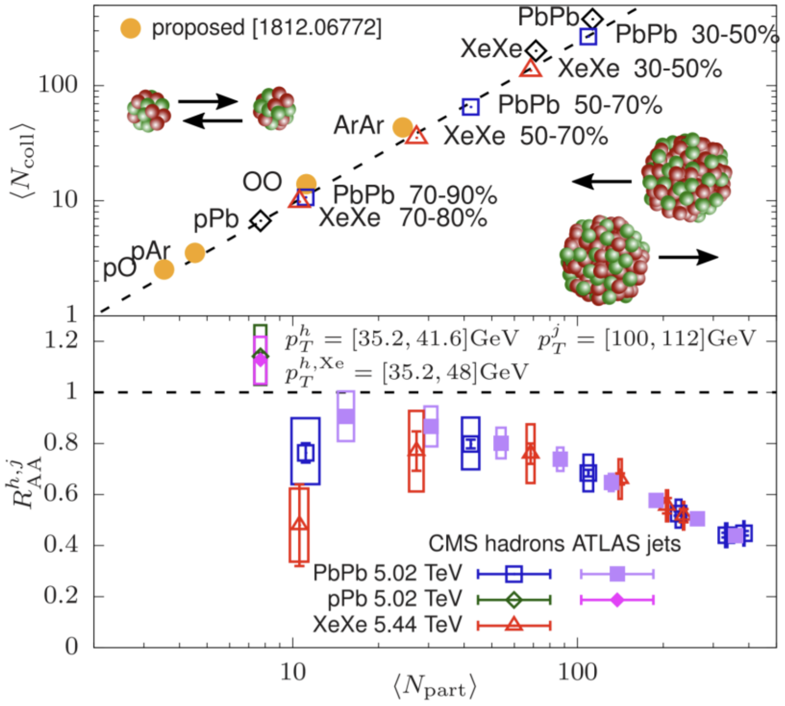
3. Also: factorisation theorems only apply to inclusive processes, careful with cuts

Nuclear modification factor – minimum bias

1. Compare hadrons/jets with expected number, *assuming no nuclear physics:*

$$R^{h,j}_{\mathrm{AA,\ min\ bias}}(p_T, y) = \frac{1}{A^2}\frac{d\sigma^{h,j}_{\mathrm{AA}}/dp_T dy}{d\sigma^{h,j}_{pp}/dp_T dy}$$

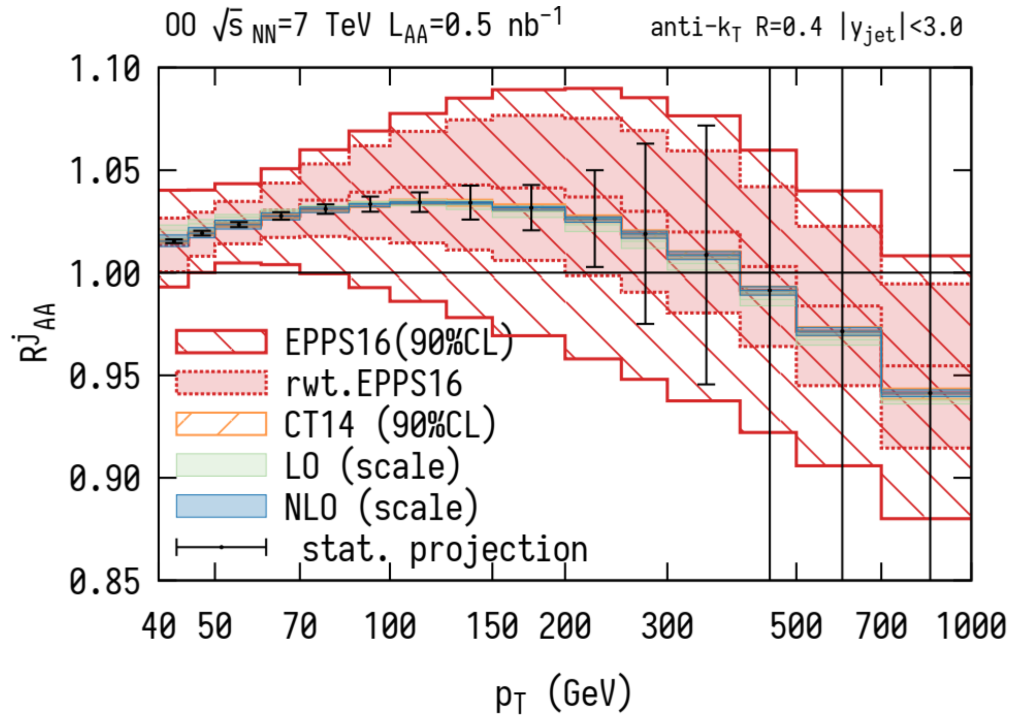
2. A clear physics case for studying jet quenching in small systems:
   - Expected effect is relatively small
   - Errors in peripheral AA are large
     - Dominated by modelling, e.g. MC Glauber
3. Solution: min-bias with smaller ions
   - How large of an effect do we expect?
   - Do we control nuclear effects?



Nuclear effects

Compare pp jet/hadron production with OO, assuming no plasma

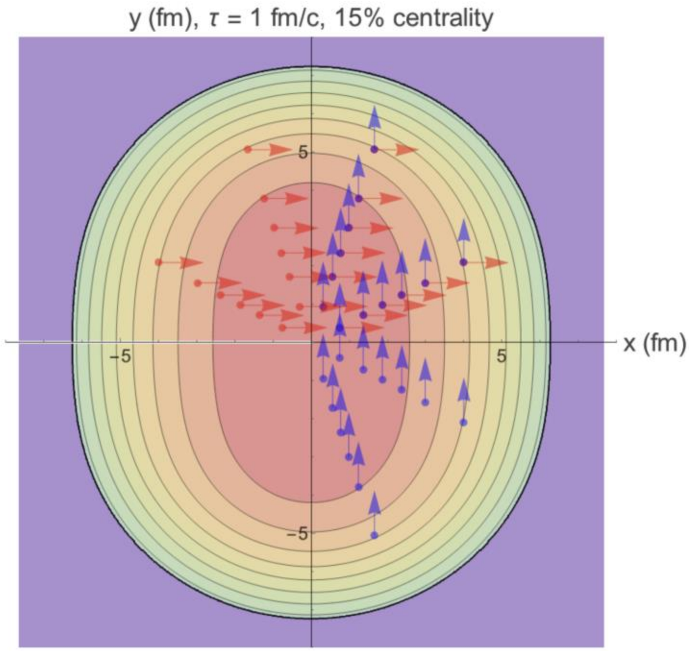
1. Factorisation: PDF + pQCD hard matrix + Fragmentation
   - PDFs: CT14 for pp, EPPS16 for OO
   - pQCD: at NLO (consistent with EPPS) vary renorm and fact scale, errors mostly cancel in ratio
   - Include extra dijet data: reweighting of nPDF set reduces error considerably
   - Expected R_{AA} ~ 5%, error 2 – 5%



A simple medium

A few important assumptions, with statistics taken from the Trento model (for OO the nucleon positions are from Lonardoni et al)

1. Average radius comes from Trento
2. Total energy ~ N_{part}
3. Only ε_2 taken into account
4. EOS is conformal
5. Hydro comes from kinetic theory



Variations: free streaming, Bjorken hydro, different starting time and freeze-out temperature

https://github.com/Duke-QCD/trento
D. Lonardoni, A. Lovato, Steven C. Pieper, R. B. Wiringa, Variational calculation of the ground state of closed-shell nuclei up to A=40 (2017)
Aleksi Kurkela, Urs Achim Wiedemann and Bin Wu, Opacity dependence of elliptic flow in kinetic theory (2018)

Energy loss variations

1. BDMPS-Z: simple coherent scattering from pQCD

   Peter Arnold, Simple formula for high-energy gluon bremsstrahlung in a finite, expanding medium (2009)

2. A simple weakly T-dependent formula: $dE/dx \sim \tau^{0.4}T^{1.2}$

   inspired by D. Zigic, I. Salom, J. Auvinen, M. Djordjevic, M. Djordjevic, Joint RAA and v2 predictions for PbPb collisions at the LHC within DREENA-C framework

3. A simple strongly T-dependent formula: $dE/dx \sim \tau T^3$

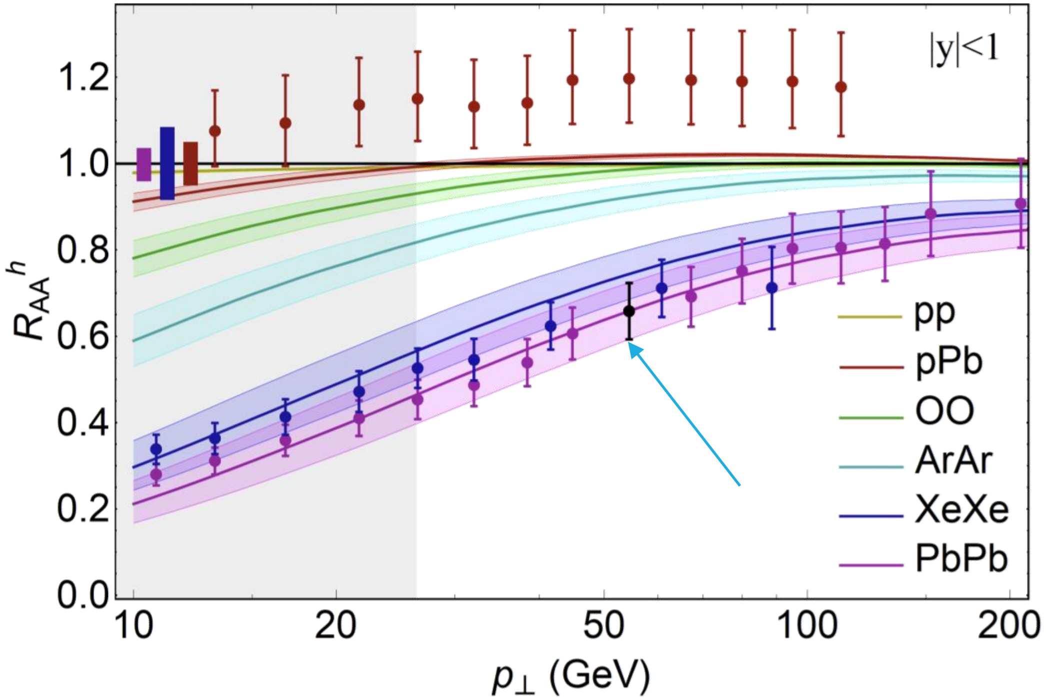
   inspired by J. Noronha-Hostler, B. Betz, J. Noronha and M. Gyulassy , Event-by-event hydrodynamics + jet energy loss: A solution to the RAA⊗v2 puzzle

4. A stopping formula: $C_s \int_{\tau_0}^{\infty} d\tau p_\perp \frac{4\tau^2}{\pi\tau_{\rm stop}^2\sqrt{\tau_{\rm stop}^2-\tau^2}}$, where $\tau_{\rm stop} = \frac{1}{2(\kappa/5)} p_{\perp,0}^{1/3} T(\tau,\vec{x}(\tau))^{-4/3}$.

   inspired by J. Casalderrey-Solana, D. Can Gulhan, G. Milhano, D. Pablos and K. Rajagopal, A Hybrid Strong/Weak Coupling Approach to Jet Quenching

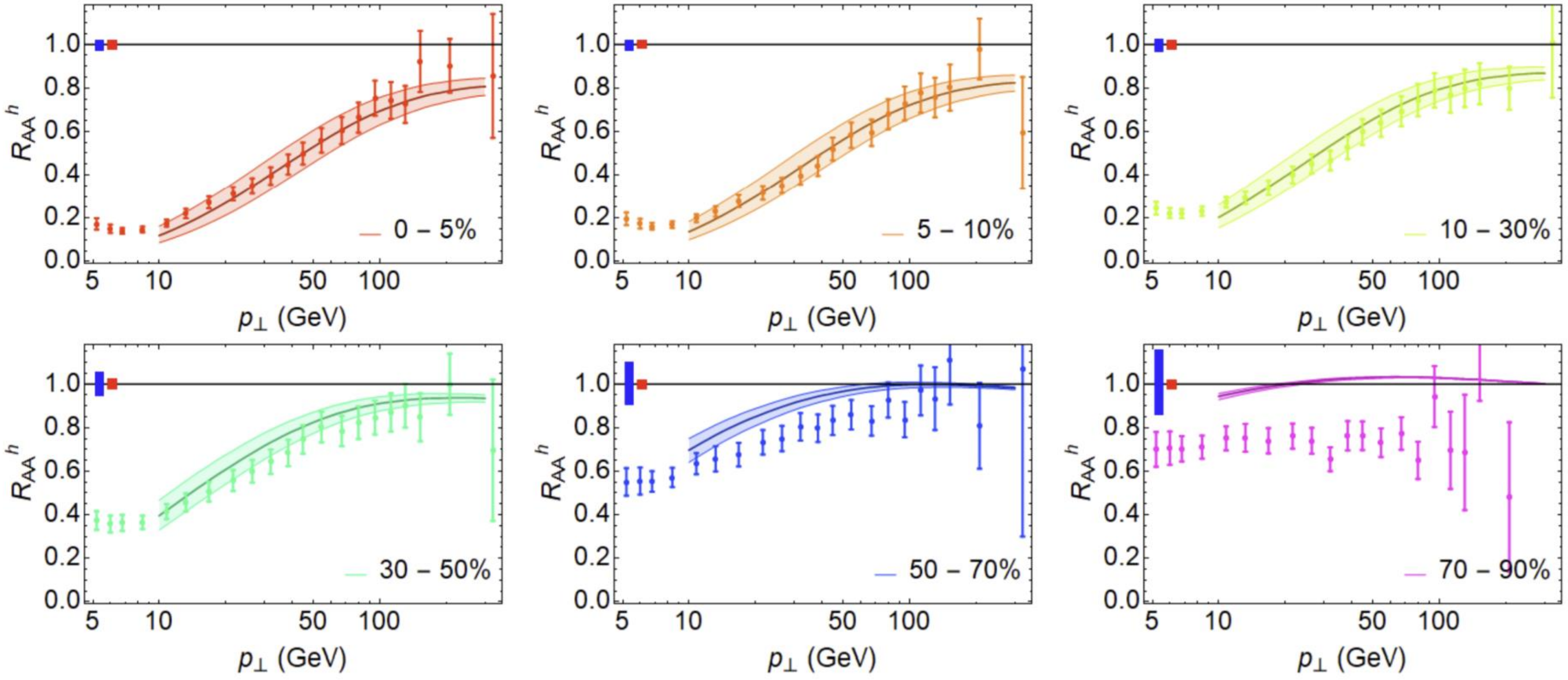
A free parameter: fix with PbPb datapoint

1. Take minimum bias point at 54 GeV PbPb at 2.76 TeV, and fix d (= $\hat{q}/T^3$)
   Note: error only from d
2. Model captures p_T dependence
3. *p*Pb perhaps consistent with T_{AA} error (boxes)
4. Also checked model for pp; almost no modification



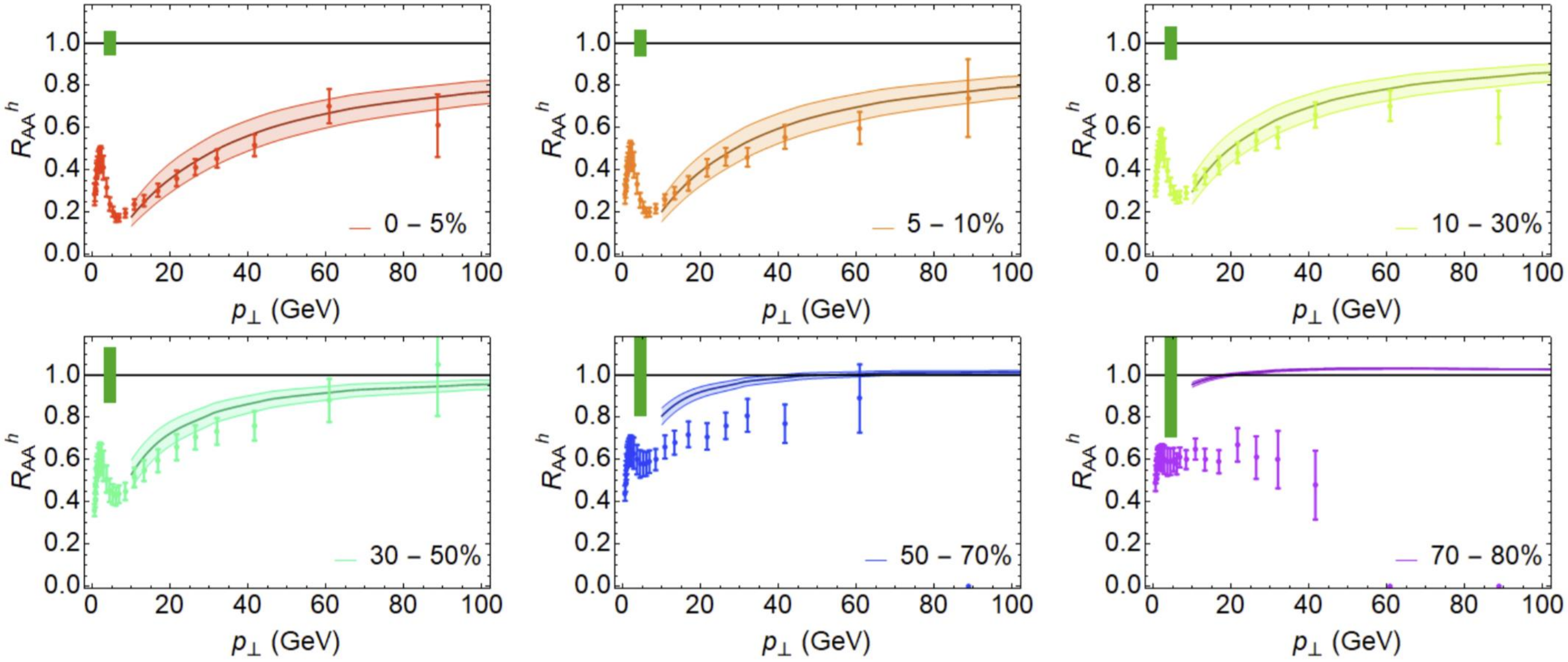
Centrality dependence

1. Captures centrality dependence, except most peripheral bin (though note box = T_{AA} uncertainty)



Centrality dependence, XeXe

1. Similar story, larger T_{AA} uncertainty



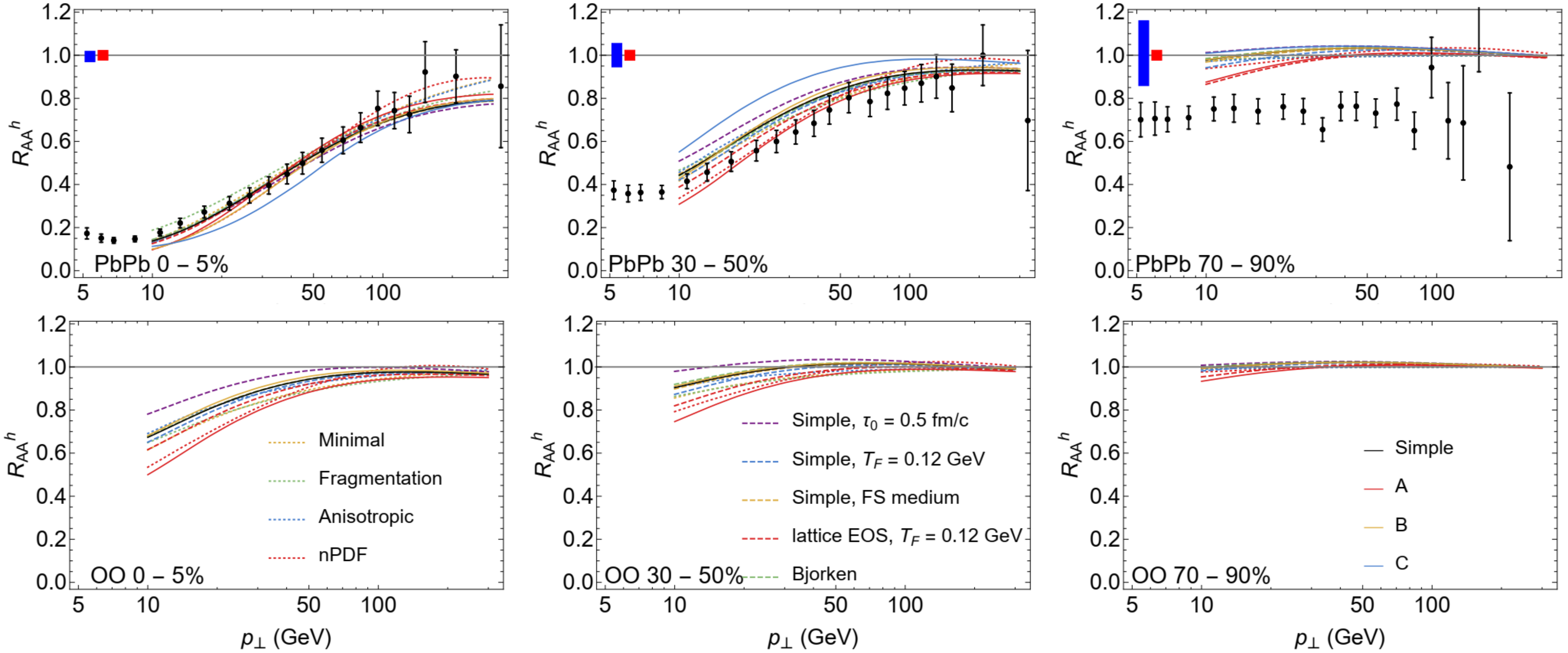
An overview of all models

1. Various variations of the `simple' model

model	nPDF	$\langle R\rangle$, $\langle N_{\rm part}\rangle$, $\langle N_{\rm coll}\rangle$	$\langle\epsilon_2\rangle$	T evolution	Energy loss	Fragmentation	$\hat{q}/T^3$ or κ
Minimal	no	optical Glauber	no	kinetic	BDMPS-Z	no	0.89 ± 0.26
Anisotropic	no	TrENTo	yes	kinetic	BDMPS-Z	no	0.85 ± 0.24
nPDF	yes	optical Glauber	no	kinetic	BDMPS-Z	no	1.08 ± 0.27
Fragmentation	no	optical Glauber	no	kinetic	BDMPS-Z	yes	3.5 ± 1.1
Simple	yes	TrENTo	yes	kinetic	BDMPS-Z	yes	4.3 ± 1.1
Simple, $\tau_0 = 0.5\mathrm{fm}/c$	yes	TrENTo	yes	kinetic	BDMPS-Z	yes	8.1 ± 2.8
Simple, $T_{\rm F} = 0.12\mathrm{GeV}$	yes	TrENTo	yes	kinetic	BDMPS-Z	yes	3.8 ± 0.9
Free streaming	yes	TrENTo	no	free streaming	BDMPS-Z	yes	2.69 ± 0.70
Lattice EOS	yes	TrENTo	yes	kinetic	BDMPS-Z	yes	2.84 ± 0.70
Bjorken	yes	TrENTo	yes	$\propto \tau^{-1/3}$	BDMPS-Z	yes	3.59 ± 0.91
A	yes	TrENTo	yes	kinetic	$dE/dx \propto \tau^{0.4}T^{1.2}$	yes	3.40 ± 0.71
B	yes	TrENTo	yes	kinetic	$dE/dx \propto \tau T^3$	yes	4.32 ± 0.95
C	yes	TrENTo	yes	kinetic	Stopping	yes	2.54 ± 0.17

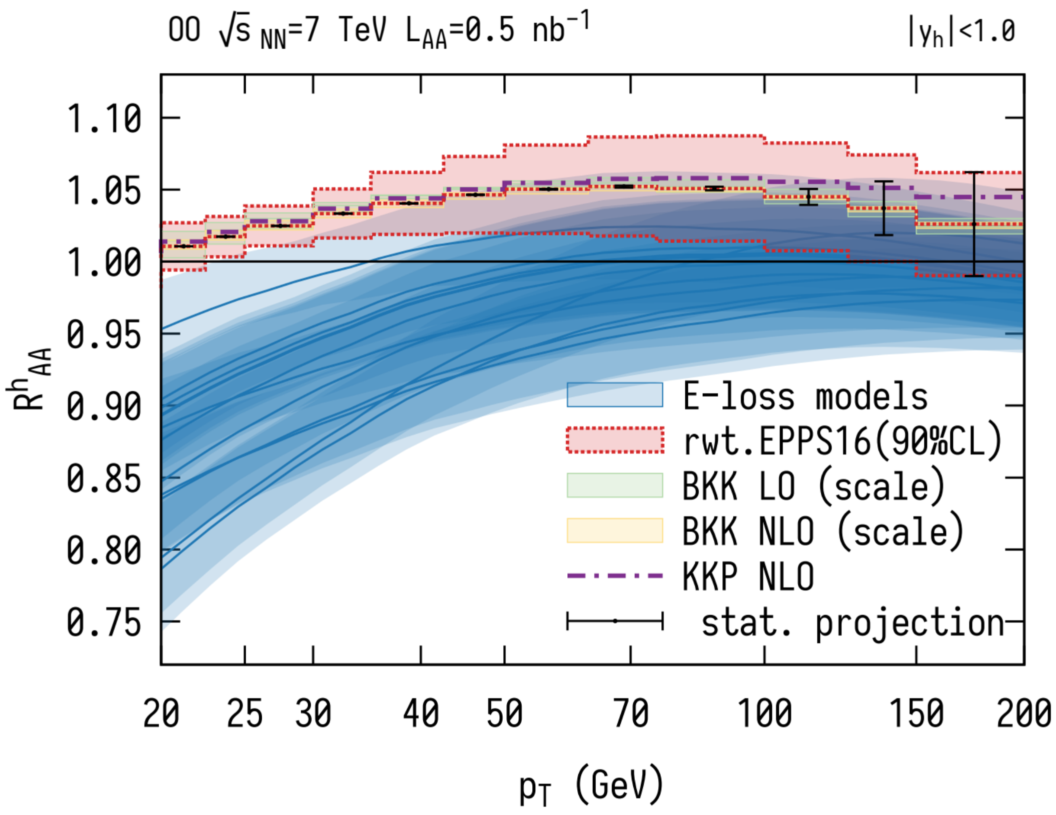
An overview of all models

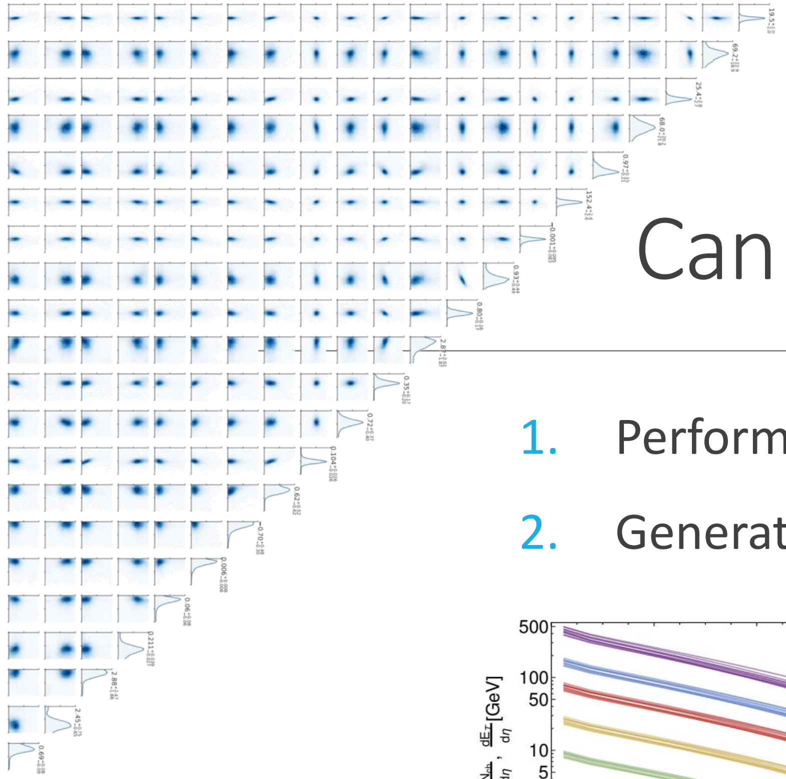
1. All except model C work reasonably well, and can provide a prediction on OO



Extrapolate to OO collisions

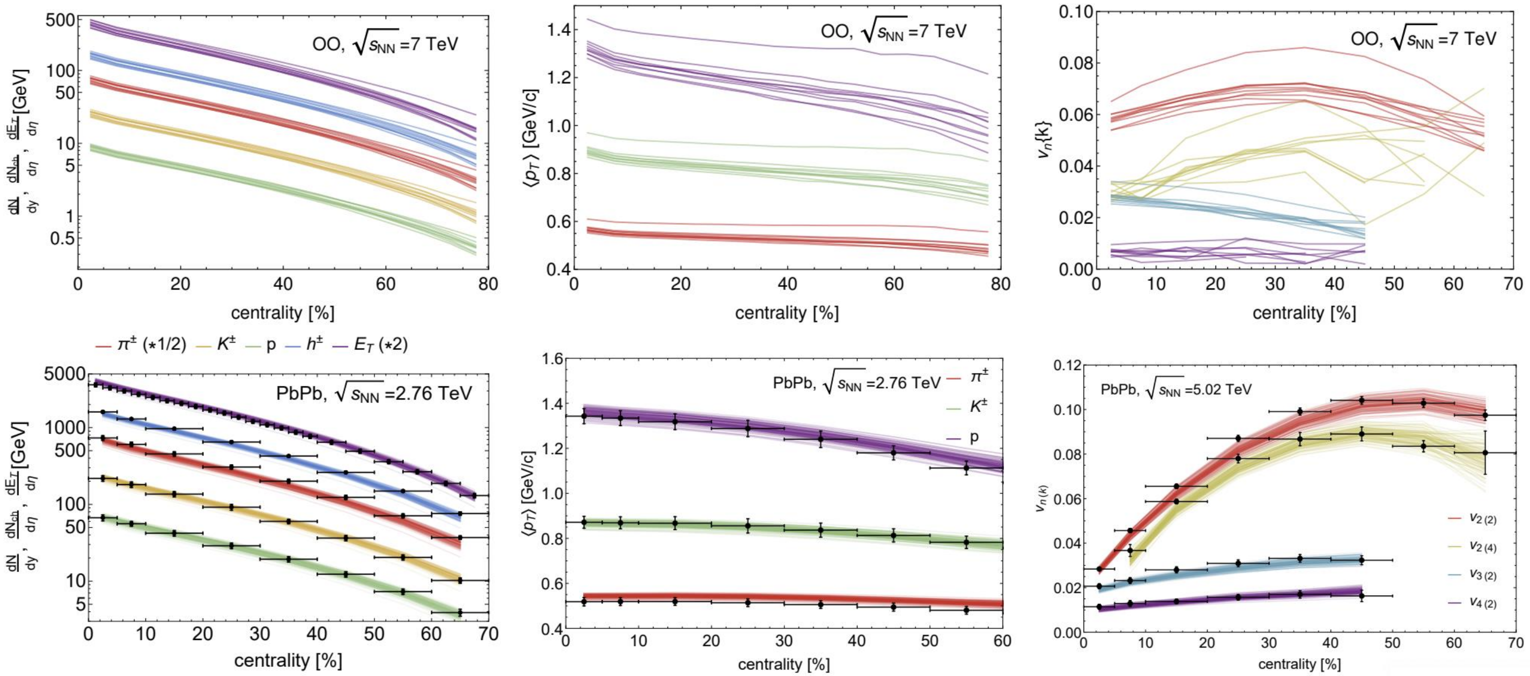
1. Final band of all model predictions to OO:
   - *As agnostic as possible*
   - *Baseline without QGP: including reweighting of nPDF set*



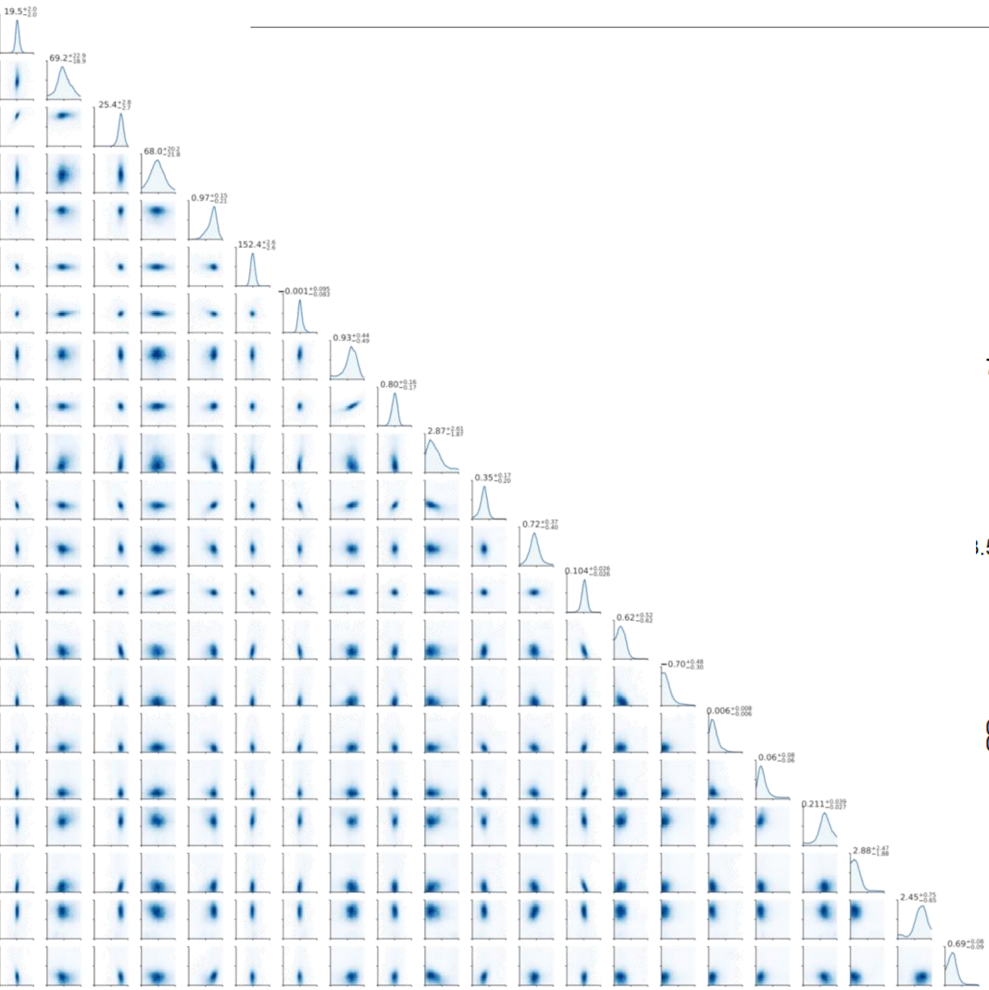


Can oxygen collisions constrain QGP properties?

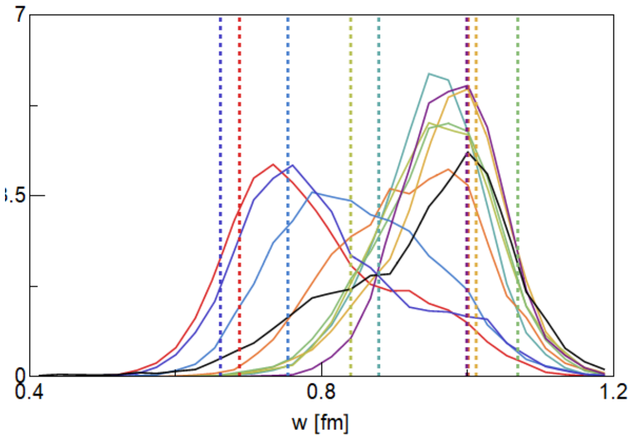
1. Perform a Bayesian estimate of likelihoods PbPb parameters
2. Generate oxygen-oxygen predictions for 10 samples:



Can oxygen collisions constrain QGP properties?

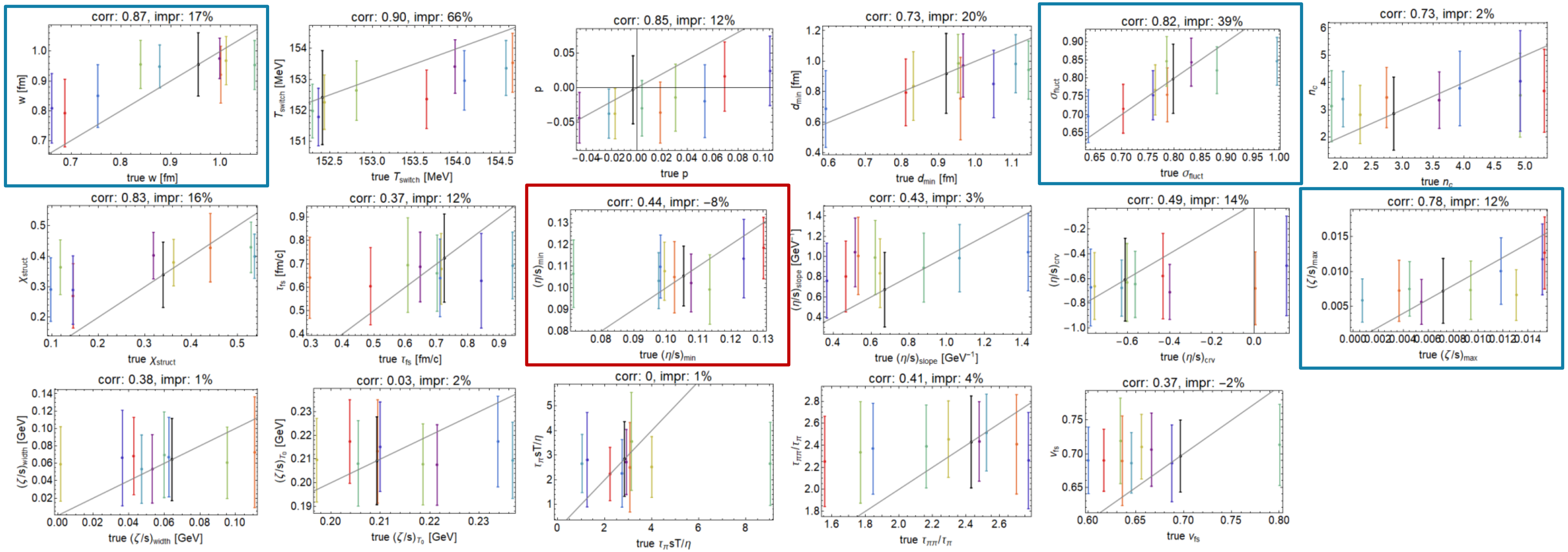


1. For the predicted OO values: rerun the Bayesian scan
2. Do we obtain tighter constraints?
   - *Example:* nucleon width:

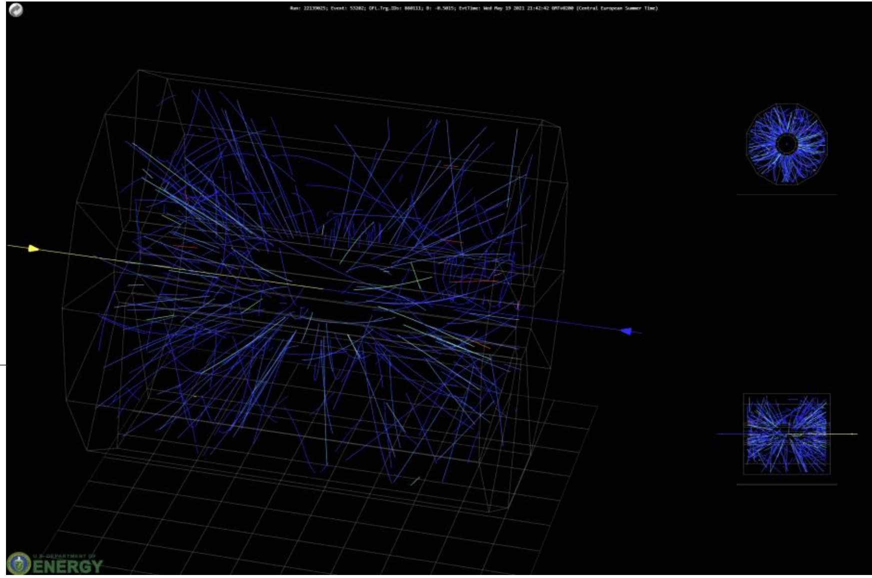


Can oxygen collisions constrain QGP properties?

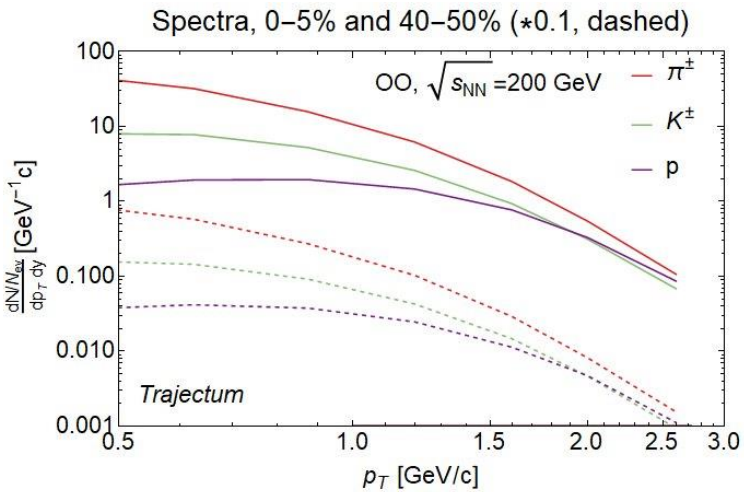
1. Improvement for ‘structure-like’ parameters, but not for viscosities
2. Strong correlation with OO ‘true’ value for most parameters

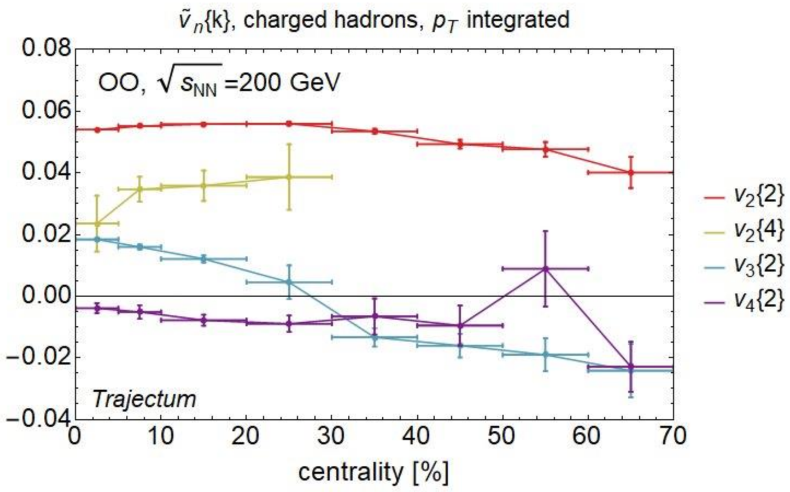


Oxygen @ RHIC
Complementary collisions @ 200 GeV

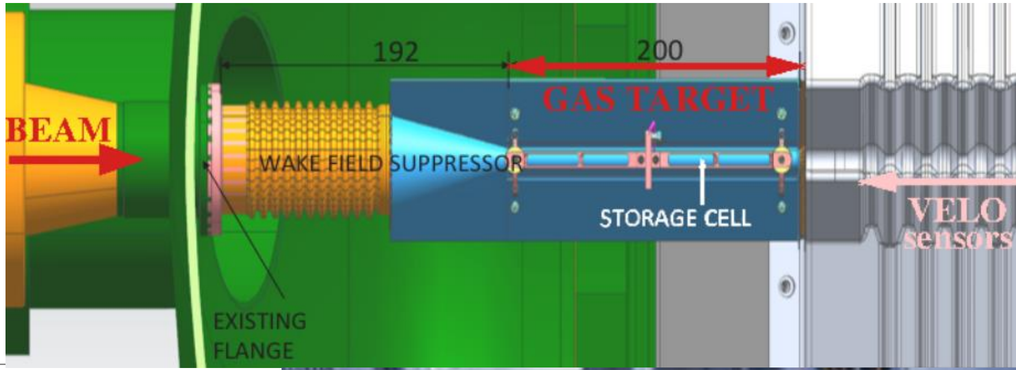


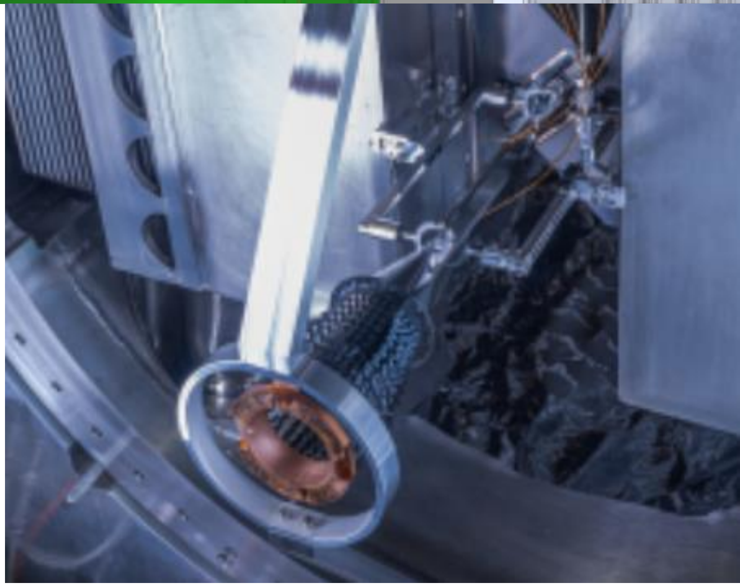
1. (Much) lower multiplicity: more comparable to *p*Pb?
2. Curious signs of anisotropic flow coefficients (typically positive)
3. Exciting time to make predictions:





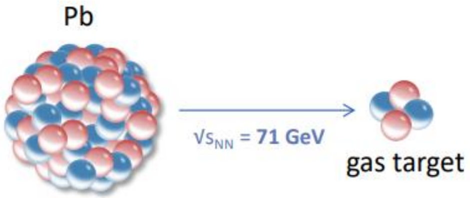
Light ions and SMOG2
LHCb at fixed target





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 (full year)
5. Data taking simultaneous: sizeable integrated lumi: 100 pb^{-1}

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



The LHC as a light ion collider

1. Oxygen can provide key to current heavy ion puzzles
   - Is there flow in small systems such as p-Pb collisions?
   - Precision analysis possible on partonic energy loss
     - Theory accurate to few percent in minimum bias collisions
     - Expected effect is larger than precision due to NLO QCD computations including accurate nPDFs
   - Can further constrain QGP properties

2. Proton-oxygen essential for high energy cosmic rays
   - Can also be very helpful to put extra constraints on nPDFs

3. Did I skip anything?
   - Structure of oxygen: is oxygen made out of four alpha particles? Seems hard to see significant consequences
   - Impressive projections by ALICE, including anisotropic flow coefficients up to 12-particle cumulants
   - Correlations between mean transverse momentum and anisotropic flow can be interesting
   - Oxygen especially interesting to constrain nPDFs: no data on oxygen so far available even at lower energy