Heavy Ion Collisions: Theory overview

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Outline

This talk:

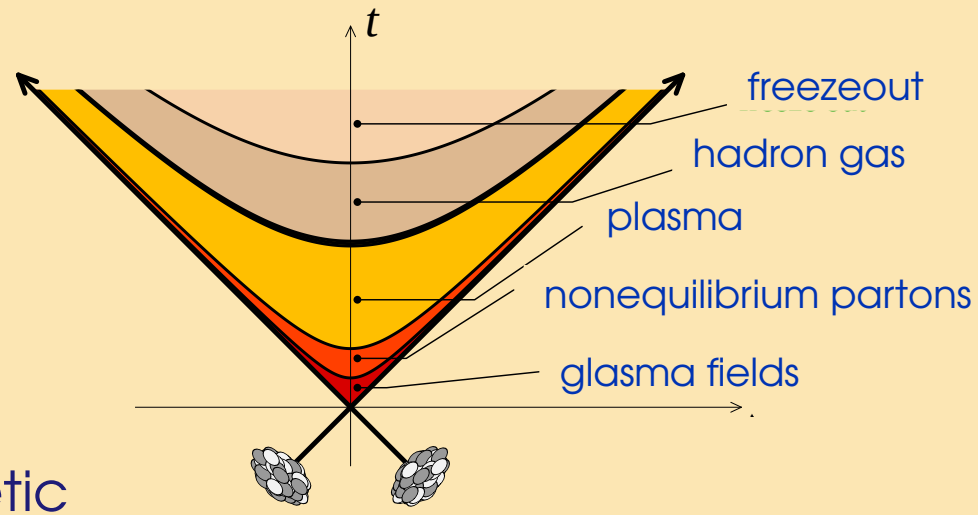
- Condensed matter physics of QCD
- Thermalization
- HI event characterization: from models to global analysis
- Small systems and limits of collectivity
- Jet quenching, EM probes

Why heavy ion collisions

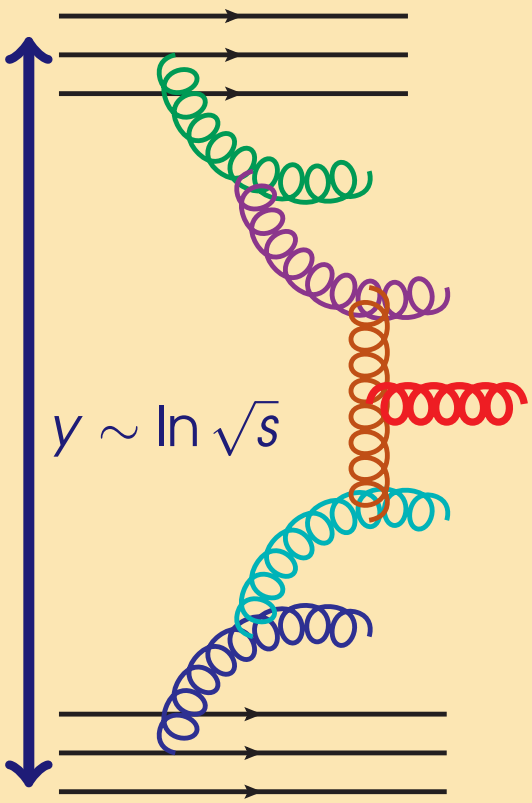
- QCD prediction: deconfined phase at $T \gtrsim 150$MeV
- QCD in the laboratory:
  fundamental (emergent) properties of QCD
- How: heavy ion collisions at various collider energies
- Not only rare events, global characteristics of collision

Simultaneously understand:

- Initial conditions, thermalization
- Spacetime evolution: hydrodynamics
- Hadronic phase
- Hard and electromagnetic probes from all stages



Initial state: small x QCD



- Gluons ending in central rapidity region: multiple splittings from valence quarks
- Emission probability $\alpha_s \, dx/x$
  $\Longrightarrow$ rapidity plateau for $\Delta y \ll 1/\alpha_s$
- Many gluons
  $\Longrightarrow$ large phase space density

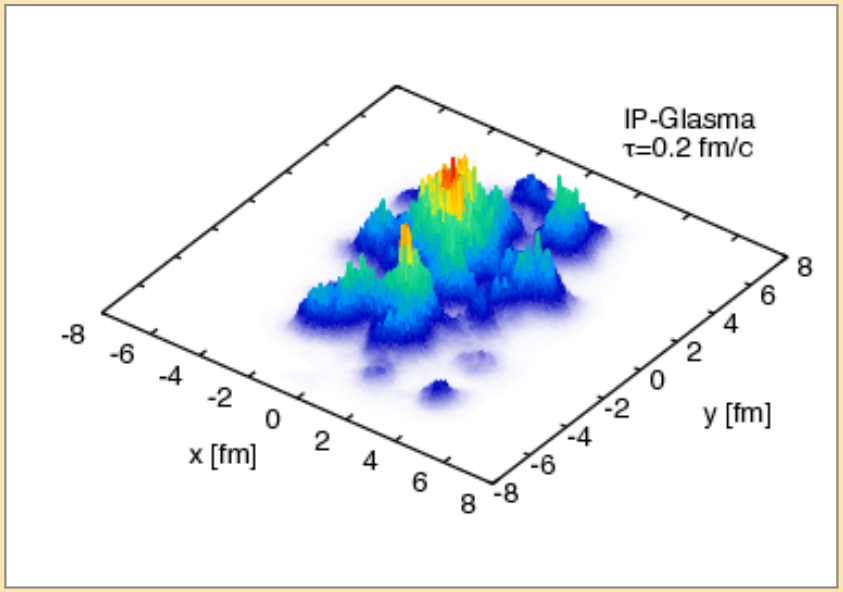
Weak coupling, but nonperturbative

- α_s small
- $f(k) \sim A_\mu A_\mu \sim 1/\alpha_s$ large

True when typical momentum $Q_s \gg \Lambda_{QCD}$
$\Longrightarrow$ gets better at large $\sqrt{s}$

Classical fields, kinetic theory, hydro

State of the art in QCD calculations for initial stages:



IPglasma Schenke et al 2012 –

- Classical color fields
- Nucleon- and subnucleon scale fluctuations

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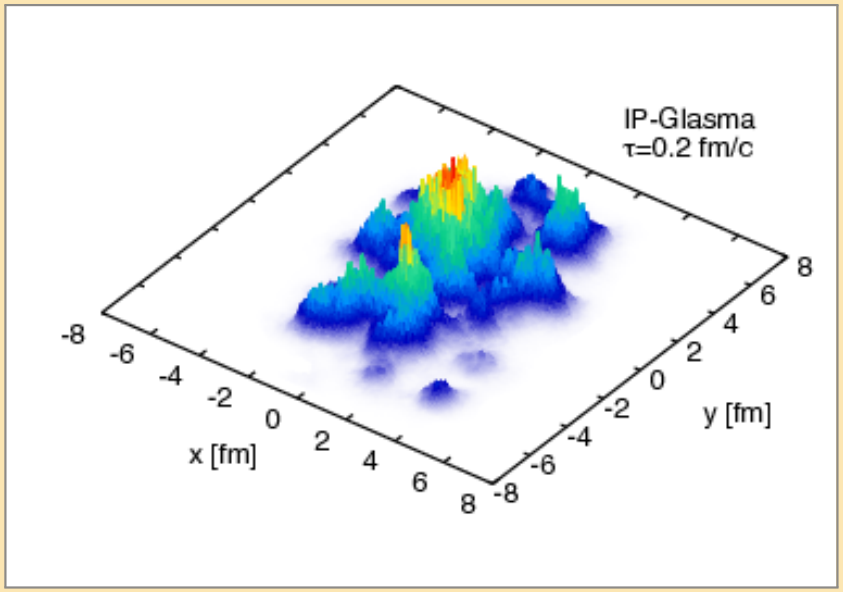

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- Classical color fields
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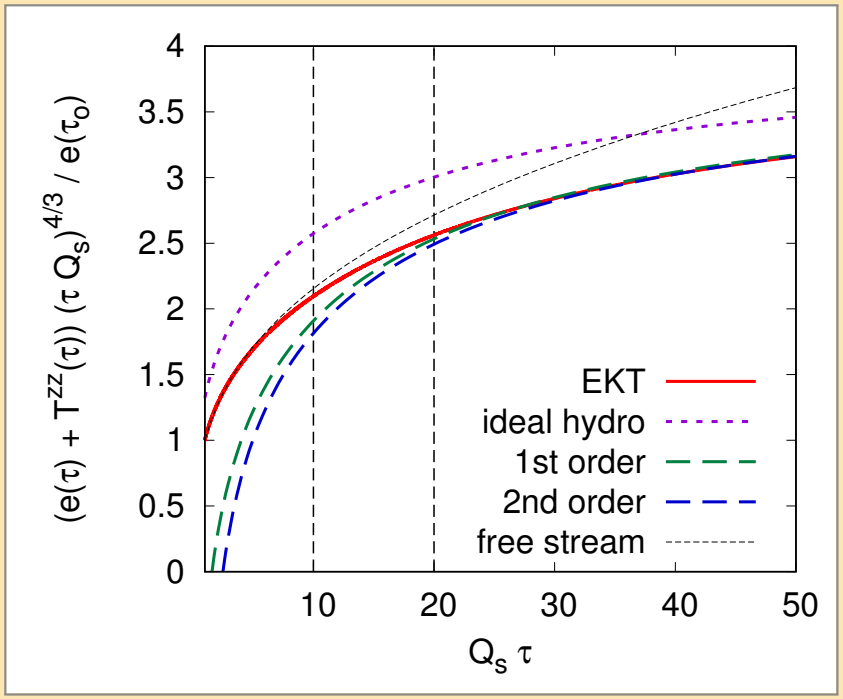
- QCD kinetic theory ("EKT") $\Longrightarrow$ follow system to hydrodynamics

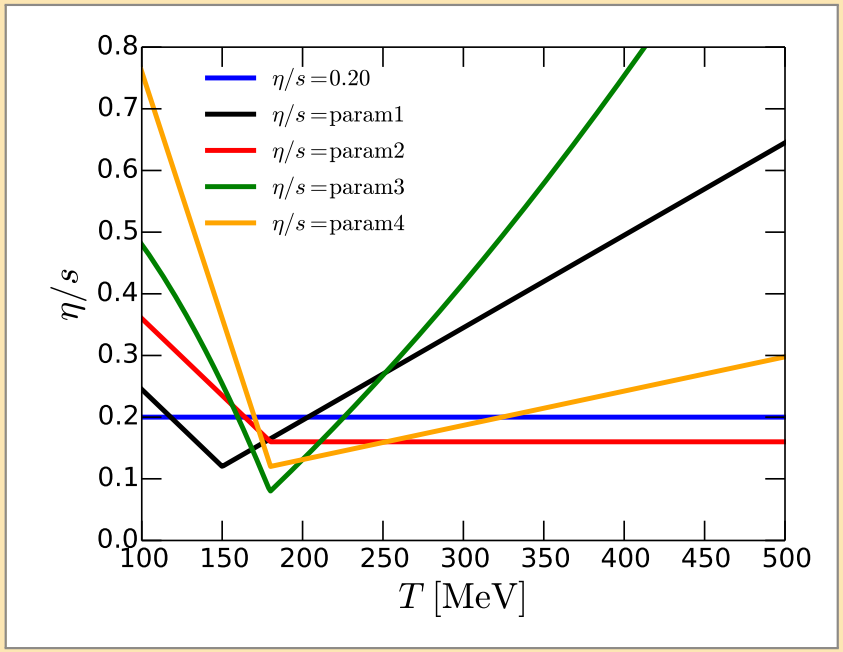


Keegan et al `arXiv:1605.04287`

Hydrodynamical description of soft observables

Need:

- Initial conditions
- Hydrodynamical evolution:
  - Energy-momentum conservation $\partial_\mu T^{\mu\nu} = 0$
  - Medium properties: EoS, **transport coefficients**
- Freezeout to particles



(E.g. viscosity η)

Niemi et al `arXiv:1504.02677`

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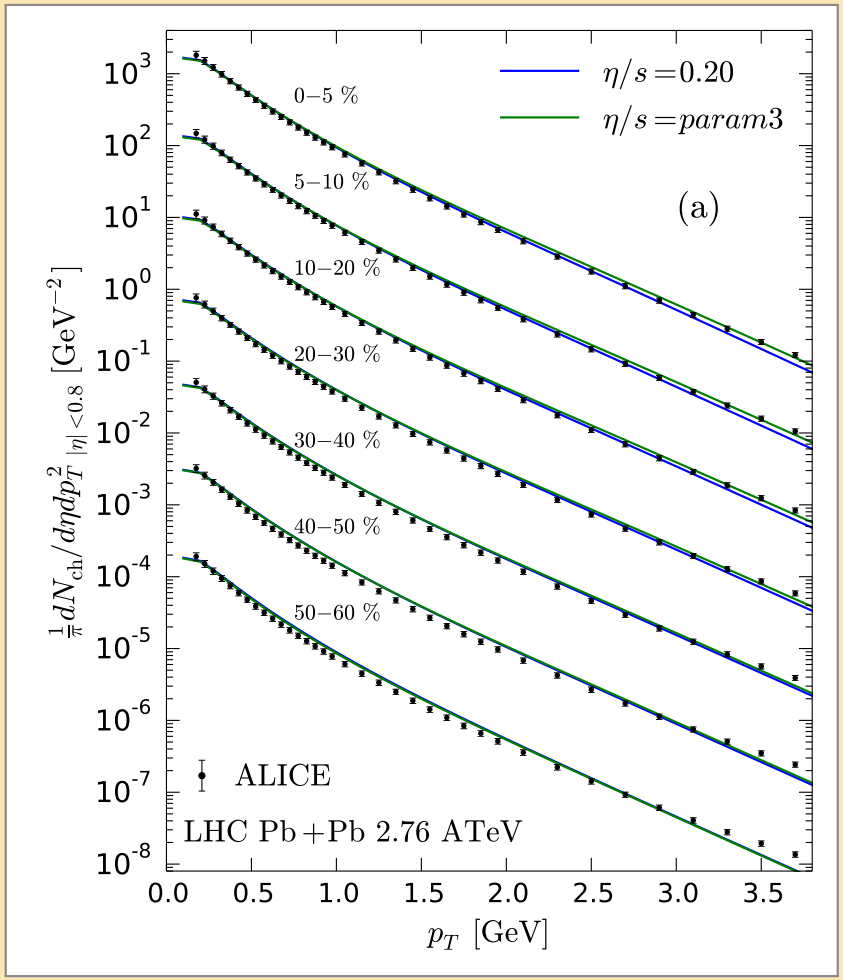
Calculate:

- **p_T-spectra (yields, $\langle p_T \rangle$)**
- Azimuthal harmonics (v_n's)
- Reaction plane correlations
- ...

All of these for

- Indentifed particles
- Centrality classes



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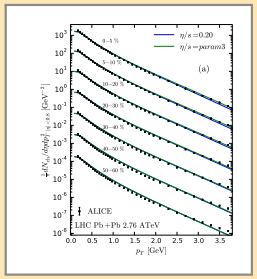

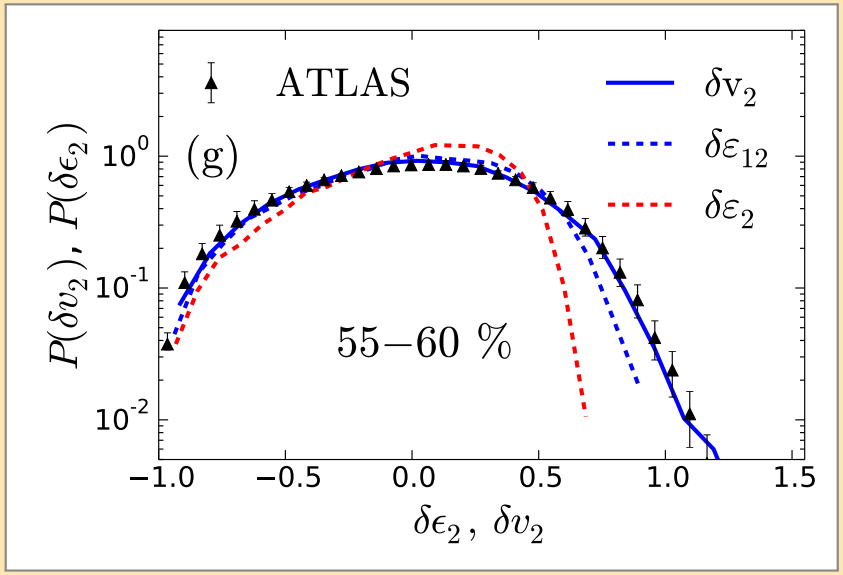

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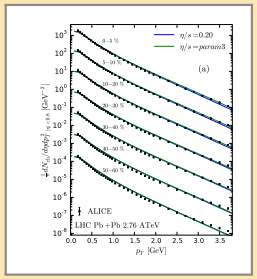
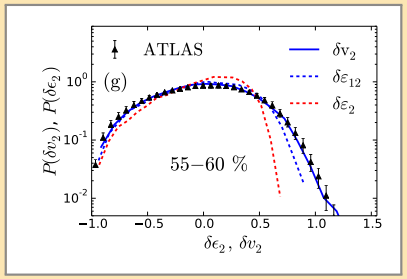
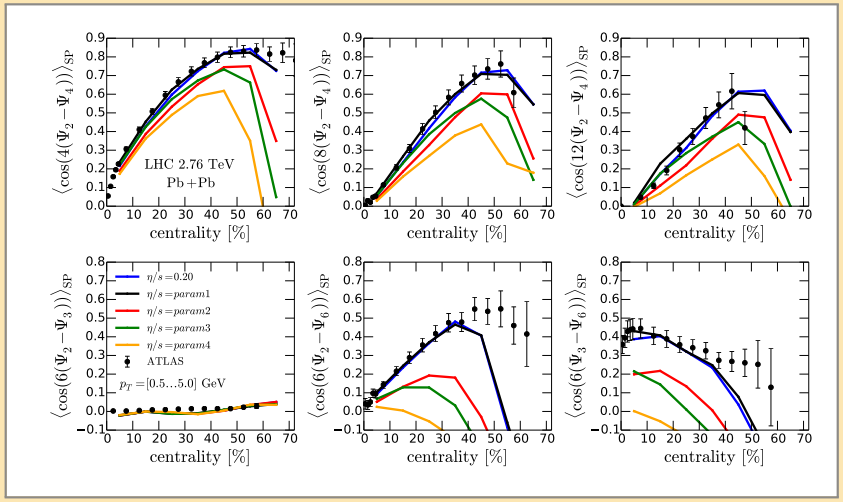






Niemi et al `arXiv:1504.02677`

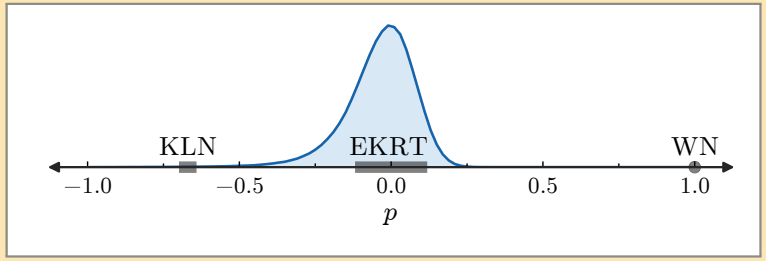
Viscosity extraction, data-driven hydro

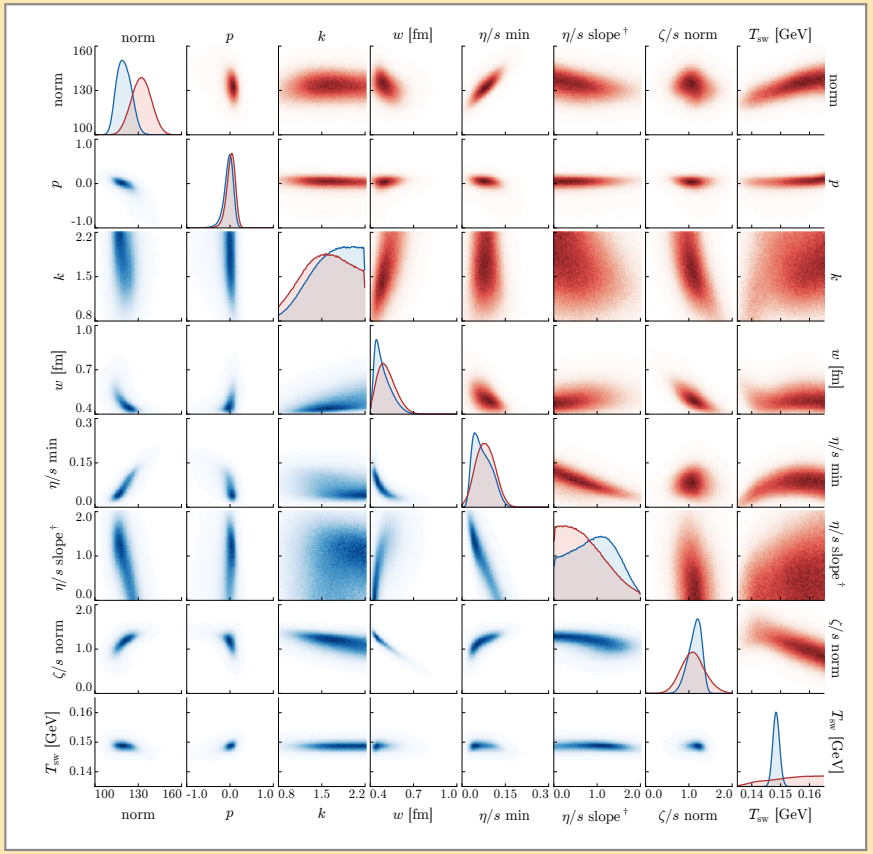
State of the art Bernhard et al `arXiv:1605.03954` : Bayesian global fit

In particular: initial entropy density parametrized & fit

$$s(\mathbf{x}_T) \sim \left(\frac{(T_A(\mathbf{x}_T))^p + (T_B(\mathbf{x}_T))^p}{2} \right)^{\frac{1}{p}}$$

Data favors gluon saturation for particle production:





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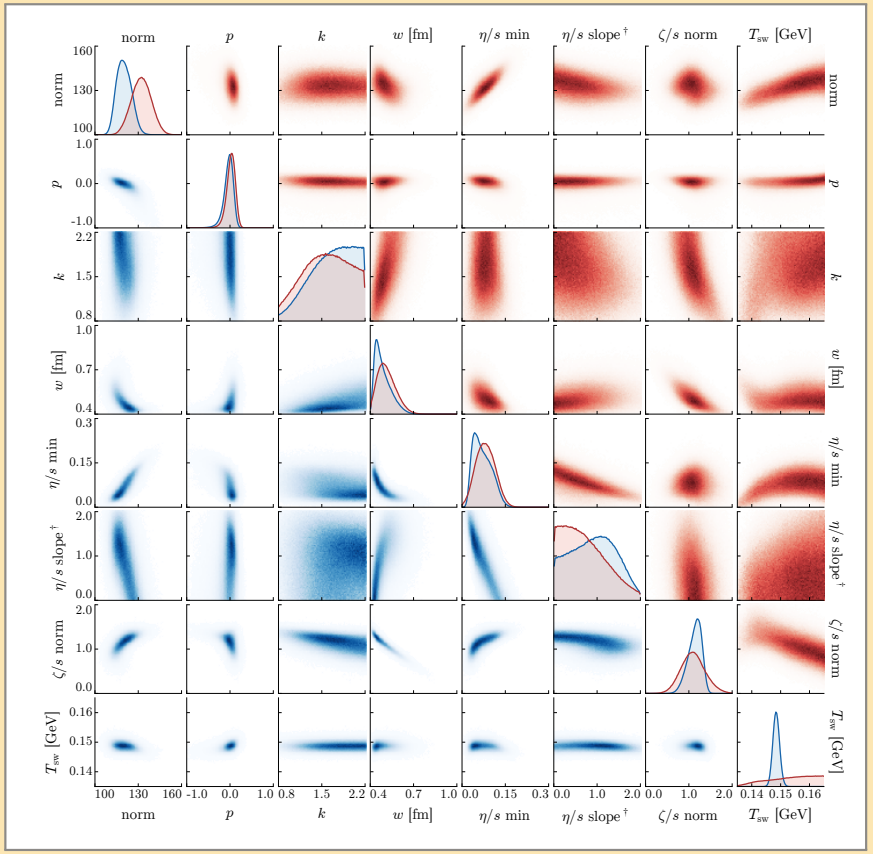
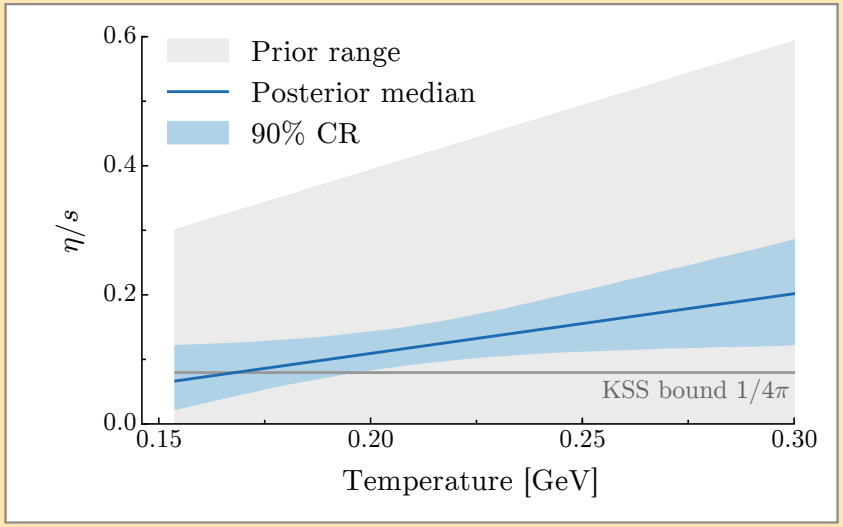


Result for QCD shear viscosity

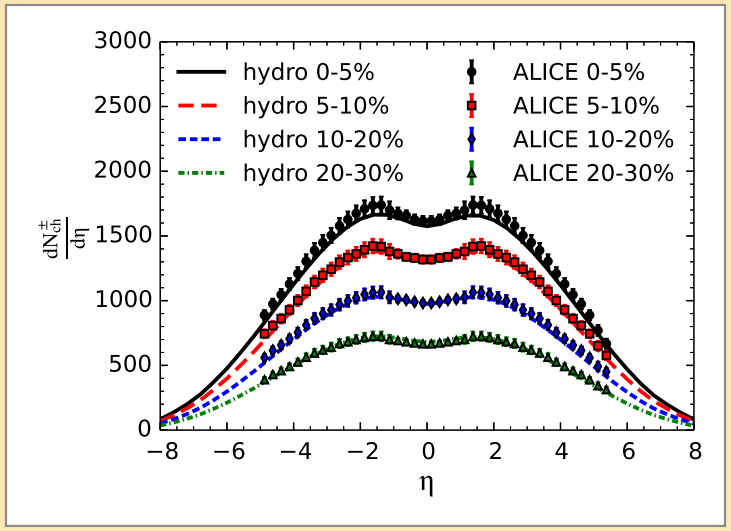


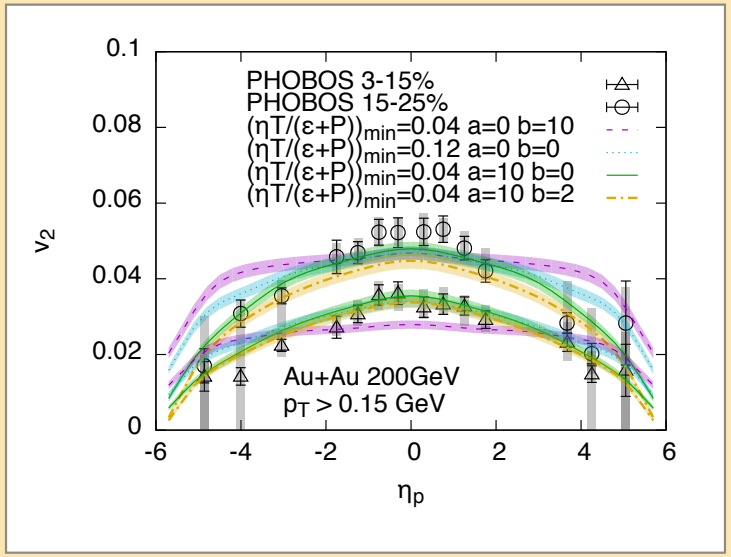
Current challenges in hydro

Improvements still needed to exploit even larger data set

- Rapidity dependence
  - Parametric/string models
    Pang et al. , Denicol et al. , Bozek et al 2015
  - How to compute in microscopic theory?
- Viscous corrections to freezeout $\Longrightarrow$ higher p_T
  - Hydrodynamics has integrated $T^{\mu\nu}$
  - At the end need to match to microscopic $f(\mathbf{p})$.
  - How to do out of equilibrium? (with viscosity)
- How low (N_{ch}) can you go?

...



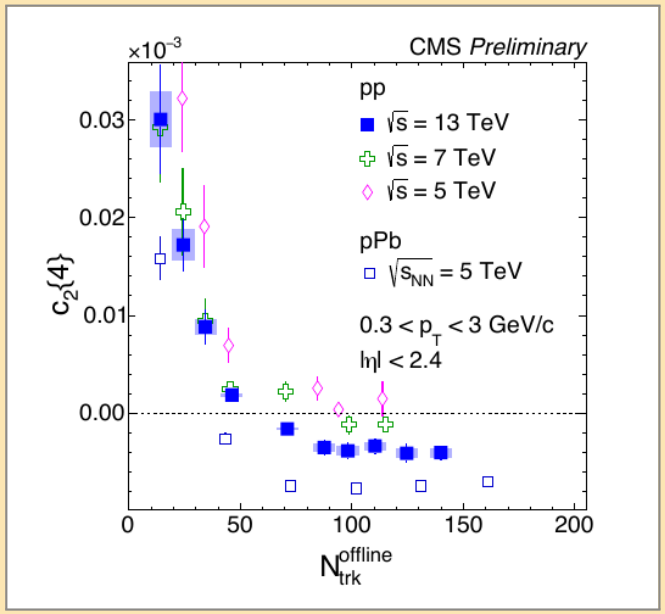


"Small systems": pPb & pp at high N_{ch}

See H.I: parallel 1 this morning

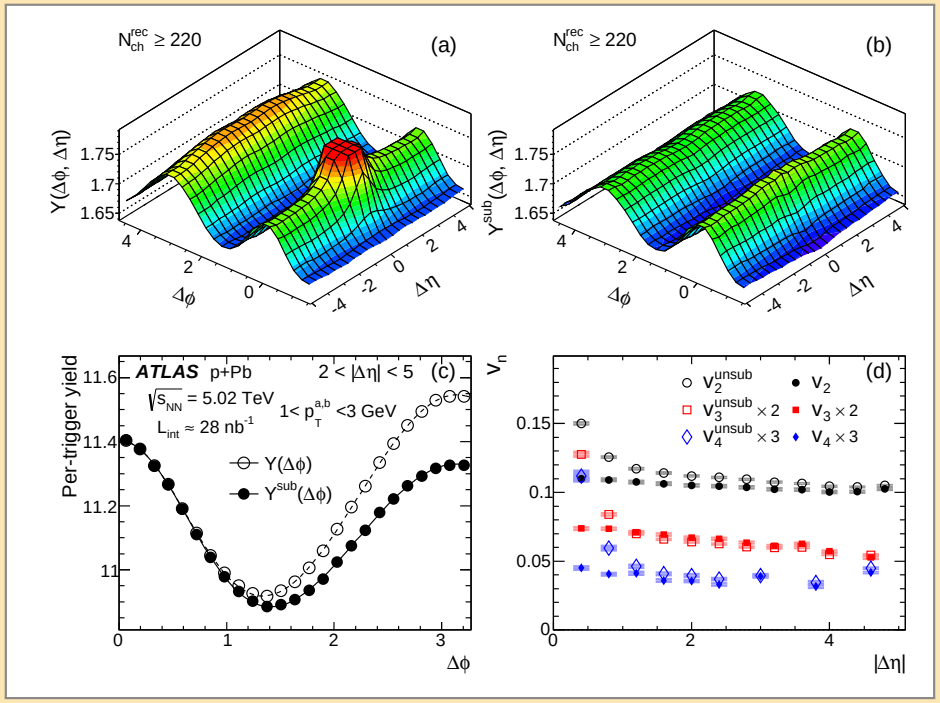
Observations

- Azimuthal correlations similar to AA
- Cumulant analysis: not a dijet correlation



($c_2\{4\}$: 4-particles, $\cos 2\varphi$)

(Note sign change at $N_{trk} \sim 60$)



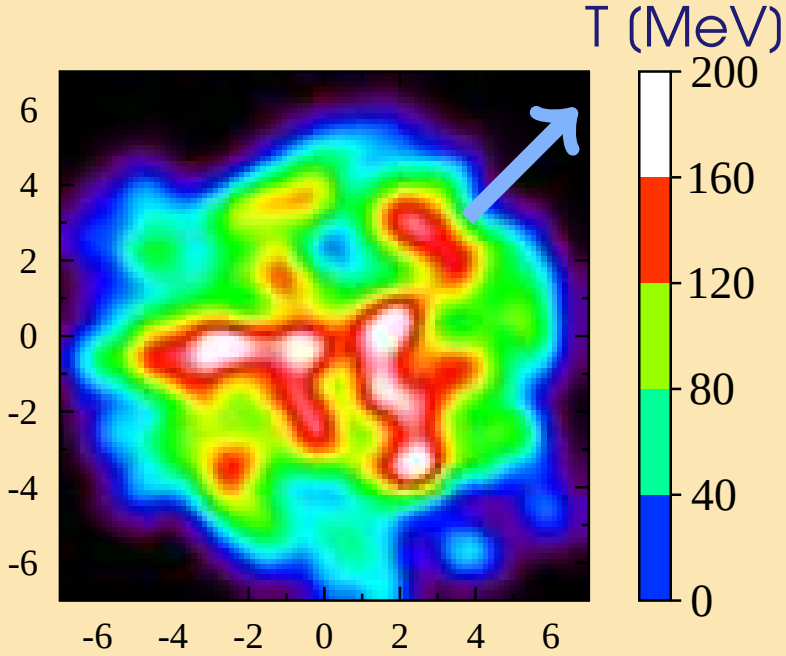
Analyze as yield/trigger or v_n:

ATLAS, `arXiv:1409.1792`.

What is the origin?

- Collective flow as in AA?
- Initial state gluon correlations?

Flow in hydro



- Interactions/collectivity
+ Temperature/pressure gradients

$\Longrightarrow$ Anisotropic force

$\Longrightarrow$ acceleration

$\rightarrow$ anisotropy in momentum

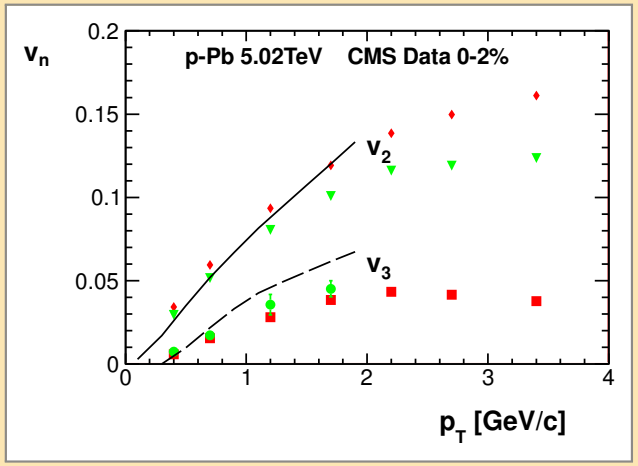
Pb-Pb collision: large system

$\Longrightarrow$ nucleon scale matters little

$\Longrightarrow$ initial geometry known

Also pp, pPb collisions?

- Hydrodynamics for $\sim$ 50 particles?
- Initial geometry not controlled



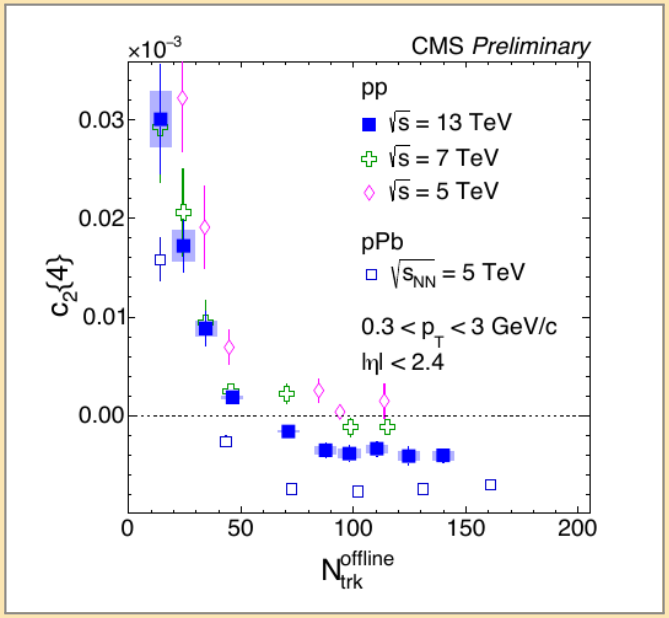
E.g. Bozek et al

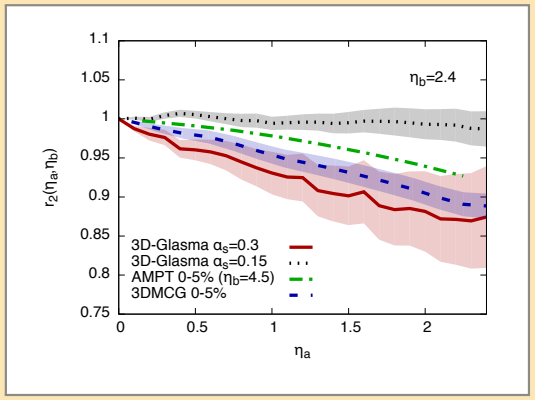
arXiv:1407.6478

How to sort out smaller systems?

- Higher cumulants:
  flow vs. "nonflow"
- Longitudinal correlations
  - Implemented in string models,
    E.g. L. G. Pang et al G. Denicol et al, Bozek et al. 2015
  - Weak coupling: first steps
- Mass ordering: hadronization?

How much collectivity from QCD scattering + hadronization vs. hydrodynamics?





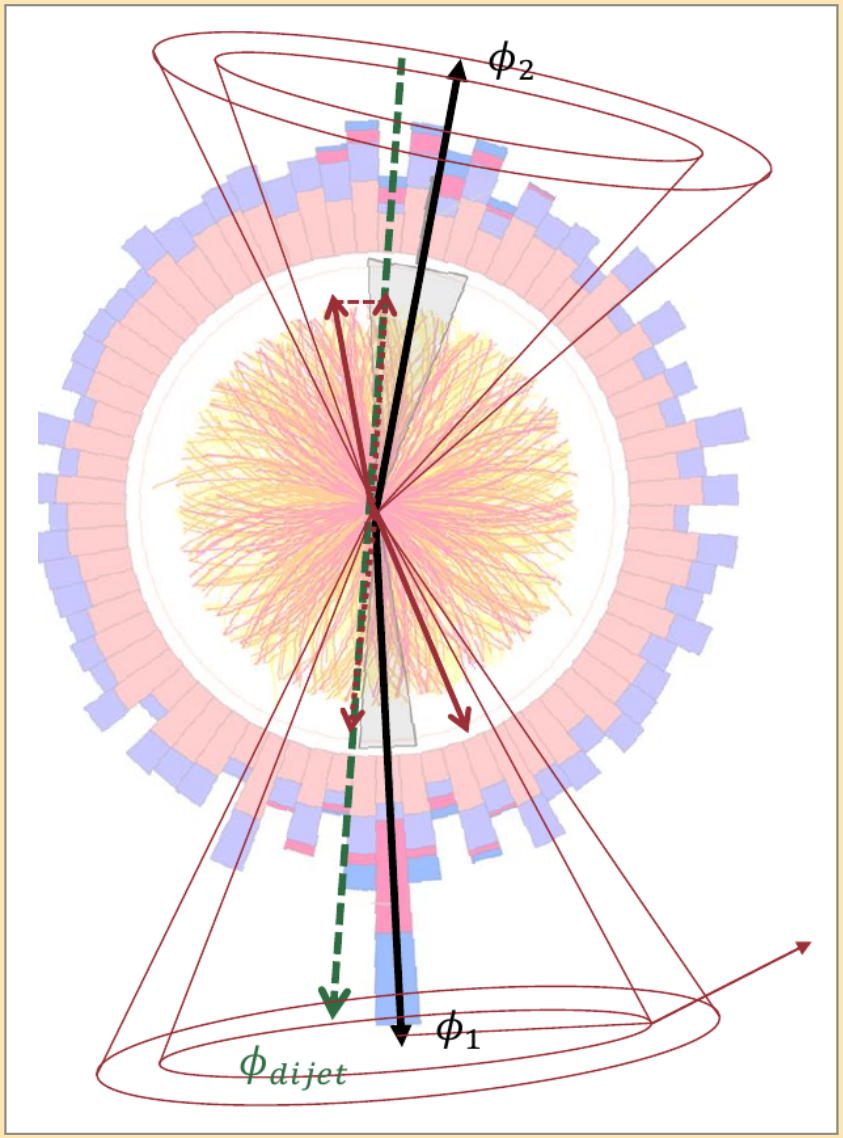
Event plane decorrelation:

Schenke et al `arXiv:1605.07158`

Jet tomography

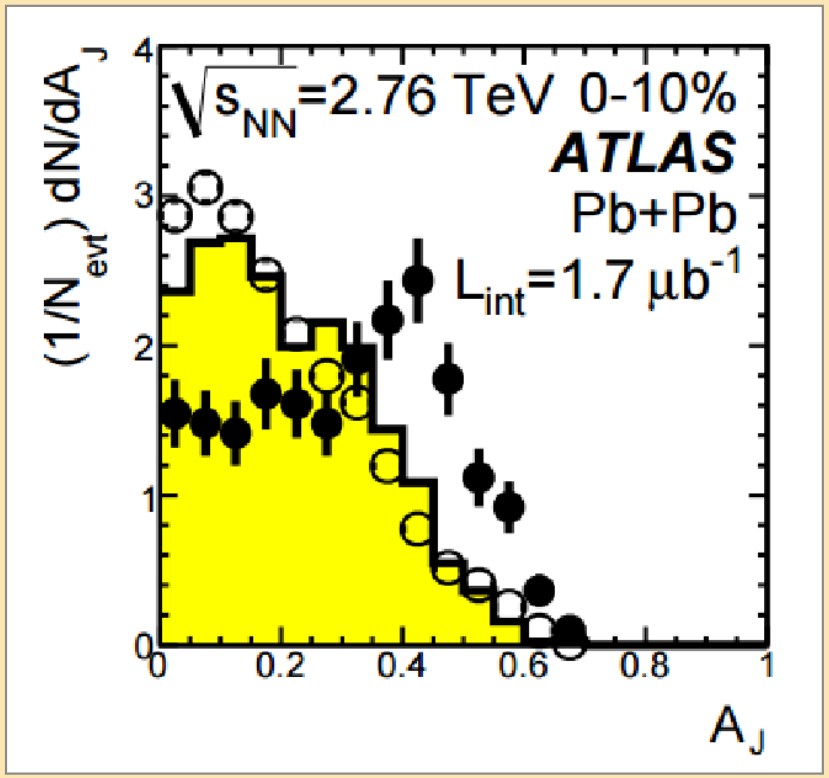
H.I. parallel 3 tomorrow

Dijet: calibration and probe



Quantify e.g. with dijet asymmetry

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$



Jet quenching: theory

Theory advances prompted by LHC data

- Structure of medium induced cascade: energy flow to soft gluons $\Longrightarrow$ large angles

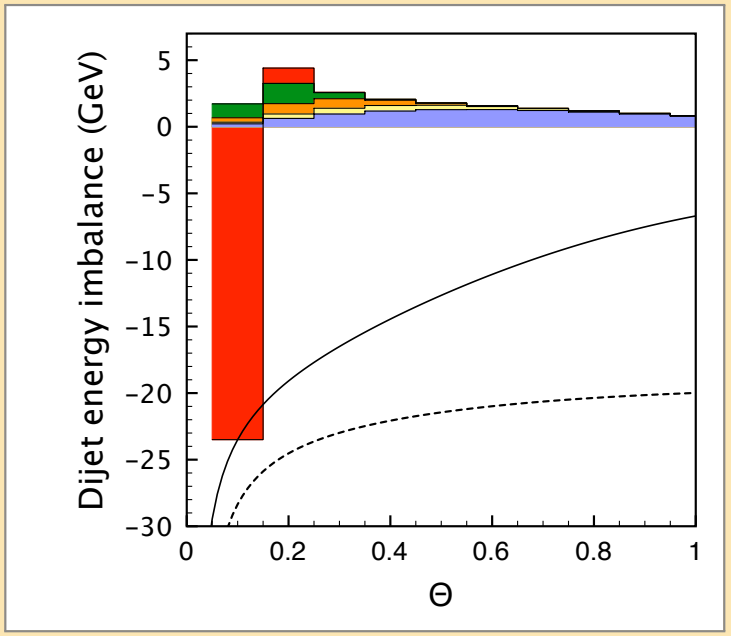
  Blaizot, Dominguez, Iancu, Mehtar-Tani; Kurkela, Wiedemann

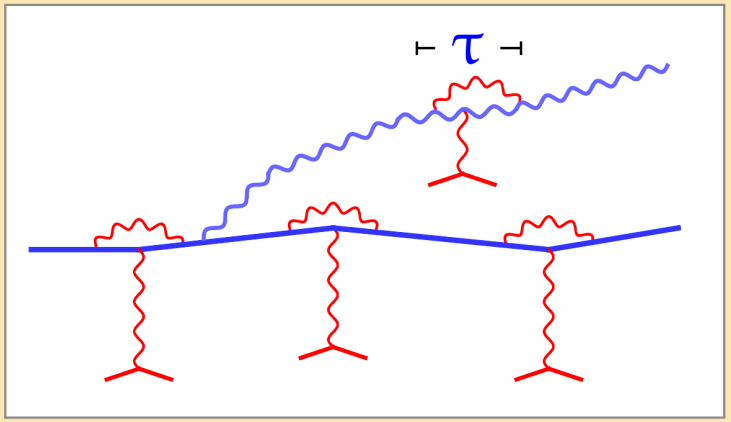
  ...

- NLO corrections to medium parameter "$\hat{q}$"

  Wu, Liou, Mueller, Mehtar-Tani, Blaizot, Dominguez, Iancu, ...

- Monte Carlo for medium cascade: JEWEL, Q-PYTHIA, Martini, YaJEM, PYQUEN, ...

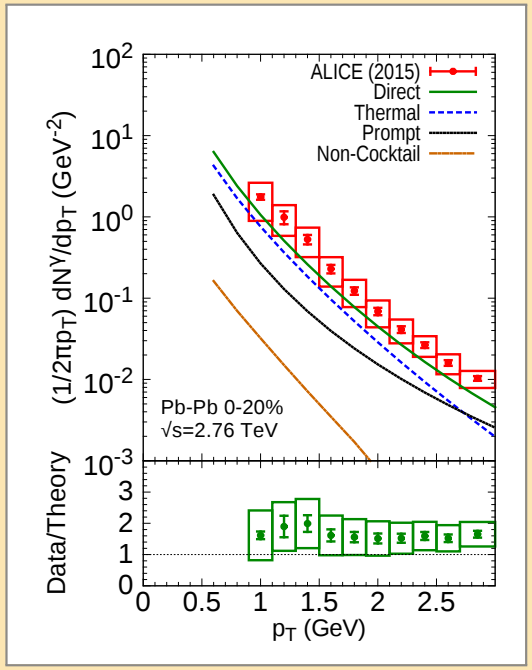


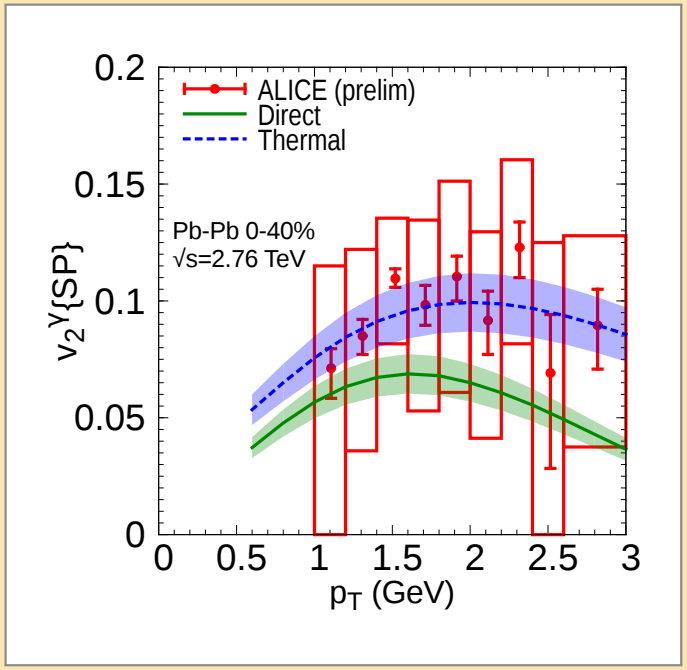


Photons

Thermal photons & dileptons from plasma stage:
only **direct** probe from deconfined phase

Problem: all these other sources of light...





Paquet et al `arXiv:1509.06738`

Edging towards solution of longstanding **photon v_2 puzzle**:

- Large yield: early plasma phase dominates
- Large $\cos 2\varphi$ asymmetry: late hadronic stage dominates

Difficult to get both

Open heavy flavor

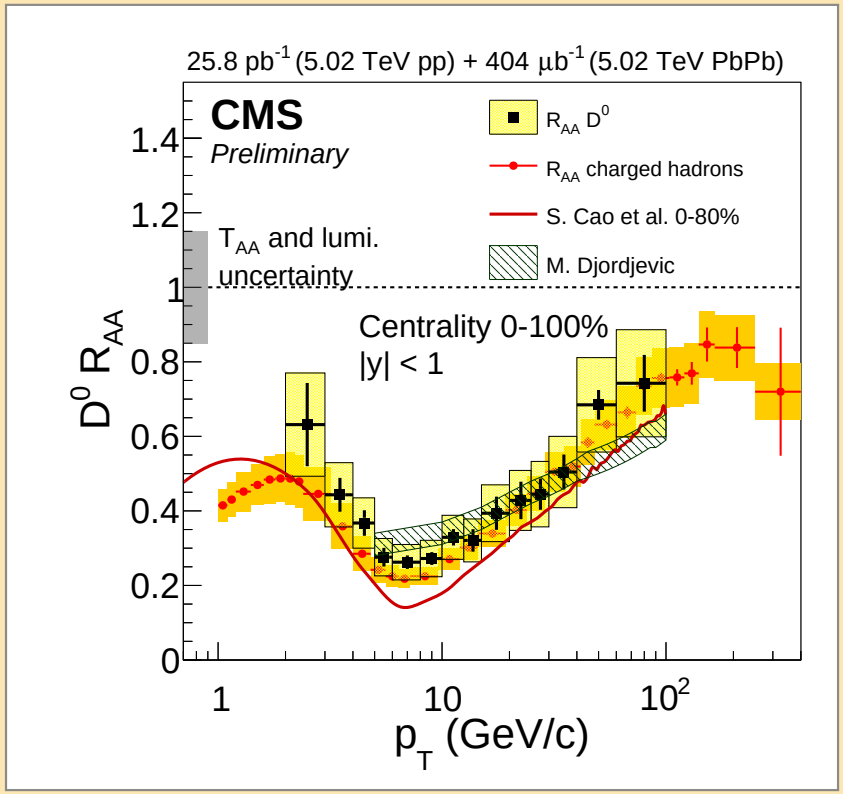
"Open"= individual c, b quarks in medium, not in bound states

At LHC:
D-meson $R_{AA} \approx$ light hadrons

(Recall $R_{AA} = \frac{1}{[\text{geometry}]} \frac{d\sigma_{AA}}{d\sigma_{pp}}$.)

But theory very different!

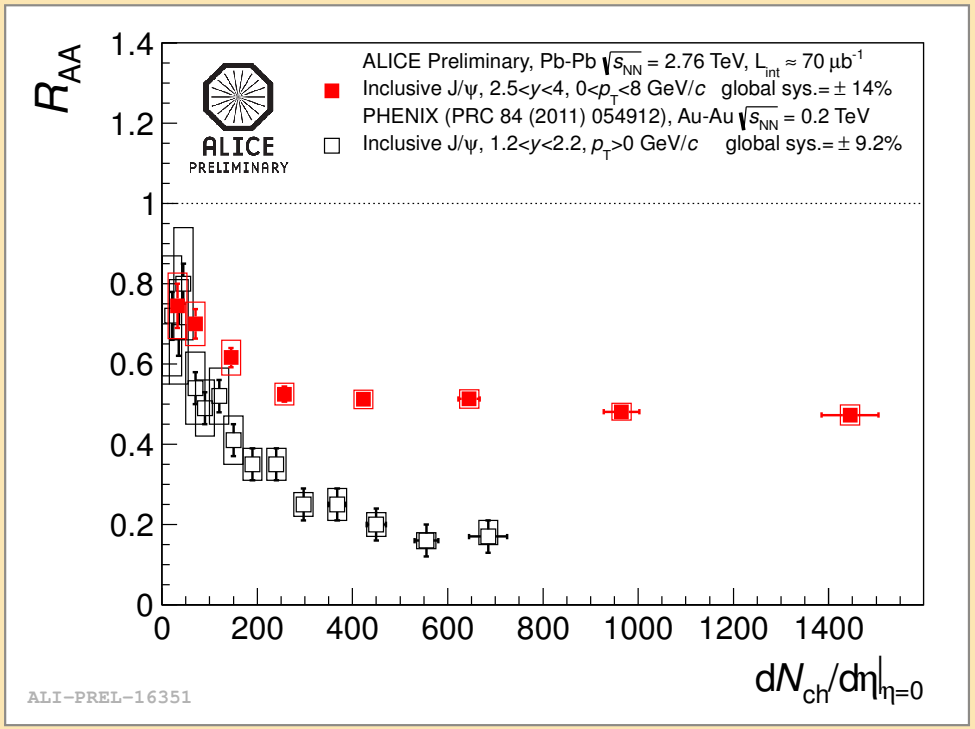
- Light: medium itself + quenched jets
- Heavy: c, b quarks pushed by medium
  - flow
  - thermal noise



CMS-PAS-HIN-16-001

Heavy quarkonia

Quarkonia "melt" in quark-gluon plasma $\Longrightarrow$ thermometer!



So why is there less J/Ψ suppression at LHC than at RHIC?

Thermometer complicated!

Need to understand:

- Production in pp & pA
- Dissociation in plasma (lattice)
- Propagation in medium (flow $\Longrightarrow p_T$)
- Regeneration from $c\bar{c}$ pairs in dense medium $\Longrightarrow$ hadronization!

Making progress in all of these, but there is still work to do!

To summarize

- Progress in systematical extraction of fundamental properties of quark-gluon matter from experiment
- Still work to do, in nucleus-nucleus collisions:
  - Electromagnetic probes: additional constraint on evolution
  - Jets: interaction of colored particles with medium
- Proton-nucleus collisions more interesting than anybody believed when LHC started!
  - Understand "cold" nuclear matter effects for heavy quarks, high p_T particles, electromagnetic probes
  - Onset of collective behavior in ever smaller systems