Parton-medium interaction from RHIC to LHC

— a systematic approach

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Why are we looking at high P_T probes?

- What is the physics of parton-medium interaction, what are the medium dof?
  - transport coefficients $\hat{q}, \hat{e}$,...
- What can we deduce about the medium geometry?
  - initial profile, fluctuations, freeze-out conditions, scales . . .
- How does the medium react to a perturbation?
  - energy redistribution, shockwaves, speed of sound. . .

Why are these questions so difficult to answer?

$\longrightarrow$ ambiguities between medium evolution and parton-medium interaction modelling
$\longrightarrow$ steeply falling spectra — energy shift $\approx$ absorption, details are lost
$\longrightarrow$ tough theoretical problems involving multiple scales

$\Rightarrow$ need systematics in theory: different models
$\Rightarrow$ need systematics in experiment: P_T, $\sqrt{s}$, reaction plane, I_{AA},. . .

The toolkit

medium evolution

- Duke 3+1 d hydrodynamical model C. Nonaka and S. A. Bass, Phys. Rev. C **75** (2007) 014902
- Jyväskylä 2+1 d hydrodynamical model

K. J. Eskola *et al.*, Phys. Rev. C **72** (2005) 044904; H. Holopainen *et al*, Phys.Rev. C **83** (2011) 034901

- VISH2+1 2+1 d viscous hydrodynamical model

H. Song and U. W. Heinz, Phys.Lett. B **658** (2008) 279; Phys.Rev. C **77** (2008) 064901; Phys.Rev. C **78** (2008) 024902

energy loss from leading parton

- ASW radiative energy loss formulation C. A. Salgado and U. A. Wiedemann, Phys. Rev. D **68**, (2003) 014008.
- parametric elastic energy loss modelling T. Renk, Phys. Rev. C **76** (2007) 064905.
- AdS/CFT - pQCD hybrid model C. Marquet and T. Renk, Phys. Lett. B **685** (2010) 270.
- elastic MC (pQCD interactions) J. Auvinen, K. J. Eskola and T. Renk, Phys.Rev. C **82** (2010) 024906.

in-medium shower

- YaJEM, YaJEM-D (MC code for induced radiation and drag)

T. Renk, Phys. Rev. C **78** (2008) 034908; Phys. Rev. C **79** (2009) 054906, Phys.Rev. C **83** (2011) 024908

Modelling outline

• LO pQCD calculation + intrinsic k_T for primary parton spectrum
→ vertices in transverse plane distributed according to binary collision density

• hydrodynamical background evolution, constrained by bulk physics
→ *no additional free parameters* for evolution when computing high P_T physics
→ *one parameter* K_{med} connecting thermodynamics (e.g. ϵ) hard physics (e.g. $\hat{q}$)
→ K_{med} chosen for given hydro to fit R_{AA} in 200 AGeV central AuAu collisions

• average over all possible in-medium paths
→ all azimuth, wrt. reaction plane, wrt. event plane,. . .

either:

• leading parton energy loss (ASW, AdS, elastic, elastic MC)
→ shift in leading parton energy, followed by vacuum fragmentation

or:

• in-medium shower evolution (YaJEM, YaJEM-D)
→ YaJEM parton shower, followed by Lund hadronization

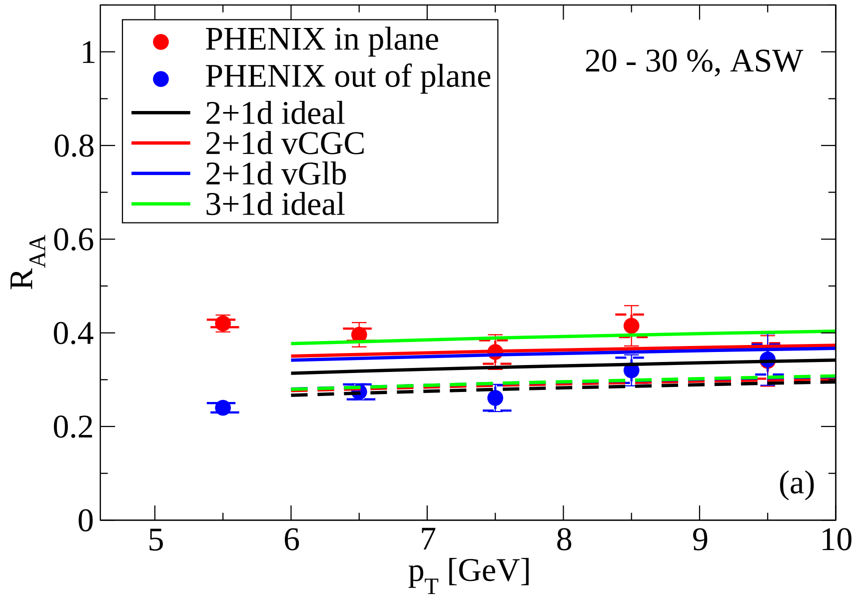
(• trigger conditions, binning, . . .)

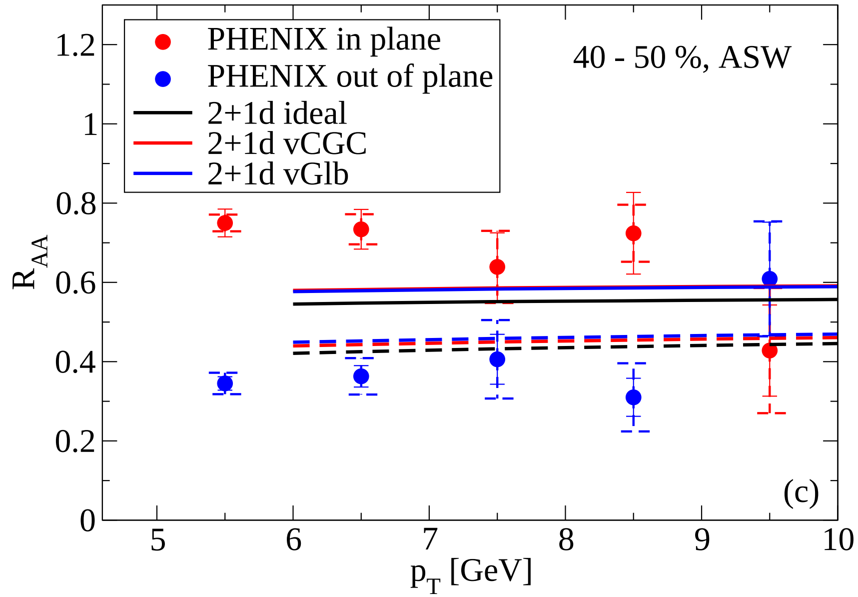
What is the influence of the medium model?

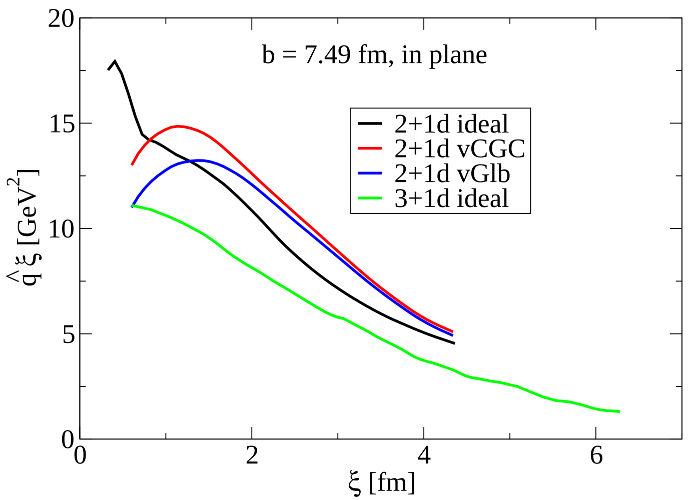
Given hydrodynamical models constrained by multiplicity, P_T spectra and v_2 and the same model for parton-medium interaction:

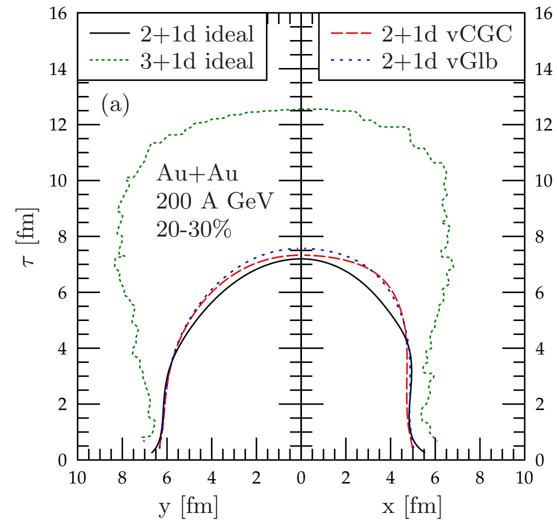
- How different is K_{med} required to describe R_{AA} in central collisions?
- How different is the resulting $\hat{q}_{max}$?
- How does $R_{AA}(\phi)$ differ for non-central collisions?
- What properties of the hydro medium do we probe?

Medium-model









T. R., H. Holopainen, U. Heinz, C. Shen, Phys. Rev. **C83** (2011) 014910.

Medium-model

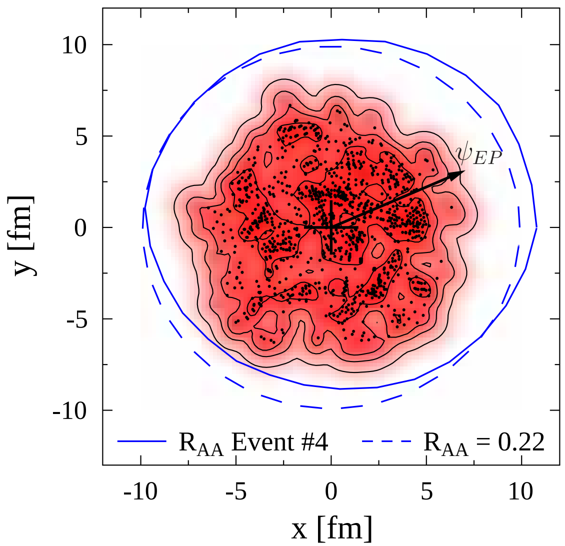
- factor 2 dependence of spread and quenching parameter on medium evolution model
- spread orders 3+1d hydro $>$ 2+1d vCGC $>$ 2+1d vGlb $>$ 2+1d ideal
  - differences unrelated to 3+1d vs. 2+1d
  - rather: initialization time, EOS, T_F, viscosity, profile
- 3+1d ideal has much larger freeze-out hypersurface, late time effects
- between vCGC and 2+1 ideal:
  - 50% difference due to difference in initialization time
  - 35% difference due to viscosity
  - 15% difference due to profile
- generically, if energy loss happens later, spread is magnified

$\Rightarrow$ we have a systematic understanding what features of medium evolution we probe

$\Rightarrow$ for *given* parton-medium interaction model, we do tomography

T. R., H. Holopainen, U. Heinz, C. Shen, Phys. Rev. **C83** (2011) 014910.

What is the influence of initial-state fluctuations?

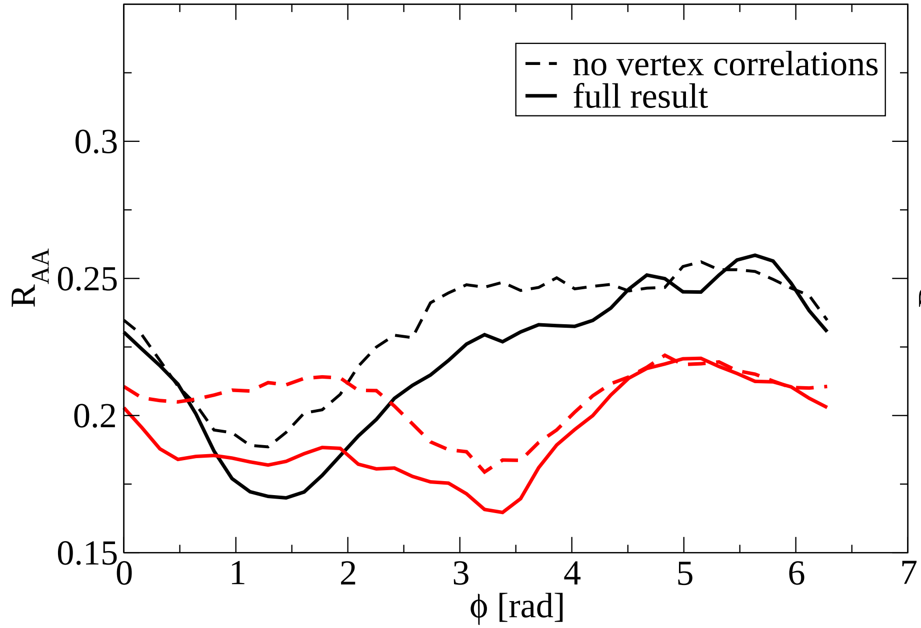


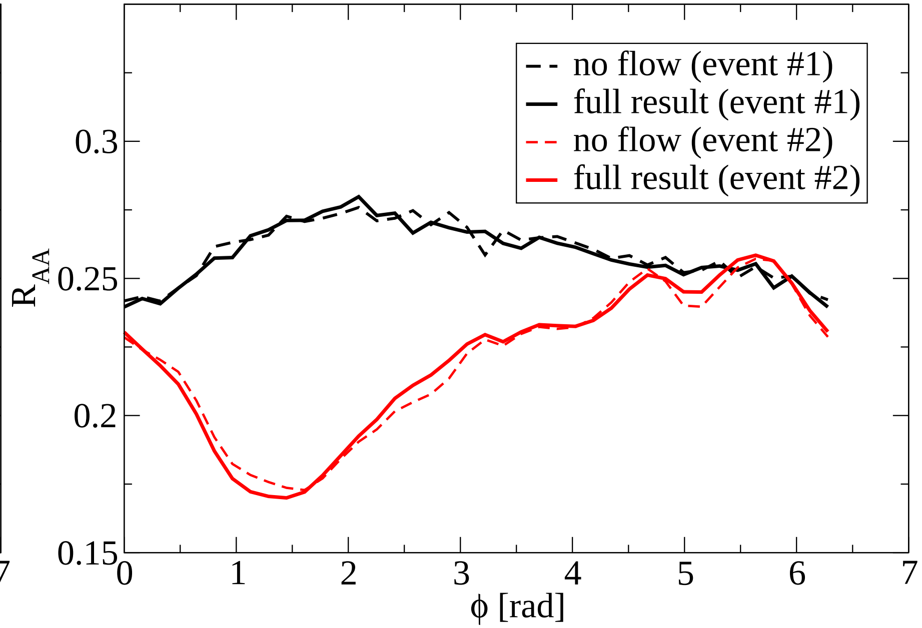
- R_{AA} is a non-linear function of density ↑
- binary vertices correlated with hotspots ↓
- irregular early flow field ↕
- event plane $\neq$ reaction plane

$\Rightarrow$ no P_T dependence, study $R_{AA}(\phi)$

Initial state fluctuations

• compute R_{AA} at fixed $P_T = 10$ GeV as a function of ϕ in ASW
$\longrightarrow$ left: with(out) vertex correlation, right: with(out) flow correction





• intra-event and inter-event fluctuations are large and about same order of magnitude

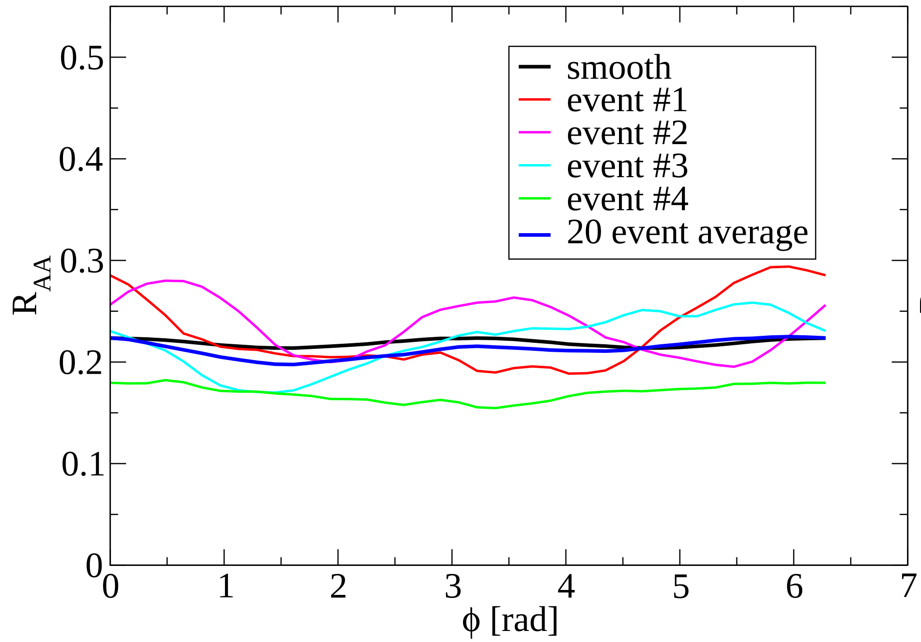
• correlation of production vertex with hotspot decreases R_{AA} by ~ 20 %

• irregular flow field is not an issue

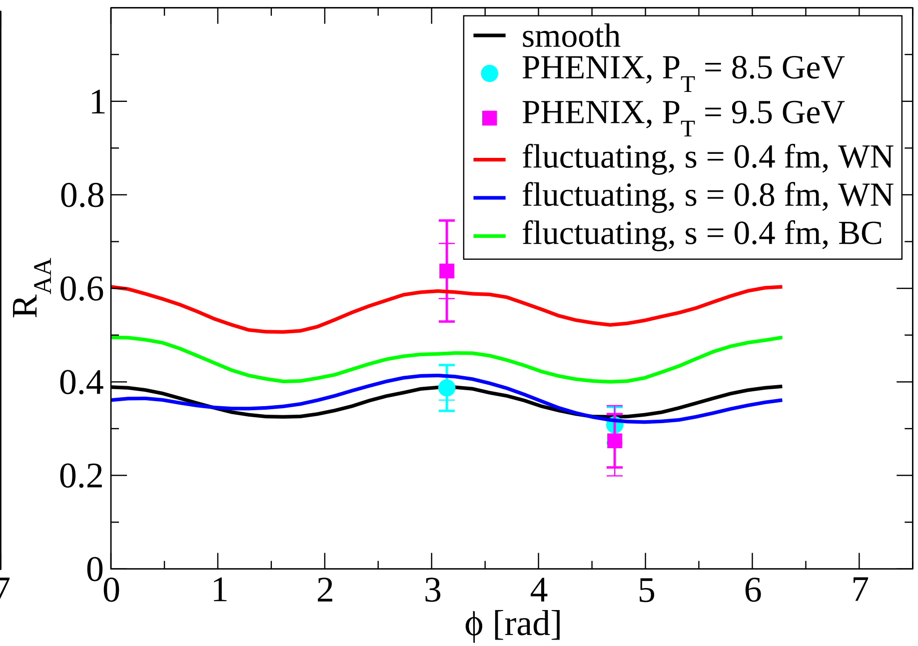
• qualitatively similar results for elastic MC model (see talk by J. Auvinen)

T. Renk, H. Holopainen, J. Auvinen, K. J. Eskola,1105.2647 [hep-ph]

Initial state fluctuations



AuAu, 200 AGeV, 30-40% centrality



- 20 event average agrees with smooth result for $\sim 20\%$ different $\hat{q}$
- extrapolation to non-central collisions depends on fluctuation size scale

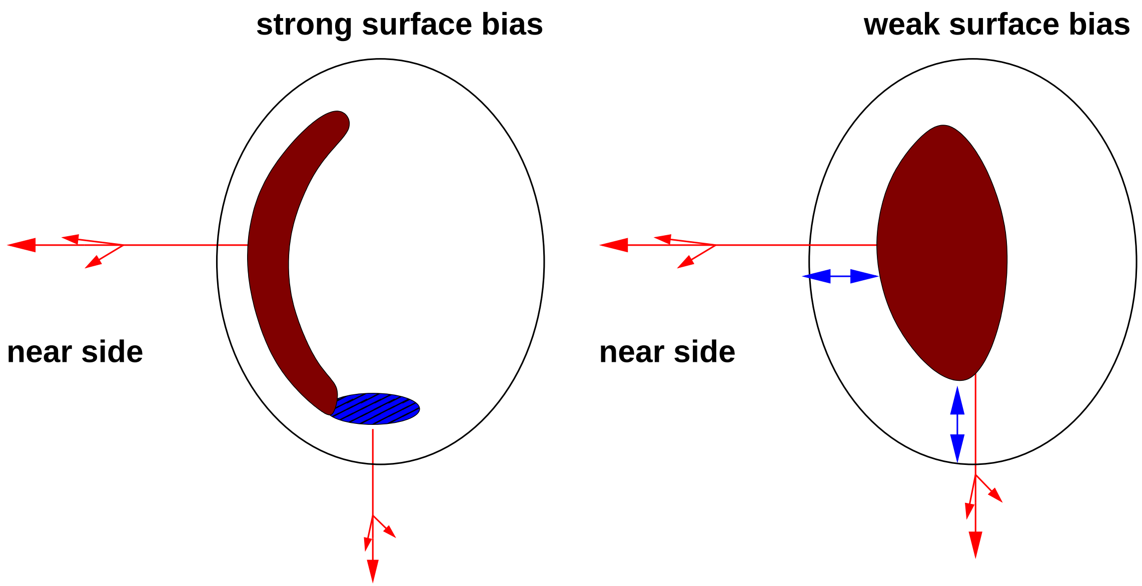
$\longrightarrow$ this observable favours large scale $s \sim 0.8$ fm

- compared with other uncertainties, fluctuations are not a big issue

$\Rightarrow$ not unexpected, as small-sized fluctuations equilibrate rapidly, but successful models require late onset of energy loss

T. Renk, H. Holopainen, J. Auvinen, K. J. Eskola,1105.2647 [hep-ph]

What is the pathlength dependence of eloss?



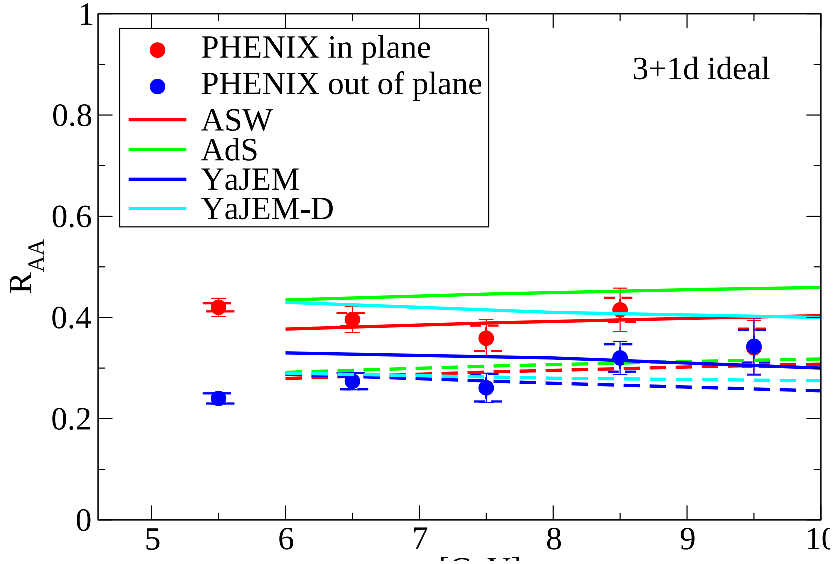
- linear for incoherent processes (elastic)
- quadratic for coherent radiation (ASW)

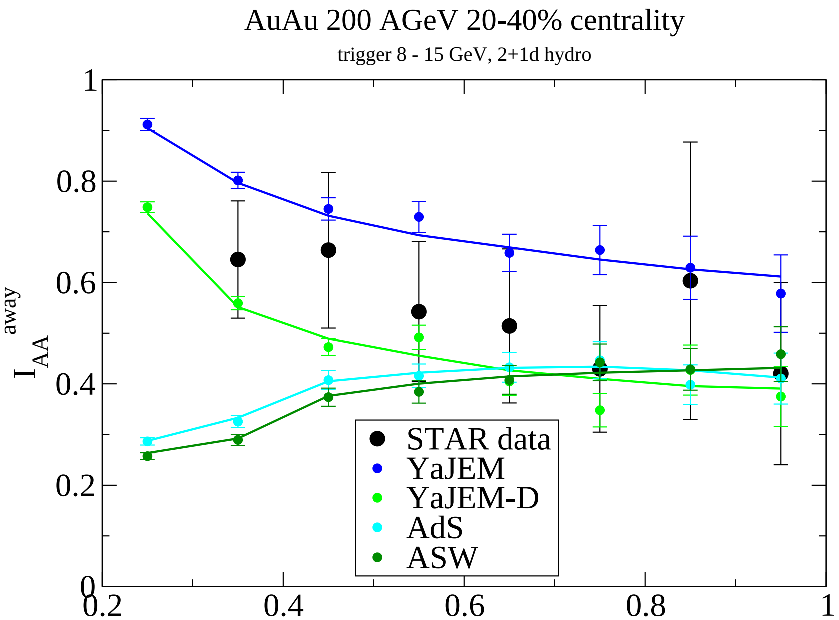
$\longrightarrow$ reverting to $\sim$linear with finite energy corrections (YaJEM)

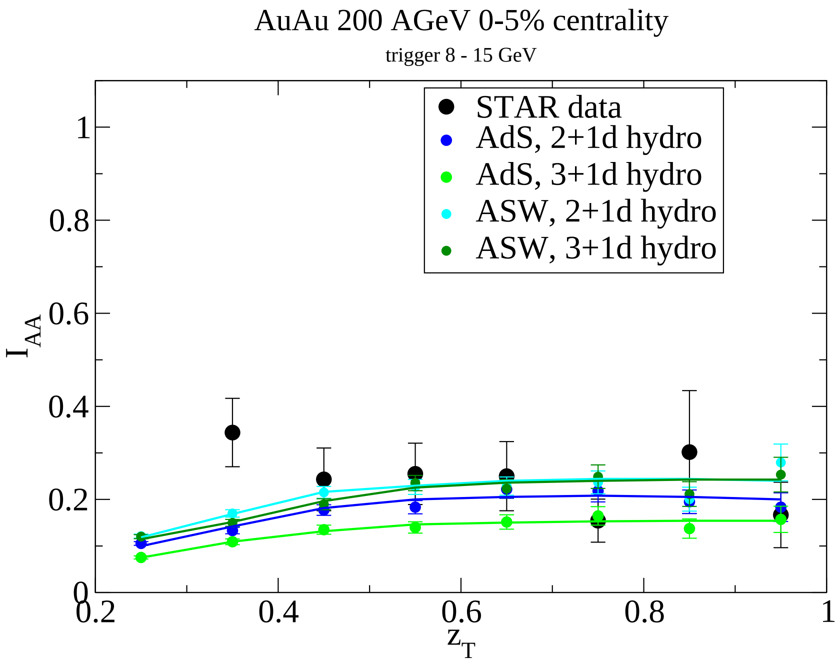
- cubic for AdS/QCD (AdS)
- in-medium shower: virtuality evolution from Q_i down to Q_0

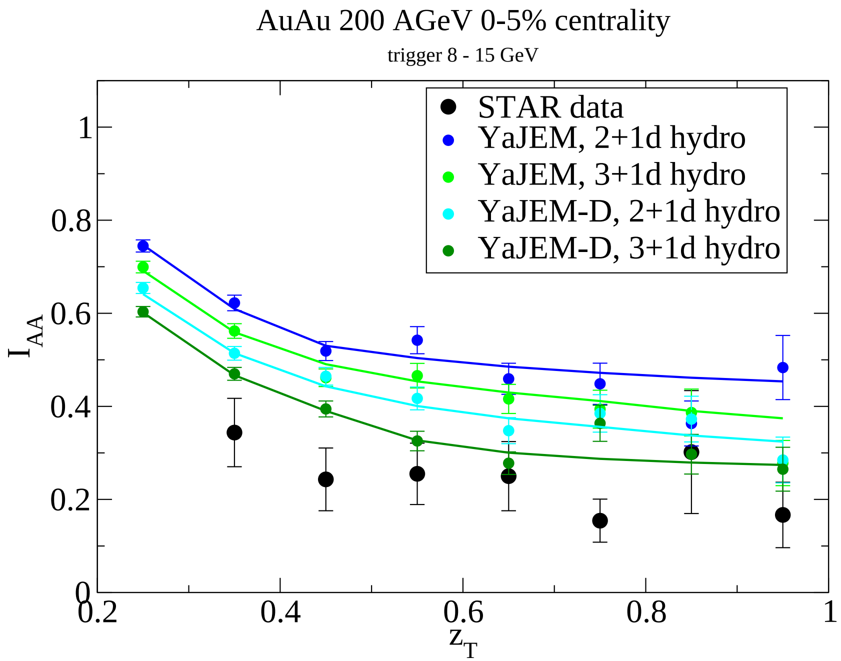
$\longrightarrow$ medium can only affect parton above $Q_{med} = \sqrt{E/L}$ (YaJEM-D)

Pathlength dependence of energy loss









PATHLENGTH DEPENDENCE OF ENERGY LOSS

model	elastic L	radiative L^2	AdS L^3	rad. finite E	min. Q_0
3+1d ideal	fails	works	fails	fails	works
2+1d ideal	fails	fails	marginal	fails	not tested
2+1d vCGC	fails	marginal	works	fails	not tested
2+1d vGlb	fails	marginal	works	fails	not tested

- quantum coherence is an important part of the answer
- finite energy corrections need to be taken seriously!

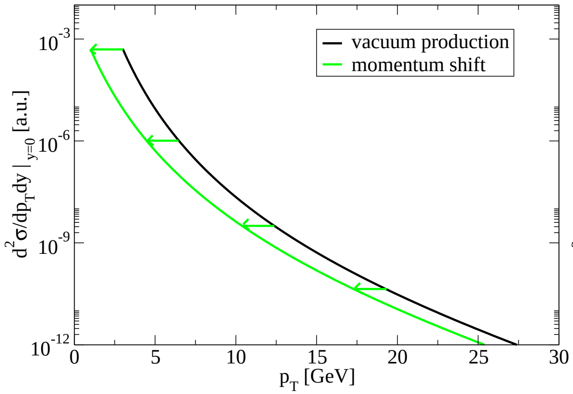
$\rightarrow$ quite possibly they destroy the success of L^2 and maybe also L^3
$\rightarrow$ quite possibly other existing shower codes do not reproduce pathlength dependence

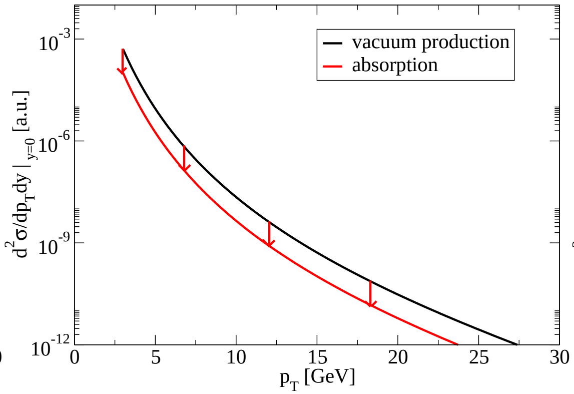
- strong constraints on **combinations** of hydro + parton-medium interaction model
- I_{AA} provides additional constraints for shower evolution

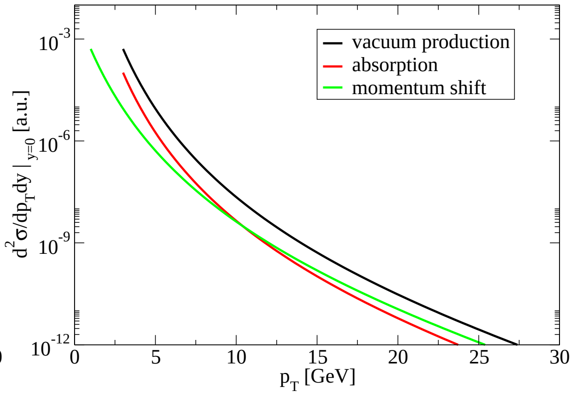
T. R., Phys. Rev. **C83** (2011) 024908; J. Auvinen, K. J. Eskola, H. Holopainen, T. R., Phys. Rev. **C82** (2010) 051901; T. R., H. Holopainen, U. Heinz, C. Shen, Phys. Rev. **C83** (2011) 014910.

$\sqrt{s}$ DEPENDENCE

What happens at LHC kinematics?







- for flatter spectrum, shift $\neq$ absorption

$\longrightarrow$ unlike at RHIC $P(\Delta E)$ for small $\Delta E < 10$GeV is probed

$\Rightarrow$ rise of $R_{AA}(P_T)$

- $I_{AA}^{LHC} > I_{AA}^{RHIC}$; $I_{AA}^{near} > 1$ for kinematical reasons
- additional non-trivial constraints

$\longrightarrow$ but not easy to do 'same hydro' at larger $\sqrt{s}$

Hydro from RHIC to LHC

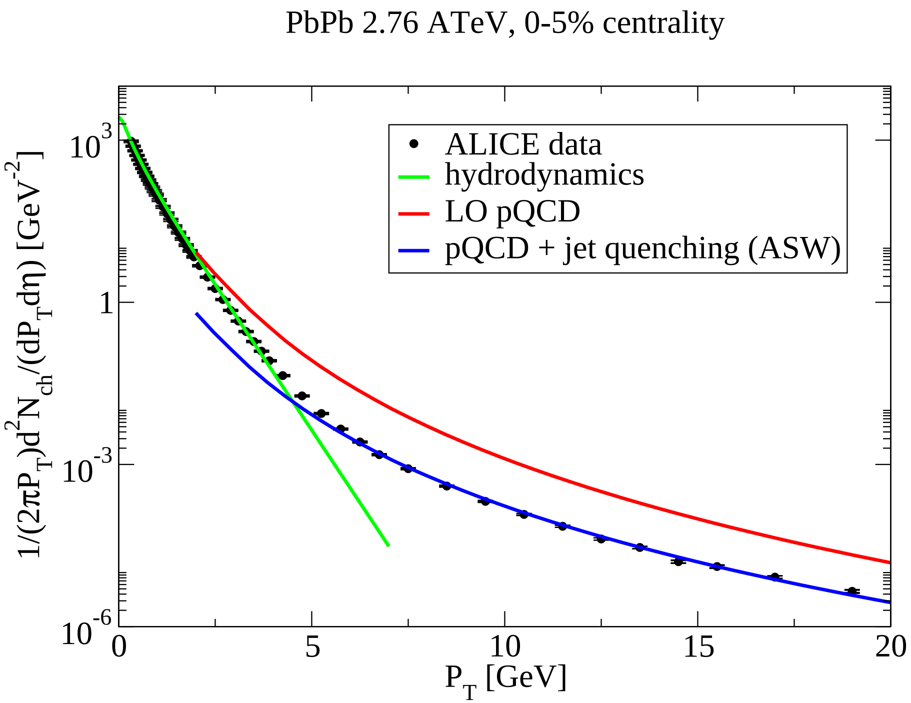
- initial state and initial time computed from pQCD minijet saturation (EKRT)
- eBC profile assumed to be unchanged from RHIC

$\longrightarrow$ largest uncertainty for jet quenching

- 2+1d ideal hydrodynamics
- $T_F = 165$ MeV assumed to be unchanged from RHIC

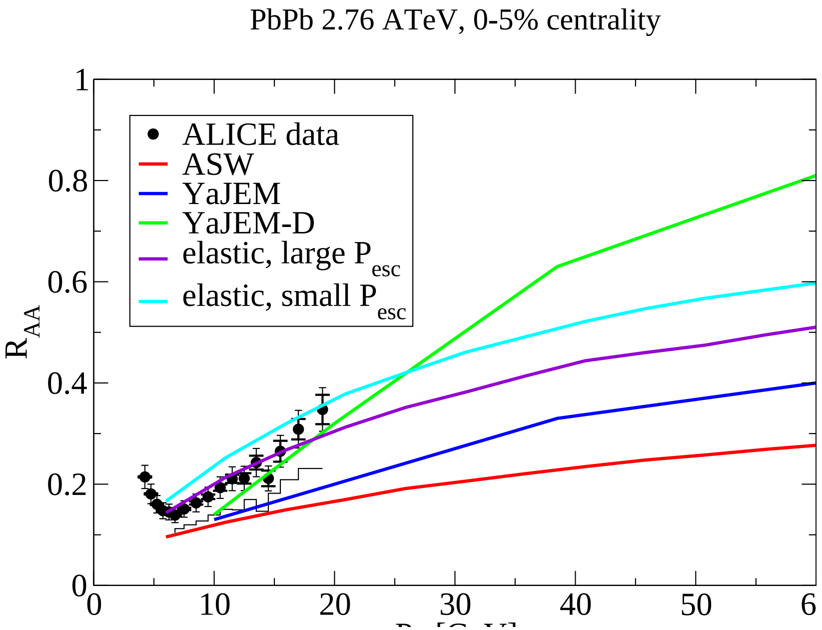
$\longrightarrow$ motivated by dynamical computations of scattering vs. expansion rate

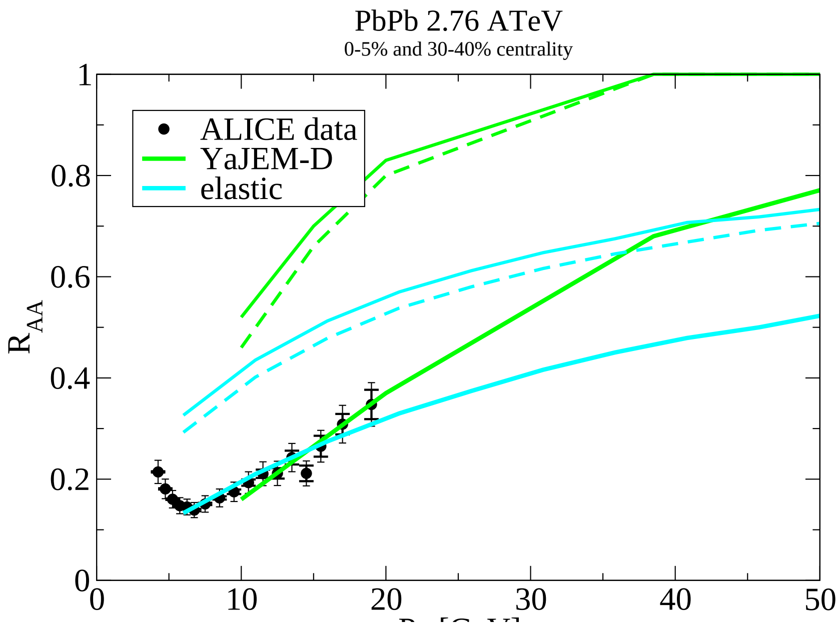
- good description of ALICE P_T spectrum

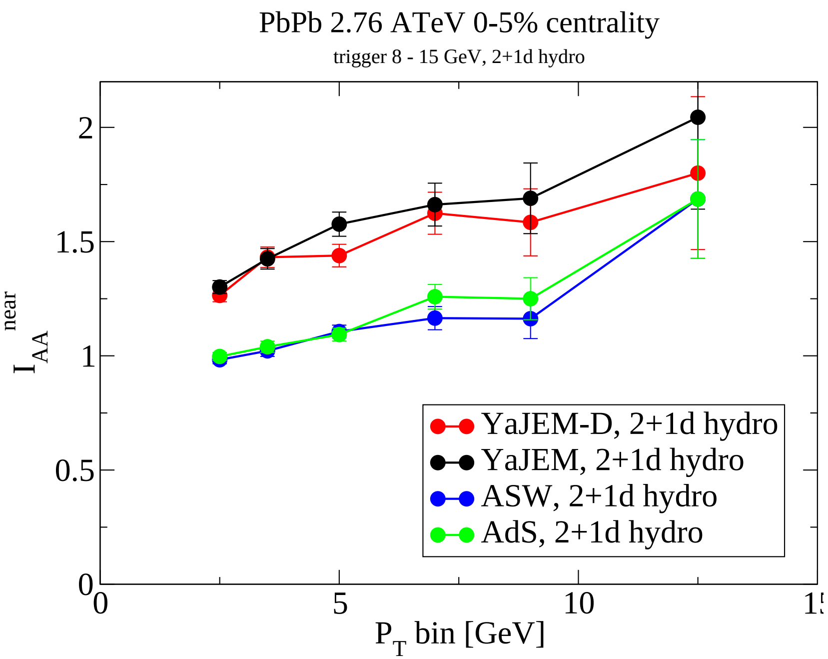


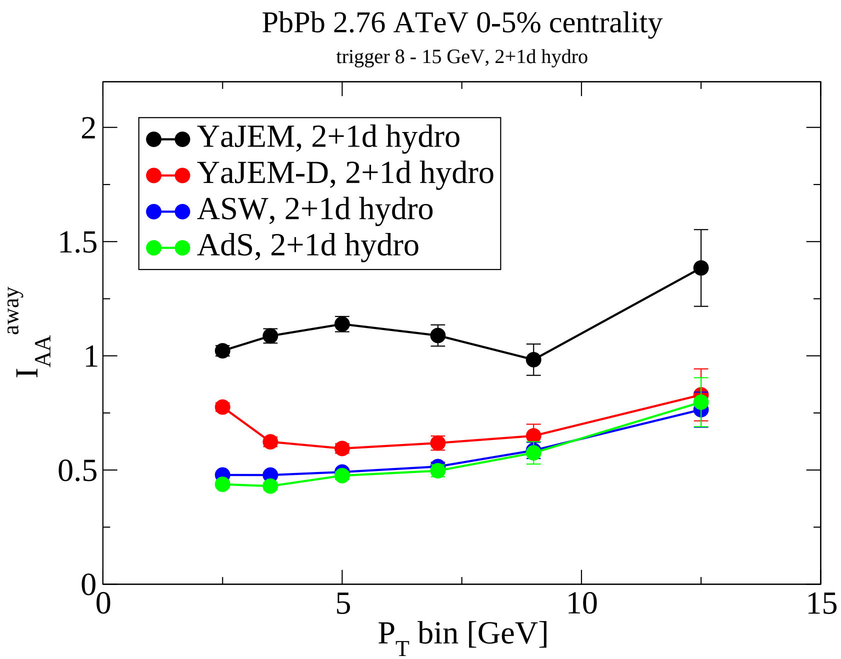
T. R., H. Holopainen, R. Paatelainen, K. J. Eskola, 1103.5308v1 [hep-ph]

R_{AA} and I_{AA} at LHC









R_{AA} and I_{AA} at LHC

- P_T dependence in models very different

$\rightarrow$ constraints different from pathlength dependence

- if we refit to default data using $R = K_{med}^{LHC}/K_{med}^{RHIC}$ to account for hydro uncertainties ($R = 1$ for smooth extrapolation in $\sqrt{s}$)

	YaJEM-D	YaJEM	ASW	AdS
R	0.92	0.61	0.47	0.31

$\rightarrow$ T^4 dependence of AdS is strongly disfavoured

- I_{AA} probes different combination of kinematical, parton type and geometrical bias

$\rightarrow$ interesting additional constraints

$\rightarrow$ relevant partonic subchannels very different from RHIC (qg vs gg)

Summary

- medium model uncertainties are as large as energy loss model uncertainties

$\rightarrow$ no reason to expect that simplified models work

- initial state fluctuations are not a major effect

$\rightarrow$ important for details

- pathlength dependence rules out elastic (incoherent) component $>\sim 10$ %

$\rightarrow$ the medium dof are not light free quasiparticles (= large elastic eloss)
$\rightarrow$ quantum coherence is important
$\rightarrow$ finite E effects change the picture completely, need to be taken seriously

- only particular combinations of medium/eloss model are viable

$\rightarrow$ both L^2 and L^3 without finite E correction describe the data
$\rightarrow$ with finite E correction, only medium-determined Q_0 is viable, L^3 may be

- $\sqrt{s}$ dep. provides independent constraints, but hydro extrapolation not unique

$\rightarrow$ disfavours AdS and ASW
$\rightarrow$ no reason to assume that strongly coupled formalisms work better

- currently YaJEM-D in 3+1d ideal hydro describes the combined data best