PARTON-MEDIUM INTERACTION FROM RHIC TO LHC
— a systematic approach
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INTRODUCTION
PATHLENGTH DEPENDENCE
- what the data show about energy loss physics
HYDRO INITIAL STATE FLUCTUATIONS
- how they affect parton-medium interaction
$\sqrt{s}$ AND $P_T$ DEPENDENCE OF $R_{AA}$
- probing into the energy loss probability distribution
CONCLUSIONS
**Why are we looking at high $P_T$ probes?**

- What is the physics of parton-medium interaction, what are the medium dof?
  - transport coefficients $\hat{q}, \hat{e}, \ldots$

- 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?

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

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

• Jyväskylä 2+1 d hydrodynamical model  

• VISH2+1 2+1 d viscous hydrodynamical model  


• YaJEM, YaJEM-D (MC code for induced radiation and drag)  
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. $\epsilon$) 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?
- factor 2 dependence of spread and quenching parameter on medium evolution model

- spread orders $3+1$d hydro > $2+1$d vCGC > $2+1$d vGlb > $2+1$d ideal
  - differences unrelated to $3+1$d vs. $2+1$d
  - rather: initialization time, EOS, $T_F$, viscosity, profile

- $3+1$d 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

What is the influence of initial-state fluctuations?

- $R_{AA}$ is a non-linear function of density $\uparrow$
- binary vertices correlated with hotspots $\downarrow$
- irregular early flow field $\uparrow$
- 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 $\phi$ in ASW
  → 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 $\sim 20\%$
- irregular flow field is not an issue
- qualitatively similar results for elastic MC model (see talk by J. Auvinen)

20 event average agrees with smooth result for $\sim 20\%$ different $\hat{q}$

extrapolation to non-central collisions depends on fluctuation size scale
→ this observable favours large scale $s \sim 0.8$ fm

compared with other uncertainties, fluctuations are not a big issue

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

What is the pathlength dependence of e\textit{loss}? 

- linear for incoherent processes (elastic) 
- quadratic for coherent radiation (ASW) 
  → reverting to \( \sim \)linear with finite energy corrections (YaJEM) 
- cubic for AdS/QCD (AdS) 
- in-medium shower: virtuality evolution from \( Q_i \) down to \( Q_0 \) 
  → medium can only affect parton above \( Q_{\text{med}} = \sqrt{E/L} \) (YaJEM-D)
Pathlength Dependence of Energy Loss

AuAu 200 AGeV 20-40% centrality
trigger 8 - 15 GeV, 2+1d hydro

AuAu 200 AGeV 0-5% centrality
trigger 8 - 15 GeV

STAR data
YaJEM, 2+1d hydro
YaJEM-D, 2+1d hydro
AdS, 2+1d hydro
AdS, 3+1d hydro
ASW, 2+1d hydro
ASW, 3+1d hydro

PHENIX in plane
PHENIX out of plane
ASW
AdS
YaJEM
YaJEM-D

3+1d ideal

I_{AA}
R_{AA}
I_{AA}
**Pathlength dependence of energy loss**

<table>
<thead>
<tr>
<th>model</th>
<th>elastic $L$</th>
<th>radiative $L^2$</th>
<th>AdS $L^3$</th>
<th>rad. finite E</th>
<th>min. $Q_0$</th>
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<tbody>
<tr>
<td>3+1d ideal</td>
<td>fails</td>
<td>works</td>
<td>fails</td>
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<tr>
<td>2+1d ideal</td>
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<td>2+1d vCGC</td>
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</tr>
</tbody>
</table>

- quantum coherence is an important part of the answer
- finite energy corrections need to be taken seriously!
  → quite possibly they destroy the success of $L^2$ and maybe also $L^3$
  → 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

What happens at LHC kinematics?

- for flatter spectrum, shift $\neq$ absorption
- $\Rightarrow$ unlike at RHIC $P(\Delta E)$ for small $\Delta E < 10\text{GeV}$ is probed
- $\Rightarrow$ rise of $R_{AA}(P_T)$
- $I_{LHC}^{AA} > I_{RHIC}^{AA}$, $I_{AA}^{near} > 1$ for kinematical reasons
- additional non-trivial constraints
- $\Rightarrow$ but not easy to do 'same hydro' at larger $\sqrt{s}$
• initial state and initial time computed from pQCD minijet saturation (EKRT)
• eBC profile assumed to be unchanged from RHIC
  → largest uncertainty for jet quenching
• 2+1d ideal hydrodynamics
• $T_F = 165$ MeV assumed to be unchanged from RHIC
  → motivated by dynamical computations of scattering vs. expansion rate
• good description of ALICE $P_T$ spectrum

PbPb 2.76 ATeV, 0-5% centrality

$R_{AA}$ AND $I_{AA}$ AT LHC

PbPb 2.76 ATeV, 0-5% centrality

- ALICE data
- ASW
- YaJEM
- YaJEM-D
- elastic, large $P_{\text{esc}}$
- elastic, small $P_{\text{esc}}$

PbPb 2.76 ATeV 0-5% and 30-40% centrality

- ALICE data
- YaJEM-D elastic

PbPb 2.76 ATeV 0-5% centrality

trigger 8 - 15 GeV, 2+1d hydro

PbPb 2.76 ATeV 0-5% centrality

trigger 8 - 15 GeV, 2+1d hydro

$P_{T}$ bin [GeV]

- YaJEM, 2+1d hydro
- YaJEM-D, 2+1d hydro
- ASW, 2+1d hydro
- AdS, 2+1d hydro

$P_{T}$ bin [GeV]
$R_{AA}$ and $I_{AA}$ at LHC

- $P_T$ dependence in models very different
  \[ \rightarrow \text{constraints different from pathlength dependence} \]

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

\[
\begin{array}{|c|c|c|c|}
\hline
 \text{Model} & \text{YaJEM-D} & \text{YaJEM} & \text{ASW} & \text{AdS} \\
\hline
 R & 0.92 & 0.61 & 0.47 & 0.31 \\
\hline
\end{array}
\]

\[ \rightarrow T^4 \text{ dependence of AdS is strongly disfavoured} \]

- $I_{AA}$ probes different combination of kinematical, parton type and geometrical bias
  \[ \rightarrow \text{interesting additional constraints} \]
  \[ \rightarrow \text{relevant partonic subchannels very different from RHIC (} qg \text{ vs } gg \text{)} \]
• medium model uncertainties are as large as energy loss model uncertainties → no reason to expect that simplified models work
• initial state fluctuations are not a major effect → important for details
• pathlength dependence rules out elastic (incoherent) component >~ 10% → the medium dof are not light free quasiparticles (= large elastic eloss) → quantum coherence is important → finite $E$ effects change the picture completely, need to be taken seriously
• only particular combinations of medium/eloss model are viable → both $L^2$ and $L^3$ without finite $E$ correction describe the data → 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 → disfavours AdS and ASW → no reason to assume that strongly coupled formalisms work better
• currently YaJEM-D in 3+1d ideal hydro describes the combined data best