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

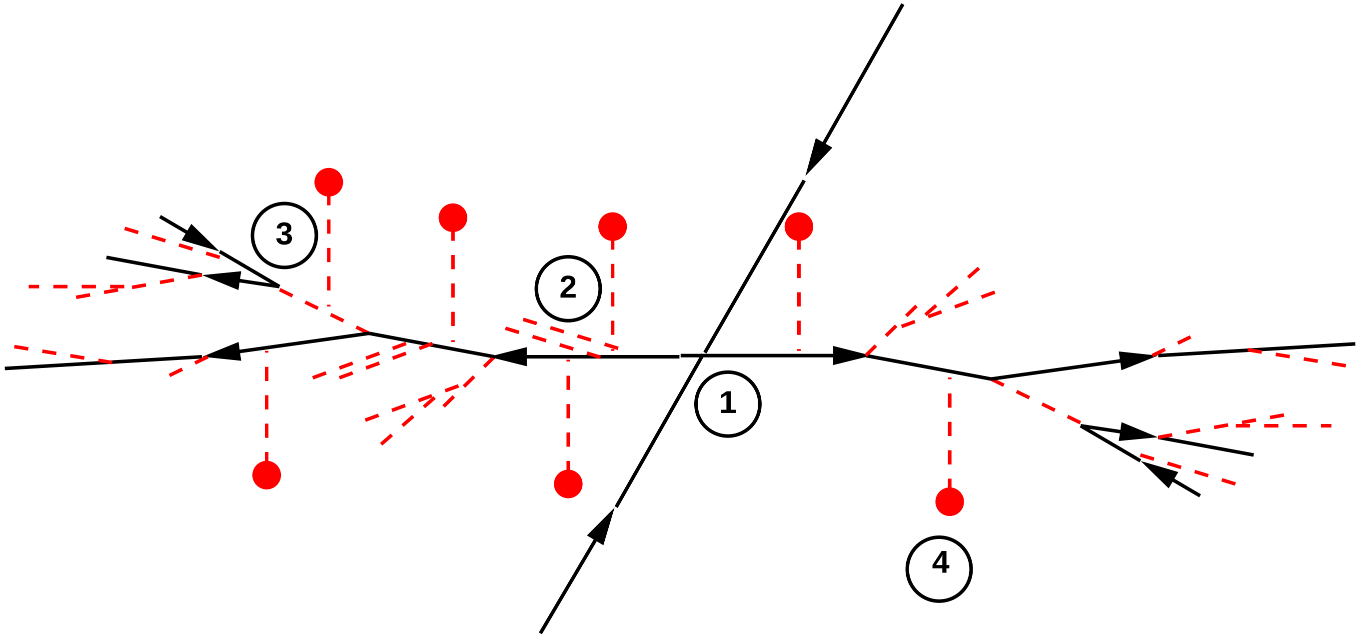
CONCLUSIONS

I. Jet quenching and leading parton energy loss

why jet modification codes are not useful unless they can describe leading hadrons

THE 'STANDARD' JET QUENCHING PICTURE

pQCD radiative energy loss for hard partons interacting with the medium



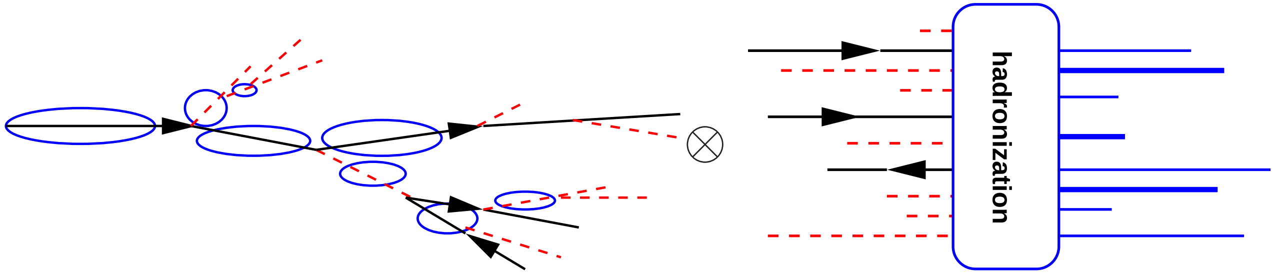
1) hard process 2) vacuum shower 3) medium-induced radiation 4) medium evolution

1) calculable in pQCD
2) calculable in pQCD, MC shower codes
3) depends on assumed parton-medium interaction, medium dof. . .
4) calculable in fluid dynamics, ambiguities since only final state is constrained

3) and 4) need to disentangled carefully!

Energy loss vs. in-medium shower

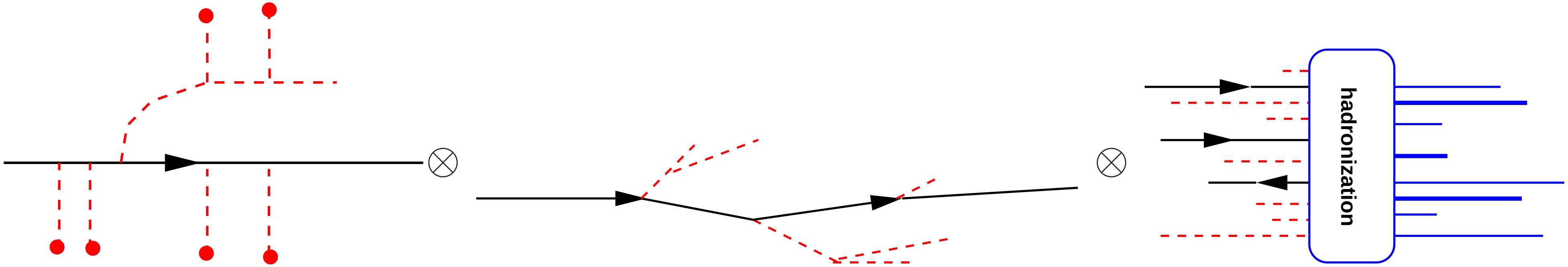
1) in-medium shower, followed by hadronization in vacuum



$$D_{med}(z, Q_i \to Q_h) \otimes D_{vac}(z, Q_h)$$

(recent HT, JEWEL, YaJEM, Q-PYTHIA, Q-HERWIG)

2) if leading parton carries most of the shower energy: **energy loss approximation**
medium-induced energy loss for the leading parton, then vacuum fragmentation



$$P(E, \Delta E) \otimes D_{vac}(z, Q_i \to Q_h) \otimes D_{vac}(z, Q_h)$$

(BDMPS, ASW, (D)GLV, AMY, some HT results)

THE 'STANDARD' JET QUENCHING PICTURE

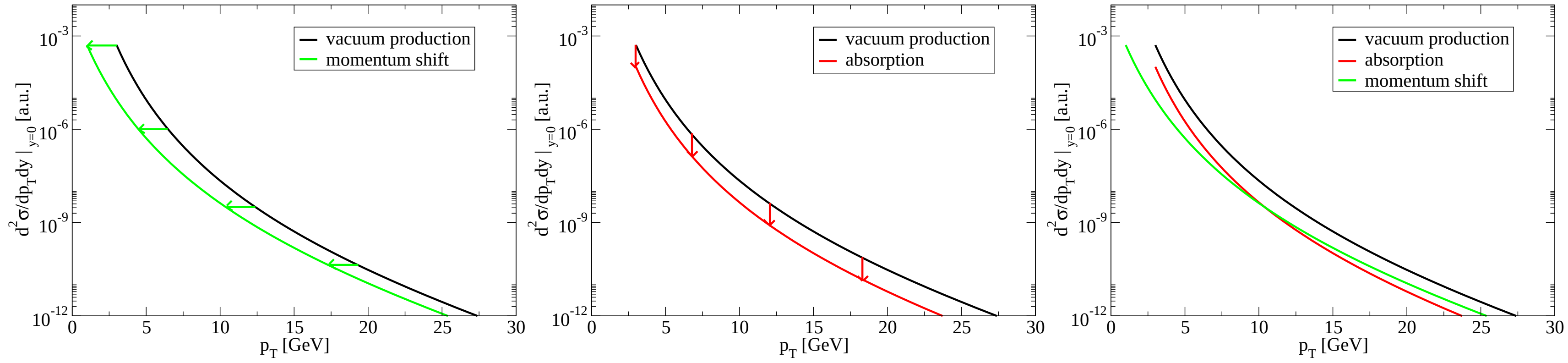
The questions:

- 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. . .

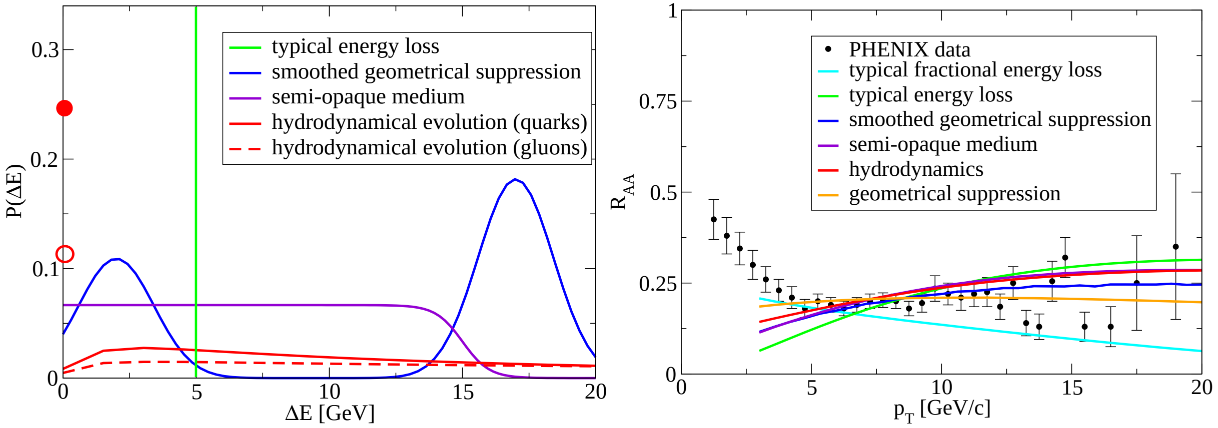
Why are these questions so difficult to answer?

THE 'STANDARD' JET QUENCHING PICTURE

- problem I: parton shift and partial absorption lead to similar results



⇒ very different energy loss scenarios lead to similar suppression



- problem II: ambiguity between choice of energy loss and medium modelling

⇒ need good systematic understanding of the issues involved

T.R., Phys.Rev. C74 (2006) 034906

THE TOOLKIT

medium

- 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 (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

Pathlength dependence

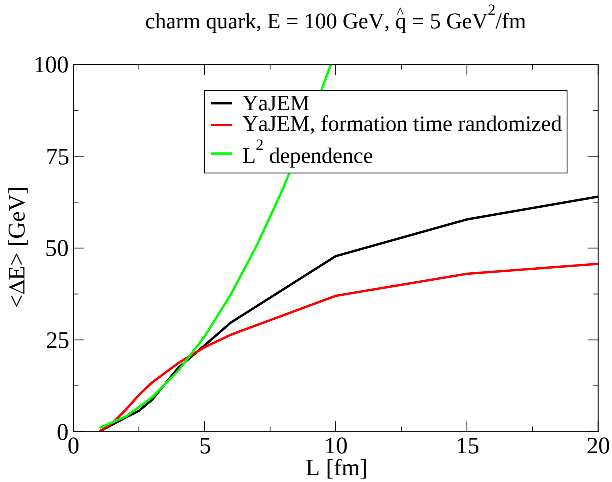
II. Pathlength dependence of high P_T observables

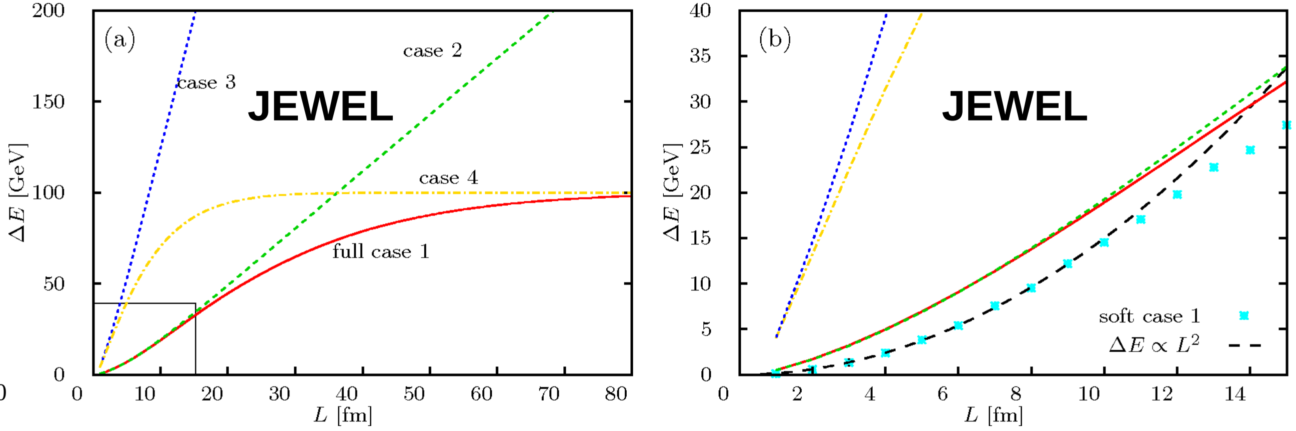
some lessons from RHIC data

(focus on plots which don't work!)

THEORY: PATHLENGTH DEPENDENCE IN CONSTANT MEDIUM

- incoherent processes: $n_{scatt} = \frac{L}{\lambda}$, since $\Delta E \approx n_{scatt} \Delta E_1$, linear $\Delta E \sim L$ (elastic)
- coherence time: rad. gluon virtuality $Q^2 = \hat{q}L$ and energy ω
  - time to radiate a gluon: $\tau \sim \omega/Q^2 \sim L$
  - virtuality picked up during that time: $Q^2 \sim \hat{q}L \sim \hat{q}\omega/Q^2$
  - typical energy $\omega_c = Q^4/\hat{q} = \hat{q}^2L^2/\hat{q} = \hat{q}L^2$, i.e. quadratic $\Delta E \sim L^2$ (ASW)
- however, subject to finite energy constraints, reverts to linear $\Delta E \sim L$ (YaJEM)





- strongly coupled medium: force $\frac{d|p_T|}{dt} = T^2$, thus $Q^2 = T^4L$ i.e. cubic $\Delta E \sim L^3$
  - finite energy corrections unknown (AdS)
- in-medium shower: virtuality evolution from Q_i down to Q_0, but medium can only affect the medium above $Q_{med} = \sqrt{E/L}$, no analytic form of $\Delta E(L)$ (YaJEM-D)

PATHLENGTH DEPENDENCE IN HYDRODYNAMICS

A hydrodynamical background is **not** a constant medium with given length L

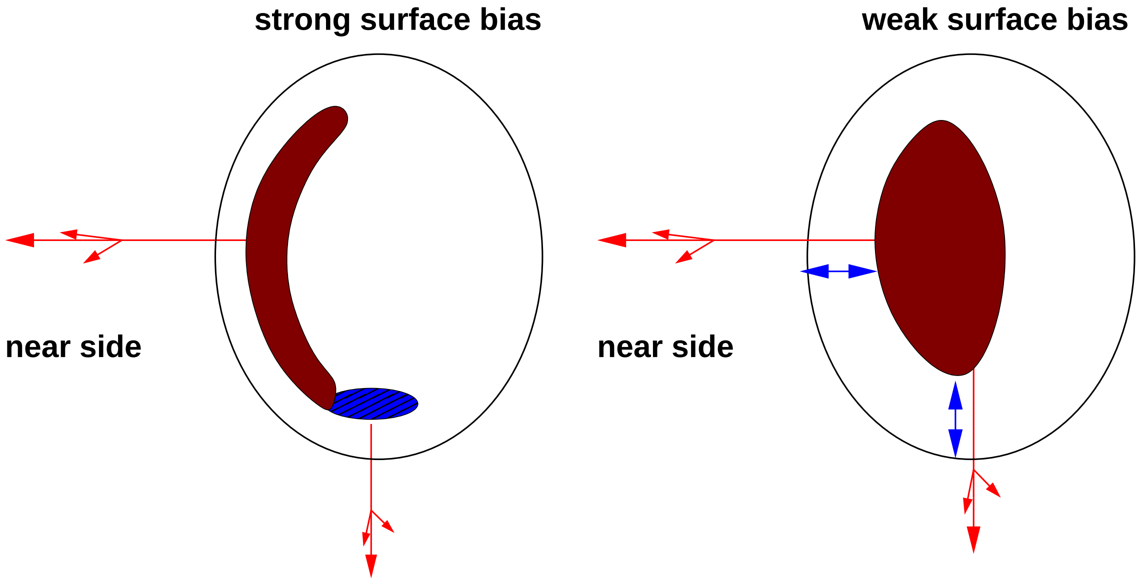
- density profile: partons probe spatially inhomogeneous medium
- longitudinal flow: density $\sim 1/\tau$, kills effectively one power in L-dependence
- transverse flow:
  - decreases medium density
  - may increase or decrease distance to surface, i.e. changes definition of L
  - explicit factor $(\cosh\rho - \sinh\rho\cos\alpha)$ (Lorentz-contraction of volume)
- viscosity: increases density over time as compared to inviscid case
- fluctuations: don't average out due to non-linear problem
  - inter-event fluctuations of density within given centrality class
  - intra-event fluctuations in initial state

⇒ not small effects: hydro : Bjorken cylinder : static cylinder $\approx 1:4:10$ for $\hat{q}$

⇒ toy models don't work

PINNING DOWN PATHLENGTH

- spread in-plane vs. out of plane in $R_{AA}(\phi)$ related to



- strong surface bias (medium very opaque for large pathlength/ high density regions)

$\longrightarrow$ more emission in-plane because the emitting surface is larger

- weak surface bias (emission also from the medium core)

$\longrightarrow$ more emission in plane because $\langle x \rangle < \langle y \rangle$

$\Rightarrow$ no qualitatively distinct signal

PINNING DOWN PATHLENGTH

Normalization of $R_{AA}(b)$ increases for peripheral collisions due to

- drop in average density

$\rightarrow$ this is seen for any scenario of parton-medium interaction

- drop in average pathlength

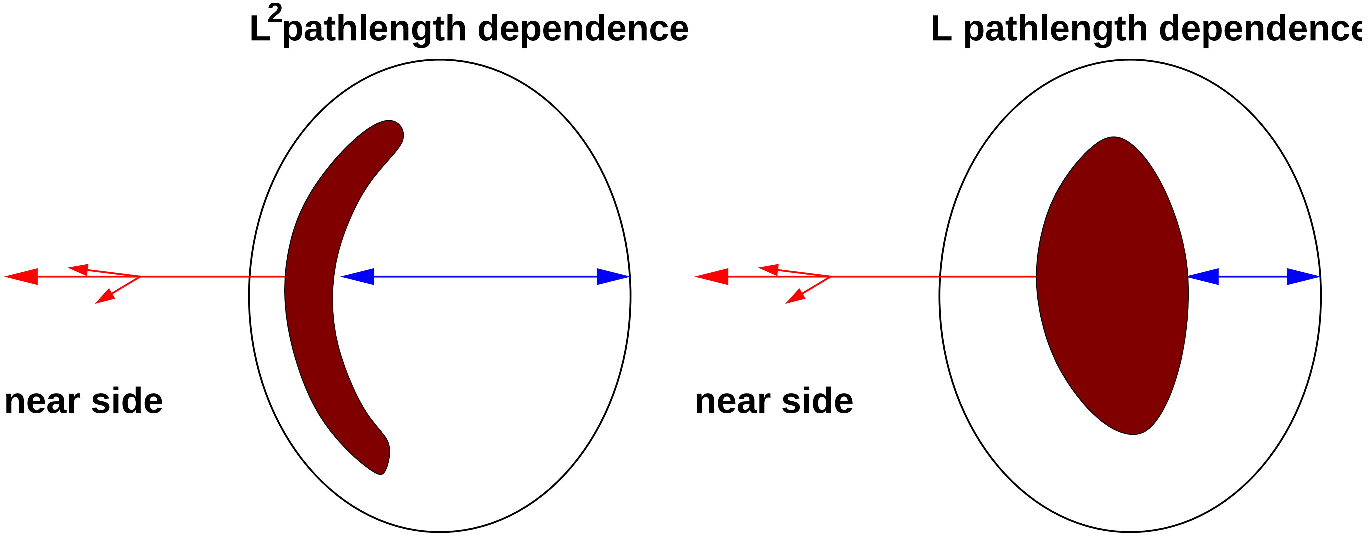
$\rightarrow$ this probes pathlength dependence in a qualitatively characteristic way
$\Rightarrow$ expect $R_{AA}^{AdS} > R_{AA}^{rad} > R_{AA}^{el}$ for non-central collisions

For increasing b, R_{AA} rises and a spread between in-plane and out of plane emission opens:

normalization $\Leftrightarrow$ average density, average pathlength
spread $\Leftrightarrow$ hydro density profile, emission geometry, pathlength difference. . .

PINNING DOWN PATHLENGTH

Advantage of back-to-back correlations:

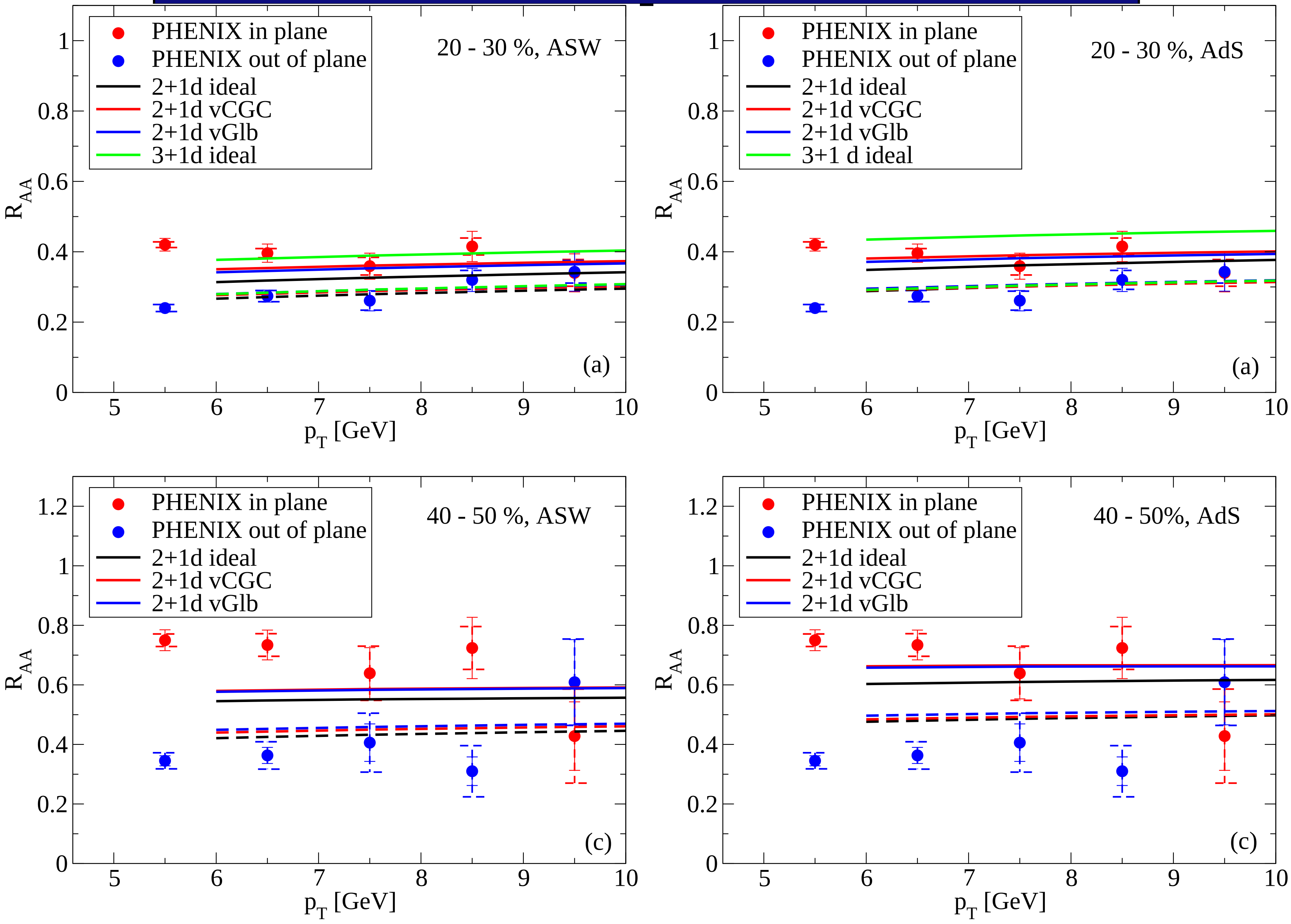


- expect (due to surface bias of trigger) ∼ factor 2 in away side pathlength

⇒ magnifies pathlength effects as compared to $R_{AA}(\phi)$

Large difference in predicted away side per-trigger yield (or I_{AA})

Pinning down pathlength - L^2 and L^3



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

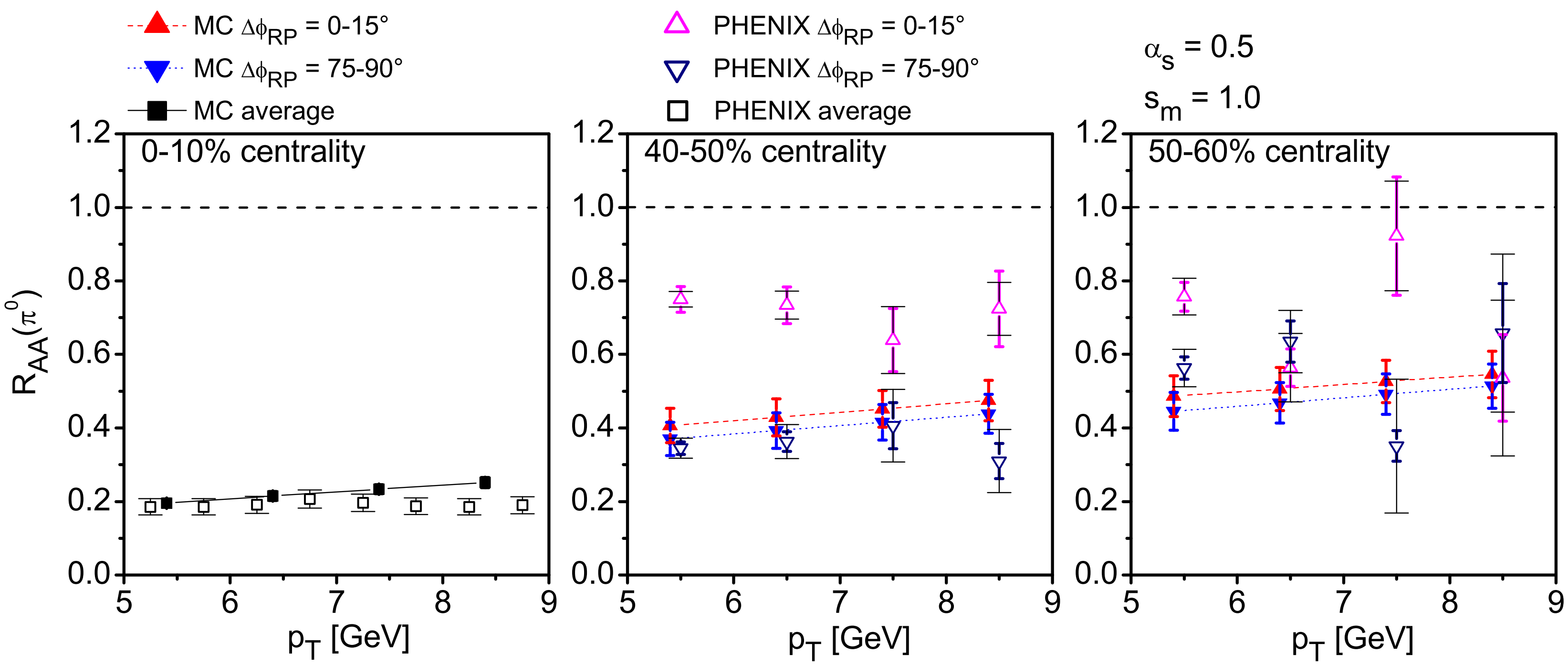
PINNING DOWN PATHLENGTH - L^2 AND L^3

- 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
- for given hydro background:
  - clear difference between ASW L^2 and AdS L^3 seen
  - unable to discriminate due to ambiguous choice of background
- generically, if energy loss happens later, spread is magnified

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

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

PINNING DOWN PATHLENGTH - L



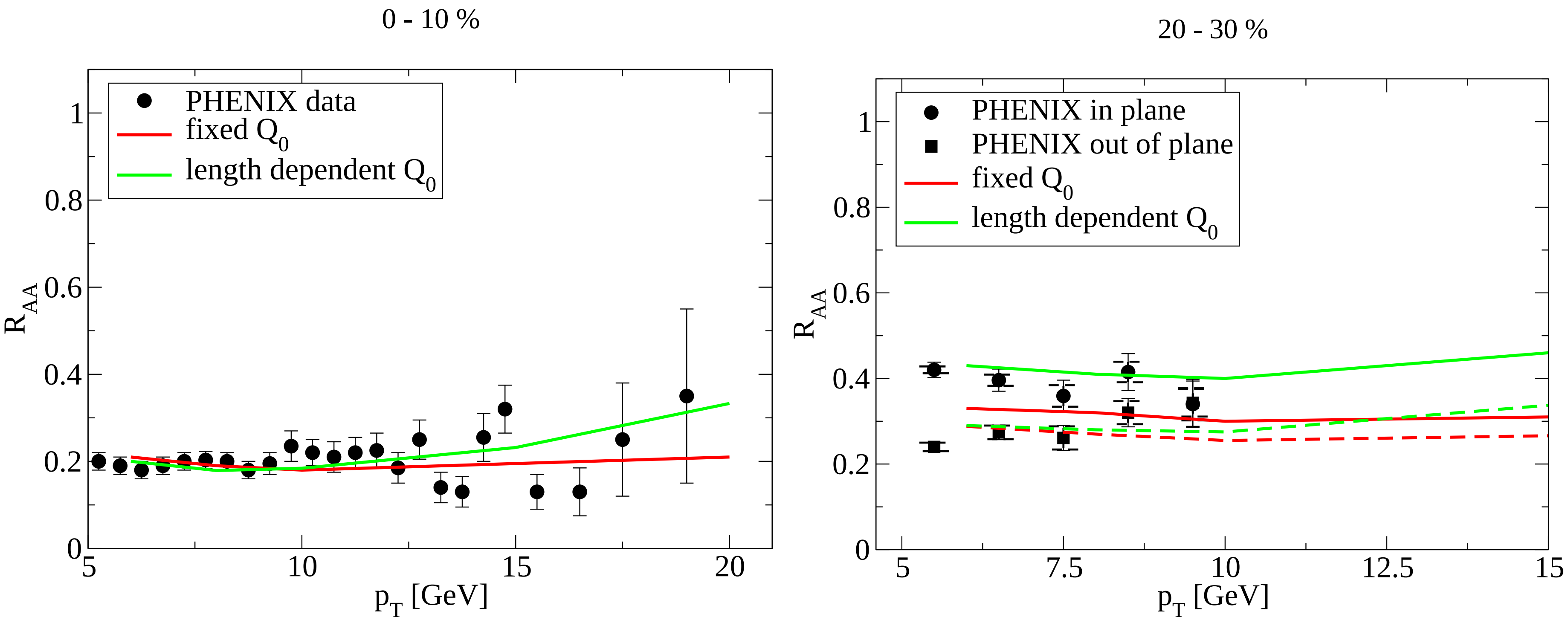
- elastic MC fails by large margin (> 2) to reproduce the spread
- incoherent energy loss component $> 10\%$ ruled out independent of medium model

$\Rightarrow$ implication: medium scattering partners are not light free quasiparticles

J. Auvinen, K. J. Eskola, H. Holopainen, T. R., Phys. Rev. **C82** (2010) 051901.

PINNING DOWN PATHLENGTH - FINITE E, L CORRECTIONS

- YaJEM and YaJEM-D with 3+1d hydro



- LPM-driven L^2 with finite energy correction ruled out by the data

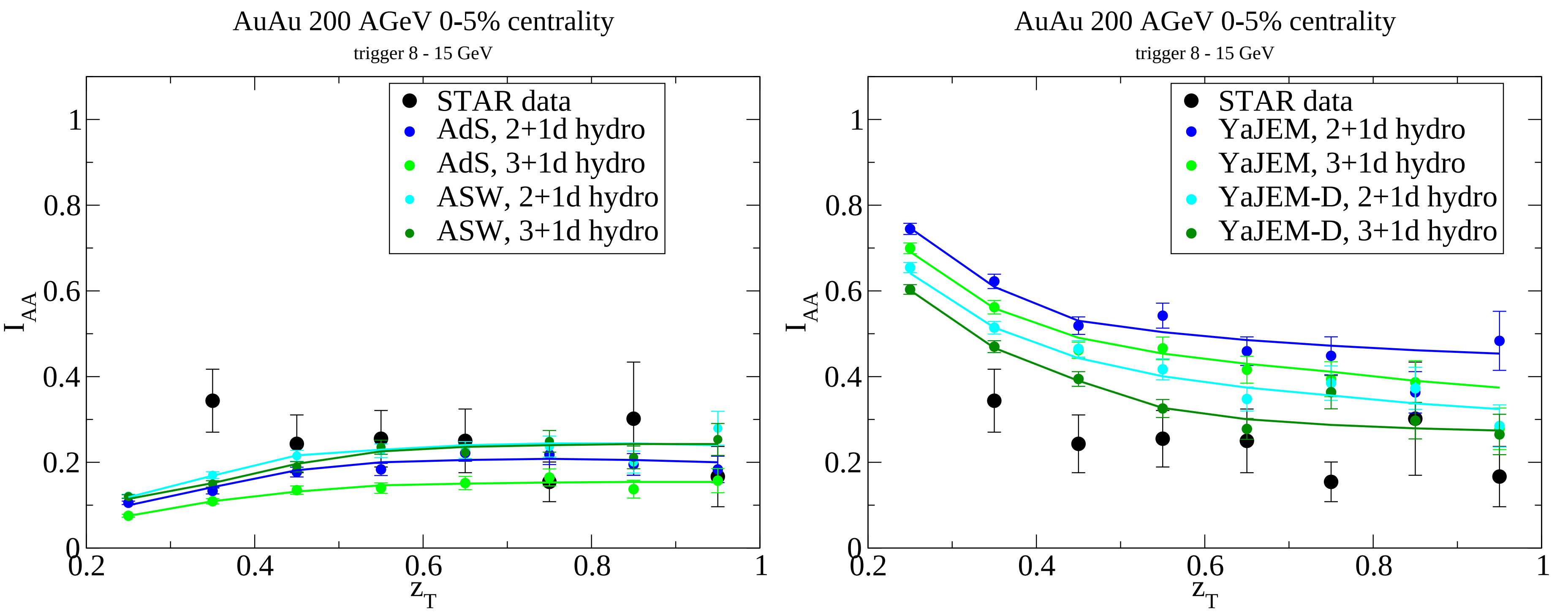
→ seriously questions the success of L^2 and L^3

- additional constraint on minimum in-medium virtuality $Q_0 = \sqrt{E/L}$ works

→ predicts additional P_T dependence of R_{AA}

T. R., Phys. Rev. **C83** (2011) 024908.

PINNING DOWN PATHLENGTH - DIHADRON CORRELATIONS



- confirms previous results:
  - ASW and YaJEM-D are viable with 3+1d hydro
  - AdS is viable with 2+1d hydro
- viscosity corrections will move this down, perhaps disfavours AdS
- leading hadron energy shift ($z < 0.5$ region): important constraint
  - too strong in ASW and AdS
  - too weak in YaJEM-D

PINNING DOWN PATHLENGTH - SUMMARY

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!

→ 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

- implications for hydro are understood

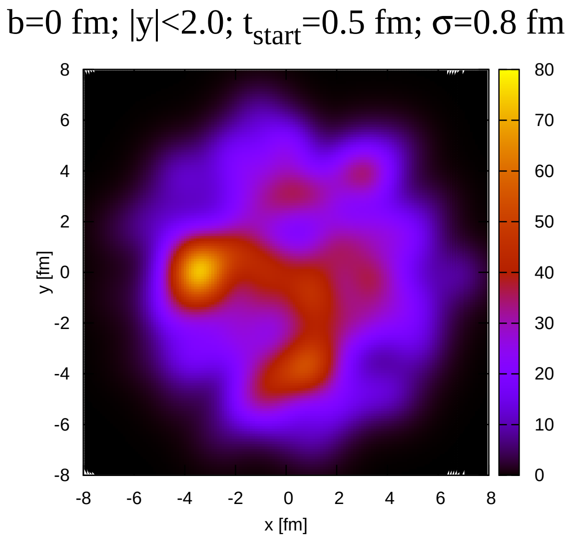
→ we can give guidance to hydro modellers how to increase/decrease spread

III. Interlude: fluctuating hydro IC

and uncertainties from event-by-event jet quenching

FLUCTUATIONS IN THE HYDRODYNAMICAL INITIAL STATE

In a real event, the medium initial state cannot be expected to be smooth:



Fluctuations affect hard partons in three ways:

- partons propagate through inhomogeneous medium

$\longrightarrow$ since R_{AA} saturates for large densities, this increases R_{AA}

- hard parton production points are correlated with density hotspots

$\longrightarrow$ decreases R_{AA}

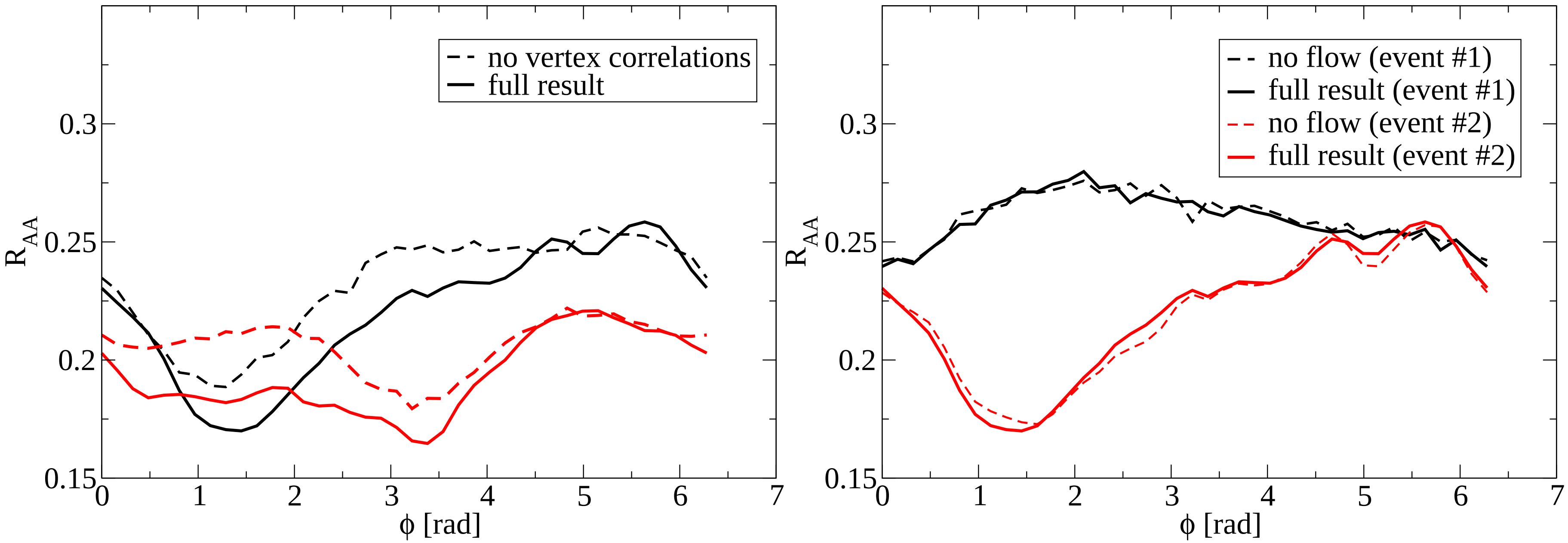
- flow correction $(\cosh\rho - \sinh\rho\cos\alpha)$ for irregular initial flow

$\longrightarrow$ sign unknown

FLUCTUATIONS IN THE HYDRODYNAMICAL INITIAL STATE

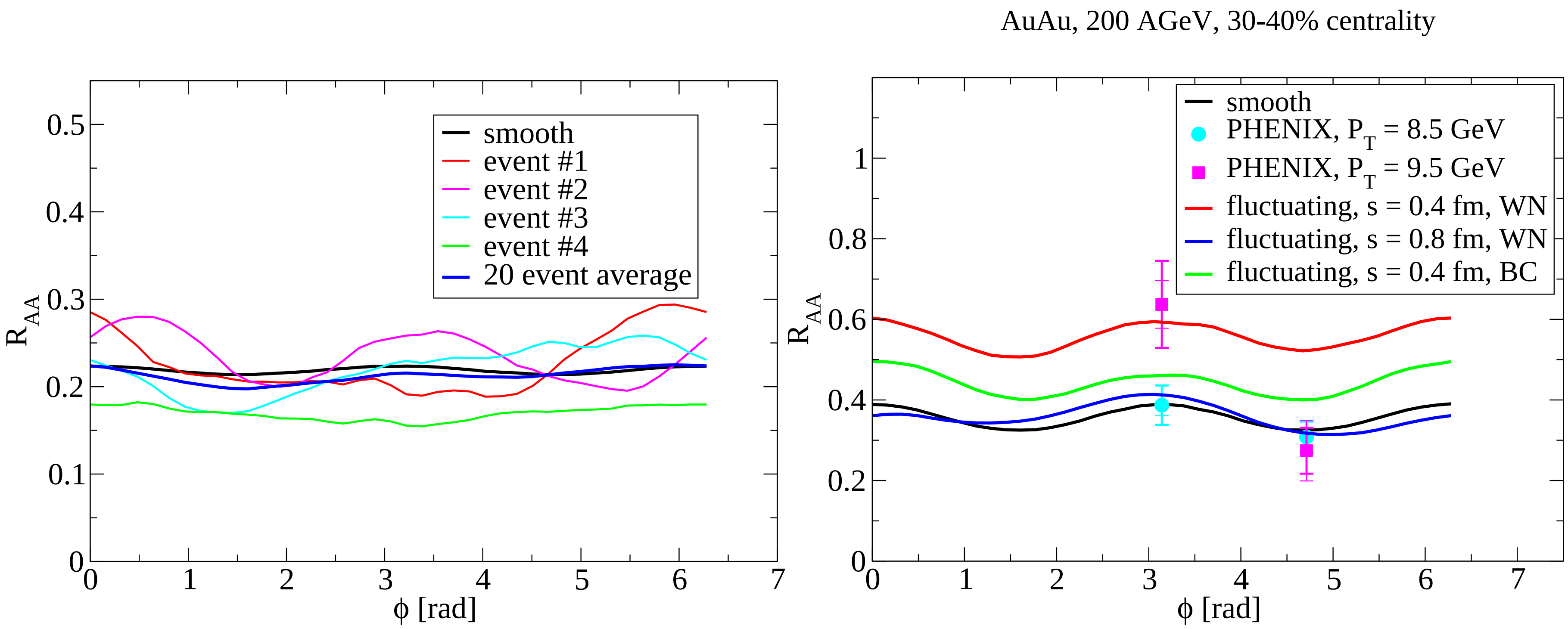
- compute R_{AA} at fixed $P_T = 10$ GeV as a function of ϕ in ASW

→ 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 ~ 20 %
- irregular flow field is not an issue
- qualitatively similar results for elastic MC model

FLUCTUATIONS IN THE HYDRODYNAMICAL INITIAL STATE



- 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

IV. P_T dependence of R_{AA} from RHIC to LHC

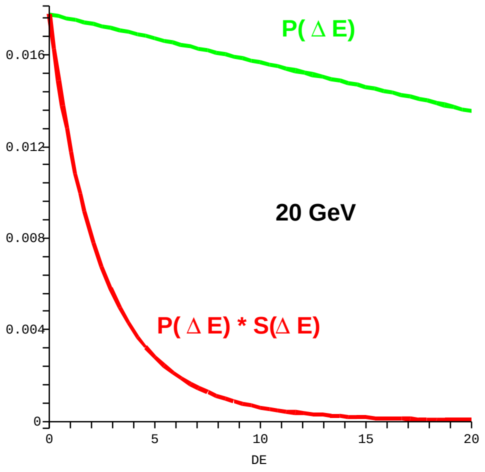
why a harder parton spectrum is very useful

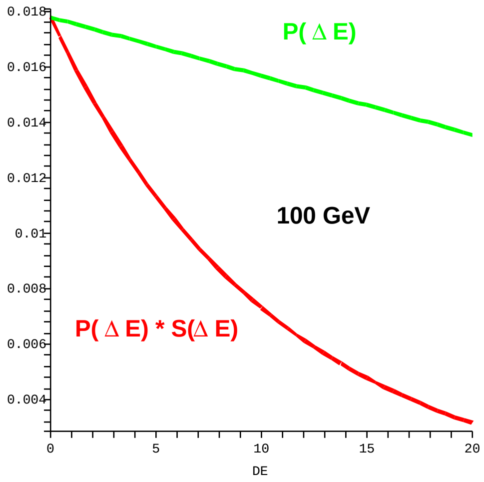
A SIMPLE MODEL FOR R_{AA}

- assume a power-law spectrum $\sim 1/p_T^n$ ($n \approx 7, 8$ at RHIC, 4,5 at LHC)
- for massless partons, energy loss ΔE changes the spectrum to $1/(p_T + \Delta E)^n$, thus

$$R_{AA} \approx P_{esc} + \int_0^{E_{max}} d\Delta E \langle P(\Delta E)\rangle_{T_{AA}} 1/(1 + \frac{\Delta E}{p_T})^n$$

- $S(\Delta E) = 1/(1 + \frac{\Delta E}{p_T})^n$ acts like the filter through which $\langle P(\Delta E)\rangle_{T_{AA}}$ is seen





- since $\langle P(\Delta E)\rangle_{T_{AA}}$ and $S(\Delta E)$ positive and $S(\Delta E)$ decreases with p_T, R_{AA} rises
- speed of the rise depends on $\langle P(\Delta E)\rangle_{T_{AA}}$ close to zero and n

A SIMPLE MODEL FOR R_{AA}

- if $\langle P(\Delta E)\rangle_{T_{AA}}$ would be the same at RHIC and LHC, $R_{AA}^{LHC} > R_{AA}^{RHIC}$ everywhere

- the medium density grows, but slowly: e.g. $\sim \sqrt{s}^{0.574}$ (EKRT)

→ R_{AA} at LHC can be smaller than at RHIC in some low P_T range

- any rise of R_{AA} at LHC then probes $\langle P(\Delta E)\rangle_{T_{AA}}$ around $\Delta E = 0$

- additional effects:
  - possible model-specific explicit dependence $P(\Delta E, E)$
  - transition from gluon-dominated to quark-dominated hadron production
  - nPDF effects (small in the range considered)

⇒ potentially very constraining for models!

- problem: ambiguity with changes in the medium modelling from RHIC to LHC

⇒ use a closed framework which predicts how the medium changes with $\sqrt{s}$

HYDRO FROM RHIC TO LHC

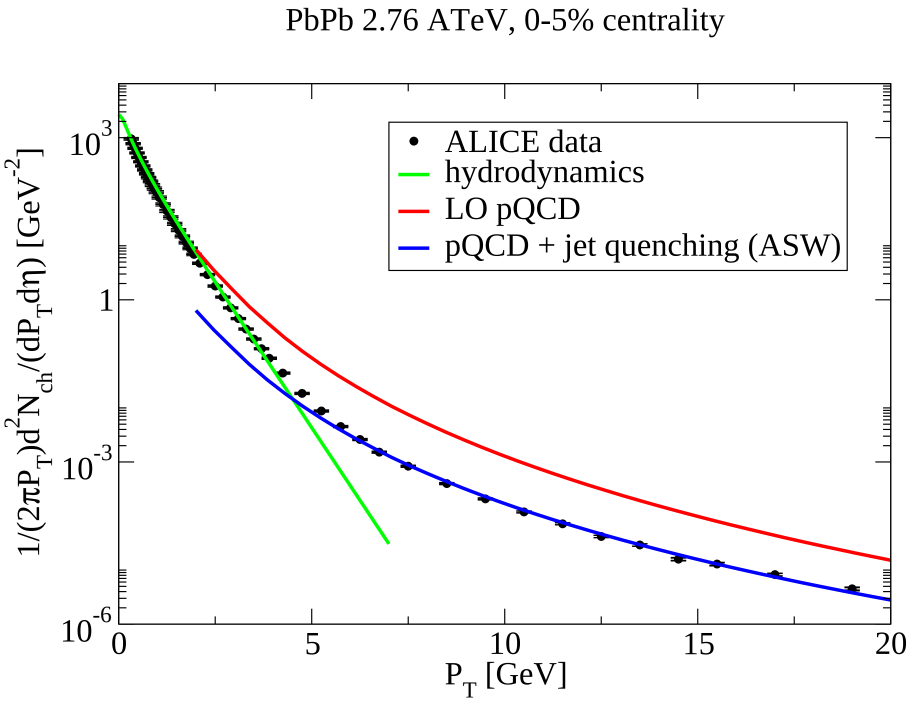
- initial state and initial time computed from pQCD minijet saturation (EKRT)
- eBC profile assumed to be unchanged from RHIC

→ 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

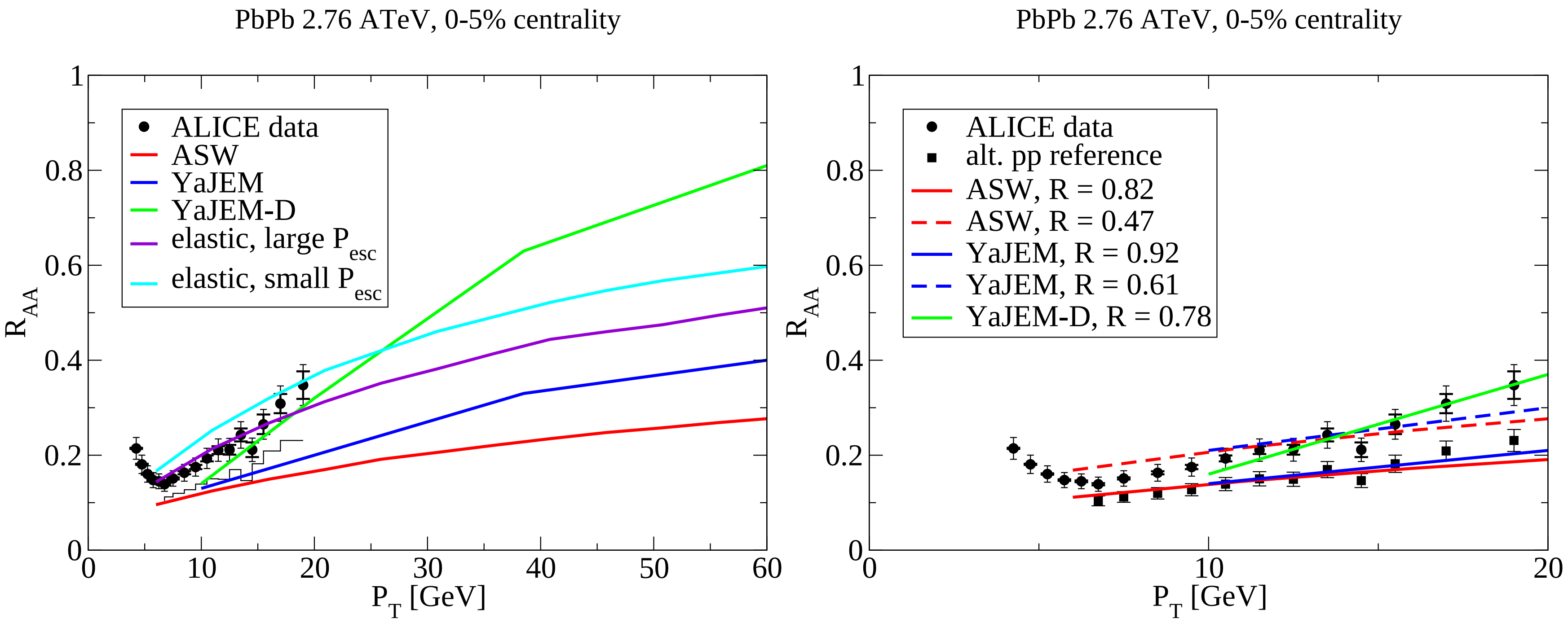
- good description of ALICE P_T spectrum



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

R_{AA} AT LHC

- model parameters K unchanged (left) and refit (right), $R = K_{LHC}/K_{RHIC}$



- models extrapolate very differently given the same hydro background
  - default pp baseline favours YaJEM-D and parametrized elastic
  - alternative baseline favours YaJEM and ASW

$\longrightarrow$ need a measured baseline

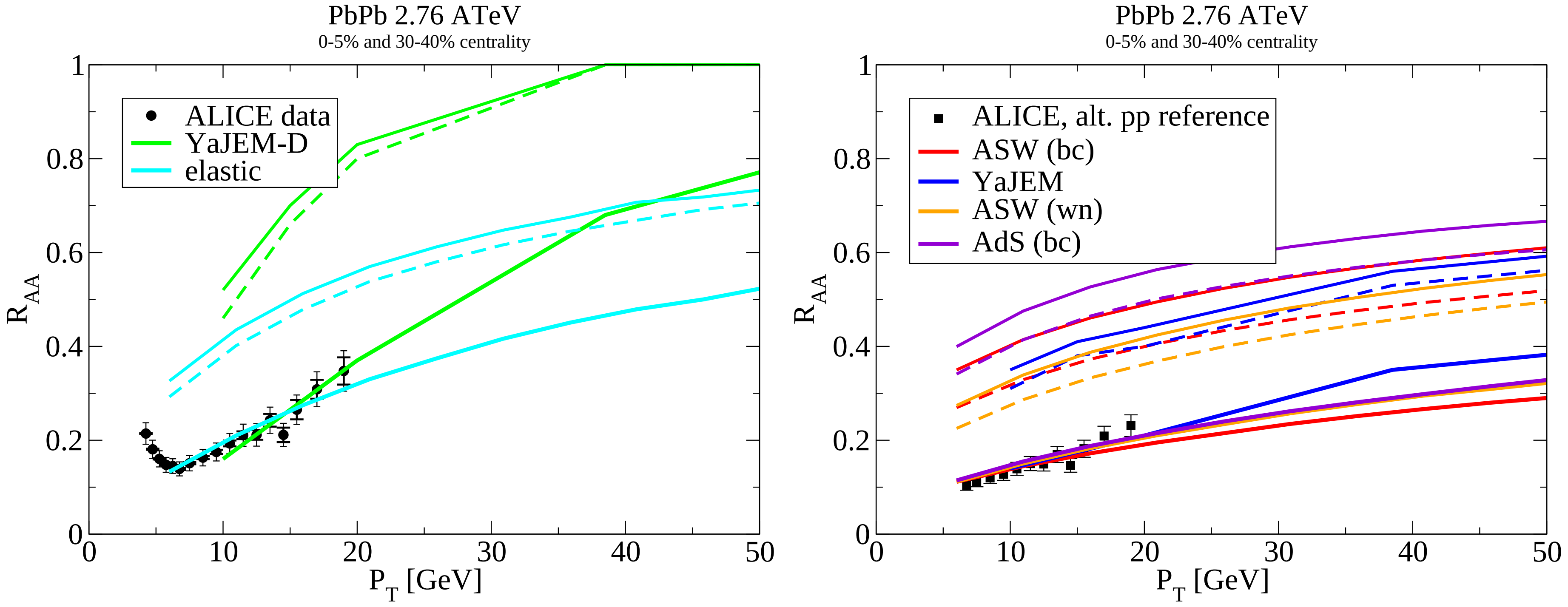
- however, we know already that YaJEM and parametrized elastic fail for $R_{AA}(\phi)$

$\Rightarrow$ different set of constaints than from pathlength

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

R_{AA} AT LHC

Combining with pathlength dependence constraints:



- expectations are wildly different

→ good tool to distinguish various models

- need to get hydro systematics under control

R_{AA} VS. JETS

- direct jet measurements are much more exciting, but. . .
  - uncertainties in (quenched) jet finding in HI environment
  - uncertainties in treating low P_T fragmentation in medium
  - blurry boundary between jet and medium at low P_T
  - strong medium effects for subleading fragments — finite E matters!

⇒ difficult to understand the relation between observed jet and parton E

- jets are less known territory for modellers, and more complicated to model
  - need to understand the systematics of models
  - need to test the assumptions underlying models

⇒ lots of systematic work needed

- leading hadrons are part of jets

⇒ test in-medium jet codes systematically against leading hadron data

⇒ then explore new territory

OTHER HIGH P_T OBSERVABLES

- hadron species dependence of R_{AA}
  - we assume $\tau_{formation} \approx \frac{E}{m_h^2} \gg L$ to treat hadronization as in vacuum

  → not true for protons, D or B mesons, makes most models questionable
  - in principle, allows to see if heavy-quark energy loss is different

- γ-h correlations
  - for wide momentum range of trigger, similar in potential to $R_{AA} + I_{AA}$
  - for narrow trigger momentum range, better handle on subleading fragments
  - due to dominance of $qg \rightarrow q\gamma$ over $q\overline{q} \rightarrow g\gamma$, allows to tag quark eloss

  → very useful cross-check, some additional potential

- jet-jet, jet-h or Z-jet correlations
  - require to understand the complications of jets first

CONCLUSIONS

Systematic investigation of pathlength dependence

• a linear pathlength component must be small (< 10 %)
$\longrightarrow$ the medium dof are not light free quasiparticles ($=$ large elastic eloss)
$\longrightarrow$ quantum coherence is important
$\longrightarrow$ finite E effects change the picture completely, need to be taken seriously

• only particular combinations of medium/eloss model are viable
$\longrightarrow$ both L^2 and L^3 without finite E correction describe the data
$\longrightarrow$ with finite E correction, only medium-determined Q_0 is viable, L^3 may be

Systematic investigation of P_T dependence

• independent set of constraints for models
$\longrightarrow$ requires closed framework to extrapolate medium
$\longrightarrow$ requires a measured pp baseline

• detective work may be tedious rather than exciting, but starts to pay off. . .