Jets in medium

— what LHC measurements of RAA and IAA can teach us about parton-medium interaction

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Introduction

Jets in Medium

- why and how?

The single hadron suppression factor R_{AA}

- pathlength dependence and medium geometry

- P_T dependence and interaction mechanism

The dihadron suppression factor I_{AA}

- various biases

Conclusions

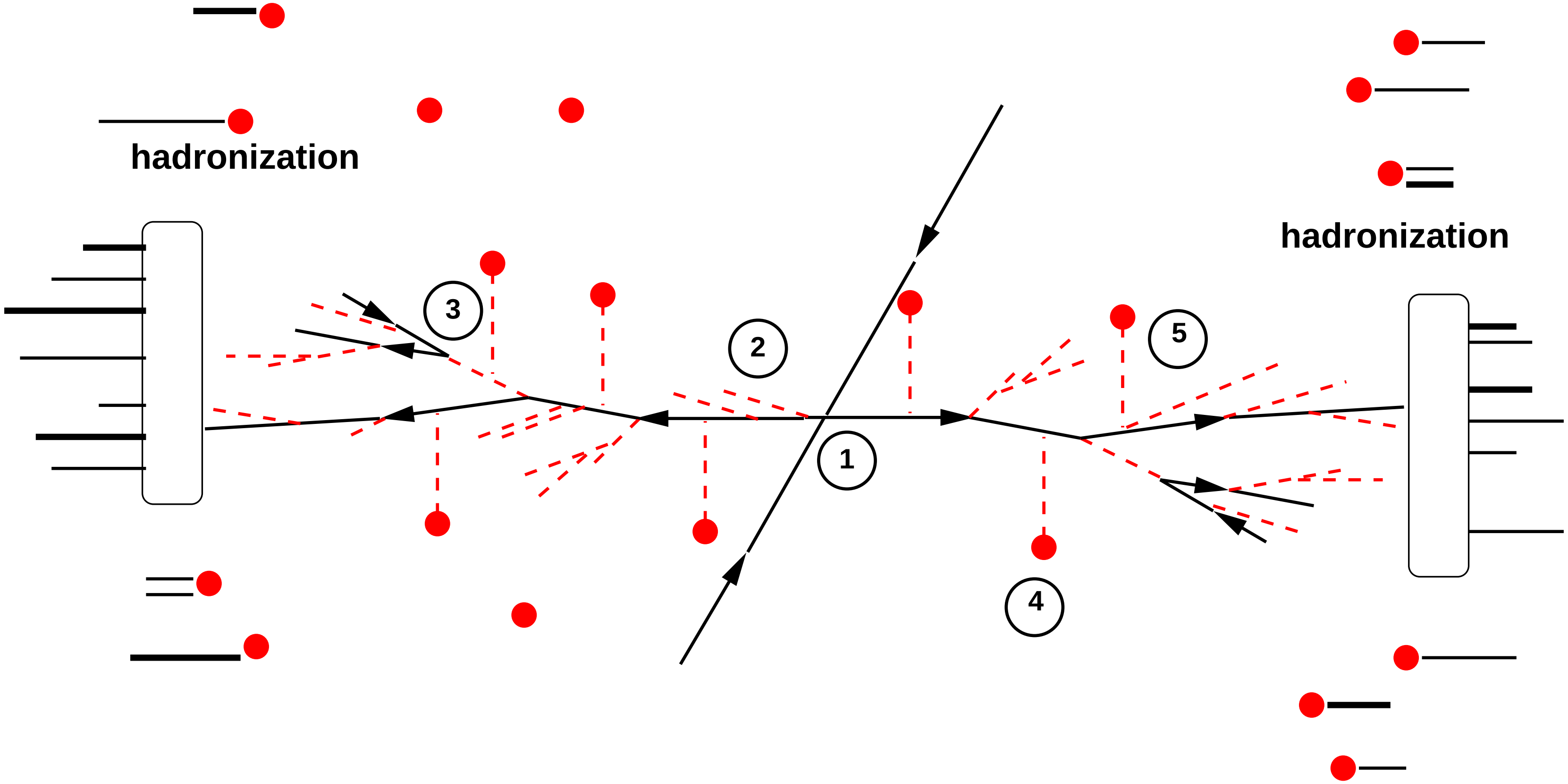
- and open issues

I. Jets in medium

why we're interested

The 'standard' jet quenching picture

pQCD radiative energy loss for hard partons interacting with the medium



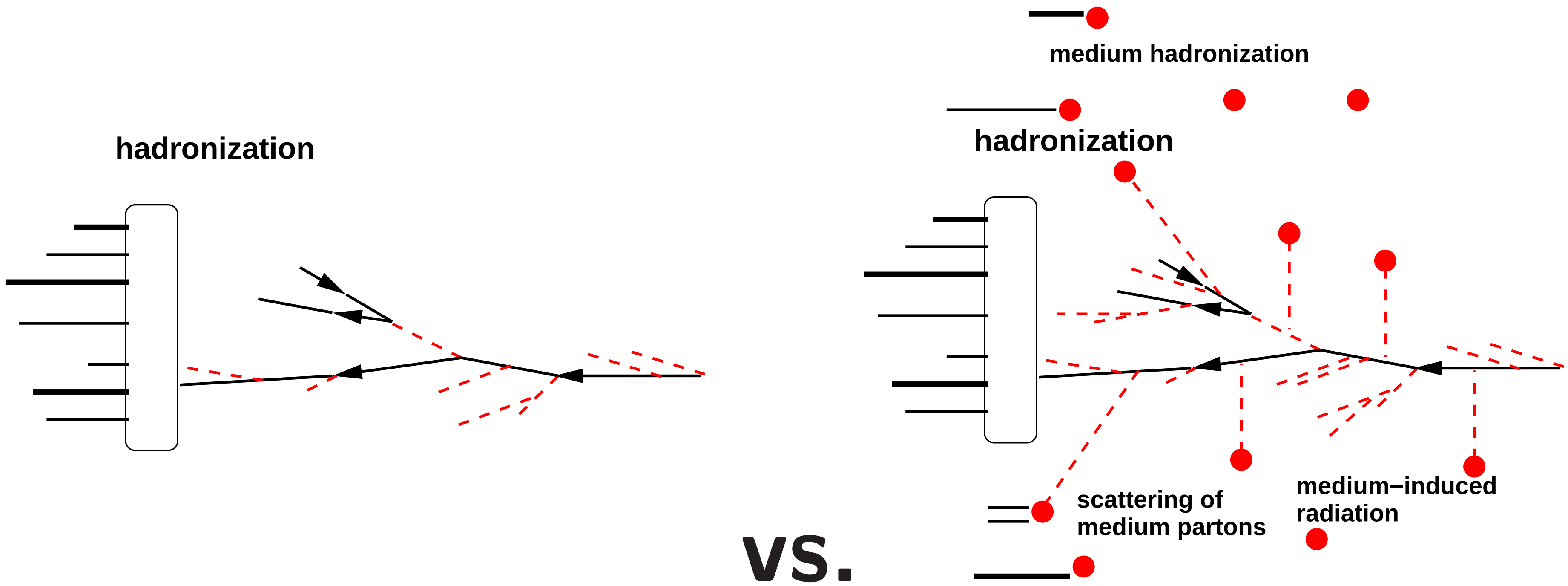
1) hard process 2) vacuum shower 3) medium-induced radiation 4) medium evolution 5) medium correlated with jet by interaction

Status: 1) calculable 2) calculable with MC codes 3) medium dof, interaction 4) calculable in hydrodynamics 5) energy transport in the medium

Physics 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. . .

How do these two differ? Obvious strategy: Compare reconstructed jets!



Concepts — jets in vacuum

Underlying (idealized) concept:

• a jet represents a virtual hard parton and its subsequent evolution
→ do pQCD without worrying about non-perturbative aspects

Experimental reality (a bit catchy):

• 'a contract between experimentalist and theorist'

What this means is:

• hadrons are combined into jets by jet definitions/algorithms (SiSCone, anti-k_T,. . .)
→ but jet definitions are chosen cleverly based on pQCD arguments
(one would not do sequential reco to search for a hydro phenomenon)

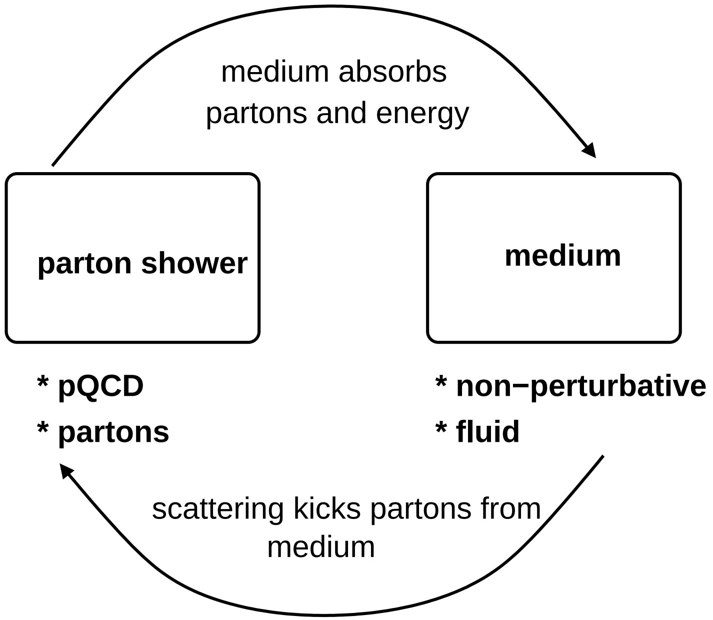
Thus, for *measured* jets:

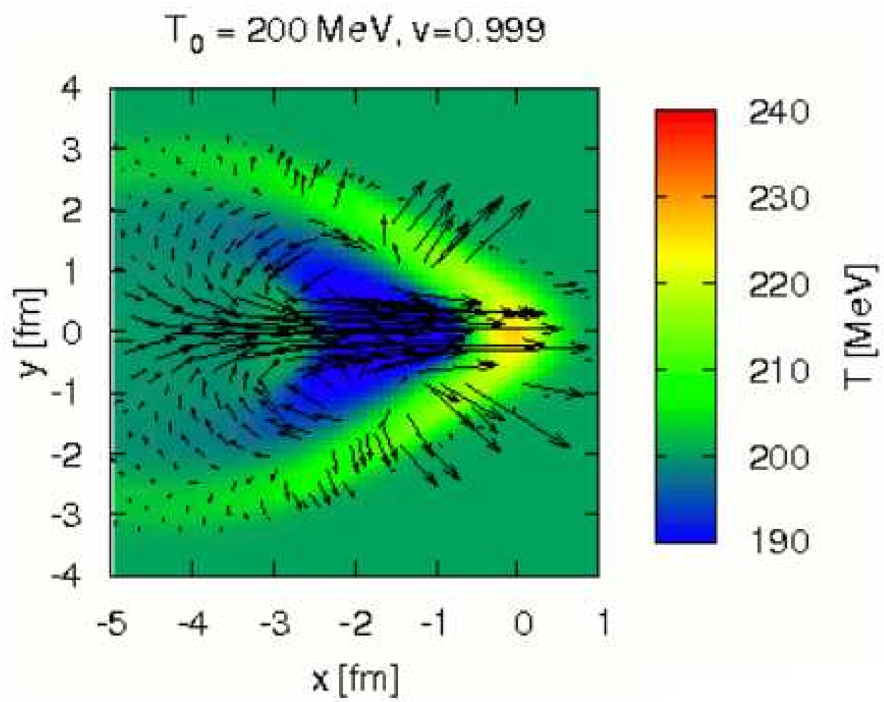
• jet finding algorithm needs to be quoted
• a bias for hard events to fit the particular definition exists
→ measured jets never capture 'all' of the parton evolution

But: parton level (pQCD) $\approx$ hadron level (particles hitting detector) $\approx$ detector level (calorimeter towers)

CONCEPTS — JETS IN MEDIUM

- momentum in perturbative and non-perturbative modes – parton $\neq$ detector level





$\rightarrow$ a hydro medium can be substantially disturbed by a jet
$\rightarrow$ perturbative shower can be broadened beyond kinematics of initial Q^2

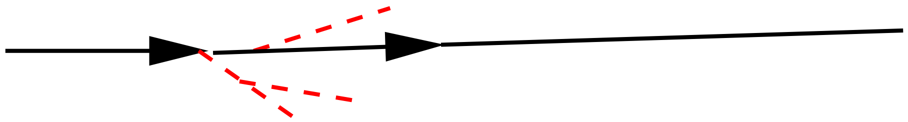
- What is the jet?
  - the perturbative part of the shower ($E_{jet} < E_{parton}$)?
  - everything causally correlated with the shower initiator ($E_{jet} > E_{parton}$)?
  - the flow of original 4-momentum ($E_{jet} = E_{parton}$)?

CONCEPTS — ENERGY LOSS VS. IN-MEDIUM SHOWER

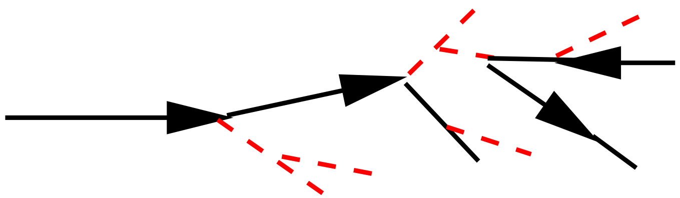
Conceptual model difference: energy loss vs. medium modified fragmentation function

Single inclusive hard hadron production:

- dominated by showers in which a single parton carries most of the momentum



- unbiased hard jet events — multiple low p_T hadron production

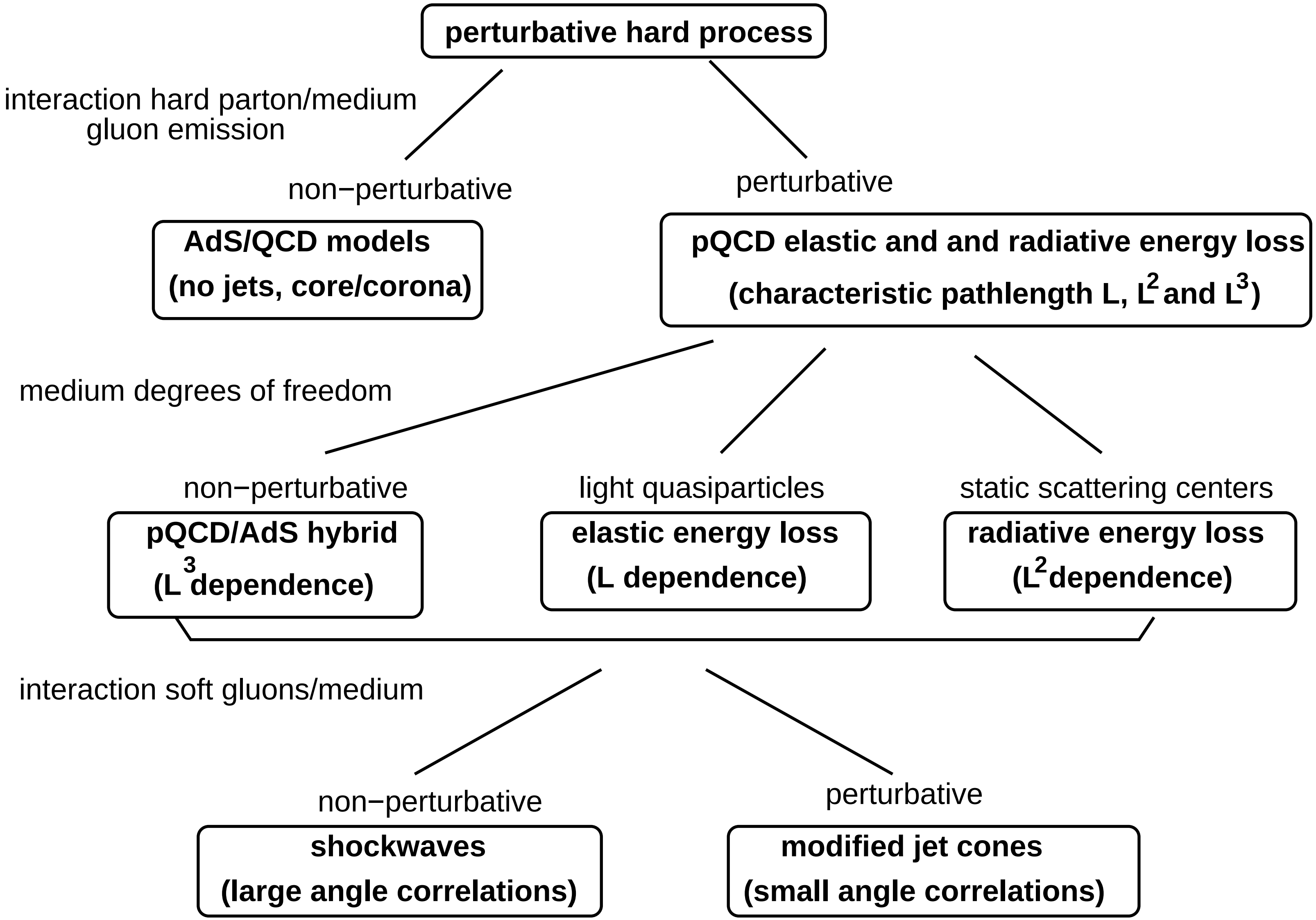


For single inclusive hard hadron production:

⇒ fragmentation function ≈ hadronization of leading parton
⇒ medium effect ≈ reduction of leading parton energy
⇒ if hadronization happens outside the medium, the two factorize!

⇒ Medium-induced energy loss good concept to describe *leading* hadron only

The zoo of jet quenching pictures



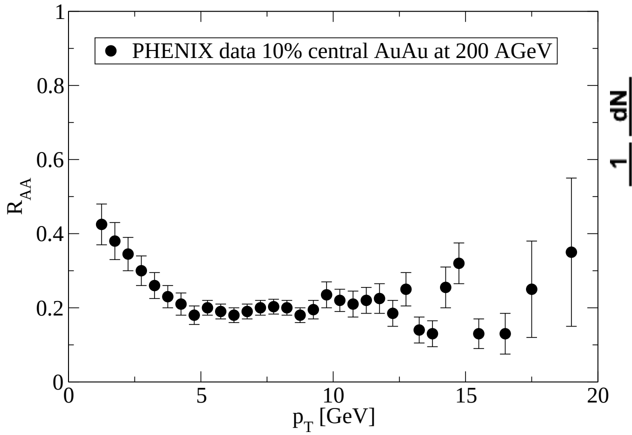
Which is correct?

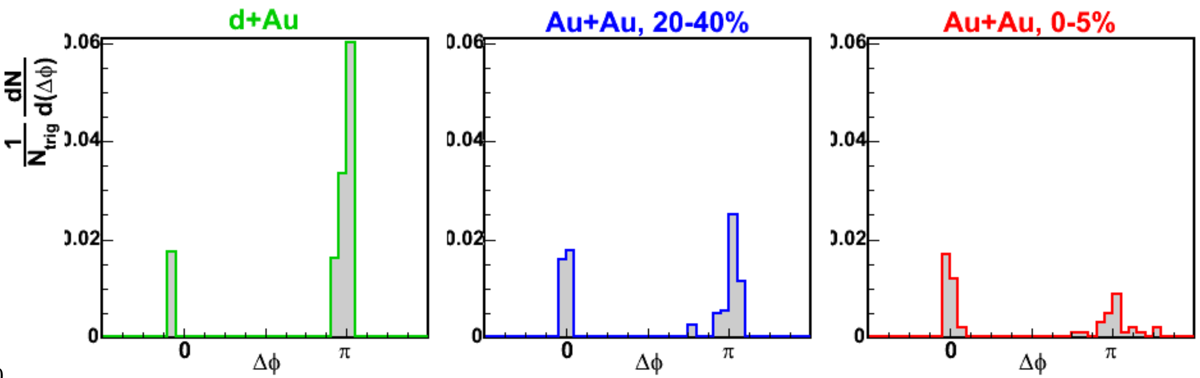
The observables

- R_{AA}, suppression of single inclusive high P_T hadrons

$$R_{AA}(P_T, y) = \frac{d^2N^{AA}/dp_T dy}{T_{AA}(0)d^2\sigma^{NN}/dP_T dy}$$

- I_{AA}, disappearance of back-to-back correlations, 'monojets'





- true reconstructed jets, dijet asymmetry

with some systematics in $\sqrt{s}$, collision centrality, reaction plane angle and P_T

Is this enough to identify the physics and to characterize the medium?

The strategy

Test systematically for pathlength dependence and correlation properties!

- test combinations of hydro and parton-medium interaction models
- require that the same model describes bulk, R_{AA} and I_{AA}
- study differential observables within *the same* hydro framework

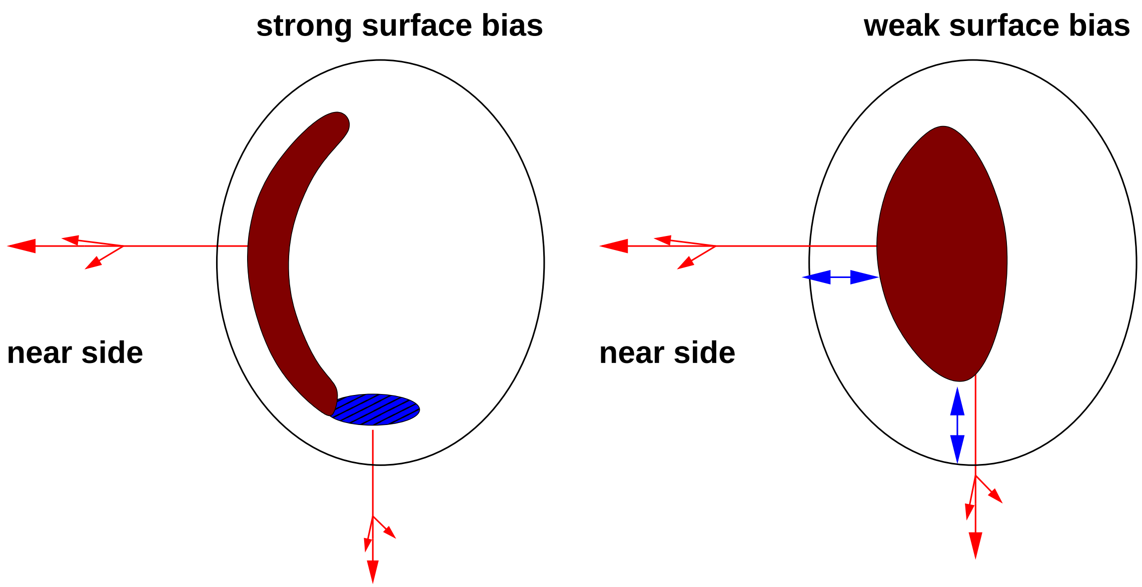
Various experimental handles on interesting parameters:

centrality dependence ⇔ in-medium pathlength and medium density
reaction plane angle ⇔ in-medium pathlength
dihadron corelations ⇔ in-medium pathlength and trigger bias, correlation width
energy ($\sqrt{s}$) dependence ⇔ medium density, kinematics
hadron species ⇔ parton type

Part II

II. Centrality dependence

For non-central collisions, study suppression as a function of reaction plane angle



• 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 $\langle x \rangle < \langle y \rangle$

$\Rightarrow$ probes pathlength dependence of models

The contenders

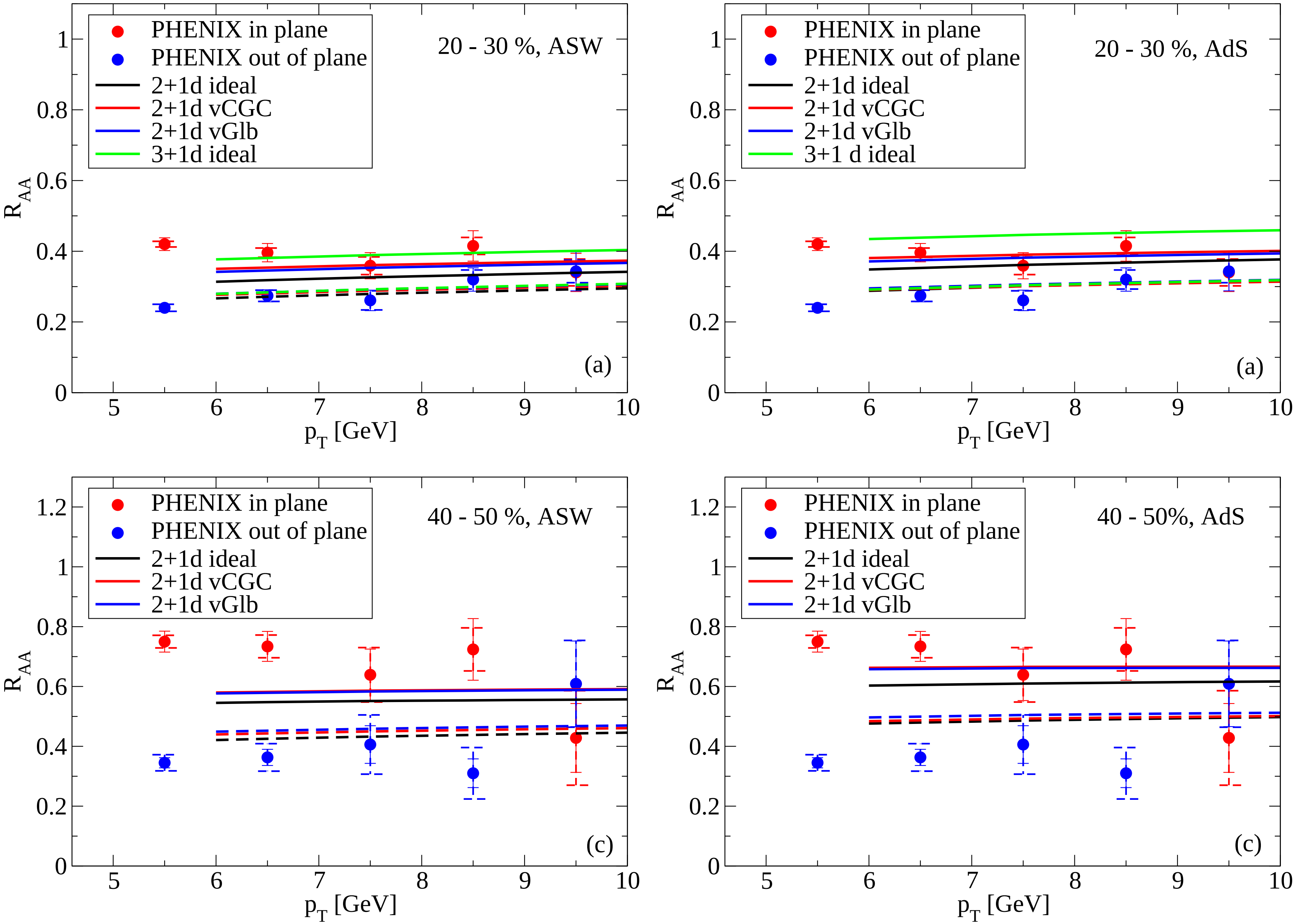
- incoherent processes: $n_{scatt} = \frac{L}{\lambda}$, since $\Delta E \approx n_{scatt} \Delta E_1$, linear $\Delta E \sim L$ (elastic)
- coherence time, dependent on gluon kinematics, implies quadratic $\Delta E \sim L^2$ (ASW)
- however, subject to finite energy constraints, reverts to linear $\Delta E \sim L$ (YaJEM)
- strongly coupled medium: force $\frac{d|p_T|}{dt} = T^2$, thus $Q^2 = T^4 L$ 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)

$\Rightarrow$ actual dependence is changed by time evolution of the medium!

- require that combination of medium/jet model describes R_{AA} in central 200 AGeV collisions

$\rightarrow$ predict $R_{AA}(\phi)$ for non-central collisions

Pinning down pathlength



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

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	fails
2+1d vCGC	fails	marginal	works	fails	marginal
2+1d vGlb	fails	marginal	works	fails	marginal

- quantum coherence is an important part of the answer

$\rightarrow$ incoherent models fail by huge margin (factor 4)!

- finite energy corrections need to be taken seriously!

$\rightarrow$ quite possibly they destroy the success of L^2 and maybe also L^3

- strong constraints on **combinations** of hydro + parton-medium interaction model

Implications for jet-medium interaction:
$\rightarrow$ no large incoherent component
$\rightarrow$ conclusively rules out light quasiparticles as medium degrees of freedom

Implications for hydrodynamics:
$\rightarrow$ favours late equilibration, long-lived medium, some viscosity

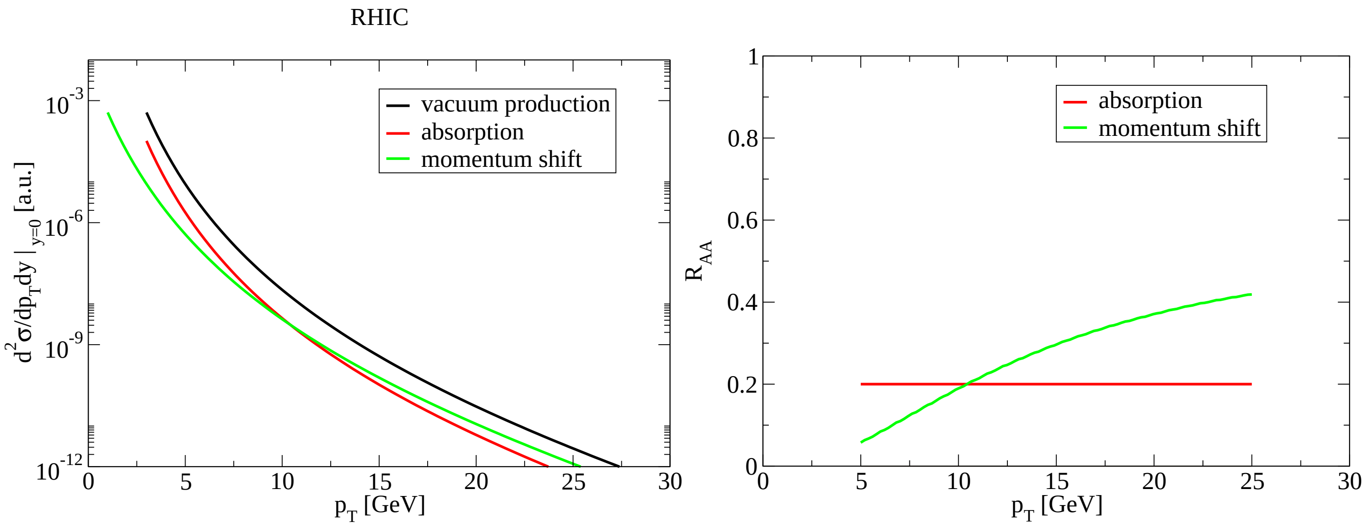
PART III

III. P_T dependence

For different $\sqrt{s}$, study suppression as a function of P_T

- results are *independent* of hydro model
- simple idea: partons can be 1) absorbed or 2) shifted in energy

$\Rightarrow$ take pQCD spectrum and shift down/sideward to roughly reproduce suppression (same effect for all partons — not very realistic!), compute R_{AA}

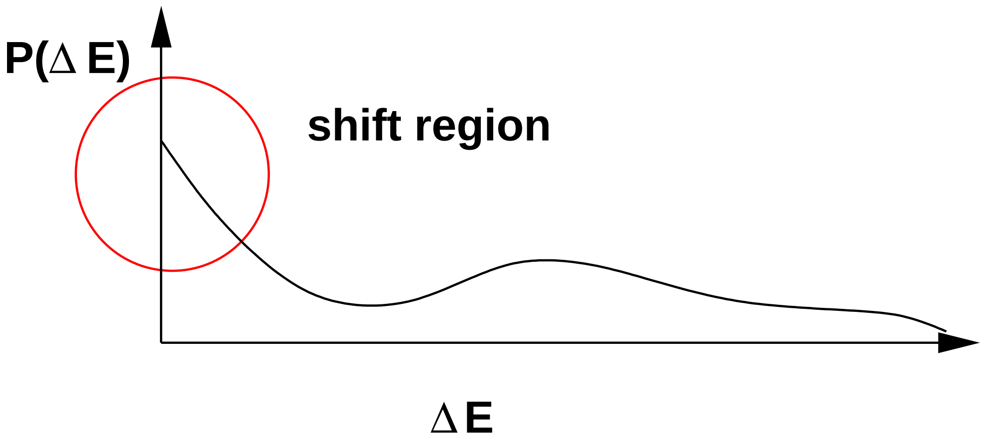


$\Rightarrow$ P_T dependence measures shift vs. absorption!

P_T DEPENDENCE OF R_{AA}

- more realistically: $\langle P(\Delta E) \rangle$ rather than absorption/shift

$\rightarrow$ $\Delta E \approx 0$: shift, $\Delta E \approx E$: absorption



$\Rightarrow$ rise of R_{AA} with P_T measures the strength of $\langle P(\Delta E) \rangle$ close to zero

$\rightarrow$ probability to not to interact (radiate), characteristic for models!

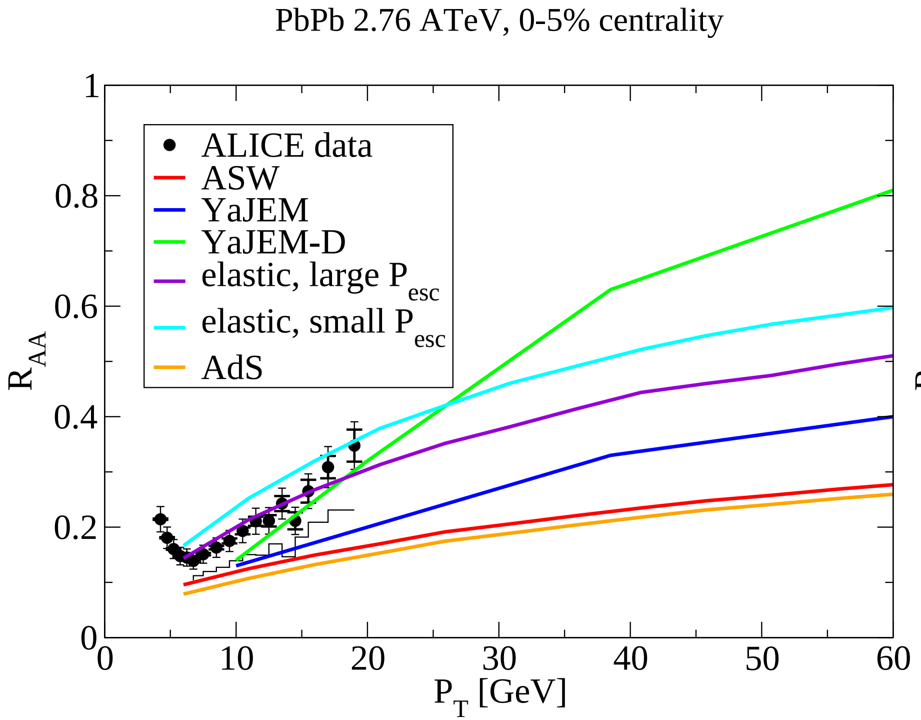
- also: *explicit* mechanisms for P_T dependence, cf. YaJEM-D

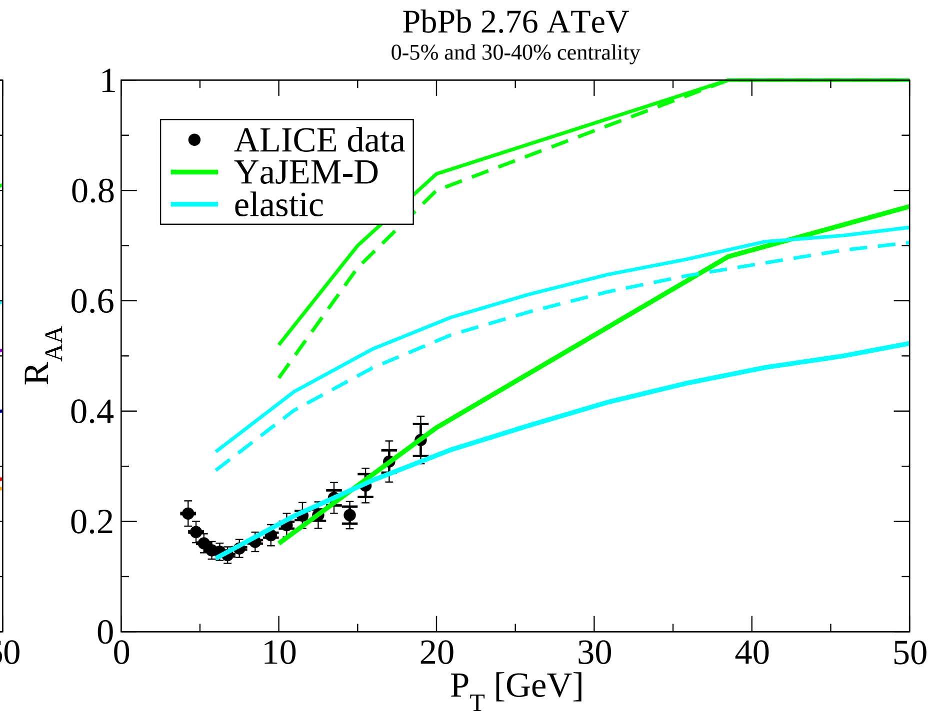
- subleading: relevant pQCD subchannels ($gg \rightarrow gg$ vs. $qg \rightarrow qg$ at larger P_T)

$\rightarrow$ not significant in RHIC kinematic range, but ideal for LHC

P_T DEPENDENCE OF R_{AA}

- data comparison with direct extrapolation using 'same' hydro or refit





- use parameter R to quantify how much refitting is done ($R = 1$ indicates no refit)

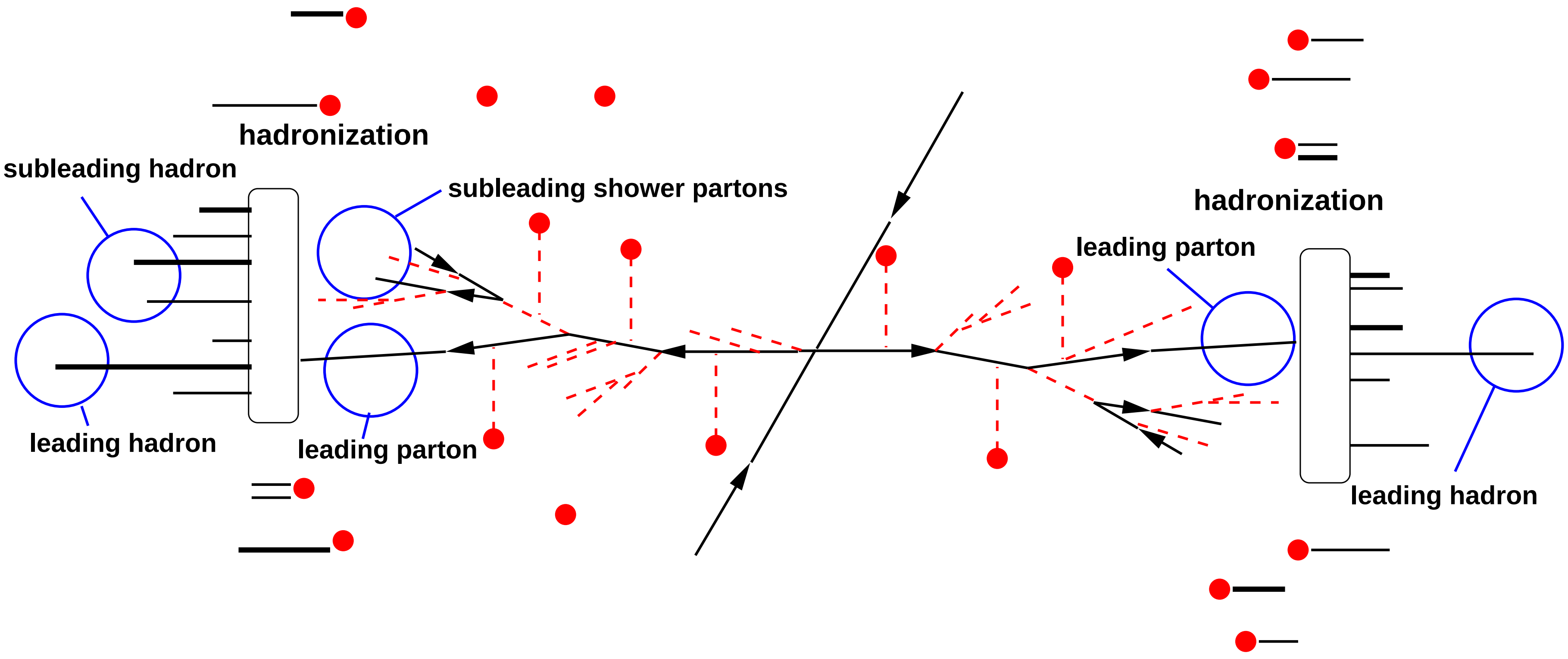
	YaJEM-D	YaJEM	ASW	AdS
R	0.92	0.61	0.47	0.31

$\rightarrow T^4$ dependence of AdS strongly disfavoured; many radiative models overquench

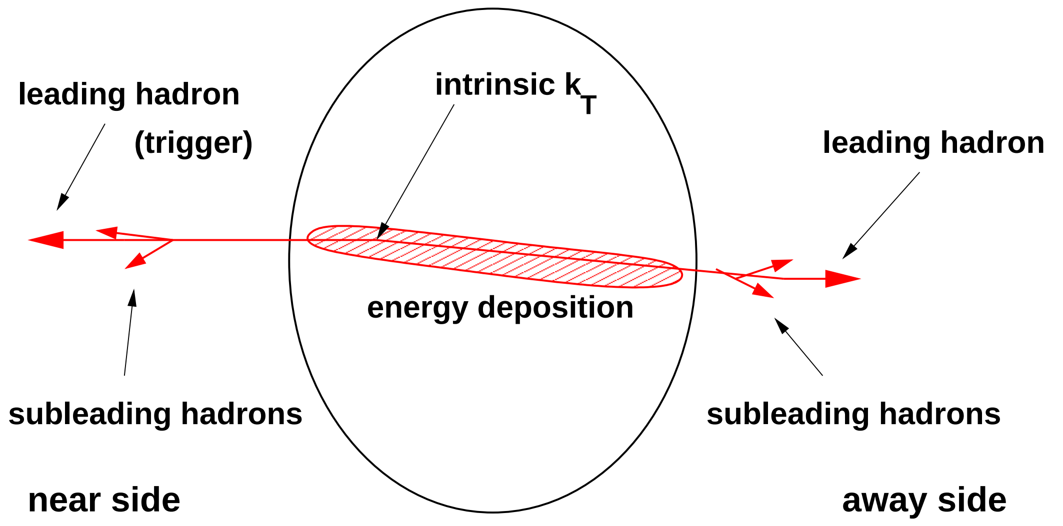
T. R., H. Holopainen, R. Paatelainen, K. J. Eskola, Phys. Rev. **C84** (2011) 014906.

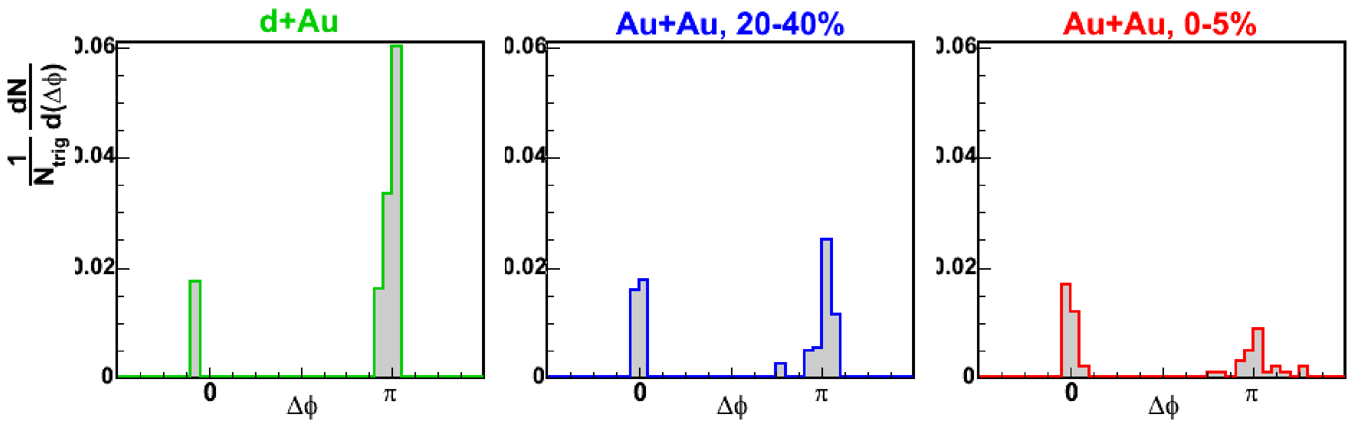
IV. Dihadron suppression

what is in I_{AA} that is not in R_{AA}?



Dihadron correlations — terminology





- I_{AA} conditional yield ratio AA/pp *given a trigger*
- z_i momentum fraction of ith hardest shower hadron given parton energy E

$\rightarrow$ thus $P_T^i = z_i E$, $\sum_i z_i = 1$ (momentum conservation)

Trigger-induced biases

• I_{AA} is related to conditional probability
→ given trigger in momentum range A, what is the chance to see yield in range B?

⇒ the trigger condition biases the shower in a certain way
→ this will turn out to be most useful

Trigger perfers hard fragmentation:

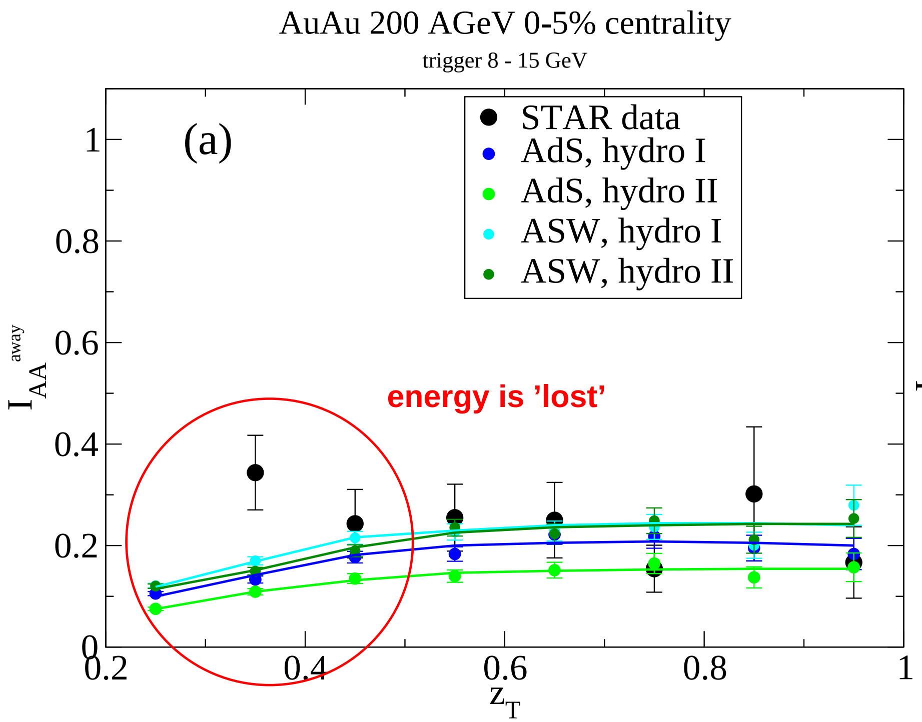
• vacuum:
→ quark jets are more likely than gluons
→ k_T imbalance points towards the trigger direction

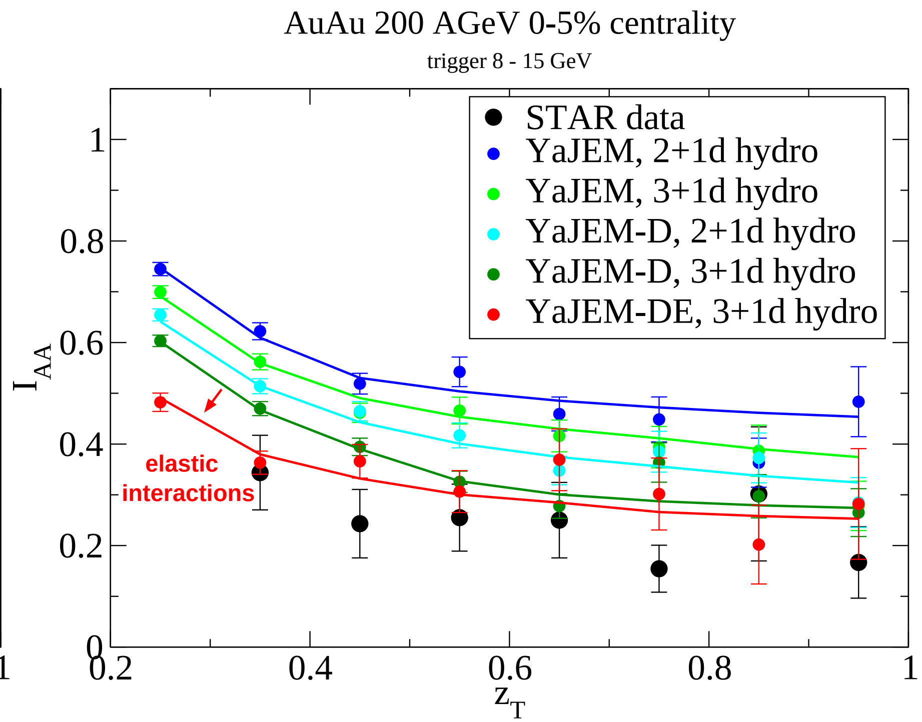
• medium:
→ energy loss softens fragmentation, thus higher parton momenta
→ gluons are filtered out by stronger interaction with $C_F = 9/4$
→ trigger side has short in-medium pathlength

T. R., K. .J. Eskola, 1106.1740 [hep-ph]

I_{AA} RESULTS — RHIC

- away side at RHIC (near side ~ 1)





- traces energy transport to subleading partons
$\longrightarrow$ beyond validity of energy loss models

- constrains the relative fraction of elastic energy loss
$\longrightarrow$ clearly seen at low z

$\Rightarrow$ about 10% of the energy transfer is elastic

ANALYSIS SUMMARY

- assuming the best choice of hydro model for each parton-medium interaction model: (all models tuned to describe R_{AA} in central 200 AGeV AuAu collisions)

	R_{AA}@RHIC (centrality)	R_{AA}@LHC (P_T)	I_{AA}@RHIC	I_{AA}@LHC
elastic	**fails!**	works	**fails!**	fails
ASW	works	fails	marginal	works
AdS	works	**fails!**	marginal	works
YaJEM	fails	fails	fails	fails
YaJEM-D	works	works	marginal	marginal
YaJEM-DE	works	works	works	works

- YaJEM-DE looks like the only viable candidate

$\longrightarrow$ needs systematic study of hydro backgrounds at LHC

Implications

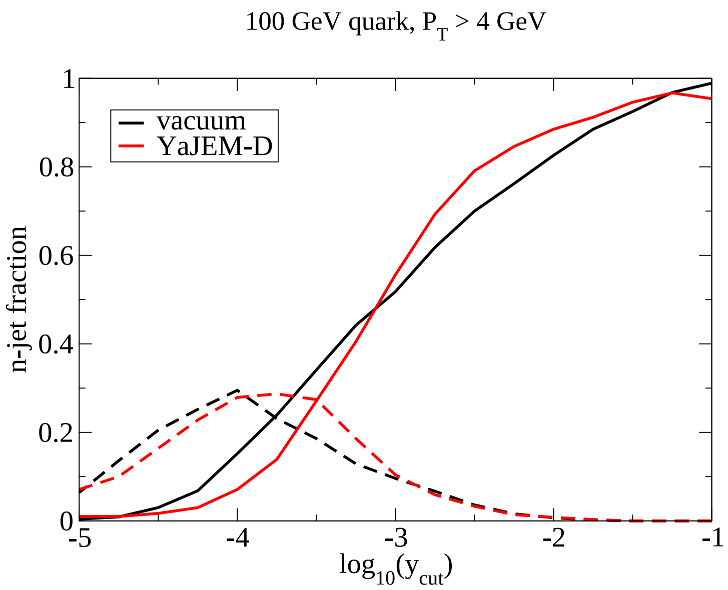
- energy loss is consistent with pQCD shower picture
- no evidence for exotic mechanisms
- medium DOF can take some recoil - massive or correlated quasiparticles?

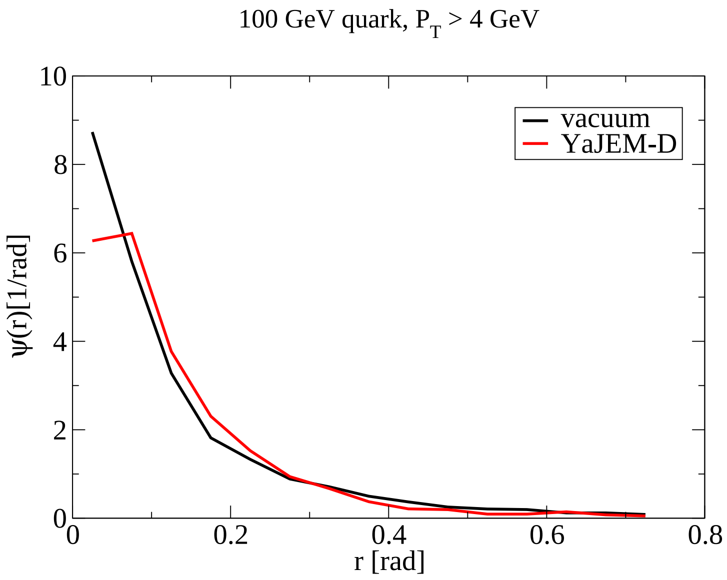
Implications for jets

- How do modified jets look like?

$\longrightarrow$ n-jet fraction: clustering at y_{min} with $y_{ij} = 2\text{min}(E_i^2, E_j^2)(1 - \cos(\theta_{ij})/E_{\text{cm}}^2$

$\longrightarrow$ jet shape $\Psi_{int}(r, R) = \frac{\sum_i E_i \theta(r - R_i)}{\sum_i E_i \theta(R - R_i)}$





- not much modified in perturbative region

$\longrightarrow$ jets look like unmodified jets at lower energy

- energy dissipated in medium in non-perturbative momentum region

$\longrightarrow$ not picked up by jet finding algorithms

T. R., Phys. Rev. **C80** (2009) 044904.

Implications for jets

• Why do jets not look modified?

$\rightarrow$ since initial hard scale $Q \gg T$, first splittings happen without knowledge of the medium

$\rightarrow$ if the dominant physics is a pQCD shower exchanging energy/momentum with medium, the structure of the jet is still determined by (at high energy) almost scale-invariant splitting kernels in z, i.e. parton distributions remain self-similar even if overall scale changes

Prediction from 2009, agrees qualitatively with measured dijet asymmetry properties

• Why does elastic interaction not change that?

$\rightarrow$ because the angular deflection of partons in elastic interactions with medium partons with momentum $O(T)$ is only significant when $k_T \approx T$, thus only the low z part of the shower gets decorrelated into the medium

Open issues

Other observables:

• γ-h correlations
$\rightarrow$ unclear if there is information beyond what is in hadronic R_{AA} and I_{AA}
$\rightarrow$ but nice to specifically tag quark jets

• heavy quarks — radiative energy loss suppressed by dead cone effect
$\rightarrow$ but *never* hadronize outside medium — theoretically unclear physics

Future questions

• What is the precise interplay between elastic and radiative energy loss?
$\rightarrow$ needs precision analysis of multiparticle correlation systematics

• What can jets tell about initial state fluctuations?
$\rightarrow$ needs measured systematics of $v_3, \ldots,$ combined analysis with photons

• Is there shockwave excitation in the medium?
$\rightarrow$ (experiment) needs triggered multiparticle correlation systematics
$\rightarrow$ (theory) needs precise spacetime picture of energy deposition into medium