Jet tomography at RHIC and LHC

— where are we today?

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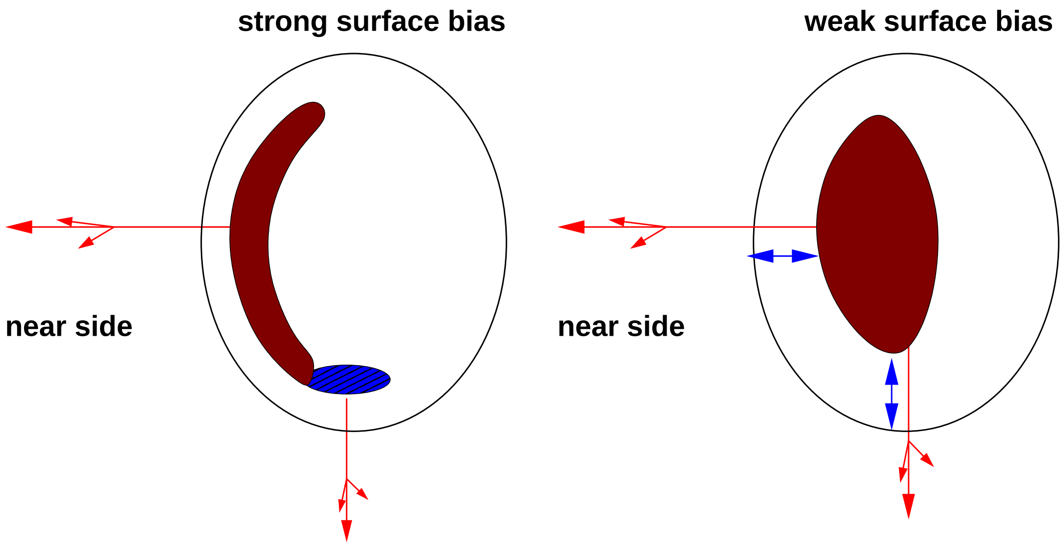
Jet tomography
- the original idea
- what are the difficulties?

Modelling jets
- a summary of constraints from data

Tomography today and tomorrow
- even-by-event hydrodynamics
- next-generation observables

Conclusions

I. Tomography 1.0



Jet tomography

Basic idea:

• the rate of hard processes in p-p collisions can reliably be calculated in pQCD
$\rightarrow$ since they happen at $\tau \sim 1/P_T^{hard}$ they come before medium formation at $\sim 1/T$
$\rightarrow$ thus hard processes in A-A should be (up to nPDFs) independent of medium

$\Rightarrow$ this is experimentally verified, hard γ, Z, W scale indeed with N_{bin}

> The rate of hard parton production in A-A collisions can be reliably calculated in pQCD.

• while γ, Z, W have negligible final state interaction, quarks and gluons do not
$\rightarrow$ expect hard hadron spectra, jets to be modified by interaction with QCD medium

$\Rightarrow$ if parton-medium interaction is known, allows to measure medium density evolution
$\rightarrow$ this is the original tomography idea — but do we know the interaction?

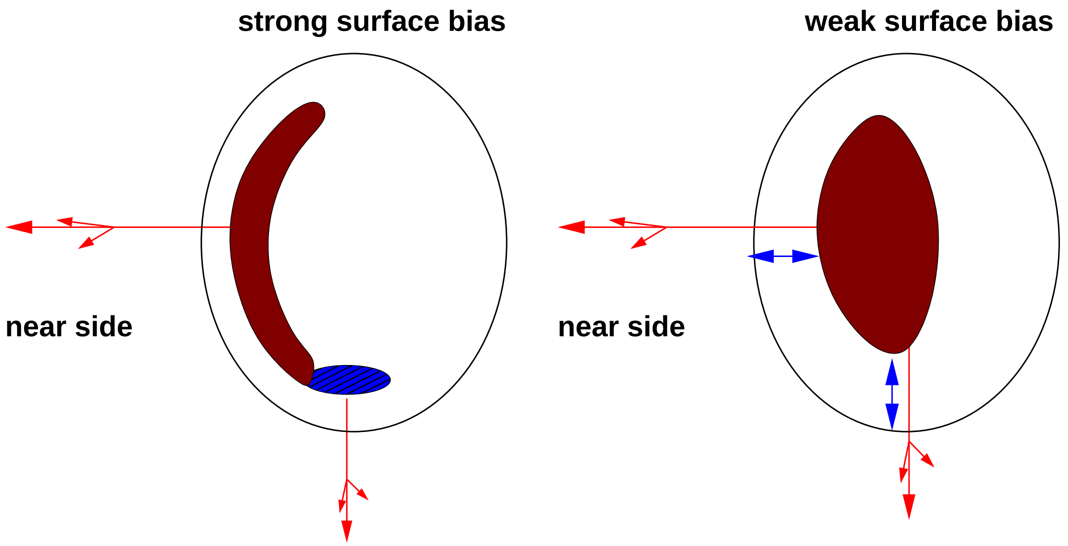
$\Rightarrow$ if medium density evolution is known, allows to measure parton-medium interaction

> Tomography in practice is complicated, because there are no perfect knowns and unknowns.

Tomography in practice

Example: tomographic measurement of ϵ_2 (spatial medium eccentricity)

• study the attenuation of the hadron yield as a function of reaction plane angle
$\longrightarrow$ identify low P_T reaction plane (event plane,. . .) event by event
$\longrightarrow$ bin high P_T yield as function of ϕ, can only be done averaged over many events

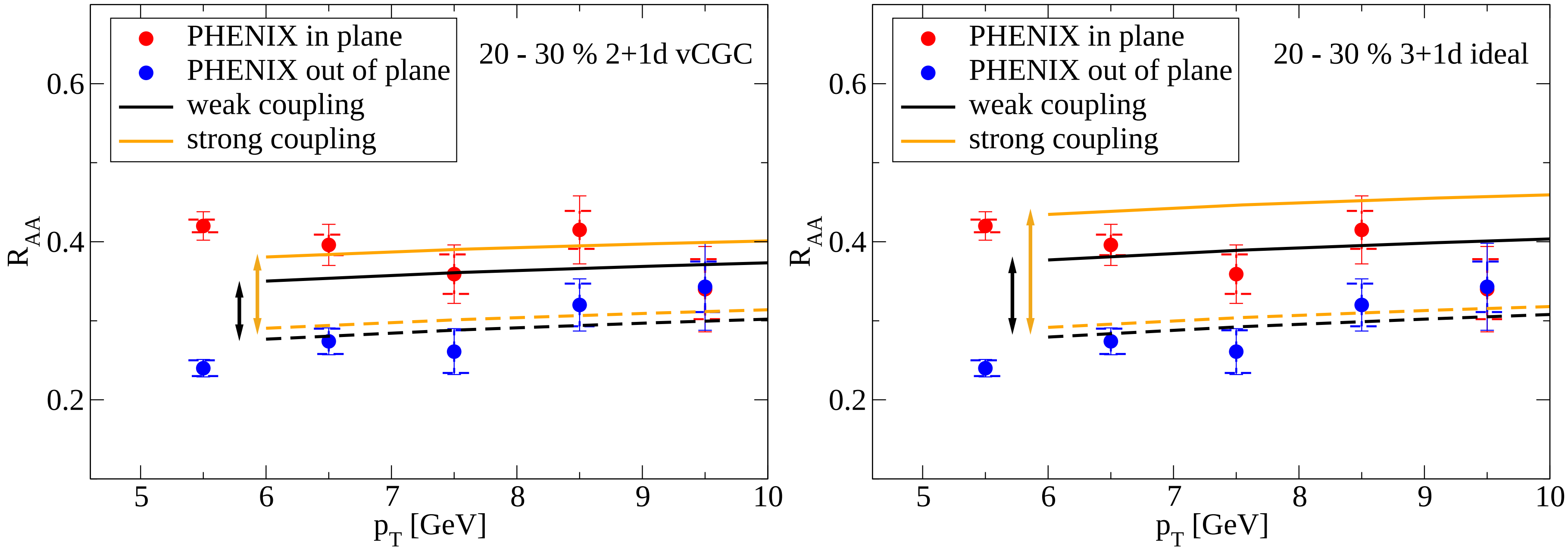


$\Rightarrow$ expect more quenching out of plane (long path) than in plane (short path)

Idea: deduce ϵ_2 from the yield difference in-plane to out of plane

Tomography in practice

Test case: weak vs. strong coupling interaction, vCGC vs. 3+1d ideal hydro
→ results in a 2x2 matrix of models representing state of the art 2 years ago



⇒ data on hadronic in-plane vs. out of plane R_{AA} is described for
→ **vCGC and strong coupling** or **3+1d ideal and weak coupling**

Only combinations of models are constrained, no straightforward ϵ_2 measurement possible.

T. R., H. Holopainen, U. Heinz and C. Shen, Phys. Rev. C **83** (2011) 014910

AMBIGUITIES

Systematic approach: generalize to larger model matrices

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

$\Rightarrow$ some parton-medium interaction scenarios never work, there is information!

Two strategies:

• generalize model matrix approach to include more observables
$\rightarrow$ this is really expensive to do in terms of time and numerics

or

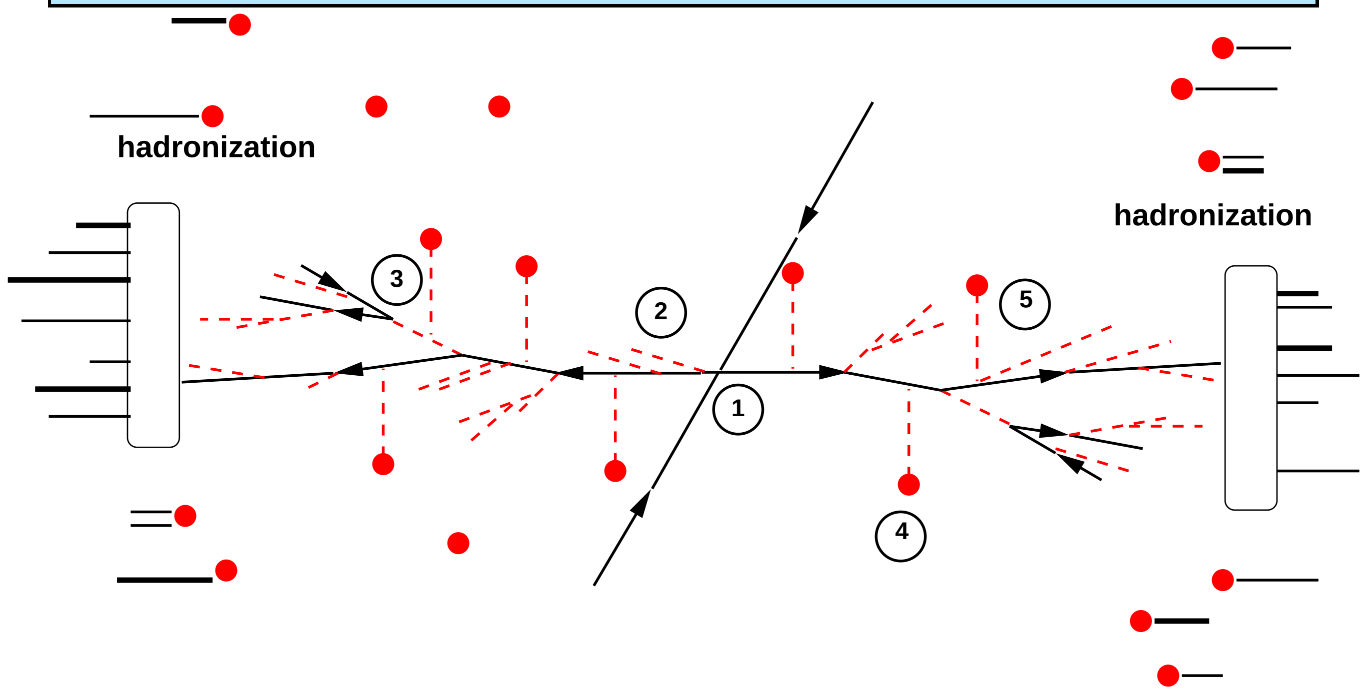
• identify observables which are insensitive to choice of hydro
$\rightarrow$ constrain parton-medium interaction based on those
$\rightarrow$ then use the constrained interaction to consider tomographic observables

This talk will follow the second strategy.

T. R., Phys. Rev. C **85** (2012) 044903

Parton-medium interaction models

II. Parton-medium interaction



'standard'-model: medium-modified parton shower
(models often based on PYSHOW)

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

QCD SHOWER EVOLUTION THE PYTHIA WAY (I)

Basic idea: Evolution as an iterated series of $1 \to 2$ splittings (parent/daughters)

• splitting phase space given by virtuality, (almost) collinear splitting:
$\to$ use $t = \ln Q^2/\Lambda_{QCD}$ and z

• differential splitting probability is

$$dP_a = \sum_{b,c} \frac{\alpha_s(t)}{2\pi} P_{a\to bc}(z) dt dz$$

• splitting kernels from perturbative QCD

$$P_{q\to qg}(z) = \frac{4}{3}\frac{1+z^2}{1-z} \quad P_{g\to gg}(z) = 3\frac{(1-z(1-z))^2}{z(1-z)} \quad P_{g\to q\bar{q}}(z) = \frac{N_F}{2}(z^2+(1-z)^2)$$

• evolution proceeds in decreasing virtuality t and leads to a series of splittings $a \to bc$ where the daughter partons take the energies $E_b = zE_a$ and $E_c = (1-z)E_a$.

• $Q \sim P_T$ is the hard scale which makes the process perturbative for $Q^2 > 1$ GeV^2

QCD shower evolution the PYTHIA way (II)

- differential branching probability at scale t:

$$I_{a\to bc}(t) = \int_{z_-(t)}^{z_+(t)} dz \frac{\alpha_s}{2\pi} P_{a\to bc}(z).$$

- kinematic limits $z_\pm$ dependent on parent and daughter virtualities and masses $M_{abc} = \sqrt{m_{abc}^2 + Q_{abc}^2}$

$$z_\pm = \frac{1}{2}\left(1 + \frac{M_b^2 - M_c^2}{M_a^2} \pm \frac{|\mathbf{p}_a|}{E_a}\frac{\sqrt{(M_a^2 - M_b^2 - M_c^2)^2 - 4M_b^2 M_c^2}}{M_a^2}\right)$$

- probability density for branching of a occuring at t_m when coming down from t_{in}:

$$\frac{dP_a}{dt_m} = \left[\sum_{b,c} I_{a\to bc}(t_m)\right] \exp\left[-\int_{t_{in}}^{t_m} dt' \sum_{b,c} I_{a\to bc}(t')\right].$$

(probability for branching, times probability that parton has not branched before)

Putting it into the medium

What is the microscopical model of the medium?

• A **free** or **perturbatively tractable** gas of quarks and gluons
→ allows to treat interaction with medium in pQCD as well, i.e. 'easy' to compute
→ in **striking disagreement** with fluid picture of bulk medium
→ large (50%) energy transfer into medium by elastic reactions and recoil
(cf. JEWEL, AMY, MARTINI, opacity expansions like GLV or WHDG, . . .)

• A **strongly coupled** system described by the AdS/CFT duality
→ cannot be decomposed into quasiparticles, but drag forces
→ rather than with density T^3, effects scale with T^4

• **Static** color dipole scattering centers
→ simplifies kinematics in pQCD interactions with medium, no recoil
→ has no elastic energy loss
→ **no physics motivation**, just an *ad hoc* assumption
(cf. ASW, Q-PYTHIA,. . .)

• No idea
→ medium appears via transport cofficients $\hat{q}$ and $\hat{e}$
→ parametrize the non-perturbative interaction in terms of exchanged momenta
(cf. YaJEM, HT, . . .)

Putting it into the medium

What part of the evolution equations gets modified?

• The splitting kernels $P_{i\to jk}(z)$
$\rightarrow$ underlying assumption: asymptotic kinematics, no scale in the problem
$\rightarrow$ okay for *vacuum QCD*, but the medium has a scale T
$\Rightarrow$ leads to **fractional energy loss** models where radiation scales $\sim zE_{jet}$
(Q-PYTHIA, BW. . .)

• The kinematics entering the evolution equations
$\rightarrow$ parton may pick up virtuality providing additional radiation phase space, $\hat{q}$
$\rightarrow$ parton may loose energy to medium degrees of freedom, $\hat{e}$
$\rightarrow$ both change the phase space limits branching by branching
$\Rightarrow$ breaks energy momentum in the shower, only recovered if medium included
(YaJEM, JEWEL, . . .)

• None - combine energy loss of on-shell partons with vacuum fragmentation
$\rightarrow$ **energy loss approximation**, not applicable for all observables
$\rightarrow$ **hybrid models** where part of the shower evolution before the medium is done
$\Rightarrow$ probabilistic **energy shift** of parton before fragmentation
(MARTINI, PYQUEN, ASW, WHDG, GLV, . . .)

Constraining parton-medium interaction

Task: use the available data to find out which of these ideas are viable

Strategy:

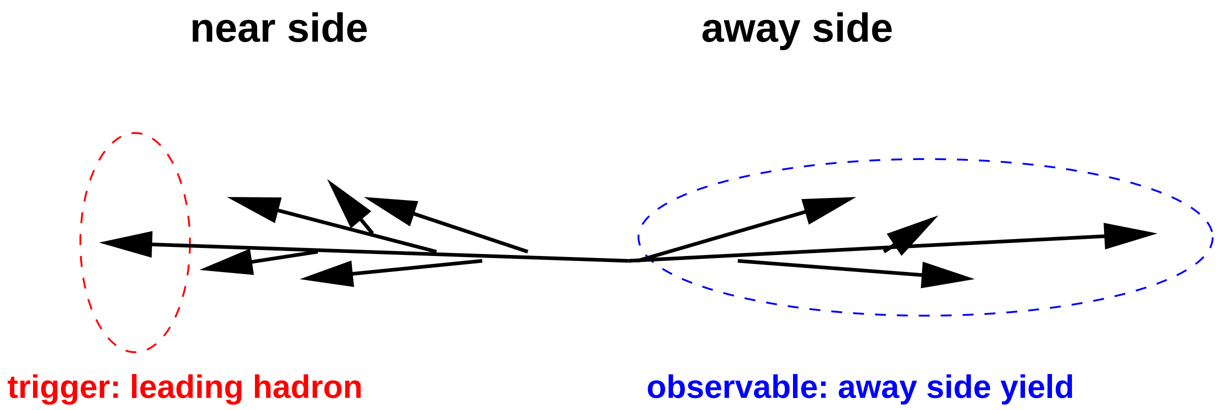
• model combination should describe all observables for given medium
$\longrightarrow$ no additional hydro ambiguity for R_{AA} and I_{AA} in 0-10% central AuAu

• find observable which is not very sensitive to choice of hydrodynamics
$\longrightarrow$ verify by using different hydro backgrounds
$\longrightarrow$ see what scenarios can be ruled out beyond hydro uncertainty

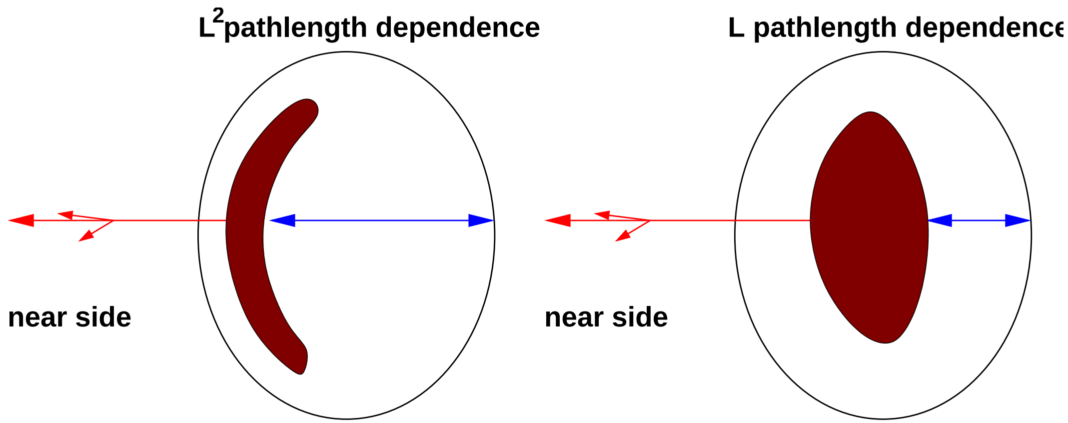
• model combination should describe $\sqrt{s}$ excitation
$\longrightarrow$ but notion of 'same hydro' at RHIC and LHC is dubious
$\longrightarrow$ allow for O(30)% background extrapolation uncertainty
$\longrightarrow$ see what scenarios can be ruled out beyond that uncertainty

$\Rightarrow$ all models in the following tuned to describe R_{AA} in central AuAu at 200 AGeV

I_{AA} OF HADRONS

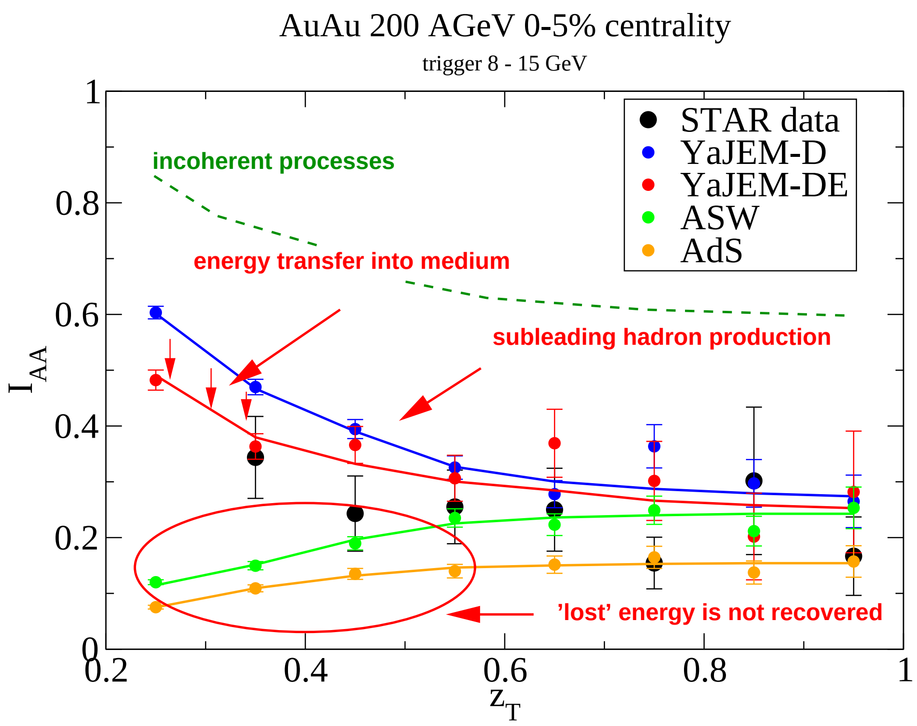


$$I_{AA} = \frac{\text{yield per trigger medium}}{\text{yield per trigger vacuum}}$$



I_{AA} OF HADRONS

RHIC 200 AGeV central collisions, $z_T = P_T^{assoc}/P_T^{trigger}$



- basic structure — suppression at high z_T, hint of upturn at low z_T

$\longrightarrow$ energy loss and medium-induced radiation

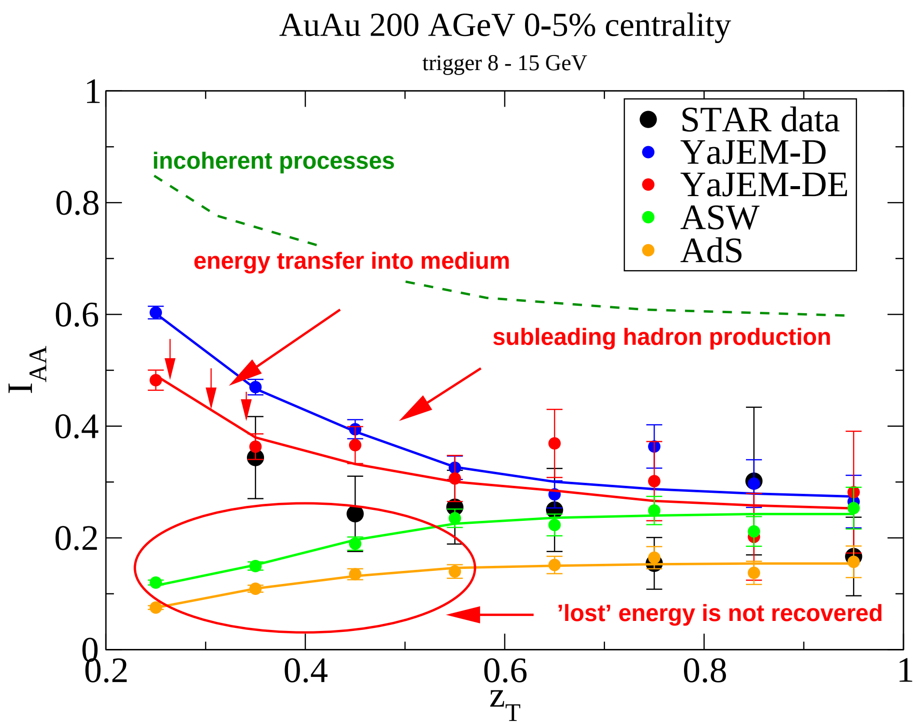
$\Rightarrow$ rules out energy loss models — energy is visibly recovered at 2-3 GeV scales

$\Rightarrow$ disfavours AdS/CFT strong coupling which does not predict induced radiation

T. Renk, Phys. Rev. C **84** (2011) 067902

I_{AA} OF HADRONS

RHIC 200 AGeV central collisions, $z_T = P_T^{assoc}/P_T^{trigger}$



- normalization is very sensitive to pathlength dependence

$\rightarrow$ just 20% hydro uncertainty

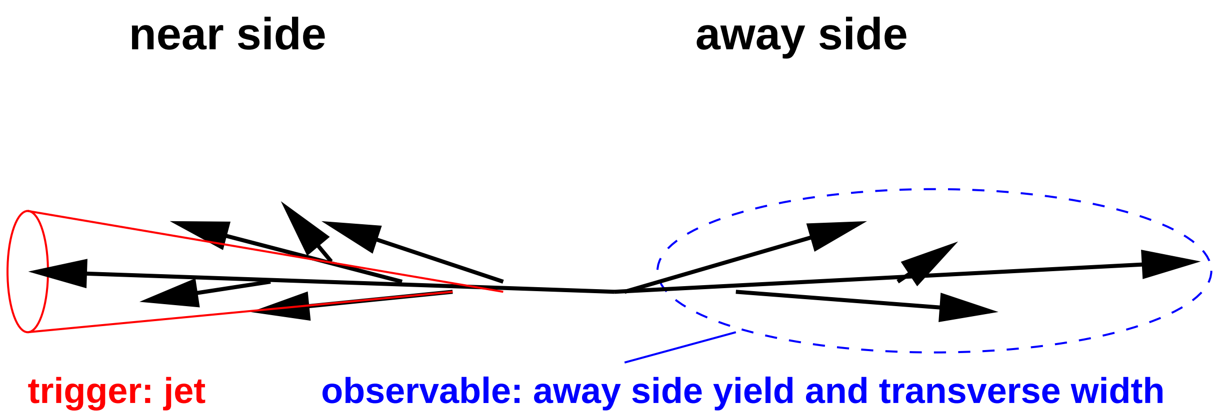
$\Rightarrow$ constrains incoherent loss into medium dof from above to 10-20%

$\Rightarrow$ disfavours models based on medium as quasi-free parton gas

- magnitude of the upturn is sensitive to loss into medium dof

$\Rightarrow$ constrains incoherent energy loss into medium from below to $\sim$ 10%

I_{AA} IN JET-H CORRELATIONS

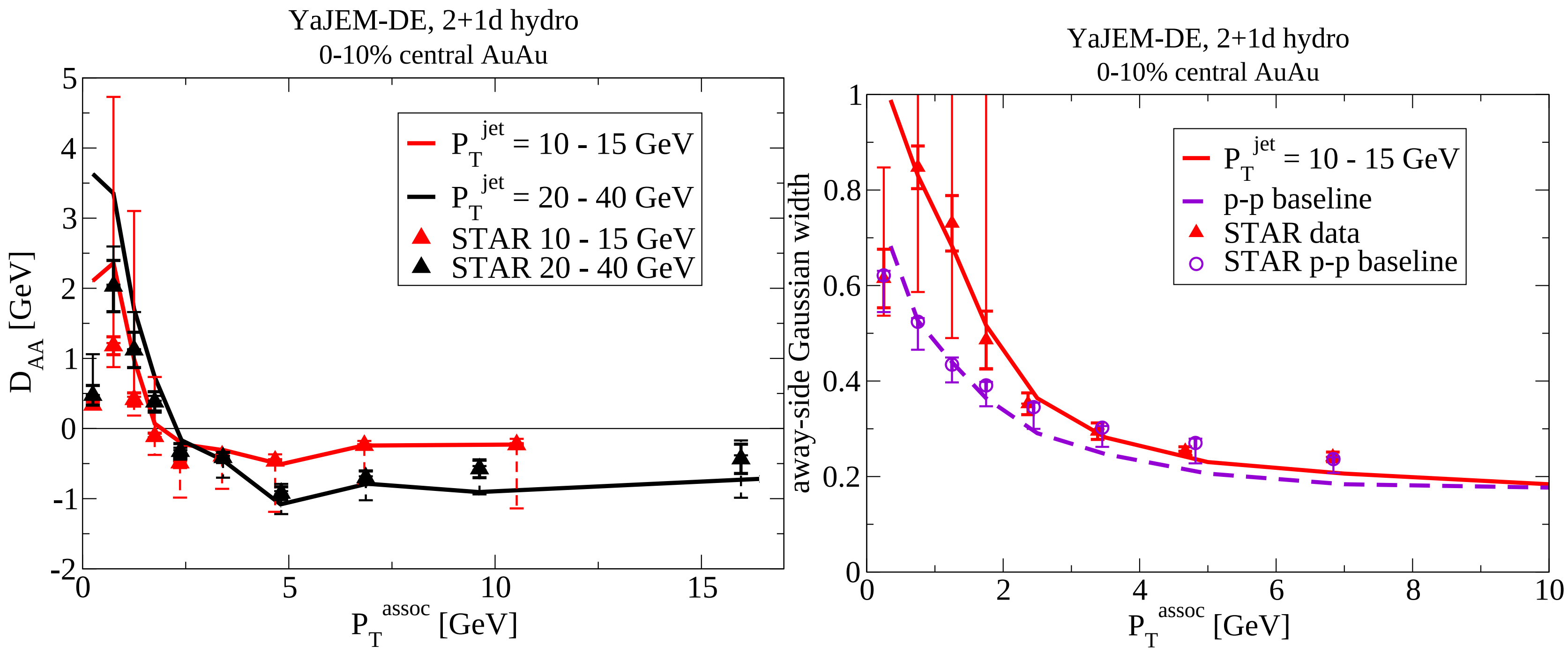


$$D_{AA} = \text{yield}_{AA}(P_T)\langle P_T\rangle - \text{yield}_{pp}(P_T)\langle P_T\rangle$$

(this is also a conditional probability, and trigger biased)

I_{AA} in jet-h correlations

- high statistics differential long. and transverse picture of away side jet



- suppression turns into enhancement of balance function at around 3 GeV

$\longrightarrow$ this happens independent of trigger energy (!)

$\longrightarrow$ transverse correlation width changes at the same scale

$\Rightarrow$ rules out fractional energy loss models

- differential picture of induced radiation spectrum, perturbatively predictable

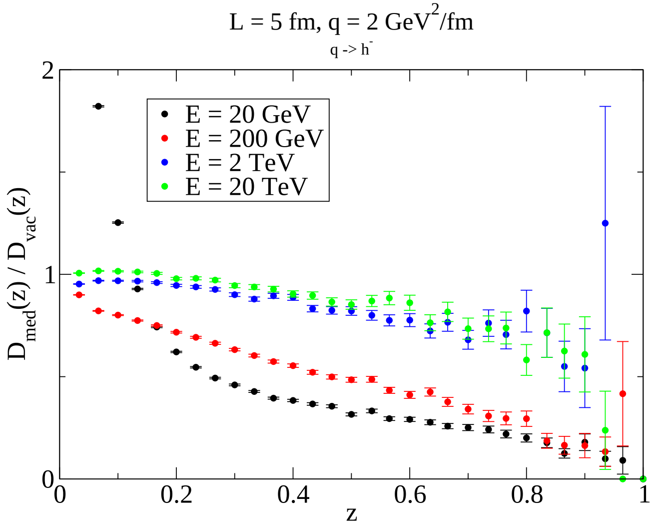
T. R., Phys. Rev. C **87** (2013) 2, 024905

Other observables

Bigger picture:

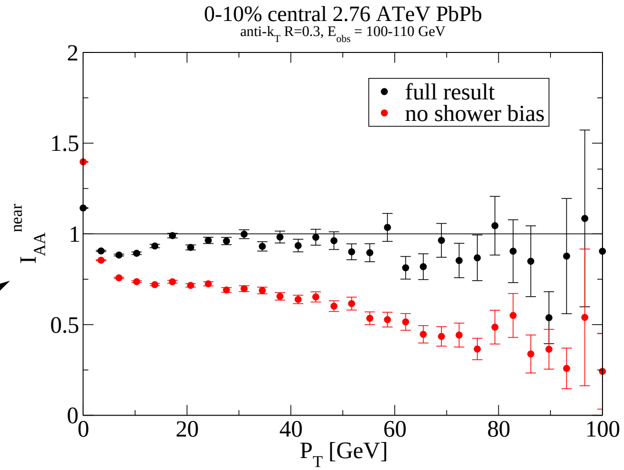
unfiltered distribution

(theoretical object)

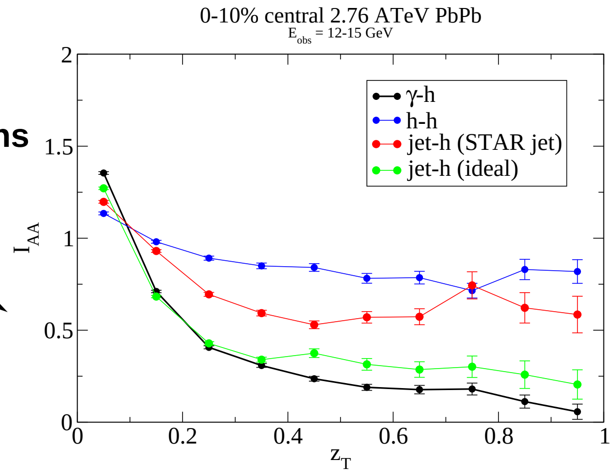


seen through

clustering



jet correlations

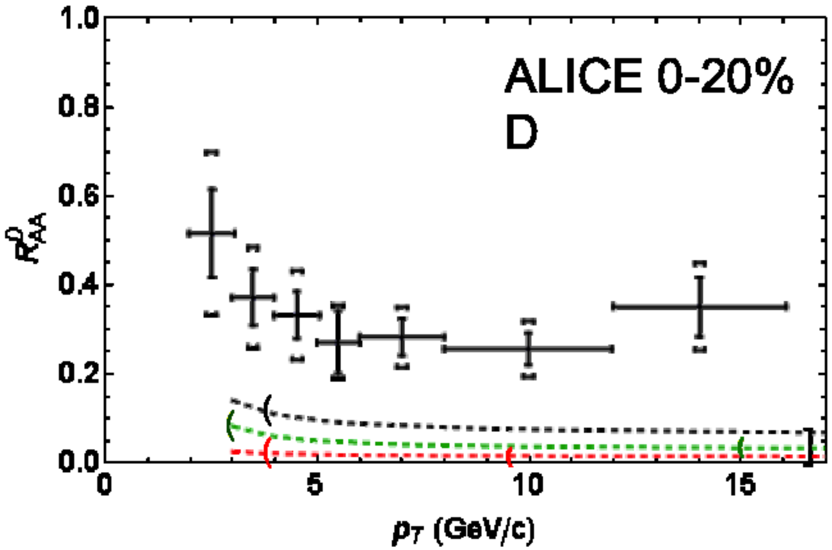


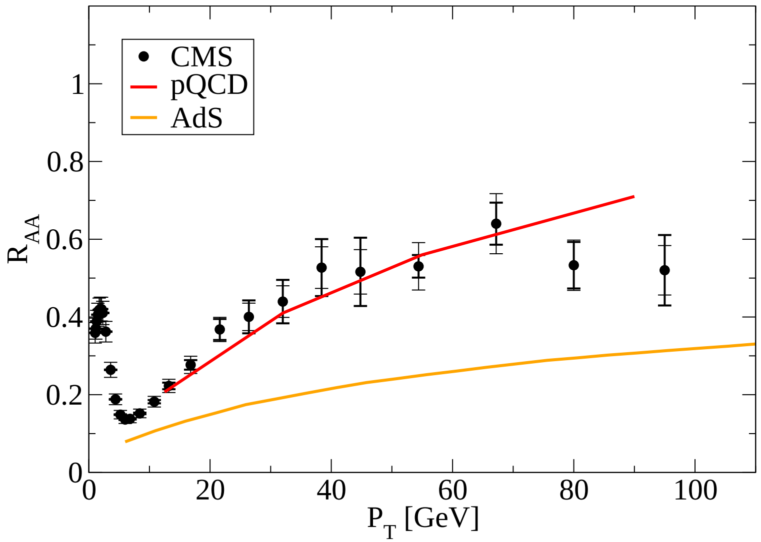
We see this same distribution in fact over and over in different observables, just filtered through a different bias caused by the trigger condition. The message remains the same.

AdS, light and heavy quarks

Different constraint: excitation functions in $\sqrt{s}$

- pQCD expects effect $\sim T^3L^2$, strong coupling instead $\sim T^4L^3$





- requires care to take 'same' hydro — predictive model for initial state (here EKRT)

$\Rightarrow$ AdS techniques do not naturally scale correctly for either light or heavy quarks
$\rightarrow$ (dispensing with realistic hydro, it is possible to make them scale for $R_{AA}\ldots$)

$\Rightarrow$ holography is out — at best it gets a subset of observables

W. Horowitz, Nucl. Phys. A904-905 **2013** (2013) 186c,T. R., Phys. Rev. C **85** (2012) 044903

Summary parton-medium interaction

• the medium modification of showers is **not**. . .
→ well described by strong coupling
→ compatible with a picture of the medium as free parton gas
→ suitably cast into the form of a fractional energy loss

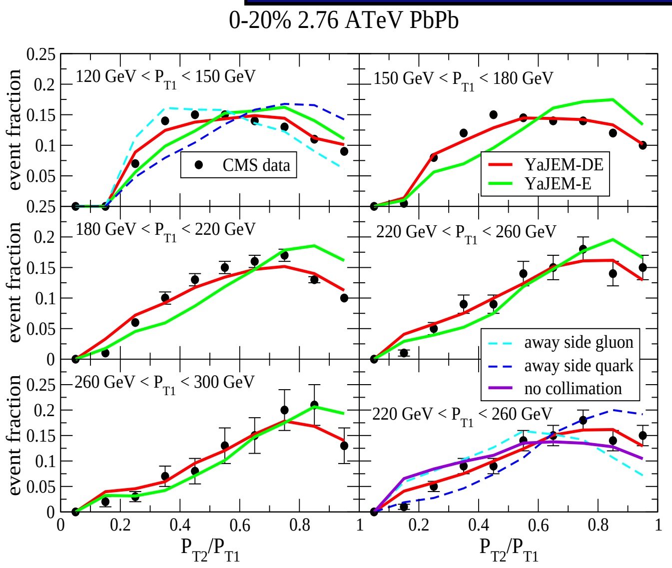
• beyond leading parton energy loss, the induced radiation pattern is. . .
→ observed in its transverse and longitudinal structure
→ able to constrain the energy transfer into medium dof
→ calculable in pQCD based models

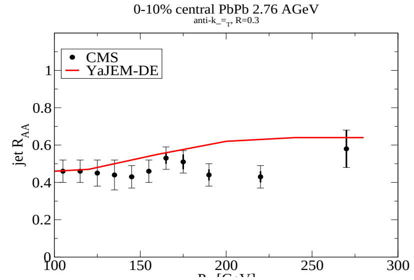
Given the constraints provided by the existing data, the properties of the aprton-medium interaction are in fact very well known. There is very little room for model assumptions left if the constraints are all taken seriously.

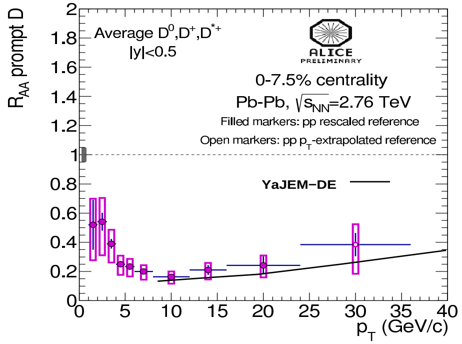
• currently the data can be explained by medium-modified radiation phase space
→ no evidence of 'interesting' effects — color reconnection, angular decoherence. . .

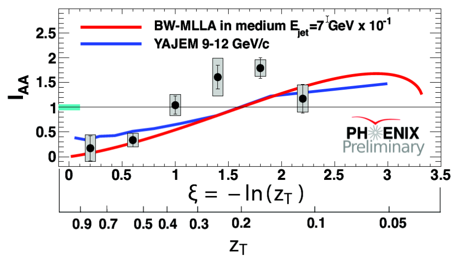
Can this explain all the other data?

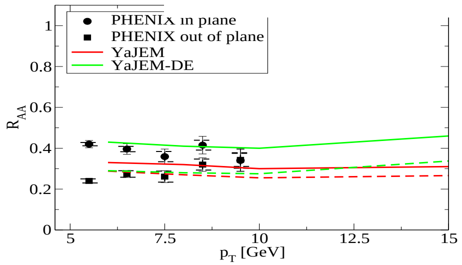
Other observables











⇒ reasonable description of different observables (only selection shown here)

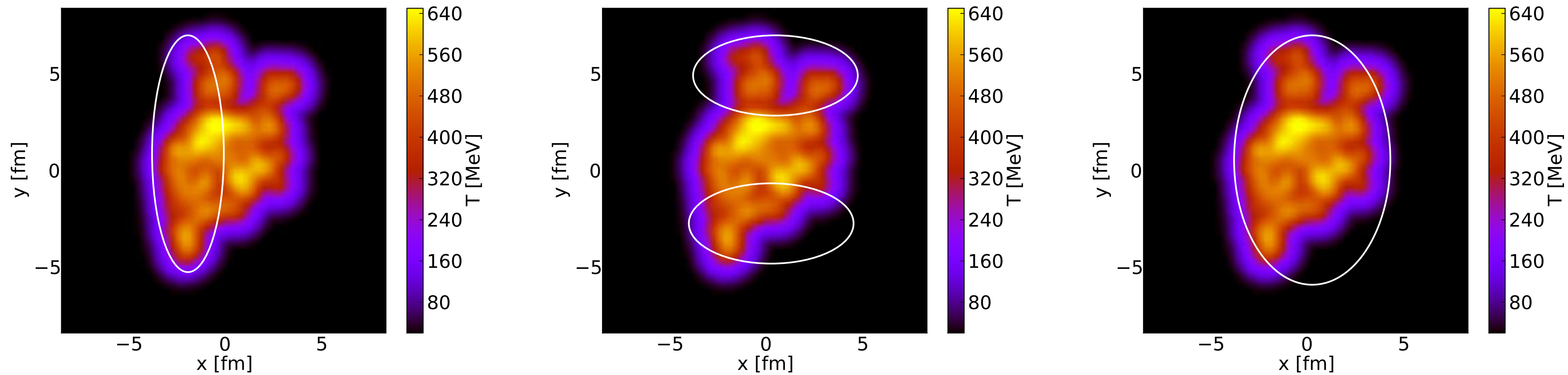
→ clustered observables — dijet imbalance, h-jet correlation, jet R_{AA}, jet FF

→ heavy quark suppression — D-meson R_{AA}

Time to think about tomography!

T. R., 1310.5458 [hep-ph]; T. R., Phys. Rev. C **86** (2012) 061901; T. R., Phys. Rev. C **83** (2011) 024908; T. R., Phys. Rev. C **85** (2012) 044903

III. Tomography 2.0

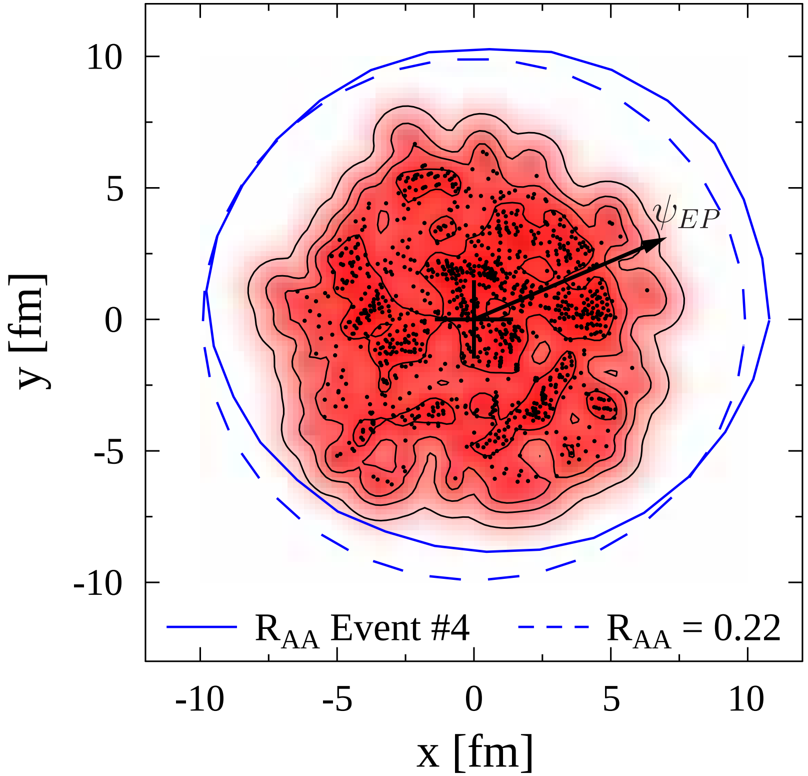


State of the art of medium description: EbyE hydro with initial state fluctuations

Challenge: probe this in a differential way!

Tomographic information content

Ideal tomography: if we could image the same event over and over in hadron R_{AA}:



$\longrightarrow$ even then, not much fine structure reflected in R_{AA}

$\longrightarrow$ $\langle \cdots \rangle$ involves massive averaging and **huge (!)** information loss

$\Rightarrow$ no hope for model-independent tomographic information by direct inversion

T. R., H. Holopainen, J. Auvinen and K. J. Eskola, Phys. Rev. C **85** (2012) 044915

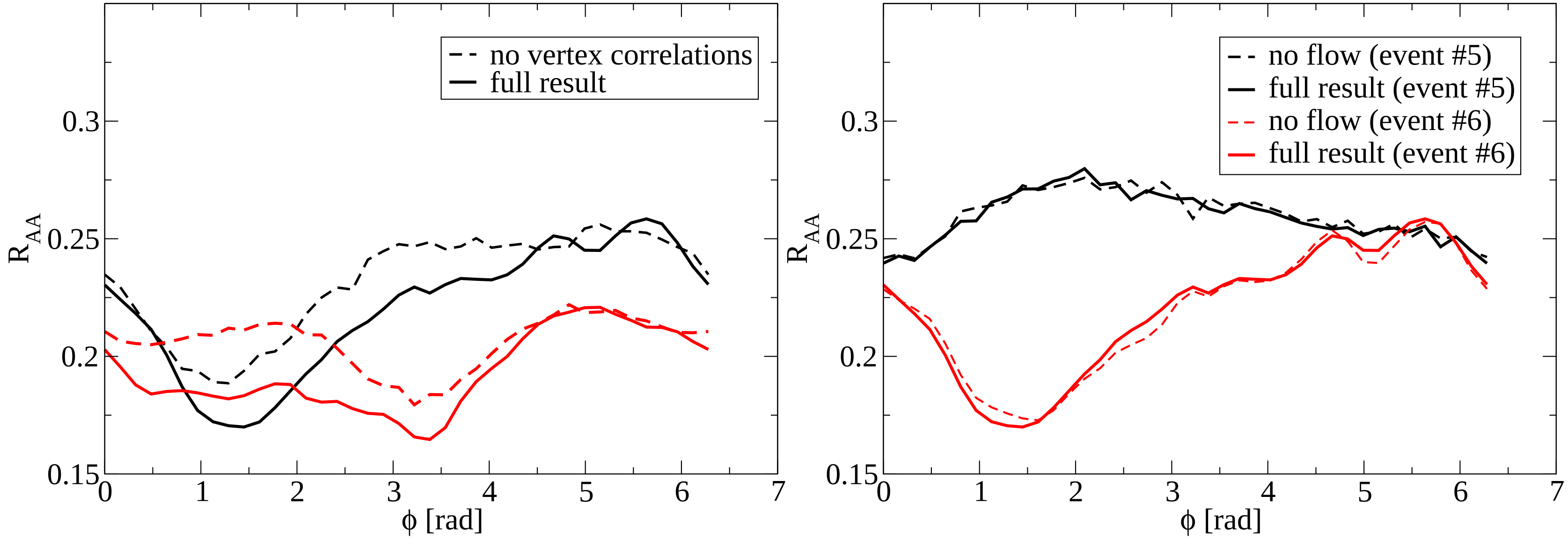
Technical issues

- event plane $\neq$ reaction plane — needs to be treated correctly
- need to use **same set** of binary collision vertices for hydro and jet

$\longrightarrow$ correlation between jet vertices and 'hotspots'

- strong initial pressure gradients lead to initially irregular flow field

$\longrightarrow$ since parton-medium interaction couples to flow, need to be considered



$\Rightarrow$ strong inter- and intra-event fluctuations

$\Rightarrow$ correlation matters in practice, flow correction does not

T. R., H. Holopainen, J. Auvinen and K. J. Eskola, Phys. Rev. C **85** (2012) 044915

Is it v_2?

Observation: Difference in-plane to out of plane is attenuation physics
$\rightarrow$ fluctuating mean pathlength
$\rightarrow$ fluctuating density
$\rightarrow$ fluctuating jet evolution even for fixed path
$\rightarrow$ $\langle \Delta E \rangle = f(\langle L \rangle)$ with f non-linear

Is this well represented by a v_2 at high P_T, i.e. is the modulation between in-plane and out of plane direction really sinusoidal?

$\Rightarrow$ Yes — when averaging over O(50) events, all structure except v_2 vanishes!
$\rightarrow$ this is neither trivial nor well understood

- binning with respect to the bulk v_3 event plane

$\rightarrow$ results in a jet v_3 modulation in the calculation

- high P_T partons image the initial ϵ_n by attenuation

$\rightarrow$ complementary to bulk imaging by pressure gradients

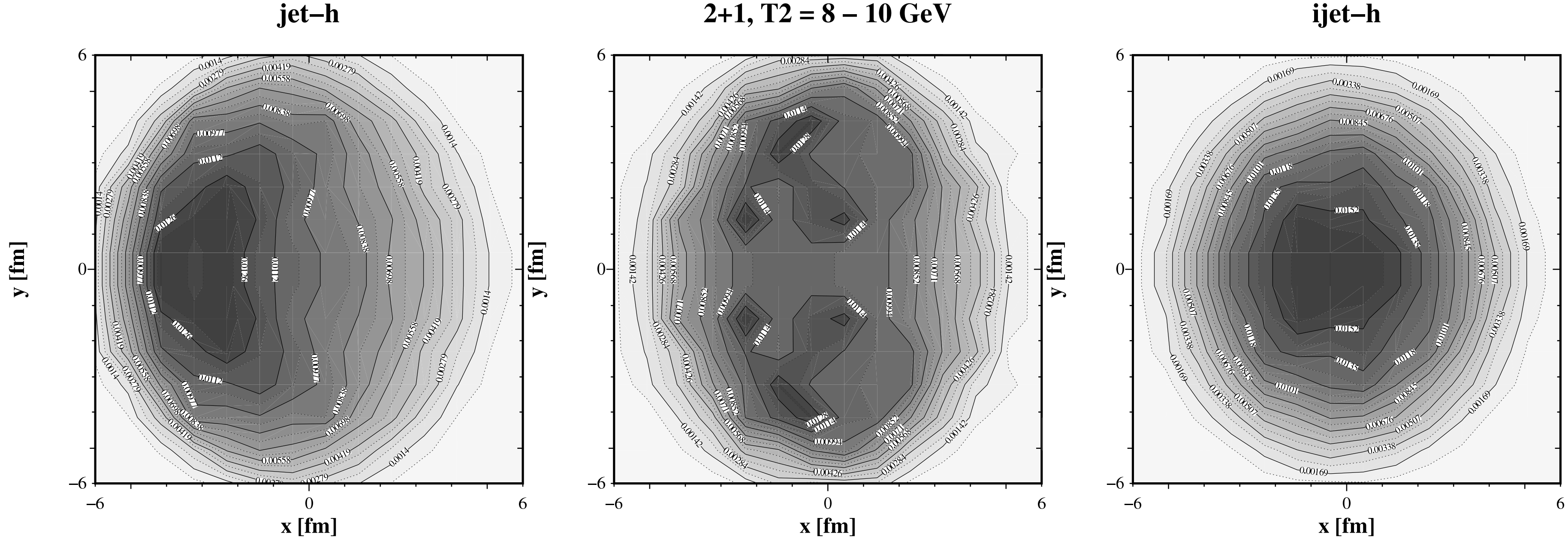
- current status: tension between hard and e.m. probes and bulk physics

$\rightarrow$ jet and photon v_2 are larger than models with moden EbyE hydro predict

$\Rightarrow$ is it possible that modern hydro models have too small initial eccentricity?

Beyond eccentricities

Observation: The geometry probed by a triggered correlation observable depends crucially on the trigger definition
→ STAR jet (PID and 2 GeV P_T cut), back-to-back hadron pair , CMS flow jets



⇒ allows to selectively probe center vs. periphery of the medium
→ can even be combined with v_n event plane dependence

• such plots have been around for years, huge difference between models
→ but with the huge set of constraining data, we can now **trust well-tested** models

T. R., Phys. Rev. C **88** (2013) 054902

Tomography 2.0

Strategy: Distinction between key and tomographic observables

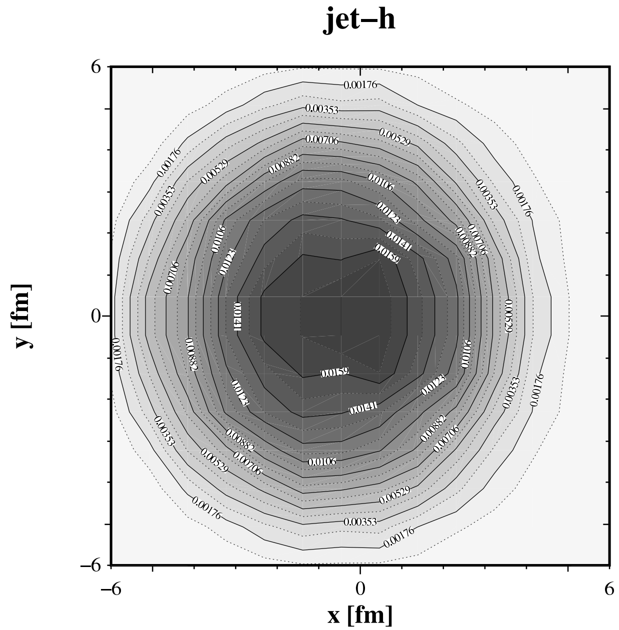
• key observables: little sensitivity to choice of hydro background
$\longrightarrow$ use to benchmark, constrain and validate models

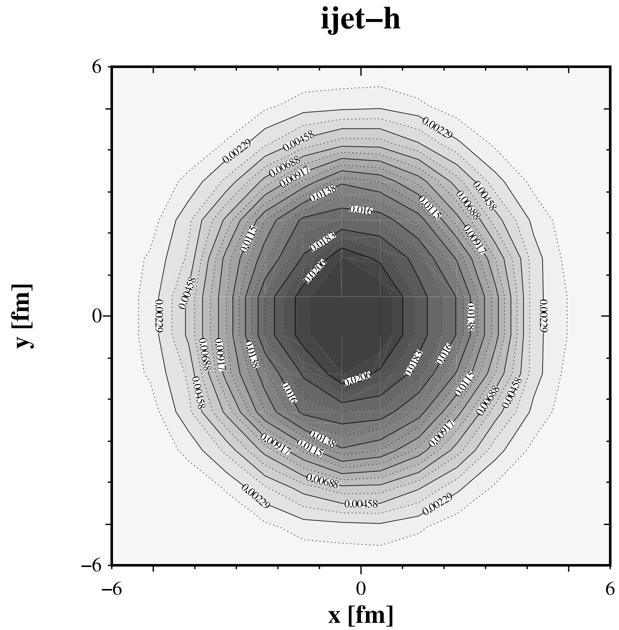
• tomographic observables: large sensitivity to choice of hydro background
$\longrightarrow$ use to test hydro evolution scenarios as imaged by jets
$\longrightarrow$ measure with biases designed to probe certain physics
$\longrightarrow$ this yields **constraints for hydro**, not for parton-medium interaction

This strategy is viable now, because unlike a few years ago we now have enough precise data sets to really constrain models. Thus, the ambiguity in selecting parton-medium interaction models is largely gone if enough data is used. We also have systematic knowledge what observables are sensitive to the background and what observables are not.

RHIC vs. LHC

- at LHC, things work less well





Observation: Having a harder primary parton spectrum unbiases geometry. The environment to do detailed tomography at RHIC is *much* better than at LHC (and would even be improved by lowering beam energy to 130 GeV or so).

T. R., Phys. Rev. C **88** (2013) 054902

Summary

Main ideas of this presentation:

• there is **no substantial uncertainty** with regard to jet-medium interaction physics
$\longrightarrow$ there are however many incompletely tested models

• distinction between **key observables** and **tomographic observables**
$\longrightarrow$ little vs. high sensitivity to the assumed geometry

• shift in the view of biases
$\longrightarrow$ the goal should not be to avoid them but to **design** them properly

• shift in the view of the role of harder primary parton spectrum
$\longrightarrow$ often (statistics!) an advantage, sometimes (tomography) clearly not
$\longrightarrow$ RHIC: tomography machine, LHC: key observable machine