The physics of parton-medium interaction

— an assessment of the current knowledge of jet quenching

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- Jet building blocks
- Jets in medium
- Pathlength and coherence
- Medium DOFs
- Breaking of FF self-similarity
- Observables and constraints
- Conclusions

Basics of Jet Physics

• factorized QCD allows us to compute the hard process given the PDFs

$$d\sigma^{NN\rightarrow h+X} = \sum_{fijk} f_{i/N}(x_1,Q^2)\otimes f_{j/N}(x_2,Q^2)\otimes \hat{\sigma}_{ij\rightarrow f+k}$$

• this yields highly virtual final state parton which branch into a parton shower
$\rightarrow$ QCD radiation, described by iterated sequence of $1 \rightarrow 2$ splittings

Radiation requires:
• charge (i.e. a vertex, coupling to color)
• open phase space
• no cancellation by interference

• $1 \rightarrow 2$ vertices give (approx.) the splitting functions (where $E_a = zE_b + (1-z)E_c$)

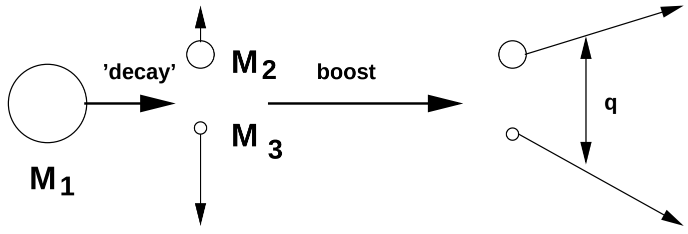
$$P_{q\rightarrow qg}(z) = \frac{4}{3}\frac{1+z^2}{1-z} \quad P_{g\rightarrow gg}(z) = 3\frac{(1-z(1-z))^2}{z(1-z)} \quad P_{g\rightarrow q\overline{q}}(z) = \frac{N_F}{2}(z^2+(1-z)^2)$$

$\Rightarrow$ depend on z only — **self-similarity** of FFs

The Phase Space

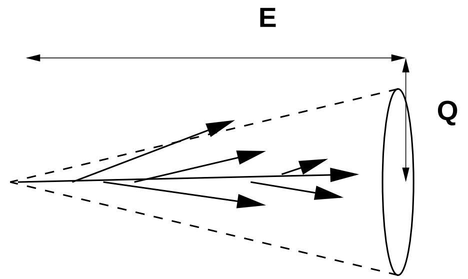
- the initial parton has a virtuality $Q_i \sim p_T$, this makes the phase space
$\longrightarrow$ this quantity is invariant and equals (for perfect reconstruction) the jet mass M_{jet}

- each branching equals the decay of a heavy resonance into two lighter ones
$\longrightarrow$ here $M_i = \sqrt{m_i^2 + Q_i^2}$ with m_i the bare parton masses



- difference between M_1 and $M_2 + M_3 \longrightarrow$ transverse momentum separation
$\longrightarrow$ remember, M_{jet} is invariant!

Translation: MLLA people rather discuss in terms of jet opening angle $\theta \approx Q/E$.
This is the 'natural' radius containing the energy of a jet with given M_{jet}



The Phase Space

- branchings happen throughout open phase space in z (here $t = \ln(Q^2/\Lambda^2_{QCD})$)

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

- kinematic limits $z_\pm$ do **not** depend on z only — breaking of self-similarity

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

- branchings can lead to any allowed M_b, M_c, need to be integrated over

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

- One experimental signature: hard fragmentation for c and b quarks

$\Rightarrow$ 'dead cone effect' — phase space reduction when m_i is large

The Spacetime Picture

- Heisenberg helps

pQCD interactions involve intermediate, highly virtual partons at scale Q
$\longrightarrow$ these have lifetimes $1/Q$
$\longrightarrow$ with boost factor E/Q, we get $\tau_{av} \sim E/Q^2$

- no exact localization, probability density, but functional form depends on small print
  $P(\tau) \sim \exp[-\tau/\tau_{av}]$ (YaJEM) or
  $P(\tau) \sim \exp[-(\tau/\tau_{av})^2]$ (Gaussian wave packets) $\longrightarrow$ no big difference in practice

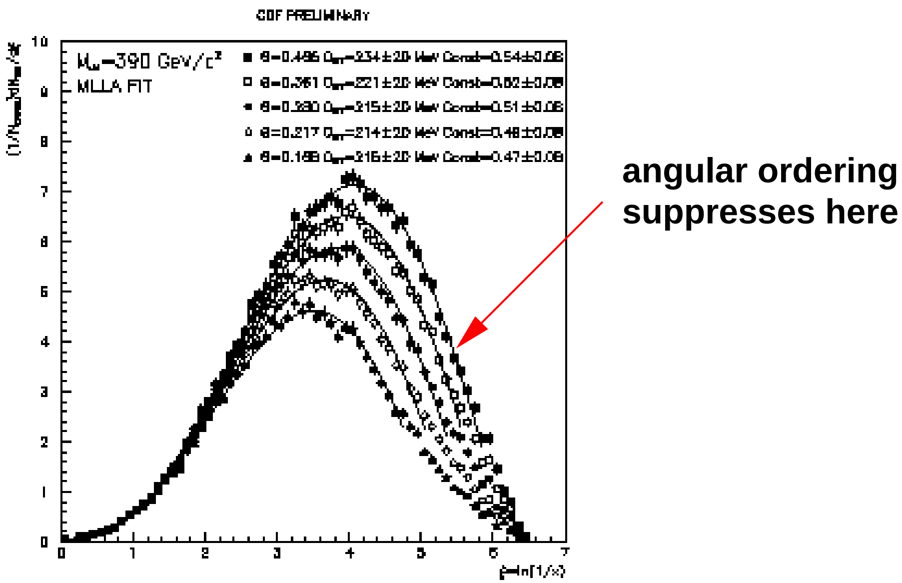
- this allows to assign a spacetime history branching by branching in a MC code

Translation: Antenna people like to discuss this in terms of spatial resolution scale. After the time τ, the spatial size of an antenna with opening angle θ is $d \sim \tau\theta \sim E/Q^2 \cdot Q/E = 1/Q$, i.e. parton virtualities set the transverse spatial resolution on average, but the Heisenberg principle smears it probabilistically.

Angular ordering

- Since $Q_a \gg Q_b, Q_c$, transverse separation of daughters decreases each generation
$\rightarrow$ virtuality-ordered showers are on average angular ordered

- The antenna interference pattern effectively requires **exact angular ordering**
$\rightarrow$ What does this do?

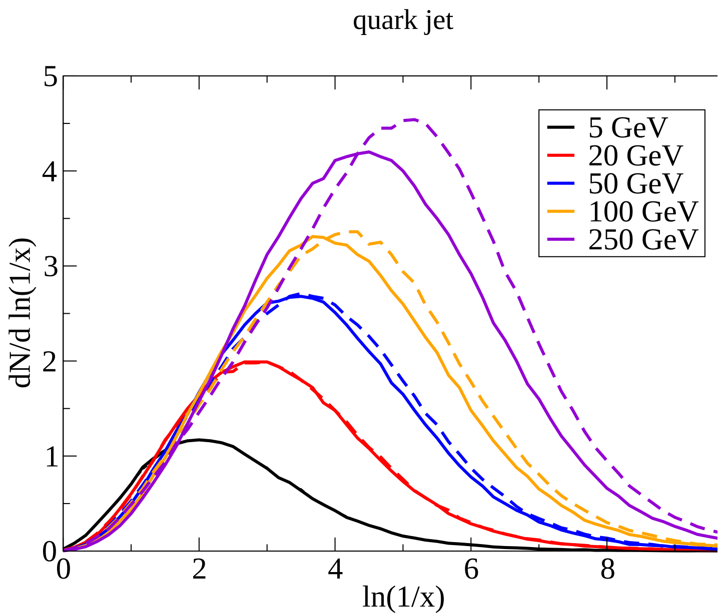


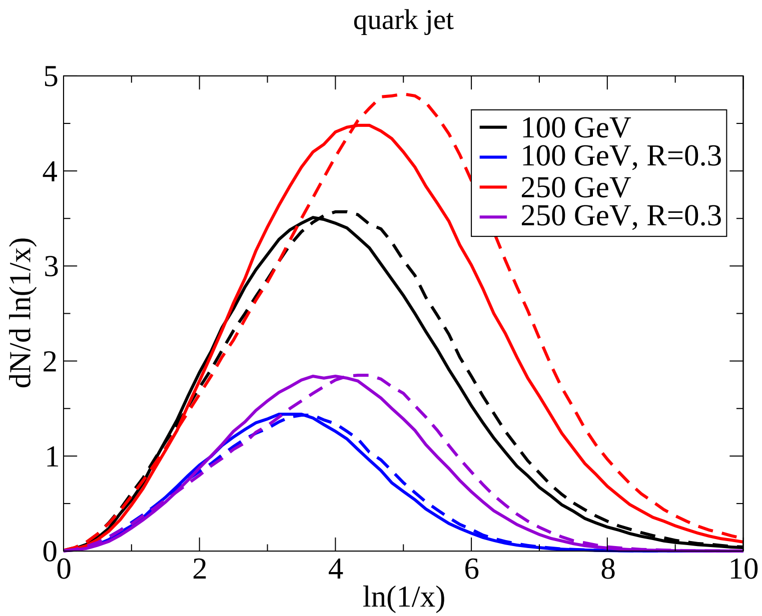
$\Rightarrow$ it cuts very soft gluon emission ($\xi = \log(1/x)$ with $x = E_{part}/E_{jet}$)

Angular ordering — the untold story

- However, if you leave MLLA where all is gluons and introduce hadron masses

$\longrightarrow$ a different picture emerges





$\Rightarrow$ cuts the same region, angular ordering makes no real difference below 100 GeV

- for A-A relevant jet radii, difference is even smaller

$\longrightarrow$ finding biases reduce this even further

$\Rightarrow$ full effect of completely breaking angular ordering is $\sim 15\%$ in relevant kinematics

Intereference is not a leading effect!

The role of the medium — basic expectations

Assume all this happens in a thermal QCD medium, and jet and medium interact

- in the limit $t \to \infty$, the jet will thermalize and isotropize

$\to$ jet is high p_T and tightly collimated

$\to$ medium is at scale T and isotropic

$\Rightarrow$ broadening and softening of jet constituents proportional to interaction time

Corollary: Qualitative broadening of jets isn't a signature of anything in particular.

- jet P_T at LHC are $O(100)$ GeV, medium temperature is $O(0.5)$ GeV

$\to$ **scale separation**, the medium can not kinematically deflect a jet
(if you calculate it, the possible angle is about 0.17 deg)

Corollary: Jet axis, subjet structure etc. are set by hard physics even in medium.

- this means the jet partons have to lose energy on average

$\to$ jet partons with $p_T \sim T$ get soaked up by the medium

The role of the medium

Two basic mechanisms (cartoon warning!):

- energy is carried by interactions from jet partons into medium dof, $\hat{e} = dE/dx$

$\rightarrow$ diagrammatically $2 \rightarrow 2$ graphs where medium parton takes recoil

- interactions increase radiation phase space, $\hat{q} = dQ^2/dx$

$\rightarrow$ medium-induced radiation, e.g. $2 \rightarrow 3$ graphs

Example: medium-induced gluon radiation, multiple soft scattering limit

$\rightarrow$ gluon decoheres with a certain p_T separation once $\Delta Q^2 \sim p_T^2$
$\rightarrow$ the formation time for this is $\tau \sim L \sim E/\Delta Q^2$
$\rightarrow$ during this time, the gluon picks up the phase space $\Delta Q^2 = \hat{q}L$
$\rightarrow$ solving for the typically emitted gluon energy yields $E = \hat{q}L^2$, **LPM interference**

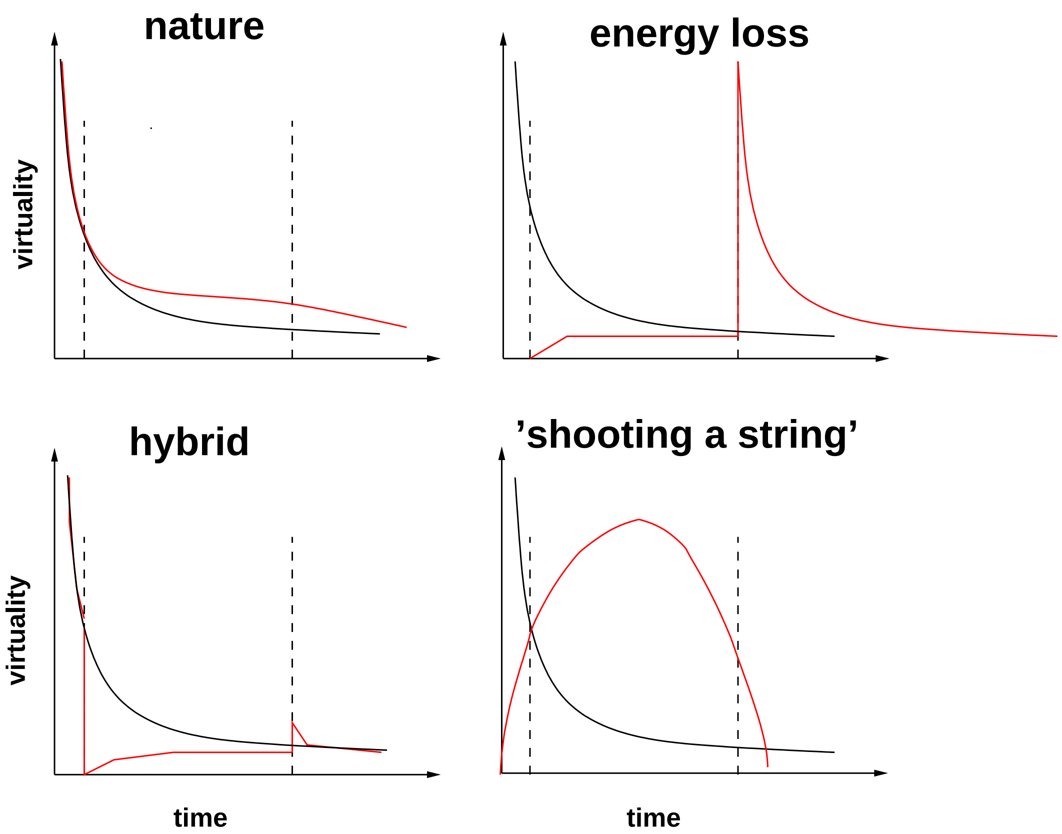
- different for direct (incoherent) energy loss, which typically has $\Delta E \sim L$

radiative vs. elastic = coherent vs. incoherent
pathlength dependence is the key

VIRTUALITY EVOLUTION OF LEADING PARTON

- virtuality evolution (cartoon) of leading parton in popular models

$\rightarrow Q_i = M_{jet}$ is invariant, but virtuality of every single shower parton drops rapidly



- many models do not get the time-ordering of virtuality evolution right

$\rightarrow$ e.g. eloss models compute ΔE for on-shell parton, then vacuum fragmentation

Does this matter?

Kinematical robustness and thermalization

Note that Q^2 can initially be O(hard scale), but ΔQ^2 is O(few T):

• for $Q^2 \gg \Delta Q^2$, the parton is **kinematically robust**, medium effect is small
$\longrightarrow$ jet evolution as in vacuum

Translation: Antenna people argue that if the medium resolution scale $d_{med} = 1/\Delta Q \gg d_{jet} = 1/Q$, the jet is not resolved by the medium and evolves as in vacuum. The condition implies $\Delta Q^2 \ll Q^2$ as above, the physics is the same.

• for $Q^2 \sim \Delta Q^2$, phase space modifications are large (but phase space isn't tagged!)
$\longrightarrow$ emission by emission, medium and vacuum radiation **cannot be distinguished**

• for $Q^2 \ll \Delta Q^2$ and $E^2 \ll \Delta Q^2$, strong parton deflection in branching
$\longrightarrow$ these partons **thermalize rapidly**, applicability of 'jet' formalism questionable

Corollary: Any soft gluon in medium is rapidly scattered to large angles. There is no need for an explanation for this, basic kinematics expects this (unless the medium is modelled in a way that it exchanges no momentum with the jet).

Kinematical robustness and thermalization

It does matter (a lot) whether you apply a ΔQ^2 to an on-shell parton or a parton with a high Q^2. On-shell partons are never kinematically robust.

$\rightarrow$ repeating gluon emission in multiple soft limit, we get now $E = Q^2 L + \hat{q} L^2$
$\Rightarrow$ very different pathlength dependence

Question: But can't we get the essentials right without getting the phase space precisely?

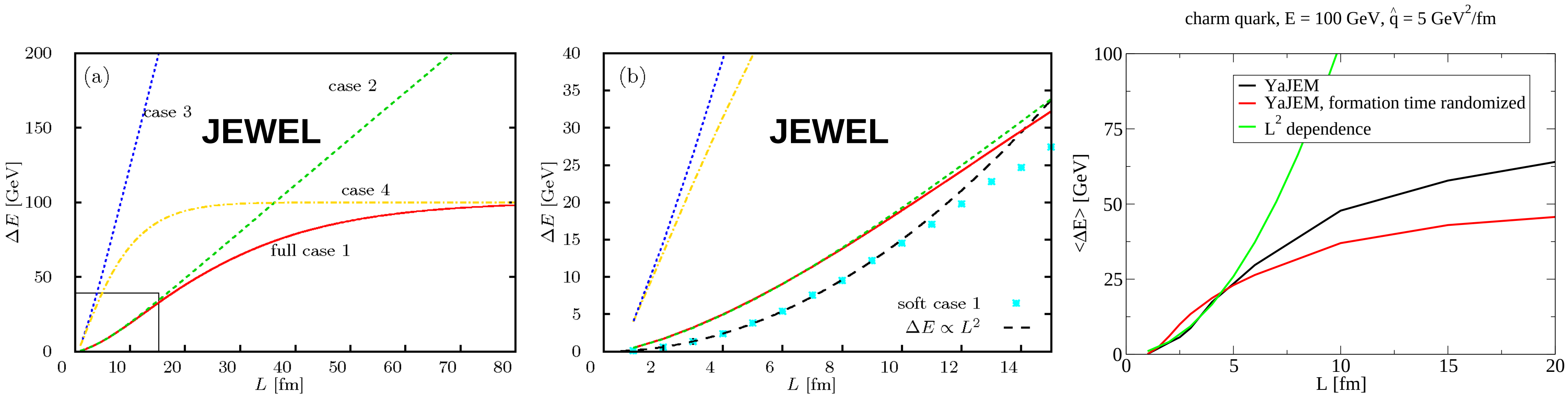
Answer: In eloss calculations, phase space needs to be cut 'by hand'. This leads to a factor 3 uncertainty in the quenching power of the medium.

W. A. Horowitz and B. A. Cole, Phys. Rev. C **81** (2010) 024909

There is no evidence known to me that we can get a good answer without computing the phase space accurately.

LPM effect in practice

- What do MC codes with exact kinematics make of the LPM effect?



$\rightarrow$ not much — L^2 dependence can be seen, but doesn't dominate the dynamics

$\Rightarrow$ any coherence seen in the data must come from somewhere else

The essentials

Let's summarize this:

• Phase space matters (a lot), hence virtuality evolution is important
→ phase space has been demonstrated to make factors three difference
→ virtuality evolution qualitatively modifies pahtlength dependence

• Once phase space is modeled, interference (LPM and AO) is a correction
→ by throwing phase space out, both LPM and AO can seem more important

• Nature does not tag vacuum from medium-induced radiation in an obvious way
→ so perhaps models shouldn't either?

• non-deflection of jets by medium is a consequence of scale separation
→ any reasonable model should predict this

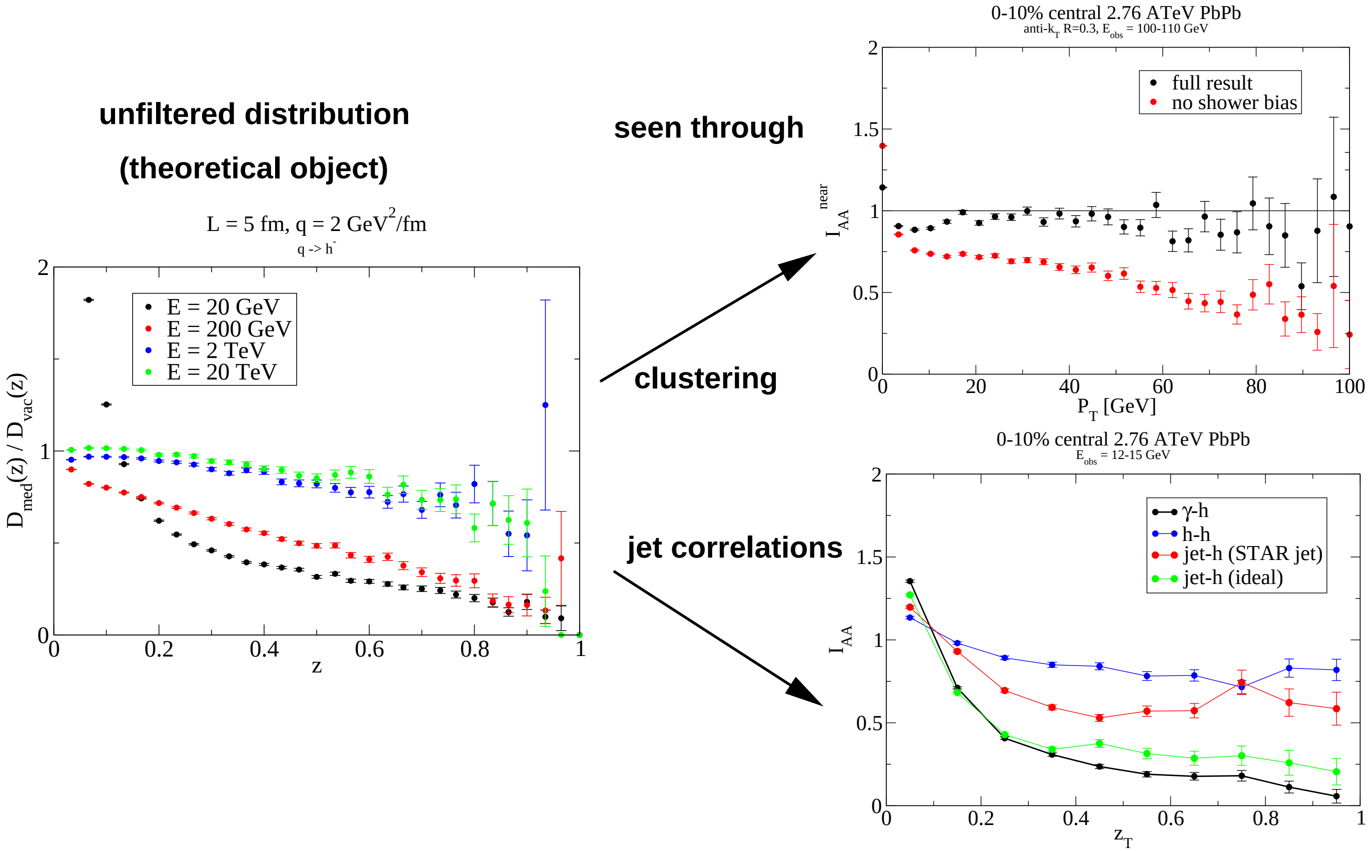
• energy flow to large angles requires only simple kinematics
→ any model which allows momentum flow between jet and medium gets this

Lots of in-medium jet properties are driven by simple physics.

→ There's more than one way to talk about the same physics.

Methodology

Idea: Observables are theoretical quantities, seen through specific biases

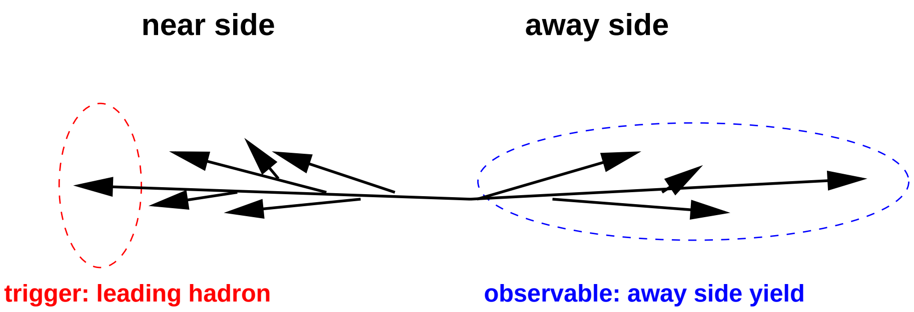


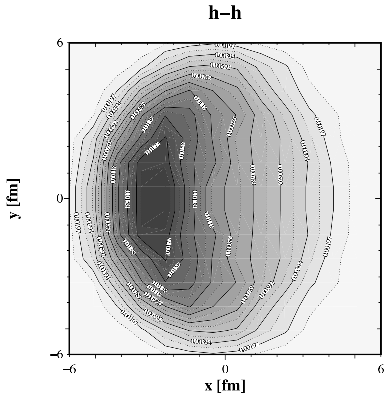
⇒ I will in the following assume that we understand the biases and focus on physics

T. R., Phys. Rev. C **88** (2013) 5, 054902

Coherence and pathlength

- focus on dihadron correlations — pathlength dependence via geometry bias





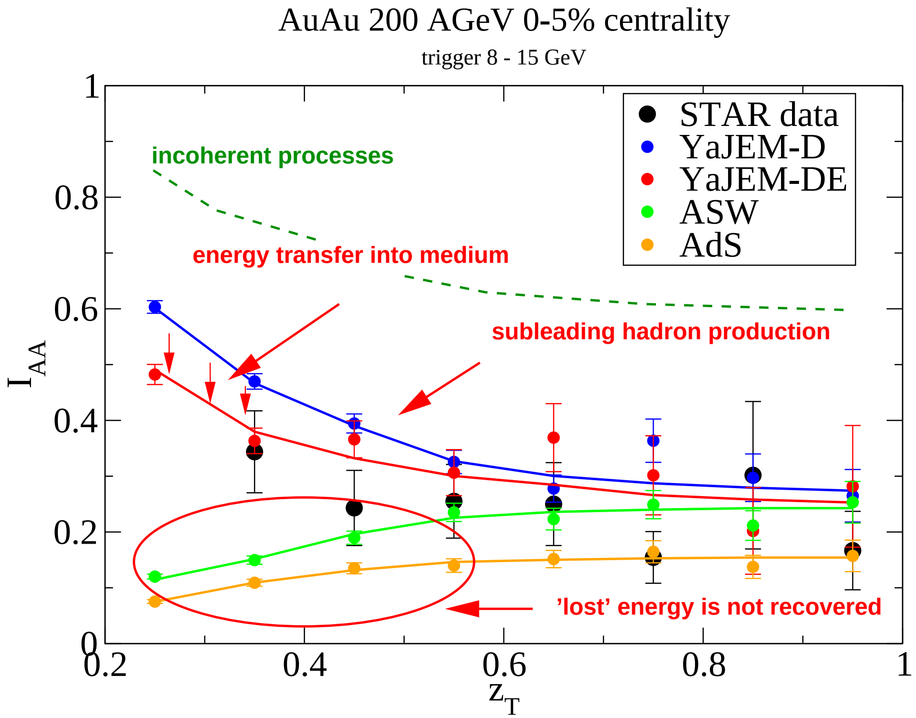
- eloss doesn't describe this
- data **require** coherence — badly

→ incoherent only is factor 2-3 wrong

→ 50% incoherent is still way above

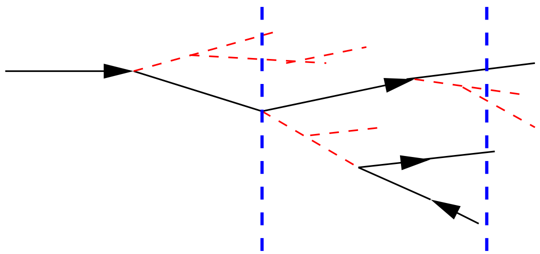
- LPM effect doesn't do this

→ then what does?



Coherence and pathlength

• A. Majumder: Q^2 evolution in medium is affected by medium size:



$\Rightarrow$ since $\tau \sim E/Q^2$, if we have only the length L there is a lower virtuality
$\rightarrow Q_{min} = \sqrt{E/L}$

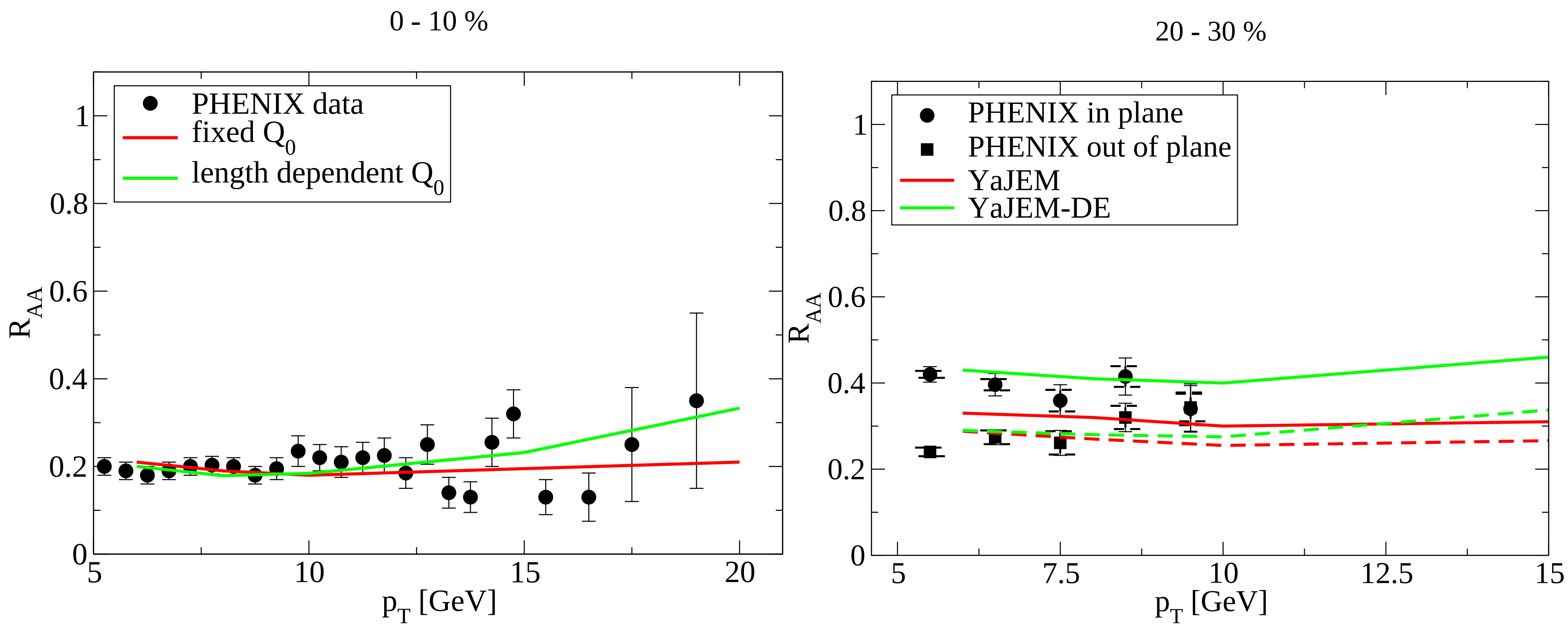
• in a long medium, the shower can evolve down to lower Q^2 than in a short medium
$\rightarrow \Delta Q^2 \sim Q^2$ much more likely to be reached
$\Rightarrow$ strongly non-linear response to pathlength, **requires virtuality evolution**

• at the same time, high E jets largely evolve outside the medium
$\rightarrow$ predicts an increase of R_{AA} with P_T

A. Majumder, 0901.4516 [nucl-th], T. R., Phys. Rev. C **83** (2011) 024908

Coherence and pathlength

- pre-LHC calculation: increase in $R_{AA}(p_T)$, fixes in-plane vs. out of plane



(I thought that's a cheap trick by Abhijit, and expected this to be ruled out due to the strong rise of R_{AA} predicted for LHC basically on day one. LHC data quickly convinced me otherwise.)

- note that YaJEM (fixed Q_0) has the LPM interference implemented
$\longrightarrow$ it just doesn't do much for pathlength

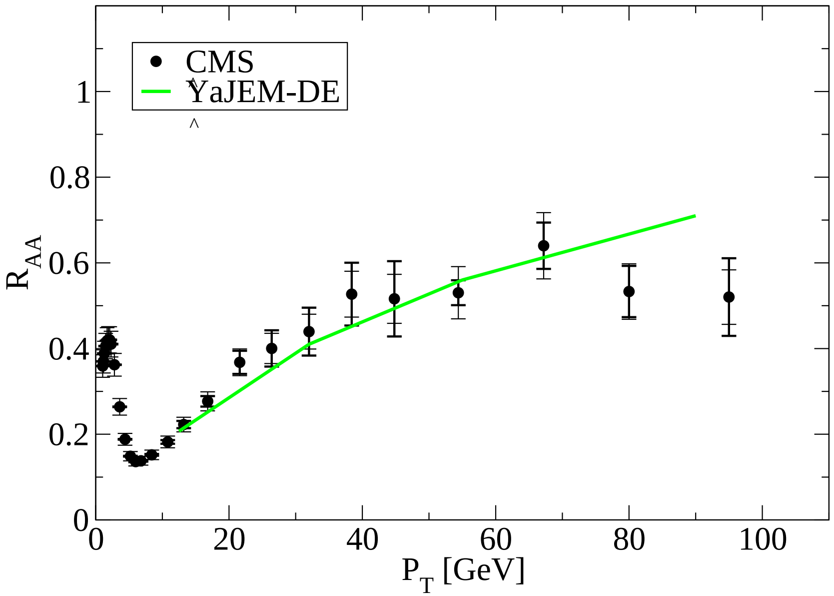
T. Renk, Phys. Rev. C **83** (2011) 024908

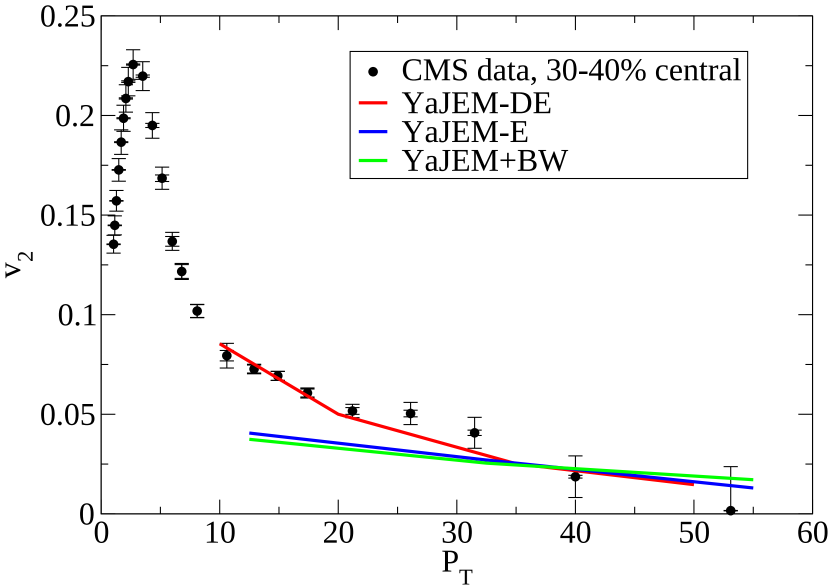
Coherence and pathlength

- this **drives** the rise with P_T

$\longrightarrow$ changing spectral slope then leads to flattening

$\longrightarrow$ postdiction of the data captures most of the details





- It's the $Q_0 \sim \sqrt{E/L}$ coherence which drives pathlength dependence!

$\longrightarrow$ interplay between E and L, should **predict** P_T dependence for v_2

$\Rightarrow$ as it does remarkably well

T. R., H. Holopainen, R. Paatelainen and K. J. Eskola, Phys. Rev. C **84** (2011) 014906, T. R., Phys. Rev. C **88** (2013) 1, 014905

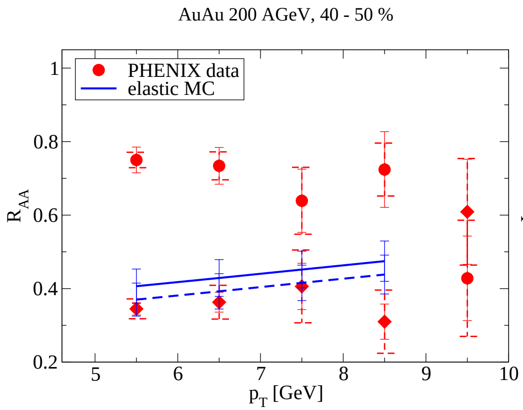
The role of the elastic channel

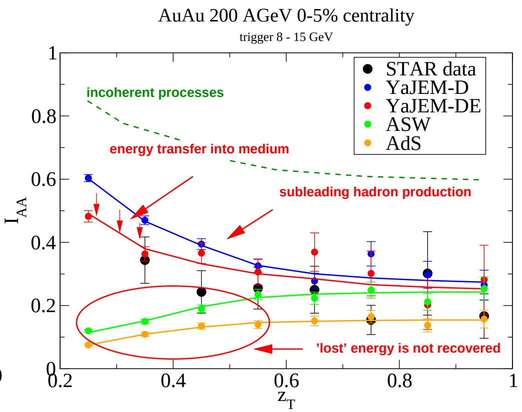
Question: What about the elastic channel?

• **If** one makes a model of pQCD scatterings on a thermal gas of quarks and gluons
$\longrightarrow$ then many calculations show that a modest α_s already gets $\sim$ 50% energy loss

S. Wicks *et al.* Nucl. Phys. A **784** (2007) 426J; Auvinen *et al.*, Phys. Rev. C **82** (2010) 024906, . . .

• and **inevitably** pathlength gets wrong by factors 3 and more





• We don't have to accept the conditional though

$\Rightarrow$ medium DOFs take a surprisingly small amount of recoil
$\longrightarrow$ in YaJEM, just about 10% gives the best description of data

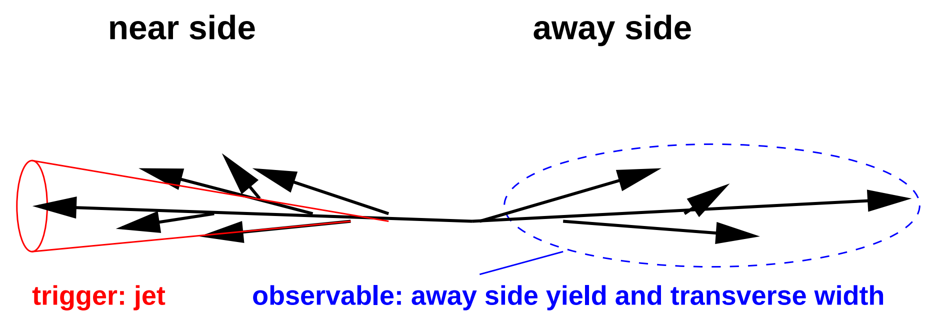
Reveals something fundamental about the medium DOFs probed by a jet!

J. Auvinen, K. J. Eskola, H. Holopainen and T. R., Phys. Rev. C **82** (2010) 051901; T. Renk, Phys. Rev. C **76** (2007) 064905

FF SELF-SIMILARITY AND ITS BREAKING

- focus on jet-h correlations

→ very differential picture of the away side induced radiation



- high P_T^{assoc}: yield reduction

→ jet quenching, energy loss

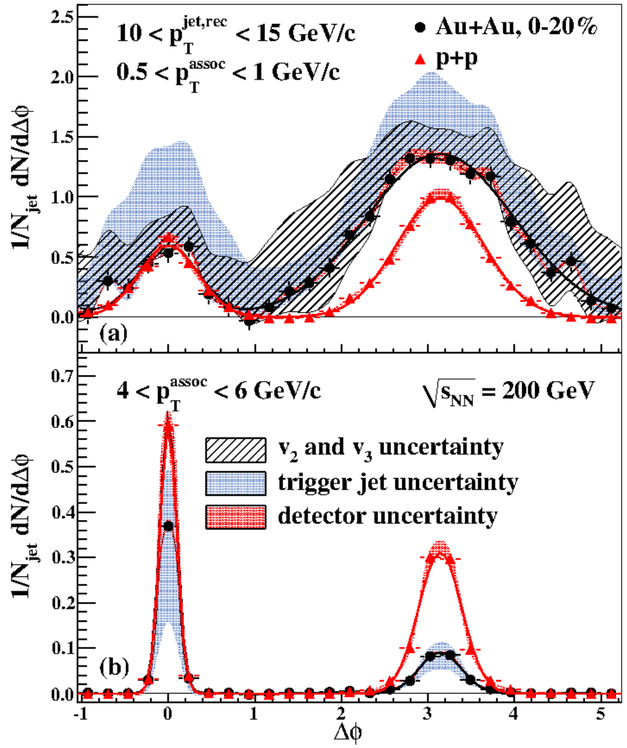
- low P_T^{assoc}: widening and yield increase

→ induced radiation

- crossing point from decrease to increase

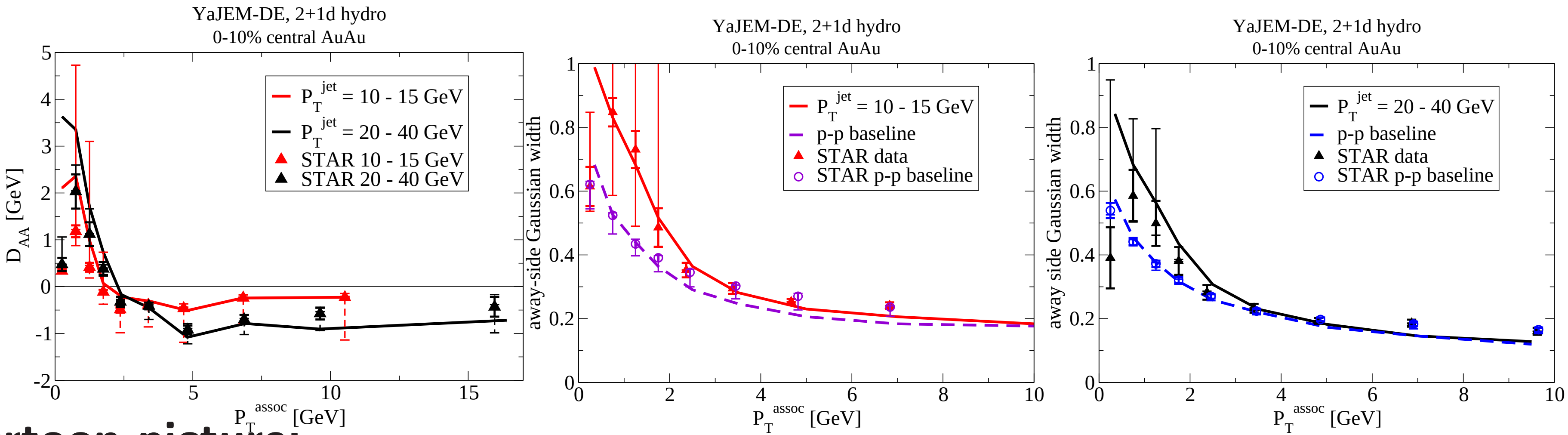
→ independent of trigger jet P_T

⇒ **self-similarity broken**



FF SELF-SIMILARITY AND ITS BREAKING

- more differential characterization — balance function and Gaussian width



Cartoon picture:

- for $E^2, Q^2 \gg \Delta Q^2, m_q$, jet evolves like in vacuum, self-similar evolution

- once $Q^2 \sim \Delta Q^2$, phase space is modified, self-similarity breaks

$\rightarrow$ ΔQ^2 is a function of the medium only, not of jet E
$\rightarrow$ assuming $Q/E \sim \theta$ the same between parents and daughters (in reality decreasing)
$\rightarrow$ $E \sim Q/\theta$ allows to relate that scale to a fixed energy (in reality increasing)
$\Rightarrow$ phase space for perturbatively tractable transverse radiation opens

- but at $E^2 \ll \Delta Q^2$, partons become thermalized (and no longer tractable)

Subleading radiation can be accounted for by phase space

Bringing it together

Ingredients for understanding jet quenching:

• detailed accounting for medium-induced radiation phase space ΔQ^2
$\longrightarrow$ combined with kinematical robustness arguments and scale comparisons

• leading hadron suppression pathlength dependence driven by $Q_{min} \sim \sqrt{E/L}$
$\longrightarrow$ once there is Q^2 evolution, LPM effect is small

• incoherent channels are small in the data
$\longrightarrow$ small ΔE, has implications for the nature of medium

• effect of AO (and its possible breaking) small
$\longrightarrow$ also no strong change of hadronization mechanism

• subleading radiation pattern again by phase space and robustness
$\longrightarrow$ thermalization and hydro transport at even lower momenta is bulk physics

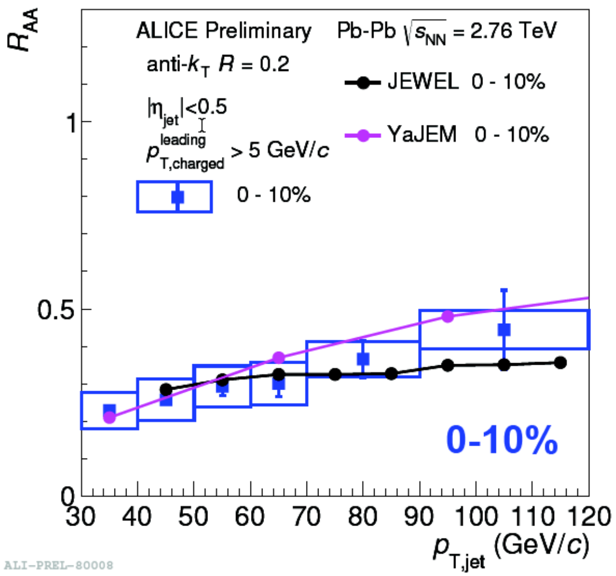
• **biases!** kinematic, parton type, geometry and jet finding bias

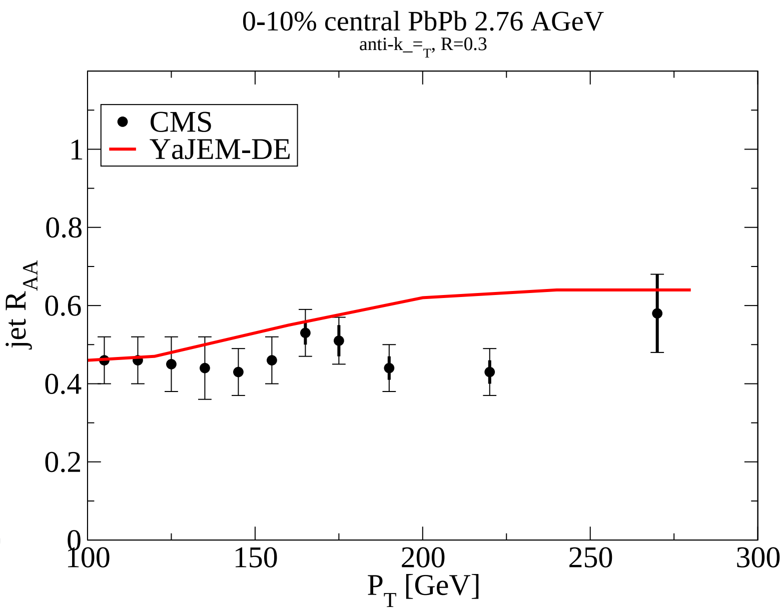
reconstructed jet = leading parton + radiation + finding bias?

$\longrightarrow$ if so, jet observables should just come out

Observables

- jet R_{AA} comes out reasonably (no attempt at simultaneous tuning to hadron R_{AA})





- flatter than hadron R_{AA}

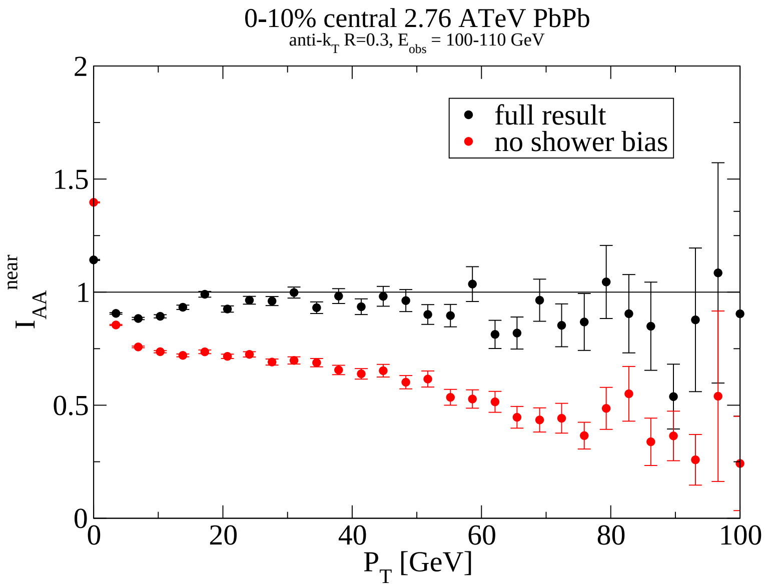
$\longrightarrow$ jet definitions are designed to suppress scale evolution physics

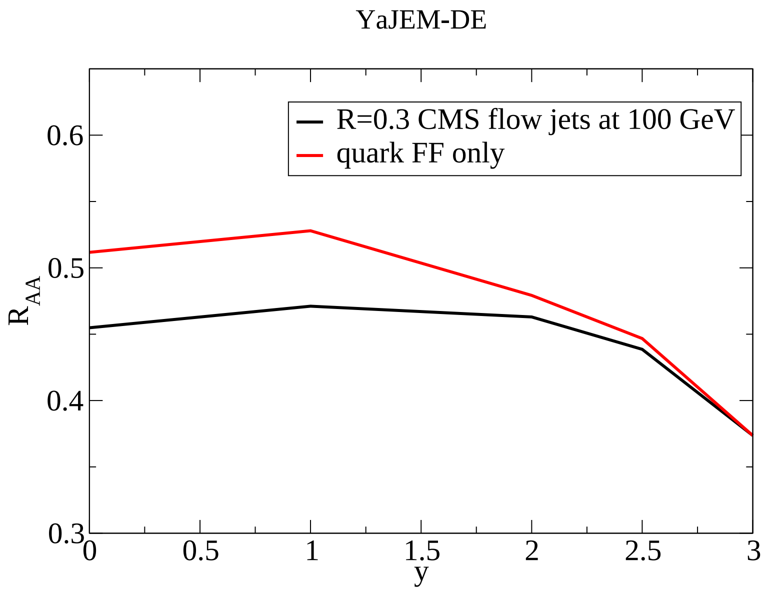
- ALICE P_T dependence is largely driven by 5 GeV track requirement

T. R., Phys. Rev. C **88** (2013) 1, 014905

Observables

• qualitative agreement with CMS/ATLAS FF analysis and rapidity dependence
→ precise experimental cuts have not been computed yet





• FF analysis result is heavily influenced by jet finding bias

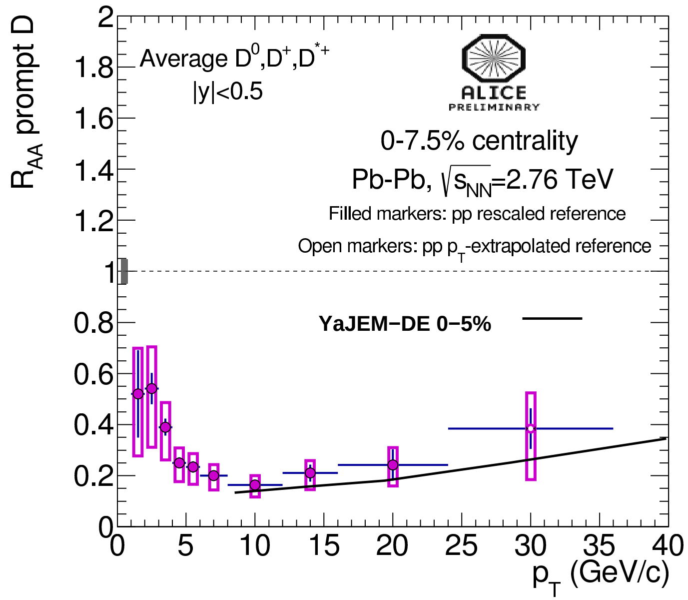
• y dependence is a combination of parton type bias and changing spectral slope
→ flat in the region accessible by ATLAS
⇒ proves the different coupling of quarks and gluons to the medium

The quark/gluon mixture matters! No generic parton jets!

T. R., Phys. Rev. C **88** (2013) 5, 054902

OBSERVABLES

- heavy-quarks — the dead cone effect should emerge naturally from phase space



→ as it does where the c-shower has a virtuality evolution in-medium

- similar magnitude of R_{AA} of charged hadrons and D mesons

→ consequence of different parton spectral slopes and FFs

If you know a prior distribution to be different, measuring the same posterior isn't a sign of the same physics. It's a sign of different physics.

T. R., Phys. Rev. C **89** (2014) 054906; M. Djordjevic and M. Djordjevic, 1407.3670 [nucl-th].

Observables

physics	status	observables
coherence in leading parton eloss	constrained	STAR h-h correlations
small incoherent contribution	constrained	STAR h-h correlations
E-dependent pathlength dep.	constrained	CMS v_2
perturbative radiation spectrum	constrained	STAR jet-h correlations
energy loss into medium, hydro response	observed	CMS jet-h correlations
parton color charge dependence	constrained	ALTAS $R_{AA}(y)$, STAR h-h
phase space restrictions by mass	constrained	ALICE D-meson R_{AA}
breakdown of AO	conjectured	—
jet mass dependence of MMFF	conjectured	—
crossing point evolution	conjectured	—
near T_C enhancement	conjectured	—
changes in hadronization	not seen	ALICE hadrochemistry in jets
fractional energy loss	not seen	STAR jet-h, ATLAS/CMS FF
medium as parton gas	not seen	STAR/CMS/ATLAS v_2, h-h

Constraining models as an experimental motivation should no longer be enough. Experimentalists have done their job marvelously and we know how jet quenching works. Time to discuss new questions?

New frontiers

Precision — extraction of transport coefficients, observation of small effects:

• inherent limitations: MC needs cutoffs, analytical computations need approximations
→ MC@NLO in heavy-ion collisions? Some people are trying this.
→ then, experimental small-print really matters for theory

• philosophy: do we accept hydro as constrained by bulk, or do we constrain it?
→ do we trust high P_T or bulk modelling more?

Kinematics — what happens at the frontiers:

• does hadronic R_{AA} flatten at very high P_T?
→ might spell the doom for most (all?) current models if so

• are our notion of what happens at extreme rapidities correct?
→ likely yes, as driven by pQCD, how much effort do we need to check?

New frontiers

Tomography — trying to fit the hydro medium to high P_T:

• largely means measuring observables against v_n event plane
→ images spatial eccentricities
→ ratio observables aiming to overcome lack of model precision

• also jet-induced shockwave propagation
→ needs coupled hard-soft modeling
→ hard work to get the theory under control

Medium constituents — what is a QGP made of:

• need to use quark mass dependence to unravel (small) elastic channel
→ precision pathlength dependence of c and b showers, D-D correlations
→ high enough to have Q^2 evolution, low enough that mass matters
→ need this at intermediate $P_T \sim 10 - 20$ GeV

• ideally look for conversion photons simultaneously
→ conversion rate depends on what you convert on

• also Molière scattering (U.A. Wiedemann)
→ rare large angle elastic scatterings on medium constituents

Conclusions

Two basic choices at this point — what is jet quenching?

A moderately well-calibrated tool to study interesting other physics?

• the key observables have been measured, we know the basic physics
→ theory: constrain models against the key observables (not the others. . .)
→ experiment: measure specific observables using the tool

A concept to be further poked at in the hope that it breaks?

• all bets are open
→ theory: produce new ideas on how jets could be suppressed
→ experiment: measure the classics at higher $\sqrt{s}$ and with more precision

Backup

A study in constraints

Idea: Start with three different scenarios, of which we know two to be incorrect
$\Rightarrow$ start to constrain with **jet** observables, see at which point we find out

- **YaJEM-DE**

$\rightarrow$ constrained by available RHIC and LHC data
$\rightarrow$ pathlength dependence driven by $Q_0 \sim \sqrt{E/L}$, 10% elastic energy loss
$\rightarrow$ broadens showers, breaks self-silimarity at fixed P_T

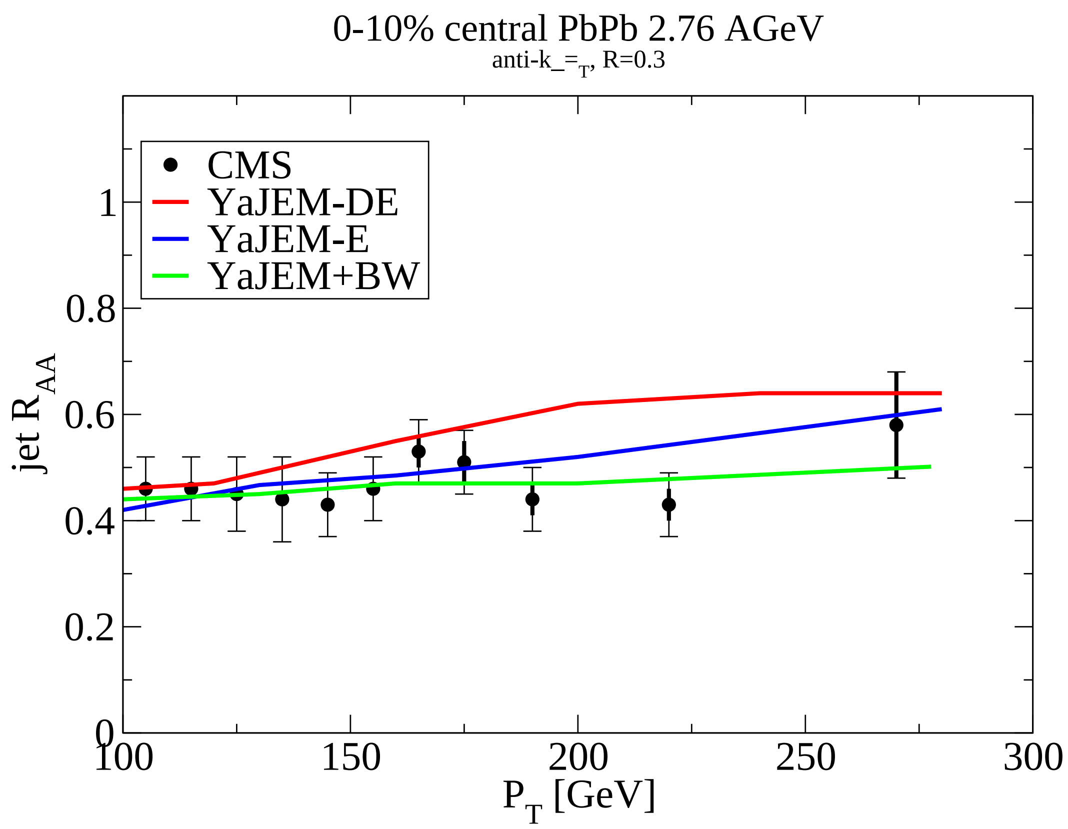
- **YaJEM-E**

$\rightarrow$ incoherent, 100% elastic energy transfer into the medium as drag force
$\rightarrow$ **collimates** showers, breaks self-similarity at fixed P_T

- **YaJEM+BW**

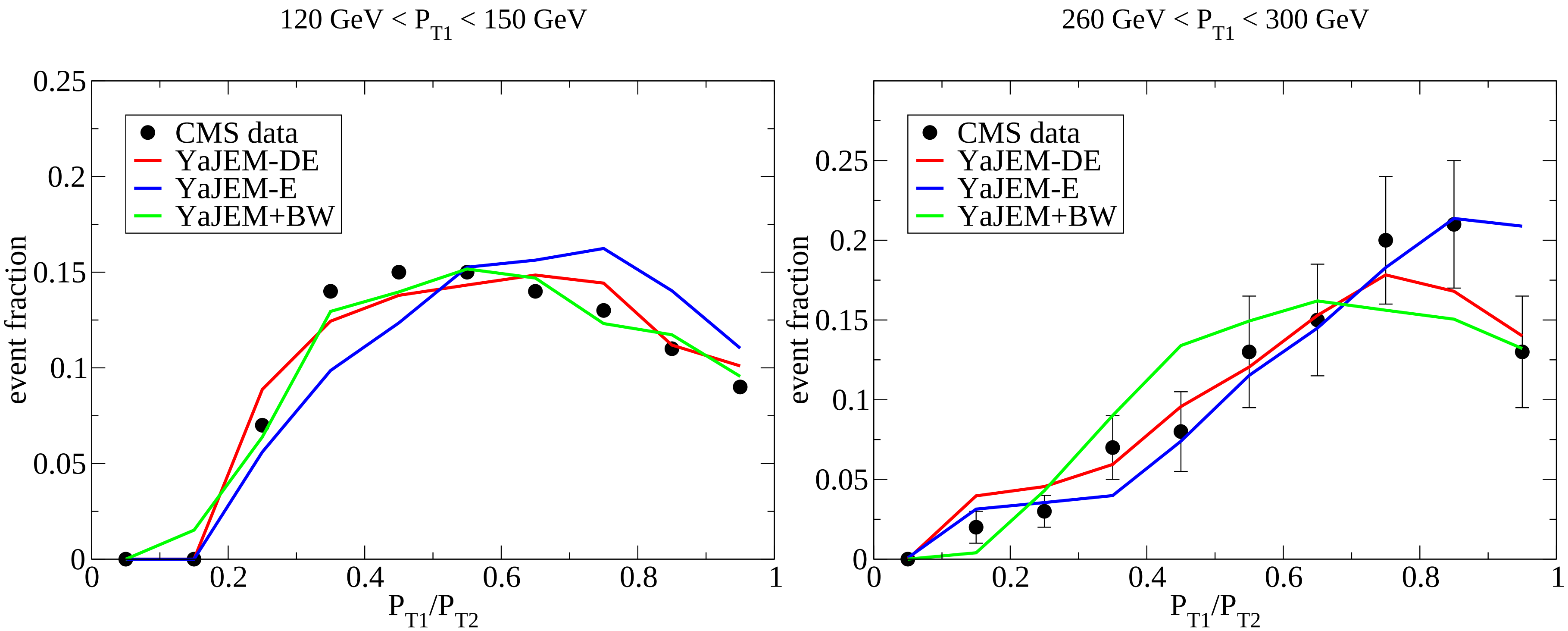
$\rightarrow$ utilizes the Borghini-Wiedemann prescription to enhance low z gluon production
$\rightarrow$ pathlength dependence implemented as incoherent
$\rightarrow$ broadens showers, **preserves** self-similarity

A study in constraints



• decent description of jet R_{AA} P_T dependence (YaJEM-DE does actually worst)
→ no sensitivity to pathlength dependence, broadening, self-similarity. . .

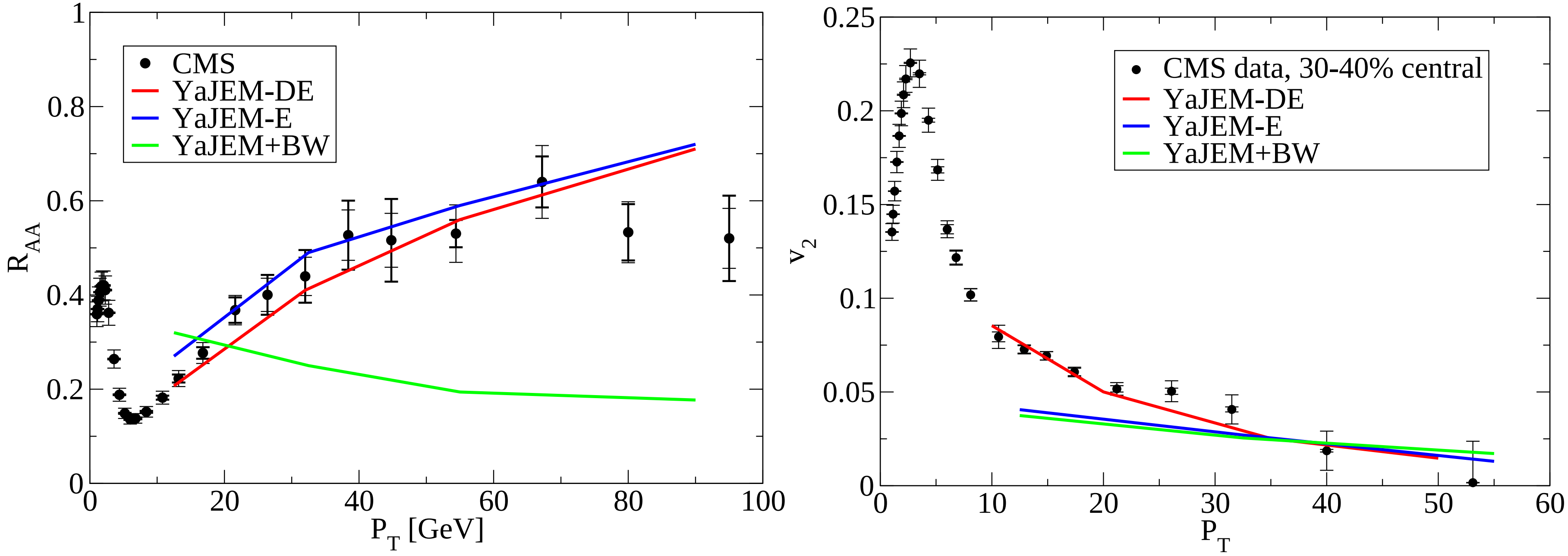
A study in constraints



- tension for both YaJEM-E and YaJEM+BW if full P_T dependence is used
$\longrightarrow$ see self-similarity of YaJEM+BW as unchanged shape

- perhaps one might rule out YaJEM-E based on this
$\longrightarrow$ however, we usually ask for higher standards

A STUDY IN CONSTRAINTS

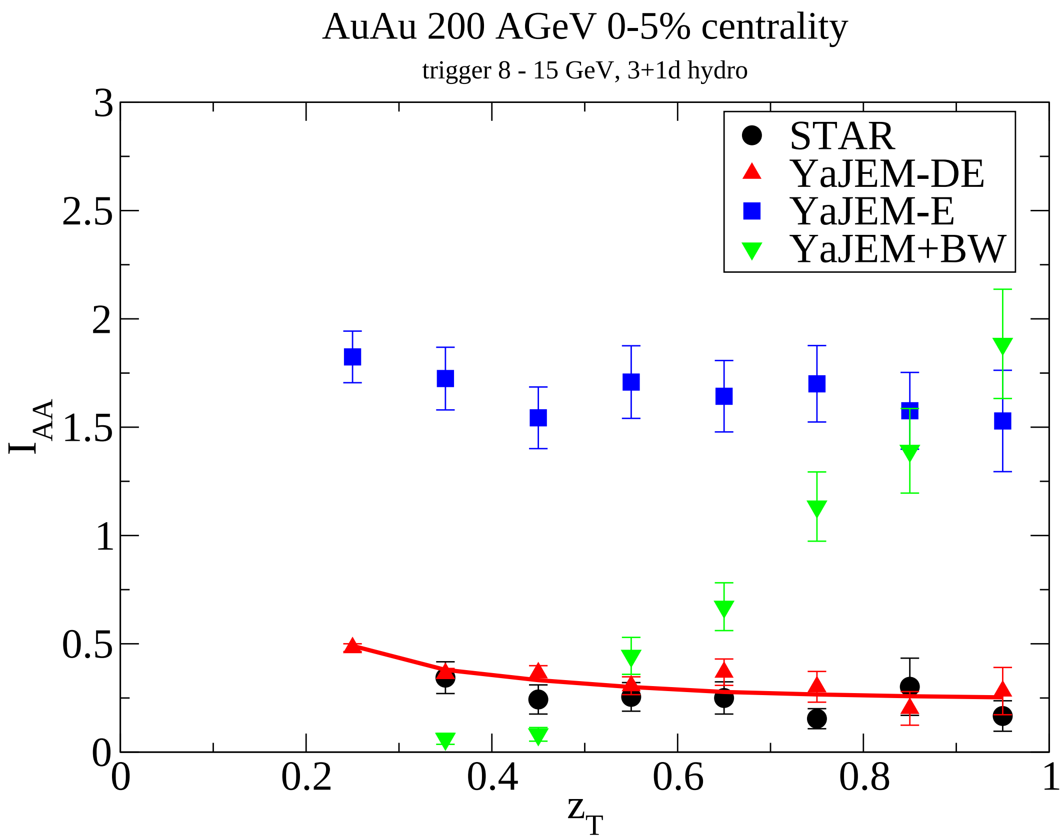


• in the hadronic sector, YaJEM+BW is completely off
$\longrightarrow$ leading hadron R_{AA} clearly is not fractional energy loss

• and even with normalization of v_2 open, an incoherent mechanism is in the shape
$\longrightarrow$ Q^2 evolution matters, and clustering obscures it

A STUDY IN CONSTRAINTS

Re-fitting such that hadron R_{AA} at RHIC is reproduced
$\rightarrow$ 10% correction for YaJEM-DE, factor 2 for YaJEM-E, factor 3.6 for YaJEM+BW



- a glance at RHIC I_{AA} would leave no doubt about what's realistic

$\rightarrow$ here's where the constraints are