YaJEM

a MC generator for in-medium shower evolution

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Guiding Principles
- idea, basic equations, limits of applicability

Benchmark results
- TECHQM brick problem results
- implementation of LPM interference

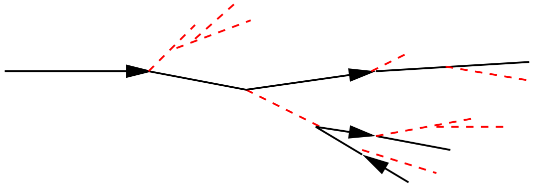
Data comparison
- leading hadron R_{AA} and I_{AA} results, jet observables

Outlook
- bremsstrahlung,conversion photons, energy deposition

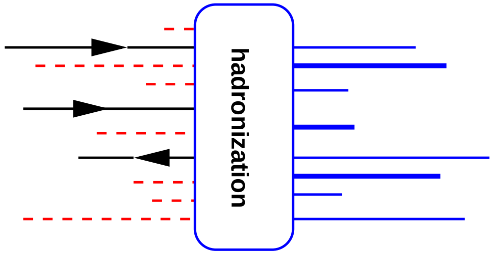
PART I: GUIDING PRINCIPLES

I. Medium-modified fragmentation

fragmentation function $D_{f\to h}(z,\mu^2)$ encodes the following physics:



→ perturbative parton radiation



→ non-perturbative hadronization

MEDIUM-MODIFIED PARTON SHOWER

- virtual parton formation time $\tau \sim E/Q^2$, hadron formation time $\tau_h \sim E_h/m_h^2$

→ part of the perturbative shower evolution happens in the medium

YaJEM (Yet another Jet Energy-loss Model) — a in-medium shower evolution code

Guiding principles

- realistic radiation phase space, easy contact with experimental analysis

→ Monte Carlo (MC) realization of shower evolution

- known and well-tested p-p baseline

→ based on PYSHOW from the PYTHIA package, uses Lund model hadronization

- minimal prior assumptions about the medium degrees of freedom

→ various *a priori* available parton-medium interaction scenarios

- to be used together with a hydrodynamical medium description

→ generic interface, used with viscous hydro, EbyE, . . .

QCD SHOWER EVOLUTION THE PYTHIA WAY (I)

Evolution in virtuality with (almost) collinear splitting: 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)

FROM SHOWER TO IN-MEDIUM SHOWER

Several questions to be answered:

- How to translate momentum space evolution (jet) to spacetime evolution (hydro)?
- How does the medium look when seen from a hard parton?
→ how do partons interact with the medium and are modified by it?
- How to distinguish jet and medium?
- How to deal with quantum interference?
→ generically, MC is a probabilistic picture without quantum effects

JET EVOLUTION IN POSITION SPACE

- **How to translate momentum space evolution to spacetime evolution?**

⇒ model average time for a parton b to branch from parent a as

$$\langle \tau_b \rangle = \frac{E_b}{Q_b^2} - \frac{E_b}{Q_a^2}$$

- actual branching time in given event from probability distribution

$$P(\tau_b) = \exp\left[-\frac{\tau_b}{\langle \tau_b \rangle} \right]$$

- assume all partons are on eikonal trajectory determined by the shower initiator
→ not strictly needed, but convenient if hydro is smooth on short scales

⇒ position of all branchings in spacetime known and connected with medium model

Note: Typically 3-4 generations of branchings happen *before* the medium forms - need to be treated as vacuum shower!

PARTON-MEDIUM INTERACTION

• How does the medium look when seen from a hard parton?
→ how do partons interact with the medium and are modified by it?

YaJEM main option:

• no explicit medium model, medium appears via transport coefficients $\hat{q}, \hat{e}$
→ altered radiation phase space (RAD) and direct energy loss into medium (DRAG)

$$\Delta Q_a^2 = \int_{\tau_a^0}^{\tau_a^0+\tau_a} d\zeta \hat{q}(\zeta) \quad \Delta E_a = \int_{\tau_a^0}^{\tau_a^0+\tau_a} d\zeta \hat{e}\rho(\zeta)$$

YaJEM alternative option:

• enchance singular part of splitting kernel by $(1 + f_{med})$ (FMED), e.g.

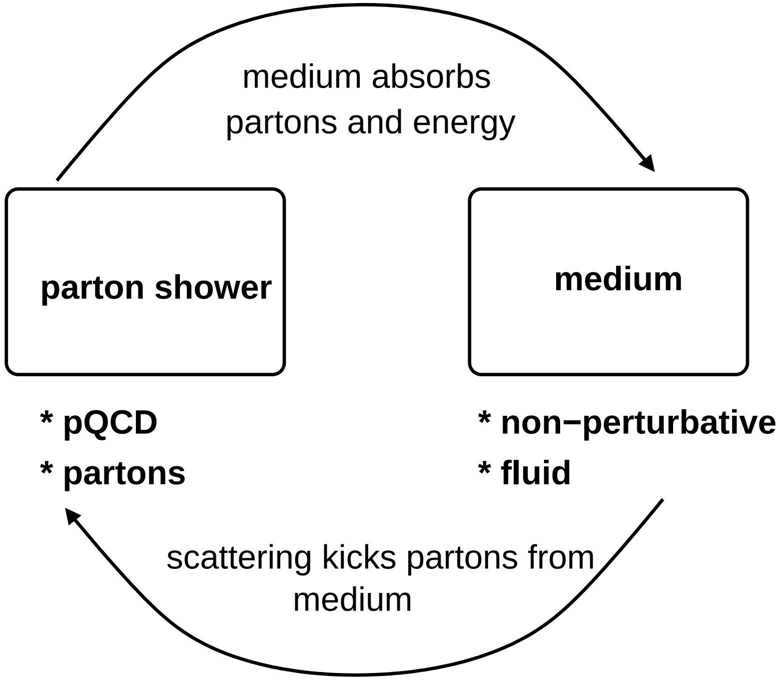
$$P_{q\to qg}(z) = \frac{4}{3}\frac{1+z^2}{1-z} \Rightarrow \frac{4}{3}\left(\frac{2(1+f_{med})}{1-z} - (1+z)\right)$$

→ consistency tests with Borghini-Wiedemann MLLA and Q-PYTHIA phenomenology

N. Borghini and U. A. Wiedemann, hep-ph/0506218; K. Zapp, G. Ingelman, J. Rathsman, J. Stachel and U. A. Wiedemann, 0804.3568 [hep-ph].

PARTON-MEDIUM INTERACTION

- a medium is not simply a 'noisy environment'



medium absorbs partons and energy

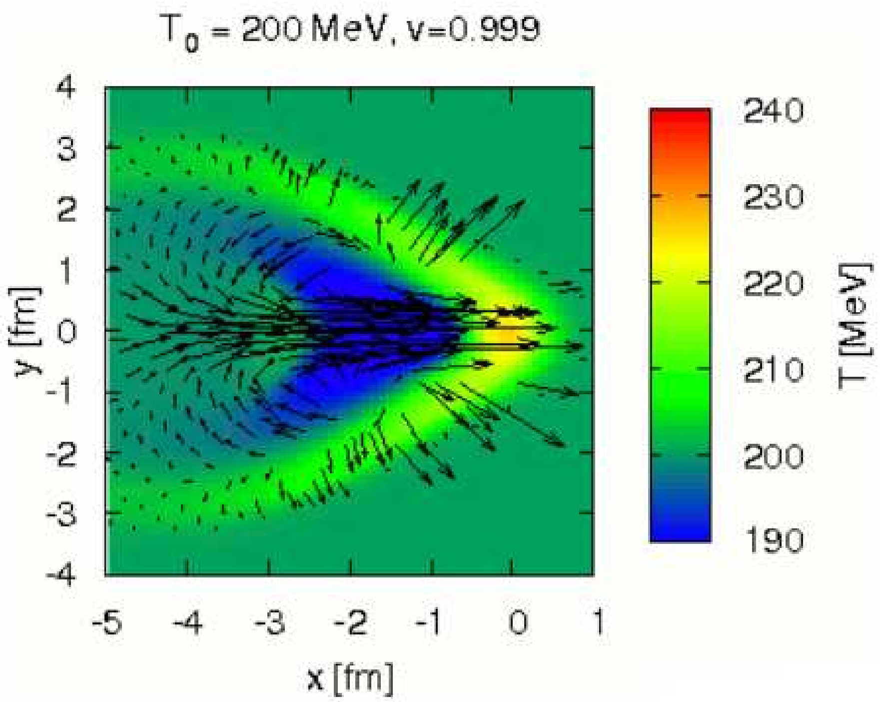
parton shower

medium

*** pQCD**
*** partons**

*** non−perturbative**
*** fluid**

scattering kicks partons from medium



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

- energy-momentum conservation holds only for coupled jet-medium simulation!

→ YaJEM RAD and DRAG do not and should not conserve momentum in shower

B. Betz *et al*, 0812.4401 [nucl-th], YaJEM and hydro: T. R., 1306.2739 [hep-ph]

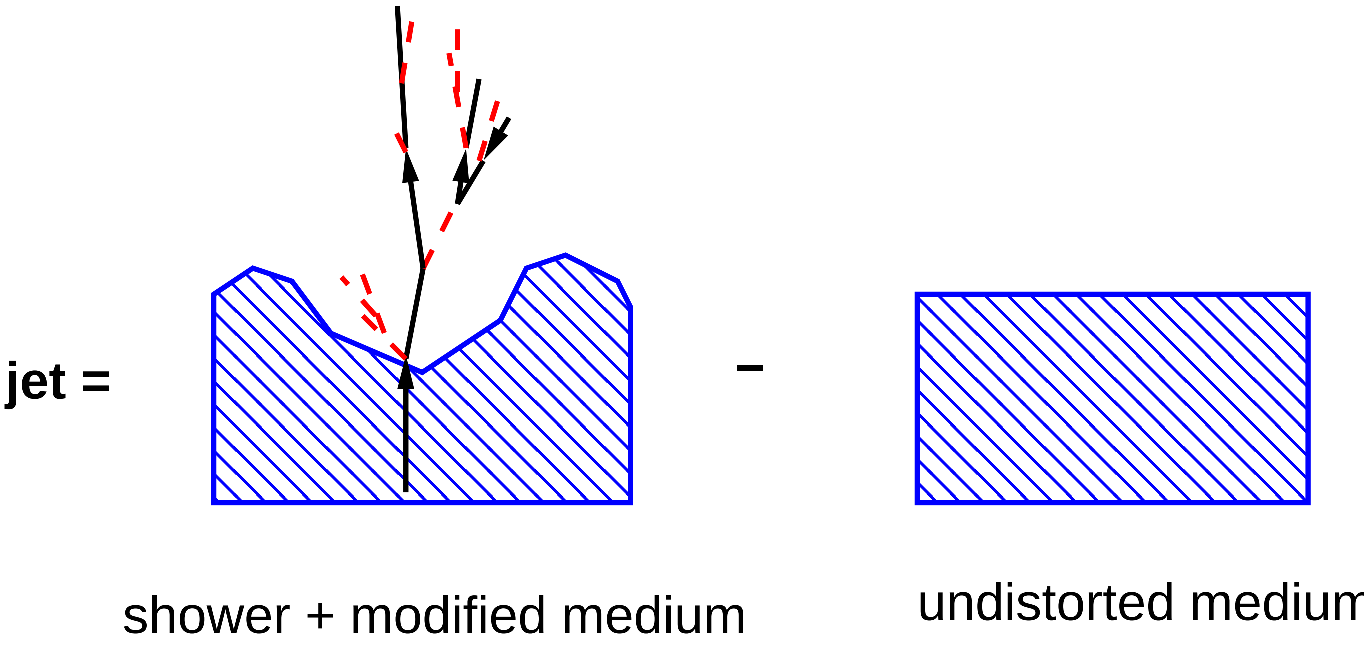
JET AND BACKGROUND

- **How to distinguish jet and medium?**

→ not a physics question, up to jet definition, scale separation,. . .

Disclaimer:

Merging YaJEM jets with event generator output will not give the complete answer!



For realistic cone radii $R < 0.6$ and current experimental procedures, a few years of experience have shown this to be numerically a non-issue.

QUANTUM INTERFERENCE

- **How to deal with quantum interference?**

→ **generically, MC is a probabilistic picture without quantum effects**

LPM interference:

- lifetime of a virtual state $\tau \sim E/(Q^2 + \Delta Q^2)$
- virtuality picked from the medium: $\Delta Q^2 \sim \hat{q}\tau = \hat{q}E/(Q^2 + \Delta Q^2)$

→ determine self-consistent solution for ΔQ^2 inside branching code

(independently coded, but conceptually similar to K. Zapp, J. Stachel and U. A. Wiedemann, Phys. Rev. Lett. **103** (2009) 152302)

Angular ordering:

- kept as in vacuum

→ needs to be, because first branchings setting jet structure happen before medium

- test: angular ordering off in medium leads to statistically identical results

→ reason: virtuality-ordered showers are on average angular ordered

⇒ the effect of any realistic angular decoherence scenario is vanishingly small

T. R., Phys. Rev. C **79** (2009) 054906

APPLICABILITY LIMITS

Caveats:

- hadronization assumed to be unmodified by medium

→ no reason to assume low P_T and/or heavy hadrons are described correctly
→ in practice, YaJEM does jet-h correlation structures down to few hundred MeV

- relies on expansion around large Q^2 scale

→ no mode for on-shell parton propagation, 'thin' medium assumption
→ no reason heavy quark jets are described correctly

- in practice scaling laws rely on medium density decrease over time

→ limited applicability to test cases like constant media
→ tested not to fail for density fluctuations

- inherits all caveats from PYSHOW (PYTHIA 6)

→ in particular, gluon fragmentation seems to be too soft

II. Brick problems

- take a chunk of matter with fixed temperature ($\hat{q}$, . . .) and length L
$\longrightarrow$ compare with energy loss models

- establish basic model properties without uncertainty from hydro

ENERGY LOSS

To determine leading quark energy loss probabilities from YaJEM:

- c-quark as shower initiator: hard vacuum fragmentation and always tagged
- extract energy loss with an ansatz

$$\frac{dN^{med}}{dE}_c(E) = \int d(\Delta E) \frac{dN^{vac}}{dE}_c(E')P(\Delta E)\delta(E' - E - \Delta E)$$

→ this assumes $P(\Delta E, E) = P(\Delta E)$ (not usually in YaJEM) and allows $\Delta E > E$

⇒ extraction of energy loss not reliable for large ΔE!

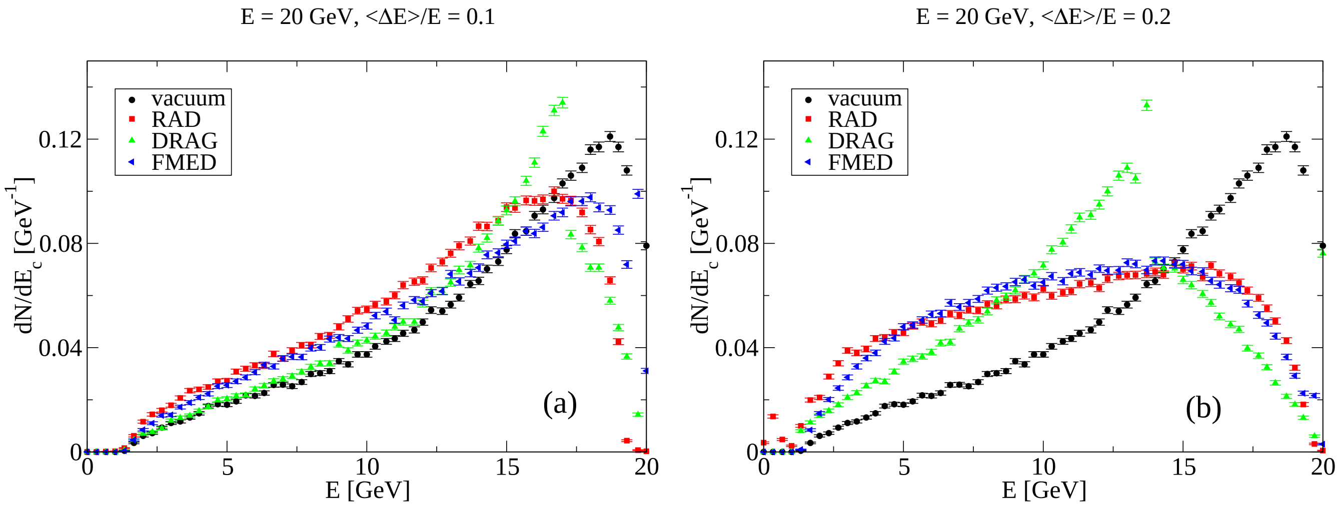
- in practice: solve matrix equation for P_j subject to $P_j > 0$ and $\sum_j P_j = 1$

$$N_i(E^i) = \sum_{j=1}^{n} K_{ij}(E^i, \Delta E^j) P_j(\Delta E^j)$$

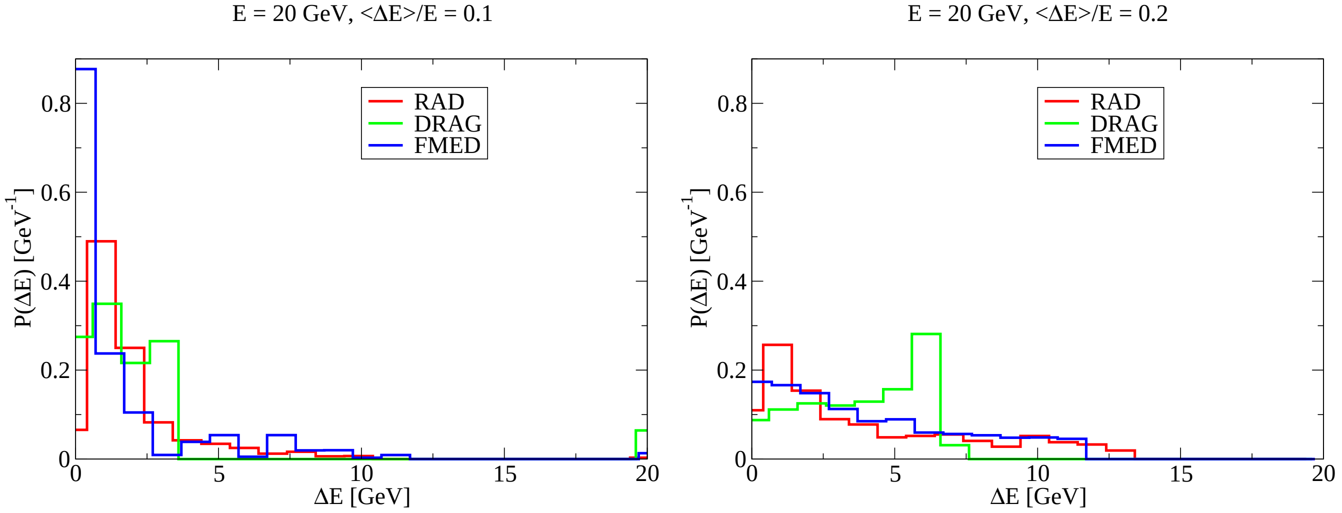
T. R., Phys. Rev. C **79** (2009) 054906

ENERGY LOSS

- fragmentation functions:



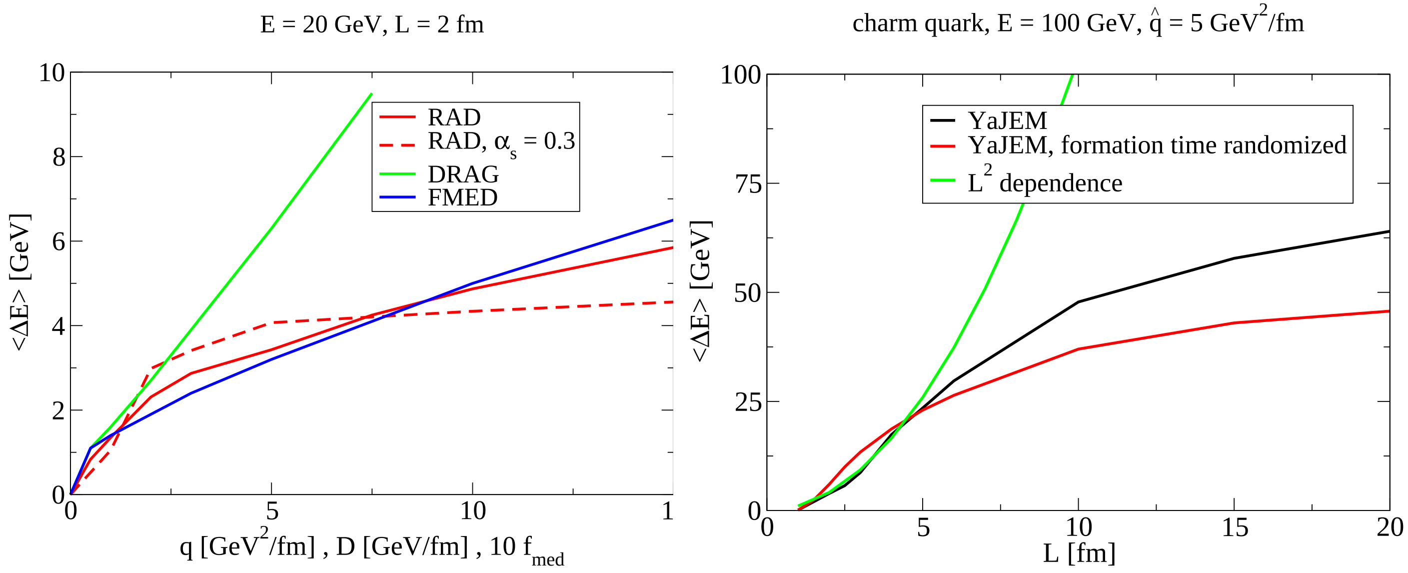
- energy loss probabilities



⇒ RAD and FMED show typical flat distribution of radiative energy loss

ENERGY LOSS

- parametric dependencies on medium density and L



- L const. increased medium effect

$\longrightarrow$ saturation of energy loss in radiative scenarios, much weaker for drag

- $\hat{q}$ const., L increased

$\longrightarrow$ if formation time not randomized: initial L^2 dependence, then finite energy limit

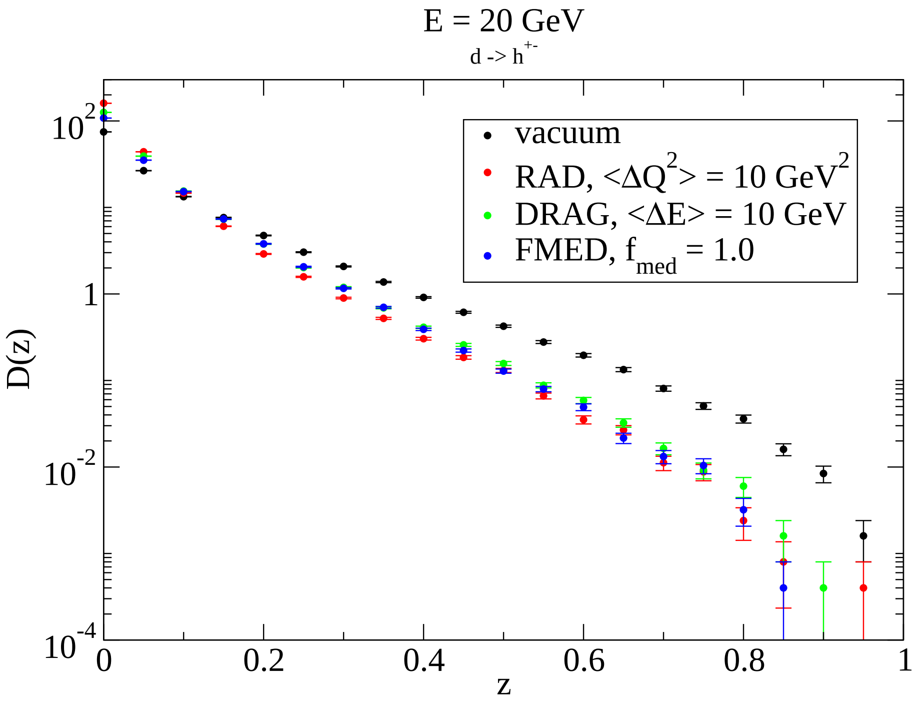
$\longrightarrow$ if formation time randomized: L^2 dependence almost invisible

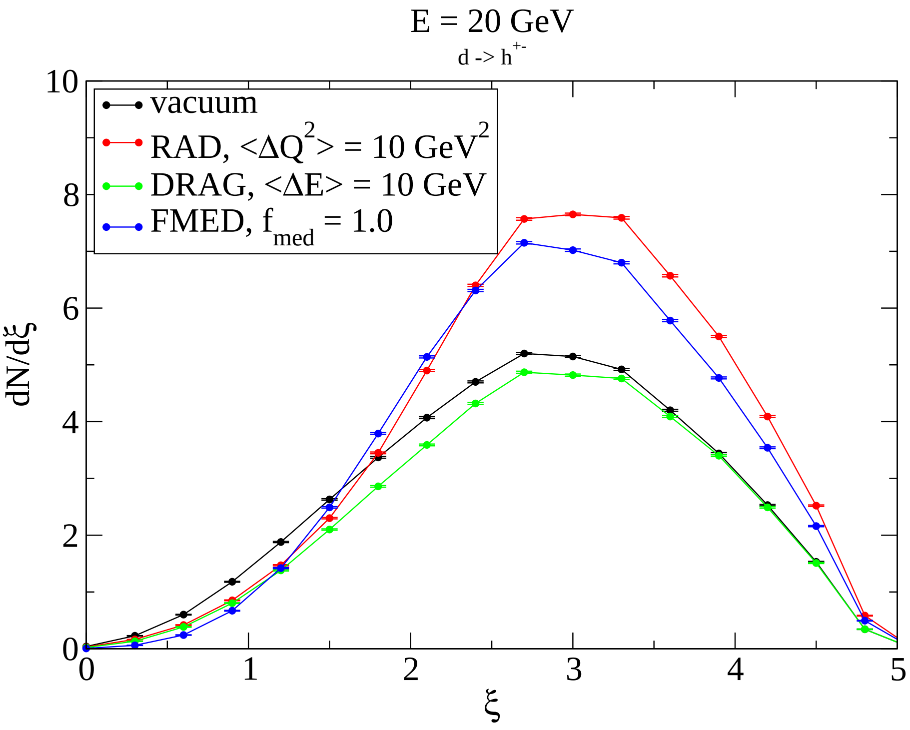
$\Rightarrow$ LPM works as expected, but is numerically not dominating pathlength dependence

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

FRAGMENTATION FUNCTIONS

- fragmentation functions





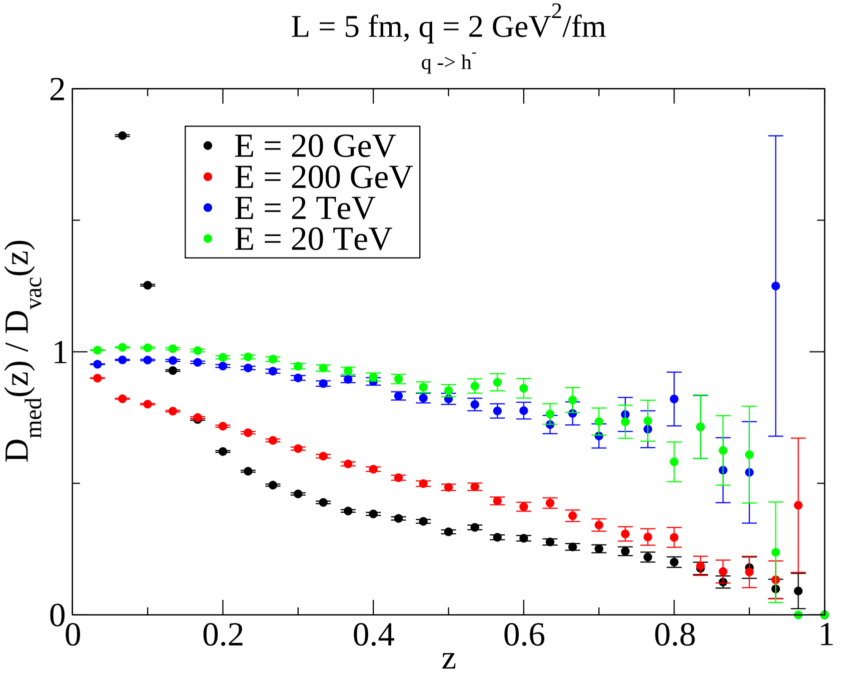
- can be made to look similar in the high z region which is probed by spectra

- differences in the low z region

⟶ enhancement from RAD and FMED, depletion from DRAG

FRAGMENTATION FUNCTIONS

- scaling with parton energy (RAD)



- for high E, modification goes away

→ medium lifetime is an increasingly smaller fraction of the shower lifetime

→ $Q^2 \gg \Delta Q^2$ is increasingly met

⇒ asymptotically, jet quenching in YaJEM goes away

- note scale up **upturn** point is fix in $p_T \approx 3$ GeV, **not** in z!

T. R., Phys. Rev. C **81** (2010) 014906

III. Comparison with data

- full averaging over hydrodynamical backgrounds

→ check systematics, never be content with a single hydro model

- full bias structure as determined by experimental analysis

→ anti-k_T routinely used for jet clustering

→ even clustering a complete hydro+jet event tested

HYDRO AVERAGING

- hard vertices for impact parameter **b** have probability distribution

$$P(x_0, y_0) = \frac{T_A(\mathbf{r_0} + \mathbf{b/2})T_A(\mathbf{r_0} - \mathbf{b/2})}{T_{AA}(\mathbf{b})},$$

where $T_A(\mathbf{r}) = \int dz \rho_A(\mathbf{r}, z)$.

- if medium-modified fragmentation function along given path is $D^{med}_{i\to h}(z, \mu|\mathbf{r_0}, y, \phi)$:

$$\langle D^{med}_{i\to h}(z, \mu)\rangle_{T_{AA}} = \frac{1}{2\pi}\int_0^{2\pi} d\phi \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 P(x_0, y_0) D^{med}_{i\to h}(z, \mu|\mathbf{r_0}, y, \phi).$$

For R_{AA}, this corresponds to a computationally rather intensive averaging of paths in a evolving hydrodynamical model with a weight given by $P(x_0, y_0)$. For back-to-back hadron correlations, the averaging is even more complicated due to the trigger bias.

- also EbyE hydro with binary collision vertices from initial condition MC

YaJEM SCENARIOS

- several physics scenarios from the basic building blocks RAD and DRAG

→ FMED is not used for any data comparison

YaJEM: using the RAD scenario
→ linear L-dependence, incompatible with $R_{AA}(\phi)$ and $R_{AA}(P_T)$, obsolete

YaJEM-D: as YaJEM, but determining lower in-medium evolution scale $Q_0 = \sqrt{E/L}$
→ much better with the data, incompatible with I_{AA} in h-h correlations, obsolete

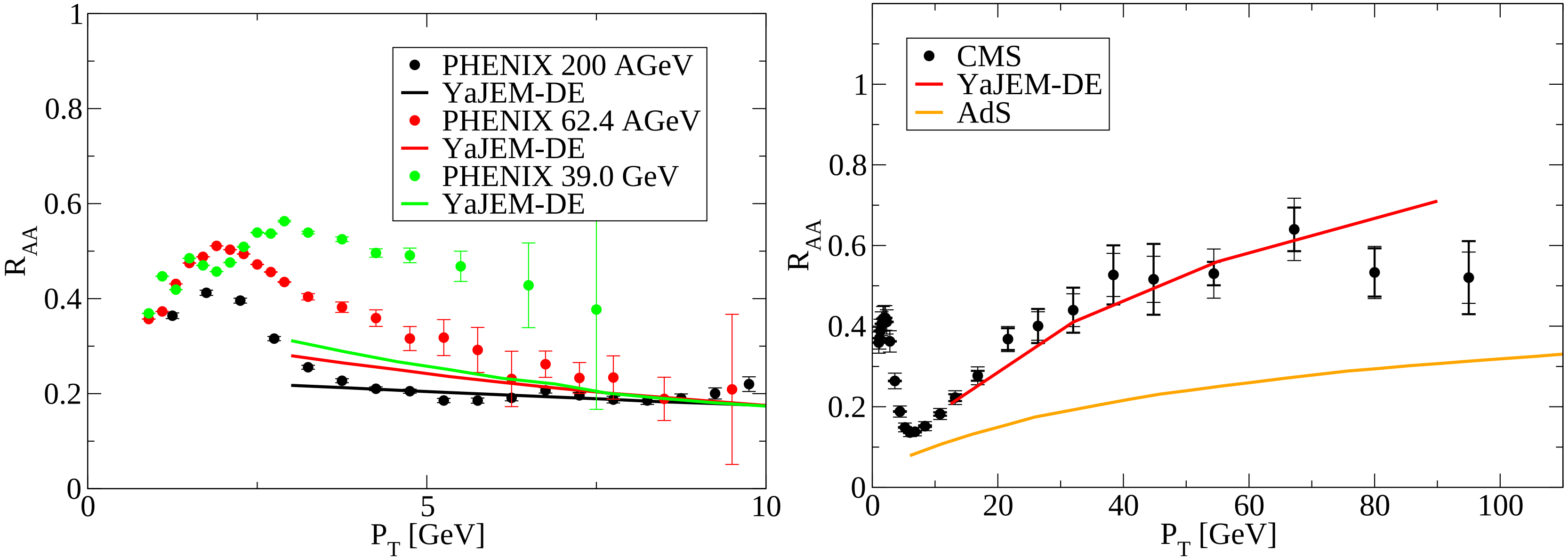
YaJEM-DE: as YaJEM-D, but using 90% RAD and 10% DRAG
→ reasonable description of all data sets tested so far

YaJEM-E: using the DRAG scenario
→ unrealistic model used to test discriminative power of observables

R_{AA} FOR CENTRAL COLLISIONS

- parameters fixed to R_{AA} in 0-10% central 200 AGeV collisions

$\longrightarrow$ extrapolation to different $\sqrt{s}$ (using EbyE for low energy scan)



- requires careful and controlled extrapolation of background hydrodynamics

$\longrightarrow$ quenching parametrically scales $\sim T^3$ (medium density)

$\longrightarrow$ non-perturbative physics obscures result below 62.4 GeV

- decent description of R_{AA} over factor 50 in $\sqrt{s}$ using YaJEM-DE

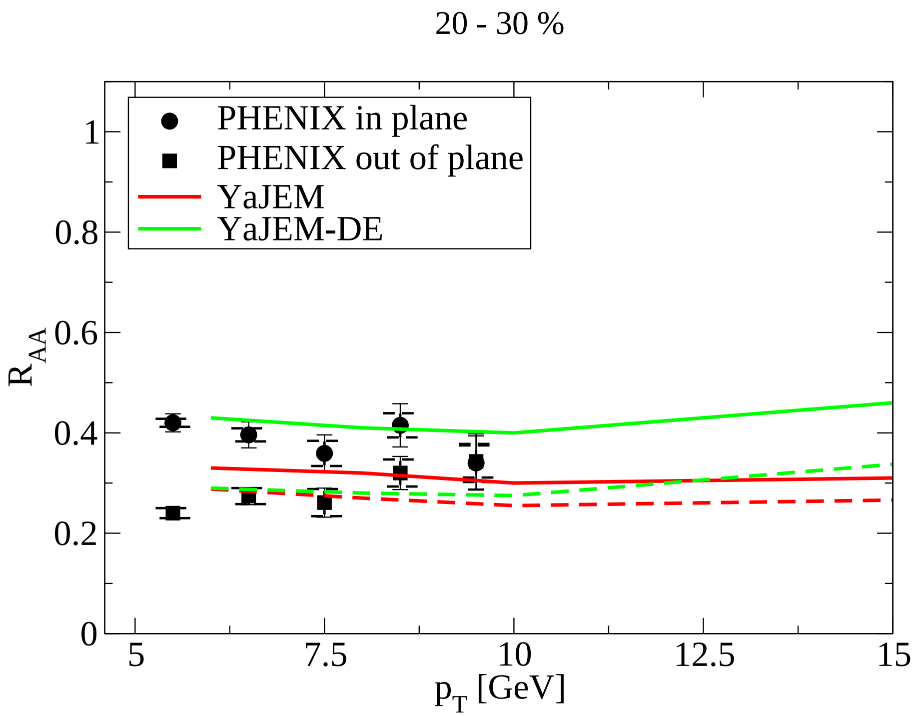
$\longrightarrow$ non-trivial, AdS scenarios fail that test

T. R., 1302.3710 [hep-ph].

R_{AA} FOR NON-CENTRAL COLLISIONS

- parameters fixed to R_{AA} in 0-10% central 200 AGeV collisions

→ extrapolation to different centrality



- decent description of the spread in-plane vs. out of plane

→ non-trivial, all models with linear pathlength dependence fail this

- huge (factor 2!) uncertainty related to choice of background hydrodynamcs

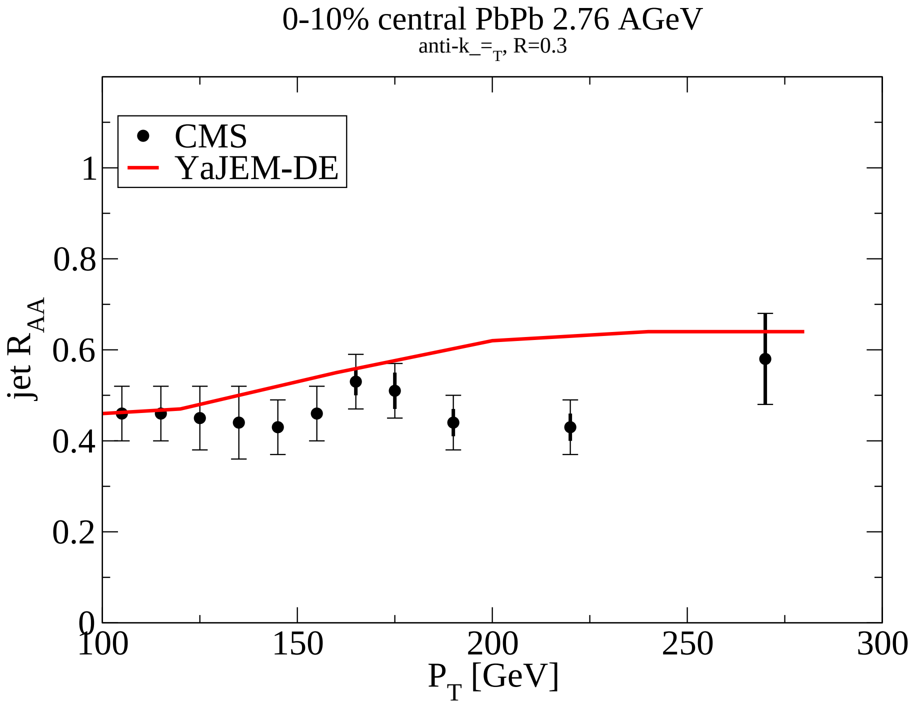
→ not obvious if model failure with data tests jet quenching or hydro

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

R_{AA} FOR JETS

- parameters fixed to R_{AA} in 0-10% central 200 AGeV collisions

→ LHC extrapolation, clustering with with anti-k_T, $R = 0.3$ following CMS analysis



- decent decription of jet R_{AA}

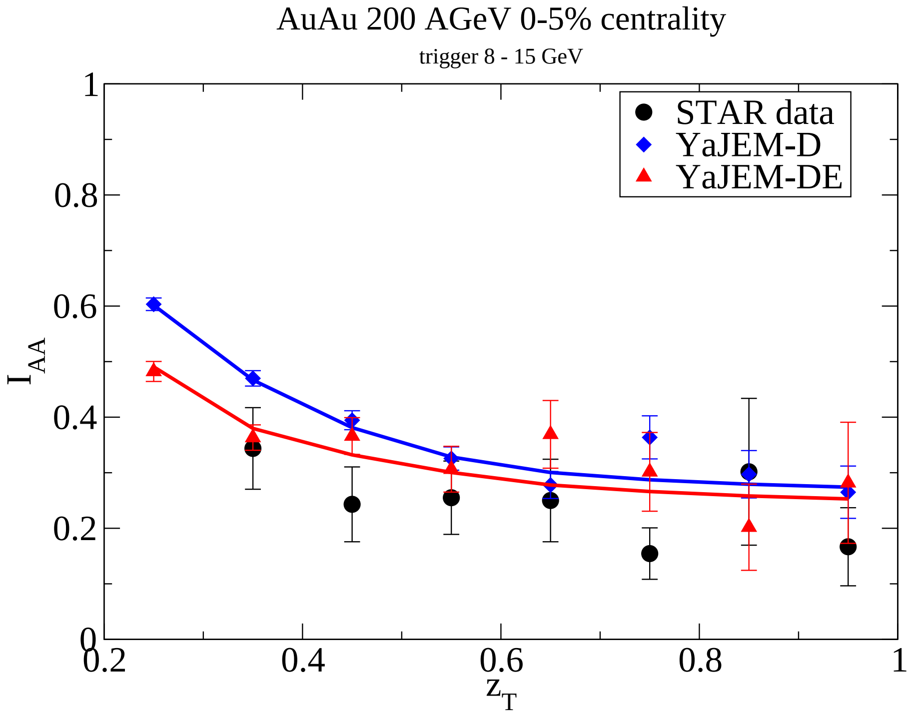
→ appears to follow for all scenarios where hadron R_{AA} describes data

T. R., 1302.3710 [hep-ph].

I_{AA} FOR HADRON-HADRON CORRELATIONS

- parameters fixed to R_{AA} in 0-10% central 200 AGeV collisions

$\longrightarrow$ back-to-back hadron correlations, away side yield



- decent description of correlated yield

$\longrightarrow$ highly non-trivial, probes pathlength dependence and subleading radiation

- dependence on hydro background weaker than for $R_{AA}(\phi)$, ~ 20 %

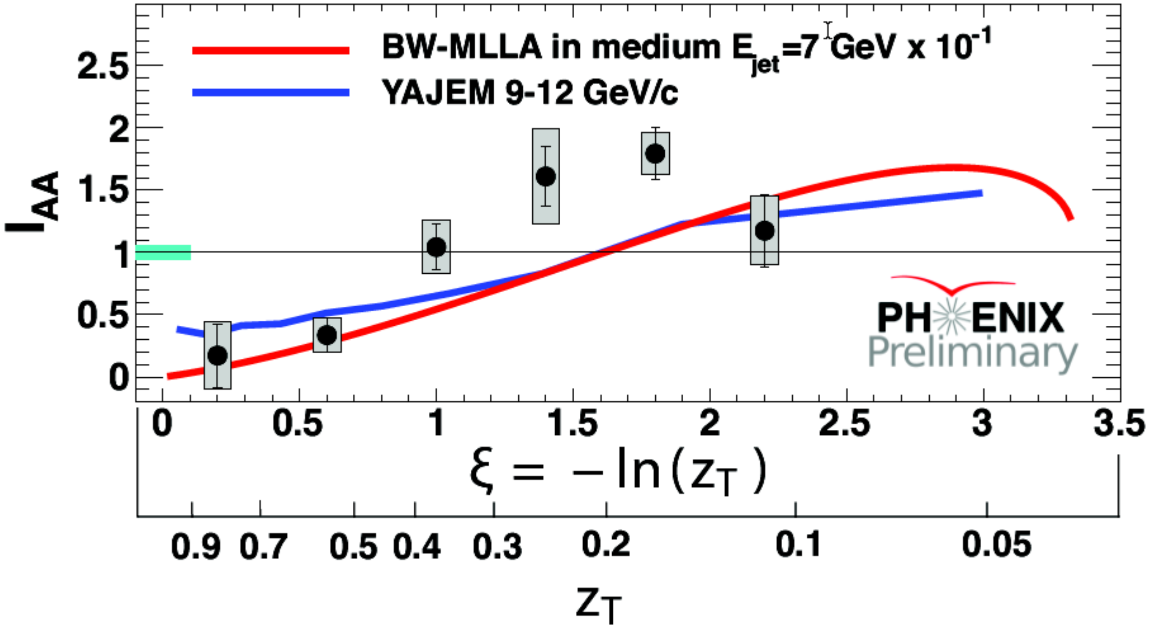
$\longrightarrow$ determines elastic energy loss component to about 10%

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

I_{AA} FOR γ-HADRON CORRELATIONS

- parameters fixed to R_{AA} in 0-10% central 200 AGeV collisions

$\longrightarrow$ γ-hadron correlations, away side yield



- decent description of correlated yield except perhaps in low P_T region

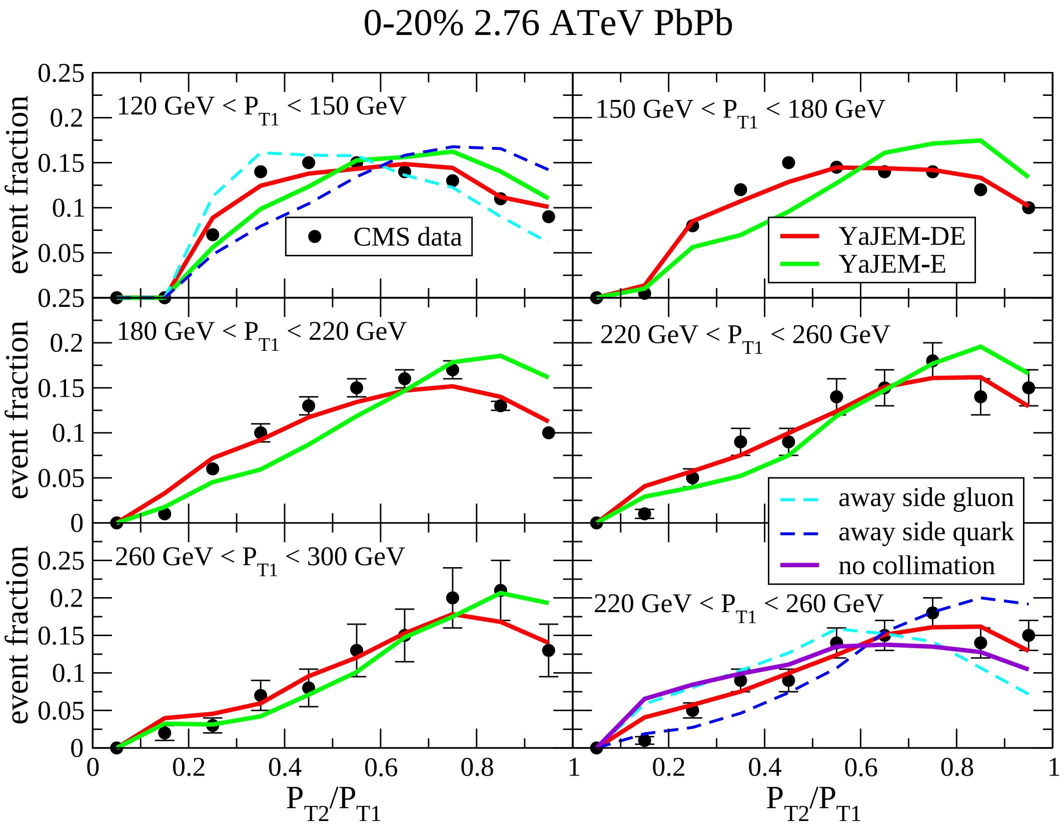
$\longrightarrow$ related to a quark R_{AA} at high z_T, i.e. constrained

- possible tension in STAR h-h and PHENIX γ-h data a low P_T

A_J FOR JETS

- parameters fixed to R_{AA} in 0-10% central 200 AGeV collisions

→ LHC extrapolation, clustering with with anti-k_T, $R = 0.3$ following CMS analysis



- decent decription of momentum depensnce of jet A_J

→ however, even YaJEM-E is sort of close to the data?!

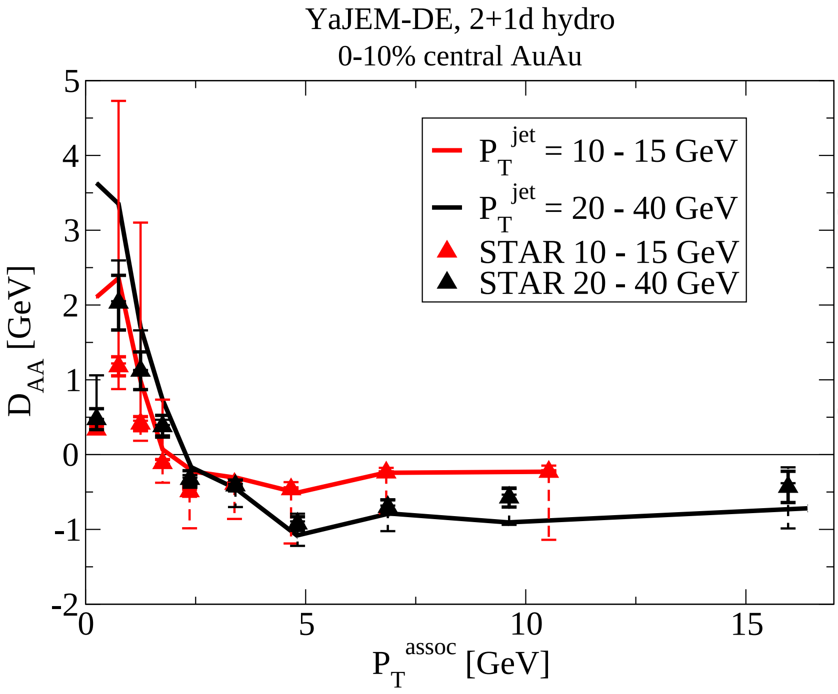
→ probes mainly kinematical collimation and quark/gluon differences

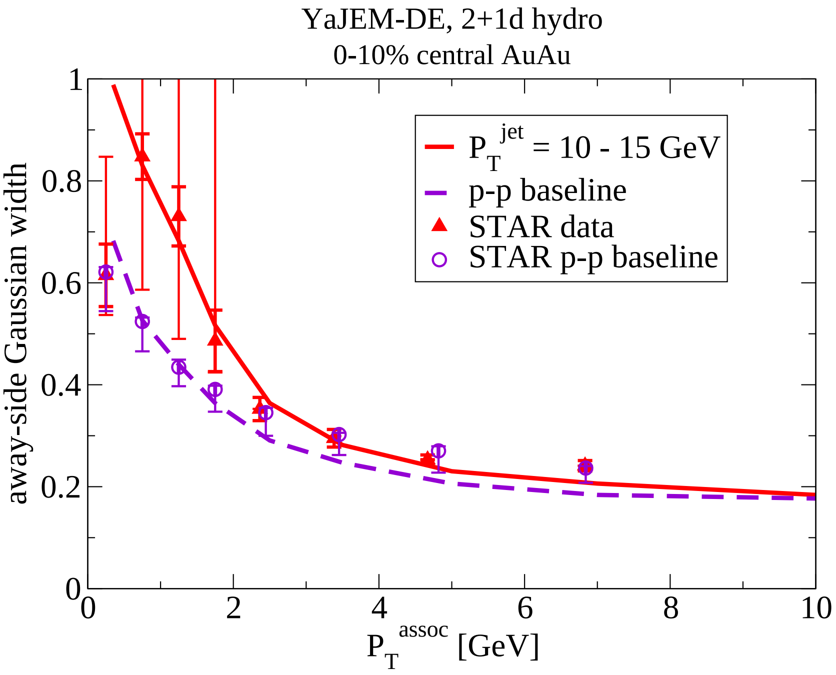
T. R., Phys. Rev. C **86** (2012) 061901

I_{AA} FOR JET-HADRON CORRELATIONS

- parameters fixed to R_{AA} in 0-10% central 200 AGeV collisions

$\rightarrow$ anti-k_T clustering with STAR PID and track p_T cuts, following STAR analysis





- good description of balance function $D_{AA} = \text{yield}_{AA}(P_T)\langle P_T\rangle - \text{yield}_{pp}(P_T)\langle P_T\rangle$

$\rightarrow$ non-trivial, note that upturn happens at fixed $P_T \approx 3$ GeV

- good description of transverse jet structure

$\rightarrow$ non-trivial and not constrained much by anything else

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

ALL THE REST

Also other observables with YaJEM-DE:

- h-jet correlations (ALICE)

→ full calculation (prediction made after LHC data), good description of the data

- h-h correlations at LHC (ALICE)

→ full calculation (prediction made before LHC data), in rough agreement with data

- jet shapes (CMS)

→ exploratory study, no tension with the data seen

- jet fragmentation function (CMS)

→ full calculation for similar kinematics, good description of the data

- dihadron 2+1 triggered correlations (STAR)

→ exploratory study, order of magnitude okay, conceptual problem with data trend

Decent agreement with a large body of very different observables in very different kinematical and differently biased regimes.

WHAT DOES THIS MEAN?

Lessons learned:

- vacuum pQCD and medium-induced radiation phase space works really well

→ important to get phase space right before looking at details

- the data are not in agreement with

→ any fractional energy loss (this would not leave the upturn fixed at 3 GeV)
→ a large elastic/incoherent component (this would overshoot away side I_{AA})
→ an AdS/CFT like T^4 scaling of the medium quenching power

- the choice of the hydro background matters!

→ dependent on observable, just a few % or factors of 2
→ proposal: let's try to constrain hydro by high P_T!

- the data show no evidence for specific medium QCD physics like

→ color decoherence (no predicted signal except unspecific broadening)
→ color reconnections (no changes in observed hadrochemistry)

- jet observables often have less constraining power than hadron correlations

→ but jet triggered correlations can do miracles!

IV. What else can YaJEM do ?

- hard photon production
- energy deposition into the medium
- jet mass dependent observables

PHOTON PRODUCTION

- at the simple expense of allowing $q \longrightarrow q\gamma$, we can get bremsstrahlung photons
- using a formula for conversion photons

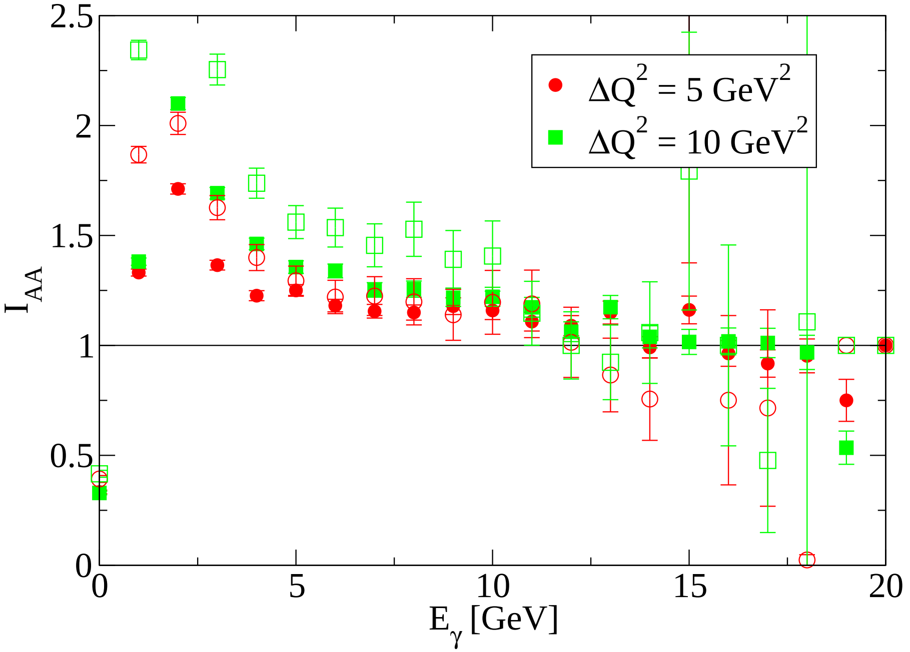
$$E_\gamma \frac{dN_\gamma}{d^3p_\gamma d^4x} = \frac{\alpha\alpha_s}{4\pi^2} \sum_{f=1}^{N_f} \left(\frac{e_{q_f}}{e}\right)^2 \times \left[f_q(p_\gamma) + f_{\overline{q}}(p_\gamma)\right] T^2 \left[\ln \frac{4E_\gamma T}{m^2} - 1.916\right].$$

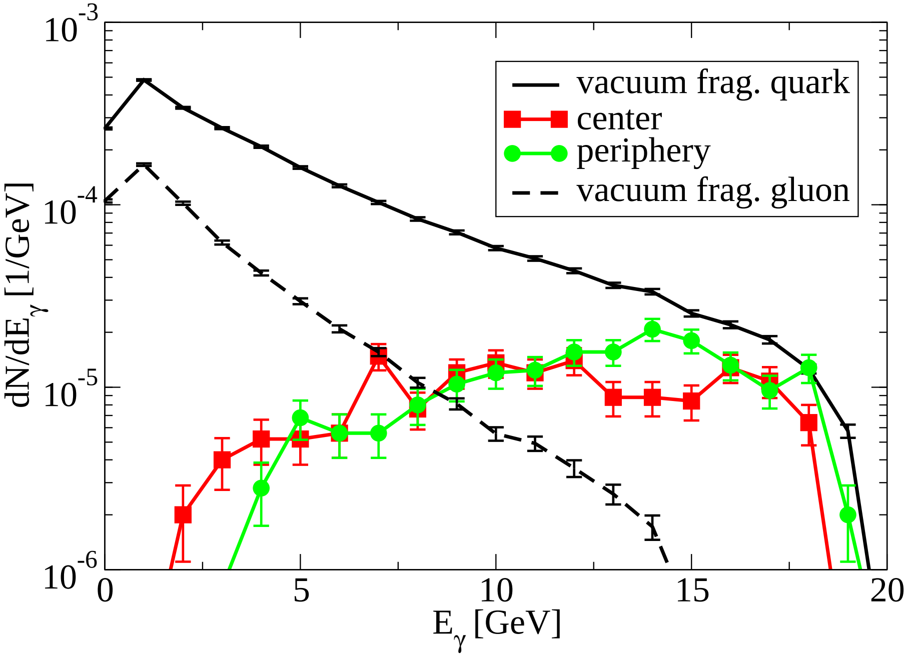
with $f_{q(\overline{q})}(p) = (2\pi)^3 \delta(x - x_0)\delta(y - y_0)\delta(z - ct)\delta^3(p)$ in evolving shower
⇒ approximate yield of conversion photons

Caveat: The above expression is derived assuming an ideal quark-gluon gas — this is different from the medium description usually used in YaJEM

Photon production

- some exploratory study (very statistics-hungry. . .)





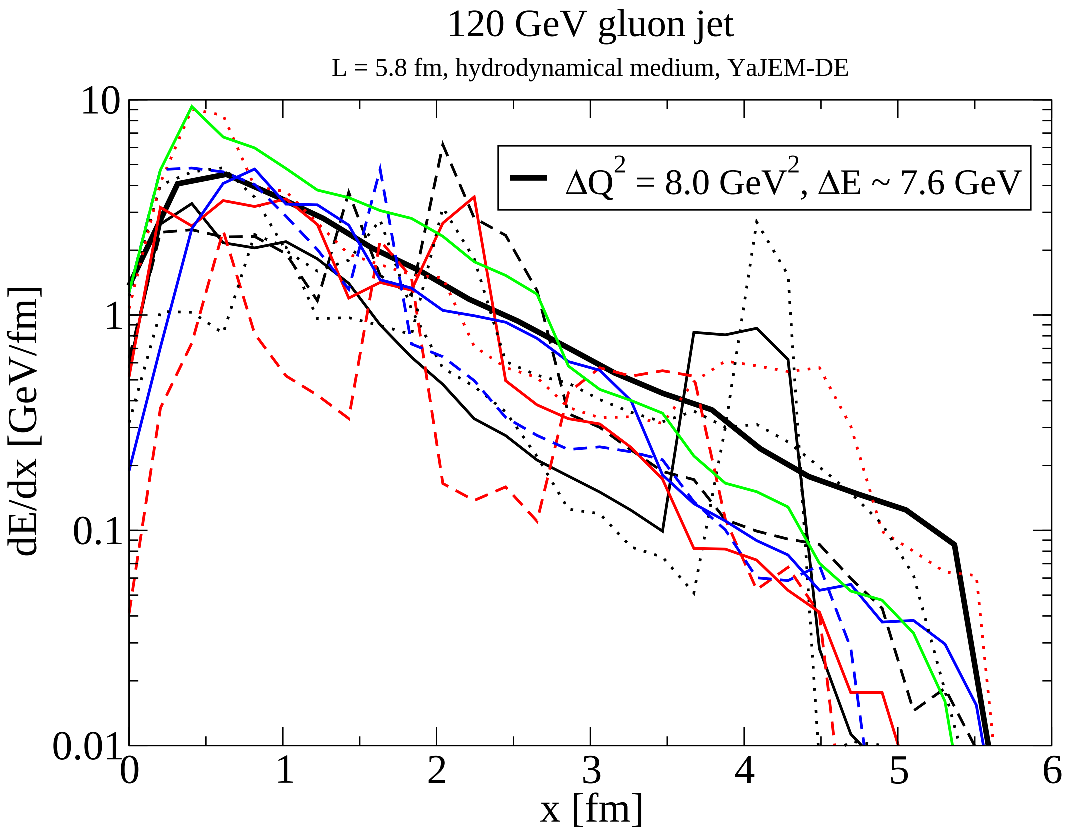
- modest low P_T enhancement of fragmentation photon yield
- conversion photons do not have a sharp peak as in energy loss approximation
- gluon jets do have photon emission, as gluons can branch into $q\overline{q}$

T. R., 1304.7598 [hep-ph].

ENERGY DEPOSITION

- plot the energy deposition into medium via $\hat{e}$ term

$\longrightarrow$ event-by-event fluctuating source term for hydrodynamics

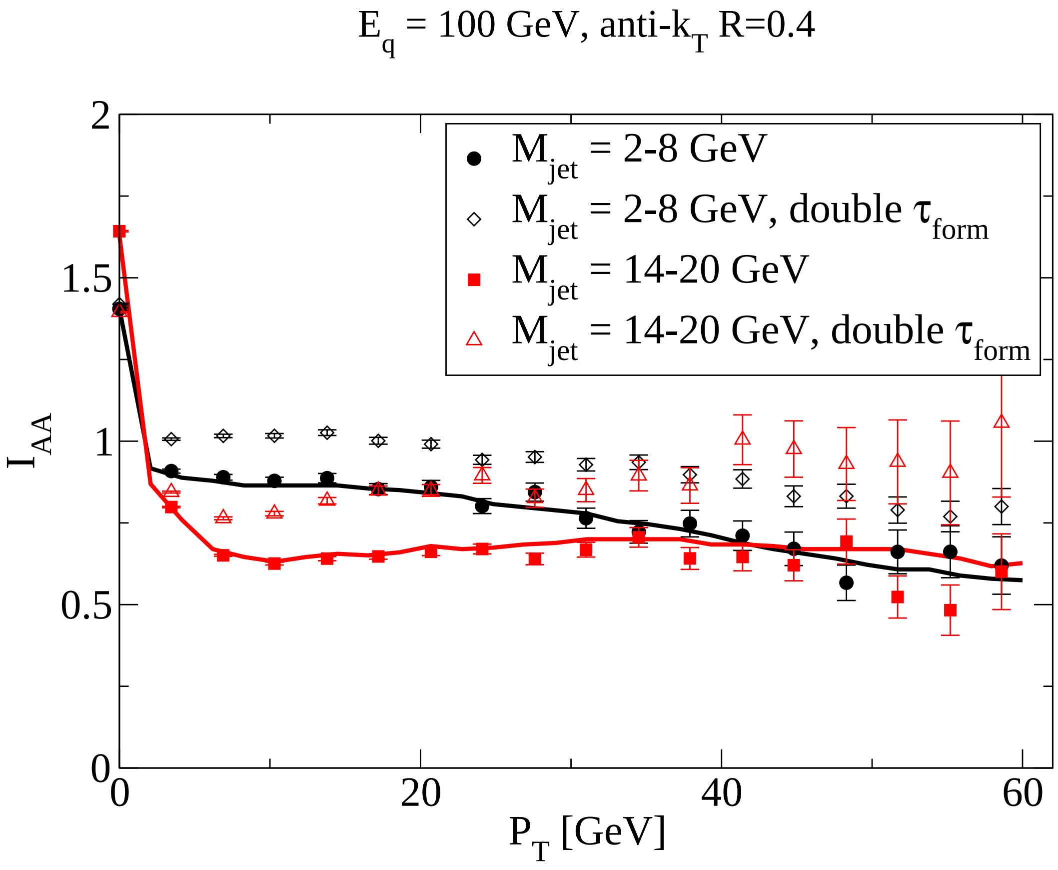


T. R., 1306.2739 [hep-ph].

JET MASS BINNING

- idea: high mass jets have stronger evolution and more multiplicity

→ multiple propagating color charges, stronger modification



⇒ should be possible to see even after clustering with $R = 0.4$

T. R., Phys. Rev. C **87** (2013) 037901

YaJEM

Some open issues:

- study systematics of high p_T v_2 in different hydro models
- phenomenology of shower and conversion photons
- application to heavy quarks at really high P_T?

If you're curious, YaJEM is available for the public on request (just drop me a mail). Sorry - no user interface, no manual, no complete event generator but only shower — the YaJEM collaboration doesn't have as many resources as the JET collaboration (= I do not have a student for code maintenance and interface coding).