YaJEM

a MC code for in-medium shower evolution

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The Model

- Guiding principles
- Model details

Leading hadron results

- Energy loss and brick problem
- Nuclear suppression factor R_{AA}

Jets results

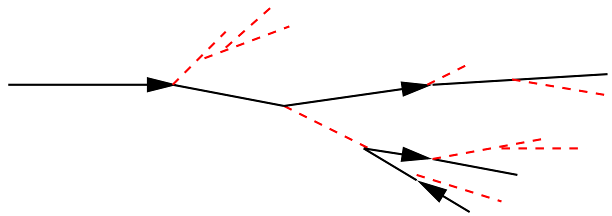
- Thrust, n-jet fraction and jet shapes
- Trigger bias

Summary

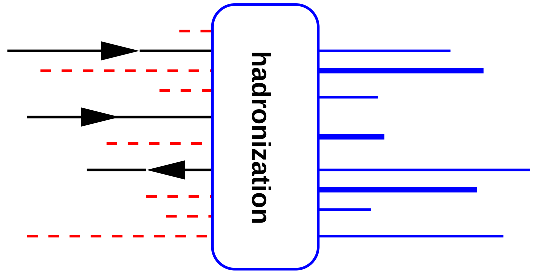
The fragmentation function

$D^{vac}_{f\to h}(z,\mu_f^2)$ encodes the following physics:

• radiation from the highly virtual initial parton via $q \to qg, g \to gg$ and $g \to q\bar{q}$ (perturbatively calculable for $Q \simeq 1$ GeV)



• hadronization (non-perturbative)



• virtual parton formation time $\tau \sim E/Q^2$, hadron formation time $\tau_h \sim E_h/m_h^2$
$\to$ part of the shower evolution for RHIC kinematics happens in the medium
$\to$ light hadrons or high P_T hadrons are produced outside the medium
$\Rightarrow$ the medium predominantly affects the perturbative parton shower

Medium-modified parton shower

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

Guiding principles

• exact energy-momentum conservation, easy contact with experimental data 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
→ issues with low P_T heavy hadrons, as they hadronize in medium

• minimal prior assumptions about the medium degrees of freedom
(ideal fluid picture — may not be thermal quasiparticles or perturbative DOF)
→ various phenomenological parton-medium interaction scenarios

• to be used together with a 3-d hydrodynamical medium description
→ issues with unrealistic situations (infinite medium, density increase . . .)

• to be constrained by all high P_T RHIC observables before LHC predictions

Jet evolution in position space

Jet evolution equations $\Leftrightarrow$ momentum space
Medium description $\Leftrightarrow$ position space

- 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

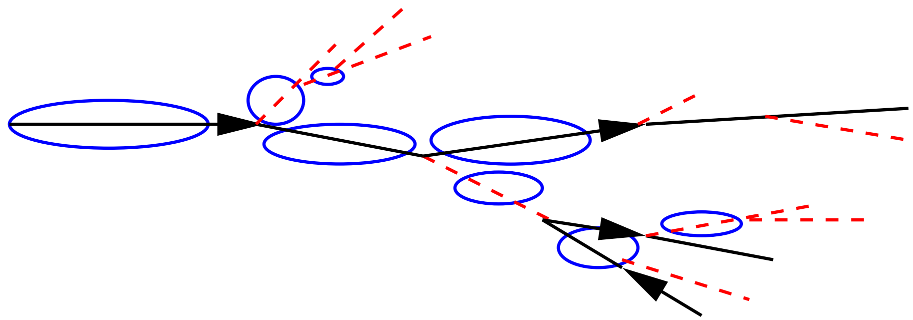
$$P(\tau_b) = \exp\left[- \frac{\tau_b}{\langle \tau_b \rangle} \right]$$

- assume all partons are on eikonal trajectory determined by the shower initiator

$\Rightarrow$ position of all branchings in spacetime known and connected with medium model

Medium-modified branching

- change parton kinematics during propagation



∗ multiple soft scattering leads to medium-induced virtuality (RAD)

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

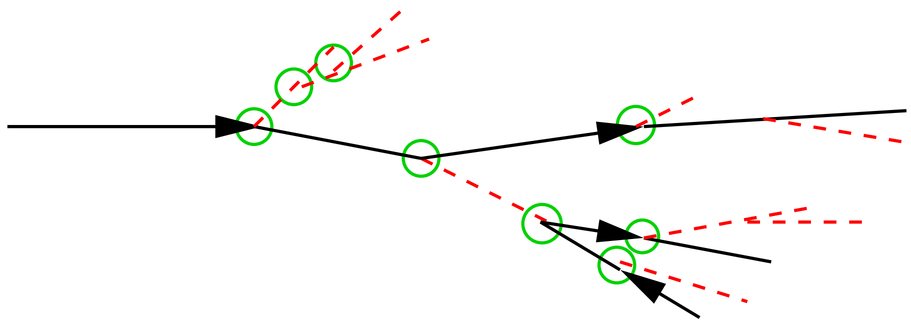
∗ in a strongly coupled medium, a drag force appears (DRAG)

$$\Delta E_a = \int_{\tau_a^0}^{\tau_a^0+\tau_a} d\zeta D\rho(\zeta)$$

T. R., Phys. Rev. C **78** (2008) 034908

Medium-modified branching

• change splitting probability in Kernel



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

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

⇒ assume $f_{med} \sim \int d\zeta \rho(\zeta)$ to link with spacetime evolution

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].

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 the medium-modified fragmentation function along a given path (determined by medium, vertex $\mathbf{r_0} = (x_0, y_0)$, rapidity y and transverse angle ϕ is $D^{med}_{i\to h}(z, \mu|\mathbf{r_0}, y, \phi)$ we can define:

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

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.

$\Rightarrow$ Thanks to Helen Caines and her group for access to the Yale **bulldogk** cluster!

Energy loss

Comparison with analytical energy loss models is not straightforward:

- vacuum baseline is *not* a single parton with energy E_0 but a shower
$\rightarrow$ leading shower parton has probabilistic $E < E_0$ — compute ΔE relative to what?

- leading parton identity may change and cannot be tagged
$\rightarrow$ 7 GeV gluon radiation from 10 GeV quark is 7 GeV energy loss in ASW but 3 GeV energy loss and parton identity change in YaJEM

Solution:

- c-quark as shower initiator: $*$ hard fragmentation $*$ identity preserved

- extract energy loss with an ansatz

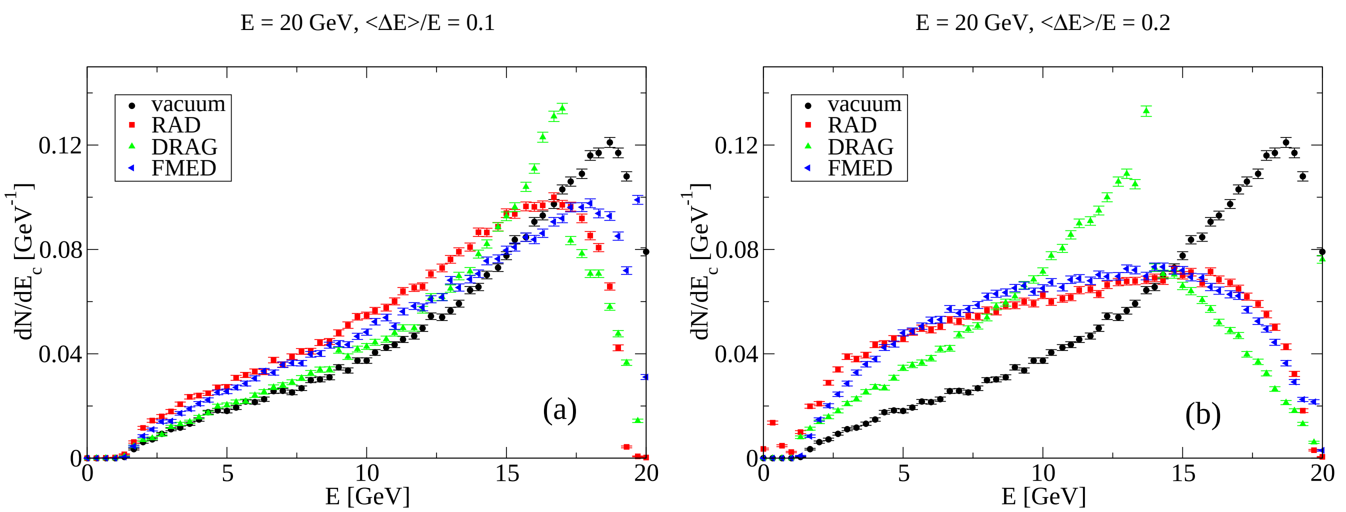
$$\frac{dN^{med}}{dE}_c(E) = \int d(\Delta E) \frac{dN^{vac}}{dE}_c(E') P(\Delta E) \delta(E' - E - \Delta E)$$

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

$\Rightarrow$ extraction of energy loss not reliable for large ΔE!

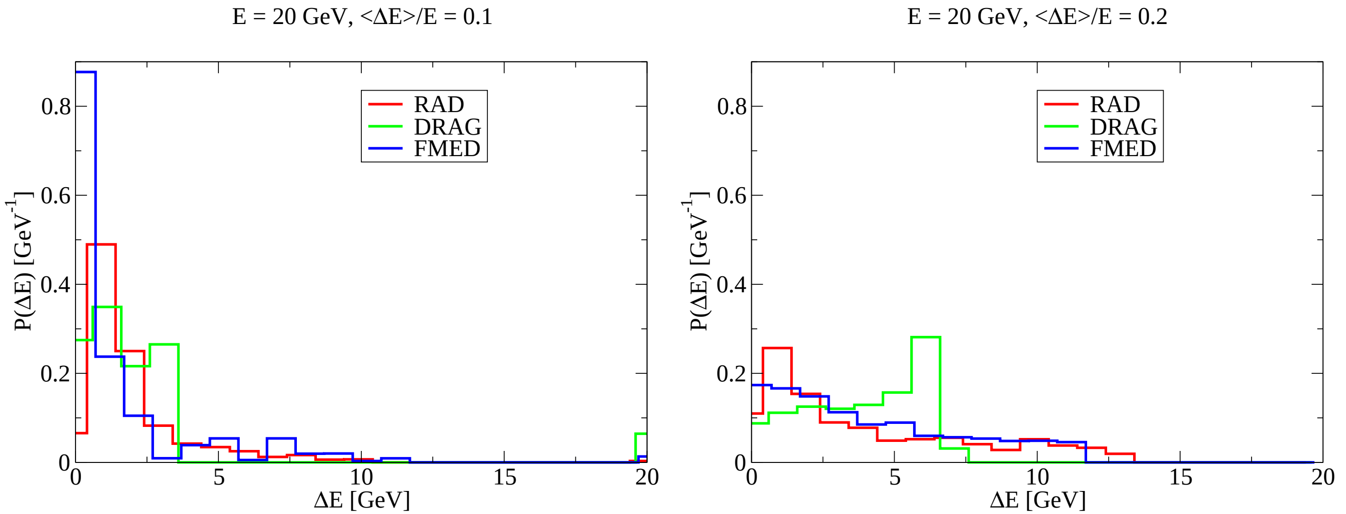
T.R., 0901.2818 [hep-ph]

Energy loss



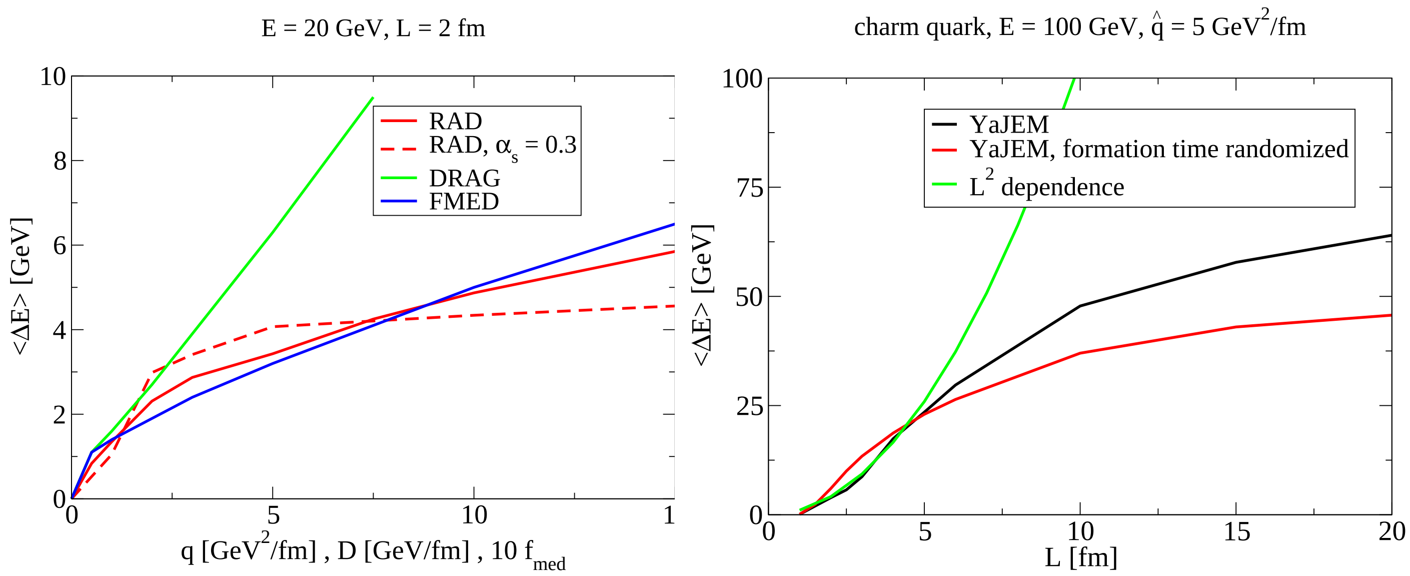
Solve matrix equation for P_j subject to $P_j > 0$ and $\sum_j P_j = 1$

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



Energy loss

Parametric dependence:



• L const. increased medium effect
$\longrightarrow$ saturation of energy loss in radiative scenarios, much weaker for drag

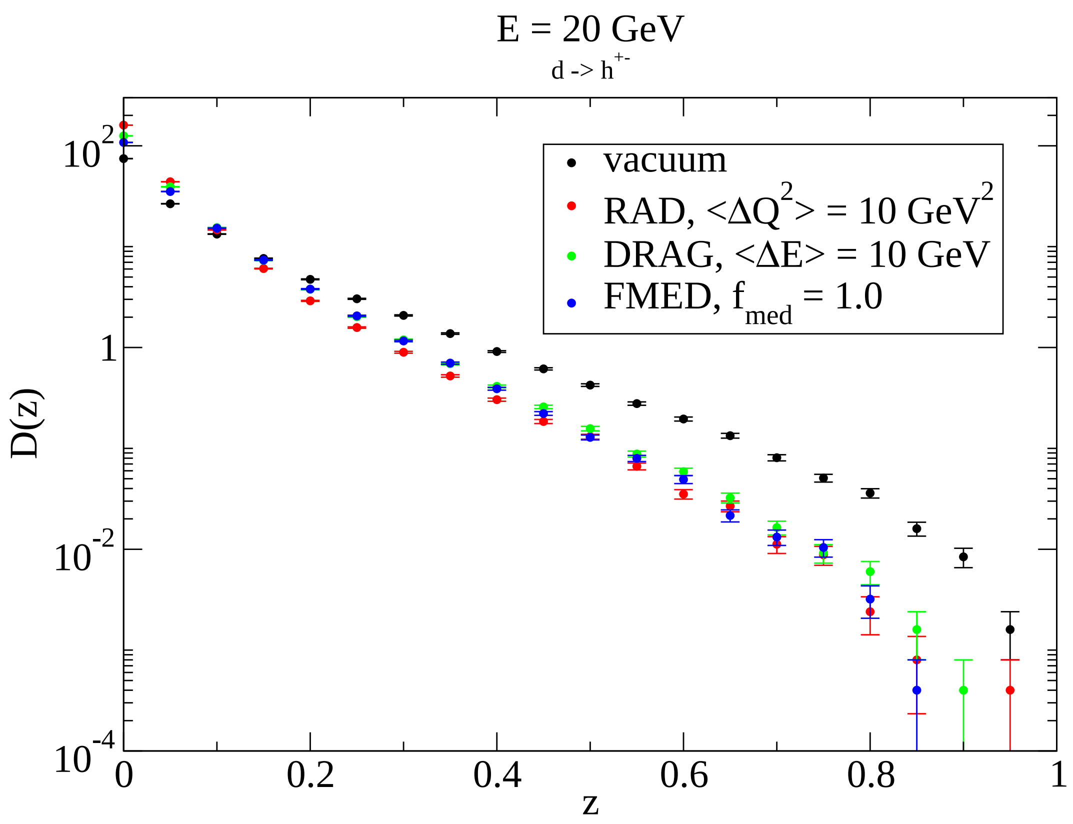
• $\hat{q}$ const., L increased (or: is the LPM effect visible?)
$\longrightarrow$ if formation time not randomized: initial L^2 dependence, then finite energy limit
$\longrightarrow$ if formation time randomized: L^2 dependence almost invisible

Reason for L^2 dependence: coherent summation of medium effect during gluon formation time in RAD scenario

see K. Zapp, J. Stachel and U. A. Wiedemann,0812.3888 [hep-ph]

Modified shower comparison (I)

Single path from center of hydro medium: Fragmentation function

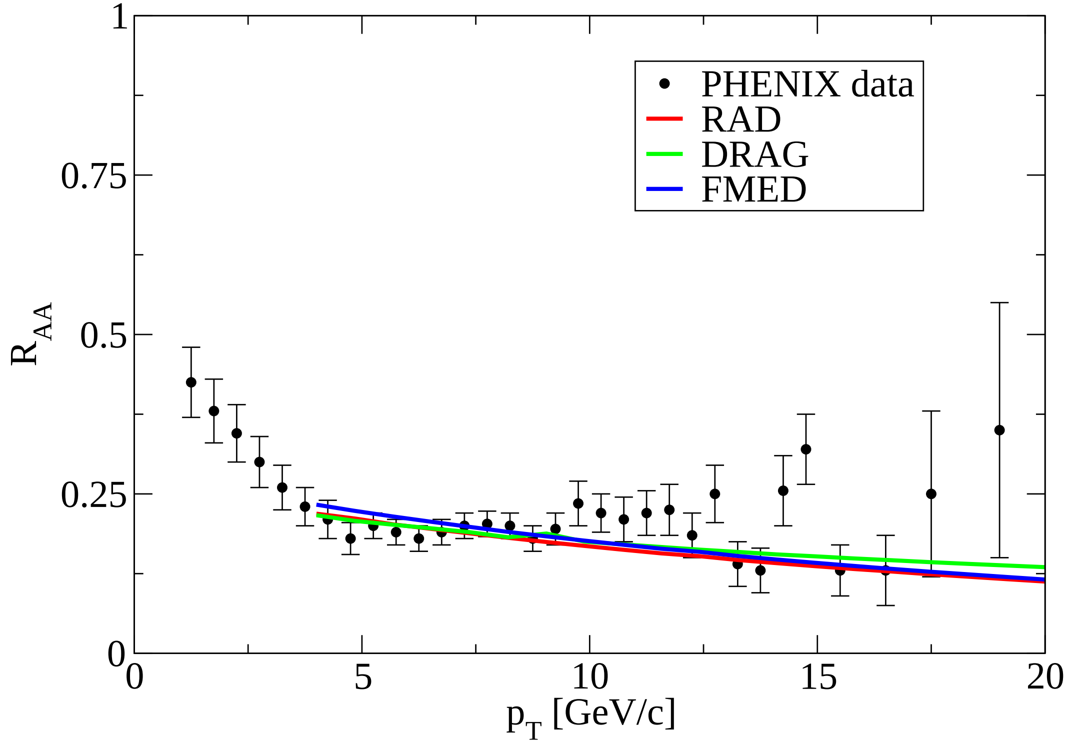


- medium-modified FF: depletion at high z
- parameters can be adjusted such that all scenarios look similar

T.R., 0901.2818 [hep-ph]

Modified shower comparison (II)

Averaged over 3-d hydrodynamical medium evolution, R_{AA} comparison is possible:

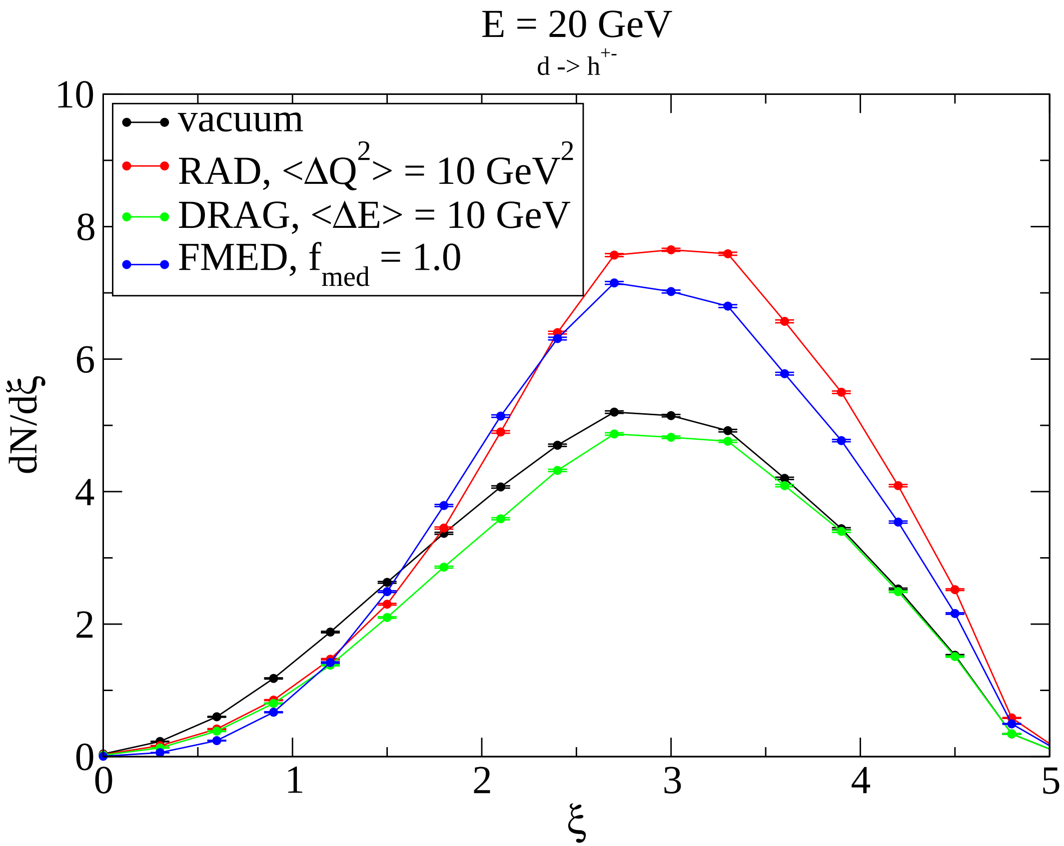


- results practically indistinguishable
- puzzling *decrease* with P_T
- also seen in other calculations of in-medium shower evolution, not an artefact

T.R., 0901.2818 [hep-ph]

Modified shower comparison (III)

Single path from center of hydro medium:
Looking at $\xi = \ln[1/z]$ magnifies low z particle production:

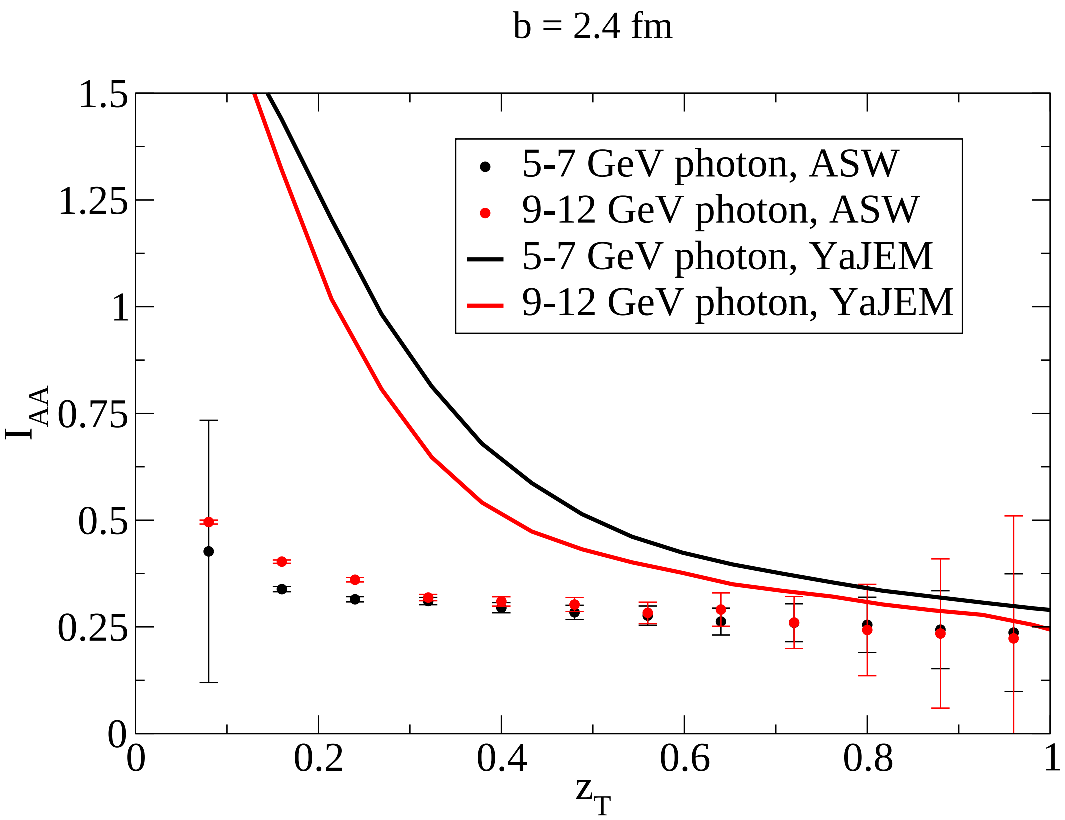


- medium-induced radiation as in RAD or FMED enhance the hump-backed plateau
- a drag force in which energy is transferred to the medium does not

T.R., 0901.2818 [hep-ph]

Modified shower comparison (IV)

Averaged over 3-d hydrodynamical medium evolution, I_{AA} in γ-h:



- assumtion: lost energy in ASW nonperturbatively distributed in medium
- perturbative low z hadron production in shower should be visible

$\Rightarrow I_{AA} > 1$ not seen in either preliminary STAR or PHENIX data

T. R., 0904.3806 [hep-ph].

Towards jet observables

Problem 1: Cannot distinguish medium and jet at low P_T:

Any low P_T hadron correlated with the jet axis may be correlated because. . .

- it is part of the hadronization of the perturbative shower
- it is bulk medium recoiling from the jet-medium interaction
- it is, due to a similar bias, accidentially correlated
  (e.g. unmodified jets tend to emerge $\perp$ surface — direction of radial flow!)

Problem 2: The hadronization models may not be valid at low P_T (in the medium)

- at present we can only compute reliably *above* a P_T cut

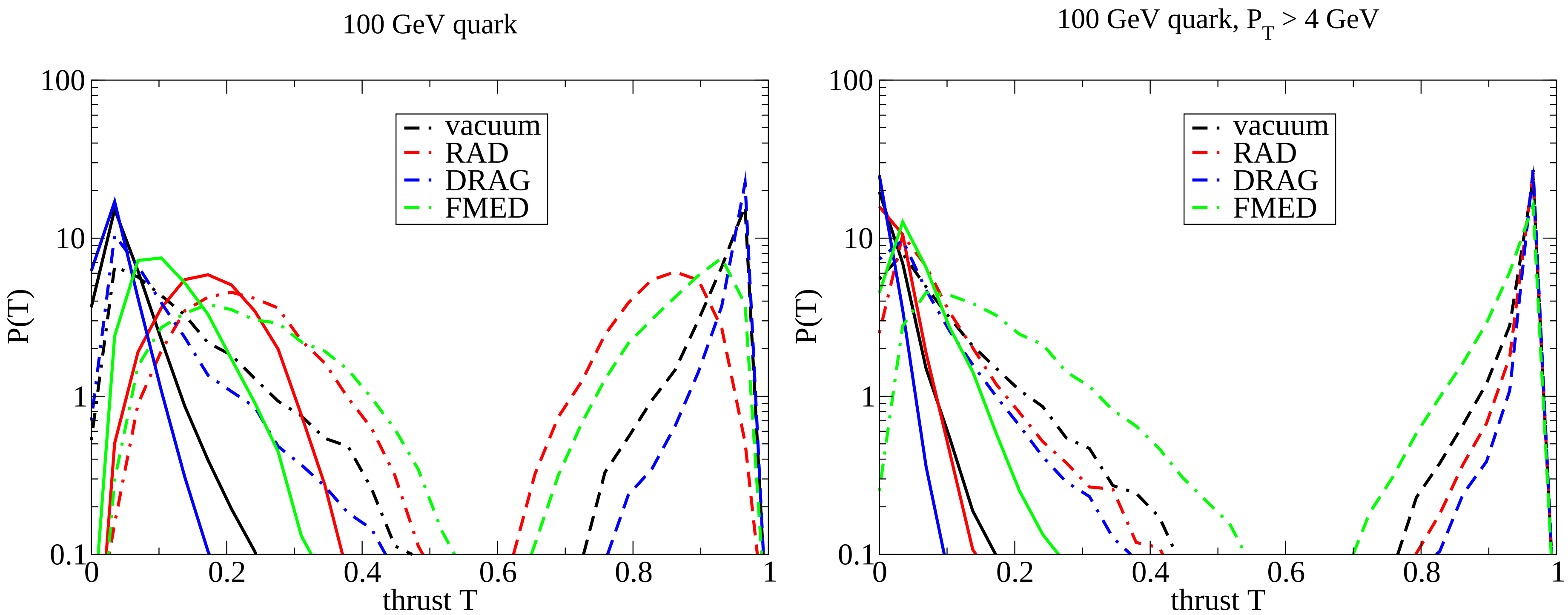
$\Rightarrow$ need to worry about bias (excluding events with lots of soft production)

LHC jet expectations are proof of principle! Real predictions will require knowledge of experimental jet finding strategy — lots of issues hidden in the small print!

Jet observables at LHC (I)

Thrust distribution for typical medium path:

$$T = \max_{\mathbf{n}_T} \frac{\sum_i |\mathbf{p}_i \cdot \mathbf{n}_T|}{\sum_i |\mathbf{p}_i|} \quad T_{maj} = \max_{\mathbf{n}_T \cdot \mathbf{n}=0} \frac{\sum_i |\mathbf{p}_i \cdot \mathbf{n}|}{\sum_i |\mathbf{p}_i|} \quad T_{min} = \frac{\sum_i |\mathbf{p}_i \cdot \mathbf{n}_{mi}|}{\sum_i |\mathbf{p}_i|}$$



- induced radiation tends to make the event more spherical
- difference between RAD and FMED for P_T cut

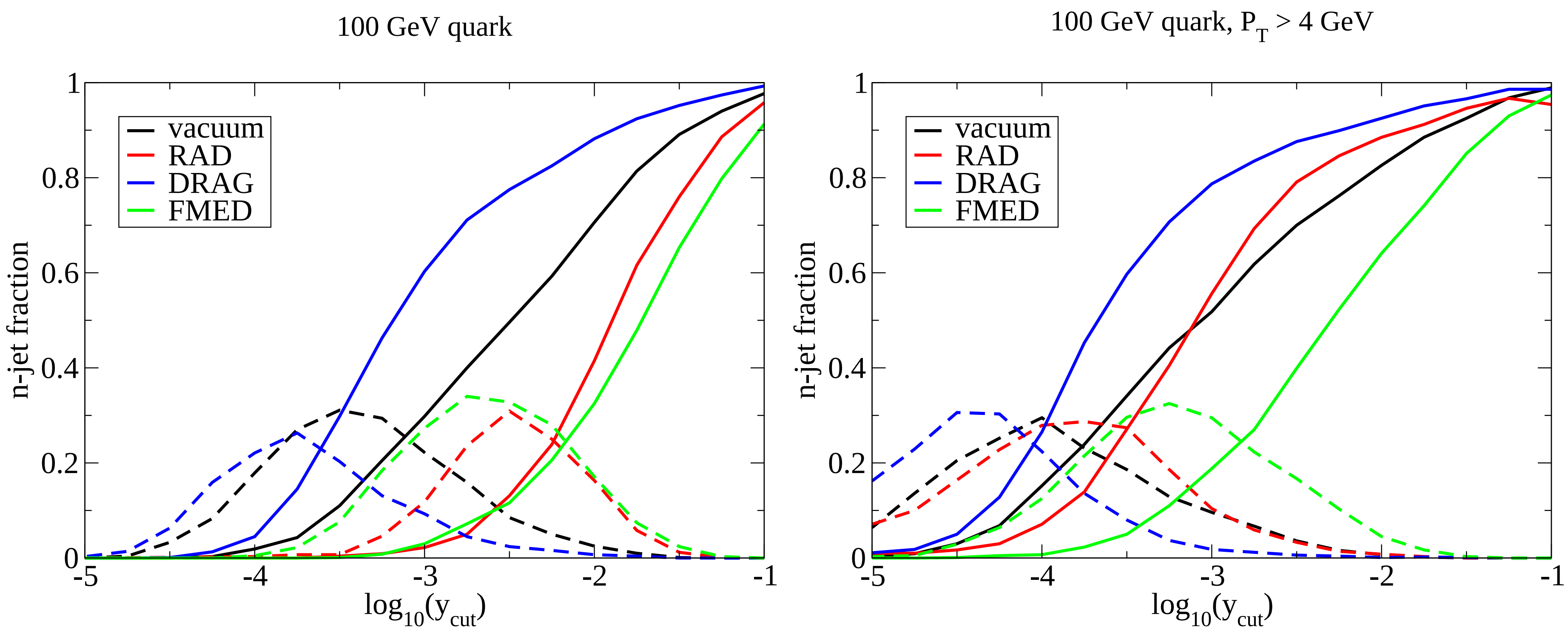
T. R., 0906.3397 [hep-ph]

Jet observables at LHC (II)

2 and 4-jet fraction for typical in-medium path for a back-to-back pair:

Clustering with a resolution scale y_{min} based on distance measure

$$y_{ij} = 2\text{min}(E_i^2, E_j^2)(1 - \cos(\theta_{ij})/E_{\text{cm}}^2$$

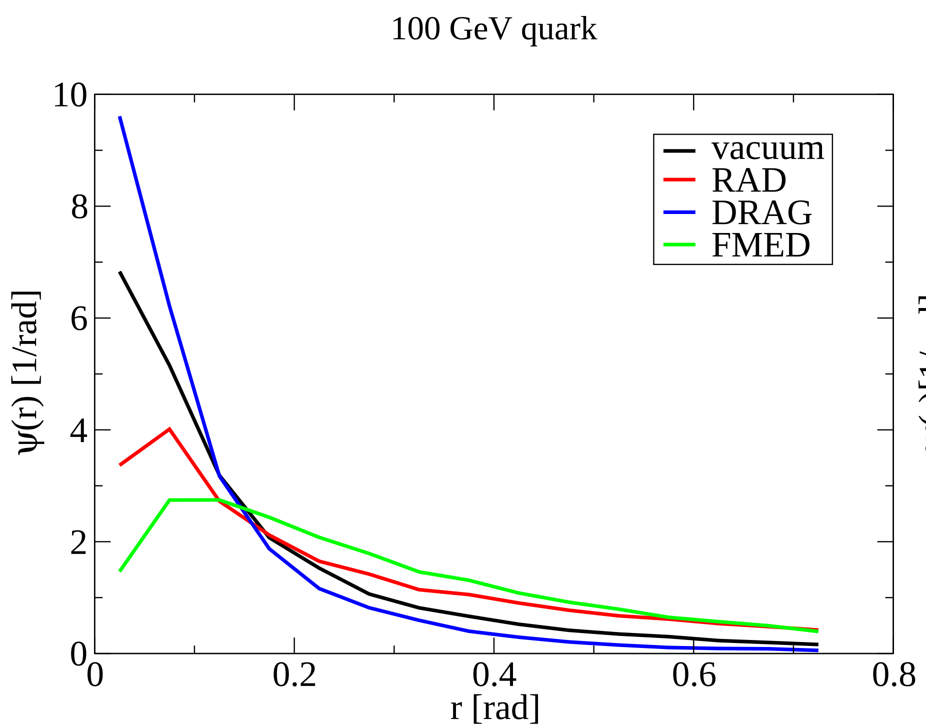


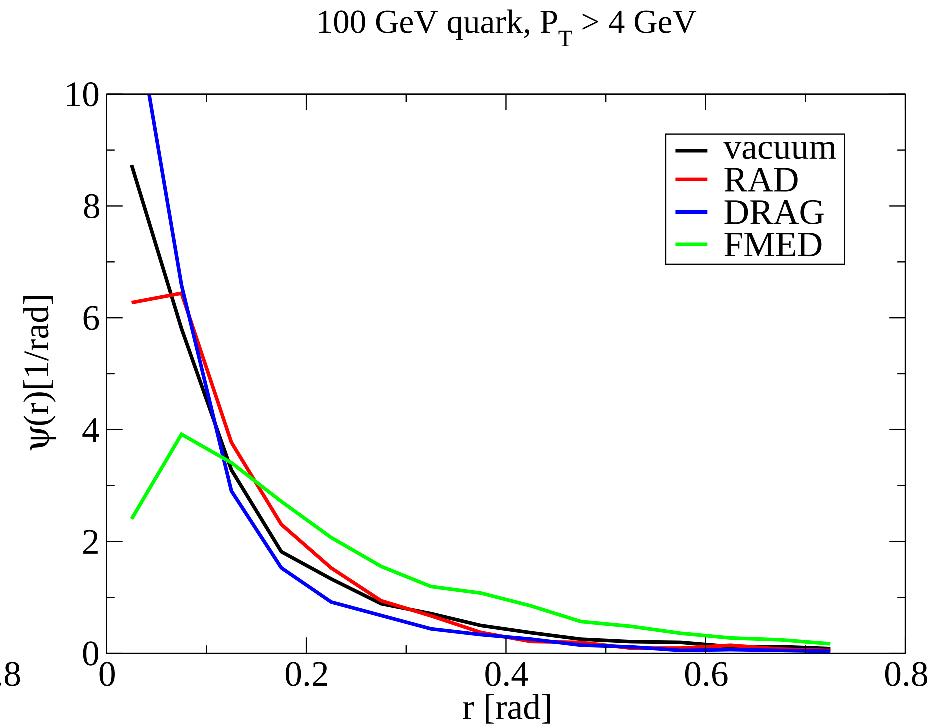
T. R., 0906.3397 [hep-ph]

Jet observables at LHC (III)

Jet shapes for typical medium path:

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

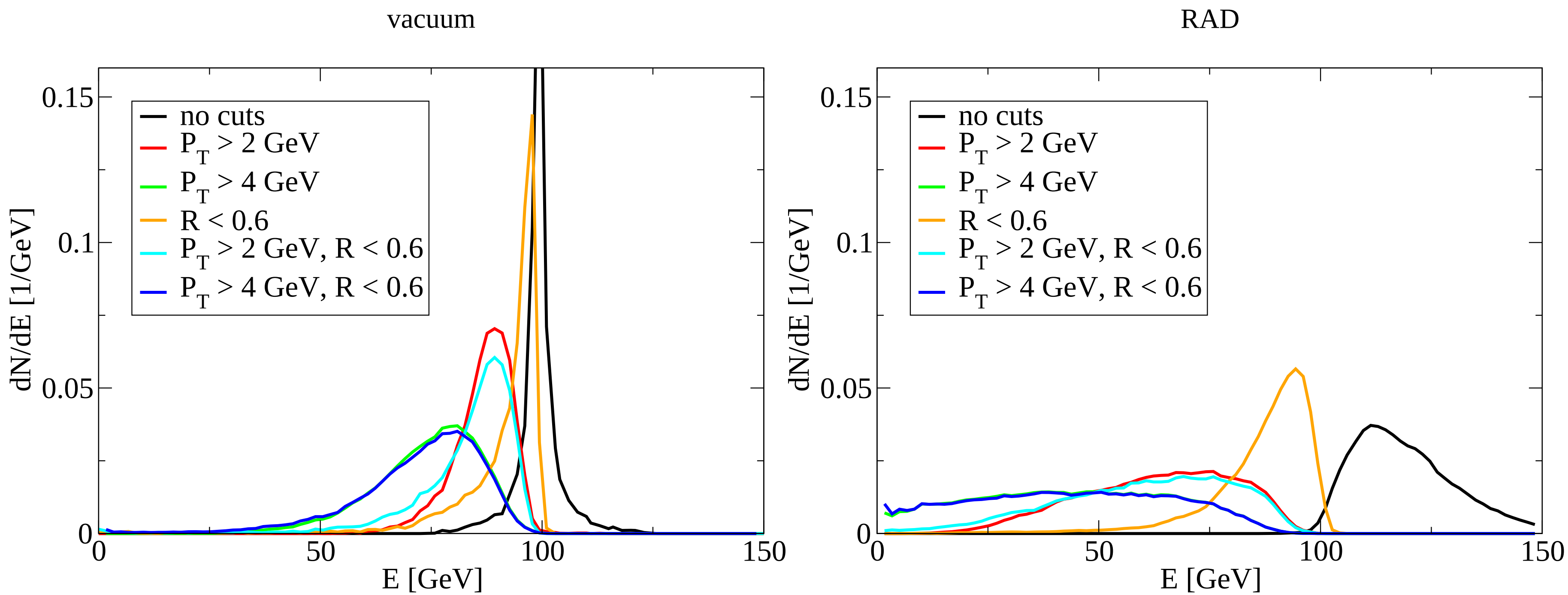




T. R., 0906.3397 [hep-ph]

JET OBSERVABLES AT LHC — TRIGGER BIAS

Given a 100 GeV quark shower initiator — what is the energy detected within typical experimental cuts (cone radius R or P_T)?



- medium-modified jets are unlikely to be found with correct energy

T. R., 0906.3397 [hep-ph]

YaJEM — current status

Theoretical

- TECHQM brick problem: Done!

→ `https://wiki.bnl.gov/TECHQM/index.php/YaJEM`, 0901.2818 [hep-ph]
(with several caveats — difficult problem in YaJEM language)

- comparison with JEWEL results on thrust, n-jet fraction, $dN/d\xi$: Done!

→ 0901.2818 [hep-ph], 0906.3397 [hep-ph] (qualitatively similar)

- LPM effect and L^2 energy loss pathlength dependence for constant medium: Done!

→ can reproduce limit, however other effects dominate.

- comparison with BDMPS or AMY limits: Not done.

→ no infinite medium limit, no infinite parton energy limit, no on-shell limit

YaJEM — current status

Phenomenology

- hydro-averaged comparison with R_{AA}: Done!

$\longrightarrow$ puzzling decrease of $R_{AA}(P_T)$, also seen in other models: Unexplained. . .

- hydro-averaged comparison with $R_{AA}(\phi)$: Not done.

- hydro-averaged comparison with I_{AA} in γ-h: Done!

$\longrightarrow$ not in agreement with preliminary data at low z: Unexplained. . .

- hydro-averaged comparison with I_{AA} in $h-h$: Almost done!

$\longrightarrow$ agreement with data questionable (pathlength dependence) Unexplained. . .

- hydro-averaged comparison with single e^- R_{AA}: Done!

$\longrightarrow$ results comparable with other radiative energy loss models: Unexplained. . .

Too many open issues to predict comfortably. . .

YaJEM — current status

The simpler ASW energy loss ansatz with static scattering centers and infinite parton energy actually works much better for all these observables!

As a theorist, I am somewhat dismayed by the fact that trying to make the model more realistic leads to less agreement with the data. As a phenomenologist however, I am excited by the fact that there's something to learn here!

My (cautious) impression is that there is part of the parton-medium dynamics which is not perturbative jet evolution, and that the medium may not have perturbatively resolvable degrees of freedom. If so, arguing theoretically from agreement with pQCD limits which model is more valid may be just a red herring.

YaJEM — publications

• T. R., "Parton shower evolution in a 3-d hydrodynamical medium," Phys. Rev. C **78** (2008) 034908.

• T. R., "Jet modification in 200 AGeV Au-Au collisions," 0808.1803 [hep-ph].

• T. R., "A comparison study of medium-modified QCD shower evolution scenarios," 0901.2818 [hep-ph] (accepted by PRC).

• T. R., "gamma-hadron correlations as a tool to trace the flow of energy lost from hard partons in heavy-ion collisions," 0904.3806 [hep-ph] (accepted by PRC).

• T. R., "Medium-modified Jet Shapes and other Jet Observables from in-medium Parton Shower Evolution," 0906.3397 [hep-ph].

Special thanks to Jörn Putschke, Helen Caines, Peter Jacobs, Barbara Jacak, Megan Connors, Ahmed Hamed, Saskia Mioduszewski, Kari Eskola and many others!