Modelling jet quenching

— and how to constrain the models

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Introduction
Basic types of models
Constraints from hadron observables
- pathlength dependence
- momentum flow and correlations
Jet physics
- fine print of clustering
- jet suppression mechanism
Conclusions

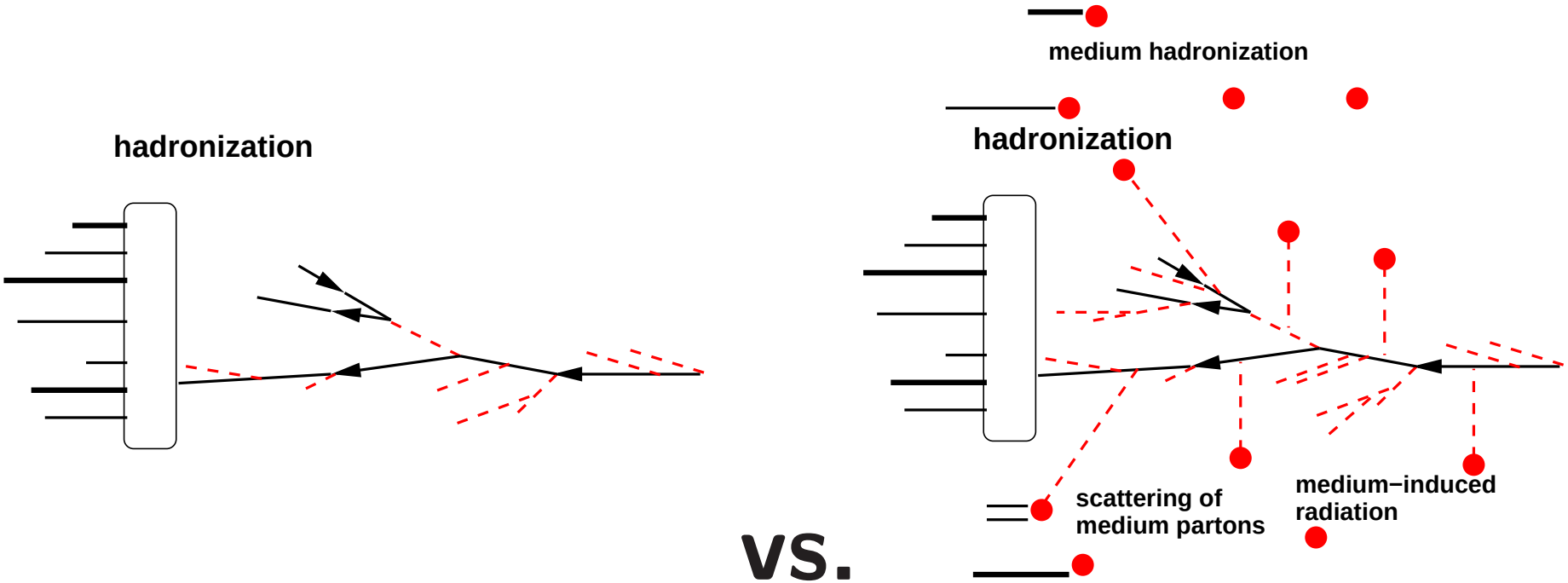
I. Modelling jet quenching

the range of options

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 modified and unmodified jets!



QCD SHOWER EVOLUTION

- start with QCD shower (here: PYSHOW virtuality ordered shower)
- evolution in virtuality with (almost) collinear splitting: use $t = \ln Q^2/\Lambda_{QCD}$ and z
- differential splitting probability is

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

with splitting kernels from perturbative QCD

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

$\longrightarrow$ kinematically regulated singularity – soft gluon emission

- series of splittings $a \longrightarrow bc$ with decreasing t

$\longrightarrow$ daughter partons take the energies $E_b = zE_a$ and $E_c = (1-z)E_a$

- terminate at a soft virtuality scale t_0 or Q_0 and hadronize (e.g. using Lund)

QCD SHOWER EVOLUTION

• note that splitting kernels $P_{q\to qg}(z)$ with $z = E_{daughter}/E_{parent}$ are **scale-invariant**
$\longrightarrow$ fragmentation functions $D(z)$ are self-similar and do not strongly depend on energy
$\longrightarrow$ logarithmic corrections due to the running of α_s

Note on timescales:

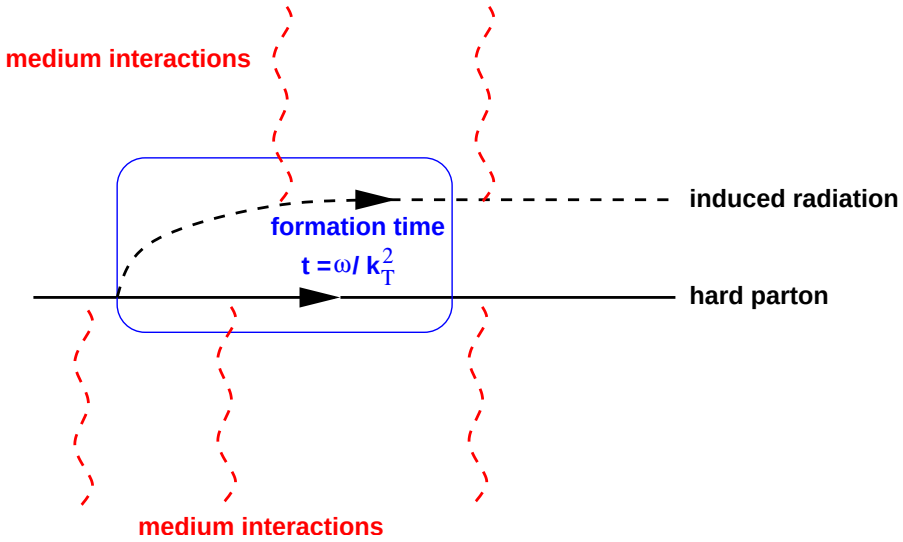
• typical timescale to split $\sim E_b/Q^2$ (uncertainty relation)
$\longrightarrow$ hard branchings occur at short times ~ 0.01 fm **before** medium can be formed
$\Rightarrow$ basic subjet structure is always formed independent of medium
$\Rightarrow$ color decoherence only relevant **after** medium is formed

• for current kinematics, significant part of the perturbative shower evolves in medium
$\longrightarrow$ top LHC energies: more and more shower is boosted out of the medium

• typical timescale to form a hadron $\tau_h \sim E_h/m_h^2$
$\longrightarrow$ pion at 10 GeV: $\tau_h \sim 100$ fm - hadronization independent of medium
$\longrightarrow$ proton at 2 GeV: $\tau_h \sim 0.45$ fm - not so good, keep this in mind!

QCD shower evolution in medium

How does the medium act on the shower?



- exchange of energy and momentum with medium changes shower evolution

- operational definition (based on transport coefficients, **not** true for a graph)

$\longrightarrow$ elastic: energy is taken by the recoil of medium constituents, $\hat{e} = dE/dx$

$\longrightarrow$ radiative: enhanced splitting into soft gluons, $\hat{q} = dQ^2/dx$

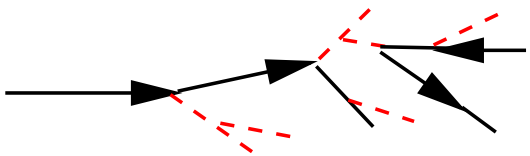
$\Rightarrow$ radiative involves a formation time, elastic does not $\longrightarrow$ pathlength dependence

- to be explored: medium can modify color flow structure

$\longrightarrow$ how does this work combined with color screening and a non-perturbative medium?

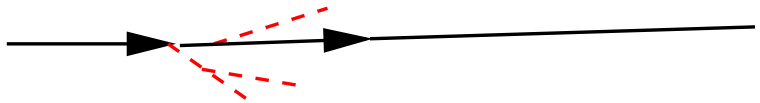
What is modelled?

- the whole shower evolution inside a medium (**shower**)



$\longrightarrow$ models all events, in particular those with multiple soft production
$\longrightarrow$ finite initial virtuality and virtuality evolution

- the fate of the leading shower parton only (**energy loss**)



$\longrightarrow$ only good for events in which dominant momentum flow is through single parton
$\Rightarrow$ fragmentation function $\approx$ hadronization of leading parton
$\Rightarrow$ medium effect $\approx$ reduction of leading parton energy
$\Rightarrow$ if hadronization happens outside the medium, the two factorize!
$\longrightarrow$ usually on-shell approximation

- approximately the whole shower (**hybrid**)

$\longrightarrow$ model shower evolution till medium forms, then do energy loss on that shower

How is the medium treated?

• the model includes a microscopical description of the medium dof (**explicit**)
$\longrightarrow$ usually implies weakly interacting quark-gluon gas and thermal field theory tools
$\Rightarrow$ such a description is **not** supported by low η/s seen in hydro!
$\Rightarrow$ **breaks** scale invariance of $D(z)$ around scale T, but not above!
$\Rightarrow$ **additional** kinematical phase space for transverse broadening

• medium appears via transport coefficients modifying splitting probabilities (**TCP**)
$\longrightarrow$ for instance Borghini-Wiedemann: enhance singular part of splitting kernel:

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

$\Rightarrow$ **changes** scale invariance of $D(z)$ to a different functional form!
$\Rightarrow$ **no additional** kinematical phase space for transverse broadening

• medium appears via transport coefficients which modify kinematics (**TCK**)
$\longrightarrow$ partons may gain additional virtuality or lose energy as the shower evolves
$\Rightarrow$ **breaks** scale invariance of $D(z)$ around scale T, but not above!
$\Rightarrow$ **additional** kinematical phase space for transverse broadening

How do we solve the equations?

- using analytical techniques (**analytical**)

$\longrightarrow$ gets quantum interference effects correct
$\longrightarrow$ often requires kinematical approximations (eikonal, infinite parent energy,. . .)
$\longrightarrow$ sometimes difficult to compare with experimental jet finding strategies

- using Monte-Carlo tools (**MC**)

$\longrightarrow$ gets energy-momentum balance for free
$\longrightarrow$ quantum interference needs to be included by hand
$\longrightarrow$ easily analyzed like experimental data

A zoo of models

	TCK	TCP	explicit
MC shower	YaJEM	Q-PYTHIA, BW	JEWEL
analytical shower	—	HT resummed	—
MC hybrid	—	PYQUEN	MARTINI
analytical energy loss	—	ASW, HT	AMY, GLV

Further differences in detail:

• length-dependent min. virtuality in shower:
$Q_0 = \sqrt{E/L}$ (resummed HT, YaJEM-D, YaJEM-DE)

• amount of elastic vs. radiative energy transfer
→ no elastic: ASW, Q-PYTHIA, HT, GLV, YaJEM, YaJEM-D,. . .
→ $\sim$ 50% elastic: AMY, WHDG, MARTINI, . . .
→ $\sim$ 10% elastic: YaJEM-DE, . . .

⇒ explicit medium modelling naturally leads to $\sim$50% elastic energy transfer

• different cutoff and z definitions (energy vs. light cone momentum)
→ mainly affect numbers extracted from the model, not qualitative features

N. Armesto, B. Cole, C. Gale, W. A. Horowitz, P. Jacobs, S. Jeon, M. van Leeuwen and A. Majumder *et al.*, 1106.1106 [hep-ph].

Pathlength issues

Different physics $\rightarrow$ pathlength dependence of energy loss in constant medium

- 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 drastically by **time evolution of the medium**!

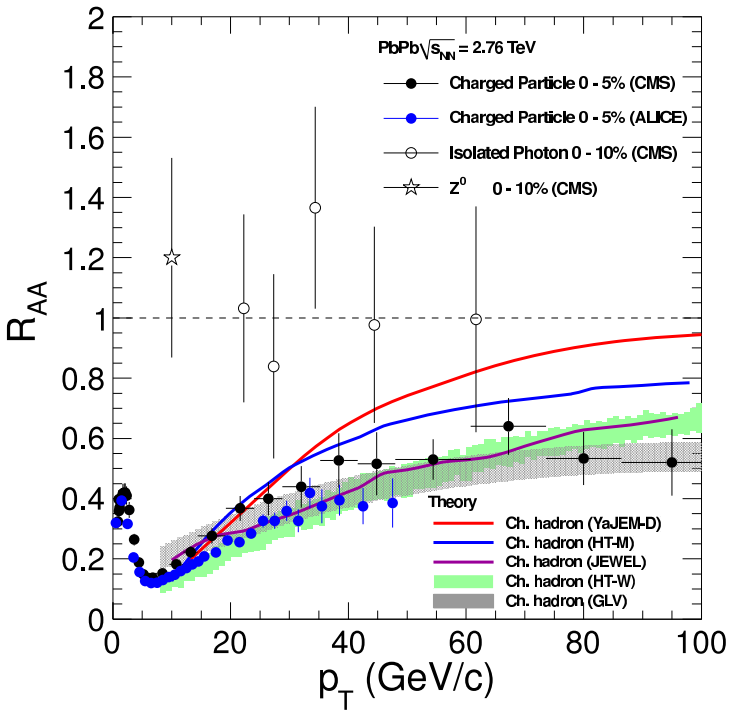
II. Single hadron suppression

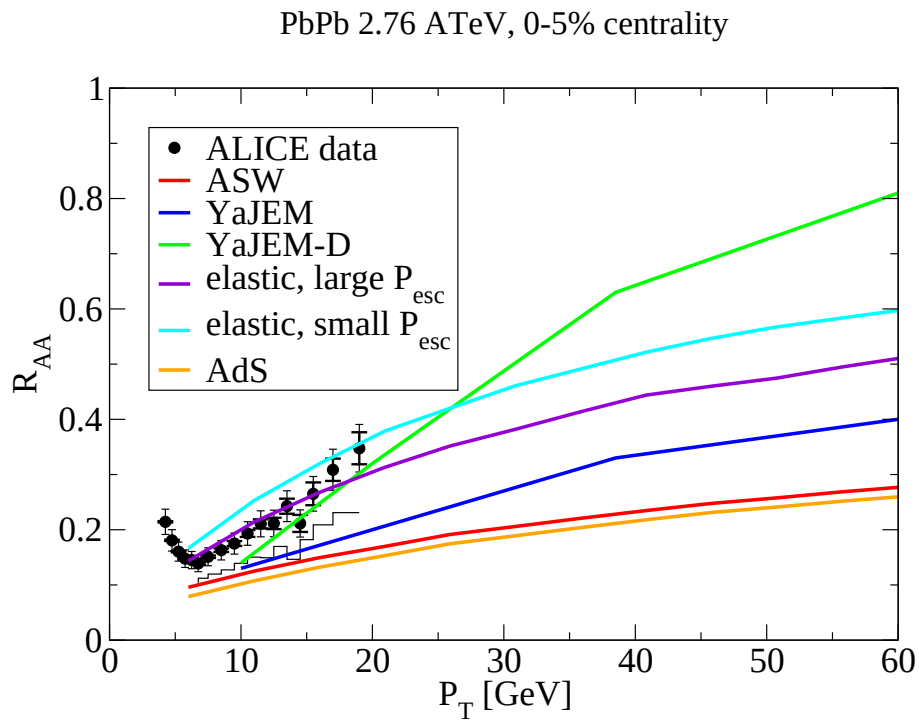
R_{AA} and dihadron I_{AA}

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

Models and R_{AA}?

- some pre- and postdictions for $R_{AA}(P_T)$ at LHC





$\longrightarrow$ within hydro uncertainty, most models can be tuned to work at LHC

- important exception: AdS — this has $\Delta E \sim T^4$ rather $\sim T^3$

$\longrightarrow$ drastically overestimates quenching at LHC when tuned at RHIC

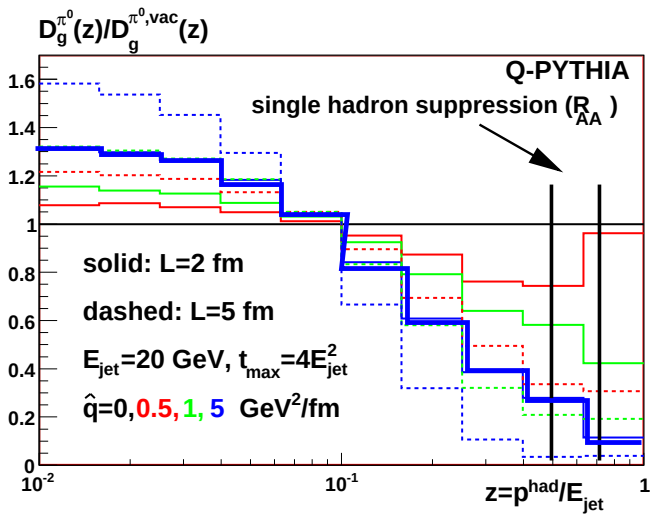
$R_{AA}(\sqrt{s})$

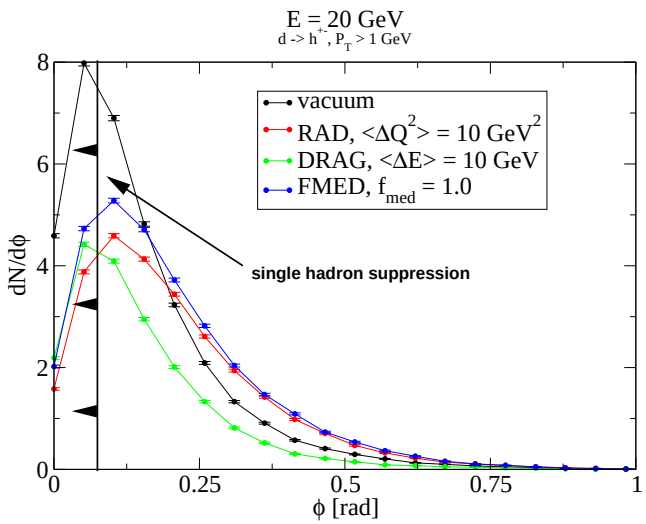
- quenching between RHIC and LHC compatible with T^3 but not T^4 scaling

* AdS/QCD models in which $\Delta Q^2 \sim L^3 T^4$ (rather than $\sim L^2 T^3$)

What is probed?

- R_{AA} involves convolution with hydro geometry and folding with pQCD spectrum





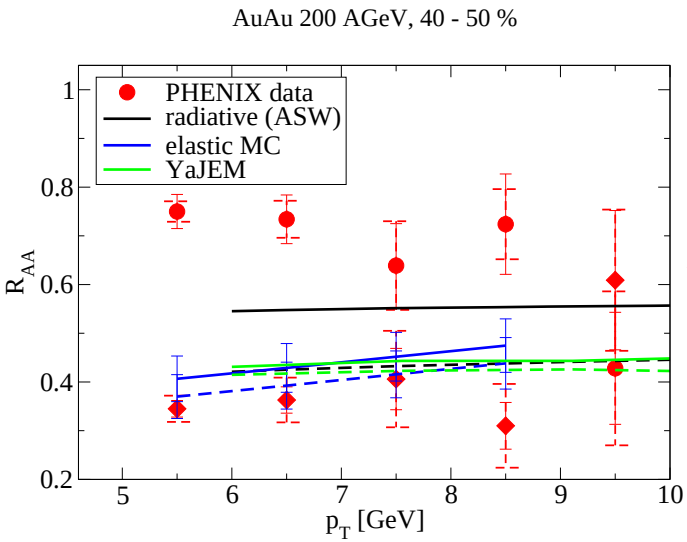
$\Rightarrow$ only **small region** of MMFF long. and transverse structure probed!

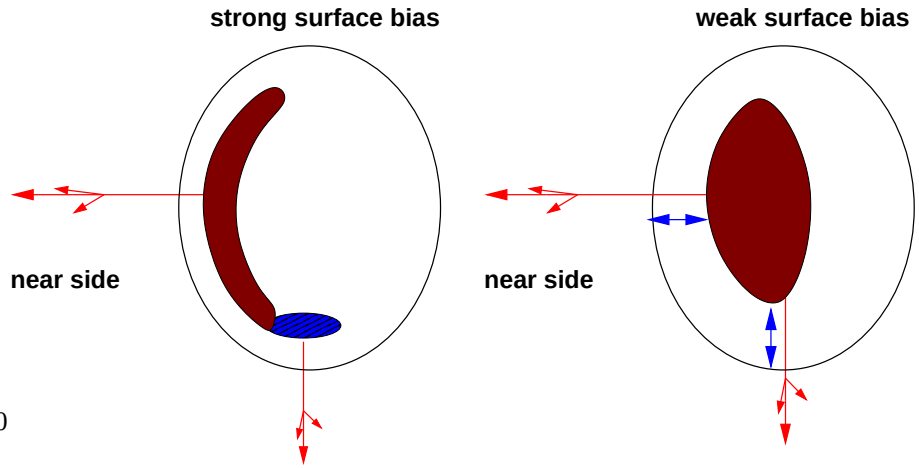
N. Armesto, L. Cunqueiro and C. A. Salgado, Eur. Phys. J. C **63** (2009) 67; T. R., Phys. Rev. C **79** (2009) 054906

Pathlength dependence and hydro geometry

- compare in-plane and out of plane R_{AA} with data

$\longrightarrow$ this probes pathlength dependence on jet quenching **and** hydro geometry





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

J. Auvinen, K. J. Eskola, H. Holopainen and T. R., Phys. Rev. C **82** (2010) 051901; (systematics summarized in T.R., 1112.2503 [hep-ph])

Pathlength dependence and hydro geometry

- factor 2(!) uncertainty within constrained hydro models

* data comparison without constrained medium model – factor 10!

- any component with linear pathlength dependence must be $< 10\%$

* 50% elastic energy loss, models based on quark-gluon gas
* LPM effect with finite energy correction (YaJEM, MARTINI,. . .)
* models without finite energy corrections (ASW, GLV, . . .)

K. Zapp *et al.*, Phys. Rev. Lett. **103** (2009) 152302; T. R., Phys. Rev. **C83** (2011) 024908; S. Caron-Huot *et al.* Phys. Rev. **C82** (2010) 064902.

- A. Majumder: In-medium showers can only develop down to $Q_0 = \sqrt{E/L}$

$\rightarrow$ models using this prescription can account for the data even with finite kinematics

Dihadron correlations

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

$\Rightarrow$ the trigger condition biases the shower in a certain way
$\longrightarrow$ this will turn out to be most useful

Trigger perfers hard fragmentation:

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

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

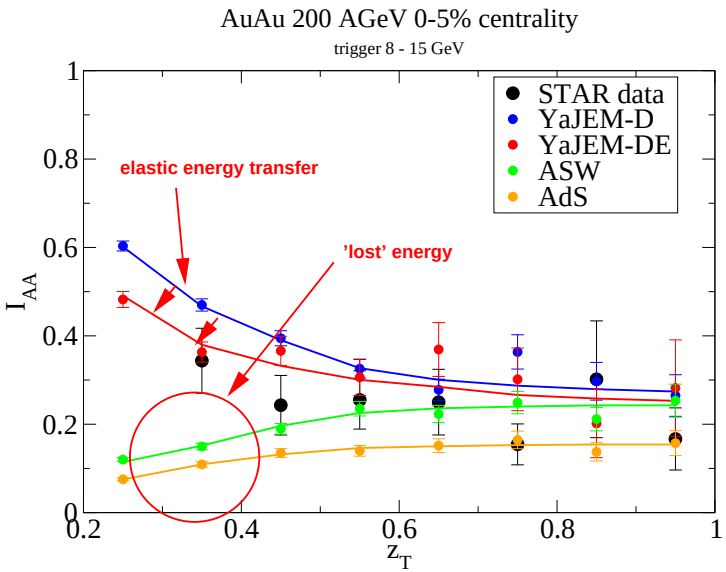
• allows (in principle) to see the full longitudinal and transverse shower structure
$\longrightarrow$ in a biased way, but it's comparatively easy to compute the bias

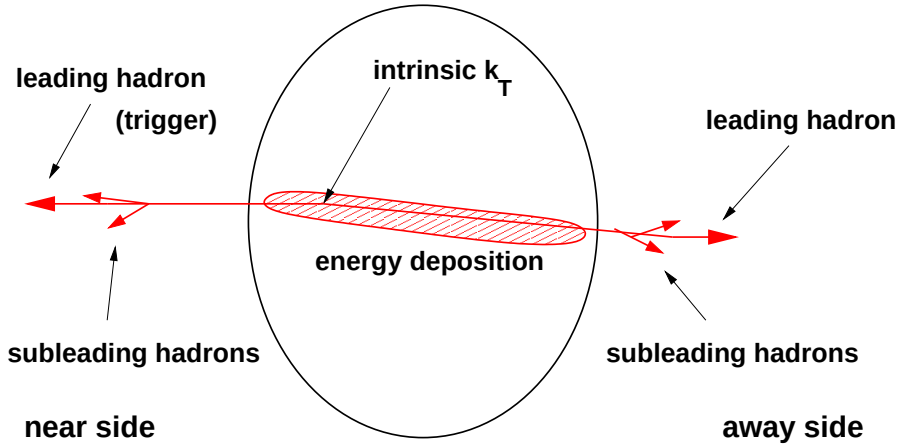
T. R. and K. J. Eskola, Phys. Rev. C **84** (2011) 054913

Energy redistribution in shower

- compare I_{AA} with data

$\longrightarrow$ this probes in addition how energy flows into soft hadron production





- energy loss models fail at low $z_T = E_h/E_{trigger}$

$\longrightarrow$ large share of 'lost' energy goes into soft hadron production

- pure medium-induced shower overshoots the data

$\longrightarrow$ part of 'lost' energy is really dissipated into the medium

- about 10% elastic contribution works nicely

$\longrightarrow$ this agrees well with upper bound from pathlength dependence

T. R. and K. J. Eskola, Phys. Rev. C **84** (2011) 054913 (systematics summarized in T.R., 1112.2503 [hep-ph])

Pathlength dependence and hydro geometry

- subleading hadron production is observed

  * leading parton energy loss models (ASW, AdS, . . .)

- need enough radiative energy loss to quench, but not too much soft production

  * models without energy transfer into the medium (YaJEM-D, . . .)

III. Clustering into jets

some words on the fine print

Medium modified jets

What is a medium-modified jet?

- theorist's first answer: the output of my jet quenching MC /my analytical result
- experimentalist's first answer: the output of jet finding, run on my event

Absolutely not the same thing!

$\Rightarrow$ for low P_T hadrons in a jet, we cannot pretend that $\tau \sim E_h/m_h^2$ is large
$\rightarrow$ ill-defined in-medium hadronization, breakdown of theory

$\Rightarrow$ jet reconstruction works different if a background is present

M. Cacciari, J. Rojo, G. P. Salam, G. Soyez, Eur. Phys. J. **C71** (2011) 1539

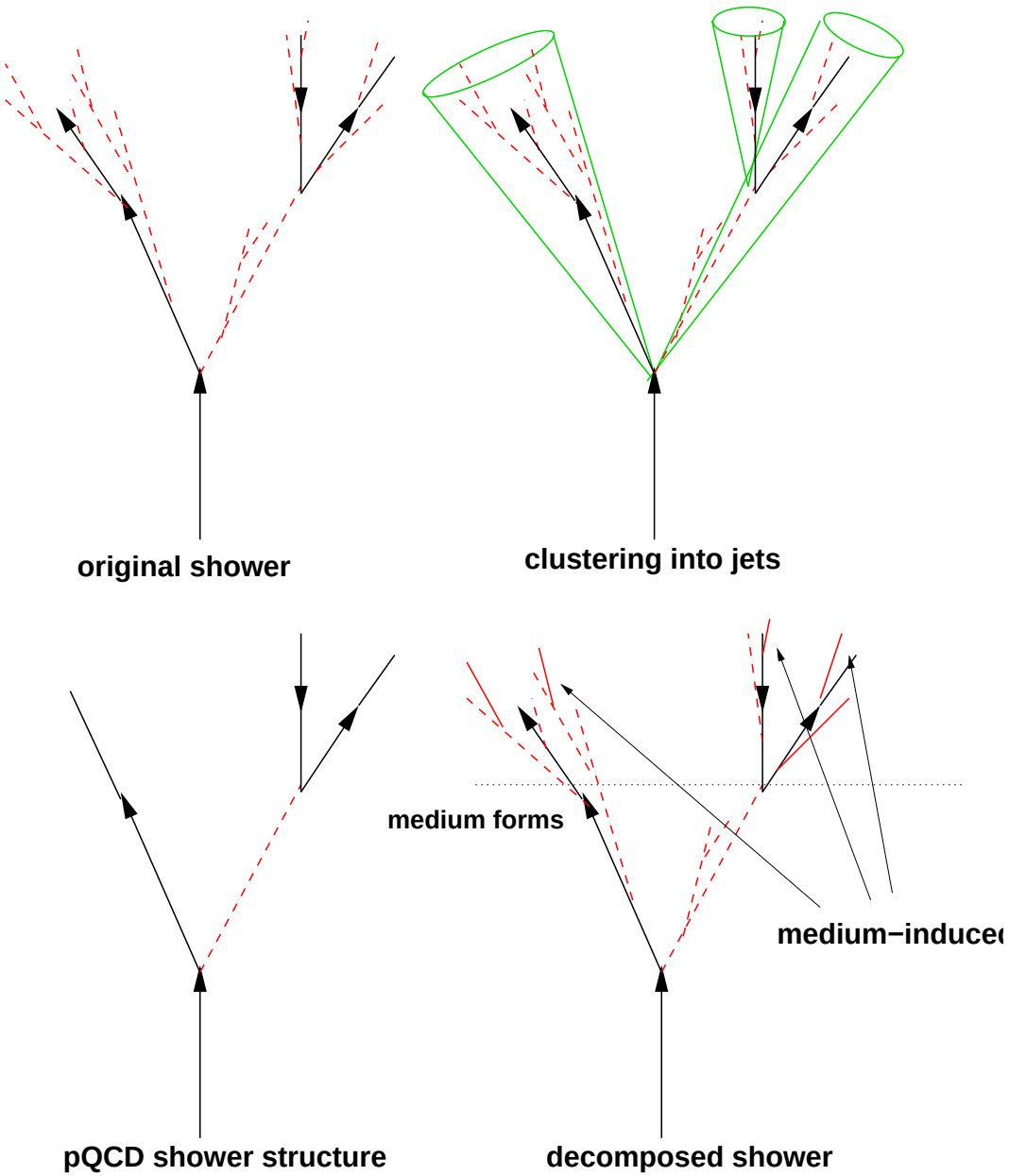
$\Rightarrow$ uncorrelated fluctuations in jet area have strong influence

M. Cacciari, G. P. Salam and G. Soyez, Eur. Phys. J. C **71** (2011) 1692

$\Rightarrow$ what about *correlated* background fluctuations? No solid theory!

Experimental in-medium jets are **not** purely perturbative objects!

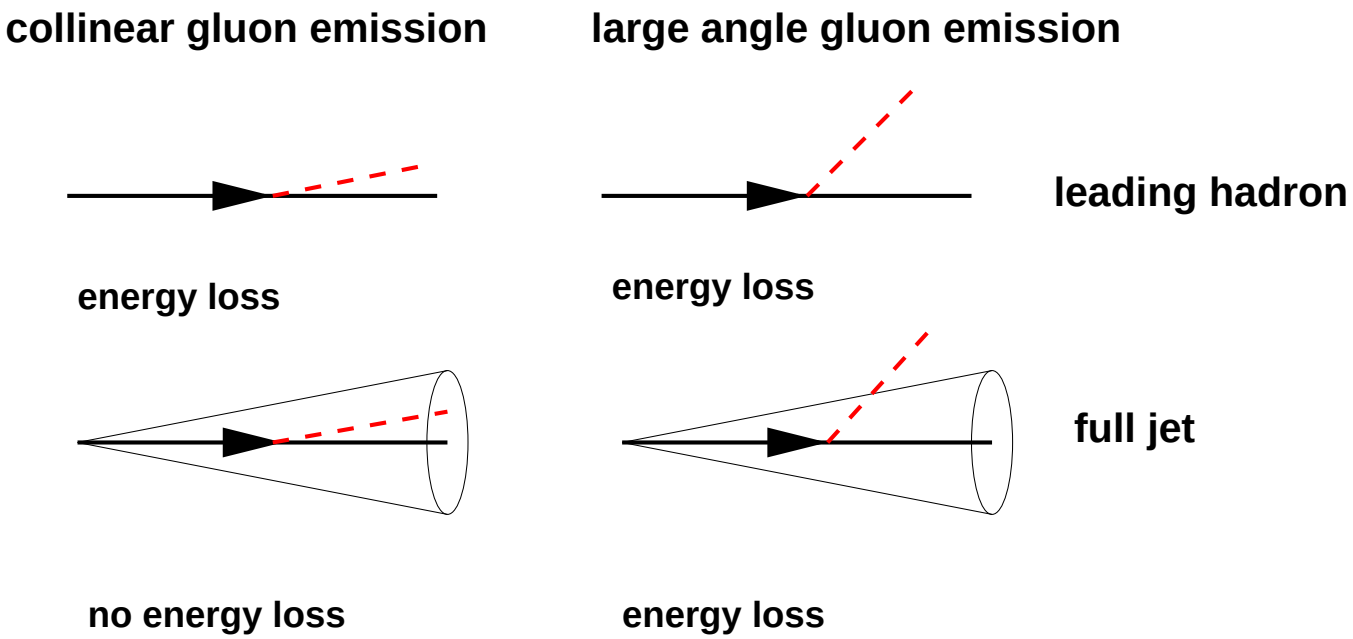
Properties of clustering



- clustering designed to focus on high Q^2 hard perturbative physics
$\longrightarrow$ typical hard scale for LHC jets: $Q^2 = 900$ GeV^2
- typical medium-induced virtuality scale $\hat{q}L$ (depends on whom you ask)
$\longrightarrow \Delta Q^2 = 2 - 20$GeV^2
- $\Delta Q^2 \ll Q^2$
$\longrightarrow$ clustering suppresses medium effect by design
- formation time $\tau \sim E/Q^2$
$\longrightarrow \tau \ll \tau_0$
$\longrightarrow$ jet structure is determined before medium is formed and color decoherence can be an issue

Properties if clustering

- jet energy loss requires transport of energy out of the jet definition

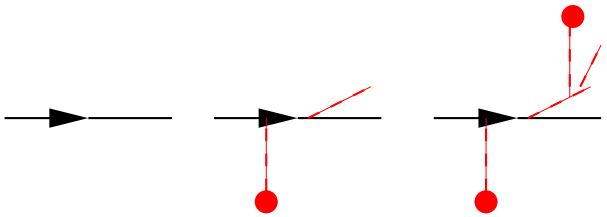


- jets are more robust against medium modification than single hadrons
$\longrightarrow$ jets are *less sensitive* to medium modifications

- this naturally explains $R_{AA}^{jets} \approx 0.5 > R_{AA}^{h}$

How to suppress jets

$\longrightarrow$ medium alters hard parton kinematics slightly
$\longrightarrow$ medium-induced soft gluon emission
$\longrightarrow$ medium alters soft gluon kinematics a lot, soft gluon thermalizes



Universal mechanism: gluons with $p_T \sim T$ are effectively out of cone

- energy flow to large angles $R \gg 0.6$, hydro degrees of freedom relevant

$\longrightarrow$ not picked up by jet finders

- probes medium physics, not jet physics

$\longrightarrow$ largely **independent** of specific shower-medium interaction assumptions

- not an issue for gluons with $p_T \sim$ few T

$\longrightarrow$ more difficult to change their kinematics

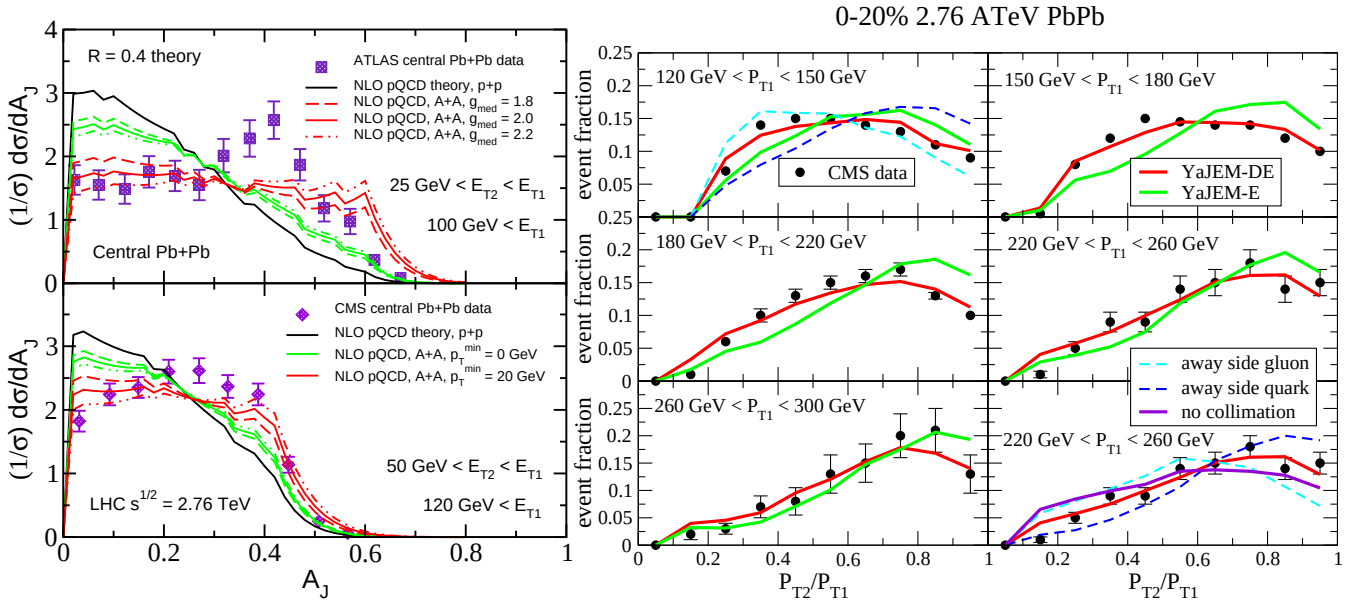
- now denoted 'frequency collimation' J. Casalderrey-Solana *et al.*, J. Phys. G G **38** (2011) 035006

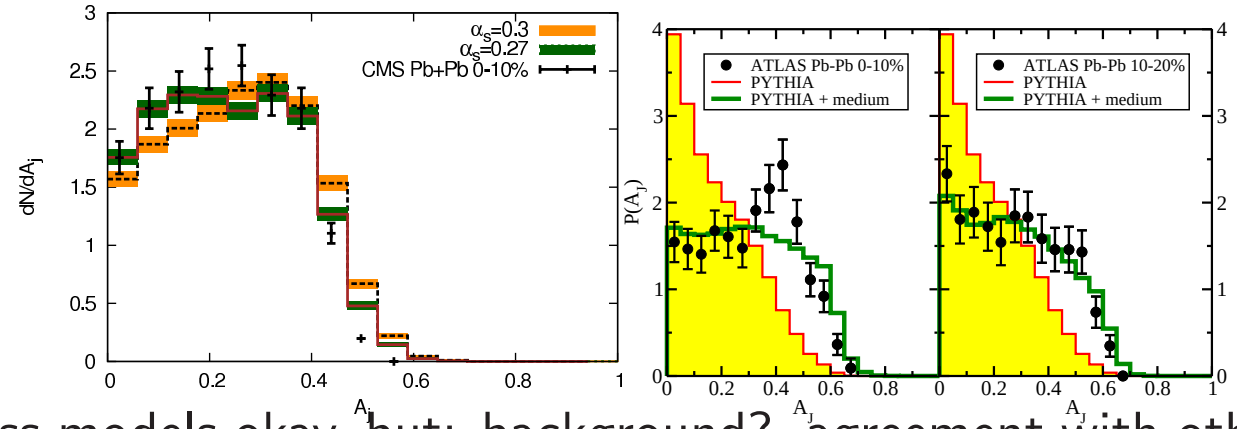
$\longrightarrow$ not novel, observed already in 2009, requires explicit kinematics in models

T. R., Phys. Rev. C **80** (2009) 044904.

Suppressed jets

- popular LHC jet quenching observables $A_J = \frac{E_{T1}-E_{T2}}{E_{T1}+E_{T2}}$ or E_{T2}/E_{T1}





$\Rightarrow$ radiative eloss models okay, but: background?, agreement with other observables?

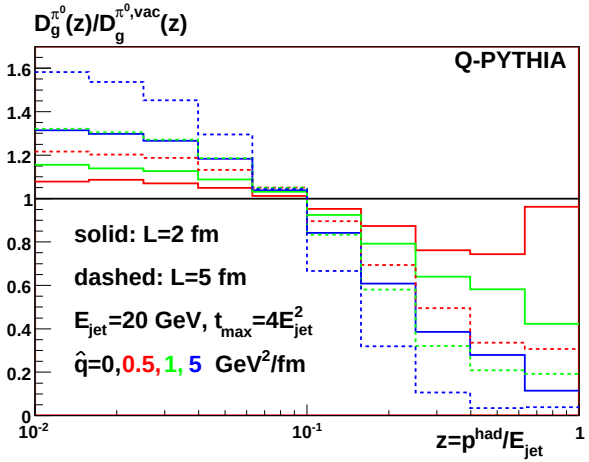
Y. He, I. Vitev and B. -W. Zhang,1105.2566 [hep-ph]; T. Renk, 1204.5572 [hep-ph]; C. Young, B. Schenke, S. Jeon and C. Gale, Phys. Rev. C **84** (2011) 024907, G. -Y. Qin and B. Muller, Phys. Rev. Lett. **106** (2011) 162302

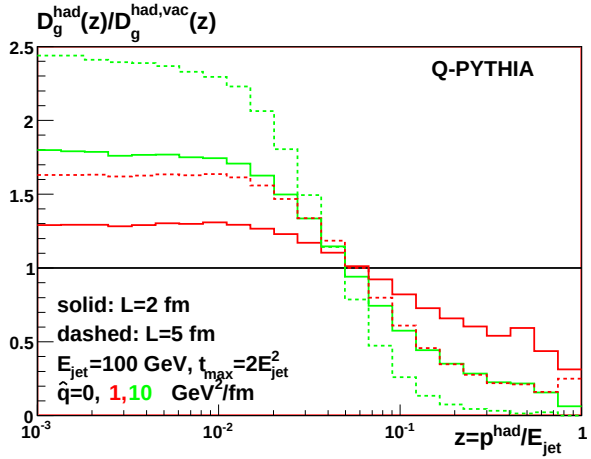
Fragmentation functions

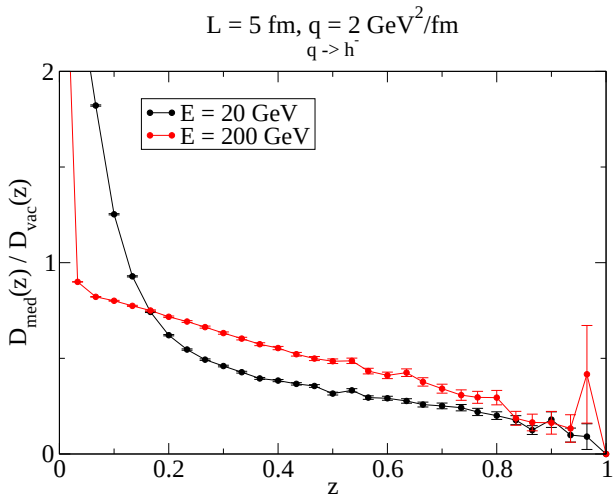
Challenge: Why is the observed longitudinal momentum distribution apparently unchanged (CMS)?
$\Rightarrow$ scale invariance of splitting functions, self-similarity of FF

- Q-PYTHIA: crossing point $z \sim 10^{-1}$ regardless of E_{jet}, modified self-similarity
$\longrightarrow$ for 100 GeV jets, around 10 GeV hadron energy, not seen

- YaJEM: crossing point at fixed $P_T^{break} \sim 3$ GeV, self-similarity broken below P_T^{break}
$\longrightarrow$ crossing point never probed by CMS analysis







$\Rightarrow$ if splitting function unchanged, $D(z)$ shows vacuum self-similarity above P_T^{break}

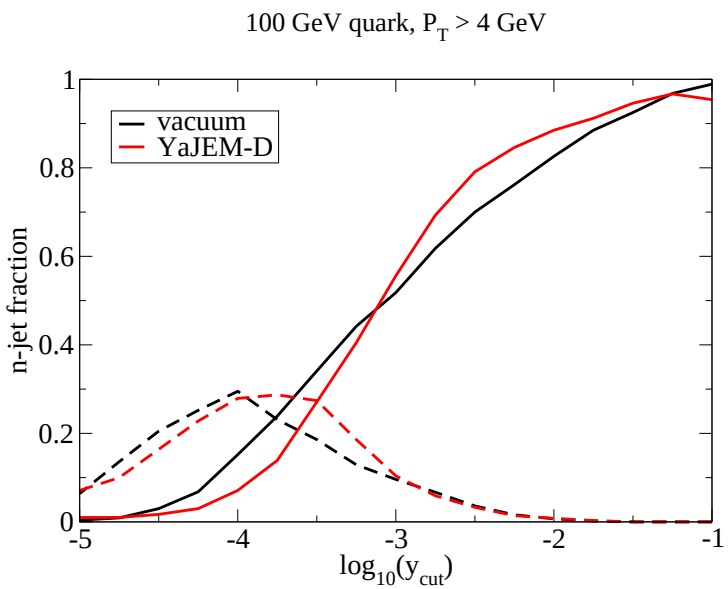
N. Armesto, L. Cunqueiro and C. A. Salgado, Eur. Phys. J. C **63** (2009) 67

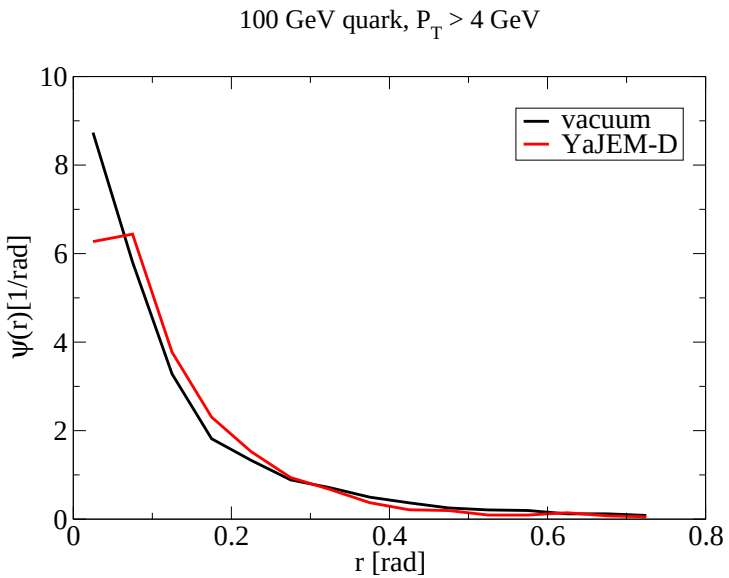
Predictions from 2009

- Jet structure predicted to be almost unmodified above $P_T = 4$ GeV in 2009

$\longrightarrow$ 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.

Dijet asymmetry

- energy dependence of asymmetry requires broadening of jet shape

* models predicting a narrow or unchanged jet shape (Q-PYTHIA, YaJEM-E . . .)

- fragmentation pattern unchanged from vacuum

* models with modified QCD splitting kernels (BW, Q-PYTHIA, . . .)

Constraints 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)

	$R_{AA}^{RHIC}(\phi)$	$R_{AA}^{LHC}(P_T)$	I_{AA}^{RHIC}	I_{AA}^{LHC}	A_J^{LHC}	$A_J^{LHC}(E)$
elastic	**fails!**	works	**fails!**	fails	works	fails
ASW	works	fails	marginal	works	N/A	N/A
AdS	works	**fails!**	marginal	works	N/A	N/A
YaJEM	fails	fails	fails	fails	works	works
YaJEM-D	works	works	marginal	marginal	works	works
YaJEM-DE	works	works	works	works	works	works

- YaJEM-DE only viable candidate out of the tested models

$\rightarrow$ can other popular models be added to this matrix?

- LHC constraints mainly from $R_{AA}(P_T)$, clearly not from A_J

Implications

- jet quenching is consistent with pQCD shower picture and with RHIC expectations
- no evidence for exotic mechanisms
- medium DOF can take some recoil - massive or correlated quasiparticles?

T. R., 1112.2503 [hep-ph].

Jets vs. Correlations

- some rough numbers from practical experience

	hadron-triggered correlations	jets
techniques	perturbative	perturbative + non-pert. bg
definition	trivial	algorithm + background
numerical effort (a.u.)	1	$\sim 100 - 1000$
model uncertainty (a.u.)	1	5
effect size (a.u.)	1	0.3

Jets are a tool designed to make comparison between theory and experiment easy in e^+e^- and $p-p$ collisions. The **opposite** is unfortunately true in heavy-ion collisions — there is **no simple comparison** between theory and experiment using jets.

$\Rightarrow$ $R_{AA}(\phi, P_T)$ runs in a few minutes on a laptop. There is no uncertainty what a hard hadron is. R_{AA} and I_{AA} currently provide all constraints in the matrix.

$\Rightarrow$ $A_J(E)$ takes a few days of supercomputing. There remain differences between calorimeter jets and MC jet event records. Discriminating models is very hard.

Lessons

• most 'puzzles' turn out to be 'we could have known, if we had looked properly'
$\longrightarrow$ systematic multi-observable studies are not a luxury, they are a **necessity**

• LHC high p_T physics is not qualitatively different from RHIC physics
$\longrightarrow$ but **statistics** and **kinematical reach** will make a lot of difference

• clustering into jets is designed to see high Q^2 vacuum physics
$\longrightarrow$ it **systematically suppresses** medium effects
$\longrightarrow$ it inevitably brings **non-perturbative medium physics** into the problem
$\Rightarrow$ use triggered multi-particle correlations instead!

High statistics multi-differential measurements and **systematic multi-observable studies** are the keys to success.

(If you want to run the YaJEM family yourself, please get in touch with me. Sorry, no user manual, nice interface of website yet.)