A systematic view of jets

— and high p_T physics at RHIC and LHC

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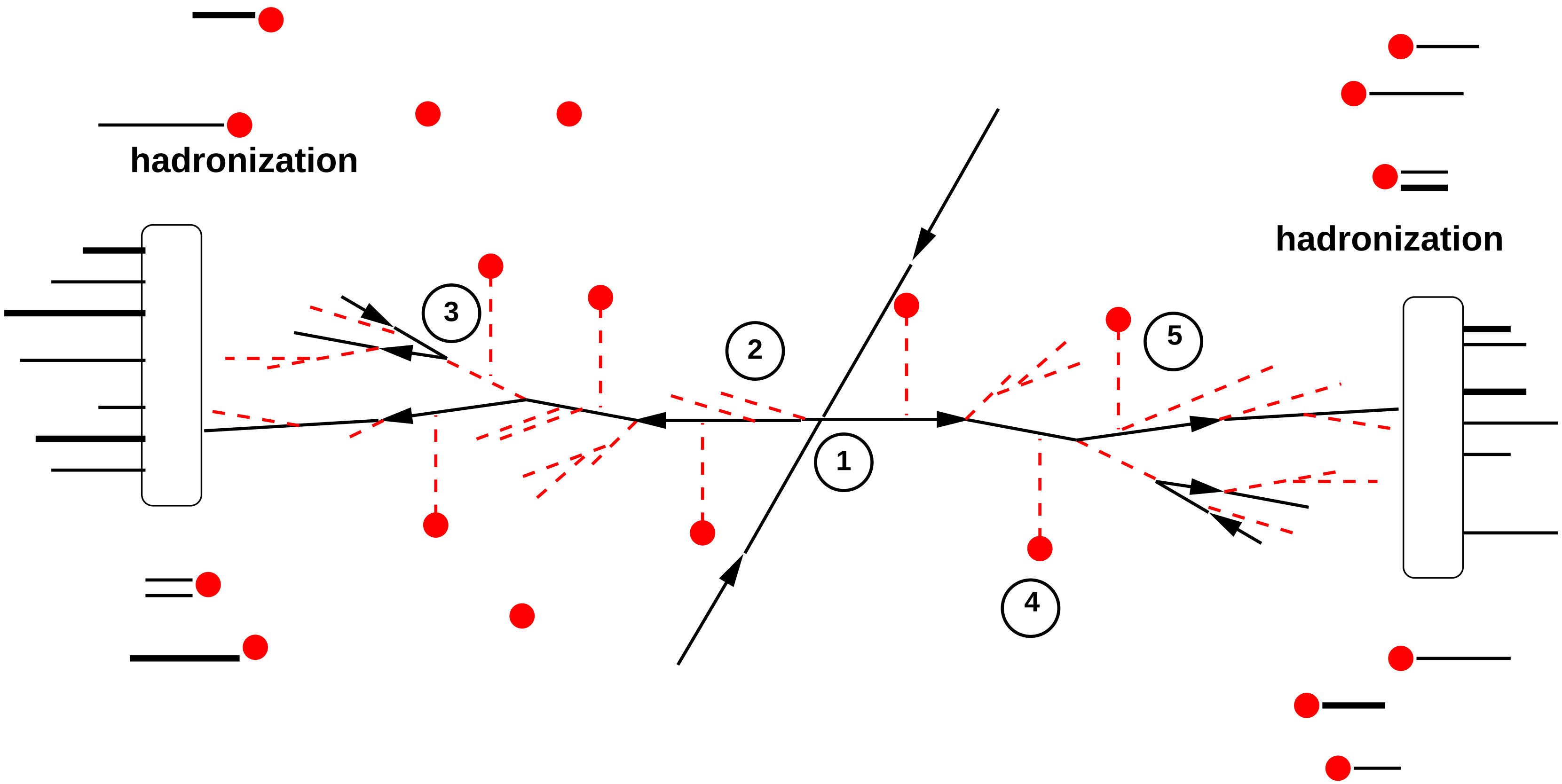
I. Jets in medium

why we're interested

THE 'STANDARD' JET QUENCHING PICTURE

pQCD radiative energy loss for hard partons interacting with the medium



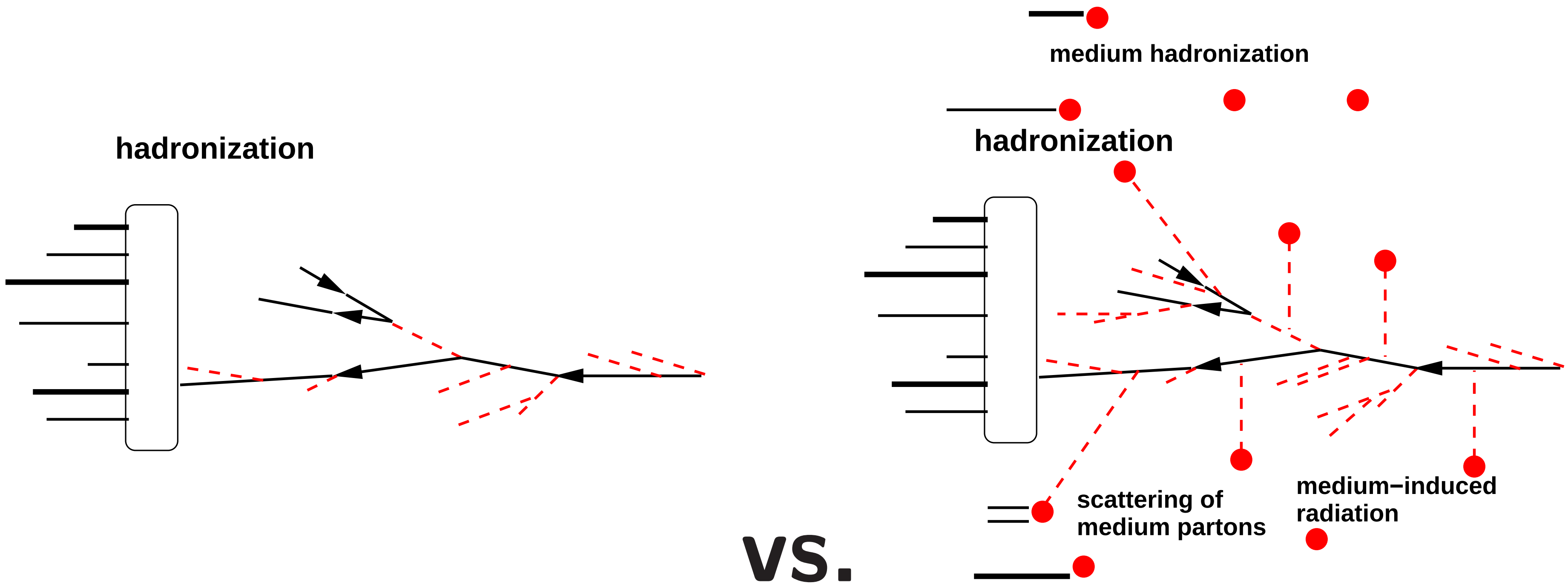
1) hard process 2) vacuum shower 3) medium-induced radiation 4) medium evolution 5) medium correlated with jet by interaction

Status: 1) calculable 2) calculable with MC codes 3) medium dof, interaction 4) calculable in hydrodynamics 5) energy transport in the medium

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

• core problem: compute a medium-modified shower
→ look at vacuum shower first

• 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

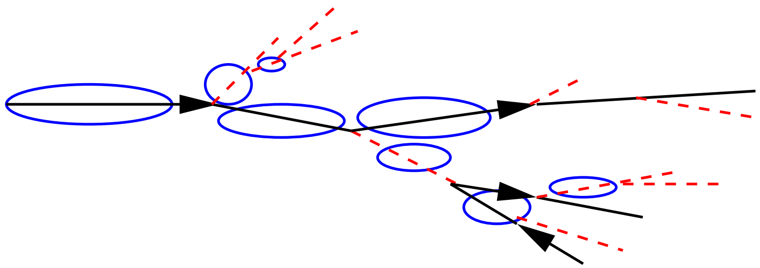
$$P_{q\to qg}(z) = \frac{4}{3}\frac{1+z^2}{1-z} \quad P_{g\to gg}(z) = 3\frac{(1-z(1-z))^2}{z(1-z)} \quad P_{g\to q\overline{q}}(z) = \frac{N_F}{2}(z^2+(1-z)^2)$$

• series of splittings $a \to bc$ with decreasing t
→ daughter partons take the energies $E_b = zE_a$ and $E_c = (1-z)E_a$

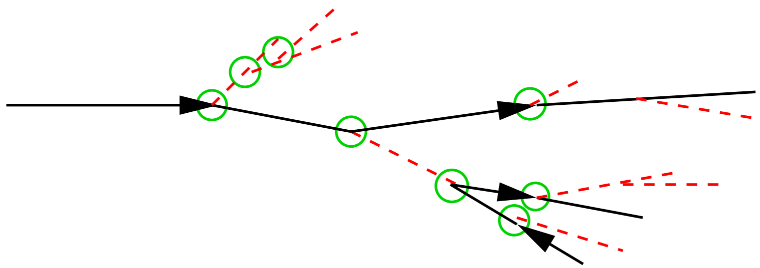
• terminate at a soft virtuality scale t_0 or Q_0 and hadronize

QCD shower evolution

• change parton kinematics during propagation
(explicit momentum transfer between shower and medium)



• change splitting probability in Kernel
(no energy-momentum transfer between jet and medium)



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

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

N. Borghini and U. A. Wiedemann, hep-ph/0506218

Model structure

- generic structure of in-medium shower models:

model of medium DOF $\Rightarrow$ **elementary $a \to bc$ branching**

$\Downarrow$

$P_{split}(z, Q^2|\hat{q}, \ldots)$

correlations between reactions $\Rightarrow$ **modified DGLAP shower evolution**

$\Downarrow$

$D(z, \mu|\hat{q}, \ldots)$

model of medium geometry $\Rightarrow$ **space-time averaging**

$\Downarrow$

$\langle D(z, \mu|\hat{q}, \ldots)\rangle$

folding with pQCD spectrum

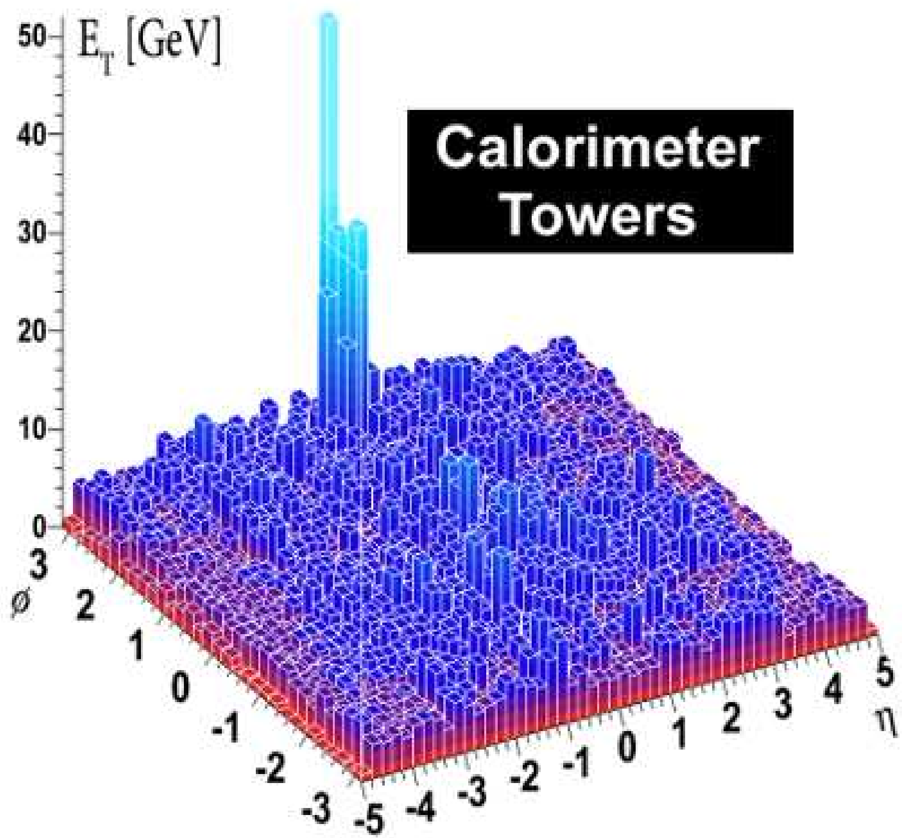
$\Downarrow$

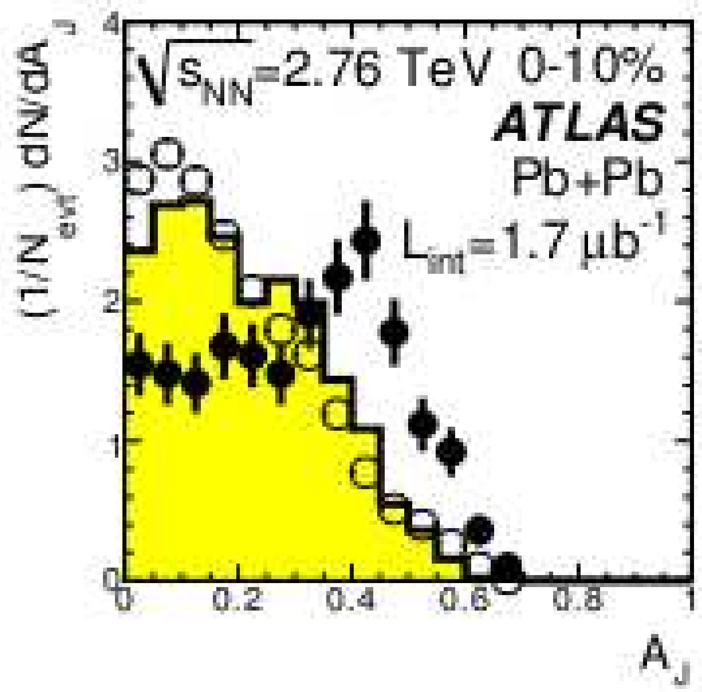
observables, R_{AA}

- always contains convolution with medium geometry!

II. Jets at LHC

very prominent monojets raising questions





LHC JET PUZZLES

• strong modification of $A_J = \frac{E_{T1}-E_{T2}}{E_{T1}+E_{T2}}$, up to 60 GeV out of cone
→ very strong energy loss?

• moderate jet $R_{AA} \sim 0.5$ in the trigger energy range, fairly independent of energy
→ weak energy loss?

• no angular imbalance of back-to-back jets
→ energy loss is not via hard gluon radiation, expected

• the 'fragmentation functions' of asymmetric jets look just like in vacuum
→ fragmentation outside the medium?

• R_{AA} and A_J fairly independent of jet cone radius $R = 0.2..0.4$
→ not connected to jet shape widening?

Many people were surprised, at QM Annecy 'serious challenges to the radiative energy loss paradigm' were claimed.

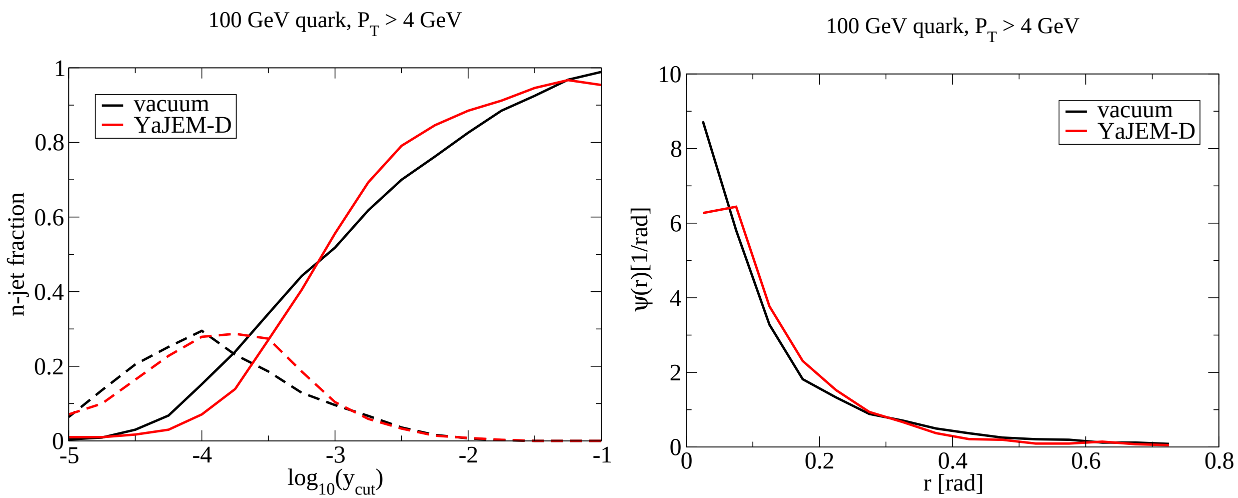
LHC JET PUZZLES

What was expected based on RHIC data? 'Unmodified' jets were predicted in 2009:

• study above some soft medium P_T cut:

$\longrightarrow$ n-jet fraction: clustering at y_{min} with $y_{ij} = 2\text{min}(E_i^2, E_j^2)(1 - \cos(\theta_{ij})/E^2_{\text{cm}}$

$\longrightarrow$ 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

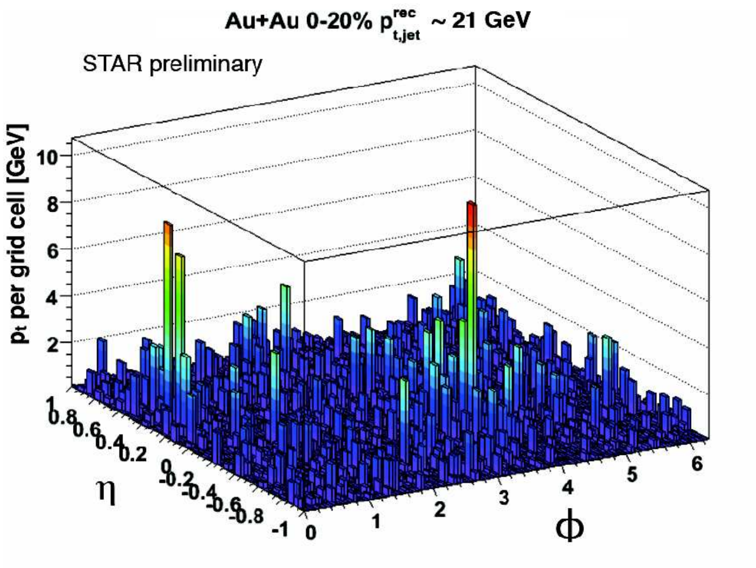
• energy dissipated in medium in non-perturbative momentum region

$\longrightarrow$ not picked up by jet finding algorithms — why and how? Look back at RHIC!

T. R., Phys. Rev. **C80** (2009) 044904.

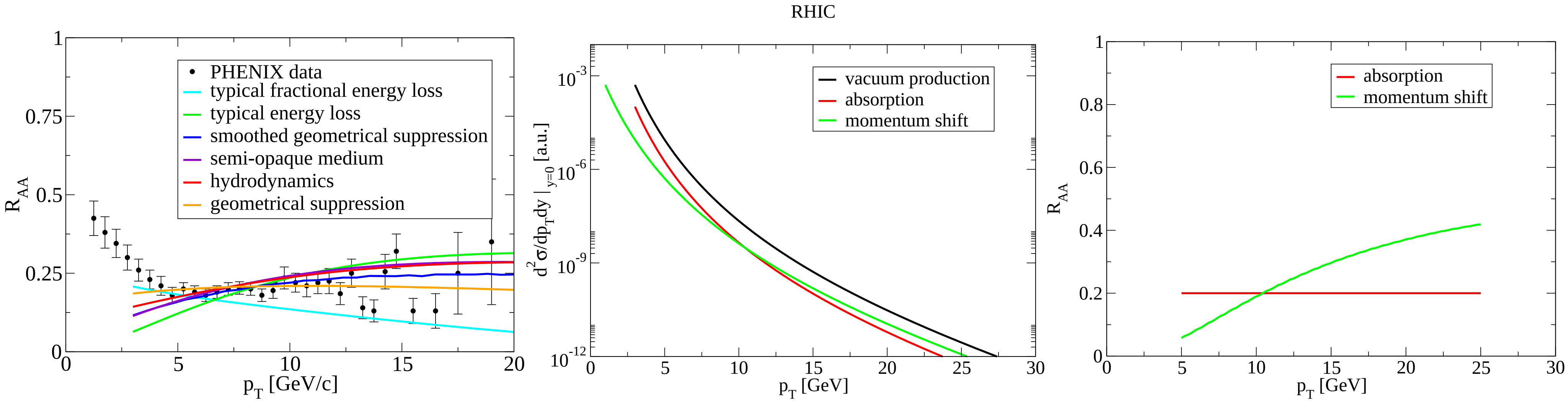
III. Hard Physics at RHIC

what did we know about jet quenching before LHC turned on?



P_T DEPENDENCE

- compare P_T dependence of R_{AA}



- in many models, probes balance of parton energy shift vs. absorption

$\longrightarrow$ due to steeply falling spectrum, not very sensitive

- exception: fractional energy loss

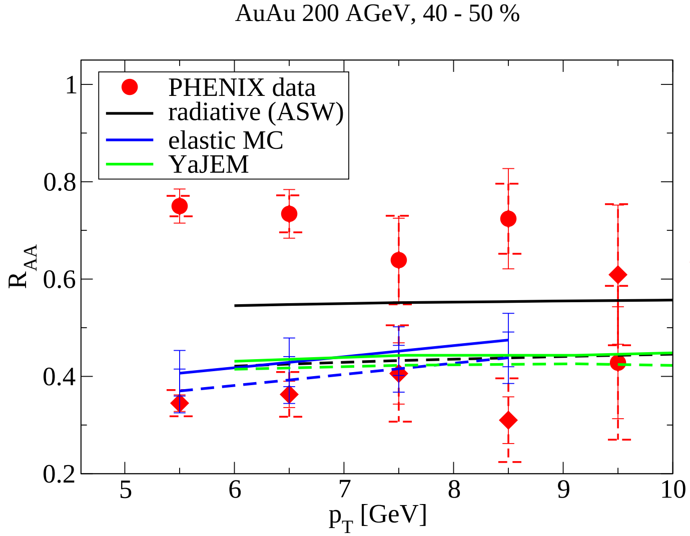
$\longrightarrow$ this has qualitatively different trend and can be ruled out

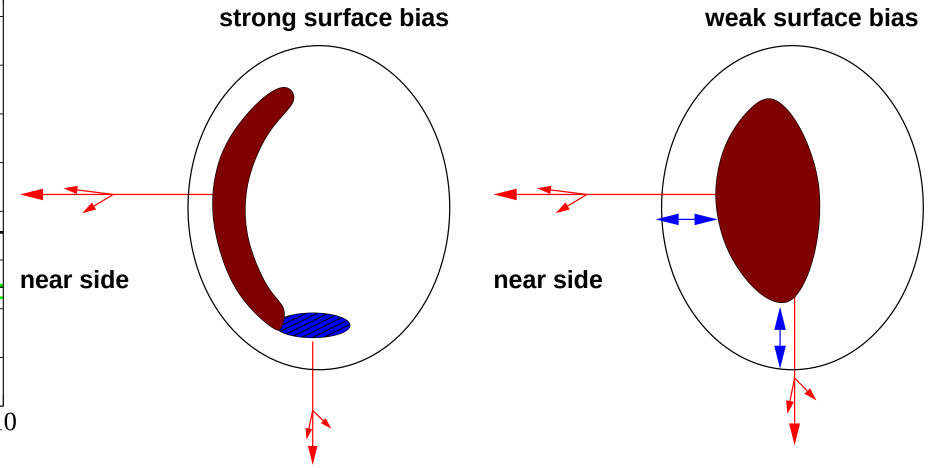
T. R., Phys. Rev. C **74** (2006) 034906

Pathlength dependence and hydro geometry

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

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





- factor two (!) uncertainty in S_{out}^{in} due to hydro model

$\rightarrow$ constrains combinations of hydro and jet quenching model

- large linear component (incoherent or LPM with finite energy corrections) ruled out

$\rightarrow$ this rules out a large number of existing models

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

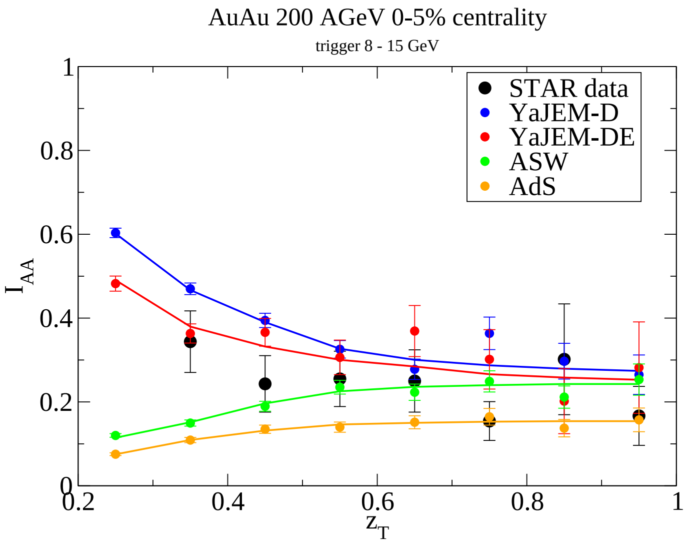
$\rightarrow$ models using this prescription can account for the data even with finite kinematics

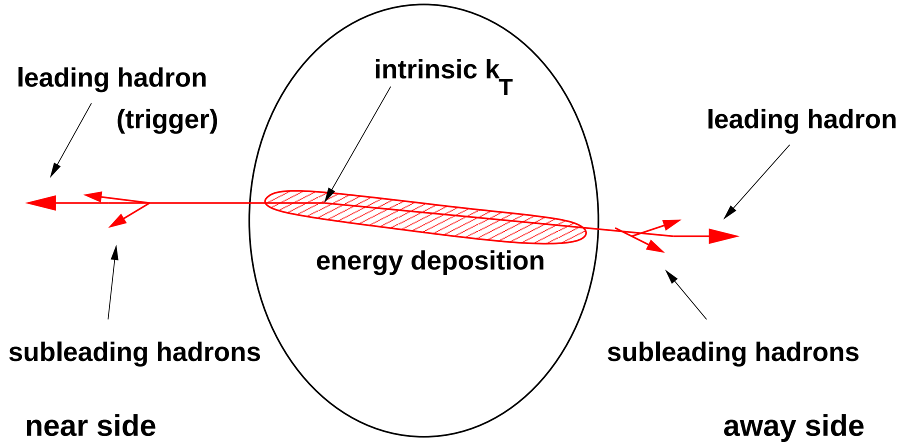
J. Auvinen, K. J. Eskola, H. Holopainen and T. R., Phys. Rev. C **82** (2010) 051901; (systematics summarized in T.R., 1112.2503 [hep-ph])

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])

RHIC EXPECTATIONS

• main mechanism is medium-induced radiation
$\longrightarrow$ we see coherence and the enhanced production of subleading hadrons

• secondary mechanism is about 10% elastic energy loss
$\longrightarrow$ we observe it limiting the soft hadron production

• energy loss takes place at fixed momentum scale $\sim T$
$\longrightarrow$ we do not observe fractional energy loss $\Delta E \sim const.E$

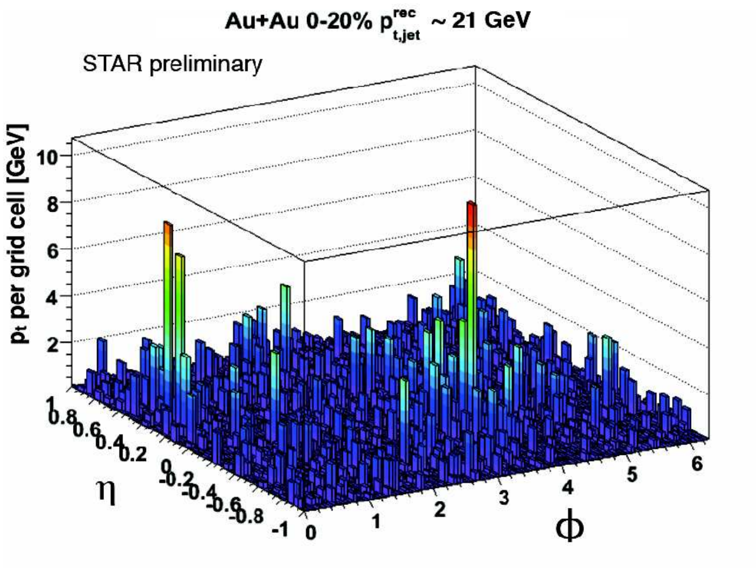
• the need to use real shower models is apparent from I_{AA}
$\longrightarrow$ even without jet reconstruction, we can constrain in-medium showers

$\Rightarrow$ YaJEM-DE: default shower scenario using the RHIC constraints

(full systematics summarized in T.R., 1112.2503 [hep-ph])

IV. 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
- 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
$\longrightarrow$ 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

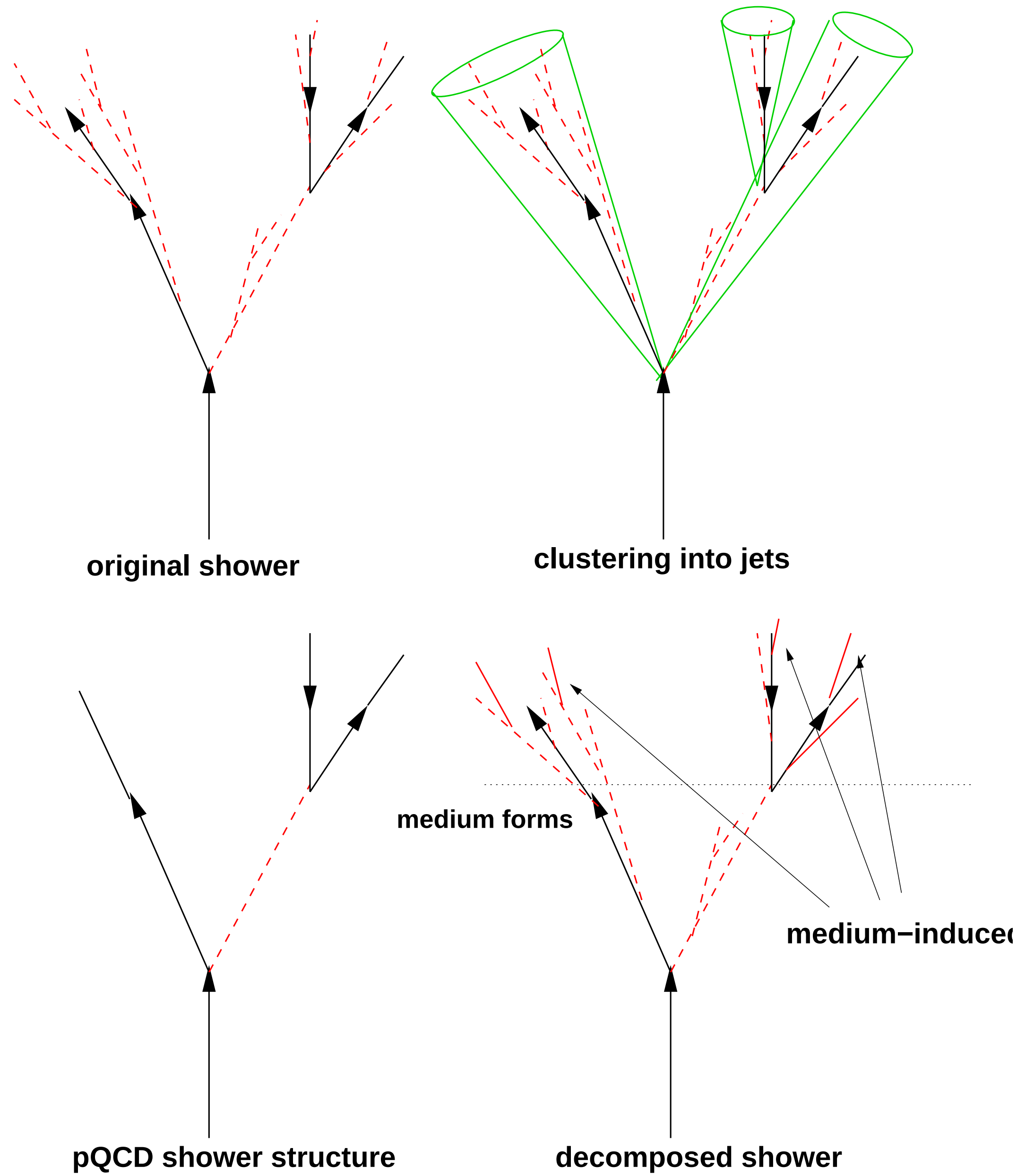
$\Rightarrow$ uncorrelated fluctuations in jet area have strong influence

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

$\Rightarrow$ what about *correlated* background fluctuations?

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

PROPERTIES OF CLUSTERING



- clustering designed to focus on high Q^2 hard perturbative physics

$\rightarrow$ typical hard scale for LHC jets: $Q^2 = 900$ GeV^2

- typical medium-induced virtuality scale $\hat{q}L$ (depends on whom you ask)

$\rightarrow \Delta Q^2 = 2 - 20$GeV^2

- $\Delta Q^2 \ll Q^2$

$\rightarrow$ clustering suppresses medium effect by design

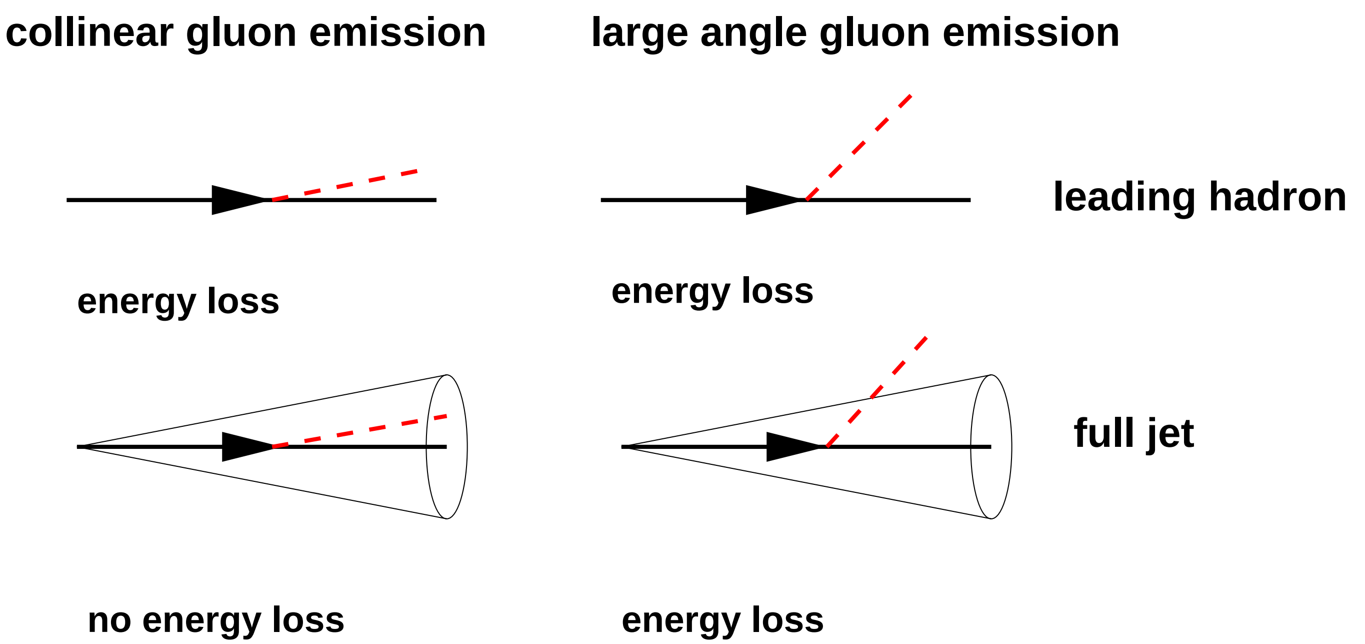
- formation time $\tau \sim E/Q^2$

$\rightarrow \tau \ll \tau_0$

$\rightarrow$ 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

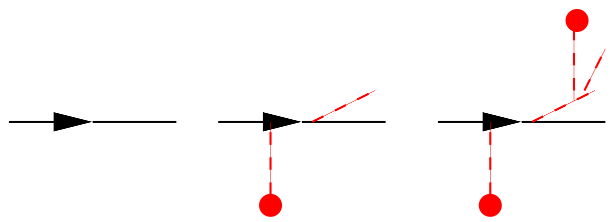


• jets are more robust against medium modification than single hadrons
→ jets are *less sensitive* to medium modifications

• 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

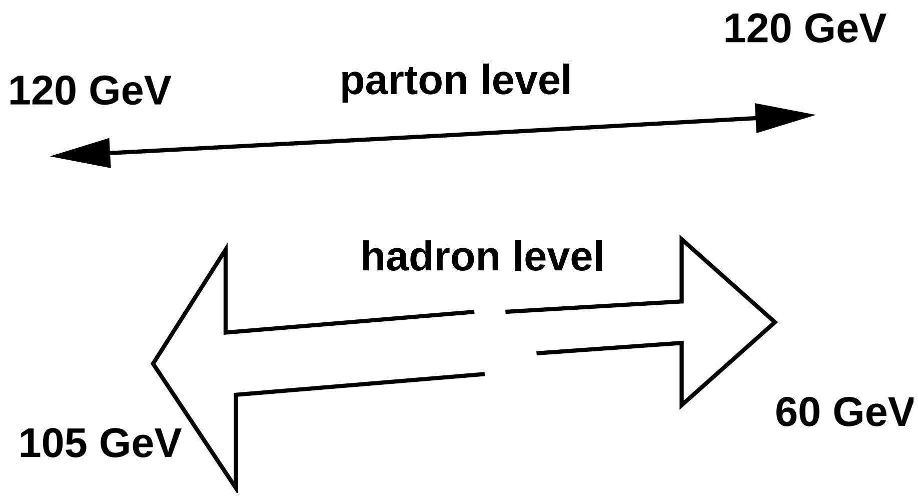
- now denoted 'frequency collimation'

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

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

Consequences

• if a model explicitly modifies shower kinematics at a scale $\sim T$
$\longrightarrow$ gluons $\sim T$ thermalize and energy flows out of cone
$\longrightarrow$ gluons $\sim$ few T are weakly modified for kinematical reasons
$\longrightarrow$ branching kernels $P_{q \to gg}(z) \ldots$ scale invariant, unmodified long. jet structure



• this doesn't mean the fragmentation function is unmodified
$\longrightarrow$ the relevant ratio is $z = E_{had}/E_{part}$
$\longrightarrow$ but CMS plots $\tilde{z} = E_{had}/E_{T2}$ — which may easily be a factor 2 different
$\Rightarrow$ the fragmentation function is massively modified
$\Rightarrow$ the long. momentum distribution remains self-similar and similar to vacuum case

Consequences

• not true in models where $P_{q \to gg}(z) \ldots$ are medium modified (Q-PYTHIA, BW,...)
$\longrightarrow$ here, the long. jet structure is expected to be different from vacuum, not seen
$\longrightarrow$ but these are fractional energy loss models which we know to be ruled out already

• not true in models where soft gluons are by assumption eikonal or 'tagged'
$\longrightarrow$ but that's not new physics, just a modelling problem

Qualitatively, this is no different from where RHIC data point to

Does it work quantitatively?

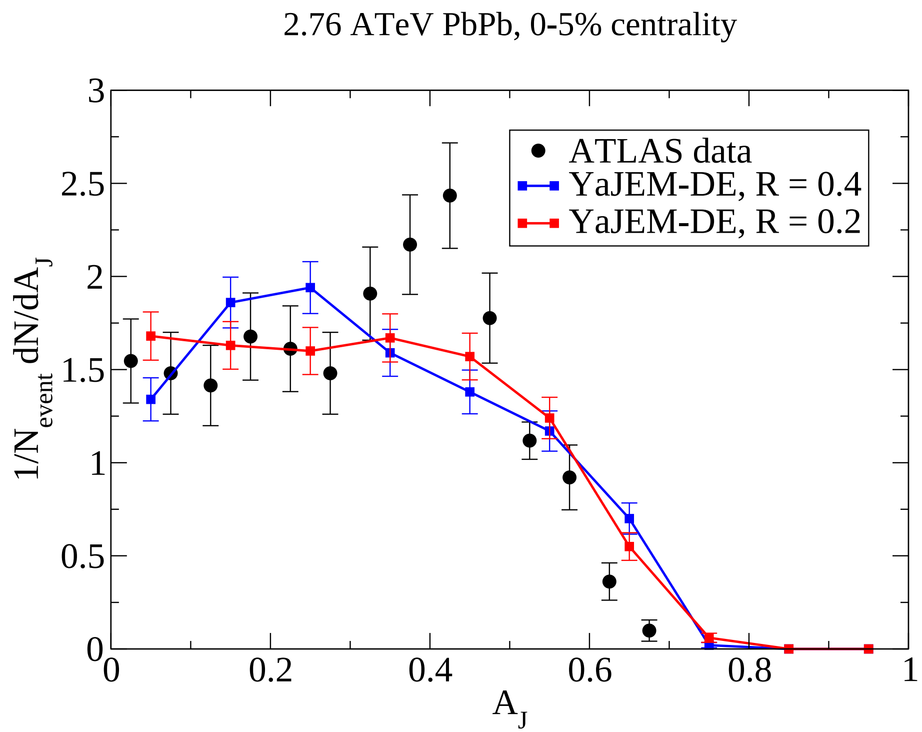
Dijet Asymmetry

- relation between MC output and ATLAS calorimeter towers is complicated

$\longrightarrow$ try to get to published PYTHIA + HIJING as closely as possible

$\longrightarrow$ add uncorrelated background fluctuations

$\Rightarrow$ the RHIC-constrained model describes both $R_{AA}^{jet} \approx 0.5$ and A_J well for all R



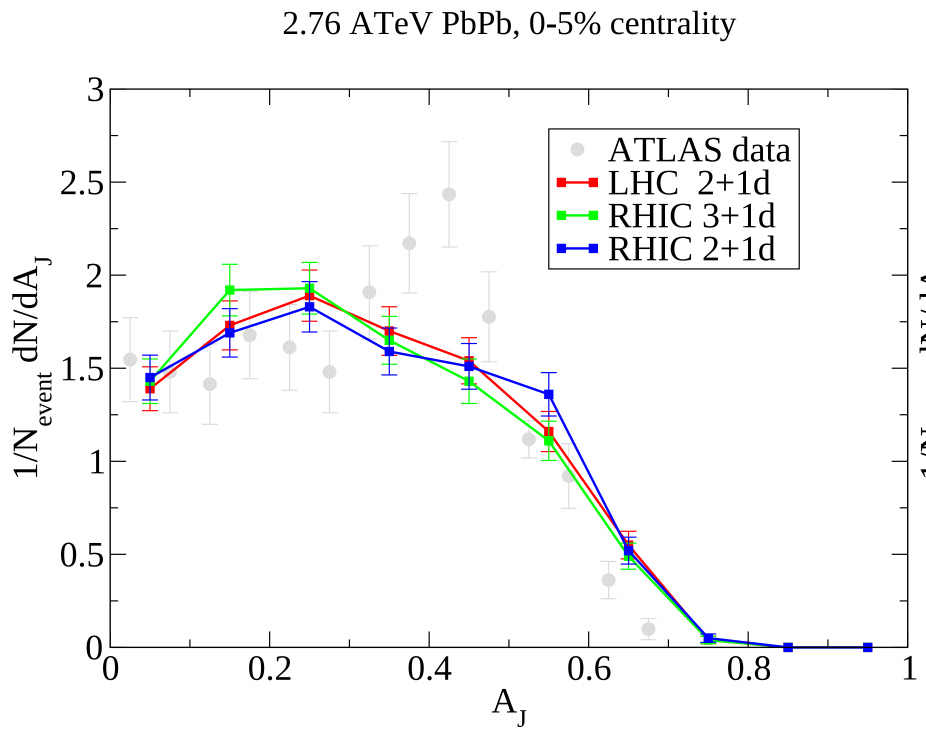
- lack of R-dependence: cancellation of background and out of cone fluctuations

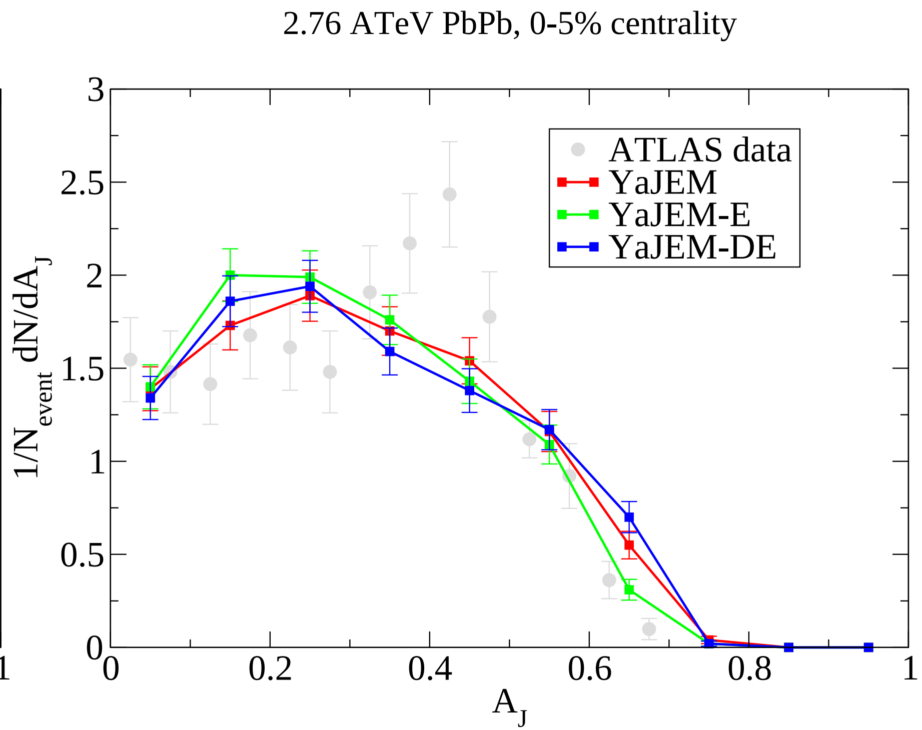
$\longrightarrow$ beware: jet physics always has a non-perturbative component!

Dijet Asymmetry

There's a catch. . . Test the Null hypothesis 'any model able to suppress jets succeeds'

• indeed — almost any model with $R_{AA}^{jet} \approx 0.5$ gets the same result
→ YaJEM (linear pathlength dependence) does for any hydro
→ YaJEM-E (pure incoherent drag, different jet shape) does for any hydro





Clustering is not the best way to probe medium physics!

Why is this so?

Explanation

• jets are quenched by soft gluons $p_T \sim T$ transferring momentum to large R
$\Rightarrow$ but this is not a model-specific mechanism

• gluon production at $p_T \sim$ few T is model-specific
$\longrightarrow$ but these gluons are largely clustered back into the jet
$\Rightarrow$ explains 'robustness', lack of surface bias
$\Rightarrow$ but implies no model-specific signal in the observable

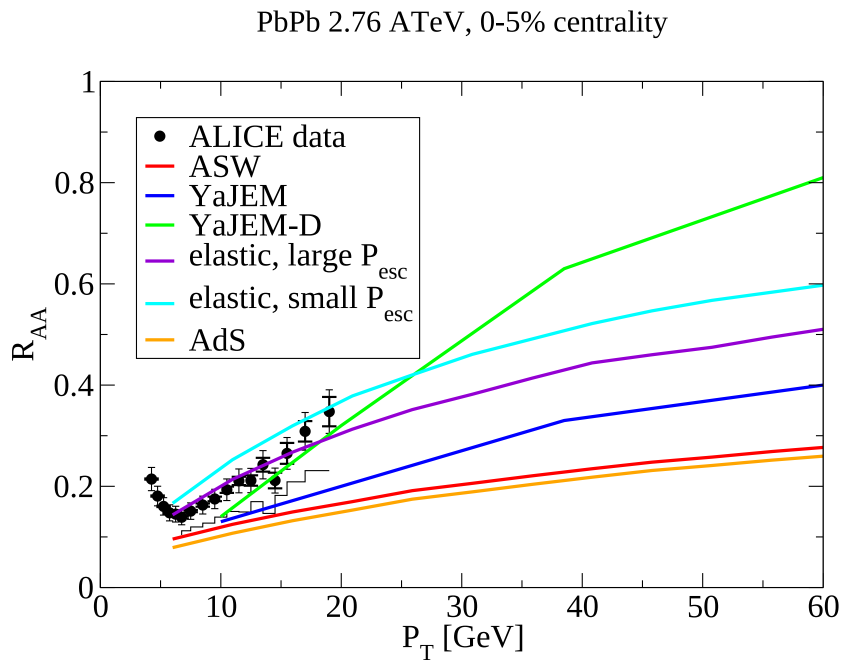
• hard gluons $p_T \sim$ few GeV are almost exclusively produced in hard branchings
$\Rightarrow$ this is vacuum physics and doesn't probe the medium

Universality of soft gluon thermalization and suppression of low Q^2 physics by clustering explain the observed insensitivity of jet observables to medium physics

Novel constraints from LHC

- single h R_{AA} comparison with direct extrapolation using 'same' hydro:

$\longrightarrow$ new constraints, a kinematic window not available at RHIC opens!



- use parameter R to quantify how much refitting is done ($R = 1$ indicates no refit)

	YaJEM-D	YaJEM	ASW	AdS
R	0.92	0.61	0.47	0.31

$\longrightarrow$ T^4 dependence of AdS strongly disfavoured; many radiative models overquench

T. R., H. Holopainen, R. Paatelainen, K. J. Eskola, Phys. Rev. **C84** (2011) 014906.

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

- YaJEM-DE looks like the only viable candidate
- 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].

Lessons

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

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

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

Resist the temptation to expect new discoveries and puzzles everywhere! No single measurement is decisive. No puzzle exists without knowing and including full theory uncertainties. No toy model can settle any question. **High statistics multi-differential measurements** and **systematic multi-observable studies** are the keys to success.