JET QUENCHING AND HEAVY QUARKS

seen from a light quark perspective

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PARTON SHOWERS IN VACUUM
THINGS WE KNOW ABOUT LIGHT QUARKS
WHAT'S DIFFERENT FOR HEAVY QUARKS
CURRENT HEAVY QUARK COMPUTATIONS
CONCLUSIONS

I. Fragmentation and pQCD in vacuum

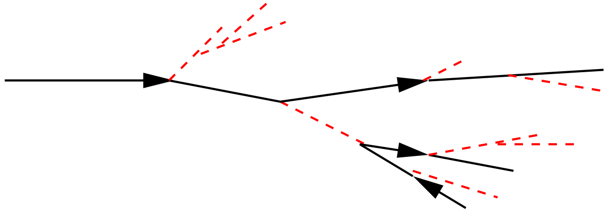
establishing the baseline

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

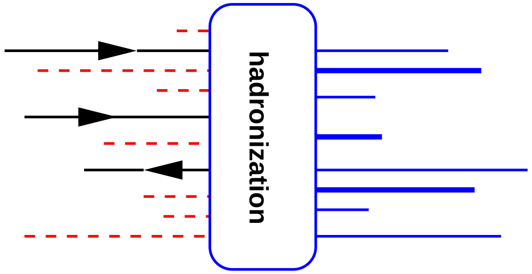
JETS, SCALES AND THE FRAGMENTATION FUNCTION

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

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



- hadronization (non-perturbative)



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

$\longrightarrow$ part of the shower evolution happens in the medium

$\longrightarrow$ light hadrons or high P_T hadrons are produced outside the medium

$\Rightarrow$ the medium predominantly affects the perturbative parton shower

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)

QCD SHOWER EVOLUTION THE PYTHIA WAY (III)

- 0th order: Q provides transverse phase space for radiation, E/Q boosts the system along original parton direction
  → a collimated spray of partons, i.e. a jet is generated

- 1st order: QCD leaves characteristic signatures (branching kernels)
  → preference for soft gluon emission, angular ordering due to interference

- a large quark mass such as m_c or m_b restricts radiation phase space
  → heavy quarks fragment harder, 'dead cone effect'

- medium interactions are parametrically small, since $Q \sim p_T$, but $\Delta Q \sim T \ll p_T$
  → expect a medium shower to be a perturbation around the vacuum shower
  → 3rd order: some extra medium-induced radiation phase space

- formation times are E/Q_i^2, hence high Q^2 vacuum radiation happens *early*
  → hard branchings occur even before a medium can be formed

Jet evolution essentials are simple physics principles

II. pQCD and light quark energy loss

Introduce medium effect on phase space by:

Time ordering in shower:

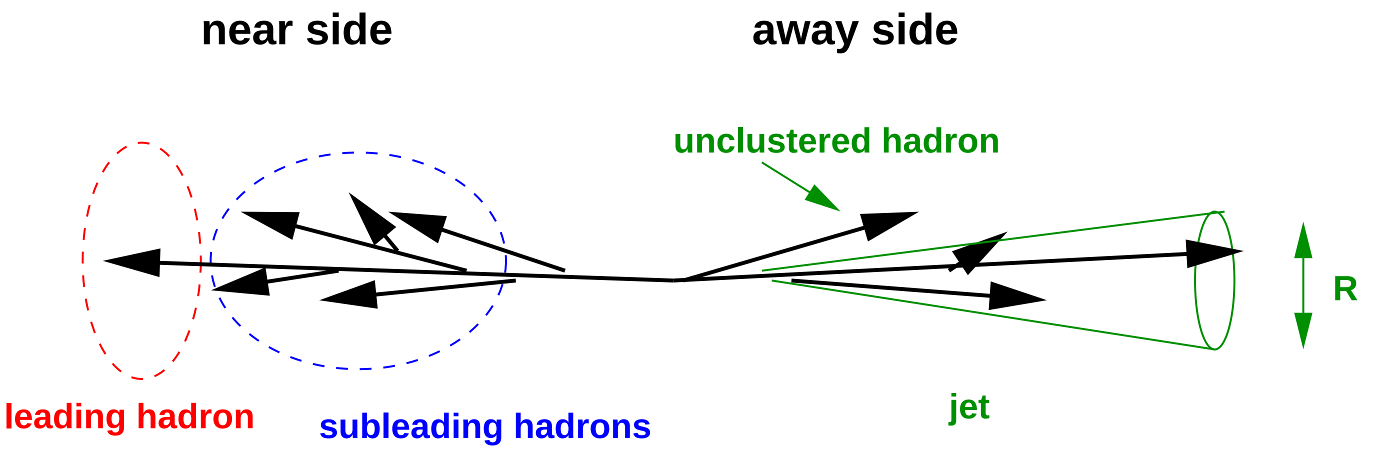
$$\langle \tau_b \rangle = \frac{E_b}{Q_b^2} - \frac{E_b}{Q_a^2} \quad P(\tau_b) = \exp\left[-\frac{\tau_b}{\langle \tau_b \rangle}\right]$$

pQCD shower plus extra radiation phase space and some drag (YaJEM):

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

(this is just *a* way to do it, not *the* way)

A BESTIARY OF OBSERVABLES



- disappearance observables: rate suppression of leading hadrons or jets

→ R_{AA} ratio of medium rate over vacuum rate

- triggered observables: rate modification of other objects given a trigger

→ I_{AA} ratio of subleading near side or away side yields
→ Gaussian width of away side distribution
→ A_J momentum imbalance of near and away side jets
⇒ triggered observables are *biased*

- geometry dependence — study the angle with the bulk event plane

Rich toolkit to design observables sensitive to specific physics

THE pQCD CASE FOR LIGHT QUARK JET QUENCHING

Hypothesis:

medium shower $=$ vacuum shower $+$ extra phase space $+$ some direct energy loss

- QCD splitting kernels remain valid

→ we should see a predictable induced radiation pattern in the FF, mostly at low P_T

- primary parton spectra are perturbatively calculable

→ we should be able to describe the $\sqrt{s}$ dependence from lower RHIC to LHC energy

- showers create jets similar to vacuum case

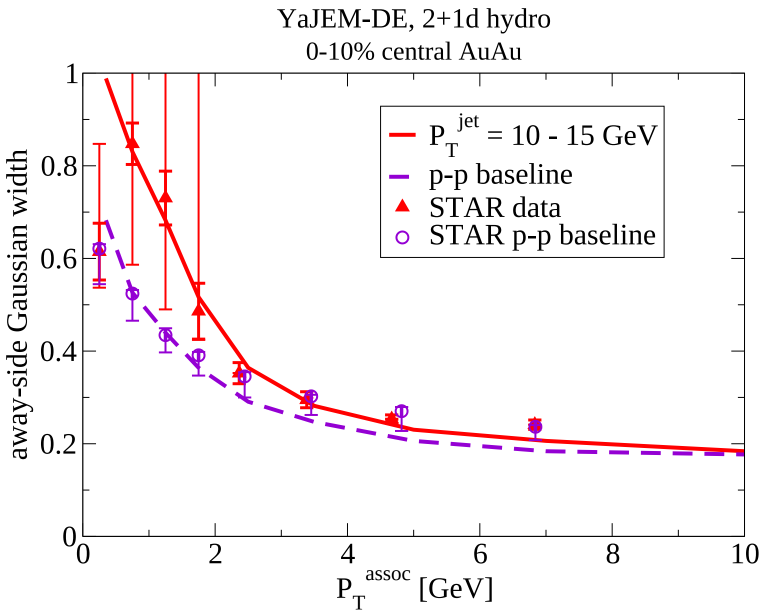
→ we should be able to account for the full pattern of LHC jet observables

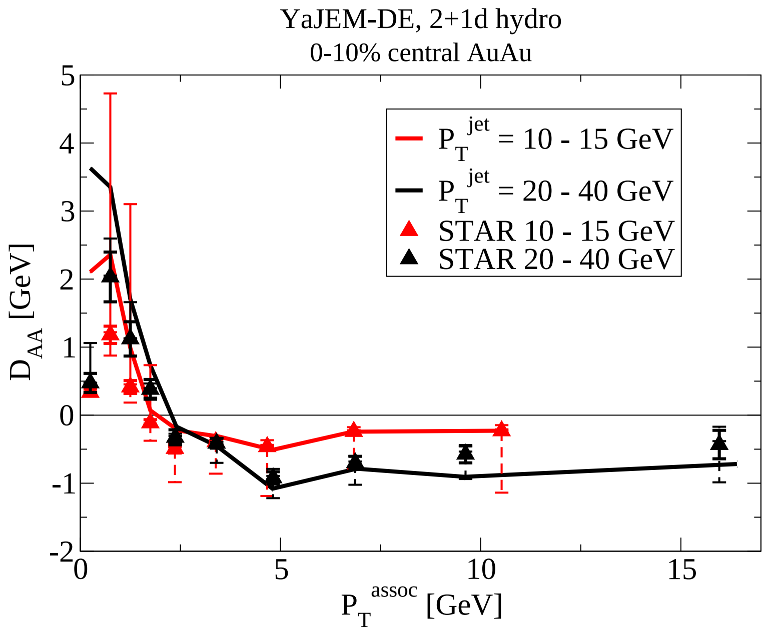
INDUCED RADIATION

- jet-h correlations by STAR reveal away side momentum distribution and width

$\longrightarrow$ observe Gaussian width of away side correlation as function of P_T

$\longrightarrow$ observe balance function $D_{AA} = \text{yield}_{AA}(P_T)\langle P_T\rangle - \text{yield}_{pp}(P_T)\langle P_T\rangle$





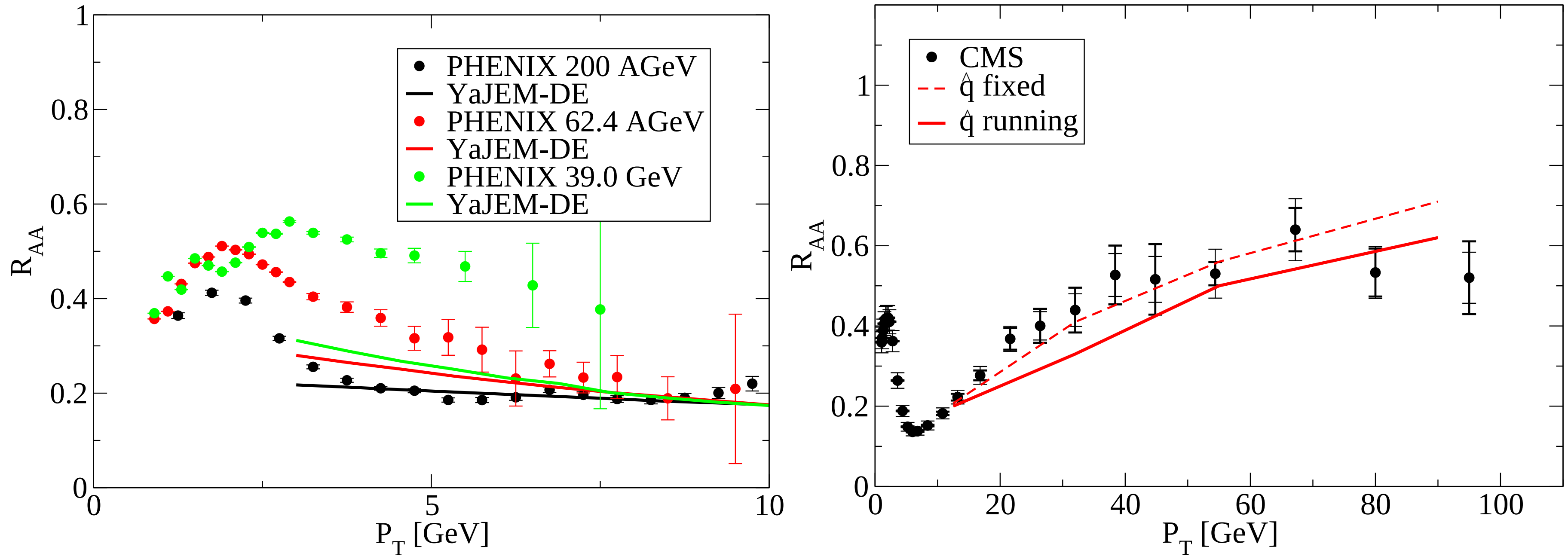
- observed radiation balances the momentum as expected
- observed radiation has transverse pattern as expected

$\Rightarrow$ medium induced radiation is observed and consistent with pQCD expectations

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

Excitation function

- nuclear suppression factor R_{AA} is measured for 39, 62.4, 200 AGeV and 2.76 ATeV



- requires careful and controlled extrapolation of background hydrodynamics

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

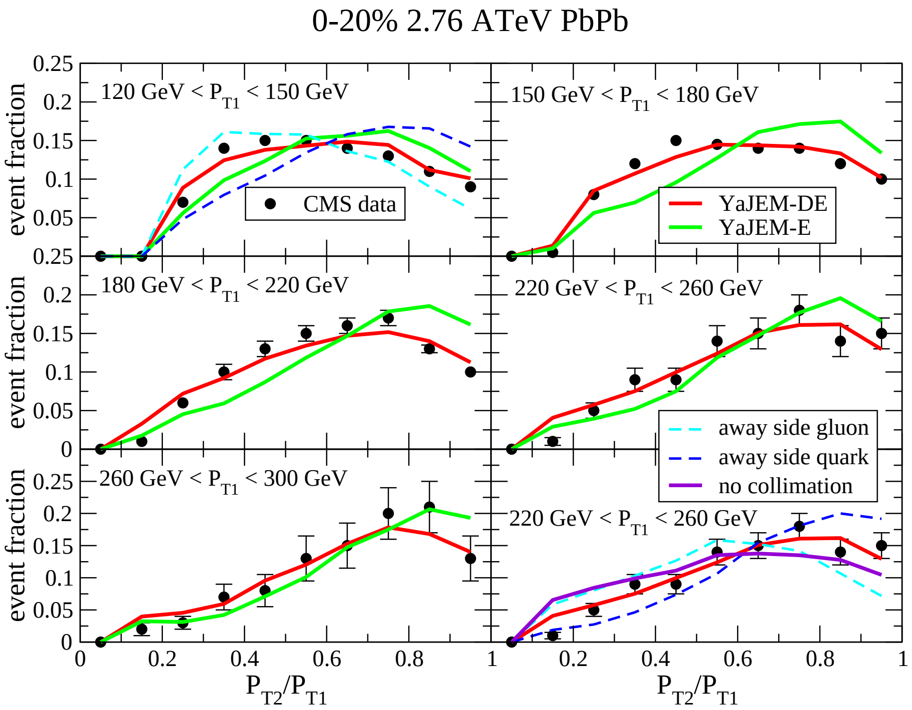
→ non-perturbative physics obscures result below 62.4 GeV

⇒ pQCD scales reasonably well across factor 50 in $\sqrt{s}$

T. Renk, 1302.3710 [hep-ph].

JETS

- momentum dependence of the dijet asymmetry



⇒ evolution from 100 to 250 GeV well reproduced by pQCD

- also $R_{AA}(\phi)$, h-jet correlations, γ-h correlations, jet R_{AA}, . . .

pQCD based light quark quenching works across a wide range of observables which probe parton type, pathlength dependence, relative amount of elastic to radiative energy loss, kinematic shifts, . . .

III. Where heavy quarks are different

GENERAL CONSIDERATIONS

QCD is flavour-blind, i.e. heavy quark jets cannot be *fundamentally* different, but:

• mass changes kinematics

– lower shower evolution scale changes from $Q_0 \sim 1$ GeV to $Q_H \sim \sqrt{Q_0^2 + m_q^2}$
→ vacuum shower evolution terminates at E/Q_H^2, i.e. (much) earlier

– heavy quark mass suppresses radiation phase space
→ dead cone effect for vacuum and induced radiation

• since $m_q \gg T$, there are no thermally excited heavy quarks in the medium

– no conversion reactions like $q\overline{q} \rightarrow gg$
→ doesn't matter numerically

– heavy quark is always tagged, i.e. hard radiations or scatterings change energy
→ not so for light quarks where leading parton identity changes

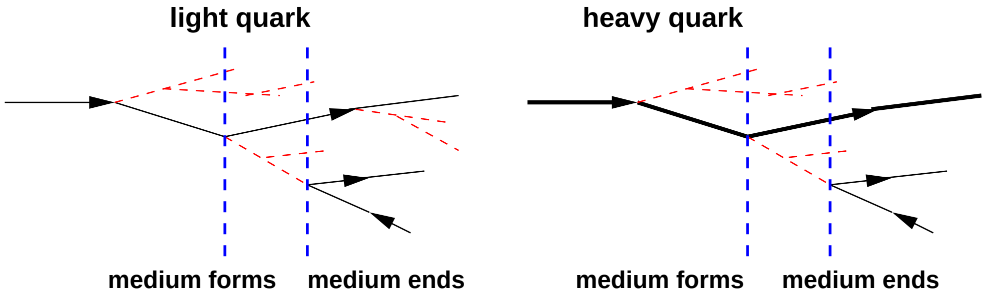
• for $E \sim$ few GeV, b-quarks are barely relativistic
→ $v \approx c$ is a bold assumption

GENERAL CONSIDERATIONS

For $Q^2 \gg m_q^2$, quark mass does not influence the shower evolution

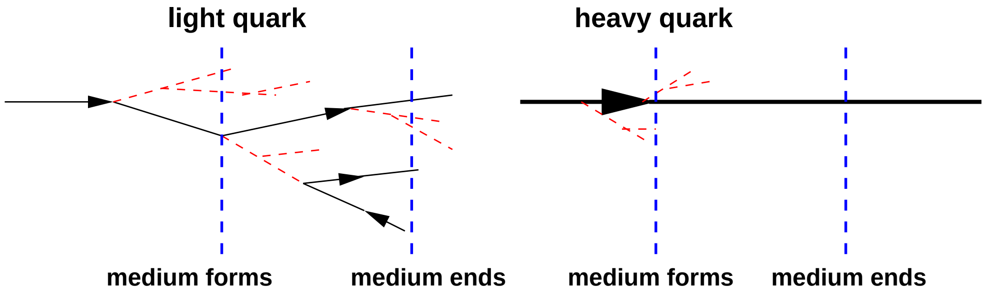
- e.g. 100 GeV charm quarks have 12 fm shower evolution length

$\Rightarrow$ their medium modification should be no different from light quarks



- e.g. 30 GeV bottom quarks have 0.4 fm shower evolution length

$\Rightarrow$ virtuality evolution is over before the medium is formed, totally different physics



- below 4 GeV, bottom quarks become non-relativistic, again different

HEAVY QUARKS AND ENERGY LOSS

Several distinct regions:

- for $E_c > 78$ GeV or $E_b > 900$ GeV, shower length > 10 fm

→ certainly medium-modified like light quark jets

- for $E_c < 3.9$ GeV or $E_b < 45$ GeV, shower length < 0.5 fm

→ certainly on-shell quarks moving through medium

- intermediate region of complicated physics — not quite on-shell, not quite a shower

→ 100 GeV b-tagged jets at CMS seem to behave like light quark jets

What is the relevant vacuum state which gets perturbed by the medium?

Evolving virtual quark? On-shell quark?

Despite frequent claims, heavy quark jets are **not** a good testing ground for constraining light quark jet quenching models unless one probes very high energies. The physics situation and the relevant approximation scheme are very different.

- energy loss of on-shell quarks

→ mostly not applicable to light quarks

→ may be different for heavy quarks

THE HEAVY QUARK PUZZLE (MY VERSION)

If low energy heavy quarks show different physics, why is electron R_{AA} the same?

Suggested old solutions. . .

- electrons all come from c-quarks, our notion about the b contribution is wrong

$\rightarrow$ experimentally demonstrated to be wrong by decay kinematics template fits

$\Rightarrow$ no longer viable

- all quarks experience more elastic energy loss than previously thought ($\sim$ 50%)

$\rightarrow$ $R_{AA}(\phi)$ and I_{AA} in dihadron correlations constrain elastic contribution $\sim 10\%$

$\Rightarrow$ not viable for light quarks in pQCD

. . . and new solutions:

- the physics isn't pQCD, strong coupling techniques should be used for all quarks

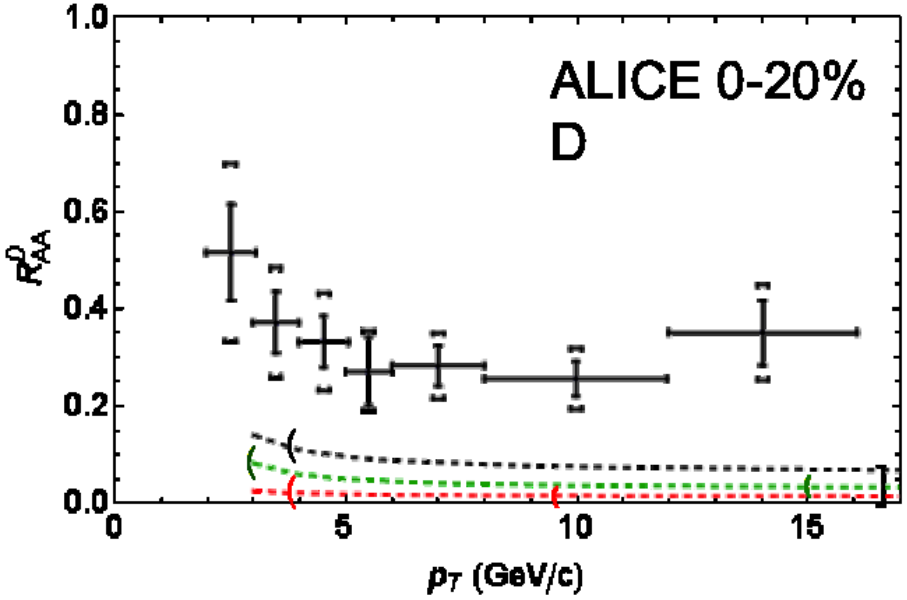
$\rightarrow$ need to test if AdS/CFT techniques work as well as pQCD

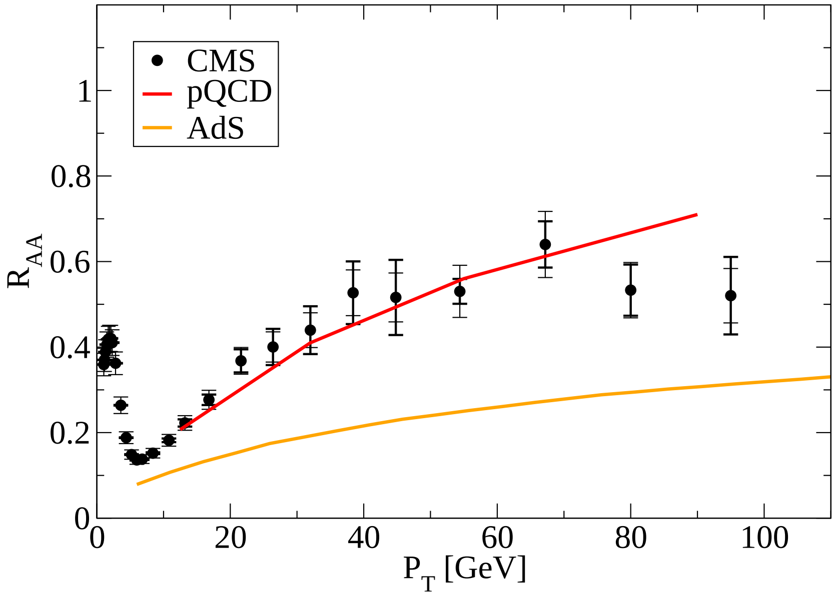
- heavy quarks do have reduced radiation, but something enhances elastic interactions

$\rightarrow$ need to test if elastic interactions for heavy quarks differ

AdS, light and heavy quarks

- Does AdS get the scaling from RHIC to LHC?





$\Rightarrow$ Clear **no** for both heavy and light quarks! AdS techniques predict too much suppression at LHC when tuned to RHIC and extrapolated.

- No viable AdS/CFT model candidate for the more involved light quark observables $\Rightarrow$ revise or abandon!

W. Horowitz, Nucl. Phys. A904-905 **2013** (2013) 186c,T. R., Phys. Rev. C **85** (2012) 044903

HEAVY QUARKS AND ELASTIC SCATTERING

Only one promising idea left:

Hypothesis: Heavy quarks have different balance of elastic to radiative energy loss

- Does this work?

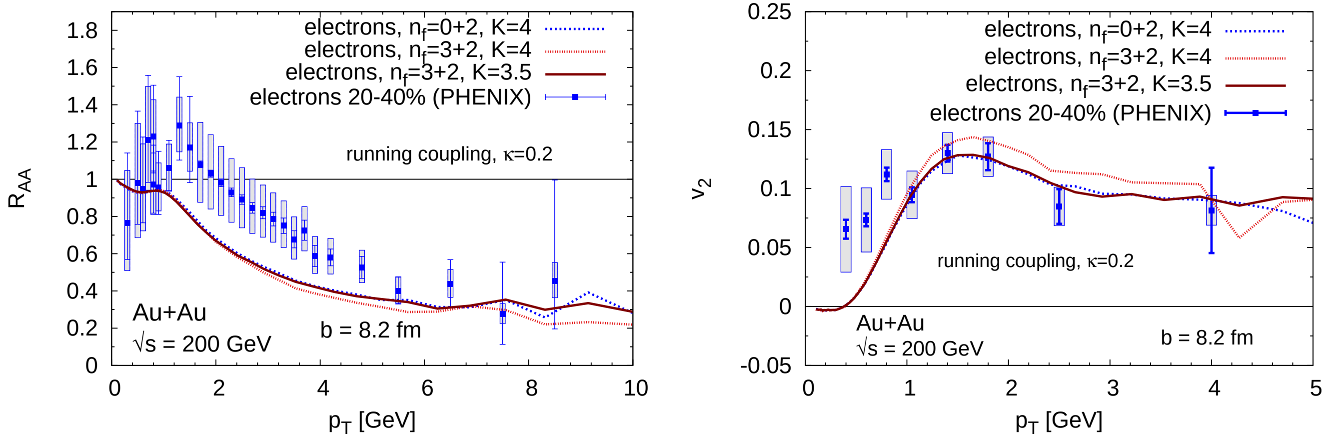
→ Demonstrate using K-factors that data can be accounted for
→ crucial: realistic modelling of the medium evolution!

- How come?

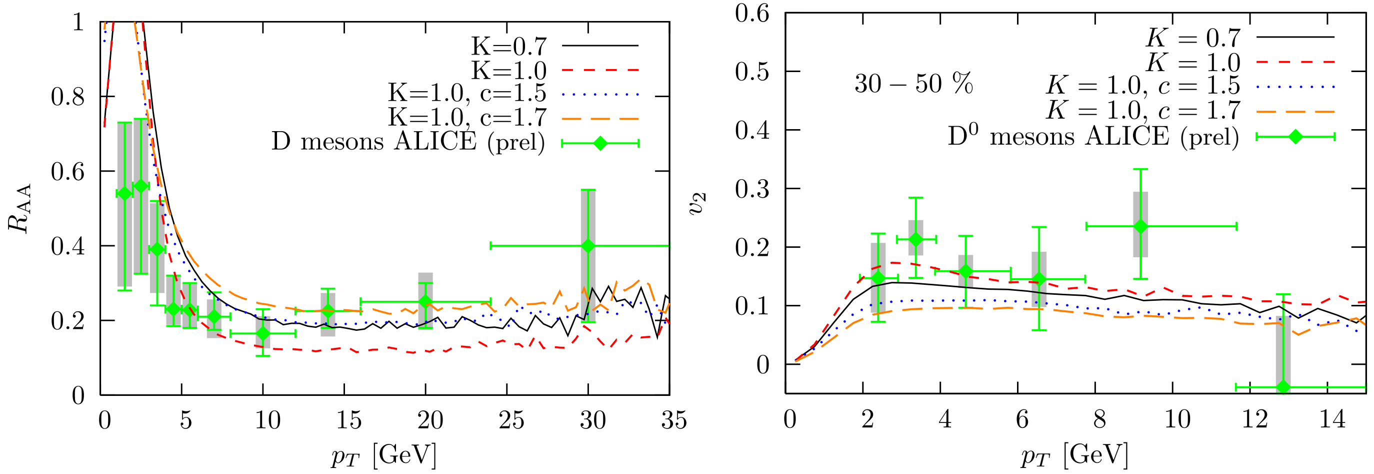
→ Provide a physics mechanism which makes heavy quarks different

COMPREHENSIVE DESCRIPTION OF OBSERVABLES

- extreme case — no radiative, just enhanced elastic ⇒ okay-ish



- including radiation ⇒ okay (note different K)



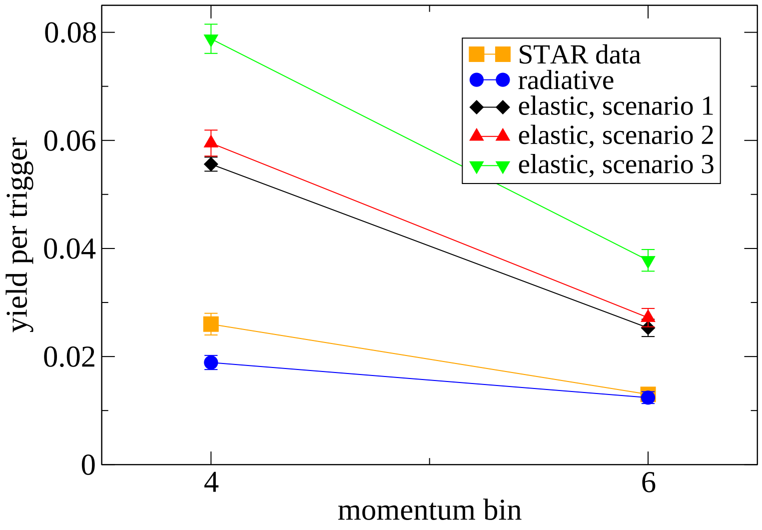
J. Uphoff, O. Fochler, Z. Xu and C. Greiner, Phys. Lett. B **717** (2012) 430; M. Nahrgang *et al.*, 1305.6544 [hep-ph].

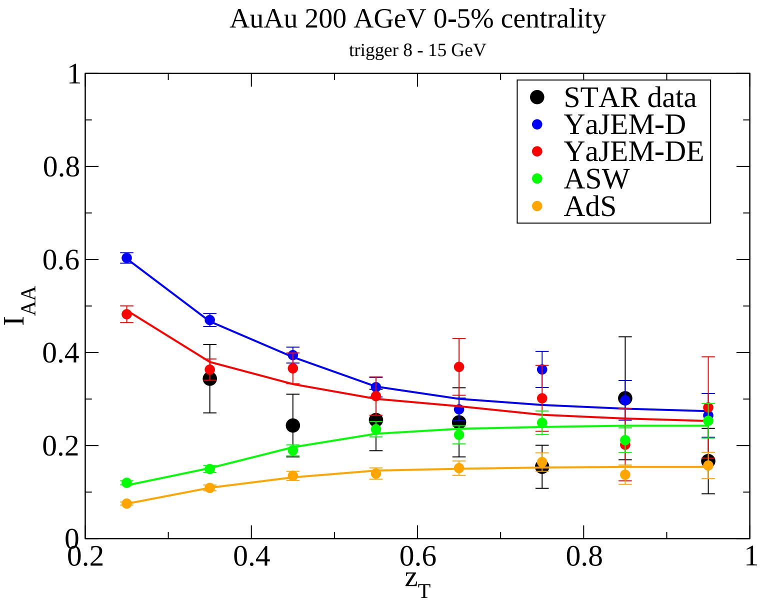
HOW STRONG IS THE ELASTIC CHANNEL?

- We know how to measure the elastic contribution for light quarks

1) Upper bound from high z_T away side I_{AA} in h-h correlations
$\Rightarrow$ $I_{AA}^{elastic} \gg I_{AA}^{radiative}$ due to pathlength effects

2) lower bound from low z_T away side side I_{AA} in h-h correlations
$\Rightarrow$ direct energy loss into medium is reflected in subleading hadron spectrum



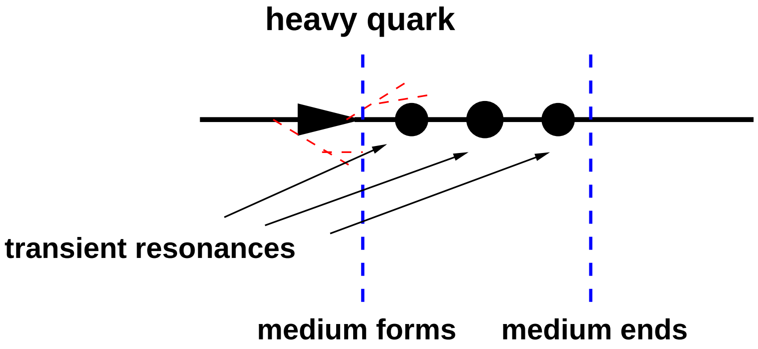


- 1) argues elastic contribution < 10 %, 2) argues $> 10\%$ — highly consistent
$\Rightarrow$ can we study back to back D or B meson coincidences?

T. R., Phys. Rev. C **76** (2007) 064905; T. R., Phys. Rev. C **84** (2011) 067902

ENHANCED ELASTIC INTERACTIONS BY RESONANCES

- Idea: D and B measons may not be stable in QGP, but resonances may persist



A. Adil and I. Vitev, Phys. Lett. B **649** (2007) 139 R. Sharma, I. Vitev and B. -W. Zhang, Phys. Rev. C **80** (2009) 054902 M. He, R. J. Fries and R. Rapp, Phys. Rev. C **86** (2012) 014903

- What it does: elastic cross section is enhanced by the resonances

→ stronger quenching due to elastic processes

- Why it doesn't affect light quarks: works specifically for on-shell states

→ would probably apply to light quarks if they would ever come on-shell

- How to test this: pathlength dependence

→ if quenching is through an elastic channel, predict $I_{AA}^{DD} \gg I_{AA}^{\pi\pi}$

RUNNING OF α_s

- many light quark computations of elastic scattering done with fixed α_s

→ but in reality it is not fixed!

- self-consistently determined Debye mass often used in heavy-quark computations

$$m_D^2 = 4\pi(1 + \tfrac{1}{6}n_f)\alpha_s(m_D^2)T^2$$ A. Peshier, J. Phys. G **35** (2008) 044028.

⇒ this gives a parametric enhancement of the elastic eloss contribution

- but the same Debye mass must regulate light quark energy loss

→ elastic light quarks eloss is constrained to be small

⇒ can this mechanism invoked for heavy-quarks without contradiction?

- with $\alpha_s = 0.3$, 50% of the light quark energy loss can be explained

What do we learn about the medium degrees of freedom and the validity of pQCD by the observation that elastic energy loss is constrained to be much smaller than calculations estimate? Are they very heavy, or large correlated patches of glue, or. . . ?

CONCLUSIONS

Compelling physics picture of heavy and light quarks

- at very high P_T mass effects become unimportant — shower physics

$\Rightarrow$ b-tagged jets look as suppressed as light parton jets

- at lower P_T, heavy quark jets probe on-shell quark energy loss

$\Rightarrow$ accessible physics different from light quarks

- the suite of observables has implications for heavy quarks

$\Rightarrow$ induced radiation is suppressed, thus elastic collisions must be enhanced
$\Rightarrow$ resonant scattering provide a plausible physics picture

To do

- close the case — I_{AA} in back-to-back correlations should be ideal

$\Rightarrow$ expect away side in D-D correlations much less suppressed than in $\pi\pi$

- determine mass dependence of elastic channel

$\Rightarrow$ work out what the implications are for medium properties

CONCLUSIONS

Open questions:

- high-quality medium modelling is available

→ but does anyone know the systematics? This is huge for light quark v_2!

- So far AdS/CFT has not managed to get the scaling right

→ artefact of bad approximations, or should we give up strong coupling?

- Are there other viable mechanisms for heavy-quark suppressions?

→ cross-check constraints with what we know from light quarks

Many thanks to Hendrik van Hees and Will Horowitz who helped me catching up with heavy quarks! (All mistakes are my own.)