The Nuclear Factor for Heavy Quarks

QM 2018

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talk by Andrea Rossi
talk by Xin-Ye Peng
talk by P.B. Gossiaux

outlook

- main physics motivation
- my gains of the nuclear factor for heavy quarks

Why heavy quarks in A-A ?

- Produced early via hard scattering, production cross sections calculable with pQCD
- Number conserved through time evolution (even at LHC)
- Strongly affected by the QGP phase
- Weakly affected by late time evolution

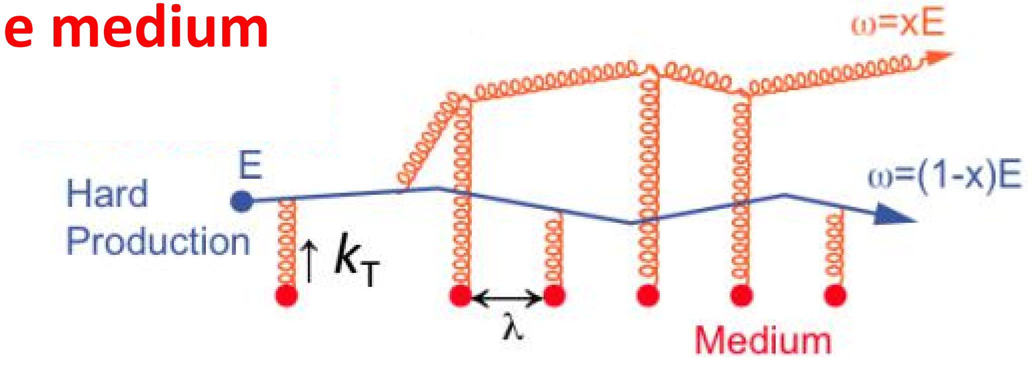
QGP tomography with heavy quarks

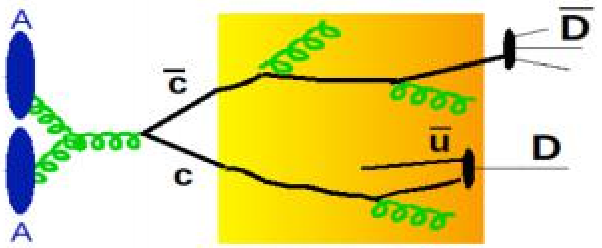
"Calibrated probes" of the medium

Study parton interaction with medium

- energy loss via radiative ("gluon Bremsstrahlung")
  collision processes
  - path length and medium density
  - color charge (Casimir factor)
  - quark mass (e.g. from dead-cone effect)

- medium modification to HF hadron formation
  - hadronization via quark coalescence





How can we measure medium effects?

Nuclear modification factor (R_{AA}): compare particle production in nucleus-nucleus (A-A) collisons with that in proton-proton (pp) scaled with the number of binary collisions.

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{N_{\mathrm{coll}}\, dN^{pp}/dp_T}$$

if $R_{AA} = 1$, $\longrightarrow$ no nuclear effects

if $R_{AA} \neq 1$, $\longrightarrow$ nuclear effects

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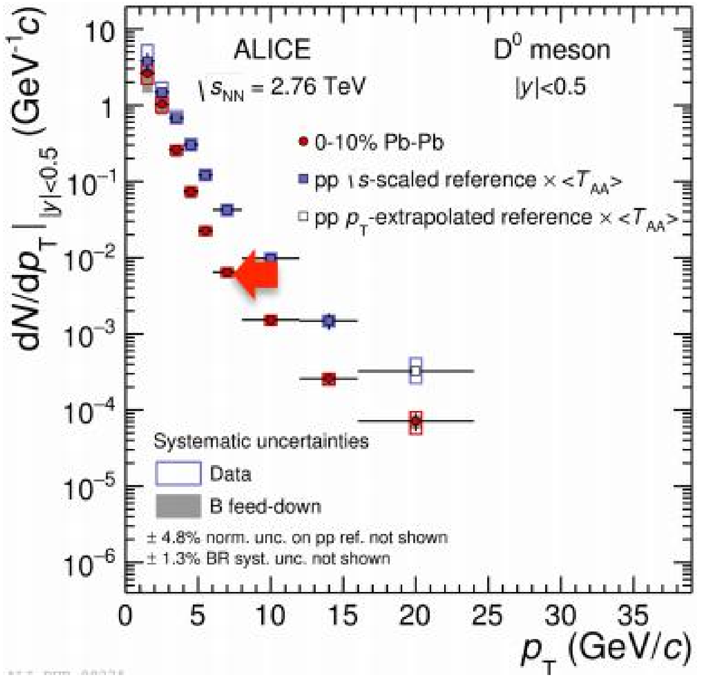
energy loss

↓

“redshift” of the initial p_T spectrum

↓

$R_{AA} < 1$ at moderate/high p_T



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Never forget: Measured spectra in AA collisions result from a convolution of many pieces

$\frac{dN_{AA}}{dp_T} =$ "Vaccum" parton spectra $\otimes$ initial-state effect $\otimes$ parton interaction with the medium $\otimes$ (modified?) hadronization $\otimes$ hadronic phase $\otimes$ decay kinematics e.g. for leptons

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$$\frac{dN_{AA}}{dp_T} = \text{"Vaccum" parton spectra} \otimes \text{initial-state effect} \otimes \text{parton interaction with the medium} \otimes \text{(modified?) hadronization} \otimes \text{hadronic phase} \otimes \text{decay kinematics e.g. for leptons}$$

- must measure observables with different sensitivity to the various ingredients
- physics program requires precise measurements in pp, p-A, A-A collisions
- interpretation of the results requires comparison with models

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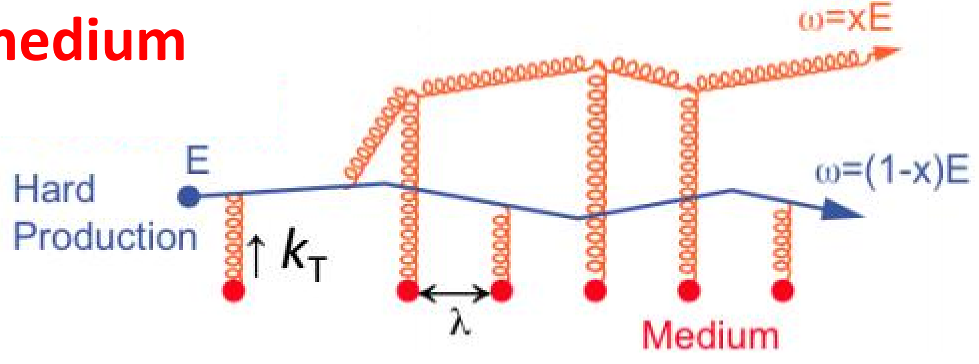
What we want to probe

$\frac{dN_{AA}}{dp_T} =$ "Vaccum" parton spectra $\otimes$ initial-state effect $\otimes$ parton interaction with the medium $\otimes$ (modified?) hadronization $\otimes$ hadronic phase $\otimes$ decay kinematics e.g. for leptons

QGP tomography with heavy quarks

"Calibrated probes" of the medium

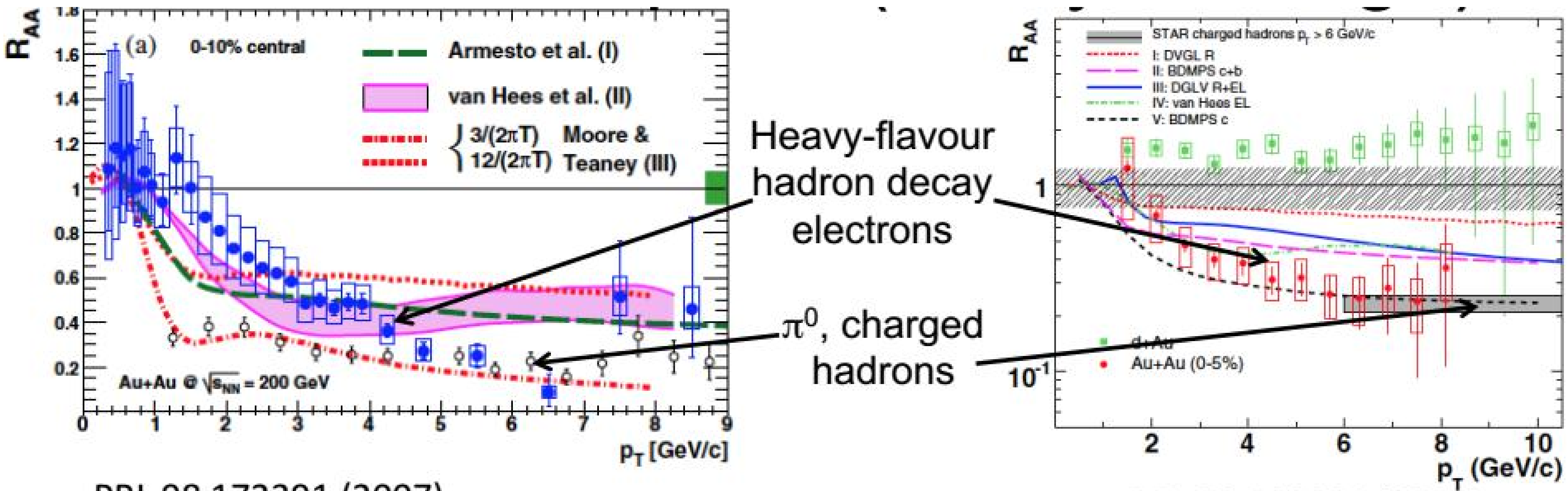


Study parton interaction with medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collision processes

?

The RHIC surprise (>10 years ago)



PRL 98 172391 (2007)

PRL 98 192301 (2007)

Look at data: similar R_{AA} of heavy-flavor hadron decay electrons and π^0/charged hadrons at moderate /high p_T

Look at model: they do incorporate proper initial spectrum and decay kinematics

Very difficult to describe data within a “radiative-only” scenario!!!
Collisional energy loss can play an important role for heavy quarks!!!

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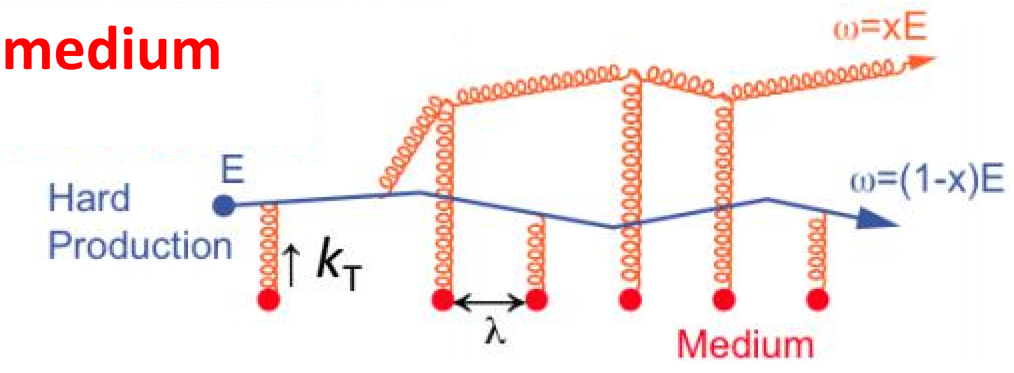

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... which dominant ?

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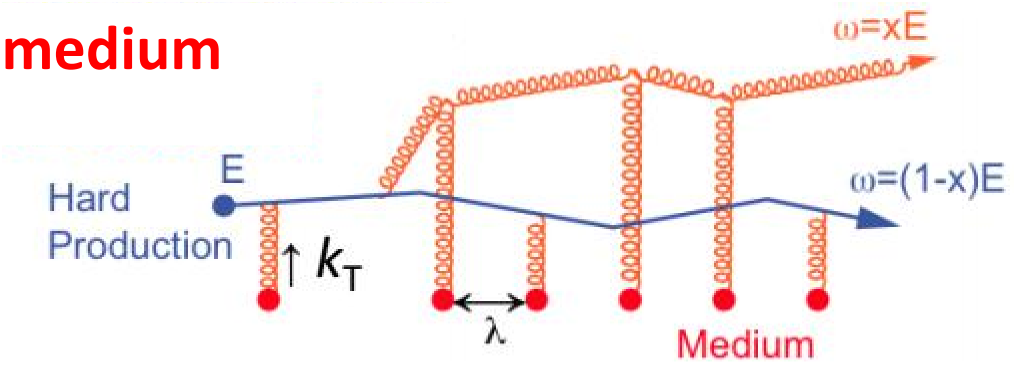

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energy loss hierarchy for different type parton ?

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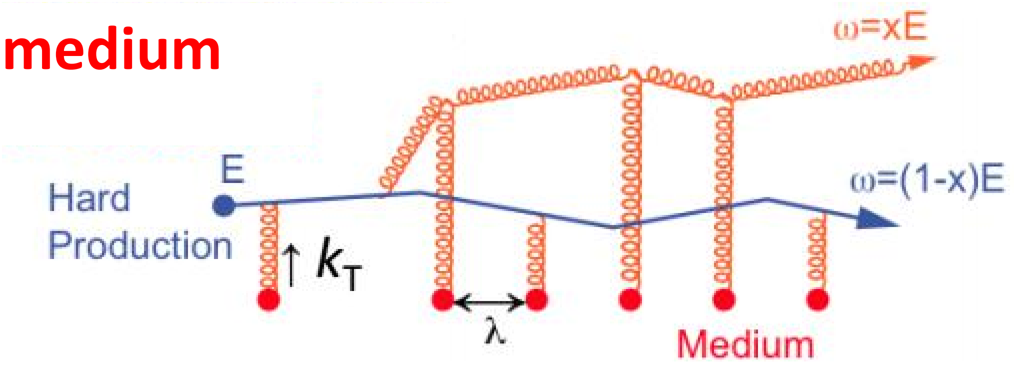

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➢ path length and medium density

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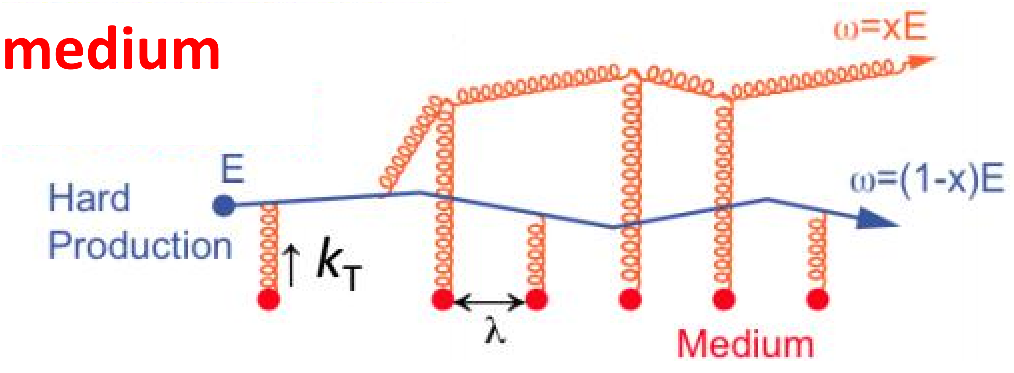

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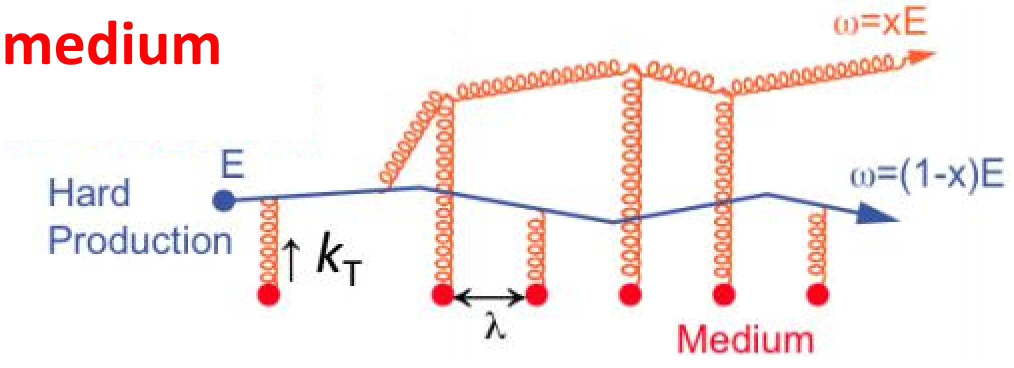

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    gluon interact with medium: gg->gg, gq->gq

    quark interact with medium: qg->qg, qq->qq

QGP tomography with heavy quarks

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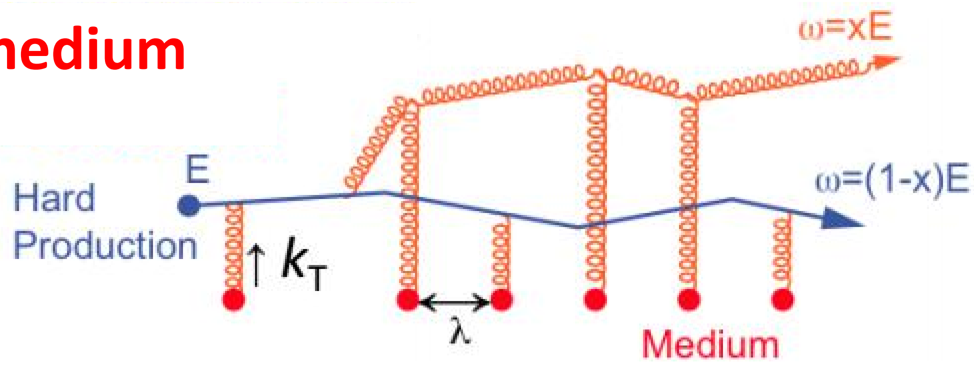

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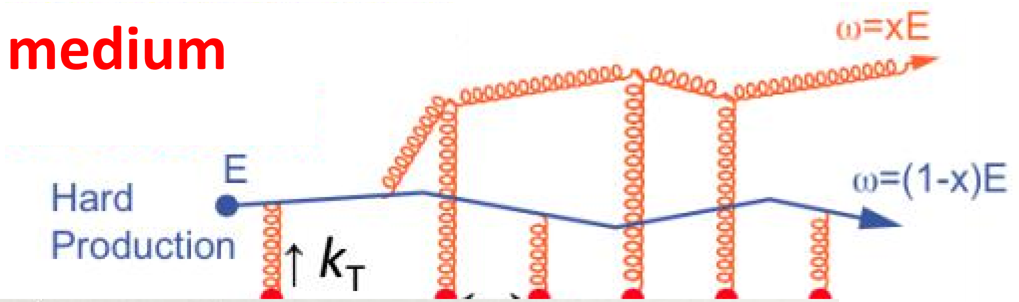

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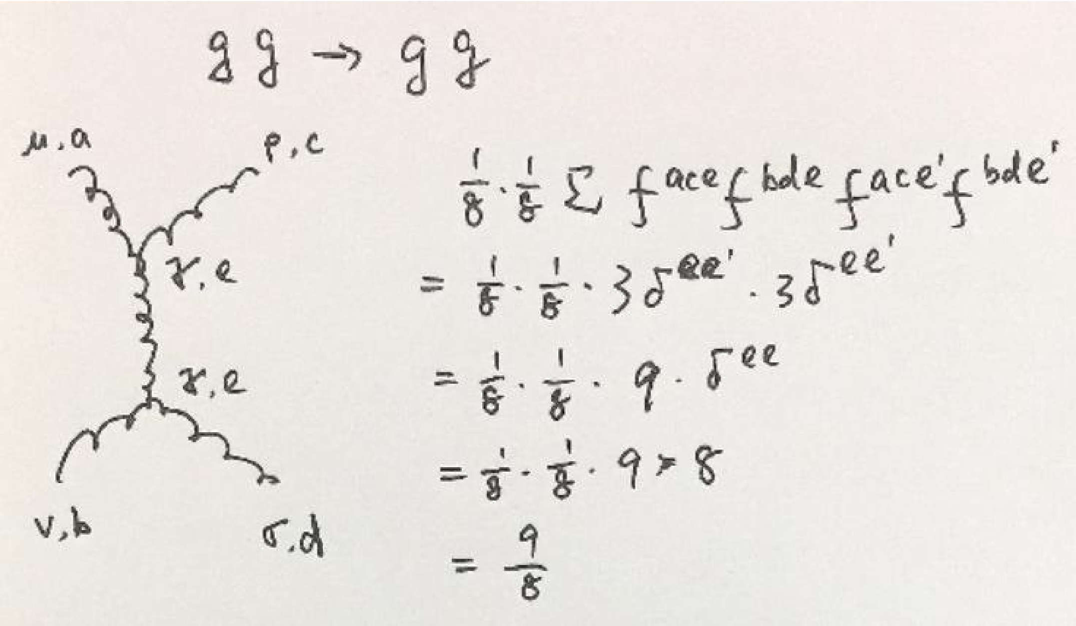

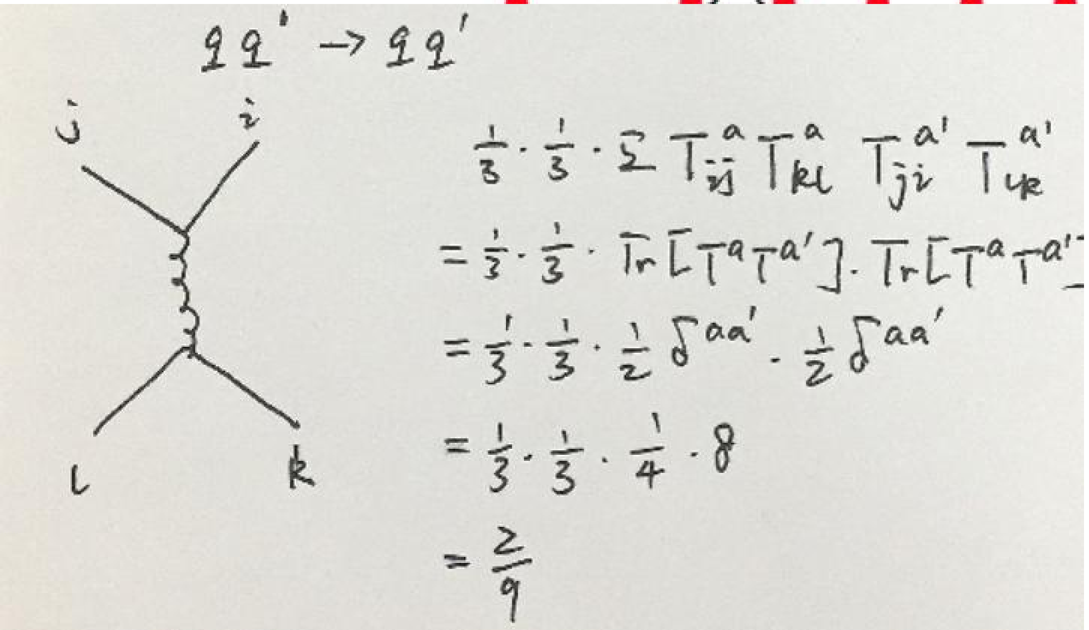

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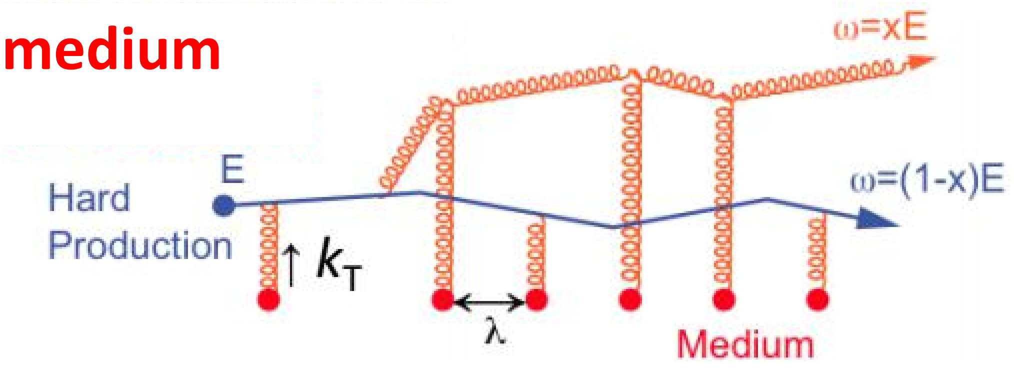

Study parton interaction with medium

- **energy loss via radiative** ("gluon Bremsstrahlung") **collision processes**

  - path length and medium density
  - color charge (Casimir factor)

$$\Delta E_g > \Delta E_q$$

QGP tomography with heavy quarks

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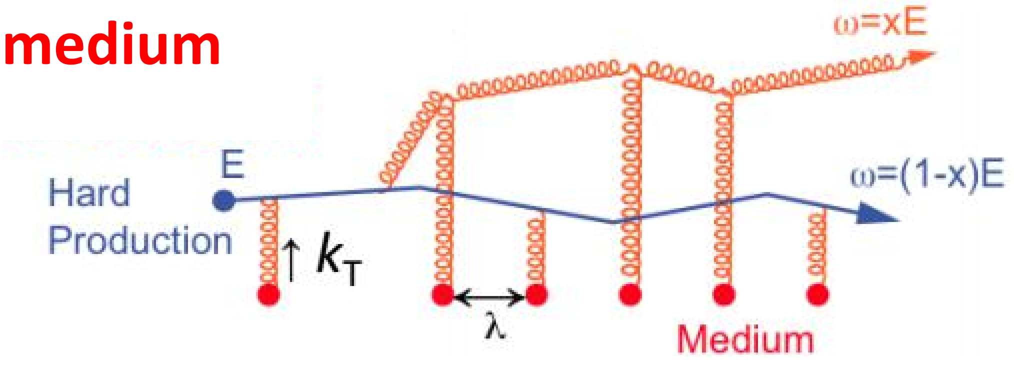

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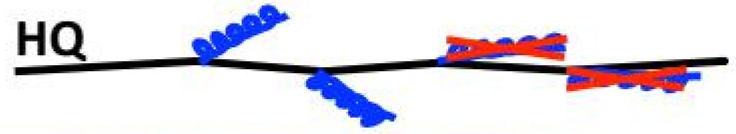

Gluonsstrahlung probability

$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

QGP tomography with heavy quarks

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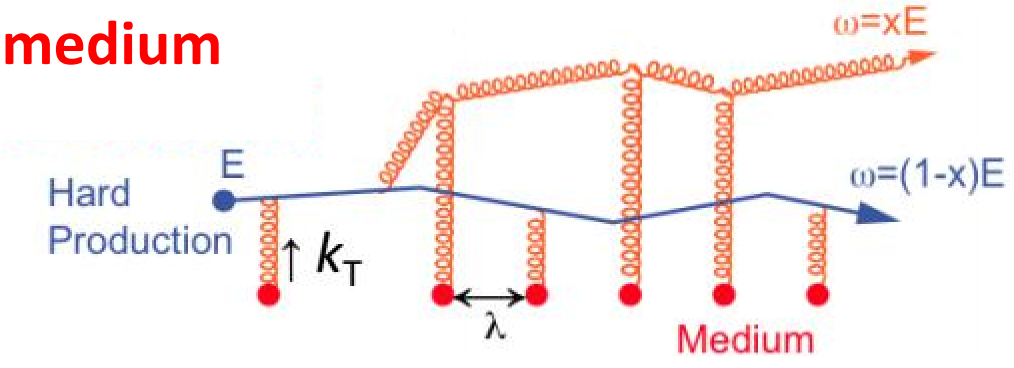

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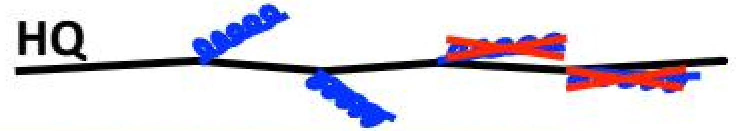
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$



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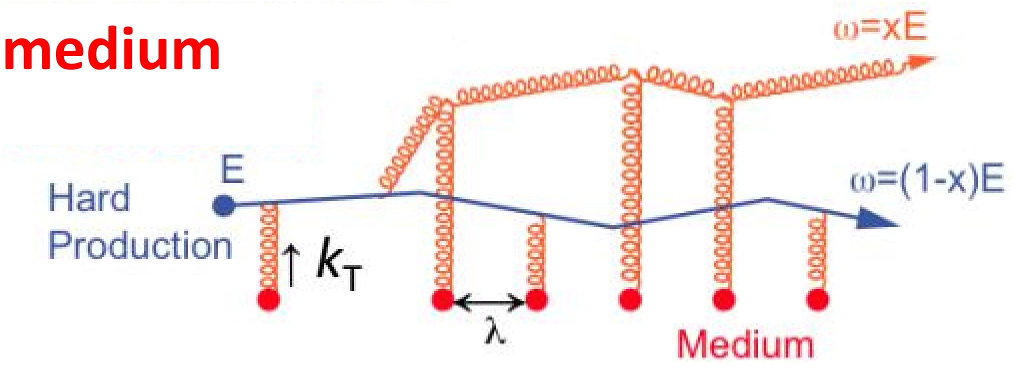

Study parton interaction with medium

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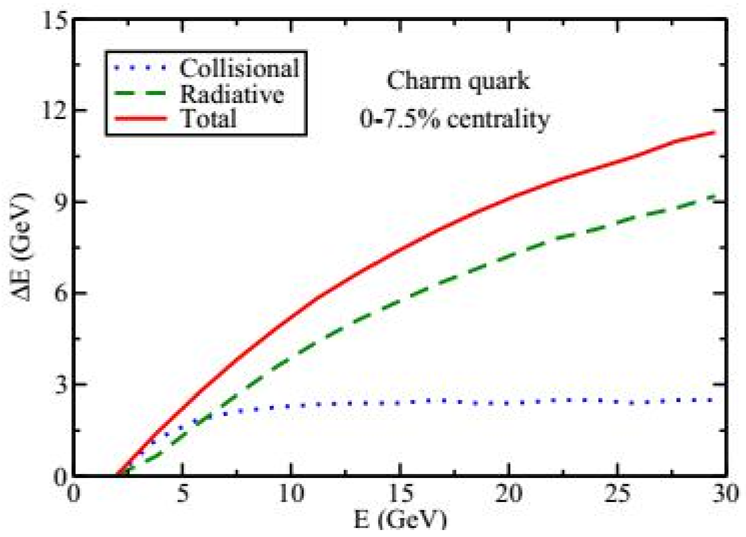
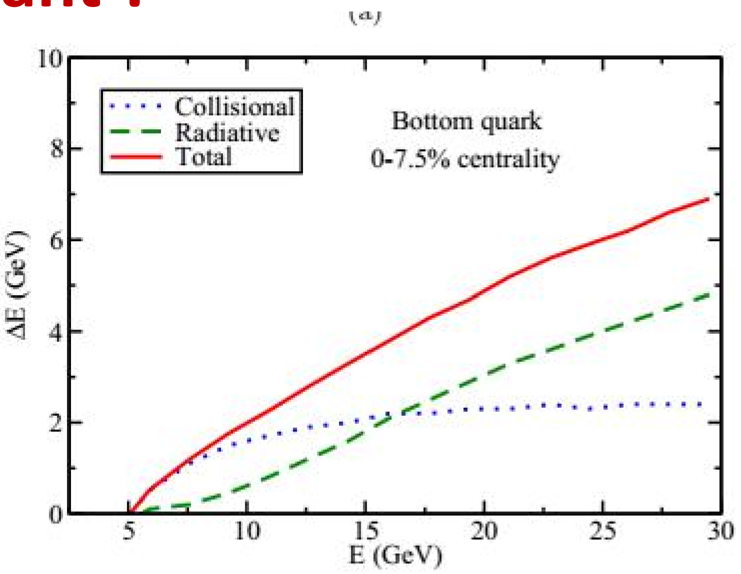
... which dominant ?



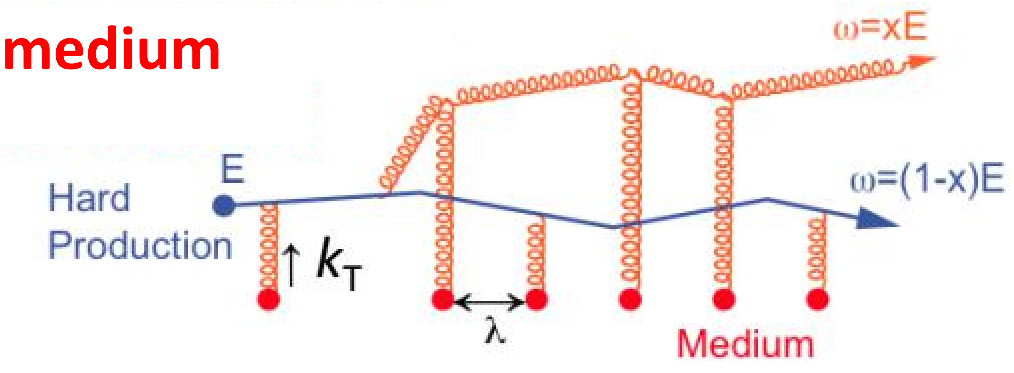


S. Cao, G. -Y. Qin, and S. A. Bass Phys. Rev. C88, 044907(2013)

- "Collision energy loss " dominant at low pt
- "Radiation energy loss" dominant at high pt

QGP tomography with heavy quarks

“Calibrated probes” of the medium



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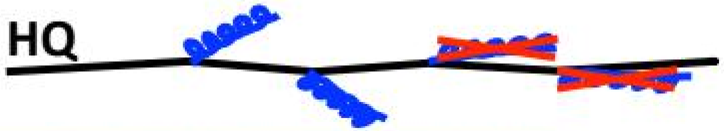
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

?

$$R_{AA}(B) < R_{AA}(D) < R_{AA}(\pi)$$



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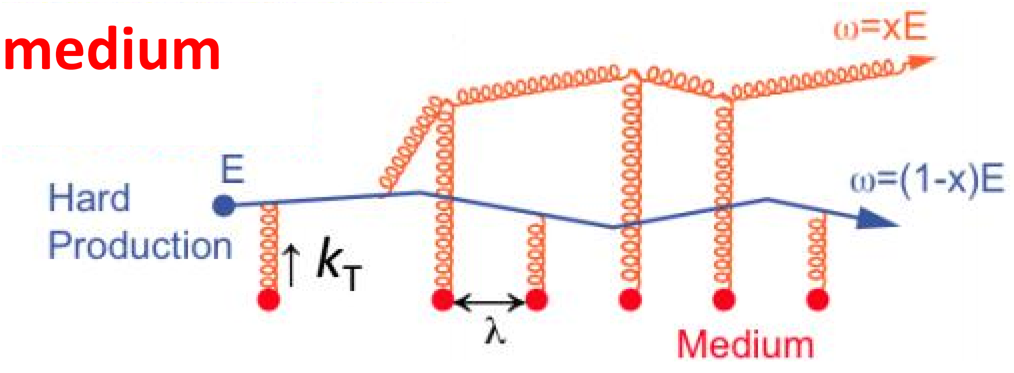

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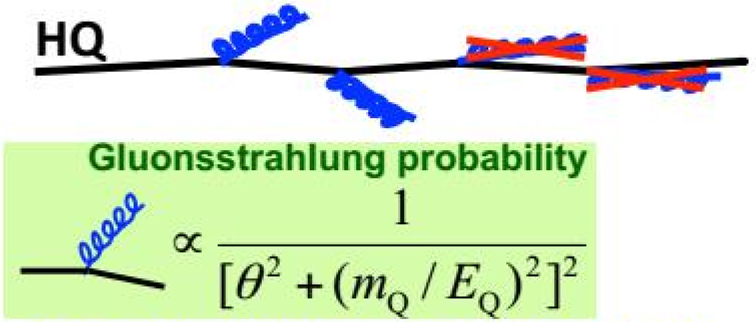

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$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

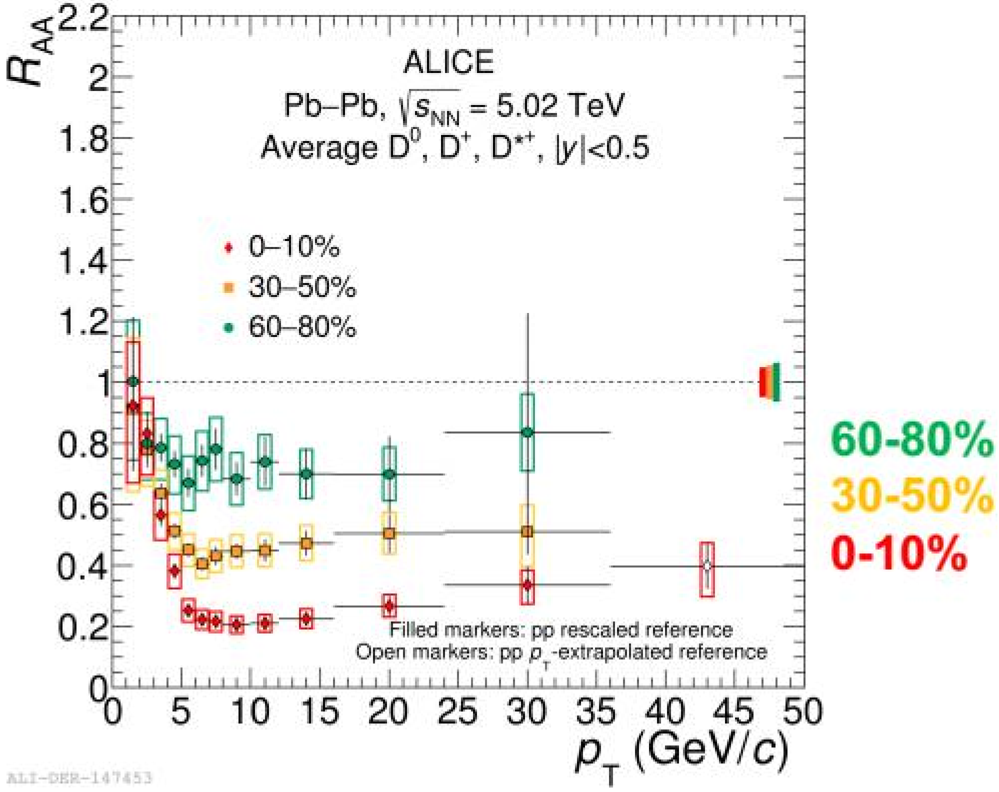
?

$$R_{AA}(B) < R_{AA}(D) < R_{AA}(\pi)$$

Not straightforward!!!

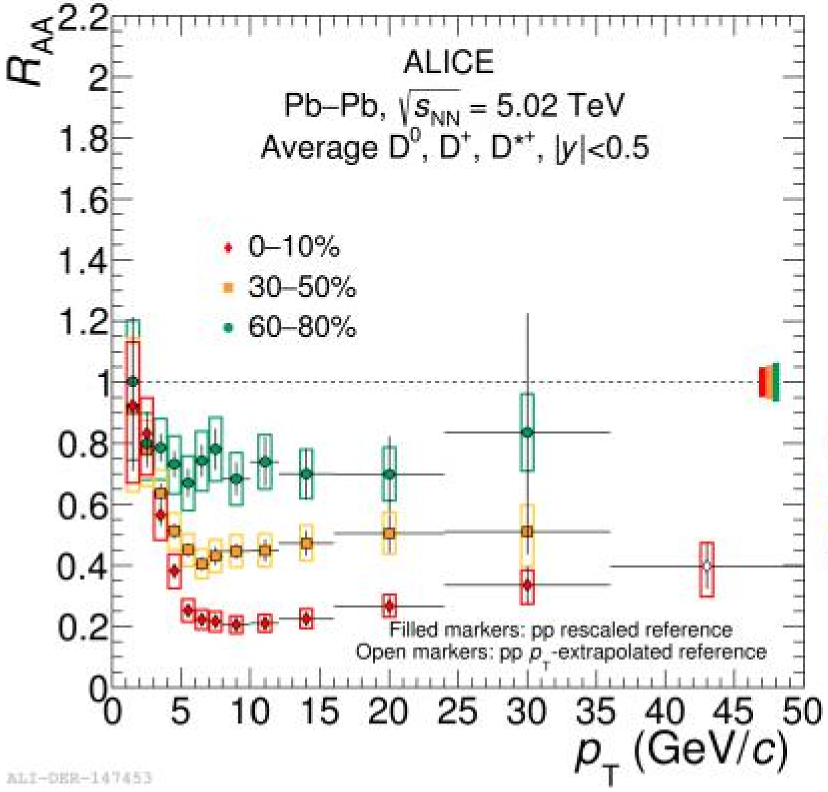
Initial spectrum function + fragmentation functions + other different effects

D-meson suppression at LHC

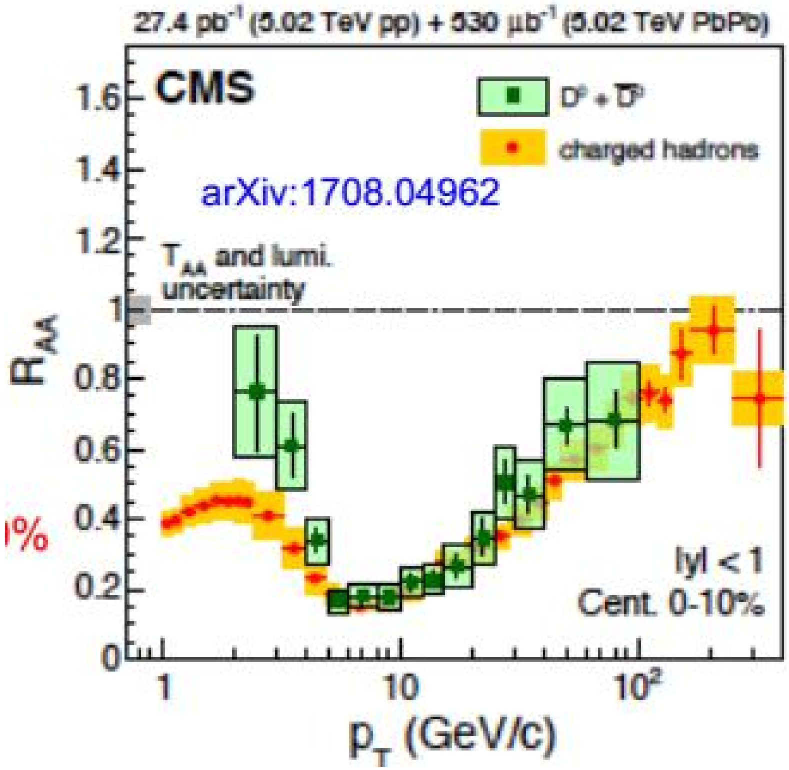


- Strong suppression of high pt D-meson, increasing with centrality

D-meson and charged-particle R_{AA} comparison



60-80%
30-50%
0-10%



- Strong suppression of high pt D-meson, increasing with centrality
- Very similar D-meson and charged-particle R_{AA} from pt~ 5 to 100 GeV/c

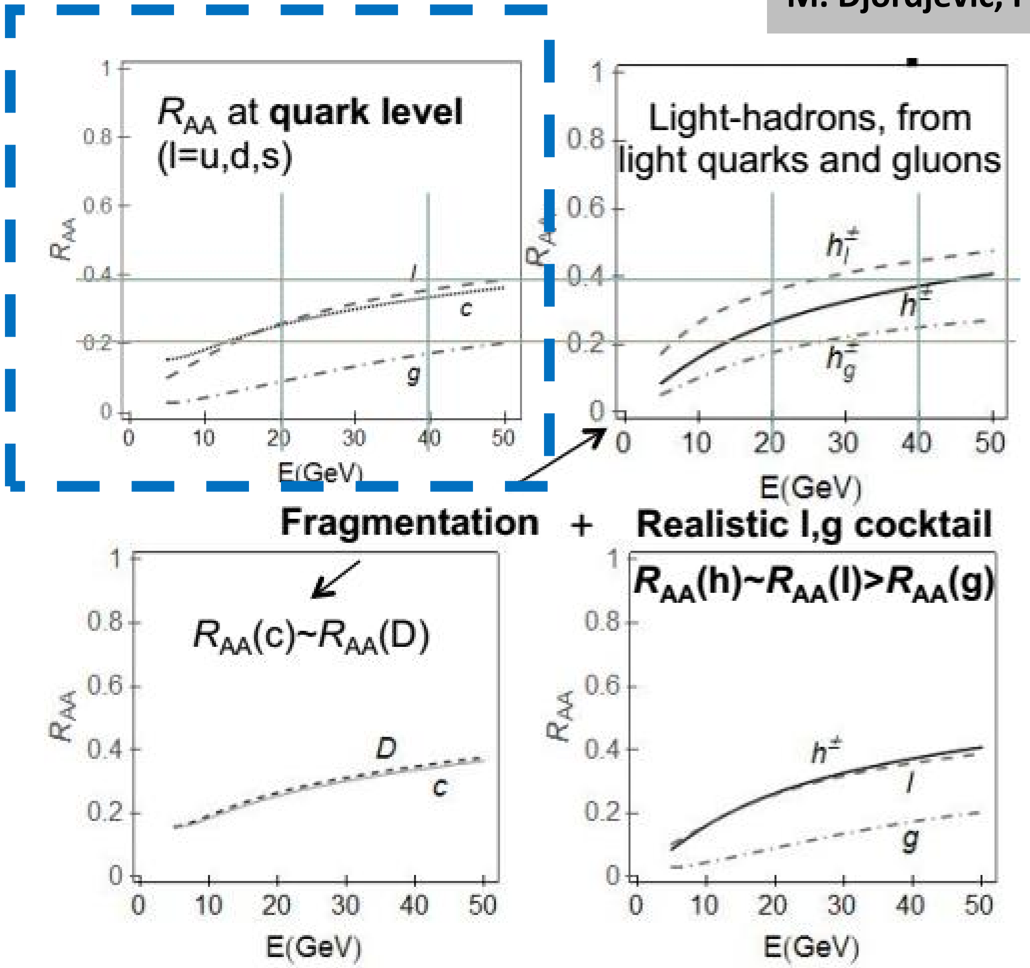
D-meson and charged-particle R_{AA} comparison

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$$

At high p_T $\quad R_{AA}(charged - particle) \sim R_{AA}(D)$?

D-meson and charged-particle R_{AA} comparison

M. Djordjevic, PRL 112 (2014) 042302



- Colour-charge dependence of energy loss and smalll charm-mass effects lead to:

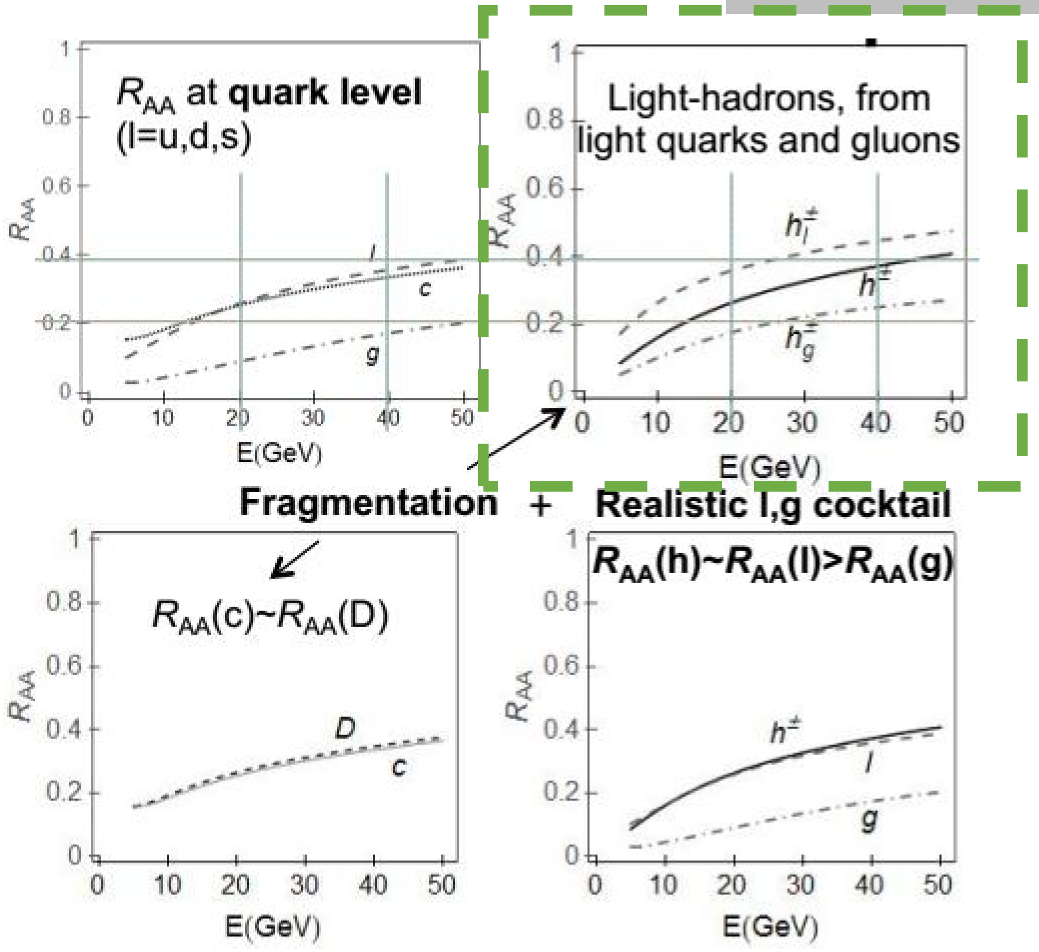
$$\Delta E_g > \Delta E_{uds} \geq \Delta E_c$$

$$R_{AA}(g) < R_{AA}(uds) \sim R_{AA}(c)$$

(effect of different partonic spectra included!)

D-meson and charged-particle R_{AA} comparison

M. Djordjevic, PRL 112 (2014) 042302



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- RAA of hadrons from light quarks ,gluon strongly influenced by (soft) fragmentation

$$R_{AA}(h_l) > R_{AA}(l)$$

$$R_{AA}(h_g) > R_{AA}(g)$$

D-meson and charged-particle R_{AA} comparison

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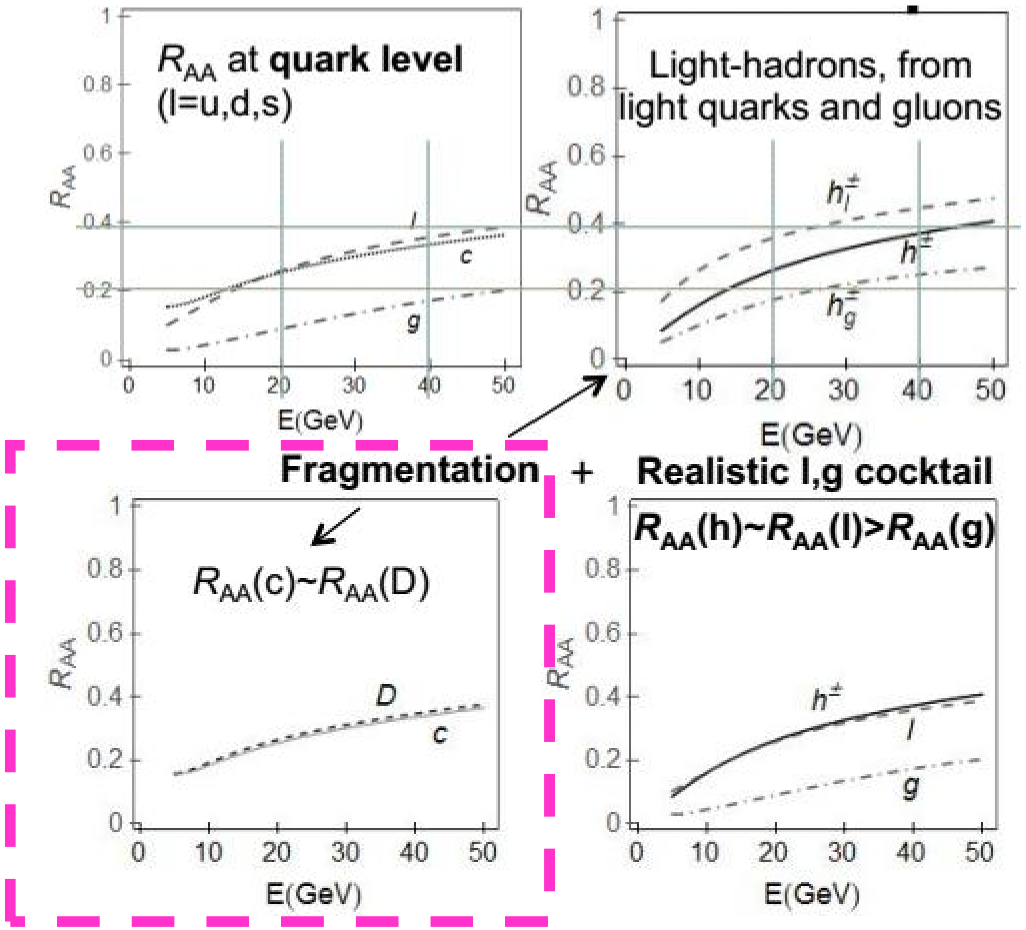

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- RAA of D-meson from c quarks weakly influenced by (hard) fragmentation

$$R_{AA}(D) \sim R_{AA}(c)$$

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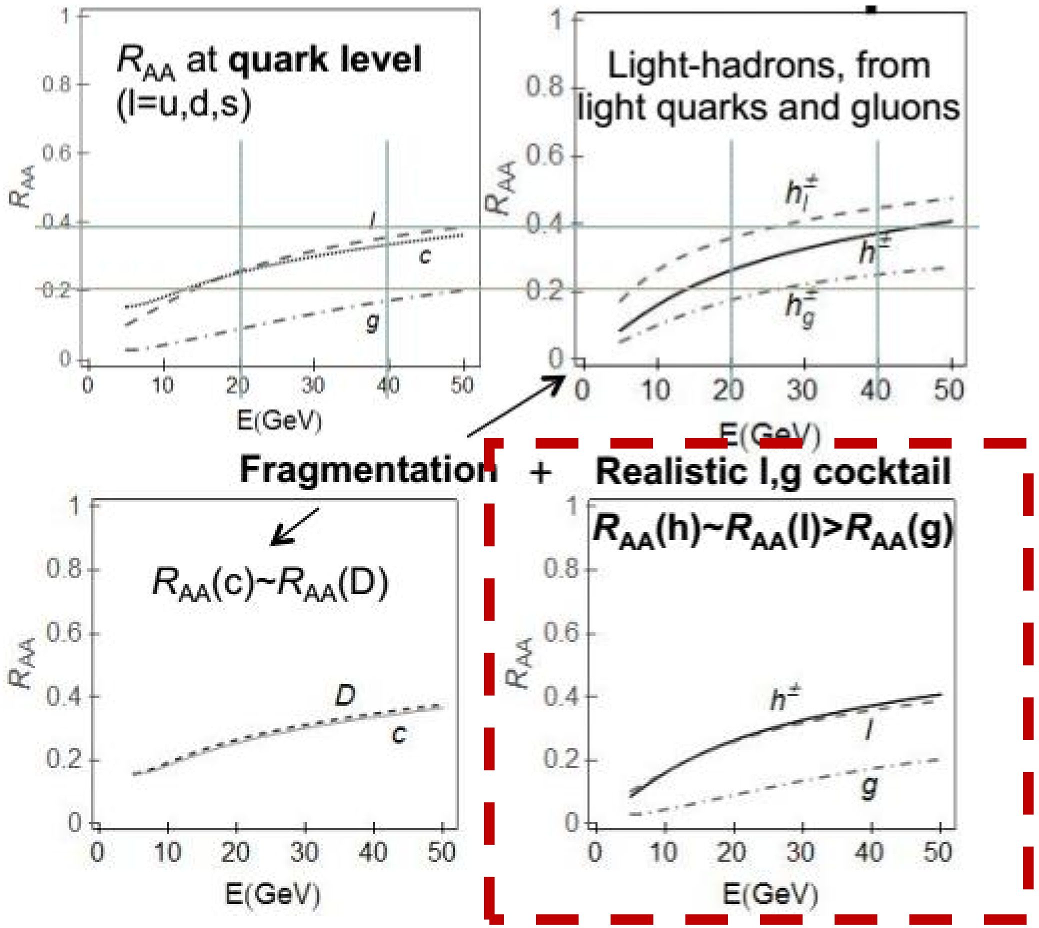
M. Djordjevic, PRL 112 (2014) 042302



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$$R_{AA}(D) \sim R_{AA}(c)$$

Expected hierarchy at high pt

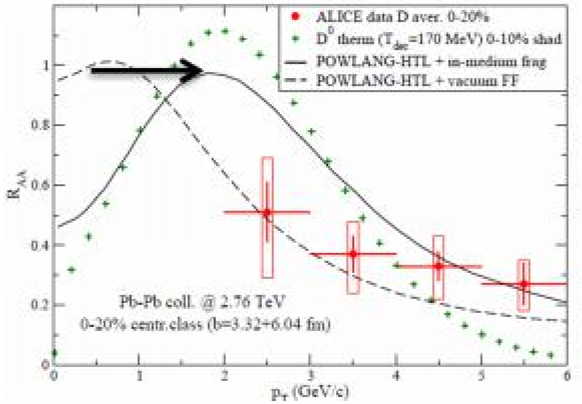
$$R_{AA}(g) < R_{AA}(uds) \sim R_{AA}(h) \sim R_{AA}(D) \sim R_{AA}(c)$$

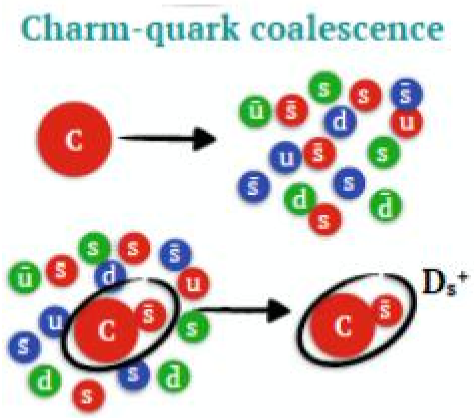
QGP tomography with heavy quarks

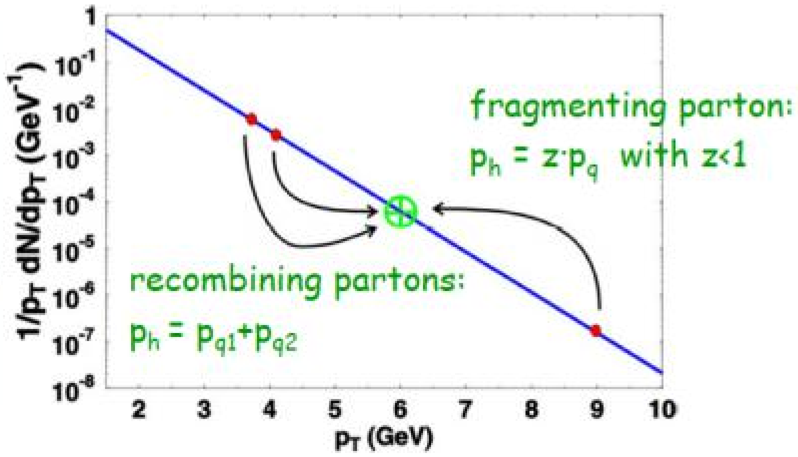
"Calibrated probes" of the medium

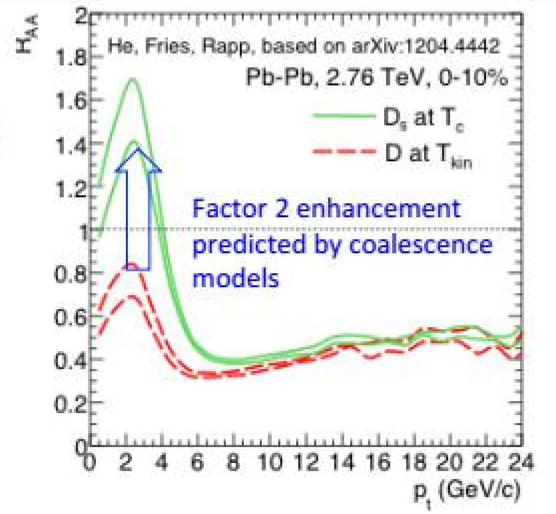
Study parton interaction with medium

- **Hadronization via coalescence**
  - Modify momentum distribution of HF-hadron
    - Radial flow "bump"
  - Enhanced HF-hadron v2 (light parton contribution)
  - Modify "hadrochemistry": D_s, Λ_c enhancement



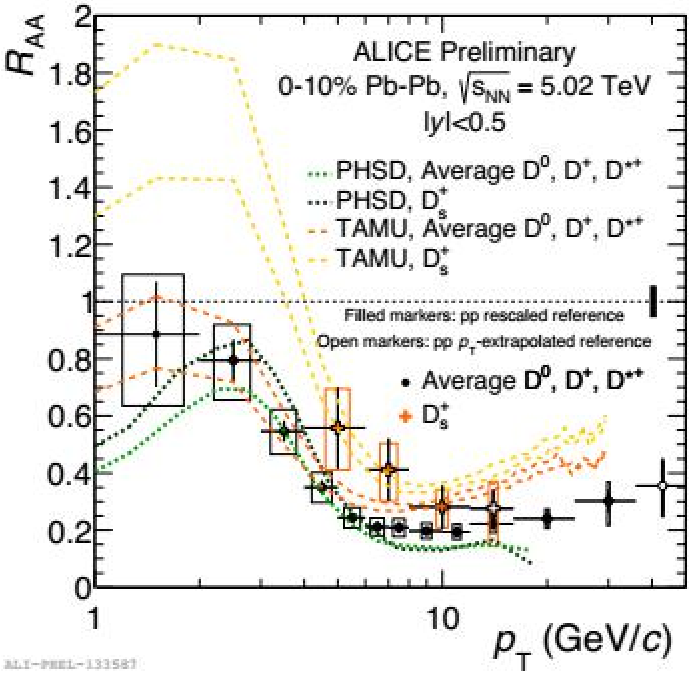


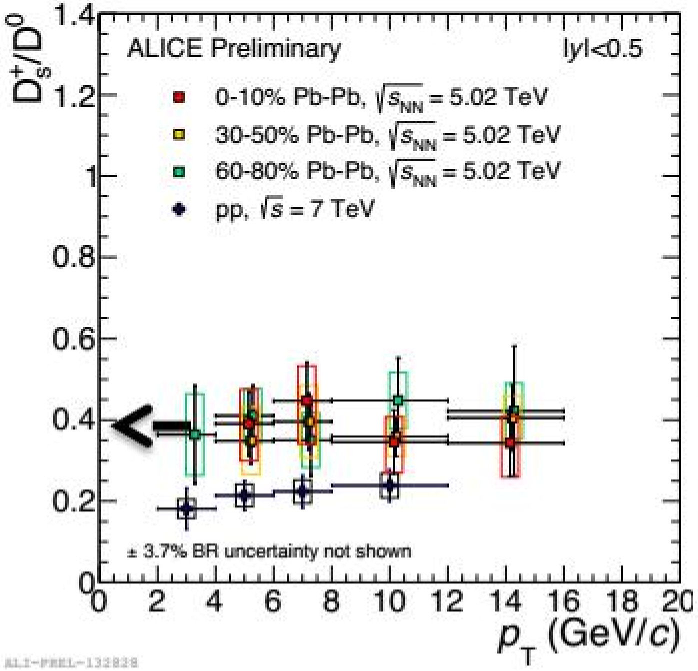




PHSD: Phys. Rev. C93 no. 3, (2016) 034906
TAMU: Phys. Lett. B735 (2014) 445-450
Catania: Eur. Phys. J. C (2018) 78:348

Hadronisation: D_s^+ enhancement





- Hint of enhanced Ds production in comparison to non-strange D-mesons in Pb-Pb collisions.
- Ds expected from model: Effect of coalescence + strange enhancement

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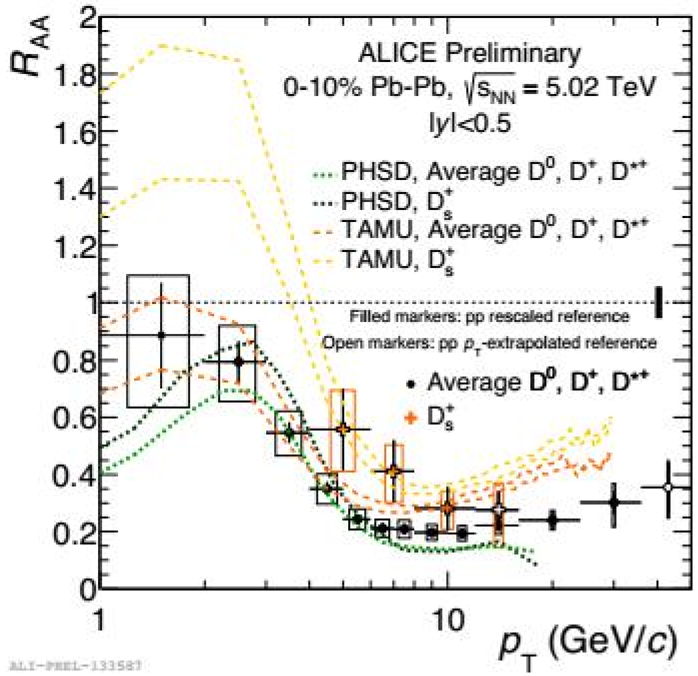
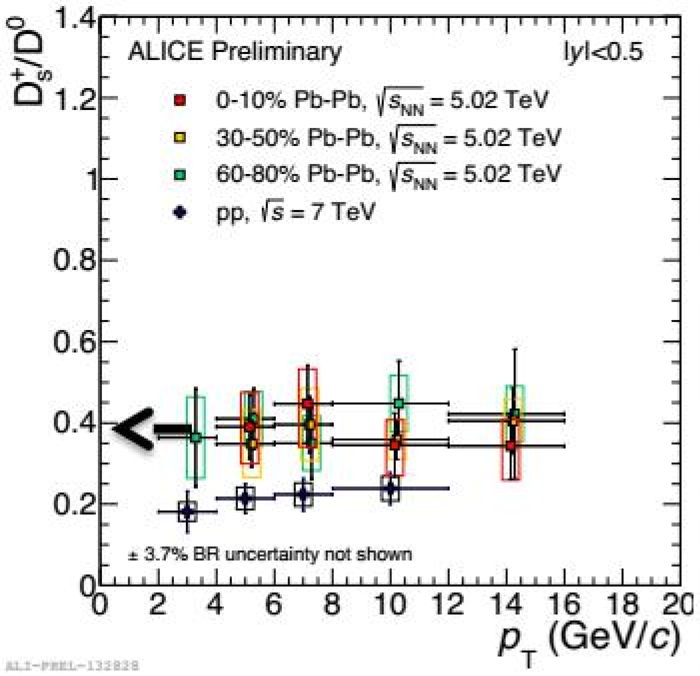
Catania: Eur. Phys. J. C (2018) 78:348

Hadronisation: D_s^+ enhancement

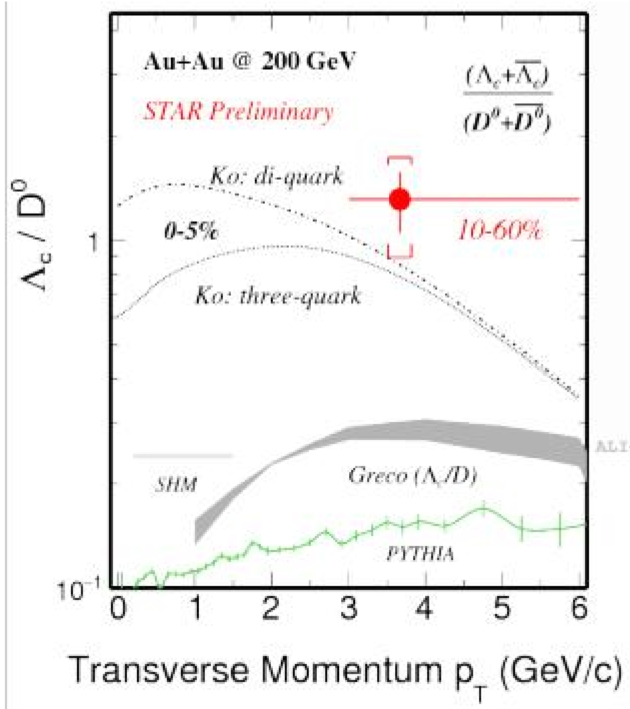


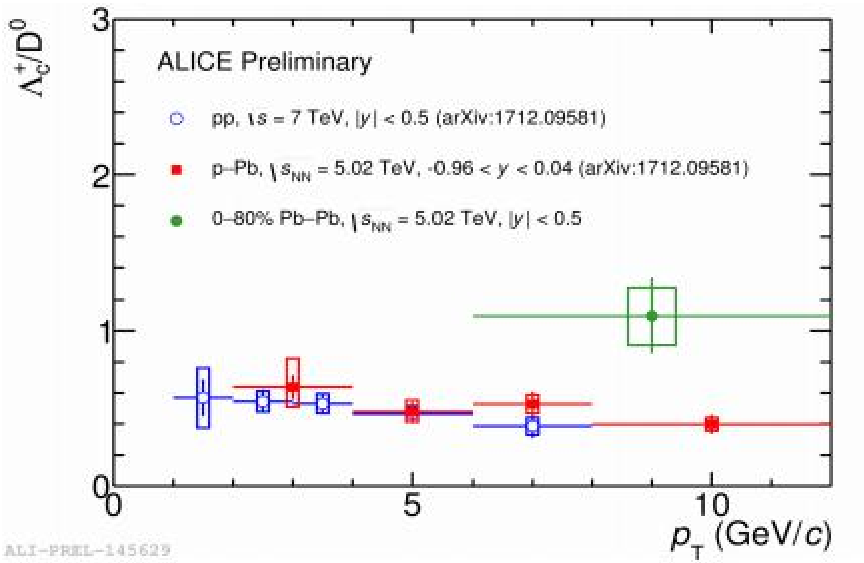


- Hint of enhanced Ds production in comparison to non-strange D-mesons in Pb-Pb collisions.
- Ds expected from model: Effect of coalescence + strange enhancement

- D^s / D^0 : no evidence for centrality dependence within uncertainties

Hadronisation: Λ_c^+ enhancement



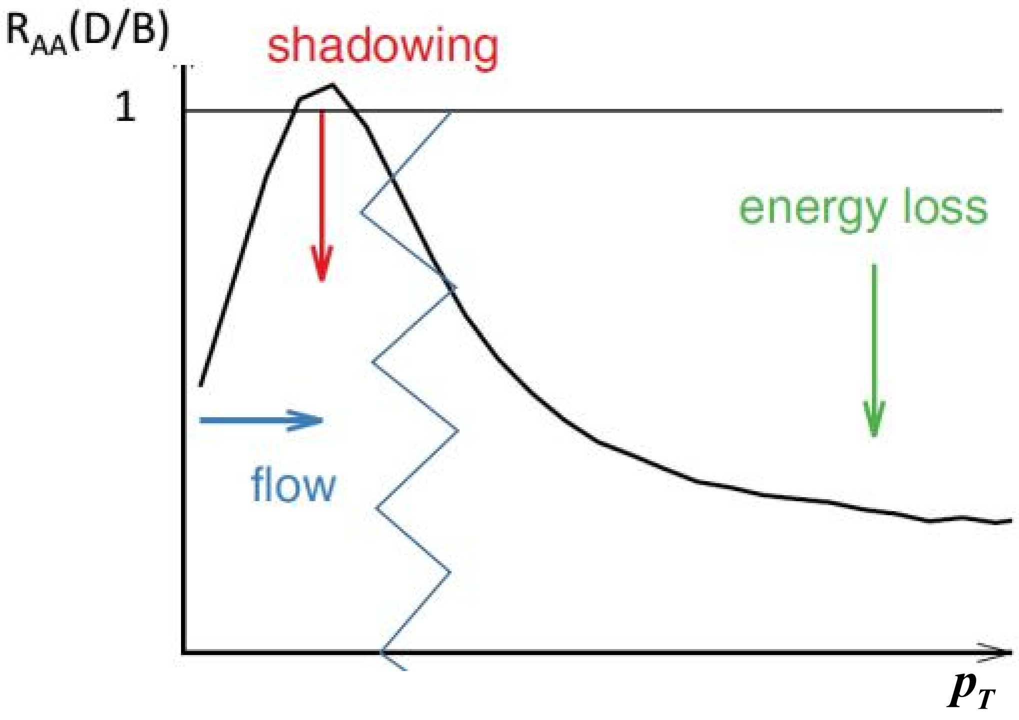


Models	System energy	Λ_c^+/D^0
Oh et al.	Au-Au (central) 200 GeV	~0.35 (p_T = 6 GeV/c)
Ghosh et al.	RHIC and LHC	0.15-0.2 (p_T = 9 GeV/c)
Das et al.	Pb-Pb (0-20%) 5.5 TeV	~0.2 (p_T = 9 GeV/c)
Plumari et al.	Pb-Pb (0-20%) 2.76 TeV	0.1-0.2 (p_T = 8 GeV/c)

- Significant enhancement of Λ_c^+ / D^0 ratio compared to PYTHIA/vaccum-fragmentation baseline.
- Λ_c^+ / D^0 ratio expected from model: coalescence + thermalized charm quarks
- Similar value than that measured in Pb-Pb @5.02 TeV, hint of enhancement w.r.t pp and p-Pb
- Comparison with model: model tend to underestimate the data

Basic Consequence of HQ interaction with QGP for the R_{AA}

The pattern seen in the data



The acknowledged effects

Flow bump: due to

- (radial) flow of the medium and coupling at small pt
- recombination with light quarks

shadowing: due to initial state nuclear effects (CNM)

Quenching & energy loss: due to

- elastic and inelastic scattering

Thank you !