Heavy quark quenching from RHIC to LHC: MC@sHQ generator compared to experiments

Strangeness in Quark Matter 2013; Birmingham UK

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with

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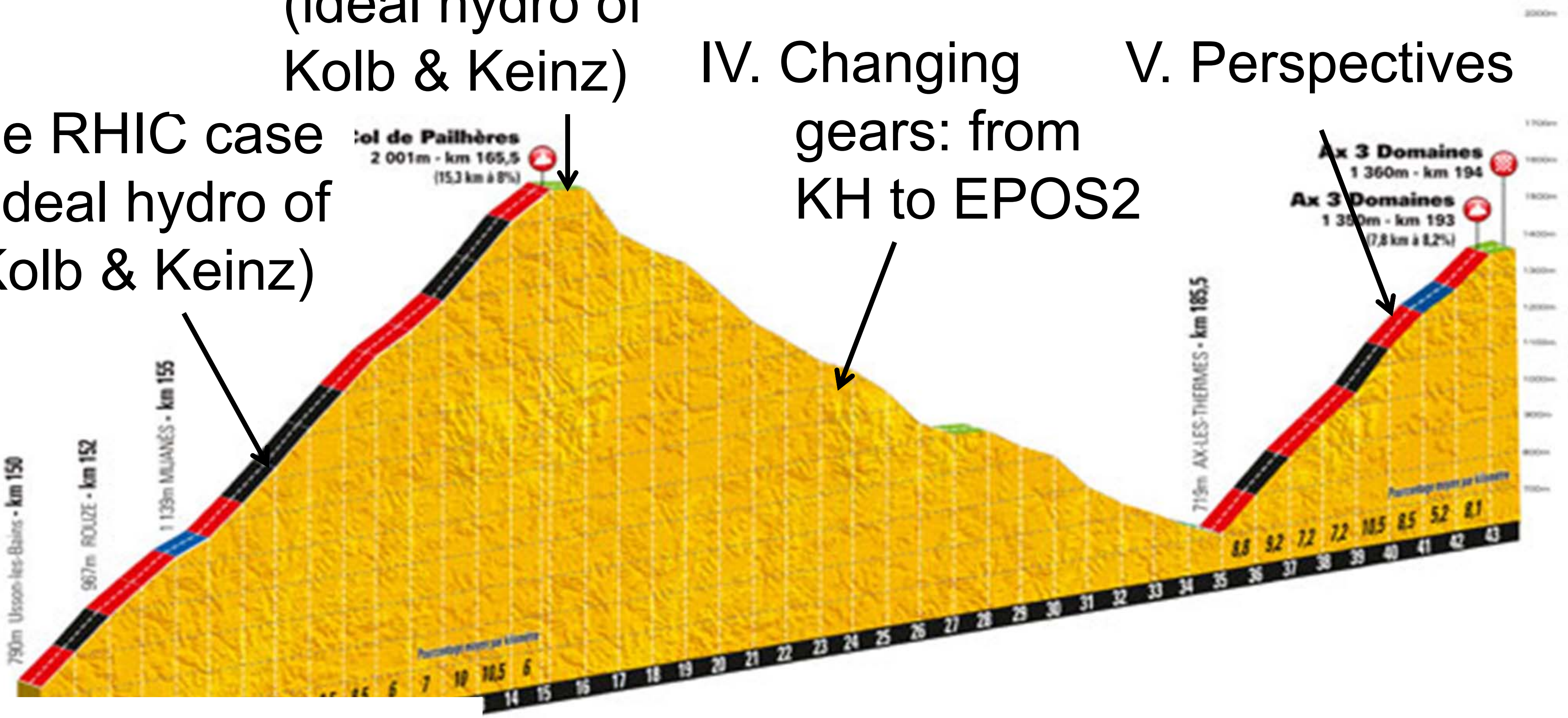
Road Map

III. The LHC case
(ideal hydro of
Kolb & Keinz)

II. The RHIC case
(ideal hydro of
Kolb & Keinz)

IV. Changing
gears: from
KH to EPOS2

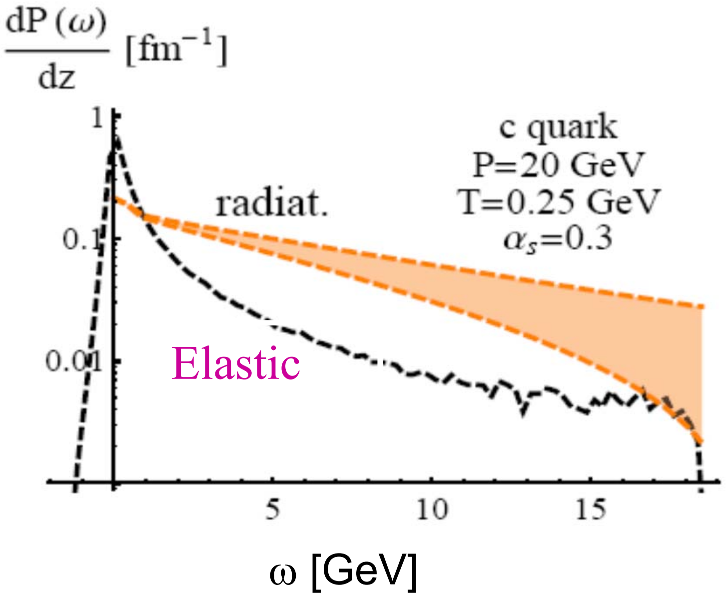
V. Perspectives



I. Start: Our models
for HF quenching

Our basic ingredients for HQ energy loss

Probability P of energy loss *w* per unit length (T,M,…):

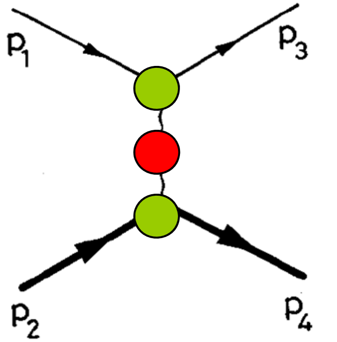


Generalized Gunion-Bertsch for finite mass

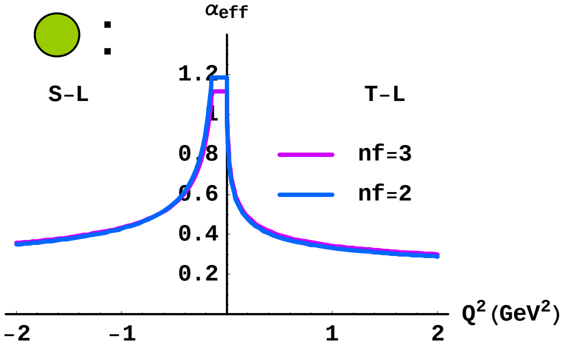
Talk by Th Gousset;

arxiv 1307.5270

Elastic



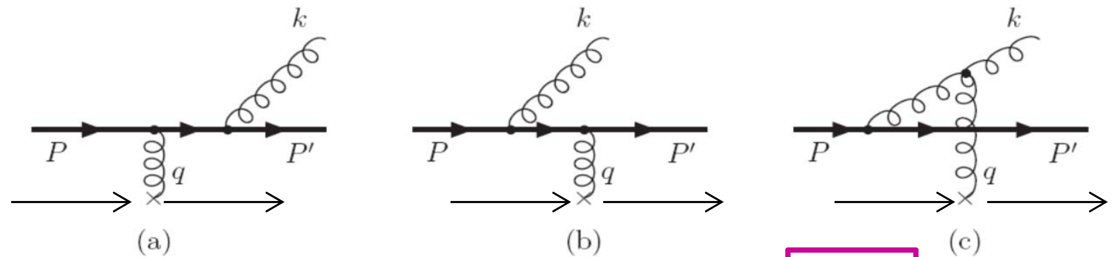
+ u and s channels



: OGE effective propagator

$m_{Dself}^2(T) = (1+n_f/6)\, 4\pi\alpha_{eff}(m_{Dself}^2)\, T^2$

Incoherent Induced Radiative



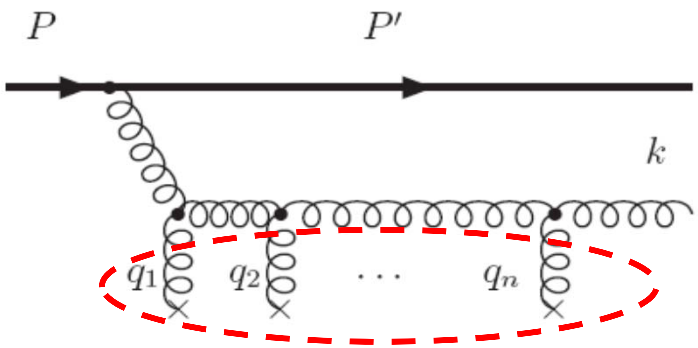
$$\omega \frac{d^3\sigma_{\rm rad}^{x\ll 1}}{d\omega\, d^2k_\perp\, dq_\perp^2} = \frac{N_c\alpha_s}{\pi^2}(1-x)\times\frac{J_{\rm QCD}^2}{\omega^2}\times\frac{d\sigma_{\rm el}^{Qq}}{dq_\perp^2}$$

$$\frac{J_{\rm QCD}^2}{\omega^2} = \left(\frac{\vec{k}_\perp}{k_\perp^2+x^2M^2+(1-x)m_g^2} - \frac{\vec{k}_\perp-\vec{q}_\perp}{\left(\vec{k}_\perp-\vec{q}_\perp\right)^2+x^2M^2+(1-x)m_g^2}\right)^2$$

Our basic ingredients for HQ energy loss

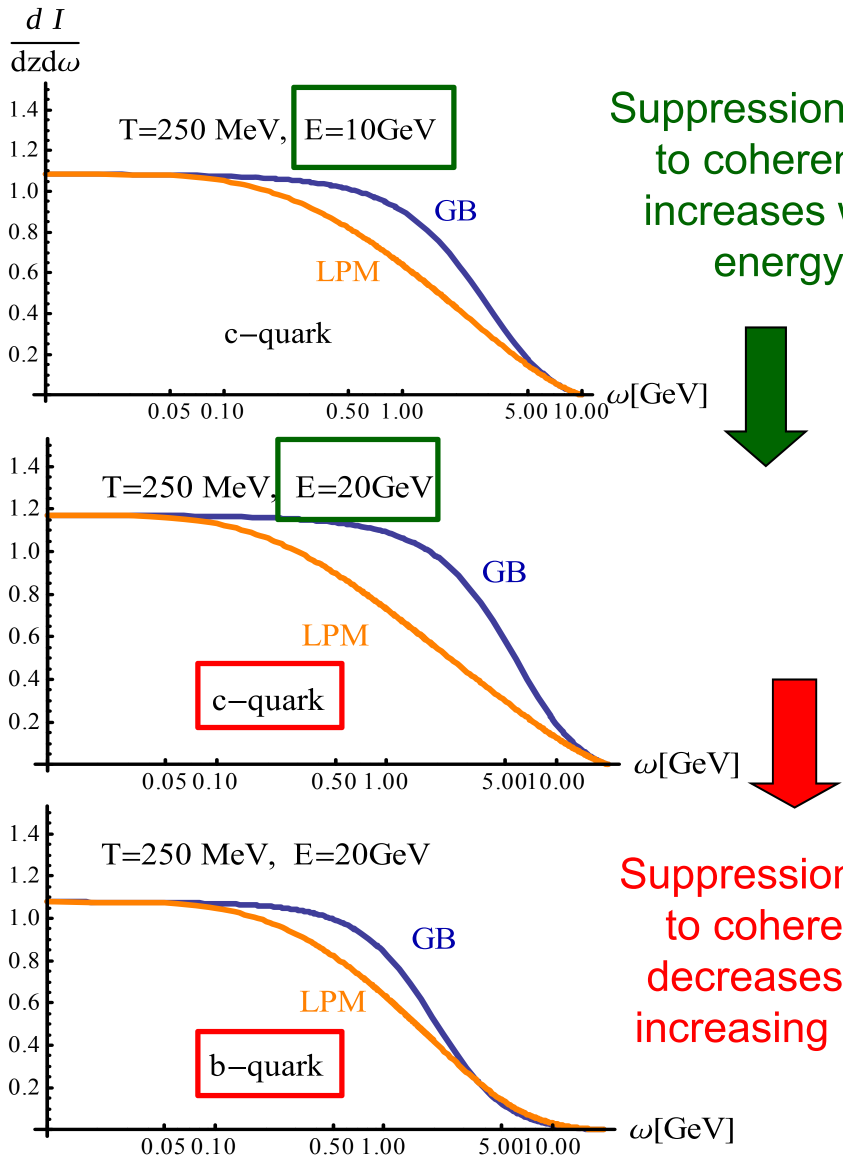
Coherent Induced Radiative

Formation time picture: for $l_{f,mult}>\lambda$, gluon is radiated coherently on a distance $l_{f,mult}$



Model: all N_{coh} scatterers act as a single effective one with probability $p_{Ncoh}(Q_\perp)$ obtained by convoluting individual probability of kicks

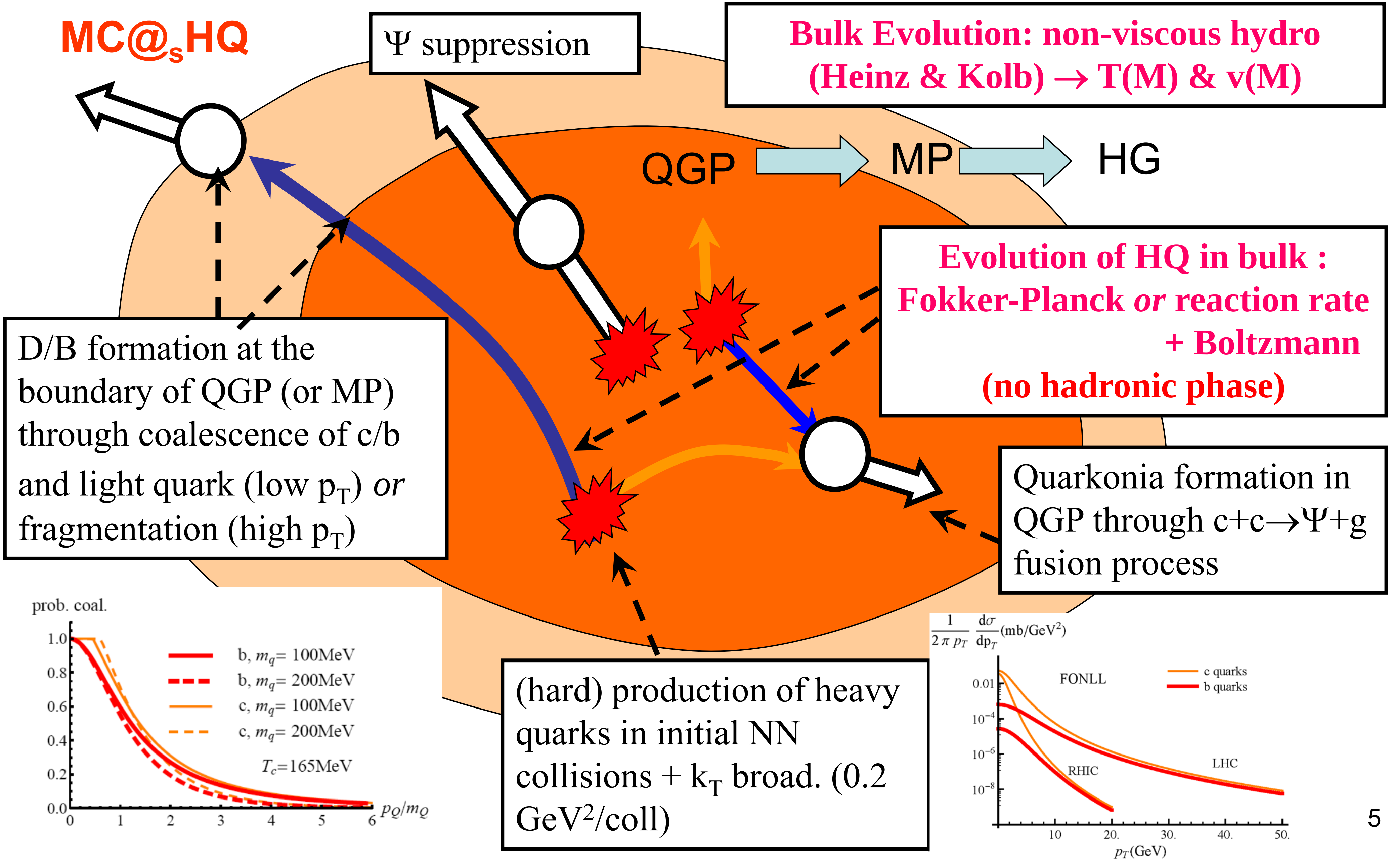
$$\frac{d^2 I_{\rm eff}}{dz\, d\omega} \sim \frac{\alpha_s}{N_{\rm coh}\tilde{\lambda}} \ln\left(1 + \frac{N_{\rm coh}\mu^2}{3\left(m_g^2 + x^2 M^2 + \sqrt{\omega \hat{q}}\right)}\right)$$



Suppression due to coherence increases with energy

Suppression due to coherence decreases with increasing mass

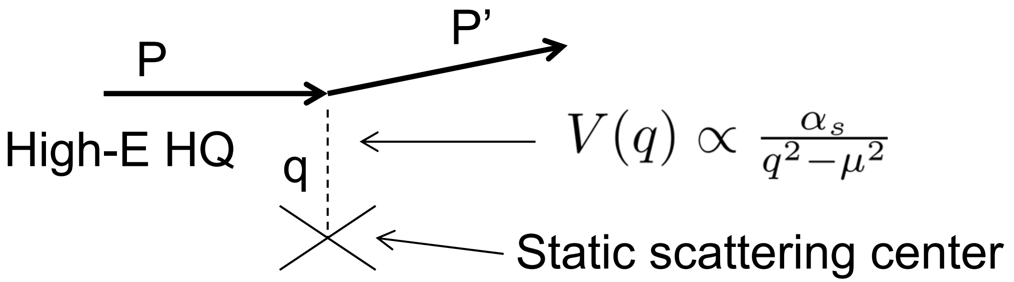
Schematic view of « Monte Carlo @ Heavy Quark » generator



Insufficient control on energy loss theory

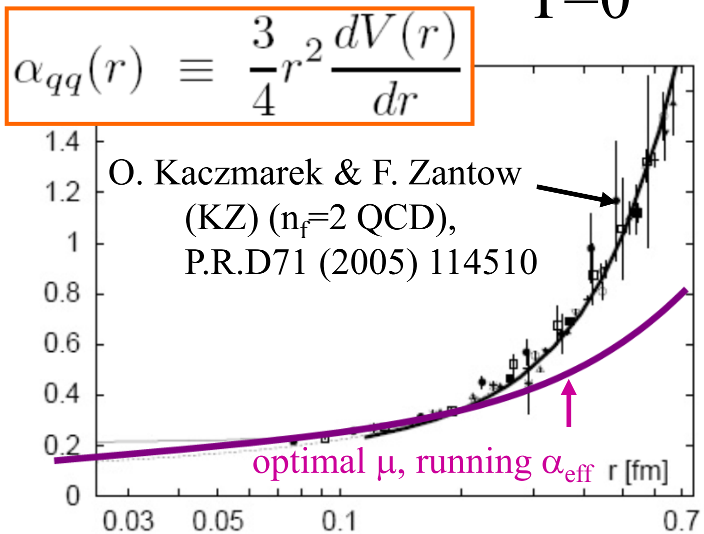
Non perturbative « corrections » even at large HQ energy

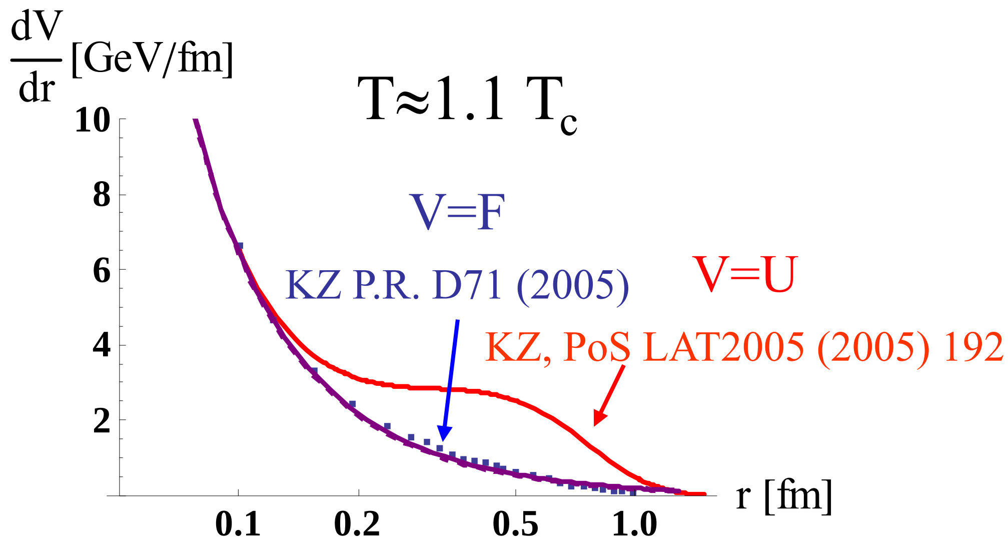
In most models:



Lattice QCD :

T=0



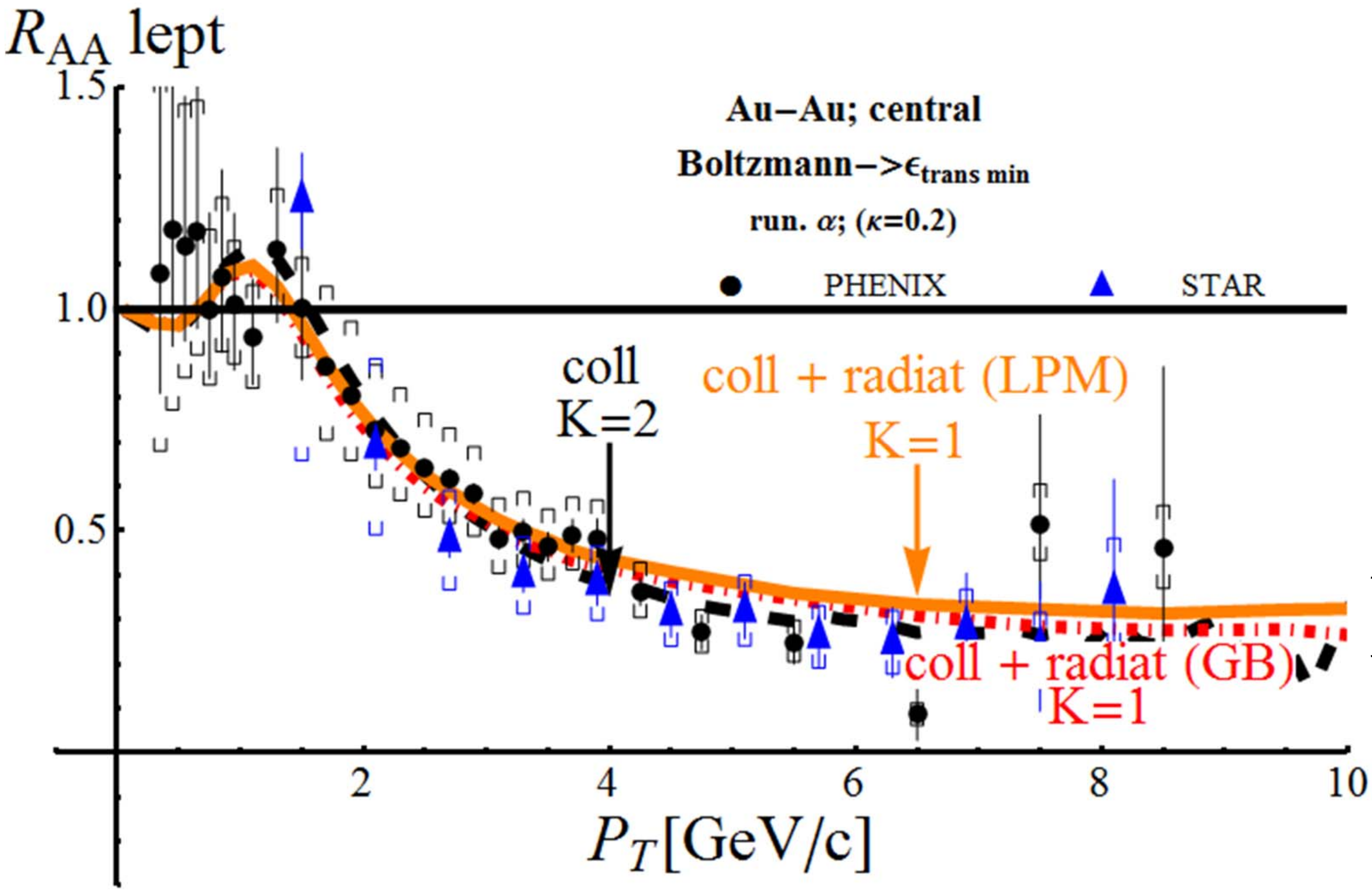


Significant r-tail in the transverse force acting on the high E HQ

=> Allow for some global rescaling of the rates: "K" fixed on experiment

{Radiative + Elastic} vs Elastic for RAA NPSE @ RHIC

El. and rad. Eloss exhibit very different energy and mass dependences. However…



0-10%

very small influence of LPM

σ_{el} alone rescaling: K=1.8-2.2

We tune K on RAA, while BAMPS does it on v2

σ_{el} & σ_{rad} cocktail: NO RESCALING

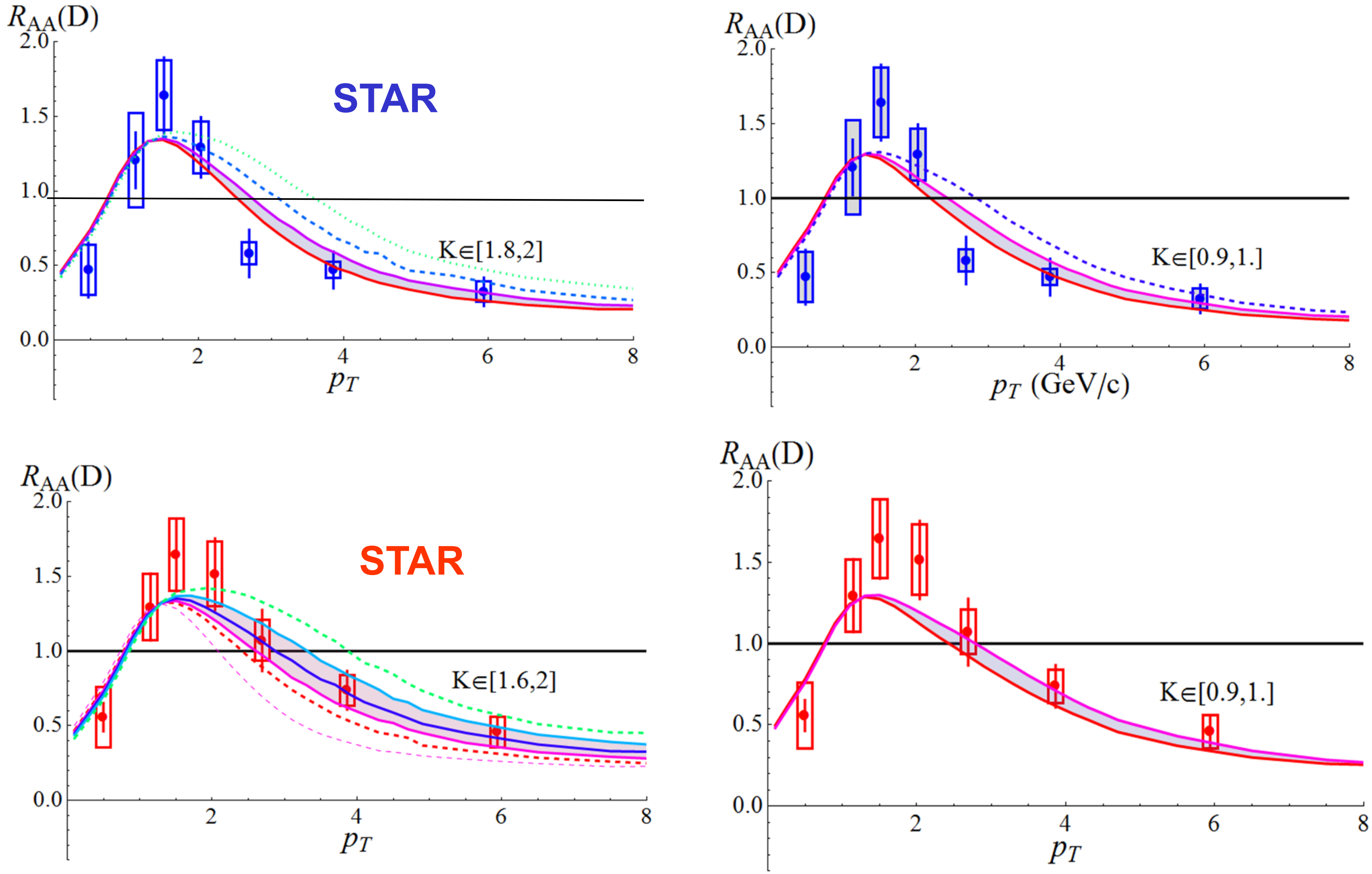
(since last QM: improvement in the phase space boundary for gluon emission; was too permissive -> K≈0.6 needed)

{Radiative + Elastic} vs Elastic D mesons @ RHIC

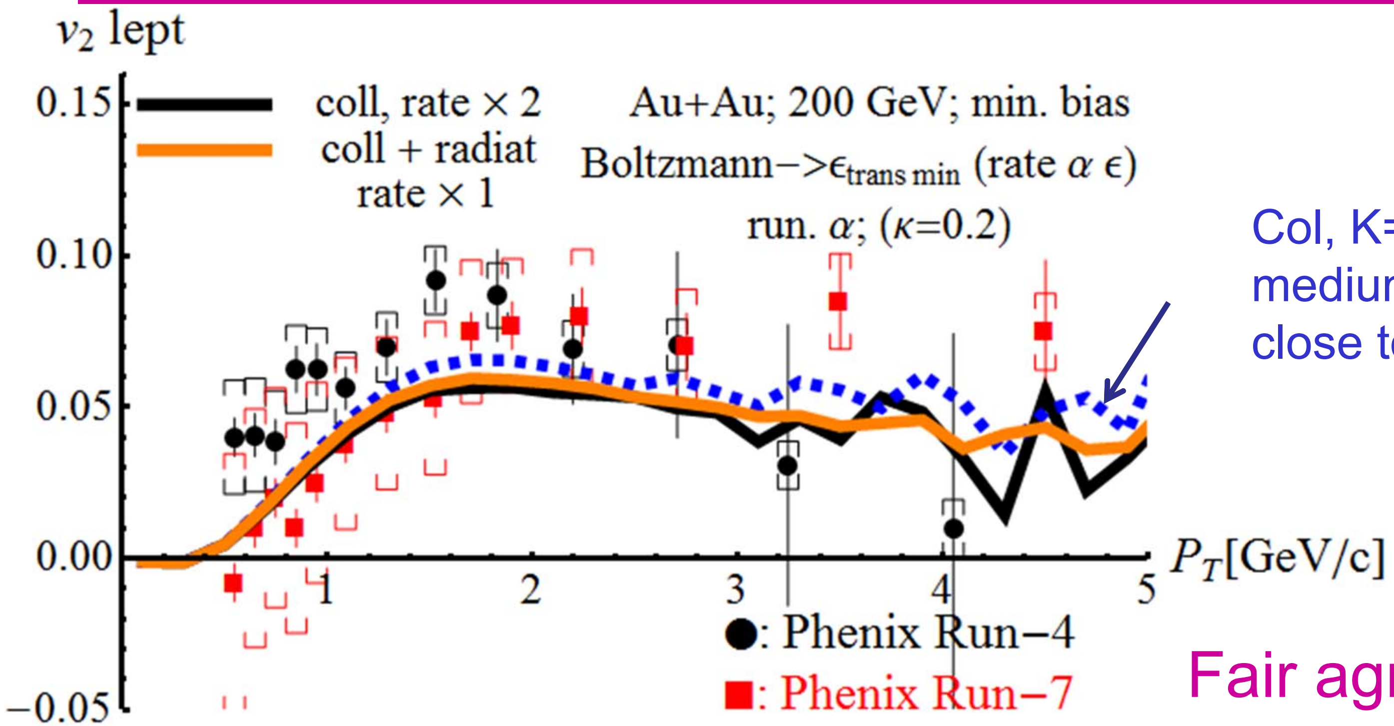
Elastic | **Elastic + radiative LPM**

0-10%

0-80%

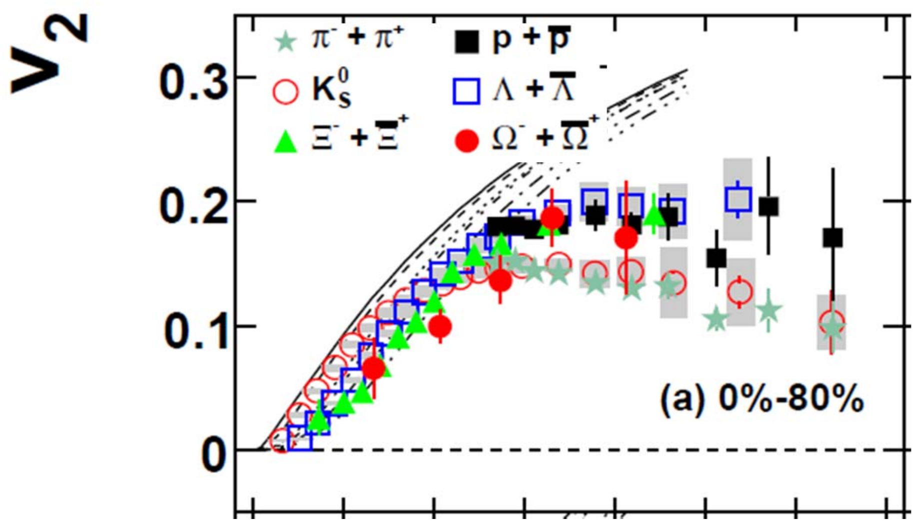


And the v2 ? (@ RHIC)



Col, K=3 (More coupling to the medium does not help, as HQ are close to thermalized at small p_T)

Fair agreement with the same K values, the ideal hydro probably helps a bit



Ideal hydro vs STAR data (2008), calculation by P. Huaovinen

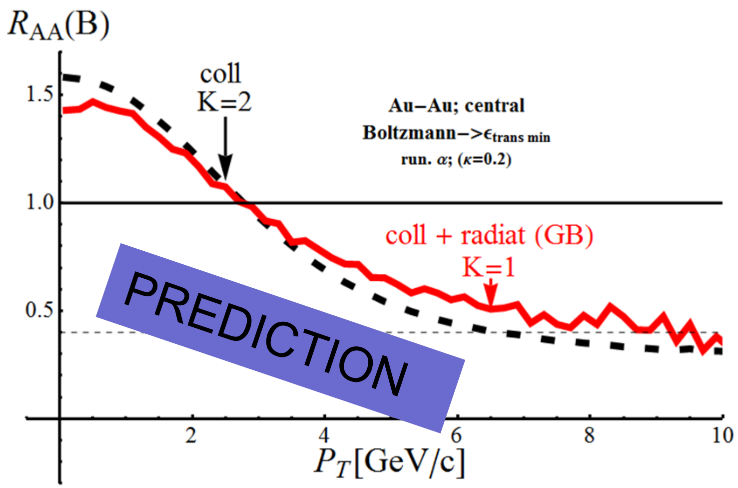
Conclusions from RHIC

➢ Present data at RHIC cannot decipher between the 3 local microscopic E-loss models (el., el. + rad GB, et. + rad. LPM) ⇒ Not sensitive to the large-ω tail of the Energy-loss probability.

➢ One "explains" all open heavy flavor physics with ΔE α L (that is, with probabilities per unit length).

➢ Good consistency between NPSE and D mesons (10% difference in K values)…

➢… within a model with mass hierarchy



Elastic

K	NPSE RHIC	D STAR central	D STAR min bias
1.4	Wrong	Wrong	Marginal
1.6	Marginal	Marginal	Acceptable
1.8	Acceptable	Good	Good
2.0	Good	Good	Acceptable
2.2	Acceptable	Marginal	Marginal

Elastic + radiative LPM: no need for rescaling

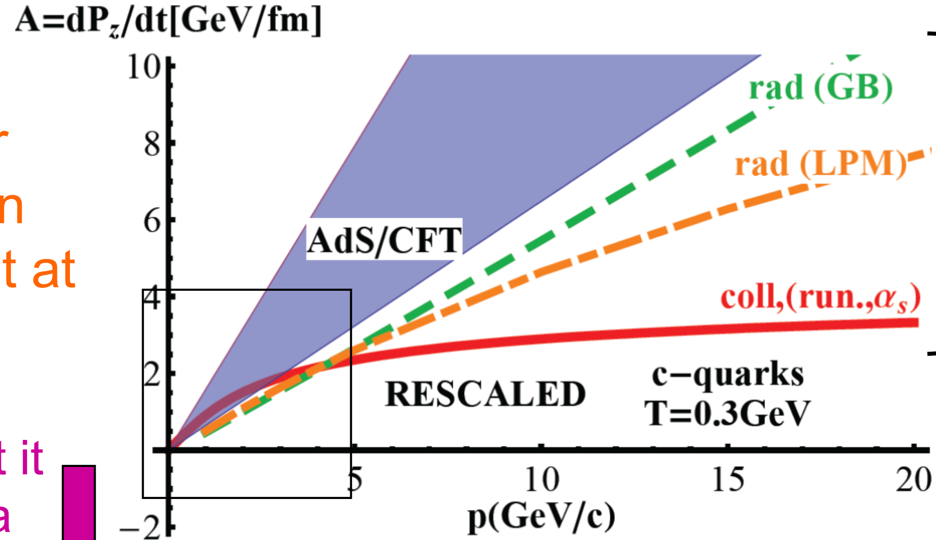
K	NPSE RHIC	D STAR central	D STAR min bias
0.7		Wrong	
0.8	Wrong	Marginal	Acceptable
0.9	Acceptable	Good	Good
1	Good	Good	Acceptable
1.1	Acceptable	Marginal	Marginal

Good **Acceptable** **Marginal** **Wrong**

QGP properties from HQ probe at RHIC

Gathering all *rescaled* models (*coll. and radiative*) compatible with RHIC R_{AA}:

Similar diffusion coefficient at low p



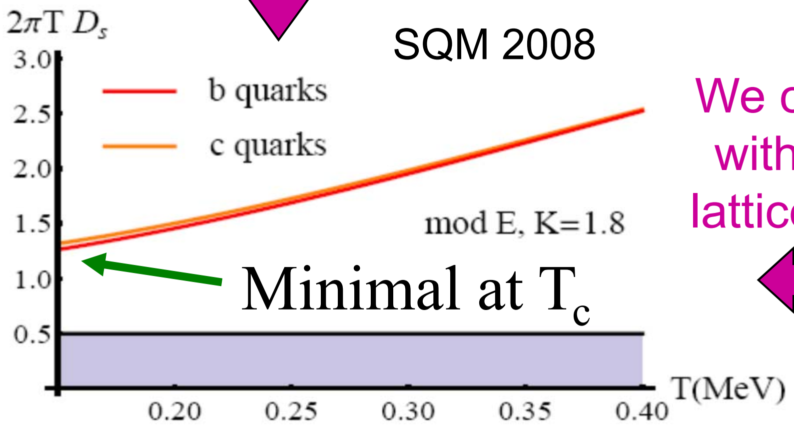
the drag coefficient reflects the average momentum loss (per unit time) => large weight on $x \sim 1$

Present RHIC experiments cannot resolve between those various trends

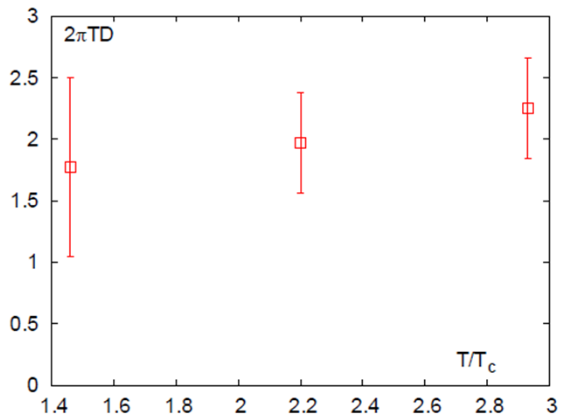
We extract it from data

Hope that LHC can do !!!

SQM 2008



We compare with recent lattice results



Kaczmarek
Bad Honnef
2011

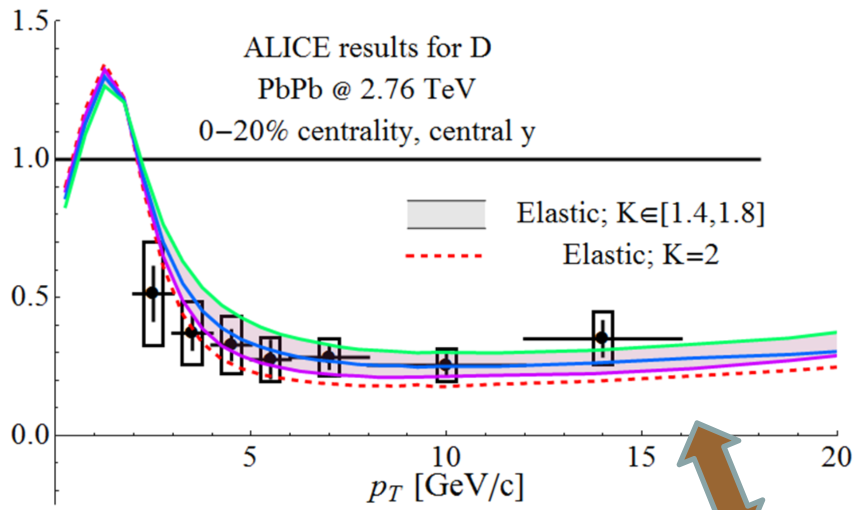
Lesson it is possible to reveal some fundamental property of QGP using HQ probes, i.e. to CONTROL the models

D mesons at LHC (vs ALICE 0%-20%)

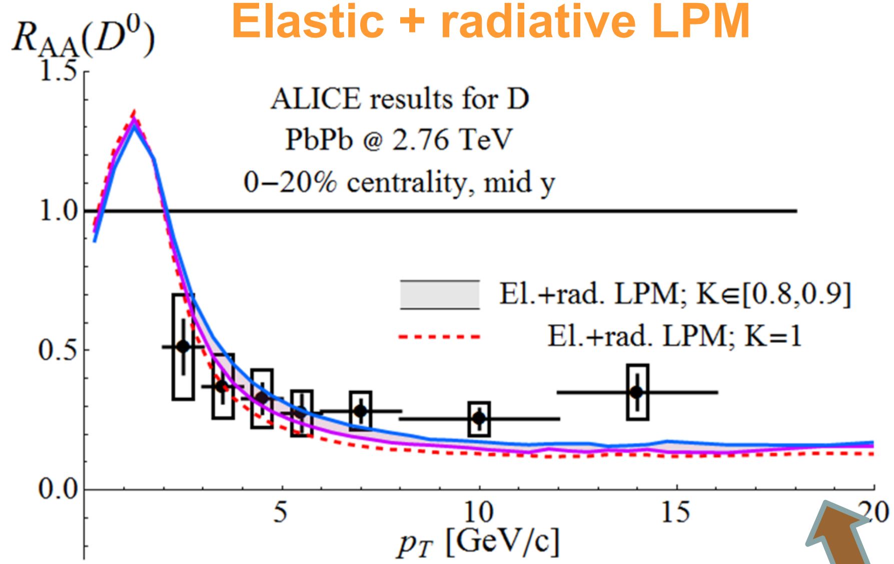
Same microscopic ingredients as for RHIC; NO SHADOWING (yet)

Kolb-Heinz Hydro adjusted to $dN_{ch}/dy =$ 1600 (s0=195);

Elastic



Elastic + radiative LPM



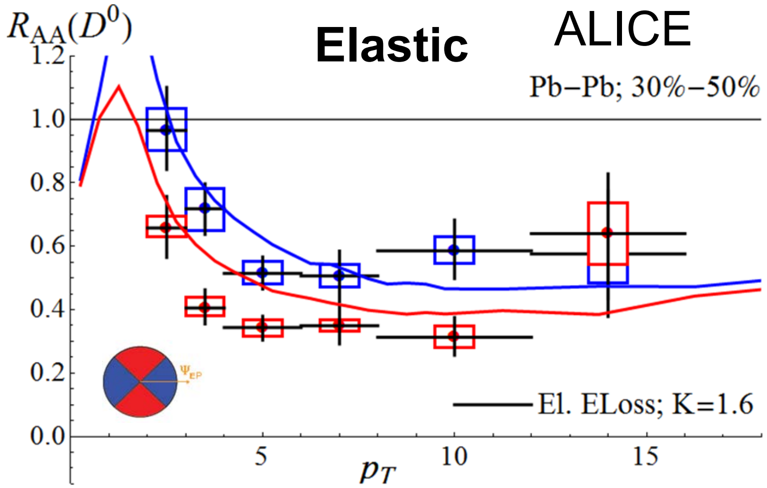
K	NPSE RHIC	D STAR central	D STAR min bias	D ALICE 0-20% (pT<15GeV/c)
1.4				
1.6				
1.8				
2.0				
2.2				

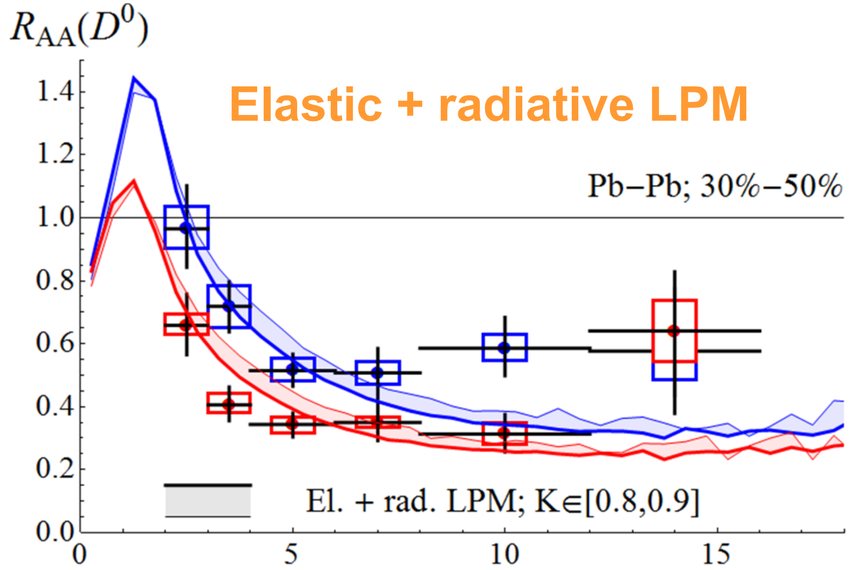
K	NPSE RHIC	D STAR central	D STAR min bias	D ALICE 0-20% (pT<15GeV/c)
0.7				
0.8				
0.9				
1				
1.1				

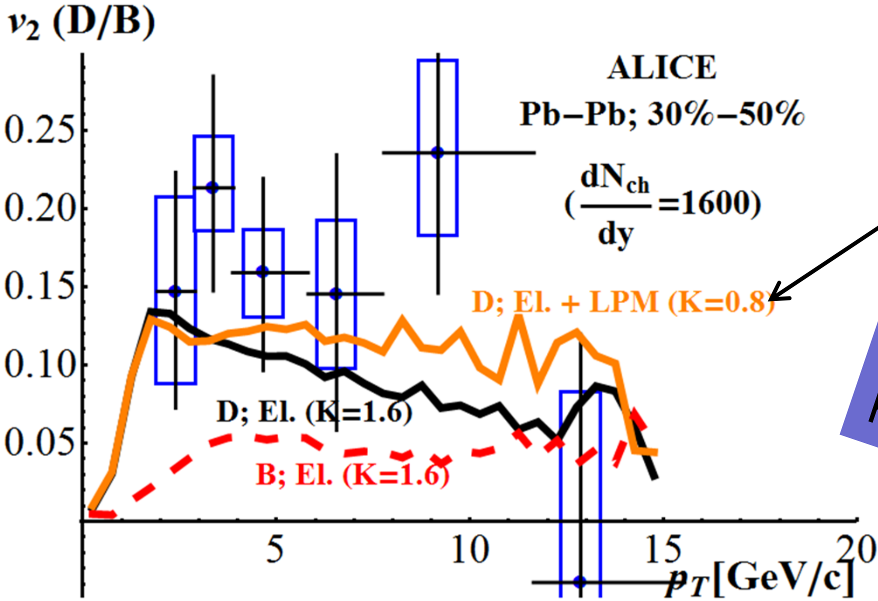
Correct agreement with ALICE data; 10-15% decrease of the rates needed for optimal agreement

D mesons at LHC (more differential observables)

"in plane" – "out of plane" analysis







Some systematic trends: el. + rad. LPM shows more coupling… sensitive to larger x in the radiation spectra

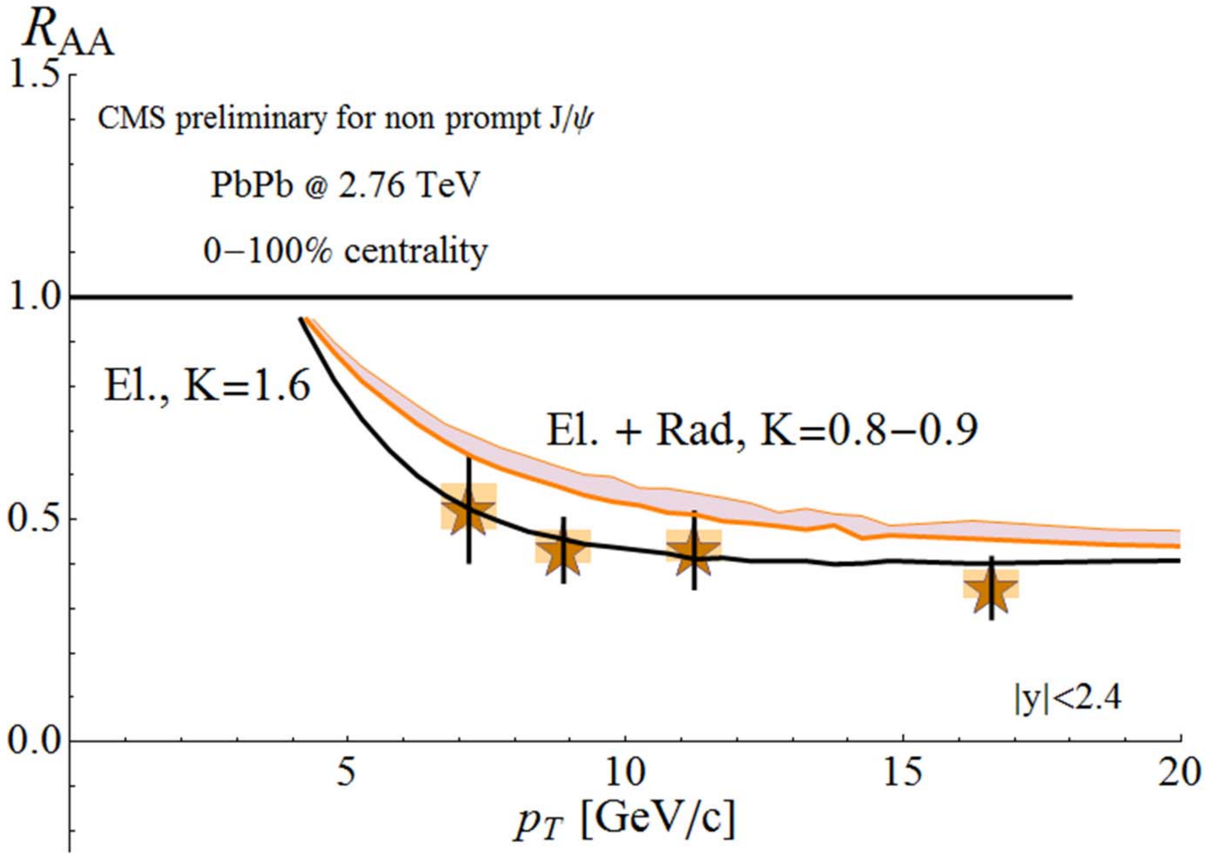
V_2(B): PREDICTION

B mesons at LHC

Same ingredients as for RHIC

Kolb-Heinz Hydro ajusted to dN_{ch}/dy = 1600;

No shadowing



Need for genuine implementation of the B->ψ feed-down in MC@sHQ

Conclusions from LHC

- **Data at intermediate p_T are well reproduced with minimalistic modifications of the model(s).**

- D suppression at Large p_T favors collisional energy loss… or suggests improvements are in order for our treatment of radiative energy loss (finite path length, finite gluon width,…)

- Discrepancy at small p_T might be explained by shadowing.

However, one should never
sleep on convenient results….

Conclusions from LHC

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➢ Discrepancy at small p_T might be explained by shadowing.

However, one should never sleep on convenient results…

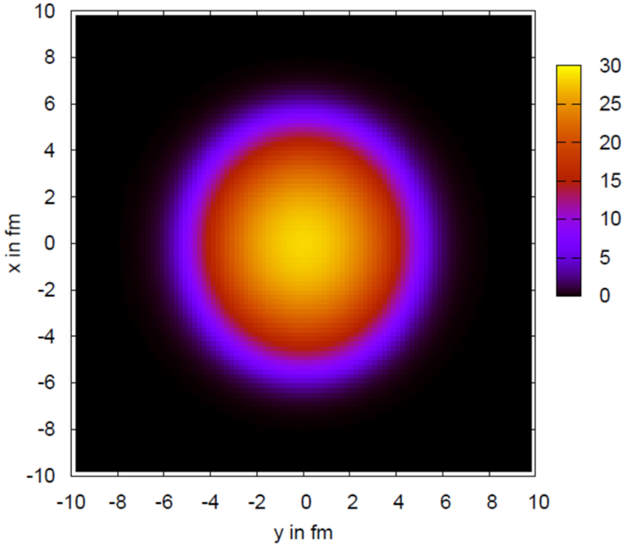
… awakening might be bitter!

EPOS as a background for MC@sHQ

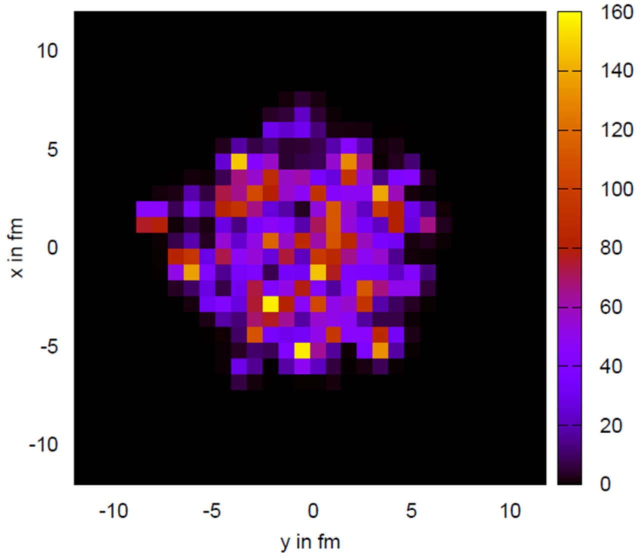
EPOS: state of the art framework that encompass pp, pA and AA collisions

See talk by K Werner

Initial energy density @ RHIC (central Au-Au)



Kolb Heinz



EPOS

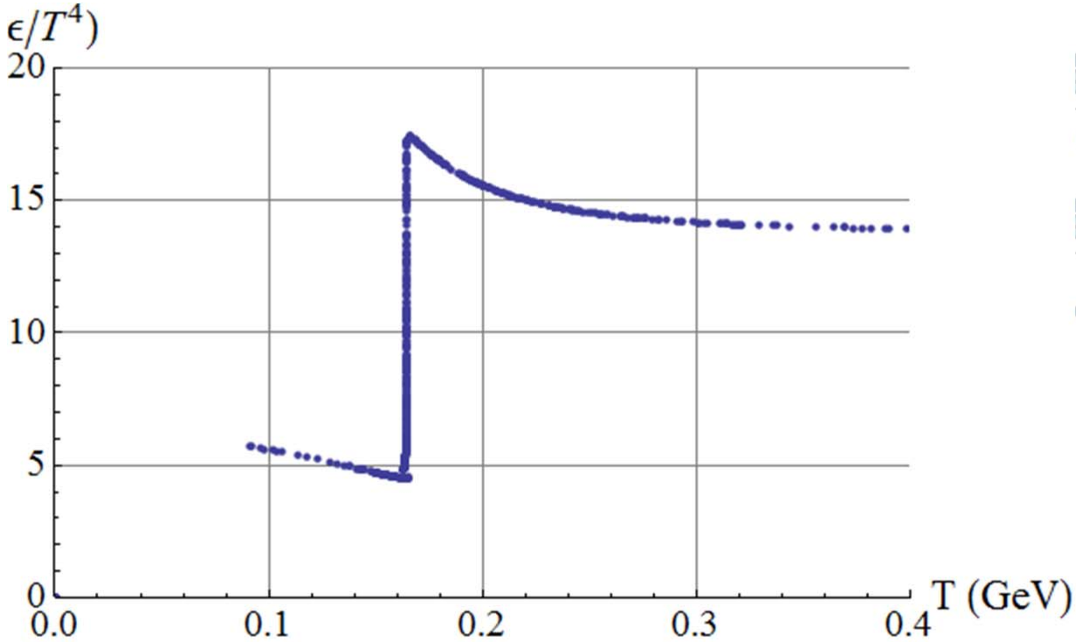
Beware: ≠ color scales

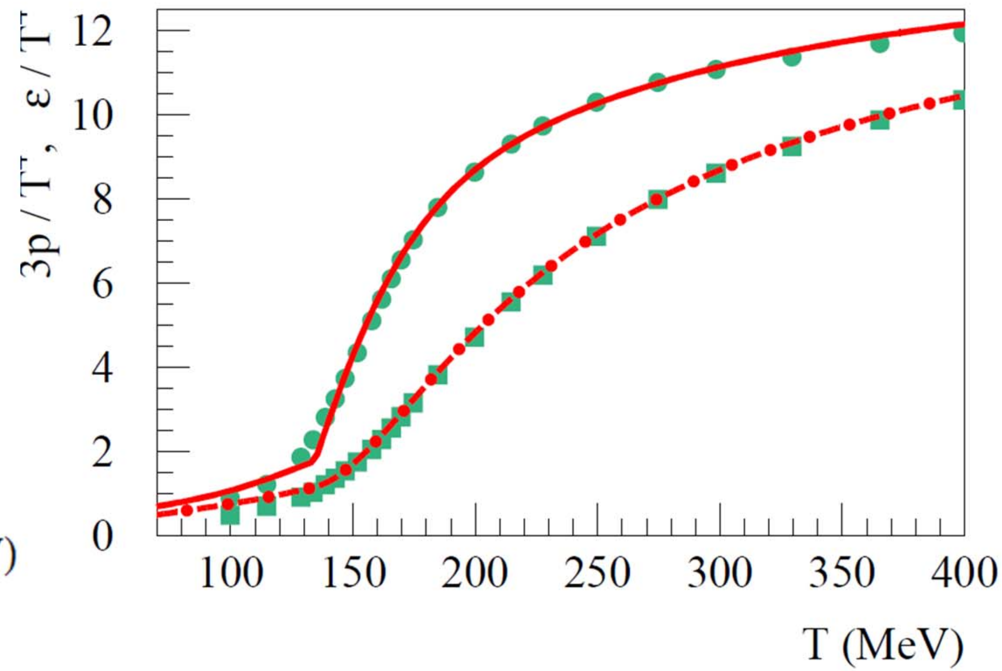
More realistic hydro and initial conditions => original HQ studies as:

1) fluctuations in HQ observables (some HQ might « leak » through the « holes » in the QGP)

2) correlations between HF and light hadrons

Large differences in the EOS !

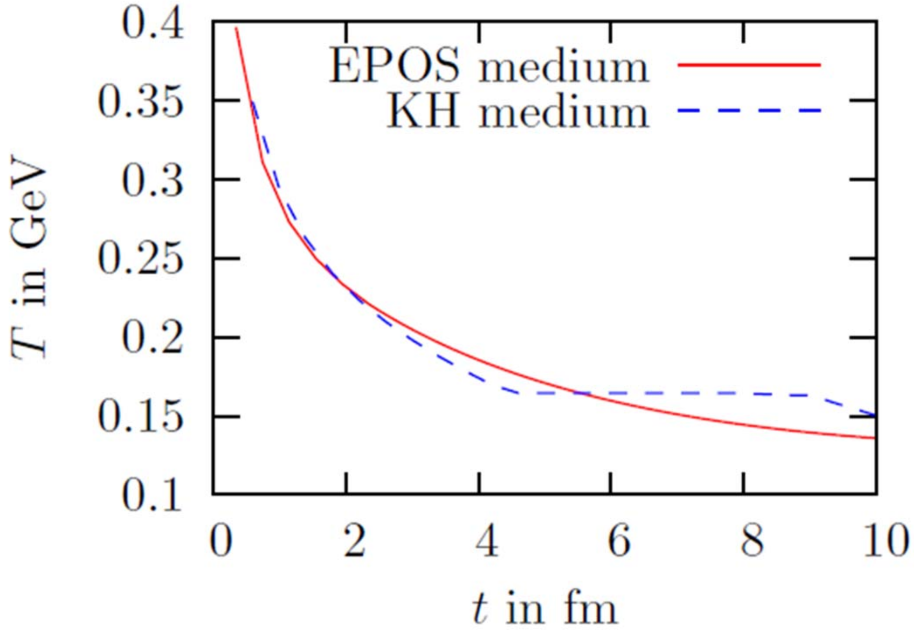


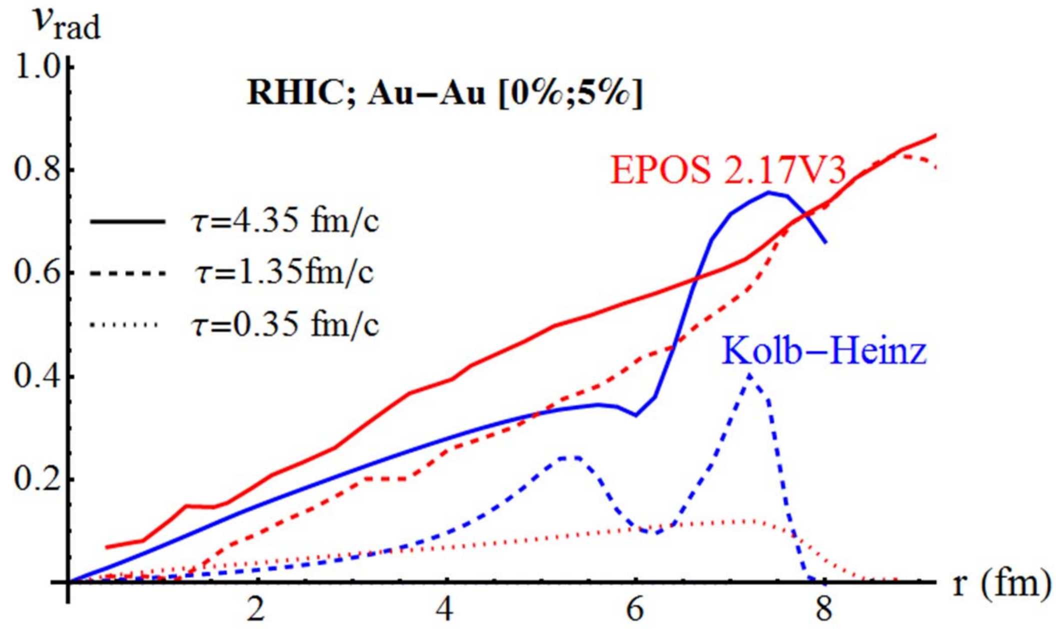


Kolb Heinz: bag model (1rst order transition btwn hadronic phase and massless partons)

EPOS2: fitted on the lattice data from the Wuppertal-Budapest collaboration

Medium comparison at RHIC



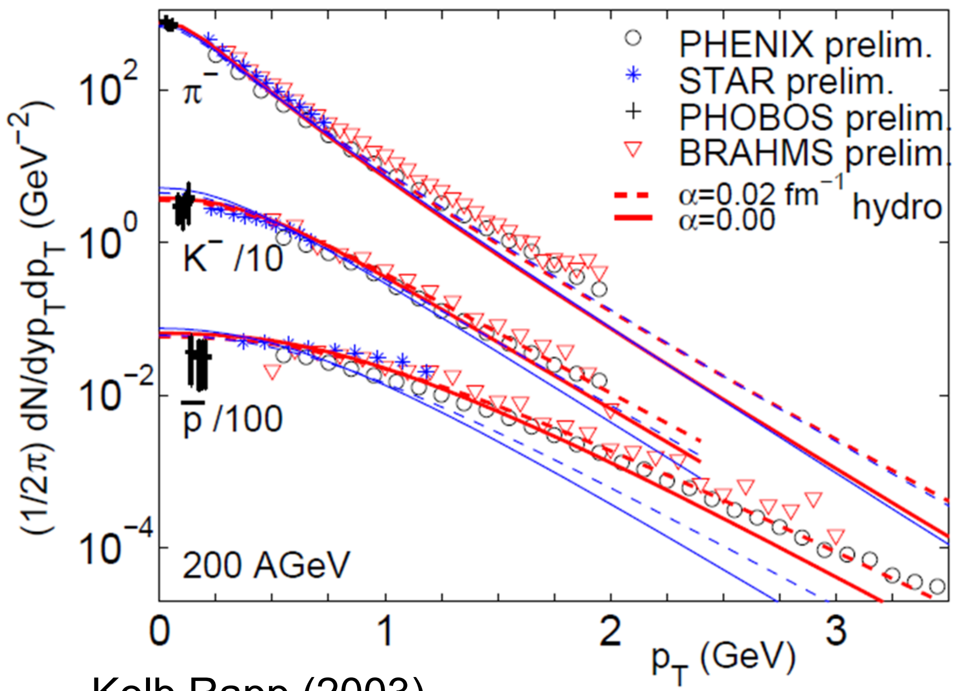


Gross features of T-evolution are identical in the « plasma » phase (T>200 MeV)

Radial velocities differ significantly, starting from the earliest times in the evolution

Identified particles spectra at RHIC

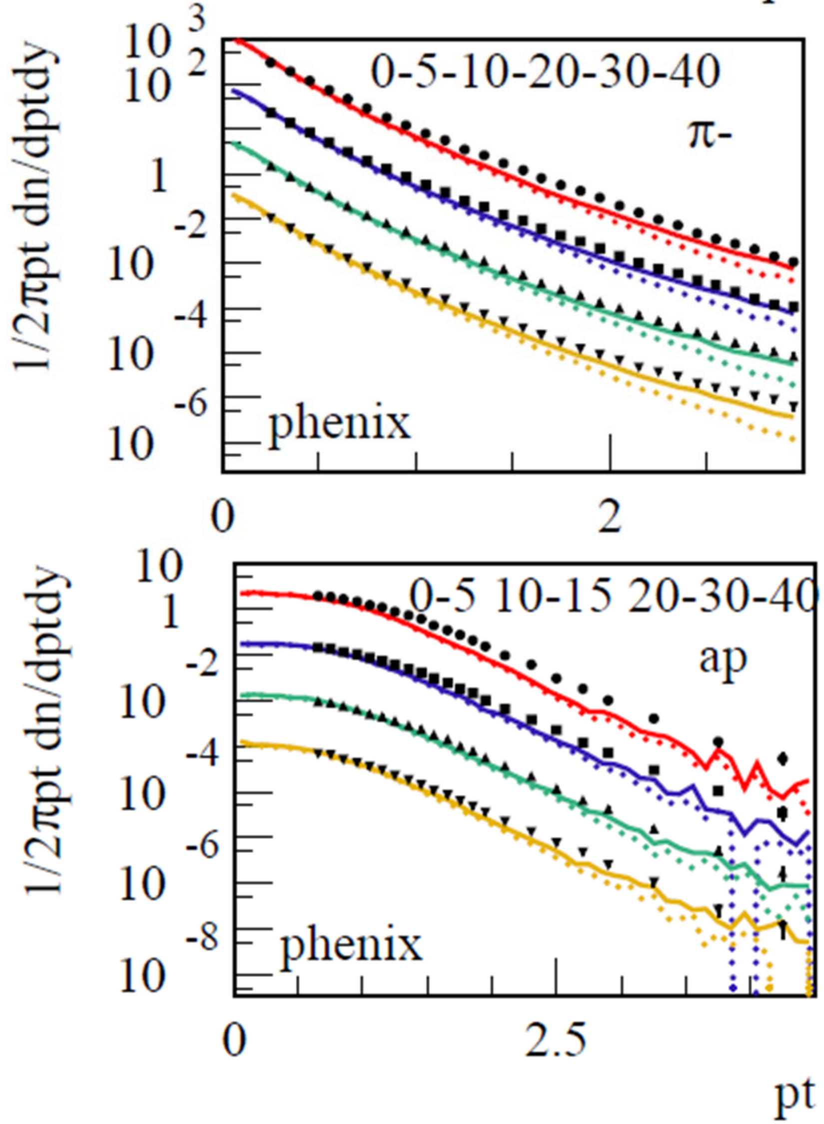
Kolb-Heinz



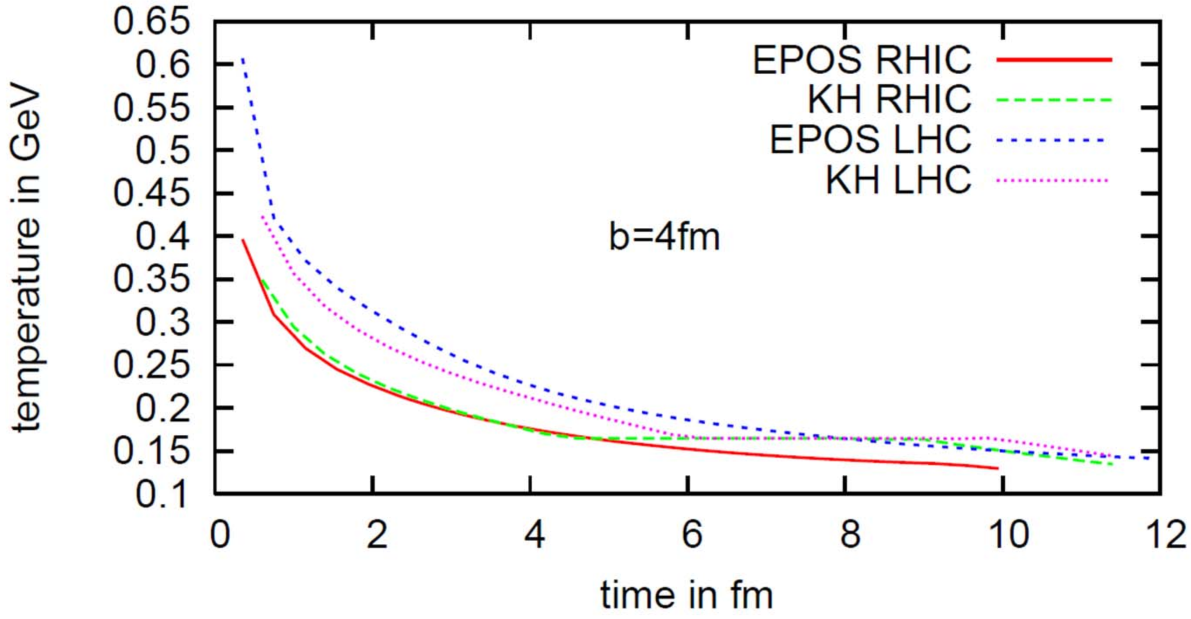
Kolb Rapp (2003)

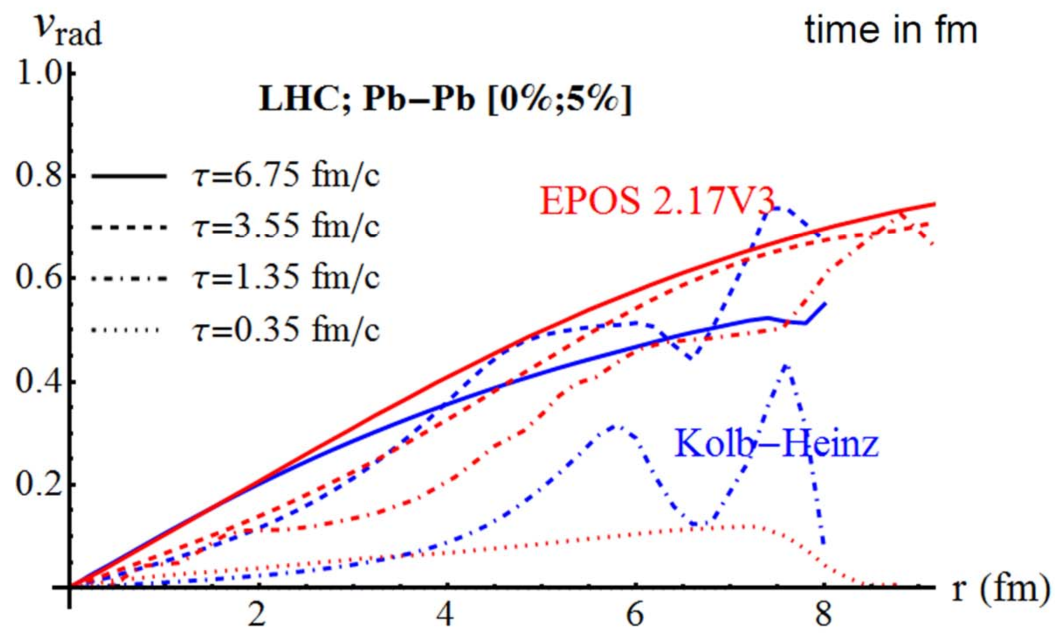
better agreement if initial flow (vr=tanh(0.02 r))

EPOS2.17V3



Medium comparison at LHC

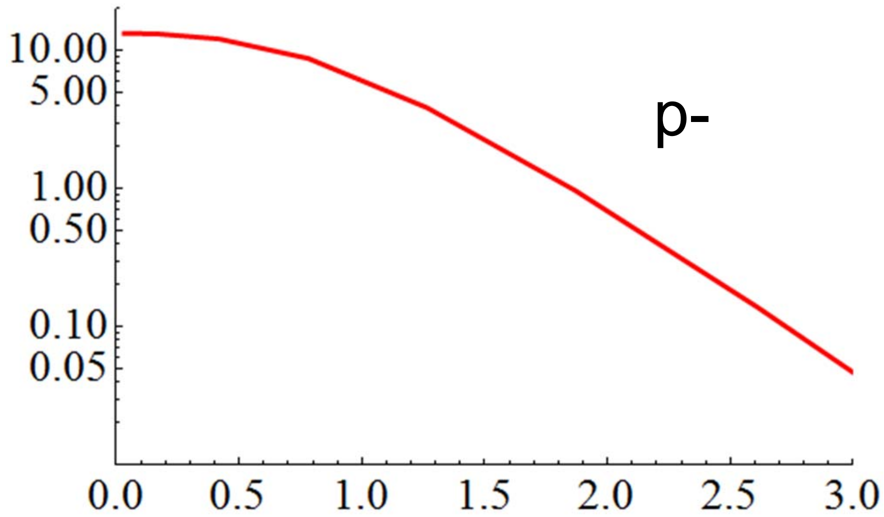




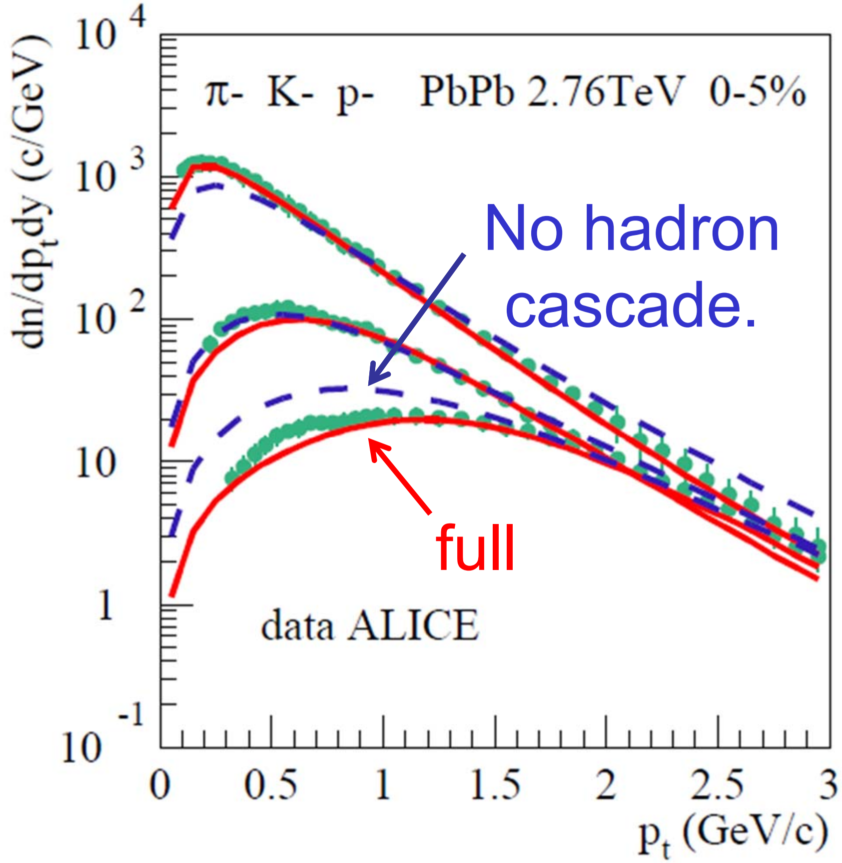
EPOS2 hotter and more explosive than Kolb-Heinz

Identified particles spectra at LHC

KH, b=3fm



EPOS2.17V3



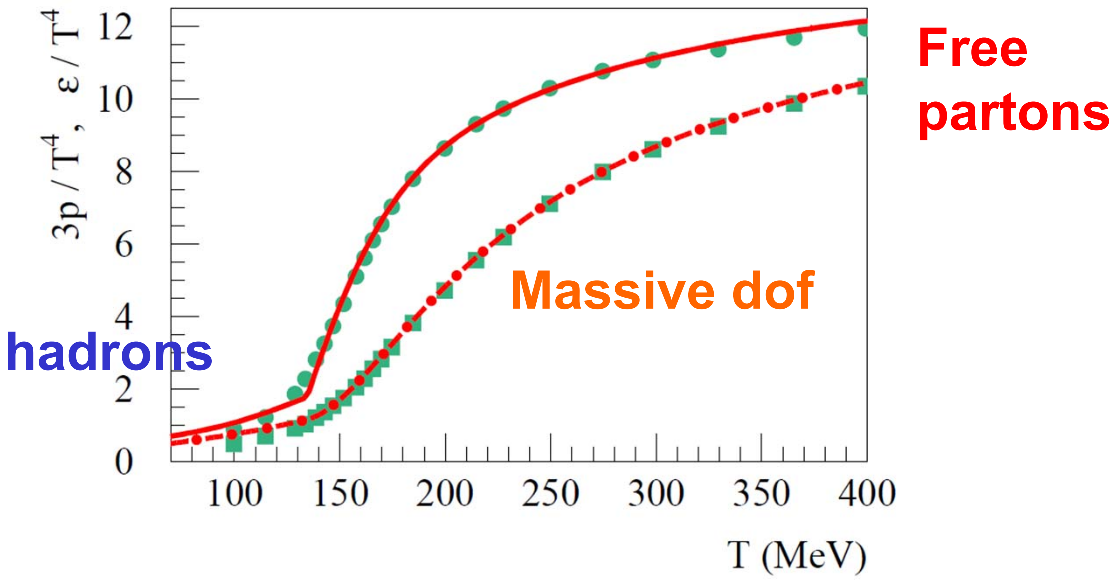
Phys. Rev. C 85, 064907 (2012)

Lack of radial flow in KH has large consequences on observables

Coupling EPOS and MC@sHQ

Two main (physical) issues:

1) Generating initial HQ consistently with the multipartonic approach in EPOS (ongoing project)
2) Dealing properly with the underlying degrees of freedom in a crossover evolution btwn hadronic phase and QGP.



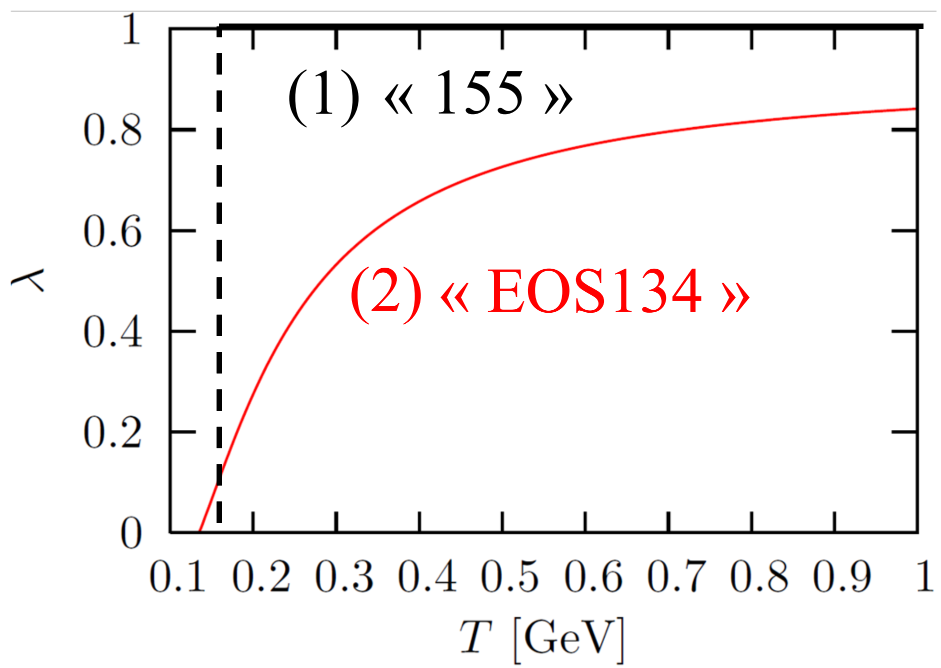
See talk by H Berrehrah

Coupling EPOS and MC@sHQ

For the time, 2 prescriptions:

1) Interactions as in KH medium (evaluated with masless partons) down to Tc=155MeV (in the middle of the range for the transition temperatures given from lattice)… most conservative
2) Reduction of effective dof (1->λ) using the EPOS parametrization of the EOS in terms of partonic and hadronic dofs… down to Tc=134MeV (value at which λ=0)

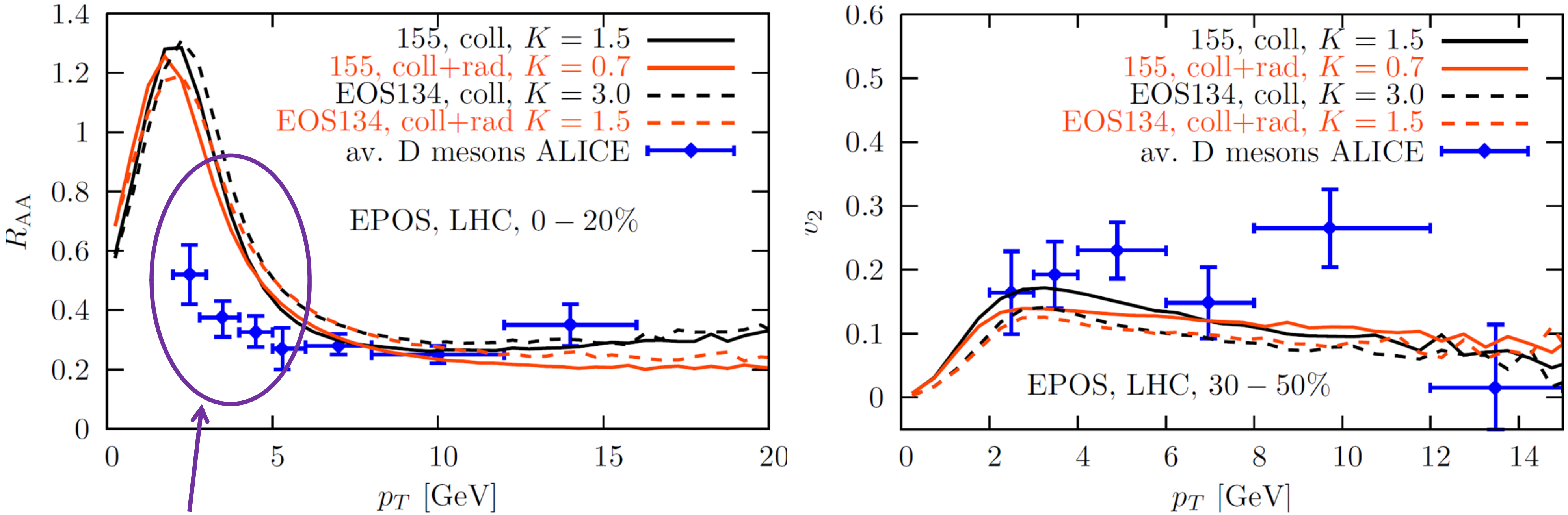
See as well: arxiv 1305.6544



Some EPOS+MC@sHQ results at LHC

K values fixed at p_T=10 GeV/c, x2 if reduction of dof according to EOS134 !

Still close to unity if rad + col considered



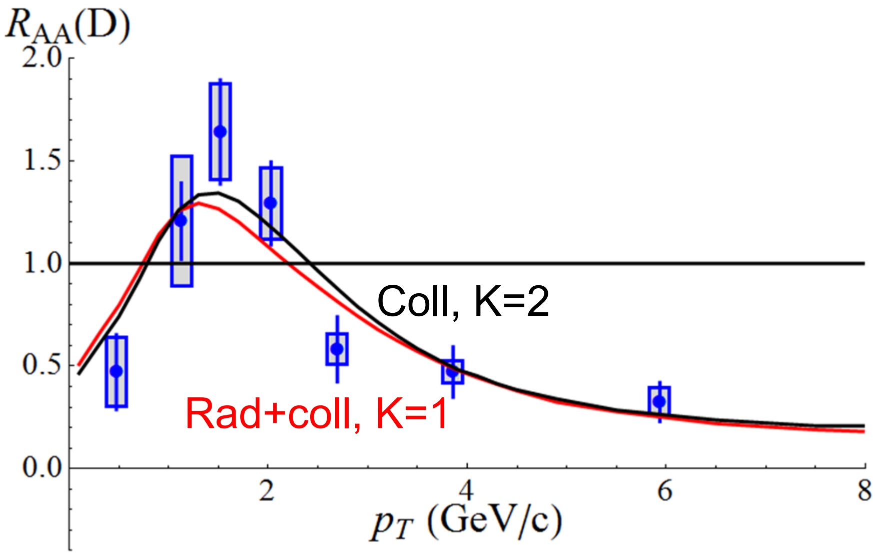
Large push from the radial flow; discrepancy unlikely to be explained by shadowing alone.

Concerns: Need to revisit the model for small p ? (Bad) consequences for v2 ?

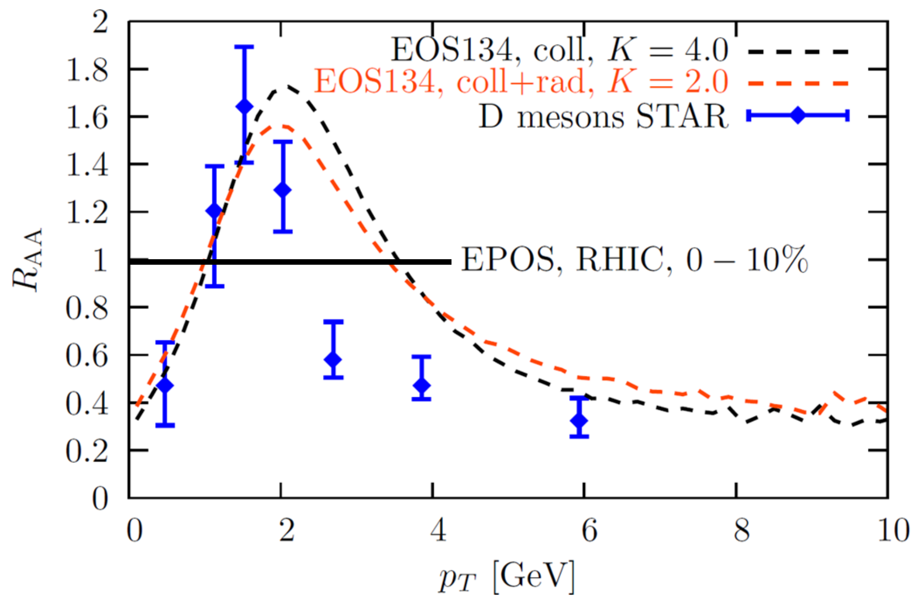
Main message: the models of HF energy loss and the background medium (including its microscopic content) are bound together

Some EPOS+MC@sHQ results at RHIC

KH background



EPOS background + reduction of dof



Larger radial flow in EPOS

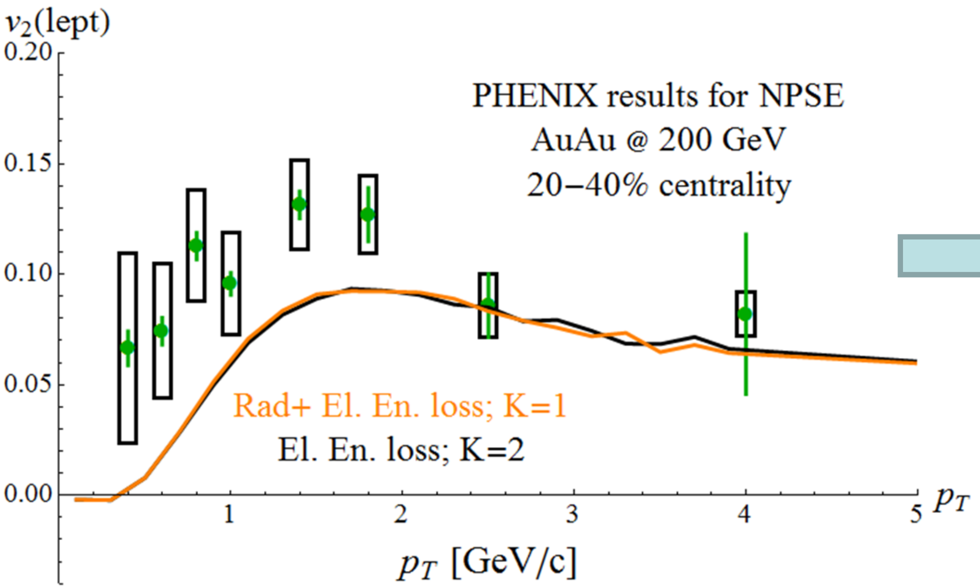
Both « cocktails » (HF energy loss + background + K factor) provide a fair agreement with the data

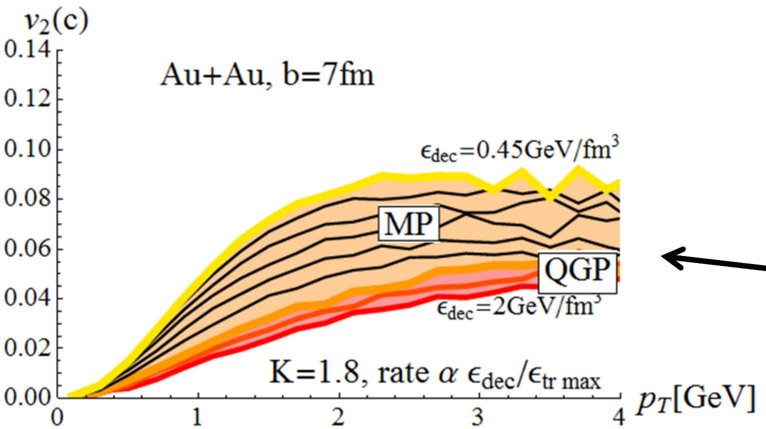
Data at larger pT would help a lot !

Main message: the models of HF energy loss and the background medium (including its microscopic content) are bound together

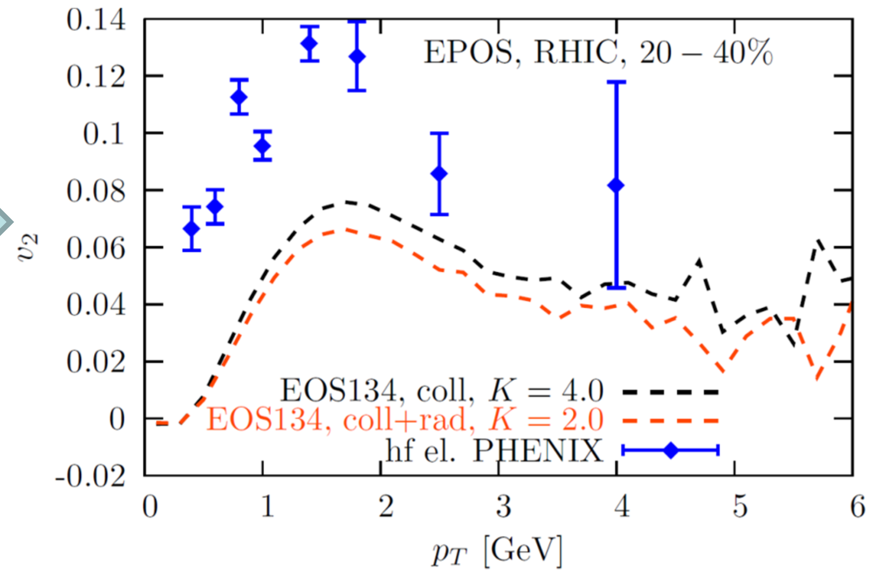
Some EPOS+MC@sHQ results at RHIC

KH background





EPOS background + reduction of dof



Elliptic flow is reduced by ≈1%

Systematic underprediction of v2, … which develops continuously in time. Probably need for hadronic afterburner in order to reach experimental values.

Conclusions & Perspectives

- Description of HQ quenching and thermalization based on QCD inspired models
- No deviation from linear path length dependence mandatory from RHIC HQ data (that I know of)
- It is possible to extract some fundamental properties of the QGP (such as the diffusion coefficient), with successful comparison to the lattice calculations
- Predictions results are in gross agreement with early LHC (dislike at the RHIC time), and seem to favor models based on pQCD or pQCD + non perturbative ingredients.
- LHC opens the window for disentangling between various models although it requires a) more precision from the experiments as well as b) global approaches
- Focus on the role of the background medium. First steps towards the coupling with one state of the art approach (EPOS) offers many future studies (correlations, quantifying HF energy loss in a strongly coupled plasma,…)

See talk by M. Nahgang

Main message: the models of HF energy loss and the background medium (including its microscopic content) are bound together. Need to study all these components at the same time !

Based on

- *Towards an understanding of the single electron data measured at the BNL Relativistic Heavy Ion Collider (RHIC)*, P.B. Gossiaux & J. Aichelin, Phys. Rev. C **78**, 014904 (2008); [arXiv:0802.2525]
- *Tomography of quark gluon plasma at energies available at the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC)*, P.B. Gossiaux, R. Bierkandt & J. Aichelin, Physical Review C **79** (2009) 044906; [arXiv:0901.0946]
- *Tomography of the Quark Gluon Plasma by Heavy Quarks*, P.-B. Gossiaux & J. Aichelin, J. Phys. G **36** (2009) 064028; [arXiv:0901.2462]
- *Energy Loss of Heavy Quarks in a QGP with a Running Coupling Constant Approach*, P.B. Gossiaux & J. Aichelin, Nucl. Phys. A **830** (2009), 203; [arXiv:0907.4329]
- *Competition of Heavy Quark Radiative and Collisional Energy Loss in Deconfined Matter*, P.B. Gossiaux, J. Aichelin, T. Gousset & V. Guiho, J. Phys. G: Nucl. Part. Phys. **37** (2010) 094019; [arXiv:1001.4166]
- *Plasma damping effects on the radiative energy loss of relativistic particles*, M. Bluhm, P. B. Gossiaux, & J. Aichelin, Phys. Rev. Lett. 107 (2011) 265004 [arXiv:1106.2856]
- *Theory of heavy quark energy loss*, P.B. Gossiaux, J. Aichelin, T. Gousset, [arXiv:1201.4038v1]

Based on

- Radiative and Collisional Energy Loss of Heavy Quarks in Deconfined Matter *Radiative*, J. Aichelin, P.B. Gossiaux, T. Gousset, [arXiv:1201.4192v1]
- On the formation of bremsstrahlung in an absorptive QED/QCD medium, M. Bluhm, P. B. Gossiaux, T. Gousset & J. Aichelin, [arXiv:1204.2469v1]
- … other recent publications all available on arxiv

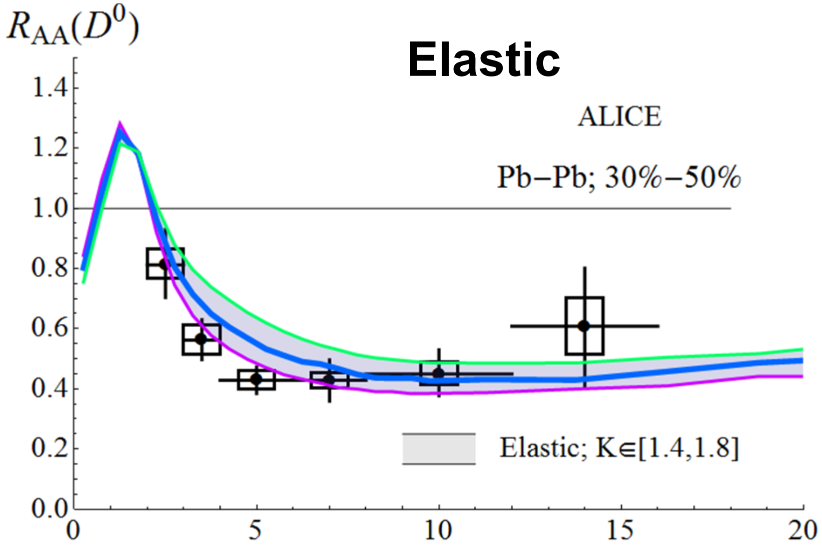
Back up

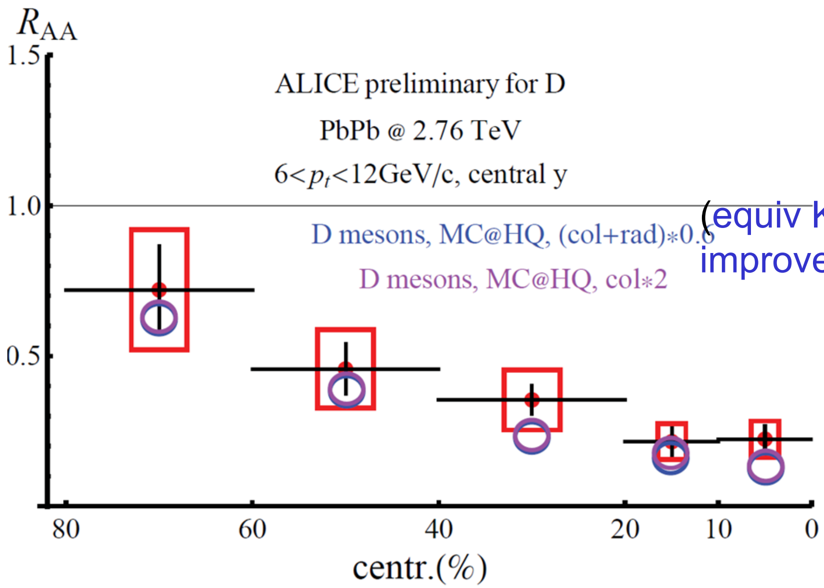
Extra results for LHC

From previous version of the model, contact gossiaux@subatech.in2p3.fr for actual values

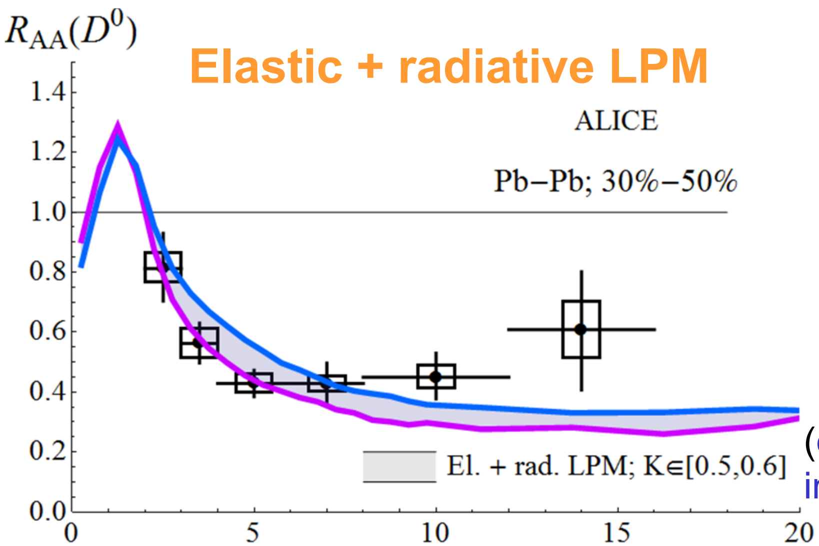
D mesons at LHC (at other centrality & vs centrality)

Important test of the path length dependence of Eloss scenario





(equiv K=1. with improved radiat.)

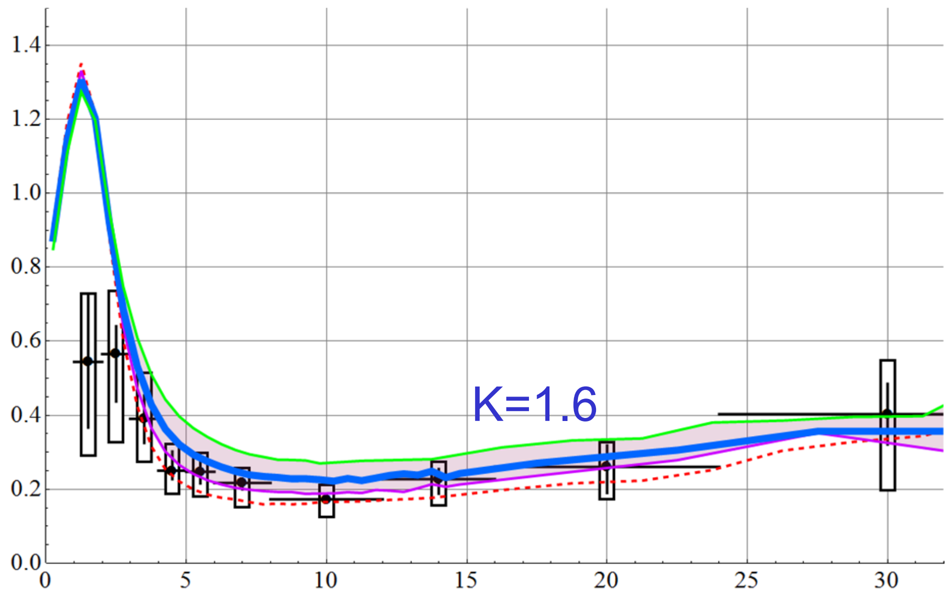


(equiv K=1. with improved radiat.)

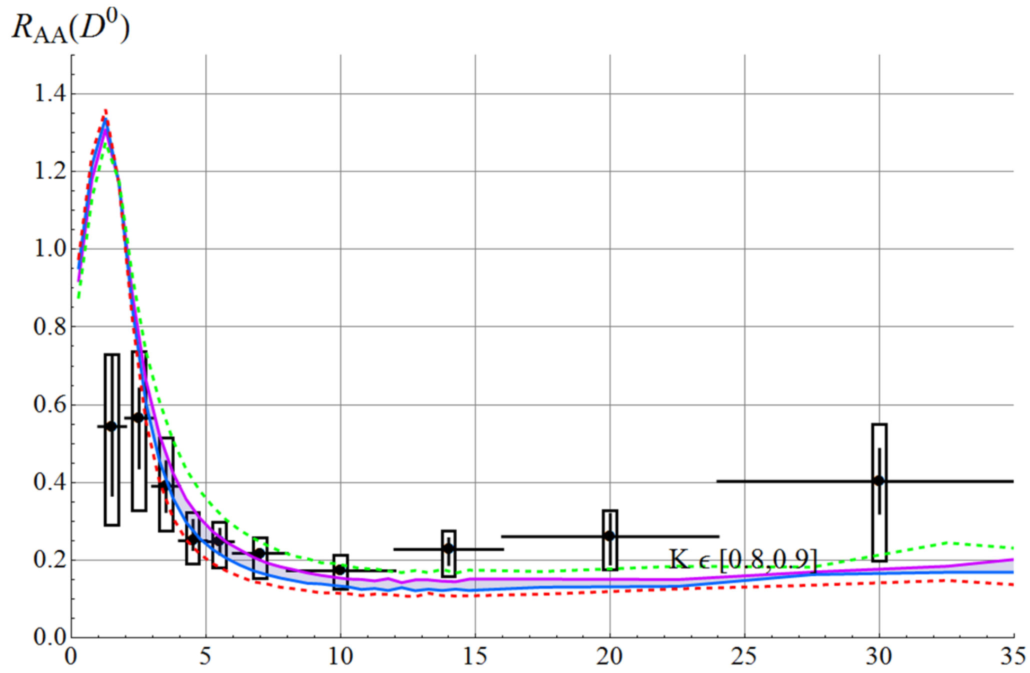
Good quantitative agreement, apart from the last p_T point in the el. + rad. LPM

D mesons at LHC (vs ALICE 0%-7.5%)

Coll

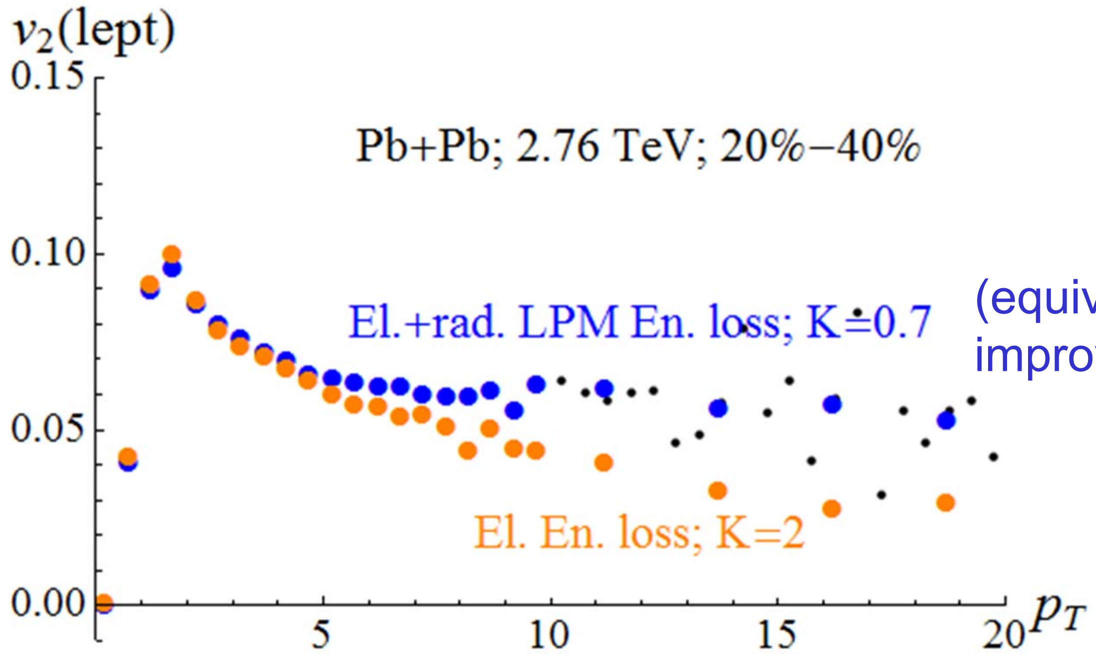


Coll + rad LPM



Big surprize: Better agreement with pure elastic Eloss; rather flat radiative Eloss on the 10-30 GeV/c p_T range

Leptons



(equiv K=1.1 with improved radiation)

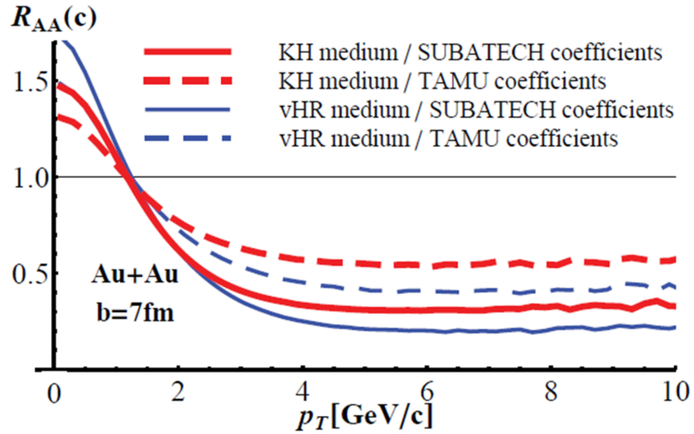
Some theoretical thoughts

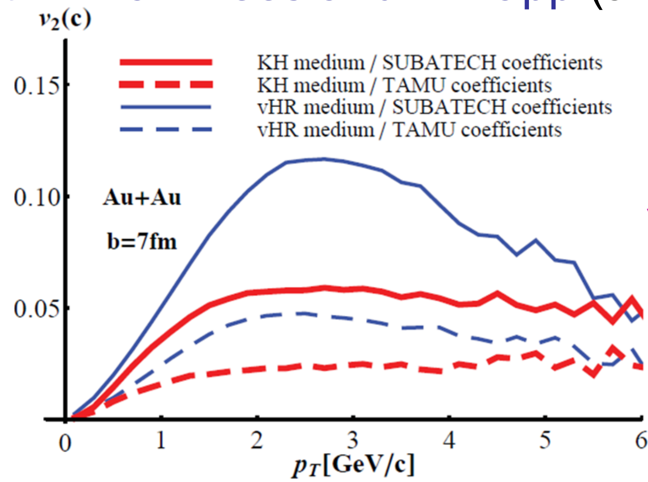
Improvements needed from the theory side

Key issue: systematic consideration of the dynamical “underlying event” (e.g. the hot medium) on the Energy loss of heavy quarks (see “global fit” approach in Steffen Bass’s talk)

<u>Exemplification:</u>

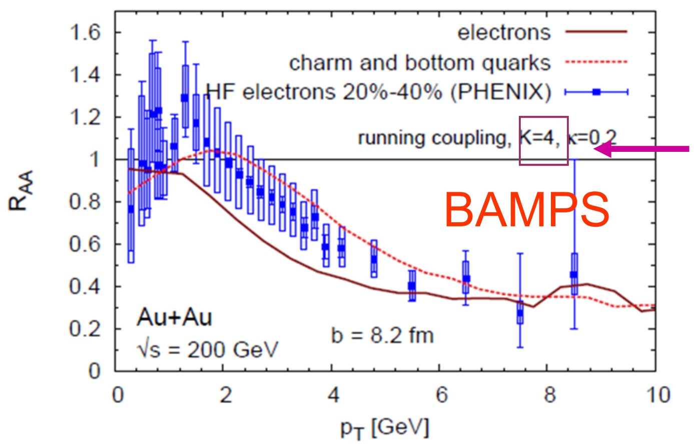
a) Systematic analysis performed with H van Hees and R Rapp (arxiv 1102.1114)



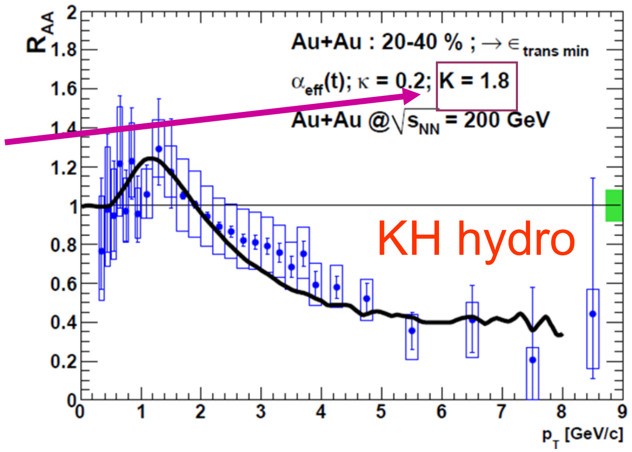


Larger thermalisation in vHR medium than in Kolb-Heinz hydro

b) Running α_s approach in BAMPS (Uphoff et al. arxiv 1104.2437)



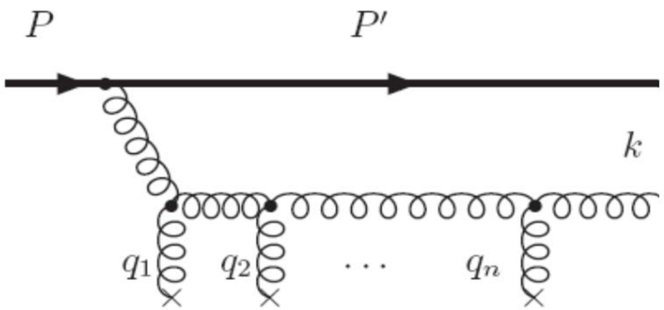
Apparently, 2 times less thermalisation in BAMPS then in Kolb-Heinz hydro



Insufficient control on energy loss theory

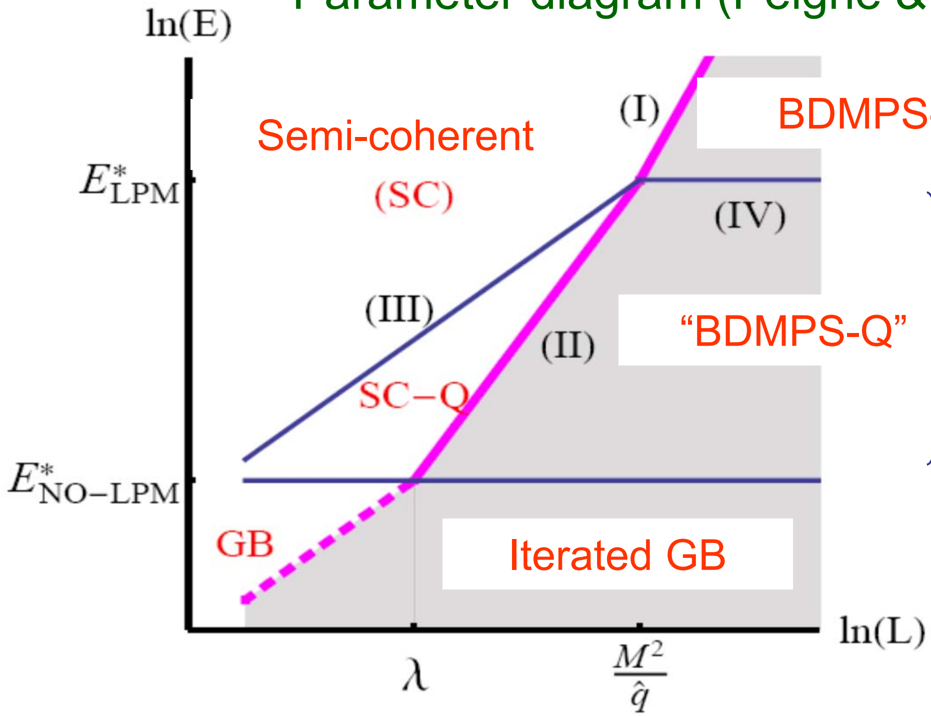
Expected dominance of radiative energy loss at high energy

When exactly ? Need for correct treatment of coherence (large formation times => LPM-like effect



Typical contribution to coherent radiative energy loss (Z-BDMPS approach)

Parameter diagram (Peigne & Smilga)



No mass dependence

$1/M^{0<a<1}$ or ln(..;/M) mass dependence

1/M mass dependence

Not aware of a tractable theory that encompass all those regimes, especially in the strongly coupled case…

Not much considered up to now: role of dispersion relation in radiative E-loss: gluon "mass" (M. Djordjevic)… but also gluon width !

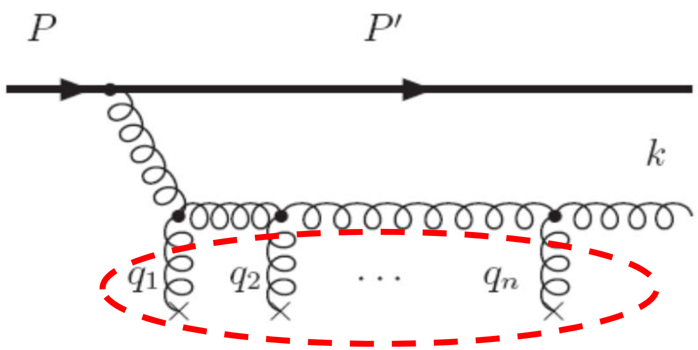
(High energy) gluon damping in pQCD and estimates for Γ

High energy: ω>>T

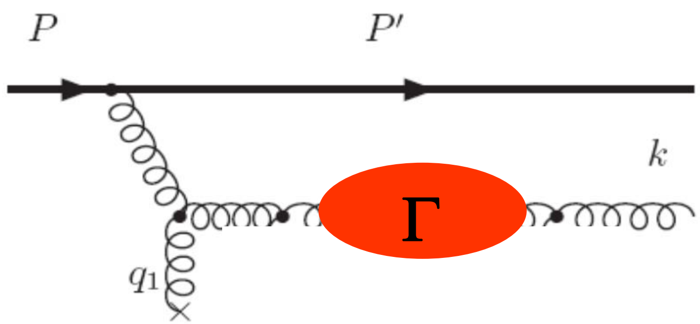
- Elastic process (collisionnal broadening): $\Gamma \approx g^2 T (\ln 1/g)$ for $\omega = O(T)$;

  R. D. Pisarski, Phys. Rev. D 47 (93); no known result for ω>>T

- But double counting with original BDMPS description:

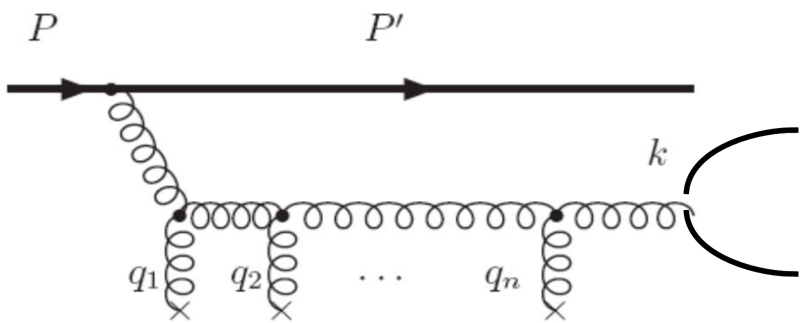


or



But not both !

- Genuine gluon absorption



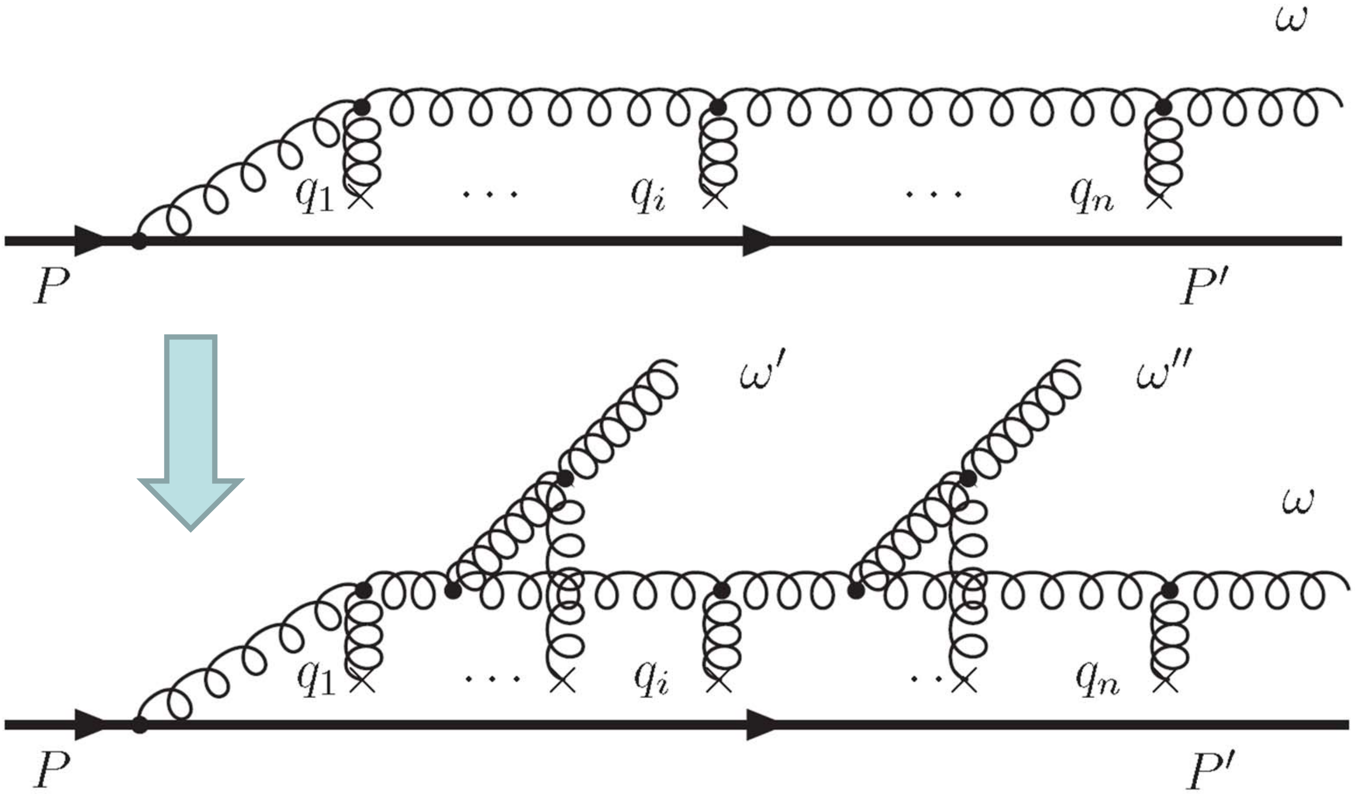
Hints that $\Gamma(\omega) \propto g^4 T^2/\omega$

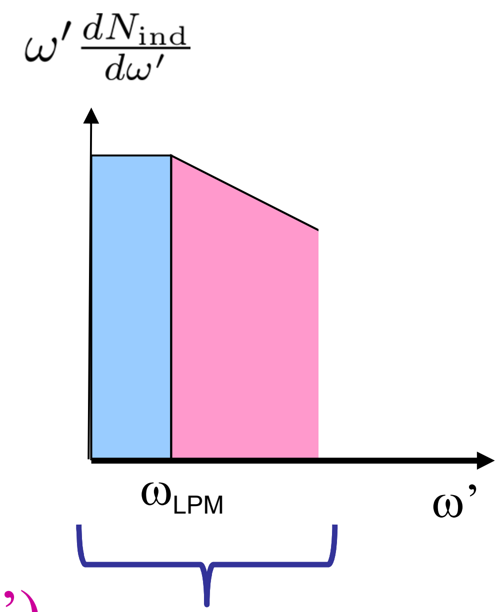
« damping rate of hard photon… »

Thoma, PRD51 (95)

(High energy) gluon damping in pQCD and estimates for Γ

- Considering the "pre-gluon" as a radiator itself and iterate (consistent if $\omega' < \omega$)





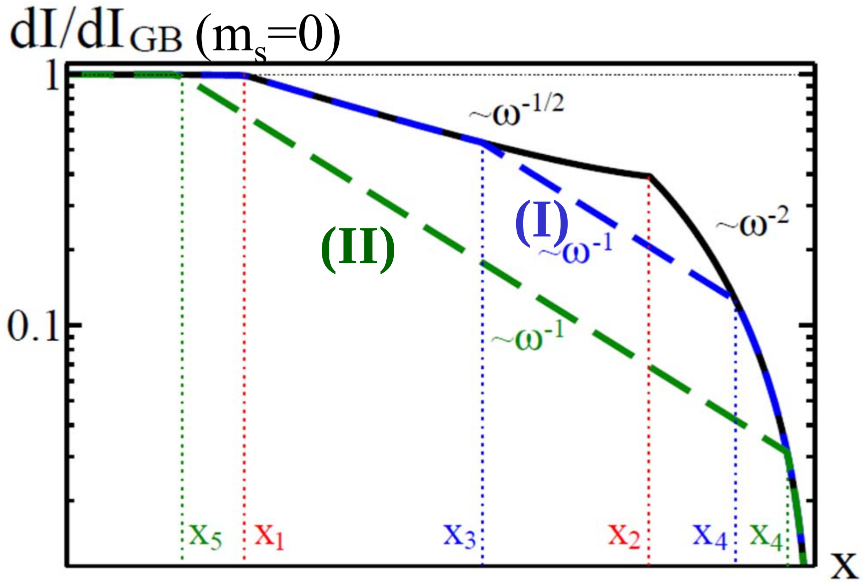
Emission of low energy quasi-isotropic gluons (ω', ω'')

$\Gamma \approx g^4\, T$

Possible candidate mechanism for di-jets imbalance and jet isotropisation observed by CMS !

Consequences on the power spectra

$\hat{q} < m_g^3$



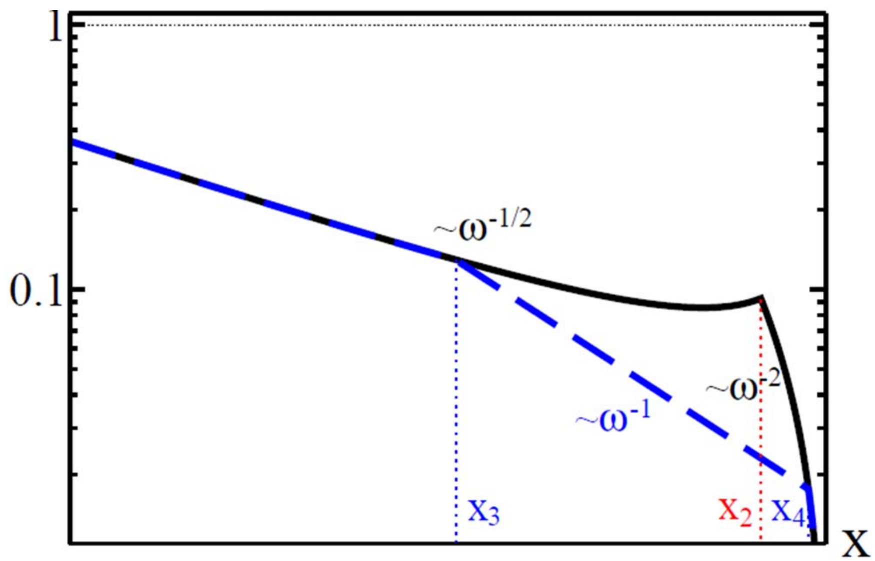
(I) and (II): moderate and large damping (see previous slide)

E= 45 GeV, m_s=1.5 GeV

m_g=0.6 GeV, $\hat{q} = 0.1\text{GeV}^2/\text{fm}$

Γ=0.05 GeV (I) & 0.15 GeV (II)

$\hat{q} > m_g^3$

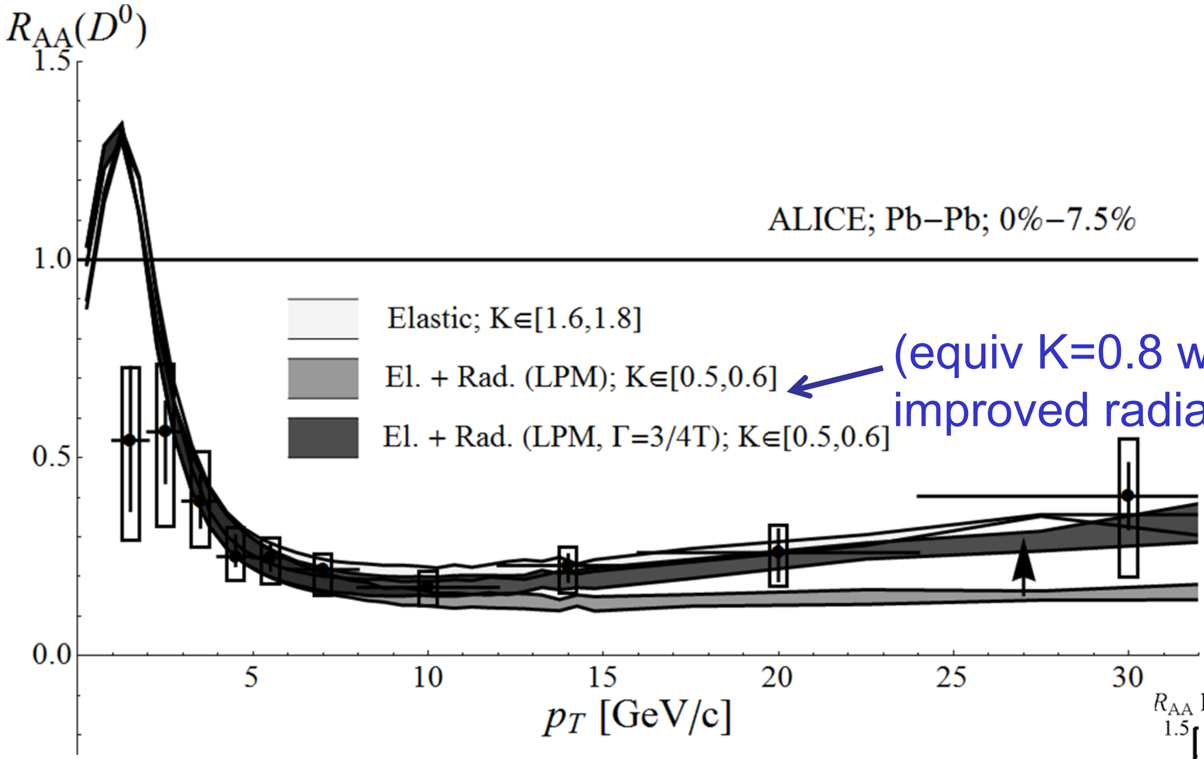


Same but

$\hat{q} = 2\text{GeV}^2/\text{fm}$

Γ=0.25 GeV

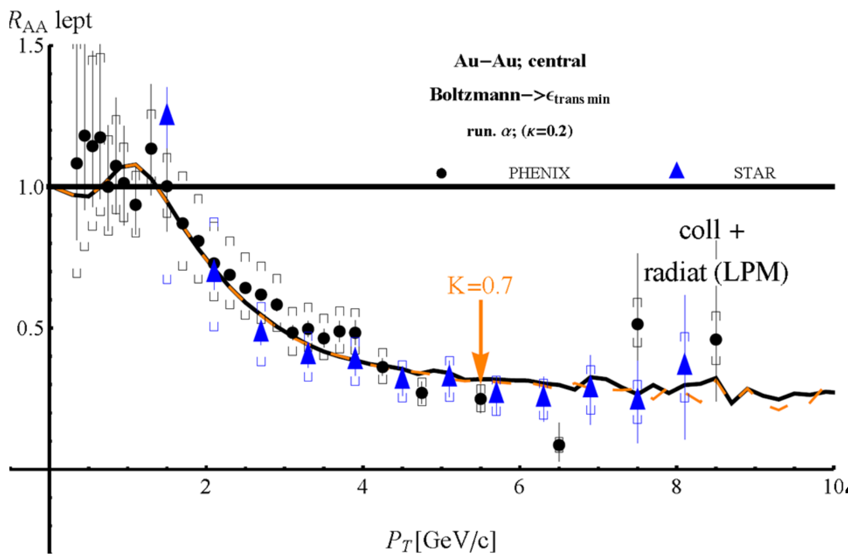
Consequences on the HQ observables



(equiv K=0.8 with improved radiation)

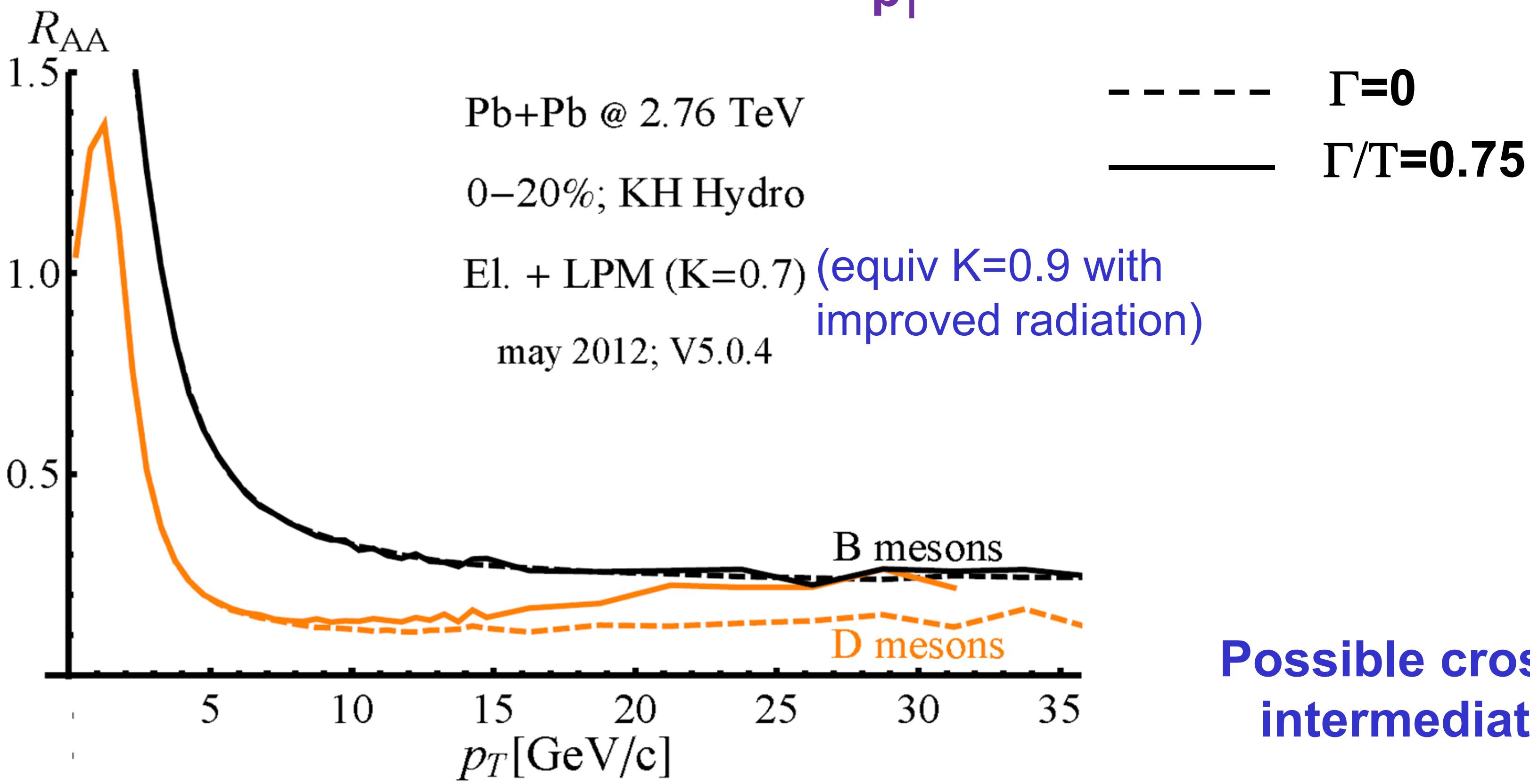
Damping of radiated gluons reduces the quenching of D mesons

RHIC « reference »: no effect seen for Γ=0.75T



Consequences on the HQ observables

Damping of radiated gluons tempers the mass hierarchy at intermediate p_T



Possible crossing at intermediate p_T ?

Ideal situation to « reveal » Eloss mechanism: initiating one HQ in QGP with a fixed p_T…