Heavy quark quenching and elliptic flow from RHIC to LHC: can the experimental results be understood by pQCD?

Hard Probes 2013; Stellenbosch (SA)

P.B. Gossiaux
SUBATECH, UMR 6457
Ecole des Mines de Nantes, Université de Nantes, IN2P3/CNRS

with

J. Aichelin, Th. Gousset, M. Nahrgang, K. Werner

Heavy quark quenching and elliptic flow from RHIC to LHC: can the experimental results be understood by pQCD–inspired models using realistic backgrounds ?

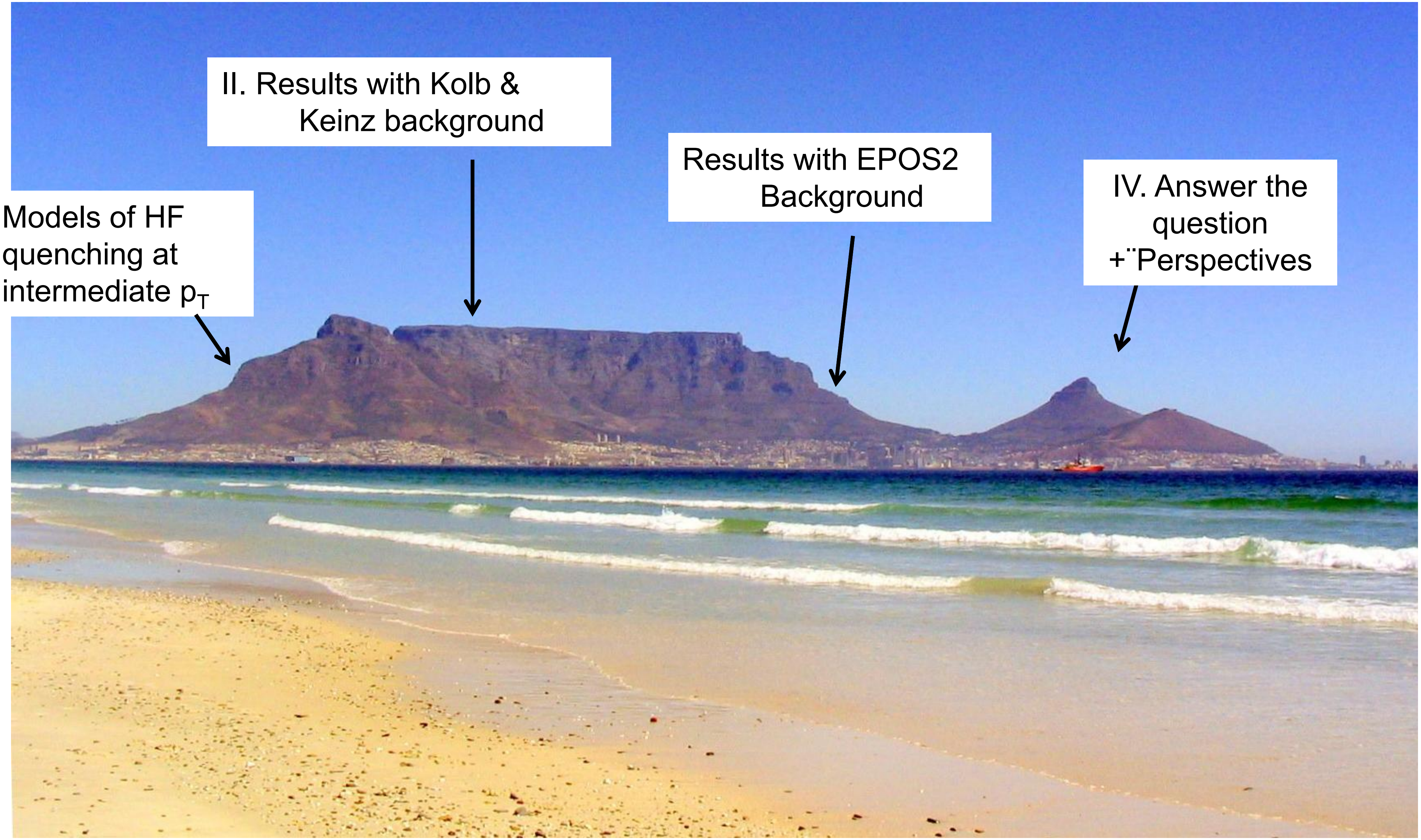
Hard Probes 2013; Stellenbosch (SA)

P.B. Gossiaux
SUBATECH, UMR 6457
Ecole des Mines de Nantes, Université de Nantes, IN2P3/CNRS

with

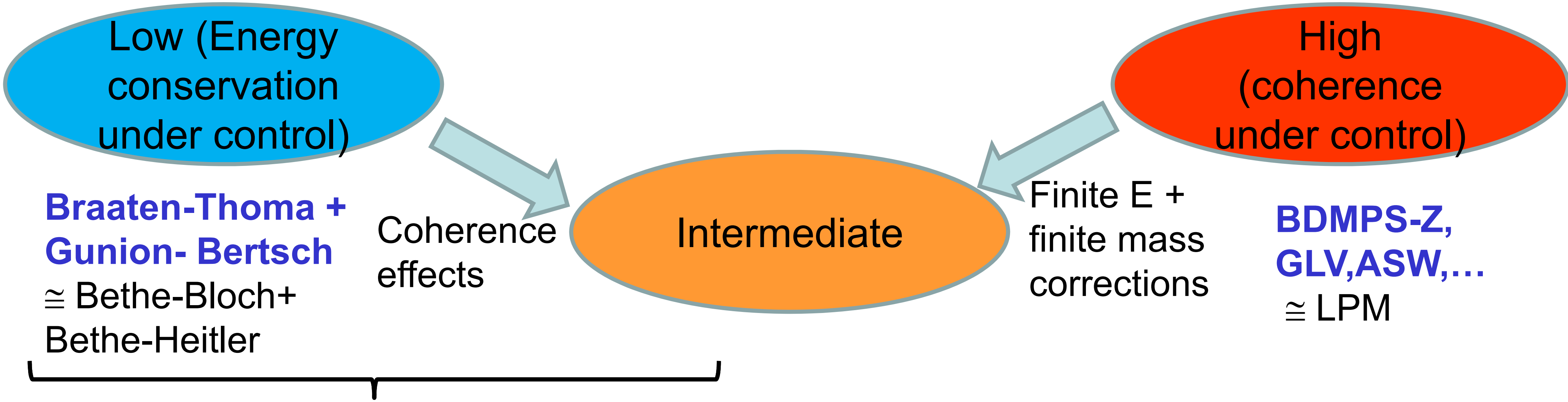
J. Aichelin, Th. Gousset, M. Nahrgang, K. Werner

Road Map


Models of HF quenching at intermediate p_T
II. Results with Kolb & Keinz background
Results with EPOS2 Background
IV. Answer the question +¨Perspectives

Motivation and context

- Most of the *interesting* HF observables so far: located at *intermediate* p_T
- Intermediate p_T: hope that pQCD (or pQCD inspired models) apply (as compared to low p_T)
- Intermediate p_T: mass effect still present and thus hope to learn something more as compared to large p_T



Approach pursued in our **models**

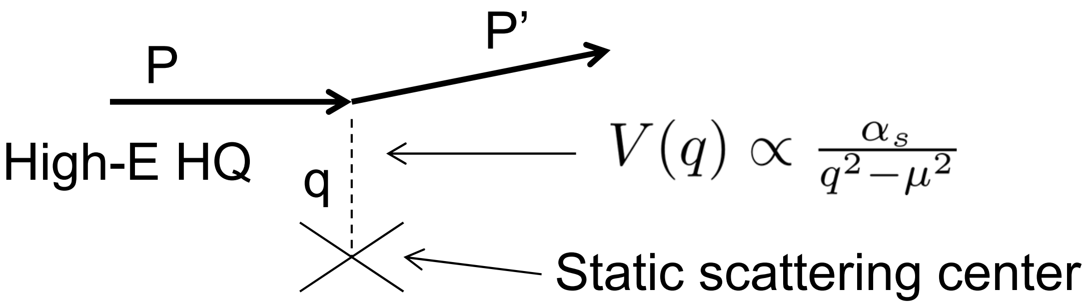
- => Need for falsification

Insufficient control on energy loss theory in QCD

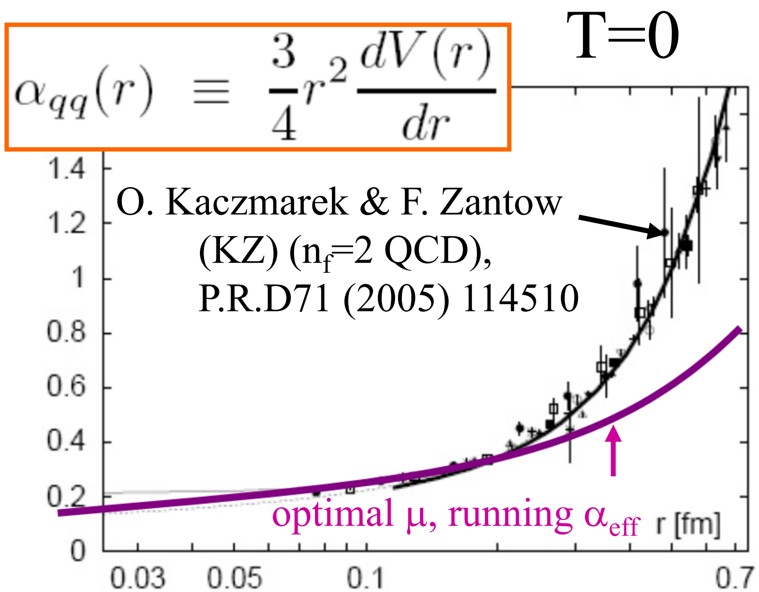
Basic ingredient in the derivation of QED collisional Eloss; transverse force

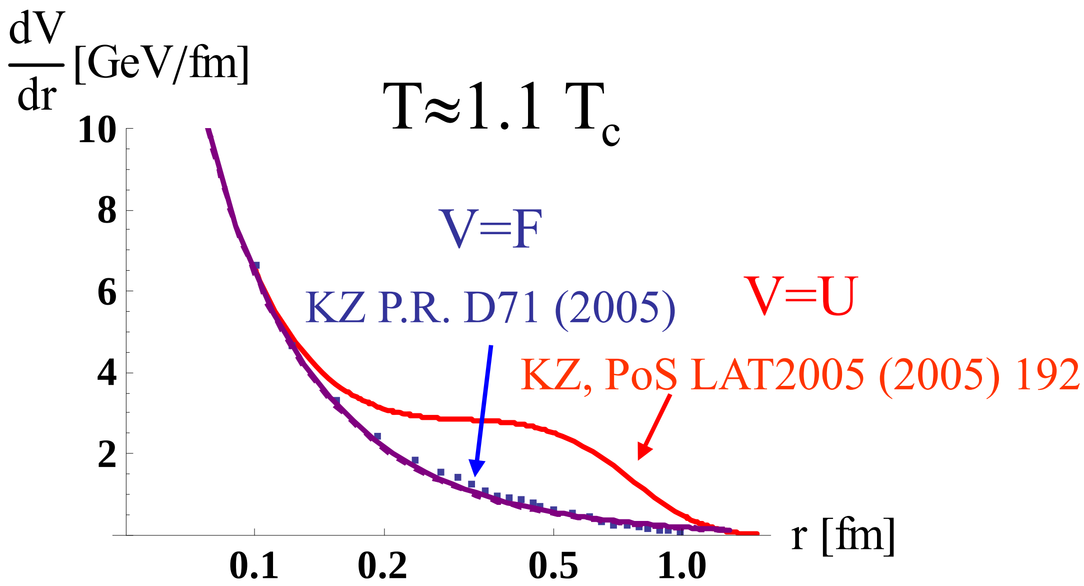
In QCD: non perturbative « corrections » even at large HQ energy

In most models:



Lattice QCD :





Significant r-tail in the transverse force acting on the high-E HQ, especially in the V=U prescription

Our basic ingredients for HQ energy loss

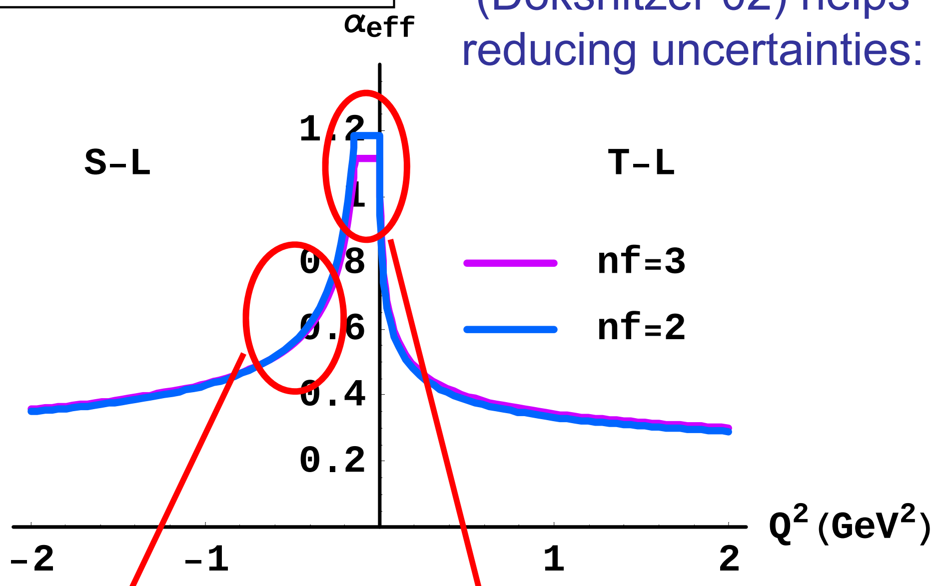
Elastic

Motivation: Even a fast parton with the largest momentum P will undergo collisions with moderate q exchange and large $\alpha_s(Q^2)$. The running aspect of the coupling constant has been "forgotten/neglected" in most of approaches

Effective $\alpha_s(Q^2)$ (Dokshitzer 95, Brodsky 02)

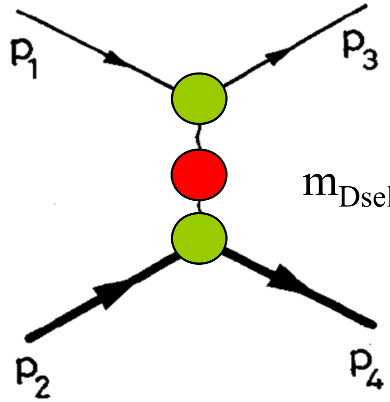
$$\frac{1}{Q_u}\int_{|Q^2|\le Q_u^2} dQ\,\alpha_s(Q^2) \approx 0.5$$

"Universality constrain" (Dokshitzer 02) helps reducing uncertainties:



IR safe. Q^2 close to 0 does not contribute to Eloss

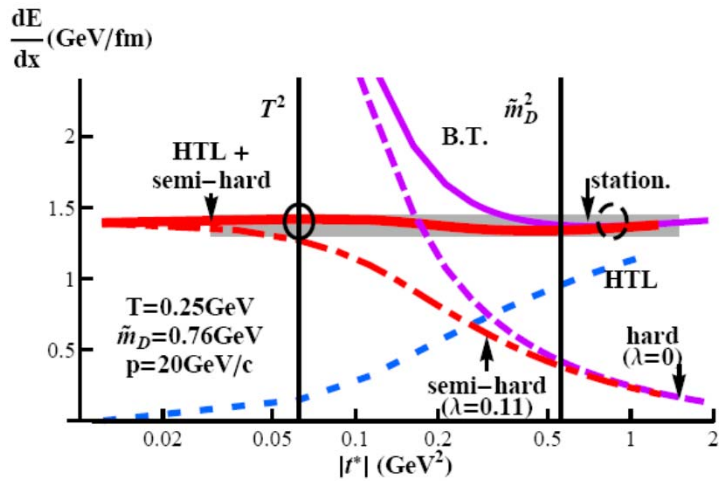
Large values for intermediate momentum-transfer => larger cross section



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

+ u and s channels

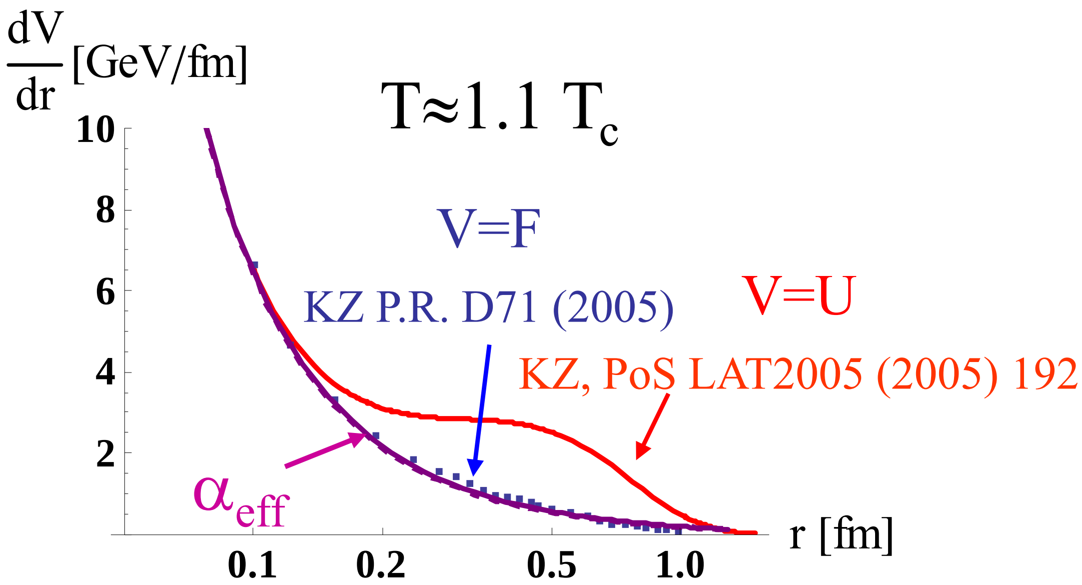
One gluon exchange effective propagator, designed in order to guarantee maximal insensitivity of dE/dx in Braaten-Thomas scheme;
Peshier, Aichelin, Gossiaux (2008)

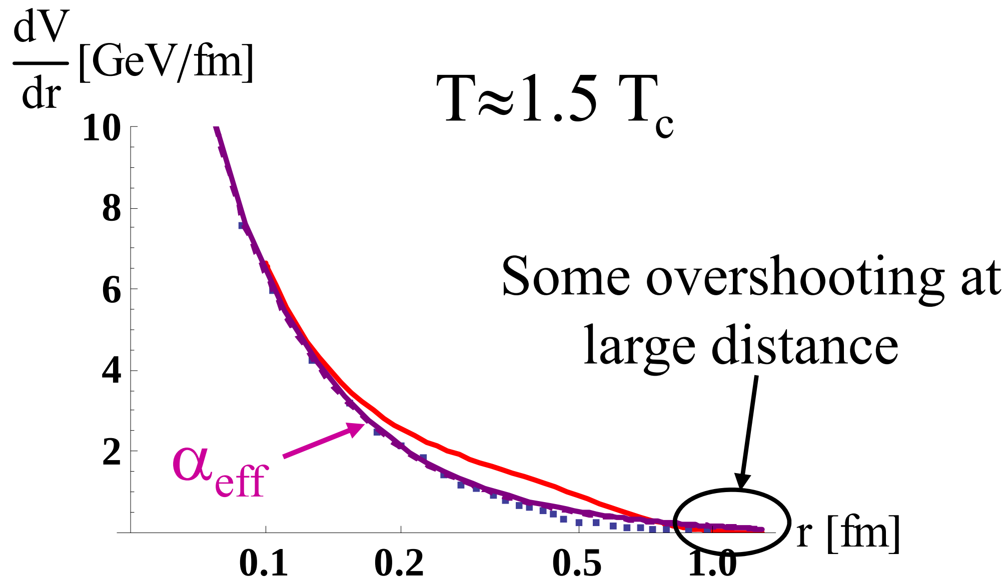


optimal μ:

$$\mu^2 \approx 0.2 m_D^2$$

Insufficient control on energy loss theory





In our model, the force is close to the one extracted from the free energy taken as a potential

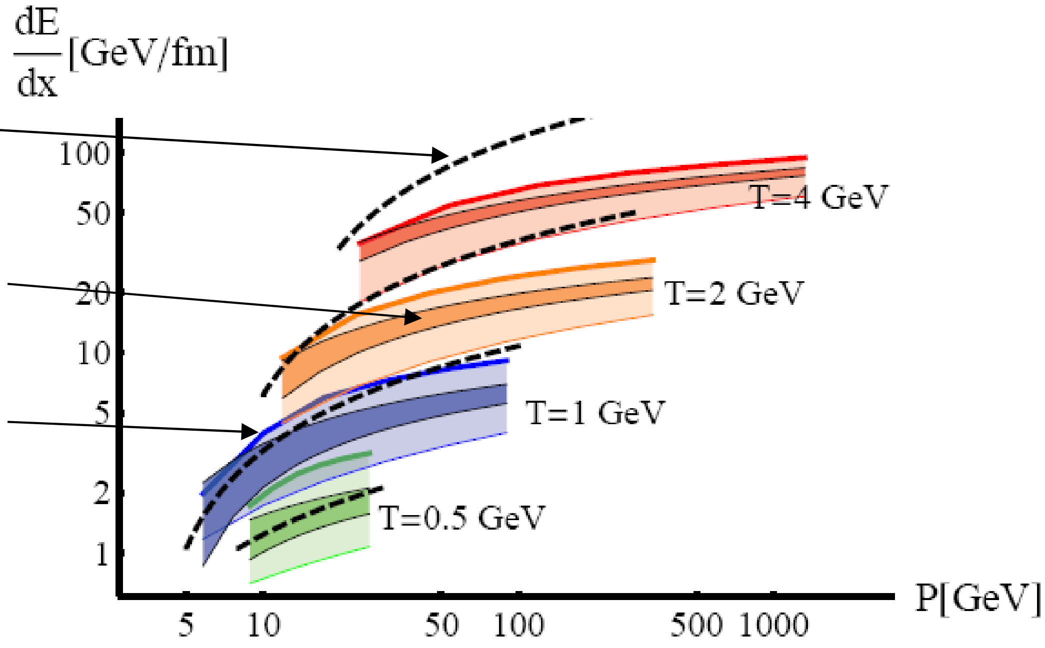
Correct Contact with pQCD

Braaten-Thoma

Dark bands: Peshier & Peigné (2008)

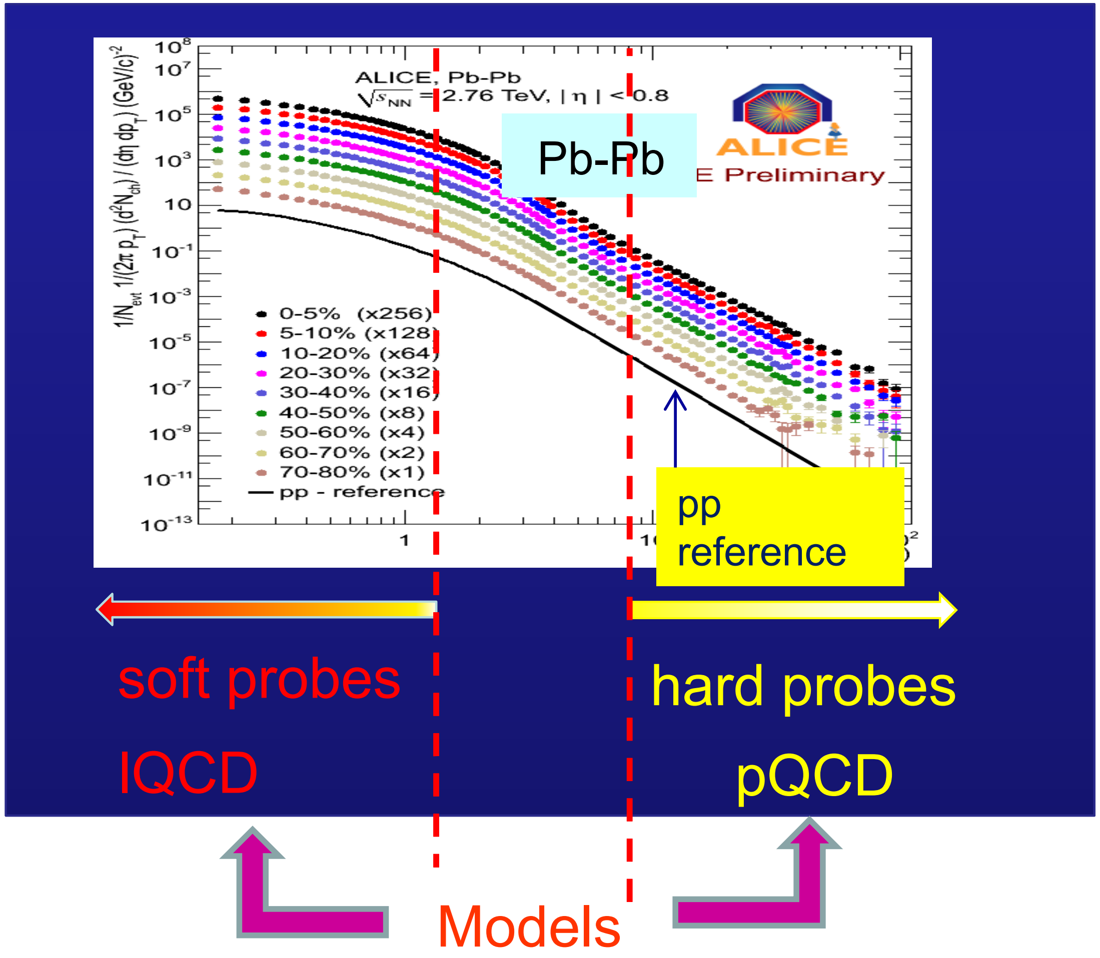
optimal μ, running α_{eff}

Light bands: theoretical uncertainty related to the prescription for the HTL-hard transition



The “Minimal Tuning” Approach

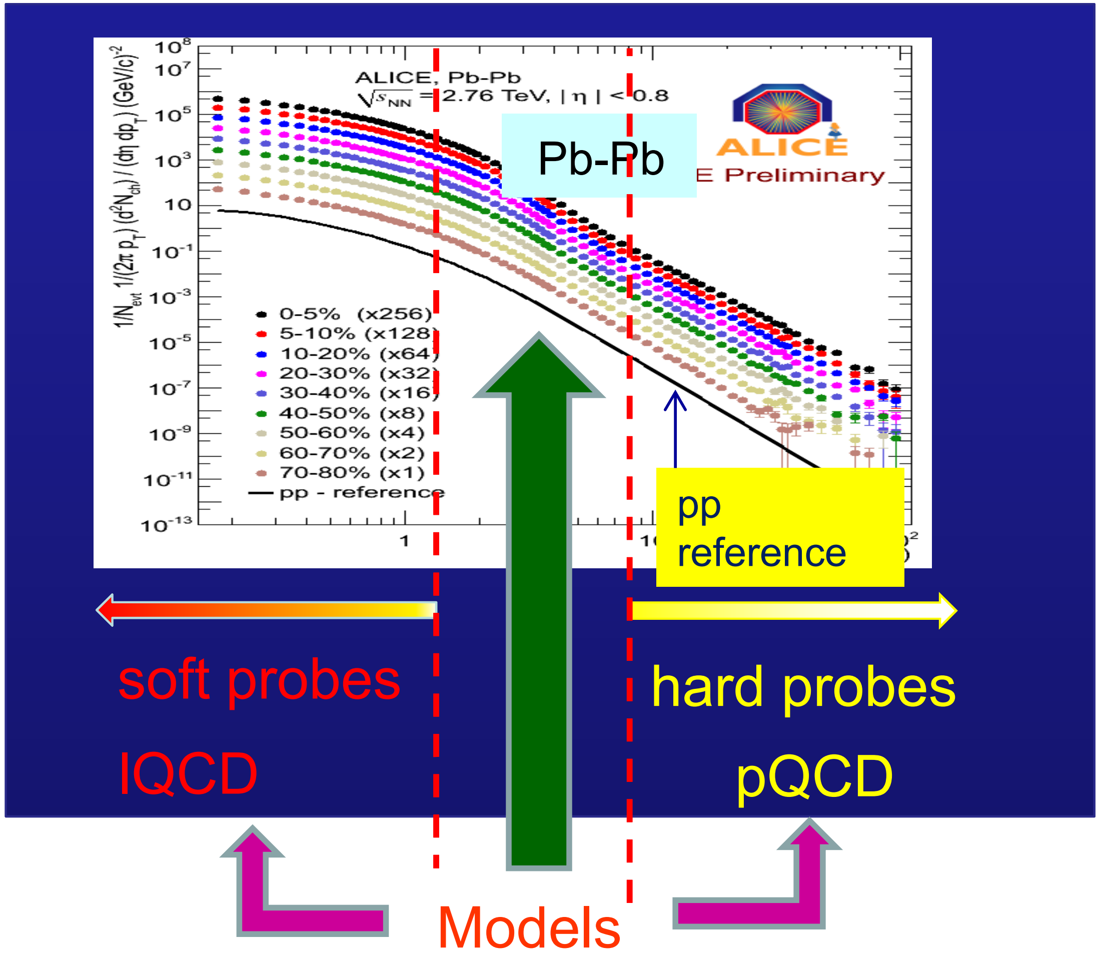
- Xin-Nian Wang:



Ideally, models should be constrained by solid link with lQCD and pQCD

The “Minimal Tuning” Approach

- Xin-Nian Wang:



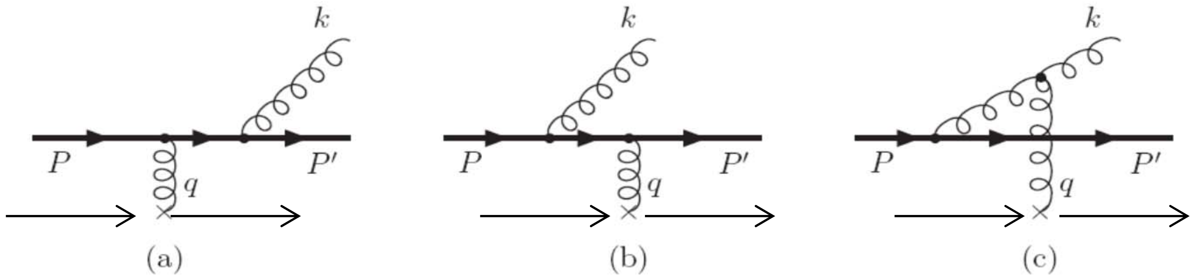
But this not always possible => allow for some “free” parameter, to be fixed by experiment.

In our case: K: multiplicative factor of microscopic cross sections

Our basic ingredients for HQ energy loss

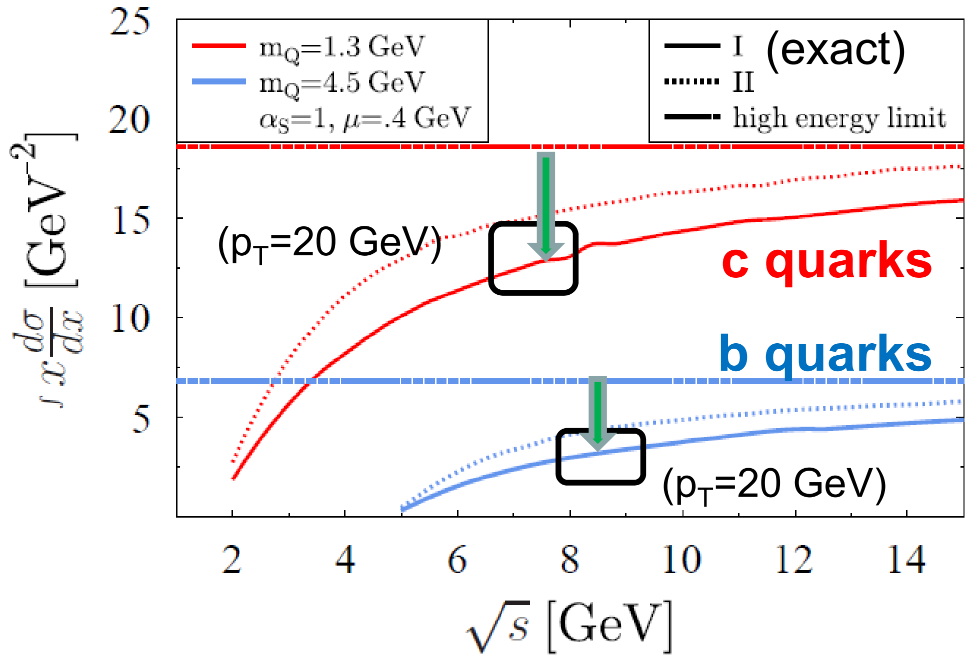
Incoherent Induced Radiative

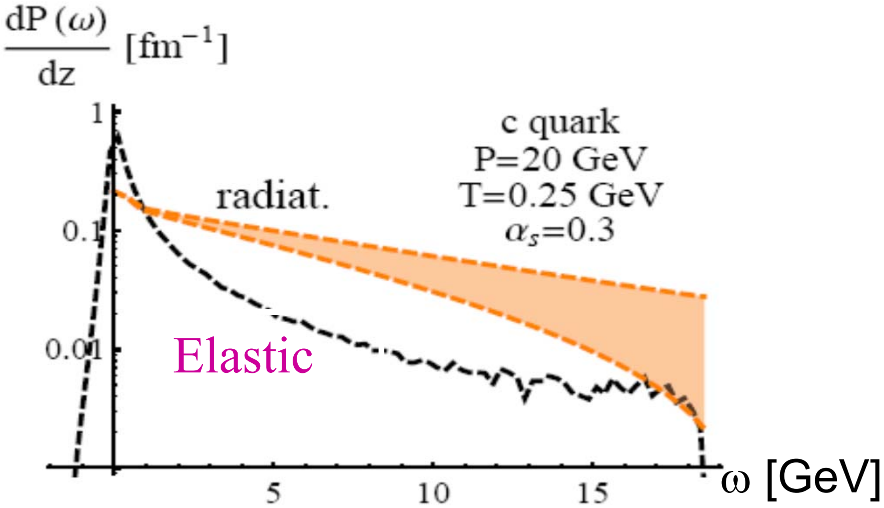
Generalized Gunion-Bertsch for finite mass, finite energy and dynamical light partons arxiv 1307.5270



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

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





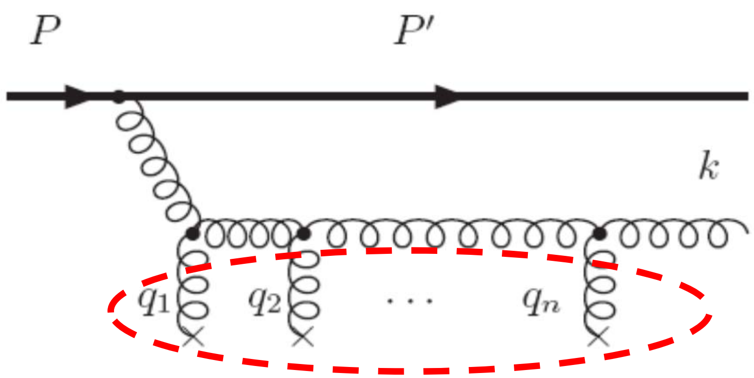
Finite energy lead to strong reduction of the radiative energy loss at intermediate p_T

differential energy loss ω per unit length (T,M,…): big differences between the 2 contributions

Our basic ingredients for HQ energy loss

Coherent Induced Radiative

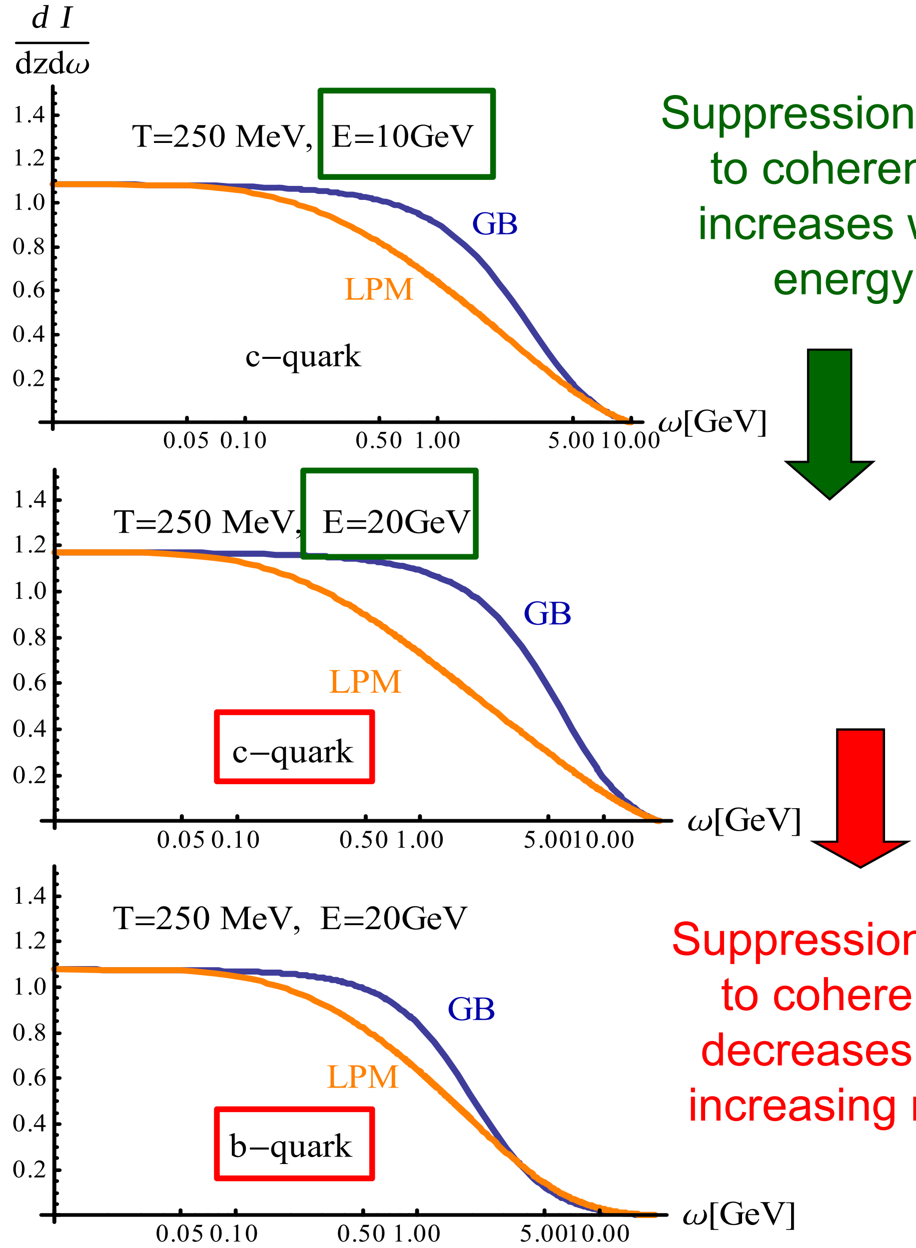
Formation time picture: for $l_{f,mult} > \lambda$, gluon is radiated coherently on a distance $l_{f,mult}$



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

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

[arXiv:1209.0844] (Hard Probes 2012)

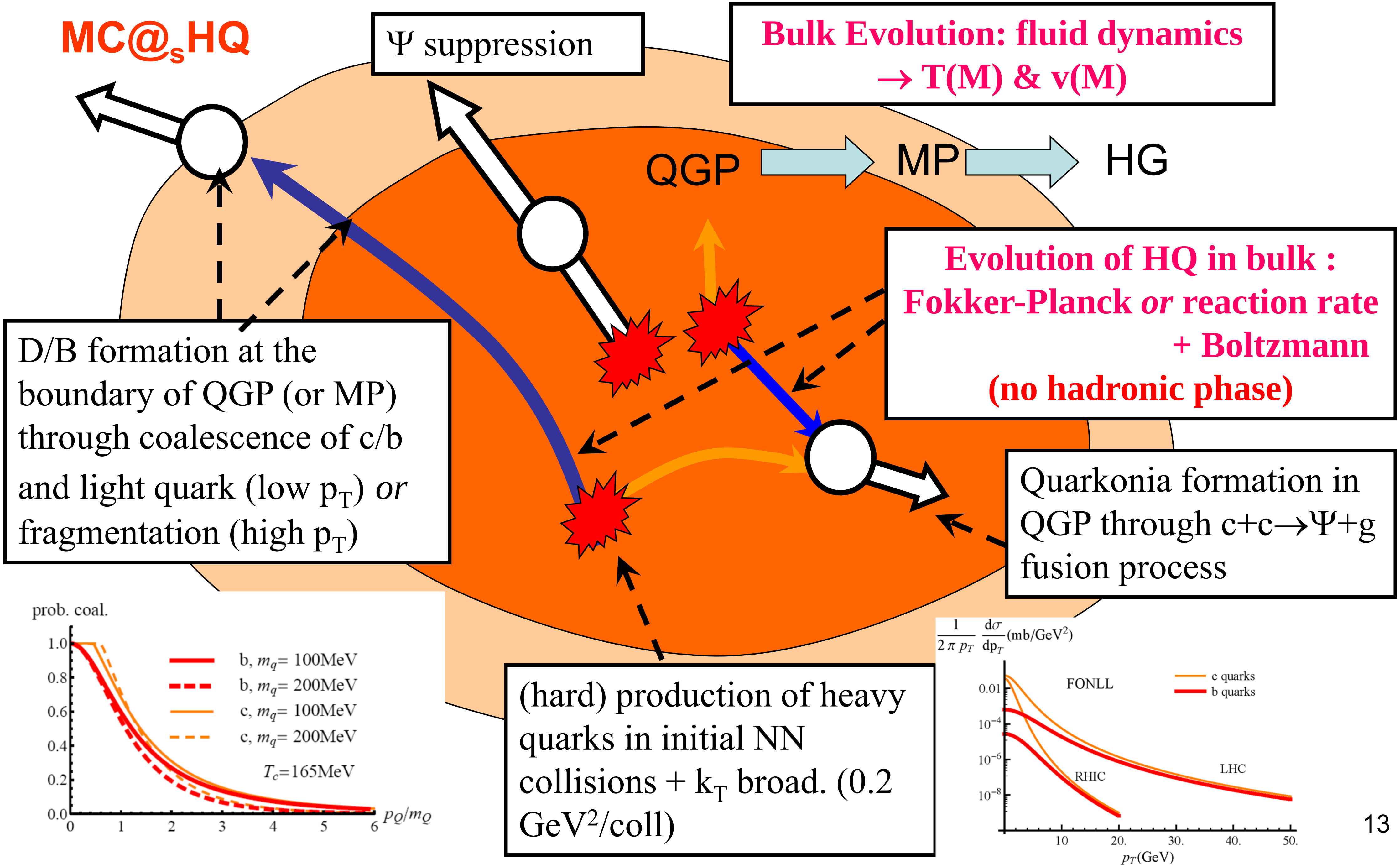


Suppression due to coherence increases with energy

Suppression due to coherence decreases with increasing mass

Up to now: no finite path length effect

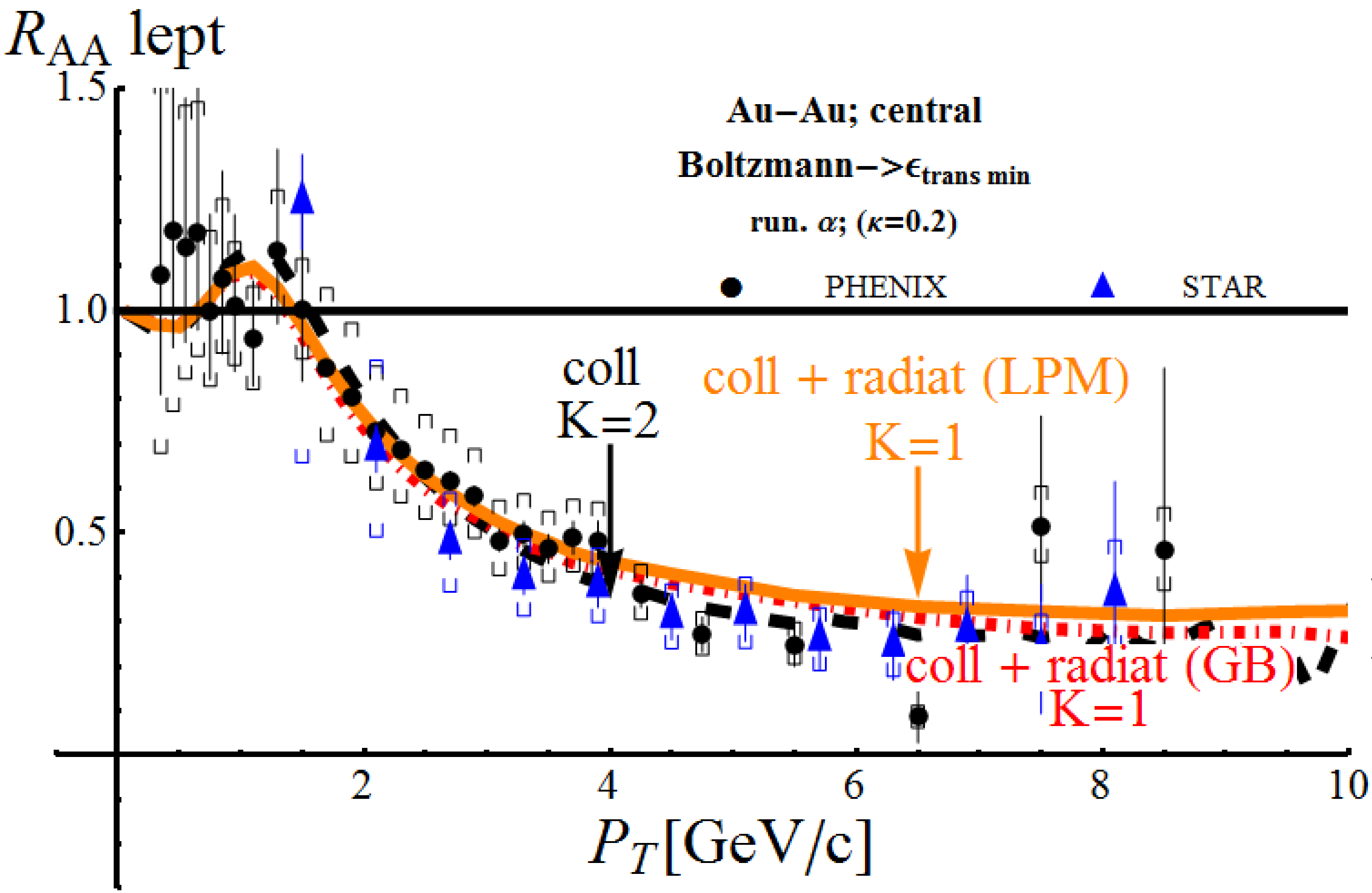
Schematic view of « Monte Carlo @ Heavy Quark » generator



Results for Heinz-Kolb (ideal hydro) Background

{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 adjust K on RAA, while BAMPS does it on v2

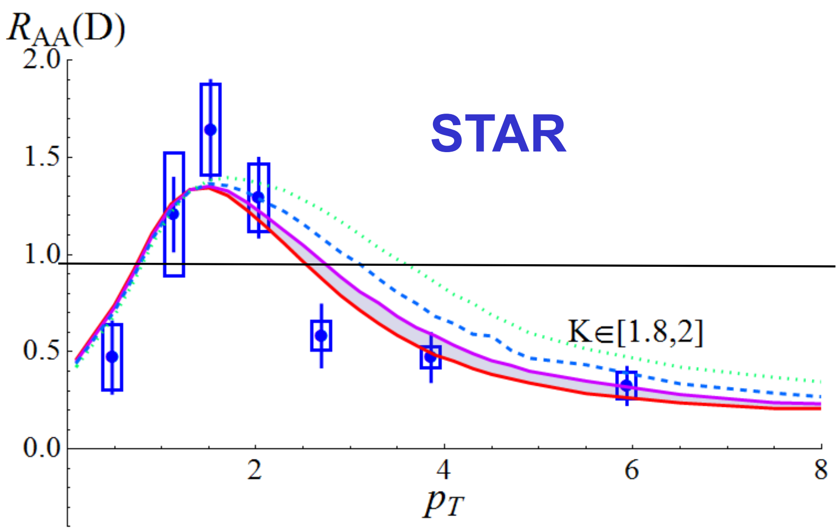
σ_{el} & σ_{rad} cocktail: NO RESCALING

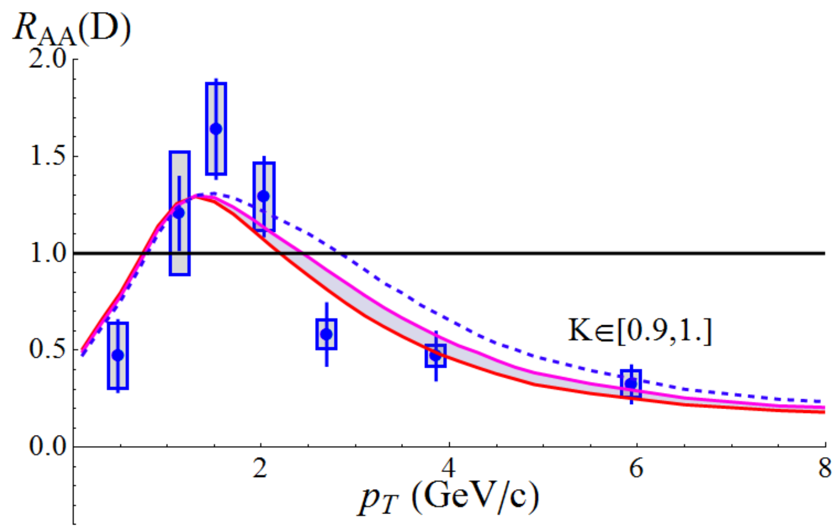
(since last QM: improvement in the phase space boundary for gluon emission; was too permissive -> K≈0.6 needed)

{Radiative + Elastic} vs Elastic D mesons @ RHIC

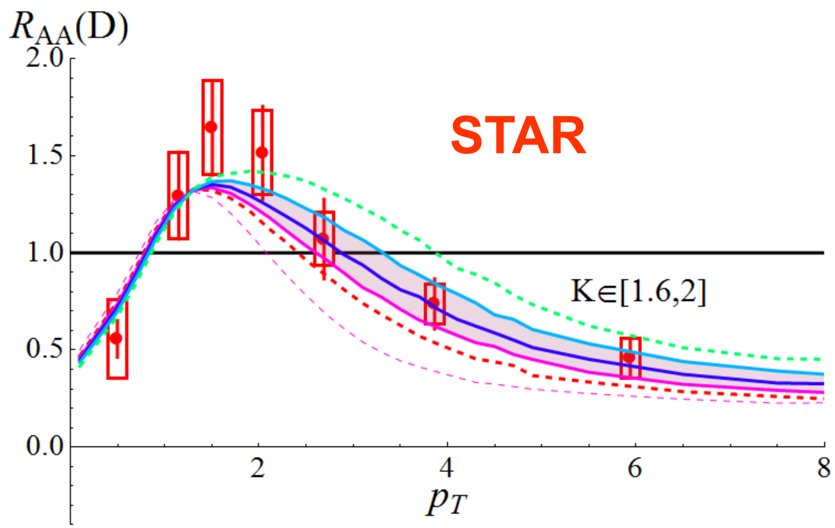
Elastic | **Elastic + radiative LPM**

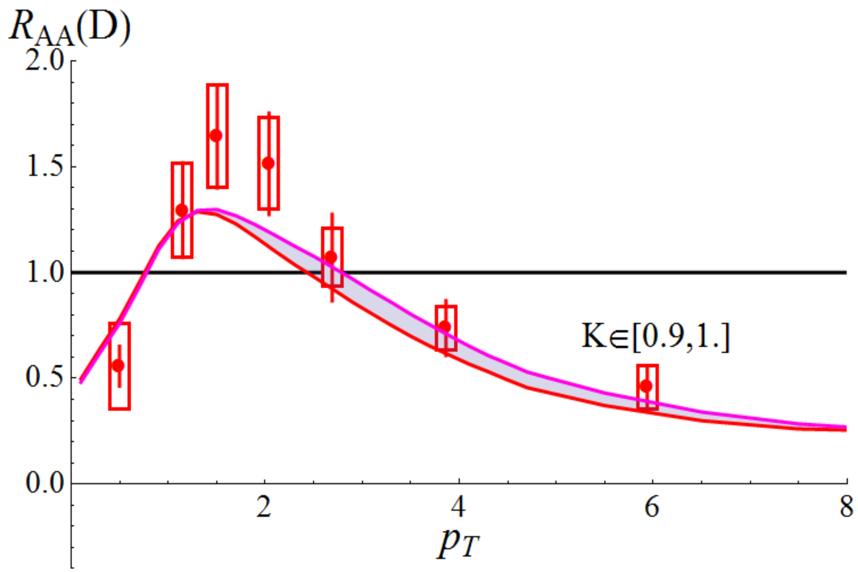
0-10%



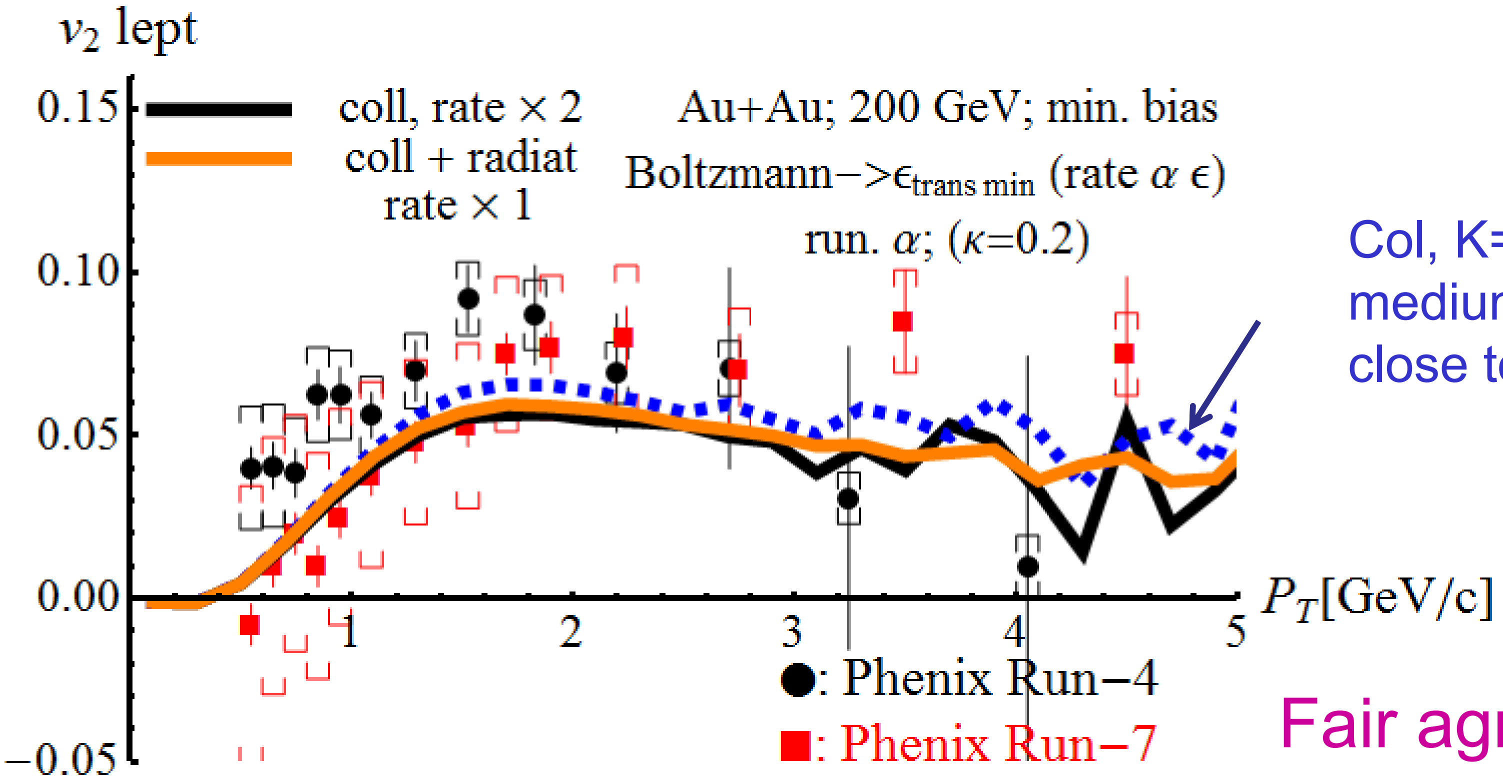


0-80%



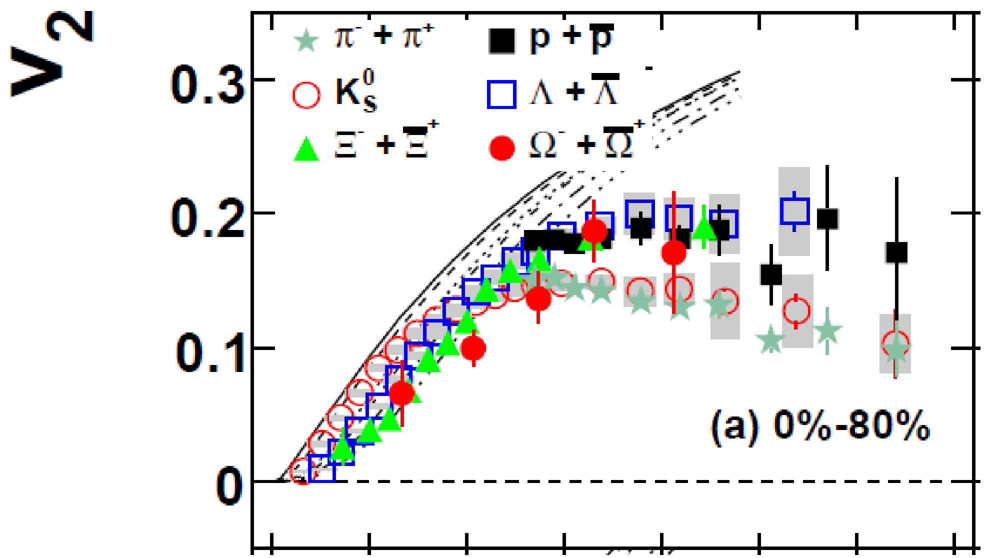


And the v2 ? (@ RHIC)



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

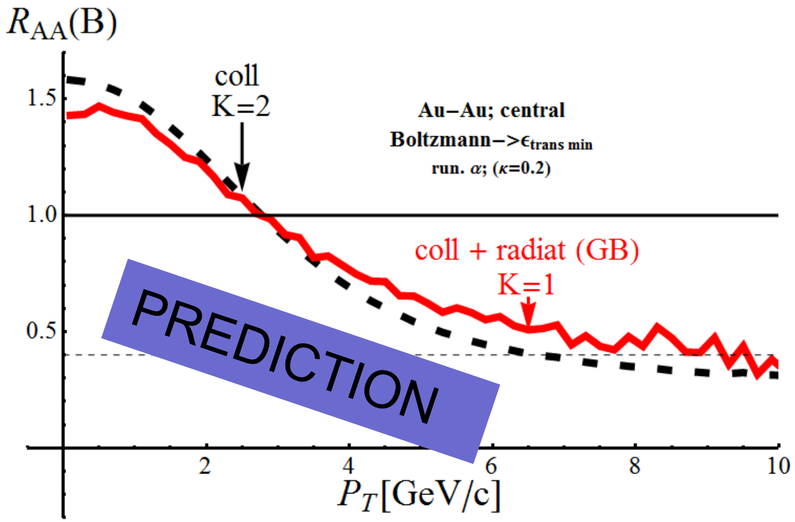
Fair agreement with the same K values, the ideal hydro probably helps a bit



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) $\Rightarrow$ Not sensitive to the large-ω tail of the Energy-loss probability.



➢ One "explains" all open heavy flavor physics with $\Delta E \propto L$ (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

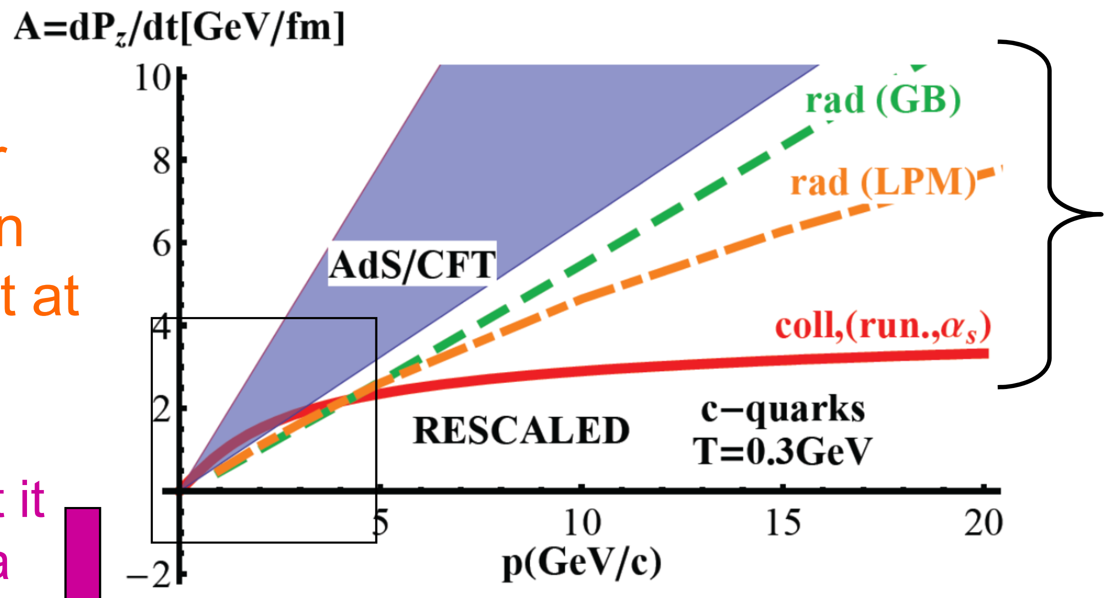
K	NPSE RHIC	D STAR central	D STAR min bias
0.7		Wrong	
0.8	Wrong	Marginal	Acceptable
0.9	Acceptable	Good	Good
1	Good	Good	Acceptable
1.1	Acceptable	Marginal	Marginal

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

QGP properties from HQ probe at RHIC

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

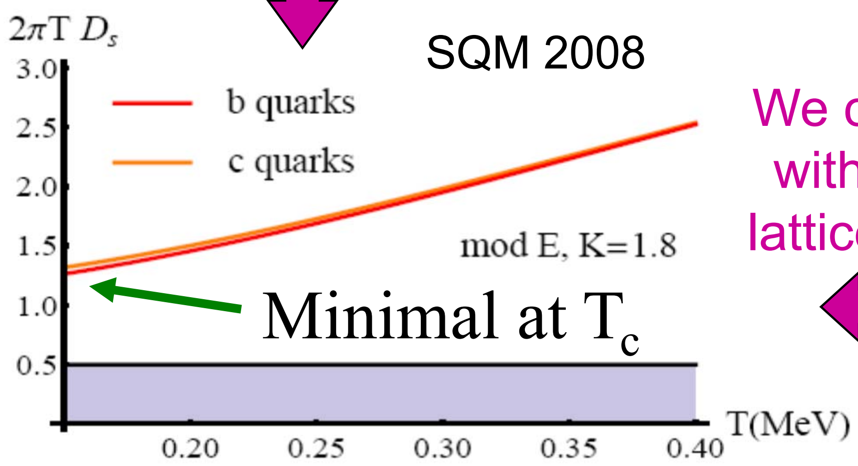
Similar diffusion coefficient at low p



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

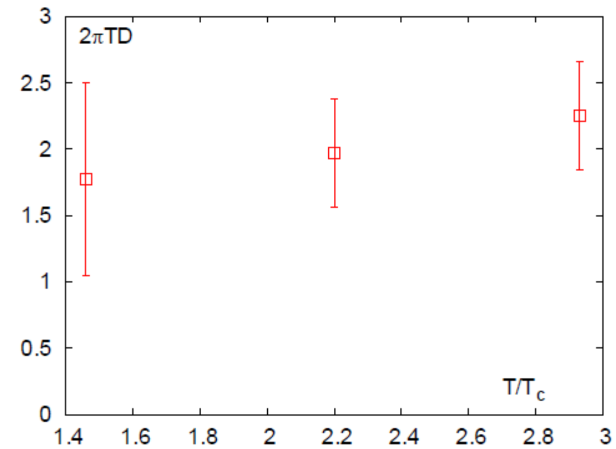
Present RHIC experiments cannot resolve between those various trends

We extract it from data



SQM 2008

We compare with recent lattice results



Kaczmarek Bad Honnef 2011

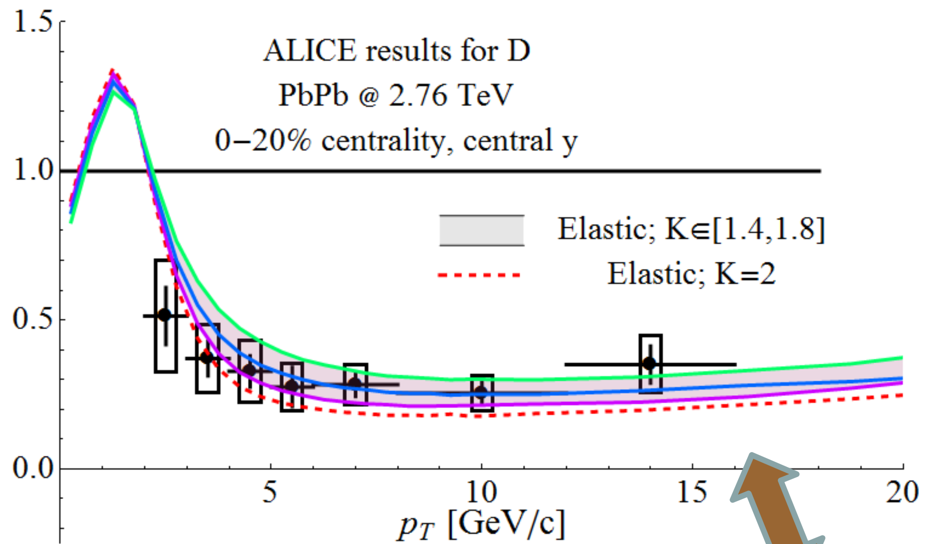
Lesson it is possible to reveal some fundamental property of QGP using HQ probes, i.e. to CONTROL the models

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

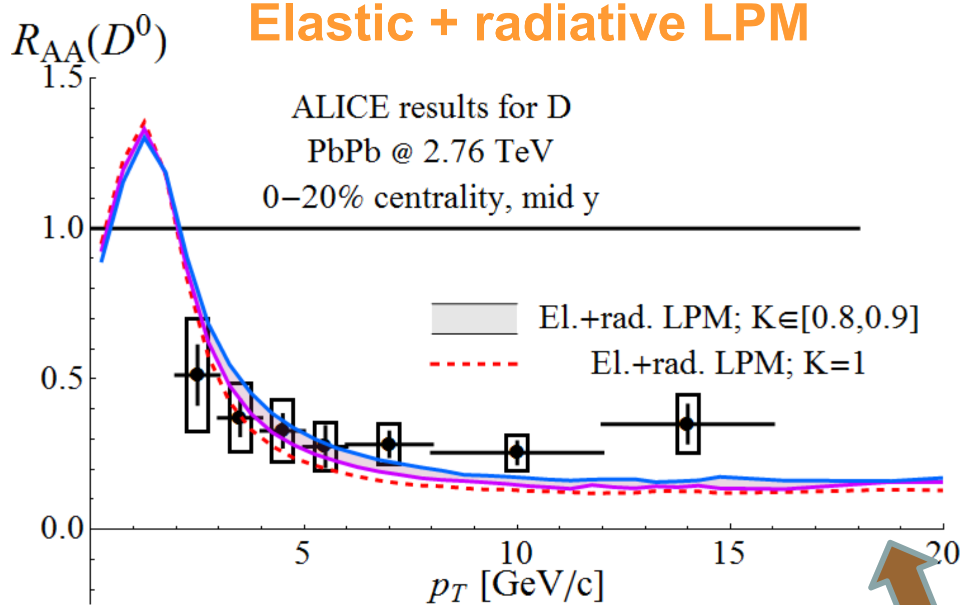
Same microscopic ingredients as for RHIC; NO SHADOWING (yet)

Kolb-Heinz Hydro adjusted to dN_{ch}/dy = 1600 (s0=195)… at our own risks !

Elastic



Elastic + radiative LPM



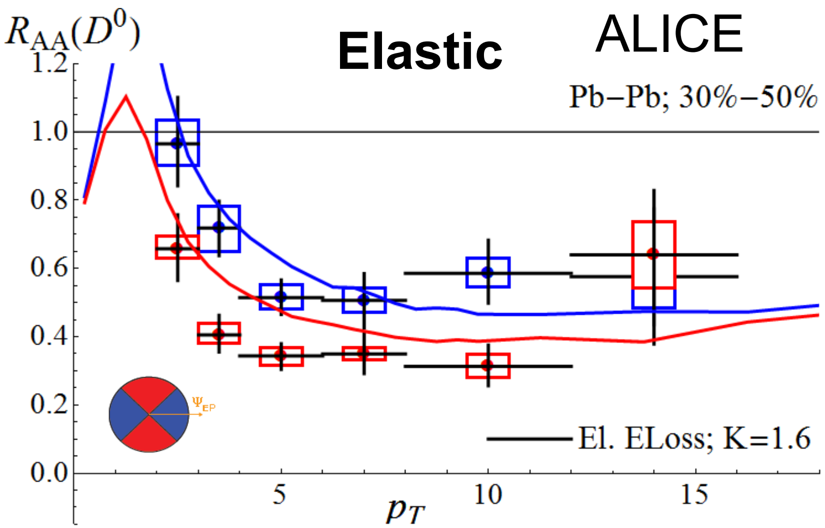
K	NPSE RHIC	D STAR central	D STAR min bias	D ALICE 0-20% (pT<15GeV/c)
1.4				
1.6				
1.8				
2.0				
2.2				

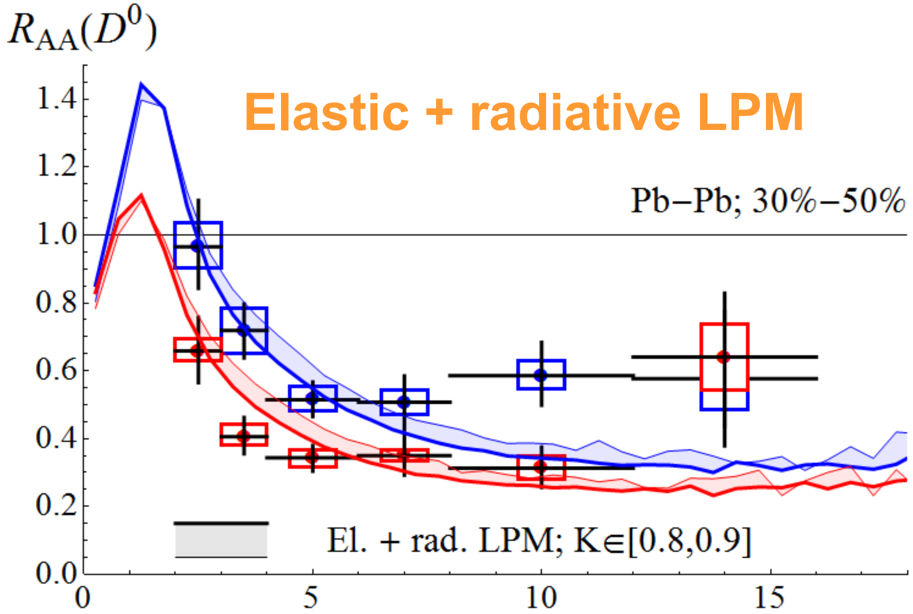
K	NPSE RHIC	D STAR central	D STAR min bias	D ALICE 0-20% (pT<15GeV/c)
0.7				
0.8				
0.9				
1				
1.1				

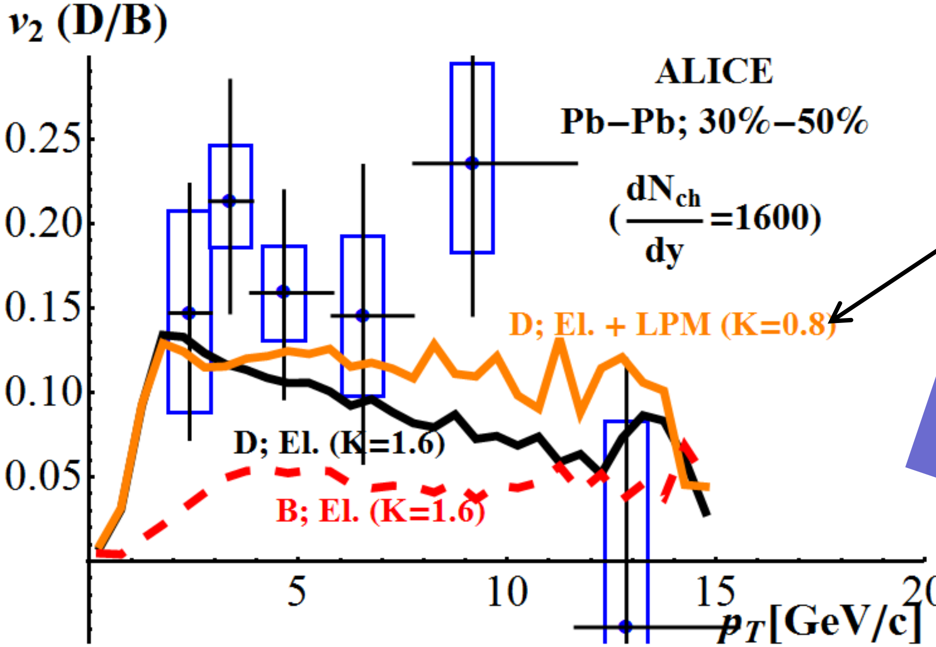
Correct agreement with ALICE data; 10-15% decrease of the rates needed for optimal agreement (does not imply the medium is more transparent, as $T_{LHC}>T_{RHIC}$)

D mesons at LHC (more differential observables)

"in plane" – "out of plane" analysis







V_2(B): PREDICTION

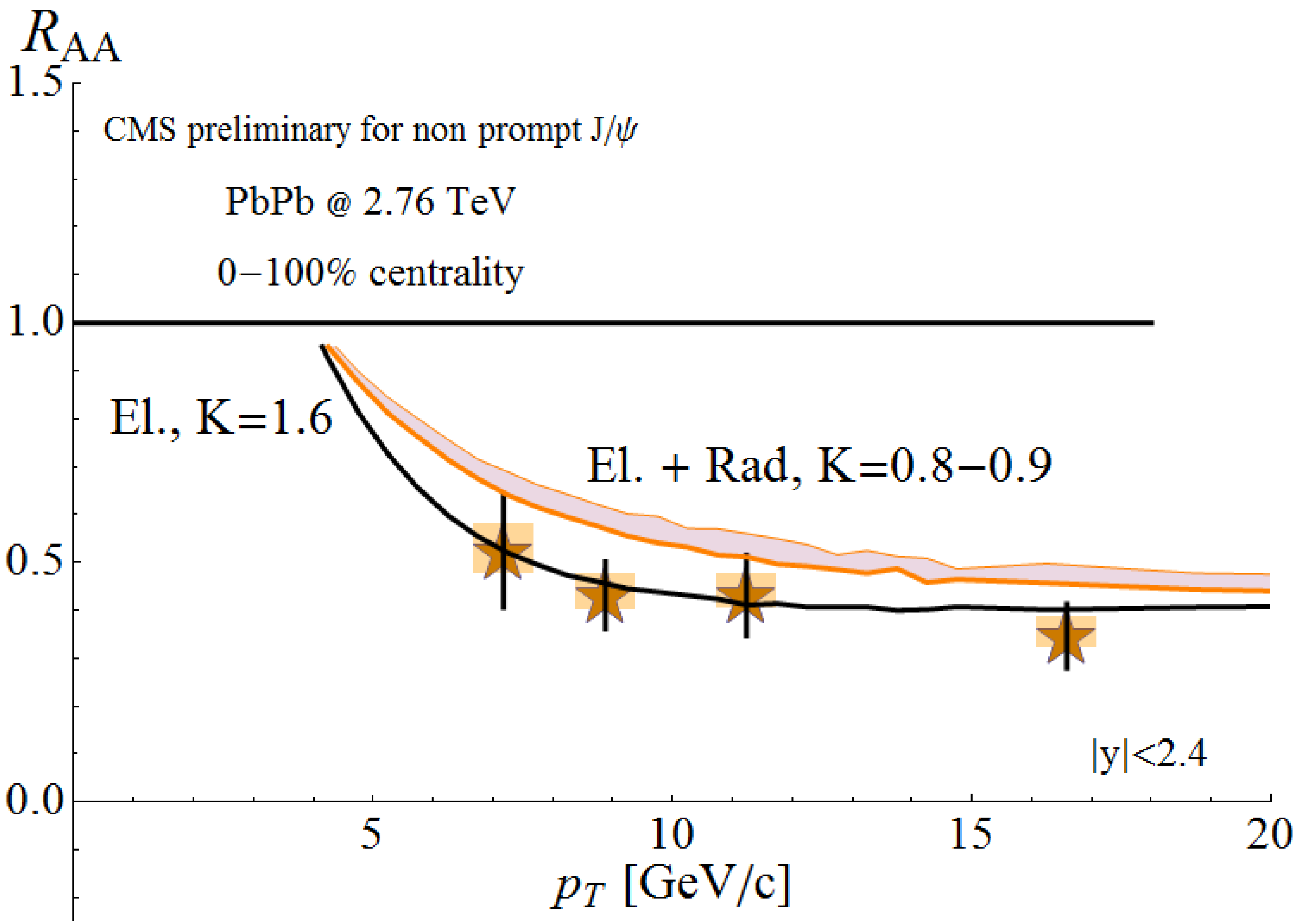
Some systematic trends: el. + rad. LPM shows more coupling… sensitive to larger *x* in the radiation spectra

B mesons at LHC

Same ingredients as for RHIC

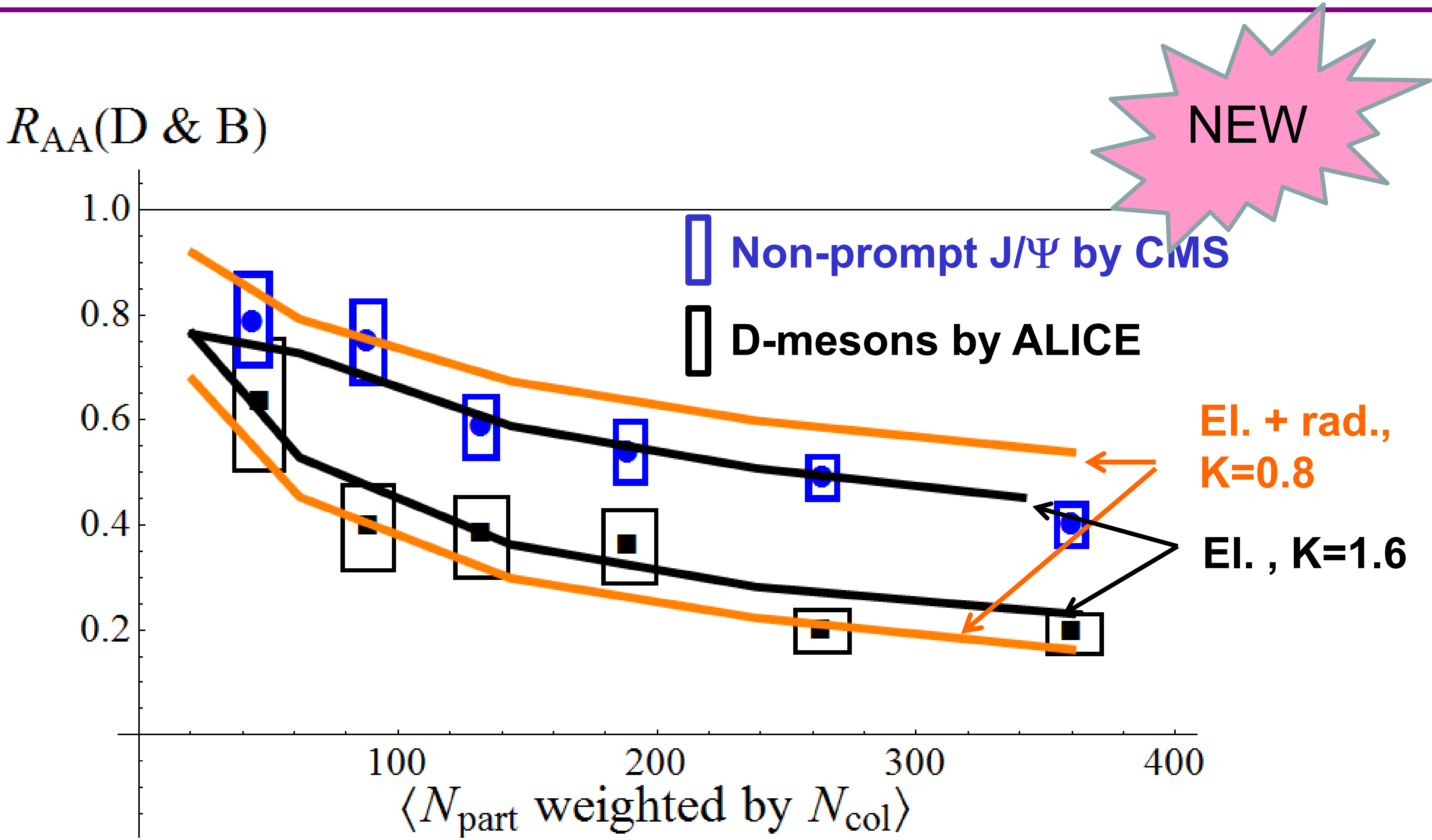
Kolb-Heinz Hydro ajusted to $dN_{ch}/dy = 1600$;

No shadowing



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

D & B mesons at LHC



Centrality dependence well reproduced

Conclusions from LHC (from the KH background)

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

➢ **In particular: NO TENSION between v_2 and R_{AA} *in the same p_T range* !**

➢ 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 (from the KH background)

- **Data at intermediate p_T are well reproduced with minimalistic modifications of the model(s).**
- **In particular: NO TENSION between v_2 and R_{AA} *in the same p_T range* !**
- 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…

… awakening might be bitter!

Results for EPOS2 Background

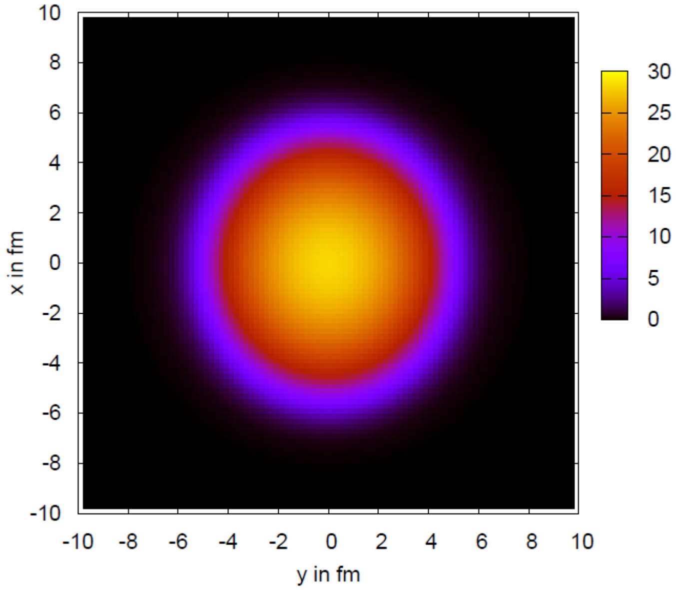
NEW

Full manuscript available soon

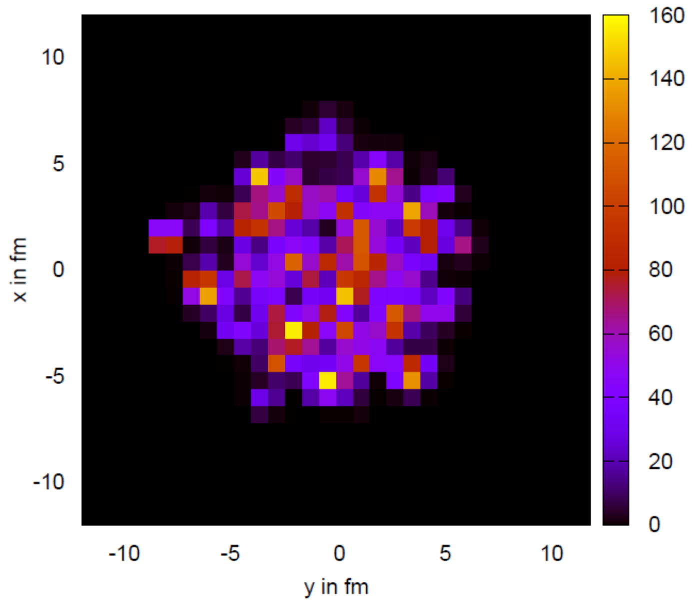
EPOS as a background for MC@sHQ

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

Initial energy density @ RHIC (central Au-Au)



Kolb Heinz



Beware: ≠ color scales

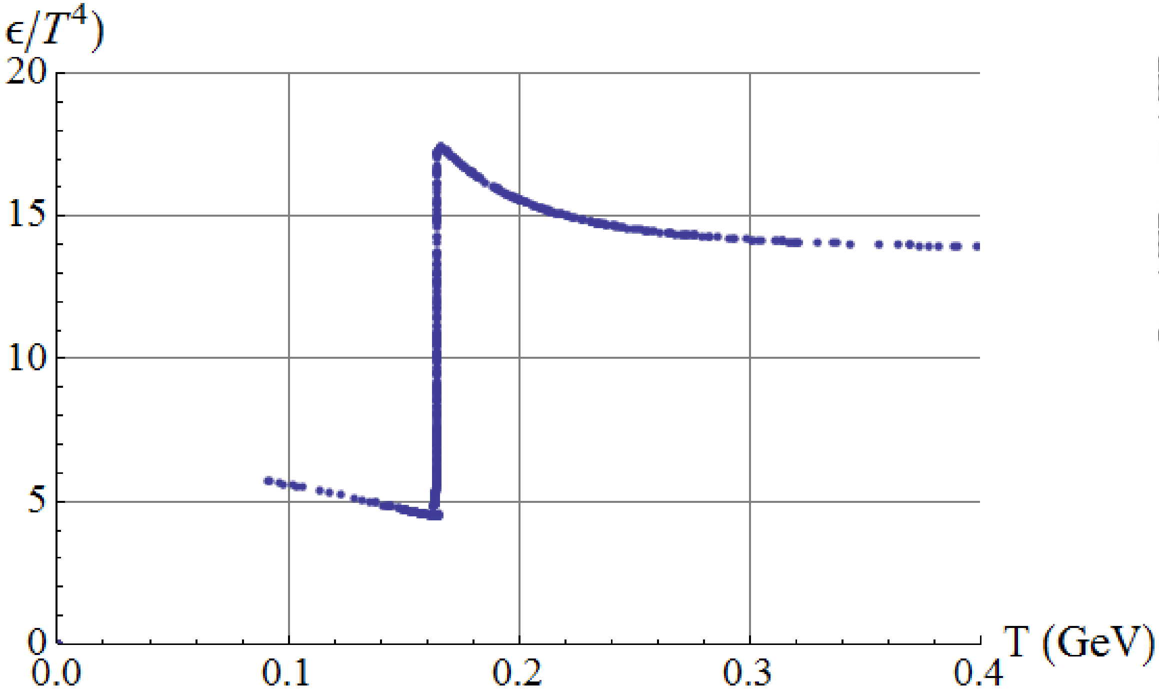
EPOS2 (still ideal hydro; viscous effect modelled by artifially large radius of the flux tubes)

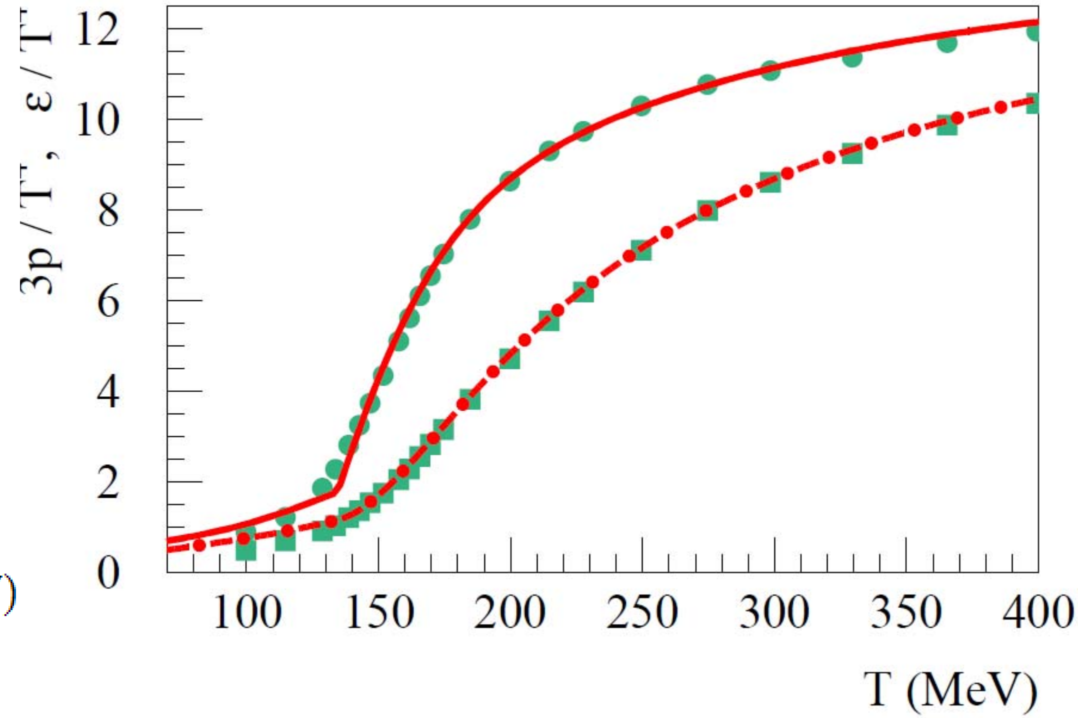
More realistic hydro and initial conditions => original HQ studies as:

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 !

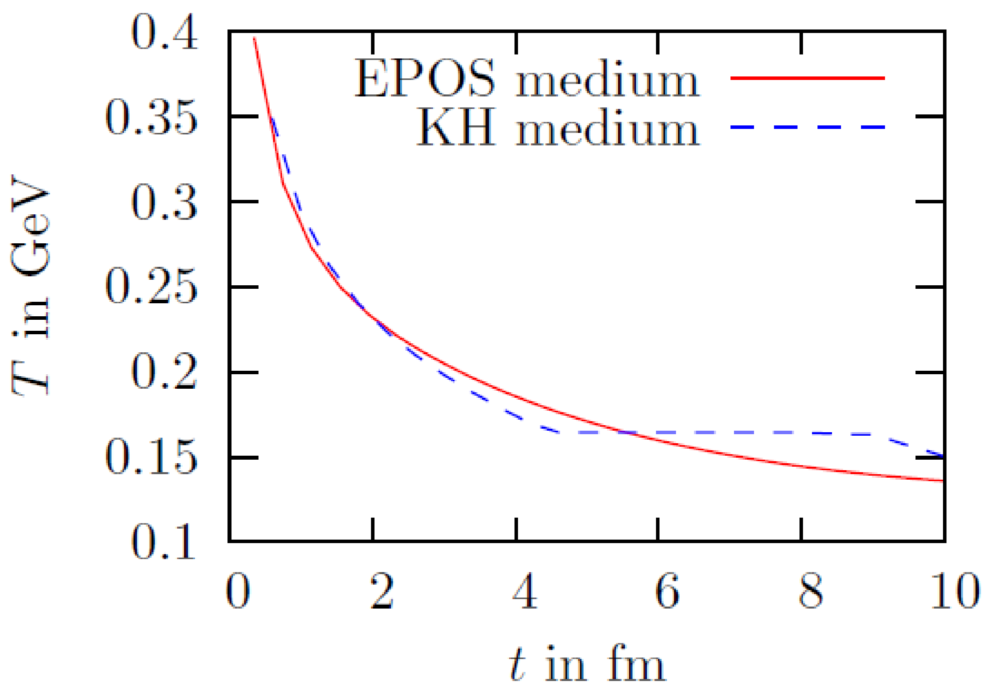


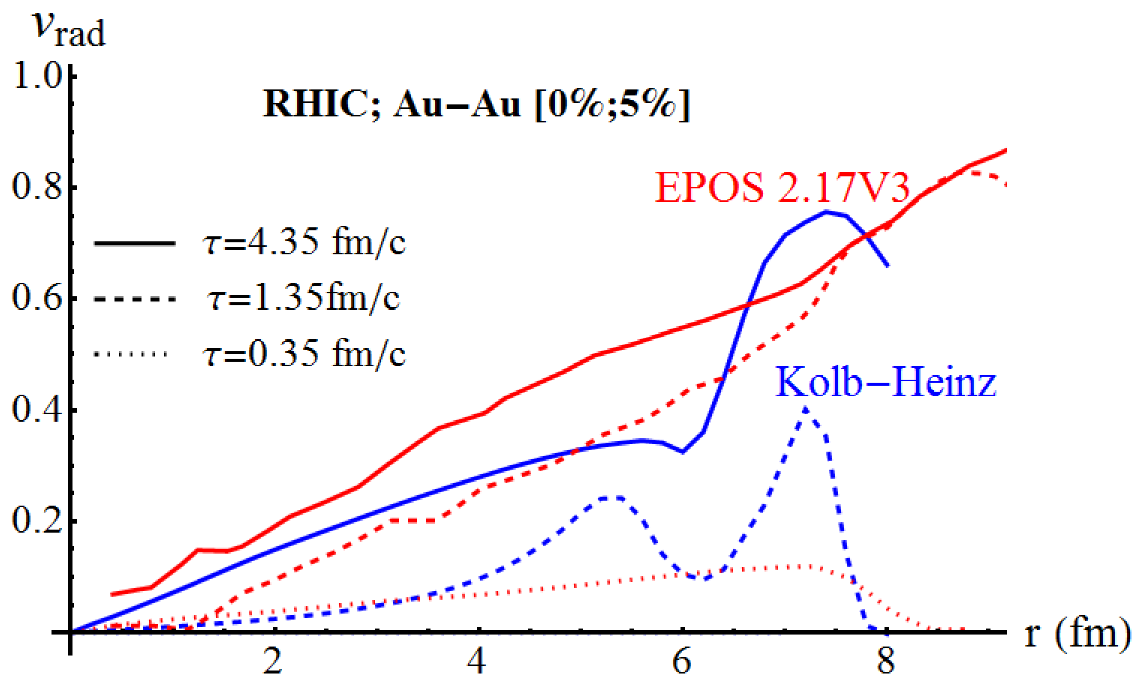


Kolb Heinz: bag model (1rst order transition btwn hadronic phase and massless partons)

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

Medium comparison at RHIC

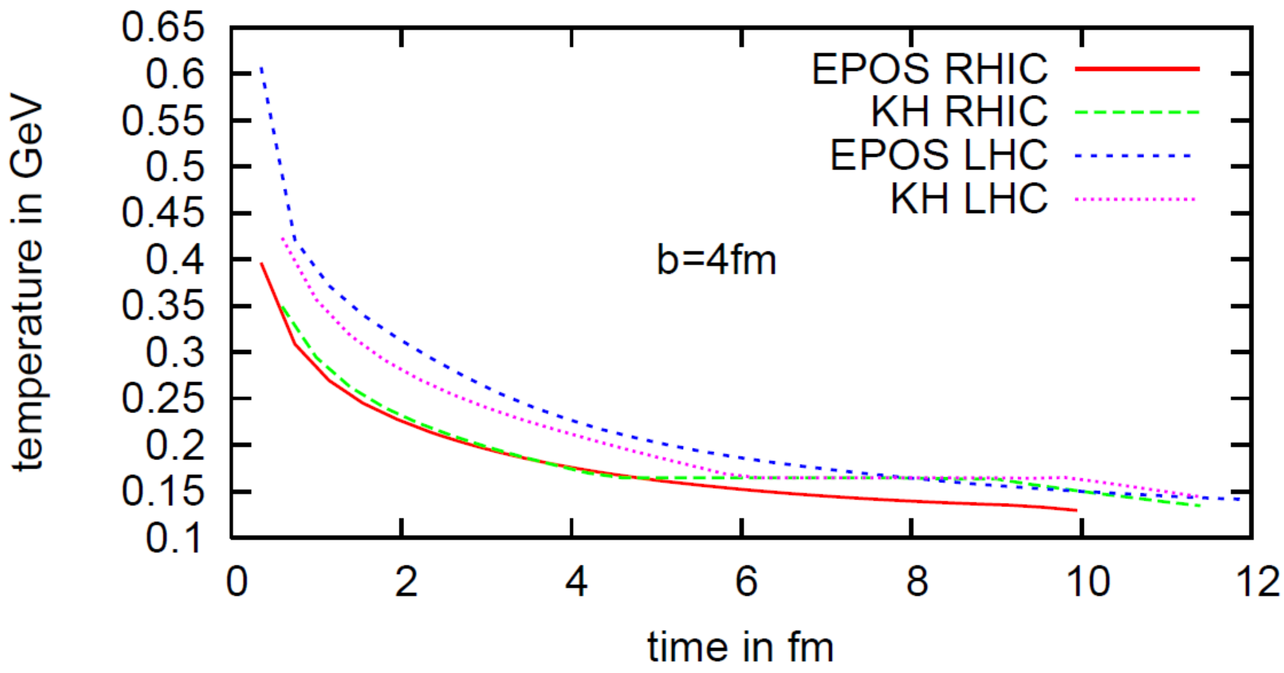


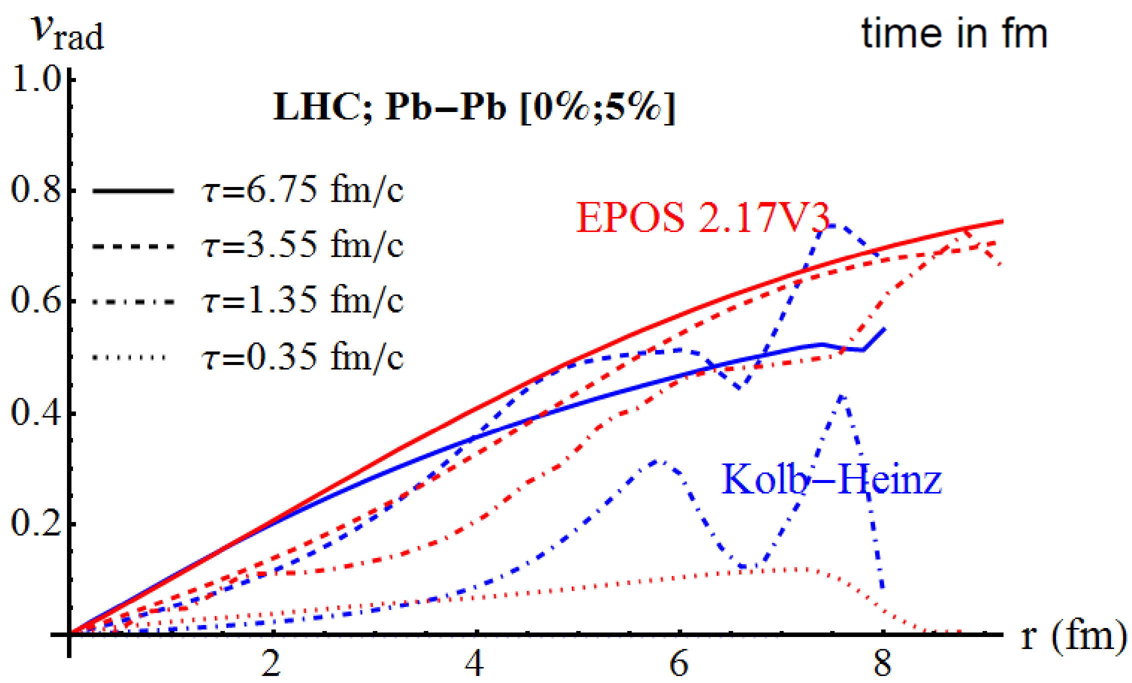


Gross features of T-evolution are identical in the « plasma » phase (T>200 MeV)

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

Medium comparison at LHC

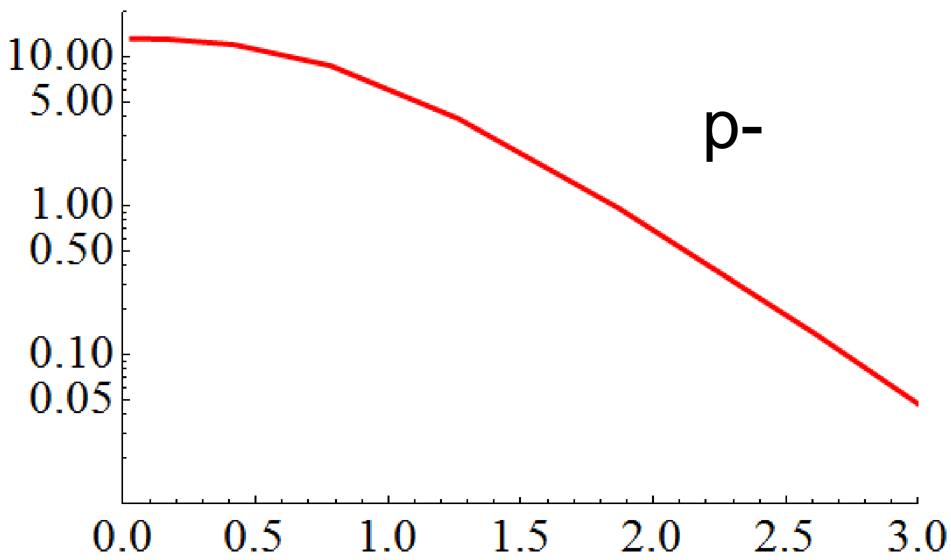




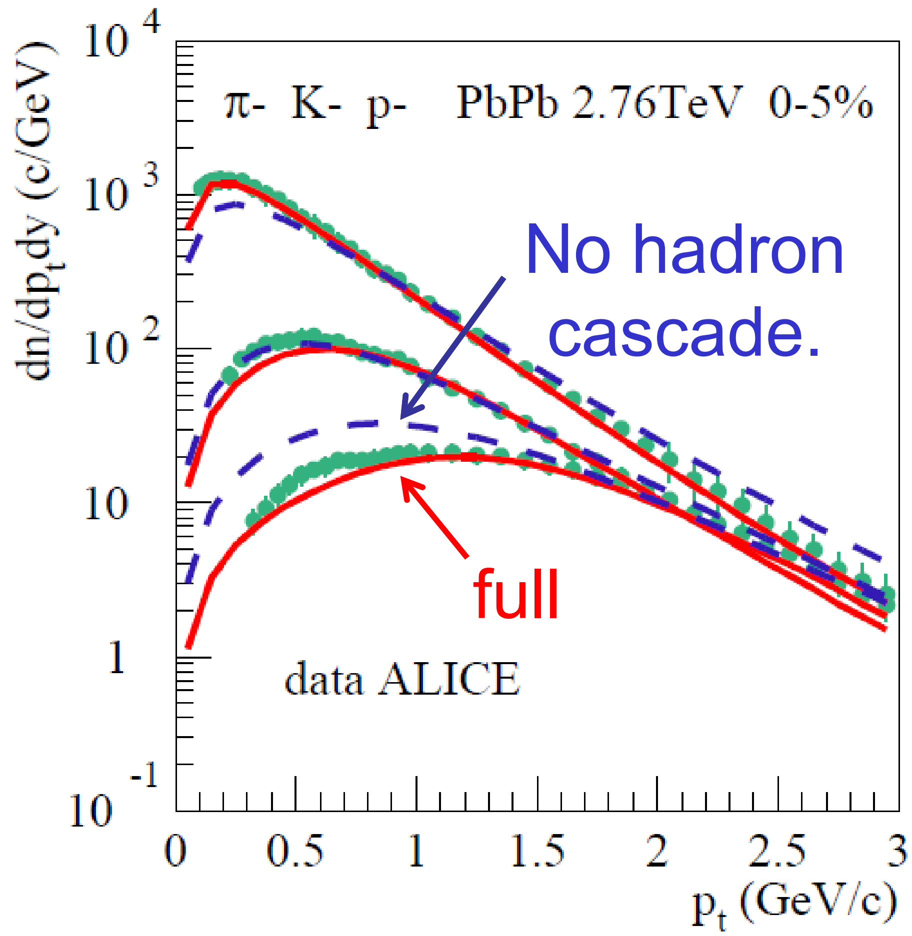
EPOS2 hotter and more explosive than Kolb-Heinz !

Identified particles spectra at LHC

KH, b=3fm



EPOS2.17V3



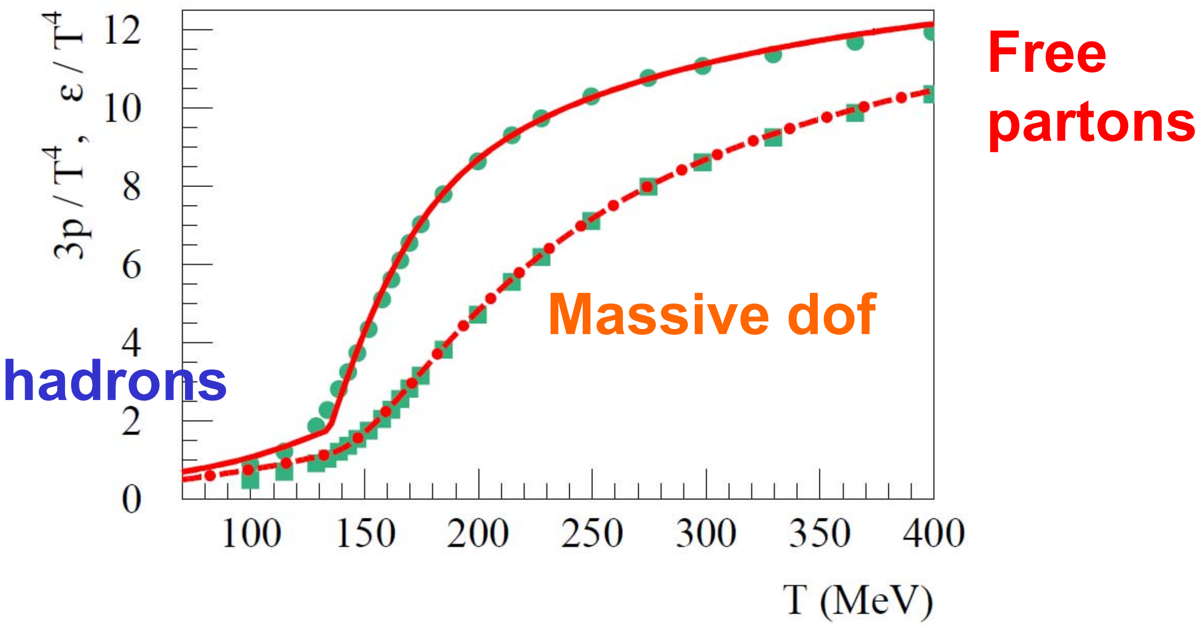
Phys. Rev. C 85, 064907 (2012)

Lack of radial flow in KH has large consequences on observables

Coupling EPOS and MC@$_s$HQ

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 between hadronic phase and QGP.

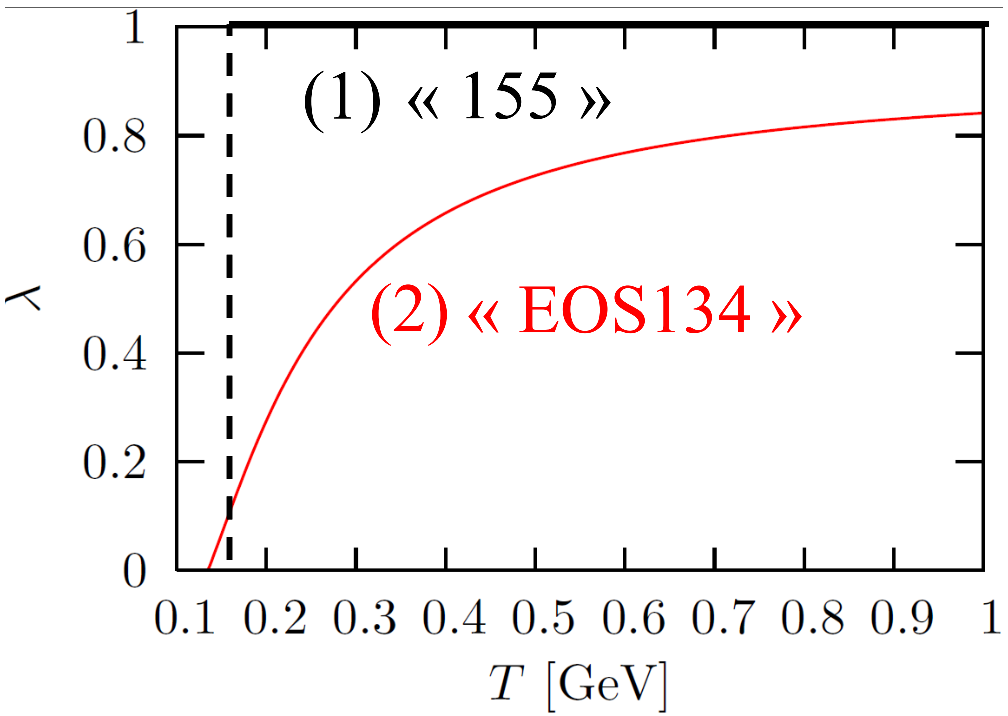


See as well: H. Berrehrah (arXiv:1308.5148) Collisional processes of on-shell and off-shell heavy quarks in vacuum and in the Quark-Gluon-Plasma

Coupling EPOS and $MC@_sHQ$

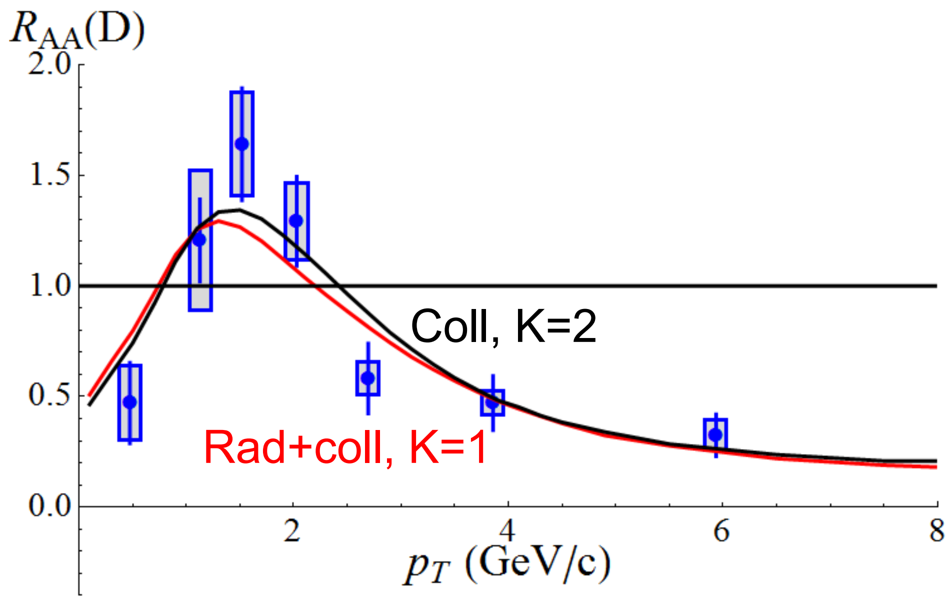
For the time, 2 prescriptions:

1) Interactions as in KH medium (evaluated with masless partons) down to T_c=155MeV (in the bulk 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 T_c=134MeV (value at which λ=0)

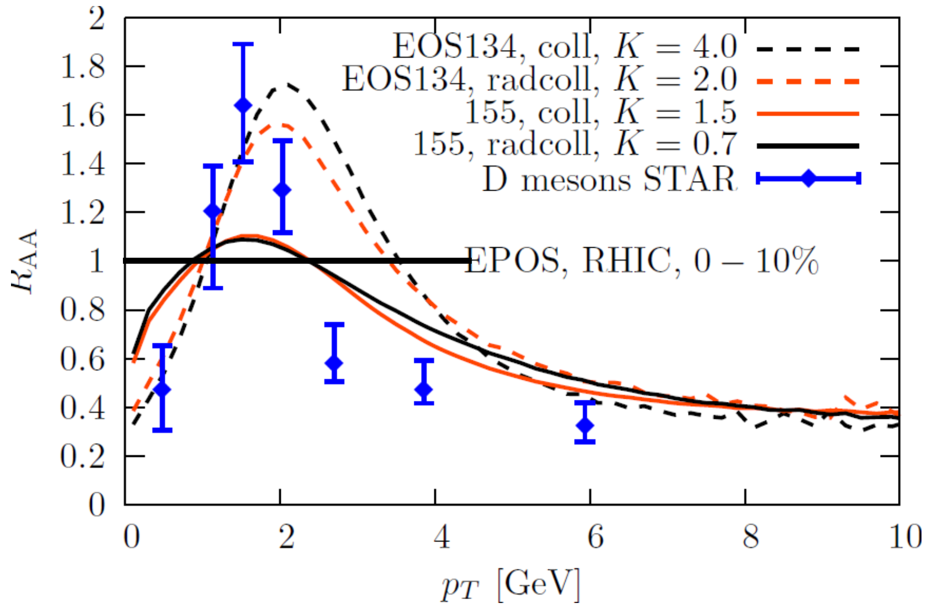


Some EPOS2+MC@$_s$HQ results at RHIC

KH background



EPOS background + reduction of dof



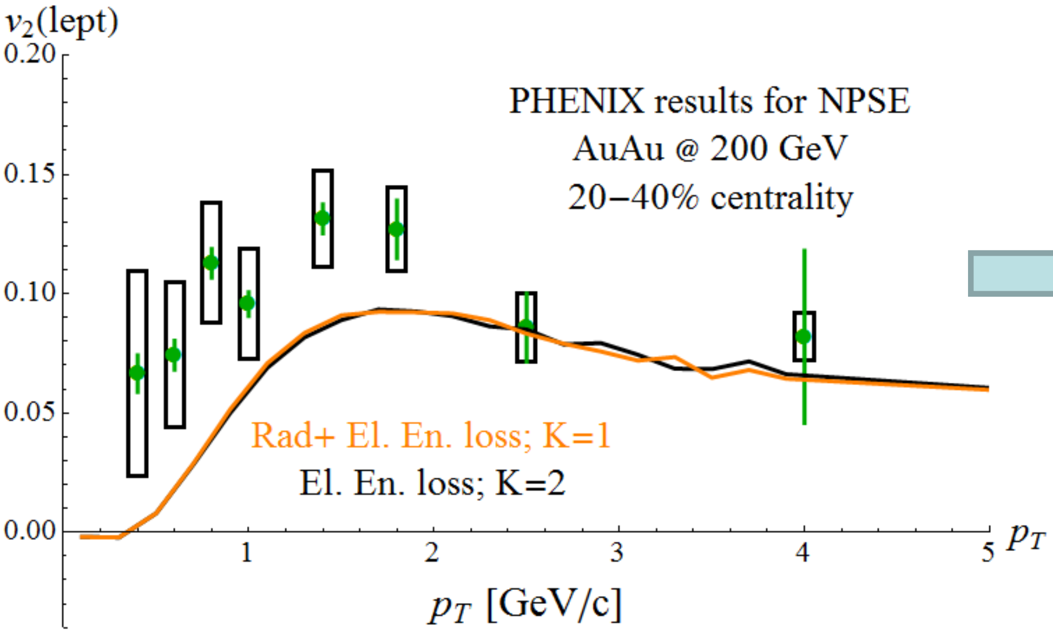
Slightly larger radial flow in EPOS

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

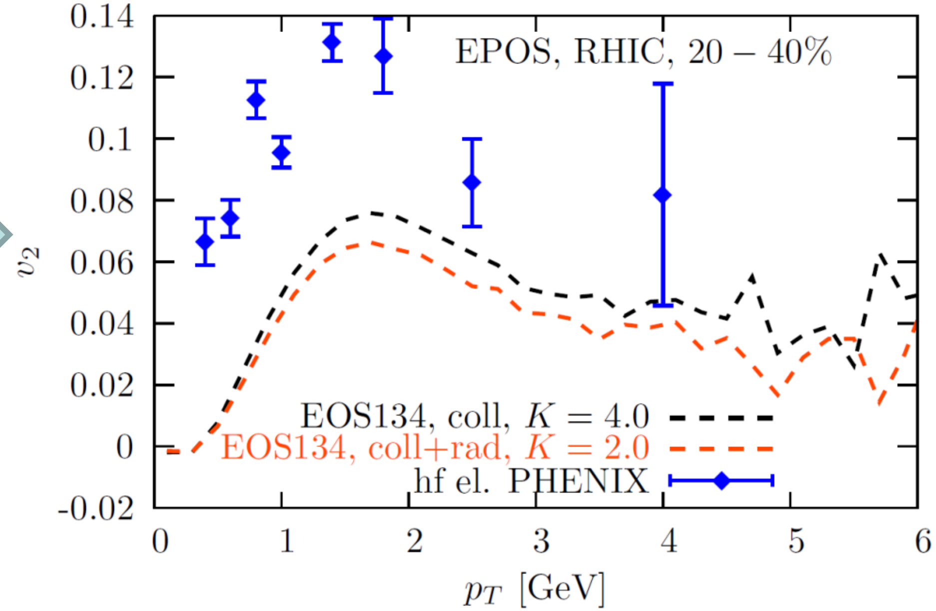
Room to investigate the role of hadronic degrees of freedom above phase space (see also arxiv 1305.6544, accepted for publication in PRC)

Some EPOS2+MC@$_s$HQ results at RHIC

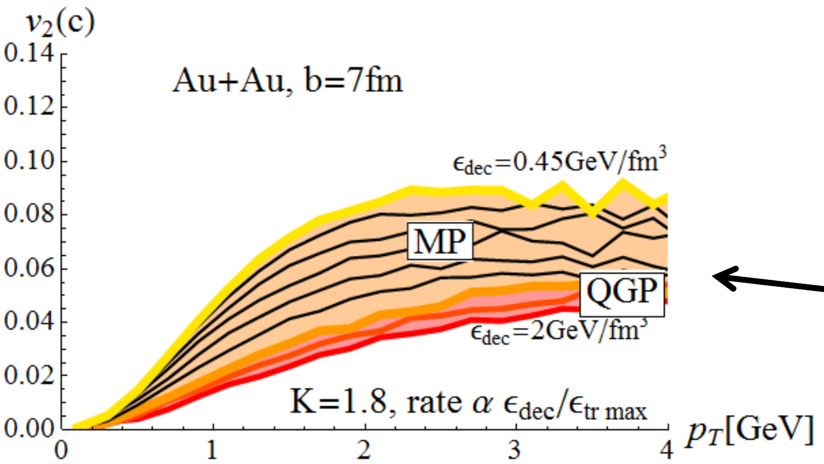
KH background



EPOS background + reduction of dof



Elliptic flow is reduced by ≈1%



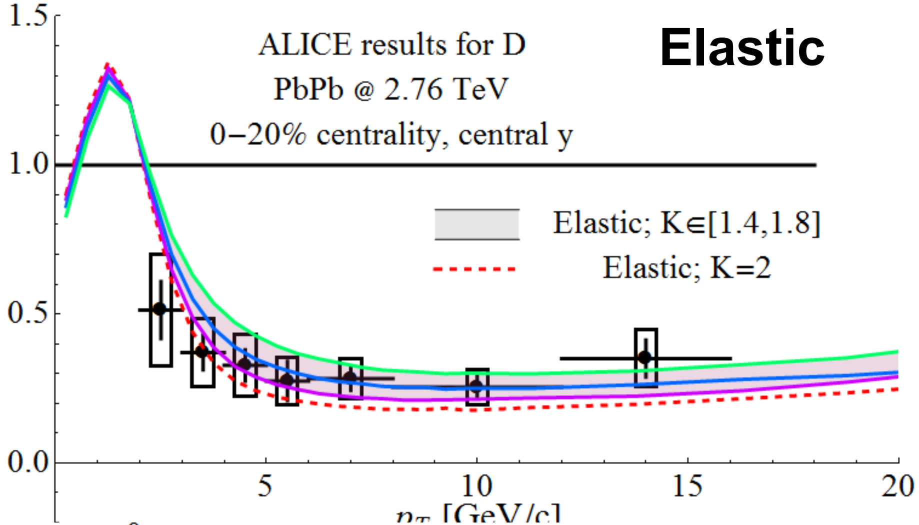
Systematic underprediction of v_2, … which develops continuously in time. Probably need for hadronic afterburner in order to reach experimental values.

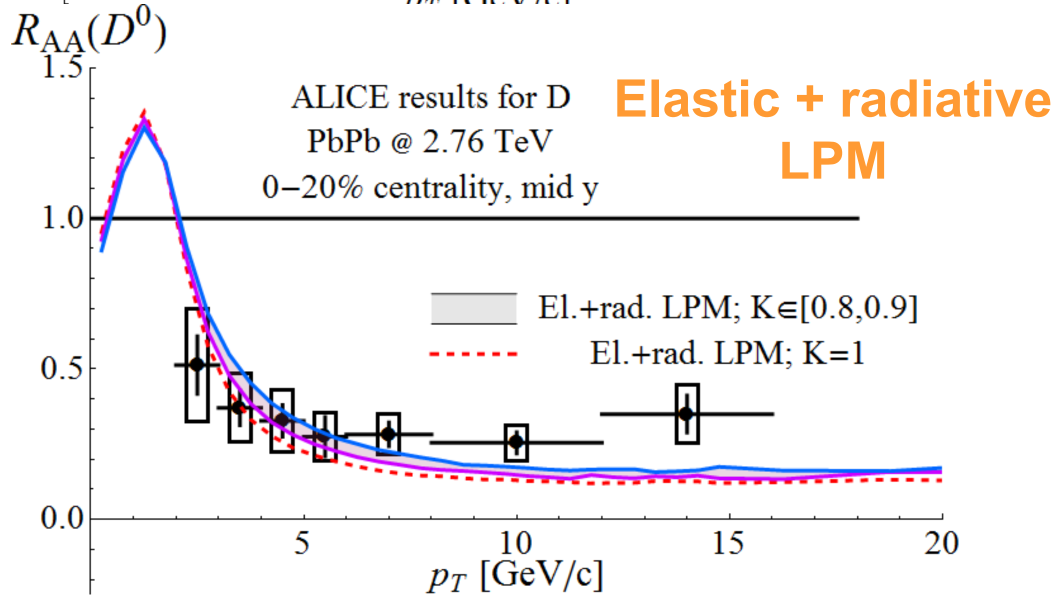
Some EPOS2+MC@$_s$HQ results at LHC

AGAIN: NO SHADOWING (yet)

Kolb-Heinz Hydro (dN_{ch}/dy = 1600)

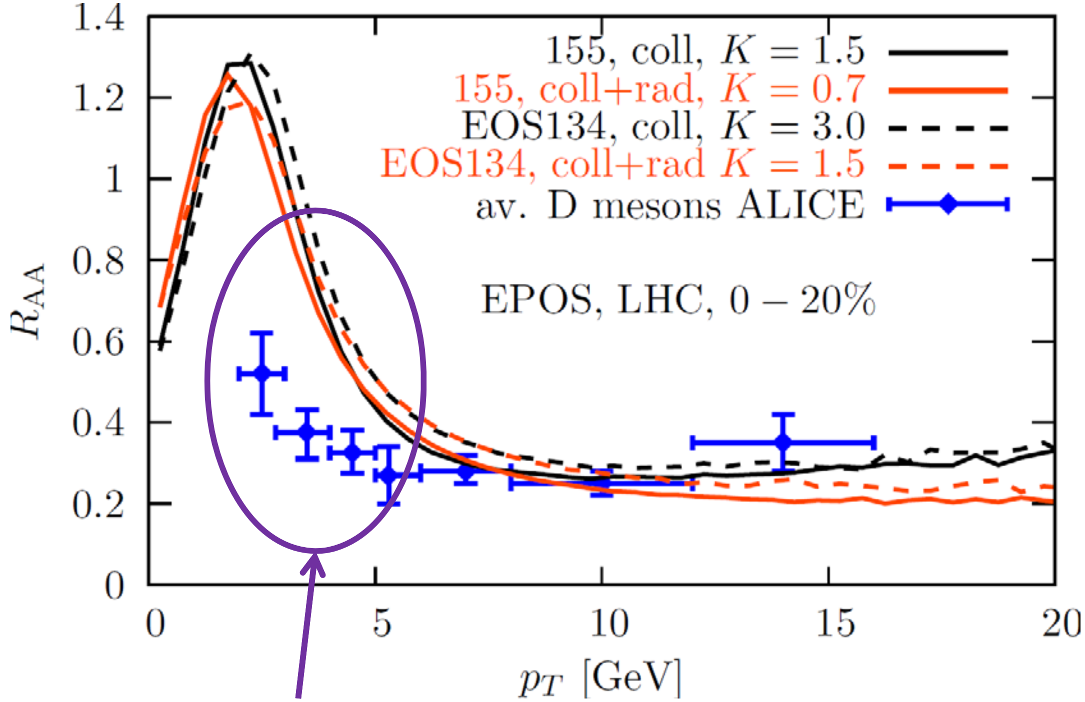
K close to unity if rad + col considered





EPOS background

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



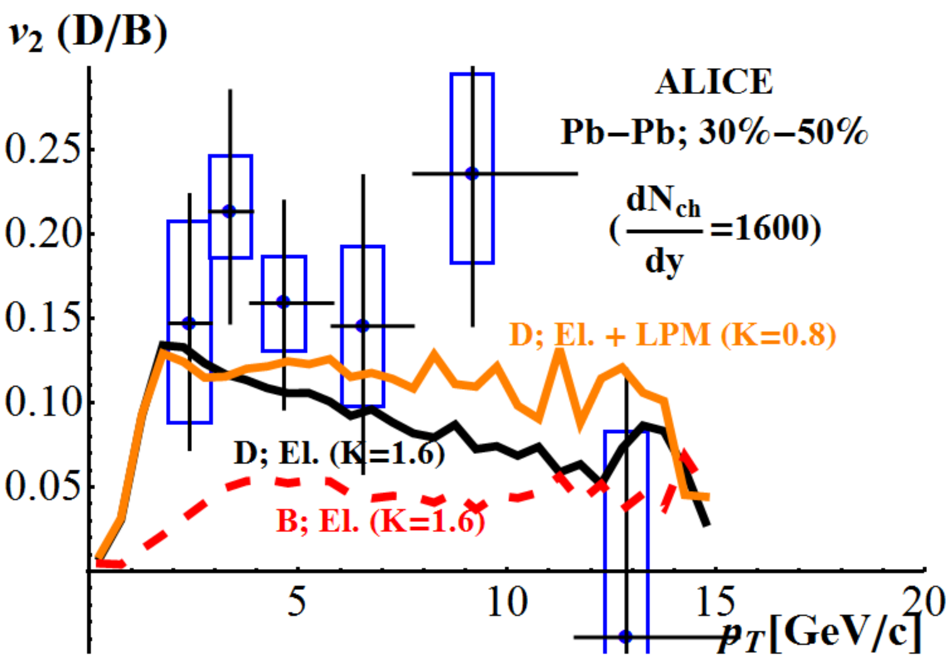
Large push from radial flow; discrepancy unlikely to be explained by shadowing alone.

Concern: Need to revisit the model for small p_T ?

Some EPOS2+MC@$_s$HQ results at LHC

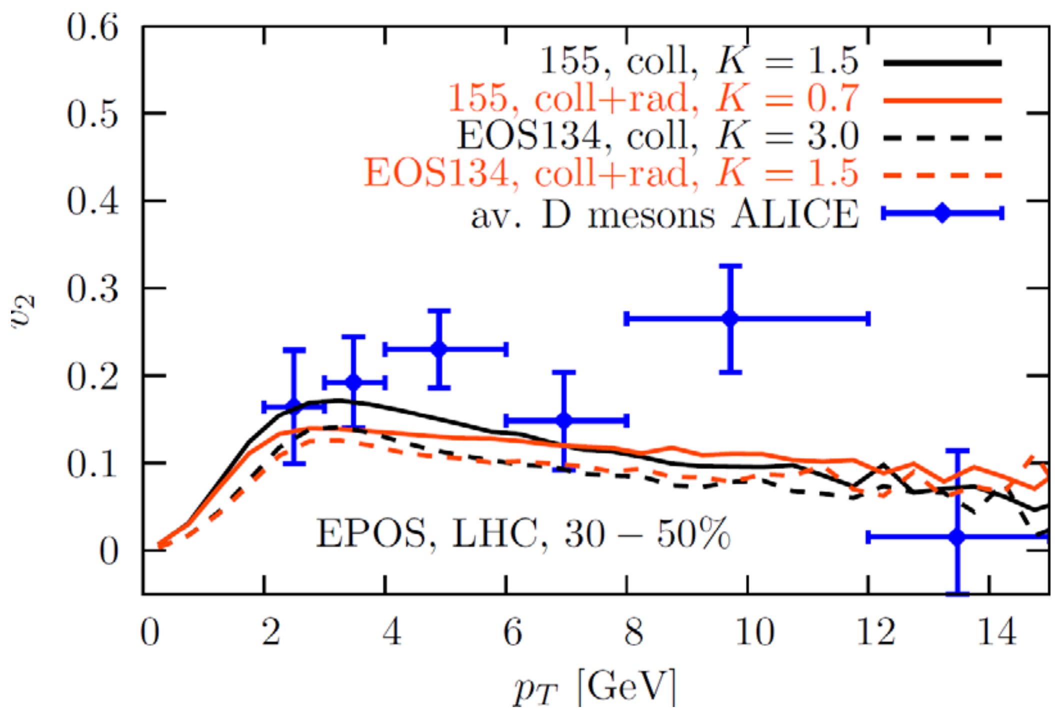
Kolb-Heinz Hydro (dN_{ch}/dy = 1600)

K close to unity if rad + col considered



EPOS background

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



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

Lessons, Answers & Perspectives

- As compared to the experimental data; larger discrepancy at small p_T using more realistic EPOS2. Lesson 1: Improving one component of your model does not always help to gain agreement with experiment (GOOD !)

- **Can the experimental HQ results be understood by pQCD-inspired models ?**
  Mostly YES

LHC opens the window for disentangling between various models although it requires more precision from the experiments.

- **Can the experimental results be understood by pQCD-inspired models using realistic backgrounds ?**

More challenging! 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 jointly !

- Perspectives: 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, viscous medium,…)

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