Recent developments for open heavy flavor observables in URHIC

NED & TURIC network-workshop

Hersonissos (Crete - Greece) ; 9-14 June 2013

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collaborators

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J. Aichelin, …

Recent developments for open heavy flavor observables in URHIC

Unknown work on right-handed neutrino physics ?

J. Aichelin, …

Recent developments for open heavy flavor observables in URHIC

For sure, famous for his works on strange quarks (& exotic pull-overs)…

J. Aichelin, …

Recent developments for open heavy flavor observables in URHIC

But mostly known (to me) for his physics on charm

J. Aichelin, …

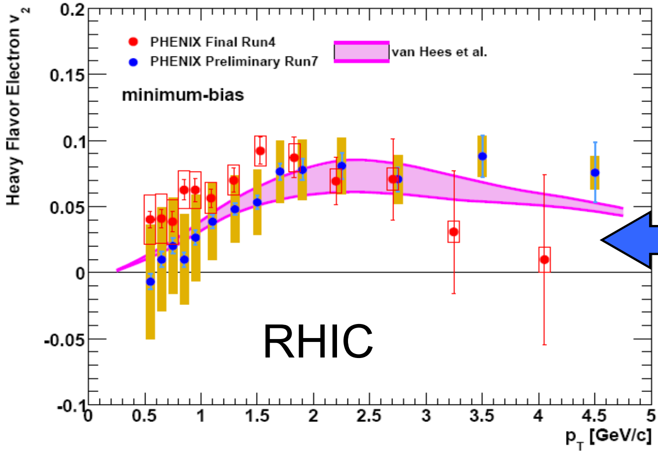
Recent (*and not so recent*) developments for open heavy flavor observables in URHIC

But mostly known (to me) for his physics on charm

J. Aichelin, …

Why *open* heavy flavors in A-A ?

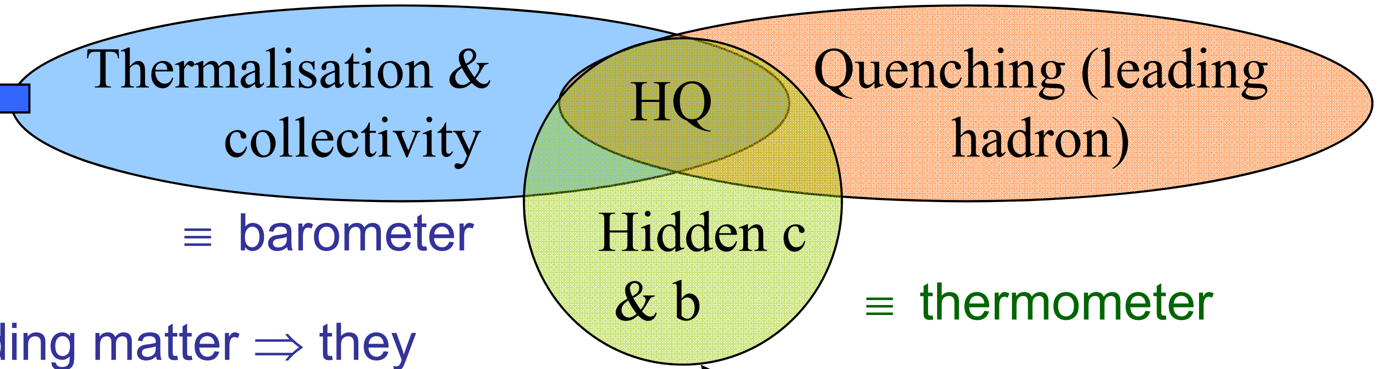
- Those are for sure sensitive to the early stages
- Much simpler then quarkonia and also sensitive to the medium properties (t_{equil} (α M_Q/T^2) $\Rightarrow$ clear hierarchy for s, c and b).
- Mandatory to understand Q-Qbar evolution in QGP & quarkonia product.



HQ are imbedded in expanding matter $\Rightarrow$ they participate to collective motion and gain elliptic flow (v_2:azimutal asymmetry) at finite b

The Trilogy:

≡ densitometer



≡ barometer

≡ thermometer

Quarkonia suppression and Dimuons product; heavy Q thermal production

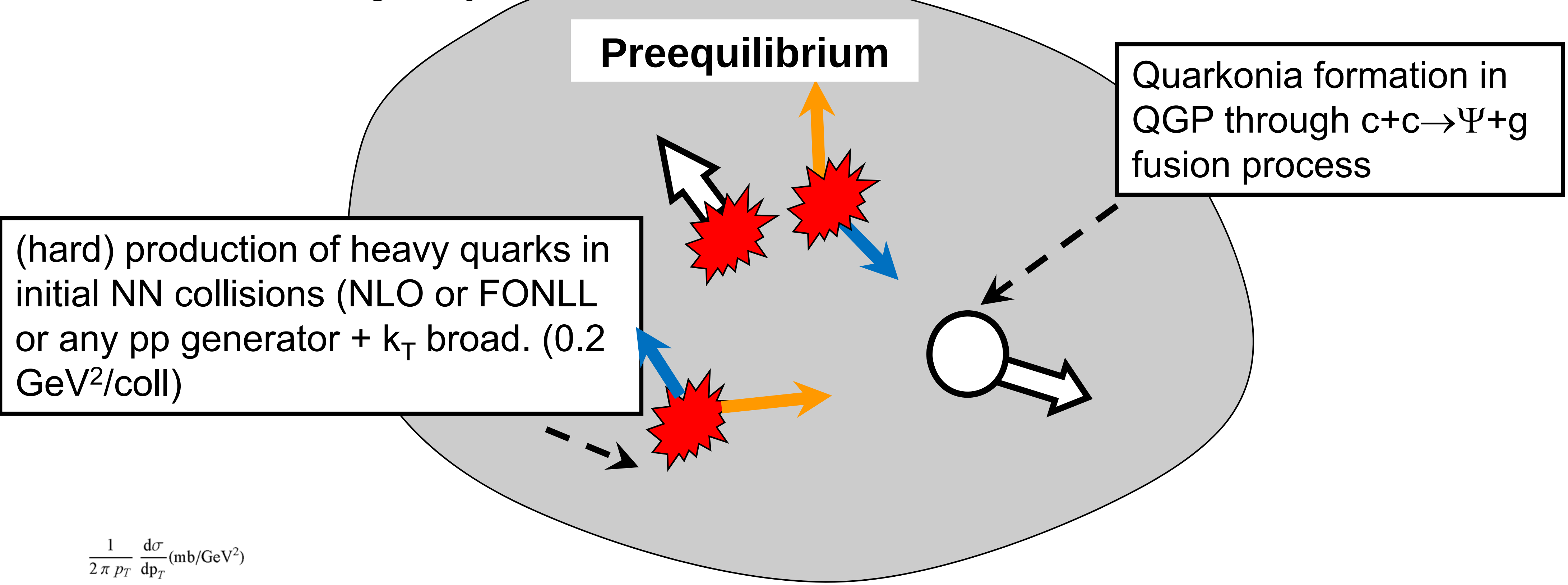
Challenges:

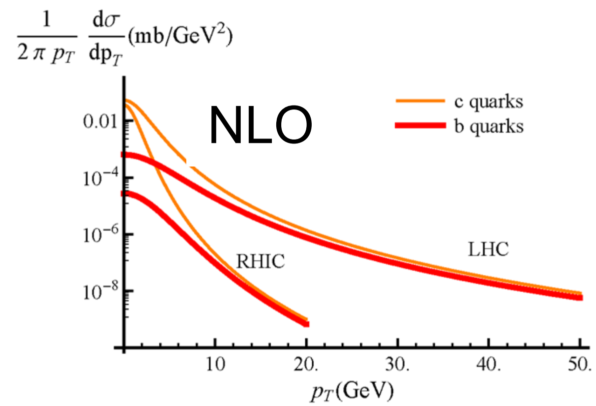
- Description of HQ E-loss / equilibration from fundamental theory
- Joint v_2-R_{AA} explanation could help to better constrain free parameters…

The Monte Carlo @ Heavy Quark Generator

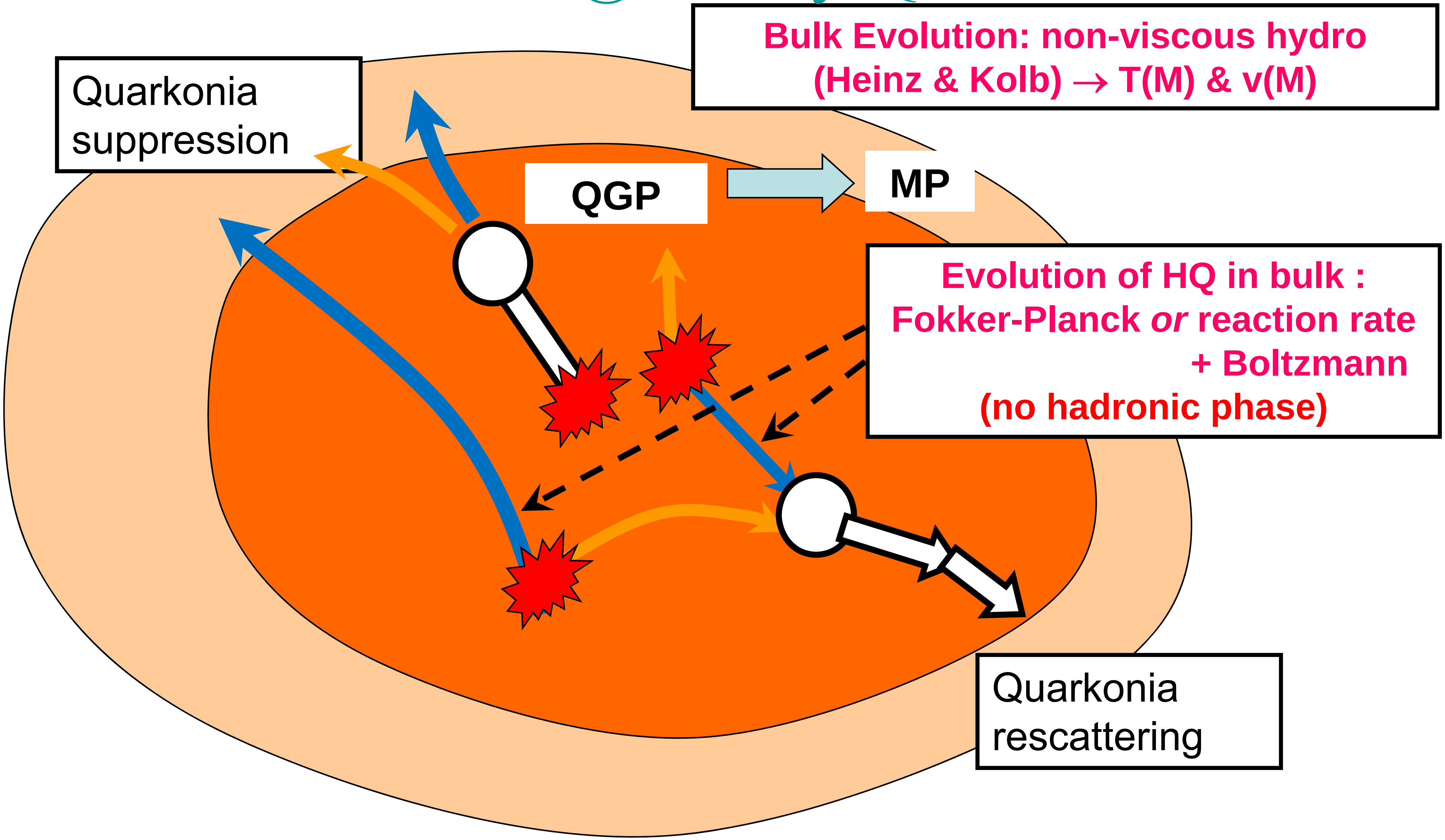
No force on HQ before thermalization of QGP (0.6 fm/c)

Evolution according to Bjorken time





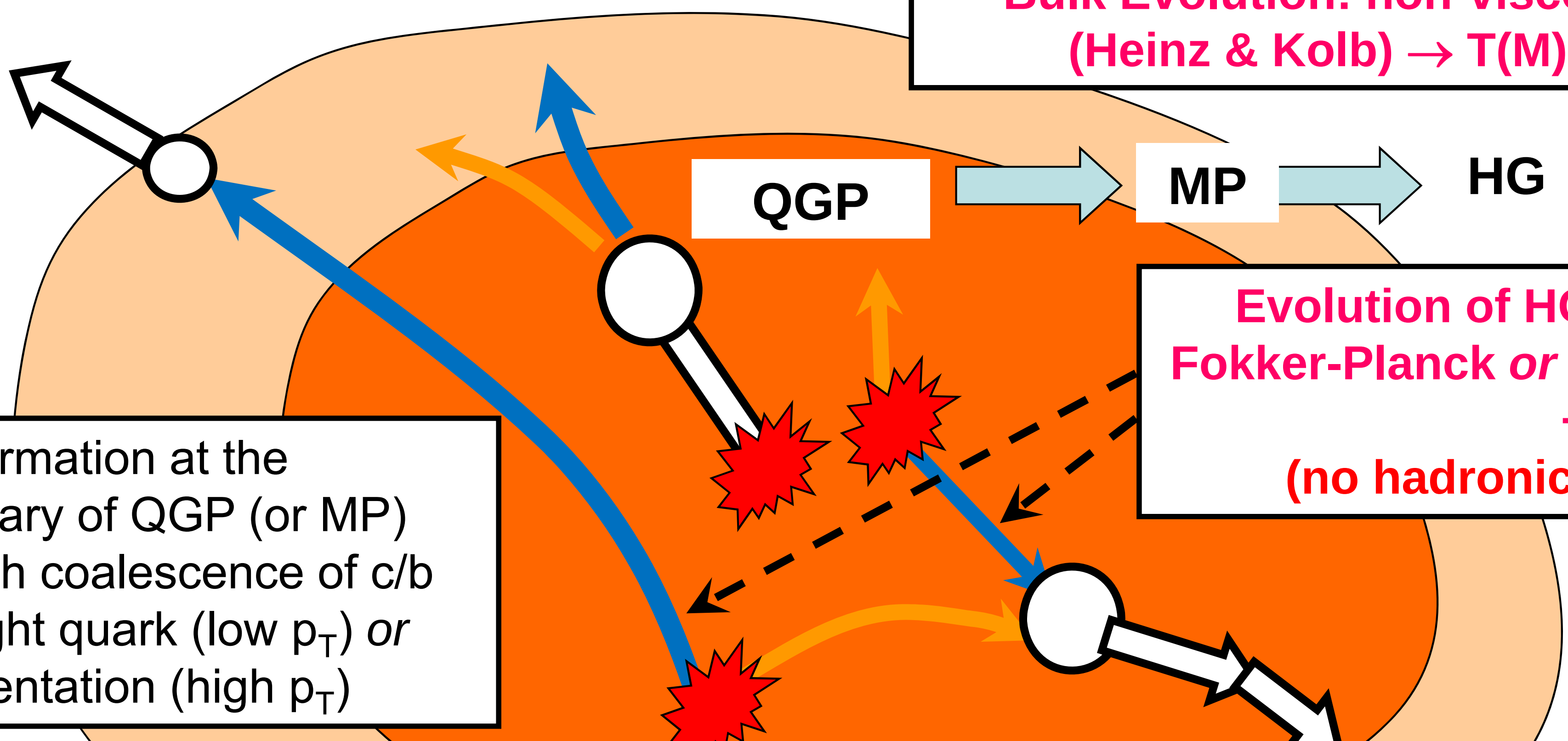
The Monte Carlo @ Heavy Quark Generator



Recently : coupling to EPOS instead of KH: some point still to be solved

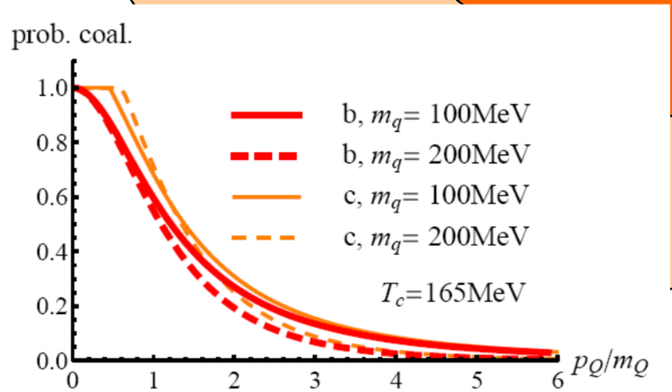
The Monte Carlo @ Heavy Quark Generator

Bulk Evolution: non-viscous hydro (Heinz & Kolb) → T(M) & v(M)



Evolution of HQ in bulk : Fokker-Planck *or* reaction rate + Boltzmann
(no hadronic phase)

D/B formation at the boundary of QGP (or MP) through coalescence of c/b and light quark (low p_T) *or* fragmentation (high p_T)



Nothing spectacular at freeze-out
(quarkonia are white objects already)

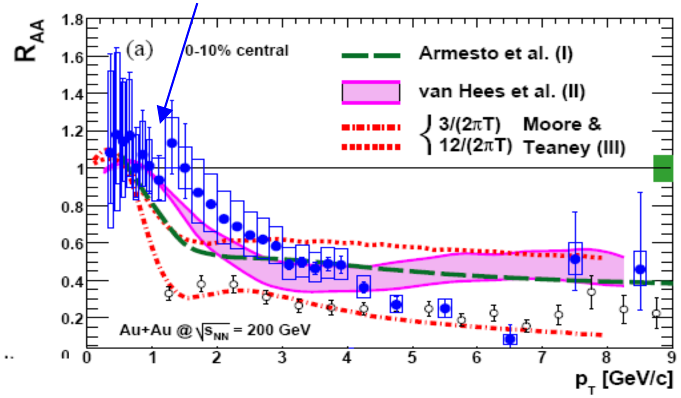
Setting the scene: E-Loss and thermalization

(init) $P_T \approx m_Q$

- Bulk part of Q production
- E gain becomes probable
- HQ scatter and can thermalize with the medium
- very ≠ from light quarks
- *Dominated by collisional processes*
- Non perturbative effect (small momentum transfert, coalescence with light quark)
- 1 dominant parameter: D_s

(Langevin Transport)

Phenix data (hep-ex 0611018)



(init) $P_T >> m_Q$

- Rare processes
- Mostly E loss
- HQ go on nearly straight lines and probe the opacity of matter. Little thermalization
- **~ light quarks**
- *Coherent radiative + collisional processes*
- Good test of pQCD… Theory at work (a priori)
- Several transport coefficients implied (dE/dx, B_T,…)

… but one should however avoid to mix those two worlds !!!

The early times… (2004-2006)

Charmonia enhancement in QGP with improved description of c-quarks phase-distribution

SQM04

P.-B. Gossiaux (with V. Guiho & J. Aichelin)

2 extreme cases considered in early 2000's:

- PBM, Stachel, Andronic: SHM (c-quarks fully thermalized)
- Thews & Rafelski: "dynamical" coalescence with f(c) from PDF (no thermalization at all)

I) c-quarks in QGP

- Model
- Results Preliminary

II) J/Psi's in QGP

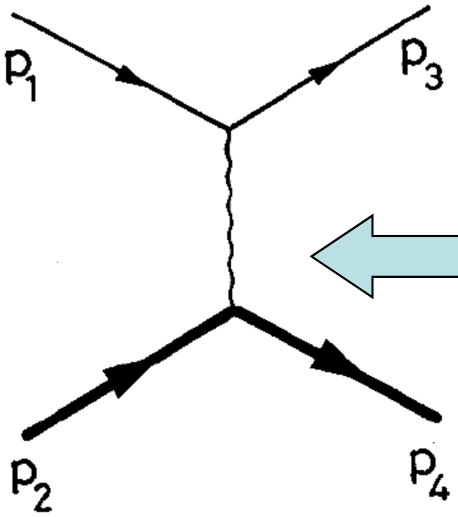
- Model
- Results Preliminary

III) Conclusion & Perspectives

SQM 2004

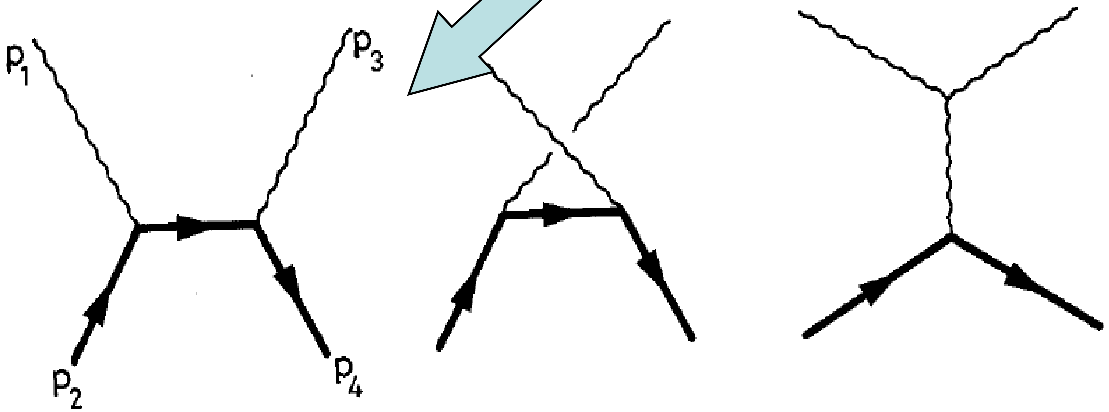
Cross sections

Starting from Combridge (79) as a basis:



$$\sum |\mathcal{M}|^2 = \frac{64\pi^2\alpha^2(Q^2)}{9}\,\frac{(M^2-u)^2+(s-M^2)^2+2M^2t}{t^2}$$

$$\sum |\mathcal{M}|^2 = \pi^2\alpha^2(Q^2)\Bigg[\frac{32\,(s-M^2)(M^2-u)}{t^2} + \frac{64}{9}\,\frac{(s-M^2)(M^2-u)+2M^2(s+M^2)}{(s-M^2)^2} + \frac{64}{9}\,\frac{(s-M^2)(M^2-u)+2M^2(M^2+u)}{(M^2-u)^2} + \frac{16}{9}\,\frac{M^2(4M^2-t)}{(s-M^2)(M^2-u)} + 16\,\frac{(s-M^2)(M^2-u)+M^2(s-u)}{t\,(s-M^2)} - 16\,\frac{(s-M^2)(M^2-u)-M^2(s-u)}{t\,(M^2-u)}\Bigg]$$



However, t-channel is IR divergent
=> modelS

$$\frac{1}{t} \rightarrow \frac{1}{t-\mu^2(T)}$$

Naïve pQCD (f.i. Svetitsky 89)

The early times… (2004-2006)

SQM 2004

C quarks in QGP (or in strongly interacting matter)

• Starting point: c quarks behave according to Brownian motion (cf. D. Molnar) / Langevin forces ⇔ c quarks distribution evolves according to Fokker – Planck equation

$$\frac{\partial f}{\partial t} = \vec{\nabla}_p \left[\vec{A} f + \vec{\nabla}_p \left(\vec{B} f \right) \right]$$

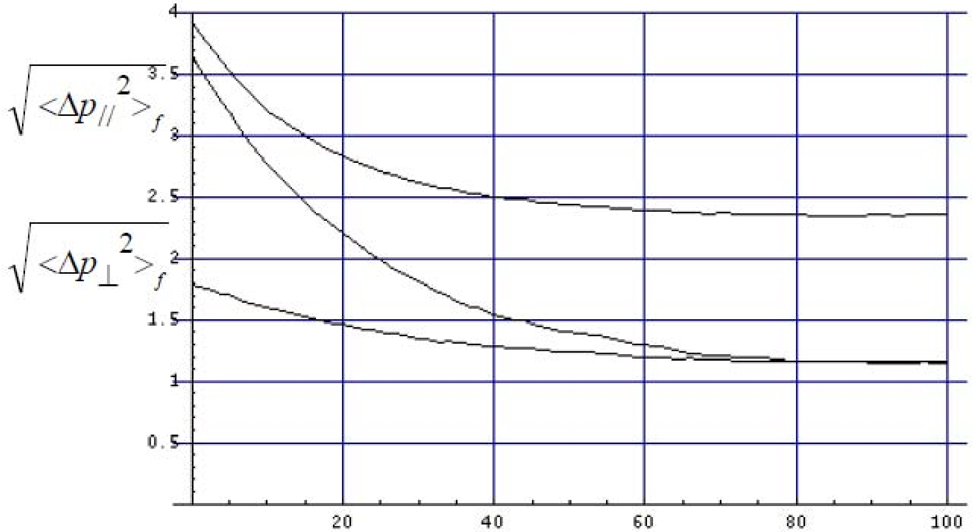
• Relaxation time >> collision time ; at large momentum (as for all quarks) but also at low momentum (thanks to inertia)

• Why not Boltzmann equation ? One first answer: not efficient.

The early times… (2004-2006)

SQM 2004

First results on c-quark evolution



Relaxation of <E>, of $\sqrt{\langle \Delta p_{\perp}^2 \rangle_f}$ and of $\sqrt{\langle \Delta p_{//}^2 \rangle_f}$ for c-quarks produced in 200 GeV p-p collisions (Δy=2).

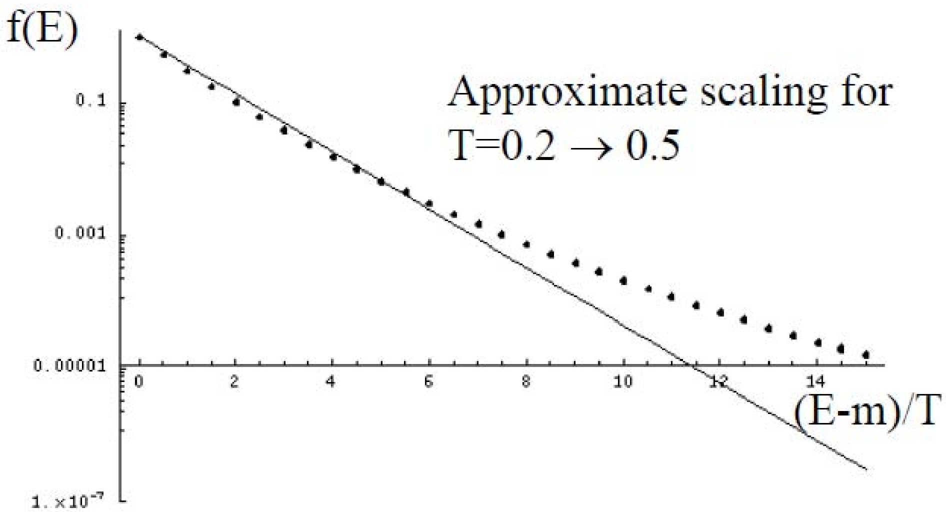
Evolution in a μ=0 -- T=400 MeV QGP.

Once again : long relaxation times

Asymptotic energy distribution: no Boltzmann; more like a Tsallis

Walton & Rafelski (1999)

Too much diffusion at large p



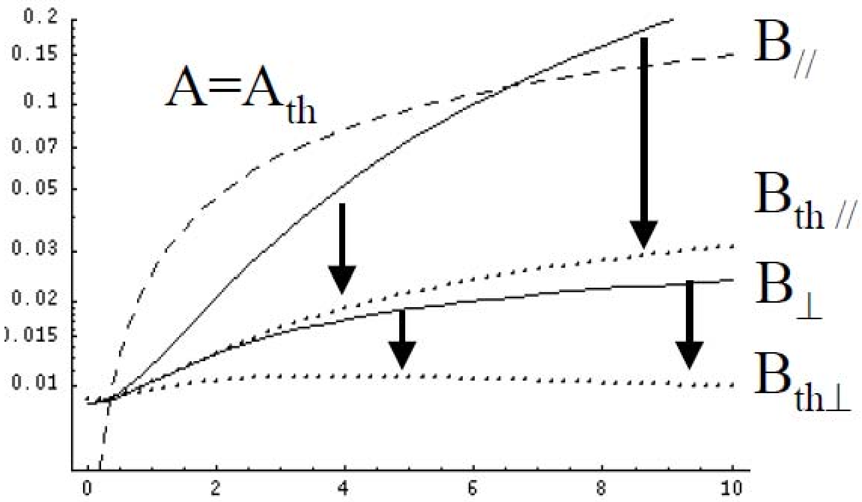
The early times… (2004-2006)

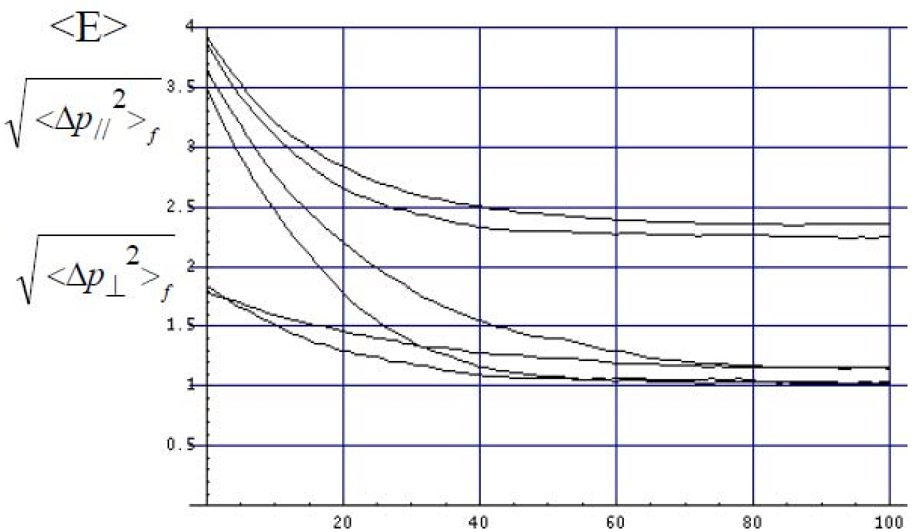
SQM 2004

So what do we do ???

Two sets:

1. FP coefficients deduced by Mustafa, Pal and Srivastava
2. Adapt $(A,B) \rightarrow (A_{th}=A, B_{th})$ such then the associated f_{asympt} is a Boltzmann distribution, and then $\rightarrow (\kappa A, \kappa B_{th})$ with κ varying from $0 \rightarrow \infty$ in order to span from free streaming $\rightarrow$ instantaneous thermalization.

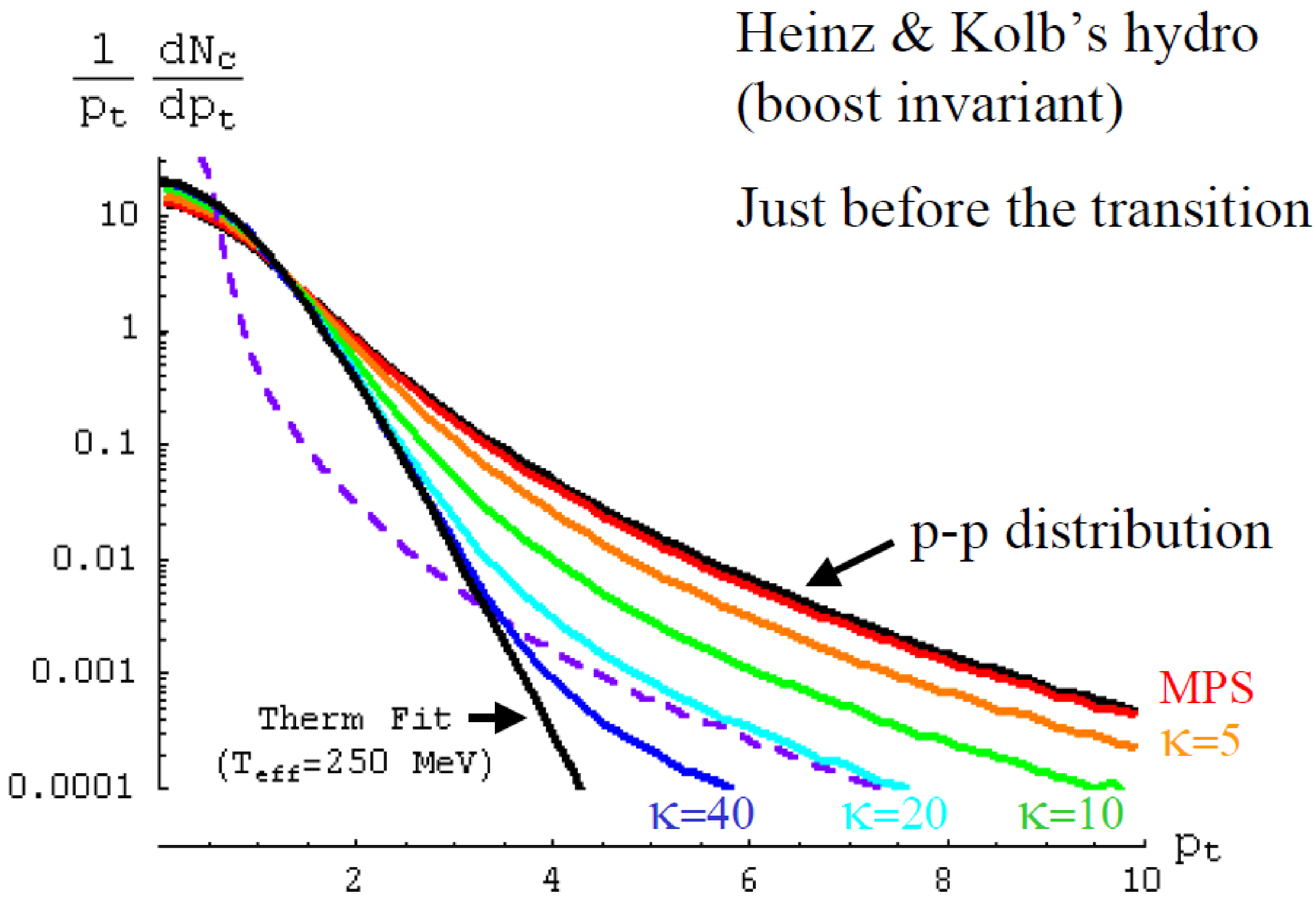




The early times… (2004-2006)

SQM 2004

c-quarks transverse momentum distribution (y=0)



The early times… (2004-2006)

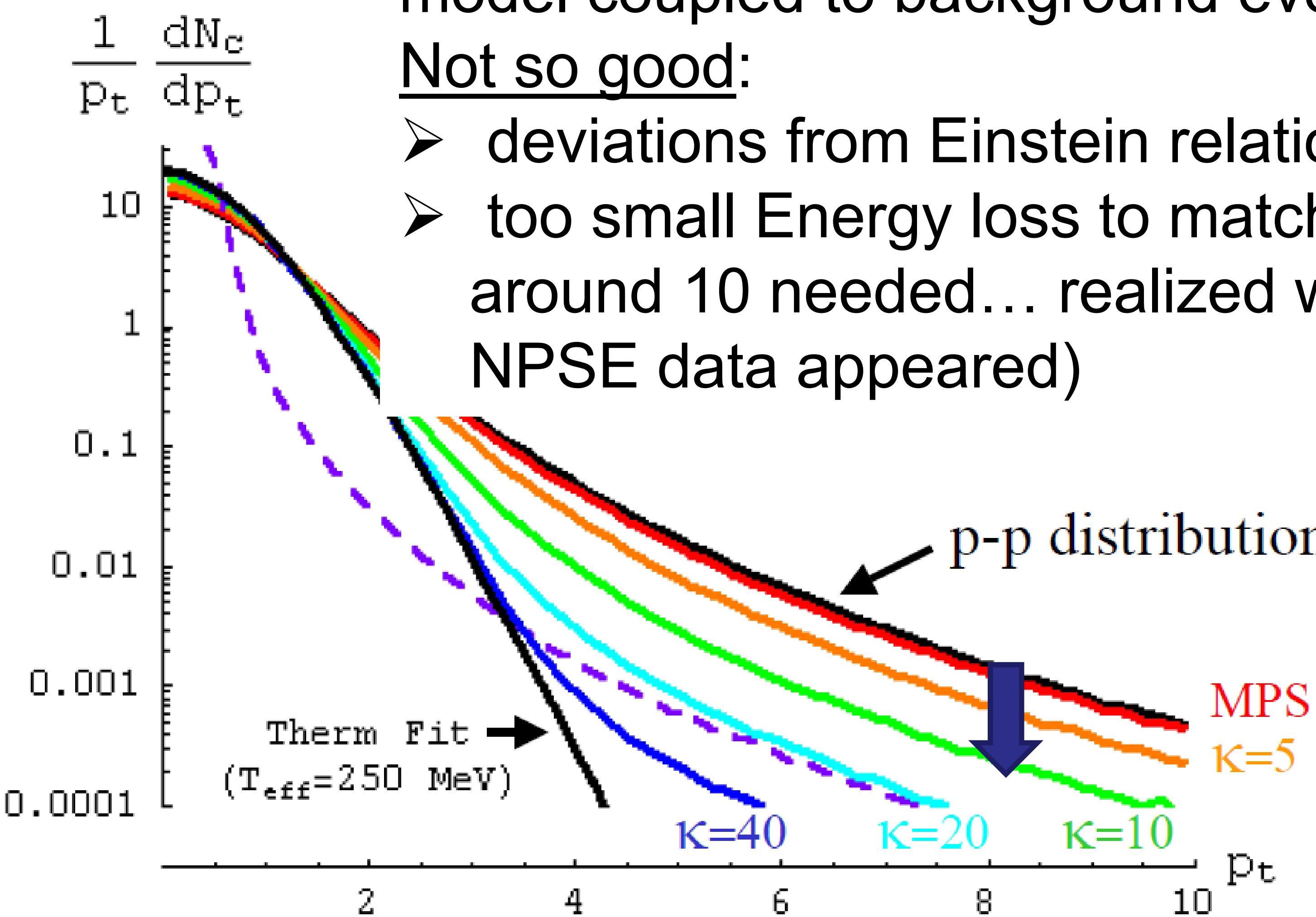
SQM 2004

c-quarks transverse momentum distribution (y=0)

<u>Good thing</u>: one of the first HQ transport model coupled to background evolution.

<u>Not so good</u>:

- deviations from Einstein relation at large p
- too small Energy loss to match the data (K around 10 needed… realized when RHIC NPSE data appeared)



Naïve regulating of IR divergence:

$$\frac{1}{t} \rightarrow \frac{1}{t-\mu^2}$$

With $\mu(T)$ or $\mu(t)$

Models A/B: 2 customary choices

$\mu^2(T) = m_D{}^2 = 4\pi\alpha_s(1+3/6)xT^2$

$$\alpha_s(Q^2) \rightarrow \begin{cases} 0.3 \text{ (mod A)} \\ \alpha_s(2\pi T) \text{ (mod B)} \end{cases} (\approx 0.3)$$

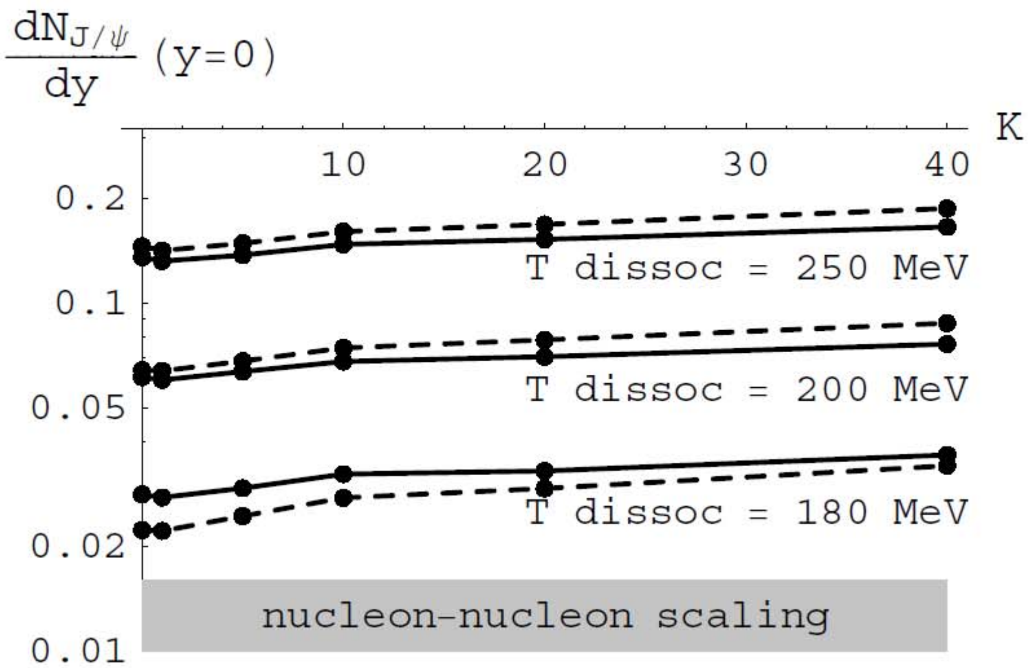
$$\frac{dE_{coll}(c)}{dx}$$

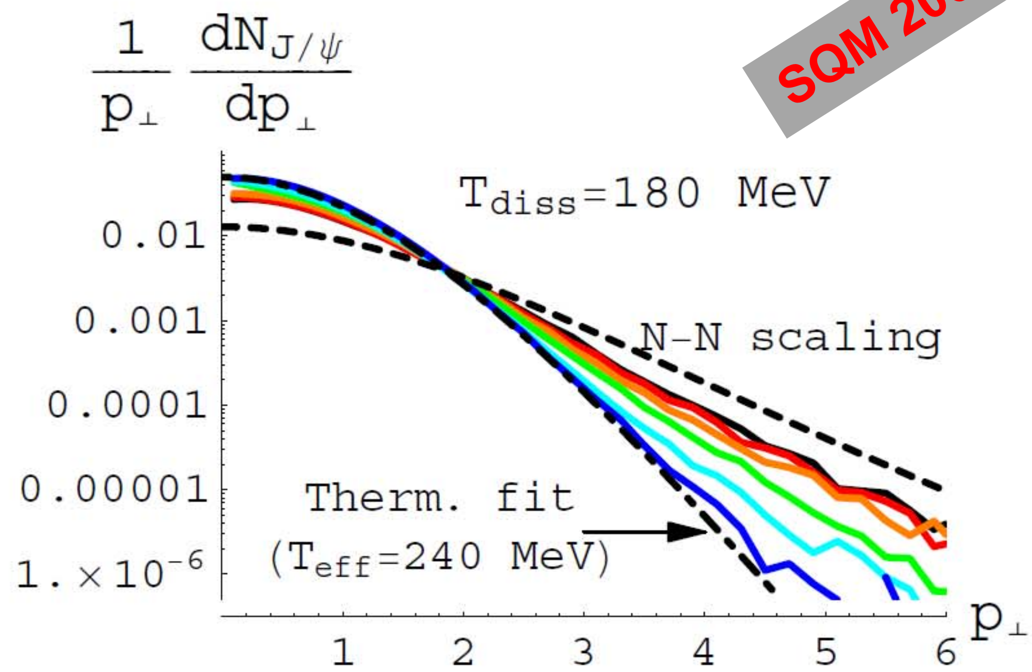
T(MeV) \p(GeV/c)	10	20
200	0.18	0.27
400	0.35	0.54

… of the order of a few % !

The early times… (2004-2006)

Journal of Physics G: Nucl. Part. Phys. **31** (2005) S1079





<u>Despite the caviats:</u> first study of the influence of the c-quark distribution on the number of J/ψ produced through coalescence + transverse momentum distribution (effective cooling, later on confirmed by RHIC)

2007: our Langevin → Boltzmann « transition » (with A. Peshier)

SQM 2008

Heavy quarks in QGP

In pQGP, heavy quarks are assumed to interact with partons of type "i" (massless quarks and gluons) with local 2→2 rate:

$$R_i = \frac{1}{2E_p}\int\frac{d^3k}{(2\pi)^3 2k}\int\frac{d^3k'}{(2\pi)^3 2k'}\int\frac{d^3p'}{(2\pi)^3 2E'}$$
$$n_i(k)\times(2\pi)^4\delta^{(4)}(P+K-P'-K')\sum|\mathcal{M}_i|^2$$

Φ inside

…depends on the QGP macroscopic parameters (T, **v**, μ) at a given 4-position (t,x). These parameters are extracted from a "standard" hydro-model (Heinz & Kolb: boost invariant)

We follow the hydro evolution of partons and sample the rates R_i "on the way", performing the Qq→Q'q' & Qg→Q'g' collisions according to Boltzmann: MC approach

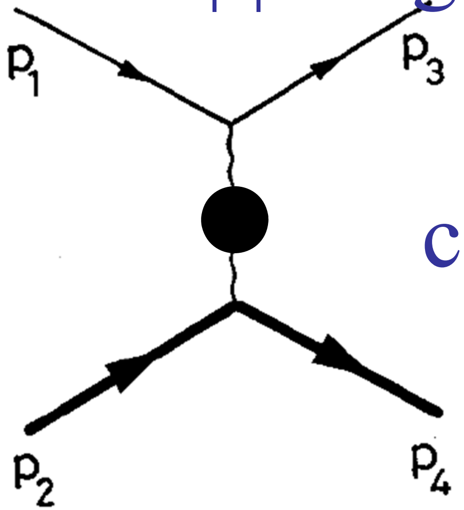
05

Braaten-Thoma:

(Peshier – Peigné)

HTL: convergent kinetic (matching 2 regions)

Low |t|: large distances



HTL: collective modes

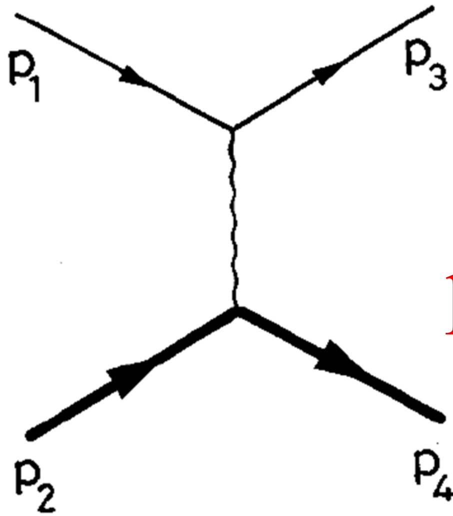
$$G_{\mu\nu}(Q) = \frac{-\delta_{\mu 0}\delta_{\nu 0}}{q^2 + \Pi_{00}} + \frac{\delta_{ij} - \hat{q}_i \hat{q}_j}{q^2 - \omega^2 + \Pi_T}$$

$$\frac{dE_{soft}}{dx} = \frac{2}{3}\alpha\, m_D^2 \ln\left(\frac{\sqrt{t^*}}{m_D/\sqrt{3}}\right) + \ldots$$

$|t^*|$

+

Large |t|: close coll.



Bare propagator

$$G_{\mu\nu}(Q) = \frac{-\delta_{\mu\nu}}{q^2 - \omega^2}$$

$$\frac{dE_{hard}}{dx} = \frac{2}{3}\alpha\, m_D^2 \ln\left(\frac{\sqrt{ET}}{\sqrt{t^*}}\right) + \ldots$$

SUM: $$\frac{dE}{dx} = \frac{2}{3}\alpha\, m_D^2 \ln\left(\frac{\sqrt{ET}}{m_D/\sqrt{3}}\right)$$

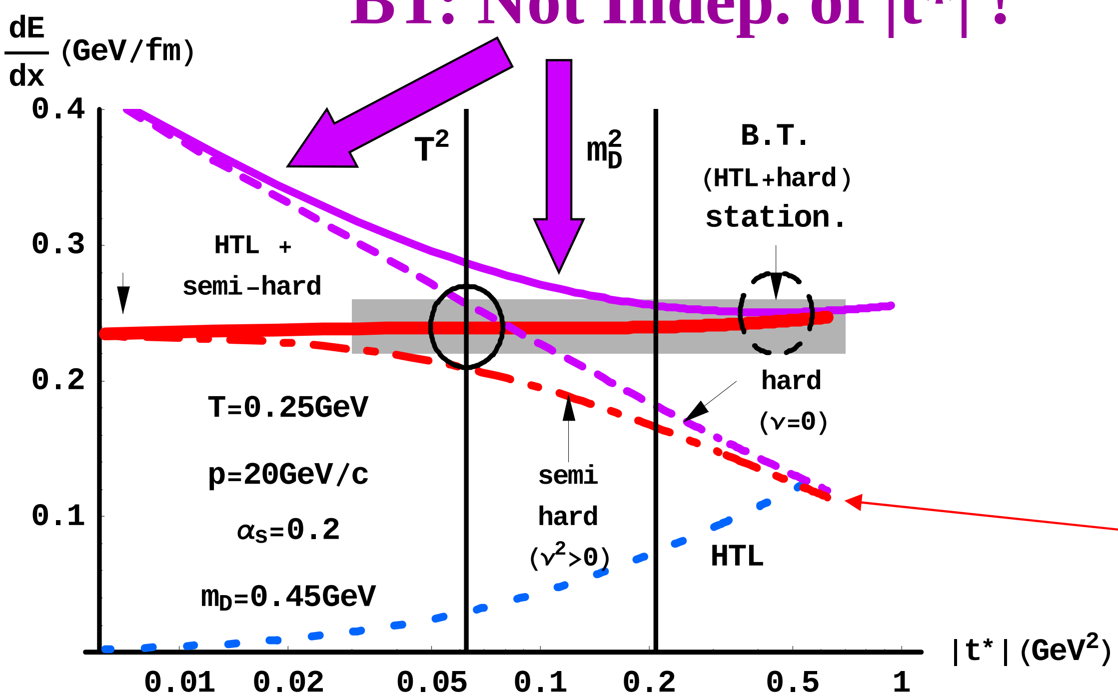
Indep. of |t*| !

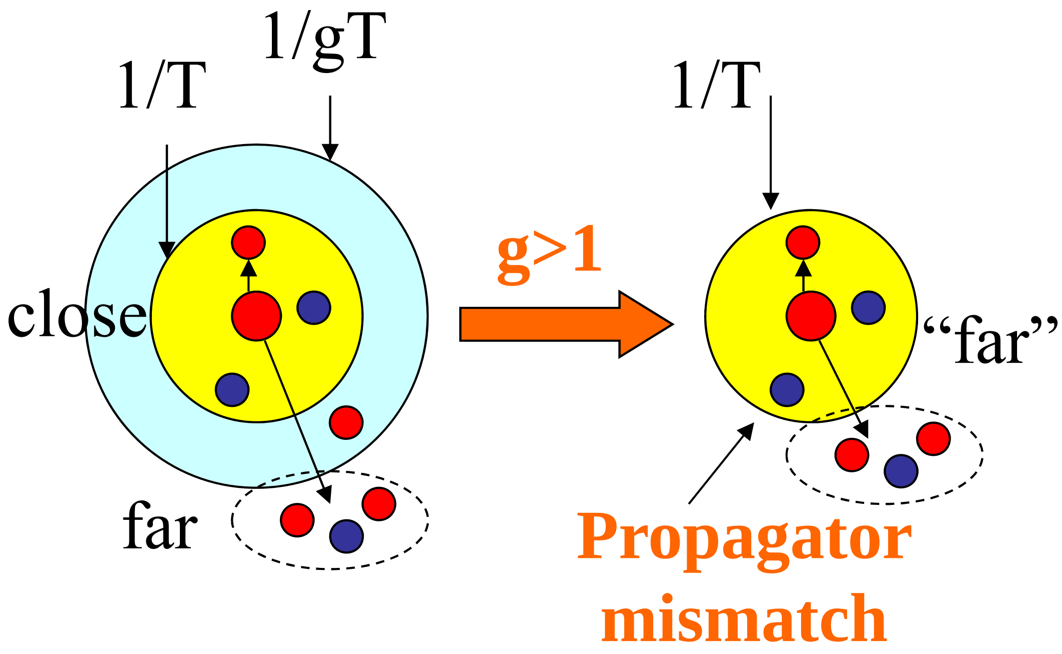
(provided $g^2T^2 \ll |t^*| \ll T^2$)

HTL at finite (not small) coupling

In QGP: $g^2T^2 > T^2$!!!

BT: Not Indep. of |t*| !





Our solution: Introduce a semi-hard propagator $1/(t-\nu^2)$ for $|t|>|t^*|$ to attenuate the discontinuities at t^* in BT approach.

Prescription: ν^2 in the semi-hard prop. is *chosen* such that the resulting E loss is maximally $|t^*|$-independent.

This allows a matching at a sound value of $|t^*| \approx T$

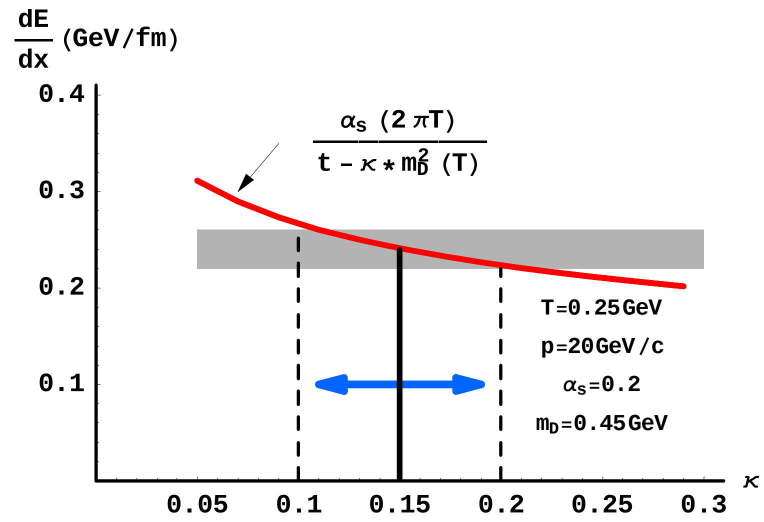
OBE Model at fixed α_s: optimal μ^2

THEN: Optimal choice of μ in our OBE model:

$$\frac{\alpha_s(2\pi T)}{t-\mu^2}$$

$$\mu^2(T) \approx 0.15\, m_D^2(T)$$

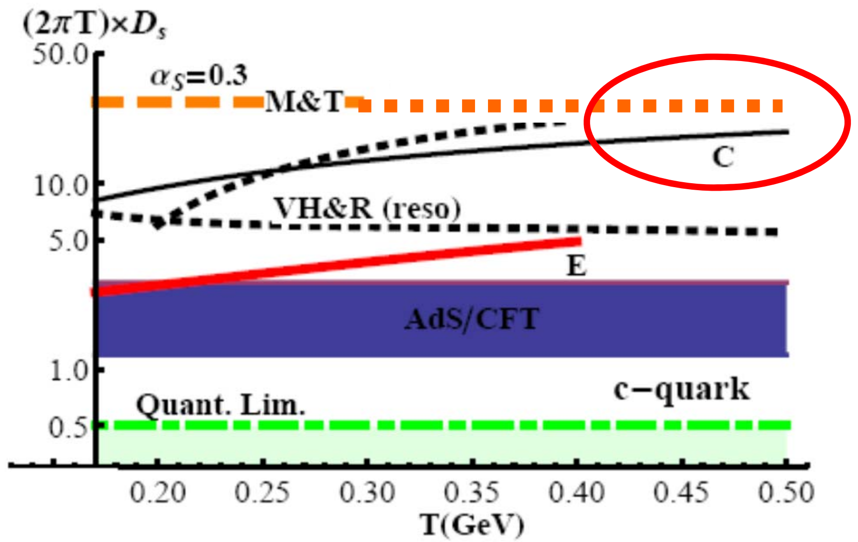
with $m_D^2 = 4\pi\alpha_s(2\pi T)(1+3/6)xT^2$



$$\frac{dE_{coll}(c)}{dx}$$ … factor 2 increase w.r.t. naïve pQCD (not enough to explain R_{AA})

T(MeV) \p(GeV/c)	10	20
200	0.36 (0.18)	0.49 (0.27)
400	0.70 (0.35)	0.98 (0.54)

Convergence with "pQCD" at high T



Running α_s …

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

…asymptotic freedom and infrared slavery

Strategy

1. Effective $\alpha_{eff}(Q^2)$
2. "generalized BT" / convergent-kinetic => dE/dx
3. Fix the optimal IR regulator in propagator
   i.e. in t-channel, fix the optimal κ

$$\frac{\alpha_{eff}(t)}{t - \kappa \tilde{m}_D^2(T)}$$

$\mu^2(T)$

Self consistent m_D (Peshier hep-ph/0607275)

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

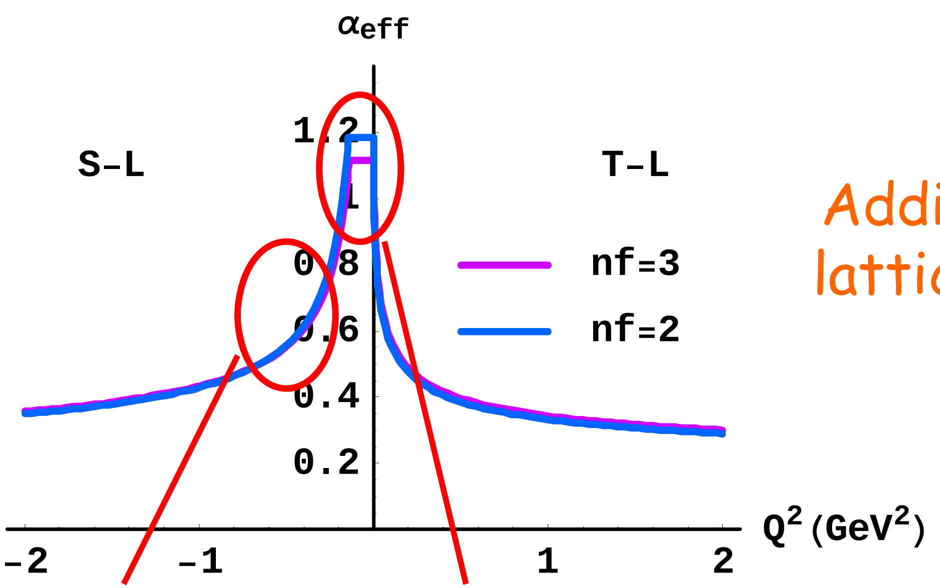
Model E : running α_s AND optimal μ^2

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

Observable = T-L effective coupling * Process dependent fct

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

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



Additional inputs (from lattice) could be helpful

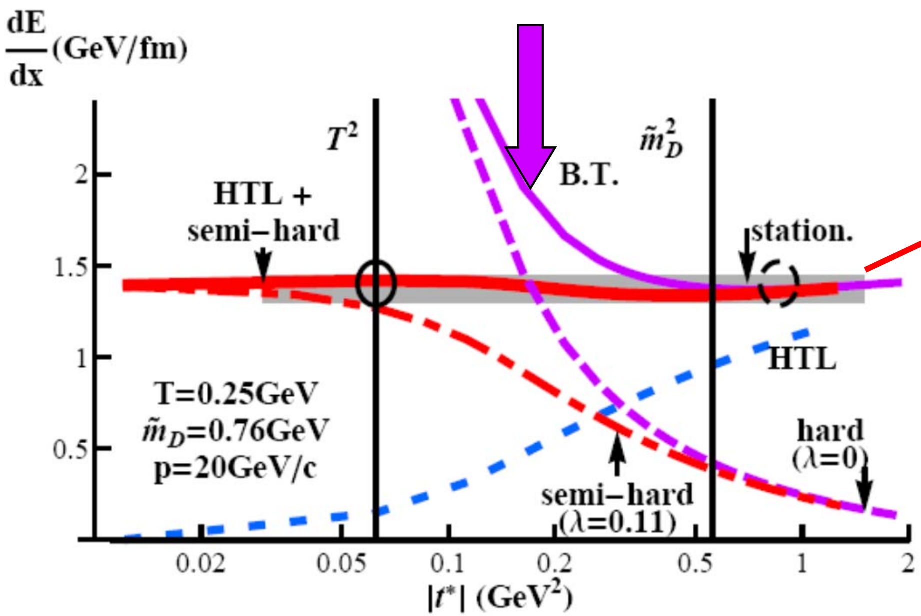
Large values for intermediate momentum-transfer

IR safe. The detailed form very close to Q^2 =0 is not important does not contribute to the energy loss

Model E : running α_s AND optimal μ^2

- Bona fide "running HTL": $\alpha_s \to \alpha_s(Q^2)$

Brute BT: Not Indep. of |t*| !



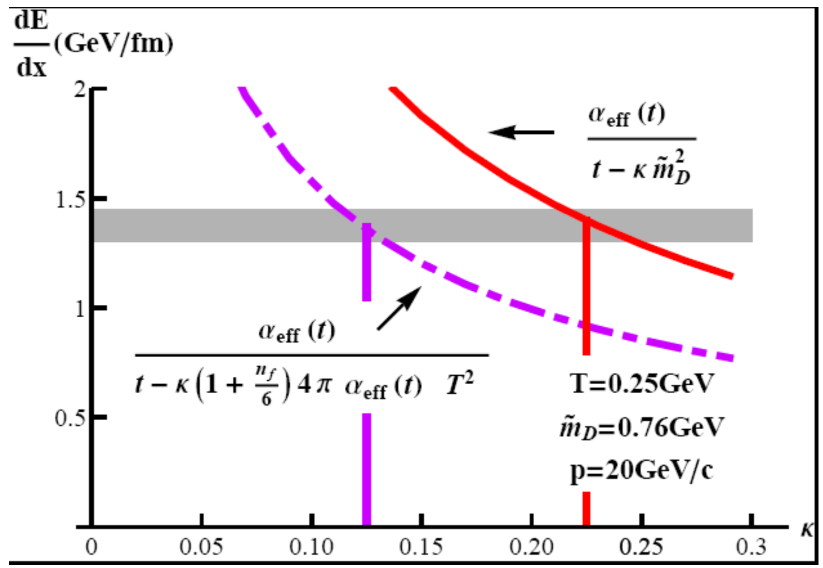
Introducing semi-hard propag…

$$\frac{\alpha_{\rm eff}(t)}{t} \longrightarrow \frac{\alpha_{\rm eff}(t)}{t-\lambda m_D^2(T,t)}$$

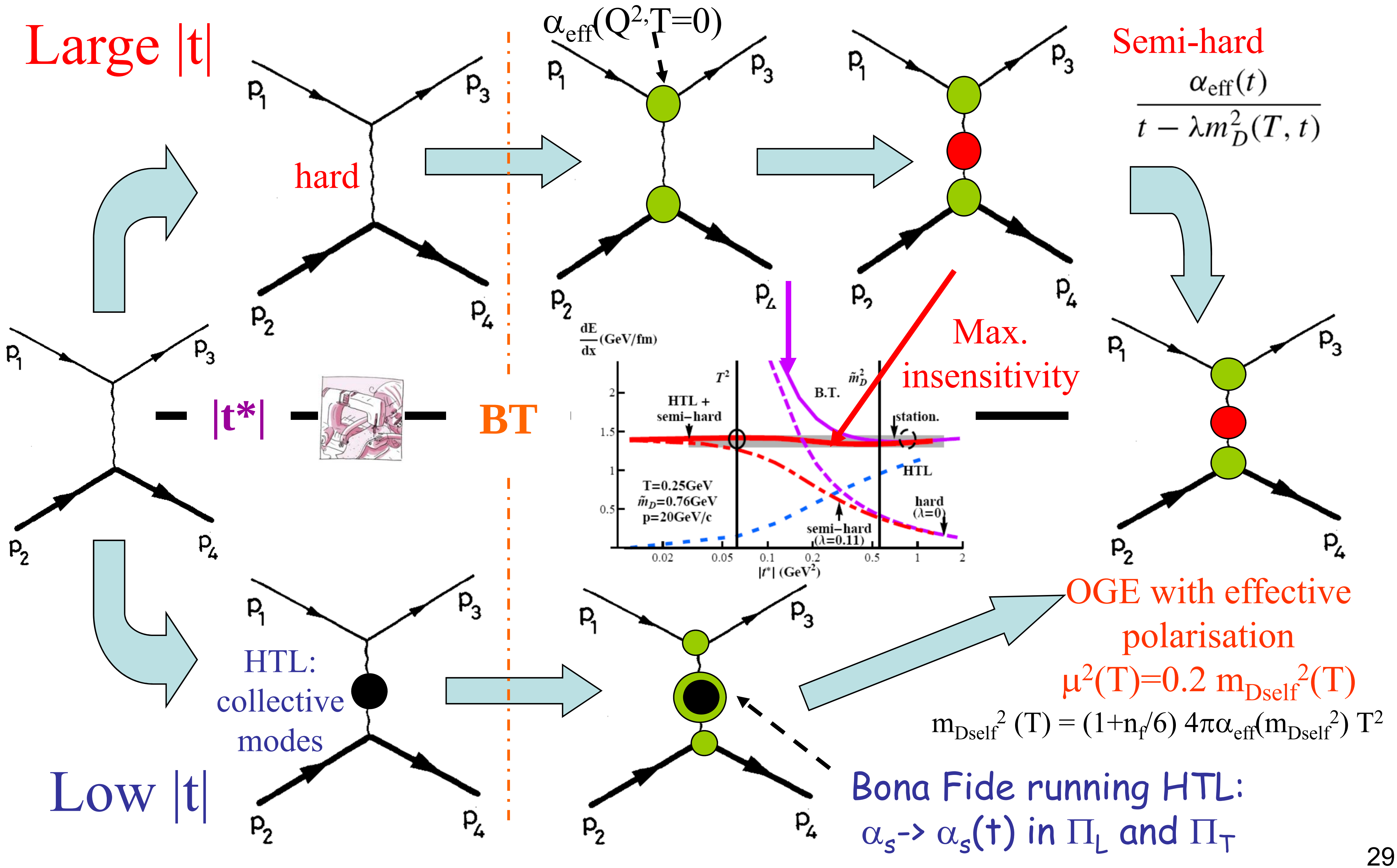
…leads to stationary results

- Optimal regulator:

$$\mu^2(T) \approx 0.2\ m_{\rm Dself}{}^2(T)$$



μ-local-model: medium effects at finite T in t-channel



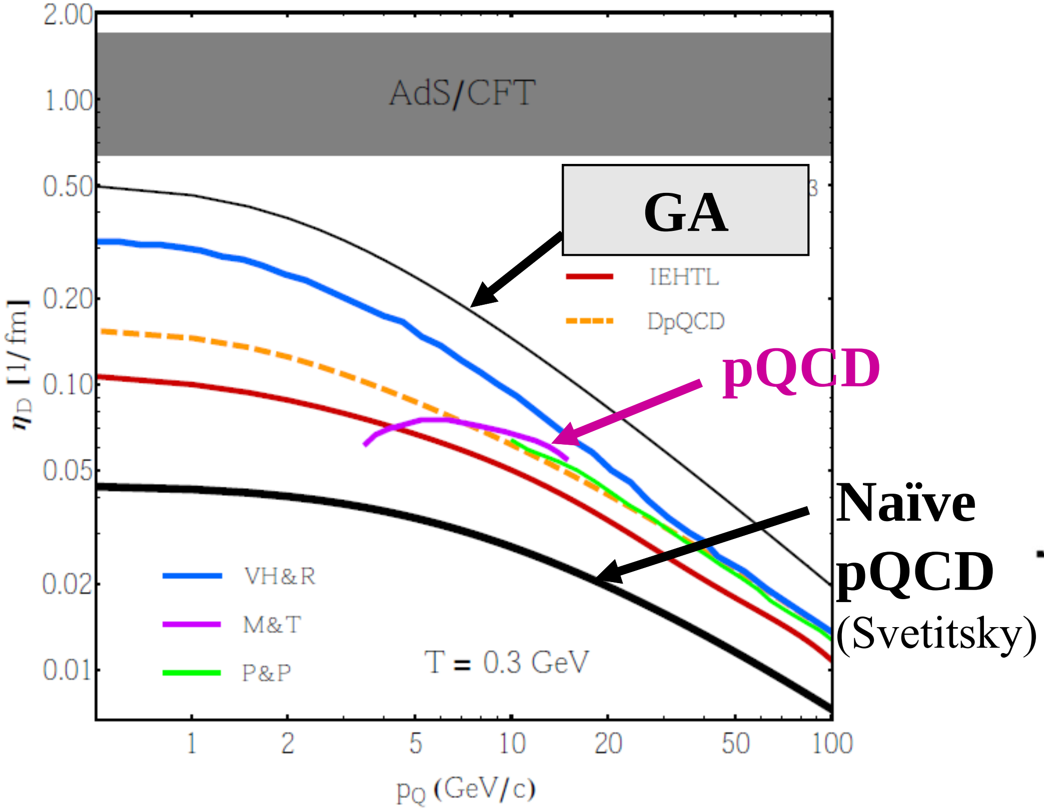
Running α_s : some Energy-Loss values

$$\frac{dE_{coll}(c/b)}{dx}$$

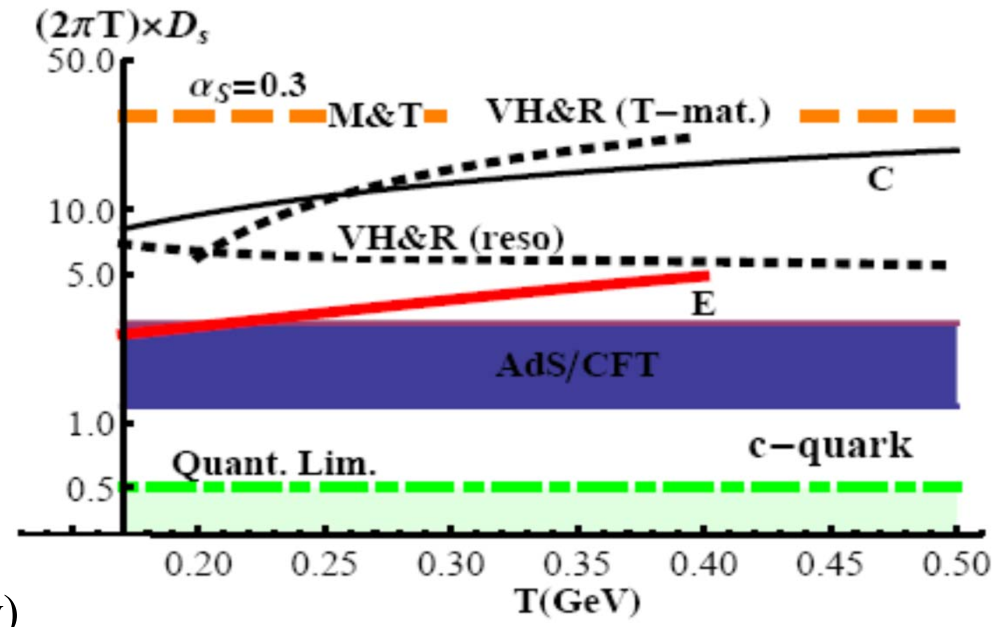
T(MeV) \p(GeV/c)	10	20
200	**1 / 0.65**	**1.2 / 0.9**
400	**2.1 / 1.4**	**2.4 / 2**

≈ 10 % of HQ energy

Drag coefficient (inverse relax. time)



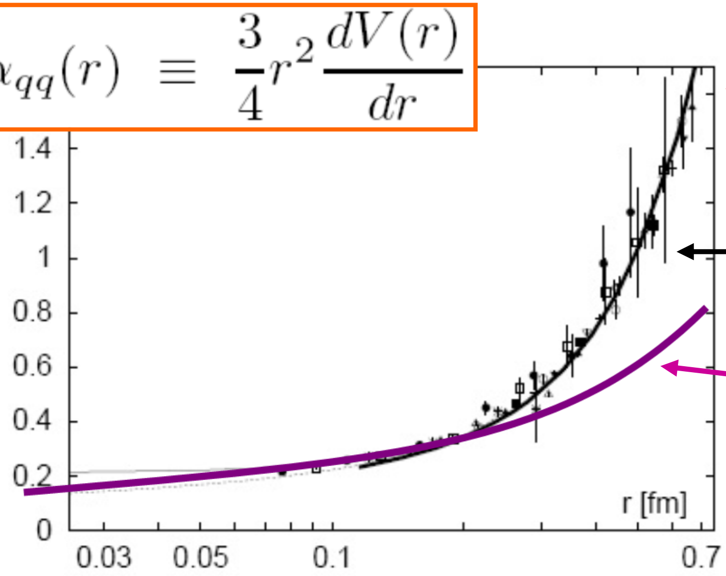
Diffusion coefficient



μ-local-model: Eff. Running α_s vs lQCD

T=0

$$\alpha_{qq}(r) \equiv \frac{3}{4} r^2 \frac{dV(r)}{dr}$$



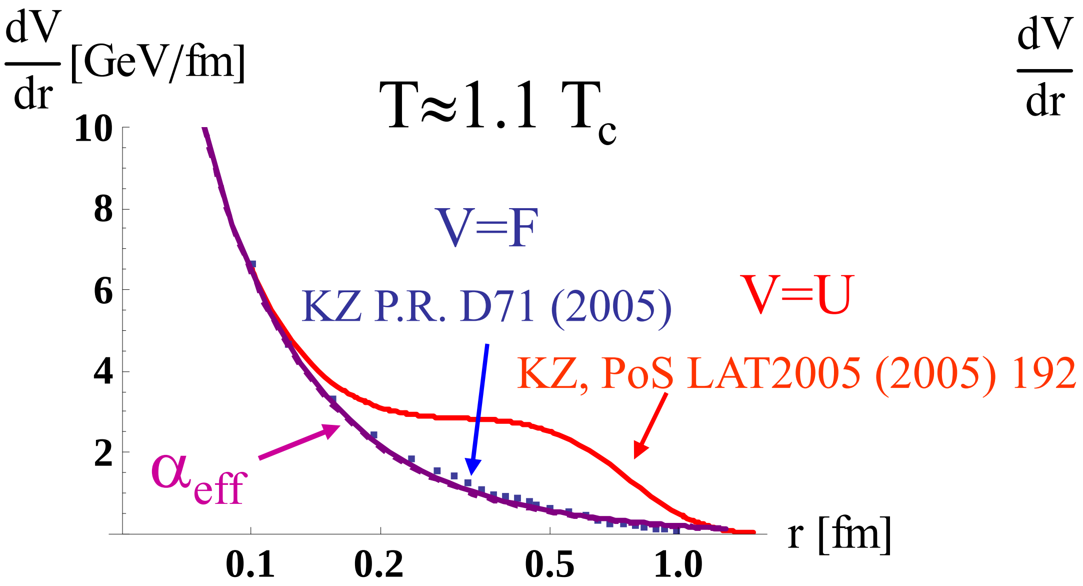
O. Kaczmarek & F. Zantow (KZ) (n_f=2 QCD), P.R.D71 (2005) 114510

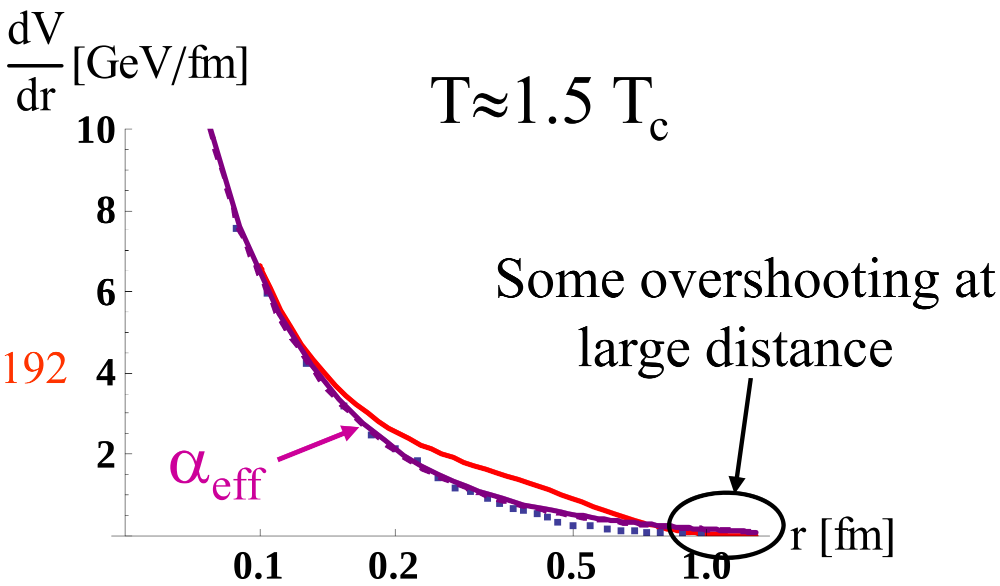
Genuine non-pert (flux tube)

optimal μ, running α_{eff}

V:ω=0 sector; dE/dx: finite ω

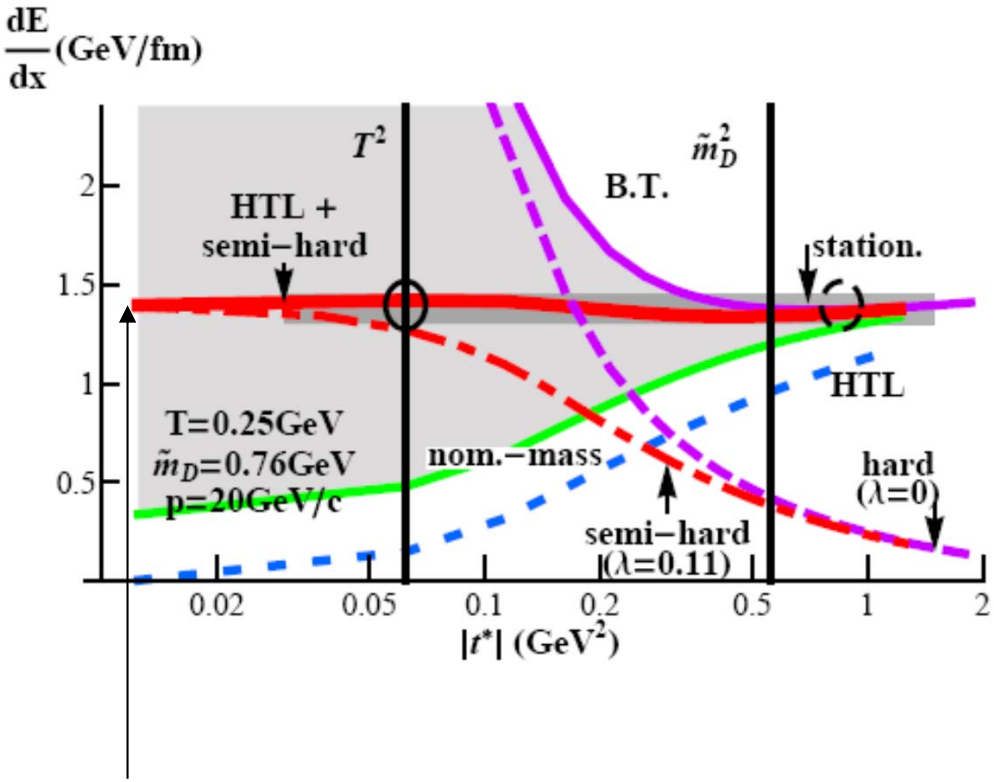
Finite T



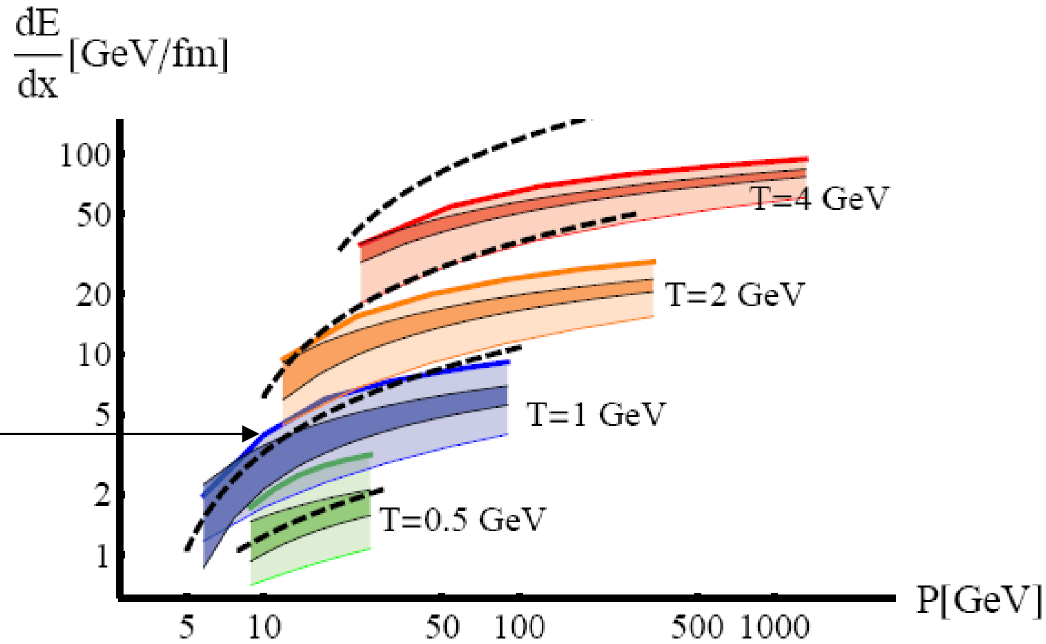


Merging at ≈2 T_c

Running α_s : theoretical uncertainties



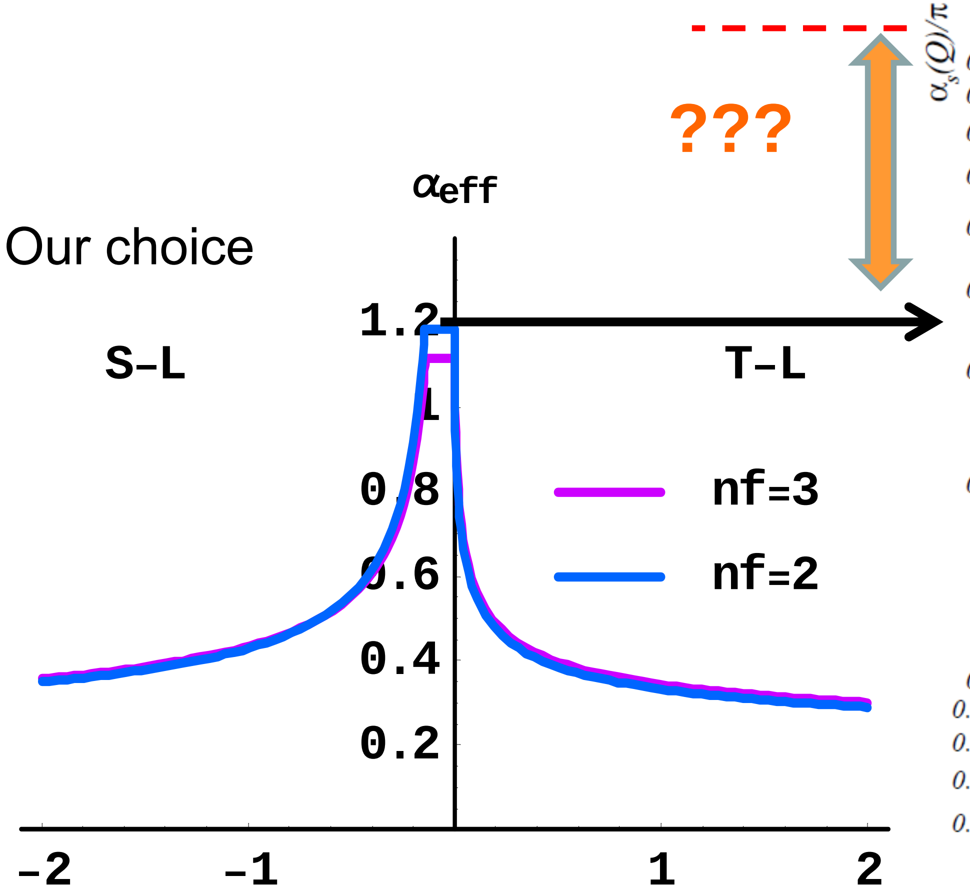
E: optimal μ, running α_{eff}

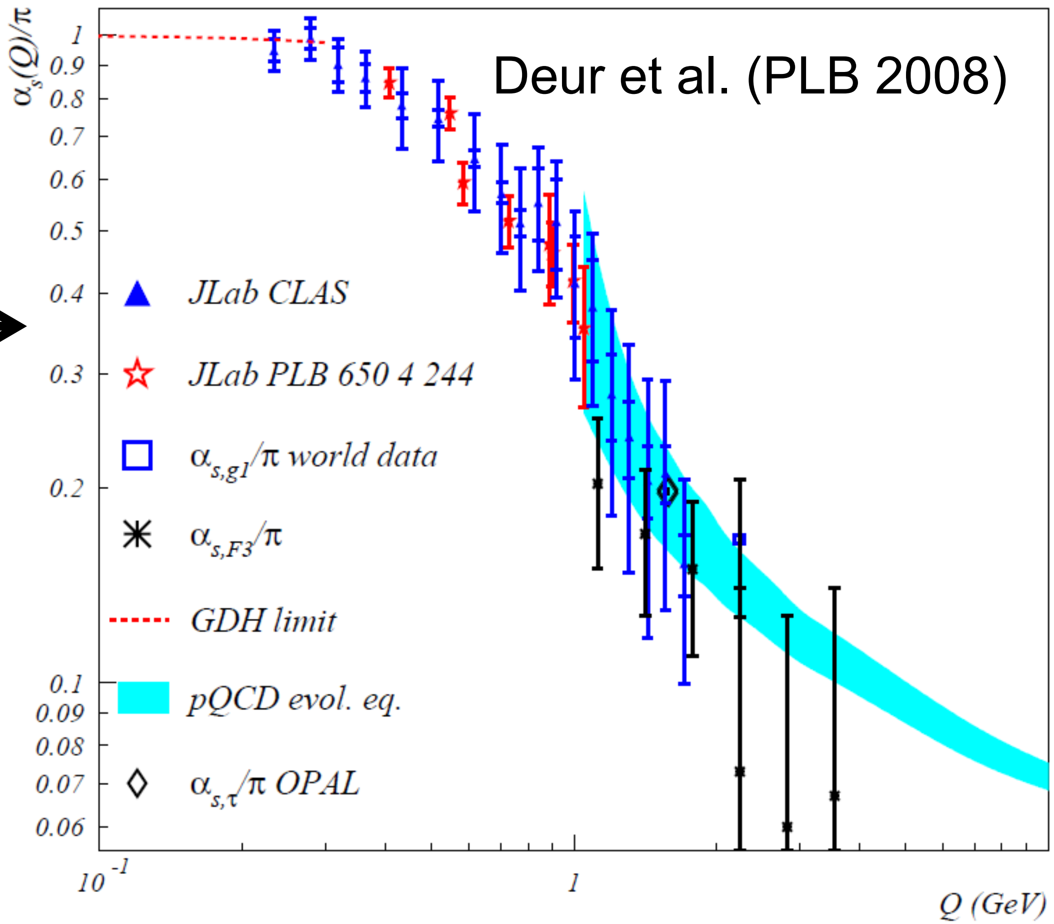


Dark zones: Peshier & Peigné (2008)

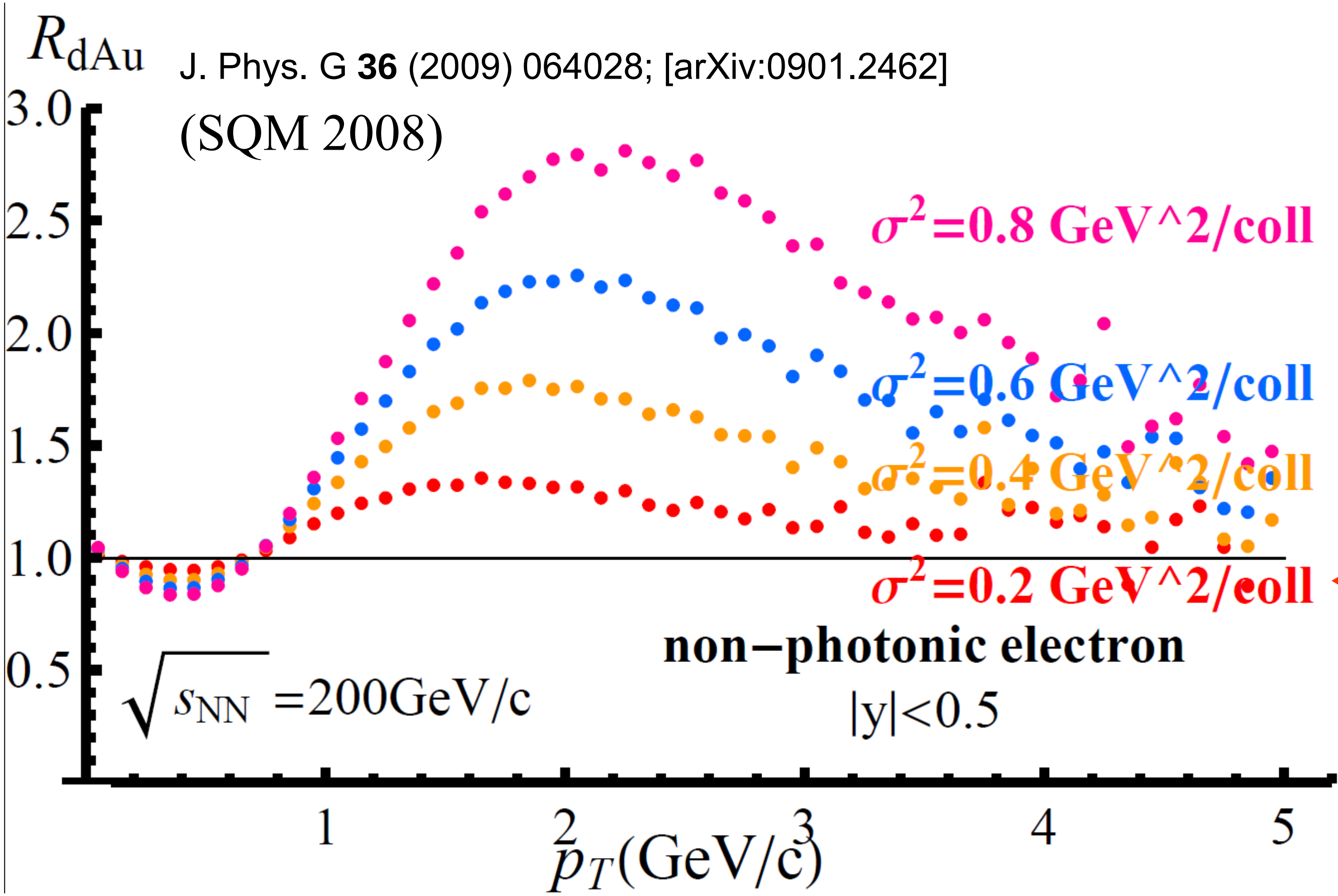
Elastic Eloss @ RHIC

Still some uncertainties on the level of the coupling constant => we allow for a multiplication of our pQCD (inspired) cross section by a factor K (fixed once and for all by comp. with exp)





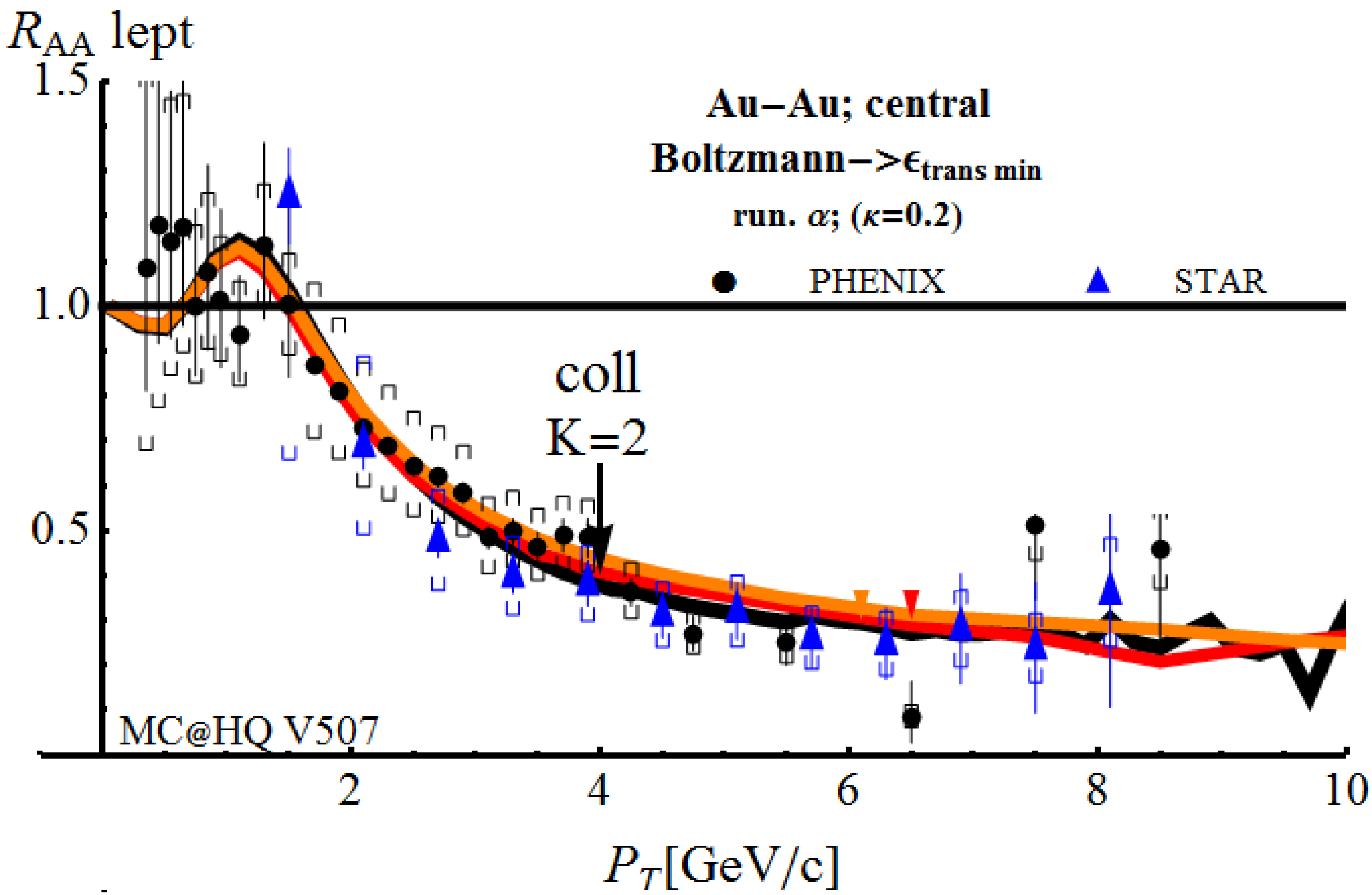
CNM effects



← Selected values; rough agreement with recent RHIC measurement, but physical origin remains unclear

Elastic for leptons @ RHIC

Gossiaux and Aichelin, PRC 78 (2008)



Good agreement for NPSE at the price of a factor K=2

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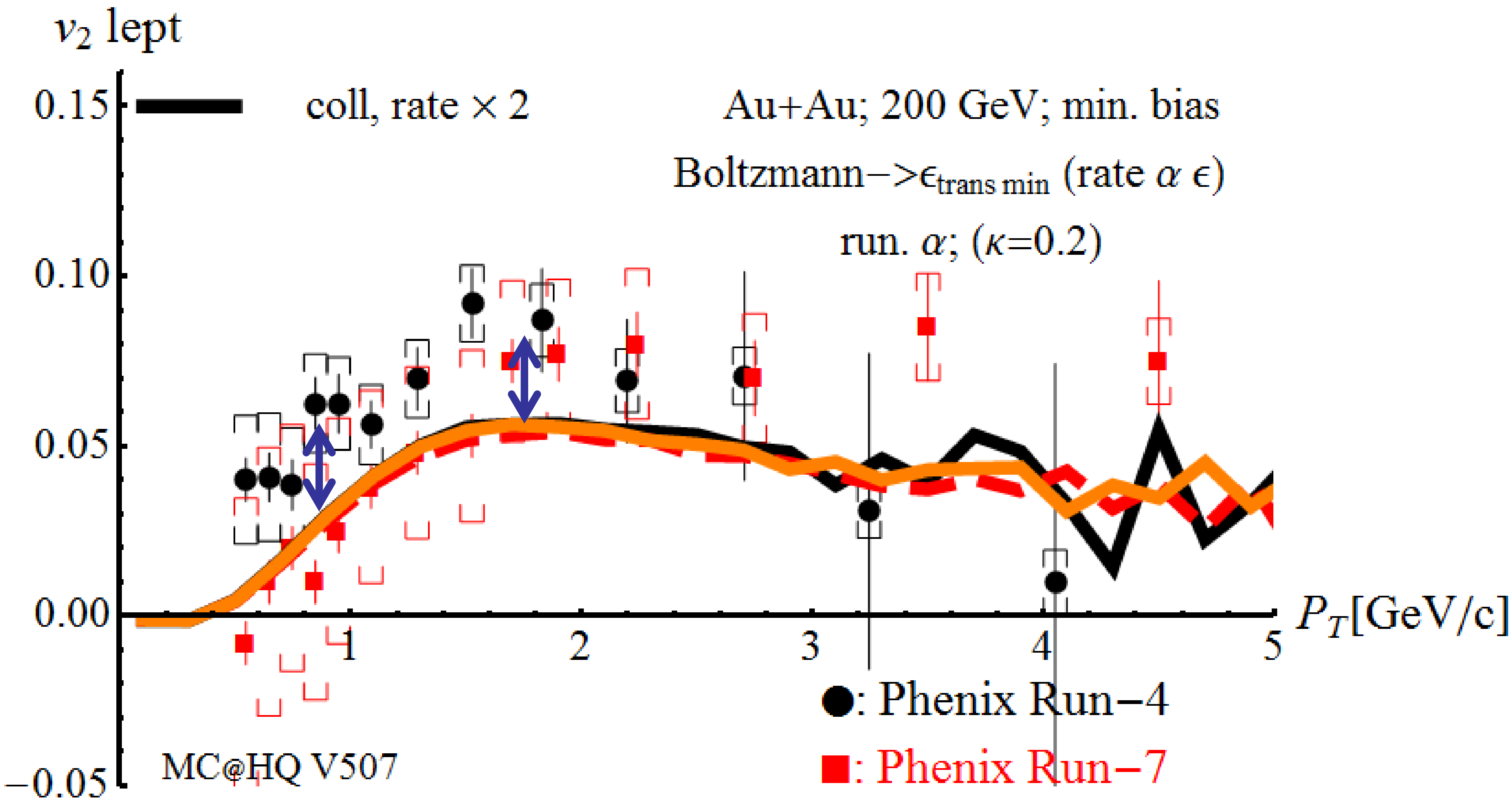
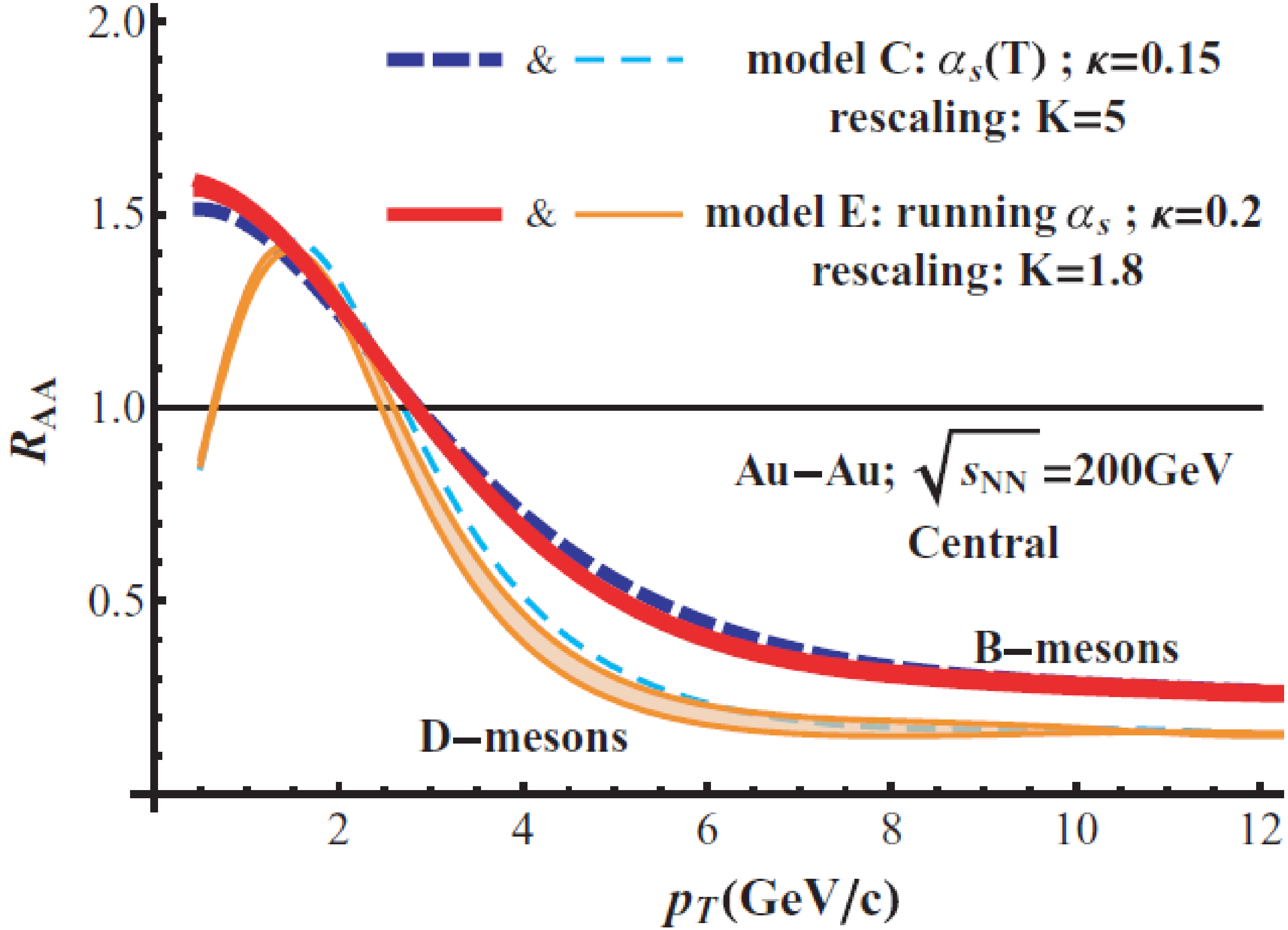


Some contribution from D meson rescattering ?

(see V. Ozvenchuk's talk)

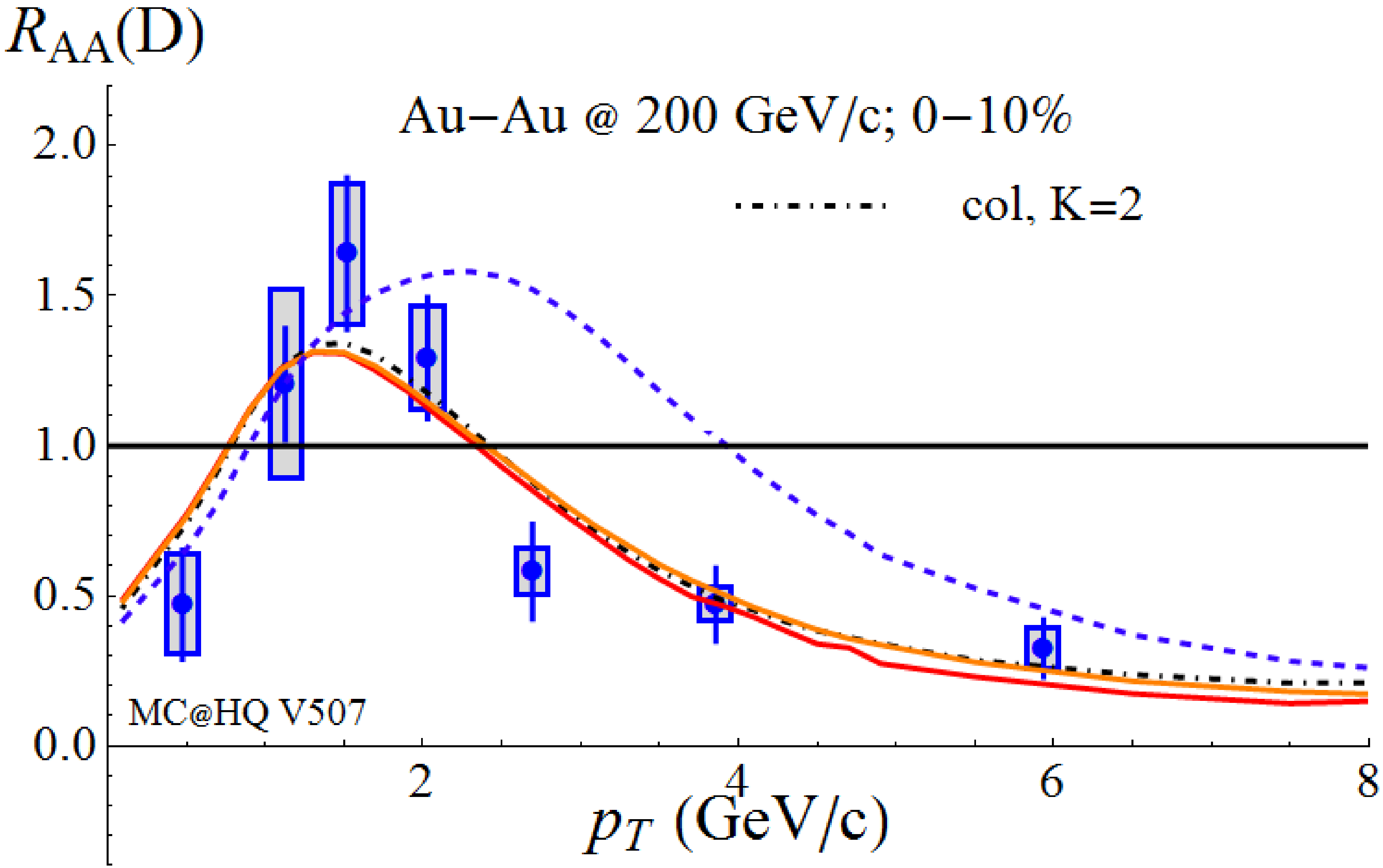
Elastic D and B mesons @ RHIC

Gossiaux, Bierkandt and Aichelin, PRC 79 (2009)



Elastic D mesons @ RHIC

3 years later: QM 2012. $R_{AA}(D)$ measured by STAR



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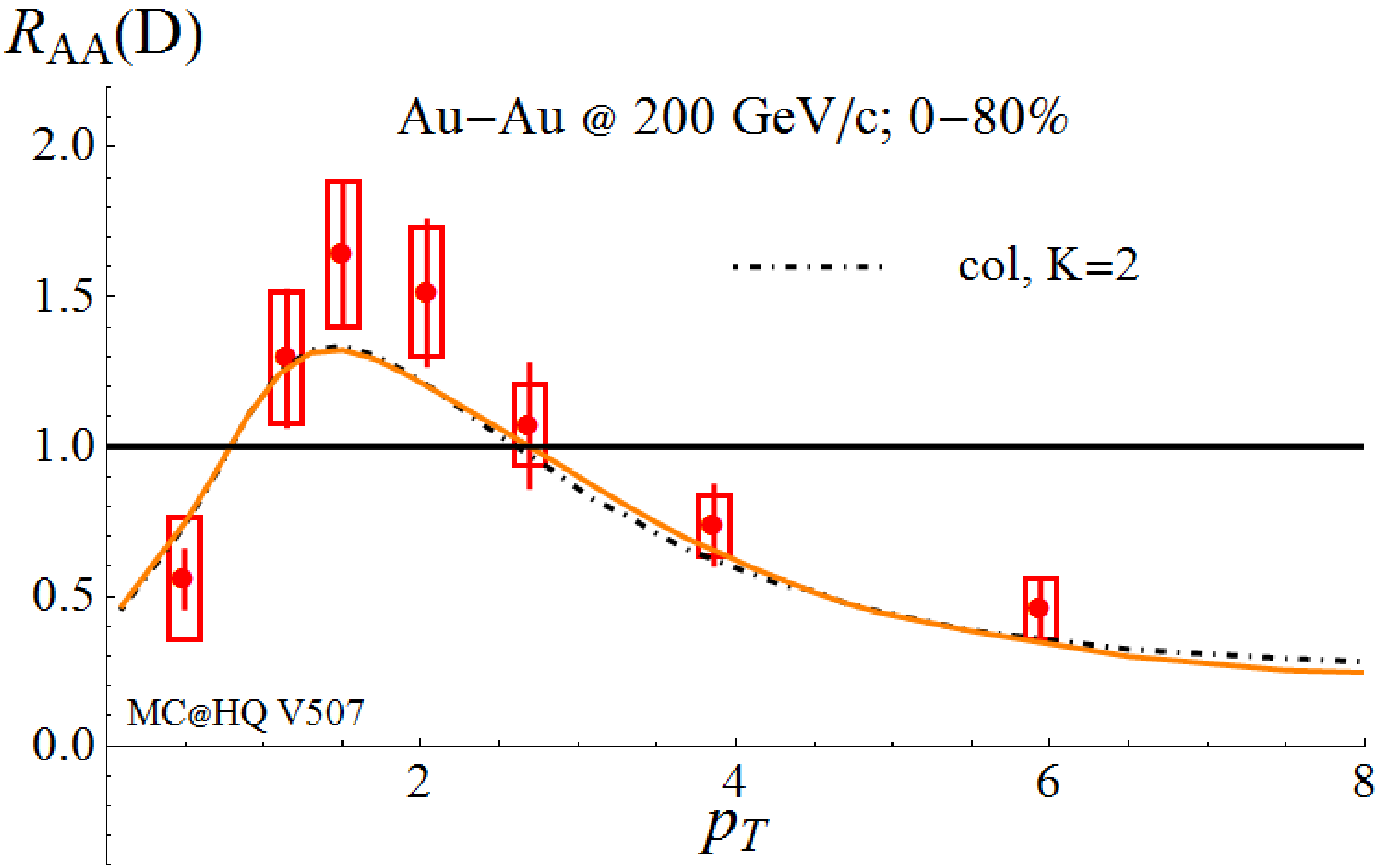
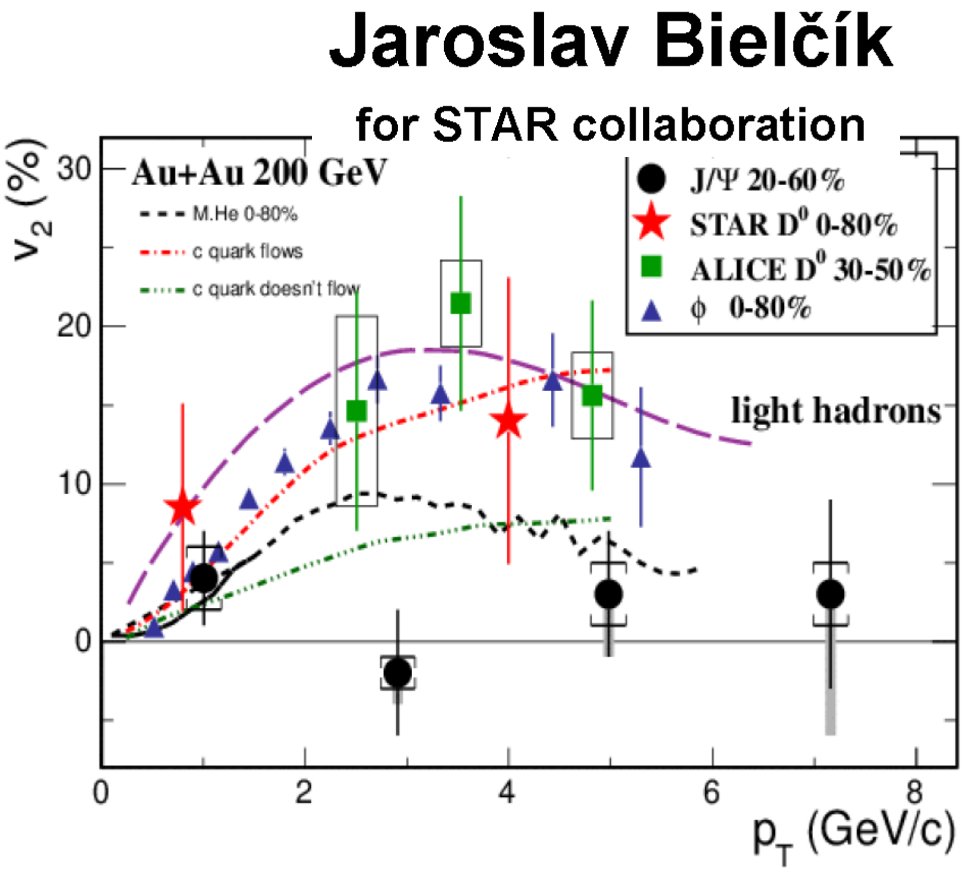
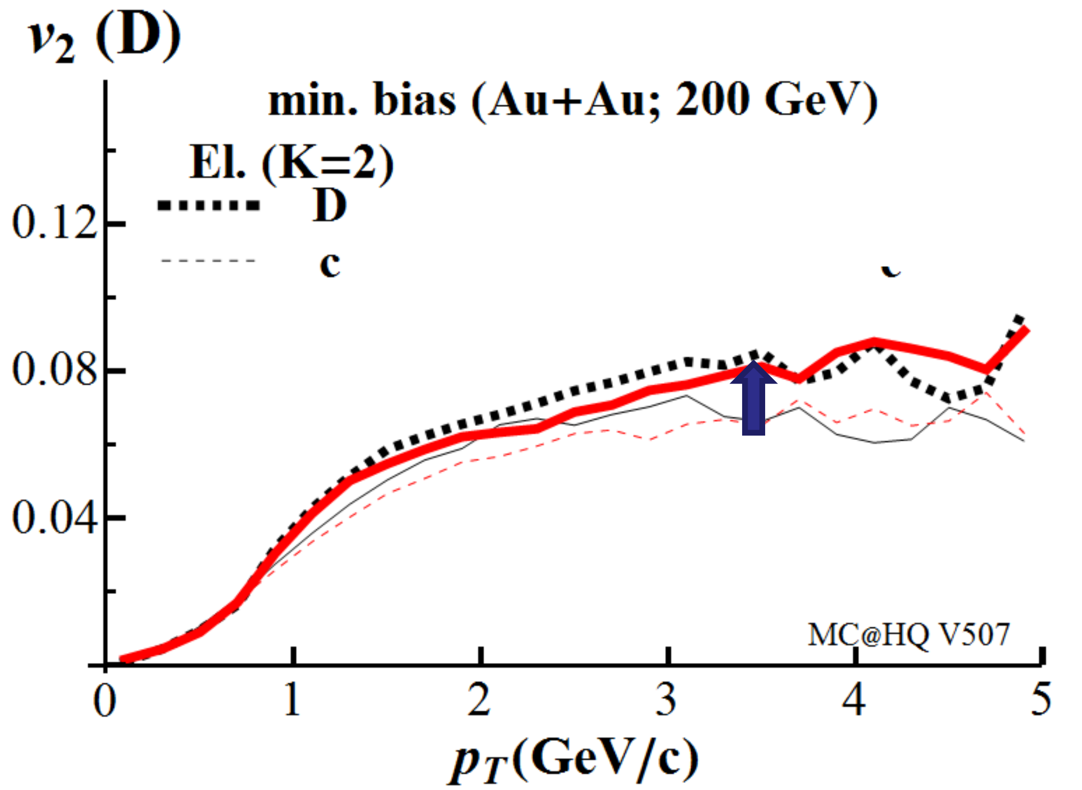


Elastic D mesons @ RHIC





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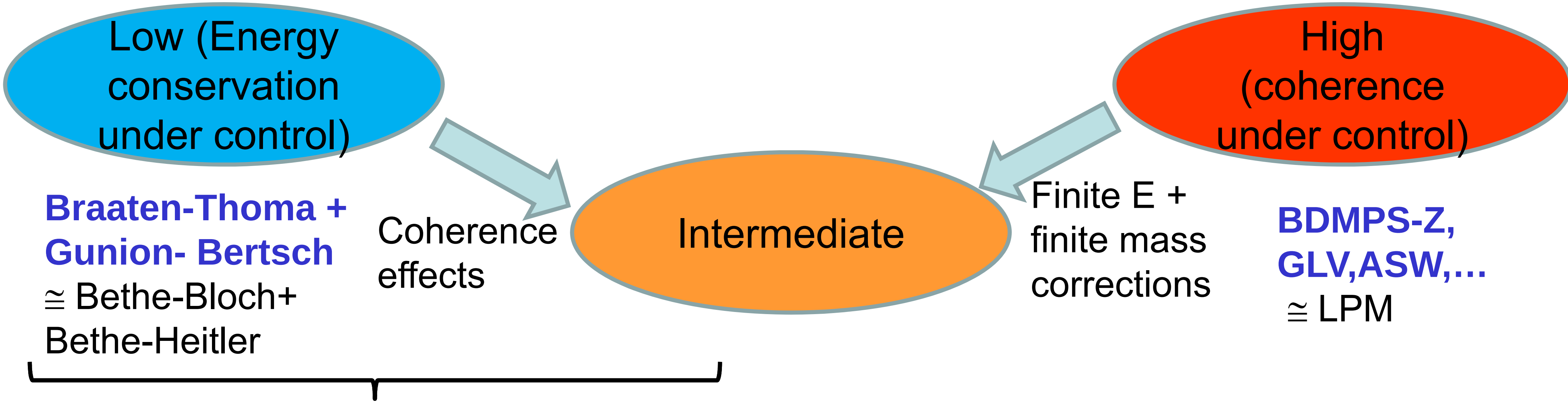
Coalescence according to extended Dover framework

(PRC 79 044906)

$$N_\Phi = \int \frac{d^3 p_q}{(2\pi\hbar)^3 E_q} \frac{p_q \cdot d\hat{\sigma}}{u_Q \cdot d\hat{\sigma}} f_q(x_Q, p_q)(\sqrt{2\pi} R_c)^3 \times F_\Phi(p_Q, p_q),$$

Radiative E loss at intermediate p_T (Aichelin & Gousset)

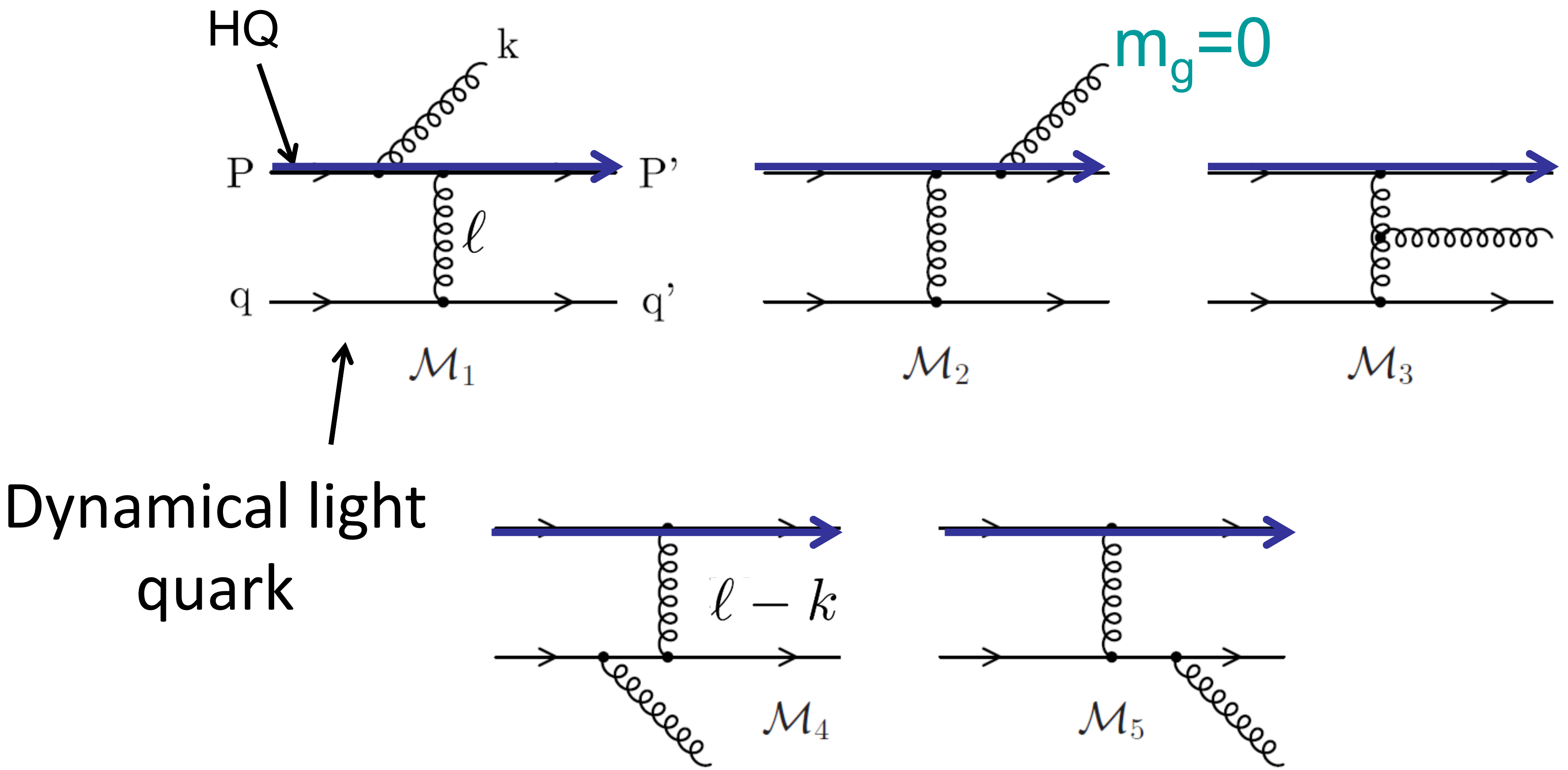
- Most of the *interesting* HF observables so far: located at *intermediate* p_T (≈3 GeV-50 GeV)
- Intermediate p_T: hope that pQCD (or pQCD inspired models) apply (as compared to low p_T)
- Intermediate pT: mass effect still present and thus hope to learn something more as compared to large p_T



Approach pursued in our **models…**

=> Need for falsification (more observables; lQCD): Azimuthal correlations ?

qQ→qQg "in the Vacuum" (see Th. Gousset's talk)



Sudakov decomposition: $P = p + \frac{m_Q^2}{s - m_Q^2} q$ $\quad p$ and q : light-like

$$k = xp + yq + \vec{k}_t$$

Momentum transfer: $\ell = q - q', \; t = \ell^2$

qQ→qQg "in the Vacuum": Exact Relation

Exact relation: $$\frac{d\sigma^{Qq\to Qgq}}{dx d^2k_t d^2\ell_t} = \frac{1}{2(s-M^2)}|\mathcal{M}|^2 \frac{1}{4(2\pi)^5\sqrt{\Delta}}\Theta(\Delta)$$

With:

Δ: phase-space and $$\mathcal{M} = \mathcal{M}^{\rm QCD} \oplus \mathcal{M}^{\rm QED-like}$$

Rapidity-plateau (↑ $\mathcal{M}^{\rm QCD}$)

Fragmentation region (↑ $\mathcal{M}^{\rm QED-like}$) (subdominant for $\tilde{s} \gg \{l_t^2, k_t^2\}$)

$$\mathcal{M}^{\rm QCD} \simeq \mathcal{M}^{\rm SQCD} + \mathcal{O}(x^2)$$

$$\mathcal{M} \simeq \mathcal{M}^{\rm SQCD} = g\, C_3 \left(\frac{-4\, g^2\, P\cdot q}{\ell^2}\right)\left(\frac{(2(1-x)-x')\, \vec{\epsilon}_t\cdot\vec{k}_t}{\vec{k}_t^2+x^2 m_Q^2} - \frac{2(1-x-x')\, \vec{\epsilon}_t\cdot(\vec{k}_t-\vec{l}_t)}{(\vec{k}_t-\vec{l}_t)^2+(x+x')^2 m_Q^2}\right).$$

$x'(\vec{k}_t, \vec{l}_t, x)$ Recoil momentum of the l.q. (in the Sudakov decomposition)

Seeked extension of the Gunion-Bertsch model

qQ→qQg "in the Vacuum": High Energy Limit

One can show: $x'(\vec{k}_t, \vec{l}_t, x) \ll 1 \quad \Leftrightarrow \quad x(s - m_Q^2) \gg \{l_t^2, k_t^2\}$

High energy condition
(when s disappears from the dσ : GB)

$$\frac{d\sigma^{Qq\to Qgq}}{dx d^2k_t d^2\ell_t} \underset{\text{HE}}{\to} \frac{d\sigma_{\rm el}}{d^2\ell_t} P_g(x, \vec{k}_t, \vec{\ell}_t)$$

with: $$P_g = \frac{C_A \alpha_s}{\pi^2} \frac{1-x}{x} \left(\frac{\vec{k}_t}{\vec{k}_t^2 + x^2 m_Q^2} - \frac{\vec{k}_t - \vec{\ell}_t}{(\vec{k}_t - \vec{\ell}_t)^2 + x^2 m_Q^2} \right)^2$$

No collinear divergence thanks to HQ mass (finite formation time), but (usual) IR divergence in the $d\sigma_{el}$ => prescription: IR regulator μ.

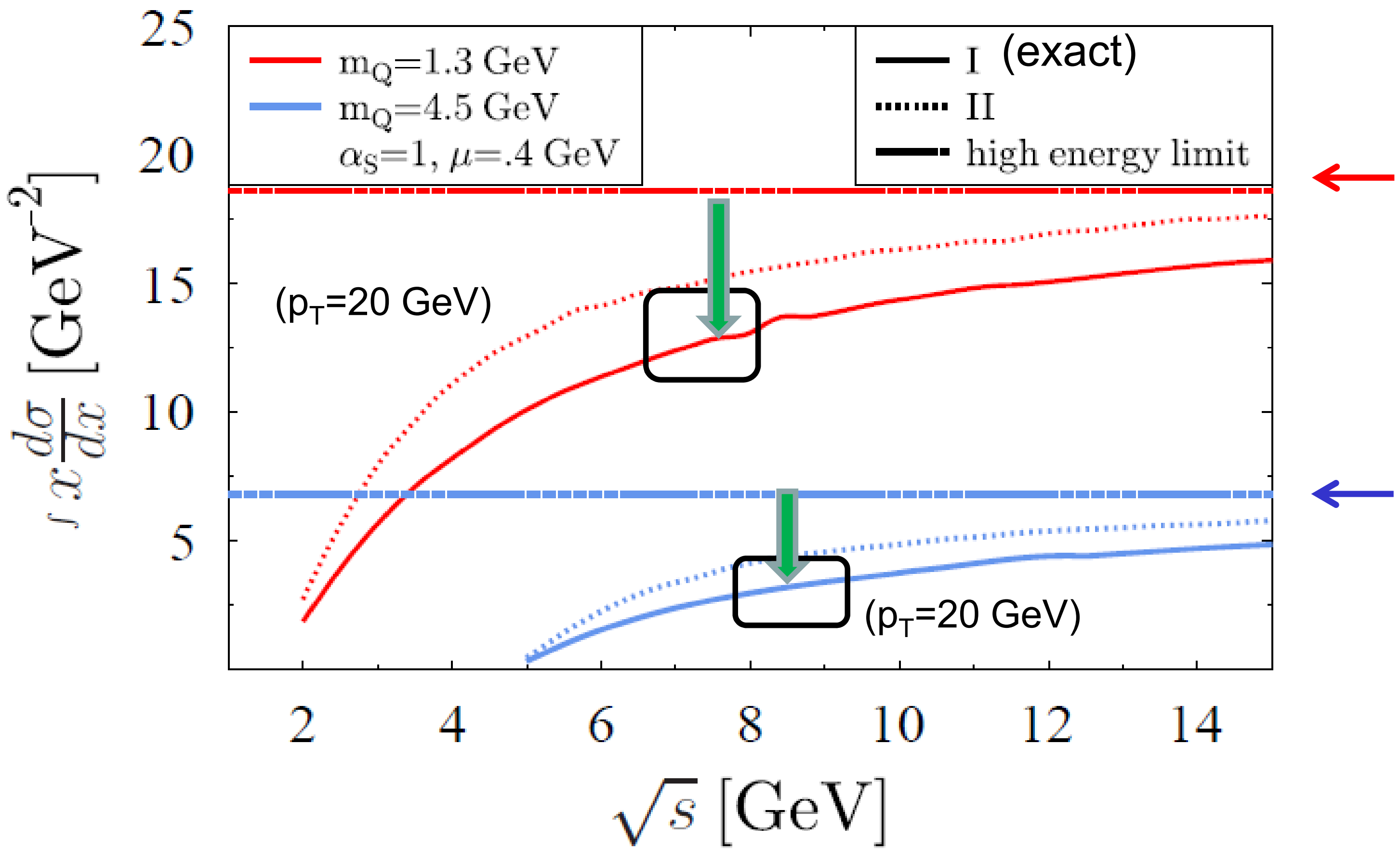
$$\frac{d\sigma_{\rm el}}{d^2\ell_t} \propto \frac{1}{t^2} \to \frac{1}{(t-\mu^2)^2}$$

μ : Natural scale for ℓ_t

Incoherent Induced Energy Loss at Finite Energy

$$\frac{dE_{\rm rad}}{dz} \approx \rho \int \omega \frac{d\sigma}{d\omega} d\omega \approx \rho E_{\rm beam} \int x \frac{d\sigma}{dx} dx.$$

Contribution from both $x<x_M$ and $x>x_M$

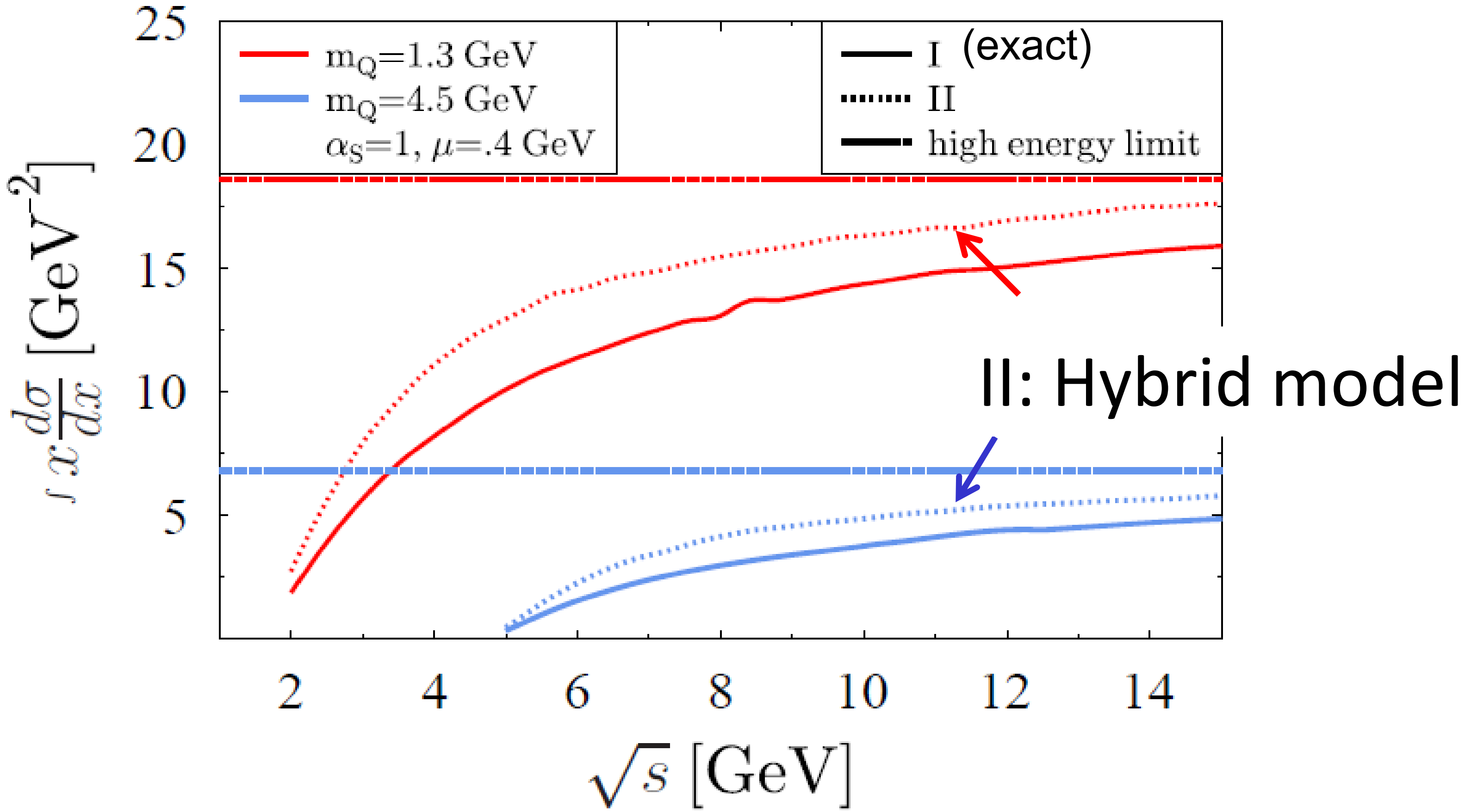


Asymptotic behaviour

$$\propto \frac{1}{\mu m_Q}$$

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

Incoherent Induced Energy Loss at Finite Energy



$$\frac{d\sigma_{II}^{Qq\to Qgq}}{dx d^2k_t d^2\ell_t} = \frac{d\sigma_{\text{el}}}{d^2\ell_t} P_g(x, \vec{k}_t, \vec{\ell}_t)\Theta(\Delta)$$

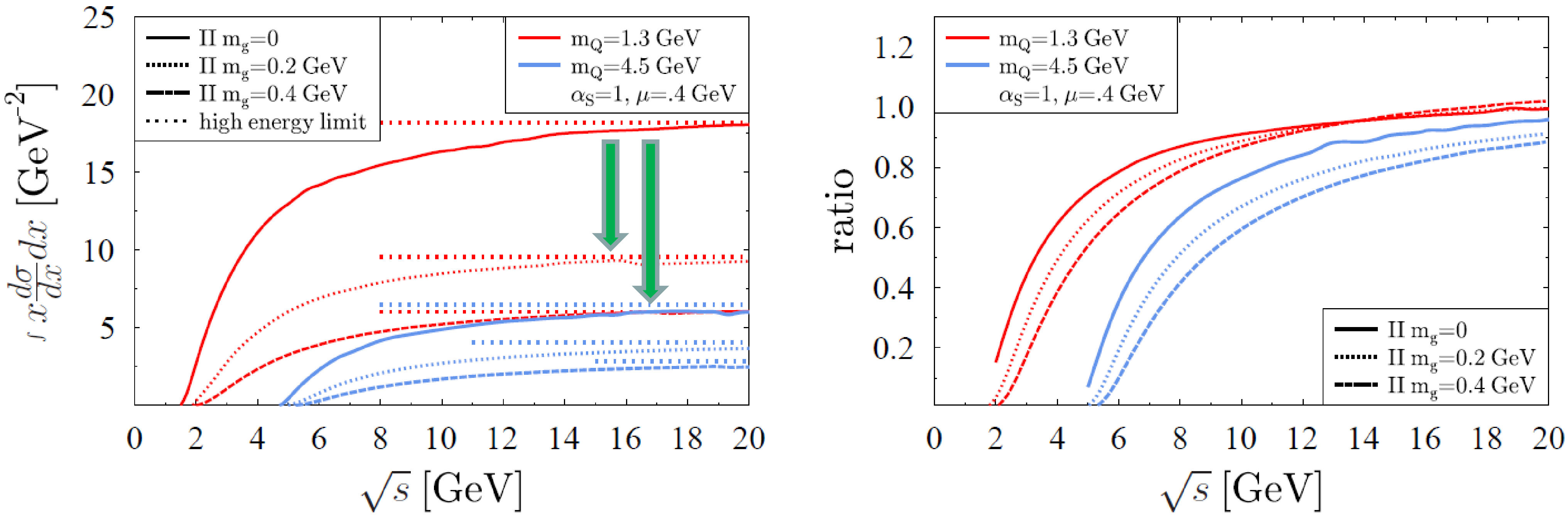
High energy P_g + finite phase space

Useful for a)MC simulations & b) gQ $\rightarrow$ gQg

Incoherent Induced Energy Loss at Finite T (m_g)

Our Prescription: Hybrid Model with

- modified phase space
- matrix el. P_g modified according to $x^2 m_Q^2 \rightarrow x^2 m_Q^2 + (1-x) m_g^2$



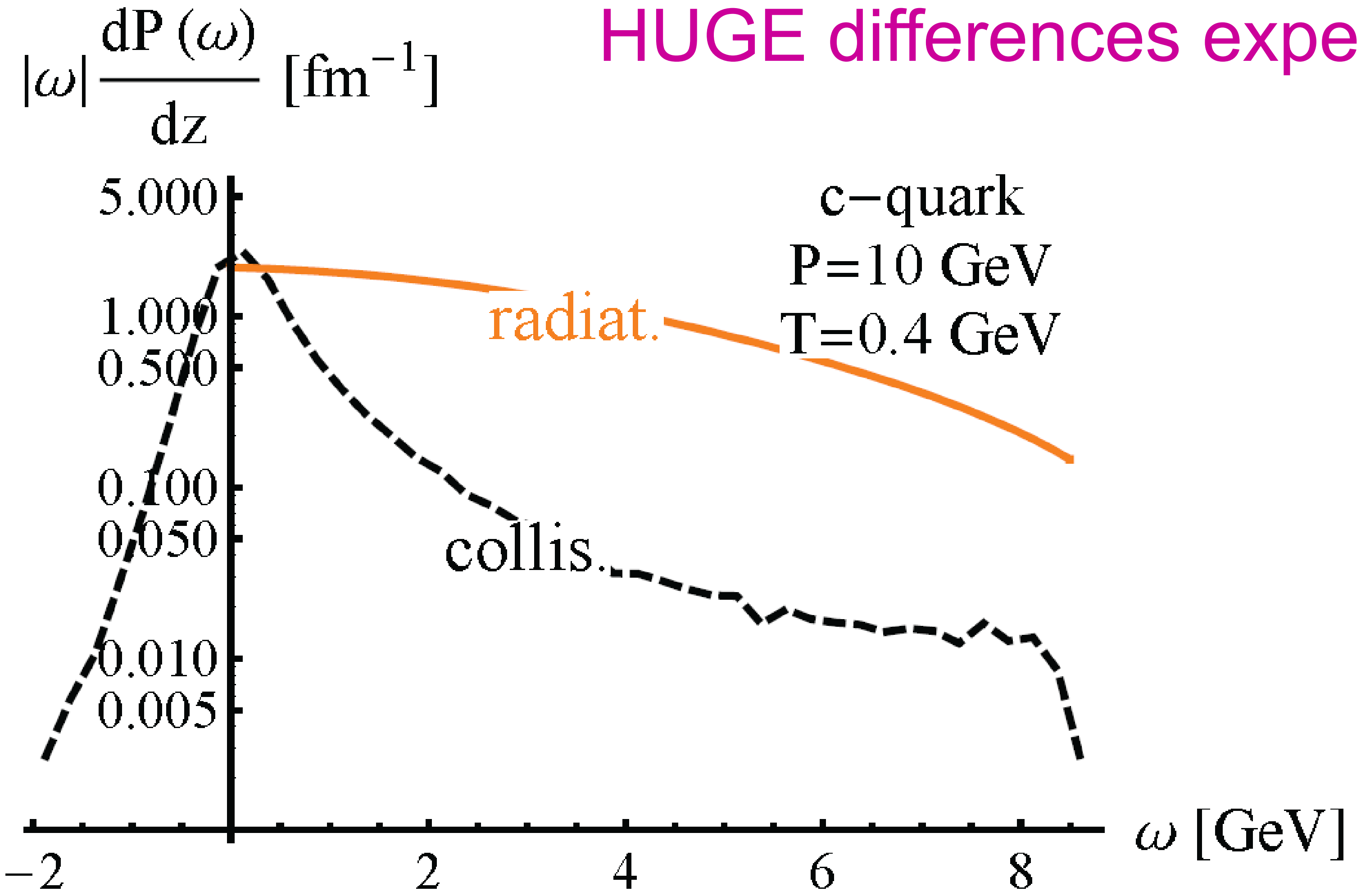
- Large reduction of the power spectra and average p-loss; scales roughly like asymptotic behaviour.

- $\Delta E_{rad} \approx \Delta E_{el.}$

Incoherent Induced Energy Loss

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

HUGE differences expected

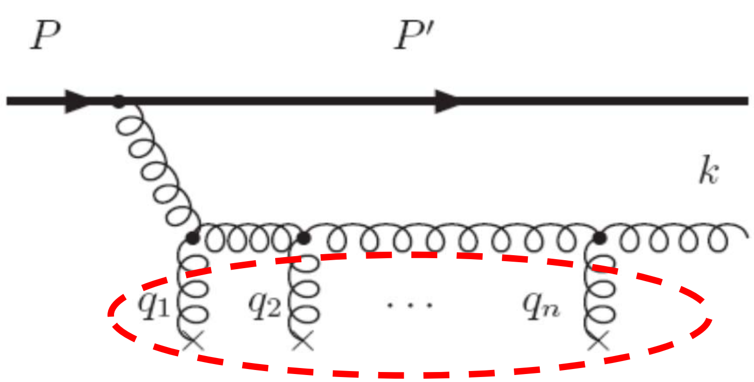


Caveat: no detailed balance implemented yet

Corrections from Coherence

Coherent Induced Radiative

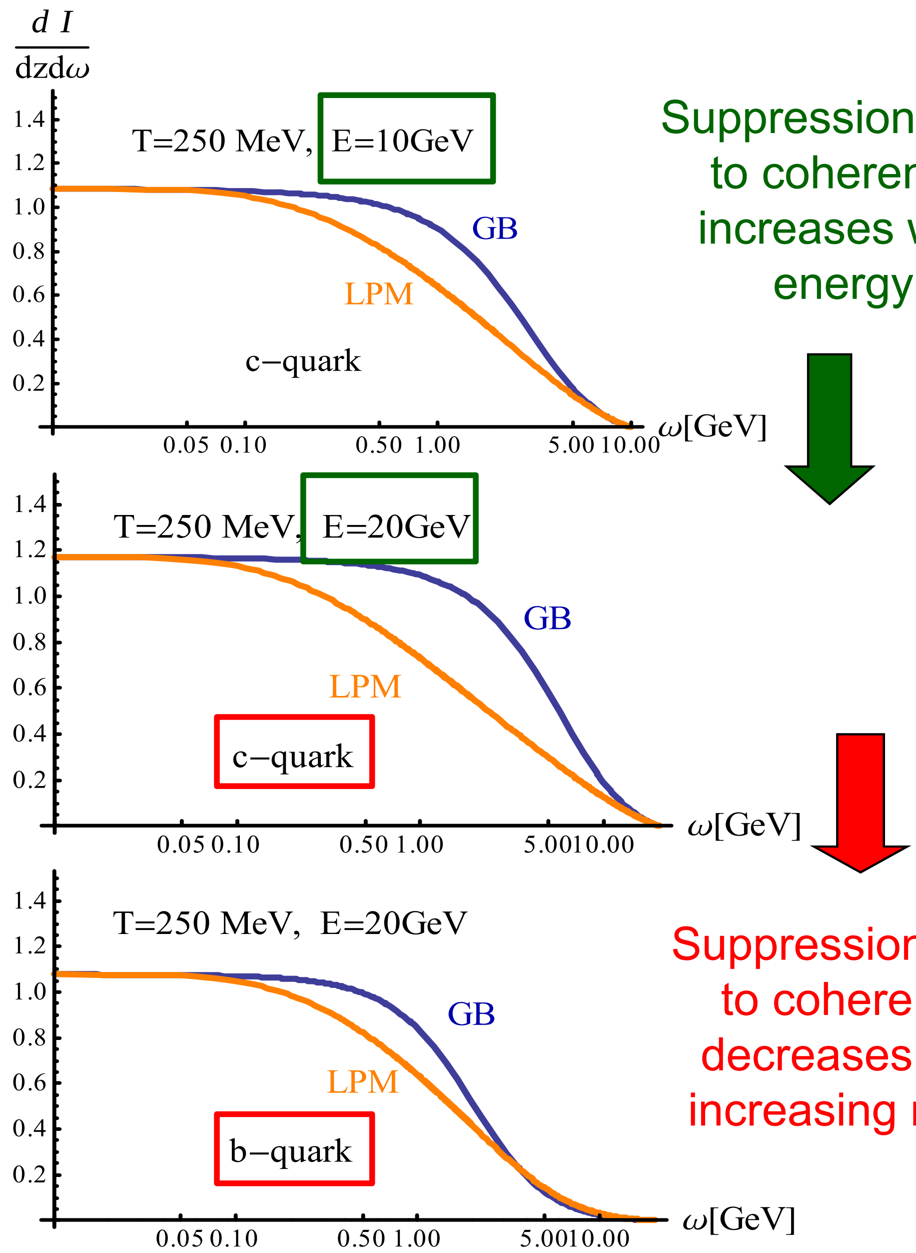
Formation time picture: for $l_{f,mult}>\lambda$, gluon is radiated coherently on a distance $l_{f,mult}$



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

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

Nuclear Physics A (2013), 301, [arXiv:1209.0844]

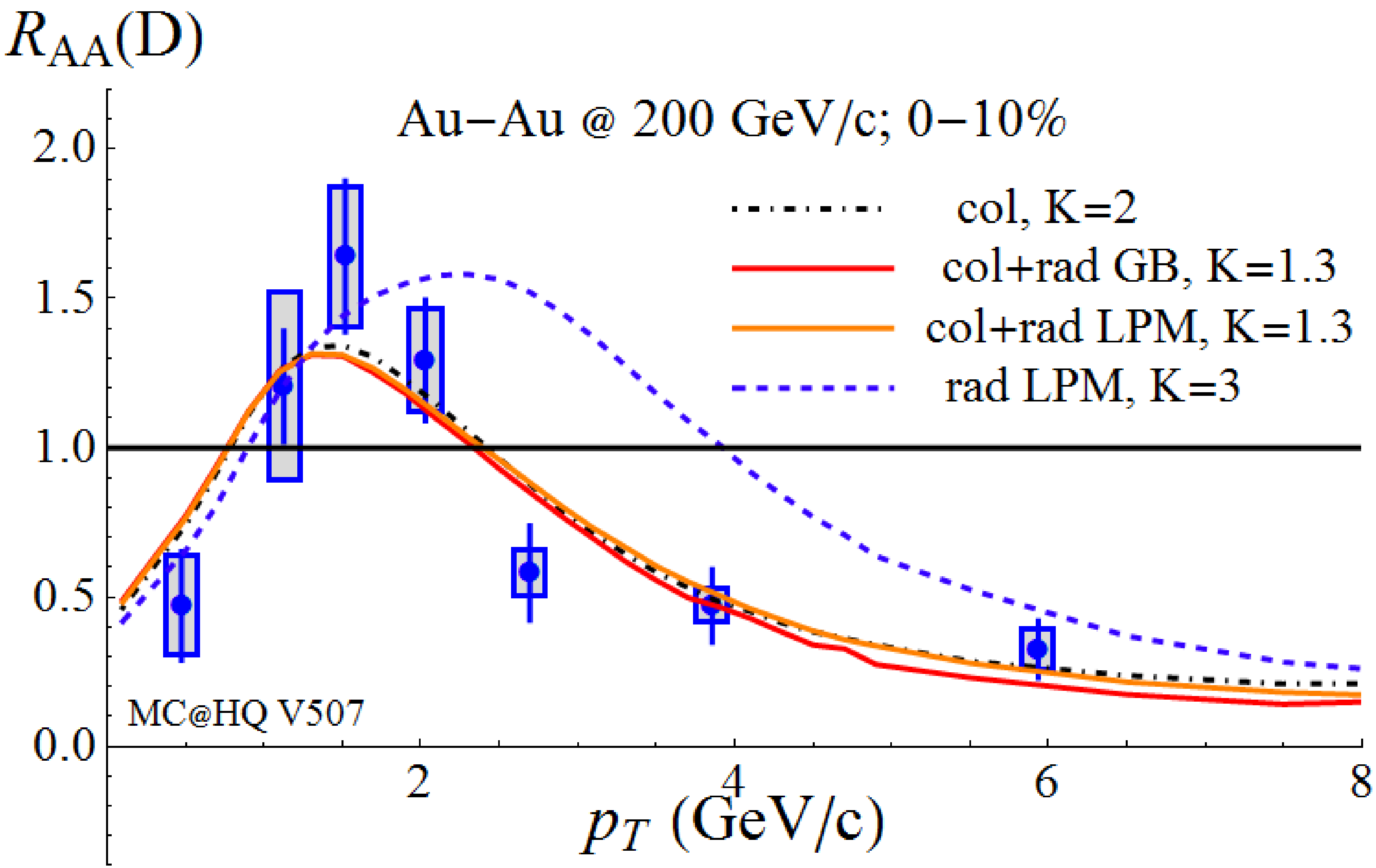


Suppression due to coherence increases with energy

Suppression due to coherence decreases with increasing mass

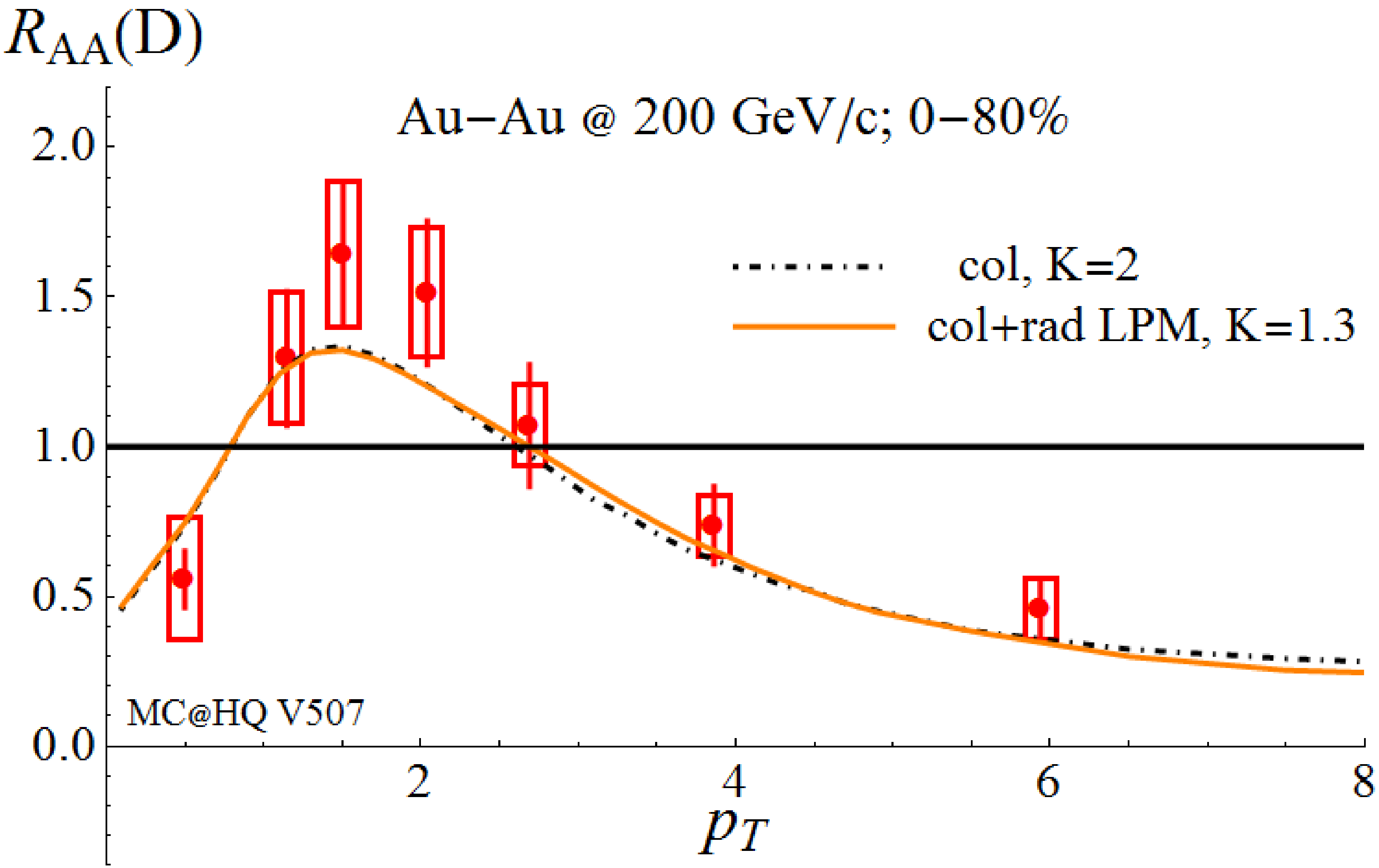
{Radiative + Elastic} vs Elastic for D mesons @ RHIC

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



K coming closer to unity if radiation included

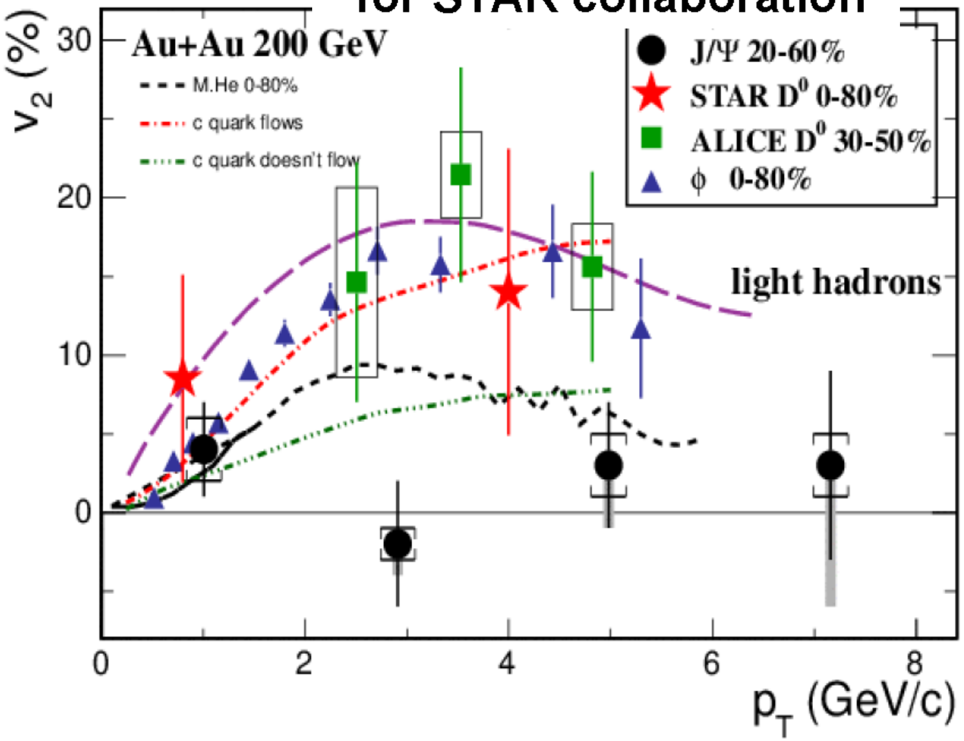
{Radiative + Elastic} vs Elastic for D mesons @ RHIC

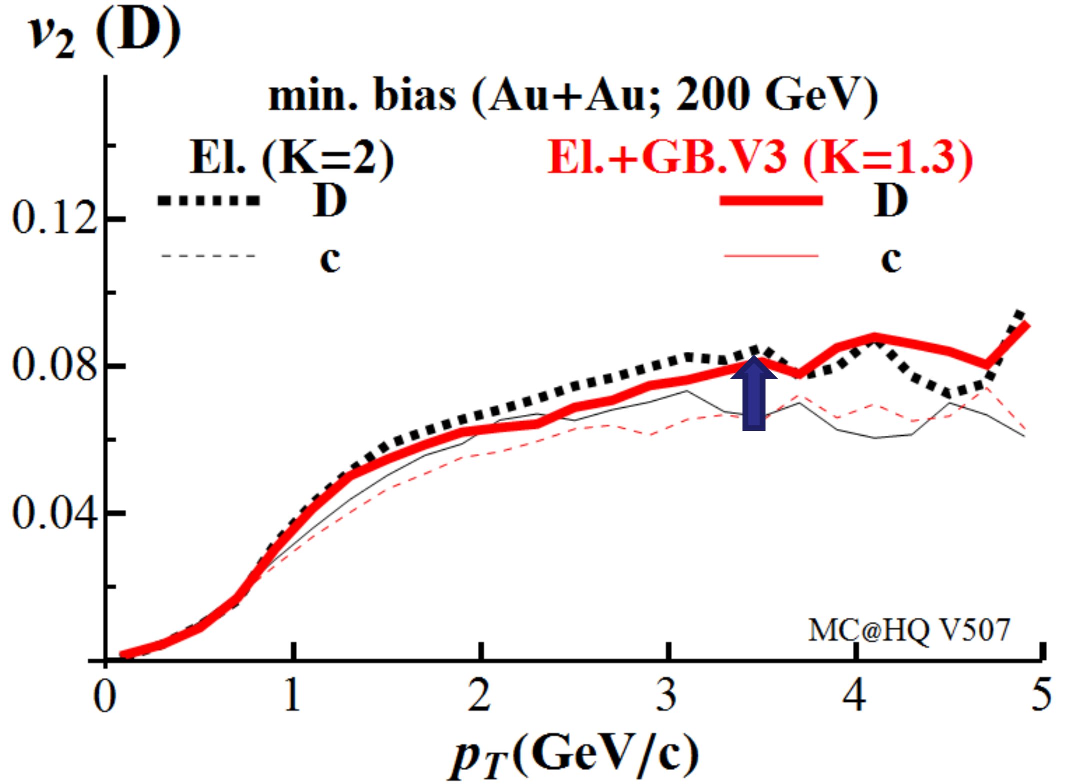


{Radiative + Elastic} vs Elastic for D mesons @ RHIC

Jaroslav Bielčík

for STAR collaboration





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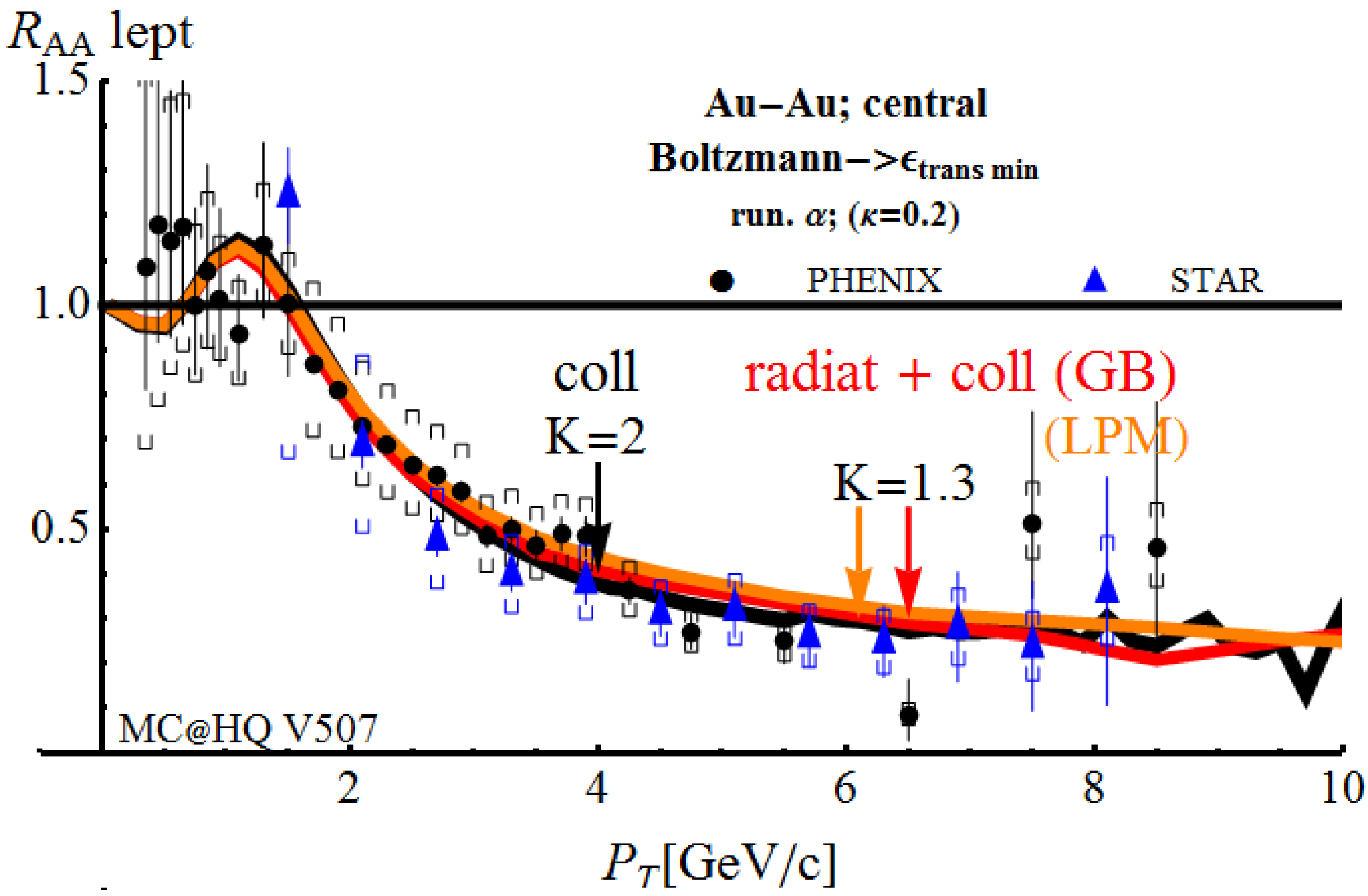
{Radiative + Elastic} vs Elastic for leptons @ RHIC



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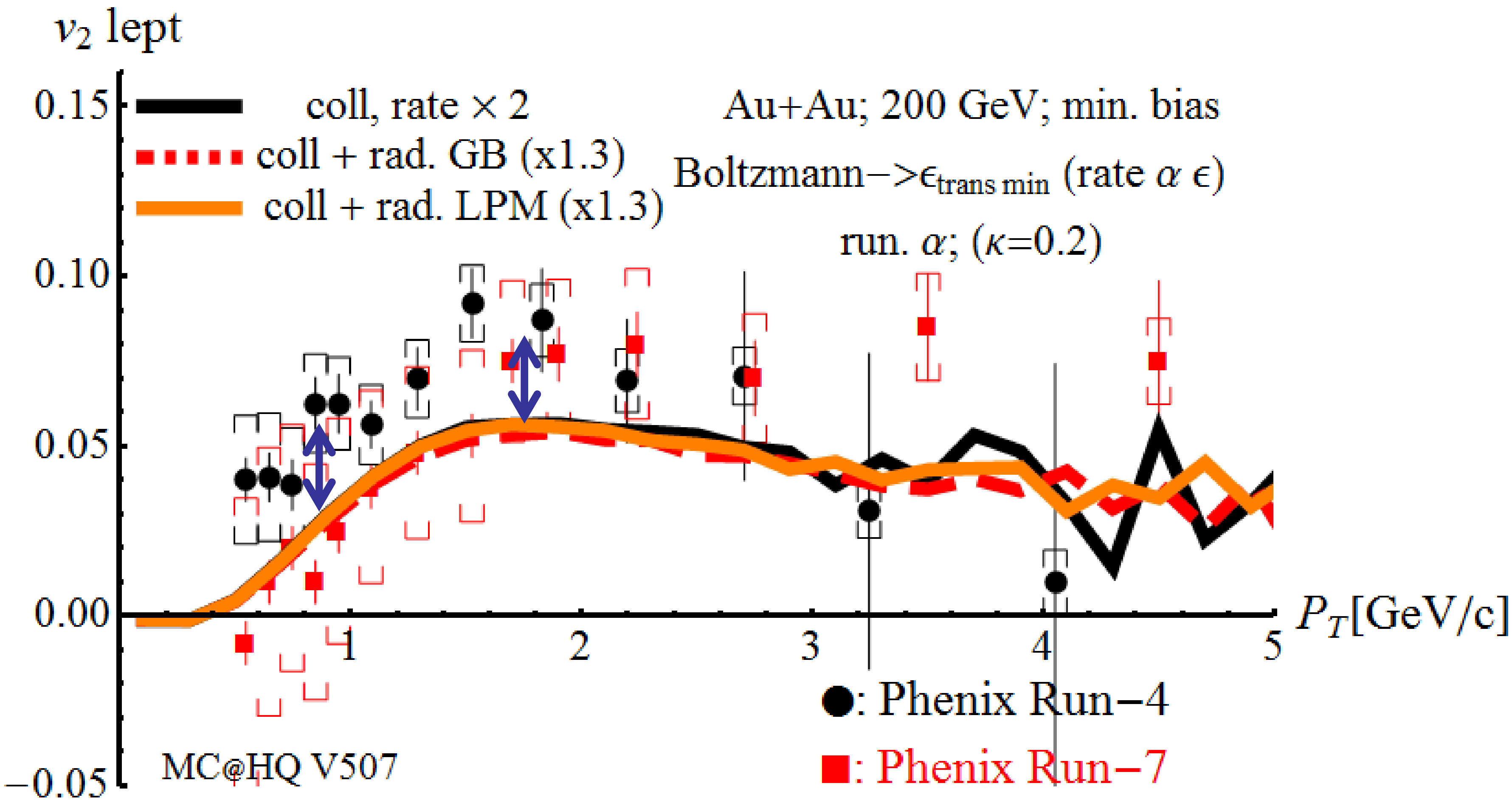
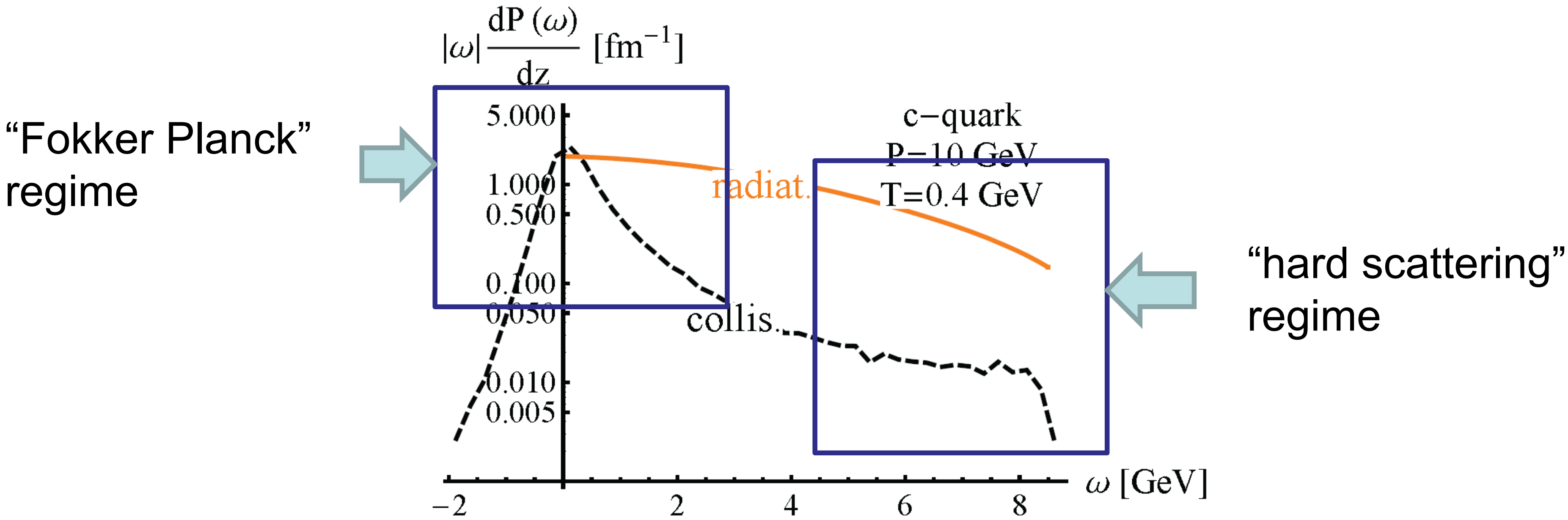


El. + rad: No lack of elliptic flow wrt pure (rescaled) elastic processes (!?)

Conclusions from RHIC

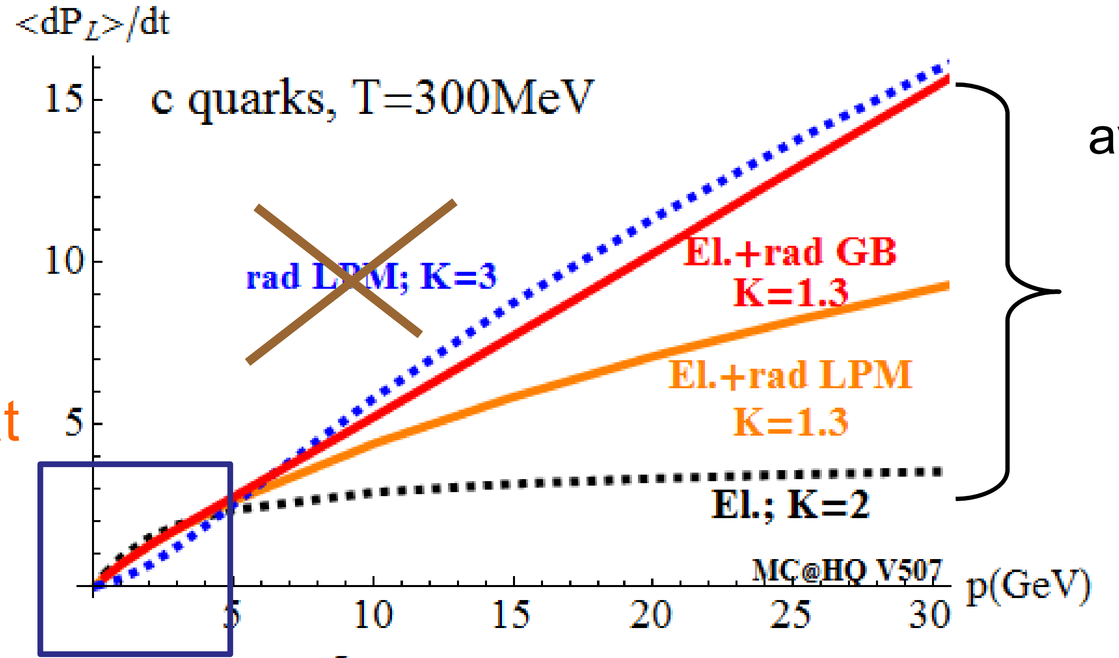
- Good consistency between NPSE and D mesons (10% difference in K values)…
- … within a model with mass hierarchy
- ΔE radiative < ΔE elastic
- Present data at RHIC cannot decipher between the 2 local microscopic E-loss models (elastic, elastic + radiative GB) $\Rightarrow$ Not sensitive to the large-ω tail of the Energy-loss probability (thanks to initial HQ distribution)



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* ~ 1

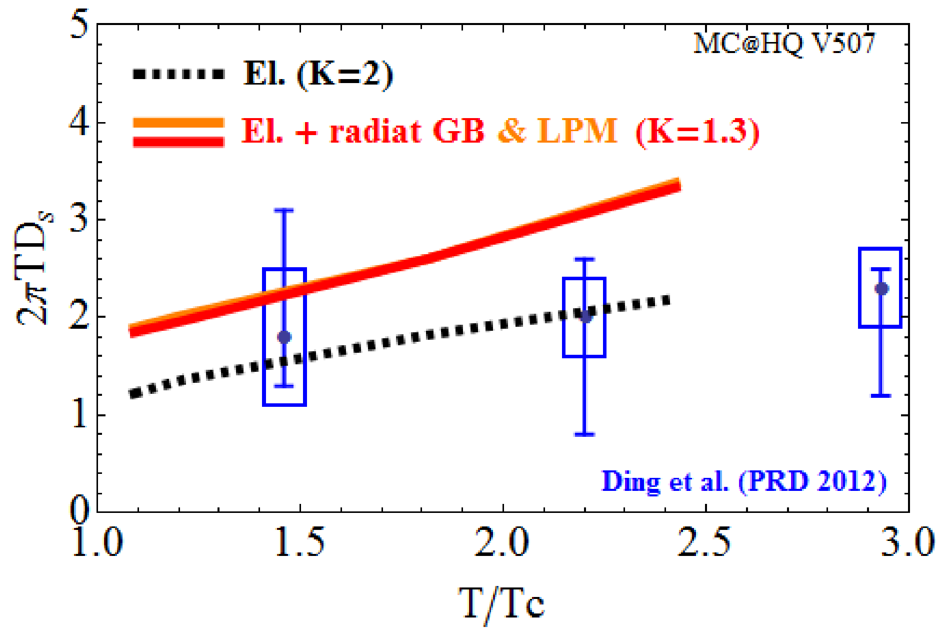
Present RHIC experiments cannot resolve between those various trends

Hope that LHC can do !!!

We extract it from data

(starting from SQM 2008)

We compare with recent lattice results

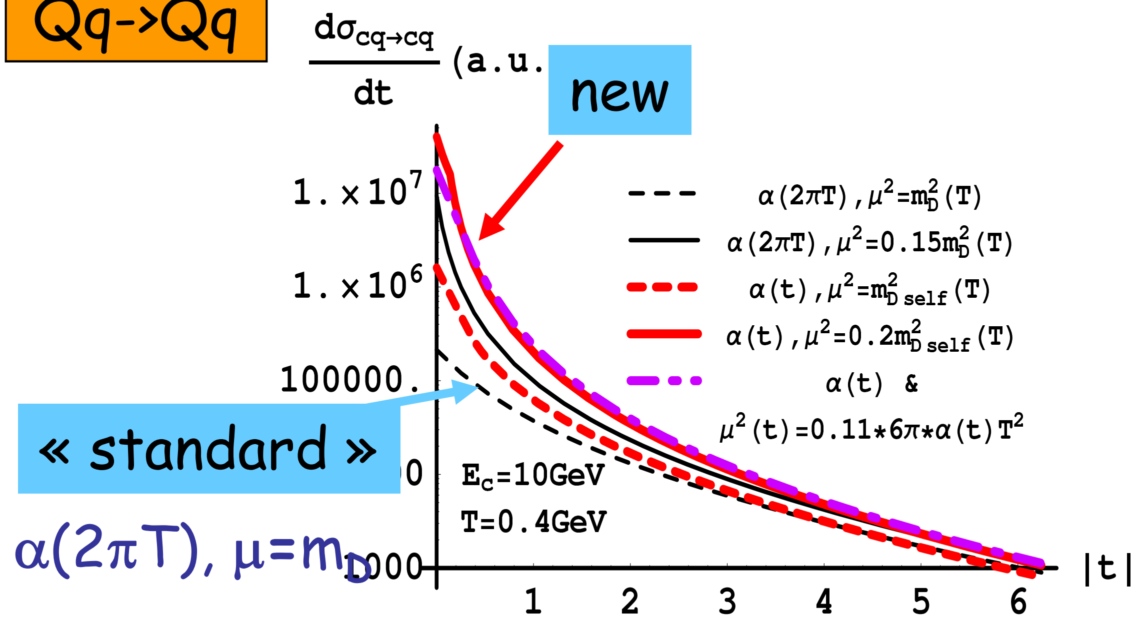


Main message

It is possible to reveal some fundamental property of QGP using HQ probes

Perspectives

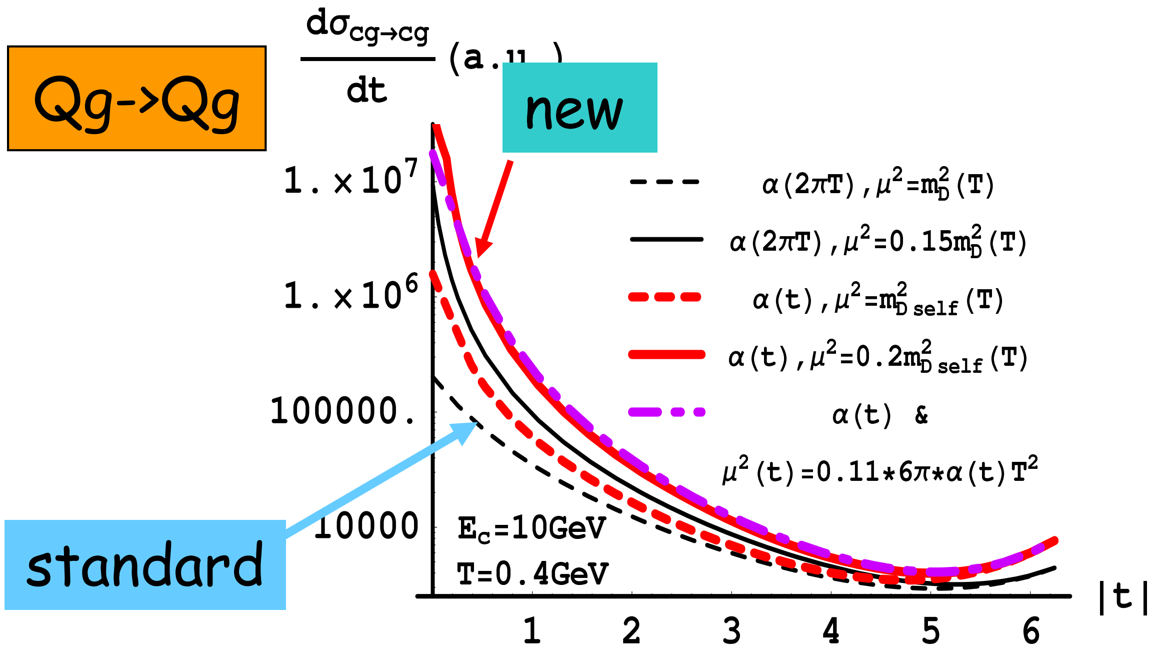
Qq->Qq



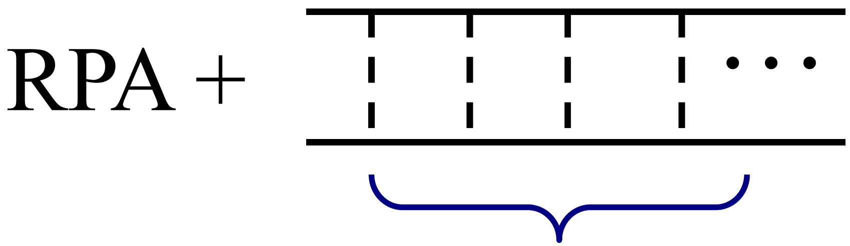
Large enhancement of both cross sections at small and intermediate |t|

Little change at large |t|

Qg->Qg



N.B: Non perturbative aspects (beyond Born). Usually in convergent kinetic:

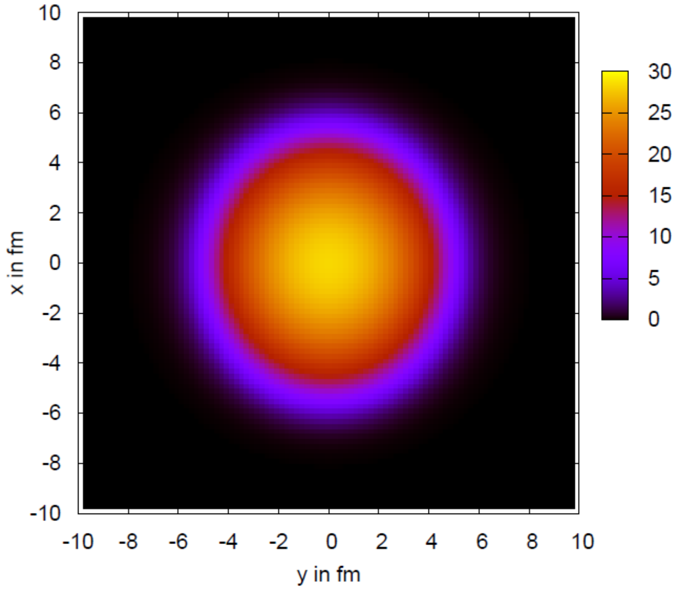


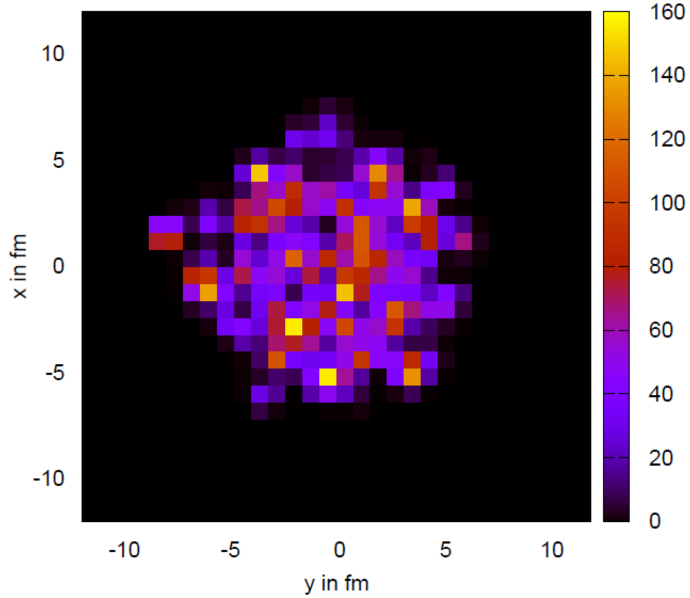
Ladders necessary at short distance (large force)

Nowadays: EPOS as a background for MC@sHQ (K.Werner, M. Nahrgang, B. Guiot, V. Ozvenchuk)

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

Initial energy density @ RHIC (central Au-Au)





Beware: ≠ color scales

Kolb Heinz (used previously)

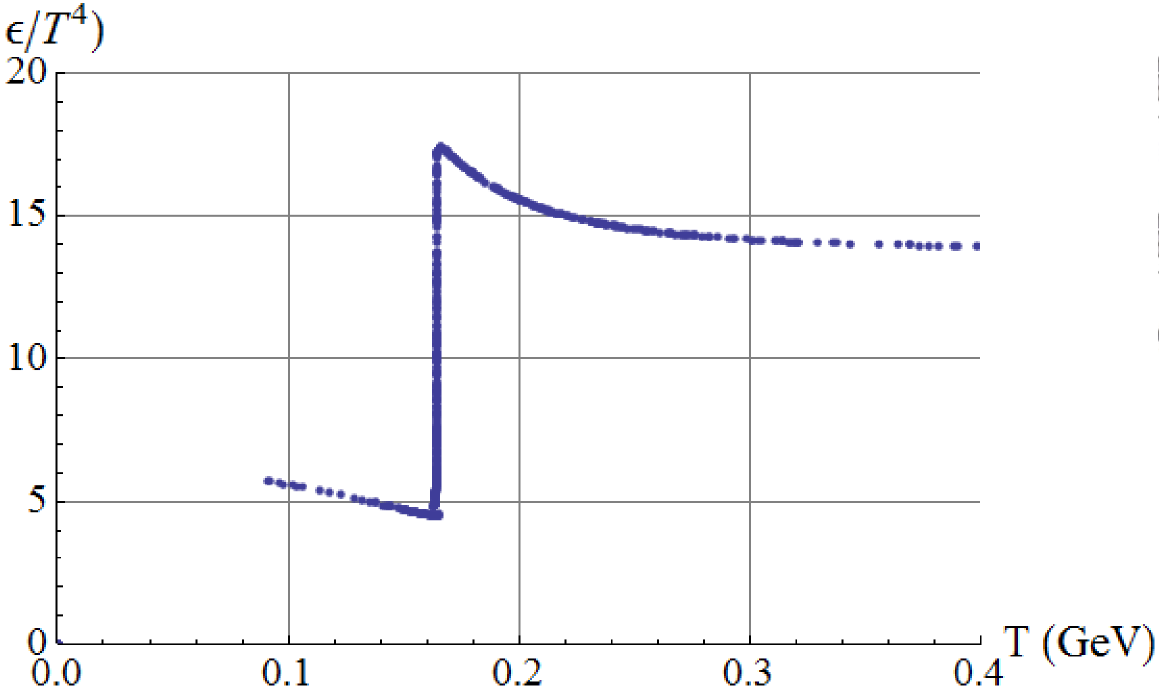
EPOS

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

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

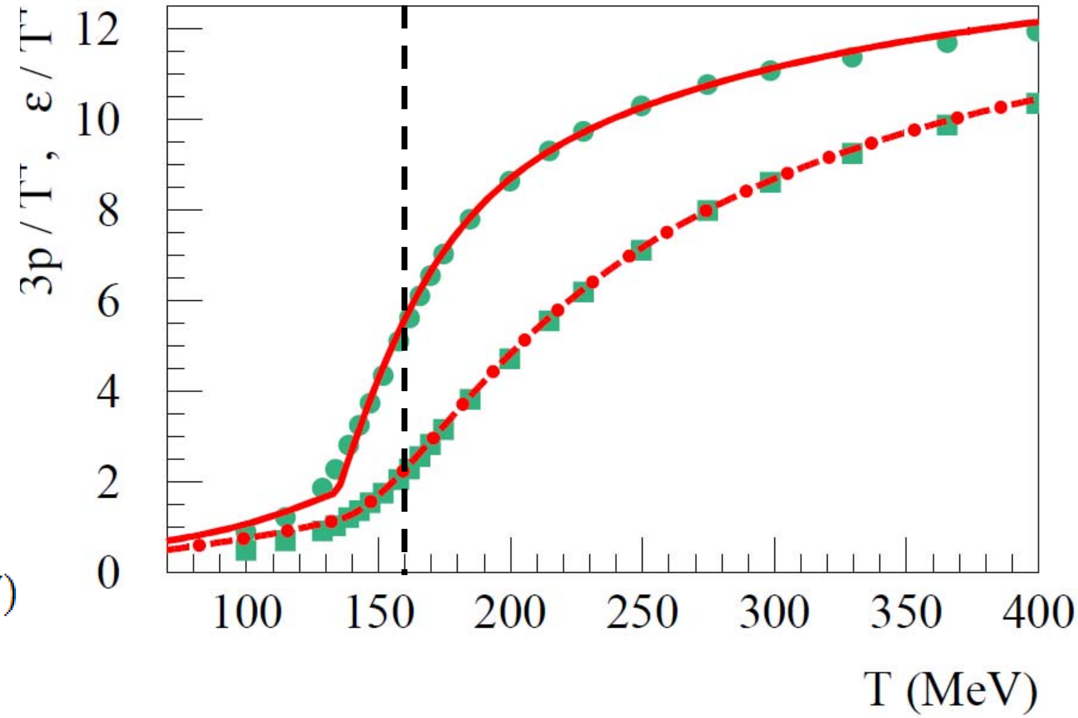
2) correlations between HF and light hadrons

Large differences in the EOS !



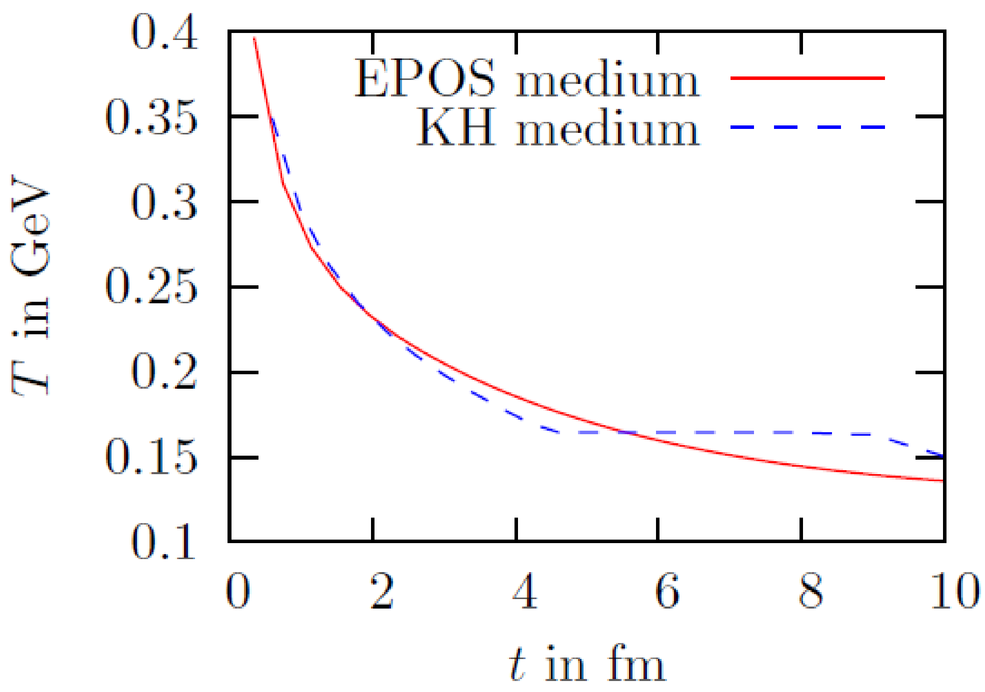
Kolb Heinz: bag model (1rst order transition btwn hadronic phase and massless partons)

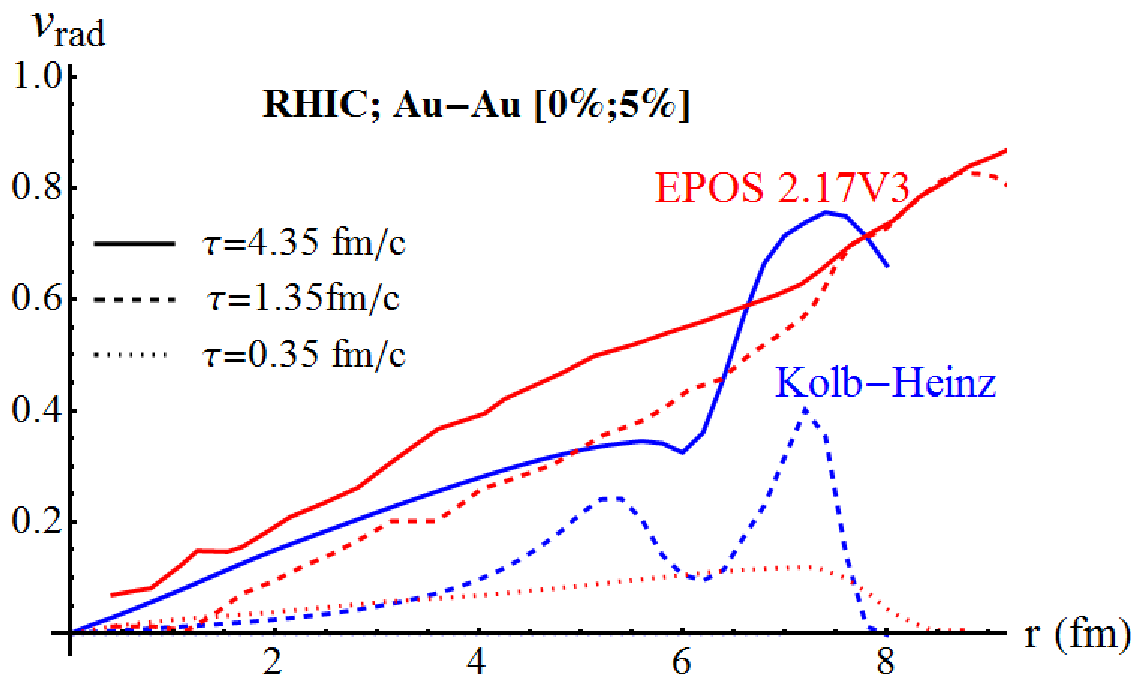
c-quark FO: 155 MeV



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

Medium comparison at RHIC



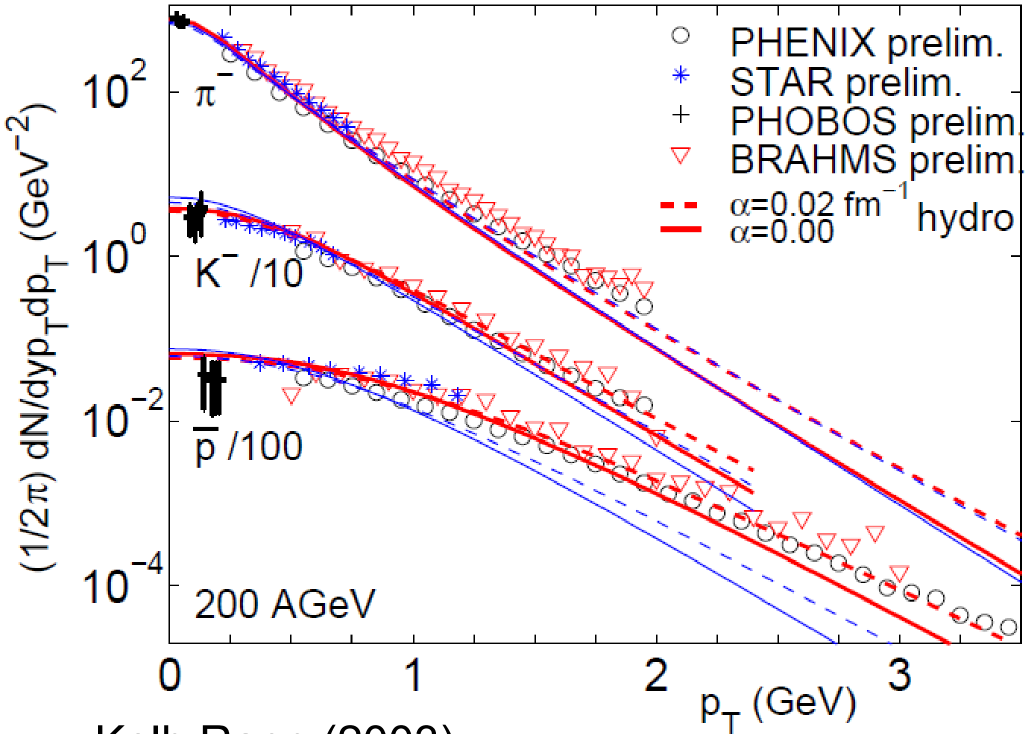


Gross features of T-evolution are identical in the « plasma » phase (T>200 MeV)

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

Identified particles spectra at RHIC

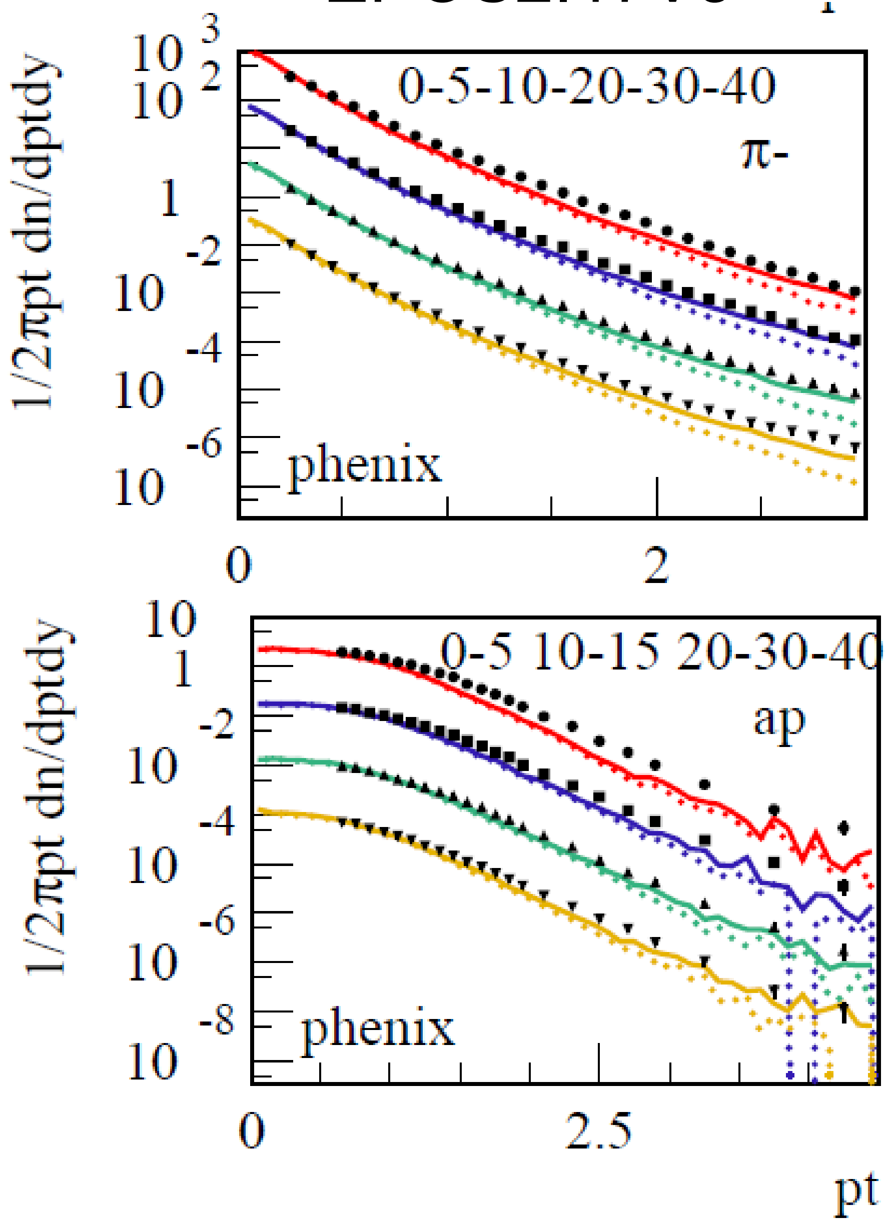
Kolb-Heinz



Kolb Rapp (2003)

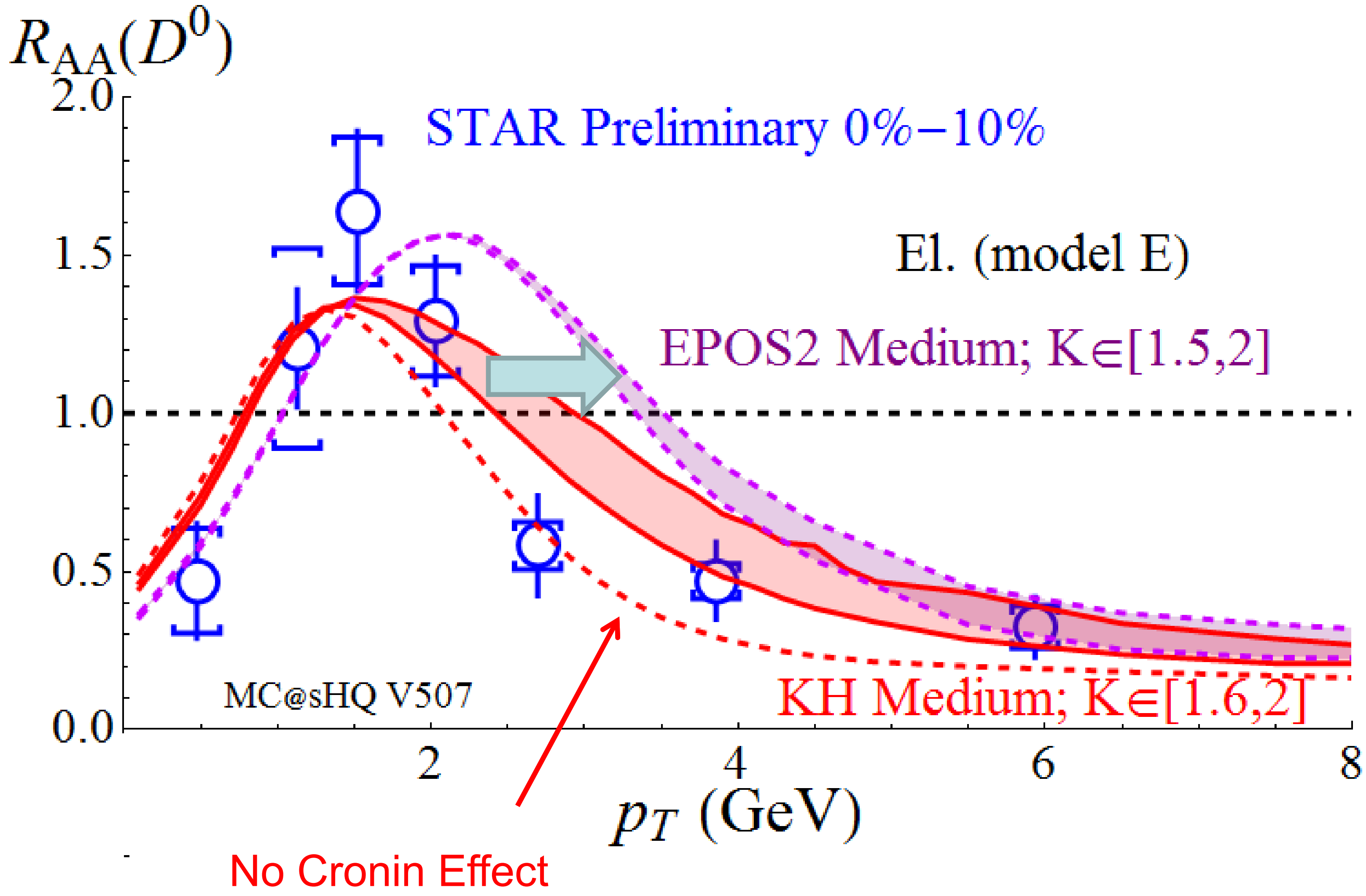
better agreement if
initial flow (vr=tanh(0.02 r))

EPOS2.17V3

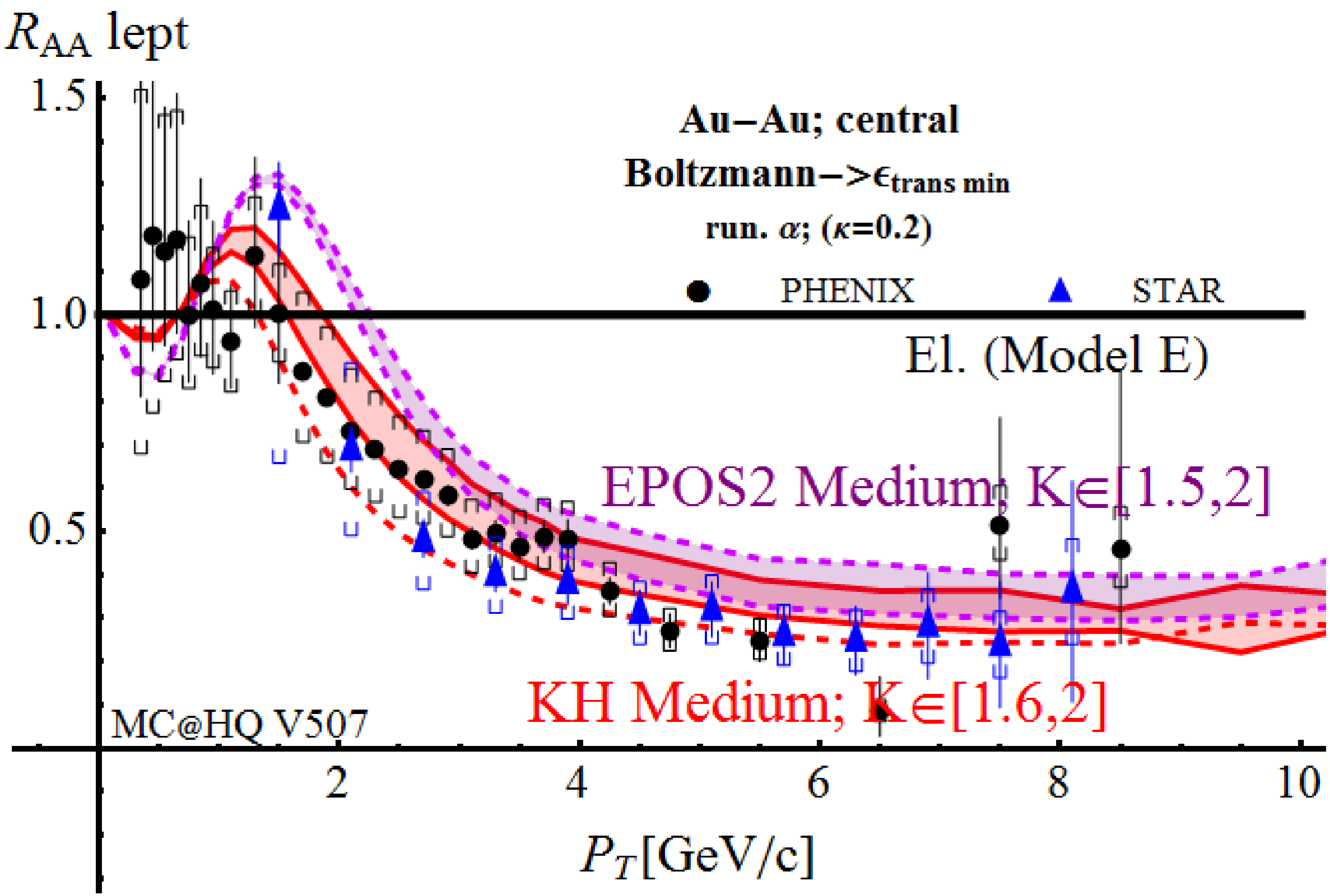


Elastic D mesons @ RHIC

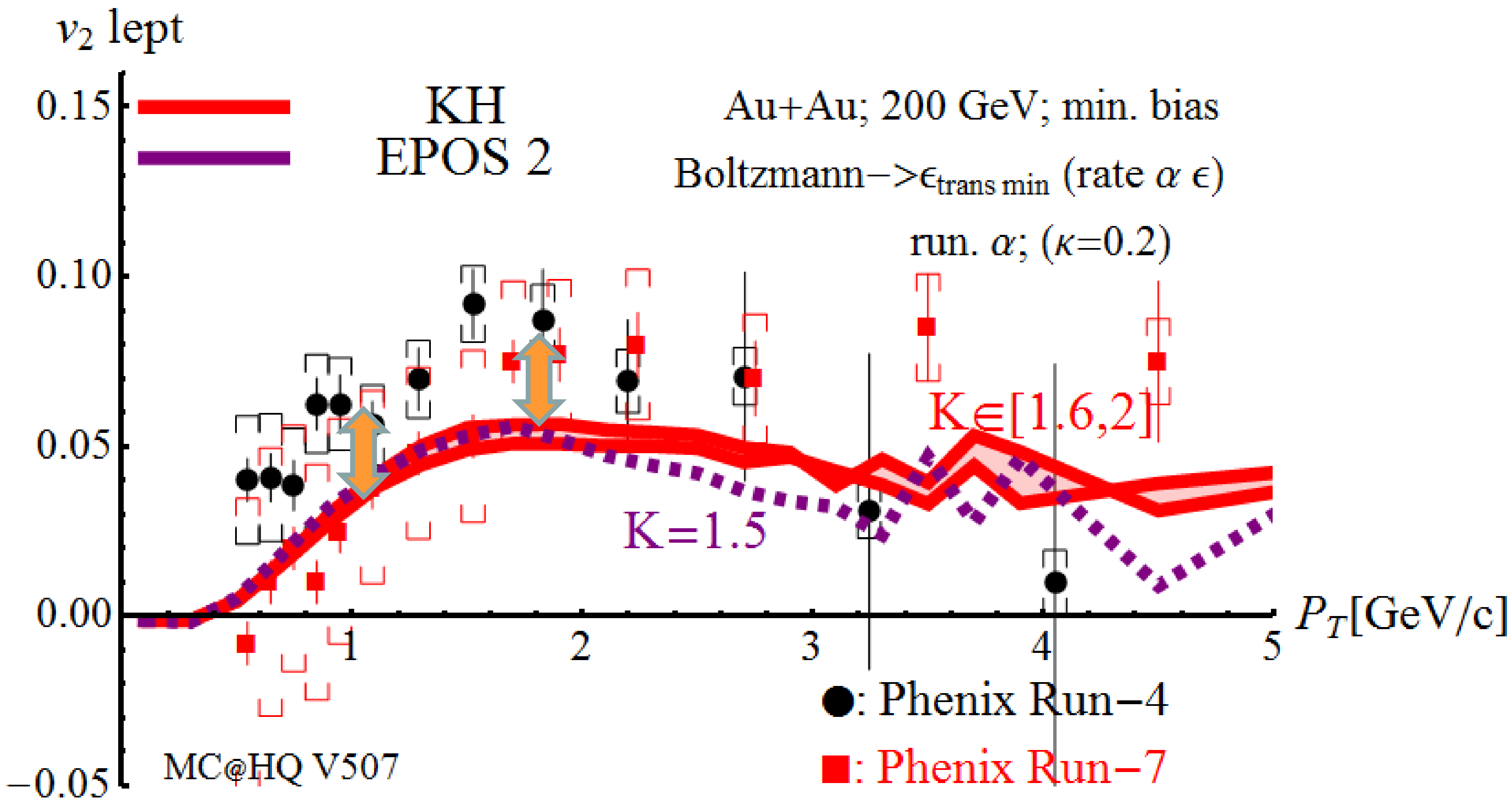
=> Allow for some global rescaling of the rates: “K” fixed on experiment



Elastic for leptons @ RHIC



{Radiative + Elastic} vs Elastic for leptons @ RHIC

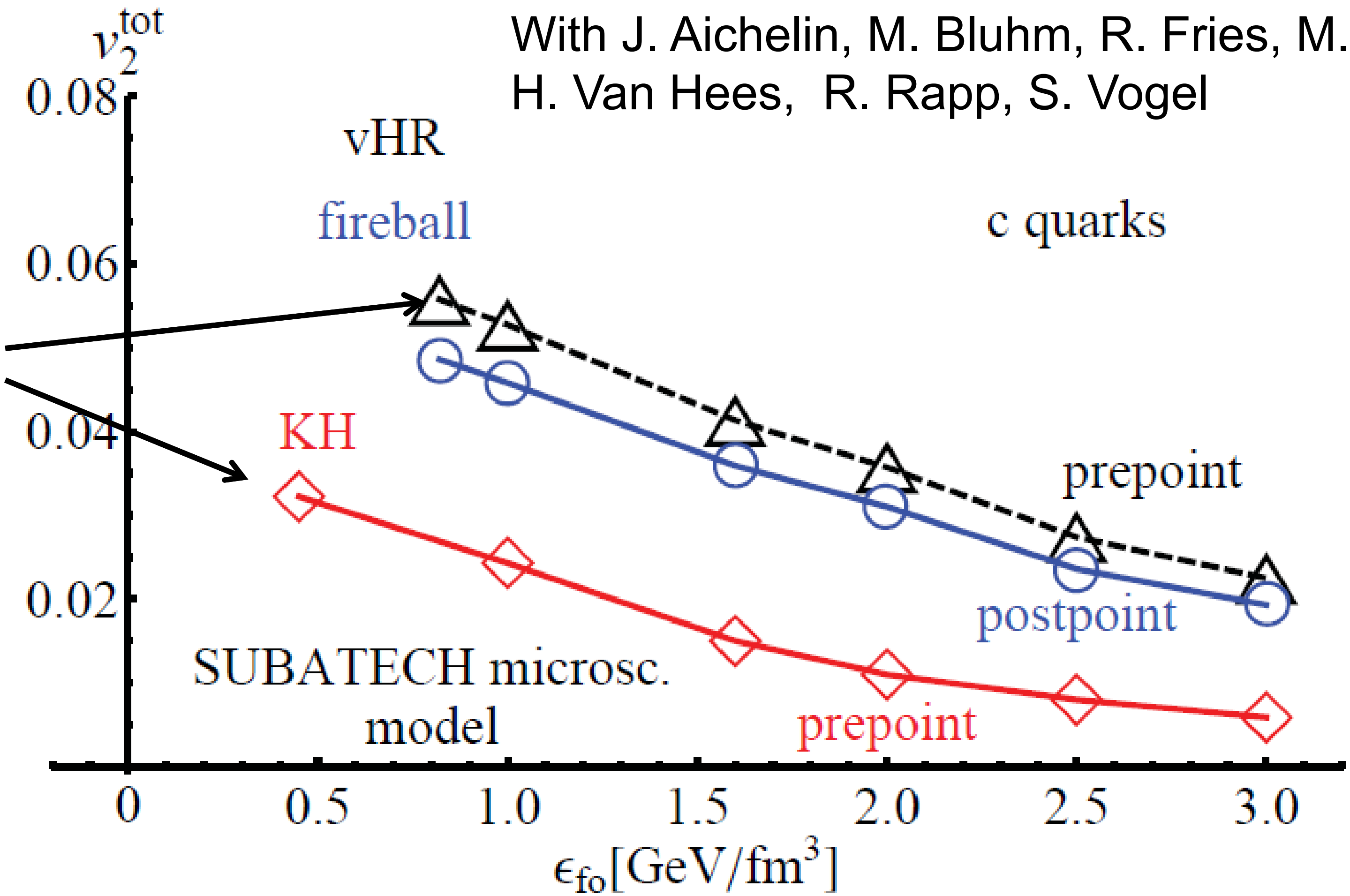


Rather systematic underestimation of the v2… sign for a significant D mesons rescattering in hadronic matter ?

{Radiative + Elastic} vs Elastic for leptons @ RHIC

With J. Aichelin, M. Bluhm, R. Fries, M. He, H. Van Hees, R. Rapp, S. Vogel

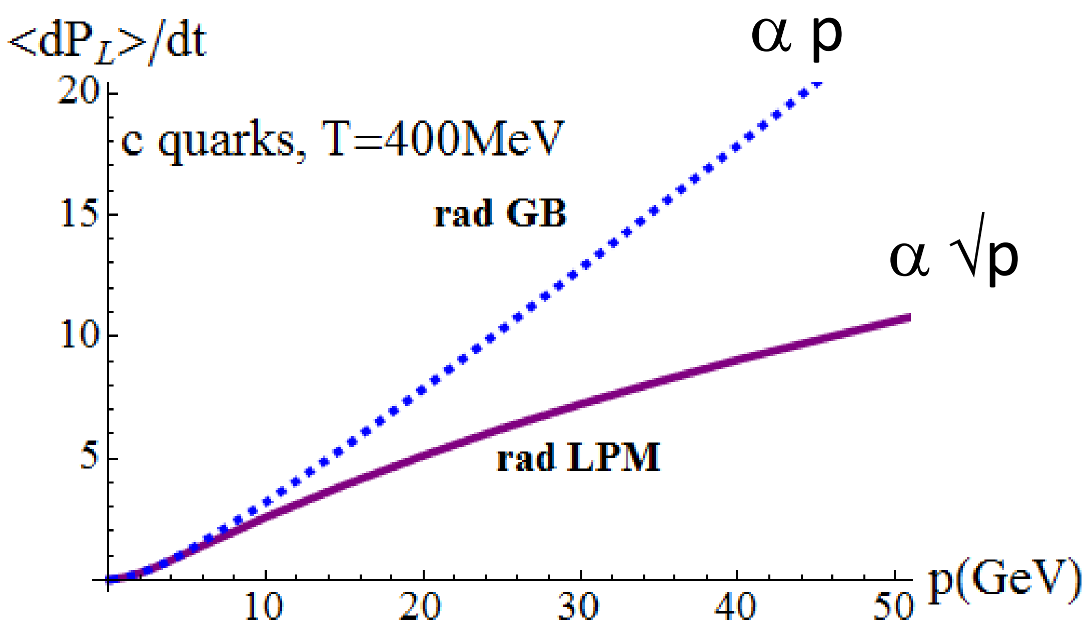
V2 builds continuously with time (large inertia) => support the need for studying the D-mesons interactions in hadronic matter

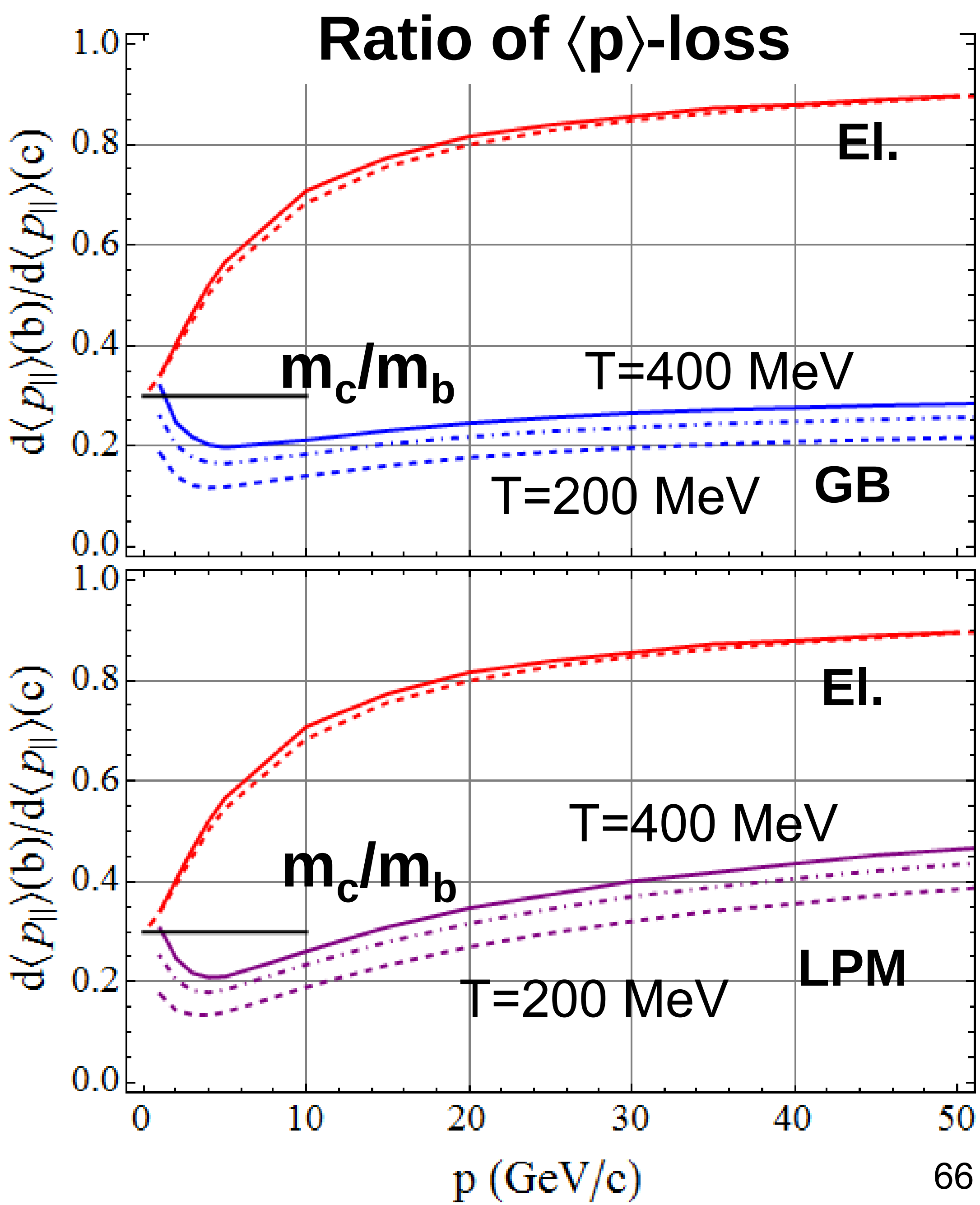


Alternative "exotic" explanation: early v2 => fundamental issue of initial state conditions in AA collisions

Having the hadronic sector under control (FAIR) will help constraining the "exotic" explanation => important cross-talk between FAIR & RHIC-LHC

Radiative Momentum Loss with Running α_s $d\sigma_{el}$



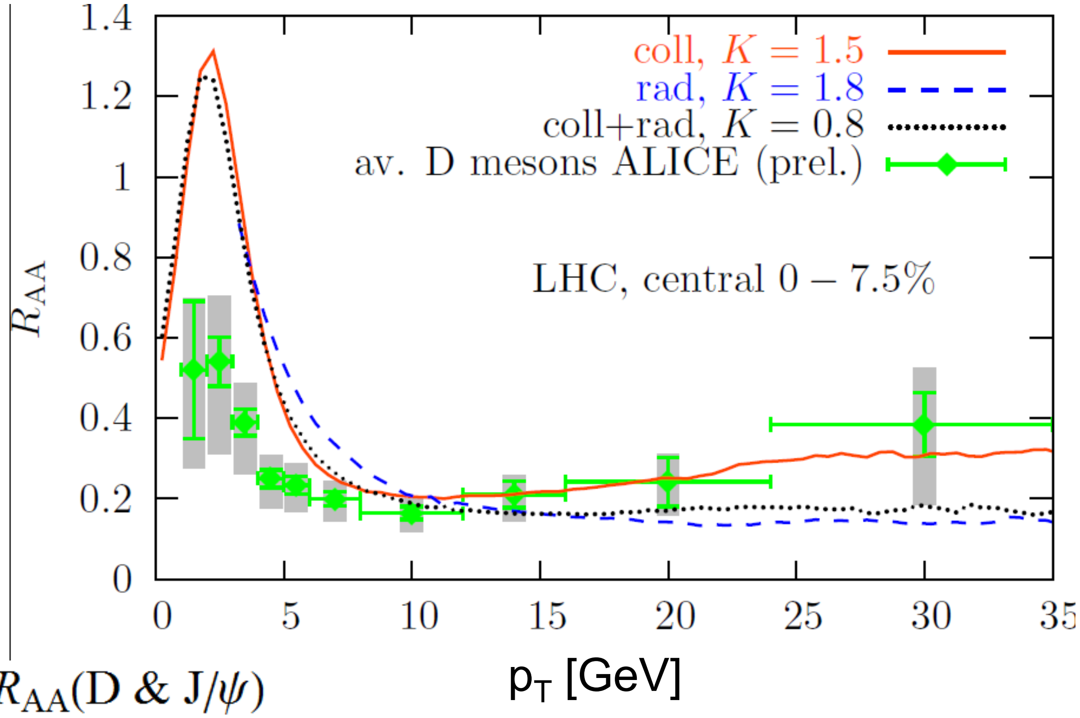


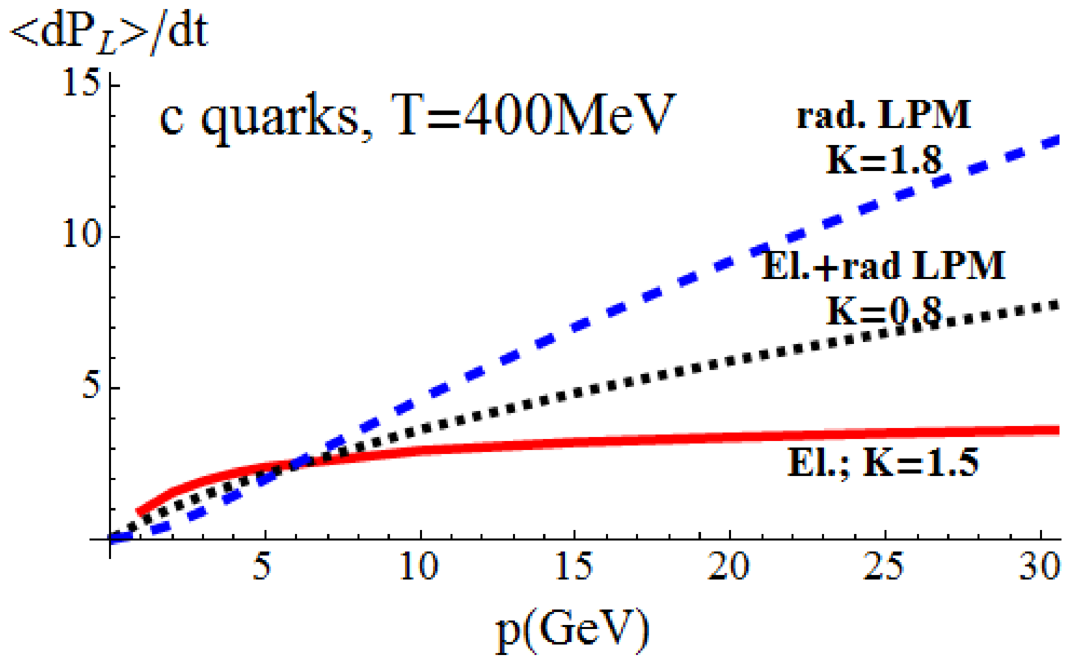
Mass hierarchy:

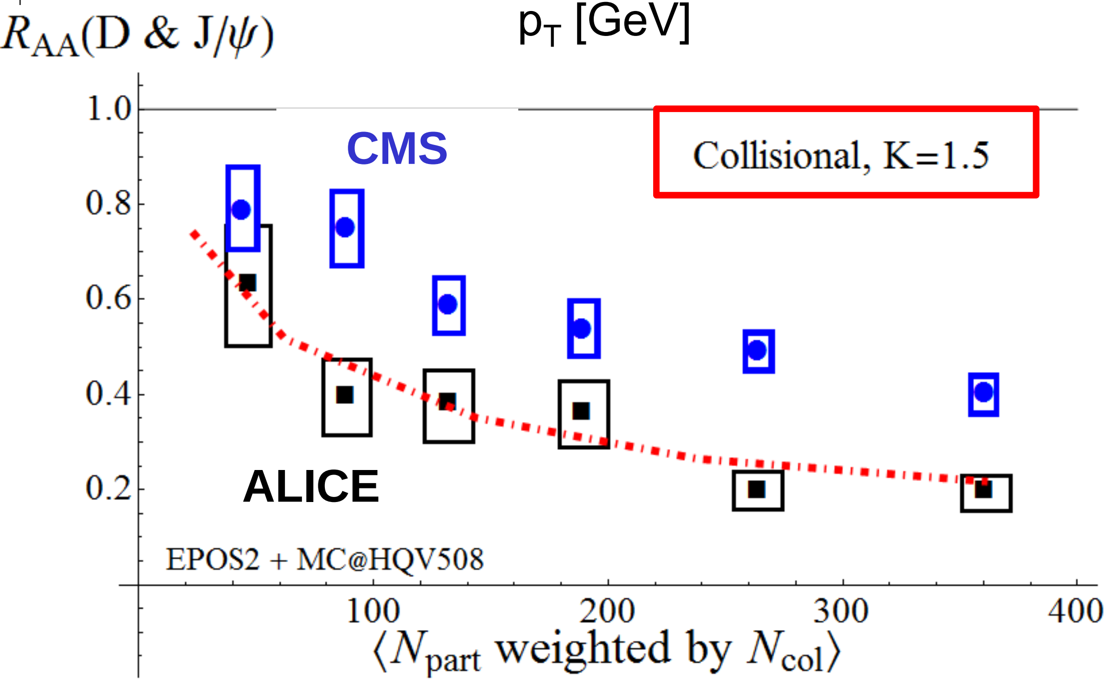
Elastic < rad LPM < rad GB

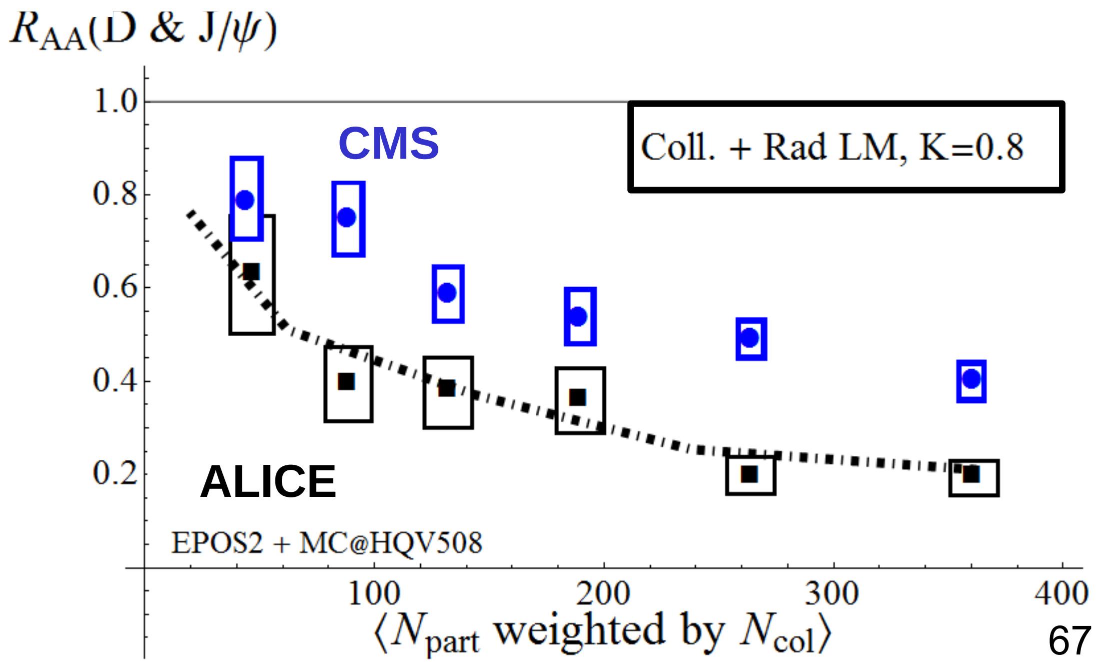
Best seen at the LHC

Contact with LHC Data: a) for c-Quarks…

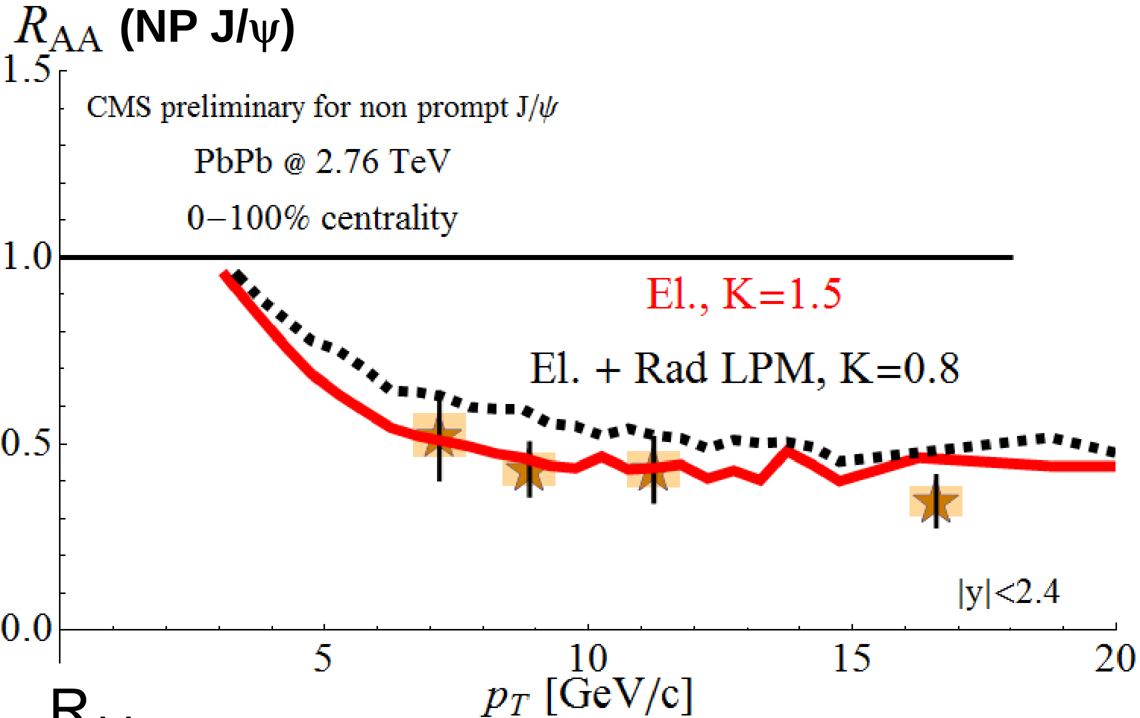


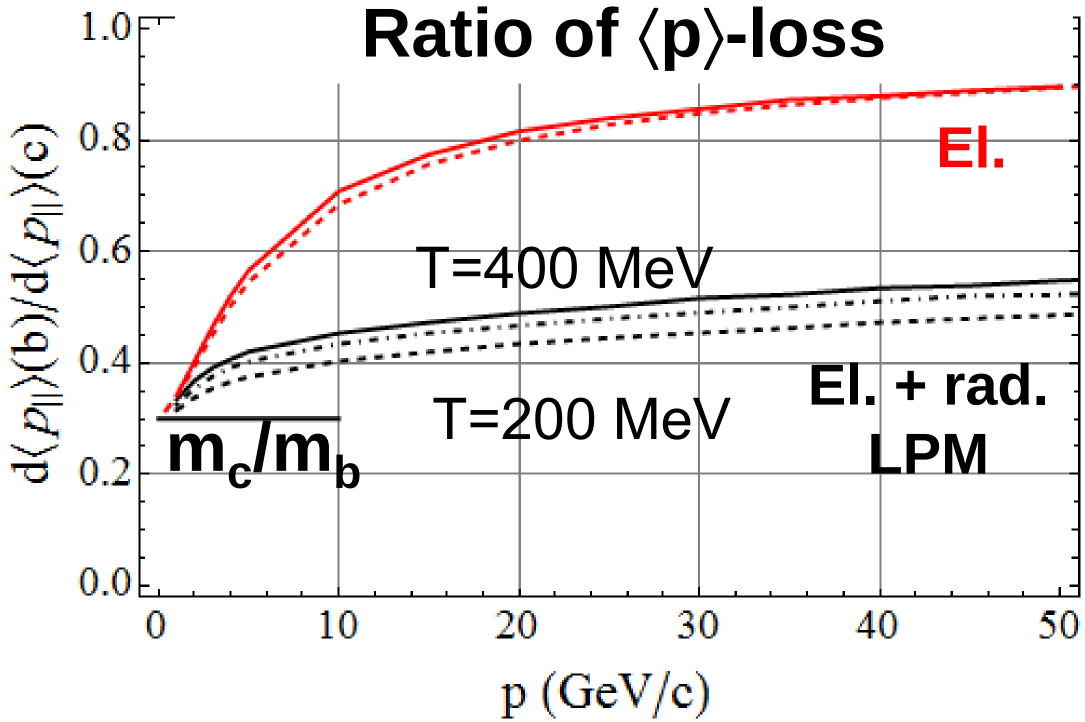


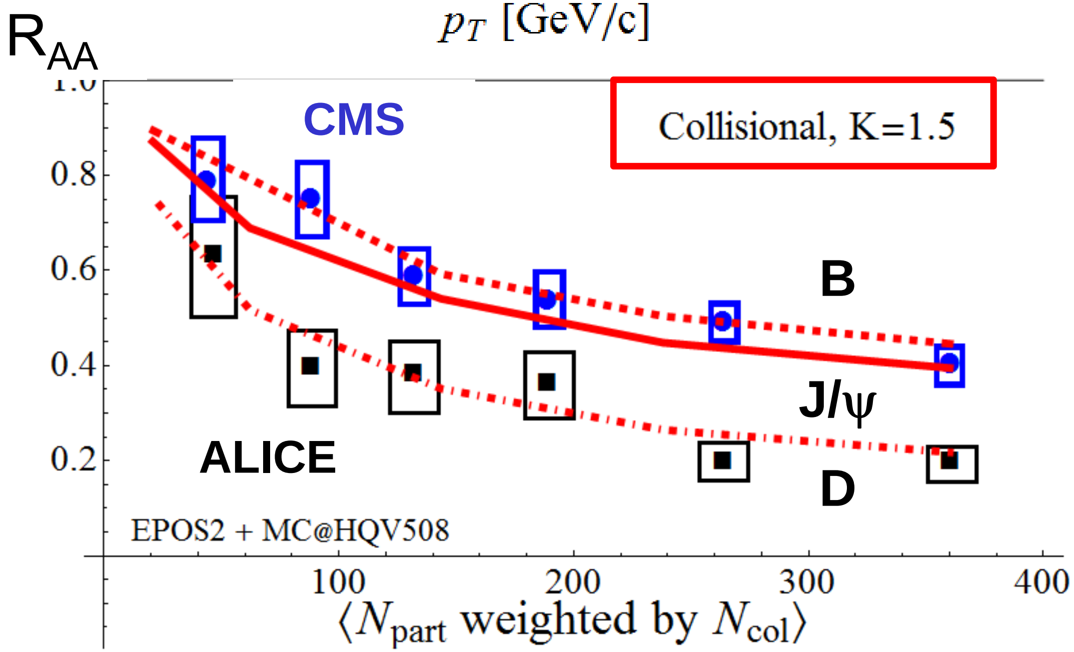


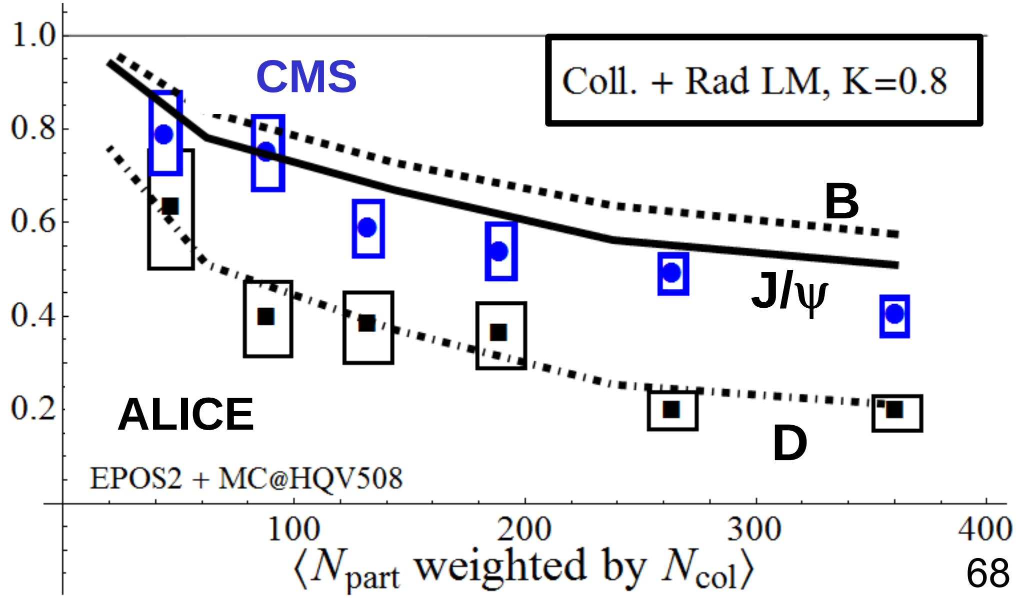


… b) for b-Quarks (& Non-Prompt J/ψ)









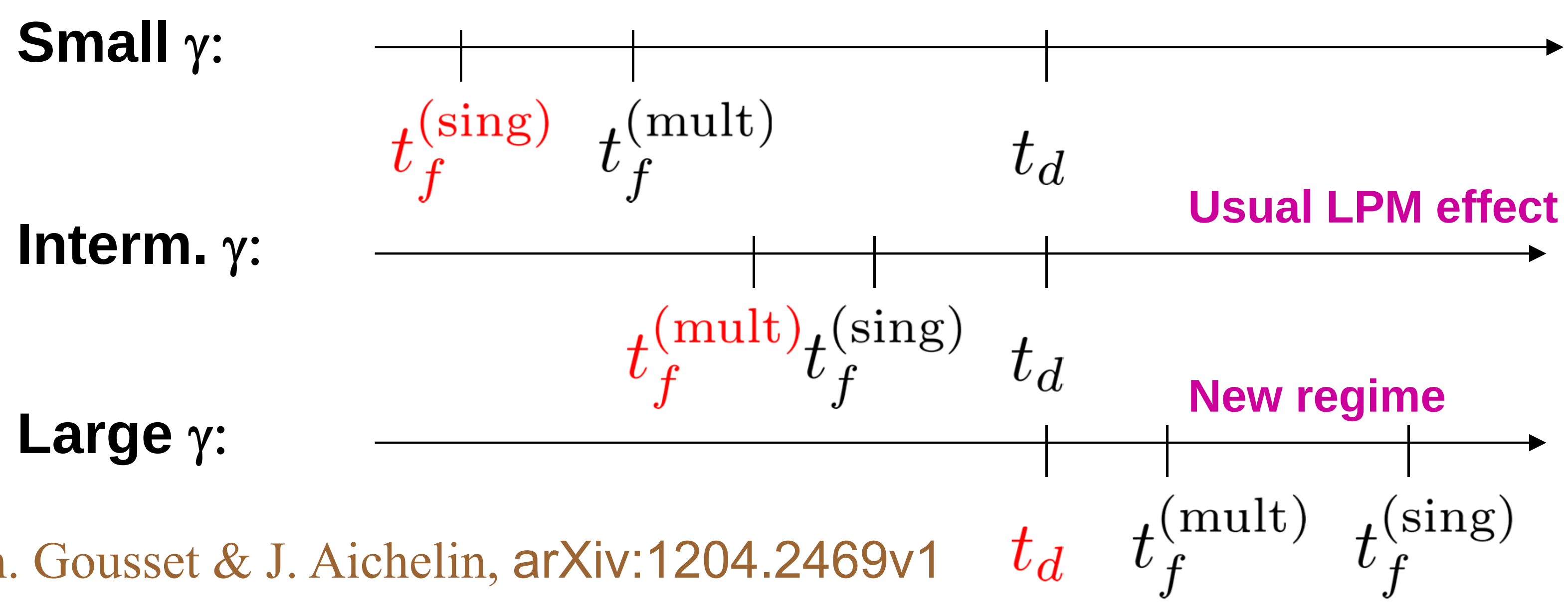
Consequences of radiation damping on energy loss; with J. Aichelin, Th. Gousset and M. Bluhm

Basic question: Implications of a finite lifetime of the radiated gluon ?

Concepts

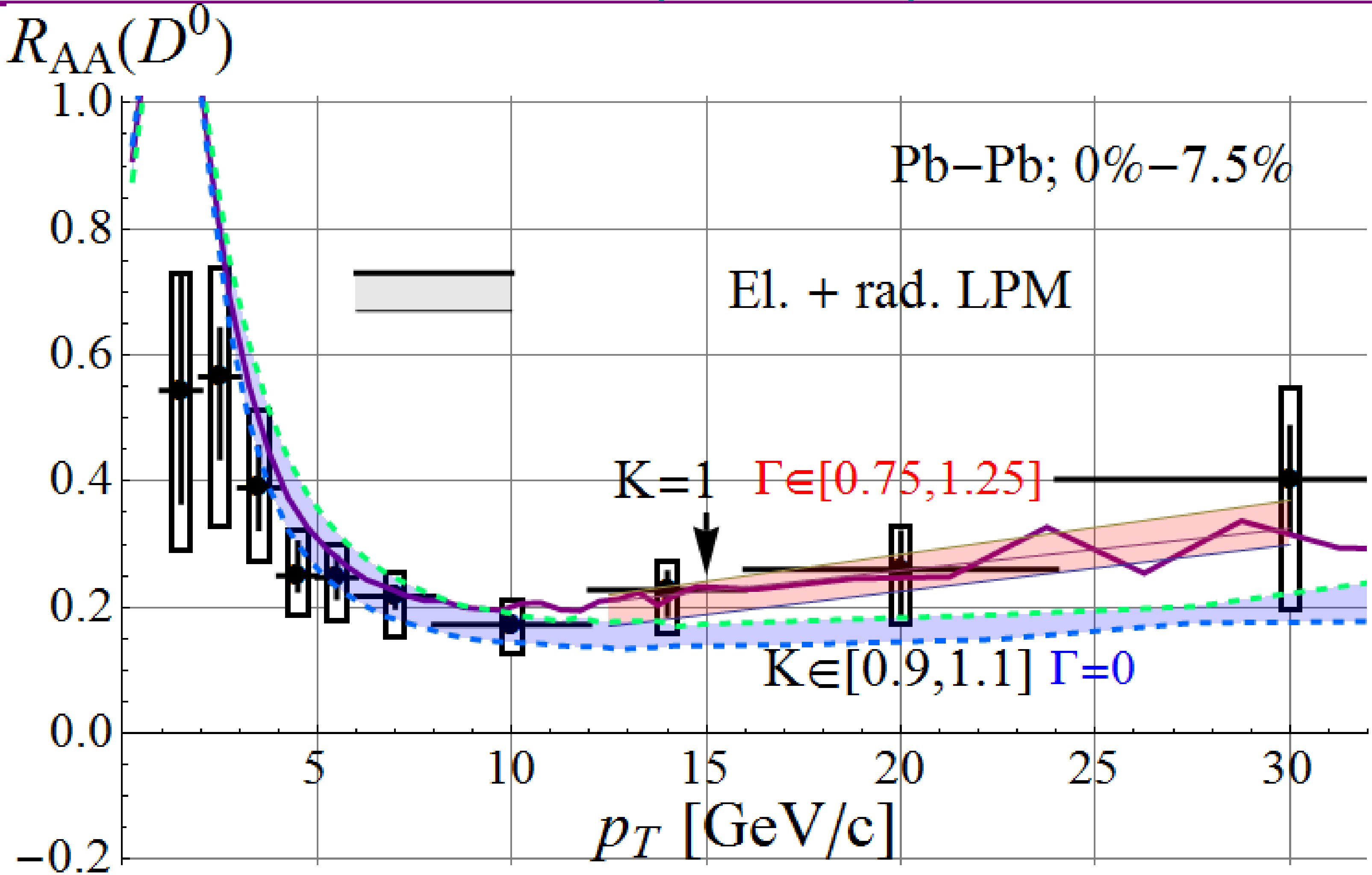
- In QED or pQCD, damping is a NLO process (damping time $t_d >> \lambda$); neglected up to now.
- However: formation time of radiation t_f increases with boost factor γ of the charge
- Expected effects when $t_f \approx t_d$ or $t_f > t_d$: in this regime, t_d should become the relevant scale (gluons absorbed being formed)

γ - hierarchy:



M. Bluhm, PBG, Th. Gousset & J. Aichelin, arXiv:1204.2469v1

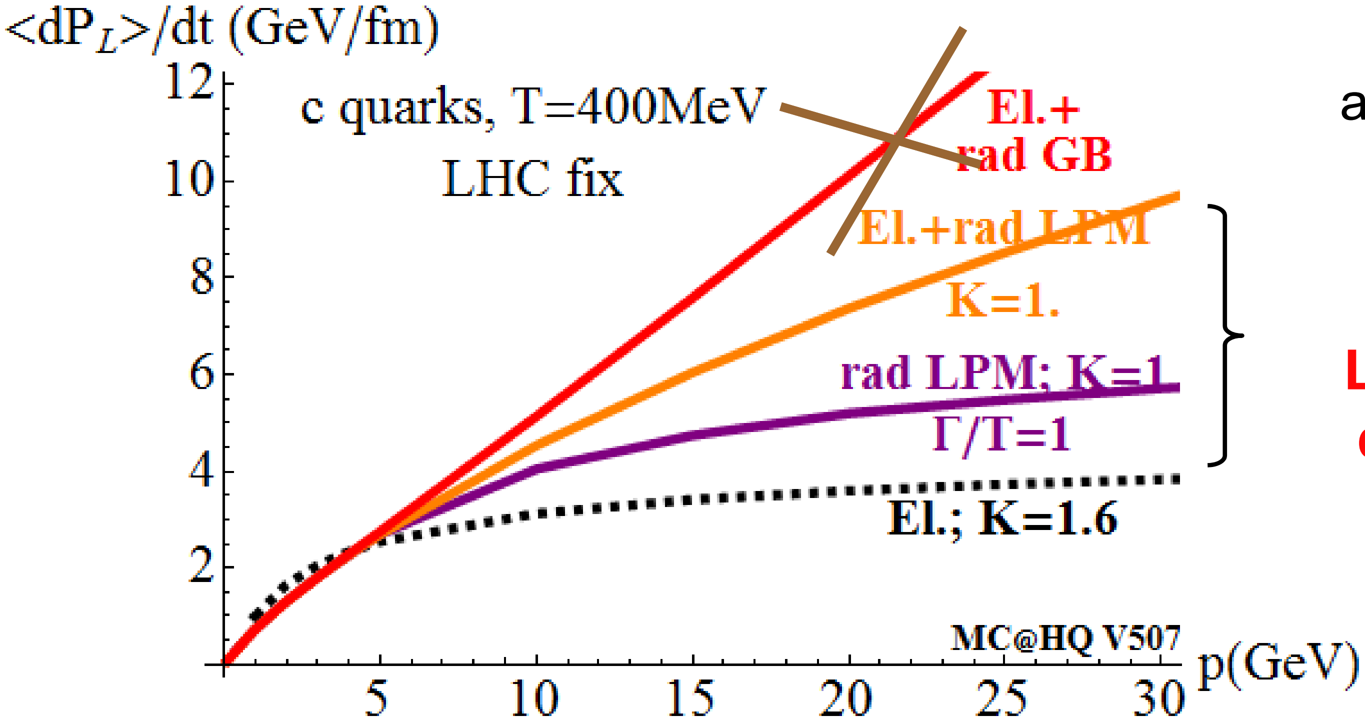
Consequences of radiation damping for mesons at LHC (central);



Damping of radiated gluons reduces the quenching of D mesons

QGP properties from HQ probe at LHC

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



(starting from QM 2012)

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

LHC has the potentiality to constrain further the drag coefficient!!!

We extract it from data

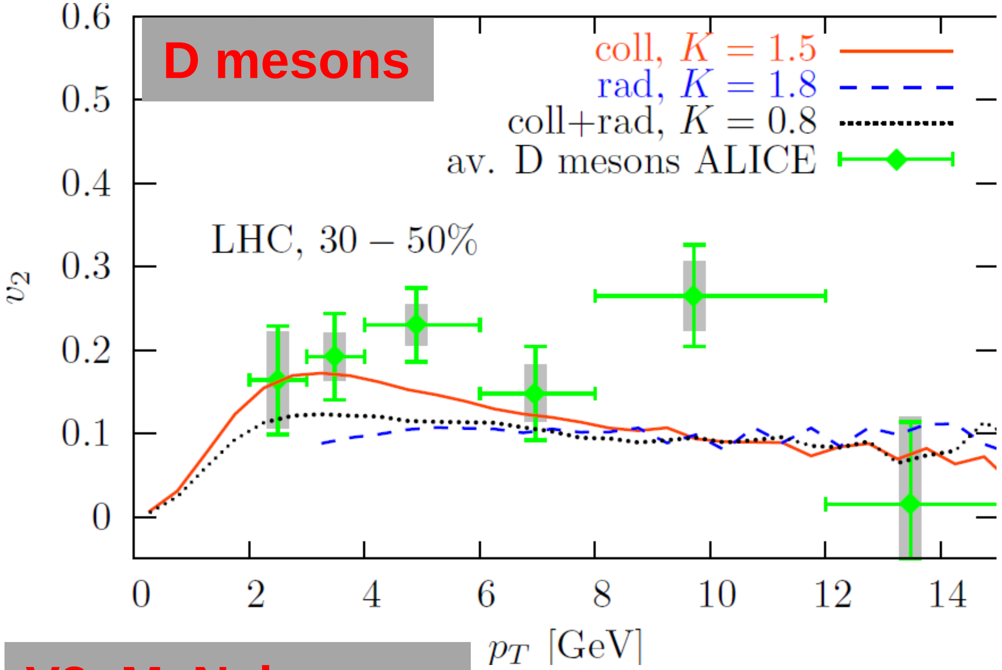
We are eager to compare with future lattice results

Main message

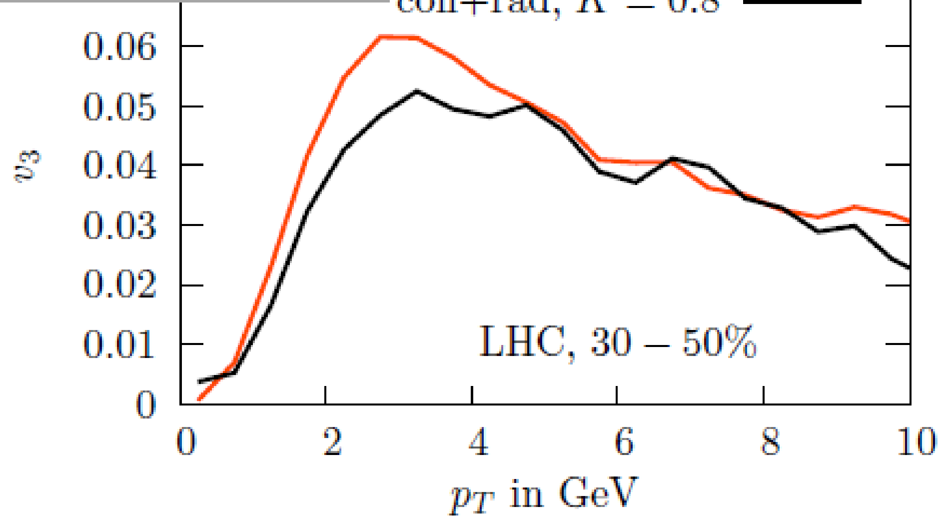
It is possible to reveal some fundamental property of QGP using HQ probes

Elliptic flow(s) @ LHC

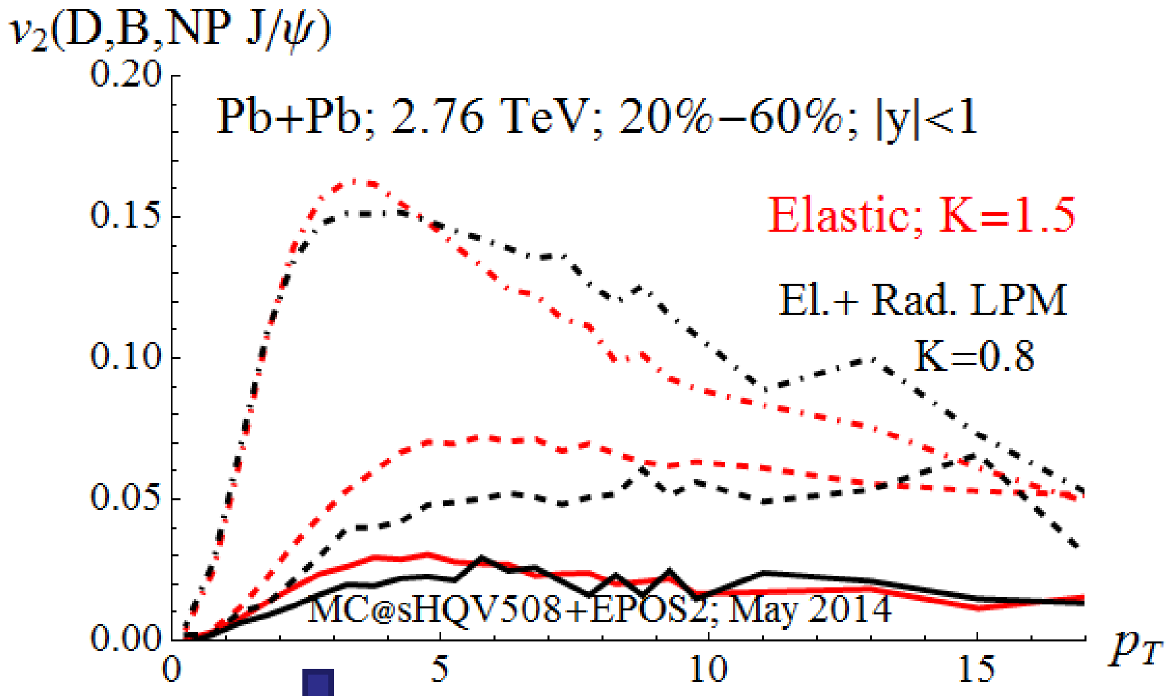
D mesons



V3; M. Nahrgang QM 2014



B mesons and NP J/psi



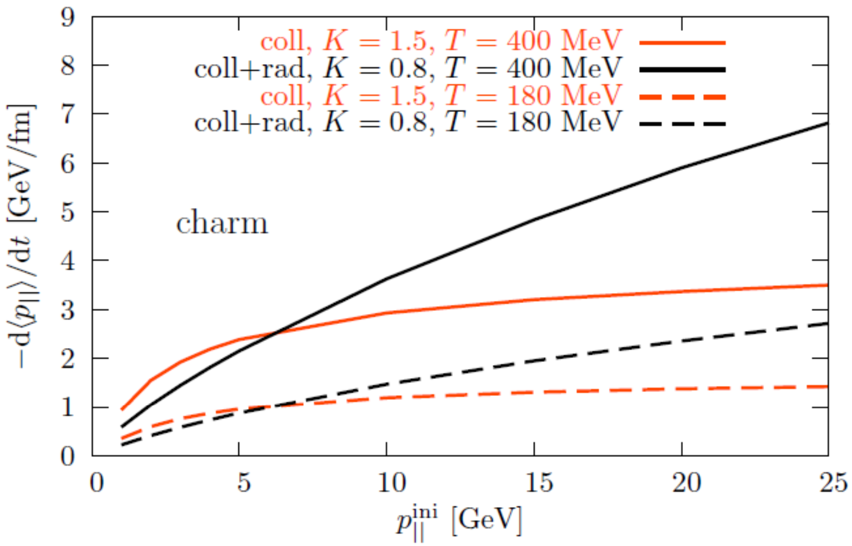
To be compared with future CMS results (in a few weeks from now)

New probe: HQ correlations (arxiv 1305.3823)

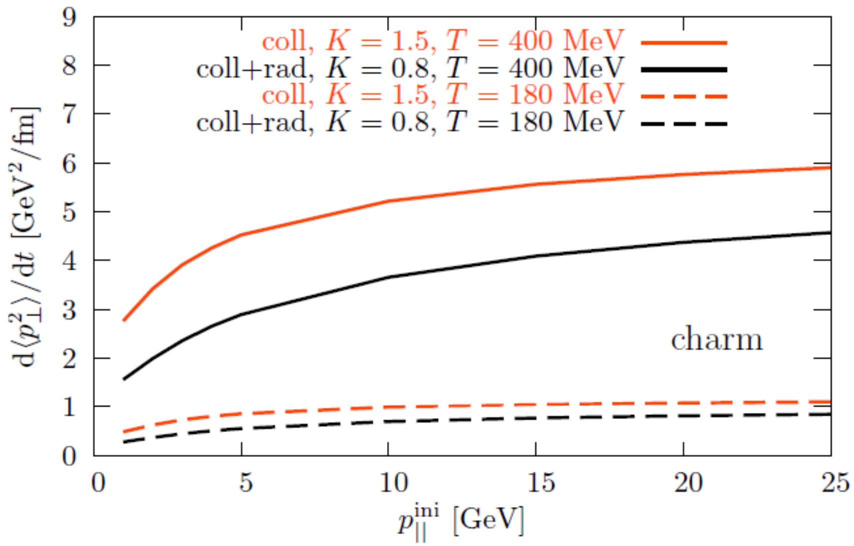
M. Nahrgang QM 2014

Properties of the interaction

Drag coefficient



Average perpendicular broadening



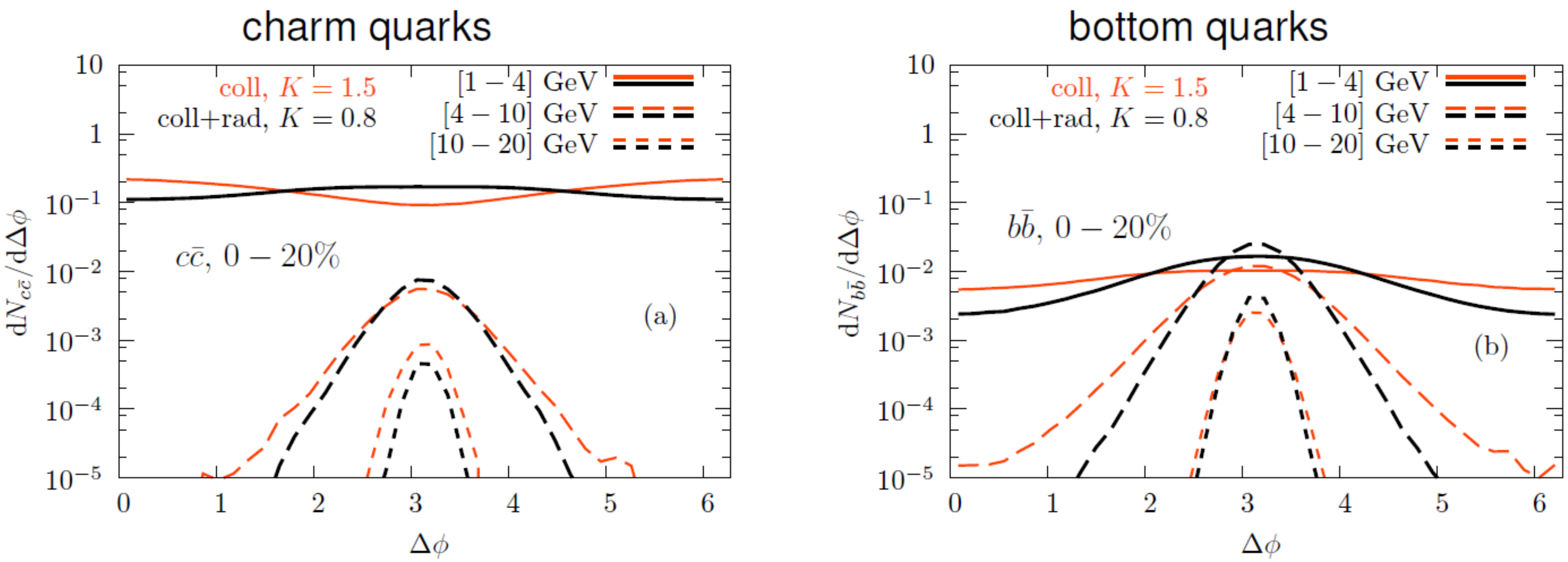
- Clearly different p_T dependence of the drag coefficient, stronger increase for **collisional+radiative(+LPM)** energy loss.
- At low p_T the drag coefficient is larger for collisional energy loss.
- Purely collisional scatterings lead to a larger average $\langle p_\perp^2 \rangle$ than **collisional+radiative(+LPM)**.
- Expectation: initial correlations are broadened more effectively by a purely collisional interaction mechanism.

New probe: HQ correlations

Heavy-quark azimuthal correlations at LHC energies

M. Nahrgang QM 2014

(central collisions, back-to-back initialization, no background from uncorrelated pairs)



- Stronger broadening in a purely collisional than in a **collisional+radiative(+LPM)** interaction mechanism
- Variances in the intermediate p_T-range: 0.22 vs. **0.13** (charm) and 0.3 vs. **0.14** (bottom)
- Initial correlations survive the propagation in the medium at higher p_T.
- At low p_T initial correlations are almost washed out: small residual correlations remain for the **collisional+radiative(+LPM)** mechanism, "partonic wind" effect for a purely collisional scenario.

New signature: HQ correlations

Realistic initial $b\bar{b}$ distributions - MC@NLO

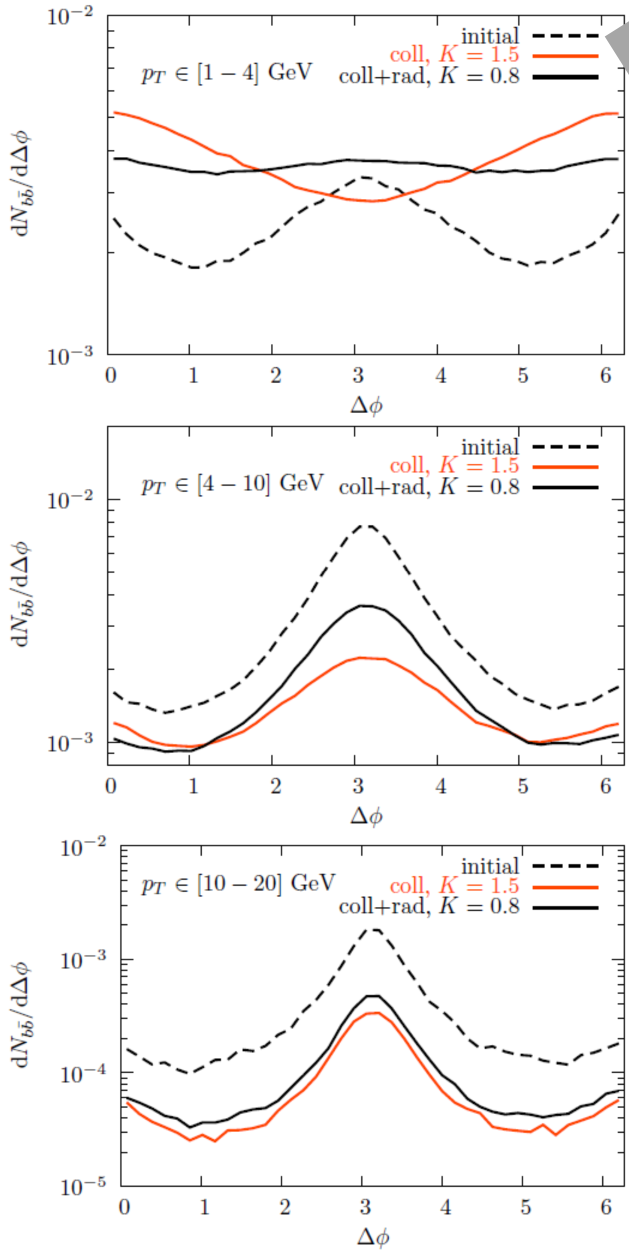
M. Nahrgang QM 2014

NLO QCD matrix elements coupled to parton shower evolution: MC@NLO+Herwig.

S. Frixione and B. R. Webber, JHEP **0206** (2002)
S. Frixione, P. Nason and B. R. Webber, JHEP **0308** (2003)

- Higher-order processes lead to an initial broadening around $\Delta\phi \approx \pi$ and an enhancement of the correlations at $\Delta\phi \approx 0$.
- For intermediate p_T: increase of the variances from initial to final by $\sim$ 20% for the purely collisional mechanism and $\sim$ 10% for **collisional+radiative(+LPM)**.
- Correlations at large p_T seem to be dominated by the initial correlations.
- Large differences between NLO+parton shower approaches on charm quark production!
- Very important: need a reliable pp reference for $\Delta\phi$ distributions!

LHC, central →



Conclusions & further studies

- **Inspired pQCD model, in reasonable agreement with RHIC (and LHC) open heavy quark physics (some resummation mandatory).**
- **Hadronization plays an important role (not shown here)**
- **There seems to be a systematic underestimation of the elliptical flows (v_2)**
- **Need for a better understanding of the effective degrees of freedom in the QGP (cross over vs phase transition): recent common work with FIAS and Giessen (see H. Berrehrah's talk)… to be continued**
- **… and many more things that could be achieved thanks to networking.**

Consequences of radiation damping on energy loss

Basic question: Implications of a finite lifetime of the radiated gluon ?

Concepts

- In QED or pQCD, damping is a NLO process (damping time $t_d >> \lambda$); neglected up to now.
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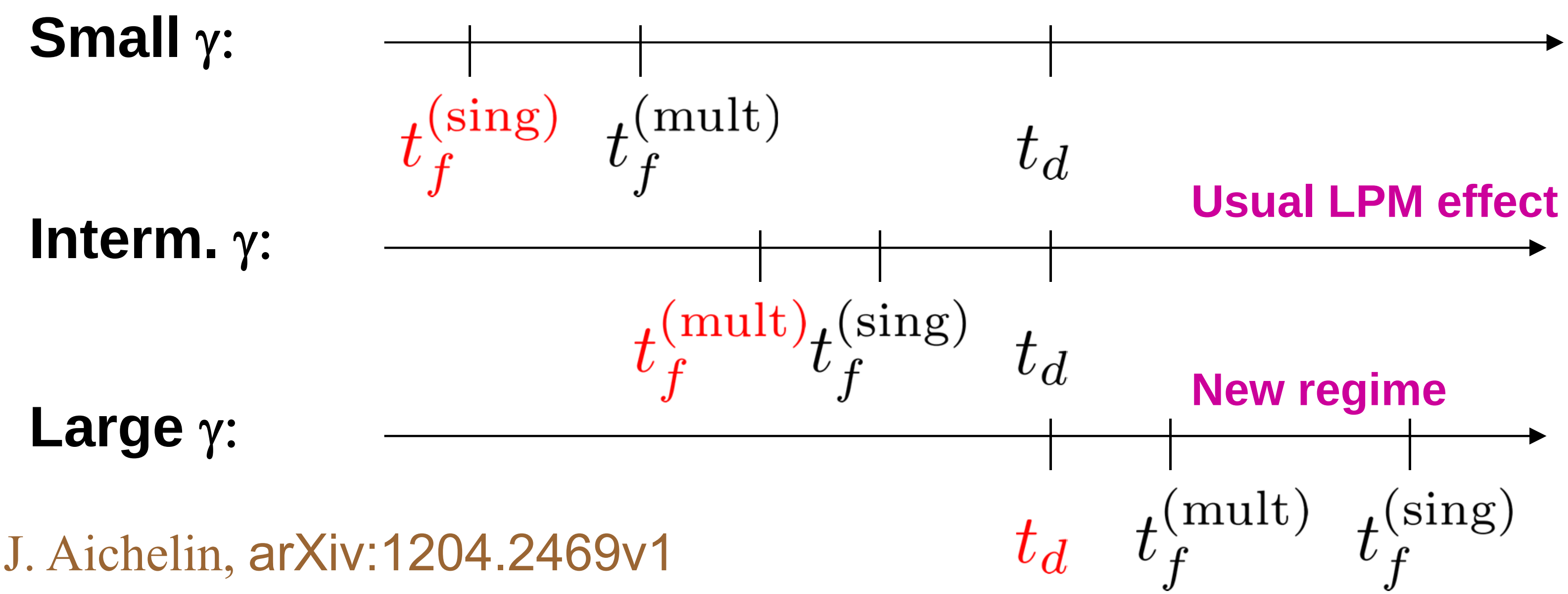
γ - hierarchy:

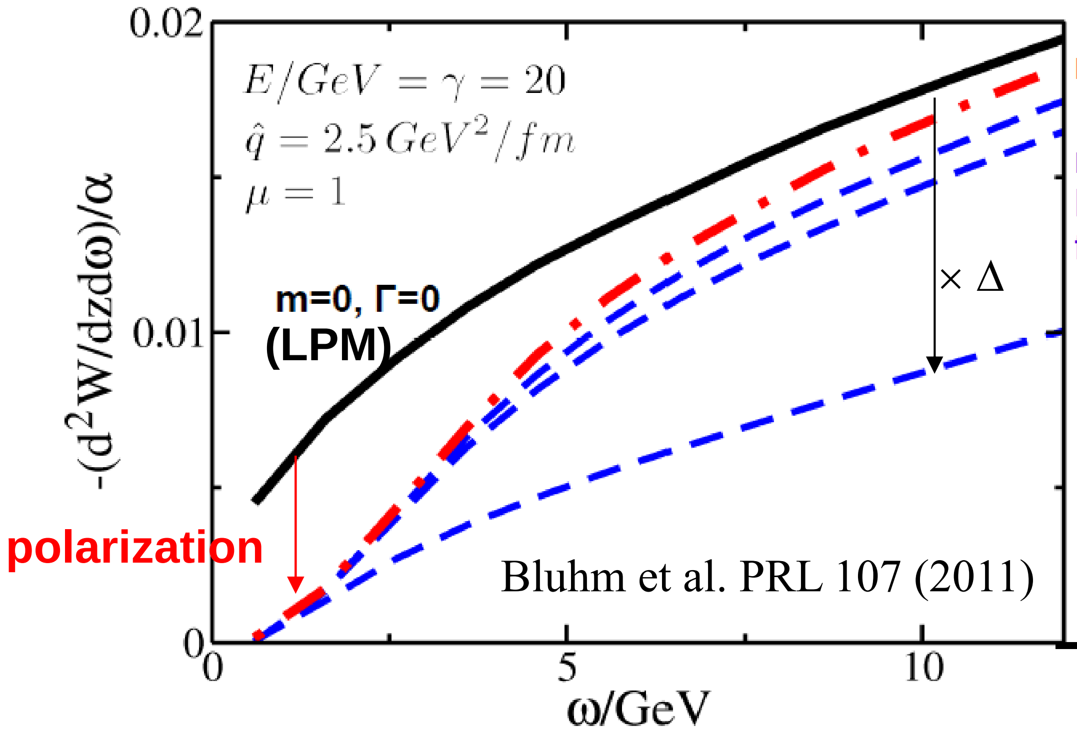


M. Bluhm, PBG & J. Aichelin, arXiv:1204.2469v1

Consequences of radiation damping on energy loss

PRL 107 (2011): Revisiting LPM effect in ED using complex index of refraction, focussing on the radiation at time of formation

$$n^2(\omega) = 1 - m^2/\omega^2 + 2\,i\,\Gamma/\omega$$

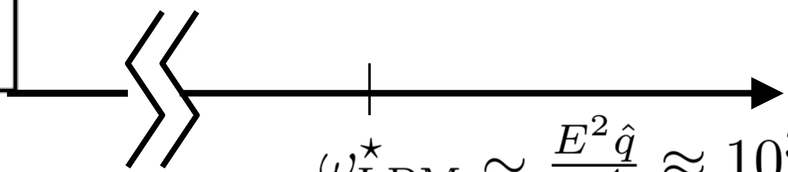


m=0.6 GeV, Γ=0 (Ter-Mikaelian; 1954)

m=0.6 GeV, Γ=5, 10, 50 MeV from top to bottom

Realistic numbers for QCD !

Strong reduction of radiation spectra and of coherence effects



$$\omega^{\star}_{\mathrm{LPM}} \sim \frac{E^2\hat{q}}{m_s^4} \approx 10^3 \gg E$$

No “BH” limit

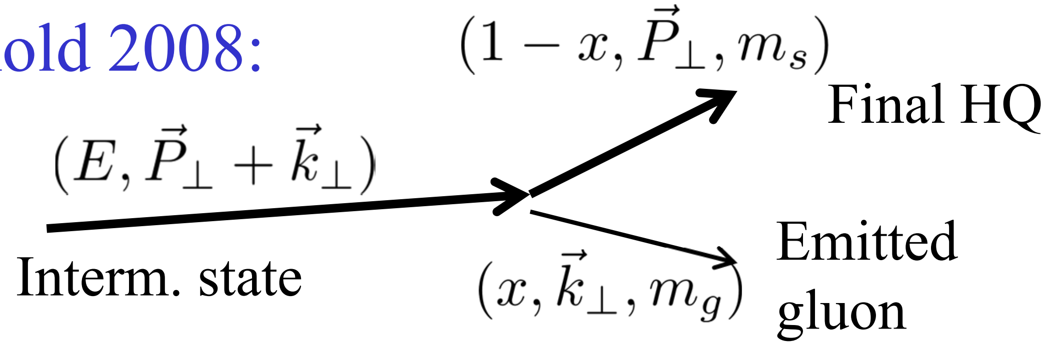
Scaling law:

$$\frac{\frac{dN}{d\omega}}{\frac{dN_{\mathrm{sing}}}{d\omega}} \approx \frac{\min(t_d, t_f^{(\mathrm{sing})}, t_f^{(\mathrm{mult})})}{t_f^{\mathrm{sing}}}$$

Allows for first phenomenological study in QCD case

Formation time of radiated gluon

Arnold 2008:



$$t_f \left[\frac{\langle p_B^2 \rangle + x^2 m_s^2 + (1-x) m_g^2}{2x(1-x)E} \right] \simeq 1$$

$$p_B^2 := \left((1-x)\vec{k}_\perp + x\vec{P}_\perp \right)^2 \quad \Rightarrow \quad \langle p_B^2 \rangle \approx (1-x)^2 \hat{q}_g t_f$$

In QCD: mostly gluon rescattering

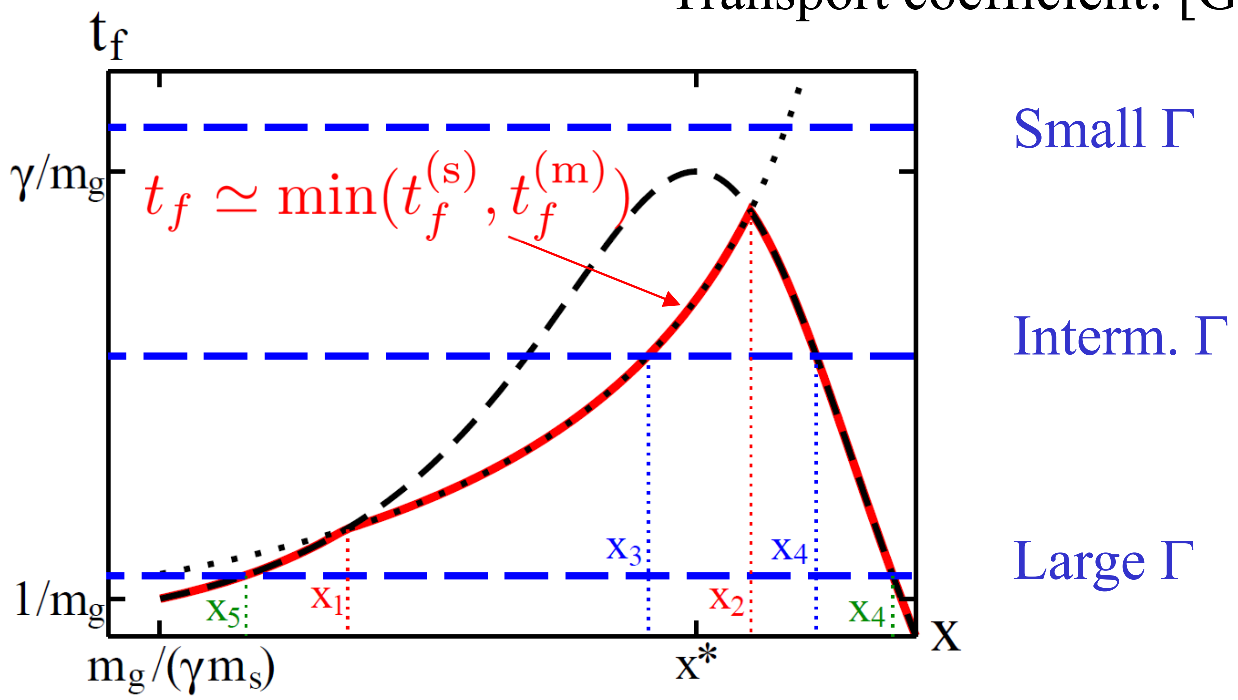
Transport coefficient: [GeV^2/fm]

=> Self consistent expression for t_f

- - - - $t_f^{(s)} \simeq \frac{2x(1-x)E}{x^2 m_s^2 + m_g^2(1-x)}$

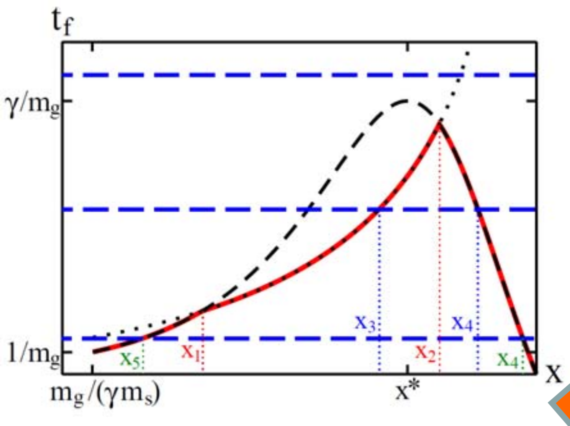
------- $t_f^{(m)} \simeq \sqrt{\frac{2xE}{(1-x)\hat{q}_g}}$

— — $t_d = \frac{1}{\Gamma}$



New regimes when including gluon damping

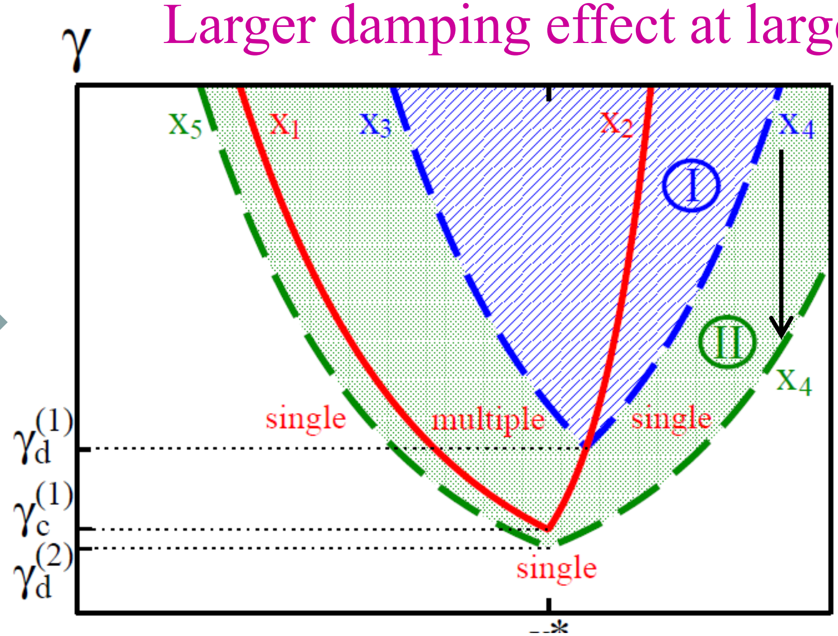
x-γ space for $\hat{q} < m_g^3$



Γ–γ space

γ-scales
$\gamma_c^{(1)} \sim m_g^3/\hat{q}_g$
$\gamma_d^{(1)} \sim \sqrt{\hat{q}_g/\Gamma^3}$
$\gamma_d^{(2)} \sim m_g/\Gamma$

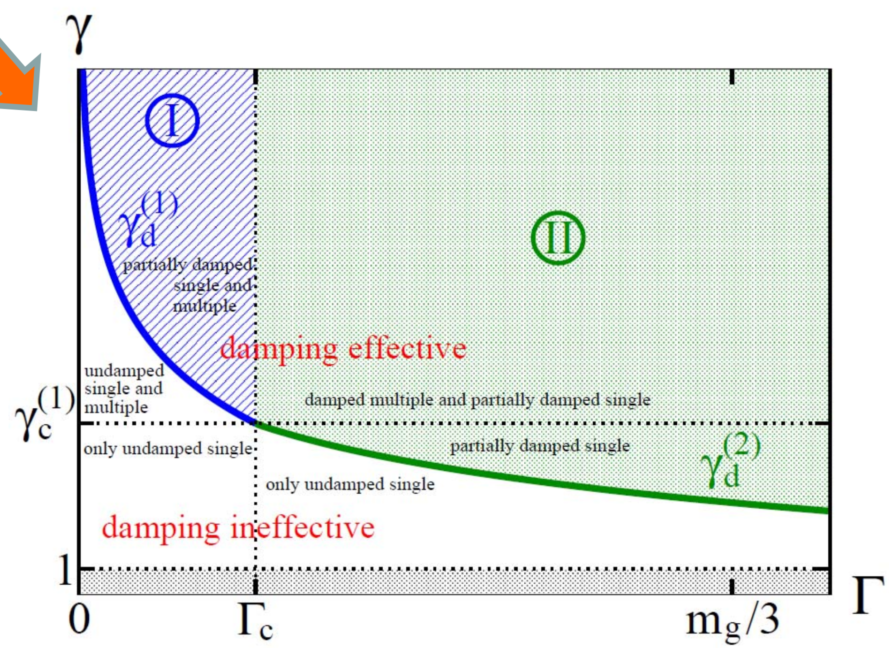
Larger damping effect at large γ



$x = \frac{\omega}{E}$

Increasing Γ

Larger and larger part of the spectrum affected by damping (shaded areas)

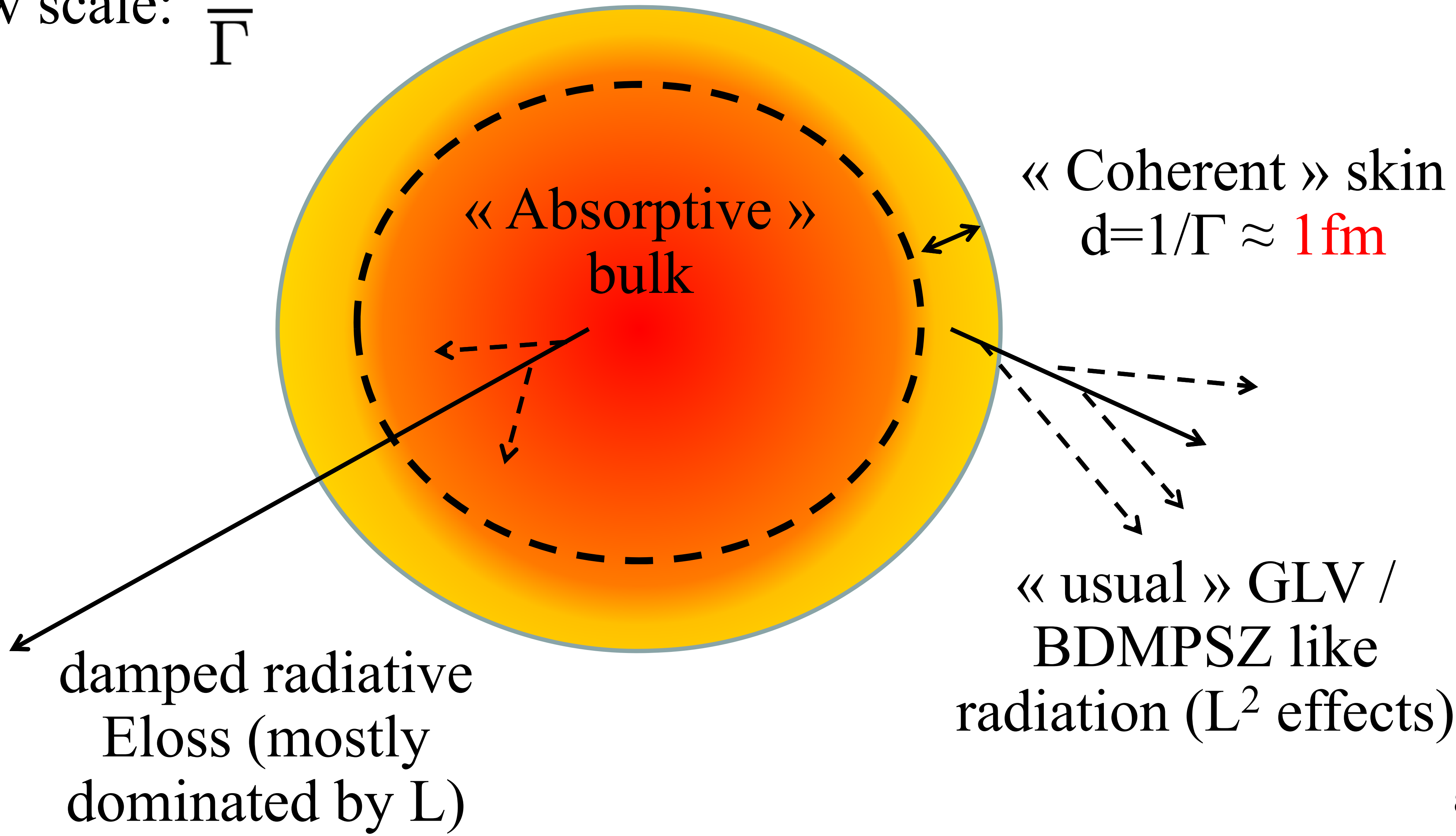


For $\Gamma > \Gamma_c \approx \frac{\hat{q}_g}{m_g^2}$ coherent radiation is totally superseeded by damping

Conclusion: Global picture for finite path length L Eloss

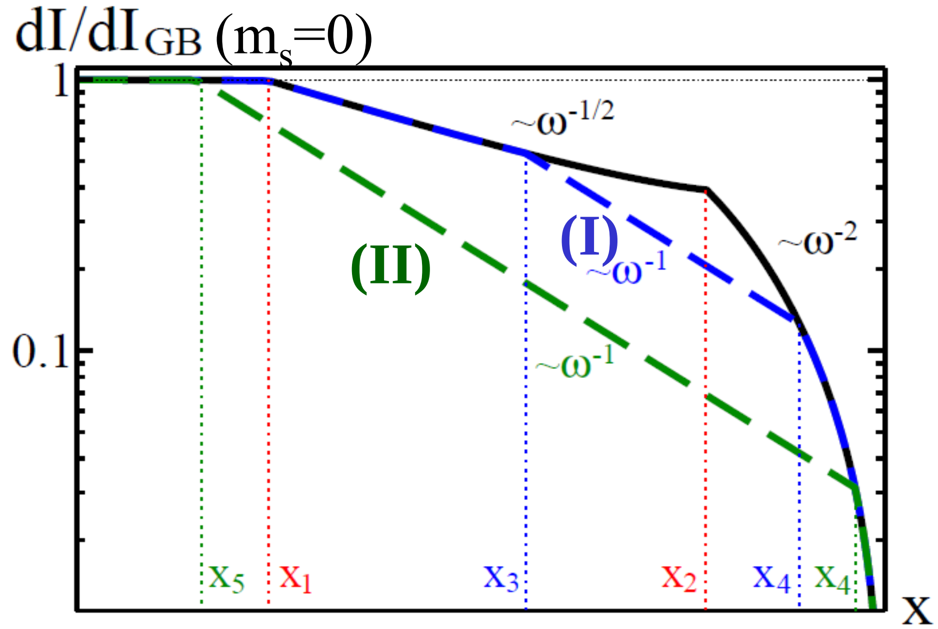
Usually: competition btwn L vs $L_\infty = \sqrt{\frac{E}{\hat{q}}}$

New scale: $\dfrac{1}{\Gamma}$



Consequences on the power spectra

$\hat{q} < m_g^3$



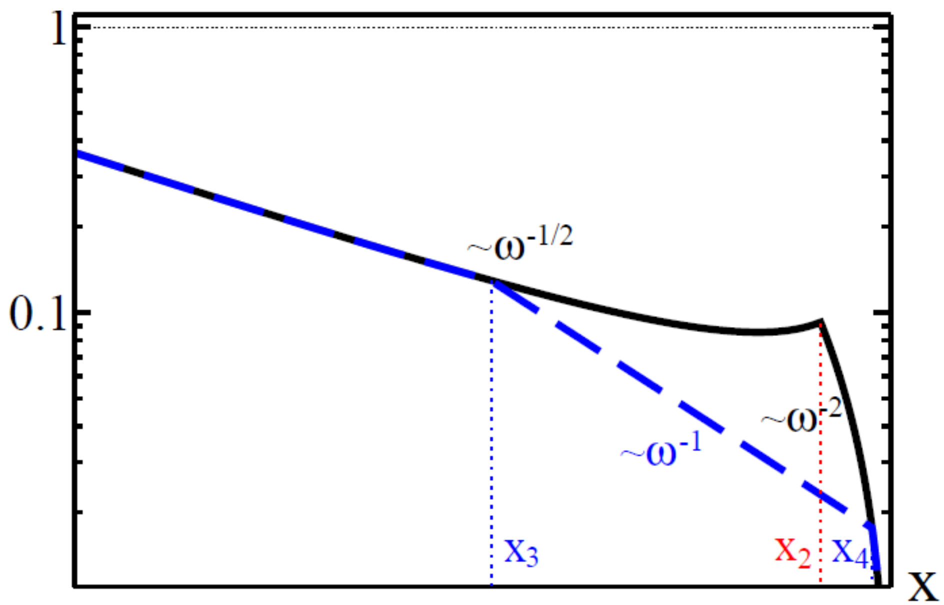
(I) and (II): moderate and large damping (see previous slide)

E= 45 GeV, m_s=1.5 GeV

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

Γ=0.05 GeV (I) & 0.15 GeV (II)

$\hat{q} > m_g^3$



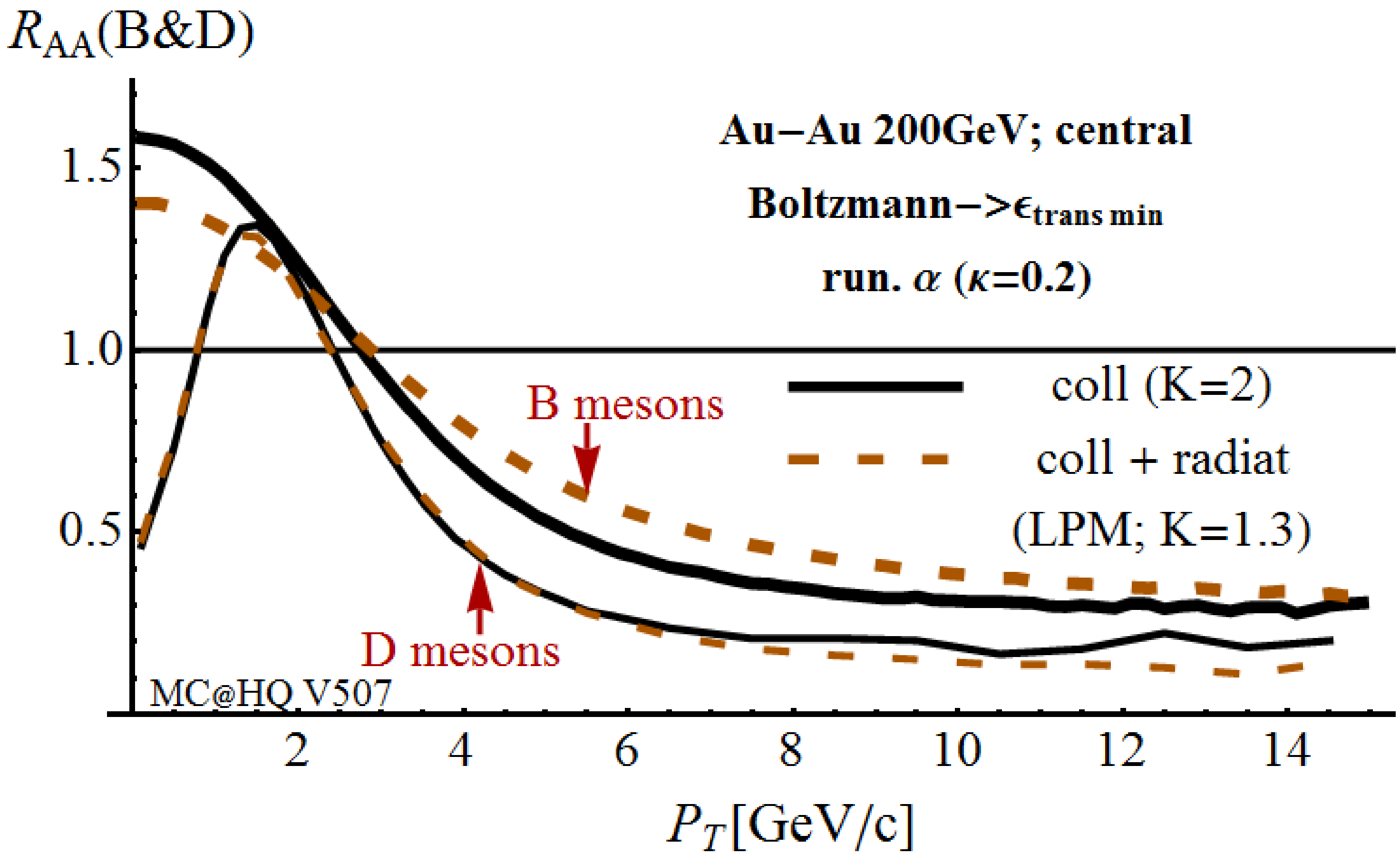
Same but

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

Γ=0.25 GeV

Bright future of RHIC

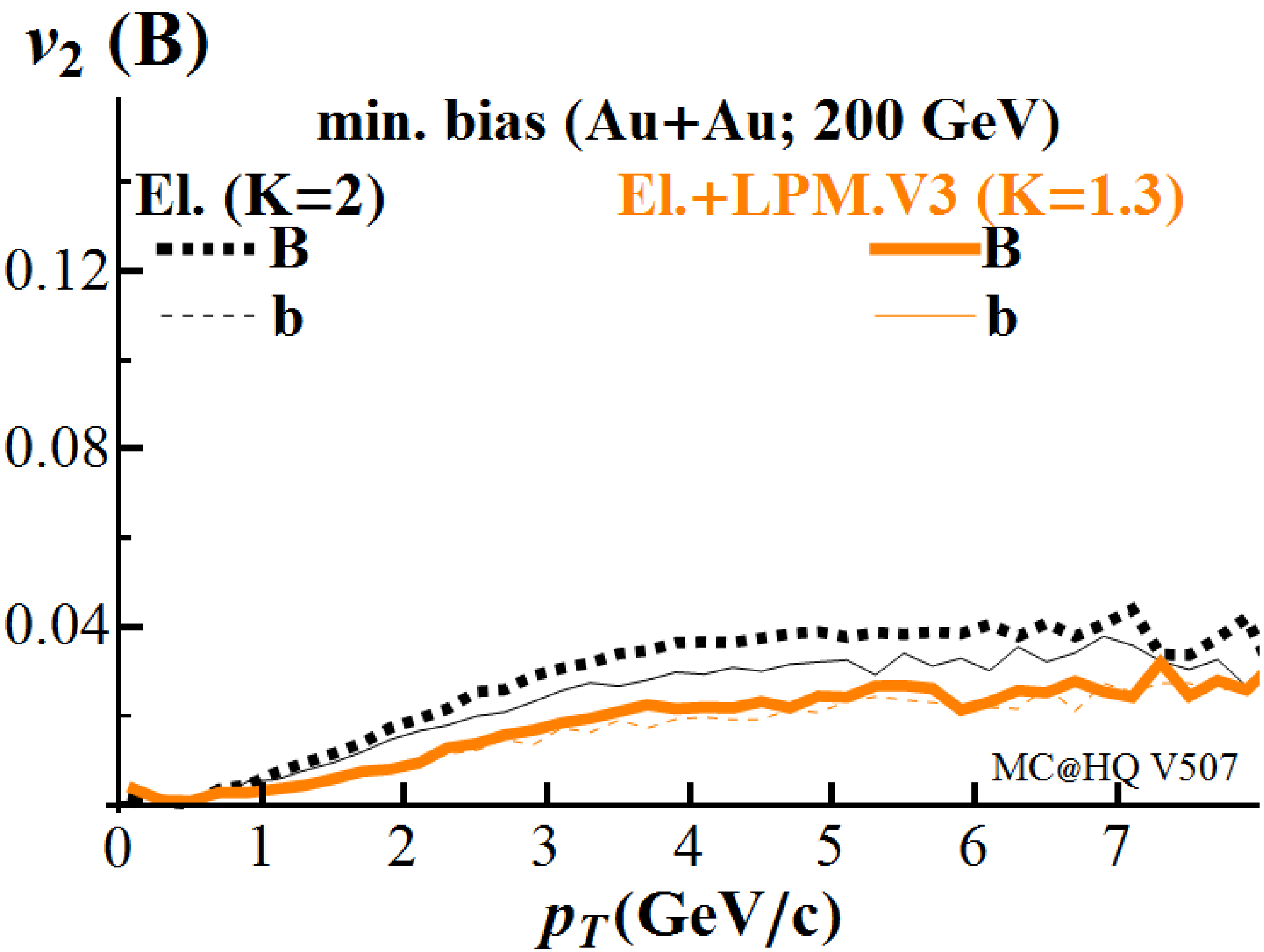
=> Discriminating power of B mesons



Larger mass hierarchy for radiative Eloss

Bright future of RHIC

=> Discriminating power of B mesons



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