Heavy-ions -- theory aspects

Simon Caron-Huot

Discovery center meeting, NBI,
Nov. 13 2012

Heavy-ions -- theory aspects

- Goal: to characterize QCD near the deconfinement transition.
- Key observables:
  -equation of state p(T)
  -viscosity eta(T)
  -jet broadening coefficient $\hat{q}(T)$
  -heavy quark broadening coeff. κ(T)
  -(quasi-particle masses,...?)

In this talk I want to stress the importance of some of these properties, and their (sometimes remote) relation to measured quantities

A key observable: eta/s

- The shear viscosity to entropy ratio measures an (inverse) interaction strength.
  In kinetic theory:

$$\eta \propto P \times \frac{1}{n\sigma}, \qquad \frac{\eta}{s} \approx \frac{\hbar}{4\pi}(2 \div 3)\lambda_{mft}T$$

- Ex.: eta for water is smaller than for honey

- It's long been argued that eta/s couldn't be arbitrary small. We now know, for strongly coupled systems with 'holographic' gravity duals:

$$\frac{\eta}{s} = \frac{\hbar}{4\pi} \qquad \text{(KSS)}$$

What do we know about eta/s in QGP?

- pQCD computation: 4π eta/s $\approx 7 \pm 4$

  (AMY; error estimate = factor of 2 from NLO computation of other transport coefficients)

- AdS/CFT: 4π eta/s $= 1 + 15\zeta(3)/\lambda^{3/2} + \ldots$

  (Myers, Paulos & Sinha)

- Experimentally (RHIC, LHC): 4π eta/s $= 1 \div 2.5$

  (Heinz 1108.5323; error mostly systematics)

What do we know about eta/s in QGP?

- pQCD computation: 4π eta/s $\approx 7 \pm 4$

  (AMY; error estimate from NLO computation of other transport coefficients)

- AdS/CFT: 4π eta/s $= 1+15\varsigma(3)/\lambda^{3/2} + \ldots$

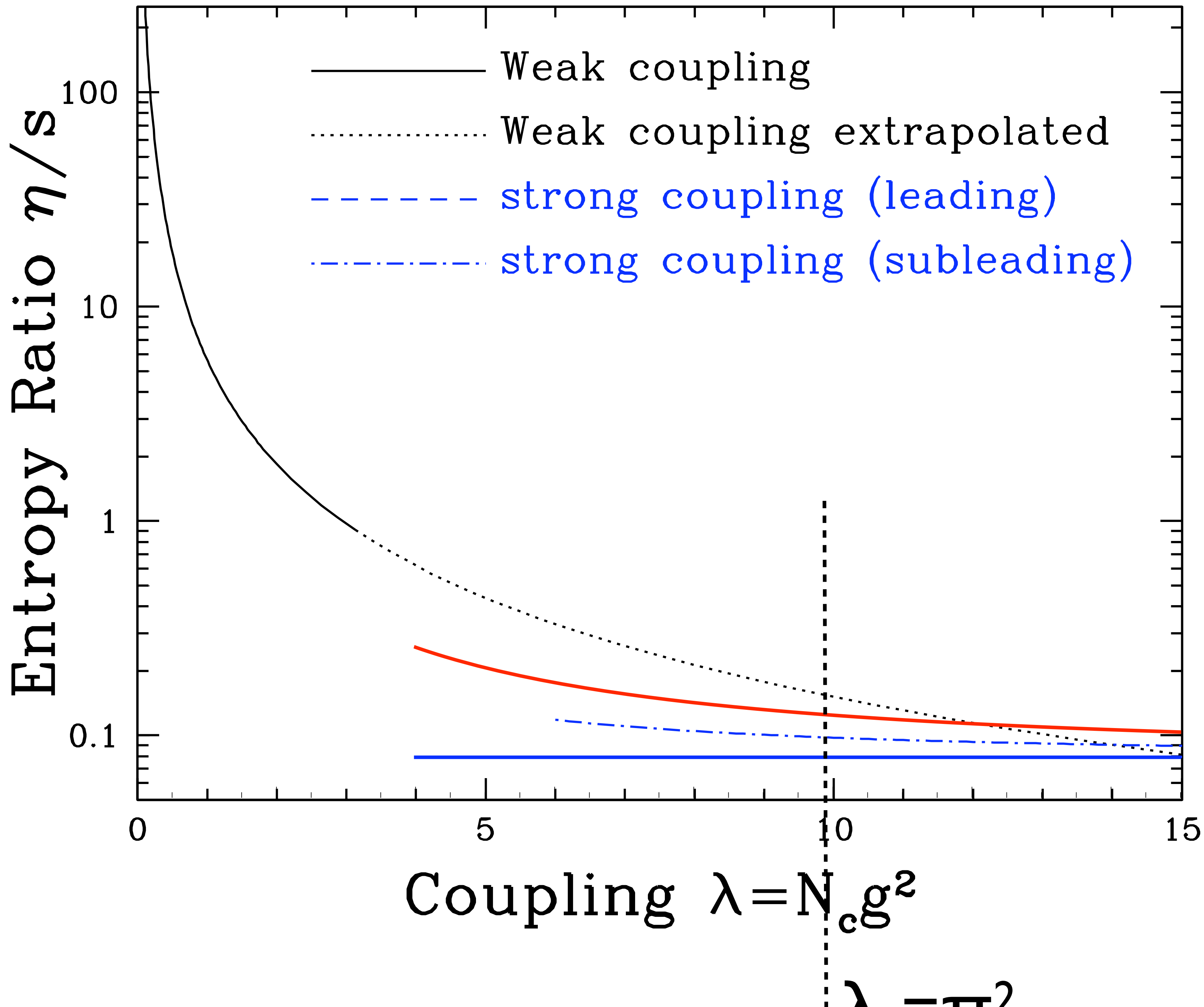
  (Myers, Paulos & Sinha)

- Experimentally (RHIC, LHC): 4π eta/s $= 1 \div 2.5$

  (Heinz 1108.5323; error mostly systematics)

Most 'perfect' fluid in Nature.
Q: Is this accuracy satisfactory?

How might one set the scale for eta/s, using N=4 SYM?



(Jeon,Moore,SCH: ph/0608062)

(w/correction!)

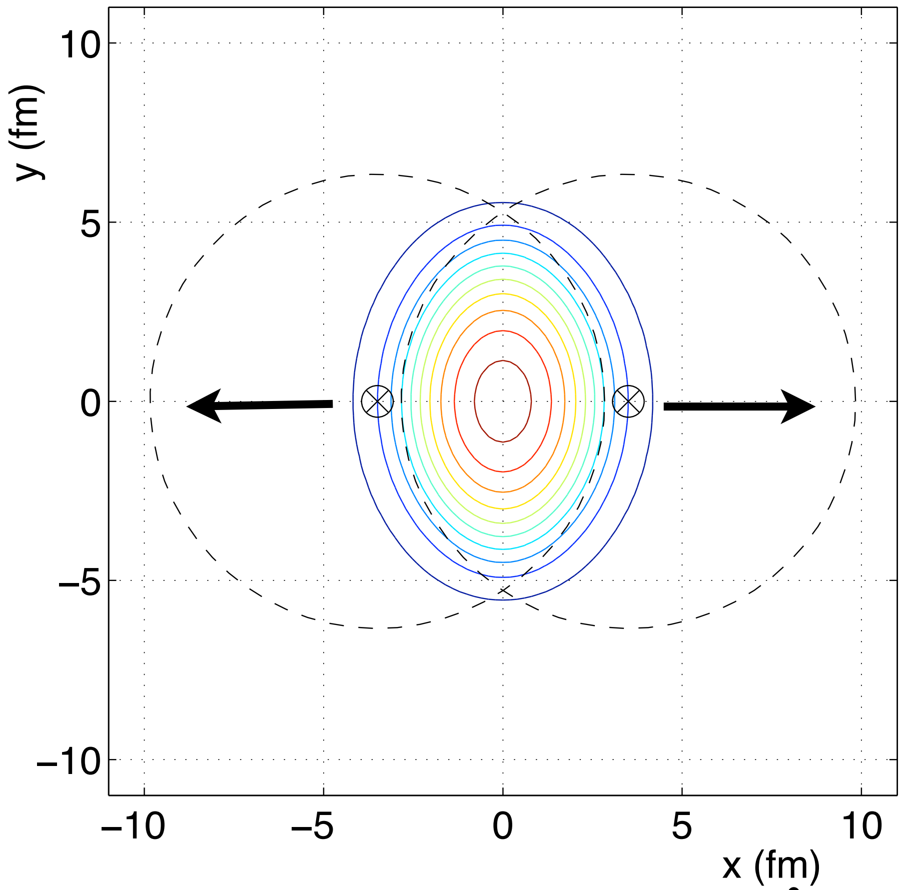
Weak-strong transition @ λ~5÷10 (BES,...)--> $4\pi\frac{\eta}{s} \sim 1.5 \div 3$

- Lesson:

  4π eta/s > 3÷4 : system made of quasiparticles

  4π eta/s = 1÷1.5 : system cannot admit a self-consistent quasiparticle description. Possibly, can have a good gravity dual description.

Measurement of eta/s



(fig. from U. Heinz, 0901.4355)

- Rescattering converts spacetime anisotropy to momentum space anisotropy
- Viscosity slows down the process. *Not* a null measurement
- "5% change in initial gradients <->1/4π change in eta/s"

Uncertainties in initial conditions ('CGC vs Glauber')

- Q: Is the gluon PDF for a stack of 7 nucleons, equal to 7 times the gluon PDF for one nucleon?

Uncertainties in initial conditions ('CGC vs Glauber')

- Q: Is the gluon PDF for a stack of 7 nucleons, equal to 7 times the gluon PDF for one nucleon?
- A: Not necessarily! Not at small *x*.

Uncertainties in initial conditions ('CGC vs Glauber')

- Q: Is the gluon PDF for a stack of 7 nucleons, equal to 7 times the gluon PDF for one nucleon?
- A: Not necessarily! Not at small *x*.
- Large gluon PDF at small x can lead to nonlinear effects, enhanced by $A^{1/3}$

Color Glass Condensate

- Gluons produced per unit area per unit y:

$$\frac{\frac{dN^{\rm ch}}{dy}}{\rm Area} = \frac{1600}{(207)^{2/3} A_{\rm proton}} \sim 50/A_{\rm proton}$$

- Related to 'saturation scale:' $\frac{{\rm d}N_{{\rm init}.g}}{{\rm d}^2\mathbf{x}_T\,{\rm d}y} = c\frac{C_{\rm F} Q_{\rm s}^2}{2\pi^2\alpha_{\rm s}}.$
Roughly:

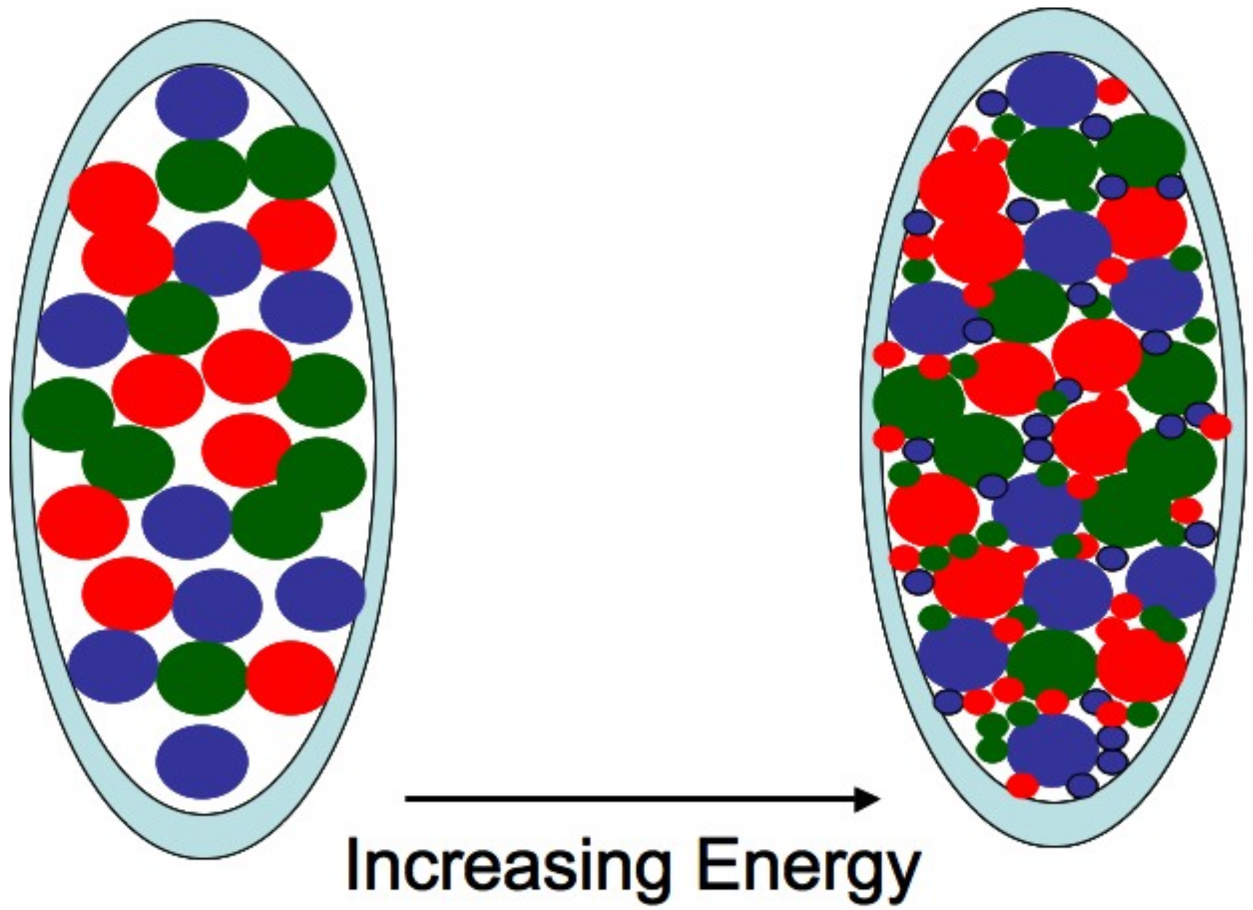
(Maclerran&Venugopalan; LHC context: Lappi 1104.3725)

$$\boxed{Q_s \sim n\Lambda_{\rm QCD}\sqrt{50} \overset{?}{\gg} \Lambda_{\rm QCD}}$$

- Interesting possibility that PDFs may be *computable* in this regime (CGC). Will be tested in p+Pb collisions!

Color Glass Condensate

N~50



Λ_{QCD} no longer a scale in the problem

(fig. from McLerran 1011.3203)

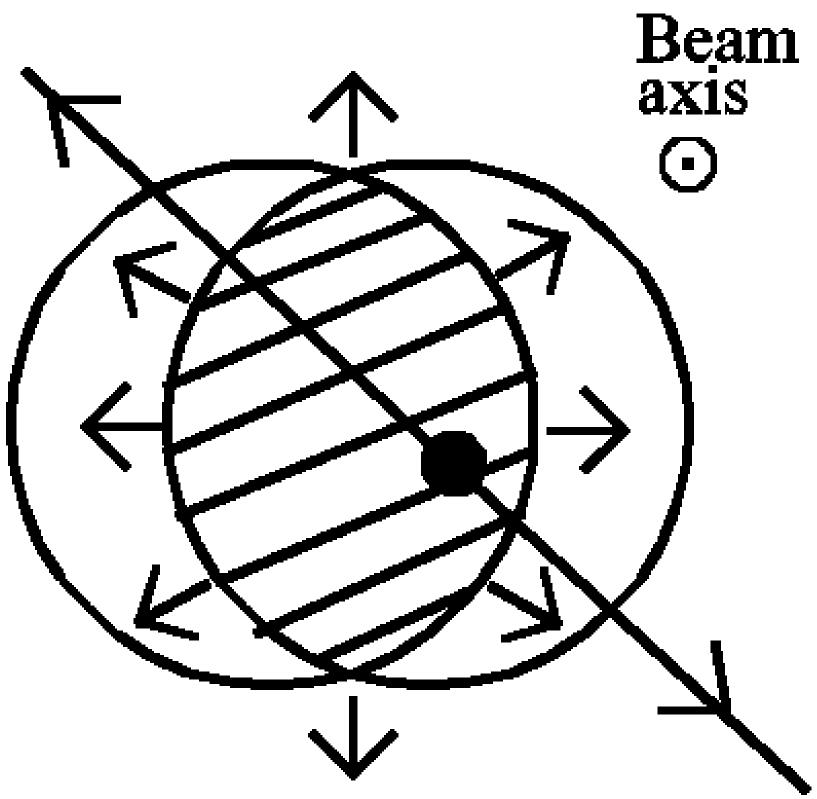
Ways to reducing systematics

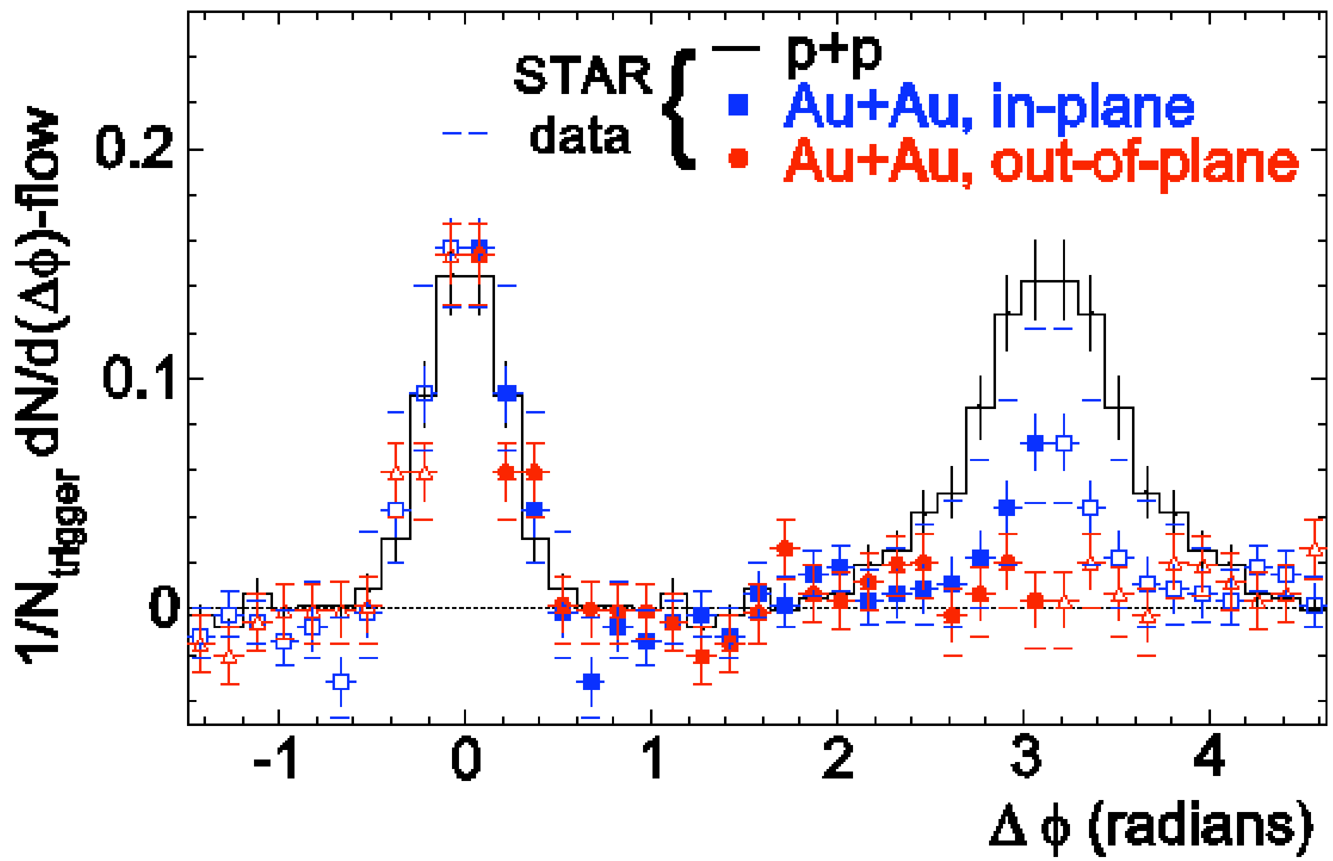
1. Understand initial conditions better (CGC, p+Pb,...)

2. Focus on higher pT part of spectrum (rest of this talk; work w/ C. Gale)

3. Study other 'hydrodynamics' observables: higher harmonics, event-by-event fluctuations, ...

Jet quenching (from RHIC)

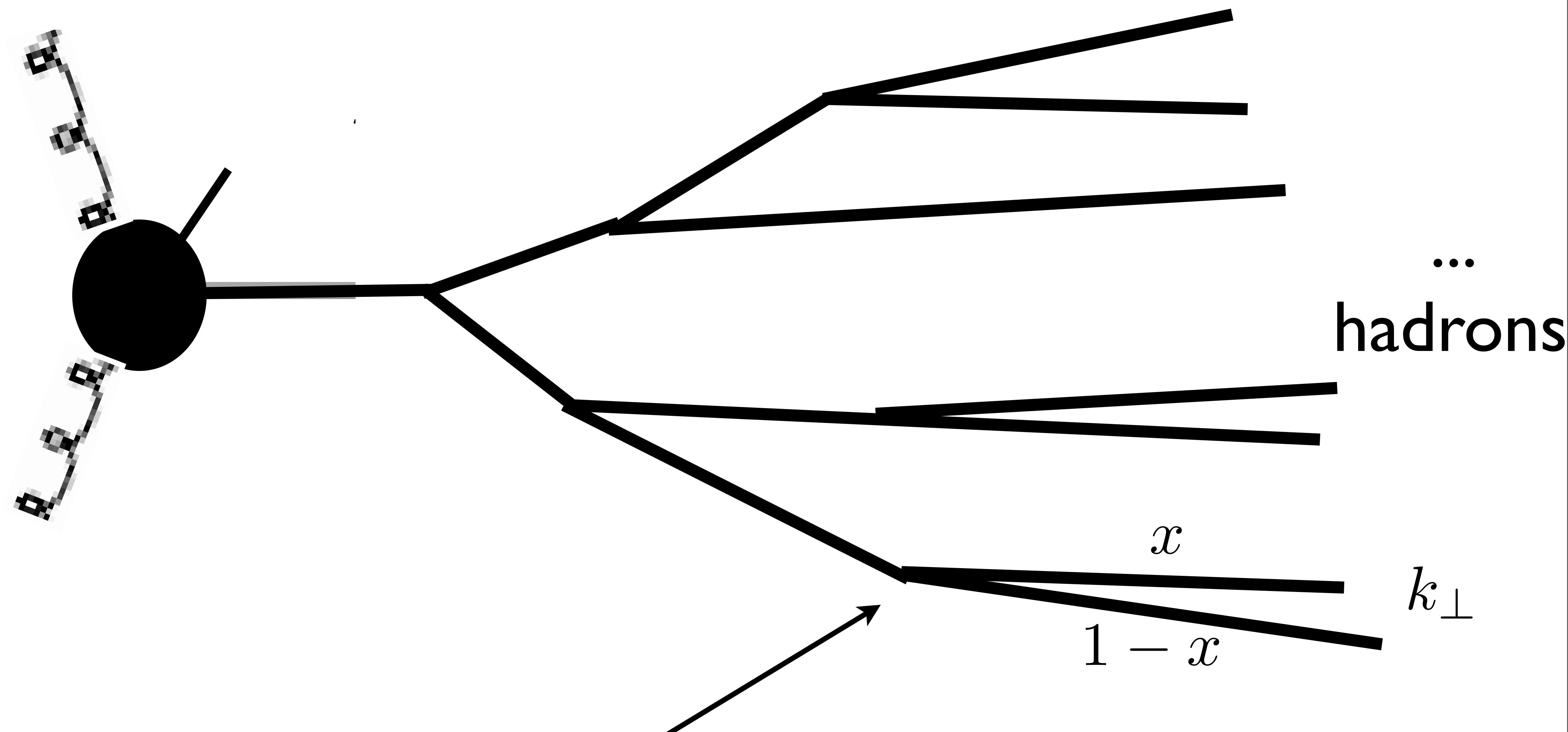




Shows that opacity covers full range 0÷1

With a working theory, should be ideal for 'tomography'

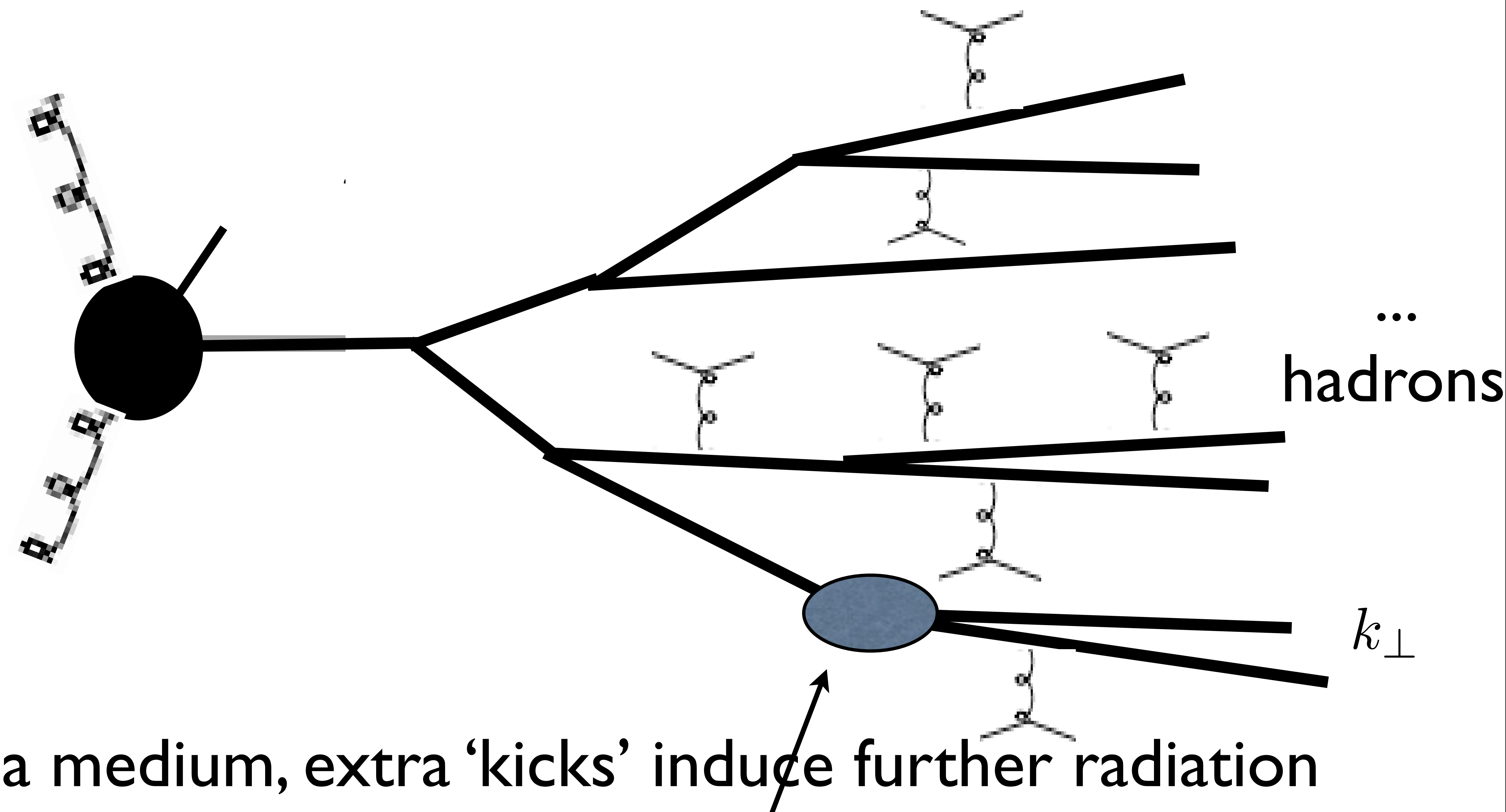
Theory cartoon: jet



$$\frac{dP}{dx\,d^2k_\perp} = \frac{P^a_{bc}(x)}{k_\perp^2}$$

DGLAP vertex

Theory cartoon: jet (2)



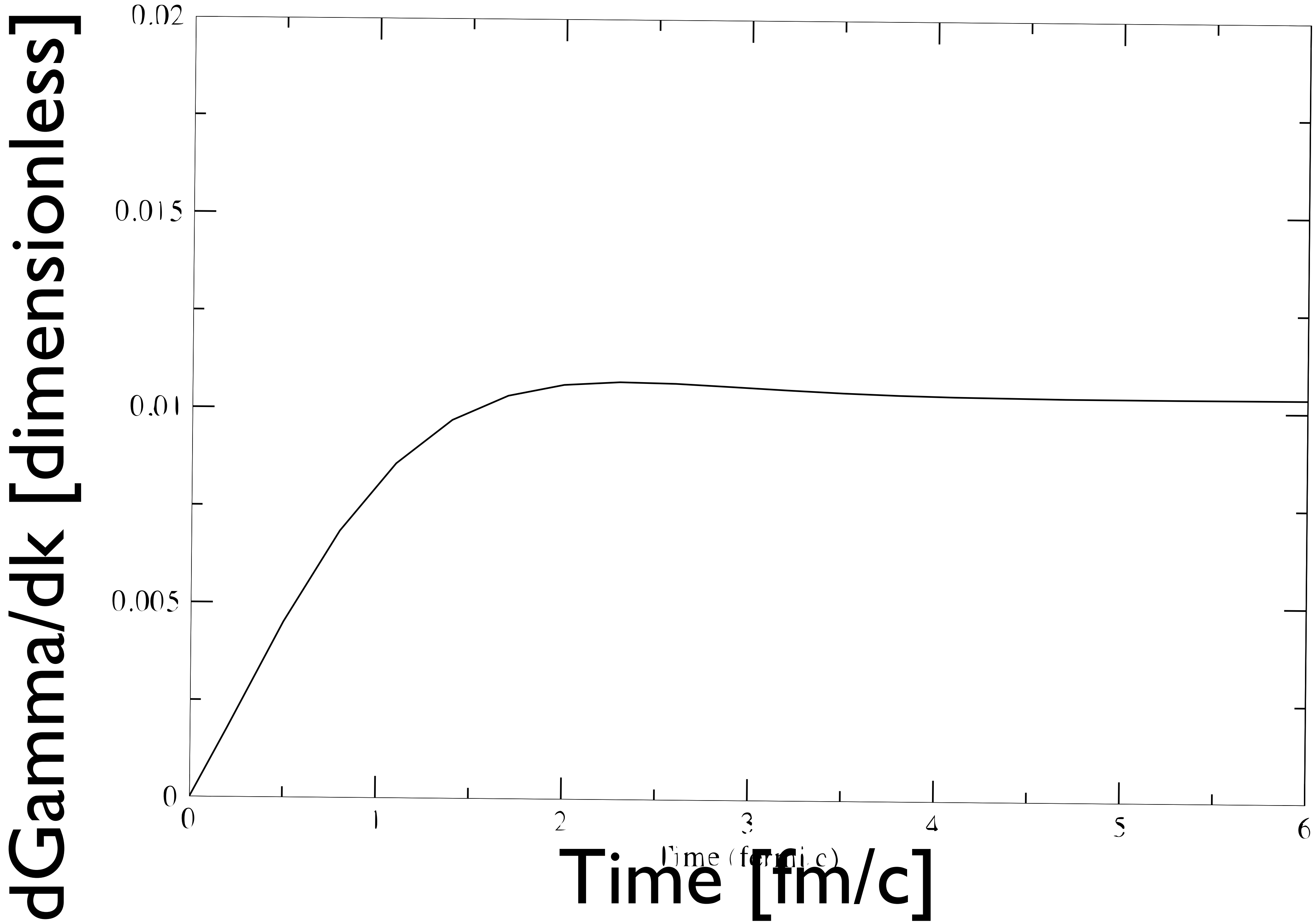
In a medium, extra ‘kicks’ induce further radiation

$$\frac{dP}{dx d^2 k_\perp} = \frac{P^a_{bc}(x)}{k_\perp^2} + P^{\text{medium}}_{\text{induced}}$$

In-medium bremsstrahlung

- Theory consists of a mysterious collection of acronyms (GLV, HT, ASW, AMY, BDMPS, -Z,...)
- Despite claims, all are based on the *same* physics (with various level of accuracy...)
- ‘Mother equation’ is BDMPS-Z. Next slide I’ll show what its general solutions look like.

Key idea is to plot a rate: $\frac{dP}{dx d^2k_\perp dL}$

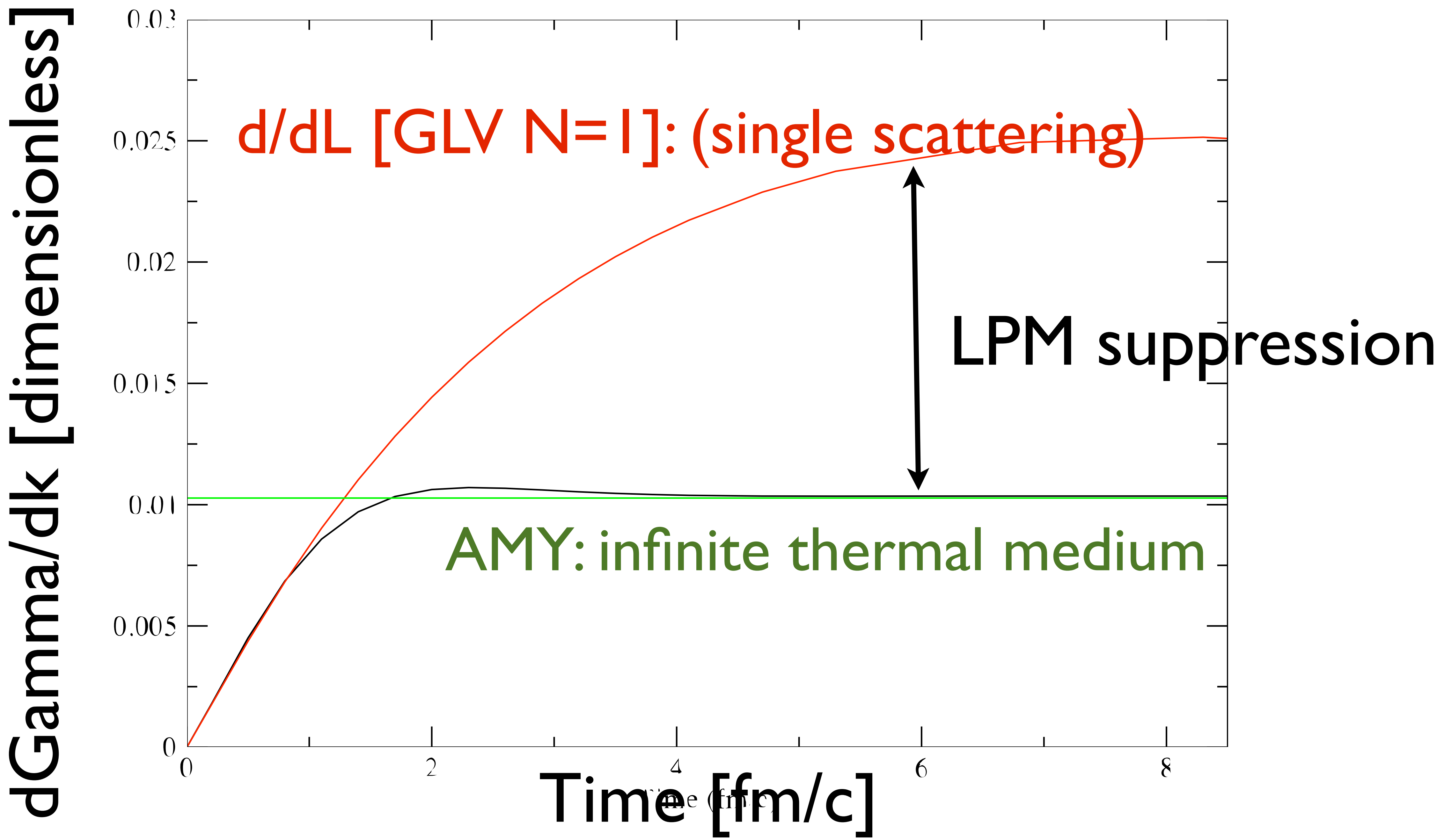


(Gale&SCH, 1006.2379)

Example: rate for a 16 GeV quark to radiate a 3 GeV gluon

Uniform brick T=250 MeV, alpha_s=0.3

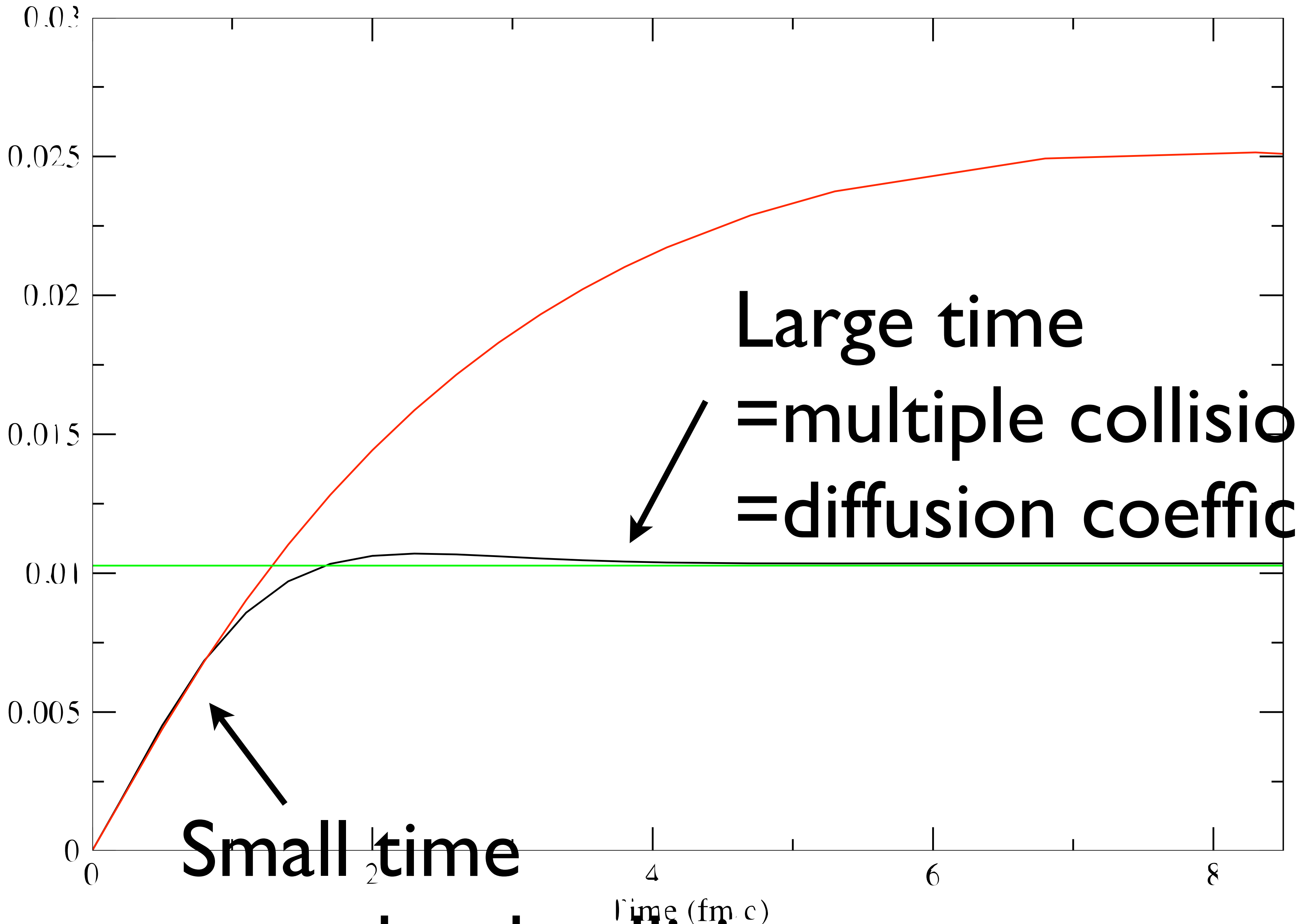
Limits have well-understood descriptions...



(Gyulassy-Levai-Vitev)

(Arnold-Moore-Yaffe)

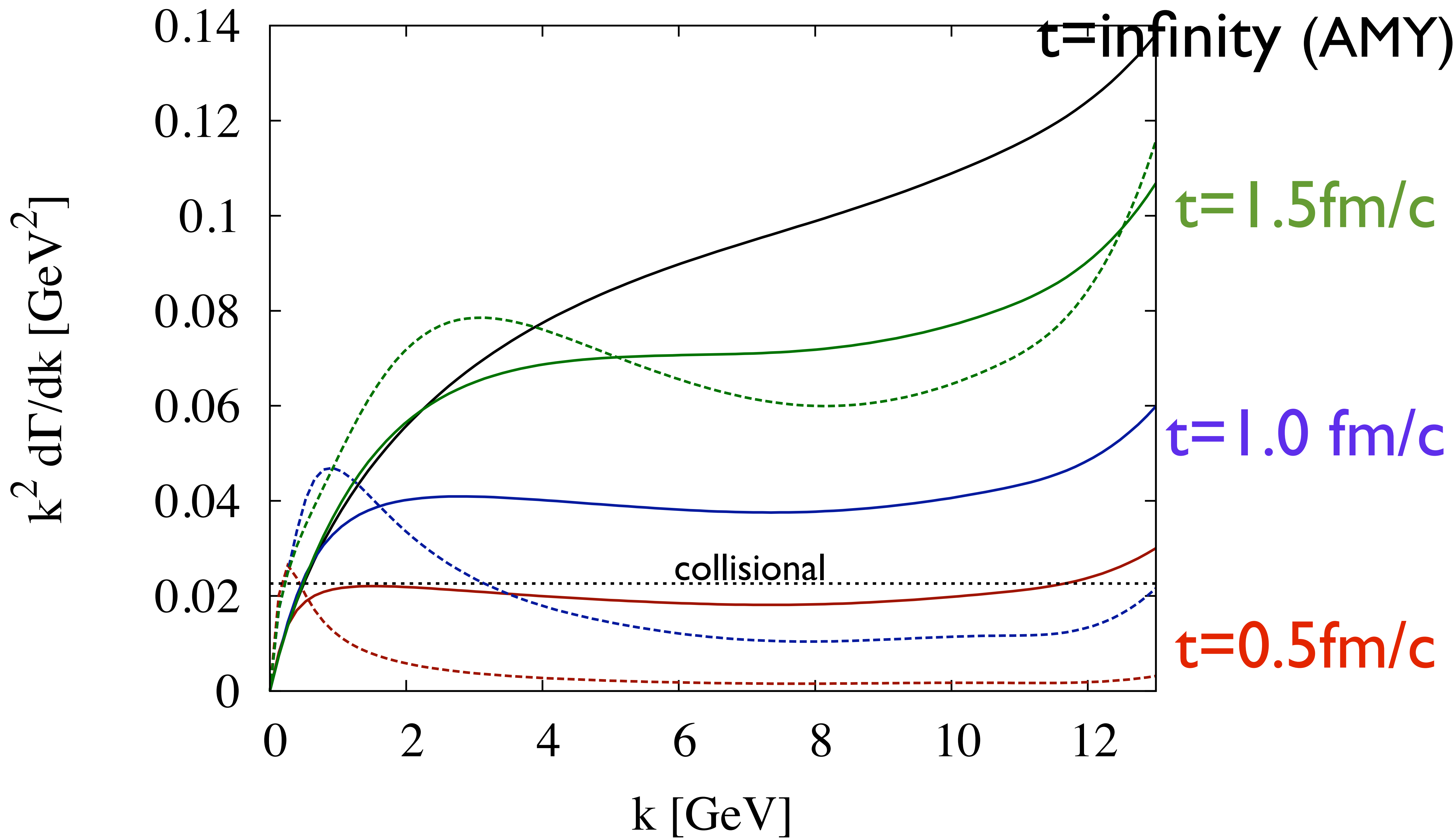
...with simple microscopic parameters:



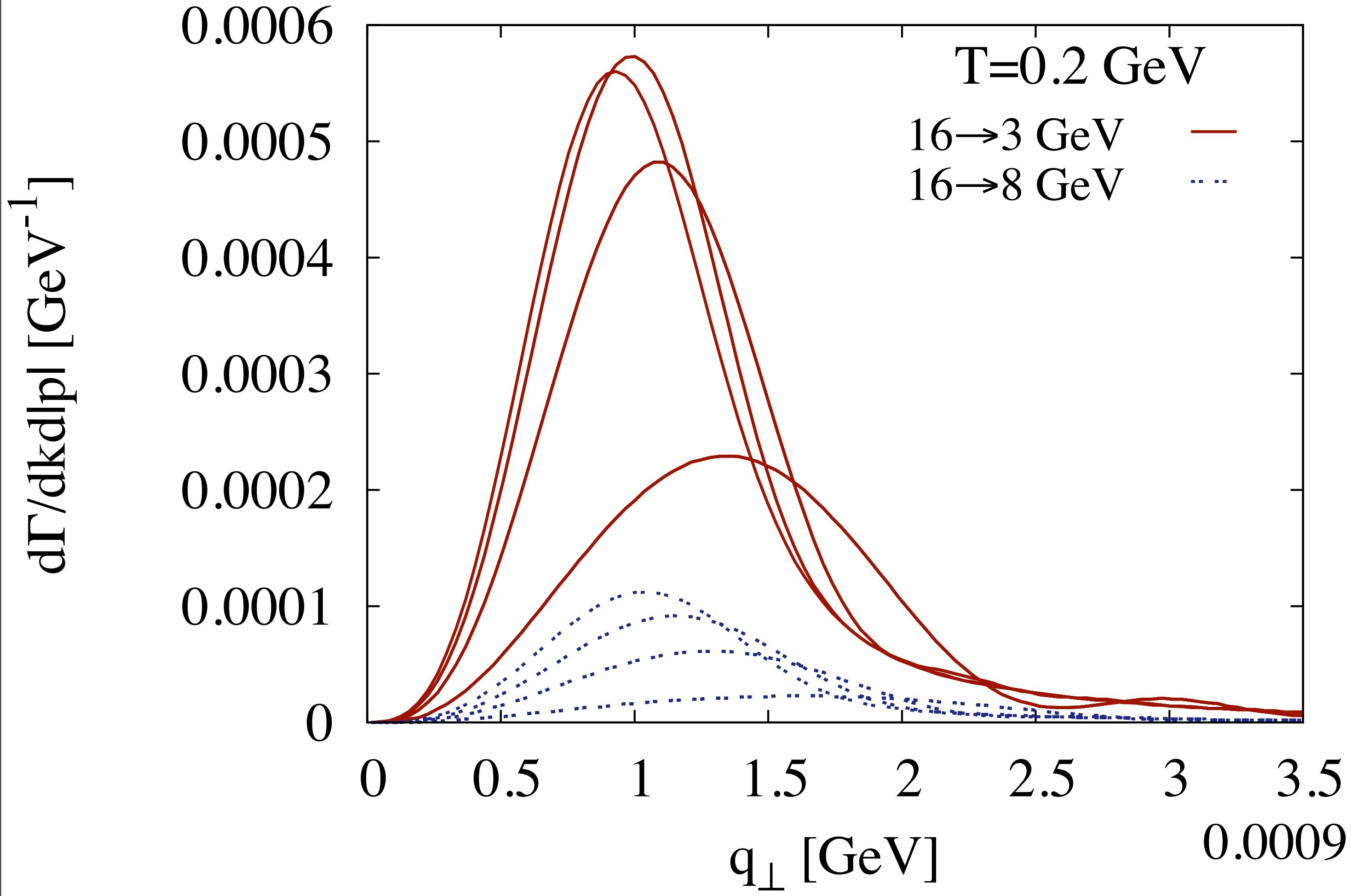
Large time
=multiple collisions
=diffusion coefficient $\hat{q}$

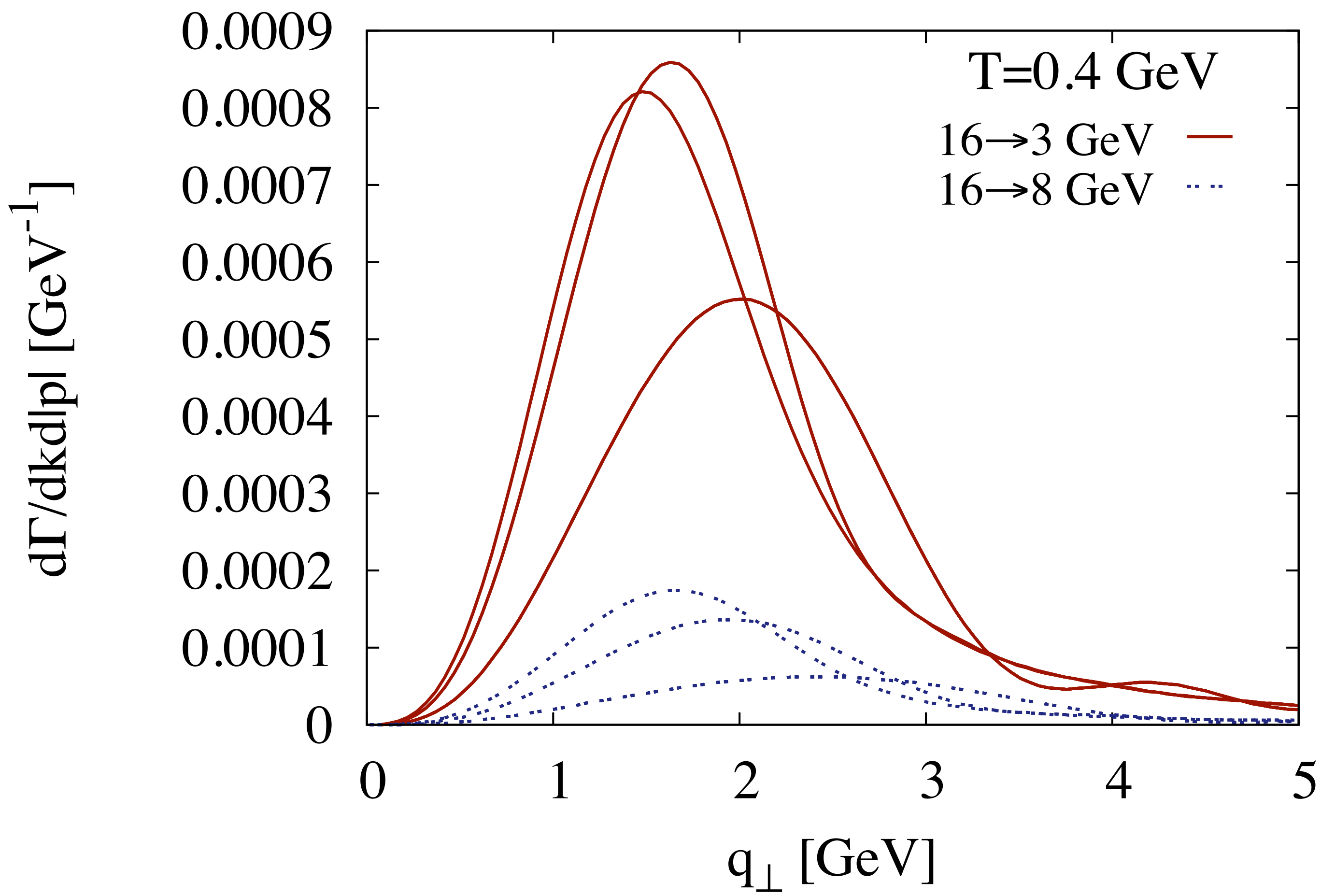
Small time
=one hard collision
=UV charge density

Rad. spectra from a 16 GeV quark: (forget about dashed lines)



Transverse momentum of radiation





Summary from jets...

- Medium-modification to vertex is rather well understood (in LO perturbation theory at the jet scale)
- "Factorized" dependence on two parameters
- We thought this was it.....

(Implementation begun by B. Schenke, C. Young)

Summary from jets...

- Medium-modification to vertex is rather well understood (in LO perturbation theory at the jet scale)
- "Factorized" dependence on two parameters
- We thought this was it.....

(Implementation begun by B. Schenke, C. Young)

Until further leading-order effects were uncovered (destruction of color coherence)!

(Leonidov & Nechitailo `10, Arnesto, Ma, Mehtar-Tani, Salgado, Tywoniuk... `10)

(parametrized by same variables)

Brief note for theorists

- The following clean theoretical problem has presently *unsolved* status:

  "Find a modification of vacuum jet shower, such that all:
  -collinear logarithms $\alpha_s \log Q^2$
  -soft logarithms $\alpha_s \log z$
  -length-enhanced effects $\alpha_s L/\ell_{\mathrm{mfp}}$
  are resummed."

Brief note for theorists

- The following clean theoretical problem has presently *unsolved* status:

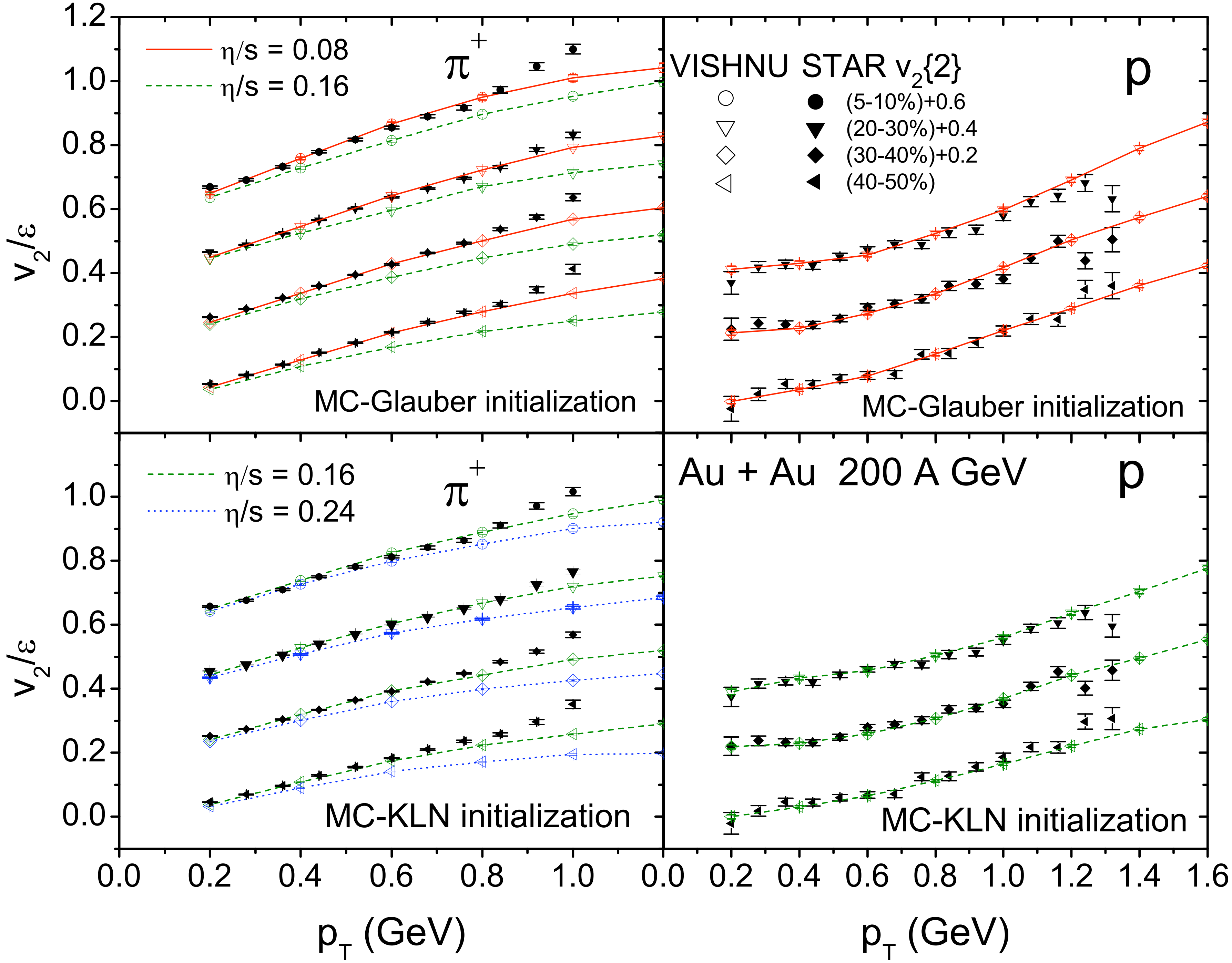
  "Find a modification of vacuum jet shower, such that all:
   -collinear logarithms $\alpha_s \log Q^2$ (DGLAP `71)
   -soft logarithms $\alpha_s \log z$ (angle-ordered parton showers, 80's)
   -length-enhanced effects $\alpha_s L/\ell_{\rm mfp}$
  are resummed."

- I would argue it's a well-defined problem, with a 'unique' and well-defined solution.

Conclusions

- QCD near the deconfinement transition characterized by few key parameters (eta/s, ...)
- What can be said about small-x physics from p +Pb collisions? (PDFs computable?)
- Hard probes (high-energy jets, heavy quarks, ...) offer i) (many open) clean theoretical problems ii) wealth of data

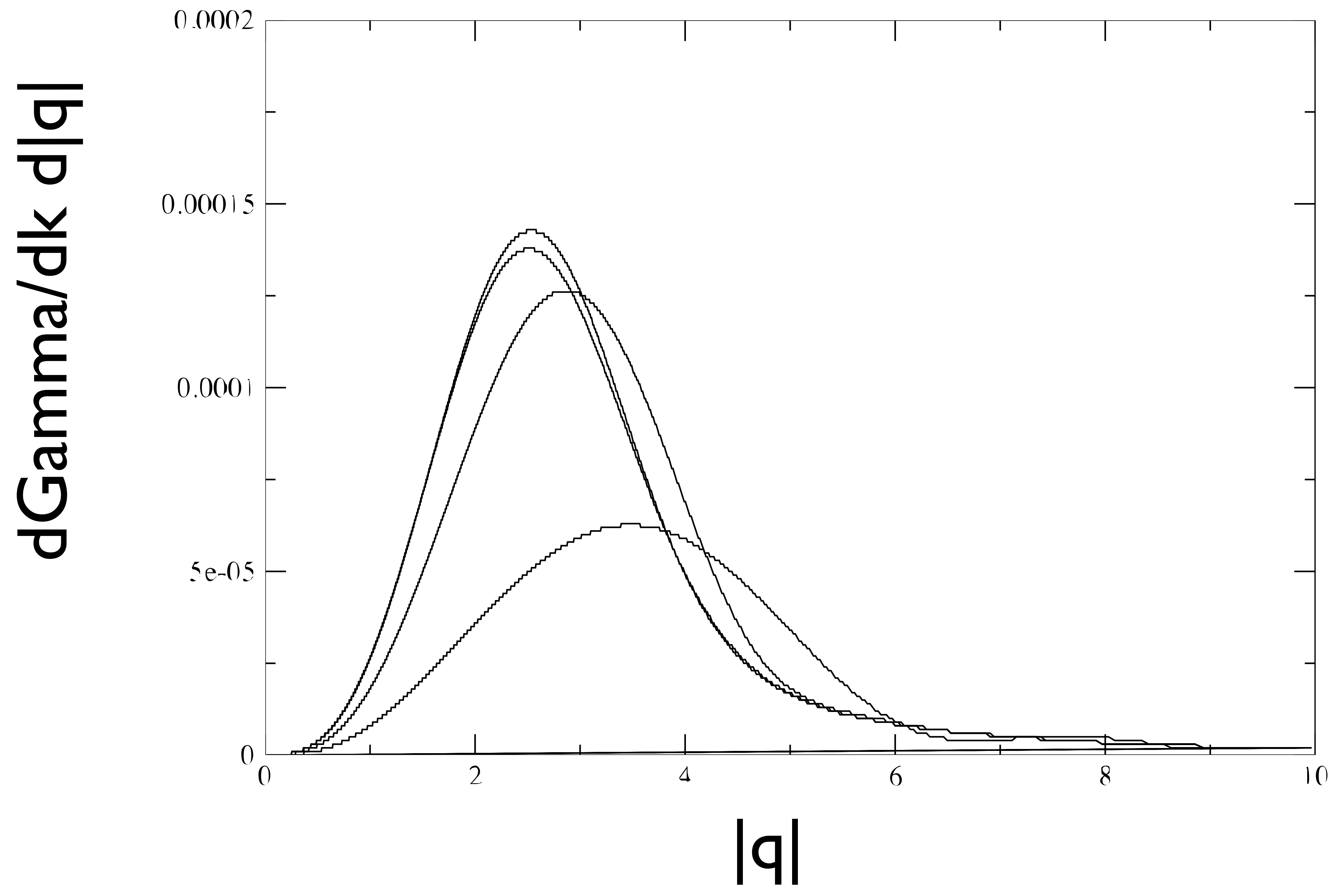
Backup



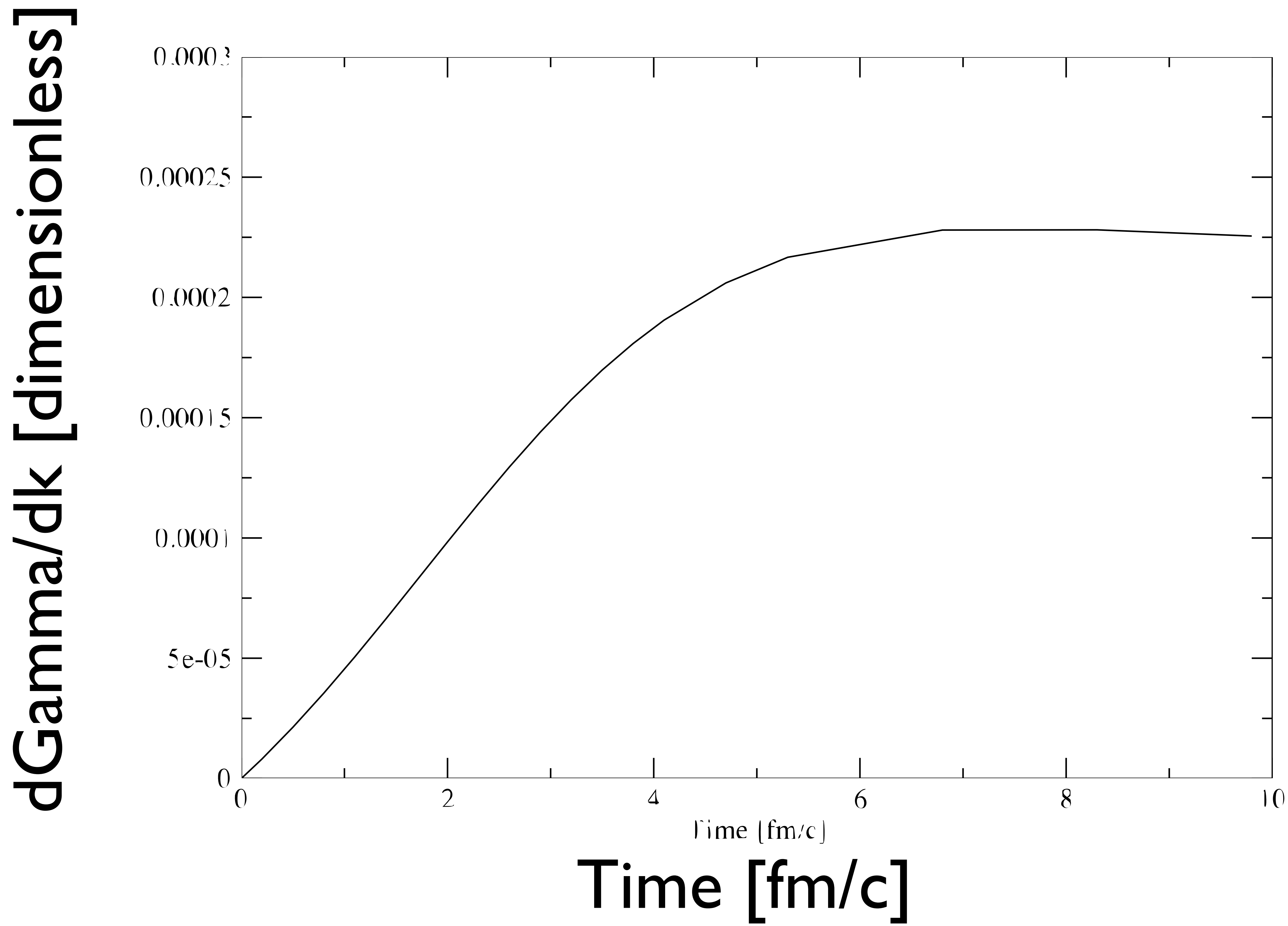
(Heinz 1108.5323)

Transverse momenta; LHC

50 GeV quark->10 GeV gluon, T=500 MeV

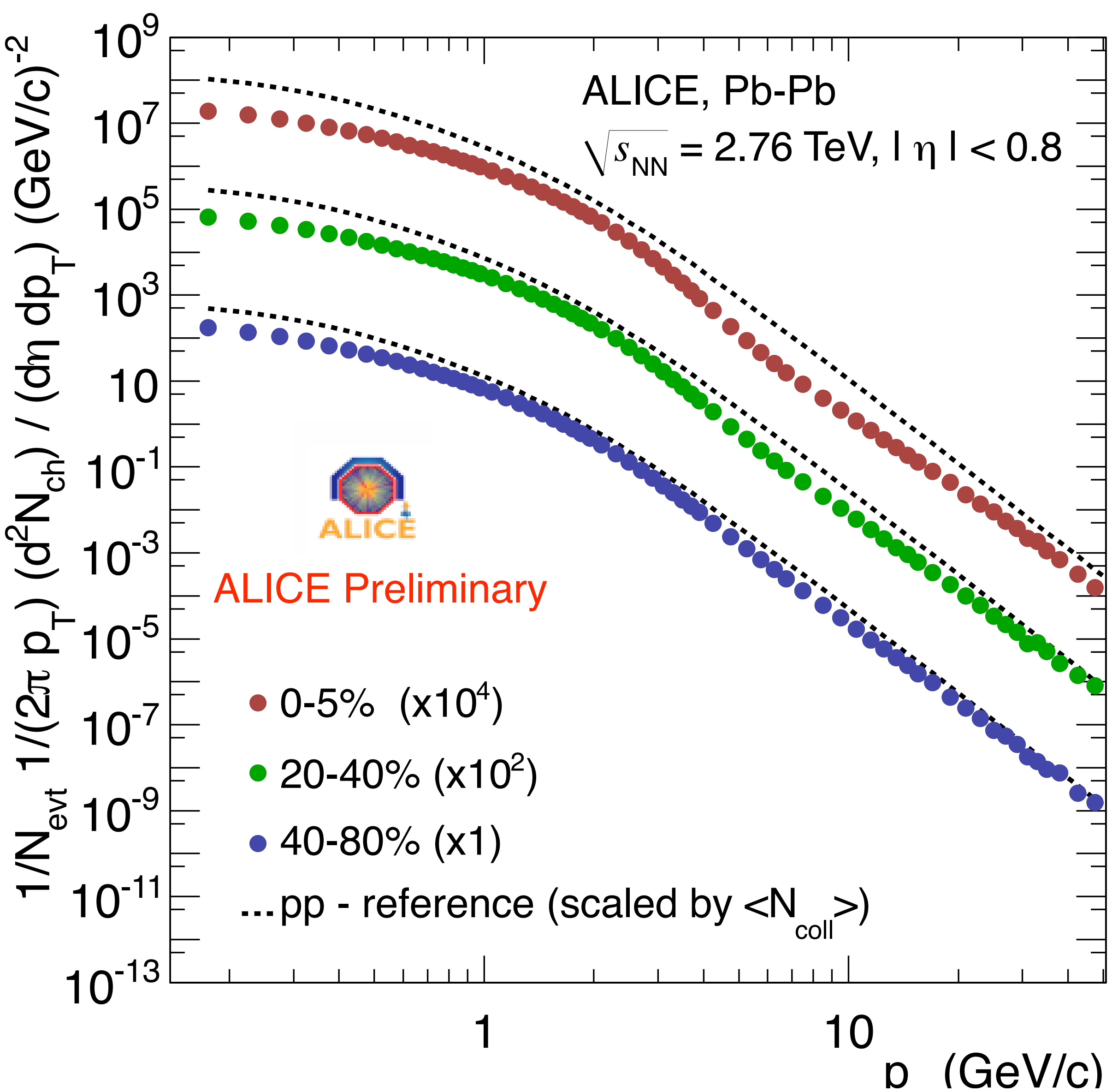


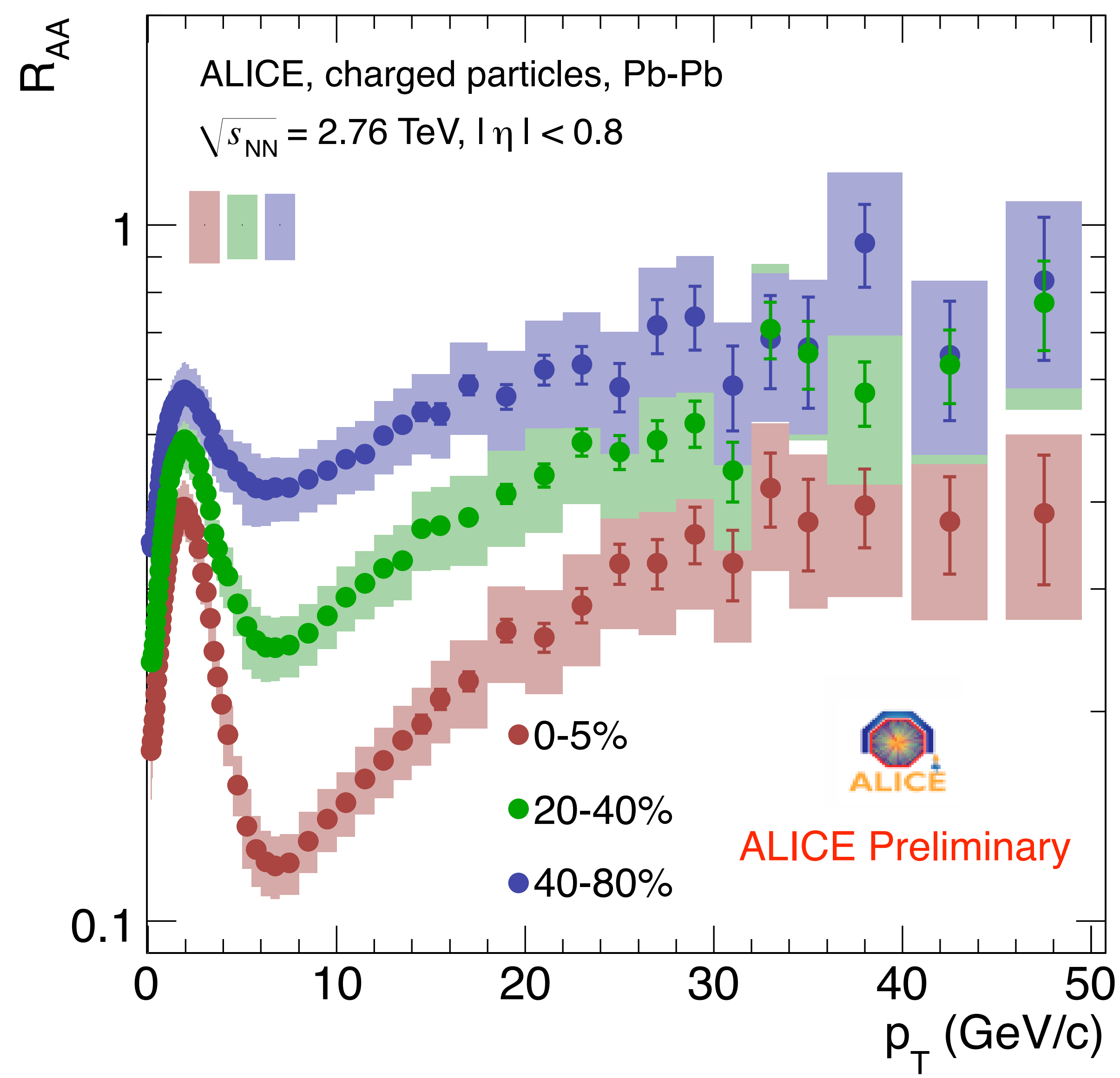
80GeV->40 GeV @ T=0.25



Much longer formation times at LHC

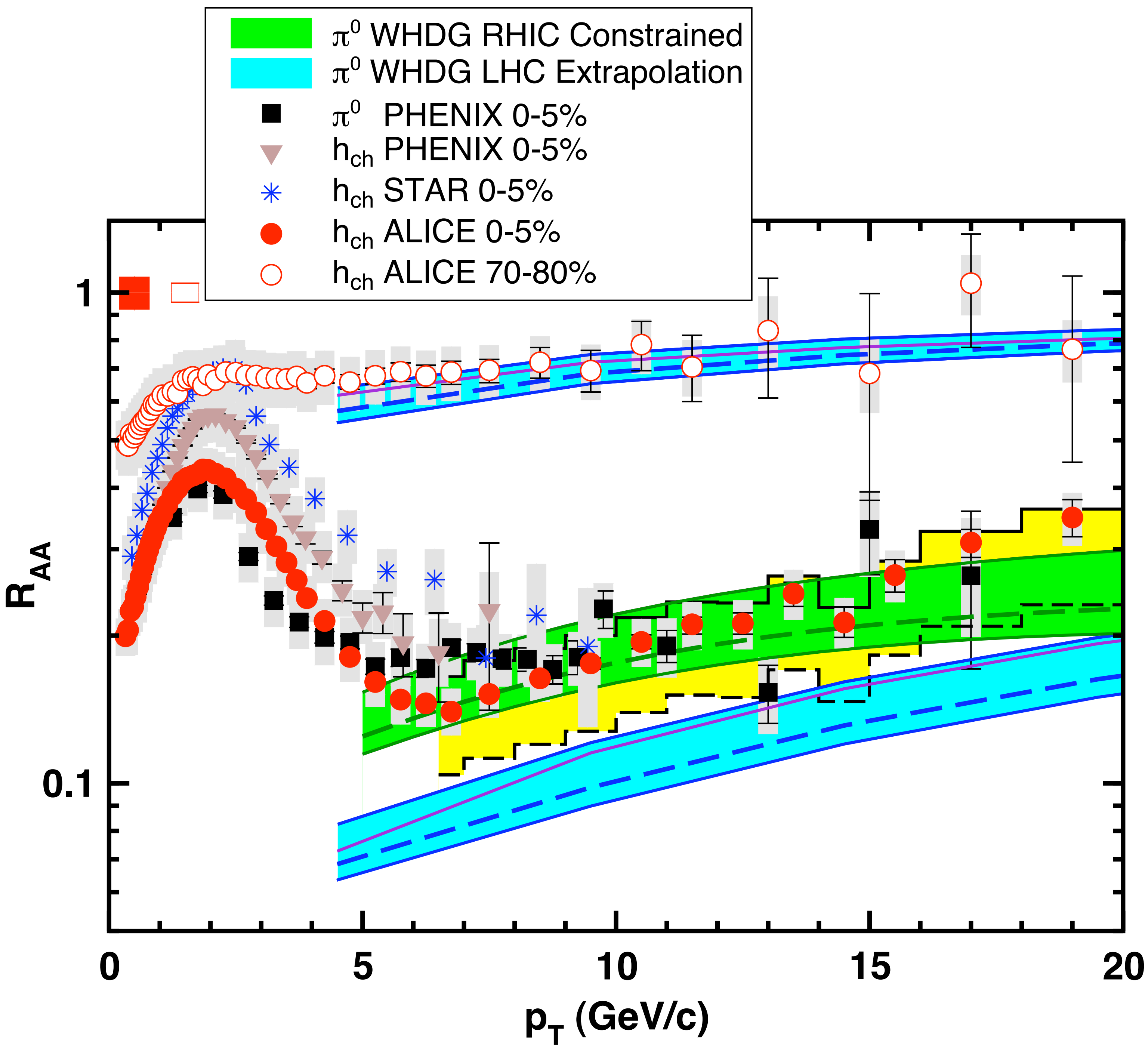
Leading hadron suppression





(van Leeuwen for ALICE, 1201.5205)

Comparison with experiment

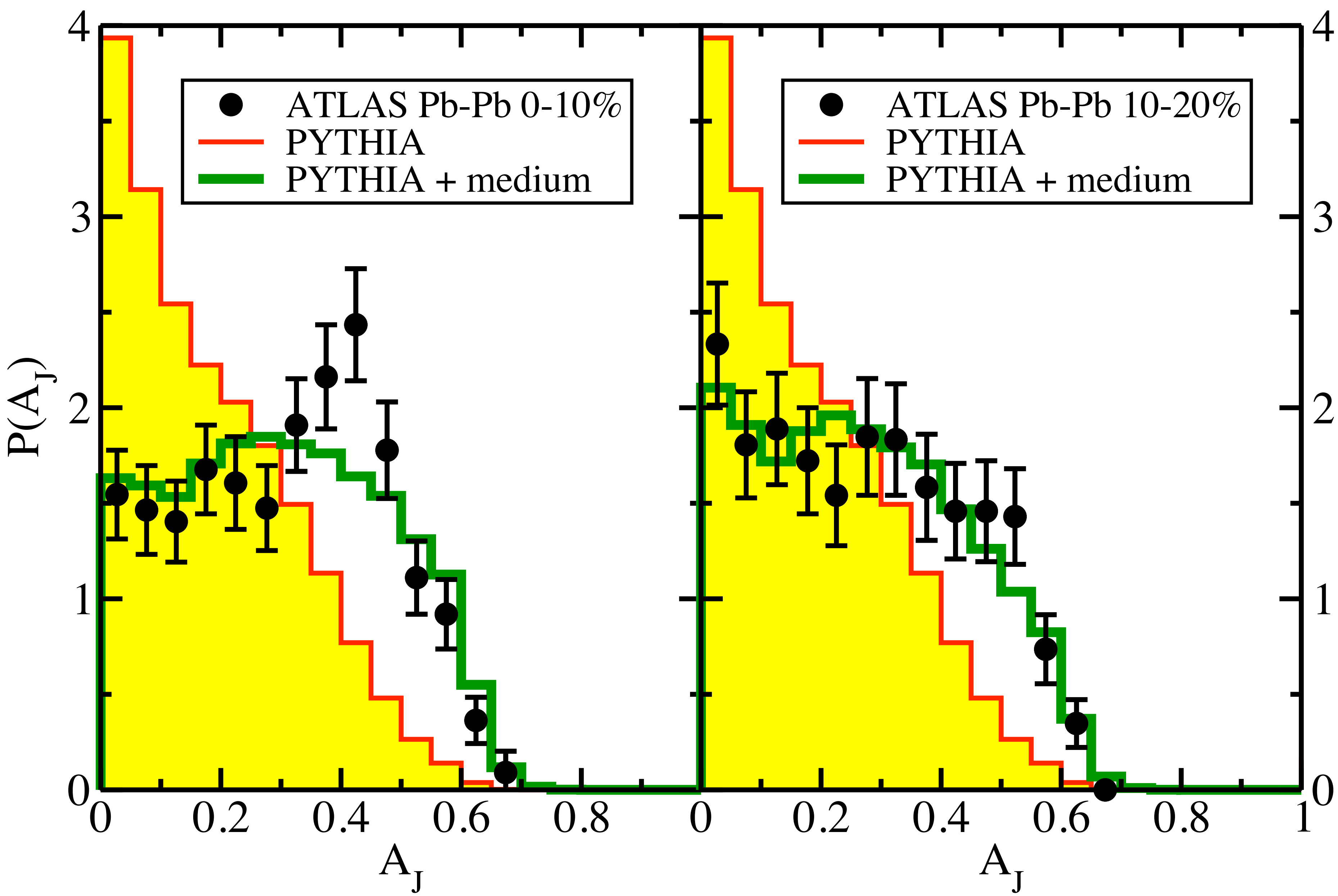


Prediction overshot the suppression a bit

Can be accounted for by a modest change in initial density -- matches hydro very well

(Gyulassy and Horowitz, 1104.4958)

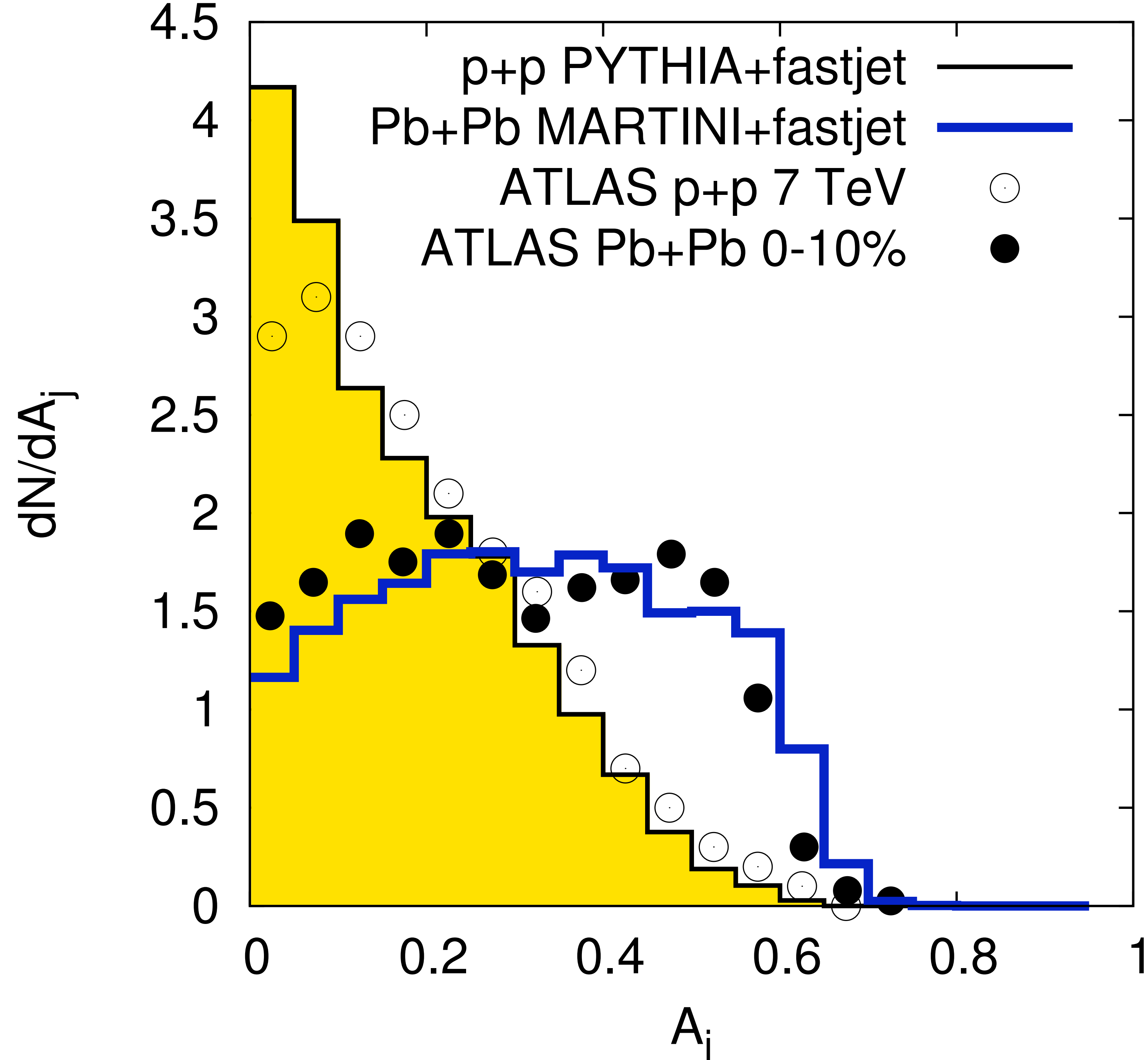
Di-jet asymmetry



(E_{T1}>100GeV, E_{T2}>25GeV, dTheta>Pi/2)

FIG. 3: (Color online) Distribution of di-jet asymmetry factor A_J for $p + p$ and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC. Left panel: 0-10% centrality; right panel: 10-20% centrality.

B.Muller & G.-Y. Qin, 1012.5280



(Young, Jeon& Gale)

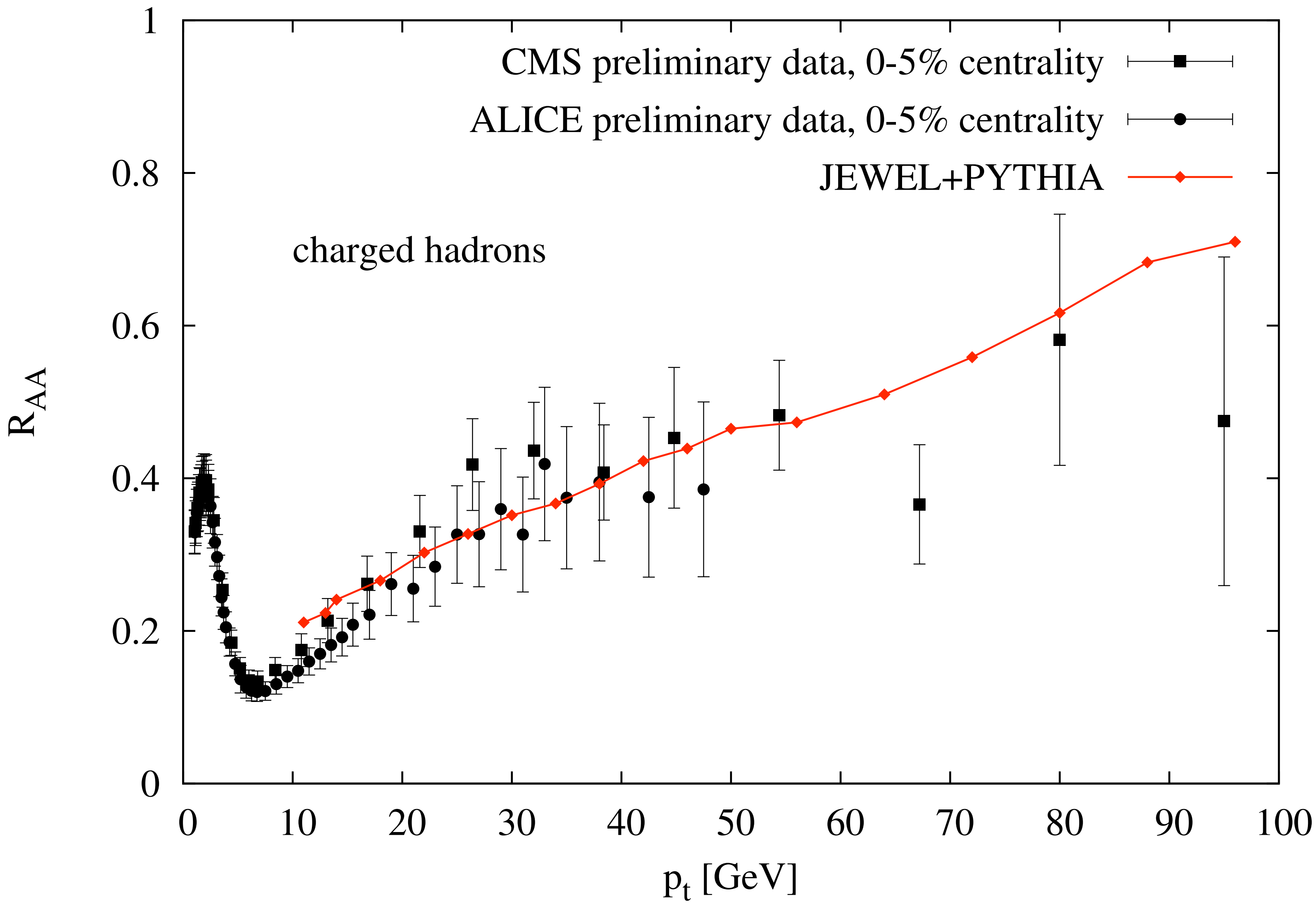
Fix the density of charge carriers, fit the coupling at the soft scale: alpha$_s$~0.27

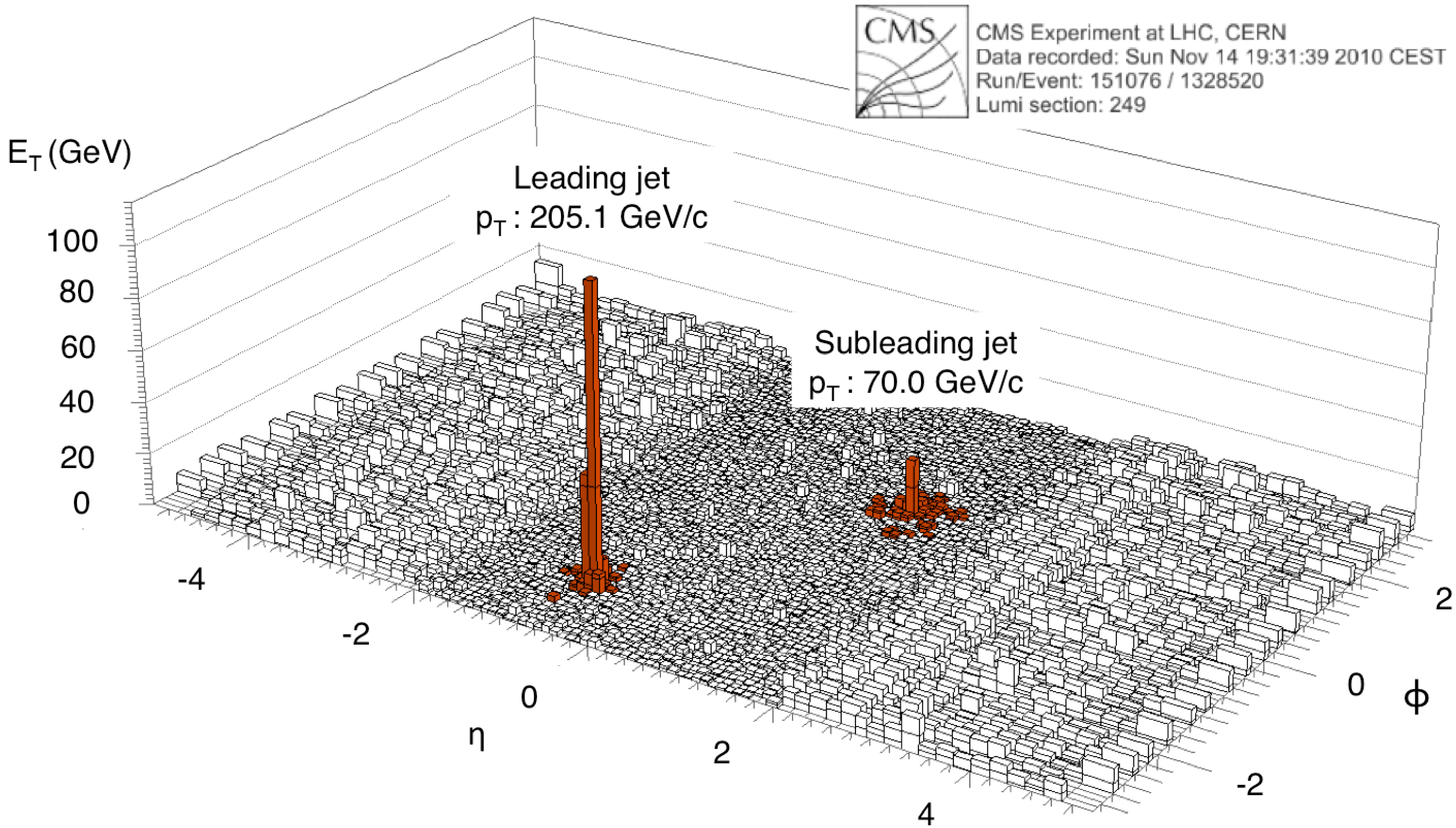
Essentially same value as RHIC

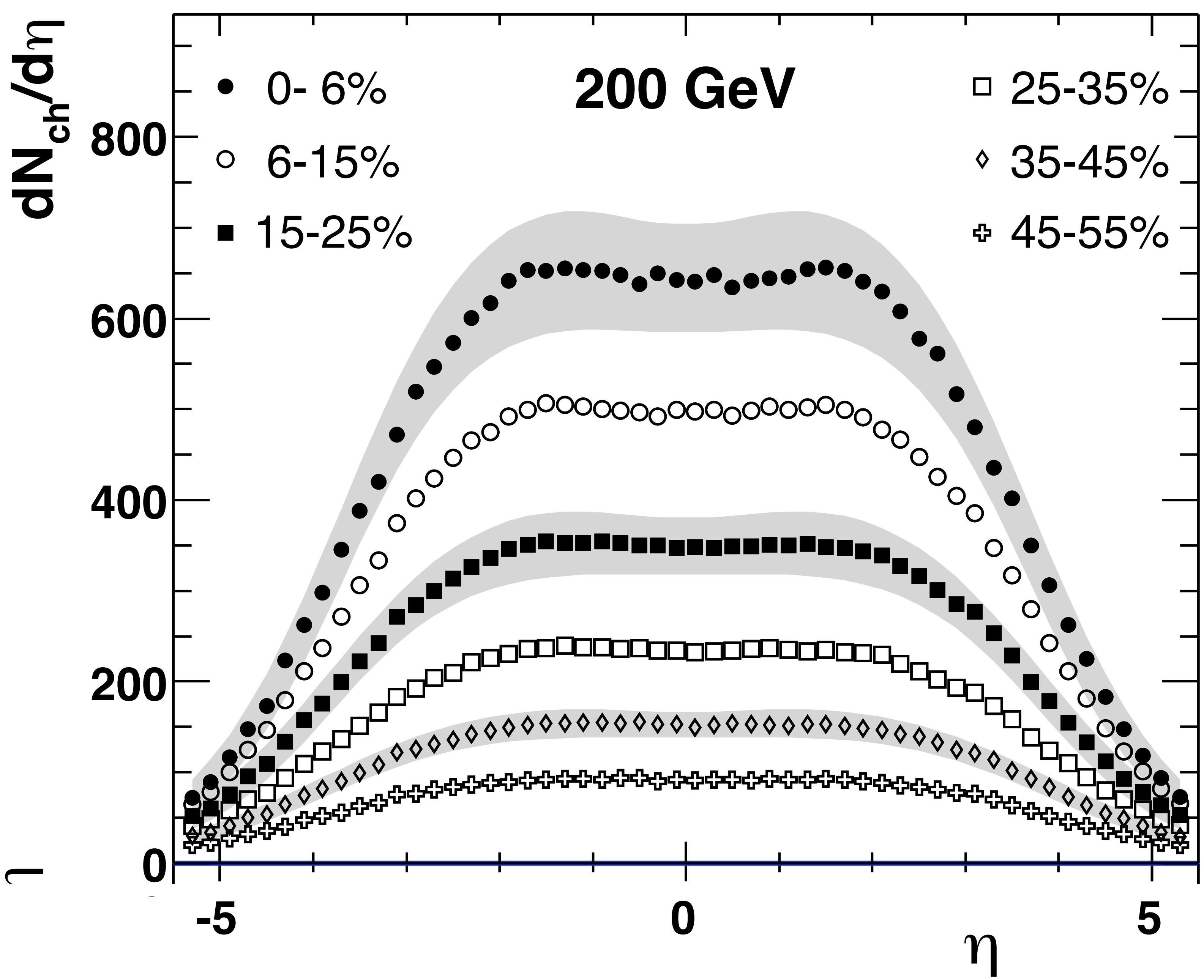
Explaining jet quenching with perturbative QCD alone

Korinna C. Zapp,[1,*] Frank Krauss,[1] and Urs A. Wiedemann[2]
[1] *Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK*
[2] *Department of Physics, CERN, Theory Unit, CH-1211 Geneva 23*
(Dated: November 30, 2011)

We present a new formulation of jet quenching in perturbative QCD beyond the eikonal approximation. Multiple scattering in the medium is modelled through infra-red-continued $(2 \to 2)$ scattering matrix elements in QCD and the parton shower describing further emissions. The interplay between these processes is arranged in terms of a formation time constraint such that coherent emissions can be treated consistently. Emerging partons are hadronised by the Lund string model, tuned to describe LEP data in conjunction with the parton shower. Based on this picture we obtain a good description of the nuclear modification factor R_{AA} at RHIC and LHC.




CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
E_T (GeV)
100
80
60
40
20
0
Leading jet
p_T : 205.1 GeV/c
Subleading jet
p_T : 70.0 GeV/c
-4
-2
0
η
2
4
2
0
ϕ
-2


dNch/dη
200 GeV
0- 6%
6-15%
15-25%
25-35%
35-45%
45-55%
800
600
400
200
0
-5
0
5
η

(PHOBOS 2002)