Finite temperature field theory and heavy ion collisions

Nordic Winter School on Particle Physics and Cosmology 2013, Skeikampen, Norway

Lecture 4: QCD shear viscosity; hard probes

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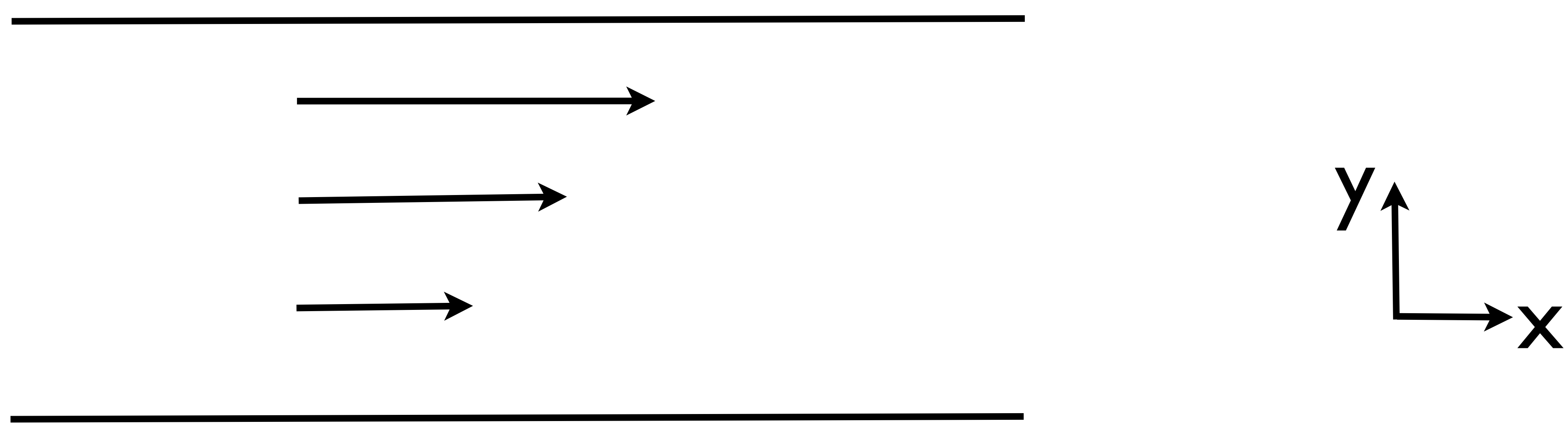
What is the shear viscosity of the QGP?

- In the presence of a y-dependent x-velocity ('shear flow')



$$\frac{\partial}{\partial t} u_x = \eta \partial_y^2 u_x \quad \longleftrightarrow \quad T^{xy} = -\eta \partial_y u_x$$

- Clear from previous picture that

$$\eta \approx \sum_{\text{momentum carriers}} \text{momentum carried} \times \text{mean free path}$$

$$\approx P \times \ell_{\text{mfp}}$$

- More precise computation in simple (e.g. hard sphere) model gives

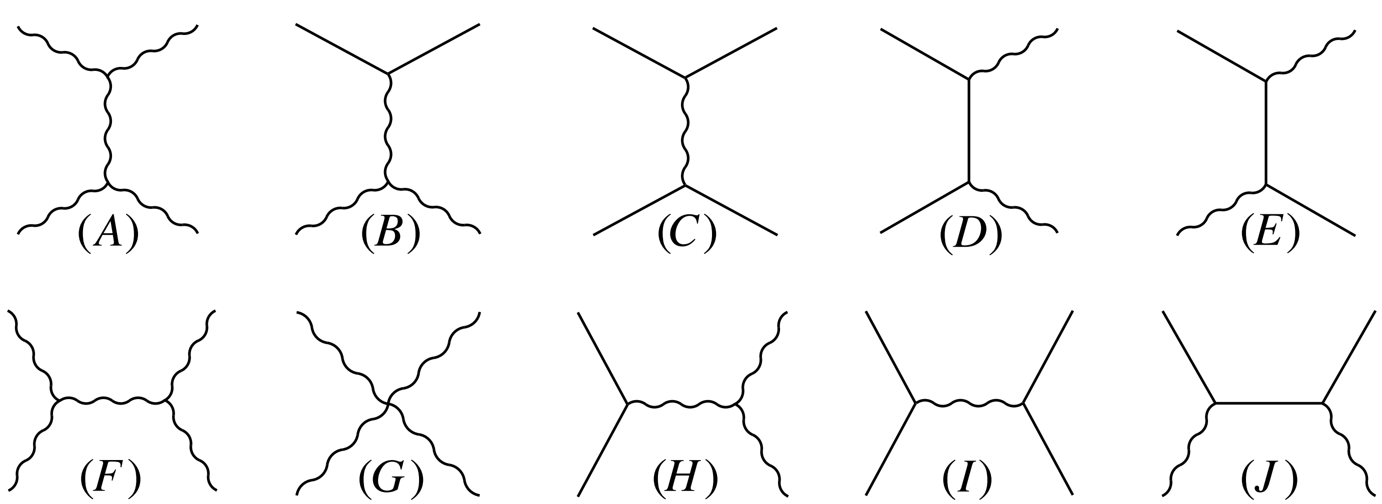
$$\frac{4\pi}{\hbar}\frac{\eta}{s} \approx (2 \div 3)\ell_{mfp}T$$

Leading order viscosity from Boltzman eq.

$$\left[\frac{\partial}{\partial t} + \vec{v}\cdot\frac{\partial}{\partial \vec{x}}\right] n(p,x) = C[p]$$

Include 2<->2 processes (and 2<->1 in QCD)

$$C[p_1] = \int_{3,4} |M_{12\to 34}|^2 \left[(1+n_1)(1+n_2)n_3 n_4 - n_1 n_2 (1+n_3)(1+n_4)\right]$$



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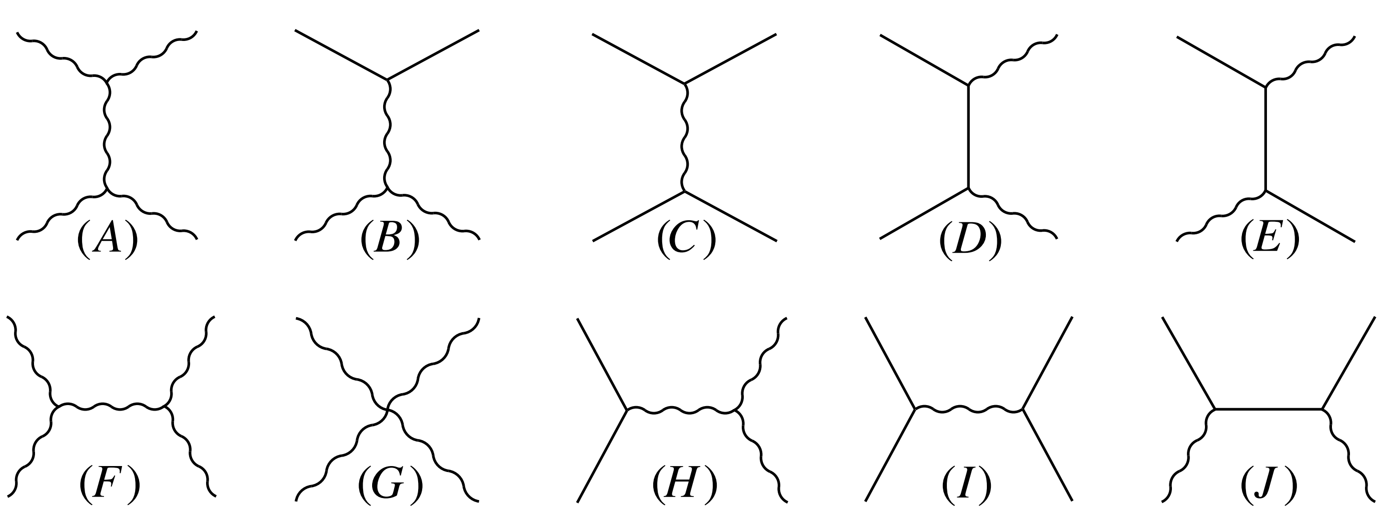


Main physics is Coulomb, cut off by screening:

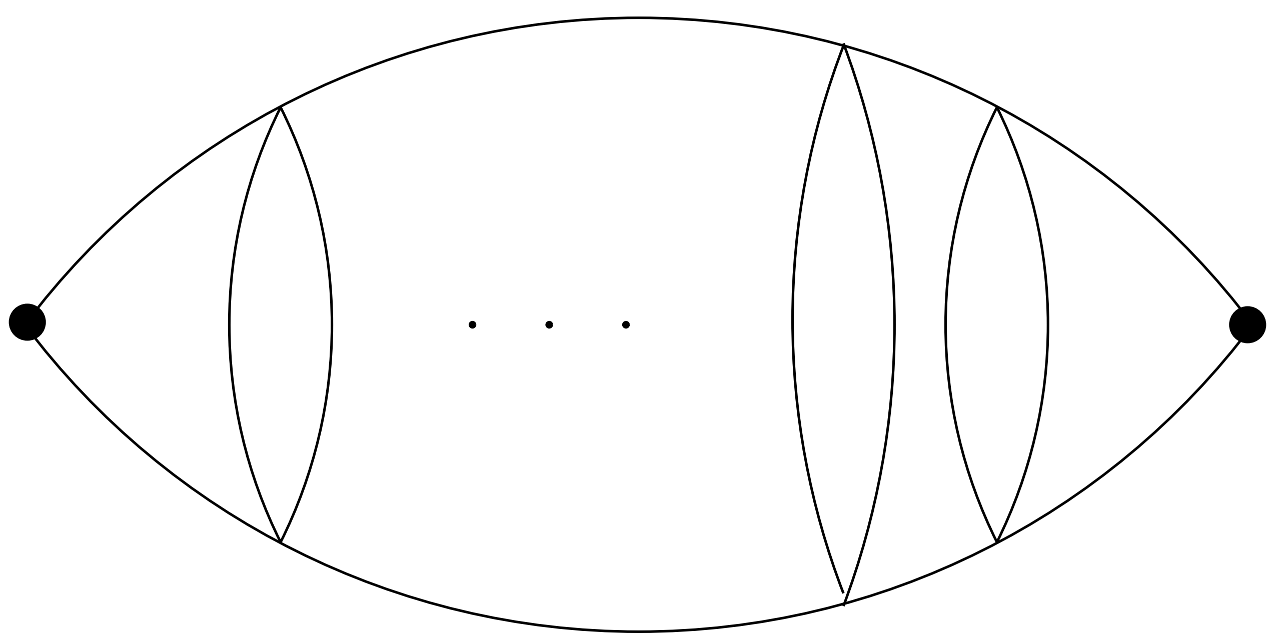
$$\Gamma^{\text{transport}} \sim \int d\sigma (1-\cos\theta)$$
$$\sim g^4 \log g^4$$

[derivation from quantum field theory]

- Effective field theory matching: Kubo formula

$$\eta = \lim_{\omega\to 0}\lim_{k\to 0}\frac{-1}{\omega}\mathrm{Im}G_R^{T_{xy}T_{xy}}(\omega,k)$$

- Boltzmann eq. arises from summing ladder diagrams



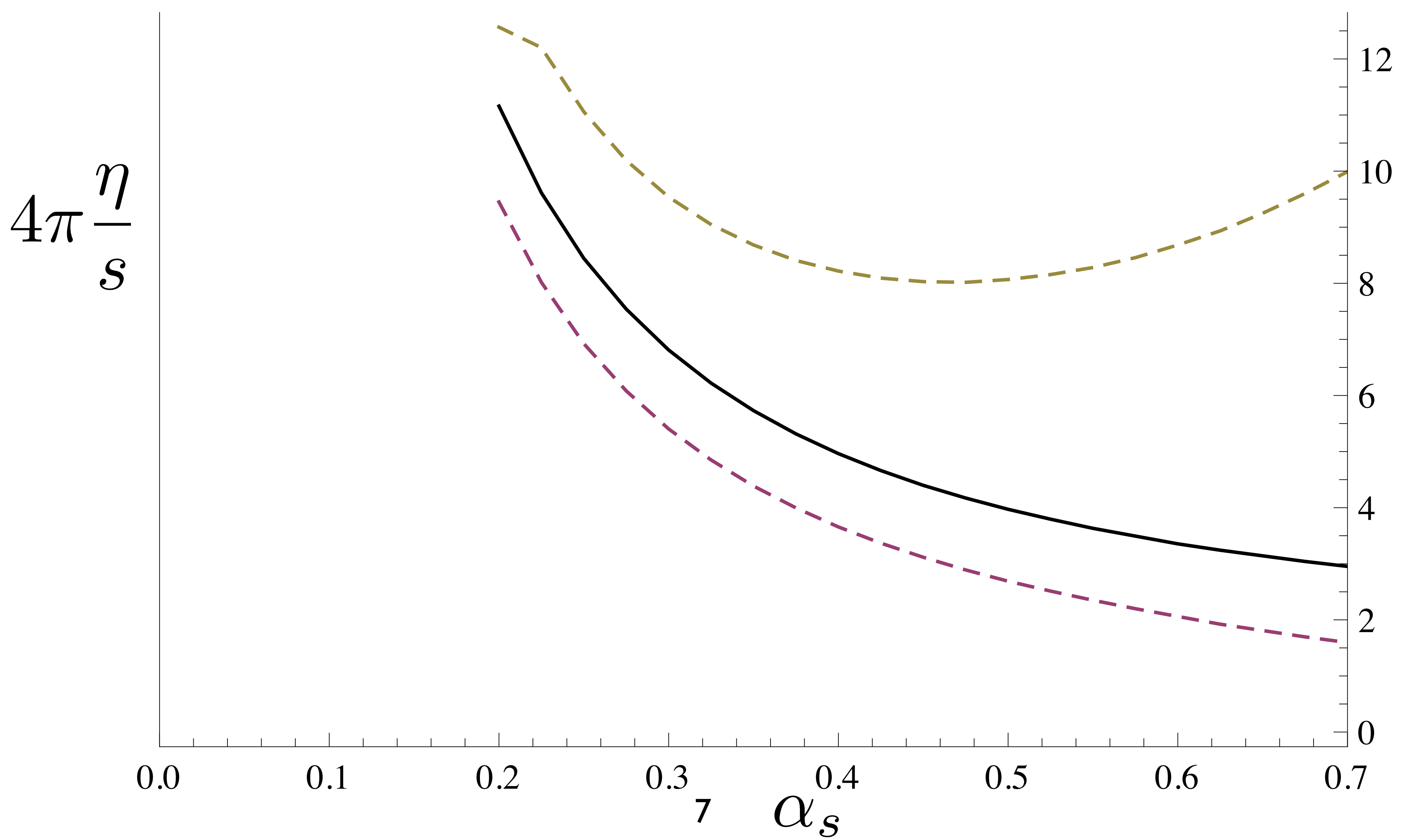
[result for phi[4]:

$$4\pi\frac{\eta}{s}\approx\frac{3.286}{(\lambda/16\pi^2)^2}$$]

(Jeon '95;
E.Wang& U.Heinz th/0201116)

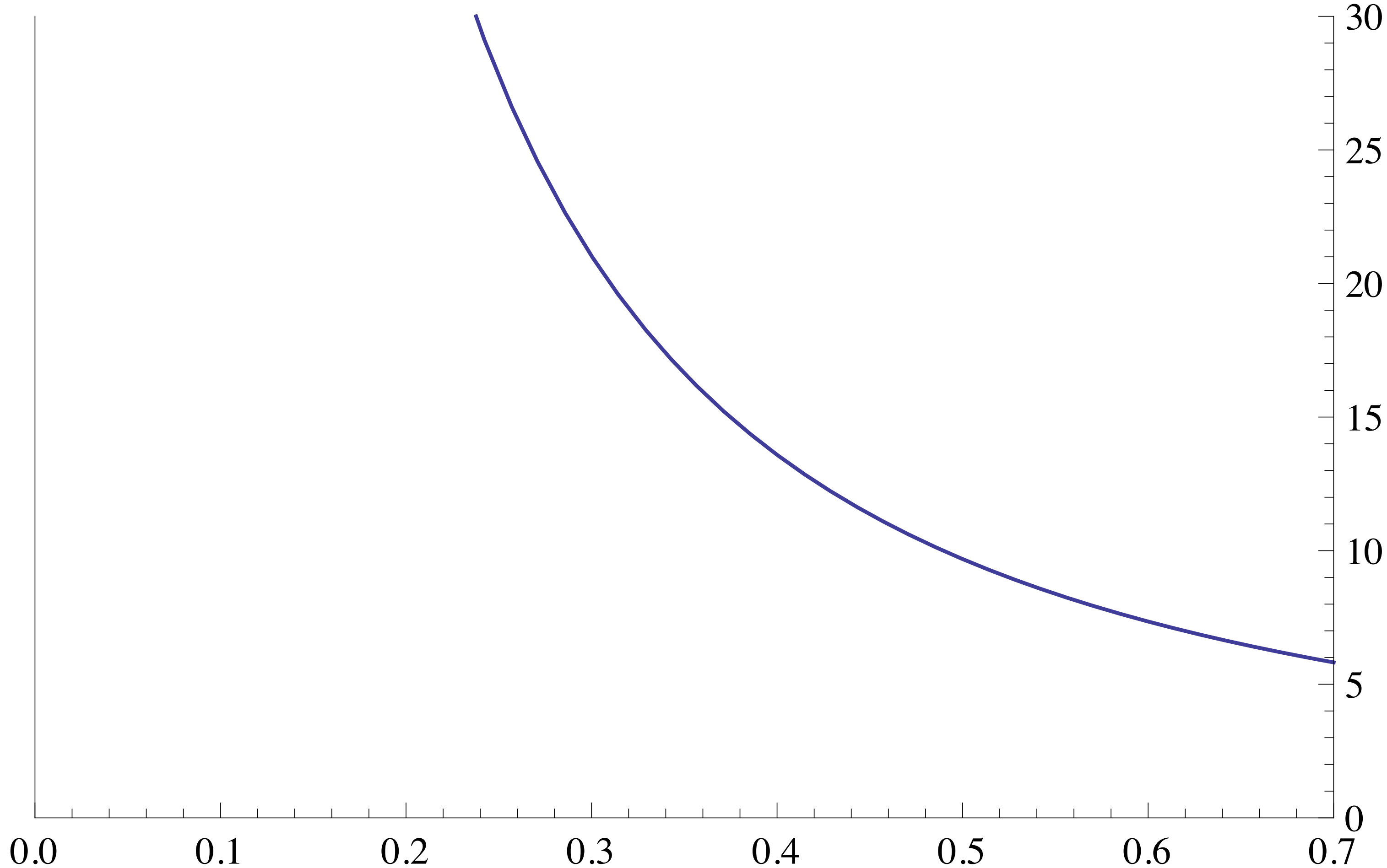
Pure Yang-Mills viscosity

- The definitive word at present is from [Chen,Deng,Dong&Wang '10], who include 2->3 splitting processes



The QCD viscosity

- Leading order QCD viscosity *[2<->2 + collinear 1<->2]*



next-to-leading log:

$$4\pi \frac{\eta}{s} \approx \frac{64.3}{g^4 \log \frac{2.41}{g}}$$

[Baym, Monien, Pethick& Ravenhall '90,
plot: full LO from Arnold, Moore& Yaffe '03]

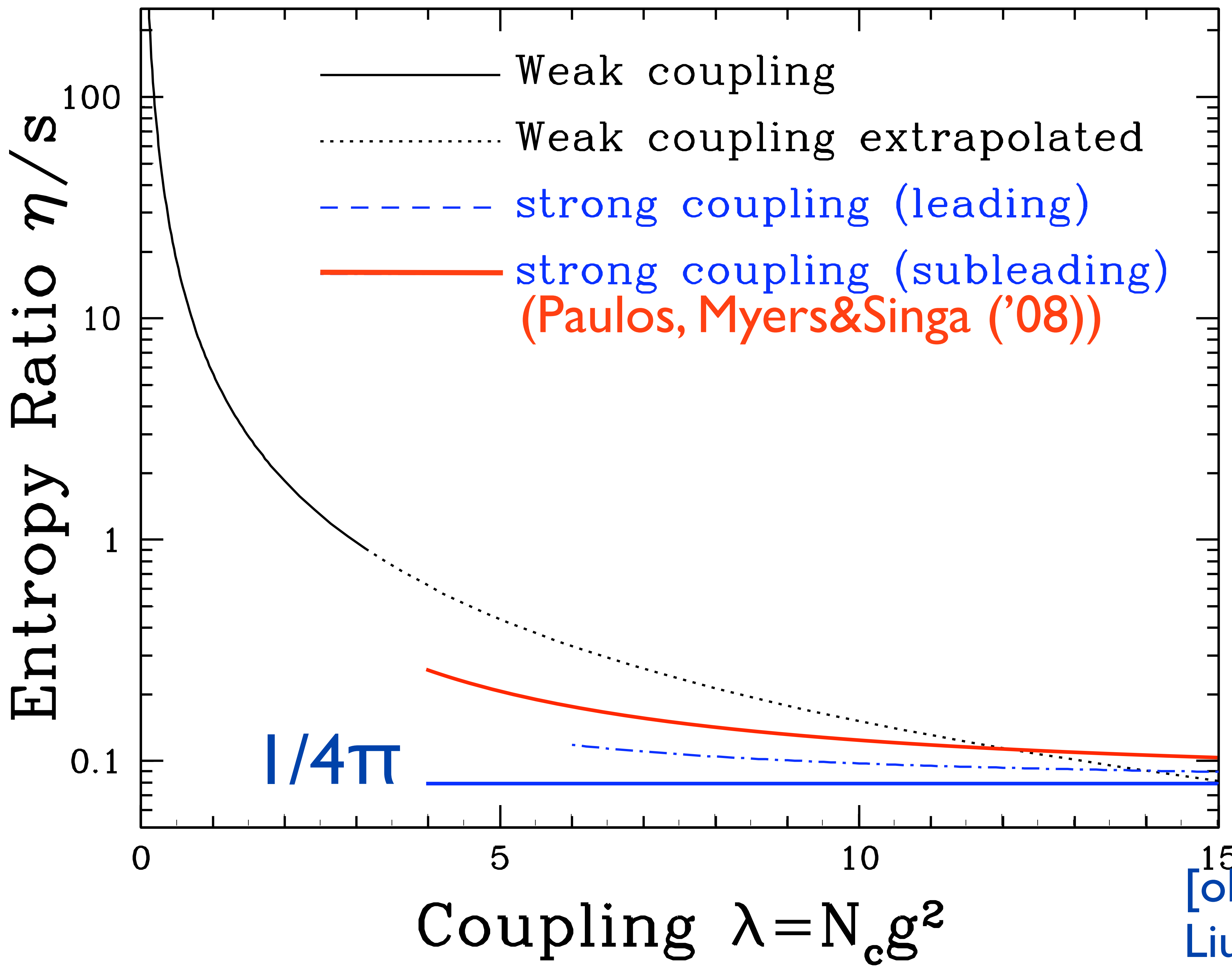
Why is it so large?

- For N_f=3 QCD, d_A=8, d_F=9, [31.5/47.5]~2/3 of the energy is in fermions

$$\frac{p}{T^4} = \frac{\pi^2}{180}(4d_A + 7d_F) + \ldots$$

- *Fundamental* fermions interact with a smaller Casimir (by 1/2)
- Difficult to avoid: $\frac{\eta}{s}(\mathrm{QCD}) \sim 2\frac{\eta}{s}(\mathrm{YM})$
- Experimental result $4\pi\eta/s < 3$: *a true puzzle*

The N=4 viscosity

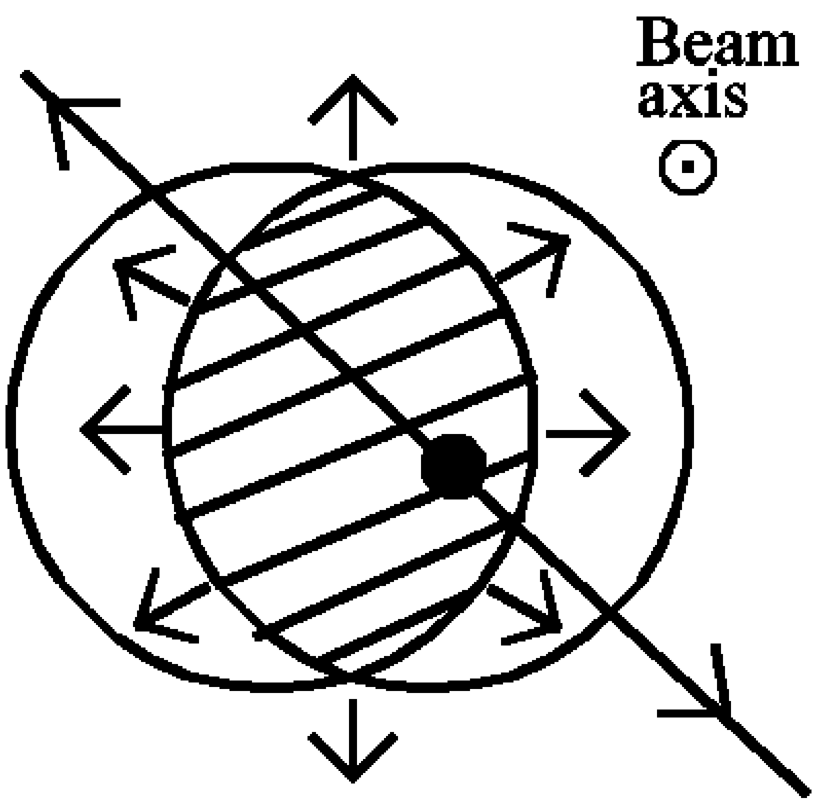


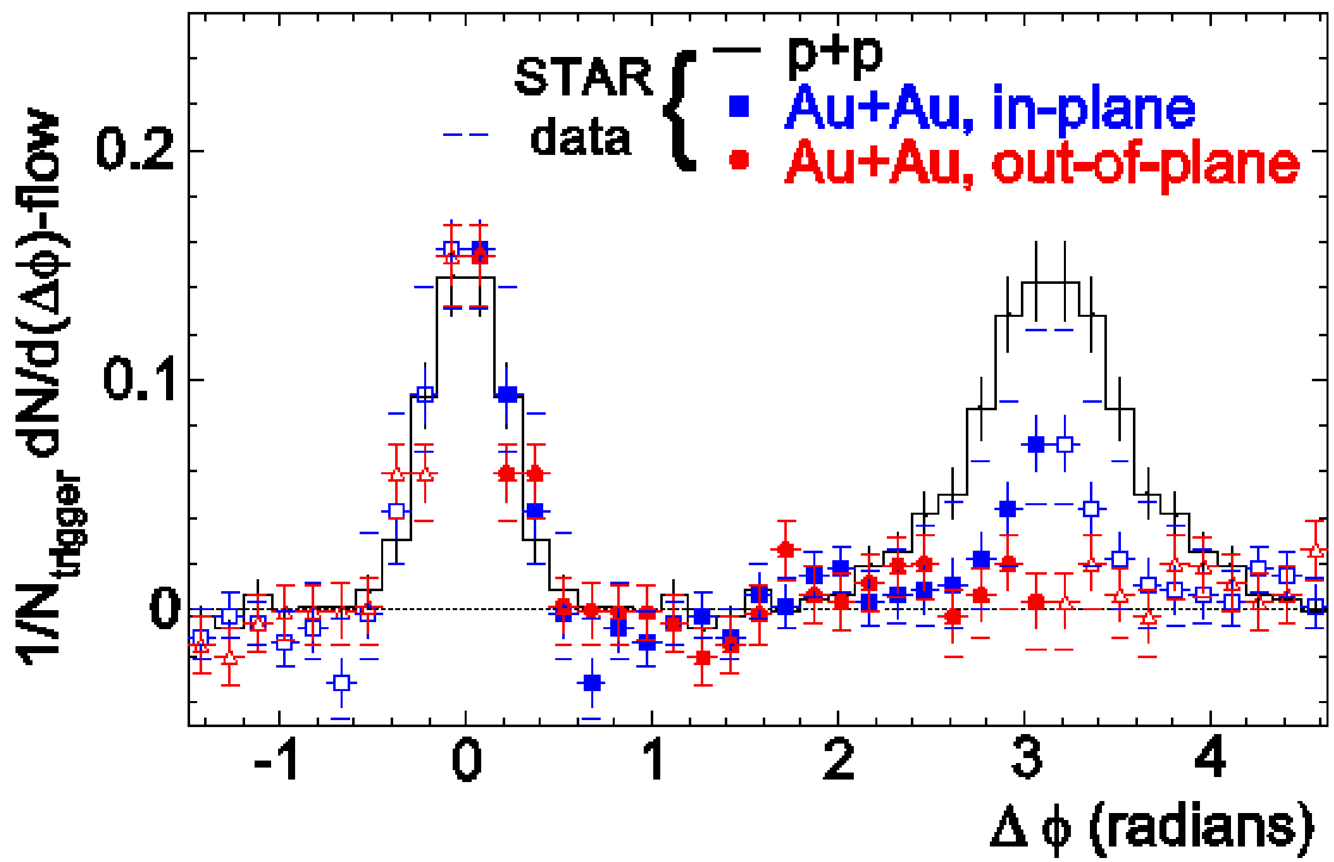
[old nlo by Buchel, Liu& Starinets ('04)

[SCH,Jeon&Moore,`06]

- Given the puzzles about strong interactions between the plasma constituents, it is a good idea to look at *hard probes*
- Partons with atypically large momenta, heavy quarks,...
- pQCD can be reasonably expected to provide a good baseline for these observables

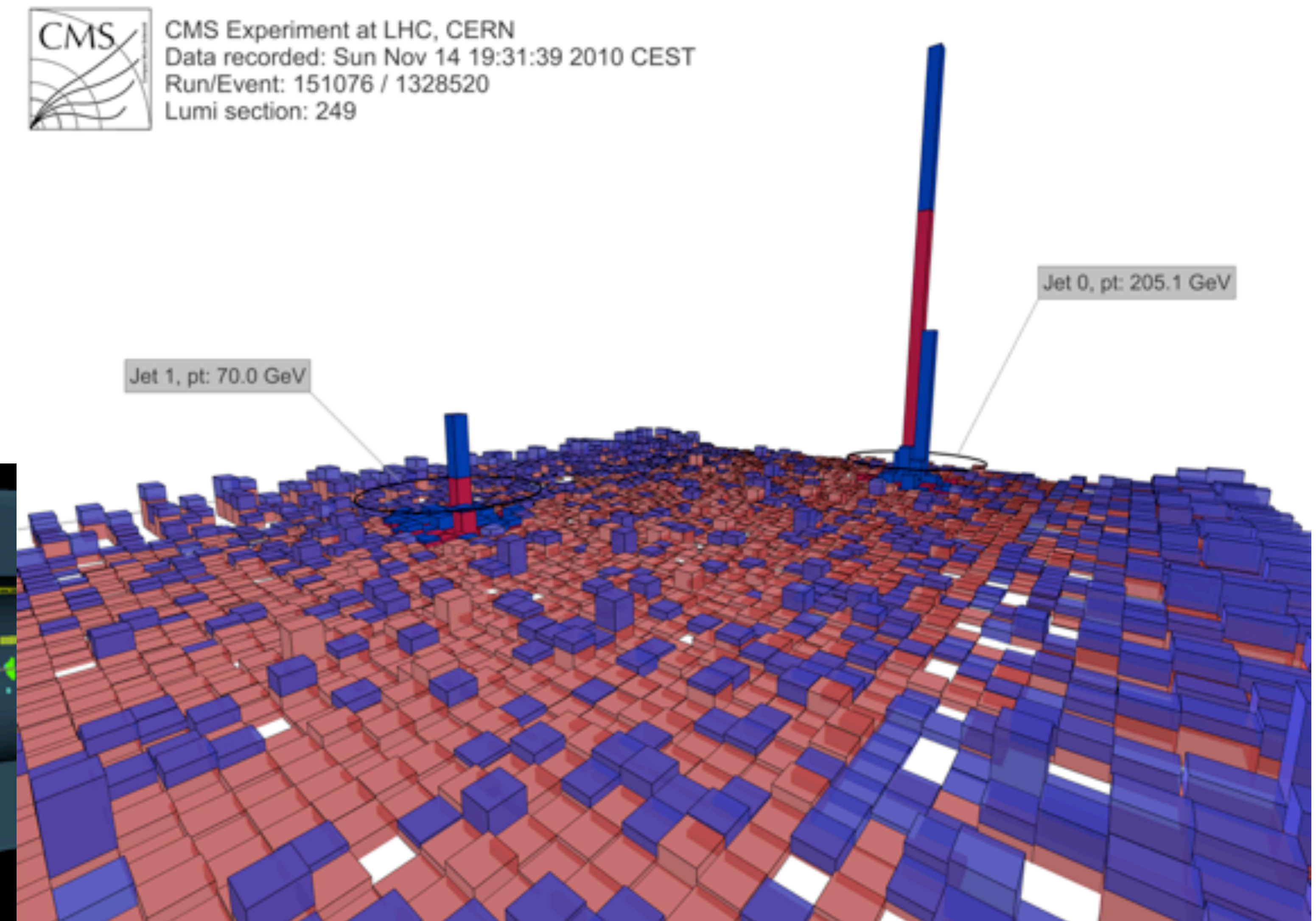
Jet quenching, I

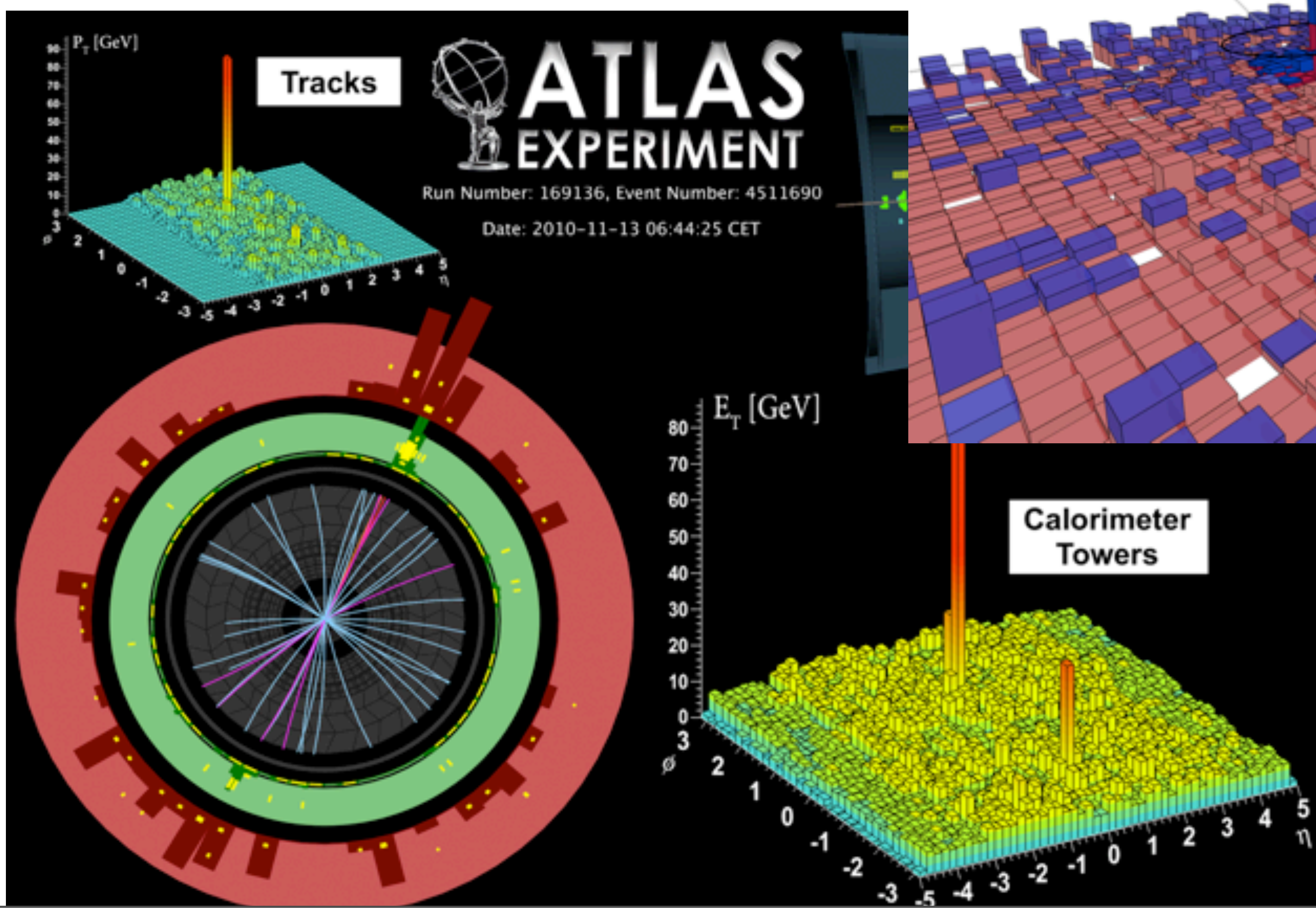




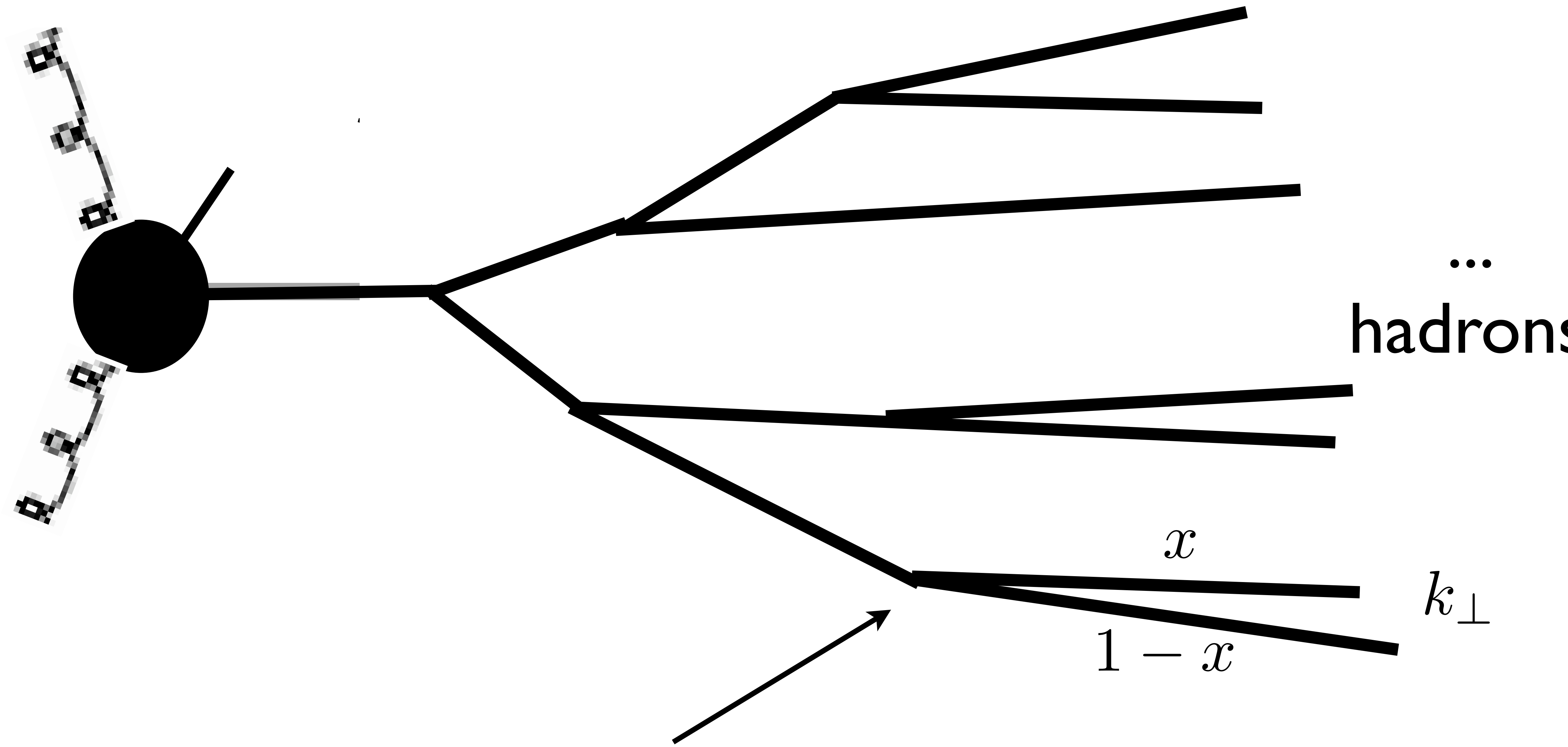
[p_T^{trig}>4GeV, p_T^{assoc}>2GeV]

Jet quenching, II





Jet quenching: theory cartoon



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

DGLAP vertex

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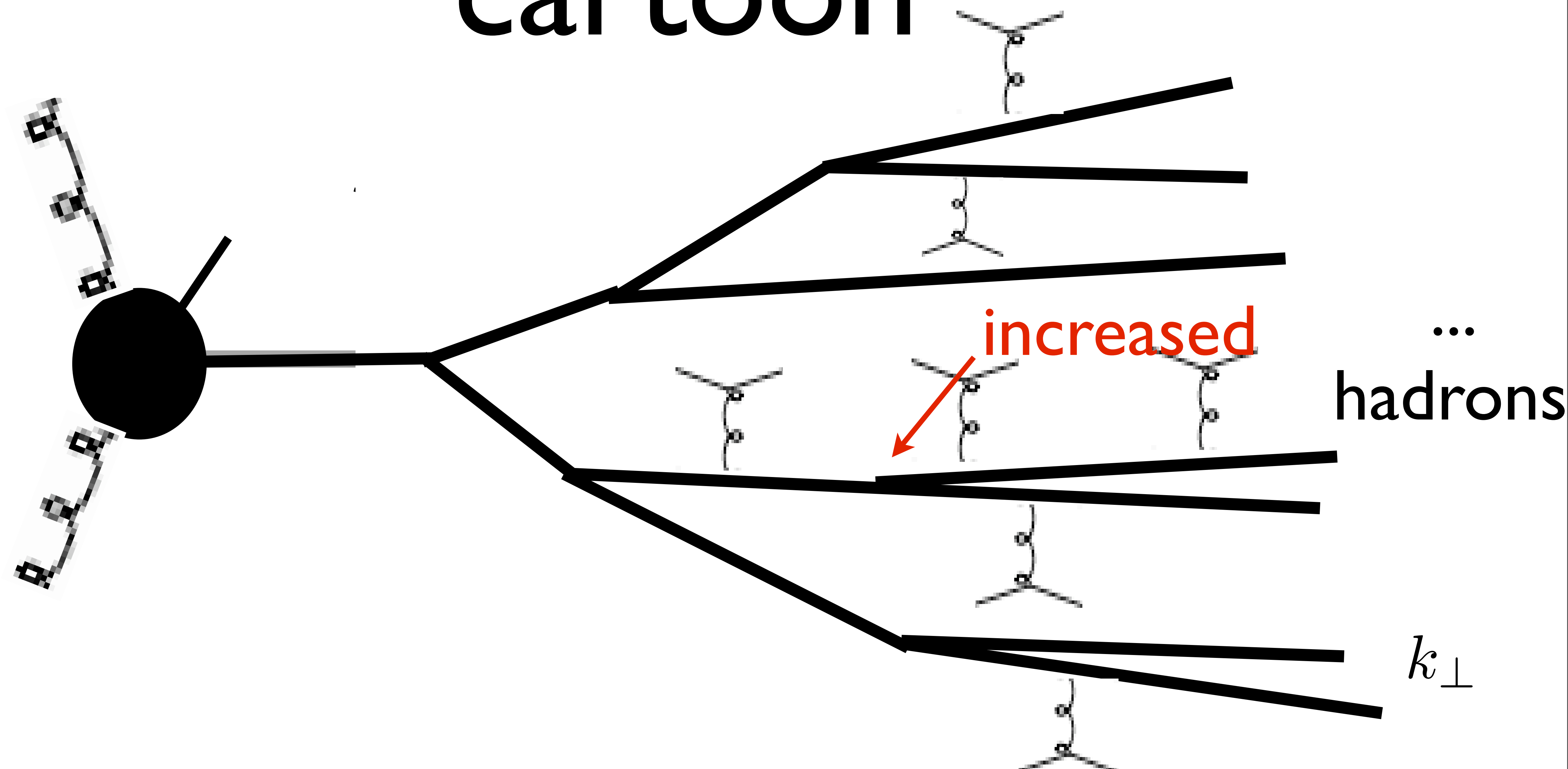
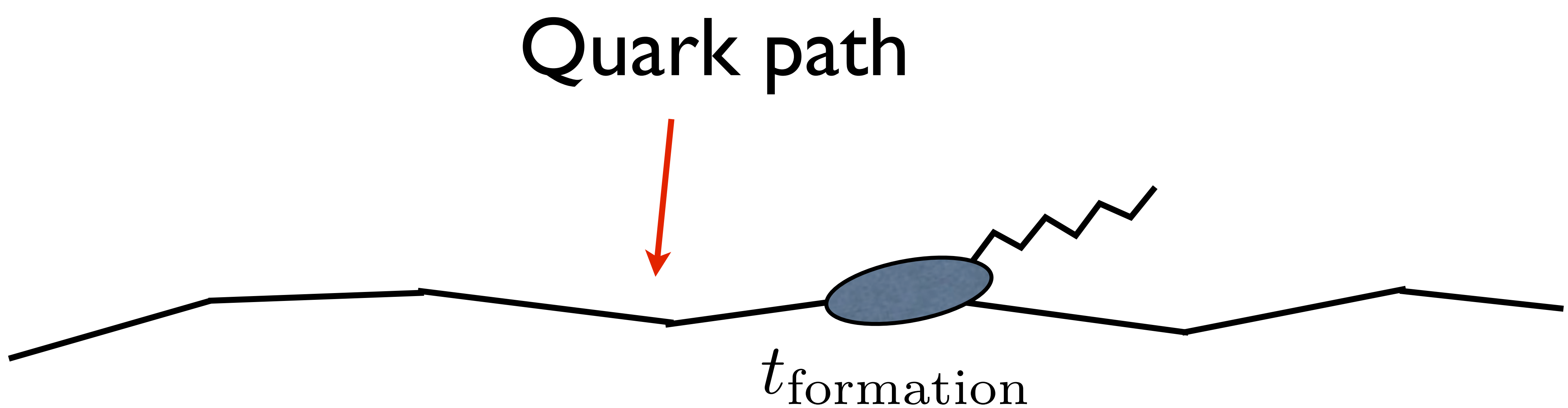


In a medium, extra 'kicks' induce further bremsstrahlung

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

Landau-Migdal-Pomeranchuk (LPM) effect



- Radiation is not instantaneous $t_{\text{formation}} \sim \frac{k_\perp^2}{2\omega}$

  [typically ~1÷3fm]

- When $t_{\text{formation}} \gtrsim t_{\text{collision}}$, gluon source gets blurred
- Less radiation per kick than for separated kicks (*destructive interference*, easily a factor 2-3 suppression)

Jet quenching

- For a while it was thought this was thought to be the whole story
- (for a pQCD jet propagating through a weak *or* strong QGP)
- Further leading-order effects were uncovered recently (destruction of color coherence)

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

- Phenomenology mostly characterized by a few microscopic parameters:
  - $\hat{q} = \int d^2 q_\perp \frac{d\Gamma_{\rm el}}{d^2 q_\perp} q_\perp^2 = \text{“}\langle q_\perp^2 \rangle\text{”}$

    momentum broadening coefficient
  - $[\eta_L] = \text{rate of elastic energy loss}$

- For heavy quarks, one can further *define*

$$\kappa = \int d^3 q \frac{d\Gamma_{\rm el}}{d^3 q} q^2 = \text{“}\langle q^2 \rangle\text{”}$$

HQ momentum diffusion coeff.

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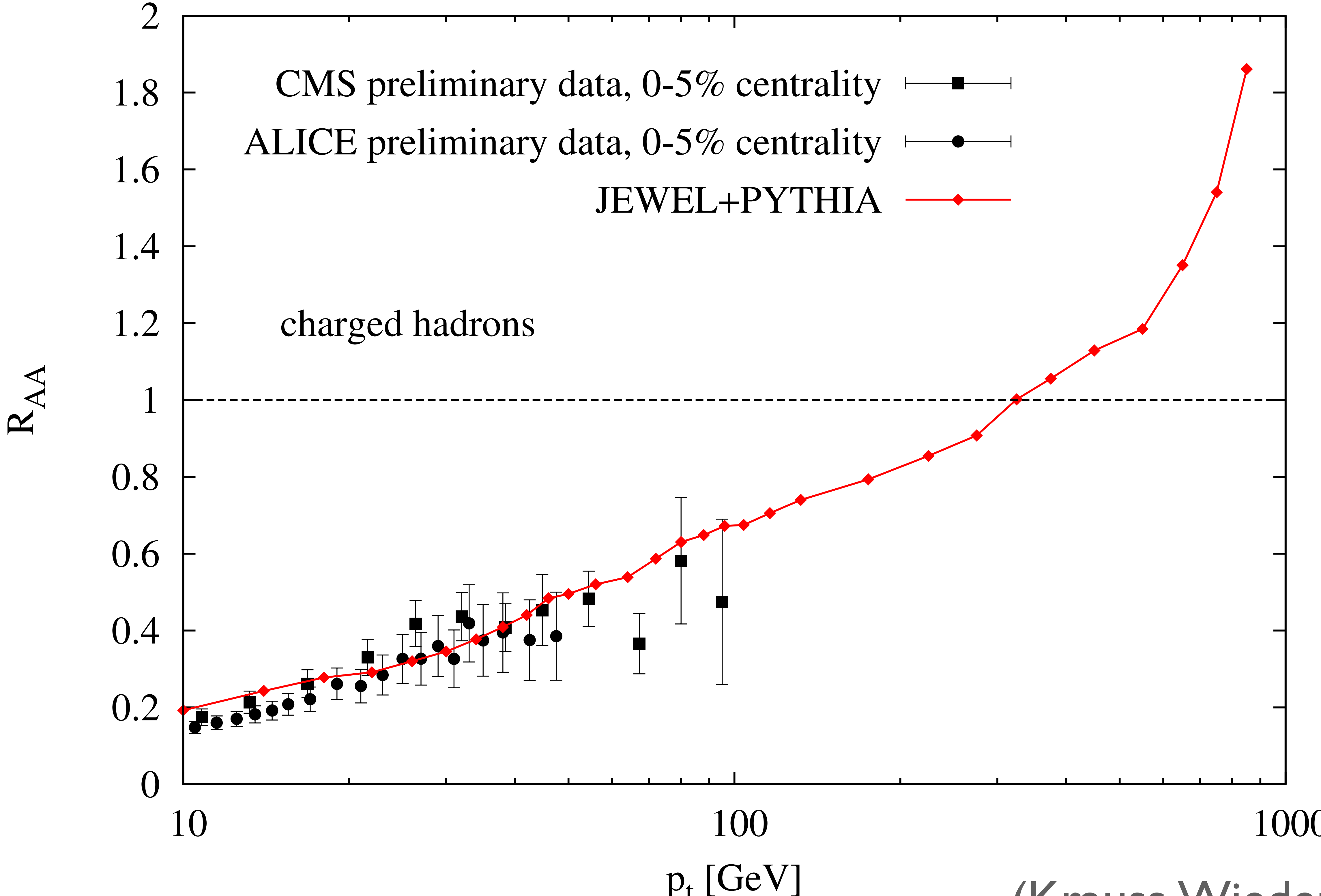
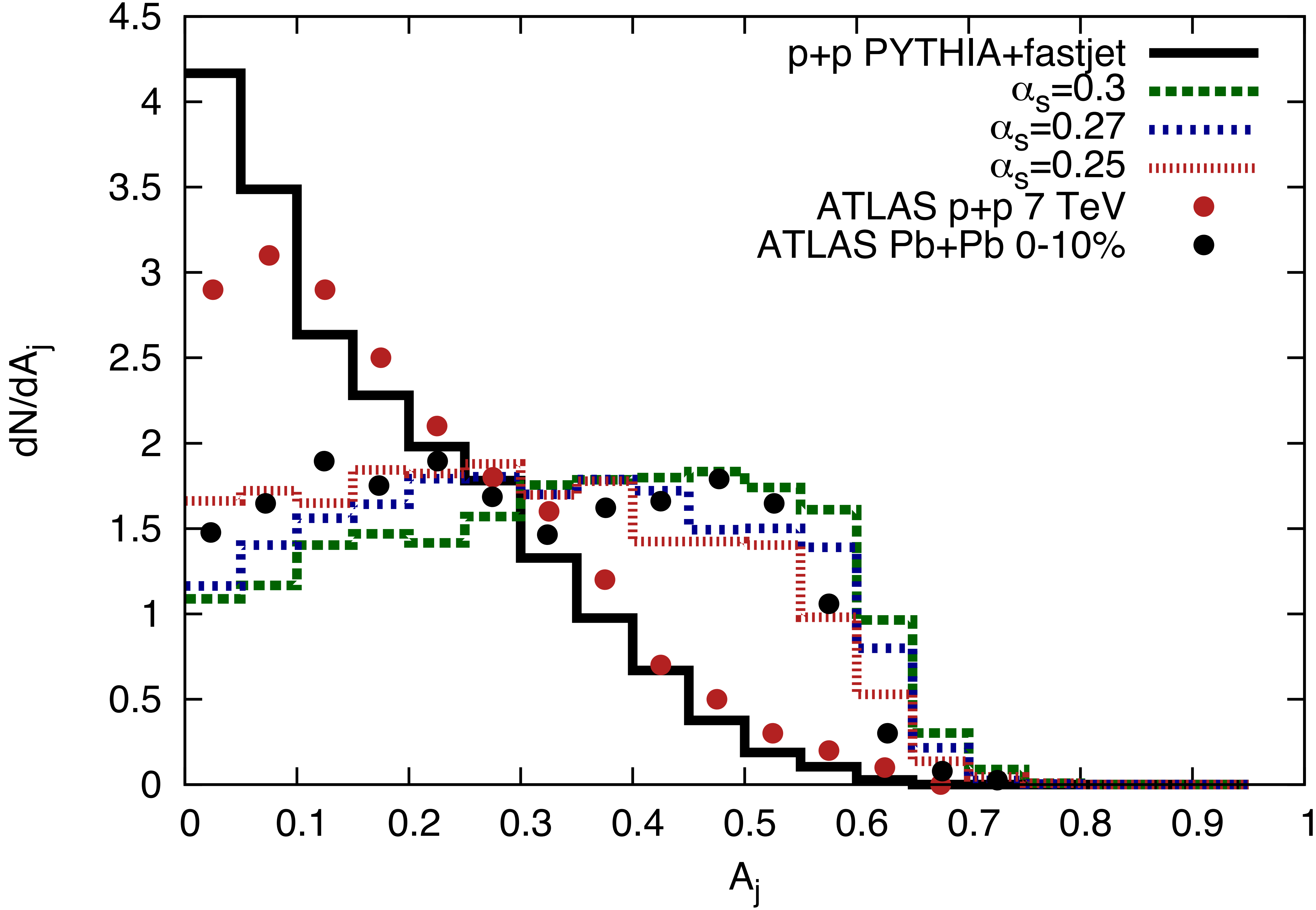
Nuclear modification factor $R_{AA} = \frac{\text{yield PbPb}}{\text{yield scaled pp}}$



(Krauss, Wiedemann & Zapp 1111.6838)

Dijet asymetry

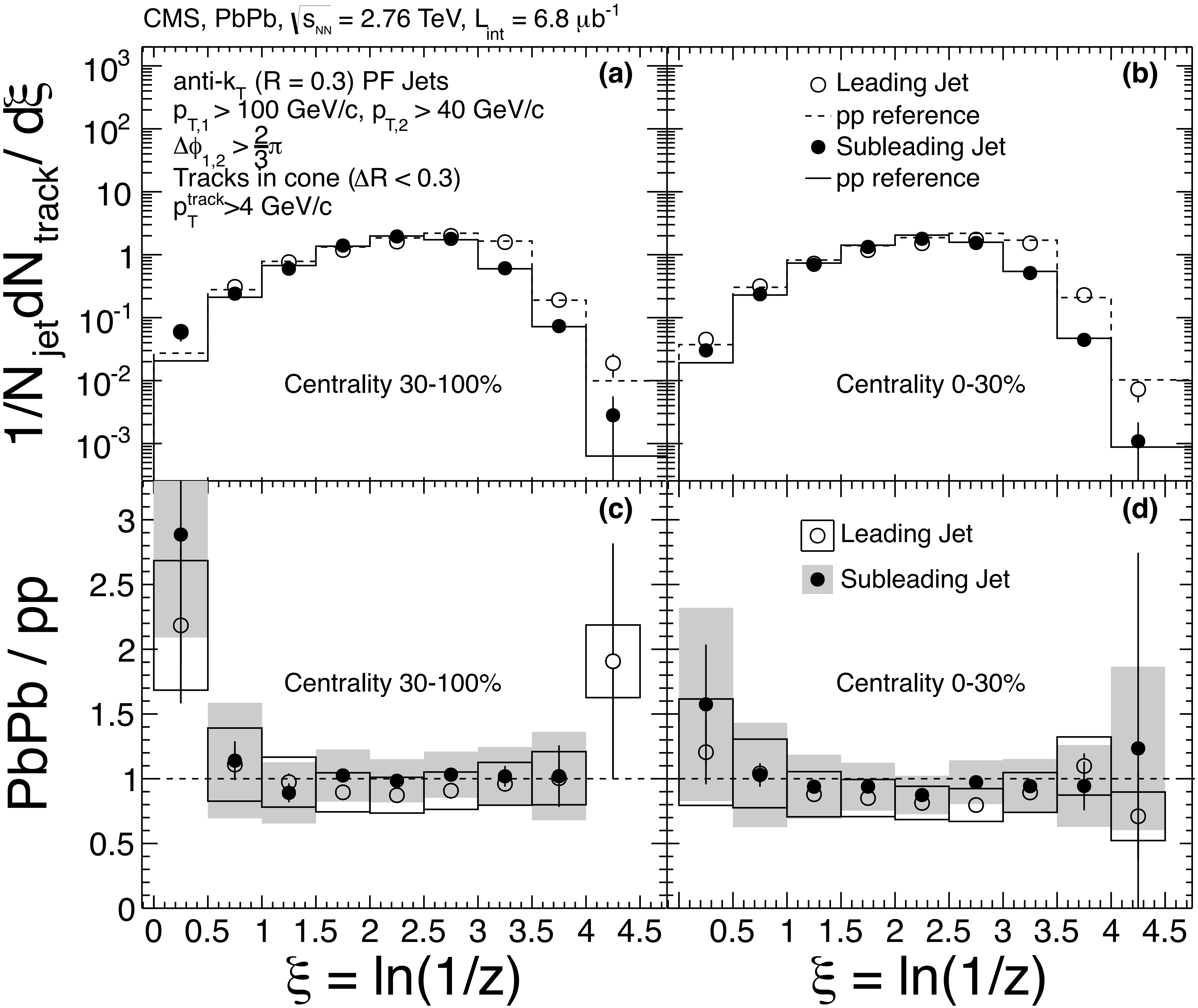


$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

(Young, Schenke, Jeon &Gale 1103.5769)

- General message from these [still preliminary studies] is that pQCD-strength cross-sections *are enough* to describe the quenching ($\alpha_s \sim 0.3$)

Fragmentation functions



Conclusions

- Heavy ions have been running for a long time, yet at the same time many new recent ideas
- Many remarkable experimental discoveries: fast apparent thermalization, low apparent viscosity,... Deep puzzles for theory!
- Hopefully, hard probes will help shed light, and a consistent picture will emerge!