Odd features of heavy flavored jets

Boris Kopeliovich

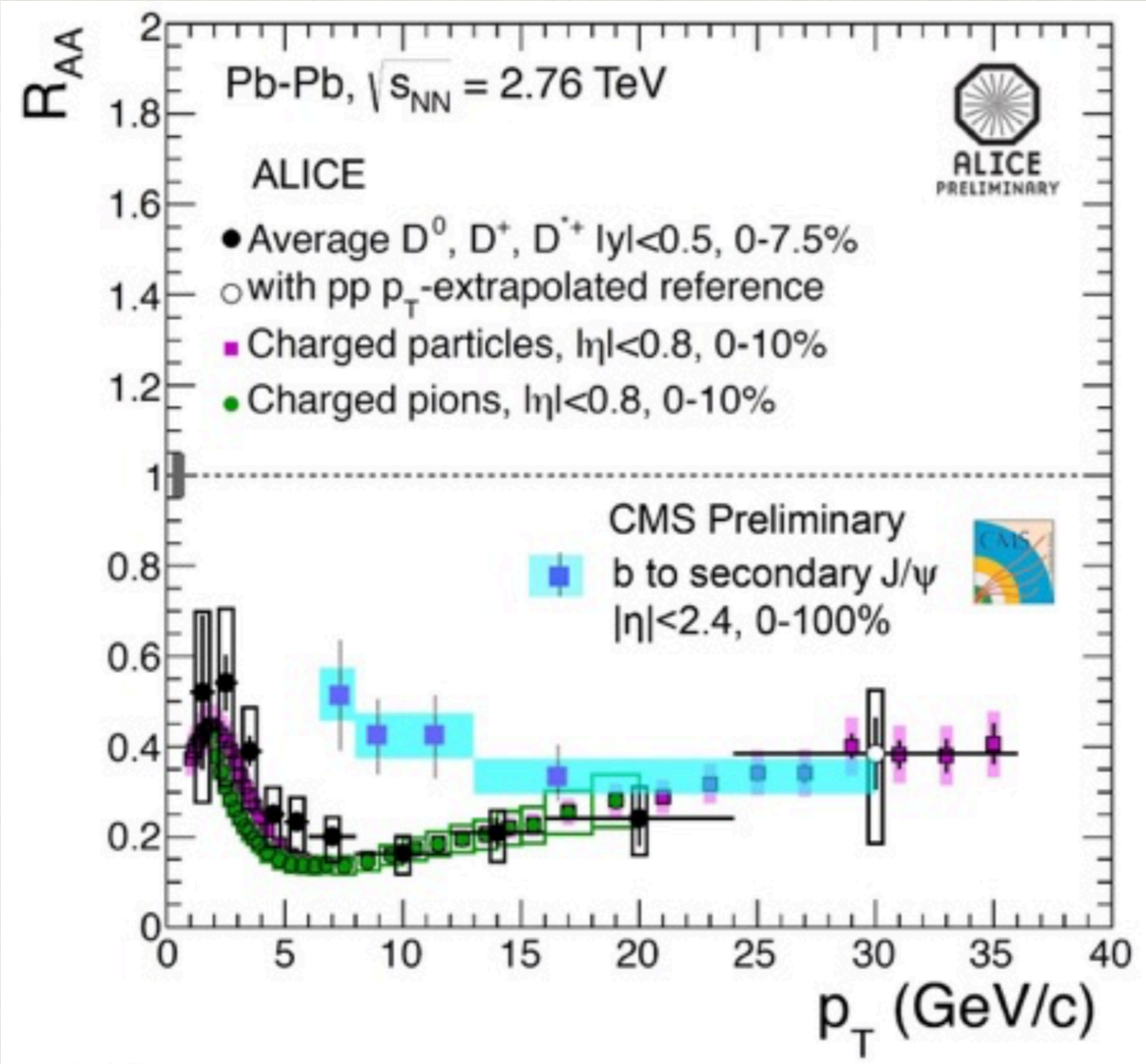
Valparaiso

In collaboration with
Jan Nemchik, Irina Potashnikova
and Ivan Schmidt

Quenching of heavy flavors at high pT

In the popular scenario, explaining jet quenching, observed in heavy ion collisions, by induced energy loss in the created hot medium, a much weaker suppression was anticipated for heavy flavored mesons, caused by the dead-cone effect.

Yu.Dokshitzer, D.Kharzeev, PLB 519(2001)199



Later, however, measurements revealed similar magnitudes of suppression for heavy and light hadrons.

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

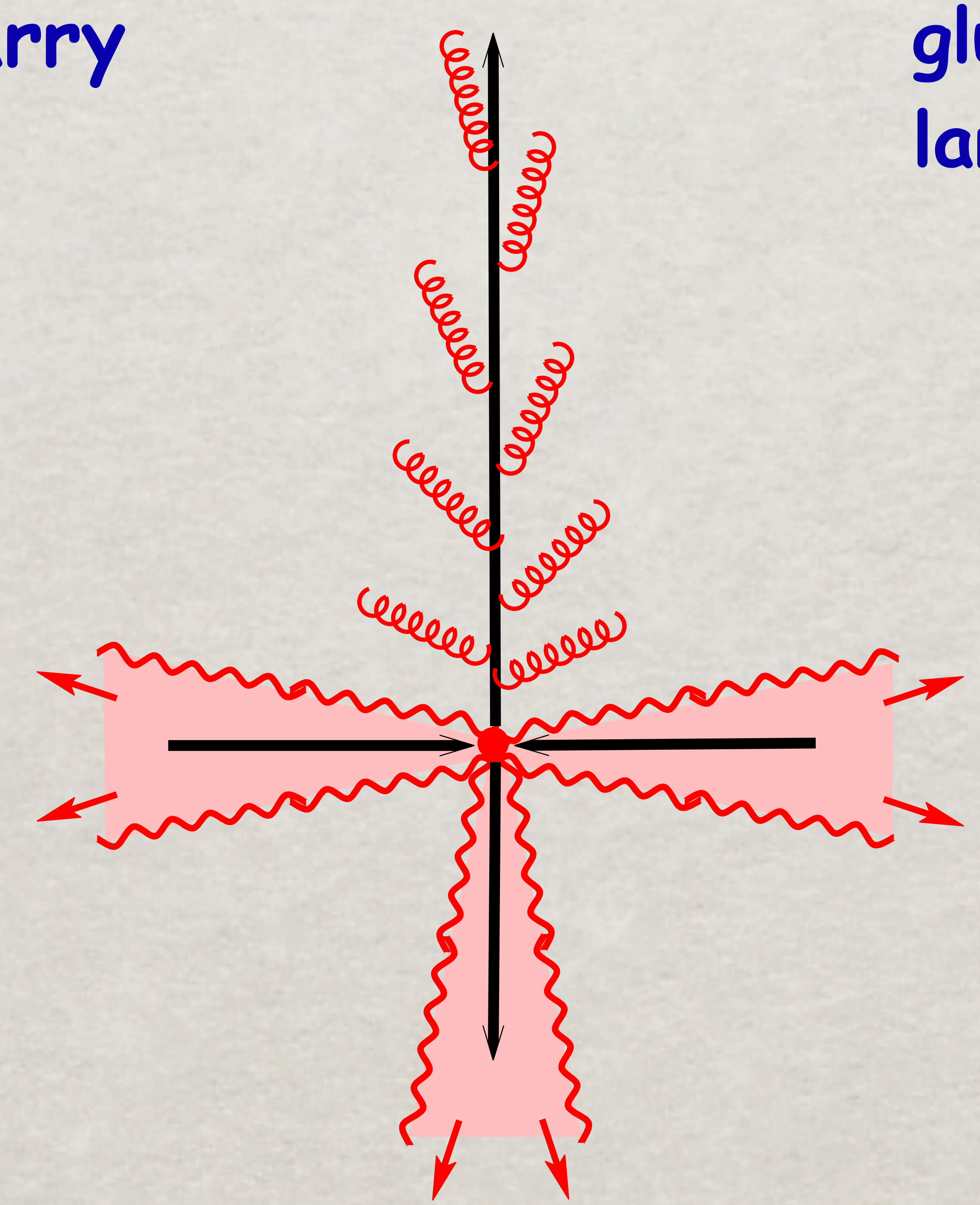
Hard parton collision

High-pt parton scattering leads to formation of 4 cones of gluon radiation:

(i) the color field of the colliding partons is shaken off in forward-backward directions.

(ii) the scattered partons carry no field up to transverse frequences k<pT.

The final state high-pT partons regenerate the lost color field by radiating gluons and forming the up-down jets.



The coherence length/time of gluon radiation

$$l_c = \frac{2E_q\, x(1-x)}{k_T^2 + x^2 m_q^2}$$

First are radiated, i.e. regenerated, gluons with small longitudinal and large transverse momenta.

In heavy ion collisions the regeneration process proceeds within a hot environment (QGP), and additional radiation (much weaker than vacuum) is induced by multiple interactions.

Heavy flavored jets

How much energy is radiated over path length L?

$$\Delta E(L) = E \int_{\Lambda^2}^{p_T^2} dk^2 \int_0^1 dx\, x \frac{dn_g}{dx\, dk^2}\, \Theta(L - l_c)$$

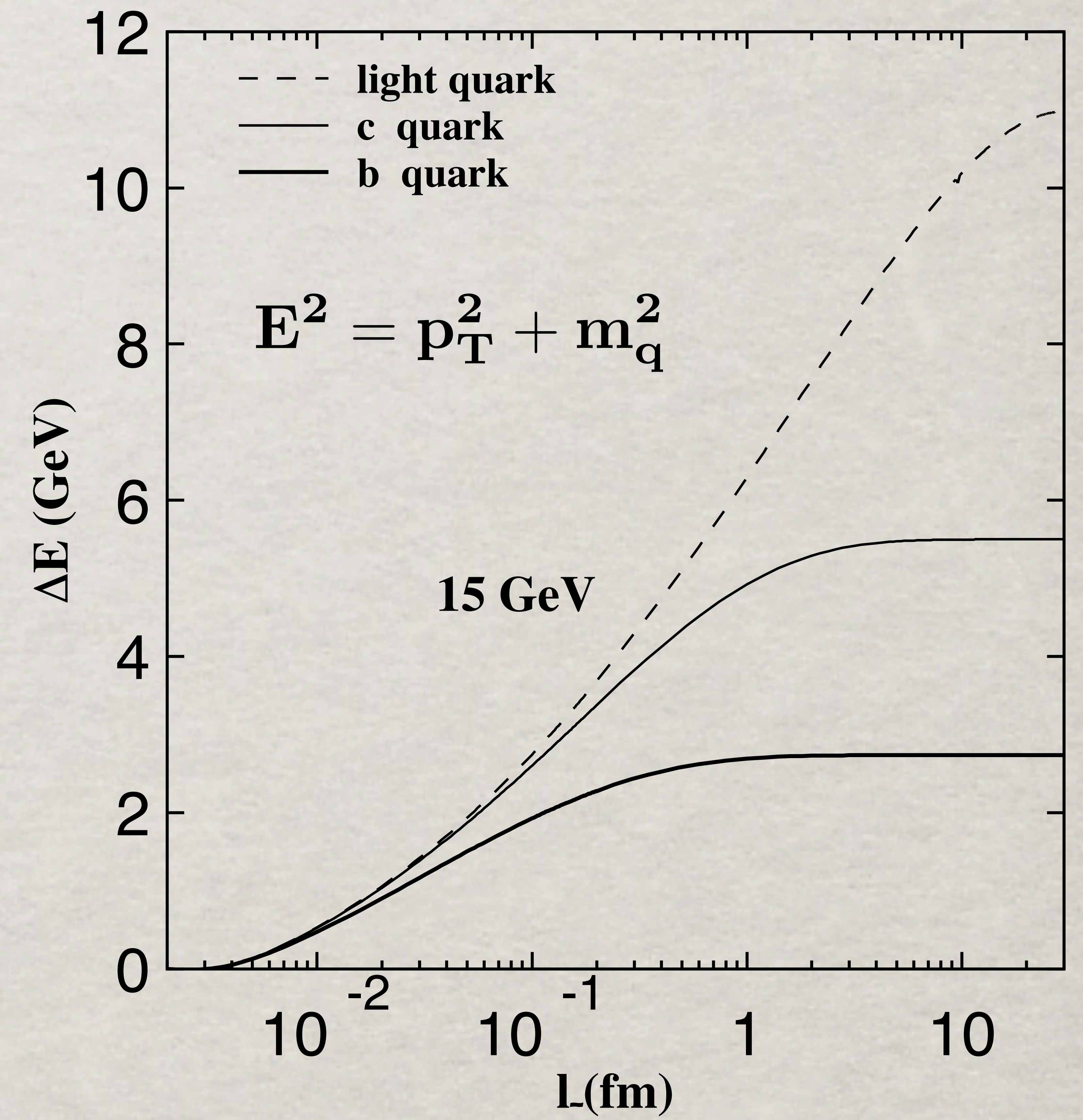
$$\frac{dn_g}{dx\, dk^2} = \frac{2\alpha_s(k^2)}{3\pi x} \frac{k^2[1+(1-x)^2]}{[k^2 + x^2 m_q^2]^2}$$

Dead-cone effect:
gluons with $k^2 < x^2 m_q^2$ are suppressed.
Correspondingly, the radiation length is short

$$l_c = \frac{2E_q\, x(1-x)}{k_T^2 + x^2 m_q^2}$$

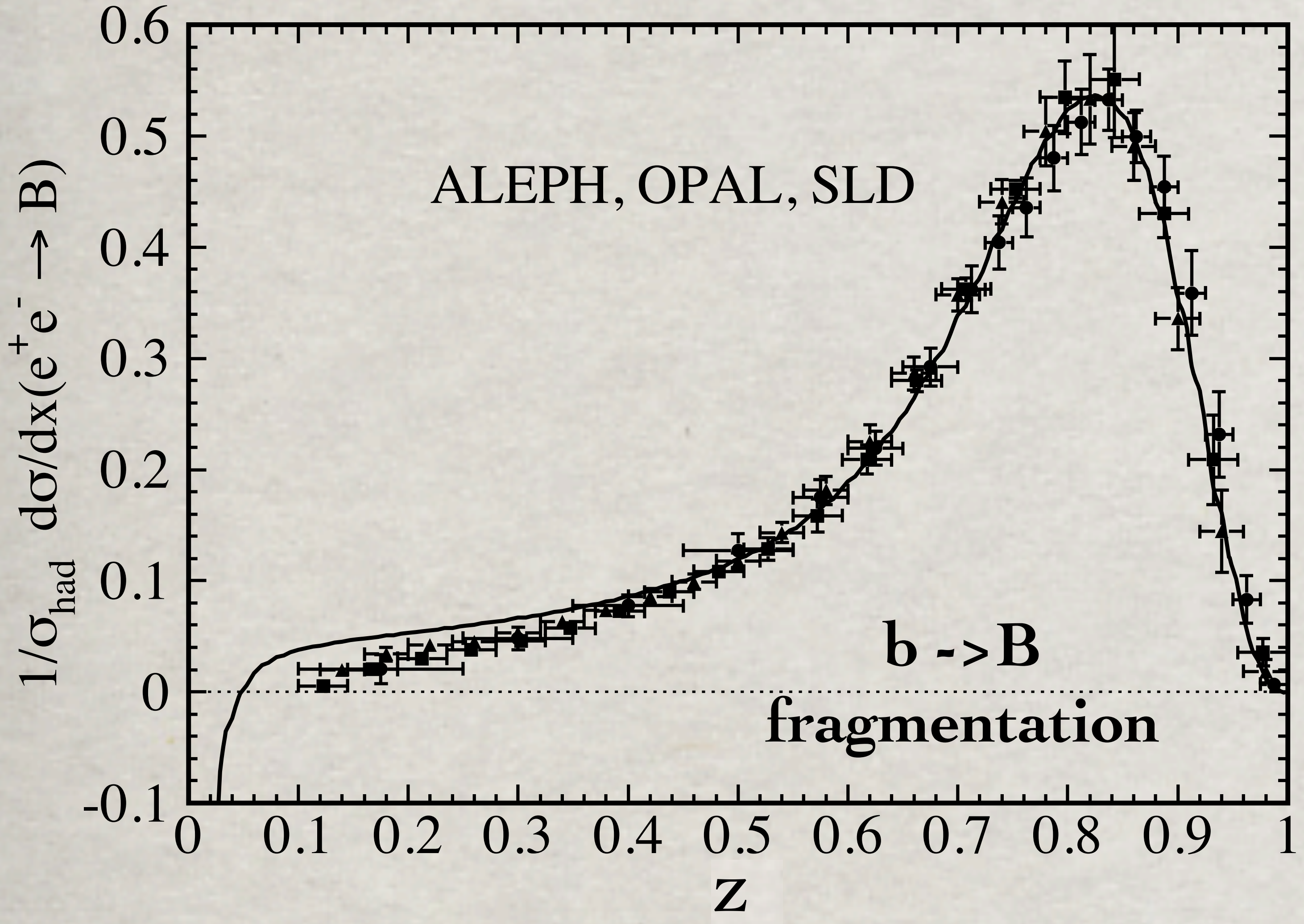
Radiation of heavy quarks ceases shortly. Only a small fraction of the quark energy, Δz~ΔE/E, is radiated (differently from light quarks). Therefore, the final B-meson carries almost the whole momentum of the b-jet.

p_T of the jet plays roles of the jet momentum and scale sumultaneously.

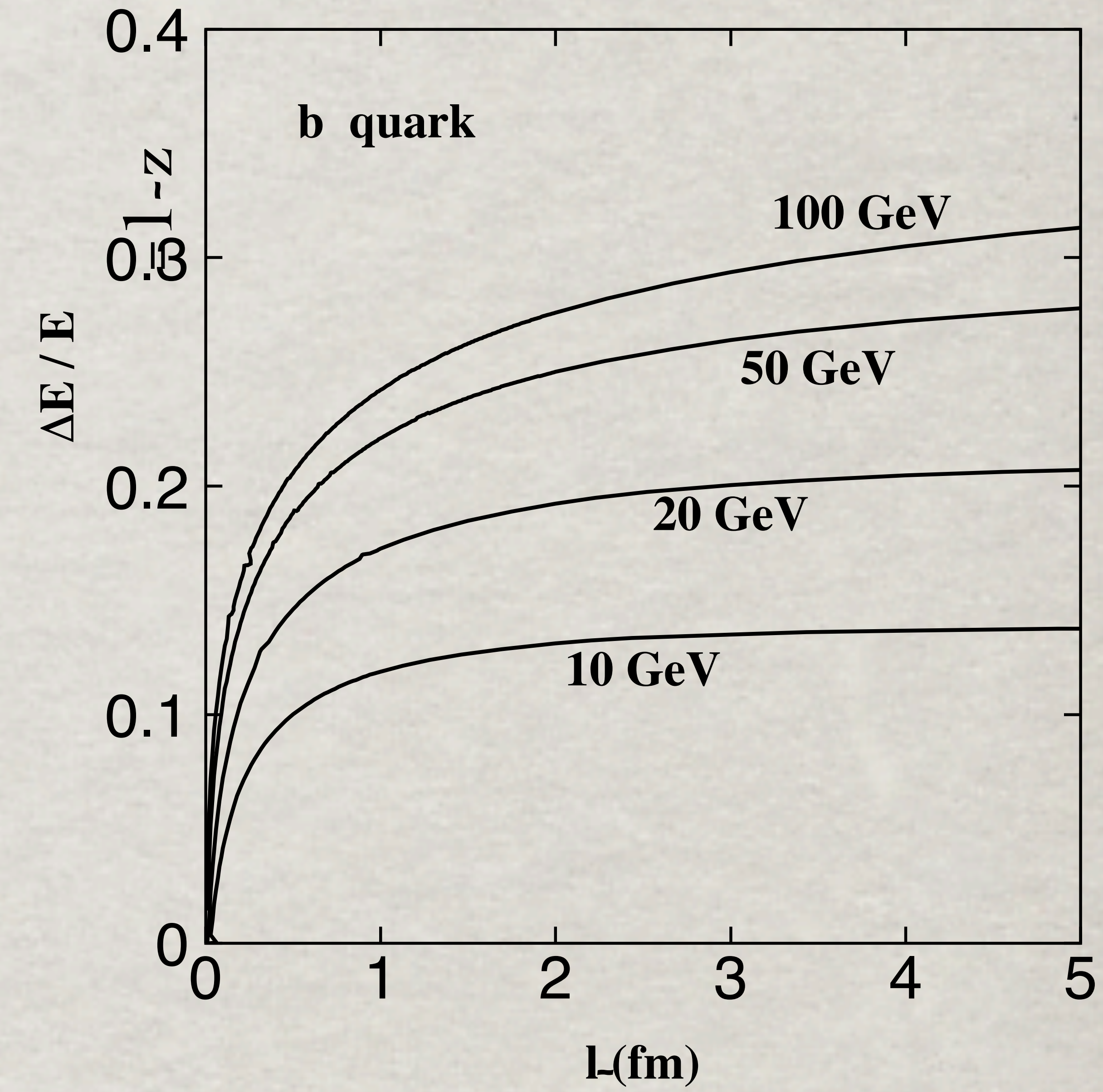


I.Potashnikova,I.Schmidt & B.K.
PRC 82(2010)037901

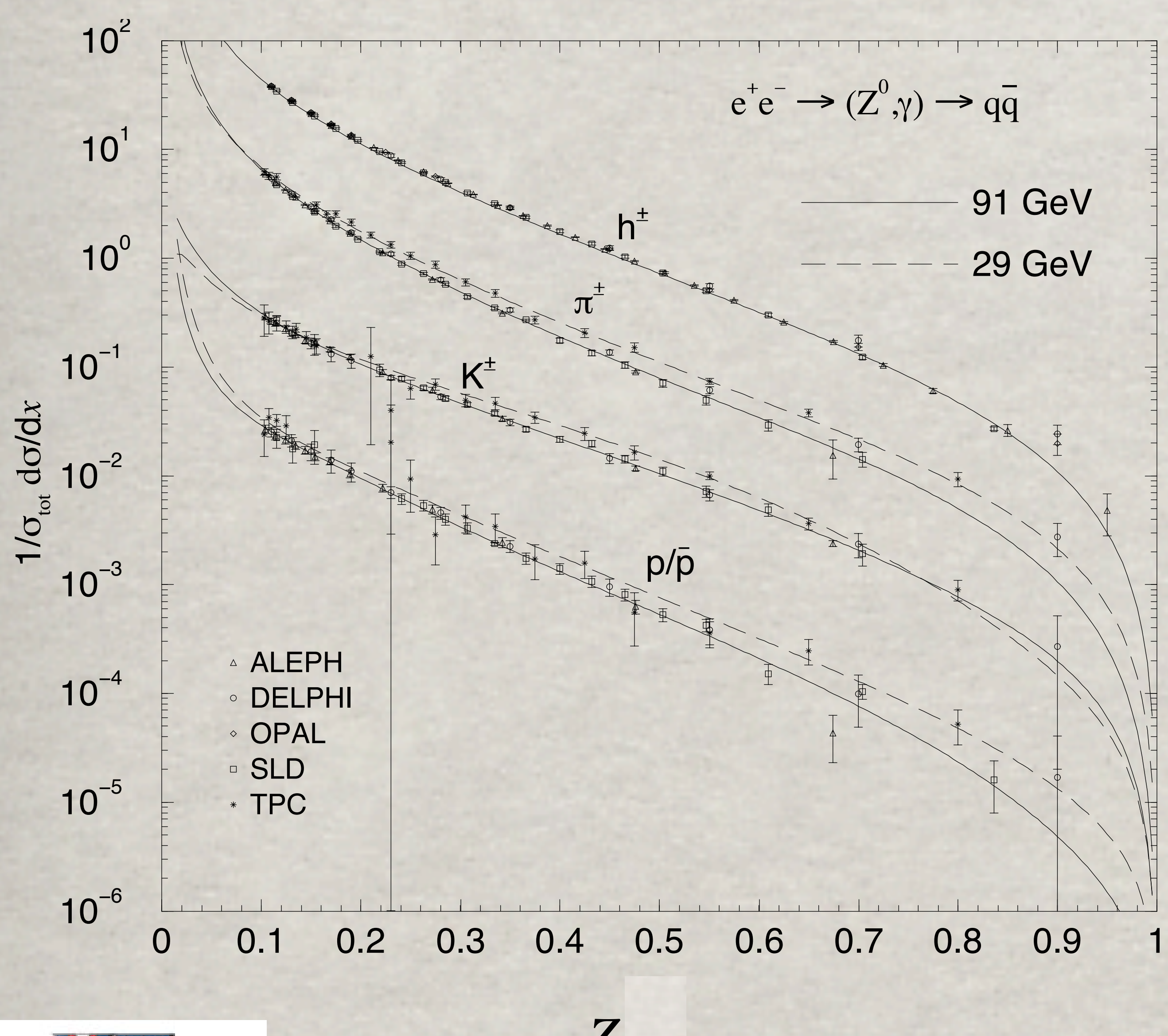
Fragmentation function of heavy quarks



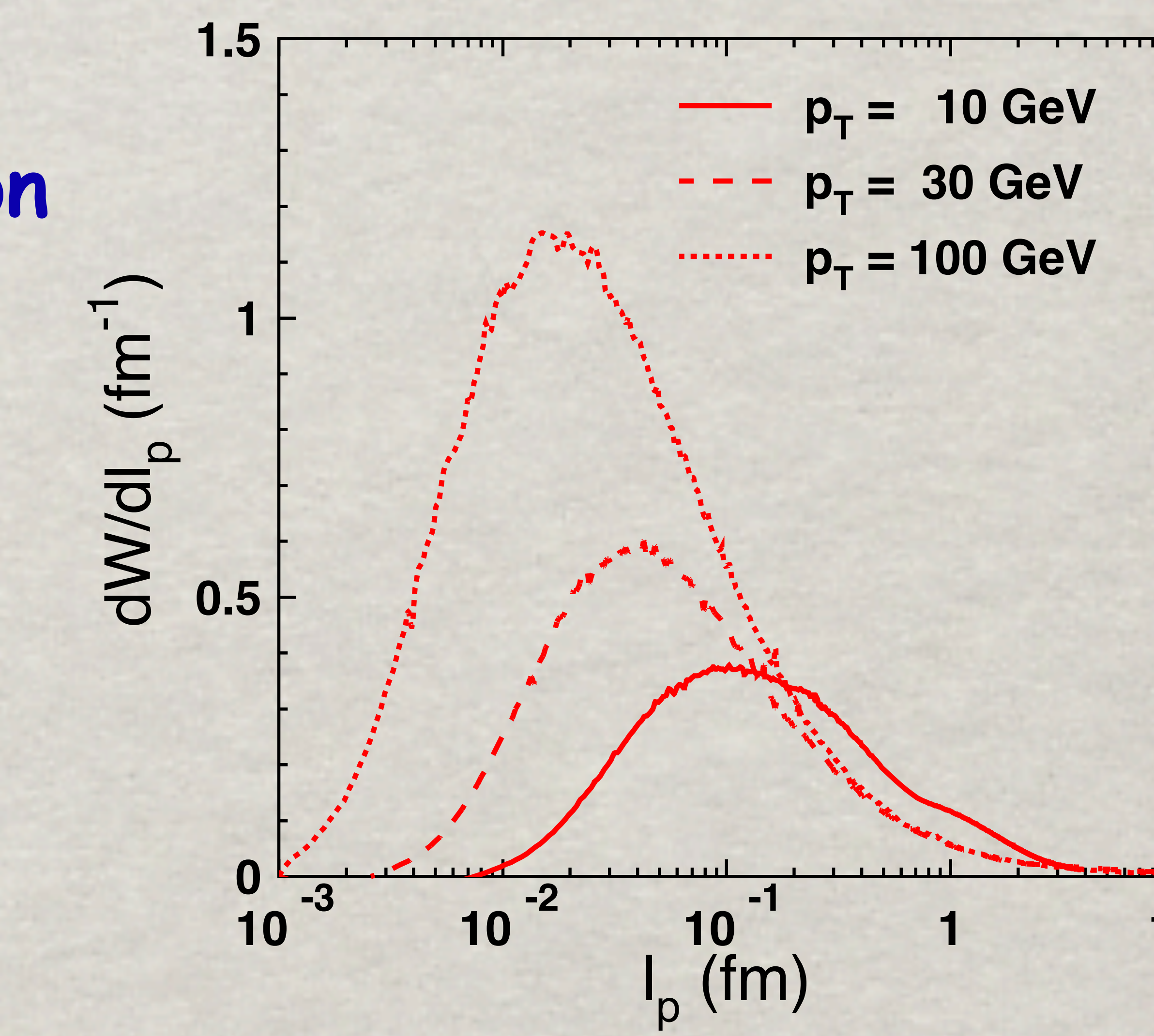
This is why large z are enhanced in the fragmentation function of heavy flavors, b->B, c->D.



On the contrary, large z fragmentation of light quarks is strongly suppressed.



As far as we are able to calculate **Δz(L)**, we can extract the production length l_p of B-mesons directly from data for $D_{b/B}(z)$



Remarkably, the mean value of l_p shrinks with rising p_T

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Attenuation in a hot medium

The light quarks in the B-meson carries a tiny fraction of the momentum,
$\mathbf{x \sim m_q/m_b \approx 5\%}$

Therefore, even if the produced b-q dipole has a small transverse separation, its size expands with a high speed, enhanced by 1/x. The formation time of the B-meson wave function (in the medium rest frame) is very short,

$$\mathbf{t_f^B = \frac{\sqrt{p_T^2 + m_B^2}}{2 m_B \omega}} \qquad (\omega\text{=300MeV})$$

The mean free path of such a meson in a hot medium is very short

$$\mathbf{\lambda_B \sim \frac{1}{\hat{q}\,\langle r_T^2\rangle}}, \qquad \text{where} \quad \mathbf{\langle r_T^2\rangle = \frac{8}{3}\,\langle r_{ch}^2\rangle}$$

B meson is nearly as big as a pion, $\mathbf{\langle r_{ch}^2\rangle_B = 0.378\,fm^2}$ [Ch.-W. Hwang (2001)]

E.g. at $\mathbf{\hat{q} = 1\,GeV^2/fm}$ $\mathbf{\lambda_B = 0.04\,fm}$, i.e. the b-quark propagates through the hot medium, picking up and losing light quarks. Meanwhile the b-quark keeps losing energy with a rate, enhanced by medium-induced effects. Eventually the detected B-meson is formed and survives in the dilute medium at the surface.

Where the nuclear suppression comes from?

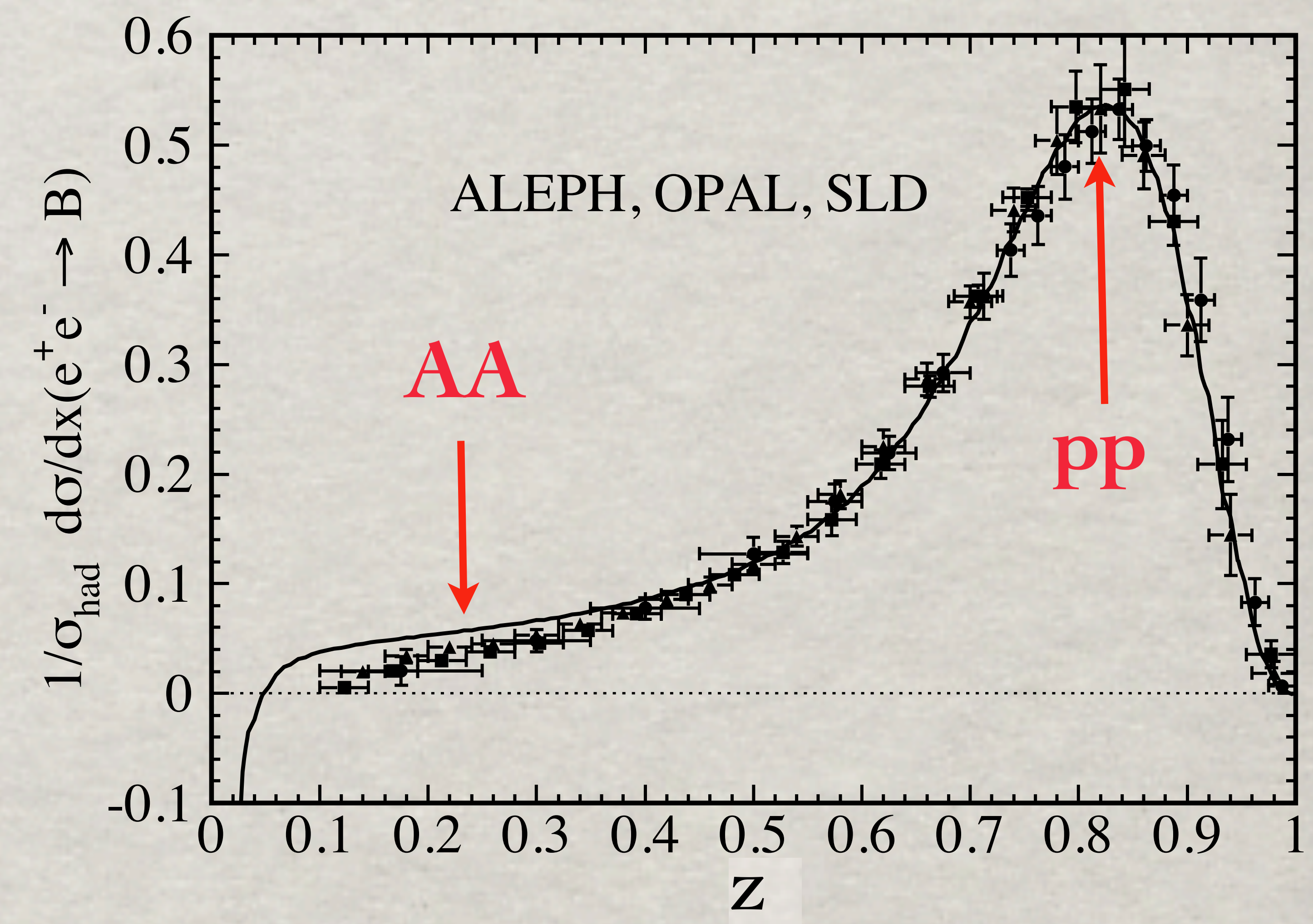
A high-pT b-quark, produced in pp collisions, starts radiating so intensely, that loses 20-30% of its initial energy on a very short distance, then picks-up a light antiquark. The produced colorless B-meson stops radiating and retains its fractional momentum z.

If, however, the b-quark is produced in a dense environment, it has to propagate a long distance up to the medium surface, where the final B-meson can survive.
All this long path the quark keeps losing energy and eventually produces a B-meson with reduced fractional momentum z, which is suppressed by the fragmentation function.

$$\frac{d\sigma(pp \to BX)}{d^2p_T} = \int d^2p_T^b \frac{d\sigma(pp \to bX)}{d^2p_+^b} \frac{1}{z} D_{b/B}(z),$$

$$\frac{d\sigma(AA \to BX)}{d^2p_T} = \int d^2p_T^b \frac{d\sigma(pp \to bX)}{d^2p_T^b} \frac{1}{z_{AA}} D_{b/B}(z_{AA})\, S(l_p^{AA})$$

$$S(l_p^{AA}) = \exp\left[-\int_{l_p^{AA}}^{\infty} \frac{dl}{\lambda_B(l)}\right]$$



Attenuation of a B-meson in a hot medium

Path-integral description

The survival probability of a qQ dipole in a medium

$$\mathbf{S}(\mathbf{l_1},\mathbf{l_2}) \propto \left| \int_0^1 d\alpha \int d^2\mathbf{r_1} d^2\mathbf{r_2}\, \Psi^\dagger_M(\mathbf{r_2},\alpha) G_{Q\bar{q}}(\mathbf{l_1},\mathbf{r_1};\mathbf{l_2},\mathbf{r_2}) \Psi_{in}(\mathbf{r_1},\alpha) \right|^2$$

The Green function describing propagation of the dipole between coordinates $\mathbf{l_1},\mathbf{l_2}$ with initial and final separations $\mathbf{r_1},\mathbf{r_2}$ satisfies the 2-dimensional LC equation

$$i\frac{d}{dl_2} G_{Q\bar{q}}(\mathbf{l_1},\tilde{\mathbf{r}}_1;\mathbf{l_2},\tilde{\mathbf{r}}_2) = \left[-\frac{\Delta_{r_2}}{2\,p_T\,\alpha\,(1-\alpha)} + V_{Q\bar{q}}(\mathbf{l_2},\tilde{\mathbf{r}}_2) \right] G_{Q\bar{q}}(\mathbf{l_1},\tilde{\mathbf{r}}_1;\mathbf{l_2},\tilde{\mathbf{r}}_2)$$

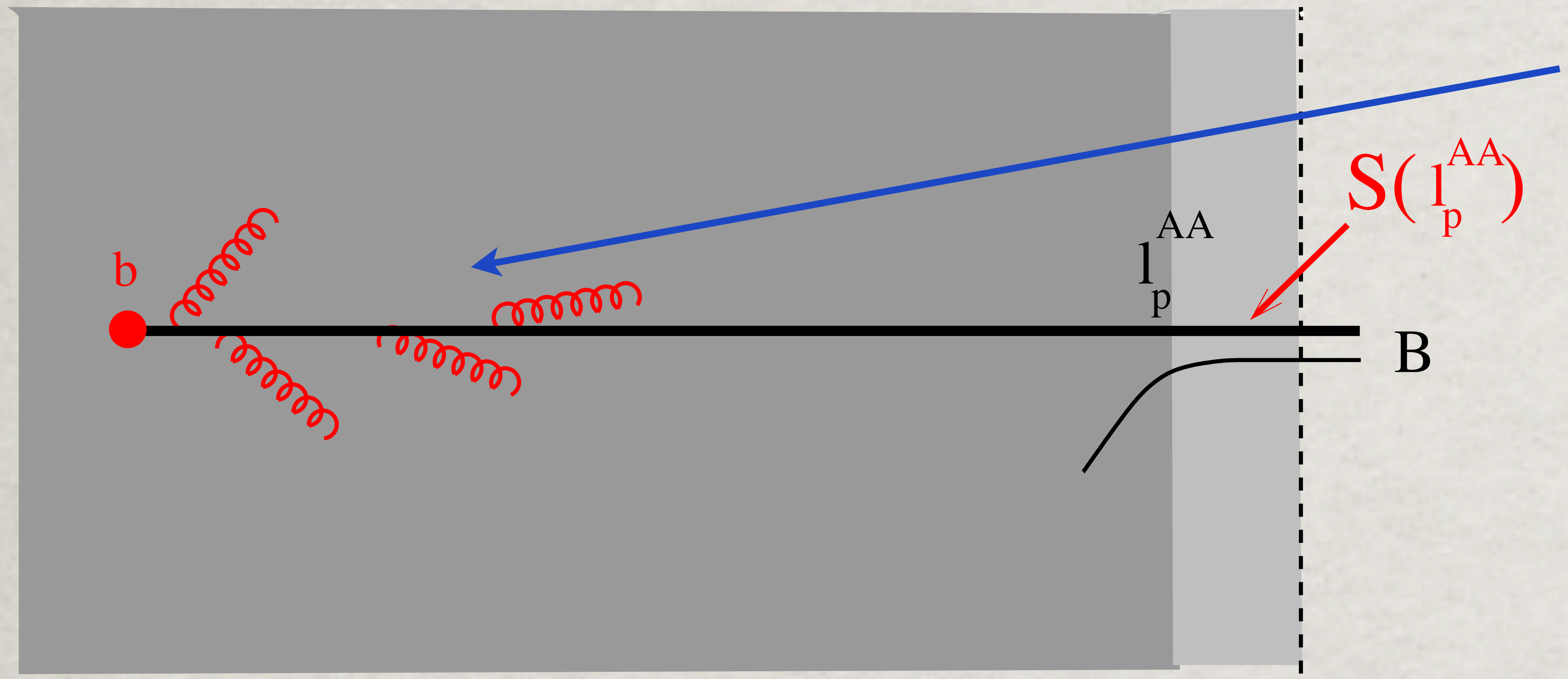
The imaginary part of the LC potential is responsible for absorption,

$$\mathrm{Im}\, V_{Q\bar{q}}(\mathbf{l},\tilde{\mathbf{r}}) = -\frac{1}{4}\,\hat{q}(\mathbf{l})\,\mathbf{r}^2$$

The real part is a phenomenological Cornell-type potential, adjusted to reproduce the masses and decay constants for B and D mesons.

Mao-Zhi Yang (2011); Ch.-W. Hwang (2002)

Interplay between energy loss & absorption



Energy loss in the medium: radiational vacuum and induced, collisional, string.

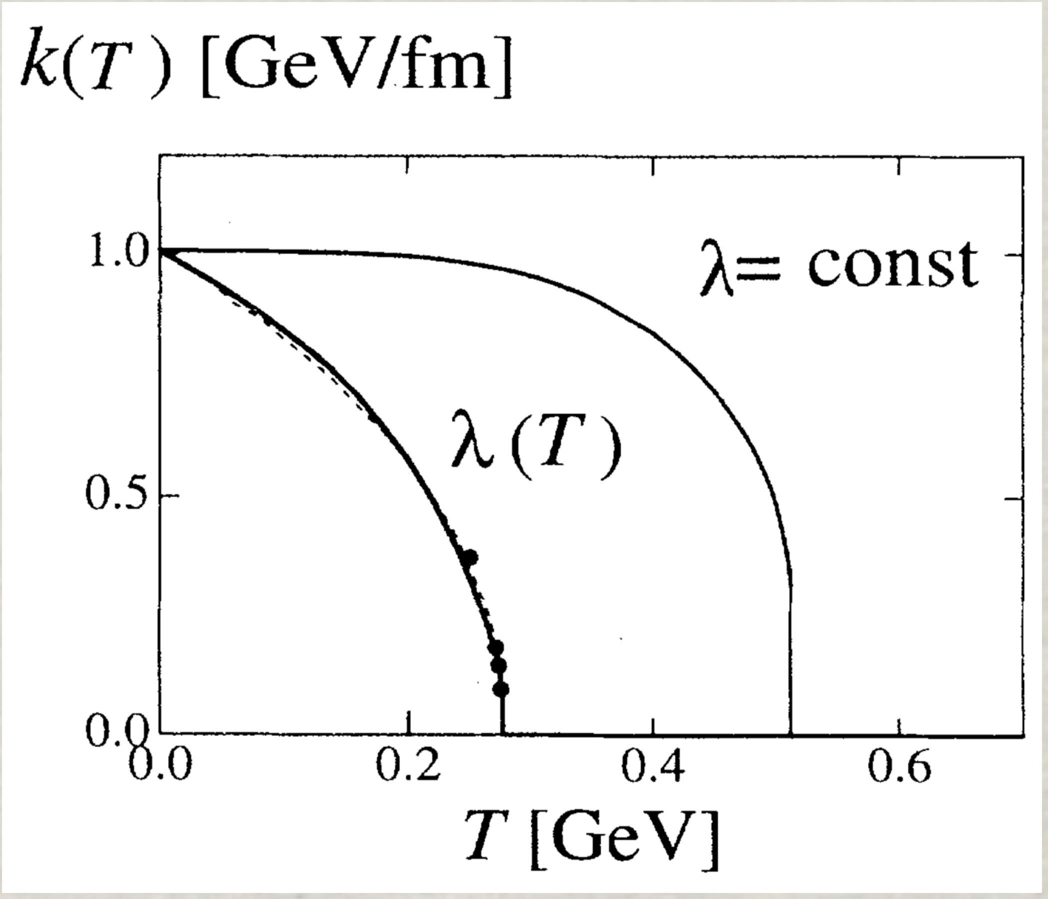
In vacuum: gluon radiation plus string

$$\mathbf{dE_{string}/dl = -\kappa \approx -1\,GeV/fm}$$

String tension is falling with temperature:

$$\kappa(\mathbf{T}) = \kappa\,(\mathbf{1 - T/T_c})^{\mathbf{1/3}}$$

While in vacuum a B-meson is produced on a very short length $l_p \ll 1\,\mathrm{fm}$, in a hot medium strong absorption pushes the production point to the dilute medium surface. However, energy loss on a longer $l_p^{AA} \gg l_p$ causes a large shift down to small z, suppressed by D(z).



H.Ichie, H.Suganuma & H.Toki(1996)

Thus, the two sources of suppression are in conflict, leaving no good solution.

Results

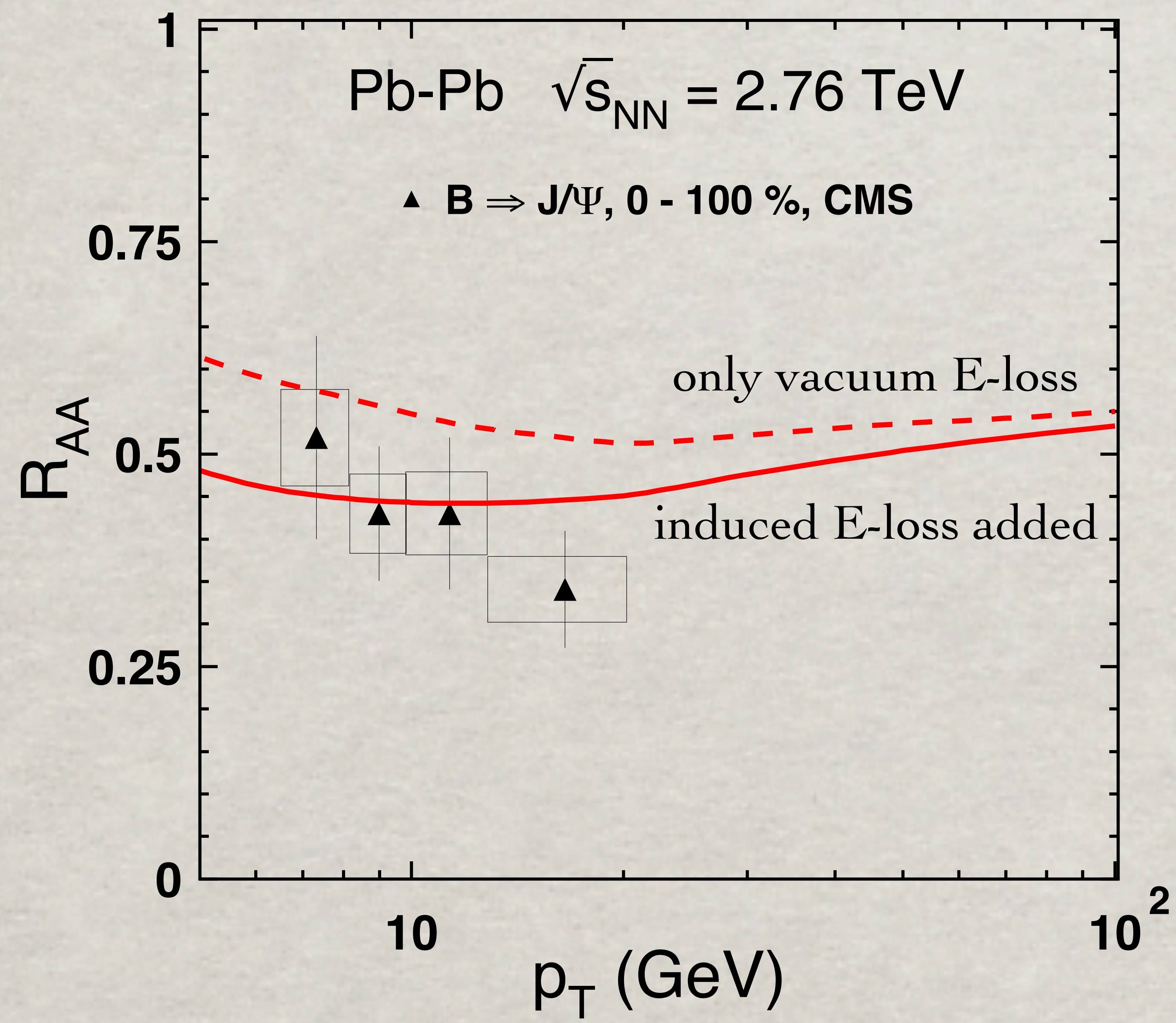
$$\hat{q}(l,\tilde{b},\tilde{\tau}) = \frac{\hat{q}_0\, l_0}{l}\,\frac{n_{part}(\tilde{b},\tilde{\tau})}{n_{part}(0,0)}\,\Theta(l-l_0),$$

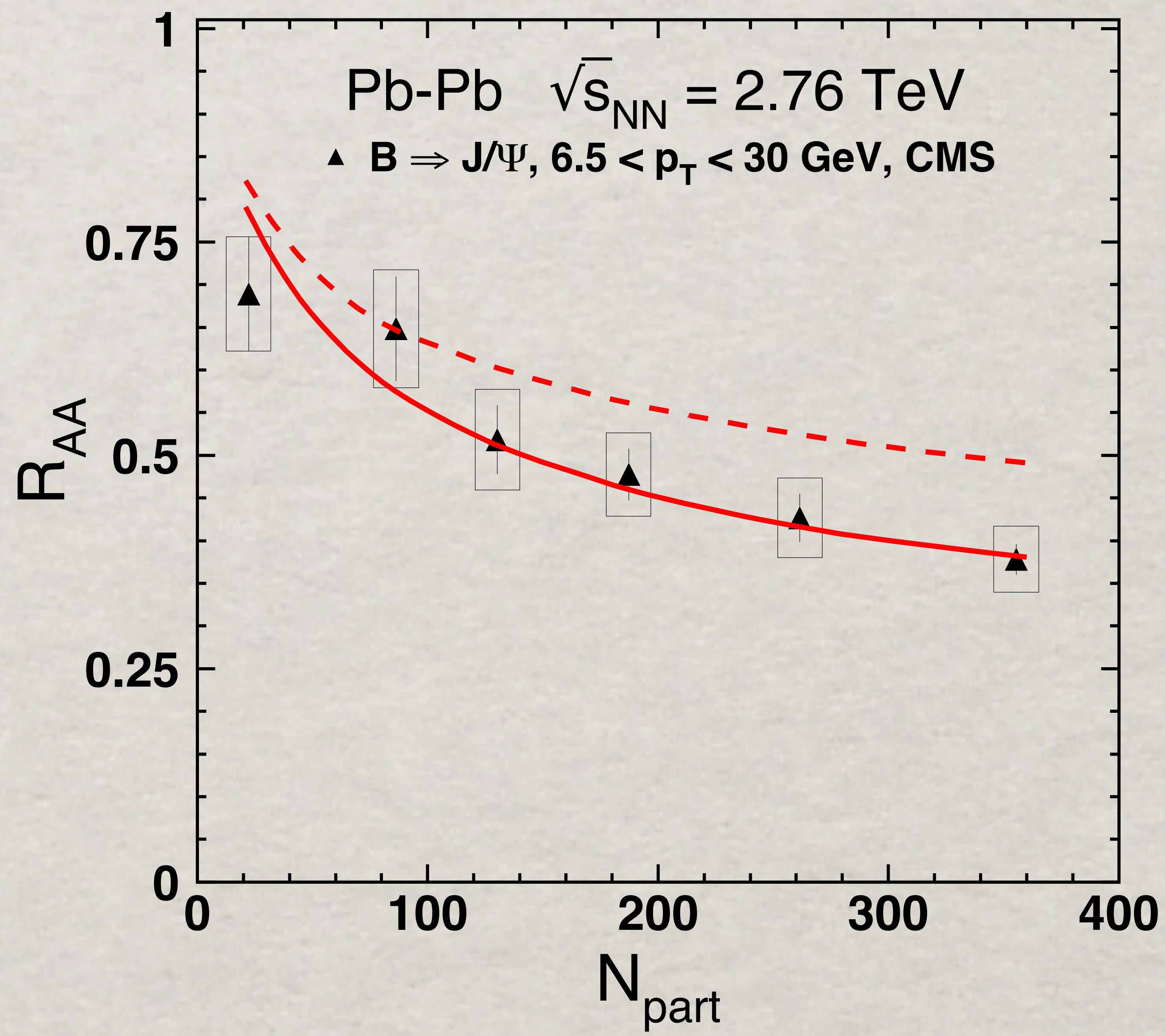
$$q_0 = 2\,\mathrm{GeV}^2/\mathrm{fm}\quad (1.6\,\mathrm{GeV}^2/\mathrm{fm})$$

fixed by quenching of pions at LHC (RHIC)

J.Nemchik,I.Potashnikova,I.Schmidt & B.K. PRC 86(2012)054904

Different sources of time-dependent energy loss should be added up. Medium-induced energy loss is much smaller than the vacuum one, and should not produce a dramatic effect. They are particularly small for heavy flavors (Yu.Dokshitzer & D.Kharzeev (2001)



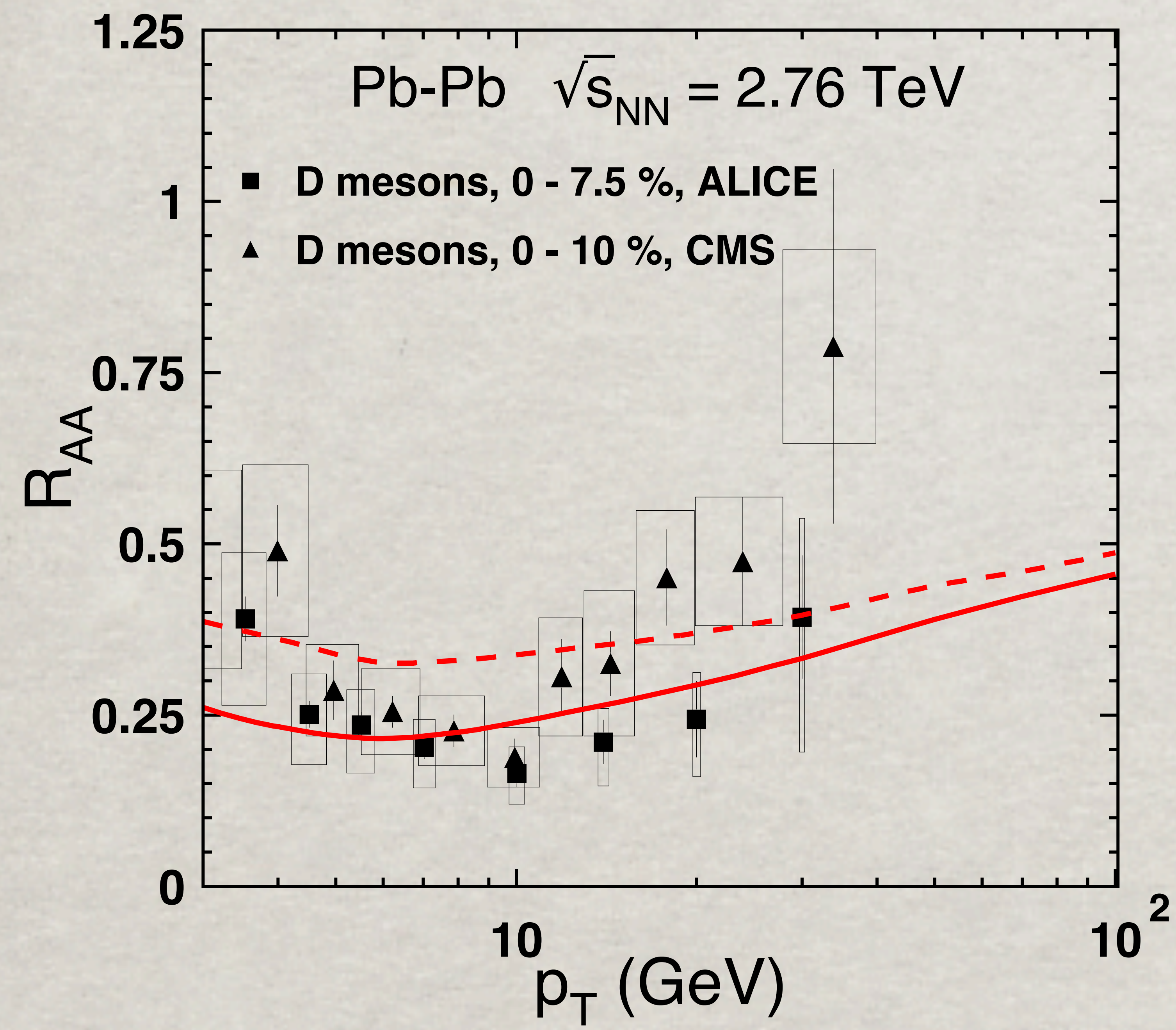


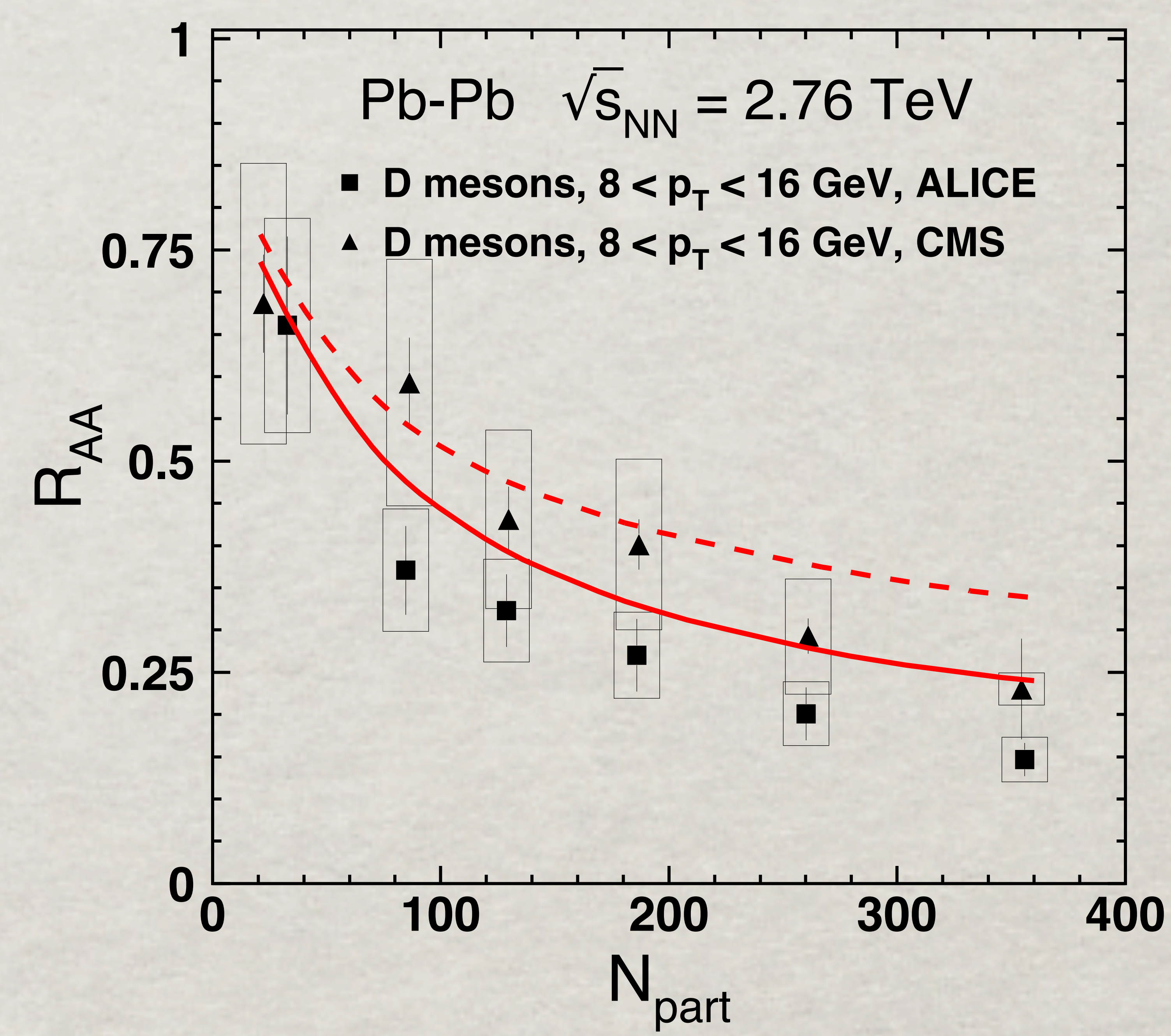
UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

B. Kopeliovich, ICNFP, Kolymbari, July 9, 2016

Results

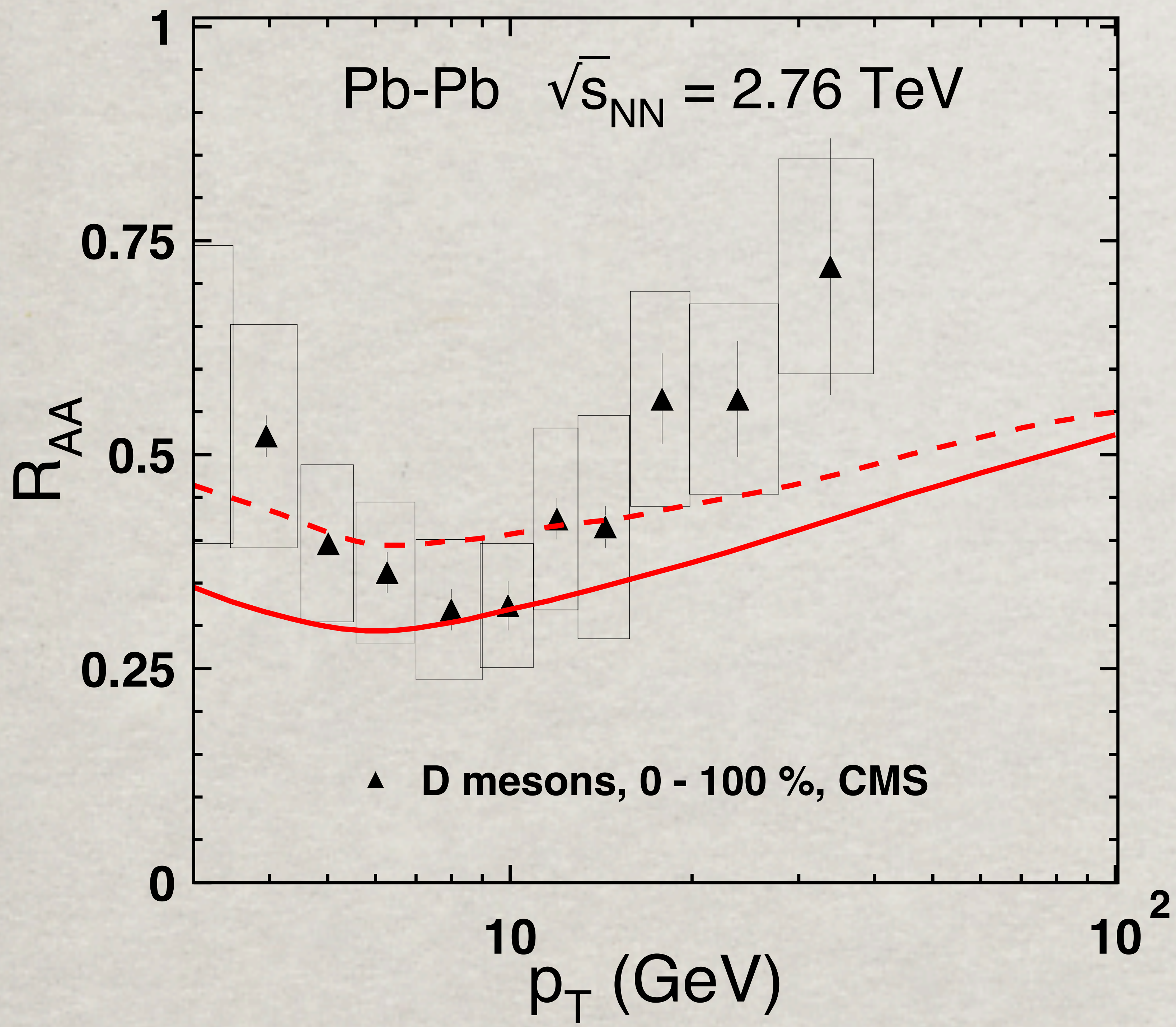
c-quarks radiate in vacuum much more energy than b-quarks, while the effects of absorption of c-q and b-q dipoles in the medium are similar. Therefore D-mesons are suppressed in AA collisions more than B-mesons.

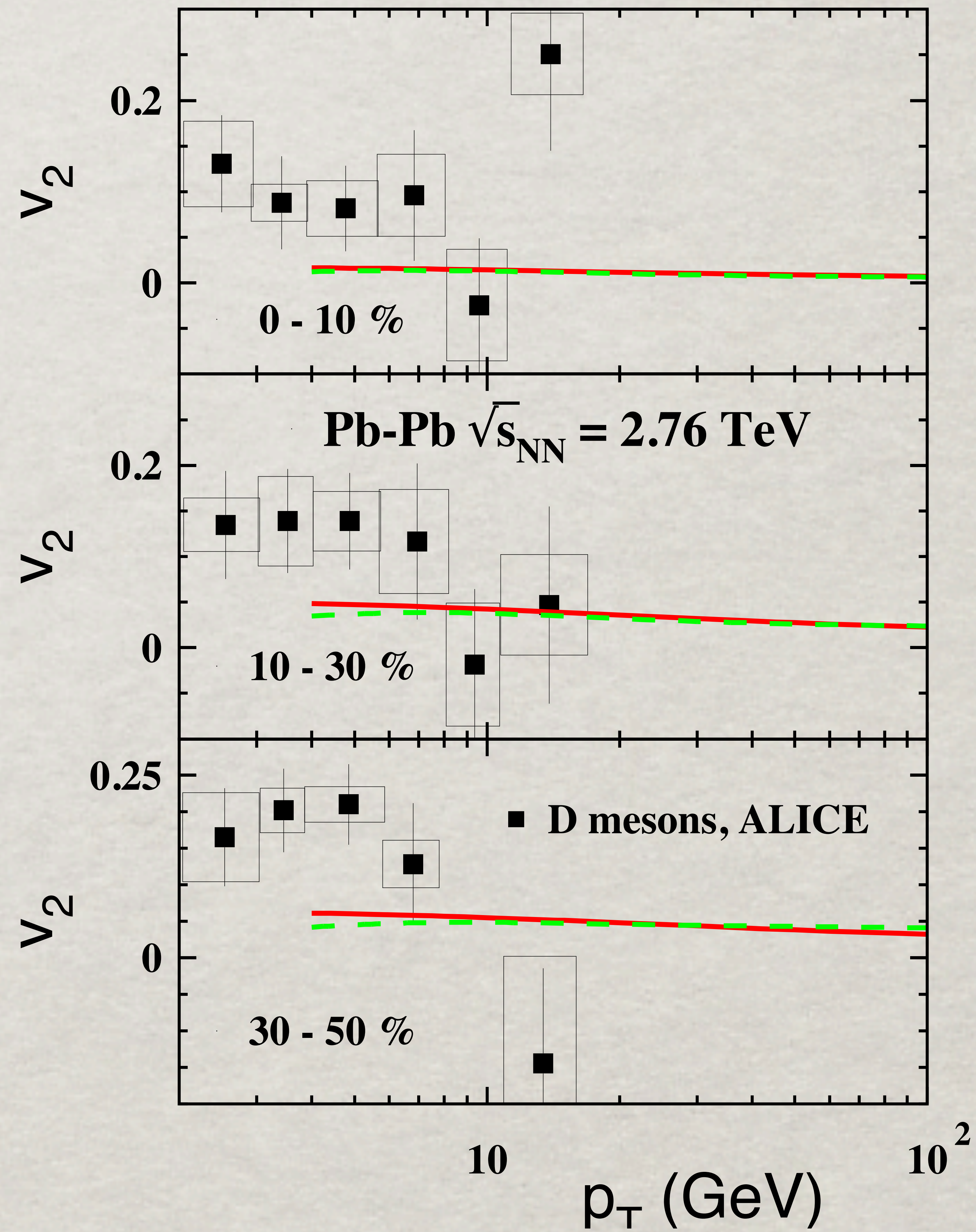




UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Results



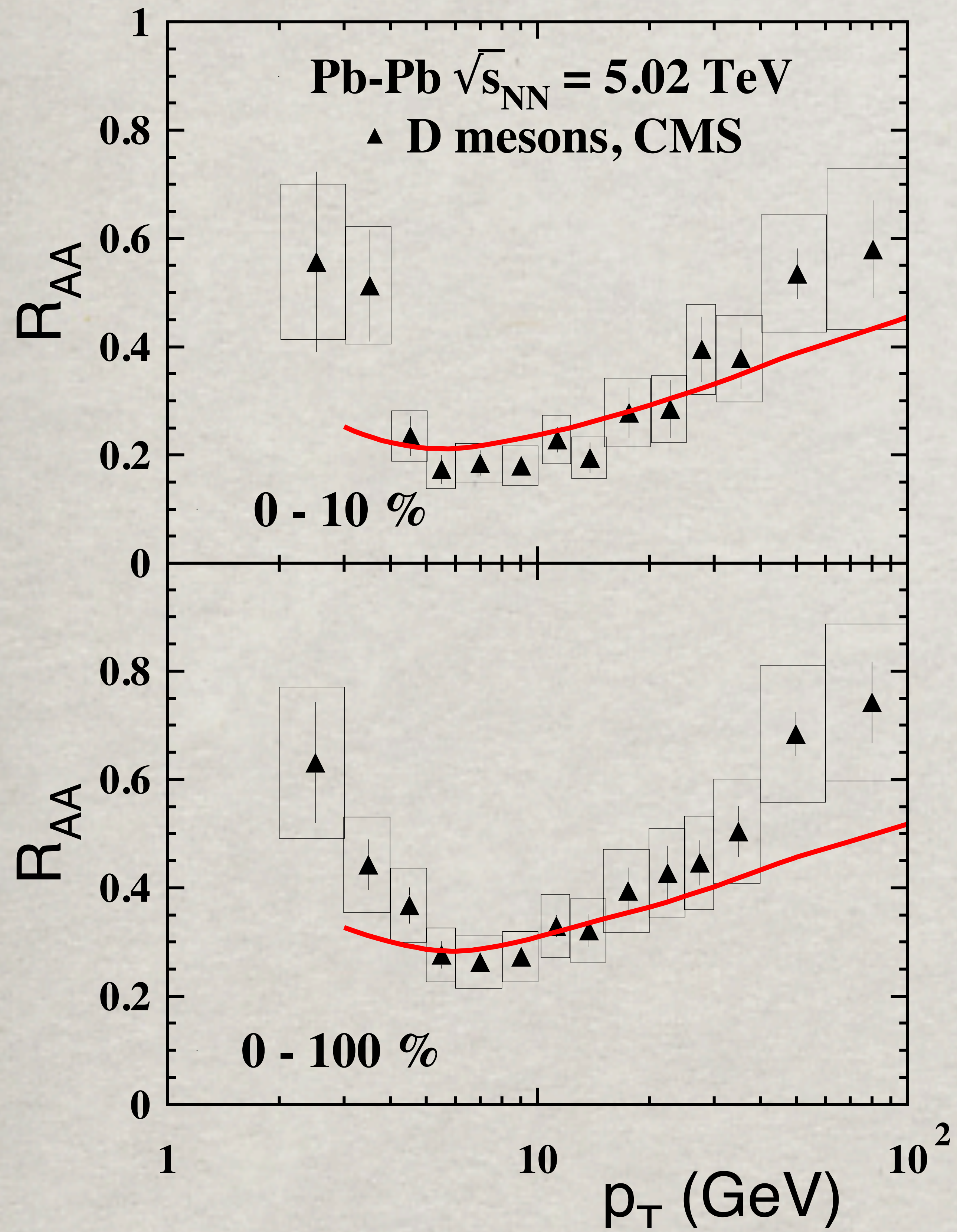


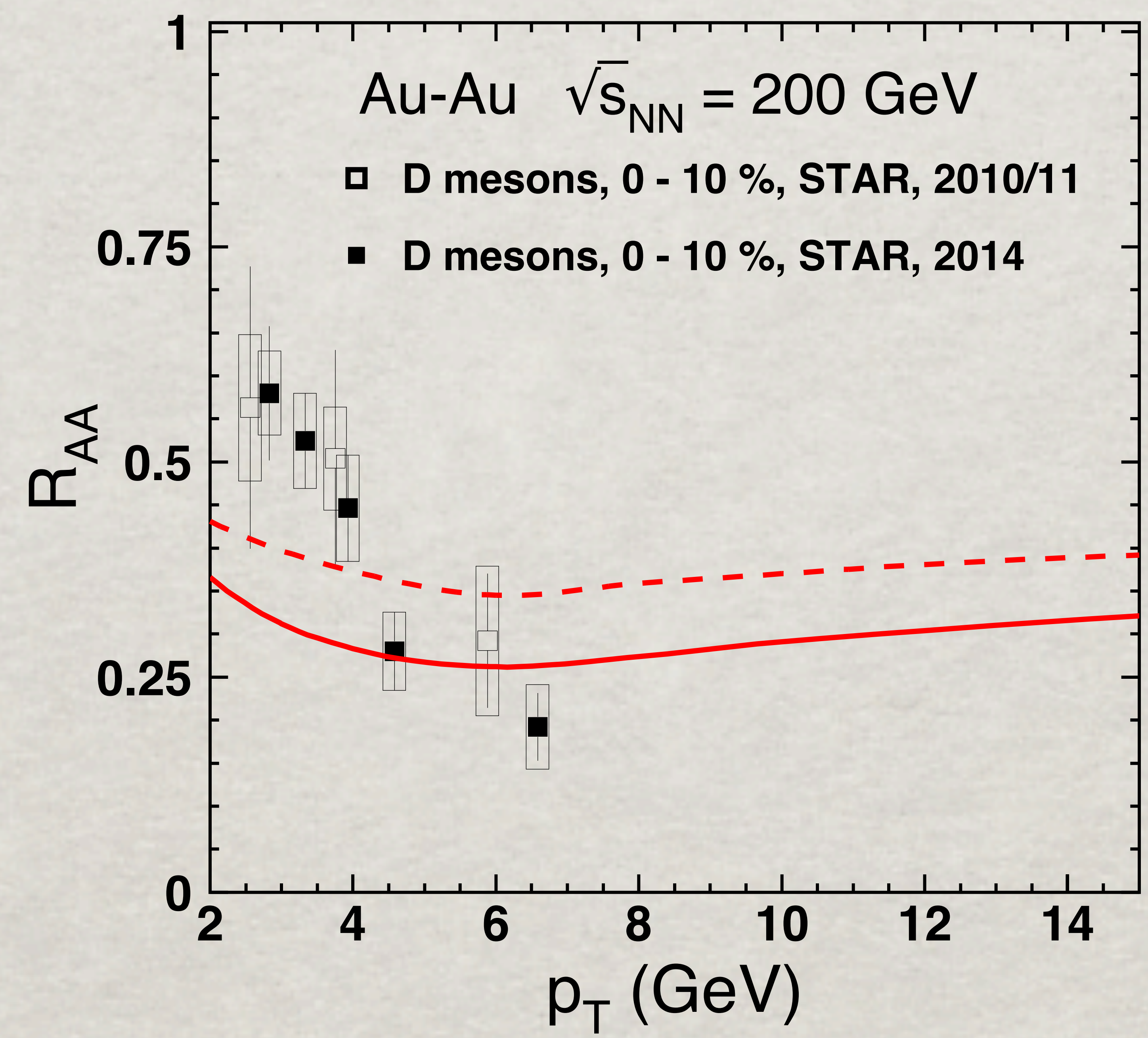
UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

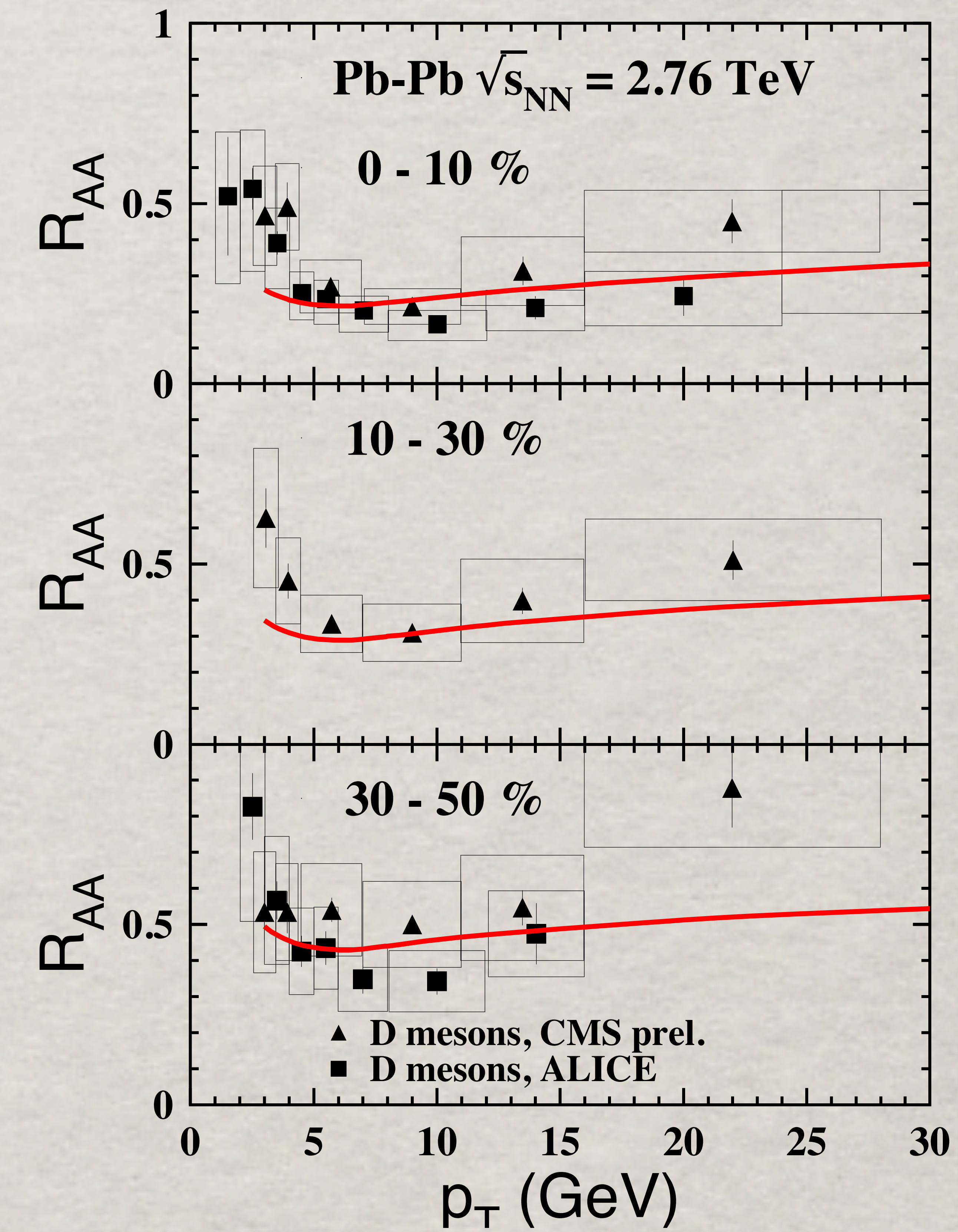
Summary

Fragmentation of high-pT heavy quarks expose nontrivial features.

- Heavy and light quarks produced in high-pT partonic collisions radiate differently. Heavy quarks regenerate their stripped-off color field much faster than light ones and radiate a significantly smaller fraction of the initial energy.
- This peculiar feature of heavy-quark jets leads to a specific shape of the fragmentation functions. Differently from light flavors, the heavy quark fragmentation function strongly peaks at large fractional momentum z, i.e. the produced heavy-light meson, B or D, carry the main fraction of the jet momentum. This is a clear evidence of a short production time of a heavy-light mesons.
- Contrary to the propagation of a small q-$\bar{q}$ dipole, which survives in the medium due to color transparency, a $\bar{q}$-Q dipole promptly expands to a large size. Such a big dipole has no chance to survive intact in a hot medium. On the other hand, a breakup of such a dipole does not suppress the production rate of $\bar{q}$-Q mesons, differently from light qq mesons.
- Data for production of high-pT B and D mesons are explained in a parameter-free way.

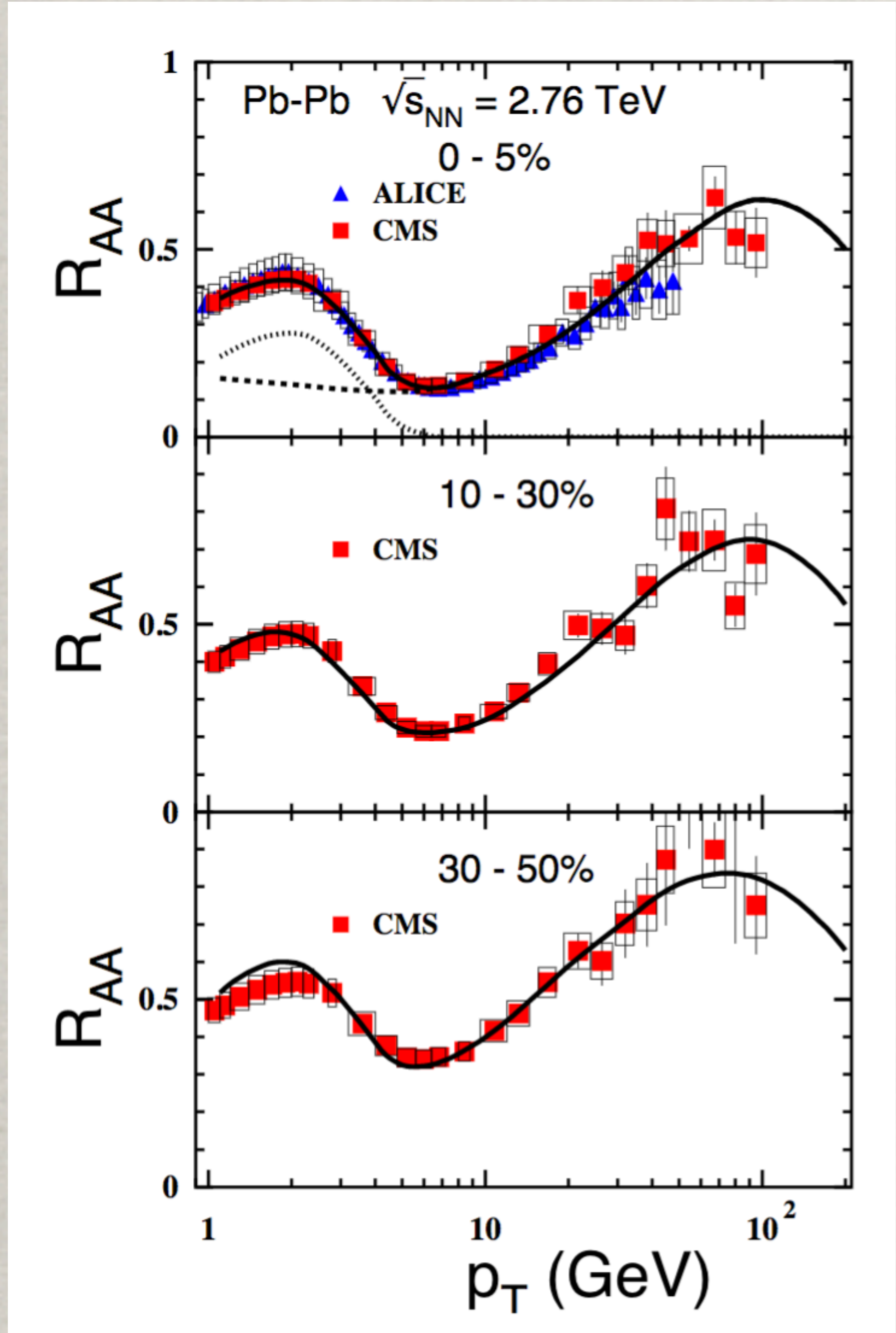






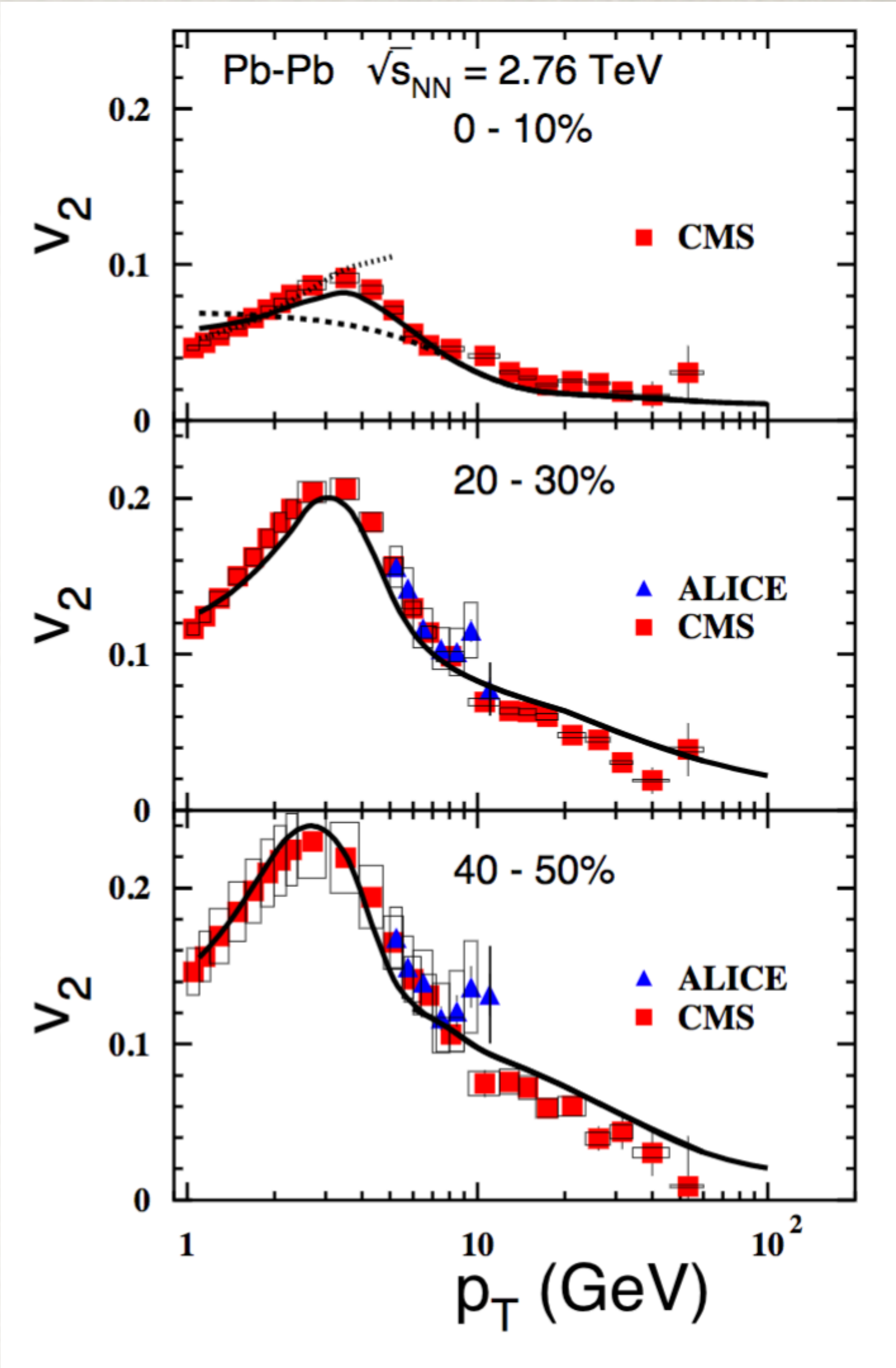
UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Quenching of high-p_T hadrons



HYDRO + pQCD

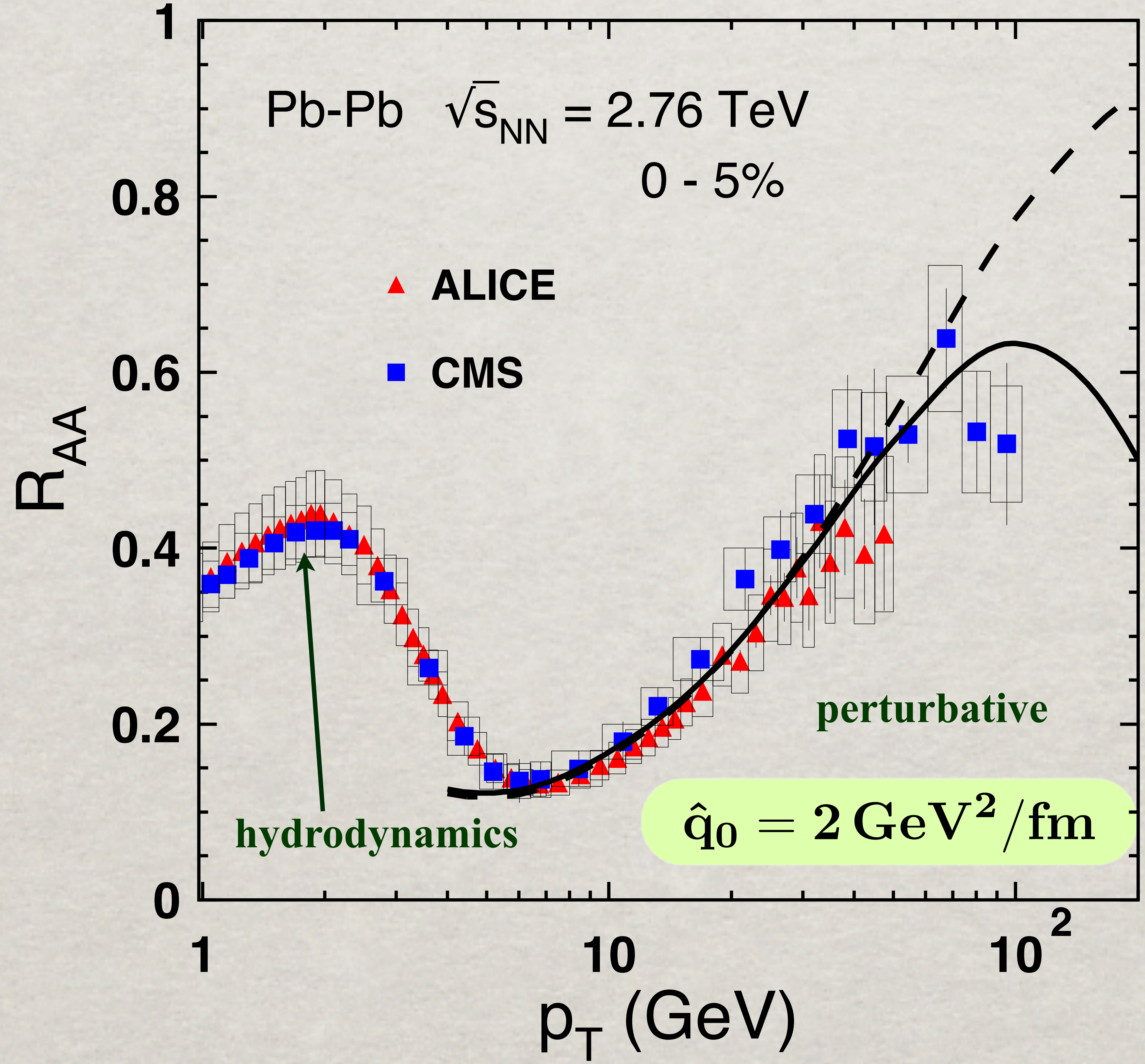
J.Nemchik,Yu.Karpenko,I.Potashnikova
I.Schmidt, Yu.Sinyukov & B.K.
arXiv:1310.3455



UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

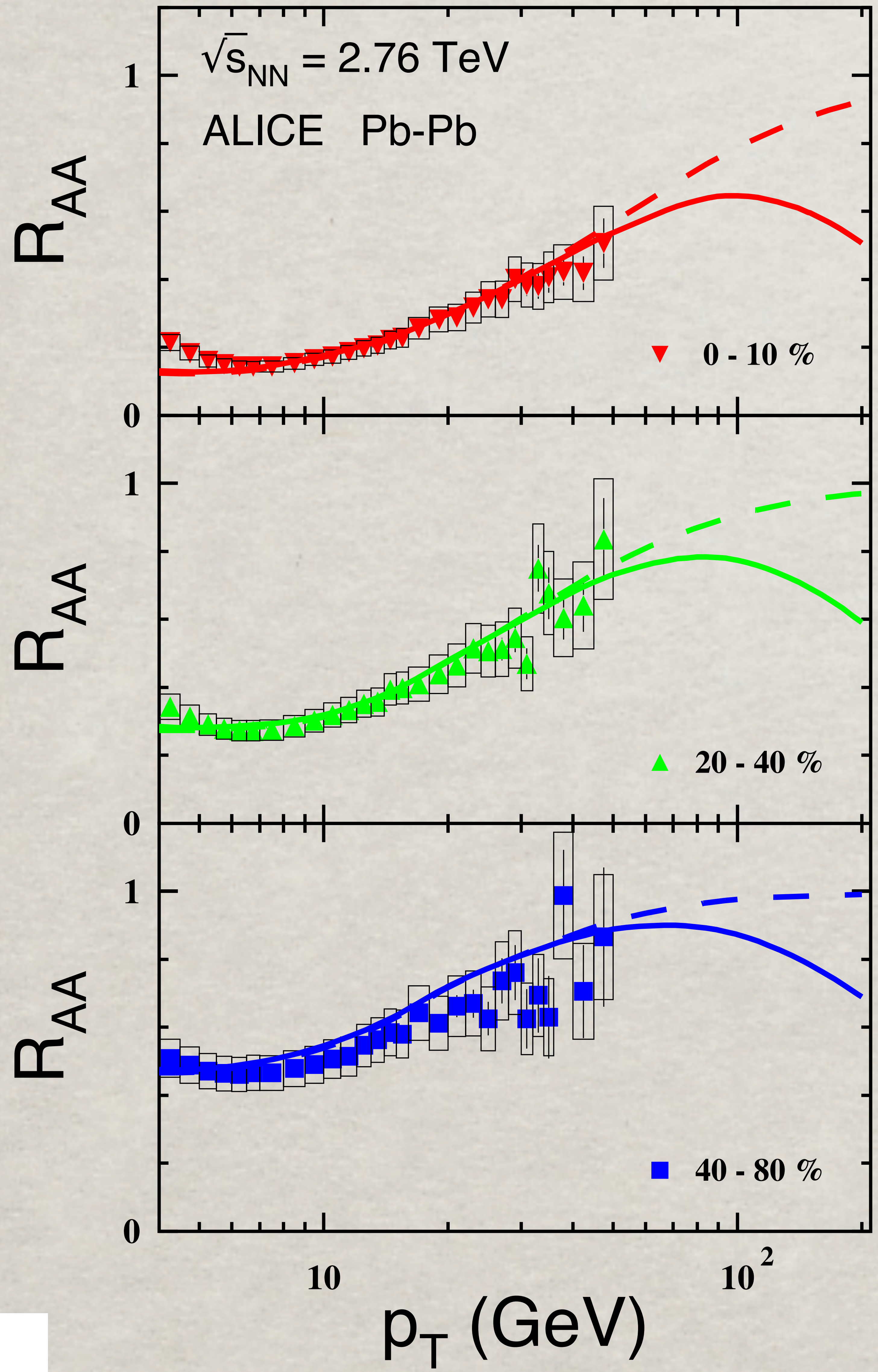
Quenching of high-p_T hadrons

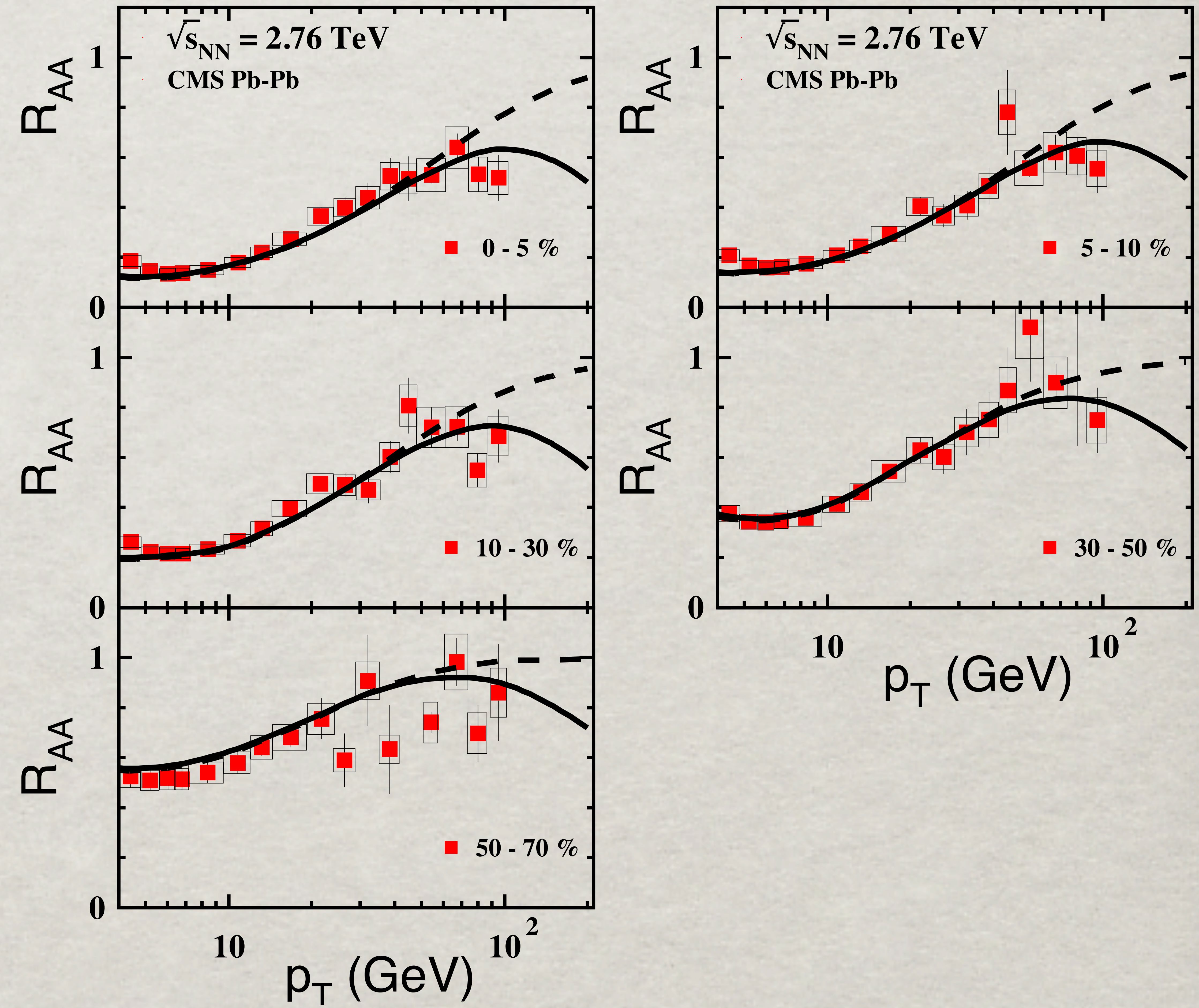
BK, J.Nemchik, I.Potashnikova, I.Schmidt
Phys.Rev. C86(2012)054904



UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Quenching of high-p_T hadrons





B. Kopeliovich, Grenoble, Sept. 27, 2013

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA