B-physics in heavy ion collisions at CMS

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1. Heavy quarks: pair creation, flavour excitation, gluon splitting

2. High-mass dimuon production and effect of energy loss of b-quarks from different sources

3. Secondary J/ψ production and effect of energy loss of b-quarks from different sources

High-mass dimuon production in ultrarelativistic nuclear collisions

Signal:

$gg \to b\bar{b} \to B\bar{B} \to \mu^+\mu^- X$ $(c\tau_{B^\pm} = 496\mu m,\ c\tau_{B^0} = 464\mu m)$

$gg \to c\bar{c} \to D\bar{D} \to \mu^+\mu^- X$ $(c\tau_{D^\pm} = 300\mu m,\ c\tau_{D^0} = 124\mu m)$

Background: $(M_{\mu^+\mu^-} \gtrsim 10$ **GeV**$/c^2)$

$q\bar{q} \to \mu^+\mu^-$ Drell-Yan

$\pi^\pm, K^\pm \to \mu^\pm\nu(\tilde{\nu})$ Combinatorial background

(can be subtracted using like-sign spectra)

If we represent nucleus-nucleus collision as a linear superposition of independent nucleon-nucleon sub-collisions (no collective effects) then:

$$\sigma^h_{AA} = A^2 \sigma^h_{pp}$$

Nuclear collective effects:

- **in initial state: modification of nuclear structure functions ("nuclear shadowing"),** $f_A(x, Q^2) \neq A f_p(x, Q^2)$
- **in final state: multiple scattering and energy losses of** $b-$ **and** $c-$ **quarks in dense QCD-matter (hadronic gas or quark-gluon plasma)**

Secondary J/ψ production in ultrarelativistic nuclear collisions

Signal:

$$gg \to b\bar{b} \to BX \to J/\psi X \to \mu^+\mu X$$

$$(c\tau_{B^\pm} = 496\mu m,\ \ c\tau_{B^0} = 464\mu m)$$

Background: $(M_{\mu^+\mu^-} \sim 3.1$ **GeV**$/c^2)$

$gg \to J/\psi \to \mu^+\mu^-$ primary J/ψ

$\pi^\pm, K^\pm \to \mu^\pm\nu(\tilde{\nu})$ Combinatorial background

(can be subtracted using like-sign spectra)

If we represent nucleus-nucleus collision as a linear superposition of independent nucleon-nucleon sub-collisions (no collective effects) then:

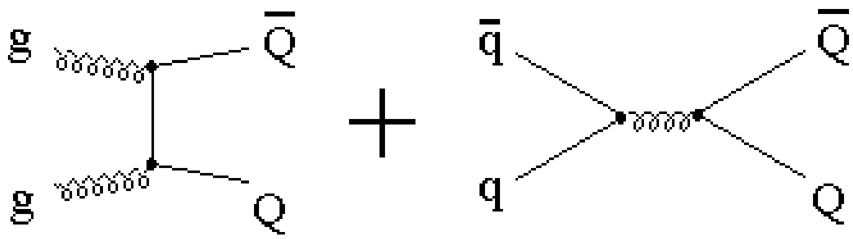
$$\sigma^h_{AA} = A^2\sigma^h_{pp}$$

Nuclear collective effects:

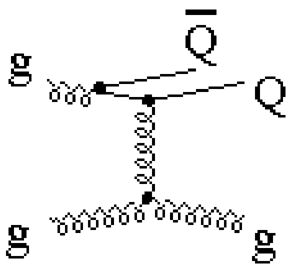
- **in initial state: modification of nuclear structure functions ("nuclear shadowing"),** $f_A(x, Q^2) \neq Af_p(x, Q^2)$
- **in final state: multiple scattering and energy losses of $b-$ and $c-$ quarks in dense QCD-matter (hadronic gas or quark-gluon plasma)**

Heavy quark production at very high energies

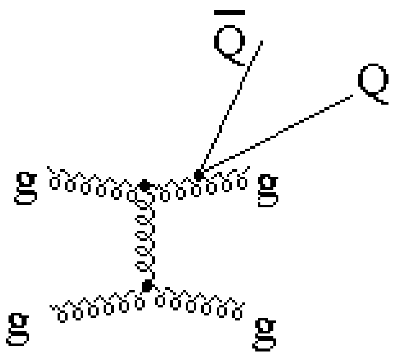
E.Norrbin, T.Sjöstrand, EPJ C 17, 137-161 (2000)



"Leading order"

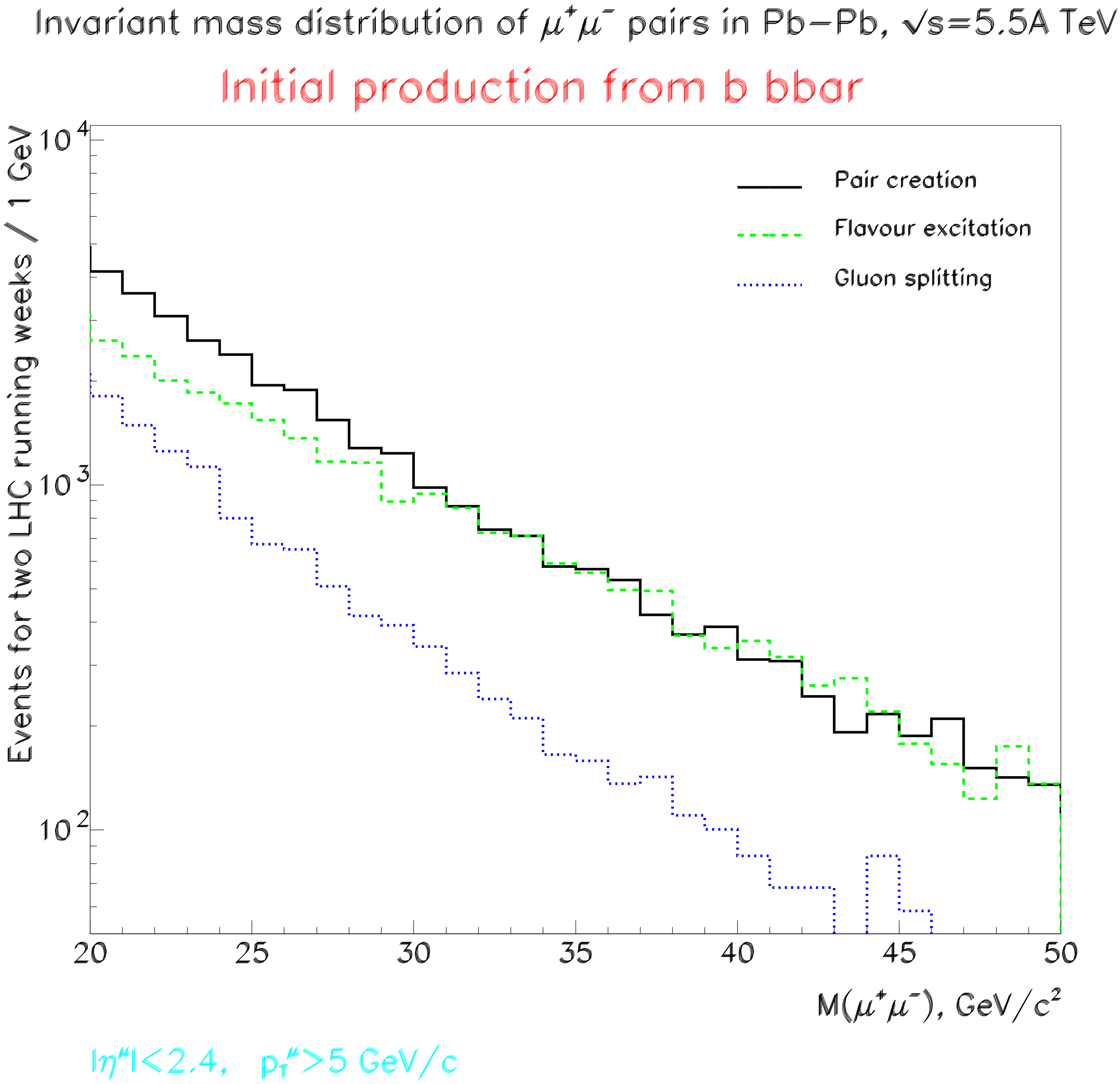


"Flavour excitation"



"Gluon splitting"

There are similar spectra of single quarks, but different correlations between Q and $\overline{Q}$!



Invariant mass distribution of $\mu^+\mu^-$ pairs in Pb−Pb, $\sqrt{s}$=5.5A TeV
Initial production from b bbar
Pair creation
Flavour excitation
Gluon splitting
Events for two LHC running weeks / 1 GeV
10^4
10^3
10^2
20
25
30
35
40
45
50
$M(\mu^+\mu^-)$, GeV/c^2
$|\eta^\mu|<2.4$, $p_T^\mu>5$ GeV/c

Medium-induced rescattering of a heavy quark

Method: *Monte-Carlo simulation of mean free path* λ

- **The transverse distance between scatterings,** $l_i = (\tau_{i+1} - \tau_i)E/p_T$**:**

$$\frac{dP}{dl_i} = \lambda^{-1}(\tau_{i+1})\cdot\exp\left(-\int_0^{l_i}\lambda^{-1}(\tau_i + s)ds\right),\ \lambda_a^{-1} = \sum_b \sigma_{ab}\rho_b$$

- **The scattering cross section** $d\sigma/dt$**:**

$$\frac{d\sigma_{ab}}{dt} \cong C_{ab}\frac{2\pi\alpha_s^2(t)}{t^2}, \quad \alpha_s = \frac{12\pi}{(33 - 2N_f)\ln\left(t/\Lambda_{QCD}^2\right)},$$

$$C_{ab} = 9/4, 1, 4/9 - gg, gq, qq$$

- **Collisional energy loss per scattering** i**:**

$$\Delta E_{col\ i} = -t_i/2m_{0i}, \quad m_{0i} \sim 3T(\tau_i)$$

- **Transverse momentum kick per scattering** i **relative to initial momentum** $\vec{p}$ **of hard quark:**

$$\Delta k_{t\ i}^2 = \left(E - \frac{t_i}{2m_{0i}}\right)^2 - \left(p - \frac{E}{p}\frac{t_i}{2m_{0i}} - \frac{t_i}{2p}\right)^2 - M_q^2$$

- **Radiative energy losses** ΔE_{rad} *of massive quark are suppressed at least for* $p_T \lesssim M_q$ *(*$M_c \simeq 1.35\ GeV$*,* $M_b \simeq 5\ GeV$*)*

Medium-induced gluon radiation of a heavy quark

General kinetic integral equation:

$$\Delta E(L,E) = \int\limits_0^L dx \cdot \frac{dP}{dx}(x) \cdot \lambda(x) \cdot \frac{dE}{dx}(x,E),$$
$$\frac{dP}{dx}(x) = \frac{1}{\lambda(x)} \exp\left(-x/\lambda(x)\right)$$

Averaging over jet vertex (φ,R) and proper time τ at $E_0 \gg \Delta E$:

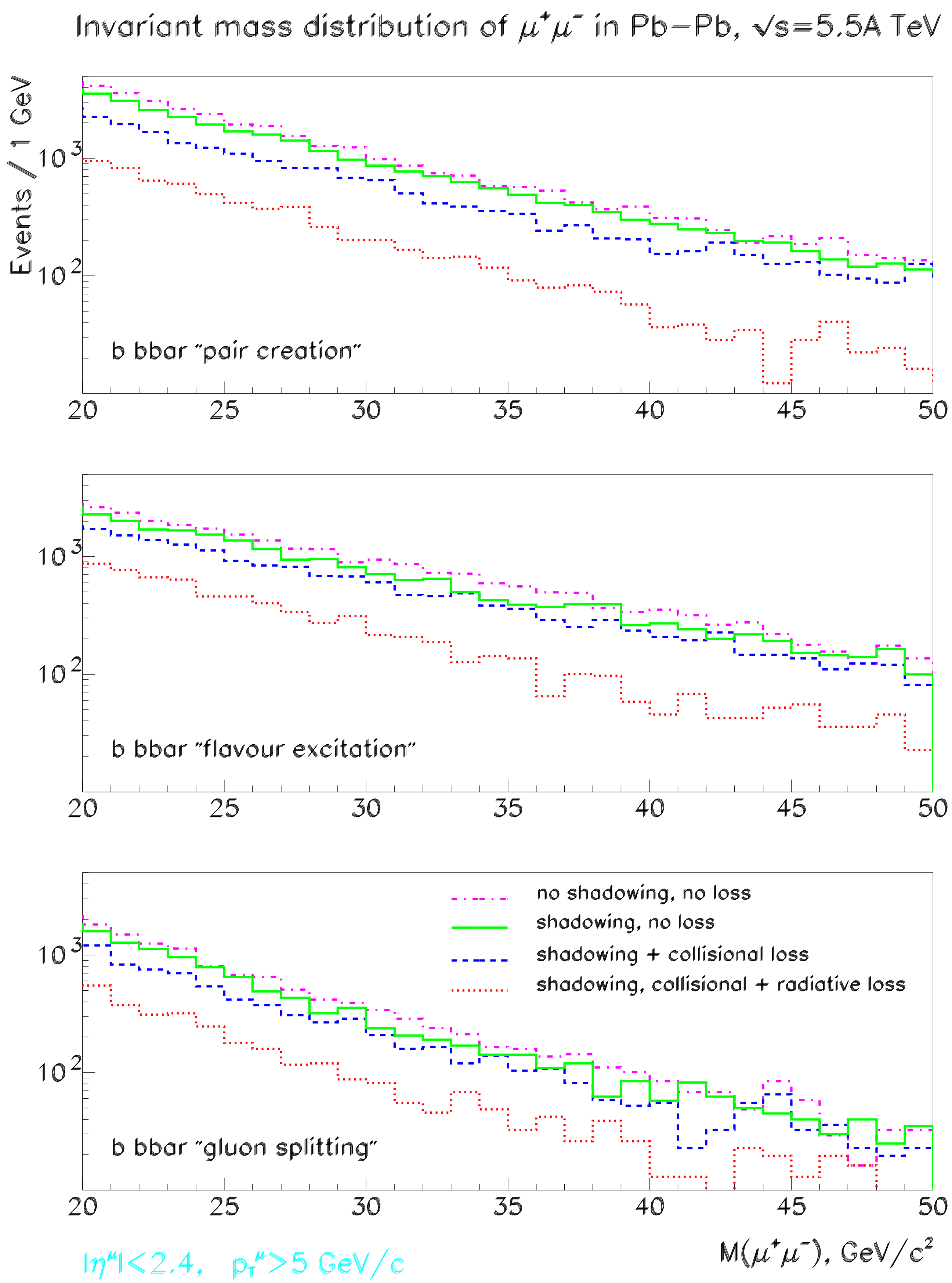
$$\langle \Delta E_{tot} \rangle = \int\limits_0^{2\pi} \frac{d\varphi}{2\pi} \int\limits_0^{R_A} dR \cdot P_A(R) \int\limits_{\tau_0}^{\tau_L} d\tau \left(\frac{dE}{dx}^{rad}(\tau) + \sum_b \sigma_{ab}(\tau) \cdot \rho_b(\tau) \cdot \nu(\tau) \right)$$

Radiative loss

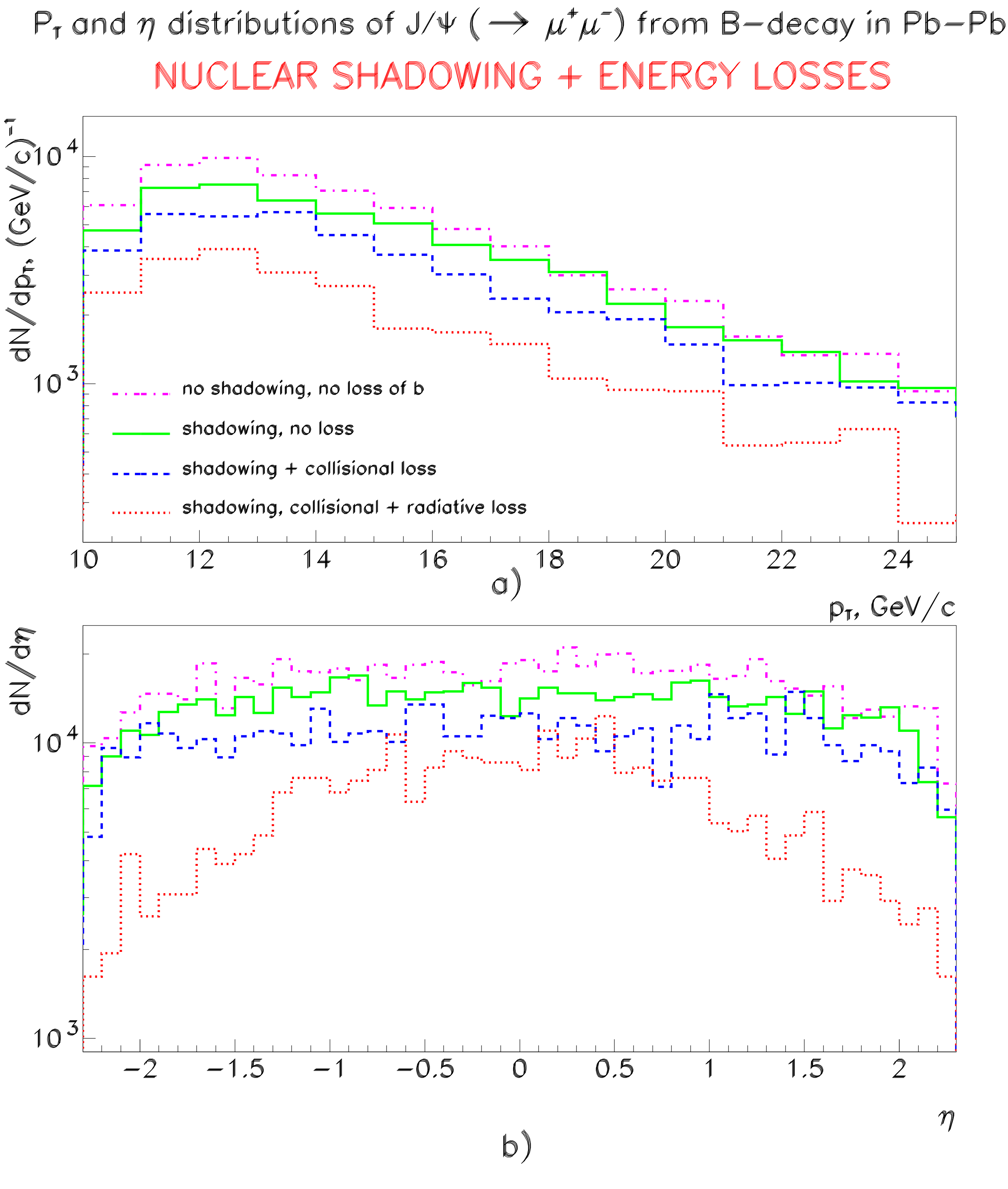
For quark of mass M_q produced inside medium,
light-cone path integral from

B.Zakharov. JETP Lett. 64 (1996) 781; 65 (1997) 615:

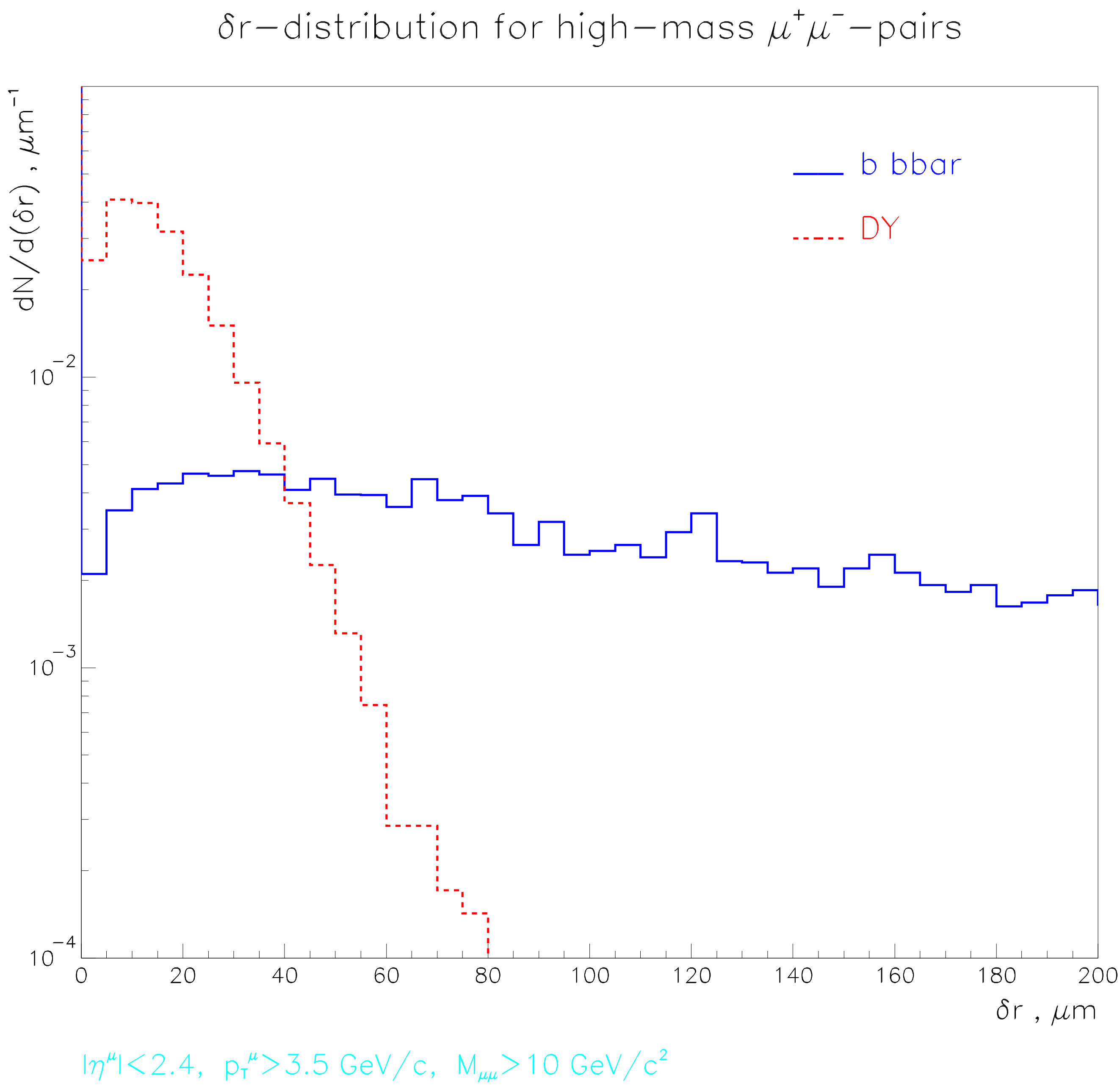
$$\frac{dE}{dx} = E \cdot \rho \int\limits_0^{1-M_q/E} dy \cdot \frac{d\sigma^{BH}}{dy} \cdot y \cdot S(y),$$
$$\frac{d\sigma^{BH}}{dy} = \frac{4\alpha_s \cdot C_3(y) \cdot (4-4y+2y^2)}{9\pi y \left[M_q^2 y^2 + m_g^2(1-y)\right]},$$
$$C_3(y) = \frac{\pi \alpha_s^2 C_{ab}}{4} \left[9(1+(1-y)^2 - y^2\right] \ln \frac{2\left(\alpha_s^2 \rho \cdot E \cdot y(1-y)\right)^{1/4}}{\mu_D},$$
$$S^{incoh} = 1, \quad S^{LPM}(y,E,\tau_L) < 1$$

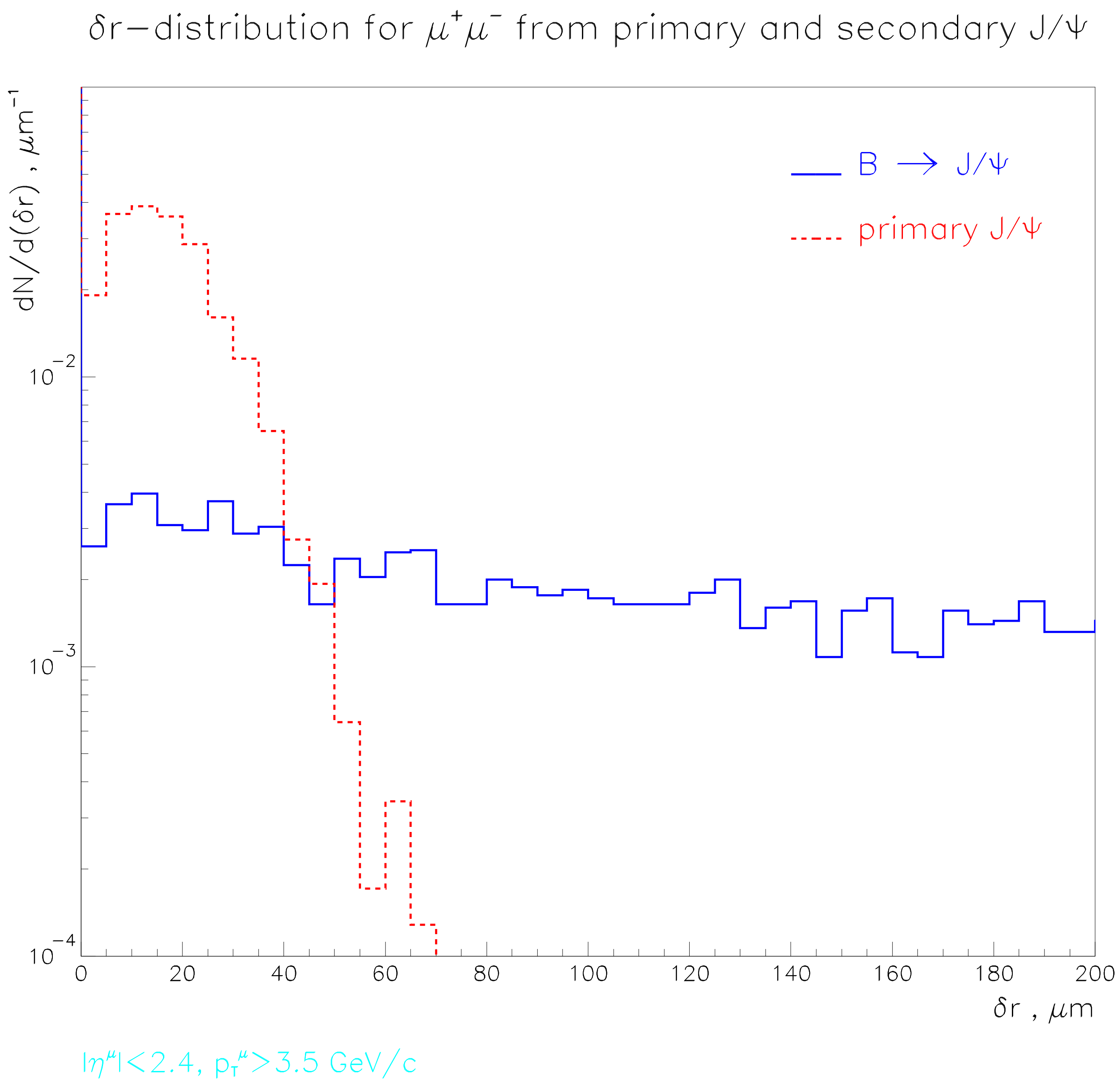


Invariant mass distribution of $\mu^+\mu^-$ in Pb–Pb, $\sqrt{s}$=5.5A TeV
Events / 1 GeV
10^3
10^2
b bbar "pair creation"
b bbar "flavour excitation"
b bbar "gluon splitting"
20
25
30
35
40
45
50
no shadowing, no loss
shadowing, no loss
shadowing + collisional loss
shadowing, collisional + radiative loss
$M(\mu^+\mu^-)$, GeV/c^2
$|\eta^\mu|<2.4$, $p_T^\mu>5$ GeV/c



"pair creation" + "flavour excitation" + "gluon splitting"


δr−distribution for high−mass μ+μ−−pairs
dN/d(δr) , μm−1
b bbar
DY
10−2
10−3
10−4
0
20
40
60
80
100
120
140
160
180
200
δr , μm
|η^μ|<2.4, p_T^μ>3.5 GeV/c, M_μμ>10 GeV/c²


δr−distribution for μ⁺μ⁻ from primary and secondary J/Ψ
dN/d(δr) , μm⁻¹
B → J/Ψ
primary J/Ψ
10⁻²
10⁻³
10⁻⁴
0
20
40
60
80
100
120
140
160
180
200
δr , μm
|η^μ|<2.4, p_T^μ>3.5 GeV/c

SUMMARY

B-physics in heavy ion collisions at CMS is important due to opportunity to study the behaviour of really "massive" colour charge in quark-gluon environment (*probably, still not at RHIC experiments*).

The "showering" $b\bar{b}$ pairs at CMS give the same order of contribution to high-mass dimuon spectra ($M_{\mu^+\mu^-} \gtrsim 20$ GeV/c^2) as direct quark pairs. The dimuon spectra from direct quarks are little more sensitive to the energy loss of b-quarks as compared with dimuons from "showering" quarks due to different kinematics (e.g. strong back-to-back correlation).

The medium-induced parton rescattering and collisional energy loss can reduce high-mass dimuon rate by factor ~ 1.5 (depending on quark production mechanism). The additional radiative energy loss can reduce the rate up to factor ~ 3-4. The relative contribution of radiative loss grows with increasing M and p_T due to the stronger energy dependence of the loss.

The $b\bar{b}$ pair production from parton showers is dominant ($\approx 80\%$) mechanism for secondary J/ψ production. Since secondary J/ψ's reflect energy loss of only one b-quark, the corresponding suppression by a factor of ~ 1.5-2 is less than for $b\bar{b}$ decays and is independent on quark production mechanism. The relative contribution of radiative loss grows with increasing p_T.