Simulation of jet quenching in HIC at CMS

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- **Scientific interest in high-p_T jets and heavy quarks, expected statistics**
- **Monte-Carlo model for simulation of jet quenching**
- **Example I:**
  Medium-modified jet fragmentation in leading particles
- **Example II:**
  Medium-modified heavy quark fragmenation in muons
- **Summary**

The interest in jet and heavy quark production in HIC

1. **Detection and studies of properties of quark-gluon plasma.**
2. **Probing QCD production in media (not in vacuum as in pp!).**

Jet observables:

- **Jet & leading particle production vs. event centrality**
- **Jet & leading particle production vs. azimuthal angle**
- **Jet fragmentation function with leading hadrons**
- **Photon+jet and Z+jet correlations**

CMS will provide adequate reconstruction of
jets, photons, charged hadrons, centrality and event plane

Heavy quark observables:

- $B\overline{B} \to \mu^+\mu^-$,
- $B \to J/\psi \to \mu^+\mu^-$
- **B-jet tagged by leading muon**

CMS will provide adequate **dimuon** *reconstruction &* **primary and secondary vertices**

Expected statistics in CMS acceptance

(no trigger and reconstruction efficiencies are taken into account)

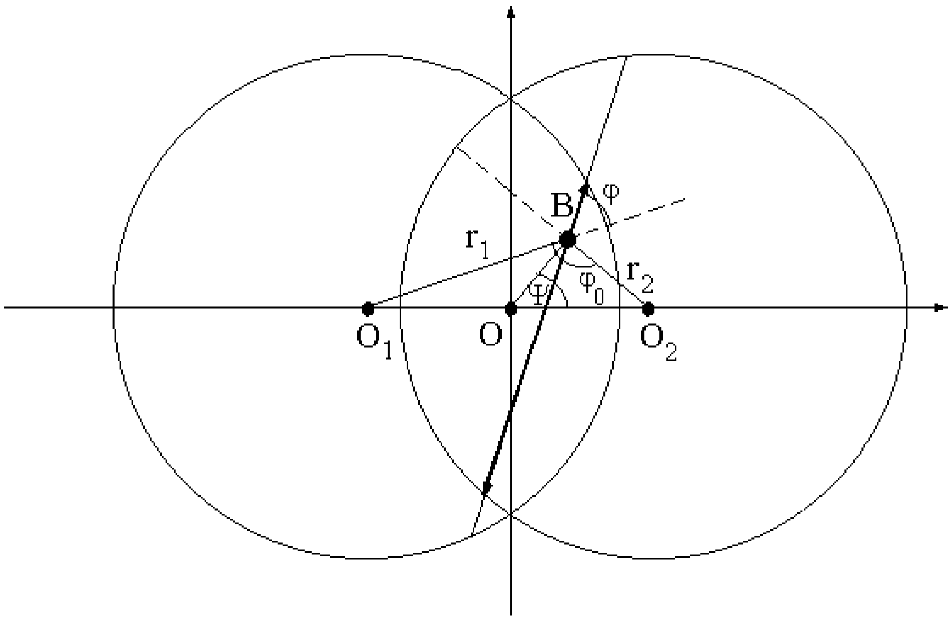
Channels including jets $|\eta^{\text{jet},\ \gamma}| < 3$, $|\eta^{h,\ \mu}| < 2.4$

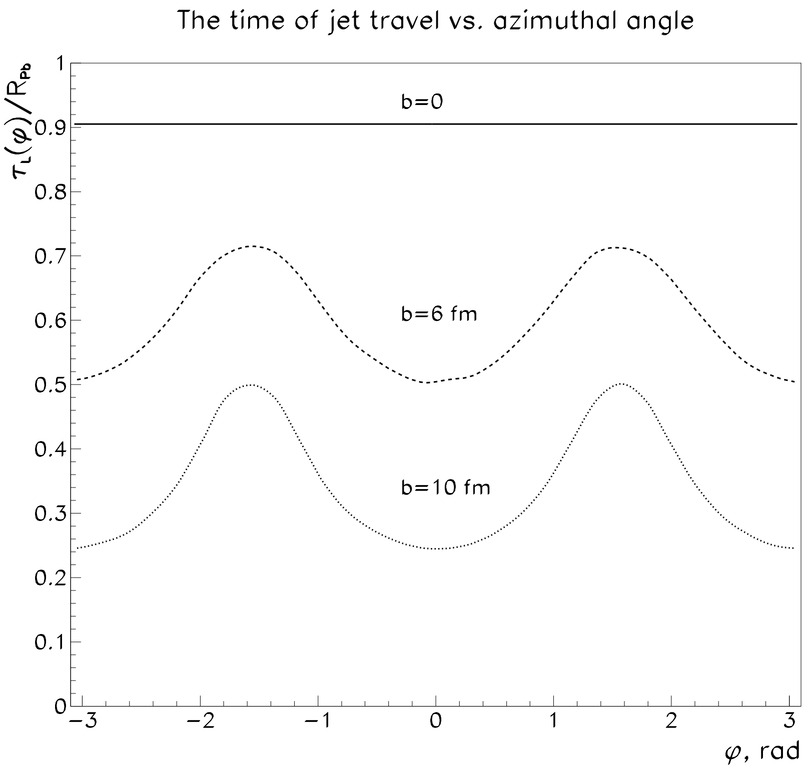
Channel	Observables	Expected 2 week rates, $\sigma_{AA} = A^2\sigma_{pp}$, $A =$Pb (Pythia6.2, CTEQ5M) $L = 5 \times 10^{26}$ cm^{-2} s^{-1}	Shadowing (EKS98)	Jet quenching (in-medium energy loss)
jet+jet, $E_T^{\text{jet}} > 100$ GeV	Spectrum suppression, azimuthal anisotropy in non-central collisions	4×10^6	negligible	up to factor ~ 10
jet tagged by $h^\pm$, π^0, $E_T^{\text{jet}} > 100$ GeV, $z^{h^\pm,\pi^0} > 0.5$	Softening of jet fragmentation	2×10^5	negligible	up to factor ~ 5
B-jet tagged by μ, $E_T^{\text{jet}} > 100$ GeV, $z^\mu > 0.3$ $E_T^{\text{jet}} > 50$ GeV, $z^\mu > 0.3$	Softening of jet fragmentation	700 2×10^4	negligible	up to factor ~ 2

Channels including heavy quarks in dimuon modes $|\eta^\mu| < 2.4$

Channel	Observables	Expected 2 week rates, $\sigma_{AA} = A^2\sigma_{pp}$, $A =$Pb (Pythia6.1, CTEQ5M) $L = 5 \times 10^{26}$ cm^{-2} s^{-1}	Shadowing (EKS98)	Jet quenching (in-medium energy loss)
$B\bar{B} \to \mu^+\mu^-$, $M_{\mu^+\mu^-} > 20$ GeV, $p_t^\mu > 5$ GeV	Spectrum suppression	2.7×10^4	15%	up to factor ~ 4
$B \to J/\Psi \to \mu^+\mu^-$, $p_t^\mu > 5$ GeV	Spectrum suppression	1.0×10^4	30%	up to factor ~ 2

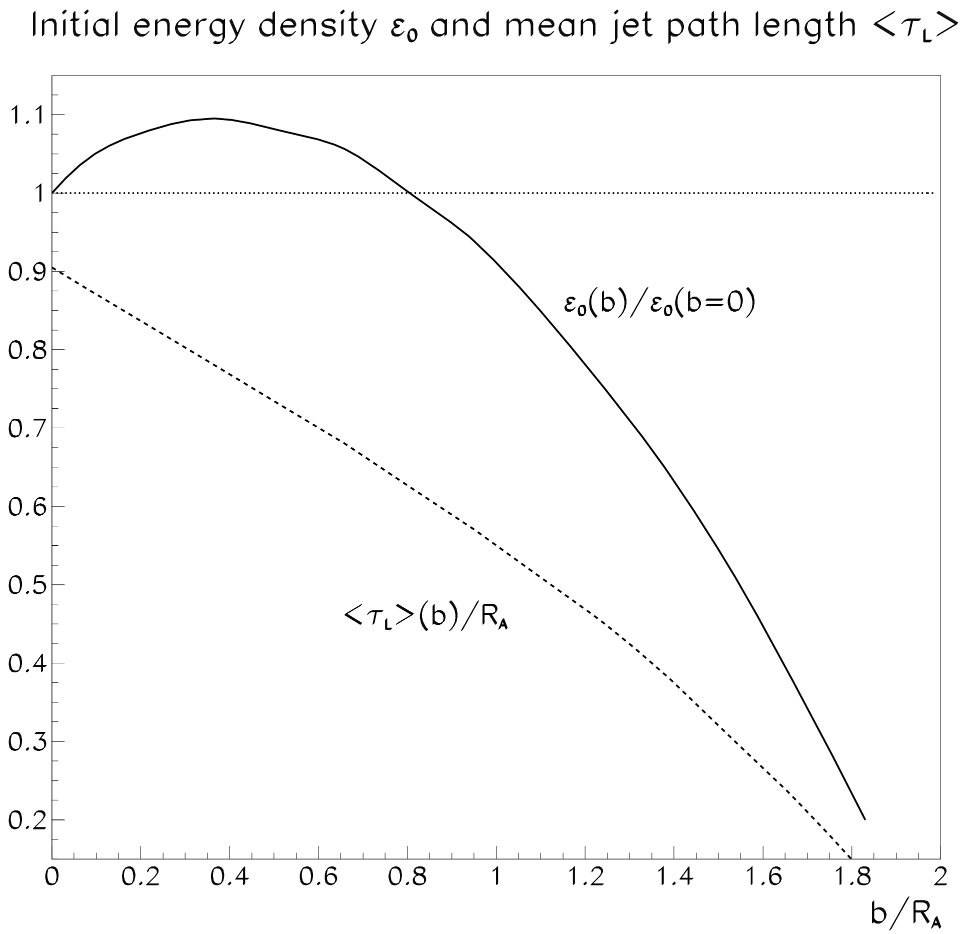
Nuclear geometry of jet quenching





Jet partons lose energy in azimuthally asymmetric volume of quark-gluon plasma

Initial energy density and jet path length vs. centrality



$$\epsilon_0(b) \propto T_{AA}(b)/S_{AA}(b)$$

Nuclear overlap function: $T_{AA}(b) = \int\limits_0^{2\pi} d\psi \int\limits_0^{r_{max}} r dr T_A(r_1) T_A(r_2), \quad T_A(\vec{r}) = \int\limits_{-\infty}^{+\infty} \rho_A(\vec{r}, z) dz$

Transverse area of dense zone: $S_{AA}(b) = \int\limits_0^{2\pi} d\psi \int\limits_0^{r_{max}} r dr = \left(\pi - 2 \arcsin \frac{b}{2R_A}\right) R_A^2 - b\sqrt{R_A^2 - \frac{b^2}{4}}$

In-medium partonic energy loss

General kinetic integral equation:

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

1. Collisional loss

$$\nu=\left\langle\frac{t}{2m_0}\right\rangle=\frac{1}{2}\left\langle\frac{1}{m_0}\right\rangle\cdot\langle t\rangle\simeq\frac{1}{4T\sigma_{ab}}\int\limits_{\mu_D^2}^{t_{\max}}dt\frac{d\sigma_{ab}}{dt}t$$

$$\frac{d\sigma_{ab}}{dt}\cong C_{ab}\frac{2\pi\alpha_s^2(t)}{t^2},\quad \alpha_s=\frac{12\pi}{\left(33-2N_f\right)\ln\left(t/\Lambda_{\rm QCD}^2\right)},\quad C_{ab}=9/4,1,4/9-gg,\ gq,\ qq$$

2. Radiative loss **(R. Baier, Yu.L. Dokshitzer, A. Mueller, D. Schiff. NPB 531 (1998) 403)**

$$\frac{dE}{dx}|_{m_q=0}=\frac{2\alpha_s C_F}{\pi\tau_L}\int\limits_{E_{\rm LPM}\sim\lambda_g\mu_D^2}^{E}d\omega\left[1-y+\frac{y^2}{2}\right]\ln\left|\cos\left(\omega_1\tau_1\right)\right|,$$

$$\omega_1=\sqrt{i\left(1-y+\frac{C_F}{3}y^2\right)\bar{\kappa}\ln\frac{16}{\bar{\kappa}}},\quad \bar{\kappa}=\frac{\mu_D^2\lambda_g}{\omega(1-y)},\quad \tau_1=\frac{\tau_L}{2\lambda_g},\quad y=\frac{\omega}{E},\quad C_F=\frac{4}{3}$$

Yu.L. Dokshitzer and D. Kharzeev, PLB 519 (2001) 199 **(“dead cone” approximation) :**

$$\frac{dE}{dx}|_{m_q\neq 0}=\frac{1}{(1+(l\omega)^{3/2})^2}\frac{dE}{dx}|_{m_q=0},\qquad l=\left(\frac{\lambda}{\mu_D^2}\right)^{1/3}\left(\frac{m_q}{E}\right)^{4/3}$$

Simulation of parton rescattering in QGP

- **The initial parton spectrum is generated with PYTHIA**
- **The transverse distance between scatterings,** $l_i = (\tau_{i+1} - \tau_i)E/p_T$**:**

$$\frac{dP}{dl_i} = \lambda^{-1}(\tau_{i+1}) \exp\left(-\int\limits_0^{l_i} \lambda^{-1}(\tau_i + s)ds\right), \quad \lambda_a^{-1} = \sum_b \sigma_{ab}\rho_b$$

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

$$\frac{d\sigma_{ab}}{dt} \cong C_{ab}\frac{2\pi\alpha_s^2(t)}{t^2}, \quad \alpha_s = \frac{12\pi}{(33 - 2N_f)\ln(t/\Lambda_{\rm QCD}^2)}, \quad C_{ab} = 9/4, 1, 4/9 - gg, gq, qq$$

- **Radiative and collisional energy loss per scattering** i**:**

$$\Delta E_{{\rm tot},i} = \Delta E_{{\rm rad},i} + \Delta E_{{\rm col},i}$$

- **Transverse momentum kick per scattering** i**:**

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

- **The final spectrum is generated after hadronization with JETSET**

Medium-modified jet fragmentation

Experimentally observable jet fragmentation function:

$$D(z) \equiv \int\limits_{zp_{T,\min}^{\rm jet}} d(p_T^h)^2 dy \frac{dN_{AA}^{{\rm h}(k)}}{d(p_T^h)^2 dy dz} \Big/ \int\limits_{p_{T,\min}^{\rm jet}} dp_T^2 dy \frac{dN_{AA}^{{\rm jet}(k)}}{dp_T^2 dy}$$

Experimentally observable integrated jet suppression factor:

$$Q^{\rm jet}(p_{T,\min}^{\rm jet}) \equiv \int\limits_{p_{T,\min}^{\rm jet}} dp_T^2 dy \frac{dN_{AA}^{{\rm jet}(k)}}{dp_T^2 dy} \Big/ \int\limits_{p_{T,\min}^{\rm jet}} dp_T^2 dy \frac{dN_{AA}^{{\rm jet}(k)}}{dp_T^2 dy}(\Delta p_T^{\rm jet} = 0).$$

Rate of jets of cone size θ_0 at impact parameter b:

$$\frac{dN_{AA}^{{\rm jet}(k)}}{dp_T^2 dy}(b) = \int\limits_0^{2\pi} d\psi \int\limits_0^{r_{\max}} r dr T_A(r_1) T_A(r_2) \frac{d\sigma^{{\rm jet}(k)}(p_T + \Delta p_T^{\rm jet}(r,\psi,\theta_0))}{dp_T^2 dy}$$

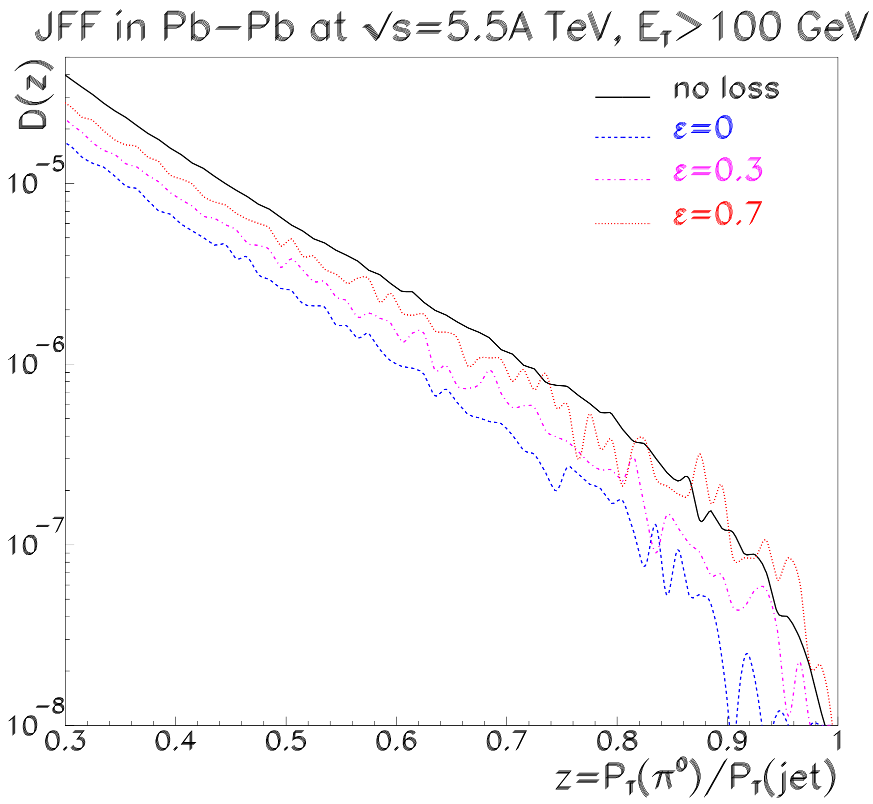
Rate of "jet-induced" hadrons at impact parameter b:

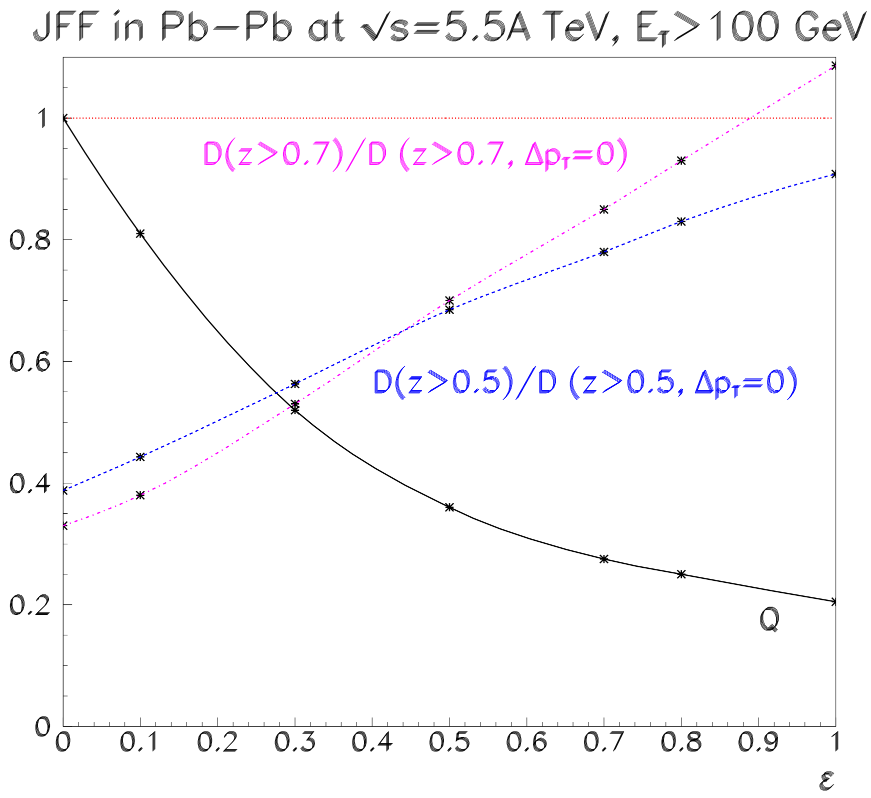
$$\frac{dN_{AA}^{h(k)}}{d(p_T^h)^2 dy dz}(b) = \int\limits_0^{2\pi} d\psi \int\limits_0^{r_{\max}} r dr T_A(r_1) T_A(r_2) \frac{d\sigma^{{\rm jet}(k)}(p_T + \Delta p_T(r,\psi))}{dp_T^2 dy} \frac{1}{z^2} D_k^h(z, p_T^2)$$

$D_k^h(z,Q^2)$ *and* $\frac{d\sigma^{{\rm jet}(k)}}{dp_T^2 dy}$ *are fragmentation function and jet cross section in vacuum.*

$\Delta p_T^{\rm jet}(\theta_0)$ *and* Δp_T *are medium-induced shifts of jet and hadron* p_T*-spectrum.*

Jet fragmentation function with leading π^0, $h^\pm$

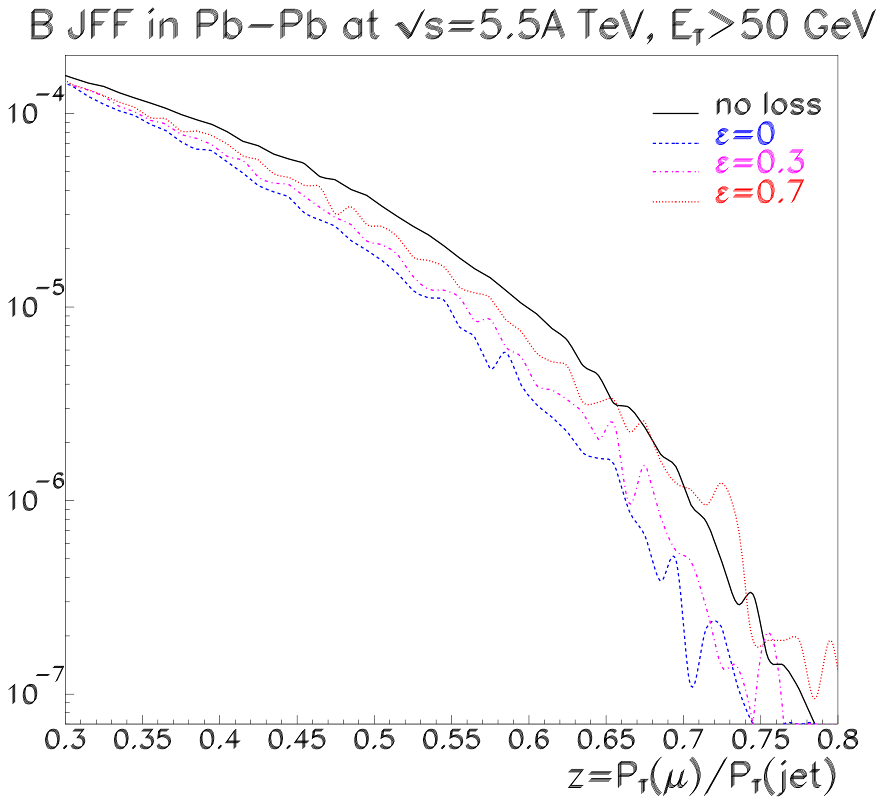


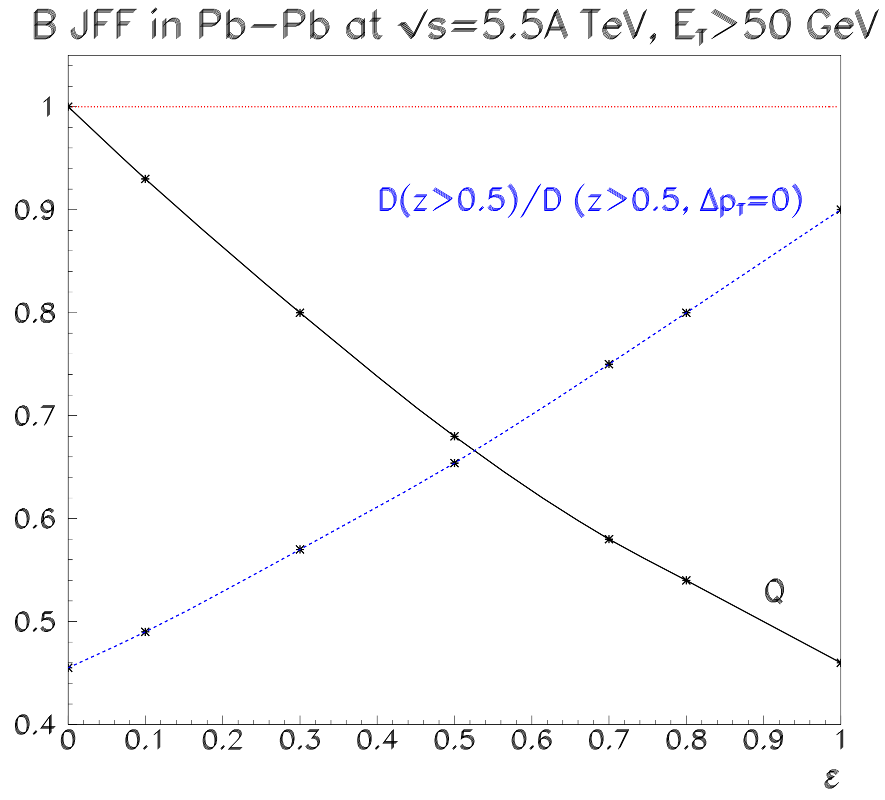


I.P. Lokhtin and A.M. Snigirev, hep-ph/0303121, Phys. Lett. B, in press

modification of jet fragmentation function crucially depends on the fraction ε of jet energy loss falling outside the typical jet cone (and being truly lost to the jet).

B-jet fragmentation function with leading μ


B JFF in Pb−Pb at √s=5.5A TeV, E$_T$>50 GeV


B JFF in Pb−Pb at √s=5.5A TeV, E$_T$>50 GeV

modification of μ-tagged B-jet fragmentation function also depends on the fraction ε of jet energy loss falling outside the typical jet cone.

Heavy quark fragmentation effects on dimuon spectra

Signal I:

$$b\bar{b} \rightarrow B\overline{B} \rightarrow \mu^+\mu^- X \;\; (c\tau_{B^\pm} = 496\mu\text{m}, \;\; c\tau_{B^0} = 464\mu\text{m})$$

$$c\bar{c} \rightarrow D\overline{D} \rightarrow \mu^+\mu^- X \;\; (c\tau_{D^\pm} = 300\mu\text{m}, \;\; c\tau_{D^0} = 124\mu\text{m})$$

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

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

$\pi^\pm, K^\pm \rightarrow \mu^\pm\nu(\overline{\nu})$ **Combinatorial background (subtracted using like-sign spectra)**

Signal II:

$$b\bar{b} \rightarrow BX \rightarrow J/\psi X \rightarrow \mu^+\mu^- X$$

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

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

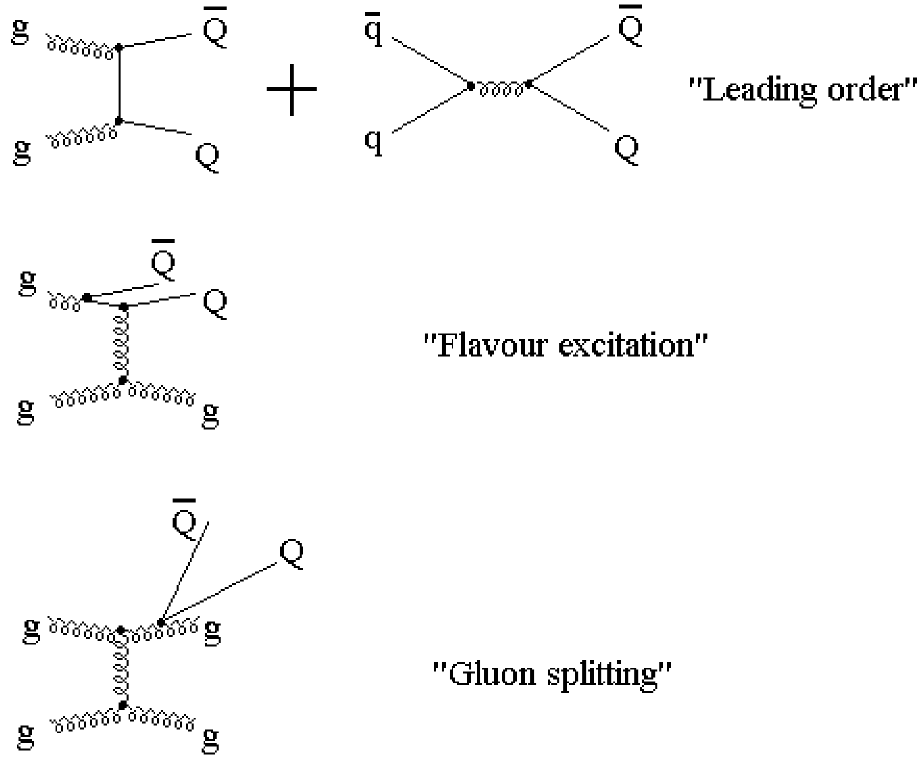
$\pi^\pm, K^\pm \rightarrow \mu^\pm\nu(\overline{\nu})$ **Combinatorial background (subtracted using like-sign spectra)**

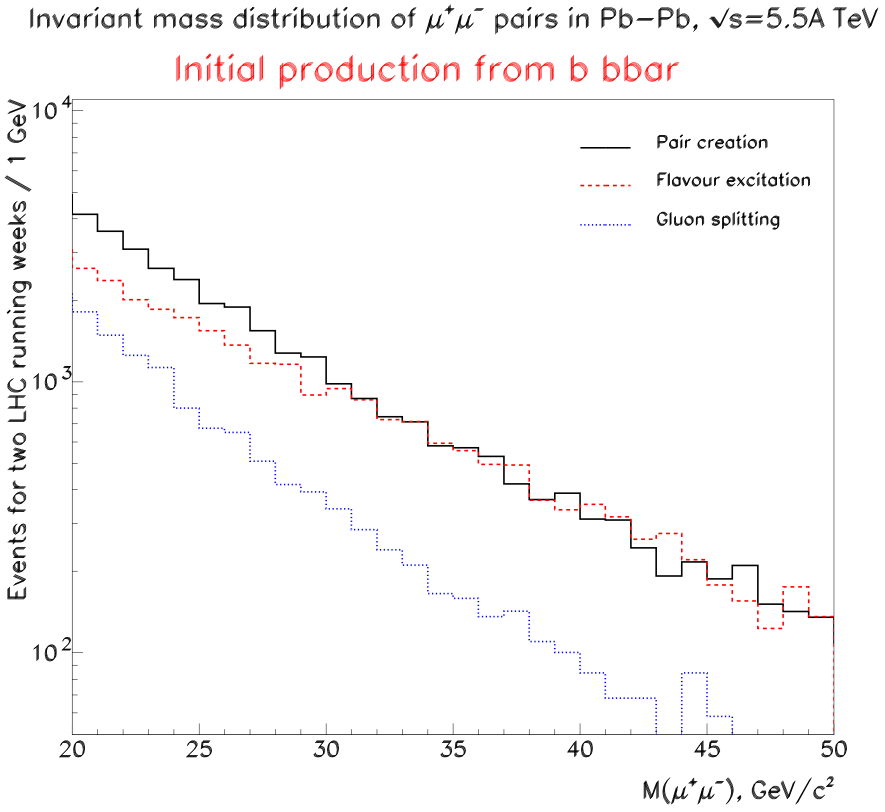
Linear superposition of independent nucleon-nucleon sub-collisions (no collective effects):

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

Nuclear collective effects (initial and final state) will modify dimuon rates & spectra

Heavy quark production at very high energies





$|\eta^\mu|<2.4$, $p_T^\mu>5$ GeV/c

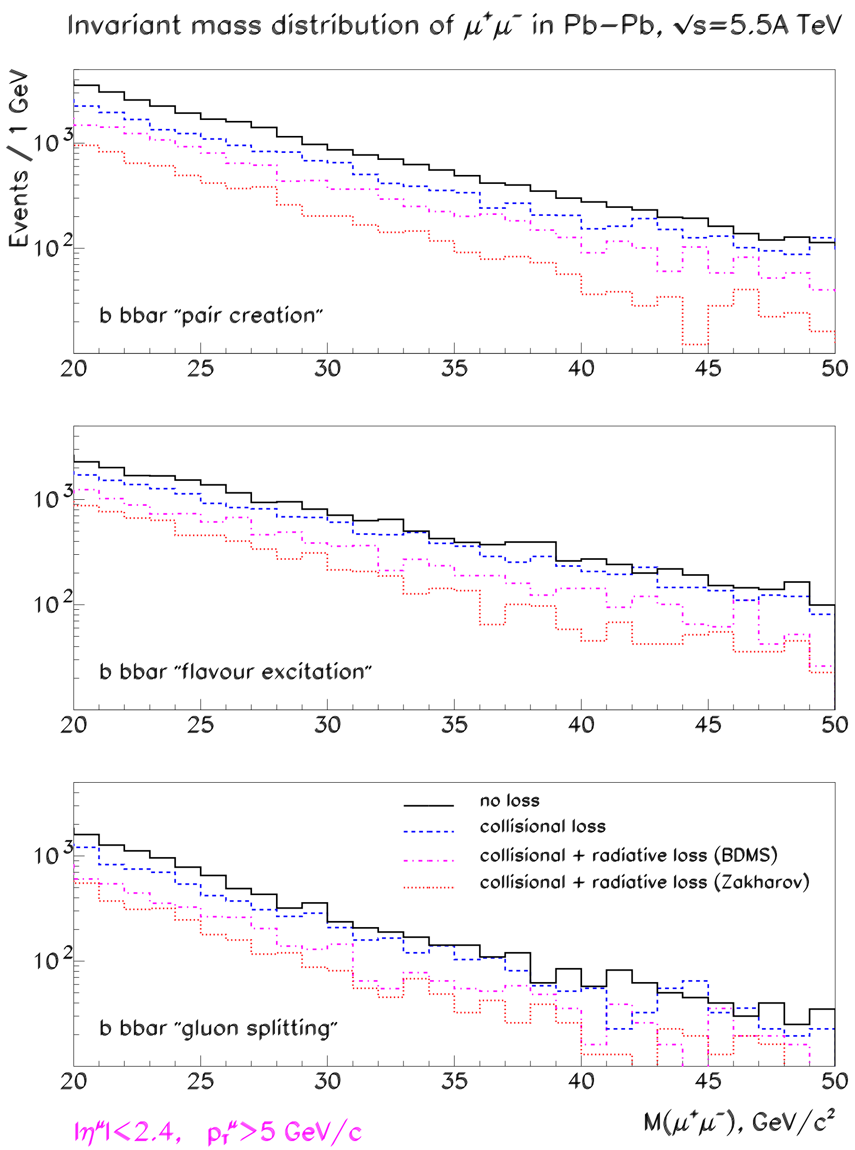
E. Norrbin, T. Sjöstrand, EPJ C 17 (2000) 137:

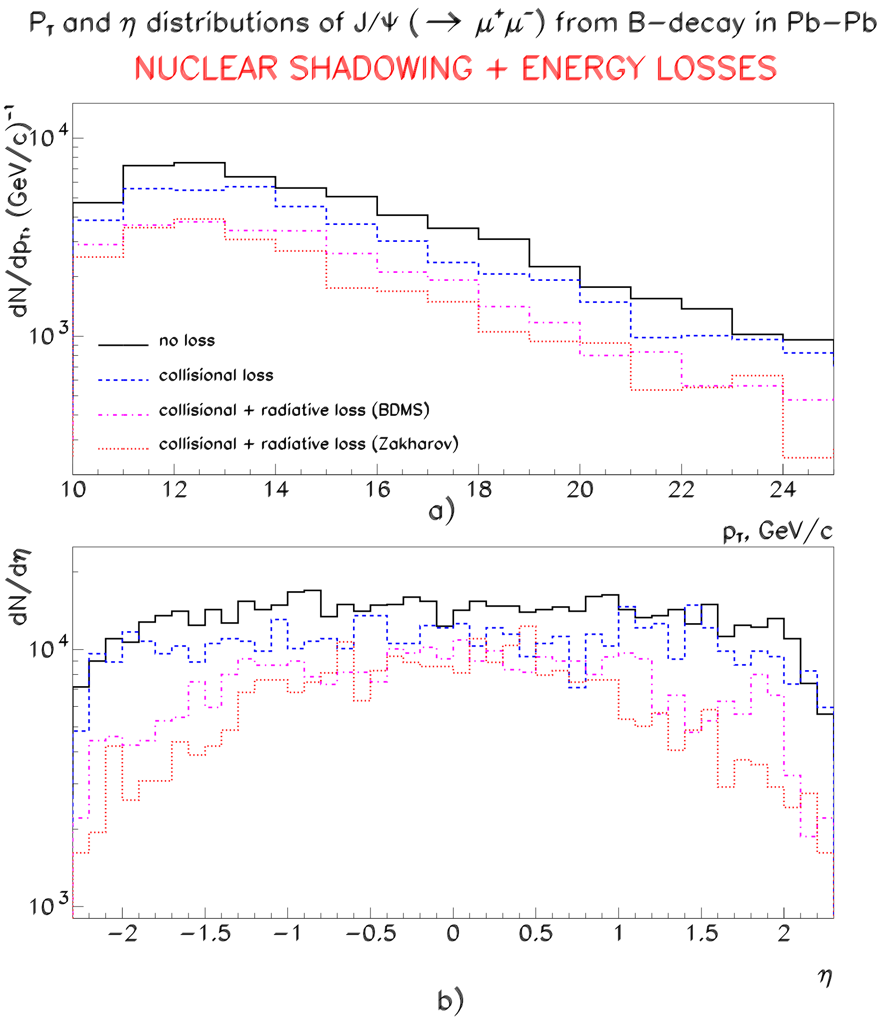
1. The "flavour excitation" and "gluon splitting" contributions in PYTHIA important and can dominate at LHC;
2. The single quark spectra are similar for all three contributions but the $Q\overline{Q}$ correlations are different.

(PYTHIA prediction)

I. Lokhtin, A. Snigirev, NPA 702 (2002) 346

B-fragmentation: $B\overline{B} \to \mu^+\mu$ ***and*** $B \to J/\psi \to \mu^+\mu^-$





I. Lokhtin, A. Snigirev, EPJ C 21 (2001) 155; JPG 27 (2001) 2365; CERN CMS Note 2001/008; NPA 702 (2002) 346 – see for details.

Jet quenching in HIC at CMS: Summary

Monte-Carlo studies show that CMS is well suited to observe and analyze jet quenching in various channels

Leading particles in jet:

- medium-modified jet fragmentation function can be measured (with fine jet, π^0 and charged hadron reconstruction)
- medium-modified b-quark fragmentation function can be measured (with fine jet and single muon reconstruction)

Heavy quarks:

- medium-modified spectra of high-mass dimuons from semilepronic $B\overline{B}$ decays and secondary J/ψ's from single B can be observed (with fine dimuon and event vertex reconstruction)