

## *Jet quenching in heavy ion collisions at LHC*

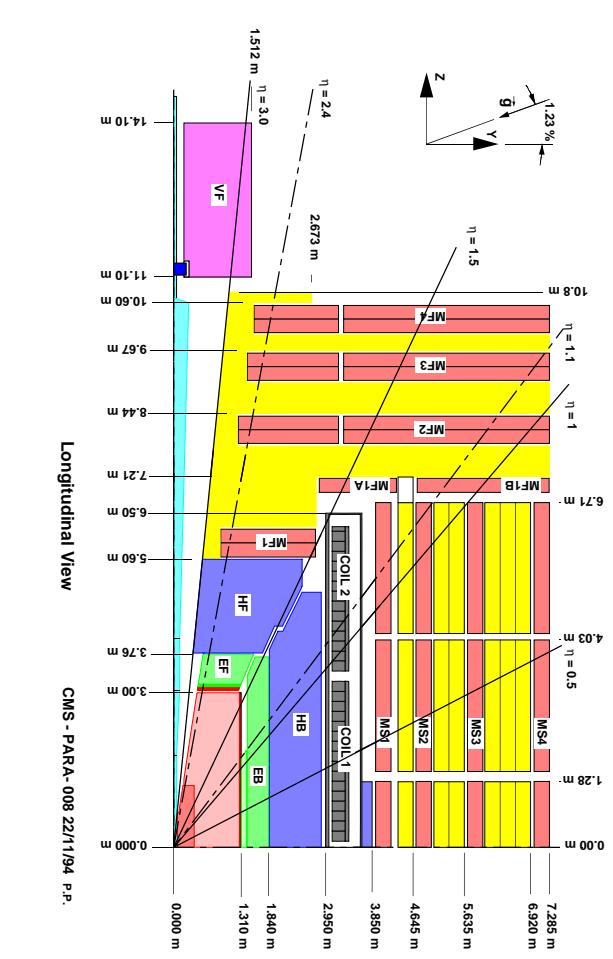
*presented by I.P. Lokhtin*

*Lomonosov Moscow State University, Institute of Nuclear Physics*

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- Expected statistics for jet and heavy quark channels in acceptance of CMS experiment at LHC
- Jet reconstruction
- Impact parameter and event plane determination
- Jets vs. impact parameter
- Jets vs. azimuthal angle
- Mechanisms for heavy quark production at LHC
- $B\bar{B} \rightarrow \mu^+ \mu^-$  and  $B \rightarrow J/\psi \rightarrow \mu^+ \mu^-$  modes

## CMS Longitudinal View



Energy resolution  $\sigma/E$  and granularity of CMS calorimeters in barrel (HB, EB), endcap (HE, EE) and very forward (HF) regions:  $E^\gamma$  (ECAL),  $E_T^{jet}$  (HCAL).

Rapidity coverage	$0 <  \eta  < 1.5$	$1.5 <  \eta  < 3.0$	$3.0 <  \eta  < 5.0$		
Subdetector	HCAL (HB)	ECAL (EB)	HCAL (HE)	ECAL (EE)	HF
$\sigma/E = a/\sqrt{E} \oplus b$					
a:	1.16	0.027	0.91	0.057	0.77
b:	0.05	0.0055	0.05	0.0055	0.05
granularity	$0.087 \times 0.087$	$0.0174 \times 0.0174$	$0.087 \times 0.087$	$0.0174 \times 0.0174$	$0.175 \times 0.175$
$\Delta\eta \times \Delta\varphi$					

The tracker and muon chambers cover  $|\eta| < 2.4$ . Muon momentum resolution  $< 1\%$  at  $p_T^\mu < 100$  GeV.

## Expected statistics at CMS acceptance

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### Channels including jets $|\eta| < 3$

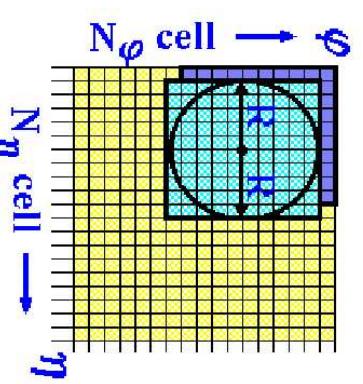
Channel	Observables	Expected 2 week rates, $\sigma_{AA} = A^2 \sigma_{pp}$ , $A = Pb$ (Pythia6.1, CTEQ5L, LO) $L = 5 \times 10^{26} cm^{-2}s^{-1}$	Nuclear shadowing effect (EKS'98)	Jet quenching effect (in-medium energy loss)
jet+jet, $E_T^{jet} > 100$ GeV	Spectrum suppression, azimuthal anisotropy in non-central collisions	$4.4 \times 10^6$	negligible	up to factor $\sim 10$
$\gamma +$ jet, $E_T^{jet,\gamma} > 100$ GeV	Spectrum suppression, $P_T$ -imbalance	$3.0 \times 10^3$	negligible	up to factor $\sim 2$
$Z(\rightarrow \mu^+ \mu^-) +$ jet, $E_T^{jet}, P_T^Z > 100$ GeV	Spectrum suppression, $P_T$ -imbalance	45	negligible	up to factor $\sim 2$
$E_T^{jet}, P_T^Z > 50$ GeV		300		

### Channels including heavy quarks $|\eta| < 2.4$

Channel	Observables	Expected 2 week rates, $\sigma_{AA} = A^2 \sigma_{pp}$ , $A = Pb$ (Pythia6.1, CTEQ5L, LO) $L = 5 \times 10^{26} cm^{-2}s^{-1}$	Nuclear shadowing effect (EKS'98)	Jet quenching effect (in-medium energy loss)
$B\bar{B} \rightarrow \mu^+ \mu^-$ , $M_{\mu^+ \mu^-} > 20$ GeV, $P_t^\mu > 5$ GeV	Spectrum suppression	$2.7 \times 10^4$	15%	up to factor $\sim 4$
$B \rightarrow J/\Psi \rightarrow \mu^+ \mu^-$ , $P_t^\mu > 5$ GeV	Spectrum suppression	$1.0 \times 10^4$	30%	up to factor $\sim 2$

# Jet reconstruction in heavy ion collisions

## Window algorithm



1. Subtract average background.
2. Find jets with sliding window.
3. Build a cone around  $E_T^{max}$ .
4. Recalculate background outside the cone.
5. Recalculate jet energy.

## Full jet reconstruction in Pb–Pb central collision ( $dN_{ch}/dy(y=0)=8000$ )

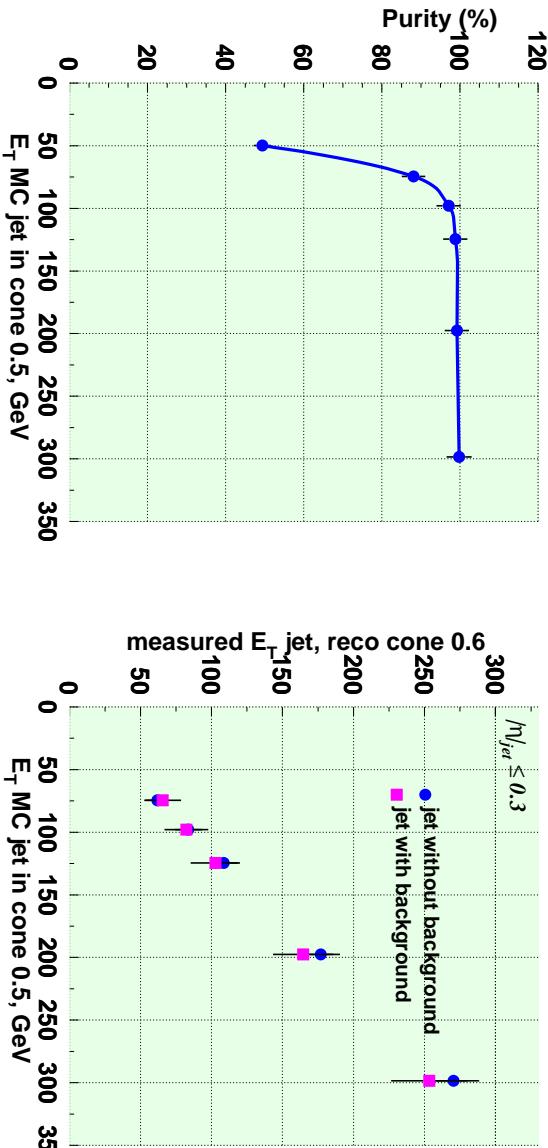
### Efficiency



### Measured jet energy



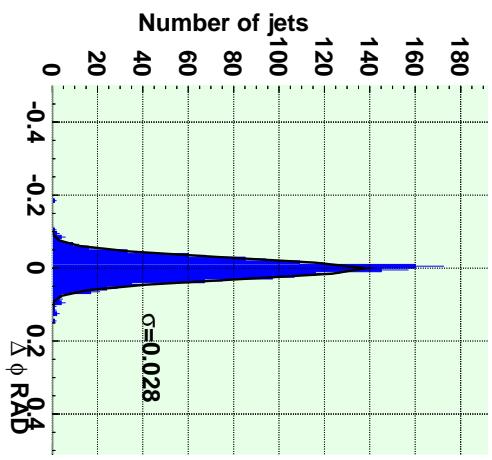
### Jet energy resolution



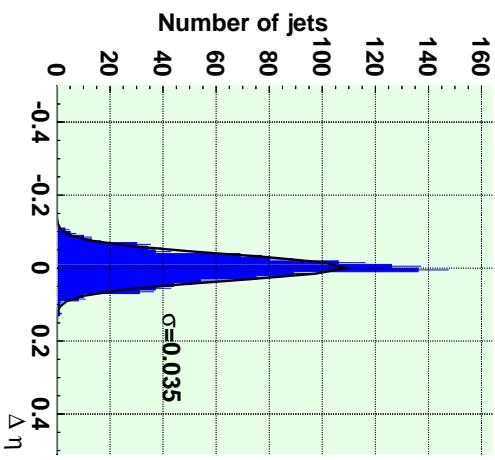
## Jet reconstruction in heavy ion collisions (cont.)

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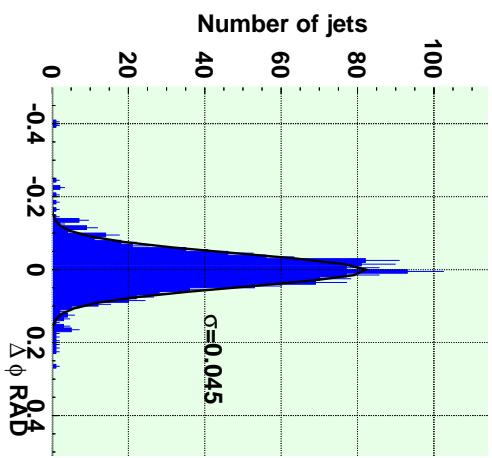
*Azimuthal angle resolution, pp.*



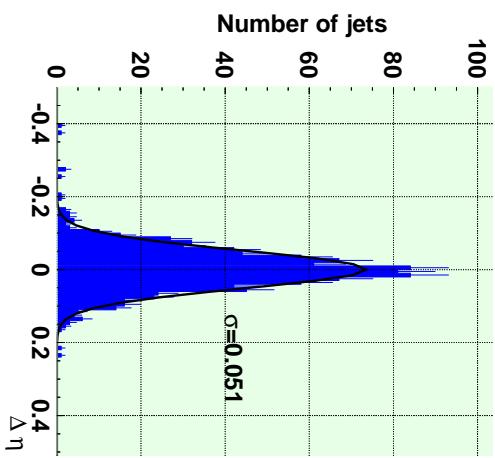
*Pseudorapidity resolution, pp.*



*Azimuthal angle resolution, Pb–Pb.*



*Pseudorapidity resolution, Pb–Pb.*



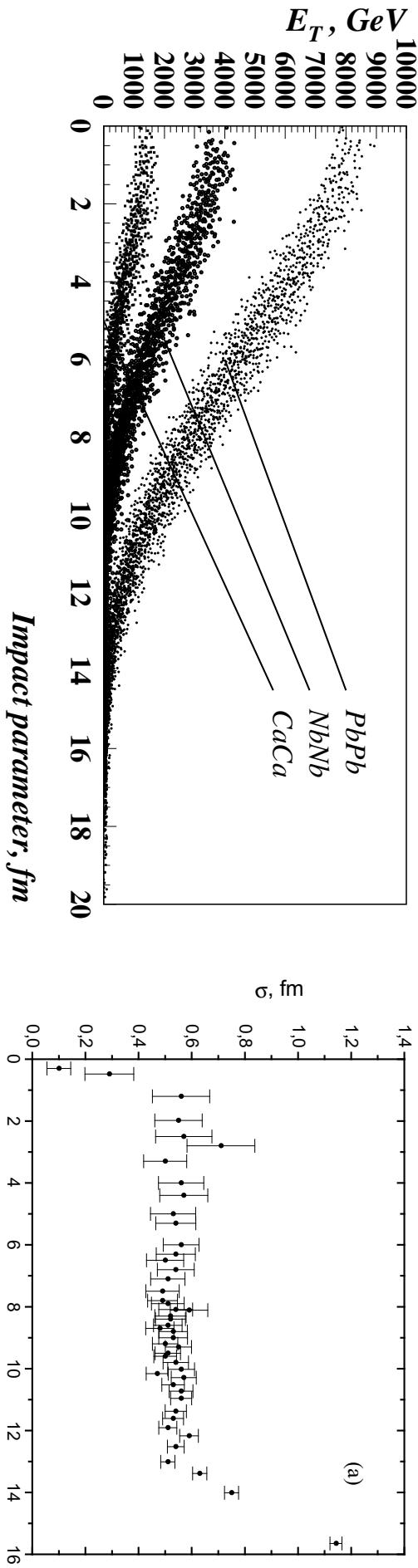
*Jet spatial resolution:*  $\sigma(\varphi_{rec} - \varphi_{gen}) = 0.045$      $\sigma(\eta_{rec} - \eta_{gen}) = 0.051$

Still it is better, than  $\eta$ ,  $\varphi$  size of HCAL tower  $0.087 \times 0.087$

## Impact parameter determination

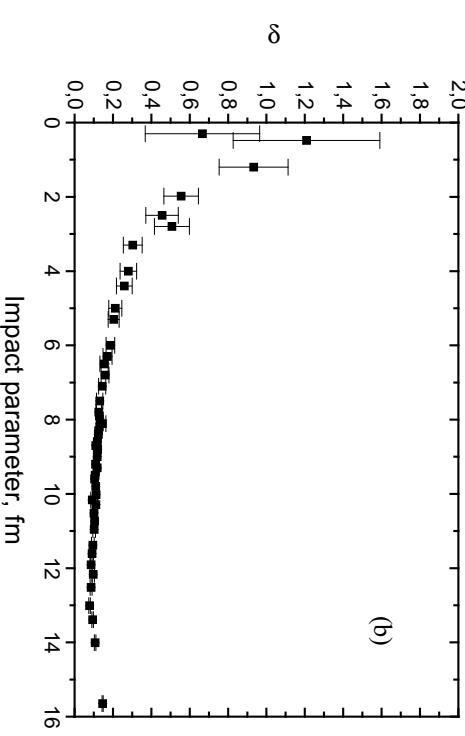
$E_T - b$  correlation in very forward rapidity  $3 \leq |\eta| \leq 5$

*Impact parameter resolution, Pb – Pb*



I. Damgov, V. Genchev, V. Kolosov, I. Lokhtin,  
 S. Petrushanko, L. Sarycheva, S. Shmatov, C. Teplov,  
 P. Zarubin, Part. Nucl. Lett. 107 (2001) 93; CERN CMS  
 Note 2001/055:

- very forward rapidity  $3 \leq |\eta| \leq 5$  is almost free of final state re-interactions, reflects initial nuclear geometry of a collision and can provide an adequate measurement of impact parameter via energy flow;
- the finite energy and spatial resolution of HF calorimeter results in no substantial degradation of accuracy of impact parameter determination.



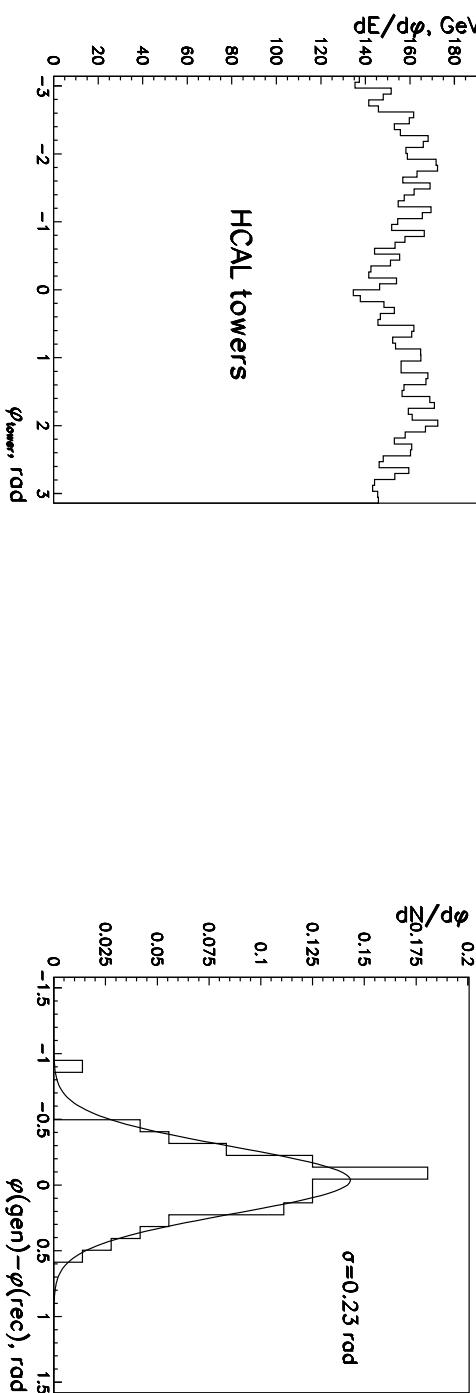
# Nuclear reaction plane determination

## 1. Event-by-event reaction plane reconstruction:

S.A. Voloshin, Y. Zhang, ZPC 70 (1996) 665; A.M. Poskanzer, S.A. Voloshin, PRC 58 (1998) 1671

$$\tan(2\varphi_{rec}) = \frac{\sum_i \omega^i \sin 2\varphi_i}{\sum_i \omega^i \cos 2\varphi_i}, \text{ weights } \omega^i = p_t^i \text{ (particle) or } \omega^i = E^i \text{ (calorimetric sector)}$$

*Azimuthal anisotropy of energy flow and event plane resolution : hydro-code, Pb-Pb, b=6 fm*



## 2. "Jet-flow" azimuthal correlation method (without event plane reconstruction):

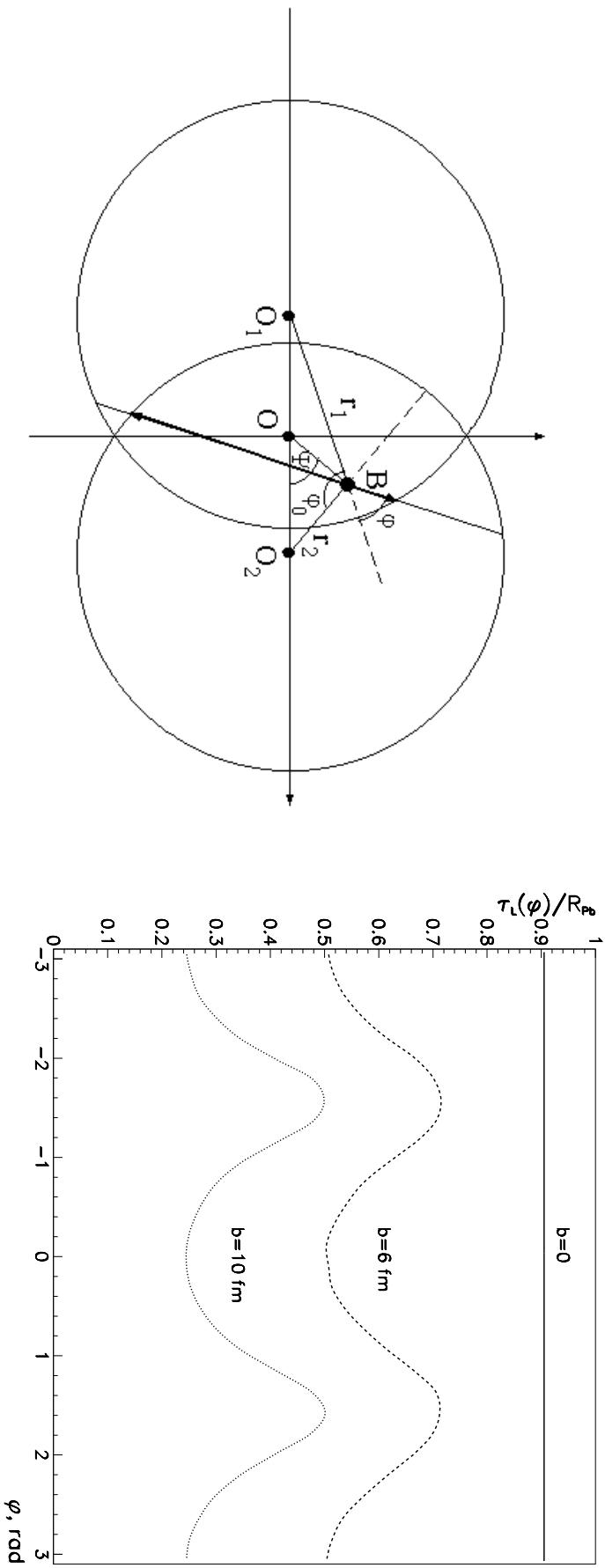
I.P. Lokhtin, L.I. Sarycheva and A.M. Snigirev, Phys. Lett. B 537 (2002) 261

$$v_2^{jet} \equiv <\cos 2\varphi_{jet}>_{event} = \sqrt{\frac{\langle \cos 2(\varphi_{jet} - \varphi) \omega(\varphi) \rangle}{\langle \cos 2(\varphi_1 - \varphi_2) \omega_1(\varphi_1) \omega_2(\varphi_2) \rangle}}.$$

The accuracy of the method improves with increasing multiplicity and particle (energy) flow azimuthal anisotropy, and is practically independent of the absolute values of azimuthal anisotropy of the jet itself. The obtained by such method accuracies of  $v_2^{jet}$  determination are comparable with one's arrived from direct reconstruction of the reaction plane.

## Nuclear geometry of jet quenching

The time of jet travel vs. azimuthal angle



$B(r \cos \psi, r \sin \psi)$  — jet production vertex,  $OO_2 = -O_1O = \frac{b}{2}r$  — distance from beam axis z to B

$$r_{1,2} = \sqrt{r^2 + \frac{b^2}{4}} \pm rb \cos \psi \quad \text{— distance from nucleus centers to B}$$

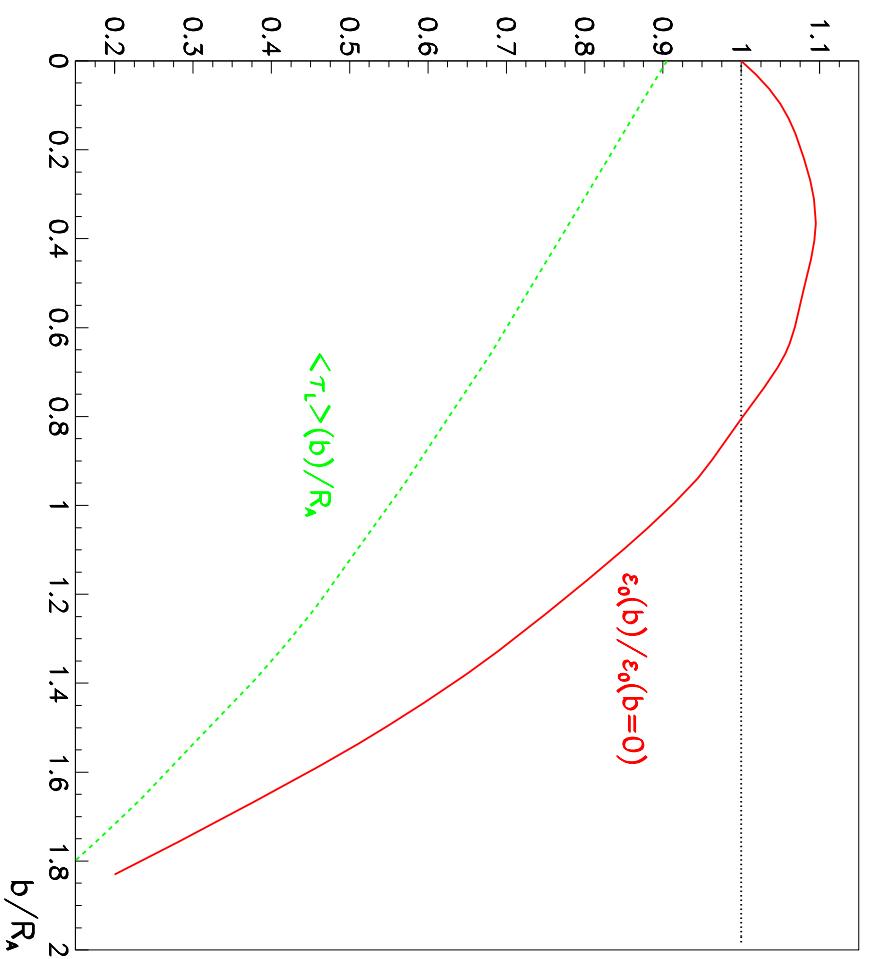
$$\text{Distribution } P_A(r, b, \psi) = \frac{\mathbf{T}_A(r_1) \cdot \mathbf{T}_A(r_2)}{\mathbf{T}_{AA}(b)},$$

$$T_{AA}(b) = \int_0^{2\pi} d\psi \int_0^{r_{\max}} dr dr T_A(r_1) T_A(r_2), \quad \mathbf{T}_A(\vec{r}) = \int_{-\infty}^{+\infty} \rho_A(\vec{r}, z) dz, \quad r_{\max} = \min\left(\sqrt{R_A^2 - \frac{b^2}{4} \sin^2 \psi \pm \frac{b}{2} \cos \psi}\right)$$

$\tau_L = \min\{\sqrt{R_A^2 - r_1^2 \sin^2 \phi - r_1 \cos \phi}, \sqrt{R_A^2 - r_2^2 \sin^2(\phi - \varphi_0) - r_2 \cos(\phi - \varphi_0)}\}$ , — proper time of jet escaping dense zone,  $\phi = \varphi - (\psi/|\psi|) \arccos \{(r \cos \psi + b/2)/r_1\}$ ,  $\varphi_0 = (\psi/|\psi|) \arccos (r^2 - b^2/4)/(r_1 r_2)$

# Initial energy density and jet path length vs. impact parameter

Initial energy density  $\varepsilon_0$  and average time  $\langle \tau_L \rangle$  of jet travel



$$\varepsilon_0(b) \propto T_{AA}(b)/S_{AA}(b)$$

Nuclear overlap function:

$$T_{AA}(b) = \int_0^{2\pi} d\psi \int_0^{r_{max}} dr T_A(\vec{r}_1) T_A(\vec{r}_2), \quad T_A(\vec{r}) = \int_{-\infty}^{+\infty} \rho_A(\vec{r}, z) dz$$

Transverse area of dense zone:  $S_{AA}(b) = \int_0^{2\pi} d\psi \int_0^{r_{max}} r dr = \left(\pi - 2 \arcsin \frac{b}{2R_A}\right) R_A^2 - b\sqrt{R_A^2 - \frac{b^2}{4}}$

# Medium-induced energy loss of massless hard parton

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*General kinetic integral equation:*

$$\Delta E(L, E) = \int_0^L dx \cdot \frac{dP}{dx}(x) \cdot \lambda(x) \cdot \frac{dE}{dx}(x, E), \quad \frac{dP}{dx}(x) = \frac{1}{\lambda(x)} \exp(-x/\lambda(x))$$

*Averaging over jet vertex  $(\varphi, R)$  and proper time  $\tau$  at  $E_0 \gg \Delta E$ :*

$$\langle \Delta E_{tot} \rangle = \int_0^{2\pi} \frac{d\varphi}{2\pi} \int_0^R dR \cdot P_A(R) \int_0^T d\tau \left( \frac{dE^{rad}}{dx}(\tau) + \sum_b \sigma_{ab}(\tau) \cdot \rho_b(\tau) \cdot \nu(\tau) \right)$$

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**1. Collisional loss**       $\nu = \left\langle \frac{t}{2m_0} \right\rangle = \frac{1}{2} \left\langle \frac{1}{m_0} \right\rangle \cdot \langle t \rangle \simeq \frac{1}{4T\sigma_{ab}} \int_0^{t_{max}} dt \frac{d\sigma_{ab}}{dt} t$

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

## 2. Radiative loss

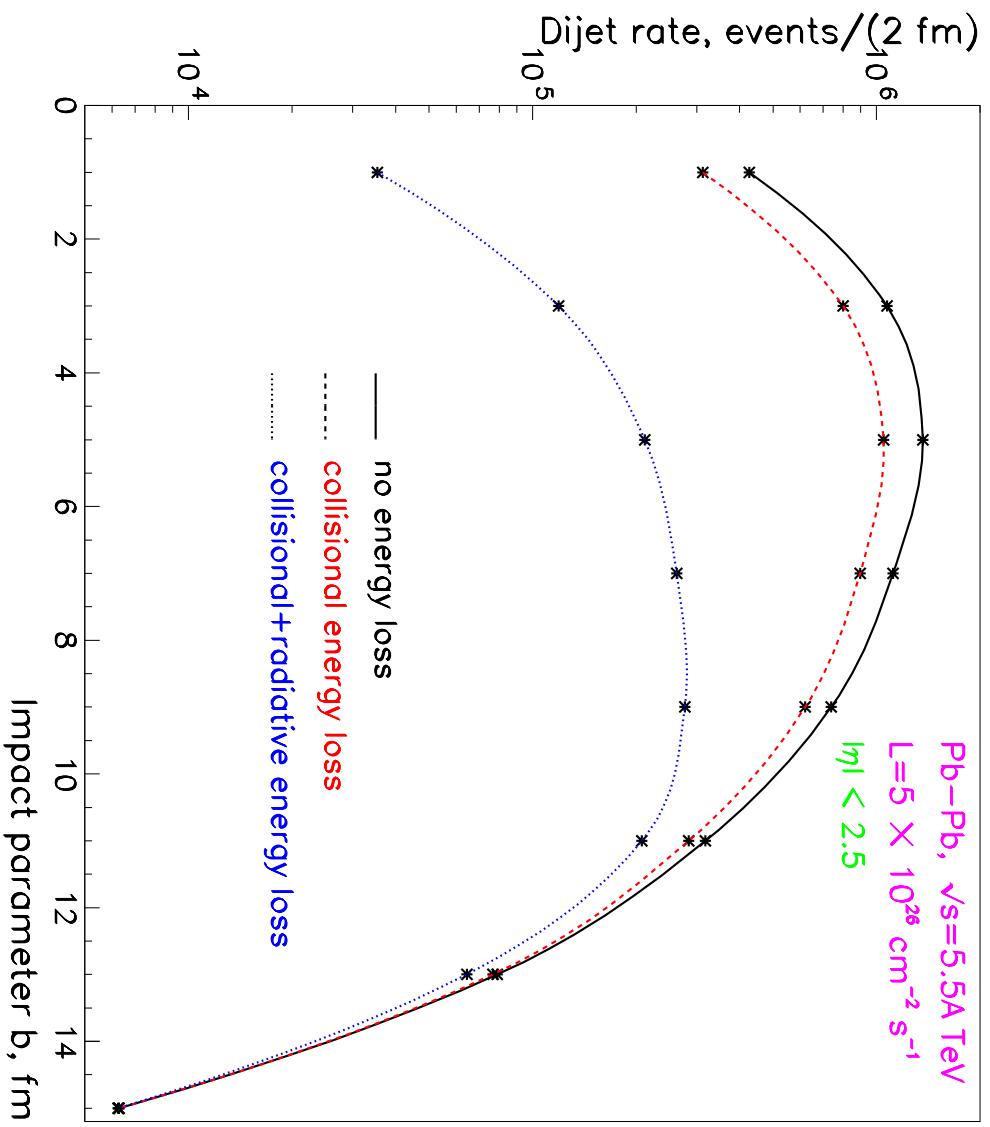
(R.Baier, Yu.L.Dokshitzer, A.Mueller, D.Schiff. NPB 531 (1998) 403)

$$\frac{dE}{dx} = \frac{2\alpha_s C_R}{\pi \tau_L} \frac{\int_E^{E_{LPM} \sim \lambda_g \mu_D^2} d\omega \left[ 1 - y + \frac{y^2}{2} \right] \ln |\cos(\omega_1 \tau_1)|}{\sqrt{i \left( 1 - y + \frac{C_R}{3} y^2 \right) \bar{\kappa} \ln \frac{16}{\bar{\kappa}}}}, \quad \omega_1 = \frac{\mu_D^2 \lambda_g}{\omega(1-y)}, \quad \tau_1 = \frac{\tau_L}{2\lambda_g}, \quad y = \frac{\omega}{E}, \quad C_R = \frac{4}{3}$$

## *Jet quenching observables: impact parameter dependence*

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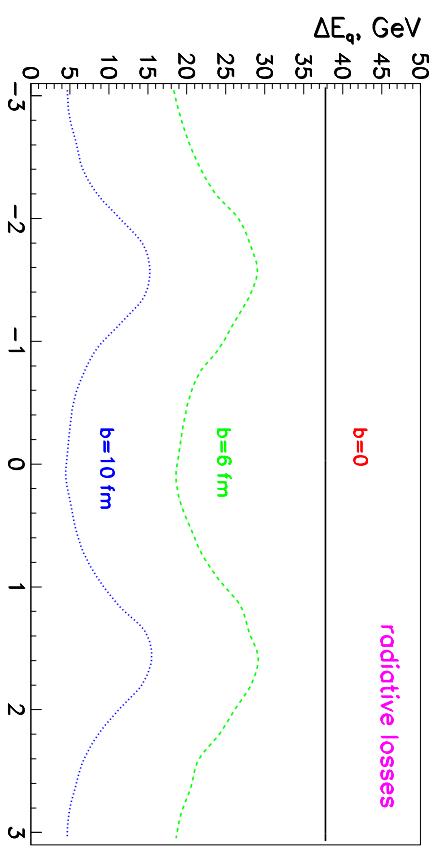
Jet+Jet rates for two LHC running weeks,  $E_{\tau}^{\text{jet}1,2} > 100 \text{ GeV}$



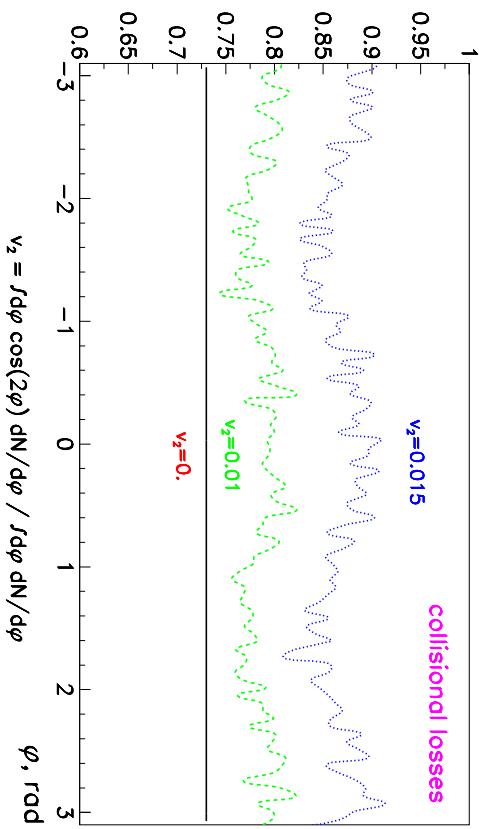
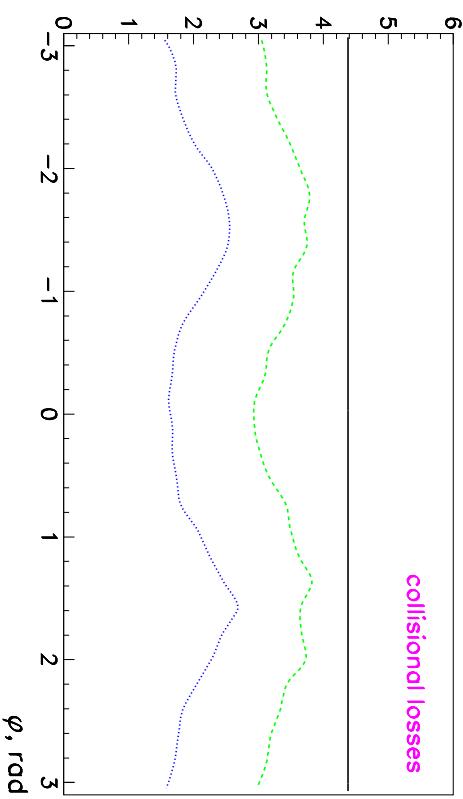
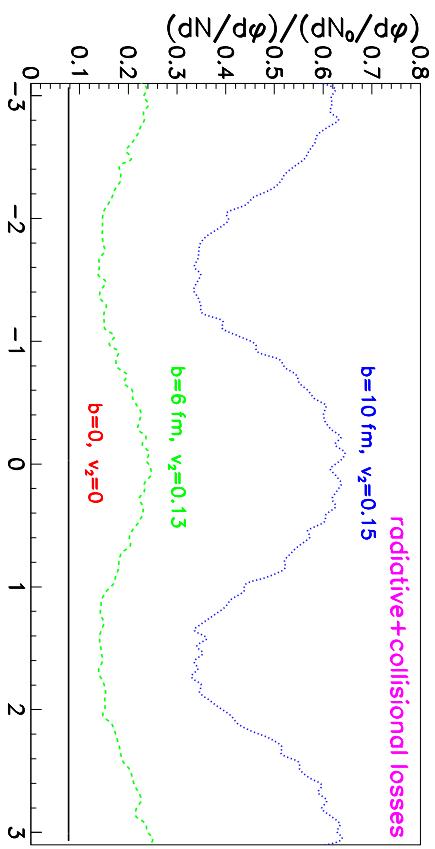
$$T = T_0 (\tau_0 / \tau)^{1/3}, \quad T_0 = 1 \text{ GeV}, \quad \tau_0 = 0.1 \text{ fm}/c, \quad N_t = 0, \quad R_{pb} = 6.8 \text{ fm}$$

# Jet quenching observables: azimuthal anisotropy

Energy losses of quark with  $p_t^0 = 100$  GeV vs. azimuthal angle



Normalized jet rates vs. azimuthal angle,  $p_t^{jet} > 100$  GeV,  $|\eta| < 1.5$



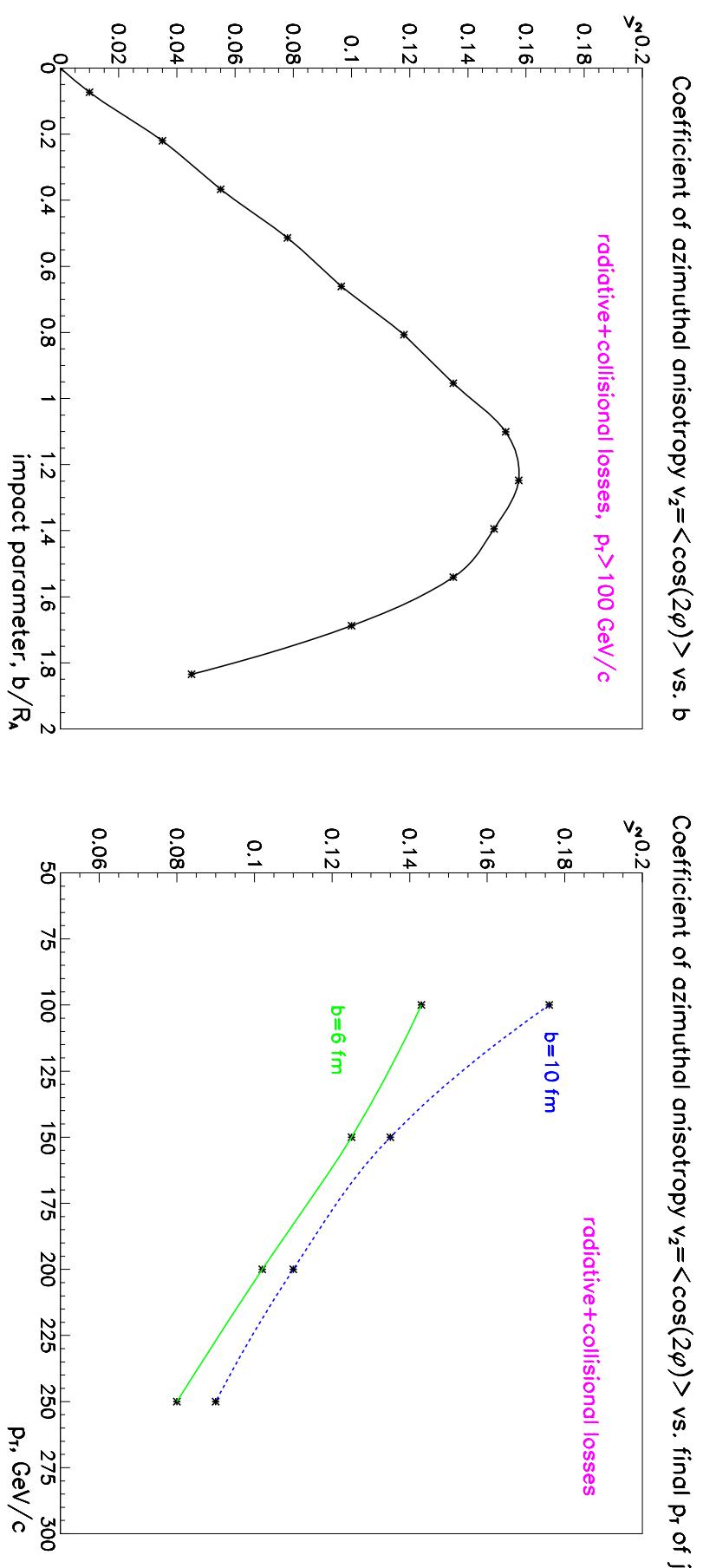
$$T = T_0(\tau_0/\tau)^{1/3}, \quad T_0 = 1 \text{ GeV}, \quad \tau_0 = 0.1 \text{ fm}/c, \quad N_f = 0, \quad R_{pb} = 6.8 \text{ fm}$$

$$T = T_0(\tau_0/\tau)^{1/3}, \quad T_0 = 1 \text{ GeV}, \quad \tau_0 = 0.1 \text{ fm}/c, \quad N_f = 0, \quad R_{pb} = 6.8 \text{ fm}$$

I.P. Lokhtin, S.V. Petrushanko, L.I. Sarycheva and A.M. Snigirev, hep-ph/0112180, in Proc. of International Conference on Physics and Astrophysics of Quark-Gluon Plasma (Jaipur, India, 26-30 Nov 2001); Phys. At. Nucl. 65 (2002) 974

## *Jet quenching observables: azimuthal anisotropy (cont.)*

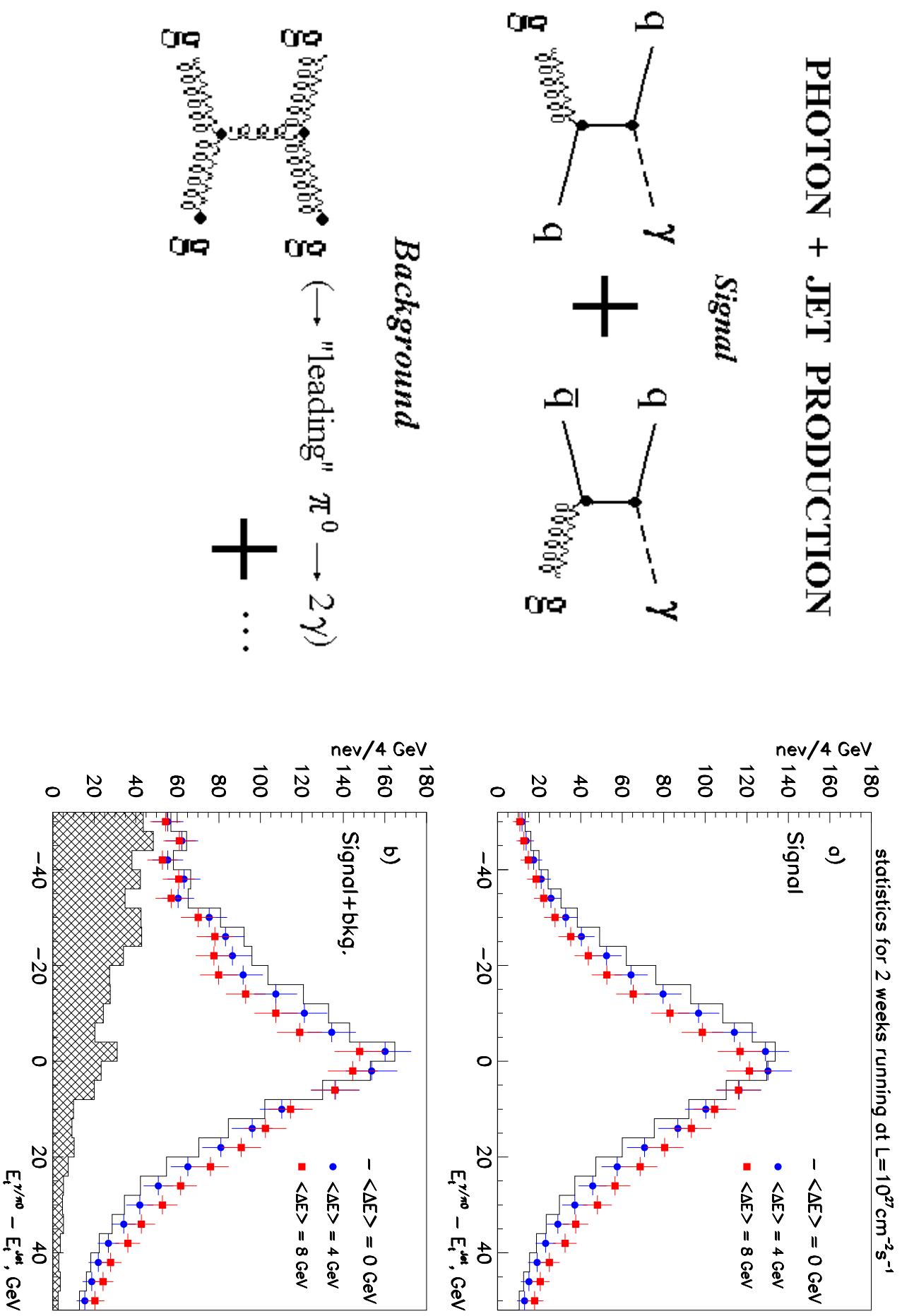
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$$T = T_0 (\tau_0 / \tau)^{1/3}, \quad T_0 = 1 \text{ GeV}, \quad \tau_0 = 0.1 \text{ fm}/c, \quad N_t = 0, \quad R_{pe} = 6.8 \text{ fm}$$

I.P. LOKHTIN, S.V. PETRUSHANKO, L.I. SARYCHEVA AND A.M. SNIGIREV, hep-ph/0112180,  
in Proc. of International Conference on Physics and Astrophysics of Quark-Gluon  
Plasma (Jaipur, India, 26-30 Nov 2001); Phys. At. Nucl. 65 (2002) 974

## Jet quenching observables: $\gamma + \text{jet channel}$



## *Jet quenching observables: dimuon modes*

**Signal I:**

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

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

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

Drell-Yan

$q\bar{q} \rightarrow \mu^+\mu^-$   
 $\pi^\pm, K^\pm \rightarrow \mu^\pm \nu(\tilde{\nu})$  Combinatorial background (subtracted using like-sign spectra)

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

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

$g \rightarrow J/\psi \rightarrow \mu^+\mu^-$  primary  $J/\psi$

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

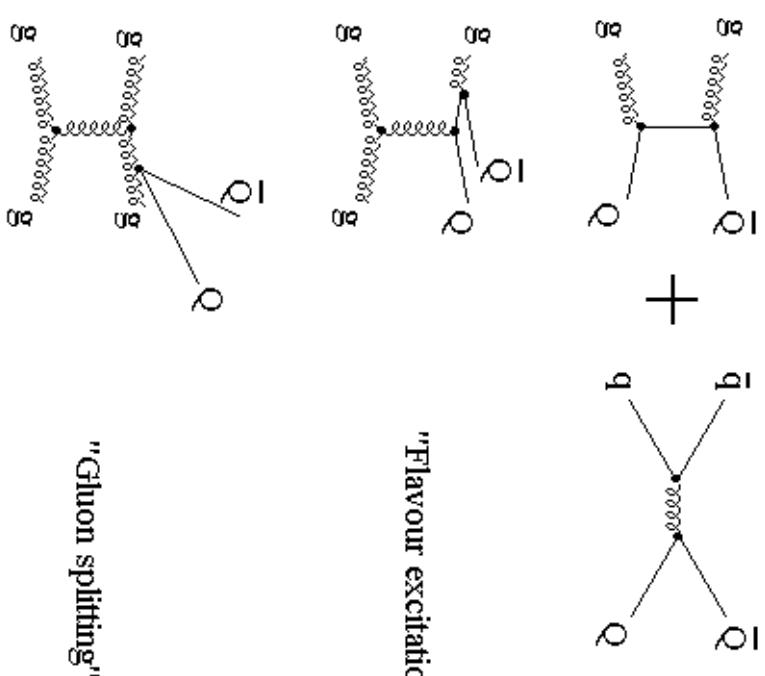
*Linear superposition of independent nucleon-nucleon sub-collisions (no collective effects):*

$$\sigma_{AA}^h = A^2 \sigma_{pp}^h$$

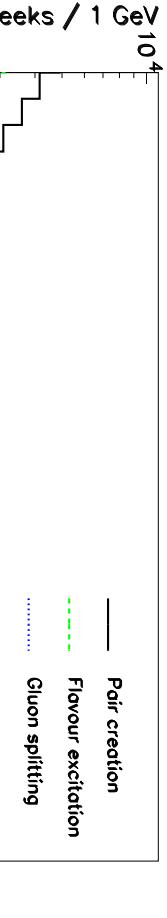
Nuclear collective effects:

- **initial state:** "nuclear shadowing",  $f_A(x, Q^2) \neq A f_p(x, Q^2)$
- **final state:** medium-induced energy loss and multiple scattering of heavy quarks

# *Heavy quark production at very high energies*



"Flavour excitation"



**Initial production from  $b\bar{b}$**

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

- the contribution of "flavour excitation" and "gluon splitting" can be important and even dominating at LHC;

- for various mechanisms there are similar spectra of single quarks, but different correlations between  $Q$  and  $\bar{Q}$ .

(PYTHIA prediction)

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

## *Medium-induced rescattering of a heavy quark*

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

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

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

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

- 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:

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

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

# Medium-induced gluon radiation of a heavy quark

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*General kinetic integral equation:*

$$\Delta E(L, E) = \int_0^L dx \cdot \frac{dP}{dx}(x) \cdot \lambda(x) \cdot \frac{dE}{dx}(x, E), \quad \frac{dP}{dx}(x) = \frac{1}{\lambda(x)} \exp(-x/\lambda(x))$$

*Averaging over jet vertex  $(\varphi, R)$  and proper time  $\tau$  at  $E_0 \gg \Delta E$ :*

$$\langle \Delta E_{tot} \rangle = \int_0^{2\pi} \frac{d\varphi}{2\pi} \int_0^R dR \cdot P_A(R) \frac{\tau_L}{\tau_0} \int_0^{\tau_L} d\tau \left( \frac{dE^{rad}}{dx}(\tau) + \sum_b \sigma_{ab}(\tau) \cdot \rho_b(\tau) \cdot \nu(\tau) \right)$$


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

$$\frac{dE^{rad}}{dx} = E \cdot \rho \int_0^{1-M_q/E} dy \cdot \frac{d\sigma^{BH}}{dy} \cdot y \cdot S(y), \quad \frac{d\sigma^{BH}}{dy} = \frac{4\alpha_s \cdot C_3(y) \cdot (4 - 4y + 2y^2)}{9\pi y [M_q^2 y^2 + m_g^2 (1-y)]^{1/4}},$$

$$C_3(y) = \frac{\pi \alpha_s^2 C_{ab}}{4} [9(1 + (1-y)^2 - y^2) \ln \frac{2(\alpha_s^2 \rho \cdot E \cdot y(1-y))}{\mu_D},$$

$$S^{incoh} = 1, \quad S^{LPM}(y, E, \tau_L) < 1$$

Yu.Dokshitzer and D.Kharzeev, Phys.Lett. B 519 (2001) 199 ("dead cone" approximation) :

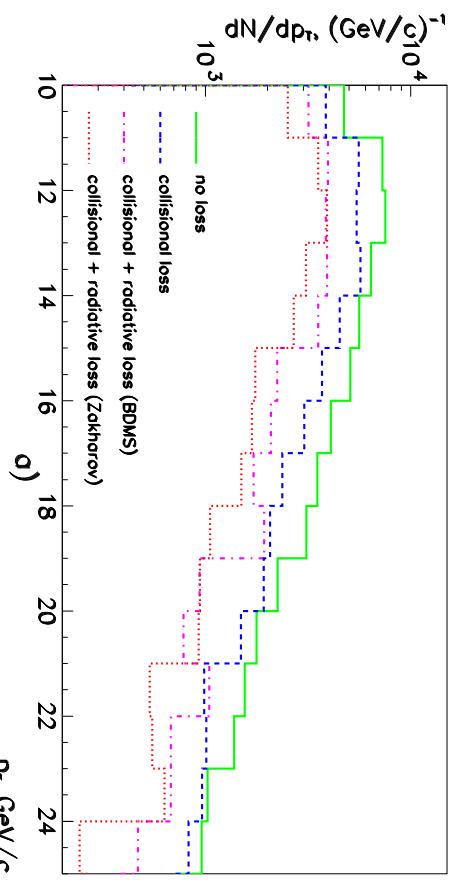
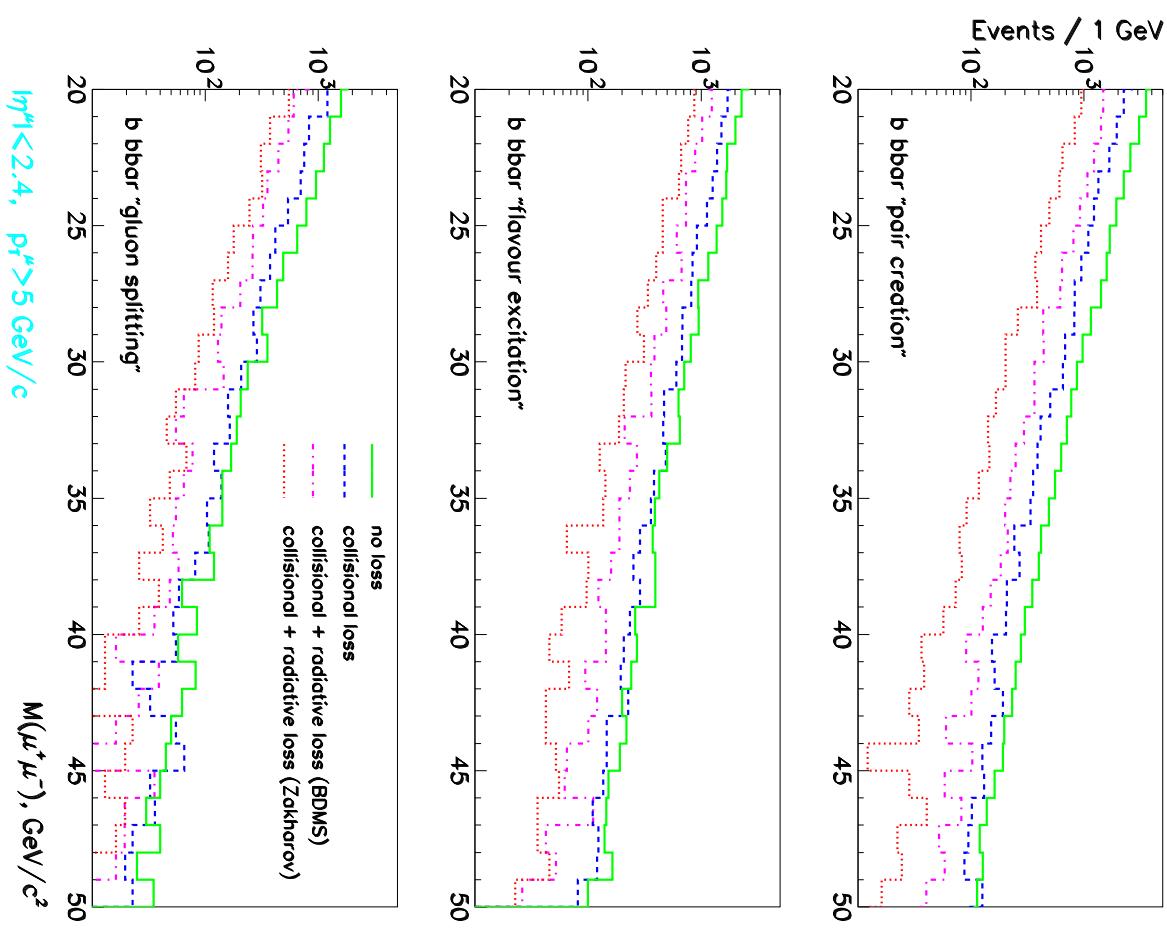
$$\frac{dE^{rad}}{dx}|_{M_q} = \frac{1}{(1 + (l\omega)^{3/2})^2} \cdot \frac{dE}{dx}|_{M_q=0}, \quad l = \left(\frac{\lambda}{\mu_D^2}\right)^{1/3} \cdot \left(\frac{M_q}{E}\right)^{4/3}$$


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# Jet quenching in $B\bar{B} \rightarrow \mu^+\mu^-$ and $B \rightarrow J/\psi \rightarrow \mu^+\mu^-$ modes

Invariant mass distribution of  $\mu^+\mu^-$  in Pb–Pb,  $\sqrt{s}=5.5$  TeV

$P_t$  and  $\eta$  distributions of  $J/\psi (\rightarrow \mu^+\mu^-)$  from B-decay in Pb–Pb  
**NUCLEAR SHADOWING + ENERGY LOSSES**



b)

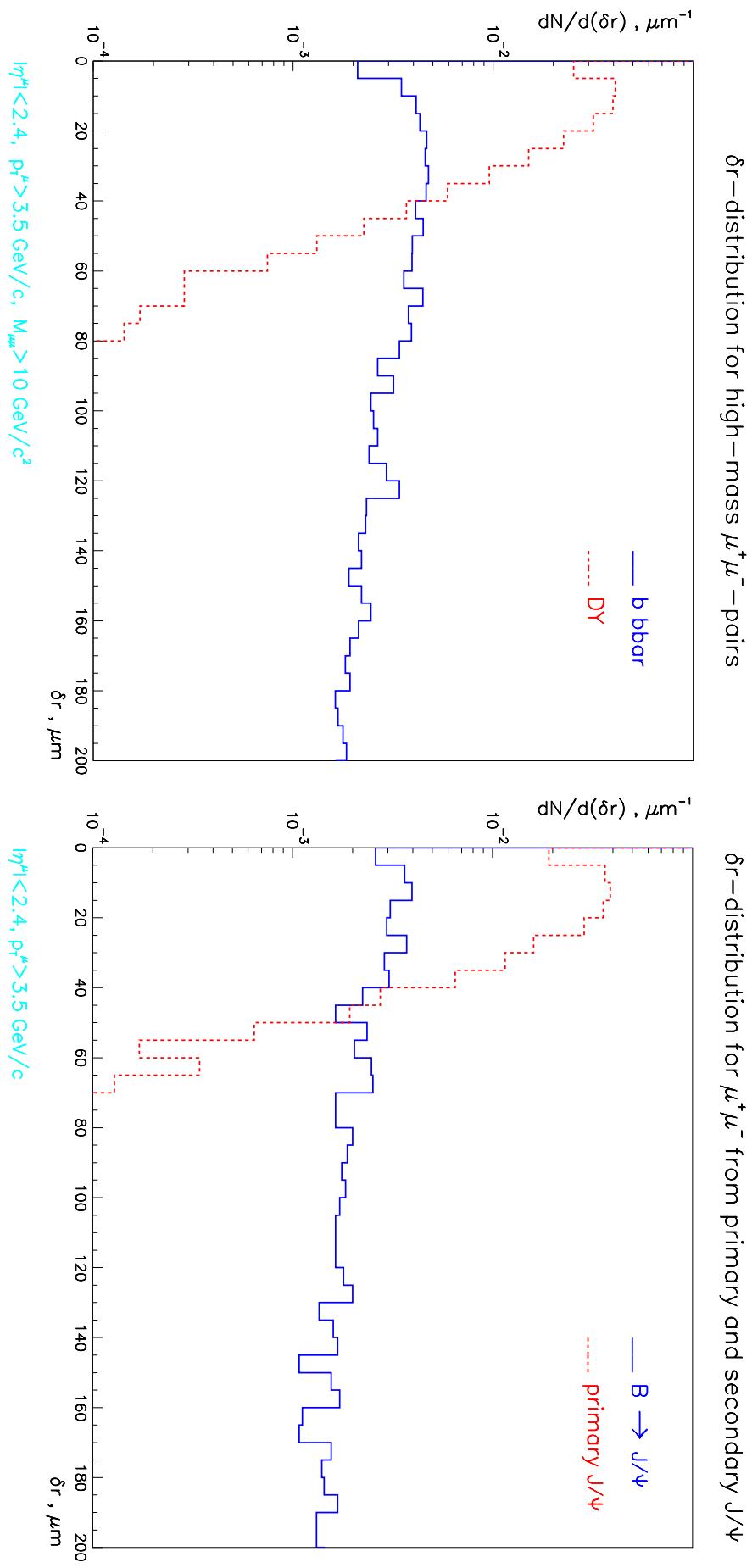
I. Lokhtin, A. Snigirev, EPJ C 21 (2001)

155; JPG 27 (2001) 2365; CERN CMS Note

2001/008; NPA 702 (2002) 346 – see for details.

$|\eta| < 2.4$ ,  $p_t > 5 \text{ GeV}/c$

# $B\bar{B} \rightarrow \mu^+\mu^-$ and $B \rightarrow J/\psi$ vs. background: vertex finding



(Fast simulation)

$\delta r$  is the transverse distance between the intersection points with the beam line (points with minimal distance to the beam axis) belonging two different muon tracks.

I. Lokhtin, A. Snigirev, JPG 27 (2001) 2365; CERN CMS Note 2001/008

## *Jet quenching at LHC: Summary*

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large acceptance CMS hadronic and e.m. calorimeters + tracker:

- good energy and spatial resolution for hard jets and photons
  - excellent momentum resolution for muons
  - primary and secondary vertex finding is possible
- 

jet pair production:

- jet reconstruction with 100% efficiency and purity is possible at  $E_T \geq 100$  GeV
  - large statistics allows to study  $b$ - and  $\varphi$ -dependences
  - impact parameter and event plane determination are possible
- 

$\gamma +$  jet production:

- statistics is enough to study  $P_T$ -imbalance
  - $\pi_0$  background problem is under solution
- 

heavy quarks in  $B\bar{B} \rightarrow \mu^+\mu^-$  and  $B \rightarrow J/\psi \rightarrow \mu^+\mu^-$  modes

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- in-medium energy loss of b-quarks can be observable over nuclear shadowing
  - contribution of "showering" heavy quark pairs can be important
  - extraction of signal from correlated and uncorrelated background is possible
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