The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

SMR/1842-17

International Workshop on QCD at Cosmic Energies III

28 May - 1 June, 2007

Lecture Notes

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CMS Heavy Ion Physics

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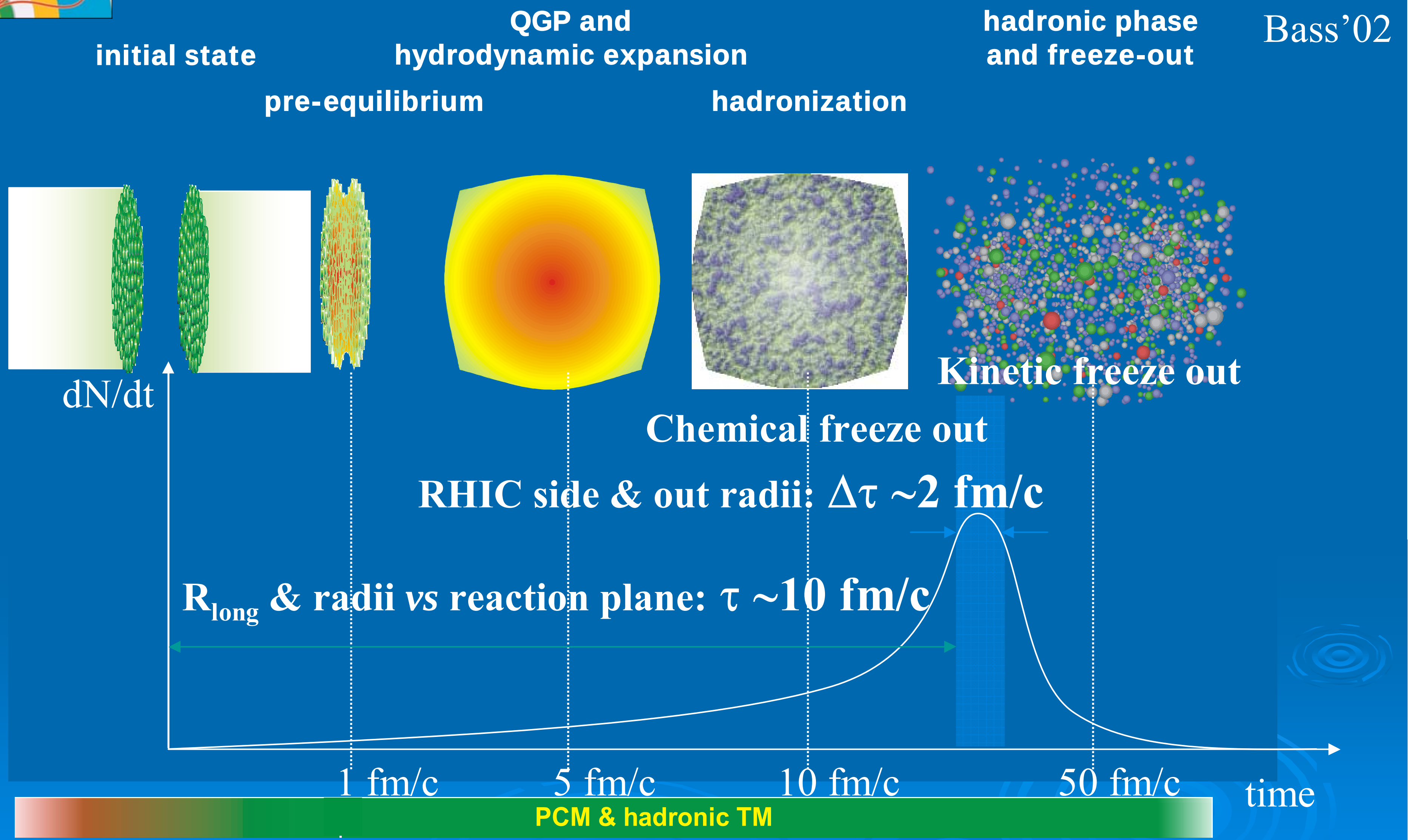
For CMS Collaboration

<u>CMS Heavy-Ion Groups:</u>
Moscow, Lyon, CERN, Budapest, Athens, Ioannina, Demokritos, Lisbon, Adana, MIT, Illinois, Los Alamos, Maryland, Minnesota, Iowa, California Davis, Kansas, Mumbai, Auckland, Seoul, Vanderbilt, Colorado, Zagreb

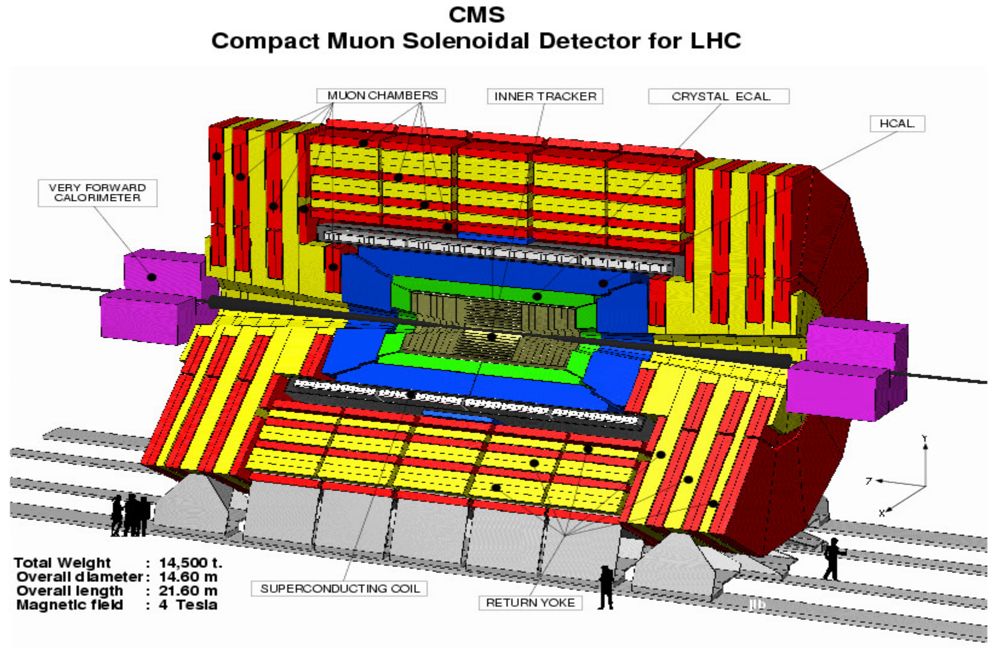
1. CMS detector and Heavy Ion program
2. Quarkonia and heavy quarks
3. Jet cross section and expected event rate
4. Jet quenching in heavy ion collisions
5. Azimuthal anysotropy
6. Global event characterization
7. Z^0/γ^*+jet correlations
8. Summary
9. Appendix

Expected evolution of HI collisions

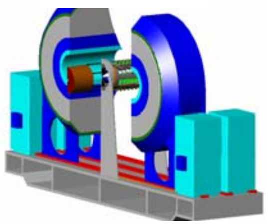


Heavy Ion Physics at LHC

1.1 CMS detector

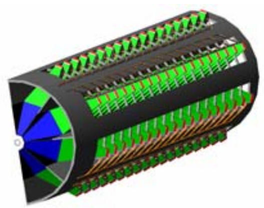


TOTEM



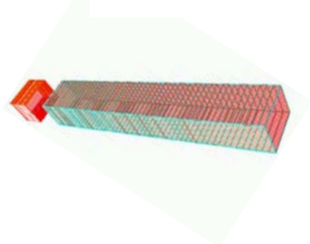
$5.3 \leq \eta \leq 6.7$

CASTOR



$5.2 \leq |\eta| \leq 6.6$

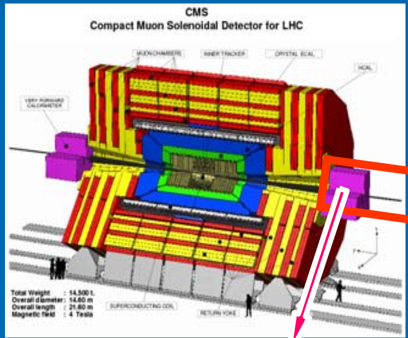
ZDC



$8.3 \leq |\eta|$

- Si tracker with pixels $|\eta| < 2.4$ good efficiency and low fake rates for $p_t > 1$ GeV, excellent momentum resolution, Δp: $\Delta p_t/p_t < 2\%$
- Muon chambers $|\eta| < 2.4$
- Fine grained high resolution calorimetry (ECAL, HCAL, HF) with hermetic coverage up to $|\eta| < 5$
- $B = 4$ T
- TOTEM ($5.3 \leq \eta \leq 6.7$)
  CASTOR ($5.2 < |\eta| < 6.6$)
  ZDC ($z = \pm 140$ m, $8.3 \leq |\eta|$)
- Fully functional at highest multiplicities; high rate capability for (pp, pA, AA), DAQ and HLT capable of selecting HI events in real time

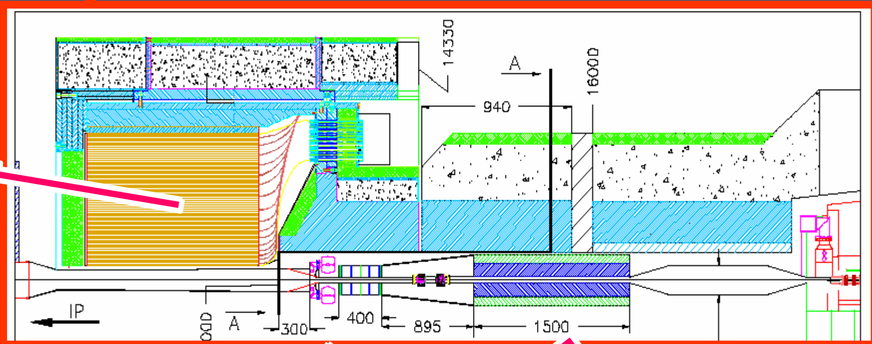
1.2 Forward Region Layout



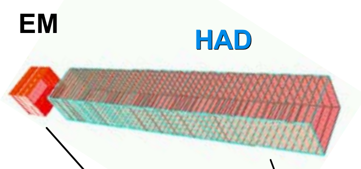
Forward HCal

$(3 \leq |\eta| \leq 5)$

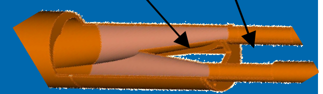
$|\eta| > 3$



ZDC

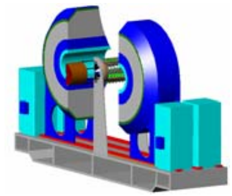


$(8.3 \leq |\eta|)$



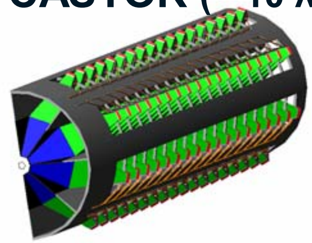
$(z = \pm 140 \text{ m})$

TOTEM



$(5.3 \leq \eta \leq 6.7)$

CASTOR $(\sim 10\ \lambda_I)$



$(5.2 \leq \eta \leq 6.6)$

1.3 CMS Trigger rates for HIC

- **Trigger**
  - **Level 1 Trigger**
    - muon chamber + calorimeter information
    - response time ~ 3μs
  - **High Level Trigger**
    - full minbias event information available
    - runs offline algorithms on every PbPb event

$\mathcal{L}(cm^{-2}s^{-1})$	10^{27}	10^{34}
Level-1	Pb+Pb	p+p
Collision rate	3kHz (8kHz peak)	1GHz
Event rate	3kHz (8kHz peak)	40MHz
Output bandwidth	100 GByte/sec	100 GByte/sec
Rejection	none	99.7%

High Level Trigger	Pb+Pb	p+p
Input event rate	3kHz (8kHz peak)	100kHz
Output bandwidth	225 MByte/sec	225 MByte/sec
Output rate	10-100Hz	150Hz
Rejection	97-99.7%	99.85%

1.4 Heavy Ion program at CMS

- **Excellent detector for high p_T probes of quark gluon plasma** (high rates and large cross sections and high acceptance for calorimeters and muon system):
  - Quarkonia (J/ψ, Υ)
  - Heavy quarks ($b\bar{b}$) and Z^0
  - High p_T jets
  - High energy photons
- **Correlations**
  - jet-jet
  - jet-γ, jet-γ^*/Z^0
  - multijets
  - angular and momentum correlation (e.g. HBT of direct γ)

1.5 Heavy Ion program at CMS

- **Global event characterization**
  - Centrality determination with forward calorimetry
  - Energy flow
  - Charged particle multiplicity
  - Azimuthal anisotropy
  - Low-p_T particle identification

- **Forward physics and ultraperipheral interactions**
  - Limiting Fragmentation, Saturation, Color Glass Condensate
  - Electromagnetic interactions ($\gamma\ \gamma$)
  - Exotica

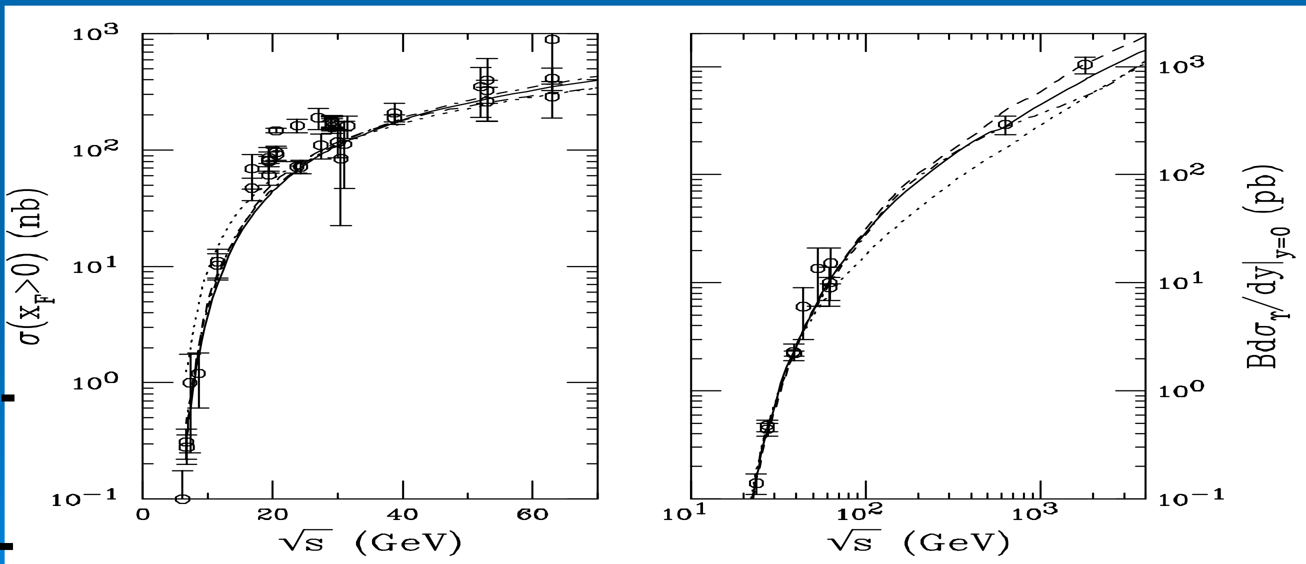
- **Monte-Carlo simulation tools:**
  - PYTHIA, HIJING, PYQUEN/HYDJET

2.1 Quarkonia and heavy quarks from SPS and RHIC to LHC

Increase energy √S=17-200 GeV/n-n → 5500 GeV/n-n

Plasma hotter and longer lived than at RHIC
Unprecedented Gluon densities
Access to lower x, higher Q^2
Availability of new probes

J/Ψ   Υ

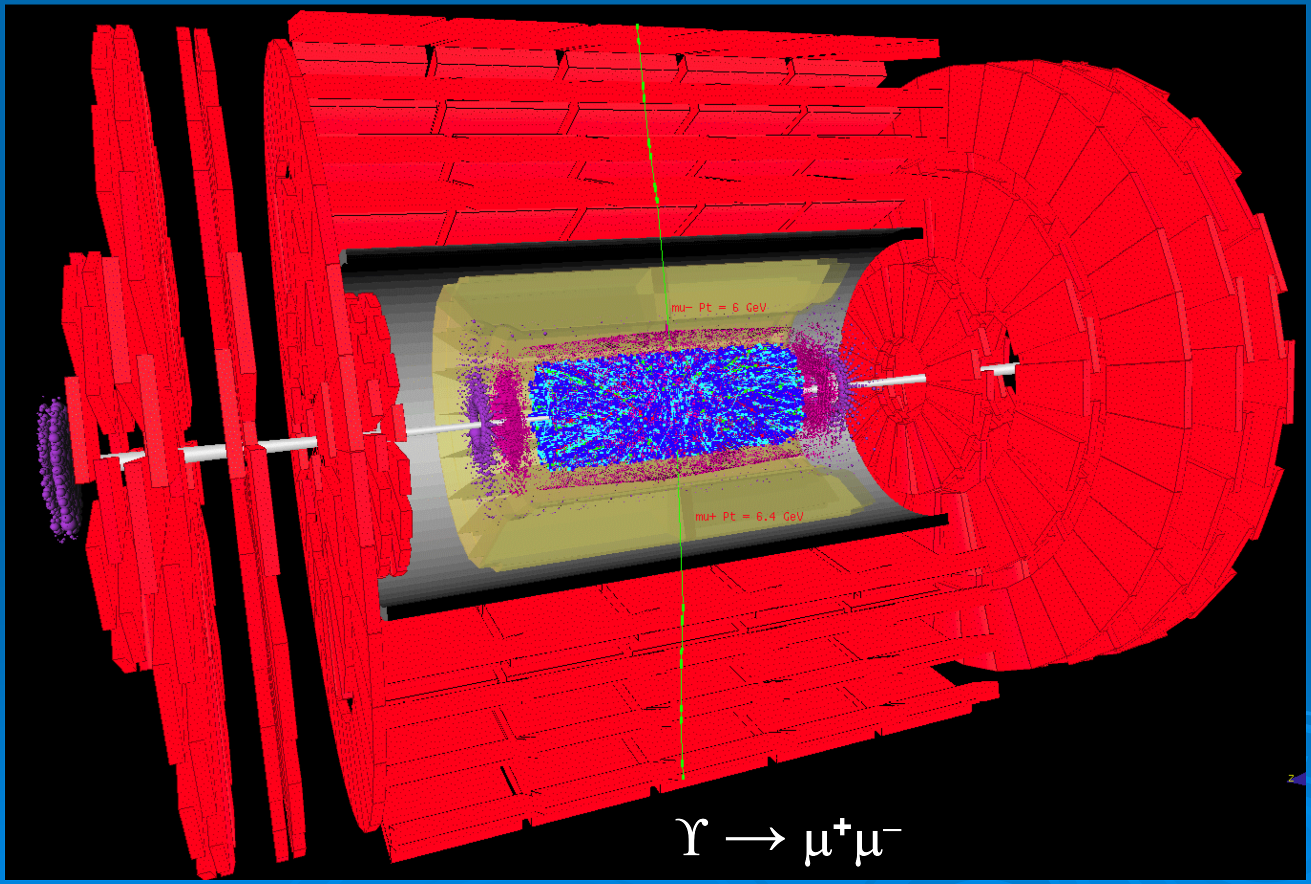


LHC

- Quarkonia with high statistics (J/ψ, ψ'; Υ, Υ', Υ'')
- Large cross-section for J/ψ and Υ families
- Different melting for Υ, Υ', Υ''
- Z^0 with high statistics. The possibility to use ET balance of $Z^0(\gamma^*)$+jet to observe medium induced energy loss.
- Large cross-section for heavy-quarks (b, c): observation of medium induced energy loss in high mass dimuon spectrum and secondary J/ψ

2.2 Quarkonia (J/ψ, ϒ): μμ reconstruction

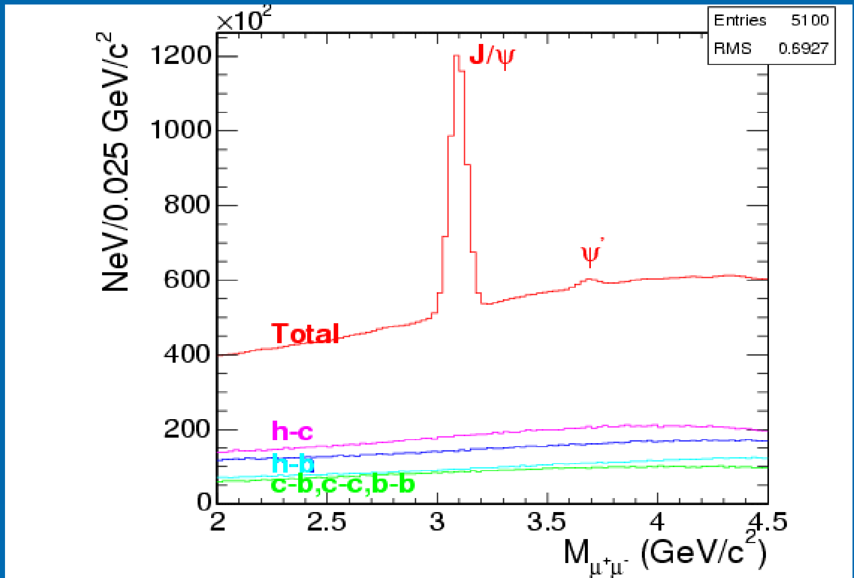
MC simulation/visualization of Pb+Pb event
($dN_{ch}/d\eta|_{\eta=0}$ ~ 3000) using the pp software framework

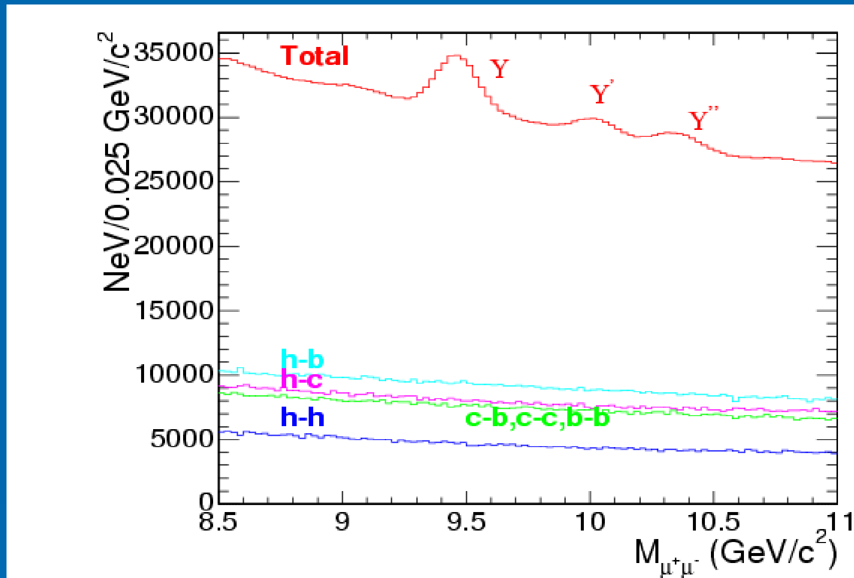


2.3 J/ψ and ϒ spectra for multiplicity $dN_{ch}/d\eta = 2500$

For Pb-Pb at integrated luminosity 0.5 nb^{-1}

π/K decays into μμ | **b,c-hadrons into μμ**

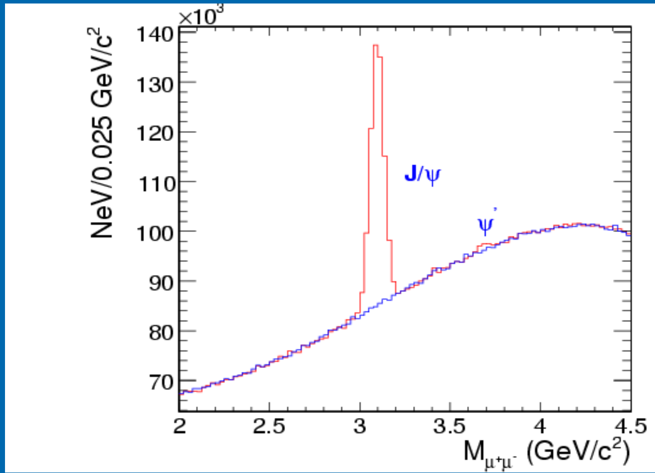




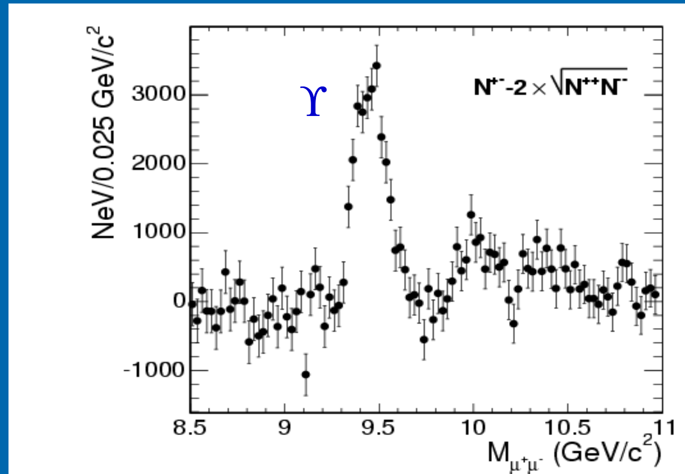
	S/B	N
J/ψ	1.2	180000
ϒ	0.12	25000

Combinatorial background:
Mixed sources, i.e.
1 μ from π/K + 1 μ from J/ψ
1 μ from b/c + 1 μ from ϒ

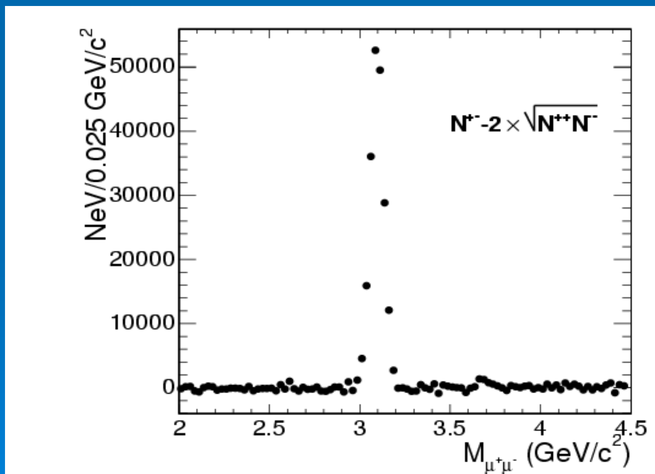
2.4 J/ψ and ϒ spectra (subtraction of the like sign spectra)



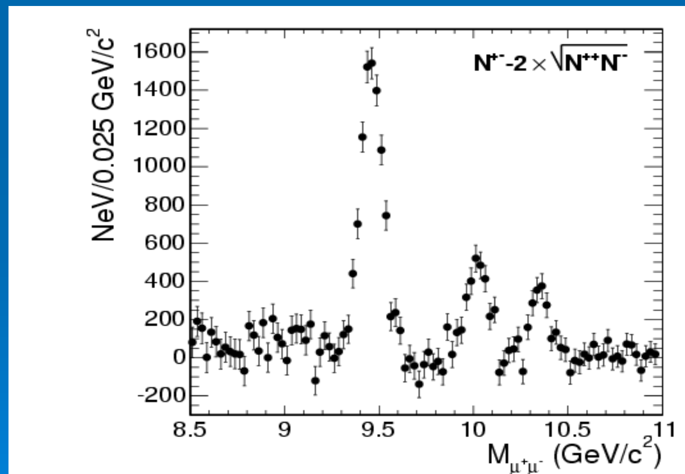
both muons $|\eta| < 2.4$



both muons $|\eta| < 2.4$

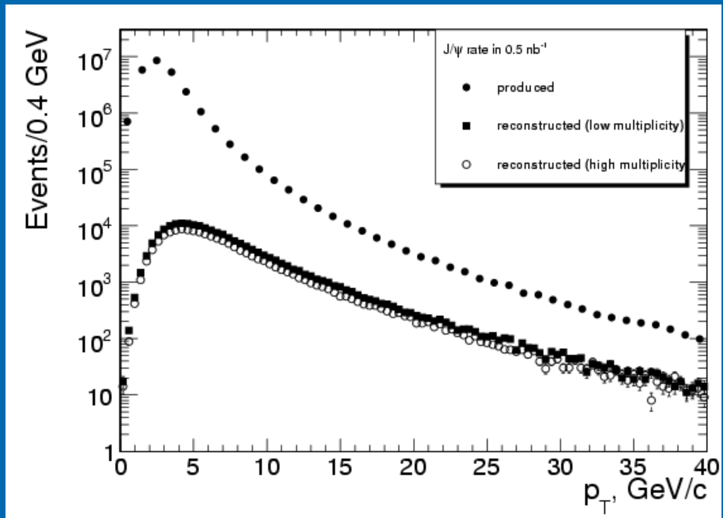


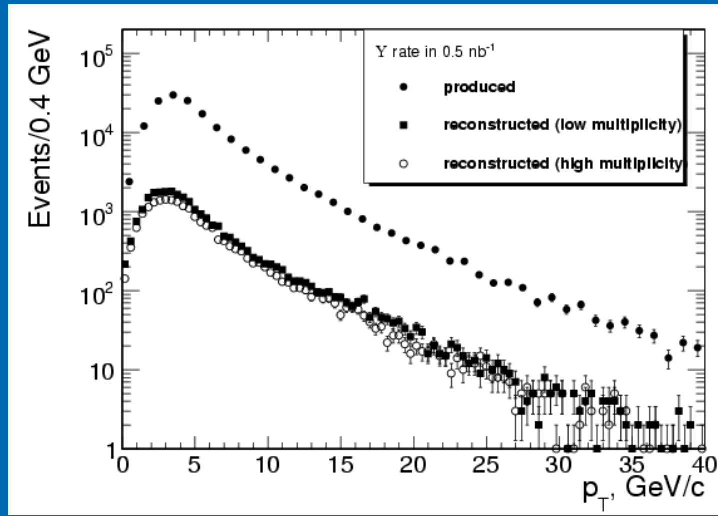
both muons $|\eta| < 0.8$

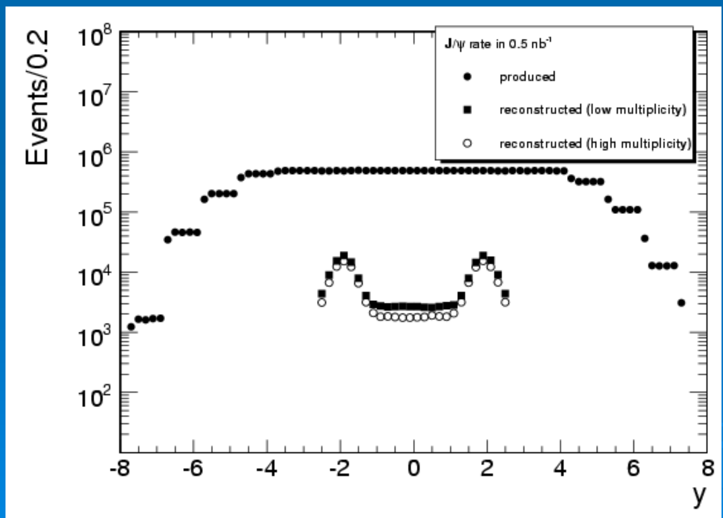


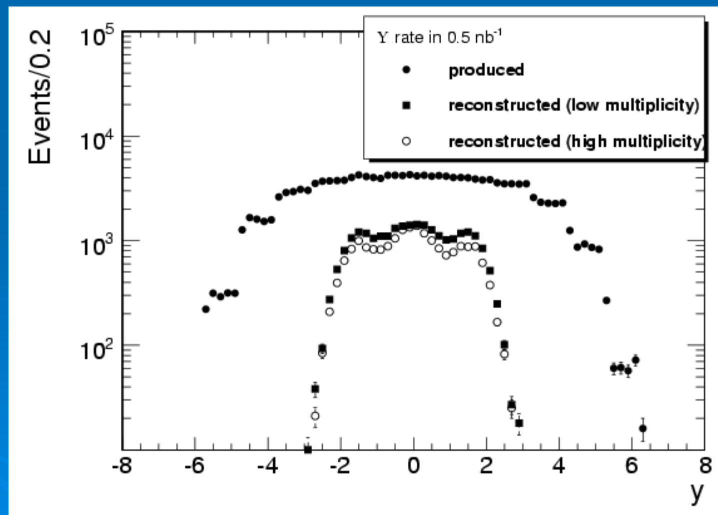
both muons $|\eta| < 0.8$

2.5 J/ψ and ϒ p_T and Y distribution, PbPb

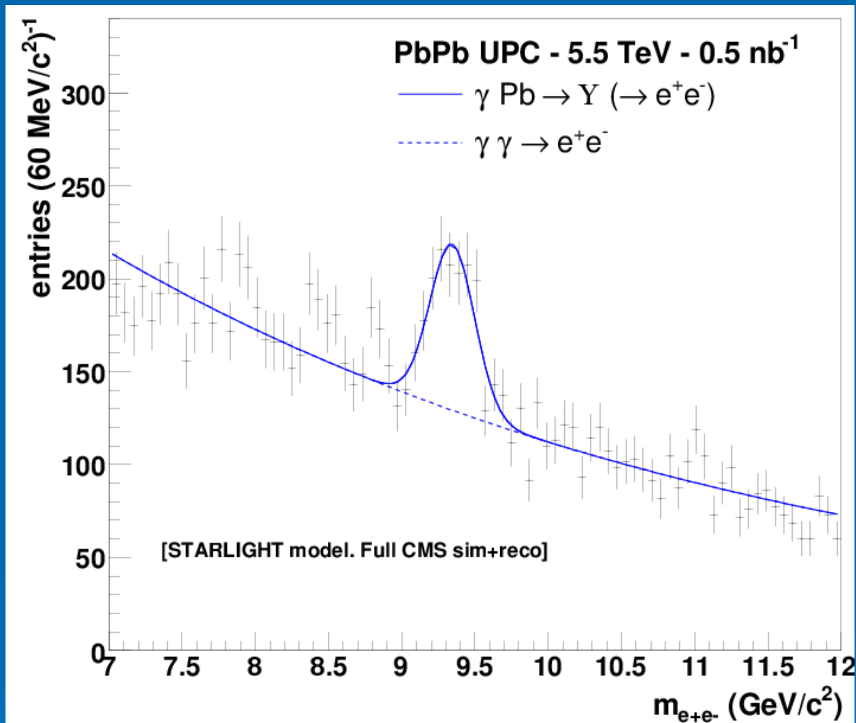


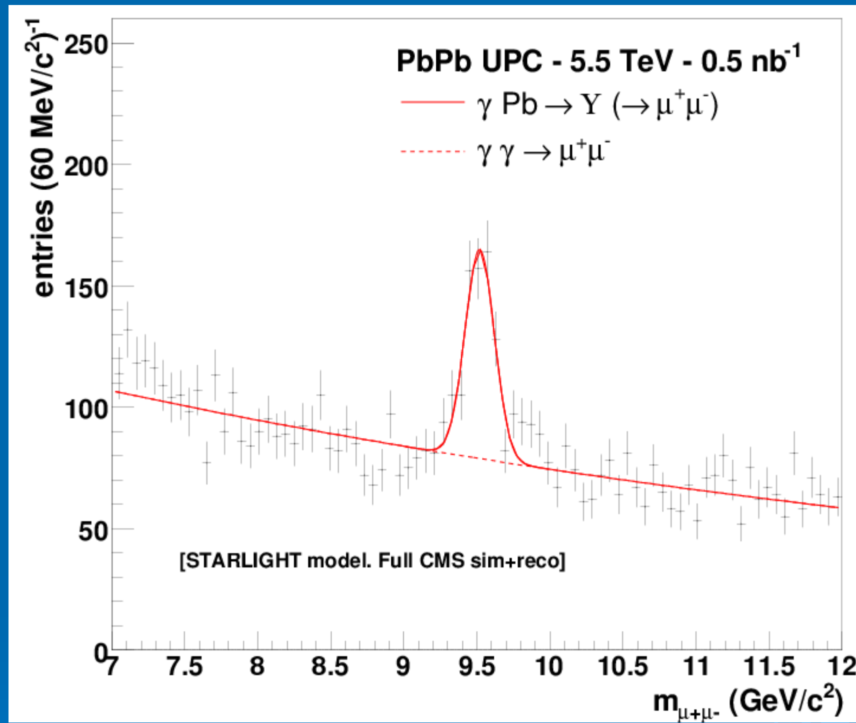






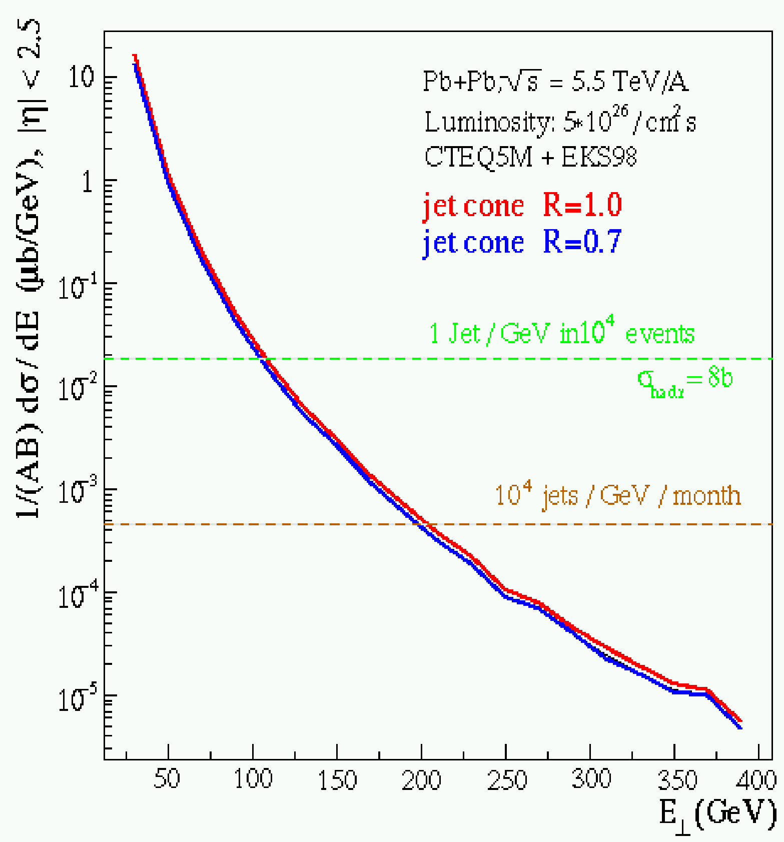
2.6 Quarkonia photoproduction in γPb collisions





Invariant mass dilepton distribution in CMS for photoproduced Y
S/B = 1 for $\mu^+\mu^-$ and S/B = 0.67 for e^+e^-

3.1 Jet cross section & expected event rate



Expected statistics for CMS acceptance
(no trigger and reconstruction efficiency)
$|\eta^{jet,\gamma}| < 3, \quad |\eta^{h,\mu}| < 2.4$

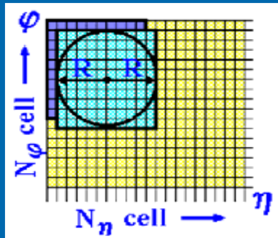
Channel	Time = 1.2×10^6 s, $\sigma_{AA} = A^2\sigma_{pp}$, $A = 208$ (Pb) (Pythia6.2, CTEQ5M)
jet+jet, $E_T^{jet} > 100$ GeV	4×10^6
jet tagged by $h^{\pm},\pi^0$, $E_T^{jet} > 100$ GeV, $z^{h\pm,\pi0} > 0.5$	2×10^5
B-jet tagged by μ, $E_T^{jet} > 100$ GeV, $z^{\mu} > 0.3$ $E_T^{jet} > 50$ GeV, $z^{\mu} > 0.3$	700 2×10^4

CERN Yellow Report, hep-ph/0310274

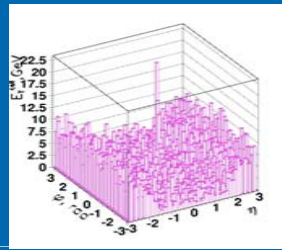
3.2 High p_T jets. Jet reconstruction in HI collisions

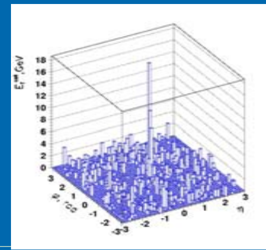
BACKGROUND SUBTRACTION ALGORITHM

The algorithm is based on event-by-event η-dependent background subtraction:

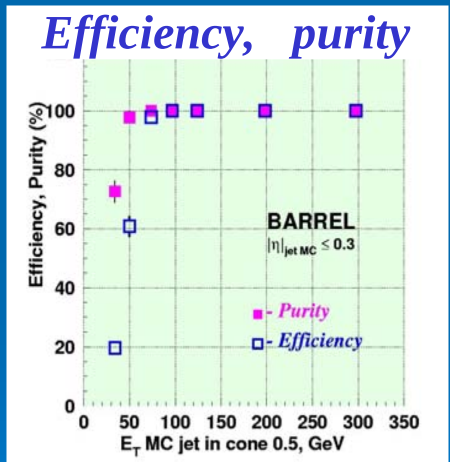


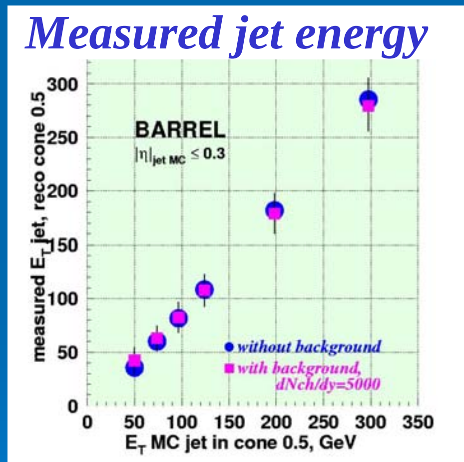
1. Subtract average pileup
2. Find jets with iterative cone algorithm
3. Recalculate pileup outside the cone
4. Recalculate jet energy

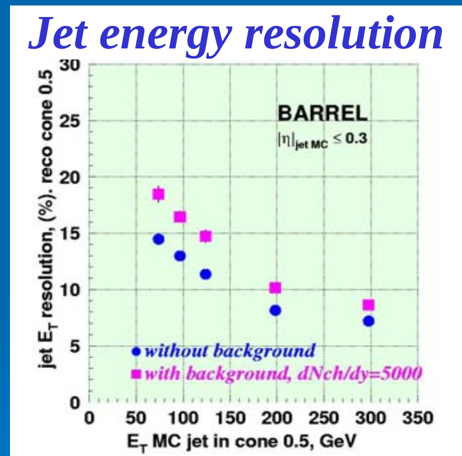




Full jet reconstruction in central Pb-Pb collision HIJING, $dN_{ch}/dy = 5000$







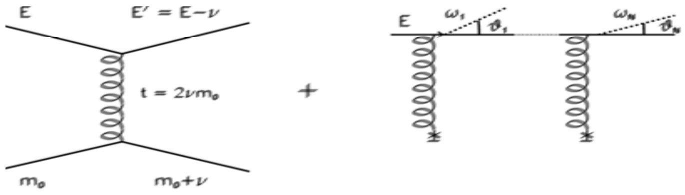
Jet spatial resolution: $\sigma(\varphi_{rec} - \varphi_{gen}) = 0.032$; $\sigma(\eta_{rec} - \eta_{gen}) = 0.028$

Better than η, φ size of tower (0.087×0.087)

4.1 Jet quenching: medium-induced parton energy loss

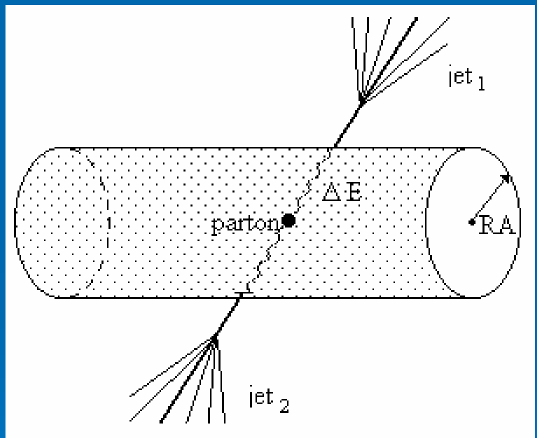
Collisional loss (incoherent sum over scatterings)

Bjorken; Mrowczynski; Thoma; Markov; Mustafa et al...



Radiation loss (coherent LPM interference)

Gyulassy-Wang; BDMPS; GLV; Zakharov; Wiedemann...



Energy lost by partons in nuclear matter:

$\Delta E \propto T_0^{\ 3}$ (temperature), g (number degrees of freedom)

$$\Rightarrow \Delta E|_{QGP} >> \Delta E|_{HG}$$

LHC, central Pb+Pb:

$$T_{0,\,QGP} \sim 1 \text{ GeV} >> T_{0,\,HG}^{\max} \sim 0.2 \text{ GeV},$$

$$\Delta E_{QGP} / \Delta E_{HG} \geq (1 \text{ GeV} / 0.2 \text{ GeV})^3 \sim 10^2$$

4.2 Fast Monte-Carlo tools to simulate jet quenching and flow effects

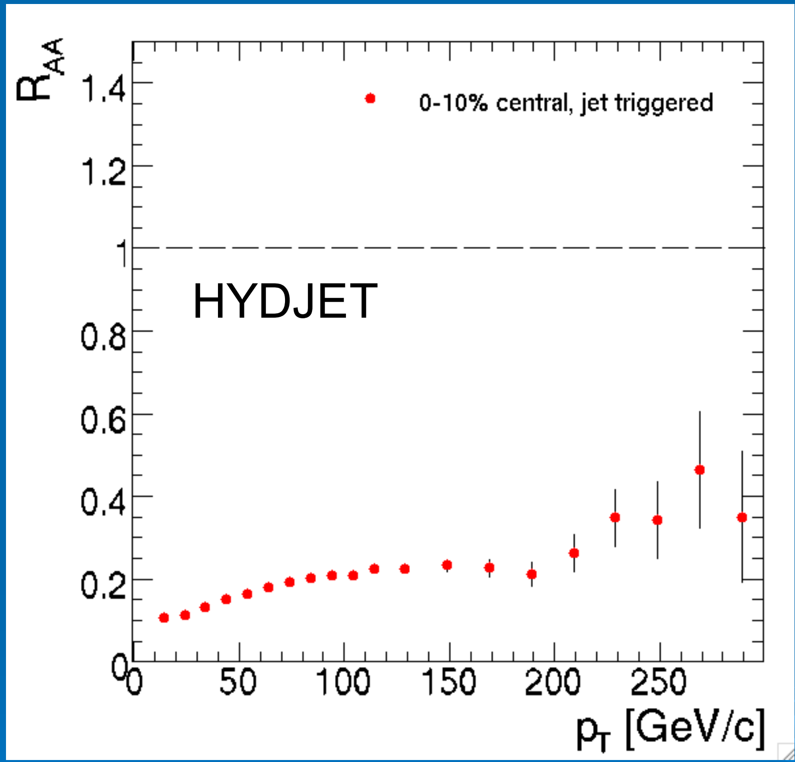
- PYQUEN - fast code to simulate jet quenching (modify PYTHIA6.4 jet event) *http://cern.ch/lokhtin/pyquen*
- HYDRO - fast code to simulate transverse and elliptic flow in central and semi-central AA collisions at LHC *http://cern.ch/lokhtin/hydro*
- HYDJET - merging HYDRO (flow effects), PYTHIA (hard jet production) and PYQUEN (jet quenching) *http://cern.ch/lokhtin/hydro/hydjet.html*

Significant progress in development of Monte-Carlo models for simulation of jet quenching is achieved (PYQUEN, HIDJET).
It describes RHIC data adequately.

4.3 Jet quenching: nuclear modification factor for charged hadrons

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

Binary scaling (T_{AA}) p+p reference ($d^2\sigma^{NN}/dp_T d\eta$)



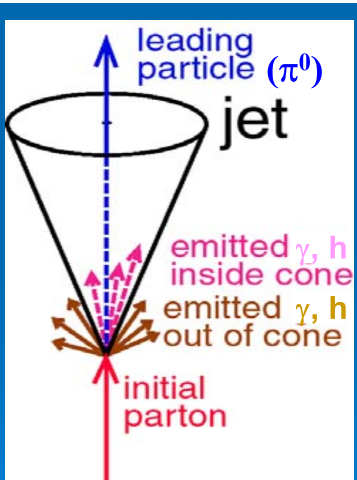
➔ Will be measured at CMS:

- ➔ jets up to $E_T \approx 500$ GeV
- ➔ charged hadrons up to $p_T \approx 300$ GeV/c

4.4 Jet quenching: jet fragmentation function D(z) for leading hadrons

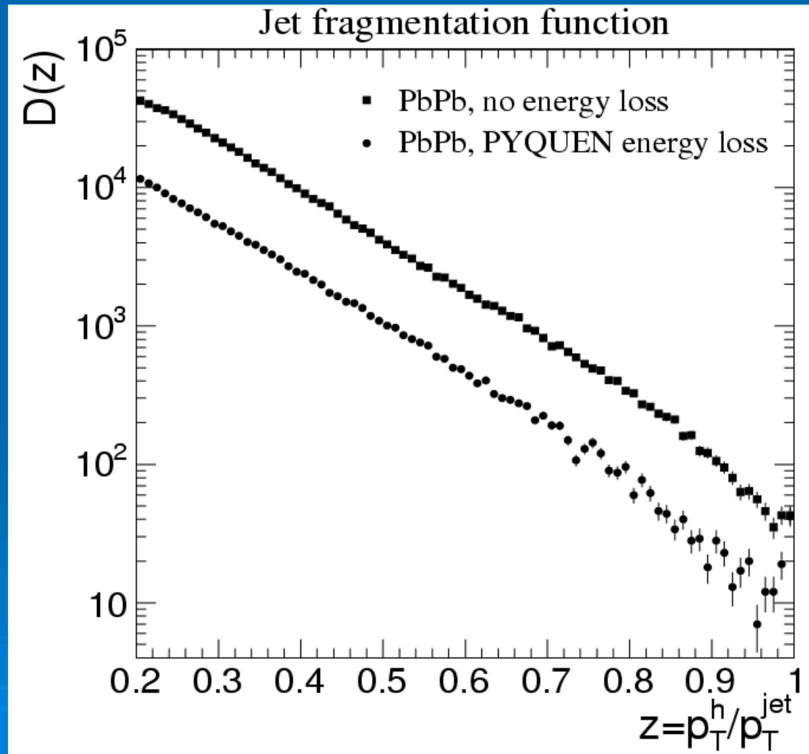
$$D(z) = \int\limits_{z\cdot p_{T\,min}^{jet}} d(p_T^h)^2 dy dz' \frac{dN_{AA}^h}{d(p_T^h)^2 dy dz'} \delta(z - p_T^h/p_T^{jet}) \Big/ \int\limits_{p_{T\,min}^{jet}} d(p_T^{jet})^2 dy \frac{dN_{AA}^{jet}}{d(p_T^{jet})^2 dy}$$

It is probability distribution for leading *hadron in the jet to carry fraction* $z = p_T^h/p_T^{jet}$ *of jet transverse momentum*



In the jet induced by heavy quark, the energetic muon can be produced and detected ("b-tagging")

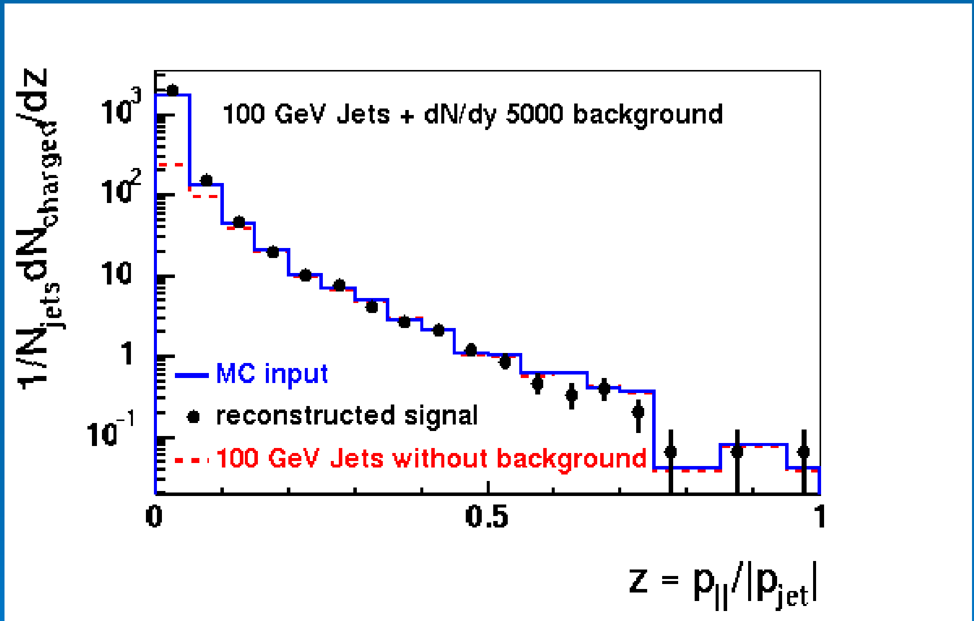
$|\eta^h|<2.4$, $|\eta^{jet}|<3$, $E_T>100GeV$, $L=0.5nb^{-1}$



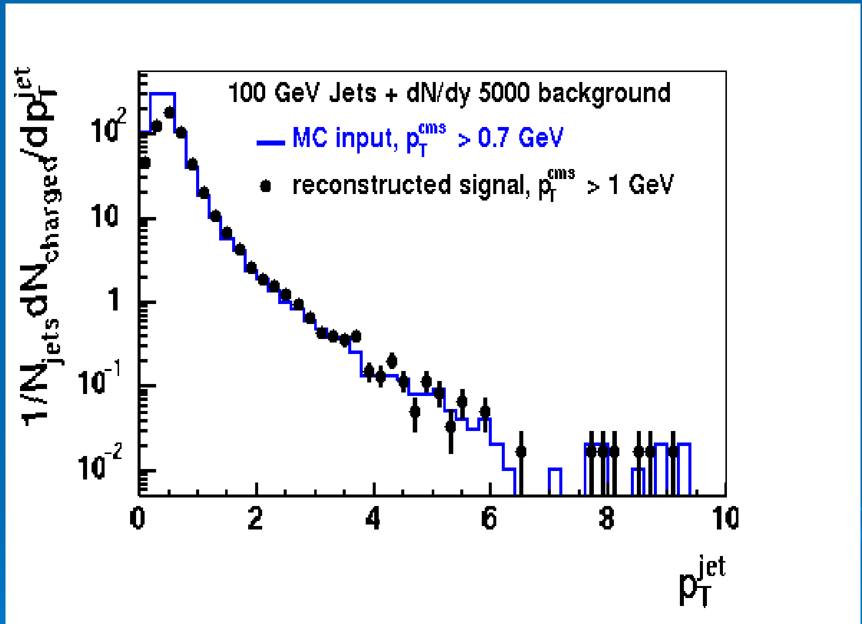
$D^{PbPb}(z)/D^{pp}(z) \sim 0.25$

4.5 Jet fragmentation function can be reconstructed with CMS tracking system

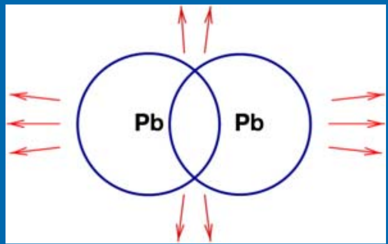
Longitudinal momentum fraction z along the thrust jet axis



Transverse momentum relative to thrust jet axis

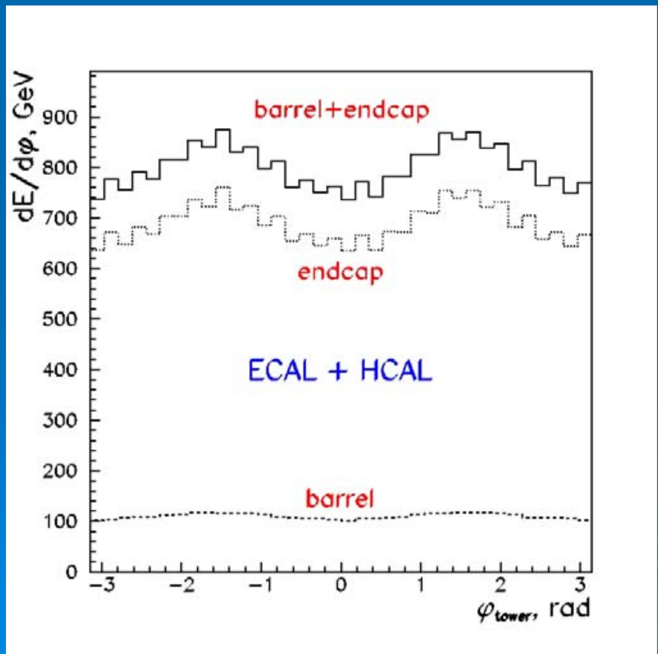


5.1 Azimuthal anisotropy in HIC with CMS Calorimeter

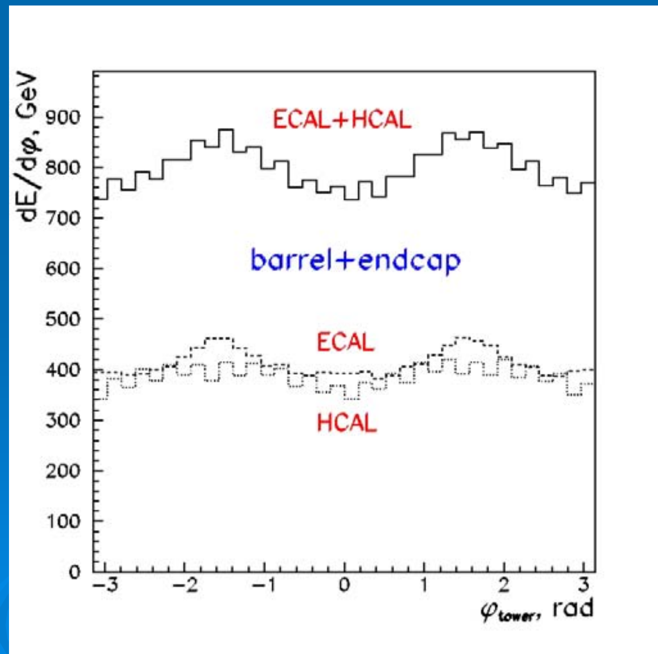


- **Non-central heavy-ion collisions (*b* ≠ 0), elliptic volume of interacting nuclear matter, energy flow illustrates azimuthally anisotropic elliptic volume.**
- **Calorimeters are used to determine event plane.**
- **Azimuthal anisotropy can be estimated with CMS calorimeters with and without the determination of event plane.**

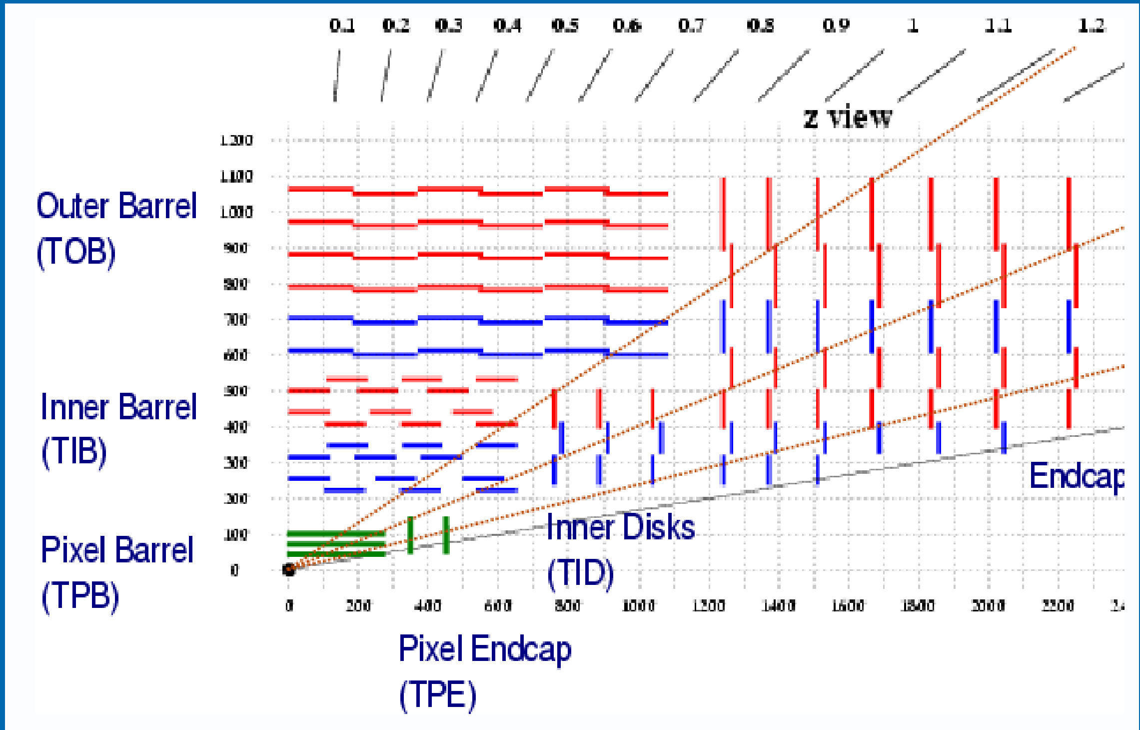
HYDRO, *Pb+Pb collisions, b = 6 fm.* *GEANT-based simulation*



Energy flow



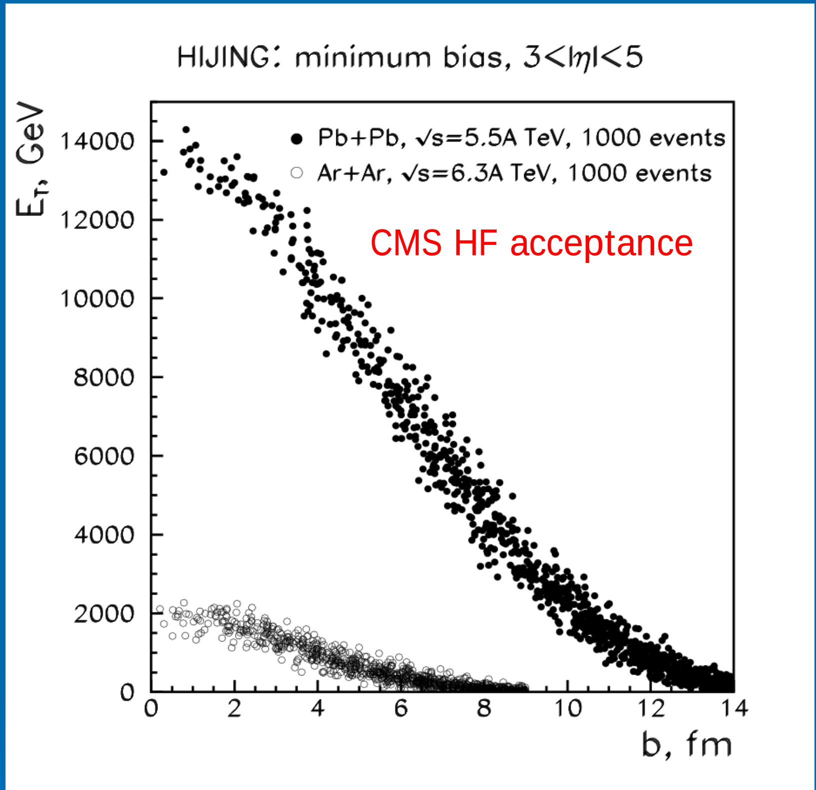
5.2 Azimuthal anisotropy in HIC with CMS Tracker

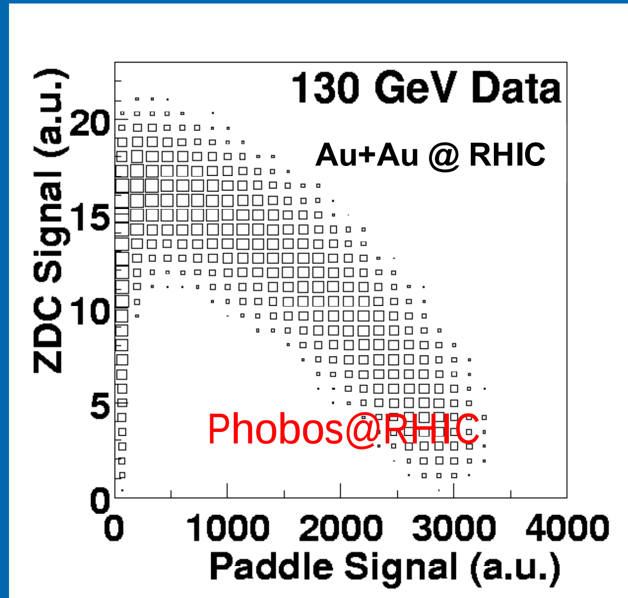


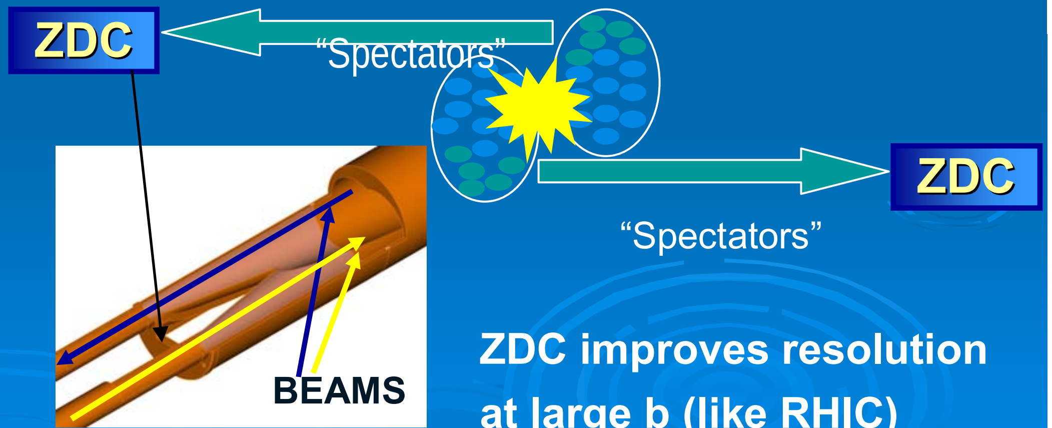
CMS Tracker

Detector	$\sigma_{rec}(\Delta\Psi)$, rad
ECAL+HCAL(Barrel+Endcap)	0.37
Tracker	0.31

6.1 Global event characterization. Centrality determination







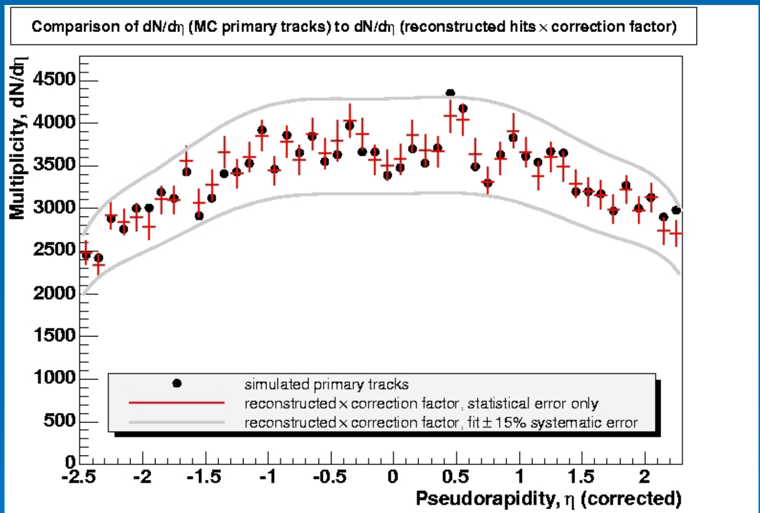
CMS HF and CASTOR will provide best correlation between energy flow and event centrality (maximal energy deposition and minimal energy relative fluctuations). Impact parameter resolution ~0.5 fm for PbPb and ArAr

ZDC improves resolution at large b (like RHIC)

6.2 Charged Particle Multiplicity: $dN_{ch}/d\eta$

Determination of the primary charged-particle multiplicity is based on the relation between the pseudorapidity distribution of reconstructed clusters in the innermost layer of the CMS pixel tracker and that of charged-particle tracks originating from the primary vertex.

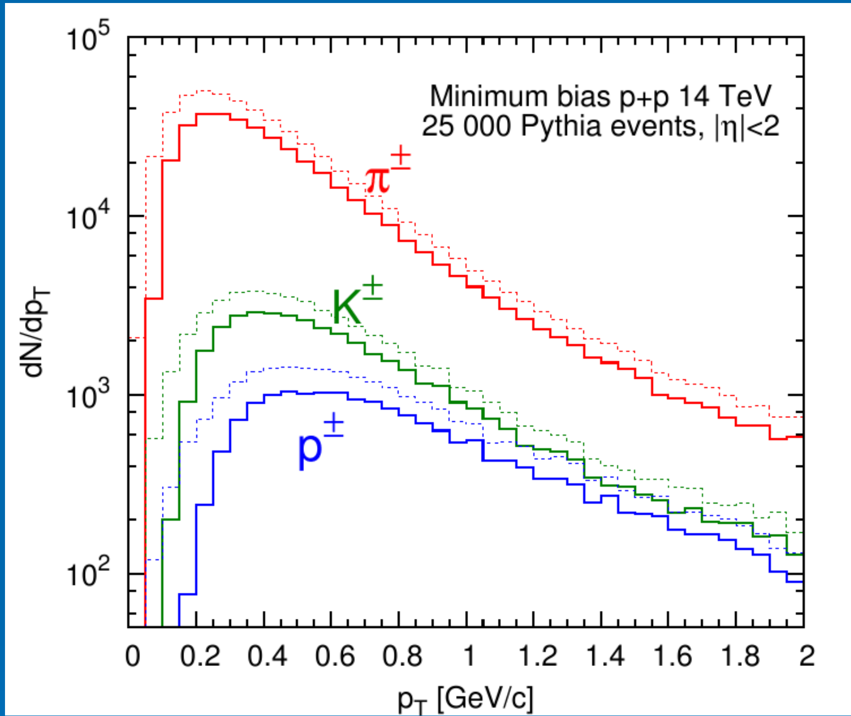
Single layer hit counting in innermost pixel barrel layer

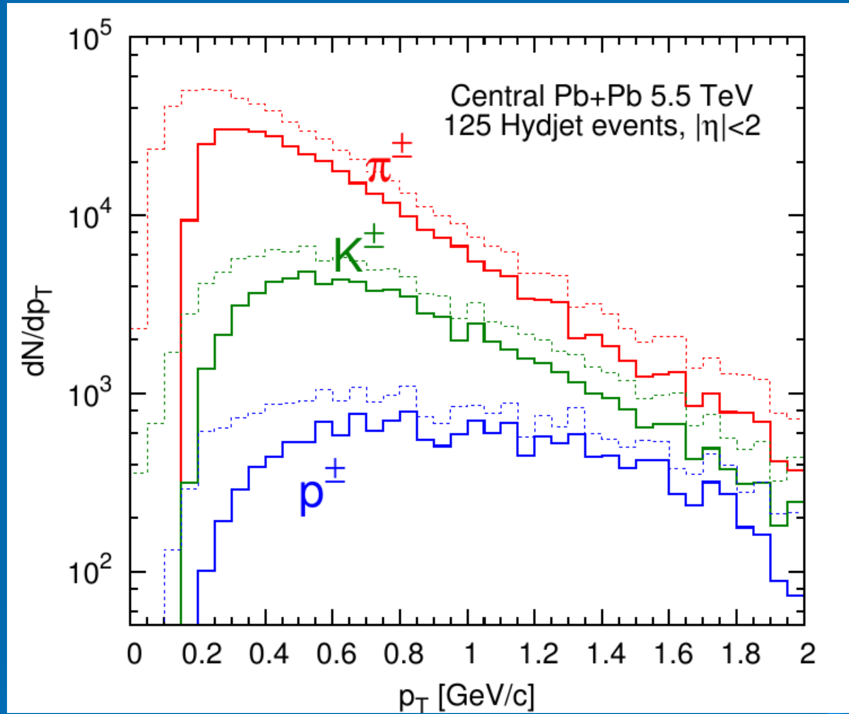


On an event-by-event basis, the reconstructed multiplicity is within 1-2% of the true value in the | η | < 2 region.

- **High granularity pixel detectors**
- **Pulse height in individual pixels to reduce background**
- **Very low p_T reach, p_T > 26 MeV (counting hits!)**

6.3 Low-pT particle identification with tracker, dE/dx

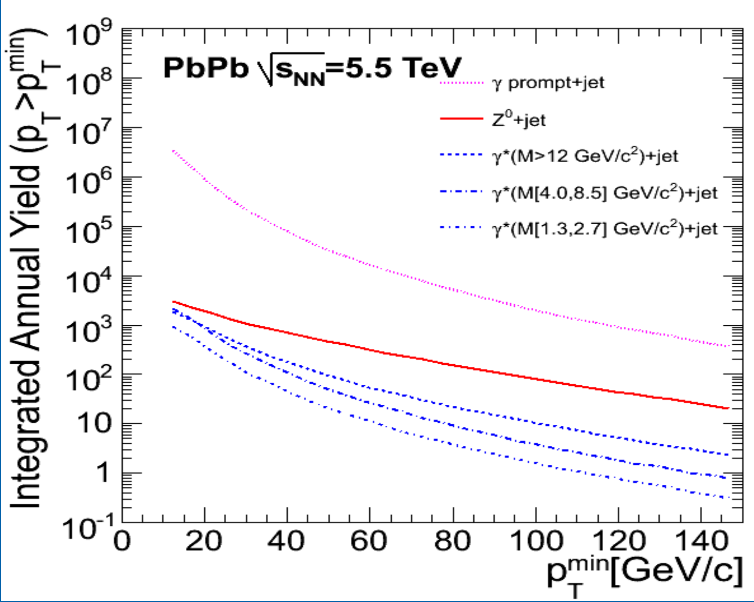




Solid lines: reconstructed, dotted lines: generated

Inclusive yield can be extracted up to $p_T \approx 1$ GeV/c for $\pi^\pm$ and $K^\pm$, and up to $p_T \approx 2$ GeV/c for $p^\pm$

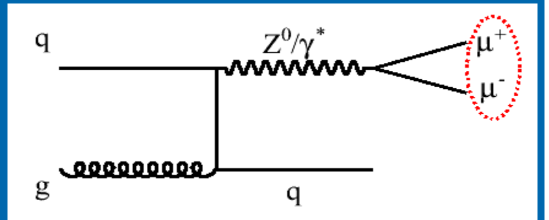
7.1 $\gamma^*/Z(\rightarrow \mu^+\mu^-)$ +jet production

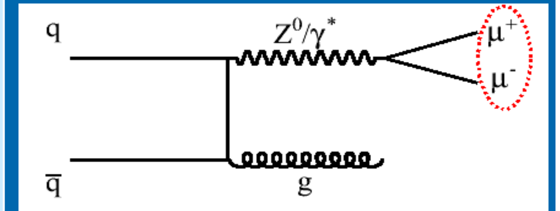


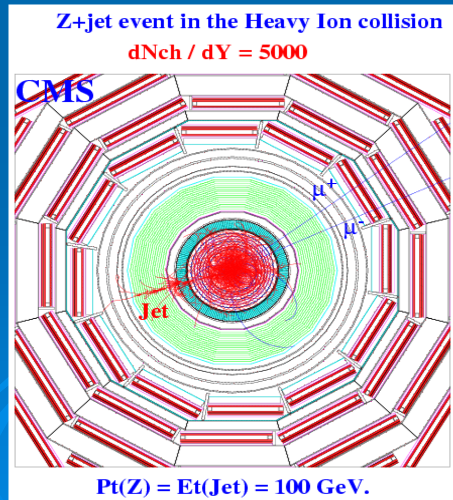
PYTHIA v6.321 at 5.5 TeV

- ➔ p_T^μ > 3.5GeV/c, $|\eta^\mu|$ < 2.4
- ➔ t = 10^6 s, L = 0.5 mb^{-1} s^{-1}

$D\bar{D}/B\bar{B}$ background (S/B > 10 for Z^0, S/B < 1 for γ^*) rejection can be done using tracker information on dimon vertex position





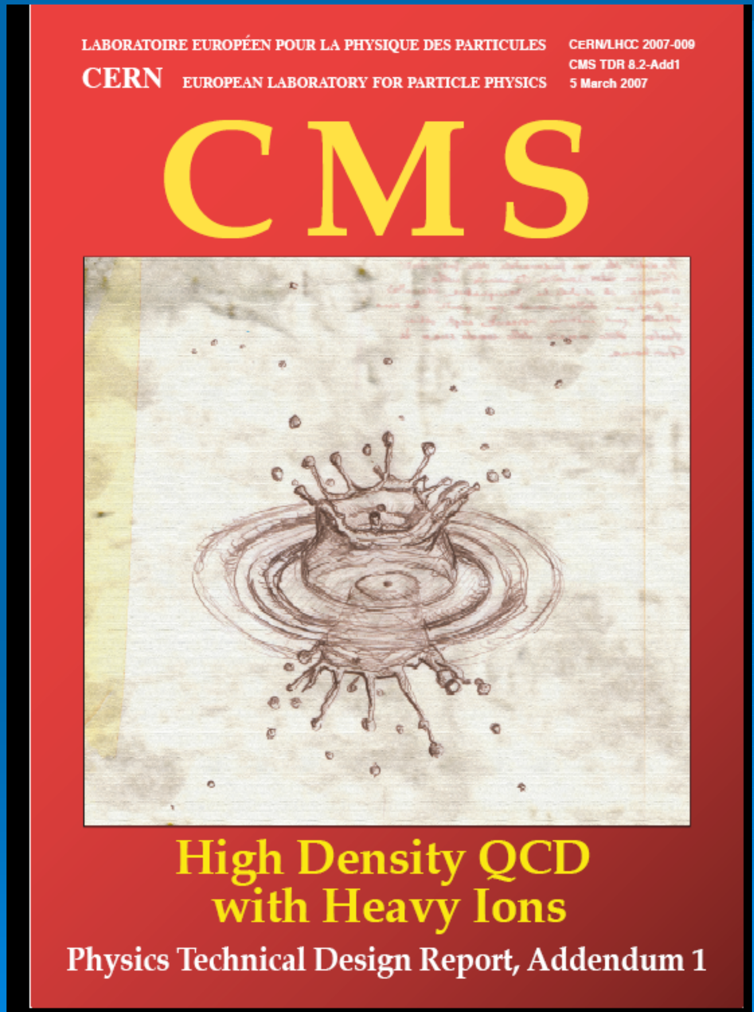


p_T ^{min}> (GeV/c)	10	20	30	50
$Z^0(\mu^+\mu^-)$+jet	3000	1800	900	500
γ^* ($M_{\mu+\mu-}$> 12 GeV/c²)	1900	750	300	90
γ^* ($M_{\mu+\mu-}$[4.0,8.5] GeV/c²)	2100	750	200	40
γ^* ($M_{\mu+\mu-}$[1.3,2.7] GeV/c²)	900	300	100	20

8 Summary and outlook

- At LHC a new regime of heavy ion physics will be reached where hard particle production can dominate over soft events, while the initial gluon densities are much higher than at RHIC, implying stronger QCD medium effects observable in new channels.
- CMS is an excellent device for the study of quark-gluon plasma by hard probes:
  - Quarkonia and heavy quarks
  - Jets and high-p_T hadrons, "jet quenching" in various physics channels
- CMS will also study global event characteristics:
  - Centrality, Multiplicity
  - Correlation and Energy Flow in wide range of p_T and η
- CMS is preparing to take advantage of its capabilities
  - Excellent rapidity and azimuthal coverage, high resolution
  - Large acceptance, nearly hermetic fine granularity hadronic and electromagnetic calorimetry
  - Excellent muon and tracking systems
  - New High Level Trigger algorithms specific for A+A
  - Zero Degree Calorimeter, CASTOR and TOTEM will be important additions extending to forward physics

More details on CMS Heavy Ion Physics:



Acknowledgement

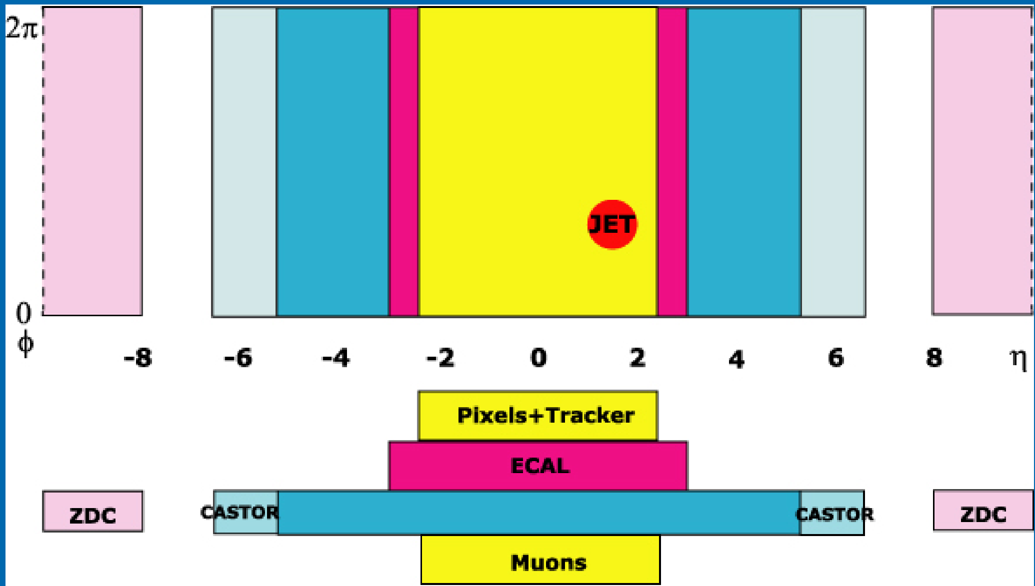
This report includes the remarks of

I.P.Lokhtin, A.M.Snigirev, O.L.Kodolova, V.L.Korotkikh, M.Bedjidian, B.Wyslouch, D.Denegri, D.d'Enterria, C.Lourenco, M.Murrey, C.Roland, L.V.Malinina, C.Mironov, I.N.Vardanyan, C.Yu.Teplov, S.V.Petrushanko, G.Kh.Eiyubova,

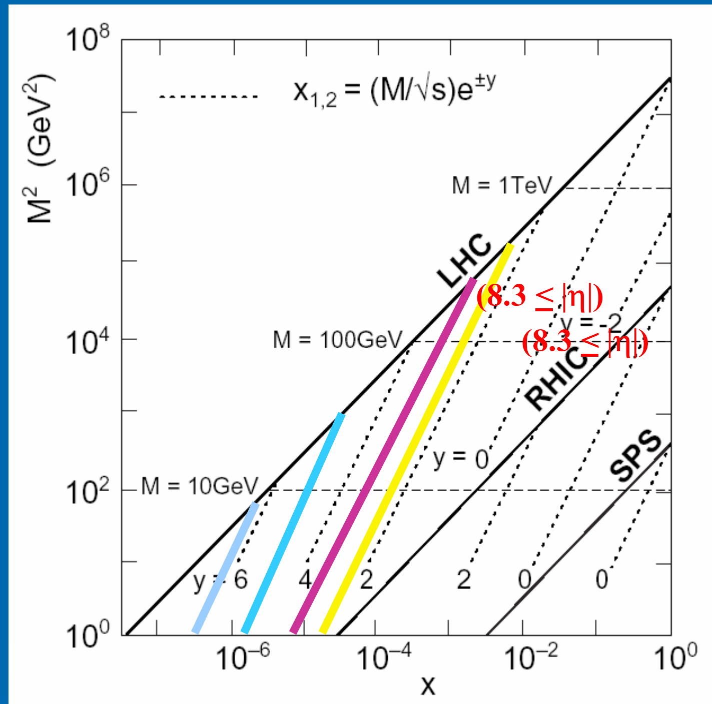
and other CMS collaborators

➢BACKUP SLIDES

Overview: CMS Detector Coverage

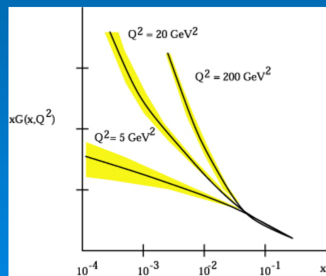


Kinematics at the LHC



Large Range of Hermetic Coverage:

Tracker, muons	$|\eta| < 2.4$
ECAL + HCAL	$|\eta| < 3$
Forward HCAL	$3 < |\eta| < 5$
CASTOR	$5.2 < |\eta| < 6.6$
ZDC	$8.3<|\eta|$

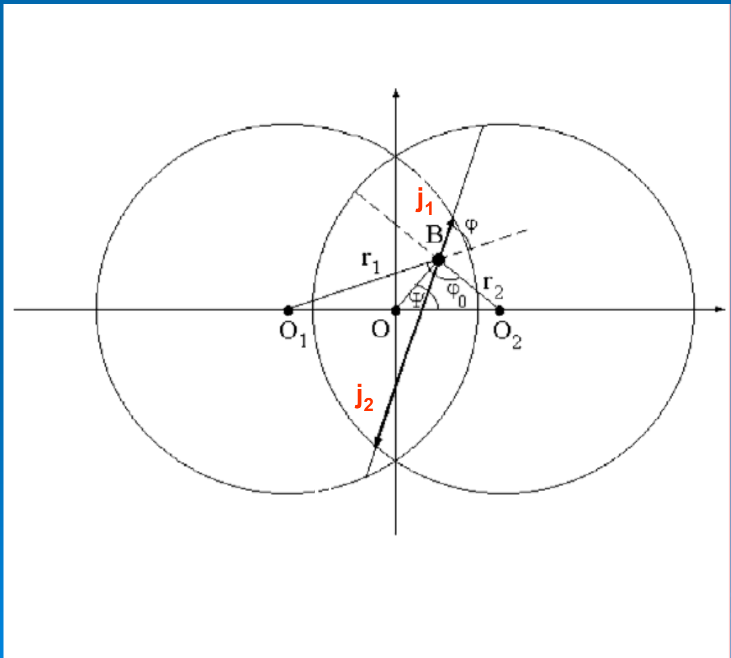


Gluon density has to saturate at low x

Jet quenching in heavy ion collisions

One of the important tools to study QGP properties in ultrarelativistic heavy ion collisions is QCD jet production: medium-induced energy loss of energetic partons (jet quenching) is very different in cold nuclear matter and in QGP, resulting in many observable phenomena.

Nuclear geometry and QGP evolution



impact parameter b ≡ $|O_1O_2|$ - transverse distance between nucleus centers

B – generation point of jets j_1 and j_2

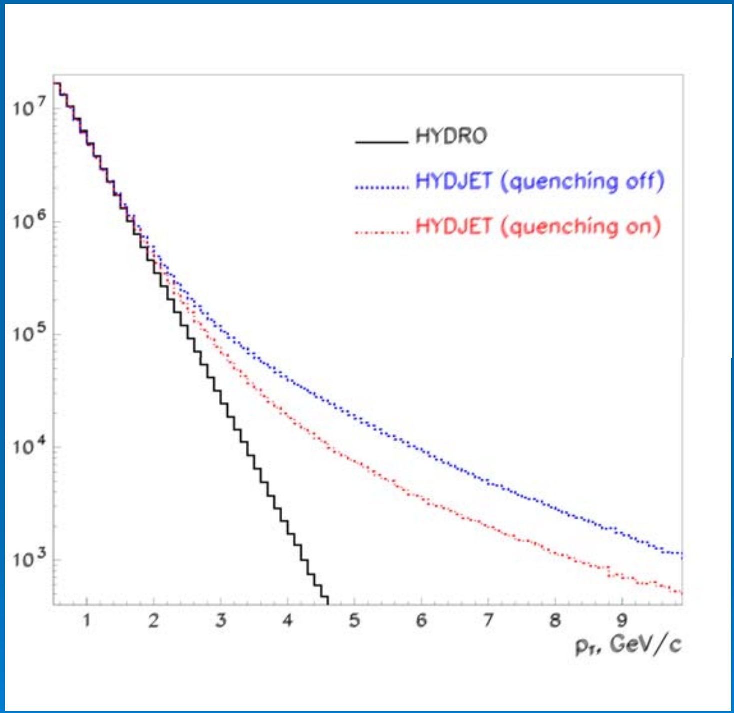
Space-time evolution of dense matter, created in region of initial overlapping of colliding nuclei, is described by Lorenz-invariant Bjorken's hydrodynamics

J.D. Bjorken, PRD 27 (1983) 140

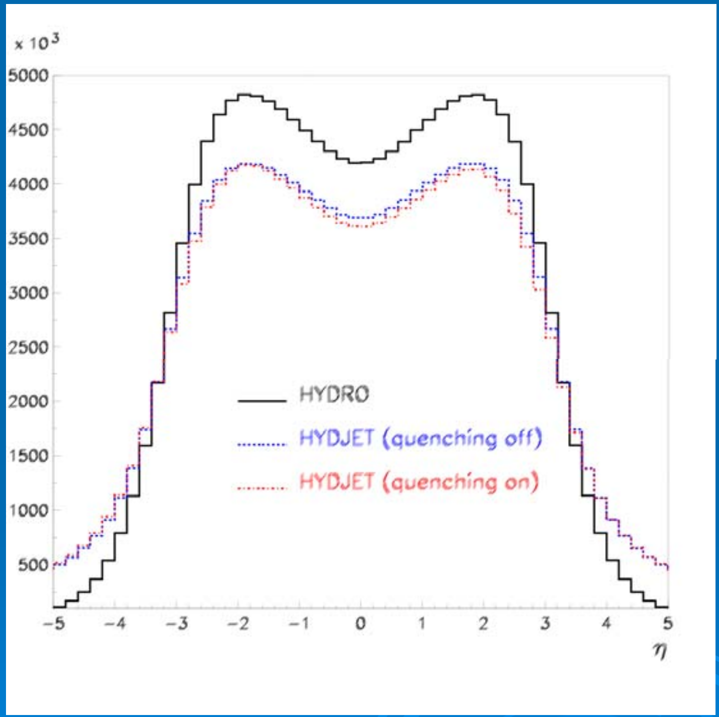
Jet quenching: p_T- and η-distribution (HYDJET)

30,000 minimum bias Pb+Pb events, $\sqrt{s}$ = 5.5A TeV (n_{tot} = 30000)

p_T-distribution



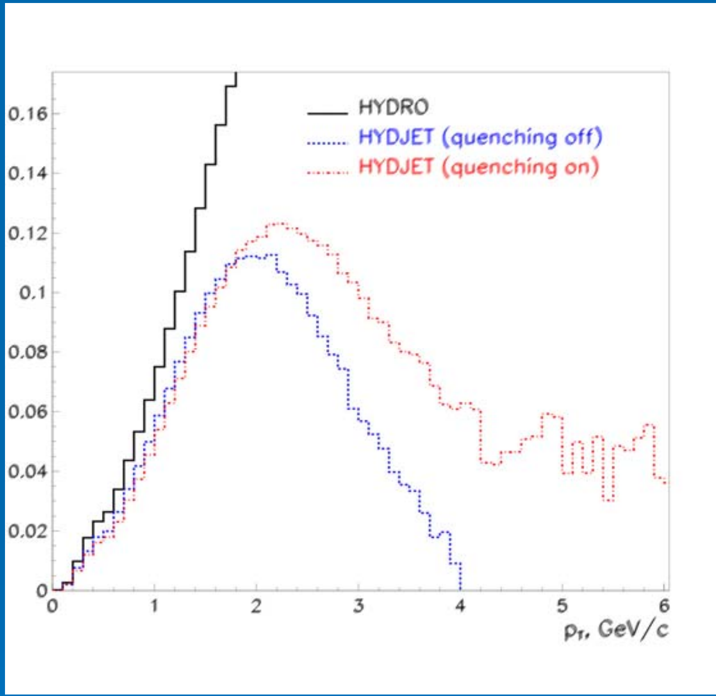
η-distribution



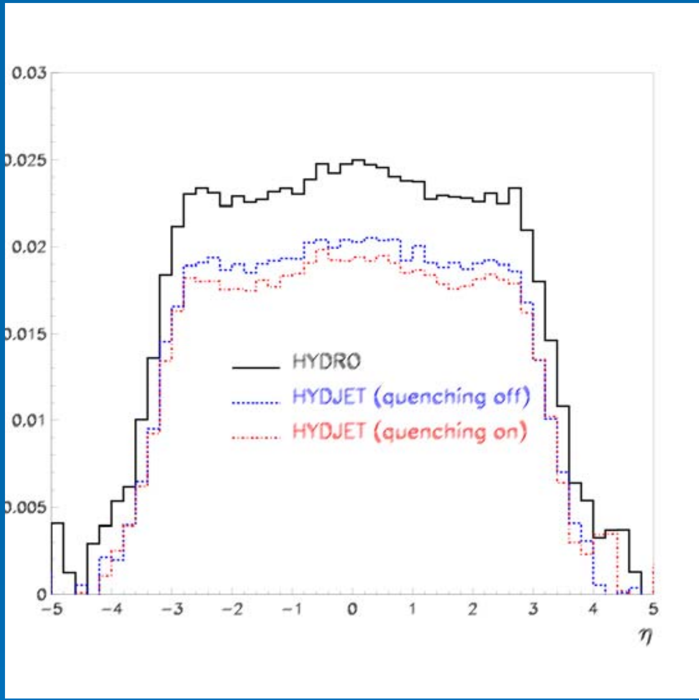
Jet quenching: elliptic flow (HYDJET)

$v_2 = \langle \cos 2\varphi \rangle$ (Elliptic flow)

v2(p_T)

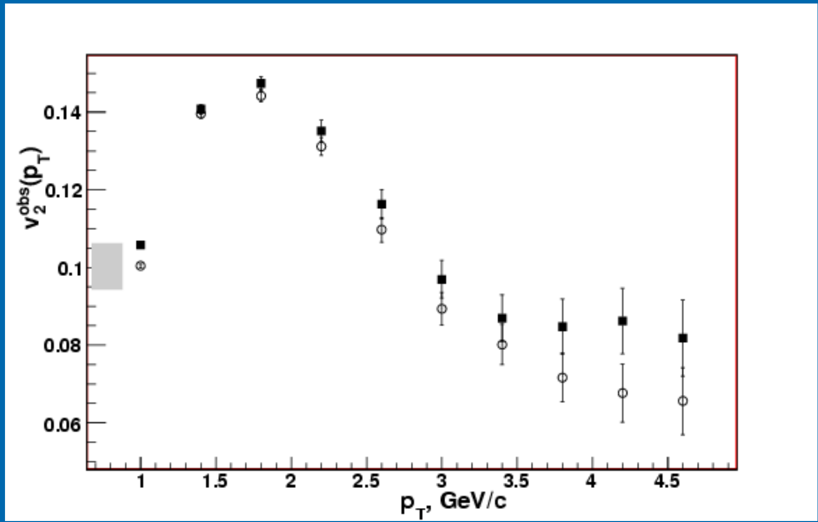


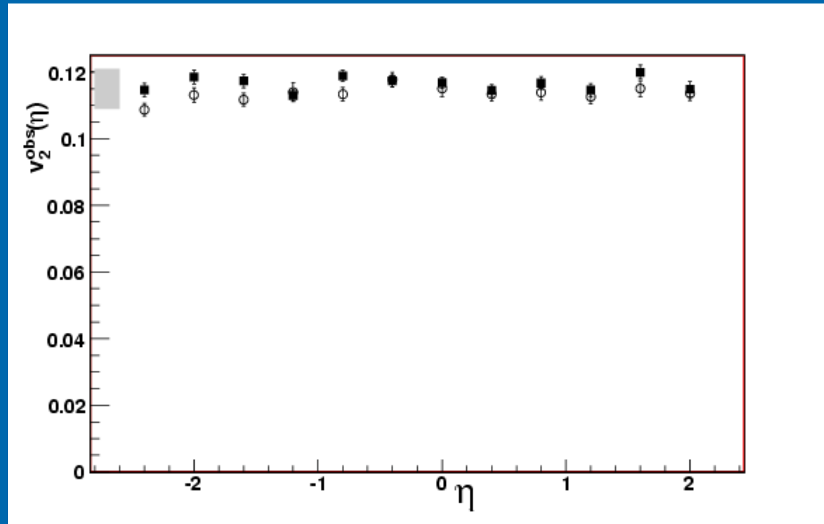
v2(η)



v_2(p_T > 2 GeV): sharp drop due to jets and additional v_2 due to jet quenching
$v_2(\eta)$: ~30%-reduction due to jets and small influence due to jet quenching

Azimuthal anisotropy in HIC with CMS Tracker (HYDJET, 10000 PbPb events, b = 9 fm)



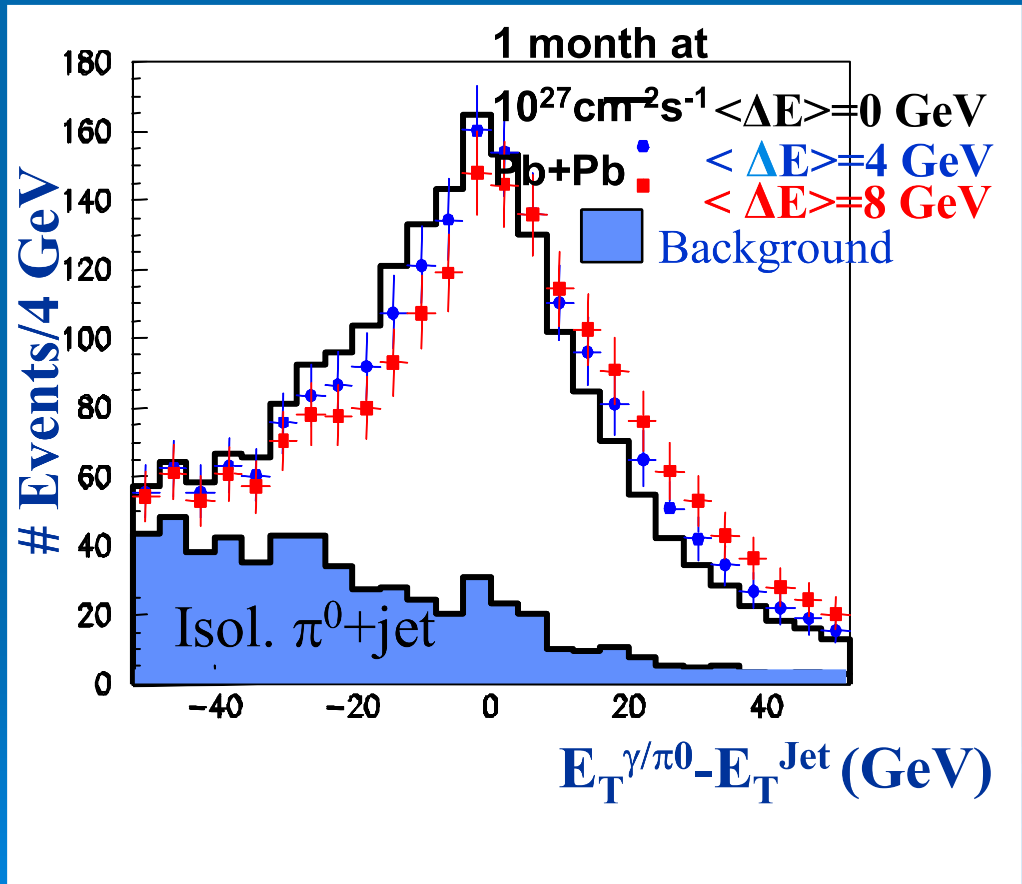


Open circles are with simulated and closed squares with reconstructed events

Method	$\langle v_2^{obs}(\text{rec})\rangle$	$\text{RMS}(v_2^{obs})$	$\langle v_2^{obs}(\text{rec})\rangle / v_2^{obs}\langle(\text{sim})\rangle$
$\langle\cos 2(\varphi-\Psi_R)\rangle$	**0.12**	**0.05**	**1.05**
$\sqrt{\langle\cos 2(\varphi_1-\varphi_2)\rangle}$	**0.12**	**0.05**	**1.05**
v_2 from fitting	**0.12**	**0.06**	**0.96**

Balancing γ vs Jets: Quark Energy Loss

γ+jet

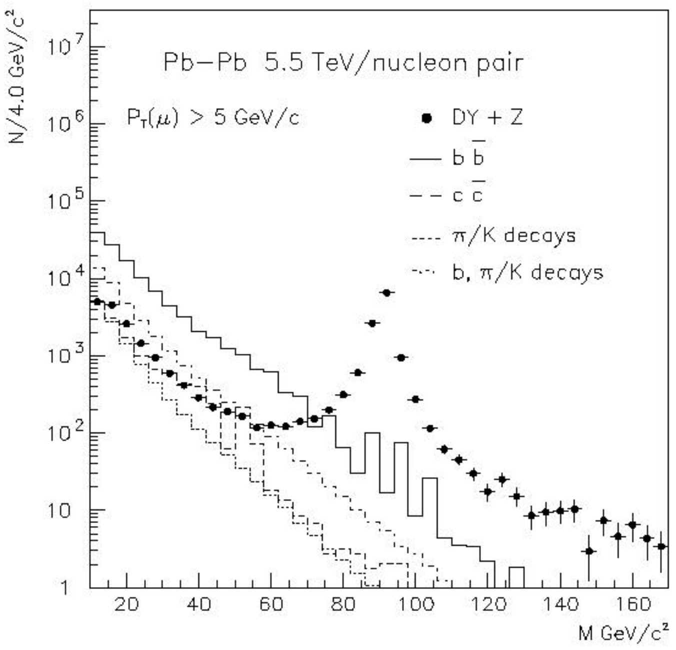


$Z^0 \rightarrow \mu^+\mu^-$ detection at CMS

$\sigma^{AA} = A^{2\alpha}\,\sigma^{pp}$ with $\alpha=1$

σ^{pp} was taken from PYTHIA, correction
k = 2 for cc and bb and
k = 1.3-1.5 for Z, W, tt

HIJING was used for AA event



The expected number of

$Z^0 \rightarrow \mu^+\mu^-$: ~$10^4$/1.3x$10^6$ s

of Pb-Pb running at L = $10^{27}cm^{-2}s^{-1}$

Z^0 can be measured with muon system alone and with muon+tracker systems.

Z^0+jet events
The expected number of Z^0+jet for jet E_T > 50 GeV and |ηjet| < 1.5:
900/1.3x106 s of Pb-Pb run at
L = 10^{27}cm–2s–1.

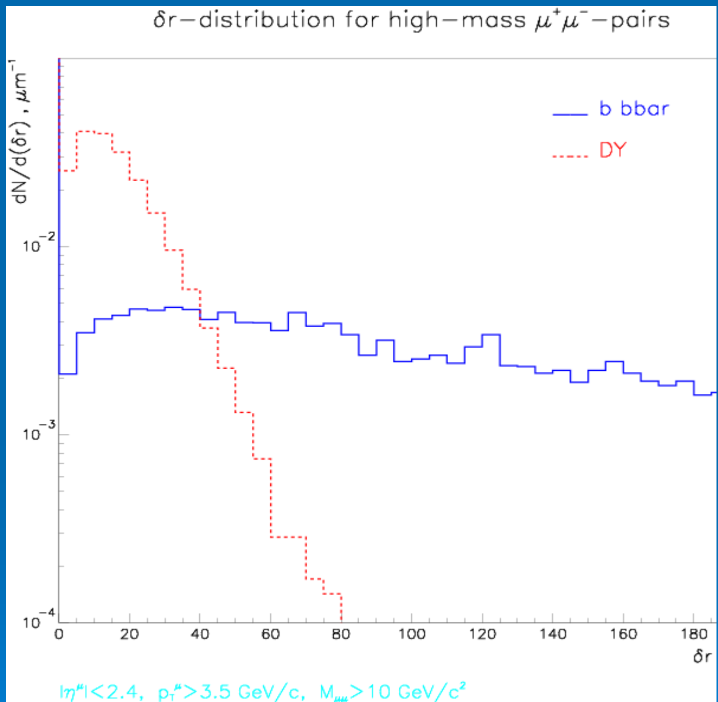
Z^0 + jet events with $p_T Z^0$ measured from pair $\mu^+\mu^-$ should allow to study effects of jet quenching using energy balance $E_T$jet = $p_T Z^0$

Heavy quarks b, c → μ / J/ψ +X.

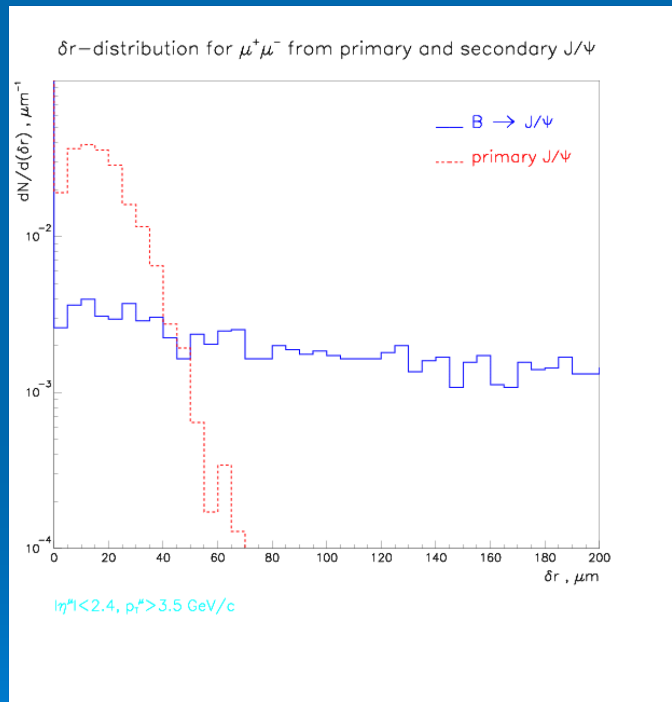
Secondary vertex finding and correlated background rejection

δr is transverse distance between the intersection points with the beam line belonging to different muon tracks

BB → $\mu^+\mu^-$



BB → J/ψ → $\mu^+\mu^-$



b-quark energy loss affects B-jet fragmentation and modifies the dimuon spectra depending on mechanism of heavy-quark production (for BB → μ+ μ–) and on the intensity of jet quenching