Heavy Ion Physics
in the CMS Experiment at the LHC

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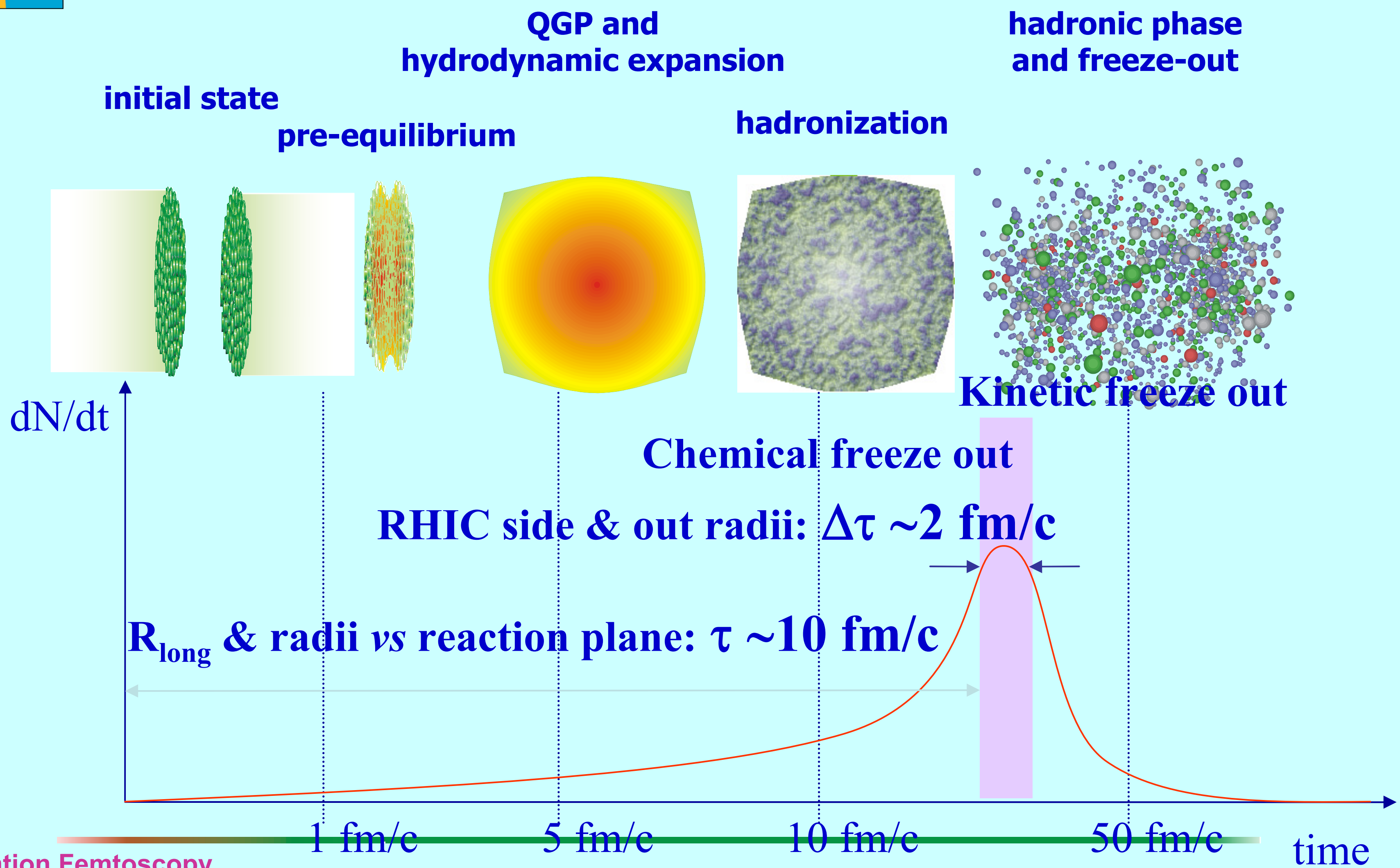
For CMS Collaboration

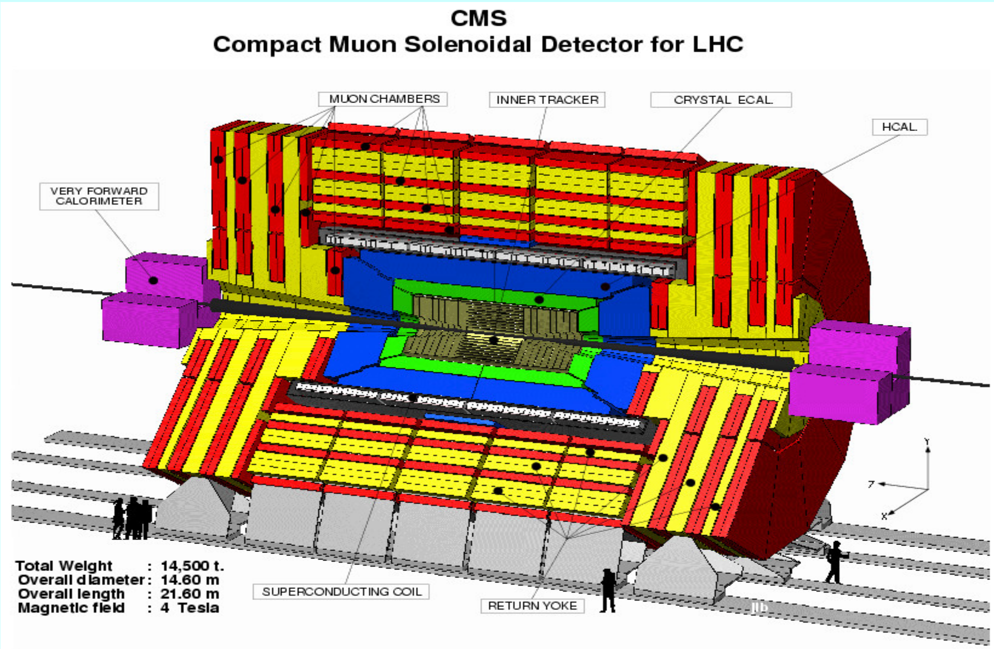
CMS Heavy-Ion Groups:
Moscow, Lyon, CERN, Budapest, Athens, Ioannina, Demokritos, Lisbon, Adana, MIT, Illinois, Los Alamos, Maryland, Minnesota, Iowa, California Davis, Kansas, Mumbai, Auckland, Seoul, Vanderbilt, Colorado, Zagreb

Expected evolution of hot and dense matter in heavy ion collisions

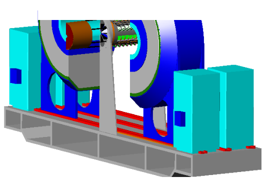


Correlation Femtoscopy
R. Lednický, JINR Dubna & IP ASCR Prague

Heavy Ion Physics at LHC
CMS detector

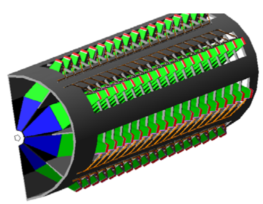


TOTEM



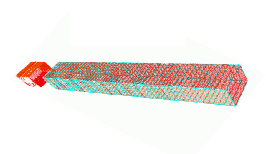
$5.3 \leq \eta \leq 6.7$

CASTOR



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

ZDC

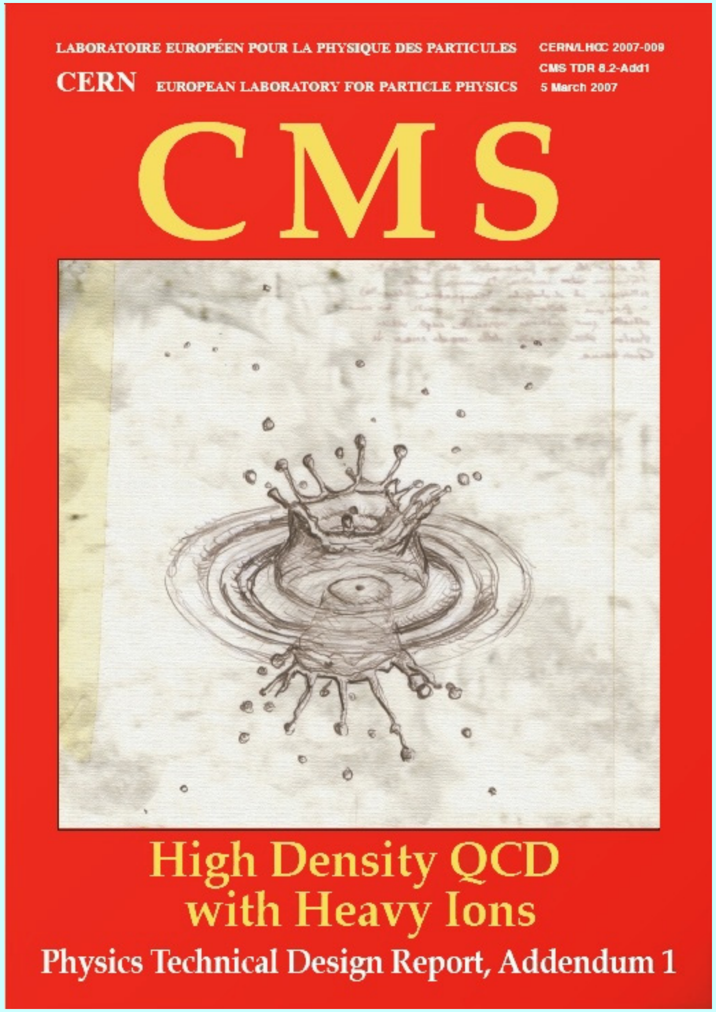


$8.3 \leq |\eta|$

- **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**

Heavy Ion program at CMS

J. Phys. G: Nucl. Part. Phys. 34 (2007) 2307-2455



Broad and exciting range of observables

- Jets and photons
- Quarkonia, Z^0 and heavy quarks in high-mass dimuon decay modes
- High-p_T hadrons
- Low-p_T hadrons
- Ultraperipheral collisions, forward physics

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, Colour Glass Condensate
  - Electromagnetic interactions ($\gamma\ \gamma$)
  - Exotica

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

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)

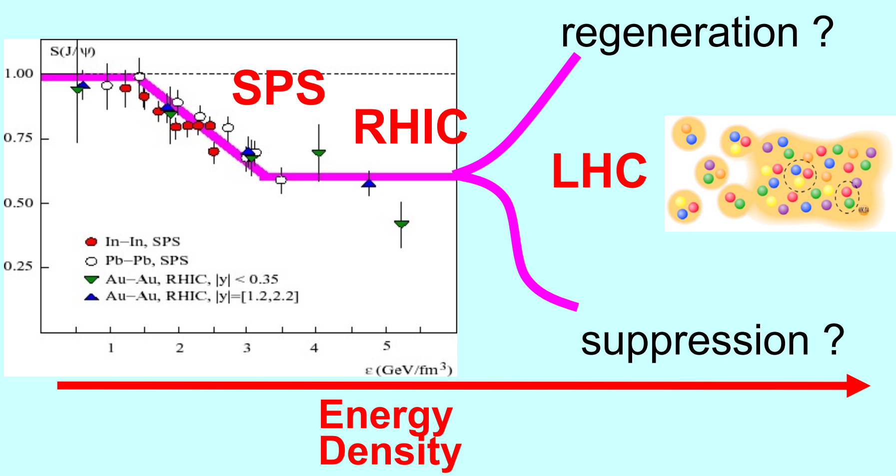
High mass dimuons at LHC: J/ψ, Υ, Z^0, B

Dissociation of Quarkonia (Debye Screening): Hot QCD Thermometer

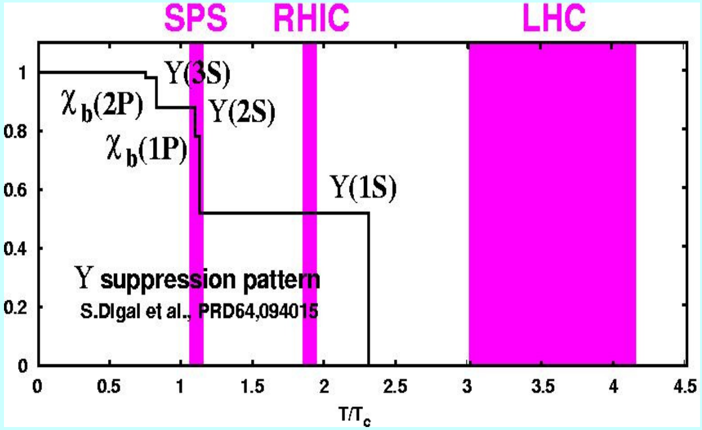
- J/ψ suppression: RHIC comparable to SPS
- Regeneration compensate screening
- J/ψ not screened at RHIC (T_D~2Tc)?

Suppression via feed down

- LHC: recombination or suppression?



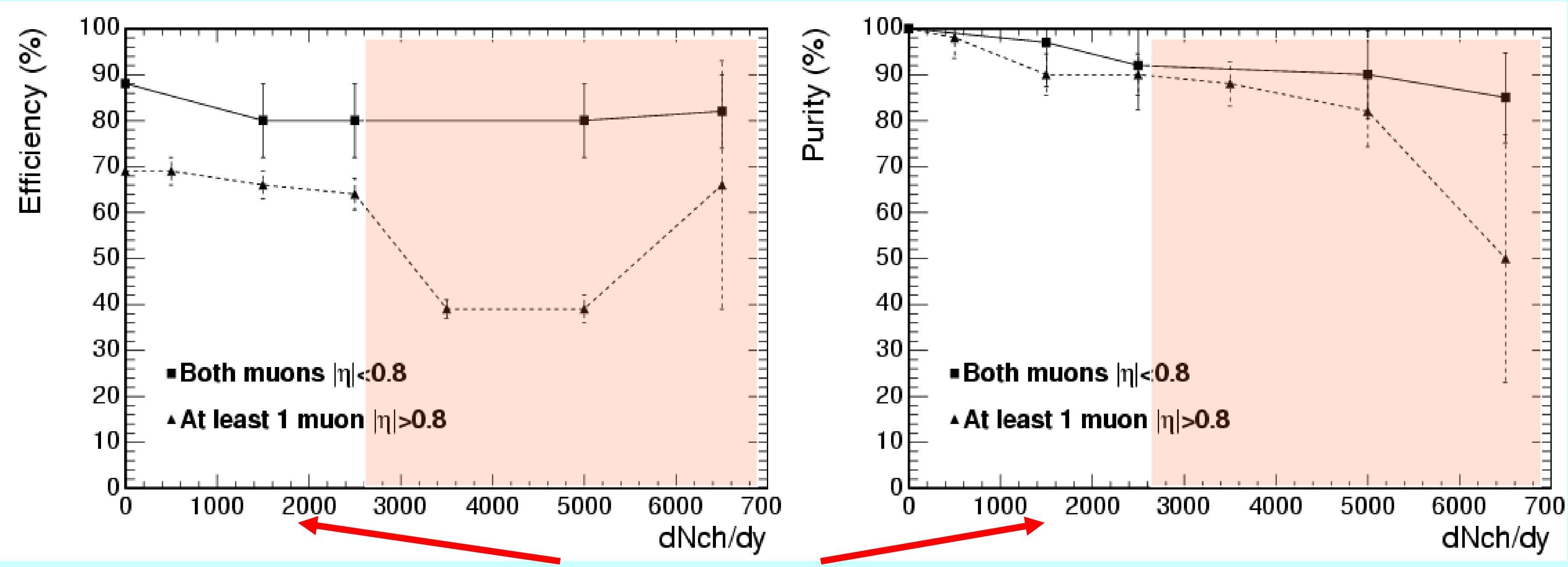
- Υ Large Cross-section: 20×RHIC
- Υ melts only at LHC: T_D~4 T_C
- small bb(bar) pairs: less regeneration
- much cleaner probe than J/Ψ
- LHC: new probe Υ vs. Υ' vs. Υ''



- Z^0 – no final state effect, baseline for quarkonia (LHC: large cross section)
- B → J/ψ, BB → $\mu^+\mu^-$ - information about b-quark in-medium rescattering & e-loss

Dimuon efficiency & purity vs dN_{ch}/dy

ϒ is embedded in PbPb events



"realistic" LHC multiplicity range

Eff = $\mathrm{Eff}_{trk\text{-}1}$ x $\mathrm{Eff}_{trk\text{-}2}$ x Eff_{vtx}

> 80% for all multiplicity (barrel)

> 65% for all multiplicity (barrel+endcap)

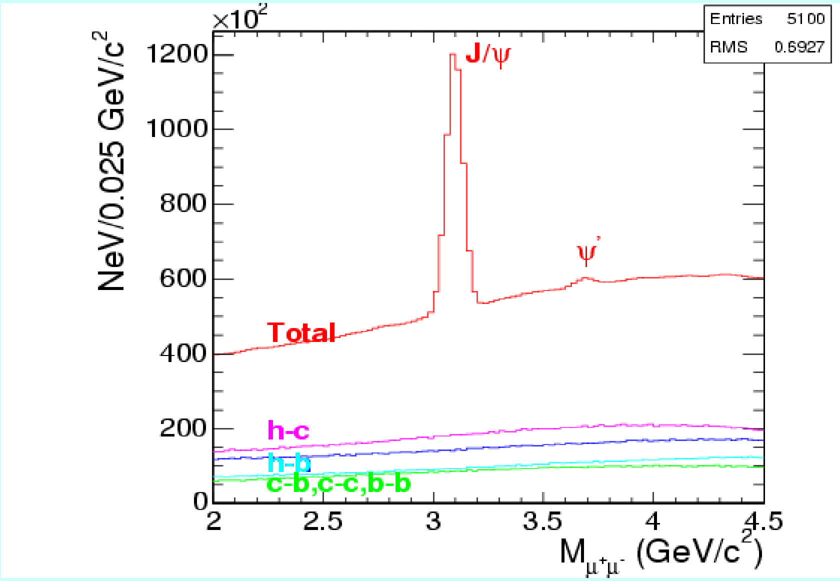
Purity = [true ϒ reco]/[all vtx reco]

> 90% (all multiplicities)

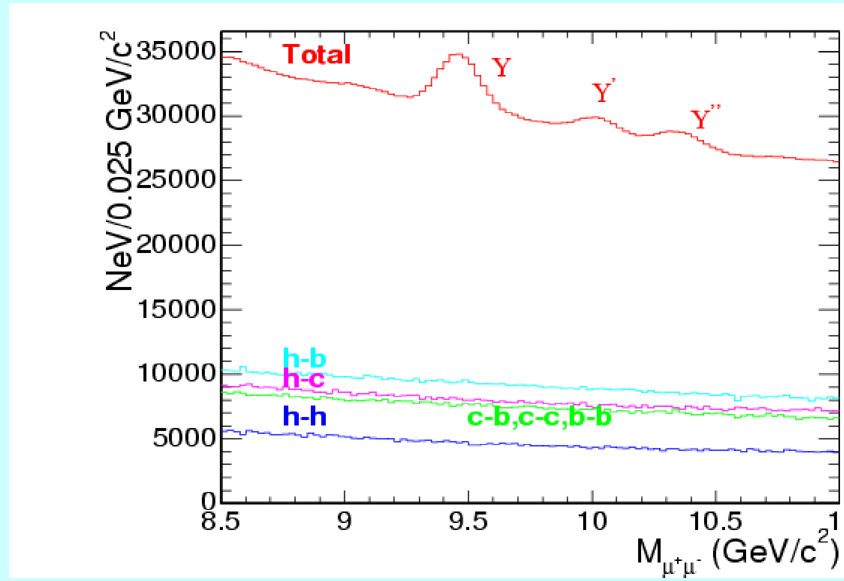
J/ψ and ϒ spectra for multiplicity $dN_{ch}/d\eta = 2500$

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:

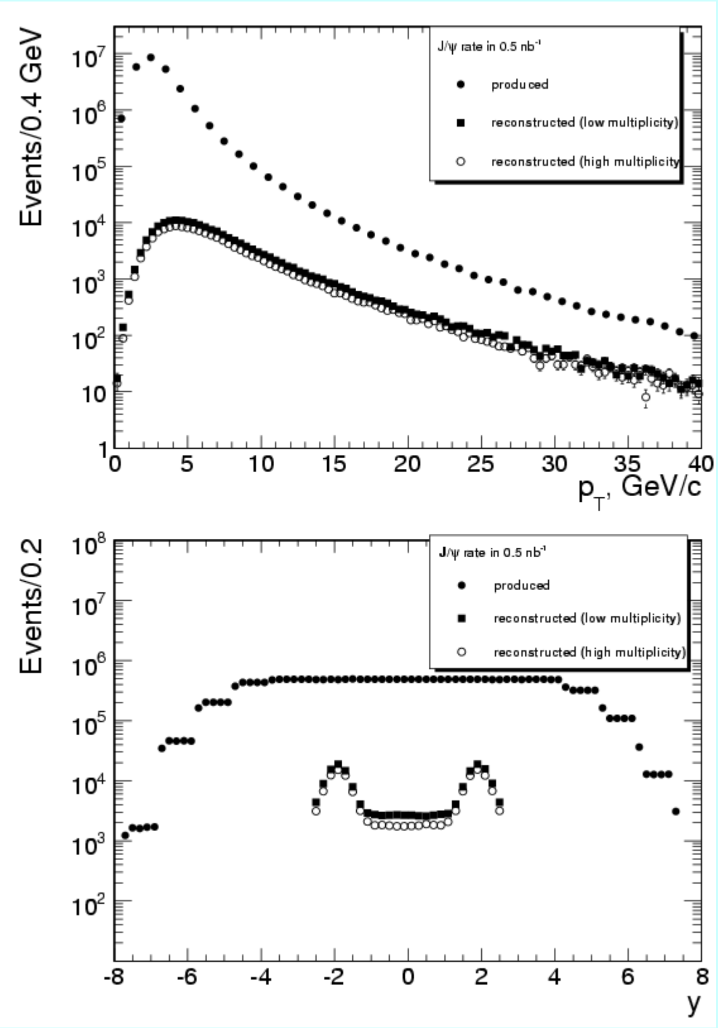
Mixed sources, i.e.

1 μ from π/K + 1 μ from J/ψ

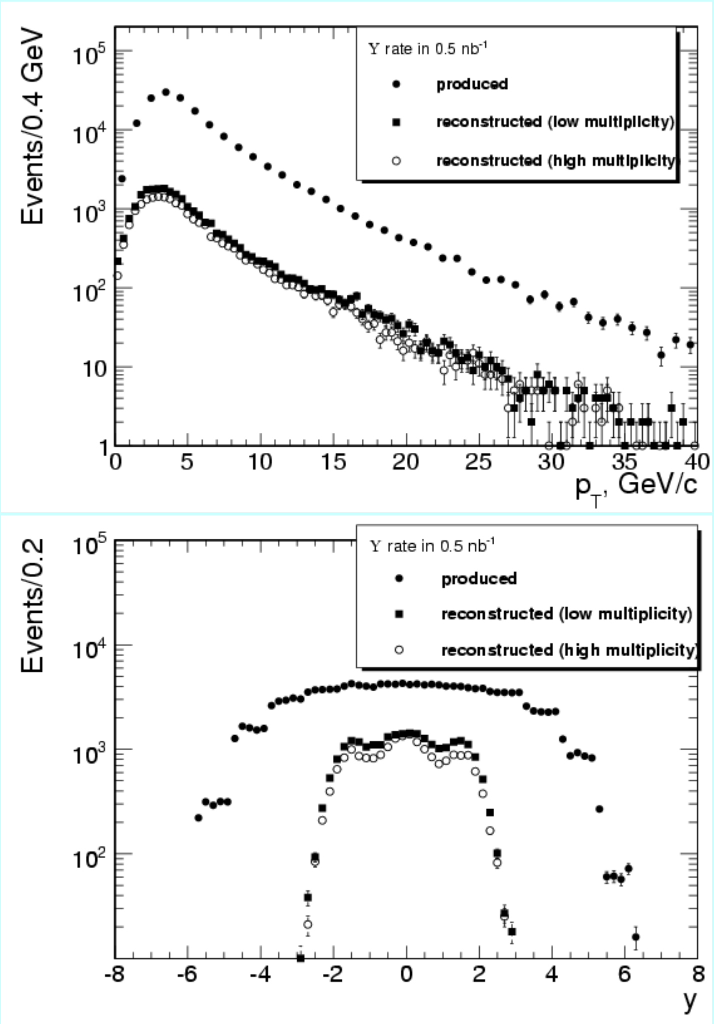
1 μ from b/c + 1 μ from ϒ

J/ψ and ϒ p_T and y distribution, PbPb

J/Ψ rate in 0.5 nb^{-1}

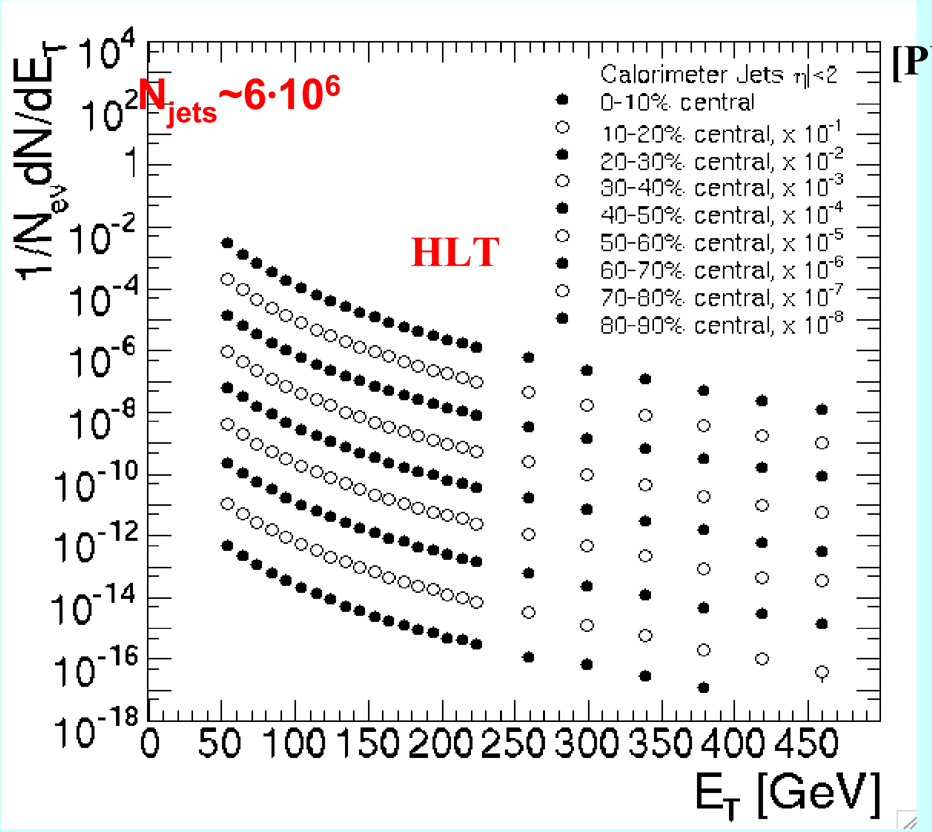


ϒ rate in 0.5 nb^{-1}



Jet spectra at CMS@LHC

Jet spectra up to E_T~ 0.5 TeV



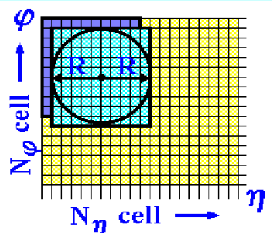
[PbPb, 0.5 nb^{-1}]

Detailed jet-quenching studies: jet fragmentation function, jet shape, jet azimuthal anisotropy, ...

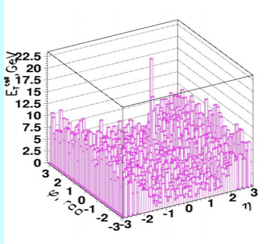
High p_T jets. Jet reconstruction in HI collisions

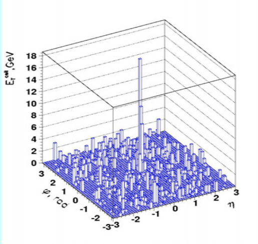
BACKGROUND SUBTRACTION ALGORITHM

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



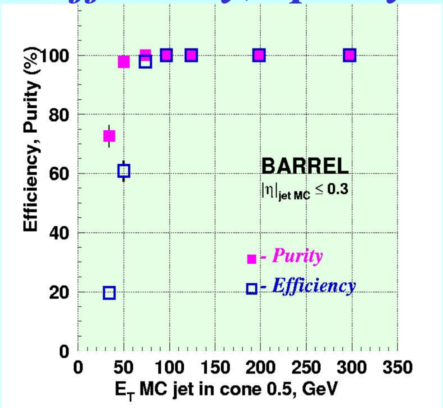
1. Subtract average pileup
2. Find jets with iterative cone algorithm
3. Recalculate pileup outside the cone
4. Recalculate jet energy



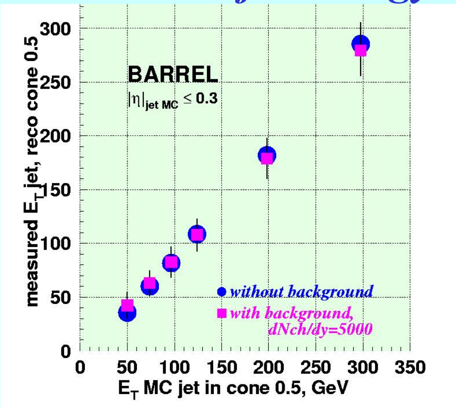


Full jet reconstruction in central Pb-Pb collision HIJING, $dN_{ch}/dy = 5000$

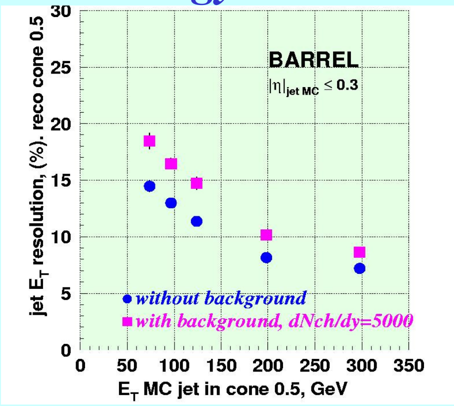
Efficiency, purity



Measured jet energy



Jet energy resolution



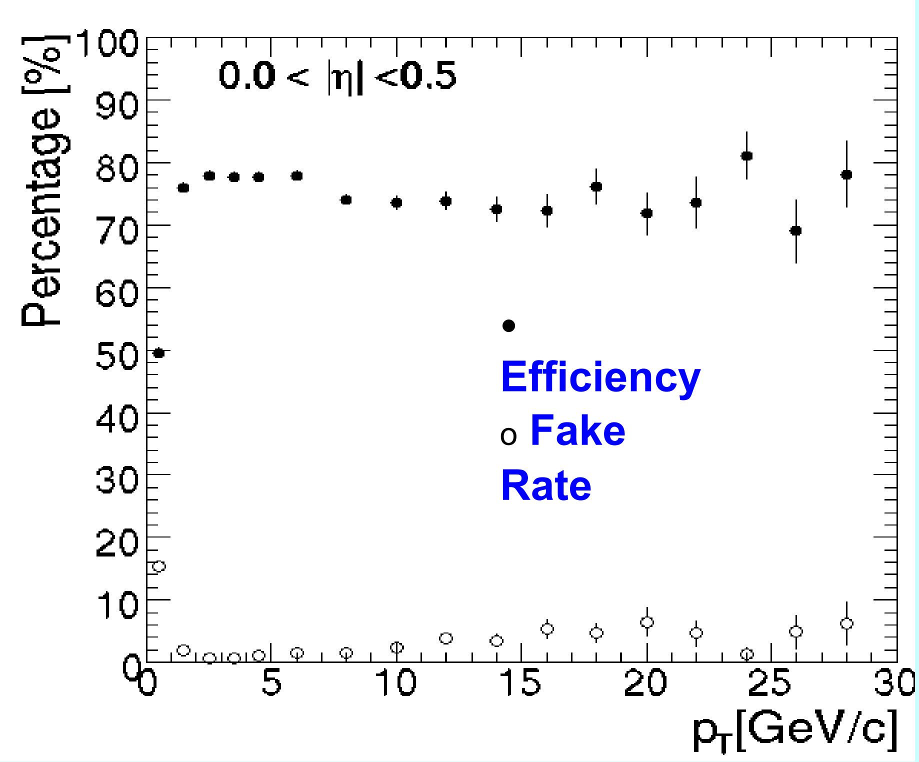
Jet spatial resolution: $\sigma(\varphi_{rec} - \varphi_{gen}) = 0.032$; $\sigma(\eta_{rec} - \eta_{gen}) = 0.028$

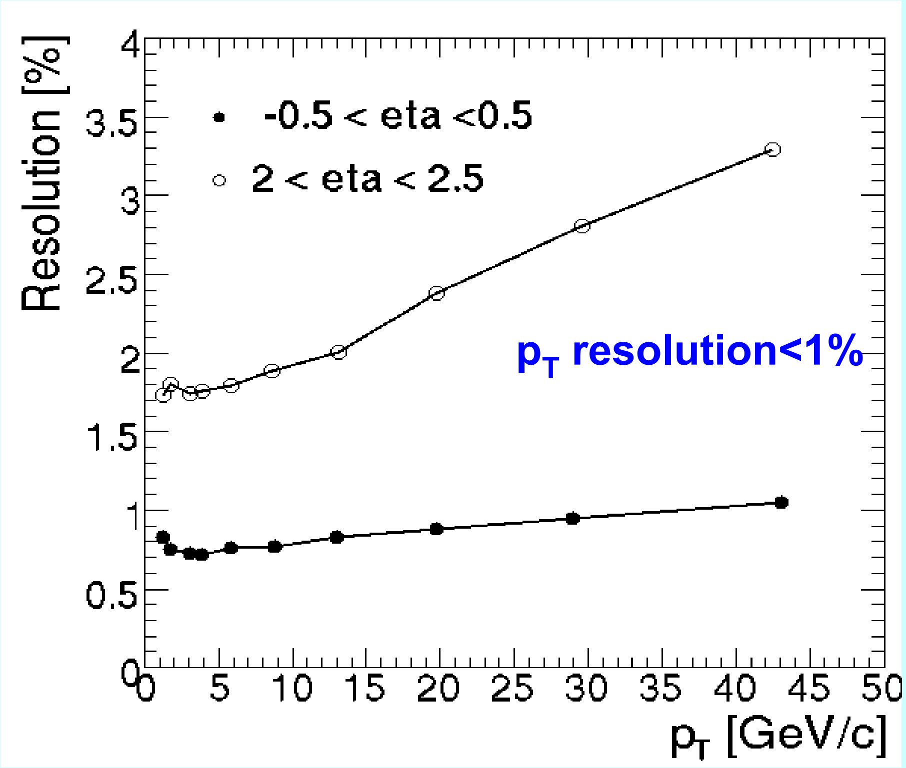
Better than η, φ size of tower (0.087×0.087)

High-p_T hadron reconstruction

C. Roland et al.: NIM A566 (2006) 123

CMS tracking performance for Pb+Pb collisions, HYDJET, $dN_{ch}/dh|_{y=0} = 3500$

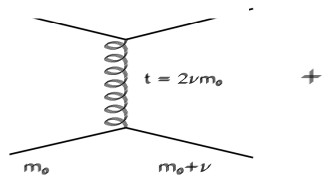




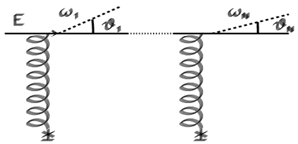
Jet quenching: medium-induced parton energy loss

Collisional loss
(incoherent sum over scatterings)

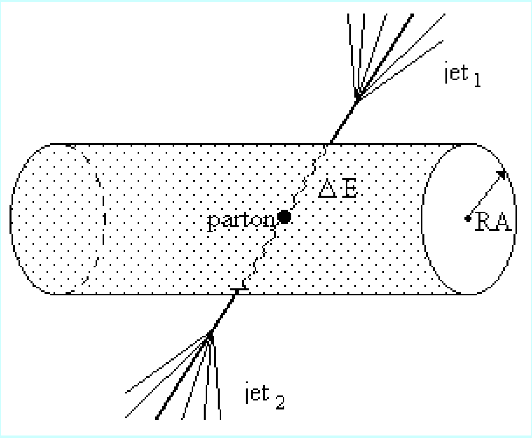
Bjorken; Mrowczynski; Thoma; Markov; Mustafa et al...



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:

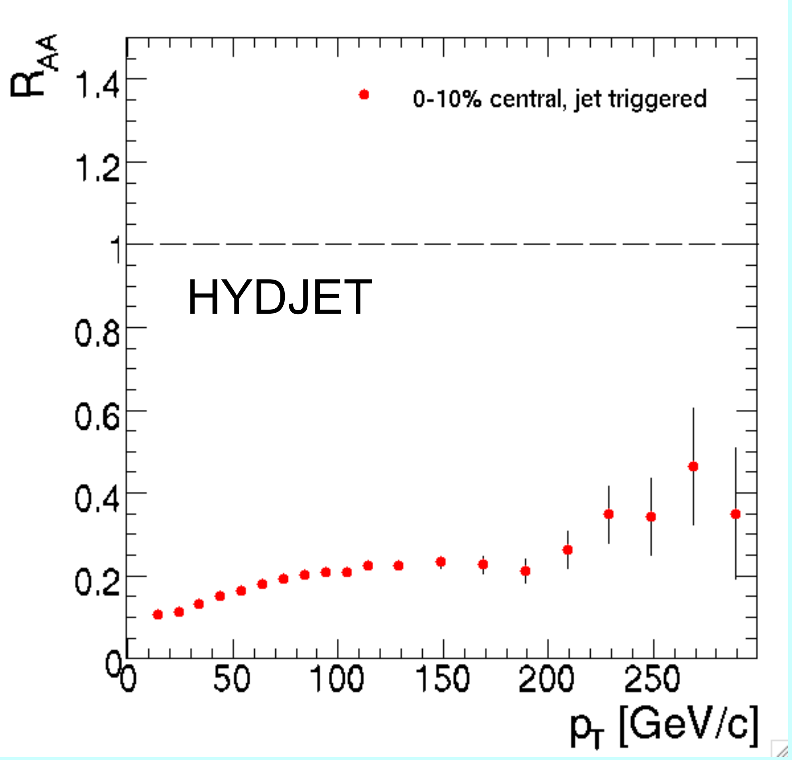
$$T_{0,\,QGP} \sim 1\ \mathrm{GeV}\ >> T_{0,\,HG}^{\ max} \sim 0.2\ \mathrm{GeV},$$

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

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 ($d^2\sigma^{NN}/dp_T d\eta$)



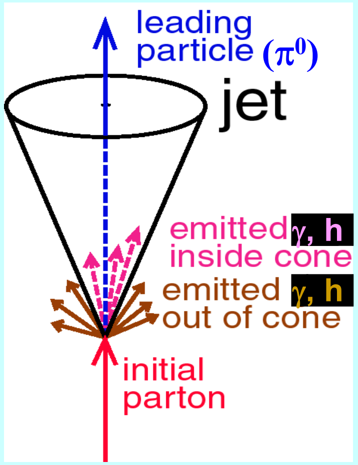
→ Will be measured at CMS:

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

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

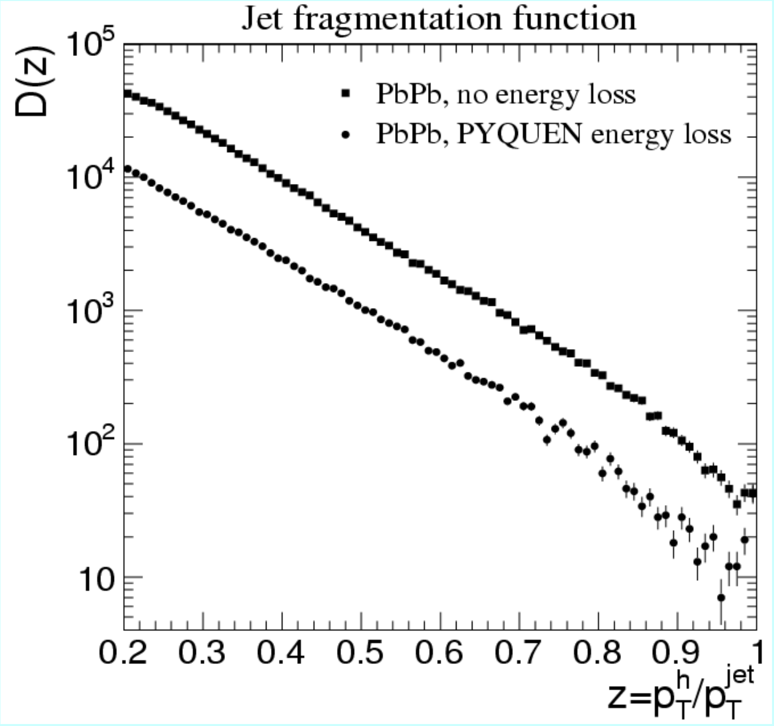
$$D(z) = \int_{z \cdot p_T^{jet}{}_{min}} d(p_T^h)^2 dy dz' \frac{dN_{AA}^h}{d(p_T^h)^2 dy dz'} \delta(z - p_T^h/p_T^{jet}) \Big/ \int_{p_T^{jet}{}_{min}} d(p_T^{jet})^2 dy \frac{dN_{AA}^{jet}}{d(p_T^{jet})^2 dy}$$

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")

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

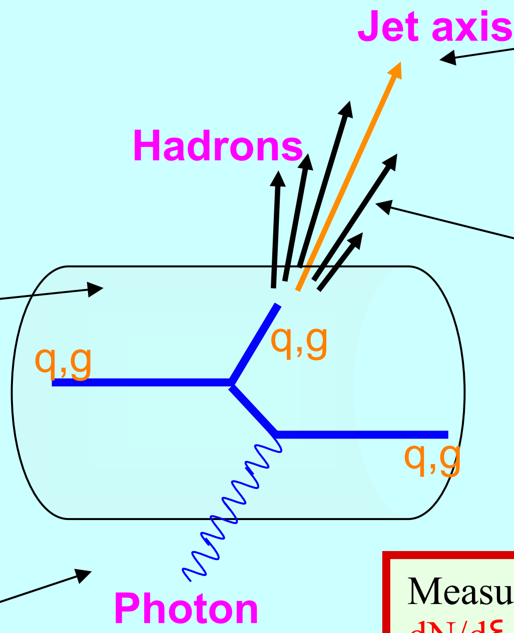


$D^{PbPb}(z)/D^{pp}(z) \sim 0.25$

Photon-tagged jet fragmentation function

$q + q \rightarrow \gamma + jet$

Multiplicity and flow measurements characterize density, path length



Jet axis provides parton direction

Charged hadron tracks used to calculate $z = p_T/E_T$

Photon energy tags parton energy E_T

Measure jet fragmentation function:
$dN/d\xi$ with $\xi = -\log z$

Main advantage

Photon unaffected by the medium

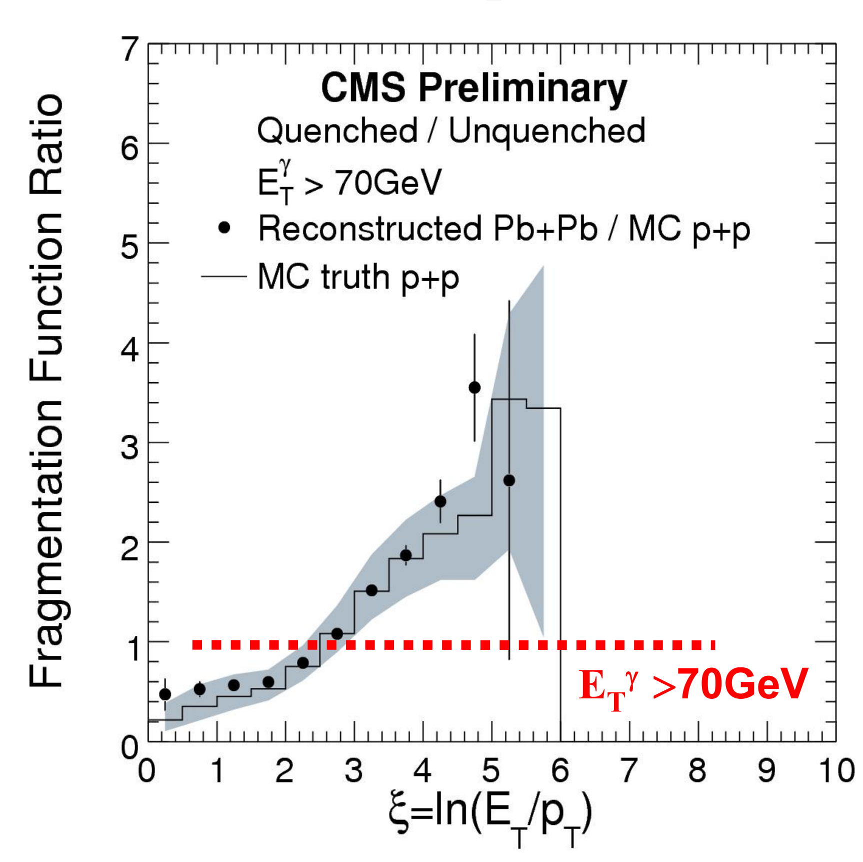
Avoids measurement of absolute jet energy

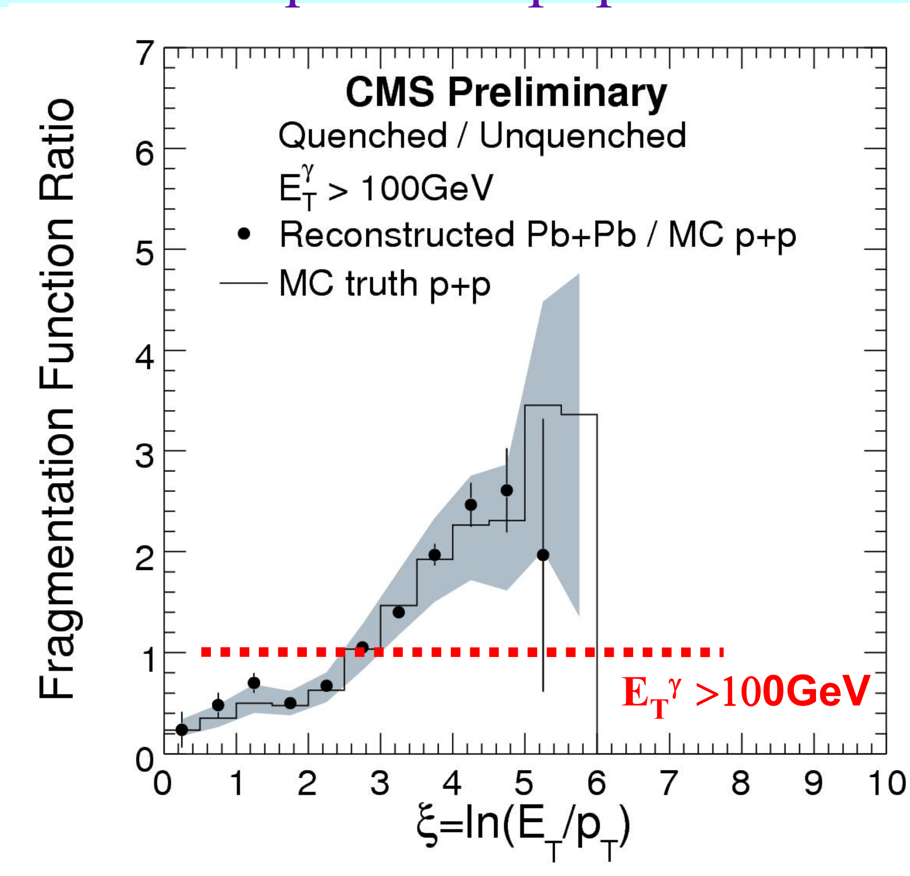
Ingredients:

- Event/Centrality selection
- Reaction plane determination
- Vertex finding
- Track reconstruction
- Jet finding
- Photon identification

Jet fragmentation function ratio

Reco quenched Pb+Pb / MC unquenched p+p

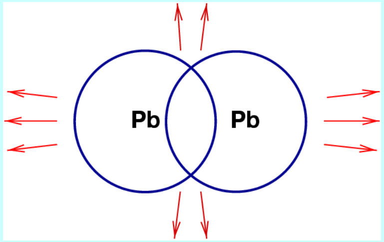




Medium modification of fragmentation functions can be measured

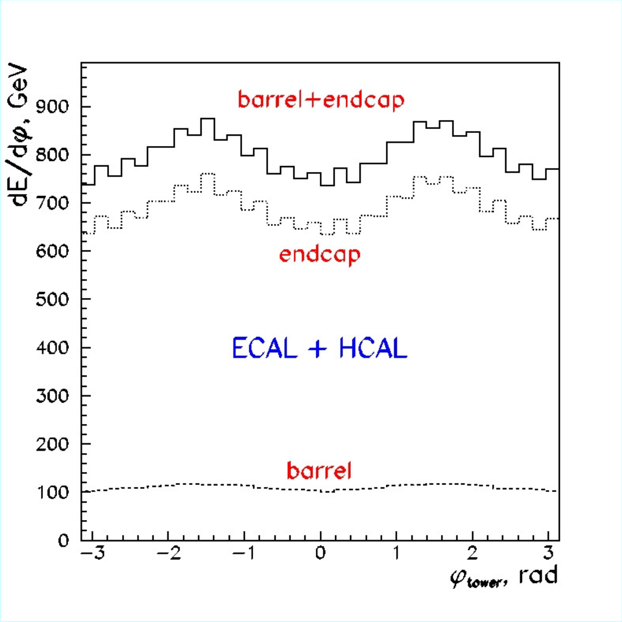
High significance for $0.2 < \xi < 5$ for both, E_T^γ >70GeV and E_T^γ >100GeV

Azimuthal Anisotropy in HIC with CMS Calorimeter

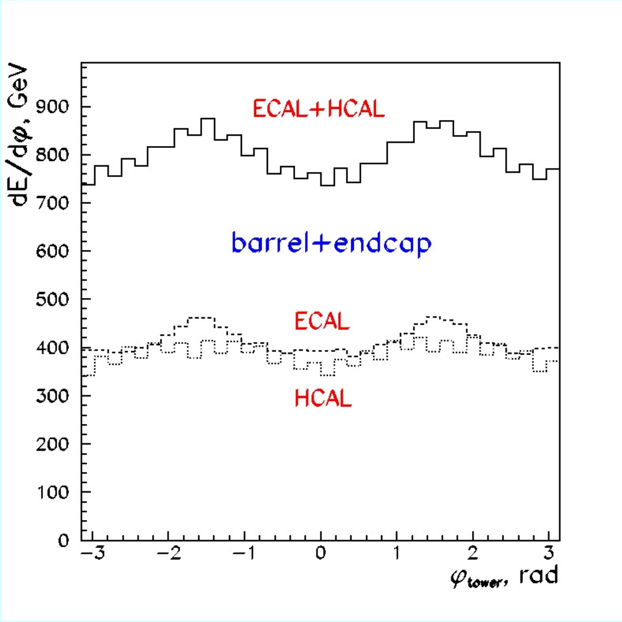


- **Non-central heavy-ion collisions (*b* ≠ 0), elliptic volume of interacting nuclear matter, energy flow illustrates azimuthally anisotropic elliptic volume.**
- **Calorimeters are used to determine event plane.**
- **Azimuthal anisotropy can be estimated with CMS calorimeters with and without the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

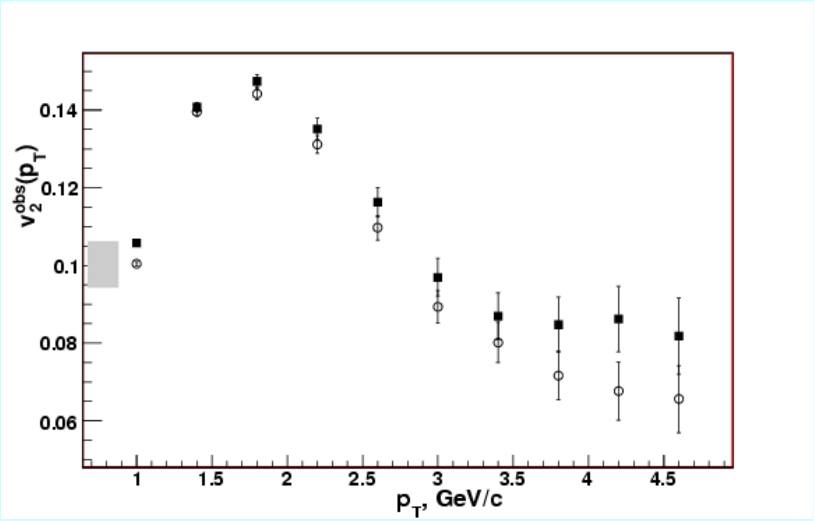
HYDRO, *Pb+Pb collisions, b = 6 fm. GEANT-based simulation*

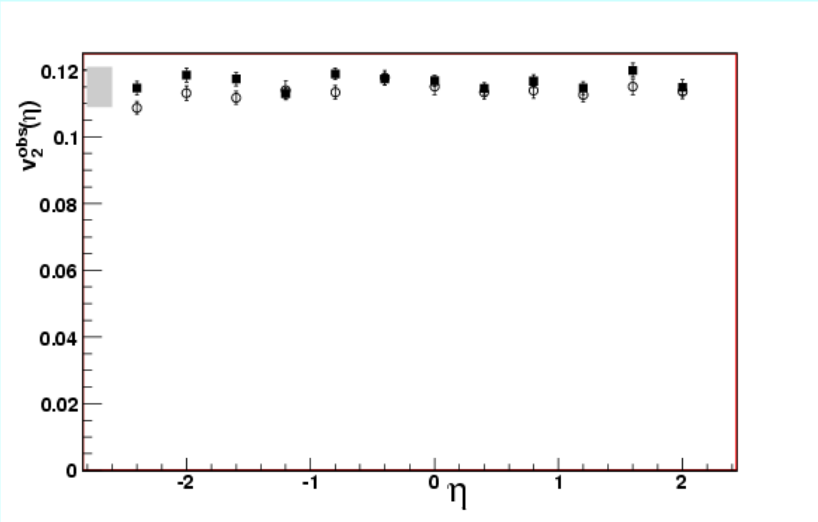


Energy flow



Azimuthal Anisotropy in HIC with CMS Tracker, Elliptic Flow Parameter v_2 (HYDJET, 10000 PbPb events, b = 9 fm)

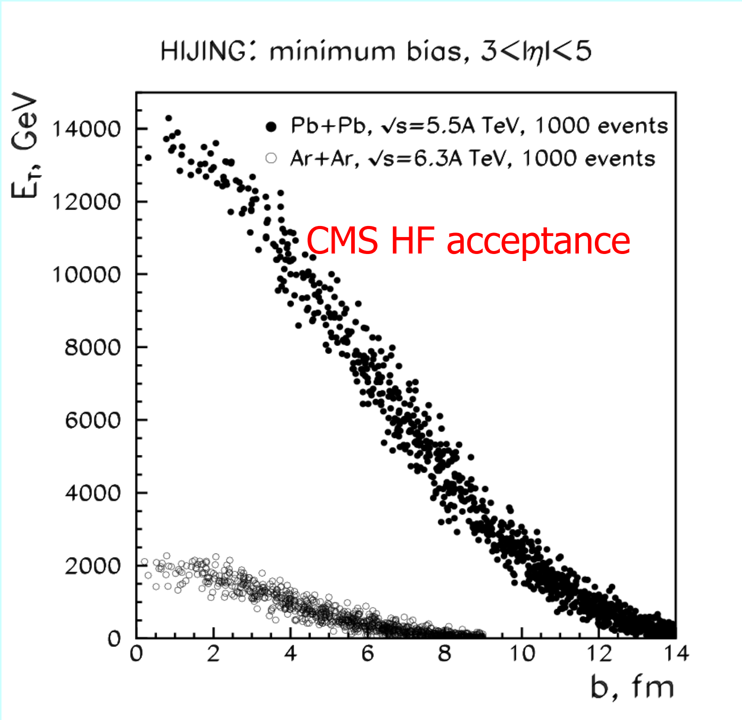


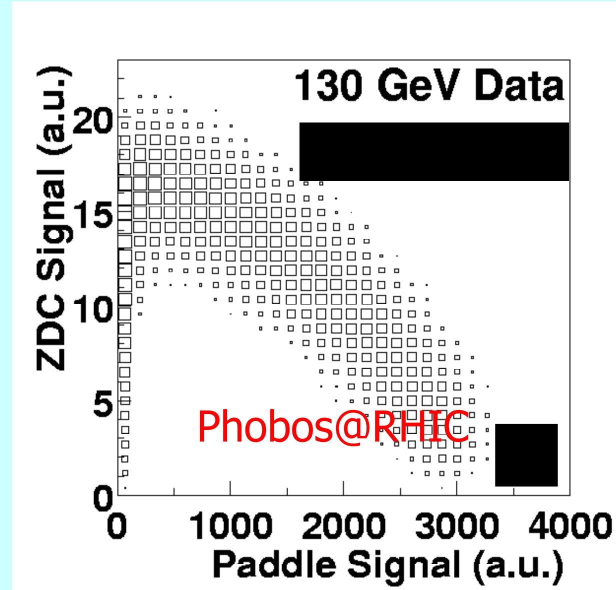


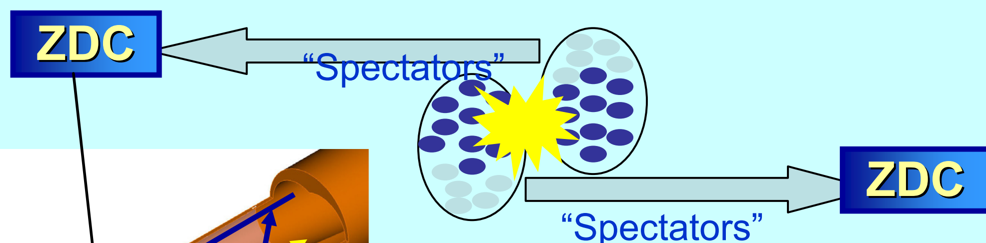
Open circles are with simulated and closed squares with reconstructed events

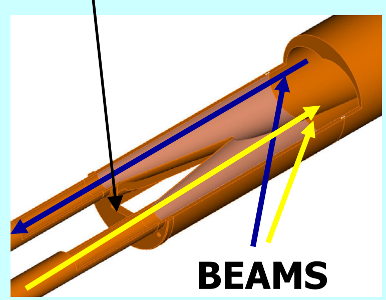
Method	$\langle v_2^{obs}(rec) \rangle$	$RMS\,(v_2^{obs})$	$\langle v_2^{obs}(rec) \rangle / v_2^{obs} \langle (sim) \rangle$
$V_2 = \langle \cos 2(\varphi - \Psi_R) \rangle$	**0.12**	**0.05**	**1.05**
$\sqrt{\langle \cos 2(\varphi_1 - \varphi_2) \rangle}$	**0.12**	**0.05**	**1.05**
v_2 from fitting	**0.12**	**0.06**	**0.96**

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)

Summary and outlook

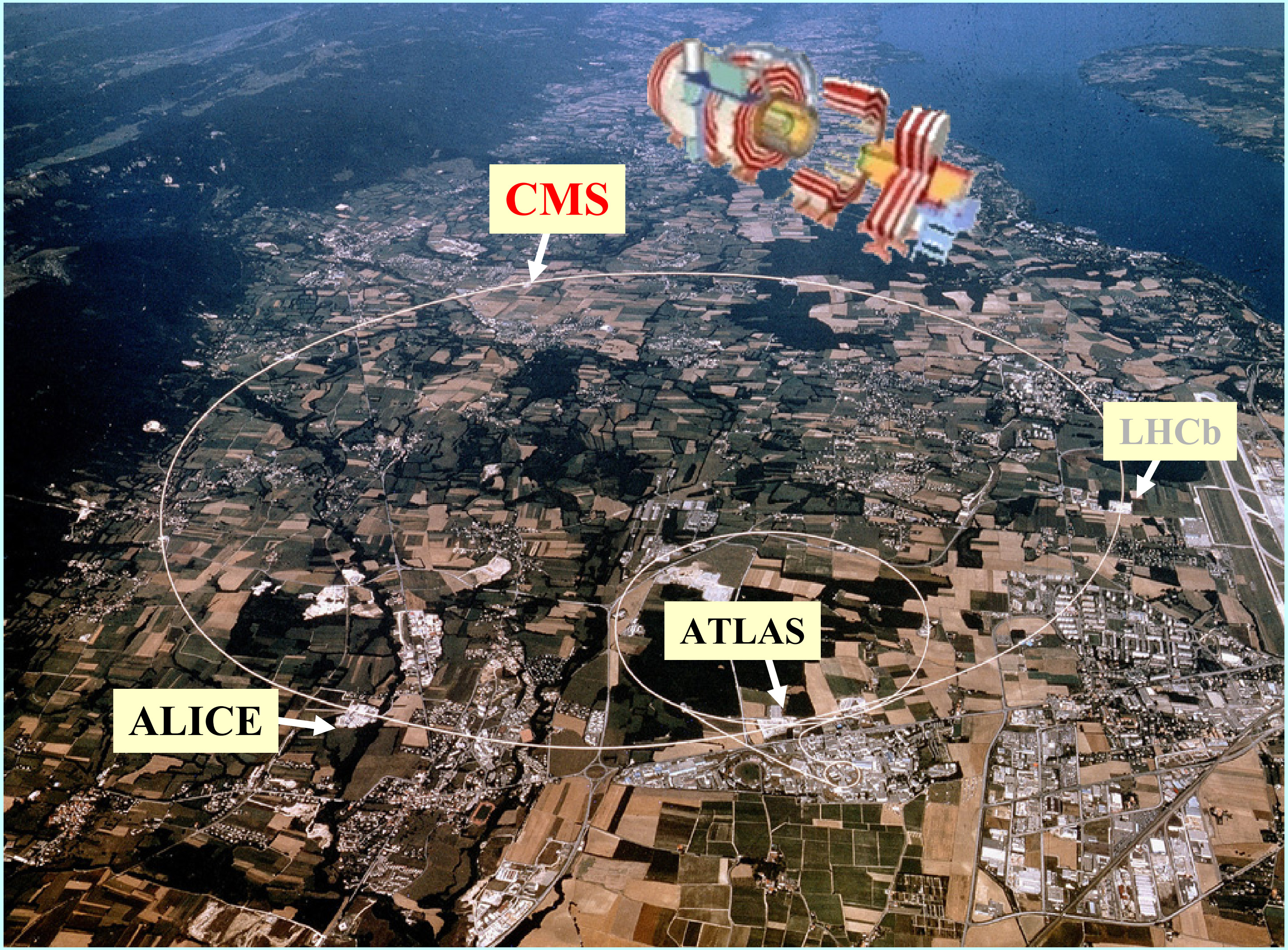
- At LHC a new regime of heavy ion physics will be reached where hard particle production can dominate over soft events, while the initial gluon densities are much higher than at RHIC, implying stronger QCD medium effects observable in new channels.
- CMS is an excellent device for the study of quark-gluon 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

Acknowledgement

Thanks to CMS Colleagues for providing the material for this talk!

- BACKUP SLIDES

CMS detector at the LHC



CMS Trigger rates for HIC

- **Trigger**
  - **Level 1 Trigger**
    - **muon chamber + calorimeter information**
    - **response time ~ 3μs**

$\mathcal{L}$ ($cm^{-2}s^{-1}$): Pb+Pb 10^{27}, p+p 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**
    - **full minbias event information available**
    - **runs offline algorithms on every PbPb event**

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%

PbPb High-Level Triggering

M.Ballitjin,C.Loizides,G.Roland, CMSAN06-099

- Unique CMS High-Level-Trigger 12k × 1.8-GHz CPUs ~ 50 Tflops !
- CMS HLT fast enough to run "offline" algos on every PbPb evt. !
- Event rates:

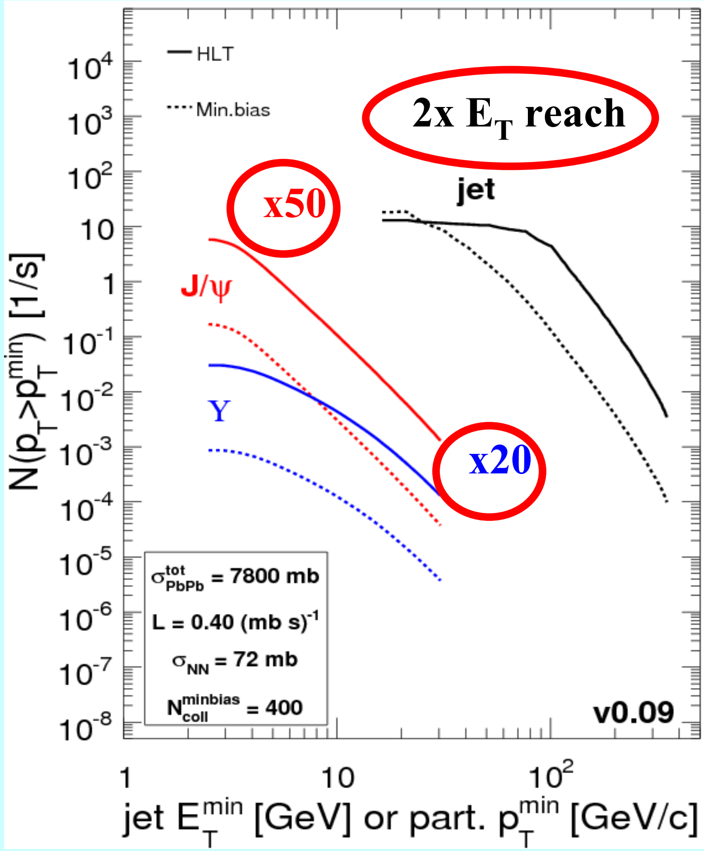
- Logging rate: 225 MB/s
- Luminosity: 10^{34} (pp), 10^{27} (PbPb)
- Evt. size (MB): 1 (pp), 2.5 (PbPb),10 (PbPb cent)

pp: 40 MHz → (1/400) 100 kHz → (1/600) 150 Hz

L1 HLT

PbPb: 5 kHz → (1/1) 5 kHz → (1/50 - 1/500) ~10-100 Hz

Significantly enhanced statistical reach for hard probes: x20 – x300



Quarkonia and heavy quarks from SPS and RHIC to LHC

Increase energy $\sqrt{S}$=17-200 GeV/n-n → 5500 GeV/n-n

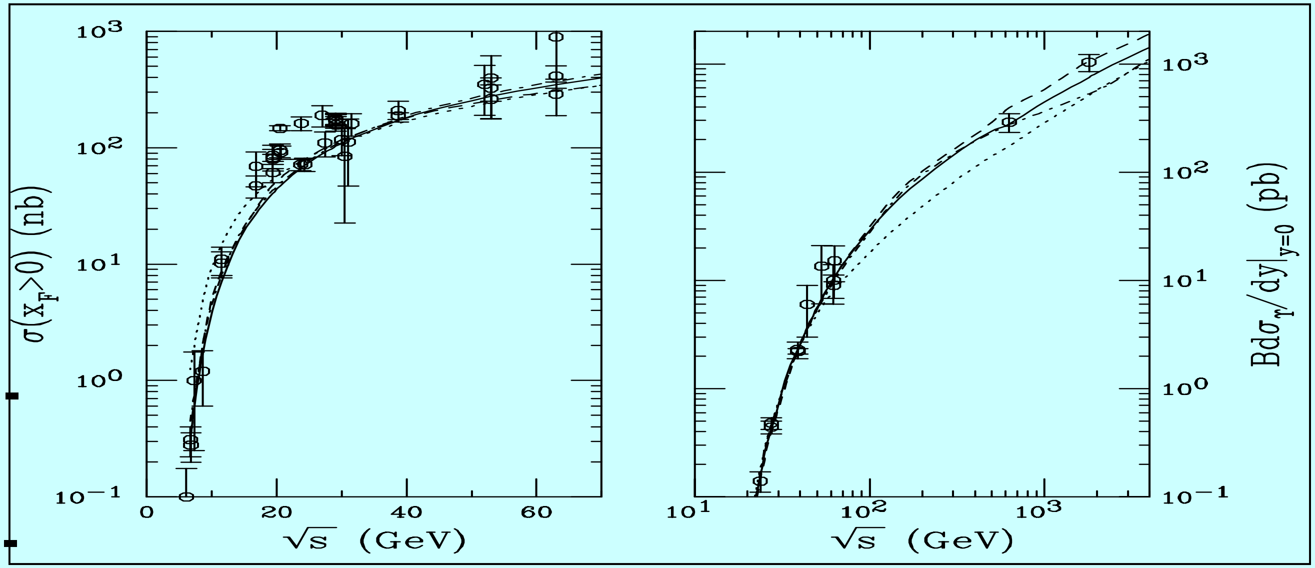
Plasma hotter and longer lived than at RHIC

Unprecedented Gluon densities

Access to lower x, higher Q^2

Availability of new probes

J/Ψ ϒ

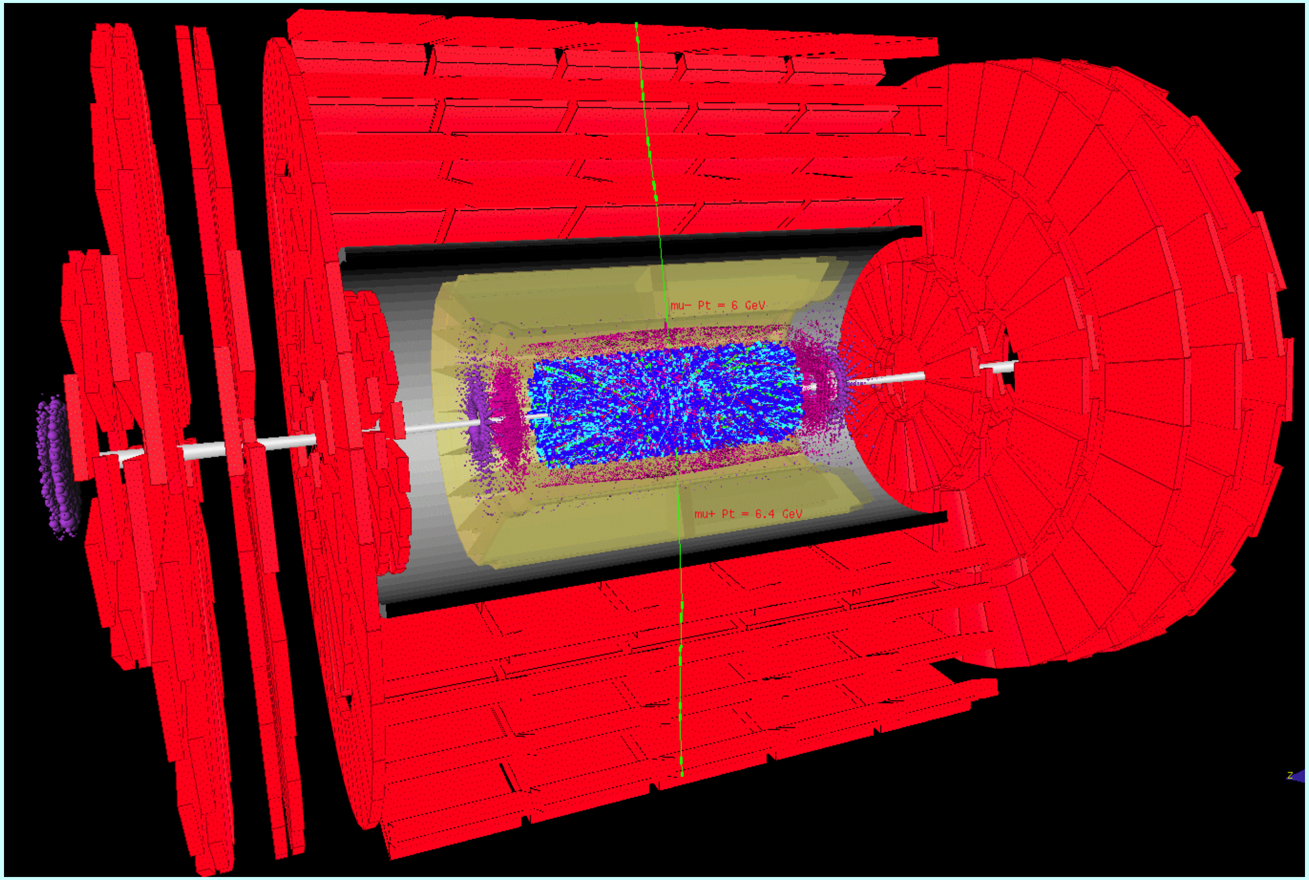


LHC

- 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

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

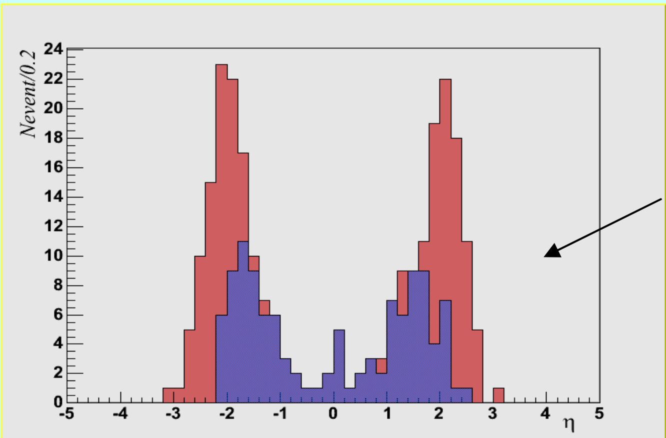


Dimuon high level trigger performance

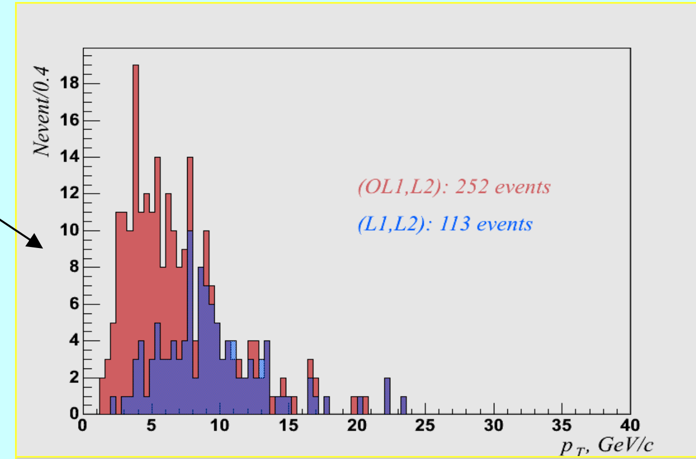
Two Different Level 1 Trigger (single muon trigger)

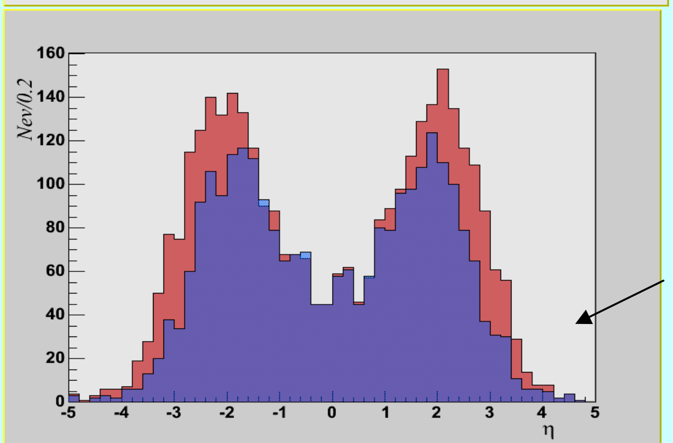
L1: optimised for high luminosity pp run, OL1: low quality muon candidates optimised for HI

L2 and L3 run on online farm, trigger conditions: two L1 or L2 opposite sign+ L3 (cut on loose)

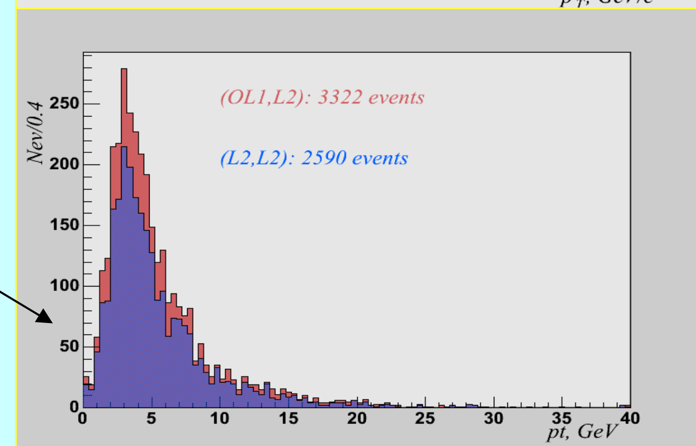


J/ψ trigger efficiency:
0.97% (OL1-L2 chain)
0.44% (L1-L2 chain)

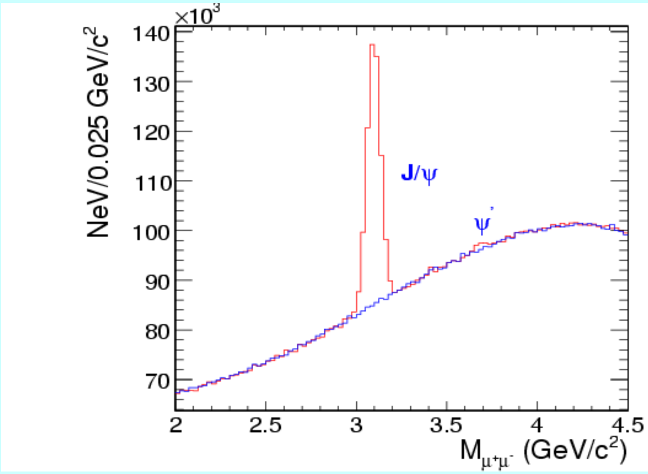




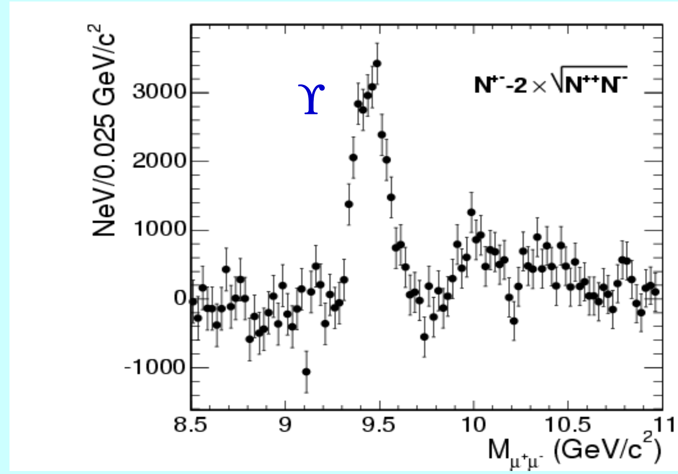
Υ trigger efficiency:
21% (OL1-L2 chain)
16.5% (L1-L2 chain)



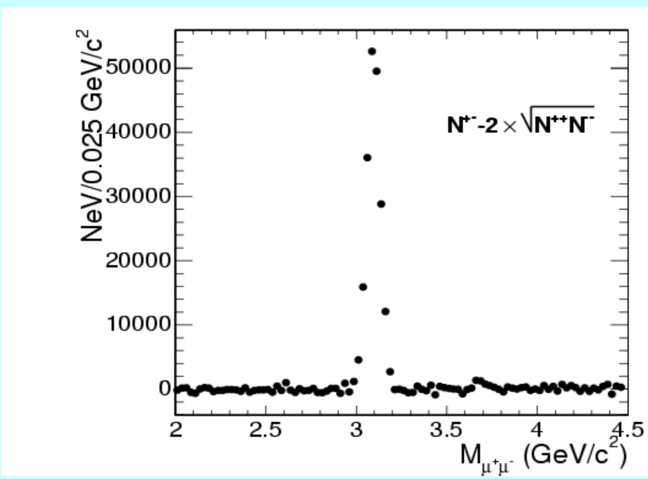
J/ψ and ϒ spectra
(subtraction of the like sign spectra)



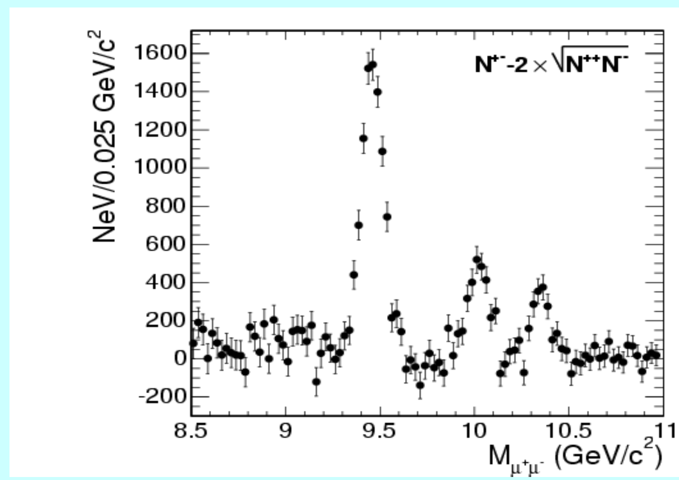
both muons $|\eta| < 2.4$



both muons $|\eta| < 2.4$

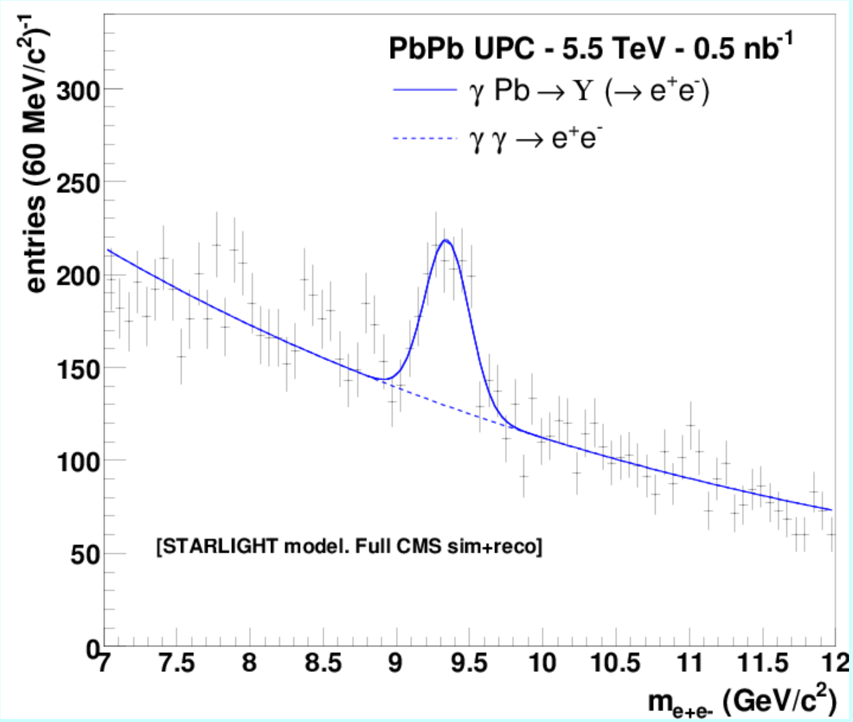


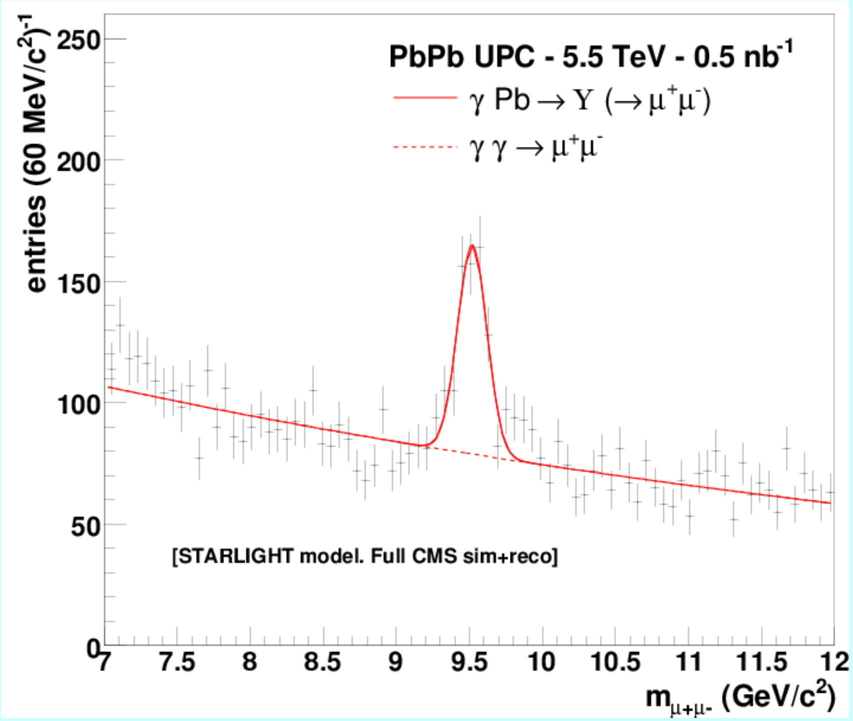
both muons $|\eta| < 0.8$



both muons $|\eta| < 0.8$

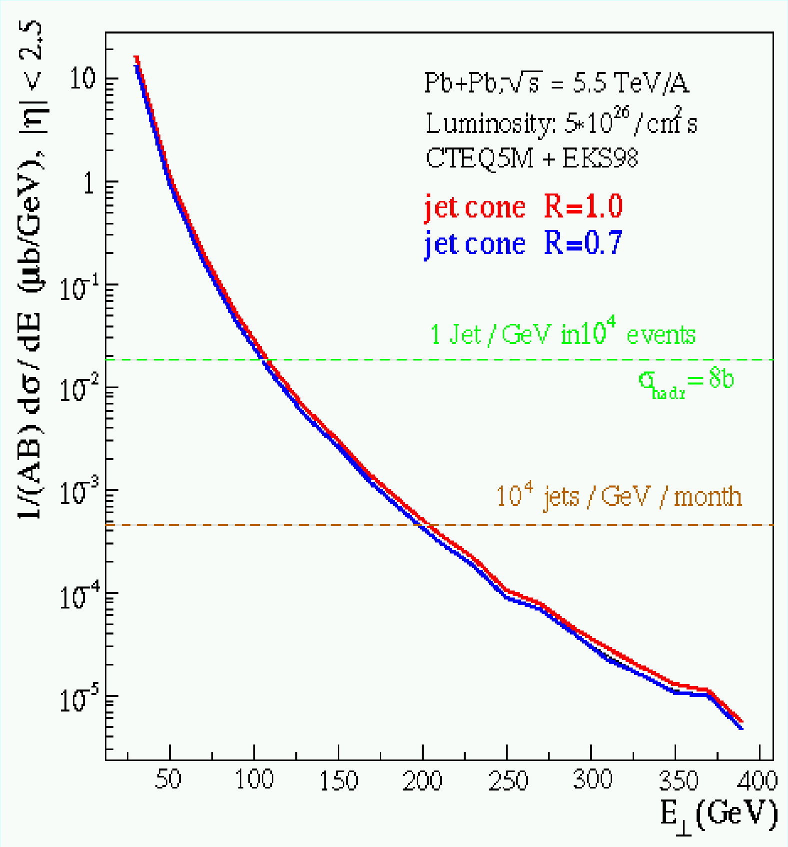
Quarkonia photoproduction in γPb collisions





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

Jet cross section & expected event rate



CERN Yellow Report, hep-ph/0310274

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, $z^{h\pm,\pi 0} > 0.5$	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

High-E_T isolated photon reconstruction

Identification

10 cluster shape variables

based on ECAL

10 isolation variables

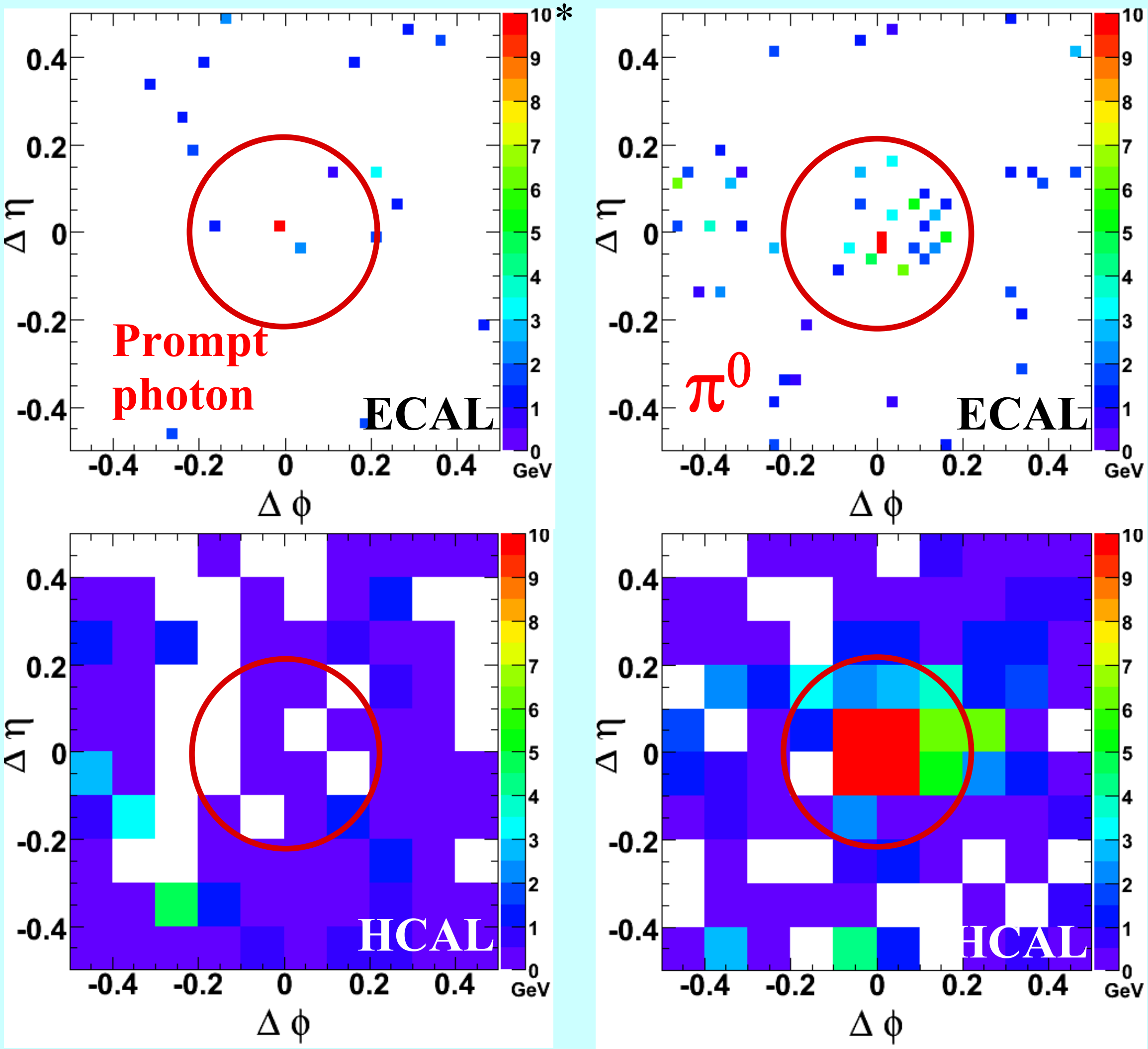
based on ECAL/HCAL

Track-based cut

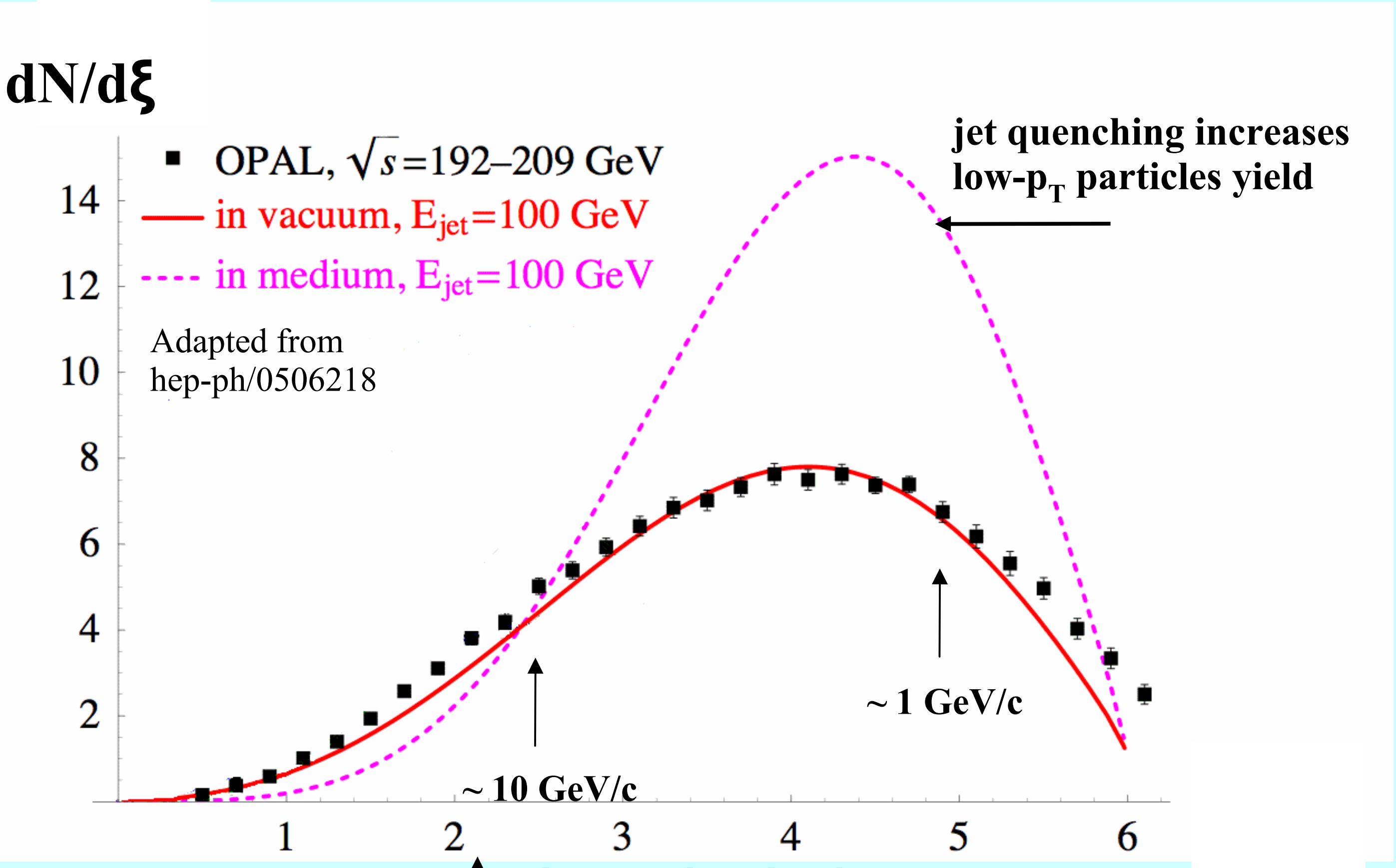
Selection

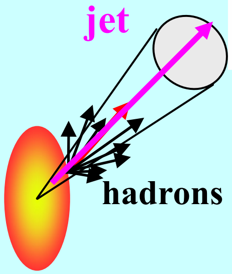
Total of 21 variables grouped into 3 sets

Linear discriminant analysis (Fisher) and cut optimization using TMVA



Medium-modified fragmentation function





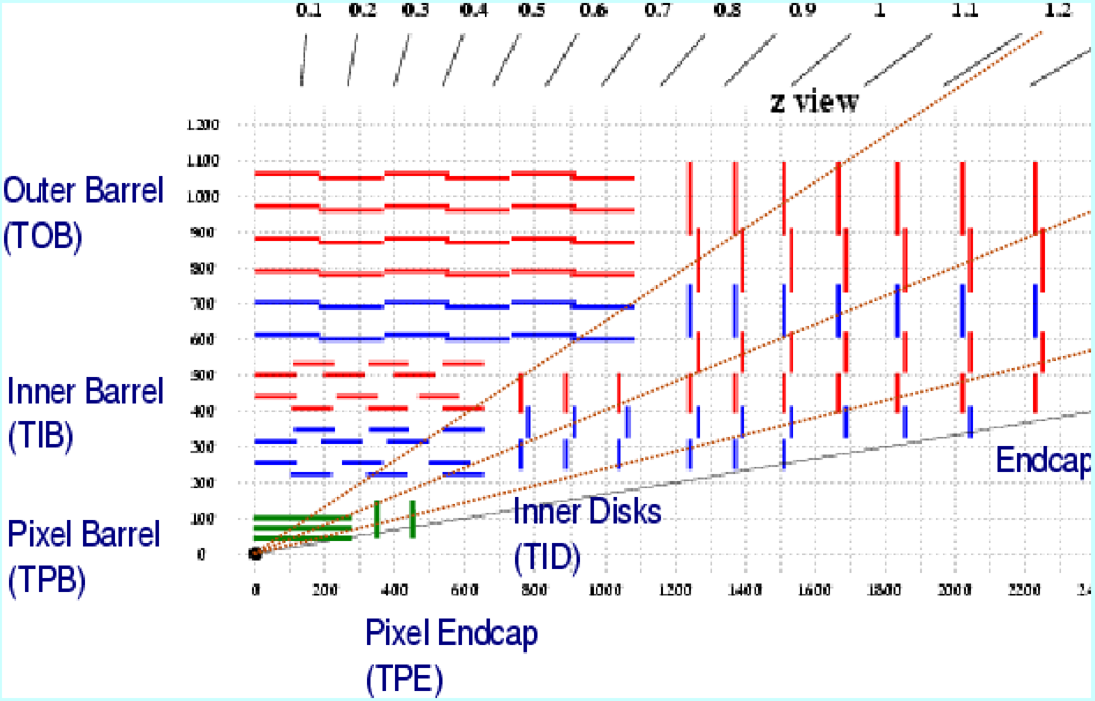
$\xi = \log(E_T/p_T)$

$z \to 1$
$(p_T \to E_T)$

$z \to 0$
$(p_T \to 0)$

jet quenching reduces
high-p_T particles yield

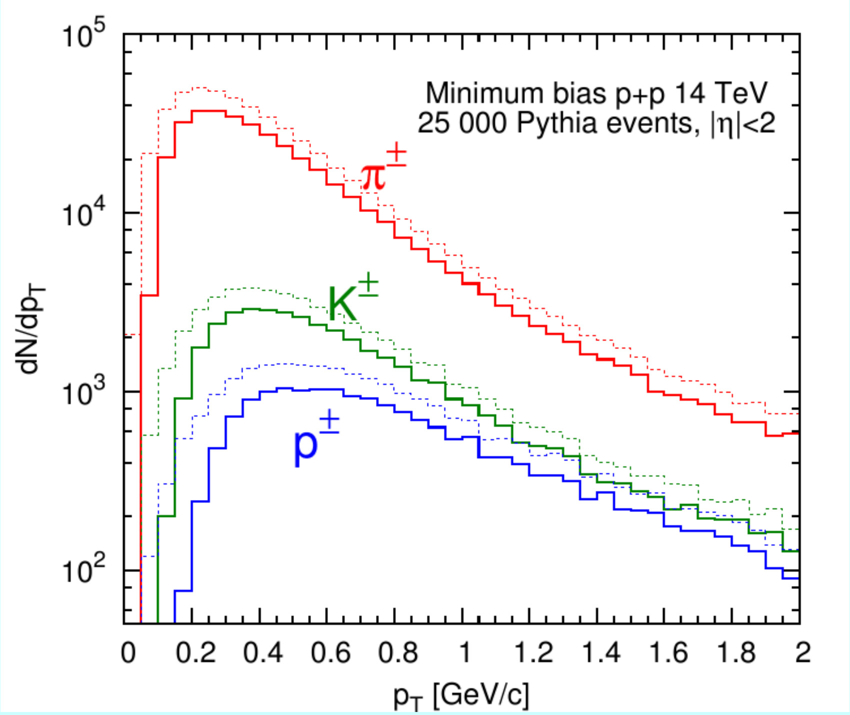
Azimuthal anisotropy in HIC with CMS Tracker

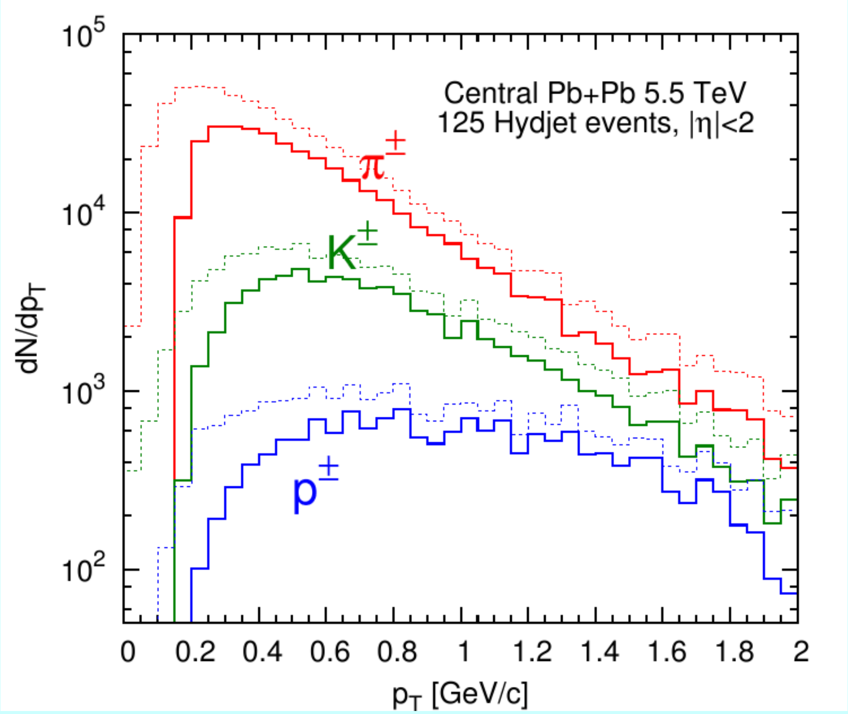


CMS Tracker

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

Low-pT particle identification with tracker, dE/dx

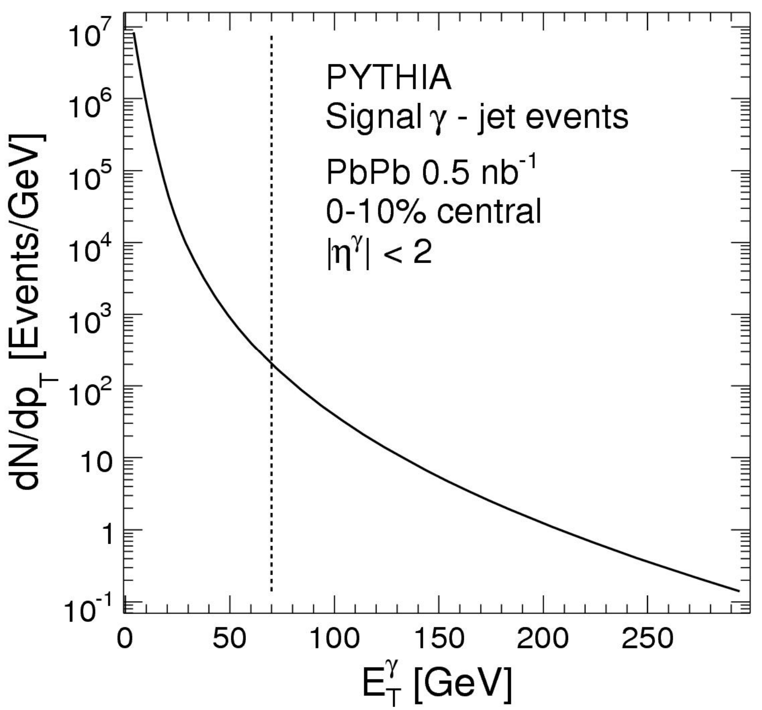




Solid lines: reconstructed, dotted lines: generated

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 $p^{\pm}$

Signal and background statistics



G. Roland et al.: CMS AN -2007/051

Study for one nominal LHC Pb+Pb run "year"

10^6 sec, $0.5 nb^{-1}$, 3.9 x 10^9 events

Use 0-10% most central Pb+Pb

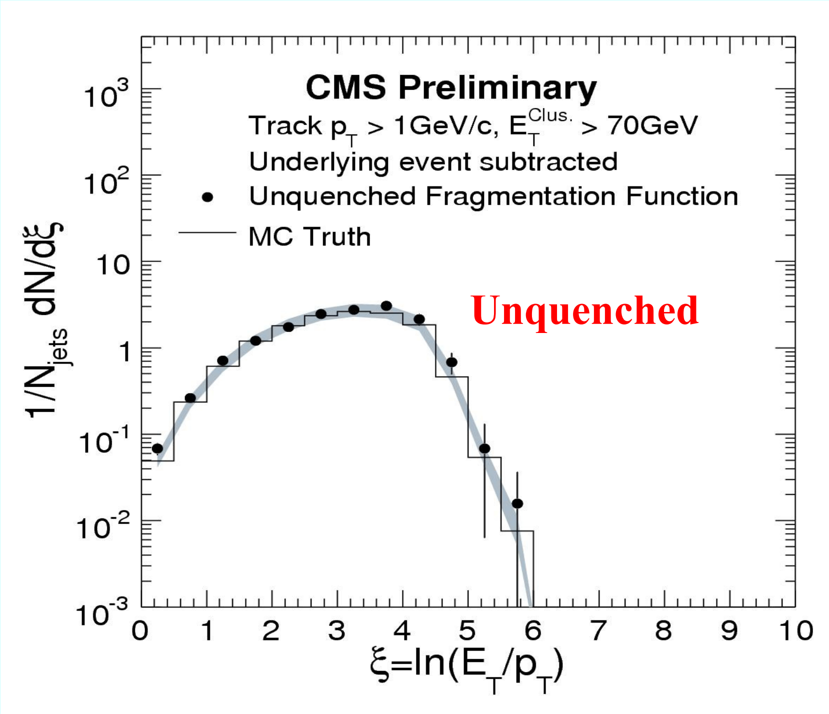
$dN/d\eta|_{\eta=0}$~2400 (HYDJET)

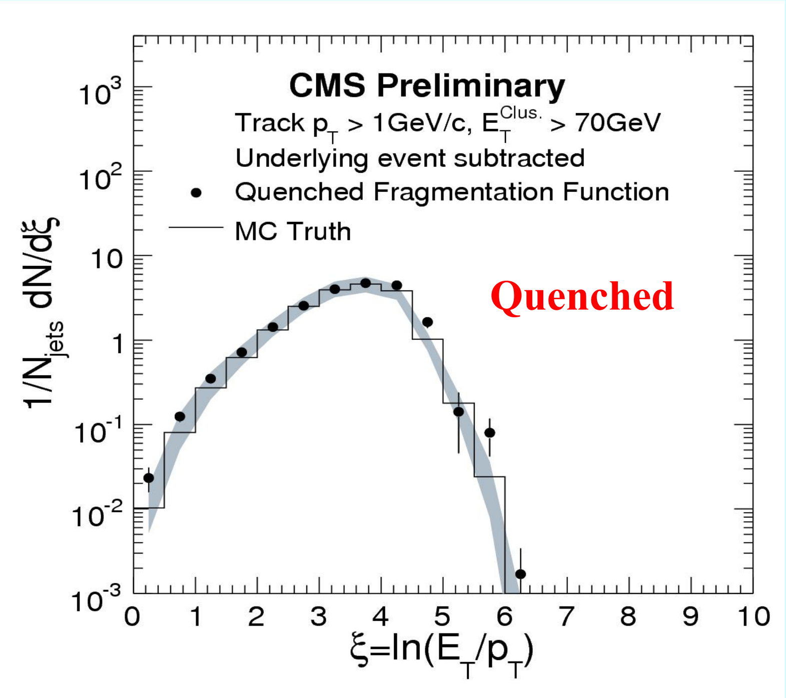
Simulate signal (PYTHIA/PYQUEN) and background QCD (p+p) events

Mix into simulated Pb+Pb events (~1000 events)

Data set	p_T [GeV/c]	signal γ-jet	π^0	$\pi^{\pm}$	η	η′	ω
unquenched	>70	4288	23675	47421	12267	8194	30601
unquenched	>100	1216	4422	9103	2357	1567	5975
quenched	>70	4209	7569	14616	3825	2445	9235
quenched	>100	1212	1562	3000	829	515	2051

Reconstructed jet fragmentation function





Major contributions to systematic uncertainty

Photon selection and background contamination (15%)

Track finding efficiency correction (10%)

Wrong/fake jet matches (10%)

No or small ξ dependence

Jet finder bias (30% in quenched case and 10% in unquenched case)