Hard probes capabilities of CMS detector in heavy ion collisions at LHC

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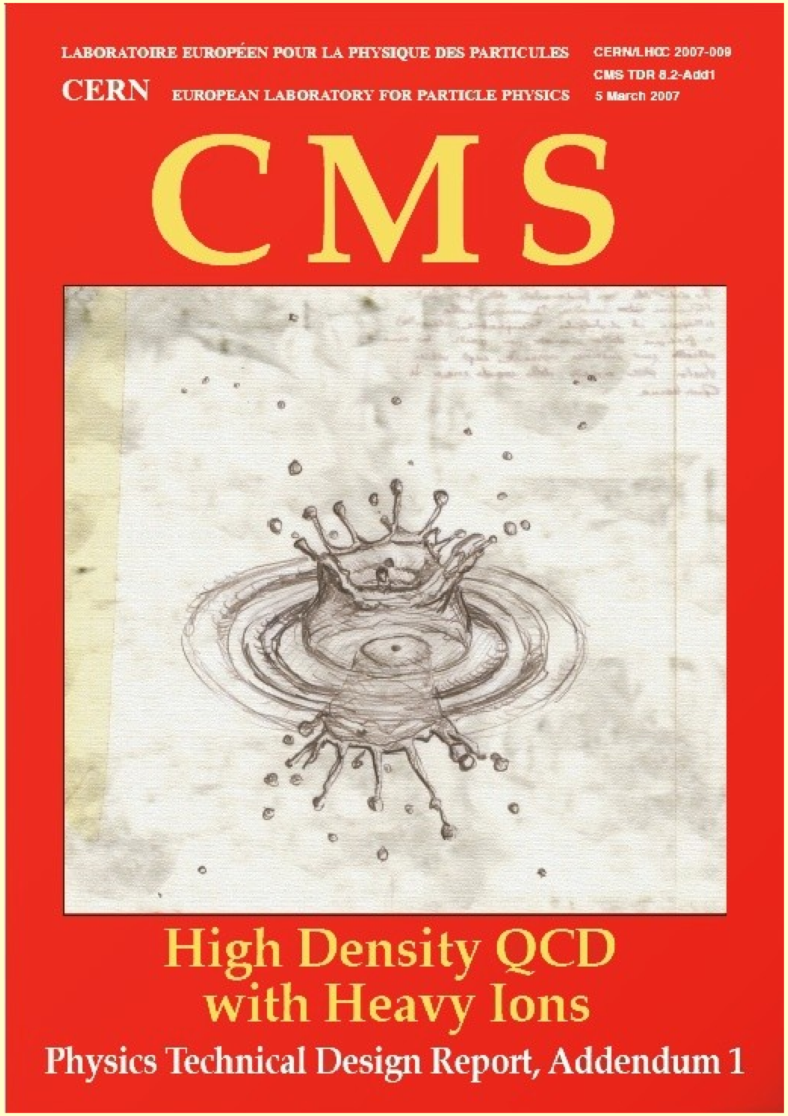
CMS Heavy Ion programme

J. Phys. G: Nucl. Part. Phys. 34 (2007) 2307-2455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CERN/LHCC 2007-009
CMS TDR 8.2-Add1
5 March 2007

CMS

High Density QCD
with Heavy Ions
Physics Technical Design Report, Addendum 1

Broad and exciting range of observables

- **Jets and photons**
(this talk)

- **Quarkonia, Z^0 and heavy quarks in high-mass dimuon decay modes** *(this talk)*

- **High-p_T hadrons**
(talk of Krisztian Krajczar)

- **Low-p_T hadrons**
(talk of Ferenc Sikler)

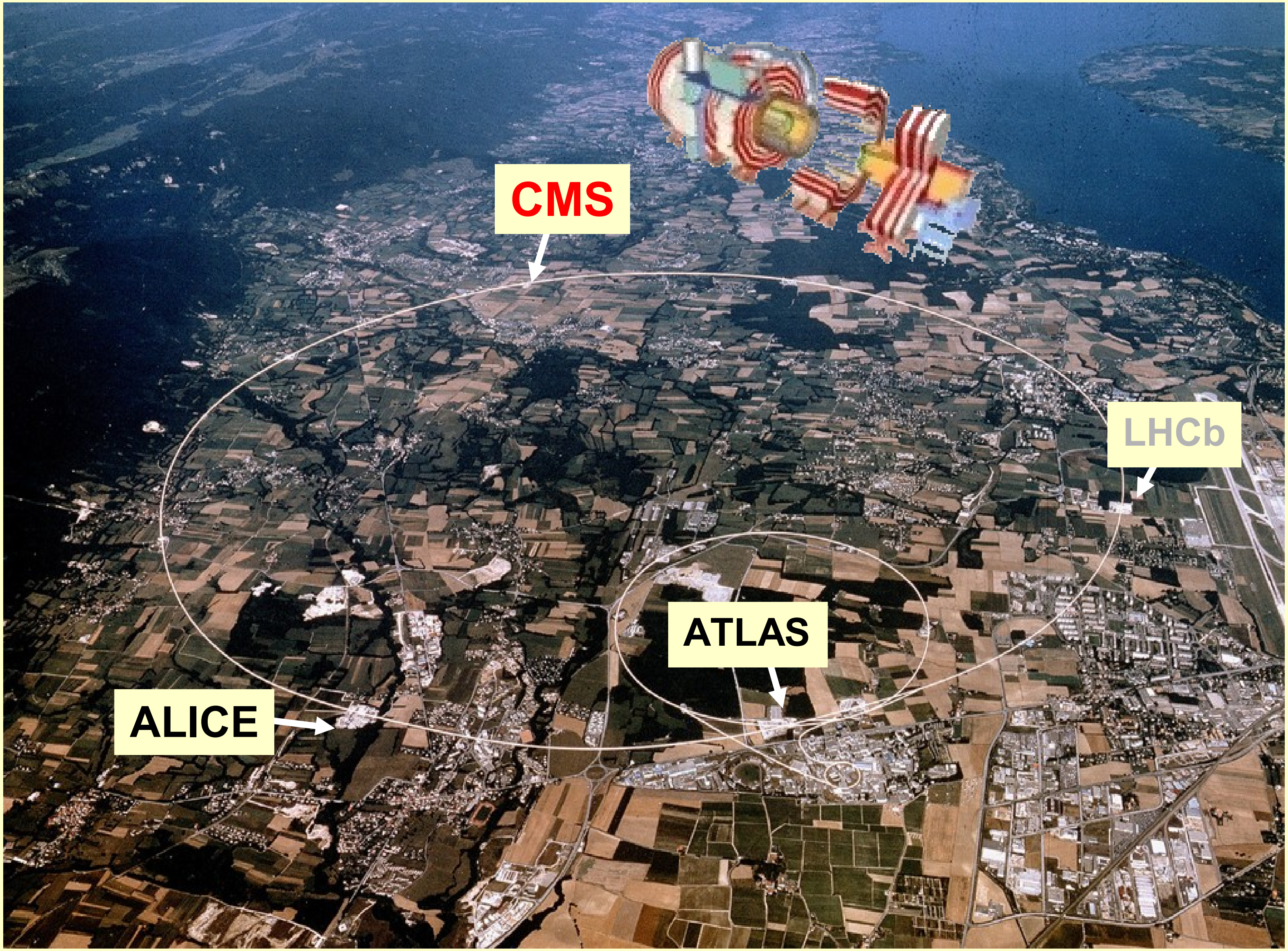
- **Ultraperipheral collisions, forward physics**
(not presented here)

Outline

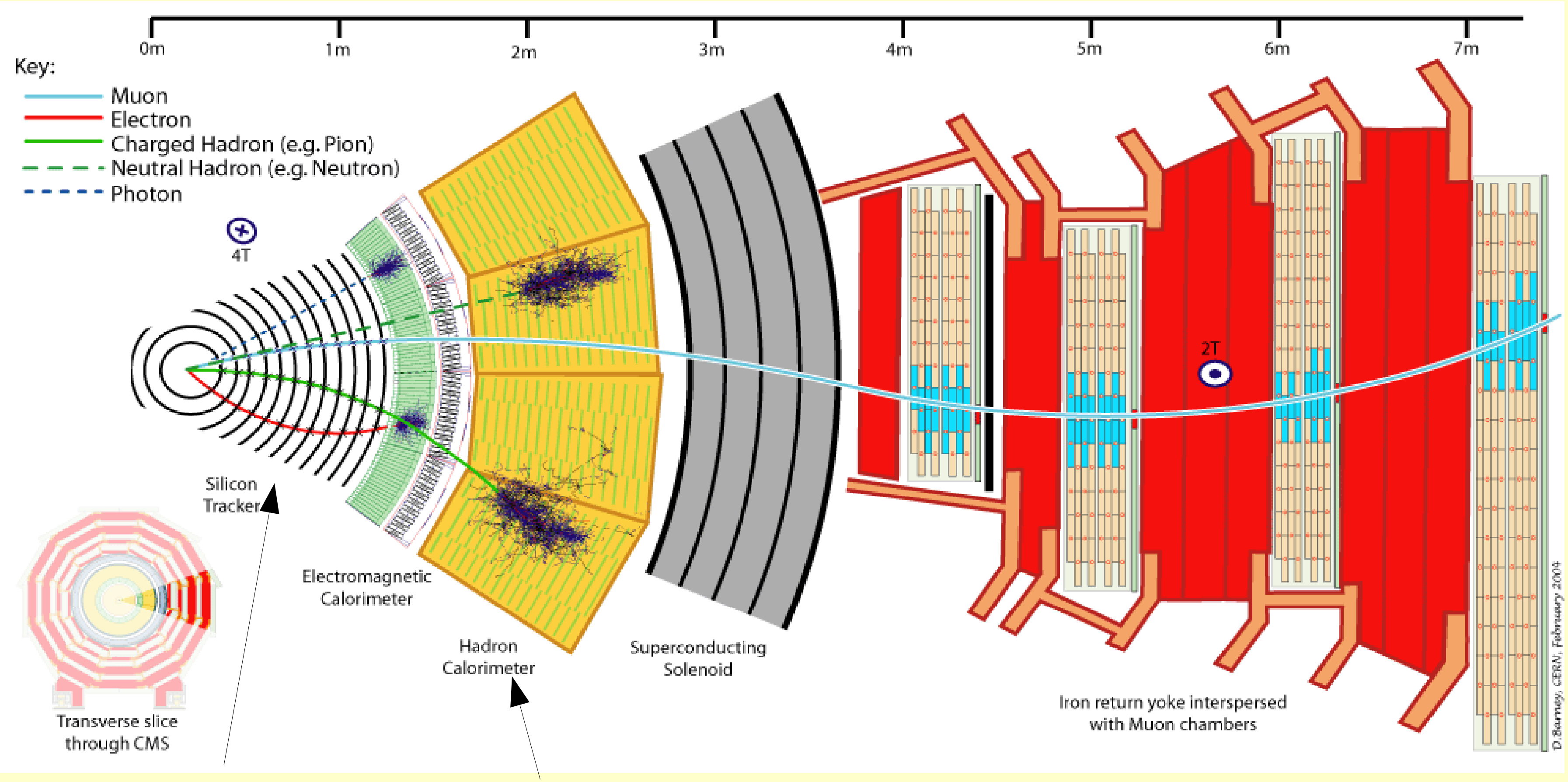
- CMS experimental setup
- Jet, high-p_T hadron and photon reconstruction
- Photon tagged jets
- High-mass dimuon resonance reconstruction
- Quarkonia, Z^0 and high-mass dimuon spectra
- Summary

* *The story is based on CMS Quark Matter 2008 talks (D. d'Enterria, C. Loizides and D. Dutta)*

CMS detector at the LHC



$h^{\pm}$, $e^{\pm}$, γ , $\mu^{\pm}$ measurement in CMS ($|\eta|<2.5$)



Si TRACKER

Silicon Microstrips and Pixels

CALORIMETERS ($|\eta|<3$)

ECAL
$PbWO_4$

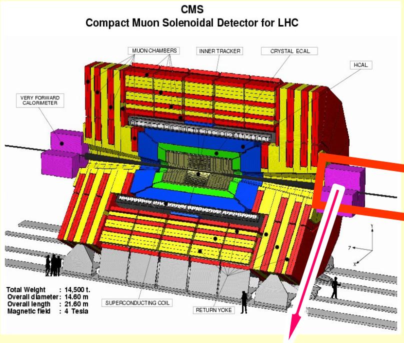
HCAL
Plastic Sci/Steel sandwich

MUON BARREL

Drift Tube Chambers (DT)

Resistive Plate

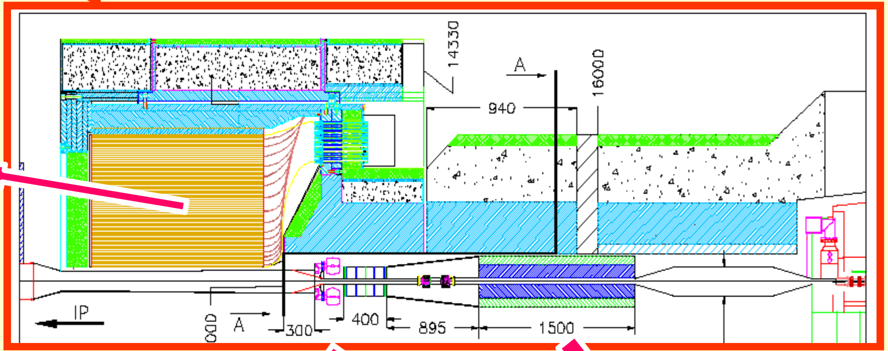
CMS Forward Region Layout

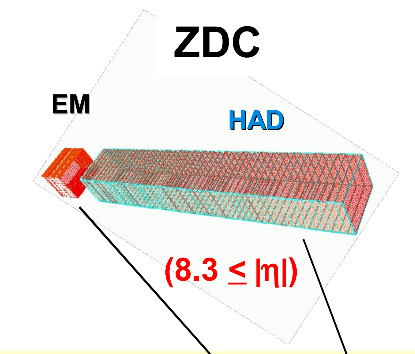


Forward HCal

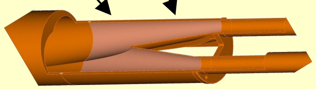
(3 ≤ |η| ≤ 5)

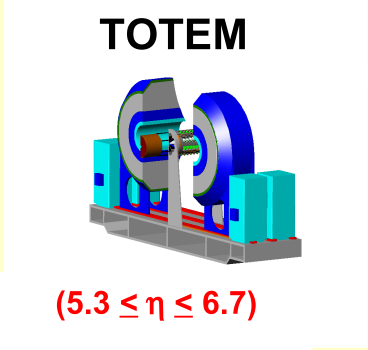
|η| > 3

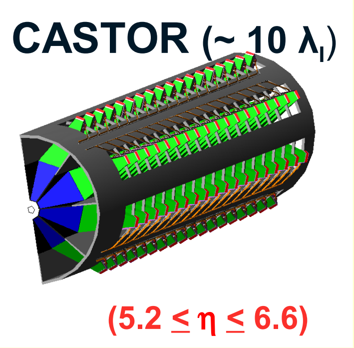




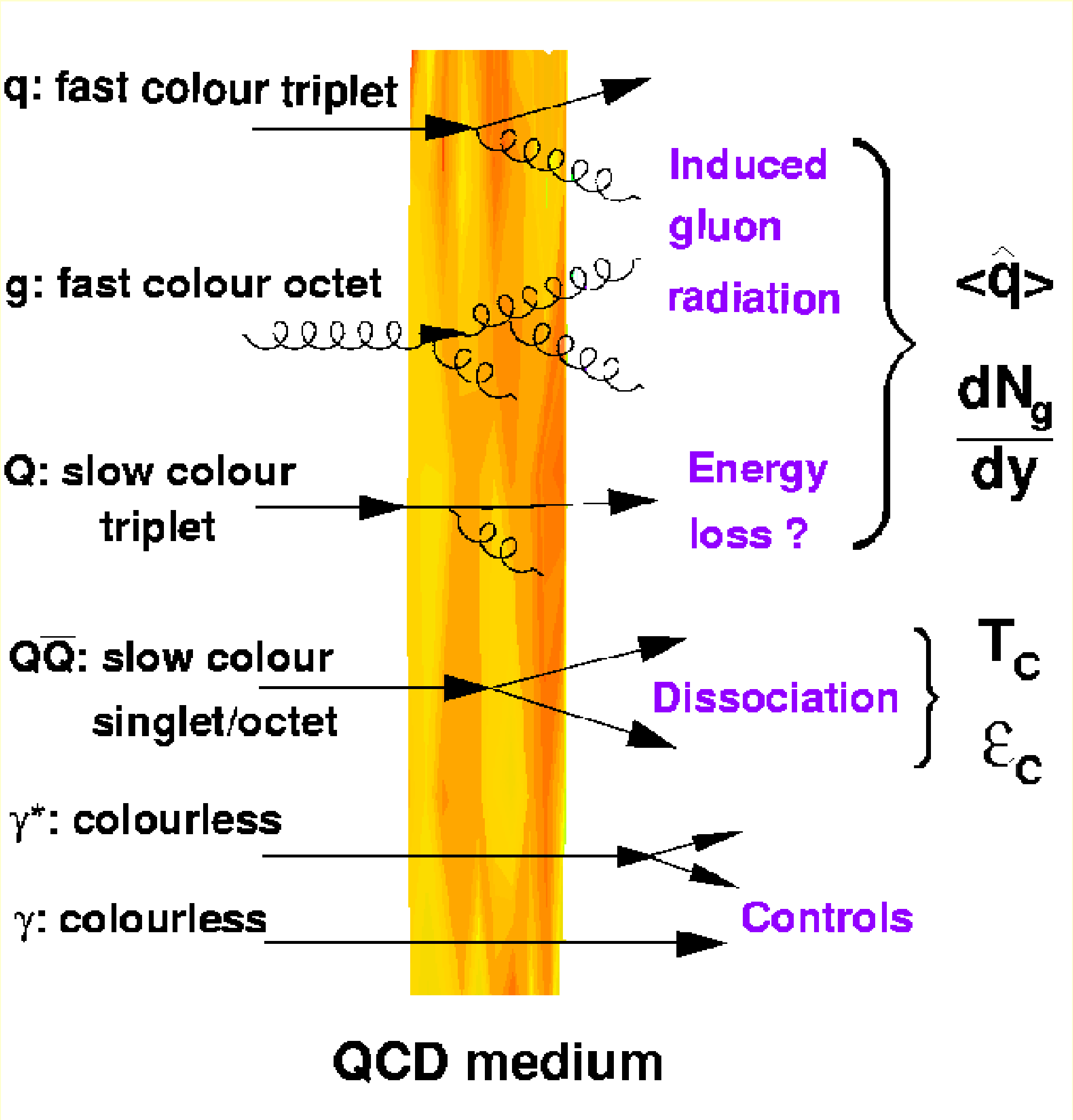
(z = ± 140 m)







Hard ("tomographic") probes of QCD-matter at CMS



Pb-Pb High-Level Triggering

M.Ballitjin,C.Loizides,G.Roland, CMS-AN06-099

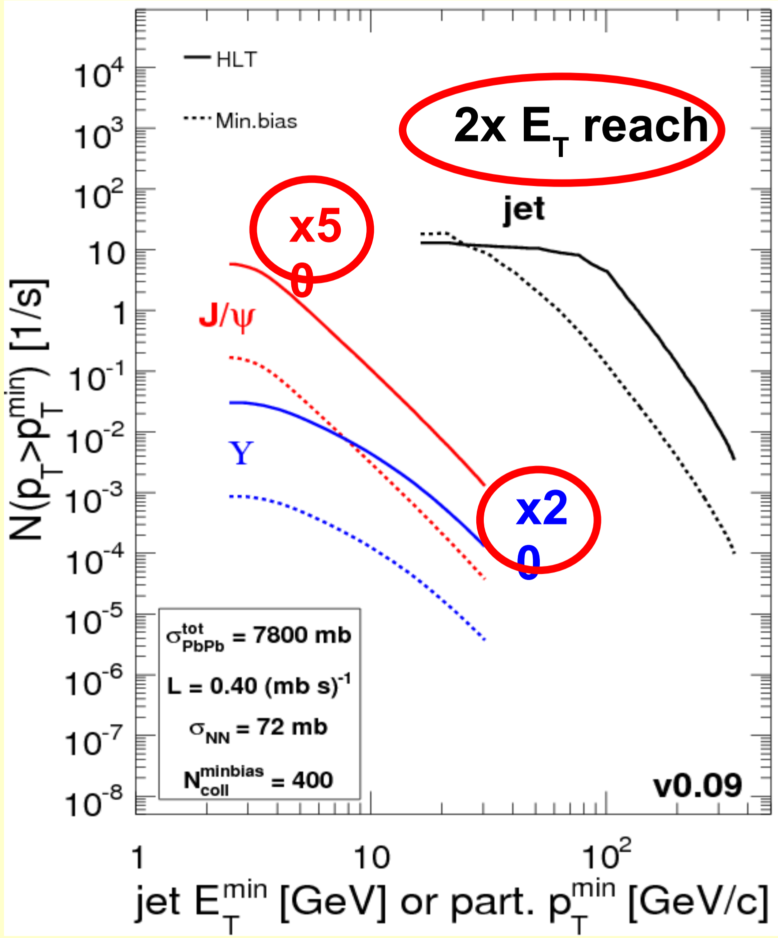
- Unique CMS High-Level-Trigger 12k × 1.8-GHz CPUs ~ 50 Tflops !
- CMS HLT fast enough to run "offline" algos on every PbPb evt. !
- Event rates:

- 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



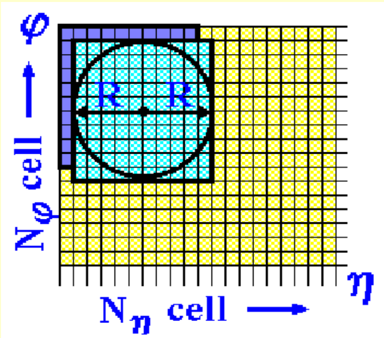
Significantly enhanced statistical reach for hard probes: x20 – x300

Jet reconstruction in HI collisions at CMS

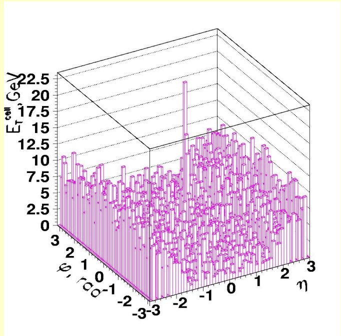
I. Vardanyan et al. Eur. Phys. J. 50 (2007) 117

BACKGROUND SUBTRACTION ALGORITHM

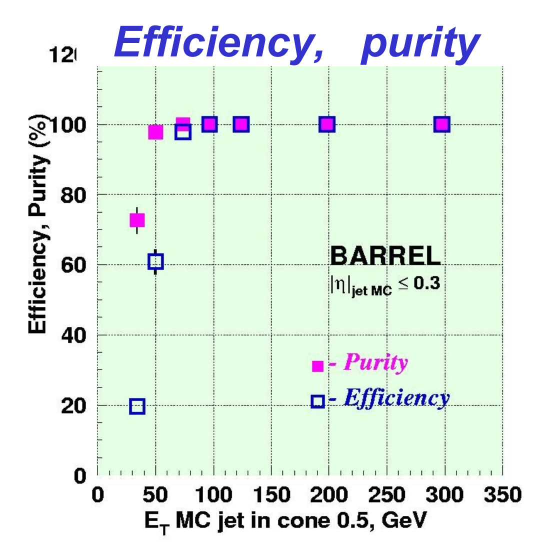
(based on event-by-event η-dependent background subtraction)

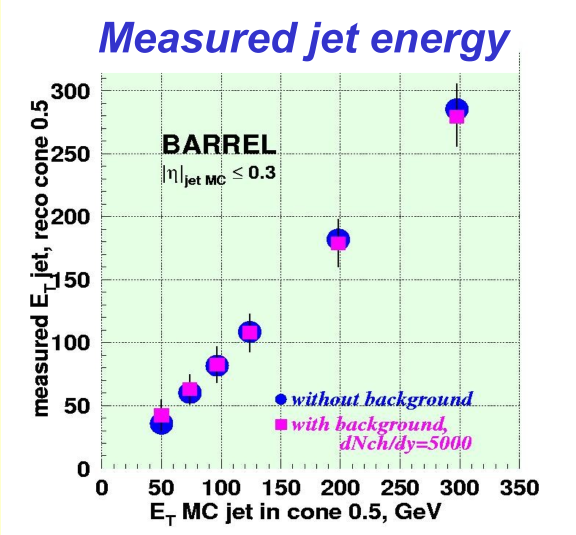


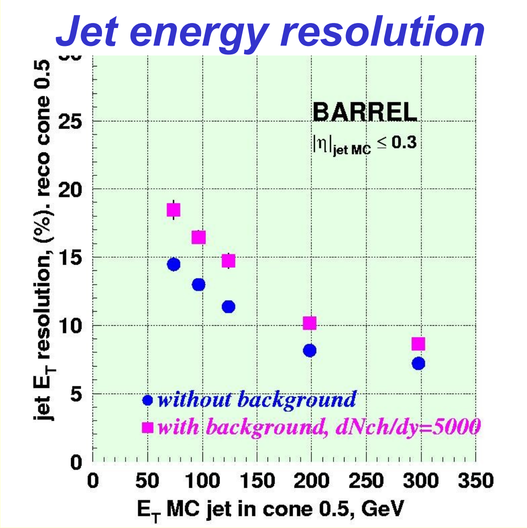
1. Subtract average soft background
2. Find jets with iterative cone algorithm
3. Recalculate pileup outside the cone
4. Recalculate jet energy



Full jet reconstruction (R=0.5) in central Pb-Pb collision, HIJING, $dN_{ch}/dy = 5000$



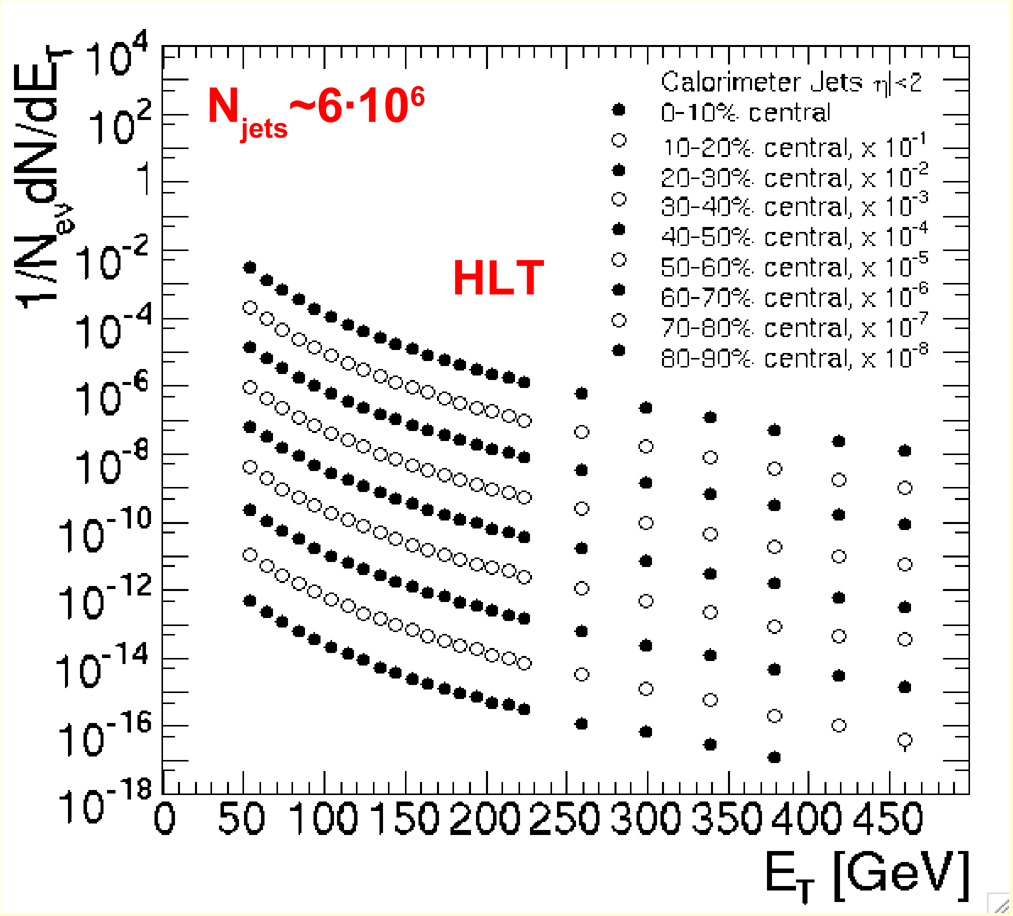




Jet spatial resolutions σ_φ=0.03, σ_η=0.02 are better than η, φ size of tower (0.087×0.087)

Jet spectra at CMS@LHC

Jet spectra up to $E_T \sim 0.5$ TeV



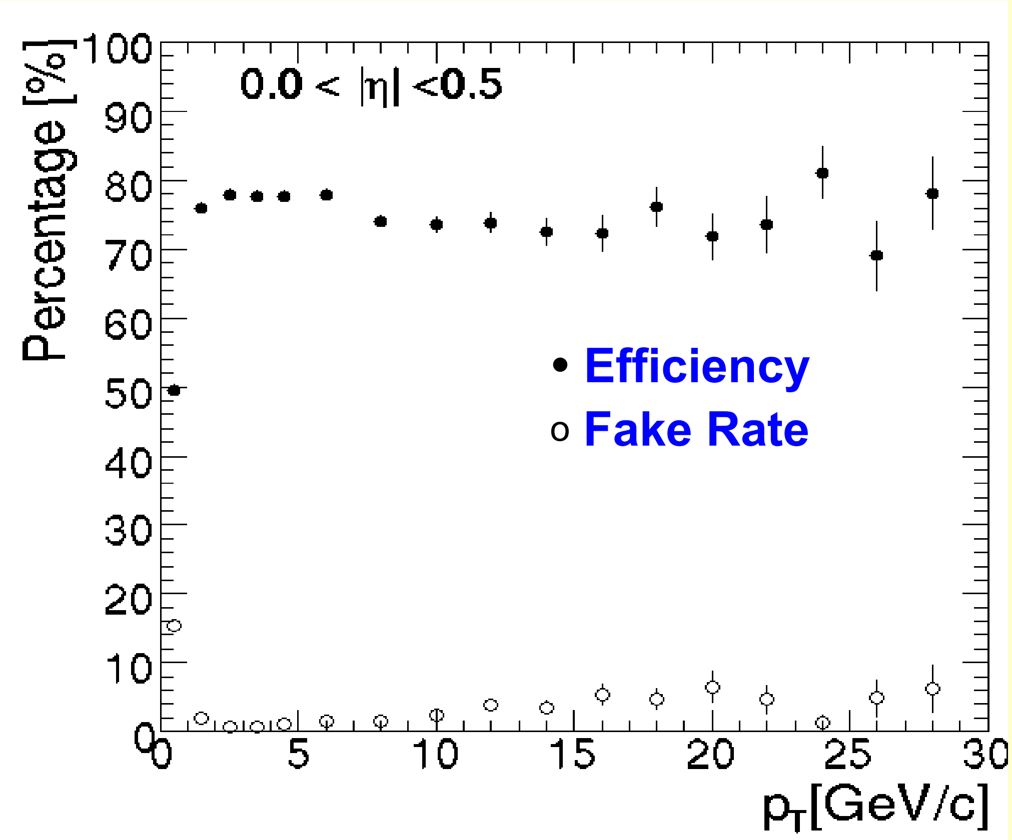
[PbPb, 0.5 nb^{-1}]

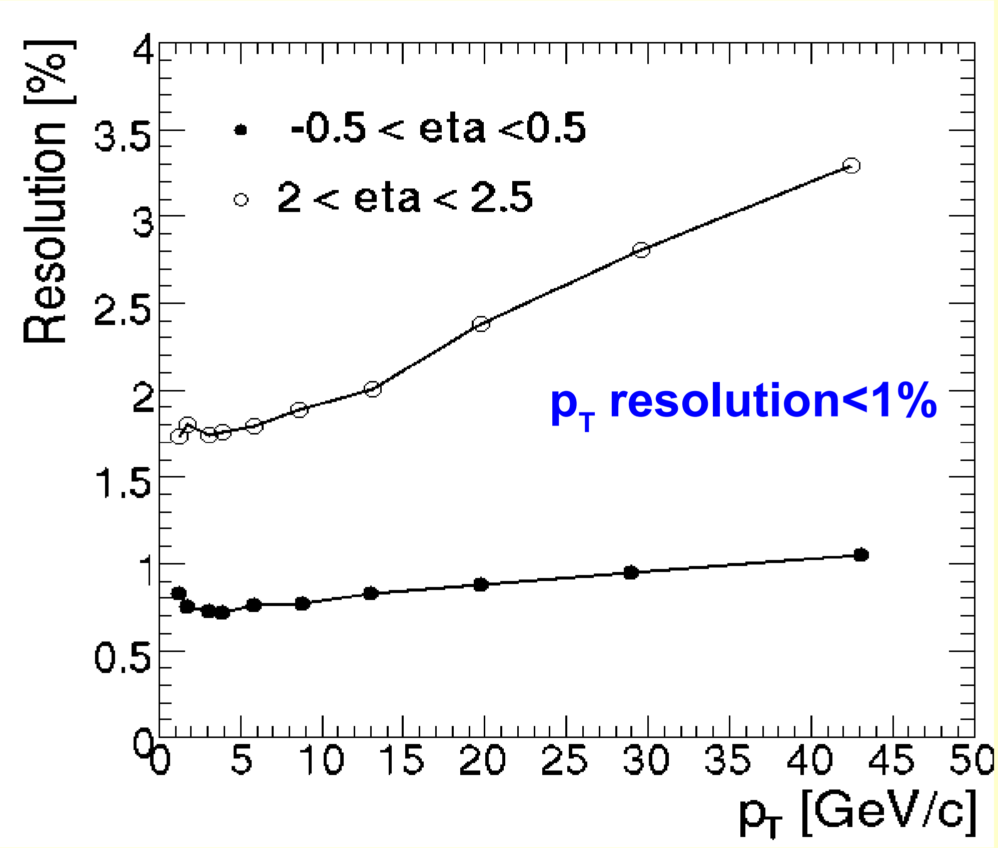
Detailed jet-quenching studies: jet fragmentation function, jet shape, jet azimuthal anisotropy,...

High-p_T hadron reconstruction

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

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

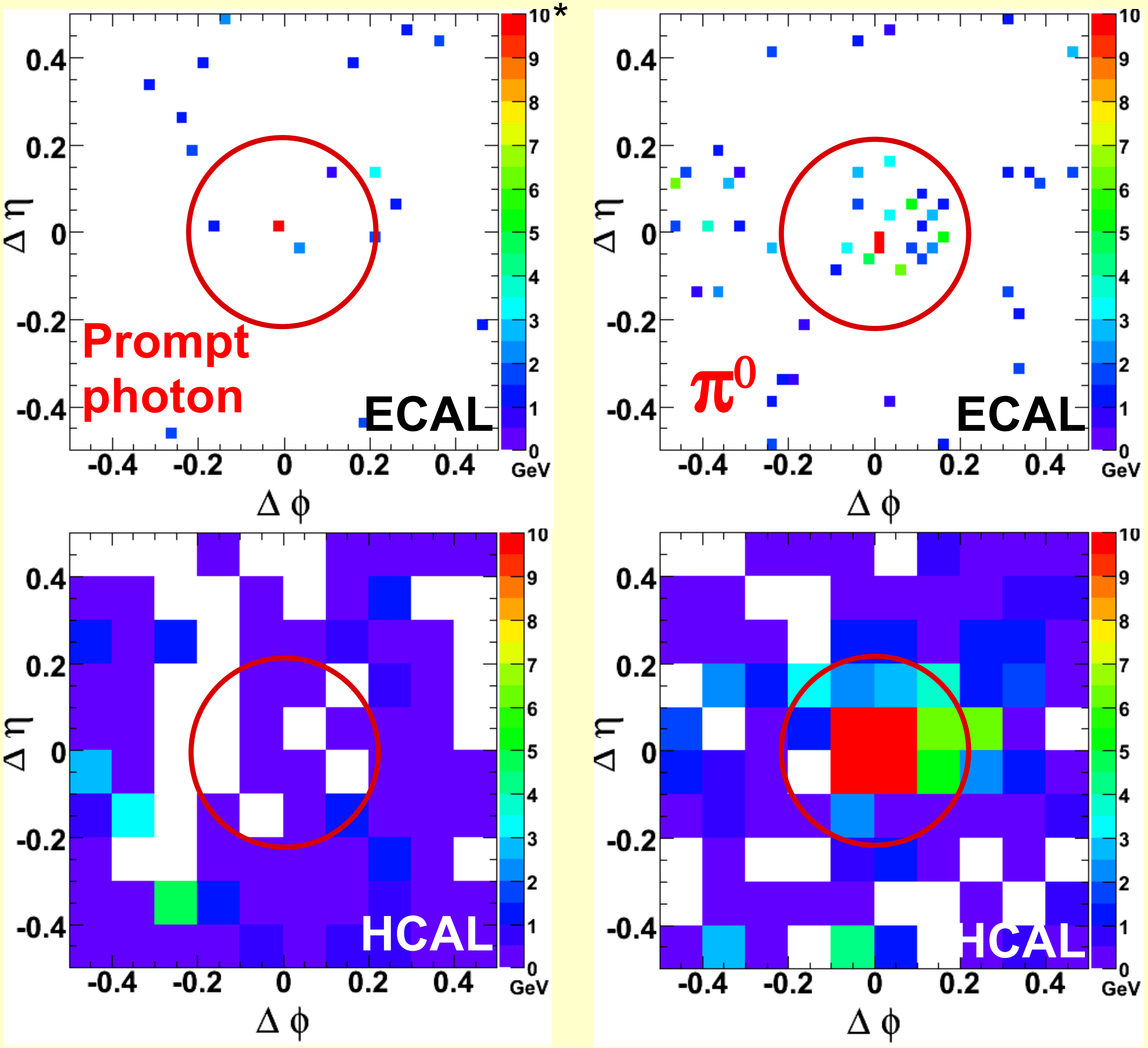




More details in the talk of K.Krajczar during this Workshop

High-E_T isolated photon reconstruction

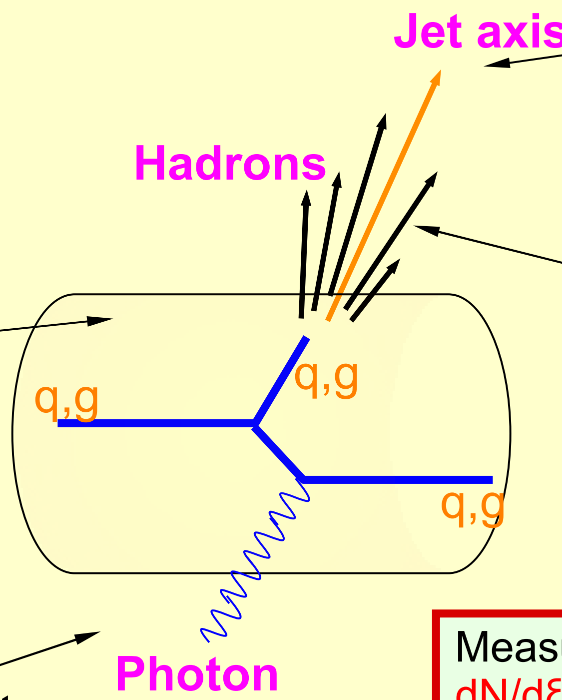
- **Identification**
  - **10 cluster shape variables**
    - **based on ECAL**
  - **10 isolation variables**
    - **based on ECAL/HCAL**
  - **Track-based cut**
- **Selection**
  - **Total of 21 variables grouped into 3 sets**
  - **Linear discriminant analysis (Fisher) and cut optimization using TMVA**



Photon-tagged jet fragmentation function

Jet axis provides parton direction

Multiplicity and flow measurements characterize density, path length



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 $\xi = -\log z$

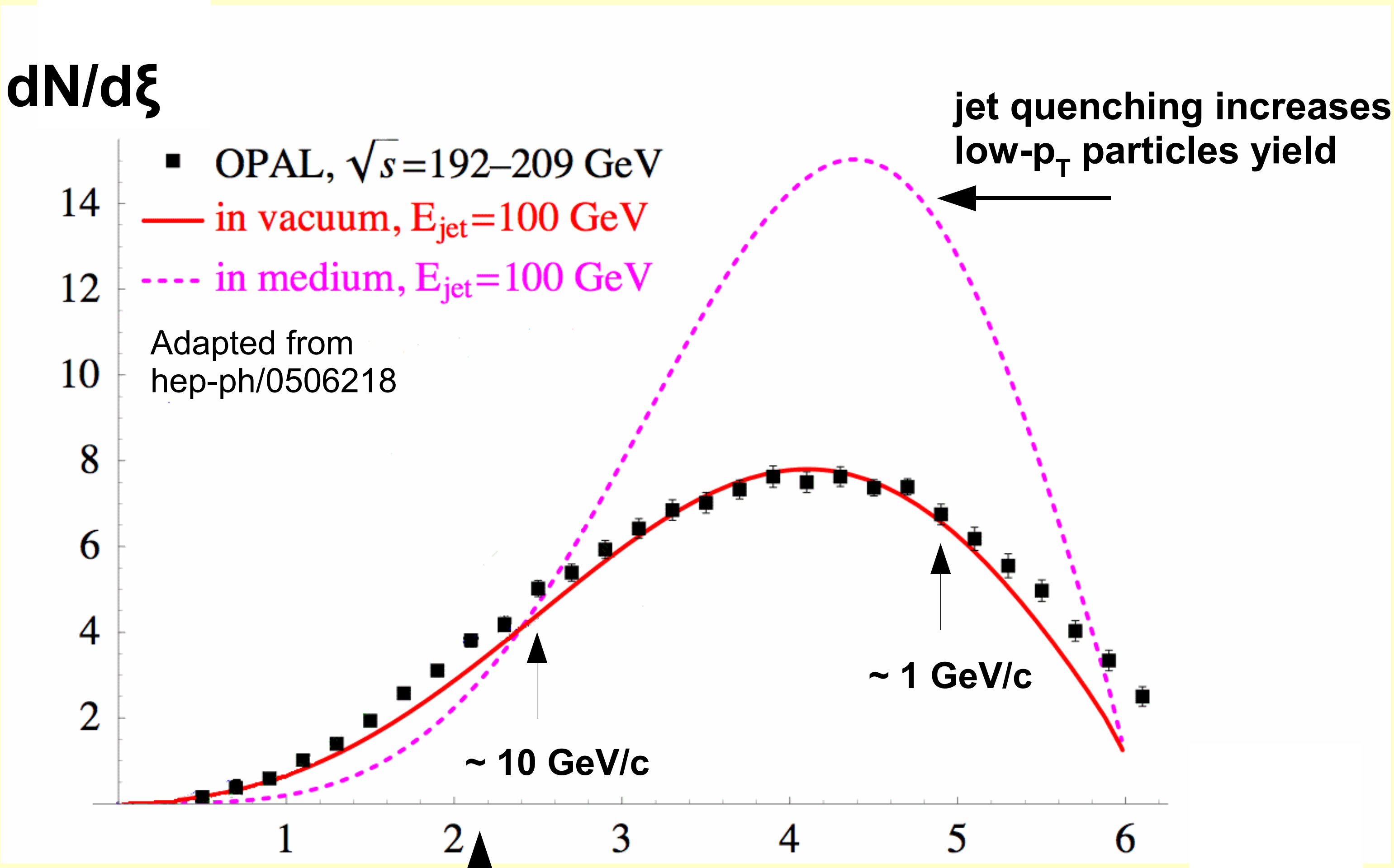
Main advantage

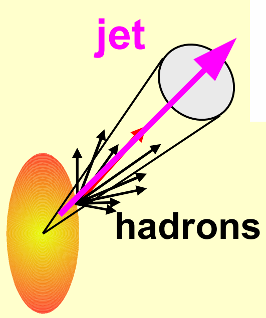
- Photon unaffected by the medium
- Avoids measurement of absolute jet energy

Ingredients:

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

Medium-modified fragmentation function





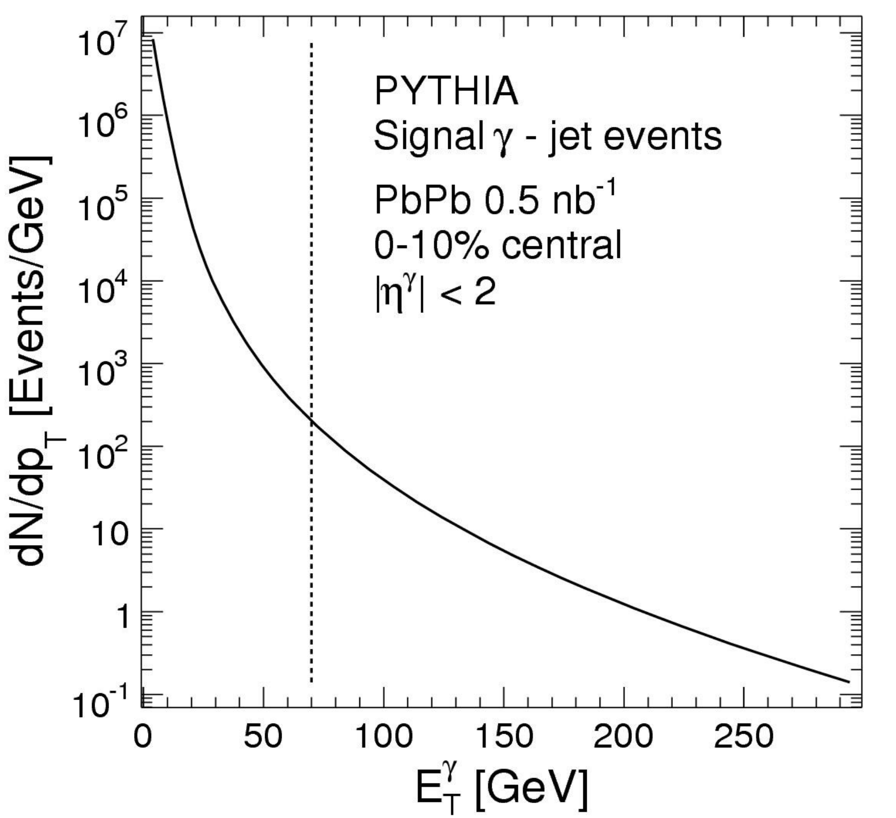
$z \to 1$
$(p_T \to E_T)$

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

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

jet quenching reduces high-p_T particles yield

Signal and background statistics



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

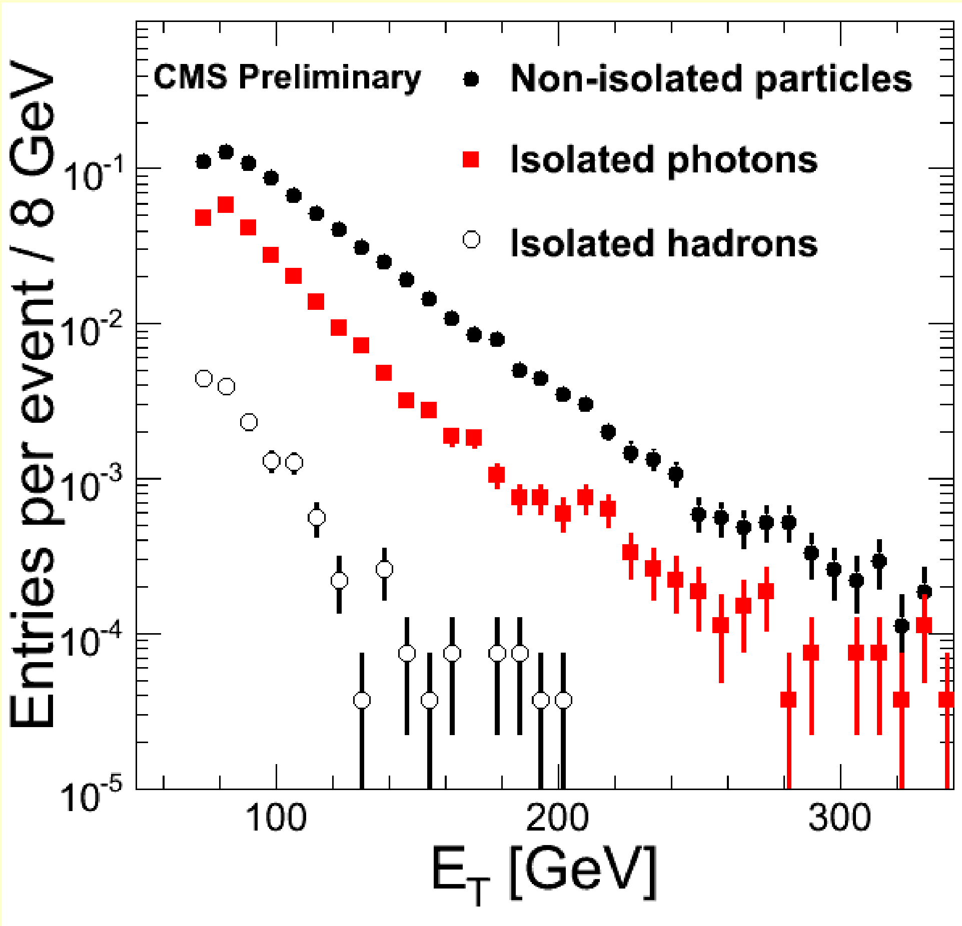
- **Study for one nominal LHC Pb+Pb run "year"**
  - **10^6 sec, 0.5nb^{-1}, 3.9 x 10^9 events**
- **Use 0-10% most central Pb+Pb**
  - **$dN/d\eta|_{\eta=0}$~2400 (HYDJET)**
- **Simulate signal (PYTHIA/PYQUEN) and background QCD (p+p) events**
  - **Mix into simulated Pb+Pb events (~1000 events)**

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

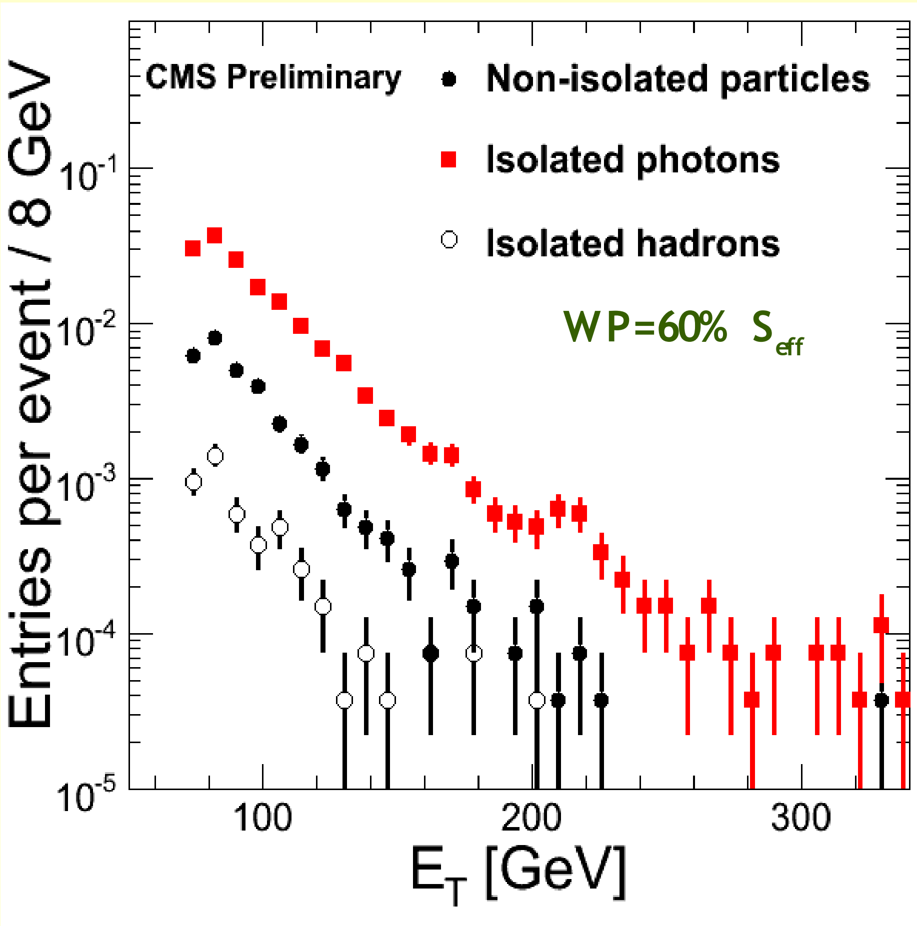
Prompt photon identification performance

Signal + Background (jet quenching on)

Before cuts: S/B=0.3

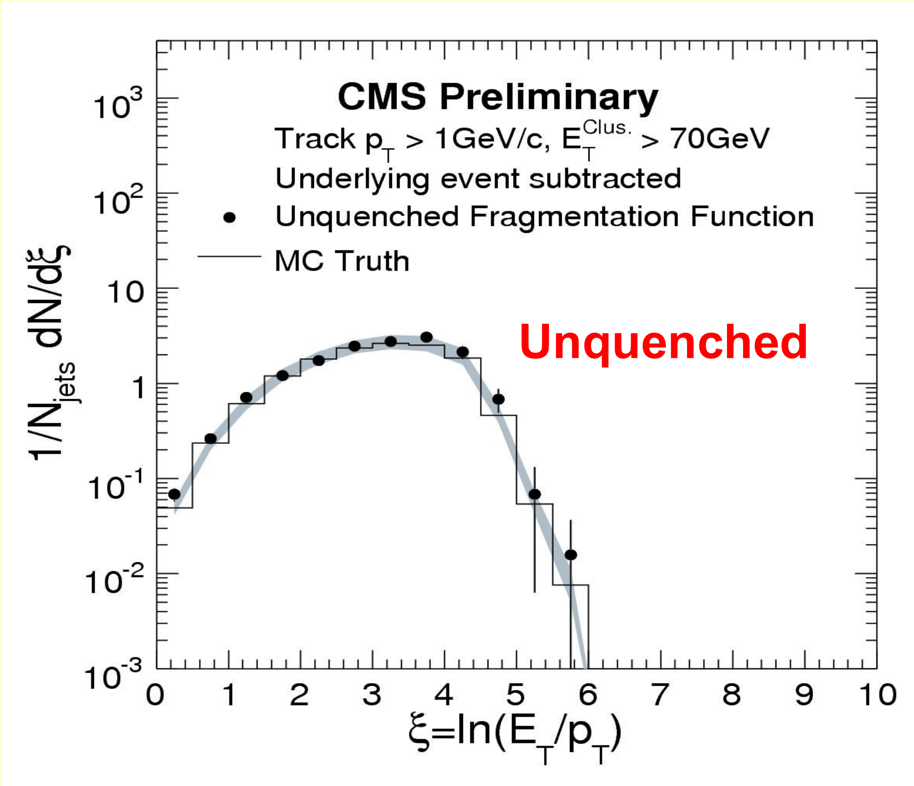


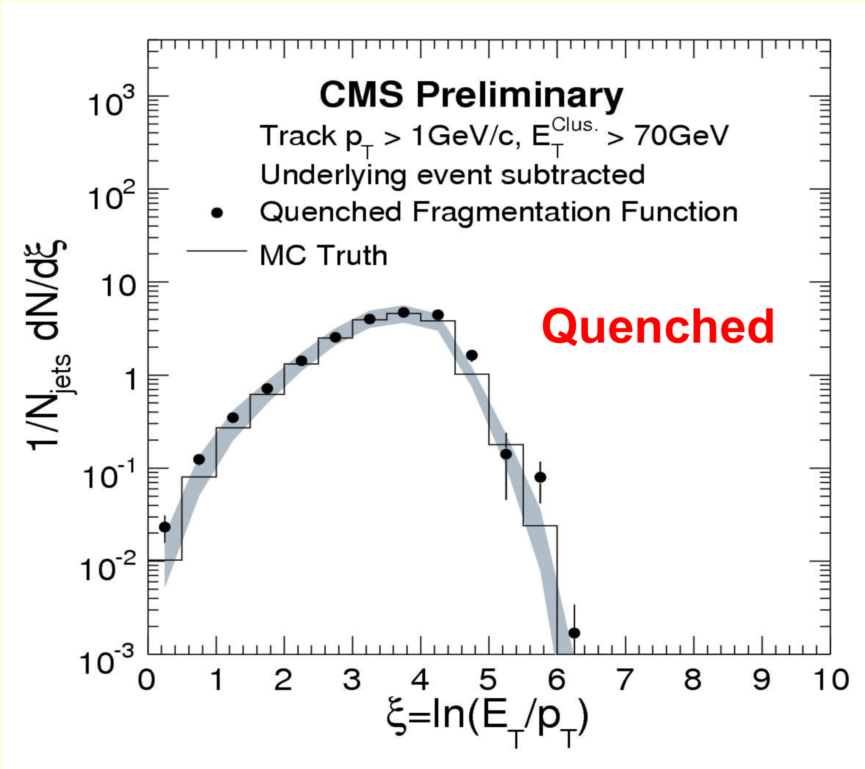
After cuts: S/B=4.5



Photon isolation and shape cuts improve S/B by factor ~15

Reconstructed jet fragmentation function



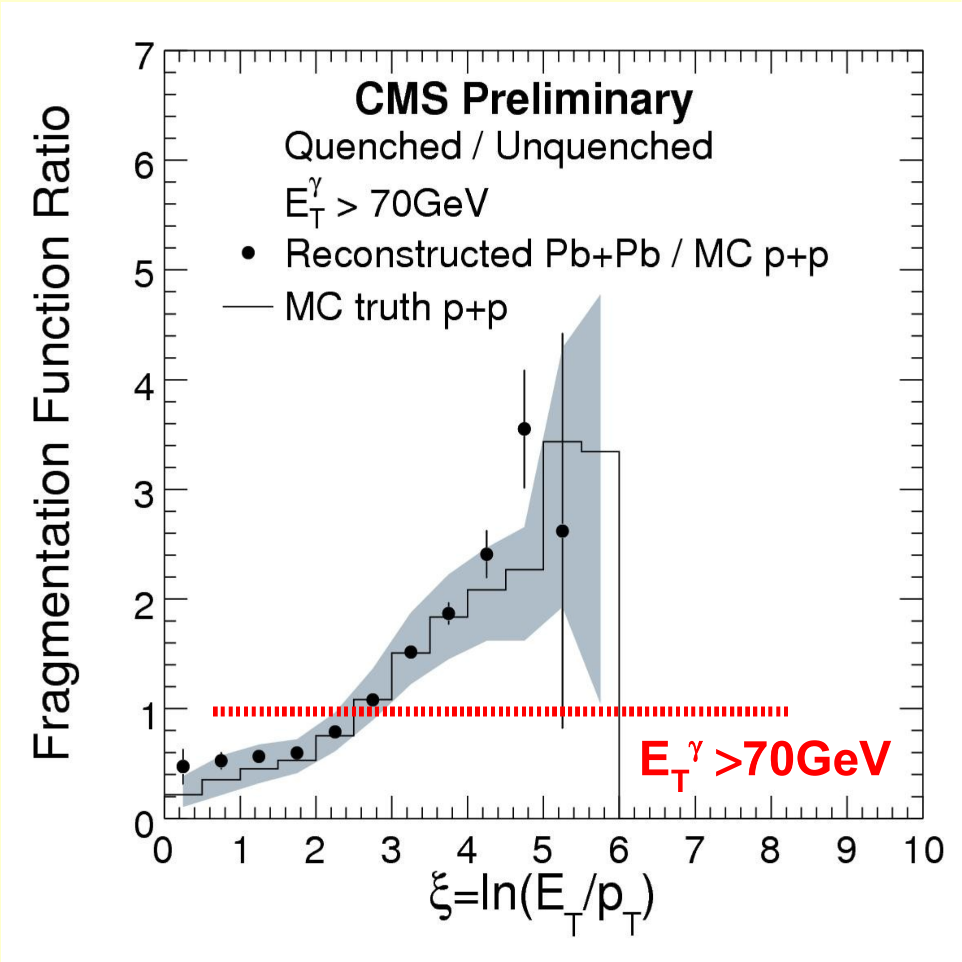


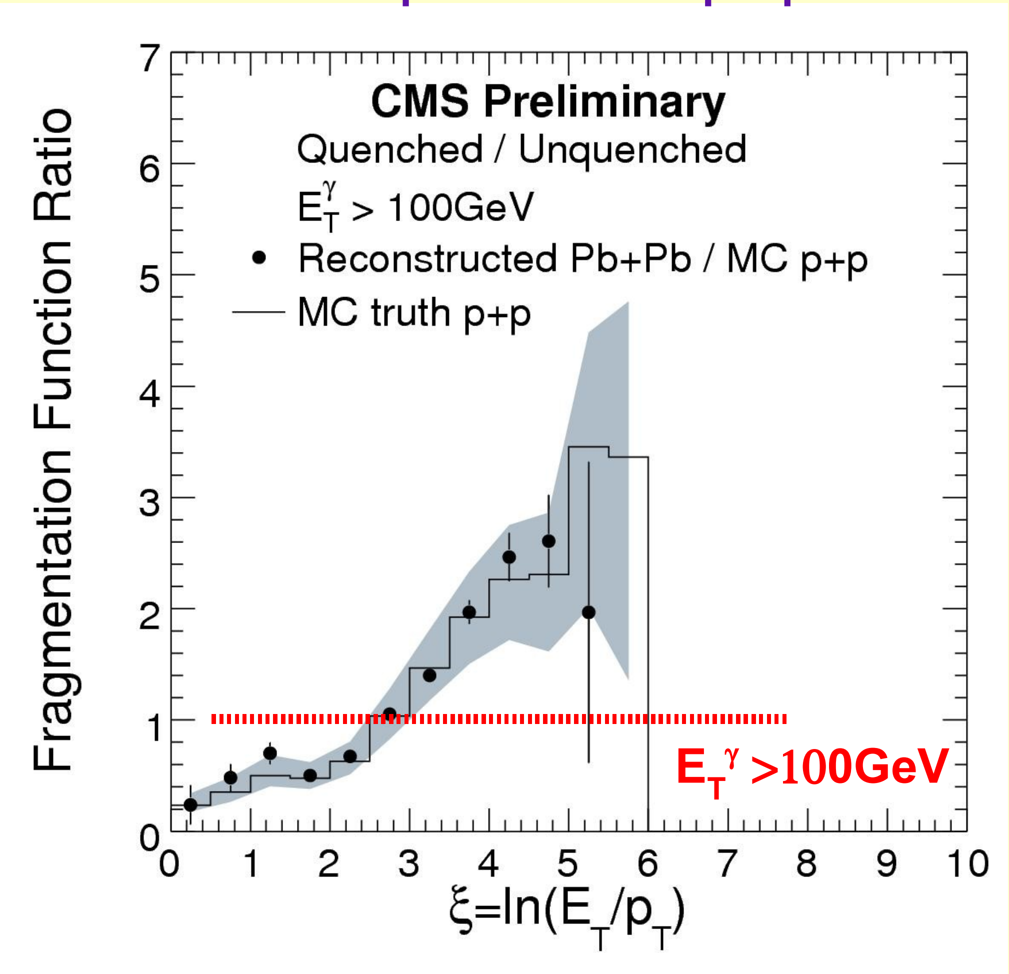
- **Major contributions to systematic uncertainty**
  - **Photon selection and background contamination (15%)**
  - **Track finding efficiency correction (10%)**
  - **Wrong/fake jet matches (10%)**
  - **Jet finder bias (30% in quenched case and 10% in unquenched case)**

No or small ξ dependence (applies to the first three items)

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**

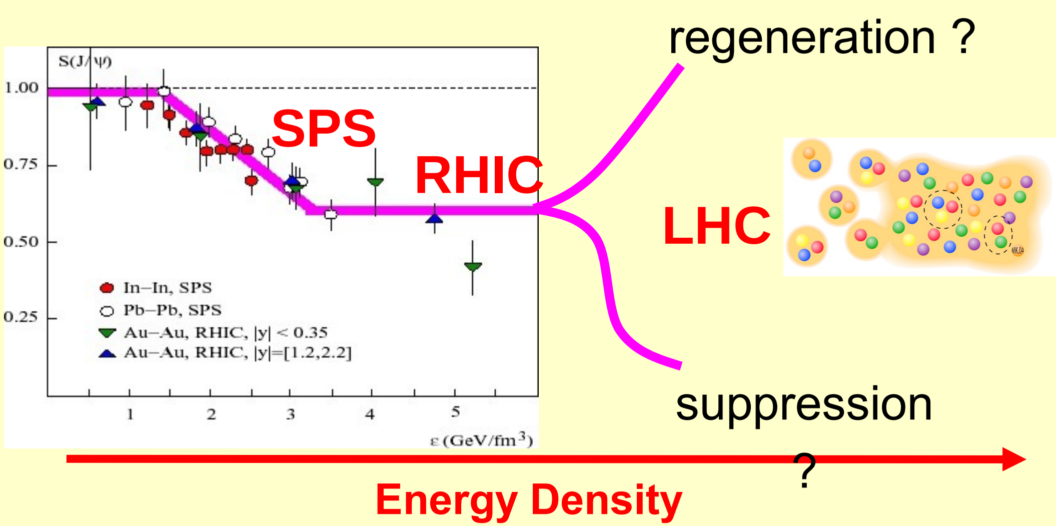
High mass dimuons at LHC: J/ψ, Υ, Z^0, B

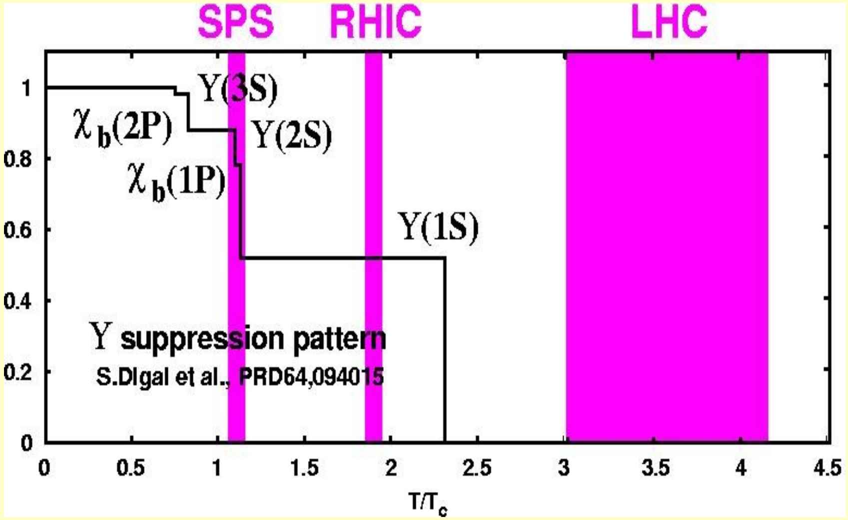
Dissociation of Quarkonia (Debye Screening): Hot QCD Thermometer

- 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 section section)
- B → J/ψ, BB → $\mu^+\mu^-$ - information about b-quark in-medium rescattering & e-loss

High-mass dimuon sources in HI collisions

Dimuon Resonances:

- **Quarkonia**: J/ψ (BR: 5.9%), ϒ (BR: 2.5%)
- **Z^0**: (BR: 3.4%)

Dimuon Continuum:

- Decays from open c and b
- Decays from π, K
- Decays from W
- Mixed muon pairs

Simulation of high-mass dimuon spectra

M. Bedjidian, O. Kodolova, CMS NOTE-2006/089

- Signal (J/ψ, ϒ): CEM, NLO-pp, (CTEQ5M+EKS98 PDF),T_{AA} scaled
- Background uncorrelated muon pairs from π/K decays:
  - –Two scenarios for the multiplicity of charged particles

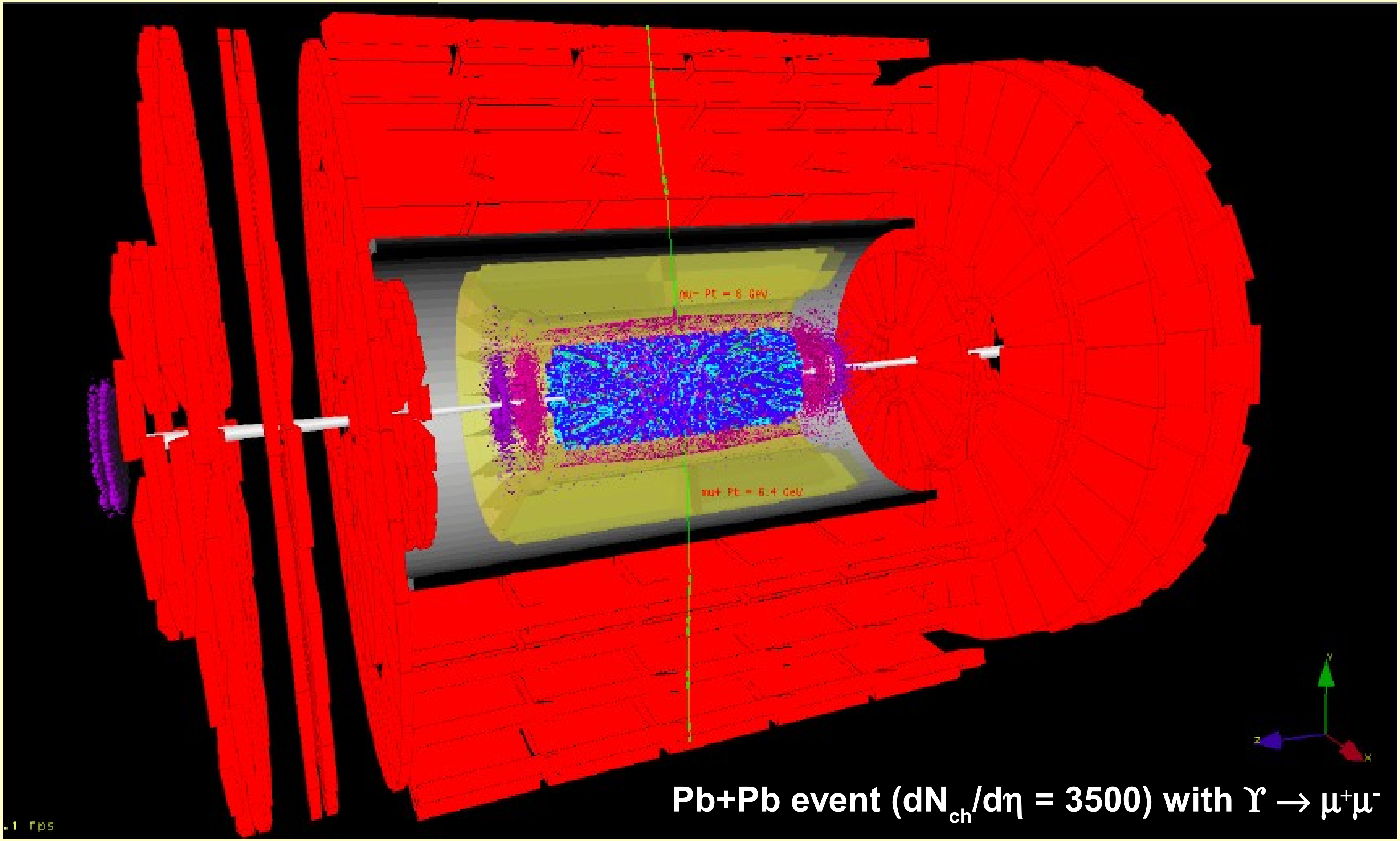
    $dN_{ch}/d\eta = 2500$ at $\eta=0$

    $dN_{ch}/d\eta = 5000$ at $\eta=0$
  - – only π and K are considered (90% of charged particles multiplicity)
  - – Kaon/pion = 11% (HIJING)
  - – p_T and η distributions of pions and kaons according to HIJING
- Background muons from open heavy quark decays (b,c):

  NLO pp, CTEQ5M+EKS98 PDF, T_{AA} scaled

Quarkonia reconstruction at CMS

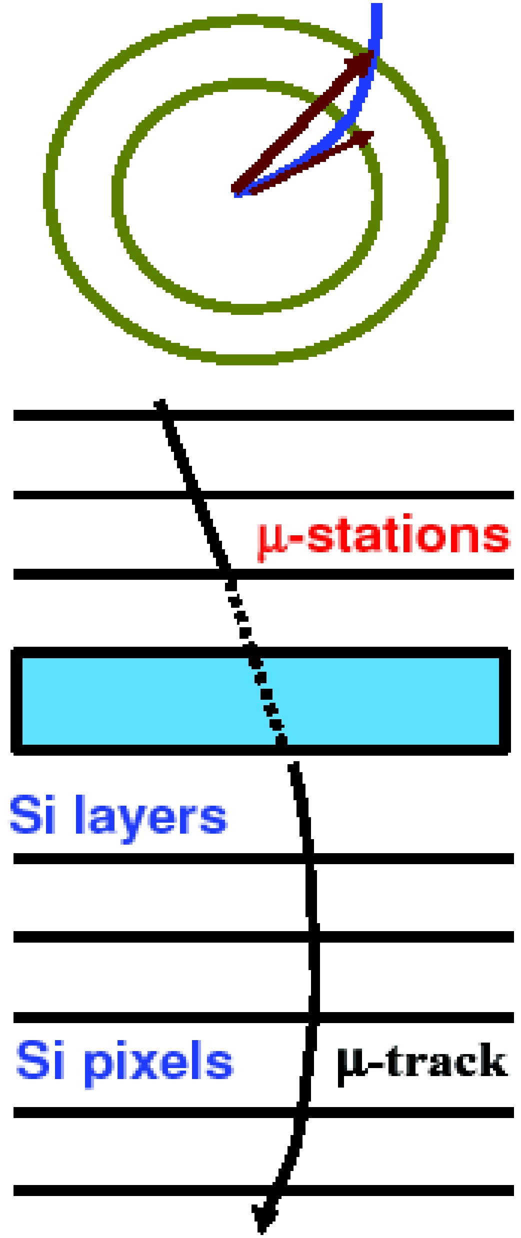
Event display with full CMS software/simulation framework

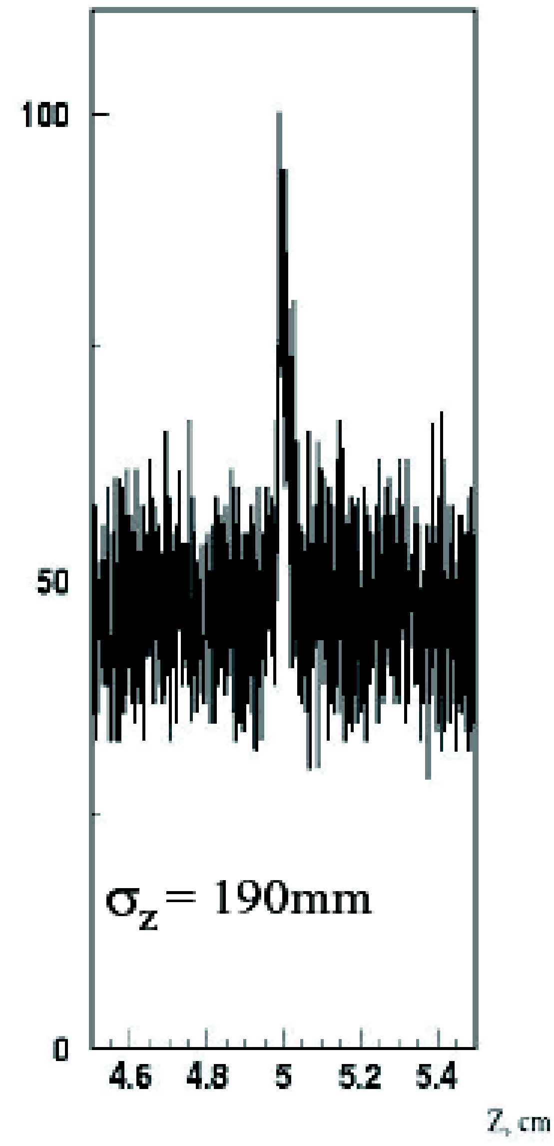


Pb+Pb event ($dN_{ch}/d\eta$ = 3500) with $\Upsilon \to \mu^+\mu^-$

Dimuon reconstruction algorithm

- Primary vertex determination:
  - select pairs of pixel hits with $\Delta\phi$ giving $0.5 < p_T < 5$ GeV
  - extrapolate each pair in RZ to the beam line.
- Track finding:
  - start from track candidate in muon stations
  - extrapolate inwards from plane to plane using vertex constraints
- Track selection by cuts:
  - fit quality (χ^2)
  - vertex constraint



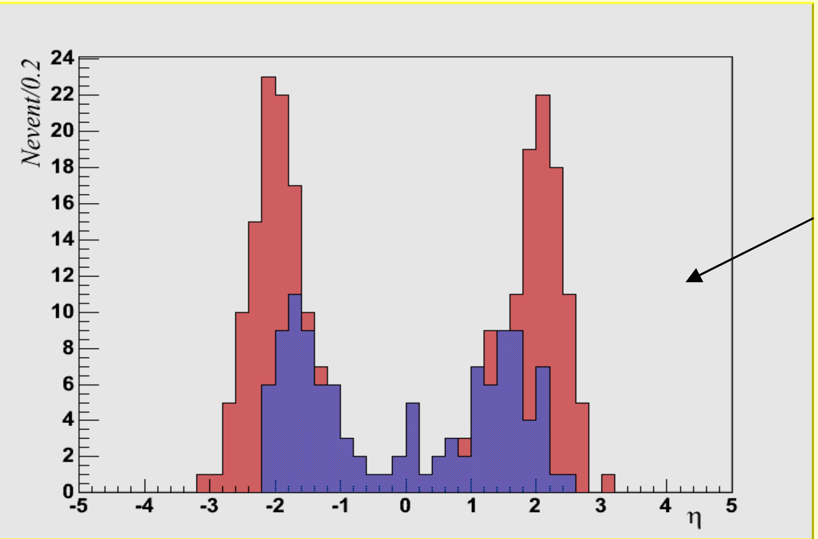


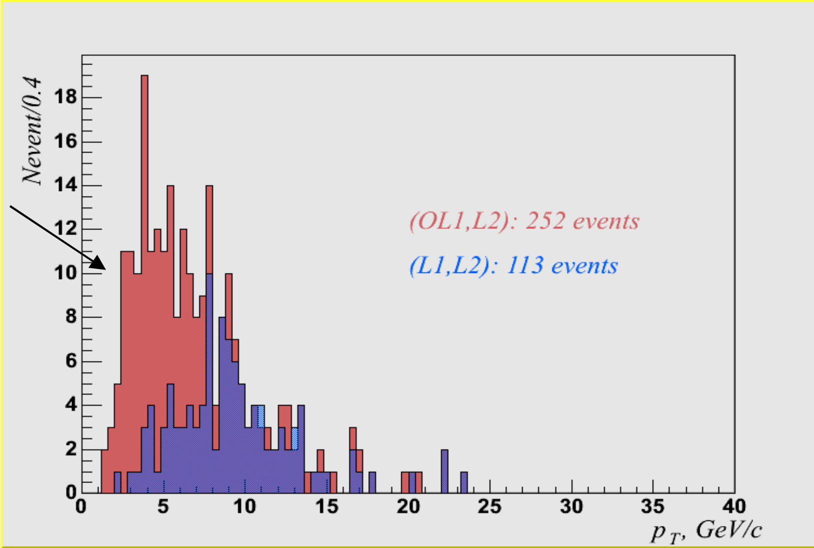
Dimuon high level trigger performance

Two Different Level 1 Trigger (single muon trigger)

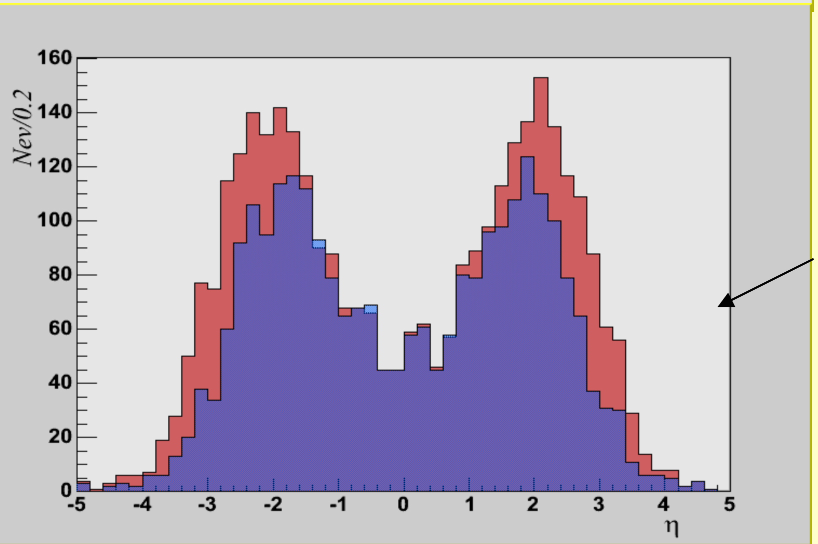
L1: optimised for high luminosity pp run, OL1: low quality muon candidates optimised for HI

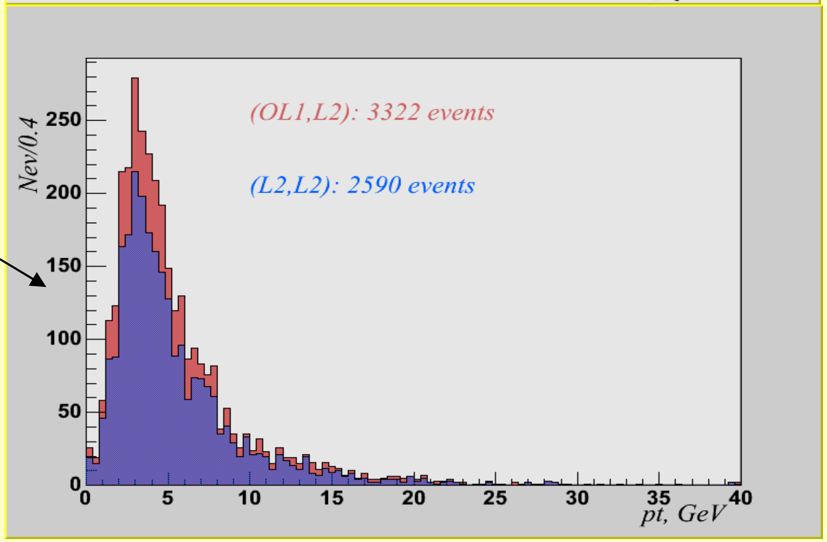
L2 and L3 run on online farm, trigger conditions: two L1 or L2 opposite sign+ L3 (cut on loose)





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

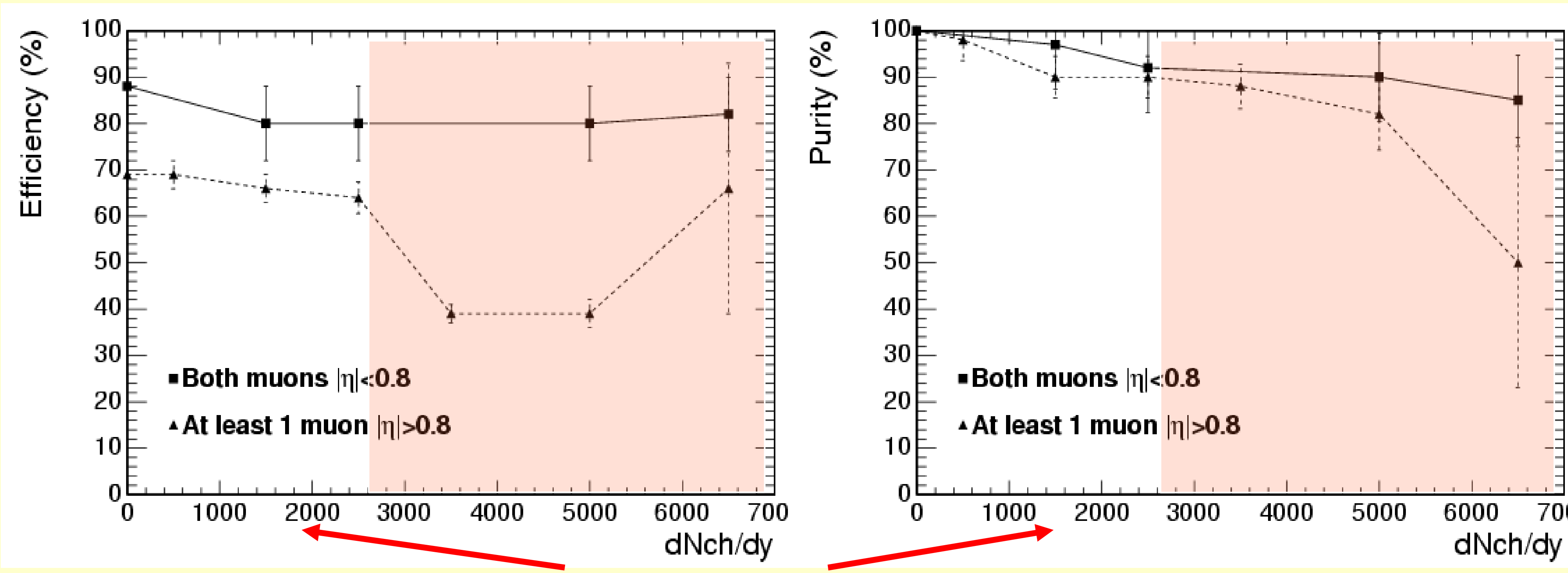




Υ trigger efficiency:
21% (OL1-L2 chain)
16.5% (L1-L2 chain)

Dimuon efficiency & purity vs dN_{ch}/dy

Y is embedded in PbPb events



“realistic” LHC multiplicity range

$Eff = Eff_{trk-1} \times Eff_{trk-2} \times Eff_{vtx}$

> 80% for all multiplicity (barrel)

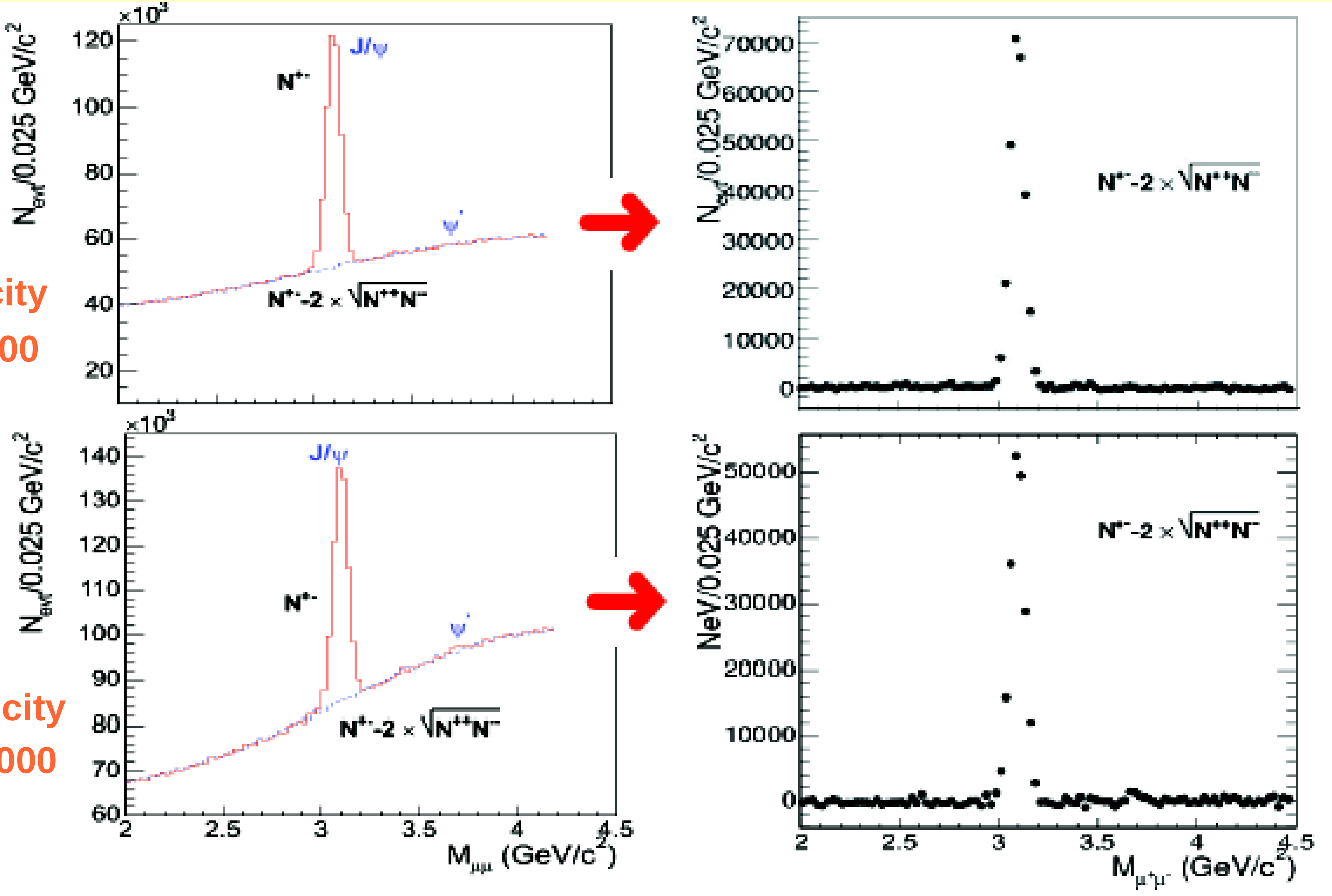
> 65% for all multiplicity (barrel+endcap)

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

> 90% (all multiplicities)

J/ψ mass spectra (like-sign subtraction)

$\sigma_{J/\psi}$ = 35 MeV/c^2 in (barrel+endcap), Both muons with |η|<2.4



“low” multiplicity

$dN_{ch}/d\eta|_{\eta=0}$ =2500

“high” multiplicity

$dN_{ch}/d\eta|_{\eta=0}$ = 5000

Υ mass spectra (like-sign subtraction)

Excellent resolution: σ_Υ = 54 MeV/c^2 (barrel), σ_Υ = 90 MeV/c^2 (barrel+endcap)

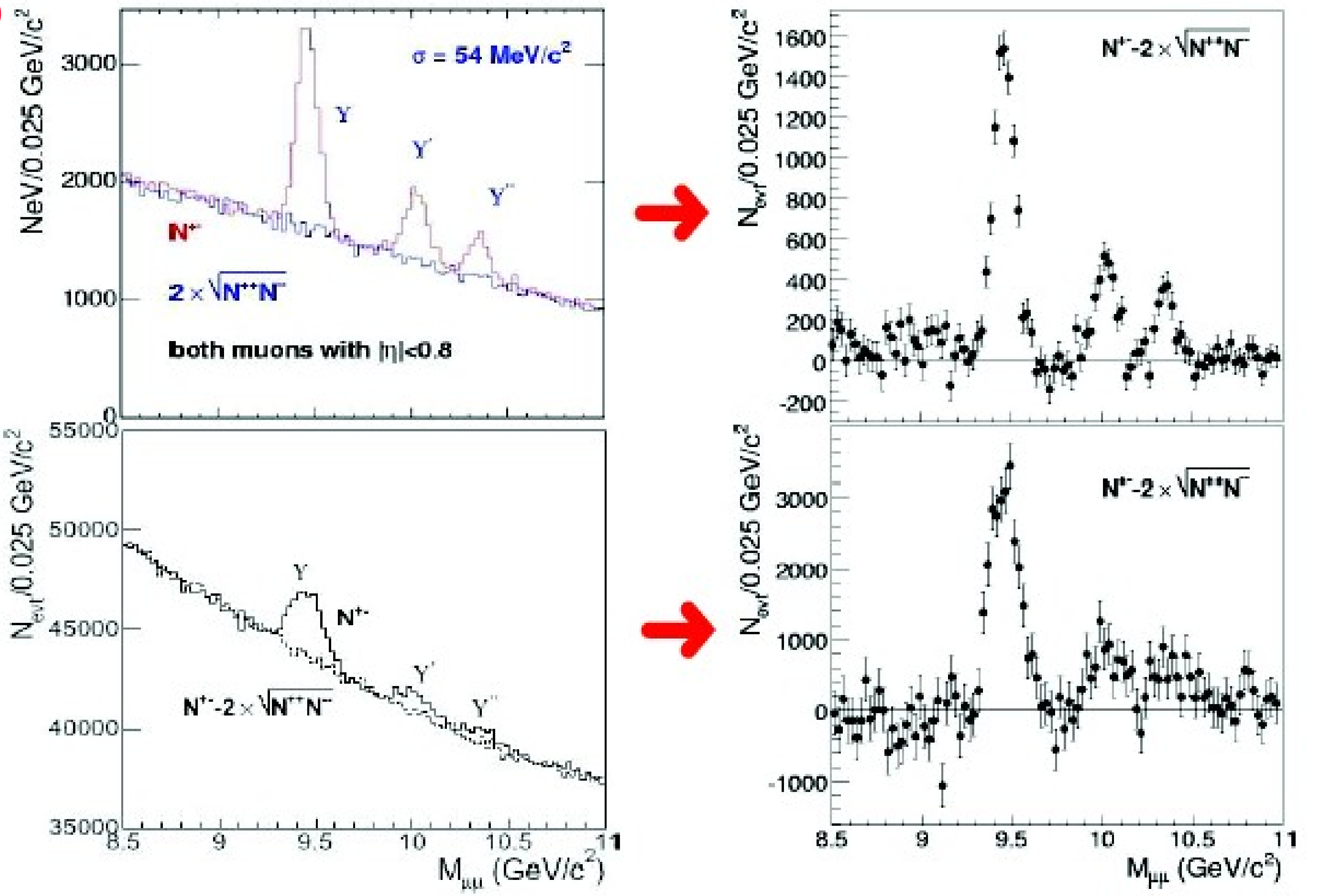
$dN_{ch}/d\eta|_{\eta=0} = 5000$

Barrel:

Both muons with |η|<0.8

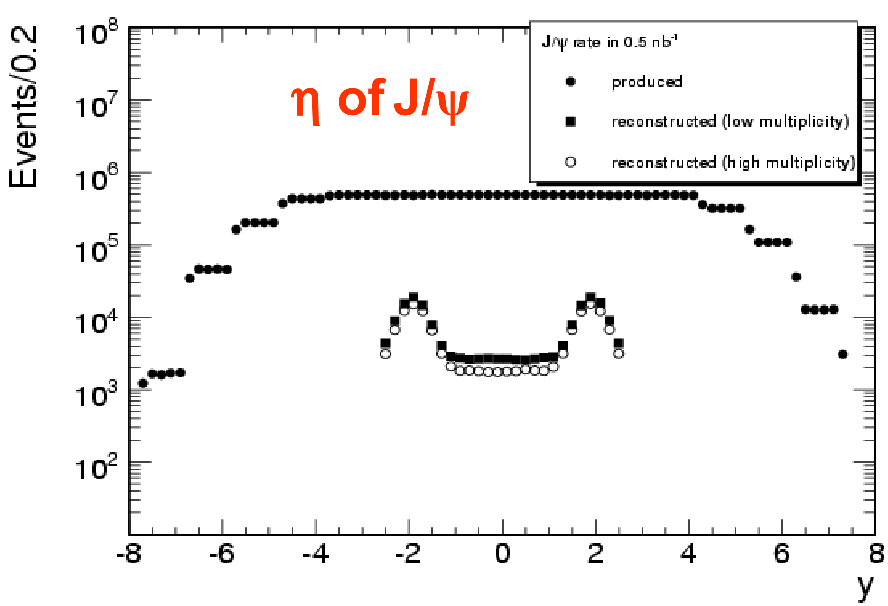
Barrel+ endcap:

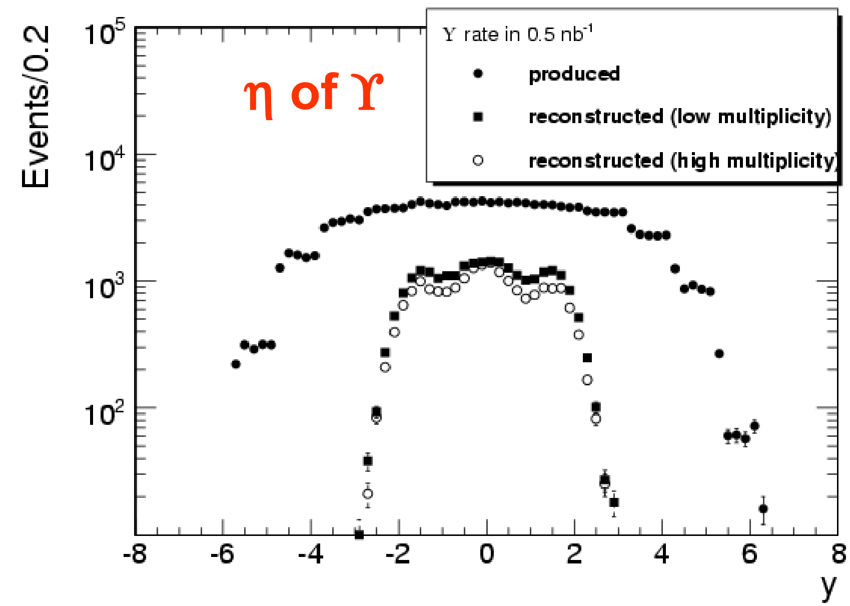
Both muons with |η|<2.4



P_T and η reach of quarkonia in CMS/PbPb

For 1 month LHC run, $L_{int} = 0.5\ nb^{-1}$

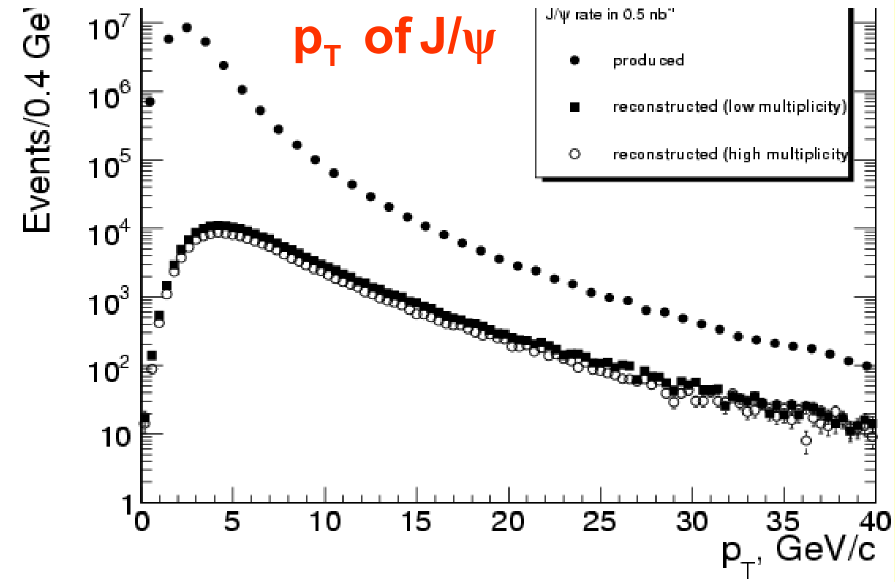


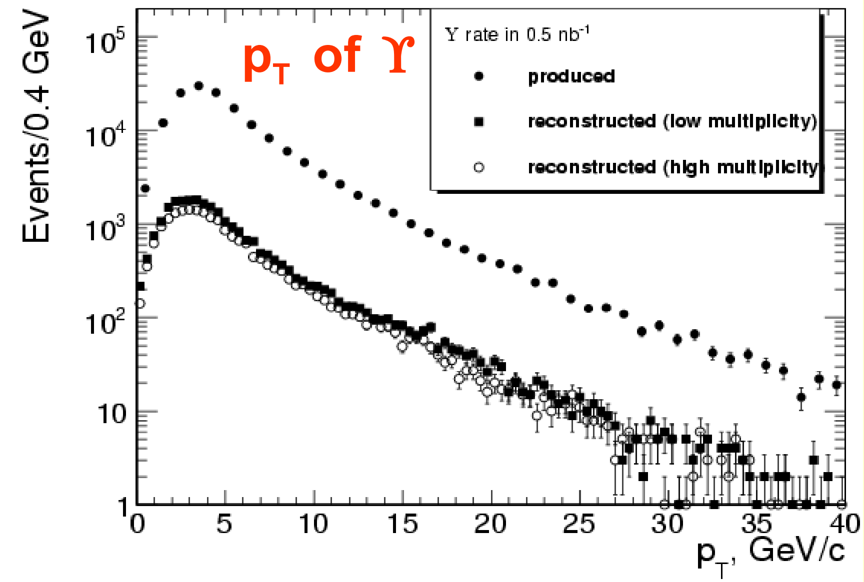


Very Large Statistics

$N(J/\psi) \sim 10^5$

$N(\Upsilon) \sim 10^4$



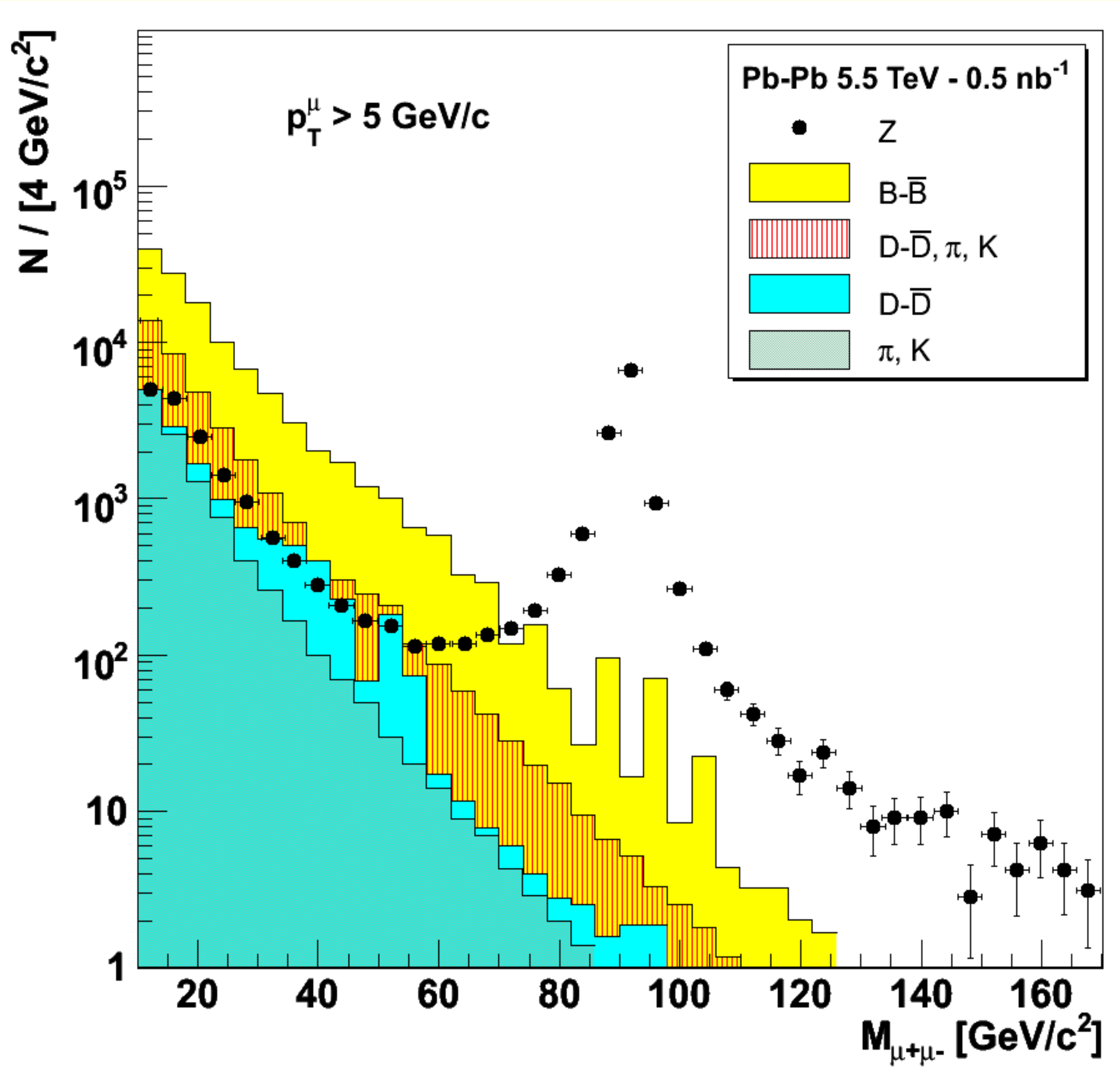


p_T reach

~40 GeV

(without in-medium modification)

Simulation for $Z^0 \rightarrow \mu^+\mu^-$ and BB $\rightarrow \mu^+\mu^-$



CMS Physics TDR: Addendum to High Density QCD with Heavy Ions, J. Phys. G, Nucl. Part. Phys. 34 (2007) 2304

Dimuons:

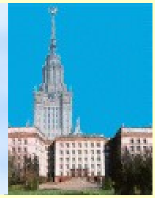
- **bb(bar) fragmentation**
~ dominant contribution
will be sensitive to b-quark in-medium effects

•Combinatorial background:
b and π,K ~16%

∀π,K and charm decay: 5-6%

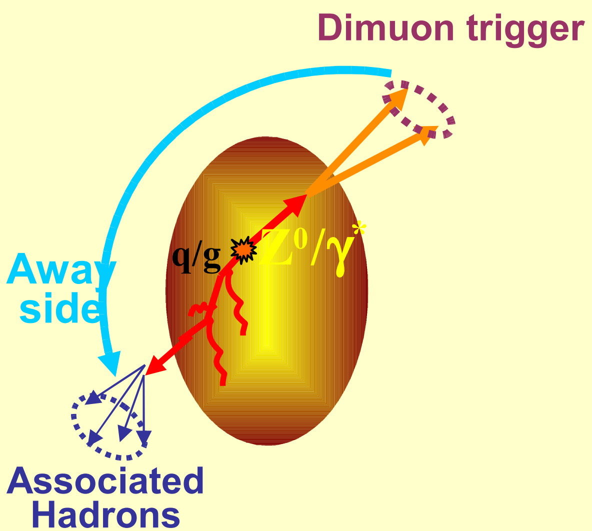
•Signal from Z^0: Clear peak
~11,000 events in
$M_Z \pm 10$ GeV/c²,
Less than 5% background

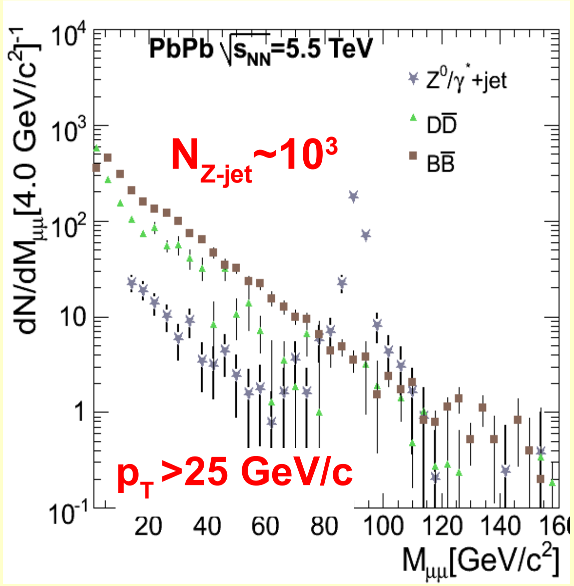
γ*/Z⁰ (→ μ⁺μ⁻) jet tagging (generator level)

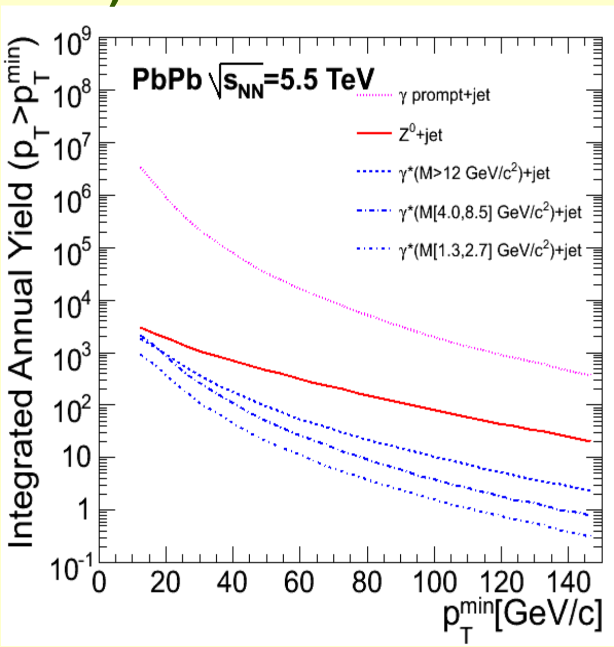


– **CMS can also calibrate jet-energy loss with back-to-back Z and/or virtual γ (large cross-sections, good detection capabilities)**

D. Dutta, C.Mironov et al.



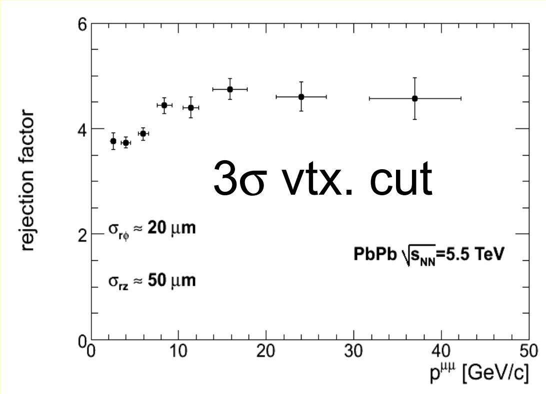


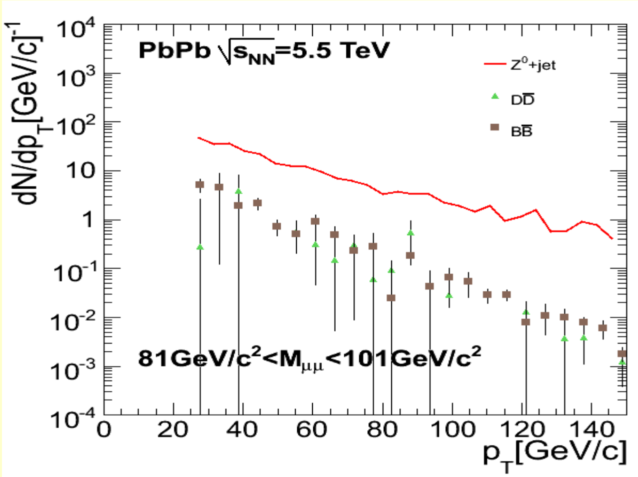


–**Dominant (heavy-Q) dimuon background "removable" via secondary vertex cut**

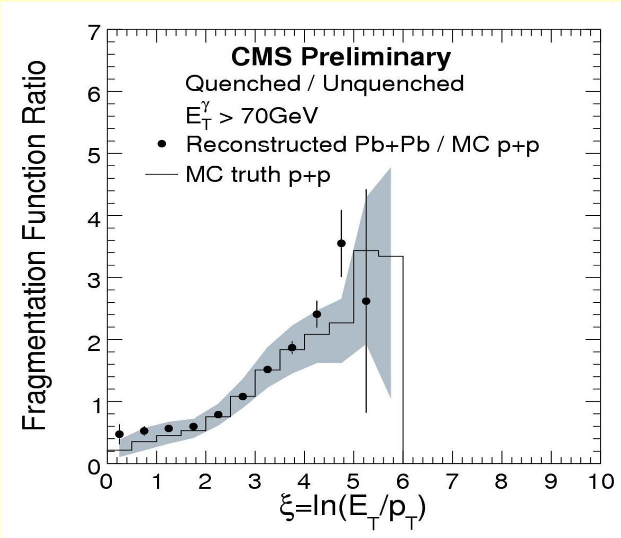
σ_r=50 μm

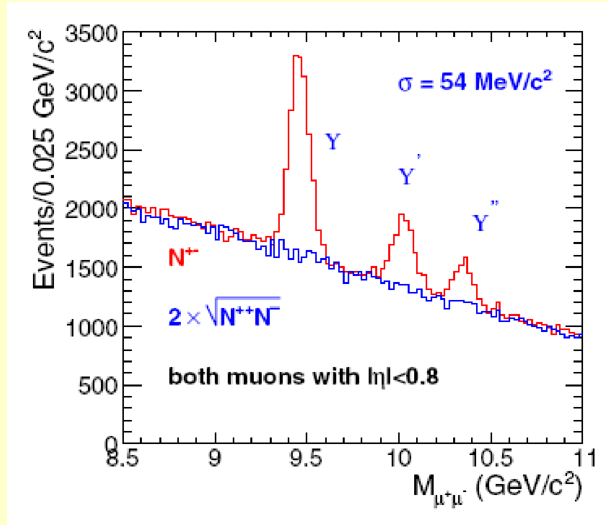
σ_φ=20 μm

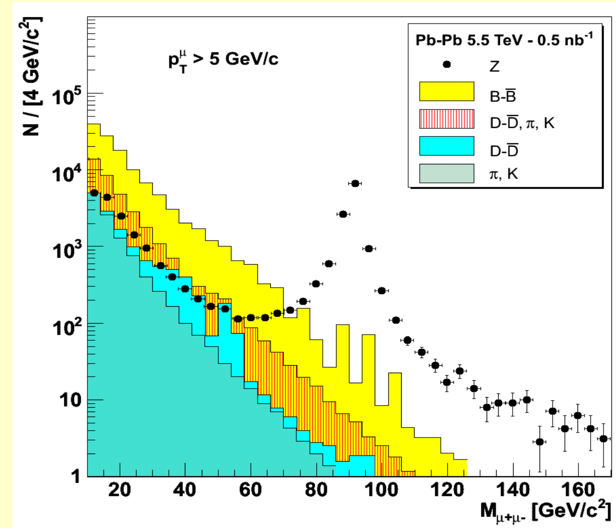




Summary







CMS is an excellent device for study of dense QCD-matter by hard probes

- **Jets, high transverse momentum hadrons and photons**
- **High-mass dimuon resonances (J/ψ, Υ', Υ'', Υ''', Z^0)**

The advantage of CMS capabilities includes

- **excellent rapidity and azimuthal coverage, high resolution**
- **large acceptance, fine granularity hadronic and electromagnetic calorimetry**
- **excellent muon and tracking systems**
- **forward calorimetry (HF, CASTOR, ZDC): event centrality determination**