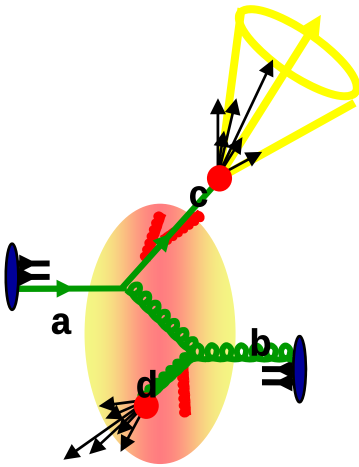
Heavy Ion Physics with the CMS Experiment at the LHC

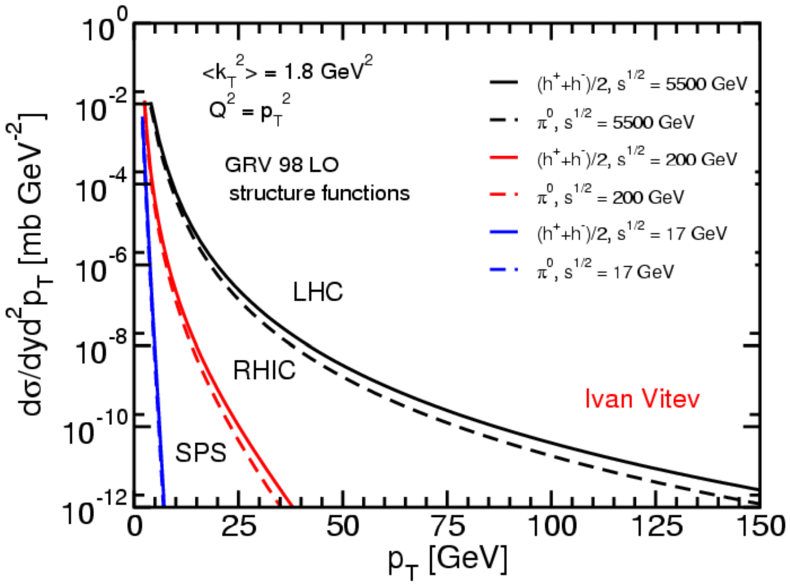


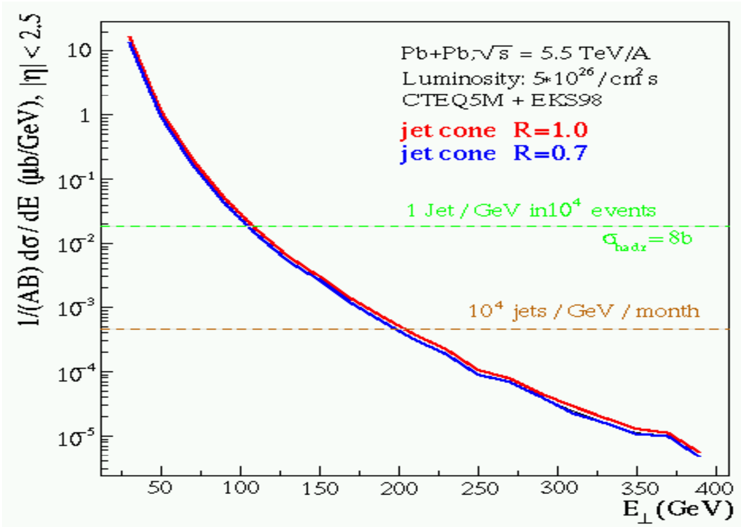
Christof Roland
Massachusetts Institute of Technology
for the CMS Collaboration

VI-SIM Workshop on
Heavy Ion Physics Perspectives
Bad Liebenzell, Germany, 2007

CMS HI groups: Athens, Auckland, Budapest, CERN, Chongbuk, Colorado, Cukurova, Ioannina, Iowa, Kansas, Korea, Lisbon, Los Alamos, Lyon, Maryland, Minnesota, MIT, Moscow, Mumbai, Seoul, Vanderbilt, UC Davis, UI Chicago, Zagreb

Heavy Ion Physics at the LHC





Pb+Pb Collisions at $\sqrt{s_{NN}}$ **~ 5.5TeV**

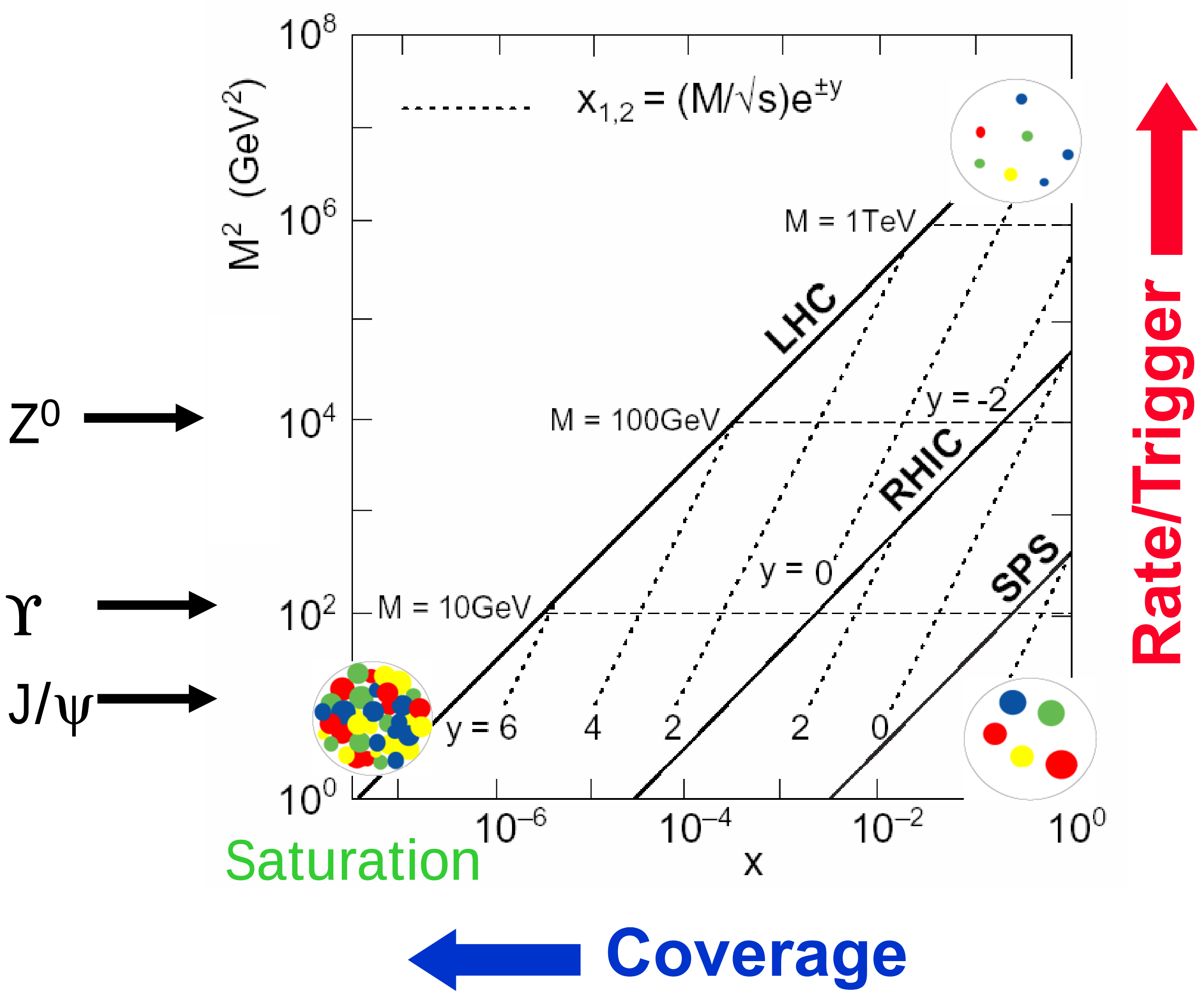
Large Cross section for Hard Probes

High luminosity $10^{27}/cm^2s$

- Copious production of high p_T particles
  - Nuclear modification factors R_{AA} out to very high p_T
- Large cross section for J/ψ and ϒ family production
  - $\sigma^{cc}_{LHC} \sim 10x\ \sigma^{cc}_{RHIC}$
  - $\sigma^{bb}_{LHC} \sim 100x\ \sigma^{bb}_{RHIC}$
  - Different "melting" for members of ϒ family with temperature
- Large jet cross section
  - Jets directly identifiable
  - Study in medium modifications

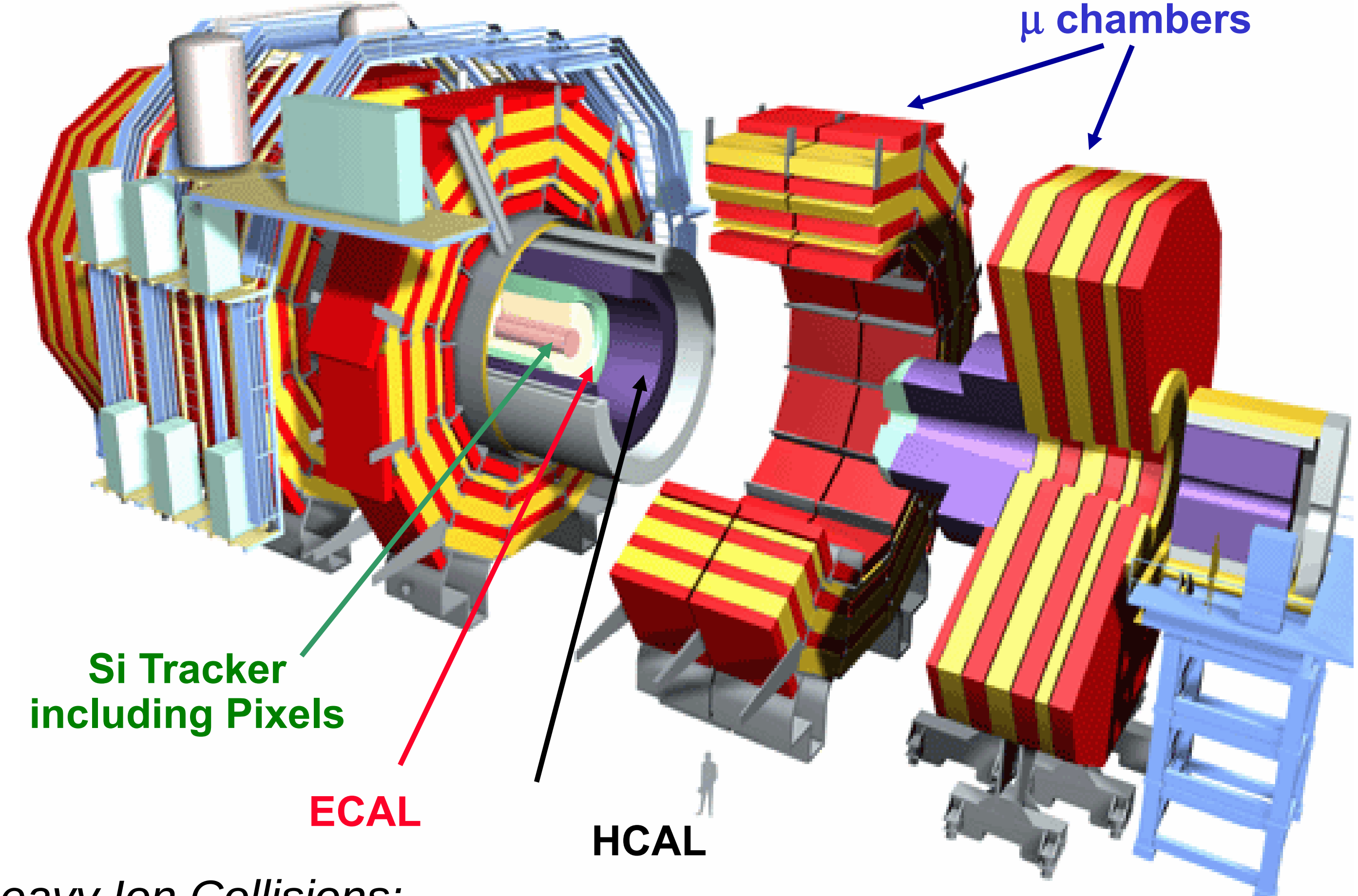
Kinematics at the LHC

Access to widest range of Q^2 and x



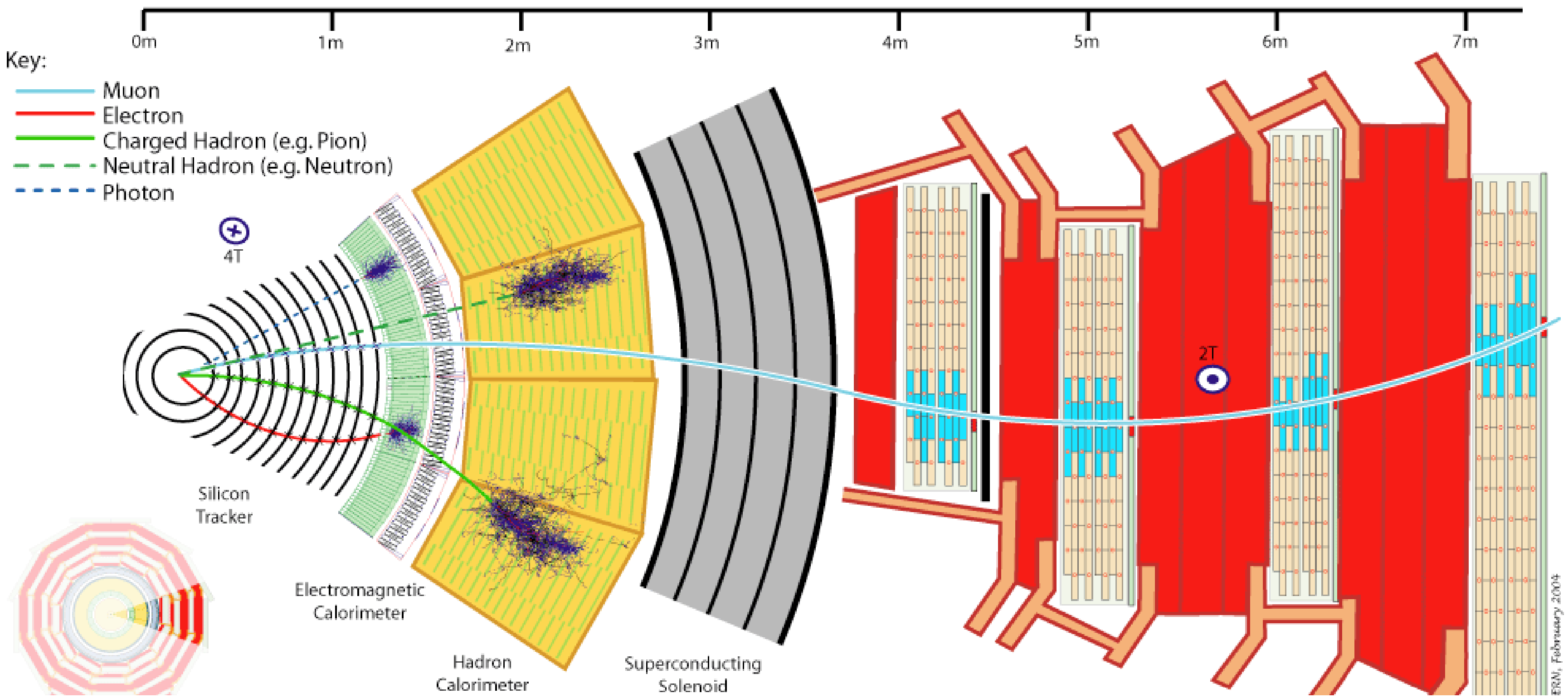
The Detectors

Designed for precision measurements in high luminosity p+p collisions

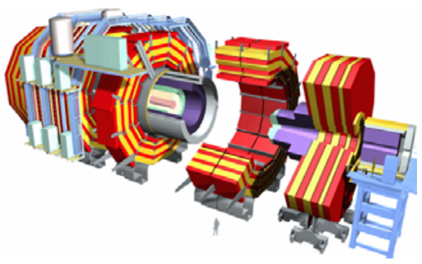


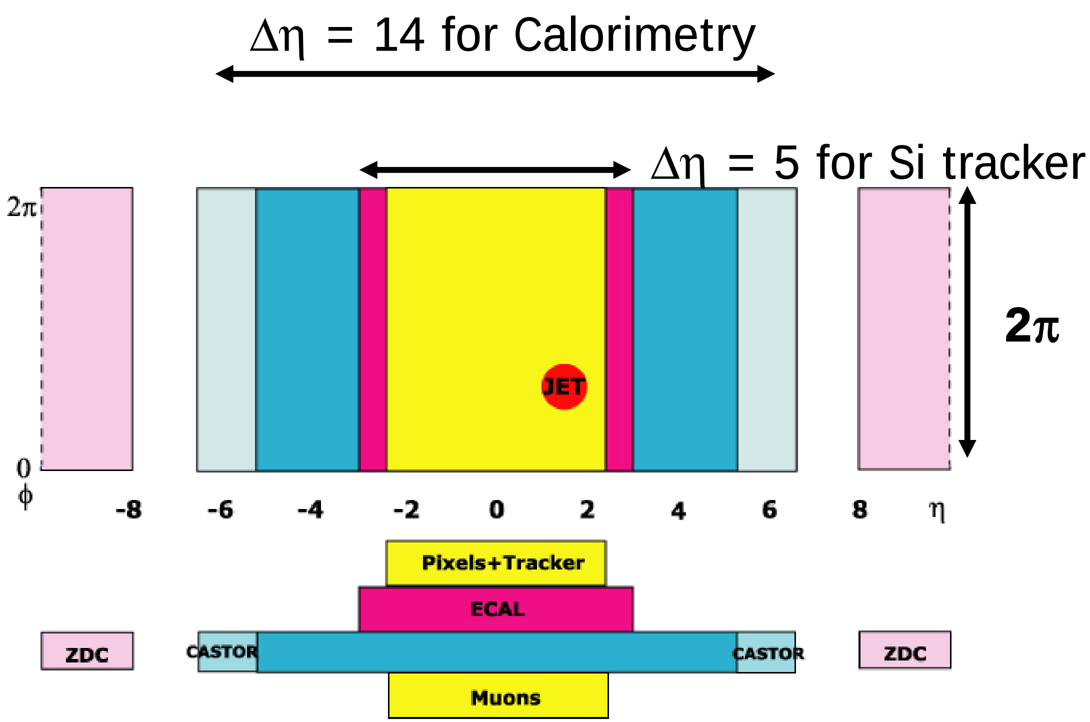
In Heavy Ion Collisions:
Functional at highest expected multiplicities
Detailed studies at ~$dN_{ch}/d\eta$ ~3000
cross-checks up to 7000-8000

Detector Concept



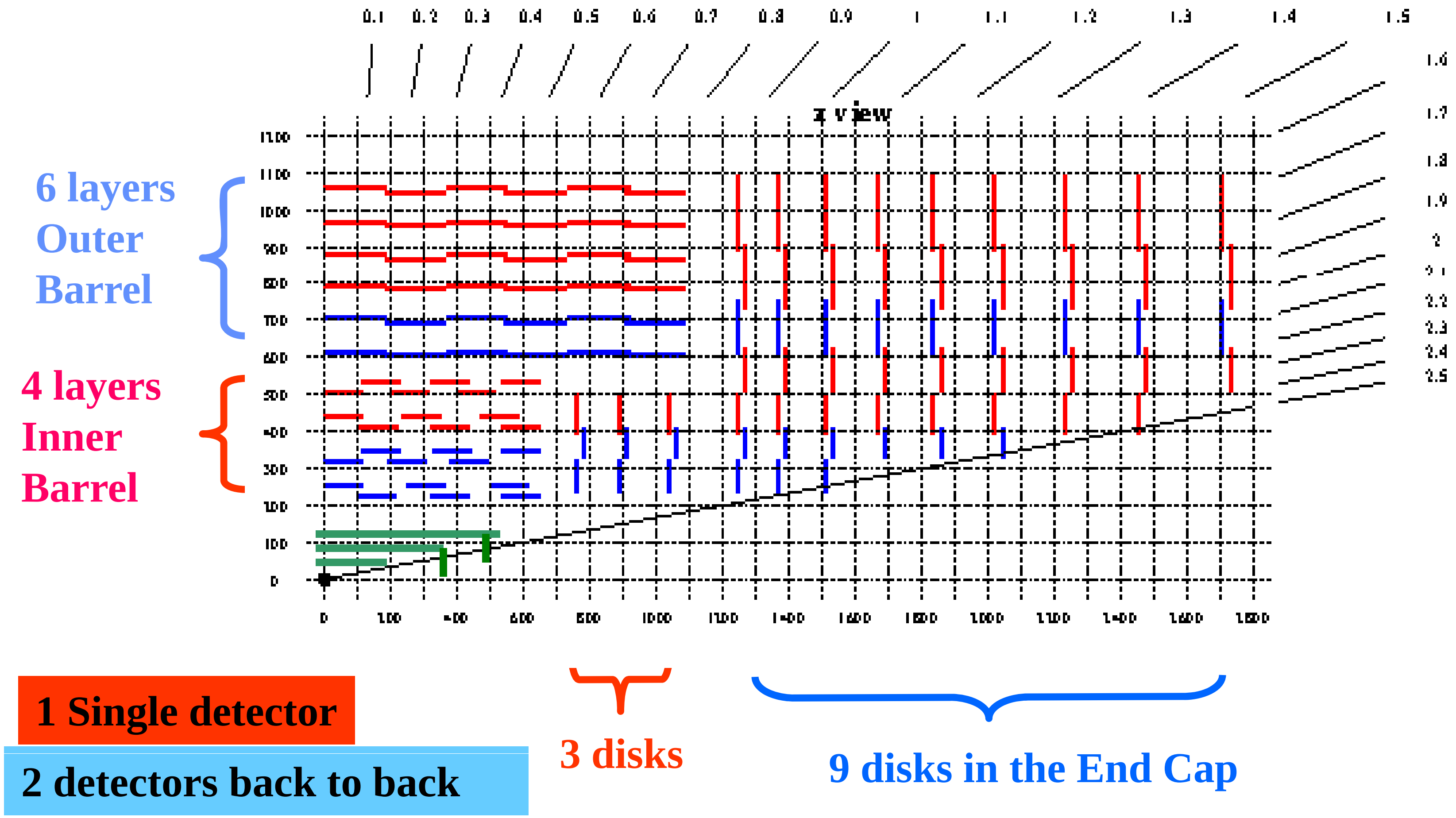
CMS Detector Coverage



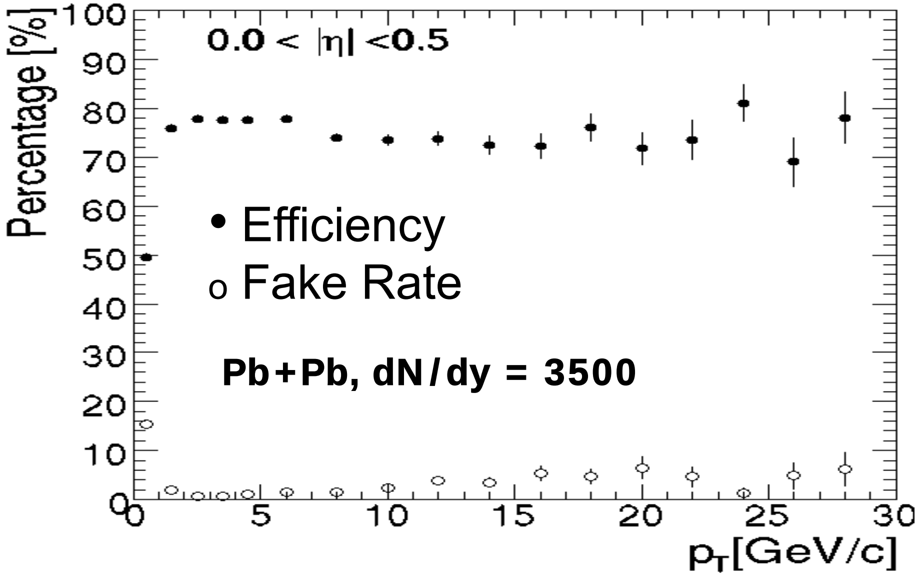


- **Hermeticity, Resolution, Granularity**
  - **Central region Δη~5 equipped with tracker, electromagnetic and hadronic calorimeters and muon detector**
- **Forward coverage**
  - **Calorimetric coverage of Δη~10**
  - **Additional calorimeters proposed to extend the coverage: CASTOR Δη~14**
  - **Zero Degree Calorimeter (ZDC)**
- **High data taking speed and trigger versatility**

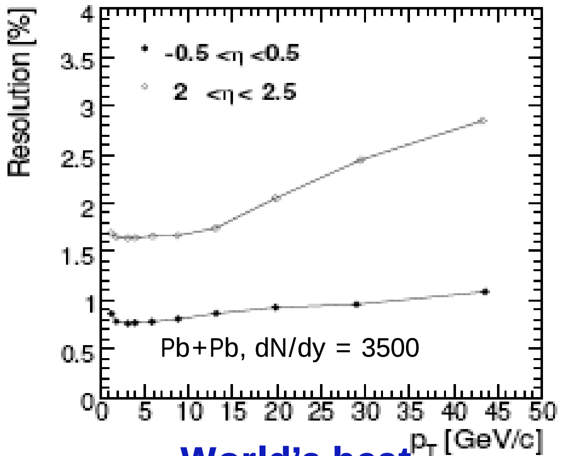
Tracker lay-out



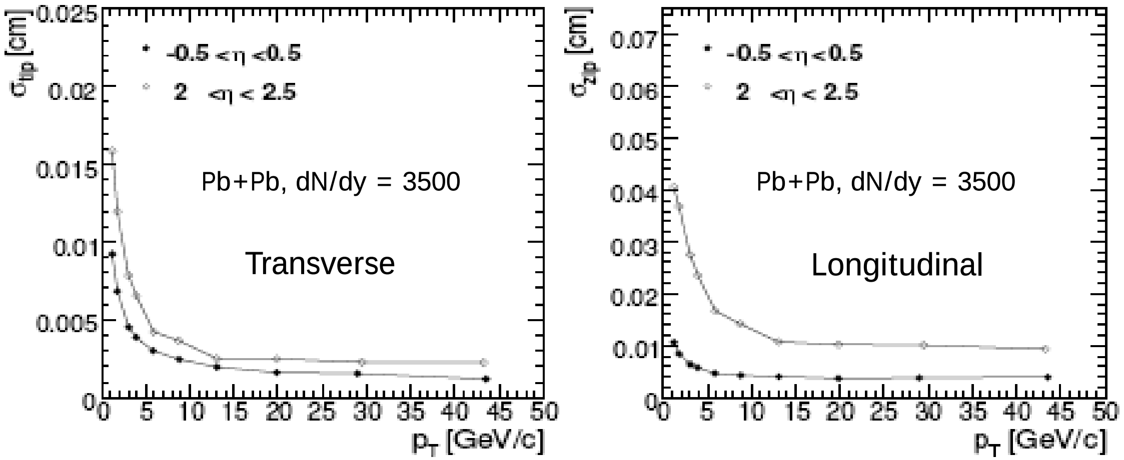
CMS Tracking Performance



- **Occupancy in Pb+Pb**
  - **dN/dy = 3500**
  - **1-2% in Pixel Layers**
  - **< 10% in outer Strip Layers**
- **Efficiency**
  - **~75% above 1 GeV/c**

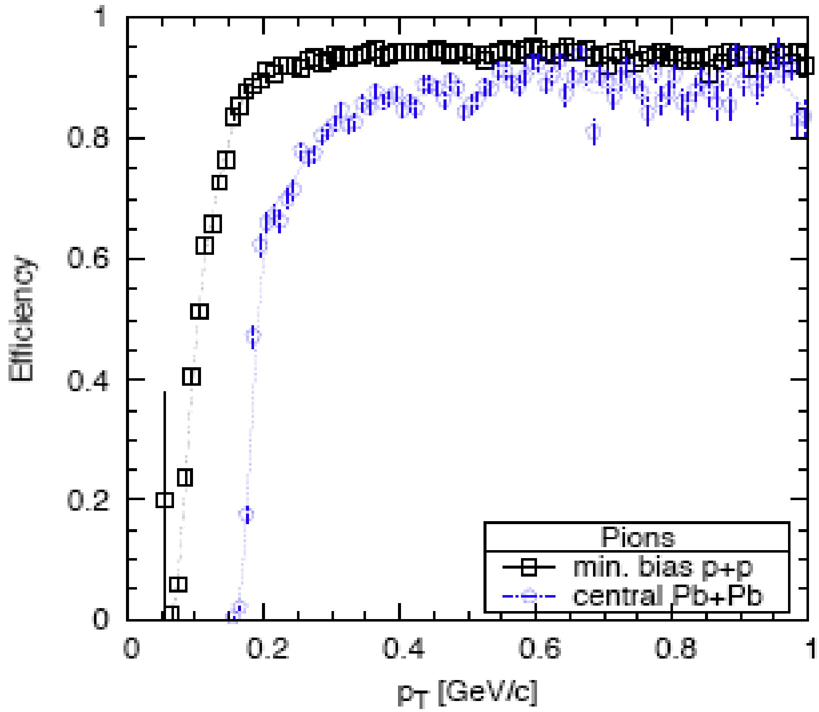


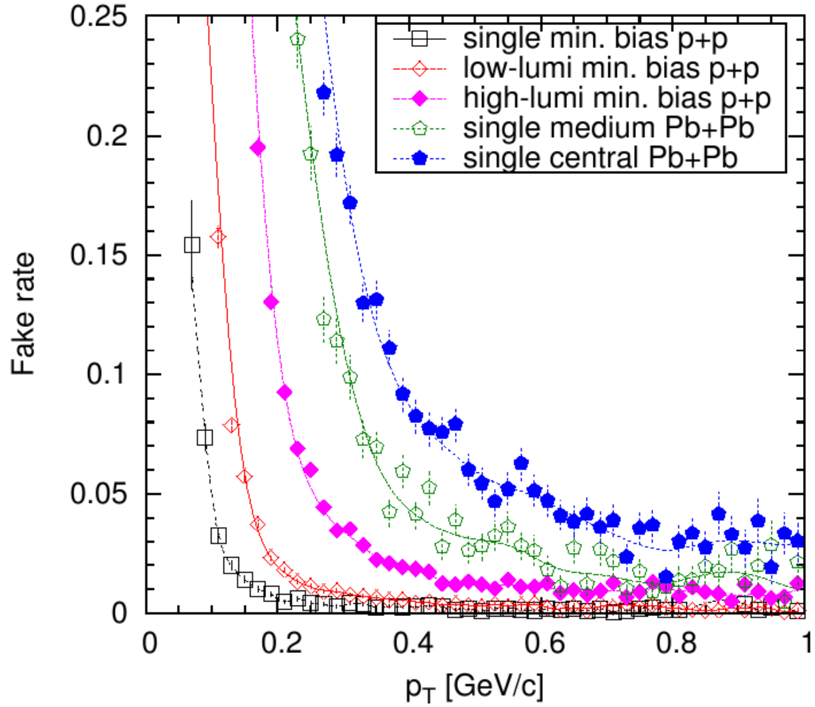
World's best momentum resolution



Excellent impact parameter resolution

Tracking at low p_T

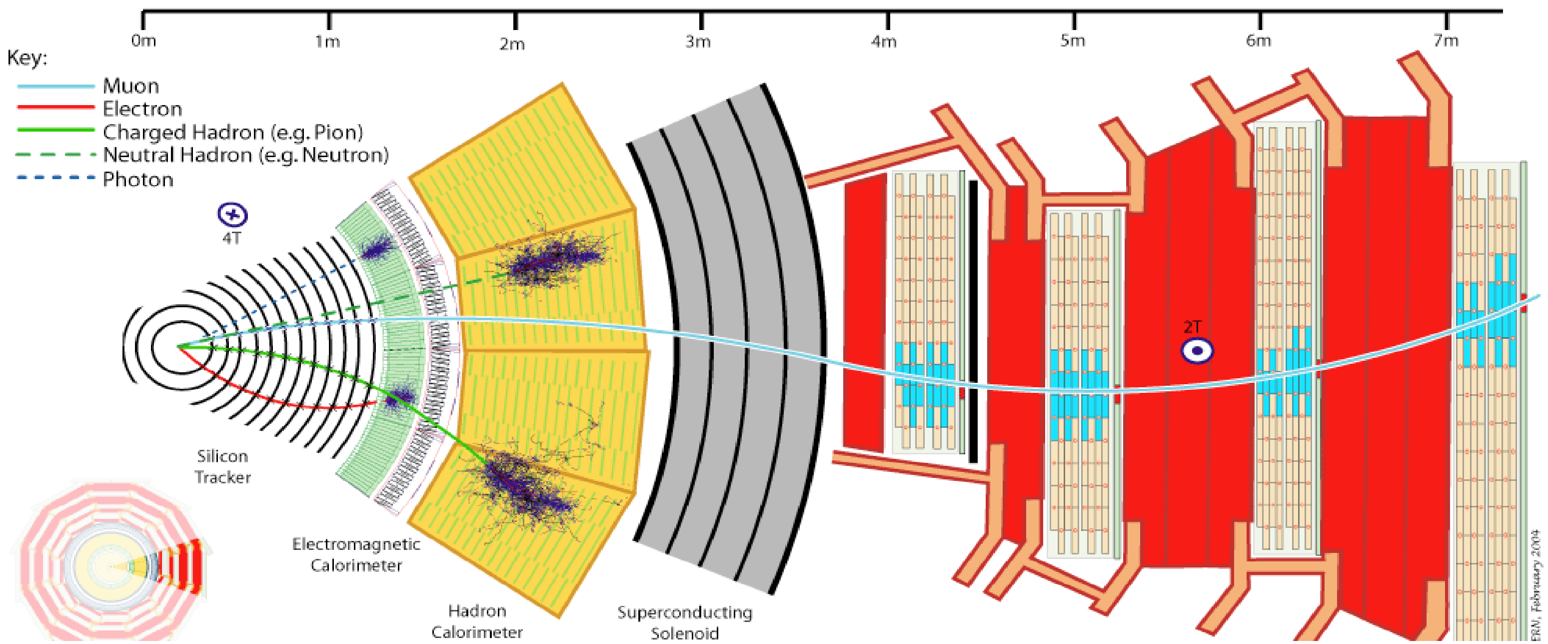




CMS HI TDR, Ferenc Sikler (Budapest)

- **Changes to tracking algorithms allow access to low p_T particles**
  - **Reconstruct three hit tracks in the pixel system**
  - **Good efficiency to ~ 300MeV/c in Pb+Pb**
  - **Particle ID by dE/dx in Silicon**

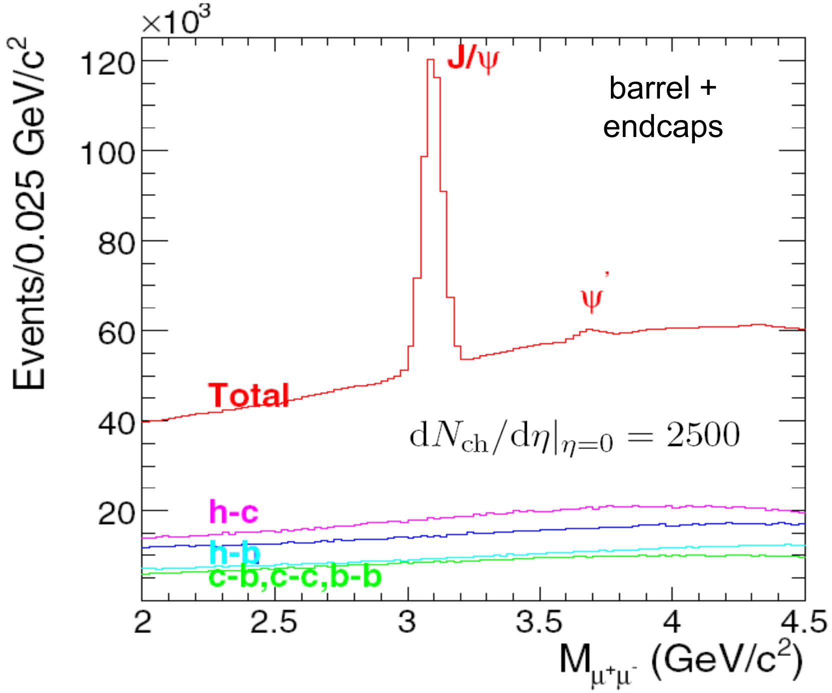
The Muon Stations

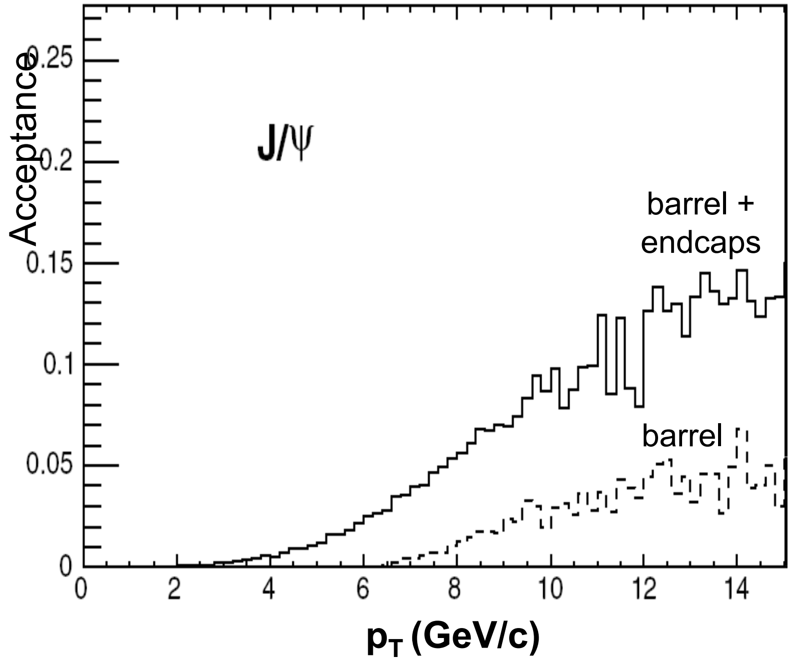


- **Muon Reconstruction**
  - **Tag from Muon chambers**
  - **Momentum resolution from Silicon Tracker**
    - Barrel $p_T^{\mu} > 3.5$, Endcap $p_L^{\mu} > 4.0$ to penetrate the absorber
  - **Excellent mass resolution for J/ψ and Υ states**
  - **Coverage in the central rapidity region**
  - **Muon reconstruction is available in the High Level Trigger**

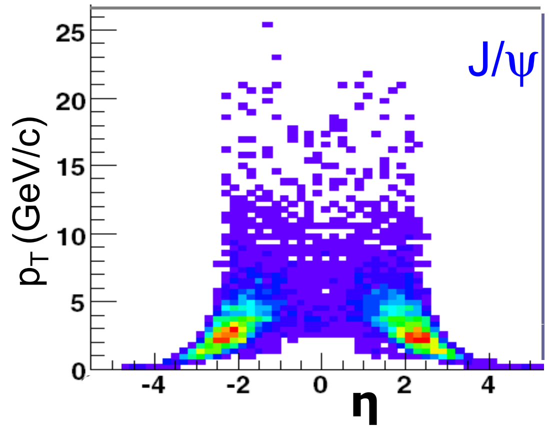
J/ψ→μμ

mass resolution and acceptance





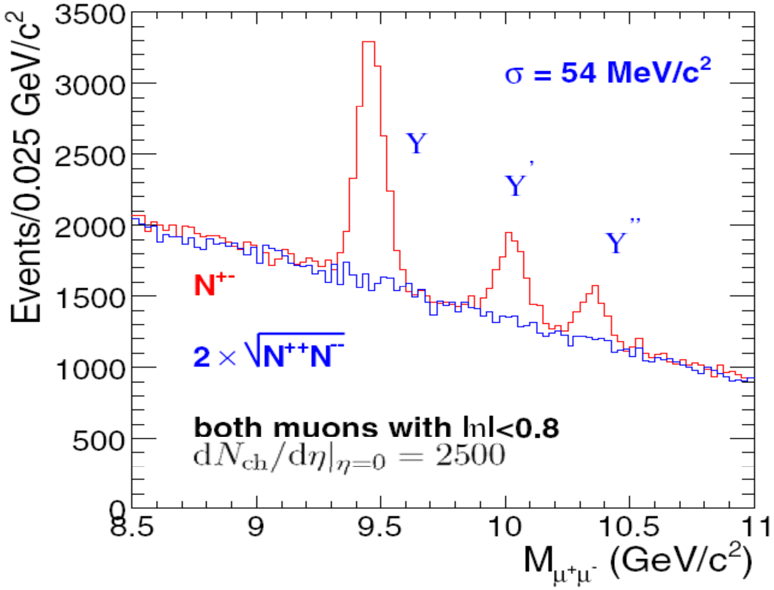
O. Kodolova, M. Bedjidian, CMS note 2006/089

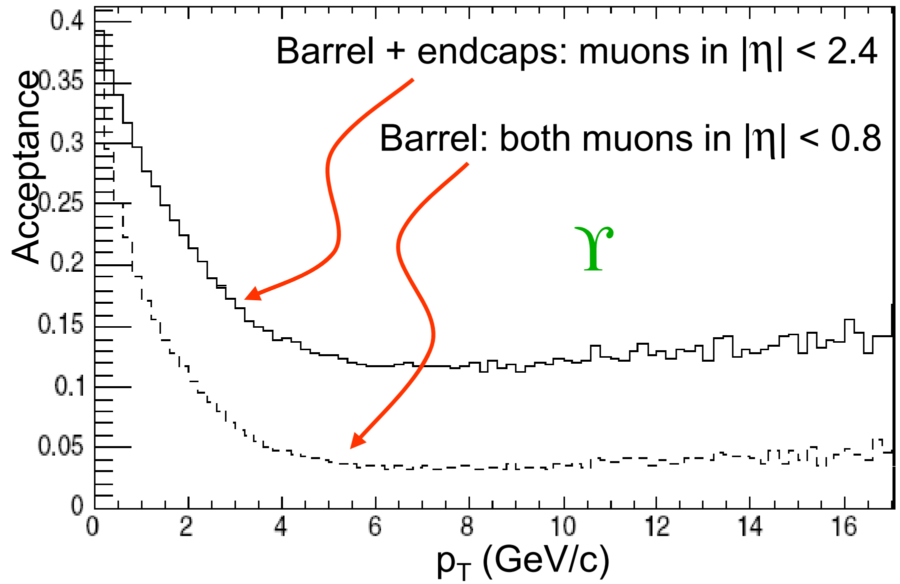


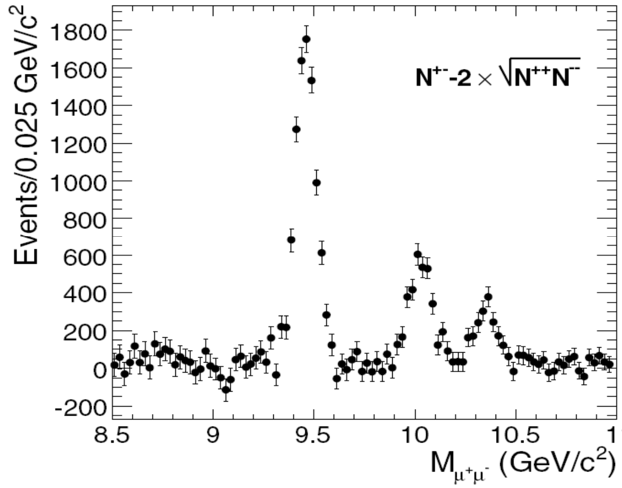
- **The dimuon mass resolution is 35 MeV, full η region.**
- **Low p_T J/ψ acceptance at forward rapidities.**

ϒ→μμ

Mass resolution and acceptance







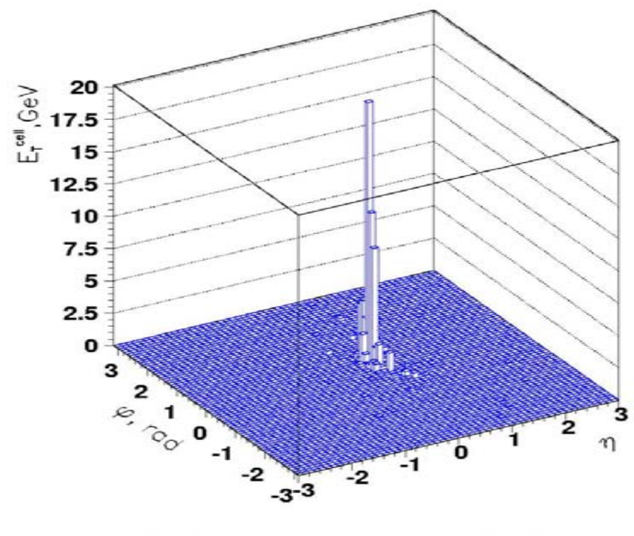
- **CMS has a very good acceptance in the Upsilon mass region**
- **The dimuon mass resolution allows to separate the three Upsilon states:**
  - **~ 54 MeV/c2 within the barrel and ~ 86 MeV/c2 when including the endcaps**

O. Kodolova, M. Bedjidian, CMS note 2006/089

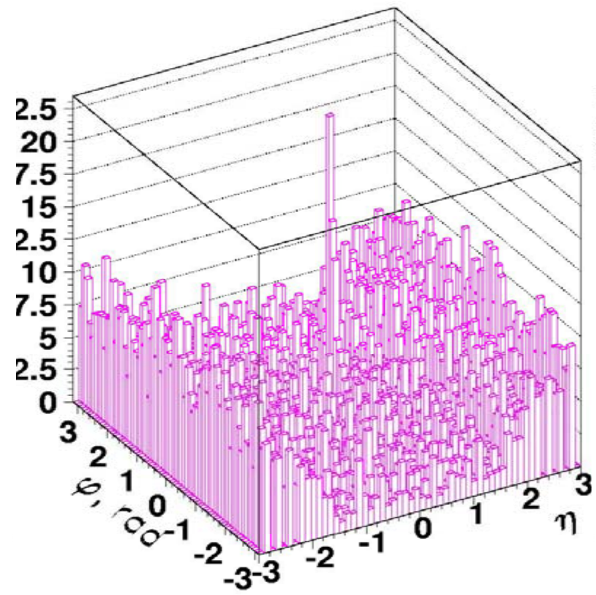
The Calorimeters: Jet Reconstruction

Jet E_T ~100GeV, Pb Pb background dN_{ch}/dy ~ 5000

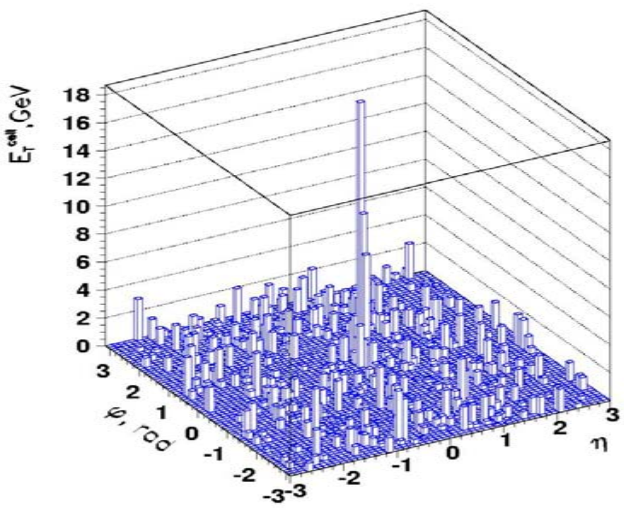
Jet in pp



Jet superimposed on Pb Pb background

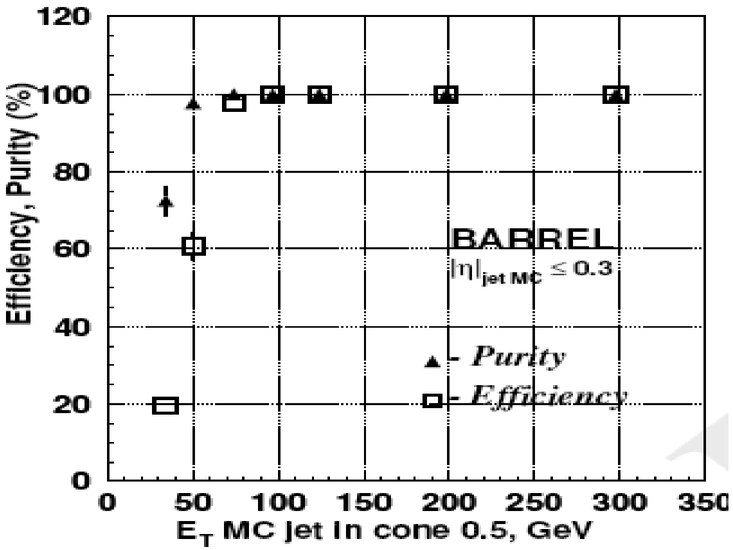


Jet in Pb-Pb after pileup subtraction

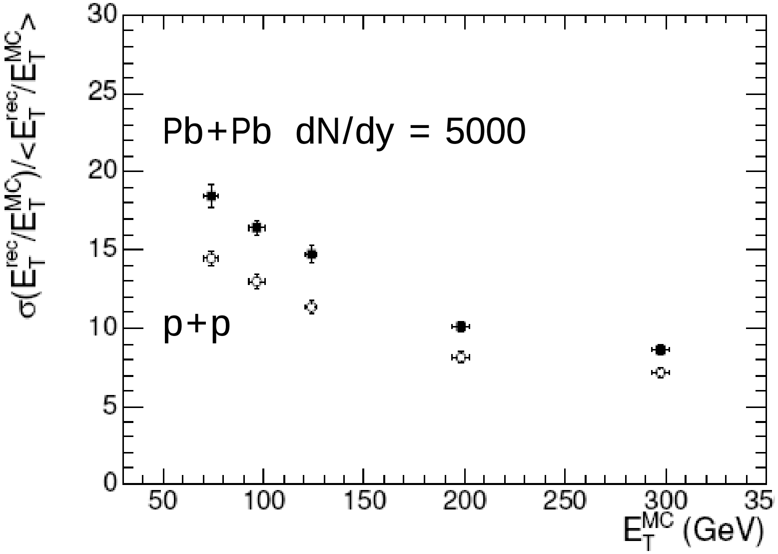


Heavy Ion Jet Finder Performance

High Efficiency



Good Resolution

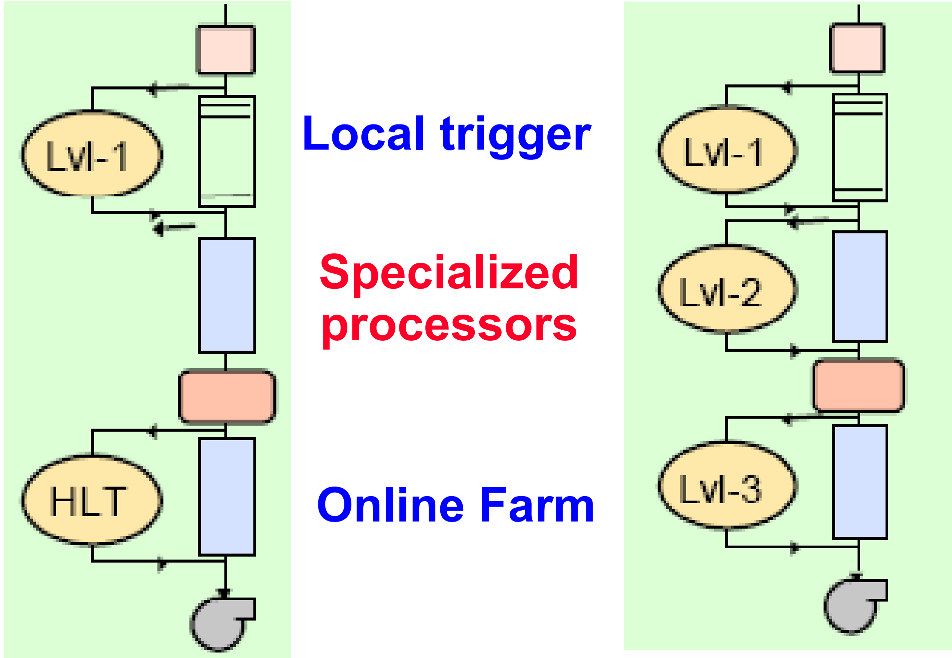


- **A modified iterative cone algorithm running on calorimeter data gives good performance in Pb Pb collisions**
- **Offline jet finder will run in the HLT**

Data Acquisition and Trigger

- **CMS has a two-level DAQ/Trigger architecture:**
  - **L1: Low level hardware trigger**
    - Muon track segments
    - Calorimetric towers
    - No tracker data
    - Output rate (Pb+Pb): ***1-2 kHz***
  - **HLT: Powerful online farm doing event building triggering**
    - ~12k CPU cores
    - Full event information available
    - Use “offline” code to trigger
    - Fully flexible
    - Data storage bandwidth 225 MB/s

    => ~100 PbPb Events/s (min. bias)
- **Special HI Triggers:**
  - **DiMuon Trigger Υ, J/psi**
  - **Jet Trigger with background subtraction**
  - **High E_T Photon Trigger**
  - **Centrality**

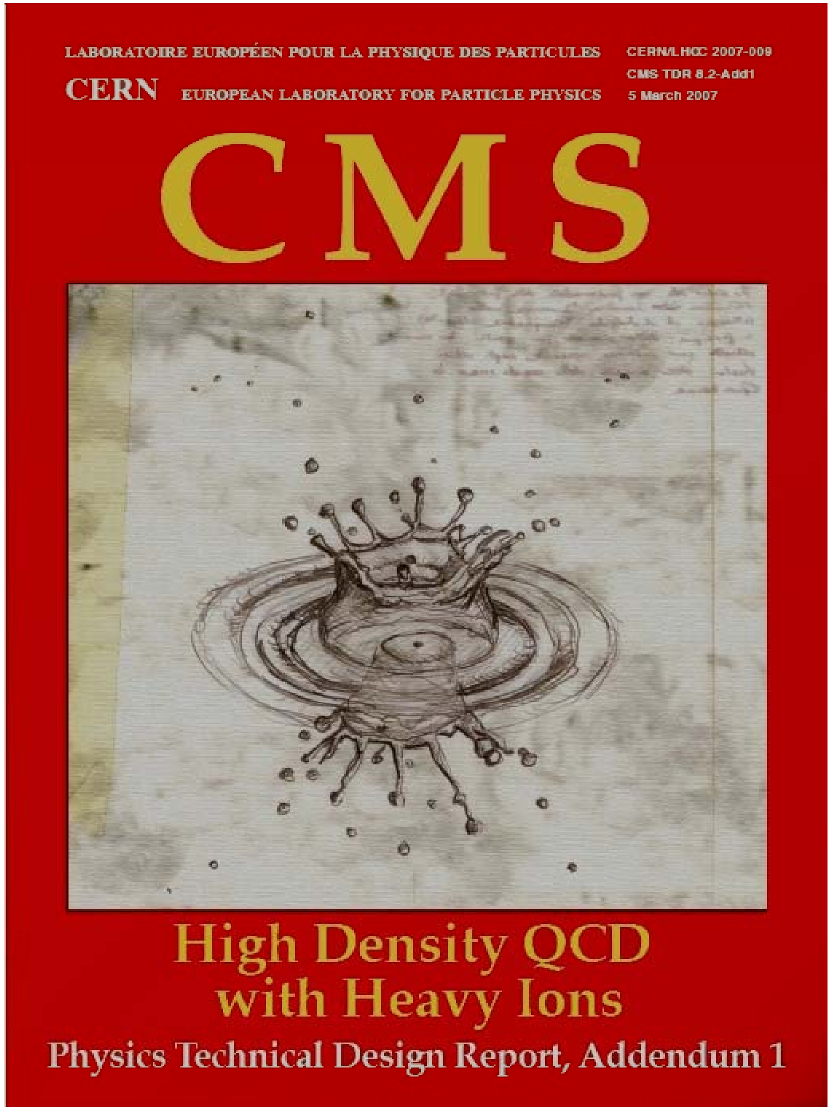


CMS **Others**

- **Every event accepted by L1 trigger must pass through online farm (HLT)**

High Density QCD with Heavy Ions

…with the CMS detector

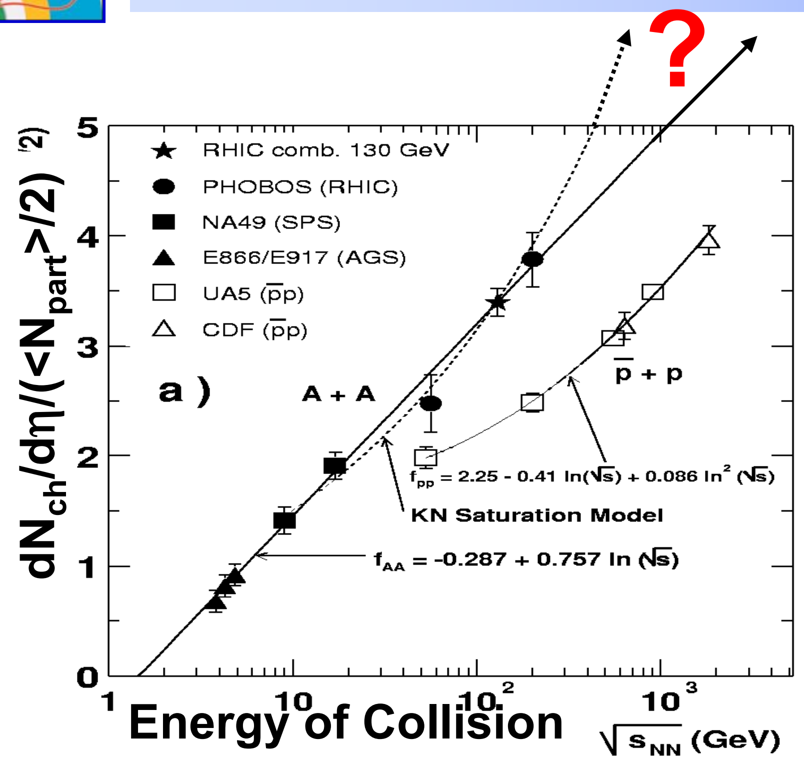


HI-Physics TDR published March 2007

Physics cases for HI@CMS

Case no.	*We will look into…*	*in order to learn about…*
0	**MB L1 trigger, centrality**	**Global event characterization**
1	**$dN_{ch}/d\eta$**	**Color Glass Condensate, $xG_A(x,Q^2)$**
2	**Low p_T π/K/p spectra**	**Hydrodynamics, Equation of State**
3	**Elliptic Flow**	**Hydrodynamics, Medium viscosity**
4	**Hard-probes (triggering)**	**Thermodynamics & transport properties**
5	**Quarkonia suppression**	**ε_{crit}, T_{crit}**
6	**Jet “quenching”**	**Parton density, $\langle \hat{q} \rangle$ transport coefficient**
7	**Upsilon photoproduction**	**CGC and $xG_A(x,Q^2)$**

dN/dη

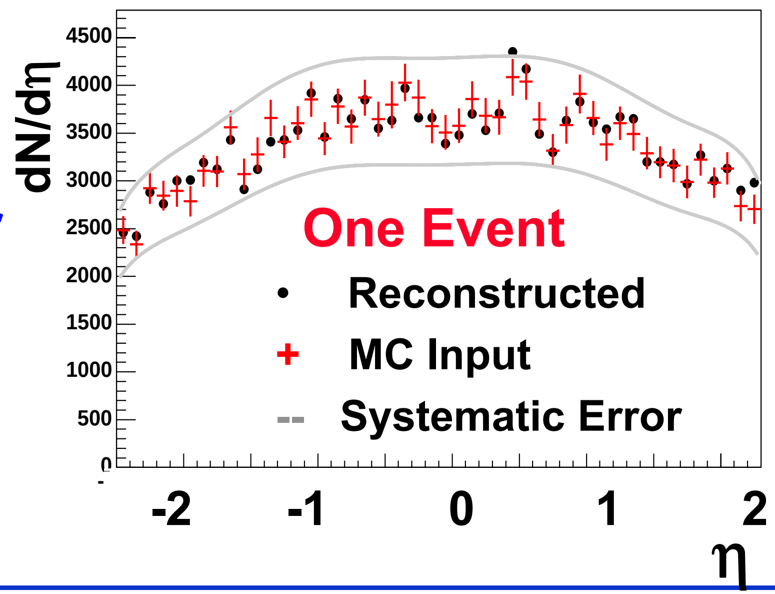


Charged Particle Multiplicities

- Predictions vary by a factor of 4!
- dN/dy ~ 1500 – 7000
- (RHIC extrapolation vs. HIJING)

Hit counting in the first pixel layer

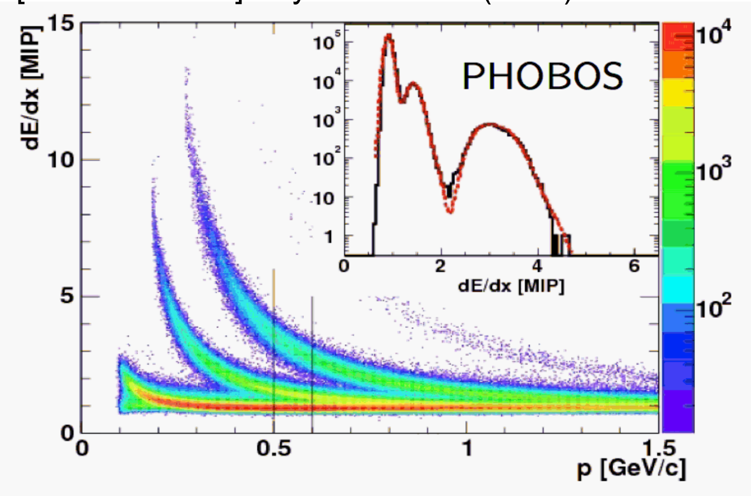
- Low p_T cutoff ~40 MeV
- Needs few events O(1000)
- Few seconds of data taking

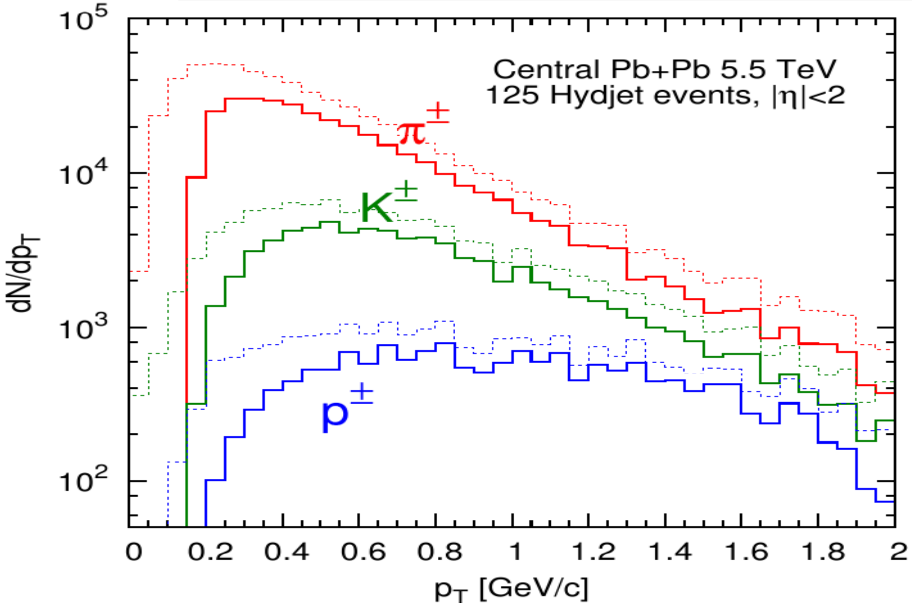


Low p_T tracking and PID

- p_T down to 200–300 MeV/c !
  - Using dE/dx information from analog pixel readout
- Pions, kaons and protons resolved…
- …opening the way for V0 reconstruction

[PHOBOS Coll.] Phys. Rev. **C75** (2007) 024910

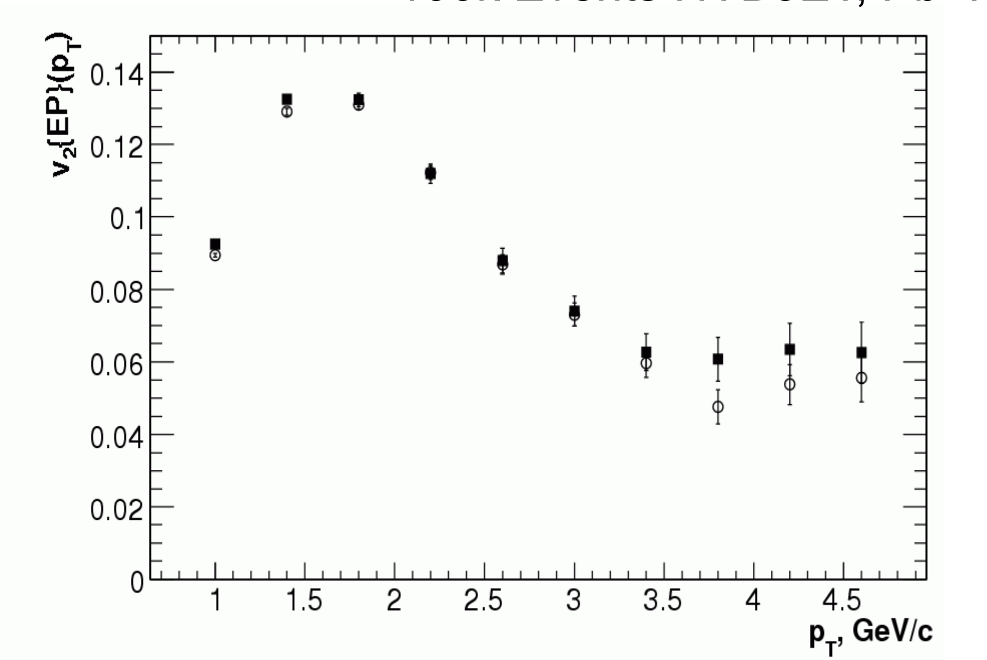


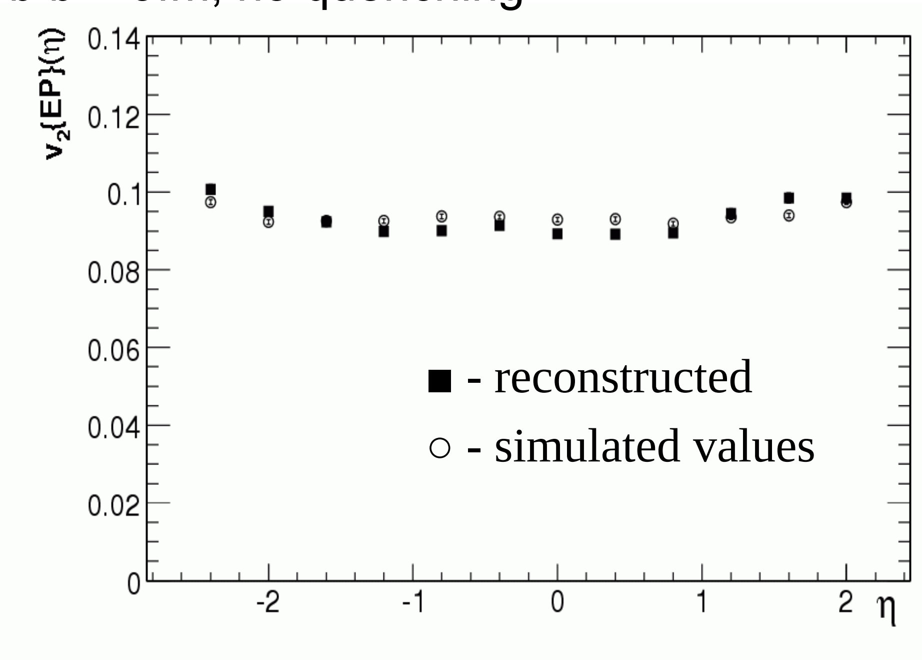


simulated (dotted) and reconstructed (solid)

Elliptic Flow

100k Events HYDJET, Pb+Pb b = 9fm, no quenching

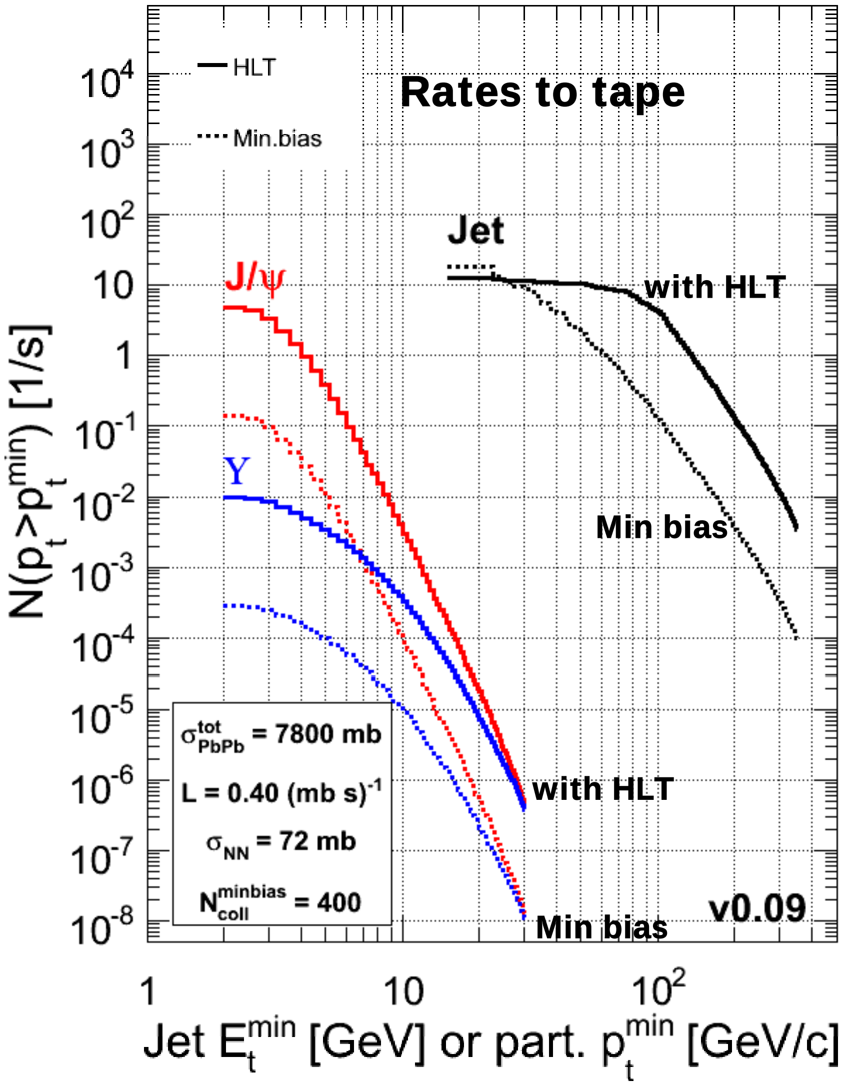




Use the tracker to measure v2 differentialy in p_T and η

- Event plane and v2 determined from independent sub-events
- No non-flow corrections applied
- Compare v2 extracted from simulated particles and reconstructed tracks
- The p_T and η dependences of v2 can be reconstructed with high accuracy.

Hard Probes: HLT vs Min Bias



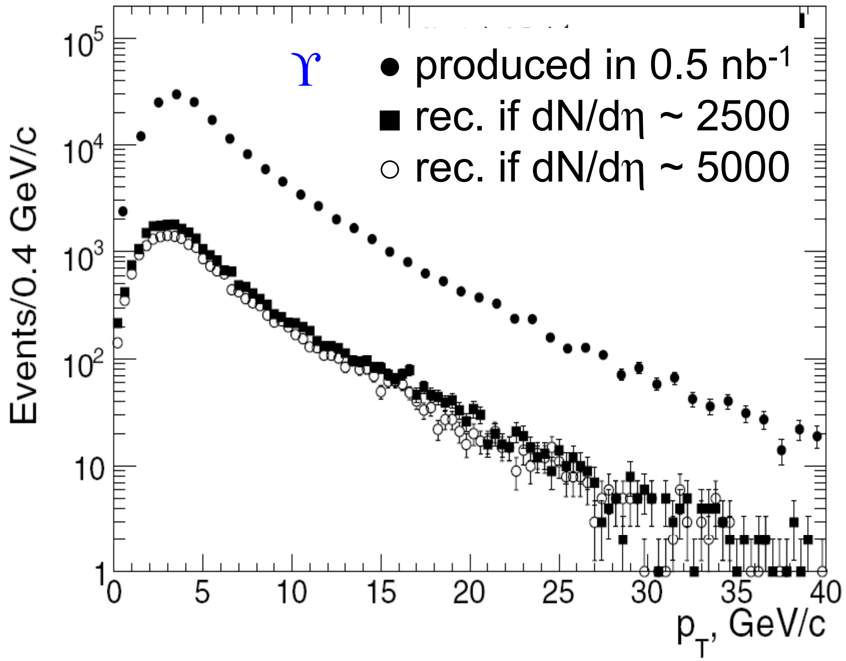
J/ψ,Y and Jet reconstruction available at HLT

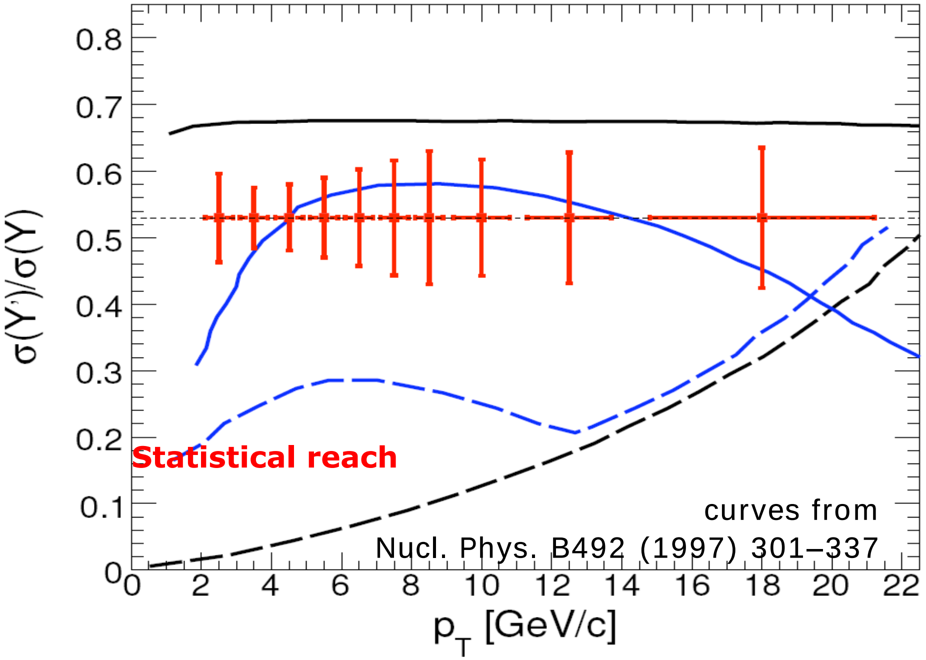
Example trigger table:

Channel	Threshold	Pre-scale	Bandwidth [MByte/s]	Event size [MByte]
min. bias	–	1	33.75 (15%)	2.5
jet	100 GeV	1	24.75 (11%)	5.8
jet	75 GeV	3	27 (12%)	5.7
jet	50 GeV	25	27 (12%)	5.4
J/ψ	0 GeV/c	1	67.5 (30%)	4.9
Υ	0 GeV/c	1	2.25 (1%)	4.9
γ^{prompt}	10 GeV	1	40.5 (18%)	5.8
UPC/forward	–	1	2.25 (1%)	1

HLT improves hard probe statistics by more than a factor of 10!

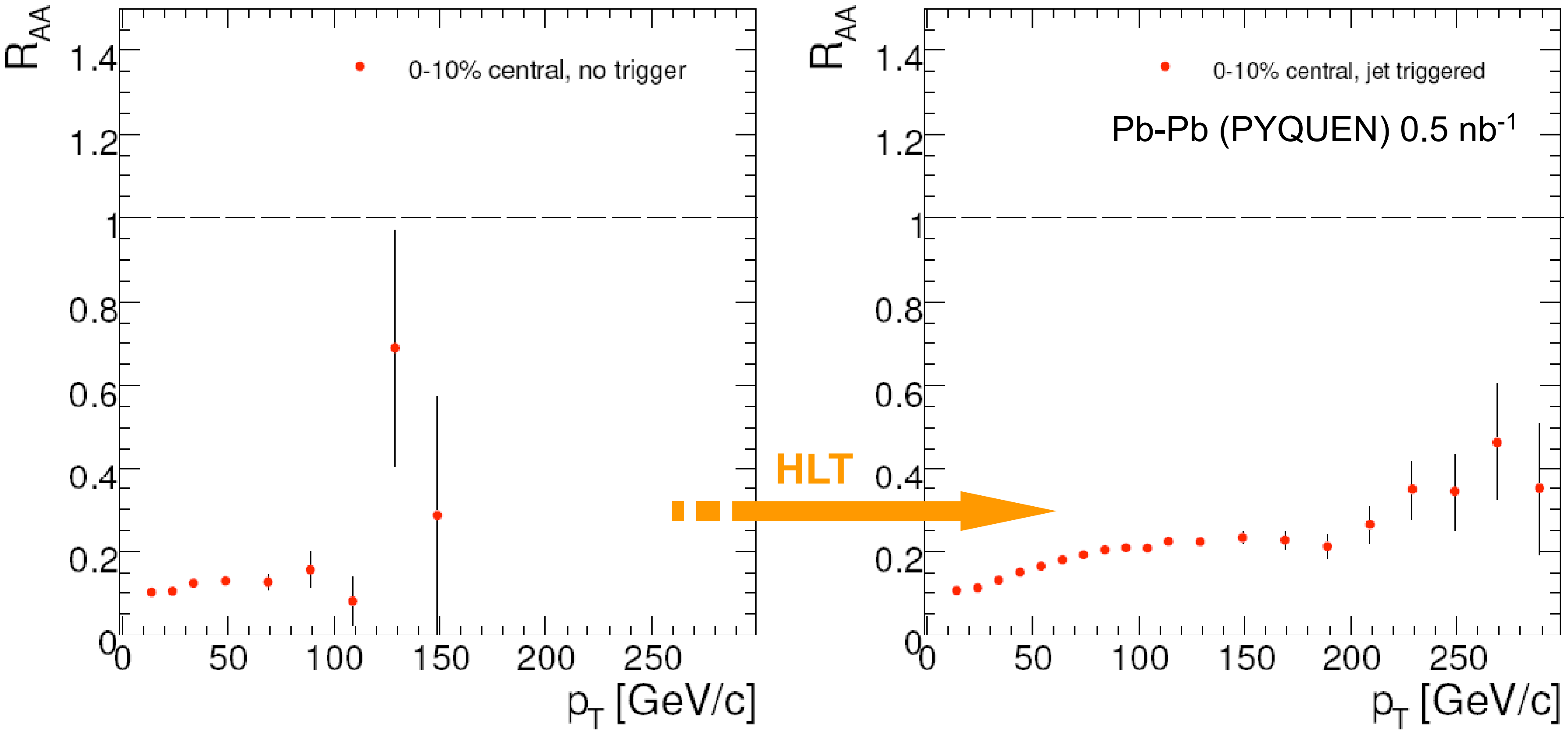
p_T reach of quarkonia (for 0.5 nb^{-1})





- **Expected rec. quarkonia yields:**
  - **J/ψ : ~ 180 000**
  - **ϒ : ~ 26 000**
- **Detailed studies of Upsilon family feasible with HLT**
- **Statistical accuracy (with HLT) of expected ϒ' / ϒ ratio versus p_T -> model killer...**

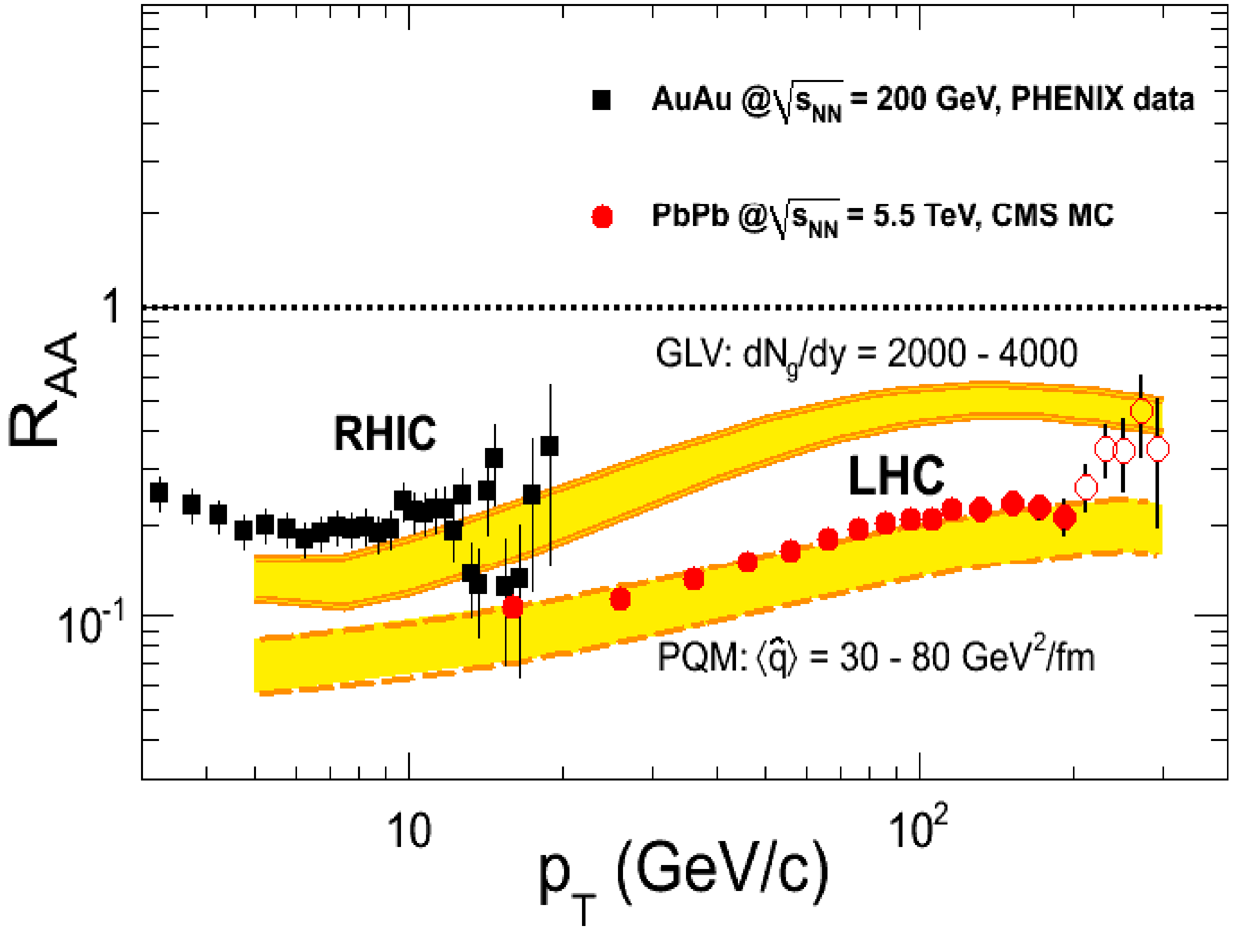
HLT impact on the p_T reach of R_{AA}



$$R_{AA}(p_T) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AB}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T}$$

- **Jet-trigger allows R_{AA} measurement to p_T > 200 GeV/c**
- **Reach improved by x 2 compared to min. bias.**

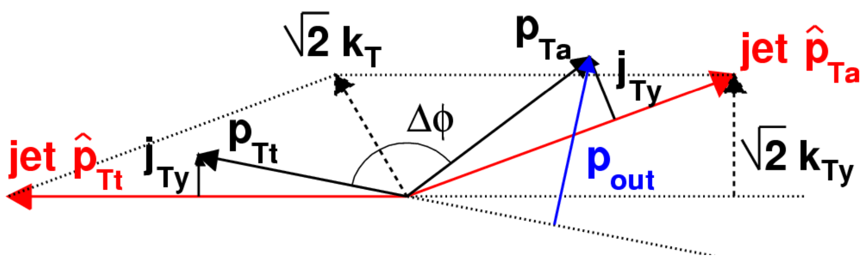
High p_T Suppression

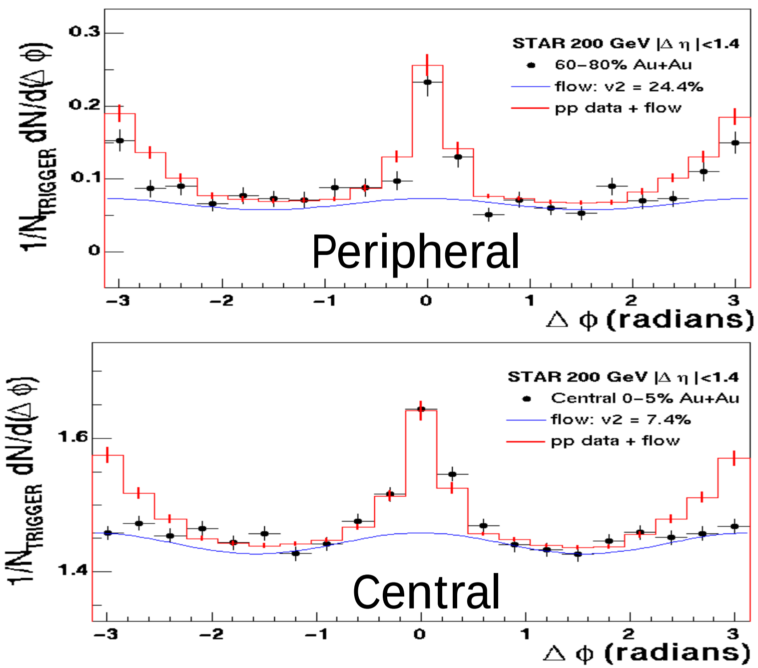


Clear separation of different energy loss scenarios

Jet Shapes: RHIC vs. LHC

- **RHIC: two particle correlations**
  - **Trigger on high p_T particles**
    - Surface bias
  - **This folds**
    - Intrinsic k_T
    - Fragmentation functions
    - …

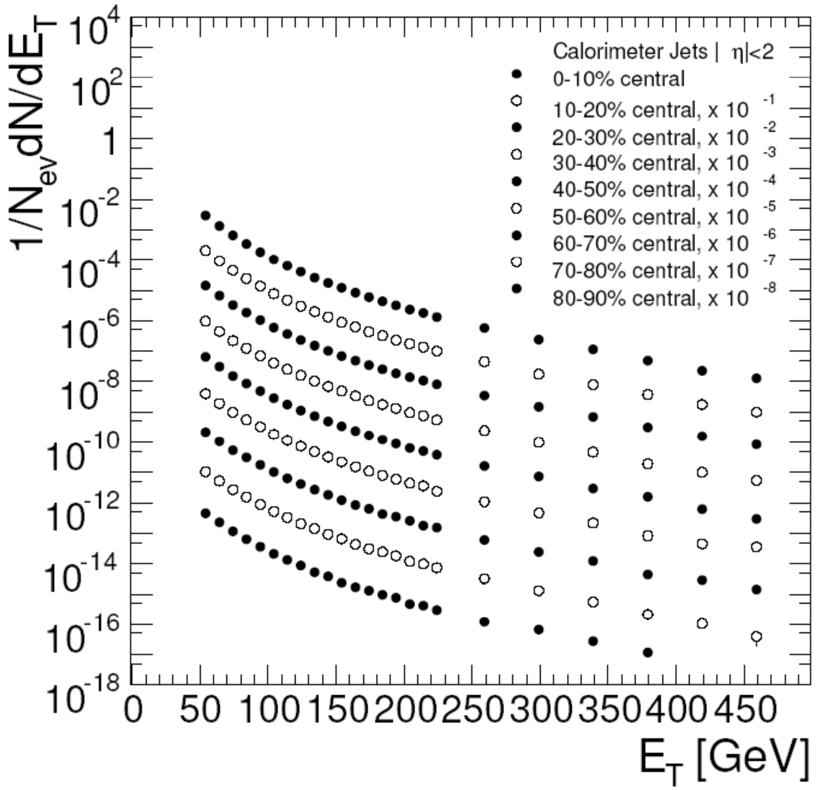




- **LHC: study fully formed Jets**
  - **Directly reconstruct Jet axis and energy!**
  - **Removes trigger biases**

Jet E_T reach

Pb-Pb, 0.5 nb^{-1}, HLT-triggered



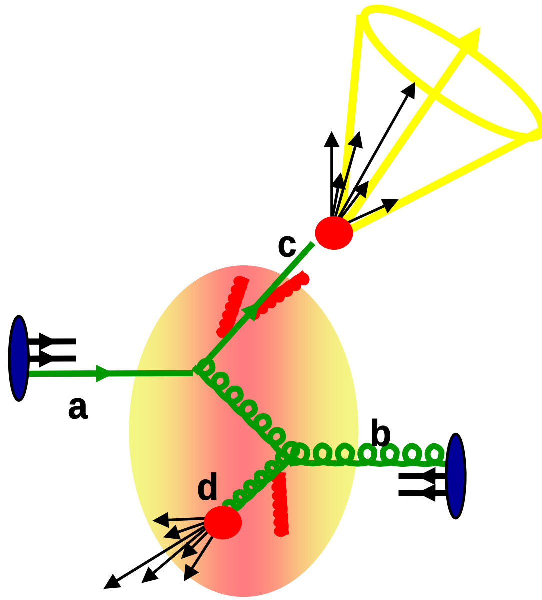
- **Jet spectra up to E_T ~ 500 GeV**
  - **Detailed studies of medium-modified (quenched) jet fragmentation functions**

What can we measure in Heavy Ions?

- **Some example Jets observables using Calorimetry**

Probe energy loss of the leading parton

- **Jet cross sections**
- **Jet - Jet correlations**
- **Jet- γ/Z correlations**

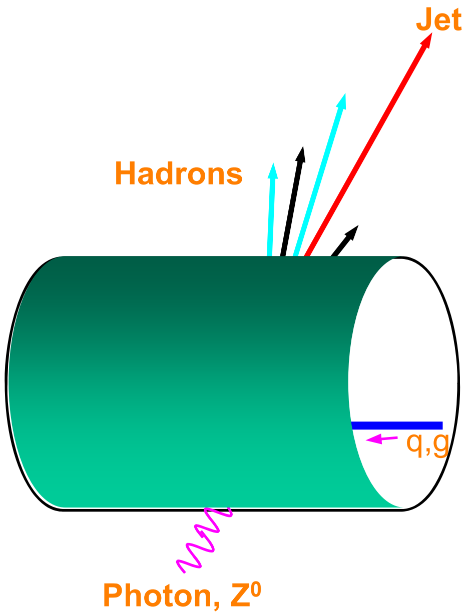


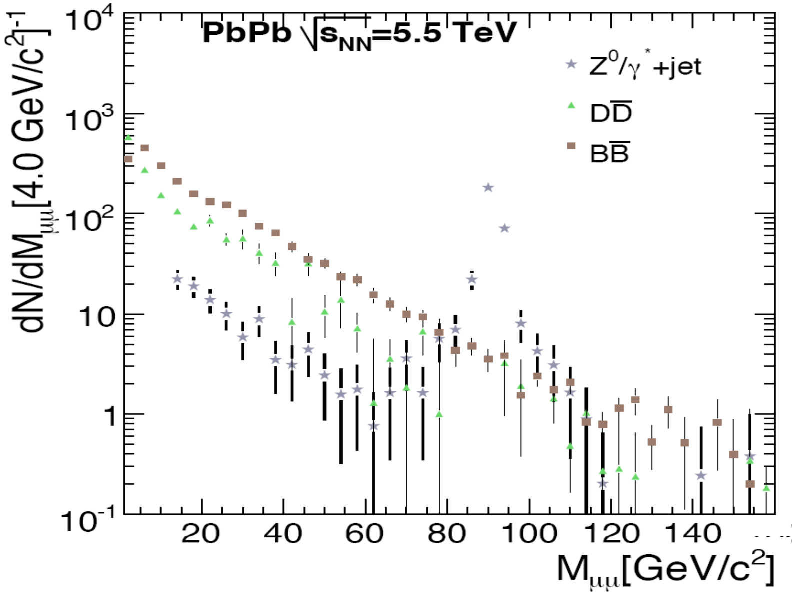
and particle reconstruction

Study details of the energy loss mechanism

- **Jet fragmentation functions**
- **Jet shapes**
- **Tagged heavy quark jets**
- **Inclusive p_T spectra**
- **Back-to-back particle correlations**

Balancing γ or Z^0 vs Jets





Jet quenching with calibrated parton energy

- Use photon to determine initial parton energy
- Use jet to determine away-side parton direction
- Use tracked hadrons on away-side to measure in-medium fragmentation function

- Z^0/Photon-tag avoids surface bias (c.f. two-hadron correlations)
- Direct test of energy loss mechanism using well controlled process

Summary

- **The CMS Detector features**
  - Precision tracker (full silicon, analog readout)
  - a state-of-the-art Calorimetry
  - large acceptance muon stations
  - a powerful DAQ & HLT system

- **This provides excellent capabilities to perform high precision studies of the dense QCD matter produced in very high energy heavy-ion collisions, through**
  - Global observables linked to hydrodynamic properties and soft physics
  - hard probes such as high-E_T (fully reconstructed) jets and heavy quarkonia

- **Known limitations:**
  - Manpower!
  - If interested please apply :-)

Backup Slides

Trigger in Pb+Pb vs pp

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Level 1 Trigger

- Uses custom hardware
- Muon chamber + calorimeter information
- Decision after ~ 3μsec

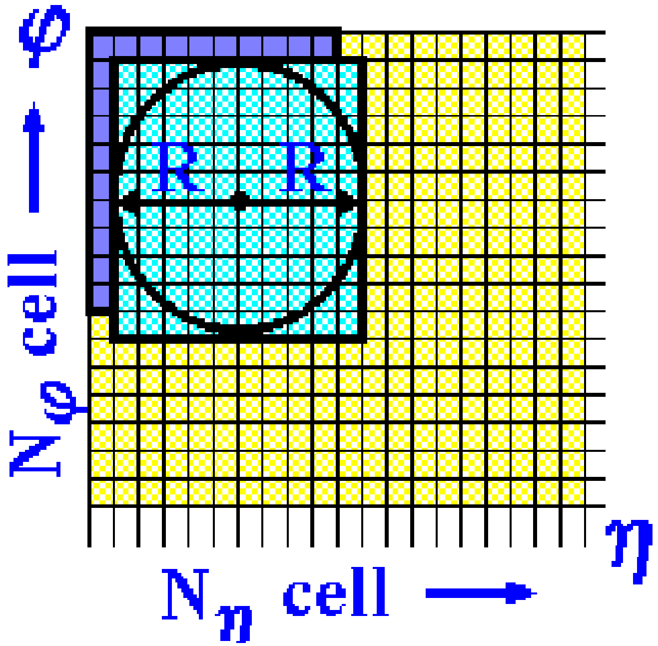
Level-1	Pb+Pb	p+p
Collision rate	3kHz (8kHz peak)	1GHz
Event rate	3kHz (8kHz peak)	40MHz
Output bandwidth	100 GByte/sec	100 GByte/sec
Rejection	none	99.7%

High Level Trigger ↔ **Main "hardware" task for CMS heavy ion running**

- ~1500 Linux servers (~12k CPU cores)
- Full event information available
- Runs "offline" algorithms

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%

Background Subtraction Algorithm



Event-by-event background subtraction:

- **Calculate $\langle E_T^{Tower}(\eta)\rangle$ and $D^{Tower}(\eta)$ for each η ring**
- **Recalculate all E_T^{Tower} tower energies:**

  $E_T^{Tower} = E_T^{Tower} - E_t^{pile\text{-}up}$

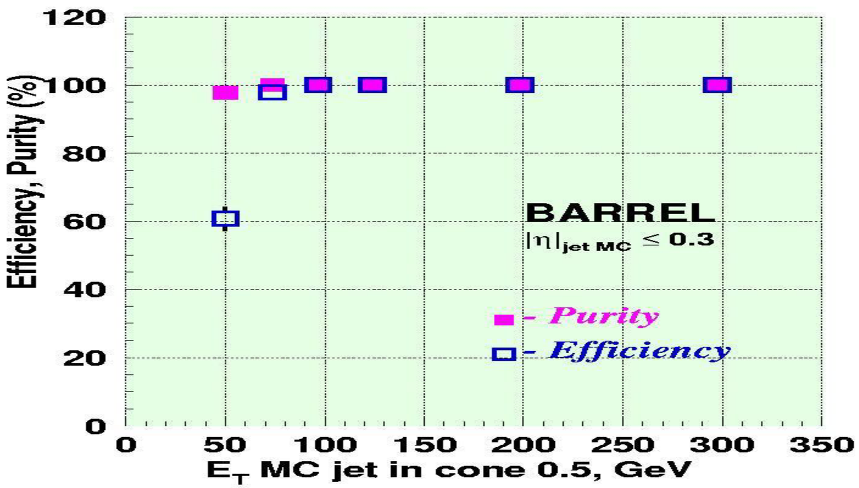
  $E_t^{pile\text{-}up} = \langle E_T^{Tower}(\eta)\rangle + D^{Tower}(\eta)$

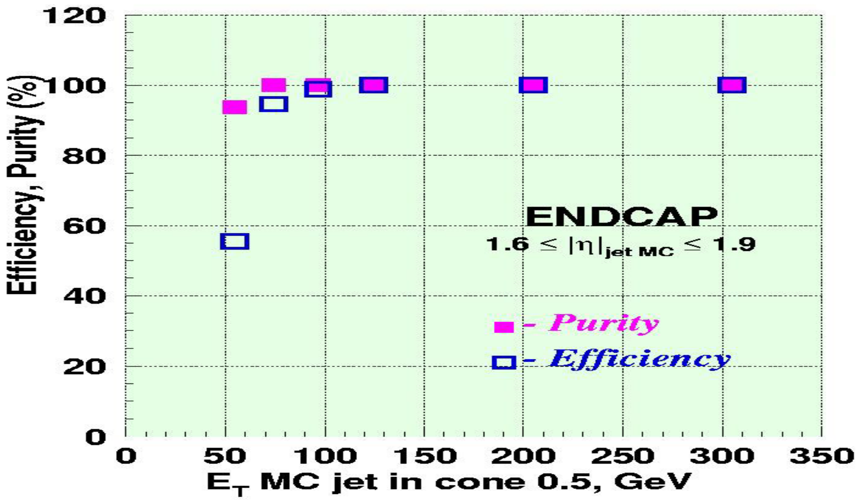
- **Negative tower energies are replaced by zero**

- **Find Jets with $E_T^{jet} > E_t^{cut}$ using standard iterative cone algorithm using new tower energies**
- **Recalculate pile-up energy with towers outside of the jet cone**
- **Recalculate tower energy with new pile up energy**
- **Final jets are found with the same iterative cone algorithm $E_T^{Jet} = E_T^{cone} - E_t^{pile\text{-}up\ new}$**

Efficiency, Purity vs. Jet Energy

Reconstructing 50-300 GeV Jets in Pb-Pb background

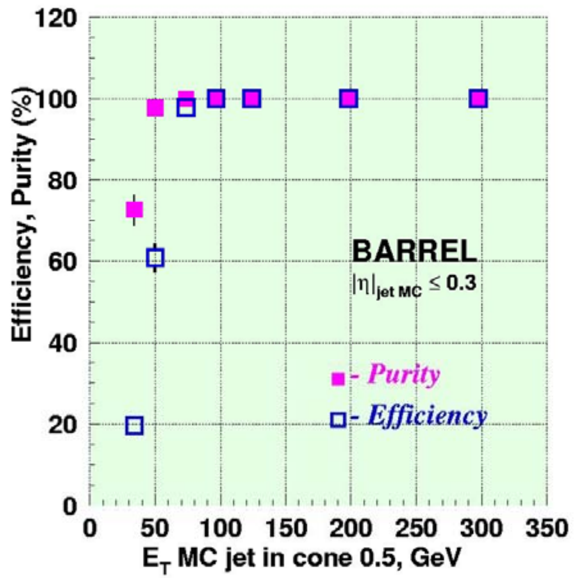




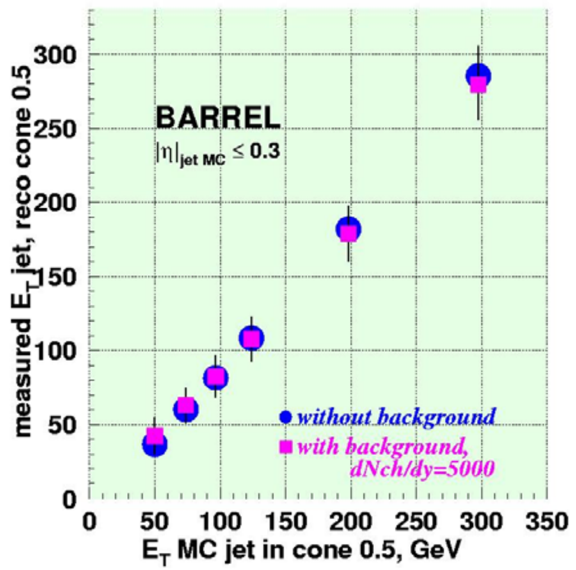
- **EFFICIENCY**
  - **Number of events with true reco. Jets/Number of all generated events**
- **PURITY**
  - **Number of events with true reco. QCD Jets/ Number of all reco. Jet events (true+fake).**
- **Threshold of jet reco. E_T >30 GeV.**
- **Above 75(100) GeV we achieve**
  - **100% efficiency and purity in the barrel (endcap)**
  - **Unbiased jet measurement**

Jet reconstruction performance

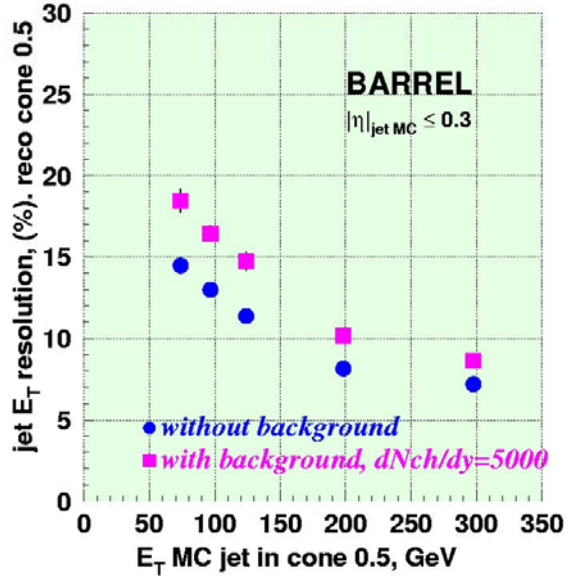
Efficiency and purity



E_T: Reconstructed vs. MC



E_T: resolution



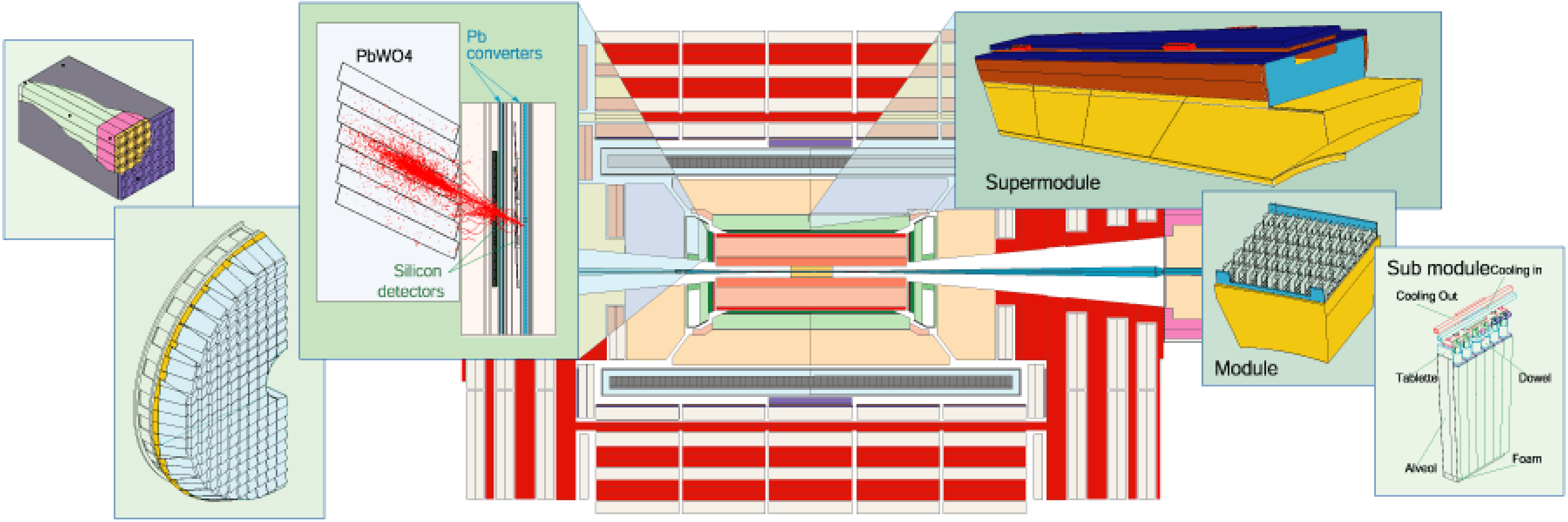
I. Vardanyan *et al.*, CMS note 2006/050

Electromagnetic Calorimeter

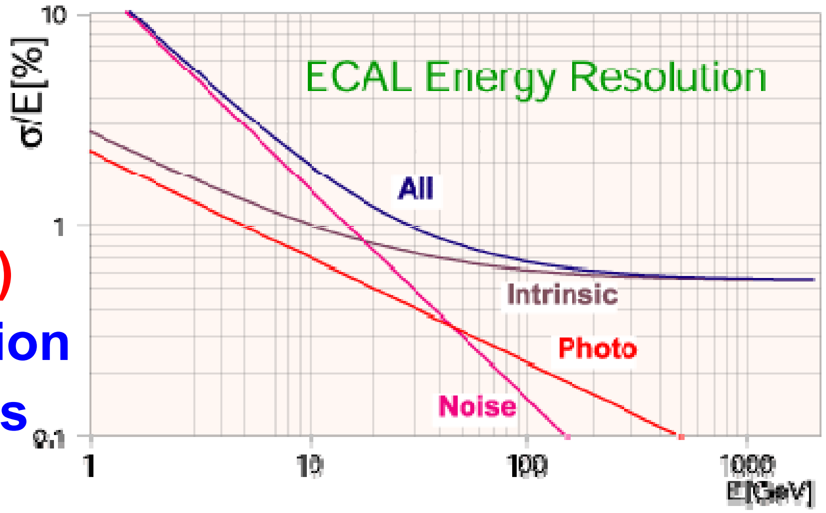
EECAL

|η|< 3 (1.5 barrel)

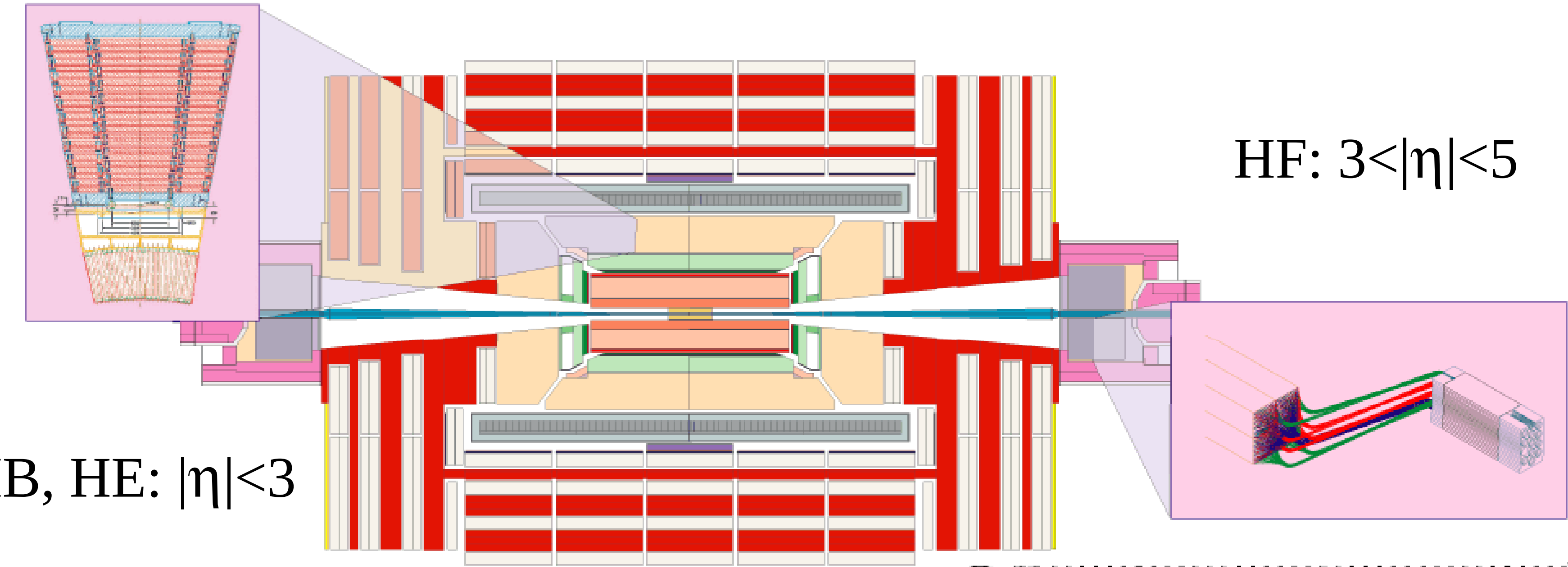
BECAL



- **76000 PbWO4 crystals**
  - **Granularity in Δη x Δϕ :**
  - **0.0174 x 0.0174 (Barrel) and**
  - **0.0174 x 0.0174 to 0.05x0.05 (Endcap)**
- **Endcap with preshower for γ/p0 separation**
- **Details in CMS Technical Design Reports**



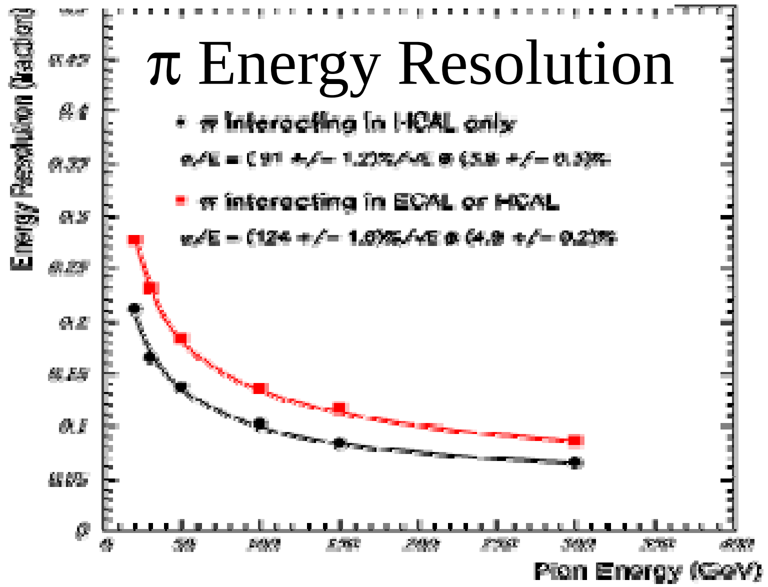
HCAL



HF: 3<|η|<5

HB, HE: |η|<3

- **Barrel (HB) and Endcap (HE): Cu/Scintillator**
- **Forward (HF): Fe/Cerenkov(fiber)**
- **High granularity: $\Delta\eta \times \Delta\phi$**
  - **0.087 x 0.087 (barrel)**
  - **0.087 - 0.35 x 0.087 - 0.175 (endcap)**
  - **0.152 - 0.3 x 0.175 (HF)**
- **5.15 interaction lengths at η=0**
- **Dynamic range: 5 MeV-3 TeV**

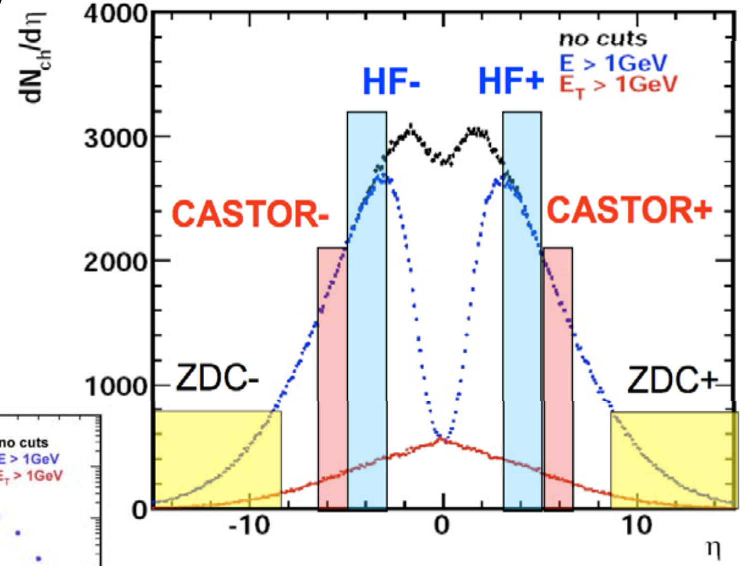


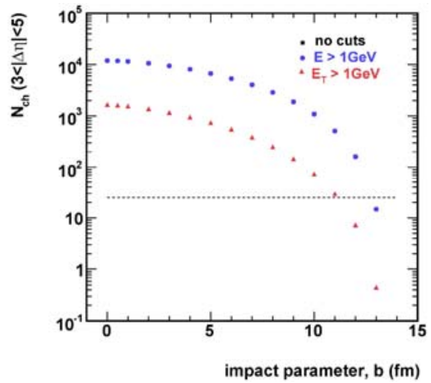
Granularity

Rapidity coverage	$0 < \|\eta\| < 1.5$		$1.5 < \|\eta\| < 3.0$		$3.0 < \|\eta\| < 5.2$
Subdetector	HCal (HB)	ECal (EB)	HCal(HE)	ECal (EE)	HF
$\sigma/E = a/\sqrt{E} \bigoplus b$ a b	 1.16 0.05	 0.027 0.0055	 0.91 0.05	 0.057 0.0055	 0.77 0.05
granularity $\Delta\eta$ x $\Delta\phi$	0,087 x 0.087	0.0174 x 0.0174	0.087 x 0.087 (except highest η)	changes from 0.0174 x 0.0174 to 0.05x0.05	0.175 x 0.175

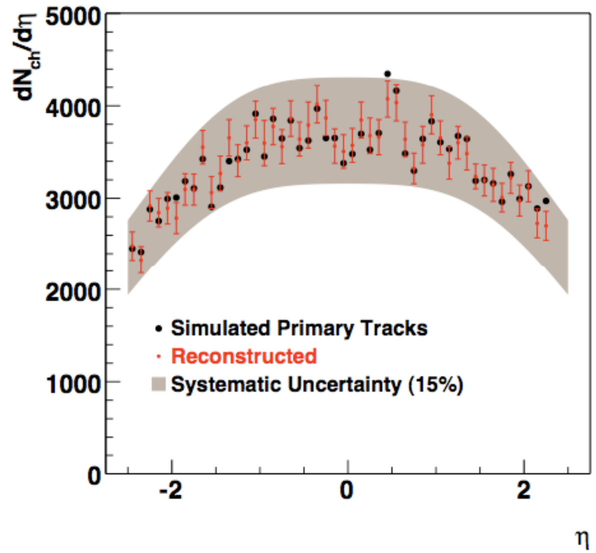
Trigger and charged particle multiplicity

- Minimum bias trigger
  - **Symmetric number of hits in the forwards calorimeters (3<|η|<5)**
  - High-efficiency **up to very peripheral Pb-Pb collisions**
- Centrality triggers
  - **From correlating barrel (ECAL+HCAL) and forward (ZDC) energies**
- Charged particle multiplicity
  - **Event-by-event, using hits in the innermost pixel layer with ~2% accuracy and systematics below 10%**

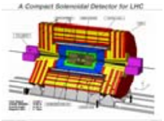




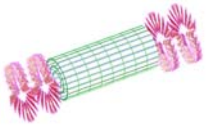
R. Hollis, A. Iordanova

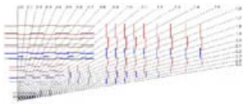


C. Smith, note AN-2003/15



B





QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.