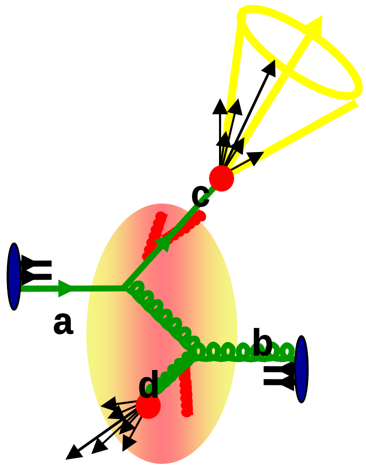
# Heavy-Ion Physics with the CMS Experiment at the Large Hadron Collider





**Bolek Wyslouch**
**Massachusetts Institute of Technology**
**for the CMS Collaboration**

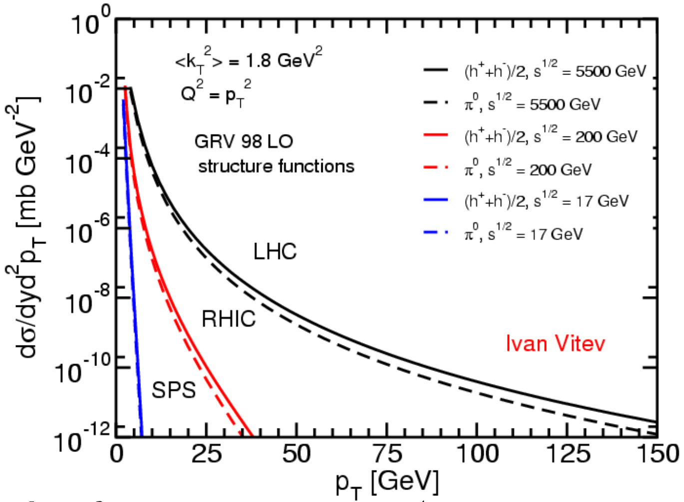

**PANIC05 LHC Satellite meeting**

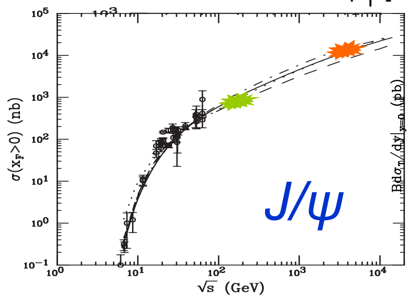
CMS HI groups: Athens, Basel, Budapest, CERN, Demokritos, Dubna, Ioannina, Kiev, Kent State, Krakow, Los Alamos, Lyon, MIT, Moscow, Mumbai, N. Zealand, Protvino, PSI, Rice, Sofia, Strasbourg, U Kansas, Tbilisi, UC Davis, UC Riverside, UI Chicago, U. Iowa, Yerevan, Warsaw, Zagreb

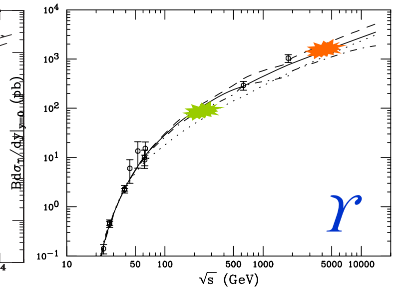
# Summary of physics opportunities

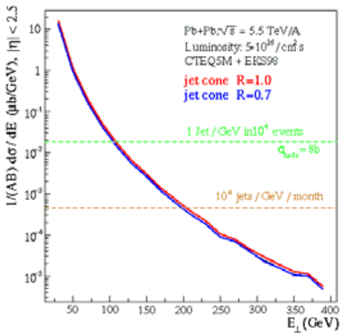
- **LHC will accelerate and collide heavy ions at energies far exceeding the range of existing accelerators**
  - **The increase of beam energy will result in:**
    - Extended kinematic reach for pp, pA, AA
    - New properties of initial state, saturation at mid-rapidity
    - A hotter and longer lived partonic phase
    - Increased cross sections of hard probes
    - New experimentally accessible hard probes
- **New energy regime will open a new window on hot and dense matter physics: another large energy jump!**

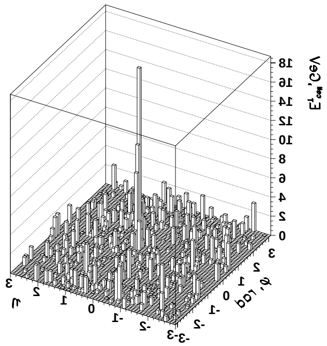
| | AGS | SPS | RHIC | LHC (Pb+Pb) |
|---|---|---|---|---|
| $\sqrt{s_{NN}}$[GeV] | 5 | 20 | 200 | 5500 |
| E increase | | x4 | x10 | x28 |
| y range | ±1.6 | ±3.0 | ±5.3 | ±8.6 |



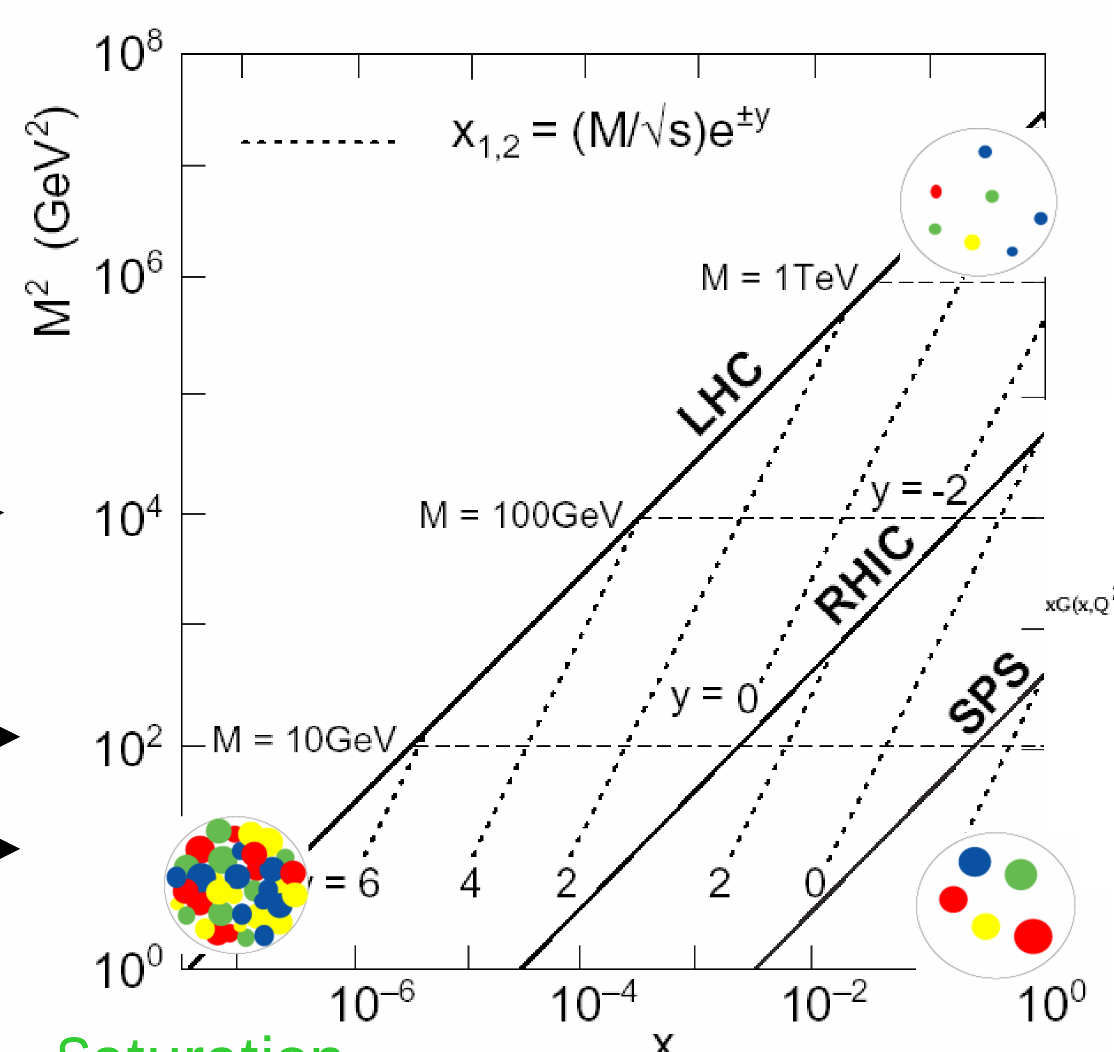
- **Medium modification at high $p_T$**
  - **Copious production of high $p_T$ particles**
  - **Large jet cross section,**
- **Different "melting" for members of $\Upsilon$ family depending on binding energy**
  - **Large cross section for $J/\psi$ and $\Upsilon$ family production**
- **Correlations, scattering in medium**
  - **jets directly identifiable**

# Kinematics at the LHC

$Z^0$ →

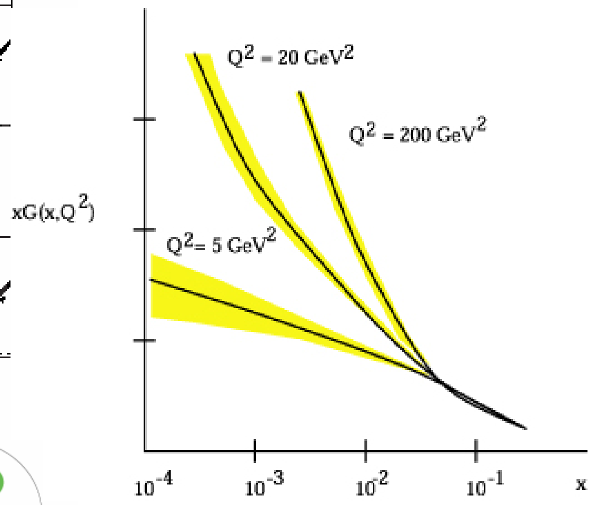
$\Upsilon$ →

$J/\psi$ →




Saturation

Access to widest range of $Q^2$ and x



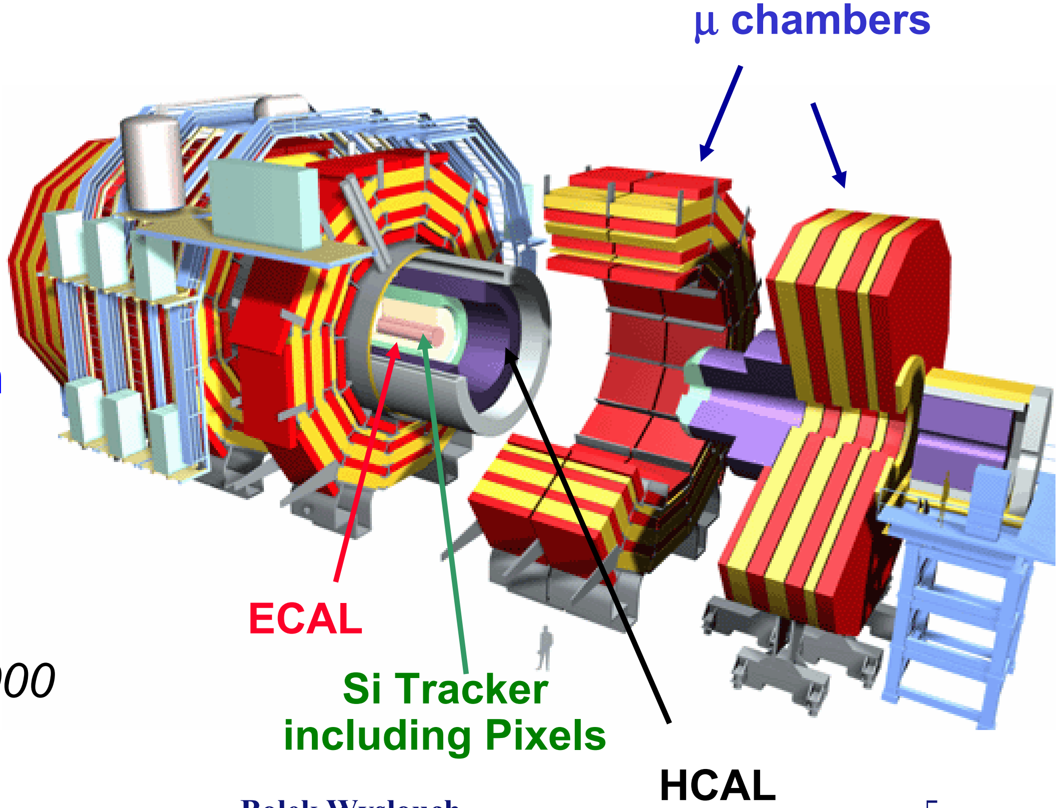

Gluon density has to saturate at low x

# CMS as a Detector for Heavy-Ion Physics

- **Fine Grained High Resolution Calorimeter**
  - Hermetic coverage up to $|\eta|<5$
  - ($|\eta|<7$ proposed using CASTOR)
  - Zero Degree Calorimeter (proposed)
- **Tracking $\mu$ from $Z^0$, $J/\psi$, $\Upsilon$**
  - Wide rapidity range $|\eta|<2.4$
  - $\sigma_m$ ~50 MeV at $\Upsilon$
- **Silicon Tracker**
  - Good efficiency and low fake rate for $p_T>1$ GeV
  - Pixel occupancy at 1-2% level even in Pb+Pb
  - Excellent momentum resolution $\Delta p/p$~2% for $p_T<70$ GeV and higher

*Fully functional at highest expected multiplicities*
*Detailed studies at ~$dN_{ch}/d\eta$ ~3000-5000 and cross-checks at 7000-8000*

- **DAQ and Trigger**
  - High rate capability for A+A, p+A, p+p
  - High Level Trigger capable of full reconstruction of most HI events in real time

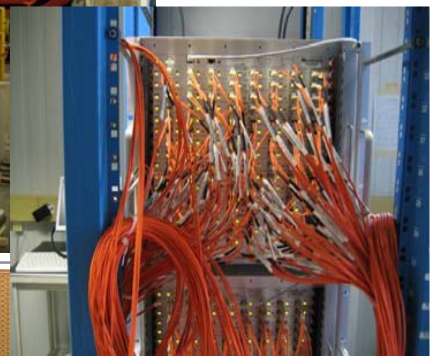


# CMS under construction

Muon Absorber

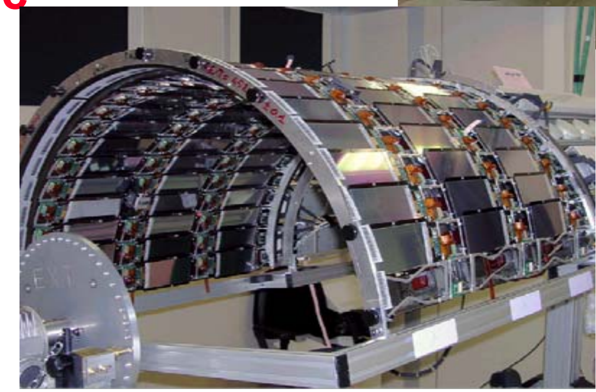
Swiveling coil

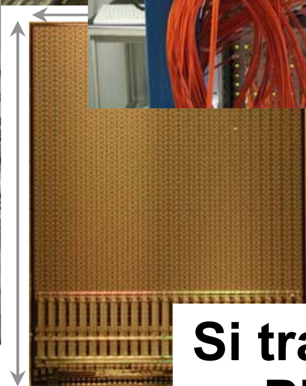

Hadron Calorimeter



DAQ

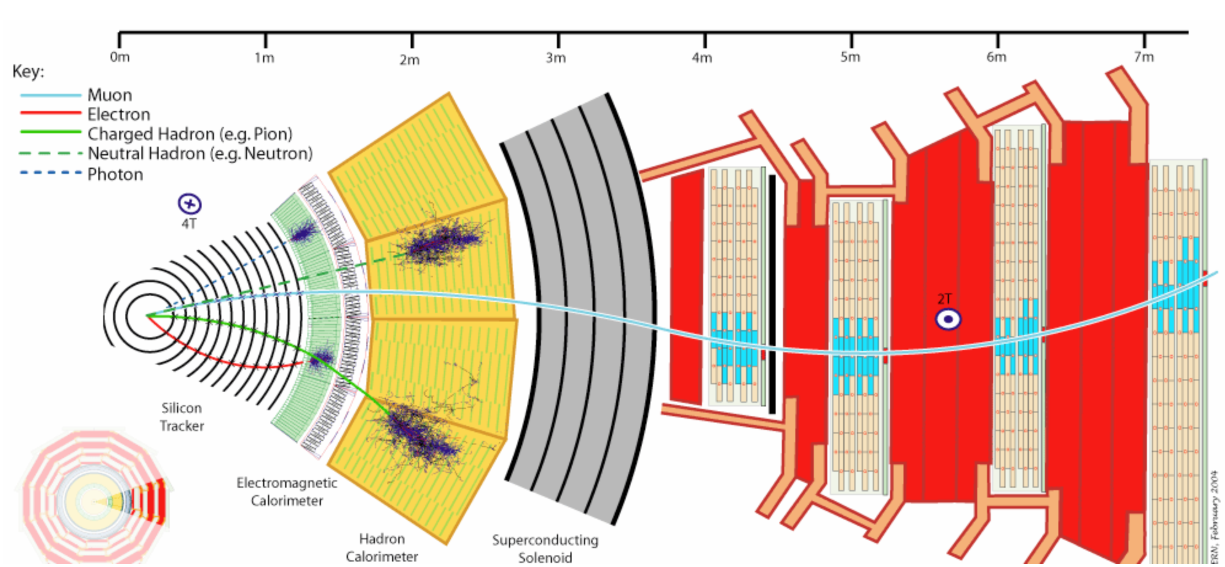
Electromagnetic Calorimeter

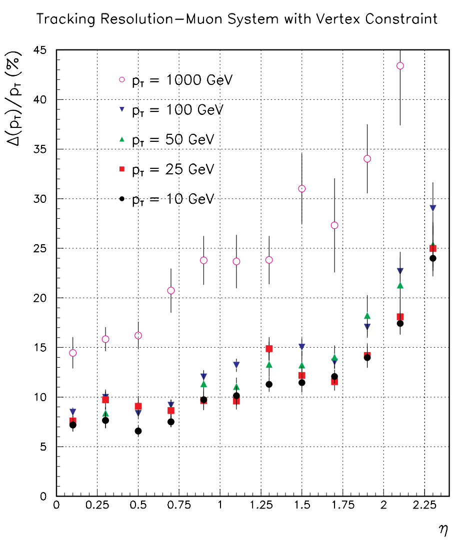


Si tracker & Pixels

# Measuring Muons



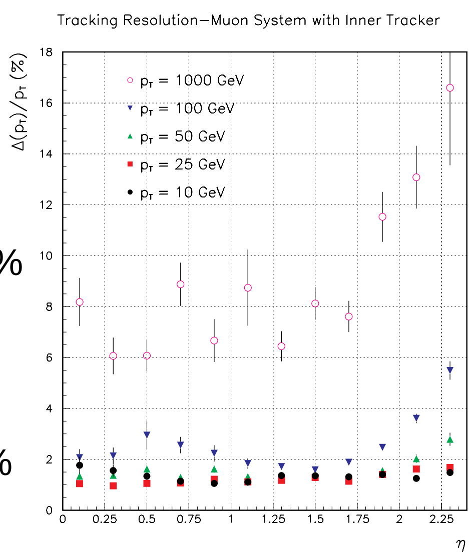





30%

20%

10%



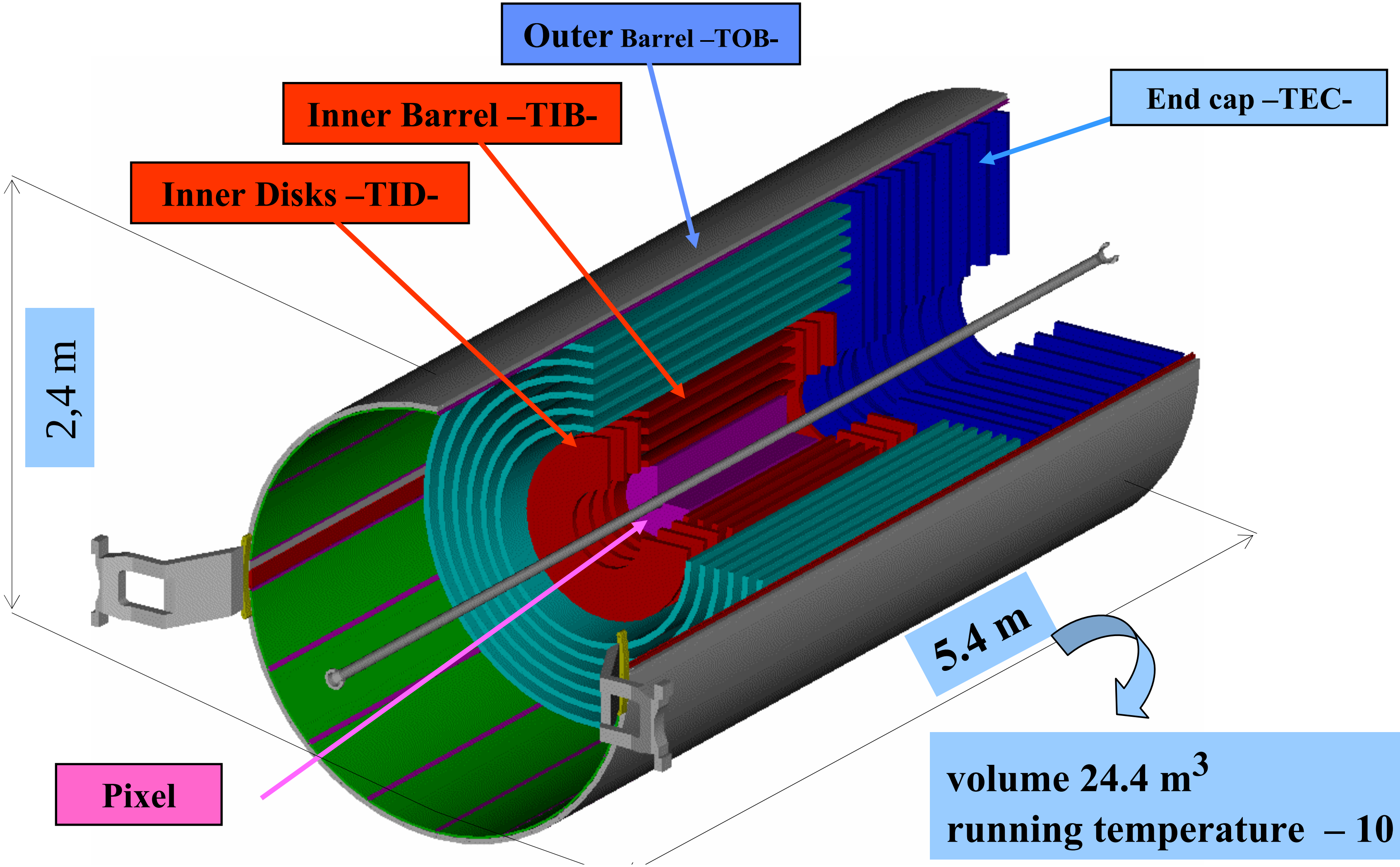

10%

2%

Resolution Standalone

Resolution with tracker

## The CMS all Silicon Tracker




**volume 24.4 m$^3$**
**running temperature – 10 $^0$C**

***~ 60 Million electronics channels***

# Tracker Layout

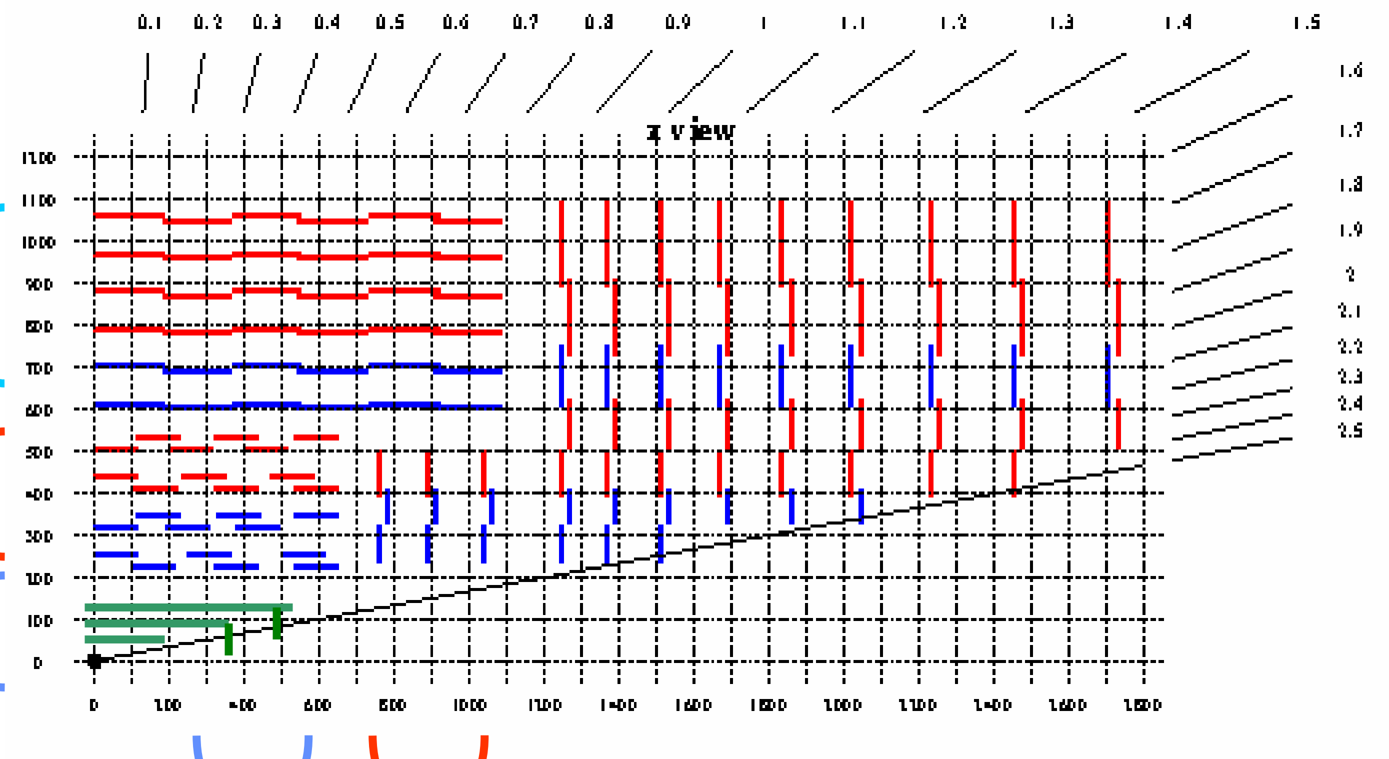
— 1 Single detector

— 2 detectors back to back

6 layers Outer Barrel

4 layers Inner Barrel

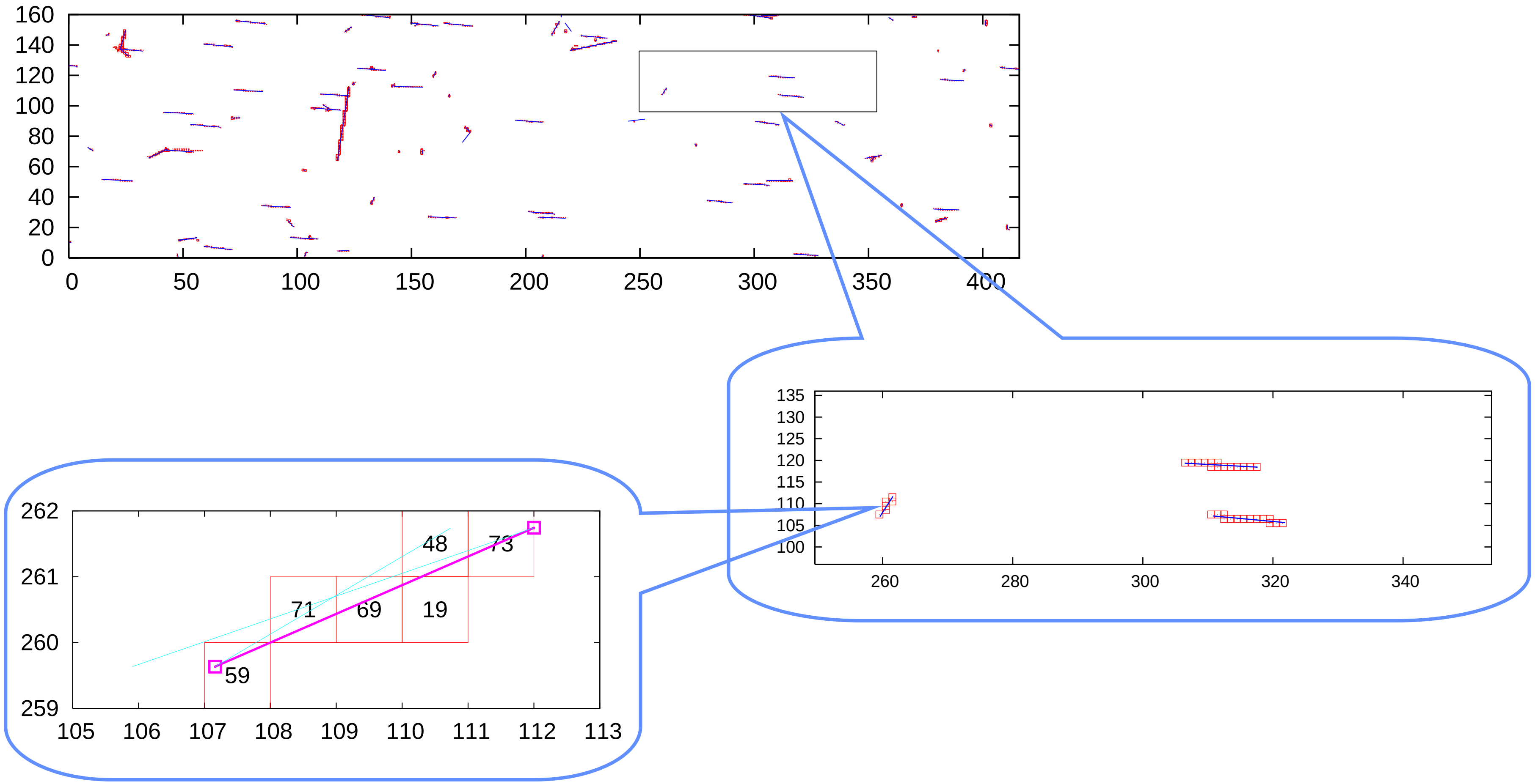
3 layers Pixel Barrel




2 Pixel Disks 3 Disks 9 Disks in the End Cap

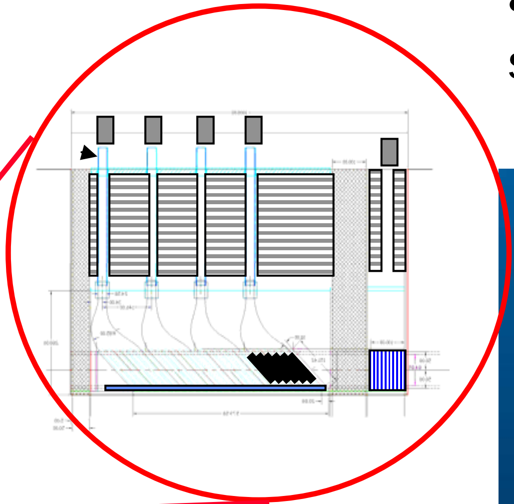
# CMS tracker is a powerful tool

- Multiple layers of Si pixel and Si strip detectors will give us plenty of information about charged tracks

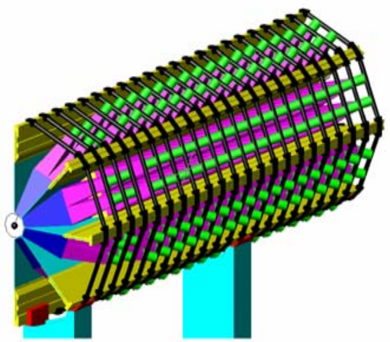


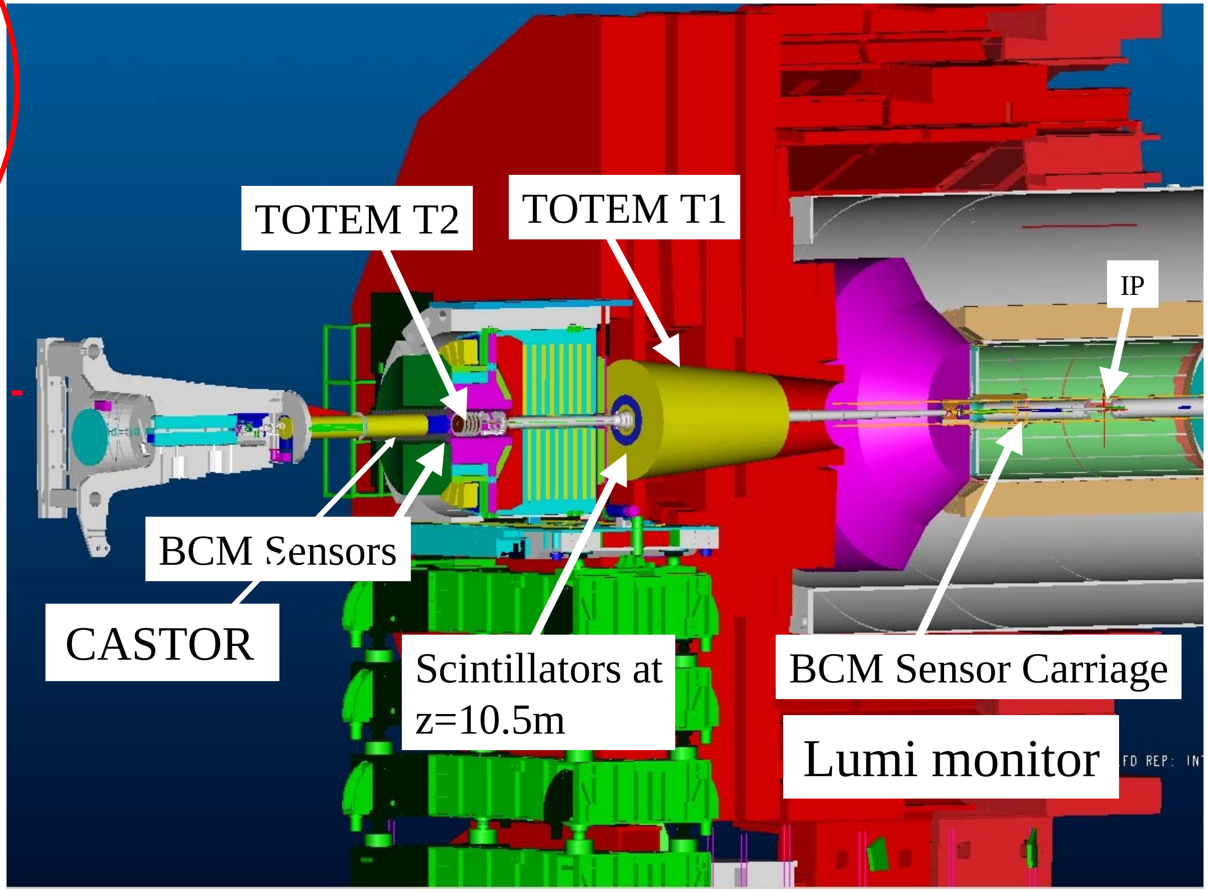
# Detectors near beamline: forward physics in p+A and A+A

- Hermetic coverage up to |η|<7
- Zero degree neutral energy
- Physics: Centrality, Low-x, Limiting fragmentation, strangelets, DCC

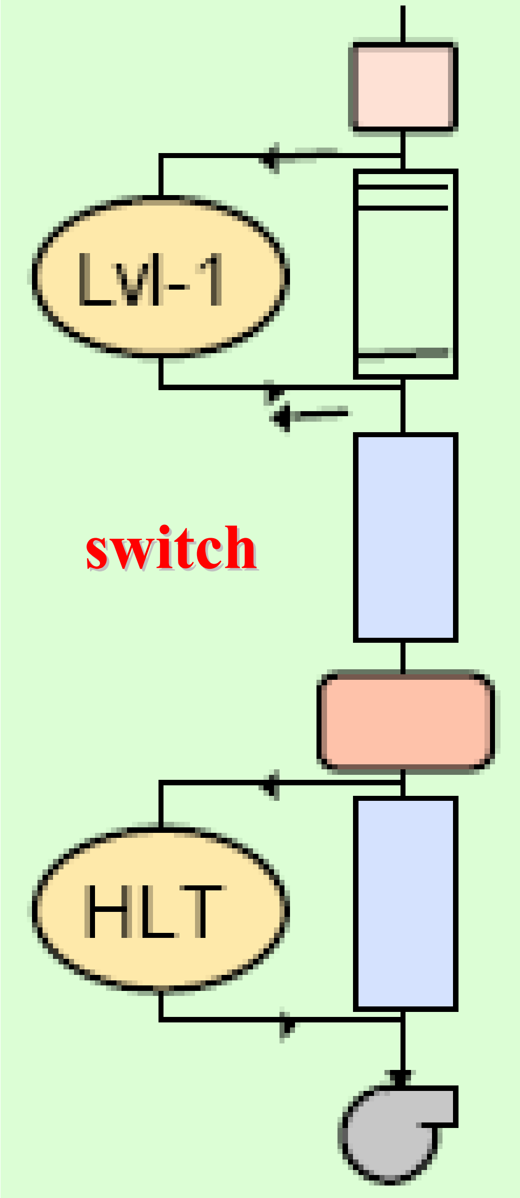


ZDC @ 140 m





# Data Acquisition and Trigger




**Level 1 hardware trigger**

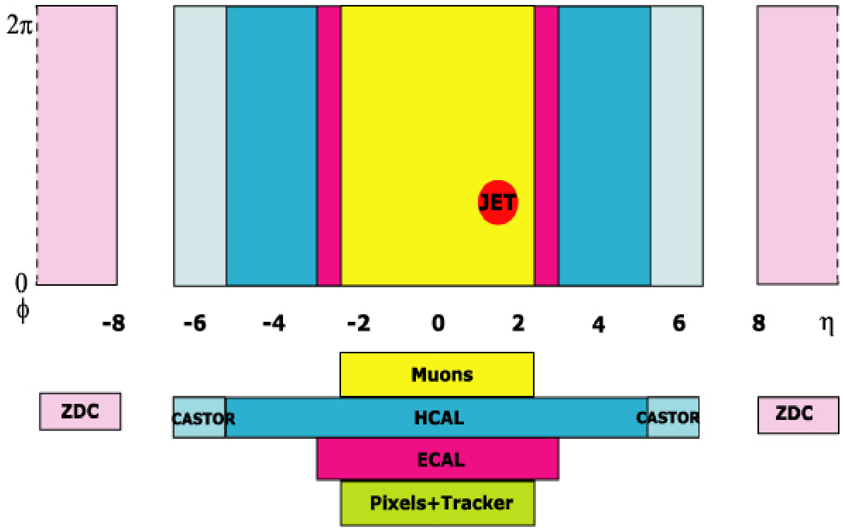
- **Muon track segments**
- **Calorimetric towers**
- **No tracker data**
- **Output rate (Pb+Pb):** *1-2 kHz comparable to collision rate*

**High level trigger**

- **Full event information available**
- **Every event accepted by L1 sent to an online farm of 2000 PCs**
- **Output rate (Pb+Pb):** *~ 40 Hz*
- *Trigger algorithm same or similar to offline reconstruction*

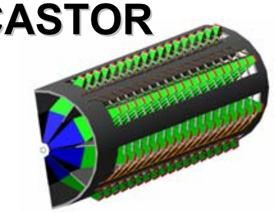
Every event must pass the whole chain
Selectivity depends on available CPU

# CMS advantages compared to other HI experiments




CASTOR

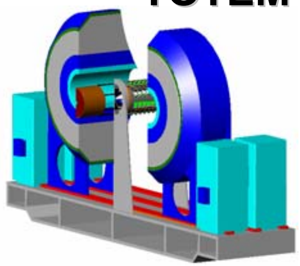
($5.32 \leq \eta \leq 6.86$)



($z = \pm 140$ m)

ZDC

TOTEM

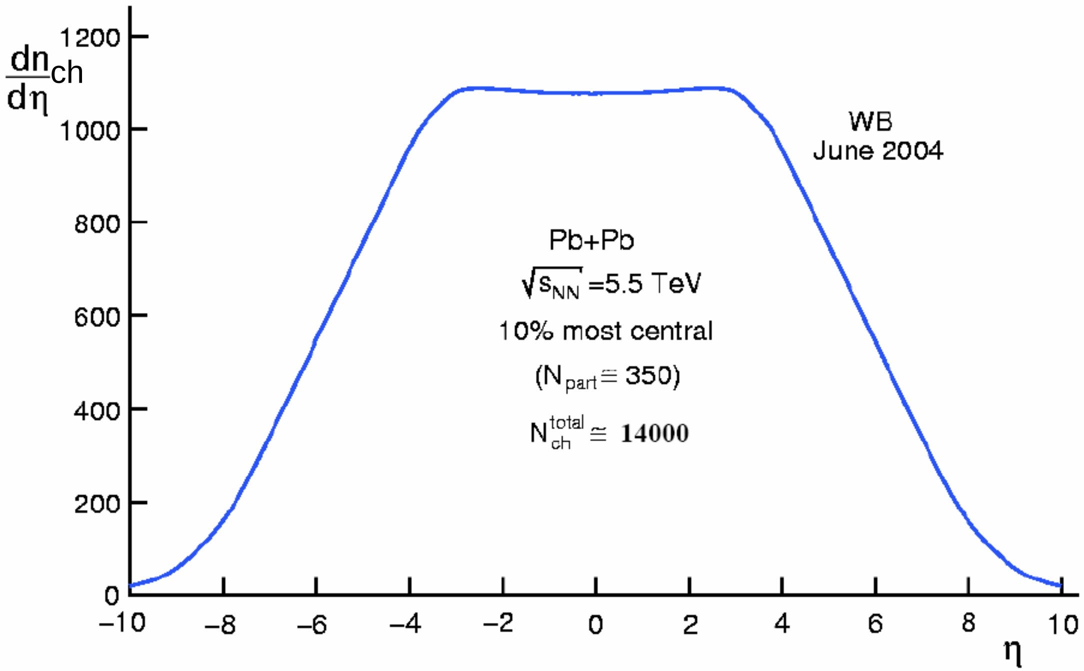


- **Hermeticity, Resolution, Granularity**
  - Central region $\Delta\eta \sim 5$ equipped with tracker, electromagnetic and hadronic calorimeters and muon detector
- **Forward coverage**
  - Base-line calorimeters extend the coverage to $\Delta\eta \sim 10$
  - Proposed additional calorimeter CASTOR extends the coverage to $\Delta\eta \sim 14$
- **High data taking speed and trigger versatility**
  - Unique two-level trigger system
  - Potential ability of "inspecting" every fully built heavy ion event on the High Level trigger farm processors

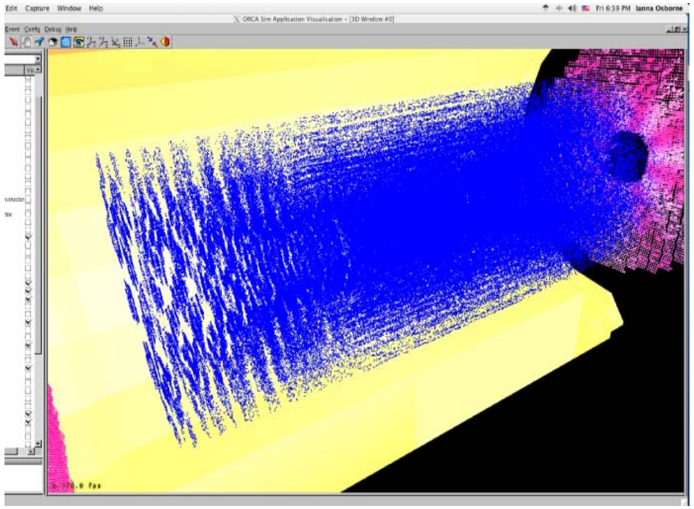
# Expectation based on RHIC results: Charged particle multiplicity

**Wit Busza, (MIT) @ CMS Workshop, June 2004**

WHEN CMS STARTS TAKING DATA WITH HEAVY IONS
THIS IS THE FIRST RESULT THAT WE WILL OBTAIN




- Determines Physics Landscape
- Influences Detector Performance

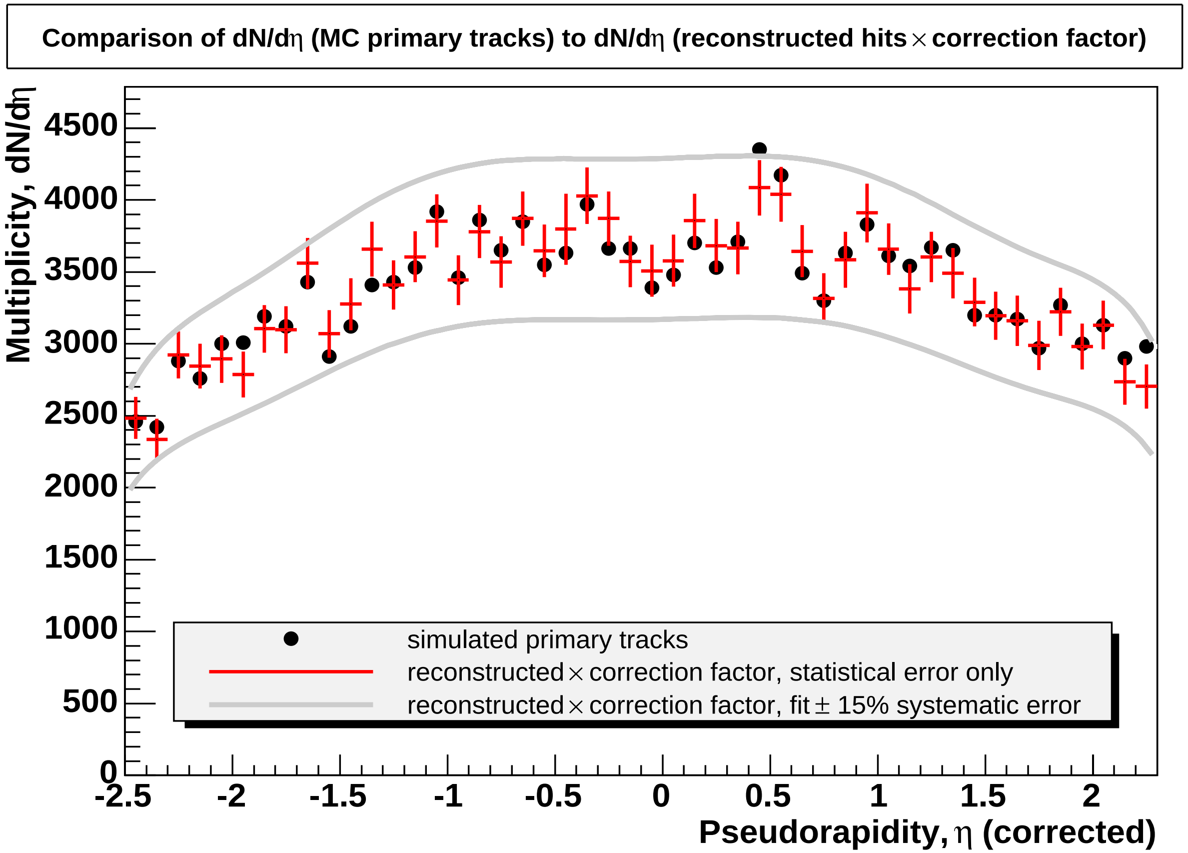


CMS Physics studies conducted for multiplicity densities up or larger than $dN_{ch}/d\eta=5000$

*Muon detection, tracking, jet finding*

# Global Measurements: $dN_{ch}/d\eta$ (single event)

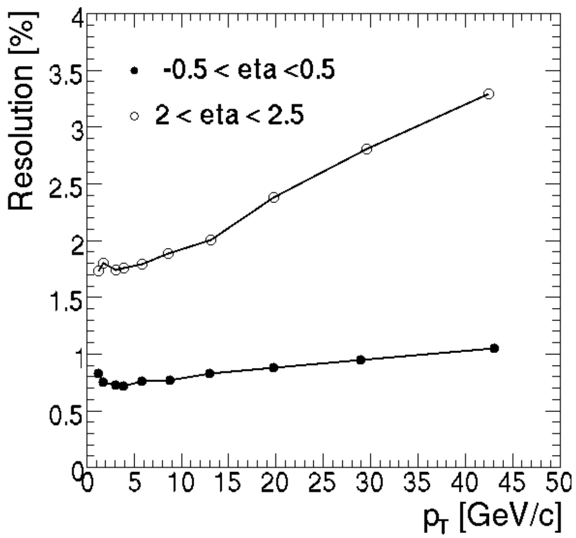
- **Use high granularity pixel detectors**
- **Use pulse height measurement in individual pixels to reduce background**
- **Very low $p_T$ reach, $p_T$>26 MeV (counting hits!)**



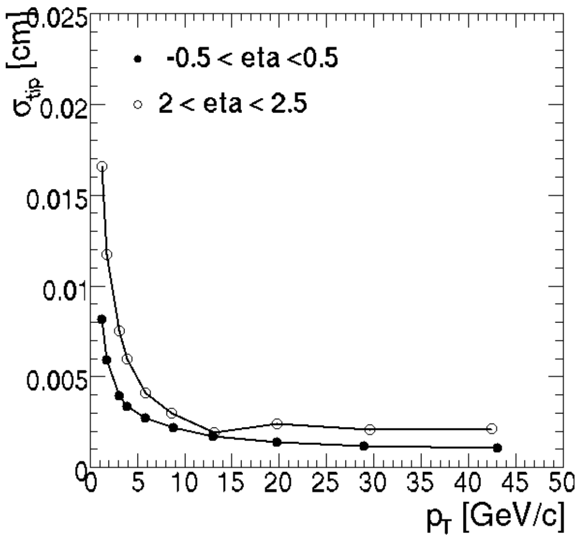
# Performance of the Track Reconstruction

- **Match Reconstructed tracks to MC input on a hit by hit basis.**

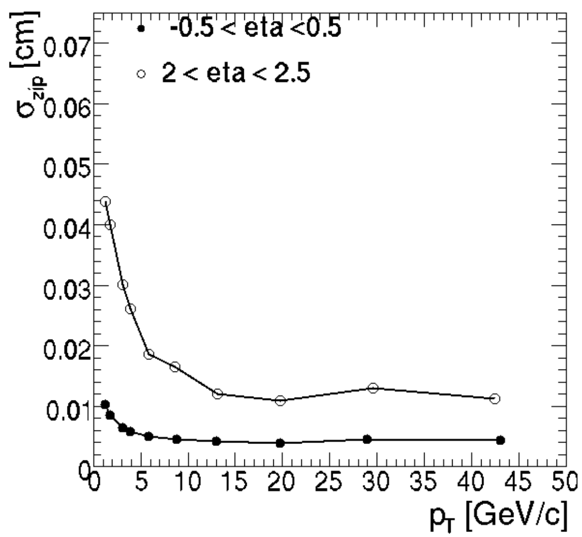
**Momentum Resolution**




**Transverse Impact Parameter Resolution**




**Longitudinal Impact Parameter Resolution**

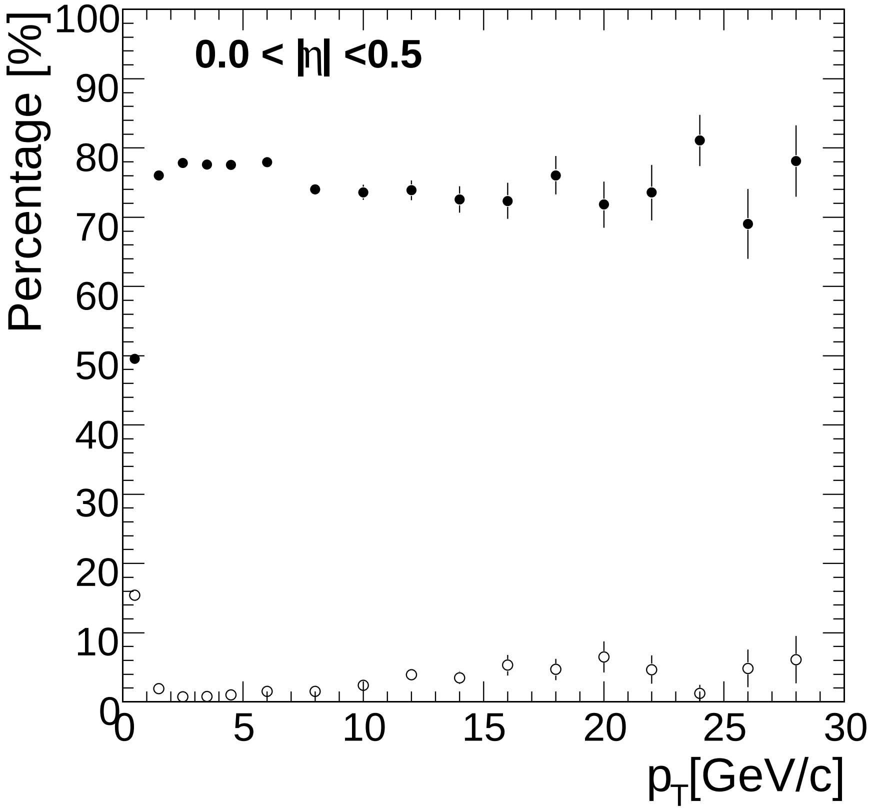



(Event sample: dn/dy ~3000 + one 100GeV Jet/Event)

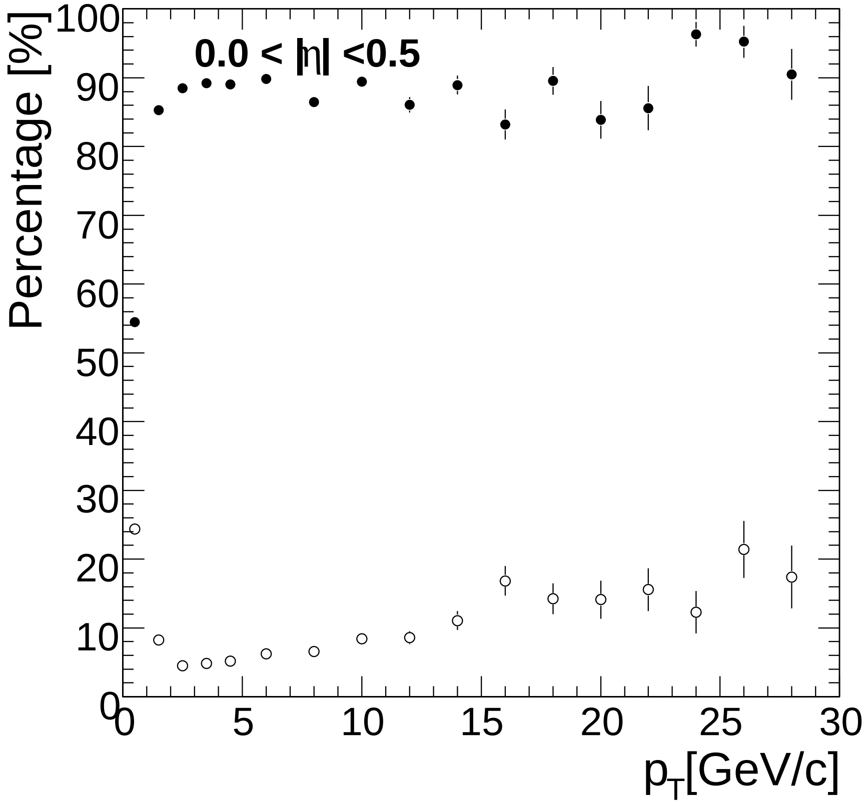
- **Excellent resolution event at the highest particle densities**

# Optimization of track reconstruction: efficiency and fake tracks

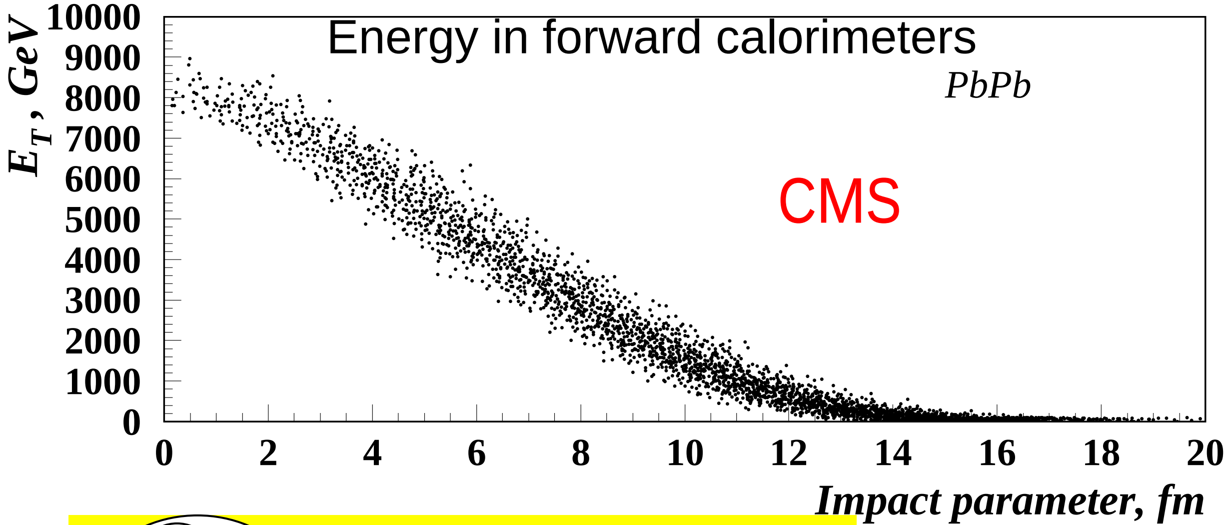
Low fake rate

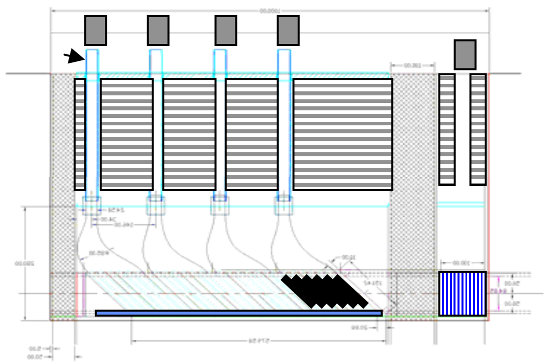


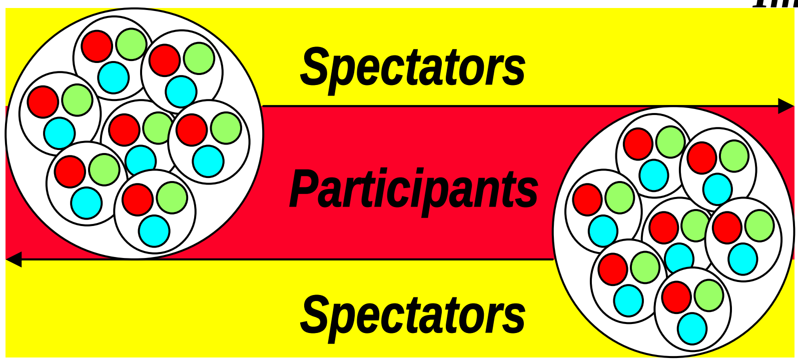

High efficiency

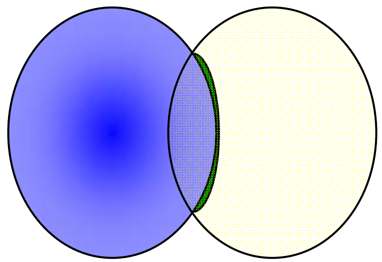


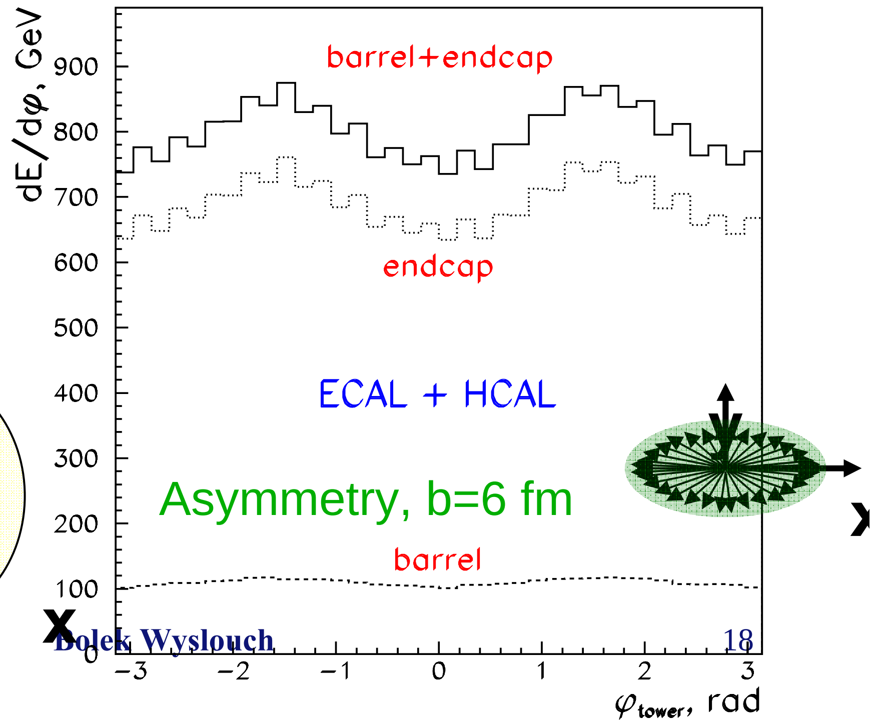
# Reaction Geometry in CMS: forward detectors



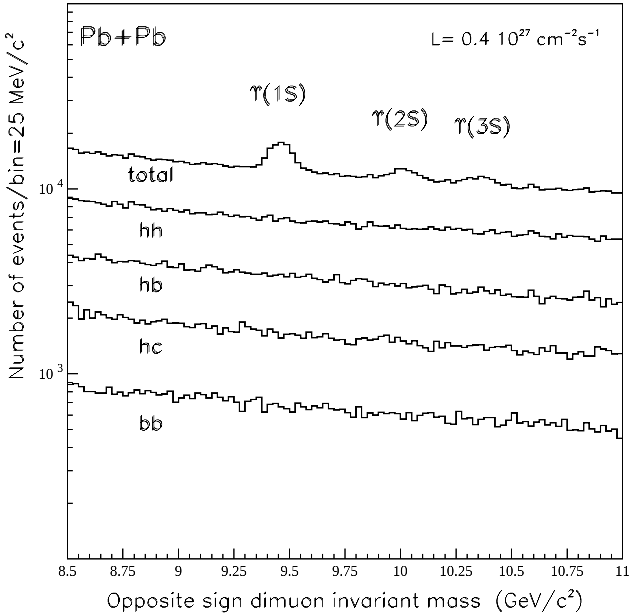



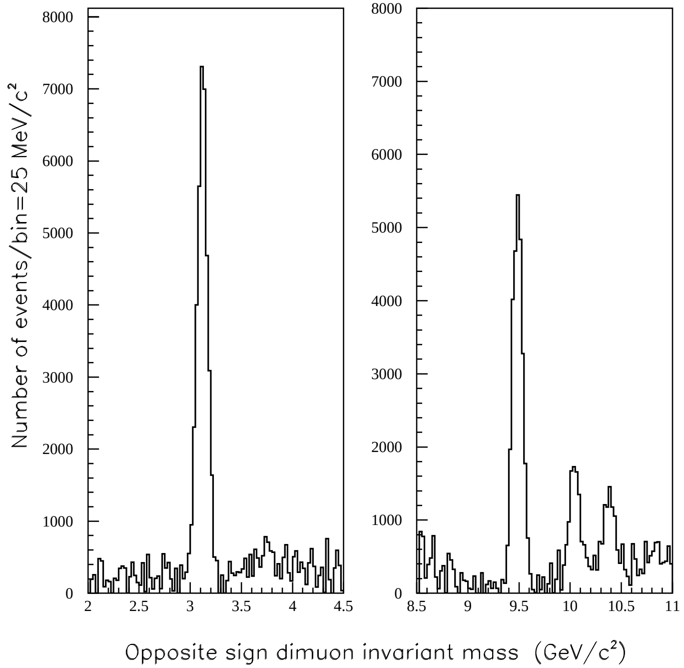


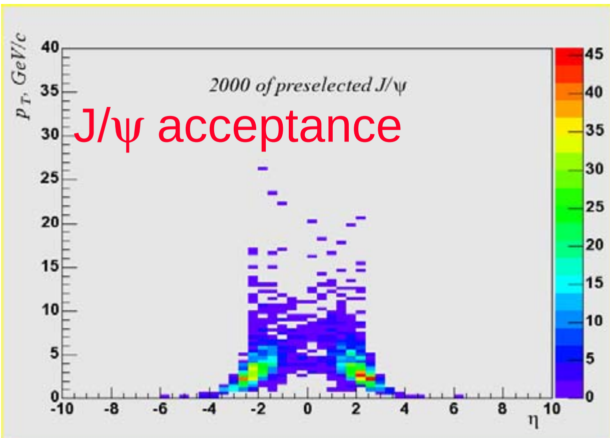
# Quarkonia in CMS

## Υ Family region $M_{\mu+\mu-}$




## J/ψ    Υ family




## $\sigma_{M\Upsilon}$=50 MeV

Expect ~24k J/ψ and ~ 18/5/3 k Υ,Υ',Υ''
After one month of Pb+Pb running at L=$10^{27}$cm$^{-2}$s$^{-1}$
with 50% efficiency

Coverage in central rapidity region

# Illustration Of Online Farm Power: Low $p_T$ J/ψ

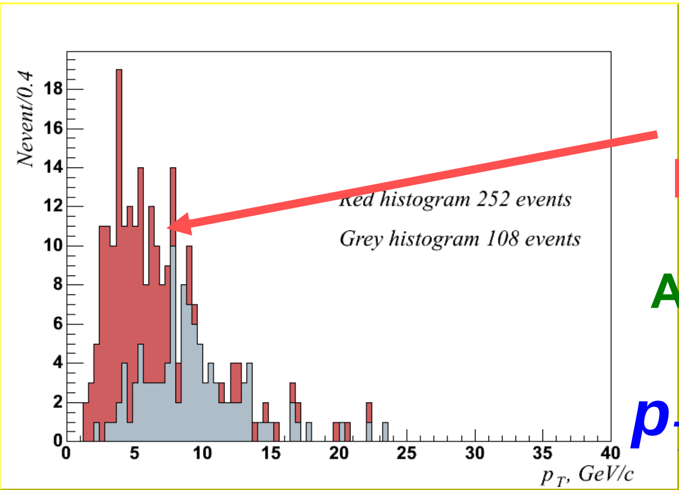
- **Only a small fraction of produced J/ψ are seen in LHC detectors**
  - **E.g. CMS J/ψ→μμ acceptance 0.1-0.2%, ~O($10^4$) per LHC run**
- **Detection of low $p_T$ J/ψ requires efficient selection of low momentum, forward going muons. Simple hardware L1 dimuon trigger is not sufficient**

## Without online farm (HLT)

| | | |
|---|---|---|
| L1 trigger | Two μ | 60 Hz |
| L2 trigger | None | 60 Hz |
| L3 trigger | None | 60 Hz |
| J/ψ $p_T$ | | >3 GeV/c |

## With online farm (HLT)

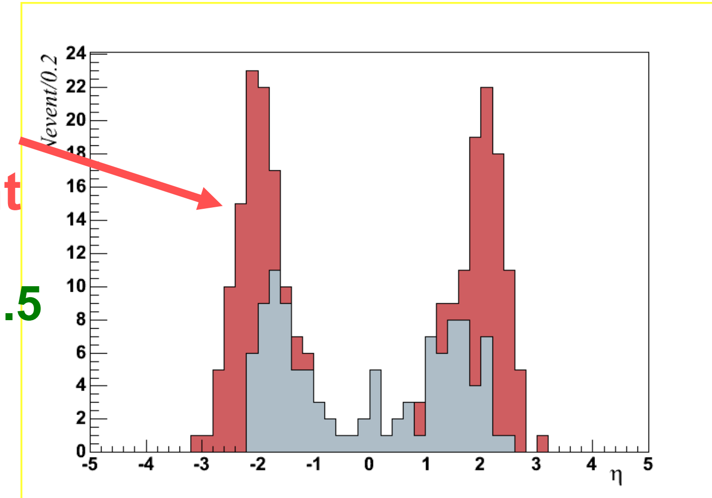
| | | |
|---|---|---|
| L1 trigger | Single μ | ~2 kHz |
| L2 trigger | Re-fit μ | 70 Hz |
| L3 trigger | Match tracker | <40 Hz |
| J/ψ $p_T$ | | >1 GeV/c |




**Online farm Improvement**

**Acceptance x2.5**

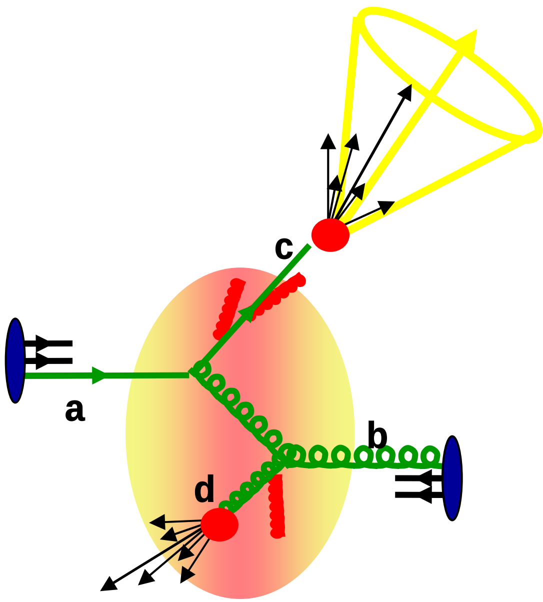
$p_T$




$\eta$

# Jets in heavy ion collisions, role of LHC

- Production of high $p_T$ partons involves hard, perturbative scale $Q \gg \Lambda_{QCD}$.
- $Q$ is much larger than any momentum scale characterizing the medium (production unaffected by the medium)
- Initial "luminosity" modified by nuclear effects
- Parton shower development affected by the medium
- At LHC in A+A collisions:
  - wider $p_T$ range for suppression studies
  - partons will appear as jets for $E_T$> 20-30 GeV, their structure will likely be modified compared to jets produced in p+p



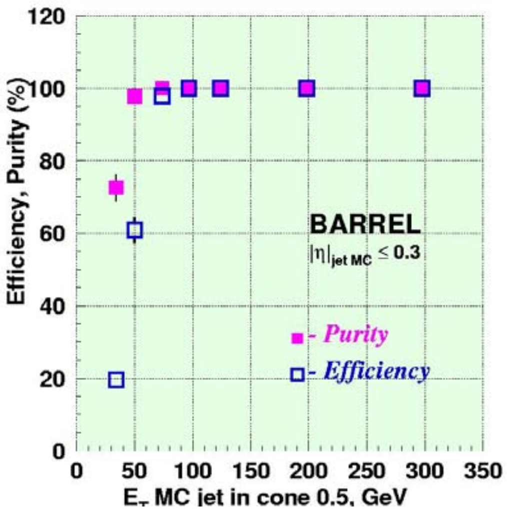
# Jets as probes: the observables

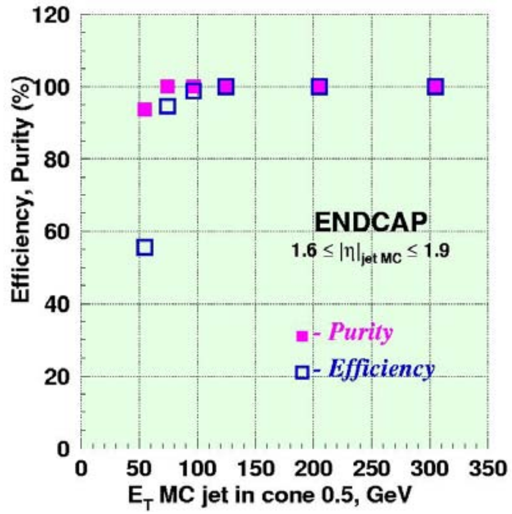
*Note: comparison to p+p and p+A is essential*

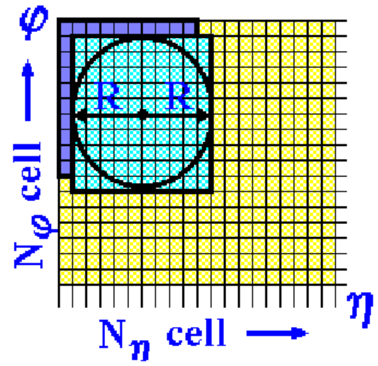
- High $p_T$ particles and particle correlations
- Jet rates: single jets, multi-jets
- Jet fragmentation and shape
  - distance *R* to leading particle
  - $p_T$ of particles for $R < R_{max}$
  - Multiplicity of particles for $R < R_{max}$
  - Heating: $k_T = p \times \sin(\theta(\text{particle, jet axis}))$
  - Forward backward correlation: $\Delta\phi$(particle, jet axis)
  - Fragmentation function: $F(z)=1/N_j \times dN_{ch}/dz$ $z=p_t/p_{jet}$
- Rates and shape aided by correlations Jets+$\gamma$, Jets+Z
- Jets originating from heavy quarks (b, c)

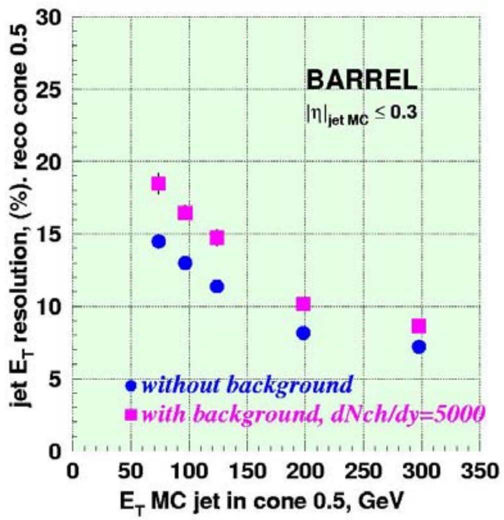
**Extensive theoretical and experimental preparatory work presently in progress**

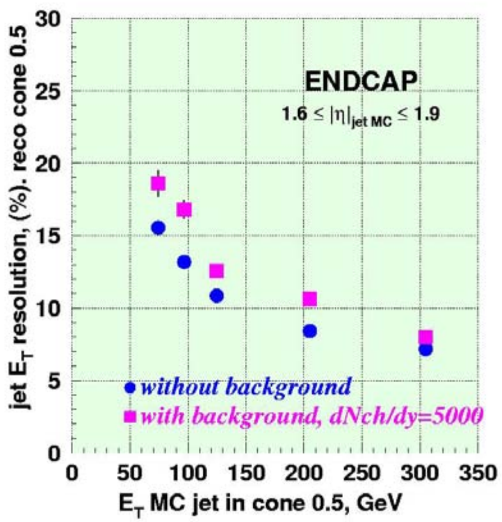
# Jet Reconstruction in CMS using Calorimeters

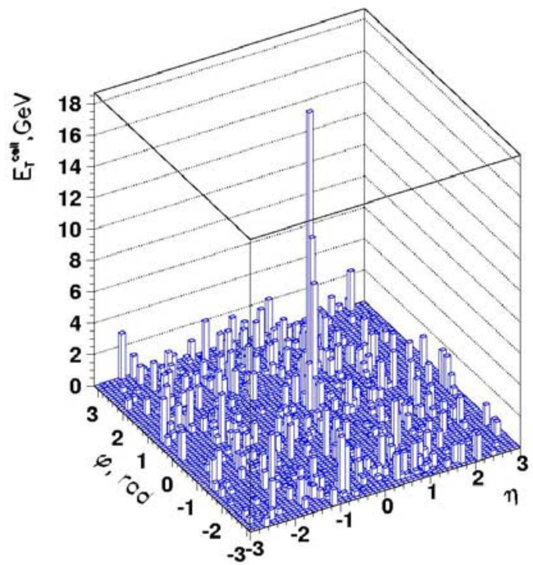


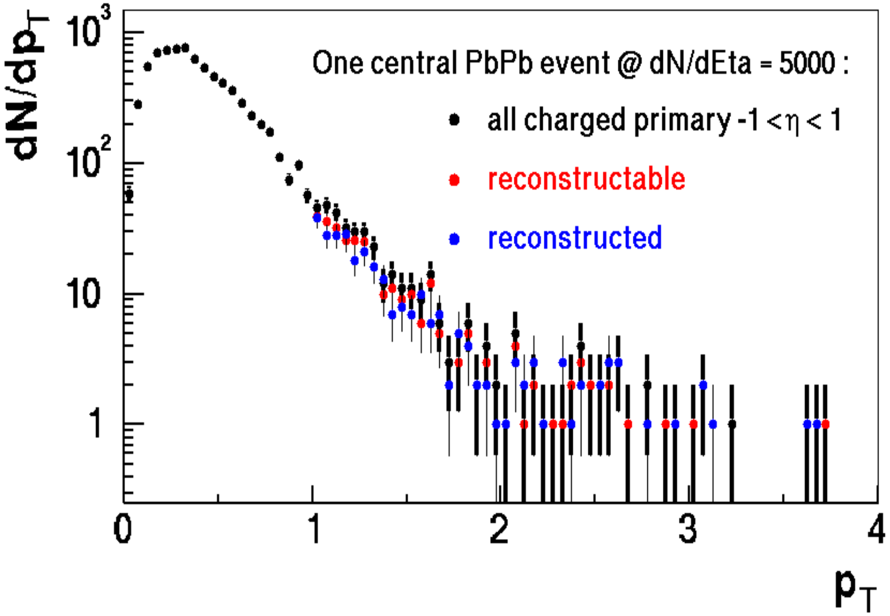



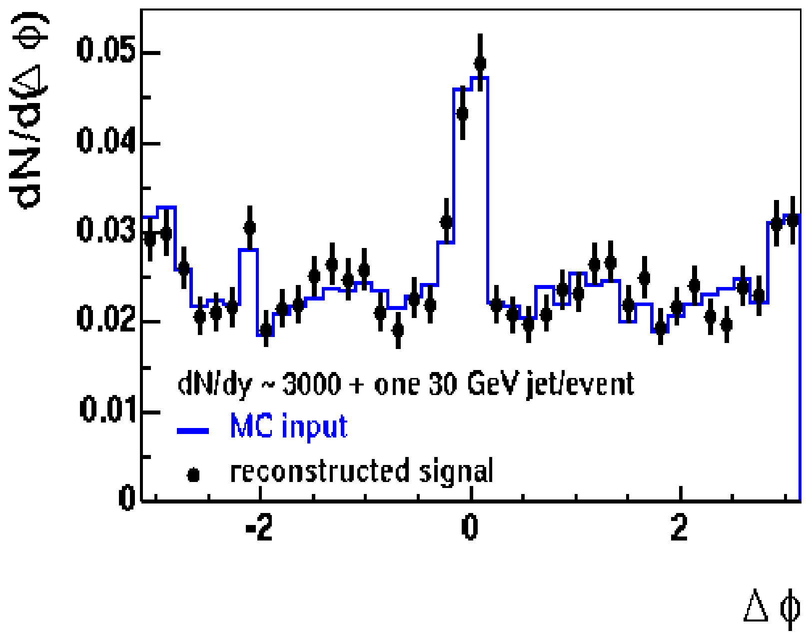



# Charged Particle Jet Studies in CMS

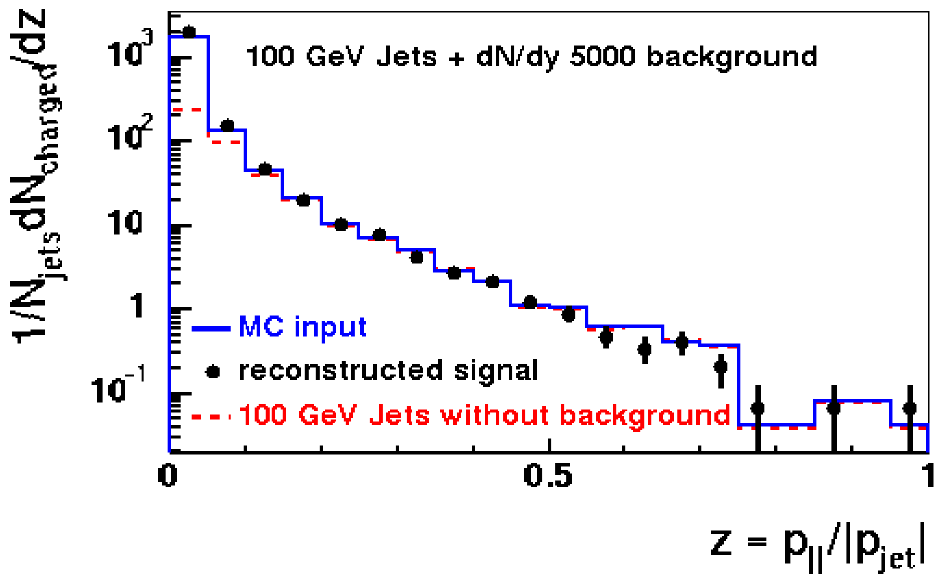


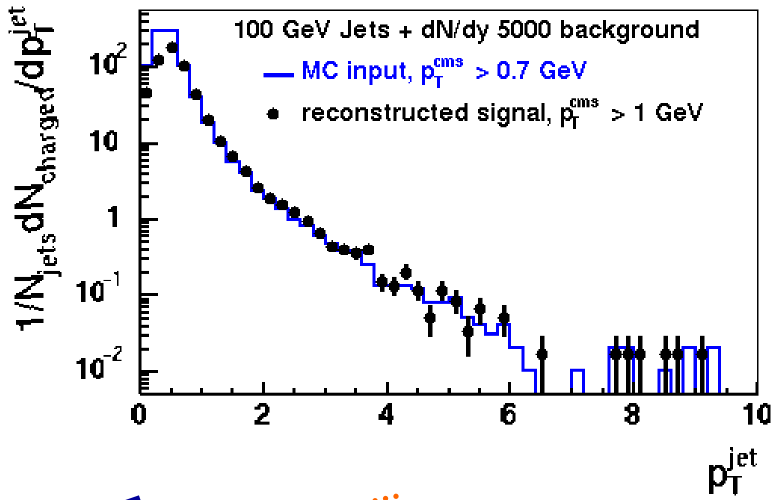

- **Detailed study of phenomena which are already apparent at RHIC**
- **Study the centrality dependence of:**
  - **Charged particle spectra starting at $p_T$~1 GeV**
    - Possibly lower $p_T$ cutoff with reduced B field
  - **Back-to-back particle correlations**
  - **Azimuthal asymmetry vs. $p_T$**

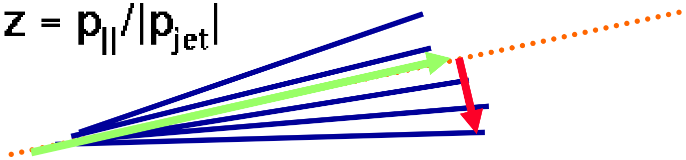
# Jet fragmentation

Longitudinal momentum fraction z along the thrust axis of a jet:




$p_T$ relative to thrust axis:



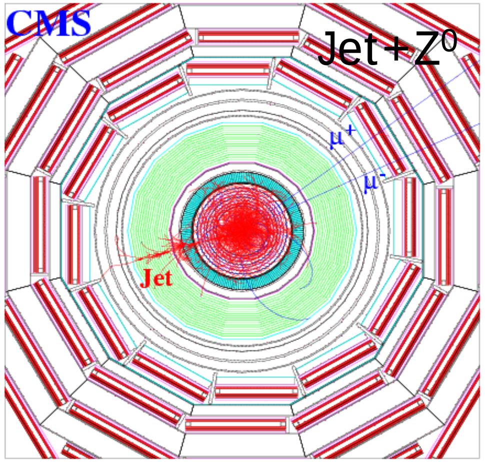
Fragmentation function for 100 GeV Jets embedded in $dN_{ch}/dy$ ~5000 events.

**High precision tracking out to high momenta will allow for detailed jet shape analysis to study the energy loss mechanism**

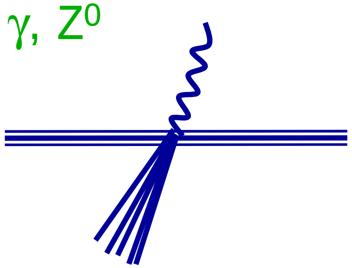
# Balancing γ or $Z^0$ vs Jets: study of jet with known energy

**Z+jet event in the Heavy Ion collision**

**dNch / dY = 5000**

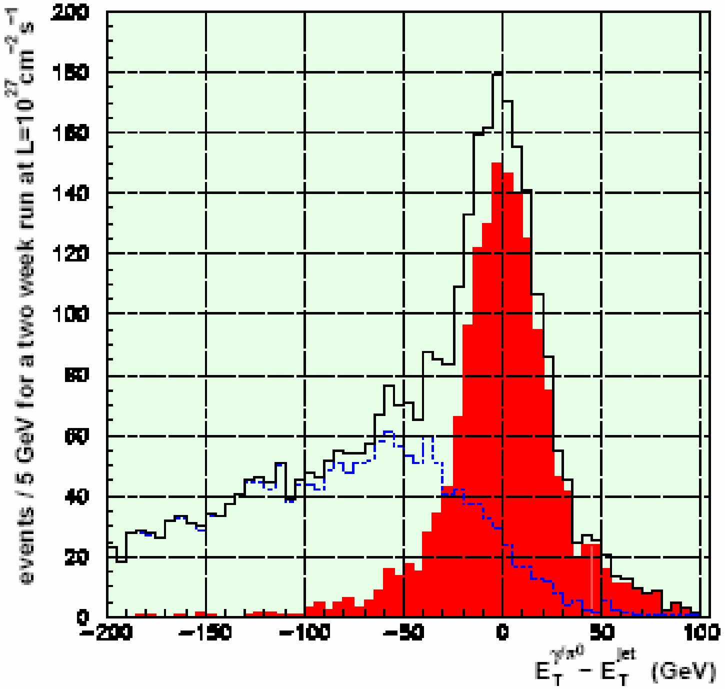


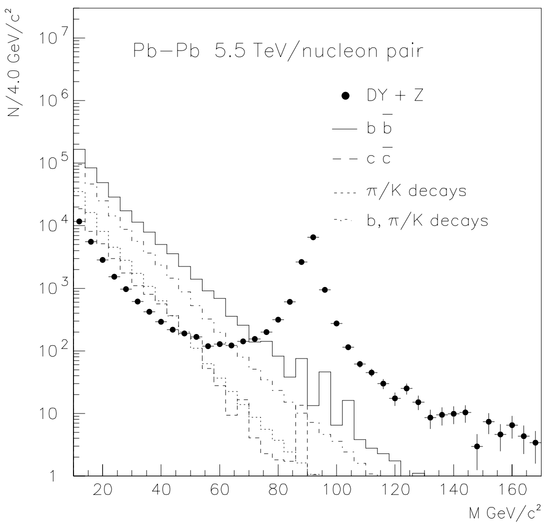

**Pt(Z) = Et(Jet) = 100 GeV.**




1 month at
$10^{27}$ $cm^{-2}s^{-1}$
Pb+Pb

$E_{Tjet,\ \gamma}$>120 GeV in Barrel



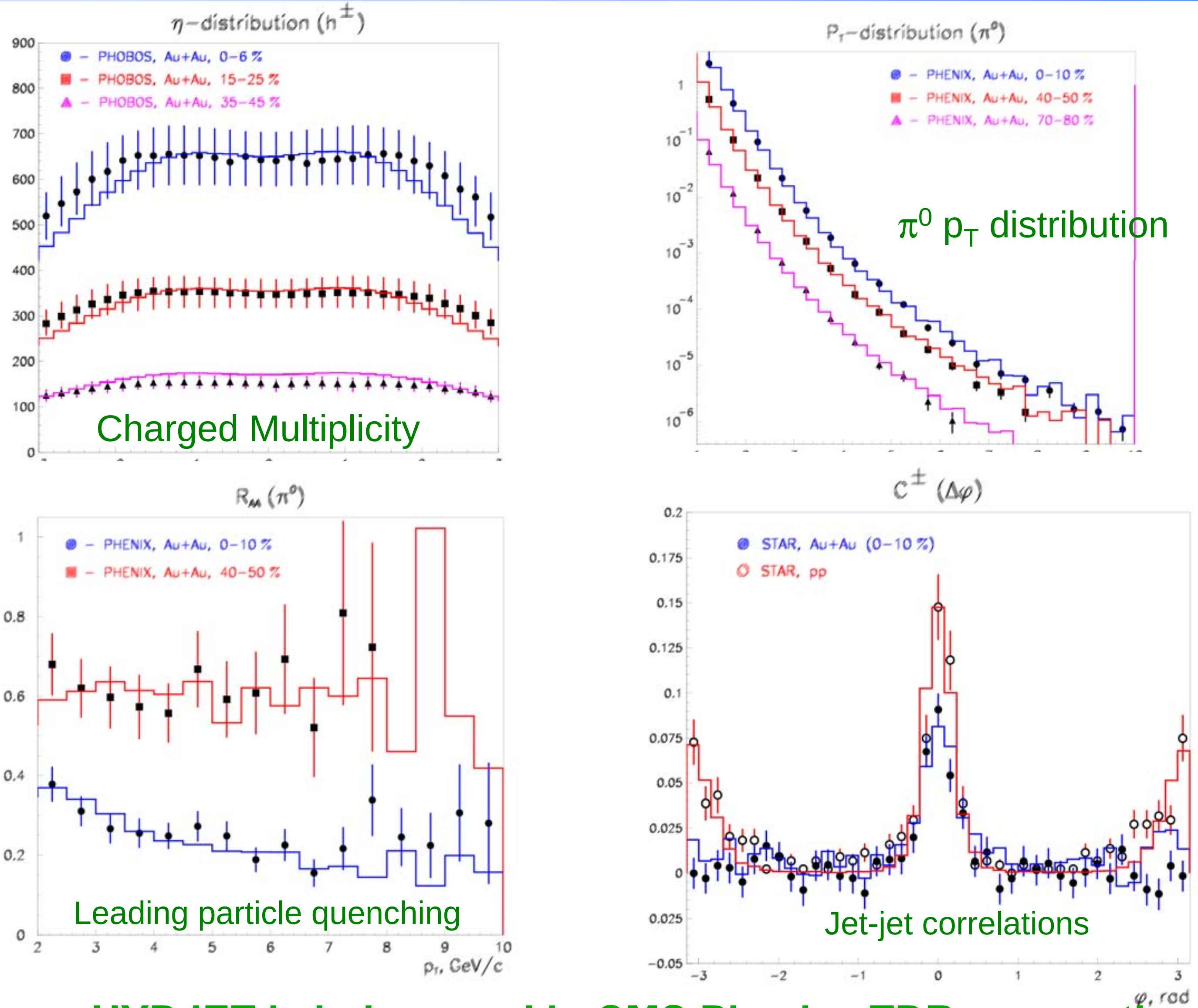




| Channel | Barrel+Endcap |
|---|---|
| jet+jet, $E_T^{jet} > 100$ GeV | $8.7\times10^6$ |
| $\gamma$+jet, $E_T^{jet,\gamma} > 100$ GeV | $6\times10^3$ |
| $Z(\to\mu^+\mu^-)$+jet, $E_T^{jet}, P_T^Z > 100$ GeV | 90 |
| $Z(\to\mu^+\mu^-)$+jet, $E_T^{jet}, P_T^Z > 50$ GeV | 600 |

# Future jet studies: new generators

- **Need better jet modeling at LHC: HYDJET**
  - **Soft particle production using Hydrodynamic model, includes flow**
  - **Jets produced using PYQUEN (PYTHIA with medium-induced quenching)**
  - **Full control of soft and hard physics assumptions**
- **Improvement compared to available generators**
  - **Centrality/geometry dependence**
  - **Energy loss modeling**
  - **Consistency with RHIC results**
- **New CMS simulations in progress:**
  - **Physics "Technical Design Report" in preparation**

# HYDJET tuned to RHIC data




**HYDJET is being used in CMS Physics TDR preparations**

***(I.P. Lokhtin and A.M. Snigirev, hep-ph/0506189)***

# Conclusions

- LHC will extend energy range and in particular high $p_T$ reach of heavy-ion physics
- CMS is preparing to take advantage of its capabilities
  - Excellent rapidity and azimuthal coverage and high resolution
    - Quarkonia
    - Jets
  - Centrality, Multiplicity, Energy Flow reaching very low $p_T$
  - Essentially no modification to the detector hardware
  - New High Level Trigger algorithms specific for A+A
  - Zero Degree Calorimeter, CASTOR and TOTEM will be important additions extending forward coverage
  - Heavy-Ion program is well integrated into the overall CMS Physics Program
- Detector construction is very well advanced and we MUST work hard to be ready for first beams (including pp)
- The extrapolations/predictions/modeling work must go on to be able to connect expected RHIC and LHC results and learn new physics from these comparisons