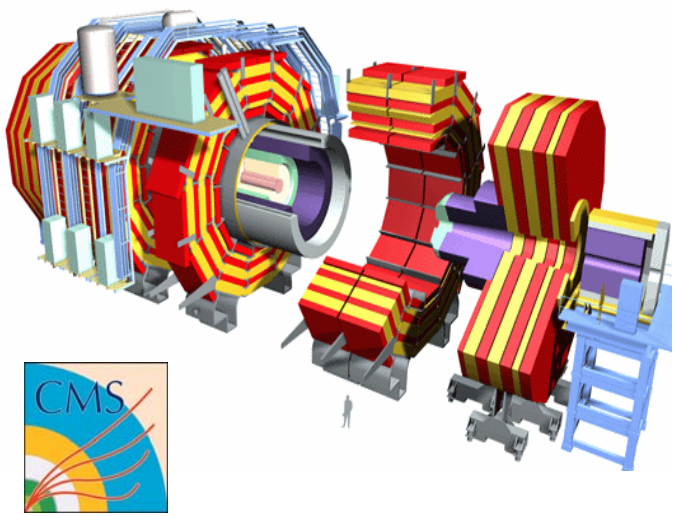
Heavy Ion Physics with CMS

VI Latin American Symposium on High Energy Physics



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University of Illinois at Chicago
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Noviembre 2006
Puerto Vallarta, México

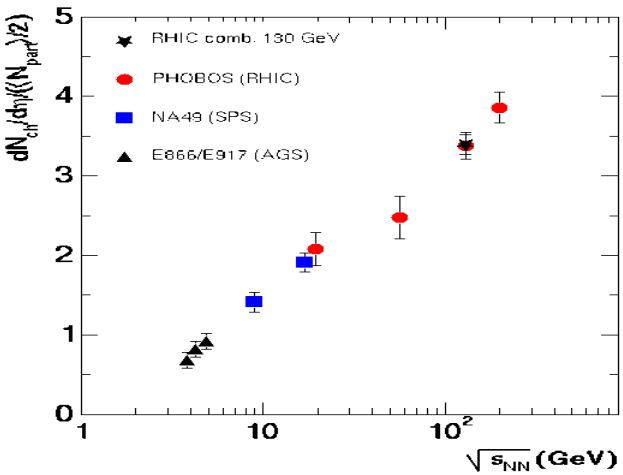
CMS HI groups: Adana, Athens, Basel, Budapest, CERN, Demokritos, Dubna, Ioannina, Kiev, Krakow, Los Alamos, Lyon, MIT, Moscow, Mumbai, N. Zealand, Protvino, PSI, Rice, Sofia, Strasbourg, U Kansas, Tbilisi, UC Davis, UI Chicago, U. Iowa, U. Minnesota, Yerevan, Vanderbilt, Warsaw, Zagreb

Outline

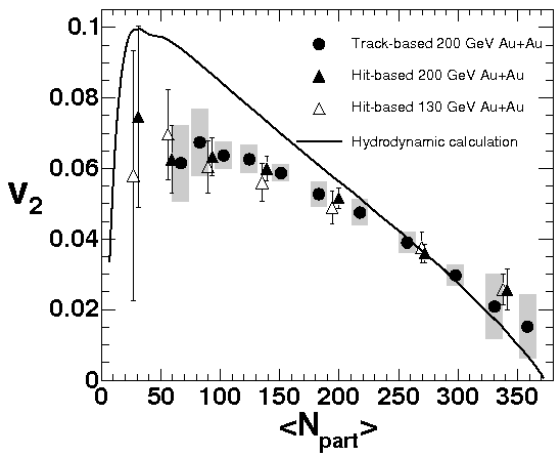
1. Introduction
2. Soft physics and global event characterization
   - Charged particle multiplicity
   - p_T spectra - tracking
   - Azimuthal asymmetry (Flow)
3. High p_T Probes
   - High p_T Jets
   - jet- γ, jet-Z^0
   - μ reconstruction: Z^0
   - Quarkonia (J/ψ, Υ)
4. Forward Physics
   - Gluon Saturation, Limiting Fragmentation
   - Ultra Peripheral Collisions

The reference: RHIC

Multiplicity

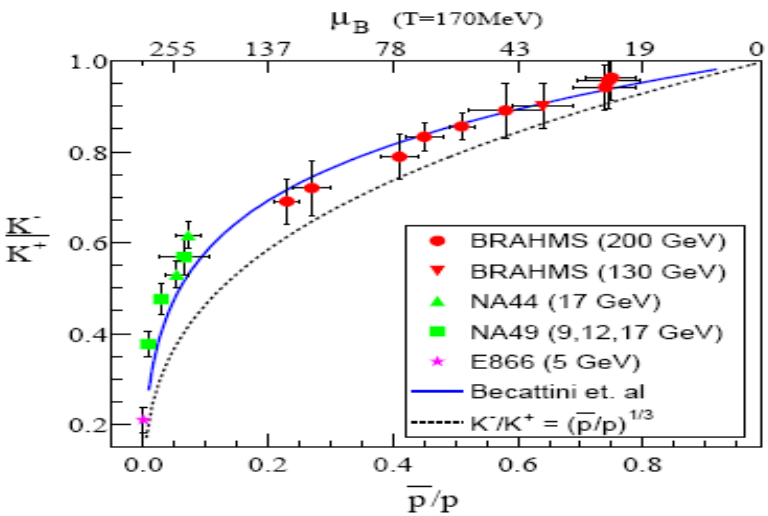


Elliptic Flow



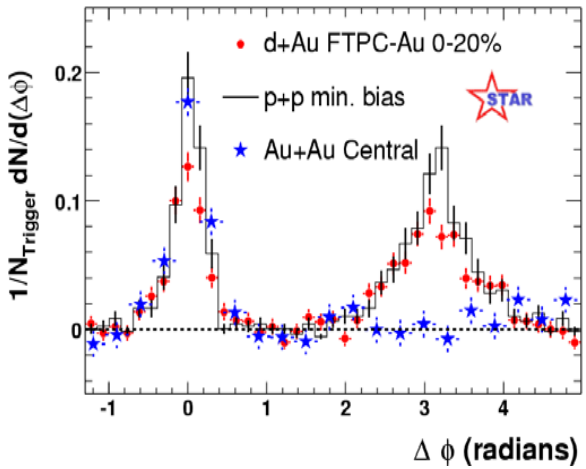
PHOBOS, Nucl. Phys. A757 (2005) 28

Applicability of thermodynamics



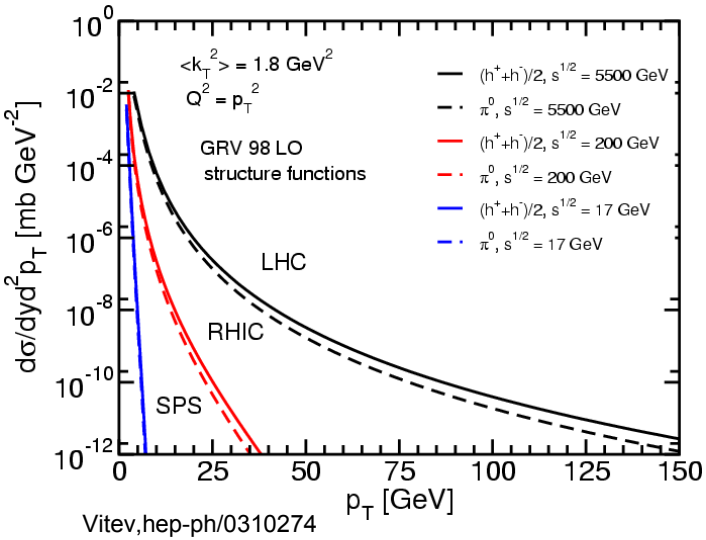
BRAHMS, Nucl. Phys. A757 (2005) 1-27

Jet Suppression



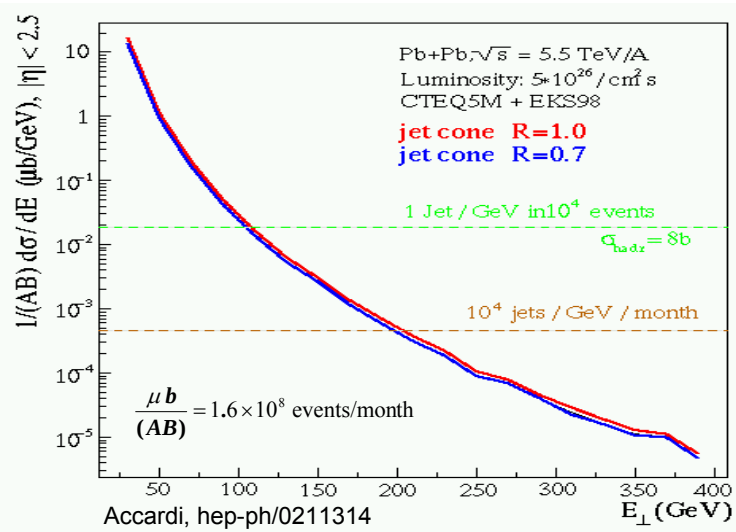
STAR, PRL 91, 072304

From RHIC to LHC

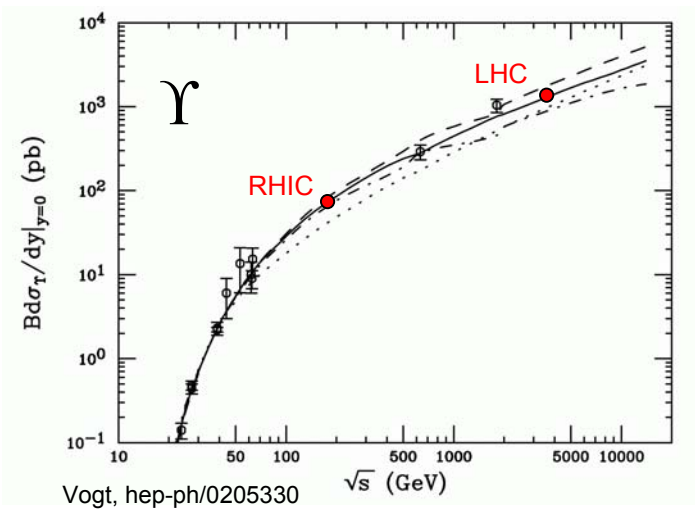


Vitev,hep-ph/0310274

- Factor 28 increase in energy to $\sqrt{s_{NN}}$=5.5 TeV
- High Luminosity
- Large Cross sections
  - High p_T particles
  - Jets, which are now directly identifiable
  - J/ψ, Z^0 and ϒ-family production

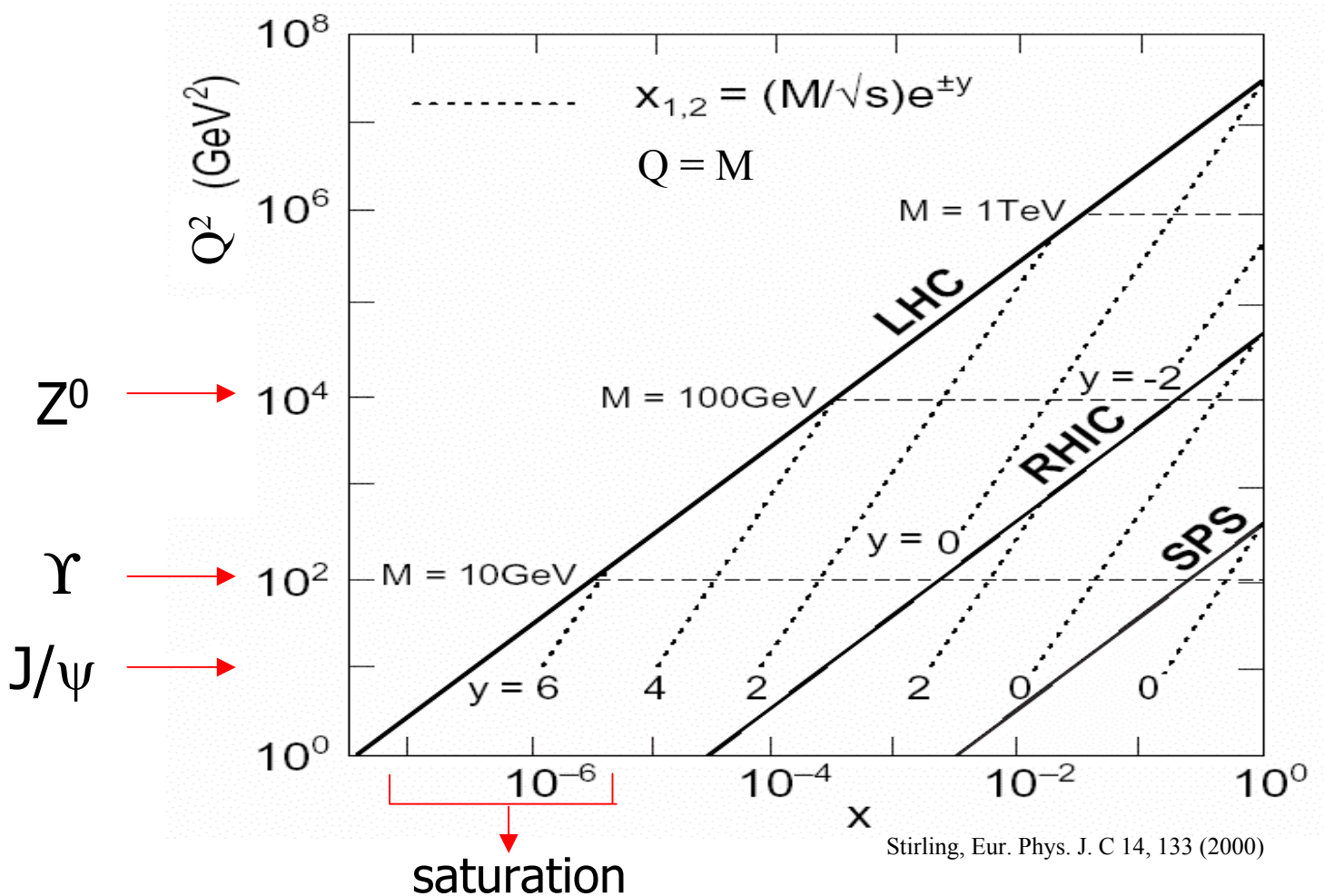


Accardi, hep-ph/0211314



Vogt, hep-ph/0205330

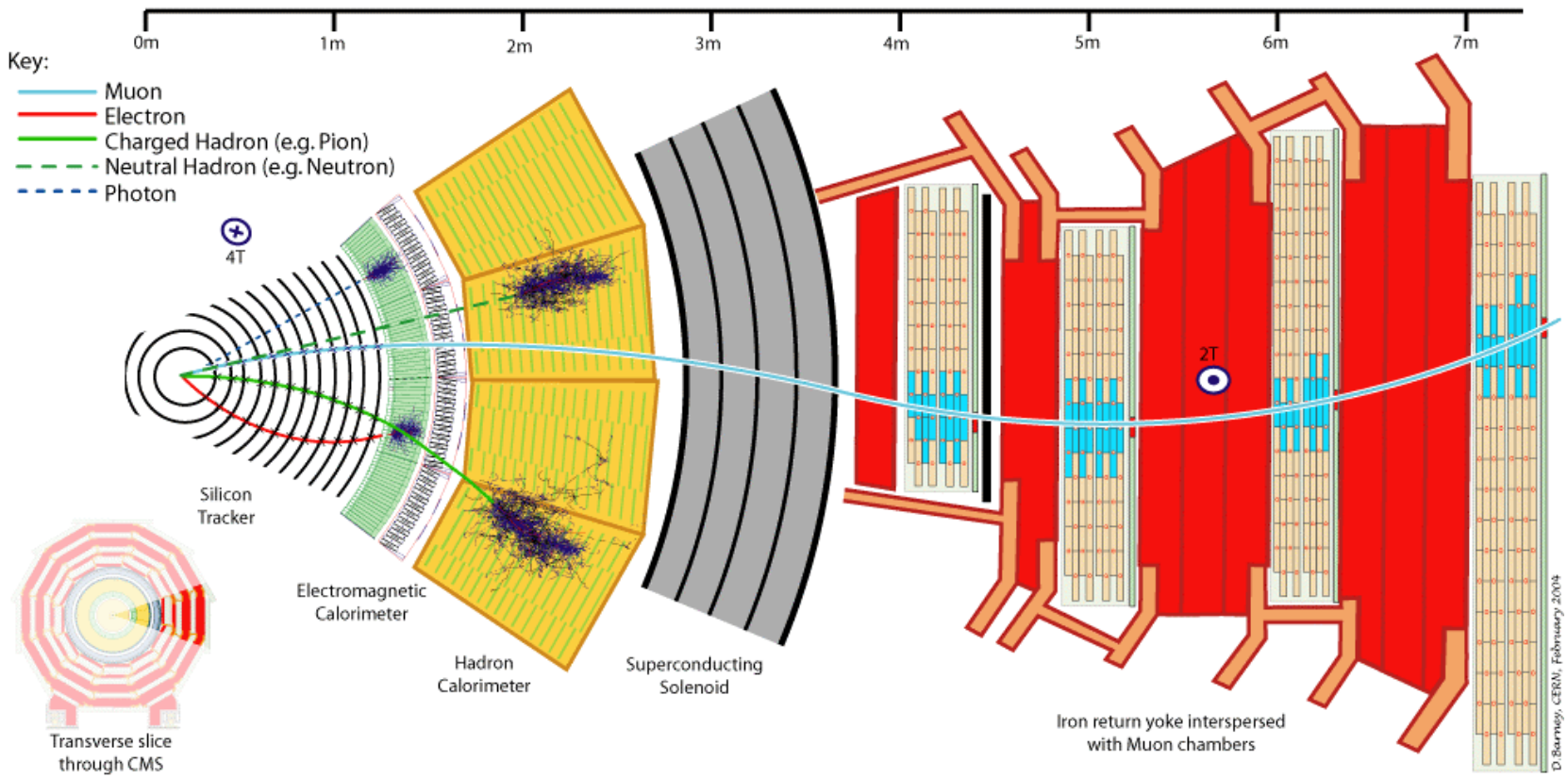
LHC kinematics



Stirling, Eur. Phys. J. C 14, 133 (2000)

- LHC provides access to the widest range of Q^2 and x, including regions where Z^0 and Υ will be accessible, and low x where gluon saturation is expected

CMS detector - $|\eta| < 2.4$



Si TRACKER

Silicon Microstrips and Pixels

CALORIMETERS

ECAL

Scintillating $PbWO_4$ crystals

HCAL

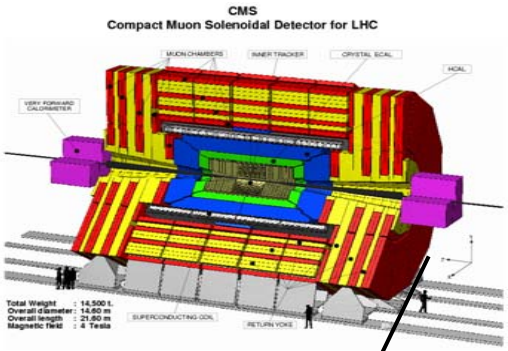
Plastic scintillator/brass sandwich

MUON BARREL

Drift Tube Chambers (**DT**)

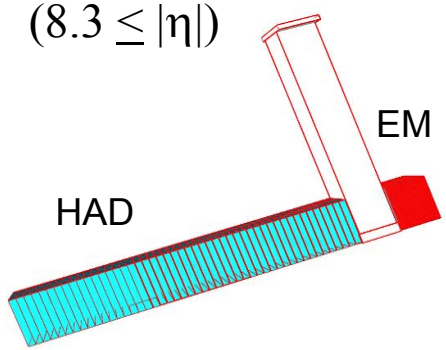
Resistive Plate Chambers (**RPC**)

Forward Region



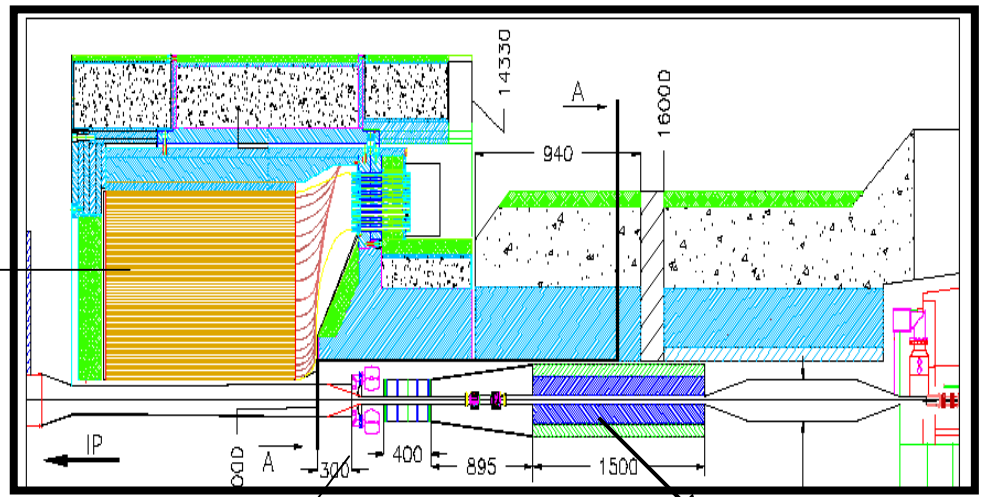
ZDC

($8.3 \leq |\eta|$)



Forward HCal

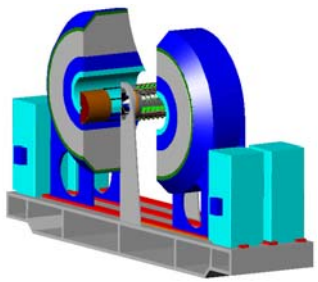
($3 \leq |\eta| \leq 5.2$)



($z = \pm$ 140 m)

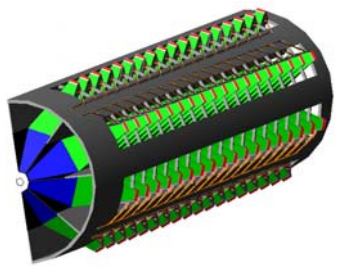
TOTEM

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

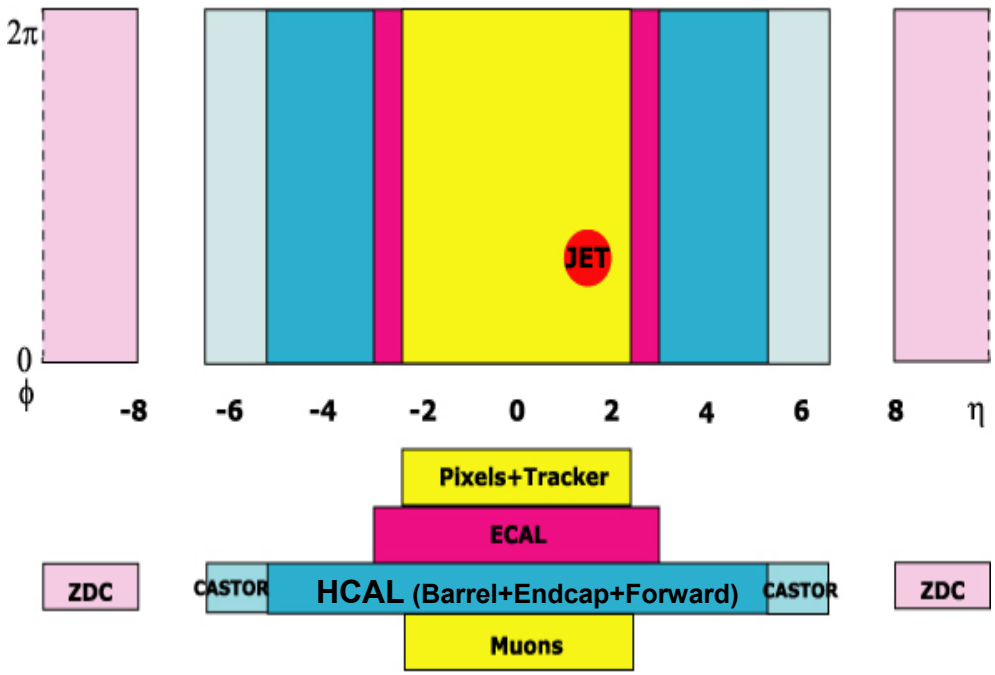


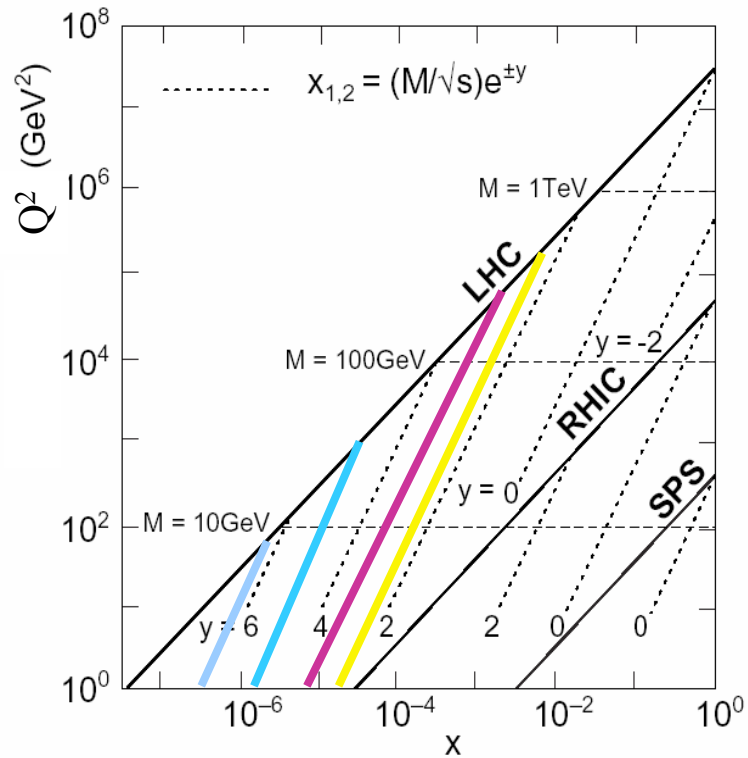
CASTOR

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



CMS coverage

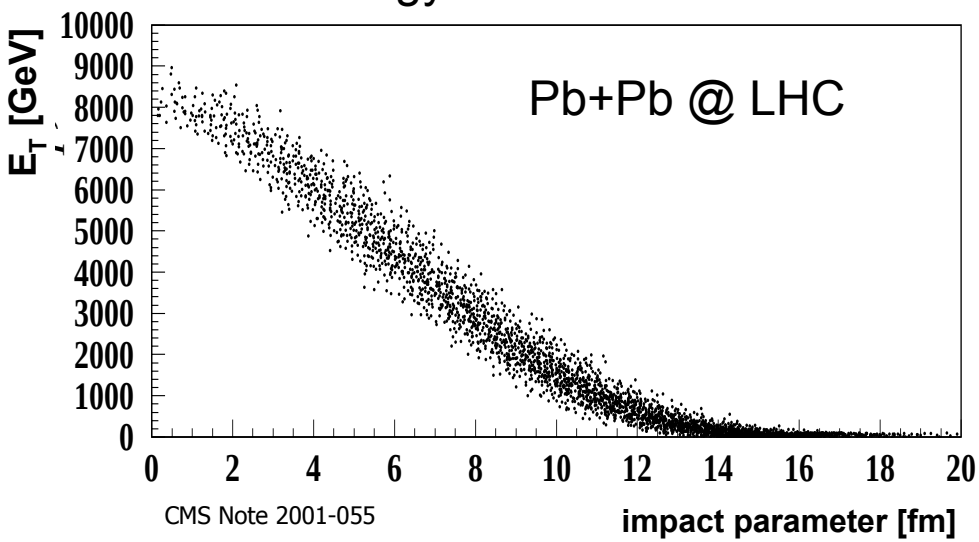




Sub detector	Coverage
Tracker, muons	$\lvert \eta \rvert < 2.4$
ECAL + HCAL	$\lvert \eta \rvert < 3.0$
Forward HCAL	$3.0 < \lvert \eta \rvert < 5.2$
CASTOR	$5.2 < \lvert \eta \rvert < 6.6$
ZDC	$8.3 < \lvert \eta \rvert$

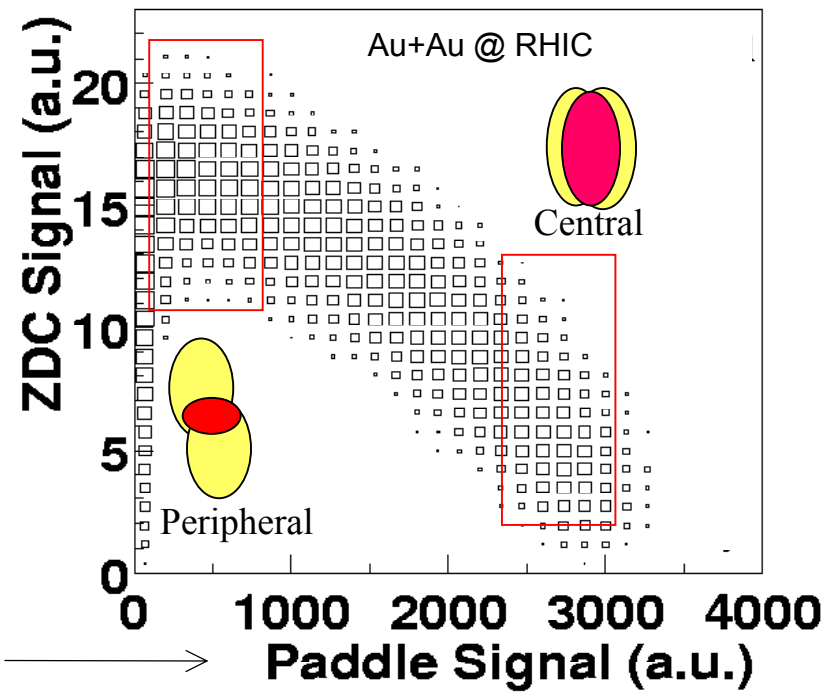
Event Characterization: Centrality

Energy in Forward HCal



CMS Note 2001-055

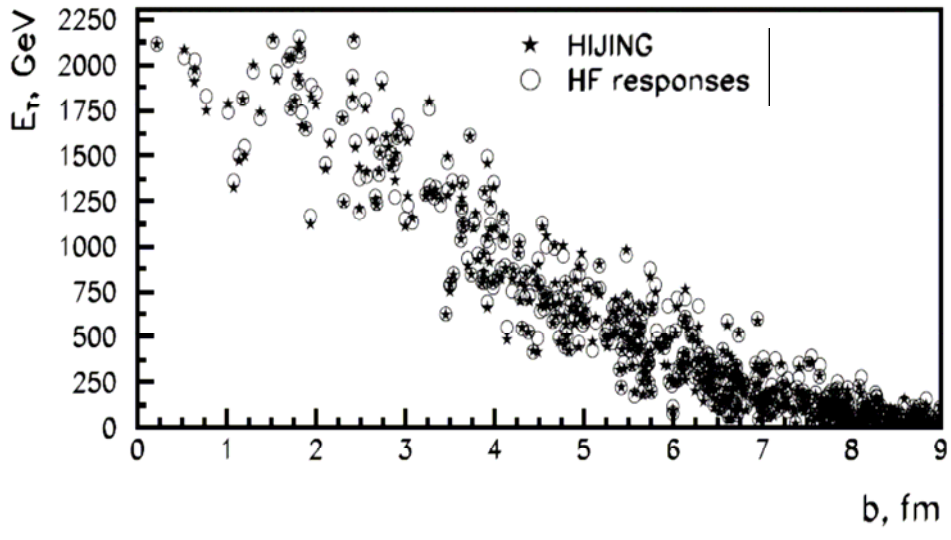
PHOBOS ZDC

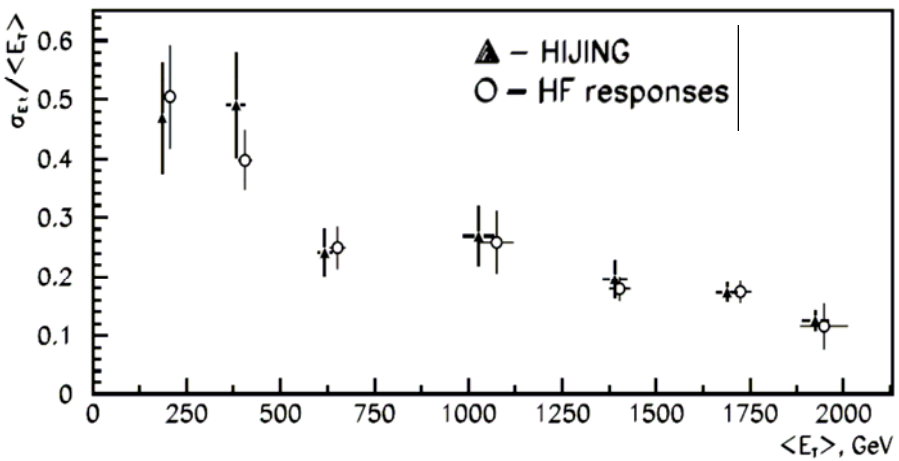


(Forward HCal or Castor signal for CMS) ⟶

- Forward HCal will provide correlation between E_T and event centrality
- In addition ZDC and Castor will improve the centrality determination and increase various physics triggers at large b.

Centrality cont.



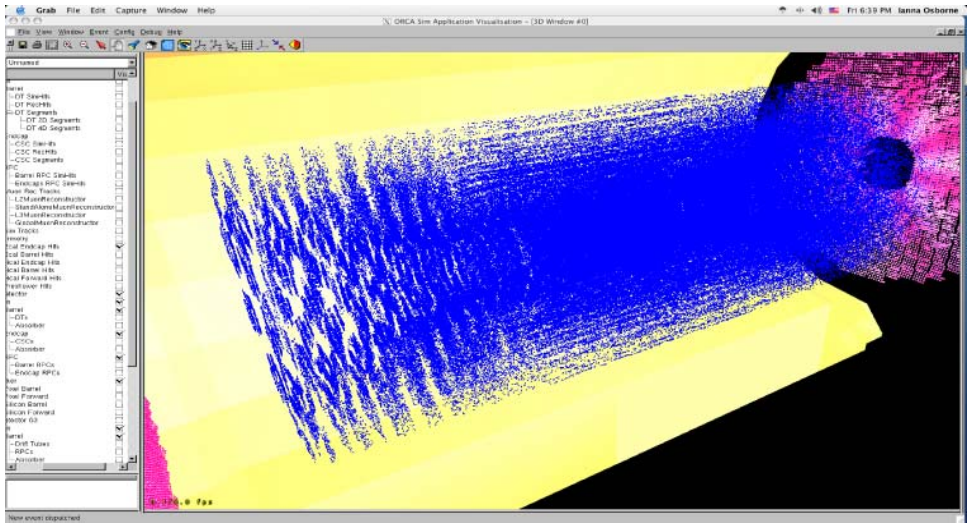


CMS Note 2001-055

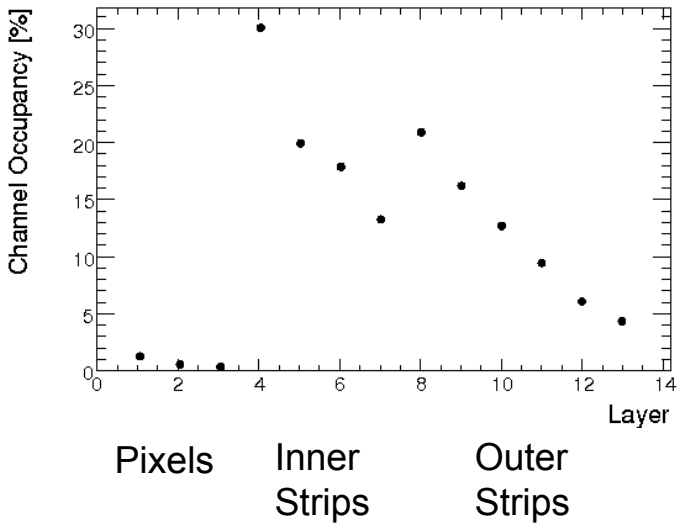
- Simulations of the calorimeter collisions indicate that over 80% of E_T will be detected.
- Shown on the left
  - 500 min bias **Ar-Ar** Hijing collisions ($3 < \eta < 5$)
  - Upper plot is the relationship between the simulation and reconstructed (HF) transverse energy vs. the impact parameter.
  - The lower plot is the accuracy ($\sigma_E/\langle E_T \rangle$) of the impact parameter measurement.

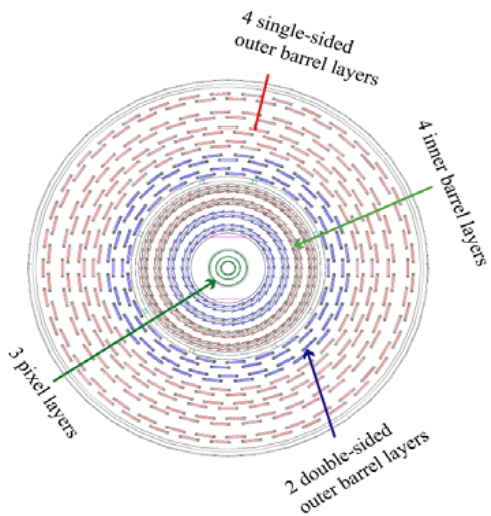
Charged particle multiplicity

Simulated central Pb+Pb event: $dN_{ch}/d\eta|_{\eta=0} \sim 3000$

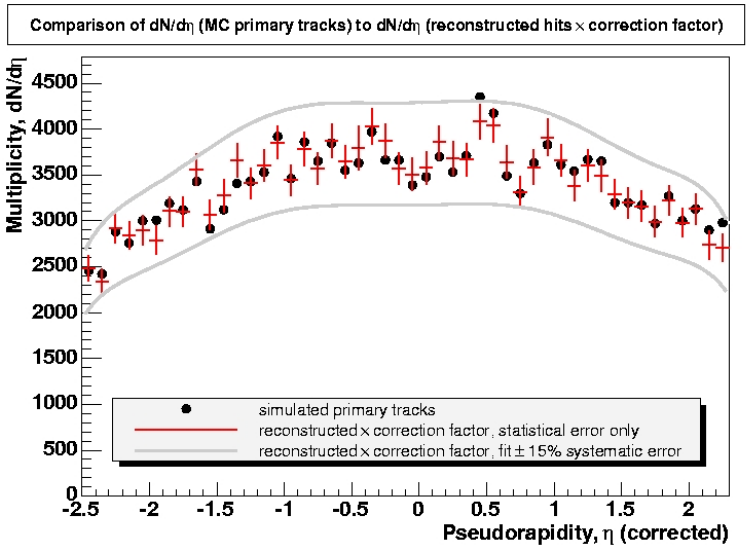


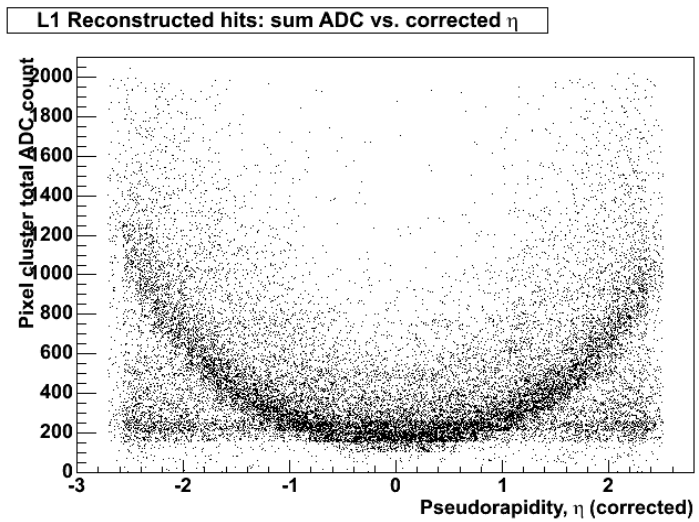
- Tracker : Pixel layers and the silicon strip counters.
  - Pixel detector: 3 pixel barrel layers and 2 endcap disks in forward and backward directions. Barrel layers cover up to $|\eta| < 2.1$.
  - T he barrel layers contain ~ 9.6, 16, and 22.4 million pixels, respectively.





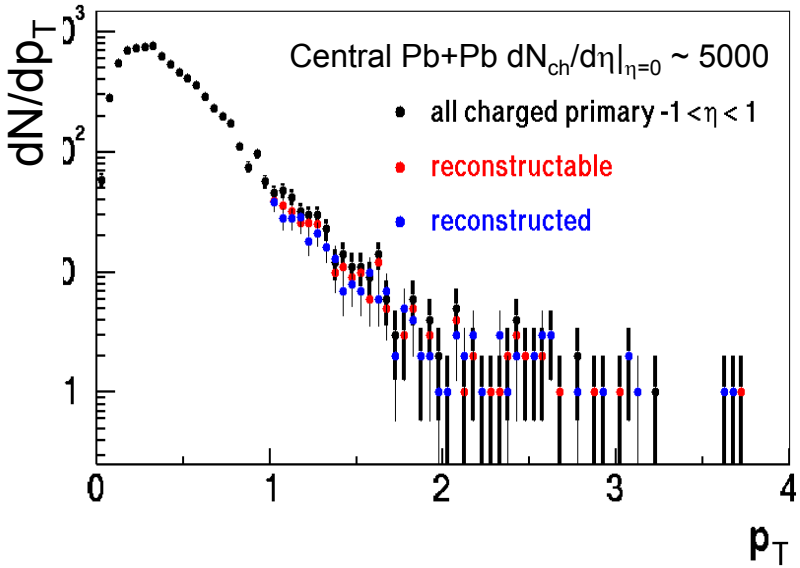
Charged particle multiplicity cont.



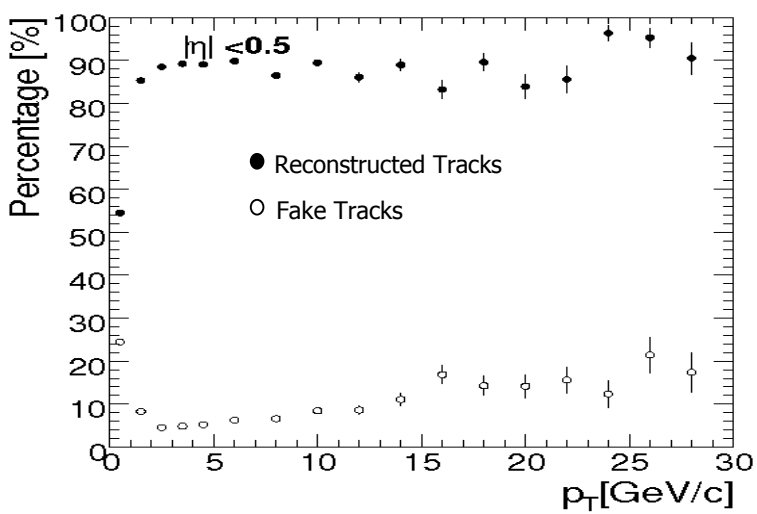


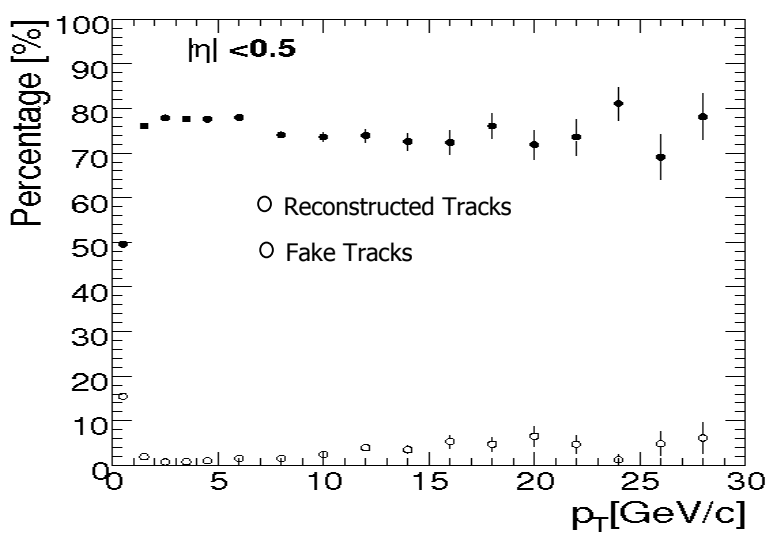
- High granularity pixel detectors
- Pulse height in individual pixels to reduce background
- Very low p_T reach, $p_T > 26$ MeV
- On the left
  - Single layer hit counting in innermost pixel barrel layer
  - cosh η dependence of SumADC

Tracking Performance



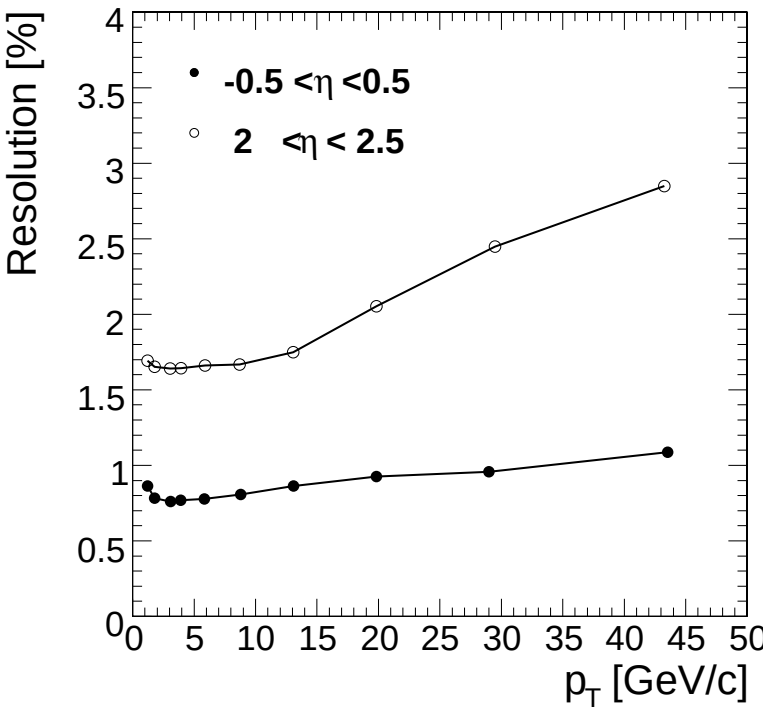
- Top: charged particle spectra
- Bottom: track reconstruction efficiency as function of p_T.
  - Pb+Pb collisions dN_{ch}/dy ~ 3000
  - Left : track quality cuts optimized for low fake track rate
  - Right: cuts optimized for high efficiency





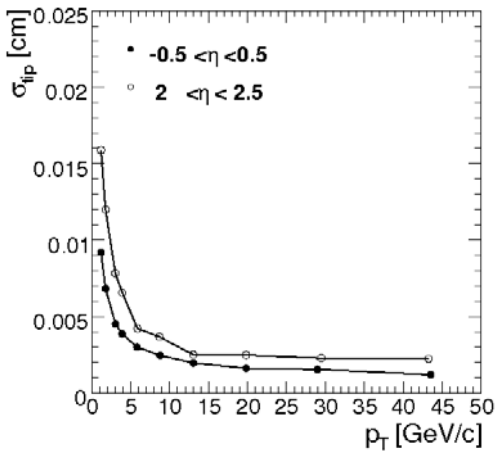
Tracking resolution

Momentum Resolution

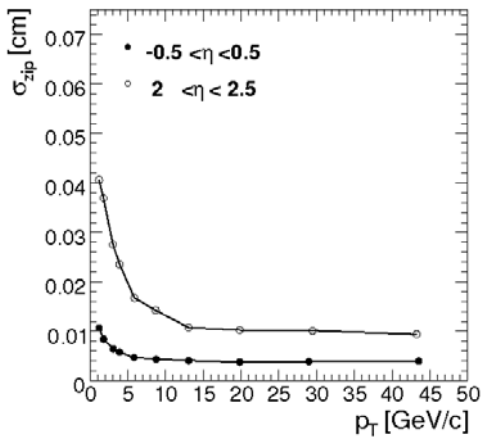


Track-pointing Resolution

Transverse (σ_t~20 μm)

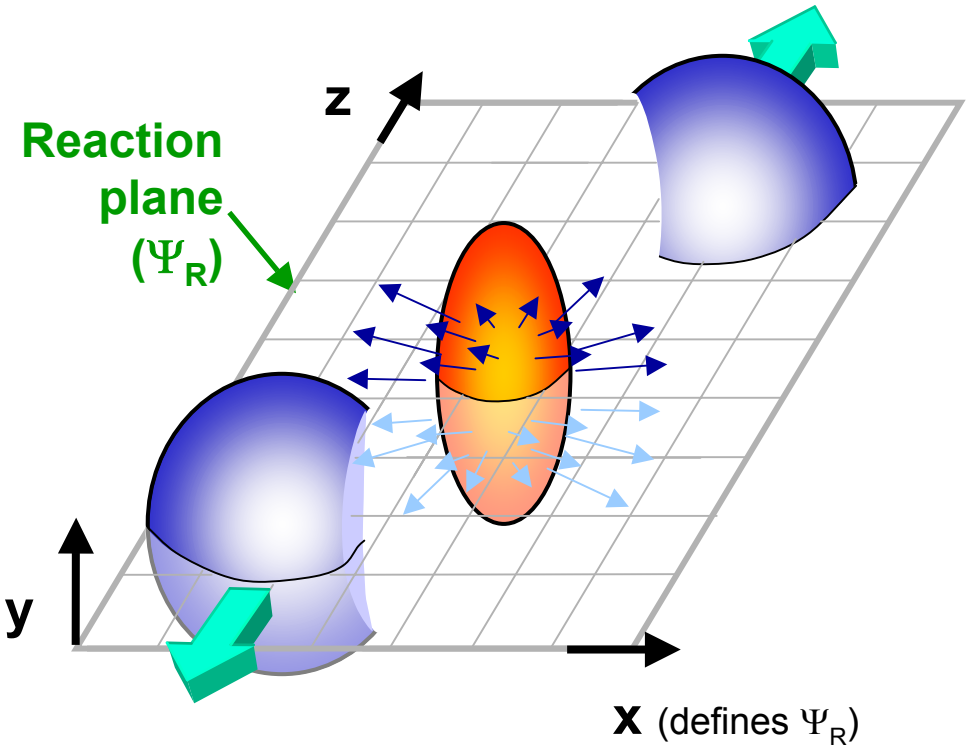


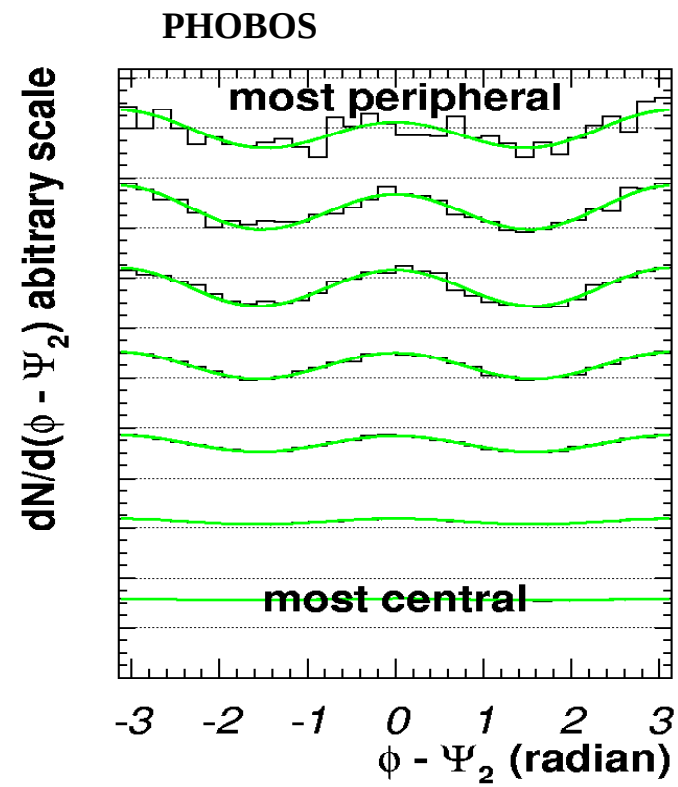
Longitudinal (σ_l~50 μm)

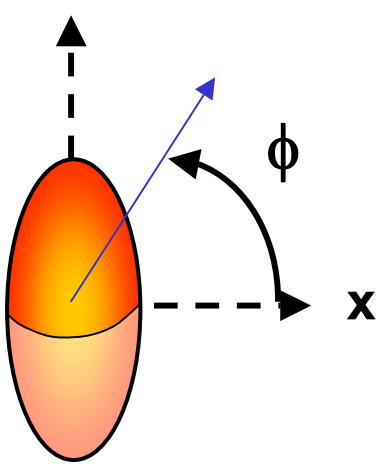


- With current studies: good tracking purity and efficiency down to p_T ~ 1GeV/c.

Flow

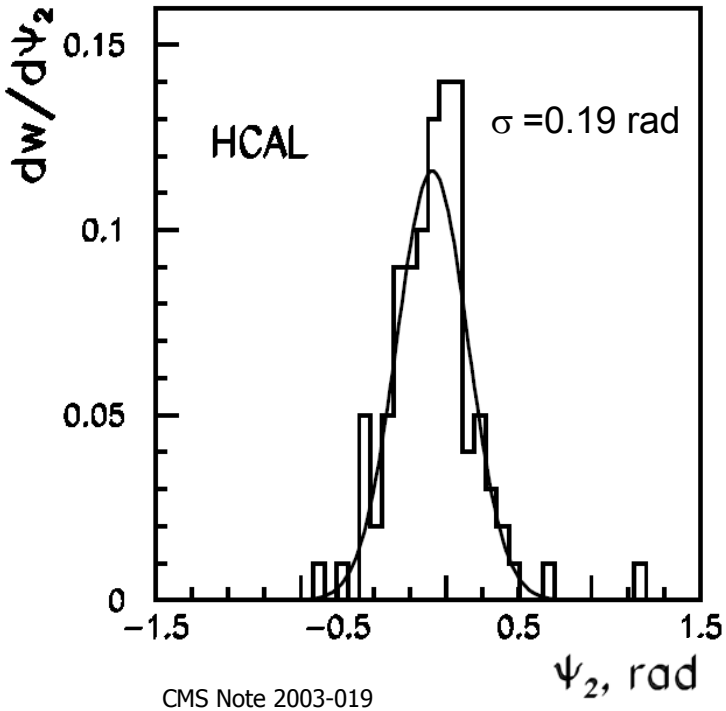




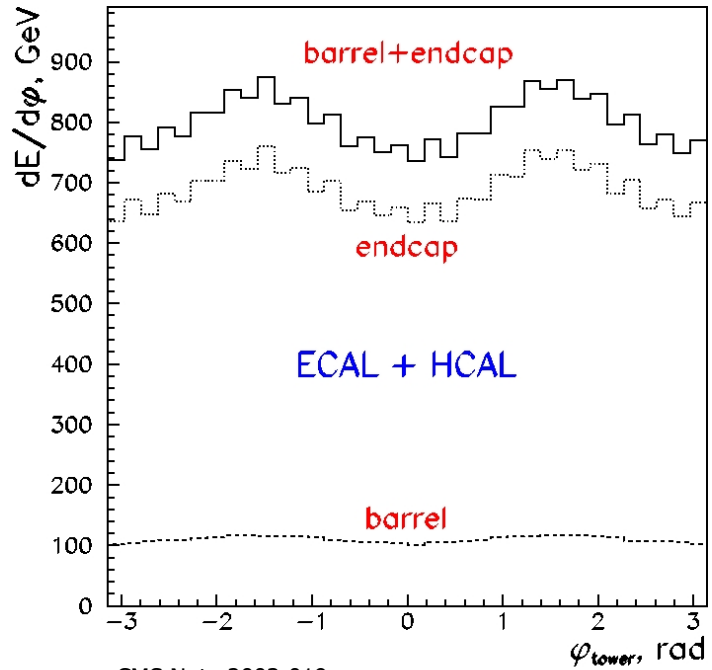


$$dN/d(\phi - \Psi_R) = N_0 (1 + 2V_1 \cos(\phi - \Psi_R) + 2V_2 \cos(2(\phi - \Psi_R)) + \ldots)$$

Flow measurements in CMS



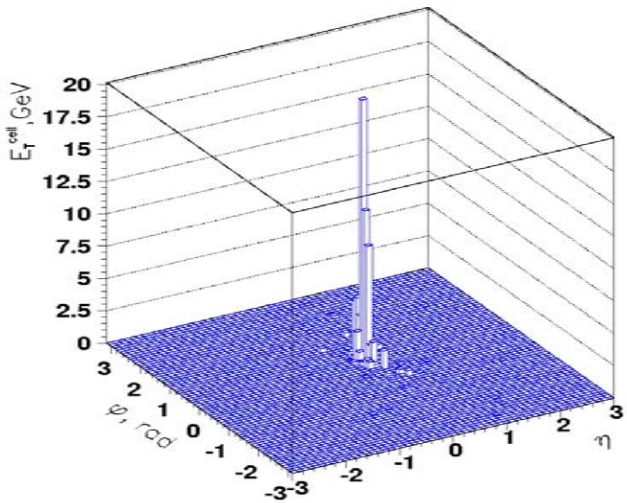
CMS Note 2003-019



CMS Note 2003-019

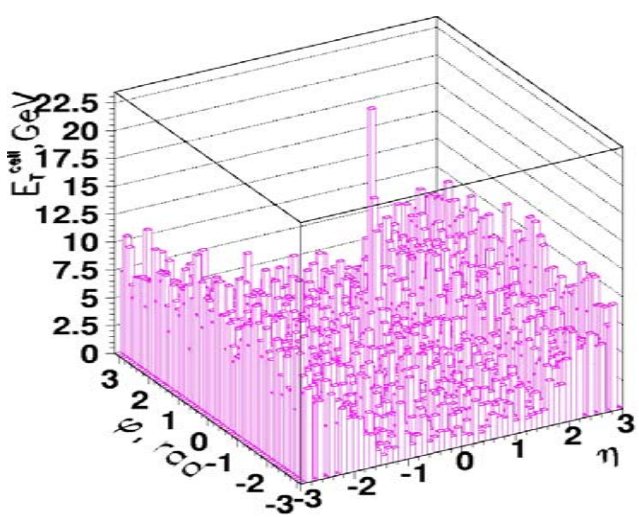
- Left: difference between generated and reconstructed reaction plane angle for Pb+ Pb collisions b = 6 fm
- Right: reconstructed energy deposition in the barrel and endcap regions for electromagnetic and hadronic calorimeters as function of as function of the azimuthal angle for b = 6 fm

Jet Reconstruction

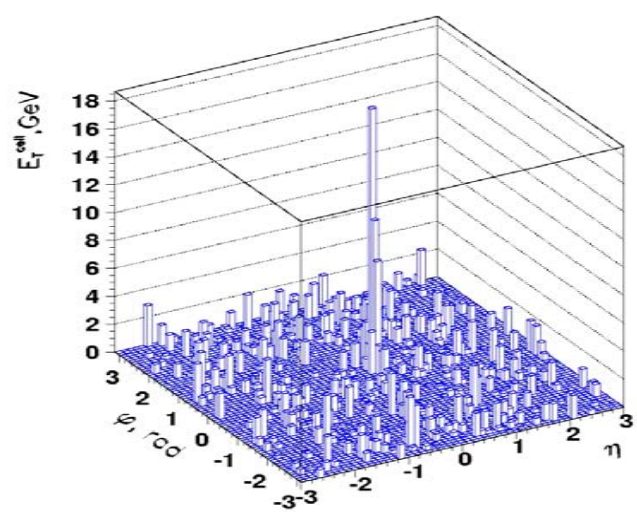


Jet in pp after pileup subtraction

- Use calorimeters for jet reconstruction
- Jet E_T ~100GeV, background dN_{ch}/dy ~ 5000
- Event-by-Event η-dependent background subtraction+ iterative jet cone-finder algorithm
- Jet resolution:
  - **$\sigma(\phi_{rec} - \phi_{gen}) = 0.032$;**
  - **$\sigma(\eta_{rec} - \eta_{gen}) = 0.028$**
  - **$\sigma(E_{Trec} - E_{Tgen}) = 16$ %**



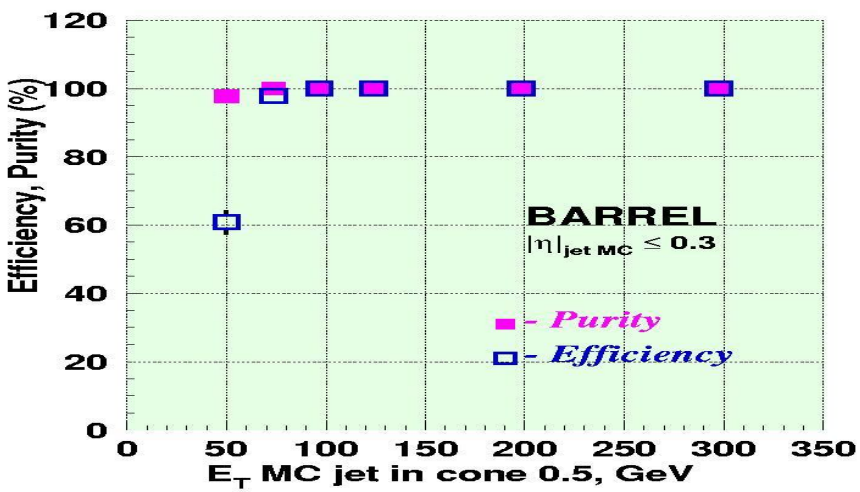
Jet superimposed on Pb + Pb background

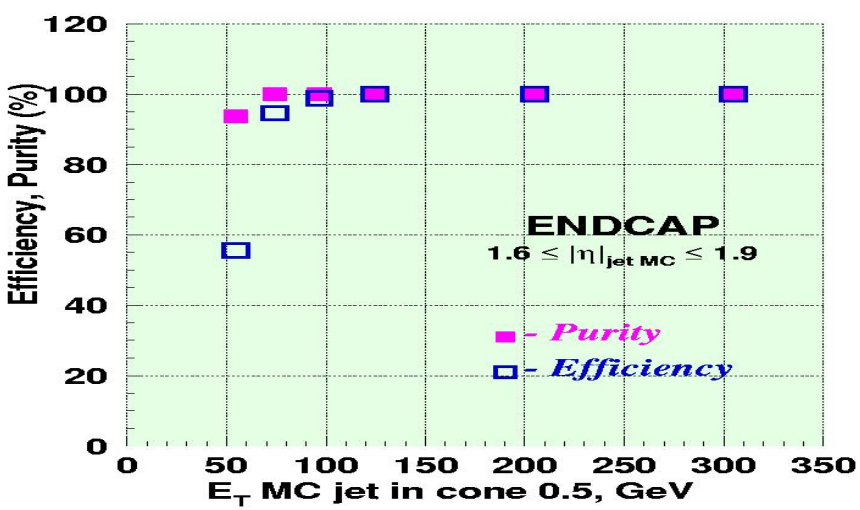


Jet in Pb + Pb after pileup subtraction

CMS NOTE 2006/050

Efficiency, Purity vs. Jet Energy



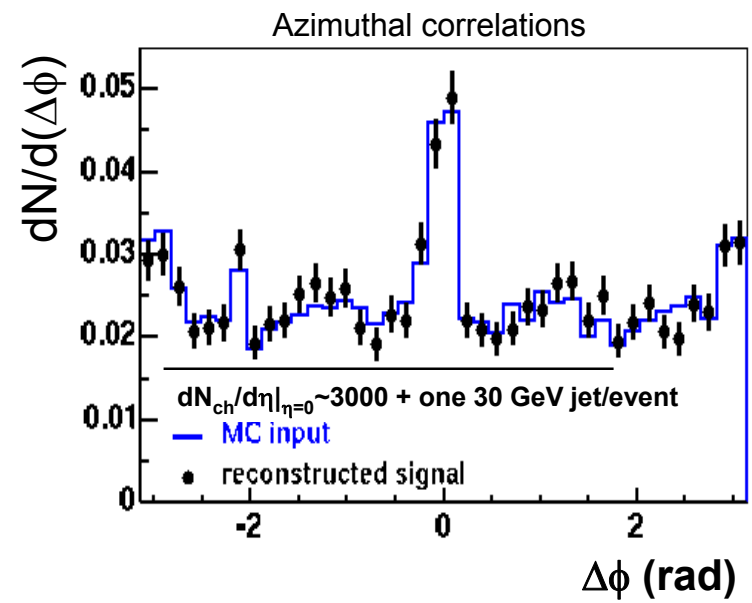


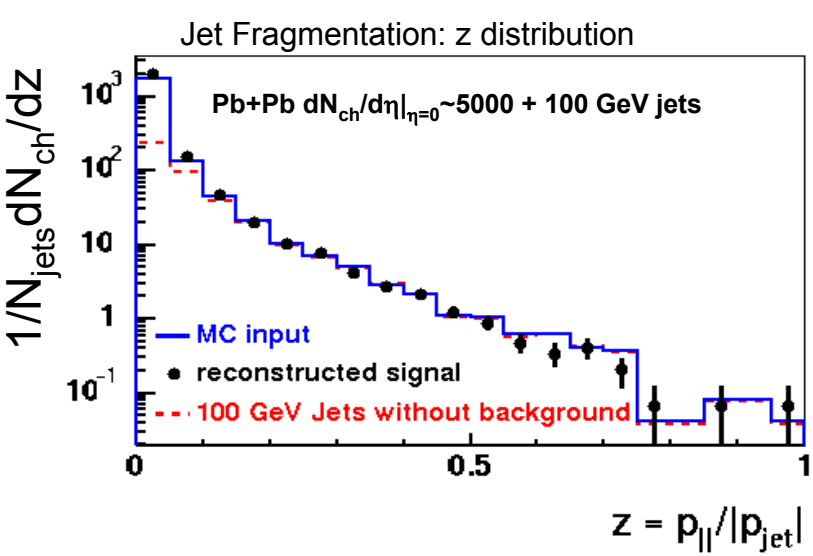
- Reconstruction of 50-300 GeV Jets in Pb-Pb background
- Efficiency: number of events with true reco. Jets/Number of all generated events
- Purity : number of events with true reco. QCD Jets/ Number of all reco. Jet events (true+fake).
- Threshold of jet reco. E_T >30 GeV.

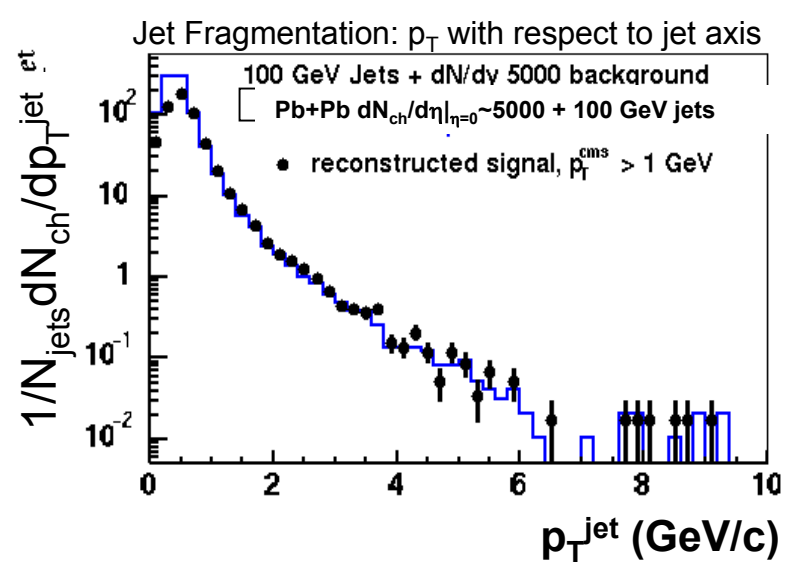
CMS NOTE 2006/050

Jet studies using calorimeter + tracking

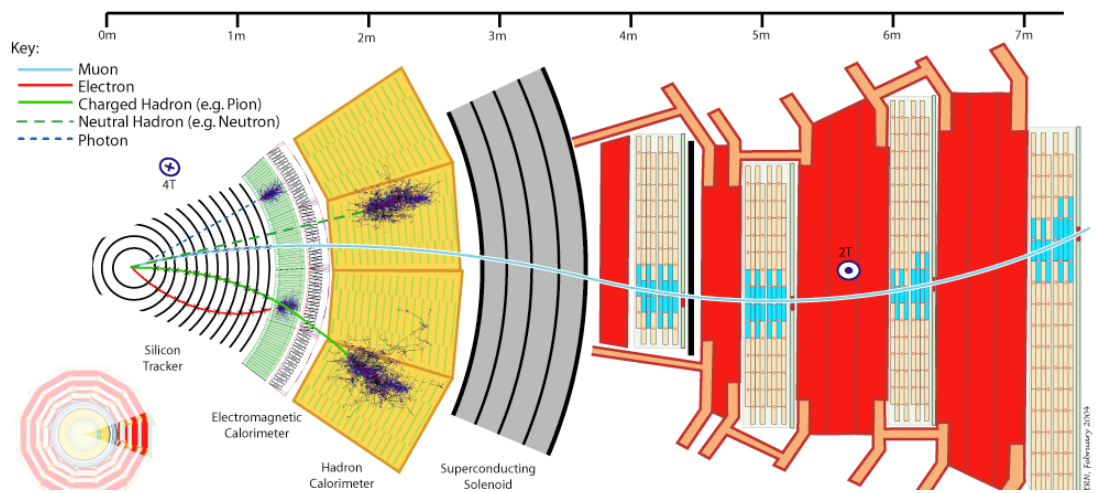
- Some example Jets observables using calorimetry
  - Jet cross sections
  - Jet - Jet correlations
  - Jet- γ/Z correlations
- Calorimetry and particle reconstruction
  - Jet fragmentation
  - Jet shape
  - Tagged heavy quark jets
  - Inclusive p_T spectra
  - Back-to-back particle correlations

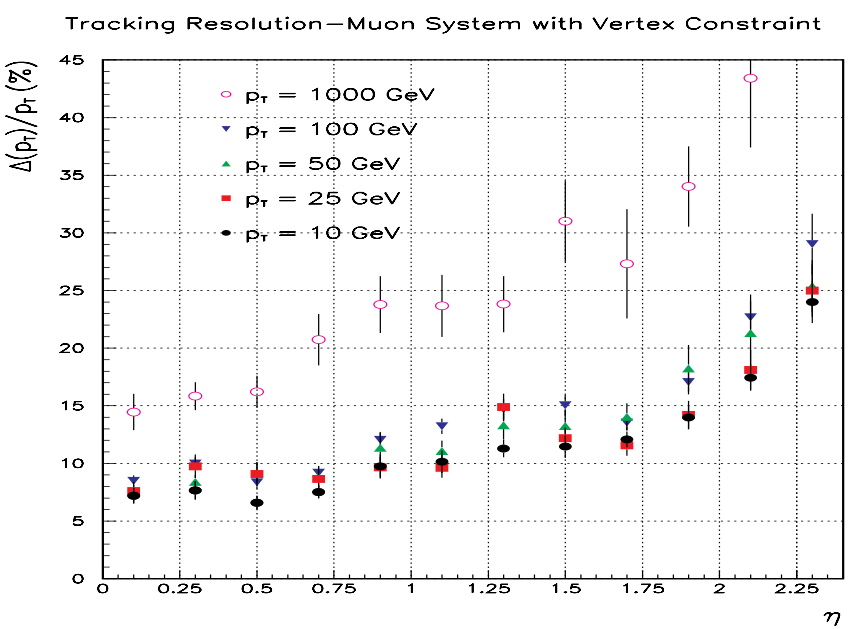


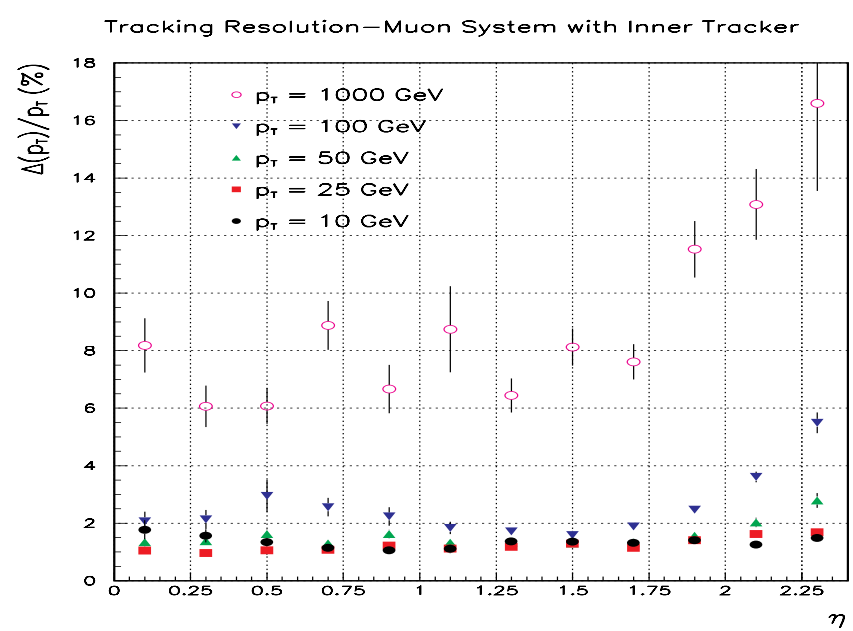




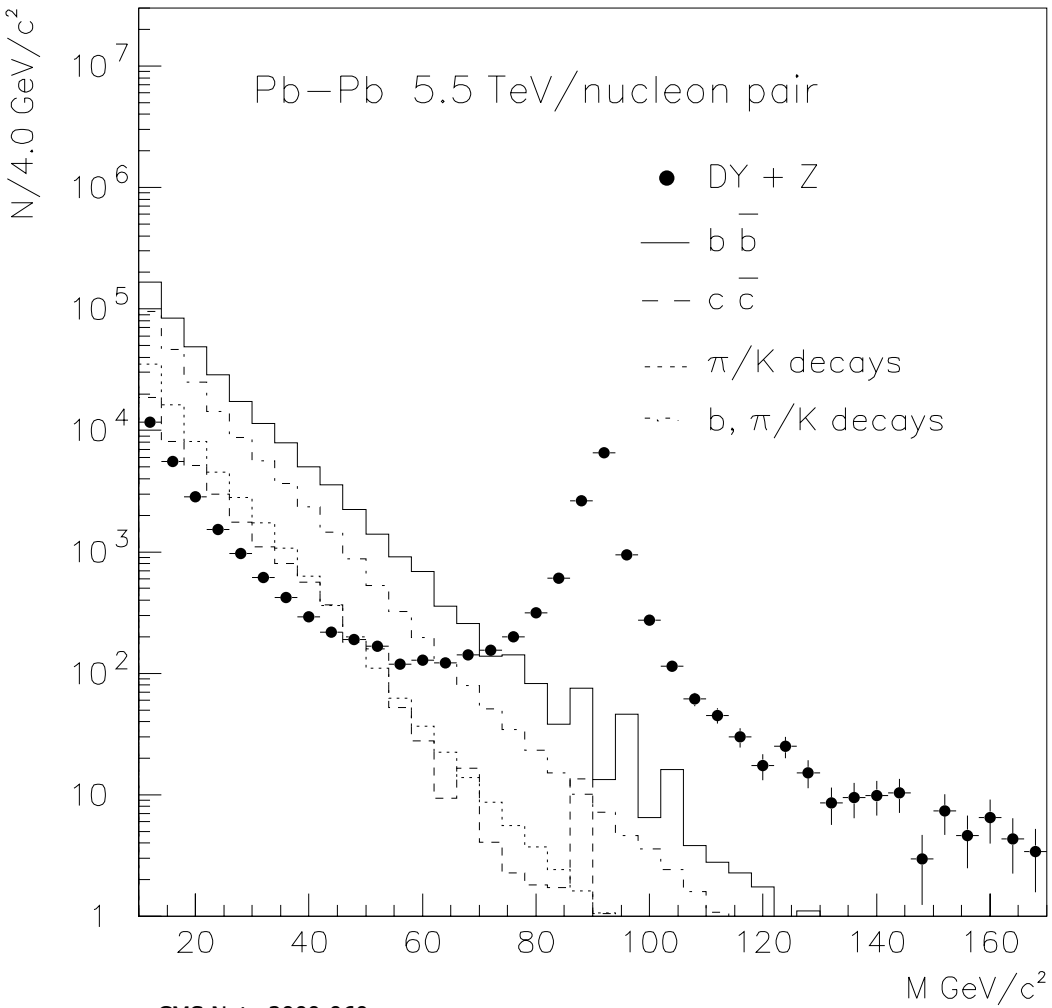
Measuring muons







Z^0 production



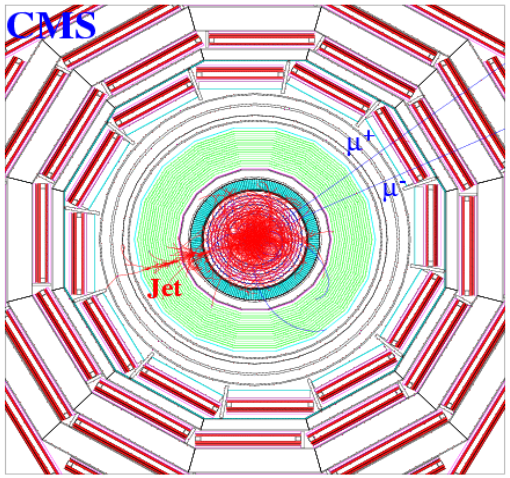
CMS Note 2000-060

- Z^0-$\mu\mu$ can be reconstructed with high efficiency
- A probe to study nuclear shadowing and parton energy loss
- Z^0 also proposed as reference to Υ production.
  - Nuclear effects may depend on mass $M_Z > M_\Upsilon$
- Different production mechanisms:
  - Z^0: antiquark-quark, quark-gluon and antiquark-gluon.
  - Υ: gluon-gluon.

jet- γ and jet-Z^0

Z+jet event in the Heavy Ion collision

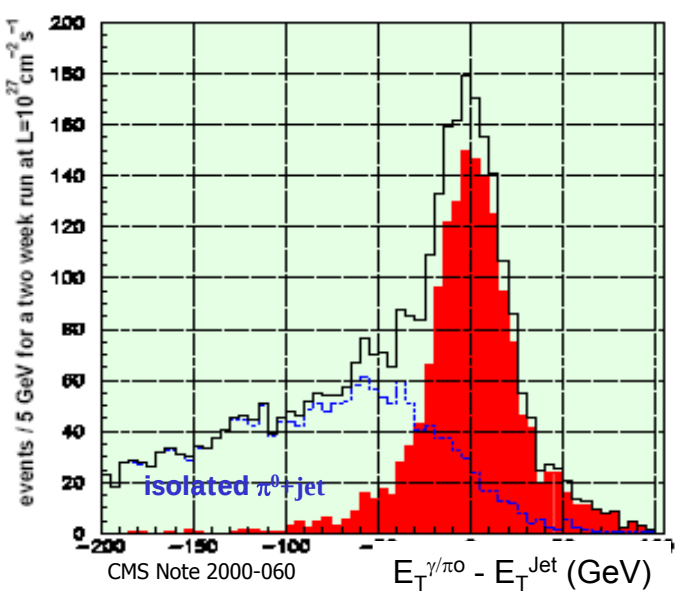
dNch / dY = 5000



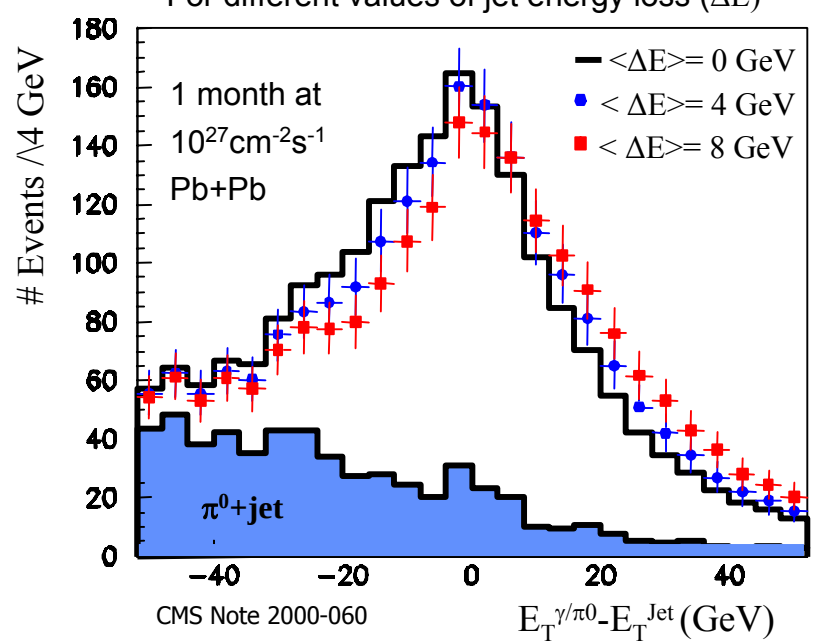
Pt(Z) = Et(Jet) = 100 GeV.

- Study of jet quenching with "calibrated" energy:
  - On average Z^0 or γ E_T and jet E_T should balance
  - Z^0 and γ can be reconstructed with very good E_T resolution
- γ - jet: Larger background from leading π^0 in QCD dijets
- Z – jet: Cleaner but lower rates

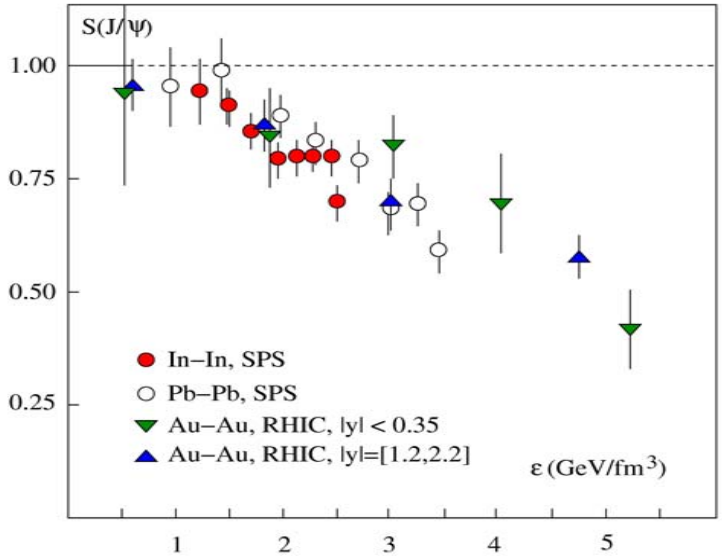
Simulation dN/dy ~7000
E_{Tjet}, γ > 120GeV in Barrel



Simulation dN/dy ~7000 E_{Tjet}, γ > 120GeV in Barrel
For different values of jet energy loss (ΔE)

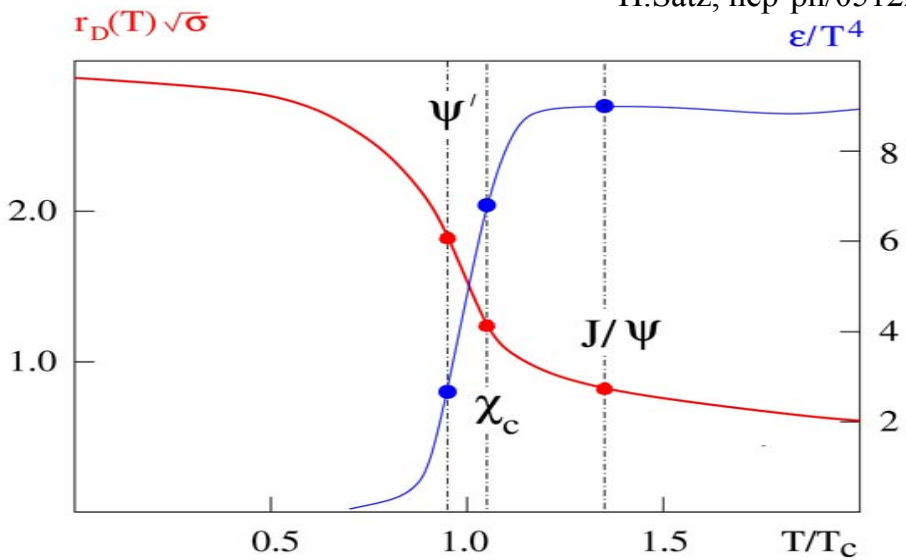


Quarkonia: probe of high-density QCD media

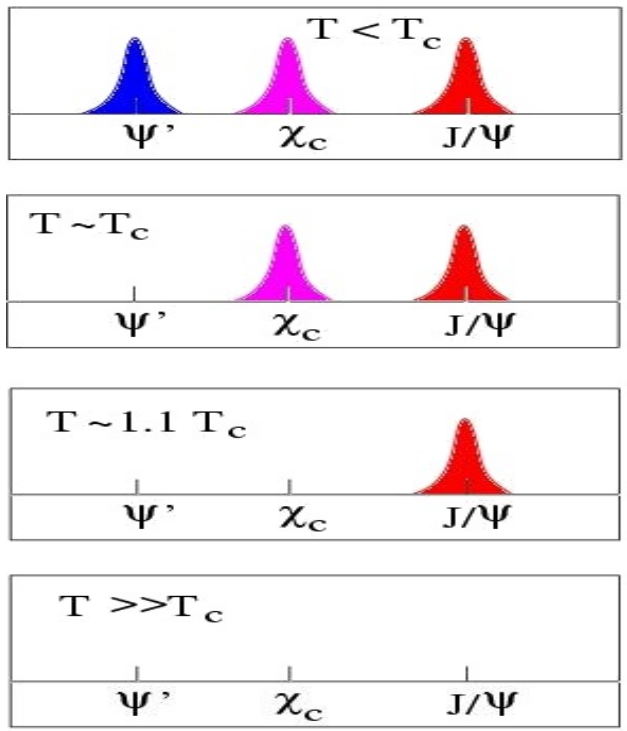


- J/ψ at LHC will clarify SPS/RHIC suppression ($\varepsilon \sim 30$ GeV/fm^3)
- Dissociation = hot QCD matter thermometer

H.Satz, hep-ph/0512217

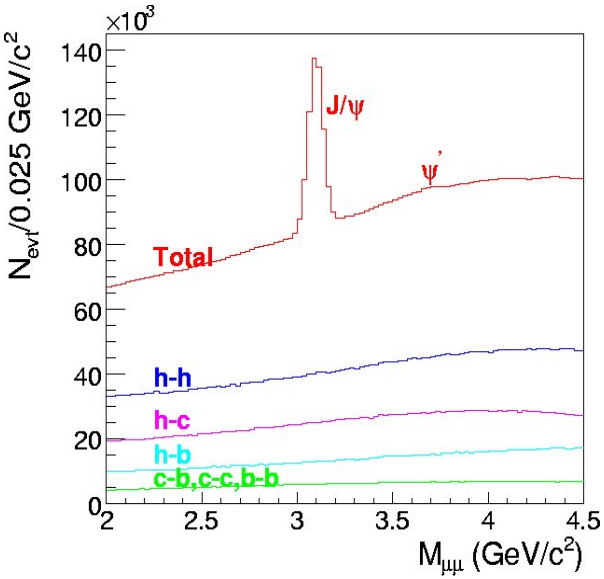


Charmonium spectral function vs T

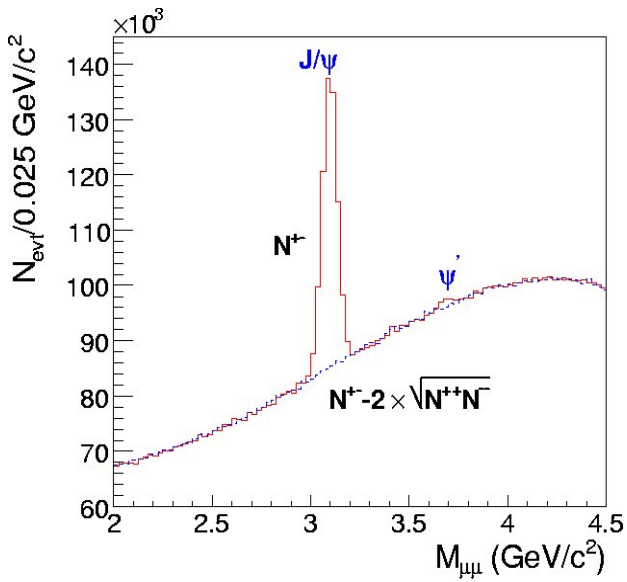


Simulation studies

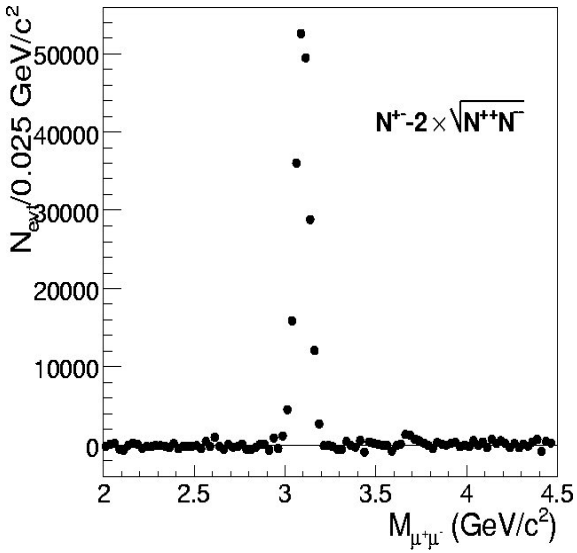
- Signals (J/ψ,Υ): CEM, NLO-pp, CTEQ5M+EKS98 PDF, T_{AA}-scaled
- Light-q background (π,K): HIJING normalized to $dN_{ch}/d\eta$=2500, 5000
- Heavy-Q background (c,b): NLO-pp, CTEQ5M+EKS98 PDF, T_{AA}-scaled
- $\sigma_{J/\psi}$= 35 MeV/c^2 in barrel+endcap (i.e. both muons $|\eta| < 2.4$)



Signal+Background



Estimate background using same sign di-muons



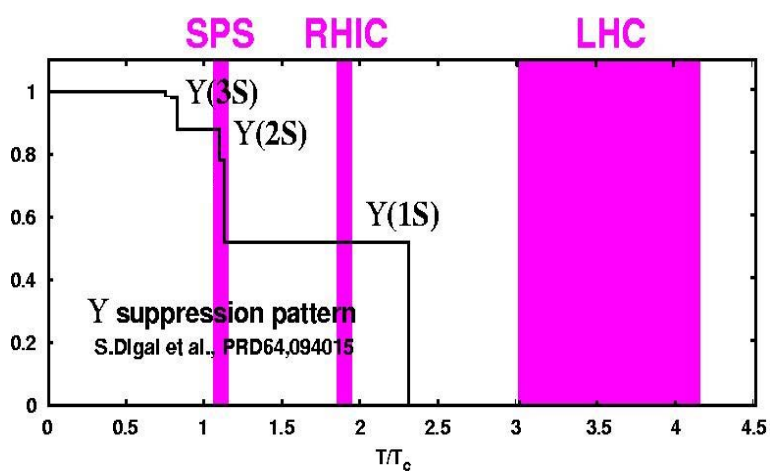
Subtracted background

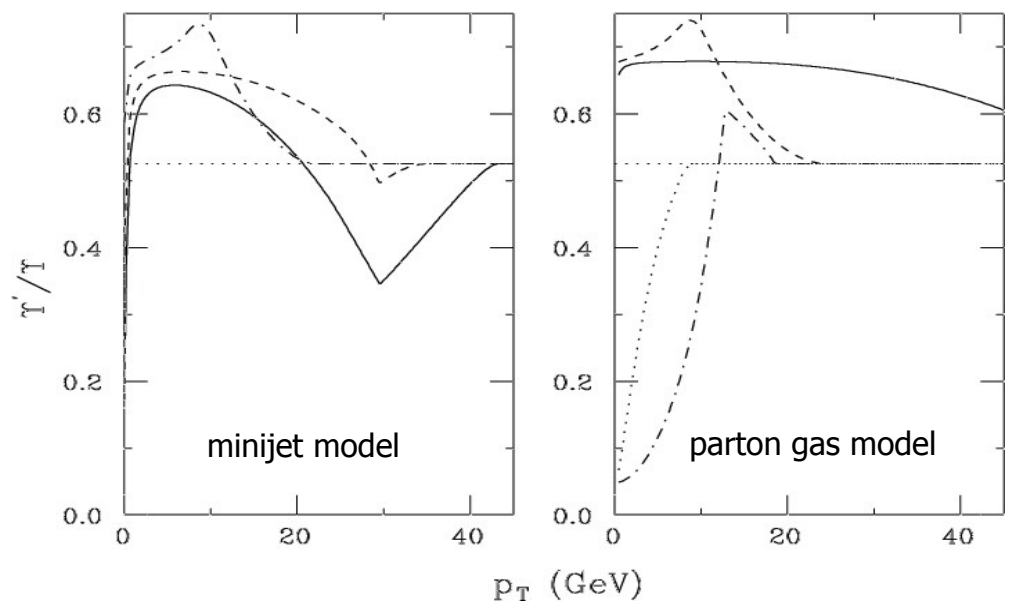
Kodolova, Bedjidian CMS Note-2006/089

ϒ production in AA at the LHC

- Large cross-sections: $d\sigma/dy \sim 20 \times$ RHIC
- ϒ melts only at LHC: $T_D \sim 4$ Tc
- ϒ unaffected by final-state interactions
  - Small hadronic absorption
  - Small # bbar pairs → small ϒ regeneration
- ϒ suppression will be a "cleaner" probe than J/ψ
- ϒ spectroscopy:

T_D (ϒ′) ~ T_D (J/ψ) - ϒ′/ ϒ vs p_T very sensitive to system temperature & size





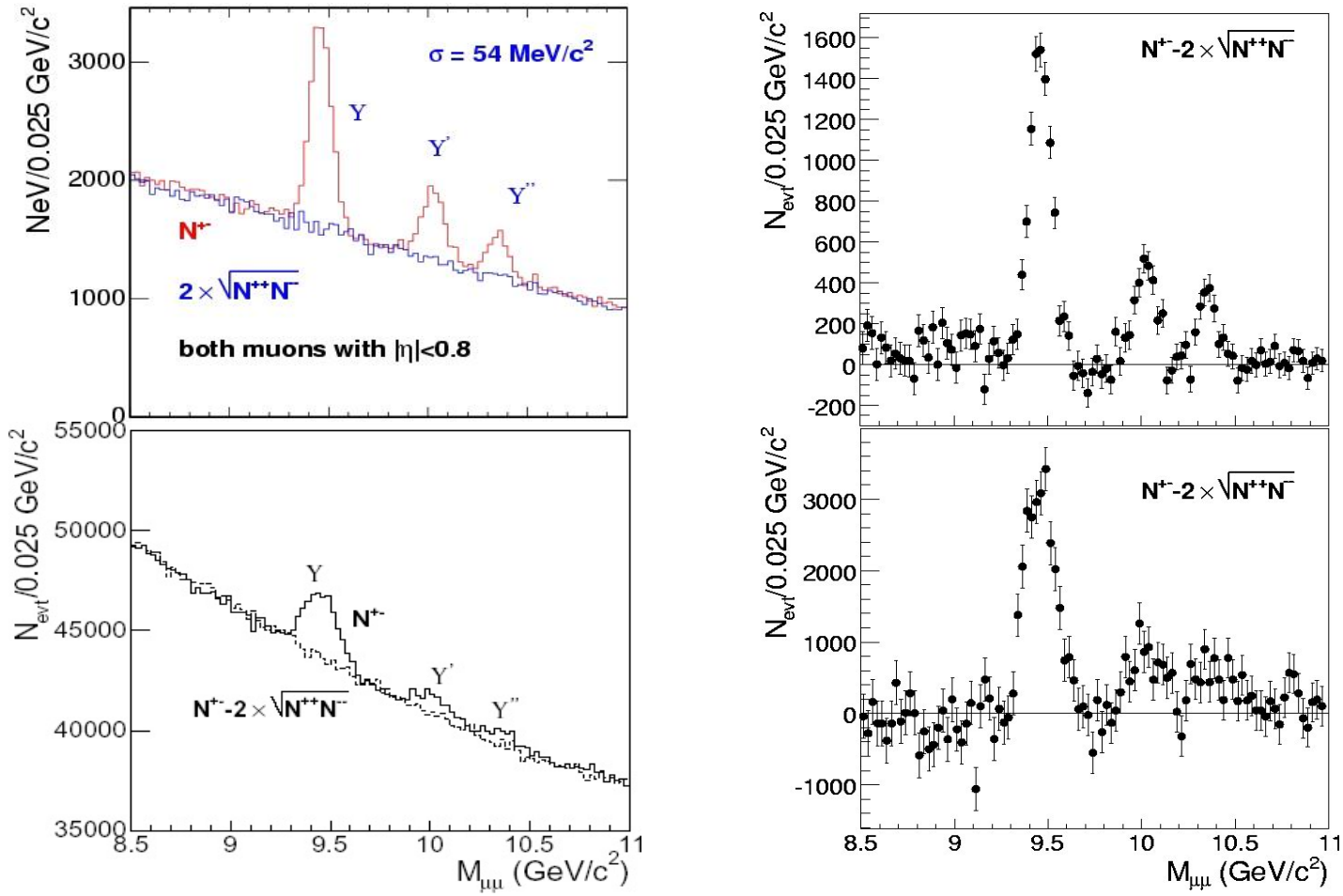
Gunion, Vogt, NPB 492 (1997) 301

ϒ mass spectra simulations

- Multiplicity $dN_{ch}/d\eta \sim 5000$
- $\sigma_{\Upsilon} = 54$ MeV/c^2 (barrel), and $\sigma_{\Upsilon} = 90$ MeV/c^2 (barrel+endcap)

Barrel:
(both muons
$|\eta| < 0.8$)

Barrel+
Endcap:
(bothmuons
$|\eta| < 2.4$)

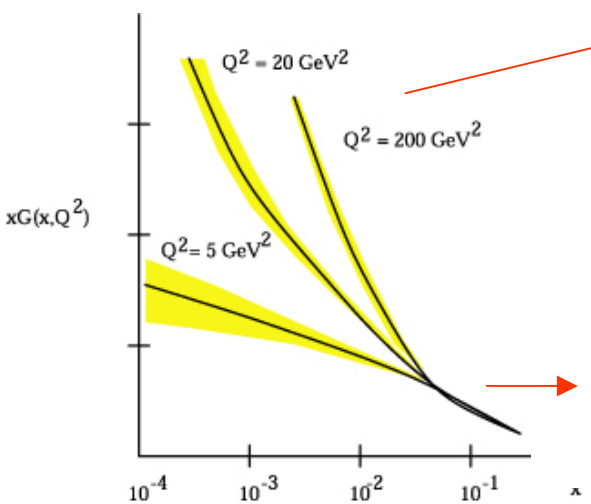


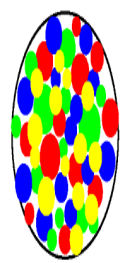
Kodolova, Bedjidian CMS Note-2006/089

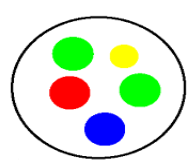
Forward Physics: Gluon saturation region

- New regime of QCD is expected to reveal at small x due to effects of large gluon density
- Forward measurements will be a good test ground for this physics

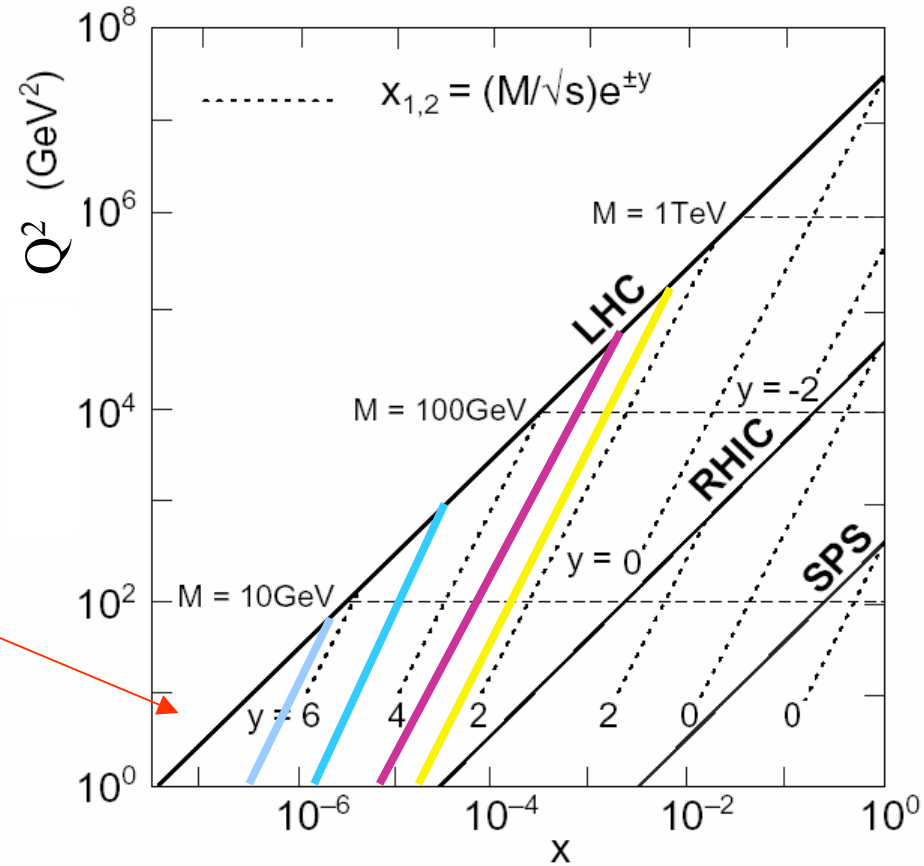
ZEUS data for gluon distribution
In partons







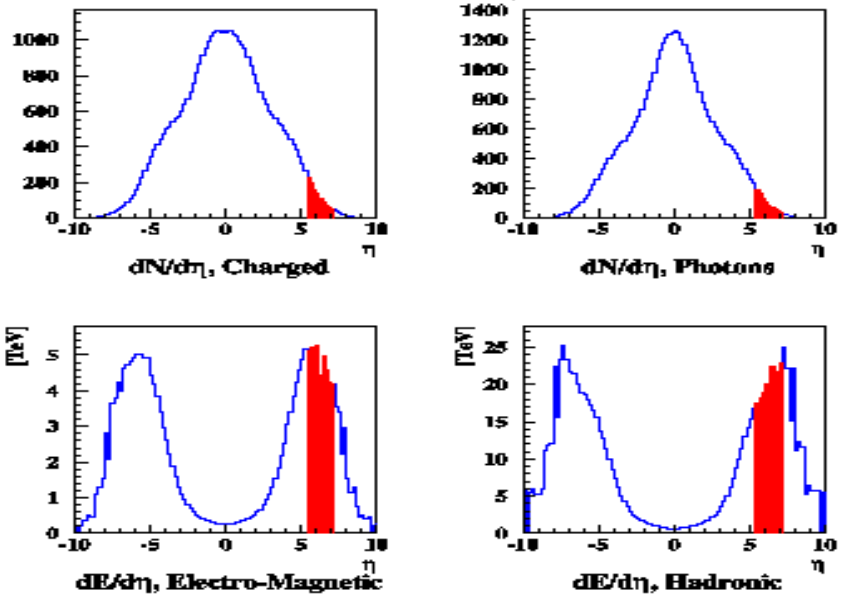
McLerran, hep-ph/0311028

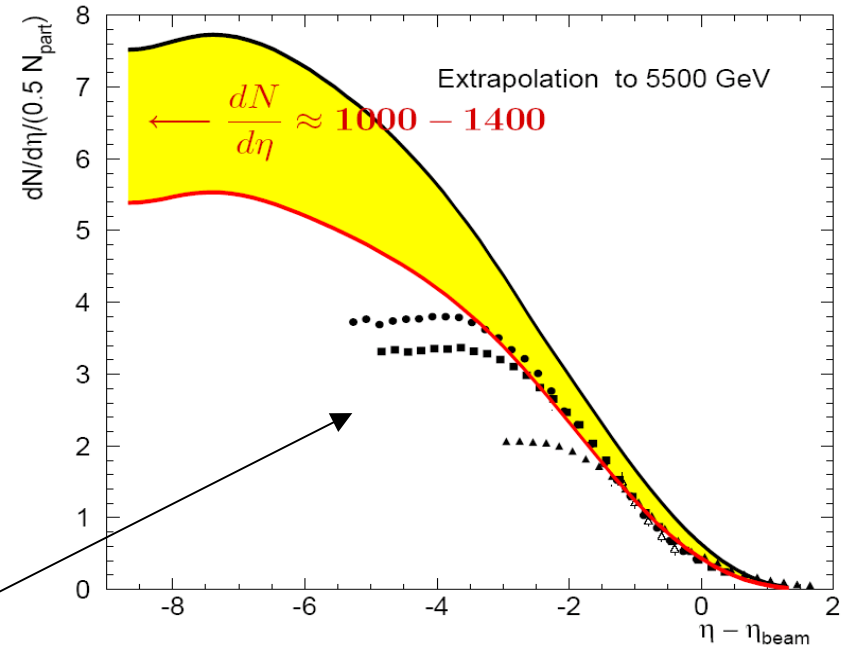


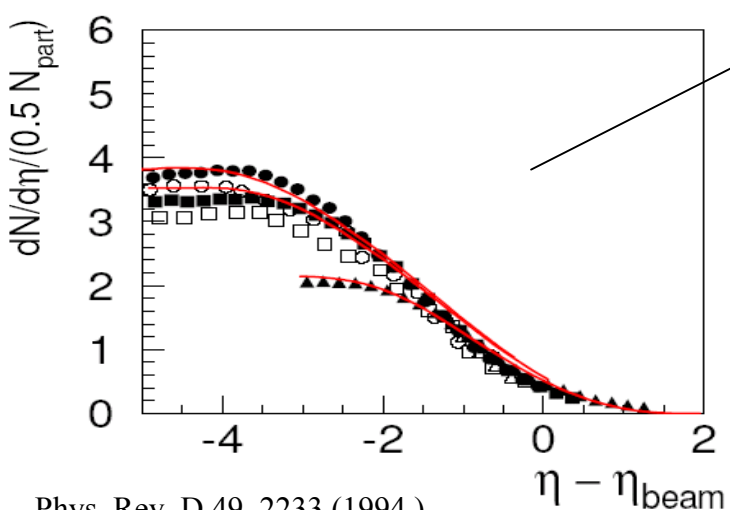
Sub detector	Coverage
Forward HCAL	3 .0< | η | < 5.2
CASTOR	5.2 < | η | < 6.6
ZDC	8.3 < |η|

Limiting Fragmentation

Castor Coverage



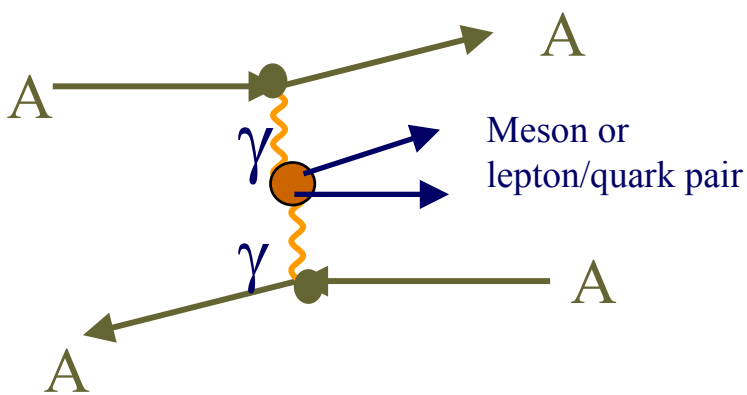


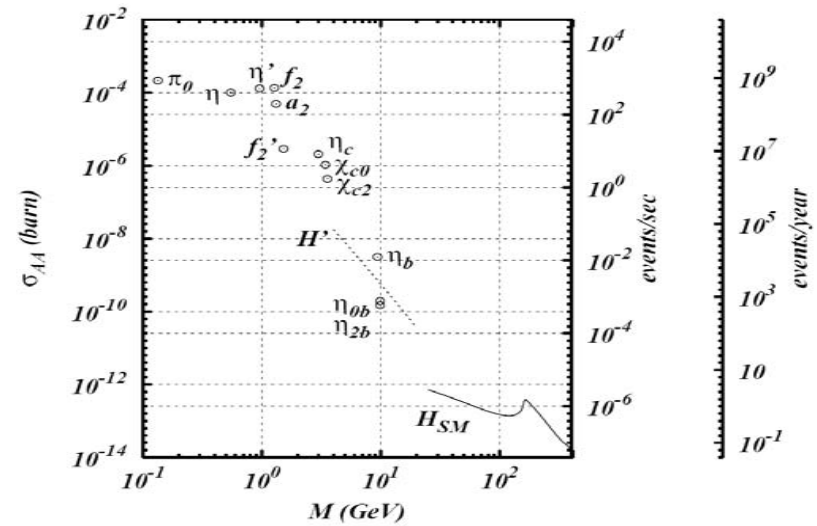


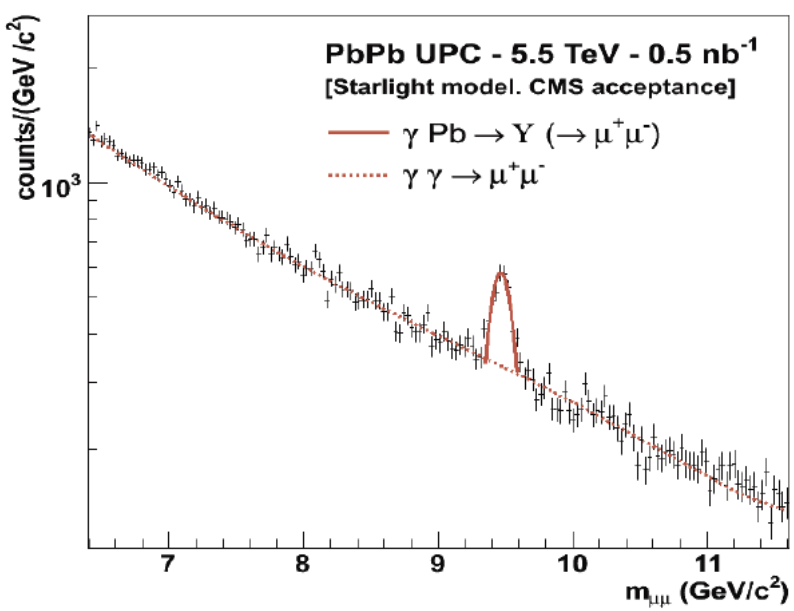
Phys. Rev. D 49, 2233 (1994)

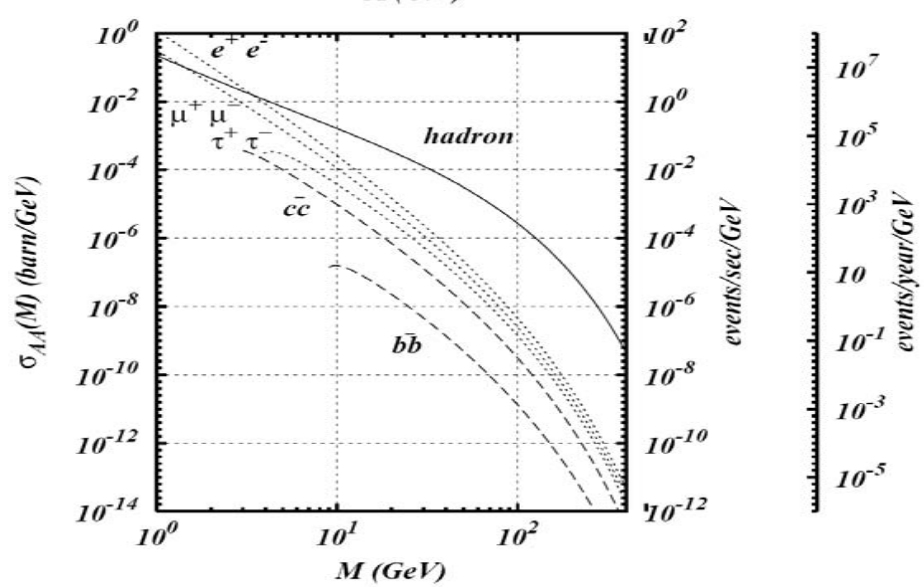
- At RHIC limited fragmentation can be explained by gluon saturation (Clolor Glass Condensate) model.
  - Data PHOBOS 200 and 130 GeV AuAu
  - Model McLerran-Venugopalan
- This can be measured also at LHC for larger gluon density region

Ultra-Peripheral collisions γγ cross sections







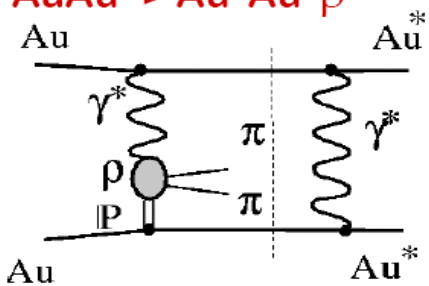


ZDC to trigger + two muons in the central detector

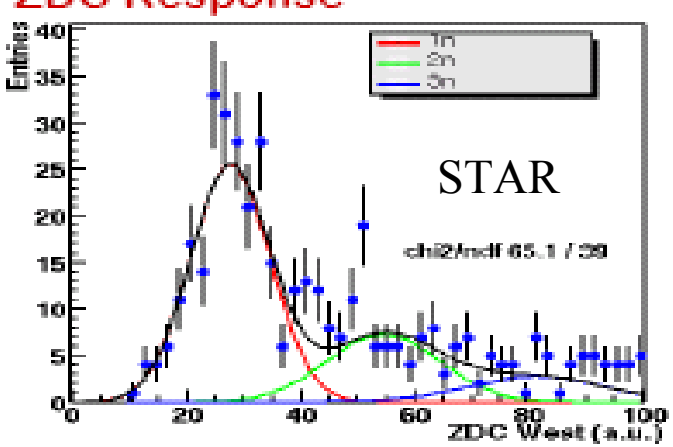
γγ Physics Cont.

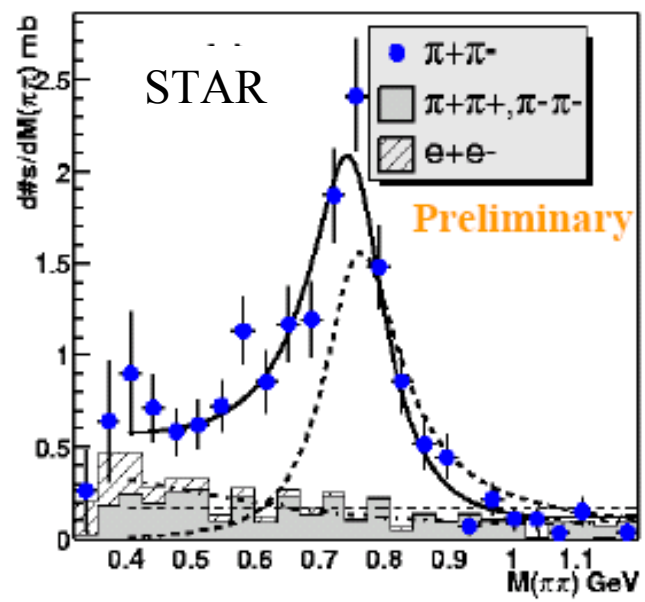
- Light quarks
  - Difficult to measure at CMS because of low p_T (~ 50 MeV) and low rate, challenge for triggering
  - ZDC + multiplicity trigger a la STAR?

AuAu -> Au*Au*ρ⁰



ZDC Response





Phys. Rev. Lett. **89** (2002) 272302

Heavy Ion Physics Program in CMS

Soft physics and global event characterization

- Centrality and good event selection
- Charged particle multiplicity
- Azimuthal asymmetry (Flow)
- Spectra + Correlations

High p_T Probes

- High p_T Jets - detailed studies of jet fragmentation, centrality dependence, azimuthal asymmetry, flavor dependence, leading particle studies
- High energy photons, Z^0
- jet-γ, jet-Z^0, multijet events
- Quarkonia (J/ψ, Υ) and heavy quarks

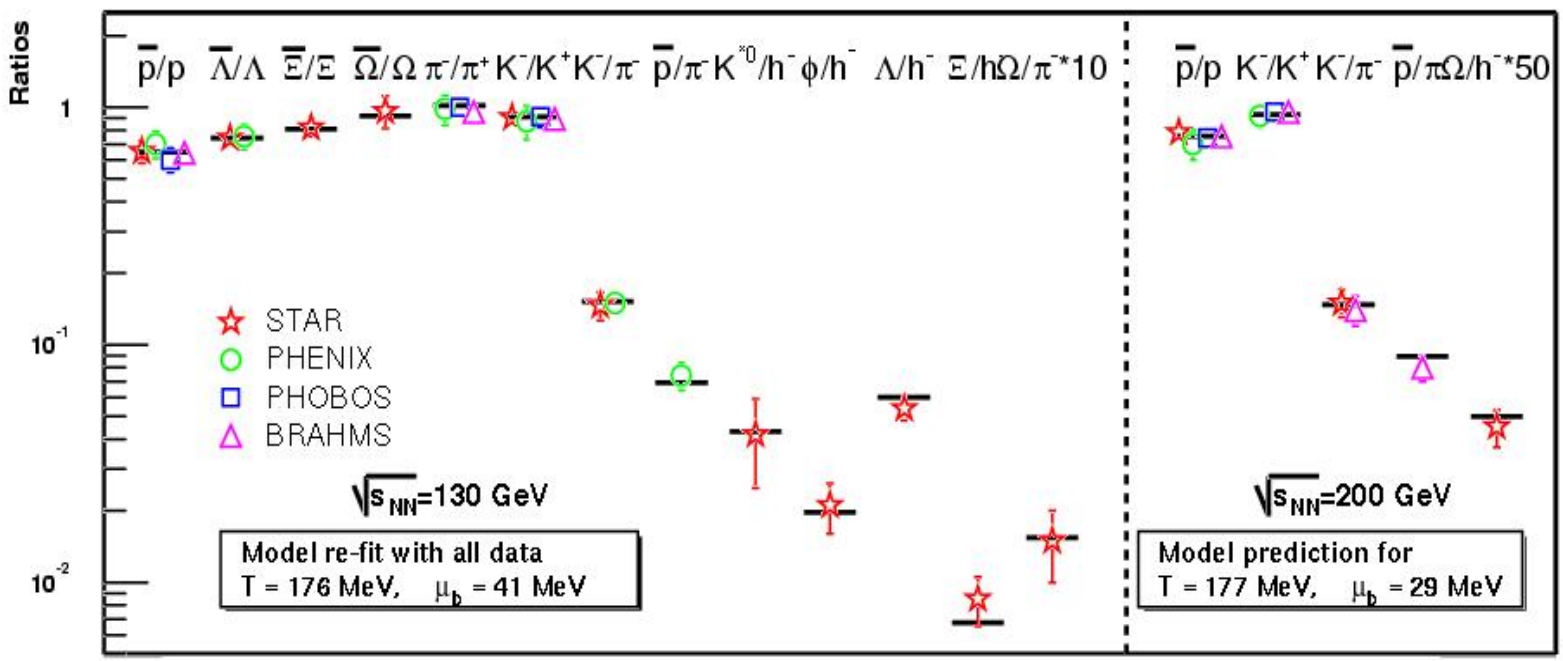
Forward Physics

- Limiting Fragmentation, Saturation, Color Glass Condensate
- Ultra Peripheral Collisions
- Exotica

Backup Transparencies

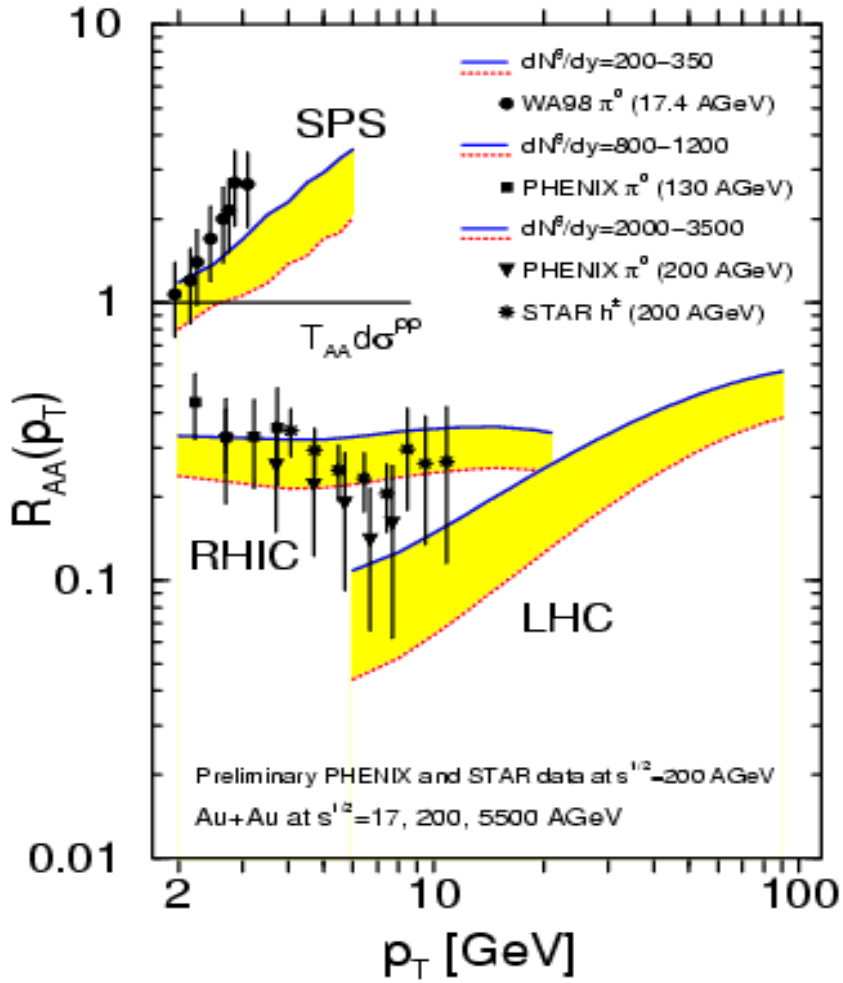
Results At RHIC Energies

Phys Lett. B. 518, 41 (2001); J. Phys G28, 1745 (2002)

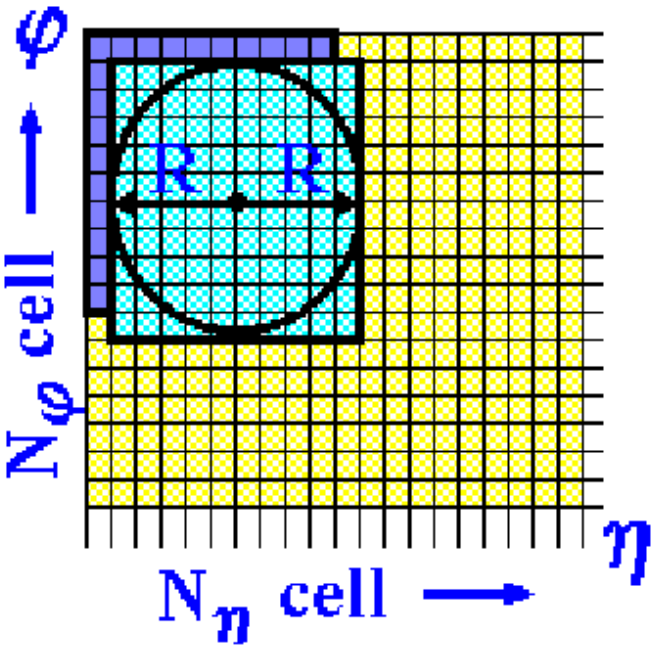


- Can fit each energy with a common chemical "freeze-out" temperature, T_{ch}, and baryon chemical potential μ_B.
- Suggests a high degree of chemical equilibrium (and thermalization) at the point where particles are "frozen-out" (created).

Nuclear modification factor RHIC to LHC



Background Subtraction Algorithm



Event-by-event background subtraction:

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

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

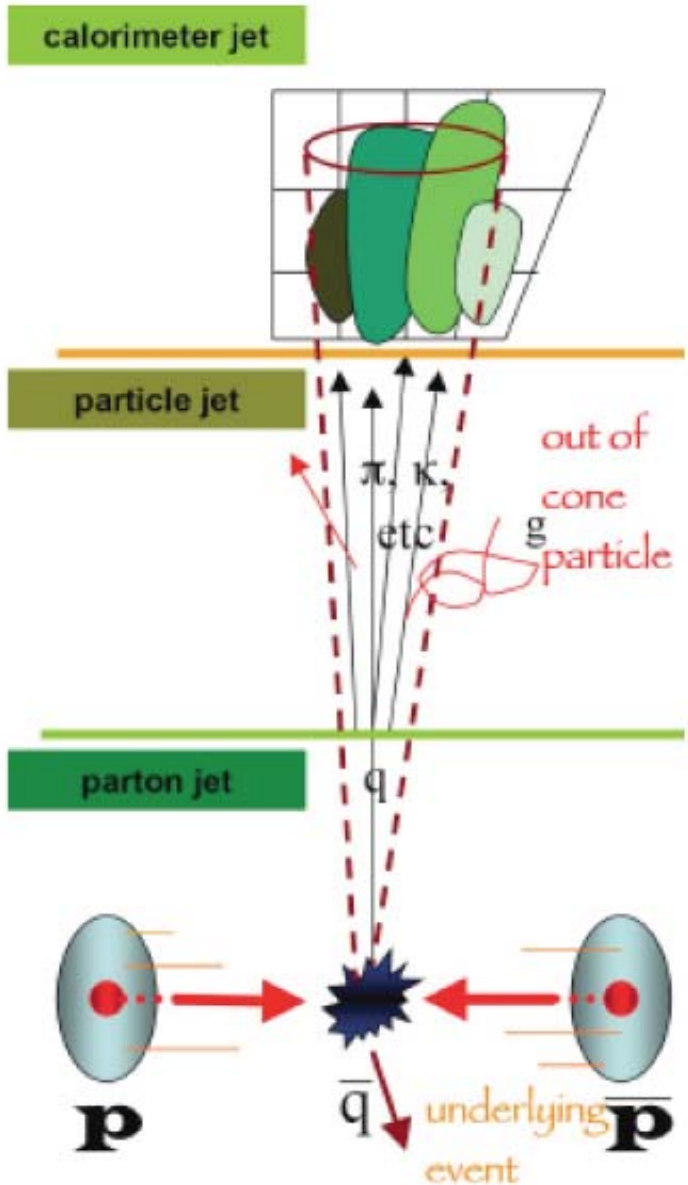
$$E_t^{pile\text{-}up} = \langle E_T^{Tower}(h)\rangle + D^{Tower}(h)$$

- Negative tower energies are replaced by zero

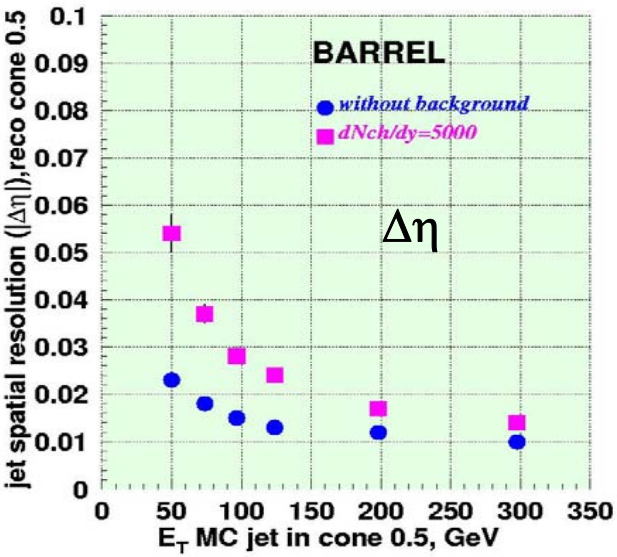
- Find Jets with $E_T^{jet} > E_t^{cut}$ using standard iterative cone algorithm using new tower energies
- Recalculate pile-up energy with towers outside of the jet cone
- Recalculate tower energy with new pile up energy
- Final jets are found with the same iterative cone algorithm $E_T^{Jet} = E_T^{cone}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

Jet Definitions

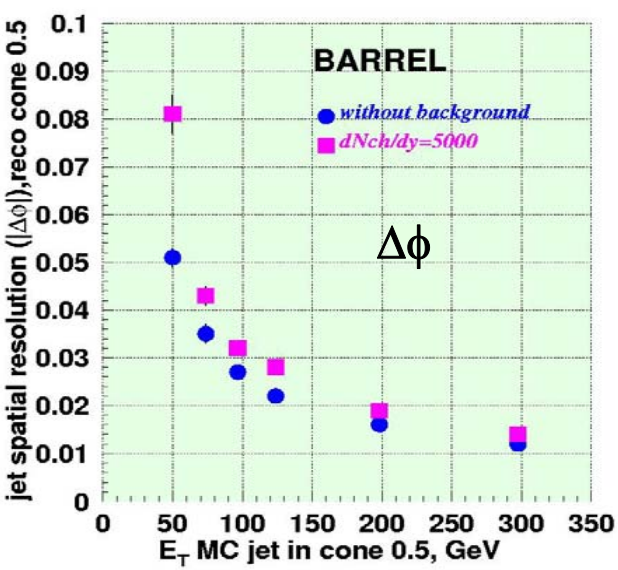
- Parton jet
  - This is what we can calculate
- Final state particle jet
  - Fragmentation/hdronization
  - Non-pertubative
  - MC generators rely on parametrizations of experimental data
- Calorimeter Jet
  - This is what we measure in the detector
- Need to associate final state particles with initial parton
  - No unique way of doing this!
  - Jet algorithms
  - => Jet Calibration

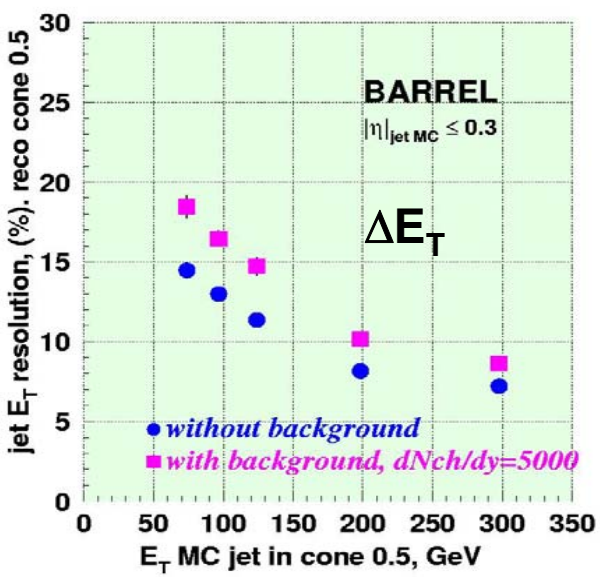


Jet Resolutions



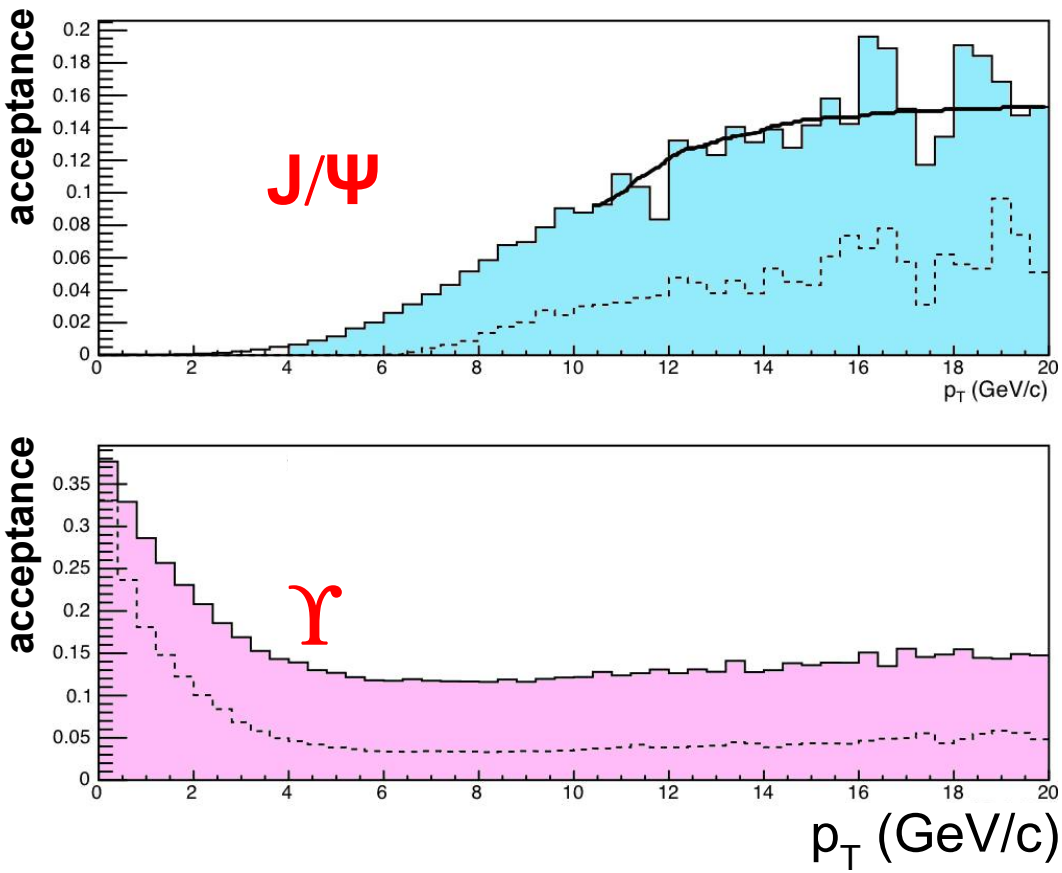
- $\Delta\eta$, $\Delta\phi$ better than size of calorimeter tower (0.087x0.087)
- E_T resolution ~16% at 100GeV
- Further improvement can be achieved by adding tracker information
  - p_T measurement of tracks is more precise than the response of the calorimeter
  - Recover charged tracks that are bent out of the jet cone by the magnetic field

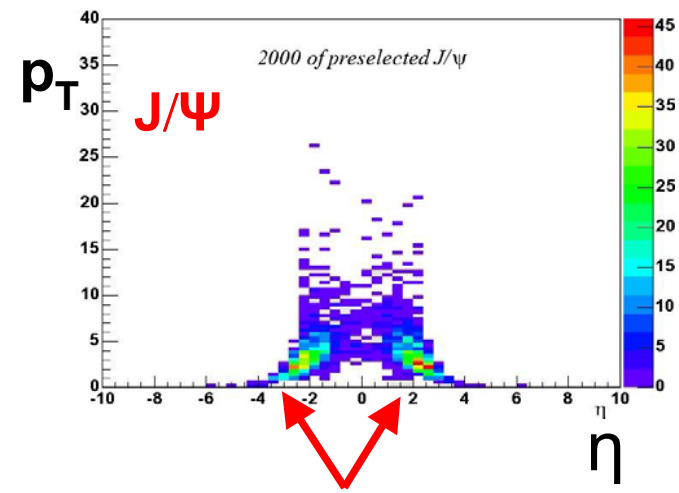




J/ψ, ϒ acceptances

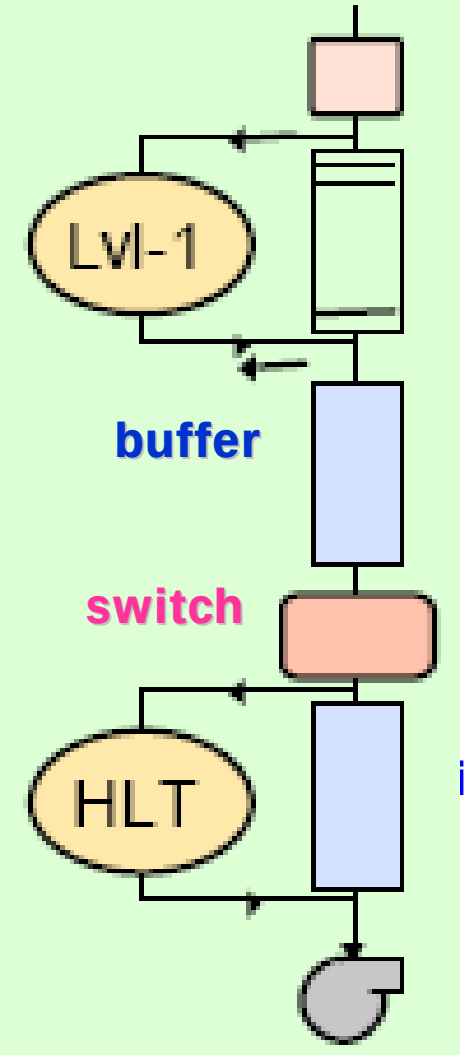
- J/Ψ accepted above p_T~2 GeV/c (low-p_T muons absorbed in material at y=0, but punchthrough at y~2). High-p_T acceptance ~15%
- ϒ accepted (~35%) down to p_T=0 GeV/c. High-p_T acceptance ~15%





Improved low p_T J/Ψ acceptance at forward rapidities

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

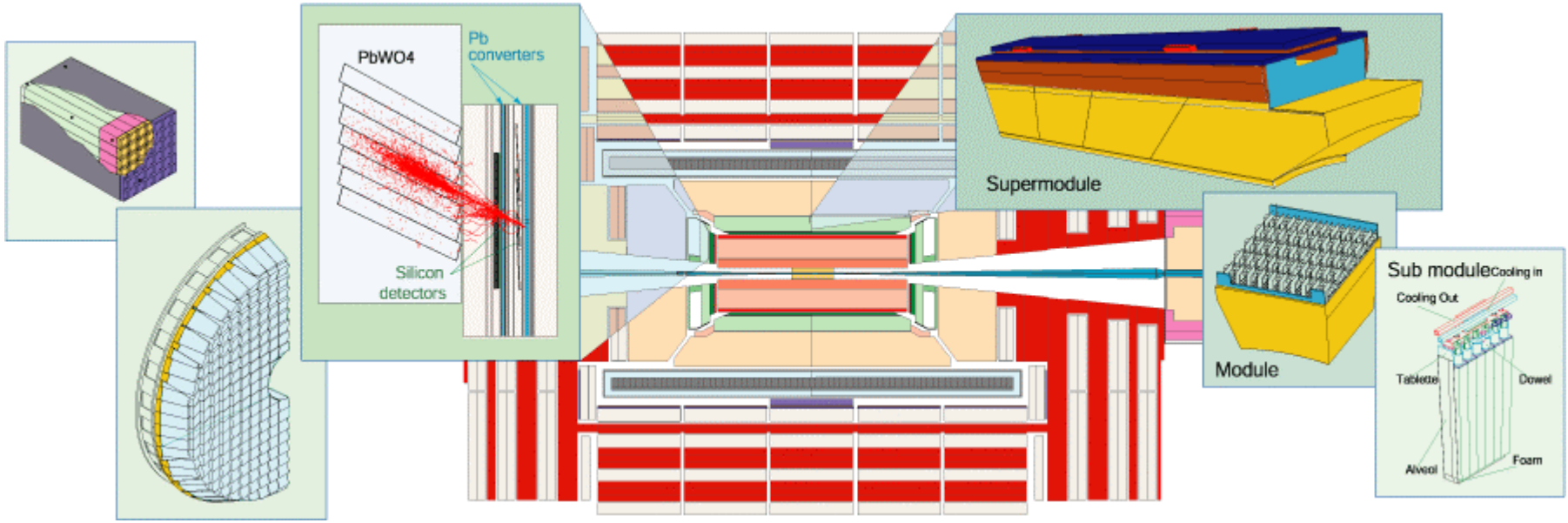
- Full event information available
- Every event accepted by L1 sent to an online farm of 2000 PCs
- Output rate (Pb+Pb): ***~ 40 Hz***
- ***Trigger algorithm same or similar to offline reconstruction***

Electromagnetic Calorimeter

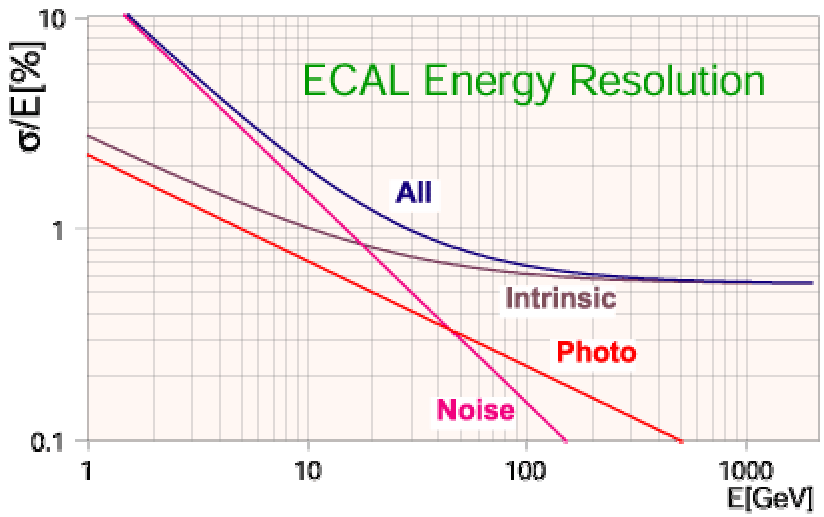
EECAL

|η|< 3 (1.5 barrel)

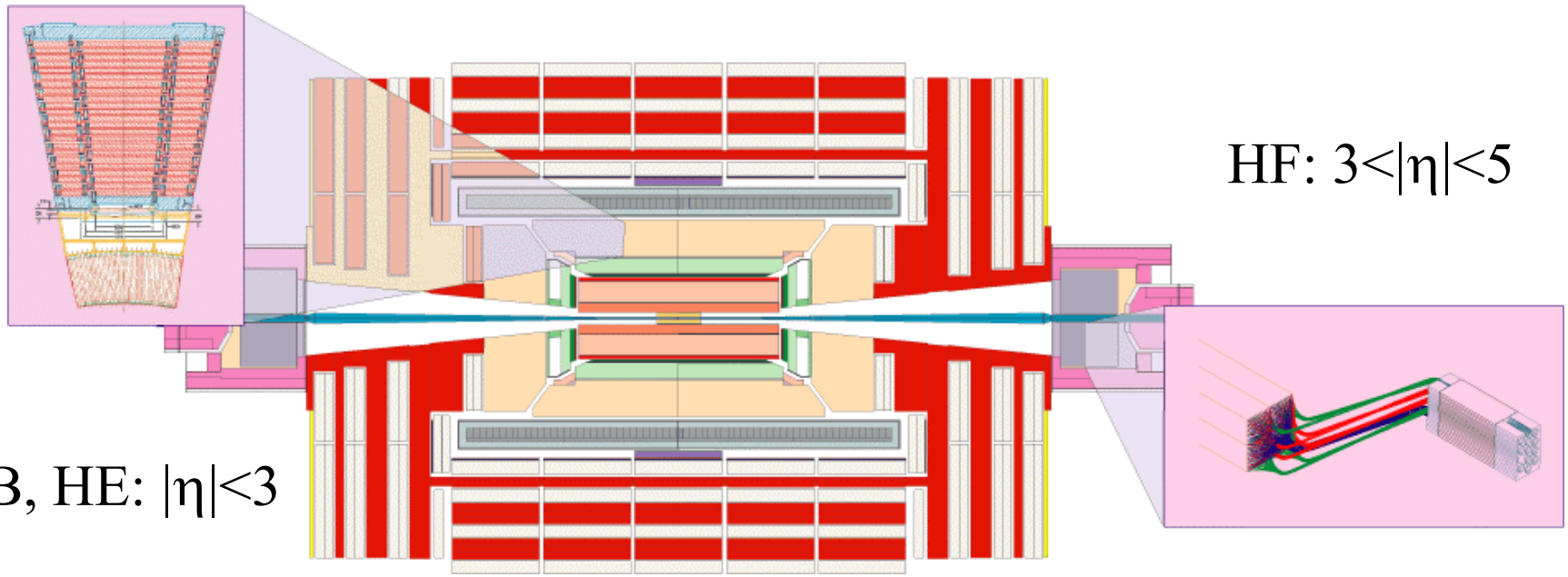
BECAL



- 76000 PbWO4 crystals
  - Granularity in $\Delta\eta$ x $\Delta\phi$:
  - 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

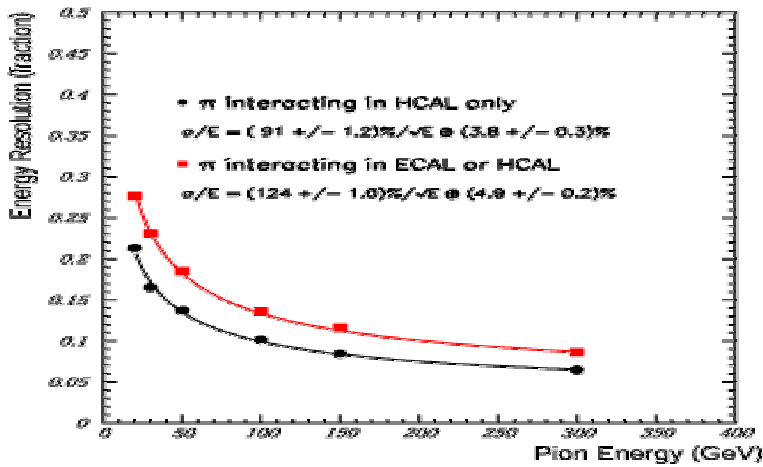


HCAL



- Barrel (HB) and Endcap (HE): Cu/Scintillator
- Forward (HF): Fe/Cerenkov(fiber)
- High granularity: $\Delta\eta$ x $\Delta\phi$
  - 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

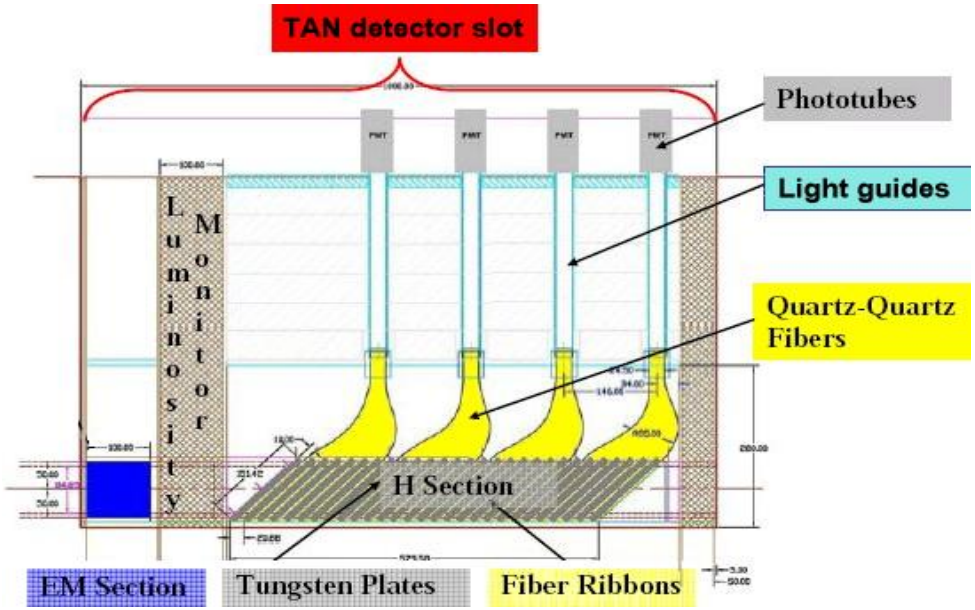
π Energy Resolution



Granularity

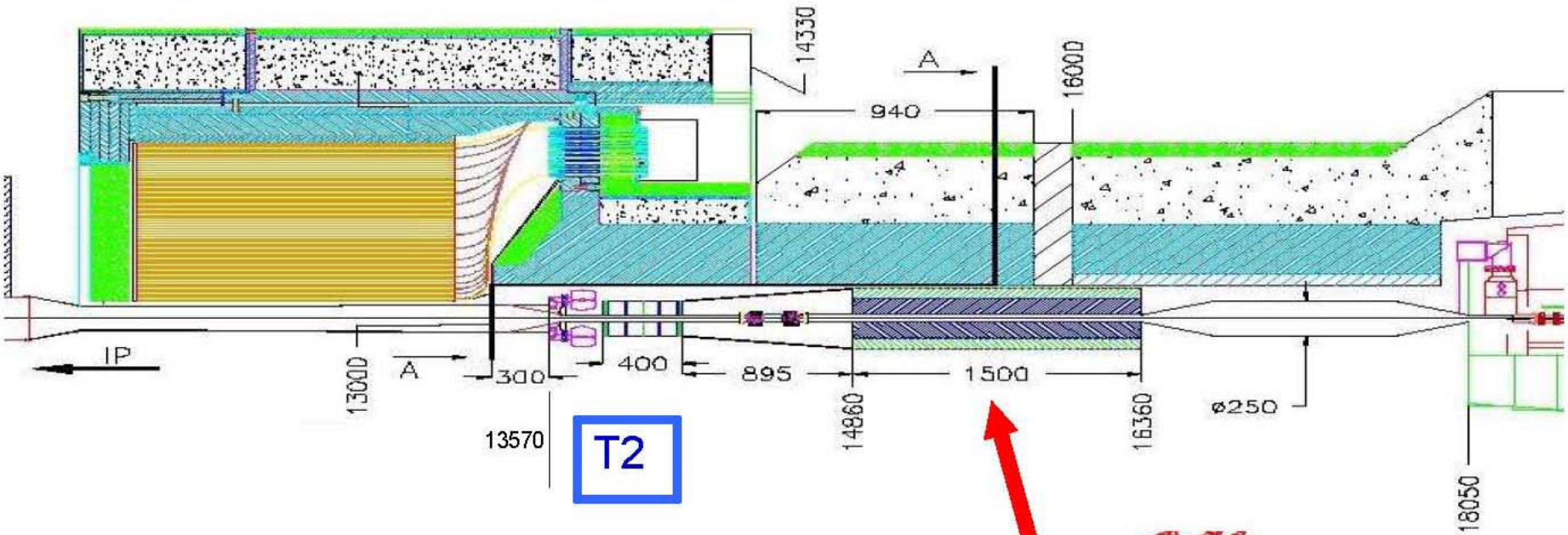
Rapidity coverage	$0 < \|\eta\| < 1.5$		$1.5 < \|\eta\| < 3.0$		$3.0 < \|\eta\| < 5.2$
Subdetector	HCal (HB)	ECal (EB)	HCal(HE)	ECal (EE)	HF
$\sigma/E = a/\sqrt{E} \bigoplus b$					
a	1.16	0.027	0.91	0.057	0.77
b	0.05	0.0055	0.05	0.0055	0.05
granularity $\Delta\eta$ x $\Delta\phi$	0,087 x 0.087	0.0174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

Zero Degree Calorimeter

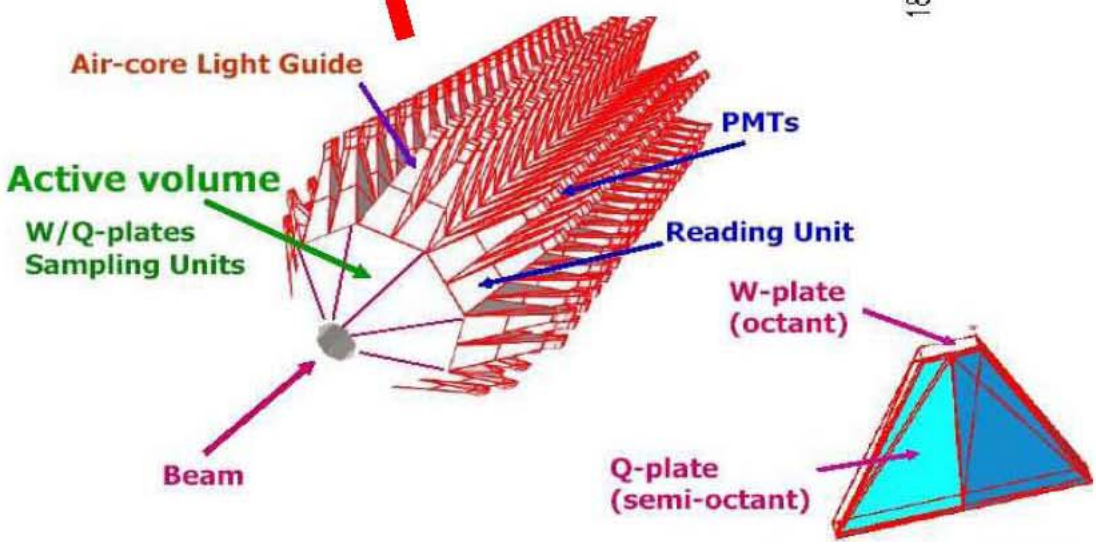


- Tungsten-quartz fibre structure
- electromagnetic section: $19X_0$
- hadronic section $5.6\lambda_0$
- Rad. hard to ≈20 Grad (AA, pp low lum.)
- Energy resolution: ≈10% at 2.75 TeV
- Position resolution: ≈2 mm (EM sect.)

CASTOR

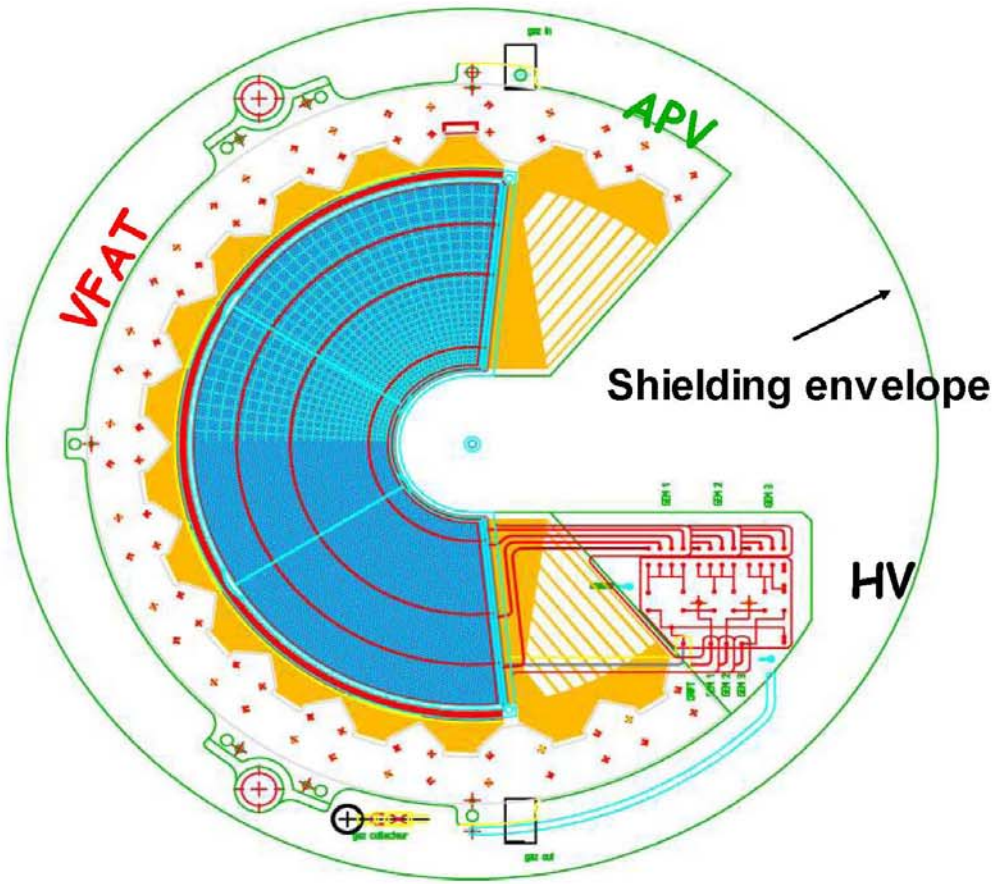


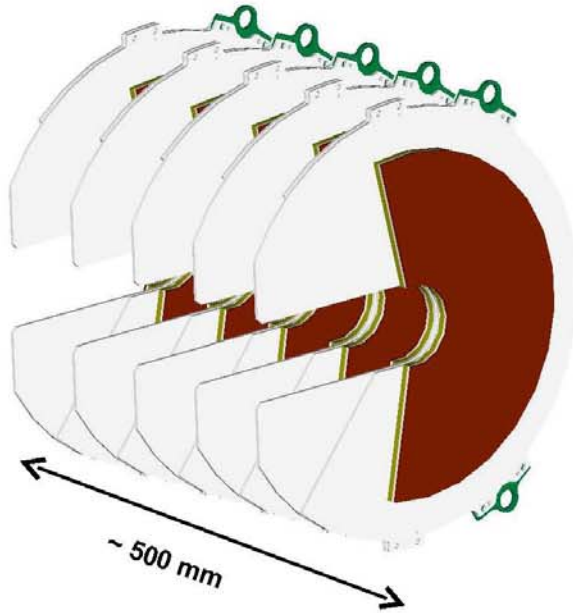
- Tungsten plates + quartz fibres
- Cherenkov sampling calorimeter
- Light-guides + APDs readout
- Azimuth segmented (8 octants)
- EM section: 11.2 cm ~ 19 X_0
- HAD+EM sections: 136 cm~ 10 λ_I
- 192 channels



TOTEM (T2)

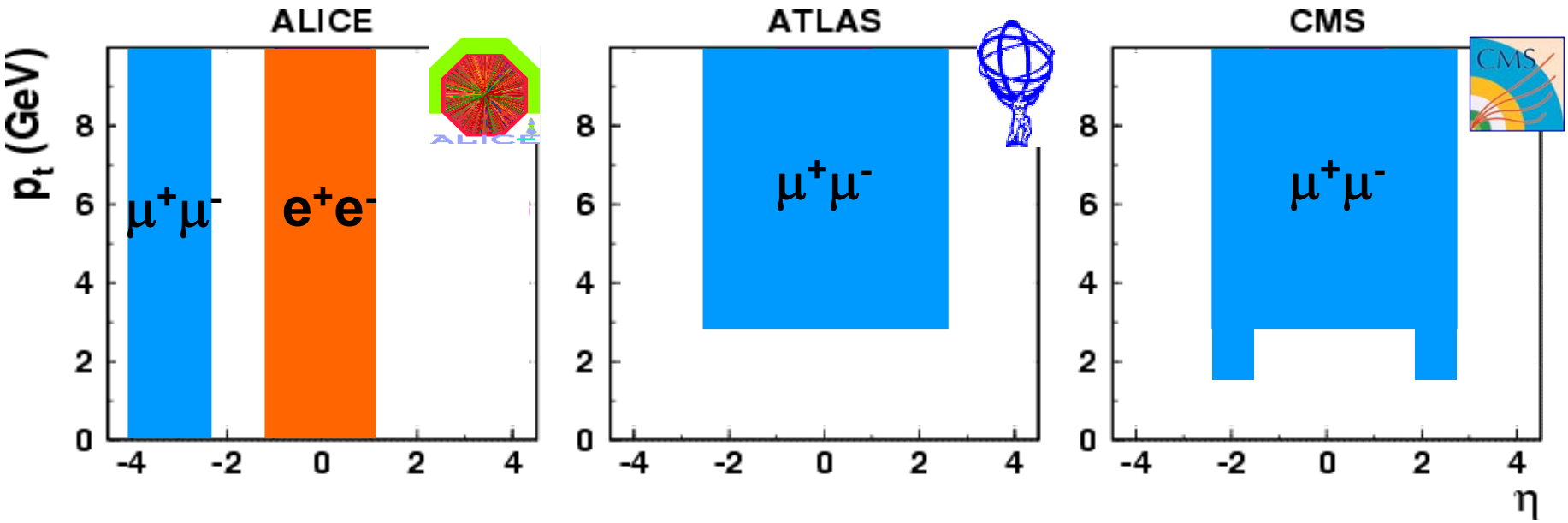
- TOTEM GEM ("Gas Electron Multiplier") charged particle telescope detector:

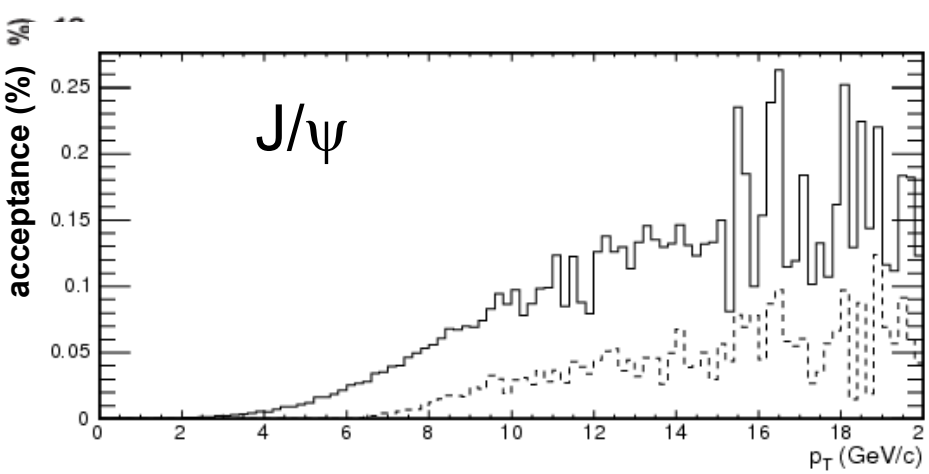


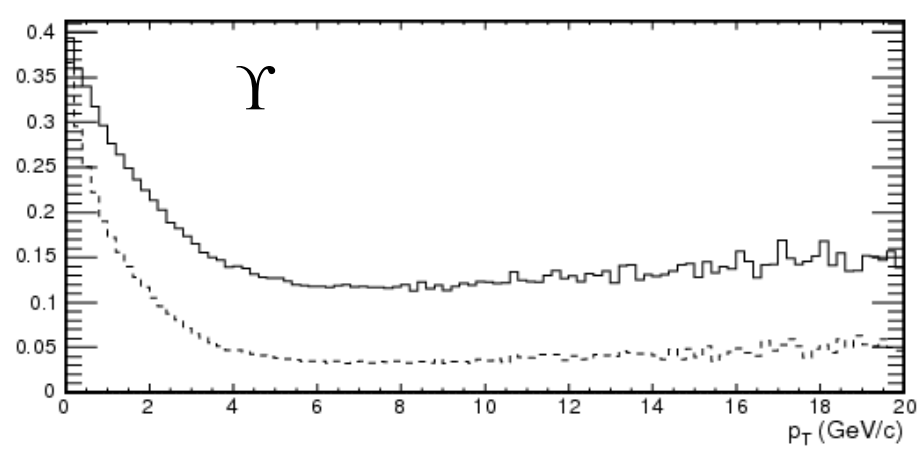


GEM half telescope

Quarkonia acceptances



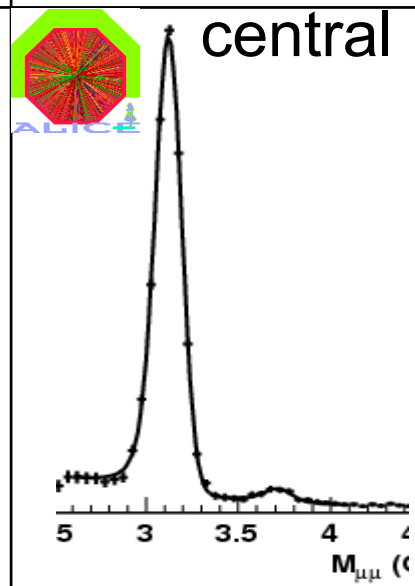
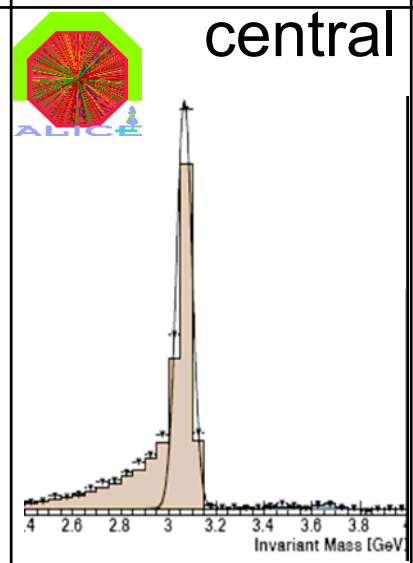
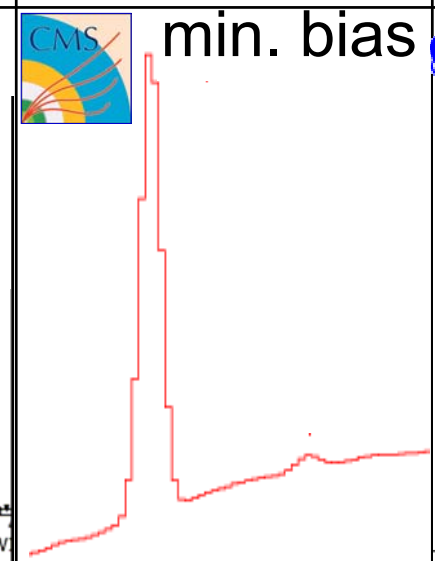
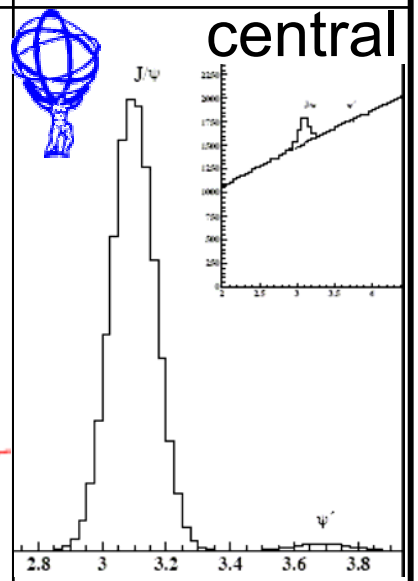




Andrea Dainese Hard Probes 2006

Charmonia Performance

Bkg input: dN_{ch}/dy~2500-4000 in central Pb-Pb. $S/\sqrt{S+B}$ for 1 month

	ALICE $\mu^+\mu^-$	ALICE e^+e^-	CMS $\mu^+\mu^-$	ATLAS $\mu^+\mu^-$
				
acc. η	$-4 < \eta < -2.5$	$\lvert\eta\rvert < 0.9$	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 2$
M res.	65 MeV	35 MeV	37 MeV	70 MeV
$S/\sqrt{S+B}$ J/ψ, ψ'	**150, 7**	**245, --**	**313, --**	**60, --**
perf.	ψ, ?ψ'	ψ, ??ψ'	ψ, ?ψ'	ψ, ψ'
p_t J/ψ	0-20 GeV	0-10 GeV	few-20 GeV	--