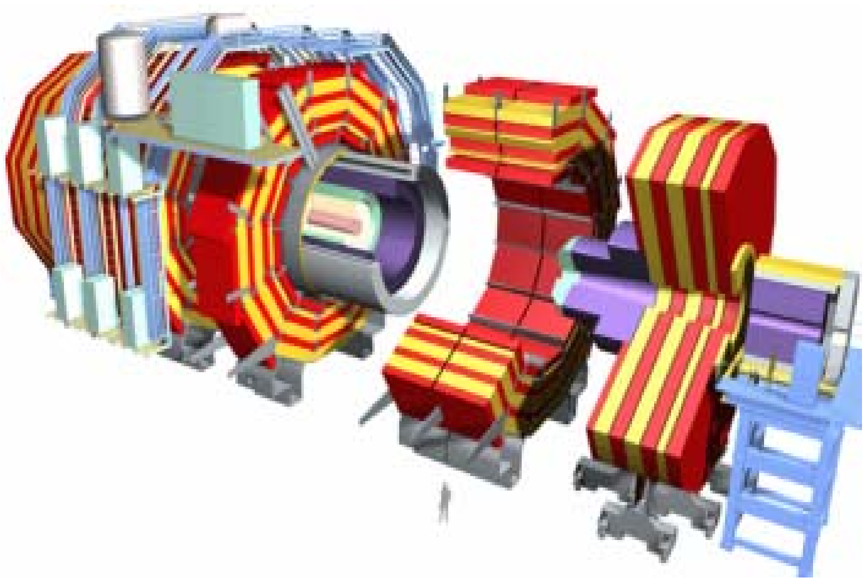
Heavy Ion Physics with CMS at the LHC



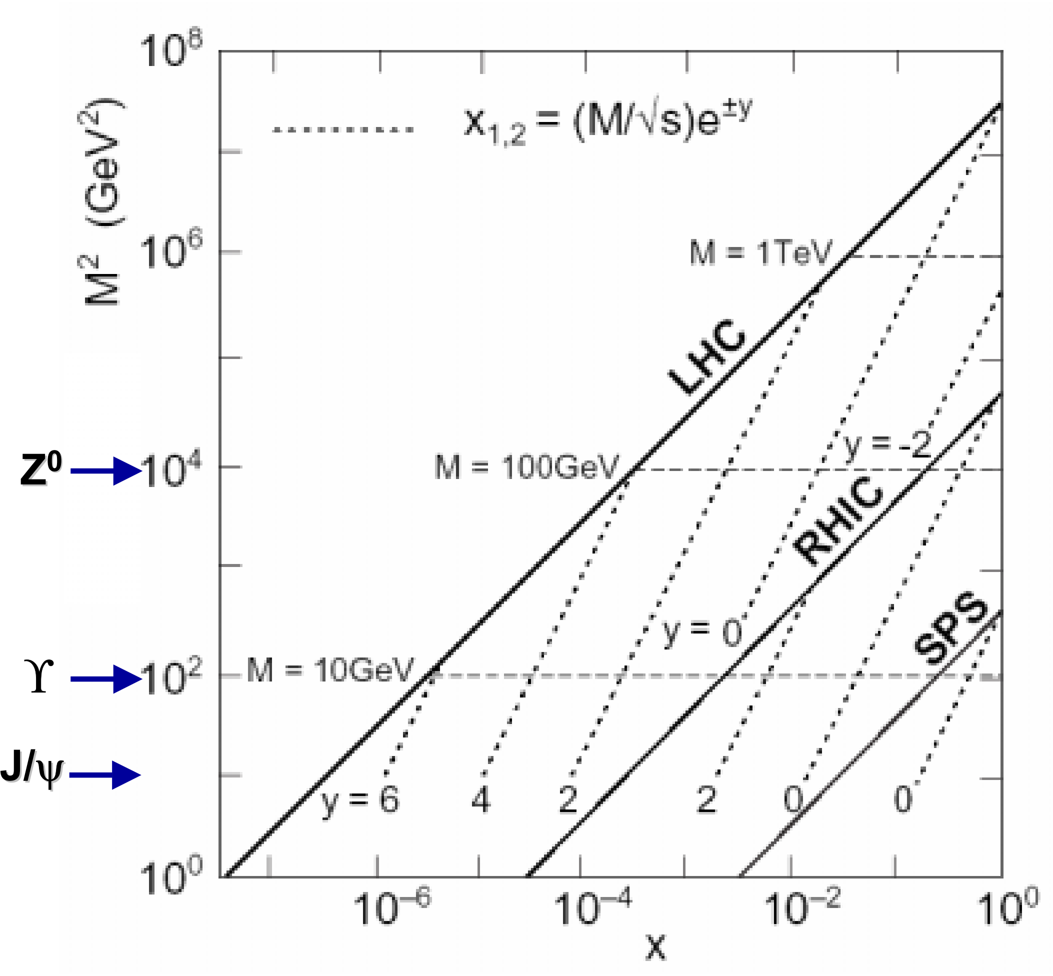
Russell Betts

UIC

June 4, 2004

Athens, Basel, CERN, Demokritos, Dubna, Ioannina, Kiev, Lyon, **MIT**, Moscow, N. Zealand, Protvino, PSI, **Rice**, Sofia, Strasbourg, Tbilisi, **UC Davis**, **UC Riverside**, **UIC**, **U. Iowa**, **U Kansas**, Warsaw, Yerevan

A New Viewpoint for QCD Matter



Initial state dominated by low-x components.

Abundant production of variety of perturbatively produced high p_T particles for detailed studies

Higher initial energy density state with longer time in QGP phase

Access to new regions of x

What will CMS Contribute ?

Full Calorimeter and Tracking Coverage

High Rate Detectors

Superior Momentum Resolution - 4T Field

No Modification to Detector Hardware for HI

New High Level Trigger Algorithms for HI

Detailed Studies with High p_T Probes

High Mass Resolution for Quarkonia

Centrality, Multiplicity, Spectra, Energy Flow to Very Low p_T

Zero Degree Calorimeter, CASTOR and TOTEM Provide Unique Access to Forward Physics

Heavy Ion Program Firmly Integrated into Overall CMS Physics Program Leadership Role for US

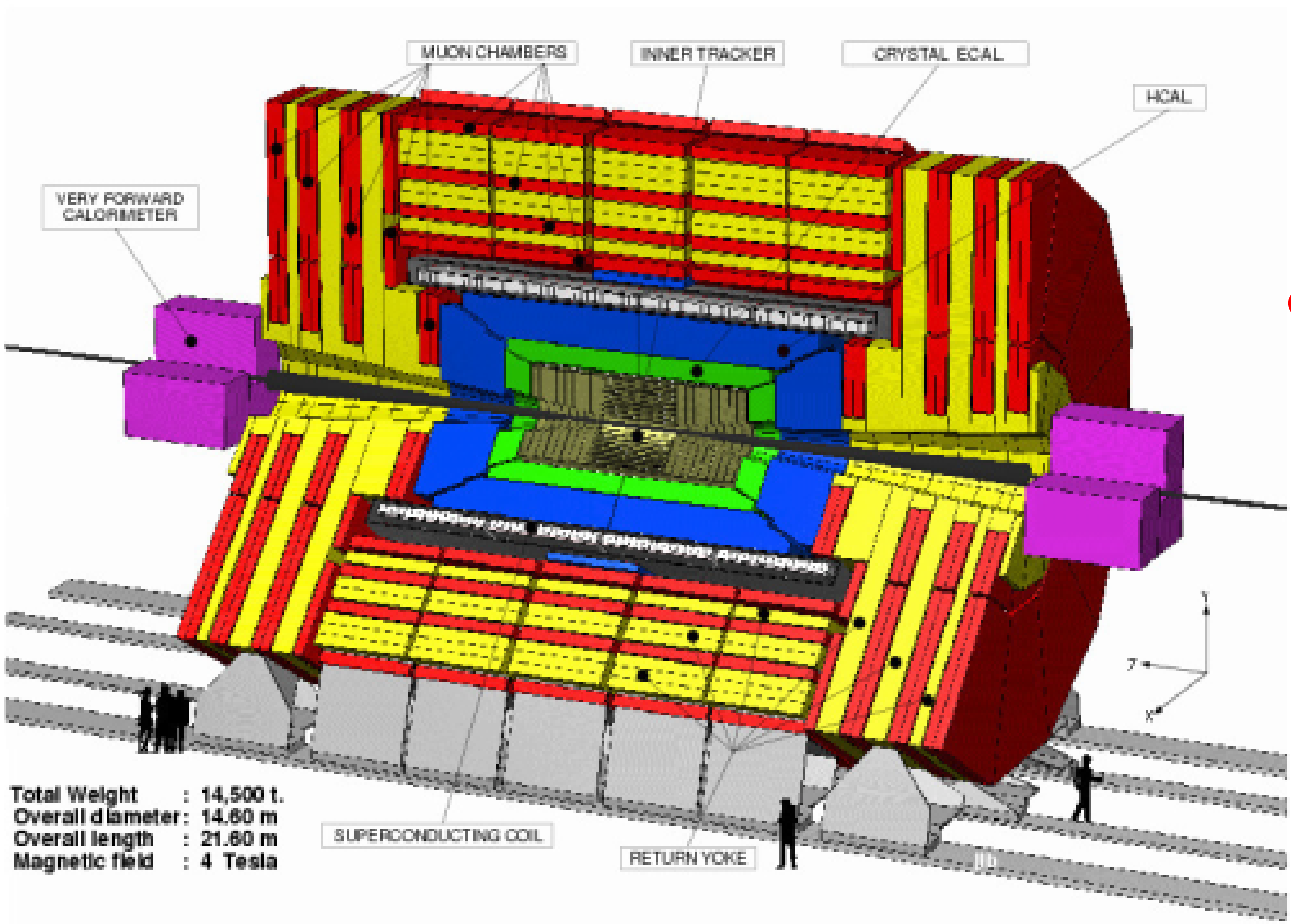
Symbiosis with US CMS HEP Groups and with FNAL Physics Center.

A Wonderful Opportunity !

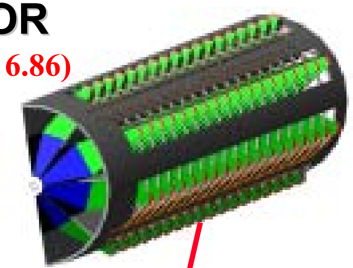
CMS Detector

Forward Detectors

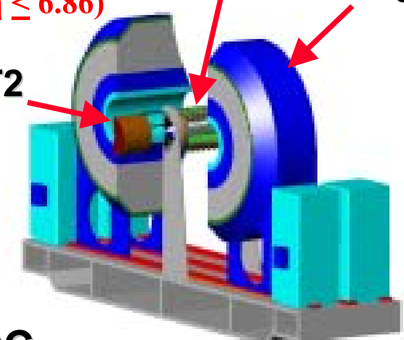
CMS
Compact Muon Solenoidal Detector for LHC



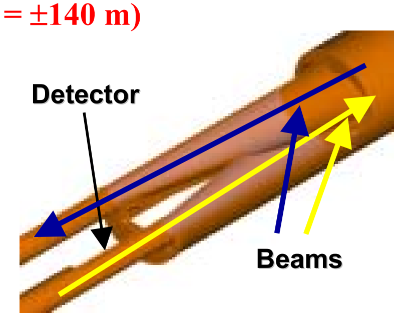
CASTOR
($5.32 \leq \eta \leq 6.86$)



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



ZDC
($z = \pm 140$ m)

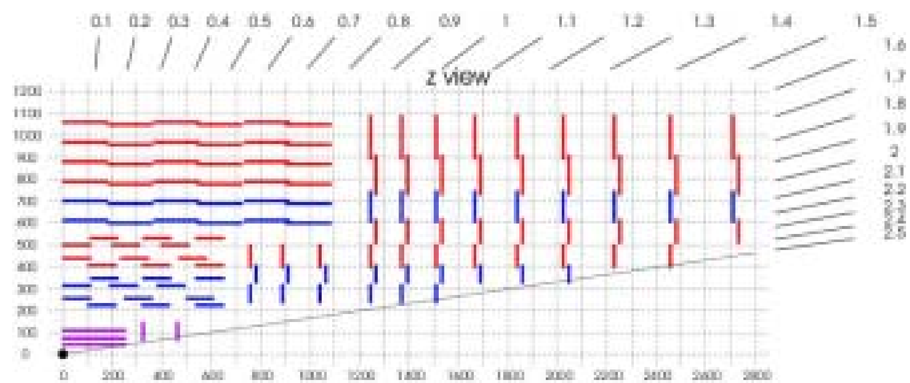


CMS as a Detector for Heavy Ion Physics

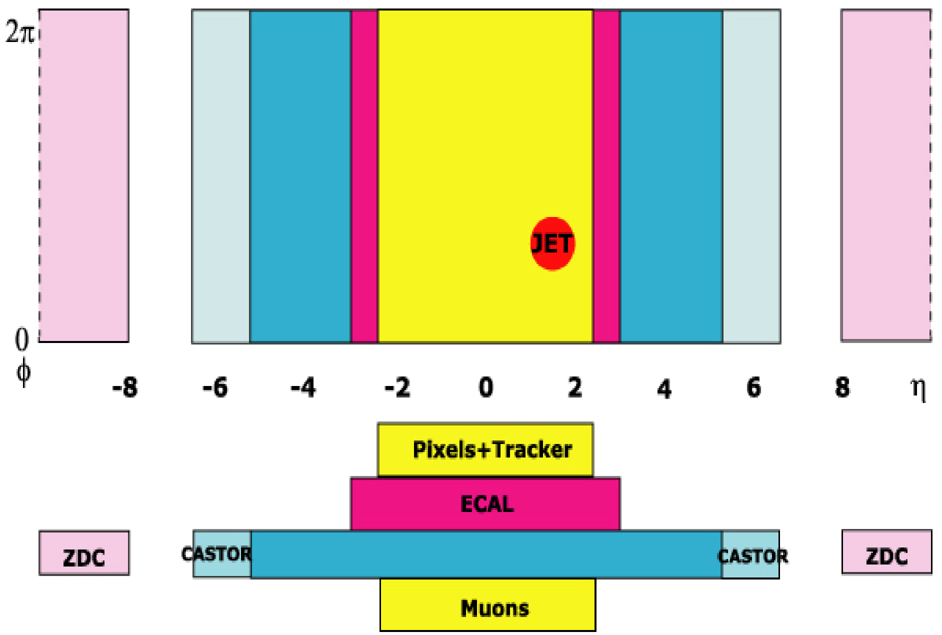
- **Muons**
  - **Wide rapidity range $|\eta| < 2.4$**
  - **$\sigma_m \sim$ 50 MeV at Υ**
- **ECAL**
  - **Barrel**
    - $|\eta| \leq 1.48$
    - $\Delta\eta x \Delta\phi = 0.0175 \times 0.0175$
    - Resolution: $0.027/\sqrt{E} \otimes 0.0055$
  - **Endcap**
    - $1.48 \leq |\eta| \leq 3$
    - Preshower $1.65 \leq \eta \leq 2.6$
- **HCAL**
  - **Barrel+Endcap**
    - $|\eta| \leq 3$
    - $\Delta\eta x \Delta\phi = 0.087 \times 0.087$
    - Resolution: $1.16/\sqrt{E} \otimes 0.05$
  - **Forward HCAL - HF**
    - $3 \leq |\eta| \leq 5$
    - $|\eta| < 7$ including CASTOR
- **Zero Degree Calorimeter**
- **TOTEM and CASTOR**

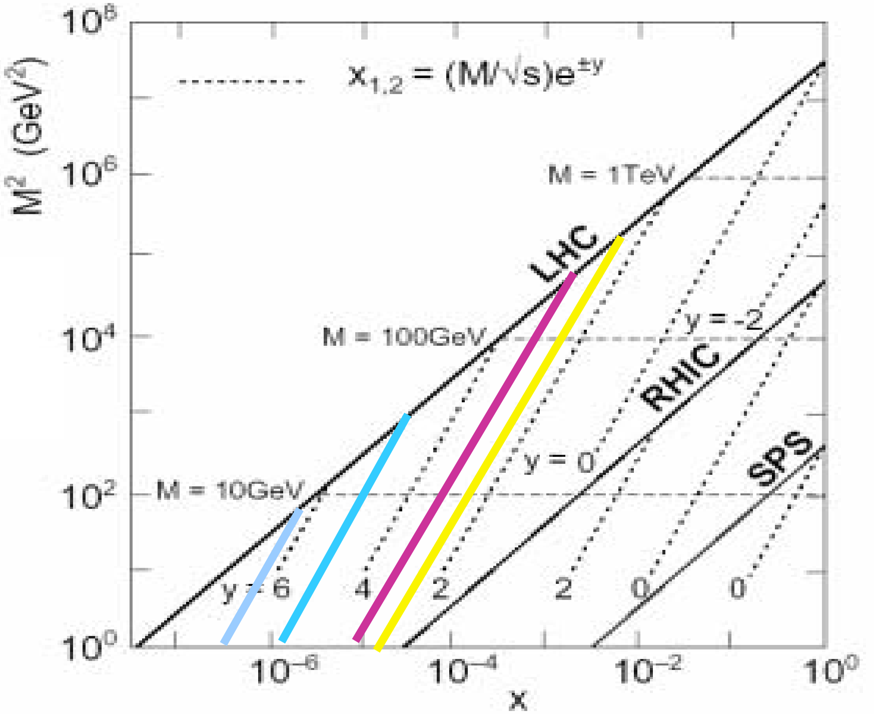
Silicon Tracker

- **Pixel Detector**
  - **3 barrel layers and 2 forward layers on each side**
  - **100x150 μm pixel size**
  - **Low occupancy: 2% for pixel L1 @ $dN/d\eta = 5000$**
- **Strip Detector**
  - **10 barrel layers of single- and double-sided silicon, 9 forward layers on each side**



Detector Coverage





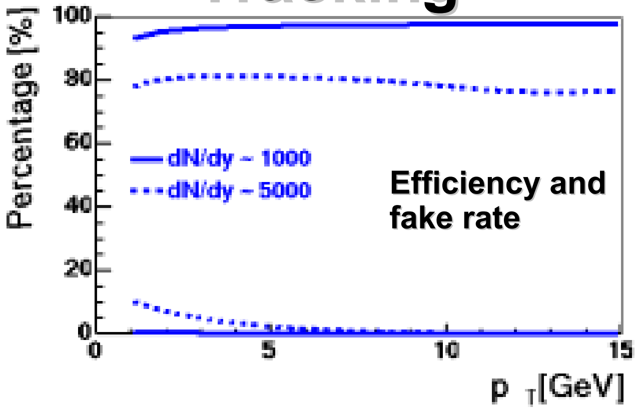
Large Range of Hermetic Coverage

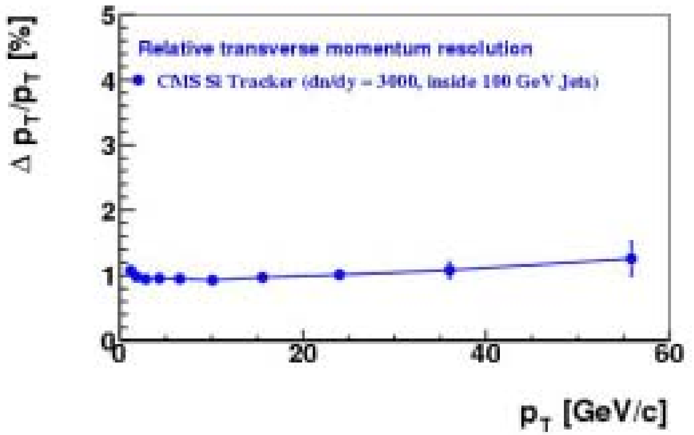
in η, x and Q²

Unique Forward Capability

Reconstruction (Baseline Studies)

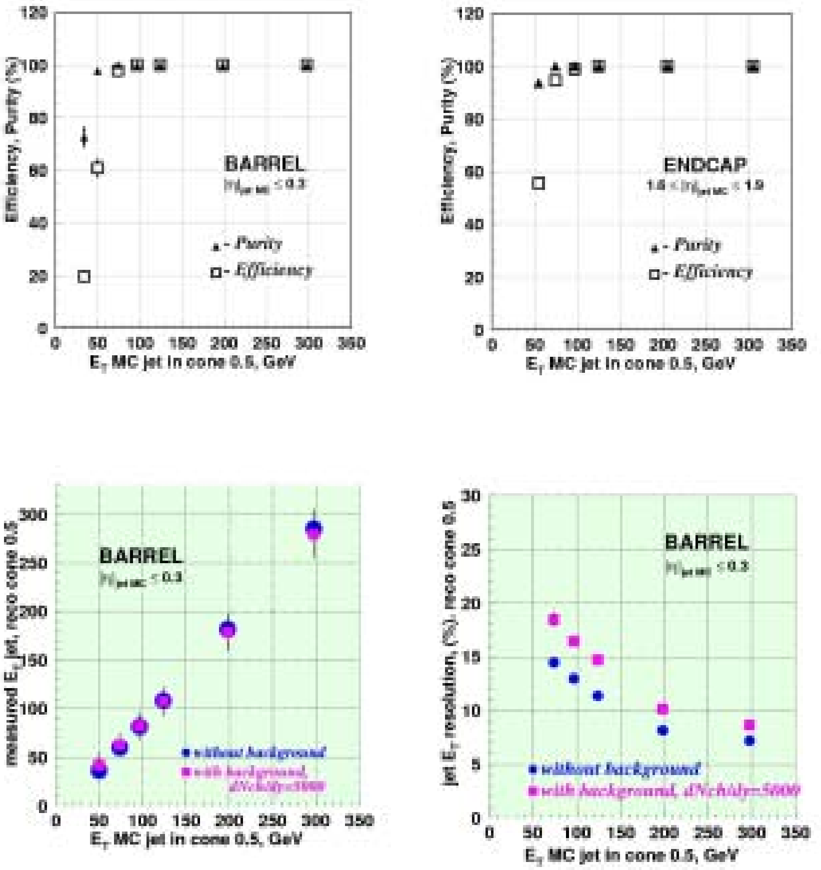
Tracking





High track reconstruction efficiency and low fake rate even at very high track density

Jets – Calorimeters Alone



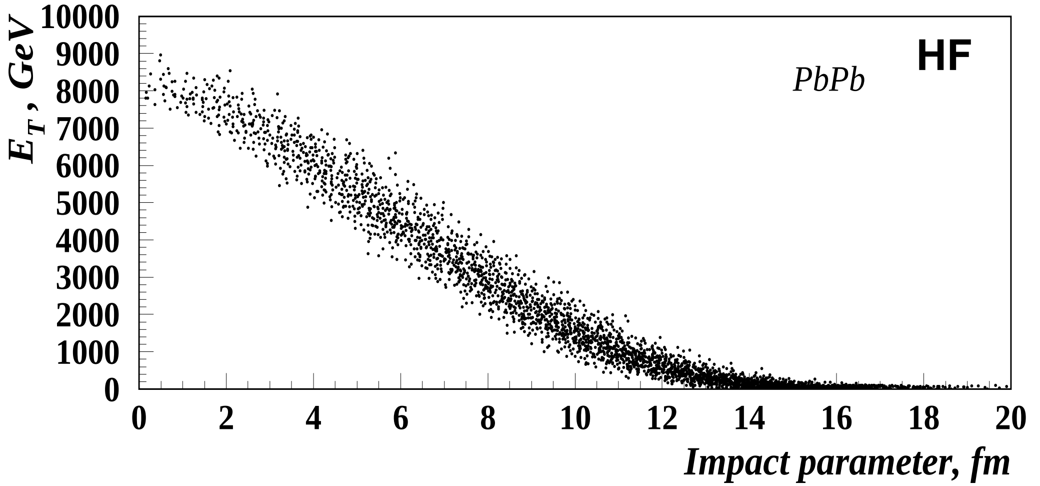
Energy resolution for 100 GeV jets is ≈ 16%

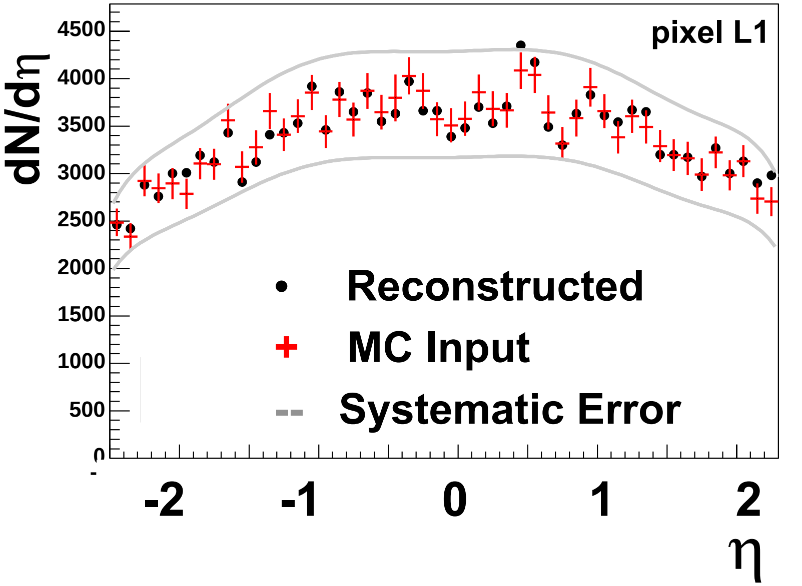
Physics Measurements in CMS

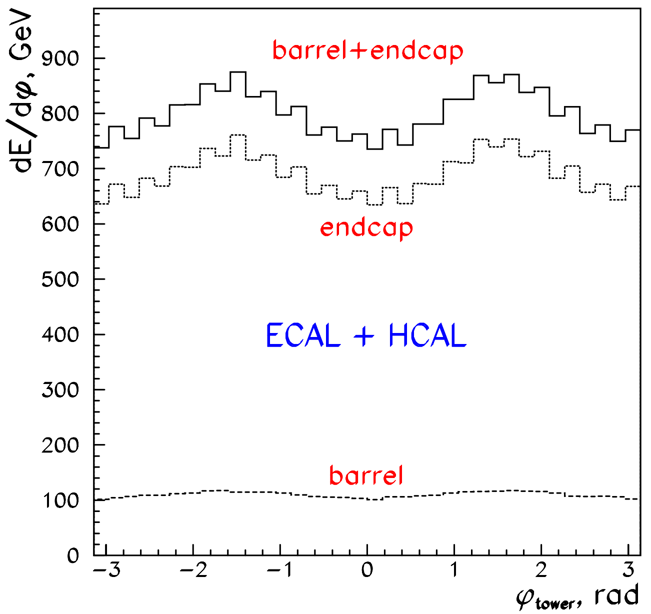
- **Soft Physics and Global Event Characterization**
  - Centrality
  - Charged Particle Multiplicity – Wide Rapidity Range
  - Spectra + Correlations – π^0, Direct Photons, Decay Topology
  - Azimuthal Asymmetry (Flow)
  - Energy Flow in Wide Rapidity Range
- **High p_T Probes:**
  - Quarkonia (J/ψ , Υ) and heavy quarks
  - High p_T jets, detailed studies of jet fragmentation, centrality dependence, azimuthal asymmetry, quark flavor dependence, leading particle studies
  - High energy photons, Z^0
  - Jet-γ, Jet-Z^0
  - Leading particle correlations a la RHIC
  - Multijet events (*e.g.* 3 Jet)
- **Forward Physics**
  - $X\sim10^{-6}$ Saturation, Color Glass, Limiting Fragmentation,
  - Ultra Peripheral Collisions
  - Exotica

Physics Technical Design Report Due at End of 2005

Global Event Characterization







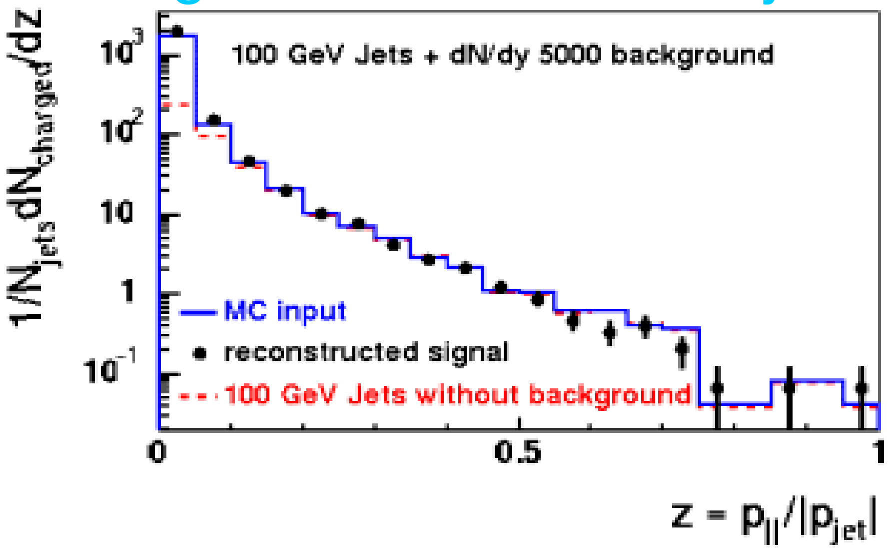
Impact Parameter

Multiplicity a la PHOBOS

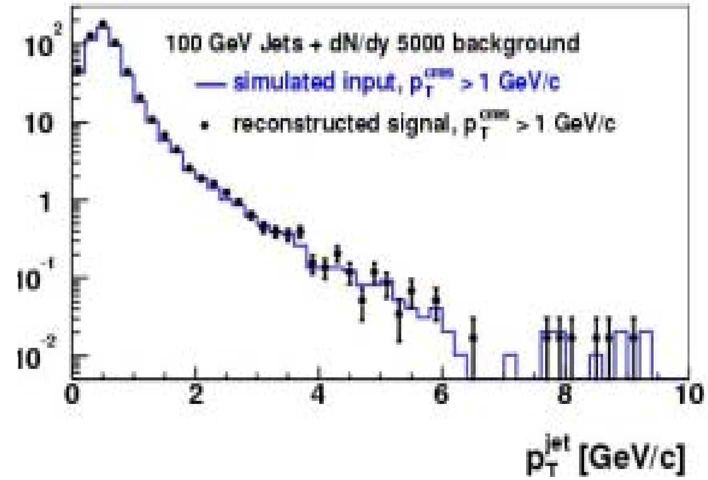
Flow of Energy and Particle Number

Jet Fragmentation

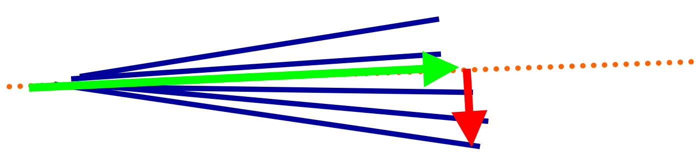
Longitudinal momentum fraction z along the thrust axis of a jet:

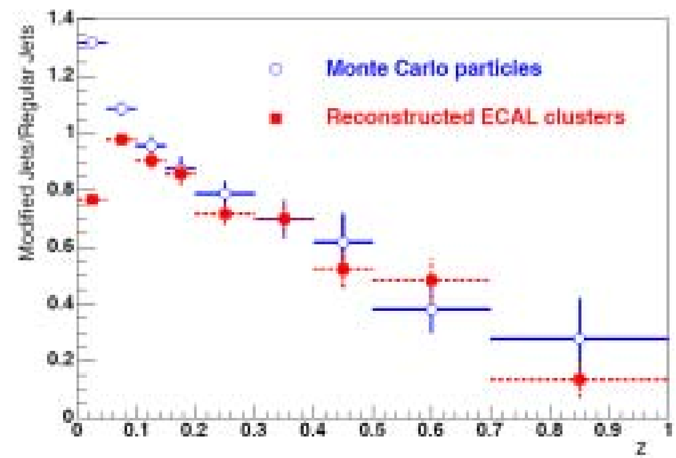


p_T relative to thrust axis:



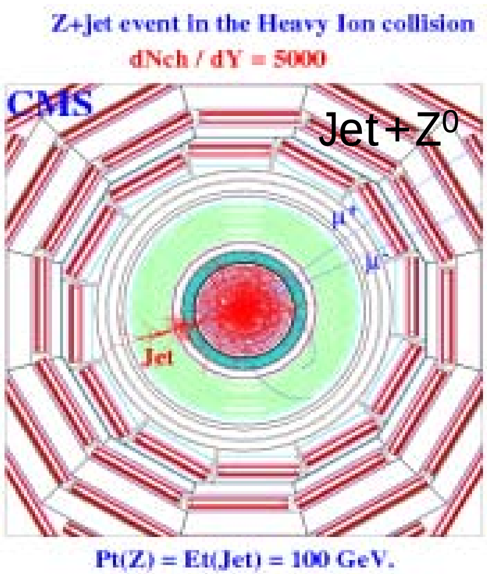
- **Fragmentation function for 100GeV Jets embedded in dN/dy ~5000 events.**
- **Use charged particles and electromagnetic clusters**

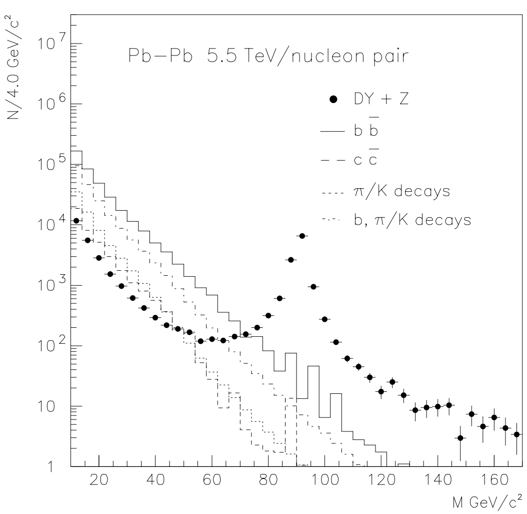




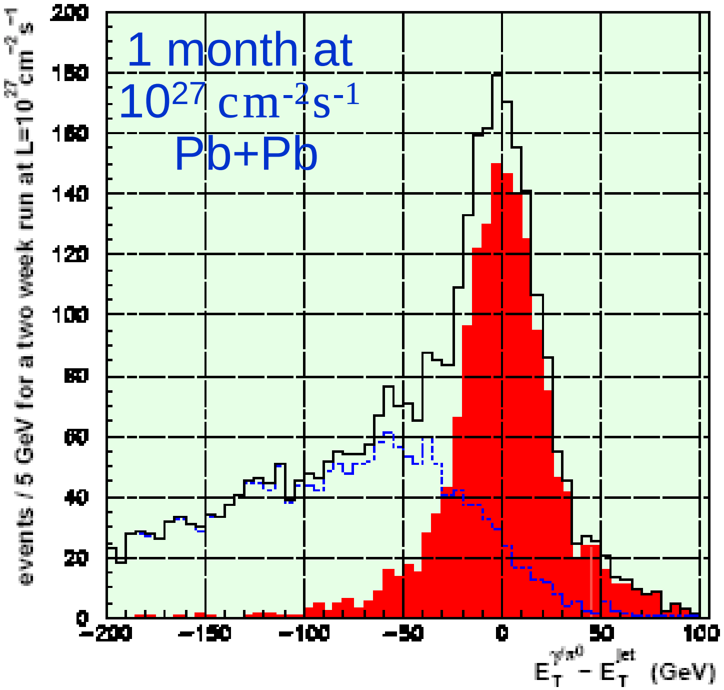
Using ECAL clusters~π^0 in CMS

Balancing γ or Z^0 vs Jets



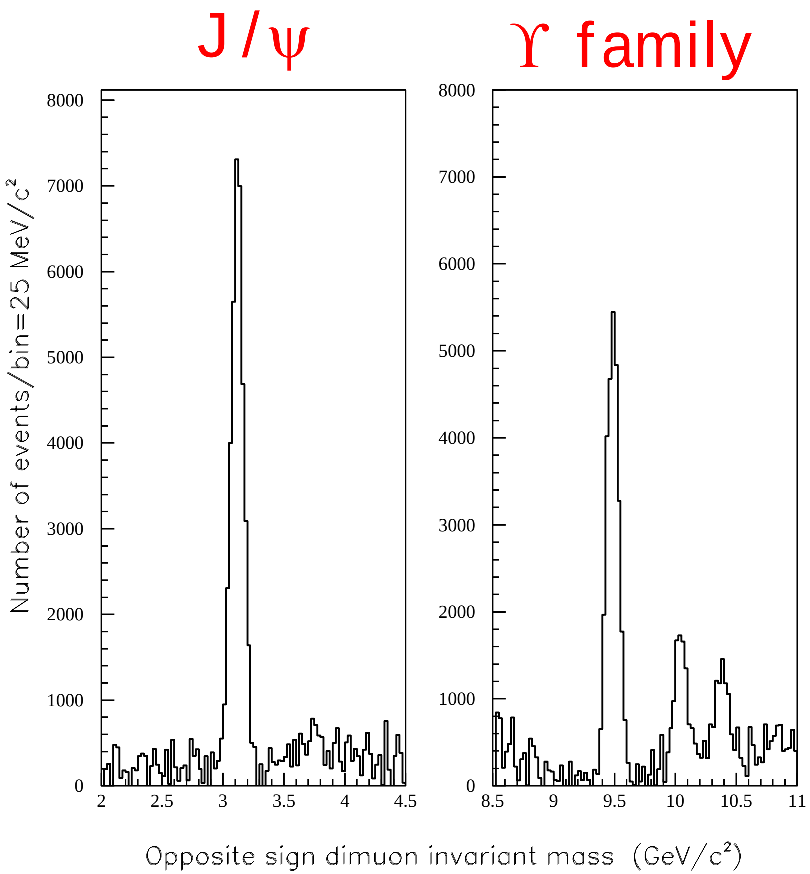


$E_{Tjet,\ \gamma}$>120 GeV in Barrel



Study of jets with known parton energy

Quarkonia in CMS

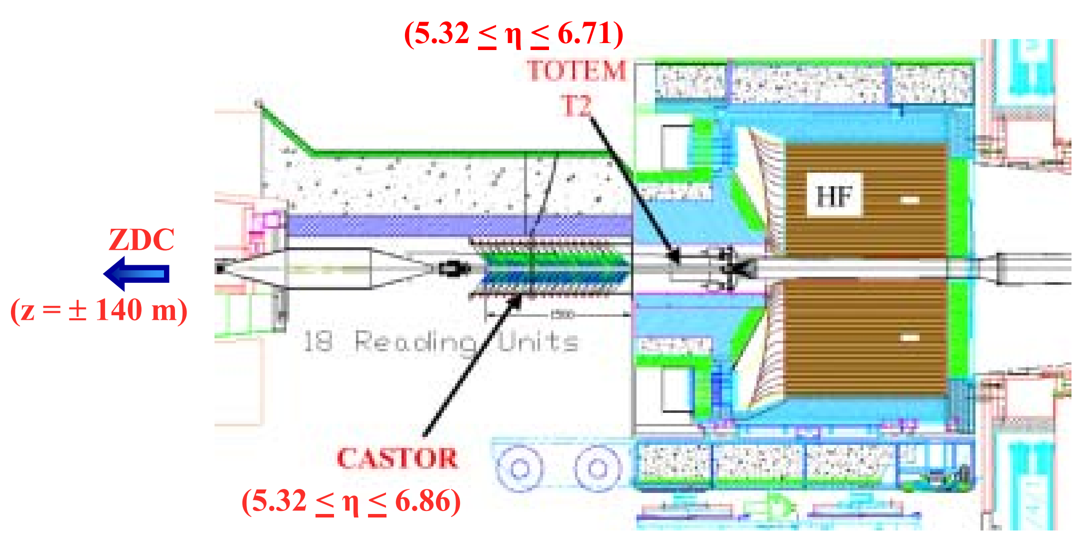


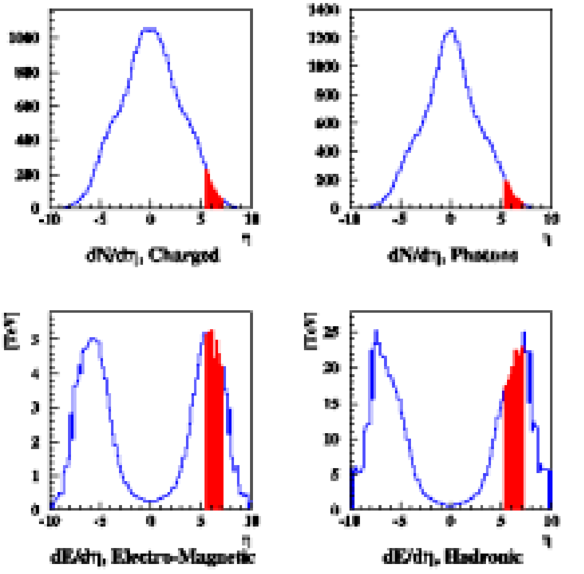
$\sigma_M = 50$ MeV

Yield/month
(with 50% duty factor)

	Pb+Pb	Kr+Kr	Ar+Ar
L	10^{27}	7×10^{28}	10^{30}
J/Ψ	28.7k	470k	2200k
Ψ´	0.8k	12k	57k
ϒ	22.6k	320k	1400k
ϒ´	12.4k	180k	770k
ϒ´´	7k	100k	440k

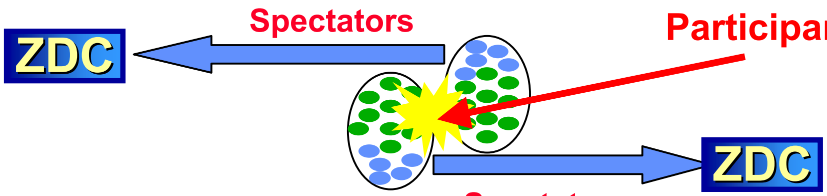
Forward Detectors: CASTOR and TOTEM

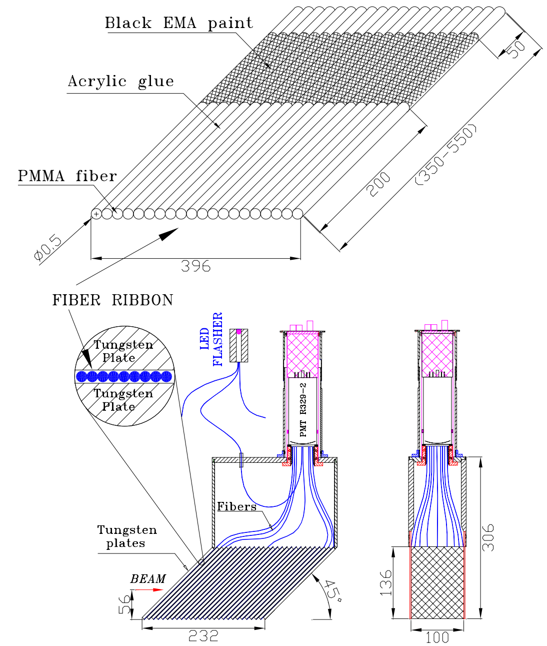




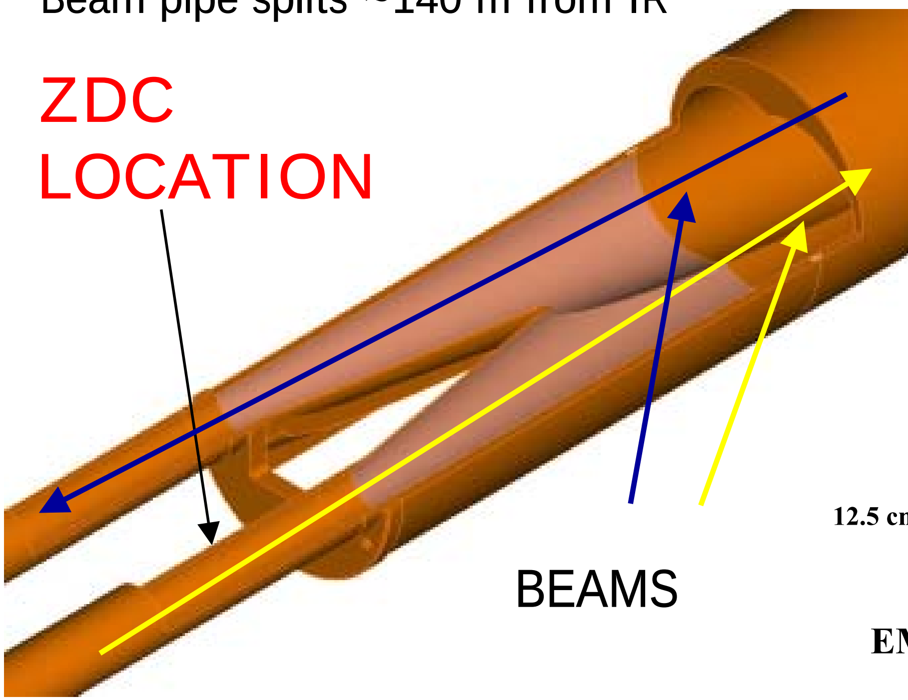
- Near Hermetic coverage (out to |η|<7 with CASTOR)
- Physics
  - Centrality
  - Nuclear PDFs - particularly gluon distributions
  - Momentum fractions x ~ 10^{-6} – 10^{-7} at scales of a few GeV^2 in pp
  - Diffractive processes (10-20% of total cross section at high energies)
  - Limiting Fragmentation
  - Peripheral and Ultra-Peripheral collisions
  - DCC, Centauros, Strangelets ……

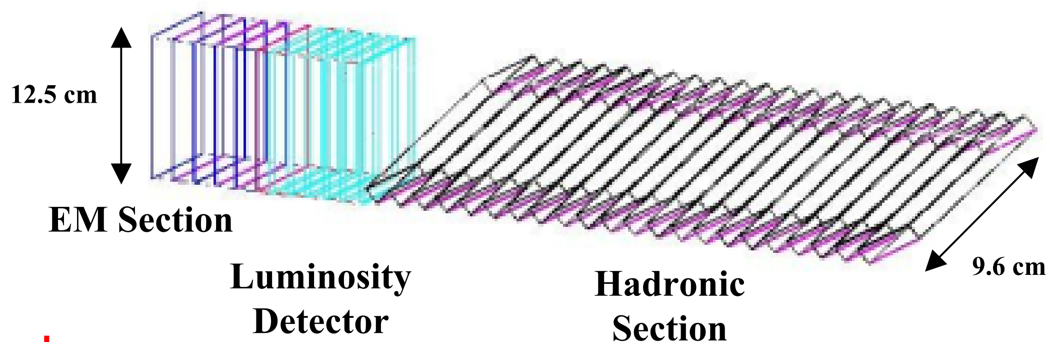
Zero Degree Calorimetry for CMS





Beam pipe splits ~140 m from IR





ZDC improves resolution at large b

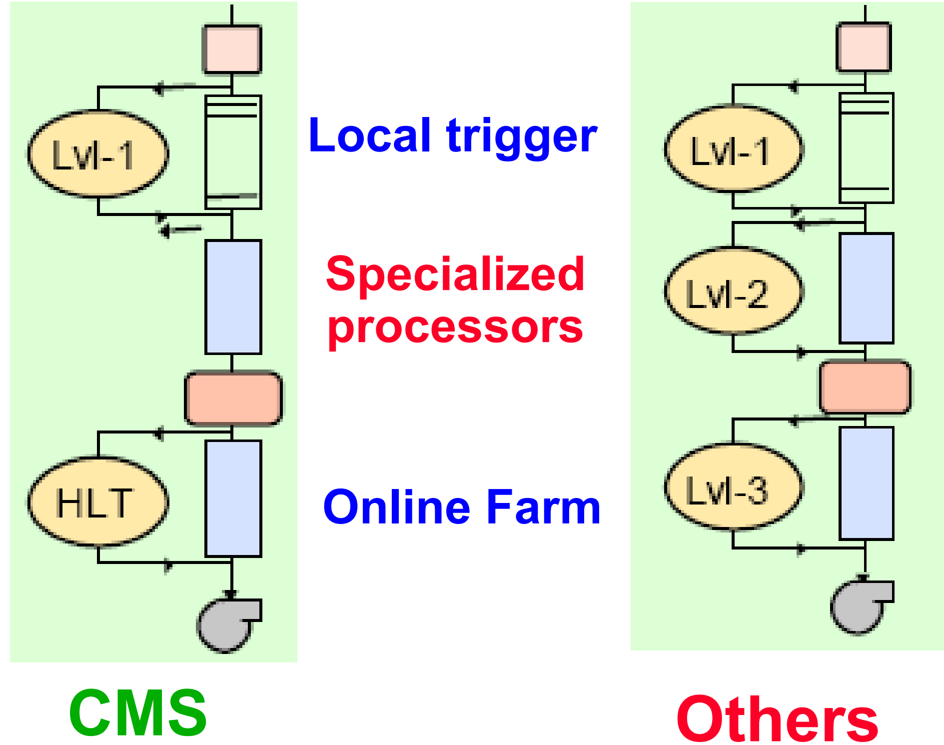
Data Acquisition and Trigger

■ **CMS has a two-level DAQ/Trigger architecture:**

- **Low level hardware trigger (L1)**
  - Muon track segments
  - Calorimetric towers
  - No tracker data
  - Output rate: a few kHz
- **Powerful online farm (HLT) doing event building and traditional L2, L3,…, LN triggering. Full event information available**
  - L2 –use only muon + calorimeter information
  - L3 –add tracker information
  - Output to tape: ~40Hz

■ **Online Farm**

- **Racks filled with processors**
- **Associated networking and storage**



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

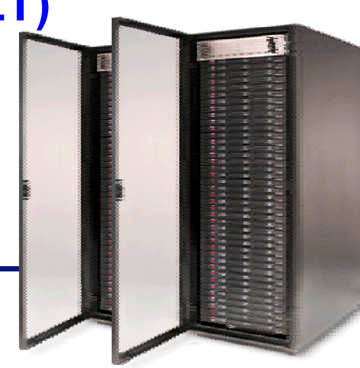


Illustration Of Online Farm Power: Low p_T J/ψ

See CMS Analysis Note 2004/02, included in Committee package

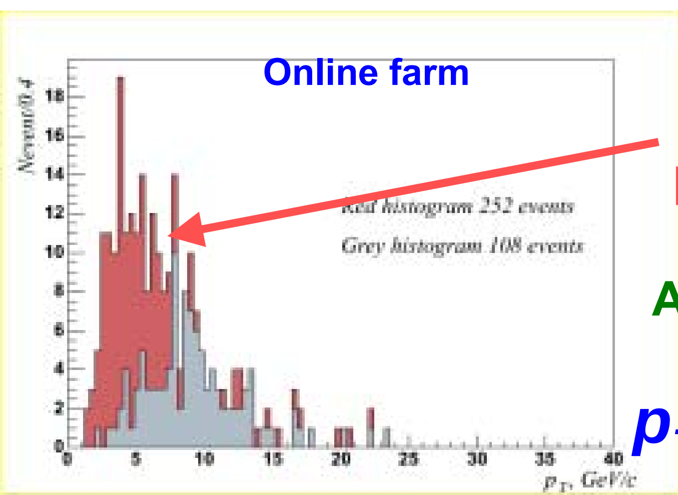
- Only a small fraction of produced J/ψ are seen in LHC detectors
  - E.g. CMS $J/\psi \rightarrow \mu\mu$ acceptance 0.1-0.2%, ~$O(10^4)$ per LHC run
- Detection of low p_T J/ψ requires efficient selection of low momentum, forward going muons. Simple hardware L1 dimuon trigger is not sufficient

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)

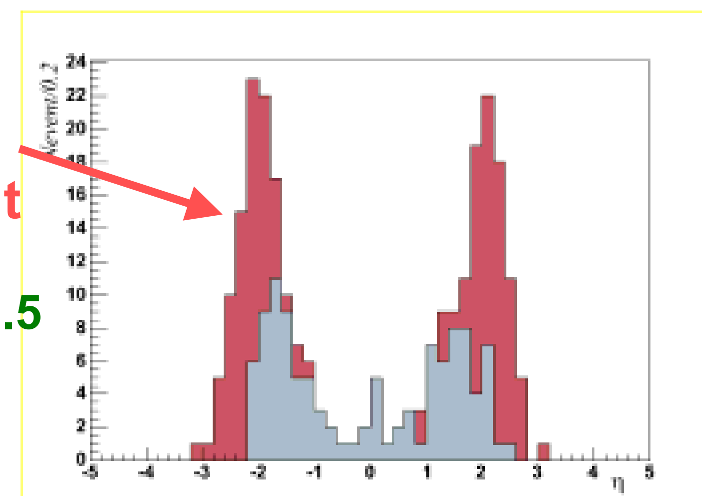
L1 trigger	Single μ	~2 kHz
L2 trigger	Re-fit μ	70 Hz
L3 trigger	Match tracker	<40 Hz
J/ψ p_T		>1 GeV/c



p_T

Online farm Improvement

Acceptance x2.5



η

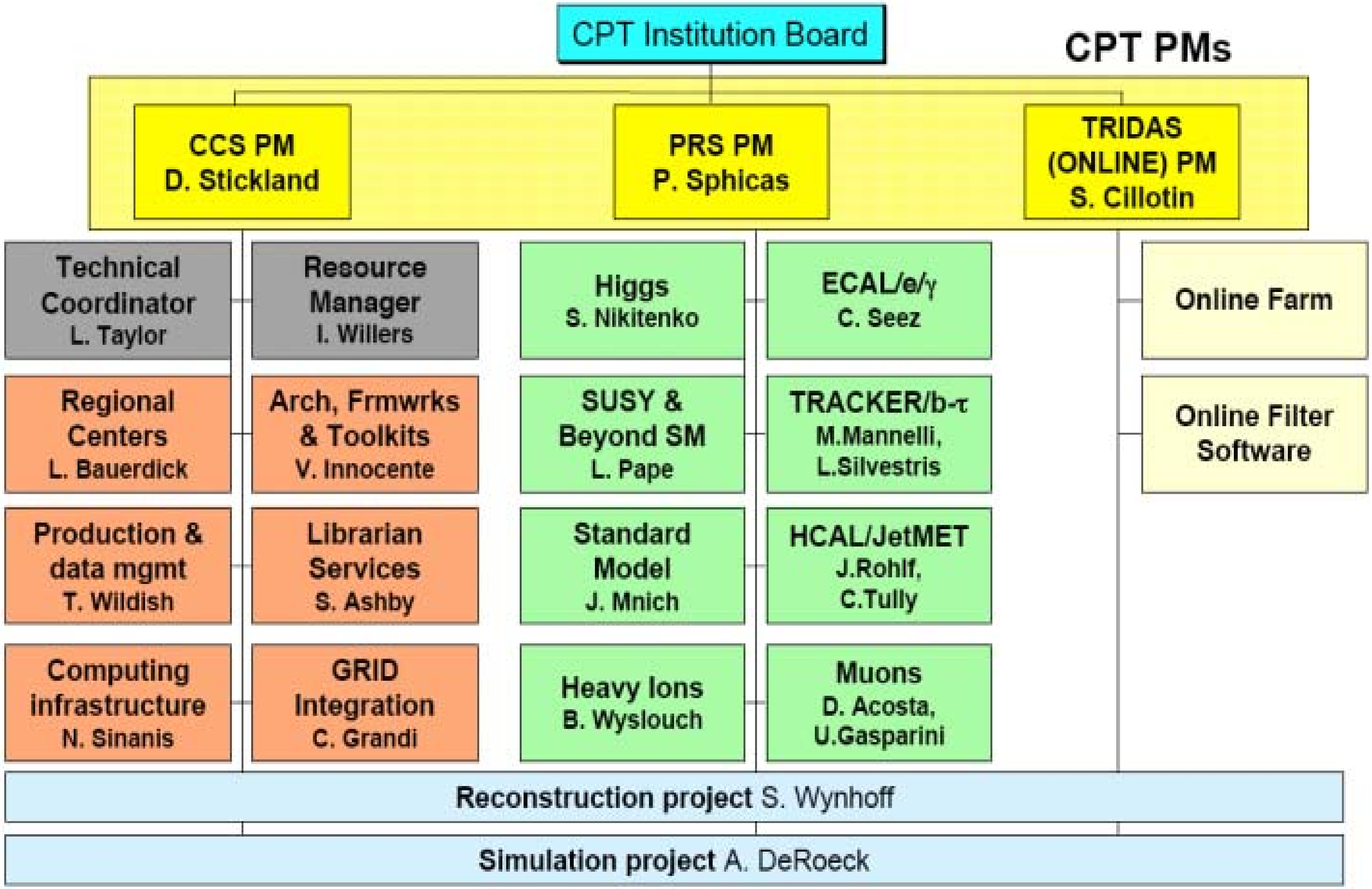
US Participation in Online Farm Construction

- HLT is essential for Heavy Ion physics, every event inspected
  - Low p_T J/ψ
  - Low p_T jets (background subtraction)
  - Jet-γ
  - Displaced vertices (CDF)
  - Electrons
- According to the present plan only 25% of DAQ will be available for the first few years of p+p running.
- Increasing p+p luminosity is more difficult than Pb+Pb:
  - Pb+Pb throughput will exceed that of p+p during first years of LHC
- Nominal luminosity of Pb+Pb requires 2x throughput of low luminosity p+p
  - Larger and more complex events
  - Reconstruction longer for each event
- Heavy Ion Physics needs additional 25% of CMS DAQ
- Heavy Ion Physics needs urgently dedicated software development program

CMS Organization and People

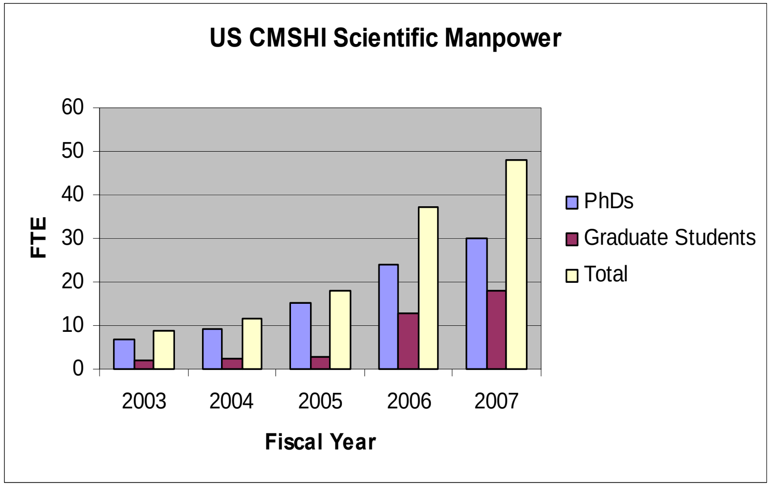
- CMS HI program originated ~1992: simulation and preparation work culminating in CMS Note 2000/60. Approved physics program in CMS:
  - Quarkonia
  - Jets
  - “Global variables”: multiplicity, energy flow
- 2001: Expressions of interest from new groups: USA(NP), Greece, New Zealand
  - Demonstration of excellent tracking capabilities
  - Inclusion of forward detectors: CASTOR, ZDC
- Presently > 30 people involved directly in studies, discussions, etc.
- Expect to grow to ~100 people by LHC startup (~50 from the US, including postdocs and graduate students)

CPT Project Organization



Projected Growth of US Manpower

- **MIT** AGS, SPS, RHIC-PHOBOS
  - Silicon, DAQ, Electronics, Computing, Project Management
- **Rice University** AGS, RHIC-STAR
  - Trigger Hardware and Software, TOF, Tracking
- **UC Davis** Bevalac, AGS, SPS, RHIC-STAR
  - TPCs, Electronics, Computing
- **UC Riverside** AGS, RHIC-PHENIX
  - Electronics, Trigger
- **UIC** AGS, RHIC-PHOBOS
  - Silicon, Trigger, RHIC ZDCs, Project Management
- **University of Iowa**
  - Calorimeters
- **University of Kansas** SPS, RHIC-BRAHMS
  - RHIC ZDCs



HEP Groups at All Institutions in CMS

US Proposal

Permission to Participate in the Program (~30 PhD + 15 GS by 2007)

ZDC (~ $0.4M)

- FY05 Prototyping and initial construction: $20k
- FY06 Construction: $230k
- FY07 Construction: $170k

High Level Trigger Farms (~ $3.9M)

- Hardware
- Software Development

Later - M&O with Main "Service" Contribution to DAQ/HLT/Computing area

Capital Budgets

YEAR	Engineers DAQ	Equip. DAQ	Engineers ZDC	Equip. ZDC	Total
FY05	275	300	0	0	575
FY06	300	770	20	210	1300
FY07	290	1240	0	170	1700
FY08	230	470	0	0	700
FY09	0	0	0	0	0
FY10	0	0	0	0	0
Total	1095	2780	20	380	4275

Online Farm and ZDC Capital Equipment costs in k$

Software Professionals (2)

Infrastructure and Processors (1/4 of On-Line Farm)

ZDC Engineering

Prototyping, Testing

Construction and Installation

Operating Budgets

YEAR	PhDs	Cat A	Cat B	Travel	Computing	Total
FY05	5	18	0	19	50	87
FY06	10	55	0	38	100	193
FY07	20	154	5	75	350	584
FY08	30	276	5	113	350	744
FY09	30	306	30	113	350	798
FY10	30	321	5	113	350	789

Maintenance and Operation Costs in k$

Cat A – Yearly Running Costs (per PhD) – Fixed by CMS

Cat B – Maintenance and Repair – NB Not for DAQ/HLT

Travel – Incremental to Current Operating Budgets of Groups

Computing – Processors and Storage for HI Data Analysis

CMS Virtual Control Room and Physics Analysis Center at FNAL

Conclusions

- LHC will Extend Energy Range - in Particular High p_T Reach - of HI Physics to Provide a New Window on QCD Matter
- CMS Will Take Advantage of its Superb Capabilities
  - Full Calorimeter and Tracking Coverage
  - High Rate Detectors
  - Superior Momentum Resolution - 4T Field
  - No Modification to Detector Hardware for HI
  - New High Level Trigger Algorithms for HI

  - Detailed Studies with High p_T Probes
  - High Mass Resolution for Quarkonia
  - Centrality, Multiplicity, Spectra, Energy Flow to Very Low p_T
  - Zero Degree Calorimeter, CASTOR and TOTEM Provide Unique Access to Forward Physics

  - Heavy Ion Program Firmly Integrated into Overall CMS Physics Program Leadership Role for US
  - Symbiosis with US CMS HEP Groups and with FNAL Physics Center.

A Wonderful Opportunity !
Needs to be addressed in a timely manner

Questions (1)

- **1. Comment on the PID capabilities vs pT of your experiment?**

  Low p_T PID by dE/dx in Si a la PHOBOS <1.5 GeV/c

  π^0 – 0-20 GeV,

  K^0, Λ_0, D^0 by decay topology

  J/ψ,(pT>1 GeV) Y(pT>0) and Z_0 from di-lepton channel pT>0

  b mesons by displaced vertex

- **2. What are the capabilities for a soft physics program in your experiment? Comment on the strengths and weaknesses.**

  dN/dη – widest range of η – variety of methods a la PHOBOS

  Flow from particle counting, tracking and energy flow vs p_T, η

  E_T from Calorimeters and Tracking including forward region

  Centrality Determination

  Particle Spectra

- **3. Which measurements used at the SPS and RHIC to test the macroscopic description of RHI collisions can your experiment contribute? What typical measurements cannot be done?**

  See above

- **4. Over what pt range can direct photons be measured in central Pb+Pb collisions?**

  All photons measured by EMCal – π^0/γ separation dependent on physics

- **5. Over what pt range can dileptons, J/Psi and upsilon be measured in central Pb+Pb?**

  See Slide 16 and above

- **6. Over what pt range can jets be measured in central Pb+Pb?**

  See Slide 10 >40 GeV, Below 40 GeV addressed by inclusive p_T spectra and particle correlations a la RHIC

Questions (2)

- 7. In what level of detail can the jet studies be performed? - e.g. fragmentation functions, f(z) and jt, with/without PID?

  See Slide 10 Identified light and heavy quark, photon jets – fragmentation functions and j_T from tracks and π^0 in jet cone

- 8. What are the most important and unique measurements which can only be performed by your experiment for central Pb+Pb and for pp collisions?

  Highest E_T jet physics, Z_0 and $(\gamma)Z_0$-jets, η coverage and very low x physics

- 9. What fraction of the operating costs (data taking, recording, analyzing) for the Pb+Pb operation of your experiment will the US be expected to cover?

  See Slide 23

- 10. What are the estimated annual operating costs to the US? Comment on the numbers in some details.

  See Slide 23

- 11. Please comment on the mom. resolution, angular resolution, S/N, backgrounds in the measurements of jets J/Psi, upsilon etc.

  Tracker $dp_T/p_T < 1.5\%$

  $dE_T/E_T=16\%$, $d\phi/\phi=d\eta/\eta=0.03$ at 100 GeV from calorimeter – see Slide 10

- 12. What is the number of US physicists who are currently committed to participate in this HI program at your detector?

  See Slide 20