Heavy-Ion Meeting, APCTP, Pohang, Korea

September 25-26, 2009

Overview of Heavy-Ion Physics Program in CMS

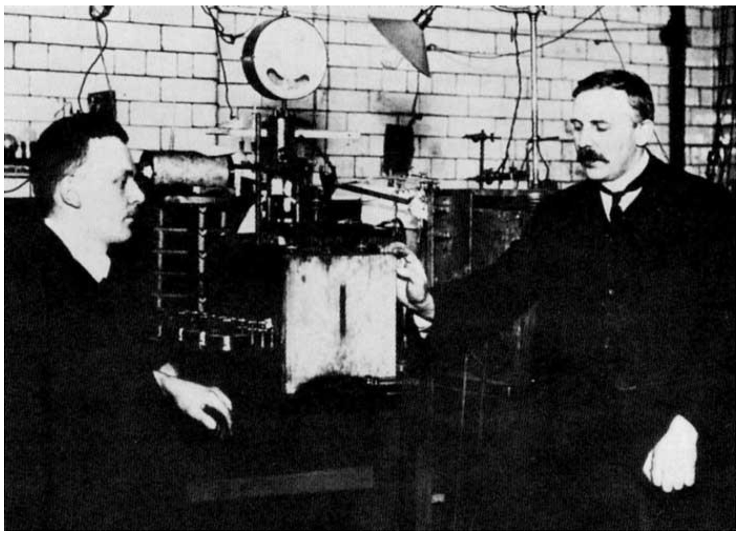
Byungsik Hong (Korea University)

for the CMS Collaboration

Historical Remark

2009 : A centennial Anniversary of Ion-Ion Collisions

1909 Rutherford gold foil experiment



2009 LHC experiments

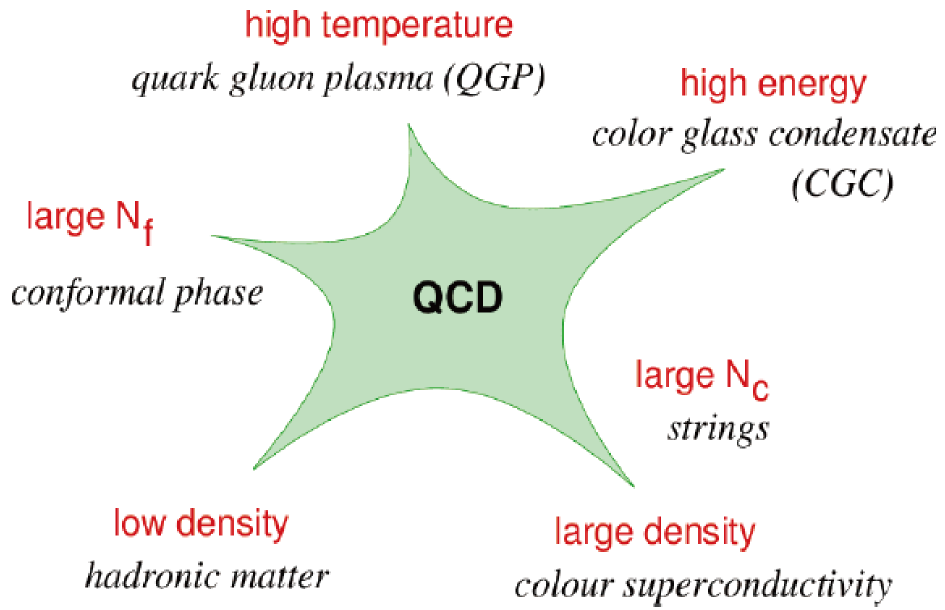
- ✓ **Beam: 5 MeV α + fixed Au ($\sqrt{s_{NN}}$~1 GeV) ⇒ 5.5 TeV (X5,000)**
- ✓ **# of collaborators: 3 (+Geiger+Marsden) ⇒ ~3,500 (X1,000)**
- ✓ **Construction cost: (X∞)**

Outline

1. Motivation
   - Importance & challenges
2. CMS Detector
   - Acceptance
   - High-level trigger
   - Plan for the first Pb+Pb run
3. Heavy-Ion Physics Capability of CMS
   - Soft probes
   - Hard probes
   - Ultra-peripheral collisions
4. Summary

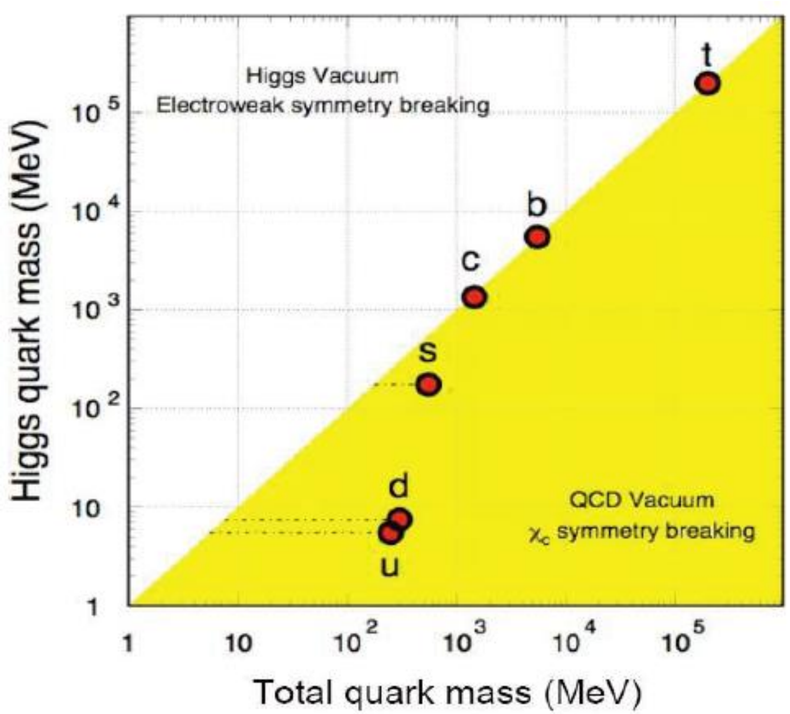
Many Facets of QCD

- Quantum Field Theory with rich dynamical content
  - ✓ asymptotic freedom, confinement, spontaneous broken chiral symmetry & its restoration at high density, non-trivial vacuum, etc.
- Standard Model of the collective behavior becomes important
  - ✓ phase transition, thermalization, flow, etc.
- Very diverse many-body phenomenology at various limits:

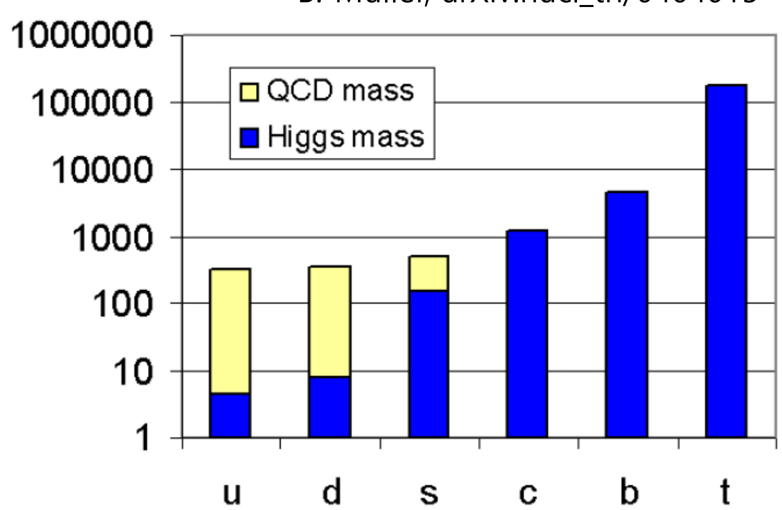


Origin of Visible Mass

- QCD (i.e. χ-sym. breaking), not Higgs (i.e. EW-sym. breaking), is truly responsible for the "origin of the *visible (baryonic) mass*"
- About 98% of the (light quark) mass generated dynamically (gluons) in the QCD confining potential



B. Müller, arXiv:nucl_th/0404015

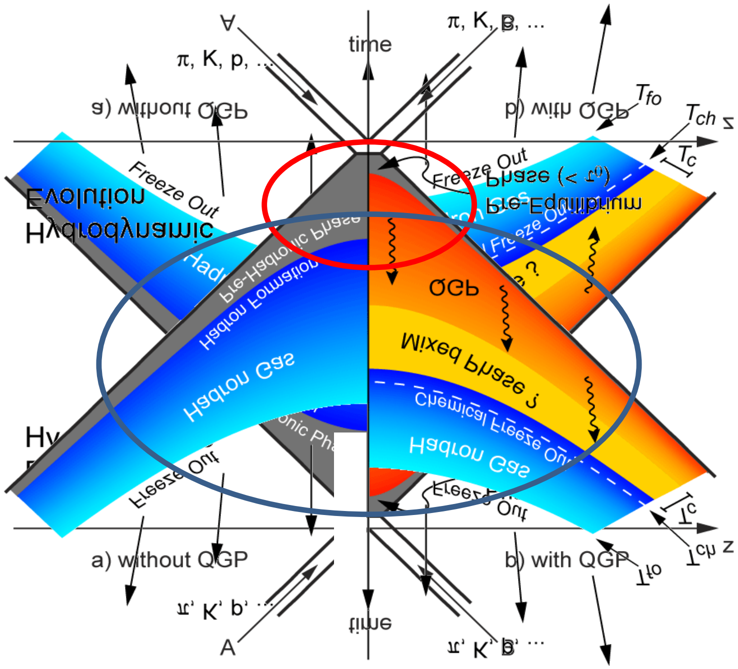


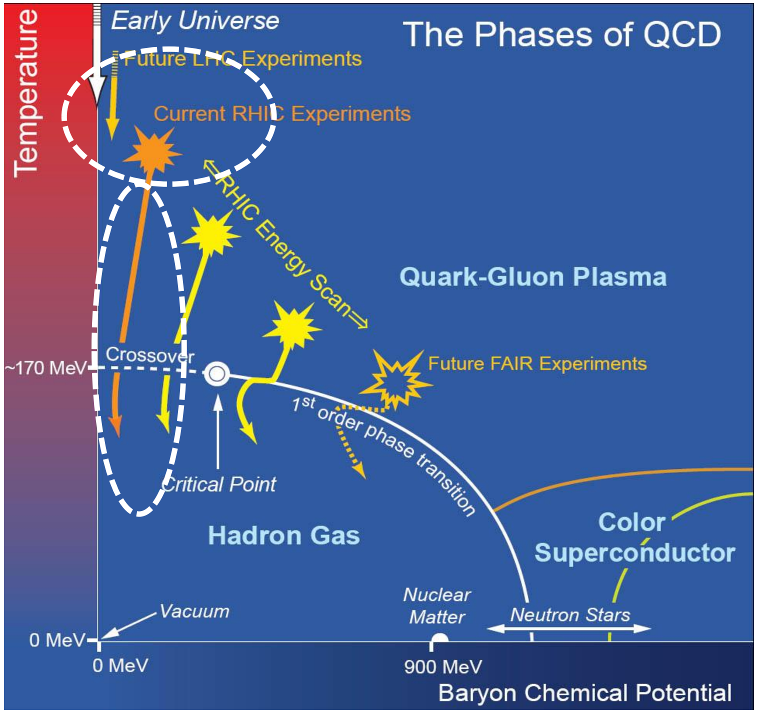
- Connection between QCD & HI
- Role of CMS for the detailed investigation of QCD

Motivation

Characterizing the early stage by hard probes

- Color charge density, Transport coefficient, QCD ε_c & T_c , Tomography, …
- High p_T spectra, Jets, γ(or γ^*, Z^0)-jet correlations, Quarkonia, …





Characterizing the later stage by soft probes

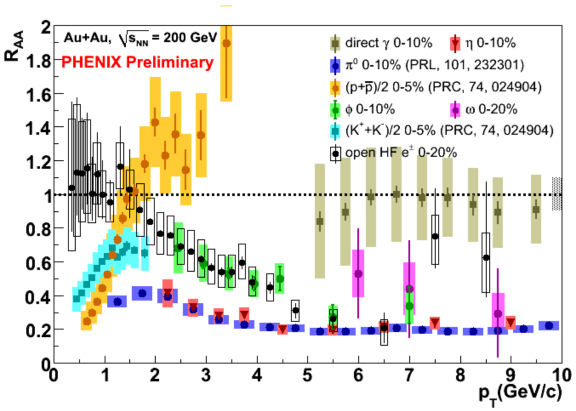
- Hydrodynamics, QCD EoS, Medium viscosity, …
- $dN_{ch}/d\eta$, Low p_T spectra, Elliptic flow, Thermal photons, …

Initial Evidence at RHIC

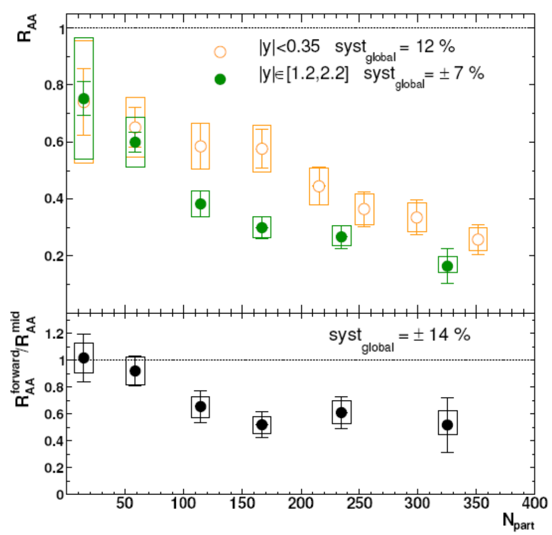
Strongly coupled matter is hot & dense!

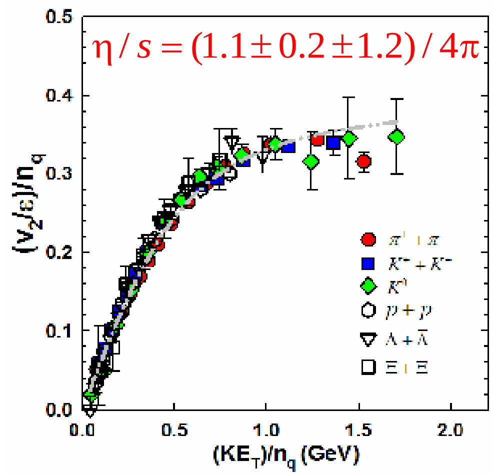
Jet quenching: strong interaction of high-p_T hadrons with dense medium

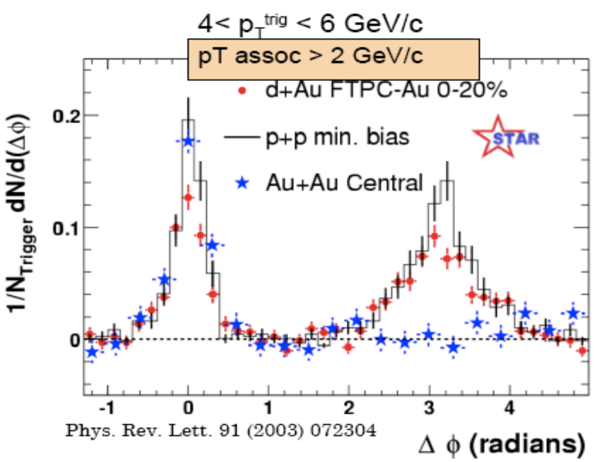
Flow & NQ scaling: quark recombination & low η/s



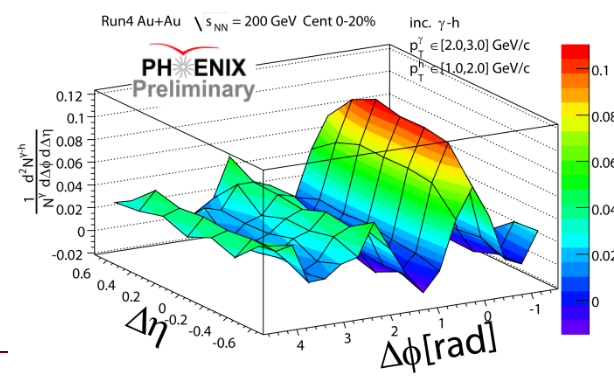
J/ψ suppression: SPS≈RHIC, larger at forward (CGC?)







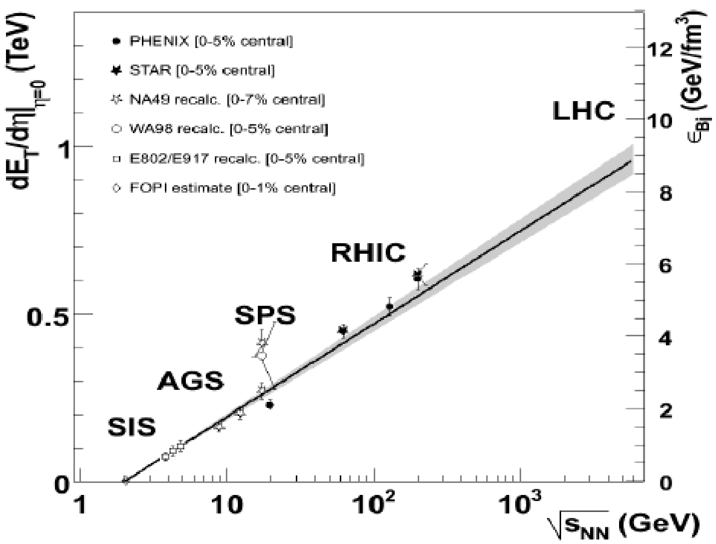
Jets are modified in medium.



What is New at LHC?

	AGS	SPS	RHIC	**LHC**
$\sqrt{s_{NN}}$ (GeV)	5	20	200	**5500**
Increasing factor		x4	x10	**x28**
η range	±1.6	±3.0	±5.3	**±8.6**

- LHC energies are far exceeding previous heavy-ion accelerators
  - A hotter, denser, and longer lived partonic matter



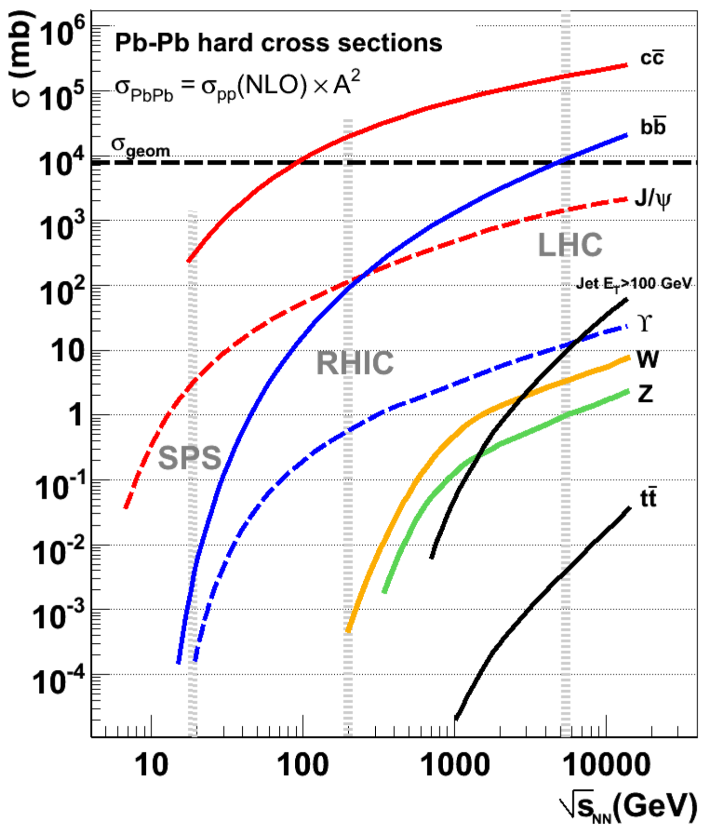
For central collisions ,

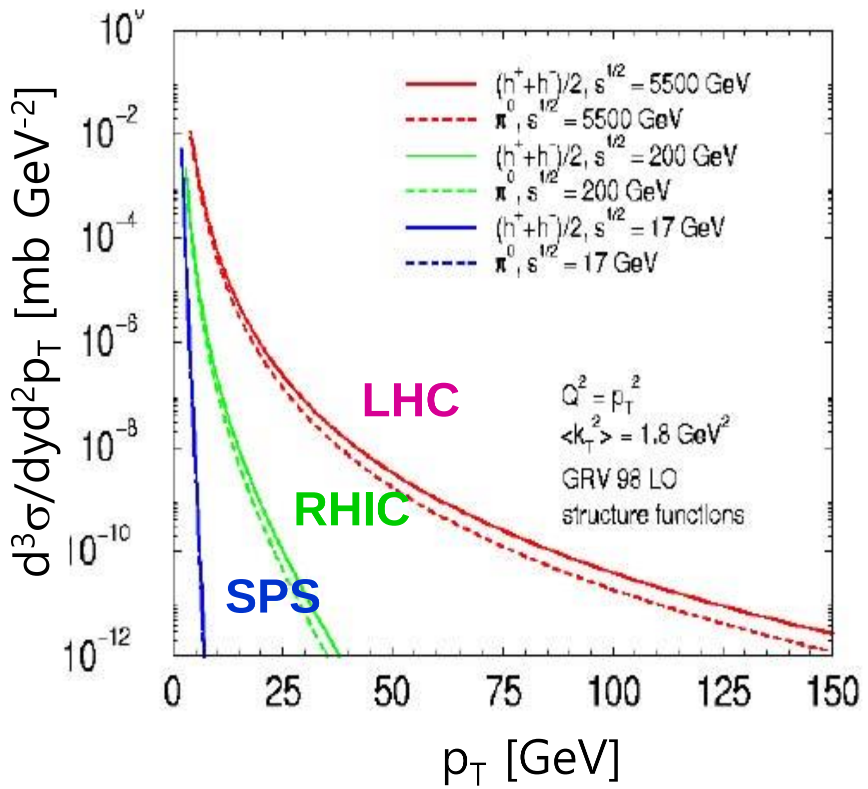
$$\varepsilon_{Bjorken} \cong \frac{1}{\tau_0(\pi R^2)}\frac{dE_T}{d\eta} \gtrsim 10\ \mathrm{GeV/fm^3}$$

with $\tau_0 \lesssim 1\,\mathrm{fm/c}$

Production Rate at LHC

- Large rates of various hard probes over a larger kinematic range
- Plenty of heavy quarks (*b* & *c*)
- Weakly interacting probes are available ($W^{\pm}$ & Z^0)

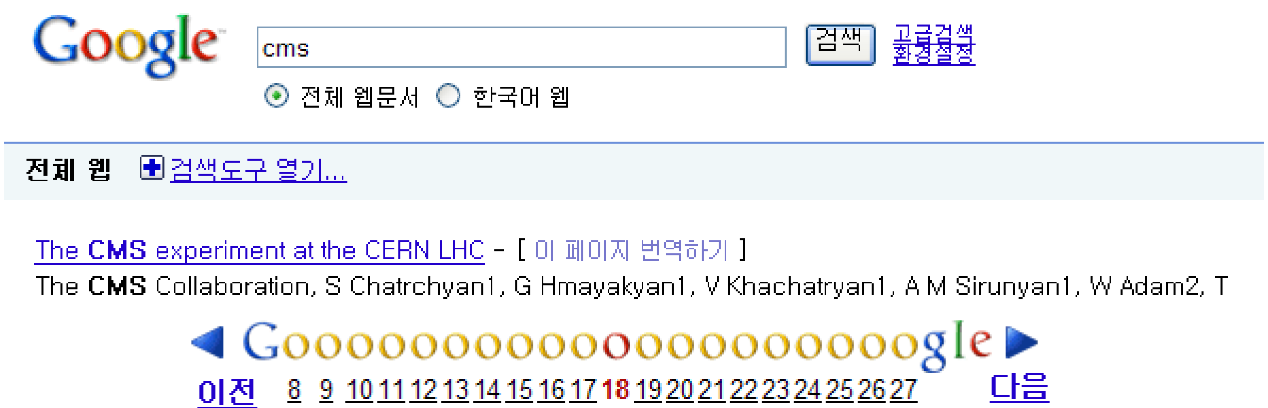


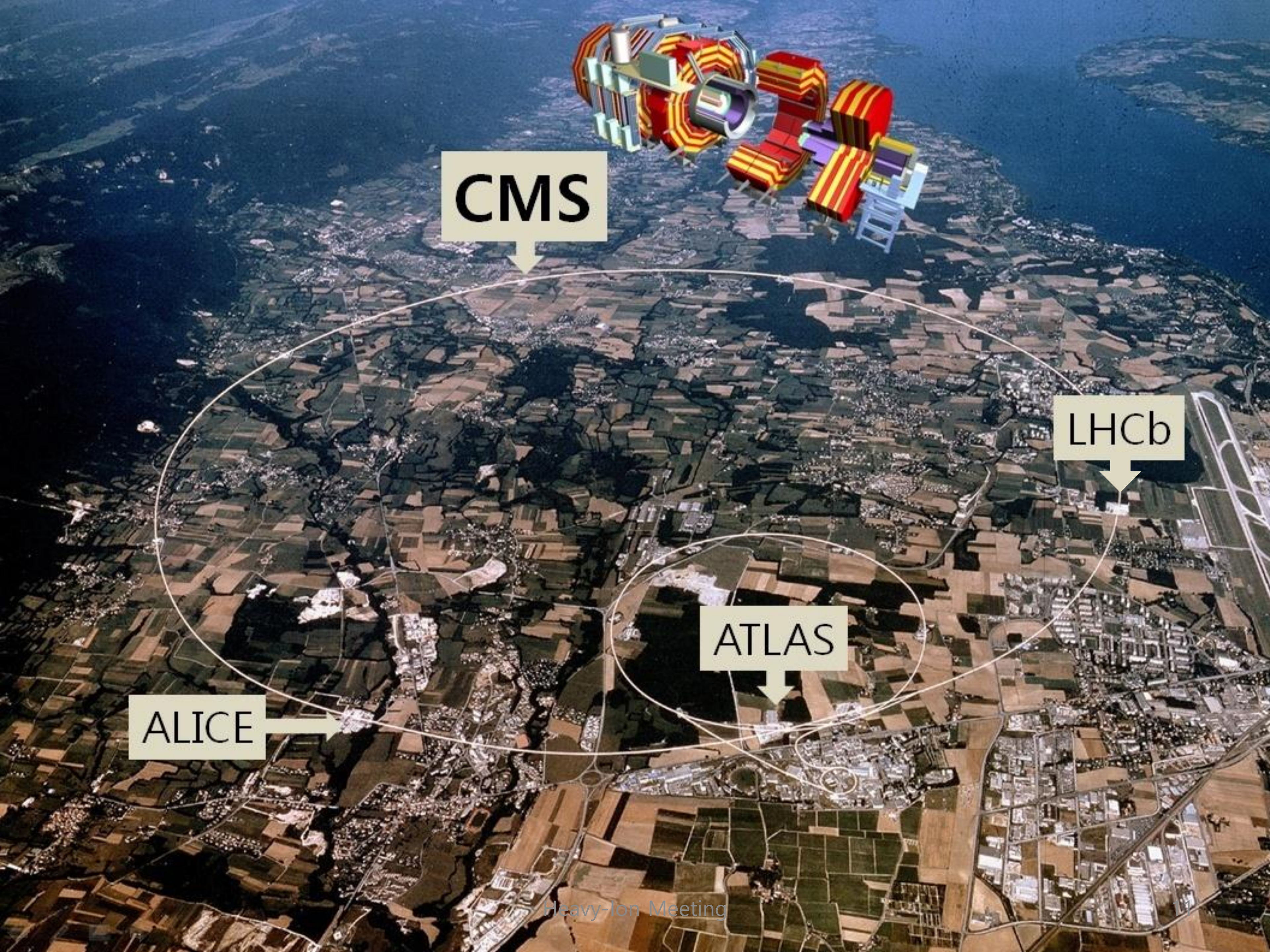


CMS Stands for

Content Management System
Creative Marketing Solutions
Centers for Medicare & Medicaid Services
Convention on Migratory Species
Cash Management Service
Church Missionary Society
College Music Society
Cryptographic Message Syntax
Canadian Mathematical Society
Classic Motorcycle Supplies
Common Management System
Credit Management Solutions
Conceptual Models for Services
…

Compact Muon Solenoid




CMS
LHCb
ATLAS
ALICE

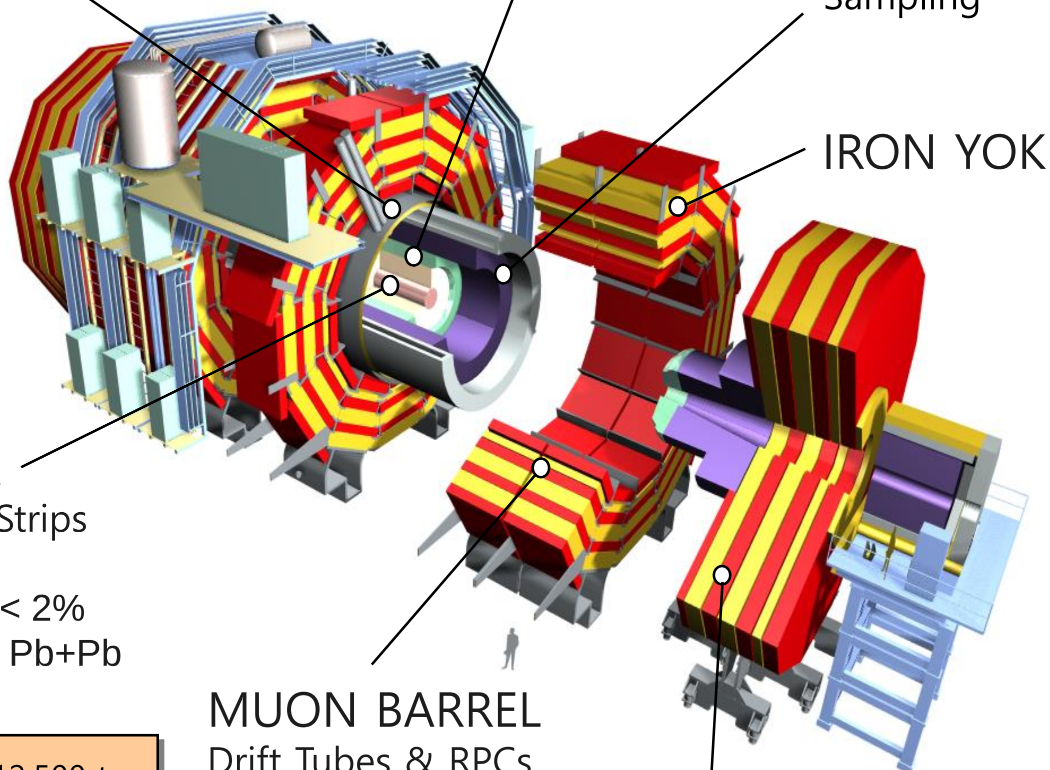
CMS Detector

SUPERCONDUCTING COILS

ECAL
$PbWO_4$ Crystals

HCAL
Cu-Scintillator Sampling

IRON YOKE



TRACKER
Si Pixels & Strips
$\Delta p/p \approx$1-2%
Occupancy < 2%
for central Pb+Pb

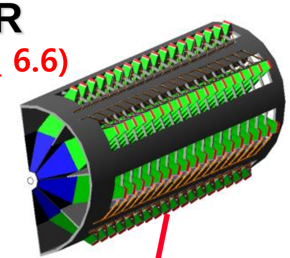
MUON BARREL
Drift Tubes & RPCs
$\sigma_m \approx$50 MeV
at 10 GeV/c^2

MUON ENDCAPS
Cathode Strip Chambers &
Resistive Plate Chambers (RPCs)

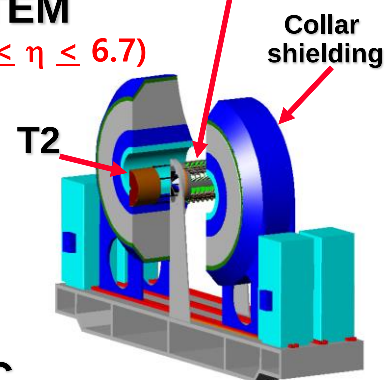
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Forward Detectors

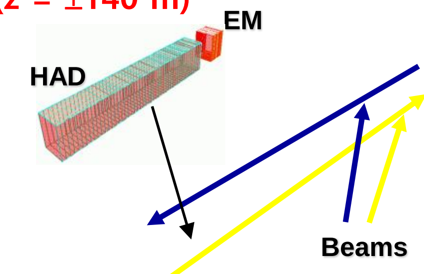
CASTOR
($5.2 \le \eta \le 6.6$)



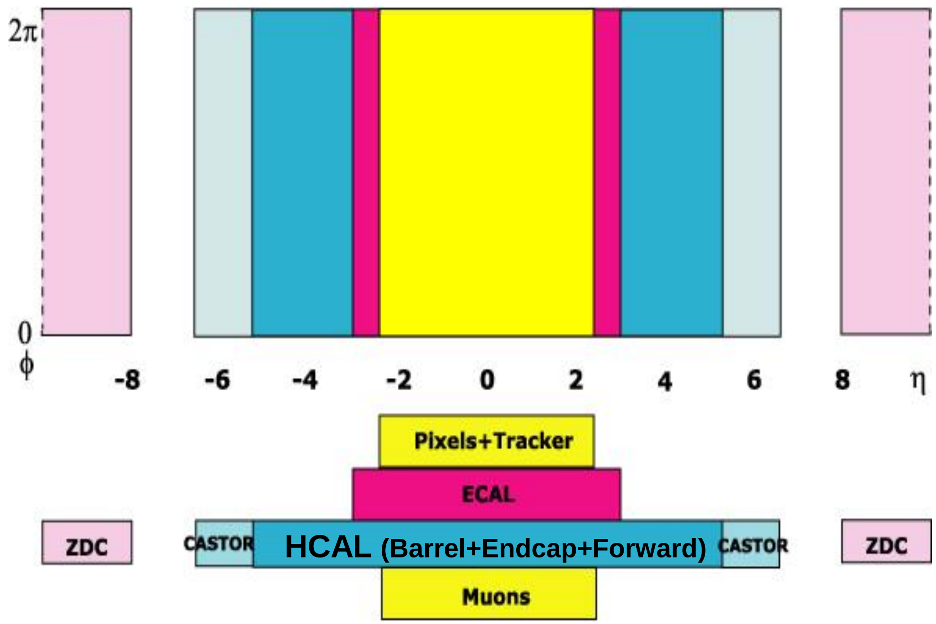
TOTEM
($5.3 \le \eta \le 6.7$)



ZDC
($z = \pm 140$ m)

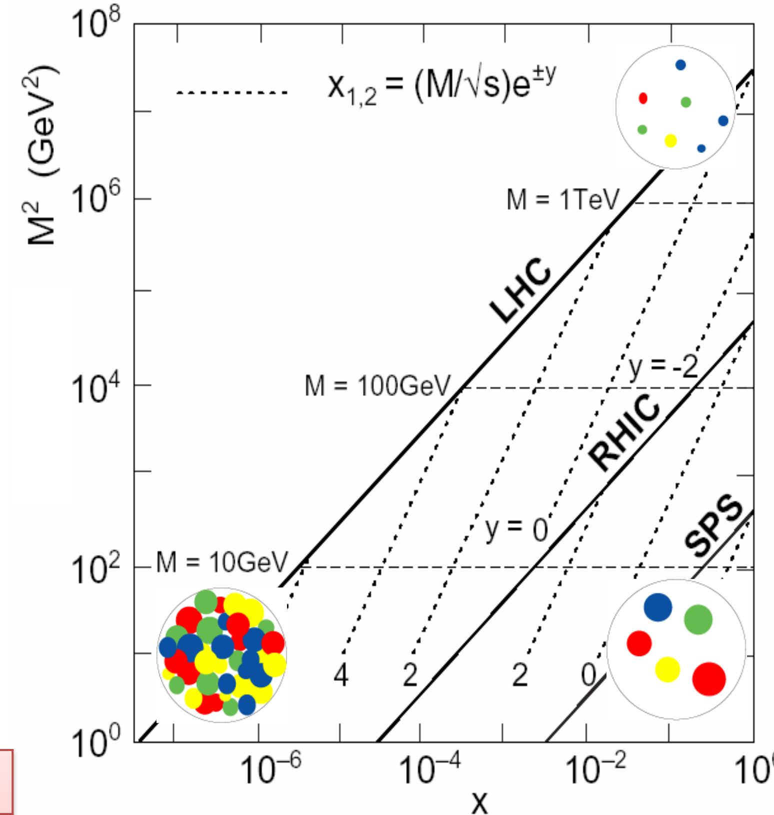


CMS Acceptance



Large Range of Hermetic Coverage

Silicon and μ Tracker	$\lvert\eta\rvert \leq 2.4$
ECAL	$\lvert\eta\rvert \leq 3.0$
HCAL	$\lvert\eta\rvert \leq 5.2$
CASTOR	$5.2 \leq \lvert\eta\rvert \leq 6.6$
ZDC	$\lvert\eta\rvert \geq 8.3$ for neutrals



- Extended kinematic reach

x~(1/40) of RHIC

<10^{-4} measurable

Plan for the First Pb+Pb Coll.

Key Parameters of "Early" Pb Ion Beam (from LHC Design Report)

Parameter	Units	Early Beam	Nominal
Energy per nucleon	TeV	2.76 → 2	2.76
Initial ion-ion Luminosity L_0	cm^{-2} s^{-1}	~ 5 ×10^{25}	1 ×10^{27}
No. bunches, k_b		62	592
Minimum bunch spacing	ns	1350	99.8
β^*	m	1.0	0.5 /0.55
Number of Pb ions/bunch		**7 ×10^{7}**	**7 ×10^{7}**
Transv. norm. RMS emittance	μm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	h	14, 7.5, 5.5	8, 4.5, 3
		Only possibility for 2009 or early 2010	Goal for 2-3 years (?) beyond

At full energy, luminosity lifetime is determined mainly by collisions ("burn-off" from ultraperipheral electromagnetic interactions) $\sigma \approx 520$ barn

J.M. Jowett, LHC Performance Workshop, Chamonix, 6/2/2009 6

Note from the Chamonix meeting: Early Pb Beam will have lower beam energy ⇒ 10 TeV in pp corresponds to 4 TeV in Pb+Pb.

Pb+Pb	$\sqrt{s_{NN}}$	Collision Rate (Max.)	Collision Rate (Avg.)
Year-1 (2010)	**4 TeV**	**~150 Hz**	**~100 Hz**
Nominal (2012)	**5.5 TeV**	**~8 kHz**	**~3 kHz**

- Low collision rate in Year-1 allows us to write **all** min. bias events to mass storage.
- Fully functional **high-level trigger (HLT)** is needed at nominal luminosity.

CMS High-Level Trigger

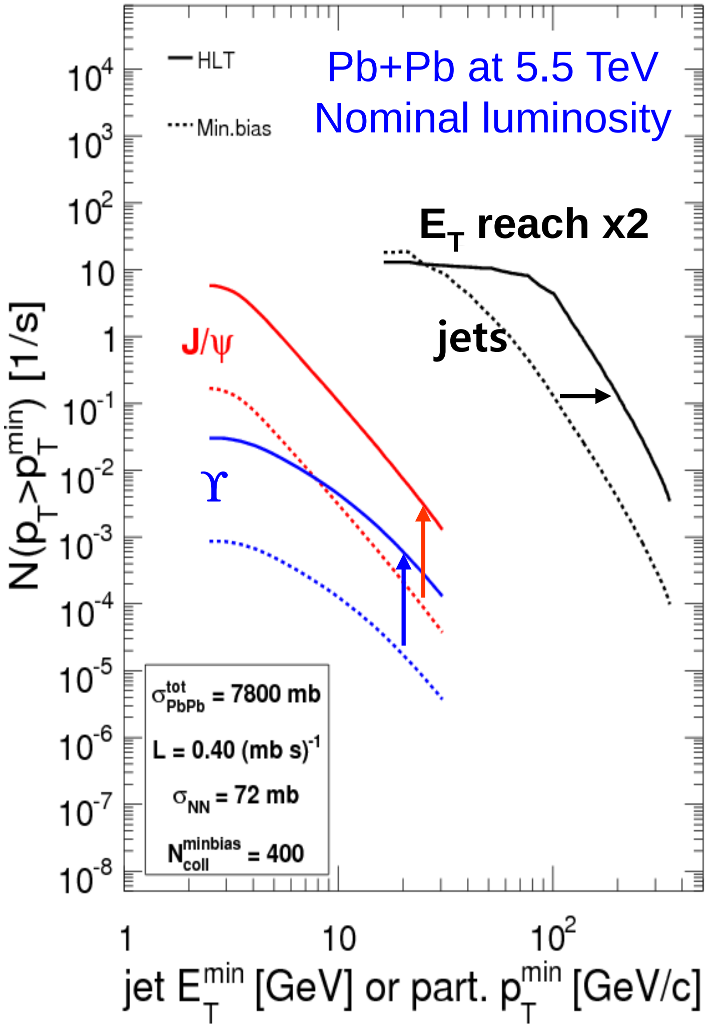
Level 1 (Muon Chambers+Calorimeters)

Level 1	Pb+Pb	p+p
Collision Rate	3 kHz (8 kHz peak)	1 GHz
Event Rate	3 kHz (8 kHz peak)	40 MHz
L1 Accept Rate	3 kHz (8 kHz peak)	100 kHz
Output Bandwidth	100 GByte/sec	100 GByte/sec

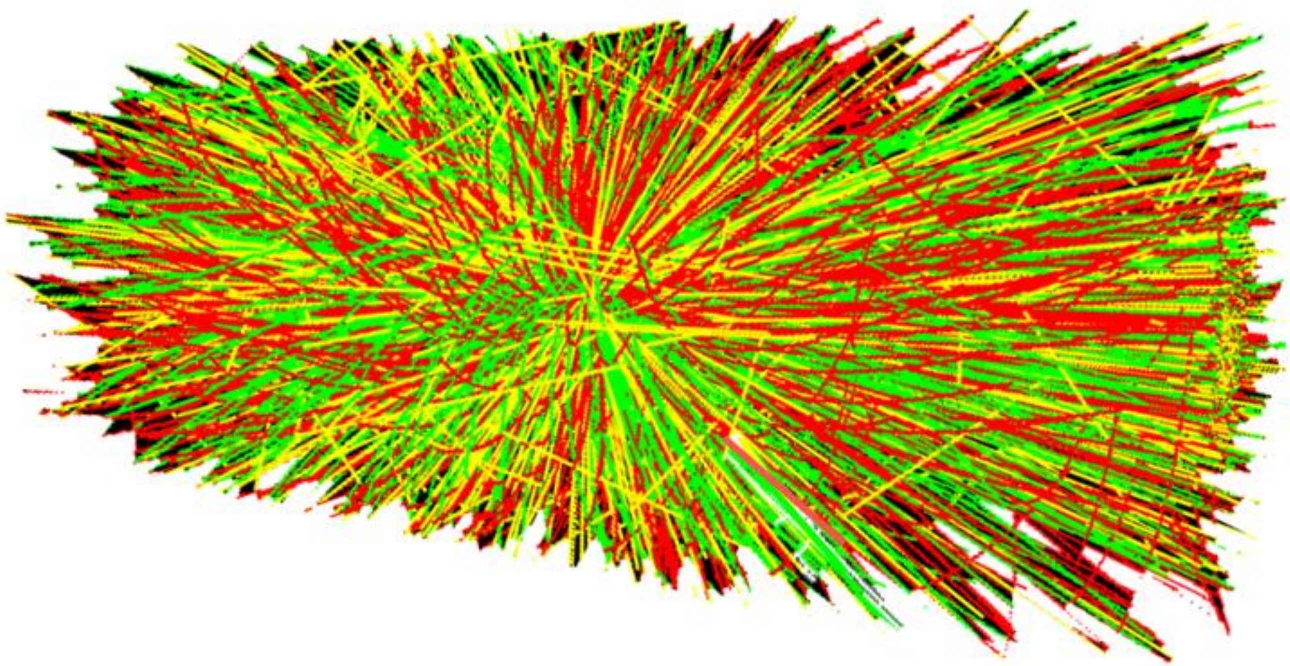
High-Level Triggers (high E_T-jet, γ, e, μ)

- Large computing farm
  (Start up with 7.2k CPU cores)
- Run “offline algorithm” on every Pb+Pb events
- Significantly enhanced statistics
  for hard processes (see the right figure)

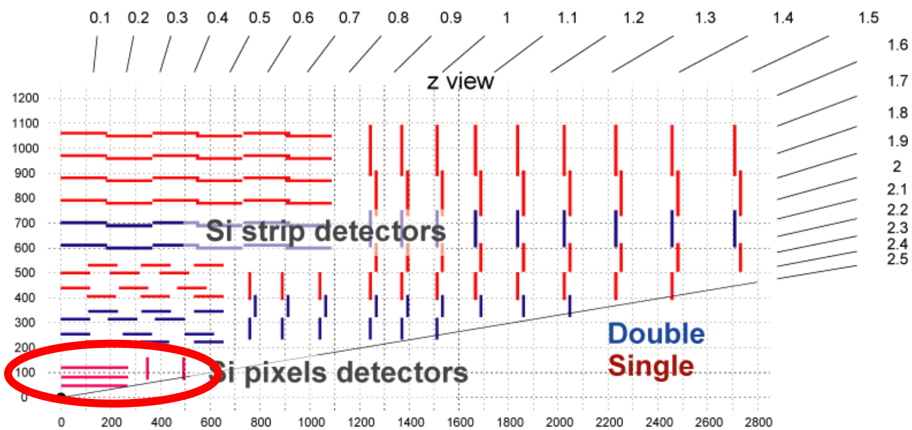
High-Level Trigger	Pb+Pb	p+p
Input Rate	3 kHz (8 kHz peak)	100 kHz
Output Bandwidth	225 MByte/sec	225 MByte/sec
Output Rate	10 – 100 Hz	150 Hz
Rejection	97-99.7%	99.85%



Soft Probes of QCD Matter in CMS

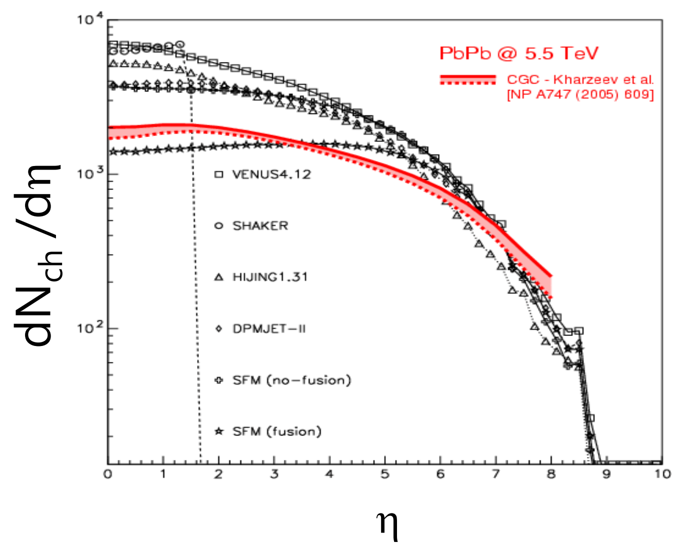


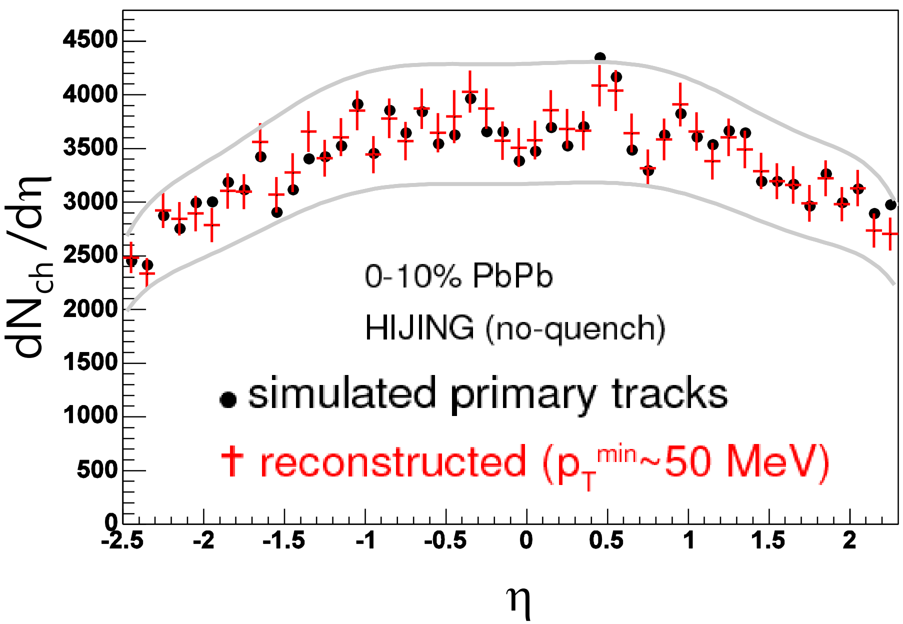
Charged Particle Multiplicity



The layout of the CMS inner tracker

Total 66M Si Pixels
Occupancy<2% at $dN_{ch}/d\eta \approx 3500$
Cluster shape or tracklet methods
Needs only a few thousand events

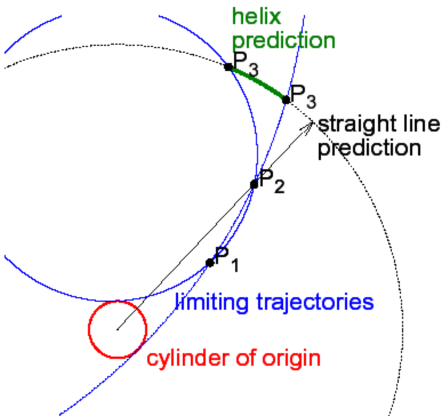


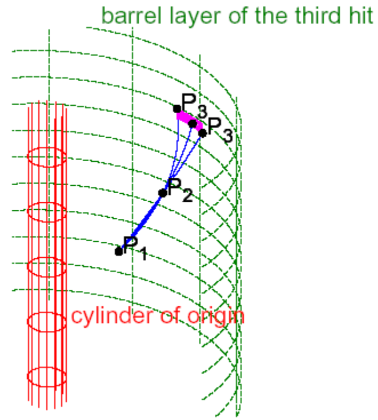


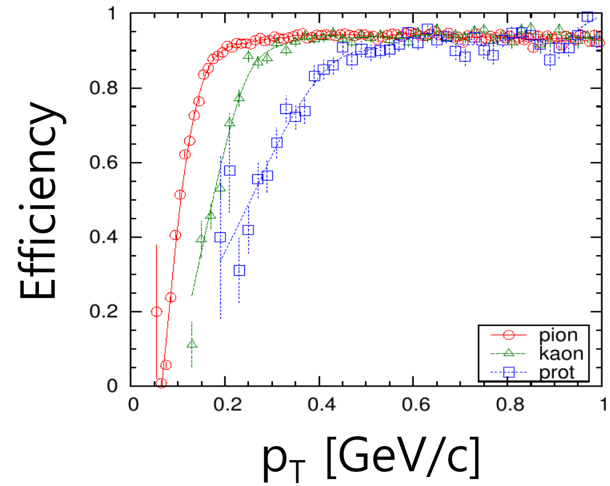
Estimation of the Gluon Density
Gluon Saturation
Color Glass Condensate (CGC)

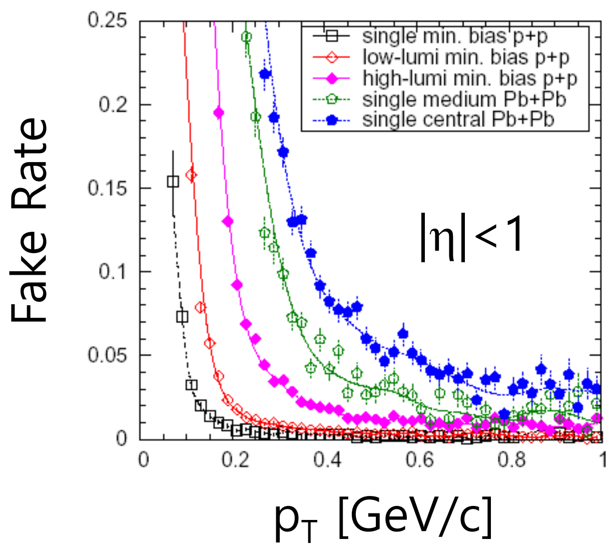
Hadron Spectra at Low p_T

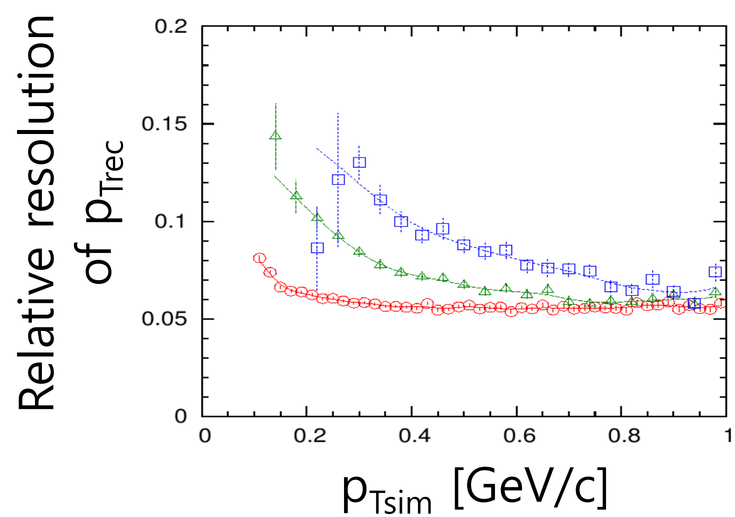
Tracking: Pixel-Triplet Algorithm





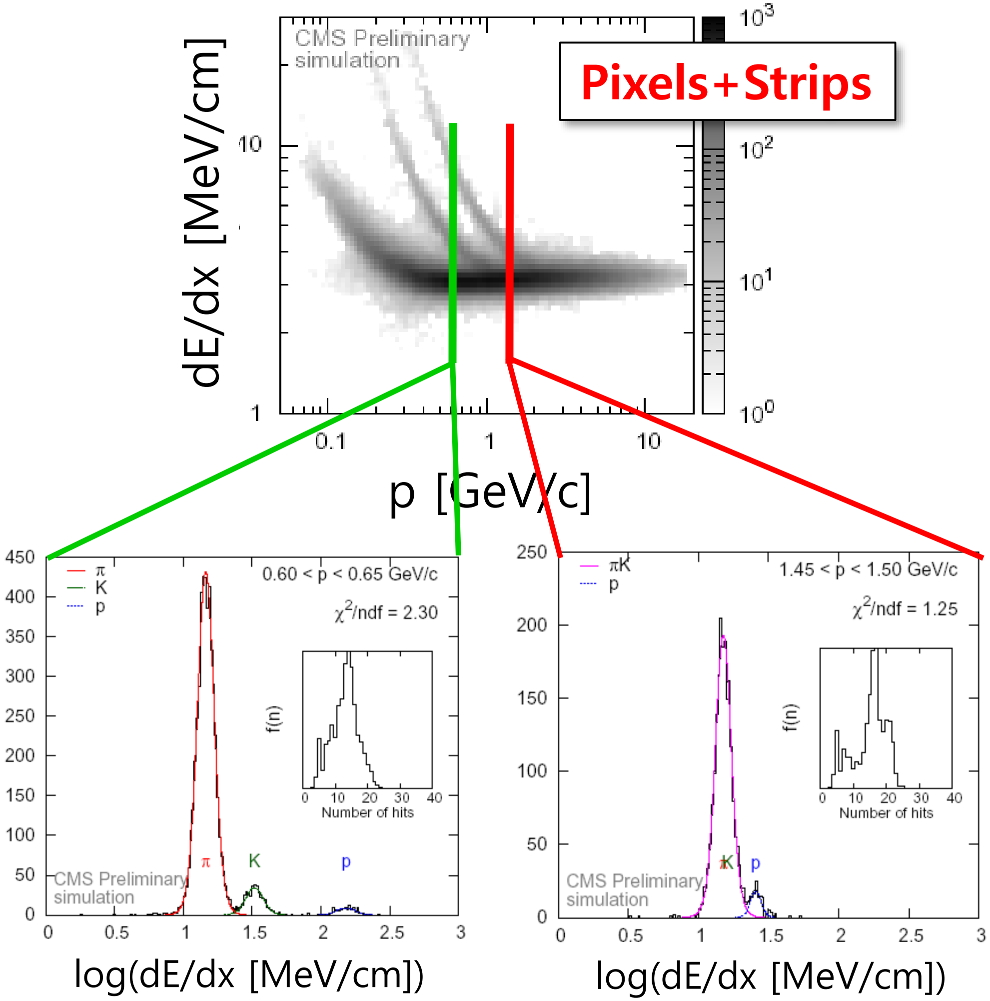


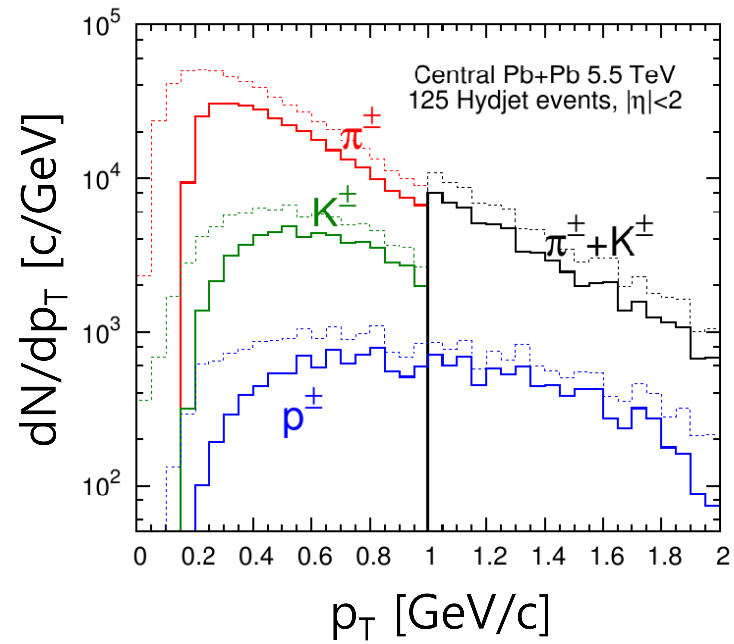




Hadron Spectra at Low p_T

PID using the Gaussian unfolding method for dE/dx

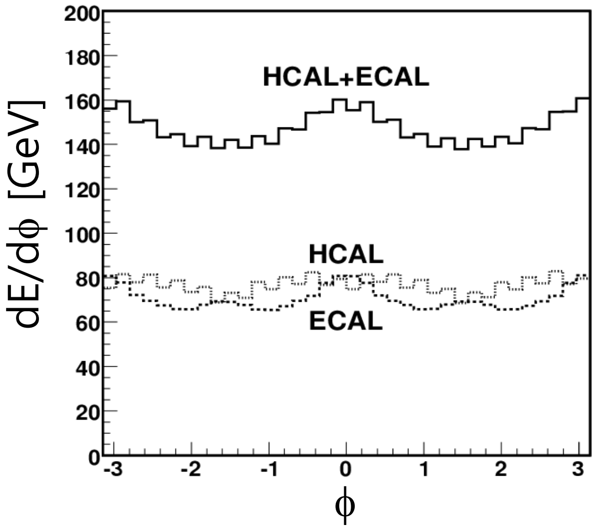




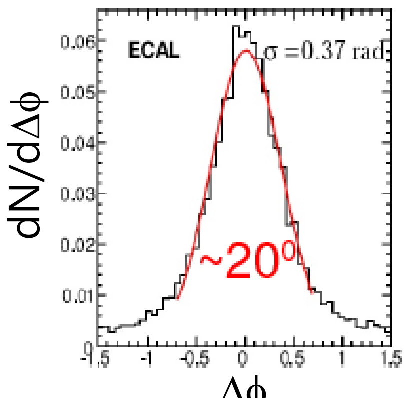
$$+K_S^0, \Lambda, \Xi, \Omega, \rho, K^*, \phi, \ldots$$

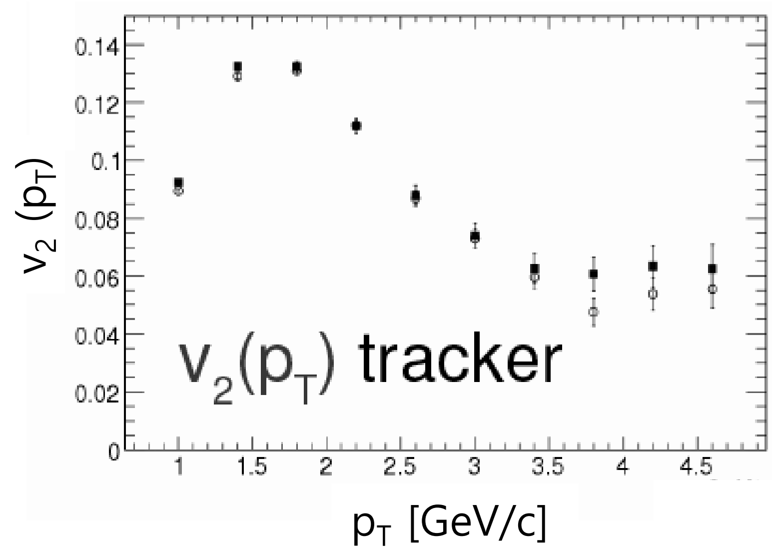
Hadron Chemistry
Expansion Dynamics
Equation-of-State
Strangeness Production

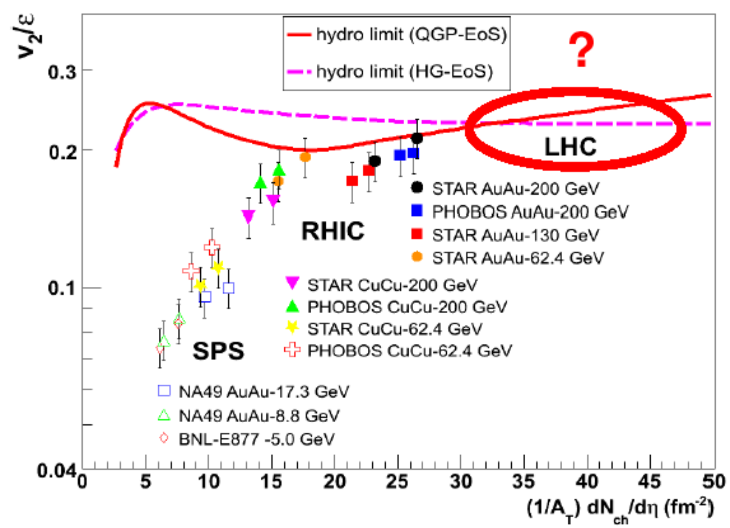
Elliptic Flow



Reaction Plane Resolution



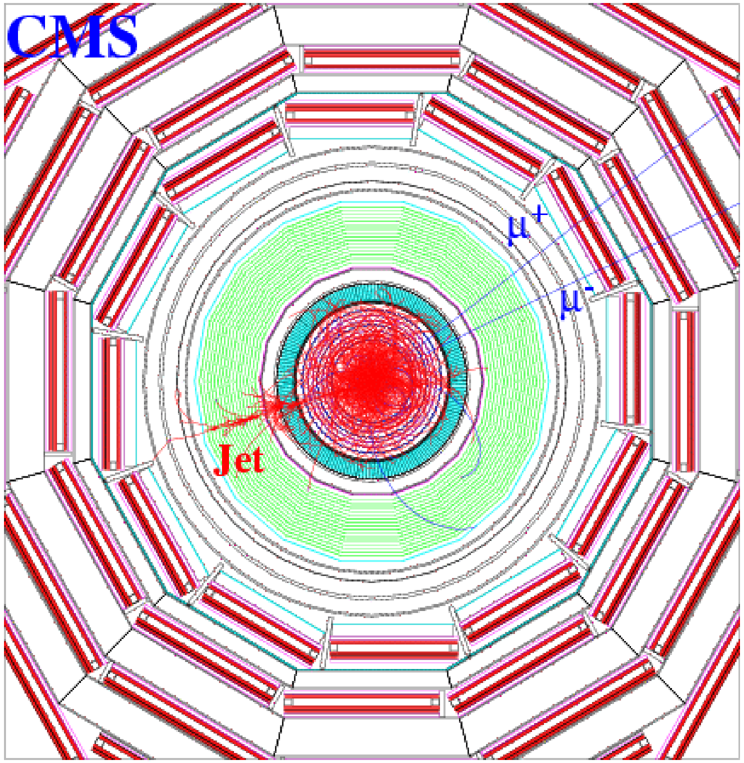




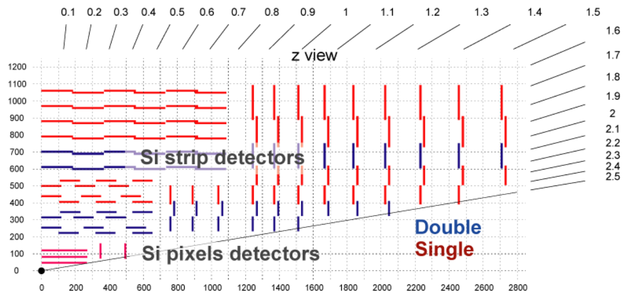
- **Open symbols: Simulated events**
- **Close symbols: Reconstructed events**

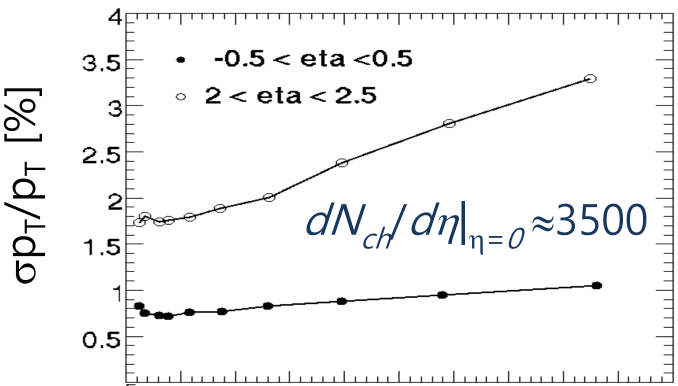
Hydrodynamic Behavior
QCD Equation-of-State
Viscosity of Fluid

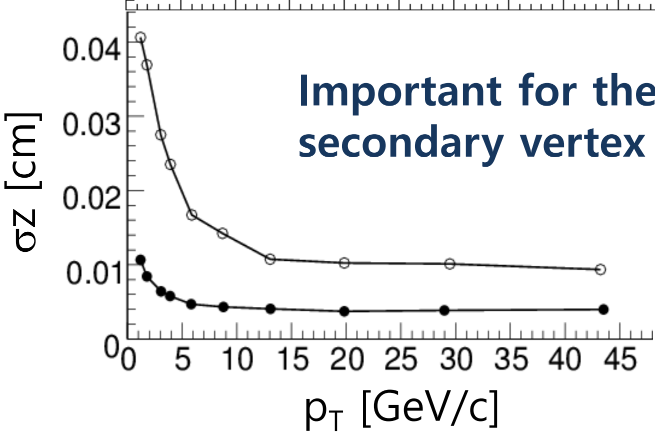
Hard Probes of QCD Matter in CMS

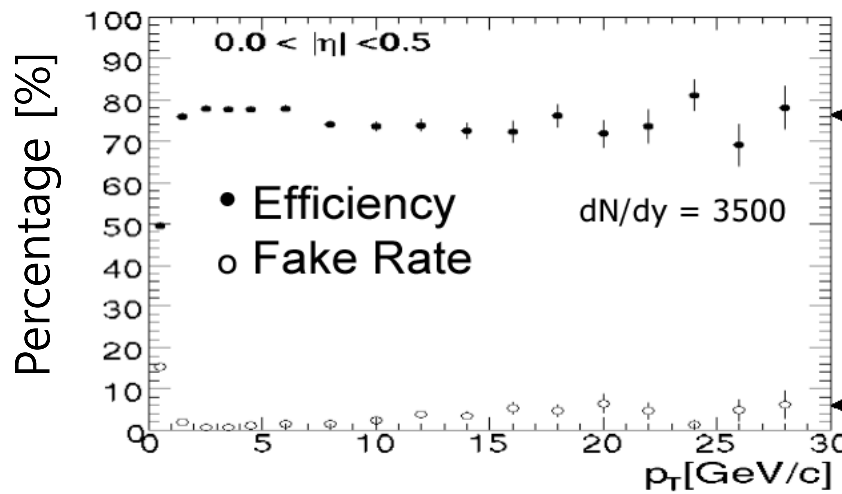


Spectra at High p_T





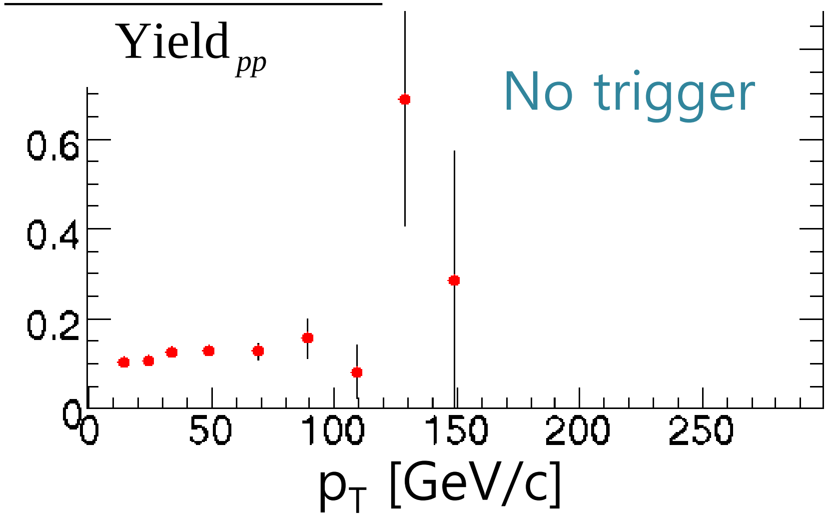




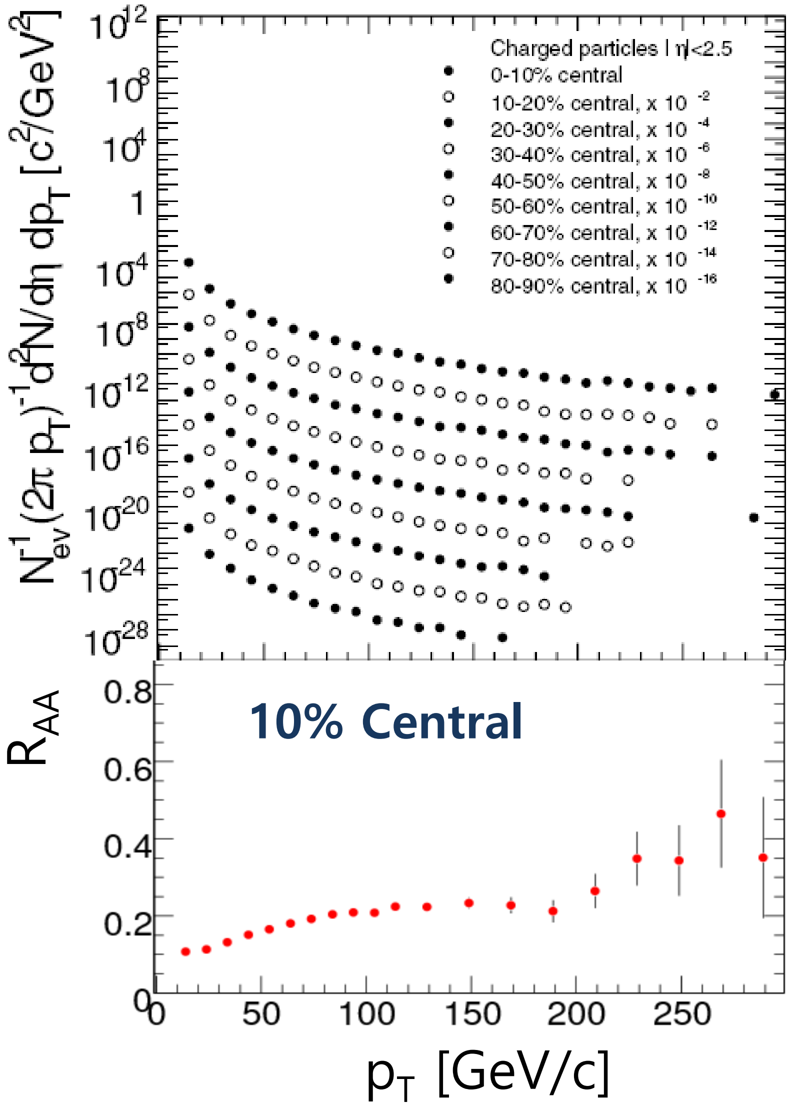
Good Efficiency

Low Fake Rate

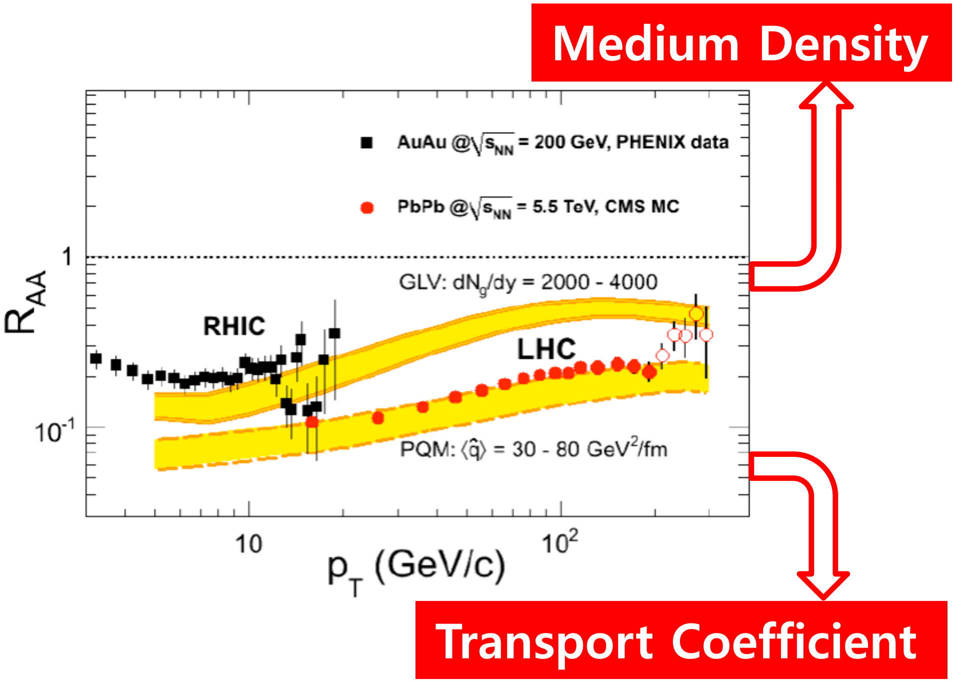
$$R_{AA} = \frac{\mathrm{Yield}_{AA} / < N_{coll} >}{\mathrm{Yield}_{pp}}$$



Spectra at High p_T

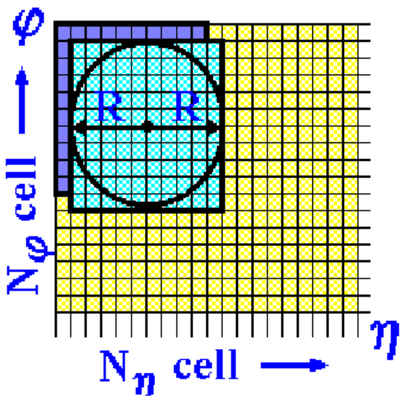


With high-E_T HLT charged particle spectra can be measured up to p_T ~300 GeV/c.

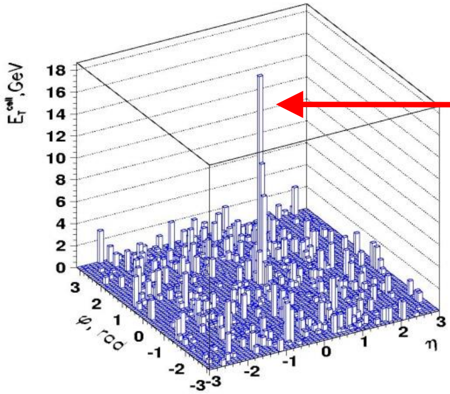


Jet Recon. in Calorimeters

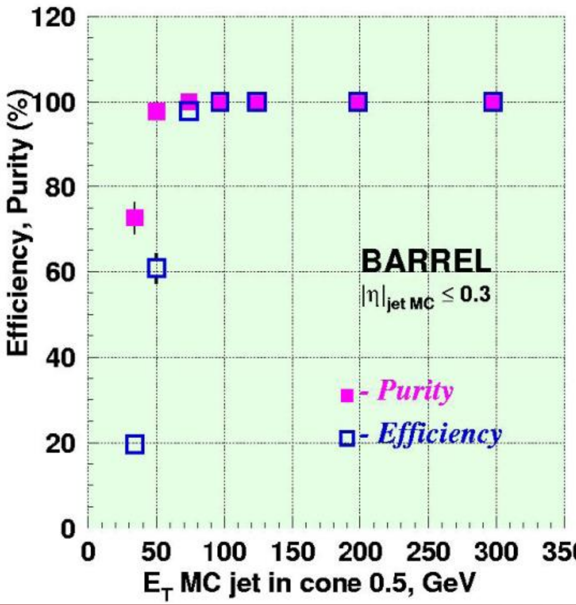
Iterative cone algorithm (R=0.5) with background subtraction



Spatial resolution
σφ = 0.032, ση = 0.028
which is smaller than
the calorimeter tower
size 0.087 x 0.087

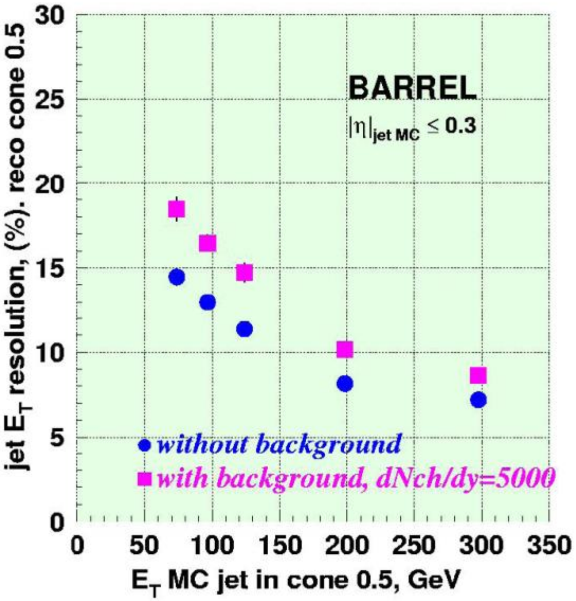


100 GeV jet in a Pb+Pb event, after the background subtraction



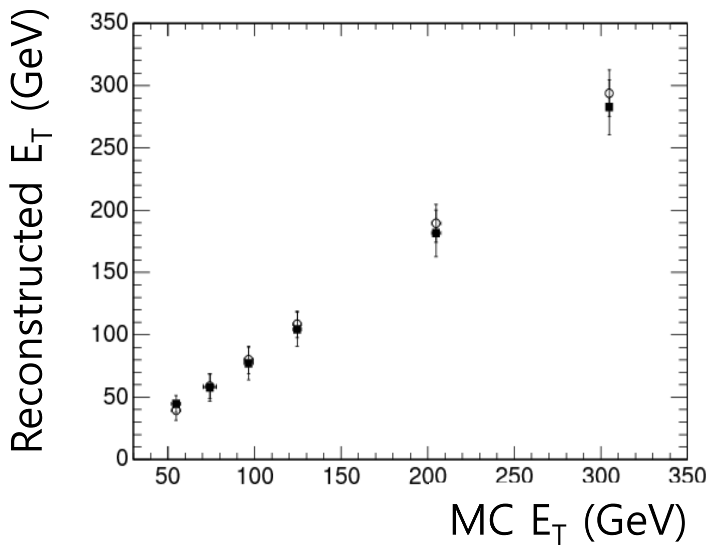
High efficiency and purity for E_T>50 GeV

Good energy resolution for E_T>100 GeV

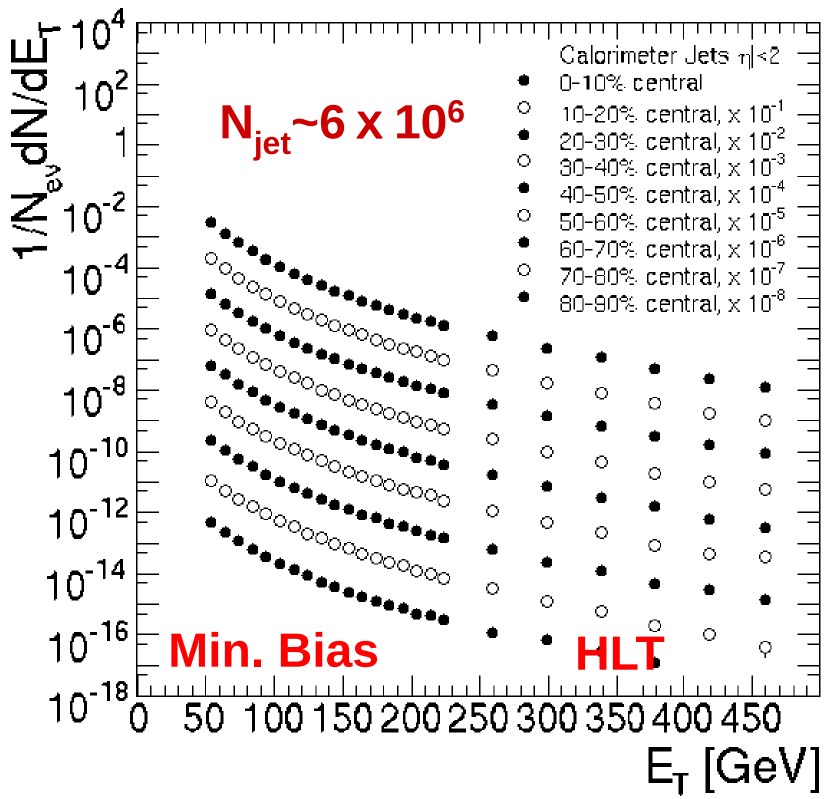


Jet Spectra

Jet Energy Reconstruction



Pb+Pb (0.5 nb^{-1})



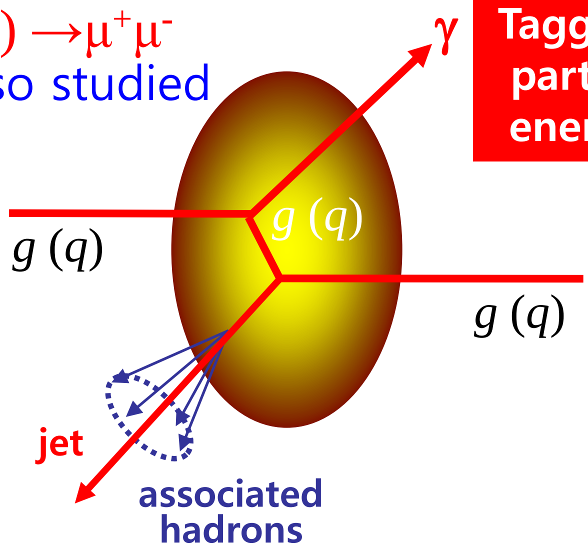
With high-E_T jet HLT
jet spectra can be measured up to E_T ~500 GeV for 1 year running @ nominal luminosity.

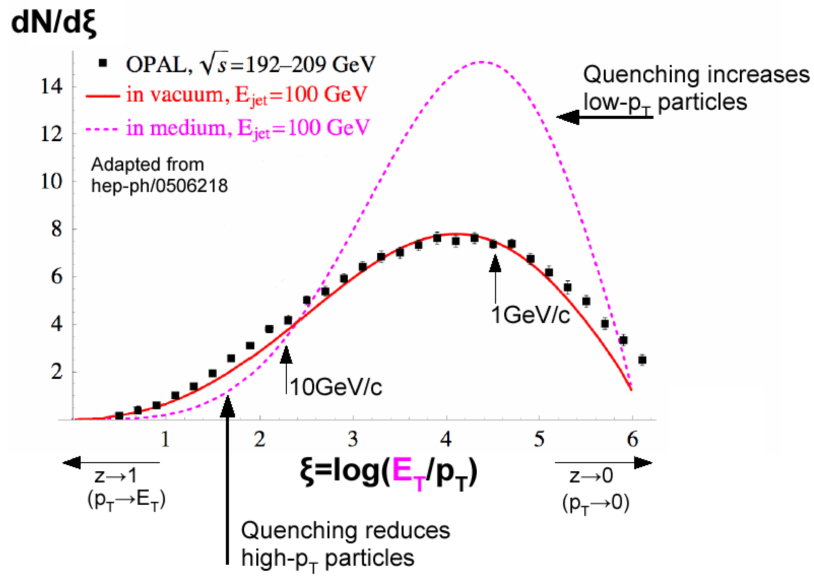
CMS can use true jets to study parton energy loss.

Photon-Tagged Jets

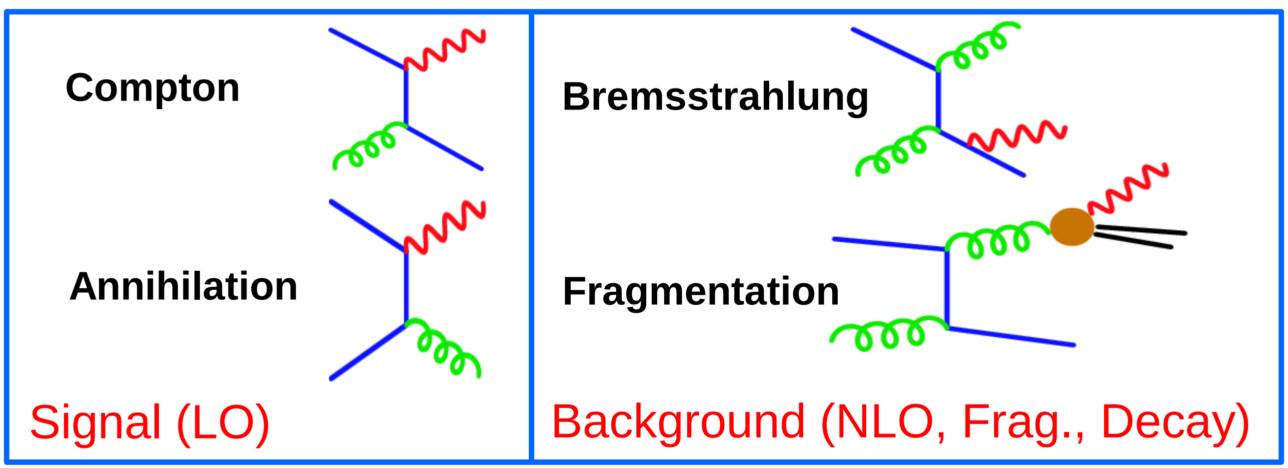
γ^* (or Z^0) $\rightarrow \mu^+\mu^-$
is being also studied

Tagging parton energy





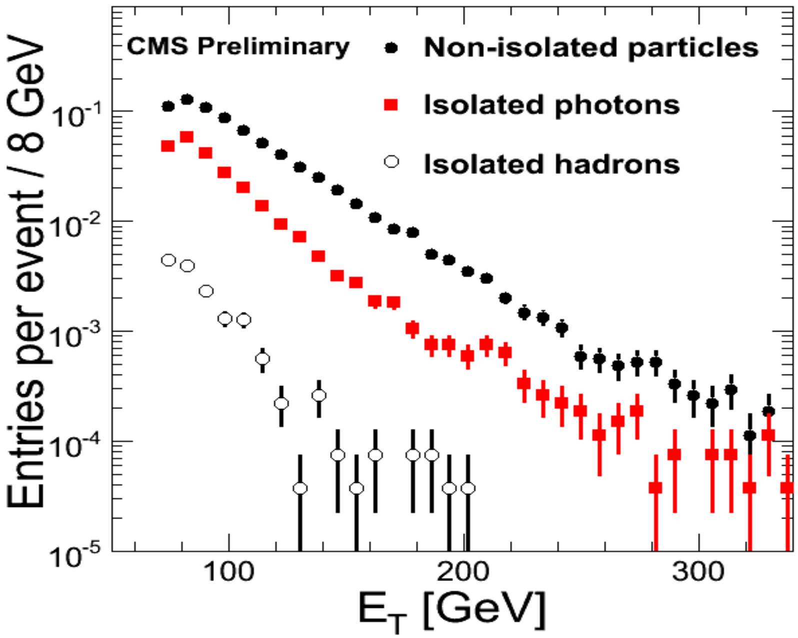
How is the energy loss distributed in the jet fragmentation cone?



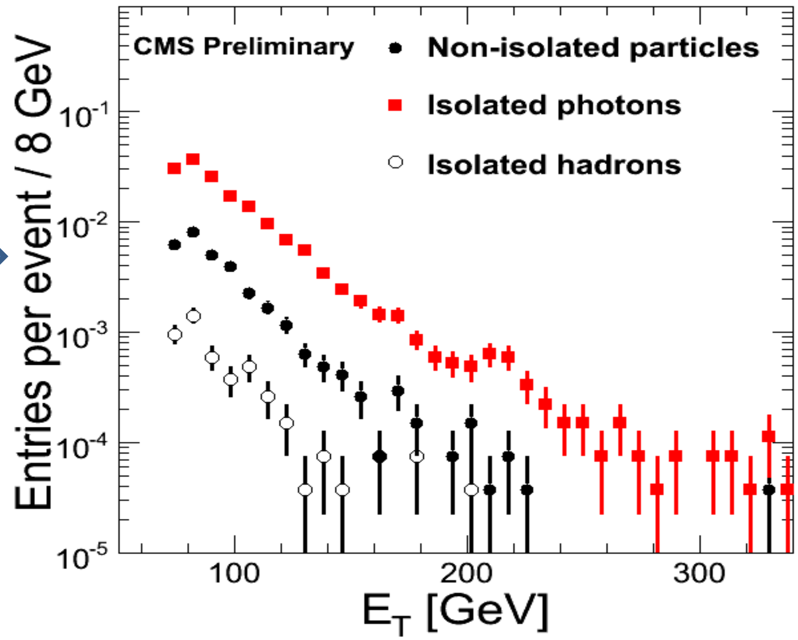
Photon-Tagged Jets

ECAL cluster distributions in the most central 10% Pb+Pb

Before cuts: S/B=0.3

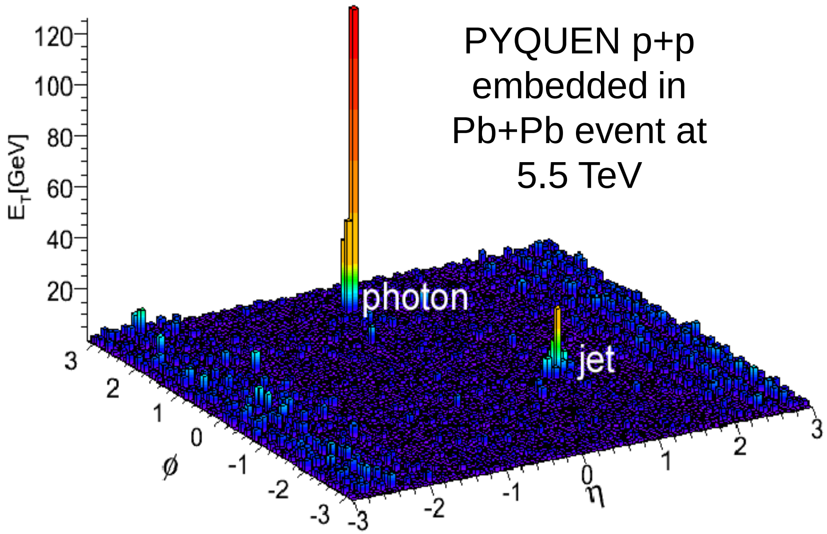


After cuts: S/B=45

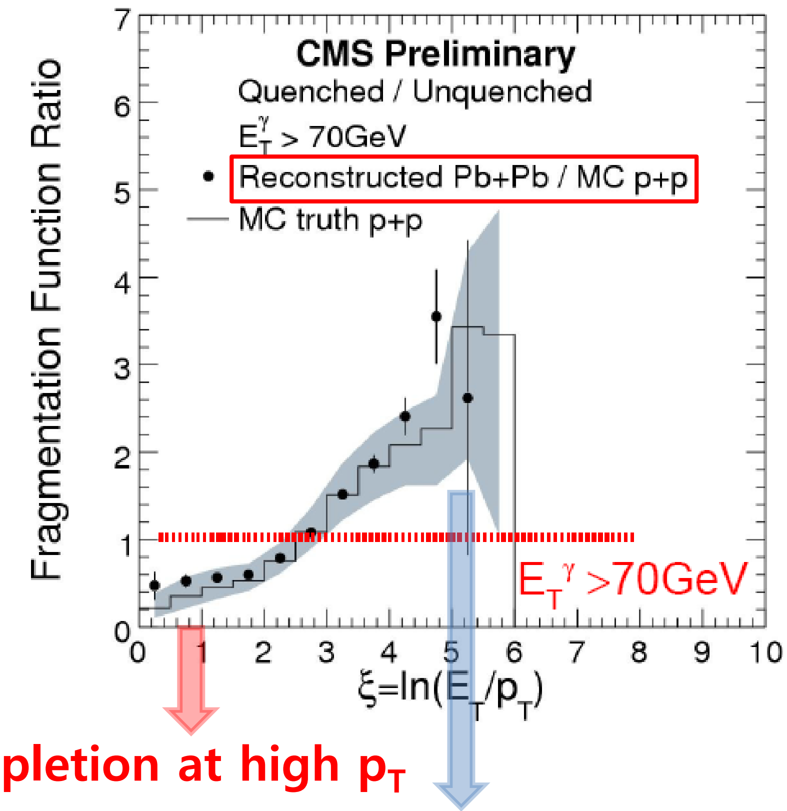


- Photons
  - Cluster shape variable is used to differentiate isolated photons from mostly non-isolated hadrons (S/B was improved by factor ~15).
  - $E_T(\gamma) > 70$ GeV

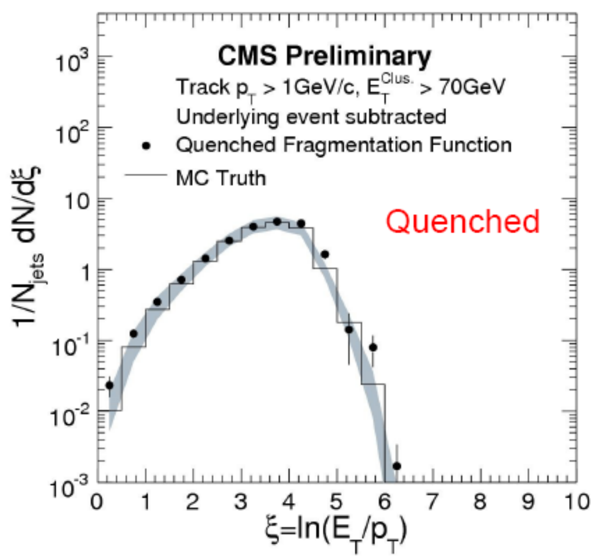
Photon-Tagged Jets



- Require the back-to-back γ-jet correlation by $\Delta\phi(\gamma,\text{jet}) > 3$ rad. with $E_T(\text{jet})>30$ GeV



Reco. FF = MC FF



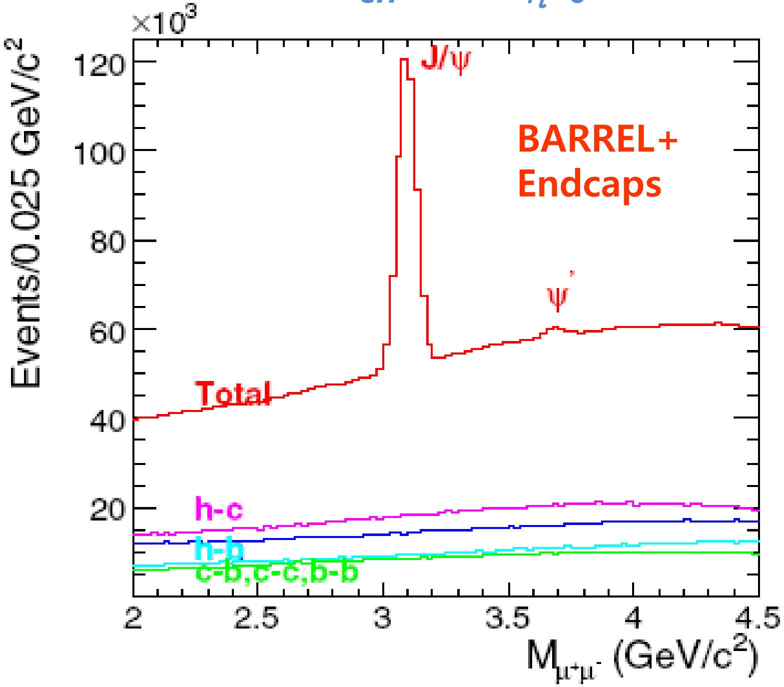
Depletion at high p_T

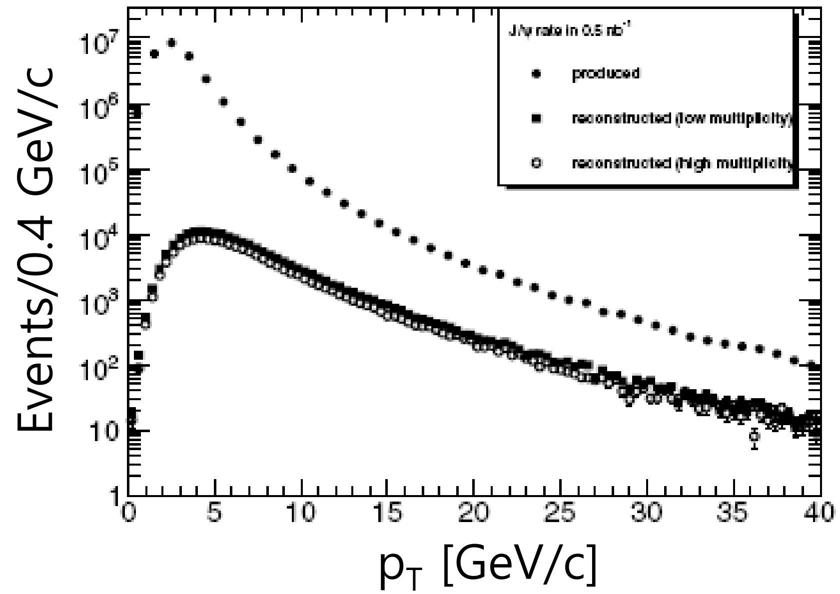
Enhancement at low p_T

Heavy Flavor (J/ψ)

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

Pb+Pb (0.5 nb^{-1})





The J/ψ spectra can be measured beyond 40 GeV/c using HLT.

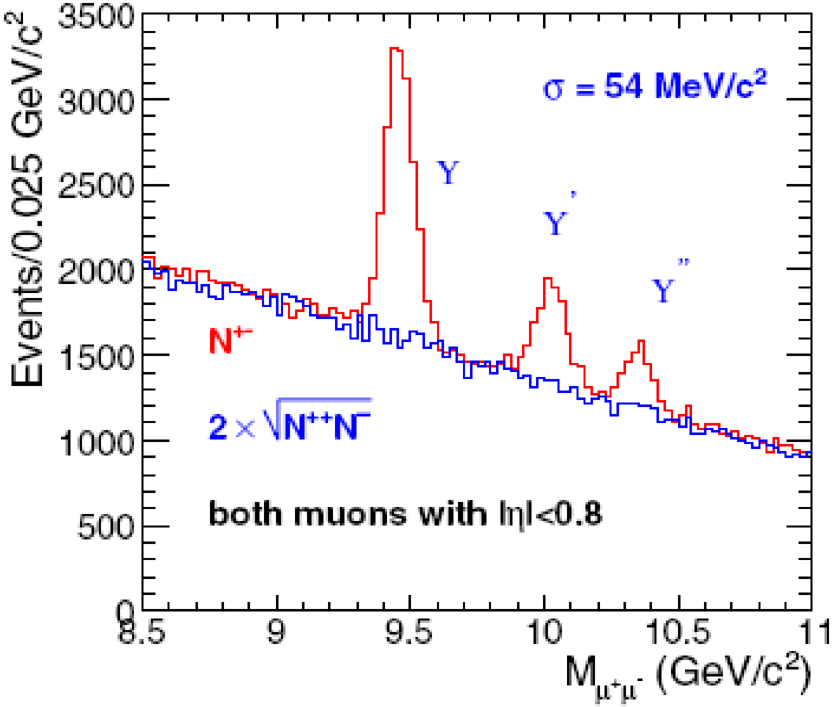
- $\sigma_{J/\Psi}$ =35 MeV/c^2 for $|\eta|<2.4$
- S/B~5 for $|\eta|<0.8$
- $N_{J/\psi} \sim 1.8 \times 10^5$ for 0.5 nb^{-1}

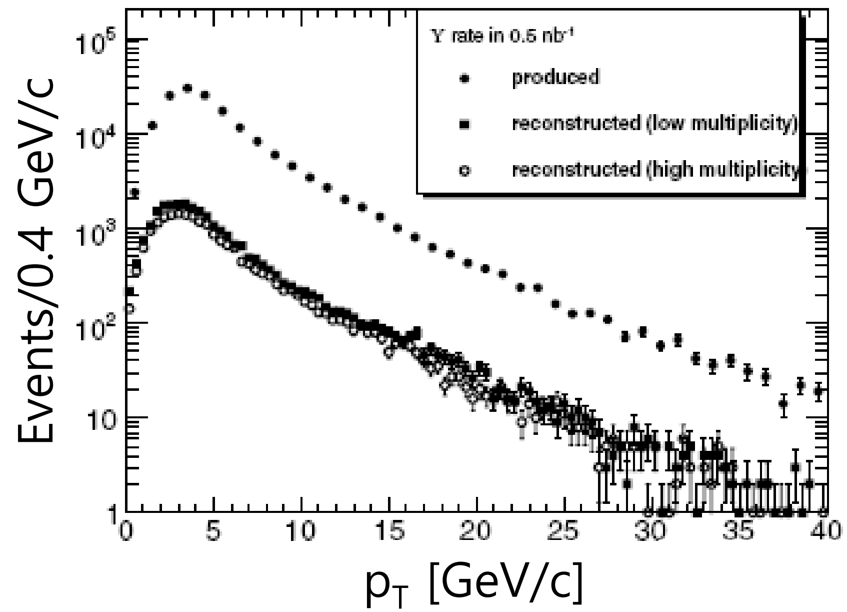
- Regeneration vs. Screening
- J/ψ may survive up to $2T_C$ (?)

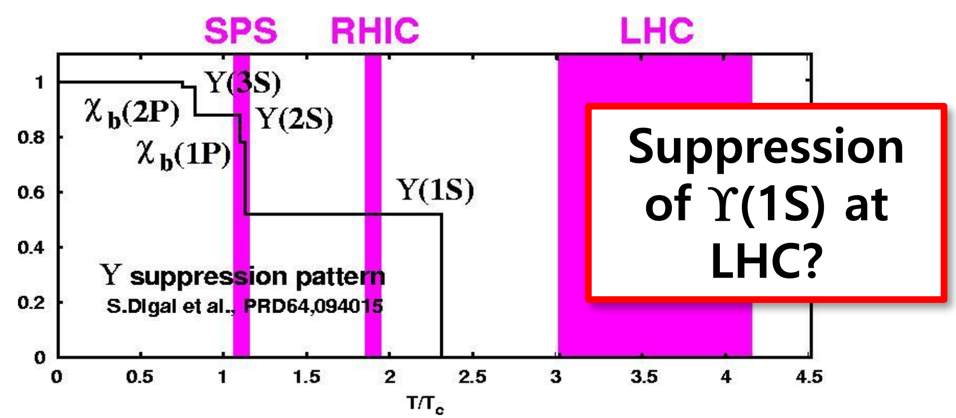
Heavy Flavor (Υ)

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

Pb+Pb (0.5 nb^{-1})



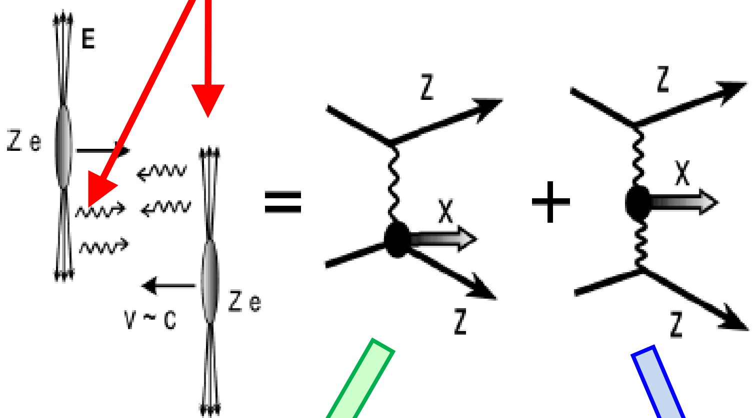




- σ_{Υ} =54 MeV/c² for |η|<0.8
- σ_{Υ} =90 MeV/c² for |η|<2.4
- S/B~1 for |η|<0.8
- N_{Υ}~2.6 x 10^4 for 0.5 nb^{-1}

Υ Production in UPC

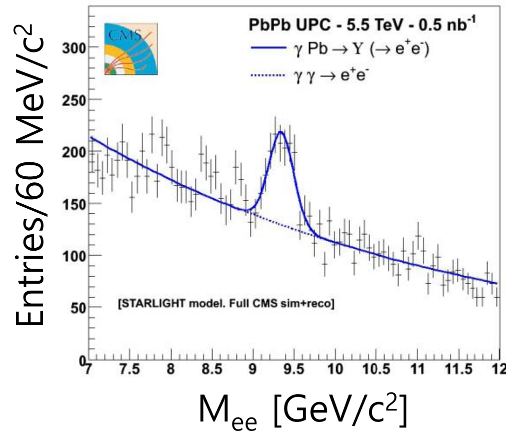
Strong E&M fields due to the coherent action of 82 protons (E_γ^{max}~80 GeV)

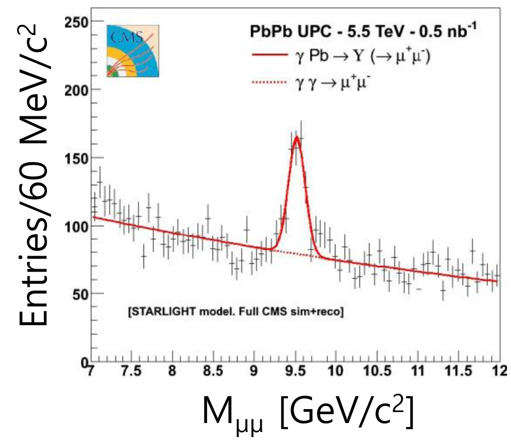


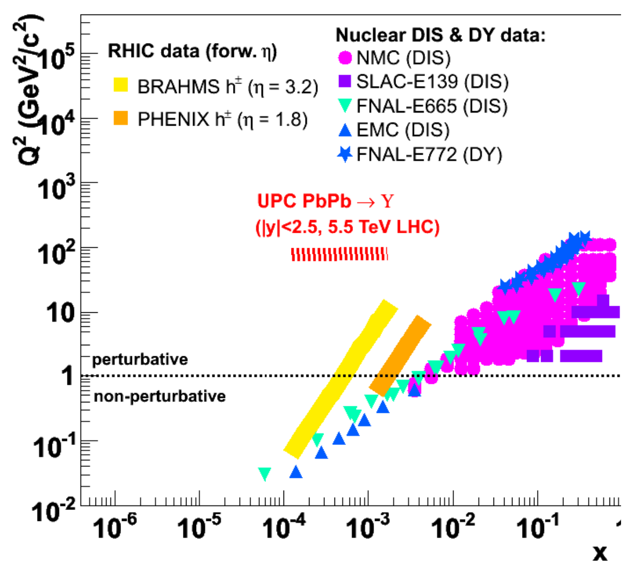
$$\max\left(\sqrt{s_{\gamma Pb}}\right)(\mathrm{LHC:HI}) \approx 1\,\mathrm{TeV/u} \approx 3\times\sqrt{s_{\gamma p}}\,(\mathrm{HERA})$$

$$\max\left(\sqrt{s_{\gamma\gamma}}\right)(\mathrm{LHC:HI}) \approx 160\,\mathrm{GeV} \approx \sqrt{s_{\gamma\gamma}}\,(\mathrm{LEP})$$

~500 Υ's/0.5nb^{-1}







Unexplored xG(x,Q^2) region

Summary

1. The CMS detector is versatile not only for *pp*, but also for heavy-ion collisions.
2. The CMS high-resolution trackers, calorimeters, and muon chambers cover almost 4π phase space.
3. The CMS detector can measure various hard probes with the best resolution at the LHC.
4. The CMS detector can also measure soft hadrons for $p_T > 200$ MeV/c with good particle identification.