2008 APCTP Workshop on
"Nuclear Physics in Science Business Belt: Future Heavy Ion Accelerator in Korea"
APCTP, Pohang, Korea

Heavy-Ion Experiments at Relativistic Beam Energies for Next Decades

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Outline

- Motivation
- Prospects of high-temperature QGP (ALICE, ATLAS & CMS at LHC)
- Prospects of high-density QGP (CBM at FAIR)
- Summary

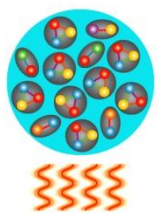
Short History

1. First ion accelerator at relativistic beam energies
   - BEVALAC: BEVATRON+HILAC (1971-1993)
   - Used a very similar language as we are using nowadays
   - Found several phenomena that we are investigating nowadays (Flow, meson production, EoS, etc.)
2. First heavy-ion accelerator at relativistic beam energies
   - SIS (1990-present)
   - Accelerate truly heavy beams up to Pb
   - Measured subthreshold particle production
   - Precise and systematic investigation
3. First heavy-ion accelerator at ultra-relativistic beam energies
   - AGS and SPS (1986-present)
   - Opened the meson dominant region
   - Found several abnormal nuclear effects (Strangeness enhancement, Dileption enhancement in low & intermediate mass regions, J/ψ suppression, etc.)
   - **Motivated new accelerators that I will discuss in this talk**

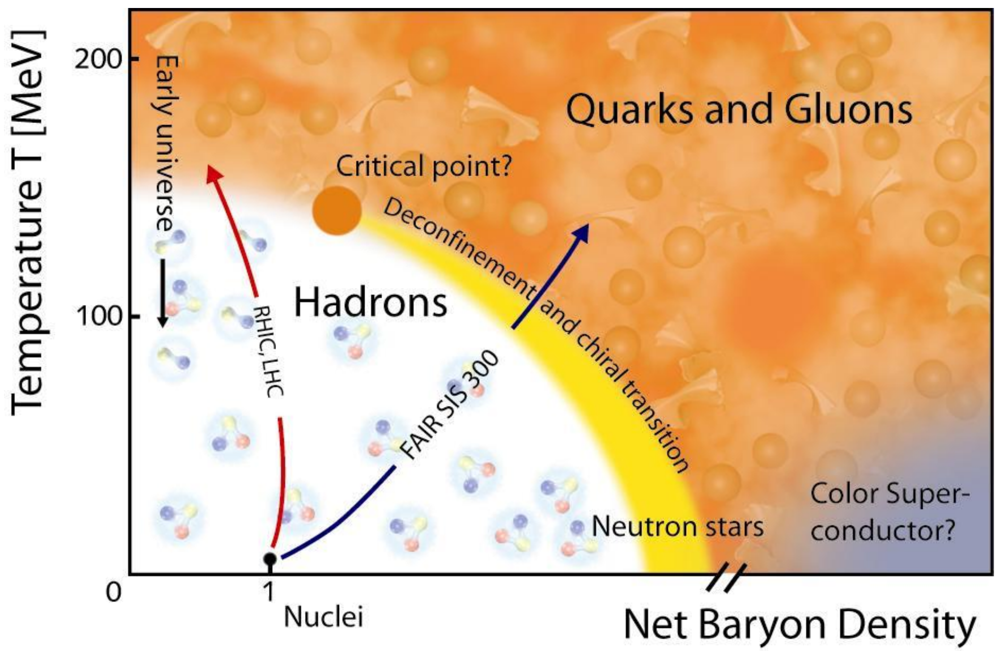
Nuclear Phase Diagram

Purpose of Relativistic Heavy-Ion Collisions

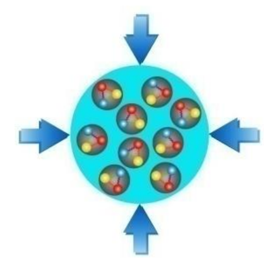
1. Production of new kinds of matter
2. Discovery and systematic investigation of nuclear effects on the fundamental interaction, in particular QCD
3. Understanding the primordial state of the universe and astronomical objects like neutron star



Colliders
RHIC & LHC



Fixed Target Expts.
SIS18 (1990~) ⇒
SIS300 (2015~)



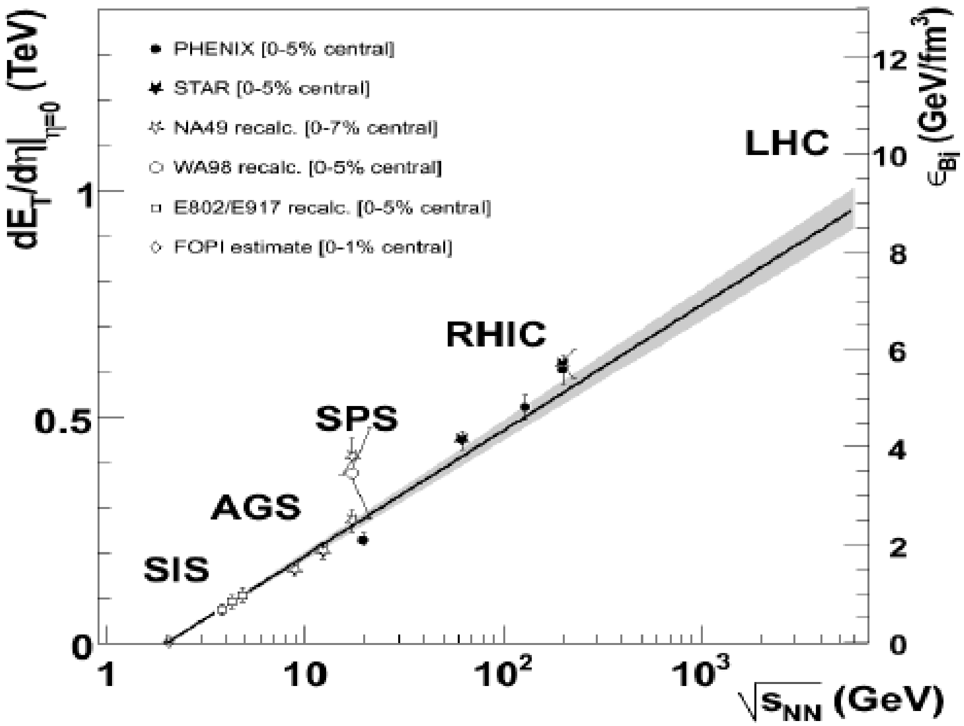
High-Temperature QGP
(ALICE, ATLAS & CMS at LHC)

LHC: New Energy Frontier

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

- LHC energies are far exceeding the range of previous heavy-ion accelerators
  - Extended kinematic reach for pp, pA, and AA collisions
  - New properties of the initial state and saturation at mid-rapidity
  - A hotter, denser, and longer lived partonic matter
  - Increased cross sections and availability of new hard probes
- New energy regime will open a new window on hot and dense QCD matter physics: another large energy jump!

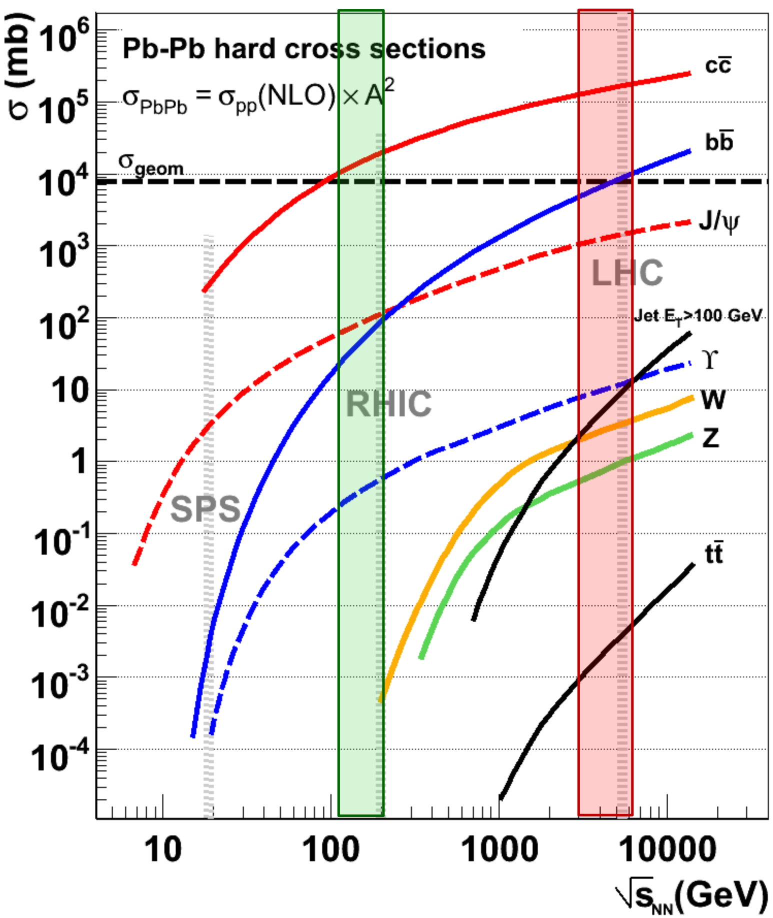
Energy Density at LHC

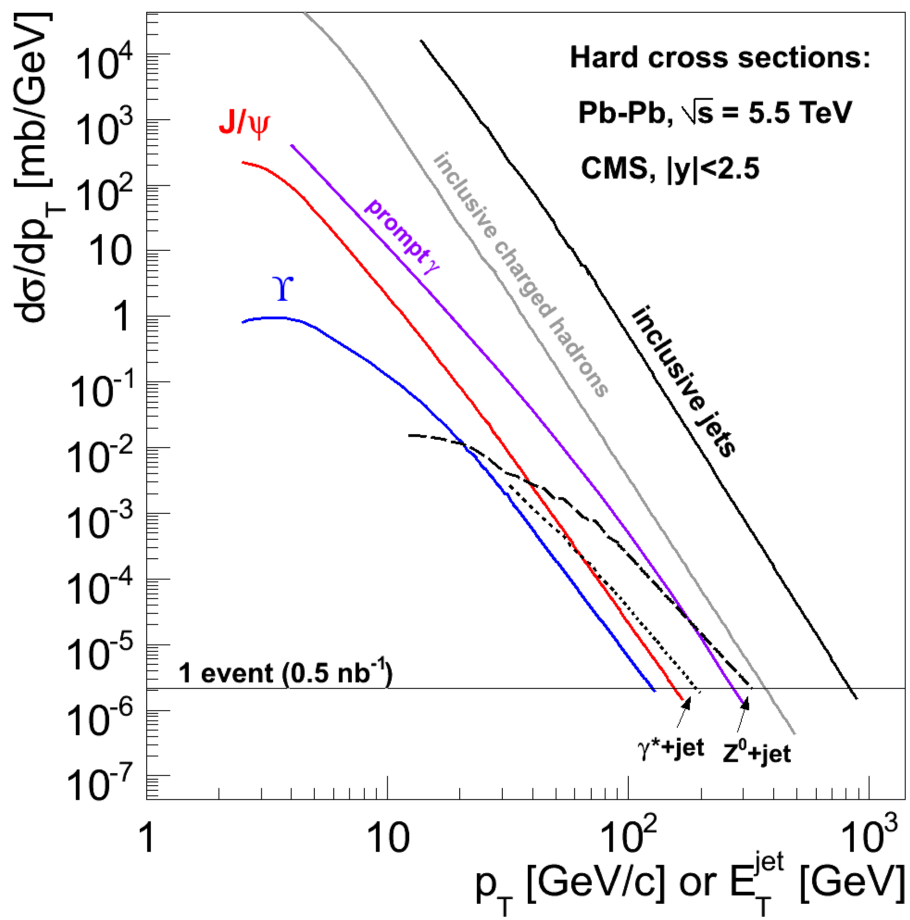


$$\varepsilon_{Bjorken} = \frac{1}{\tau_0(\pi R^2)}\frac{dE_T}{d\eta} \geq 10\ \mathrm{GeV/fm}^3$$

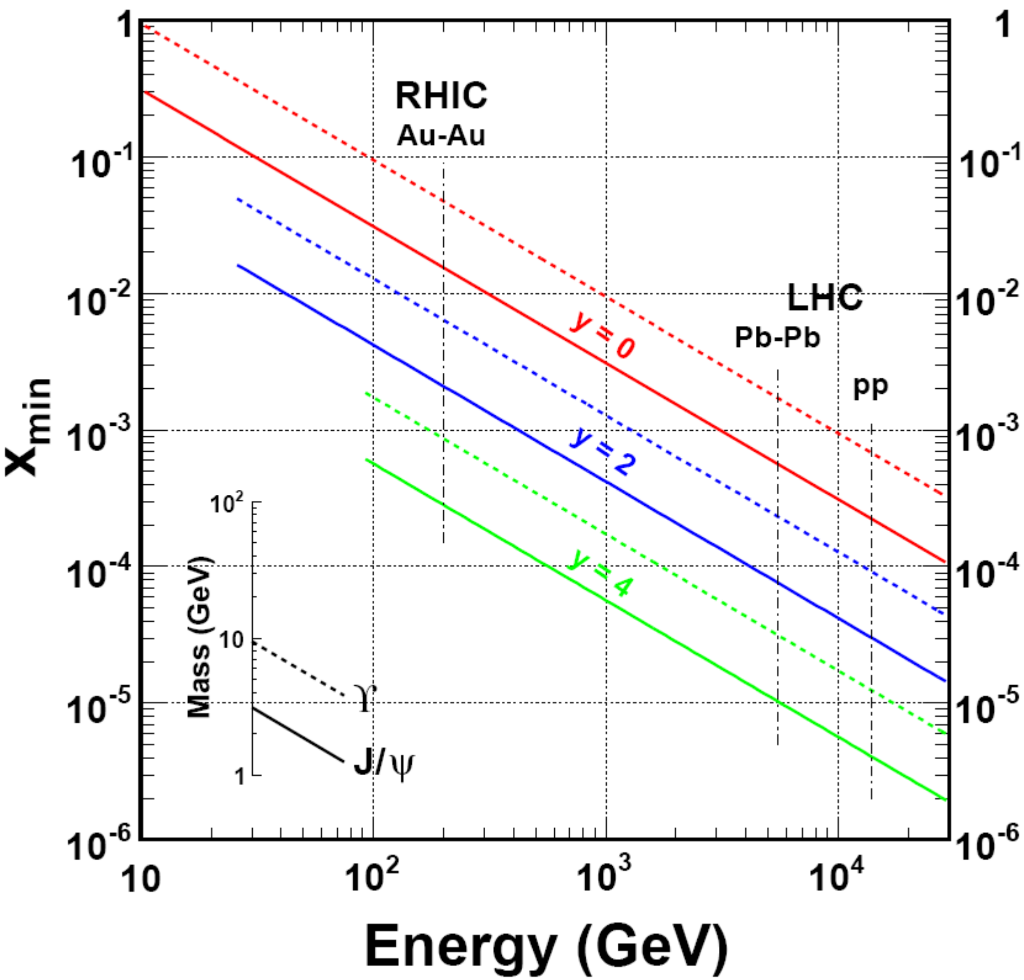
$$\text{with}\quad \tau_0 \sim 1\,\mathrm{fm/c} > 2R/\gamma\ (\sim 0.004\,\mathrm{fm/c})$$

Production Rate at LHC

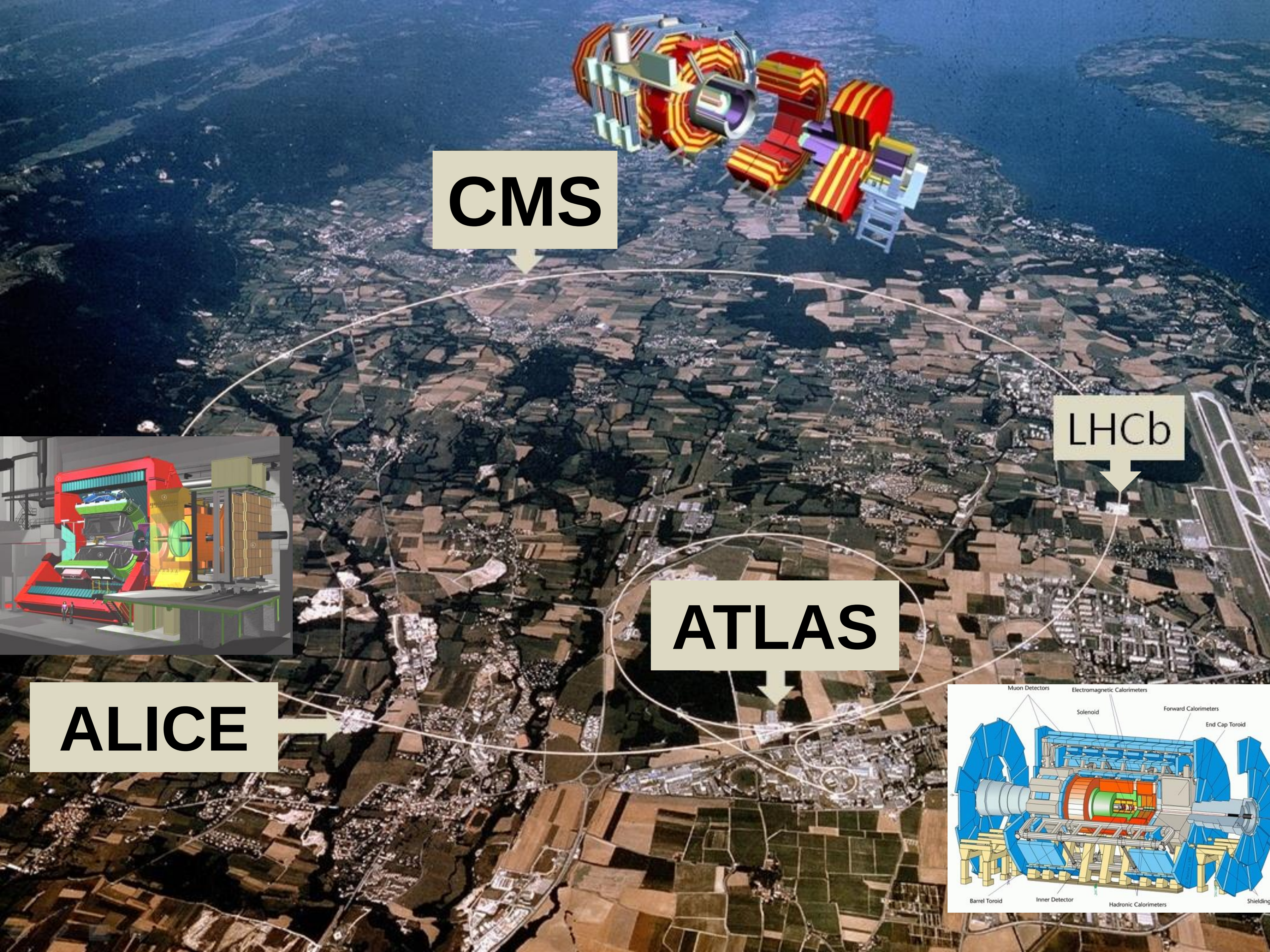




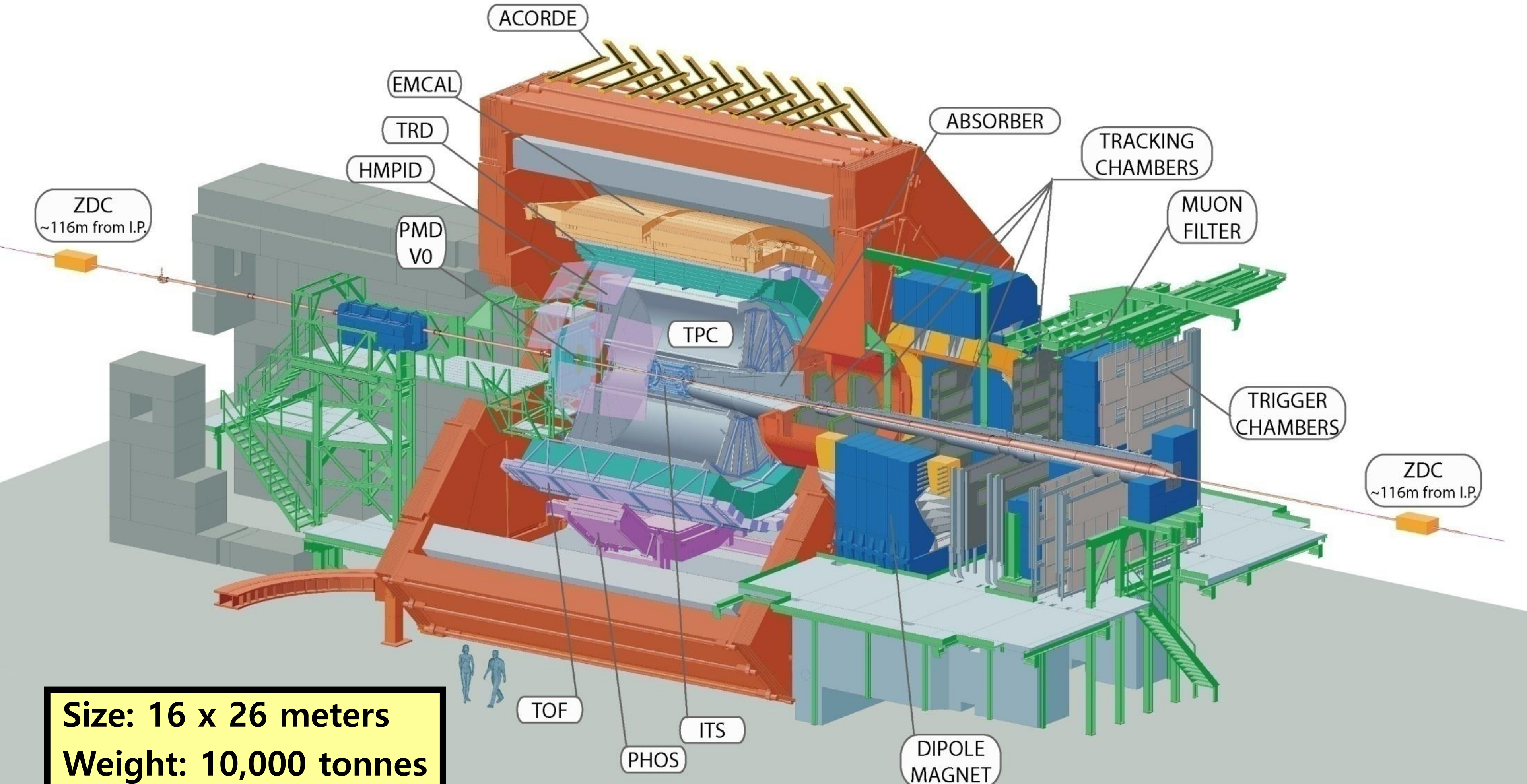
Extension of Low-x Reach



- RHIC first opened the low-x region for new physics (CGC?)
- LHC will lower the low x-reach by another factor 30
- Lowest x at LHC
  - ~3 x 10^{-6} in pp
  - ~10^{-5} in PbPb


CMS
LHCb
ATLAS
ALICE
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

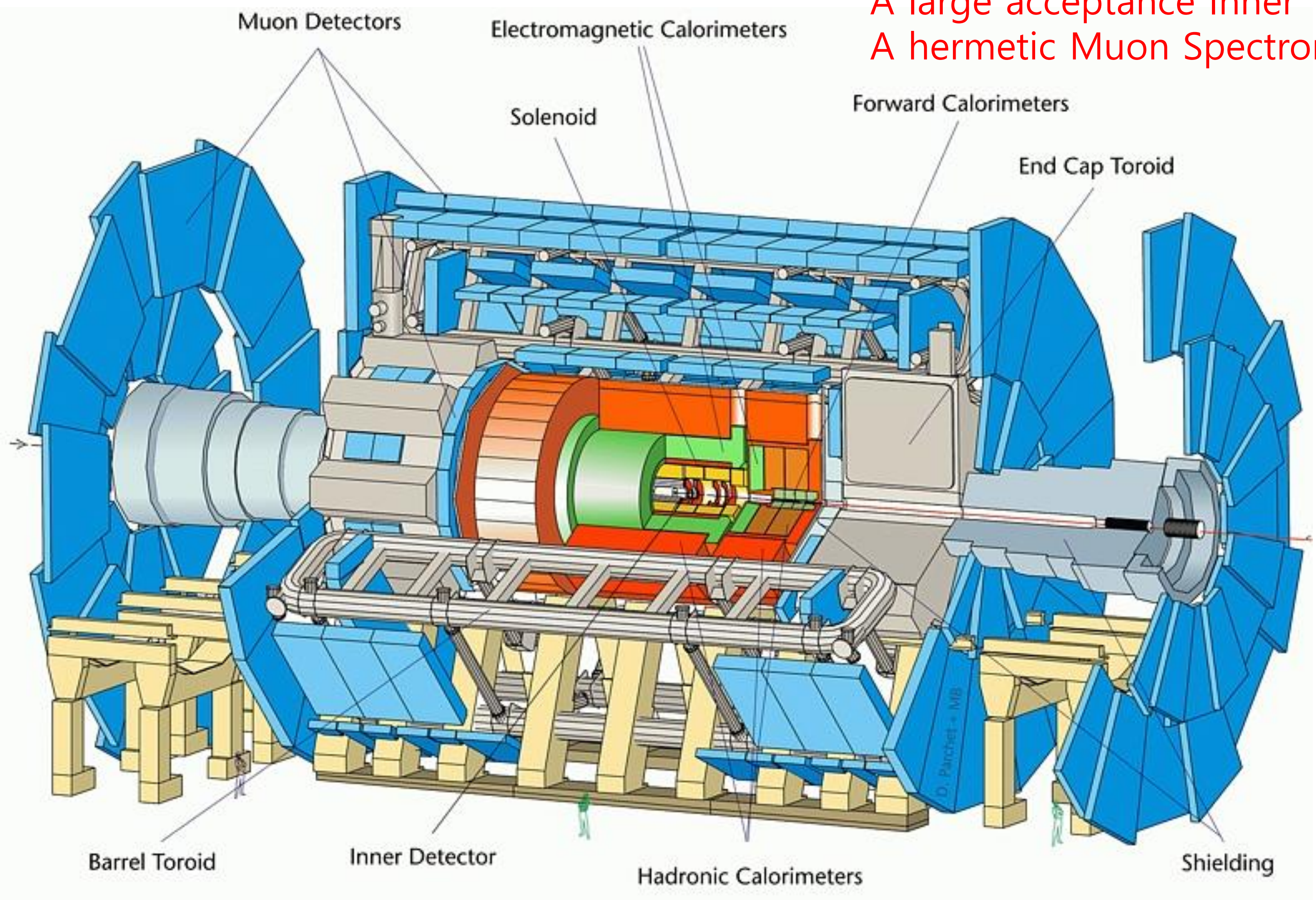
ALICE Detector



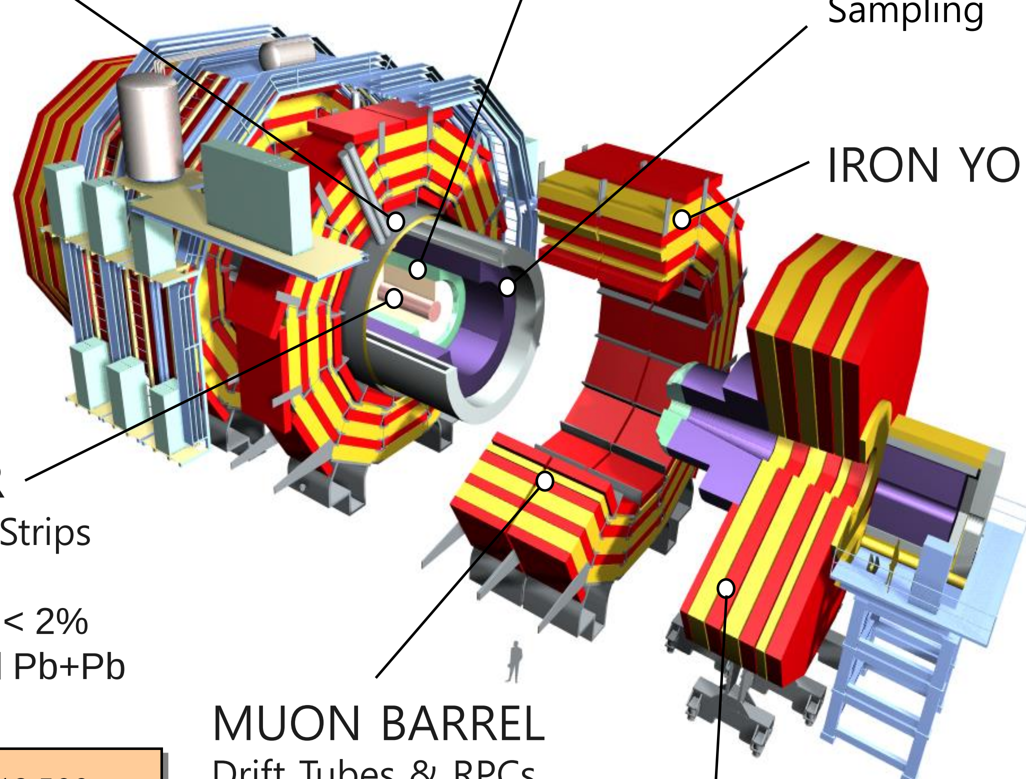
Size: 16 x 26 meters
Weight: 10,000 tonnes

ATLAS Detector

An Excellent Calorimetry
A large acceptance Inner Tracker
A hermetic Muon Spectrometer



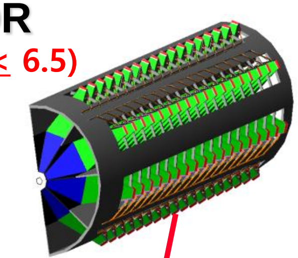
CMS Detector



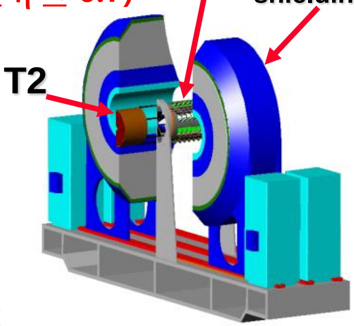
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Forward Detectors

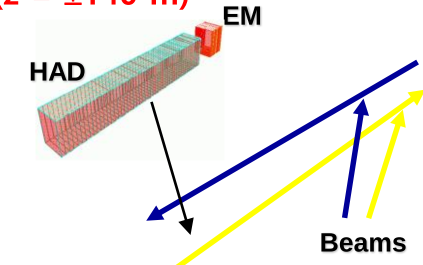
CASTOR
($5.2 \leq \eta \leq 6.5$)



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

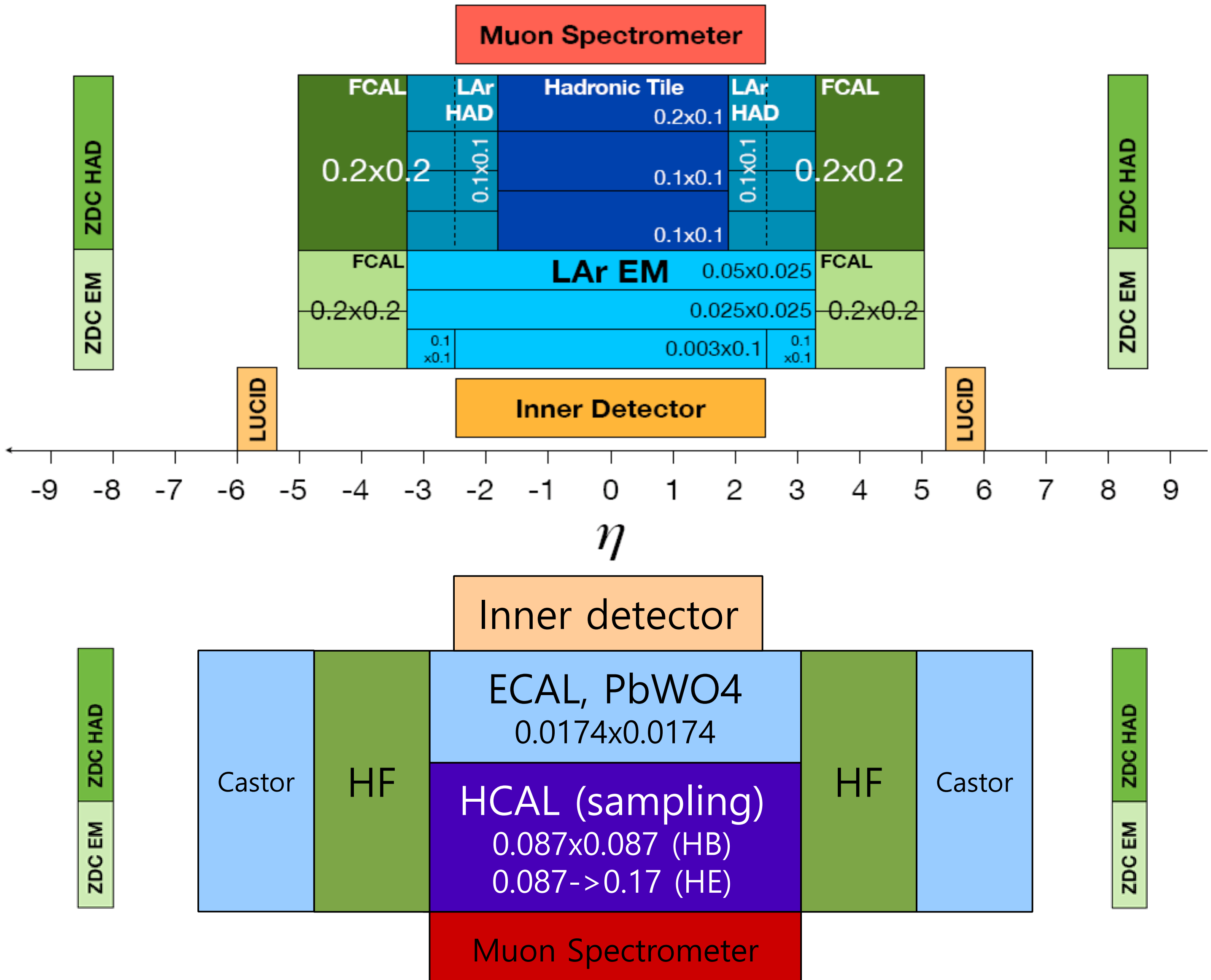


ZDC
($z = \pm140$ m)



Detector Acceptance

Different technologies but close acceptances – possibility to cross-check



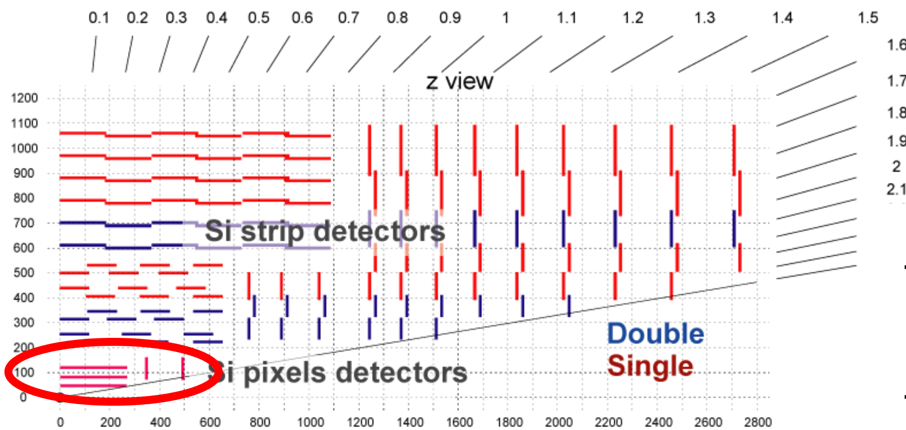
ATLAS

- Inner Det. (|η|<2.5)
- ECAL (|η|<3.2)
- HCAL (|η|<3.2)
- HF (3.2<|η|<5)
- Muon (|η|<2.7)
- Lucid (5.5<|η|<6)
- ZDC (|η|>8)

CMS

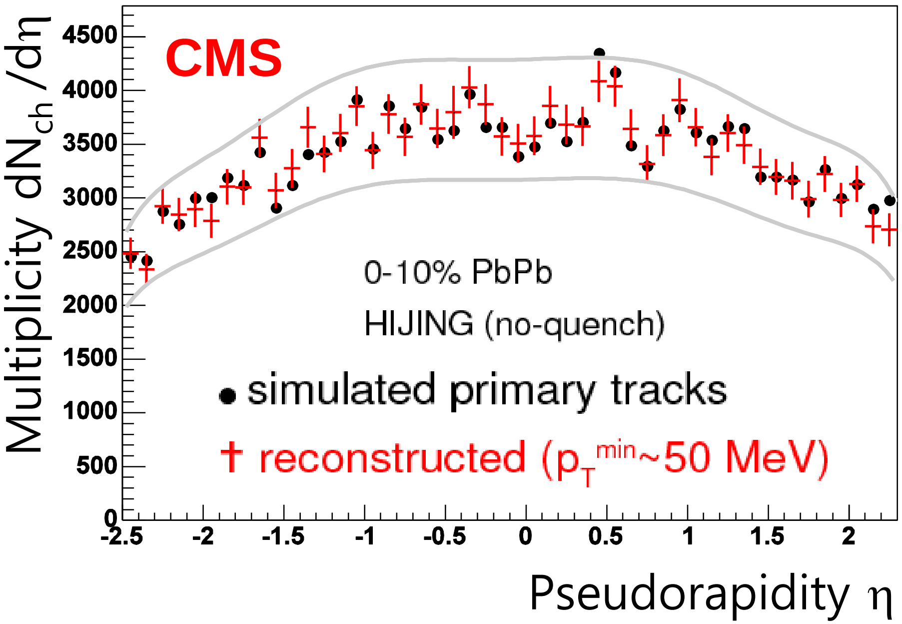
- Inner Det. (|η|<2.5)
- ECAL (|η|<3)
- HCAL (|η|<3)
- HF (3<|η|<5)
- Muon (|η|<2.4)
- Castor (5<|η|<6.7)
- ZDC (|η|>8)

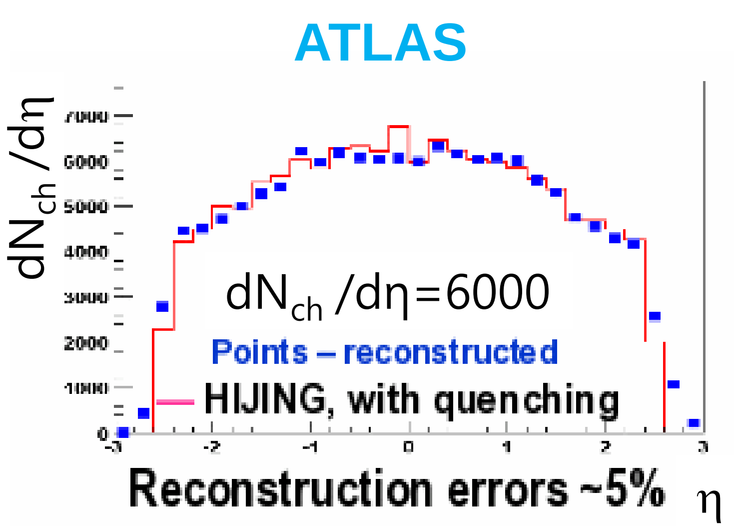
Charged Particle Multiplicity



The layout of the CMS inner tracker

Total 66M Si Pixels
Occupancy < 2% at $dN_{ch}/d\eta=5000$



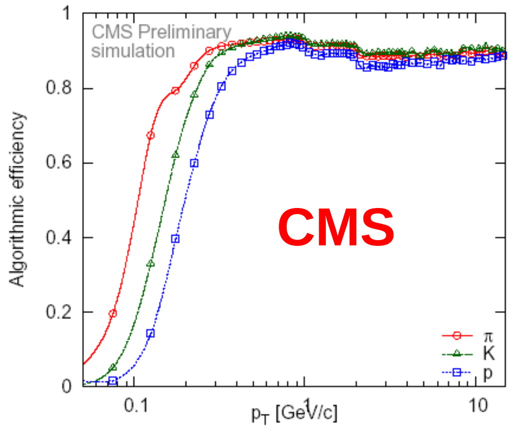


Estimation of the Gluon Density
Does the Gluon Saturation Exist?
Color Glass Condensate (CGC)

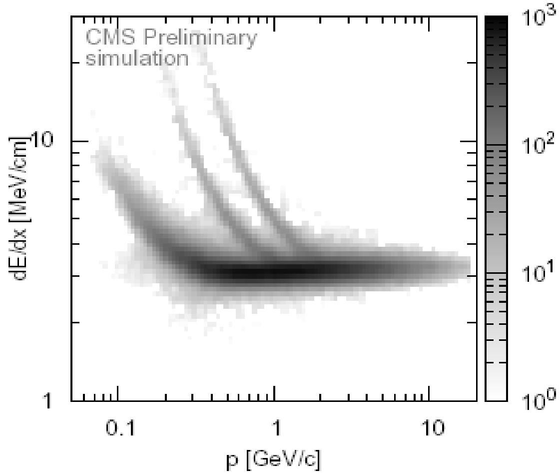
Hadron Spectra at Low p_T

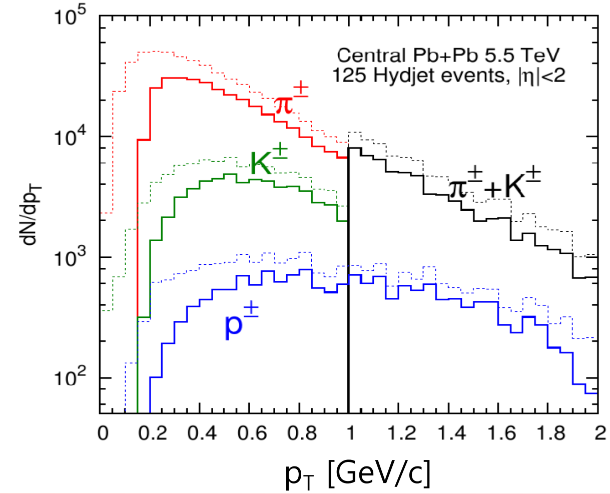
Efficiency

PID: Gaussian Unfolding for dE/dx

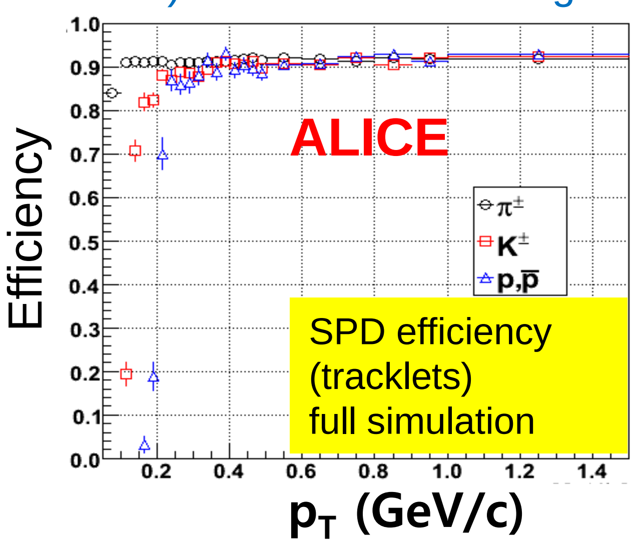


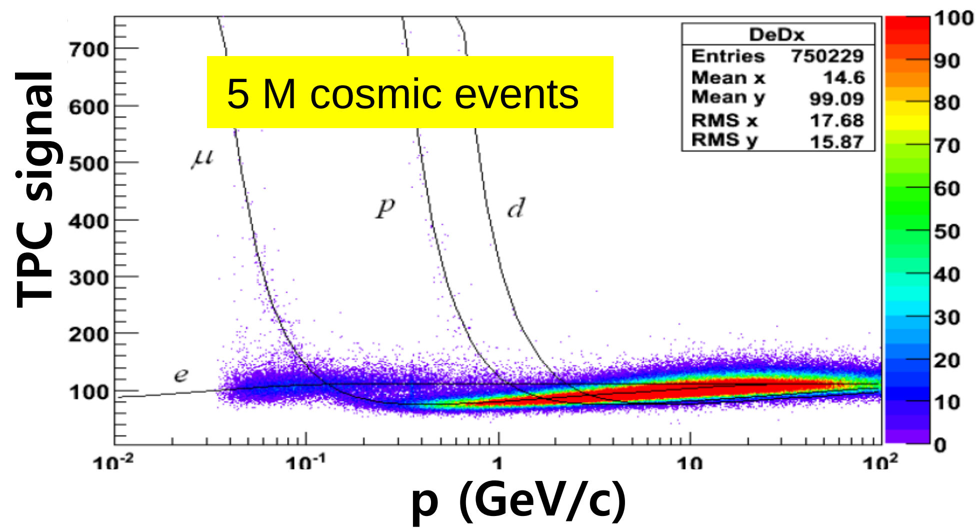
Pixels+Strips





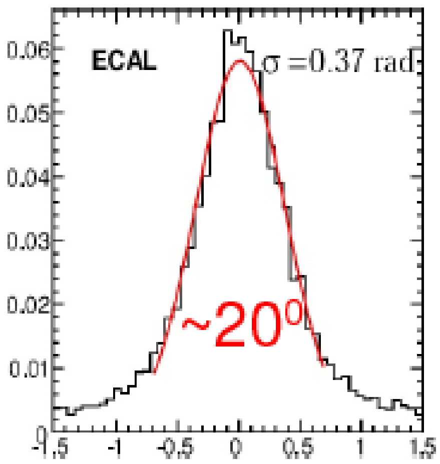
Ref) J. F. Grosse-Oetringhaus, Physics at LHC 2008, Split

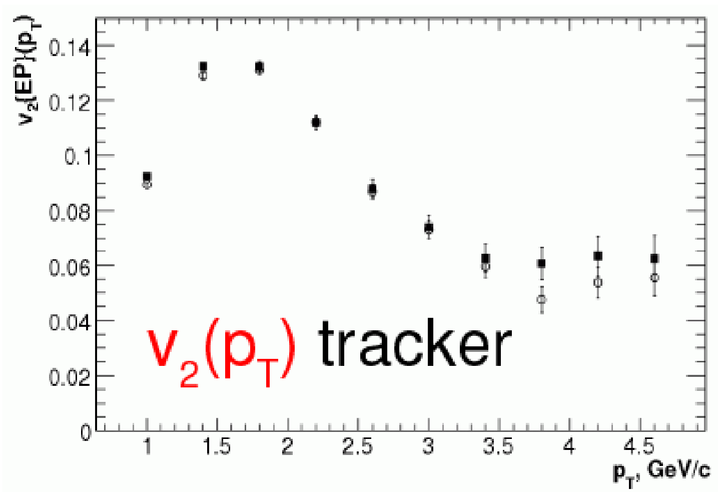




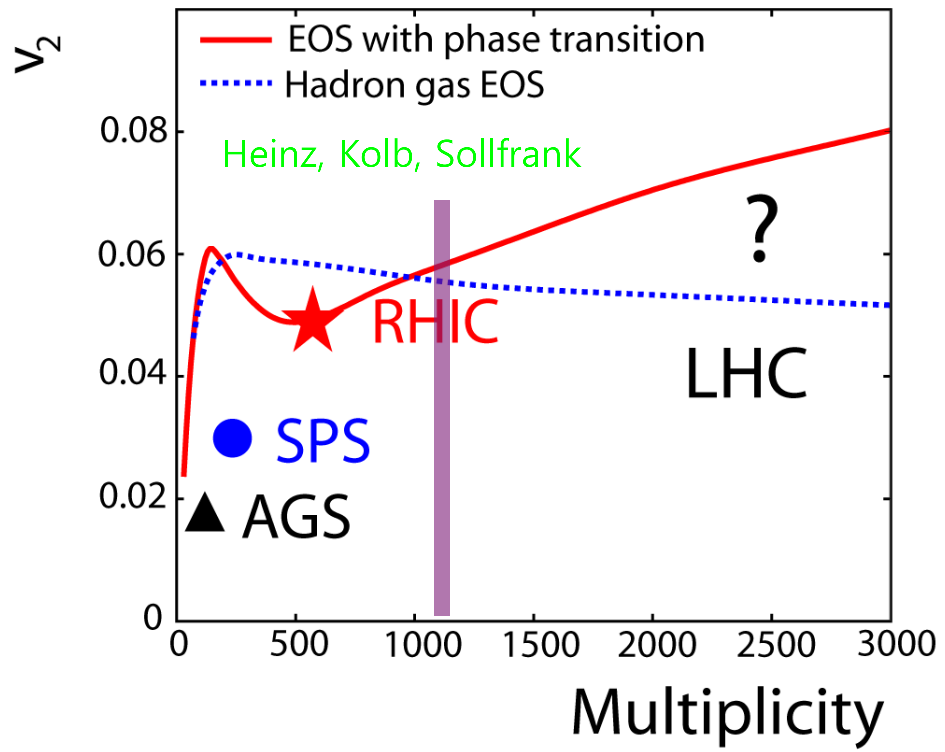
Elliptic Flow

CMS





Hydro prediction for low LHC multiplicity



- Equation-of-State/Viscosity of Fluid
- Characterization of microscopic dynamics underlying collectivity

High-Level Trigger in CMS

Level 1 (Muon Chambers+Calorimeters)

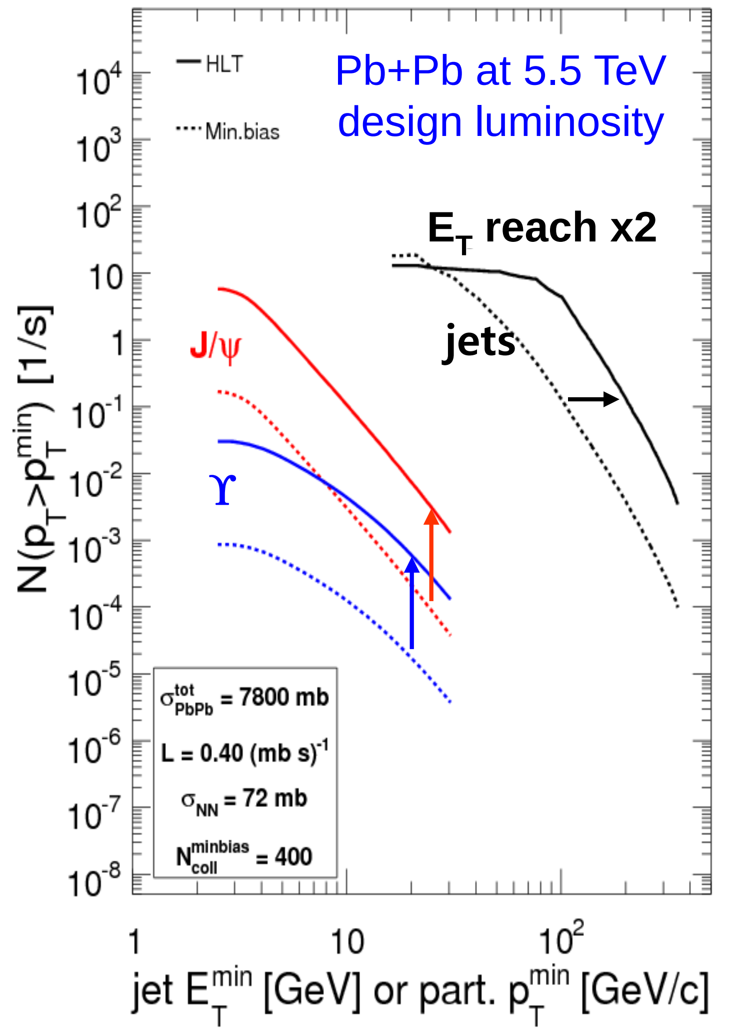
M. Ballitjin, C. Loizides, G. Roland, CMS-NOTE-2006-099

Level 1	Pb+Pb	p+p
Collision Rate	3 kHz (8 kHz peak)	1 GHz
Event Rate	3 kHz (8 kHz peak)	32 MHz
Output Bandwidth	100 GByte/sec	100 GByte/sec
Rejection	None	99.7%

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

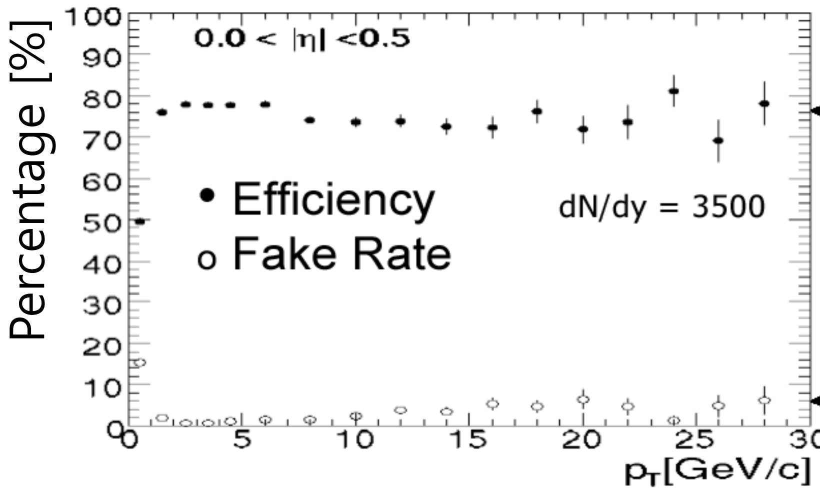
- 12k CPU x 1.8 GHz ~ 50 Tflops (x 2 RCF)
- Run "offline algorithm" on every Pb+Pb event
- Significantly enhanced statistics for hard processes (see the right figure)

High-Level Trigger	Pb+Pb	p+p
Input Event 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%



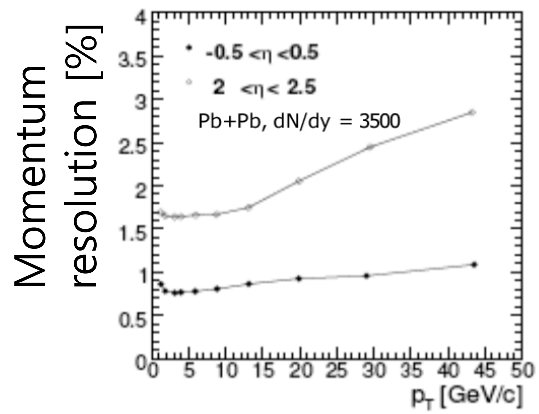
High-p_T Hadrons in CMS

C. Roland,
CMS-NOTE-2006-001 & 110

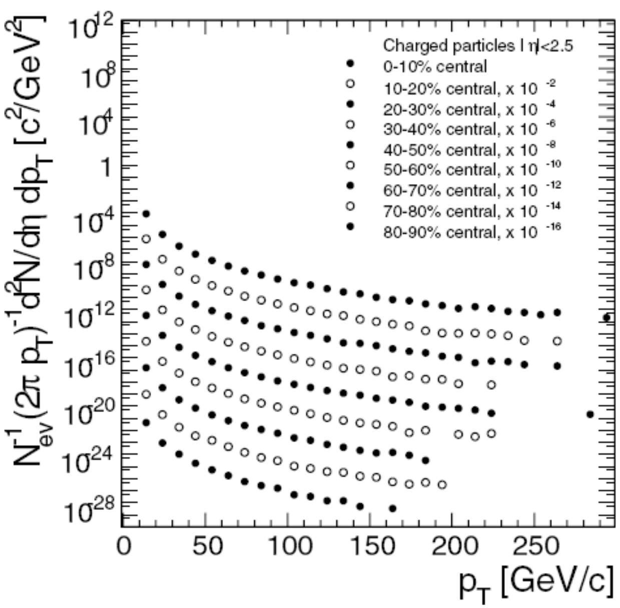


Good efficiency

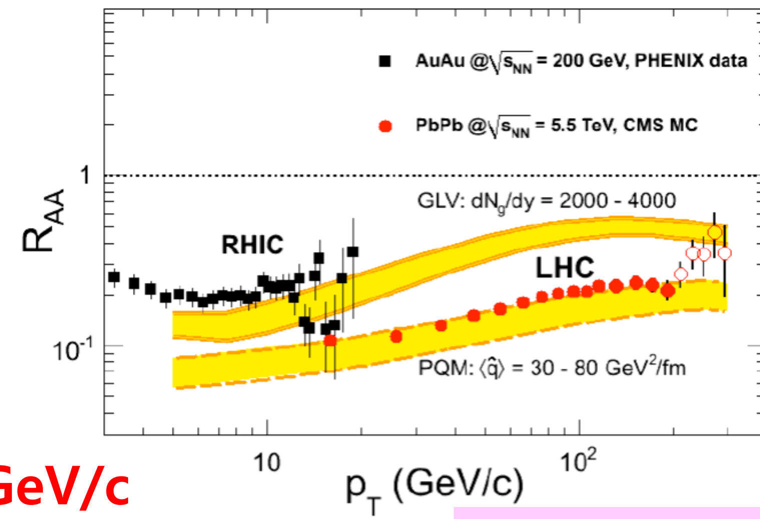
Low fake rate



Medium Density



Charged particle spectra up to p_T ~300 GeV/c (High E_T HLT)

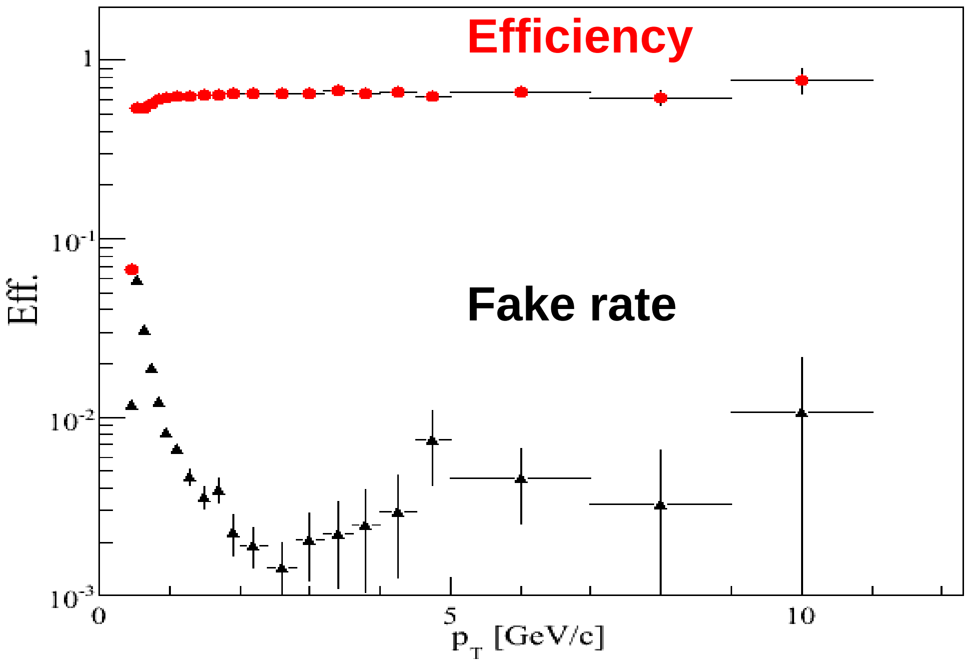


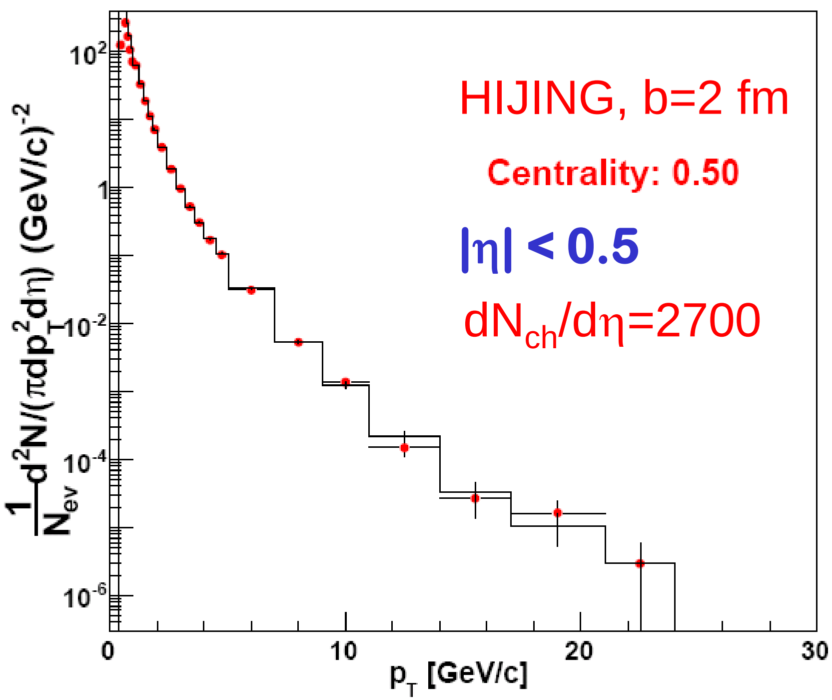
Transport Coefficient

High p_T Hadrons in ATLAS

without TRT
3 pixel layers and
4 double-sided strip layers

Pb+Pb 5.5 A TeV, b=2.3 fm, |η|<1



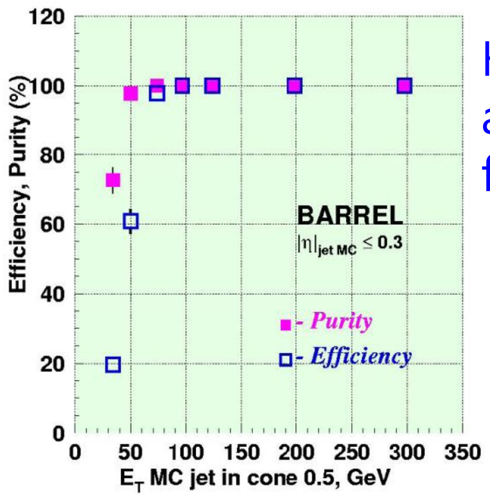


No jet trigger

Momentum resolution ~ 3%
(2% in barrel, 4-5% in endcap)

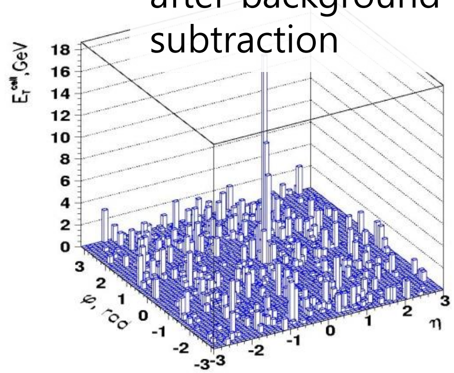
Full Jet Finder in CMS

Iterative cone(R=0.5)+Background subtraction

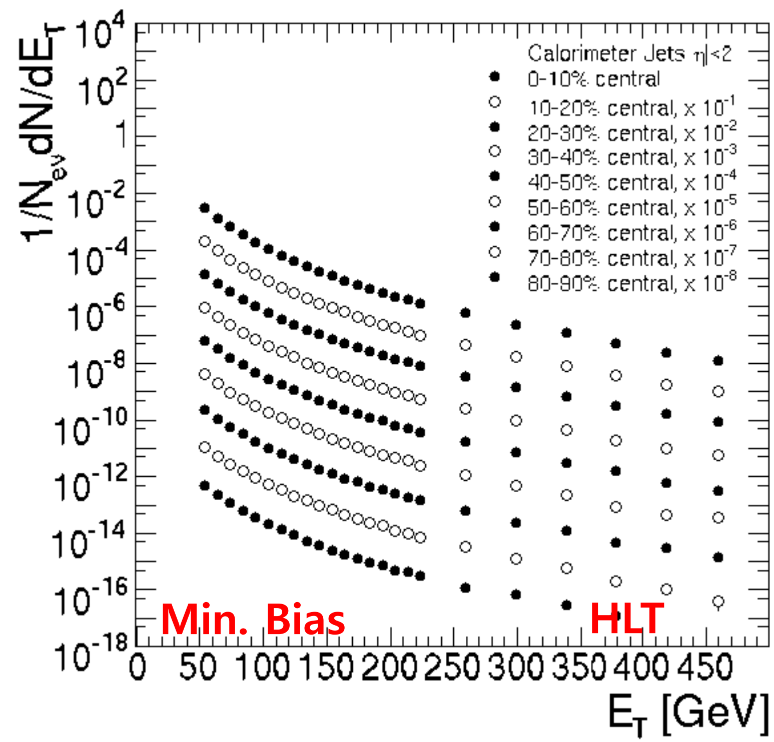


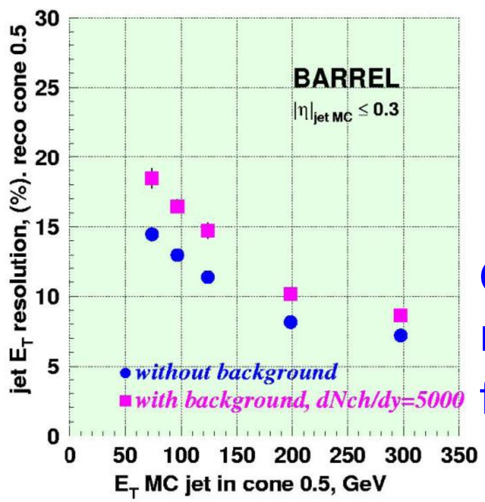
High efficiency and purity for $E_T>50$ GeV

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



Pb+Pb (0.5 nb^{-1}: 1 year of running)





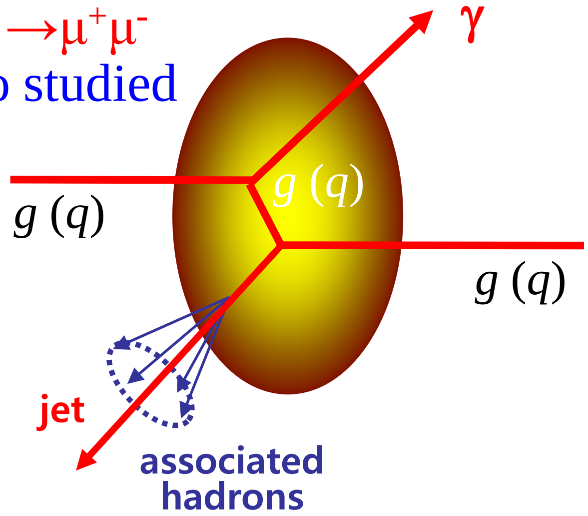
Good energy resolution for $E_T>100$ GeV

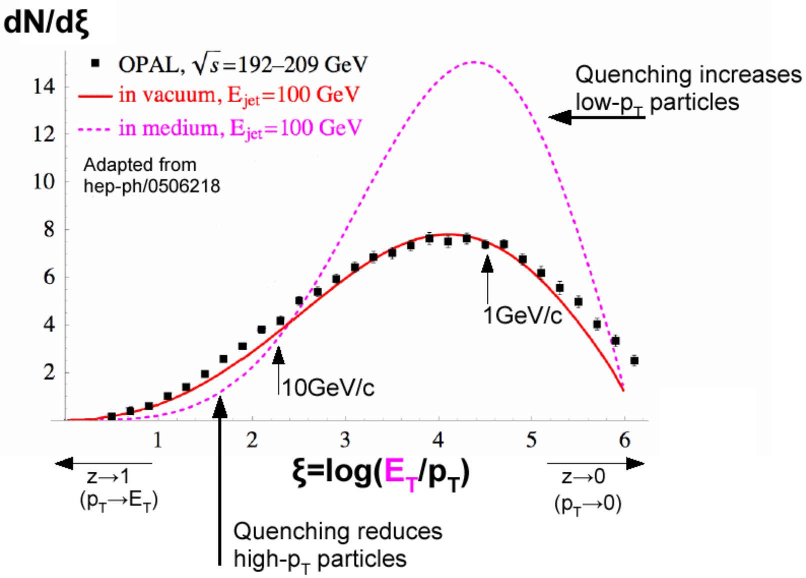
Jet spectra up to E_T ~500 GeV

Jet Quenching Effect by using True Jets

Photon-Tagged Jets in CMS

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

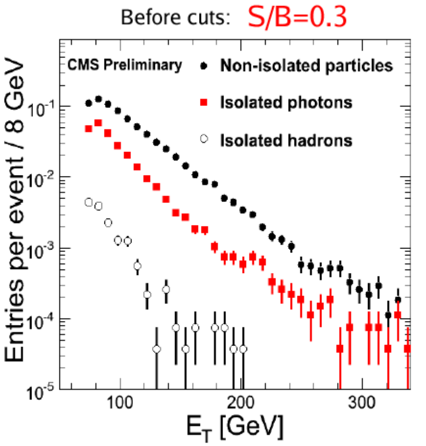


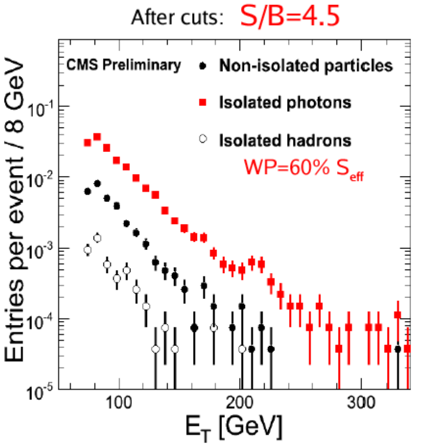


How is the energy loss distributed in the jet fragmentation cone?

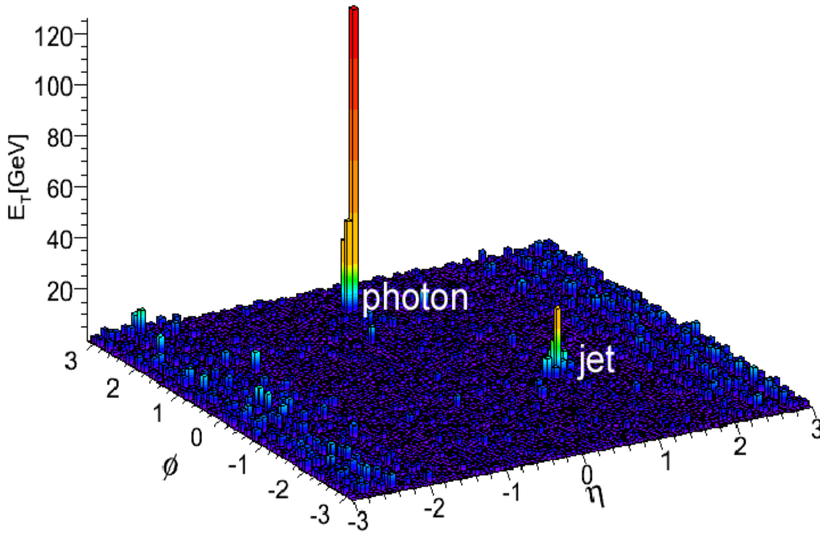
C. Loizides, QM08

- Photons
  - -Tagging parton energy
  - -Sophisticated isolation/shape cut technique was developed (S/B was improved by about 15)
  - $-E_T(\gamma)$>100 (or 70) GeV

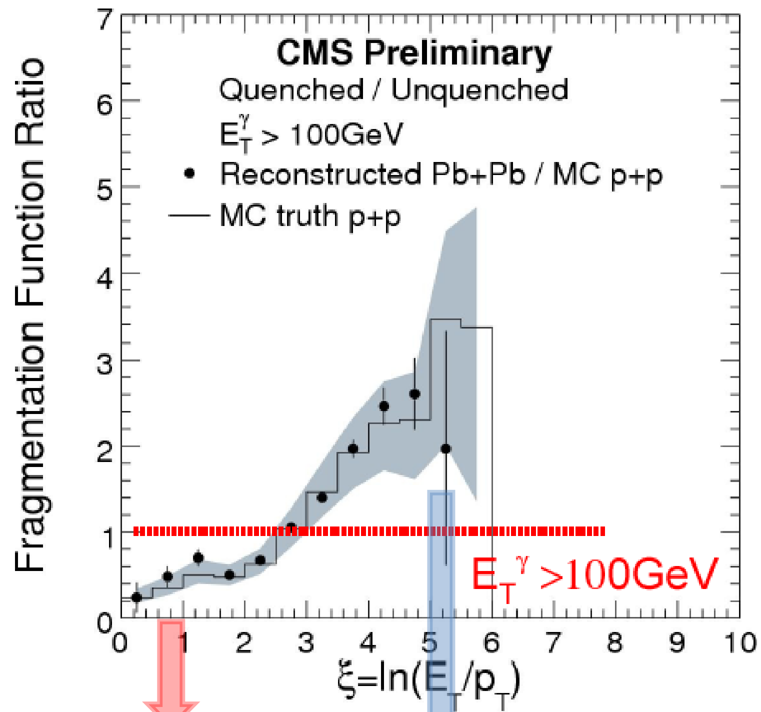




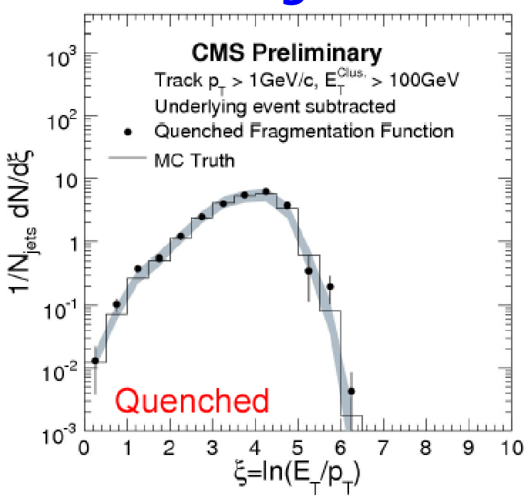
Photon-Tagged Jets in CMS



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



Reconstructed FF agrees with the MC FF



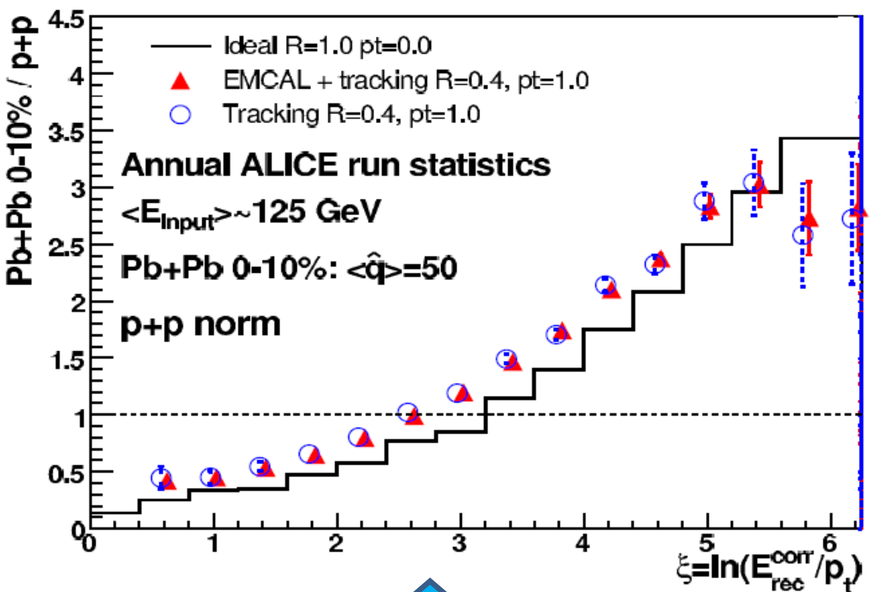
Depletion at high p_T

Enhancement at low p_T

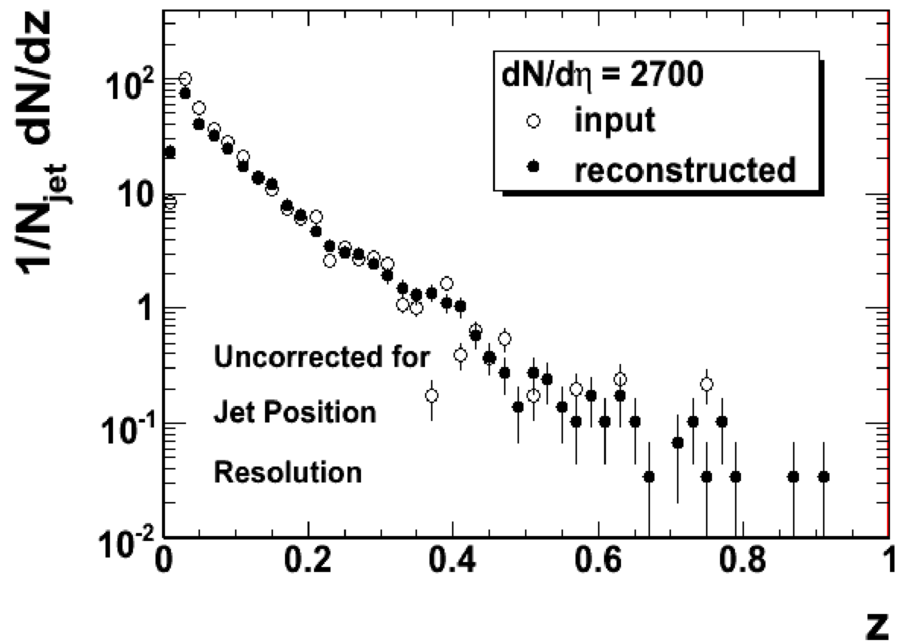
Other Jet FF Measurements

ALICE

Ref) C. W. Fabjan, QM 2008, Jaipur



ATLAS



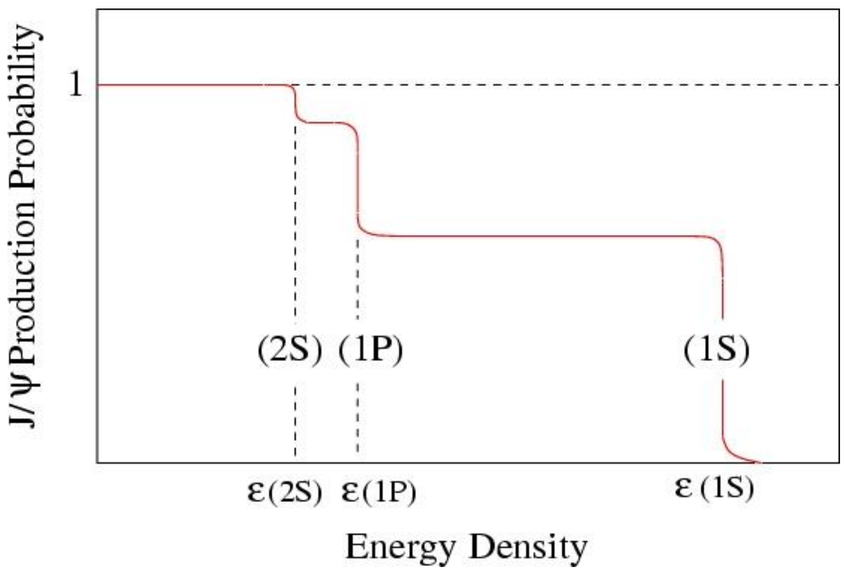
- Initial measurements up to 100 GeV (untriggered charged jets only)
- Detailed study of fragmentation possible
- Sensitive to energy loss mechanism
- Accuracy on transport coefficient <q-hat> ~20%

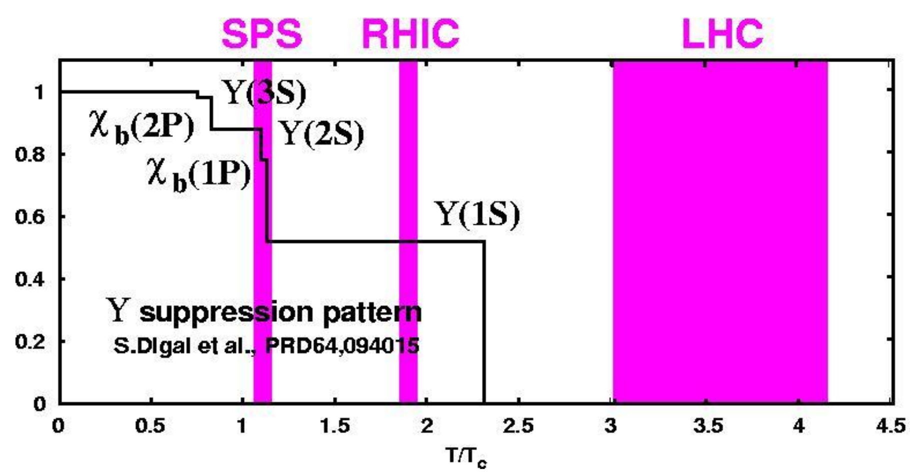
Quarkonium Production

H. Satz, J. Phys. G 32, R25 (2006)

State	J/ψ	χ_{c0}(1P)	ψ(2S)	ϒ(1S)	χ_{b0}(1P)	ϒ(2S)	χ_{b0}(2P)	ϒ(3S)
Mass [GeV]	3.096	3.415	3.686	9.46	9.859	10.023	10.232	10.355
B.E. [GeV]	0.64	0.2	0.05	1.1	0.67	0.54	0.31	0.2
T_d/T_c	1.1	0.74	0.15	2.35	1.13	0.93	0.83	0.74

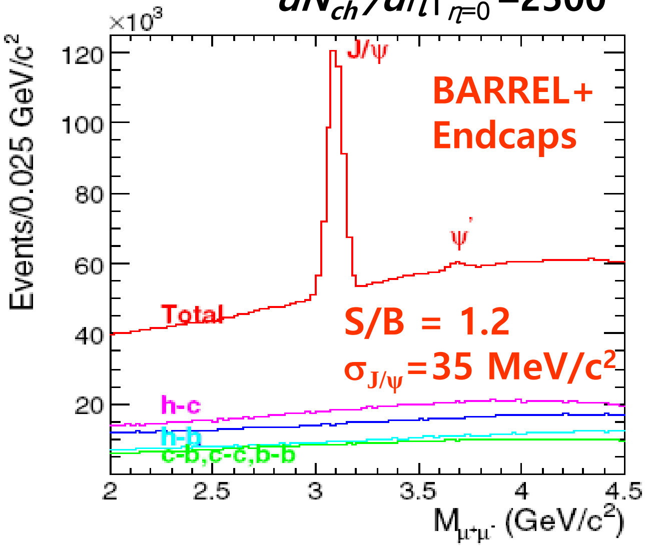
Due to the feed down from higher states, we expect the step-wise suppression of J/ψ and ϒ ⇒ Measure as a function of p_T and also of collision centrality

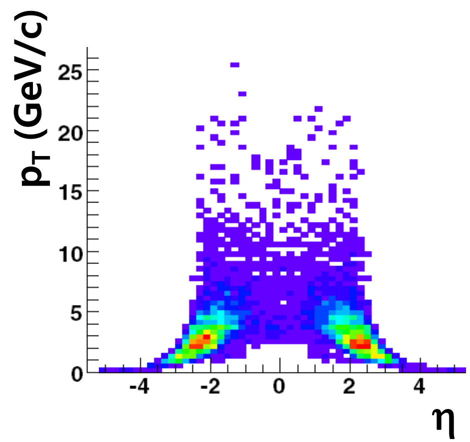




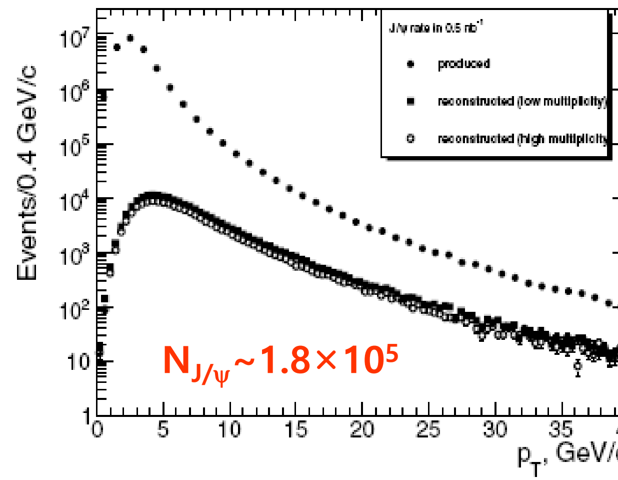
Quarkonia in CMS

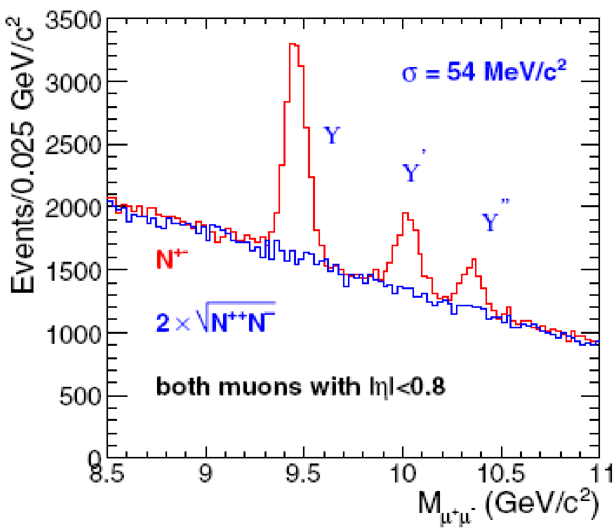
$dN_{ch}/d\eta|_{\eta=0}$ =2500

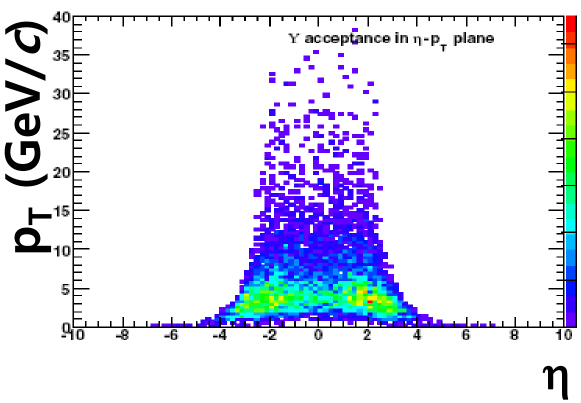


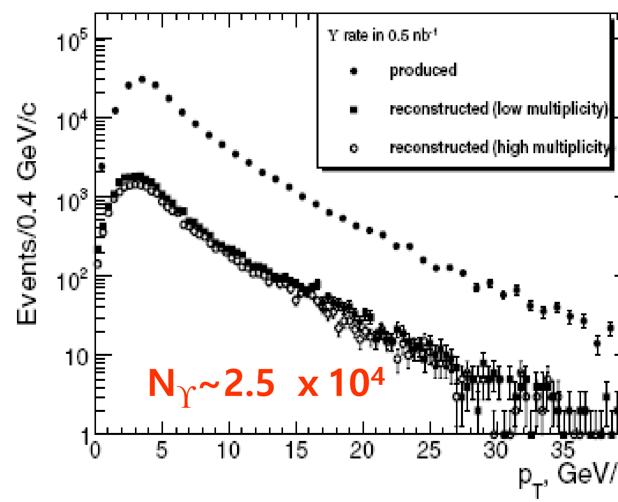


Pb+Pb (0.5 nb^{-1})





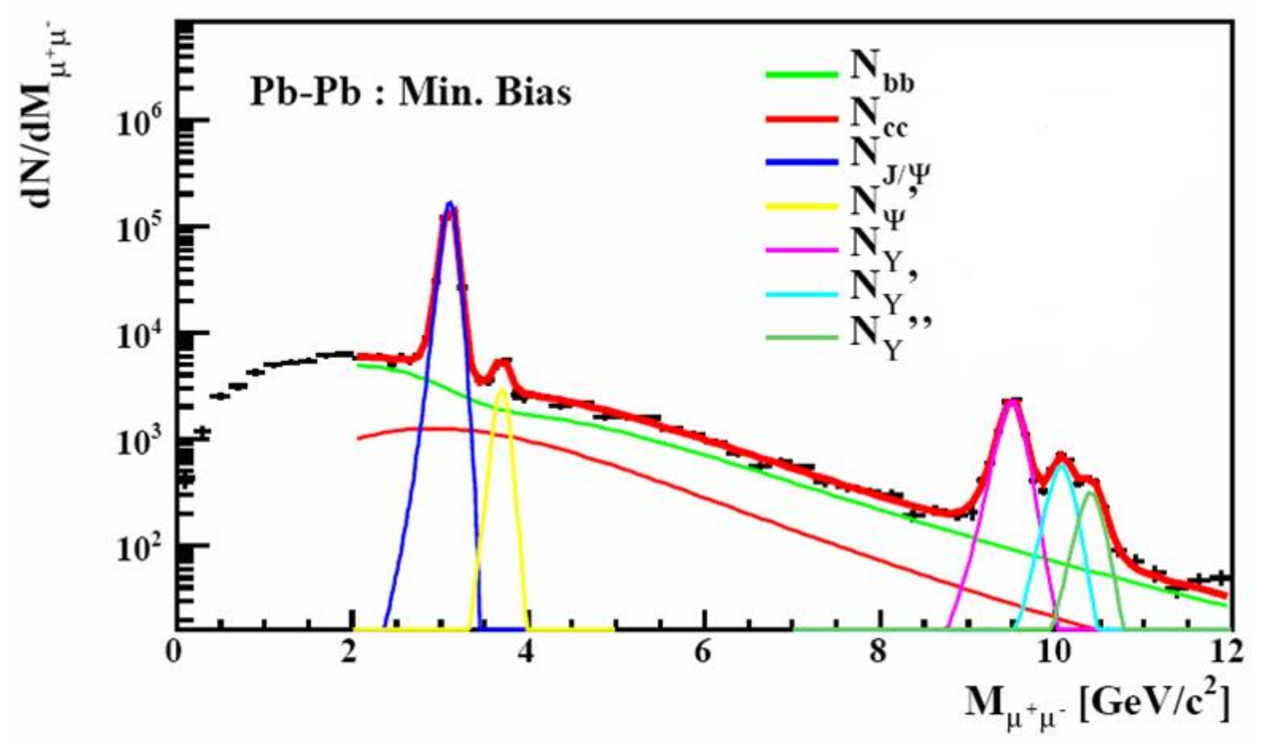




Quarkonia in ALICE

Ref) C. W. Fabjan, QM 2008, Jaipur

One Month (10^6 sec) Pb+Pb collisions at nominal luminosity

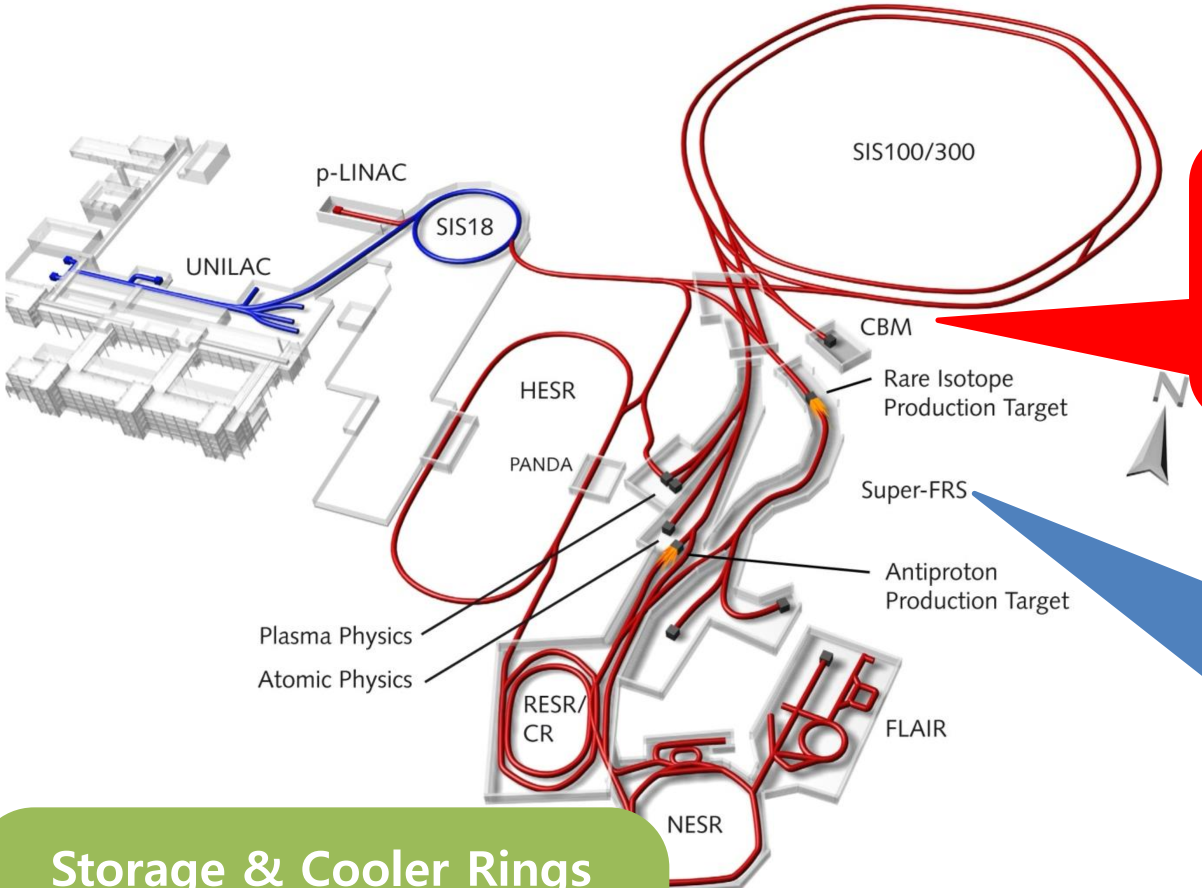


Expected number of quarkonia in dimuon channel:
J/Ψ ~ 3 x 10^5, Υ ~ 8000

High-Density QGP
(CBM at FAIR)

FAIR: Facility for Antiproton and Ion Research

FAIR Overview



Primary Beams

Intensity: X10~1,000
p : 4×10^{13}/s @ 90 GeV
^{238}U : 10^{10}/s @ 35 GeV/u

Secondary Beams

Intensity: X10,000
Rare Isotopes @ 1.5~2 GeV/u
Anti p @ 3~30 GeV

Storage & Cooler Rings

Beams of Rare Isotopes
Stored and Cooled Anti p @ 0.8~14.5 GeV
e-A Collider

Research Program at FAIR

1. Rare Isotope Beams (Super FRS)
   - Nuclear structure far off stability
   - Nuclear synthesis in stars and supernovae
2. Antiproton Beams (Panda)
   - Quark confinement potential
   - Search for gluonic matter and hybrids
3. High-Energy Nuclear Beams (CBM)
   - **CBM : Compressed Baryonic Matter**
   - Baryonic matter at the highest density (neutron stars)
   - Phase transition and critical endpoint
   - In-medium properties of hadrons
4. Short pulse Heavy Ion Beams
   - Fundamentals of nuclear fusion
5. Atomic Physics and Applications
   - Highly charged atoms & low energy antiprotons
   - Radiobiology
6. Accelerator Physics
   - High intensity heavy-ion beams
   - Rapidly cycling superconducting magnets
   - High-energy electron cooling & dynamical vacuum

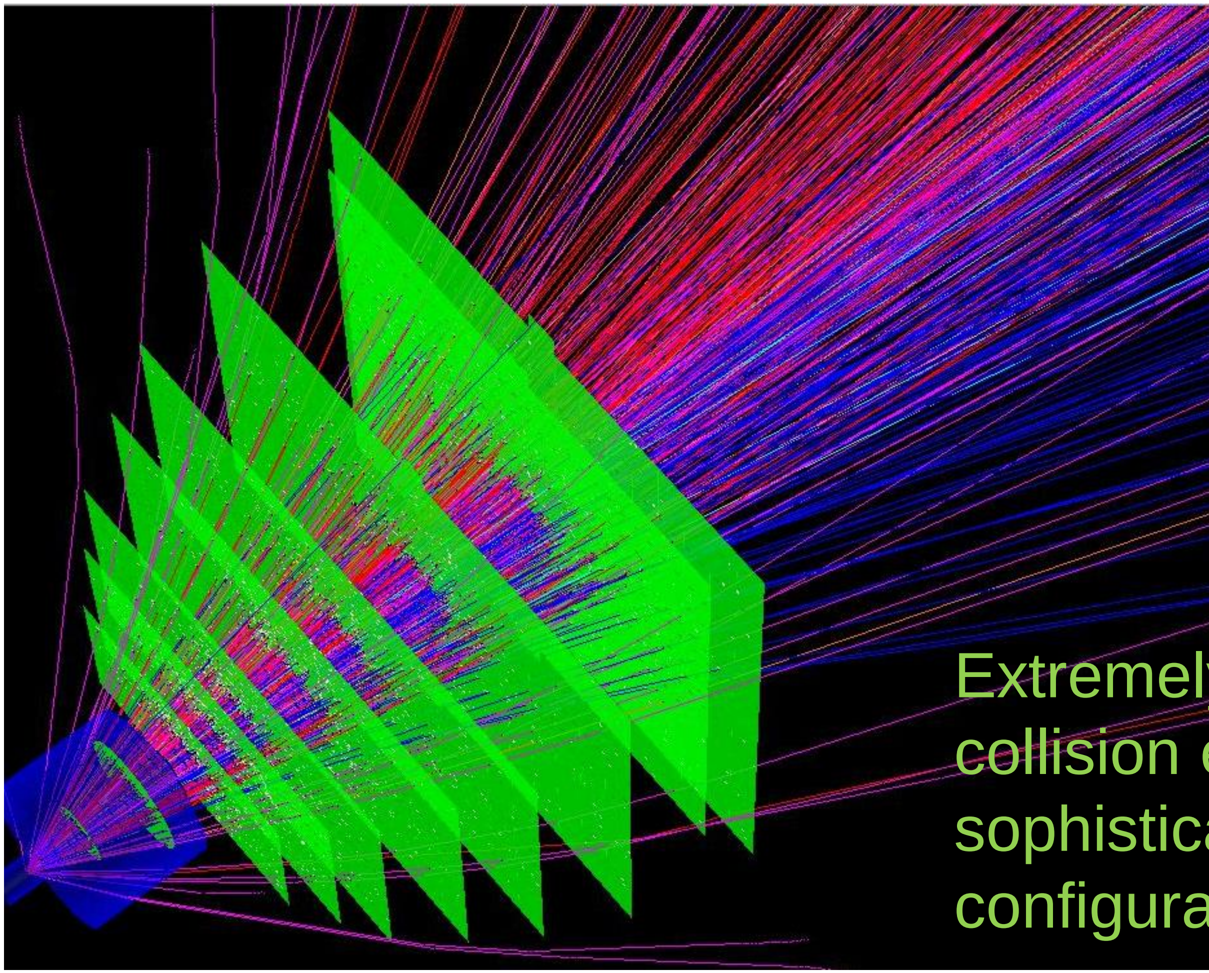
CBM: Physics Observables

1. QCD Critical Endpoint
   – Excitation function of event-by-event fluctuation (K/π, ...)
2. Onset of Chiral Symmetry Restoration at High ρ_B
   – In-medium modification of hadrons (ρ, ω, $\phi \rightarrow e^+e^-$ or $\mu^+\mu^-$, ...)
3. Deconfinement Phase Transition at High ρ_B
   – Excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω, ...)
   – Excitation function and flow of charm (J/ψ, ψ', D, Λ_c, …)
   – Disappearance of quark-number scaling of elliptic flow
4. Equation-of-State (EoS) at High ρ_B
   – Collective flow of hadrons
   – Particle production at (sub)threshold energies (Ξ, Ω, J/ψ, D, …)

Simulation of Collision Event

Central Au+Au collision at 25A GeV (UrQMD+GEANT4)

Total ~1000 particles: 160 p + 400 π^- + 400 π^+ + 44 K^+ + 13 K^-

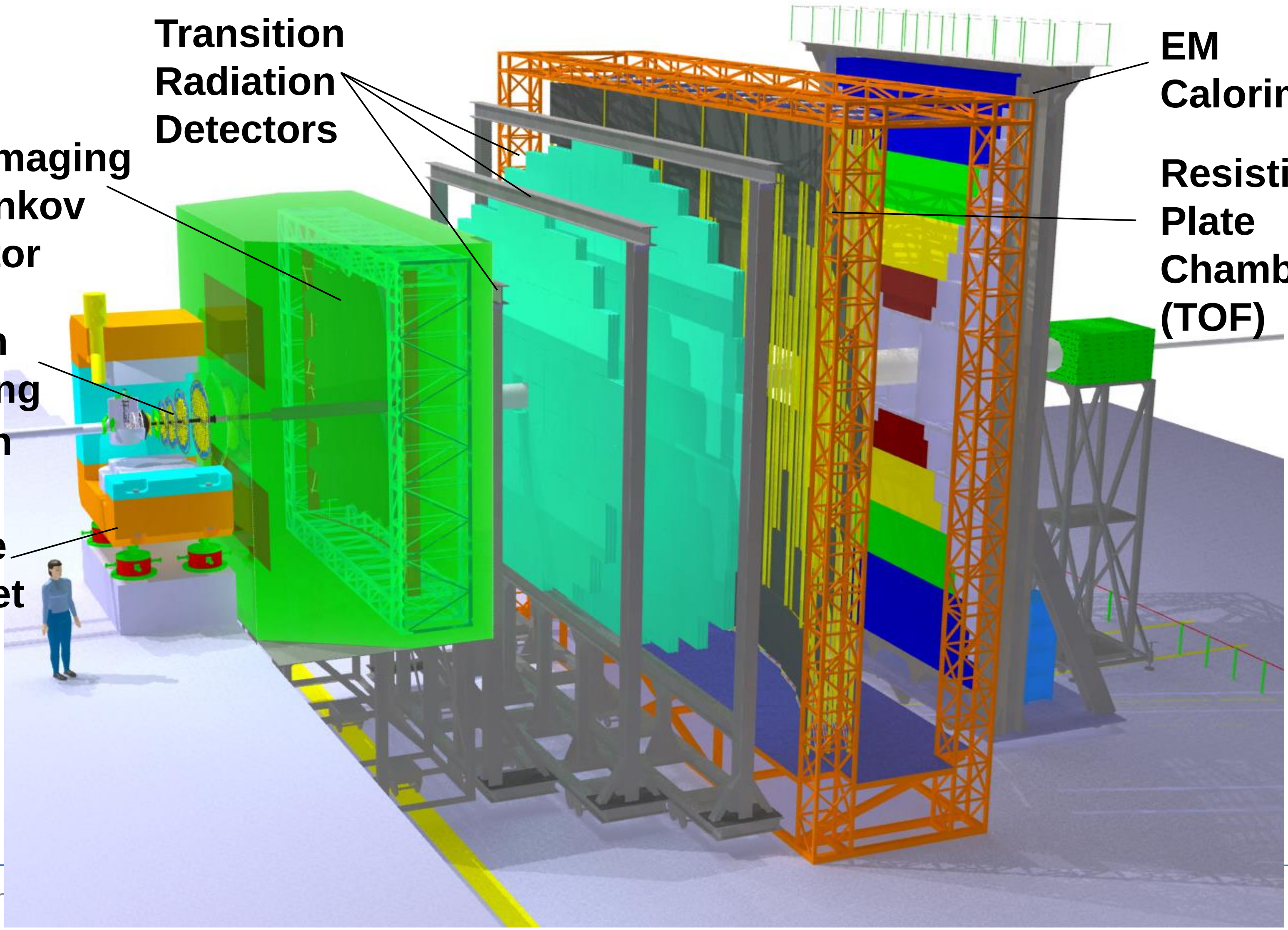


Extremely complicated collision event requires sophisticated detector configuration!

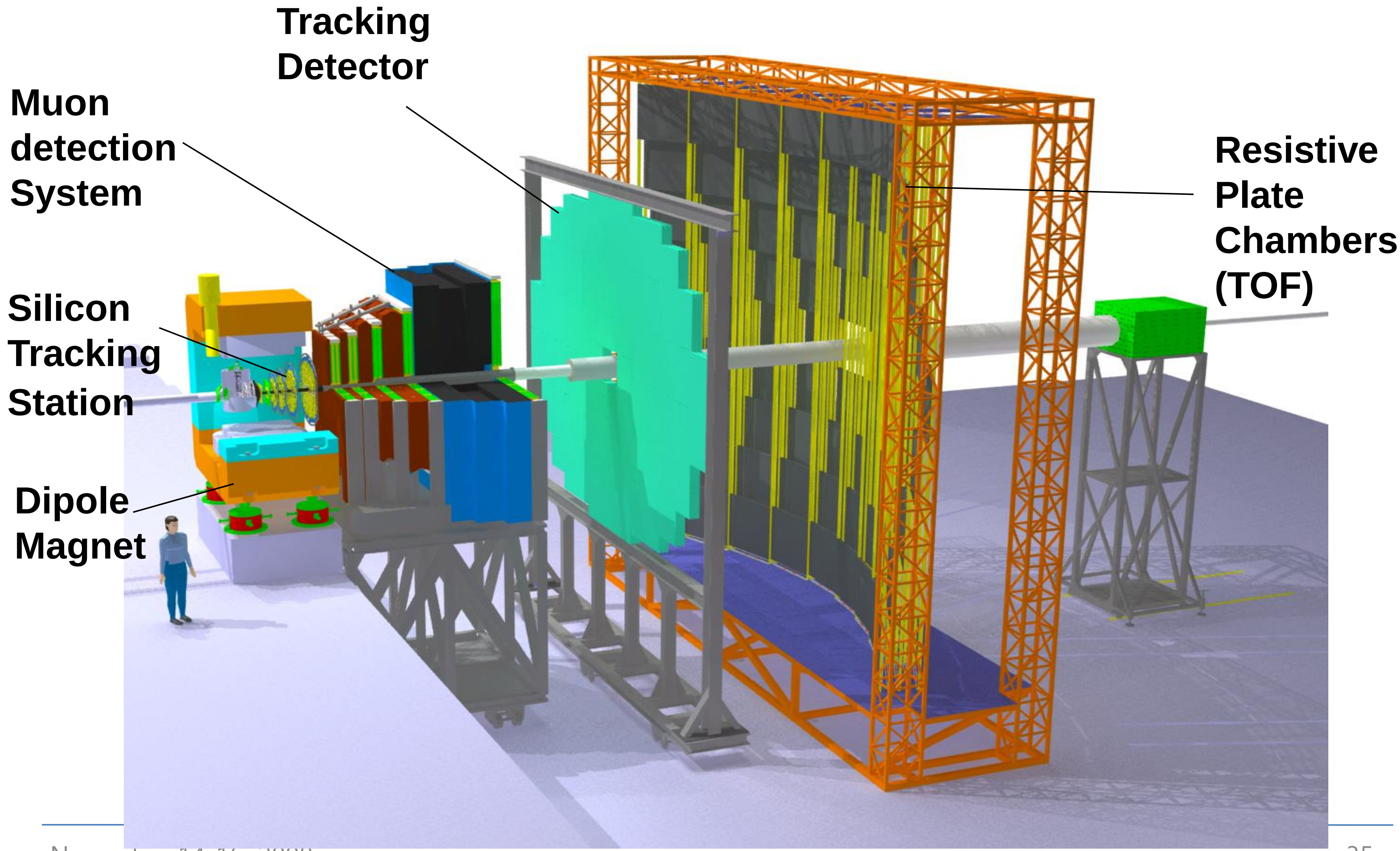
Detector Requirements

1. High-Rate Performance
   - Expected collision rate : ~10^7 Au+Au reactions/sec
2. Precise Reconstruction of Displaced Vertex
   - Required resolution : ~50 μm
3. Particle Identification
   - Electrons and muons
   - High-p_T hadrons
4. Radiation Hard Detectors
5. Self-Triggered Readout Electronics
6. High Speed DAQ + Online Event Selection

CBM Detector: e-version

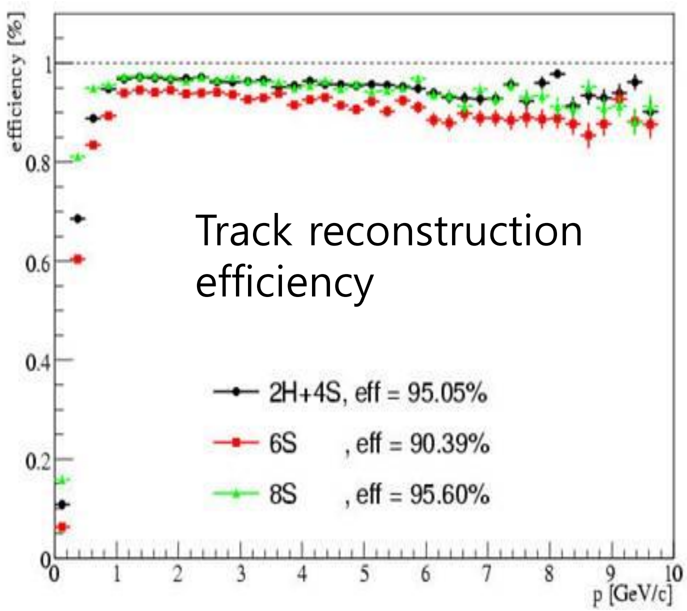


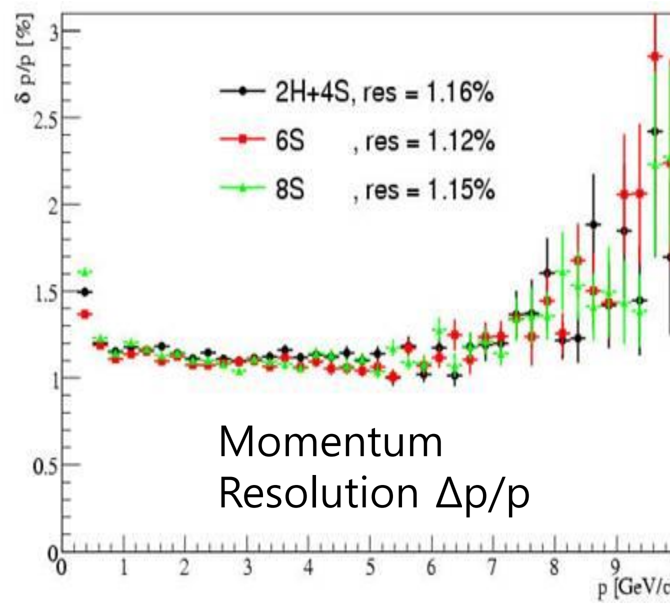
CBM Detector: μ-version



Tracking Peformance with STS

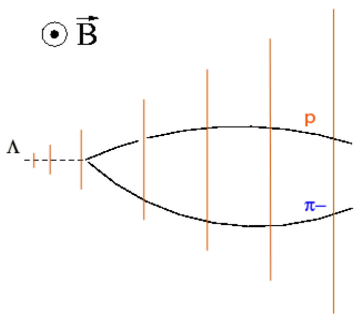
- Software Tools
  - Framework FAIRroot
  - Transport codes GEANT4, FLUKA + Event generators(UrQMD, HSD, PLUTO)
  - Fast track reconstruction algorithms for online event selection
- Simulation input
  - Realistic signal and background multiplicities
  - Realistic detector layouts and responses

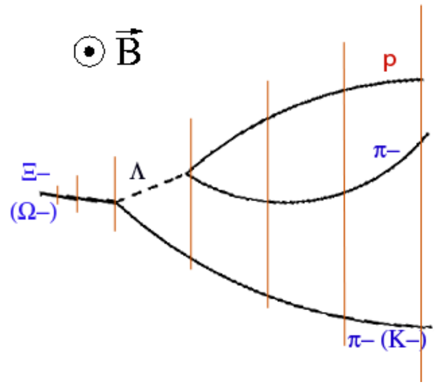


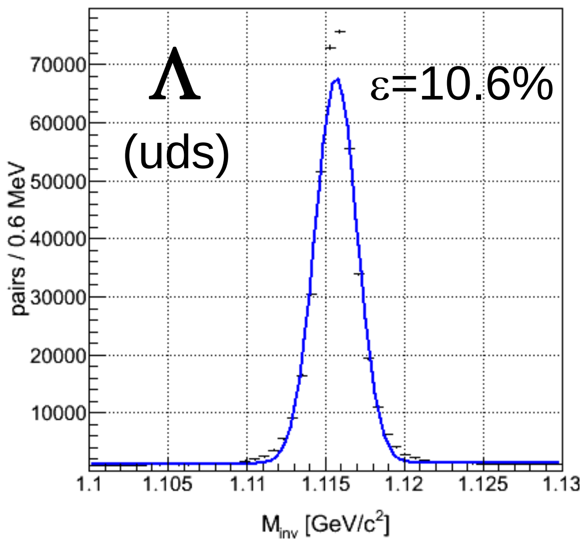


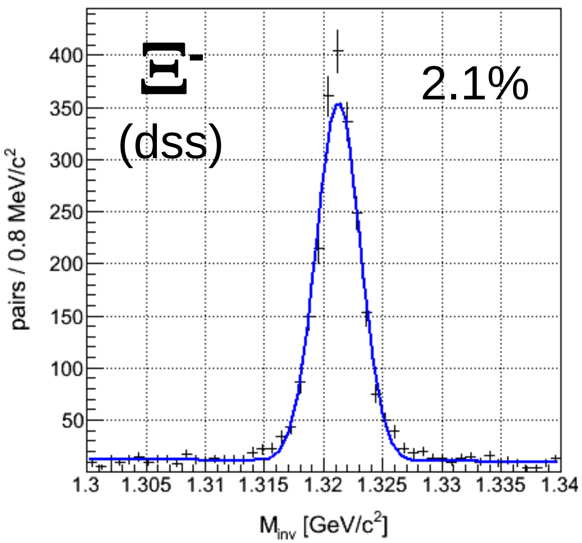
Hyperon Recon. with STS

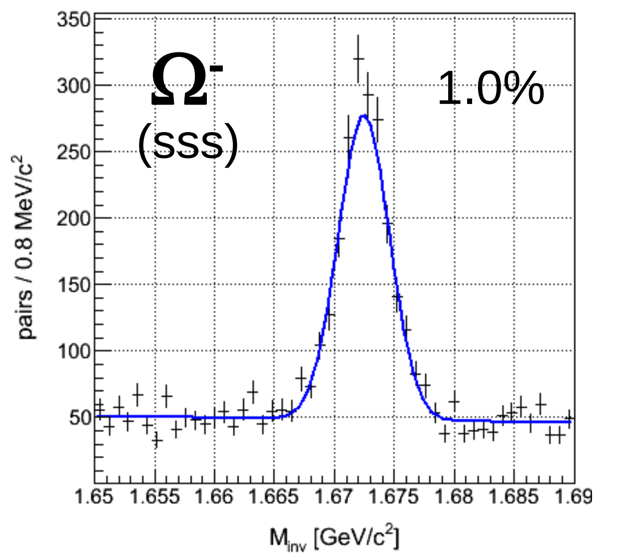
- Silicon tracker
  - 2 hybrid pixels (750 μm each), 4 micro-strips (400 μm each)
  - Strips with 50 μm pitch and 5º stereo angle
- Full event reconstruction





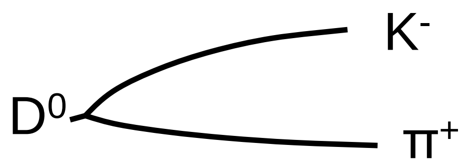






D and Λ_c Reconstruction

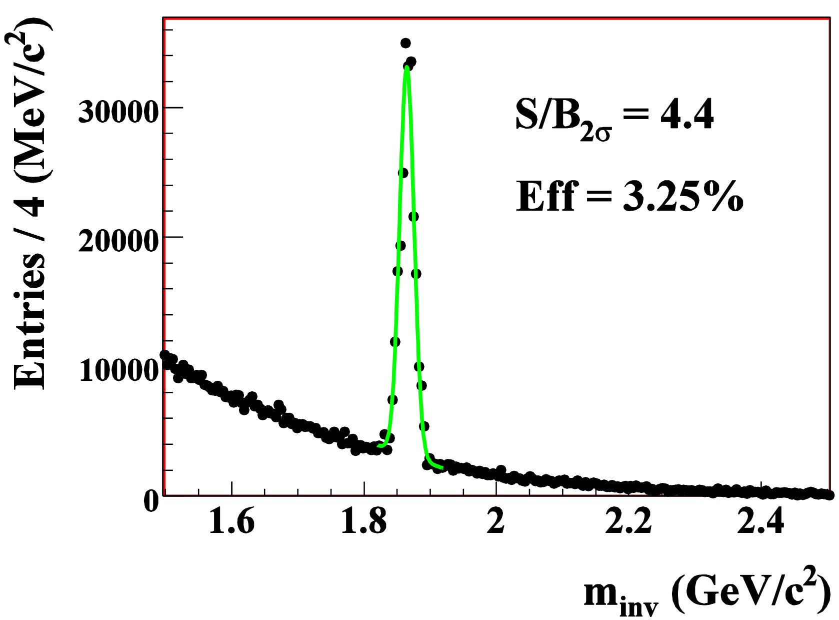
- Full track reconstruction
  - 2 MAPS (150 μm thickness each) + 6 silicon micro-strips
  - Hadron identification via TOF from multigap RPCs

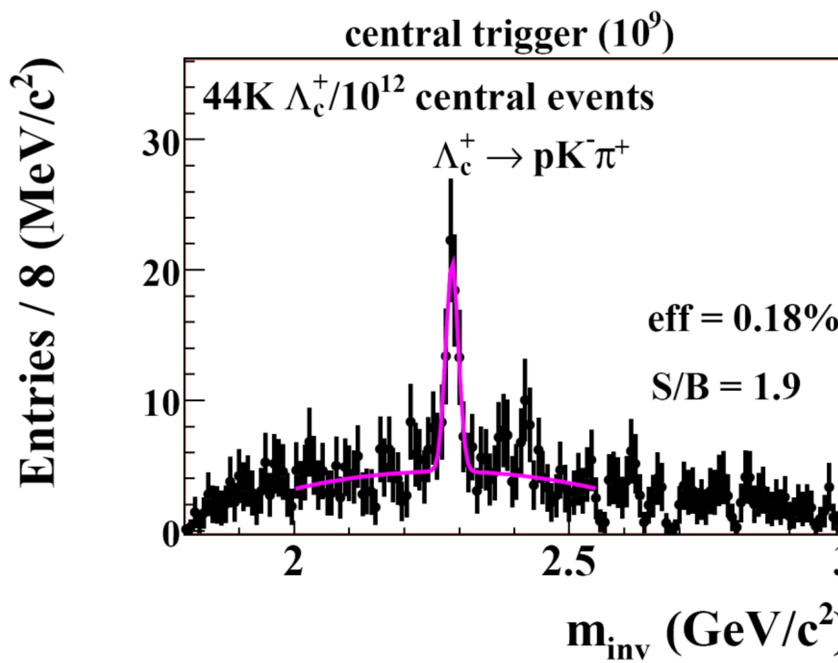


τ = 123 μm/c

$\Lambda_C \rightarrow \pi^+ K^- p$

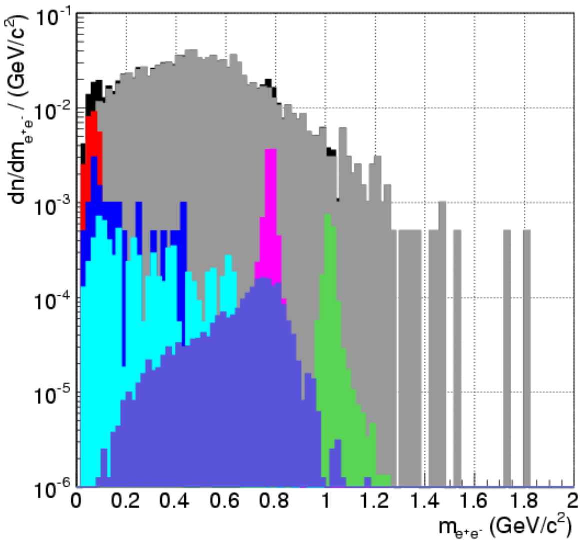
τ = 60 μm/c



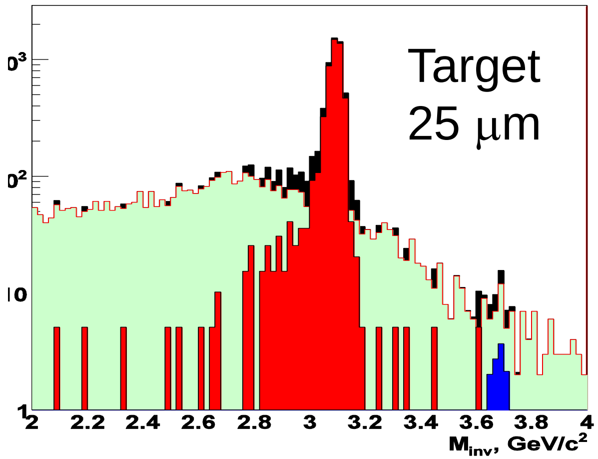


Vector Meson Identification

$\rho, \omega, \varphi \rightarrow e^+e^-$

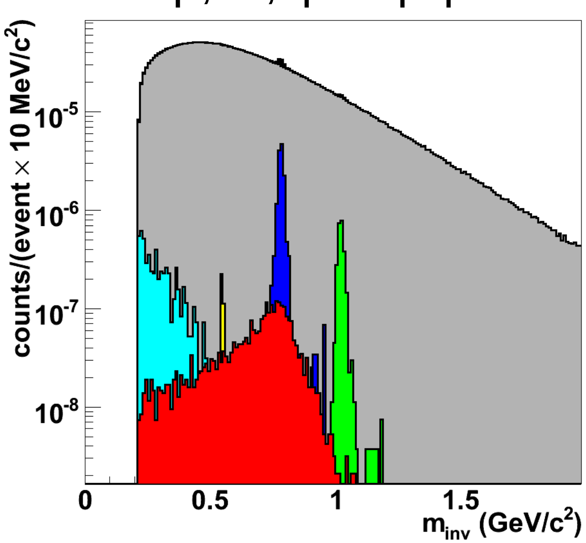


$J/\psi \rightarrow e^+e^-$

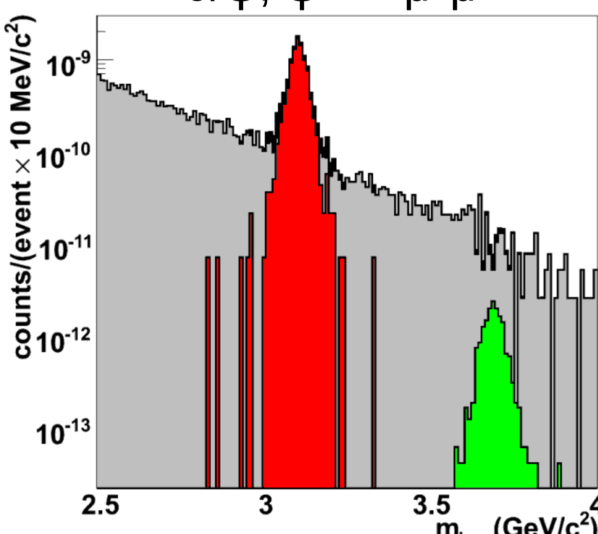


Particle	S/B	ε (%)	σ_m (MeV)
ω	0.15	7.5	14
ϕ	0.13	9.1	14
ρ	0.002	4	
J/ψ	10	12	38
ψ'			

$\rho, \omega, \varphi \rightarrow \mu^+\mu^-$



$J/\psi, \psi' \rightarrow \mu^+\mu^-$



particle	S/B	ε (%)	σ_m (MeV)
ω	0.11	4	10
ϕ	0.06	7	12
ρ	0.002	3	
J/ψ	18	13	21
Ψ'	1	16	27

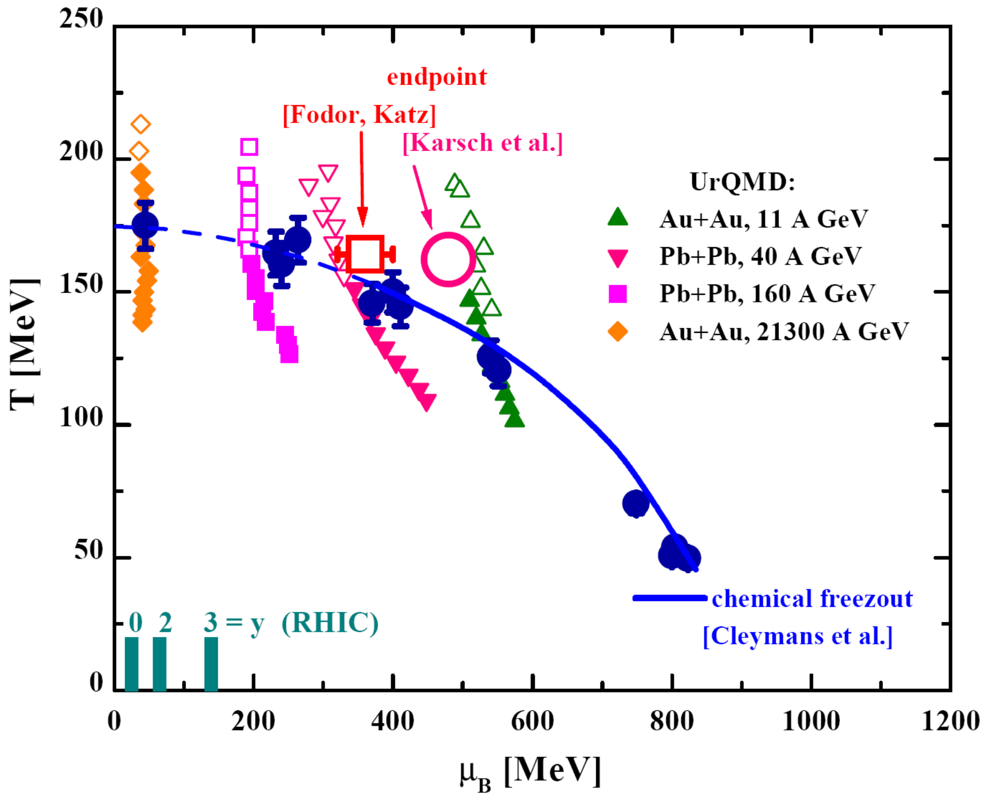
Summary

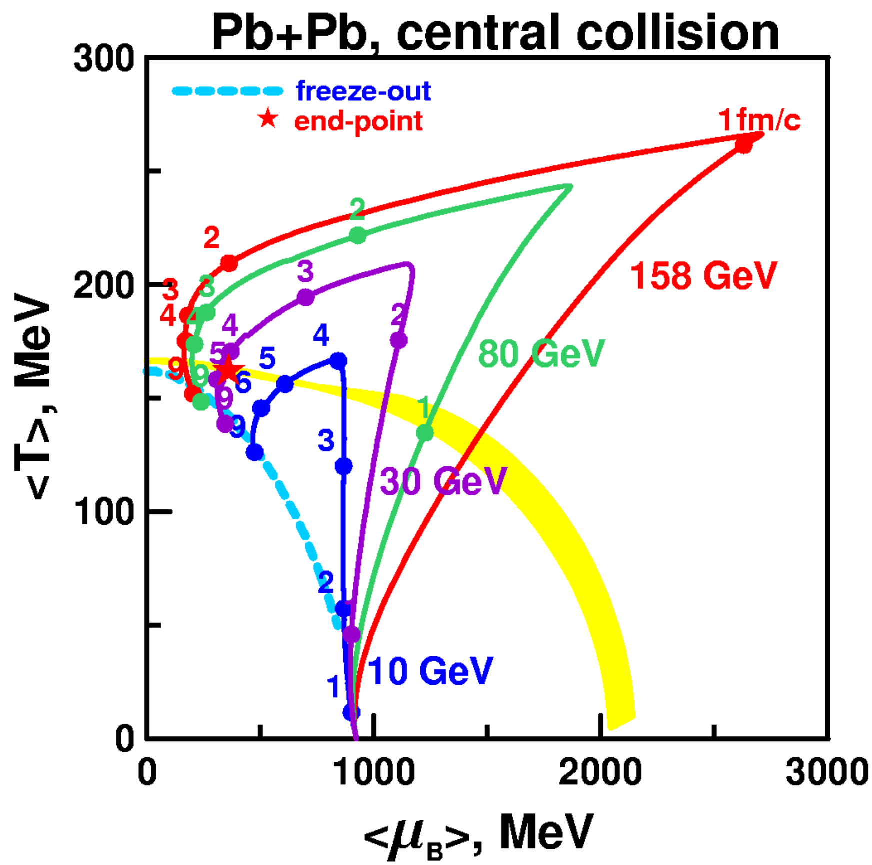
1. LHC detectors have excellent characteristics not only for *pp*, but also for heavy-ion collisions to investigate high-temperature QCD matter in details.
2. CBM detector at FAIR is presently designed for the study of high baryon density matter.

- Our dream is to understand the phase diagram.
- We will be very busy to realize our dream for the next two decades.

Backup Slides

Trajectories from Models



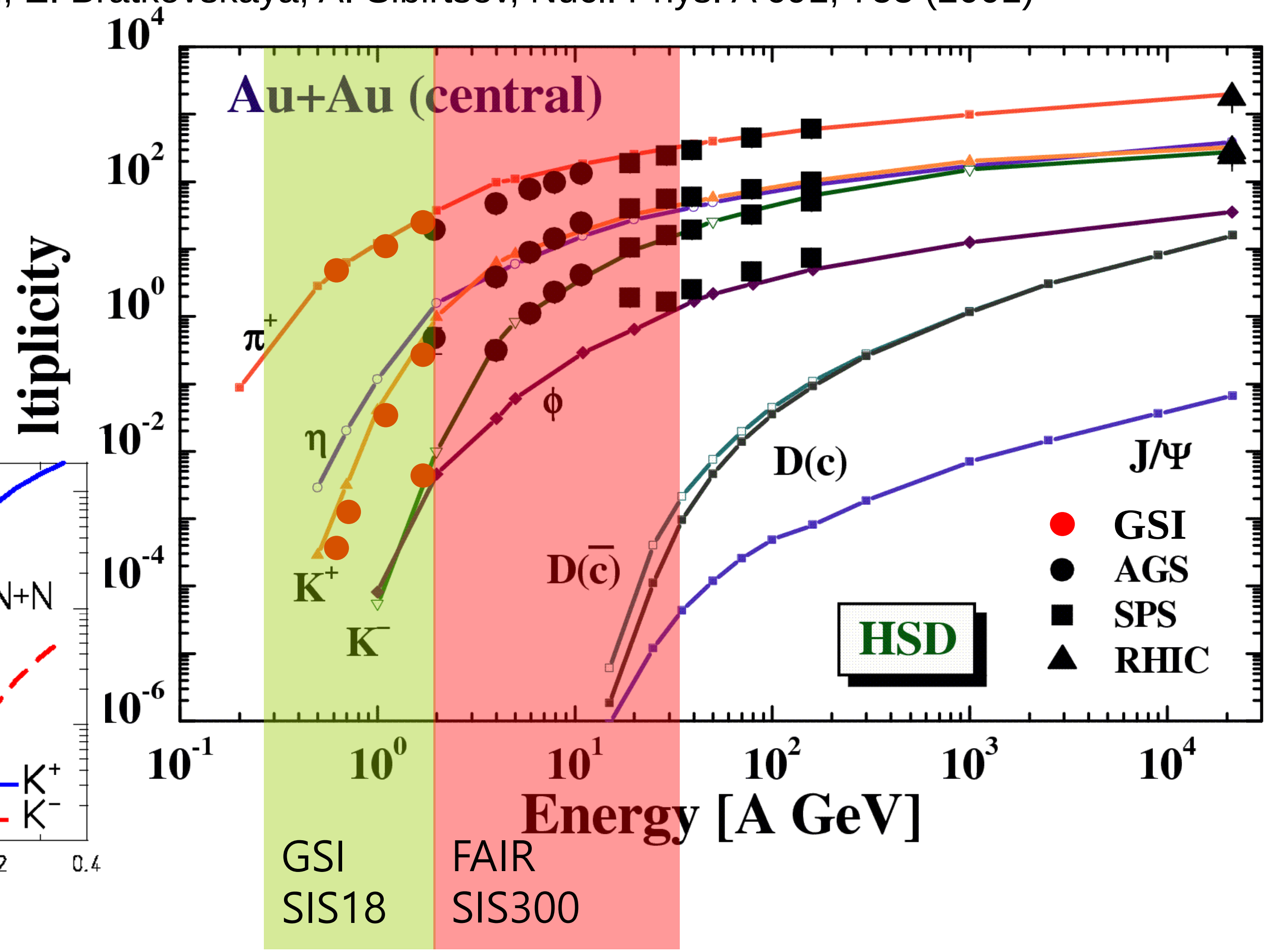


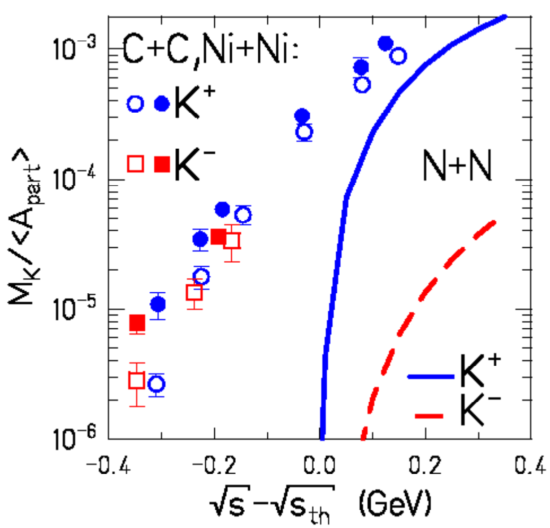
<u>UrQMD:</u>
L.V. Bravina et al.,
Phys. Rev. C 60, 044905 (1999)

<u>3-Fluid Hydro:</u>
Y. Ivanov, V. Russkikh, V.Toneev,
Phys. Rev. C 73, 044904 (2006)

Subthreshold D and J/ψ

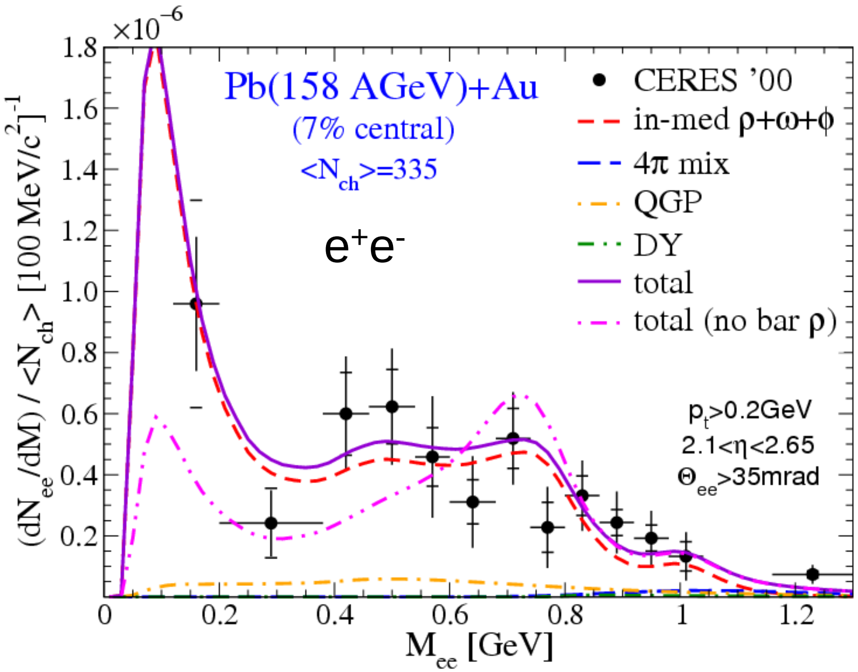
W. Cassing, E. Bratkovskaya, A. Sibirtsev, Nucl. Phys. A 691, 753 (2001)

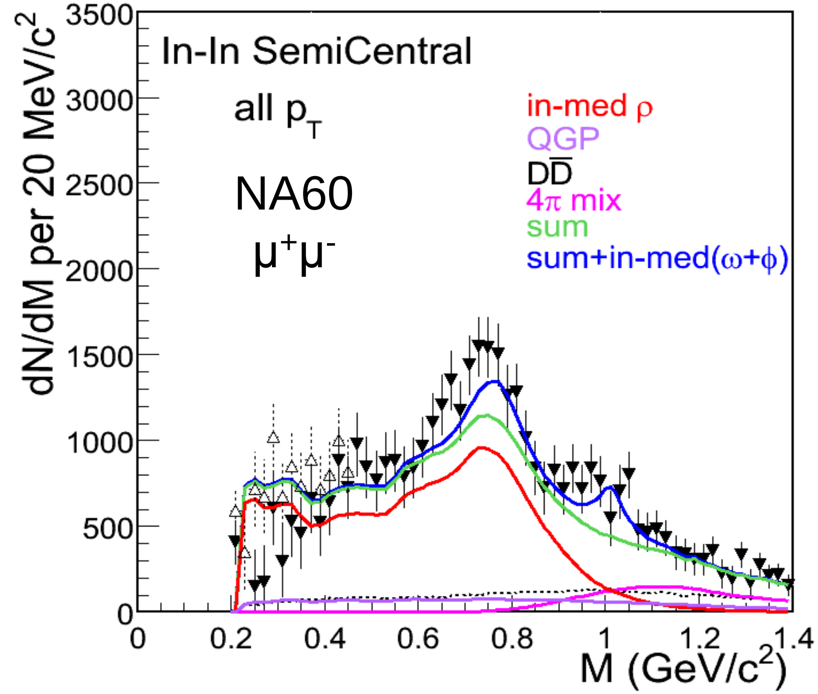




In-medium Effect of Hadrons

Calculations by H. van Hees and R. Rapp, Nucl. Phys. A 806, 339 (2008)



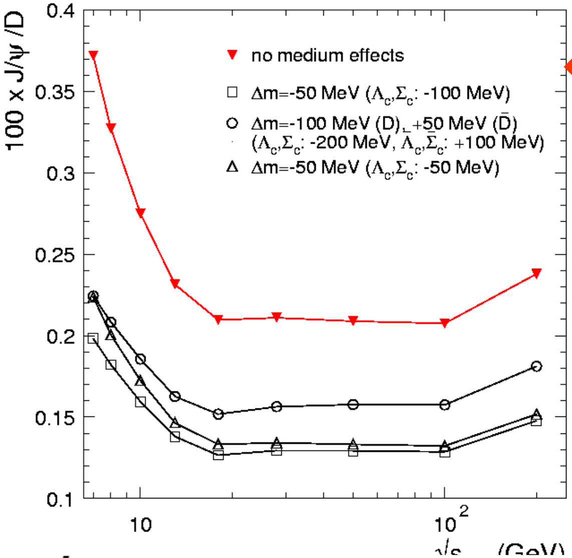


Electrons: access in M_{inv}< 200 MeV/c^2

Muons: better statistics (trigger)

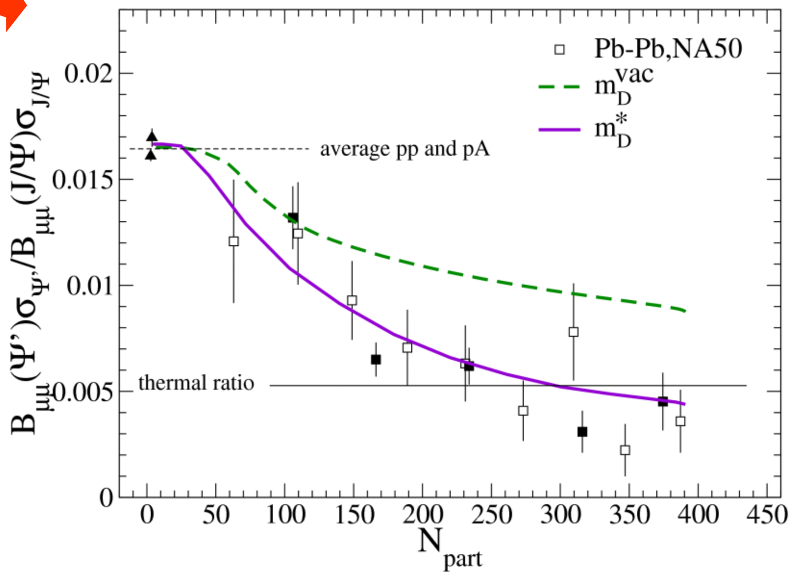
no data on ρ, ω, φ → e^+e^- ($\mu^+\mu^-$) between 2 and 40A GeV
no data on J/ψ, ψ' → e^+e^- ($\mu^+\mu^-$) below 160A GeV

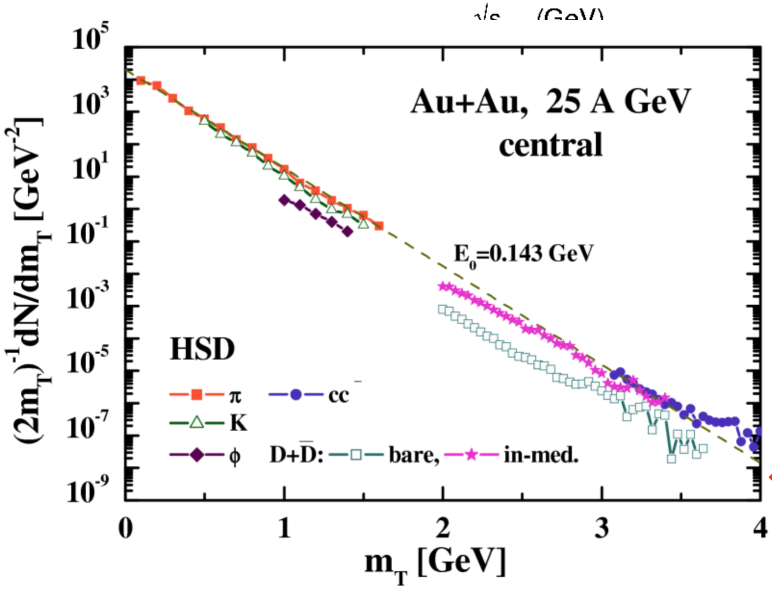
In-Medium Properties of D



Statistical hadronization model
A.Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, arXiv:0708.1488 [nucl-th]

Kinetic rate equation in thermal fireball
L. Grandchamp, R. Rapp, G.E. Brown, Phys. Rev. Lett. 92, 212301 (2004)

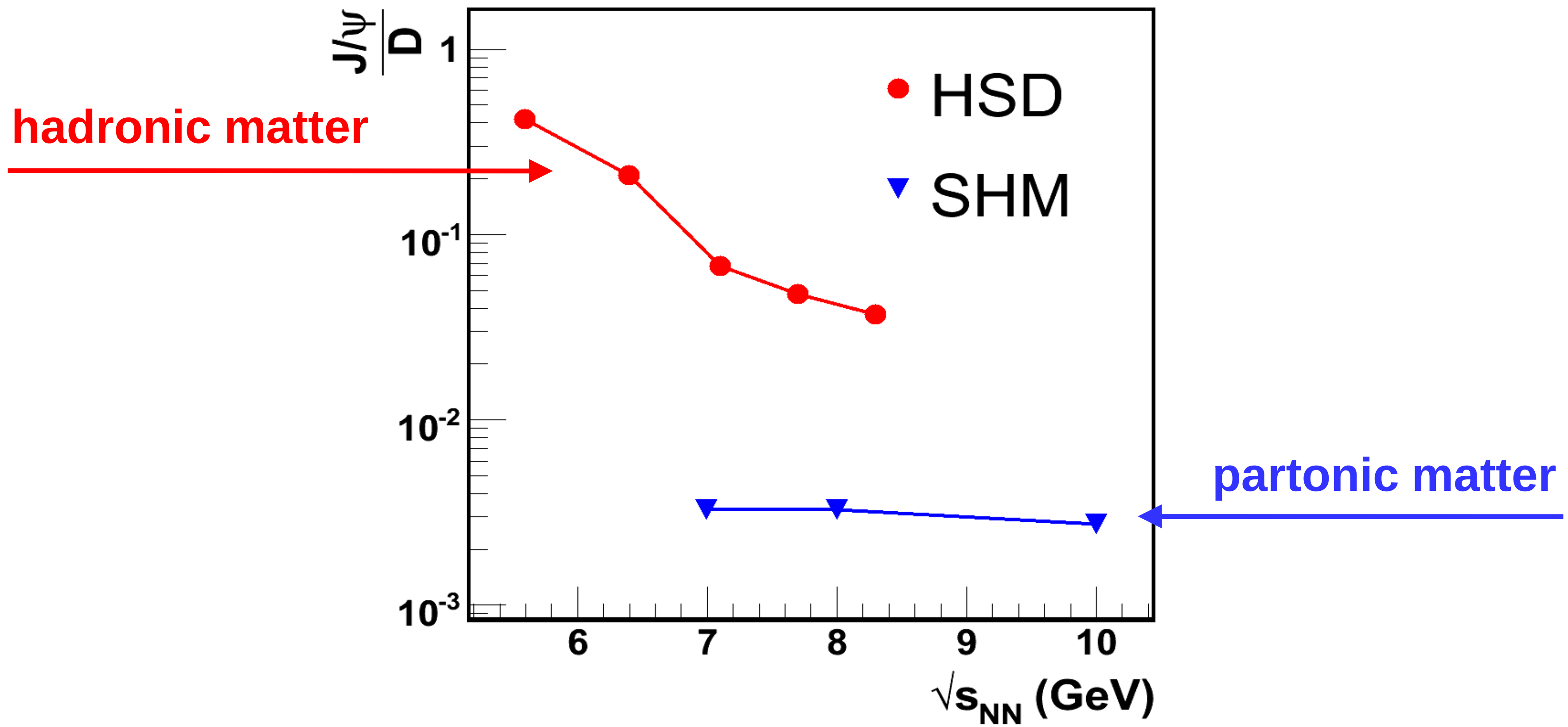




HSD microscopic transport model
W. Cassing, E. Bratkovskaya, A. Sibirtsev, Nucl. Phys. A 691, 753 (2001)

Ratio of Hidden and Open Charms

Charmonium / open charm

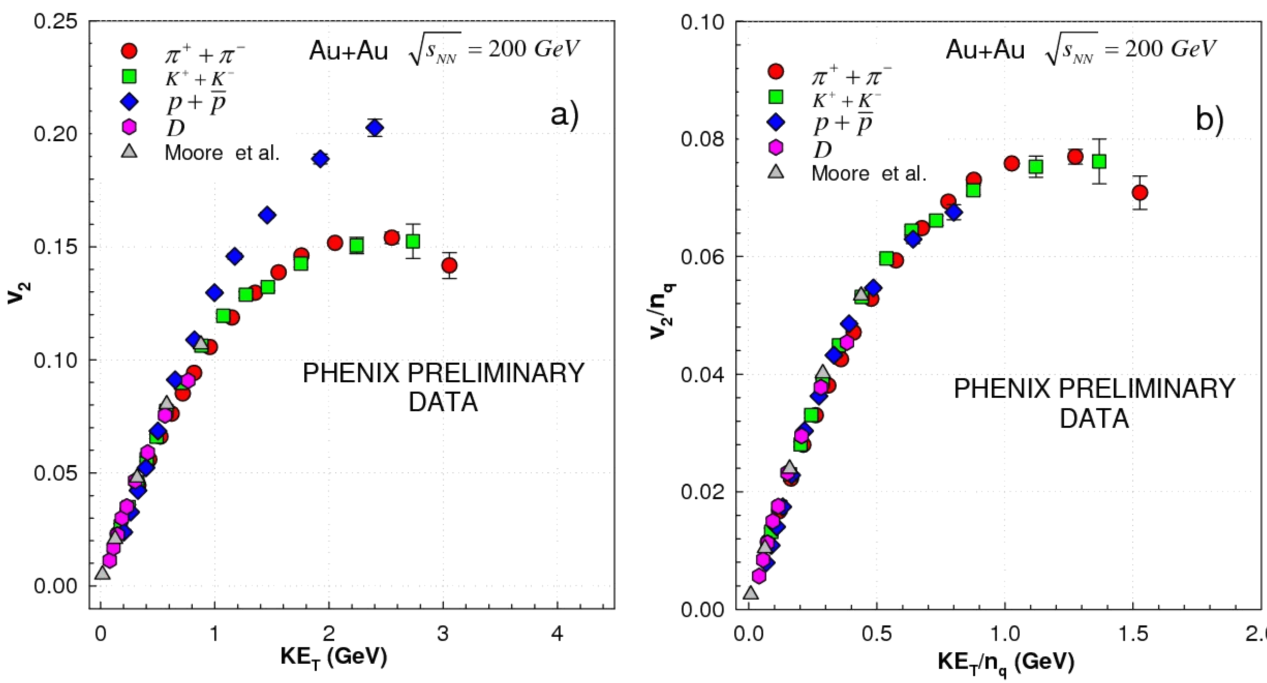


Charmed particle ratios (ψ/D, Λ_c/D, D/D_s, ...) are expected to be sensitive to the medium they are formed in.

Signature of QGP Formation

Prominent signatures of the QGP formation at RHIC

- Constituent quark scaling of the elliptic flow parameter
- Suppression of high-momentum hadrons (jet quenching)



CBM will look for the disappearance of these QGP signatures.