Heavy-Ion Physics with CMS at the LHC

Heavy Ion Meeting

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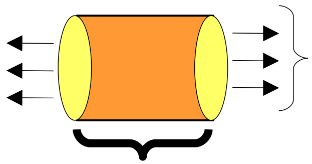
Massachusetts Institute of Technology

for the CMS Collaboration

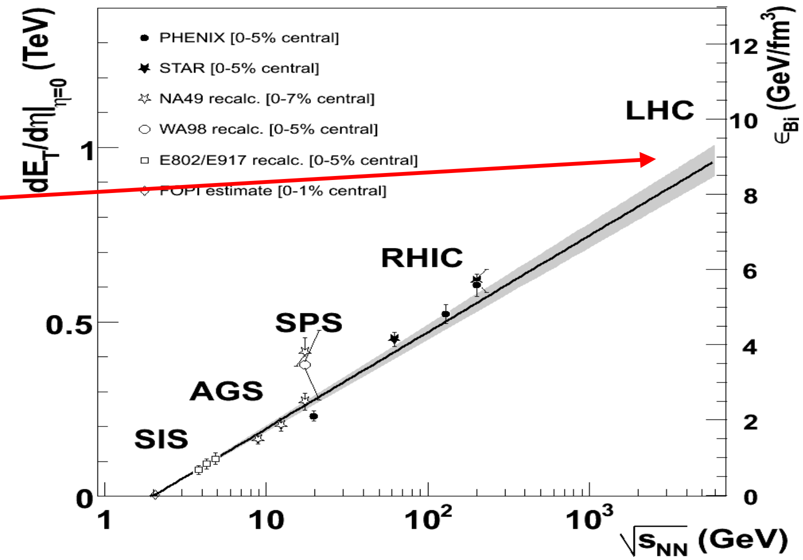
LHC: new energy frontier for QCD matter

- Very large energy densities:



ϵ_{Bj} > 10 GeV/fm³

τ_0 ~ 1 fm/c (~200×$\tau_{crossing}$)



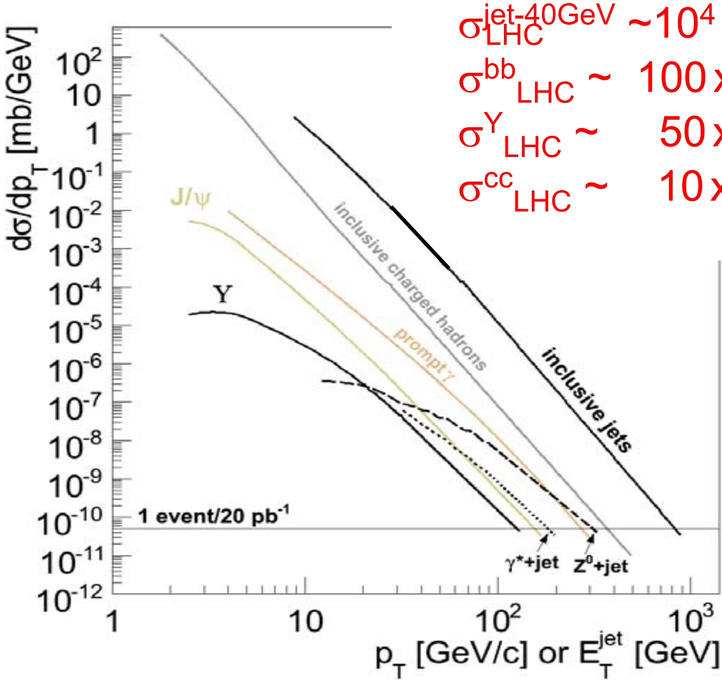
- Copious hard-probes yields:

$\sigma^{jet\text{-}40GeV}_{LHC}$ ~10⁴ x $\sigma^{jet\text{-}40GeV}_{RHIC}$

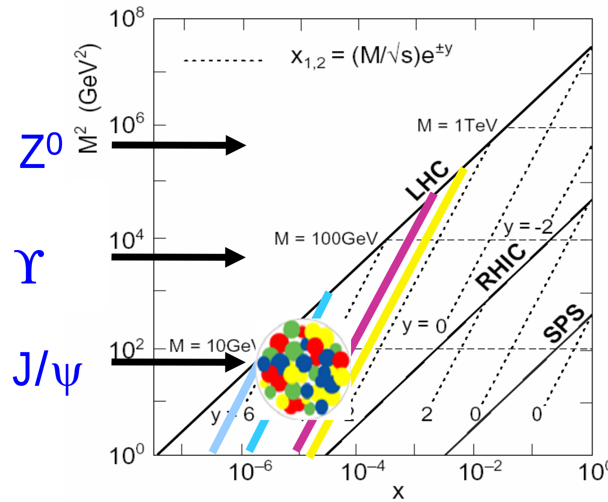
σ^{bb}_{LHC} ~ 100 x σ^{bb}_{RHIC}

σ^{Υ}_{LHC} ~ 50 x σ^{Υ}_{RHIC}

σ^{cc}_{LHC} ~ 10 x σ^{cc}_{RHIC}



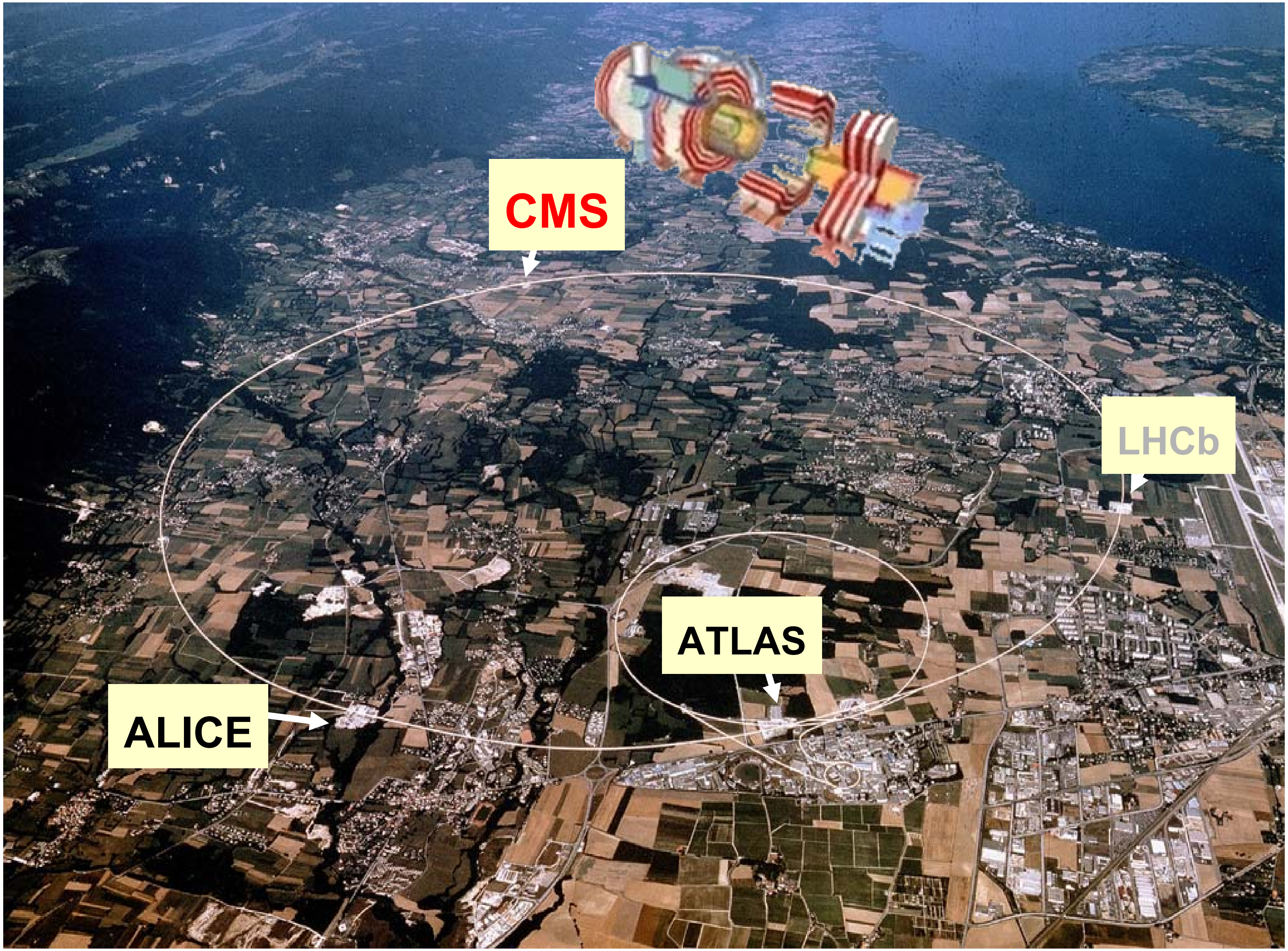
- Unexplored low-x regime: ~10⁻⁴-10⁻⁵



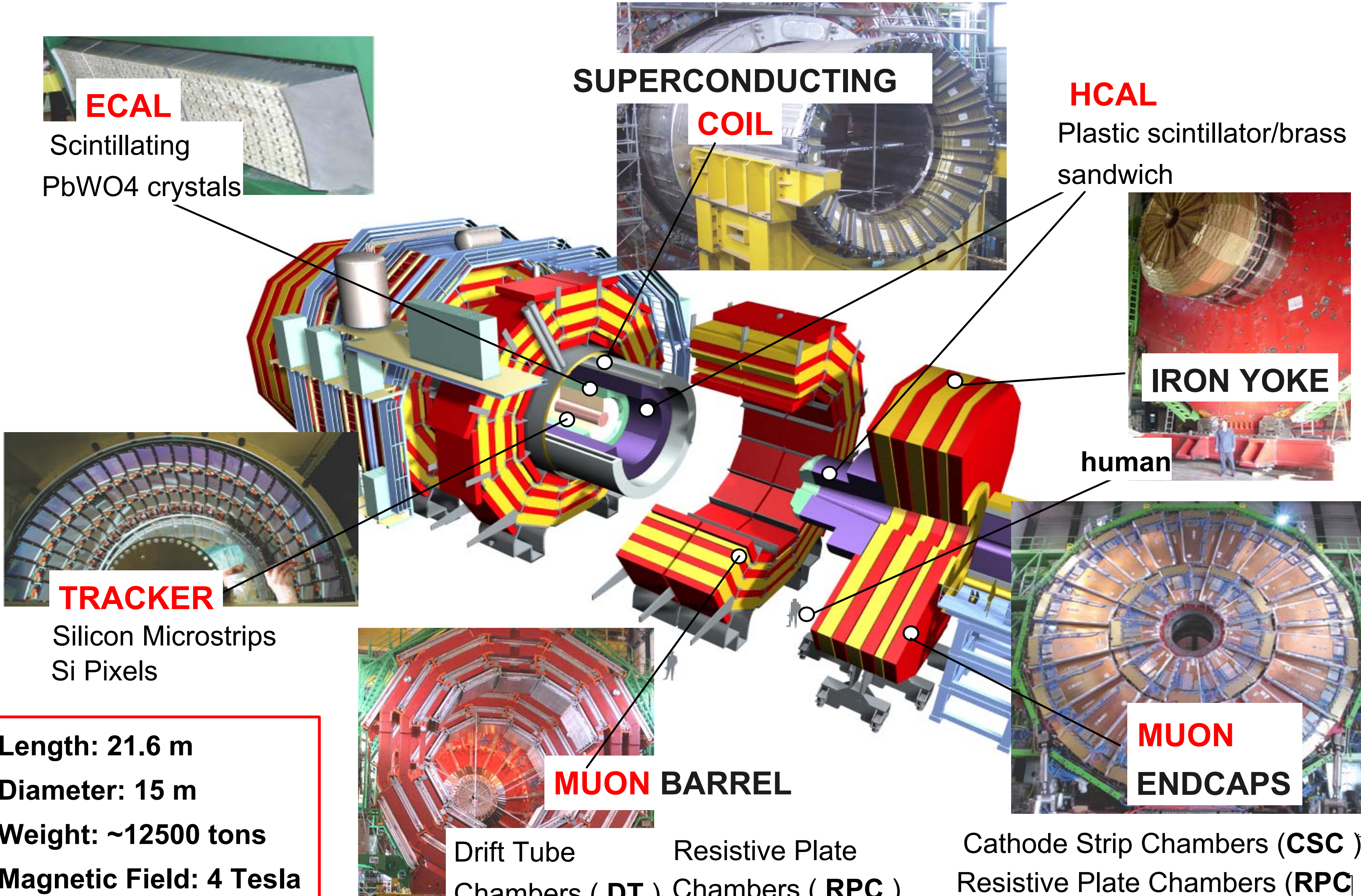
x~1/40 RHIC

Q_s^2 ~ ×3 RHIC

CMS detector at the LHC



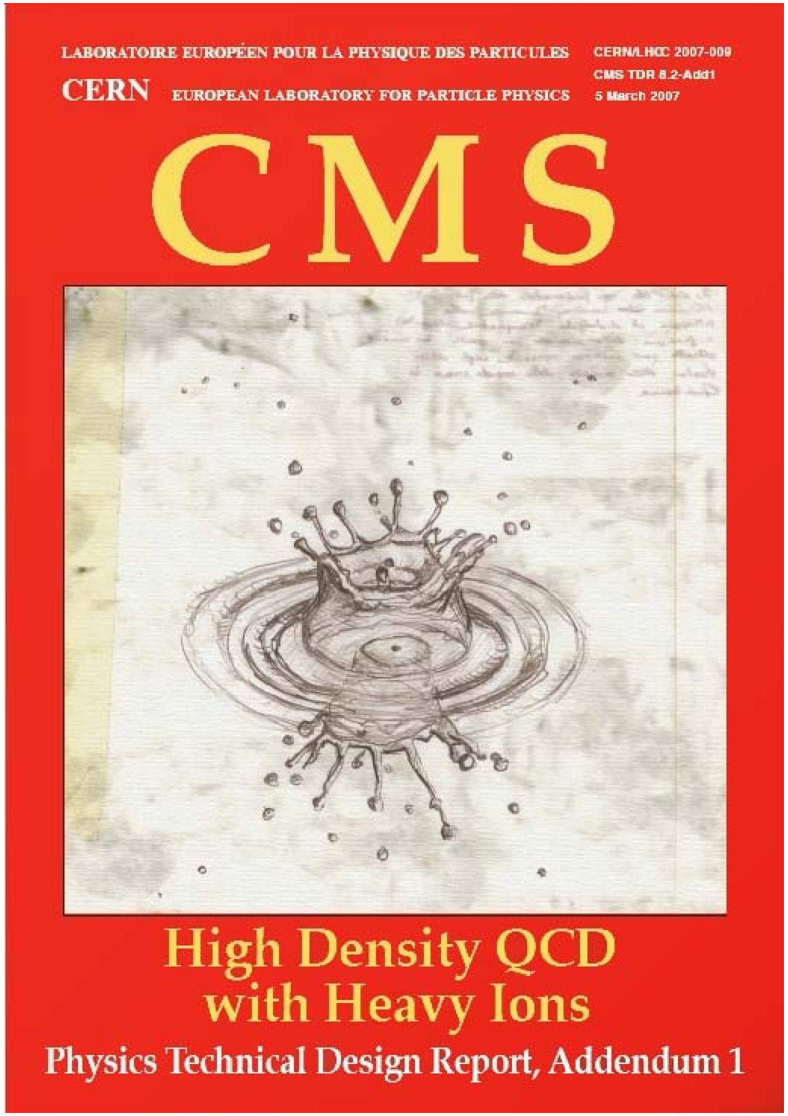
CMS detector at the LHC



Length: 21.6 m
Diameter: 15 m
Weight: ~12500 tons
Magnetic Field: 4 Tesla


Tracker Insertion
Dec.'07

CMS Heavy-Ions programme



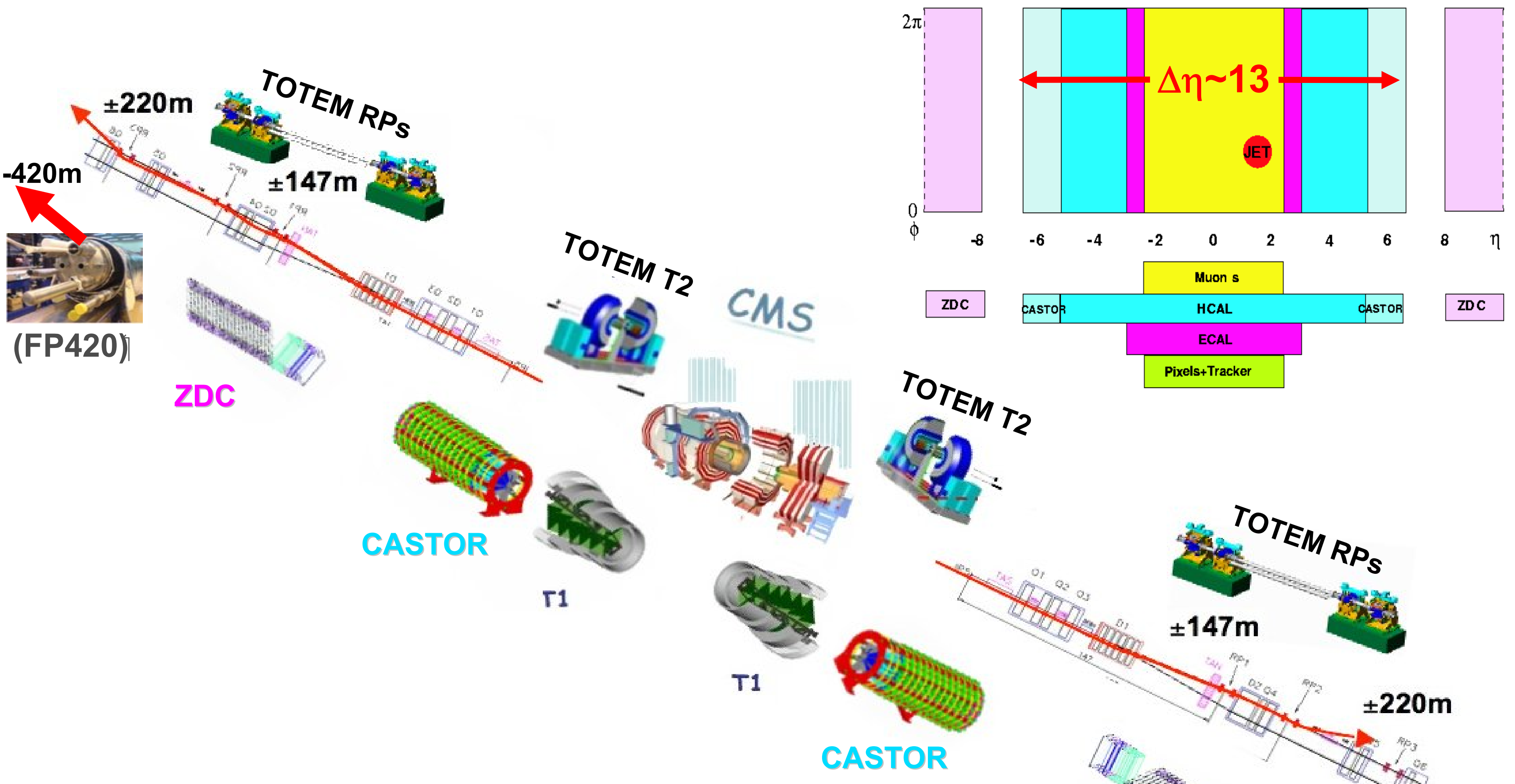
~25 CMS-HI institutions

~100 collaborators

Adana, Athens, Auckland, Budapest-KFKI, Budapest-Eötvös L., CERN, Chicago, Chonbuk, Colorado, Davis U.C., Demokritos, Ioannina, Iowa, Kansas, Korea Univ., Lisbon, Lyon, Los Alamos, Maryland, Minnesota, MIT, Moscow, Mumbai, Seoul Univ., Vanderbilt, Zagreb

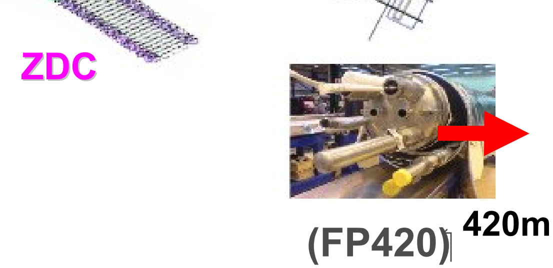
D.d'E (ed.) et al. CERN-LHCC-2007-009; J.Phys.G. 34, 2307-2455 (2007)

CMS detector at the LHC

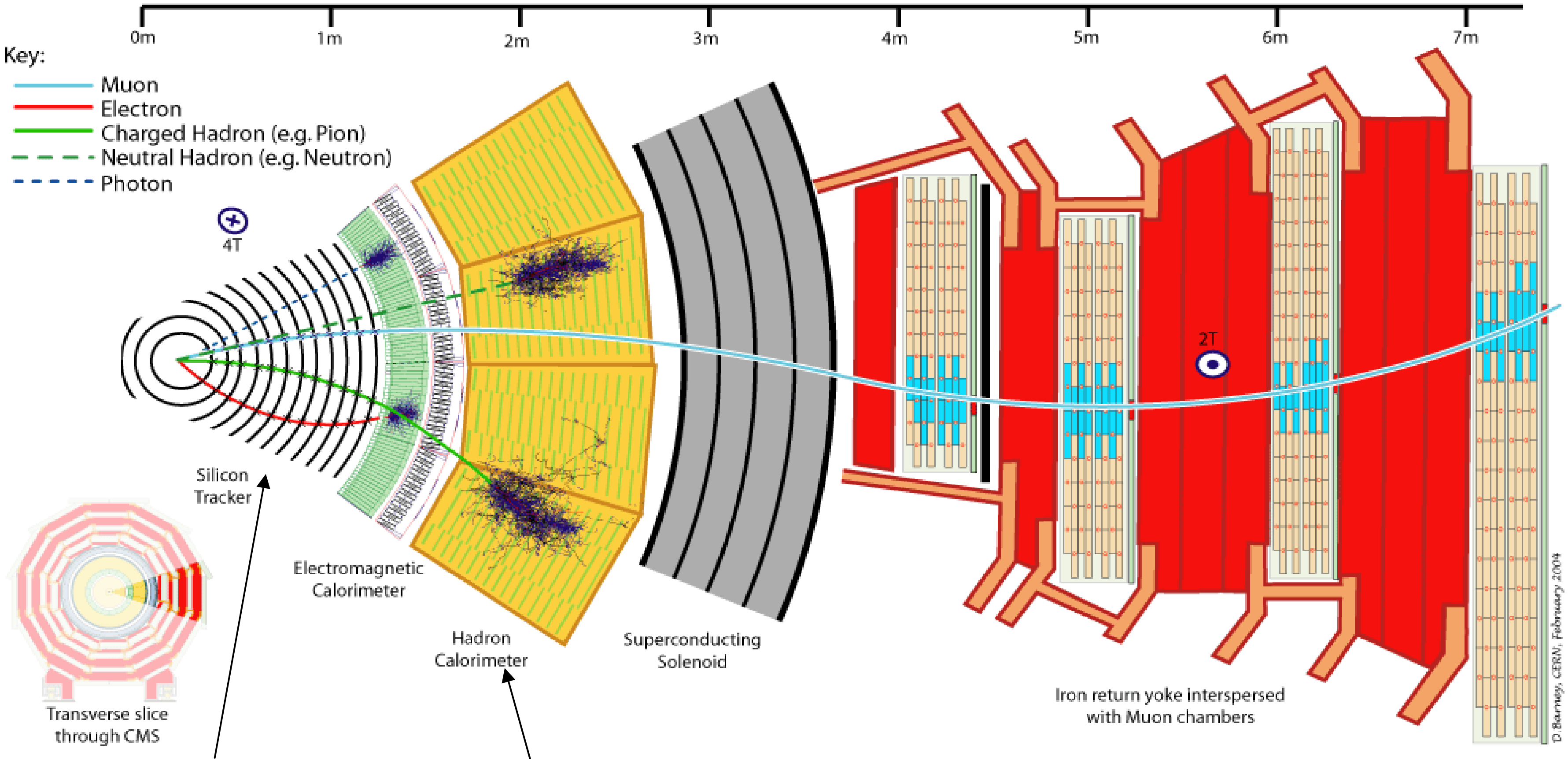


- CMS (+TOTEM):

Largest phase-space coverage ever in a collider.



$h^{\pm}$, $e^{\pm}$, γ , $\mu^{\pm}$ measurement in CMS ($|\eta|<2.5$)



Si TRACKER

Silicon Microstrips and Pixels

CALORIMETERS

ECAL
$PbWO_4$

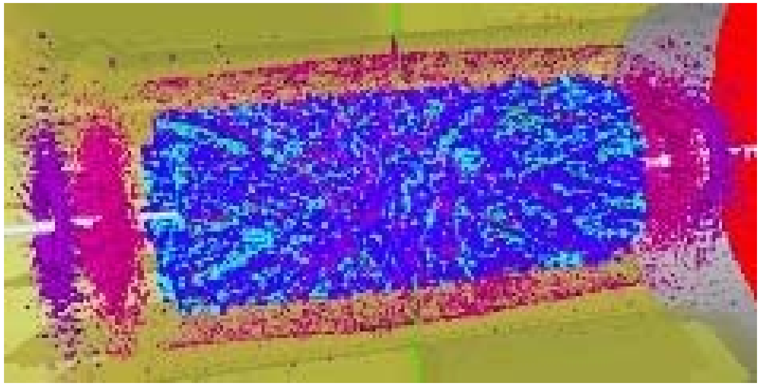
HCAL
Plastic Sci/Steel sandwich

MUON BARREL

Drift Tube Chambers (**DT**)

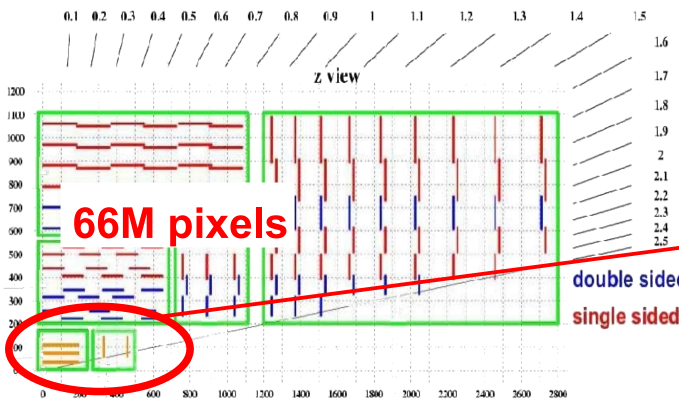
Resistive Plate Chambers (**RPC**)

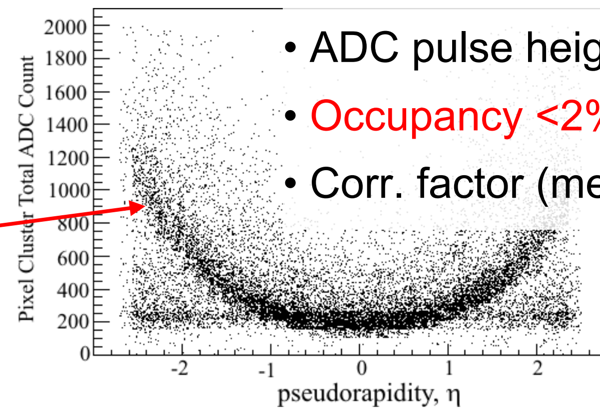
QCD matter in CMS, bulk properties



PbPb hadron multiplicity: gluon density

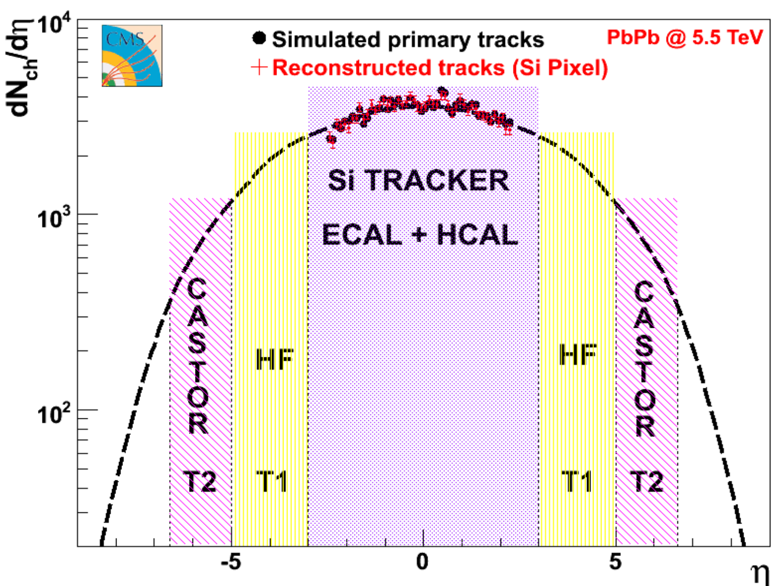
- $dN_{ch}/d\eta$ ($|\eta|<2.5$) via hit counting in Si pixels "à la PHOBOS":





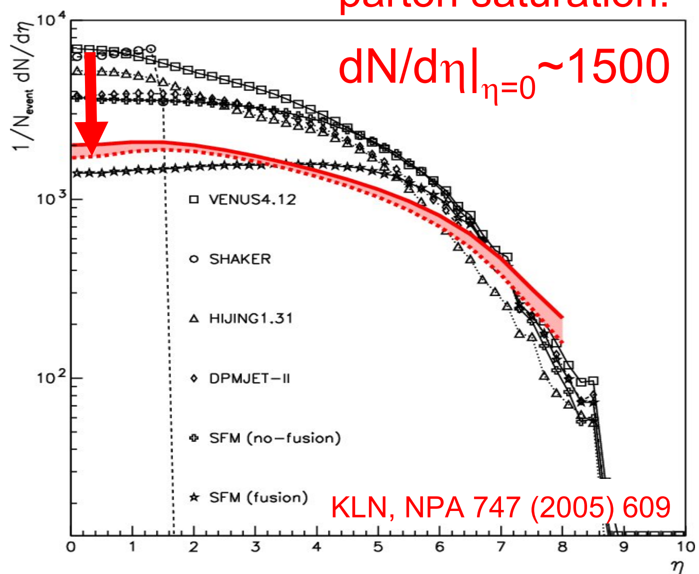
- ADC pulse height vs. η
- Occupancy <2% ($dN_{ch}/d\eta$=5000)
- Corr. factor (meas.→primary)~0.83

- Final A-A multiplicity ∝ Initial number of released gluons:



parton saturation:

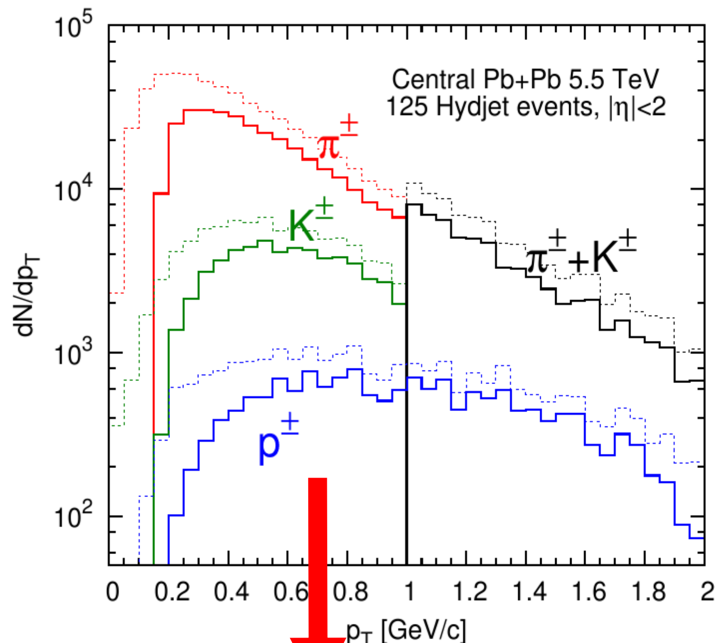
$dN/d\eta|_{\eta=0}$~1500



KLN, NPA 747 (2005) 609

Soft hadron spectra: medium EoS

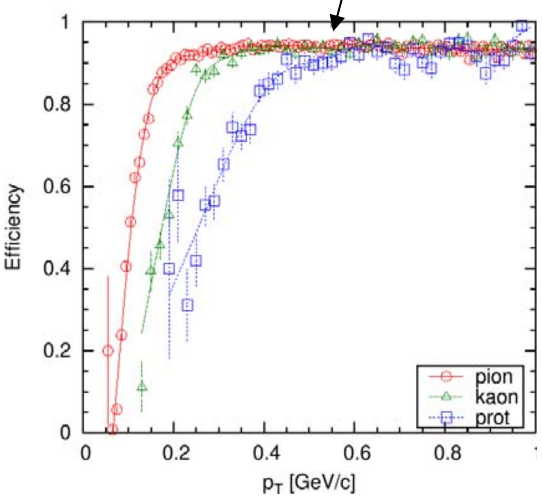
- Single hadron ($\pi^\pm$, $K^\pm$, $p,\bar{p}$) p_T spectra in p_T~ 0.2 – 2. GeV/c via pixel-triplet algorithm in 3 layers of Si tracker.
- PID via dE/dx (Gaussian unfolding).
- Performances (p_T>0.2 GeV/c):

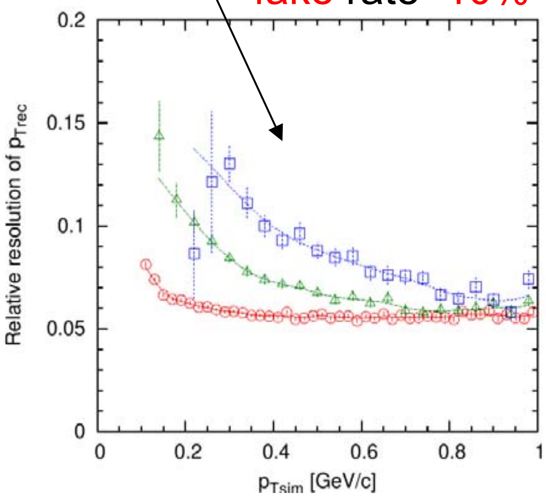


accept./effic.~80-90%

p_T resol.~10%

fake rate<10%





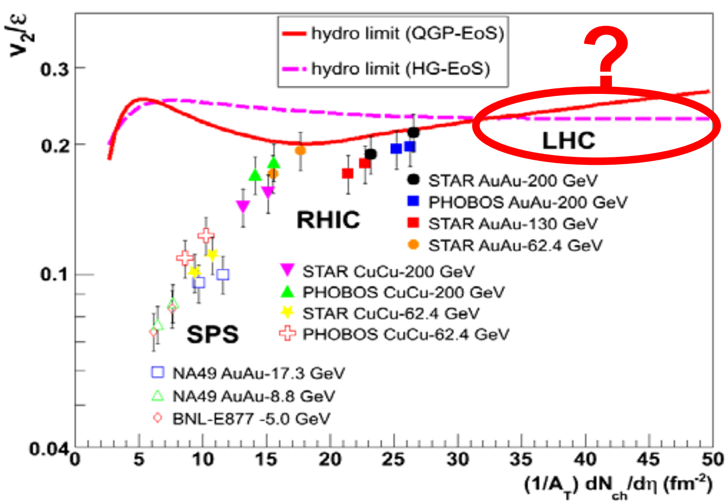
collective radial flow,
hadron ratios, ...

- Data vs. hydro: thermalization time, medium EoS constraints

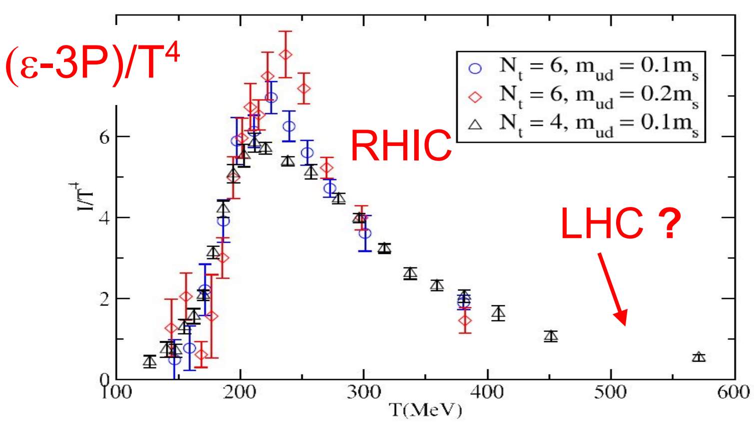
Elliptic flow: medium viscosity

- Elliptic flow (v_2) measurement:

RHIC: zero-viscosity fluid



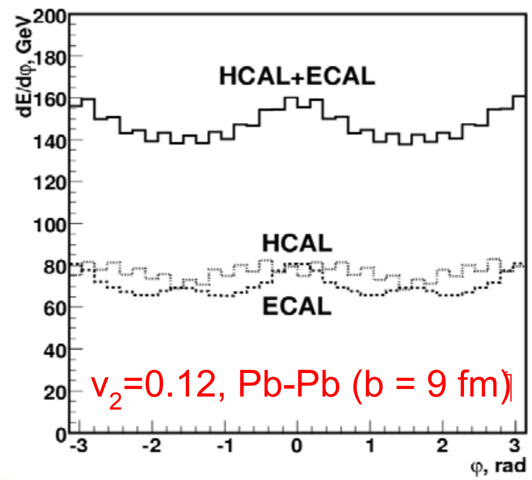
LHC: weakly interacting QGP ?



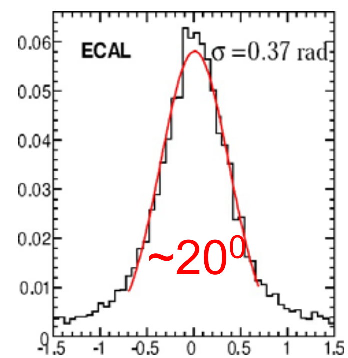
- 2 different methods :

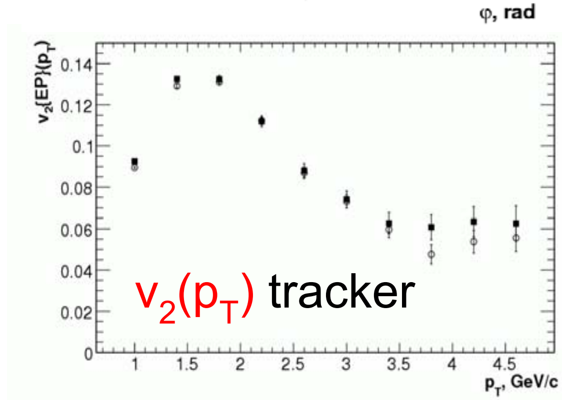
(1) reaction-plane in HCAL+ECAL, tracker

(2) cumulant analysis



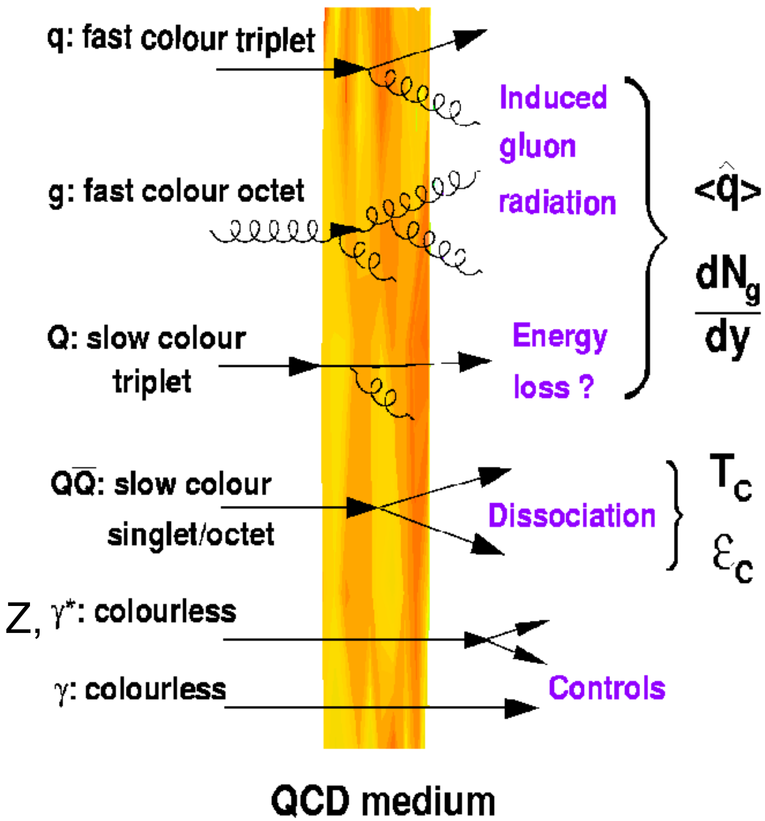
Good react-plane angle resolution





[Non-flow systematic uncertainties not included]

QCD matter in CMS
Hard ("tomographic") probes



Pb-Pb High-Level Triggering

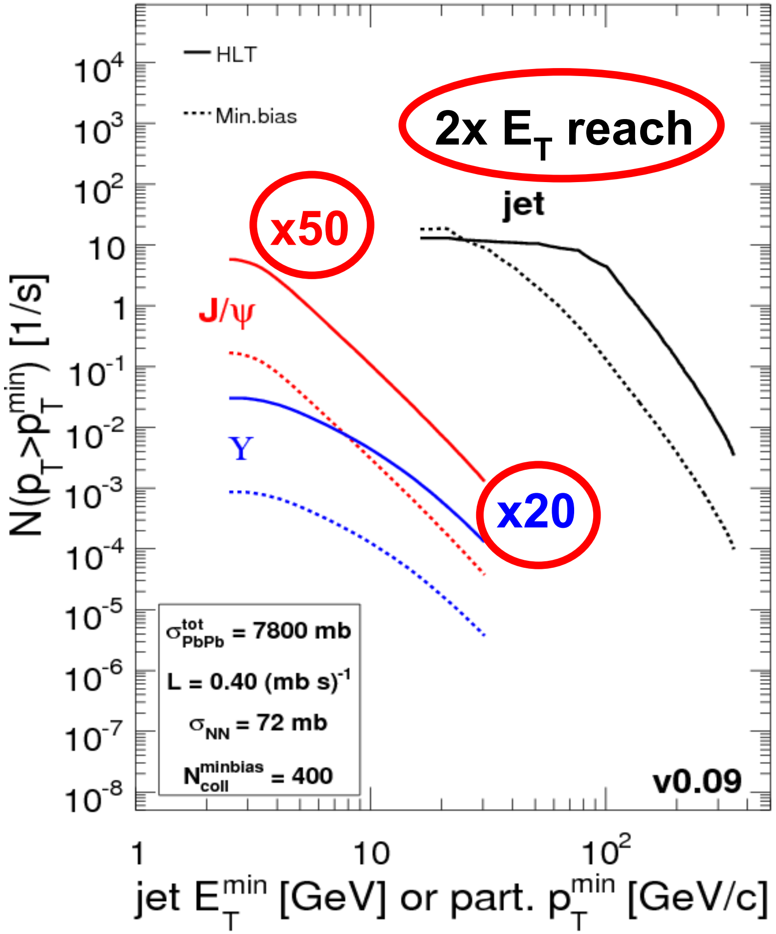
- Unique CMS High-Level-Trigger ≈ 12k × 1.8-GHz CPUs ~ 50 Tflops !
- CMS HLT fast enough to run "offline" algos on every PbPb evt. !
- Event rates:

- Logging rate: 225 MB/s
- Luminosity: 10^{34} (pp), 10^{27} (PbPb)
- Evt. size (MB): 1 (pp), 2.5 (PbPb),10 (PbPb cent)

pp: 40 MHz —1/400→ 100 kHz —1/600→ 150 Hz

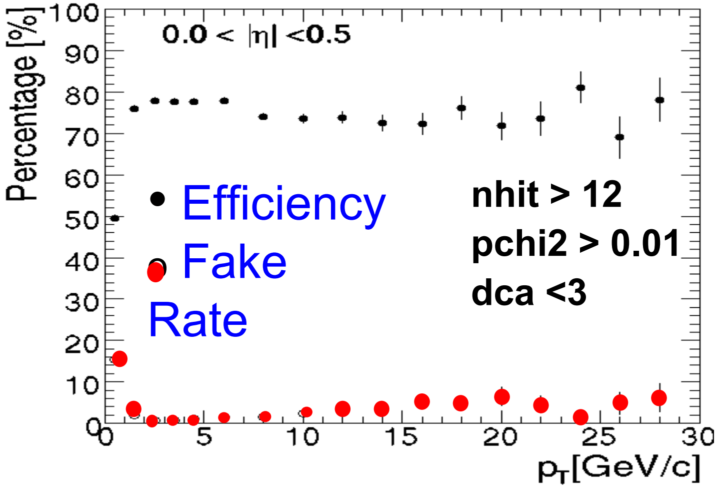
PbPb: 5 kHz —L1 (1/1)→ 5 kHz —HLT (1/50 - 1/500)→ ~10-100 Hz

Significantly enhanced statistical reach for hard probes: x20 – x300

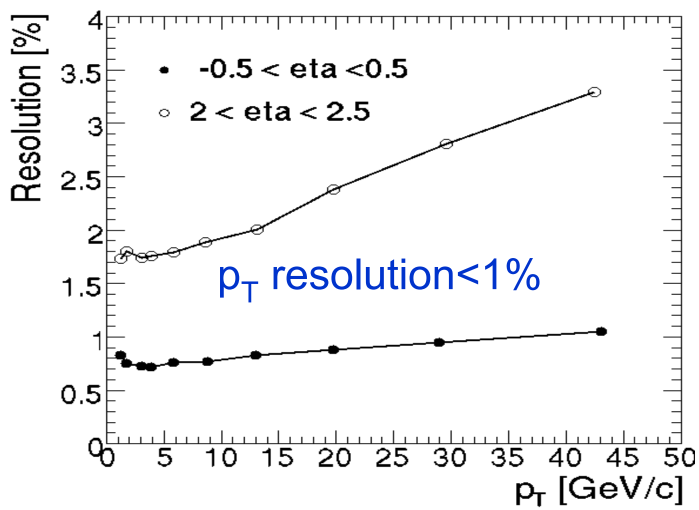


High-p_T hadron spectra: $\langle\hat{q}\rangle$, $dN^g/d\eta$

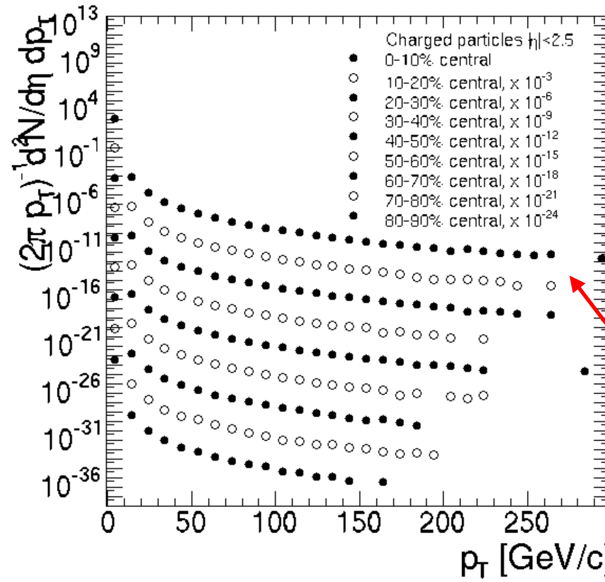
- Tracking performance:



[PbPb, $dN_{ch}/d\eta|_{y=0}$ = 3500]



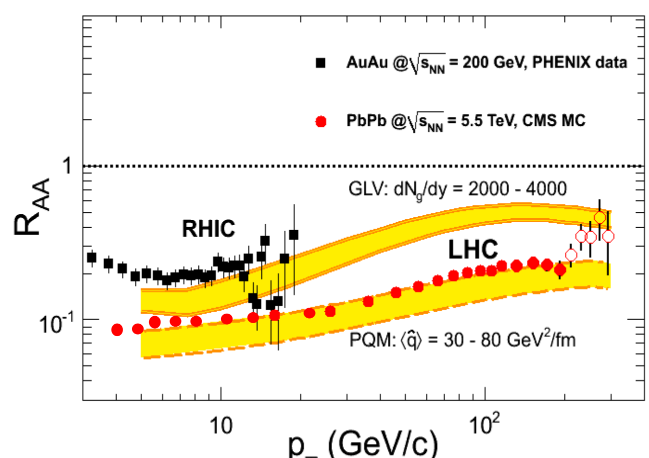
- Physics reach (HLT):



[PbPb, 0.5 nb^{-1}]

p_T~300 GeV/c

- Medium density / transport-coefficient:



GLV:

$dN_g/dy \sim 2\text{-}4\cdot10^3$

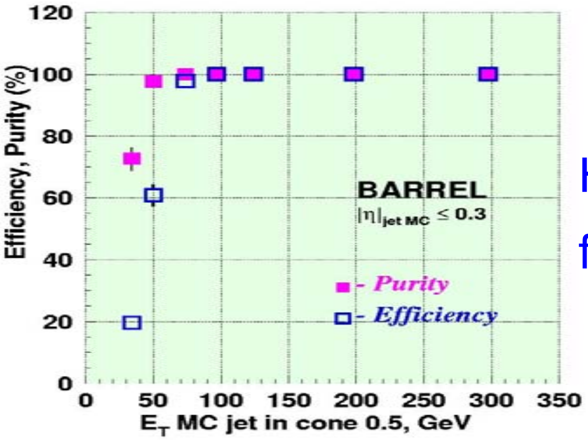
PQM:

$\langle q\rangle \sim 30\text{-}80\ GeV^2/fm$

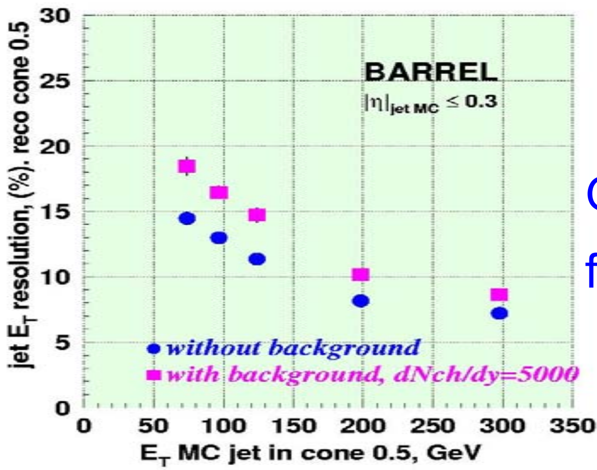
Full jet reconstruction: $\langle\hat{q}\rangle$, $dN^g/d\eta$

- Iterative-cone (R=0.5) + Backgd subtraction:

[New developments (fastJet) under study]



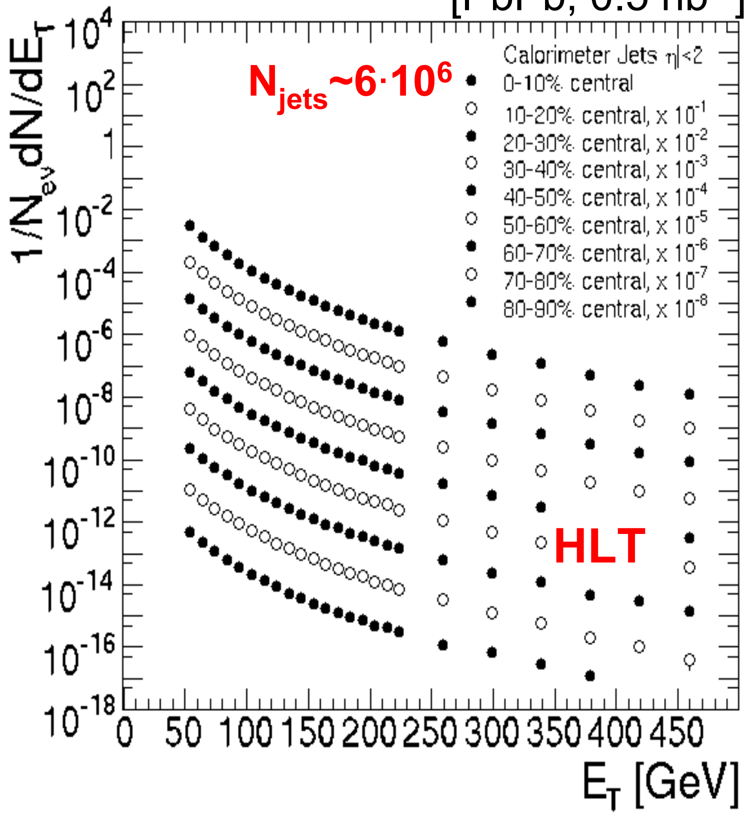
High effic./purity for E_T>50 GeV



Good energy resol. for E_T>100 GeV

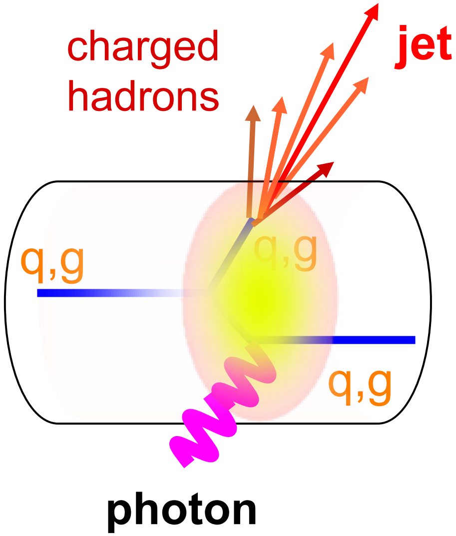
- Jet spectra up to E_T~ 0.5 TeV:

[PbPb, 0.5 nb^{-1}]

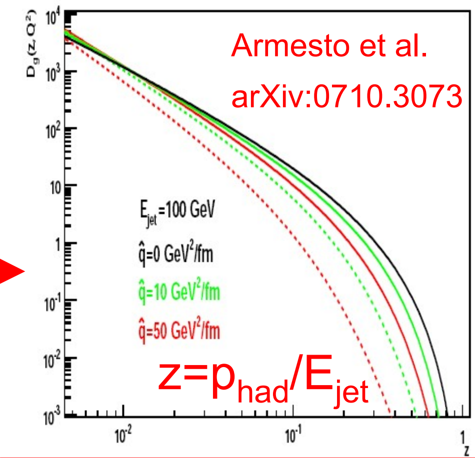


- Detailed jet-quenching studies: jet shapes, energy-particle flow, ...

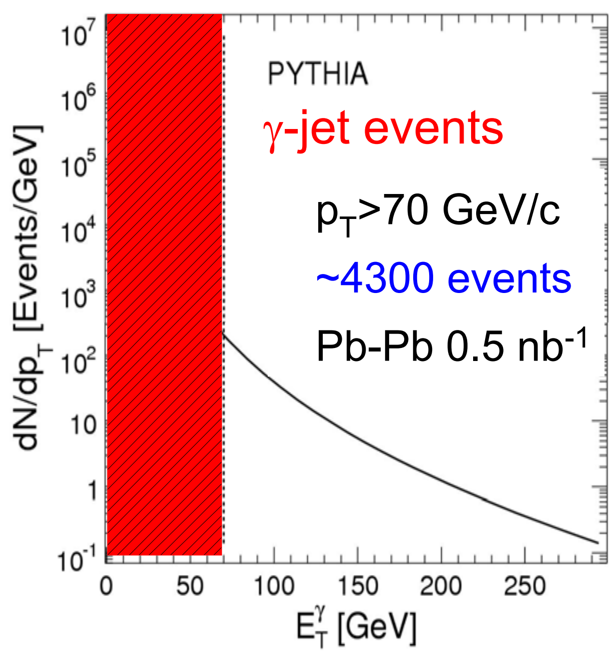
γ– jet in Pb-Pb (I): medium frag. functions

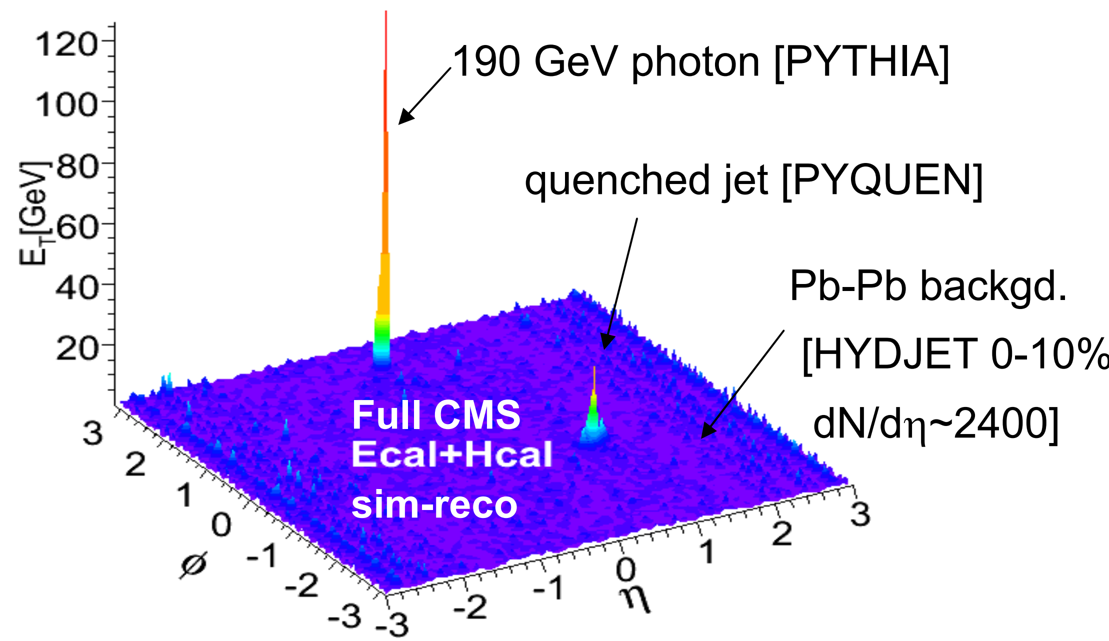


- Isolated γ ($|\eta|<2$, $R_{isol}<0.5$): E_T^{parton}
- Jet ($|\eta|<2$, $|\Delta\phi_{jet-\gamma}|>3$): away axis
- Hadrons ($|\eta|<2.5$, $R_{jet}<0.5$): p_T^{had}



FF($z,\hat{q}$): dN/dz,dN/dξ

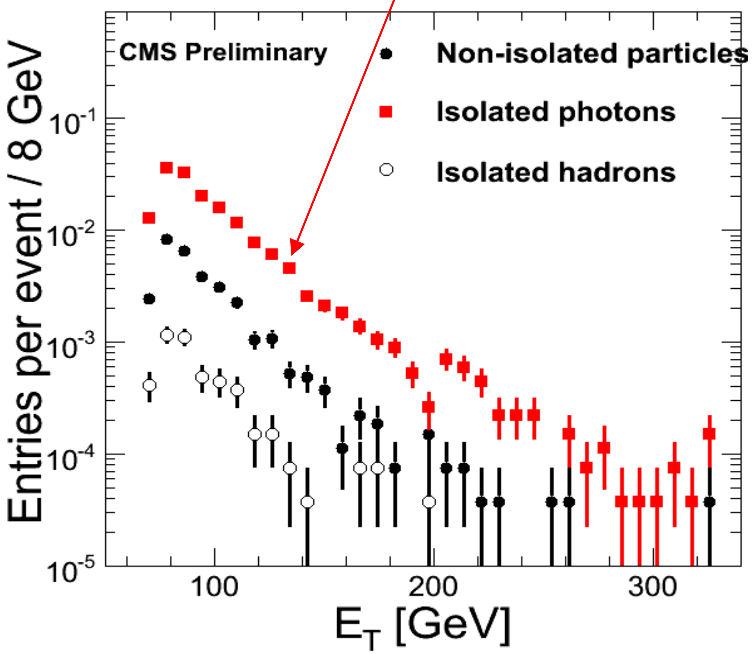




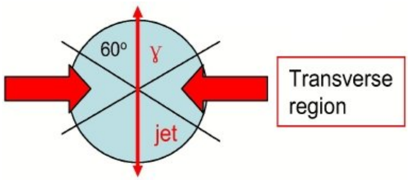
γ– jet in Pb-Pb reconstruction details

- Photon ID via "Fisher LD" Multi-Variate-Analysis w/ 21 vars: ECAL cluster-shape & ECAL/HCAL/tracker isolation cuts
- Performances:

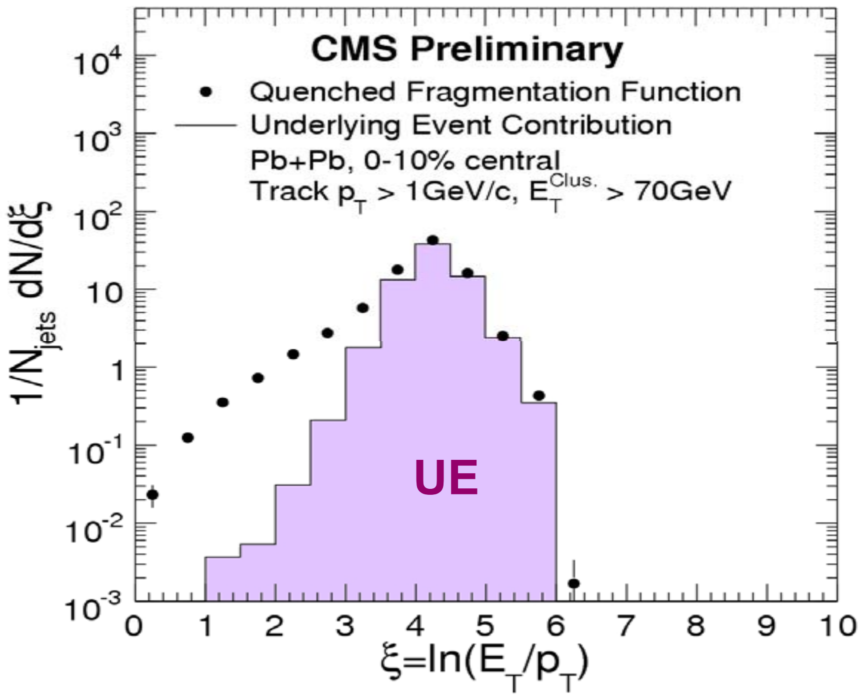
ε = 60%
fake γ = 3.5%
S/B=4.5



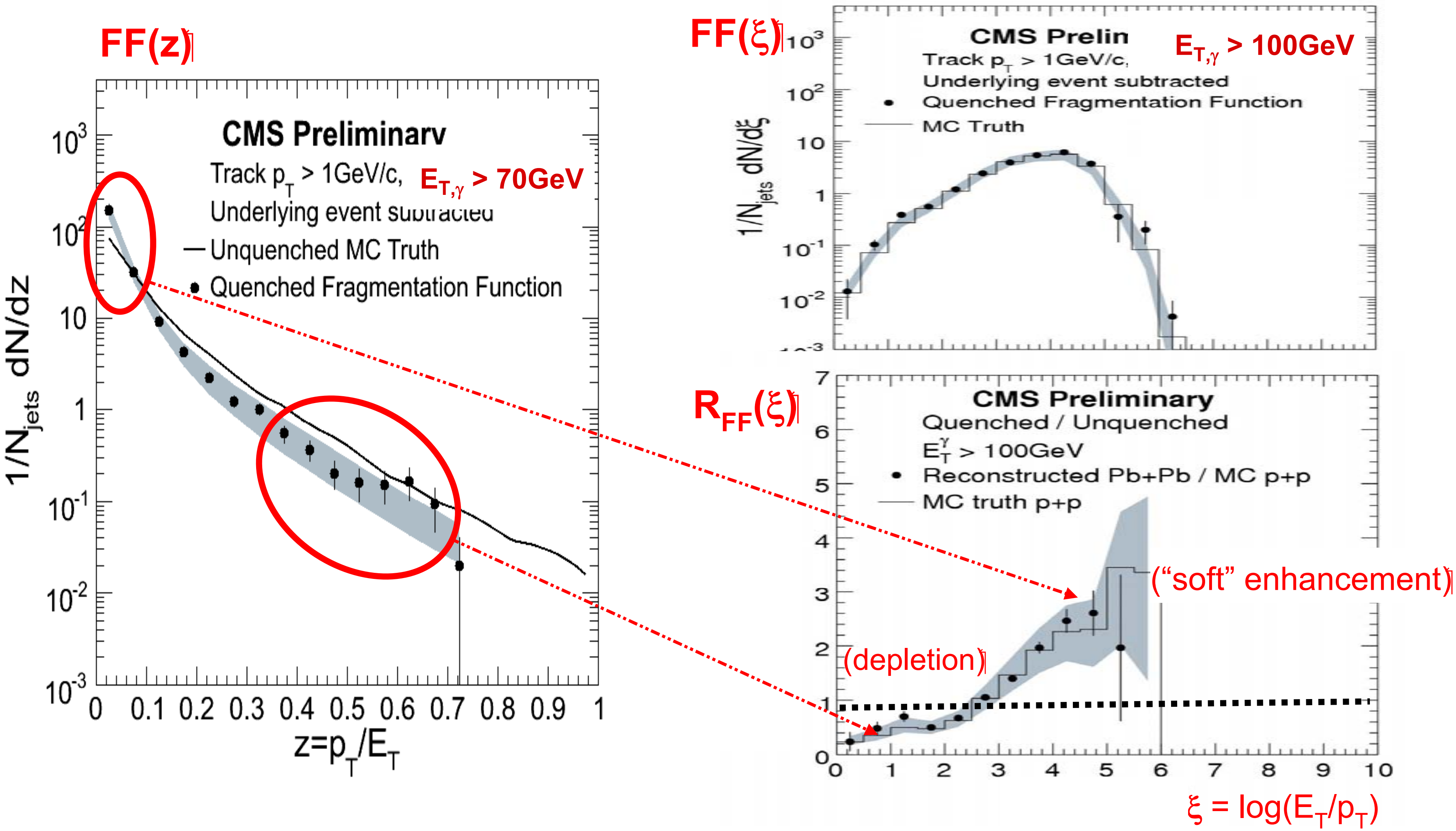
- UE hadron backgd. subtracted using R=0.5 cone transverse to jet axis



FF(z): dN/dξ



Medium-modified Fragmentation Functions

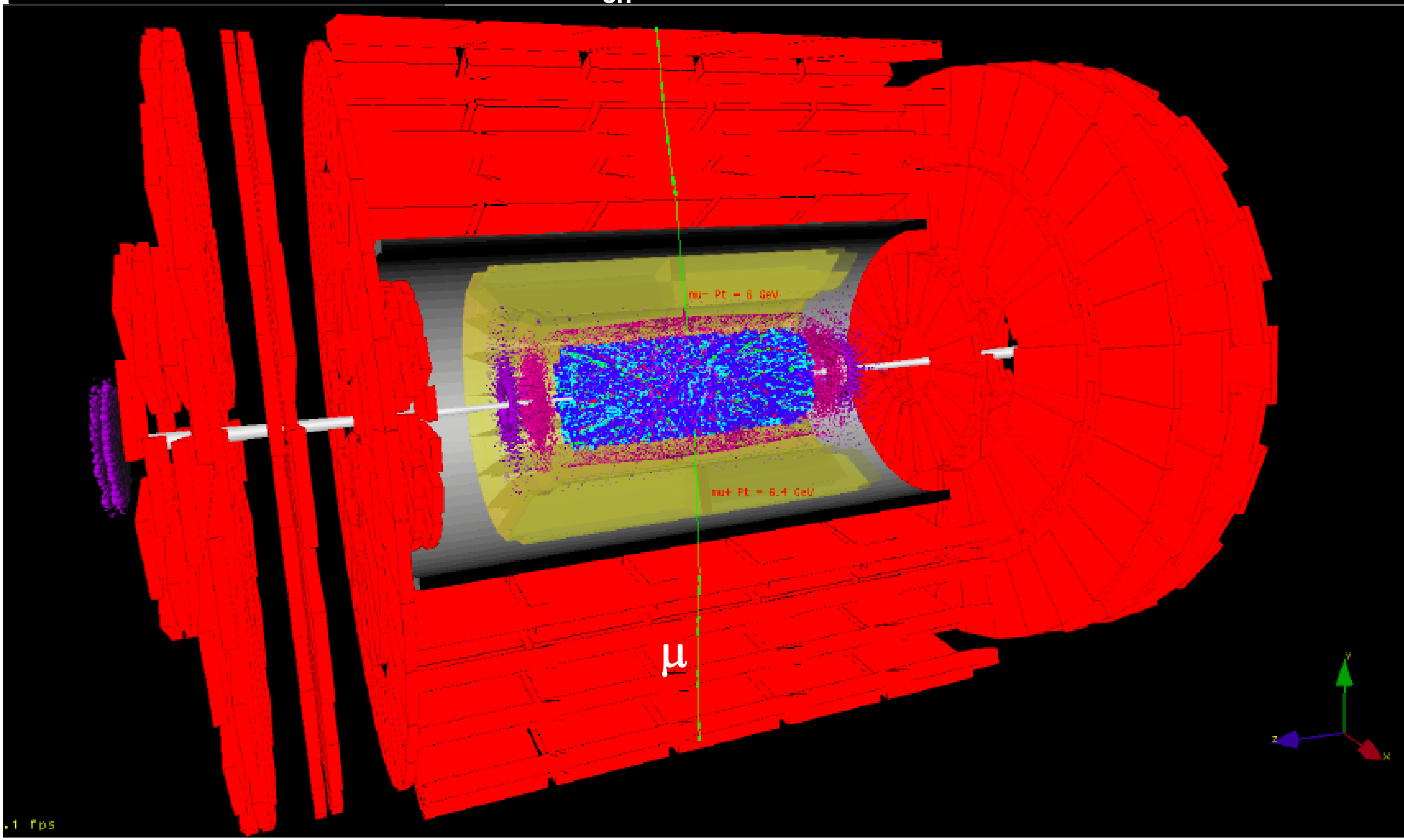


- Medium mod. FFs measurable for z<0.7 & 0.2 <ξ< 5 with high significance
- Syst. uncertainties dominated by (low) jet reco effic. 30-70 GeV

PbPb → ϒ+X event in CMS

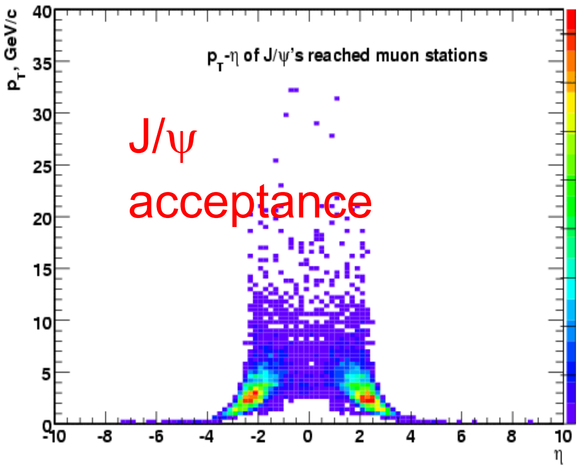
- Event display with full CMS software/simulation framework

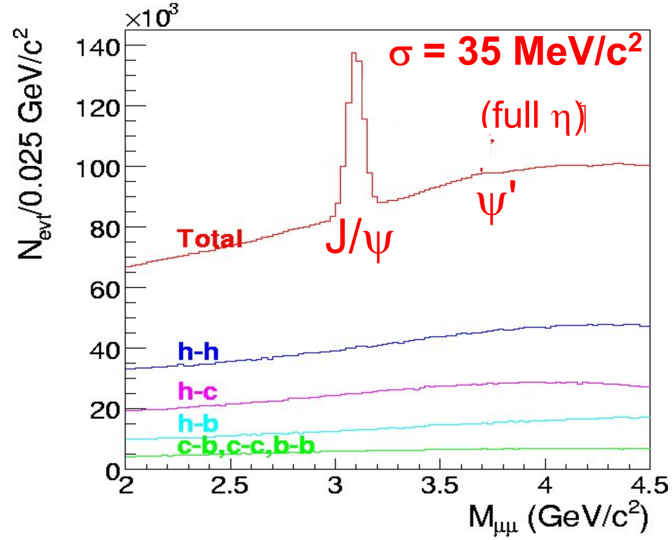
Pb+Pb event ($dN_{ch}/d\eta$ = 3500) with $\Upsilon \rightarrow \mu^+\mu^-$



J/ψ suppression(?): critical energy density

- Reconstruction performances :



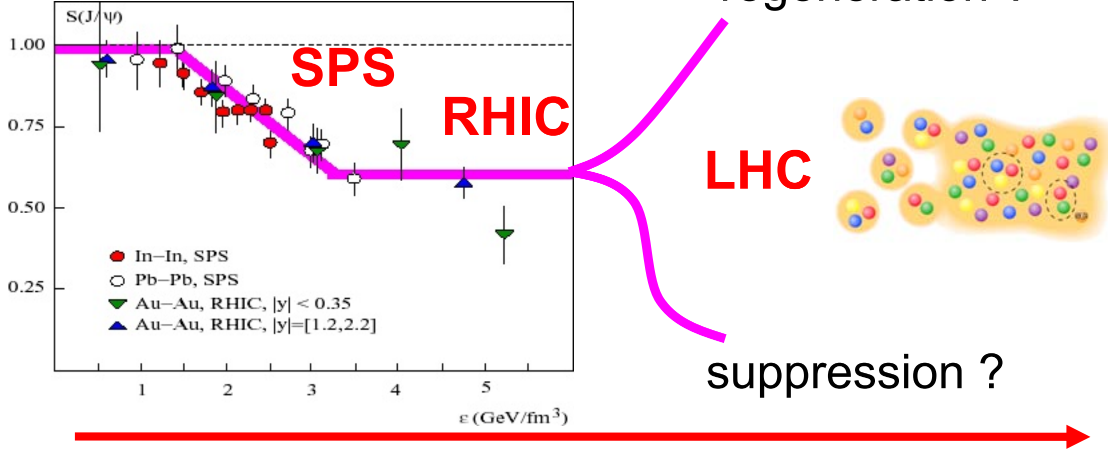


best LHC dimuon mass resolution.

S/B~4.5

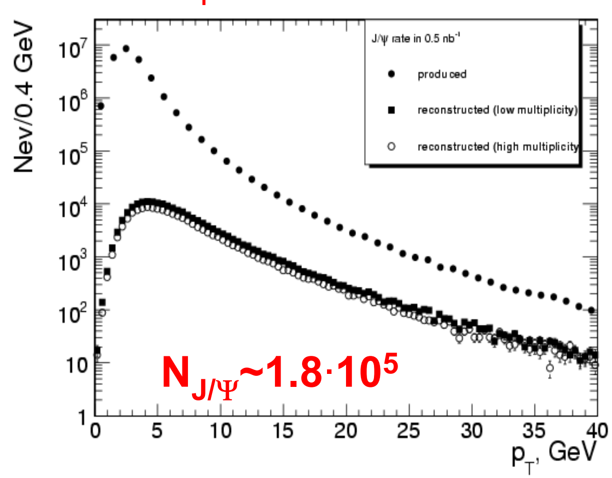
- Physics reach:

regeneration ?



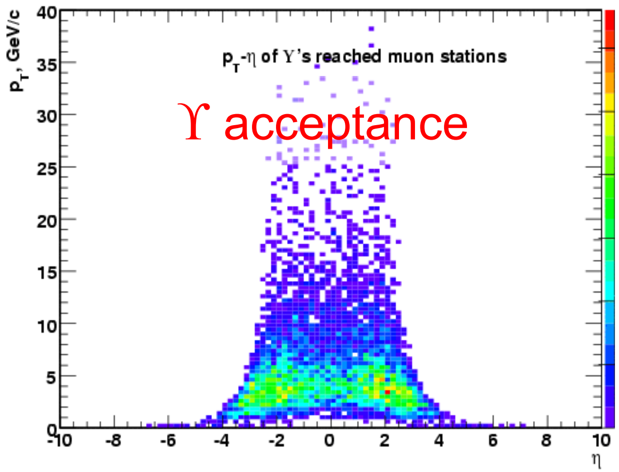
Energy Density

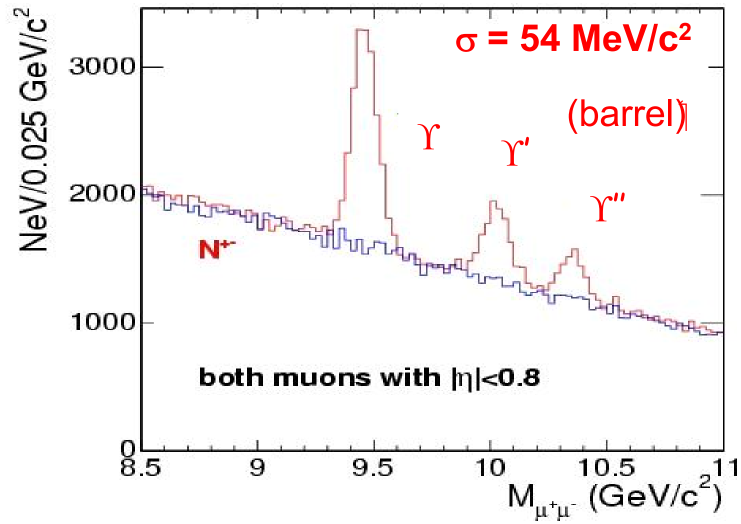
p_T reach [0.5 nb^{-1}]



Υ suppression(?): critical energy density

- Reconstruction performances :



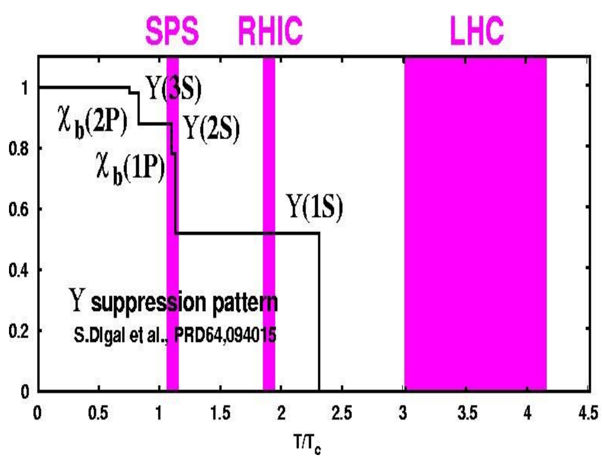


best LHC dimuon mass resolution.

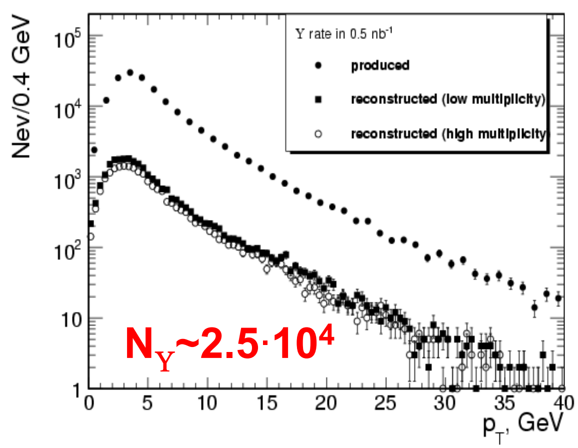
S/B~1.

- Physics reach:

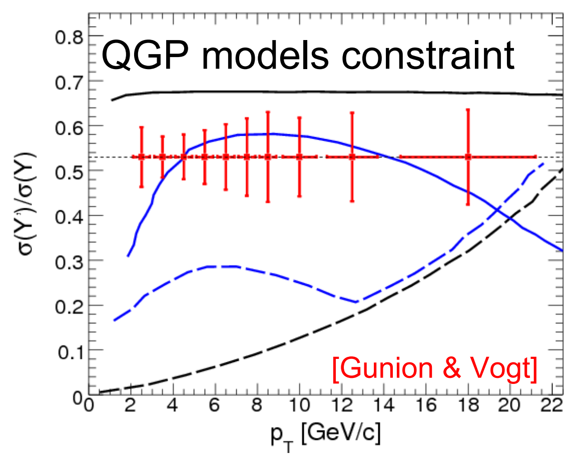
Υ spectroscopy (seq. suppression)



p_T reach (0.5 nb^{-1})

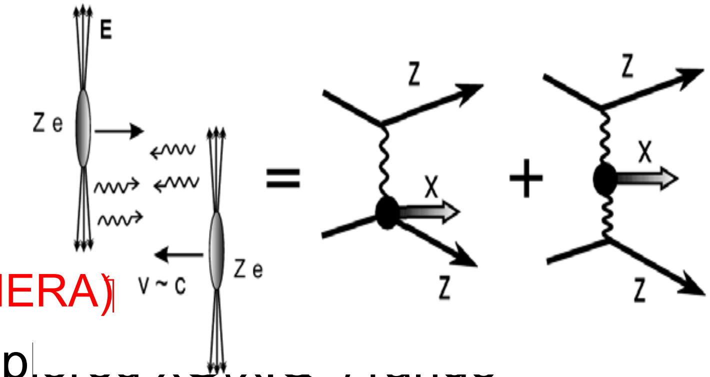


Υ′/ Υ stat. reach (HLT)



UPC γ Pb→ϒ+Pb: low-x gluons

- High energy heavy-ions produce strong electromagnetic fields due to coherent action of Z = 82 protons:



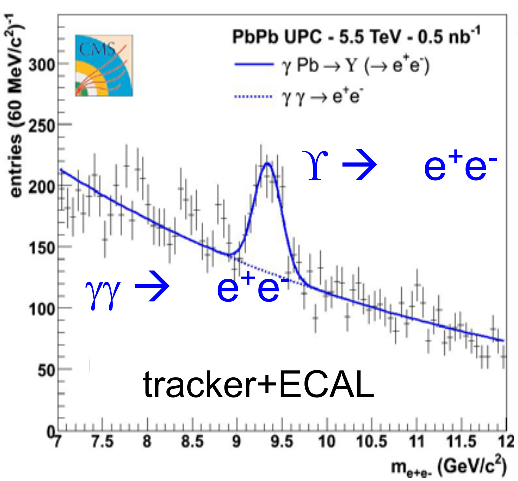
- Equivalent flux of photons in UPCs:

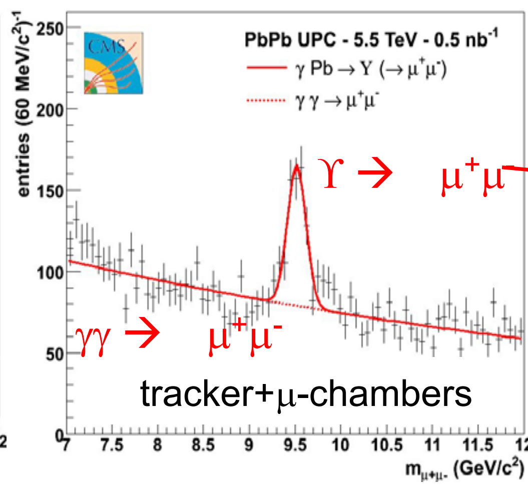
  $E_{\gamma max}$ ~ 80 GeV (PbPb-LHC)

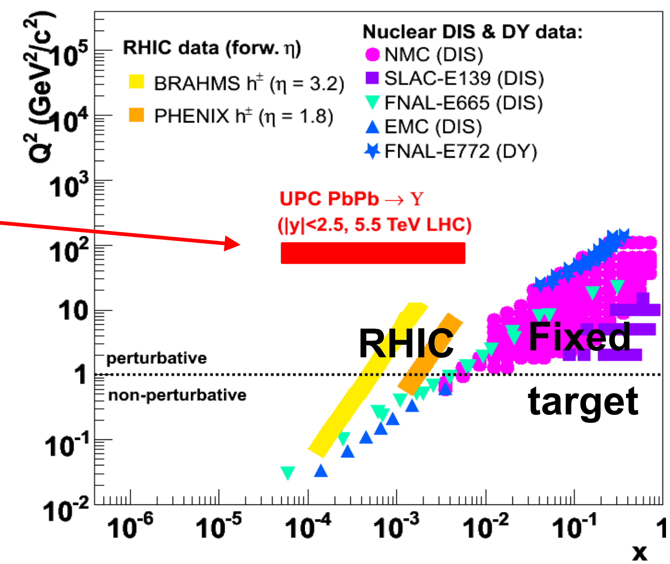
  γ Pb: max. $\sqrt{s_{\gamma Pb}} \approx$ 1. TeV ≈ 3. – 4. × $\sqrt{s_{\gamma p}}$(HERA)

- ϒ photoproduction (~500 ϒ/0.5 nb^{-1}): unexplored $xG(x,Q^2)$ range

  $\gamma\gamma$: max. $\sqrt{s_{\gamma\gamma}} \approx$ 160 GeV ≈ $\sqrt{s_{\gamma\gamma}}$ (LEP)

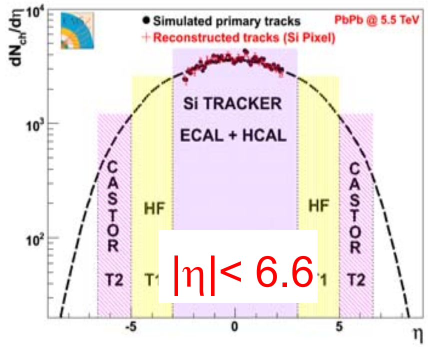




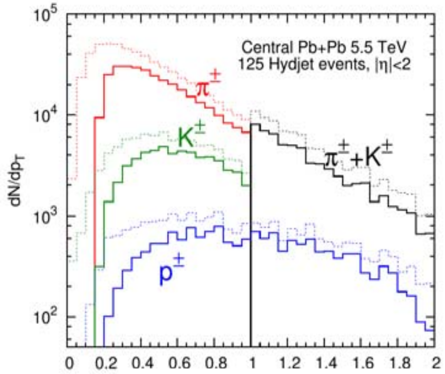


Summary: QCD matter with CMS @ LHC

multiplicity: entropy

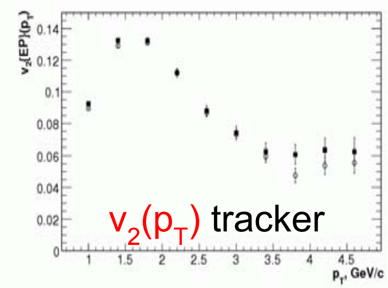


soft spectra: EoS

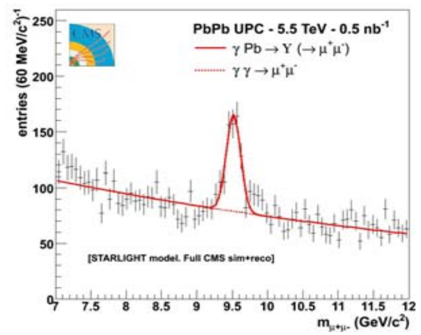


[$0.2<p_T<2$ GeV/c]

v_2: QGP viscosity

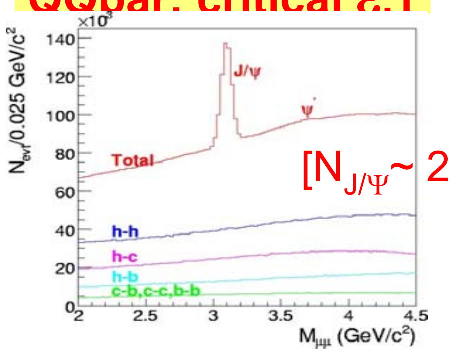


UPC: low-x gluons

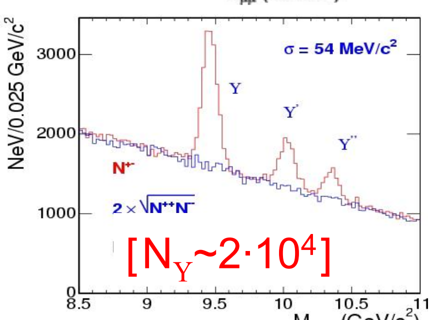


[N_{Υ}~500]

QQbar: critical ε,T

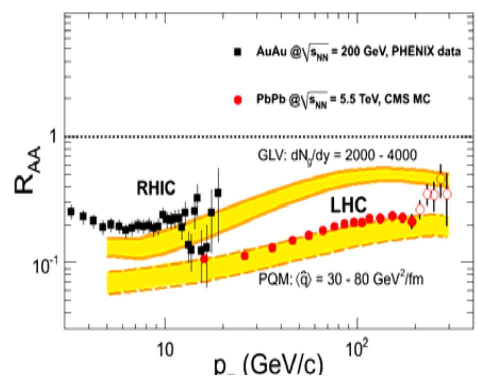


[$N_{J/\Psi}$~ $2\cdot10^5$]

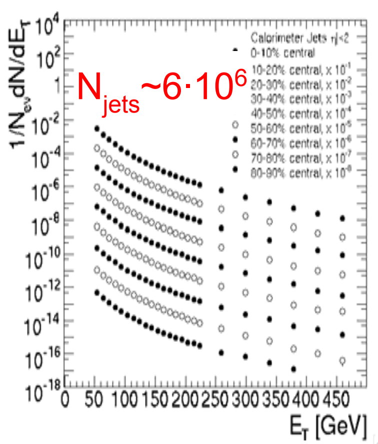


[N_{Υ}~$2\cdot10^4$]

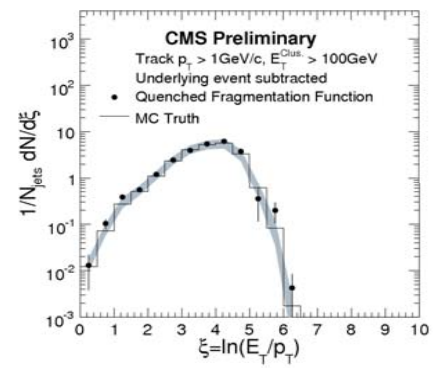
high-p_T hadrons, jets, γ - jet: ⟨q̂⟩, dN^g/dy



[p_T~300 GeV/c]



[E_T~0.5 TeV]



FFs [$0.2<\xi< 5$]

Heavy Ion Group goals for 2008

➢ CMS-HI activities around 3 main axes:

1. Fully incorporating HI software objects into CMSSW:

- Add HYDJET/PYQUEN & other HI gens. to Physics Validation & Prod. chain
- All physics objects fully available/validated/maintained in CMSSW:
  tracks, jets, muons, b-jet tagg., photons, electrons, centrality, v2, ...
- All ongoing/missing physics analyses completed:
  Z, b-jets, Z(γ^*) - jet, B-->J/ψ, D/B mesons, prompt photons, (di)electrons, ...

2. Participation to first p-p run:

- Contributions to QCD studies
- Benchmark measurements for Pb-Pb

} (dN/dη, dN/dp_T h±, jets, quarkonia, ...)

3. Detector / DAQ / Trigger (L1, HLT) readiness for Pb-Pb:

- Confirmation of detector/DAQ functioning/configuration (tracker, calorimeters, muon spectrometers, ...) under expected Pb-Pb conditions
- Finalize L1 & HLT trigger-menus for Pb-Pb.

HI reco algorithms / physics-objects

Algorithm development, commissioning, validation, tag, performance:

- Tracking / Vertexing (low & high p_T)
- Jets: Pileup subtraction with different jet finders
  JetPlusTrack (JPT)
- Muons (L3 & offline reconstruction)
- b-tagging
- Photons
- Reaction-centrality
- Reaction-plane/v2
- …

HI Physics analyses

The priority is to finalize ongoing analyses:

- dN/deta
- QQbar porting to CMSSW
- $Z \rightarrow \mu\mu$
- b-jets
- $B \rightarrow J/\psi$
- $Z(\gamma^*)$ - jet
- Direct photons
- Cosmic-rays
- ...

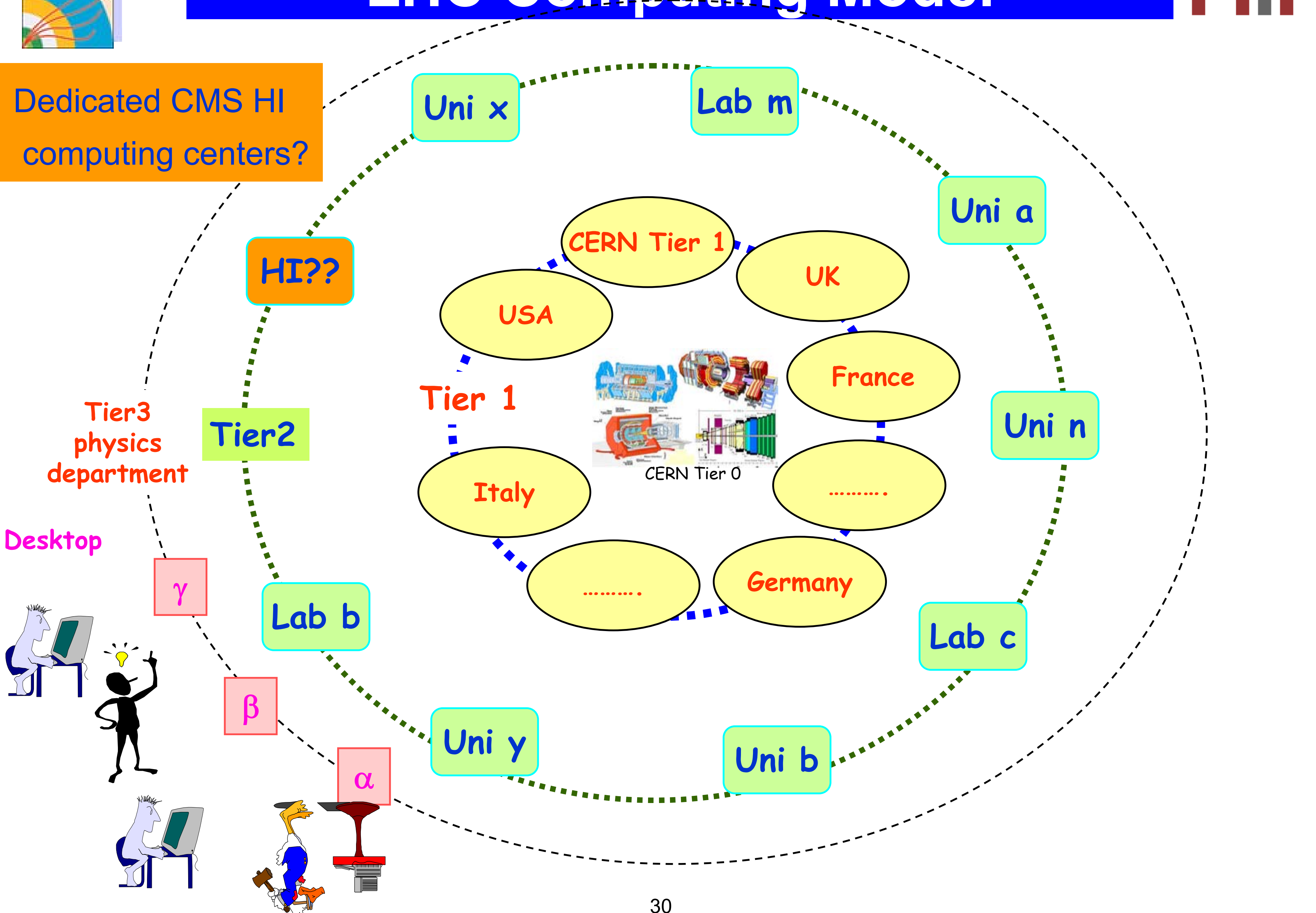
Detector preparation for HI

- DAQ
  - need to reestimate maximal occupancy for subdetectors tracker/ECAL/HCAL/Muons
  - evaluate with DAQ-team the bottlenecks
  - estimate maximal possible rate through DAQ to online farm
- Online
- Trigger
  - check needed paths in L1 and HLT
  - timing issues for L3 muon trigger

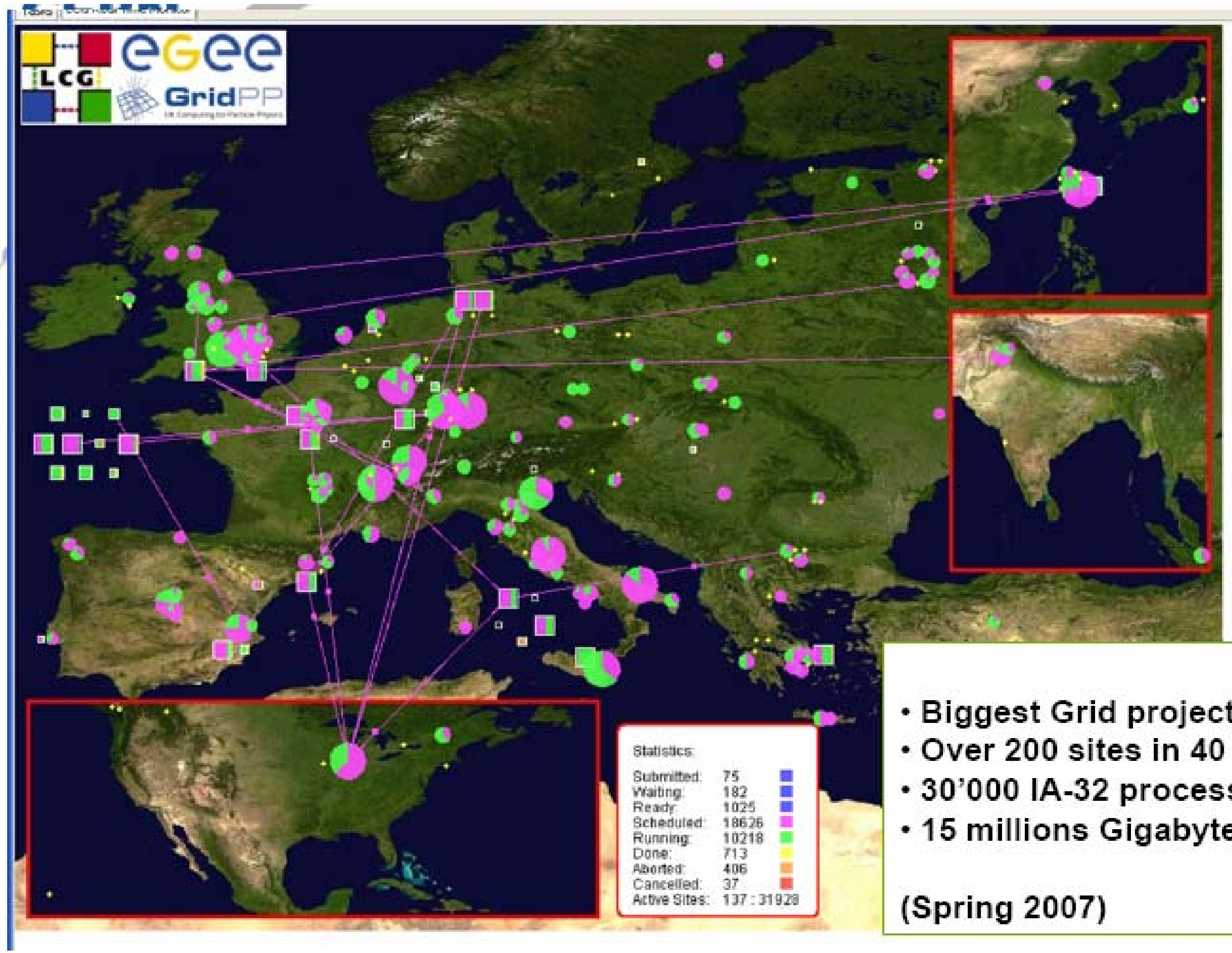
And always: Computing

- We will need a lot of CPU and disk space to conduct preparations of heavy-ion trigger algorithms and data reconstruction while taking and analysing pp data
- Good progress in making the heavy-ions software usable in the overall CMS framework
- Planning to run on the grid using standard CMS job handling tools
- Worldwide collaboration possible: it takes some effort to get started..

LHC Computing Model



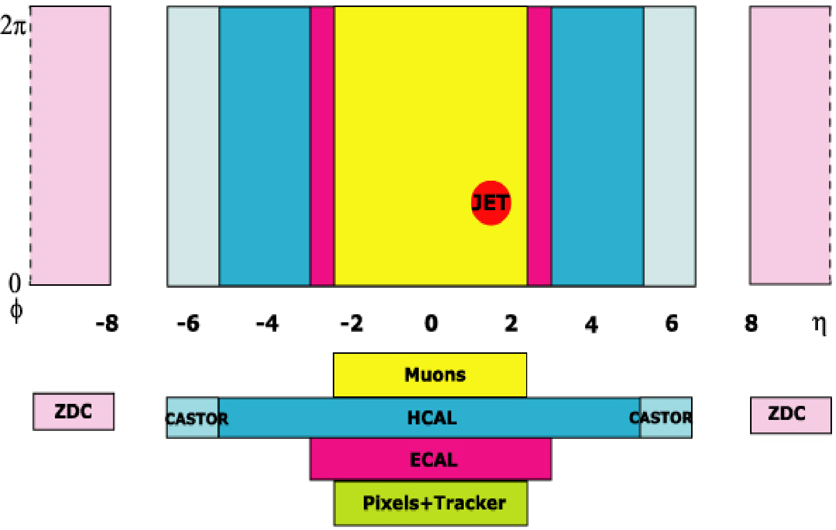
LHC Computing Grid



- Biggest Grid project in the world
- Over 200 sites in 40 countries
- 30’000 IA-32 processors (w/Linux)
- 15 millions Gigabytes storage

(Spring 2007)

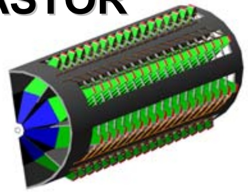
Advantages of CMS over other HI experiments



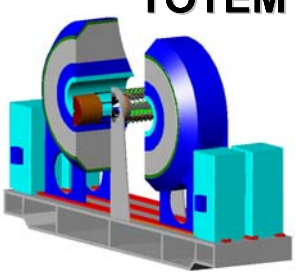
- Hermeticity, Resolution, Granularity
  - Central region: tracker, electromagnetic and hadronic calorimeters and muon detector
  - Excellent muon and charged track momentum resolution
- Forward coverage
  - Calorimeters extend to $\Delta\eta\approx10$
  - Proposed CASTOR calorimeter to $\Delta\eta\approx13$
- High data taking speed and trigger versatility
  - Two-level trigger
  - Ability to "inspect" every heavy ion event on the High Level Trigger computer farm

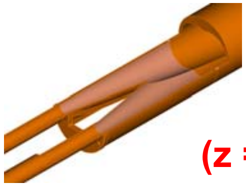
(5.32 ≤ η ≤ 6.86)

CASTOR



TOTEM





(z = ±140 m)

ZDC

CMS vs. ALICE

- Exceptional acceptance, hermeticity and resolution
  - Calorimeters: $\Delta\phi=2\pi$, $\Delta\eta=10$ (13 with CASTOR), high granularity and energy resolution
  - Tracker: $\Delta\phi=2\pi$, $\Delta\eta=5$, $\Delta p_T/p_T<1\text{-}2\%$
  - Muons: $\Delta\phi=2\pi$, $\Delta\eta=5$, $\sigma_{M\Upsilon}$ ~50 MeV
- Simple and fast DAQ
  - Triggering flexibility
- Unique HI measurements in hard-sector (starting at Day-0):
  - Fully reconstructed jets, high-p_T hadrons up to 200 GeV, Υ spectroscopy at y=0 (hot&dense medium), Z^0, ...
- While covering basic global/soft-sector observables:
  - Centrality determination
  - Multiplicity, elliptic flow
  - Some low p_T capabilities with π/K/p particle ID
- *Note: ALICE has more extensive low p_T particle ID capabilities*

CMS vs. ATLAS

- Very similar physics goals
- Very similar detector configuration
- Detailed performance advantages
  - Better muon resolution
  - Better charged particle tracking: more layers, pulseheight resulting in better resolution and fewer fakes
  - Simpler and more powerful DAQ/trigger
  - Unique forward detector coverage (ATLAS has no effective coverage within $5<|\eta|<8$)
  - *Note: ATLAS has possibly better calorimetry due to longitudinal segmentation*
- Longer heavy-ion tradition within collab.: HI physics included in all CMS reports starting from first proposal. Stronger HI groups continuously working since 1994.

Physics Plan

- Comprehensive heavy ion physics program with emphasis on hard probes
- Program follows increasing luminosity
  - Continuously extend p_T range
  - New probes
  - Increase level of precision and detail
  - Tighten and optimize trigger
- Pb+Pb for the first few years, expect other ions and p+Pb later

Calendar Year	Physics (known physics)	Total Υ on tape
2008	Preparations: HLT, Reconstruction, first p+p physics at low energy	0
2009	Reference p+p, global observables, jets E_T<200 GeV, charged particle spectra, first dimuon events,	0.3 k
2010	Centrality and event plane dependence of global obs., charged particle spectra to 200 GeV, multi-100 GeV jets, open b,c, first quarkonia	10k
2011	Detailed jet fragmentation studies, multi-jets, quarkonia physics, first tagged jet studies, detailed open b,c studies	30k
2012	Extensive studies of rare channels, centrality, event plane dependence of quarkonia, tagged jets, heavy quarks	50k
2013	Detailed studies of rare channels	70k

Summary

- CMS is getting ready for pp data this summer
- Heavy-ion specific preparations are well underway
- Tremendous excitement at CERN
- Large role for Korean collaborators: already very active
  - B physics
  - muon reconstruction
  - Computing
- Thank you very much for the hospitality!