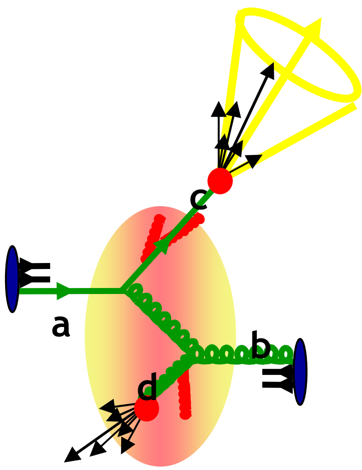
CMS Experiment at LHC: Detector Status and Physics Capabilities in Heavy Ion Collisions

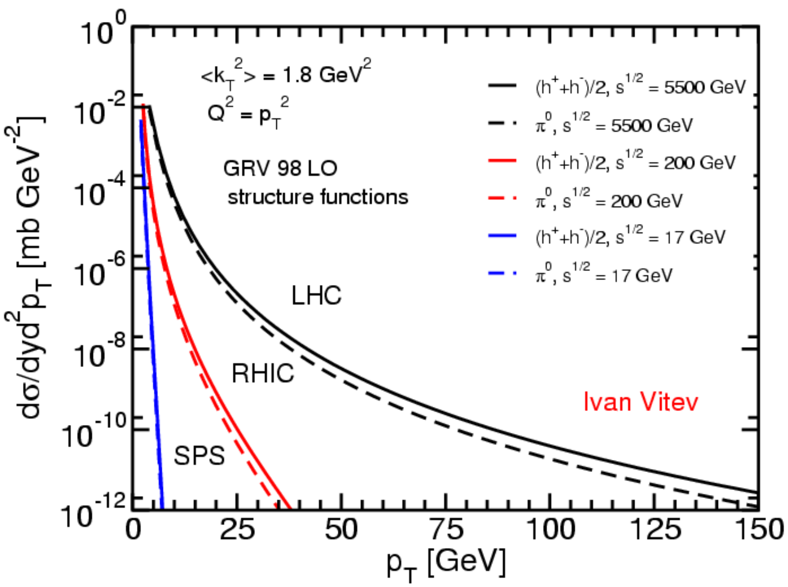


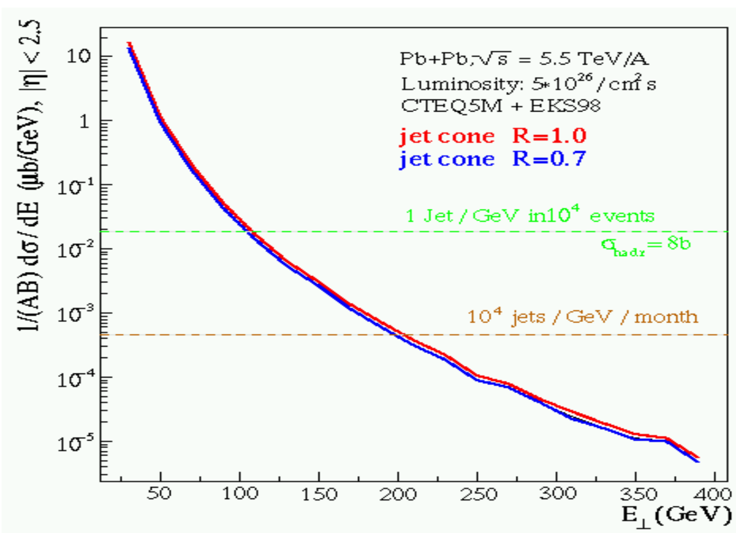
Bolek Wyslouch
Massachusetts Institute of Technology
for the CMS Collaboration

Nuclear Physics Seminar
Brookhaven National Laboratory
August 5, 2008

CMS HI groups: Athens, Auckland, Budapest, CERN, Colorado, Cukurova, Ioannina, Iowa, Kansas, Korea, Lisbon, Los Alamos, Lyon, Maryland, Minnesota, MIT, Moscow, Mumbai, Paris, Seoul, Vanderbilt, UC Davis, UI Chicago, Zagreb

Heavy Ion Physics at the LHC





Pb+Pb Collisions at $\sqrt{s_{NN}}$ ~ **5.5TeV**

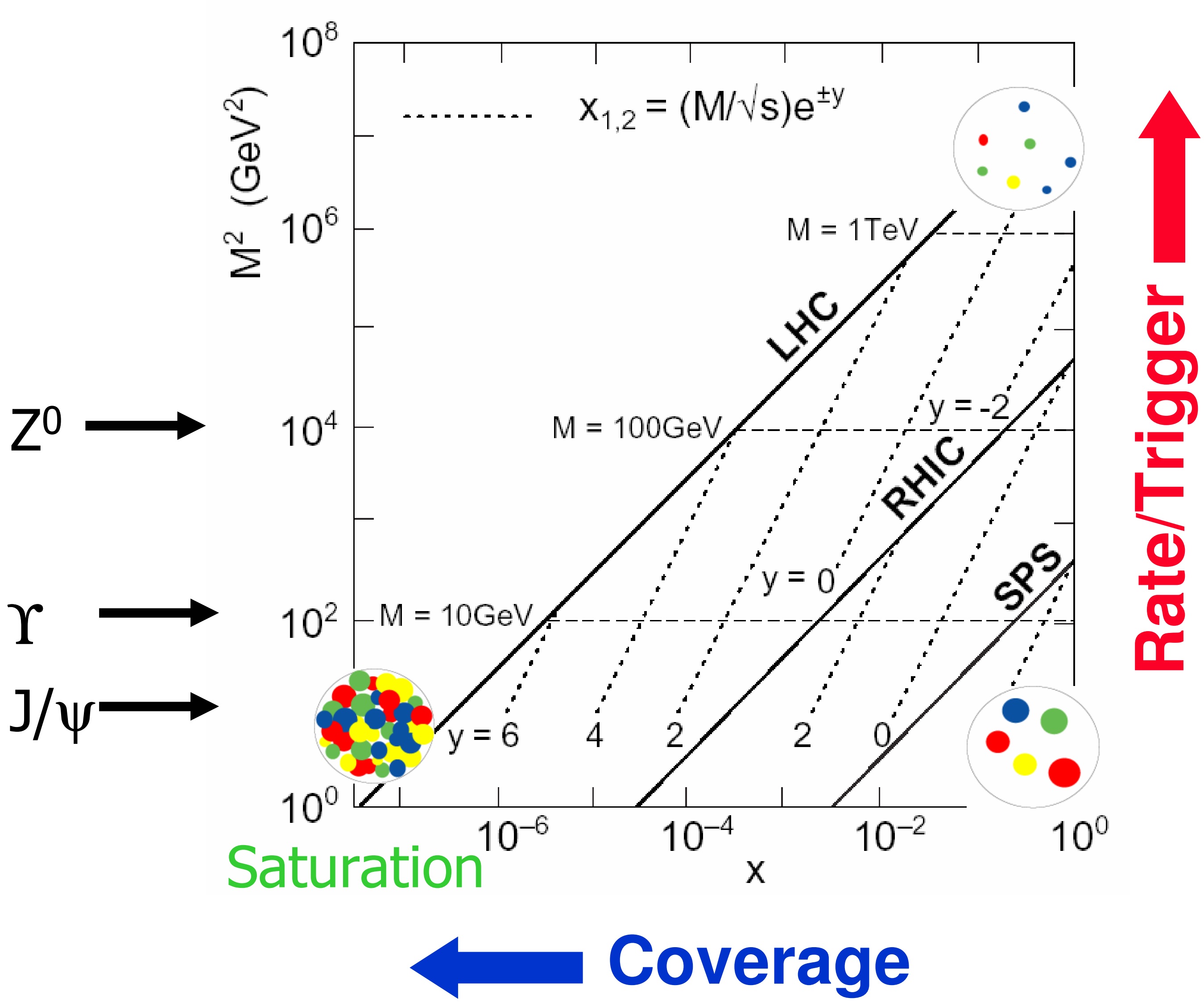
Large Cross section for Hard Probes

High luminosity $10^{27}/cm^2s$

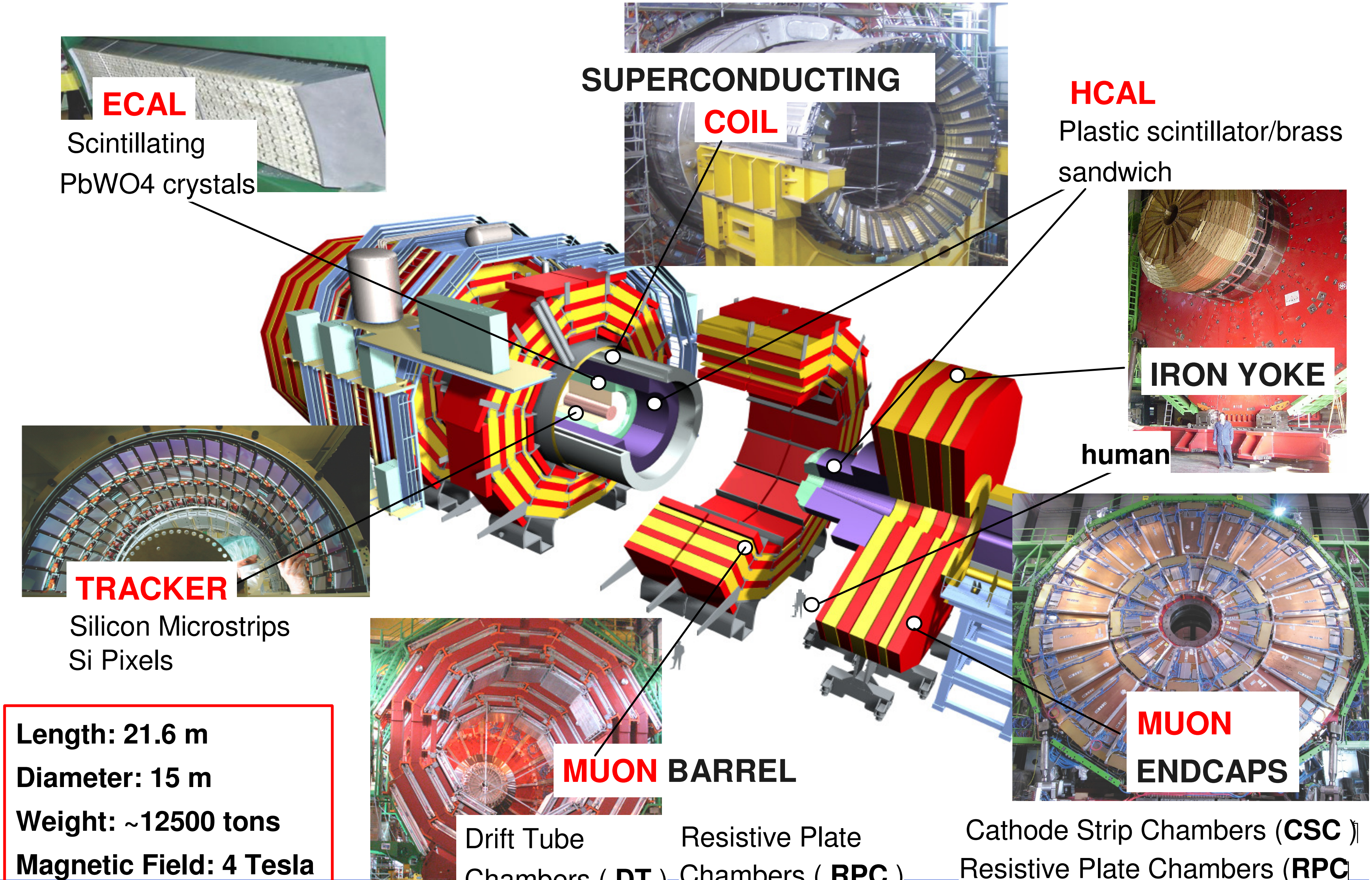
- Copious production of high p_T particles
  - Nuclear modification factors R_{AA} out to very high p_T
- Large cross section for J/ψ and ϒ family production
  - σ^{cc}_{LHC} ~ 10x σ^{cc}_{RHIC}
  - σ^{bb}_{LHC} ~ 100x σ^{bb}_{RHIC}
  - Different “melting” for members of ϒ family with temperature
- Large jet cross section
  - Jets directly identifiable
  - Study in medium modifications

Kinematics at the LHC

Access to widest range of Q^2 and x



CMS detector at the LHC



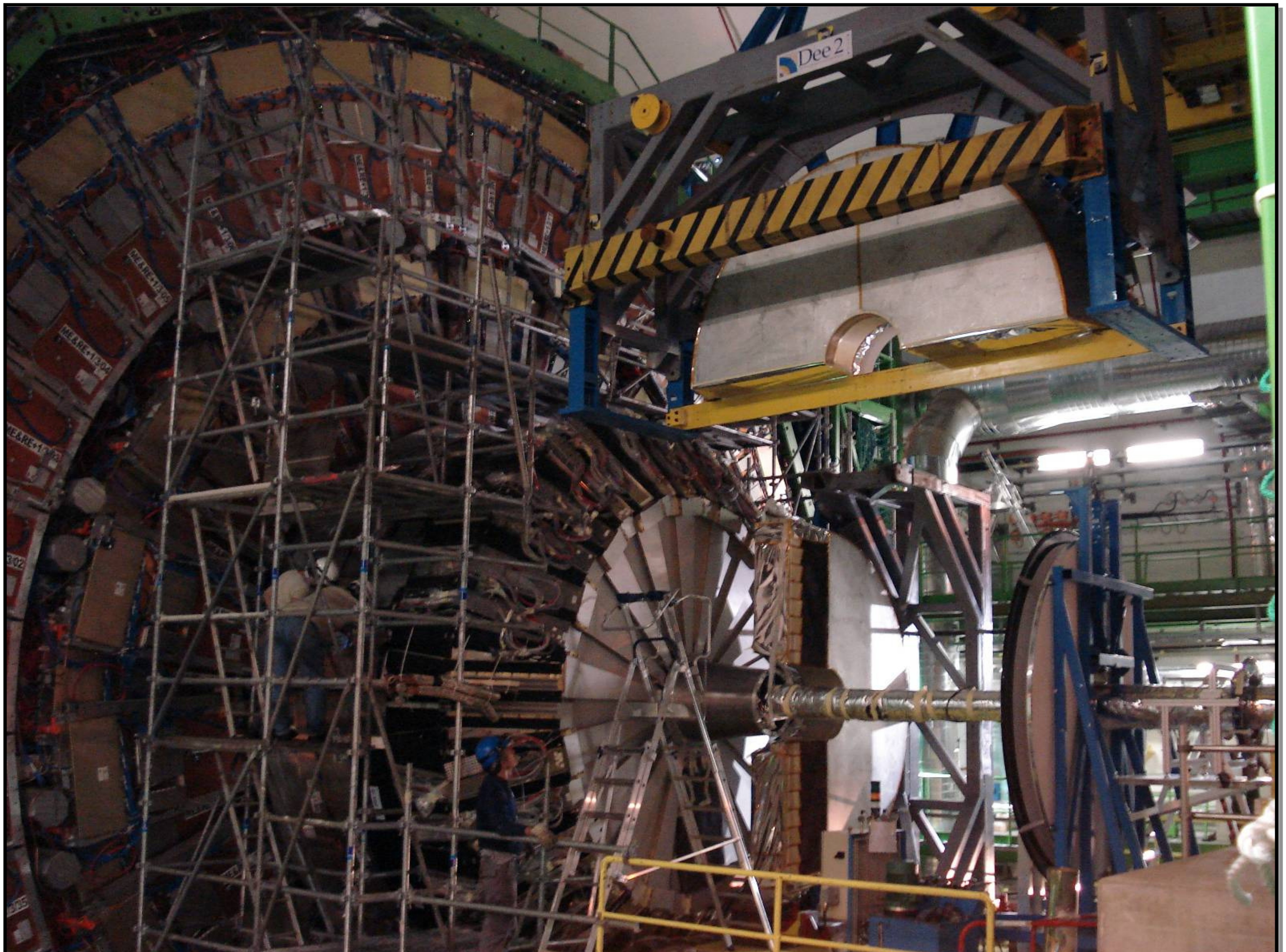
Length: 21.6 m

Diameter: 15 m

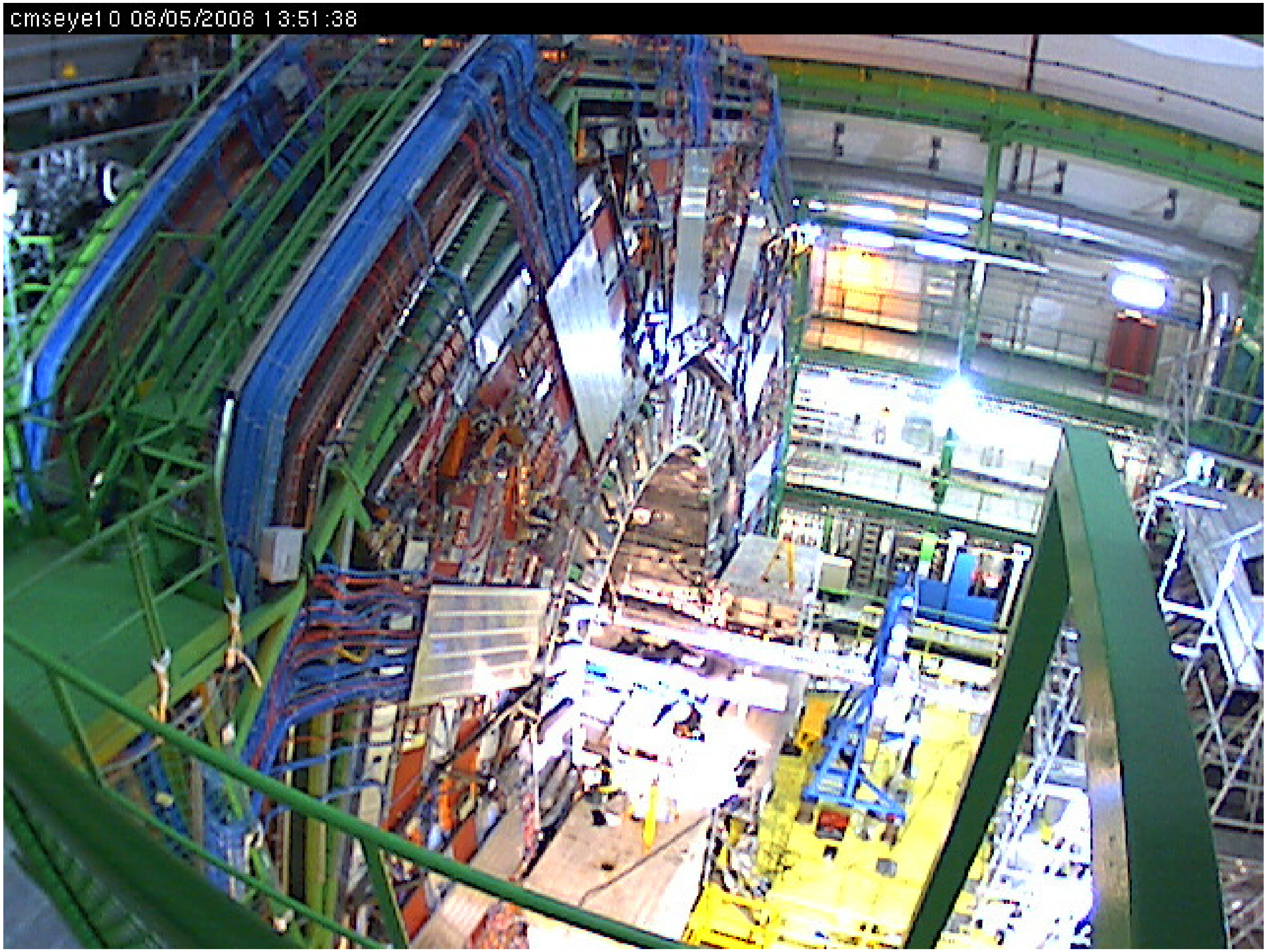
Weight: ~12500 tons

Magnetic Field: 4 Tesla

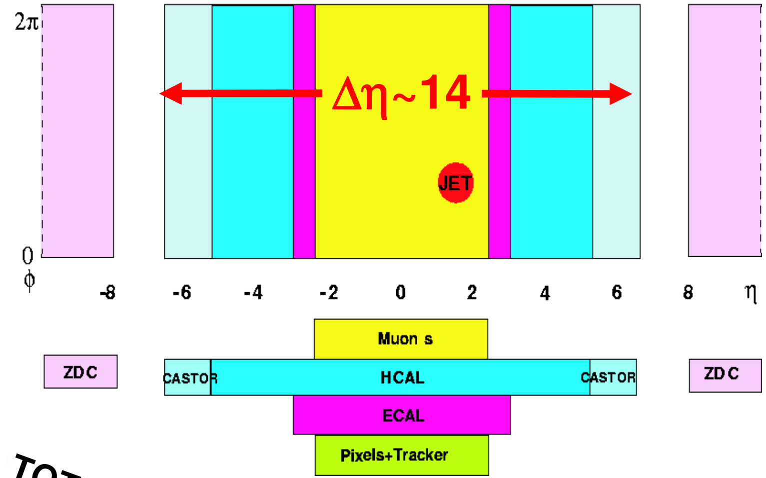
August 1, 2008: CMS is fully installed

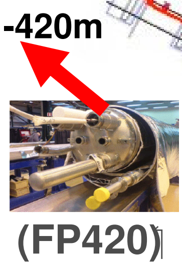


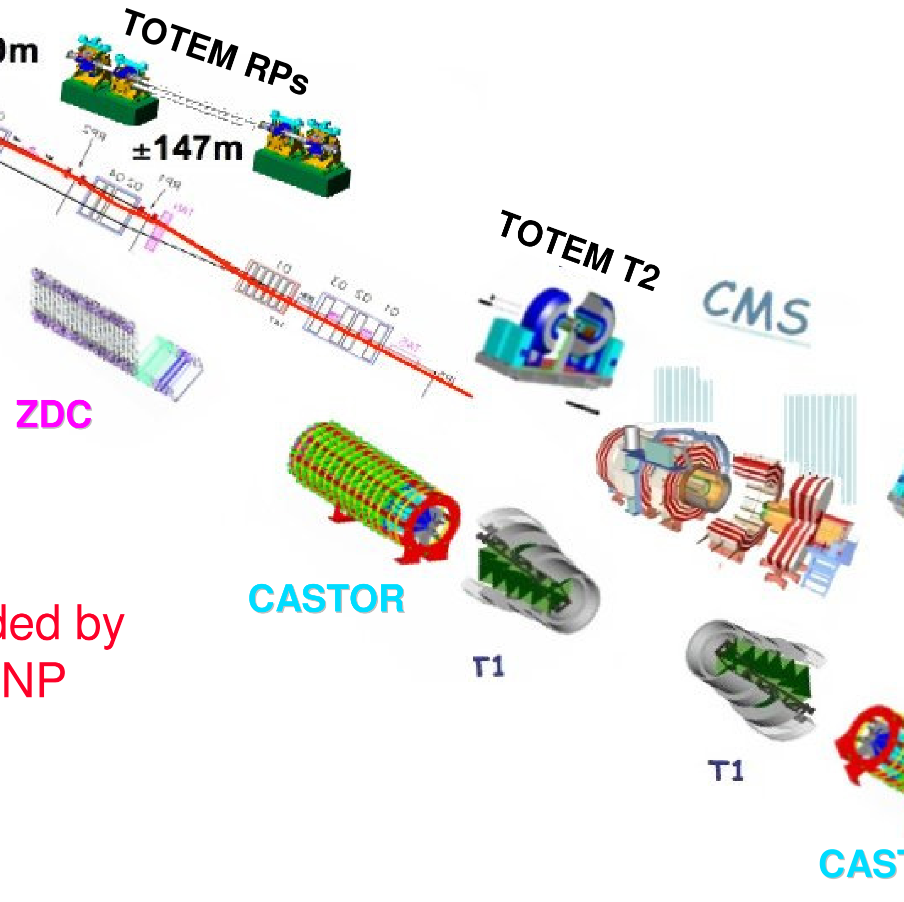
This afternoon…



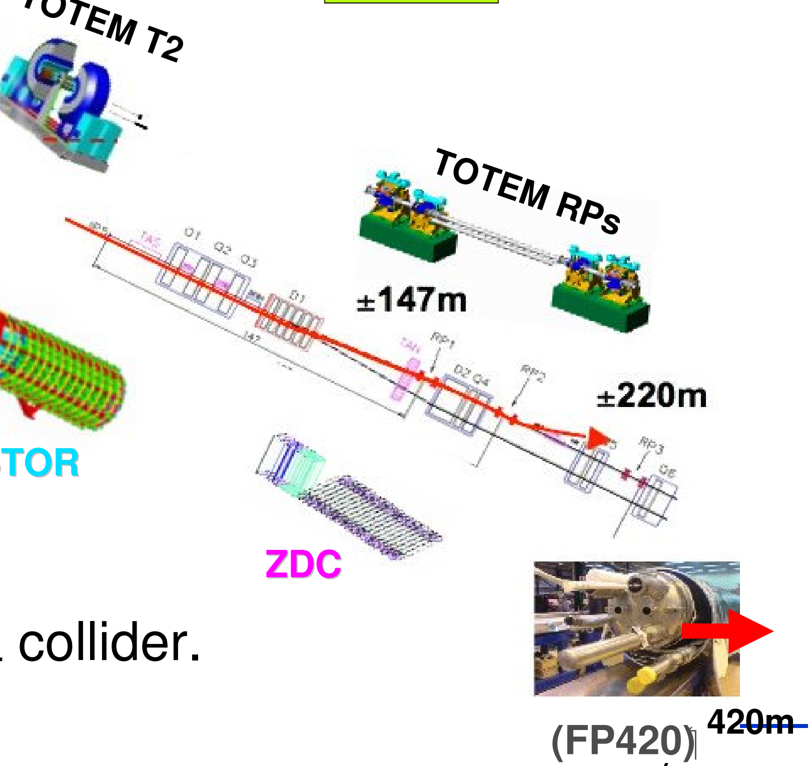
CMS detector will extend deep into LHC







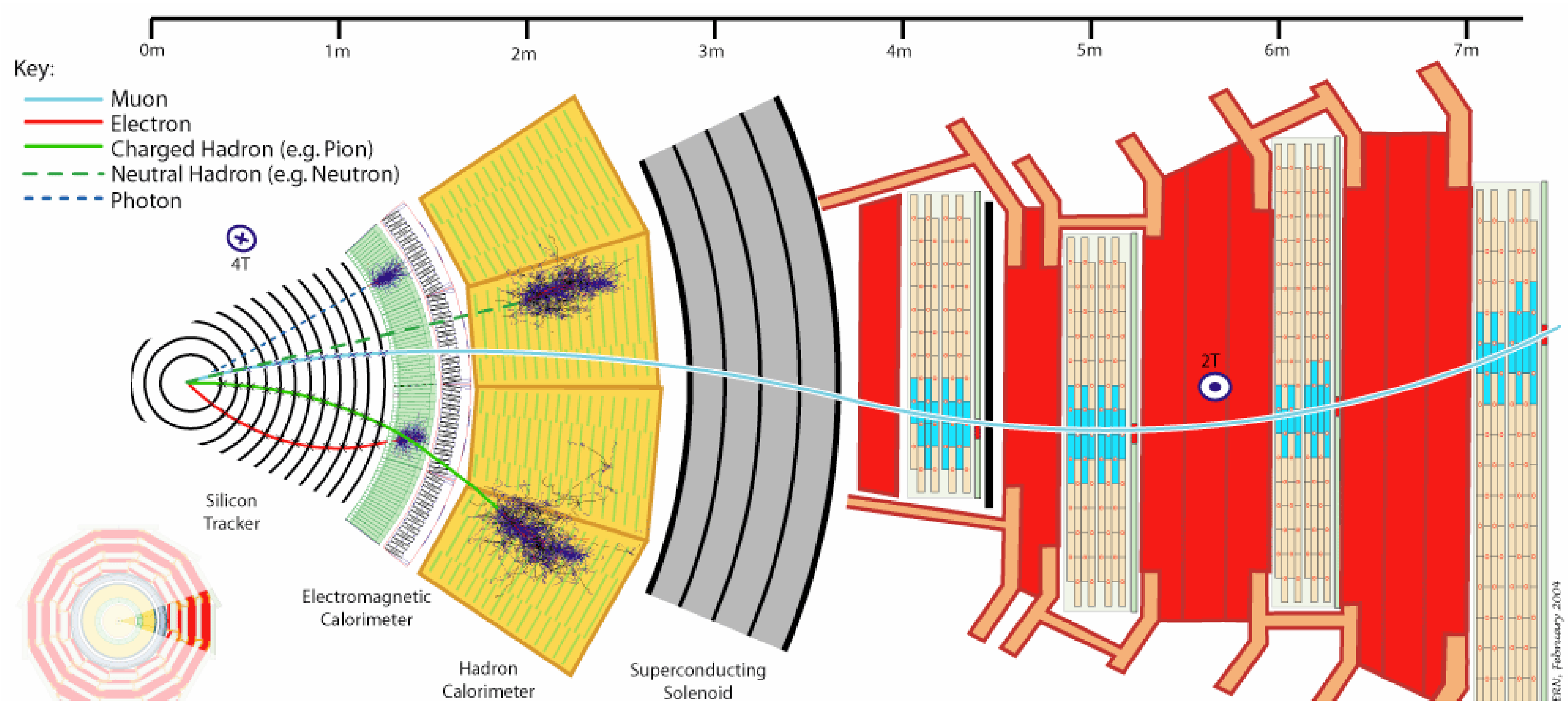
ZDC funded by
US DOE NP
& NSF



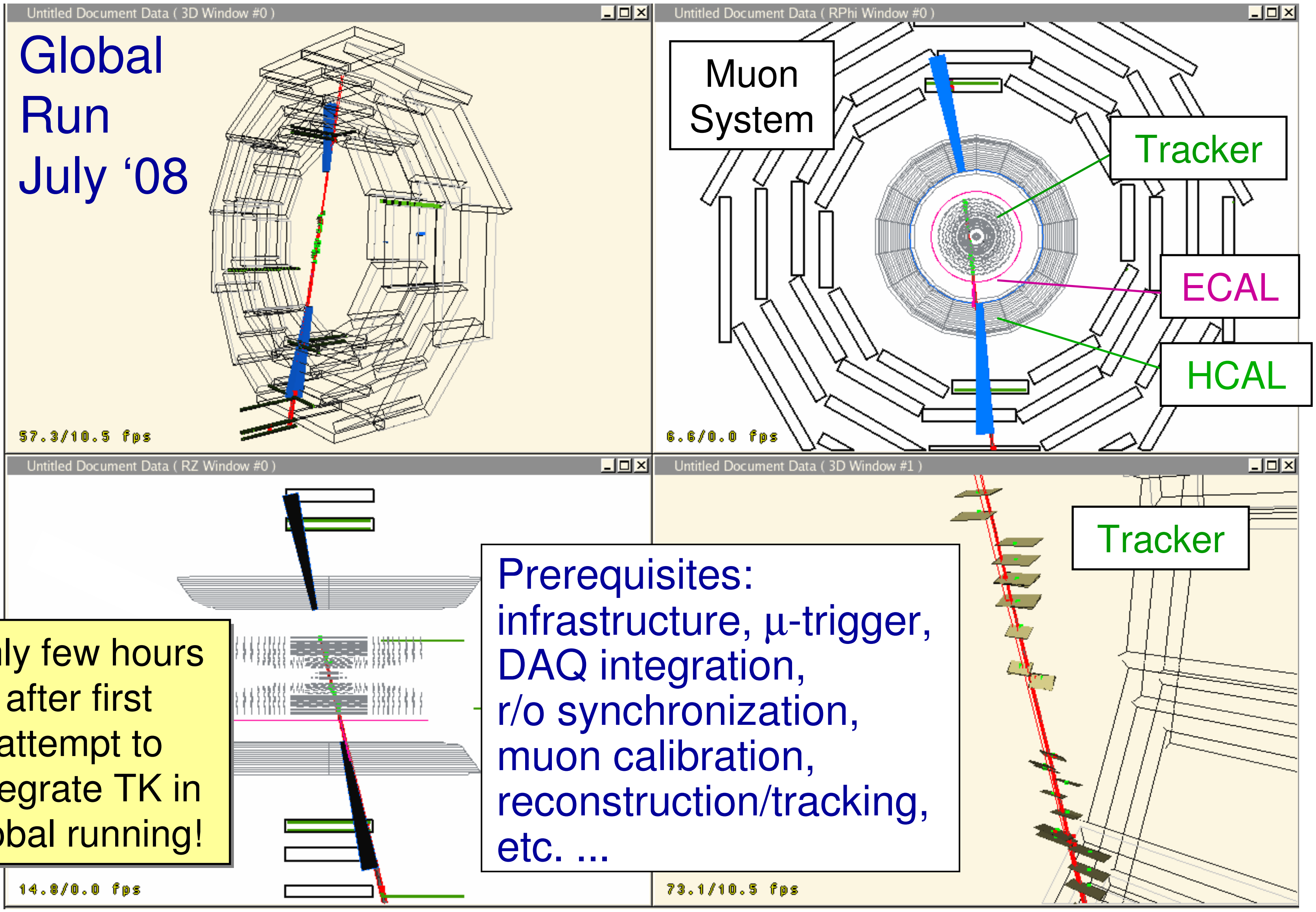
- CMS (+TOTEM):

Largest phase-space coverage ever in a collider.

Particle detection layers in CMS



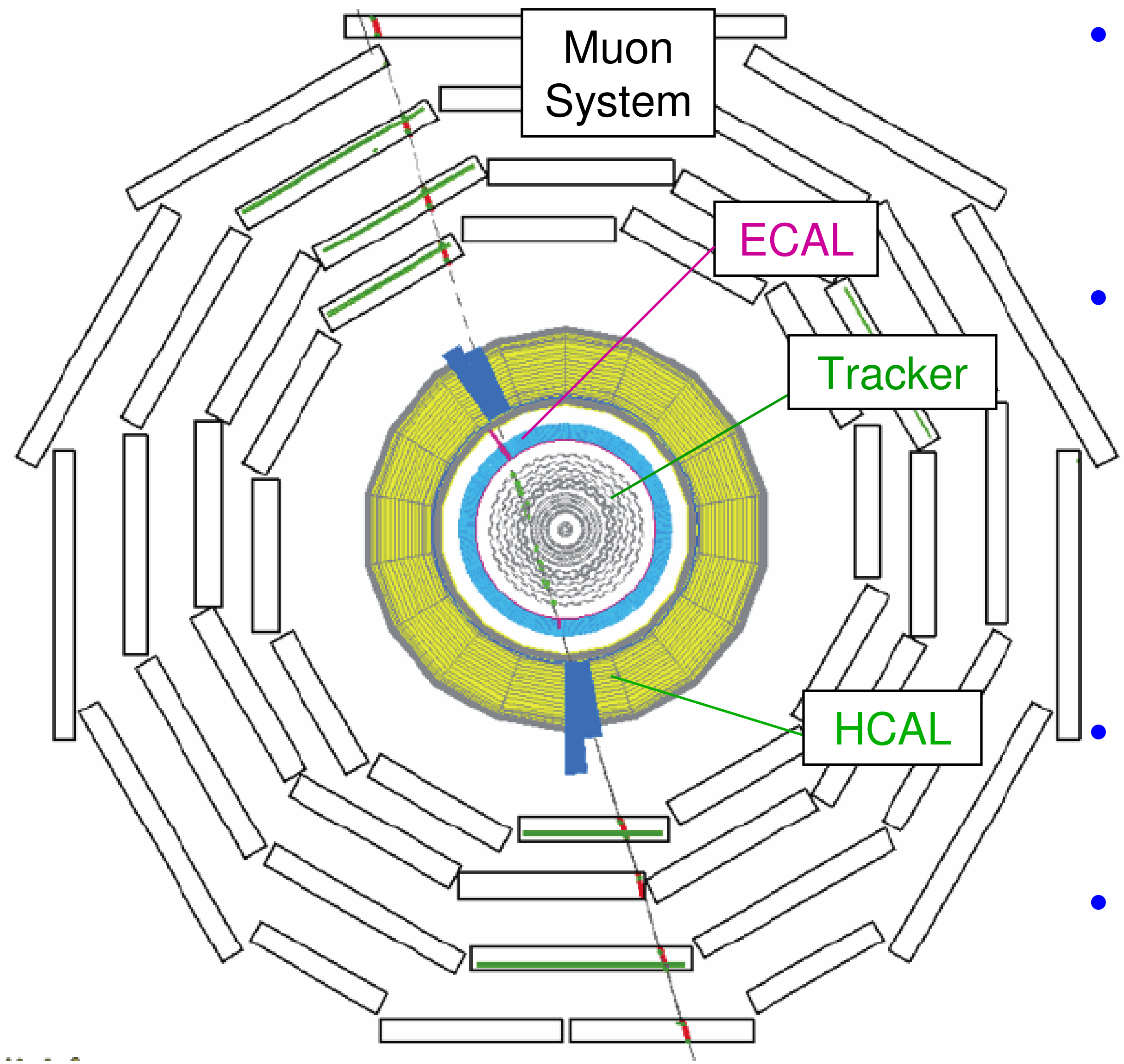
CMS is collecting cosmics..



Only few hours after first attempt to integrate TK in global running!

Prerequisites: infrastructure, μ-trigger, DAQ integration, r/o synchronization, muon calibration, reconstruction/tracking, etc. ...

CMS is collecting cosmics..

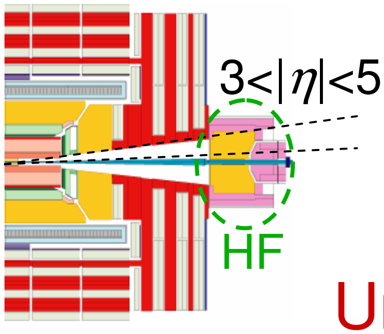


- **Di-muon Trigger:**
  - **Drift-Tube coinc. in top+bottom, each ≥ 2 station segments**
- **Muon signals traced through**
  - **muon system**
  - **Tracker TOB+TIB**
  - **ECAL**
  - **HCAL**
- **Global track fit**
- **Excellent data - being used for alignment**

Physics cases for HI@CMS

Case no.	*We will look into…*	*in order to learn about…*
0	**MB L1 trigger, centrality**	**Global event characterization**
1	**$dN_{ch}/d\eta$**	**Color Glass Condensate, $xG_A(x,Q^2)$**
2	**Low p_T $\pi/K/p$ spectra**	**Hydrodynamics, Equation of State**
3	**Elliptic Flow**	**Hydrodynamics, Medium viscosity**
4	**Hard-probes (triggering)**	**Thermodynamics & transport properties**
5	**Quarkonia suppression**	**ε_{crit}, T_{crit}**
6	**Jet "quenching"**	**Parton density, $\langle\hat{q}\rangle$ transport coefficient**

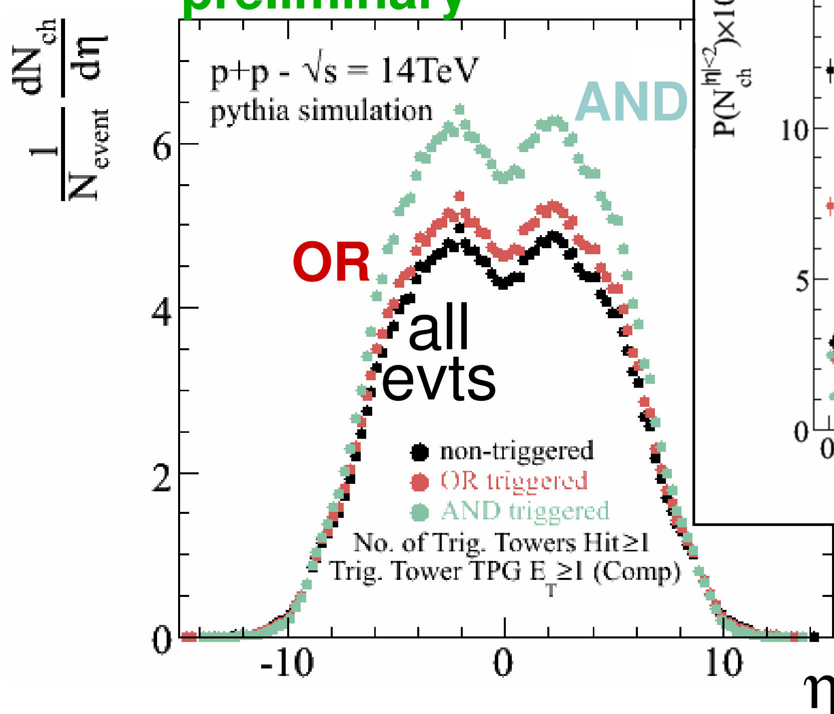
pp Minimum Bias using Forward HCAL

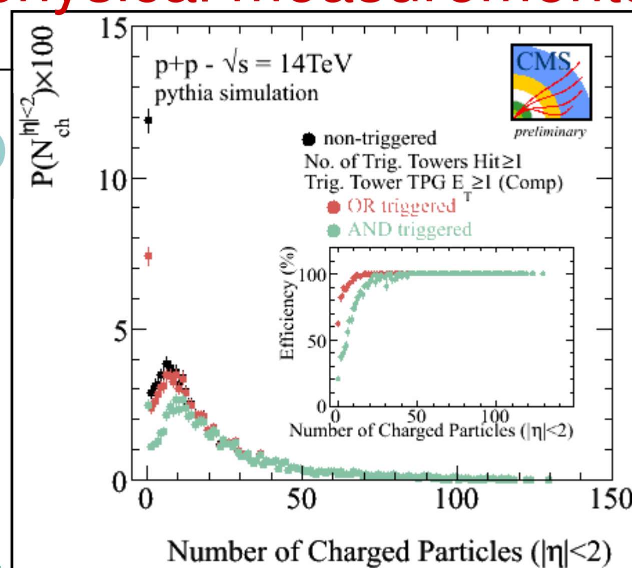


Min-bias trigger: Number of HF trigger towers over threshold > *N*:
any side (**OR**), or on both sides (**AND**) of I.P.

Unfolding the effect of HF min-bias triggering on physical measurements

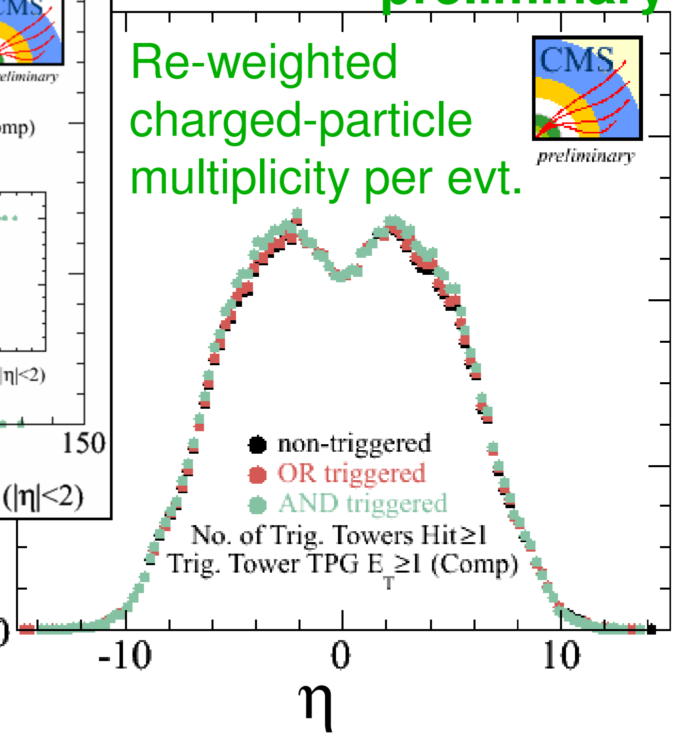
preliminary



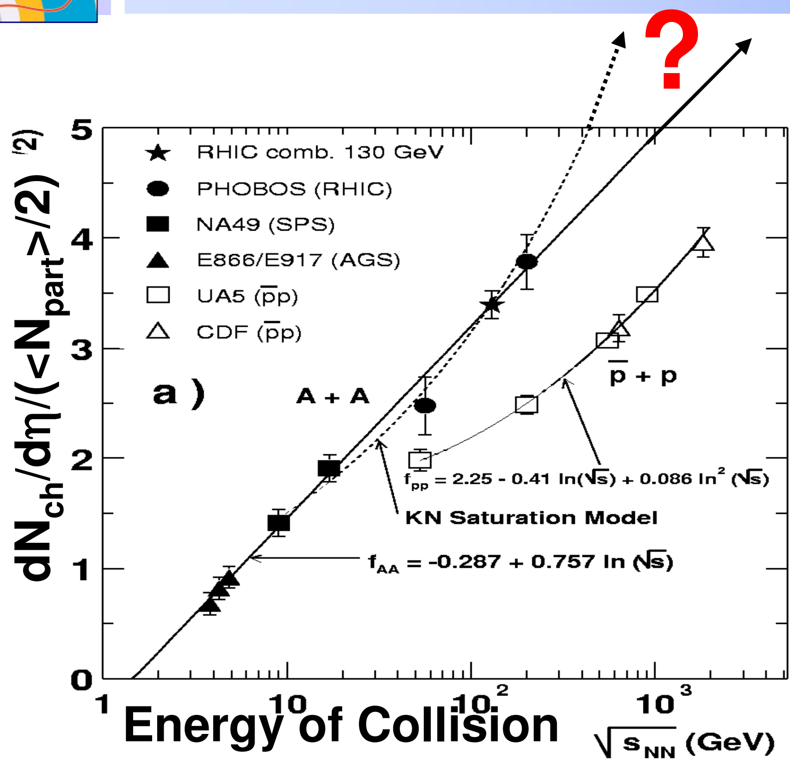


Inverse weighting

preliminary



dN/dη

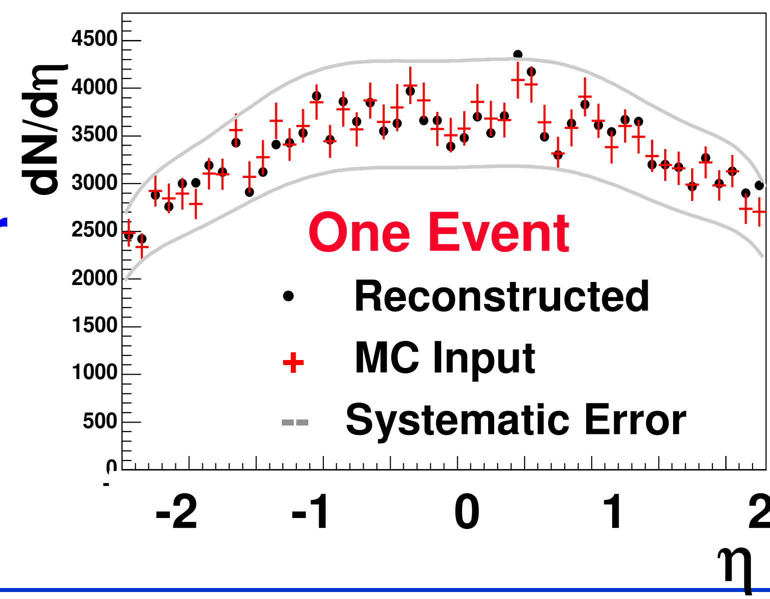


Charged Particle Multiplicities

- Predictions vary by a factor of 4!
- dN/dy ~ 1500 – 7000
- (RHIC extrapolation vs. HIJING)

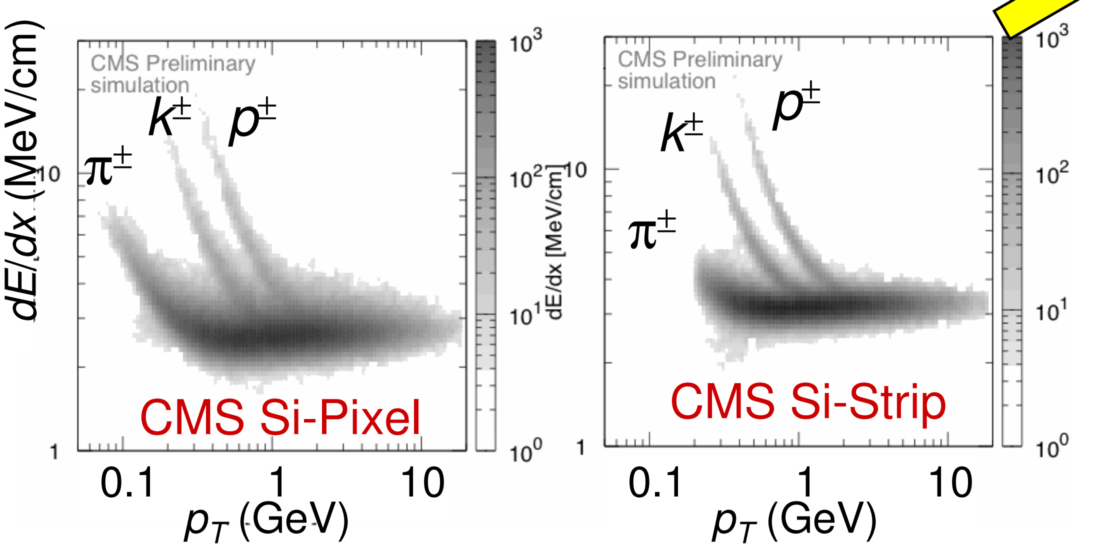
Hit counting in the first pixel layer

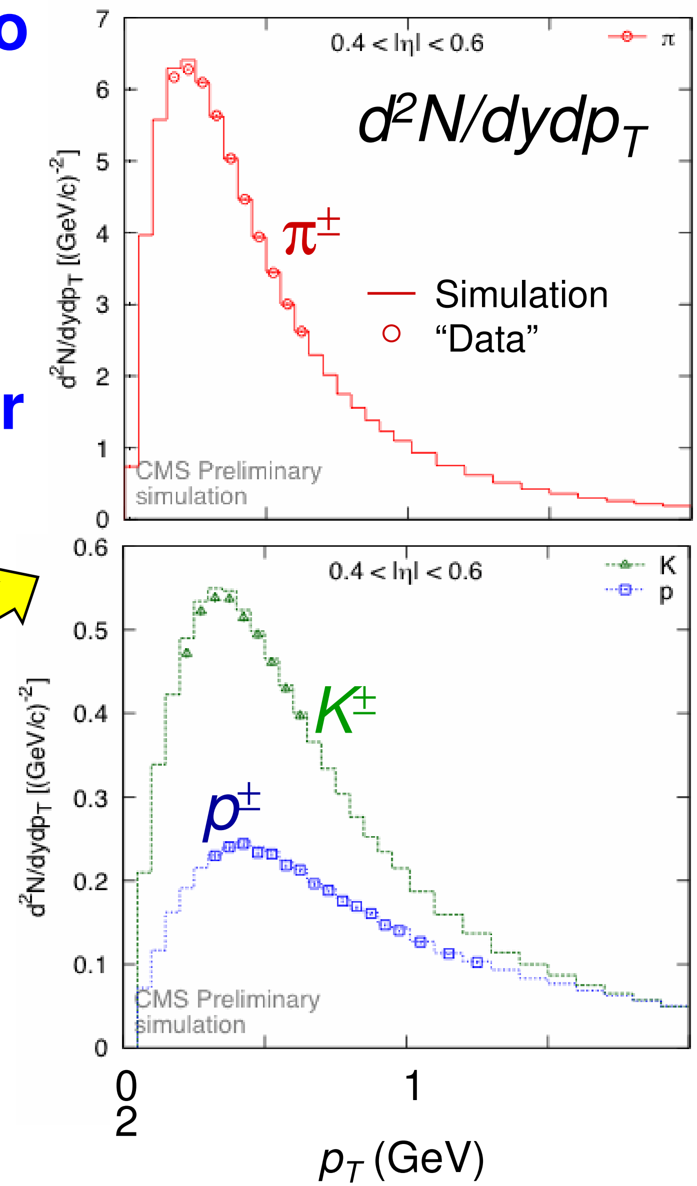
- Low p_T cutoff ~40 MeV
- Needs few events O(1000)
- Few seconds of data taking



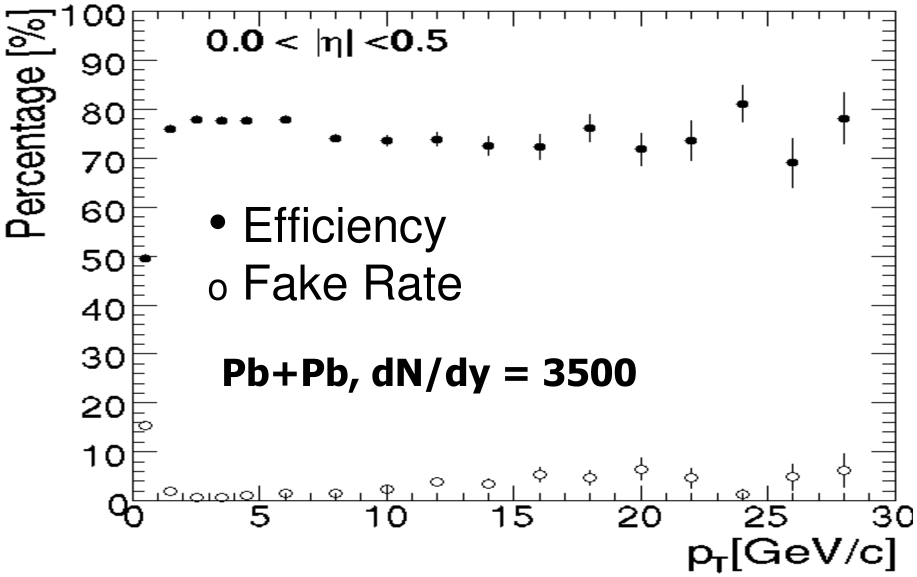
Charged-Hadron Spectra pp

- **One of the first measurements to be done: charged-hadron spectrum**
  - **Important tool for calibration, alignment & understanding of detector response**
- **Min-bias and/or Zero-bias trigger**
  - **Statistics: ~ 2 million events**

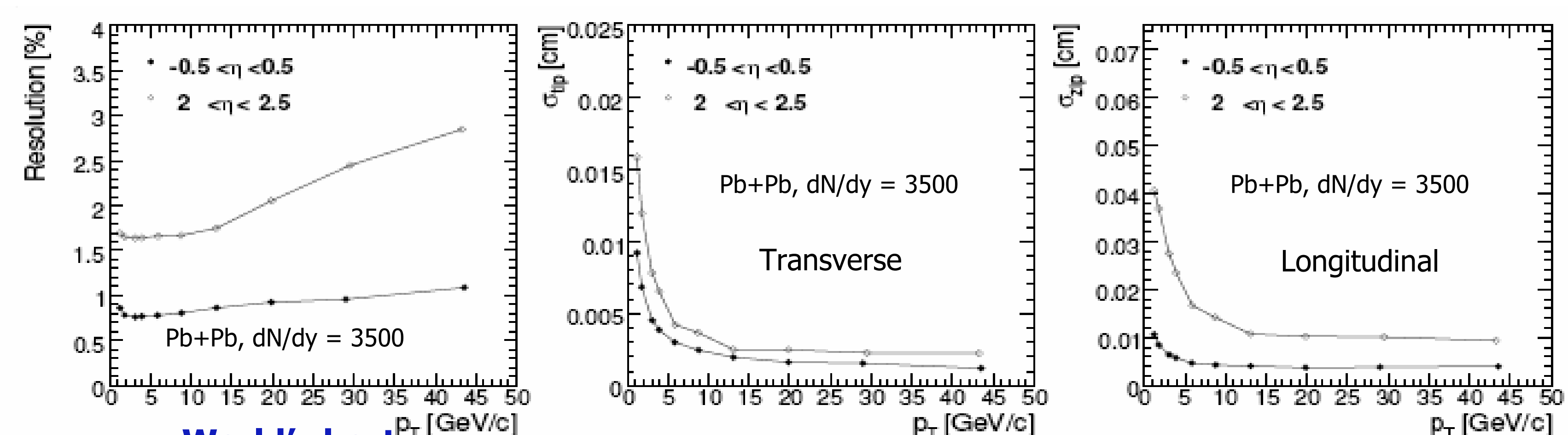




CMS Tracking Performance PbPb



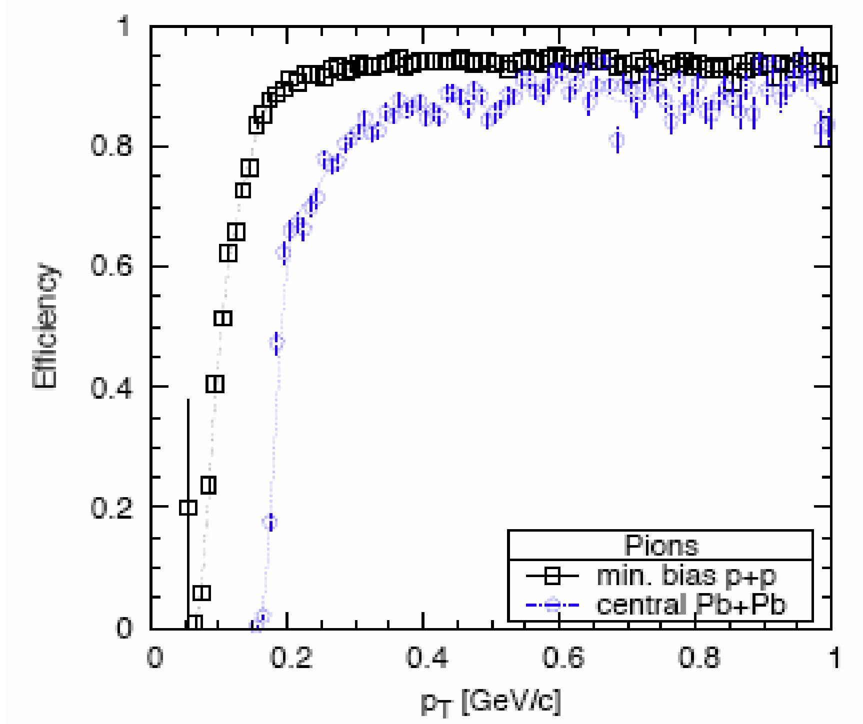
- **Occupancy in Pb+Pb**
  - **dN/dy = 3500**
  - **1-2% in Pixel Layers**
  - **< 10% in outer Strip Layers**
- **Efficiency**
  - **~75% above 1 GeV/c**

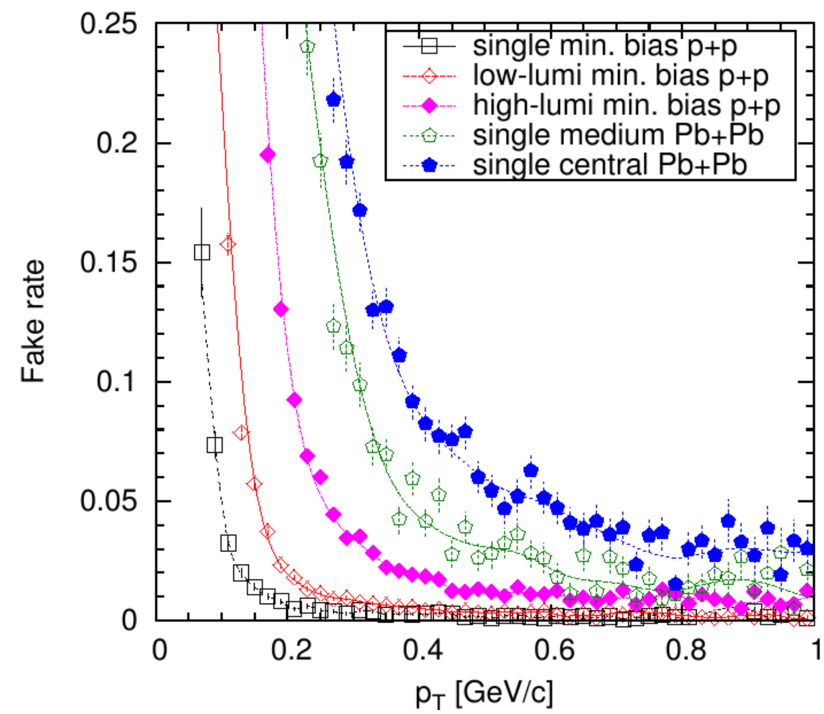


World's best momentum resolution

Excellent impact parameter resolution

Tracking at low p_T



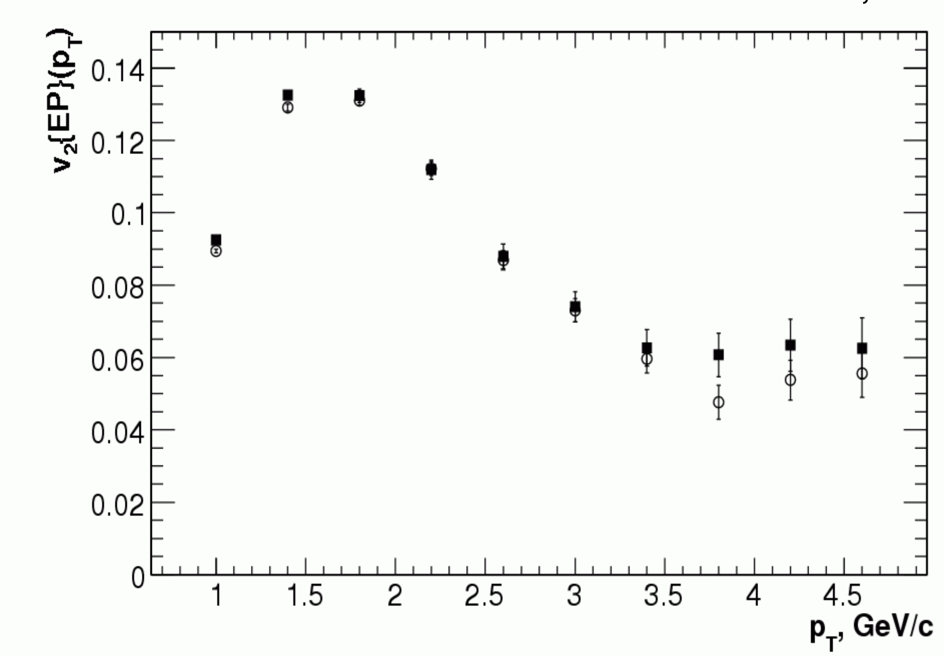


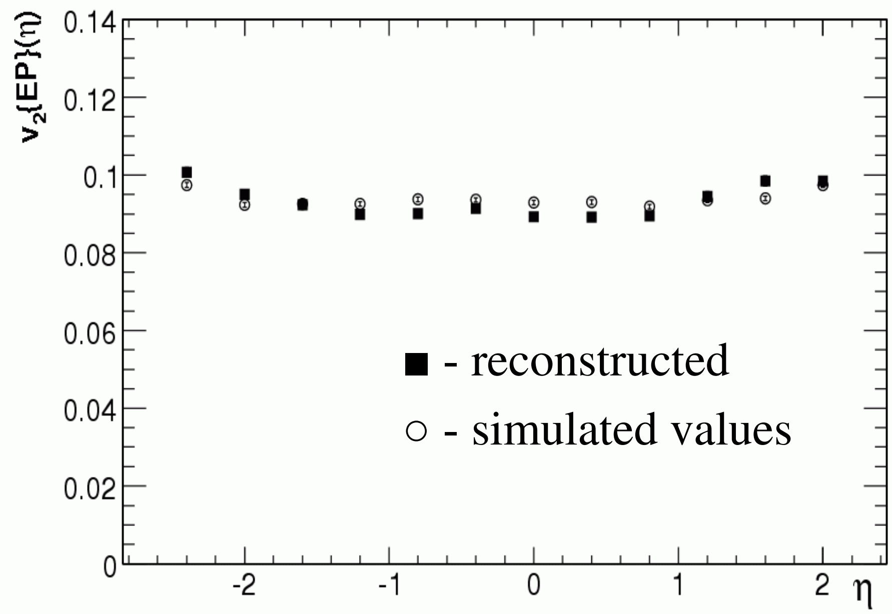
CMS HI TDR, Ferenc Sikler (Budapest)

- **Changes to tracking algorithms allow access to low p_T particles**
  - **Reconstruct three hit tracks in the pixel system**
  - **Good efficiency to ~ 300MeV/c in Pb+Pb**
  - **Particle ID by dE/dx in Silicon**

Elliptic Flow

100k Events HYDJET, Pb+Pb b = 9fm, no quenching

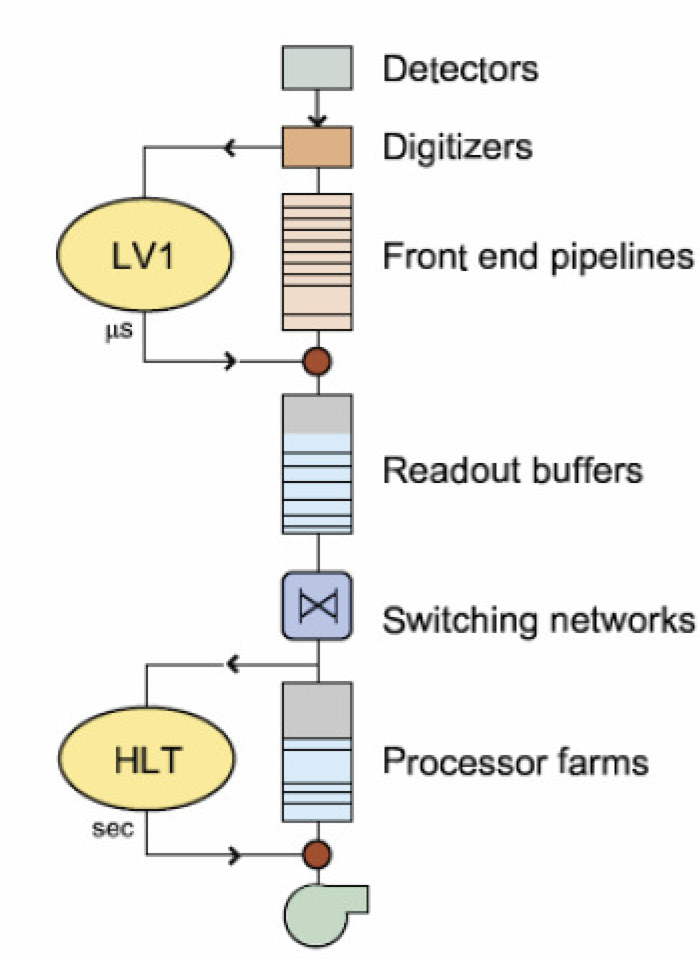




Use the tracker to measure v2 differentialy in p_T and η

- Event plane and v2 determined from independent sub-events
- No non-flow corrections applied
- Compare v2 extracted from simulated particles and reconstructed tracks
- The p_T and η dependences of v2 can be reconstructed with high accuracy.

CMS Trigger and DAQ in p+p



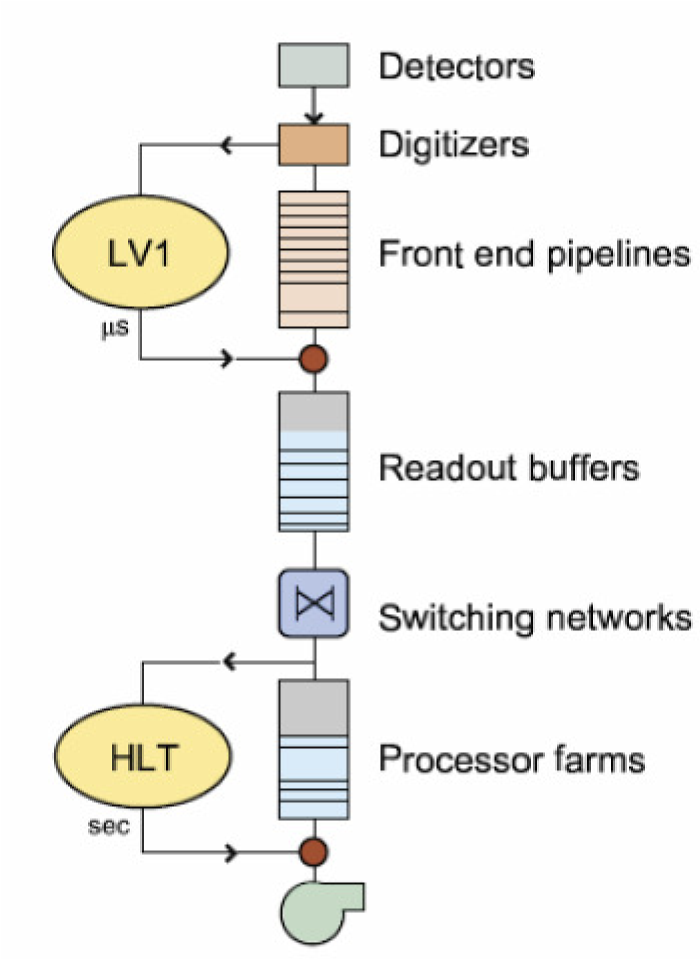
Level 1 trigger
- Uses custom hardware
- Muon tracks + calorimeter information
- Decision after ~ 3µsec

Level-1		p+p
Collision rate		1GHz
Event rate		32MHz
Output bandwidth		100 GByte/sec
Rejection		99.7%

High level Trigger
- ~1500 Linux servers (~10k CPU cores)
- Full event information available
- Runs "offline" algorithms

High Level Trigger		p+p
Input event rate		100kHz
Output bandwidth		225 MByte/sec
Output rate		150Hz
Rejection		99.85%

CMS Trigger and DAQ in Pb+Pb vs p+p



Level 1 trigger
- Uses custom hardware
- Muon tracks + calorimeter information
- Decision after ~ 3µsec

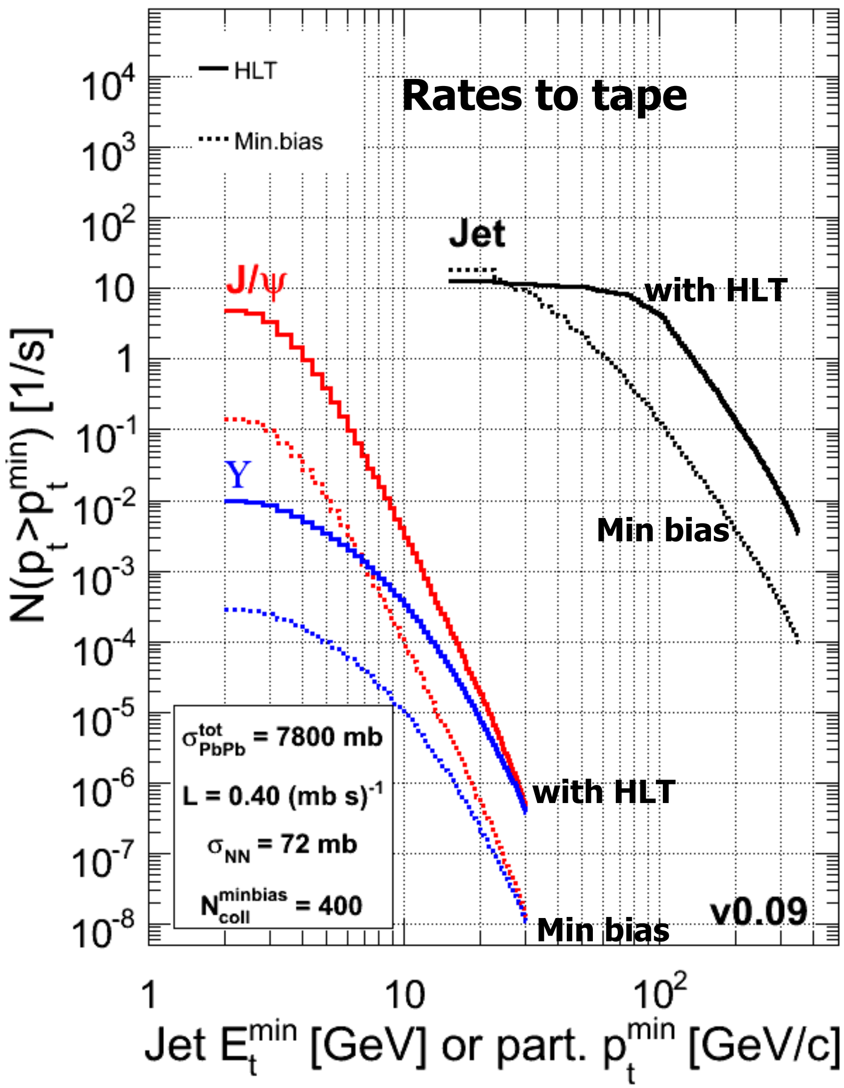
Level-1	Pb+Pb	p+p
Collision rate	3kHz (8kHz peak)	1GHz
Event rate	3kHz (8kHz peak)	32MHz
Output bandwidth	100 GByte/sec	100 GByte/sec
Rejection	none	99.7%

High level Trigger
- ~1500 Linux servers (~10k CPU cores)
- Full event information available
- Runs "offline" algorithms

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

to be partially funded by US DOE NP

Hard Probes: HLT vs Min Bias



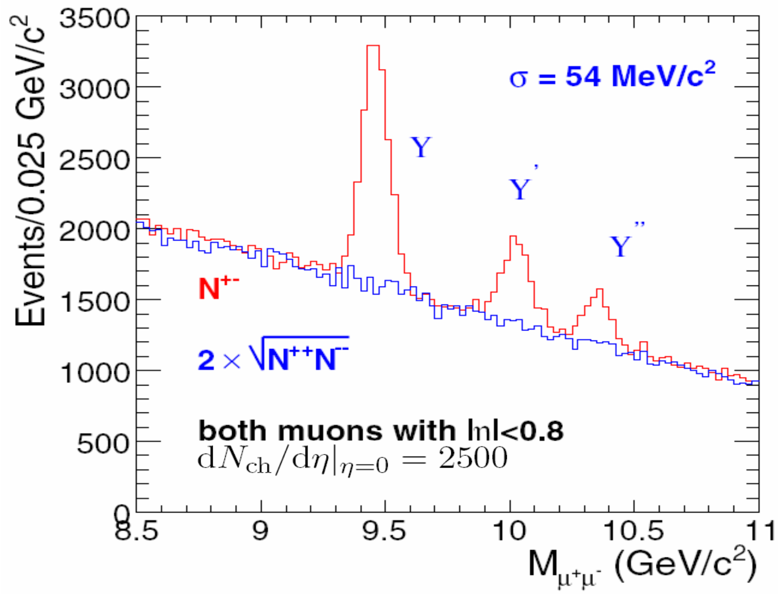
J/ψ,Υ and Jet reconstruction available at HLT

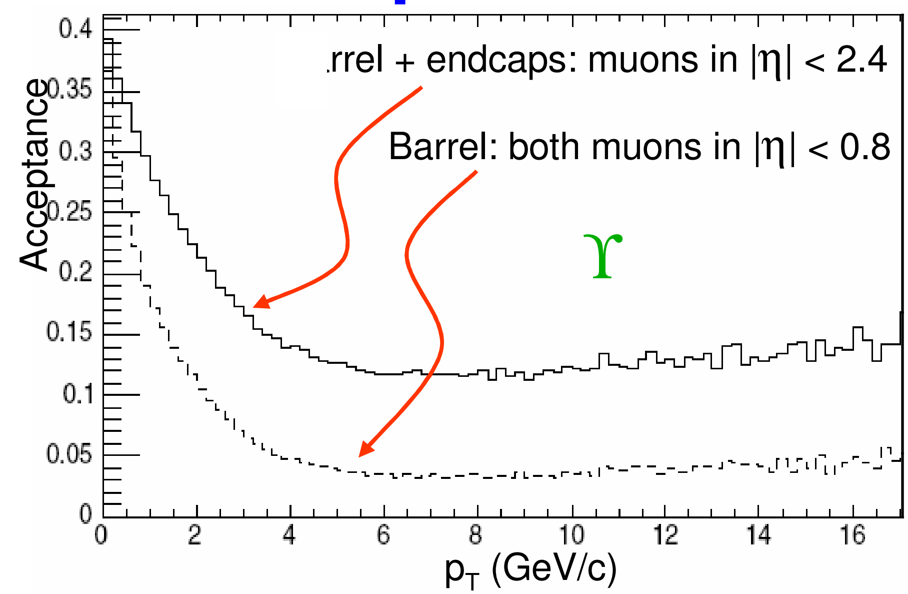
Example trigger table:

Channel	Threshold	Pre-scale	Bandwidth [MByte/s]	Event size [MByte]
min. bias	–	1	33.75 (15%)	2.5
jet	100 GeV	1	24.75 (11%)	5.8
jet	75 GeV	3	27 (12%)	5.7
jet	50 GeV	25	27 (12%)	5.4
J/ψ	0 GeV/c	1	67.5 (30%)	4.9
Υ	0 GeV/c	1	2.25 (1%)	4.9
γ^{prompt}	10 GeV	1	40.5 (18%)	5.8
UPC/forward	–	1	2.25 (1%)	1

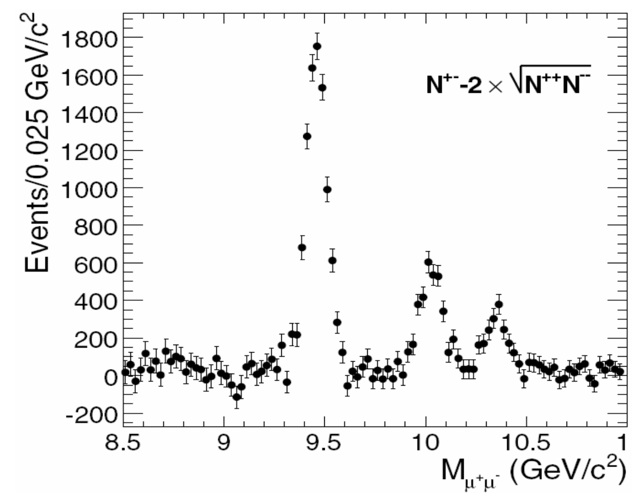
HLT improves hard probe statistics by more than a factor of 10!

Mass resolution and acceptance





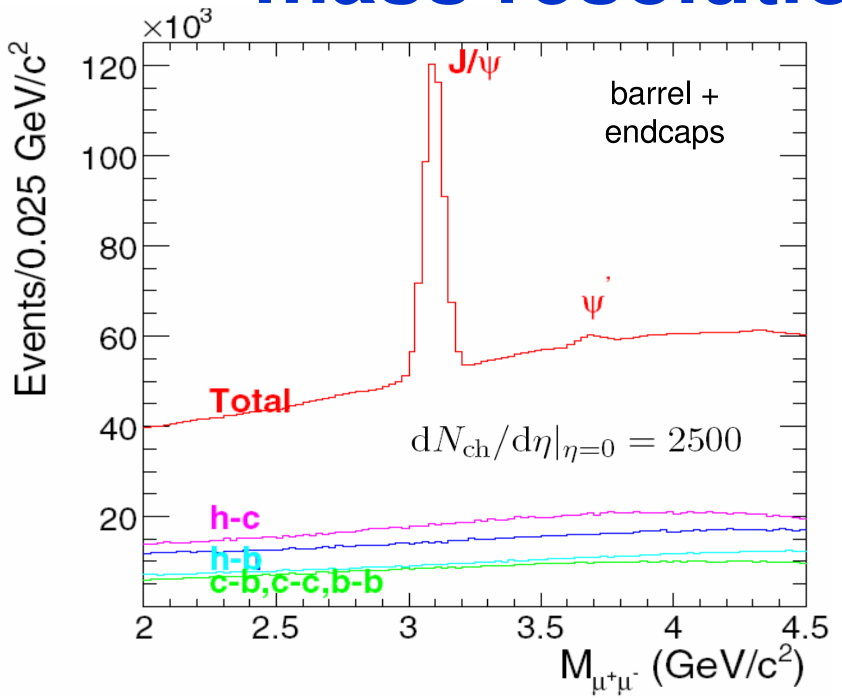
- **CMS has a very good acceptance in the Upsilon mass region**
- **The dimuon mass resolution allows to separate the three Upsilon states:**
  - **~ 54 MeV/c2 within the barrel and ~ 86 MeV/c2 when including the endcaps**

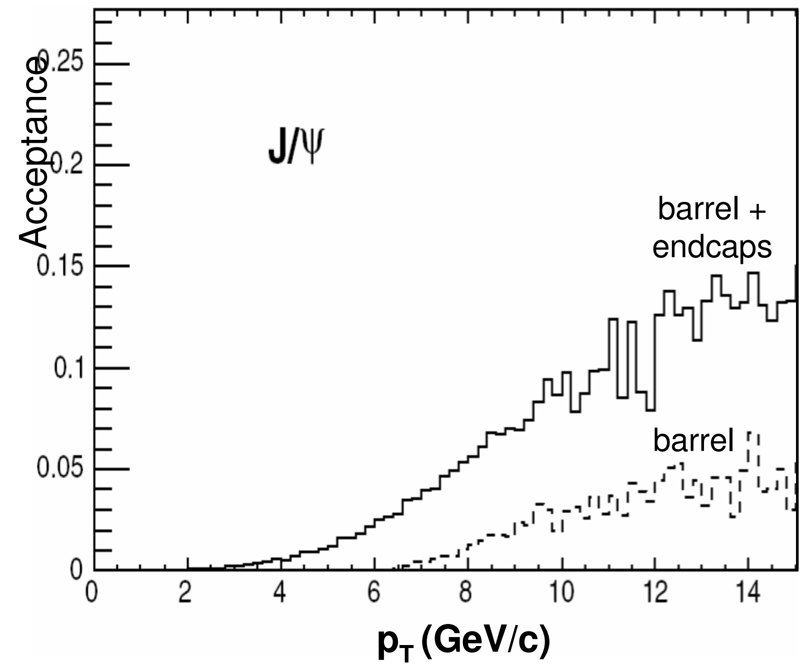


O. Kodolova, M. Bedjidian, CMS note 2006/089

J/ψ→μμ

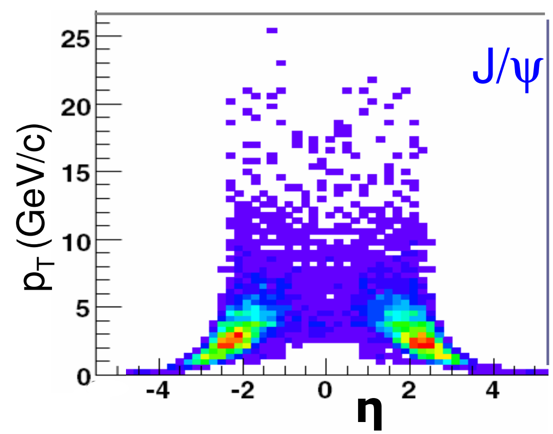
mass resolution and acceptance

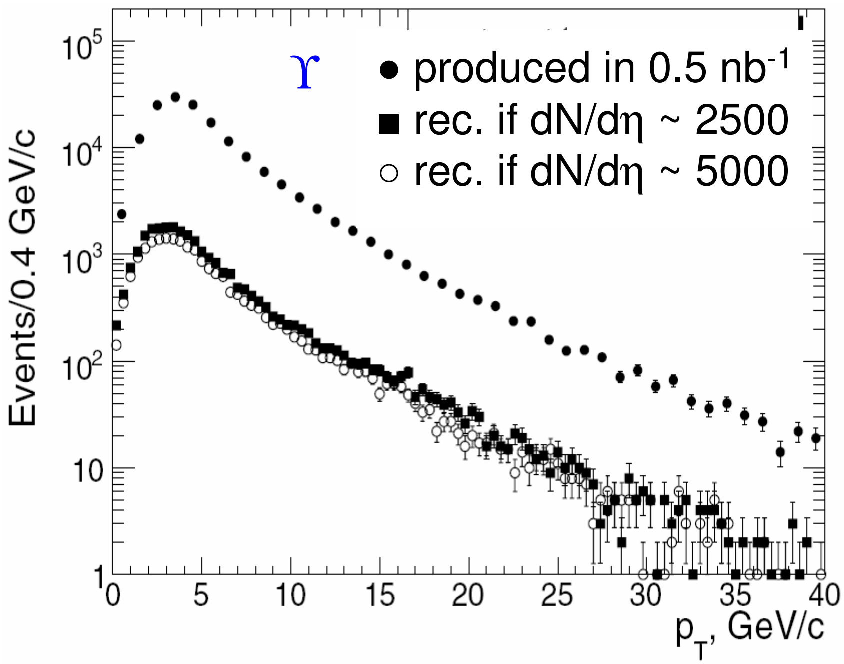


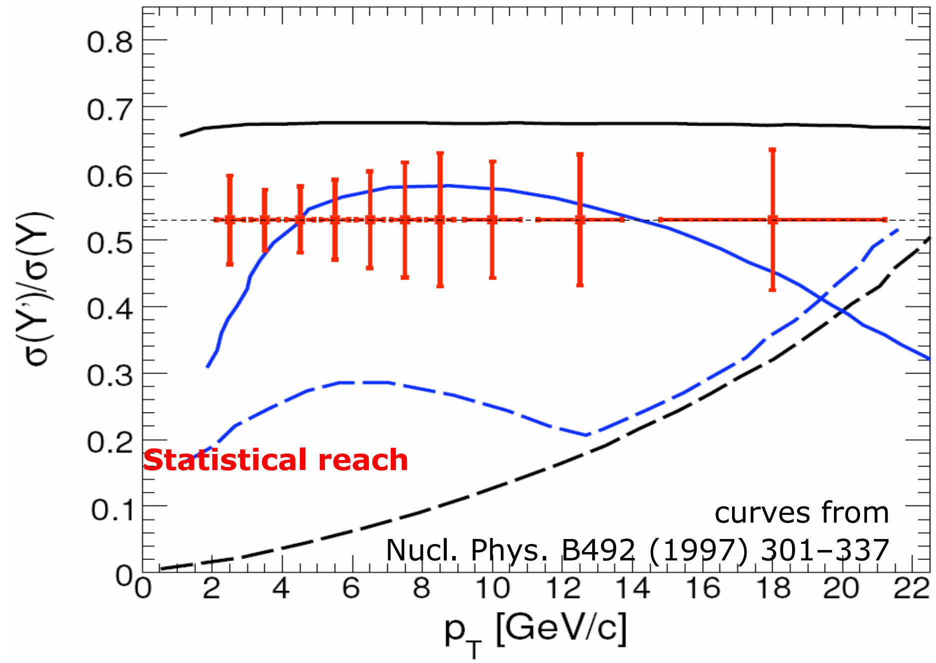


O. Kodolova, M. Bedjidian, CMS note 2006/089

- **Low p_T J/ψ acceptance at forward rapidities.**
- **The dimuon mass resolution is 35 MeV, full η region.**





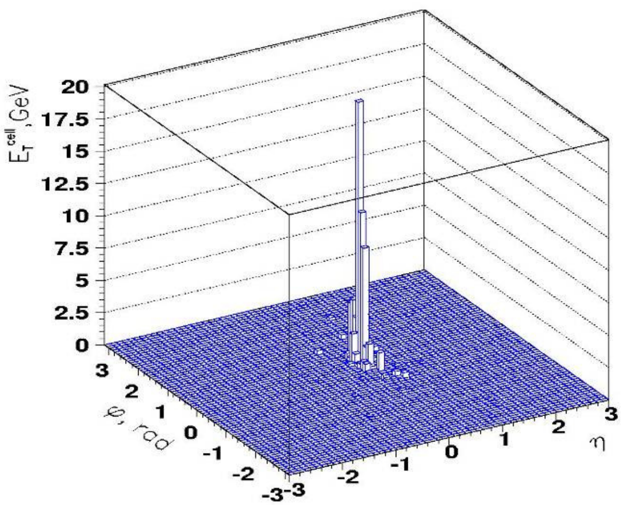


- **Expected rec. quarkonia yields:**
  - **J/ψ : ~ 180 000**
  - **ϒ : ~ 26 000**
- **Detailed studies of Upsilon family feasible with HLT**
- **Statistical accuracy (with HLT) of expected ϒ' / ϒ ratio versus p_T -> model killer...**

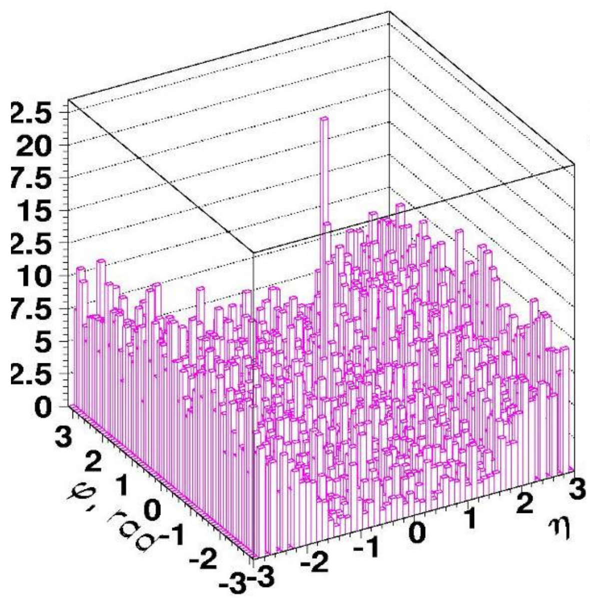
The Calorimeters: Jet Reconstruction

Jet E_T ~100GeV, Pb Pb background dN_{ch}/dy ~ 5000

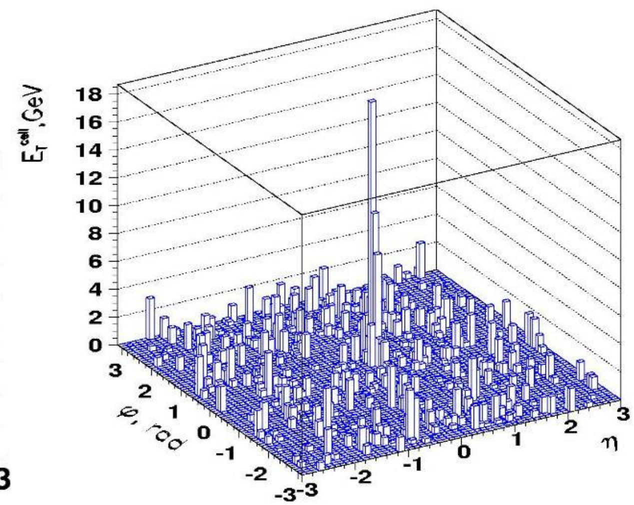
Jet in pp



Jet superimposed on Pb Pb background

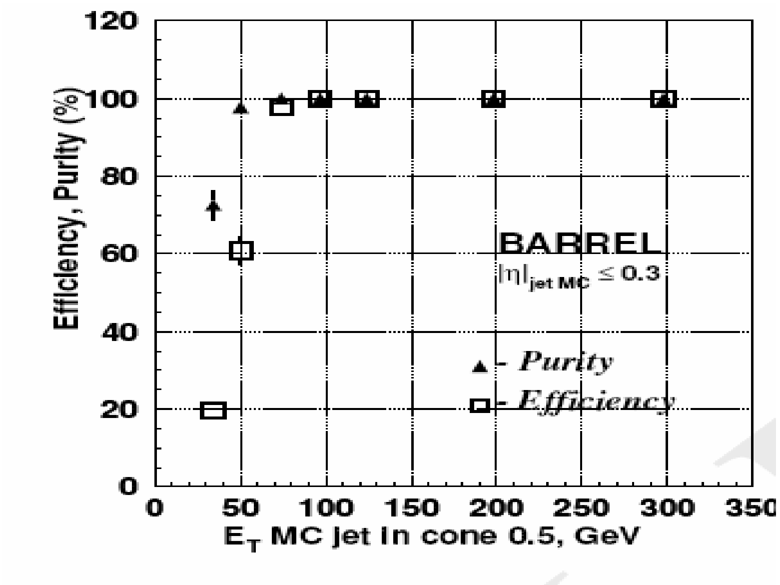


Jet in Pb-Pb after pileup subtraction

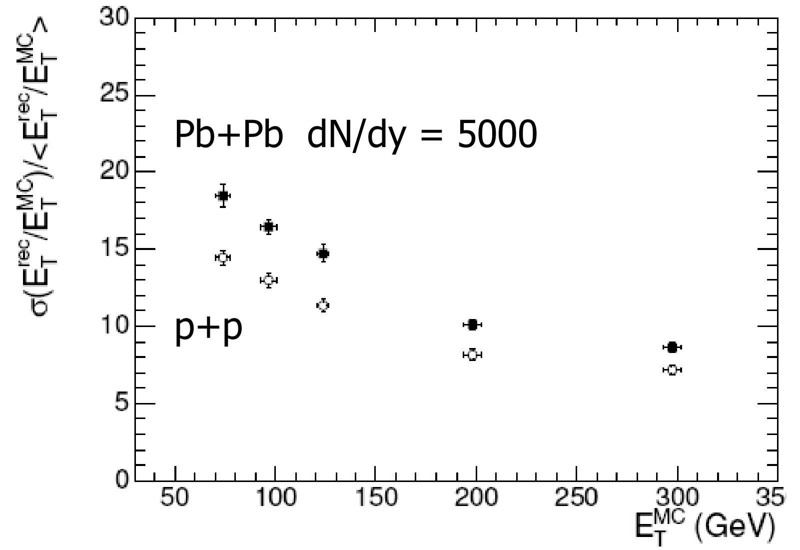


Heavy Ion Jet Finder Performance

High Efficiency



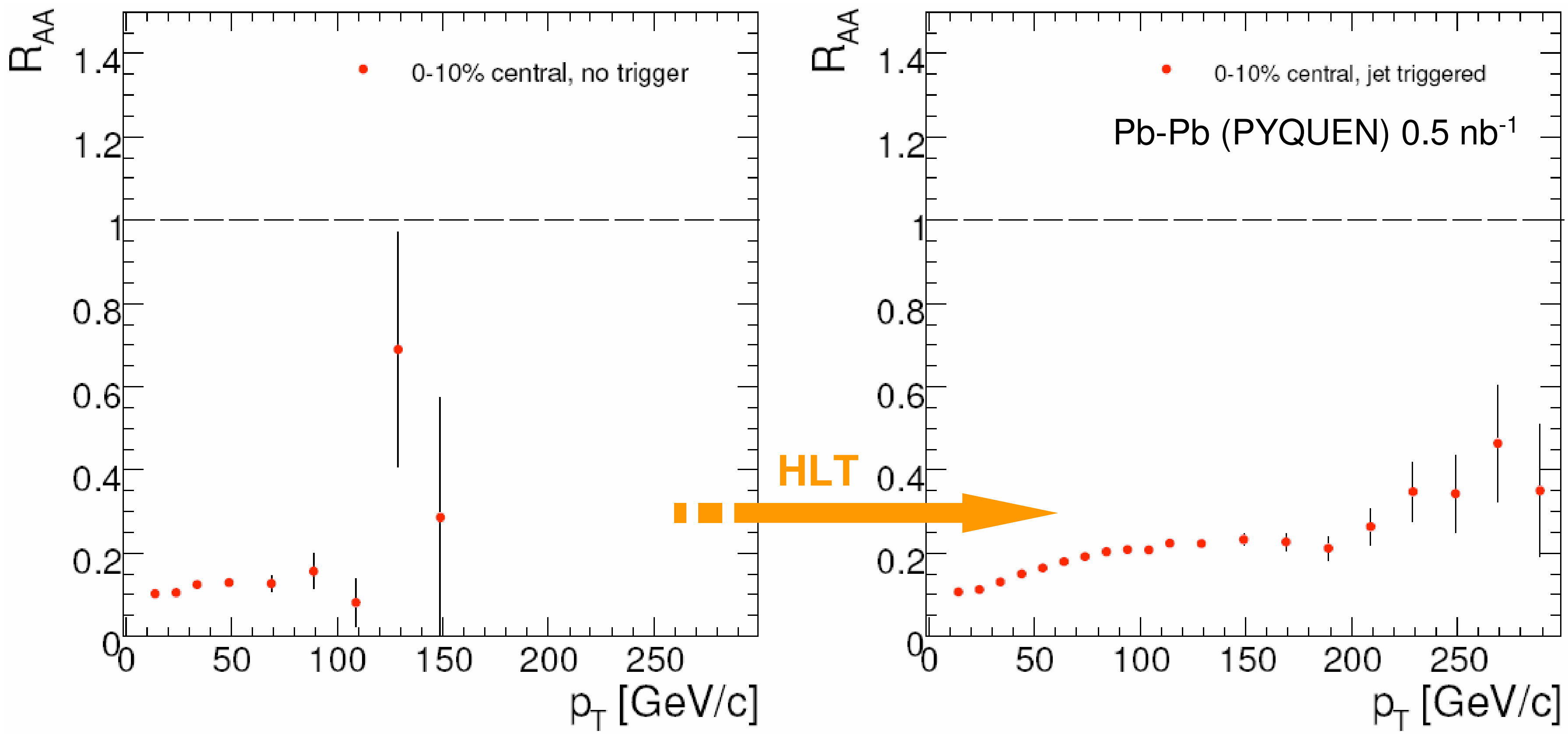
Good Resolution



Jet studies from CMS Note 2003/004

- **A modified iterative cone algorithm running on calorimeter data gives good performance in Pb Pb collisions**
- **Offline jet finder will run in the HLT**

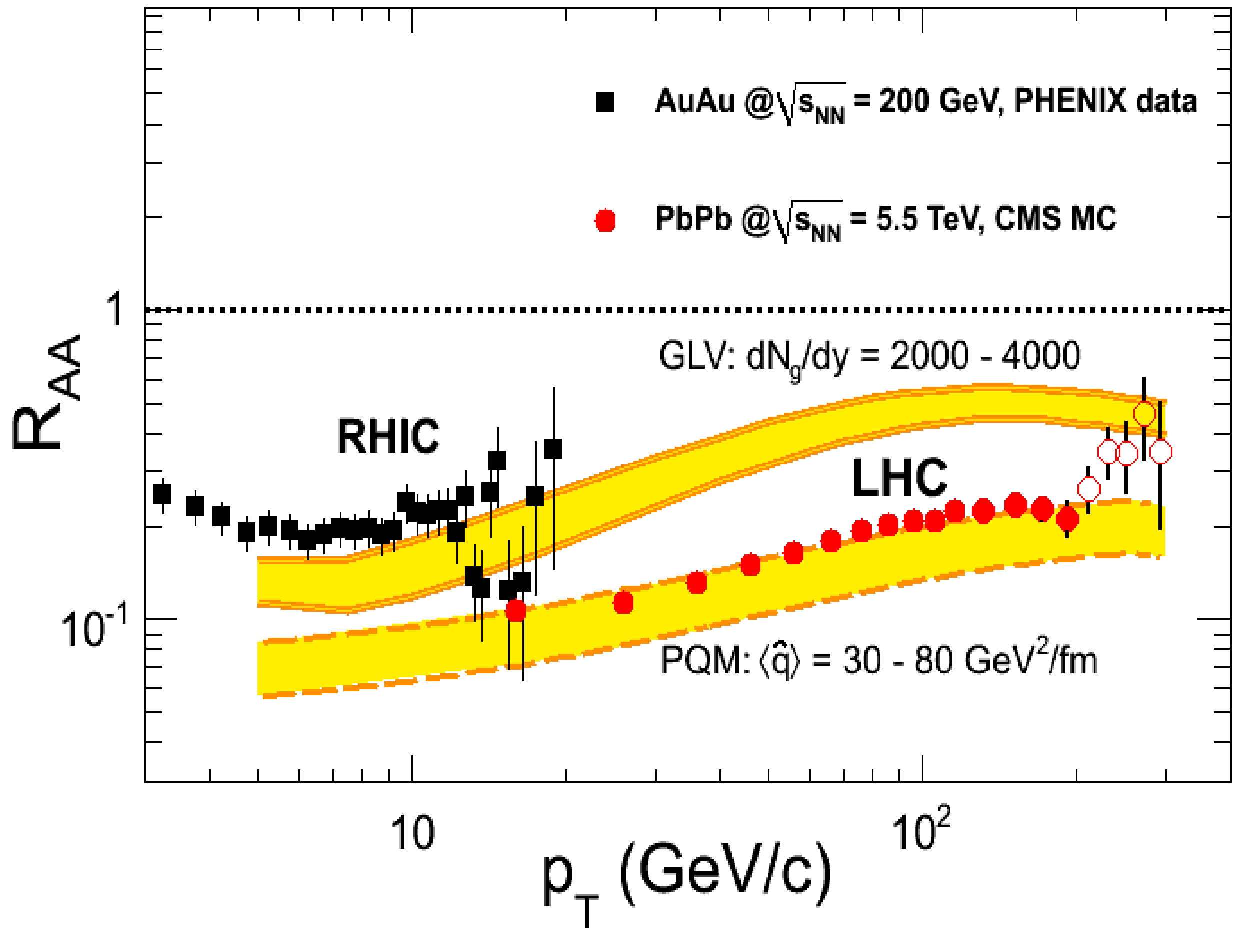
HLT impact on the p_T reach of R_{AA}



$$R_{AA}(p_T) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AB}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T}$$

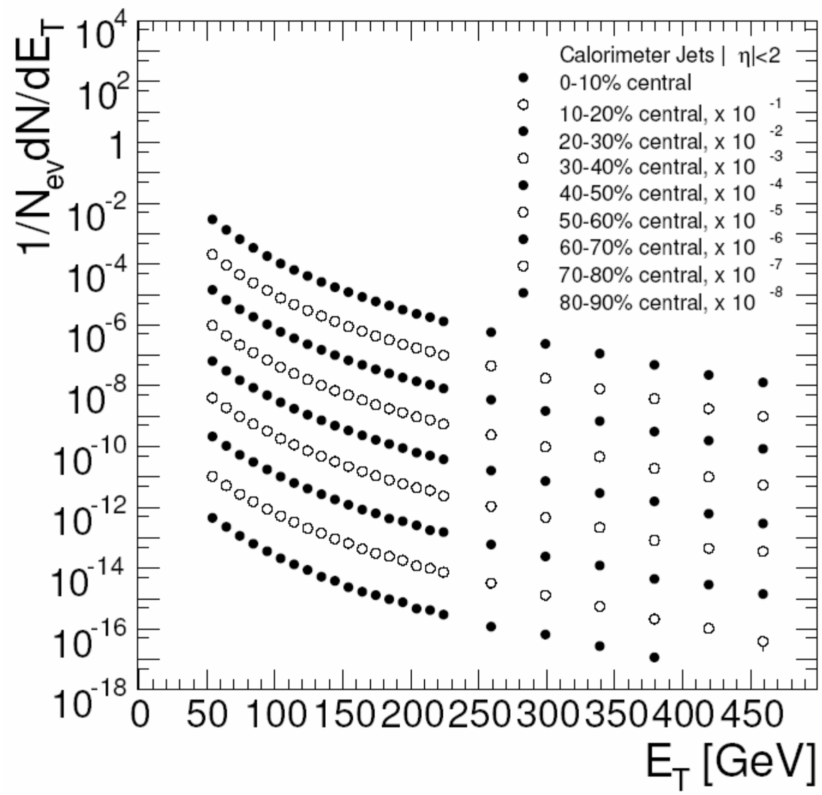
- **Jet-trigger allows R_{AA} measurement to pT > 200 GeV/c**
- **Reach improved by x2 compared to min bias**

High p_T Suppression



Clear separation of different energy loss scenarios

Jet E_T reach

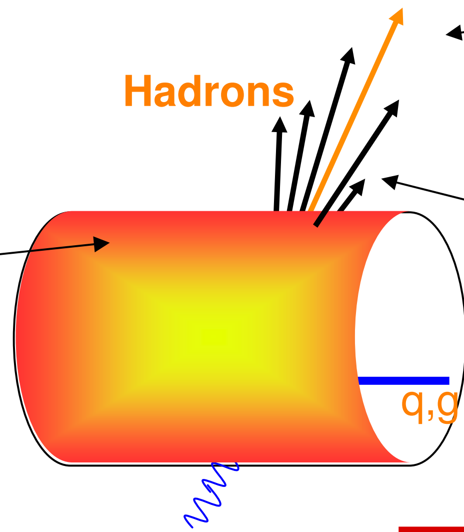


- **Jet spectra up to E_T ~ 500 GeV (Pb-Pb, 0.5 nb^{-1}, HLT-triggered)**
  - **Detailed studies of medium-modified (quenched) jet fragmentation functions**

Photon-tagged jet fragmentation functions

DOE Review Driven..

Jet axis provides parton direction



Multiplicity and flow measurements characterize density, path length

Charged hadron tracks used to calculate $z = p_T/E_T$

Photon energy tags parton energy E_T

Measure jet fragmentation function:
$dN/d\xi$ with $\xi = -\log z$

Main advantage

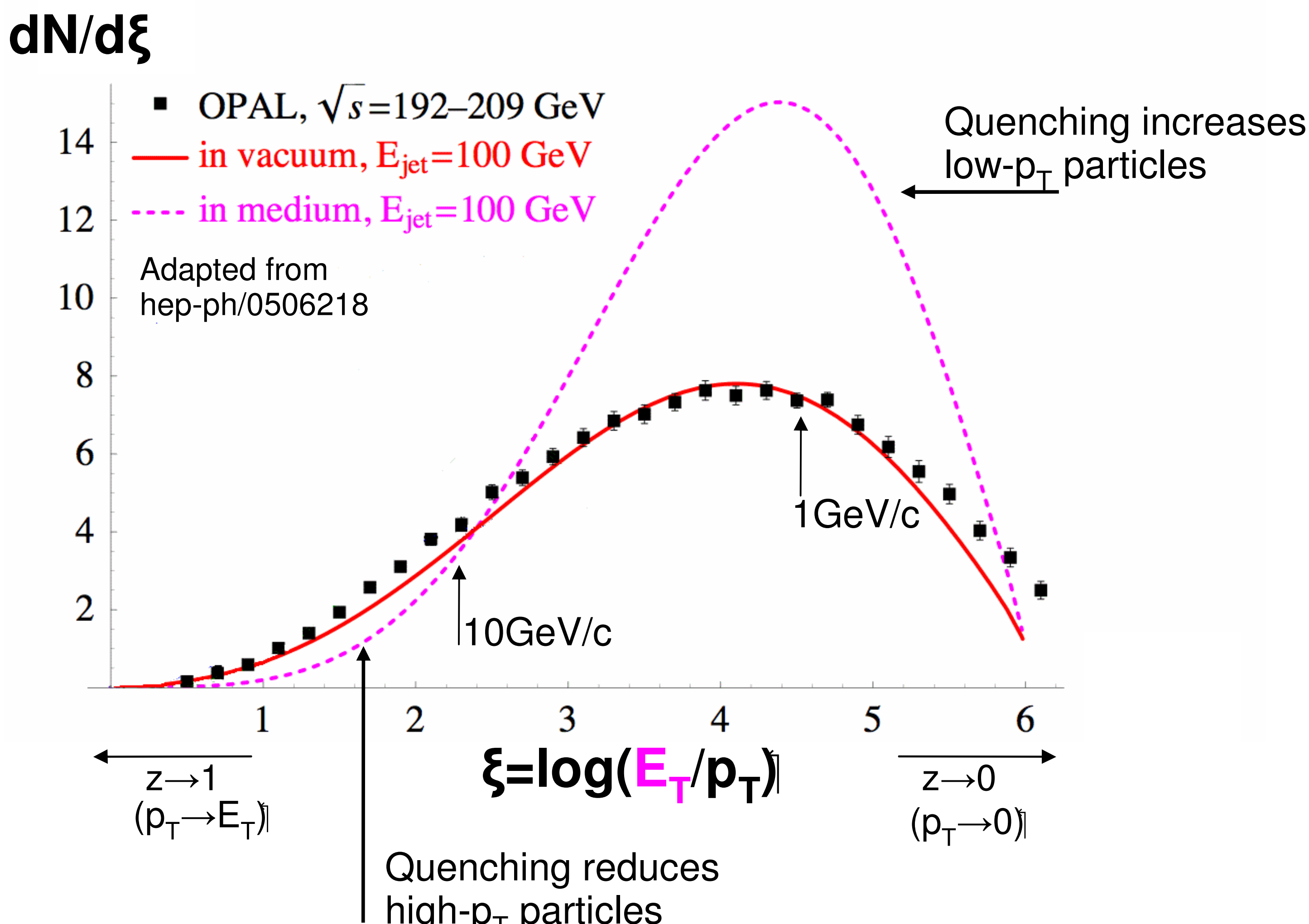
- Photon unaffected by the medium
- Avoids measurement of absolute jet energy

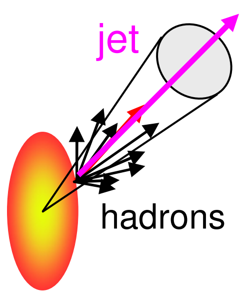
Ingredients:

- Event/Centrality selection
- Reaction plane determination
- Vertex finding
- Track reconstruction
- Jet finding
- Photon identification

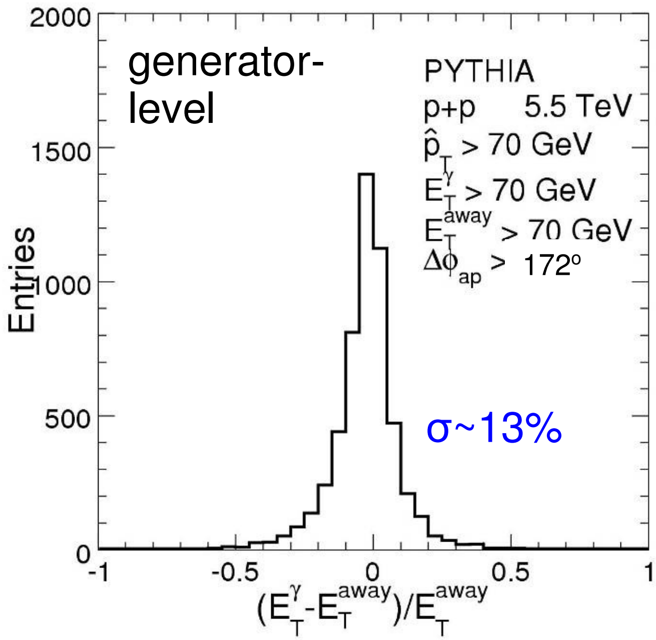
All results based on full GEANT-4 simulations using full reconstruction algorithms on expected one run-year statistics

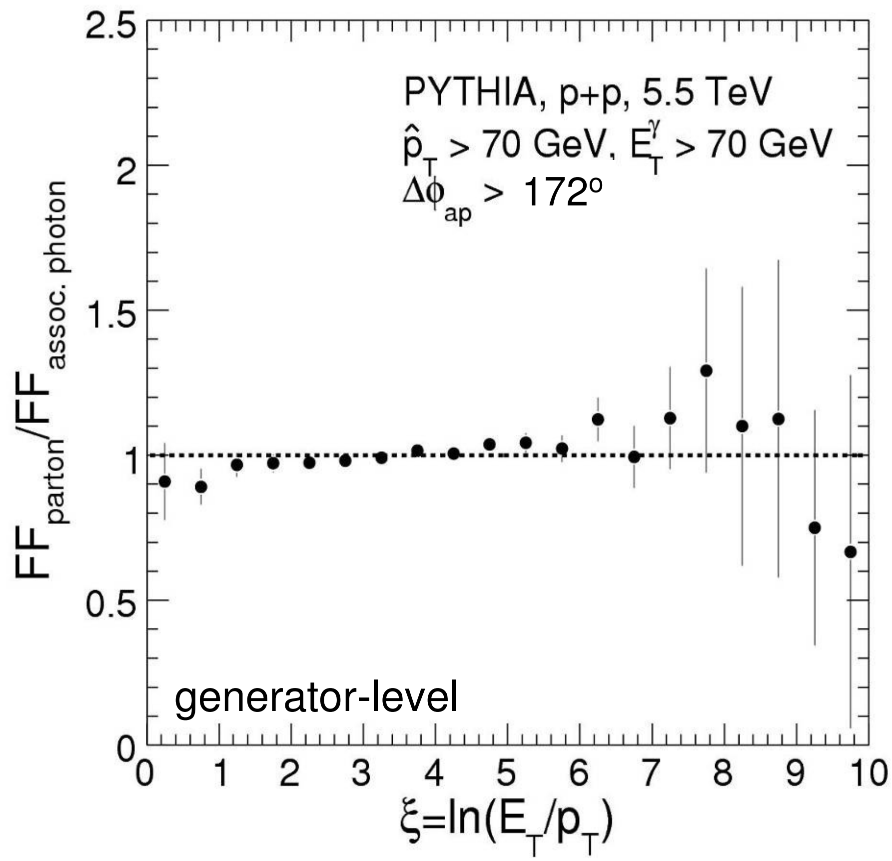
In-medium modified fragmentation functions

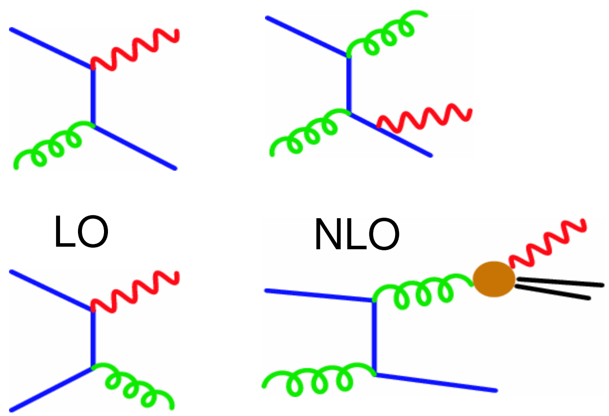




Photon-tagged fragmentation functions







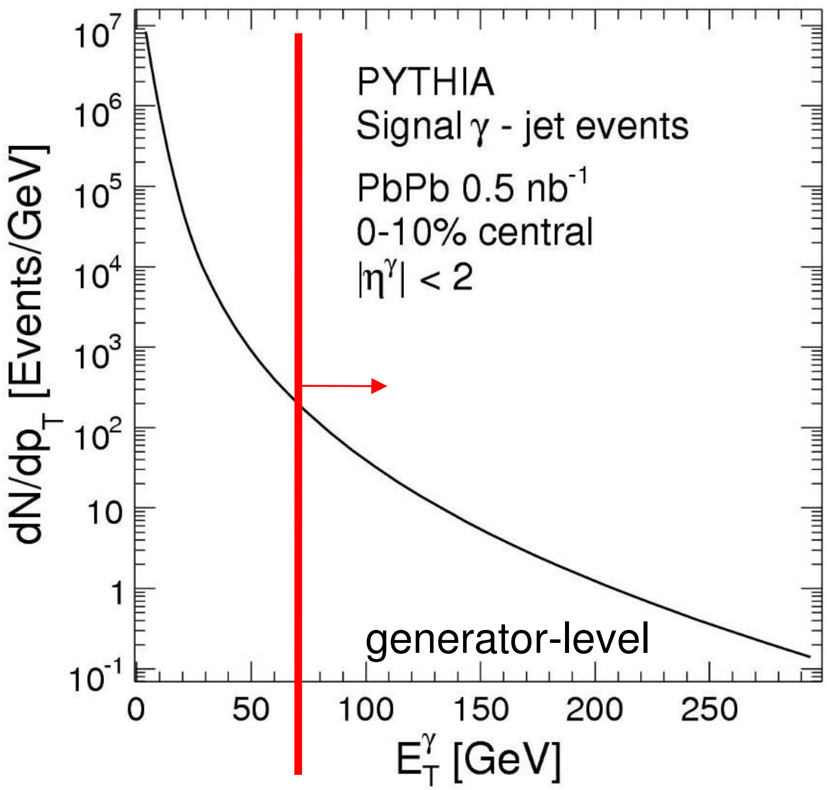
- Use isolated photons + "back-to-back" cut on azimuthal opening angle between the photon and the jet to suppress NLO and background events
  - Determines FF with <10% deviation

Event generation

- **Study two scenarios**
  - **No quenching: PYTHIA signal and QCD background (p+p) events mixed with central unquenched Pb+Pb HYDJET events**
    - No high-p_T particle suppression
    - Leads to high background rates
  - **Quenching: PYQUEN signal and QCD background (p+p) events mixed with central quenched Pb+Pb HYDJET events**
    - Suppression of high-p_T particles
    - Energy loss radiated out of jet cone
    - Challenging for jet finder

PYQUEN v1.2: Eur. Phys. J. C 45 (2006) 211
HYDJET v1.2: hep-ph/0312204

Signal and background statistics



- **Study for one nominal LHC Pb+Pb run "year"**
  - **10^6 sec, $0.5 nb^{-1}$, 3.9×10^9 events**
- **Use 0-10% most central Pb+Pb**
  - **$dN/d\eta|_{\eta=0}$~2400**
- **Simulate signal and background QCD (p+p) events**
  - **Mix into simulated Pb+Pb events (~1000 events)**

Data set	p_T [GeV/c]	signal γ-jet	π^0	$\pi^\pm$	η	η'	ω
unquenched	>70	4288	23675	47421	12267	8194	30601
unquenched	>100	1216	4422	9103	2357	1567	5975
quenched	>70	4209	7569	14616	3825	2445	9235
quenched	>100	1212	1562	3000	829	515	2051

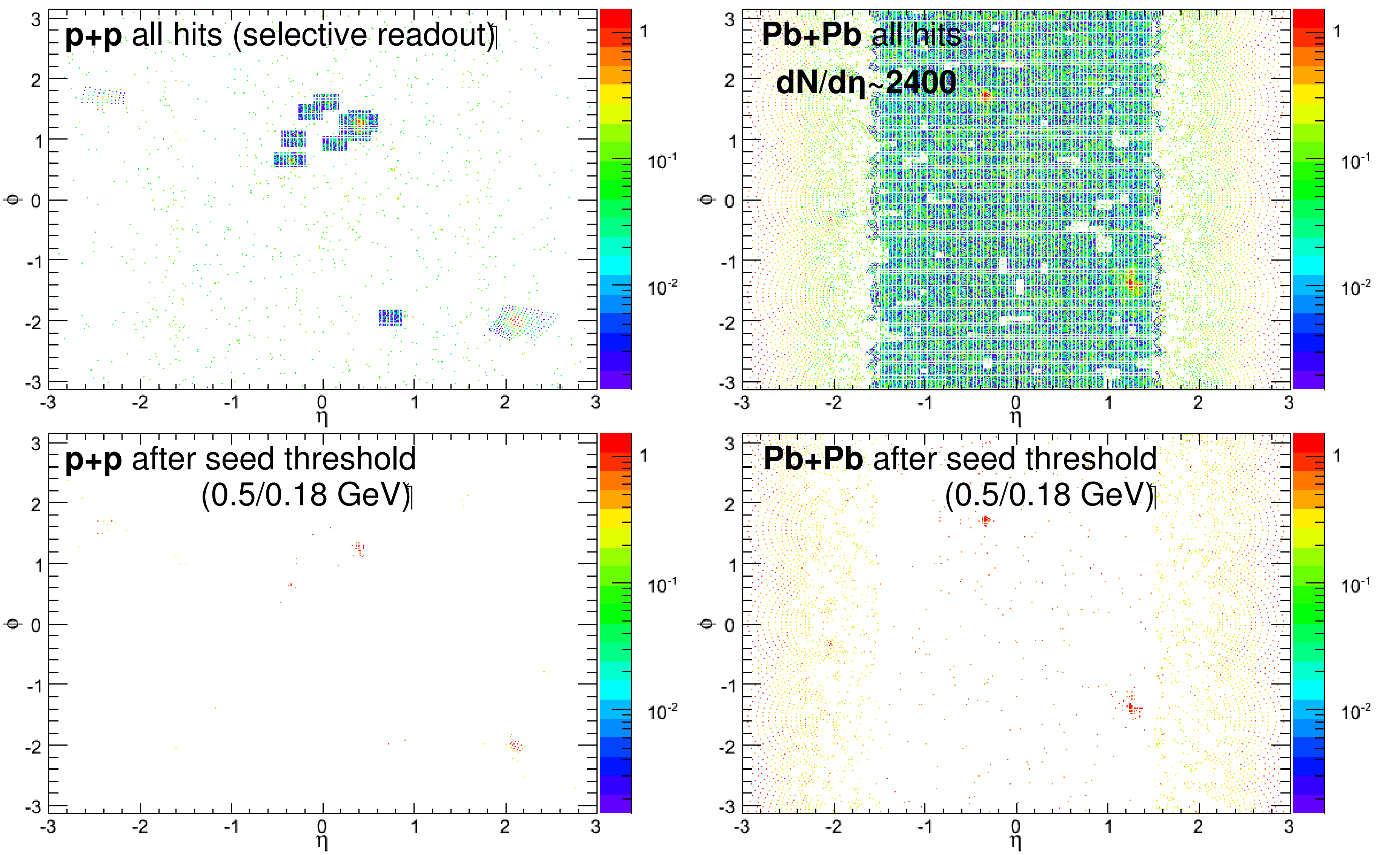
Reconstruction

- **Tracking**
  - Low p_T cutoff at 1GeV/c
  - Efficiency (algorithmic + geometric) ~ 50-60%
  - Fake rate ~ few %
- **Jet finding**
  - Iterative cone algorithm with underlying event subtraction (R=0.5)
  - Performance studies on away-side jet finding (see later)
- **Photon ID**
  - Reconstruction of high-E_T isolated photons
  - New for this analysis (see next slides)

Tracking: NIM A566 (2006) 123

Jet finding: Eur. Phys. J. 50 (2007) 117

ECAL response in p+p and Pb+Pb

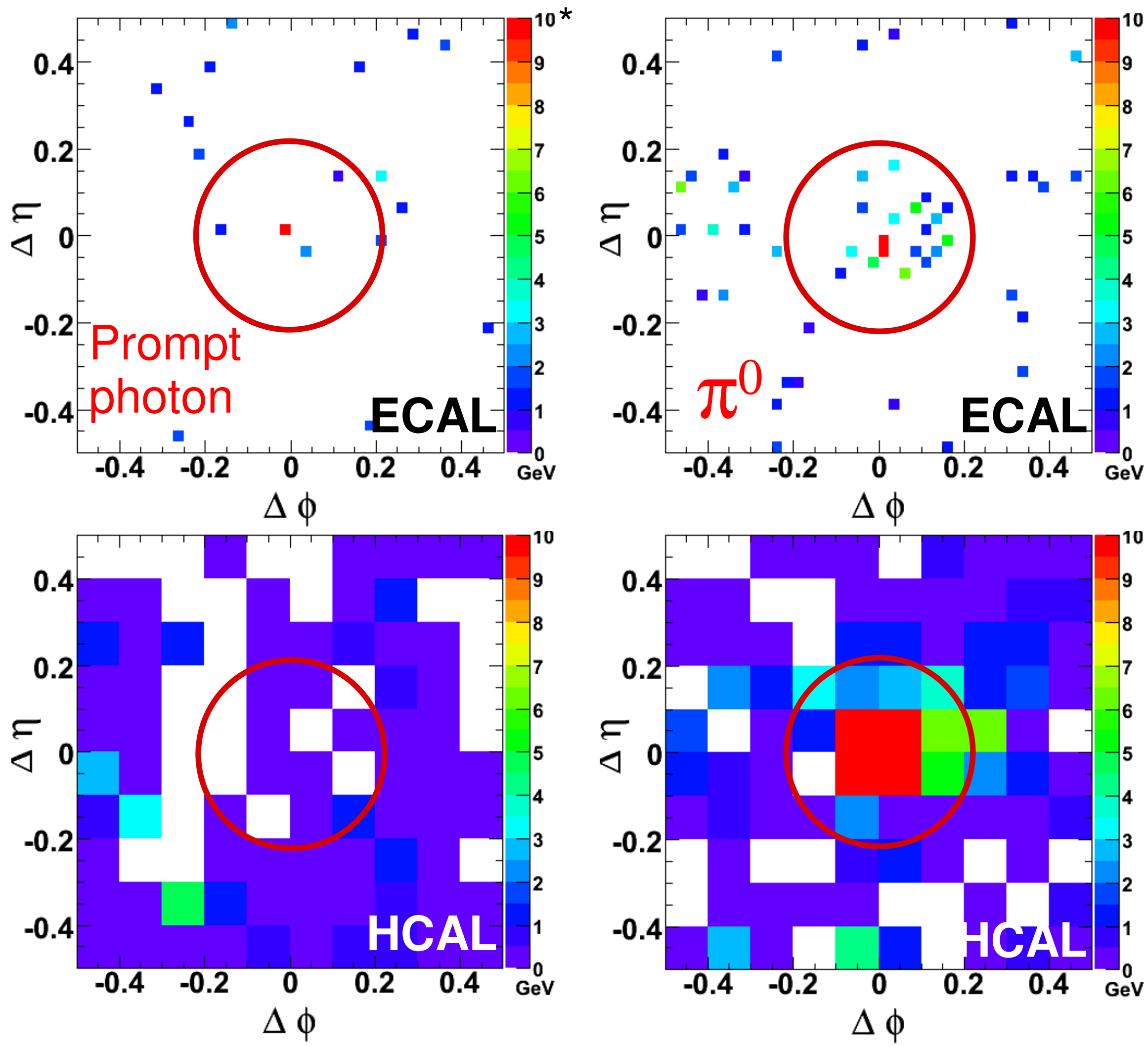


ECAL reconstruction chain used with standard p+p settings

NB: The two p+p (QCD) events are not the same.

Photon ID: Isolation and cluster shape cuts

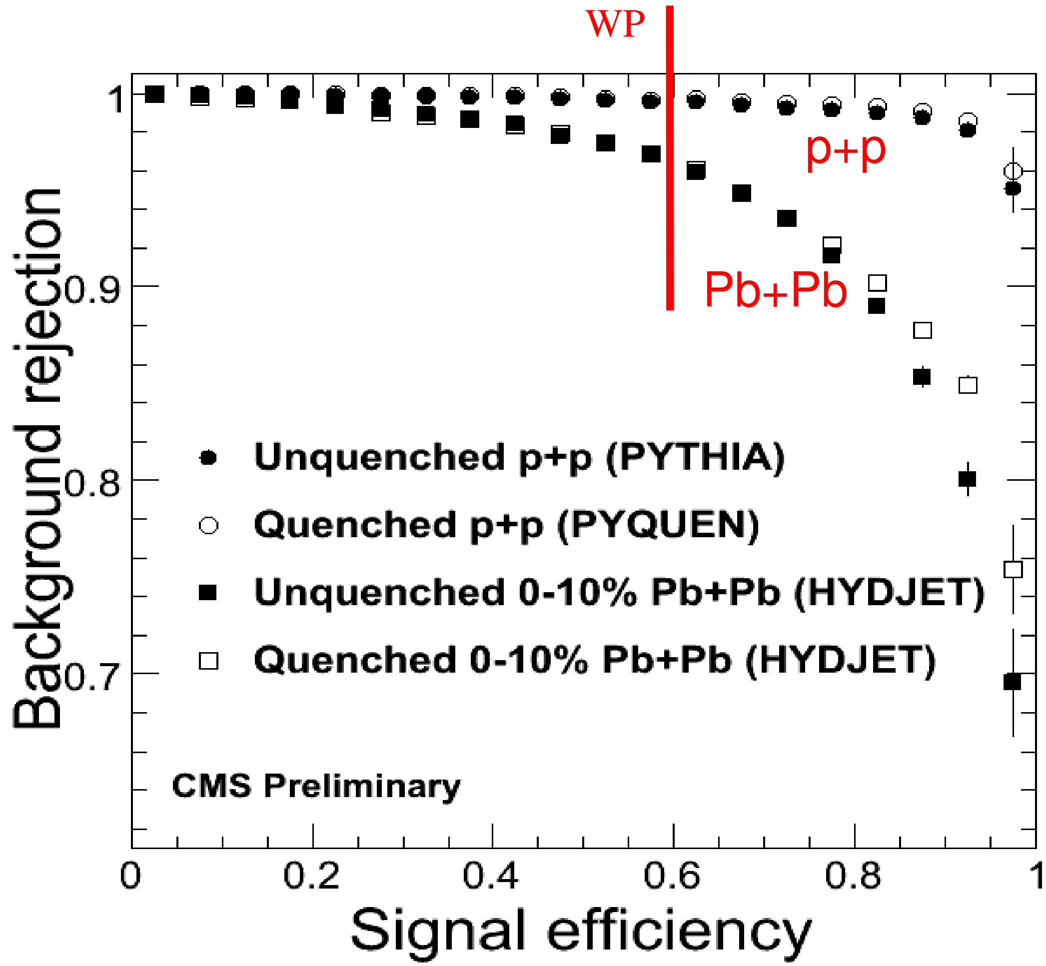
- **Identification**
  - **10 cluster shape variables**
    - based on ECAL
  - **10 isolation variables**
    - based on ECAL/HCAL
  - **Track-based cut**
- **Selection**
  - **Total of 21 variables grouped into 3 sets**
  - **Linear discriminant analysis (Fisher) and cut optimization using TMVA**



TMVA: http://tmva.sourceforge.net

Photon identification performance

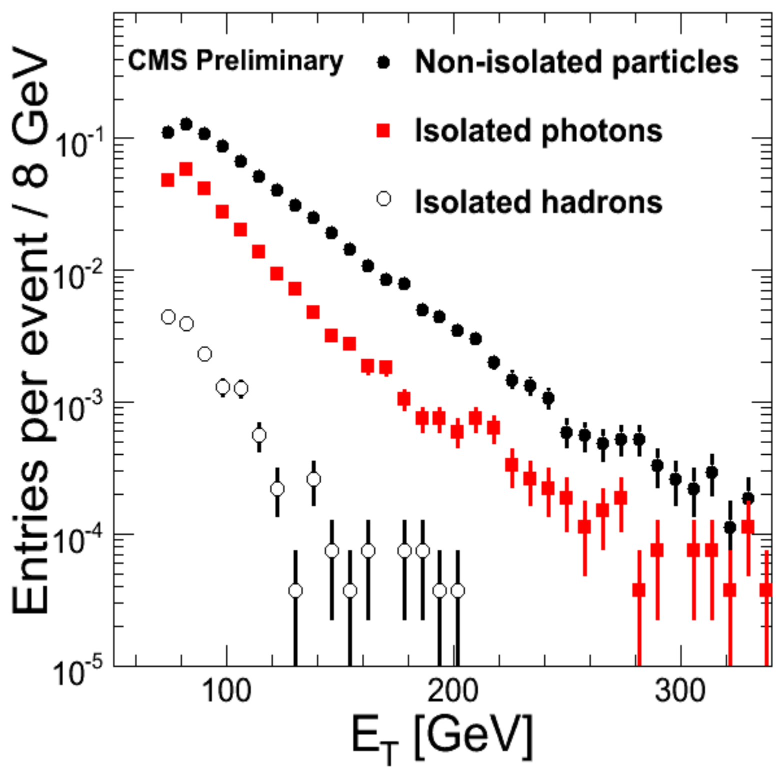
- Set working point to 60% signal efficiency
- Leads to 96.5% background rejection
- Training is done on unquenched samples only



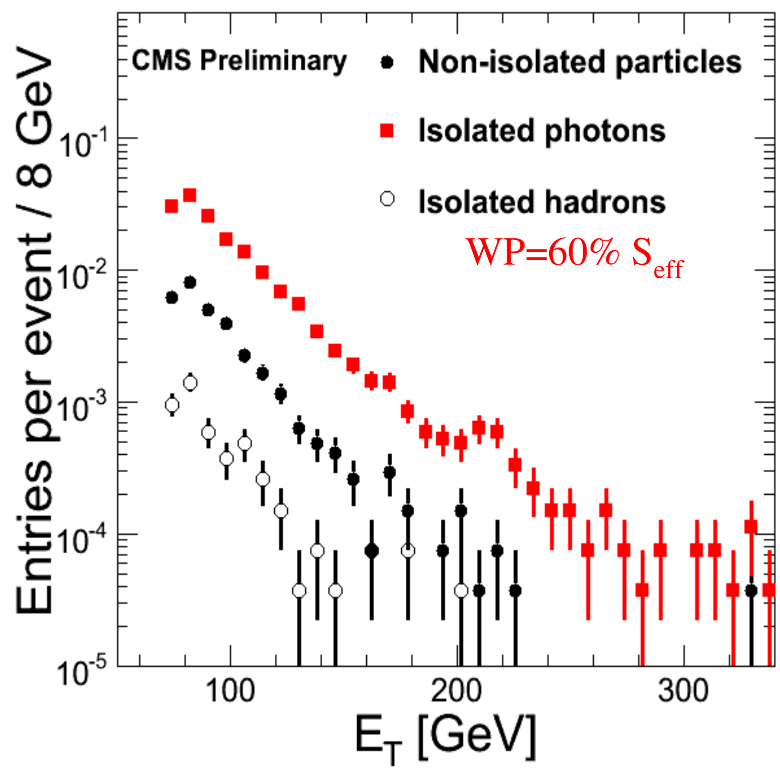
Photon identification performance

Quenched Pb+Pb

Before cuts: S/B=0.3



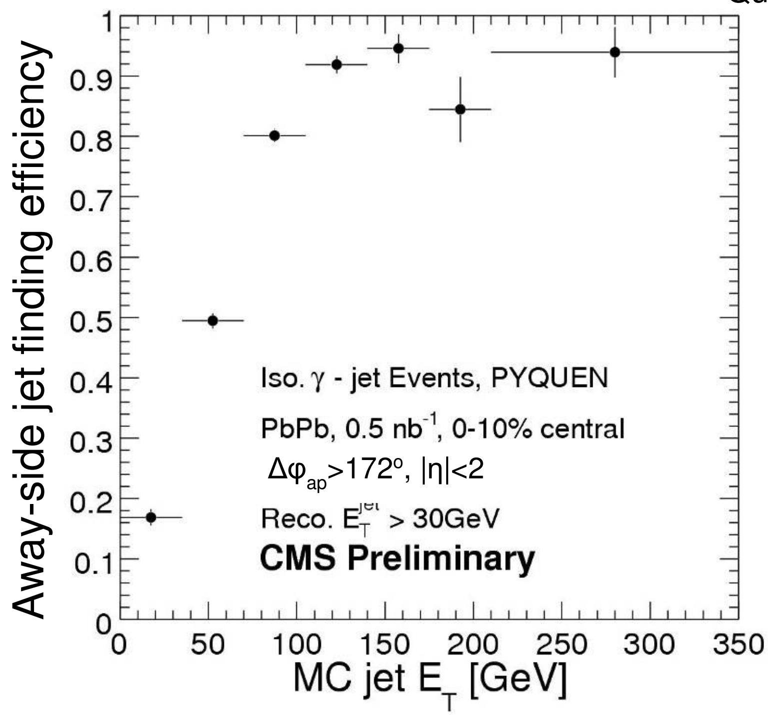
After cuts: S/B=4.5

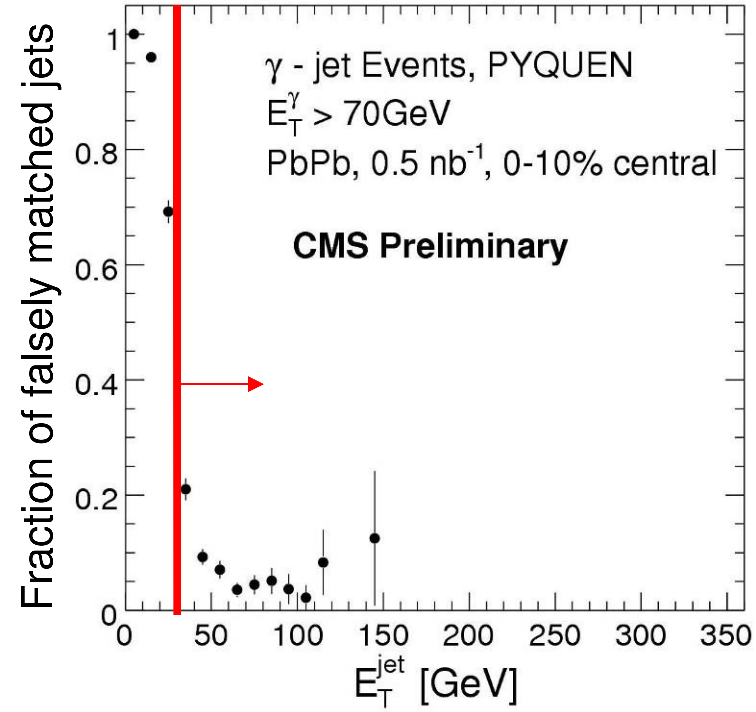


Photon isolation and shape cuts improve S/B by factor ~15

Jet finding (away-side)

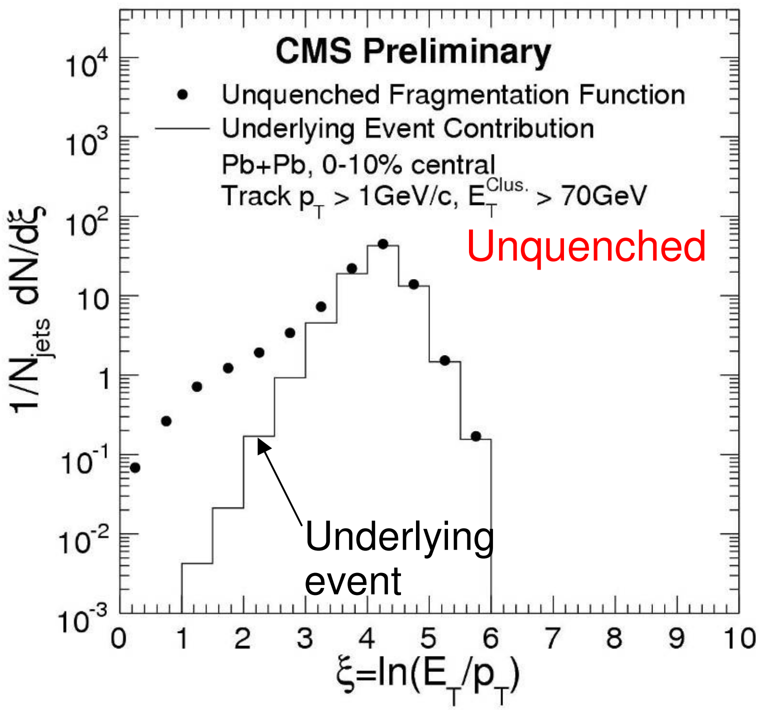
Quenched Pb+Pb

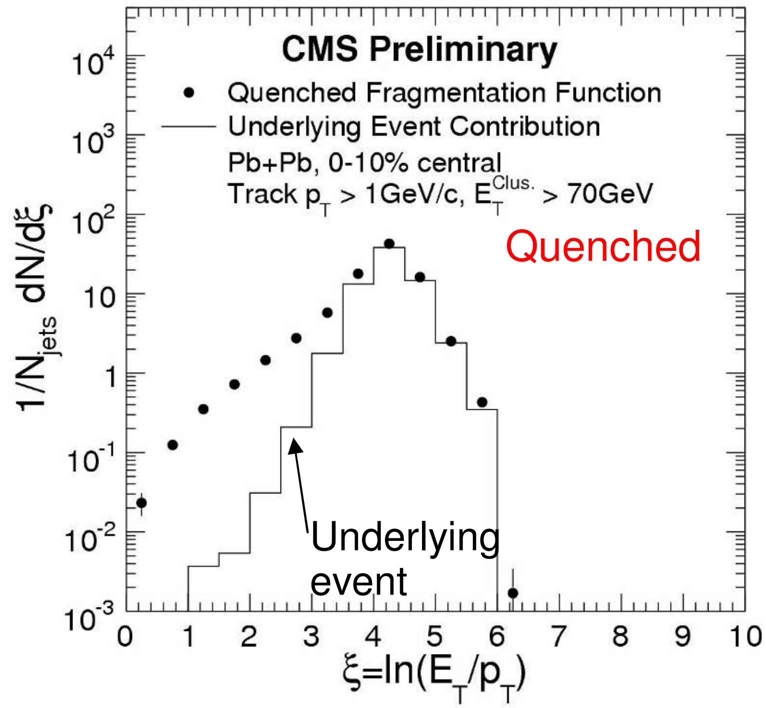




- **Select away-side jet with $\Delta\phi(\gamma,jet) > 172^0$, $|\eta| < 2$ and $E_T > 30$ GeV**
  - **The energy cut reduces the false rate to 10% level**
    - Analysis does not use jet energy otherwise
  - **Jet finding efficiency rises sharply between 30-100 GeV MC jet E_T**
    - Main source of systematic uncertainty in reconstructed FFs

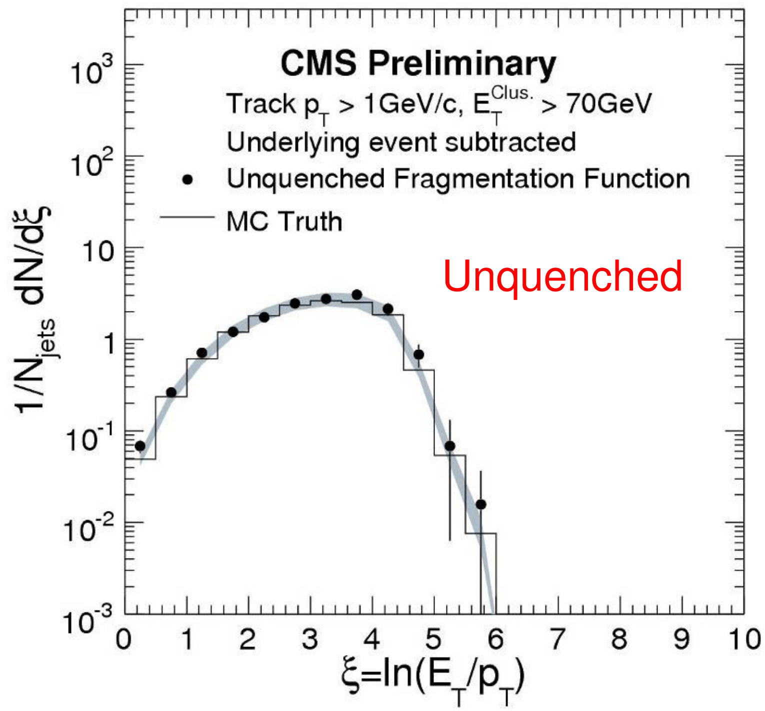
Fragmentation Functions

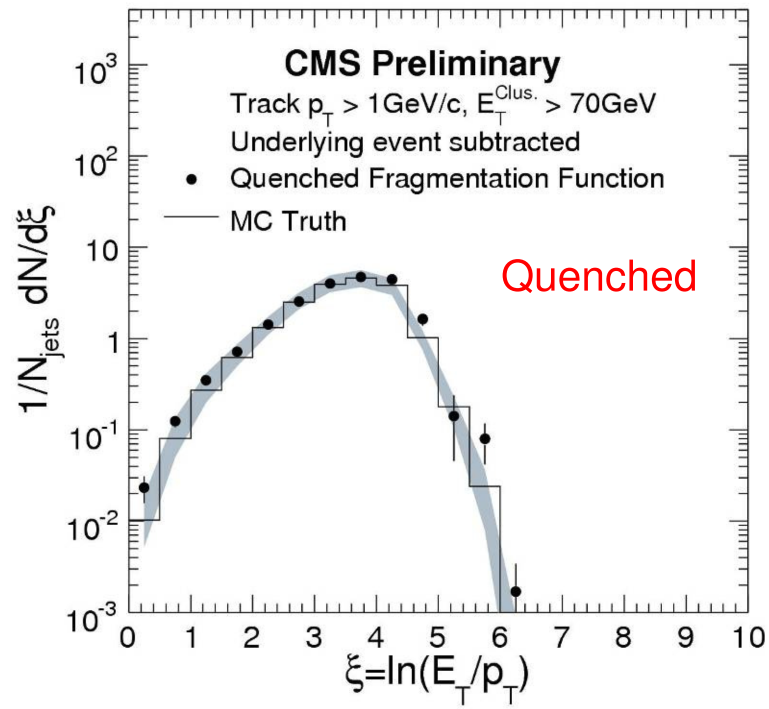




- **Obtain dN/dξ using tracks in R=0.5 cone around jet axis**
- **For ξ>3 (~p_T<4GeV/c) dN/dξ dominated by underlying Pb+Pb event**
  - **Estimate background using R=0.5 cone rotated in φ by 90º relative to jet**
  - **Sum event-by-event backgrounds and subtract**

Reconstructed fragmentation functions



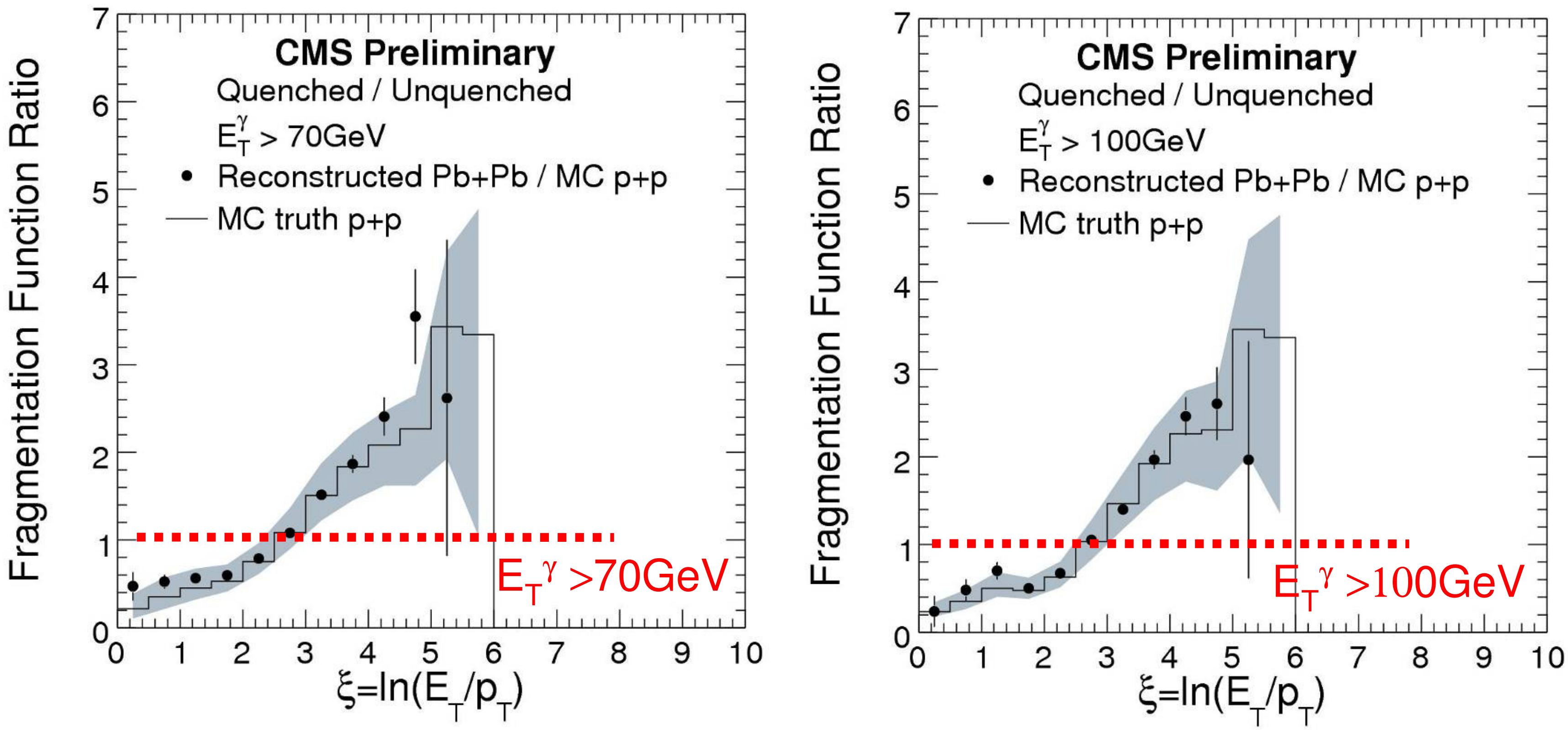


- **Major contributions to systematic uncertainty (added in quadrature)**
  - **Photon selection and background contamination (15%)**
  - **Track finding efficiency correction (10%)**
  - **Wrong/fake jet matches (10%)**
  - **Jet finder bias (largest contribution in quenched case)**

No or small ξ dependence

Fragmentation function ratio

Reco quenched Pb+Pb / MC unquenched p+p



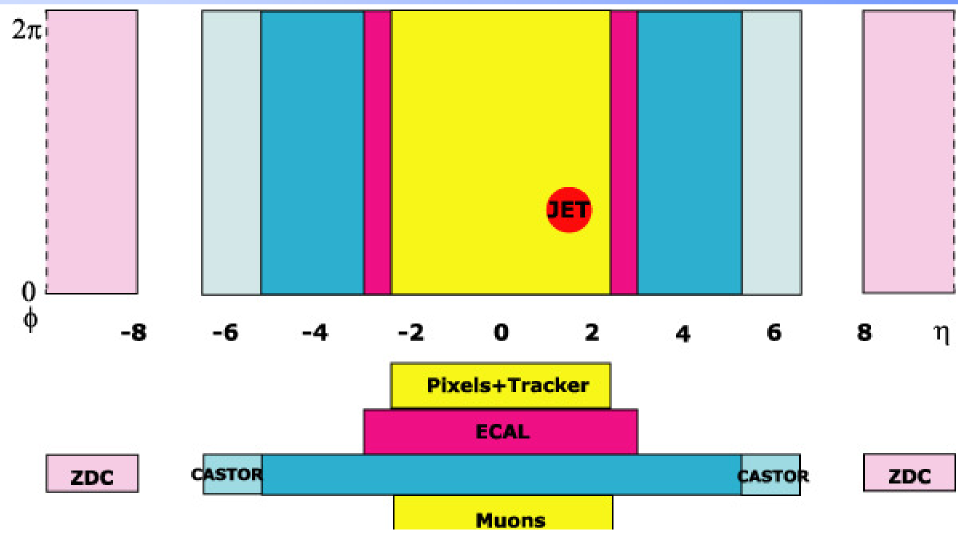
- **Medium modification of fragmentation functions can be measured**
  - **High significance for $0.2 < \xi < 5$ for both, E_T^γ >70GeV and E_T^γ >100GeV**

Summary

- **The CMS detector has excellent capabilities to study the dense QCD matter produced in very high energy heavy-ion collisions, through the use of hard probes such as high-ET (fully reconstructed) jets and heavy quarkonia**
- **With a high granularity inner tracker (full silicon, analog readout), a state-of-the-art crystal ECAL, large acceptance muon stations, and a powerful DAQ & HLT system, CMS has the means to measure charged hadrons, jets, photons, electron pairs, dimuons, quarkonia, Z^0, etc !**
- **The CMS Heavy Ion group is busily preparing for the upcoming physics runs in pp and PbPb next year**

- **The usual question…**

Why CMS?



- **Hermeticity and resolution**
  - largest coverage in η
  - best in resolution: muons (upsilon), charged tracks
  - fully equipped with all detection layers, including tracker and calorimeters in 2π and 5 units of η
- **DAQ and Trigger**
  - Unique arrangement, reliance on HLT
  - EVERY HI collision can be inspected at HLT
  - Transparent switchover from pp to HI
- **Collaboration**
  - Well integrated into CMS, just ask in the CERN cafeteria..
  - CMS HI group at CERN (~20 people) are working full time on preparation for specifics of HI datataking: lots of work
- **Special feature**
  - E.g. analog silicon and pixel readout: there would be no PHOBOS without that..