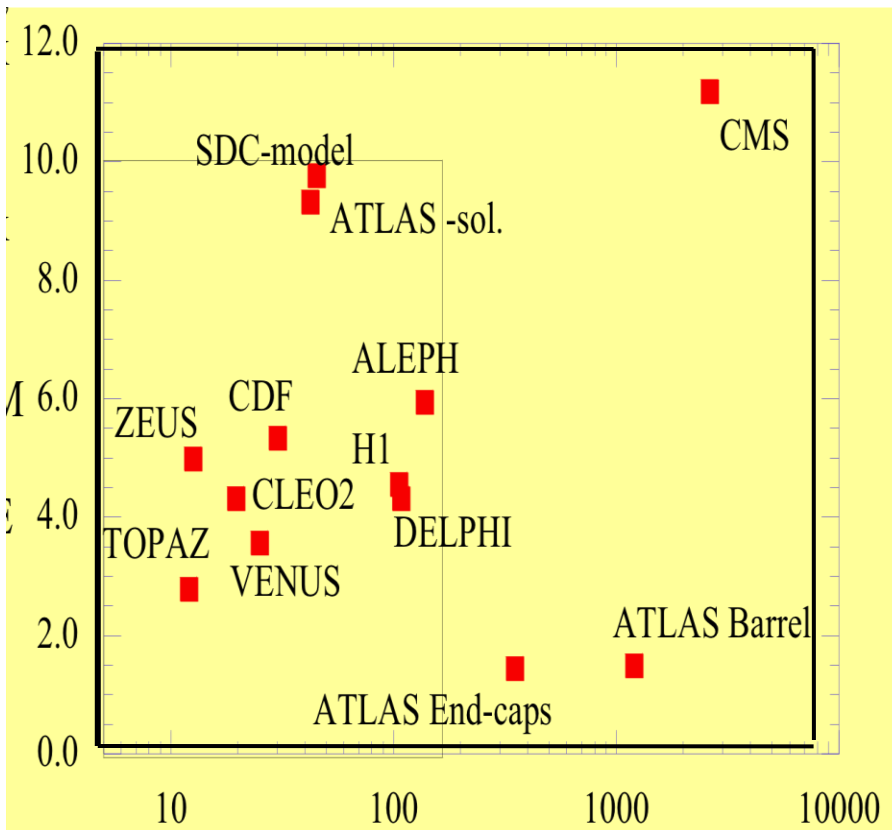
Superconducting Magnets

Design Goal: Measure 1 TeV/c muons with < 10% resolution



E/M (kJ/kg)

Stored Energy (MJ)

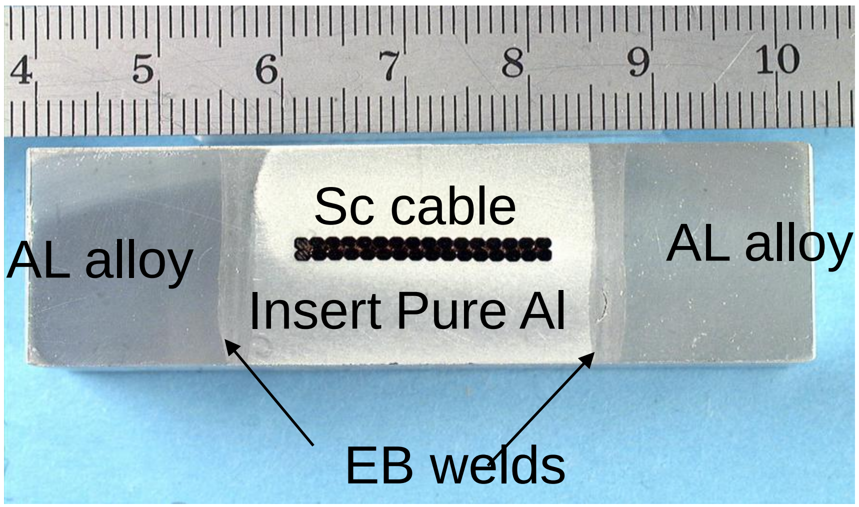
Key Features

As ALEPH

- Passive protection by Quench-Back effect
- Al stabilized NbTi conductor (insert of CMS)
- Indirectly cooled at 4.5 K by thermo siphon circuits
- Inner winding vacuum impregnated with epoxy resin

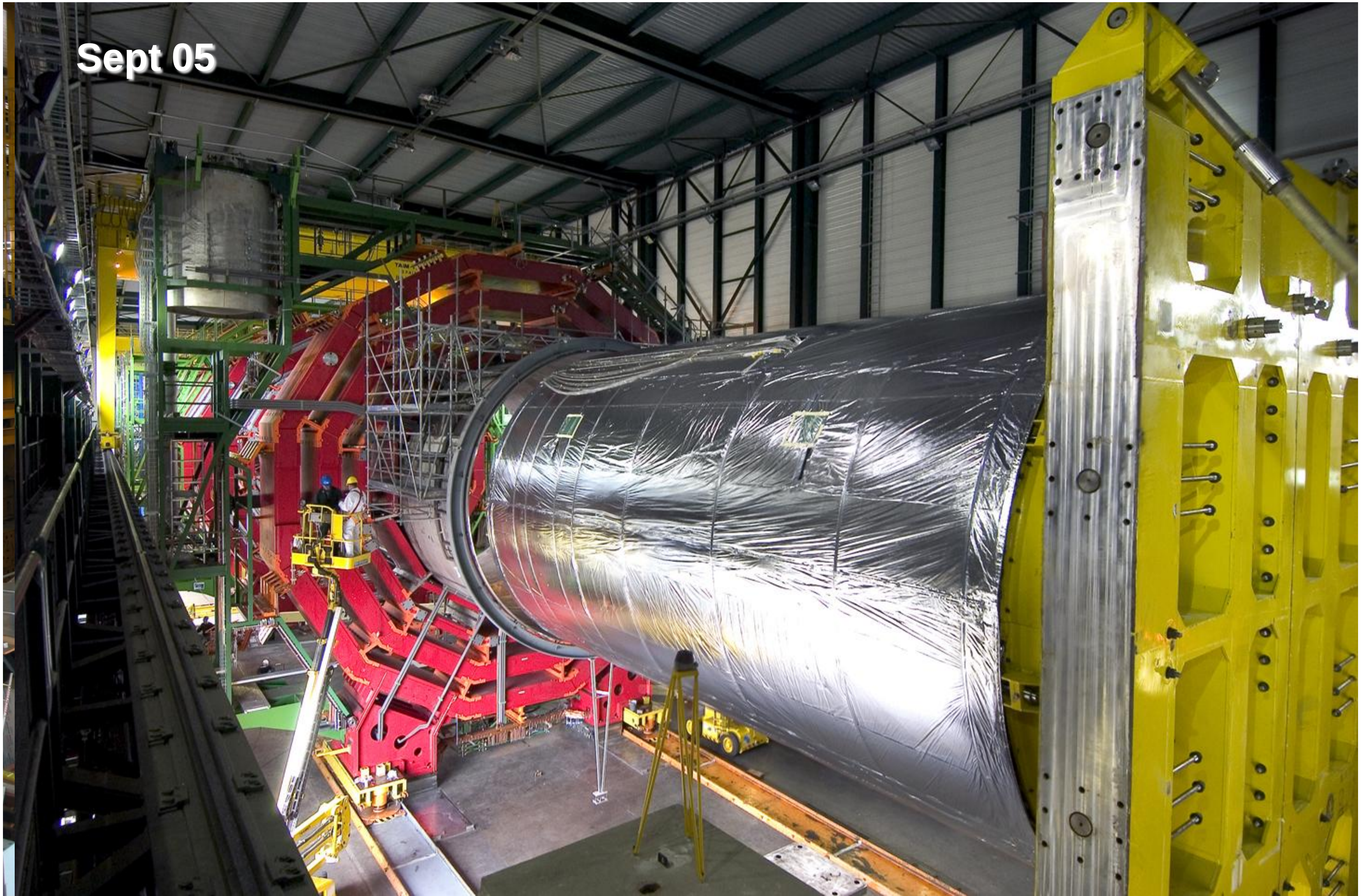
Improvements from ALEPH

- Mechanically reinforced conductor (to contain magnetic forces)
- 4 Layers (because of needed Ampere-turns)
- 5 modules (to limit unit length of conductor)



Assembly of a Coil

Assembly of a Coil

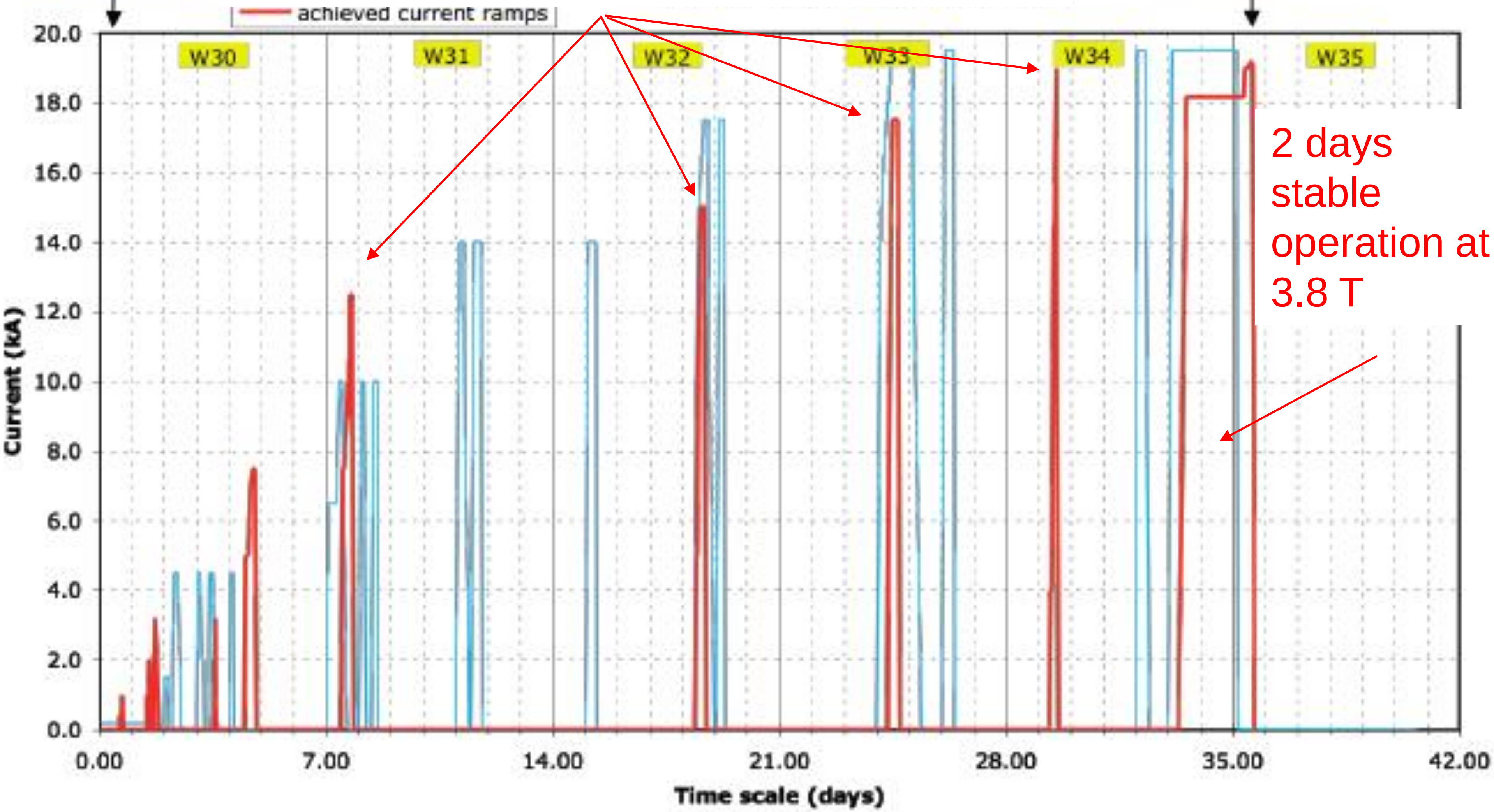


Test of the Magnet (2006)

24 July

Magnet Current Cycles achieved during August

28 August
19 kA, 4 Tesla!



2 days stable operation at 3.8 T

CMS Solenoid

- After 15 years, starting from early design, R&D, pre-industrialization, 6 years of construction, about one year of installation, the CMS coil has been tested successfully.
- From cryogenic, electrical and mechanical tests the coil fulfills all specifications and seems easy to operate.

(A. Hervé Sept 06)

Challenging Detectors

Si Microstrip Detectors

CMS Example: Tracking Technologies Considered

Scintillating fibres, MSGCs, Si Pixels, Si Microstrips

Si technology (ideally) suited to LHC environment

Early 1990's: At the time of the Conceptual Design of the pp Experiments

- Radiation damage poorly understood
- Cost/unit area was prohibitively large
- Large no. of channels required

- **What was known**
  - leakage current increased linearly with fluence
  - type inversion – higher and higher bias voltage required
  - reverse annealing

Development History: Si Microstrip Detectors

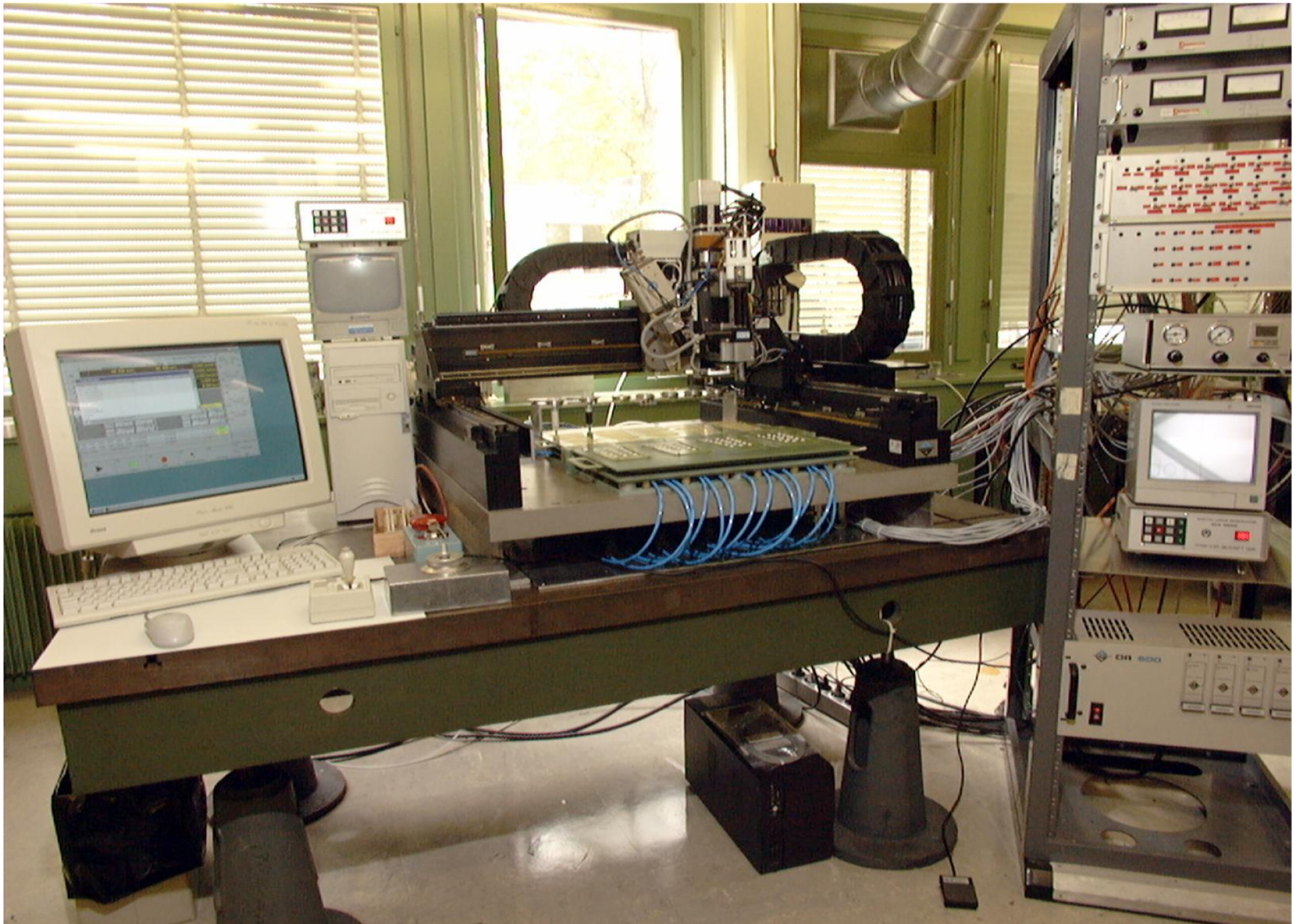
What was done

- leakage current dealt with fast amplifiers
- HV behaviour improved by careful processing (pioneered by Hamamatsu) and use of multiple guard rings
- Si detectors had to be kept permanently cold
- Cost/unit area significantly reduced by growing larger diameter ingots (6” instead of 4”), simpler single-sided processing (p-on-n)
- Implementation of front-end read-out chip in industry standard deep sub-micron technology

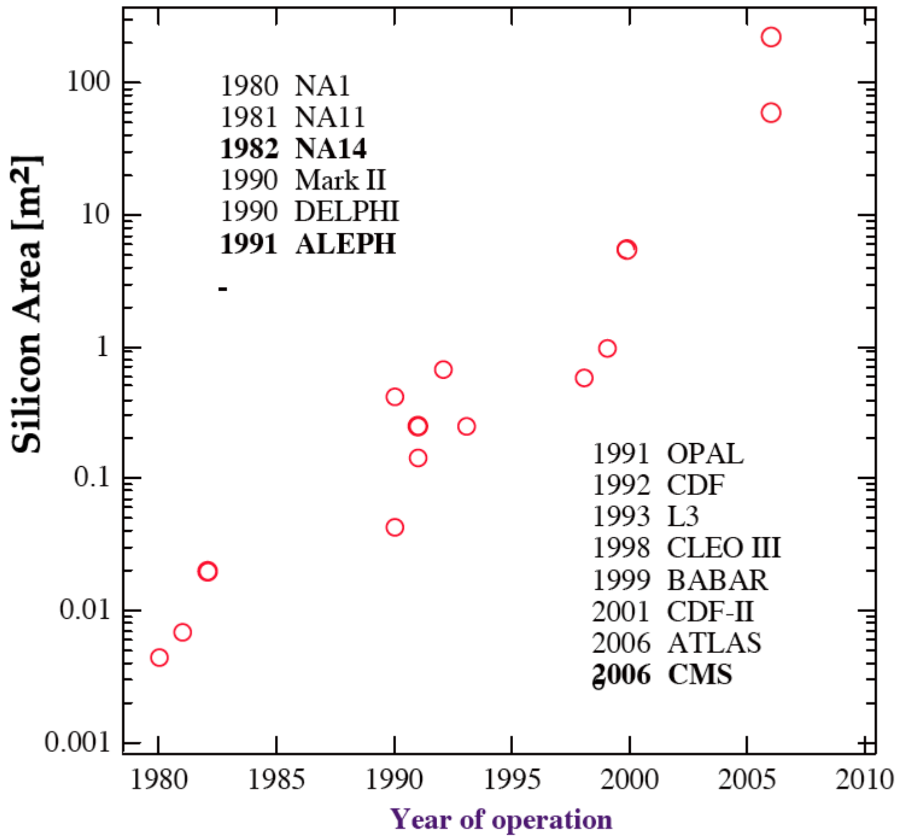
- In 1999 progress over the previous 10 years had been sufficient for CMS to go to an “**all silicon” tracker**
- **Small matter of producing 200 m^2 of Si microstrip detectors**
    - Introduce a large degree of automation usual in microelectronics industry

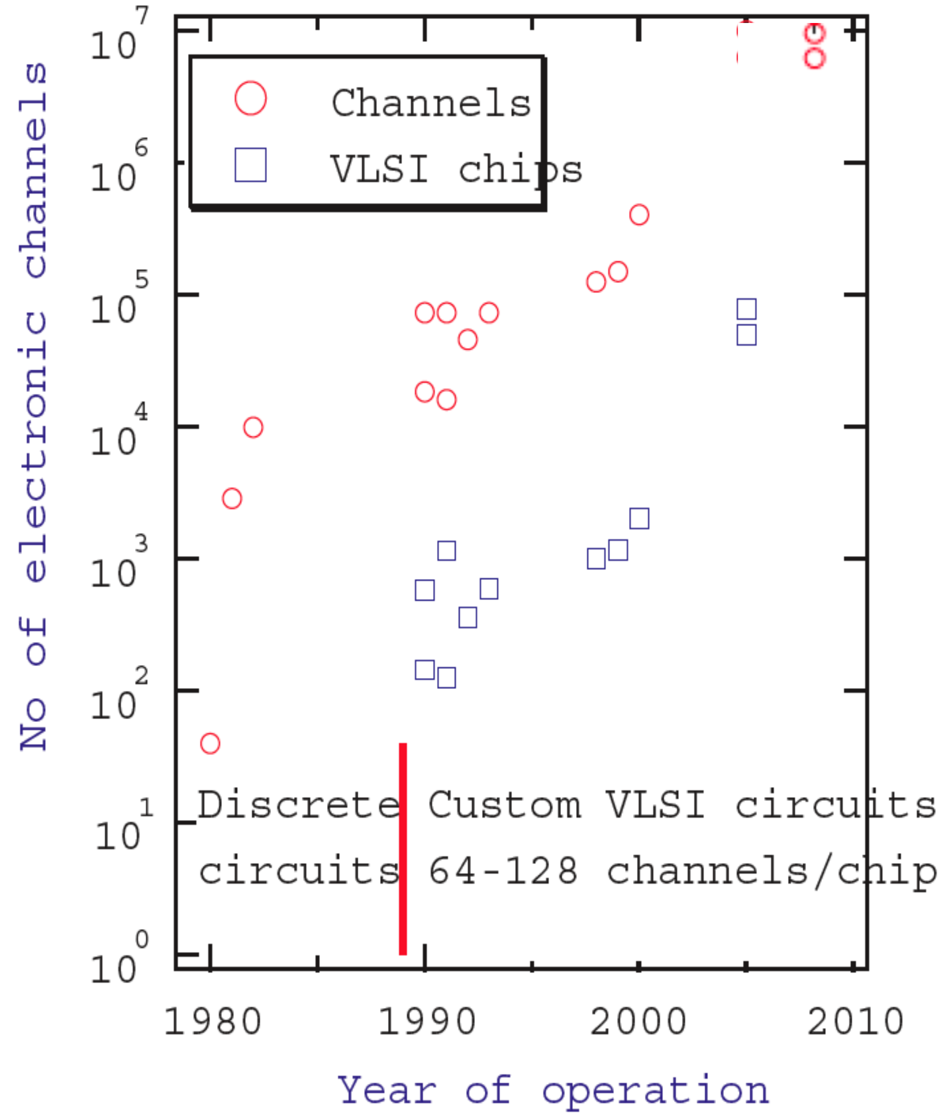
Automation in Si Module Production

Automated module assembly and micro-bonding (17k modules)

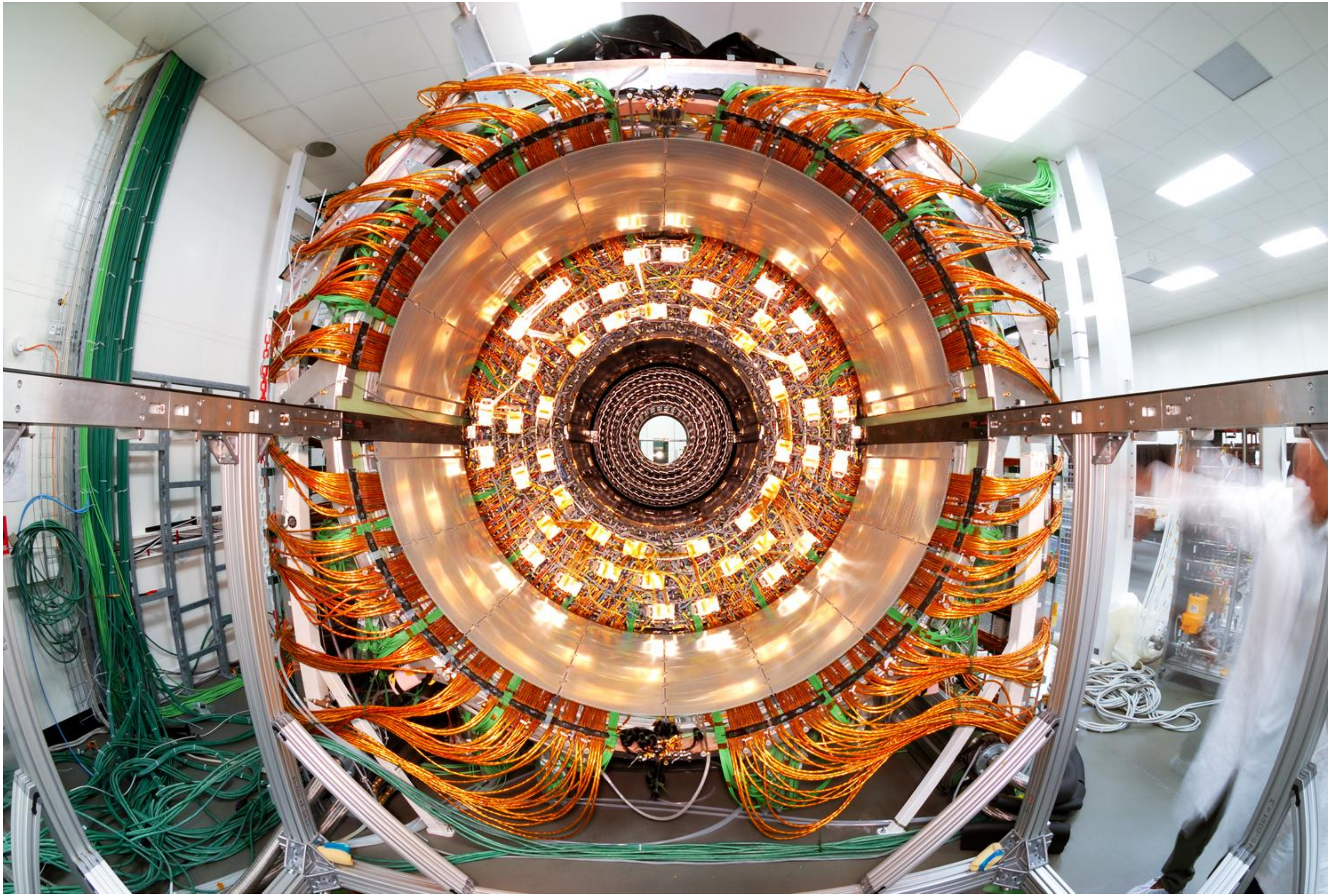


Evolution in Si Detectors and Electronics





CMS Si Tracker



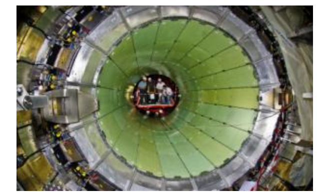
Si Tracker

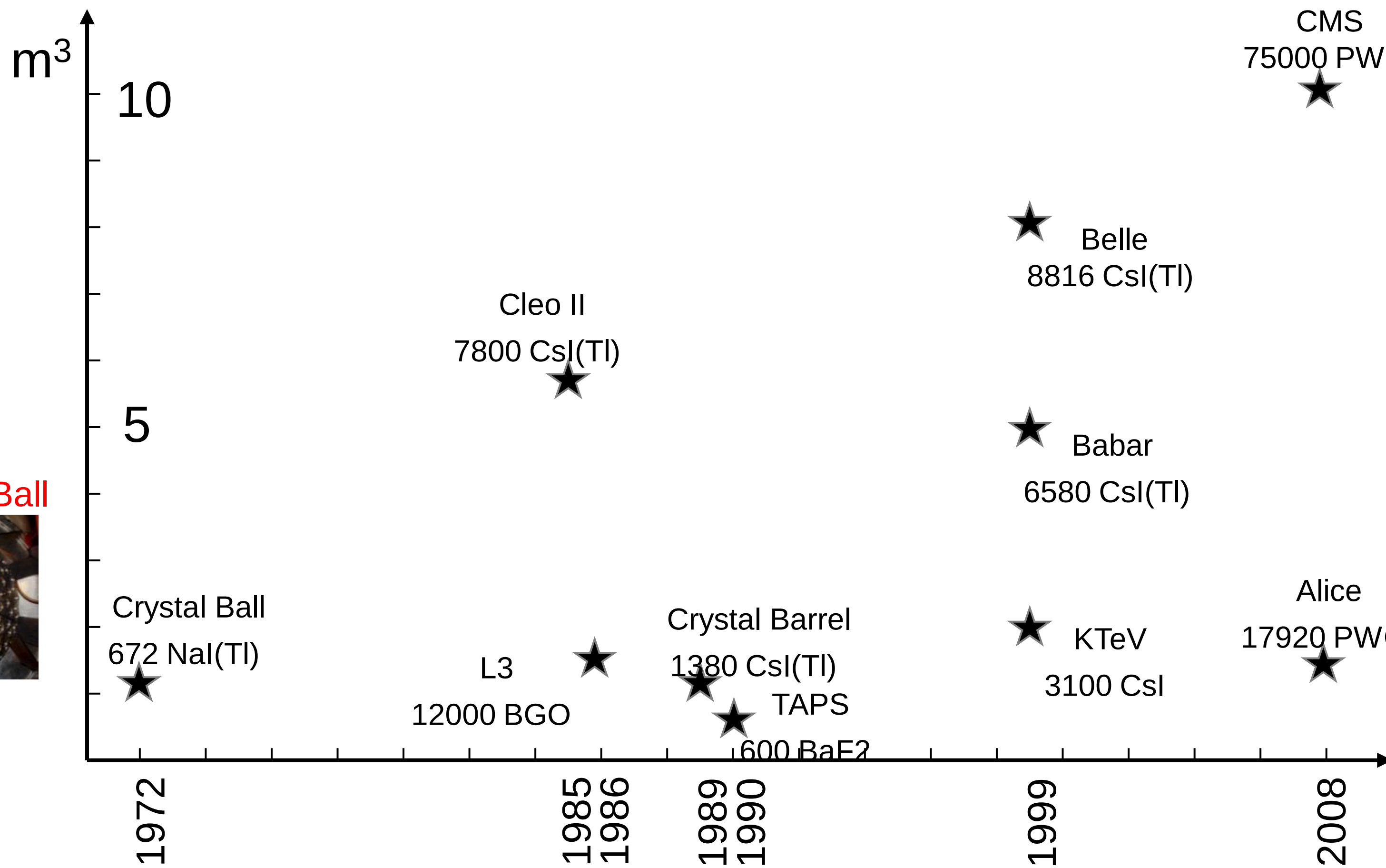
Lead Tungstate ECAL

Design Goal: Measure the energies of photons from a decay of the Higgs boson **to precision of ≤ 0.5%**

CMS chose scintillating crystals

CMS





From Crystal Ball

P. Lecoq

Timeline for the Preparation of LHC Experiments

e.g. $PbWO_4$ Crystals for CMS

Idea (1993 – few yellowish cm³ samples)

→ **R&D** (1993-1998: improve rad. hardness: purity, stoechiometry,defects)

→ **Prototyping** (1994-2001: large matrices in test beams, monitoring)

→ **Mass manufacture** (1997-2008: increase industrial capacity, QC)

→ **Systems Integration** (2001-2008: tooling, assembly)

→ **Installation and Commissioning** (2007-2008)

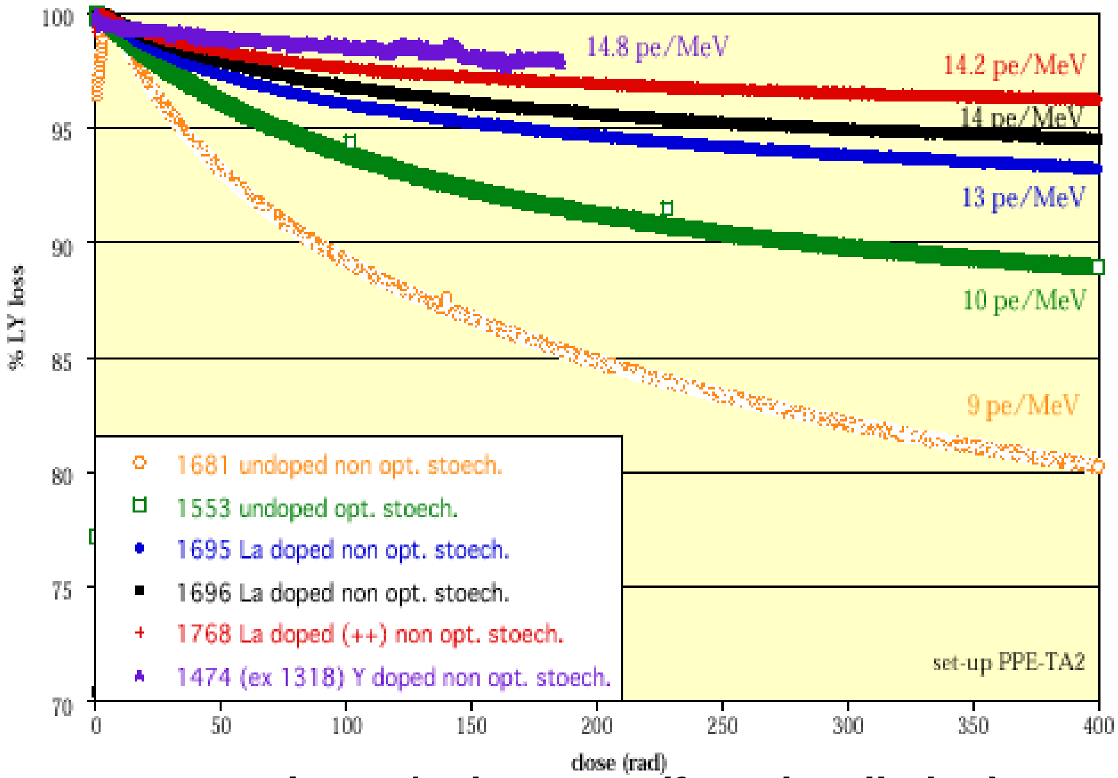
→ **Data Taking** (2008 onwards)

Δt ~ 15 years !!!

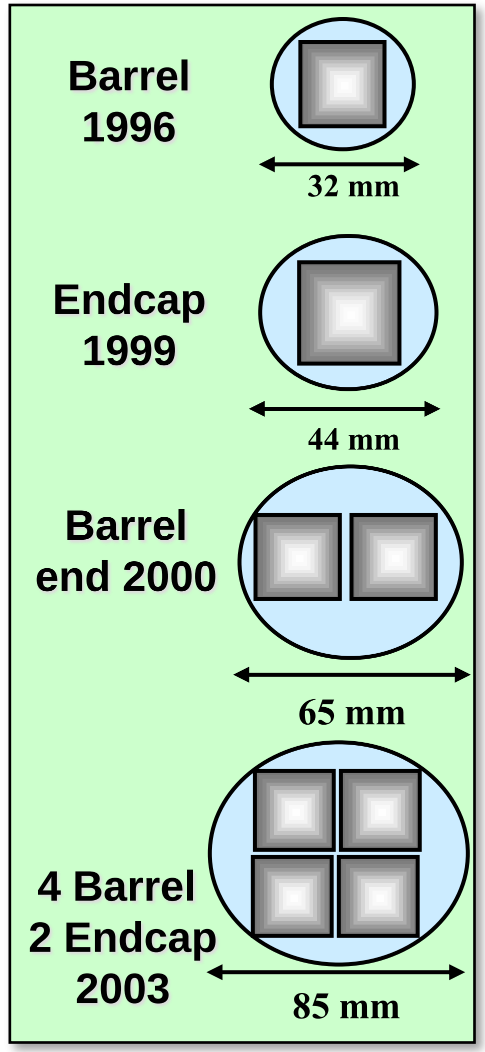
Detector Development

To improve radiation tolerance of $PbWO_4$ crystals

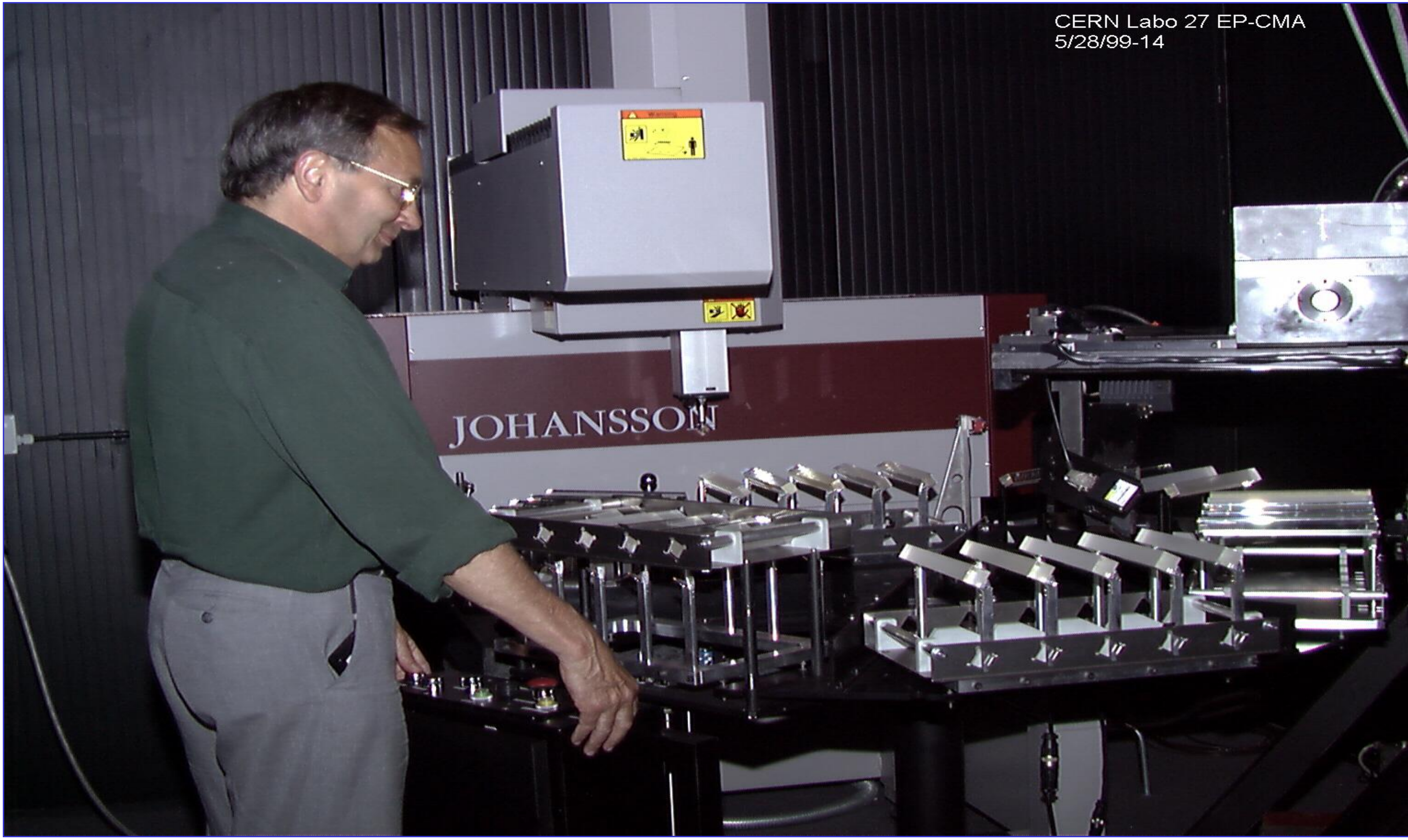
- Decrease concentration of defects
  - Stoechiometry, annealing
- Compensation of remaining defects
  - Control of purity of raw material, specific doping



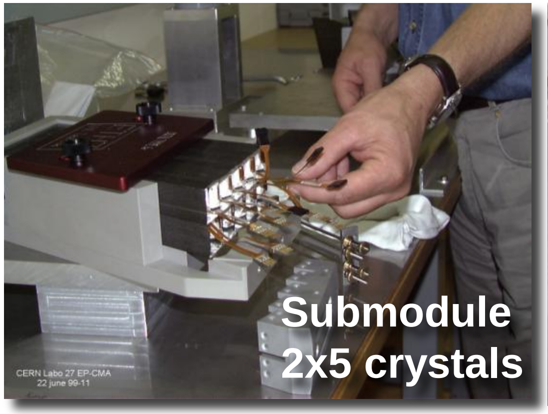
LY loss v/s dose rate (front irradiation)

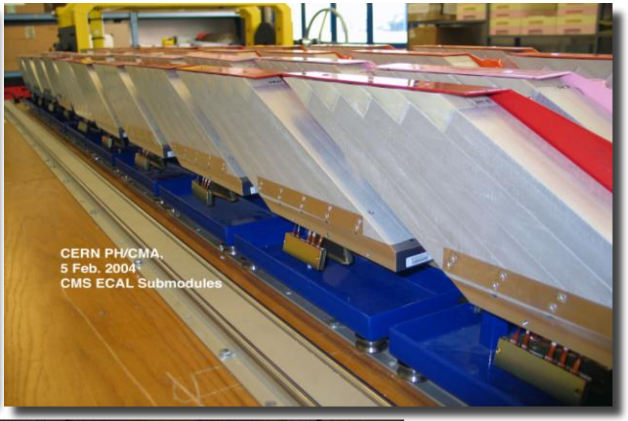


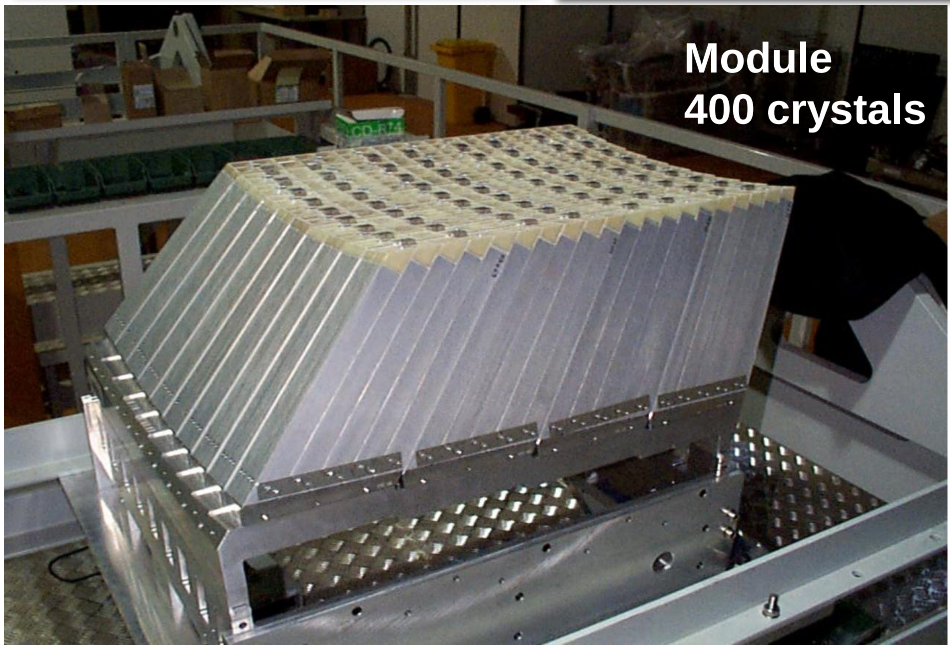
Crystals Production

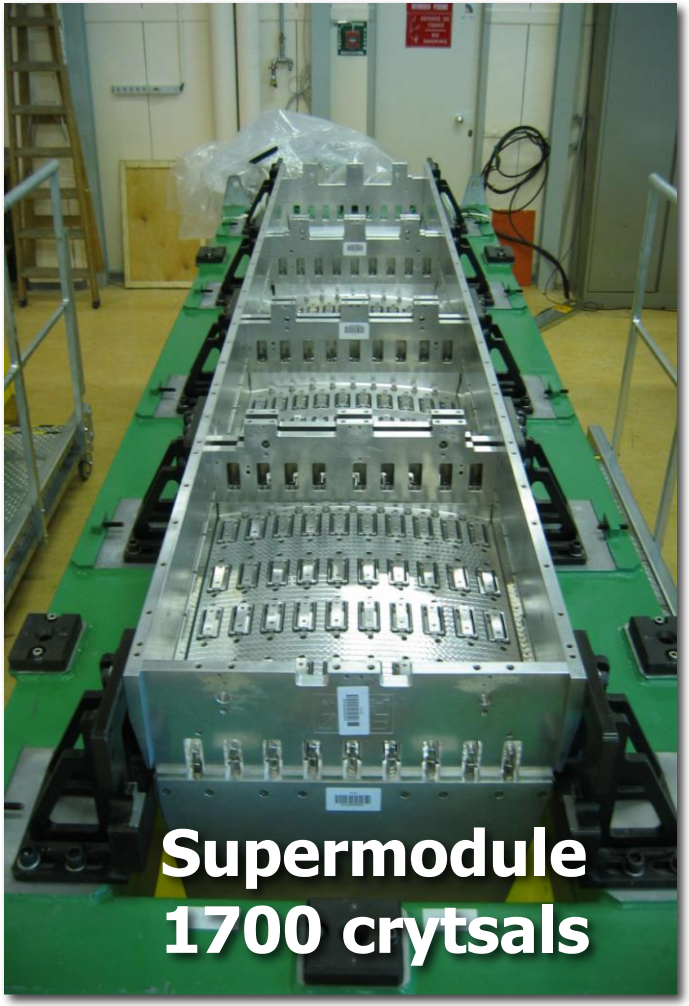


Assembling the Calorimeter





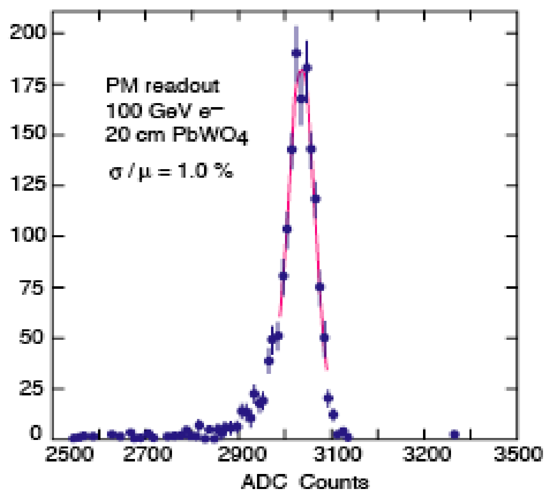




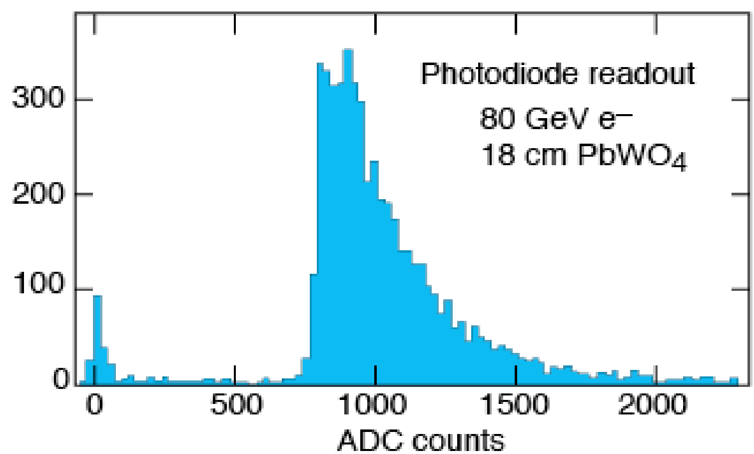
Total 36 Supermodules

Choice of the Photodetector

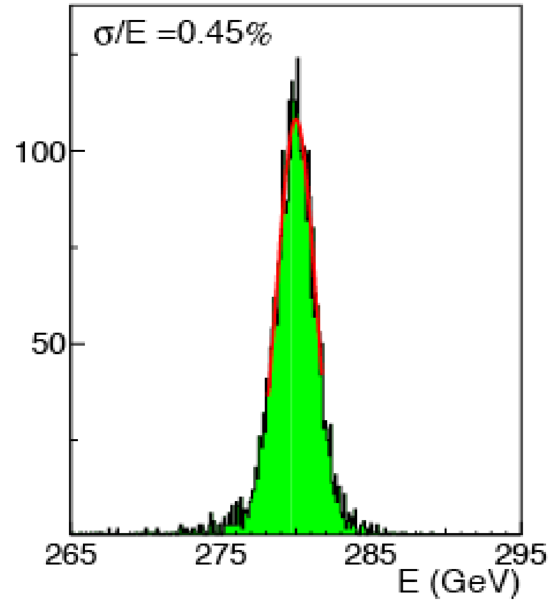
Photomultiplier Readout



Si Photodiode Readout

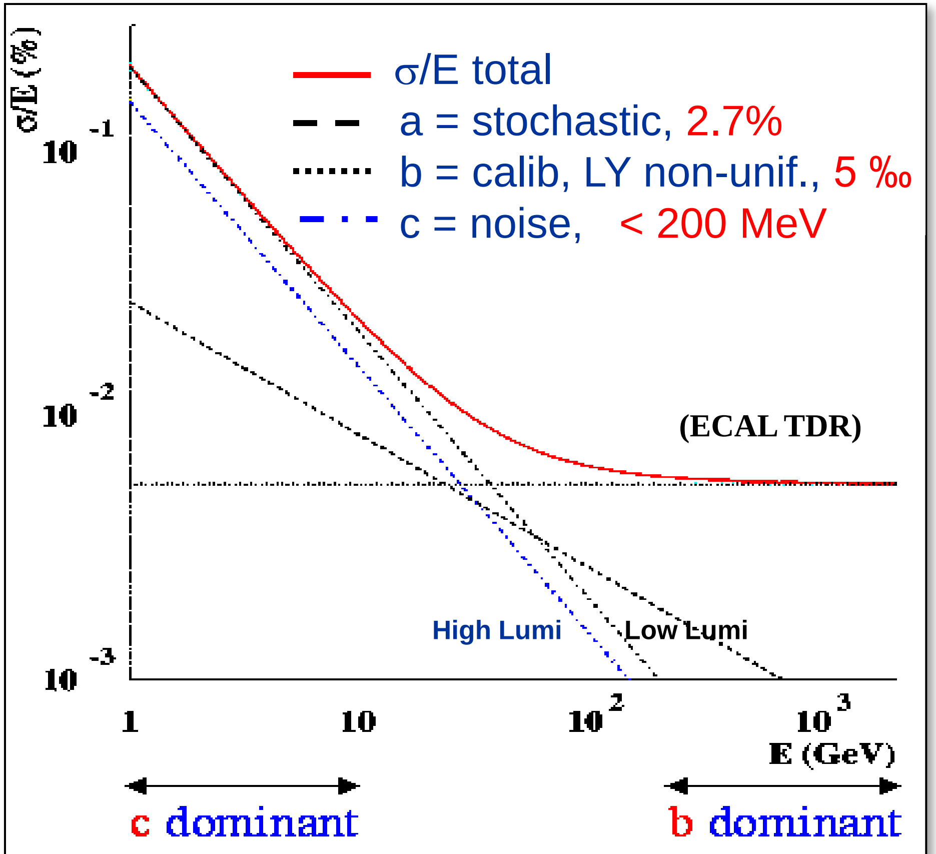


Avalanche Photodiode Readout



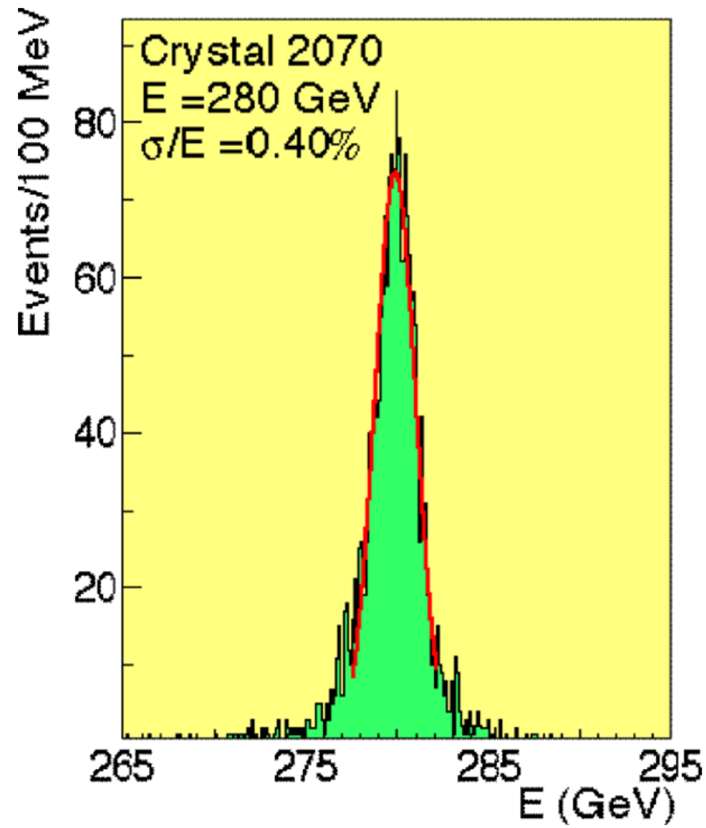
Transparency from 1993

CMS ECAL: Performance



$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

3 x 3 Crystals

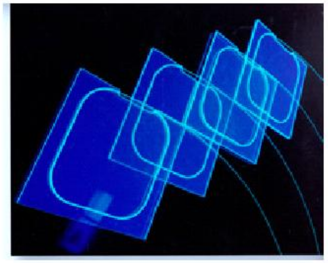


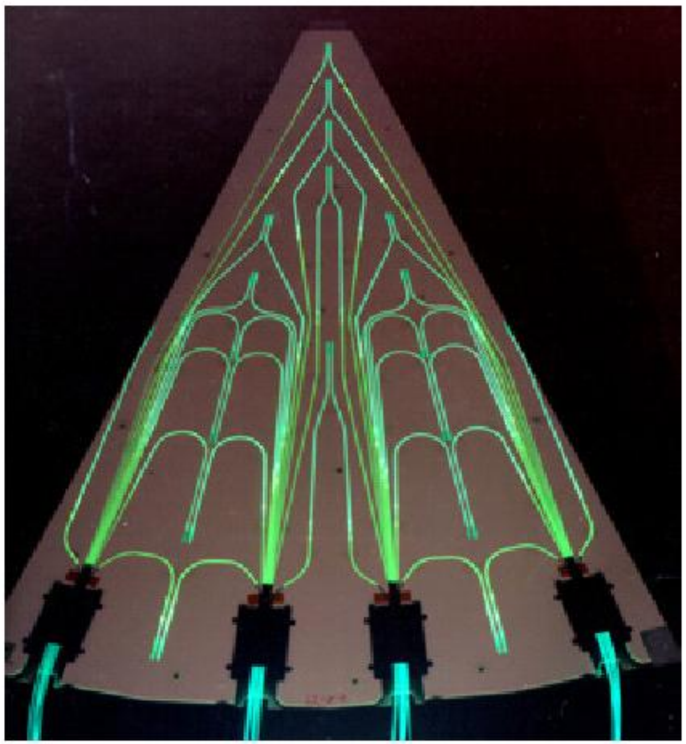
Goal $$\frac{\sigma}{E} = \frac{2.7\%}{E} \oplus 0.5\% \oplus \frac{200\ MeV}{E}$$

CMS HCAL

Routing of clear fibres to optical disconnects

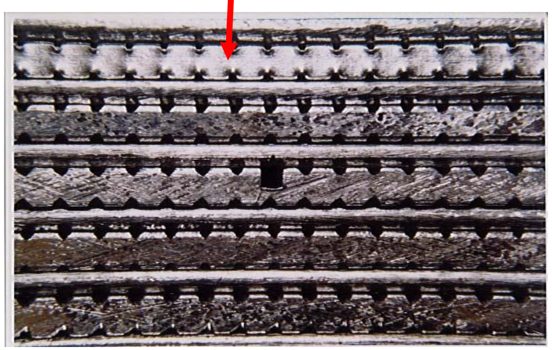
WLS fibres Embedded in plastic scint. plates





Central Region (|η|<3) : Brass/Scintillator with WLS fibre readout, projective geometry, granularity $\Delta\eta \times \Delta\phi = 0.0875 \times 0.0875$

CMS: Very Forward Calorimeter



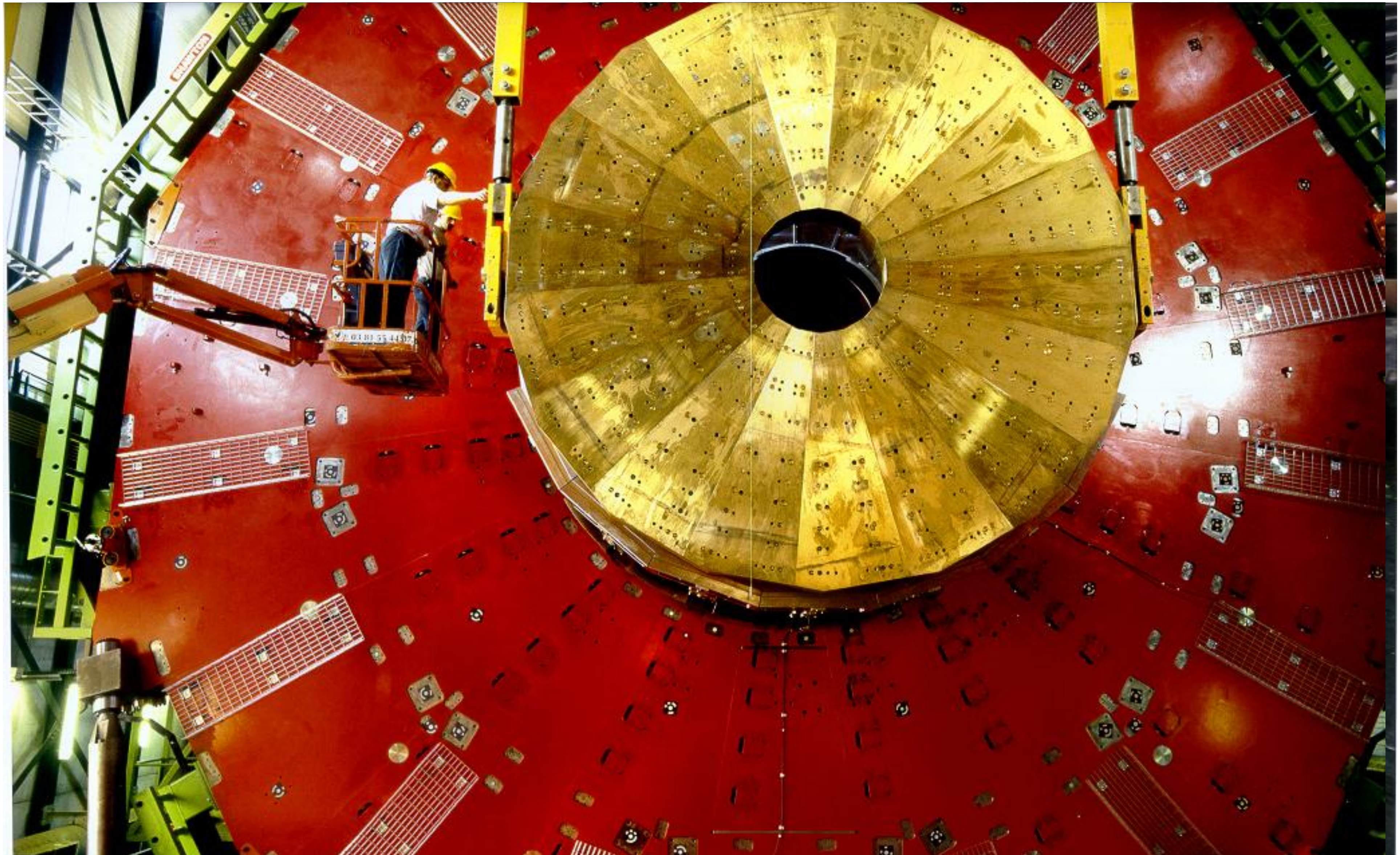
Fibres insertion in
HF wedges

Forward Region (3<|η|<5): Fe/Quartz Fibre, Cerenkov light

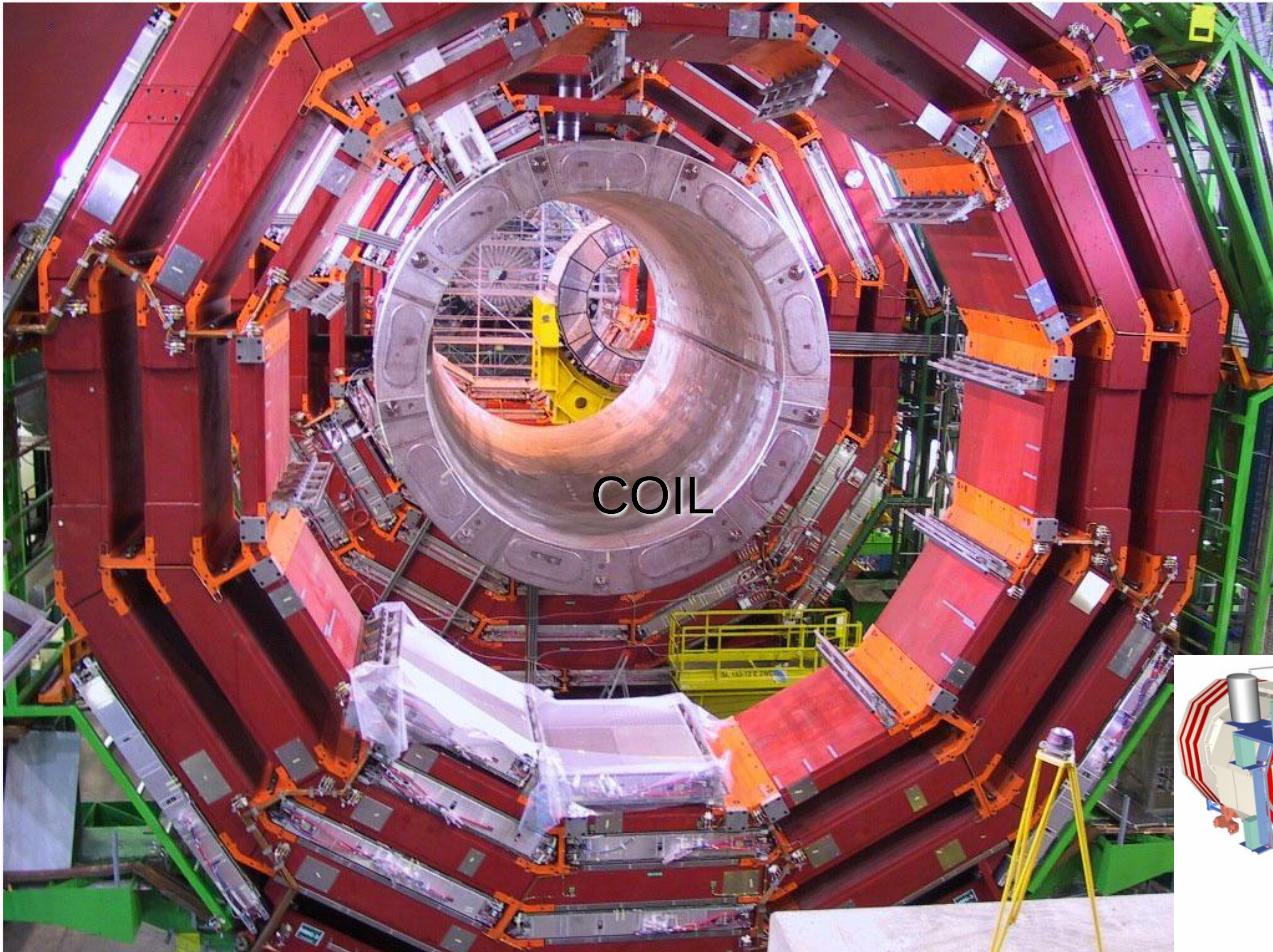
Resistive Plate Chambers

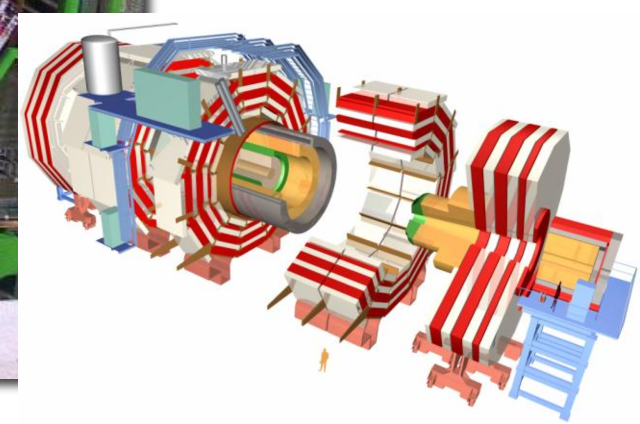
CMS: Surface Site in 2000

CMS: Swords to Ploughshares



CMS: Surface Hall in Feb 2006

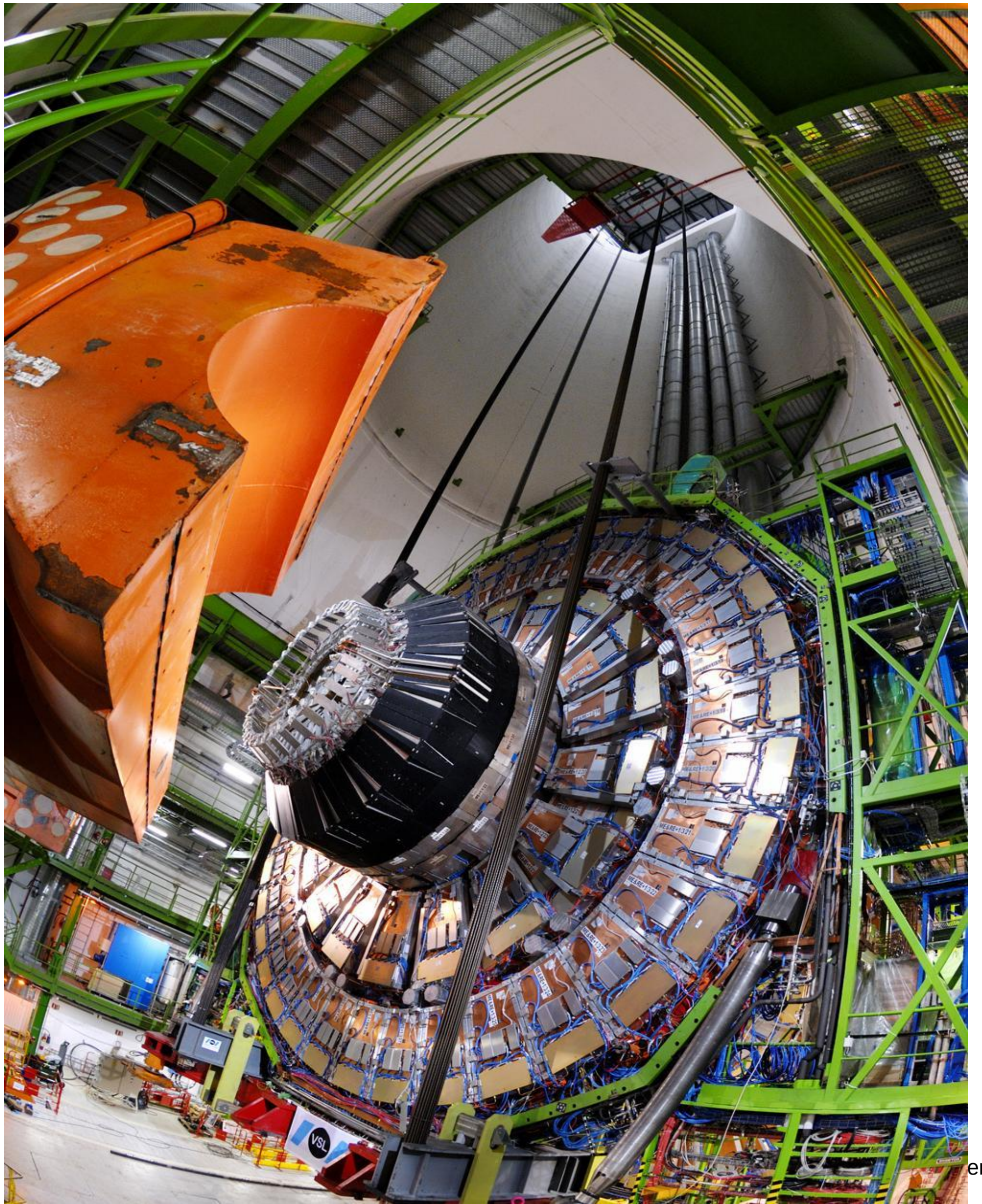




Underground Experiment Cavern

Late 2004

Spectacular Operations



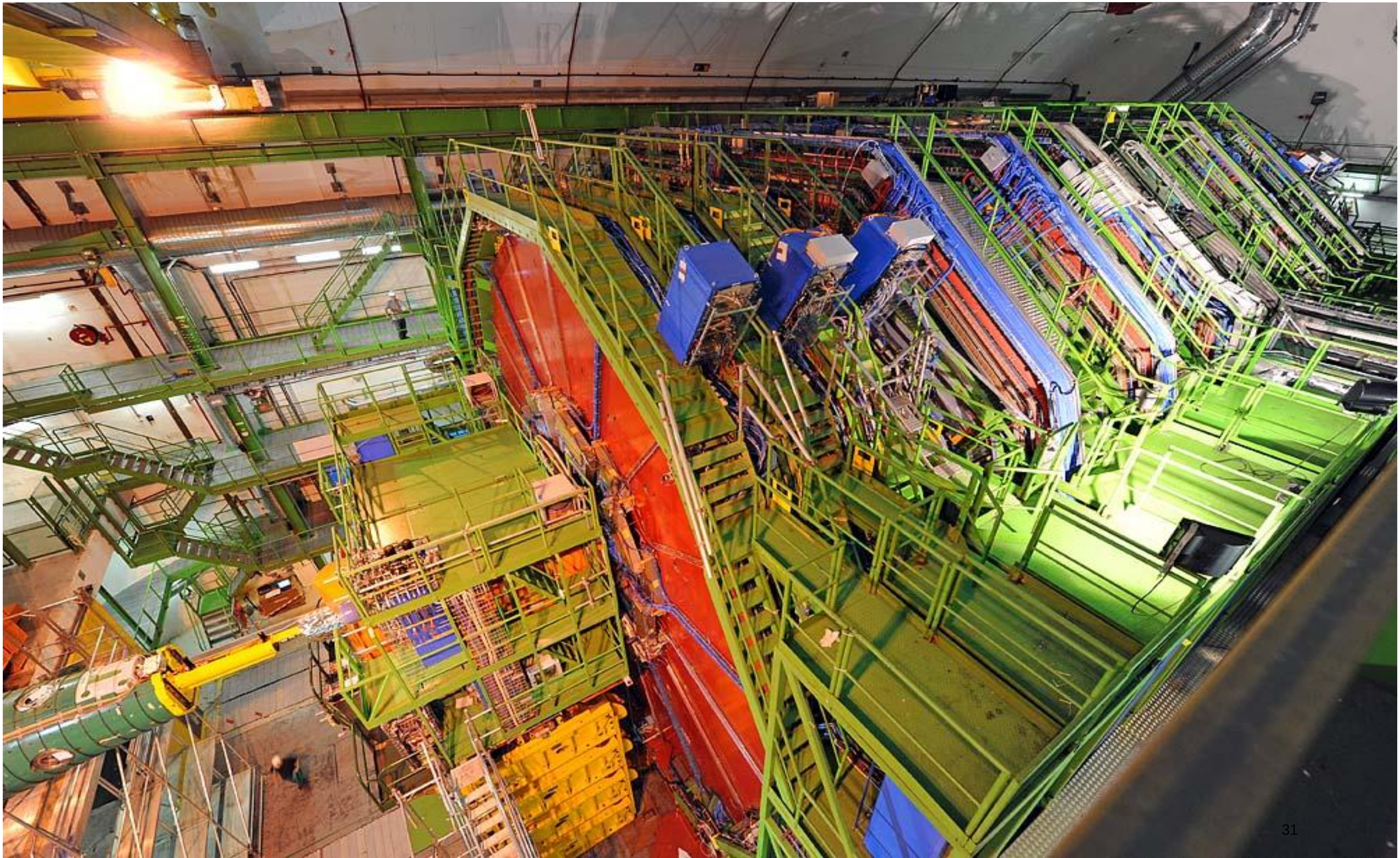
Spectacular Operations (Feb. 2007)

Cables, Pipes and Oprical Fibres !

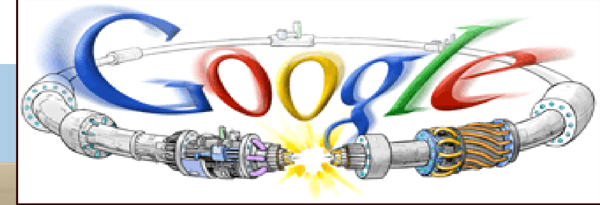
Nov 2007

Took 50’000 man hours

CMS Detector First Closed (Sep'08)



10 September 2008: LHC inauguration day



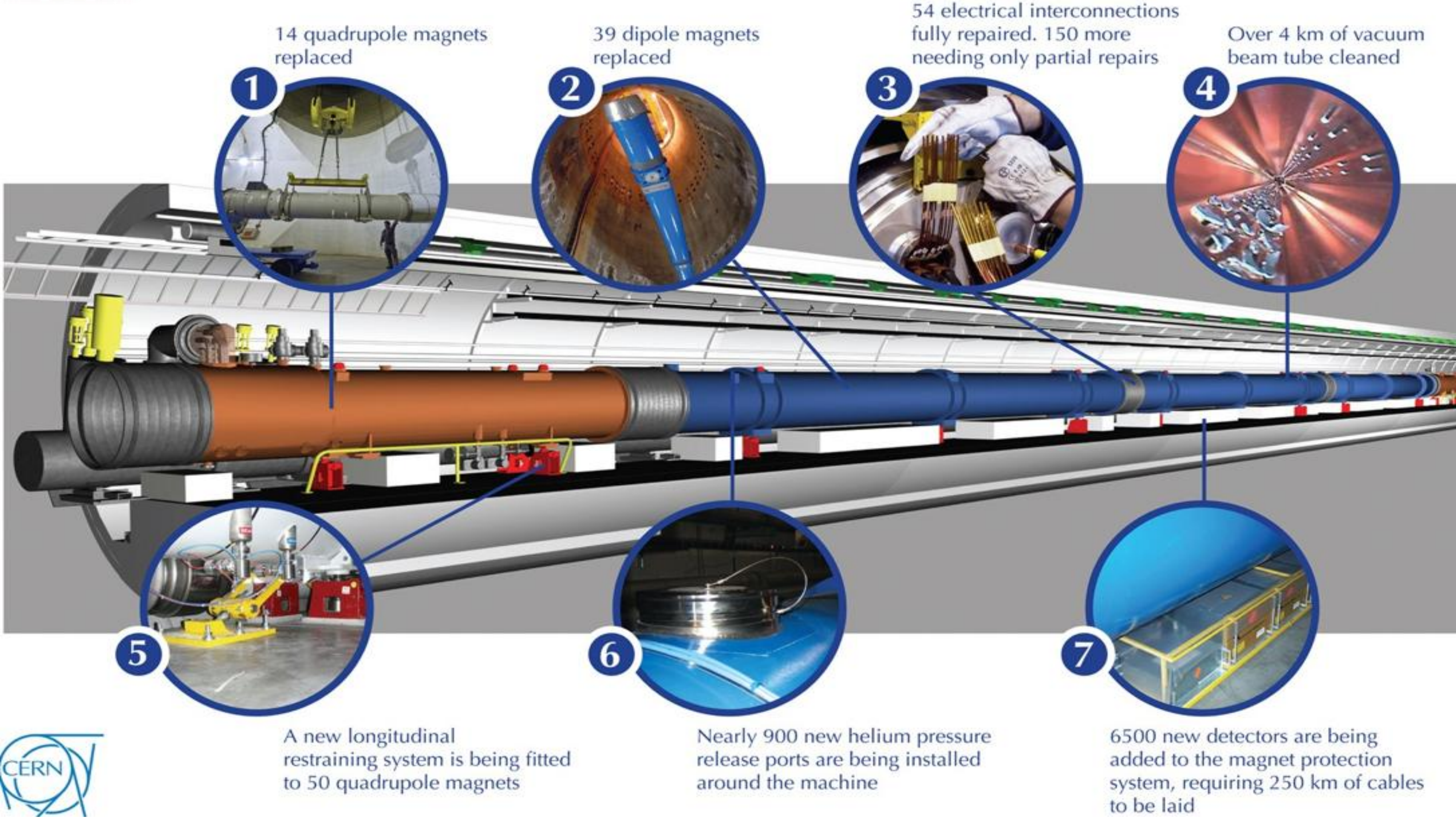
First (single) beams circulating in the machine

Five CERN DGs, from conception to realization: Schopper, Rubbia, Llewellyn Smith, Maiani, Aymar (from right to left) 5 year terms!!

Sept 19 2008 Incident: Collateral Damage

1. During powering test of the last main-bend circuit to just above 5 TeV an incident occurred resulting in the triggering of quench heaters of about 100 magnets and a large He discharge into the tunnel, provoking a shock-wave within 2 cells (about 300 m)
2. High pressure build up damaged the magnet interconnects and the super-insulation
3. Perforation of the beam tubes resulted in pollution of the vacuum system with soot from the vaporization and with debris from the super insulation.

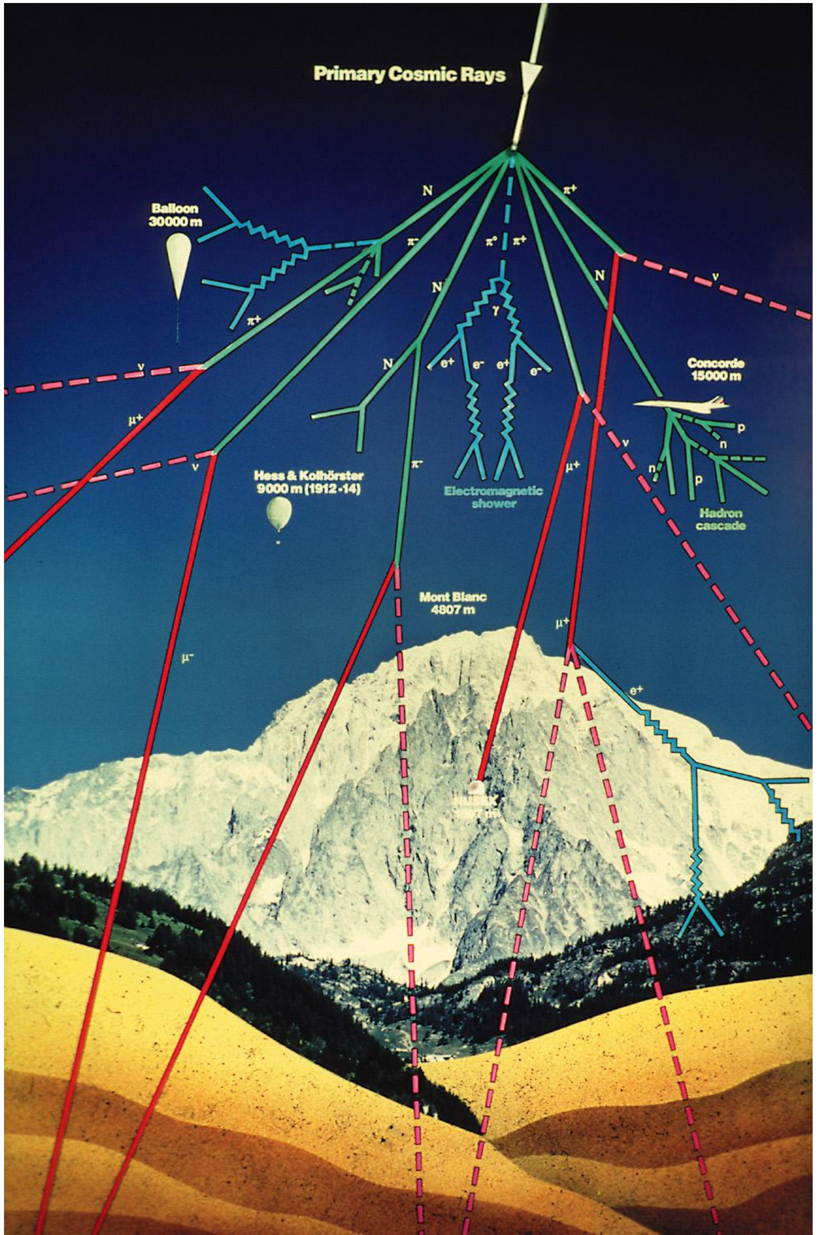
The LHC repairs in detail

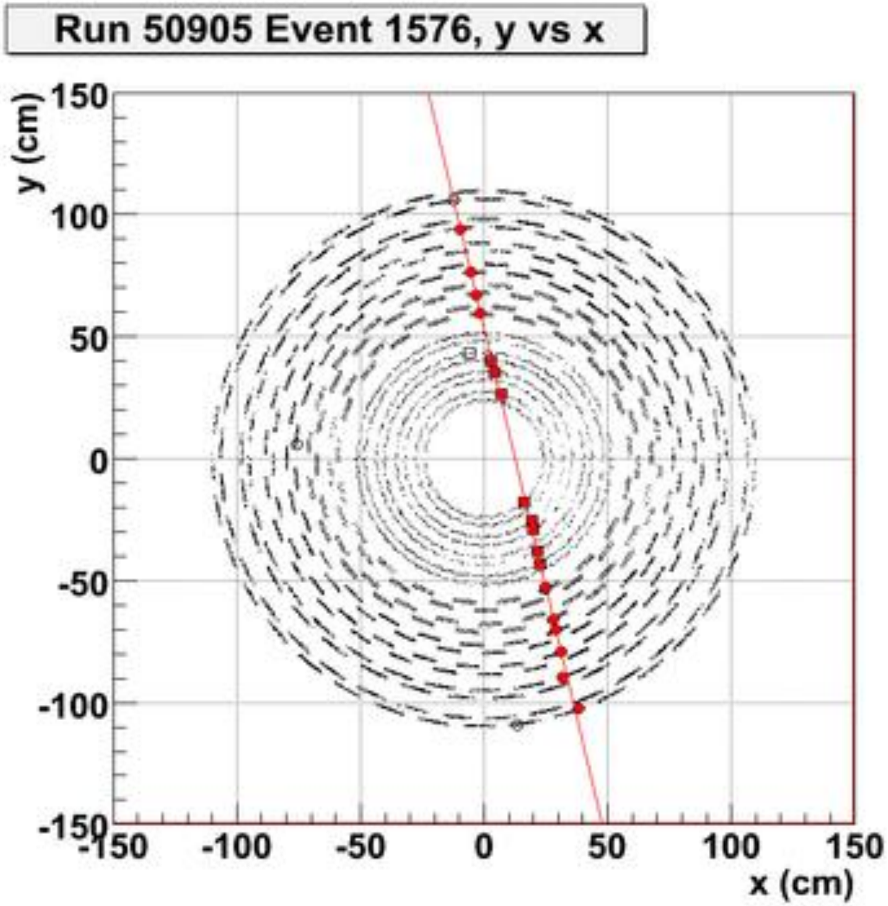


Preparation of the Experiments and Data Taking

The Experiments recorded data
i) using cosmic ray muons
ii) LHC beams

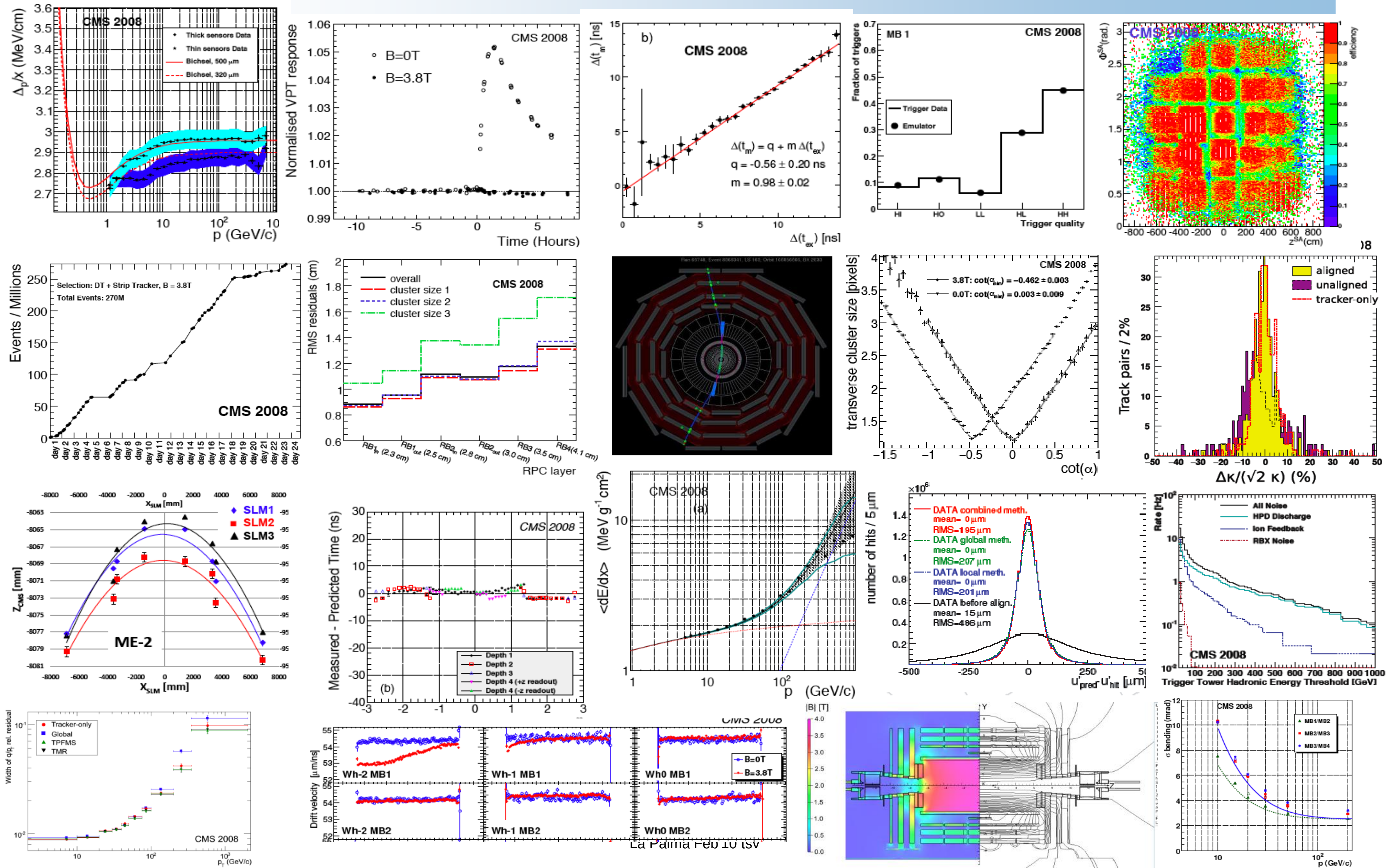
Cosmic Rays



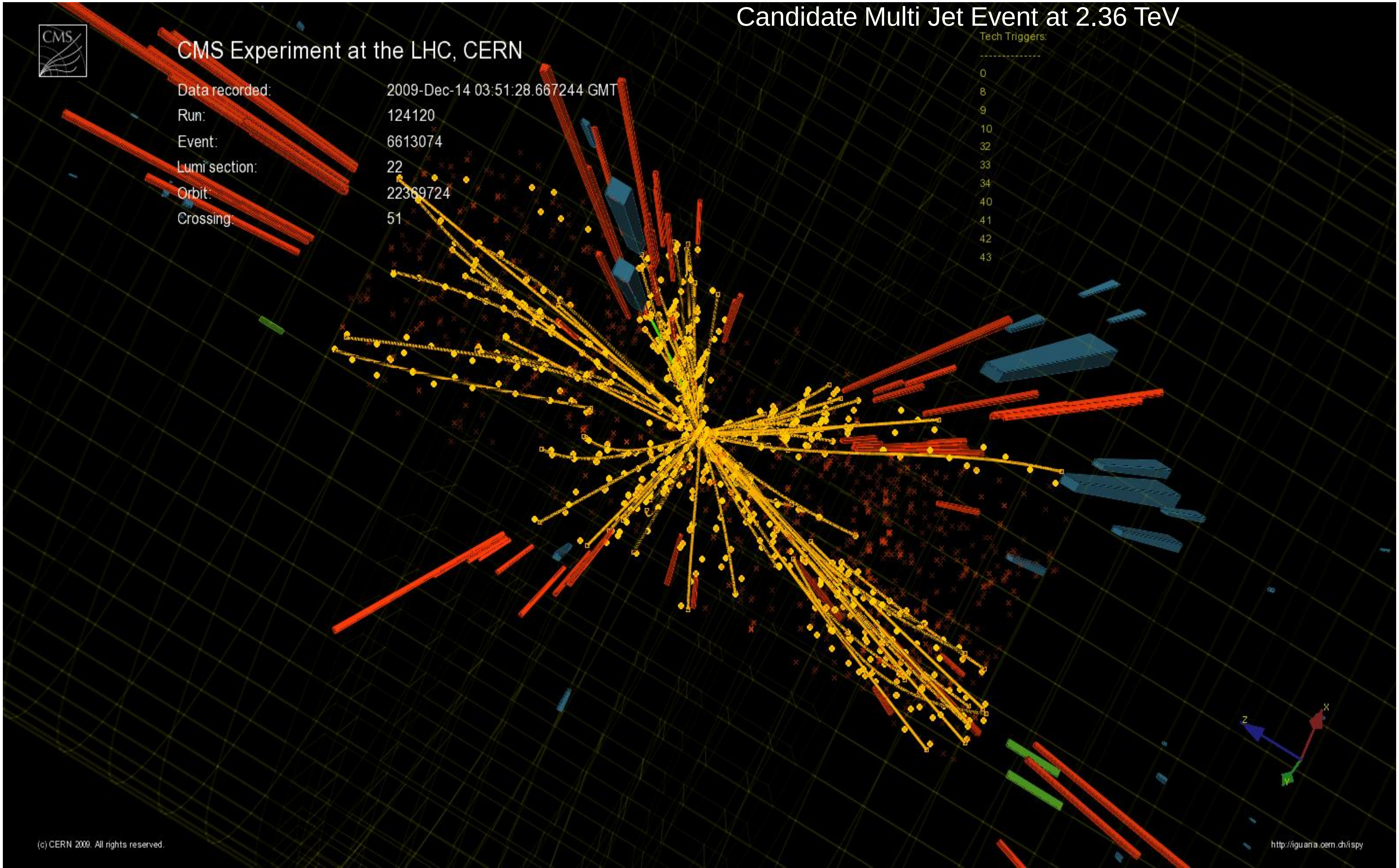


Approx. 1 billion cosmic ray muon "events' recorded by CMS (2008/2009)
Over 20 papers published

CRAFT: Publishing 23 Papers in JINST

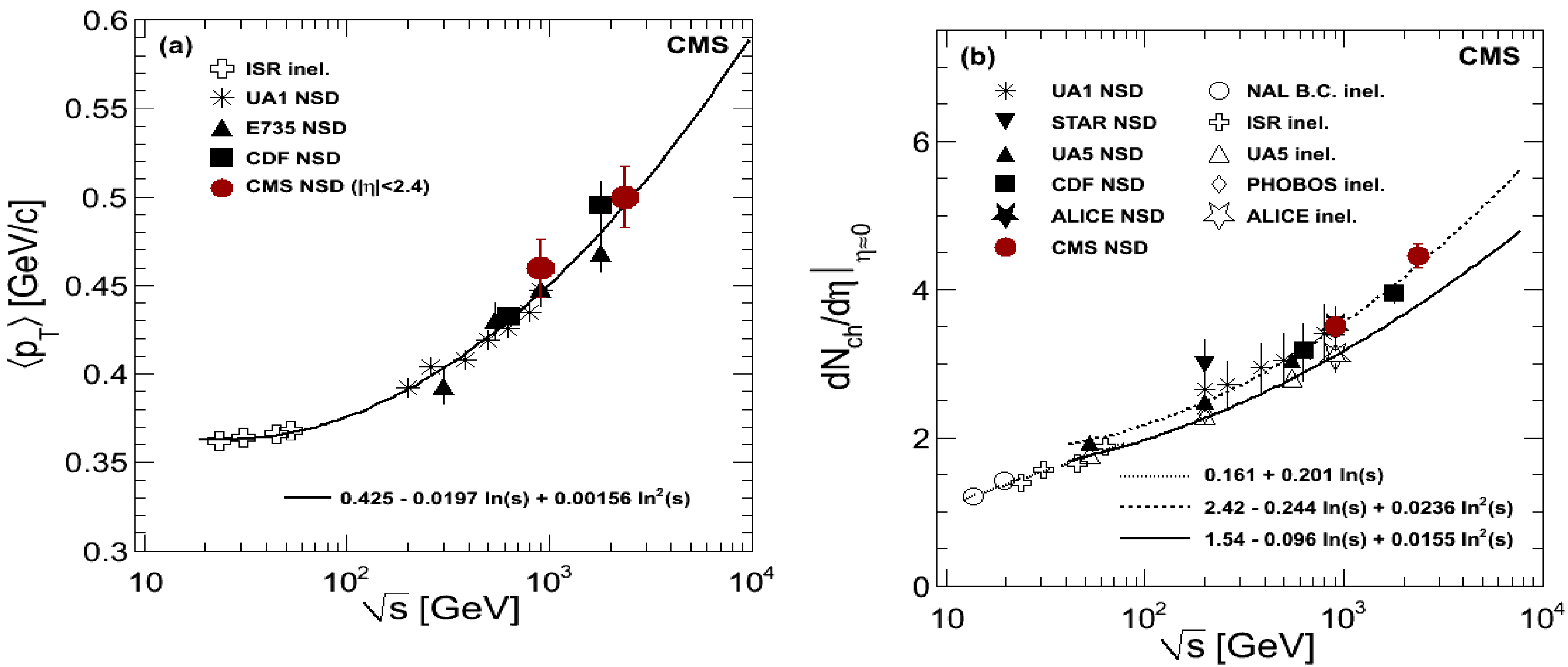


First Collisions at 0.9 and 2.36 TeV (Nov/Dec'09)



First Published Results within Months

"Transverse momentum of charged hadrons at √s =900 and 2360GeV"
JHEP02(2010)041



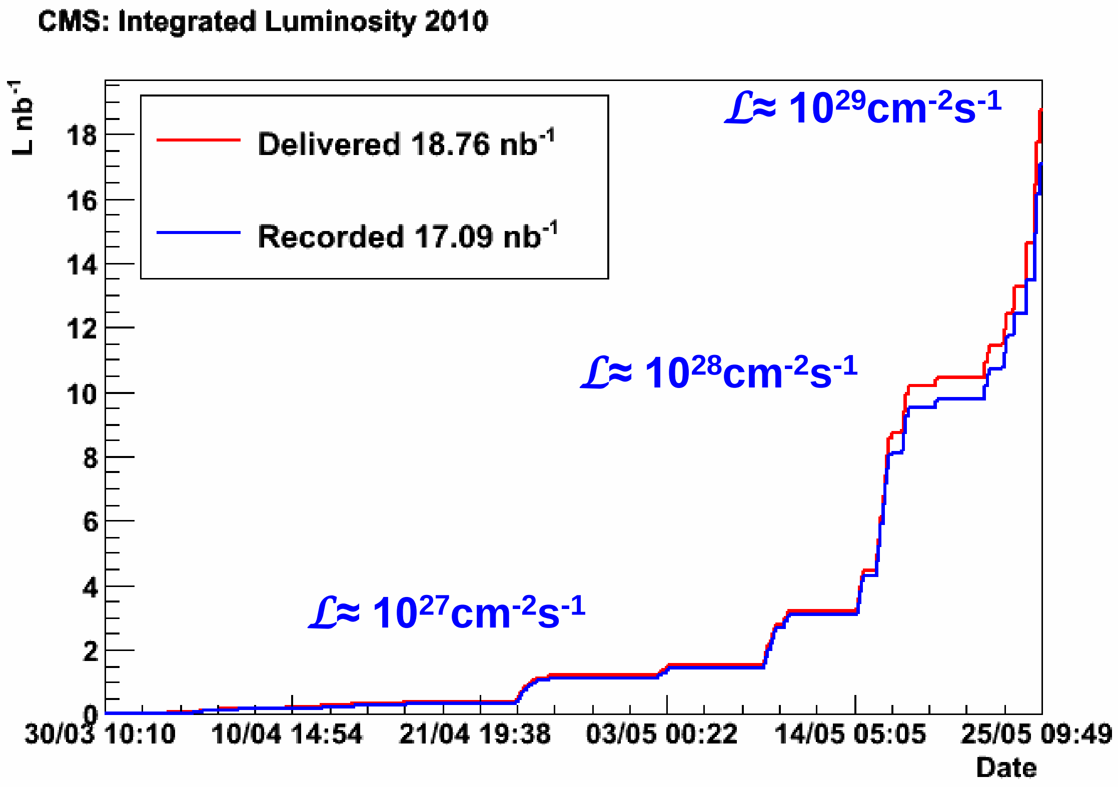
CMS Detector Recording Collisions at 7 TeV
A Big Step Up in Energy

Started in March 2010

LHC Experiments are performing according to the exacting design requirements set out 15 years ago – auguring well for the future

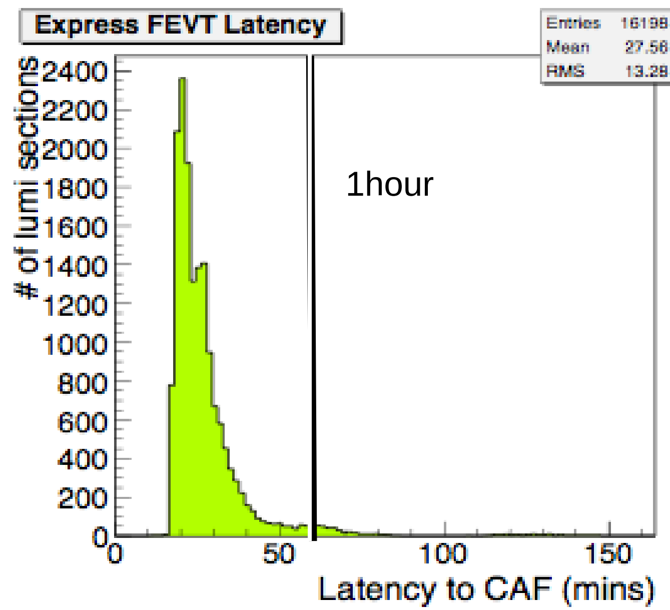
First 2 months of 7 TeV operations

Reliable operations with **~19nb^{-1}** delivered by LHC and **~17nb^{-1}** of data collected by CMS. Overall data taking efficiency **>91%.** After quality flags and data certification for physics (**~95%**) we end up with **~16nb^{-1}** of good data for physics.

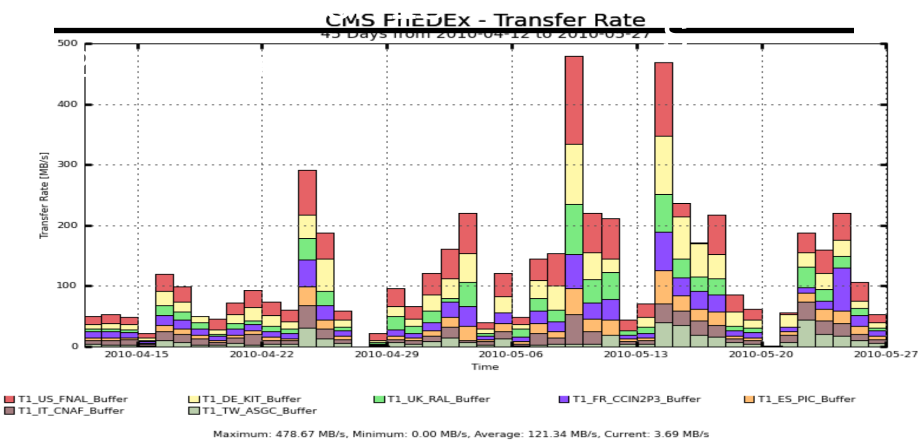


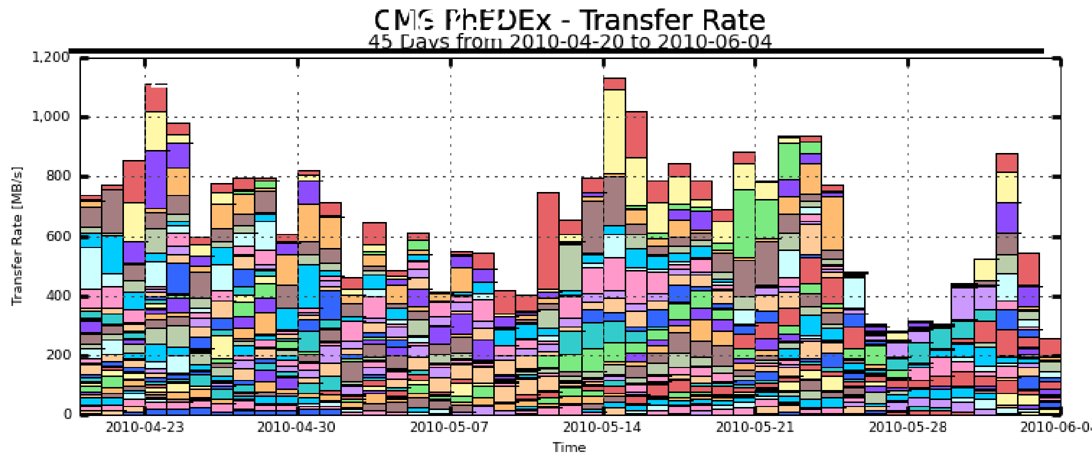
Computing: Processing/Transfer

- Data processing proceeded very smoothly.
  - Tier-0. Software and infrastructure are stable
- Tier-1s and Tier-2s making reliable contributions
  - All 7 Tier-1 fully participating.
  - Many re-processing cycles handled very well so far .
- 49 Tier-2s received collision data and 57 Tier-2s participate to simulation
- > 465 users submitting jobs for analyses (and number increasing weekly)

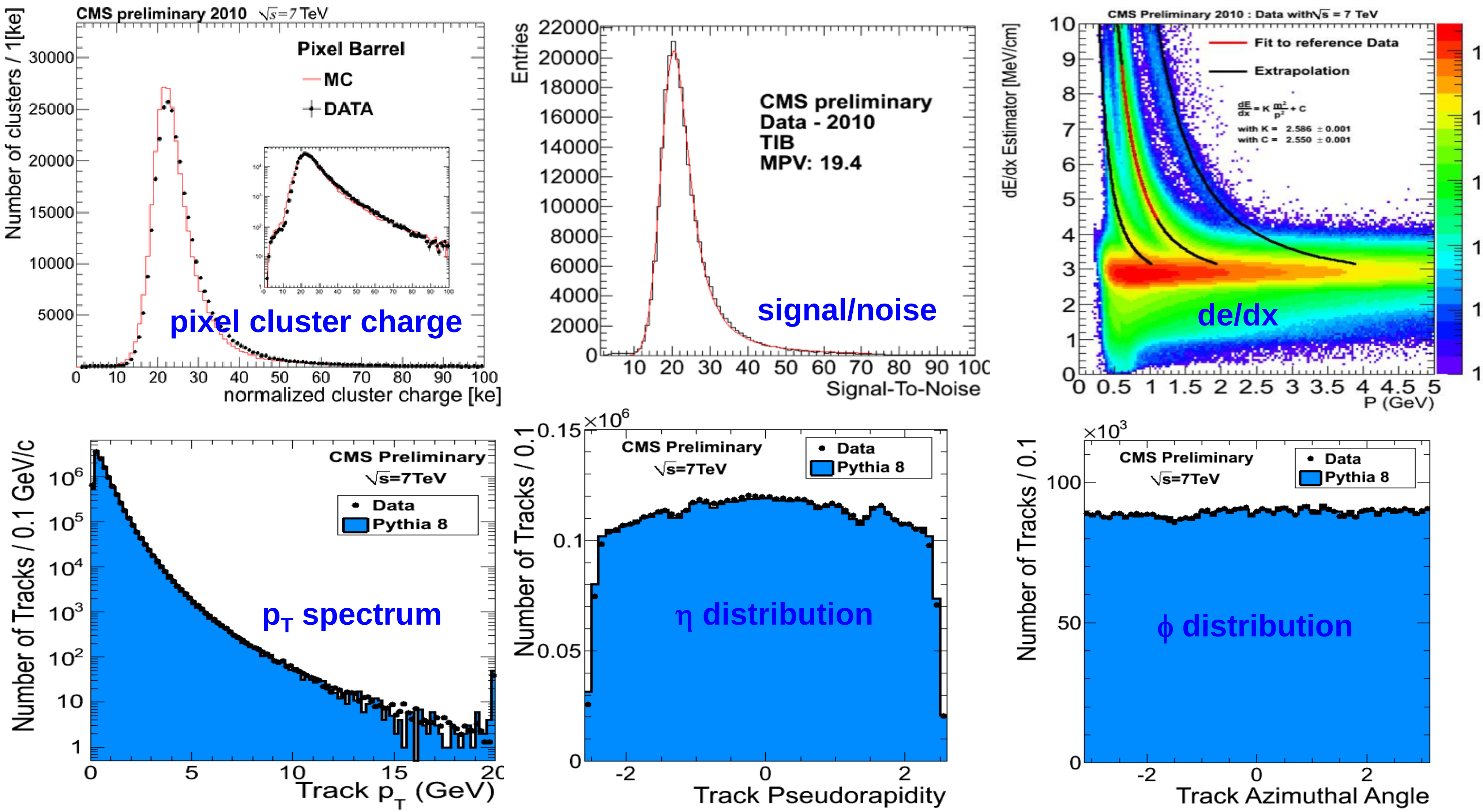


(a) Express Latency

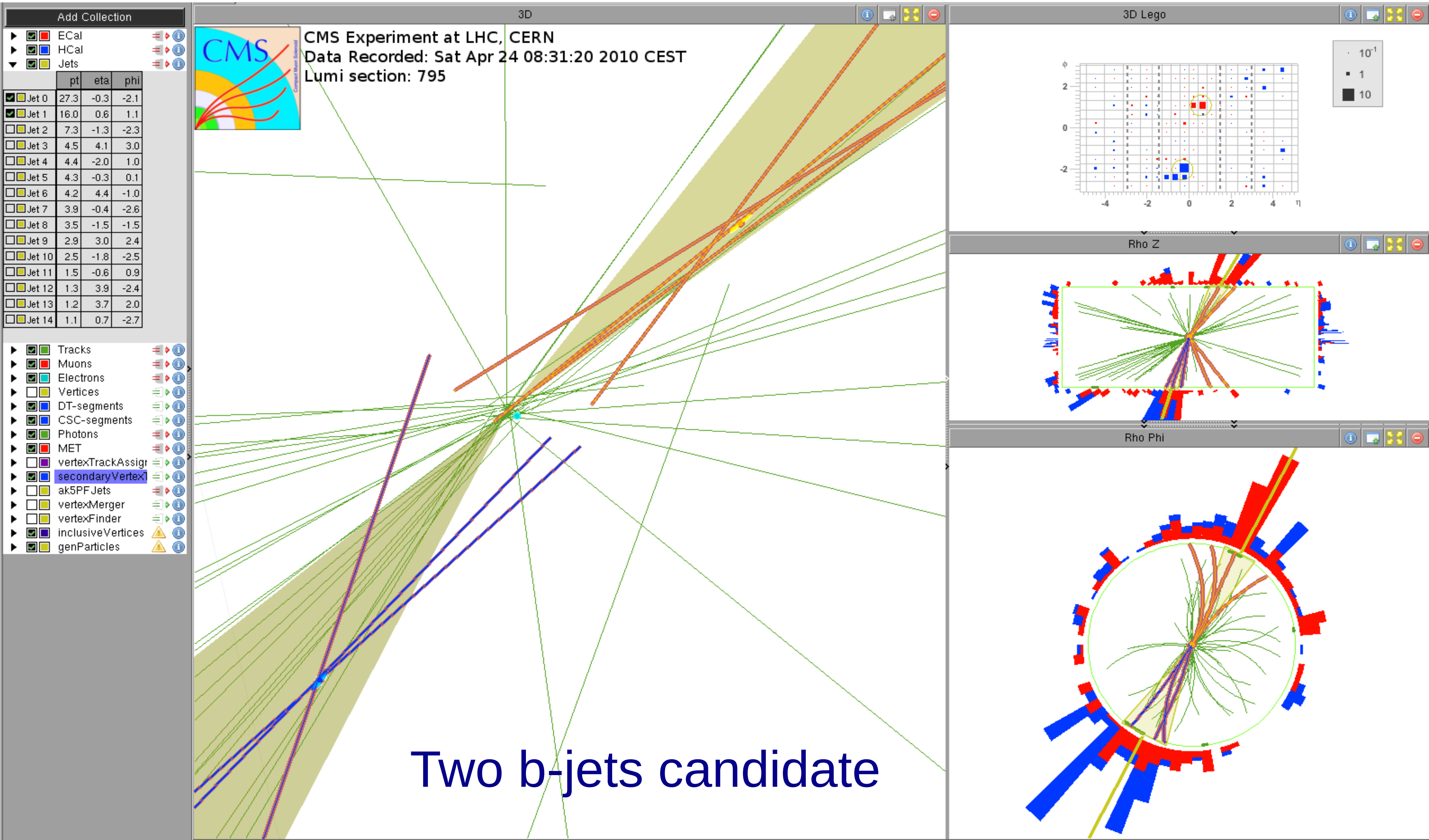




Tracker Performance



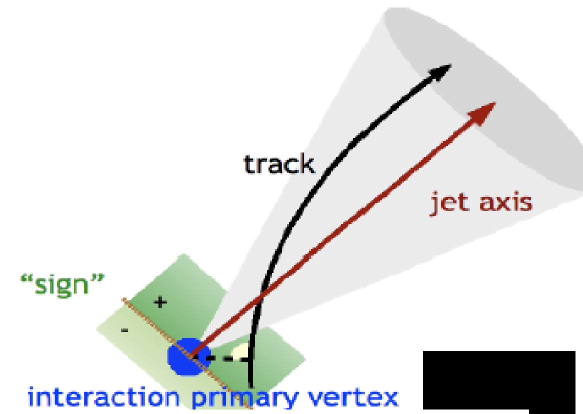
Ready for b physics (and b-tagging in general)



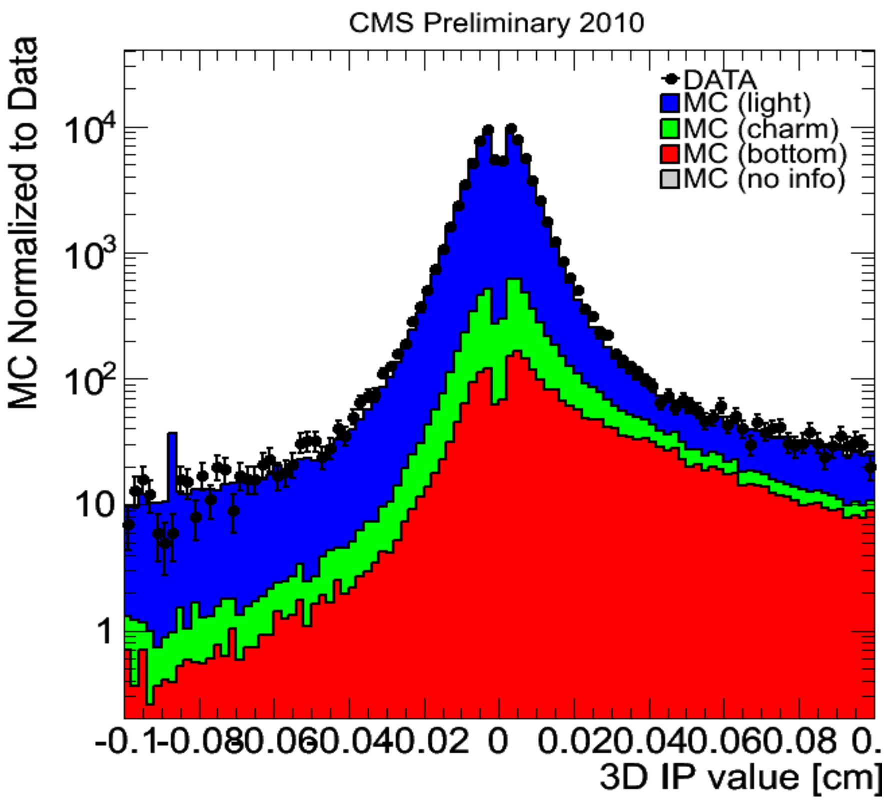
Two b-jets candidate

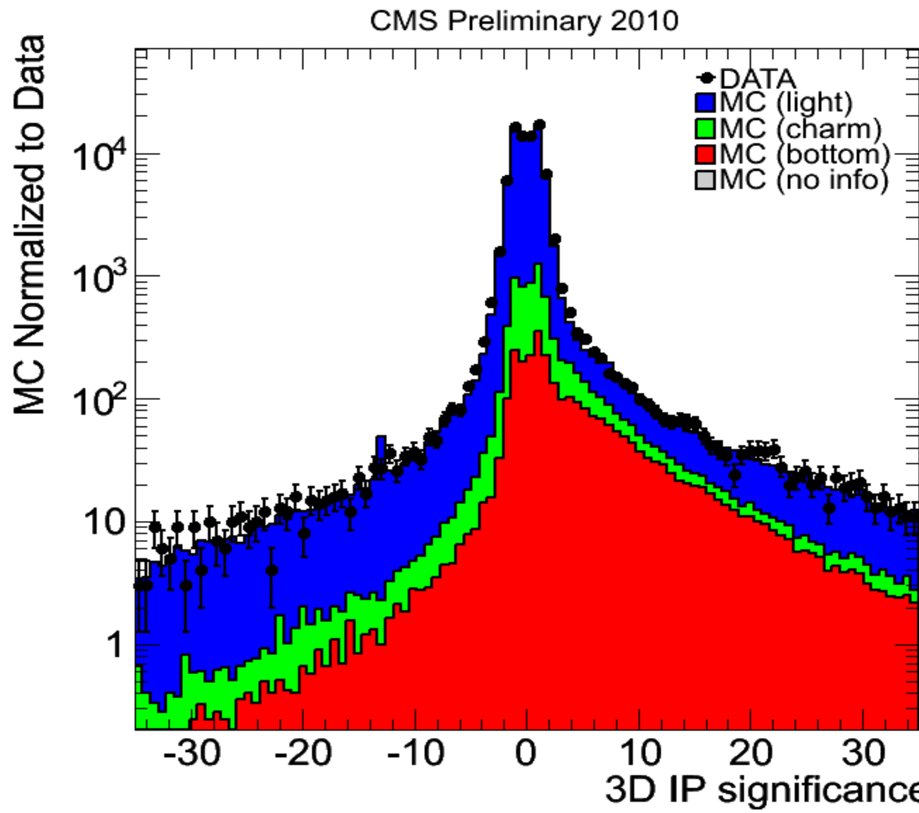
b-tagging : 3D IP significance

3D impact parameter value and significance (+zoom into ±2 region) for all tracks with Pt>1GeV belonging to jets with p_T > 40 GeV and $|\eta|$ < 1.5 (*PFlow Jets anti-k_T R=0.5).*



Excellent alignment and general tracking performance

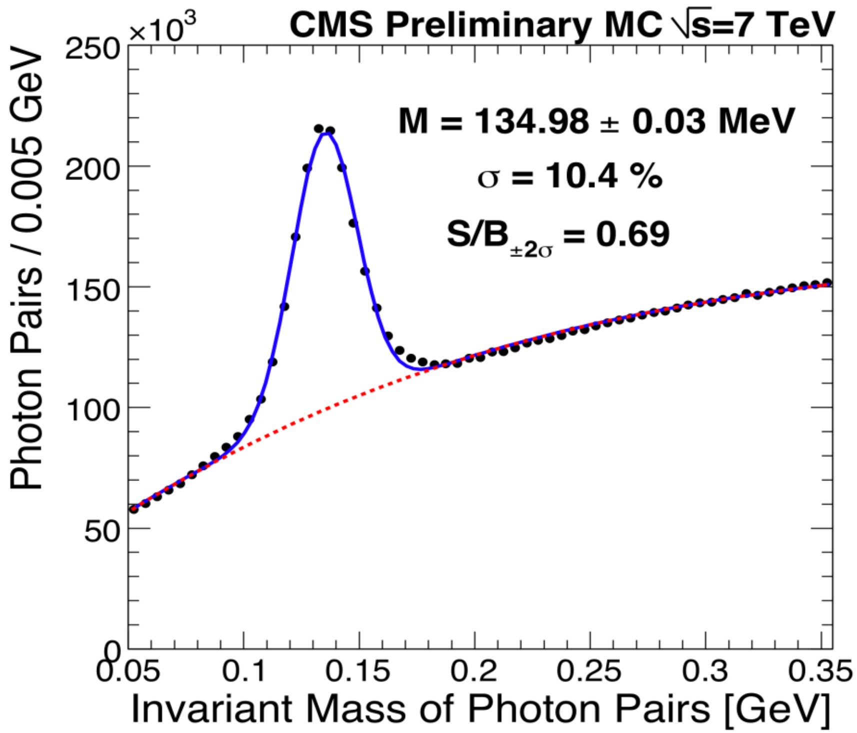




Low mass di-photons: □^{0} and |

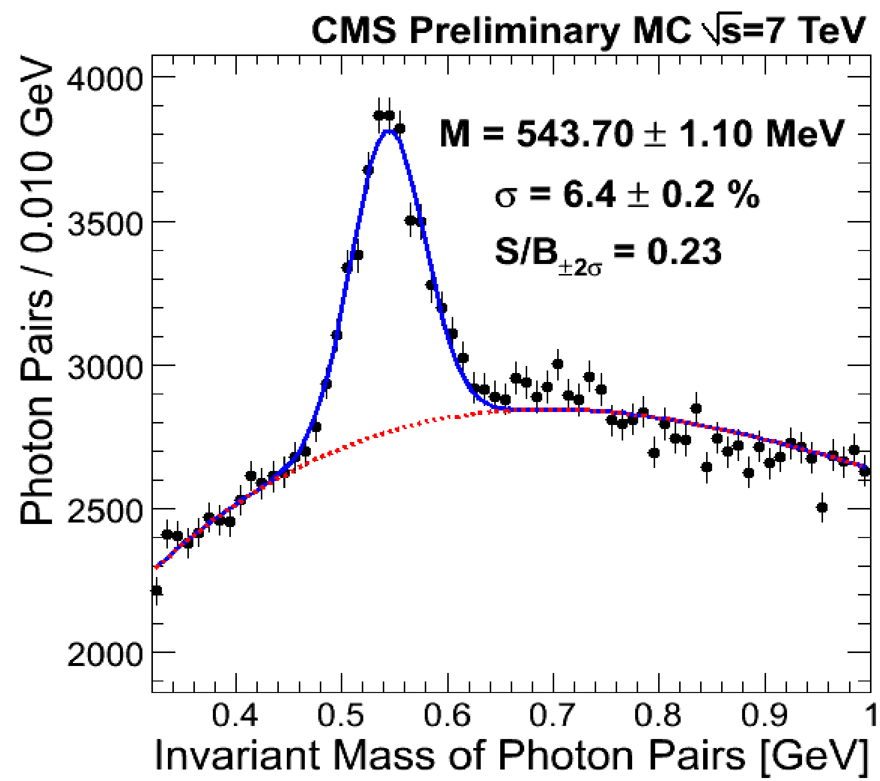
1.46M of □^{0} → γγ

$P_T(\gamma)$ > 0.4 GeV, P_T(pair) > 1 GeV



25.5K | → ©©

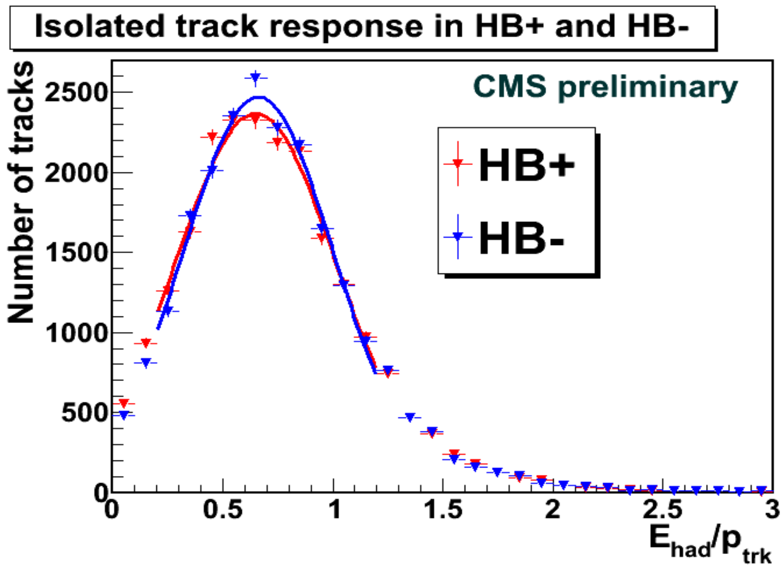
$P_T(\gamma)$ > 0.5 GeV, P_T(pair) > 2.5 GeV



MC based correction applied according to cluster η and energy

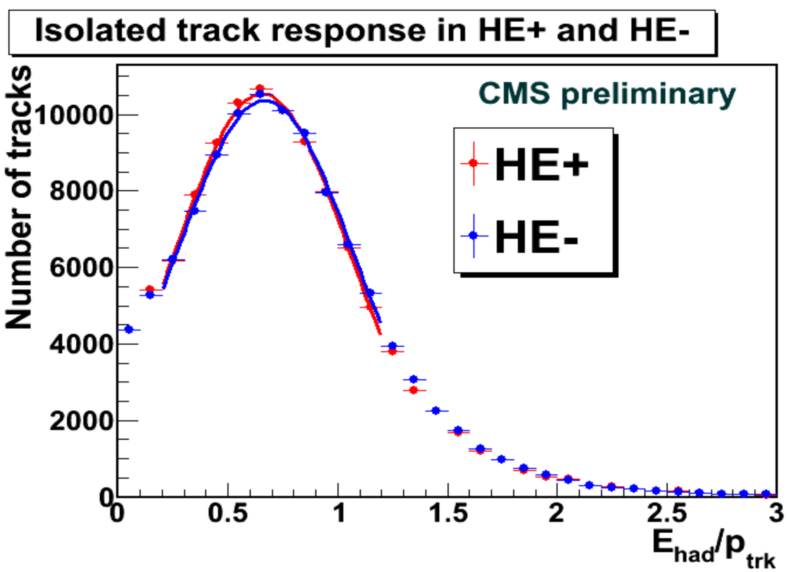
Numbers refer to ~10% of the currently available statistics. Very useful tool to intercalibrate the crystals.

HCAL Calibration
Response to Isolated Tracks in HB± and HE±



	mean	RMS	peak
HB+	0.728±0.003	0.393±0.003	0.650±0.004
HB-	0.737±0.003	0.388±0.003	0.661±0.004

Symmetric response ± z



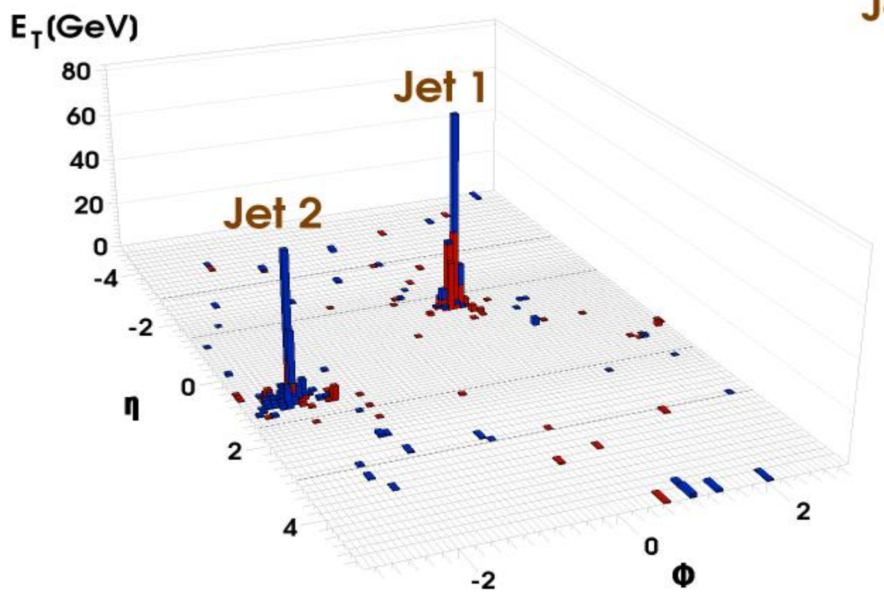
	mean	RMS	peak
HE+	0.757±0.001	0.453±0.001	0.656±0.002
HE-	0.766±0.001	0.454±0.001	0.669±0.002

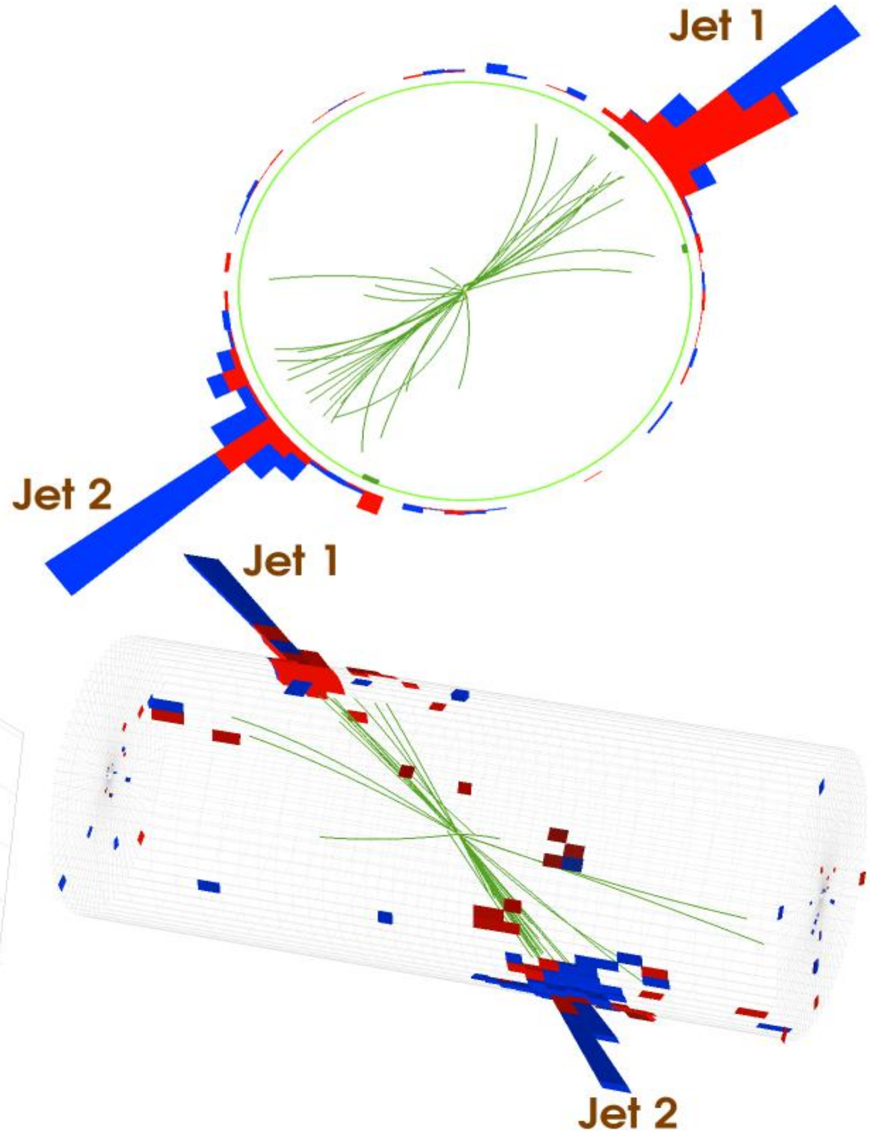
Uncertainties are statistical.
Systematics (under study) will dominate.

Jets and Missing E_T

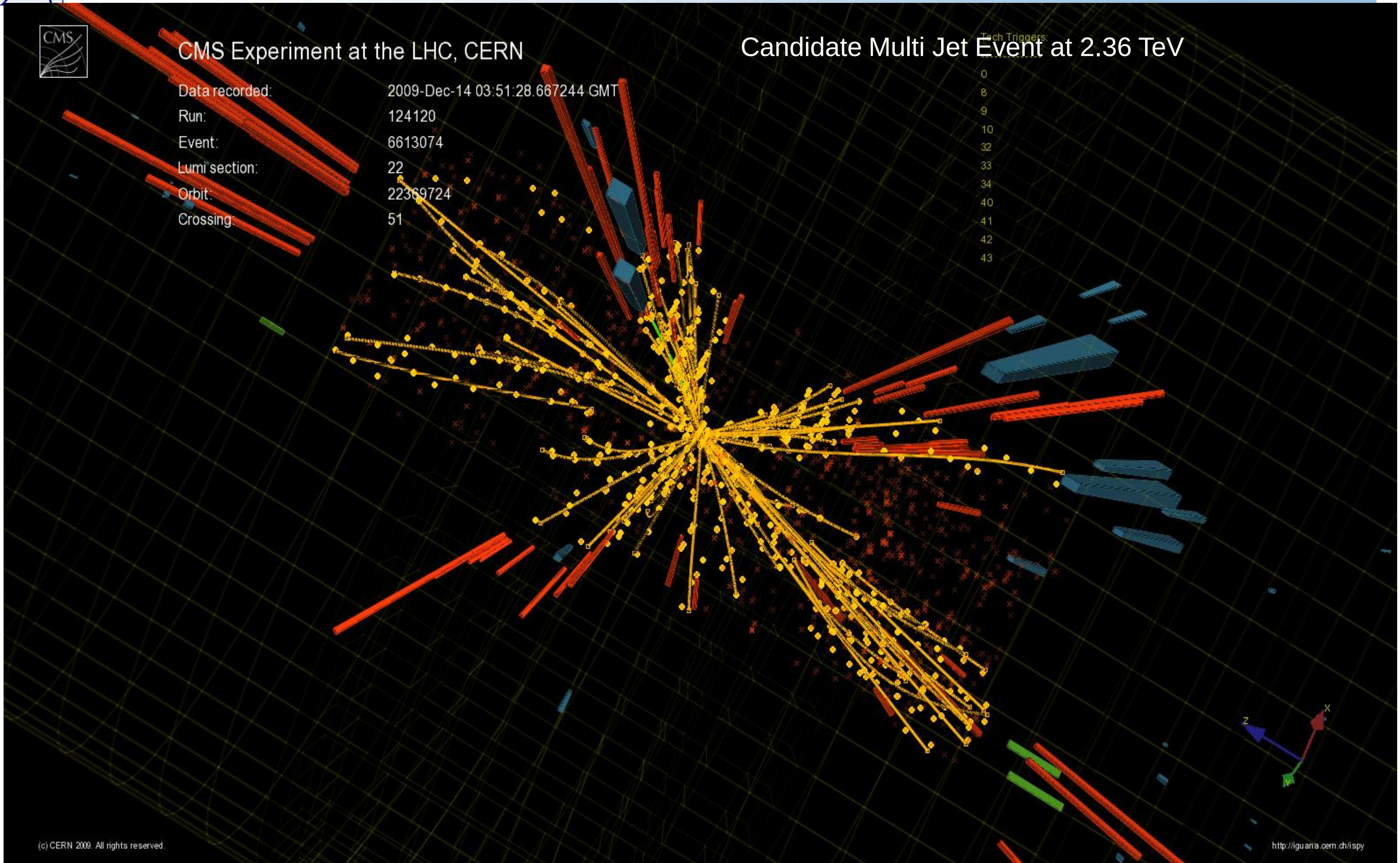
CMS Experiment at LHC, CERN
Run 133450 Event 16358963
Lumi section: 285
Sat Apr 17 2010, 12:25:05 CEST

Jet1 p_T : 253 GeV
Jet2 p_T : 244 GeV
Dijet Mass : 764 GeV





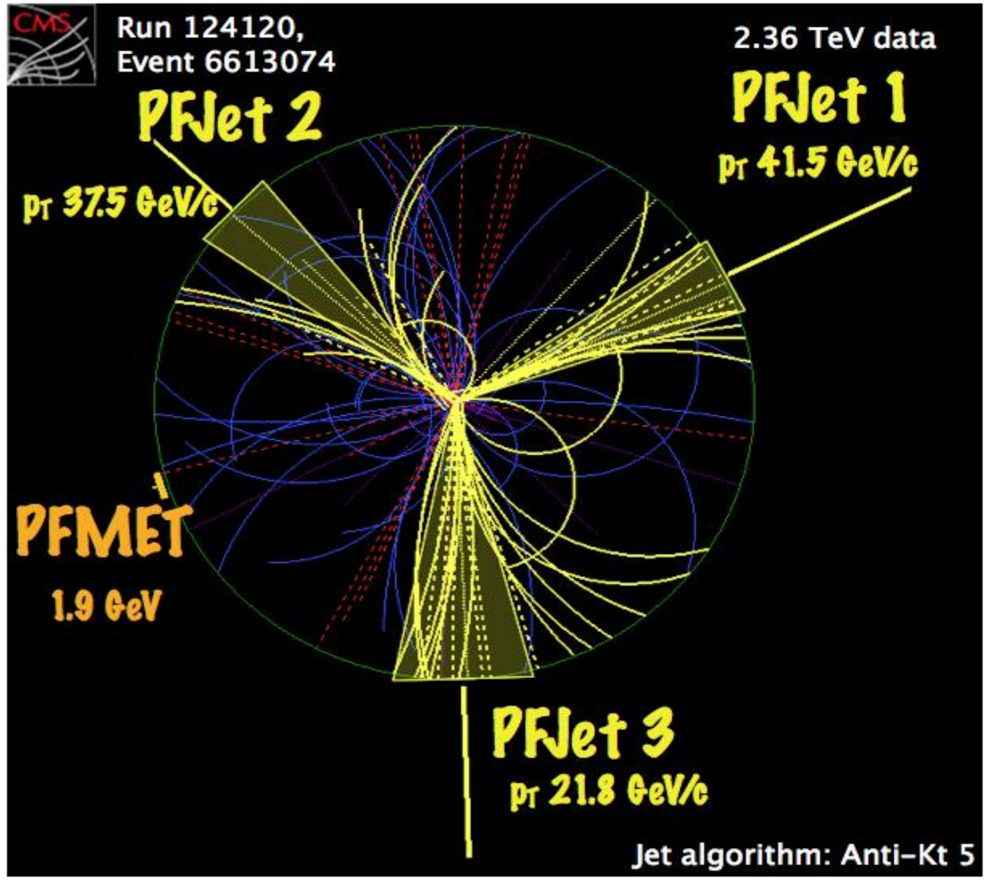
Detector Performance: Particle Flow



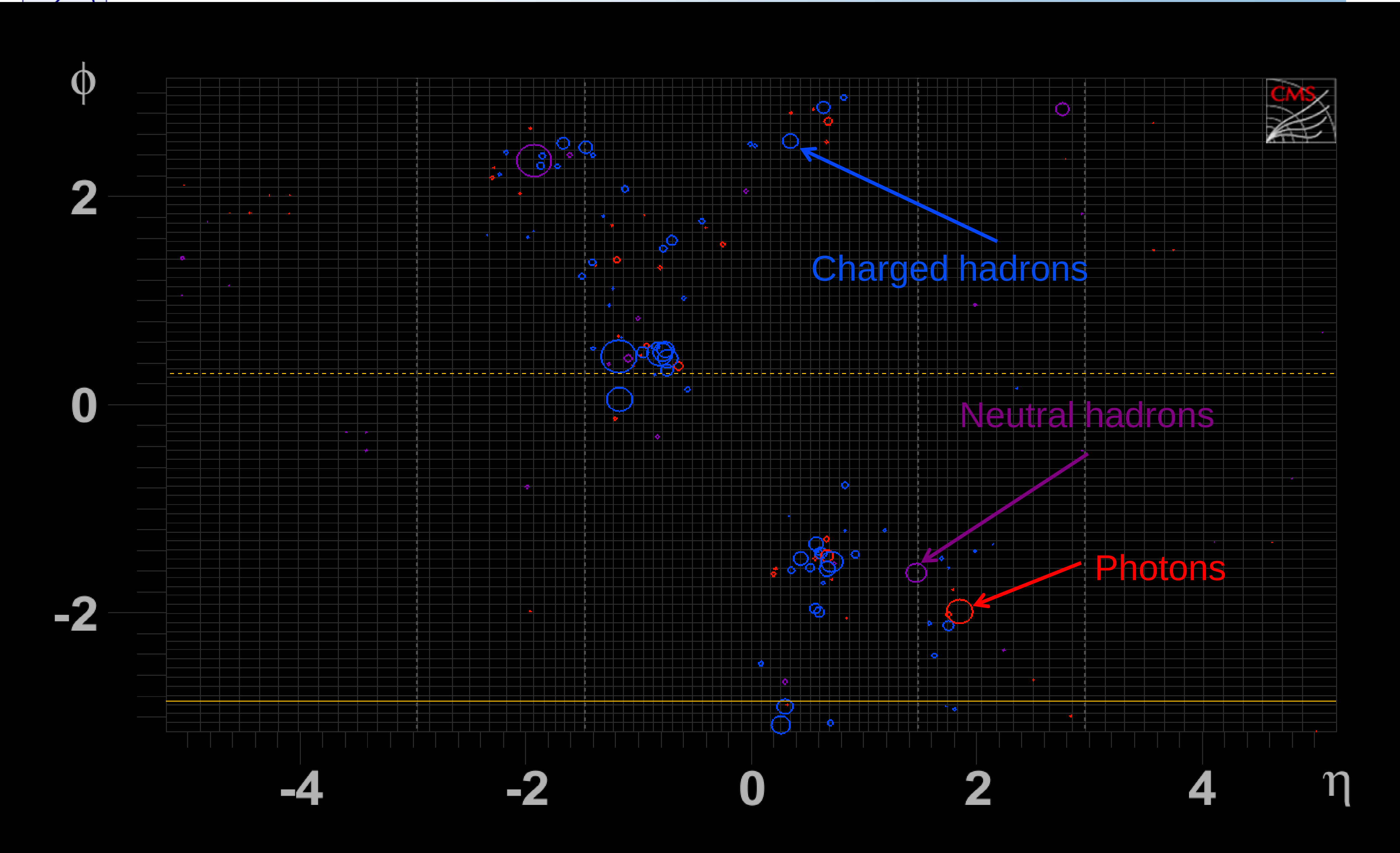
Combining Calorimetry and Tracking

Particle Flow aims at reconstructing all stable particles in the event, i.e., electrons, muons, photons & charged and neutral hadrons from the combined information from all CMS sub-detectors, to optimize the determination of particle types, directions and energies

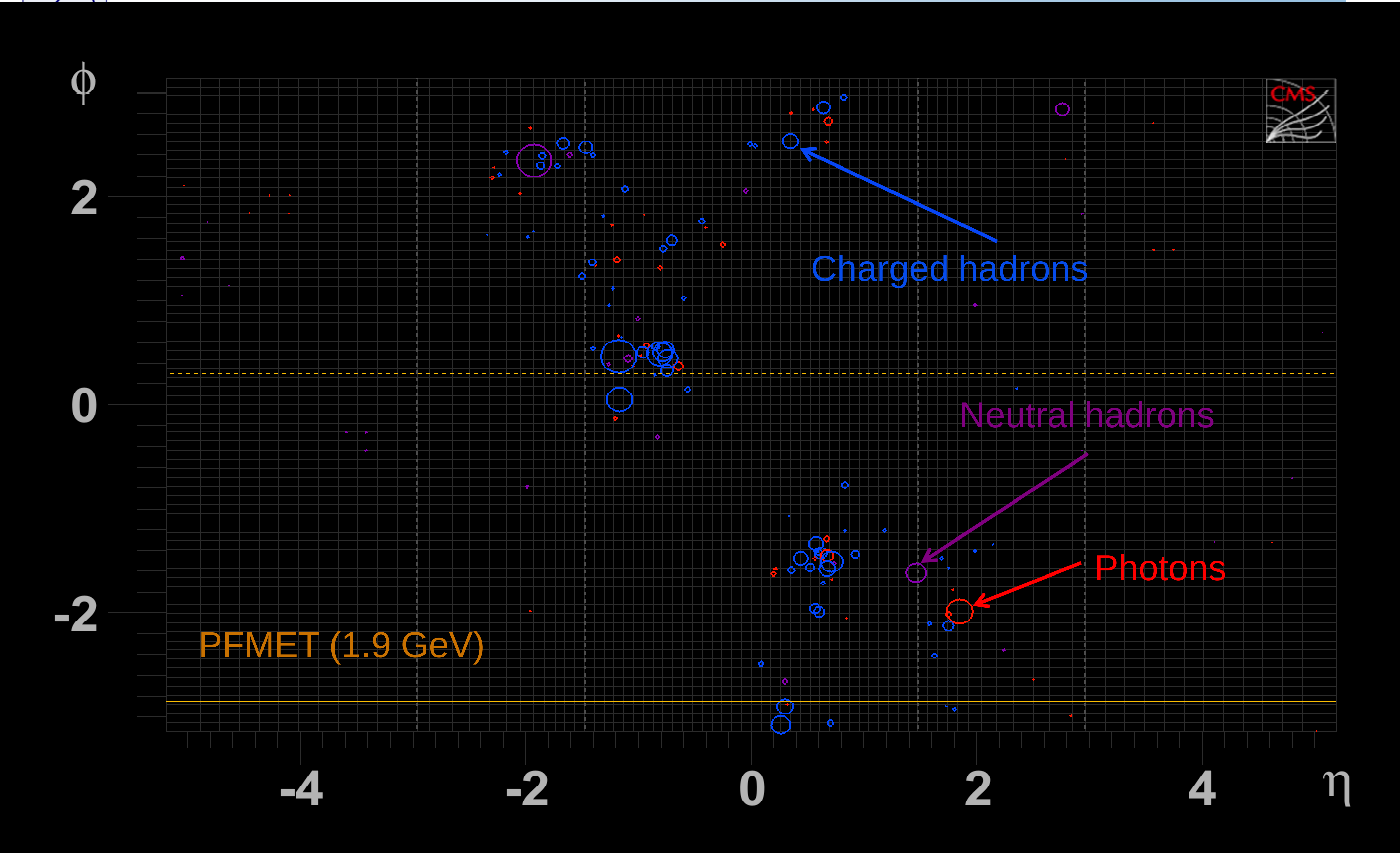
CMS is well suited for this:
- Powerful Si tracker
-EM calorimeter with fine granularity & small Moliere radius
(NB: CMS has 4T B-field & HCAL has moderate performance)



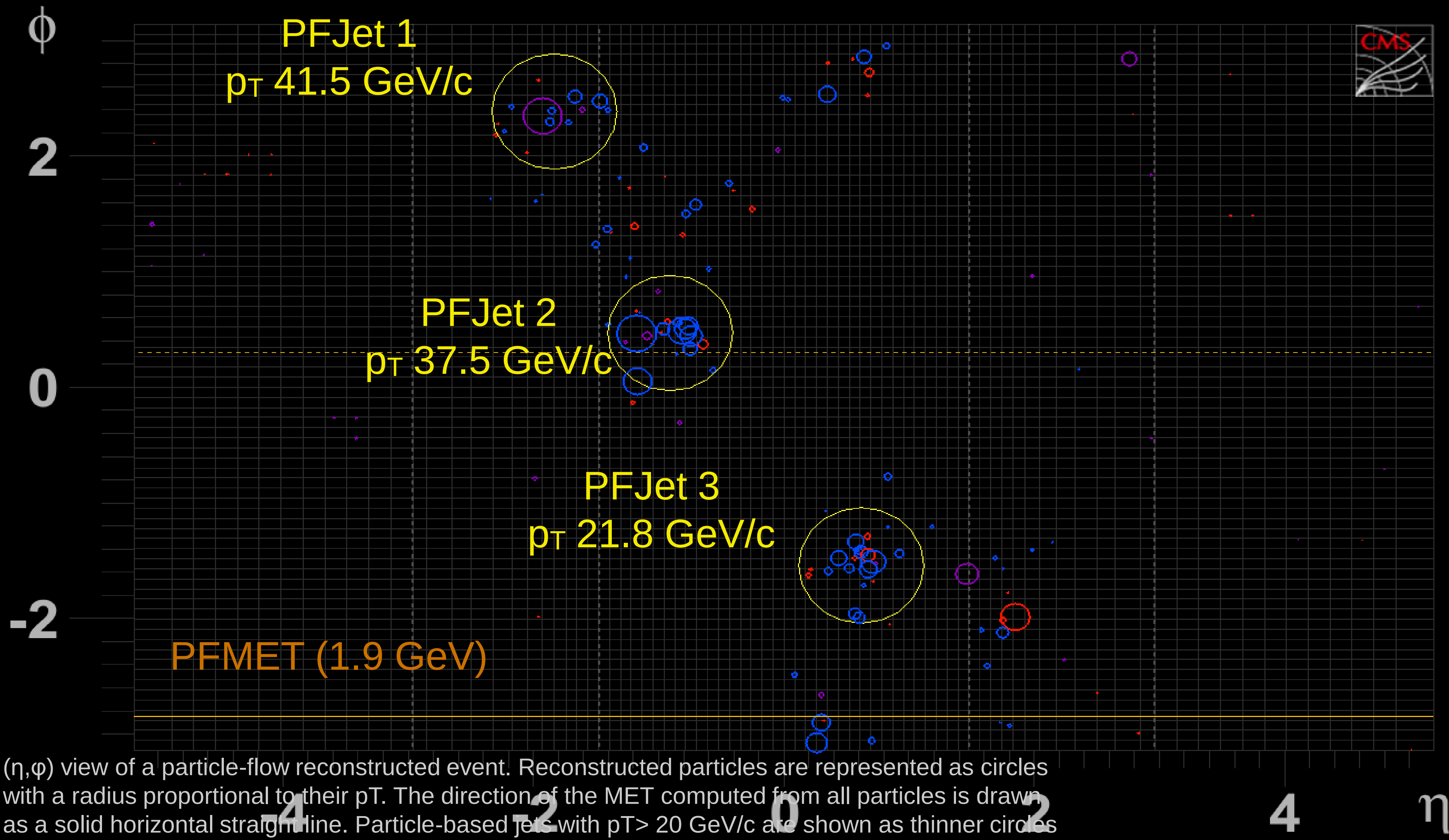
Analysing Complex Events



Analysing Complex Events



Analysing Complex Events



(η,φ) view of a particle-flow reconstructed event. Reconstructed particles are represented as circles with a radius proportional to their pT. The direction of the MET computed from all particles is drawn as a solid horizontal straight line. Particle-based jets with pT> 20 GeV/c are shown as thinner circles representing the extension of the jet in the (η,φ) coordinates.

Dijet Mass distributions

- *Jets reconstructed with the anti-k_T R=0.5 algorithm*
- *Dijet selection : Jet Pt > 25 GeV, ΔΦ > 2.1, $|\eta| < 3$*
- *Loose ID cuts on number of components and neutral/charged* energy fraction
- *Three different approaches: pure calorimetric, track corrected calo and particle flow.*

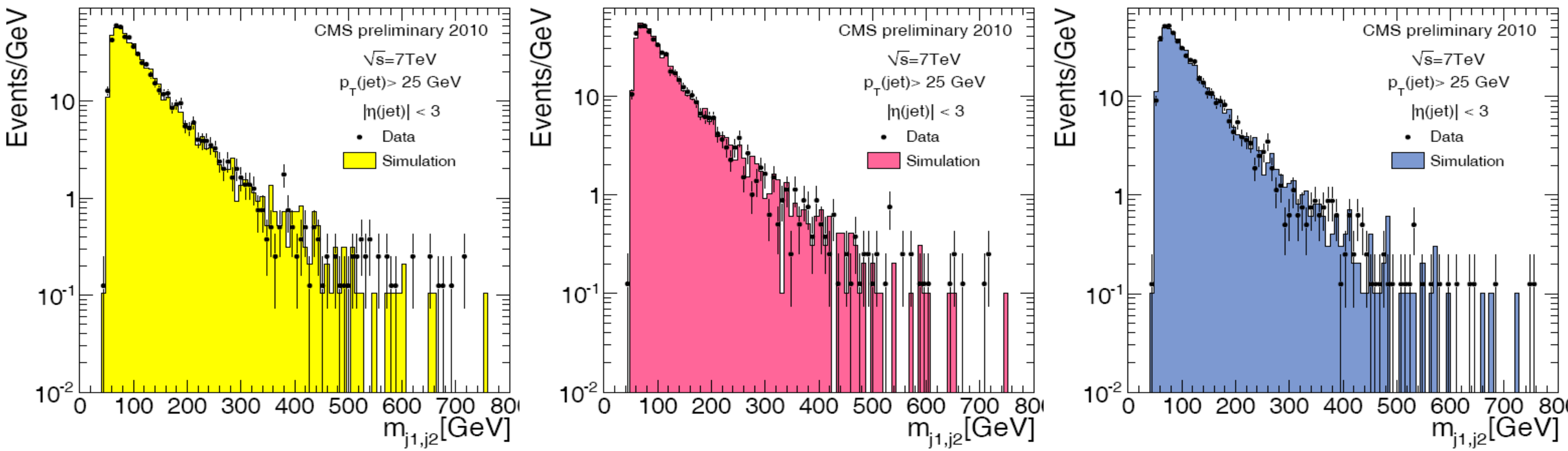
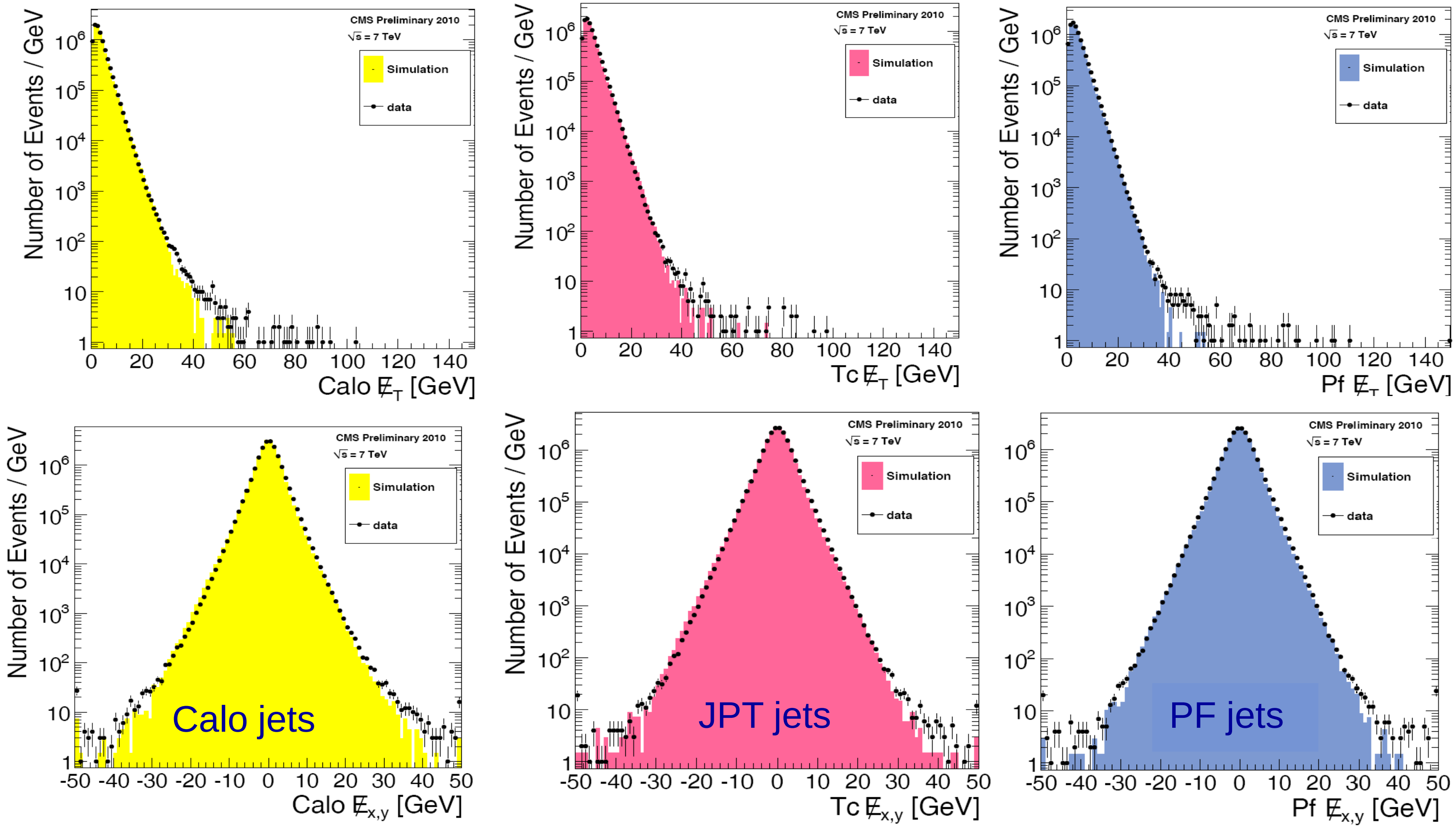


Figure: Data vs MC: Di jet mass $m_{j1,j2}$ for Calorimeter Jets, JPT jets, PFjets.

Missing Transverse Energy in inclusive jets



- *Monte-Carlo reproduces data over 5 orders of magnitudes*
- *MET tails understanding is in progress*

MET resolution vs Sum E_T

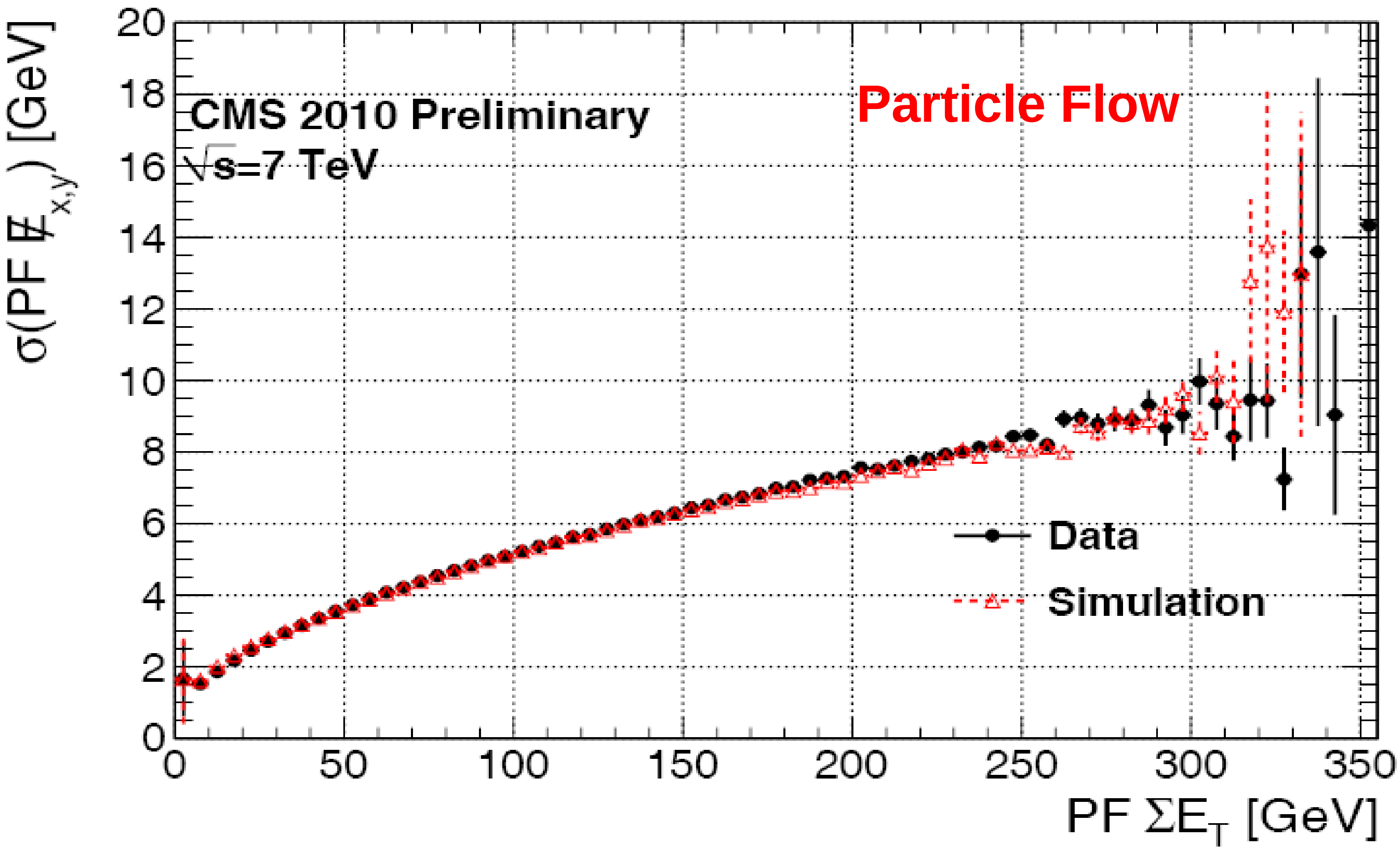
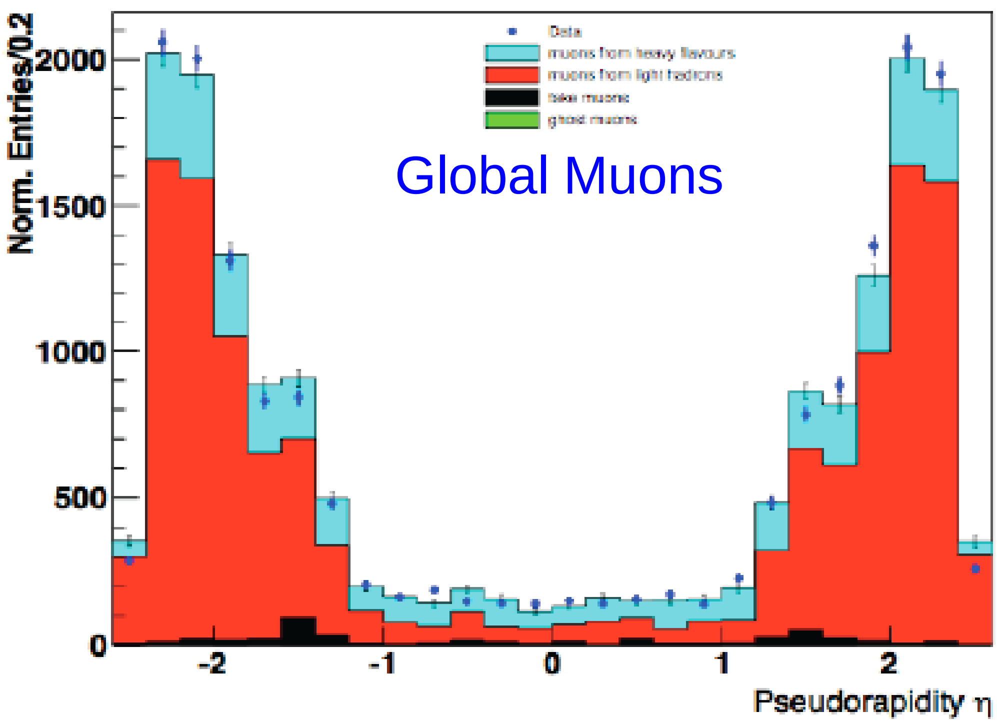
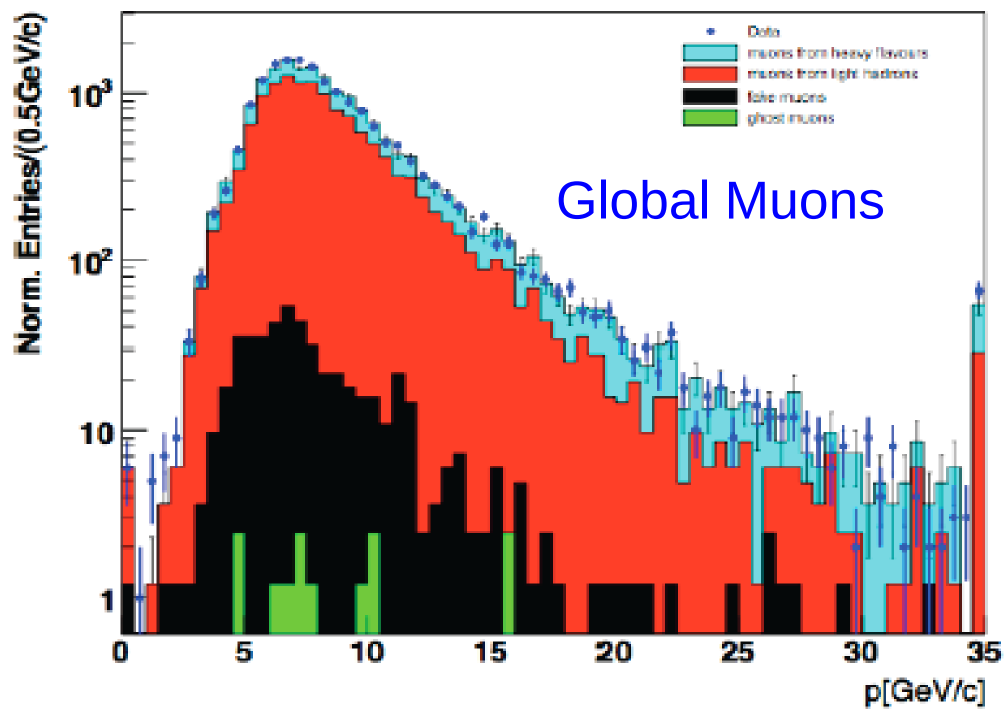


Figure: Data vs MC: PF $\not{E}_{xy}$ resolution as function of PF ΣE_{T}

Muons

"Global Muons" matched tracks from Muon system and Tracker
"Tracker Muons" tracker tracks matched to one Muon station segment

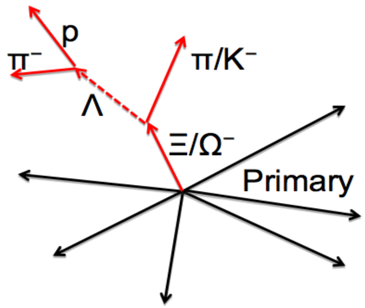




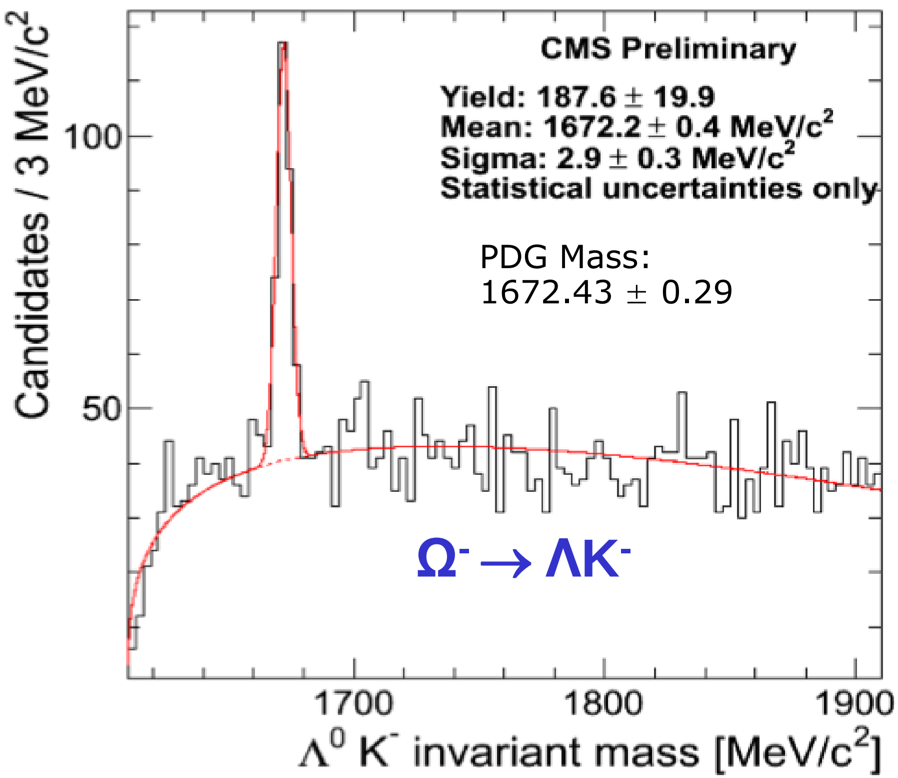
η and p_T distributions dominated by light hadron decay muons (red), good agreement with MC prediction including heavy flavor decays (blue), punch-through (black) and fakes (green).

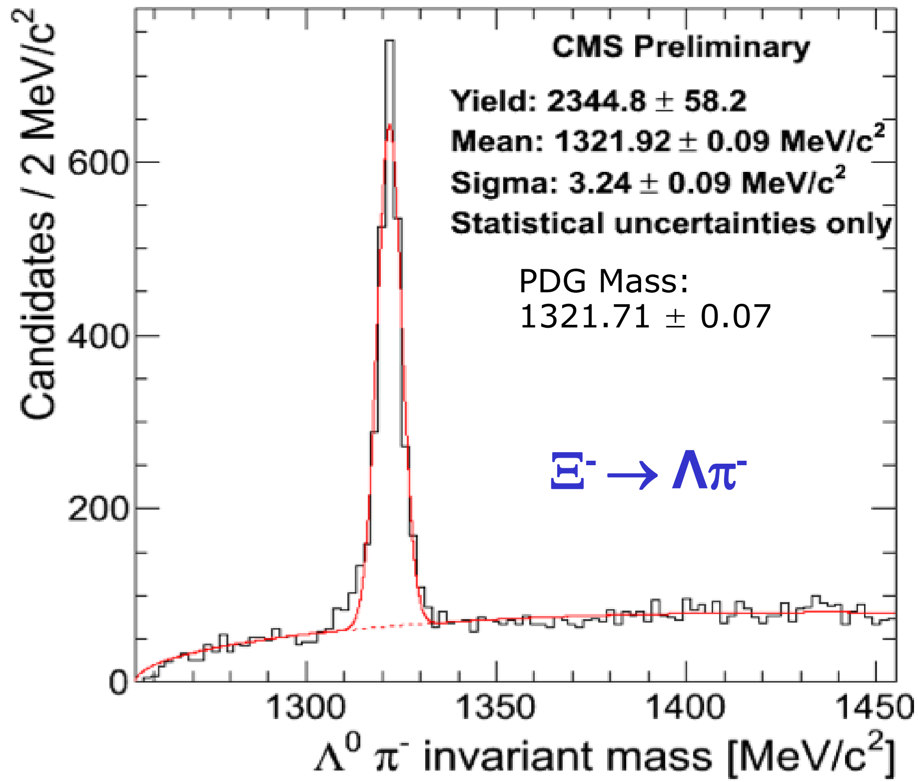
Low Mass Resonances

- Tracks displaced from primary vertex ($d_{3D} > 3\sigma$)
- Common displaced vertex ($L_{3D} > 10\sigma$)

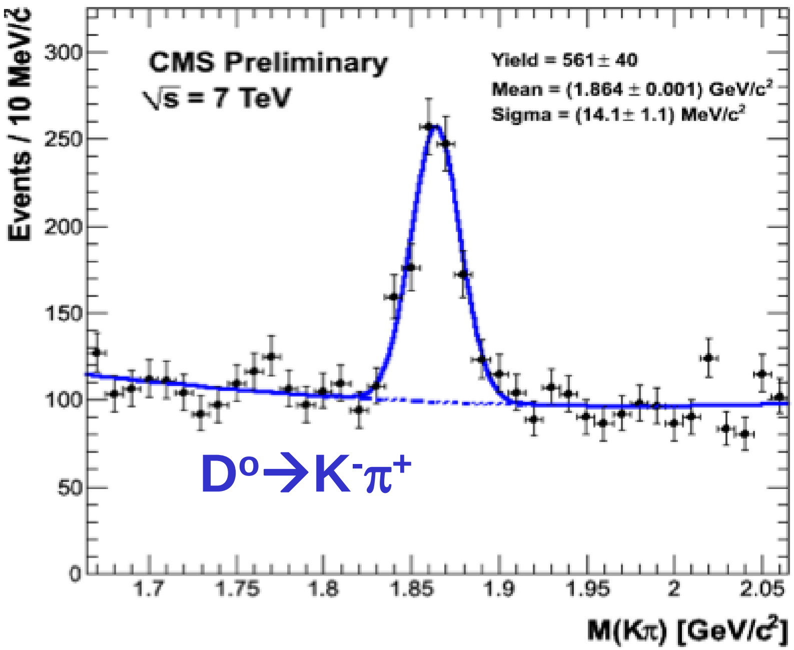


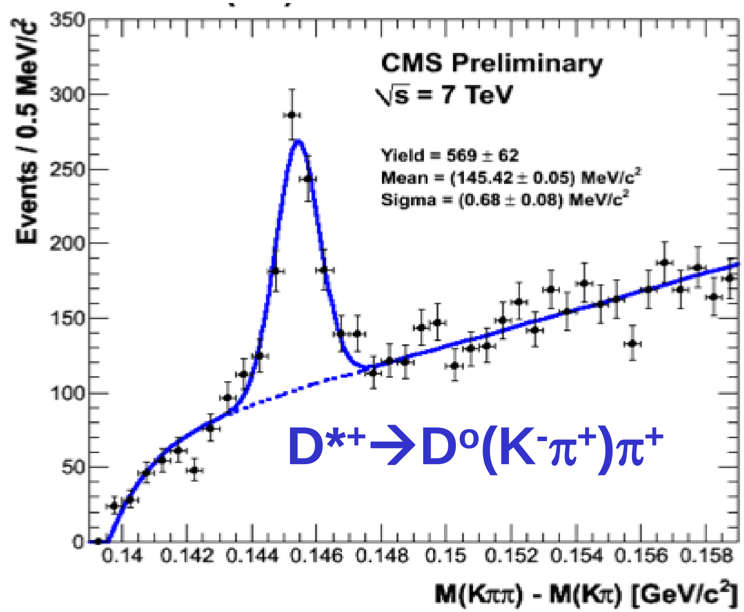
Invariant mass distribution for different combinations ($\Omega^{\pm} \rightarrow \Lambda K^{\pm}$ or $\Xi^{\pm} \rightarrow \Lambda\pi^{\pm}$) fit to a common vertex.

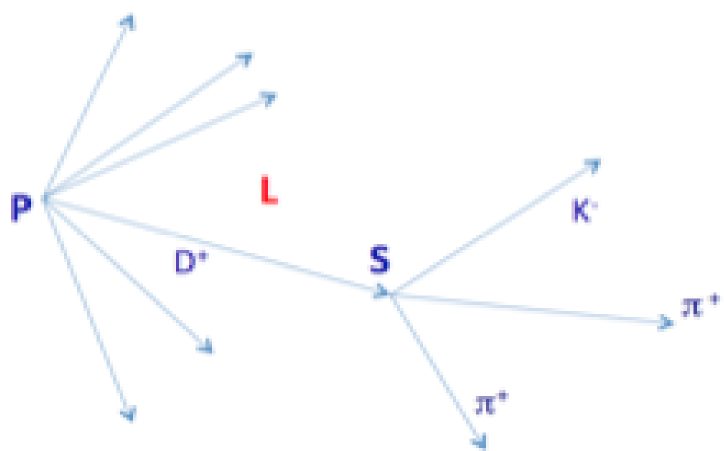


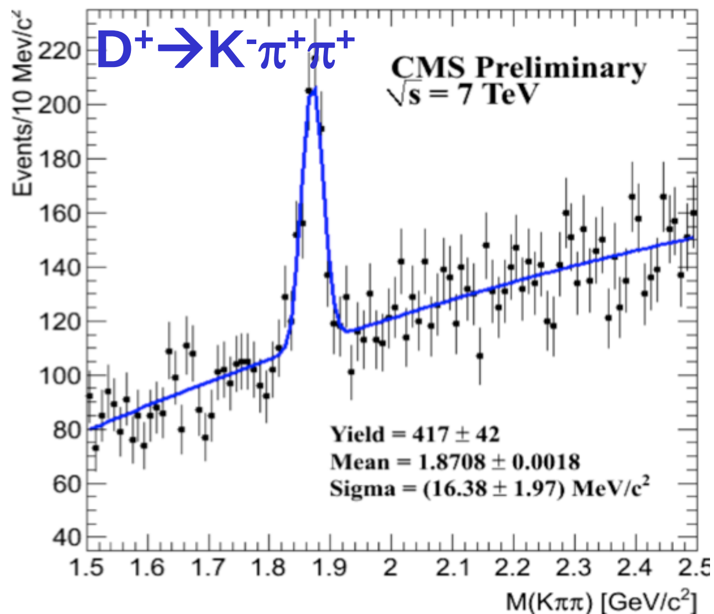


Charm Production



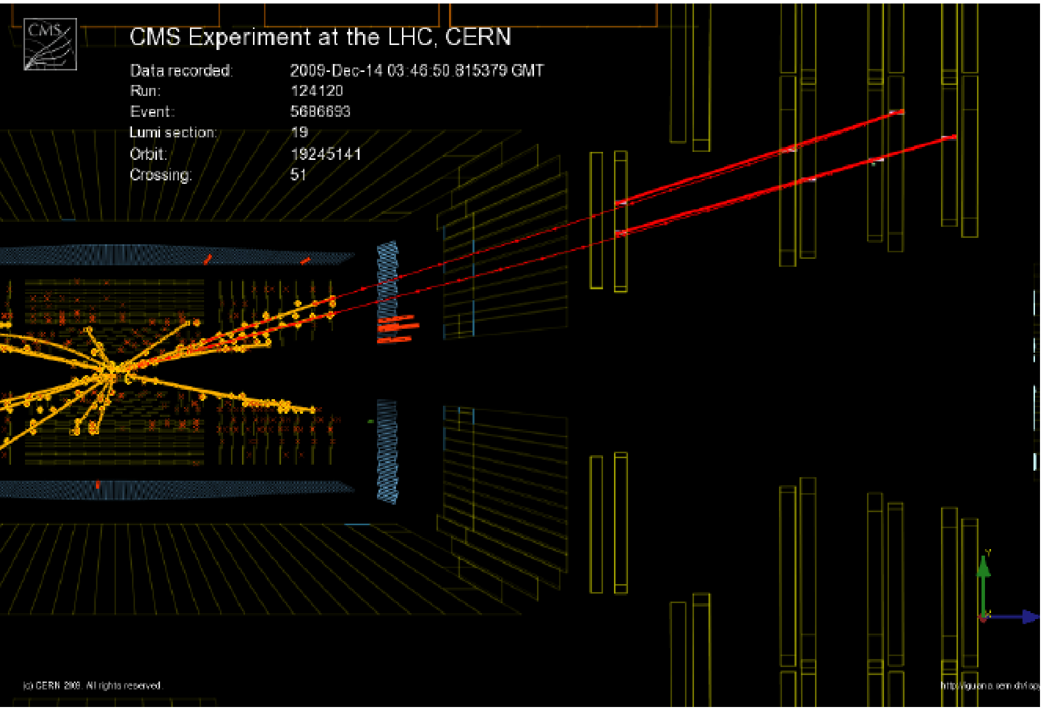


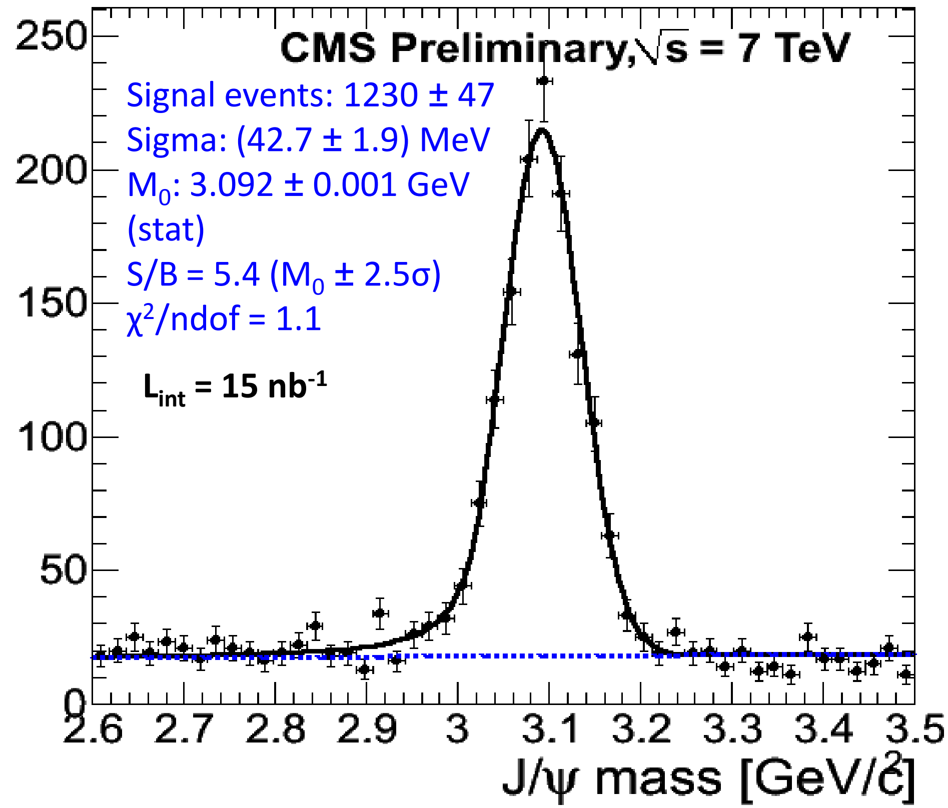




Low mass dimuon resonances J/ψ→⌈+⌈−

All muon tracks, Nhits ≥ 11 (≥ 2 in Pixels



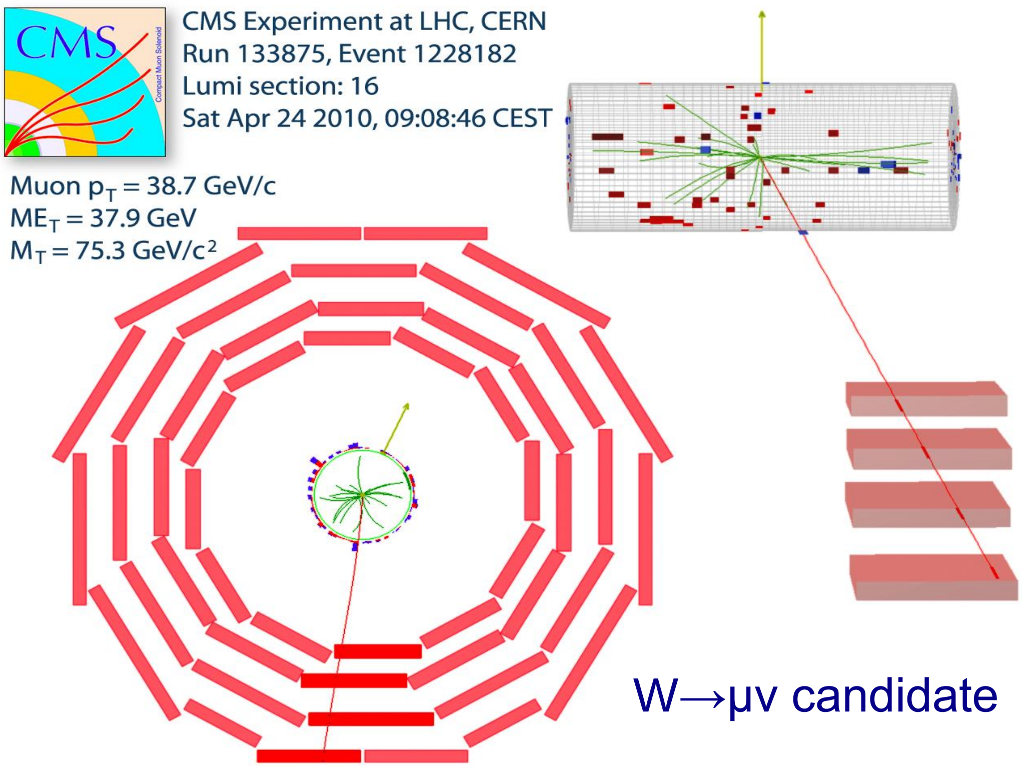


On going studies

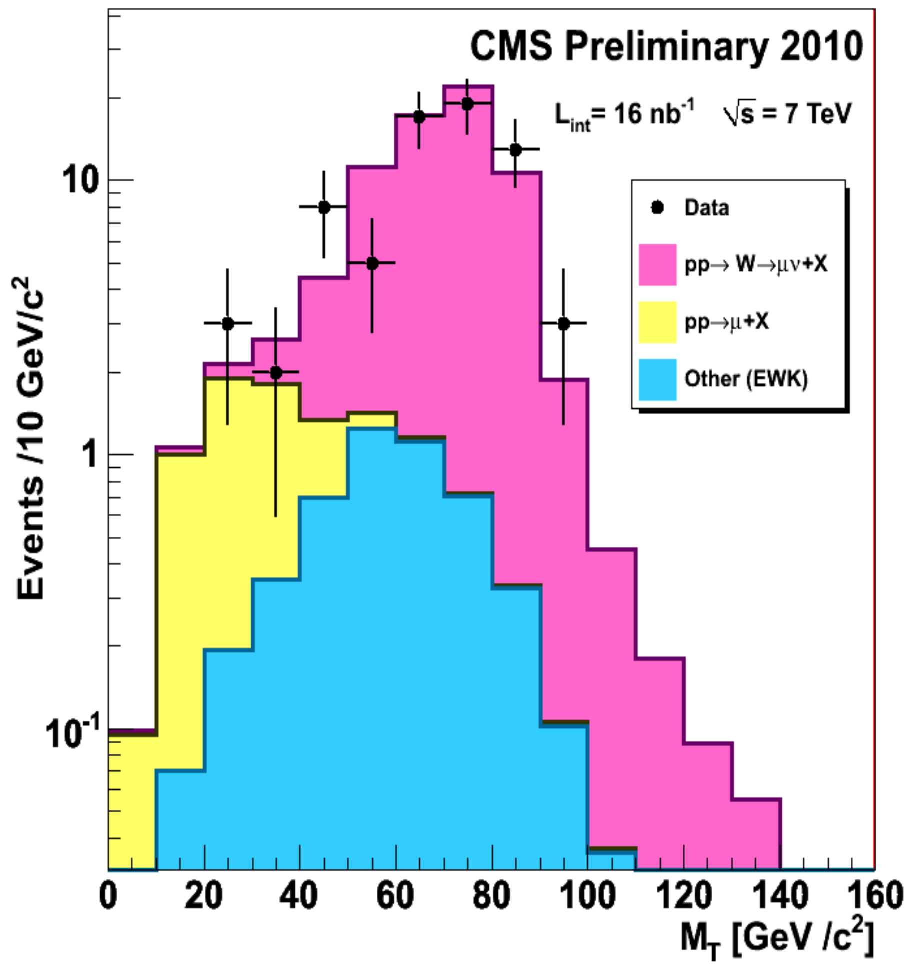
- Mass w.r.t. η and p_T → *track momentum scale*
- Tag and Prob rates → *tracking efficiency*
- Flight distance → *prompt and decay J/⟋ from*
- ϒand B→ J/ψ + K → *on tape*

Observation of $W^{\pm} \to \ell^{\pm}\nu$

Event selection: ***Muon id cuts (global and tracker muons), Isolation, pT cut and MET***
Monte Carlo : ***Cross section normalized to 16 nb^{-1} integrated luminosity***



W→μν candidate

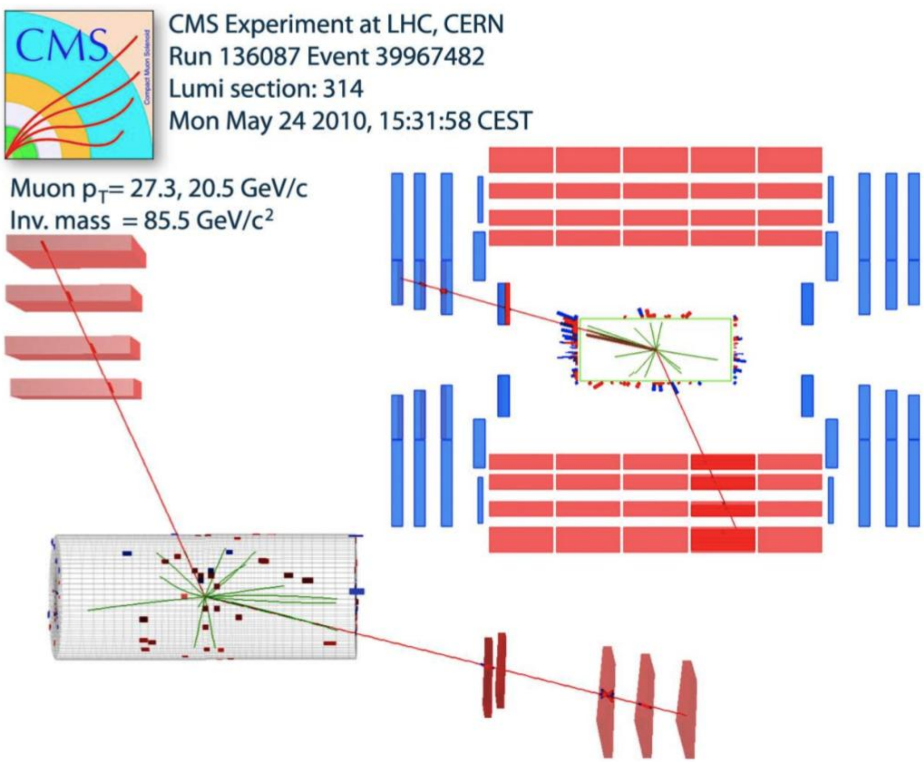


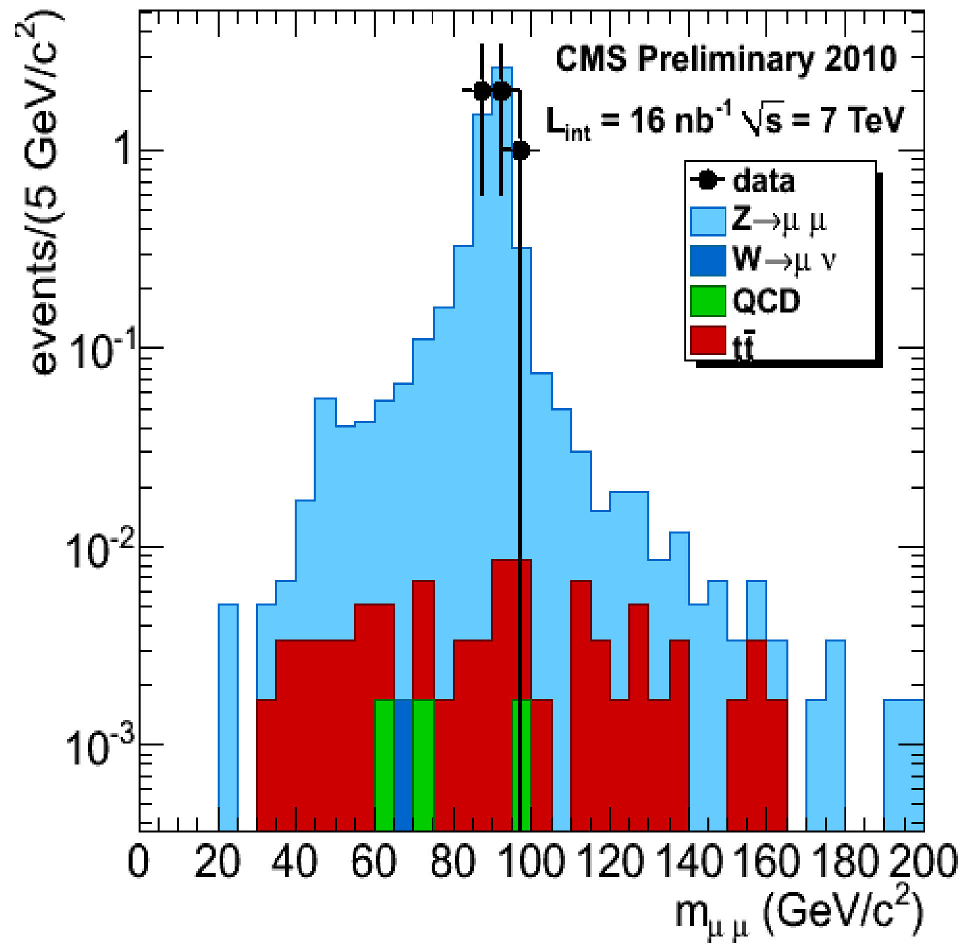
57 candidates with M_T > 50 GeV

Observation of $Z \rightarrow \ell^+\ell^-$

Event selection : ***muon id selection (global and tracker muons) ; loose Isolation, p_T cut.***

Monte Carlo : ***cross section normalized to 16 nb^{-1} integrated luminosity.***



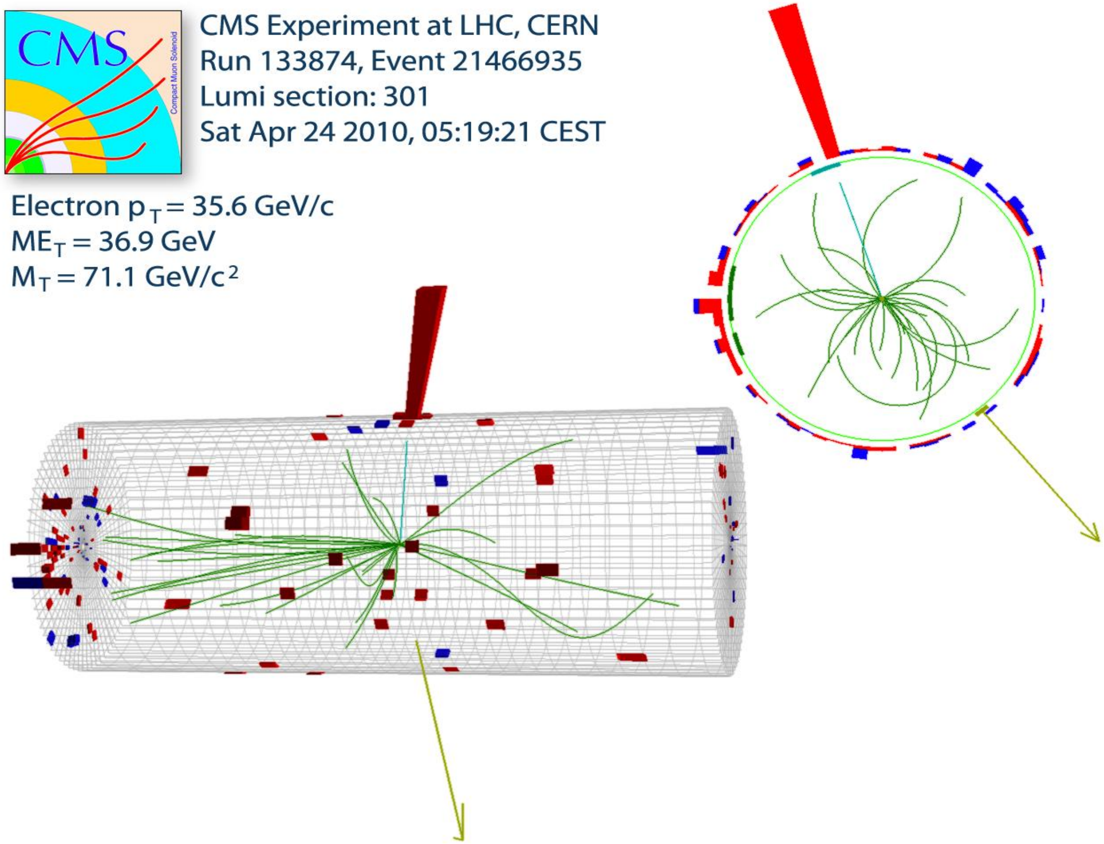


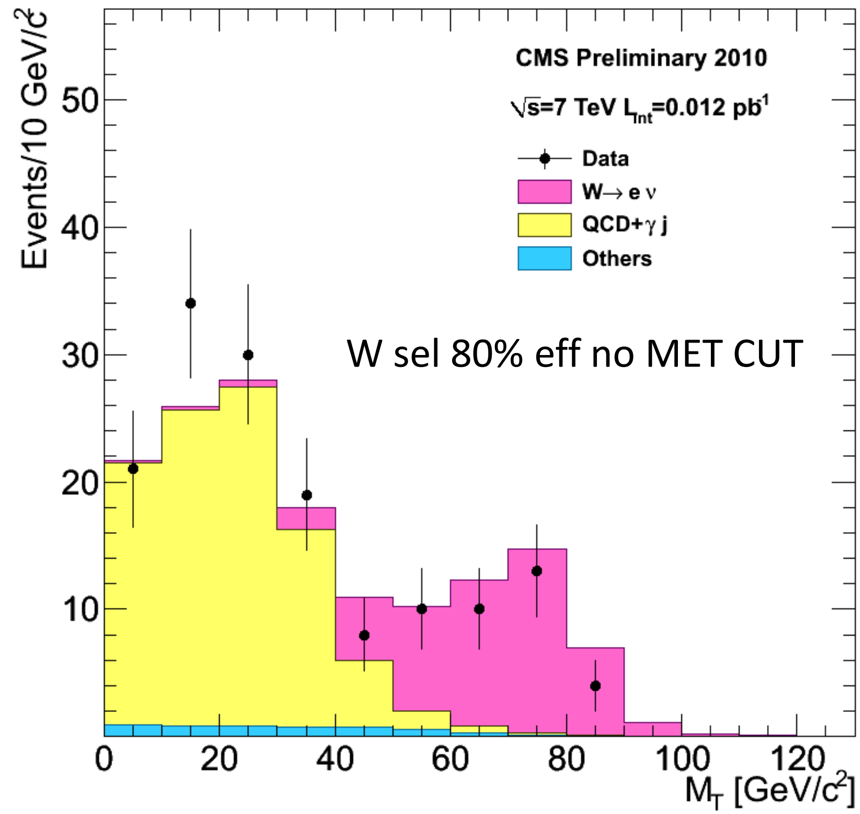
5 $Z \rightarrow \mu^+\mu^-$ candidates

Observation of W± →e±ν

Event selection:

- ***basic electron id and no MET cut***
- ***Cross section normalized to 12 nb⁻¹***

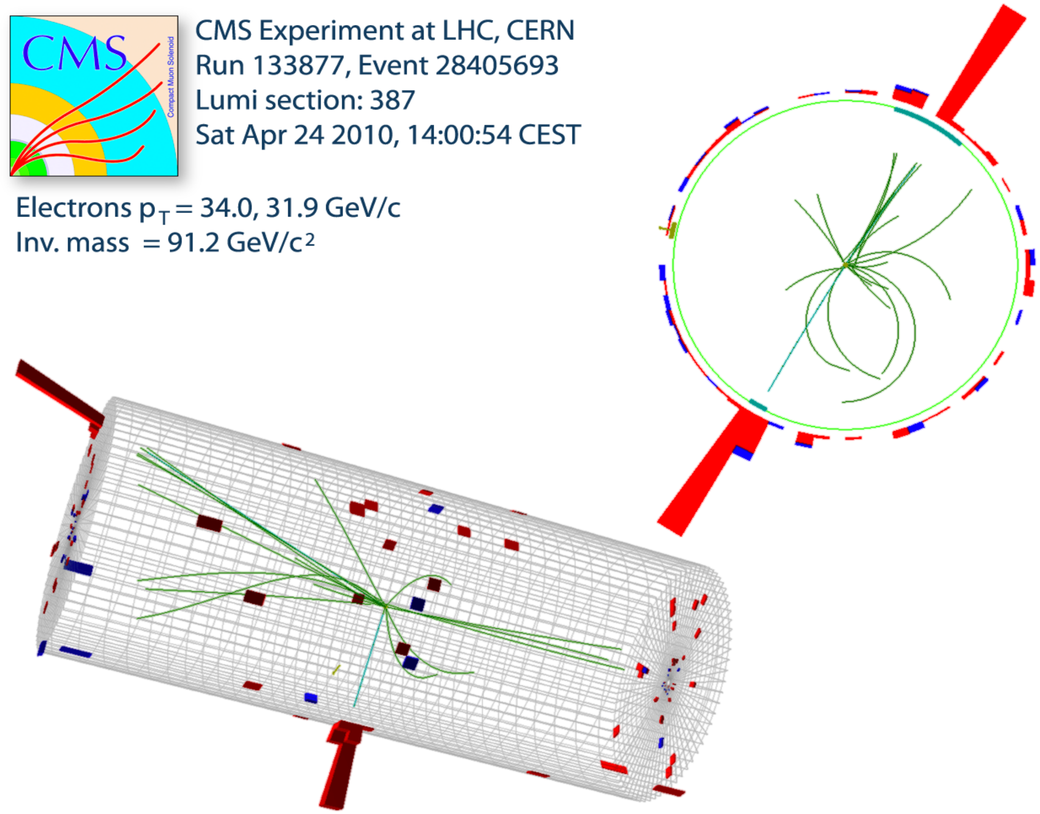


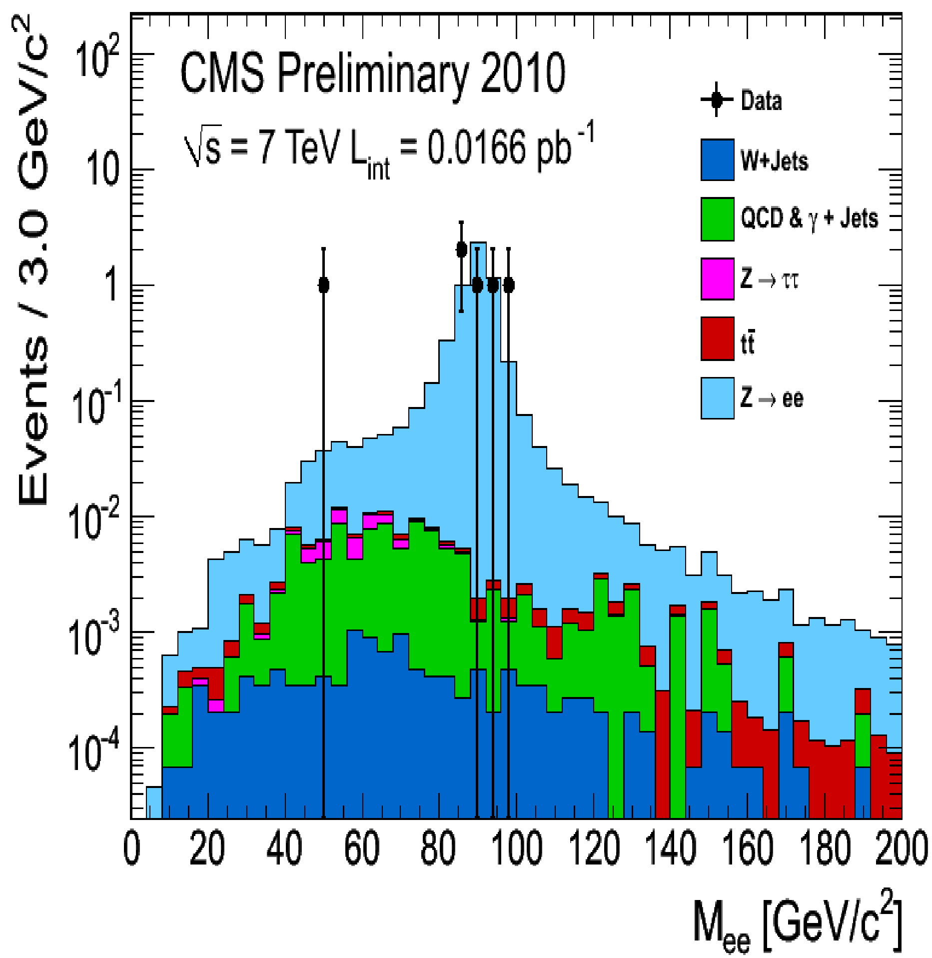


37 candidates with M_T > 50 GeV

Observation of Z → e^+e^-

Event selection: both electrons with a SuperCluster with E_T > 20 GeV
Monte Carlo : cross section normalized to 17 nb^{-1} integrated luminosity

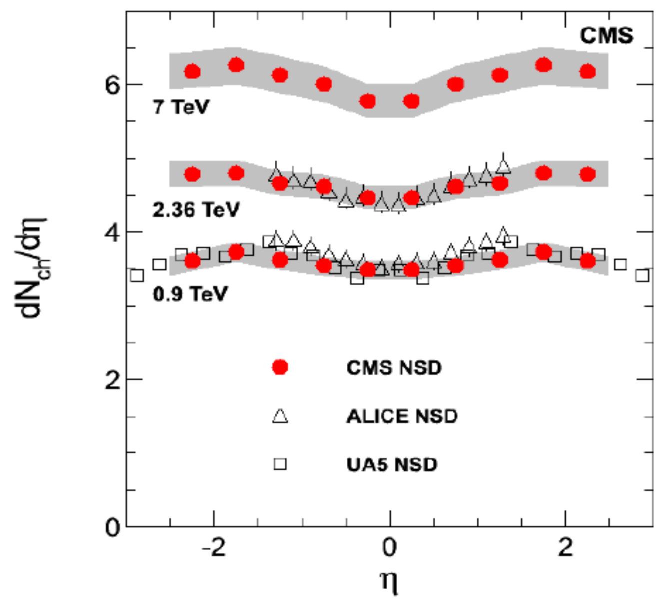


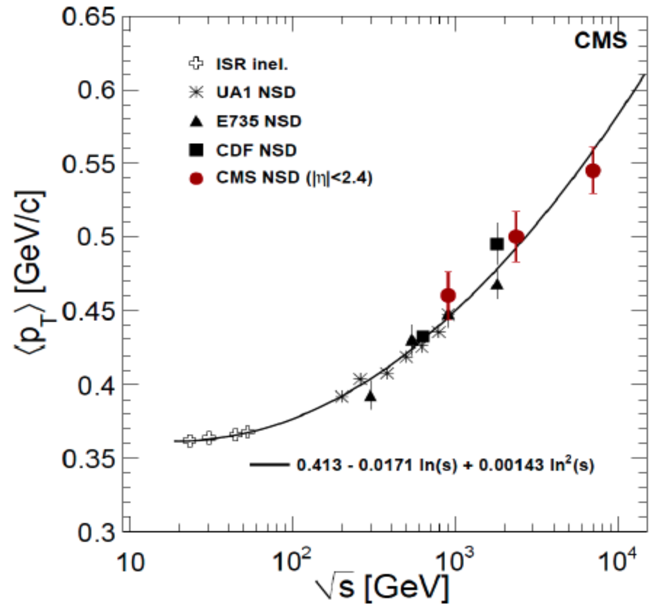


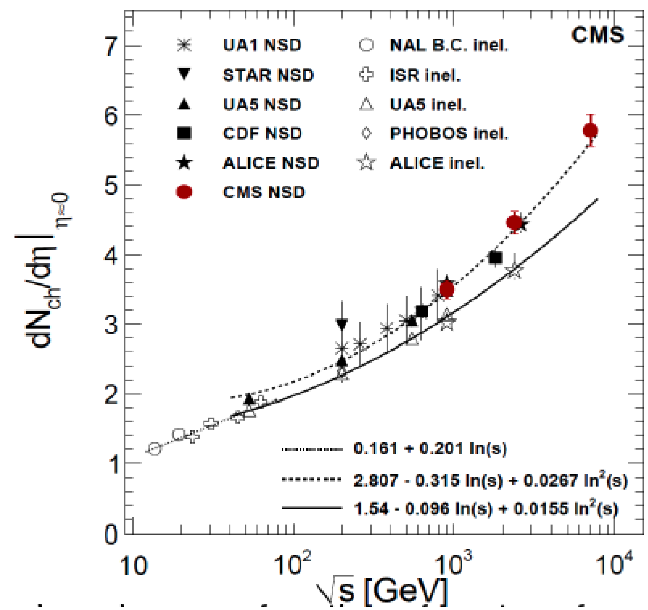
5 Z →e^+e^- candidates

First 7 TeV paper

“Transverse Momentum and Pseudorapidity Distributions of Charged Hadrons in pp Collisions at √s=7TeV”

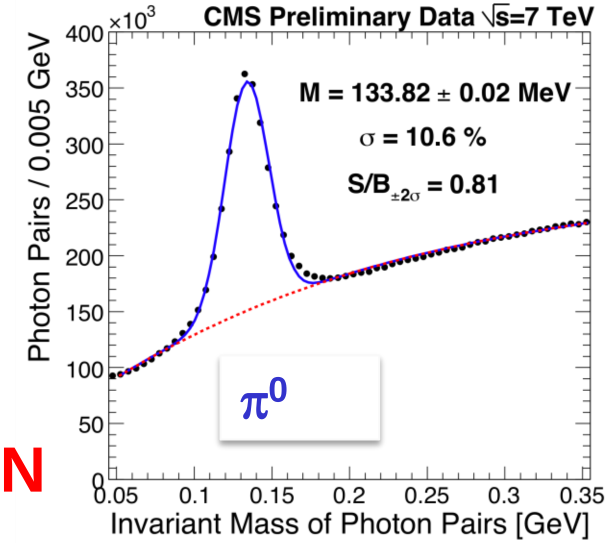




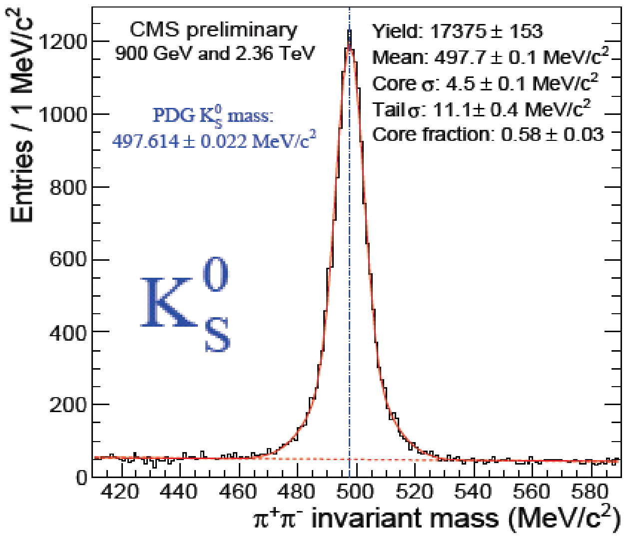


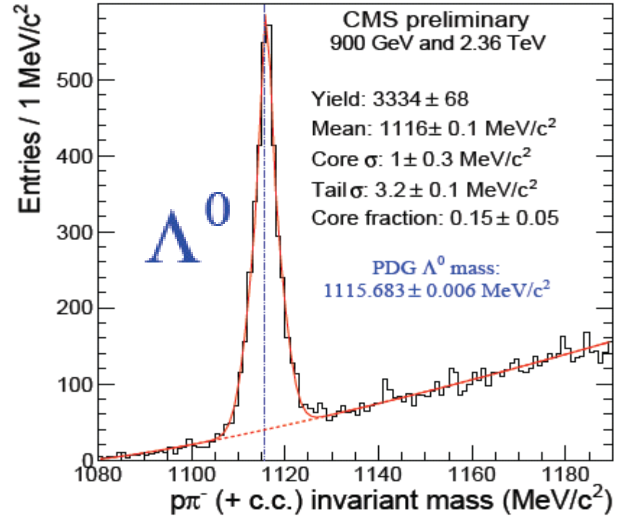
Rise of the particle density at (2.36) 7 TeV steeper than in model predictions. Tuning of MC generators is ongoing.

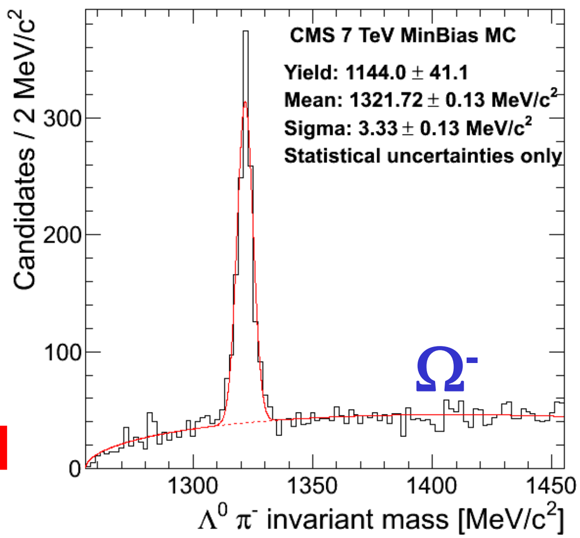
CMS: 35 Years of Particle Physics



N







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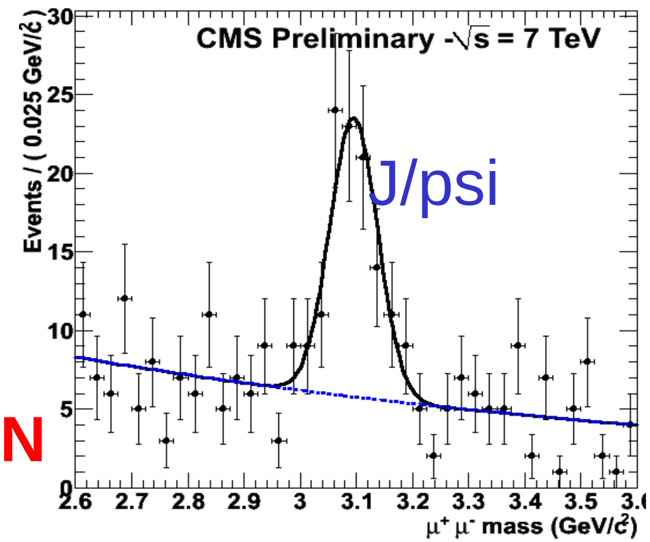

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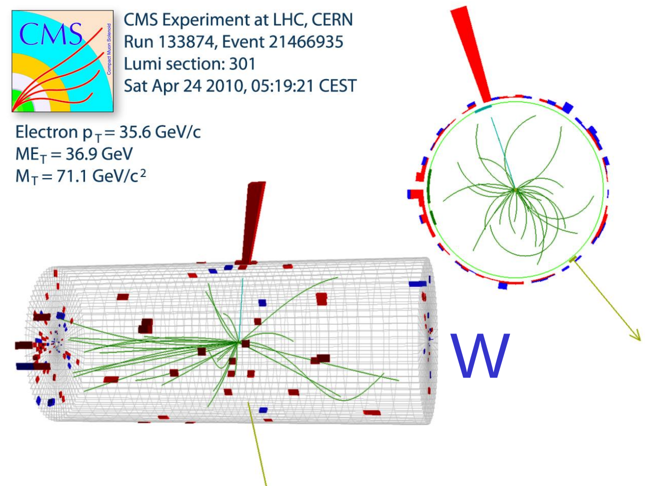
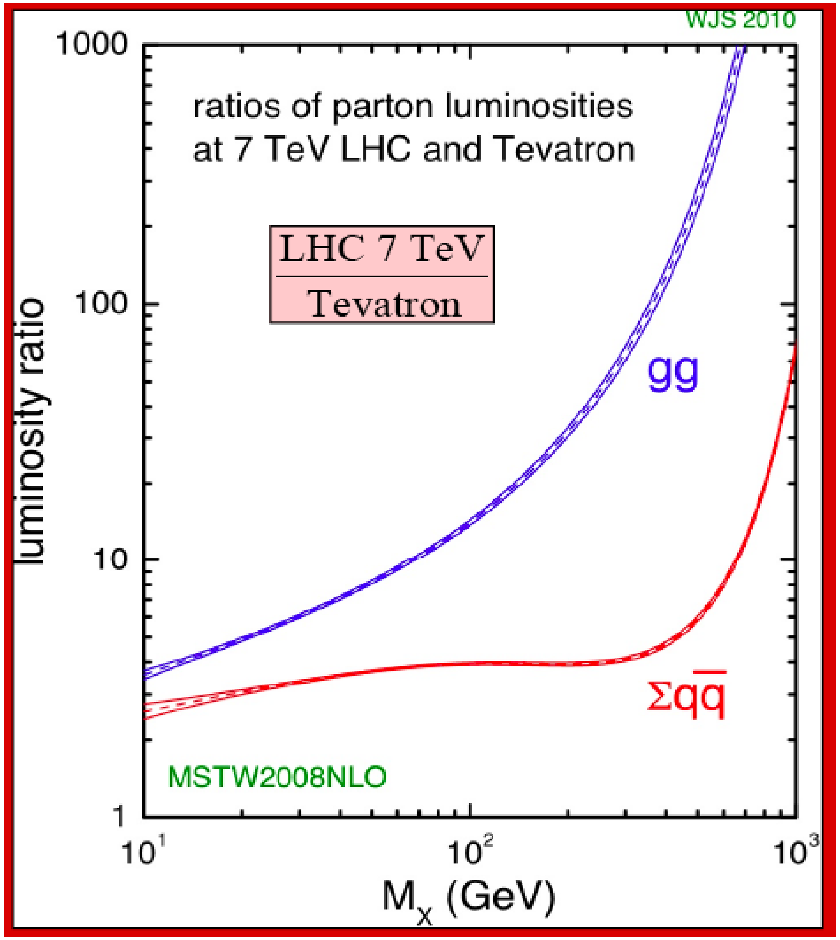


N

Sophisticated software and computing systems had to put in place

LHC is a gluon collider



F. Gianotti

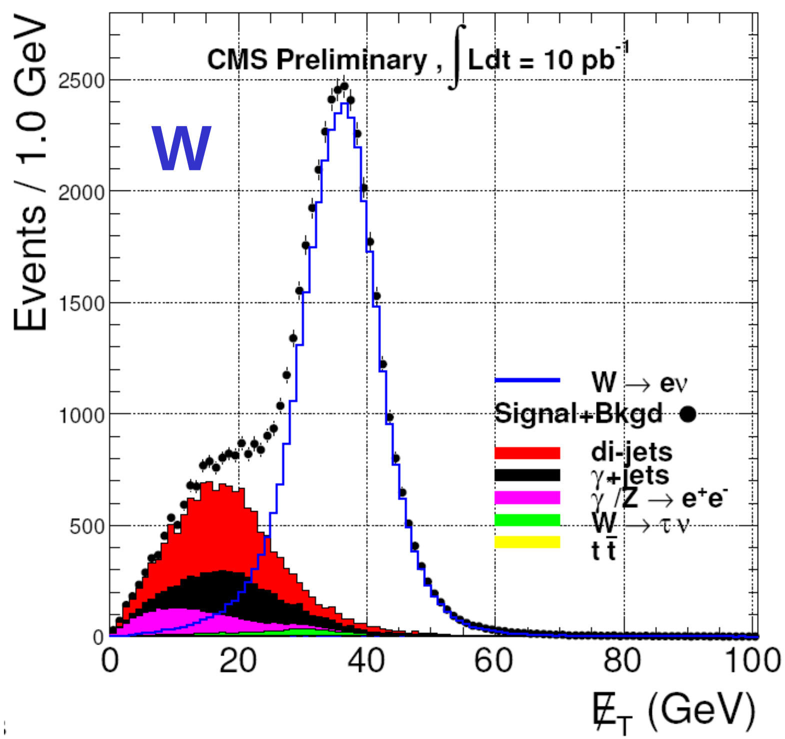
Cross-section	Tevatron	LHC@7TeV/Tevatron	LHC@14TeV/Tevatron
$W/Z \to l\nu, ll$ tt production	2.5/0.25 nb per family 7.2 pb	~ 5 ~ 20	~ 10 ~ 100

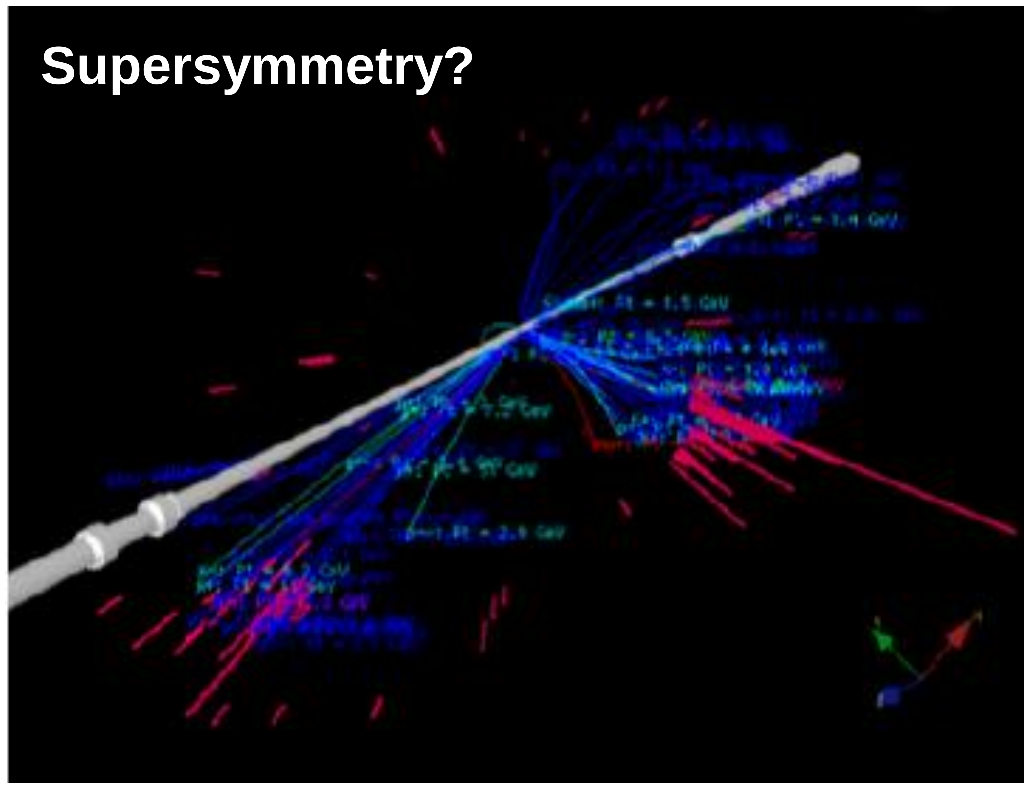
Looking into the Future: In 2010

First verify that we find exactly what is predicted for known physics

"signals of yesterday are backgrounds of today"

AND Start Looking for New Physics !





Comparing Tevatron and LHC (7 TeV)

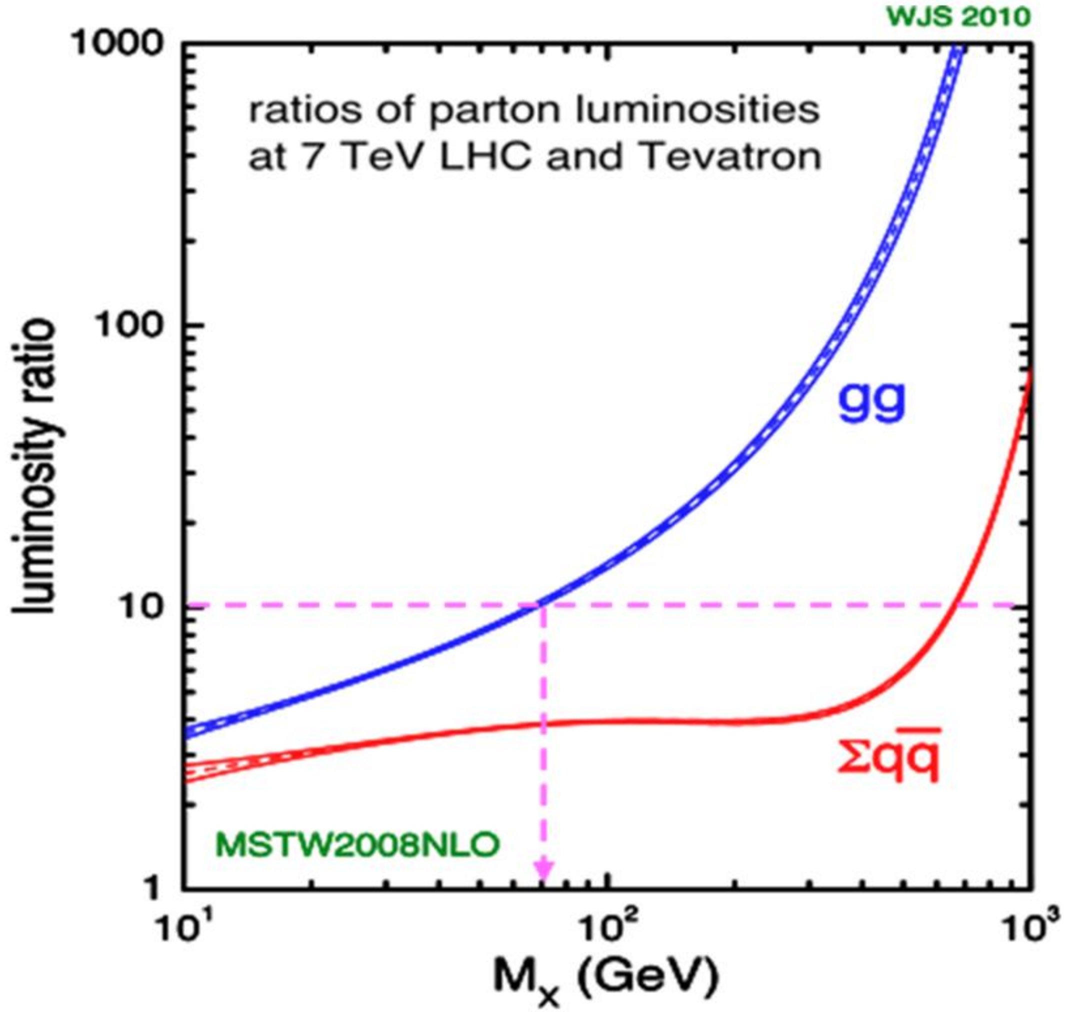
Use parton luminosties to illustrate the gain:

Example: mainly gg
Higgs: pp → H, H→WW and ZZ
Factor ~15

Example: gg and qq
Top: (85% qq, 15% gg at Tevatron)
Factor: 0.85 x 5 + 0.15 x 100
➔ ~ 20

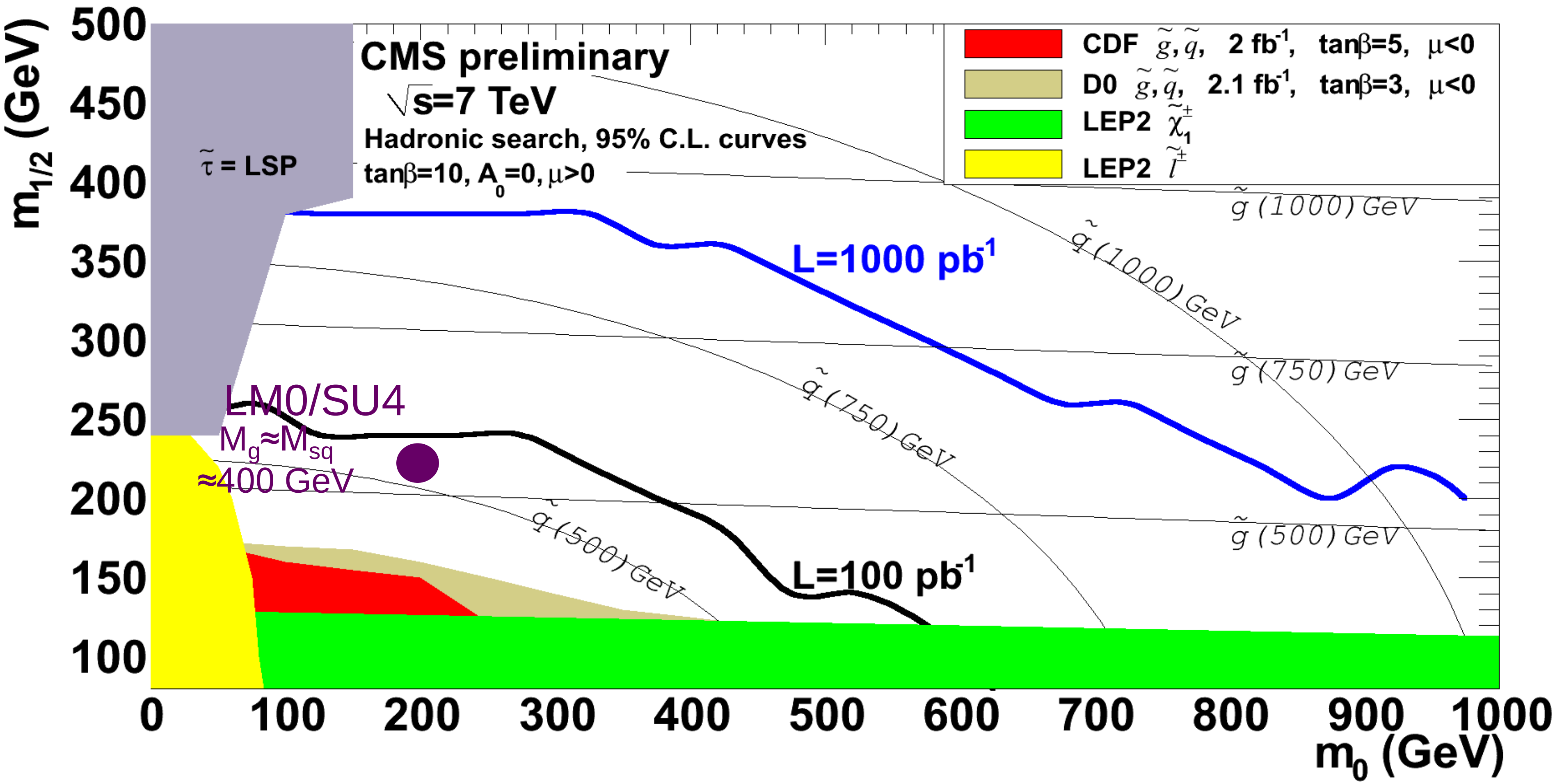
Squarks: ~350 GeV (assume top):
Factor: 0.85 x 10 + 0.15 x 1000
➔~ 150 to 200

Z′: ~1 TeV (qq)
Factor: ~ 50 to 100



O. Buchmuller

Jets+E_T^{miss} Signature



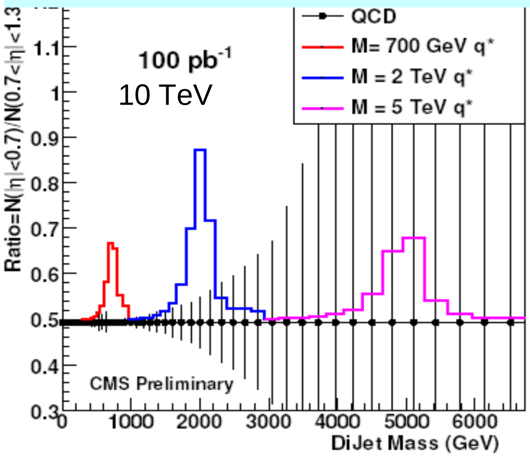
O. Buchmuller

- 95% CL exclusion for all-hadronic search (≥ 3 jets + MET + e/μ veto)
- Systematic uncertainty of 50% assumed on Standard Model background
- *Sensitivity significantly beyond previous experiments (~50/pb to surpass Tevatron)*

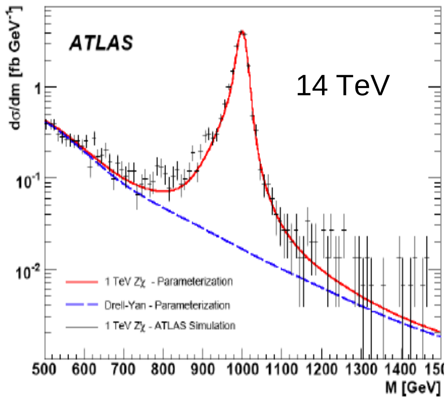
From the Possible to the Unexpected

Large zoo of models that predict different incarnations of New Physics at the LHC

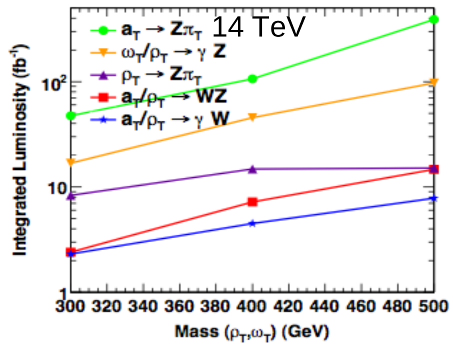
Contact Interaction /Excited Quarks?



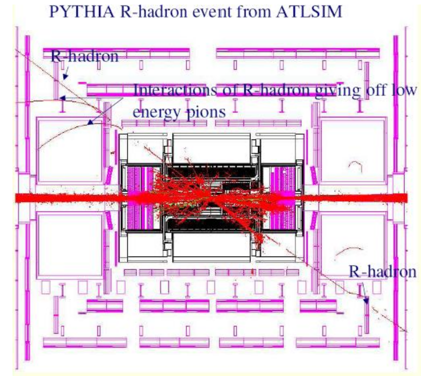
New Gauge Bosons?



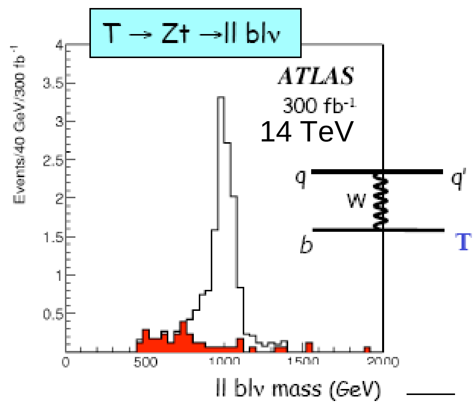
Technicolour?



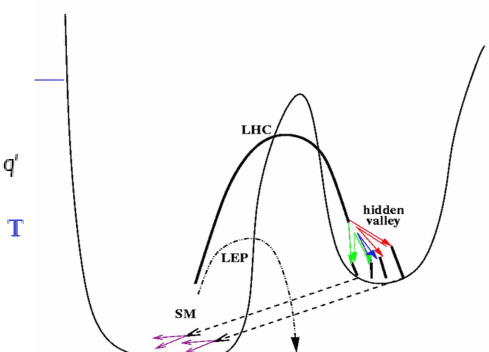
Split Susy?



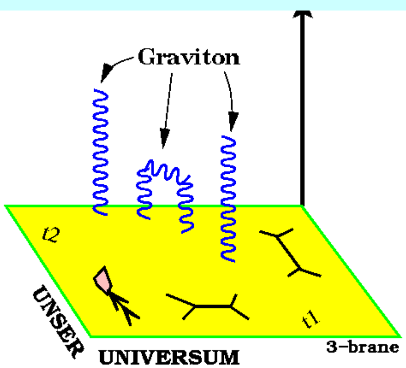
Little Higgs?



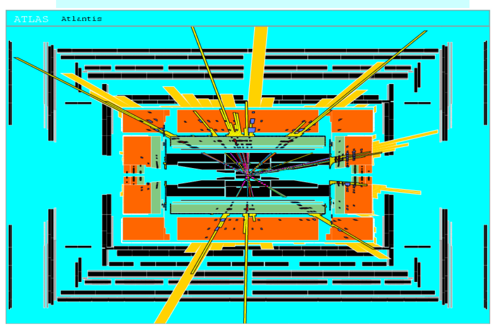
Hidden Valley??



Extra Dimensions?



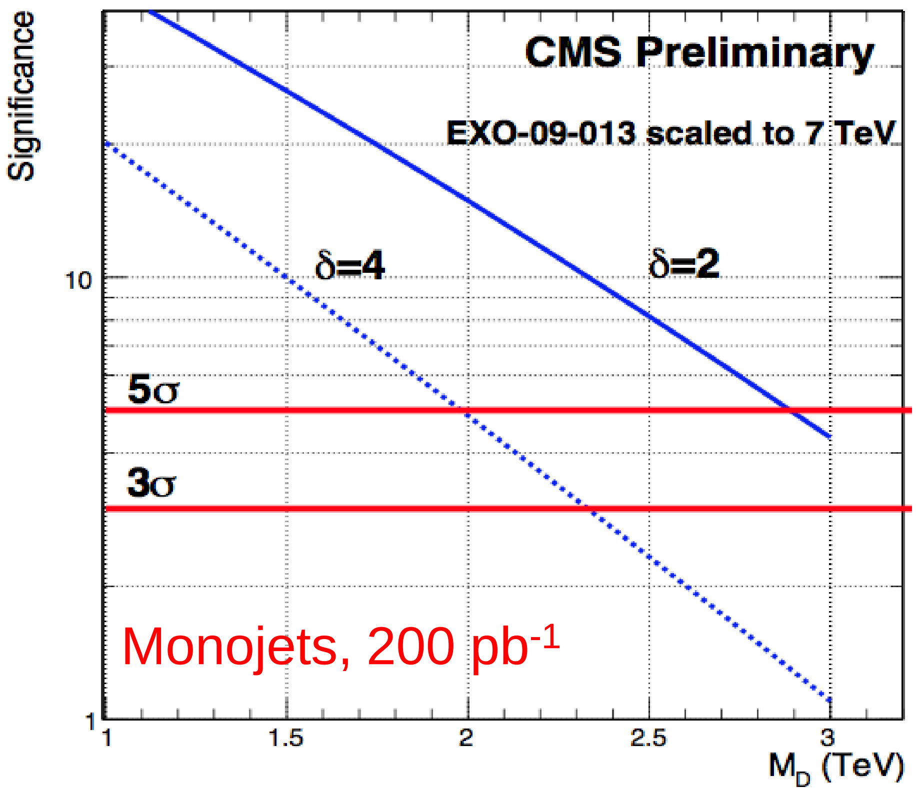
Black Holes???



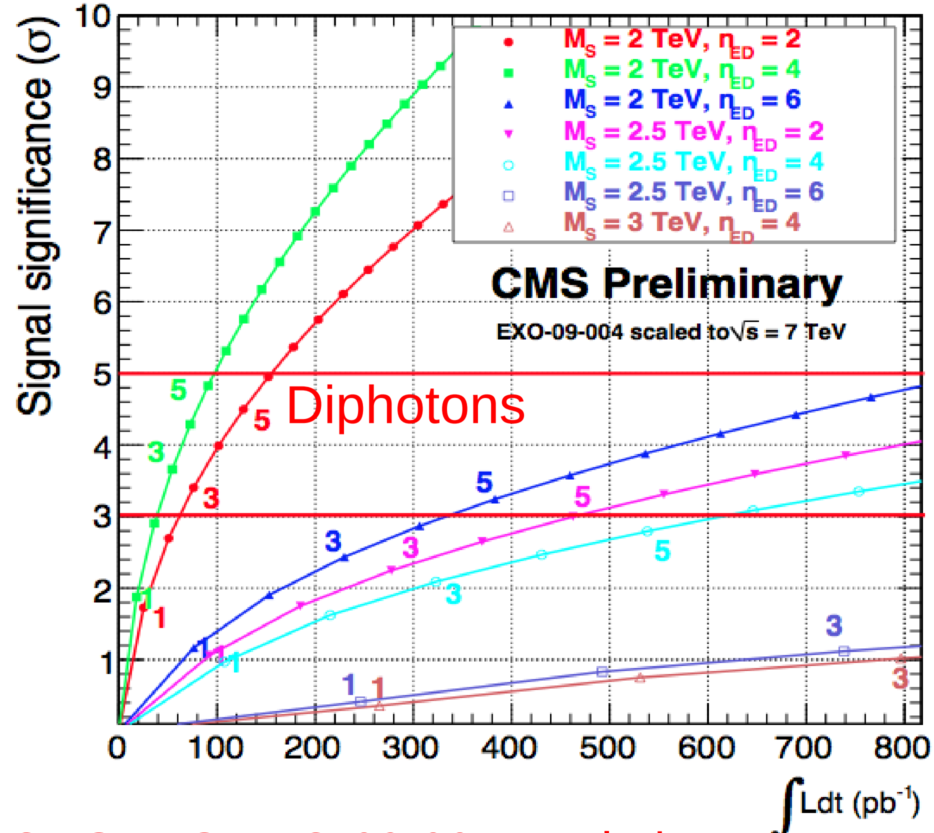
Non exhaustive list (by far)

Large Extra Dimensions

- Several channels offer doubling and tripling of sensitivity compared with the Tevatron limits with 0.1-1.0 fb^{-1} at 7 TeV
- Classical signatures: monojets and photon pairs



CMS PAS EXO-09-013, scaled to 7 TeV

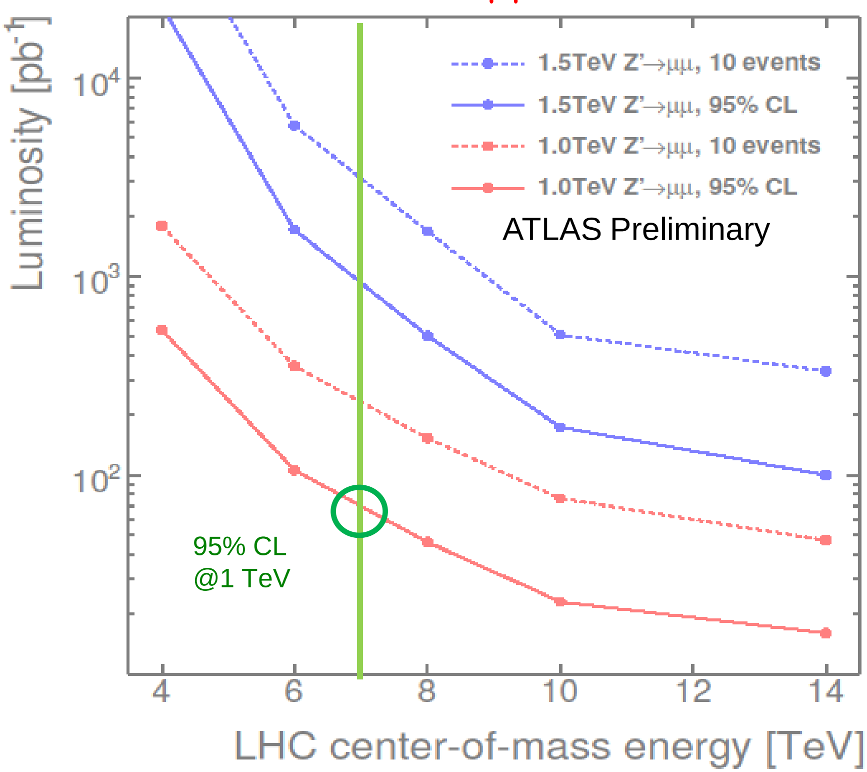


CMS PAS EXO-09-004, scaled to 7 TeV

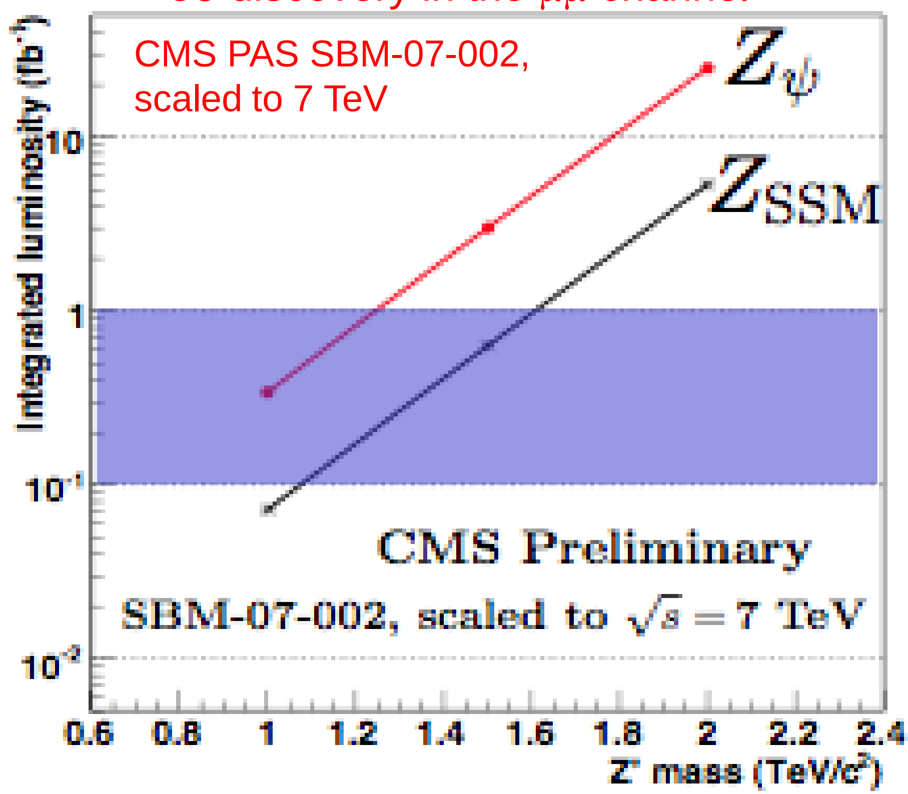
Dilepton Resonances (Example Z')

- Predicted in many SM extensions (Extra Dimensions, Technicolour, Little Higgs)
- Low, well understood background dominated by DY
- 95% CL exclusion O(100/pb) at 1 TeV
- Sensitivity beyond the Tevatron (1 TeV SSM Z') with ~100 pb^{-1}

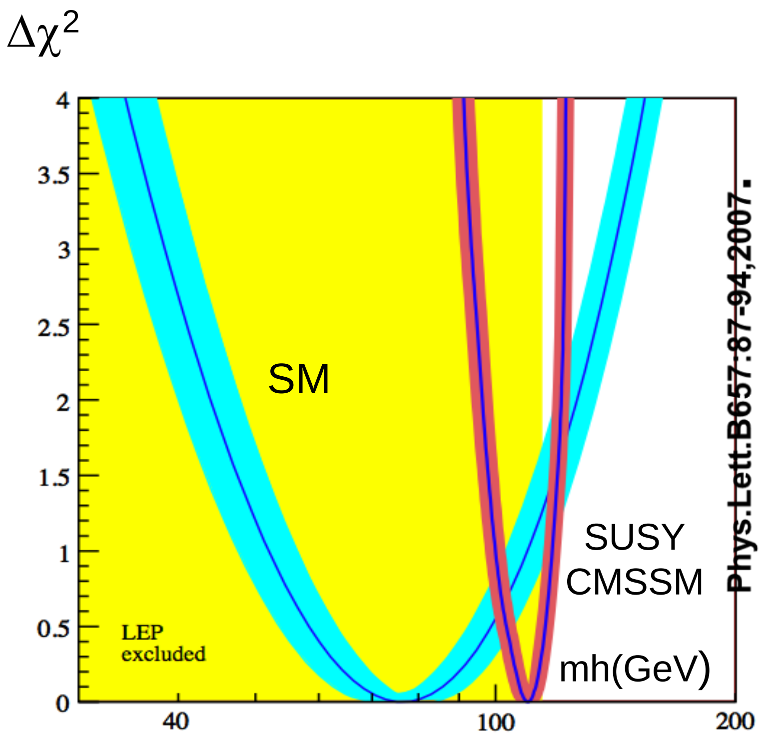
95% exclusion in μμ

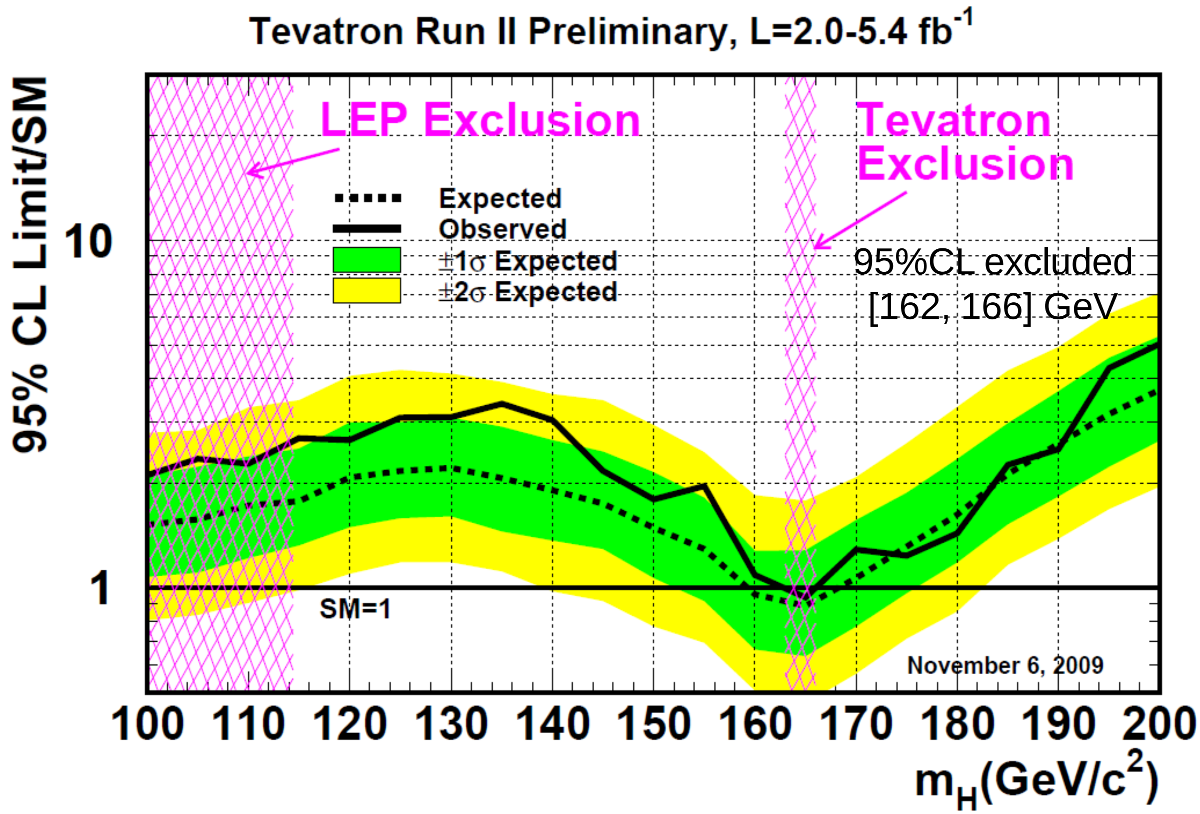


5σ discovery in the μμ channel



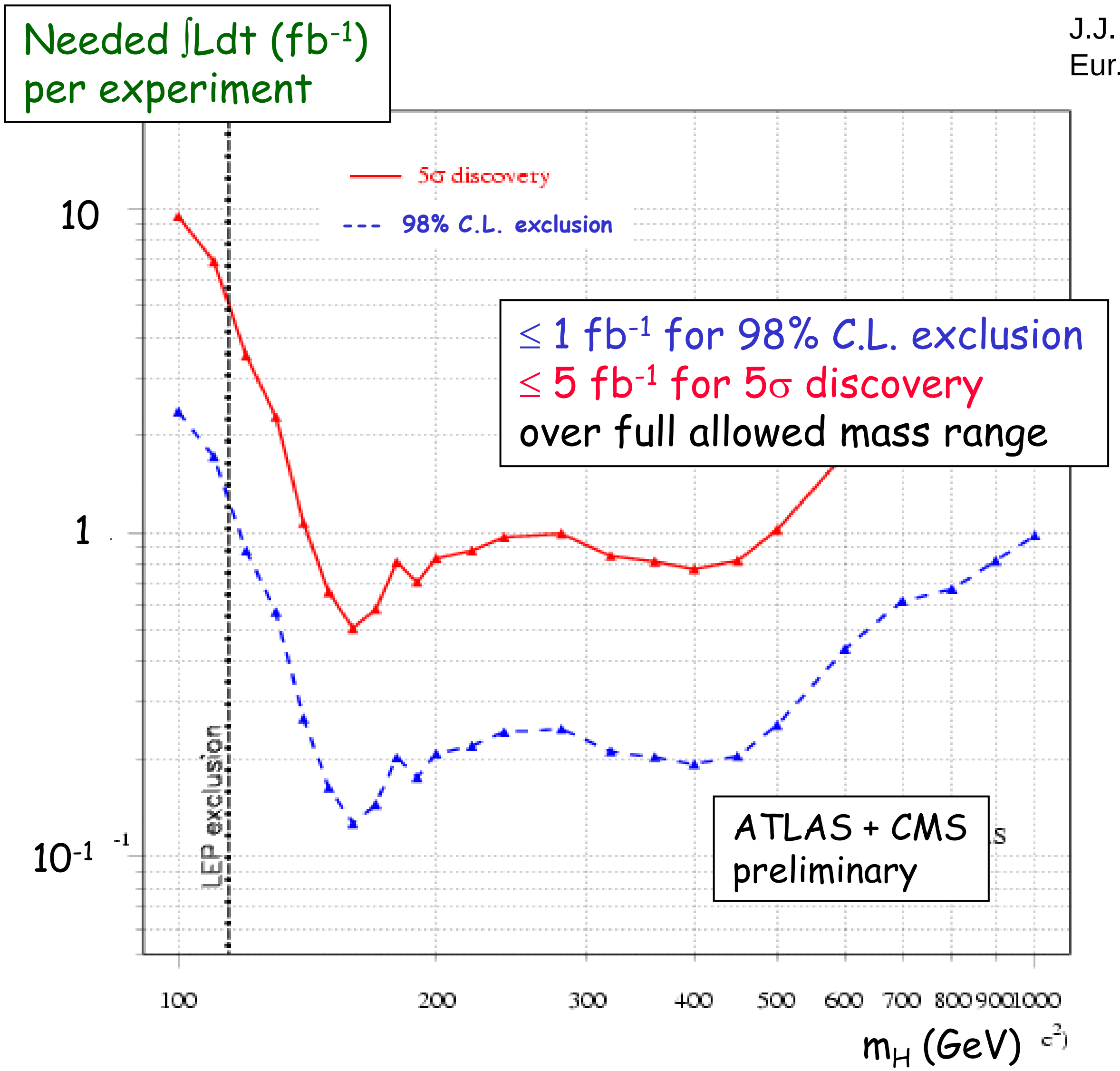
Standard Model (like) Higgs



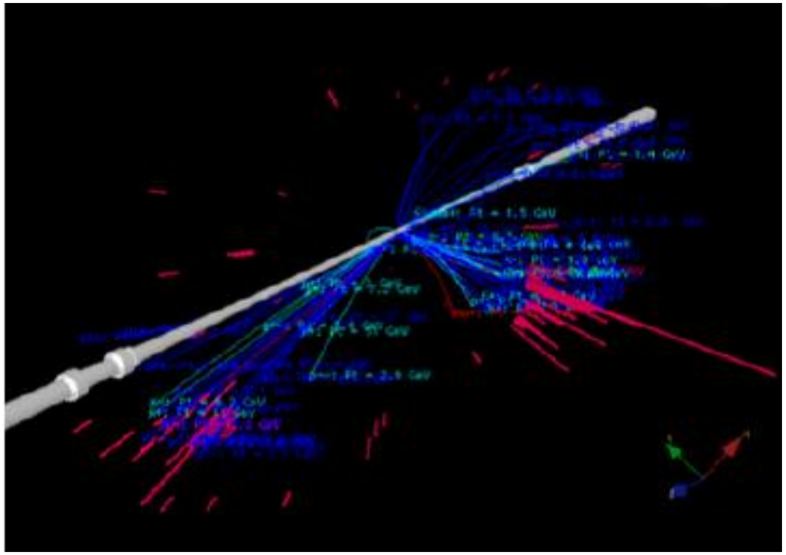


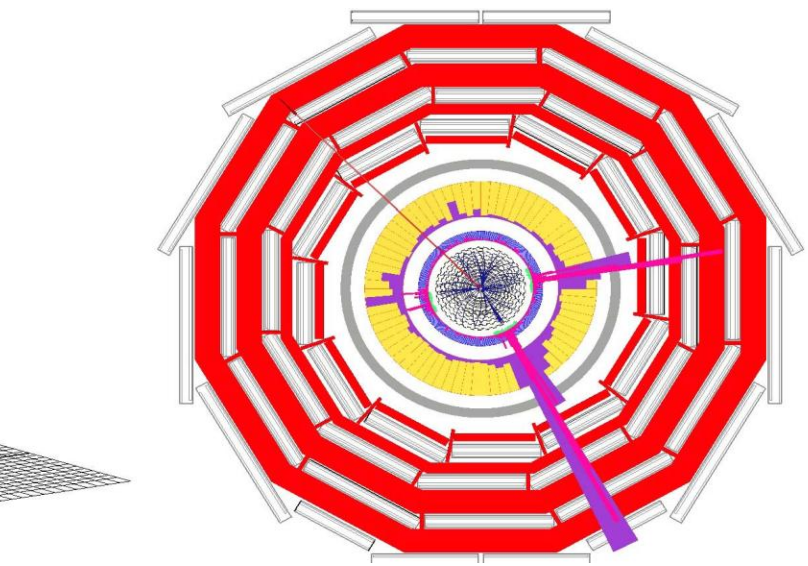
ATLAS +CMS: SM Higgs @14 TeV

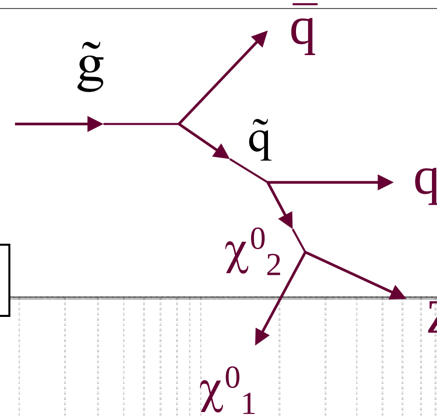
J.J. Blaising et al, input to
Eur. Strategy workshop

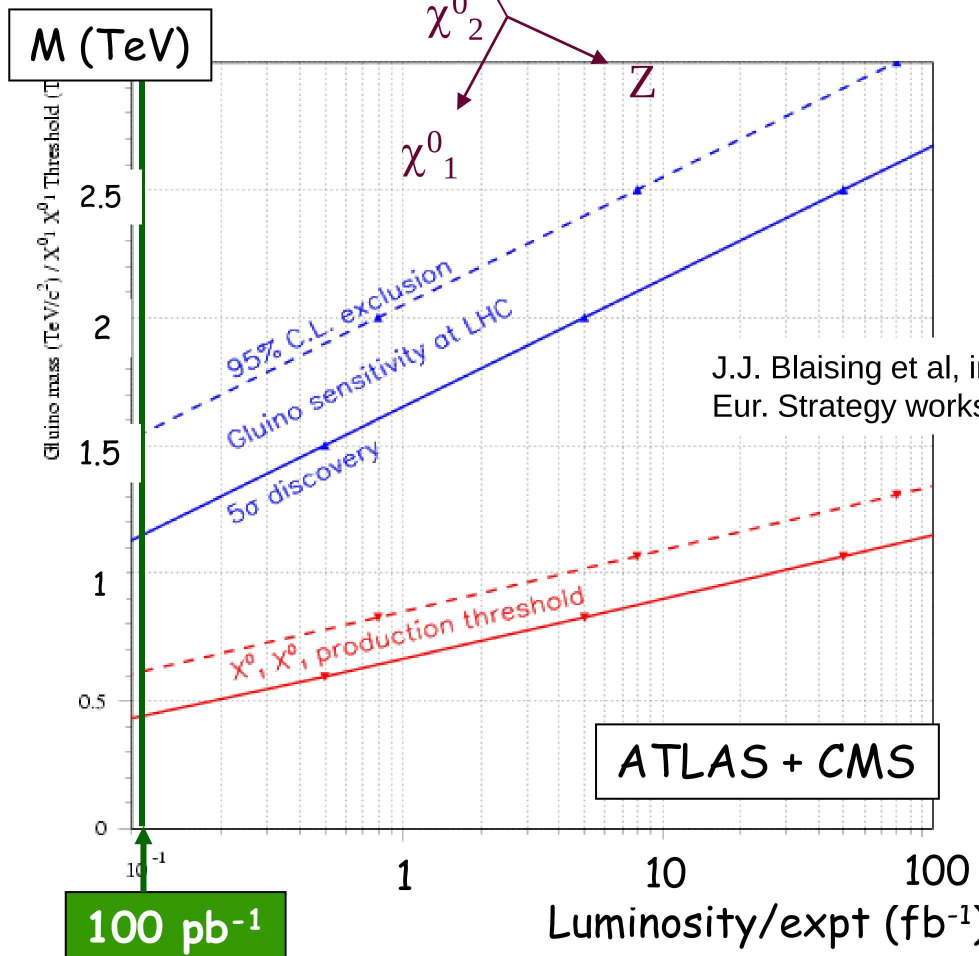


ATLAS + CMS: Supersymmetry @ 14 TeV



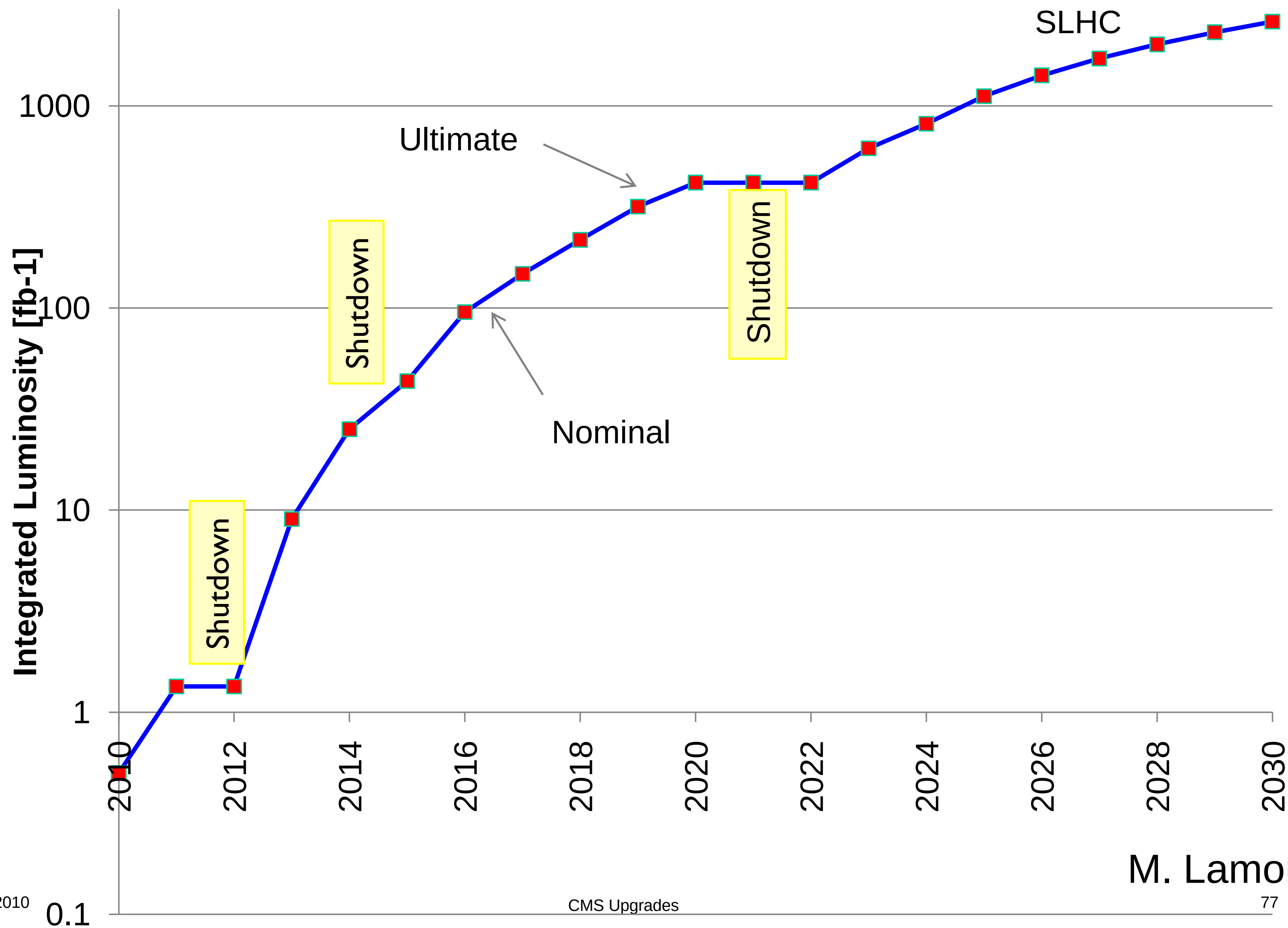






J.J. Blaising et al, input to
Eur. Strategy workshop

Possible Luminosity Evolution



M. Lamont

LHC Machine Shutdowns

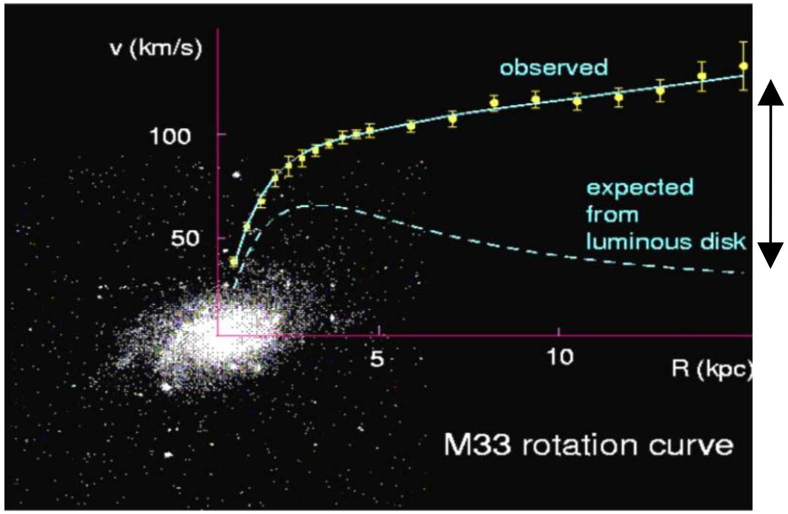
- **The shutdowns required are**
- 2012
  - To finish repairs to allow the machine to reach full energy
  - A full year shutdown
- 2015
  - To install components needed to reach design luminosity and slightly beyond
    - Connection of Linac 4
    - Installation of additional collimators
  - a full year shutdown - could be one year later
- ~2020
  - Major changes to the machine to reach highest possible luminosity in the LHC
  - Probably a two year shutdown

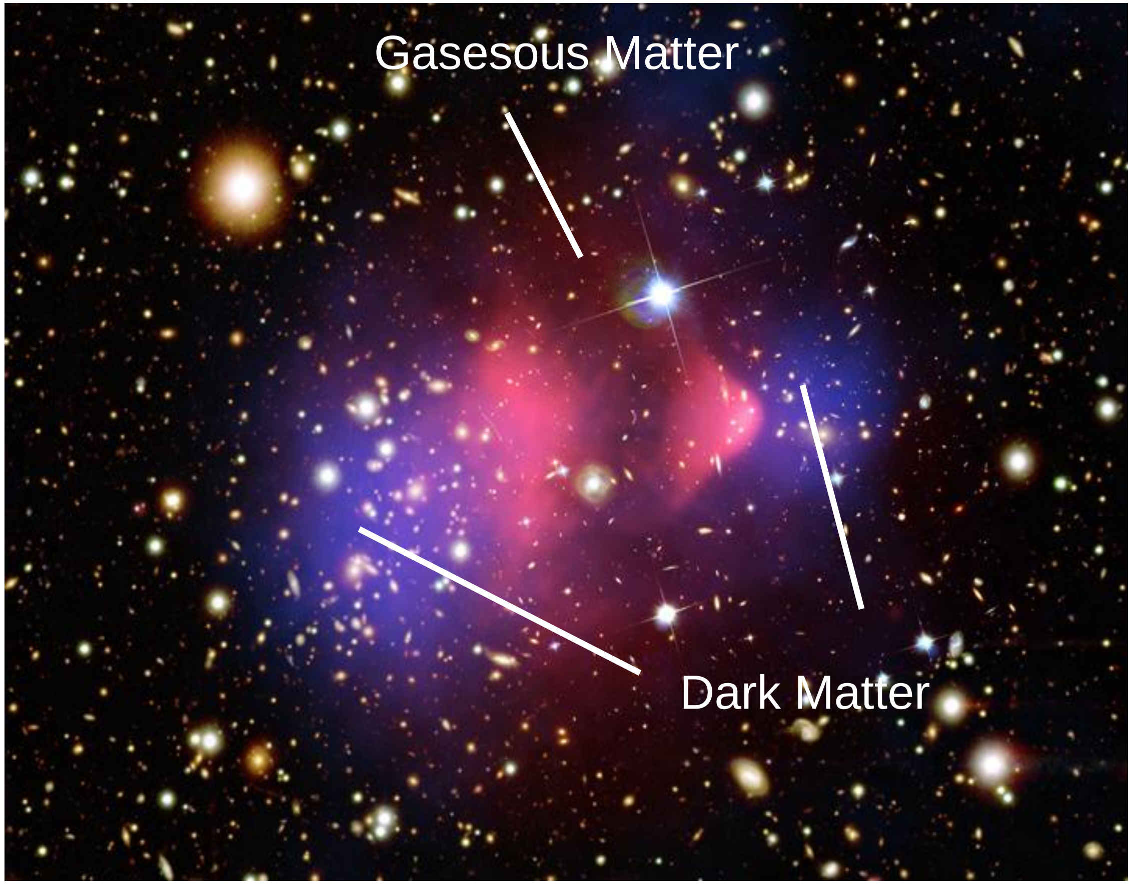
CMS Upgrades: Ideal Scenario

- **2012 Shutdown**
  - Install forward muon systems (Forward RPCs and ME4/1 CSCs)
  - HO SiPMs
  - HF PMTs
  - PLT
- **2015 Shutdown**
  - Install new beampipe
  - Install new pixel detector
  - Install HB/HE photo-detectors
  - Install new trigger system
- **2020 Shutdown**
  - Install new tracking system
  - Major consolidation/replacement of electronics systems
    - Including potentially ECAL electronics

Dark Side of the Universe: Dark Matter

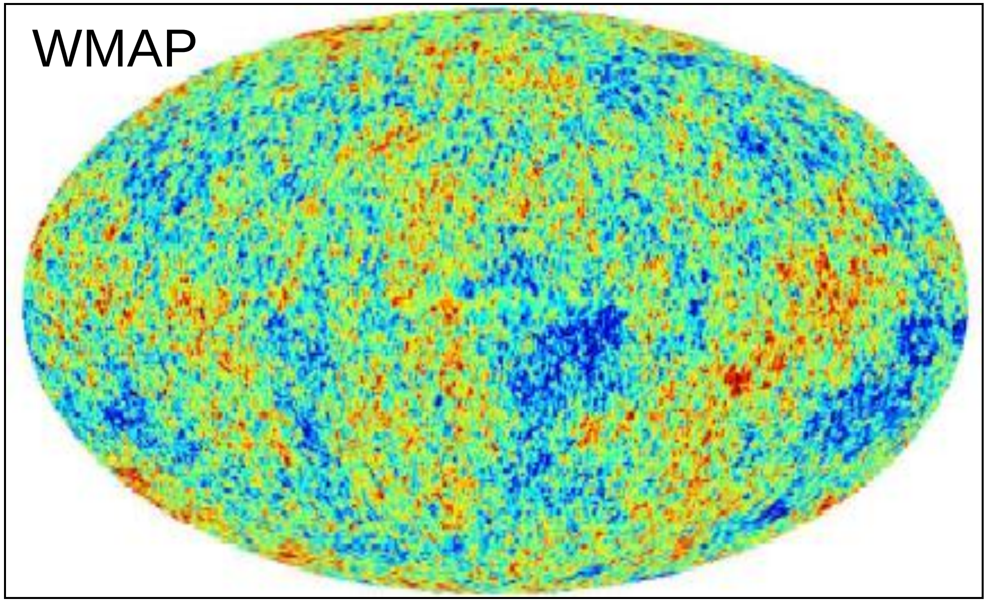
Dark (invisible) matter!



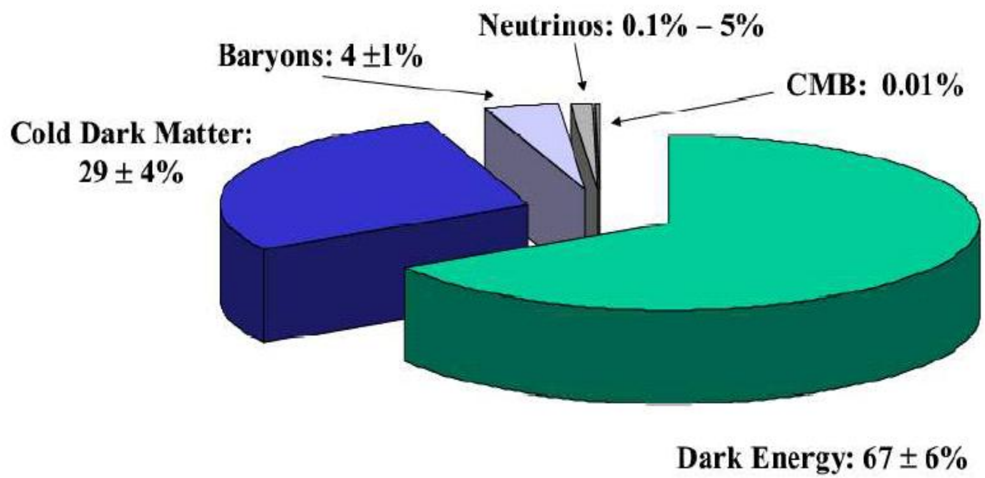


Dark Matter is weakly interacting massive particle
Lightest SUSY particle has these properties !

Dark Side of the Universe Dark Energy



"The Standar Model of Cosmology"
Convergence Model



It appears that the rate of expansion of the universe is accelerating !!
Dark Energy?
Remnant of some elementary scalar field analagous to the Higgs field?

Conclusions: The LHC Project

• **The LHC project (the accelerator and experiments) was conceived & designed to attack fundamental questions in science:**
about the origin, evolution and composition of our universe.
In particular, what is the origin of mass, what constitutes dark matter, do we live in more than 3 space dimensions, why is the universe composed of matter, and not antimatter.

• **Unprecedented instruments in scale and complexity operating in an unprecedented & hostile environment.**

• **Driven by the science many technologies pushed to their limits.**

• **The Project has required a long and painstaking effort on a global scale – a tribute to human ingenuity and collaboration.**

• **The accelerator and the experiments are unparalleled scientific instrument(s) - powerful "microscopes" as well as powerful "telescopes".**

Outlook

After twenty years of design, construction the 2nd half of the journey of extraction of physics has started in earnest. A new era in modern physics has been launched.

The accelerator and the experiments are now operating and all systems are performing very well. The LHC is delivering high energy collisions.

It is just the beginning - but tremendous encouragement for the future. A long and interesting journey lies ahead.

All expectations are that what we find at the LHC will reform our understanding of nature at the most fundamental level.

Only experiments reveal/confirm Nature's inner secrets.

Pathway of an Innovation

Dirac's Equation
a most beautiful equation of physics

$$i\frac{\partial\psi}{\partial t} = (-i\alpha.\nabla + \beta m)\psi$$

1928: description of electrons consistent with Einstein's special theory of relativity and quantum mechanics
Predicted existence of anti-particles (**e.g. positron - basis of Positron Emission Tomography (PET)**)
and explained spin (**- basis of Magnetic Resonance Imaging (MRI)**)

1932: Operation of first cyclotron , the anti-electron (positron) discovered

Radionuclides used in PET scanning are produced by cyclotrons in hospitals – glucose labeled with positron emitters e.g. Fluorine 18.
PET cameras today use APDs (and Si PMs) and heavy scintillating crystals and starting to be combined with MRI scanner.

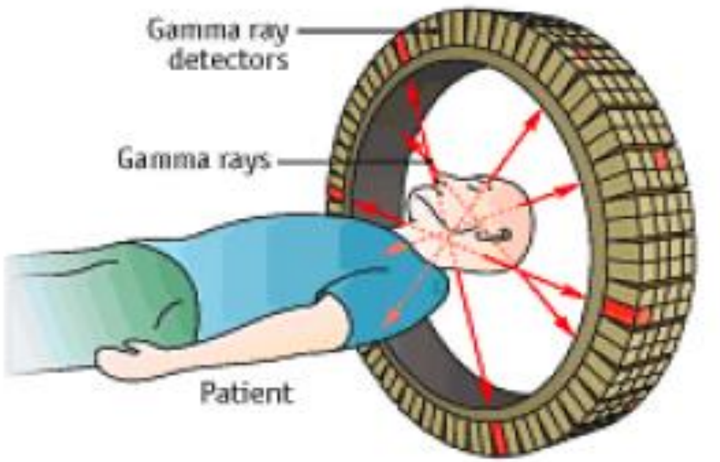
The scientific basis for all medical imaging (functional & physiological) are steeped in nuclear/particle physics

Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI)

CT, MRI etc scanners good at showing show anatomical detail

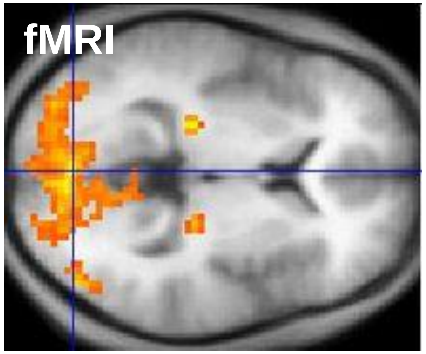
PET makes metabolic activity visible
-determine how patients respond to drugs
- distinguish early Alzheimer's from other types of dementia

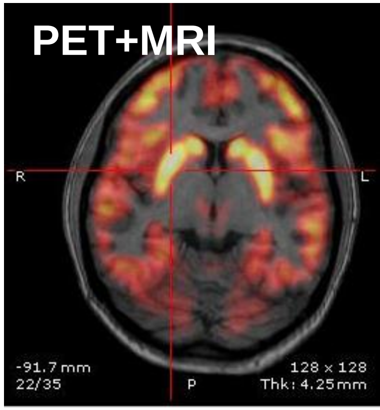
PET Scanning



Costs

PET (+CT today) ~ 2.5 M$ + 0.2M$/yr
Cyclotron ~ 2.0 M&
Infrastructure ~1.5 M&
Cost/Pet scan ~1'500$





NB: 1 cyclotron can service many PET scanners
Worthwhile reducing cost of PET scanners – new crystals, new photodevices (e.g. Si APDs – combine PET and MRI)– reduce cost/complexity.

Most Accelerators are used for Medicine

Category of accelerators	Number in use
High-energy accelerators (E>1 GeV)	~ 120
Radiotherapy accelerators	>7500
Research accelerators incl. biomedical research	1000
Medical radioisotope production	~200
Accelerators for industrial processing and research	>1500
Ion implanters, surface modification centres	>7000
Synchrotron radiation sources	~50
TOTAL IN 2002	~17370

Around 9000 of the 17000 accelerators operating in the World today are used for medicine.

Recent Development: Hadron Therapy