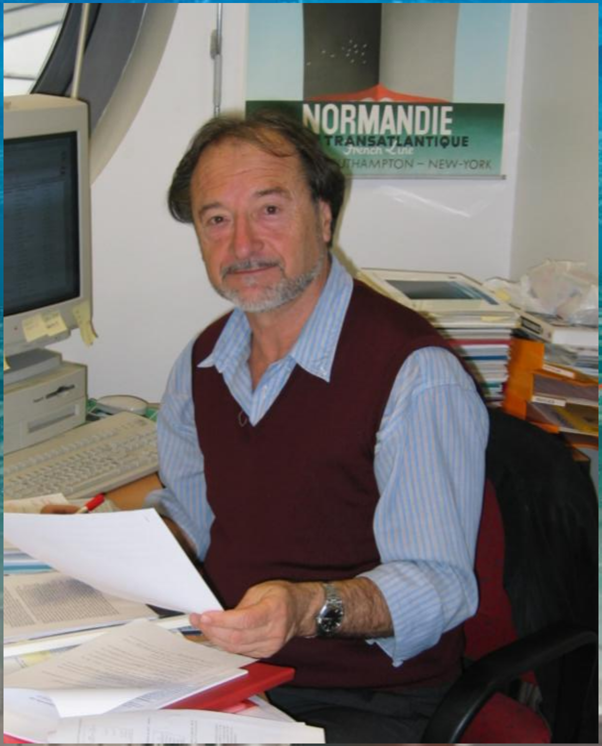
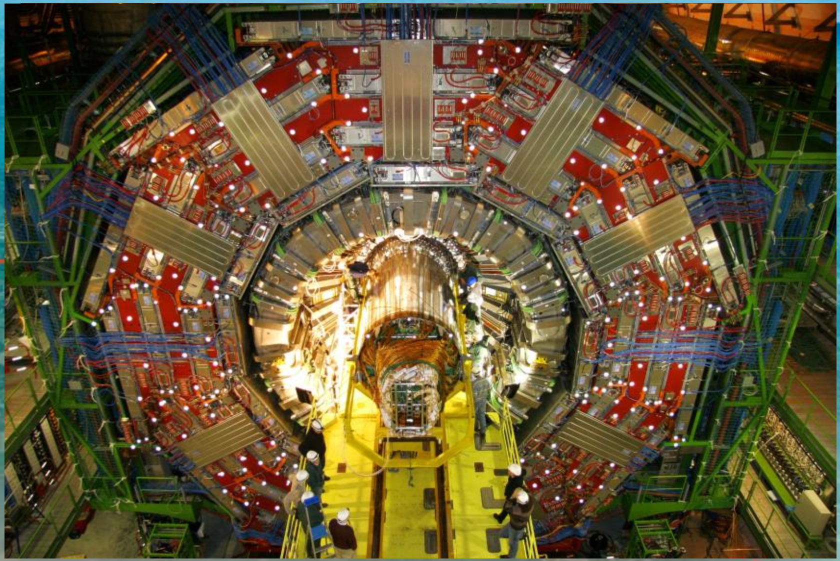
The History of CMS and Daniel Denegri

daniel® inside





Tejinder S. Virdee

Physics Landscape in the 90’s: Questions

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

2. SM has an unproven element: the generation of mass

Higgs mechanism ? or other physics ?

Answer will be found at **LHC energies**

e.g. why $M_\gamma = 0$

M_W, M_Z ~ 100,000 MeV!

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature’s slap on the wrist!

Higgs mechanism provides a possible solution

4. Supersymmetry?

Even if the Higgs exists all is not 100% well with SM alone: next question is “why is (Higgs) mass so low”?

*If a new symmetry (Supersymmetry) is the answer, it must show up at O(**1TeV)***

5. SM is logically incomplete – does not incorporate gravity

*Superstring theory ⇨ dramatic concepts: supersymmetry , extra space-time dimensions ? **New physics at TeV scale?***

Physics Landscape: Alternatives (incomplete set)

Fundamental Higgs unattractive in all but SUSY theories

If no fundamental Higgs boson found at FNAL/LHC then SSB may proceed via a dynamical mechanism

QCD inspired

Identify W_L and Z_L with ‘pions’ of a new interaction

rescale f_π to $1/\sqrt{G_F}$ leading to strong interaction in TeV range

V_L- V_L scattering is a replica of π - π scattering

Technicolour

Dampening of Higgs-less SM via a techni-ρ

Wealth of new states predicted

Transparency from the early 90’s

Strong breaking of E-W symmetry

No Higgs boson but a triplet of massive bound states - vector bosons V^0, $V^\pm$ (similar to techni-ρ)

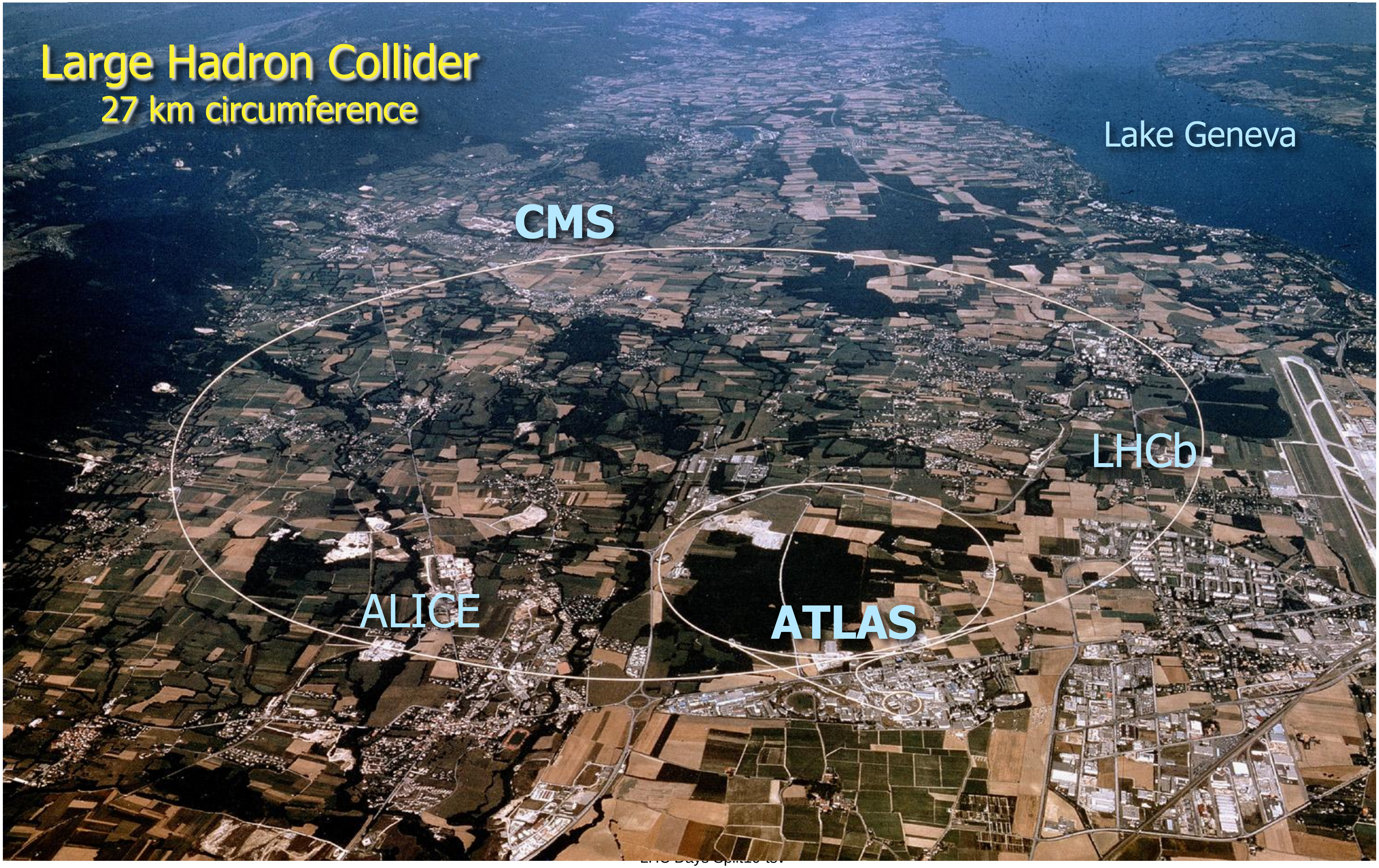
Experimentally at LHC

Find new particles/new symmetries/new forces?

- ⇨ **Origin of Mass -** Higgs boson(s)
- ⇨ **Supersymmetric particles** - a new zoology of particles, dark matter particle? …
- ⇨ **Extra space-time dimensions:** gravitons, Z’ etc. ?
- ⇨ **The Unexpected !!**

Studies of CP Violation and Quark Gluon Plasma

The LHC Project



LHC and CMS Timeline

1984	Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne
1987	Rubbia "Long-Range Planning Committee" recommends Large Hadron Collider as the right choice for CERN's future
1990	ECFA LHC Workshop, Aachen (CMS design first presented)
1992	General Meeting on LHC Physics and Detectors, Evian les Bains
1993	Letters of Intent (ATLAS and CMS selected by LHCC)
1994	Technical Proposals Approved
1996	Approval to move to Construction (ceiling of 475 MCHF)
1998	Memorandum of Understanding for Construction Signed
1998	Construction Begins (after approval of Technical Design Reports)
2000	CMS assembly begins above ground. LEP closes
2004	CMS Underground Caverns completed
2008	CMS ready for LHC beams. The LHC incident 19th Sept
2009	**CMS records first collisions**

Daniel and CMS Physics

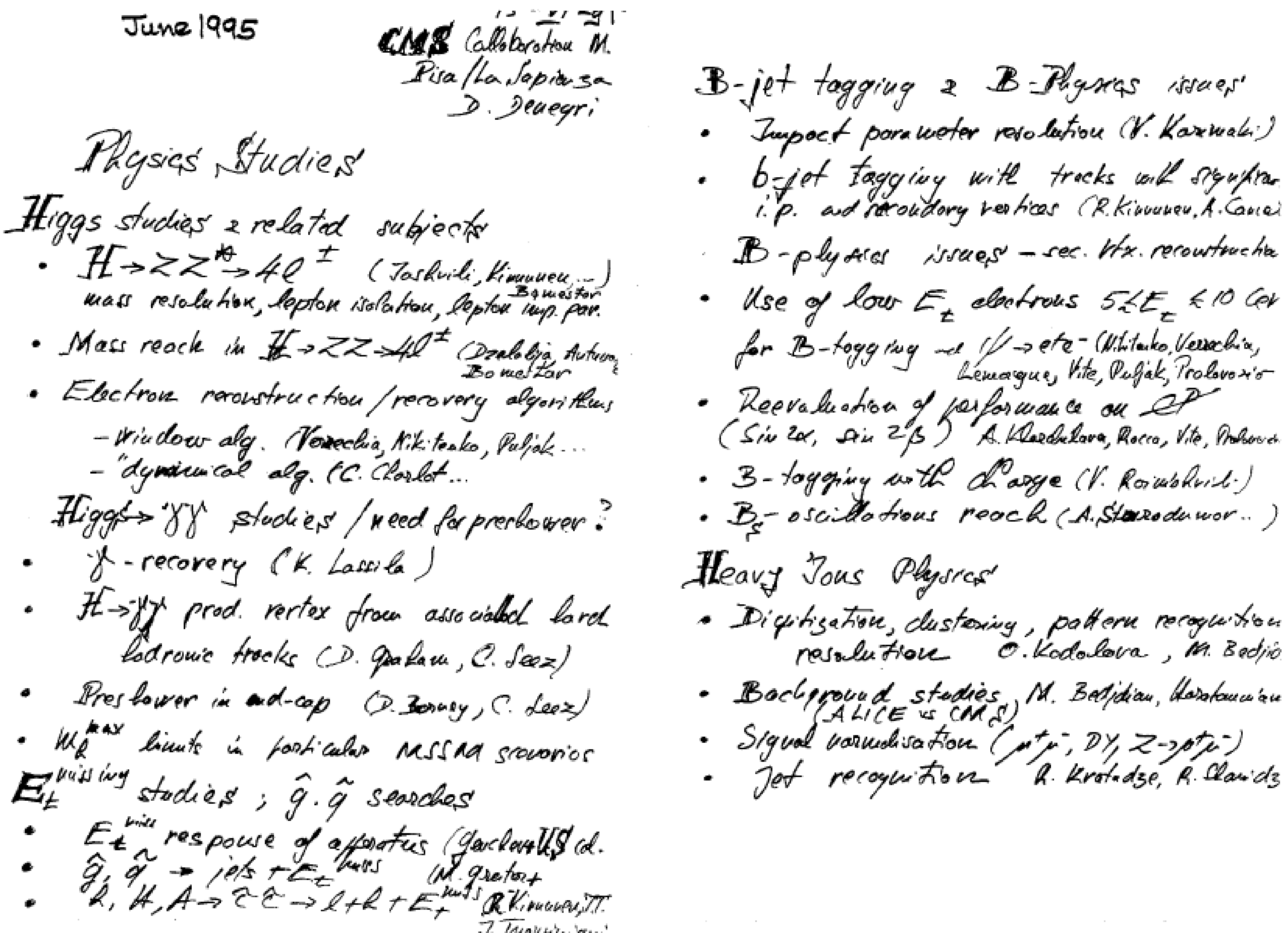
Courtesy: Sergio di Vittorio Veneto

CMS Physics
“coordinator”
until 2003

Building the Collaboration: The Grand Tours

In the early 1990s we went far and wide to build the CMS collaboration.

Physics According to the Gospel of Daniel



June 1995

CMS Collaboration M.
Pisa / La Sapienza
D. Denegri

Physics Studies

Higgs studies & related subjects

- $H \to ZZ^* \to 4\ell^\pm$ (Jaskvili, Kinnunen, ...)
  mass resolution, lepton isolation, lepton imp. par. Bomestar
- Mass reach in $H \to ZZ \to 4\ell^\pm$ (Dzelalija, Antunovic, Bomestar
- Electron reconstruction / recovery algorithms
  - window alg. (Vecchia, Nikitenko, Puljak ...
  - "dynamical" alg. (C. Charlot ...

Higgs → "γγ" studies / need for preshower?

- γ - recovery (K. Lassila)
- $H \to \gamma\gamma$ prod. vertex from associated hard hadronic tracks (D. Graham, C. Seez)
- Preshower in end-cap (D. Barney, C. Seez)
- M_h^{max} limits in particular MSSM scenarios

$E_t^{missing}$ studies ; $\hat{g}$. $\tilde{q}$ searches

- E_t^{miss} response of apparatus (Yarba US col.
- $\hat{g}, \tilde{q} \to$ jets + E_t^{miss} (M. Gratoff
- $\hat{h}$, H, A $\to \tilde{\tau}\tilde{\tau} \to \ell + h + E_t^{miss}$ R. Kinnunen, T. Tuuva

B-jet tagging & B-Physics issues

- Impact parameter resolution (V. Karimaki)
- b-jet tagging with tracks with significant i.p. and secondary vertices (R. Kinnunen, A. Caner
- B-physics issues – sec. Vtx. reconstruction
- Use of low E_t electrons $5 \leq E_t \leq 10$ GeV for B-tagging and $J/\psi \to e^+e^-$ (Nikitenko, Vecchia, Lemaigue, Vite, Puljak, Prokofiev
- Reevaluation of performance on CP (Sin 2α, sin 2β) A. Khodinkova, Rocco, Vite, Prokofiev
- B-tagging with charge (V. Roinishvili)
- B_s - oscillations reach (A. Starodumov ..)

Heavy Ions Physics

- Digitisation, clustering, pattern recognition resolution O. Kodolova, M. Bedjidian
- Background studies (ALICE vs CMS) M. Bedjidian, Kodolova
- Signal normalisation ($\mu^+\mu^-$, DY, $Z \to \mu^+\mu^-$)
- Jet recognition A. Kharadze, R. Shanidze

CMS Collaboration

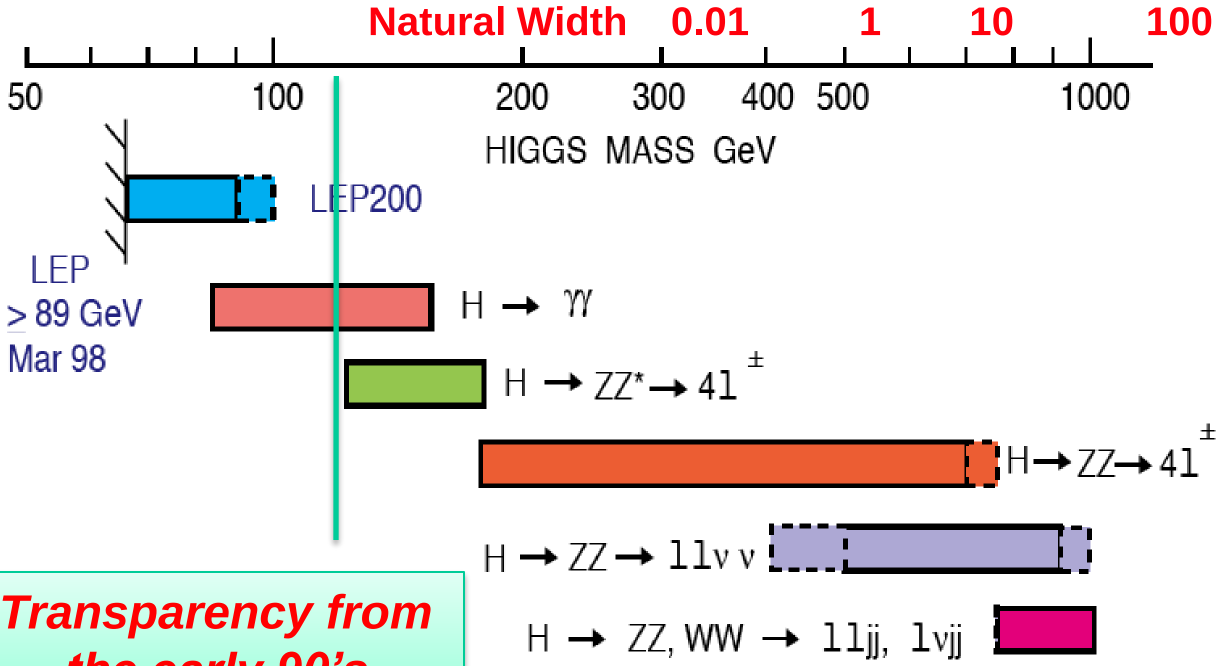
AACHEN-1, AACHEN-3A, AACHEN-3B, ADANA-CUKUROVA, ANKARA-METU, ANTWERPEN, ATHENS, ATOMKI, AUCKLAND, BARI, BEIJING-IHEP, BOGAZICI, BOLOGNA, BOSTON-UNIV, BRISTOL, BROWN-UNIV, BRUNEL, BRUSSEL-VUB, BRUXELLES-ULB, BUDAPEST, CALTECH, CANTERBURY, CARNEGIE-MELLON, CATANIA, CCCS-UWE, CERN, CHANDIGARH, CHEJU, CHICAGO, CHONNAM, CHUNGBUK, CHUNGLI-NCU, COLORADO, CORNELL, DEBRECEN-IEP, DELHI-UNIV, DEMOKRITOS, DESY, DONGSHIN, DUBLIN-UCD, DUBNA, EINDHOVEN, FAIRFIELD, FERMILAB, FIRENZE, FLORIDA-FIU, FLORIDA-STATE, FLORIDA-TECH, FLORIDA-UNIV, FRASCATI, GENOVA, GHENT, HAMBURG-UNIV, HEFEI-USTC, HELSINKI-HIP, HELSINKI-UNIV, HEPHY, IOANNINA, IOWA, IPM, ISLAMABAD-NCP, JOHNS-HOPKINS, KANGWON, KANSAS-STATE, KANSAS-UNIV, KARLSRUHE-IEKP, KHARKOV-ISC, KHARKOV-KIPT, KHARKOV-KSU, KONKUK-UNIV, KOREA-UNIV, KYUNGPOOK, LAPP, LAPPEENRANTA-LUT, LIP, LIVERMORE, LONDON-IC, LOUVAIN, LYON, MADRID-CIEMAT, MADRID-UNIV, MARYLAND, MEXICO-IBEROAM, MEXICO-IPN, MEXICO-PUEBLA, MEXICO-UASLP, MILANO-BICOCCA, MINNESOTA, MINSK-INP, MINSK-NCPHEP, MINSK-RIAPP, MINSK-UNIV, MISSISSIPPI, MIT, MONS, MOSCOW-INR, MOSCOW-ITEP, MOSCOW-LEBEDEV, MOSCOW-MSU, MOSCOW-RDIPE, MUMBAI-BARC, MYASISHCHEV, NAPOLI, NEBRASKA, NICOSIA-UNIV, NORTHEASTERN, NORTHWESTERN, NOTRE DAME, NUST, OHIO-STATE, OVIEDO, PADOVA, PAVIA, PEKING-UNIV, PERUGIA, PISA, POLYTECHNIQUE, PRINCETON, PROTVINO, PSI, PUERTO RICO, PURDUE, PURDUE-CALUMET, RAL, RICE, RIE, RIO-CBPF, RIO-UERJ, ROCHESTER, ROCKEFELLER, ROMA-1, RUTGERS, SACLAY, SANTANDER, SAO PAULO, SEONAM, SEOUL-EDU, SEOUL-SNU, SHANGHAI-IC, SKK-UNIV, SOFIA-CLMI, SOFIA-INRNE, SOFIA-UNIV, **SPLIT-FESB, SPLIT-UNIV,** ST-PETERSBURG, STRASBOURG, SUNY-BUFFALO, TAIPEI-NTU, TALLINN, TASHKENT, TBILISI-IHEPI, TBILISI-IPAS, TENNESSEE, TEXAS-TAMU, TEXAS-TECH, TIFR-EHEP, TIFR-HECR, TORINO, TRIESTE, UCDAVIS, UCLA, UCRIVERSIDE, UCSB, UCSD, UNIANDES, VANDERBILT, VILNIUS-ACADEMY, VILNIUS-UNIV, VINCA, VIRGINIA-TECH, VIRGINIA-UNIV, WARSAW-IEP, WARSAW-INS, WARSAW-ISE, WAYNE, WISCONSIN, WONKWANG, YEREVAN, **ZAGREB-RUDJER**, ZURICH-ETH, ZURICH-UNIV

October 2009: 182 Institutions with about 3110 scientists and engineers
~ 2000 Signing Authors (including students)

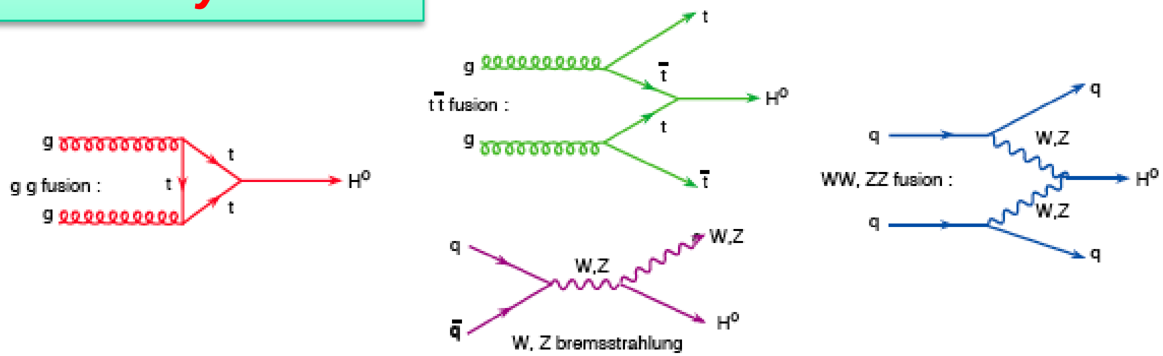
Detector Design: Benchmarks in Early 90's

Explorable mass range at $\sqrt{s}$ =14 TeV with 10^5 pb^{-1}

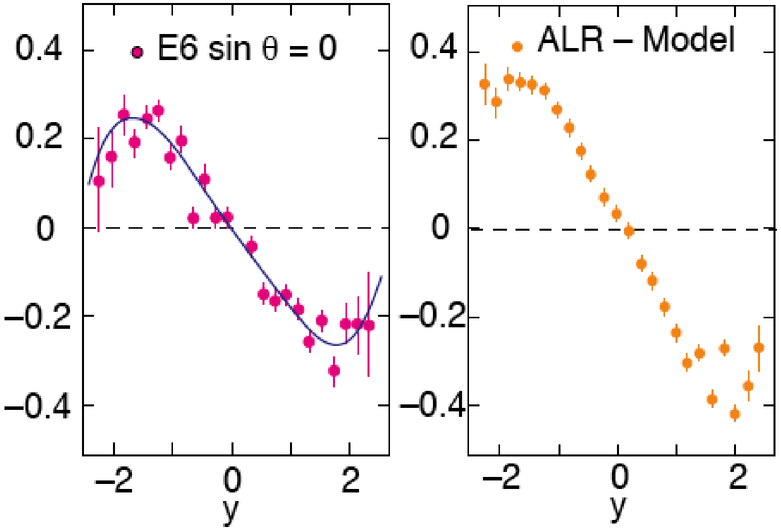
taken at 10^{34} $cm^{-2}s^{-1}$

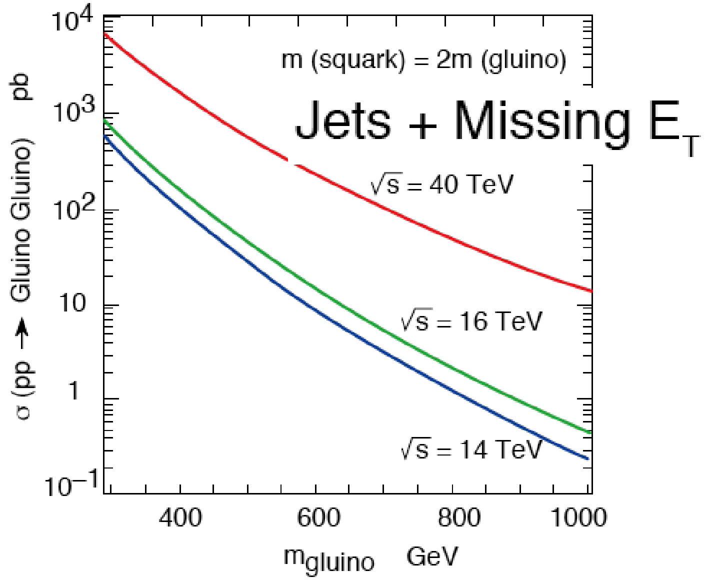


Transparency from the early 90's



F-B Asymmetry : M(z') = 1 TeV





Criteria Driving Design of LHC Experiments

Very good muon identification and momentum measurement
Trigger efficiently and measure sign of TeV muons dp/p < 10%

High energy resolution electromagnetic calorimetry
~ 0.5% @ E_T ~ 50 GeV

Transparency from the early 90's

Powerful inner tracking systems
Momentum resolution a factor 10 better than at LEP

Hermetic calorimetry
Good missing E_T resolution

(Affordable detector)

Detector Landscape circa 1990

Magnets

Solenoids, 2T, length/radius ratio ~ 1

Trackers

TPCs, wire chambers, fibre trackers, ~ 10% @ p_T ~ 100 GeV

LEP detectors had not yet introduced Si micro-vertex detectors

Calorimeters

Sampling, granular, low volume crystals

Muon Chambers

Mostly for identification purposes rather than momentum measurement

Often needing upgrading

Trigger & Data Acquisition

Multiple levels of hardware triggers before going into computer farms

Crucial Selections and Stages

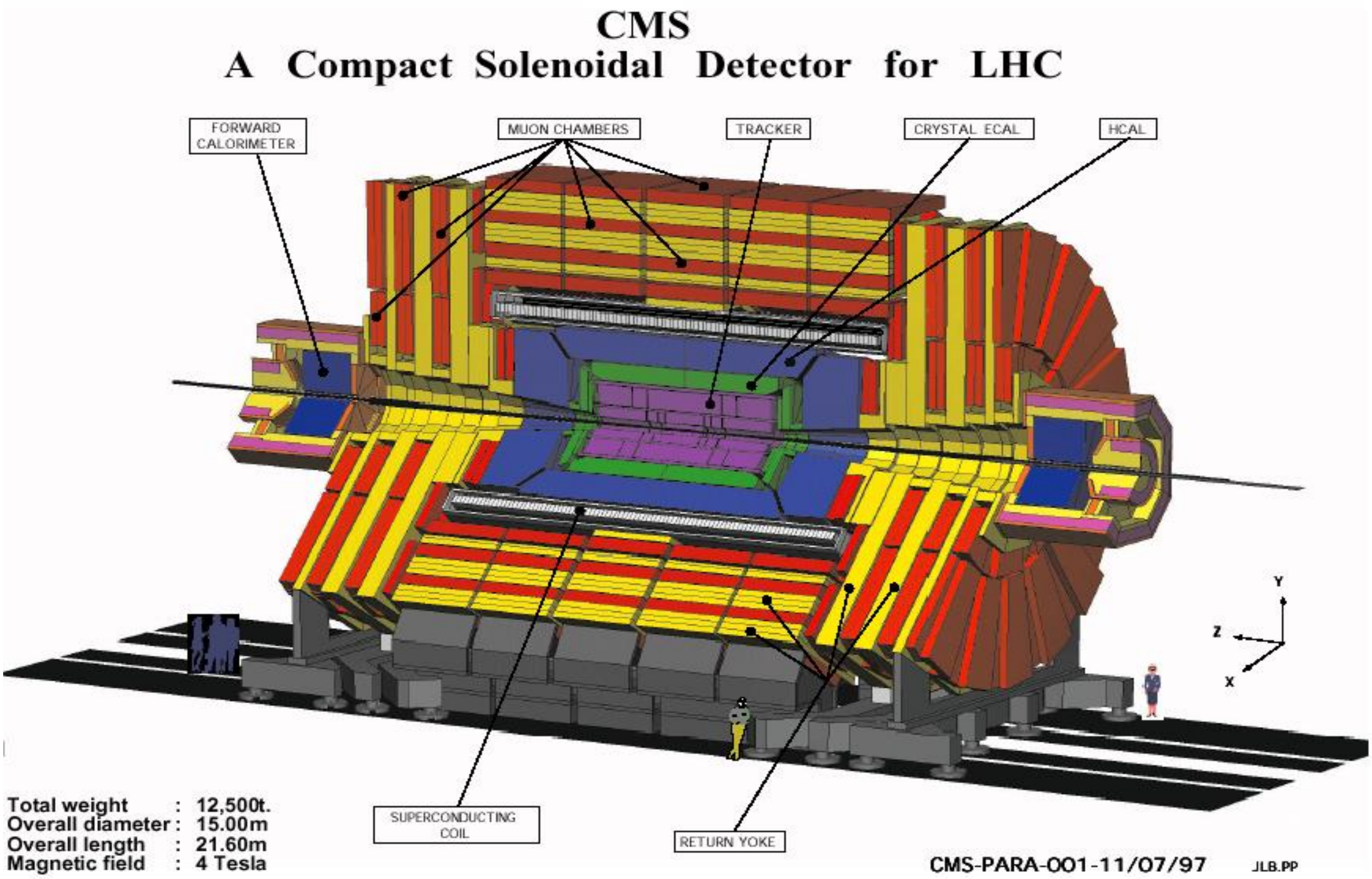
Selection of

1. High magnetic field solenoid
2. All silicon tracker
3. ¼ um rad hard electronics
4. Lead tungstate crystals coupled to APDs
5. Redundancy in the muon system
6. Single hardware Level-1 trigger and then in HLT in computer farm

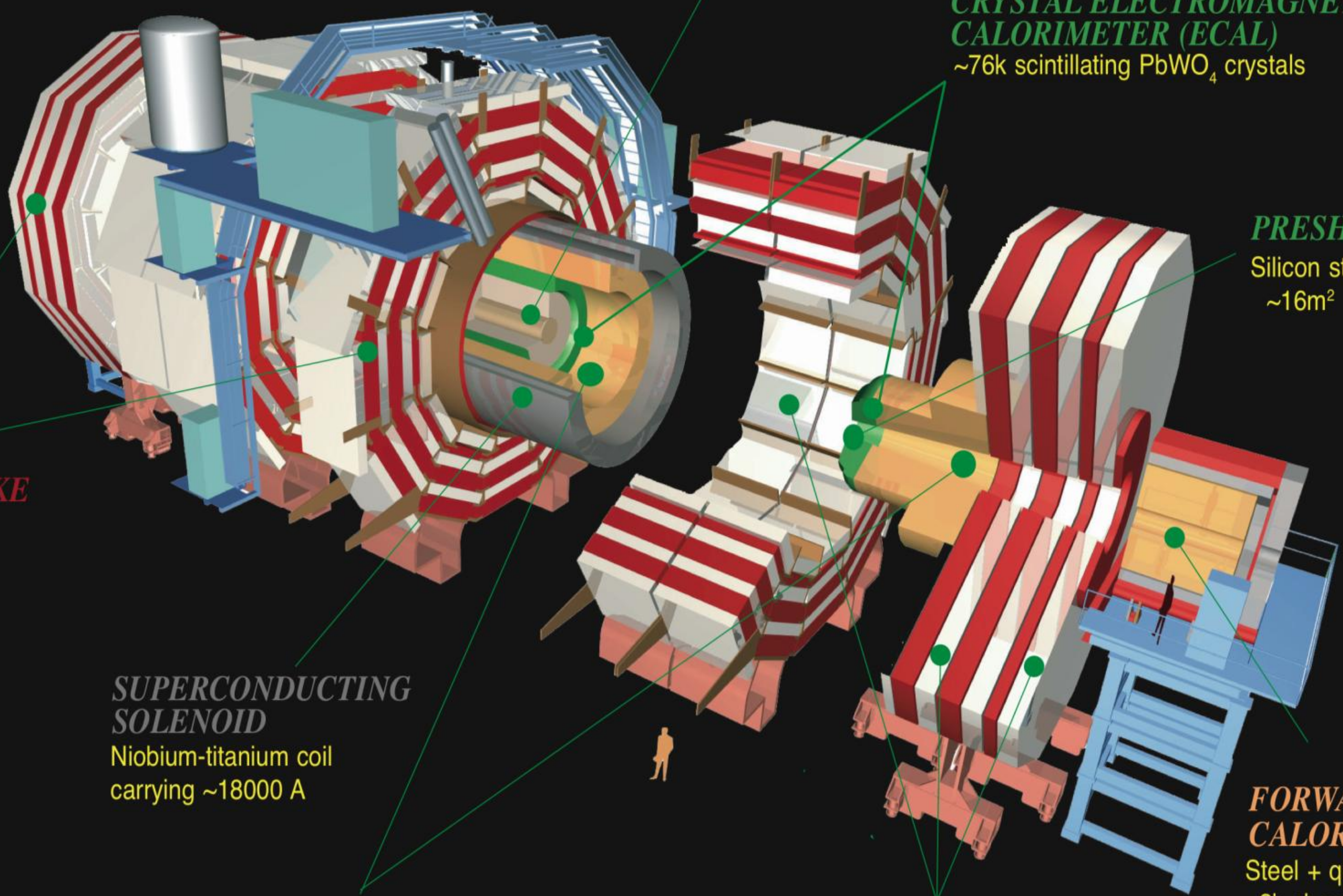
Accomplish

1. Assembly and Installation
2. Detectos Commissioning and Running
3. Preparation of Computing, Software and Physics Analysis (code and people)

The CMS Detector (1990s)



CMS Detector



SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers

Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Proposal: Assembly of CMS

A. Herve
From ‘92 CMS LoI Presentation

Surface Hall

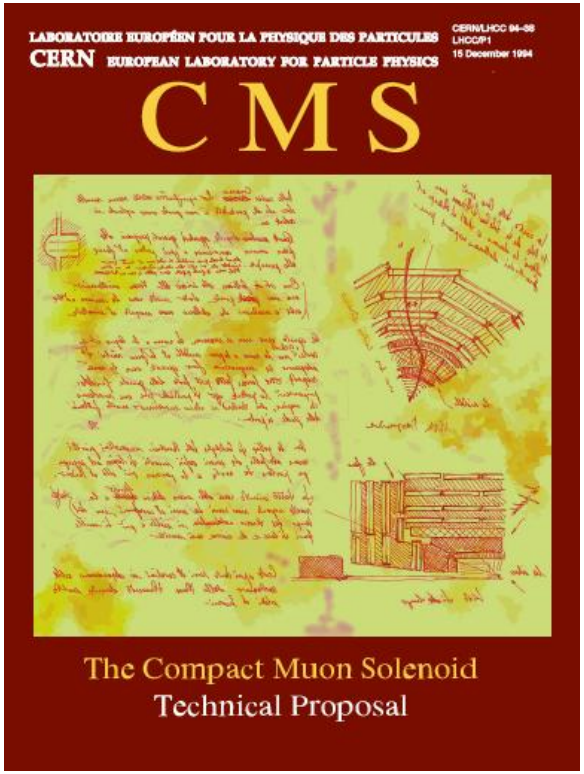
The CMS magnet will be assembled and tested in the surface Hall
The muon detector will be mounted on the magnet
This necessitates a hall of 94 m x 23 m x 23 m

Underground Cavern

The modular CMS detector allows an easy transfer to and installation in the underground cavern
The size (L = 60 m, Ø = 26 m) is chosen such that an easy access for maintenance is possible

A Key Player in the Approval of CMS

Courtesy: Sergio di Vittorio Veneto



LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN/LHCC 94-38
LHCC/P1
15 December 1994

CMS

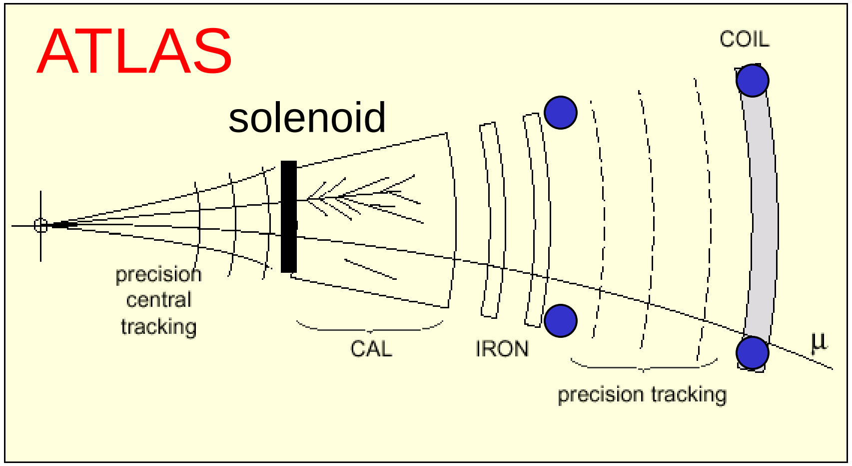
The Compact Muon Solenoid
Technical Proposal

Presented by
M. Della Negra Concept and Design
E. Radermacher Tracking and Muon System
T. Virdee Calorimetry, Trigger and DAQ
D. Denegri Physics

Starting Point for Design: Magnetic Field for Muons

Complementary Conception

The Choice of the Magnetic Field configuration for the measurement of muons drives the experiment design



Identify and measure muons after full absorption of hadrons

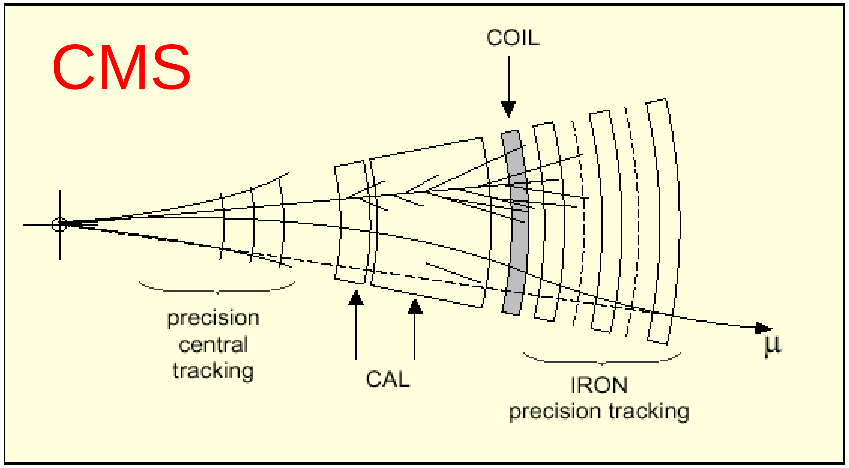
Air-core toroid

Good stand-alone p_μ measurement

p_μ measurement safe at high multiplicities

solenoid needed for inner tracking

σ_{pT} flat with η



High field solenoid placed after calorimetry

Fe flux return

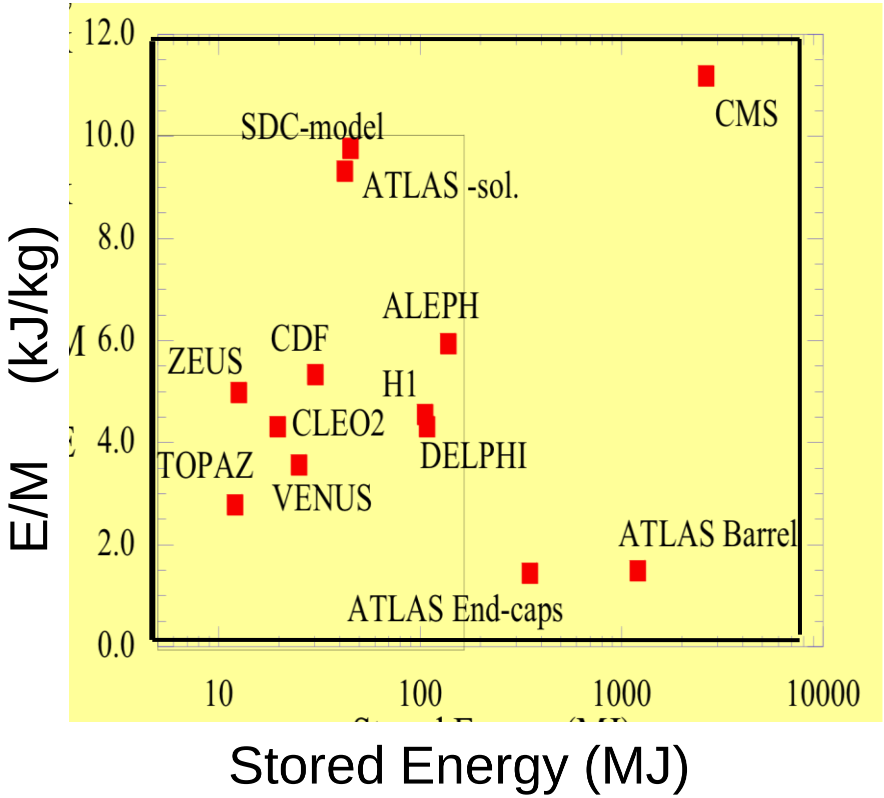
Measurement of p in tracker and B return with single magnet

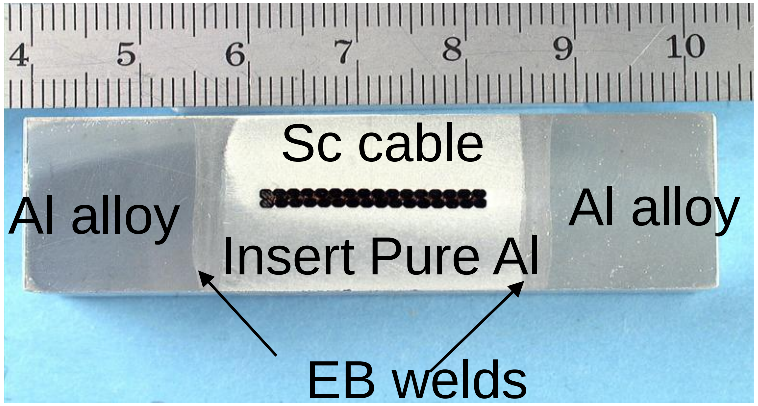
Solenoid: Hi p muon tracks point back to vertex

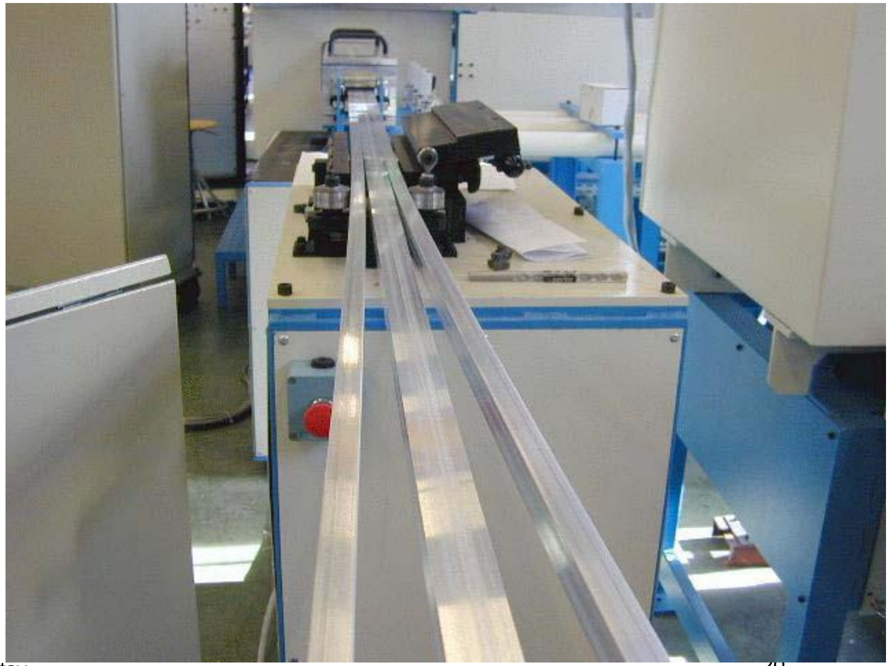
Reasonable stand-alone measurement

σ_{pT} degrades progressively with η for tracks exiting the open end of the solenoid

CMS Superconducting Solenoid



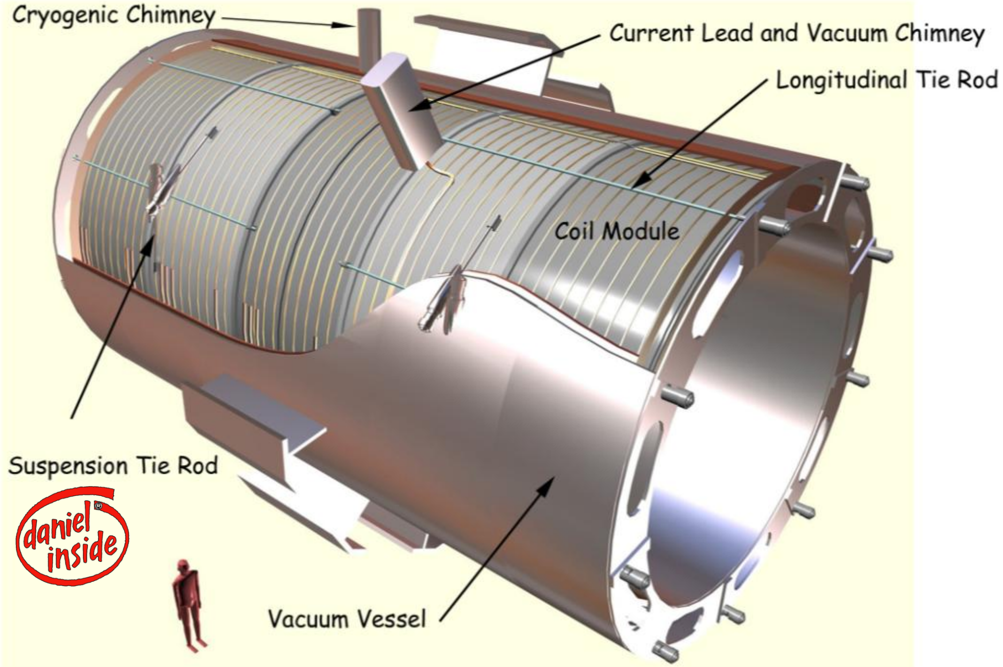




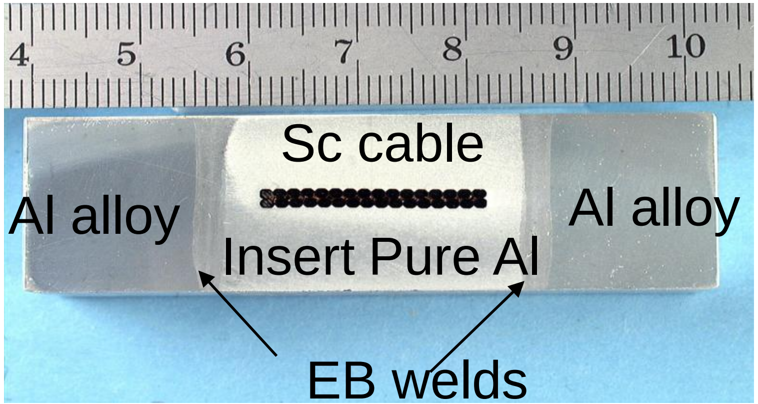
Mechanically reinforced conductor,

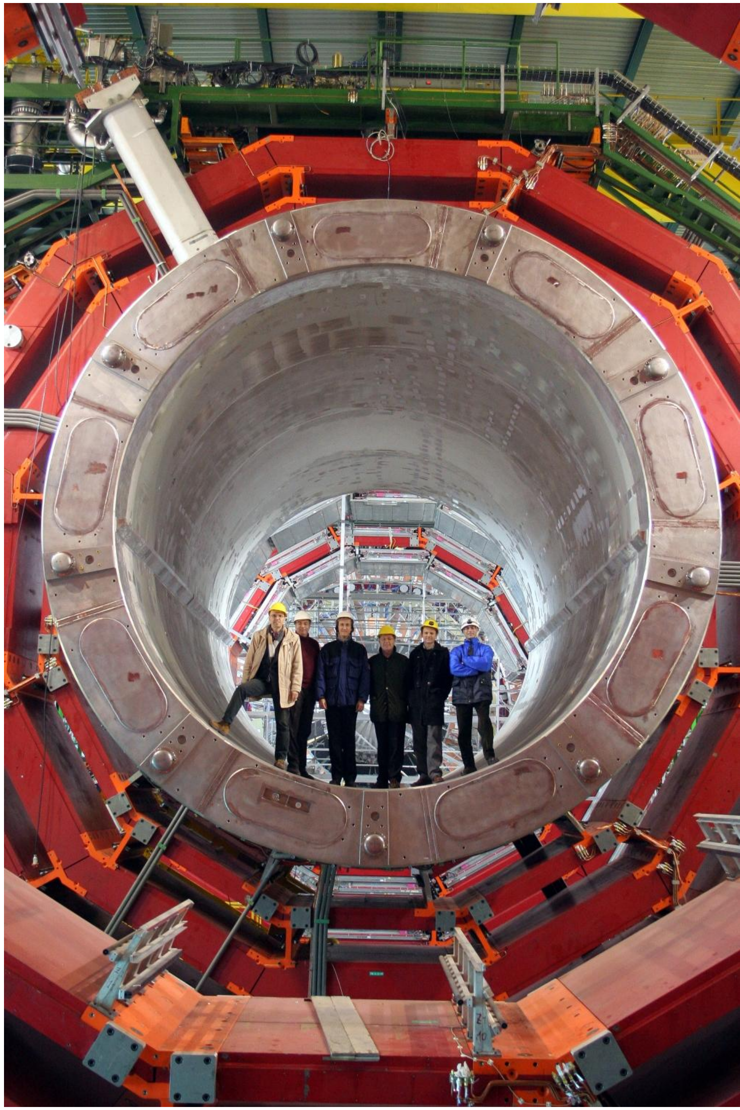
4 layers winding (enough Ampere turns)
5 modules (to limit unit length of conductor)

CMS Superconducting Solenoid



Mechanically reinforced conductor, 4 layers)
5 modules (to limit unit length of conductor)





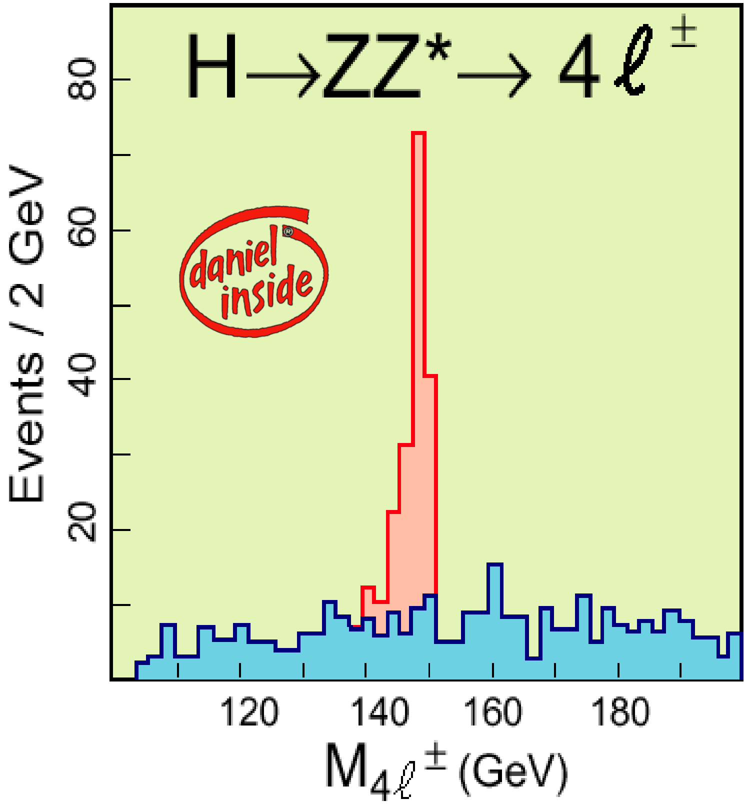
Choosing Tracking at LHC

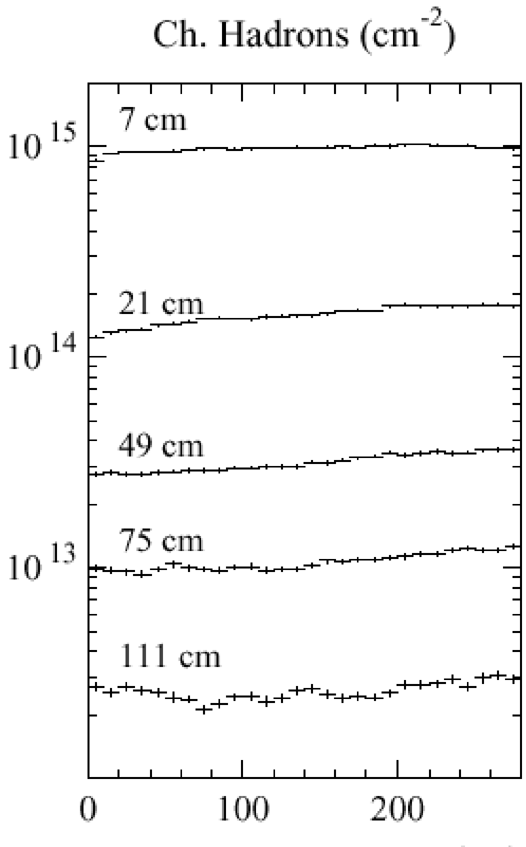
Factors that determine performance

Track finding efficiency – occupancy/crossing

Momentum resolution

Secondary vertex reconstruction





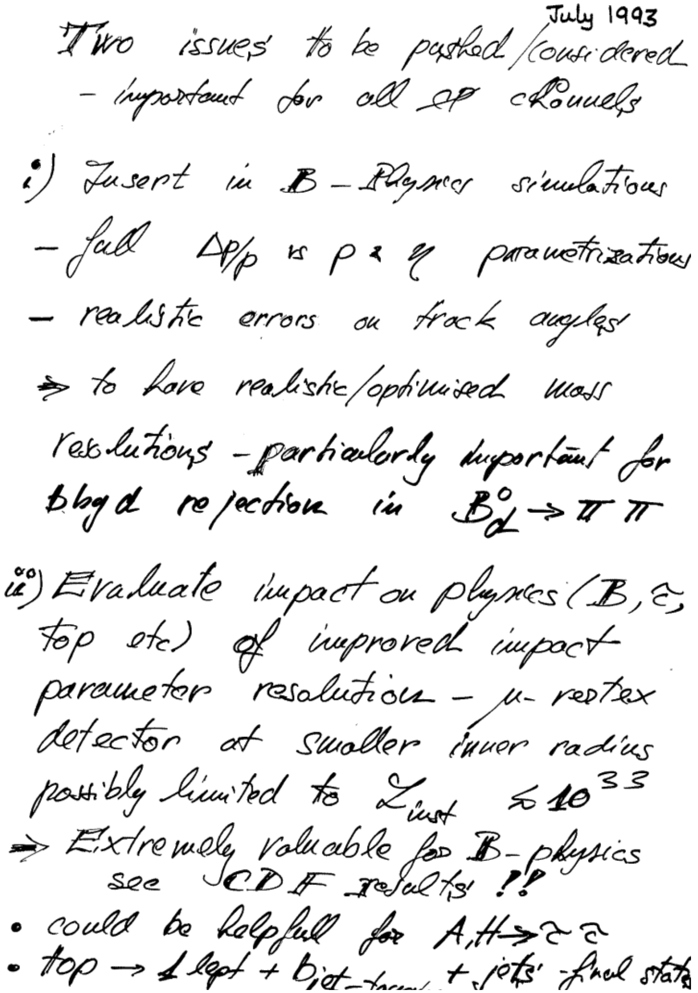
≤ 4.10^7 $h^\pm/cm^2/s$
pixels (≈10^4 μm^2)
occupancy ≈ 10^{-4}

≤ 4.10^6 $h^\pm/cm^2/s$
Si μ-strip det.
(≈10 mm^2)
occupancy ≈ 1%

≤ 4.10^5 $h^\pm/cm^2/s$
Si or Gas detectors.
(≈1 cm^2)
occupancy ≈ 1%

Contemplations ……

Choosing Tracker Technologies



July 1993

Two issues to be pushed/considered
- important for all of channels

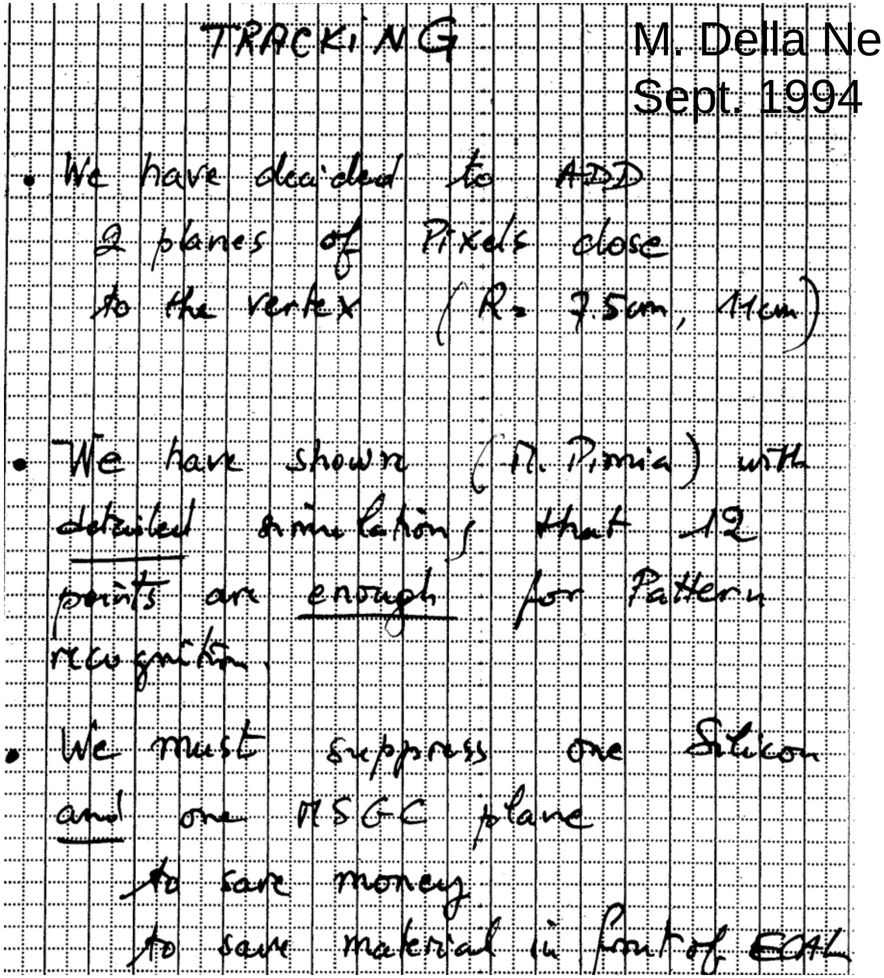
i) Insert in B-Physics simulations
- full Δp/p vs p & η parametrizations
- realistic errors on track angles

⇒ to have realistic/optimised mass resolutions - particularly important for bkgd rejection in $B_d^0 \to \pi\pi$

ii) Evaluate impact on physics (B, τ, top etc) of improved impact parameter resolution - μ-vertex detector at smaller inner radius possibly limited to $\mathcal{L}_{inst} \lesssim 10^{33}$

⇒ Extremely valuable for B-physics see CDF results !!

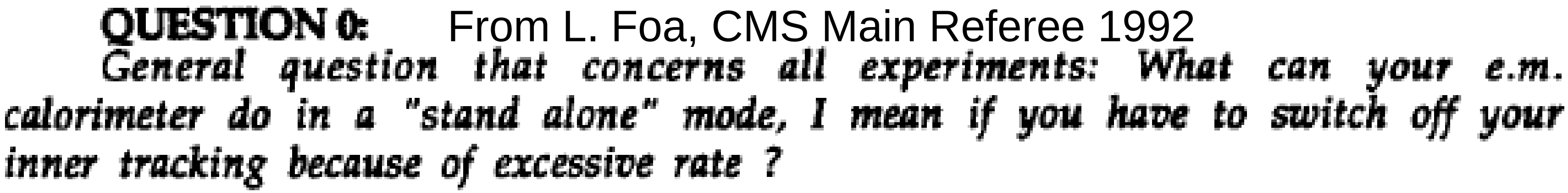
- could be helpfull for A,H → τ τ
- top → 1 lept + bjet-tag + jets -final state



TRACKING

M. Della Negra
Sept. 1994

- We have decided to ADD 2 planes of Pixels close to the vertex (R = 7.5cm, 11cm)
- We have shown (N. Pimia) with detailed simulations that 12 points are enough for Pattern recognition.
- We must suppress one Silicon and one MSGC plane
  - to save money
  - to save material in front of ECAL



QUESTION 0: From L. Foa, CMS Main Referee 1992

General question that concerns all experiments: What can your e.m. calorimeter do in a "stand alone" mode, I mean if you have to switch off your inner tracking because of excessive rate ?

All Silicon Tracker

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

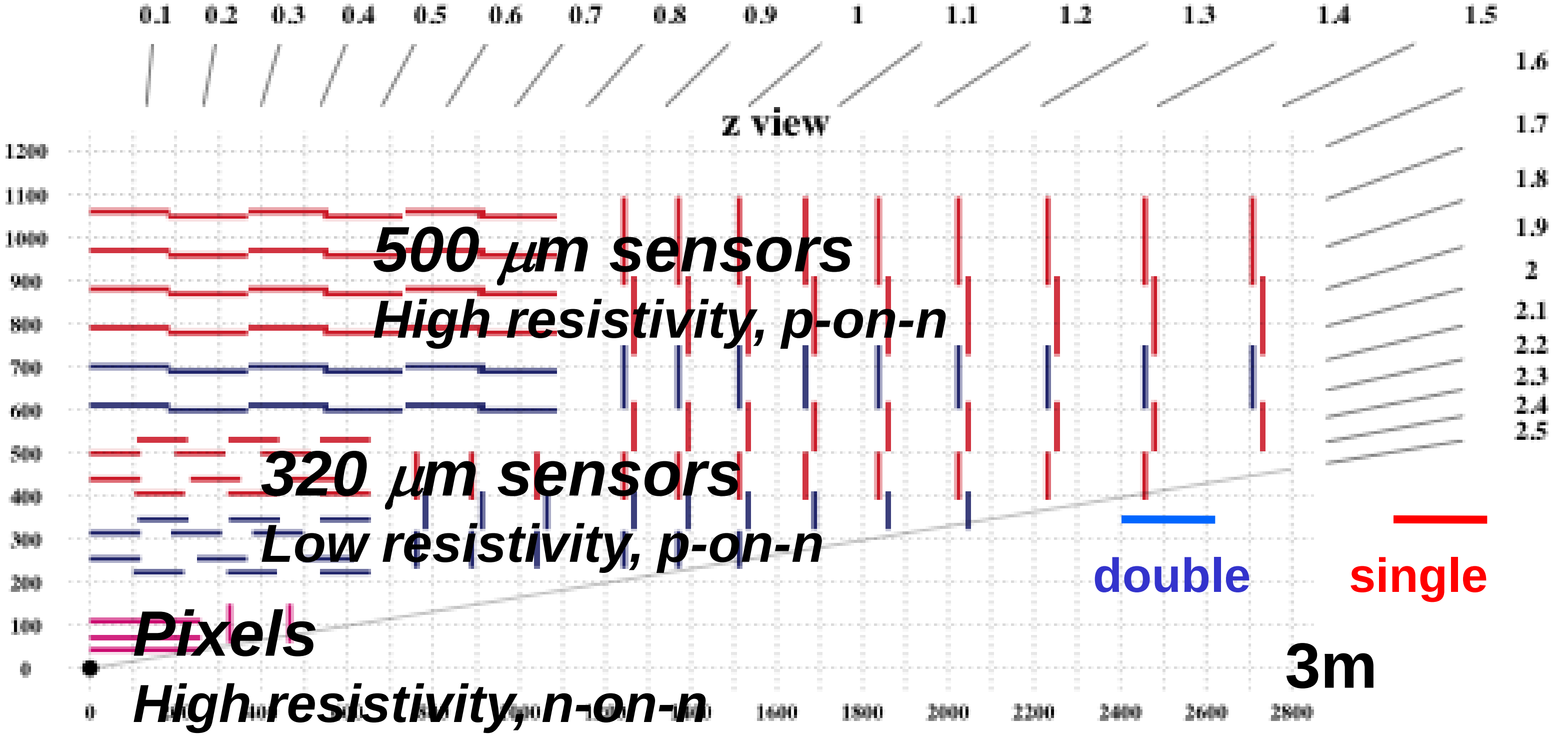
- Radiation damage poorly understood
- Cost/unit area was prohibitively large
- Large no. of channels required

What was done

- leakage current dealt with fast amplifiers
- HV behaviour improved by careful processing
- 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

Choosing Tracker Technologies: All Si Layout

- 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



1.2m

500 μm sensors

High resistivity, p-on-n

320 μm sensors

Low resistivity, p-on-n

Pixels

High resistivity, n-on-n

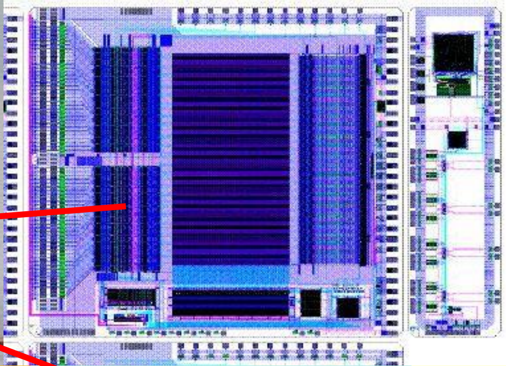
double **single**

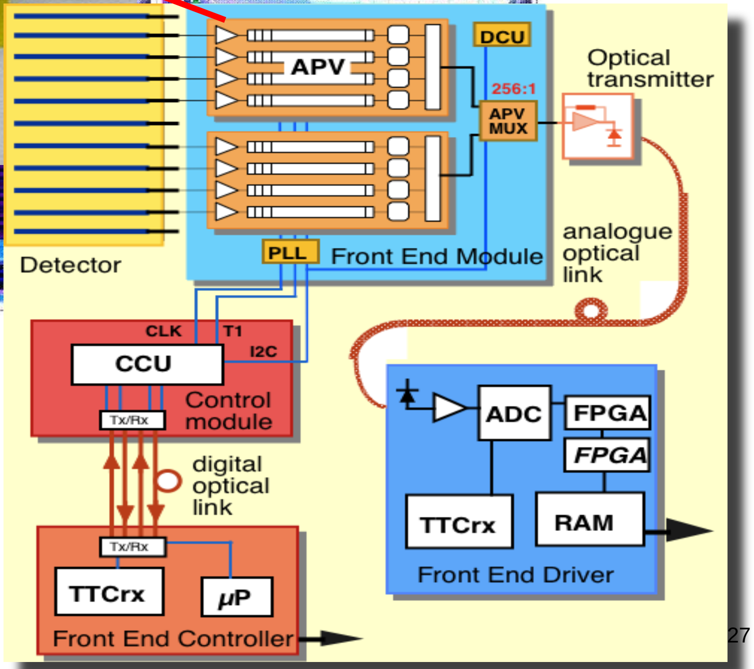
3m

Hybrid Pixels: ~ 1 m^2 of silicon sensors, 67 M pixels, 100x150 μm^2 , 3 pts, r = 4, 7, 11 cm

Si μ-strips : 223 m^2 of silicon sensors (15 k modules) , 10 M strips, 10 pts, r = 20 – 120 cm

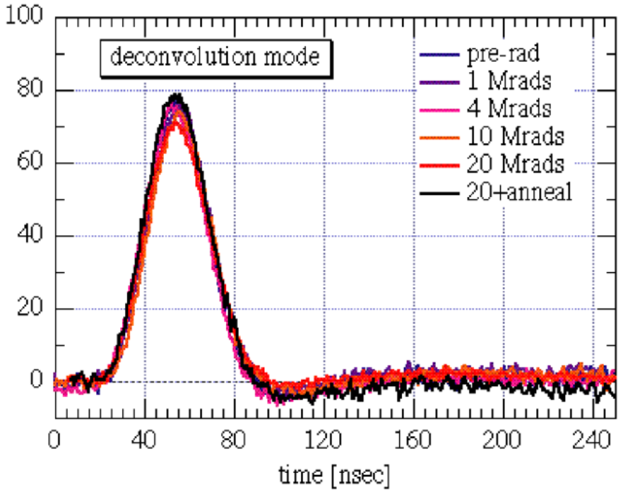
Choosing Radhard Electronics:
Deep Sub-micron Tracker Electronics Chain



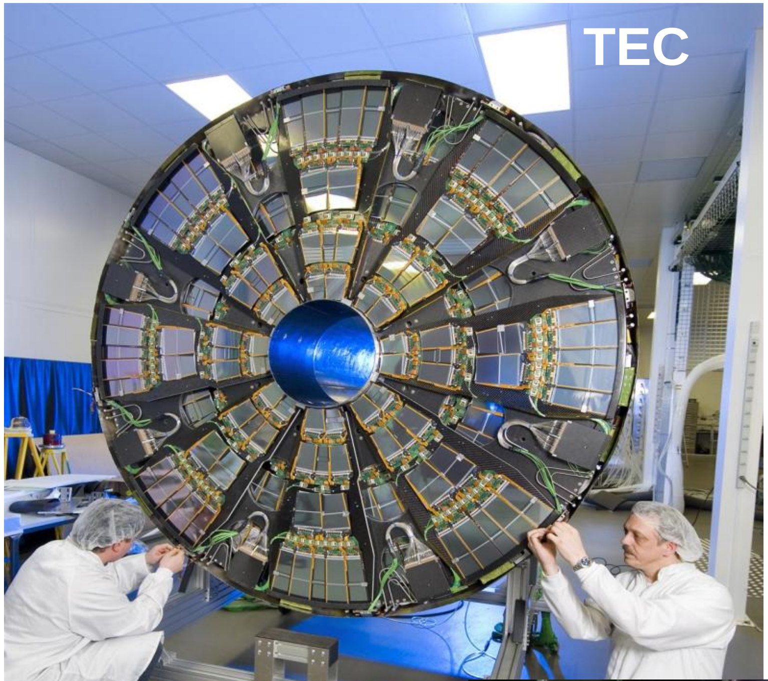


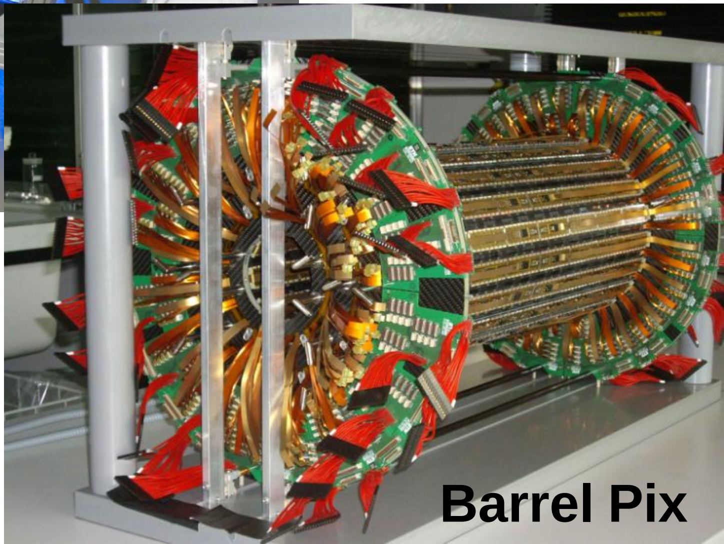
Ride on technology wave

75k chips using 0.25μm technology



CMS Tracker Components

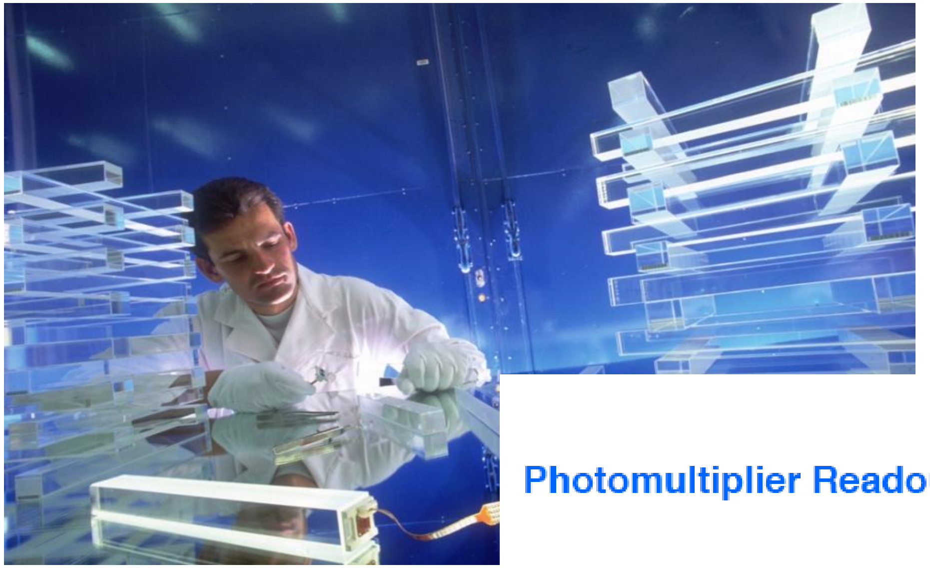




Choosing the Technology for ECAL

CMS chose Lead Tungstate Scintillating Crystals coupled with APDs

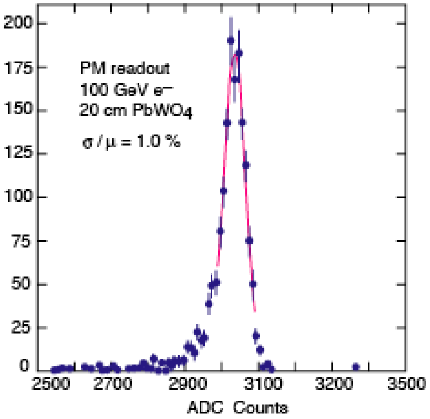
3 other technologies were considered (shashlik, CeF_3, heavy glass)



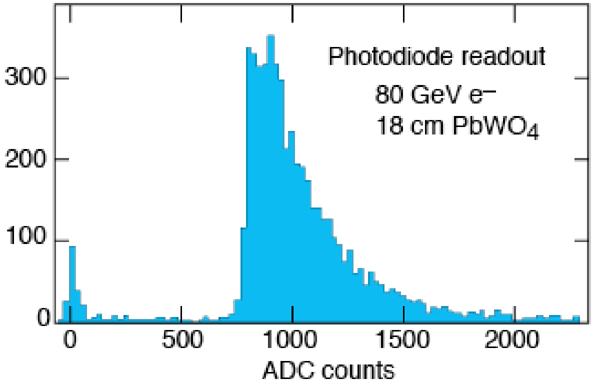
Driving Physics Design Goal

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

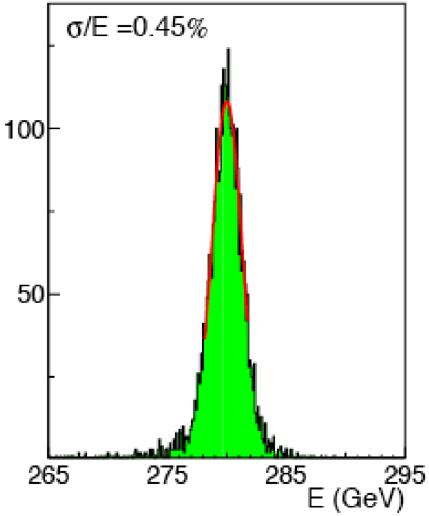
Photomultiplier Readout



Si Photodiode Readout



Avalanche Photodiode Readout



Timeline for Lead Tungstate Crystals

Idea (1993 – few yellowish cm^3 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 production, QC)**

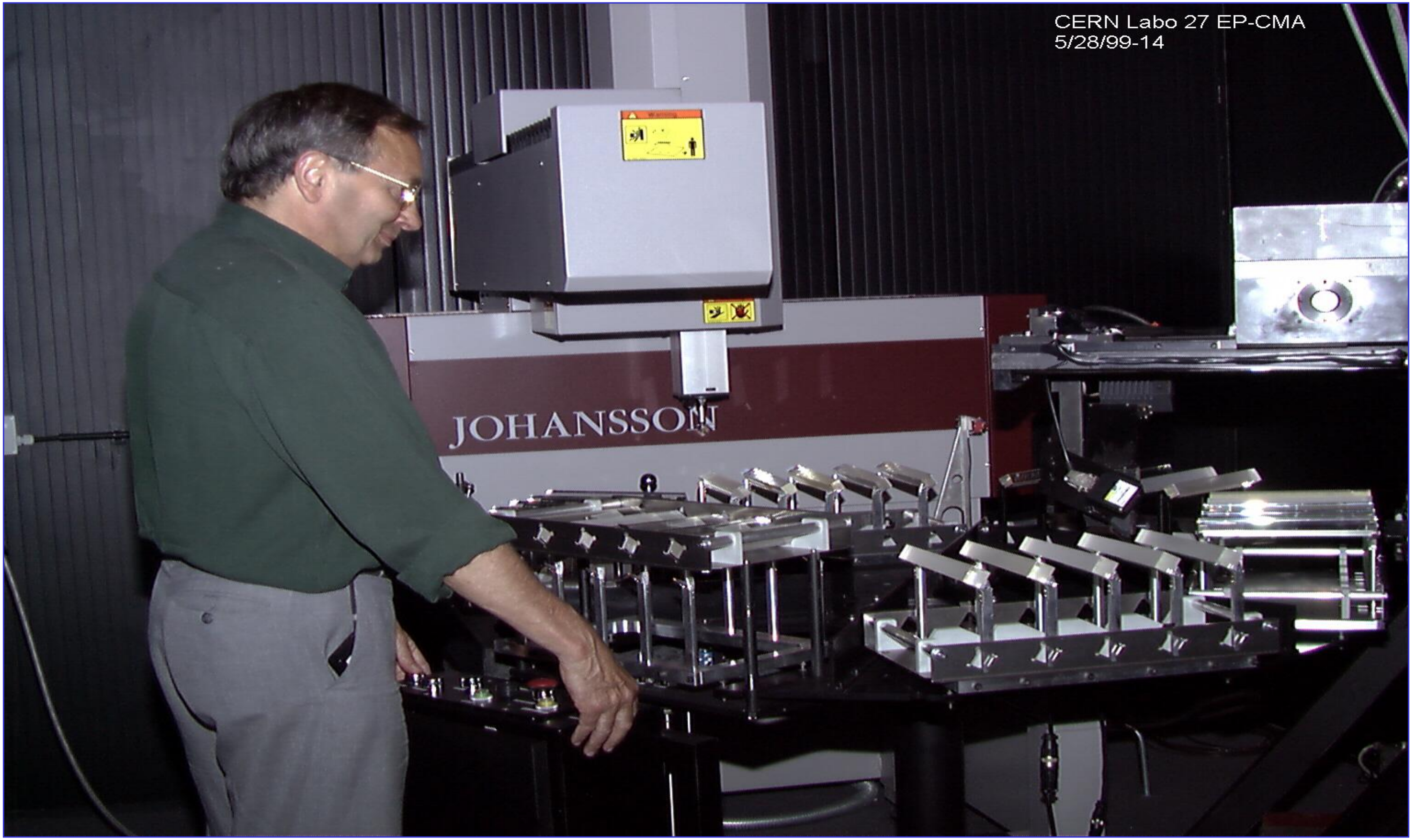
→ **Systems Integration (2001-2008: tooling, assembly)**

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

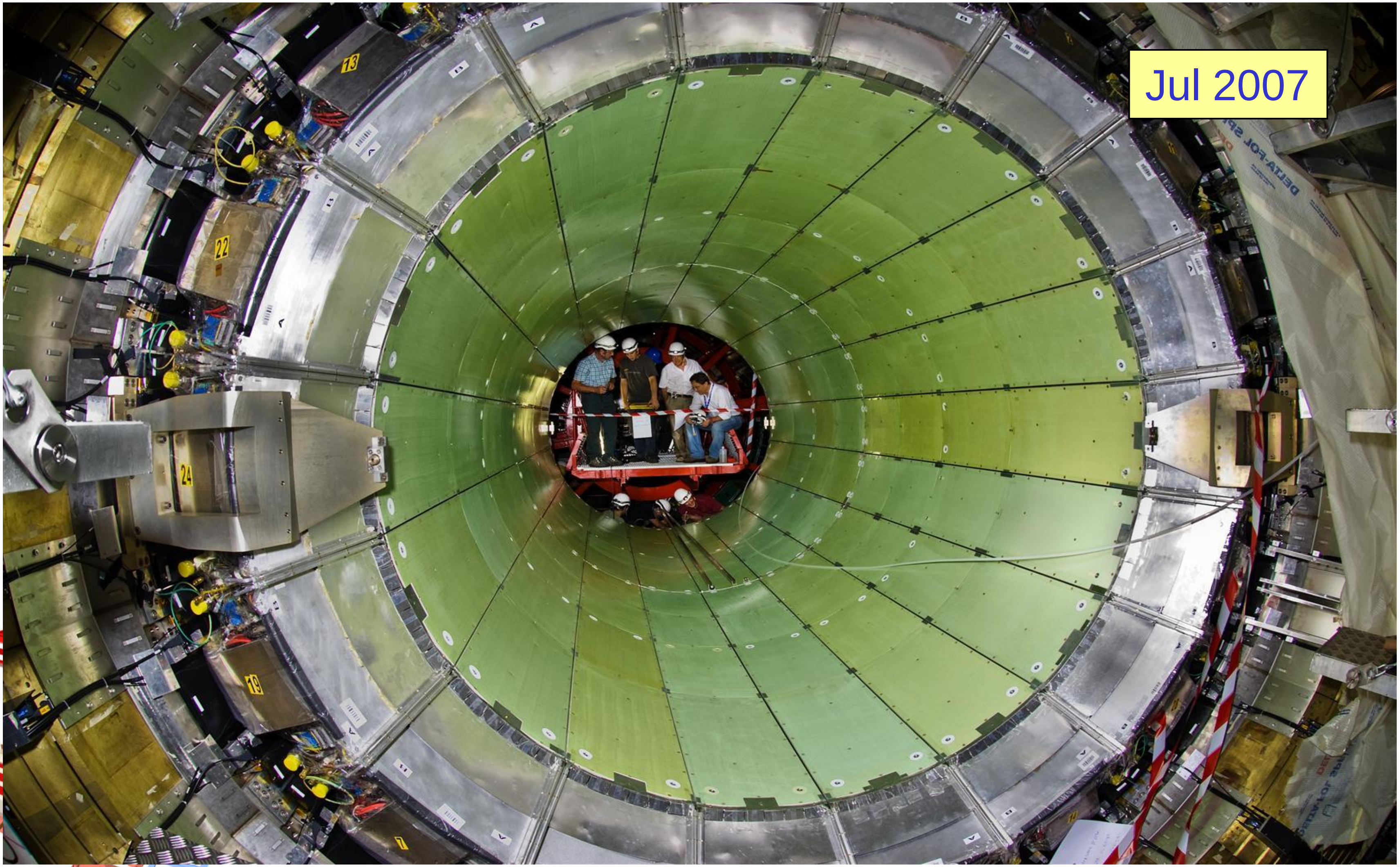
→ **Data Taking (2008 onwards)**

Δt ~ 15 years !!!

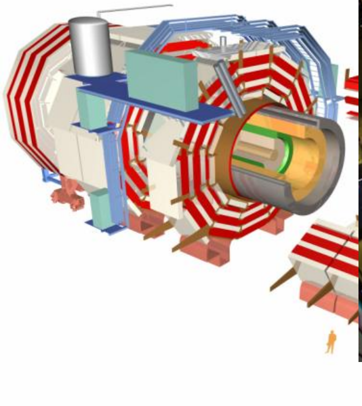
Production of Crystals



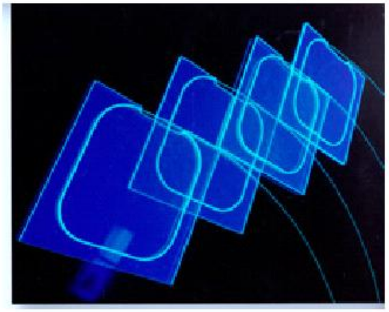
Installation of Barrel ECAL



Jul 2007

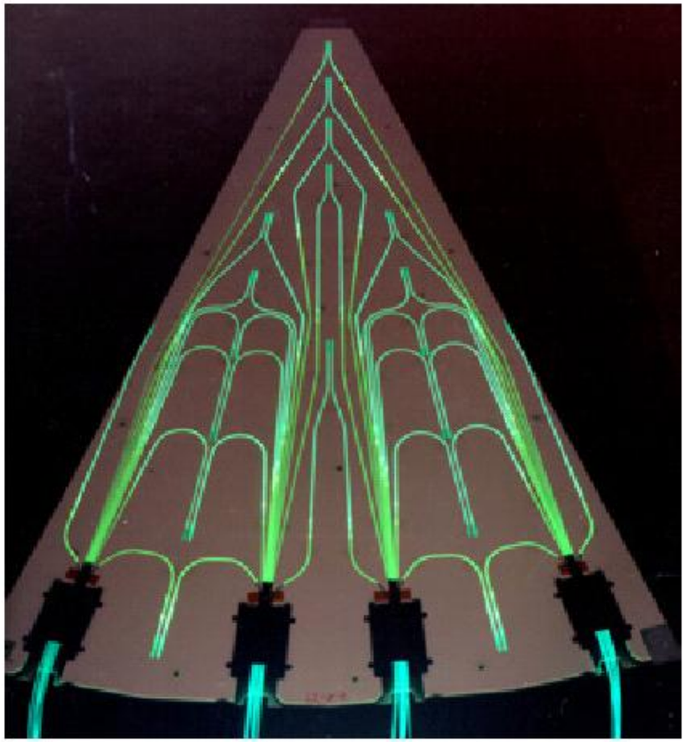


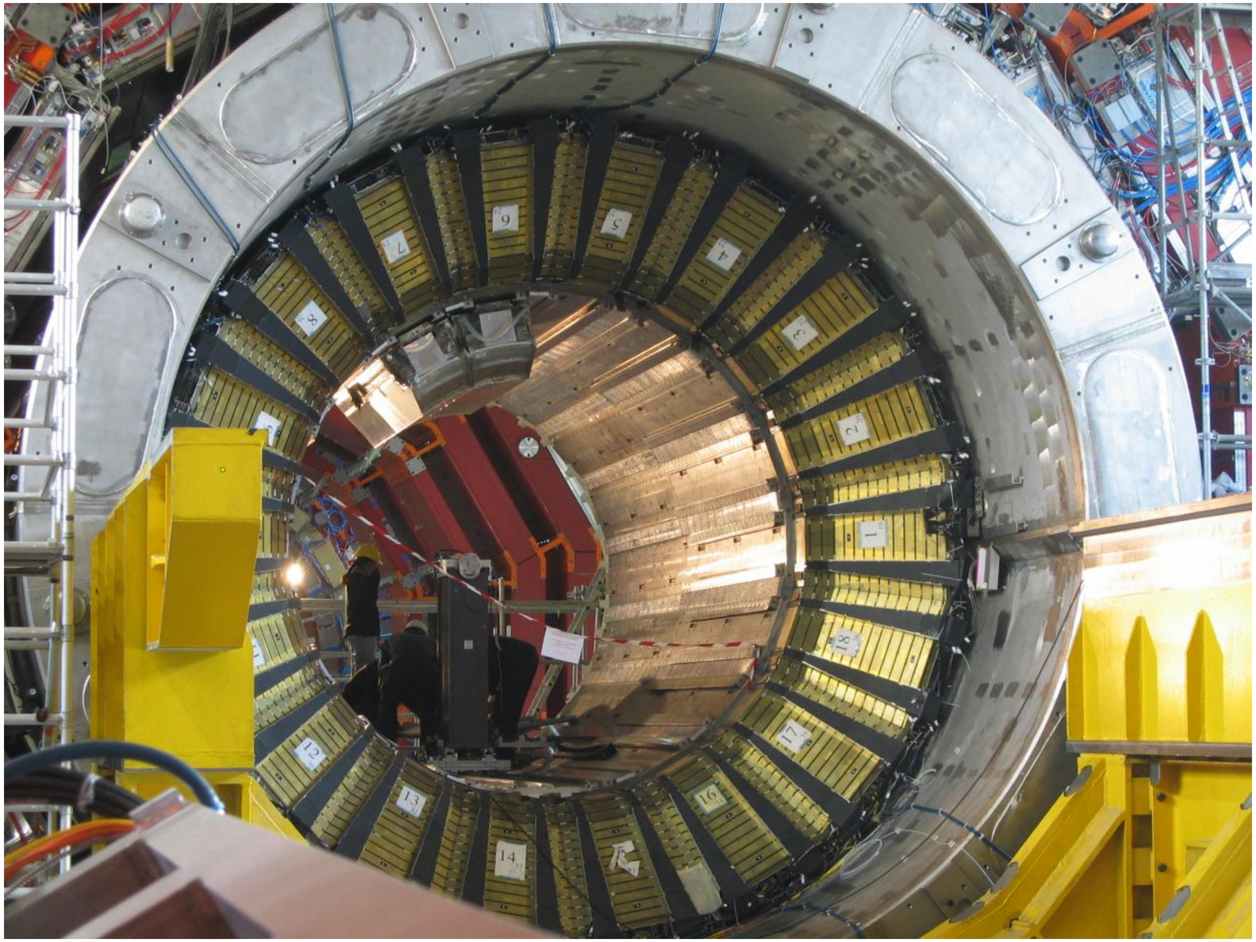
Choosing the Technology for the HCAL



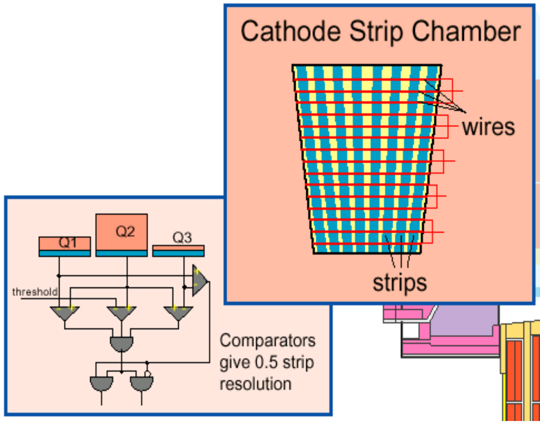
WLS fibres embedded in plastic scintillator plates a technique first proposed for the upgrade of UA1

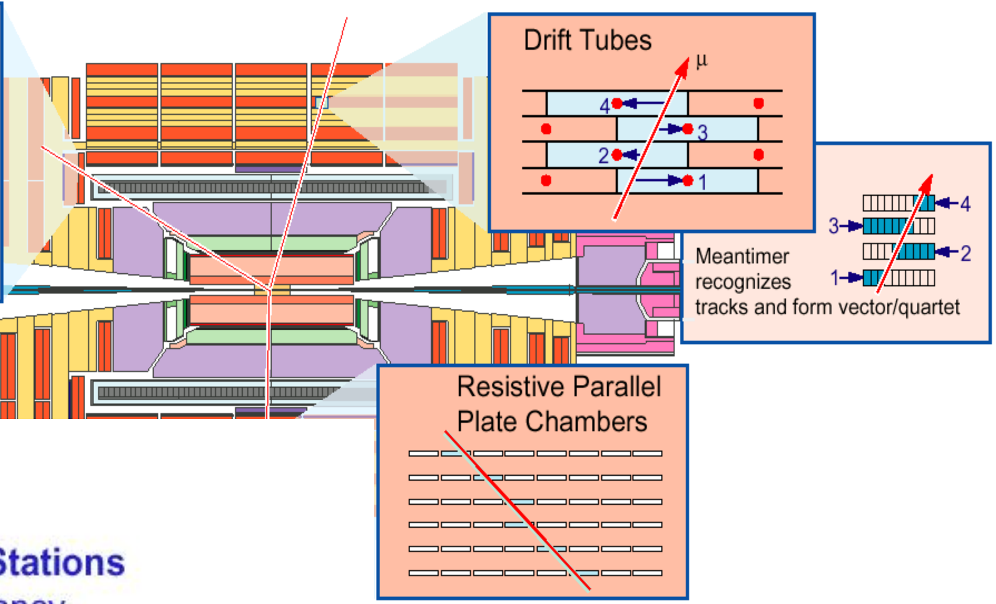
Routing of clear fibres to optical disconnects

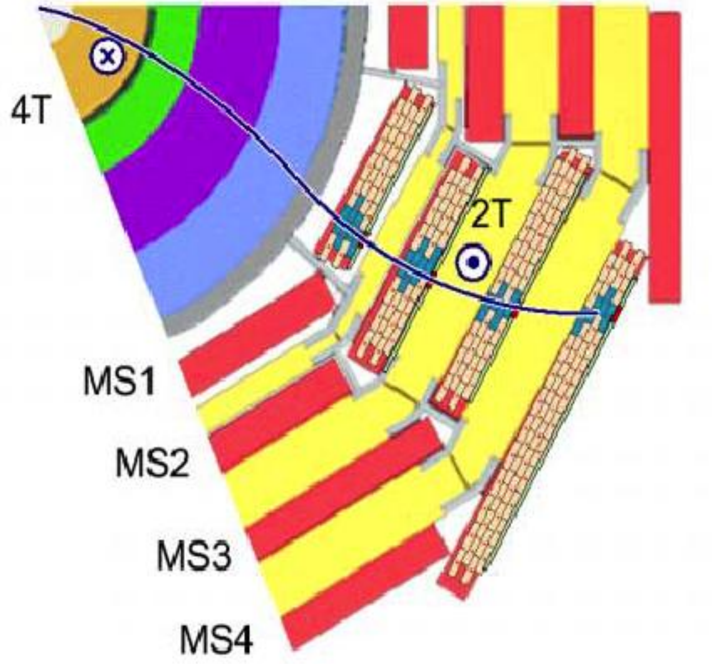




Choosing Technologies for the Muon System





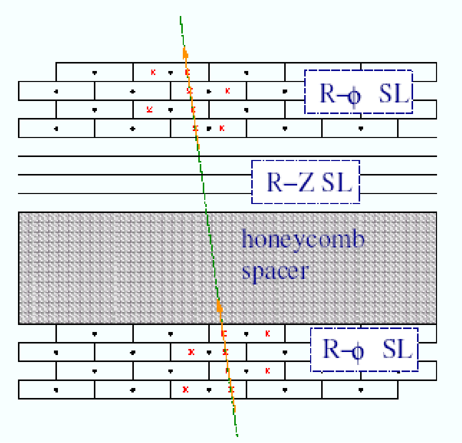


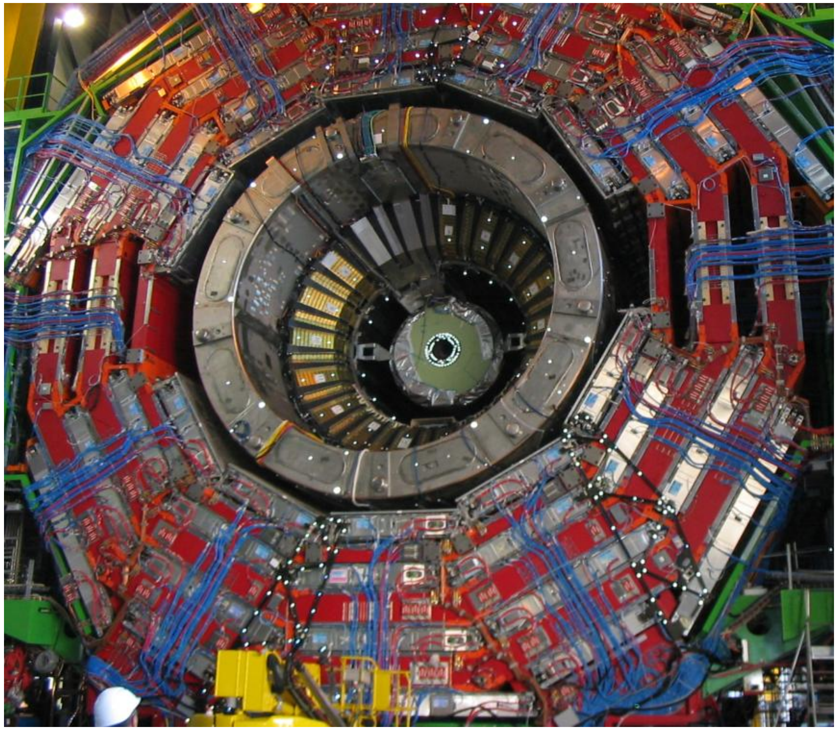
4 Muon Stations
- redundancy
- acceptance

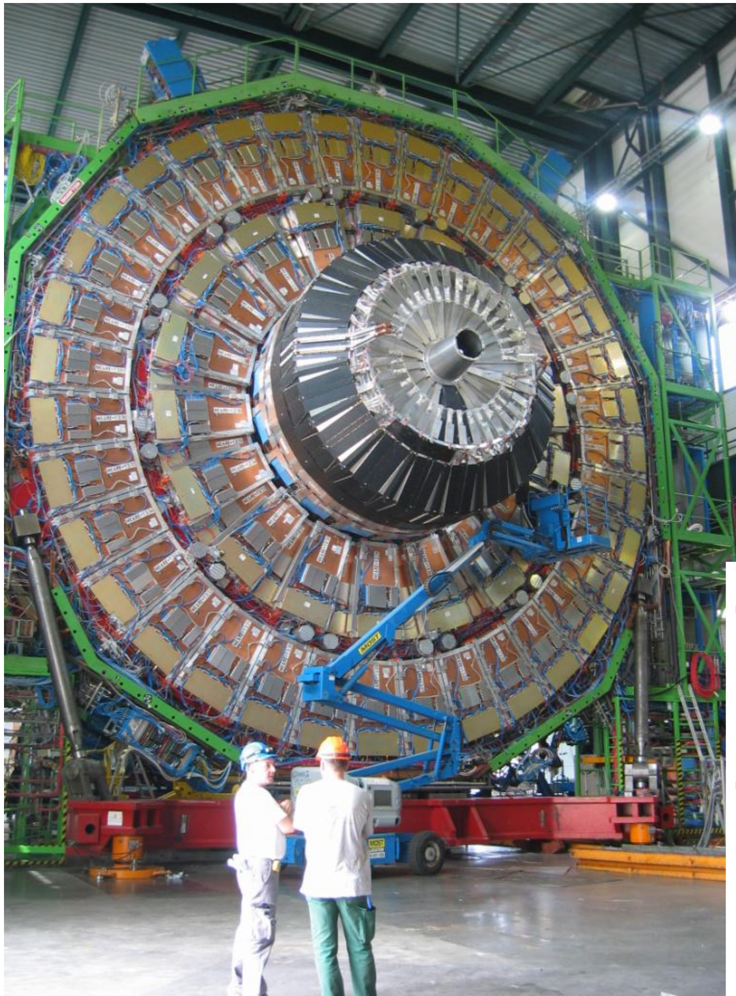
Per Station
- barrel – 12 measuring planes
- endcap – 6 measuring planes

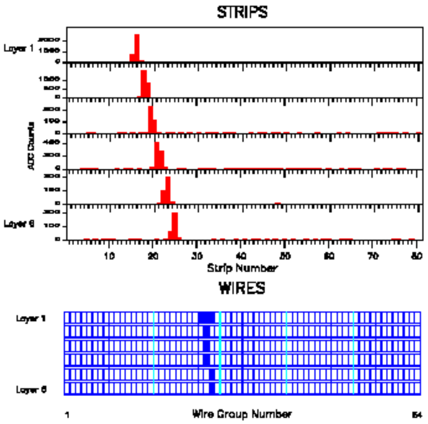
Measurement Accuracy
- position 70 – 100 μm /station
- direction ~ 1 mrad

CMS Muon Detectors: DTs and CSCs









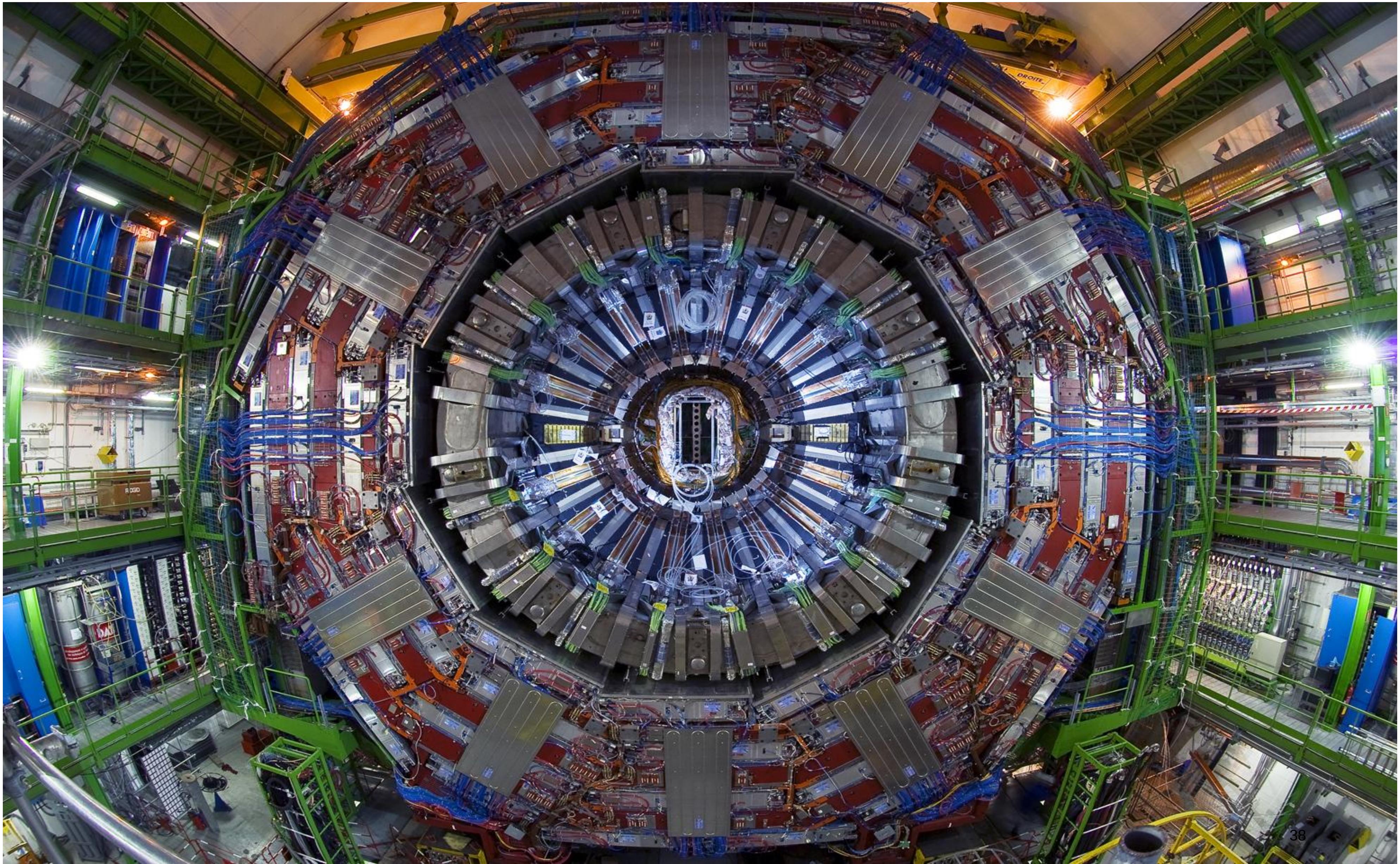
Assembly and Installation

Assembling and Installing Cables, Pipes and Optical Fibres !

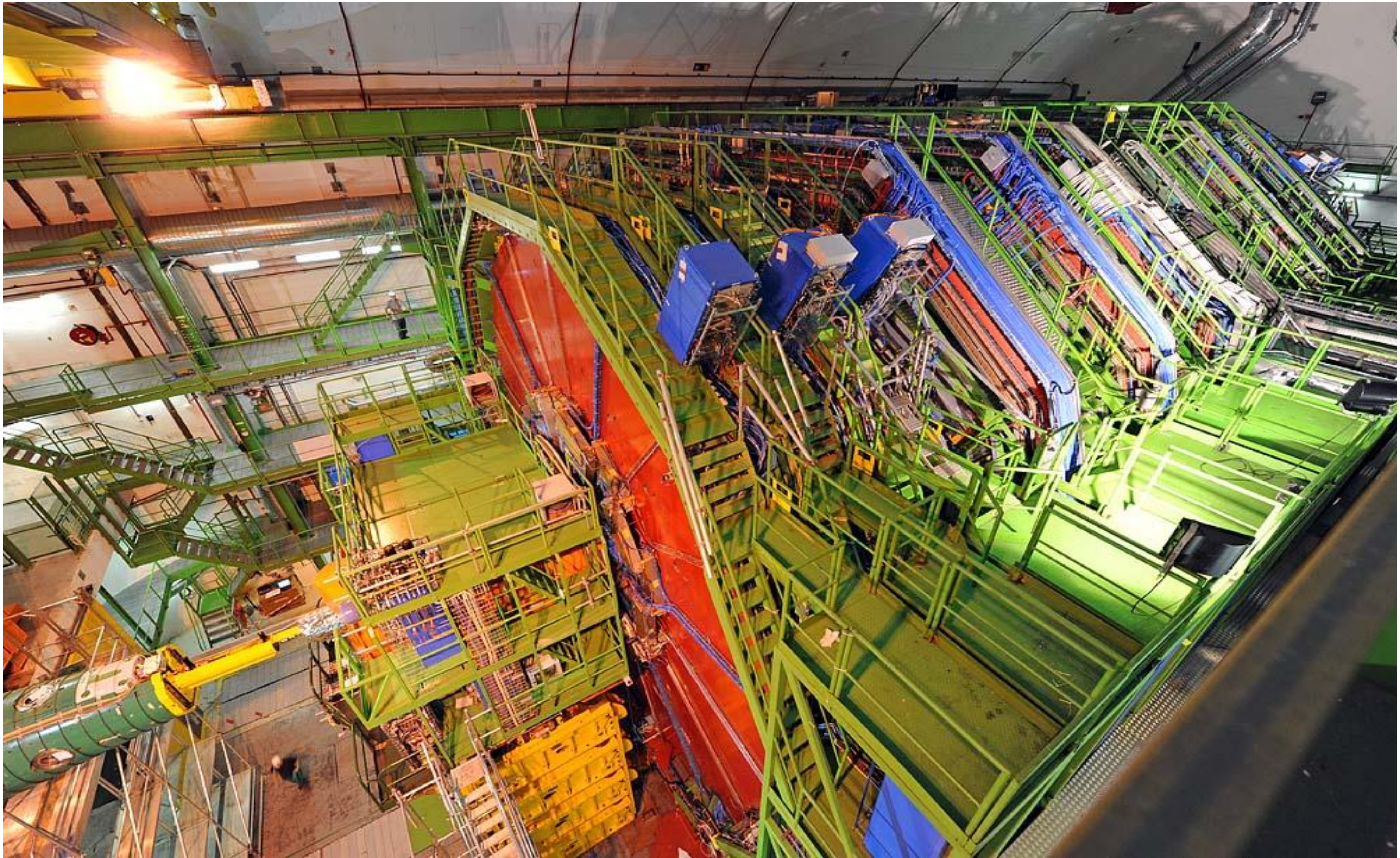
Nov 2007

Took 50’000 man hours

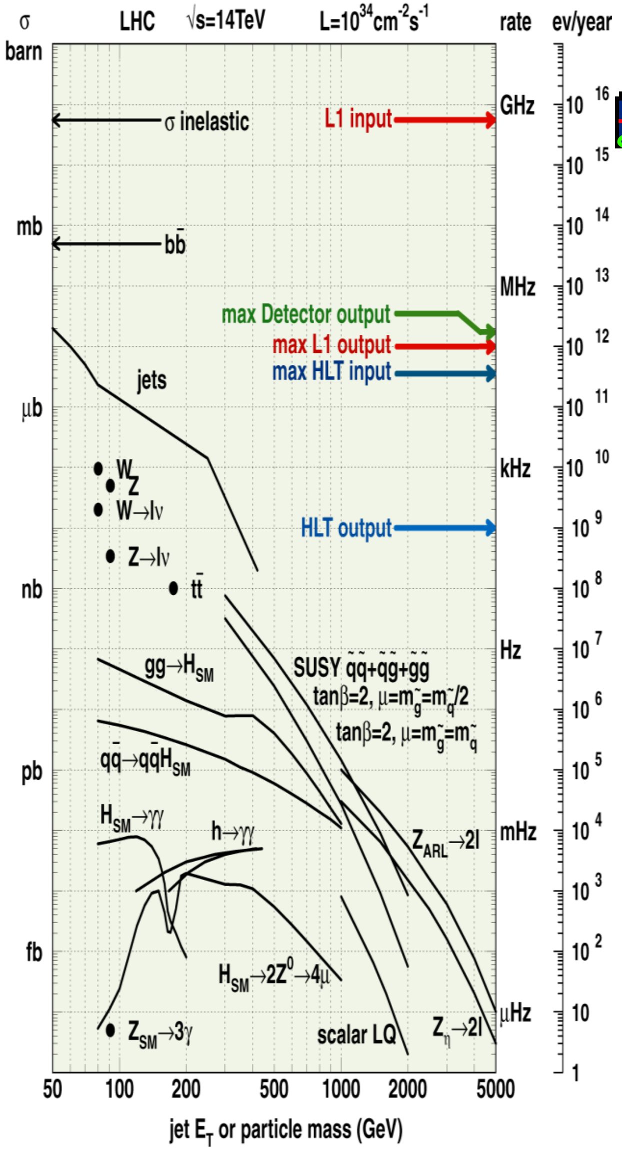
CMS Detector in Dec 2007

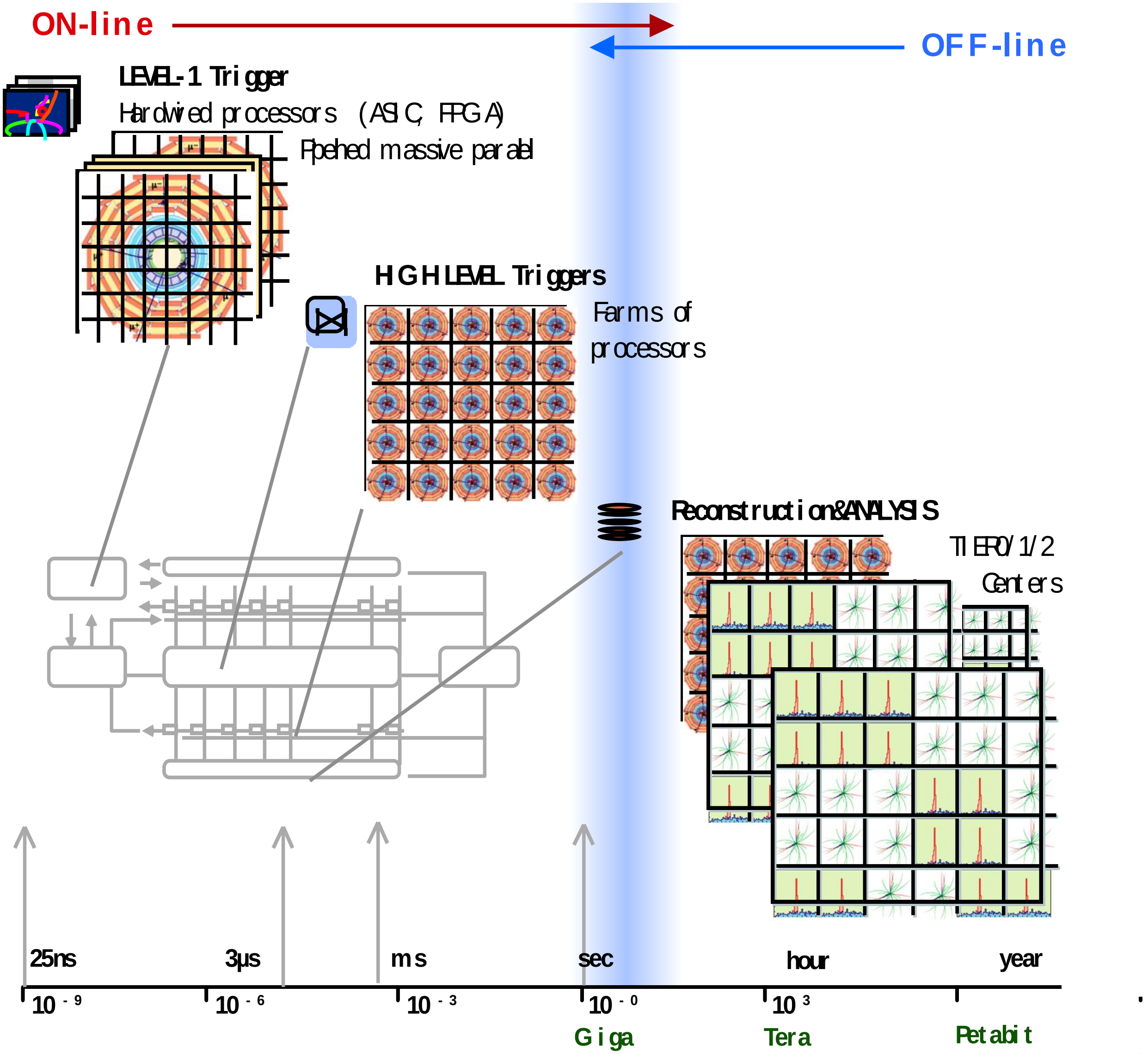


CMS Ready for Beam in Sept’08



Choosing Technologies for Event Selection





ON-line

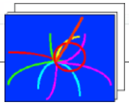
OFF-line

LEVEL-1 Trigger
Hardwired processors (ASIC, FPGA)
Pipelined massive parallel

HIGH LEVEL Triggers
Farms of
processors

Reconstruction&ANALYSIS
TIER0/1/2
Centers

Data communication and processing at LHC



40 MHz
COLLISION RATE

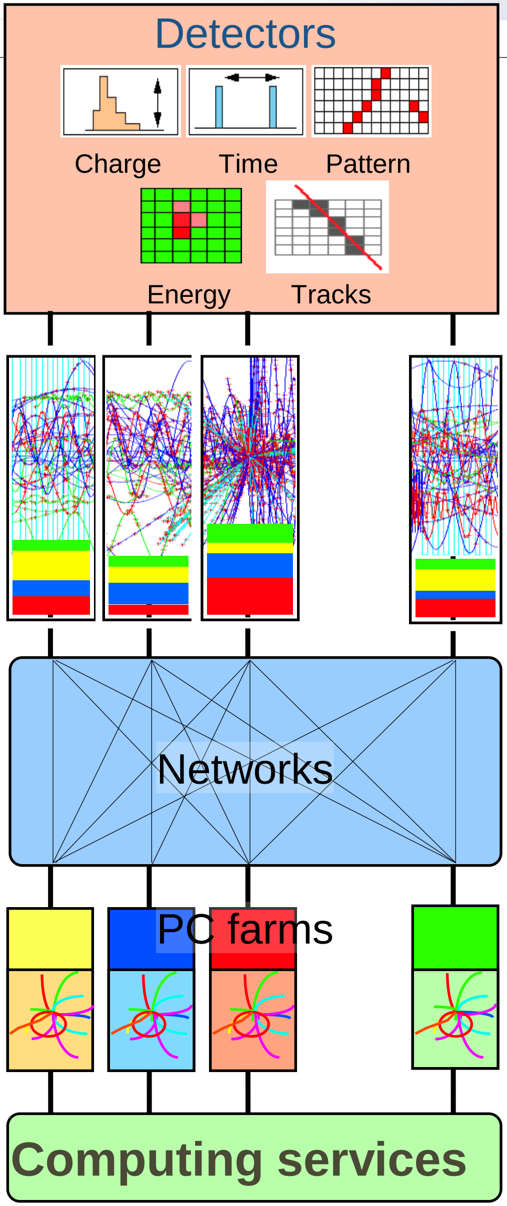
100 kHz
LEVEL-1 TRIGGER

2 Terabit/s
(2000 Gb/s links)

2 Terabit/s
(GBE switches)

10 TeraFlops

Gigabit/s
SERVICE LAN



Detectors

Charge Time Pattern

Energy Tracks

Networks

PC farms

Computing services

2 Gigacell
(Sensors/Buffers/

10 Million channels

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

EVENT BUILDER. A large switching network (1920x3840 ports) with a total throughput of approximately 2000 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

5 Petabyte
ARCHIVE

Preparing Computing, Software and Physics Analysis

These activities were not as visible as the hardware but are equally important

Many years of preparation by many

Software for calibration, alignment, reconstruction, high level trigger online, physics analysis

Computing at Point 5, CERN main site, distributed, link with WLCG

Physics analysis worldwide

Preparation via more and more realistic Data Challenges

(DC04, CSA06, CCRC08 and CSA08, October 09 Exercise)

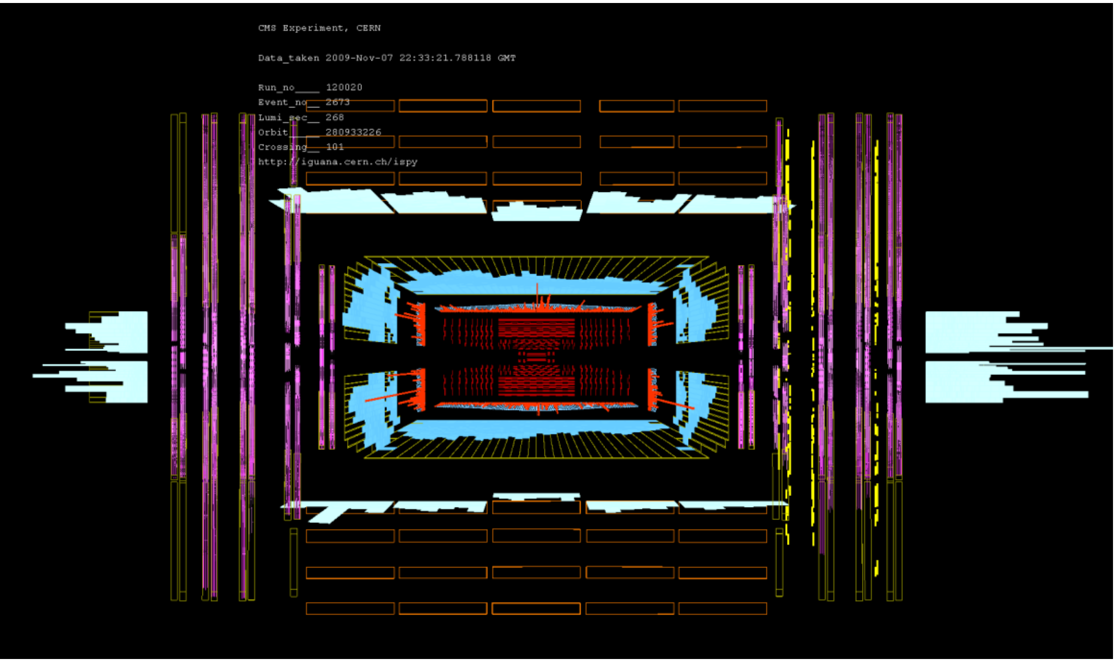
Re-engineer CMS software in 2005-2006 (CMSSW)

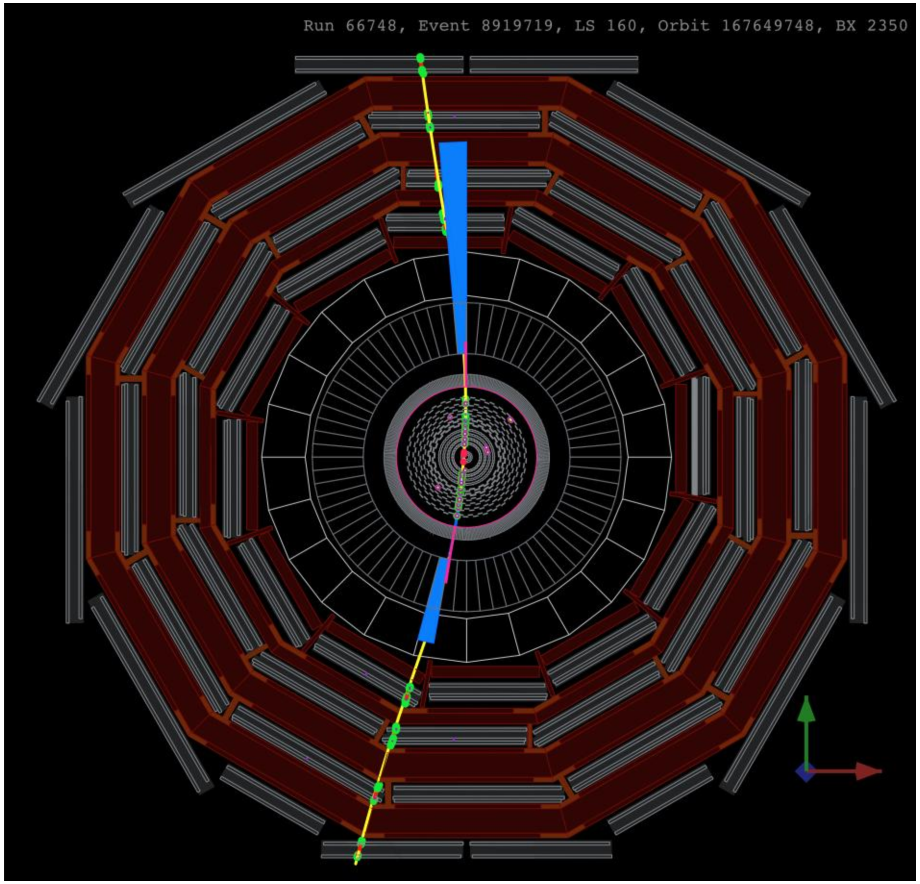
Physics TDR in 2006 (Vol1 performance, Vol2 physics up to 30fb^{-1})

MTCC in 2006 and CRAFT in 2008 and 2009

MTCC- Magnet Test and Cosmic Challenge, CRAFT – Cosmics Run At Four Tesla)

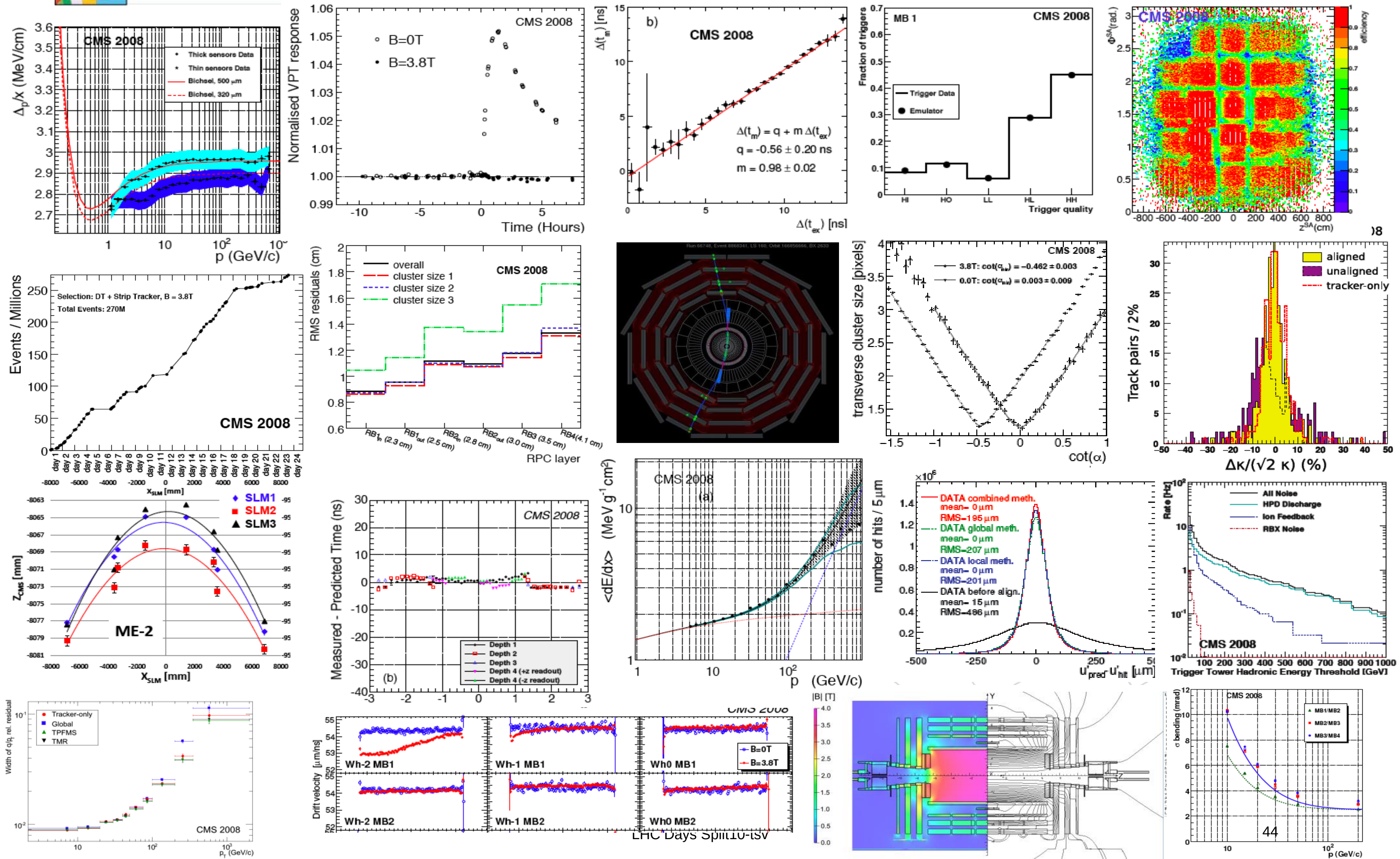
Commissioning using Cosmics and Beam Splashes



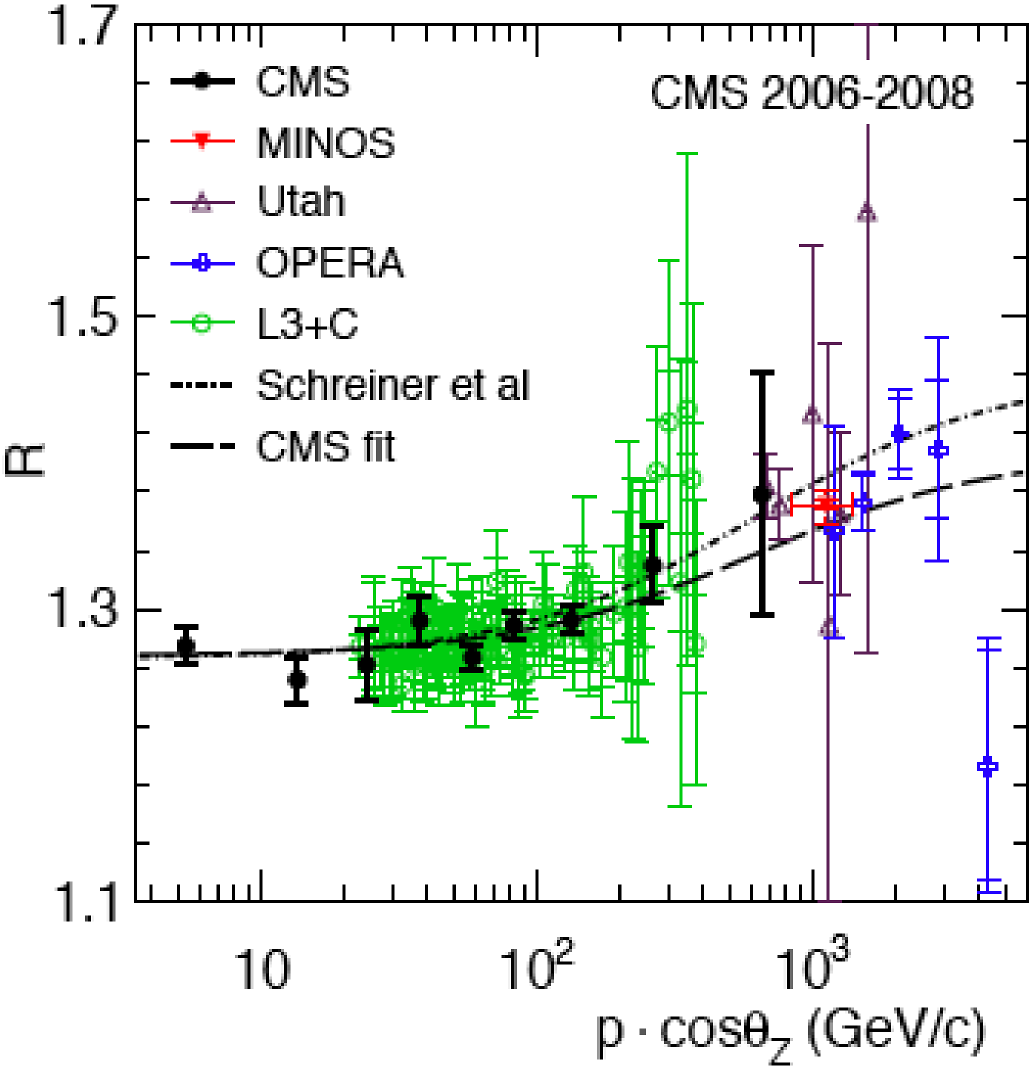


Great state of readiness at start of run thanks to extensive studies with ~1G cosmic μ events (2008-09), beam splash events (2009), and detector description in MC.

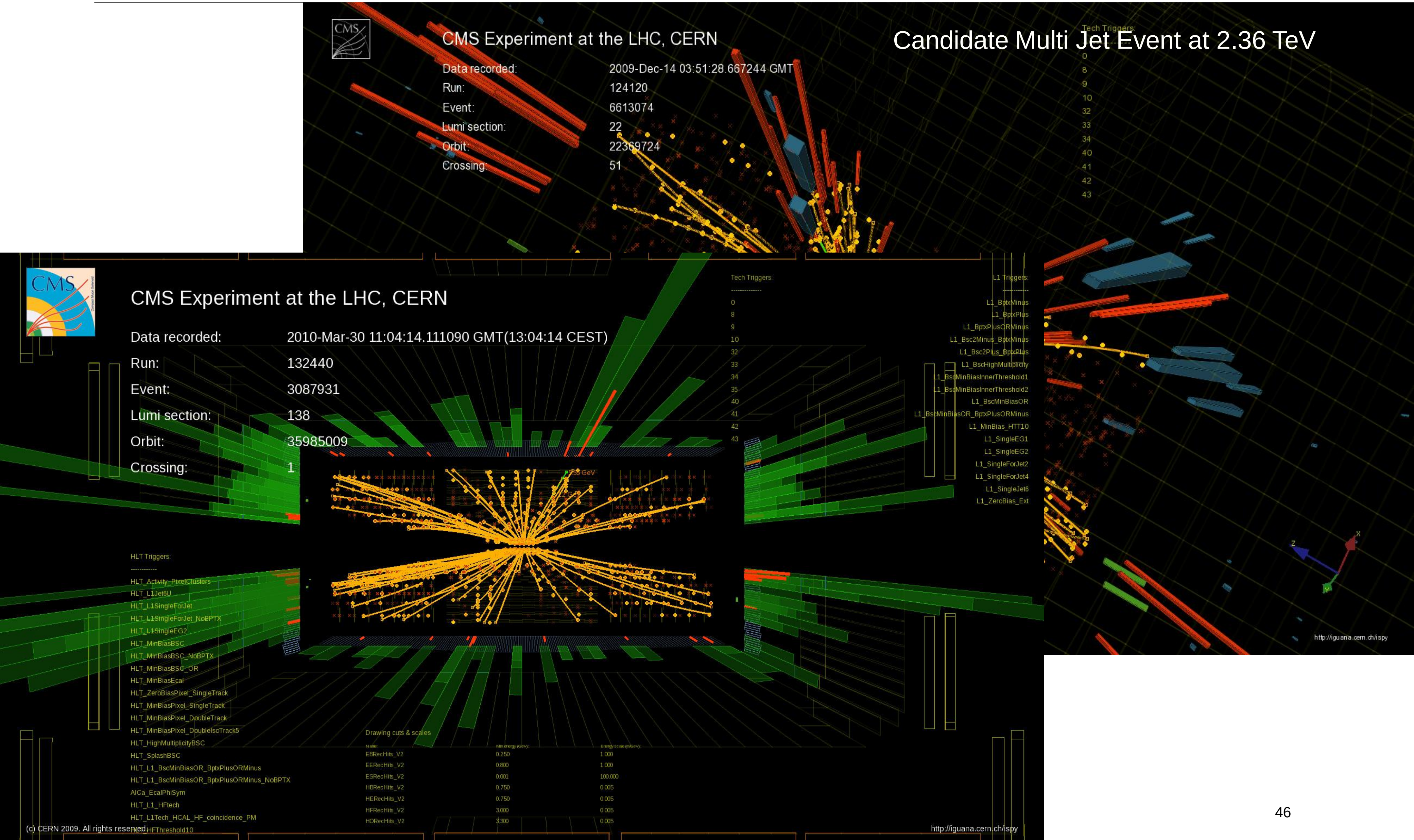
Example: CMS – 25 Performance papers published



Muon Charge Ratio



Collisions at 2.36 and 7 TeV!



Candidate Multi Jet Event at 2.36 TeV

CMS Experiment at the LHC, CERN

Data recorded:	2009-Dec-14 03:51:28.667244 GMT
Run:	124120
Event:	6613074
Lumi section:	22
Orbit:	22369724
Crossing:	51

Tech Triggers:

0
8
9
10
32
33
34
40
41
42
43

http://iguana.cern.ch/ispy

CMS Experiment at the LHC, CERN

Data recorded:	2010-Mar-30 11:04:14.111090 GMT(13:04:14 CEST)
Run:	132440
Event:	3087931
Lumi section:	138
Orbit:	35985009
Crossing:	1

Tech Triggers:

0
8
9
10
32
33
34
35
40
41
42
43

L1 Triggers:

L1_BptxMinus
L1_BptxPlus
L1_BptxPlusORMinus
L1_Bsc2Minus_BptxMinus
L1_Bsc2Plus_BptxPlus
L1_BscHighMultiplicity
L1_BscMinBiasInnerThreshold1
L1_BscMinBiasInnerThreshold2
L1_BscMinBiasOR
L1_BscMinBiasOR_BptxPlusORMinus
L1_MinBias_HTT10
L1_SingleEG1
L1_SingleEG2
L1_SingleForJet2
L1_SingleForJet4
L1_SingleJet6
L1_ZeroBias_Ext

HLT Triggers:

HLT_Activity_PixelClusters
HLT_L1Jet6U
HLT_L1SingleForJet
HLT_L1SingleForJet_NoBPTX
HLT_L1SingleEG2
HLT_MinBiasBSC
HLT_MinBiasBSC_NoBPTX
HLT_MinBiasBSC_OR
HLT_MinBiasEcal
HLT_ZeroBiasPixel_SingleTrack
HLT_MinBiasPixel_SingleTrack
HLT_MinBiasPixel_DoubleTrack
HLT_MinBiasPixel_DoubleIsoTrack5
HLT_HighMultiplicityBSC
HLT_SplashBSC
HLT_L1_BscMinBiasOR_BptxPlusORMinus
HLT_L1_BscMinBiasOR_BptxPlusORMinus_NoBPTX
AlCa_EcalPhiSym
HLT_L1_HFtech
HLT_L1Tech_HCAL_HF_coincidence_PM
HLT_HFThreshold10

Drawing cuts & scales

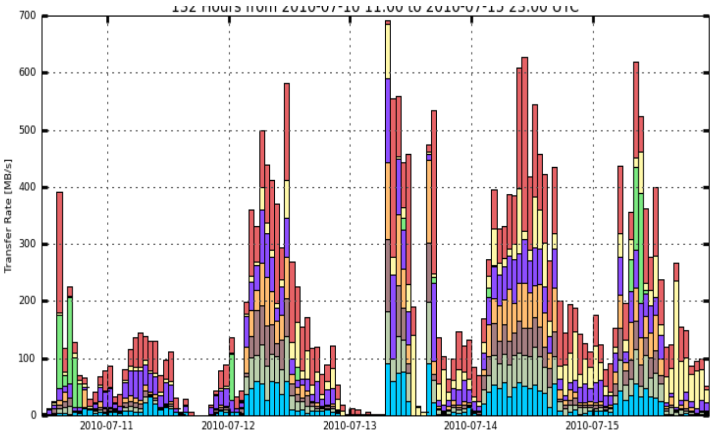
Name:	Min energy (GeV):	Energy scale (m/GeV):
EBRecHits_V2	0.250	1.000
EERecHits_V2	0.800	1.000
ESRecHits_V2	0.001	100.000
HBRecHits_V2	0.750	0.005
HERecHits_V2	0.750	0.005
HFRecHits_V2	3.000	0.005
HORecHits_V2	3.300	0.005

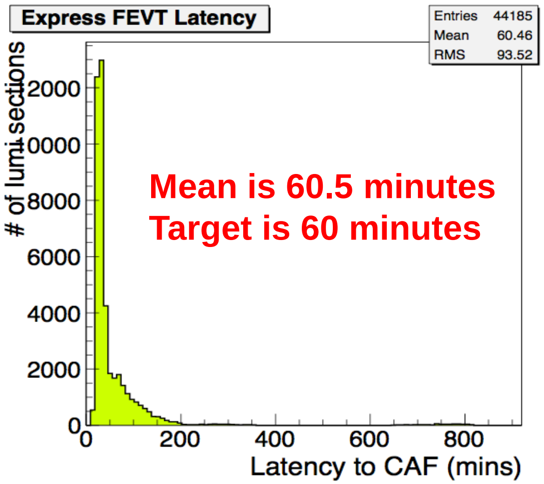
http://iguana.cern.ch/ispy

Data Transfers, CPU, Analysis (jobs, people,..) ...

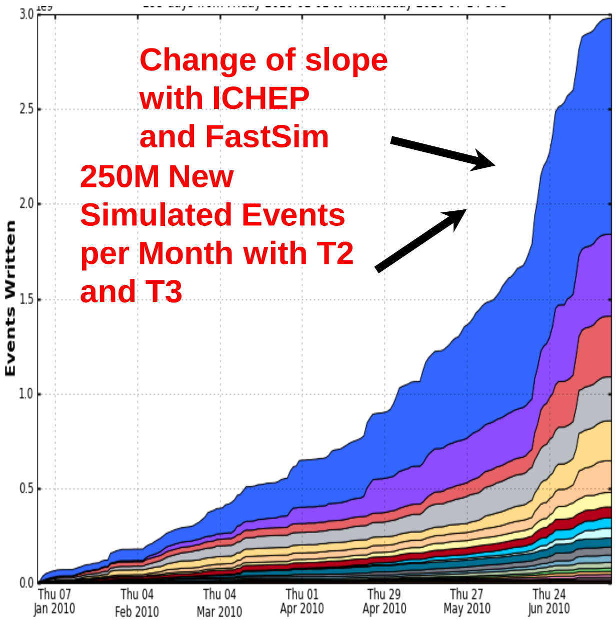
Good experience so far: the whole offline and Computing organization + GRID infrastructure performing very well.

Hourly Peaks to Tier-1s of 600MB/s



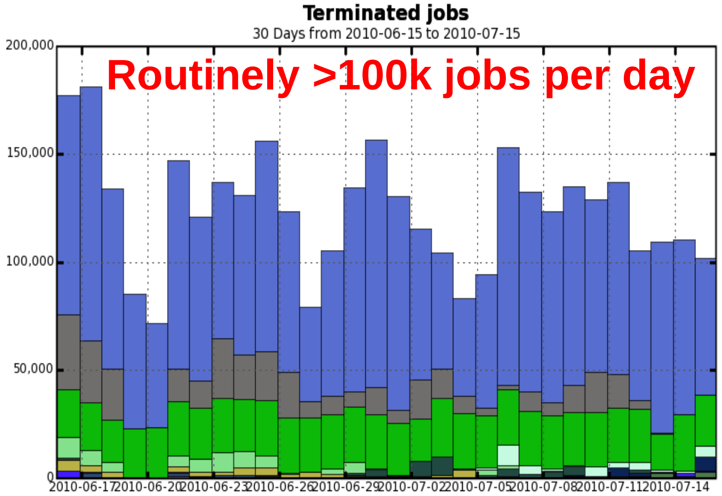


Mean is 60.5 minutes
Target is 60 minutes

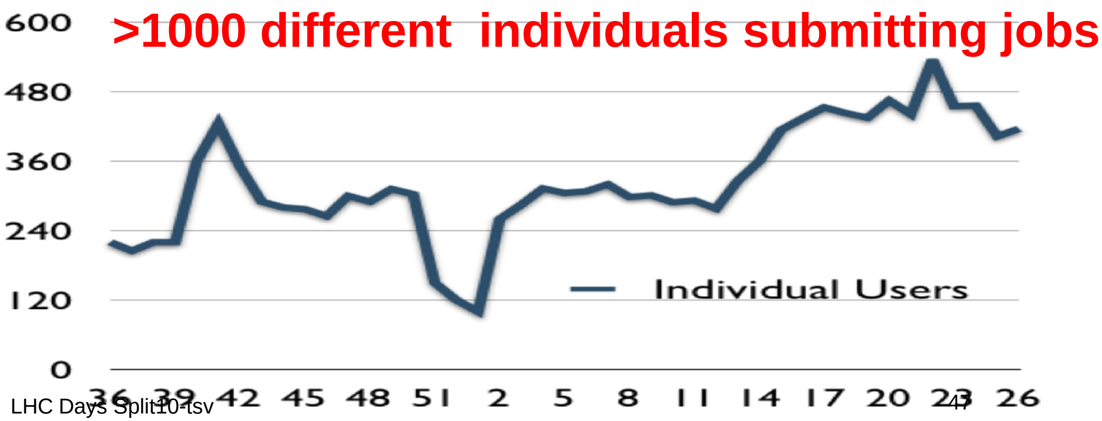


Change of slope
with ICHEP
and FastSim

250M New
Simulated Events
per Month with T2
and T3



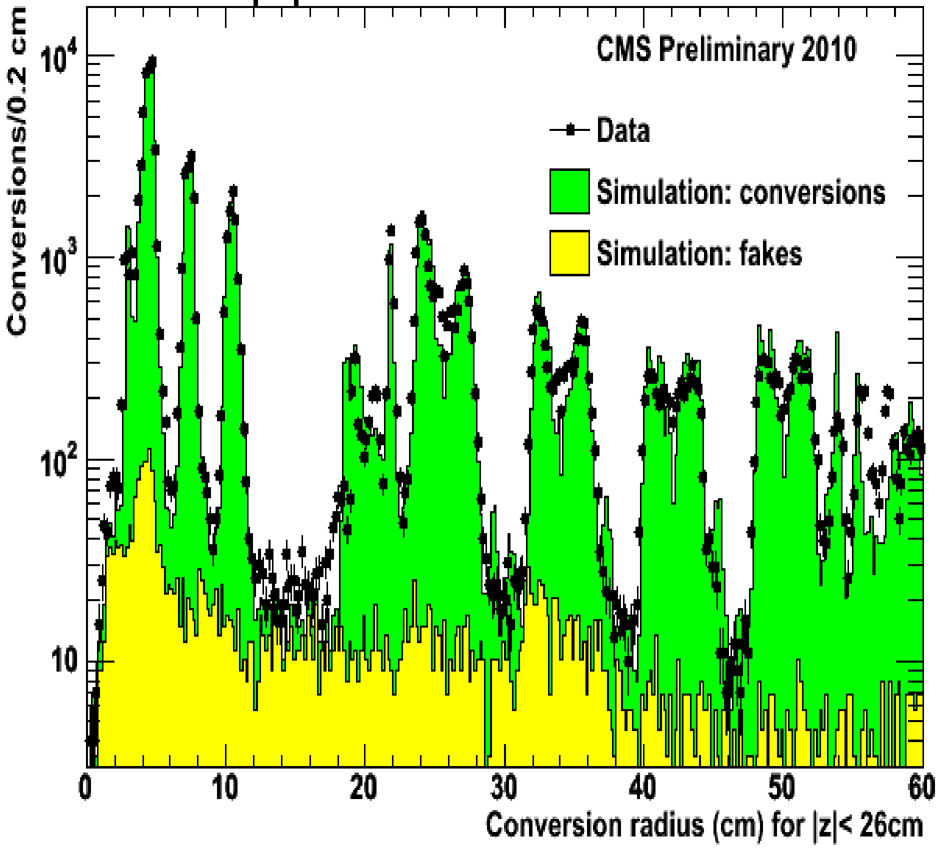
Routinely >100k jobs per day

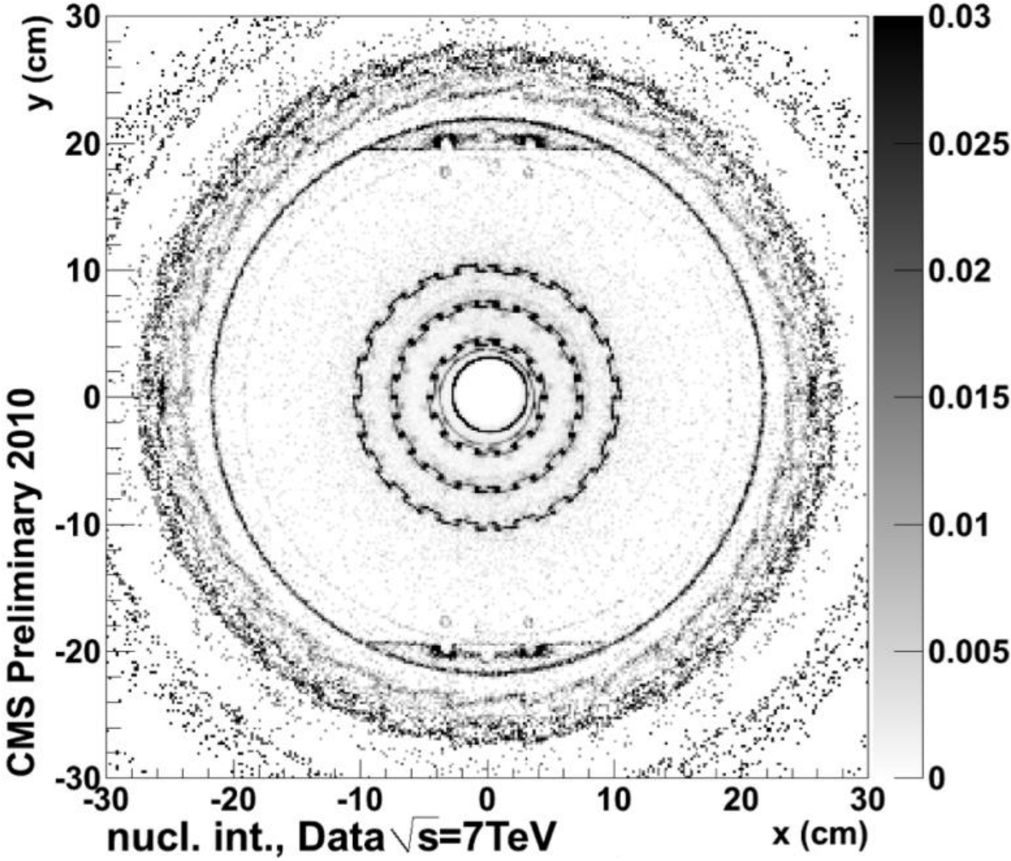


>1000 different individuals submitting jobs

CMS is well-described in simulation e.g. Tracker

|z|<26 cm





Using complementary methods: conversions, nuclear interactions, multiple scattering etc

Material uncertainty today better than 10%→Systematics uncertainties on physics quantities related to material budget <1% .

Physics Objects

The CMS detector is performing very well

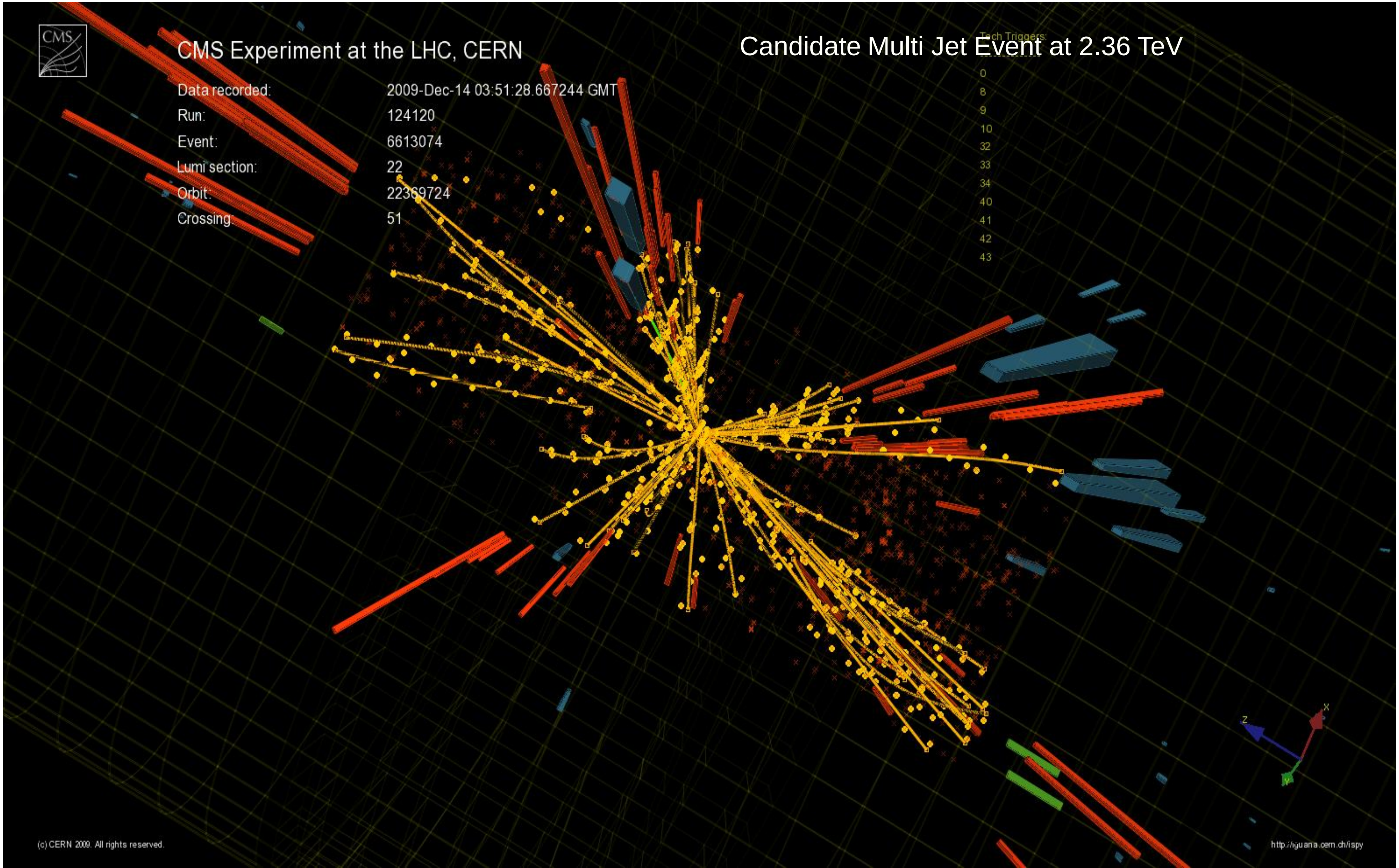
Commissioning of Physics Objects is well advanced

- **Charged track reconstruction, electrons, photons, muons and taus**
- **Jets & MET**
  - Refine noise filters, cleaning algo's
  - Optimization of jet algorithms for resolution, scale, lepton and γ fakes, etc.
- **Commission higher level algo's**
  - B tagging
  - Particle Flow

Also calibrate with known objects

- Study candles for leptons and photons
  - □ $\pi^0,\eta,..\Upsilon,\psi,...$ initially to understand the detector, tracking, object id's
  - Extend to W, Z →leptons

Combining All Information: Particle Flow

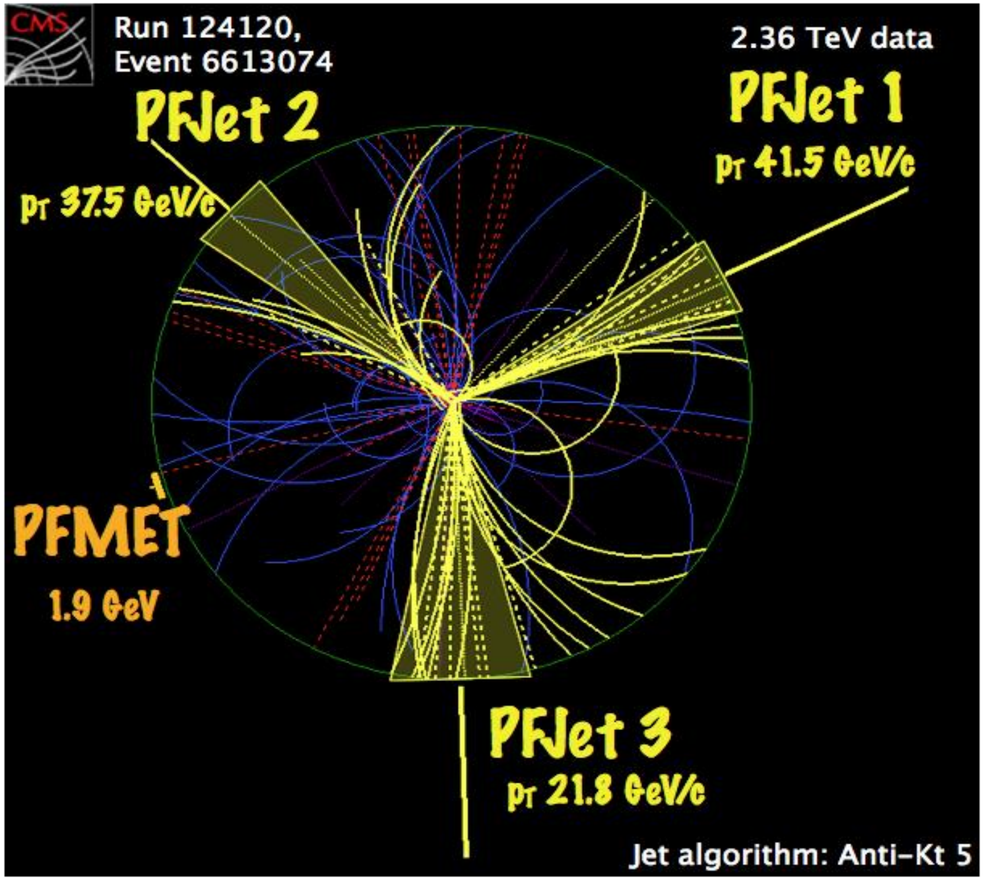


Candidate Multi Jet Event at 2.36 TeV

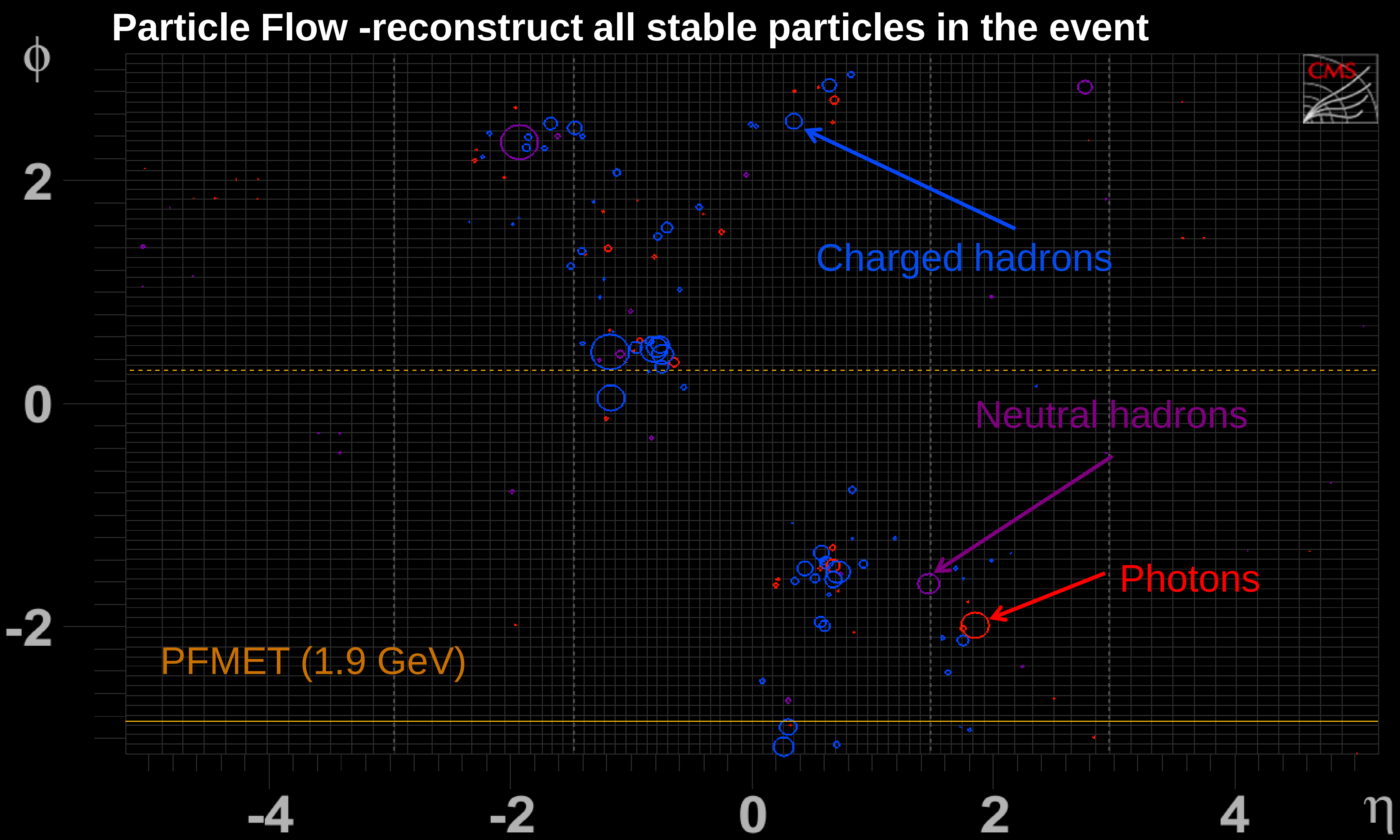
Combining Calorimetry and Tracking

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



Combining Calorimetry and Tracking


Particle Flow -reconstruct all stable particles in the event

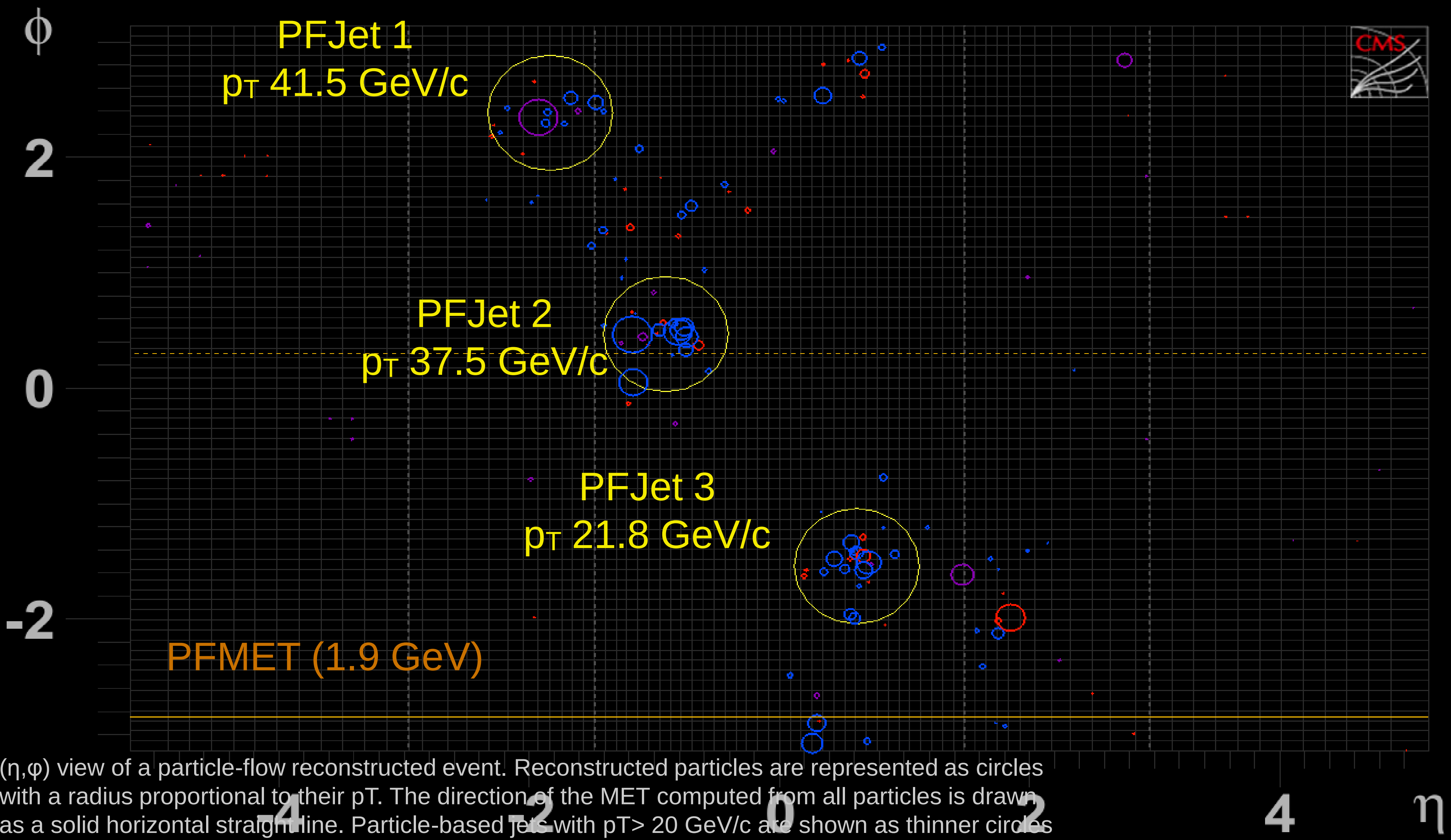
Charged hadrons

Neutral hadrons

Photons

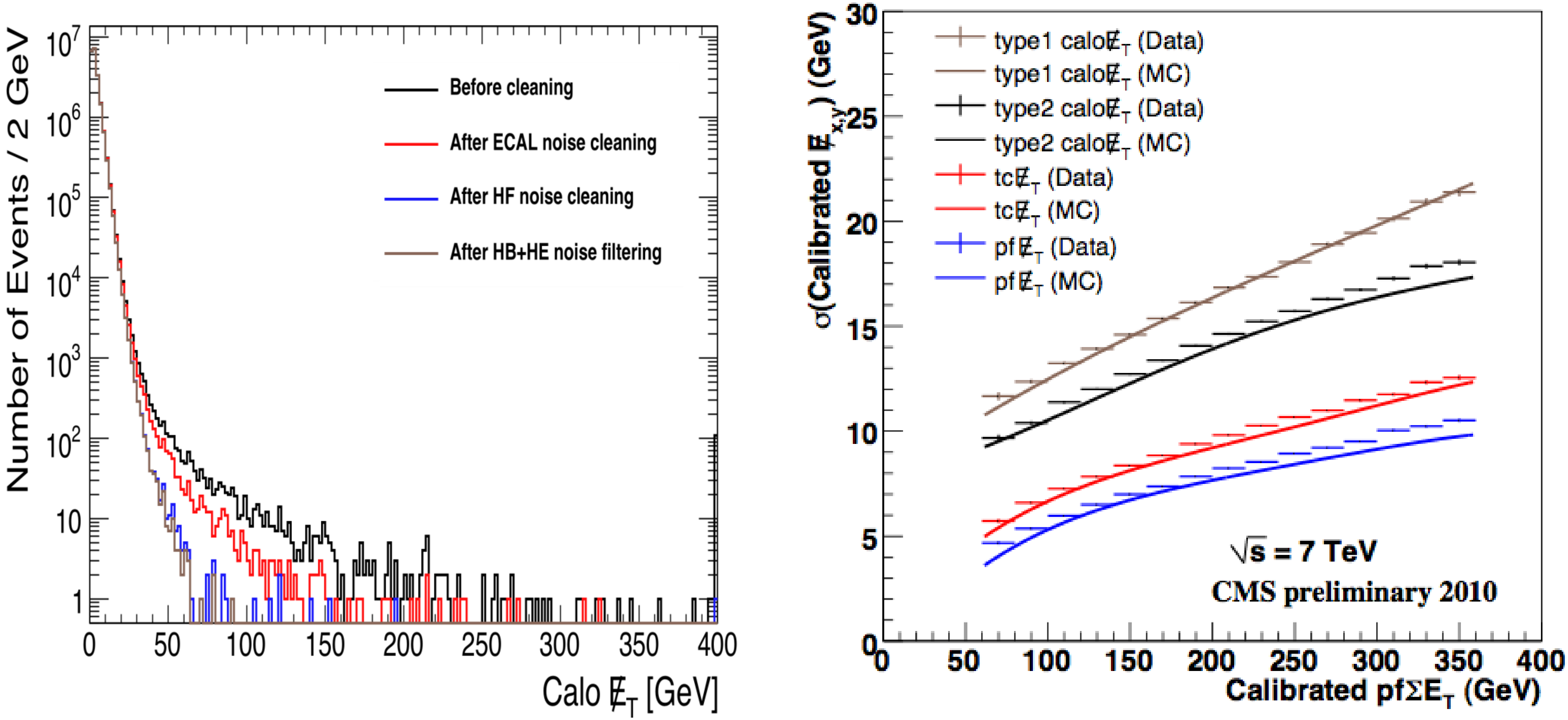
PFMET (1.9 GeV)

Analysing Complex Events



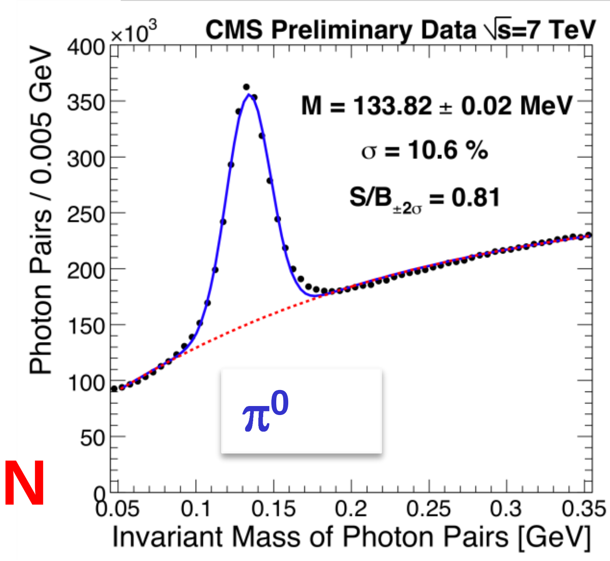
(η,φ) view of a particle-flow reconstructed event. Reconstructed particles are represented as circles with a radius proportional to their pT. The direction of the MET computed from all particles is drawn as a solid horizontal straight line. Particle-based jets with pT> 20 GeV/c are shown as thinner circles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

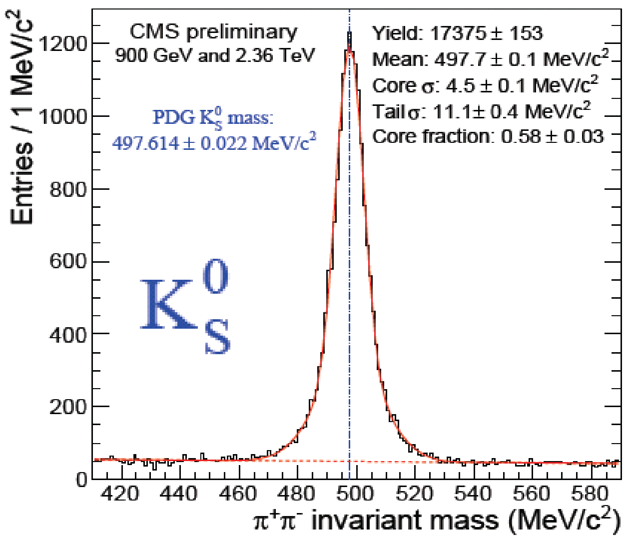
Progress in MET

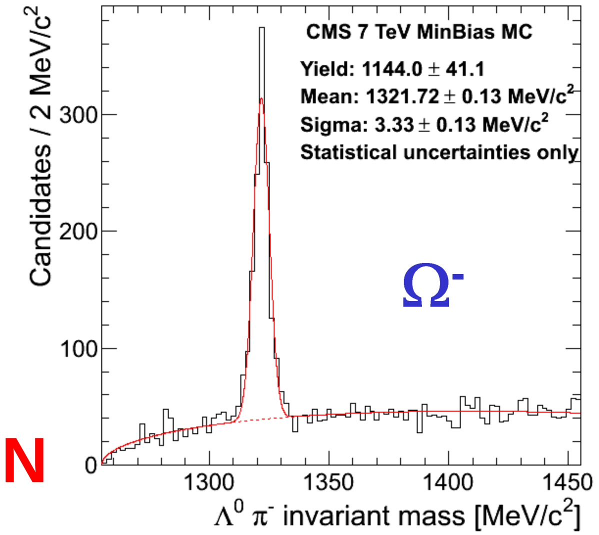


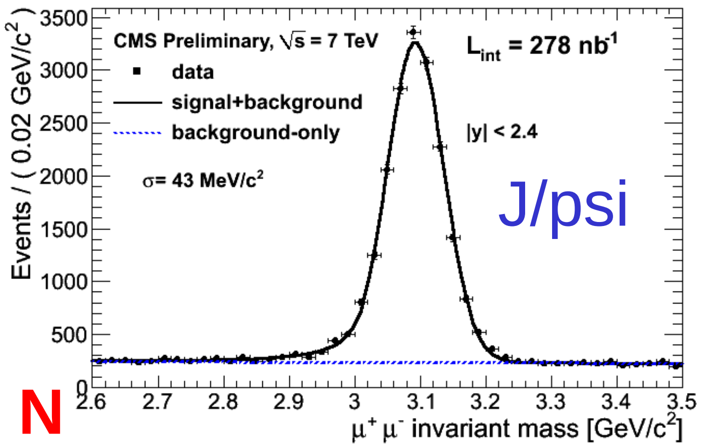
Excellent resolution and small non-gaussian tails. Understanding all sources of erratic noise is very important for cleaning the distributions. MET ready for physics.

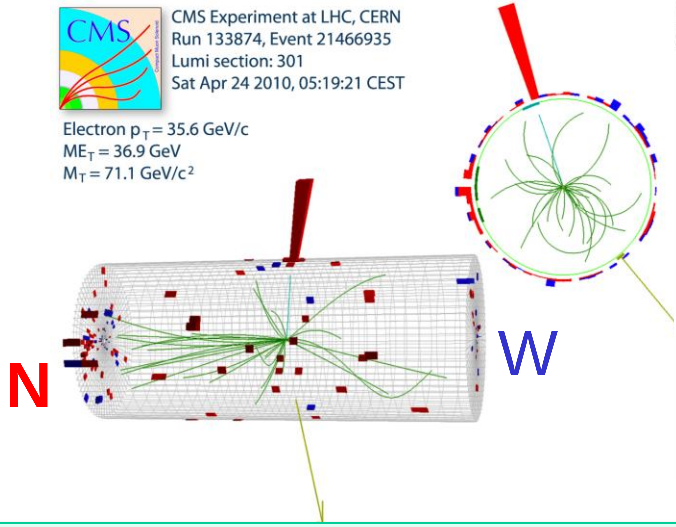
CMS - 50 Years of Particle Physics

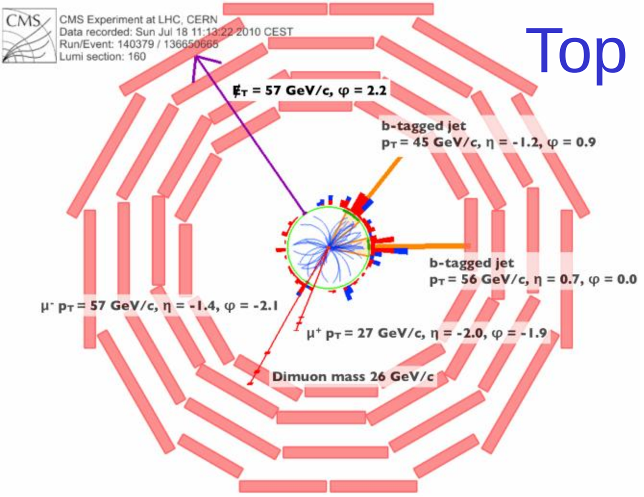






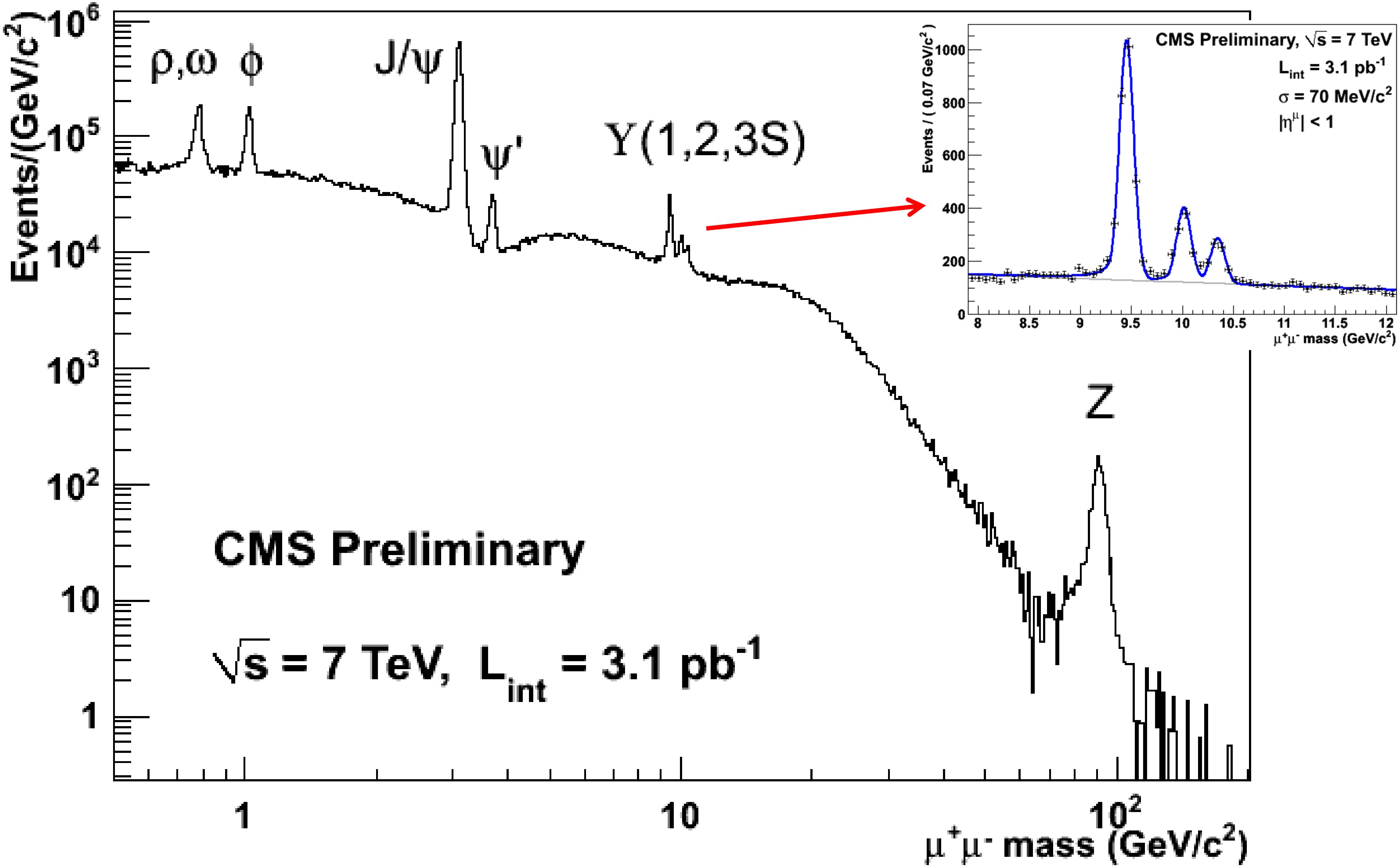




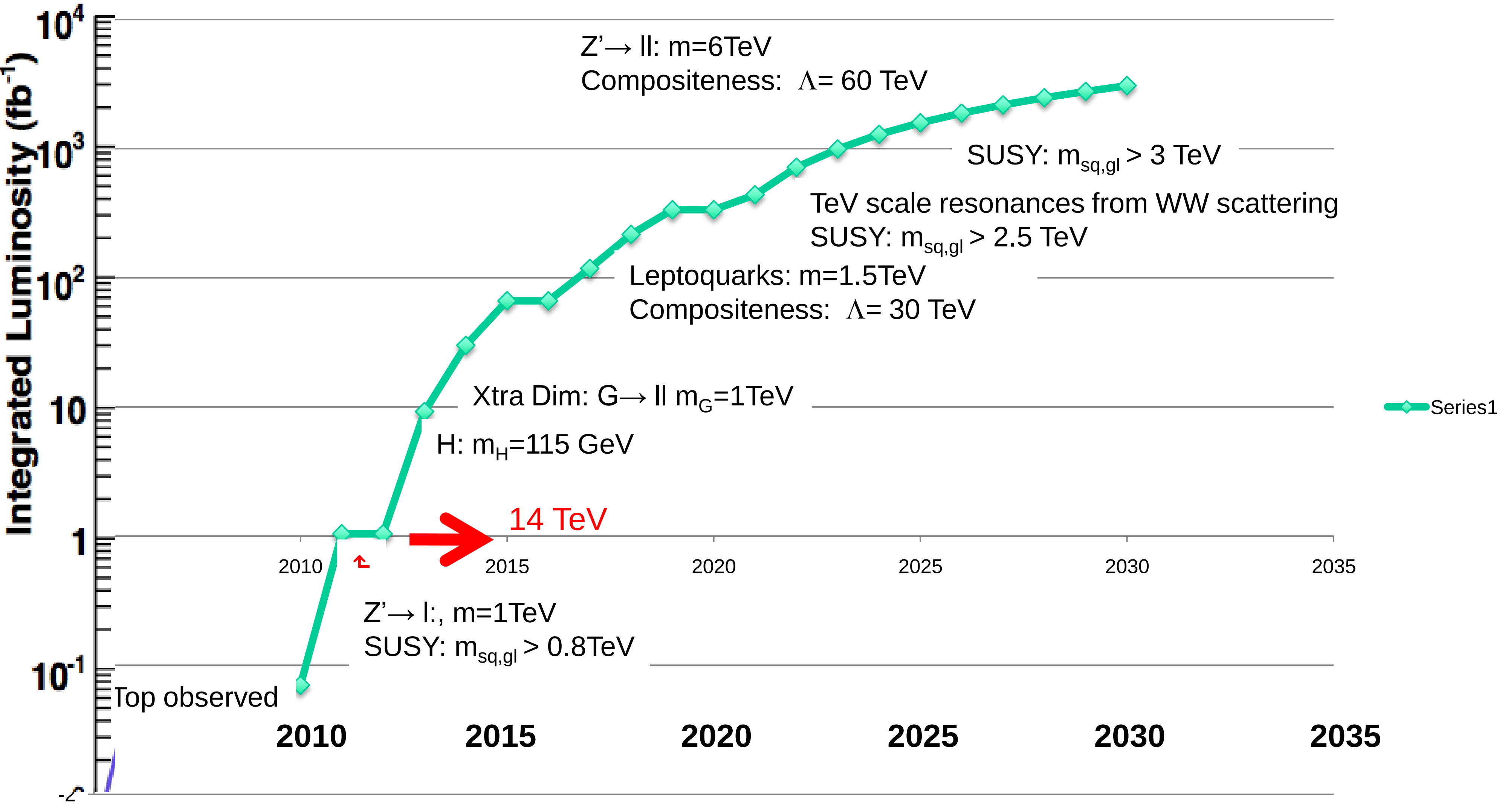


Sophisticated software and computing systems in place and functioning

Muons in CMS


Events/(GeV/c^2)
10^6
10^5
10^4
10^3
10^2
10
1
ρ,ω
φ
J/ψ
ψ'
Υ(1,2,3S)
Z
CMS Preliminary
$\sqrt{s}$ = 7 TeV, L_{int} = 3.1 pb^{-1}
1
10
10^2
$\mu^+\mu^-$ mass (GeV/c^2)
CMS Preliminary, $\sqrt{s}$ = 7 TeV
L_{int} = 3.1 pb^{-1}
σ = 70 MeV/c^2
$|\eta^\mu| < 1$
Events / (0.07 GeV/c^2)
1000
800
600
400
200
0
8
8.5
9
9.5
10
10.5
11
11.5
12
$\mu^+\mu^-$ mass (GeV/c^2)

LHC / HL-LHC Reach



Z’→ ll: m=6TeV
Compositeness: Λ= 60 TeV

SUSY: $m_{sq,gl}$ > 3 TeV

TeV scale resonances from WW scattering
SUSY: $m_{sq,gl}$ > 2.5 TeV

Leptoquarks: m=1.5TeV
Compositeness: Λ= 30 TeV

Xtra Dim: G→ ll m_G=1TeV

H: m_H=115 GeV

14 TeV

Z’→ l:, m=1TeV
SUSY: $m_{sq,gl}$ > 0.8TeV

Top observed

Conclusions

- The LHC project (the accelerator and experiments) was conceived & designed to attack fundamental questions in science.
- CMS (and ATLAS) are 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.
- After twenty years spent on the design, R&D, prototyping, construction, assembly and commissioning CMS is recording high energy collisions.

The thorough preparation of the experiment, the offline and computing systems, and physics analysis work flows has allowed very rapid extraction of quality physics results.

All systems are performing very well – CMS is already approaching design performance in many areas! Much physics is streaming out and CMS is already exploring new territory in certain areas.

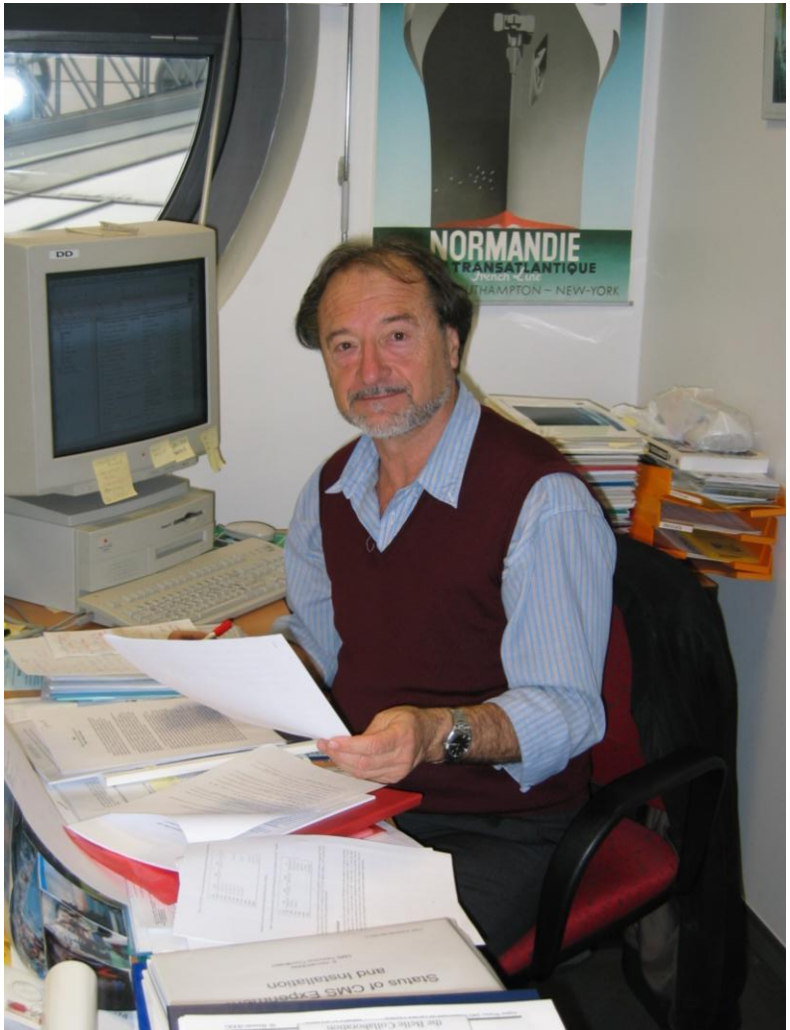
We are just at the beginning - all expectations are that the future is bright .

Daniel the Polymath

Daniel – the Scientist

To me there has never been a higher source of earthly honour or distinction than that connected with advances in science.

Sir Isaac Newton



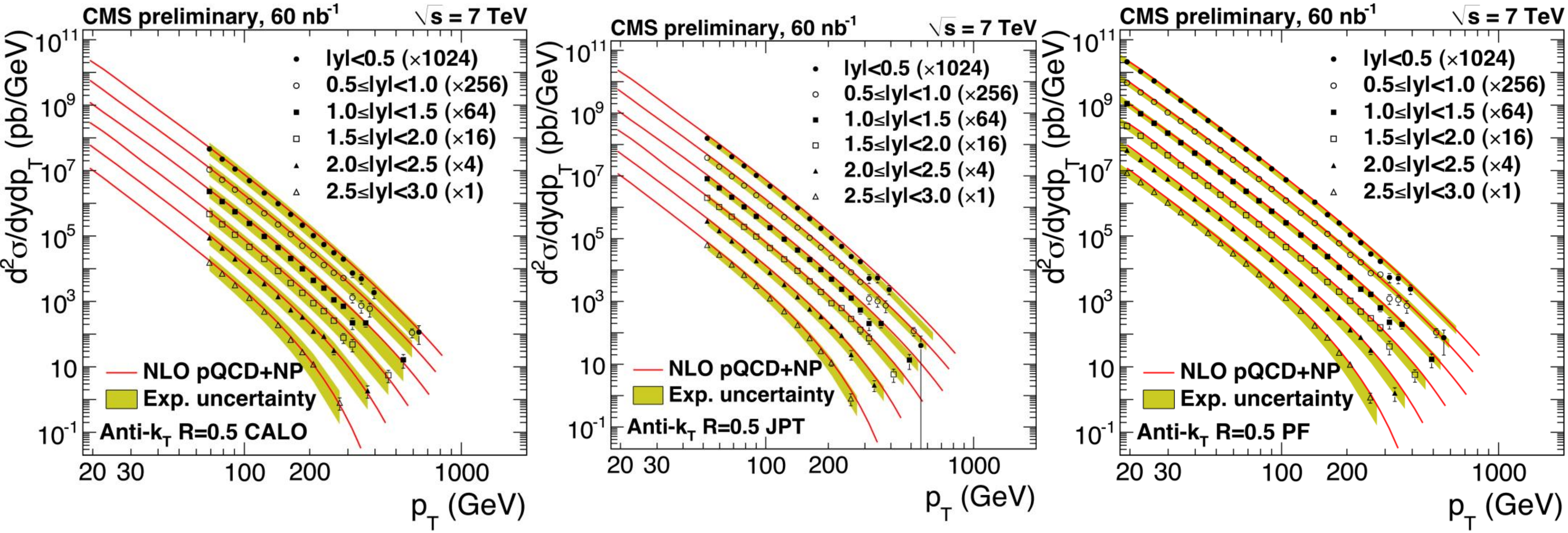
**And Daniel,
to the next
20 years**

Inclusive jet cross section

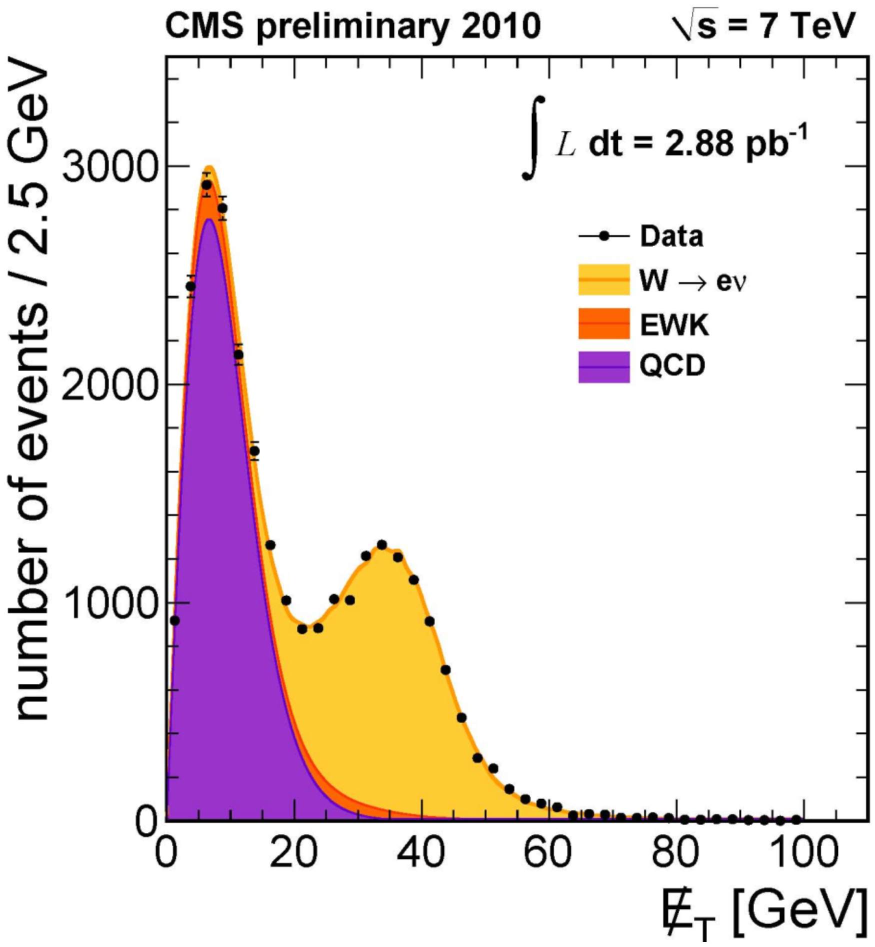
Inclusive jet p_T spectra measured for all three jet approaches used in CMS.

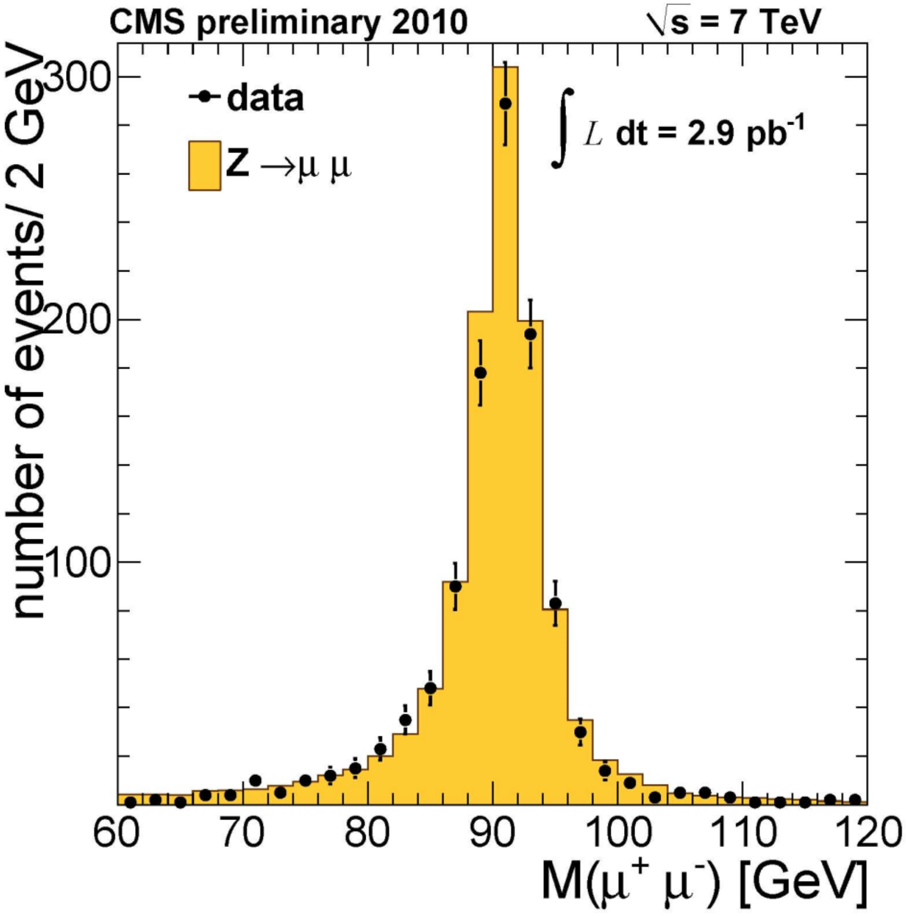
All results are in good agreement with NLO theory.

With the new Particle Flow approach the distributions can be extended to a low p_T value of 18 GeV.



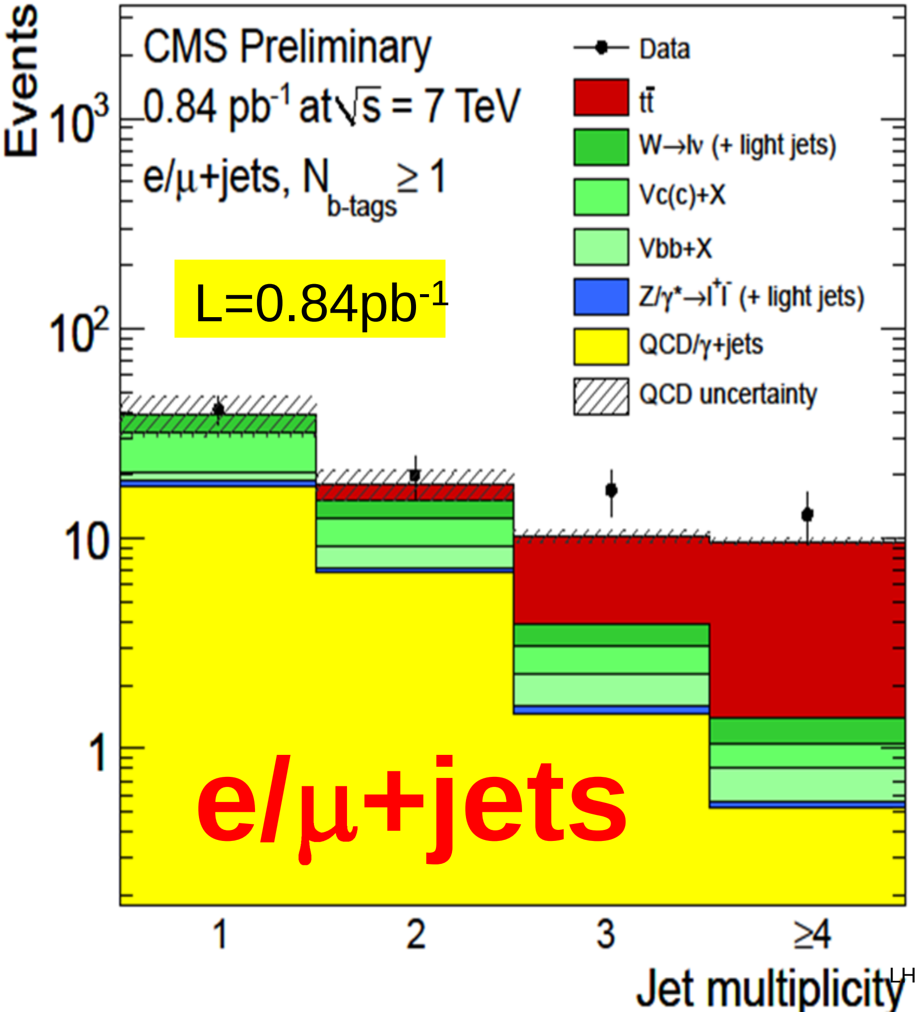
Extraction of the $W^{\pm}$ (Z^{o})→$e^{\pm}\nu$ ($\mu^{+}\mu^{-}$) yield signal





Lepton+jets Top selection

Require at least 1 jet b-tagged (secondary vertex tagger with ≥2 tracks; high efficiency with ~1% fake rate)



Use 0.84 pb^{-1} (HCP Toronto dataset)

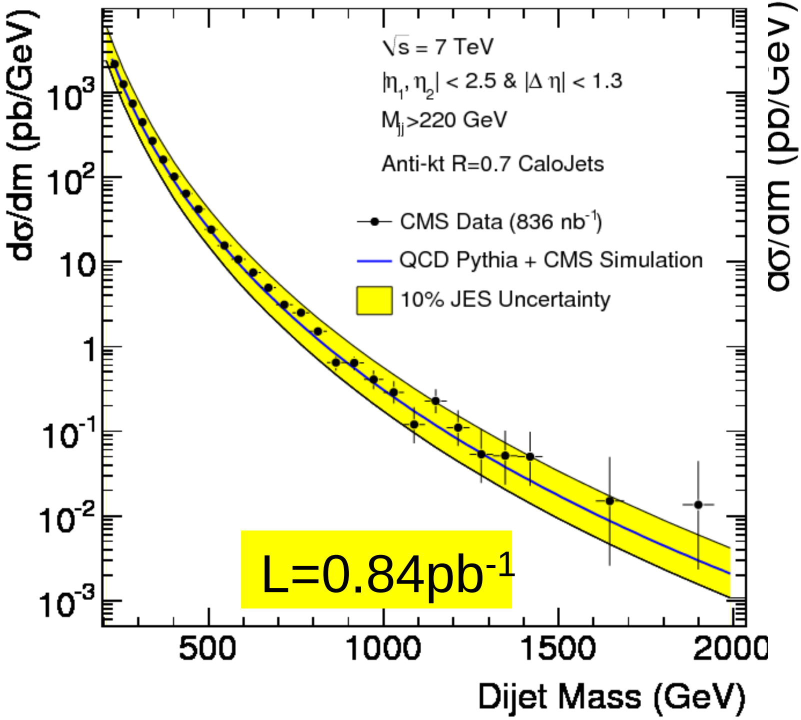
For N(jets)≥3 we count **30 signal candidates over a predicted background of 5.3**

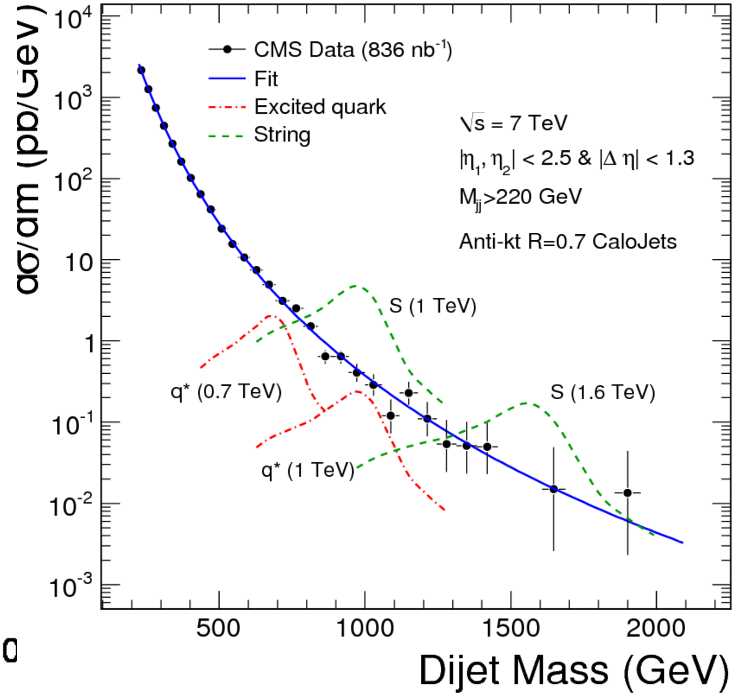
t-tbar events are observed in CMS at a rate consistent with NLO cross section, considering experimental (JES, b-tagging) and theoretical (scale, PDF, HF modelling, …) uncertainties.

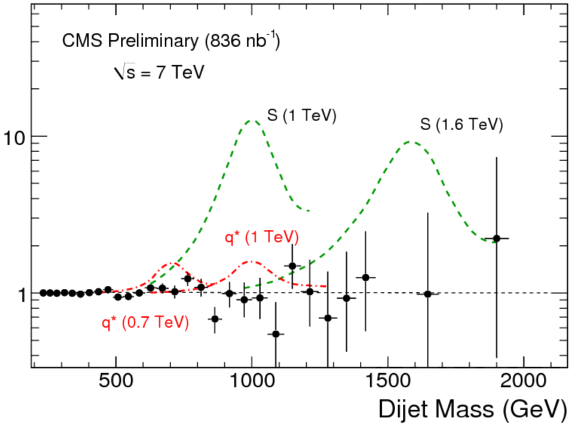
Exploring new territory

Search for narrow resonances in di-jet final states.

We have measured, in 0.84pb^{-1} of data, the dijet mass differential cross section for $|\eta_1,\eta_2|<2.5$ and $|\Delta\eta_2|<1.3$. The distribution is sensitive to the coupling of any new massive object to quarks and gluons.







95% CL mass limits for String resonances >2.1TeV; Excited quarks >1.14TeV; Axigluons/Colorons >1.06TeV; E$_6$ Diquarks >0.58