12th Pisa Meeting on Advanced Detectors
La Biodola, Isola d'Elba (Italy) May 20 - 26, 2012

Performance and Upgrade Plans for the CMS Detector

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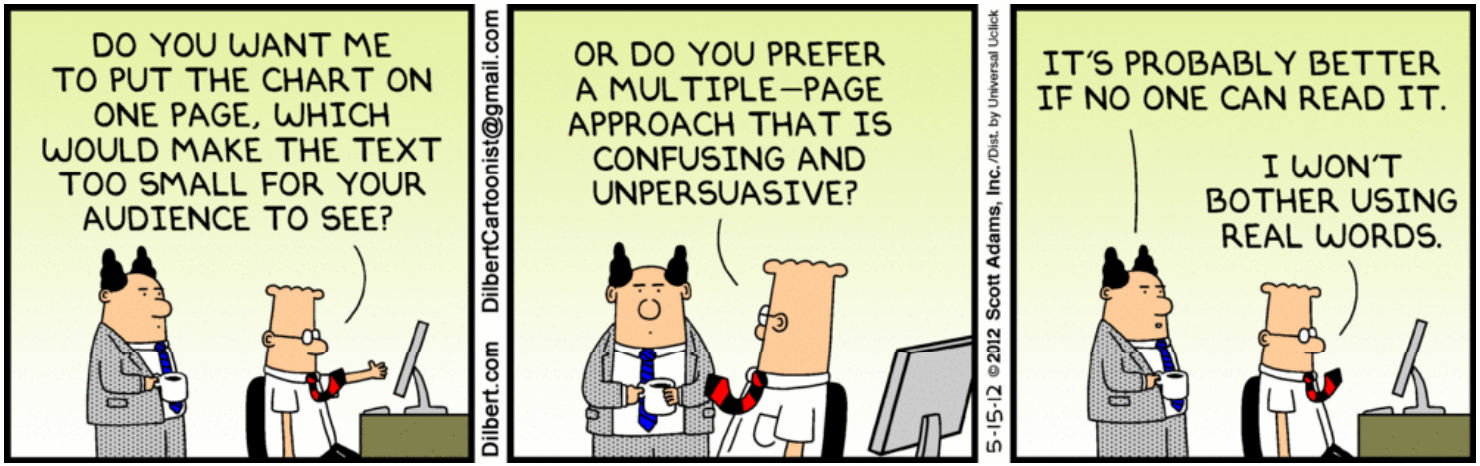
Outline

- CMS Detector
- LHC and CMS run 2011 summary, 2012 highlights, luminosity, data taking
- Subsystems status (not exhaustive)
- Hints on detector performance and progress
- General view of the upgrades:
  - Long Shutdown 1
  - Phase 1
  - Phase 2



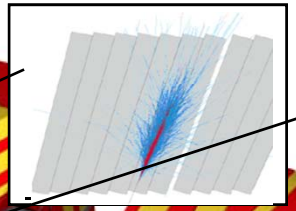
The CMS detector

12.5kt mass
21.6m long
14.6m diam.

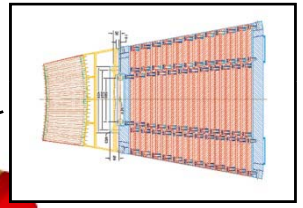
SUPERCONDUCTING COIL 3.8T field

CALORIMETERS

ECAL Scintillating $PbWO_4$ Crystals

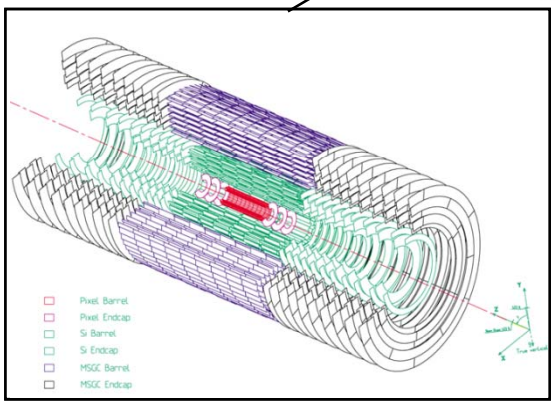


HCAL Plastic scintillator brass sandwich



IRON YOKE

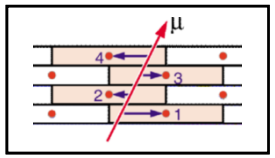
TRACKER



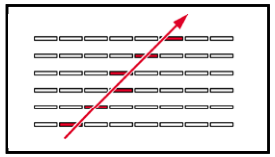
Silicon Microstrips, 10 barrel layers, 3+9 fw disks, 9.3M strips

Pixels 3 barrel layers, 2 fw disks, 66M channels

MUON BARREL

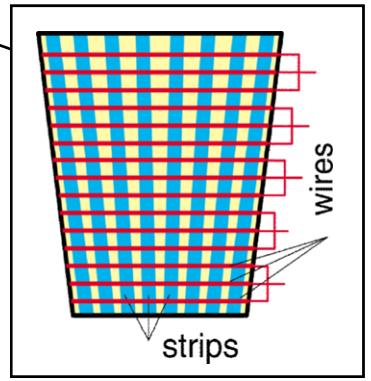


Drift Tube Chambers (**DT**)



Resistive Plate Chambers (**RPC**)

MUON ENDCAPS



Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

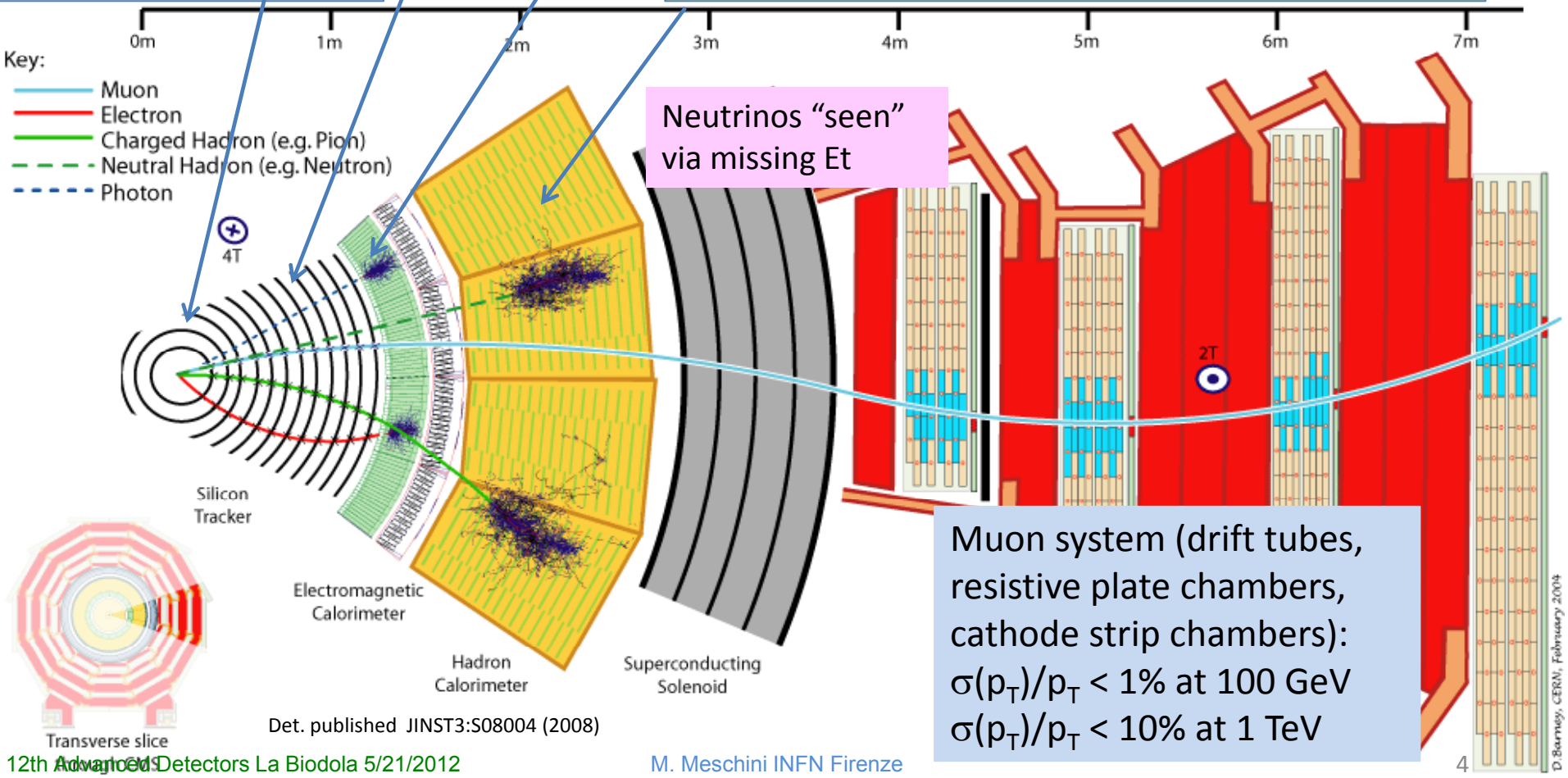
CMS in a Cake-slice

Silicon tracker:
$\sigma(p_T)/p_T$ ~ 15% at 1 TeV

EM Calorimeter (lead tungstate crystals):
$\sigma(E)/E$ ~ 3%/$\sqrt{(E)}$ [GeV] $\oplus$ 0.3%

Silicon pixel detector:
~20μm hit resolution

Hadron calorimeter (brass + scintillator):
$\sigma(E_T)/E_T$ ~ 100%/$\sqrt{(E_T)}$ [GeV] $\oplus$ 5%



Neutrinos "seen" via missing Et

Muon system (drift tubes, resistive plate chambers, cathode strip chambers):
$\sigma(p_T)/p_T$ < 1% at 100 GeV
$\sigma(p_T)/p_T$ < 10% at 1 TeV

Det. published JINST3:S08004 (2008)

LHC Startup 2012

Changes from 2011 → 2012

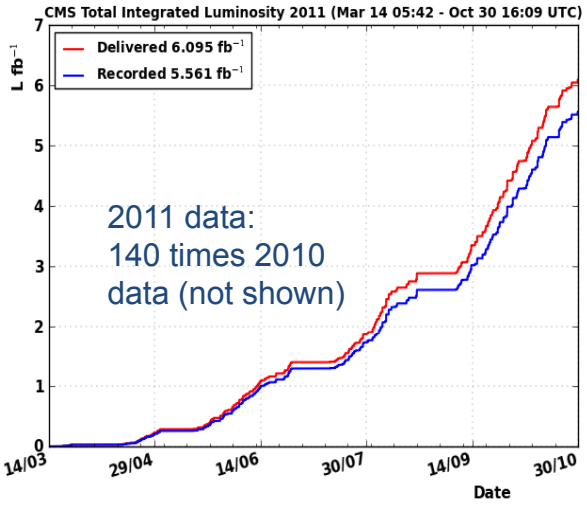
- $\sqrt{s}$ = 7 TeV in 2011 → $\sqrt{s}$ = 8 TeV in 2012
- β^* = 1m in 2011 → β^* = 0.6m in 2012
  - Higher instantaneous luminosity → more interactions per crossing → higher pileup
- 50ns bunch spacing in 2011 → as in 2012
- Maximum instantaneous luminosity was $3.5 \times 10^{33}/cm^2/s$ in 2011 → $5.6 \times 10^{33}/cm^2/s$ in 2012
  - reached on April 20th, fill 2536 with 1380 bunches, after a wonderful, steep rise.
    - Technical Stop 23-27 Apr., then a bit slow restart
    - 1380 bunches foreseen (again) on May 1st, reached on May 10th
- Now ~1.3×10^{11} protons/bunch, goal is ~1.6×10^{11}

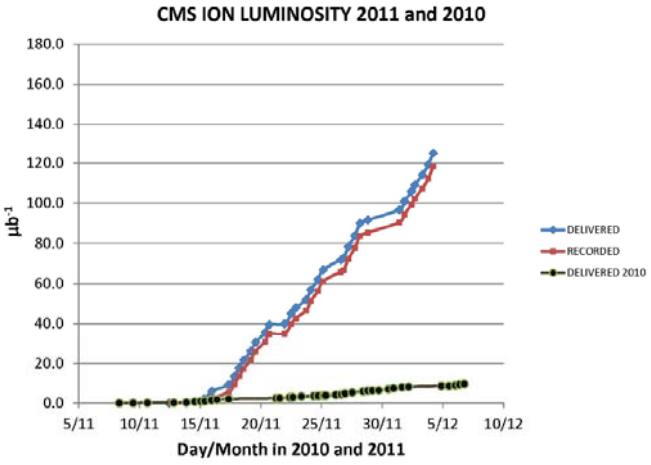
Last minute update: record lumi $6.05 \times 10^{33}/cm^2/s$ on May 19

CMS Luminosity 2011 & 2012

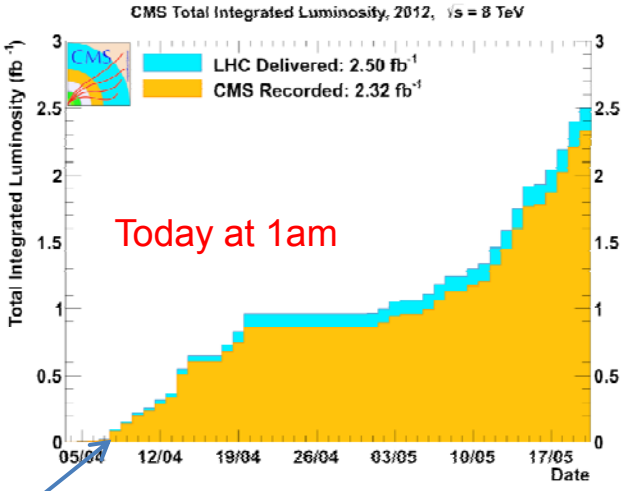
In 2011 6.1fb^{-1} delivered by LHC and **5.6fb^{-1}** recorded by CMS. A ~7% correction has been applied after end of 2011 run, and a new method to calculate lumi published in CMS-PAS-SMP-12-008.

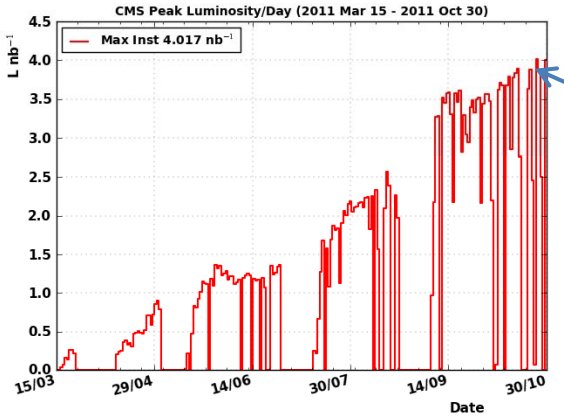
2011





2012

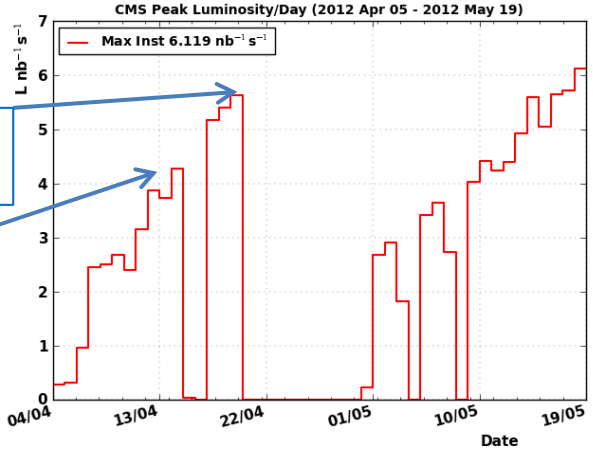




CMS recommissioned on Apr 8

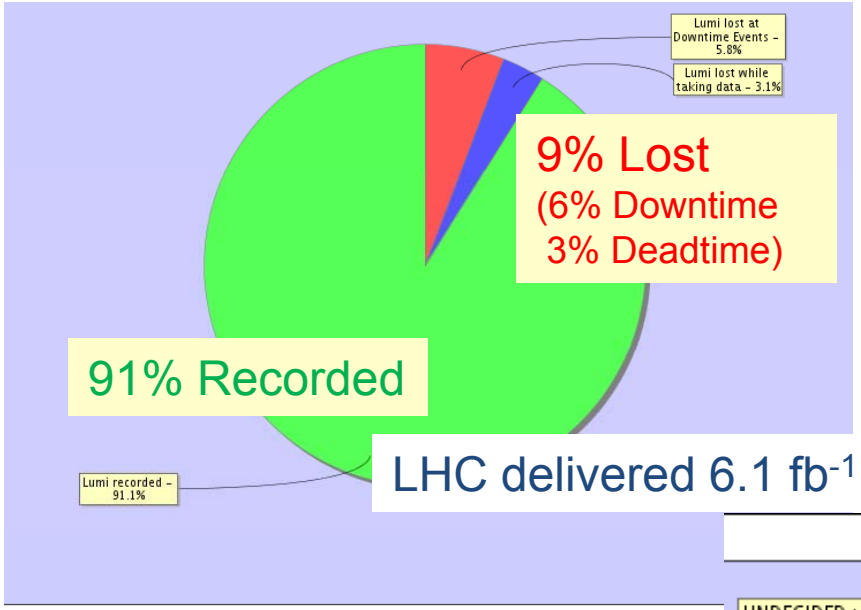
Two wks to reach reach Max Instantaneous Lumi

One wk to reach same Inst. Lumi as Max 2011



Excellent LHC 2012 Startup Performance

CMS 2011 Data Taking Efficiency



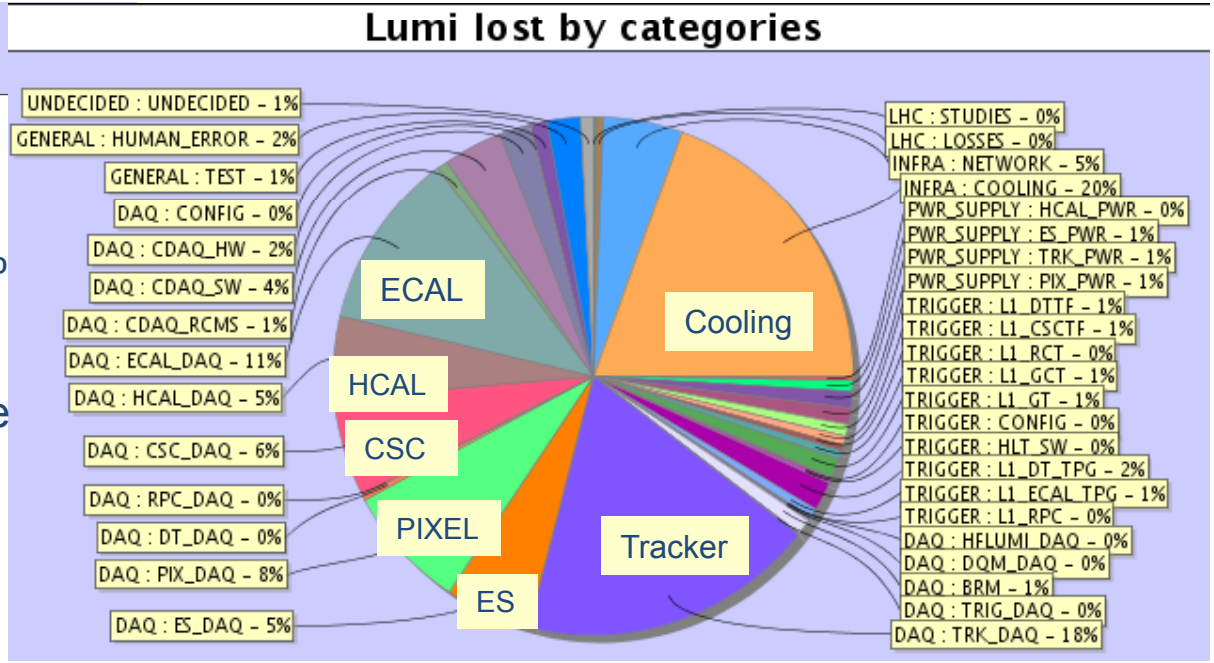
Sources of Downtime

- Largest downtime single source:
a cooling failure affecting 2 fills (August)
- Other Downtime sources:
Detector/DAQ, Special runs, Trigger, Power
-Single Event Upsets (affecting Pixel, ECAL, CSC, HCAL): addressed during winter stop to prevent problems in 2012

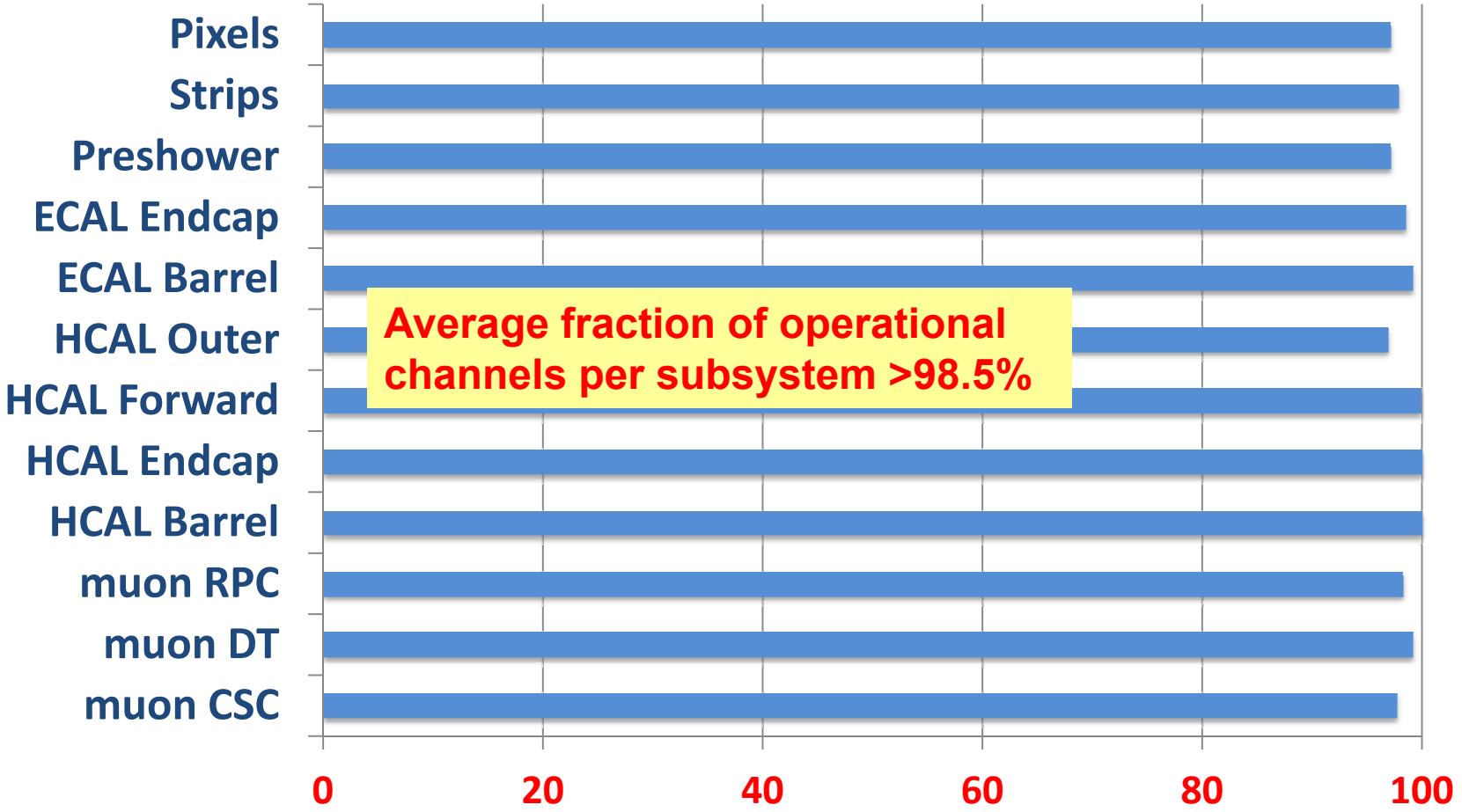
Sources of Deadtime

Trigger rules ~0.7%
Partition control sub-detectors ~0.5%
HLT (High Level Trigger) at start of runs ~0.5%
Short stops not counted as downtime

Efficiency is increasing in 2012:
92.3% global, 94% last week



CMS Detector Operational Status April 2012

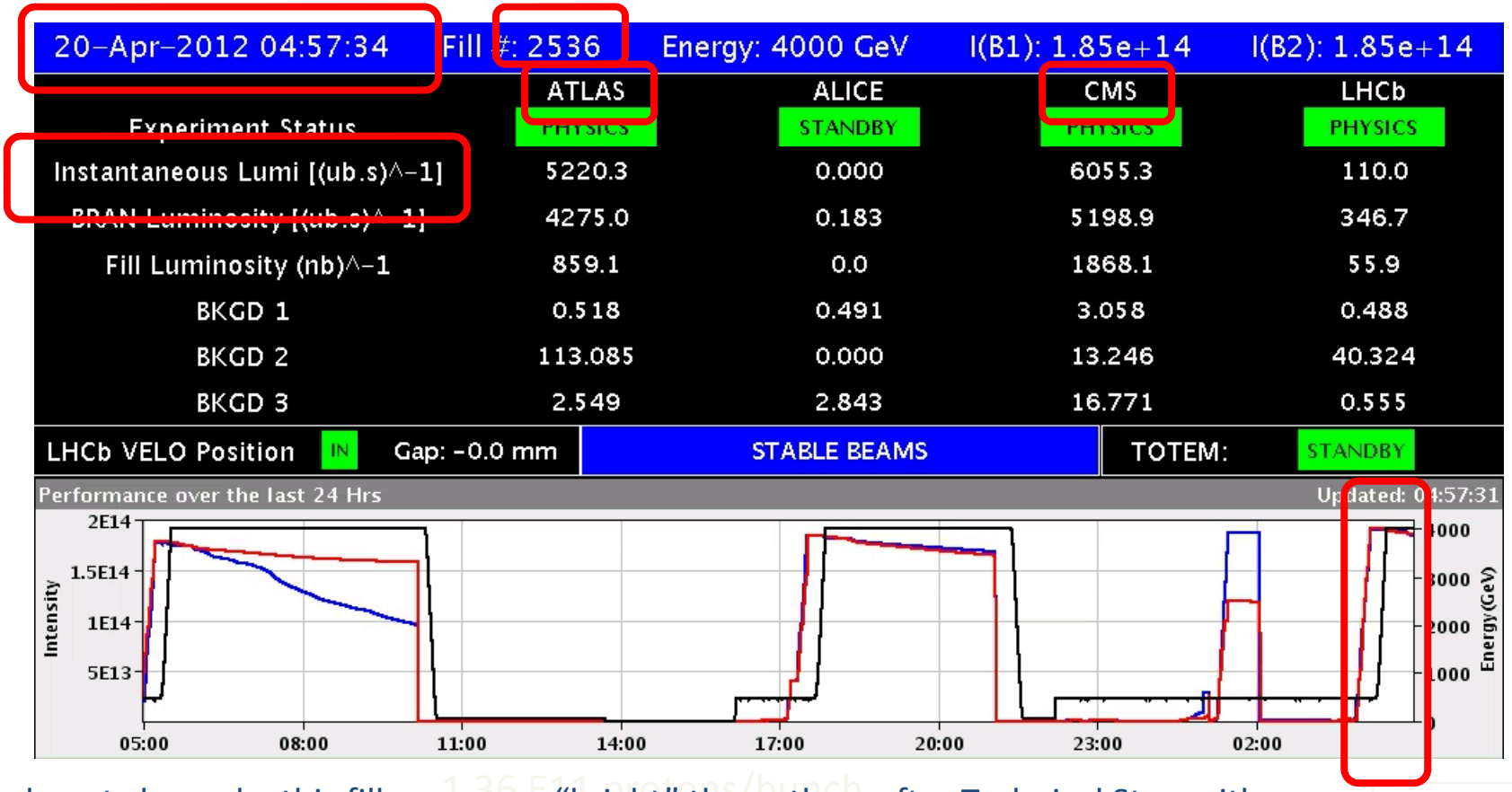


Pixel Tracker	Strip Tracker	ECAL Barrel	ECAL Endcaps	HCAL Barrel	HCAL Endcaps	HCAL Forward	HCAL Outer	Muon DT	Muon CSC	Muon RPC
97.1%	97.75%	99.16%	98.54%	99.92%	99.96%	99.88%	96.88%	99.1%	97.67%	98.2%

A Snapshot from the "Text Book" Fill #2536

yesterday!

Average CMS/ATLAS Lumi 5.6e33 $cm^{-2}s^{-1}$: highest Inst. Lumi up to ~~now~~!

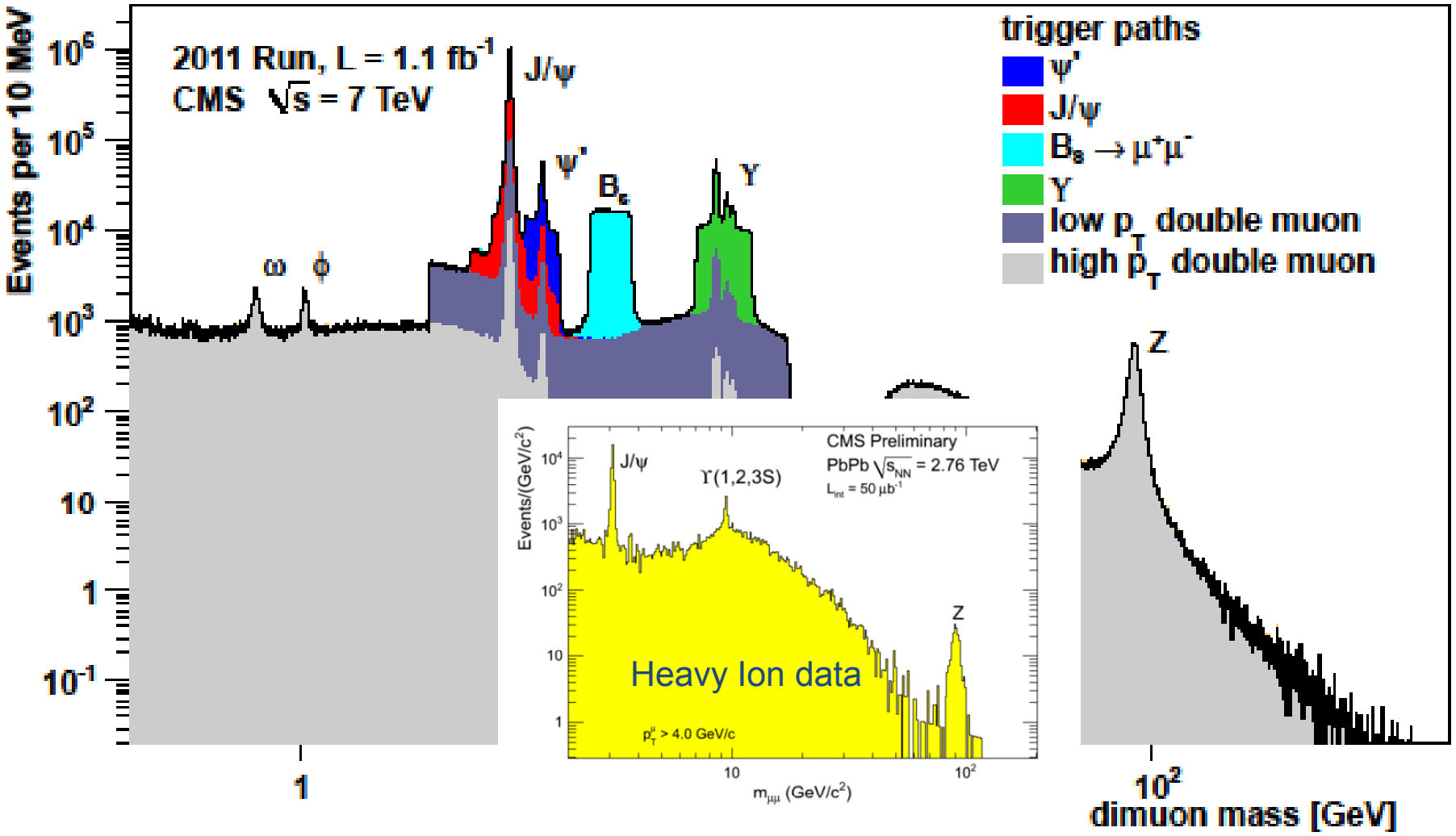


Fill 2536

Remark: not clear why this fill was more "bright" than others after Technical Stop with same current → Now understood? Leftovers settings from TS; more work to do on emittance

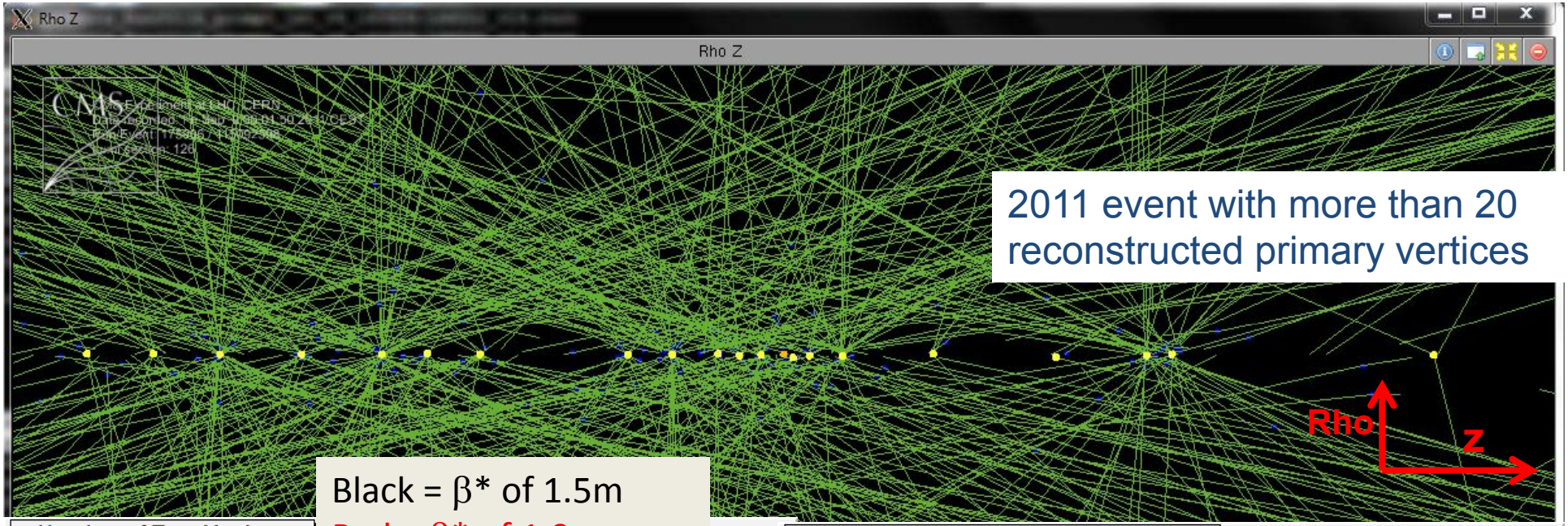
Triggering on di-muons in 2011

Dimuon triggers are fundamental for Searches, Heavy Flavors (and used also for calibrations)



Dimuon mass distribution obtained from overlapping several trigger paths

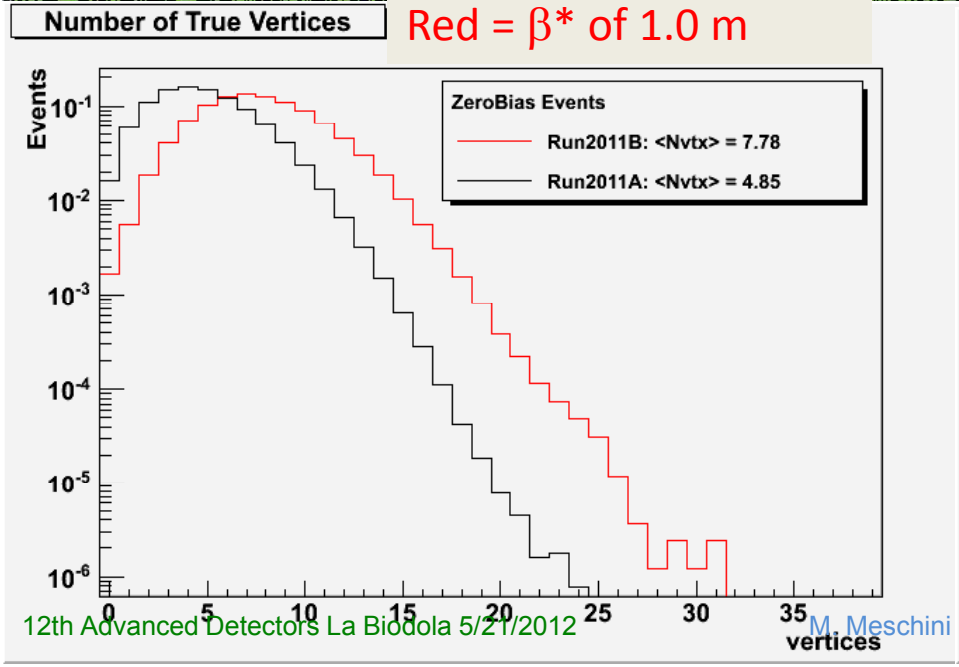
“The Challenge”: Tracking at High Pile Up

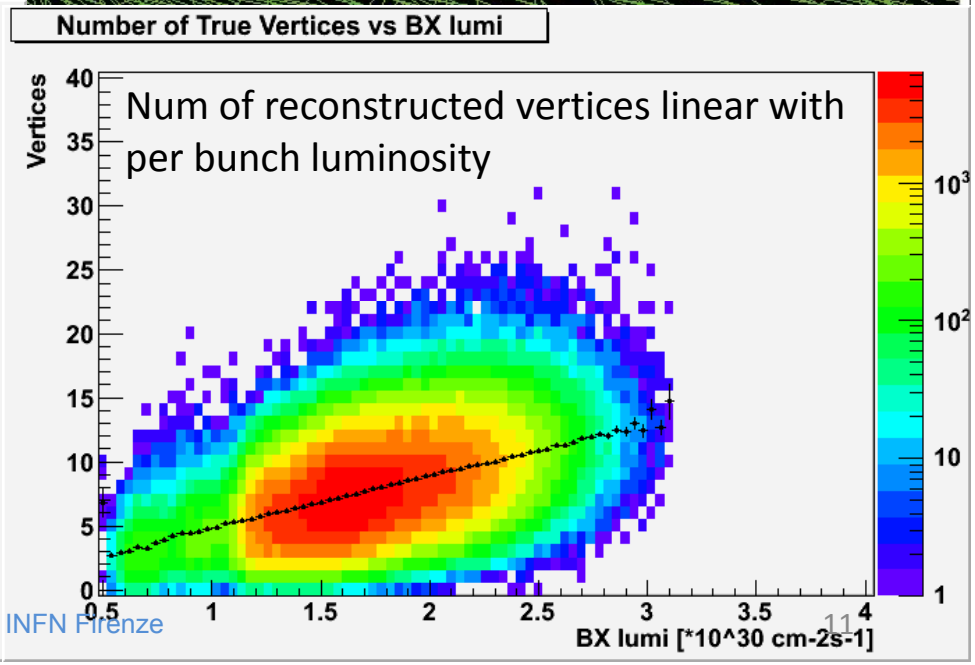


2011 event with more than 20 reconstructed primary vertices

Black = β* of 1.5m

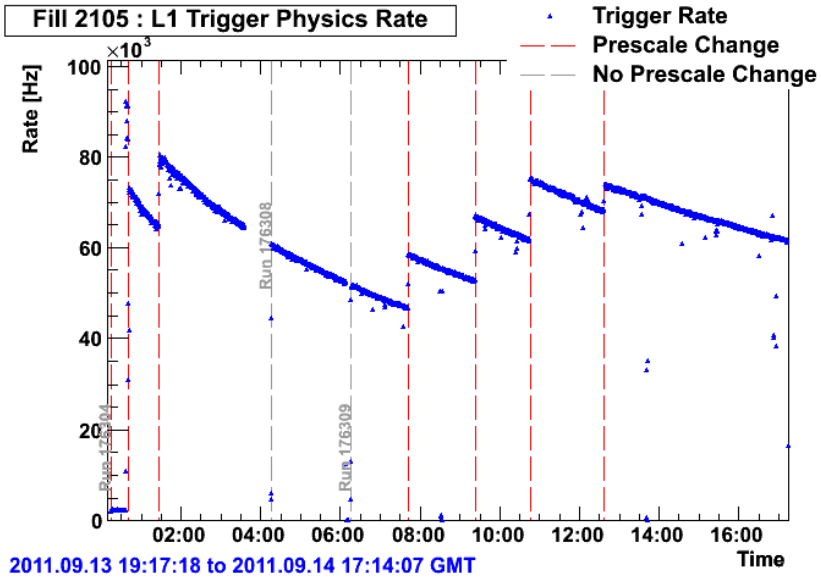
Red = β* of 1.0 m

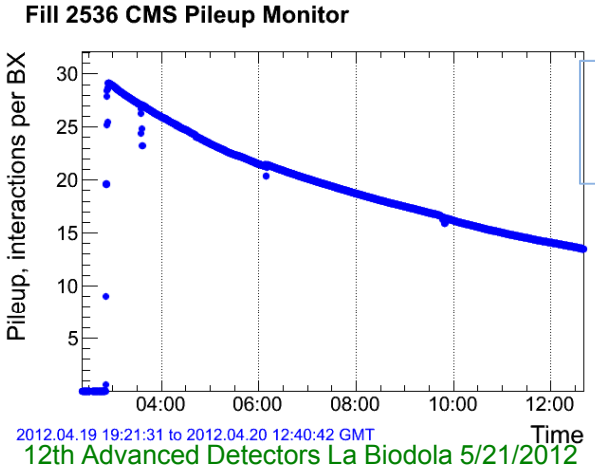




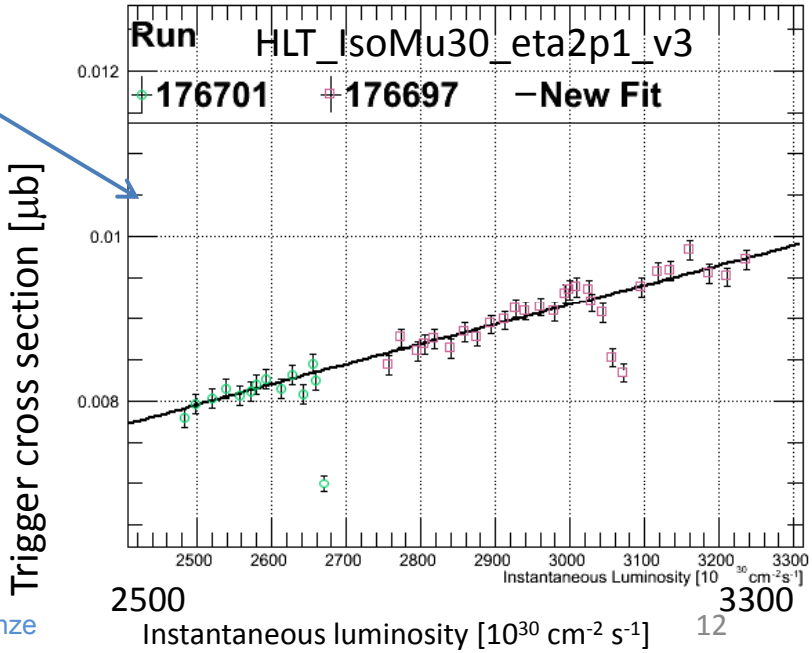
Trigger at high PU

- 2011 Level 1 trigger running at ~80 kHz
  - Total deadtime <3%
- High level trigger output rate 300-400 Hz
  - Challenge is to keep thresholds low as PU increases
    - Work ongoing on integrating offline advances (e.g. particle flow, noise rejection) into HLT→ almost done
  - Some PU dependence
    - This slope is ~typical (some are better, some are worse)
- Menu for Lumi 5e33 deployed Oct 2011
- Menu for Lumi 7e33 deployed mid-May



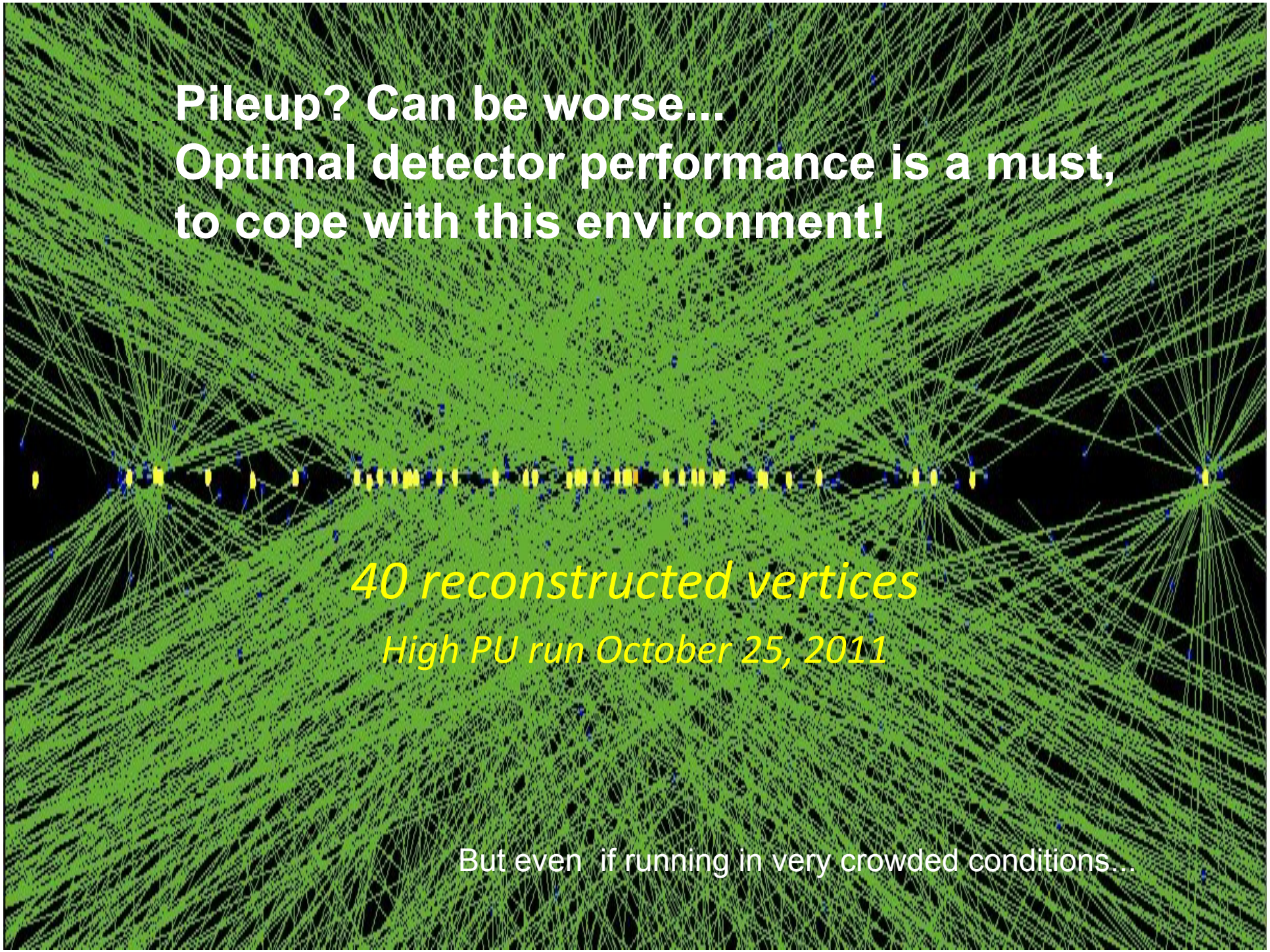


Pileup Monitor in 2012 for Fill 2536



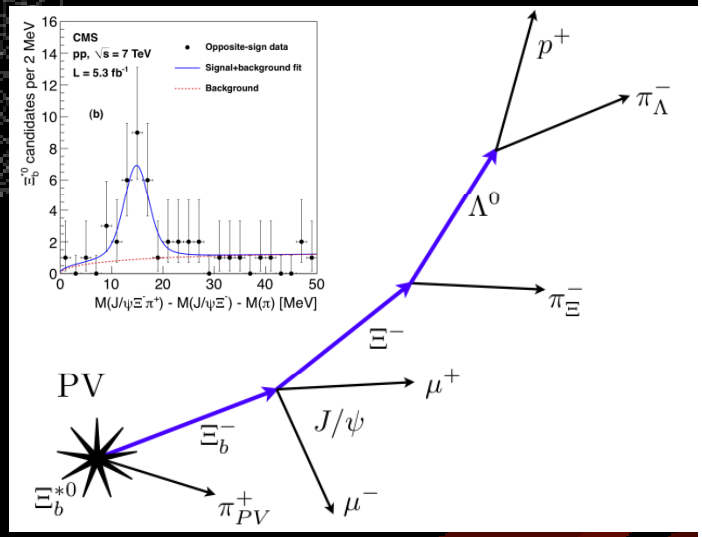
Adapted from J. Thompson

M. Meschini INFN Firenze


Pileup? Can be worse...
Optimal detector performance is a must,
to cope with this environment!
40 reconstructed vertices
High PU run October 25, 2011
But even if running in very crowded conditions...

CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 05:38:12 2011 CEST
Run/Event: 178421 / 533709680

CMS 1st New Particle Discovery



π from PV

proton

Λ^0

π from Λ^0

π from Ξ^-

muons

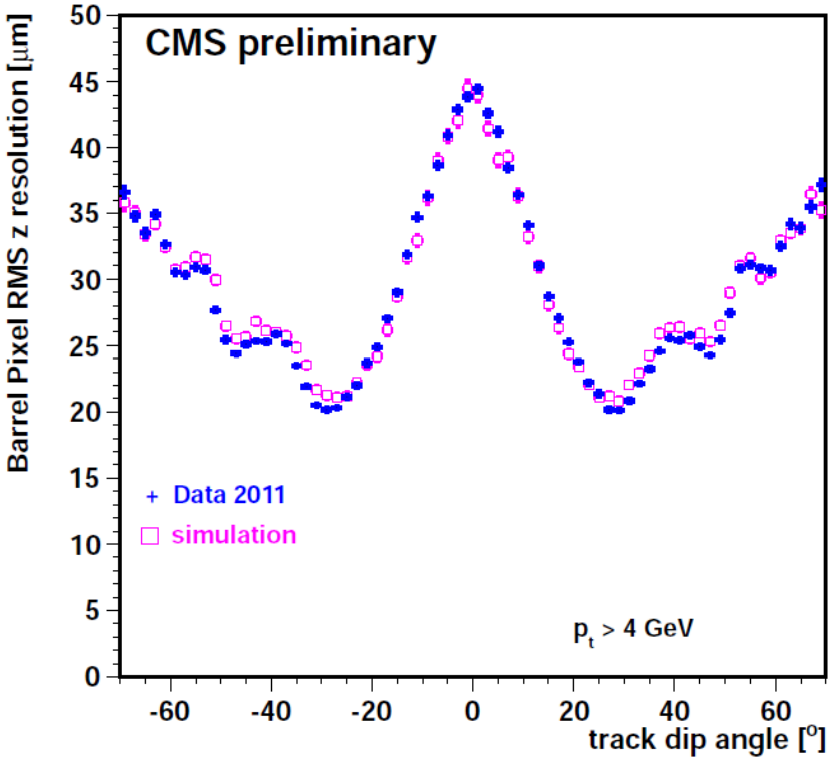
$$M(p^+\pi^-) = 1116.7\ MeV$$
$$M(\Lambda^0\pi^-) = 1315.5\ MeV$$
$$M(\mu^+\mu^-) = 3117.1\ MeV$$
$$M(J/\psi\Xi^-) = 5787.8\ MeV$$
$$Q(J/\psi\Xi^-\pi^+) = 15.7\ MeV$$

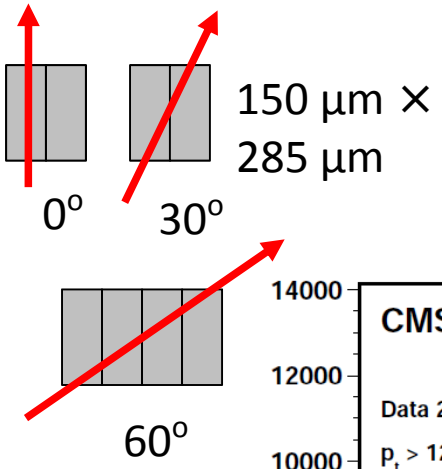
$$\Xi_b^{*0} \to \Xi_b^- \pi^+ \to \Xi^- J/\psi \pi^+ \to \Lambda\pi^-\mu^+\mu^-\pi^+ \to p^+\pi^-\pi^-\mu^+\mu^-\pi^+$$

5945.0 ± 2.8 MeV

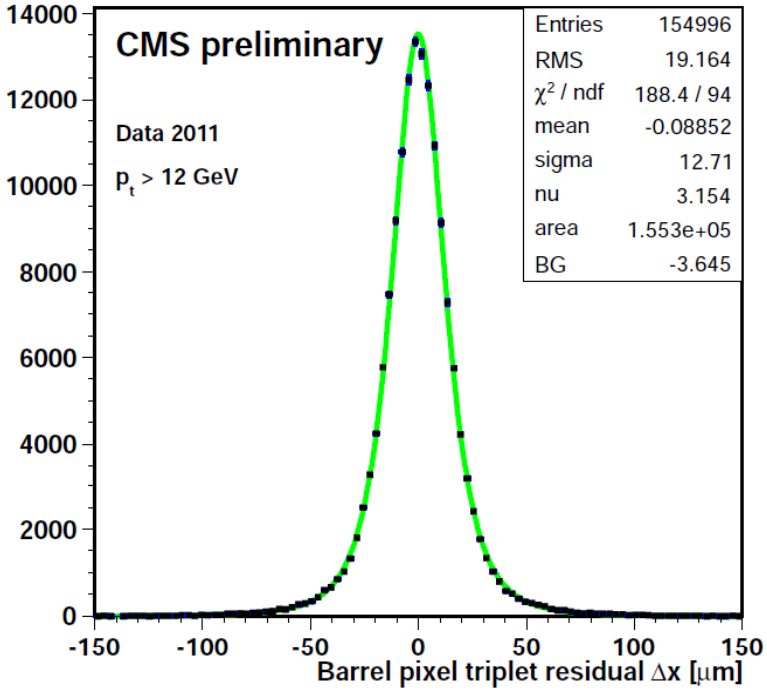
Pixel Detector resolution

Dip angle dependence of *z* resolution





- dip angle:
  - λ = π/2 – θ.
- optimal resolution at λ = ±30°:
  - sharing between neighboring pixels



Barrel pixel triplet rϕ residuals at high p_t

Pixels are a fundamental building block for CMS. Heavily used also by HLT: seeding, vertex reconstruction, b_tag, high pile up combinatorial reduction

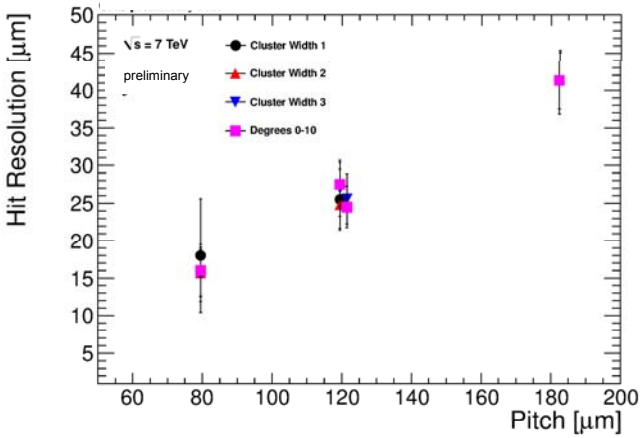
Tracker Status

More than 97% Good Channels

- Offline SiStrip Bad Component calibration runs automatically, about 0.1% channels are masked
- Offline Analysis performed for every run

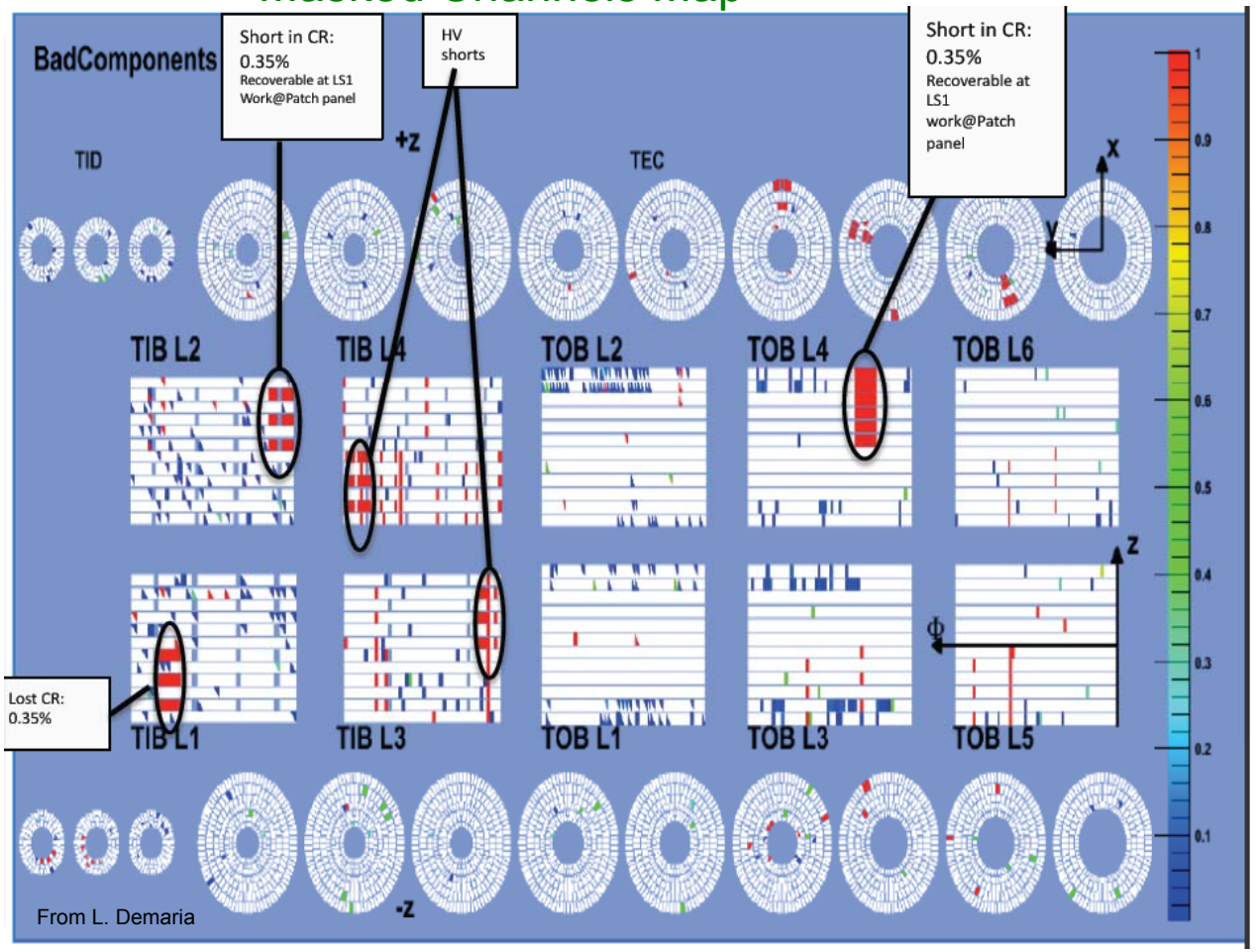
- 3 CRs not working, 1% loss
- HV problems, 0.8% loss
-CCU/Fibres/other 0.4% loss
(CR Ctrl Ring
CCU Communication Ctrl Unit)

Silicon Strip Resolution



Hit resolution vs Strip Pitch

Masked Channels Map 2011 Run, preliminary



120s to configure the TK in DAQ (was 160s in 2010)
437 Front End Drivers (70% CMS)

Some Control Rings can be recovered in LS1, up to 1% channels possible

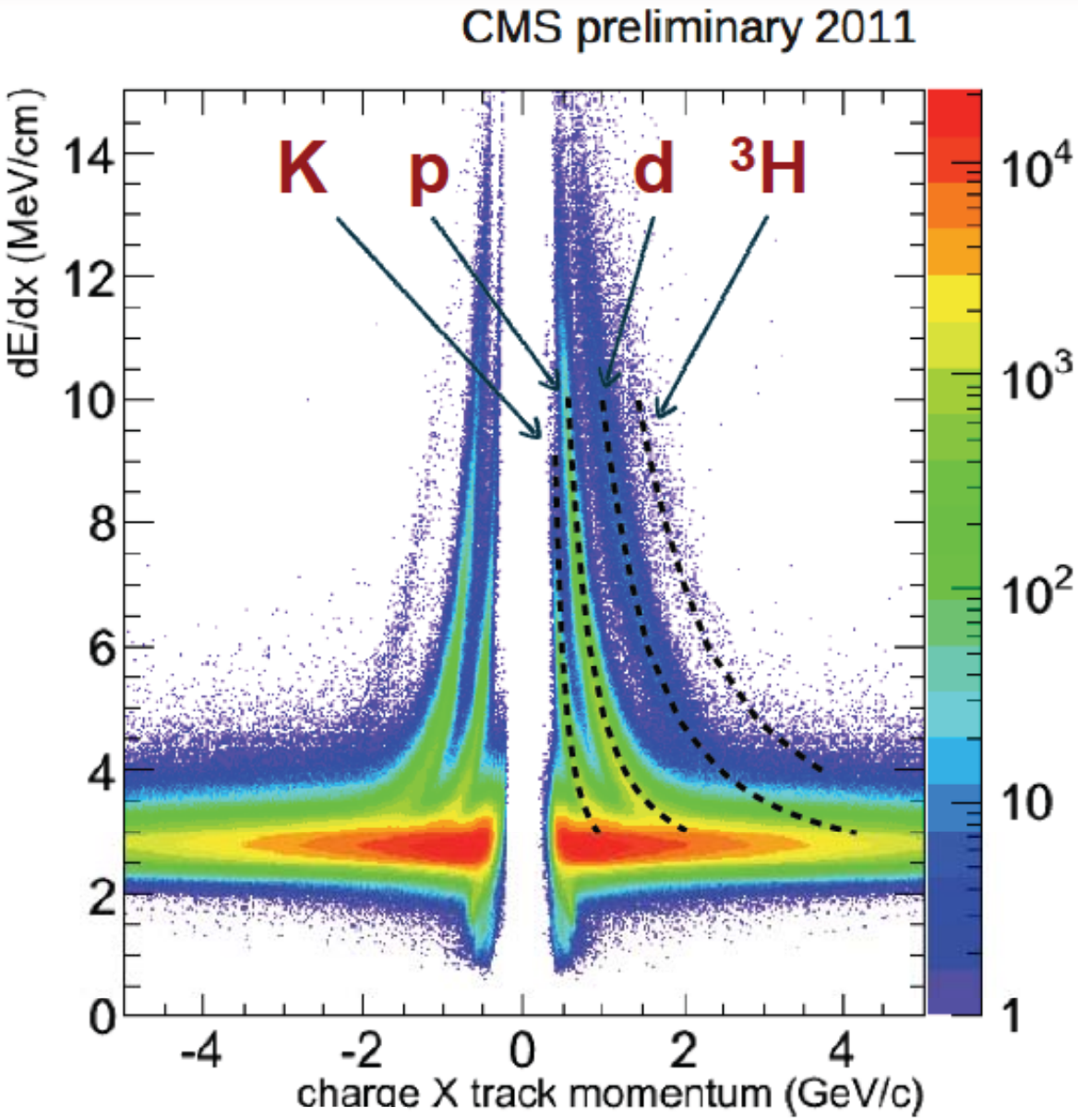
dE/dx

Analog readout; many independent measurements (in total more than $1/2$cm of silicon)

Charge asymmetry is appreciable when plotting dE/dx vs. q×p.

$$\frac{dE}{dx} = K\frac{m^2}{p^2} + C$$

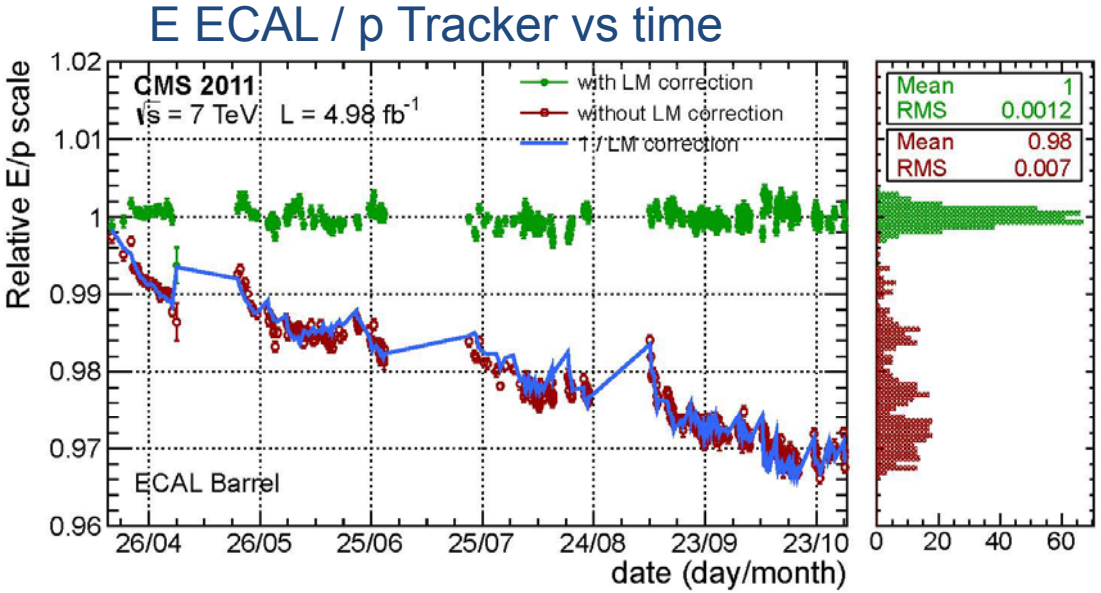
(Lines drawn by hand to guide the eye!)



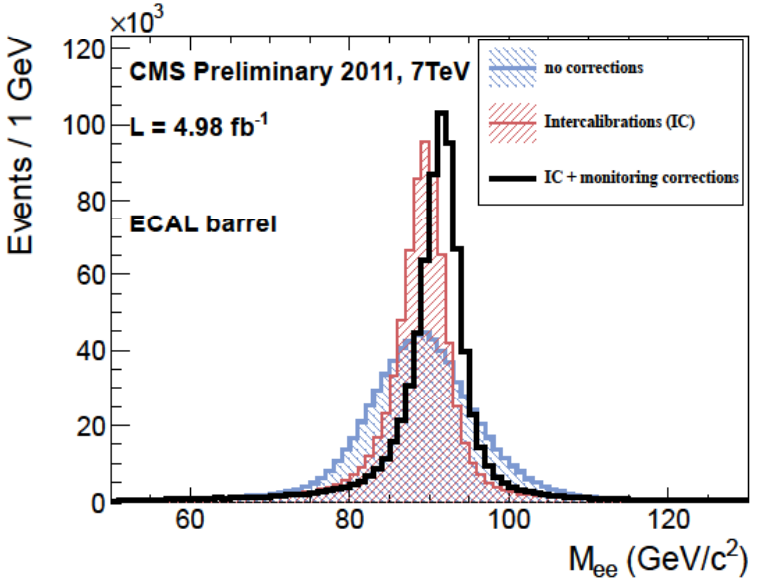
Courtesy G. Sguazzoni

Very Latest Results on ECAL Calibration

Single electron energy scale (E/p) stability in the ECAL barrel measured using W →ev events



Overall effect of single channel inter-calibration and transparency corrections on the Z→ee invariant mass in the ECAL barrel (*)



Stable energy scale throughout 2011 run after applying laser corrections:

- Barrel: average signal loss ~ 2.5%, RMS stability after corrections 0.13%
- Endcap: average signal loss ~ 10%, RMS stability after corrections 0.45% (not shown)

Good energy resolution with preliminary energy calibration for 2011:

- Instrumental resolution (obtained from Z → e+e- invariant mass with ECAL energies and electron track directions): **1.0 GeV in ECAL Barrel** (**)

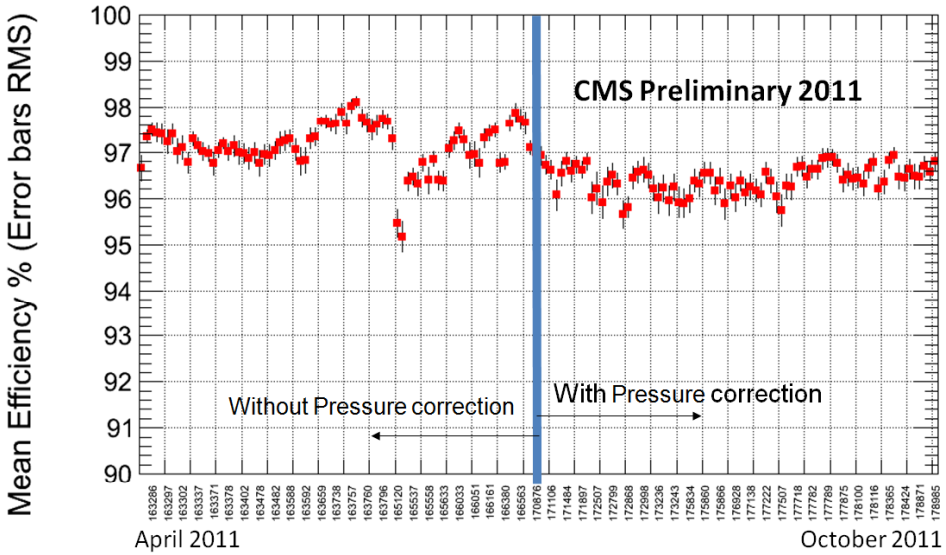
(*) The plot includes only electrons with low energy loss through bremsstrahlung in the CMS tracker

(**) Width of Crystal Ball function convoluted to the Z→ee Breit-Wigner shape

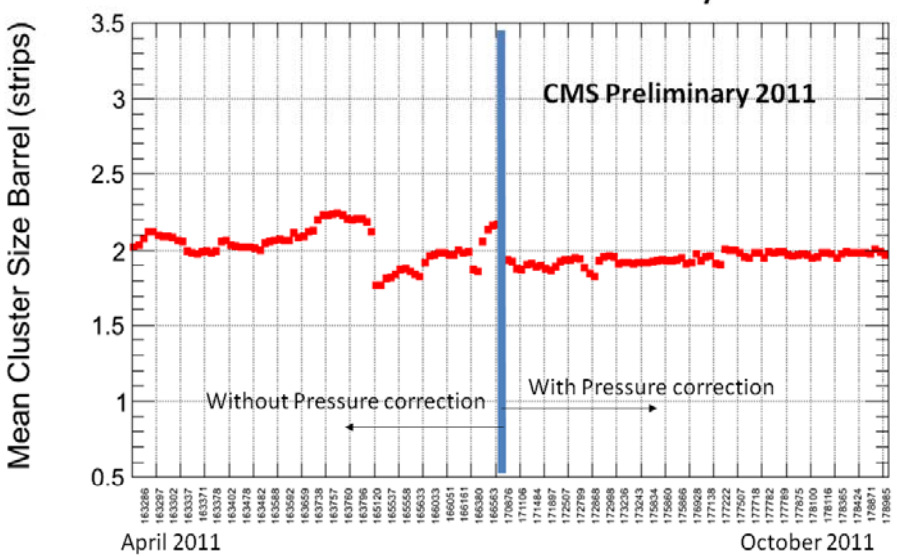
RPC Status

HV working point corrected for atmospheric pressure

RPC Barrel Efficiency History Plot



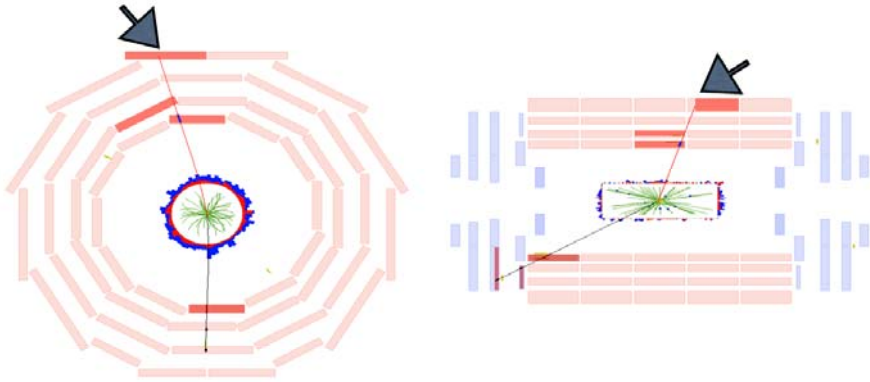
RPC Barrel Cluster Size History Plot



- Data Loss for RPC — 19 pb^{-1} – 0.37%
- Overall Operating Channels — 98.4%
- Average Efficiency — 95%
- Average Cluster Size — < 2
- Average Noise rate (3 ·10^{33} cm^{-2} s^{-1}) — 1.3 Hz/cm^2
- Max Noise rate (3 ·10^{33} cm^{-2} s^{-1}) RE-2/2/C — < 7 Hz/cm^2
- Average intrinsic noise (no-beam) — ~ 0.1 Hz/cm^2
- Average current (no-beam) — ~ 1 μA
- Average current (with beam) — ~ 1.5 μA
- Temperature — < 21.5 °C

Example of muon recovered by RPCs

Run 173406, Event 57918504, m = 90.900GeV

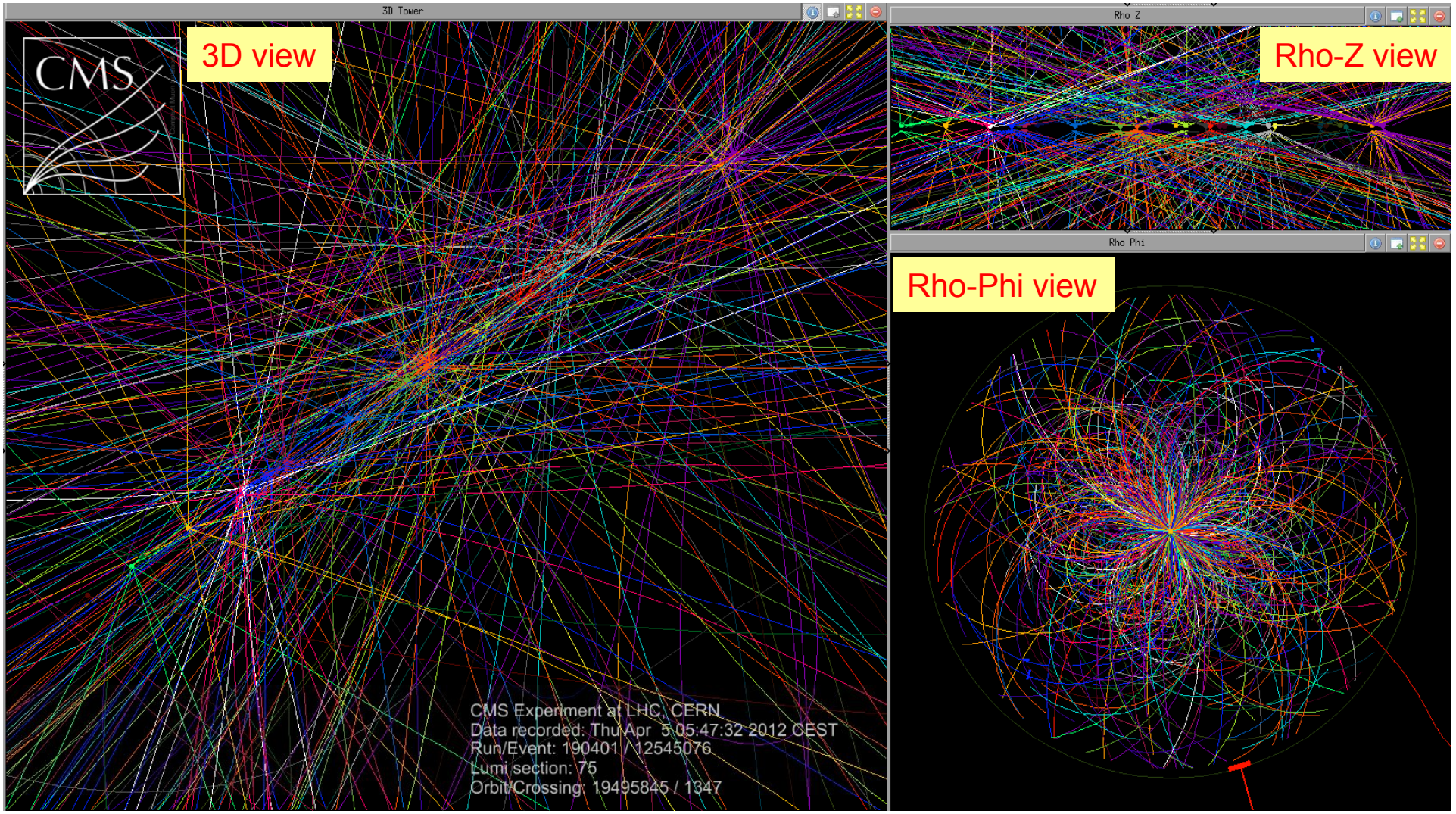


The red track will fail in reconstruction when the RPC hits are removed in the track fitting

1 DT segment + 2 RPC hits

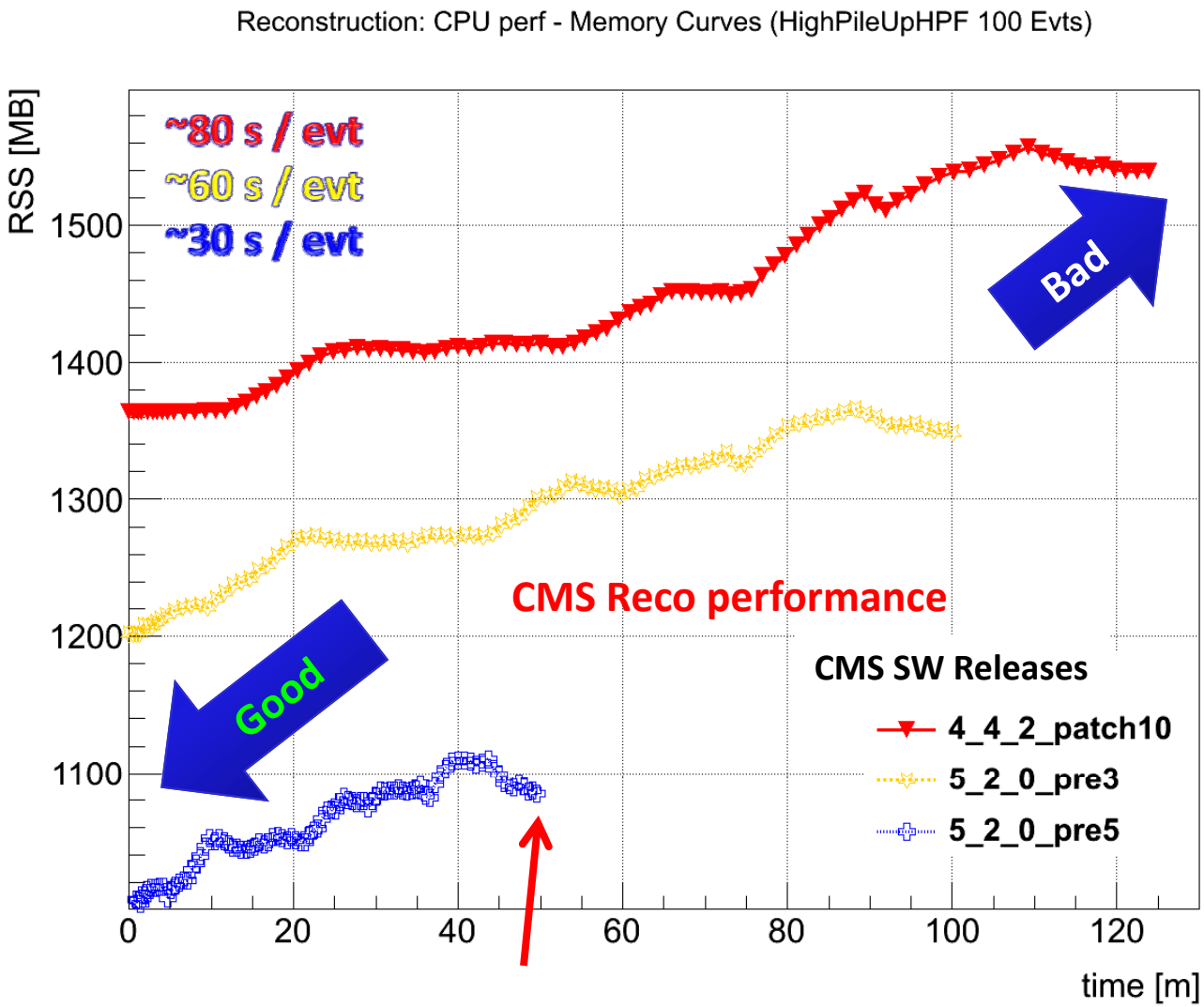
This is not a Simulation

Just to give you the feeling, this is a real 2012 event (and not the highest lumi): heavy CPU load
We need to do something now to continue to reconstruct “dense” events with increasing pileup



High Pileup Mitigation Working Group

Reconstruction Performance Evolution



- 50 % reduction in memory footprint
- A factor 2.5 gained in reconstruction time
- Physics performance unchanged

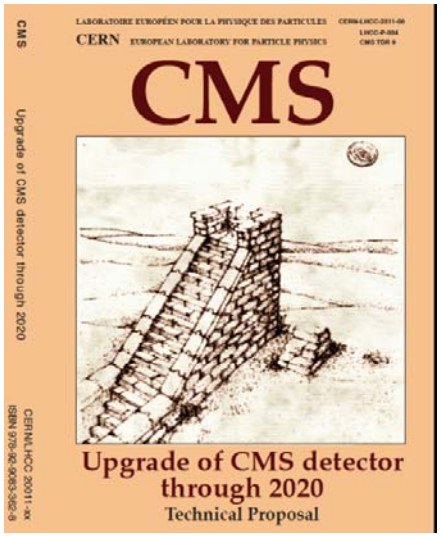
Technical Improvements

Compiler, ROOT, JEMalloc
Vectorization, Devirtualization

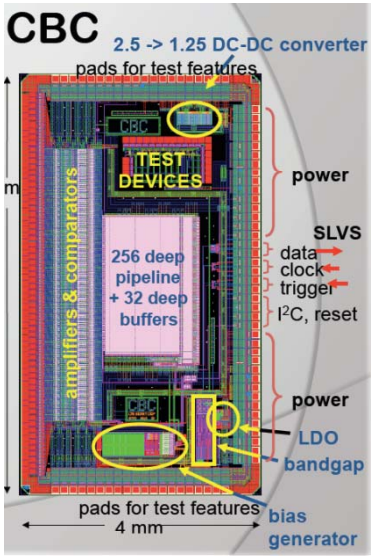
Algorithmic (mainly tracking)

Seed filtering (extended to pairs) and seed combinations, Merging strategies, Loopers identification, Strip Template & cluster splitting, K2Tree template class

CMS Upgrades



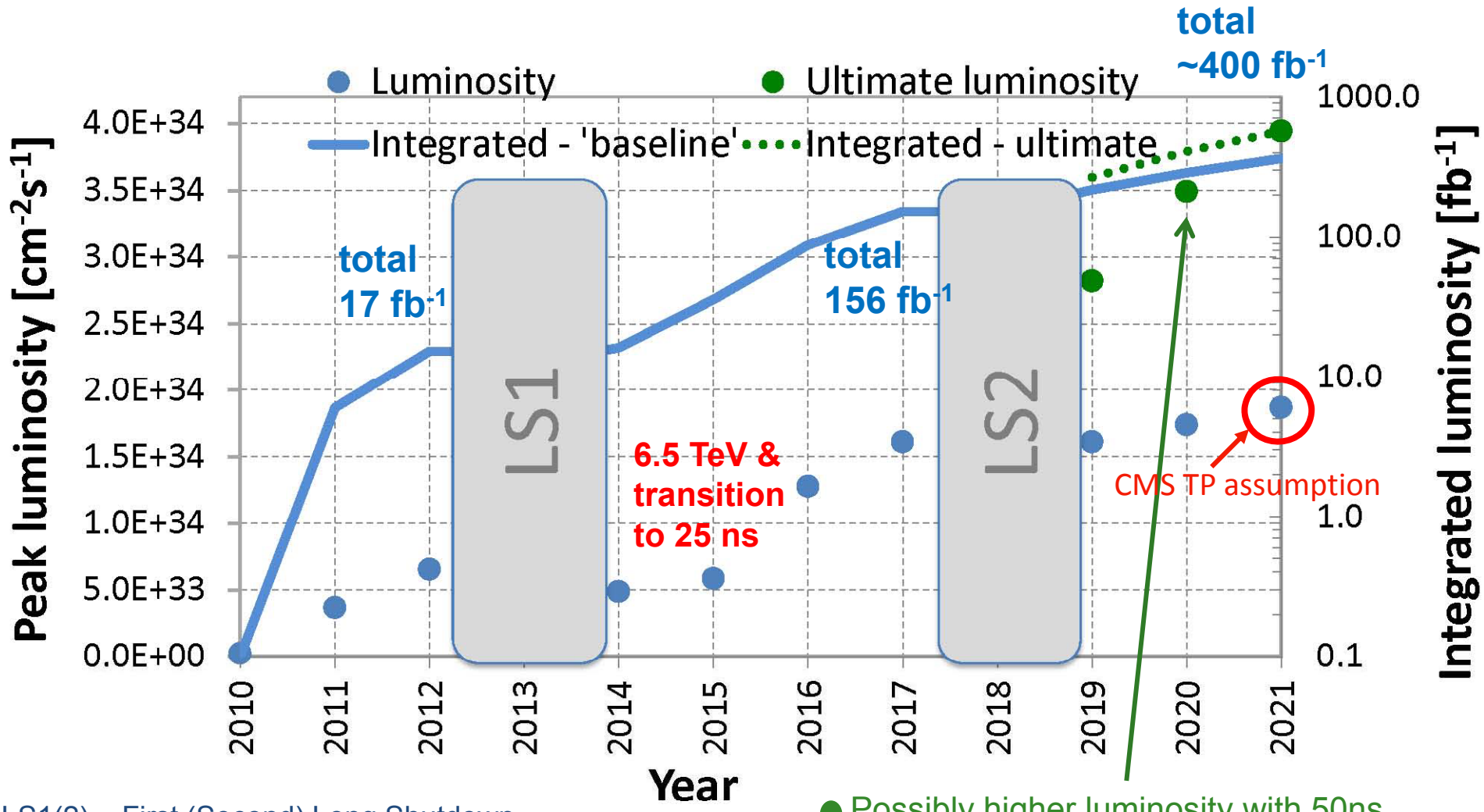
- Phase 1 Upgrade Technical proposal through 2020: published June 2011, LHCC-P-004
- TDR (Technical Design Report) for Pixel, HCAL, will come by end summer 2012, Trigger 6 months later
- Upgrades goals: cope with lumi increase, solve issues spotted during operation, maximize efficiency, Physics output and discovery potential
- Phase 2 Technical proposal foreseen in 2014: detector design depends (also) on physics results
  - Simulation and R&D in many areas already ongoing since years
- Make best use of 2011-12 physics results and LS1 experience to define new detectors for Phase 2



CSC winding

PLEASE NOTE: more specialistic and detailed presentations on CMS Upgrades at this conference:
-M. Jeitler Upgrade of the CMS Level-1 Trigger
-A. Sharma Upgrade plans for CMS Calorimeters and Muon system
-G. Bolla The upgrades of the CMS tracker: status and plans

A 10-Year Luminosity Scenario



LS1(2) = First (Second) Long Shutdown

Possibly higher luminosity with 50ns bunch spacing after injection upgrade, but then pileup up to 200!

Modified from D. Contardo, F. Zimmerman, O. Brüning, M. Lamont, L. Rossi

CMS Upgrade Plan in a Nutshell

Shutdown	System/Det	Action	Result	Physics
LS1 2013-2014	Muon (ME42,ME11)	RPC and CSC (Complex YB4 installation) New electronics	Improved μ trigger and reconstruction ($1.1<\|\eta\|<1.8$, $2.1<\|\eta\|<2.4$)	W acceptance WH, $H^{\pm} \rightarrow \tau\nu$
LS1 2013-2014	Hadron Outer	Replace HPDs with SiPMs to reduce noise	Single μ trigger Tails of very high p_T jets	Muons from τ $Z/H \rightarrow \tau\tau \rightarrow \mu X$
LS1 2013-2014	Hadron Forward	Install new PMT to reduce window hits	Forward jet tagging Improved MET	Vector-boson fusion H
LS1 2013-2014	Beam Pipe	Install new beam pipe 45mm outer diameter	Easier pixel detector installation	b-tagging
LS2 2018	New Pixel system (LS 1.5?)	Low mass, 4 Layers, 3 Disks with new ROC	Reduced dead time Improved b-tag.	$H \rightarrow bb$, SUSY decay chains
LS2 2018	HCAL Barrel and Endcap μTCA trigger	Replace HPDs with SiPMs for longitudinal segmentation New electronics	Reduced pileup effects Improved MET Improved τ, e, γ clustering and isolation	SUSY $H \rightarrow \tau\tau$ $H \rightarrow ZZ \rightarrow ll\tau\tau$
LS3 2022 onwards	TRACKER Trigger Endcap Calorim.	Replace tracker Replace trigger Upgr. EC Calorimetry	Maintain performance at HL-LHC Luminosity L1 Tracking trigger	Uncharted waters? Ph. 1 discoveries?

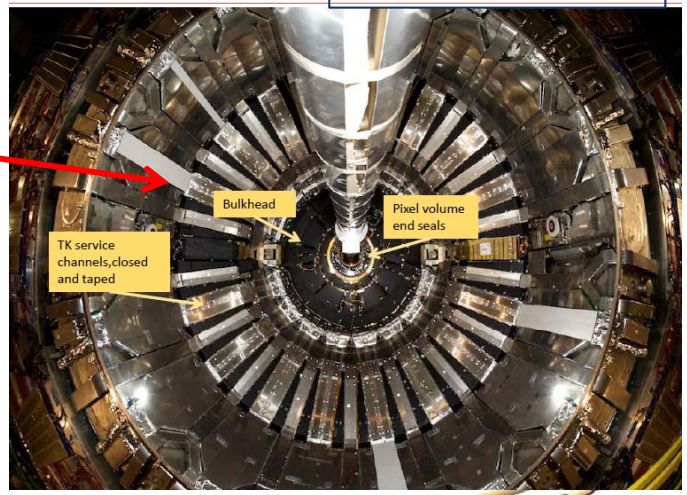
Adapted from G. Tonelli

* LS1 →CMS ready for beam on Sep 1st 2014

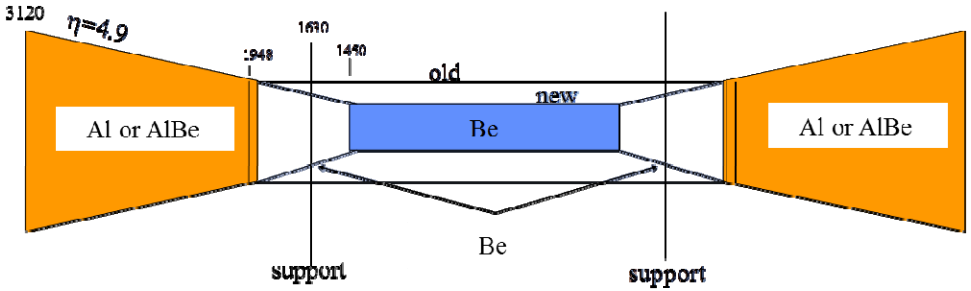
LS1: Maintenance and New Goals

- LS1 (presently foreseen date Nov 2012-Sept 2014) is approaching fast!
- Beyond standard maintenance tasks, by the end of LS1, CMS should have reached the following objectives:
  - Complete muon upgrade tasks requiring shutdown (Endcap disk 4 construction, 4th muon endcap stations CSC and RPC, barrel electronics consolidation
  - Complete 1st stage of HCAL photo-transducers consolidation
  - Install 45mm outer diameter beampipe
  - Piping and demonstrators for 4-layer pixel cooling
  - Barrel-endcap seal revision for colder Tracker operation
  - Tracker cooling fluid capable to run at –25°C
  - N2/dry-air system upgrade for colder Tracker operation

Present Humidity Barriers outside TK

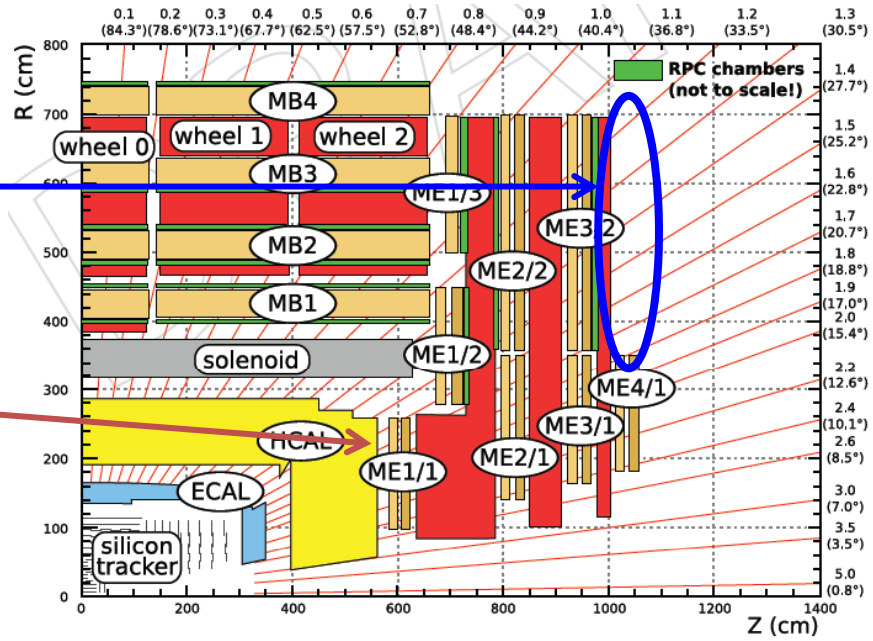


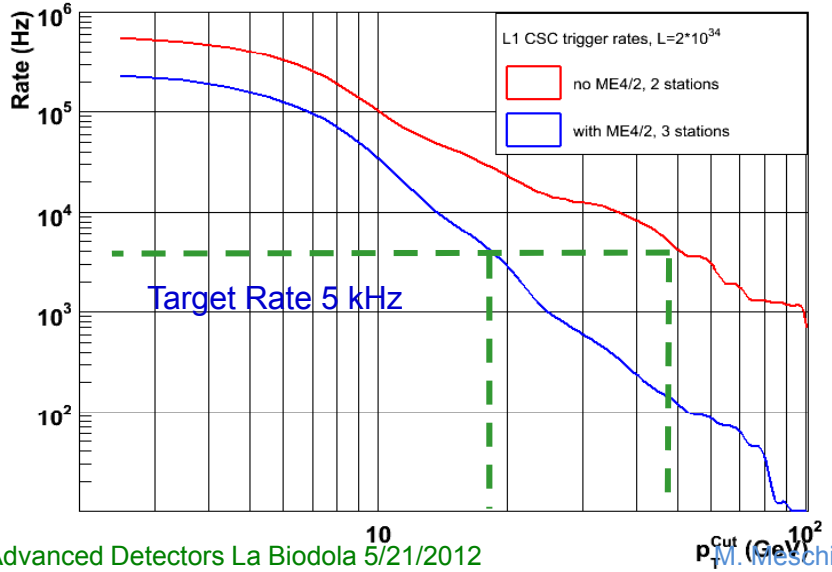
New CMS beampipe

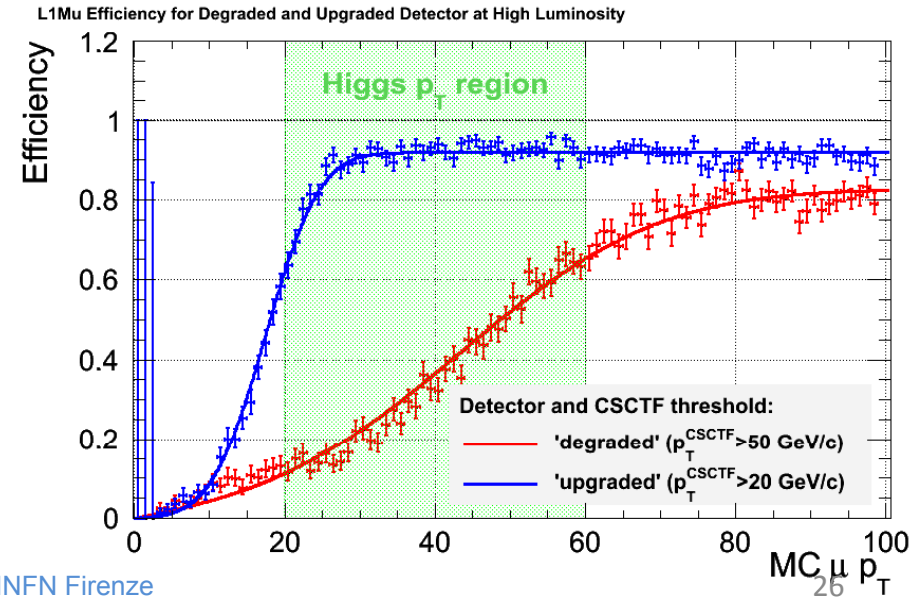


Muon Upgrade Plan

LS1 : Trigger performance, install more robust electronics
CSC end RPC ME4/2 (1.25< |η| <1.8)
More hits : better Pt resolution, better efficiency, lower rates
CSC M1/1 (2.1< |η| <2.4) new digital boards and trigger cards : higher strip granularity
More track segments, improved Pt assignment, new algorithms







HCAL Upgrade LS1 and Phase 1 Plans

Replace HPDs with SiPMs in HO (LS1) then in HE/HB
- Increased granularity : depth segmentation (in HE/HB) (LS2)
- Higher gain (reduced noise effects, pulse shape usage)

Avoid discharges, better isolation and particle ID, improved calibration

New PMT (multi anode) for HF (LS1) 32 already in place

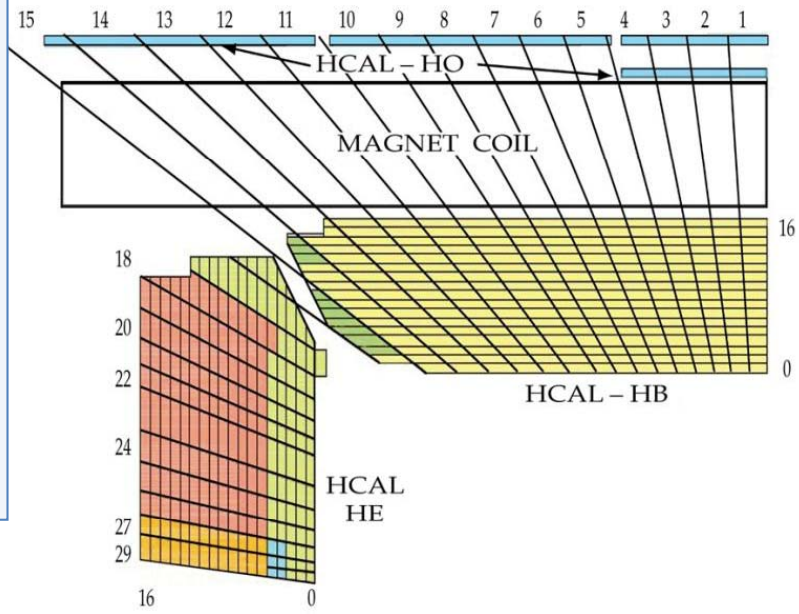
Avoid background from PMT windows

New 8 bit multi-scale ADC and 6 bit rising edge TDC

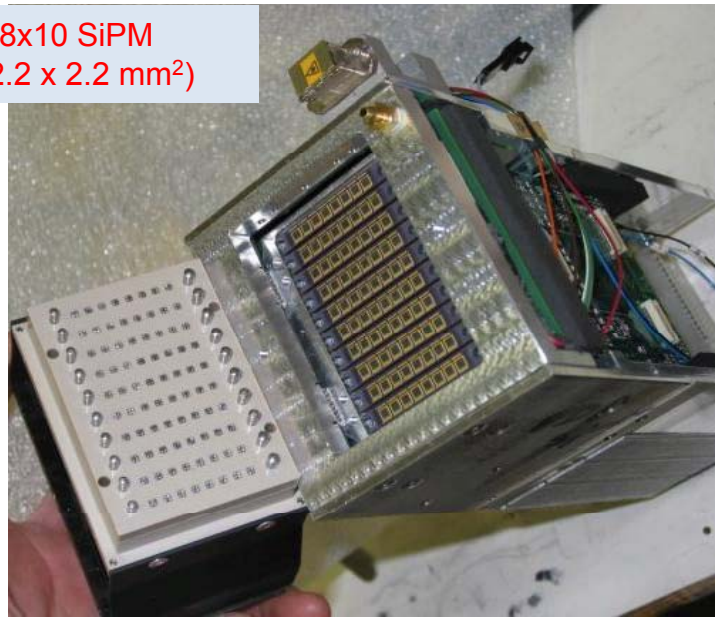
Anomalous signal rejection

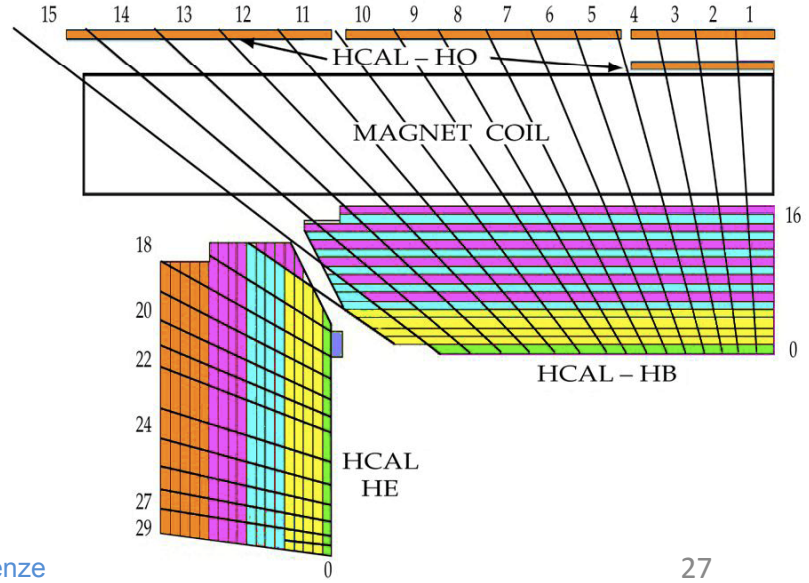
New OL (GBT) and back-end electronics
- Increased bandwidth

Trigger granularity improved



Regular 8x10 SiPM arrays (2.2 x 2.2 mm^2)





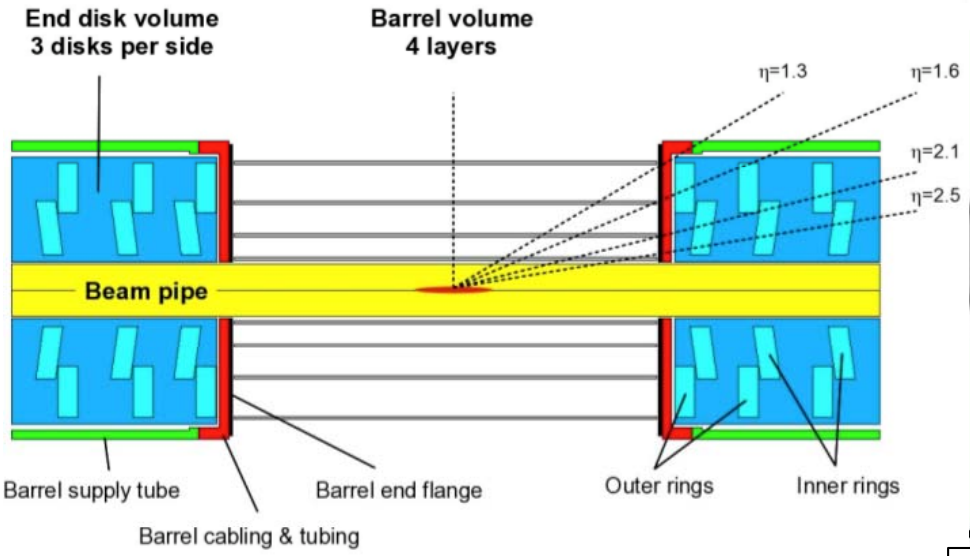
Pixels Phase 1 Upgrade Plan

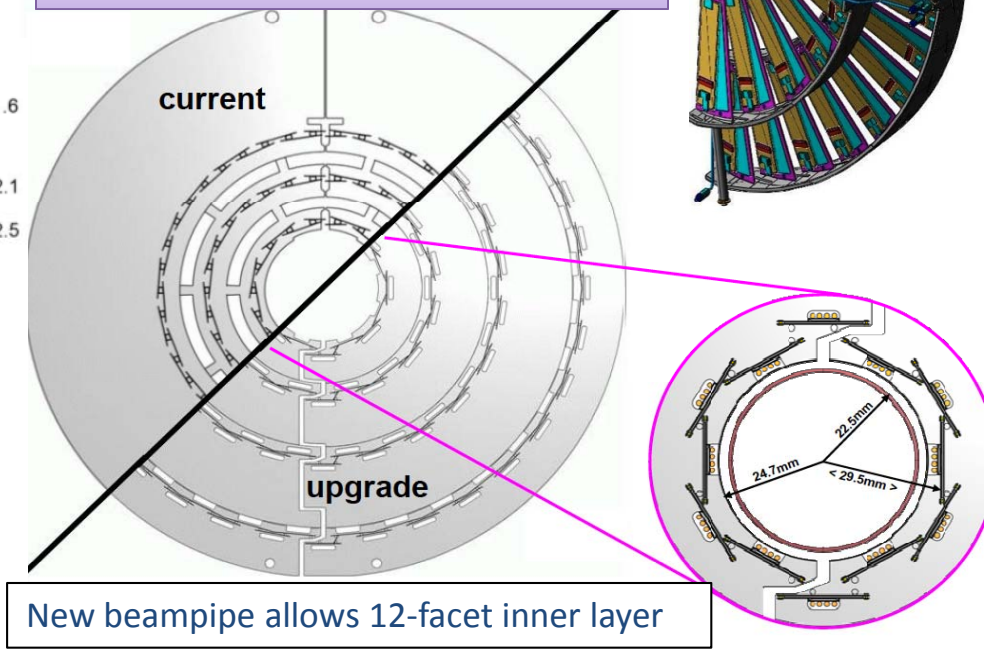
New ROC chip
Avoid 15% data loss in the innermost barrel pixel layer at 2×10^{34} $cm^{-2}s^{-1}$ and 25ns crossings
4 layers (smaller inner radius) in barrel, 3 disks in end caps → 1 layer and 1 disk more than present detector, new cabling, powering and cooling systems, improved material budget and less multiple scattering
Improved tracking efficiency and reduced fake rate at higher pile-up, improved IP and vertex resolutions and b_tagging efficiency

Foreseen to be ready by late 2016, it can be installed in a 5 months stop

FPIX Disk

BPIX Layout



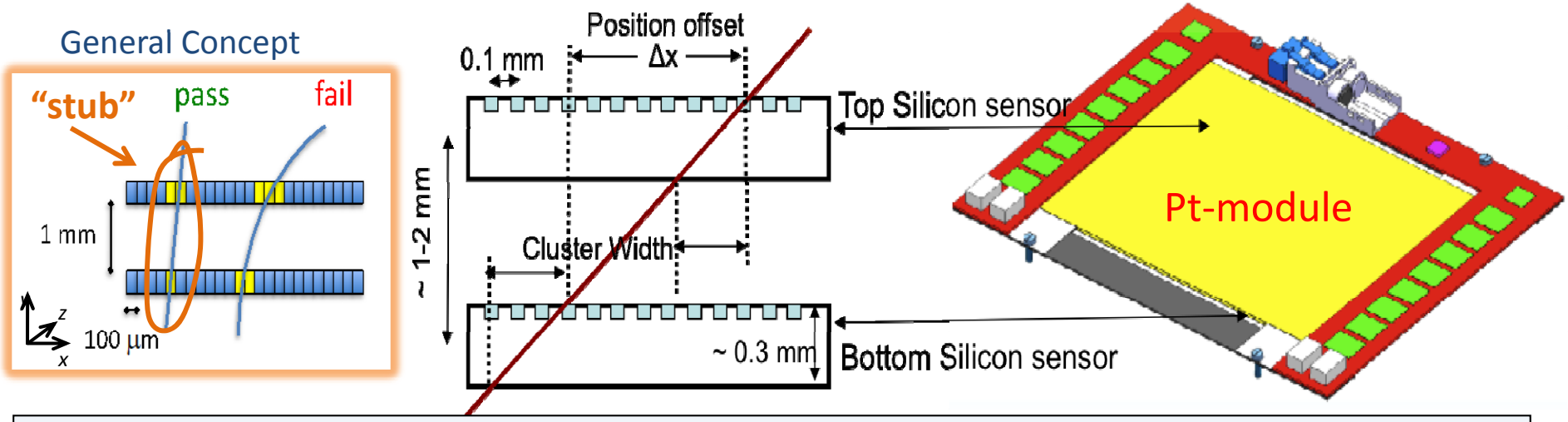


New beampipe allows 12-facet inner layer

Strip Tracker Phase 2 Upgrade Plan

New Tracker with higher granularity and radiation hardness
Maintain tracking performance at higher multiplicity
Trigger capabilities at L1
Maintain trigger performance
- Precise transverse momentum measurement of muons for sharp threshold ~ 10-20 GeV/c
- Matching and isolation for electron and tau identification and veto for photons.
- Association at IP (vertices) to reduce rate of accidentals due to pile-up.

Improved Material Budget
New cooling (bi-phase CO2) and powering (DC/DC) schemes



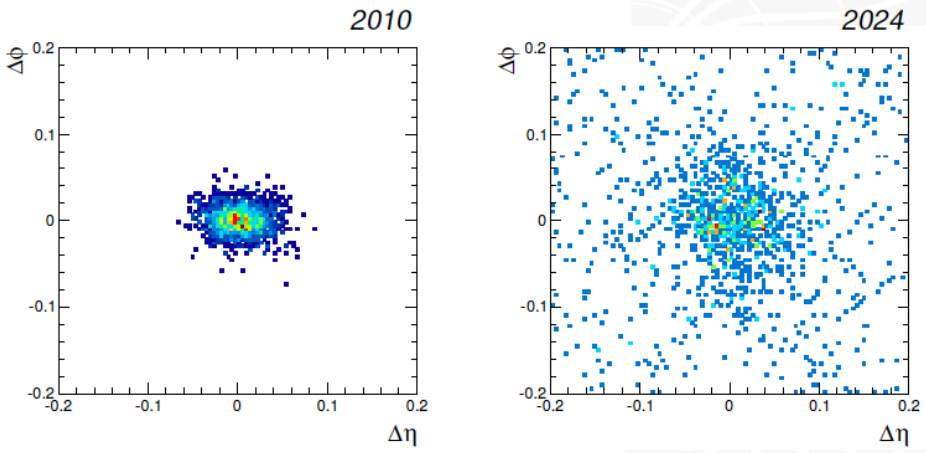
Trigger capability concept based on
-Pt modules, 2 strip sensors or 1 strip and 1 macropixel sensor coupled to same FE chip to reduce data bandwidth
-Hardware track reconstruction at back-end for L1 global trigger (in 6.4 µs)

Forward Calorimetry Phase 2 Upgrade Plan

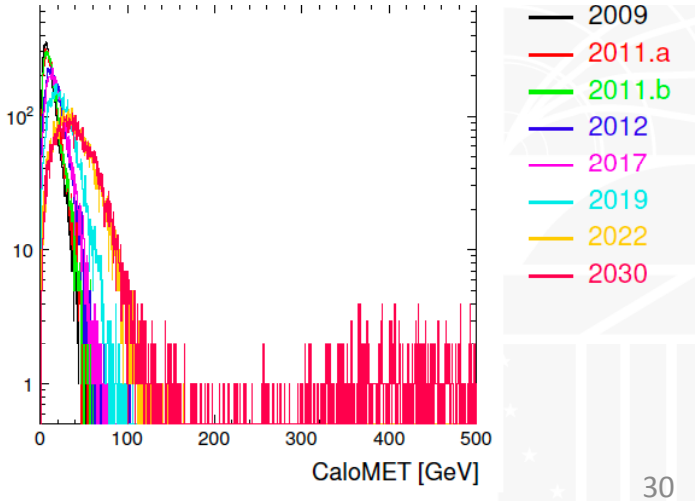
Investigate future calorimetry in the forward region for ECAL and HCAL (~ up to η =5)
Improve performance for VB fusion/scattering, MultiTeV SUSY, heavy Z'
Evaluate long term performance of current detectors (HF, EE, HE)
Find radiation hard technologies for calorimetry materials and photo-detectors up to 3000fb^{-1}
Propose a detector configuration based on performance simulation, optimize longitudinal and transverse segmentation, E/H value

Very preliminary

Position resolution for 80 GeV jets at η = 2.5 Before and after irradiation



Met from Z → ee events



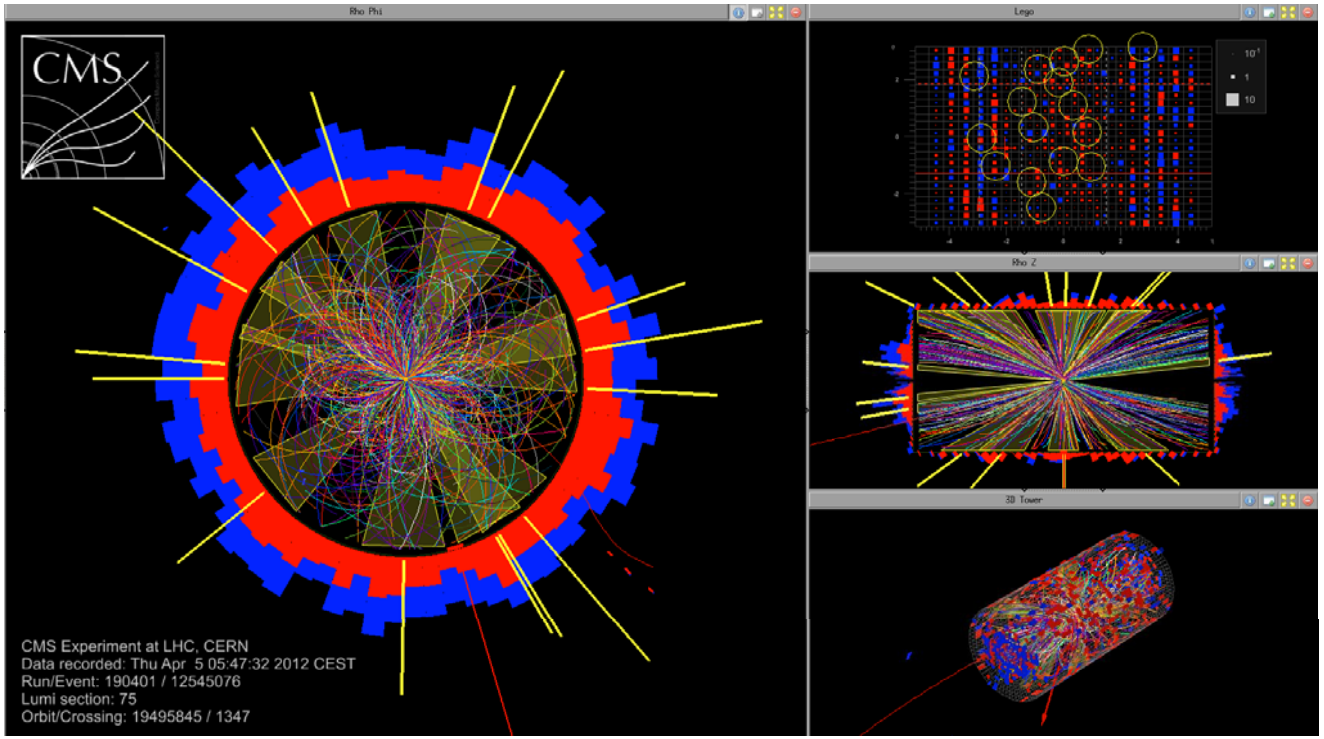
Upgrade Comments

- The CMS upgrades are a multi-year project: they are already ongoing
- LS1 projects are on track, but the LS1 schedule is extremely tight
- Option for an intermediate LS1.5 (~5 months) of interest to both CMS and LHC remains, to be reviewed as circumstances develop
  - LS1.5 new pixel detector installation
  - LS1.5 would allow HCAL endcap photodetectors to be replaced earlier (in parallel with pixel upgrade), barrel PD to LS2 (not compatible with pixel installation)
- CMS is developing a strategy to adapt to possible changes in LHC projections and plans. More news after LS1 startup
- Phase 2 R&D needs continuing support in both manpower and funds to be successful

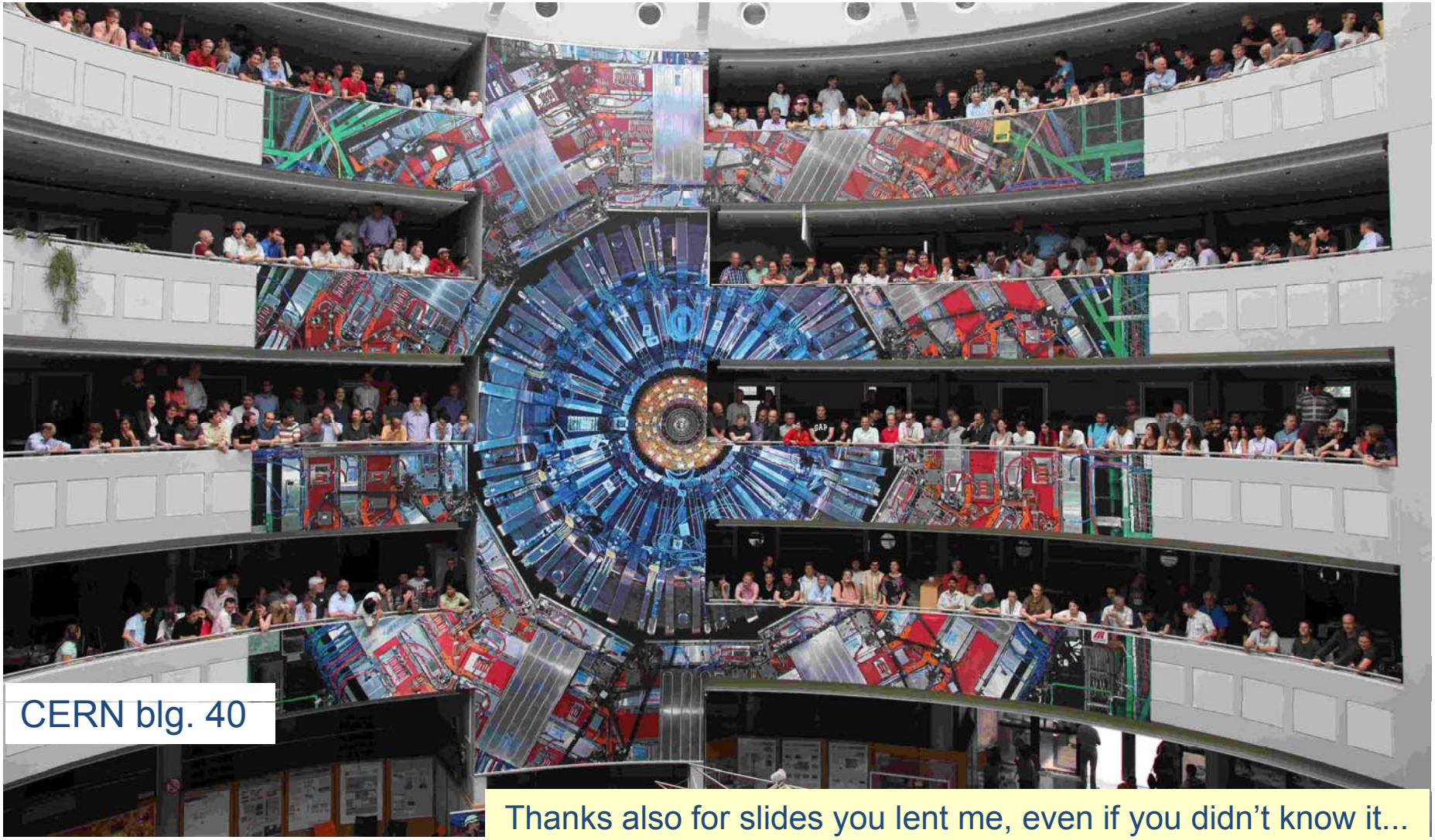
Conclusions

- The 2011 run has been exciting
- The 2012 is promising to be even better
- The Long Shutdown 1 is knocking at the door
- CMS is performing extremely well
- A lot of work to do on all fronts: run, maintenance, upgrade, physics...

No time to rest!



Thanks You All Folks!



Thanks also for slides you lent me, even if you didn't know it...

Many thanks to all La Biodola Meeting Organizers!