Beam Monitoring for Experiments at Particle Accelerators

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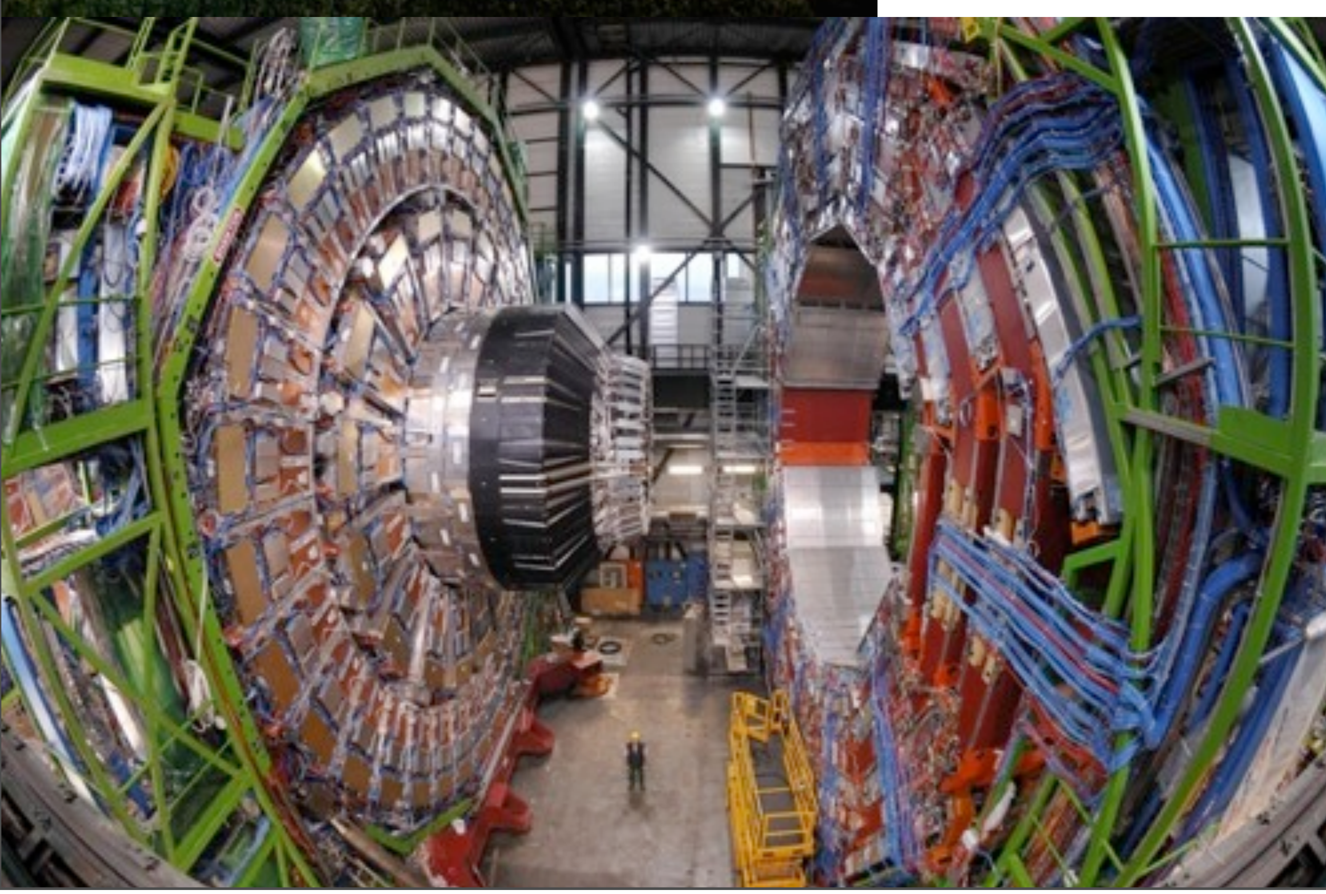
I would like to thank all my former colleagues in the CMS Beam and Radiation Monitoring Group



Beam Monitoring

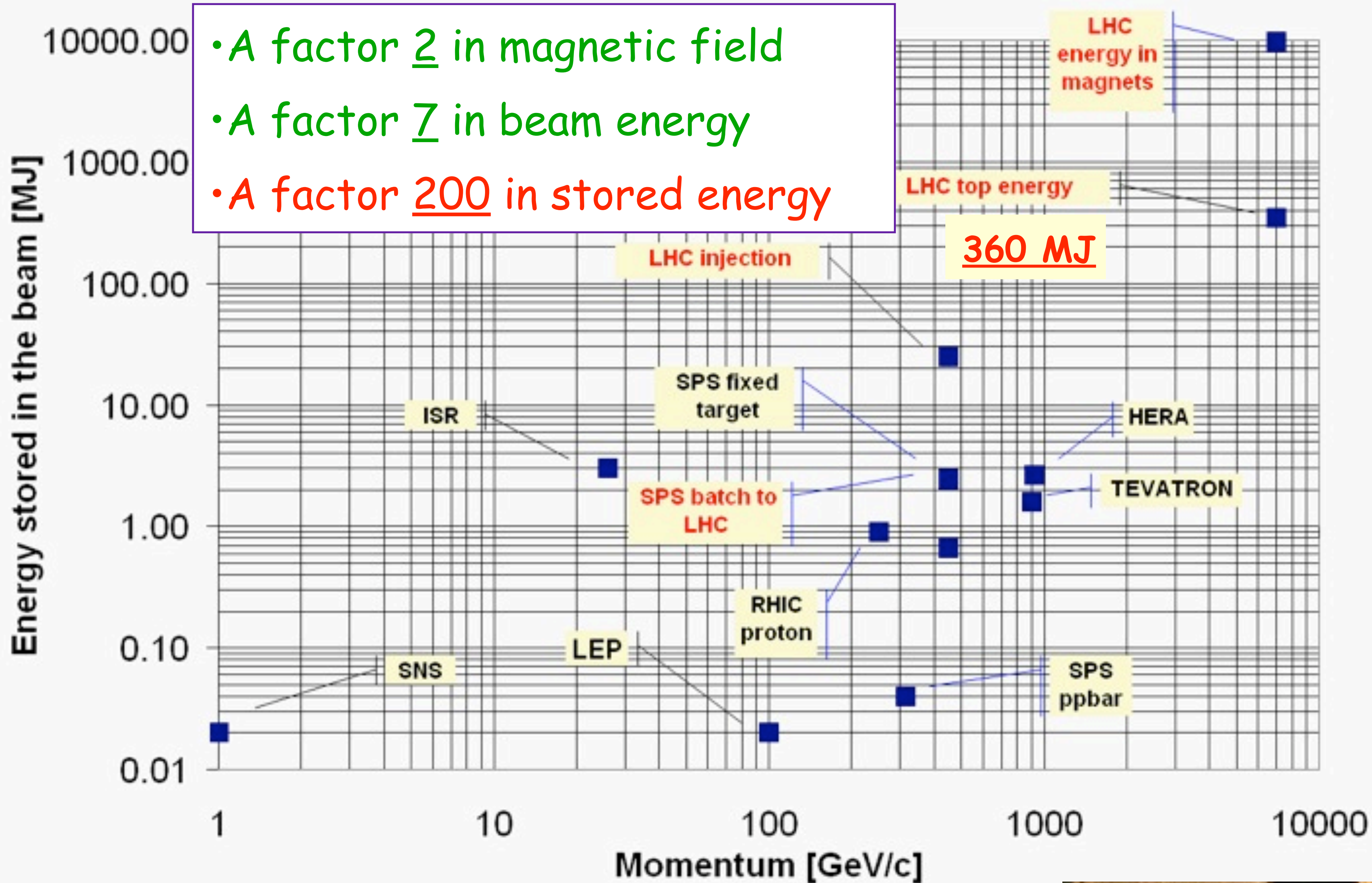
- Beam Monitoring is about understanding:
  - where the beam is,
  - when it is there
  - how much of it is there, and
  - how much of it isn't there (i.e. loss levels in terms of flux and energy, or radiation dose)
- A key aspect of this for high energy hadronic machines is the fact that for losses the flux and energy spectra vary greatly with distance from the beamline

- To emphasise the importance of beam monitoring for safety, see next slide
- In terms of protection, this can be from physical or electronic damage (for experiments), or for example quenching of accelerator superconducting magnets
- However, much of beam monitoring about optimising the beam provision

- I will present beam monitoring from the context of the LHC experiments
- By way of example, I will show implementations and results from the CMS experiment
- Technology-wise for instrumentation: this talk will concentrate on diamond detectors
- Due to time restrictions, I will basically only talk about beam losses

Slide from Jorg Wenninger

Stored Energy



- A factor 2 in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored energy

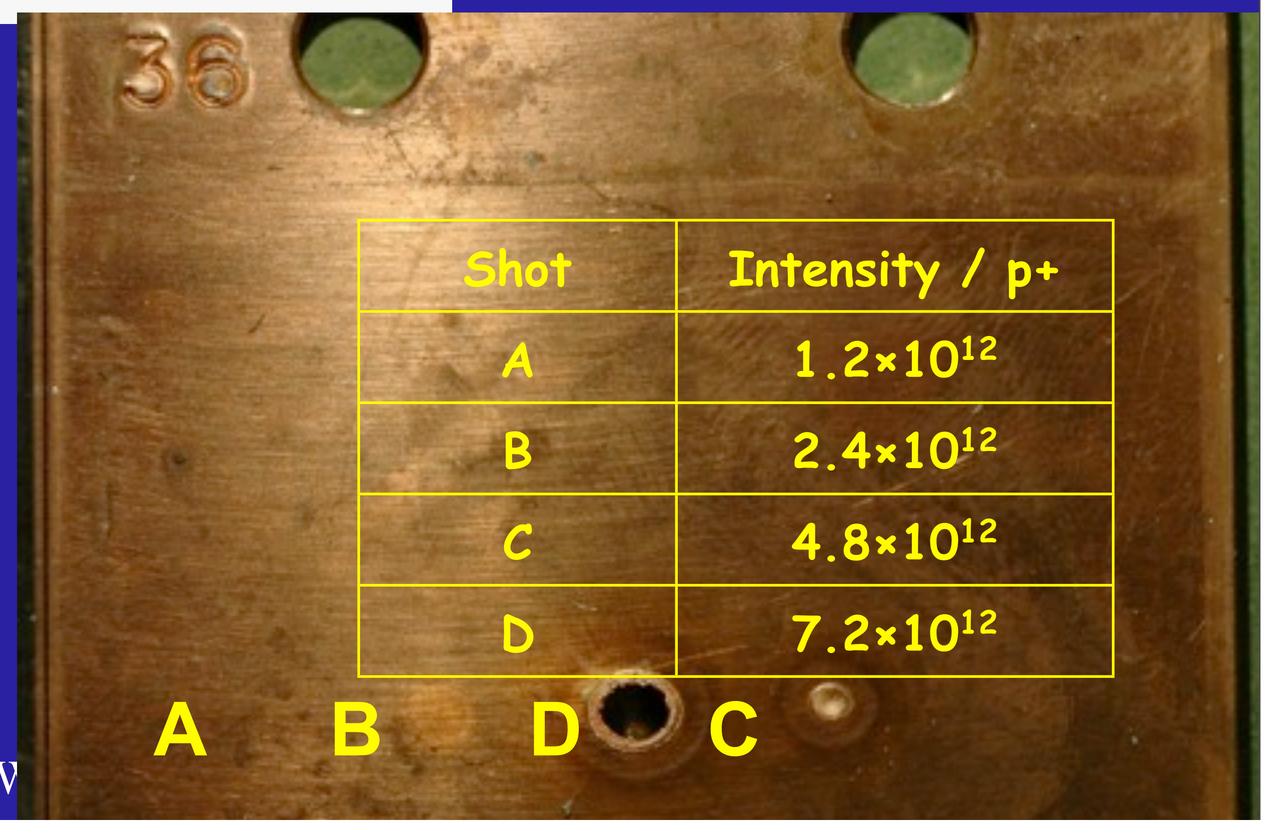
Large damage potential from uncontrolled beams means that comprehensive protection system is needed

BCM Systems perform this role for the experiments

Damage Potential of High Energy Beams

Controlled experiment with 450 GeV beam shot into a target (over 5 μs) to benchmark simulations:

- Melting point of Copper is reached for an impact of ≈ 2.5×10^{12} p, damage at ≈ 5×10^{12} p.



Shot	Intensity / p+
A	1.2×10^{12}
B	2.4×10^{12}
C	4.8×10^{12}
D	7.2×10^{12}

Large Hadron Collider

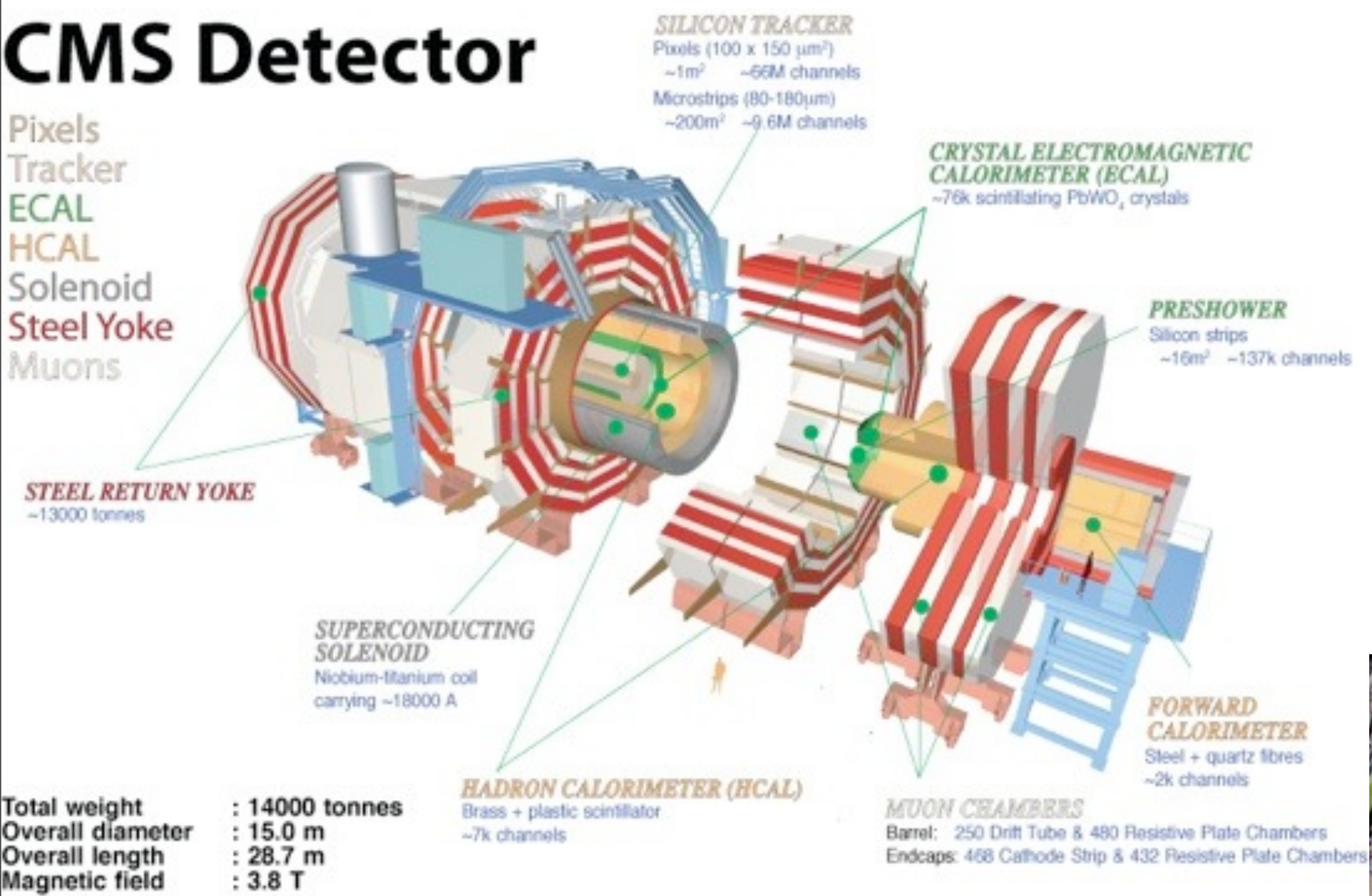
- A discovery machine for new physics

- 7 TeV proton beam collider
- 14 TeV centre of mass energy design

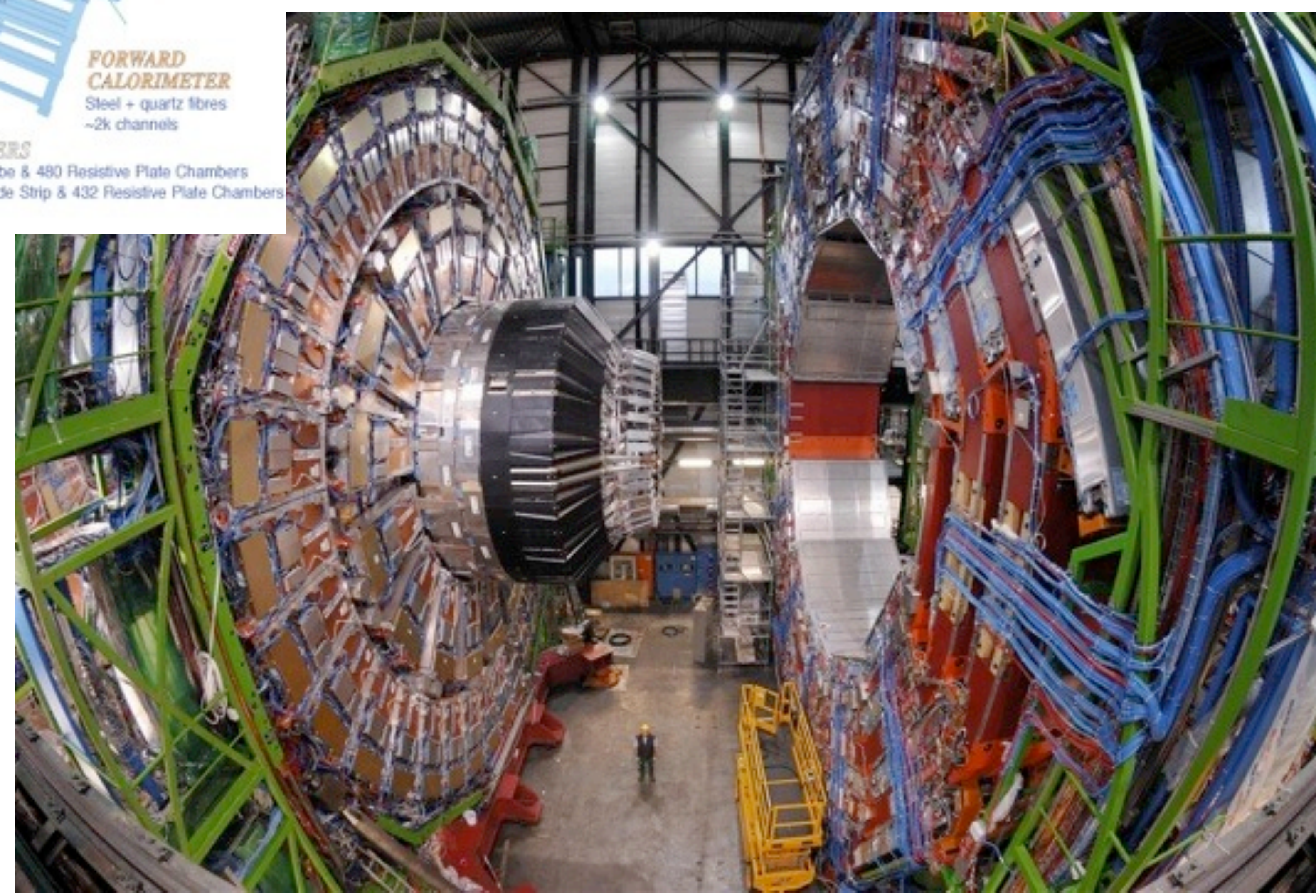
- 27 km long tunnel
- 89 us orbit period
- 25ns between bunches
- ca. 3500 bunches
- Nominal bunch current of 10^11 protons

- Collisions provided for 4 main experiments
- 2 general purpose large experiments

Compact Muon Solinoid (CMS Experiment)



- One of the two large general purpose experiments
- Situated 120m underground, at the foot of the Jura mountains
- 15m diameter, 20 long
- 15 000 tons



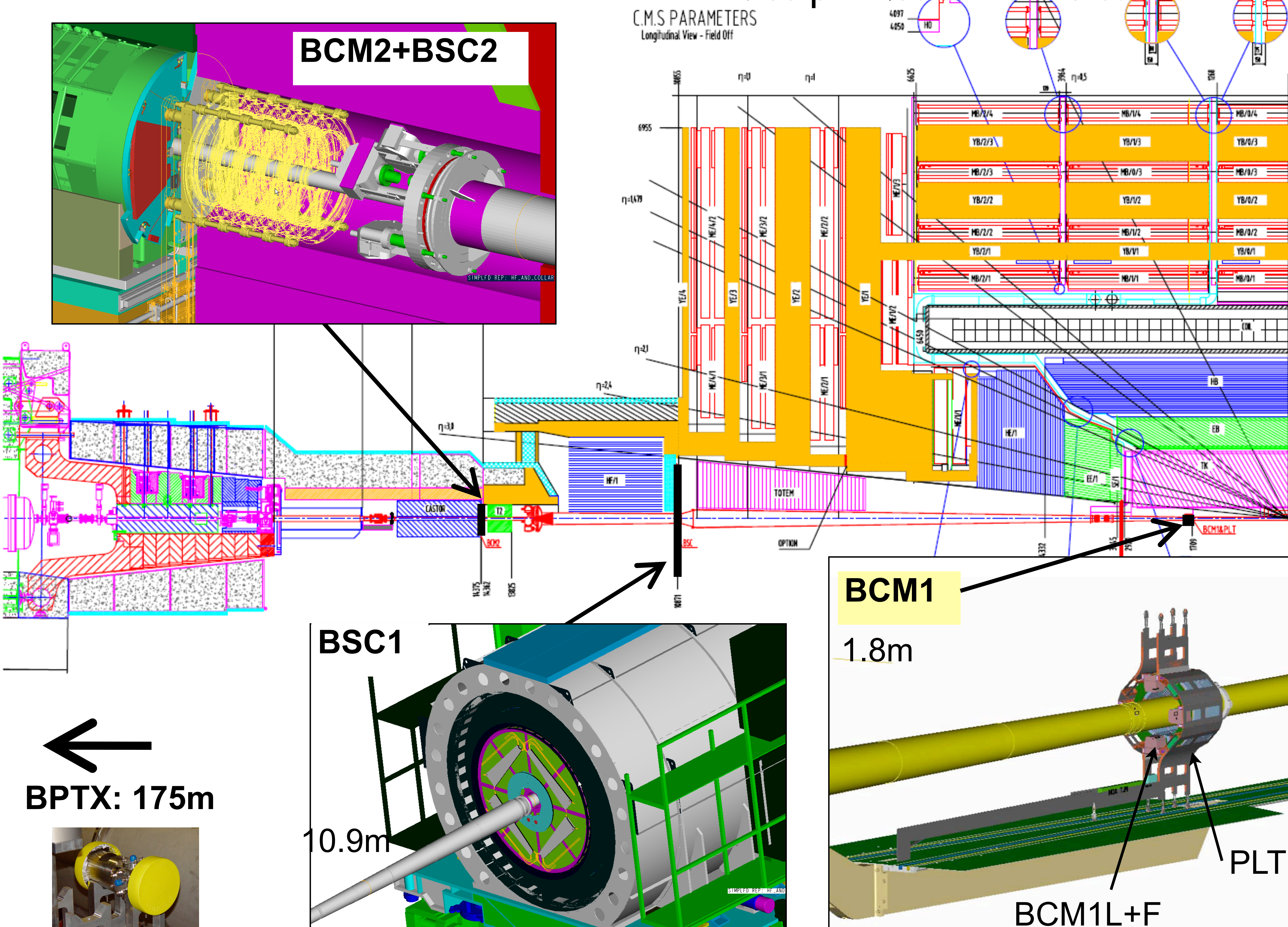
- Cost in region of billion euros
- Motivates protection from beam accidents
- Lots of delicate equipment close to the beamline ...
- ... in particular sensitive electronics

Overview of the CMS Beam and Radiation Monitoring

RADMON: 18 monitors around UXC

PASSIVES: Everywhere

Medipix Neutron Camera:3

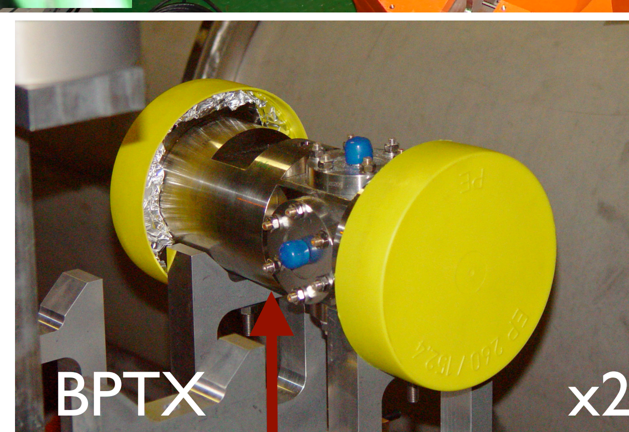


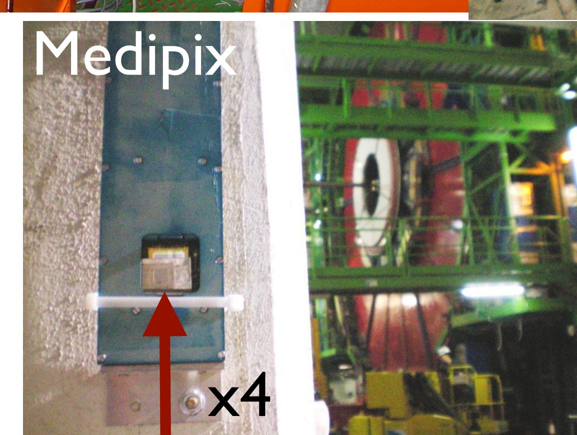
... and the reality ...

single and polycrystalline CVD diamond (8+8)

polycrystalline CVD diamond (24)

plastic scintillator + PMTs





RADFET, Pin diode, SRAM

button monitor

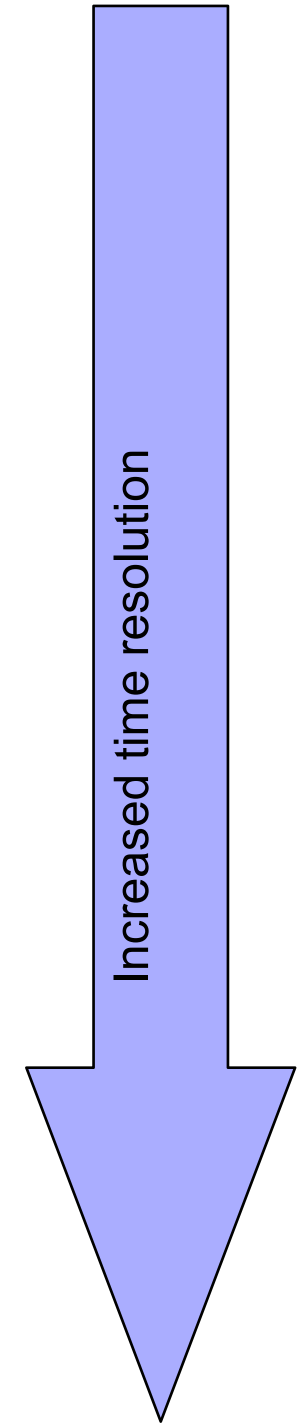
Silicon pixel detector

TLDs

BRM Subsystem Hardware Summary

Emphasis on detectors that are relative flux monitors

Subsystem	Location	Sampling time	Function	Readout + Interface
Passives TLD + Alanine	In CMS and UXC	Long term	Monitoring	---
RADMON	18 monitors around CMS	1s	Monitoring	Standard LHC
BCM2 Diamonds	At rear of HF z=±14.4m	40 us	Protection	CMS + Standard LHC
BCM1L Diamonds	Pixel Volume z=±1.8m	Sub orbit ~ 5us	Protection	CMS + Standard LHC
BSC Scintillator	Front of HF z=±10.9,14.4 m	(sub-)Bunch by bunch	Monitoring	CMS Standalone
BCM1F Diamonds	Pixel volume z=±1.8m	(sub-)Bunch by bunch	Monitoring + protection	CMS Standalone
BPTX Beam Pickup	175m upstream from IP5	200ps	Monitoring	CMS Standalone



Simulation

PP-simulations:

- •Collisions generated with DPMJET III (450GeV & 7TeV)
- •Full tracking of all particles through CMS with FLUKA

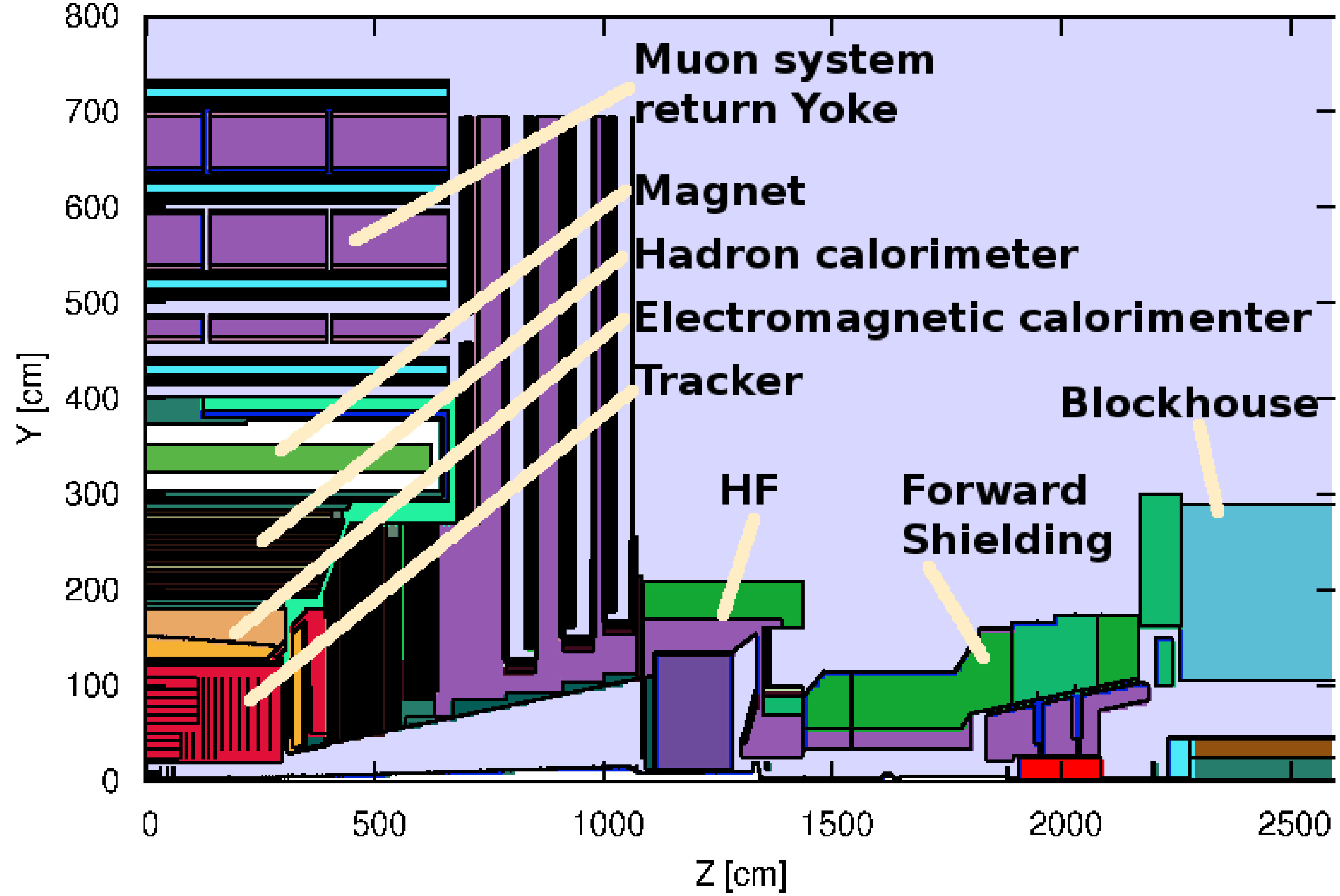
•Machine-induced background

•Beam Halo:

- •Loss maps simulated with SixTrack for ideal machine
- •Shower simulated with Mars code outside cavern
- •At 22.6m interface to CMS FLUKA geometry, full tracking

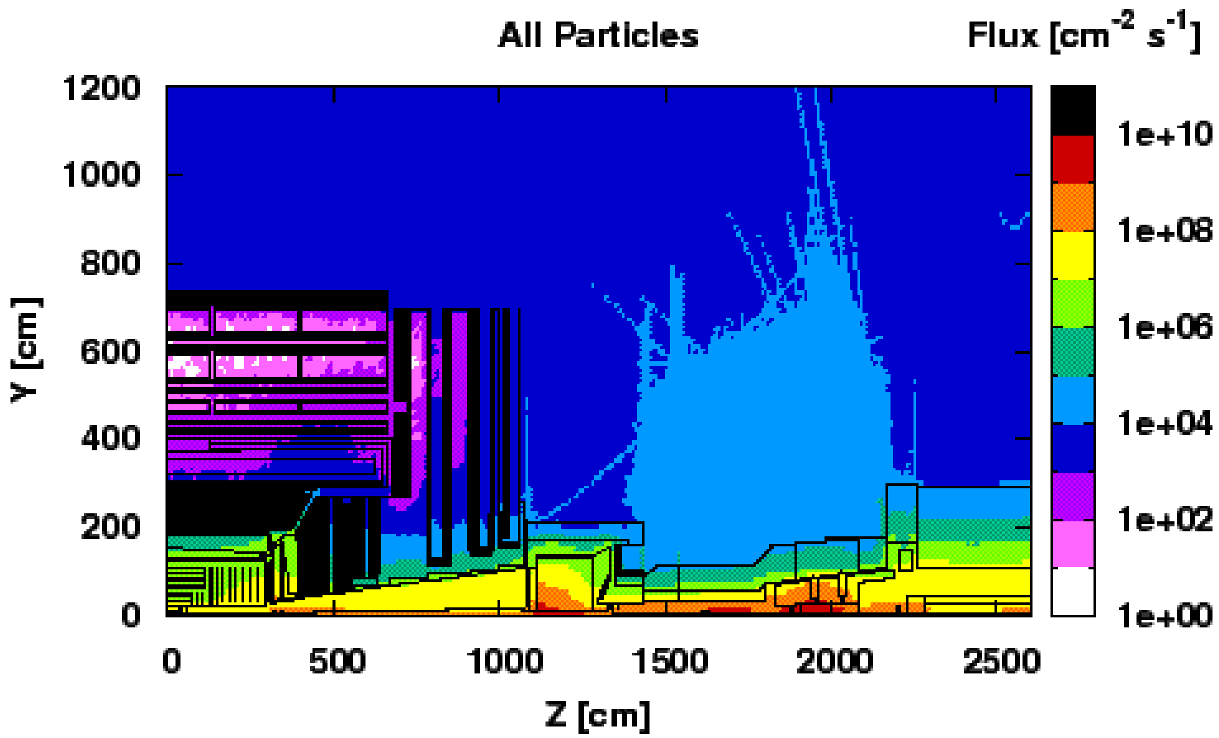
•Beamgas:

- •interactions with Mars in LSS 22.6m up to 550m

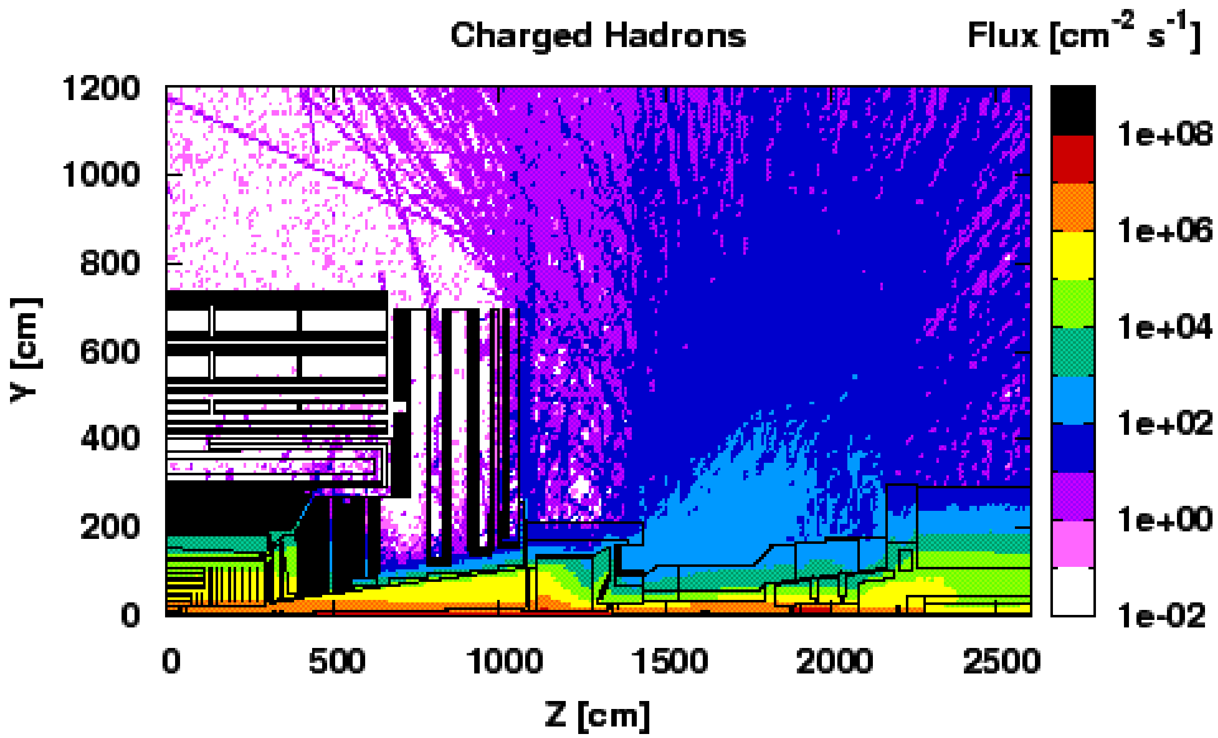


All simulation results given are scaled to “nominal” luminosity for comparison purposes (L=10^34 /cm^2/s^1)

Simulation - pp collisions



(a)



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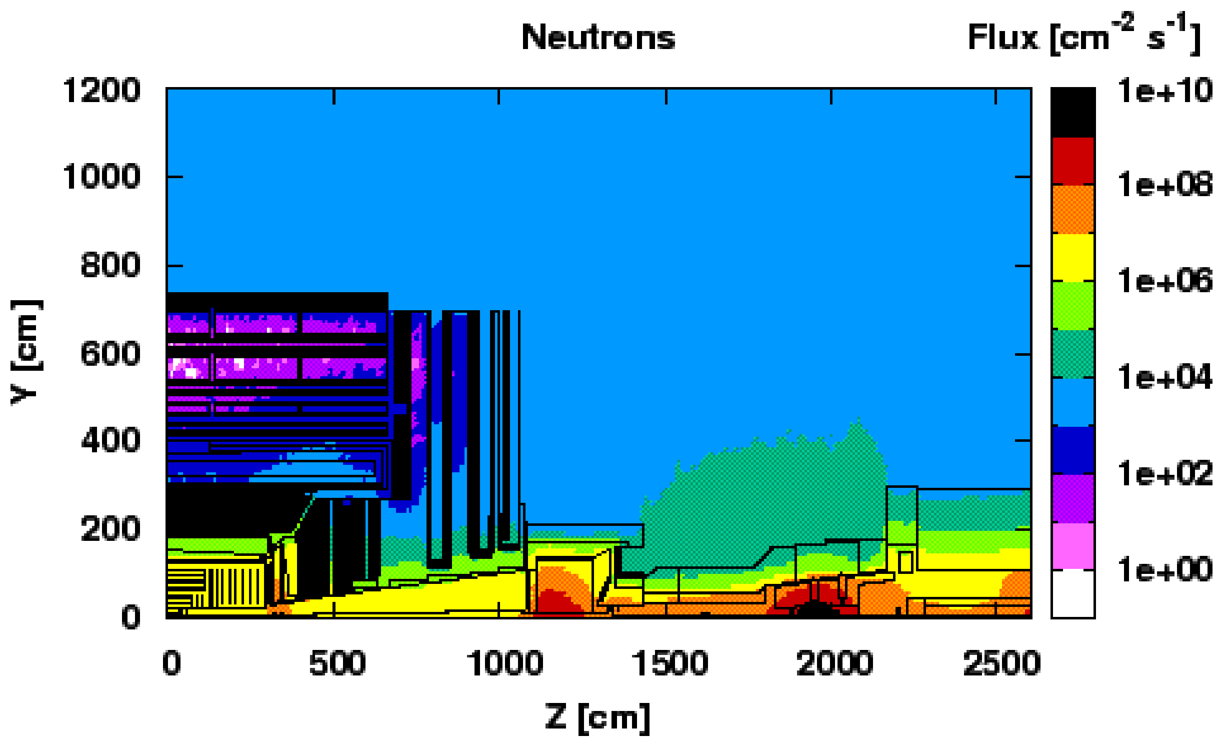
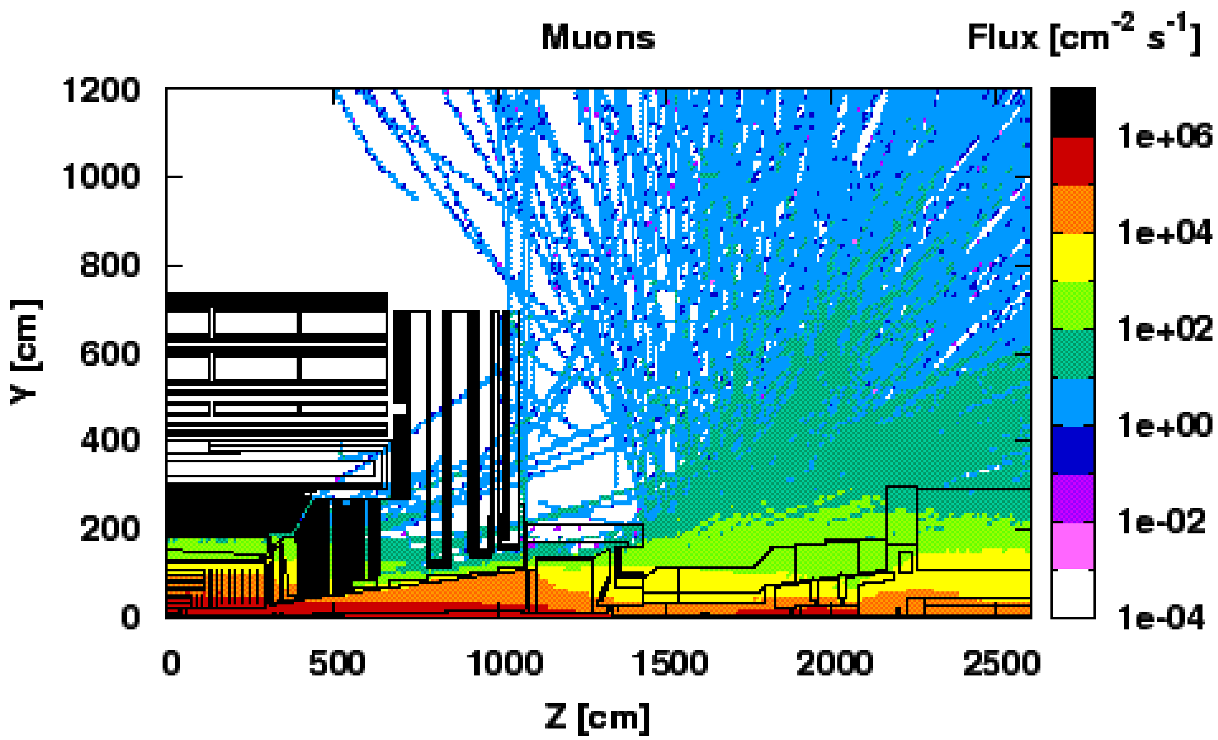
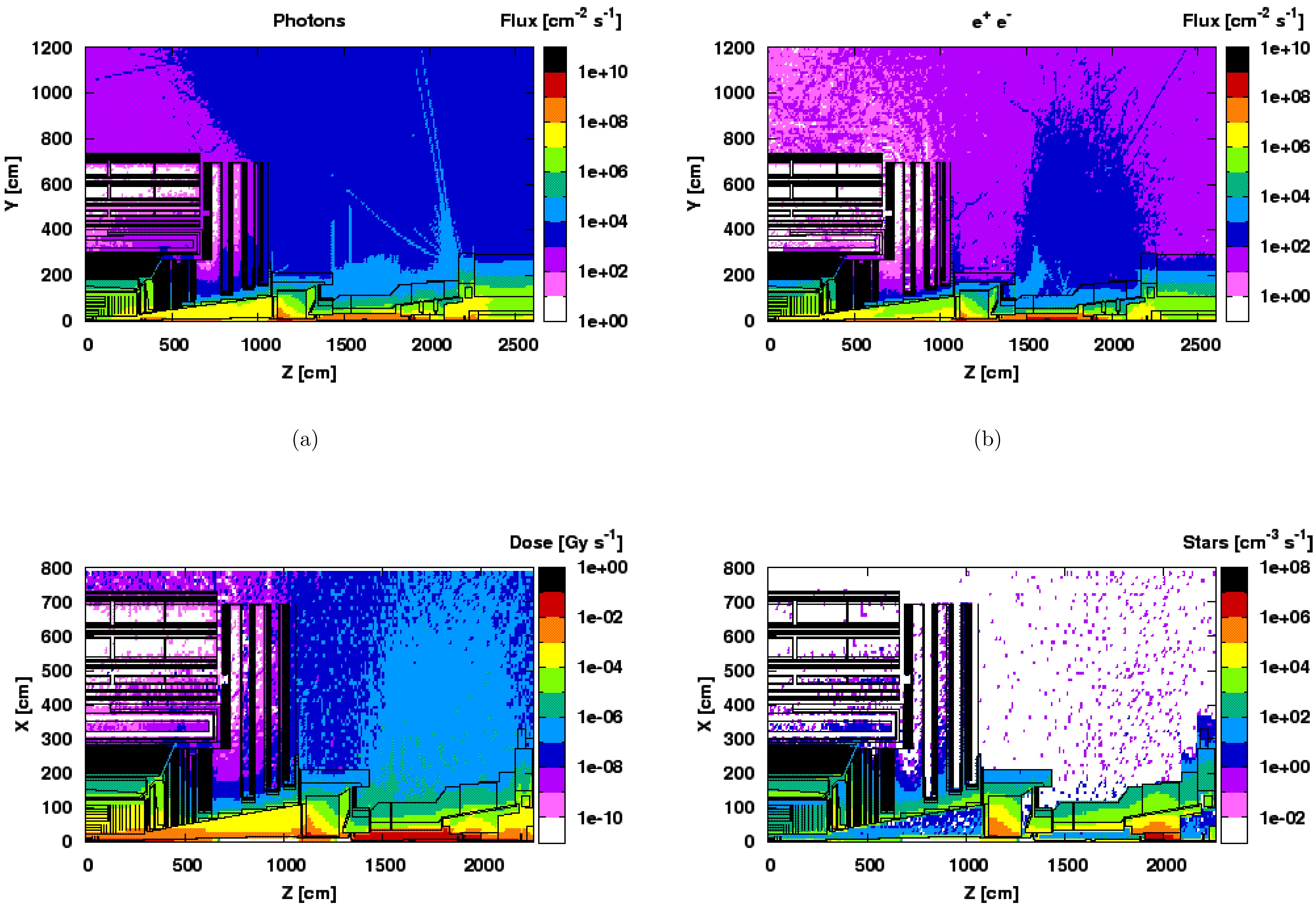
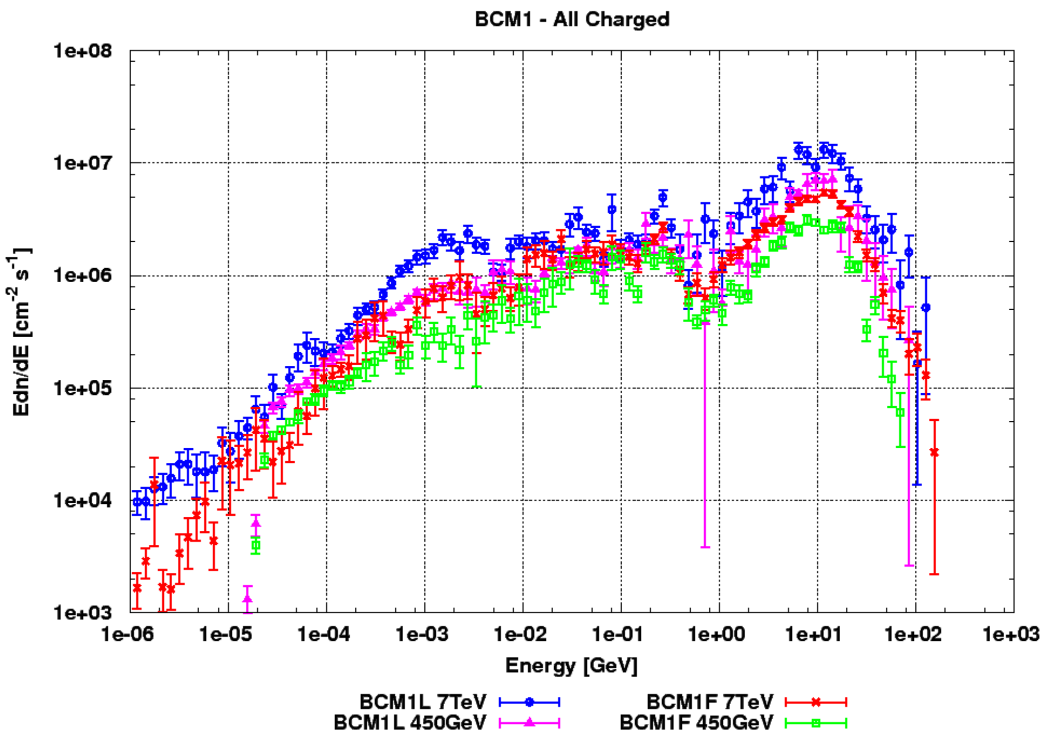


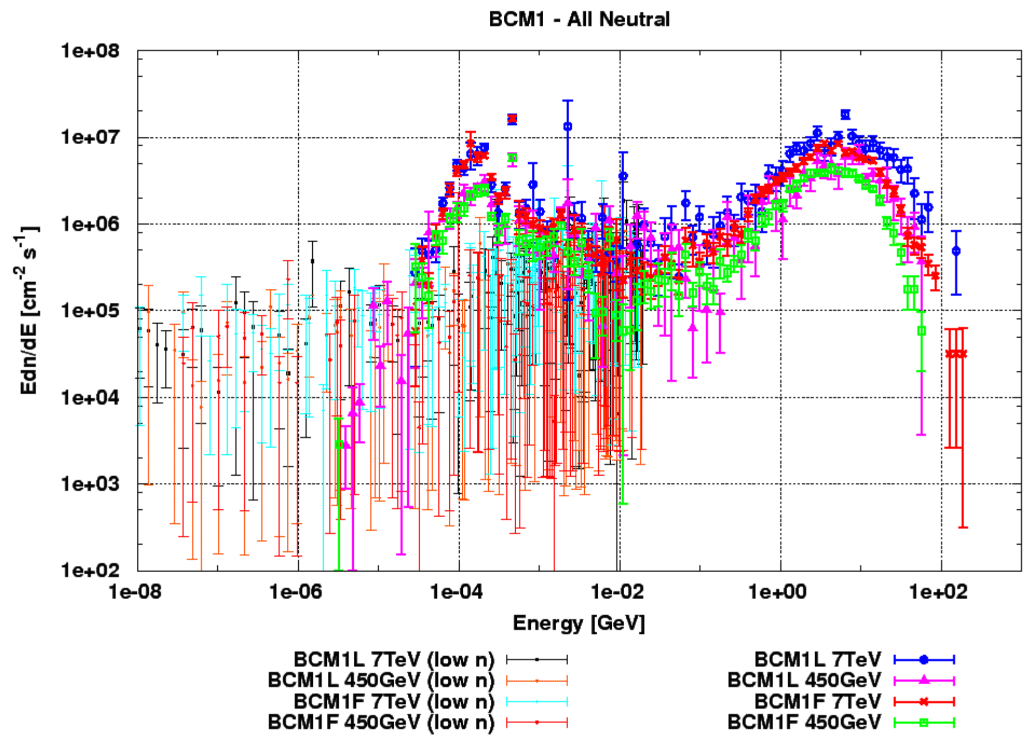


Simulation - pp collisions

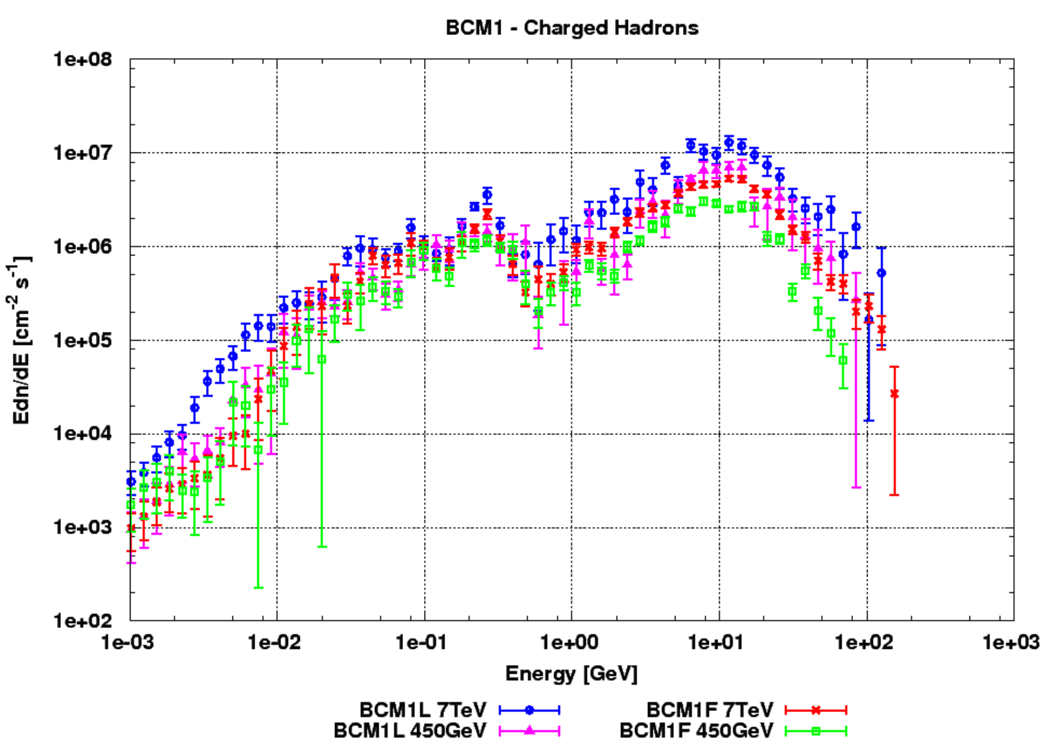


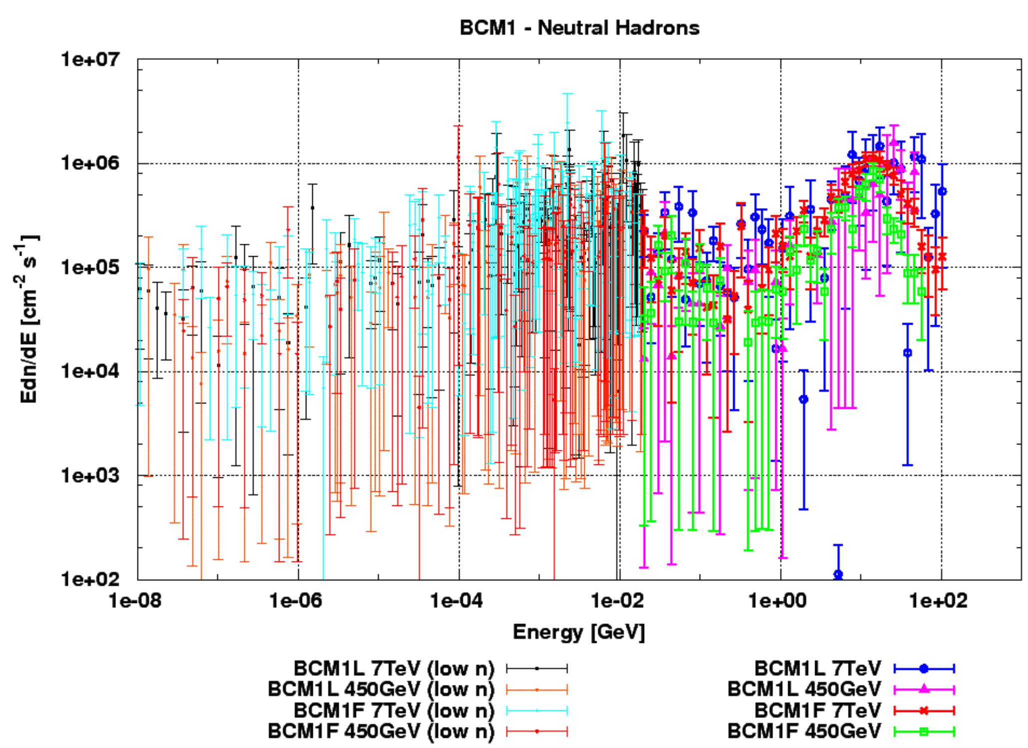
Simulation pp collisions - Energies of Particles



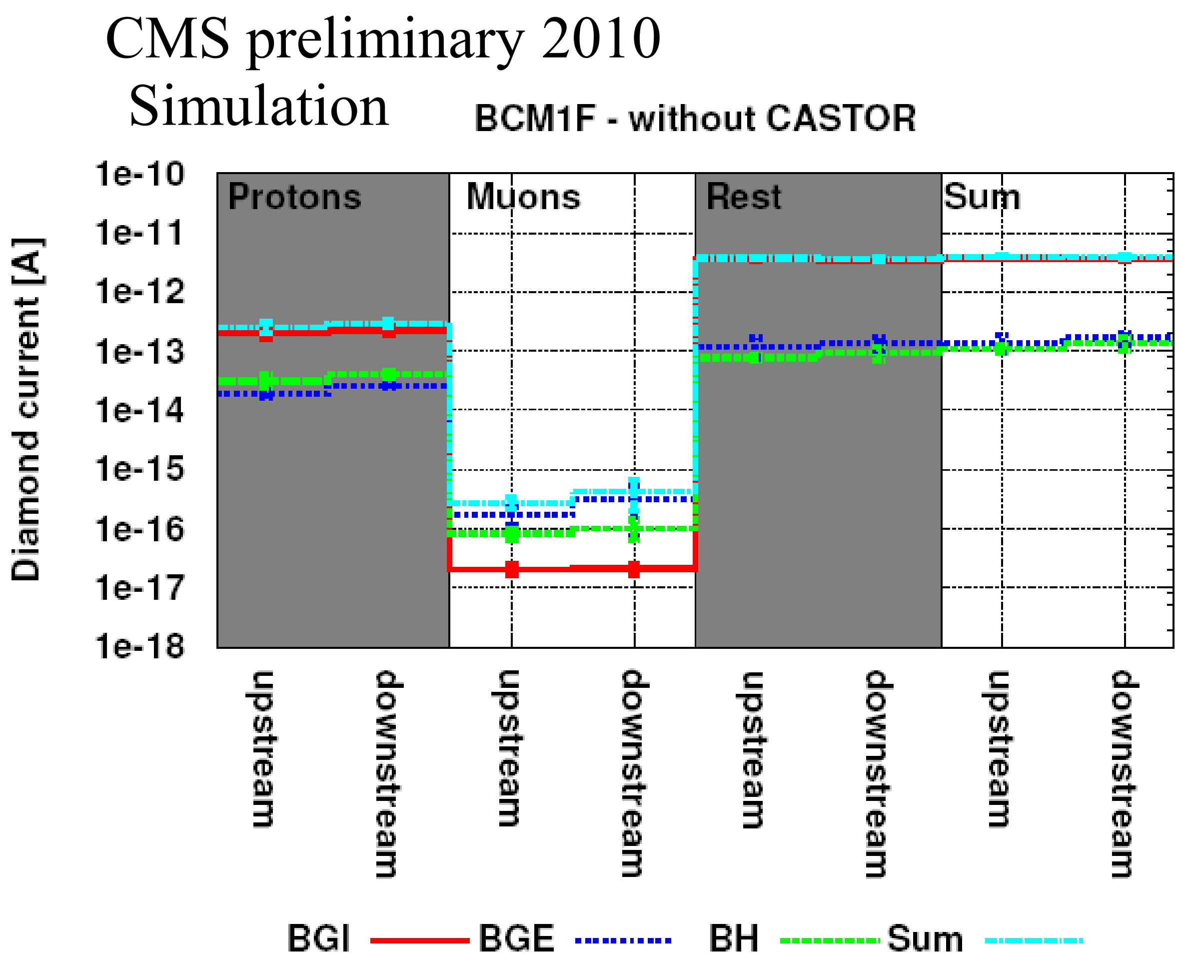


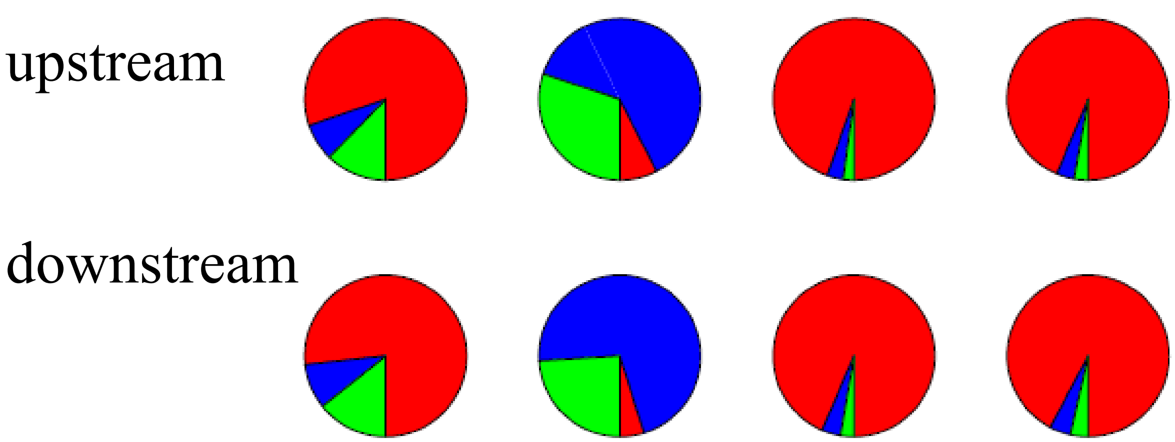
- Spectra is very flat - all energies of particles over many orders of magnitude
- Very dependent upon the material surrounding the location
- Very important to take the spectra into account when considering losses

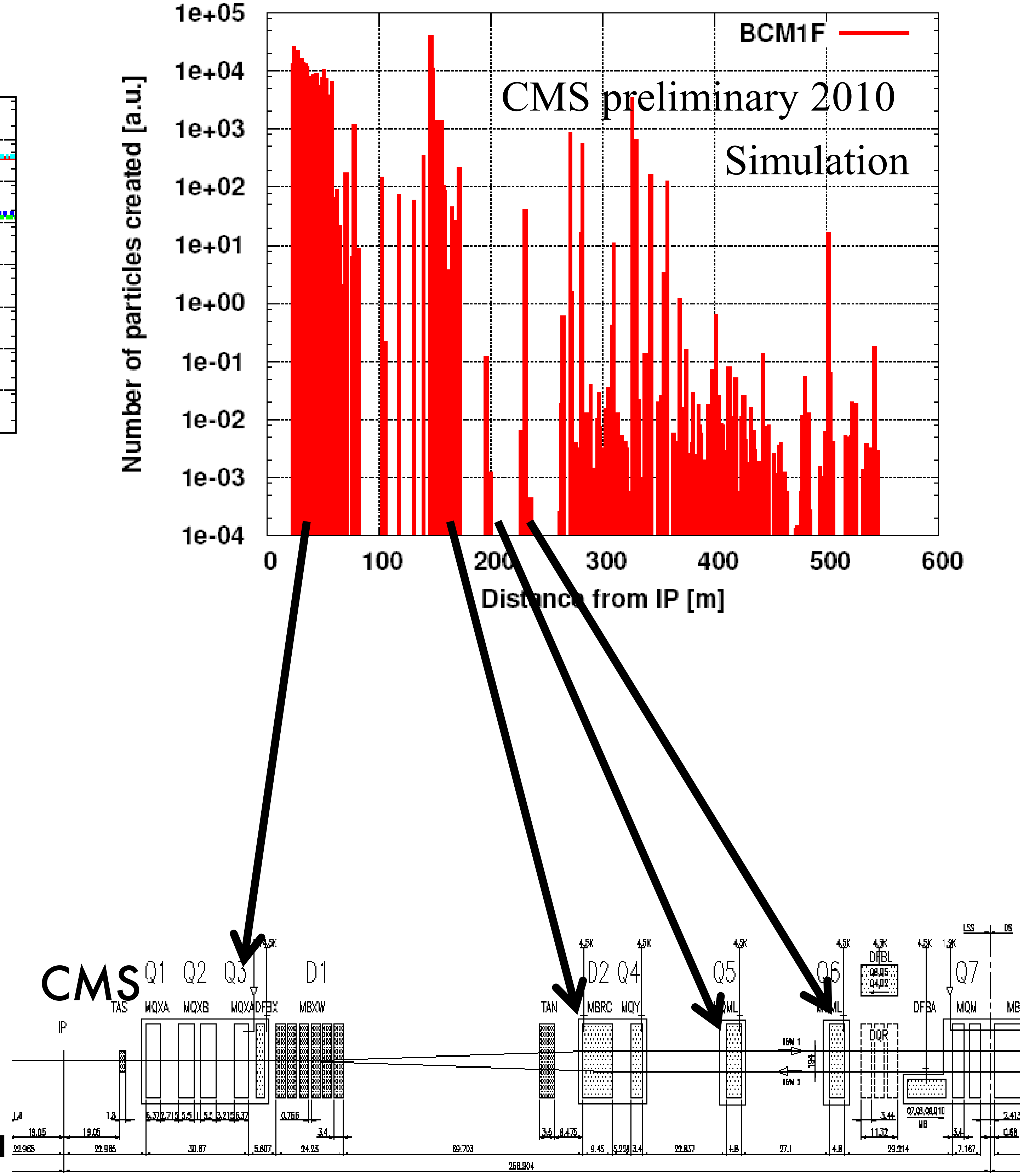




Contribution and Origin of the Background



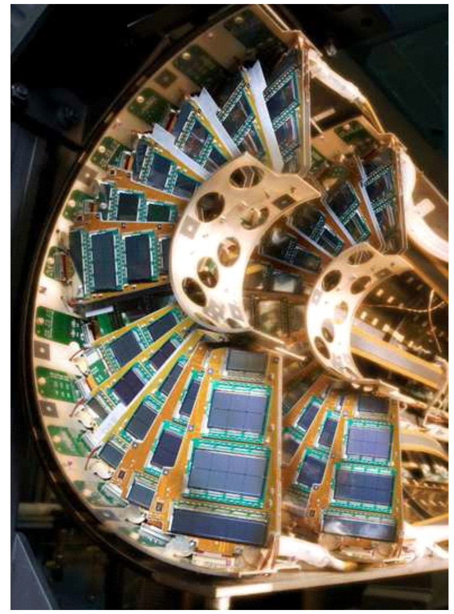


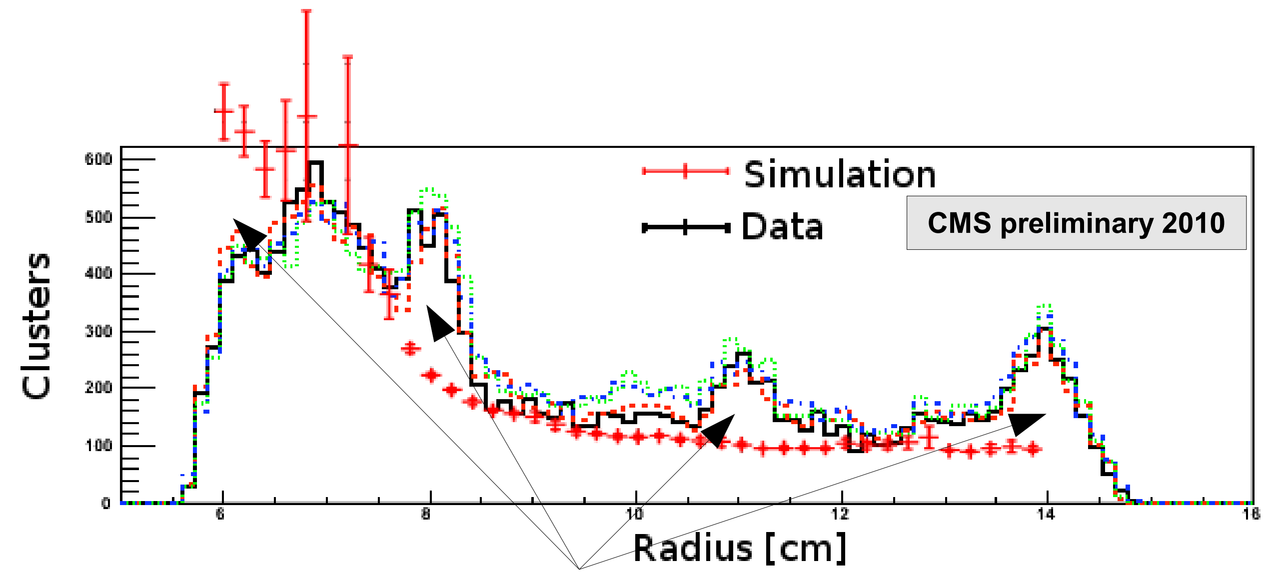


- Majority of background is beamgas interactions, close to the experimental area

Background: Simulation and Data

Radial-Shape comparison with pixel detector:





Detector geometry effect causes multiple counting of tracks.

- Comparing the measurements of background to the simulations

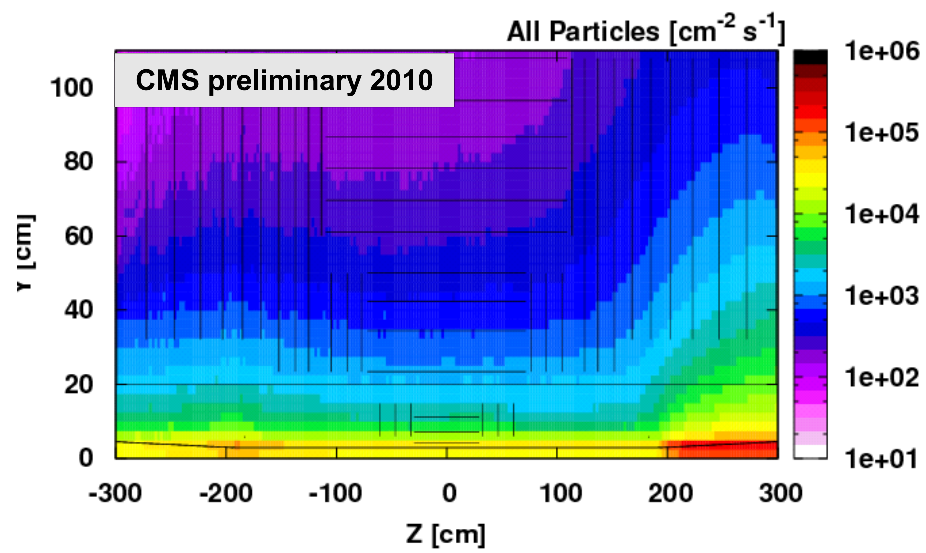
- Good qualitative and quantitive agreement

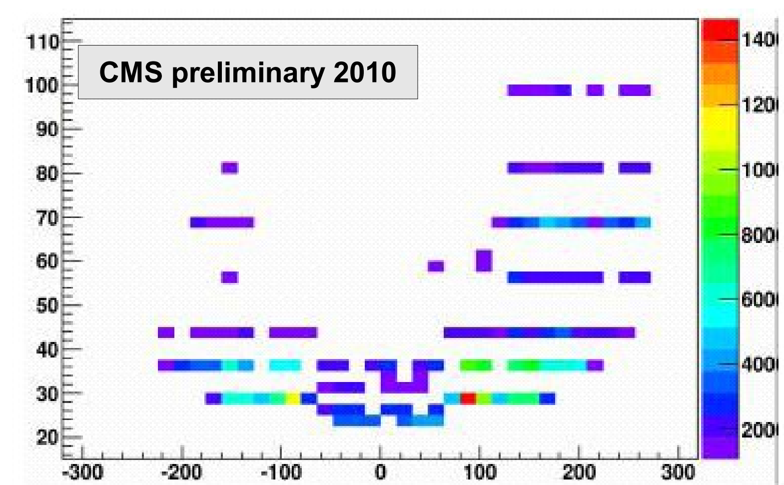
- No major surprises

- Background is suppressed by 5 orders of magnitude compare to pp collisions under normal conditions

Good agreement between simulation prediction and measurement for background events.

Z-Shape comparison with tracker detector:

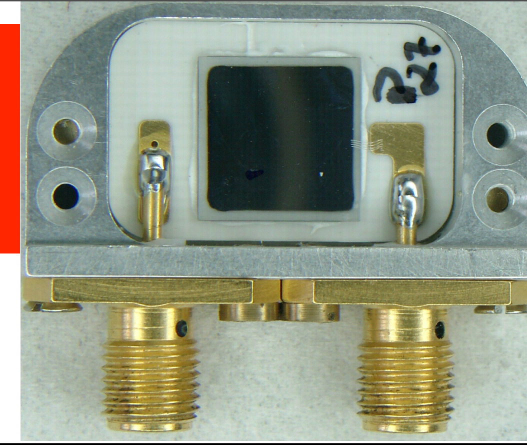




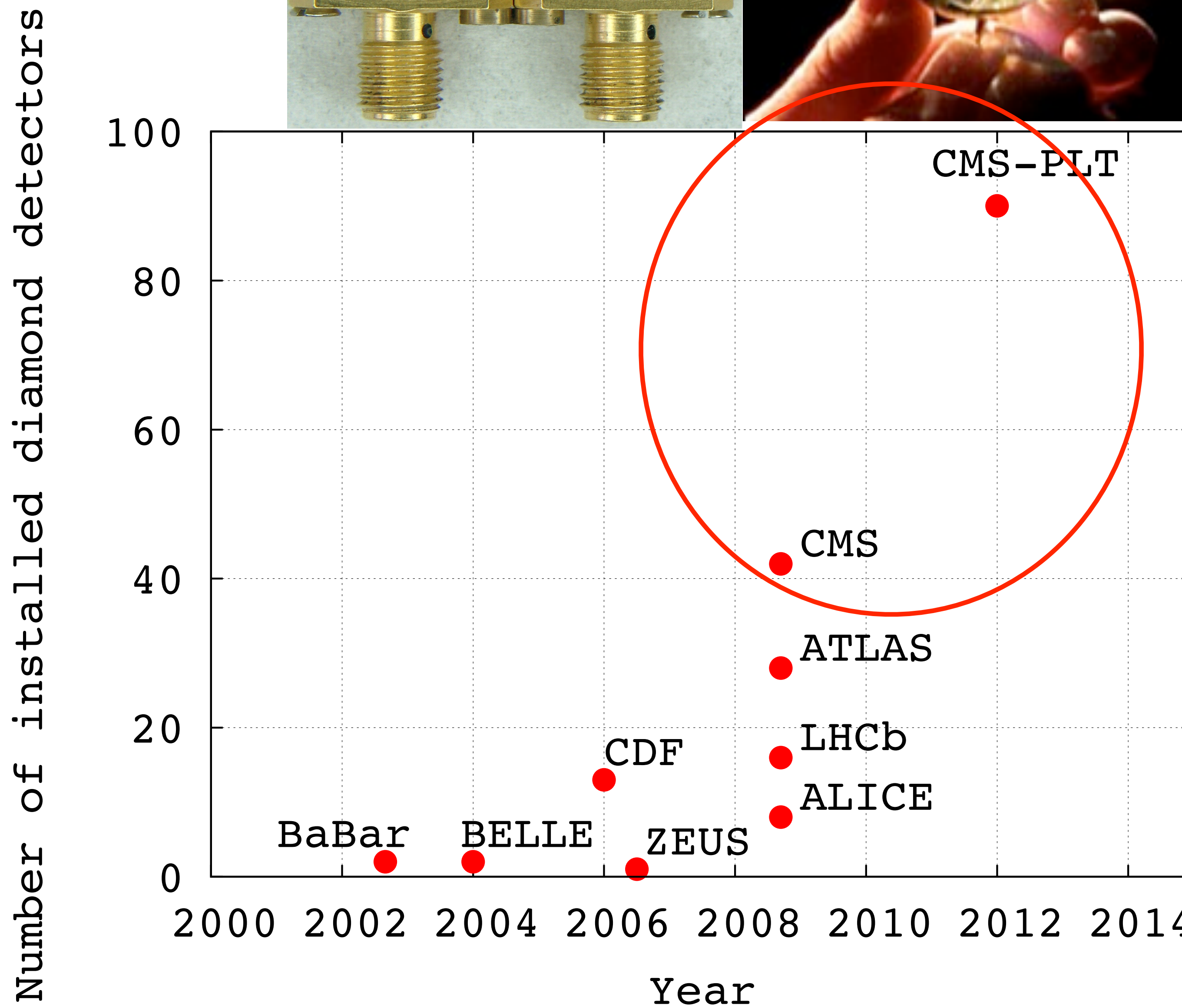
Beam 2 only

Background cluster distribution in the tracker silicon strip detector remarkably similar to simulation

Diamond Detectors



- Diamond is a special material:
  - thermal conductivity
  - almost perfect insulator
  - (partially) radiation hard
- For detector properties, only chemical vapour deposition diamond suitable.
- Diamond is an alternative to silicon as detector medium
- For beam monitoring, diamond excels in locations where there is small space available, or adverse environmental conditions (magnetic field or cryogenics)
- Possible to make very small detector units
- No cooling needed

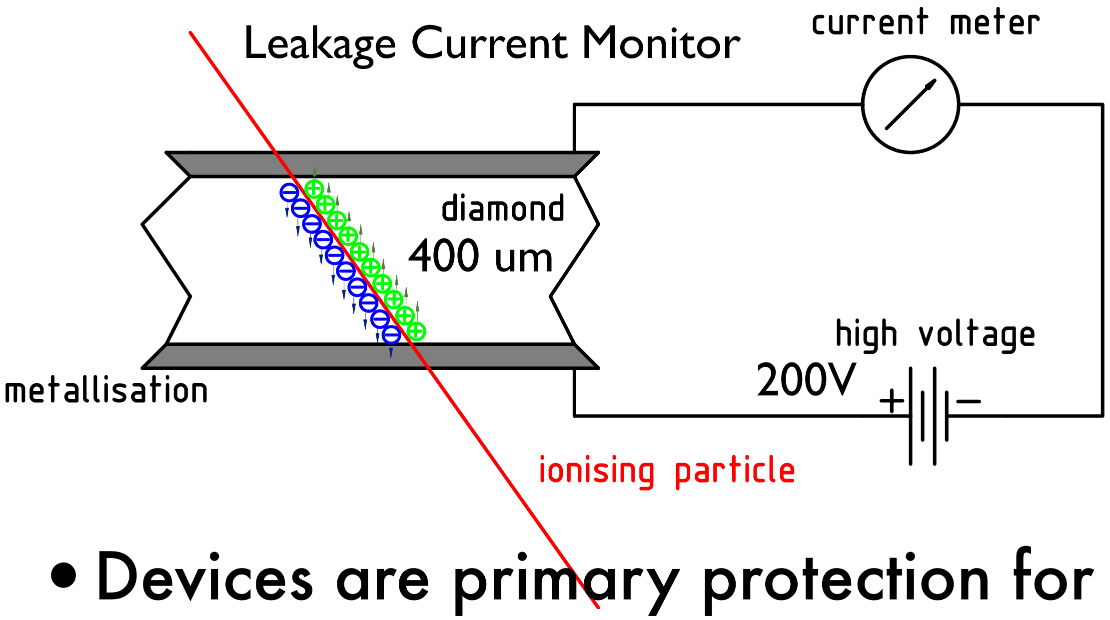


The CMS installations: largest usage in high energy physics

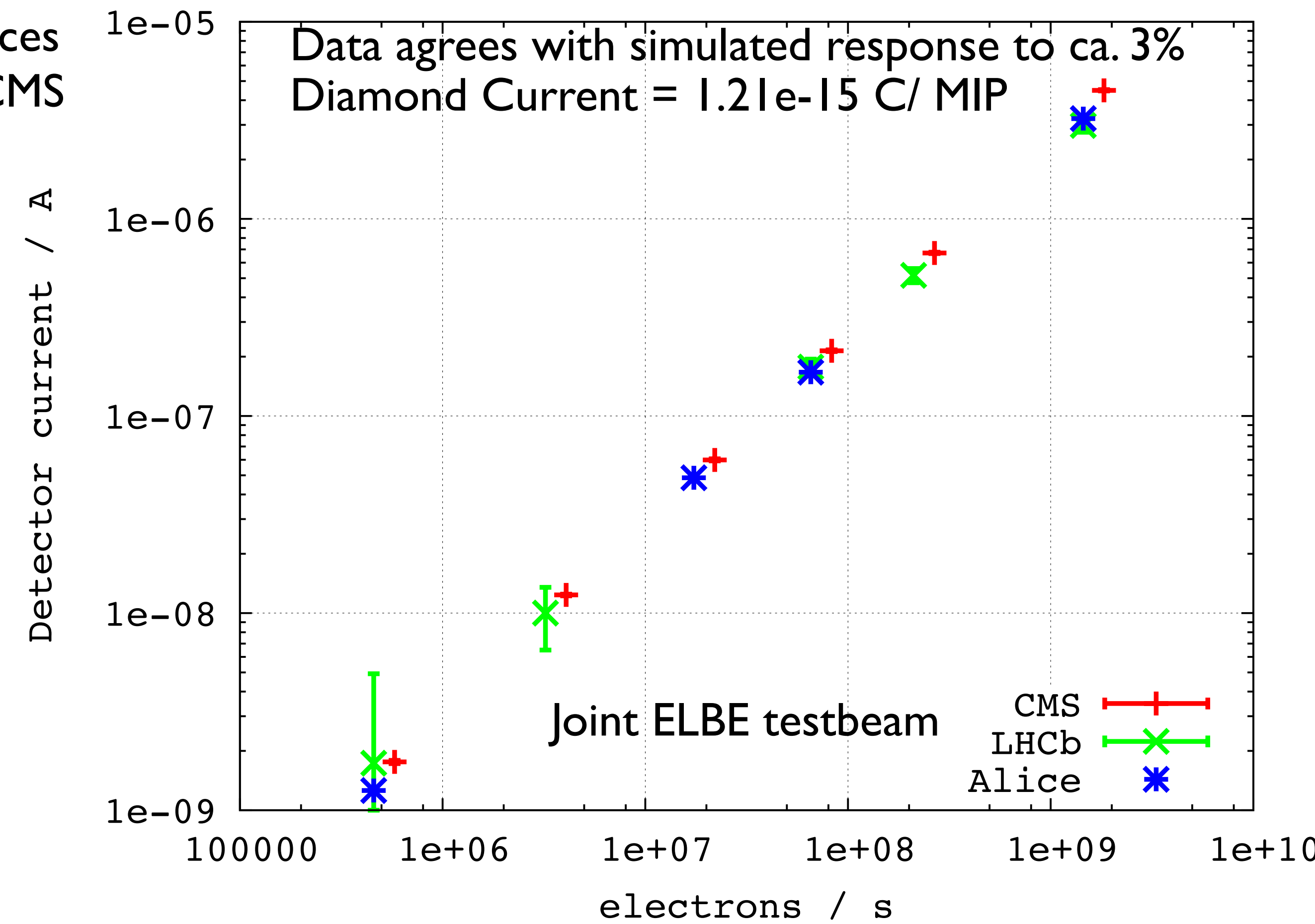
- Have benefitted from the CARAT collaboration and involved in RD42 Collaboration
  - “Diamond detector development for LHC”
- Using the large sample of diamonds to define a procedure for evaluation good diamonds with the (sole-) supplier.
- Trying novel material (unpolished diamond in CMS cavern) and alternative supplier

Beam Conditions Monitors

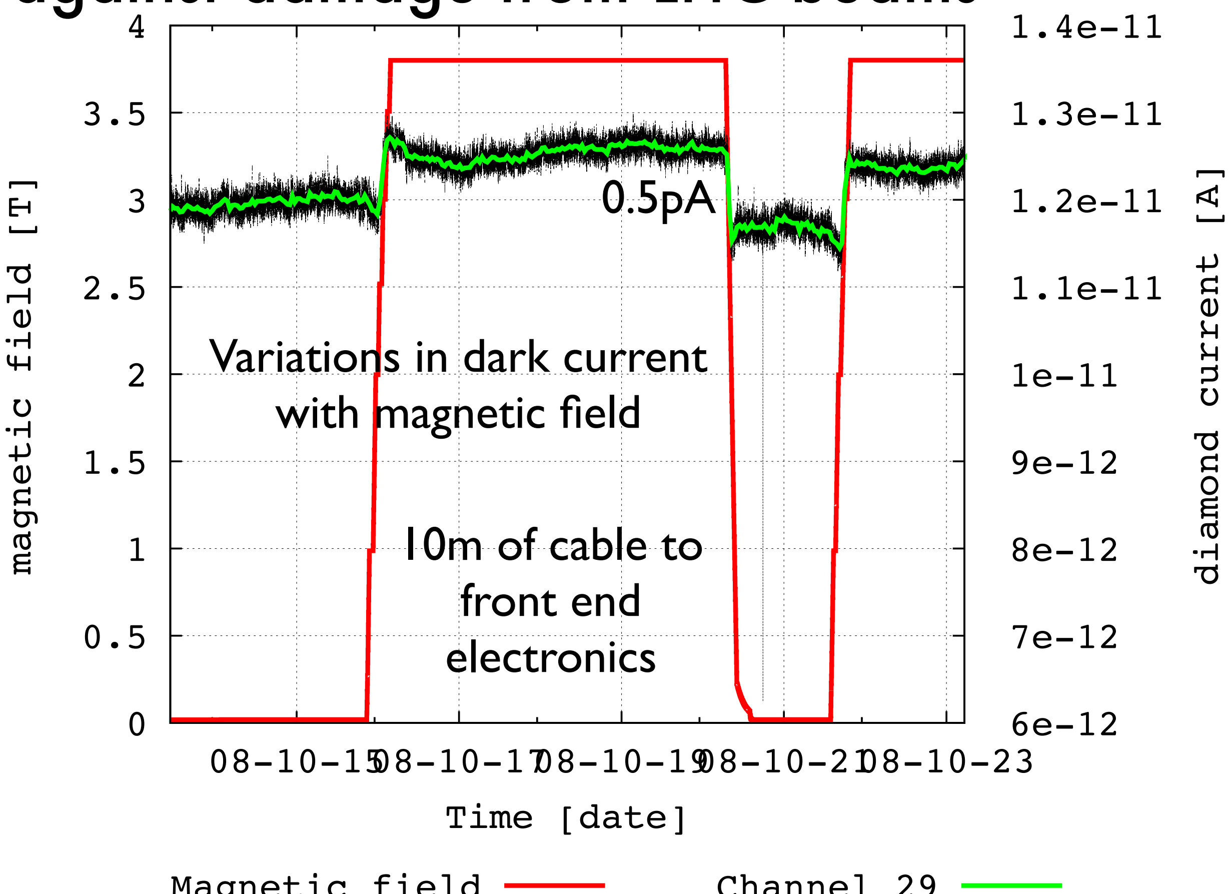
- 100% Reliable
- 100% Available



36 such devices installed in CMS



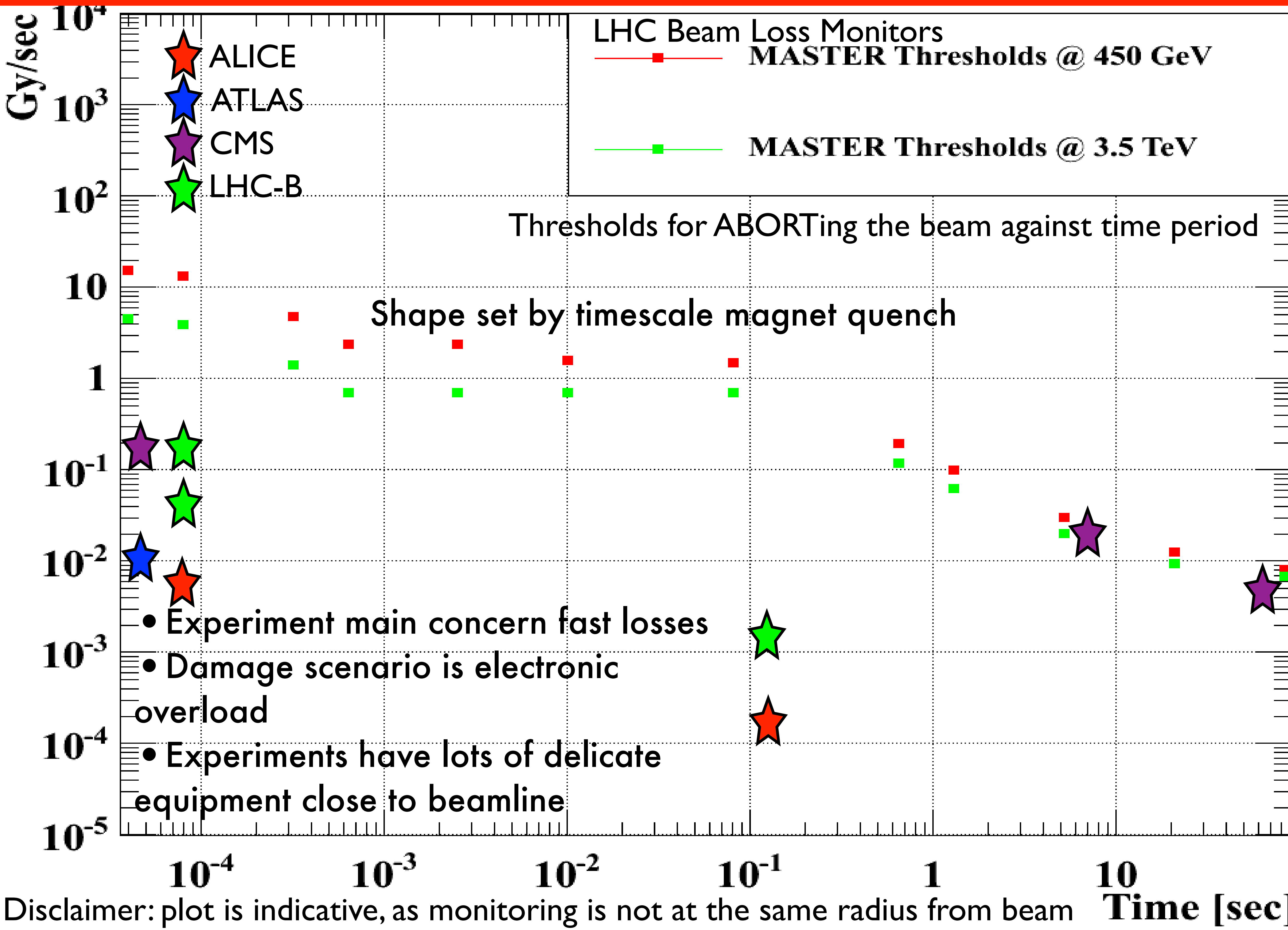
- Devices are primary protection for CMS against damage from LHC beams



- 8 have 100m cable to front-end electronics
  - 200 pA sensitivity achieved

- 7 testbeams to check diamonds response
- Also evaluating radiation damage
- As the installed system is the largest in HEP, can use to investigate systematic effects
- Dark current variations with magnetic field
- *(Paper in Phys. Stat. Solidi.)*
- Large dynamic range: pA-mA
  - Necessary for beam monitoring

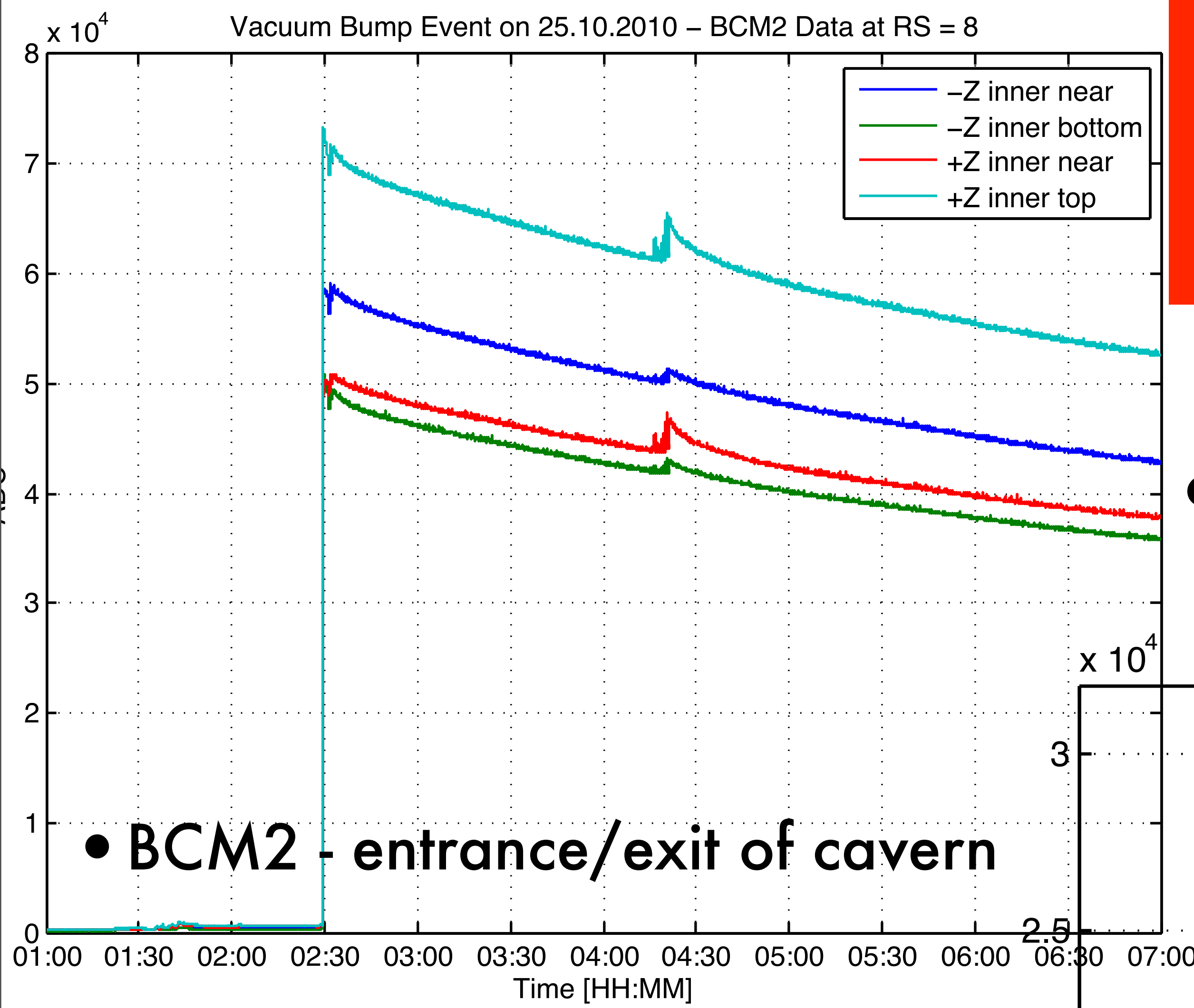
Protection from Beam Losses: Machine cf Experiment



- Experiment main concern fast losses
- Damage scenario is electronic overload
- Experiments have lots of delicate equipment close to beamline

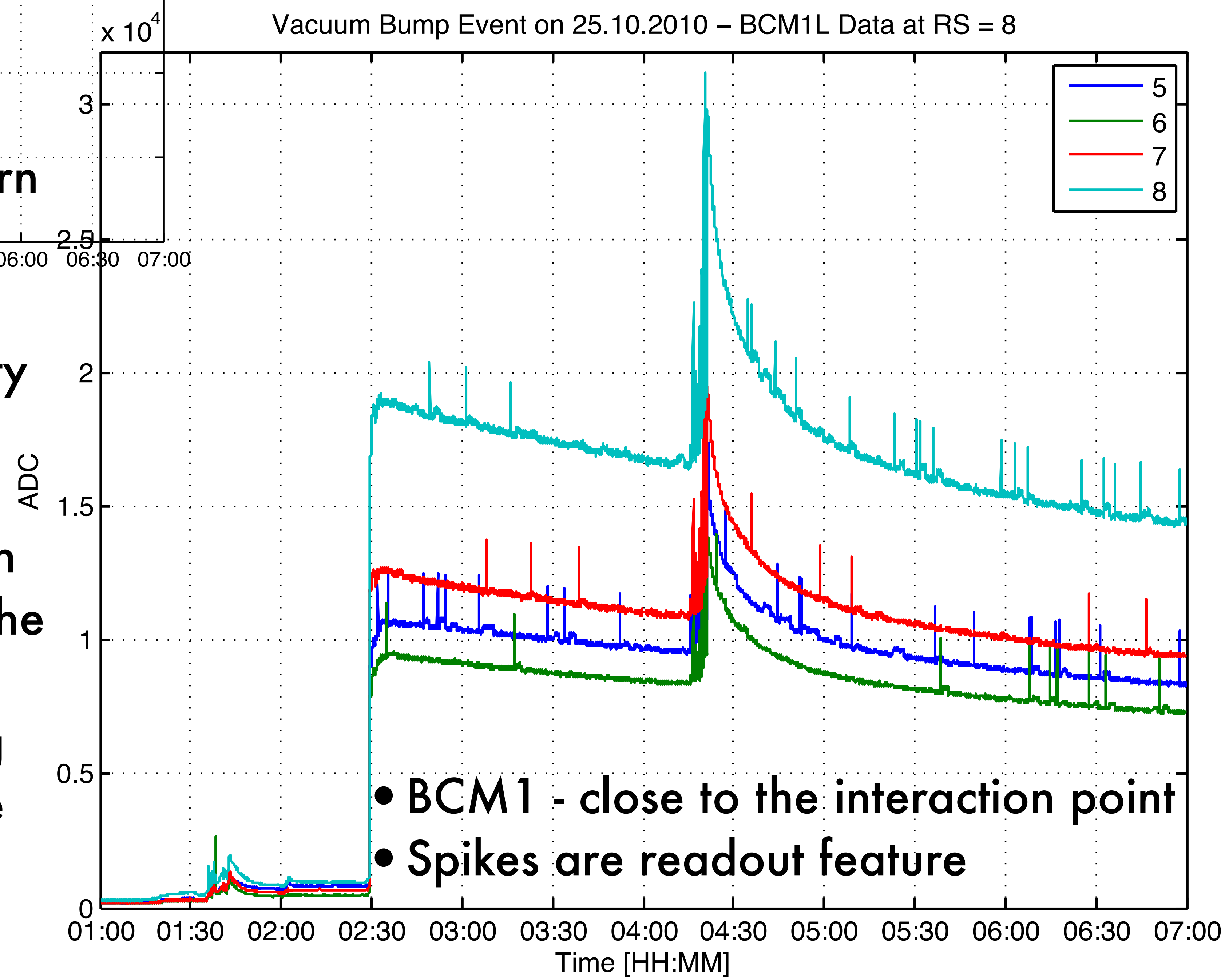
Disclaimer: plot is indicative, as monitoring is not at the same radius from beam

Local Vacuum Bump, close to Experimental Area



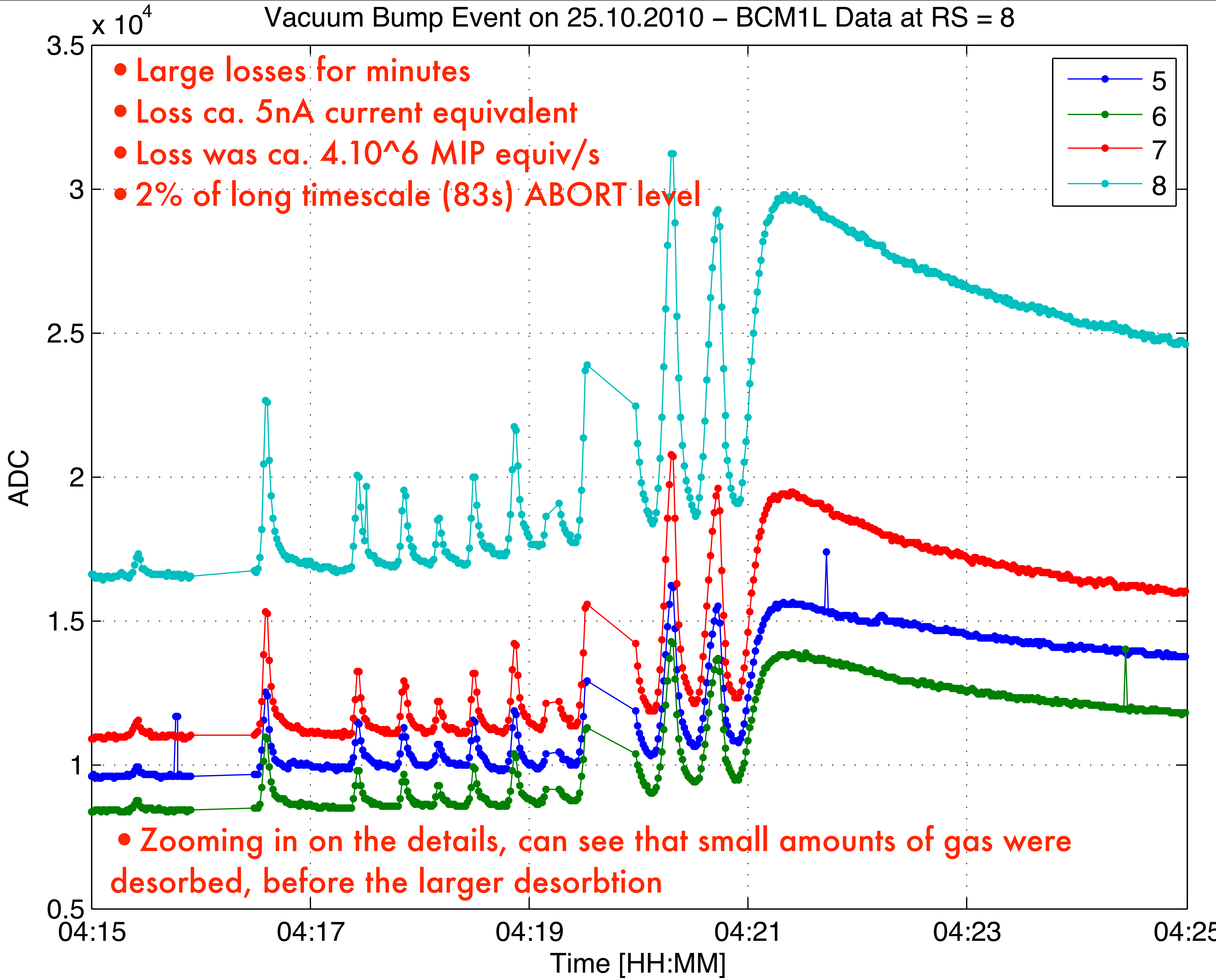
- BCM2 - entrance/exit of cavern

- Beam induced local degradation of the vacuum close to the CMS experimental cavern



- BCM1 - close to the interaction point
- Spikes are readout feature

- Data demonstrates the necessity of local monitoring
- Loss is close enough to BCM2 location, that it is not clearly seen
- Effect is very clear looking at the BCM1 data
- Important for beam monitoring to have comprehensive coverage

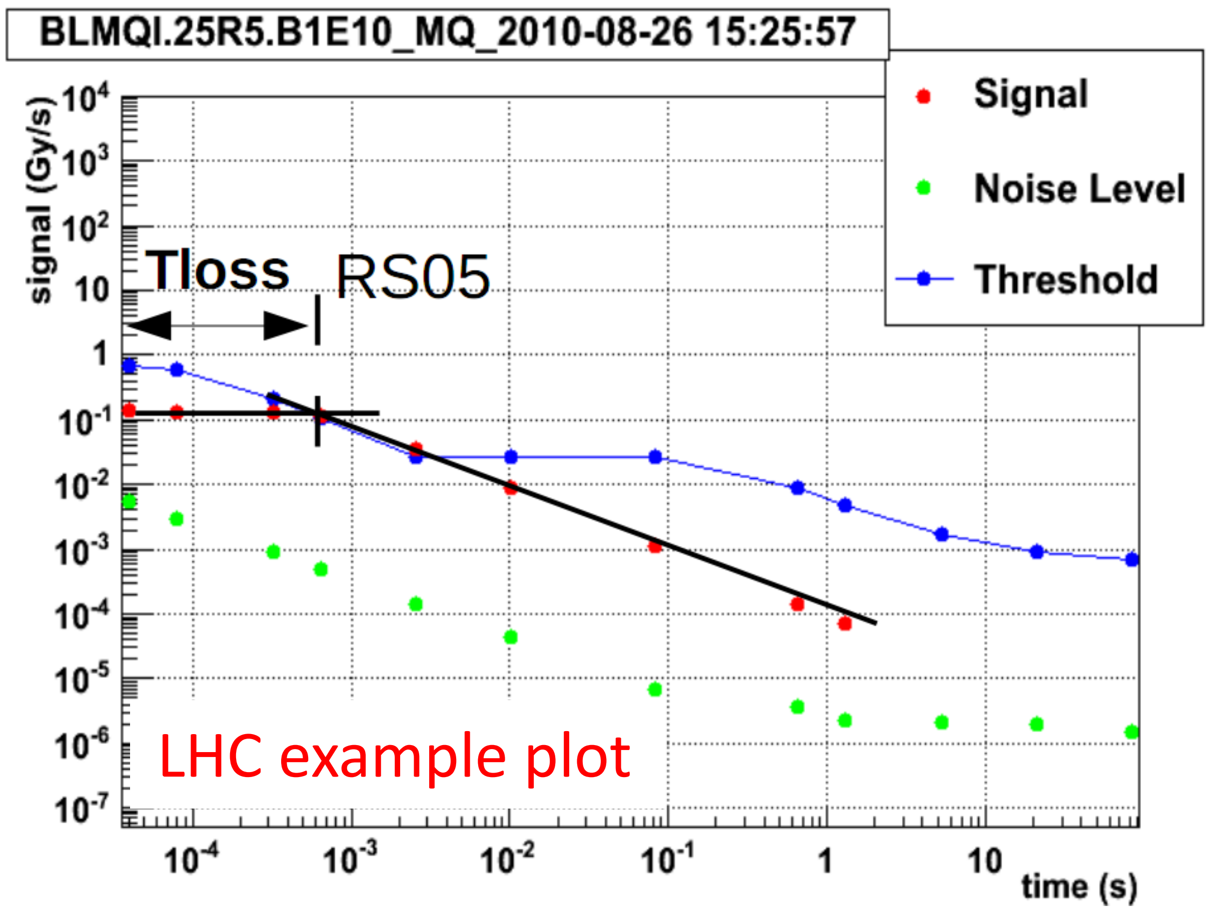

Vacuum Bump Event on 25.10.2010 – BCM1L Data at RS = 8
x 10^4
3.5
3
2.5
2
1.5
1
0.5
ADC
• Large losses for minutes
• Loss ca. 5nA current equivalent
• Loss was ca. 4.10^6 MIP equiv/s
• 2% of long timescale (83s) ABORT level
5
6
7
8
• Zooming in on the details, can see that small amounts of gas were desorbed, before the larger desorbtion
04:15
04:17
04:19
04:21
04:23
04:25
Time [HH:MM]

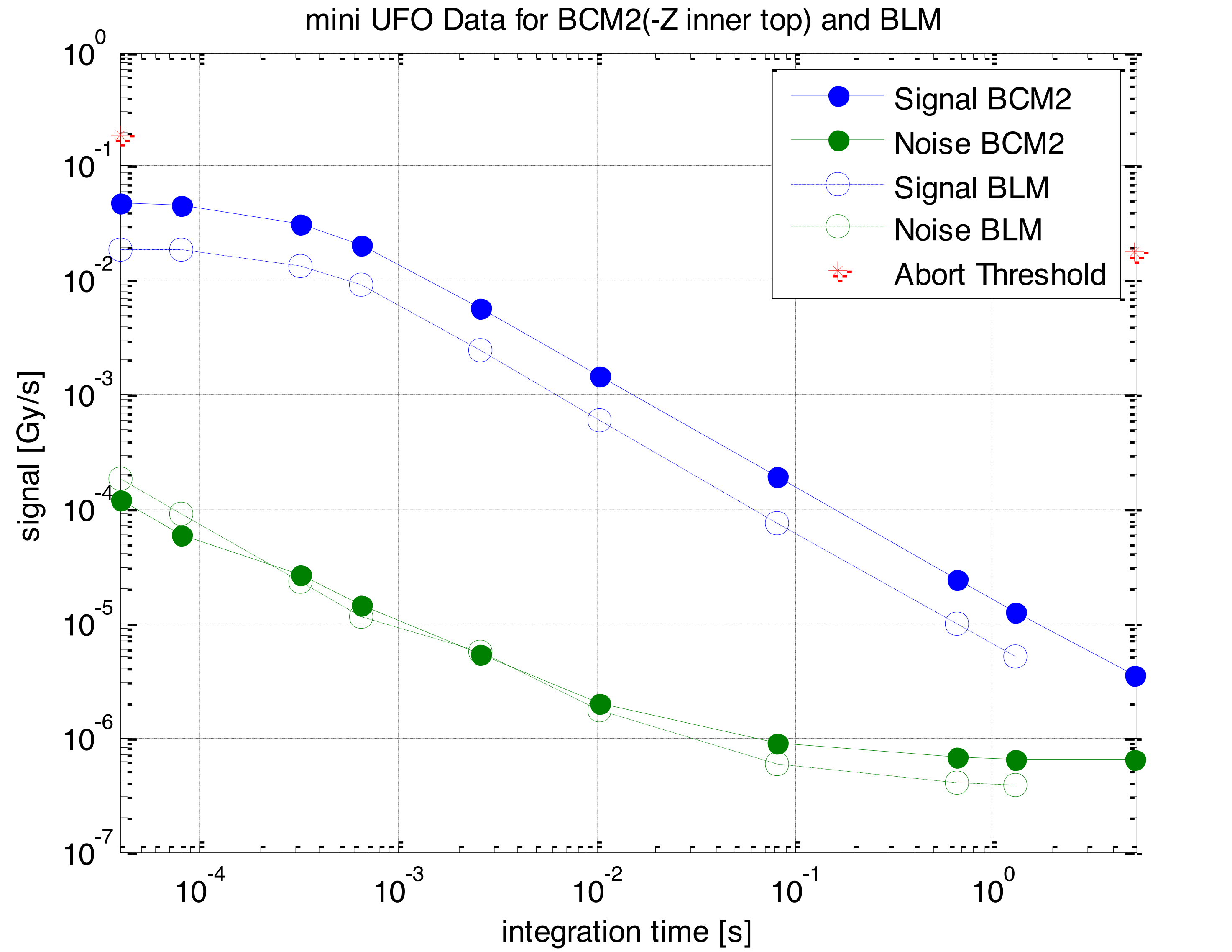
Small piece of Dust falling through the beam

- Seen in all CMS beam monitoring
- Reaches 25% of ABORT level
- Losses were very large

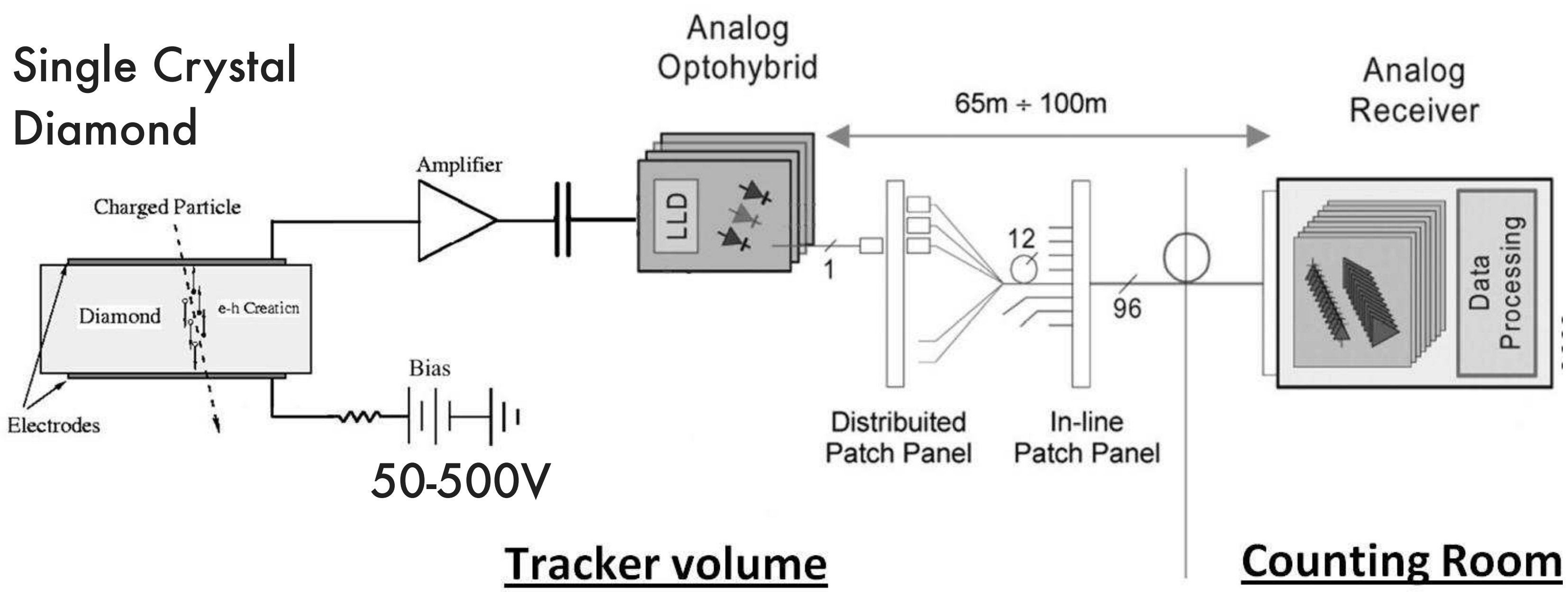
- Can again see the importance of local monitoring
- Time structure of loss is crucial in determining cause

- Duration of ~300µs



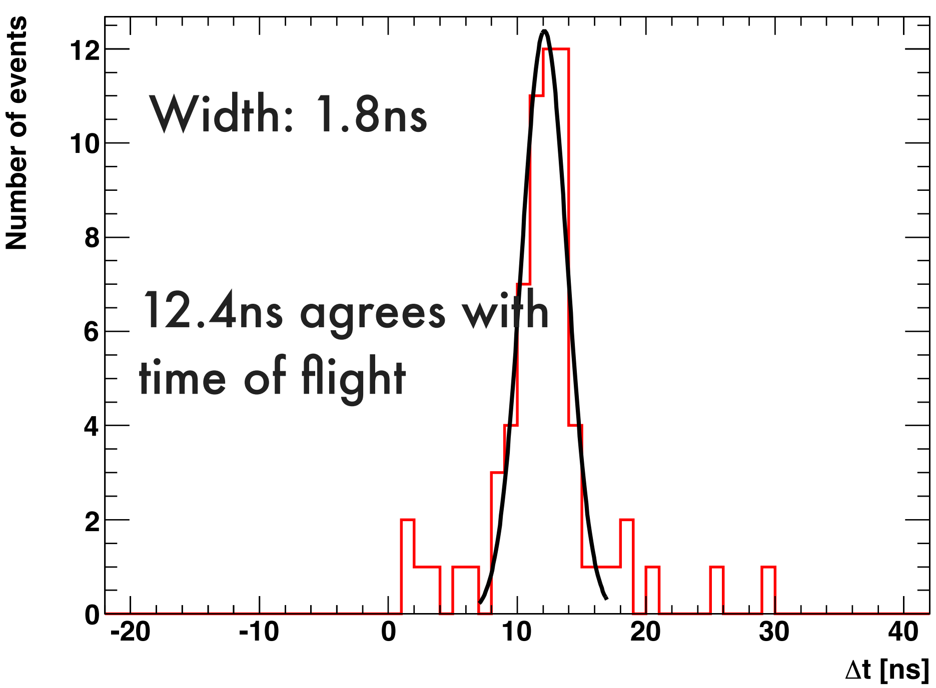


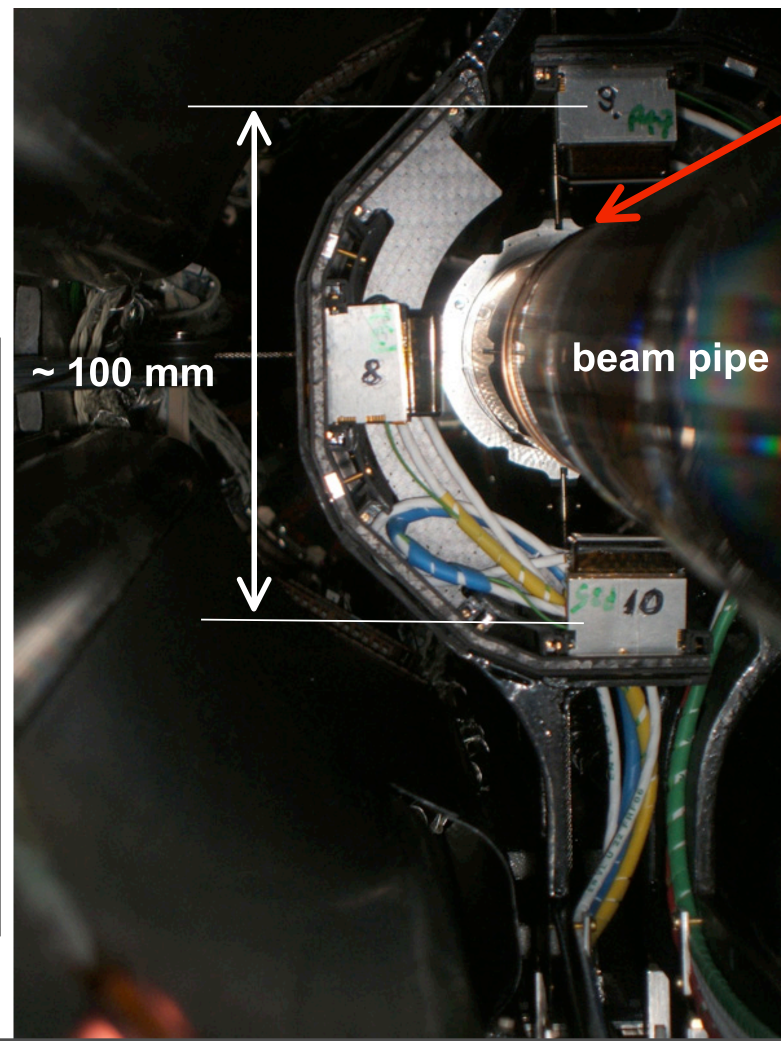
Fast Beam Conditions Monitor (BCM1F)

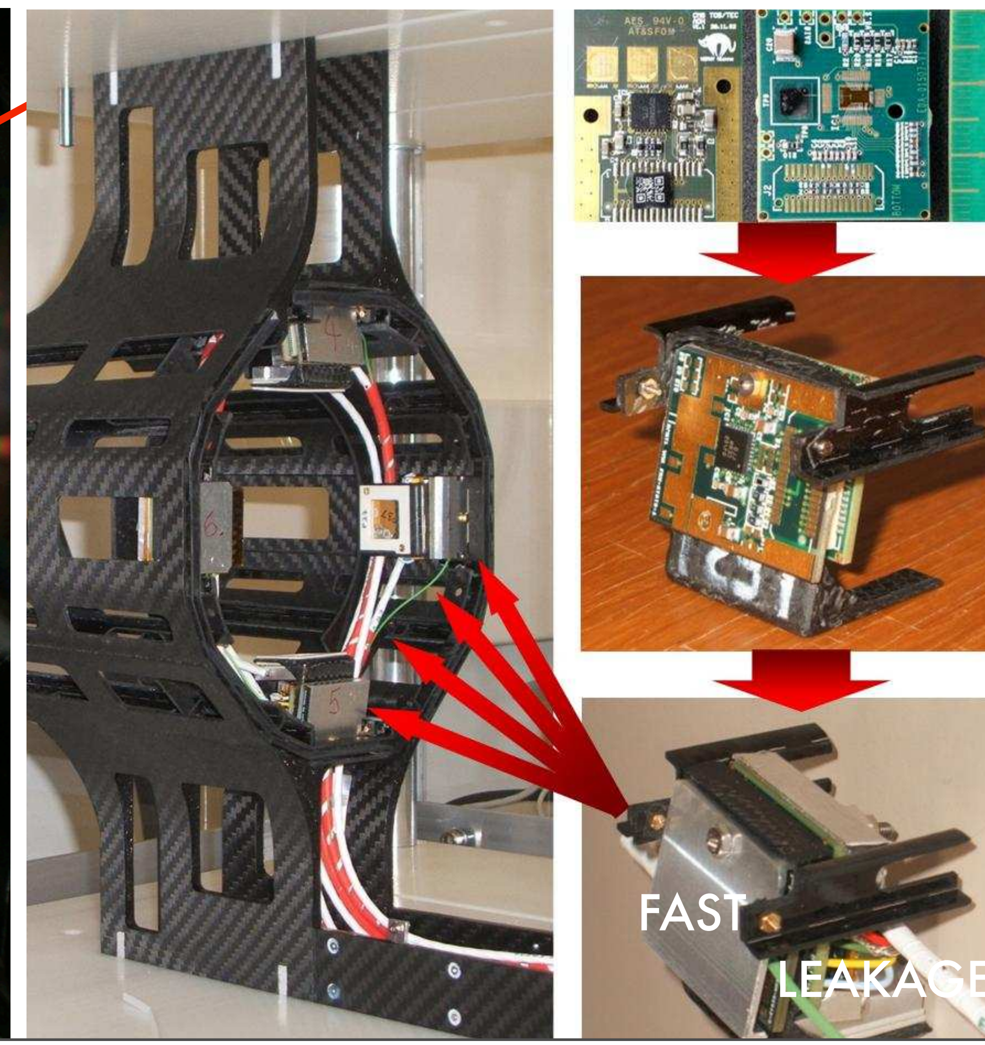


- MIP-sensitive
- Analogue-optical readout
- Dynamic range of 1-10 MIPs in 25ns
- Zero-noise
- Radiation hard
- *W. Lohmann et al., "Fast Beam Conditions Monitor BCM1F for the CMS Experiment", NIM A614 (2010) 433*

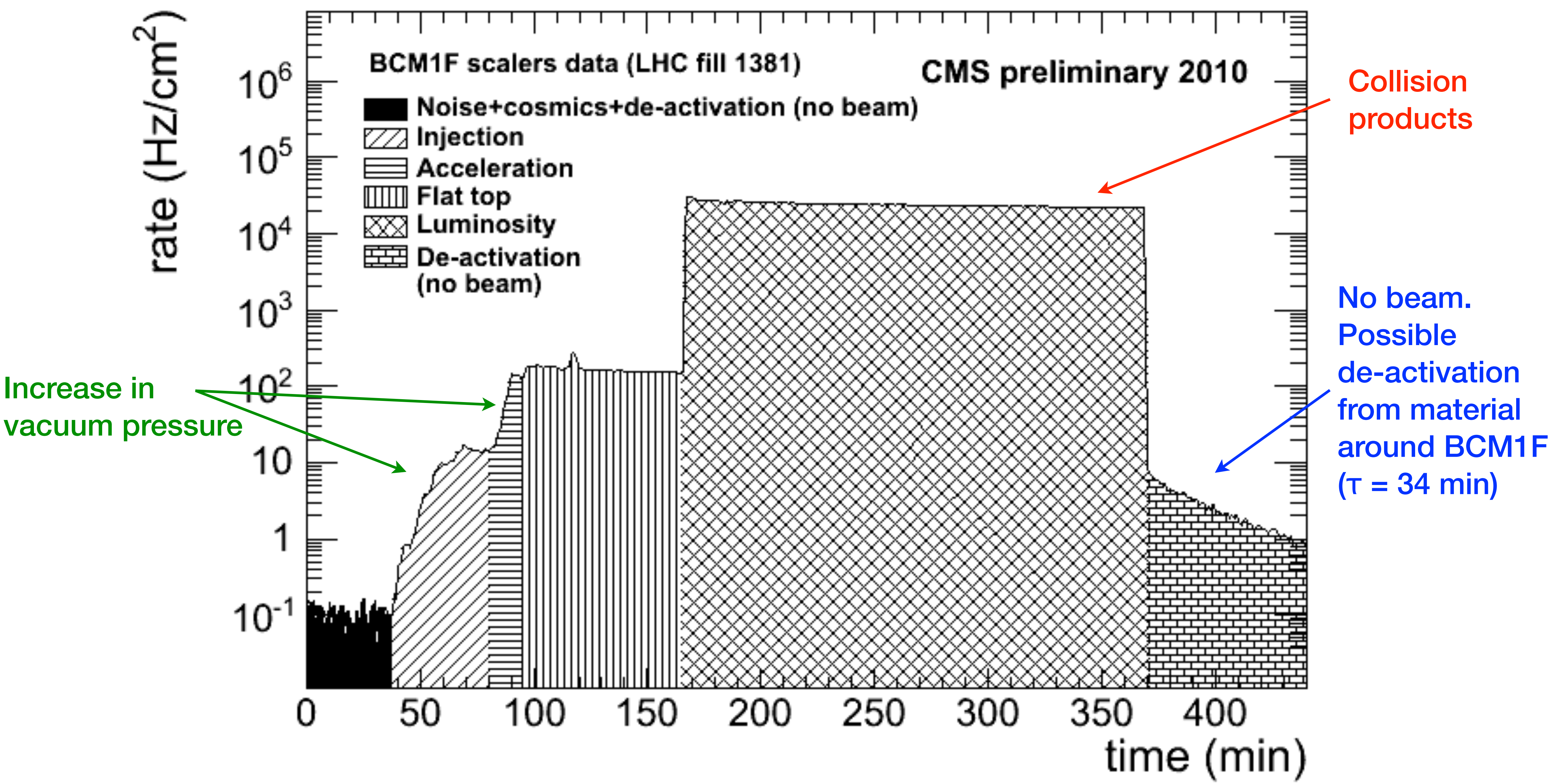
- S/N ranges from 15-28
- Single hit timing resolution of 1.3 ns





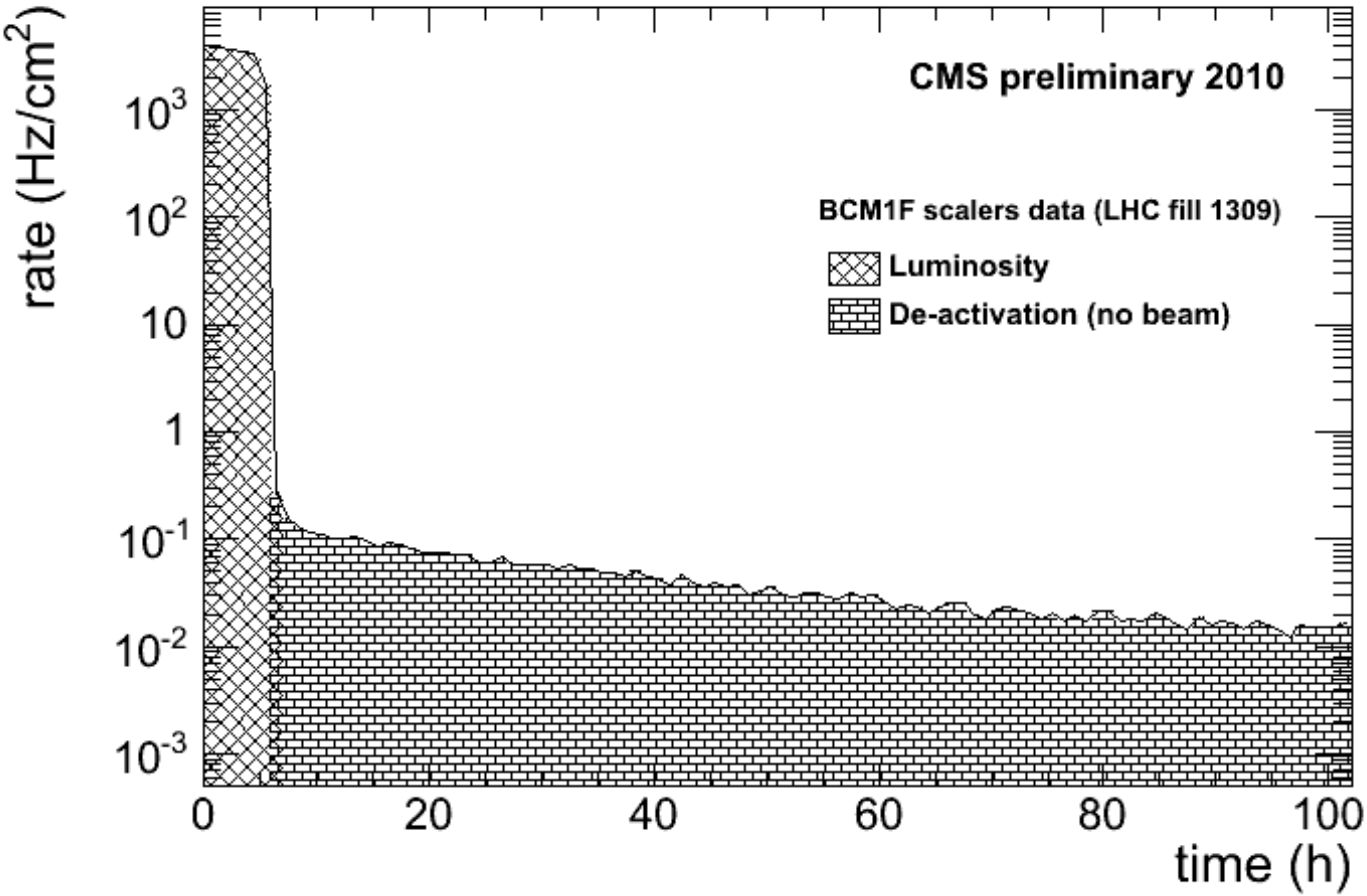


Fast Beam Conditions Monitor (BCM1F): A Typical LHC Fill



- Dynamic range > 6 orders of magnitude

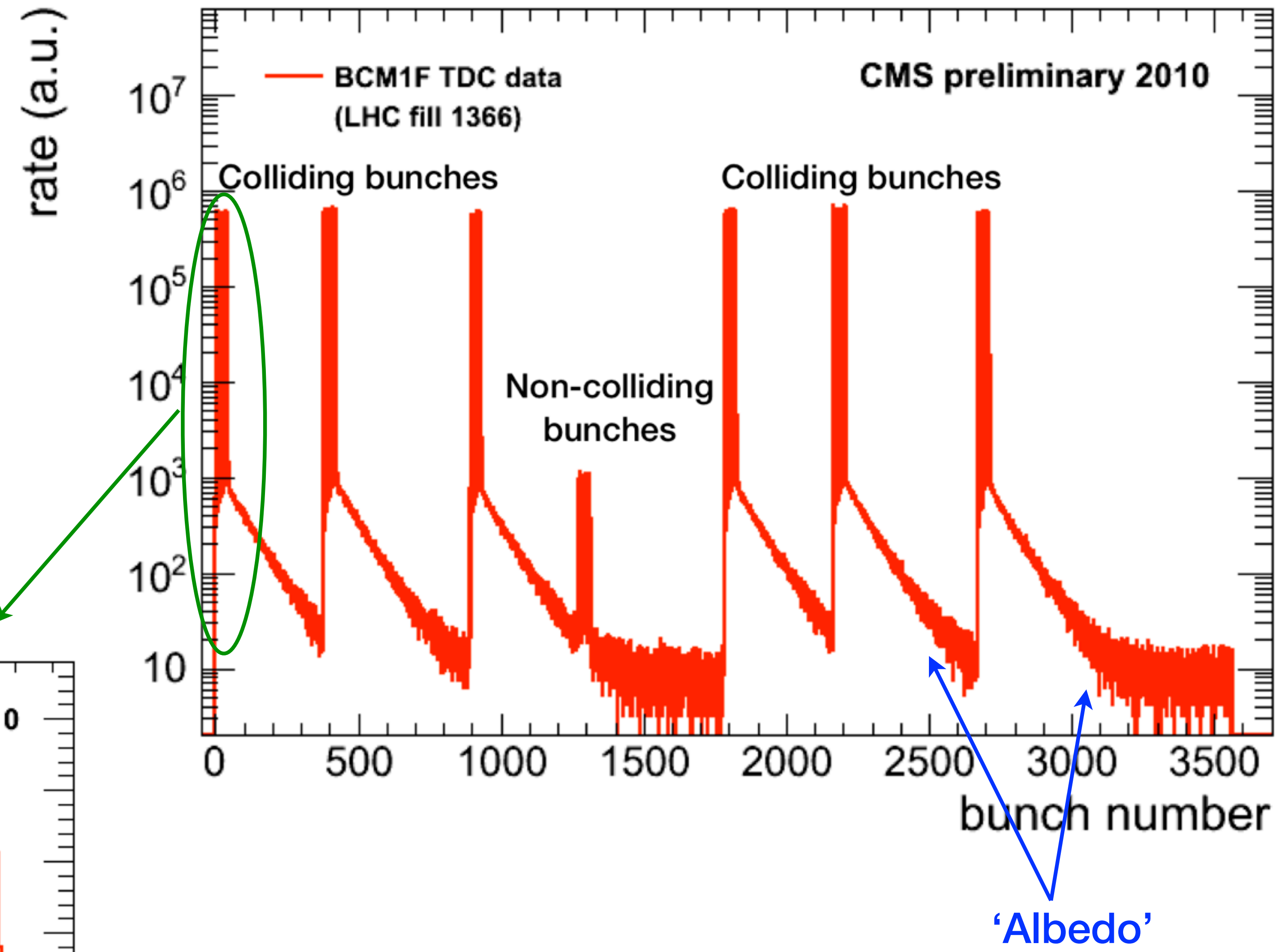
Fast Beam Conditions Monitor (BCM1F): After a LHC Fill

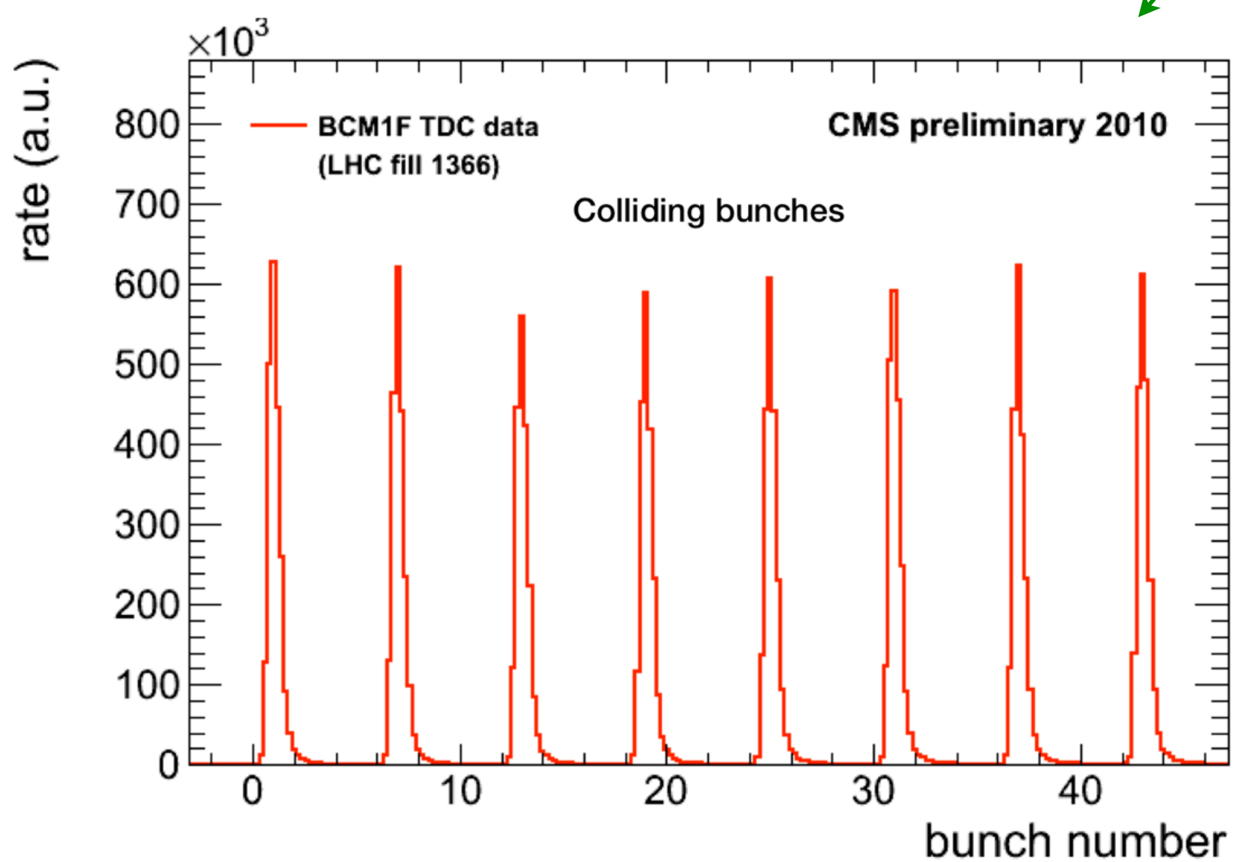


During a long period without beams, a slope in the BCM1F rates is observed (τ = 40 h)
Due to de- activation of the material around BCM1F. Might become a useful tool ...

Fast Beam Conditions Monitor (BCM1F): Monitoring the Full LHC Orbit

- The time provided by the TDCs with respect to the orbit trigger is converted into bunch number following the LHC number scheme.
- Important to identify 'bad-behaving' bunches...

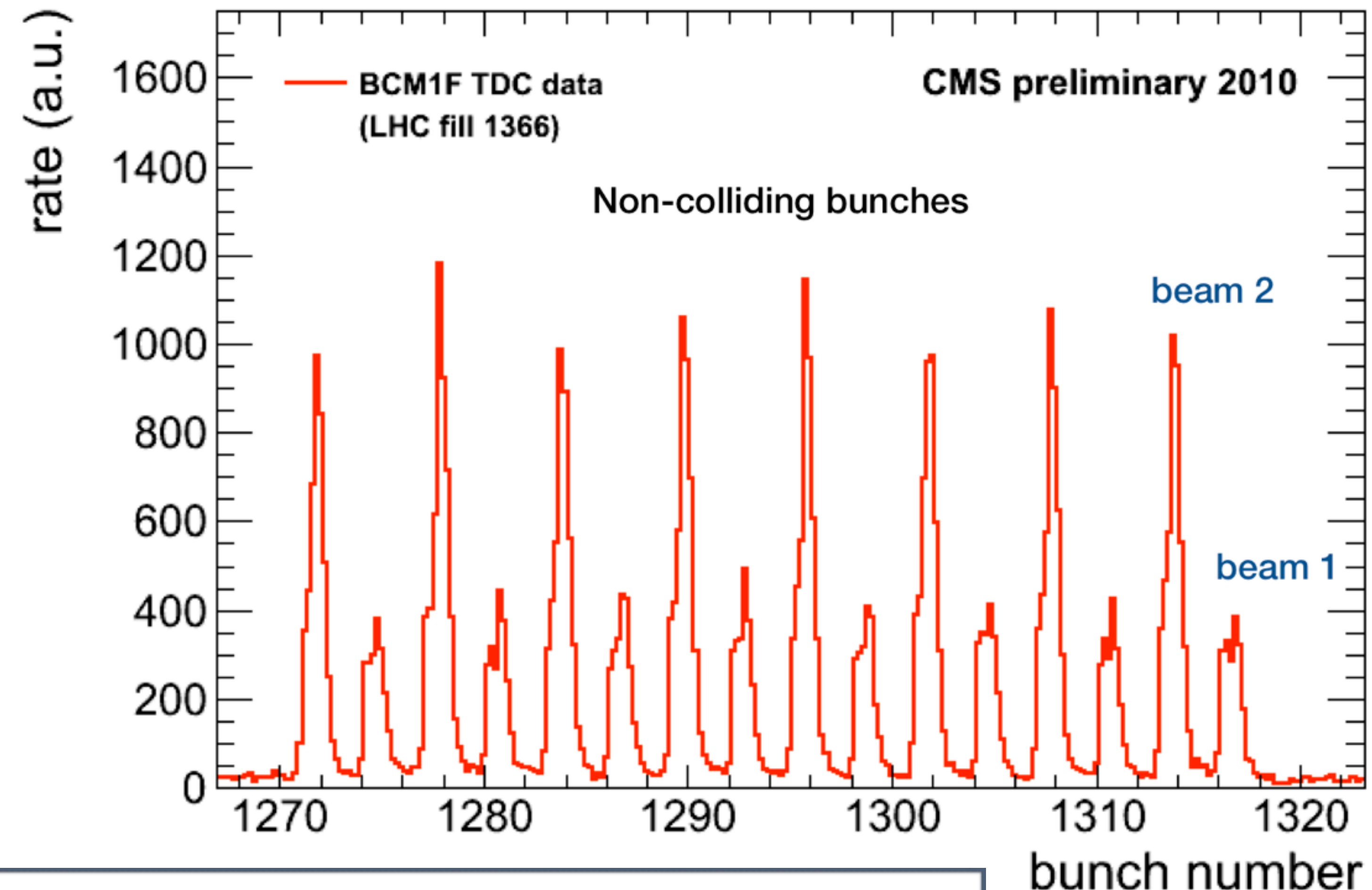


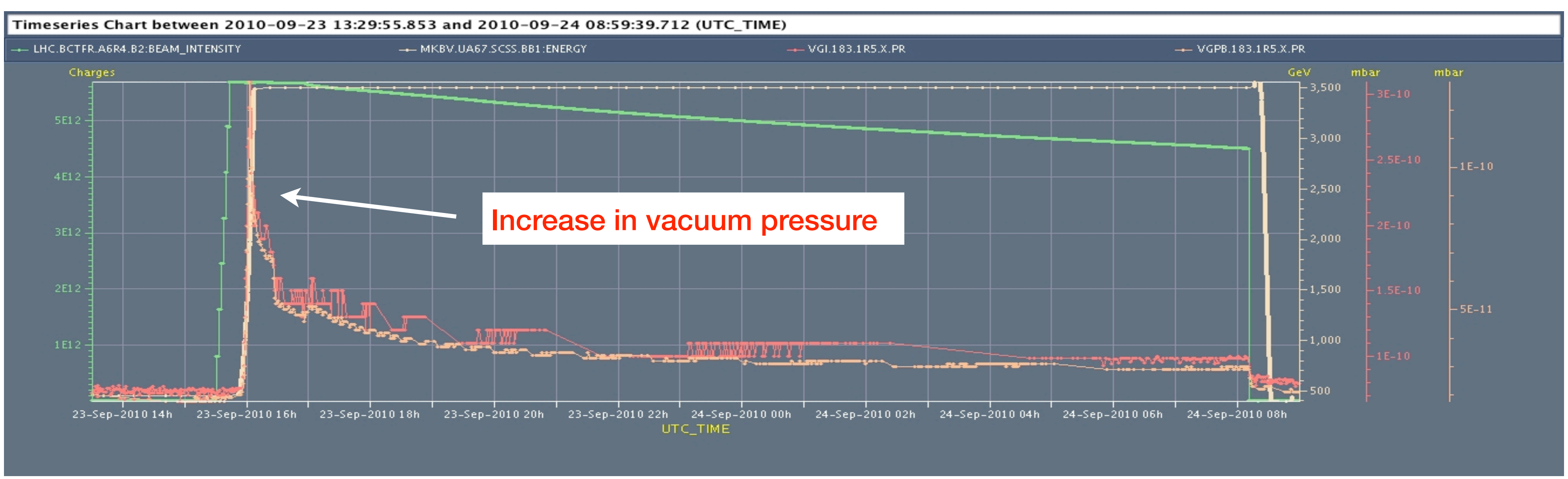


Train with 8 bunches;
150 ns bunch spacing

Fast Beam Conditions Monitor (BCM1F): Vacuum Bump

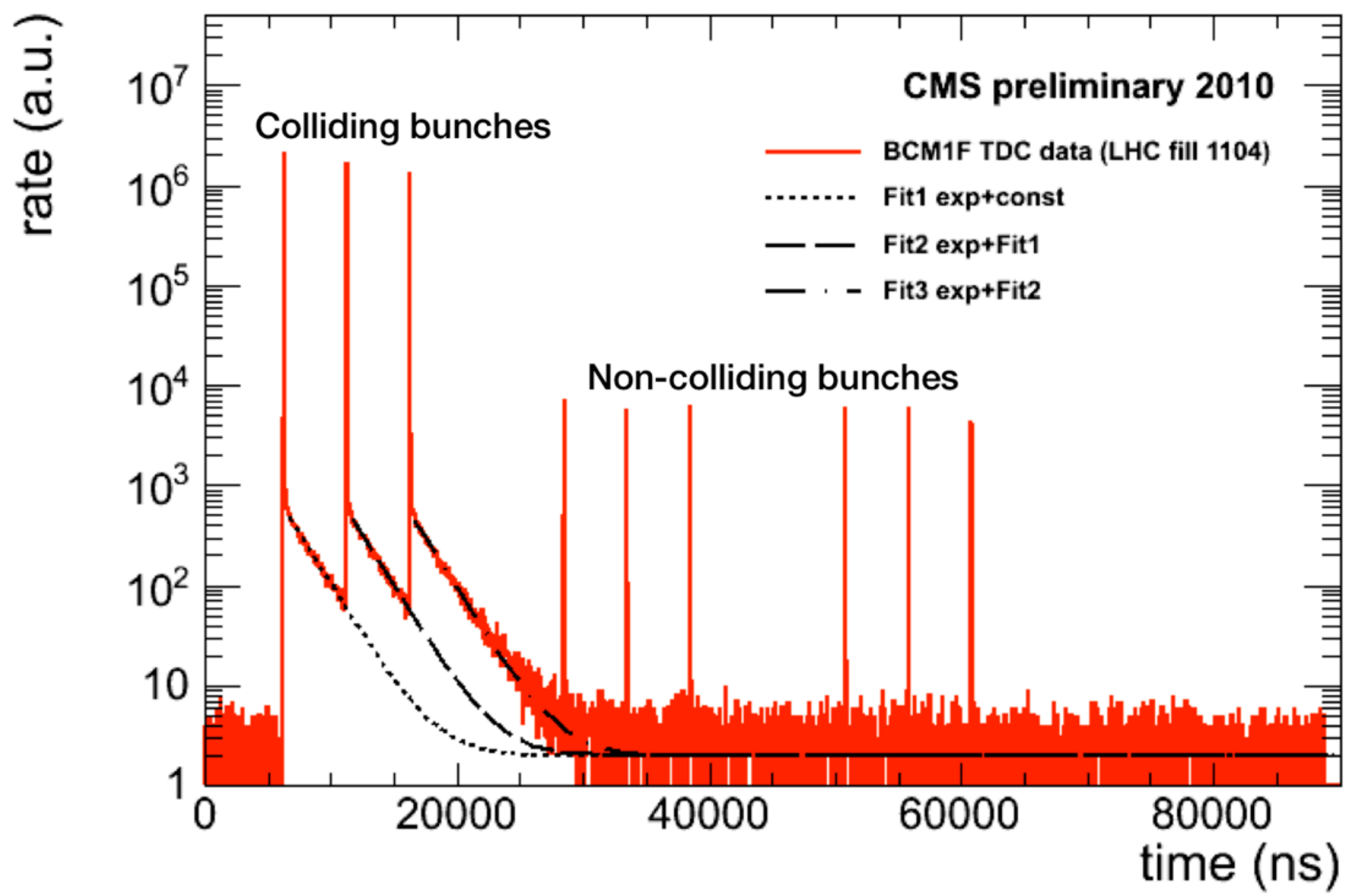
- Looking non-colliding bunches one can infer different beam conditions bunch-by-bunch.
- Here the difference from beam 1 and beam 2 is possibly due to an increase in the vacuum pressure on the side where beam 2 enters the CMS detector.

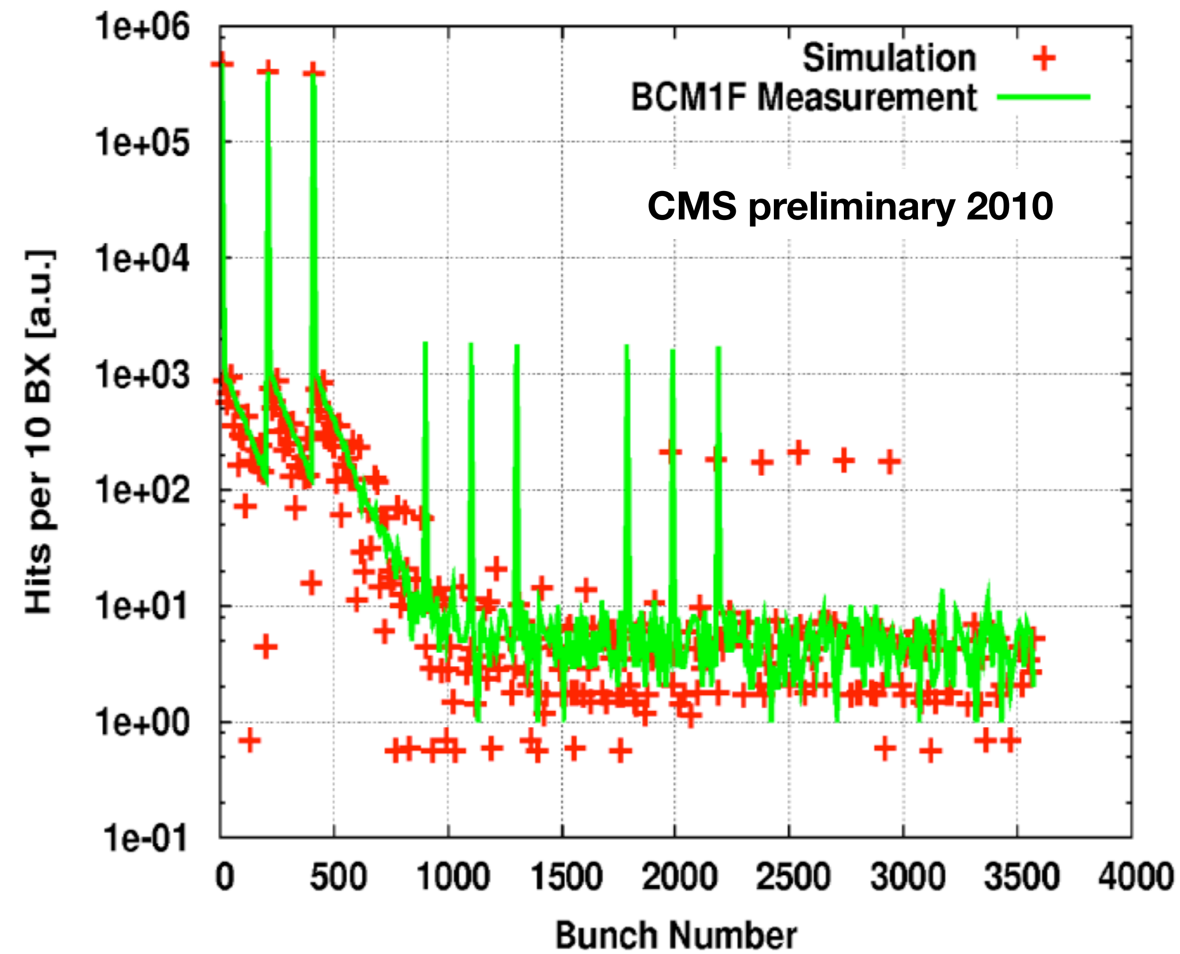




Fast Beam Conditions Monitor (BCM1F): “Albedo” Effect

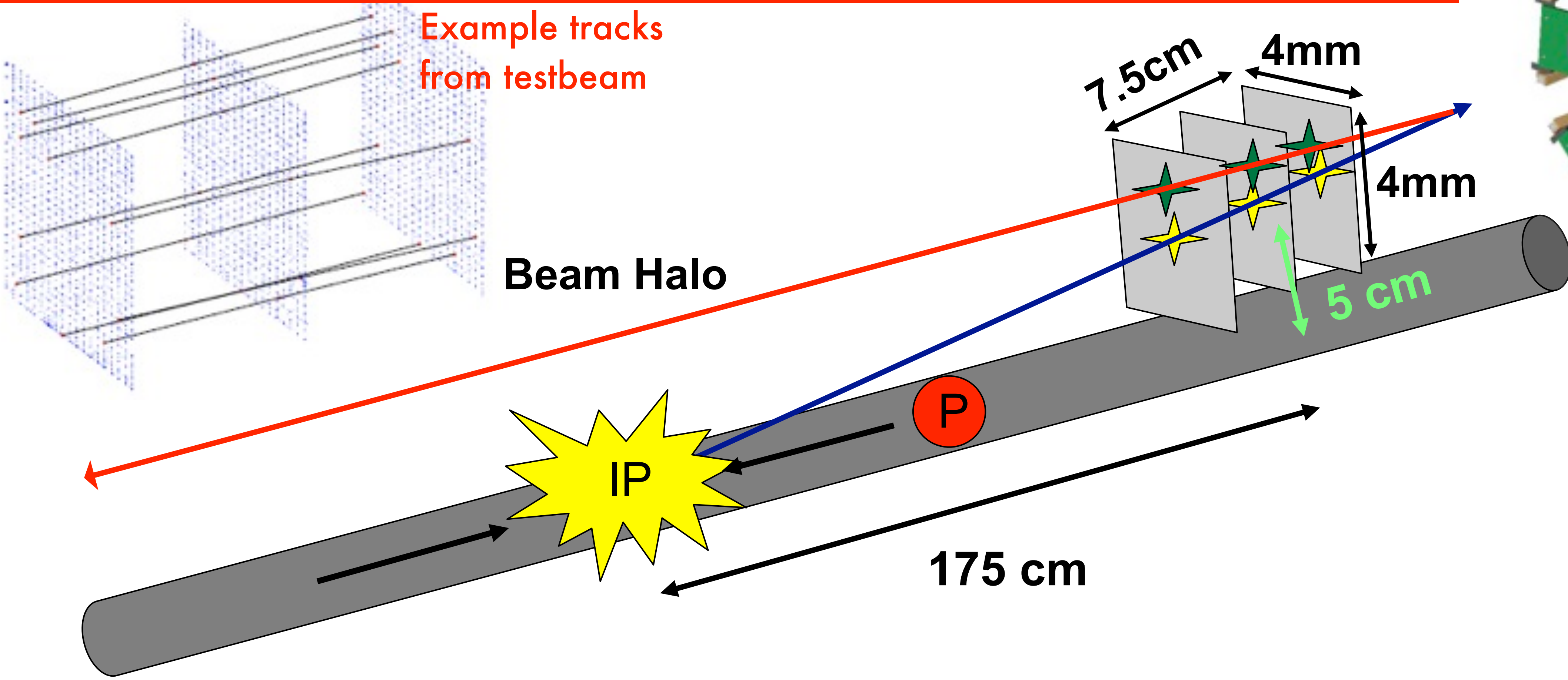
- Collisions produce long tails, of exponential and constant shapes.
- The long exponential component has a ‘lifetime’ of (2.12 ± 0.02) μs.
- Simulation (FLUKA) was performed and show good agreement with the data. Tails are mostly populated by electrons and positrons (up to 400 bunch crossing) and by neutrons and photons.

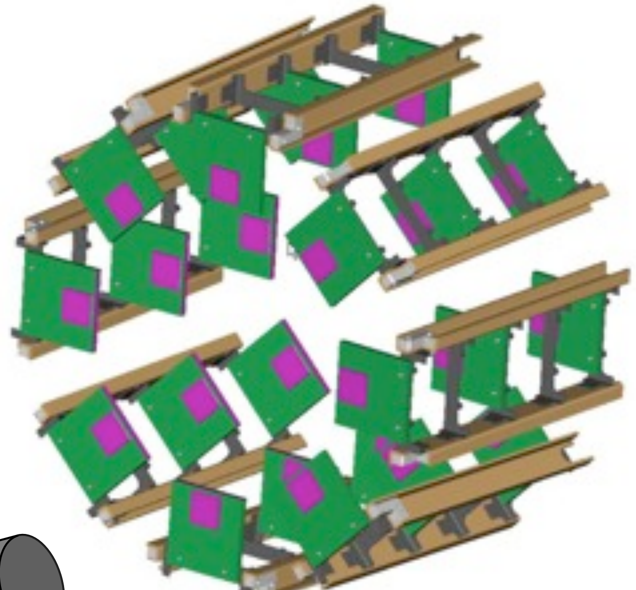




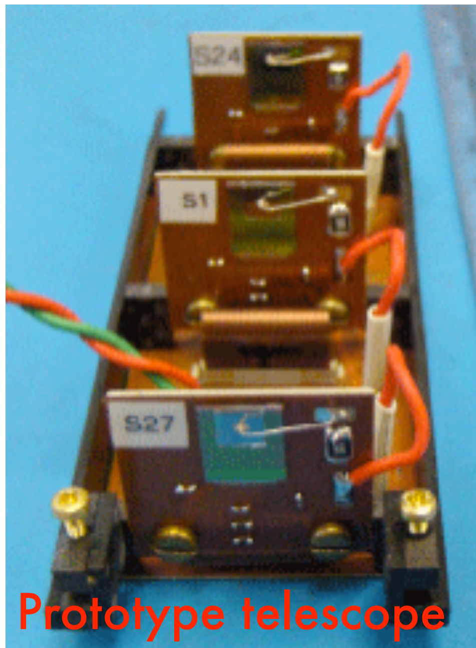
- Simulation also describes similar data from other detectors in good detail

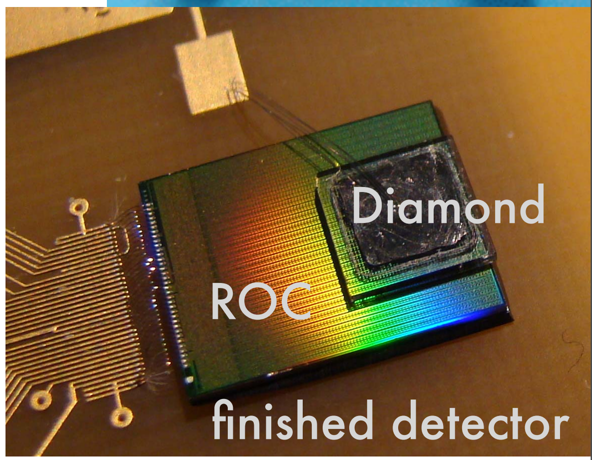
Pixel Luminosity Telescope





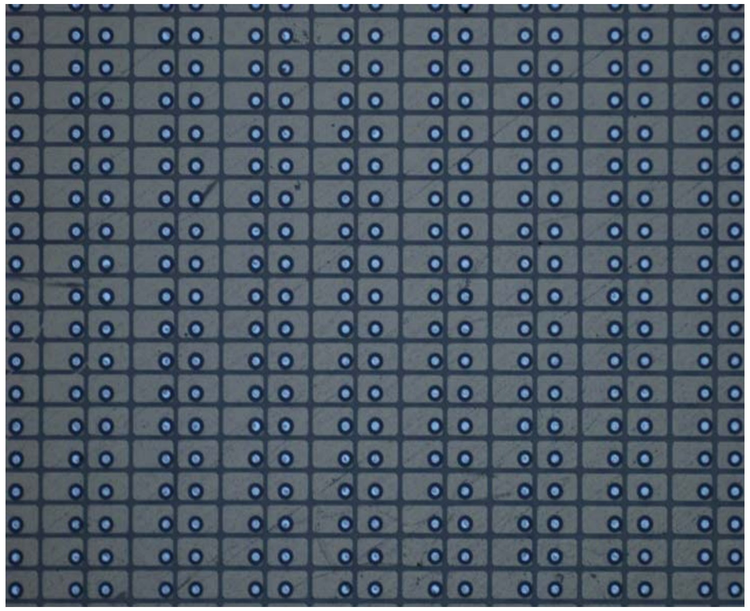
8 telescopes per "end"



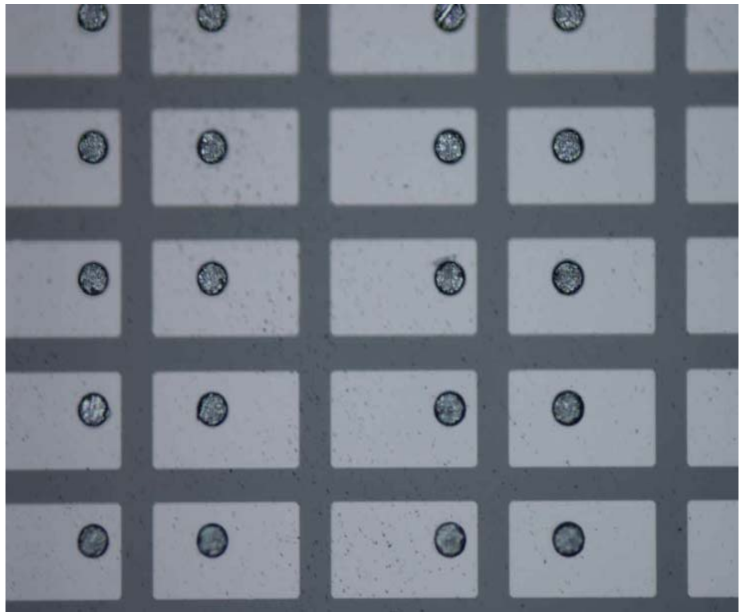


- Beam monitoring is also about optimising the number of collisions
- Luminosity is the measure of the number of pp collisions
- Measure luminosity by counting tracks from the IP every 25ns
  - Online relative luminosity to a precision of 1%
- Use single crystal cvd diamond, bump bonded to pixel chip PSI46
- Tested in numerous test beams - pixel yield and fast-OR >98%
- Planes produced, assembly > 50% complete, ready for installation in next long shutdown
- Will be first diamond pixel tracker to be installed in HEP
- *Testbeam results published: NIM A (2010)*

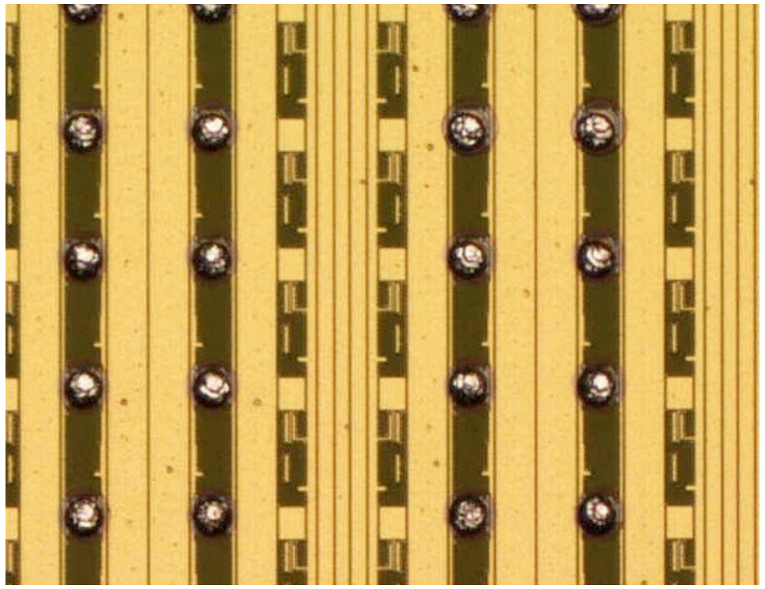
Detector Fabrication



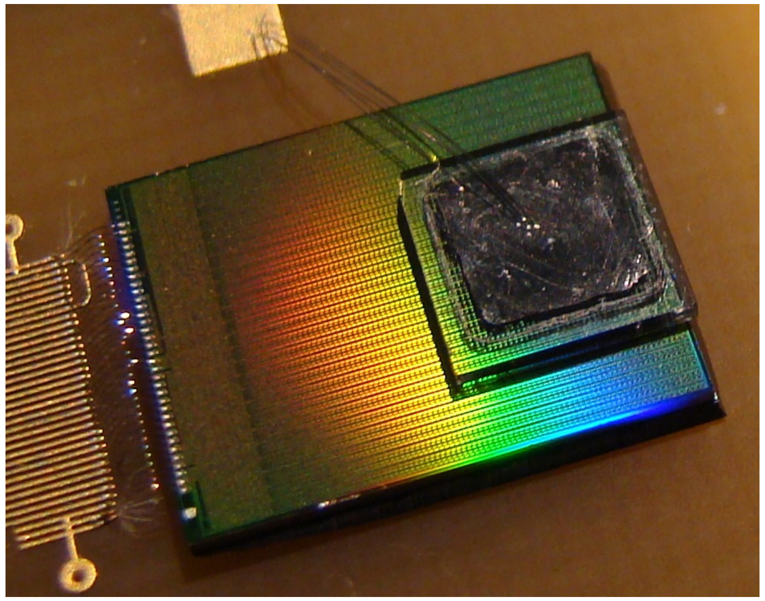
patterned diamond



indium bumps



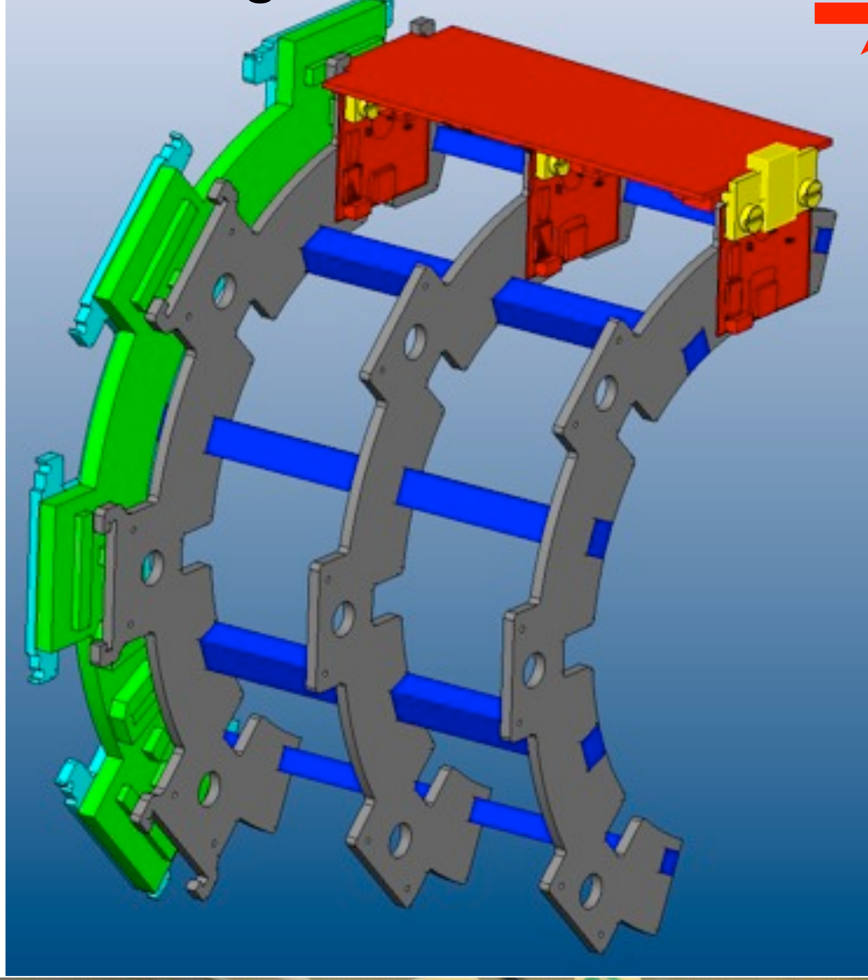
bumped ROC

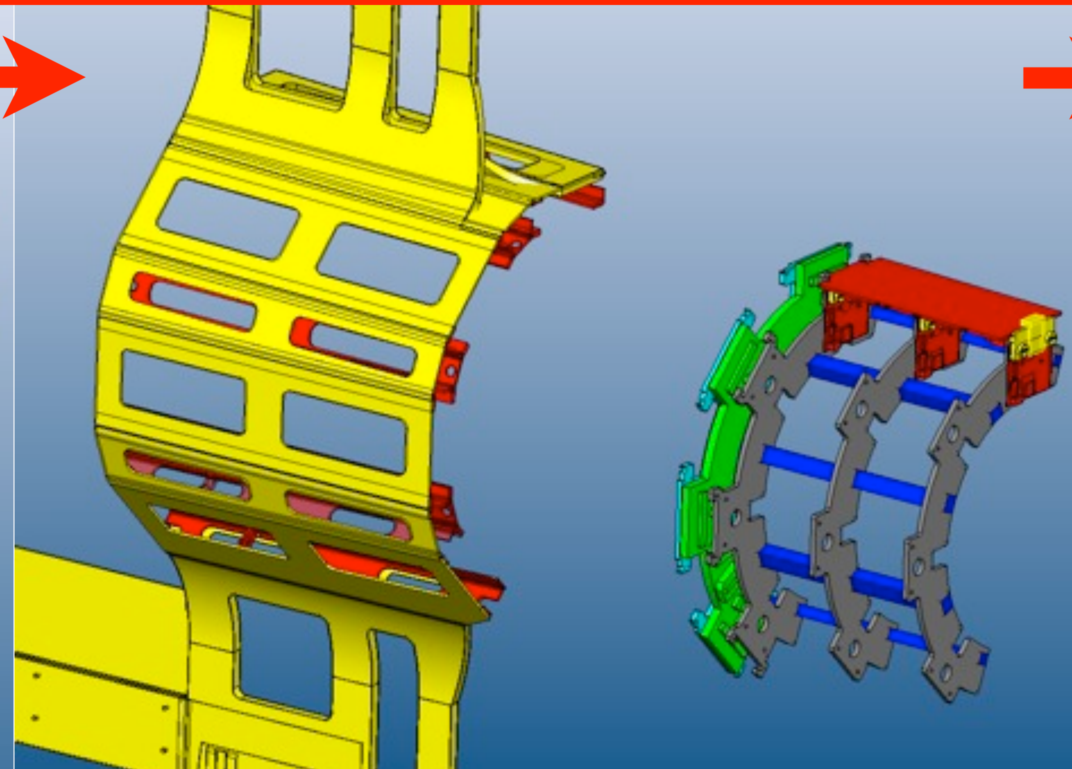


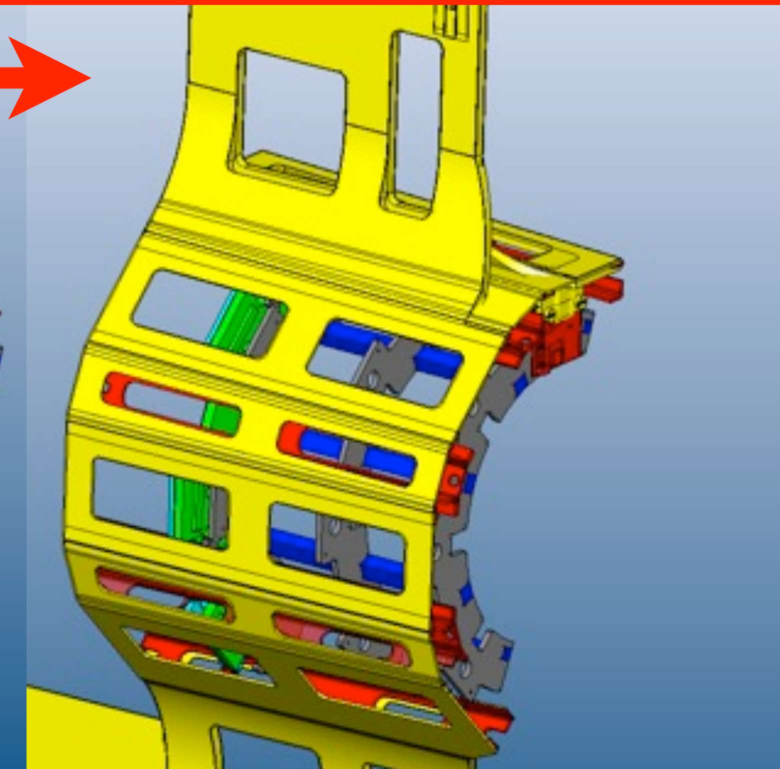
bumped detector

Pixel Luminosity Telescope

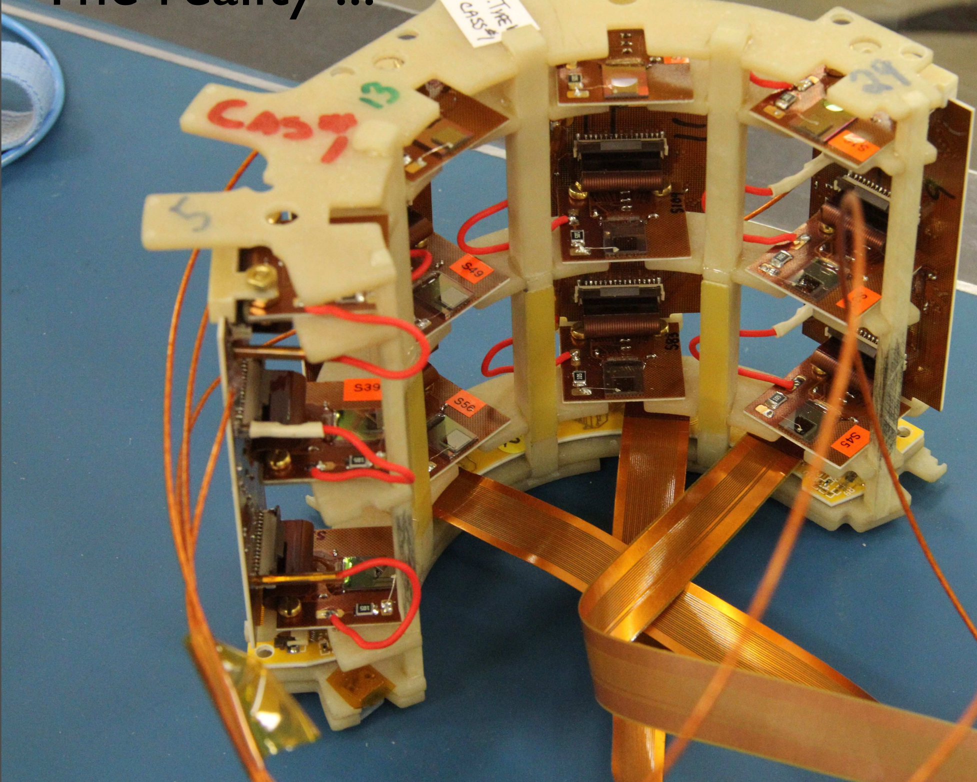
The design ...

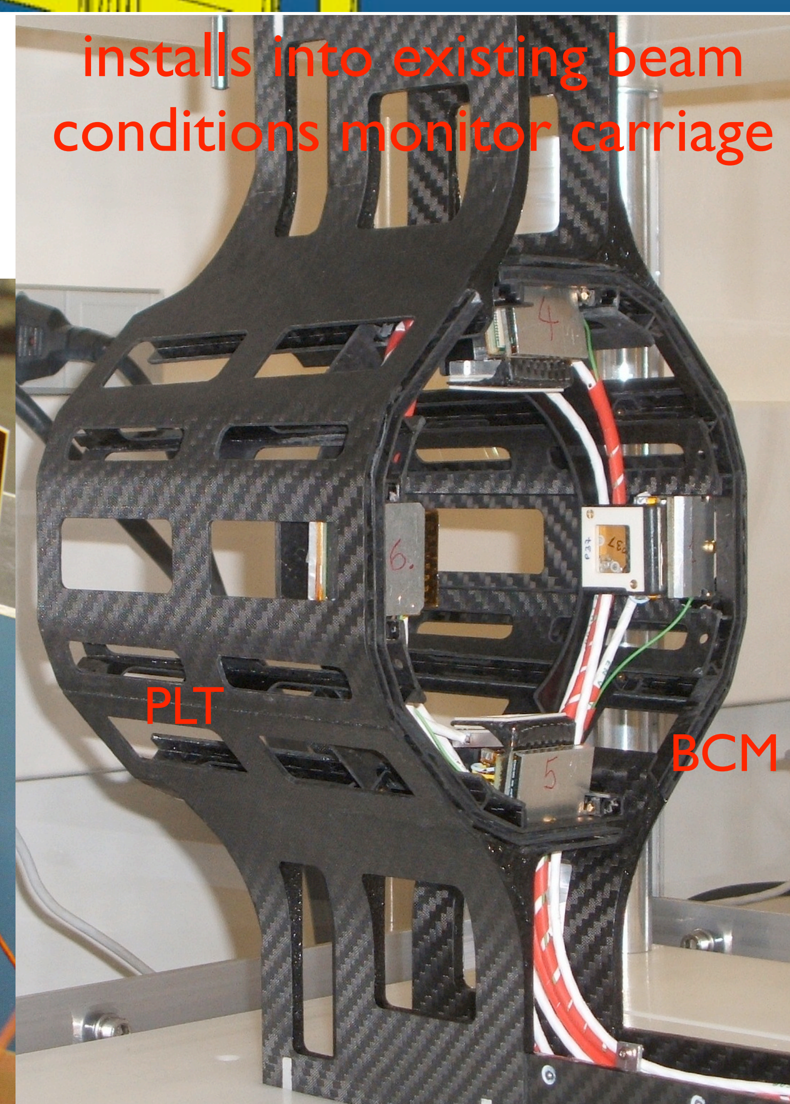


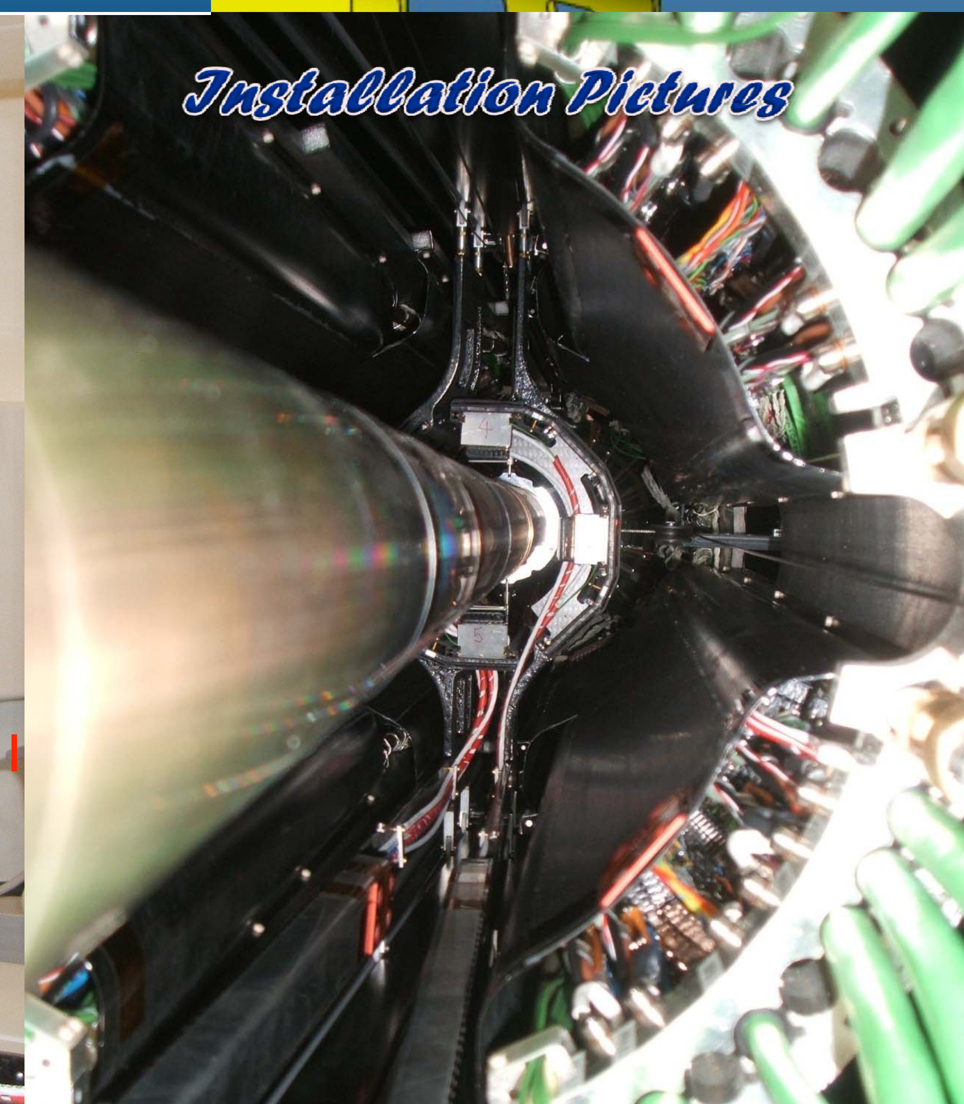




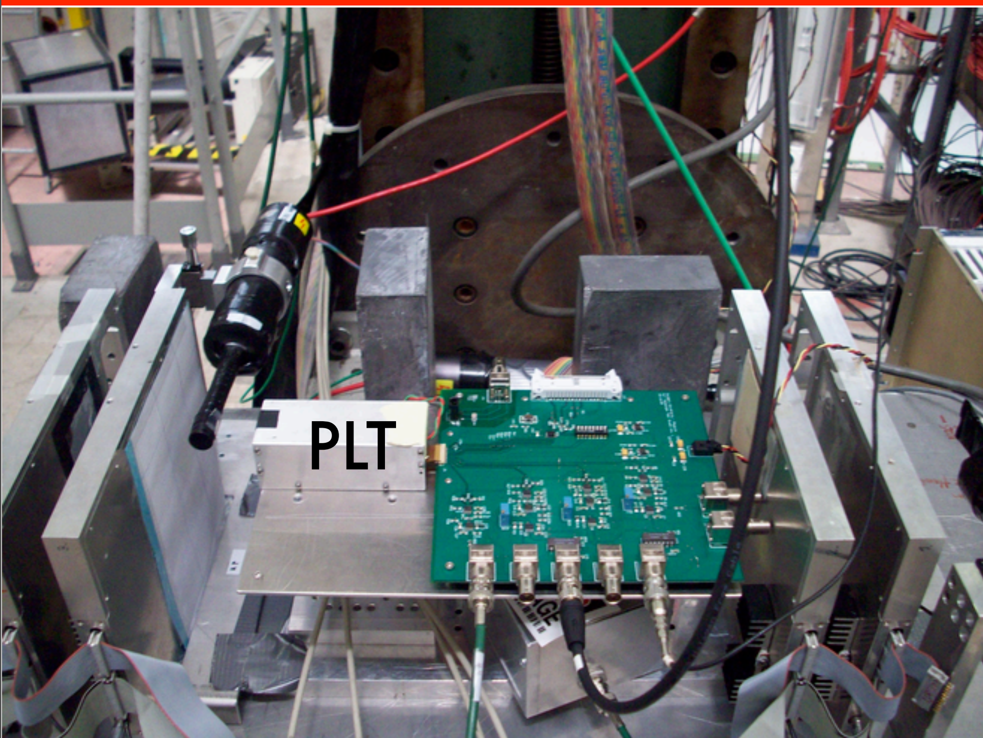
The reality ...



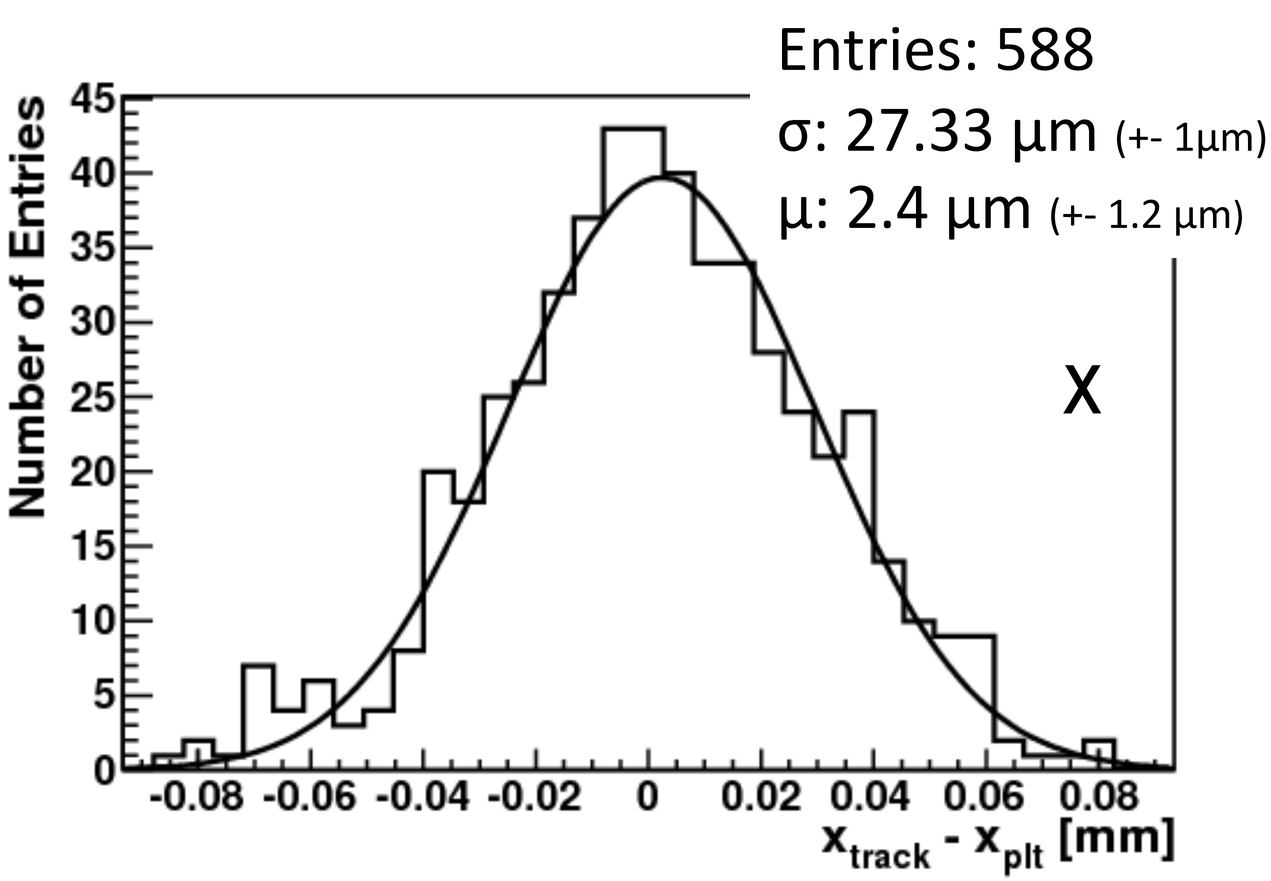


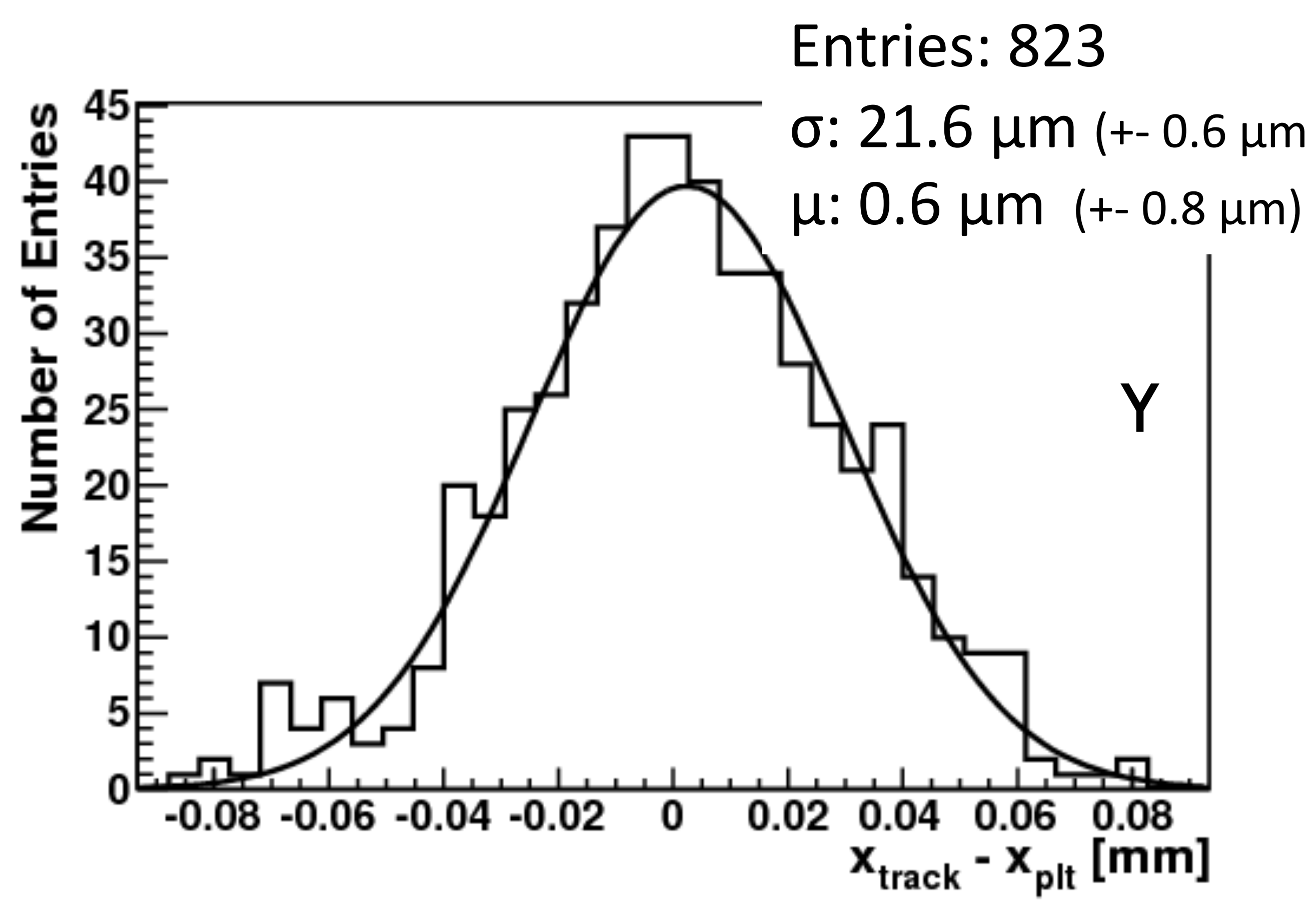


Pixel Luminosity Telescope: Spatial Resolution



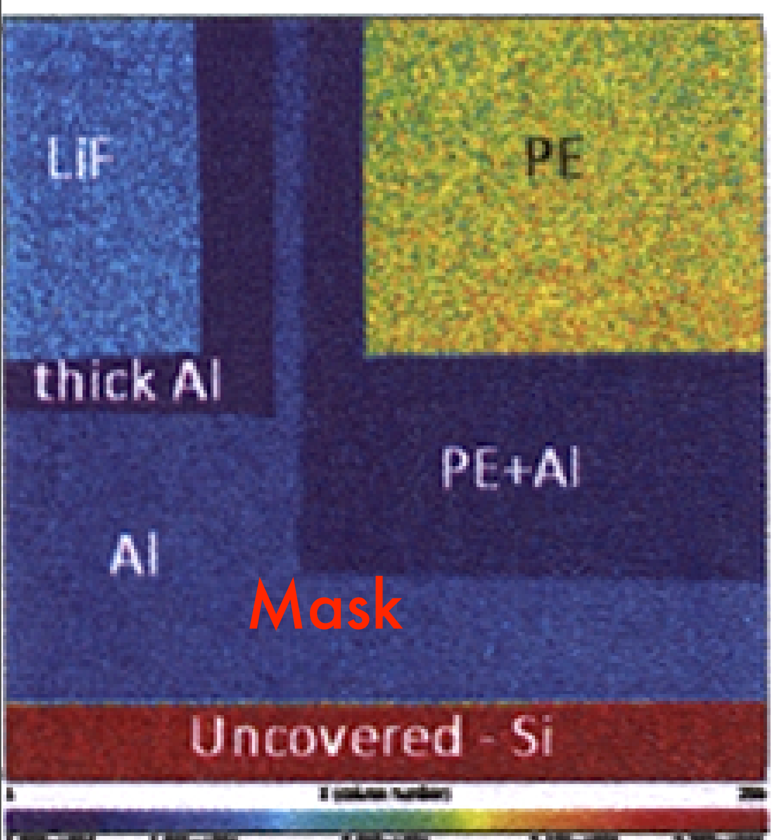
- 8 GeV proton testbeam from May 2010
- Look at the spatial resolution with perpendicular incidence
- Digital resolution:
  - X: 43 um
  - Y: 29 um
- Measured resolution:
  - X: 27 um
  - Y: 22 um





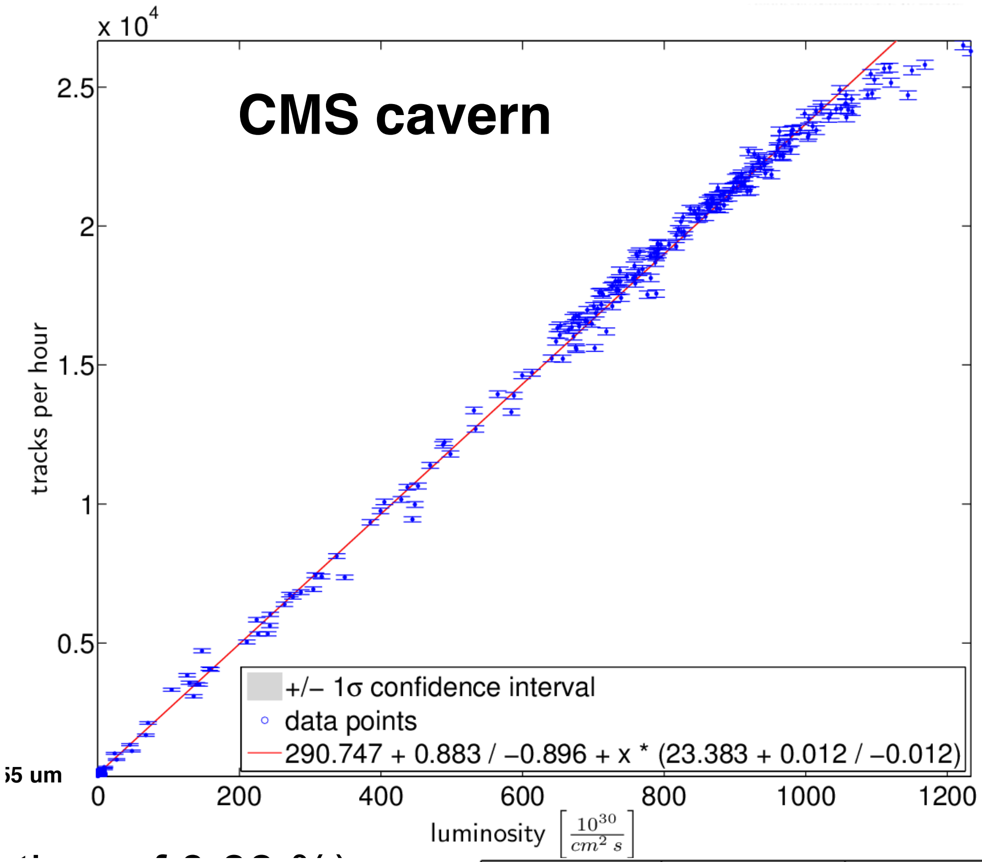
Radiation Environment in the CMS Cavern

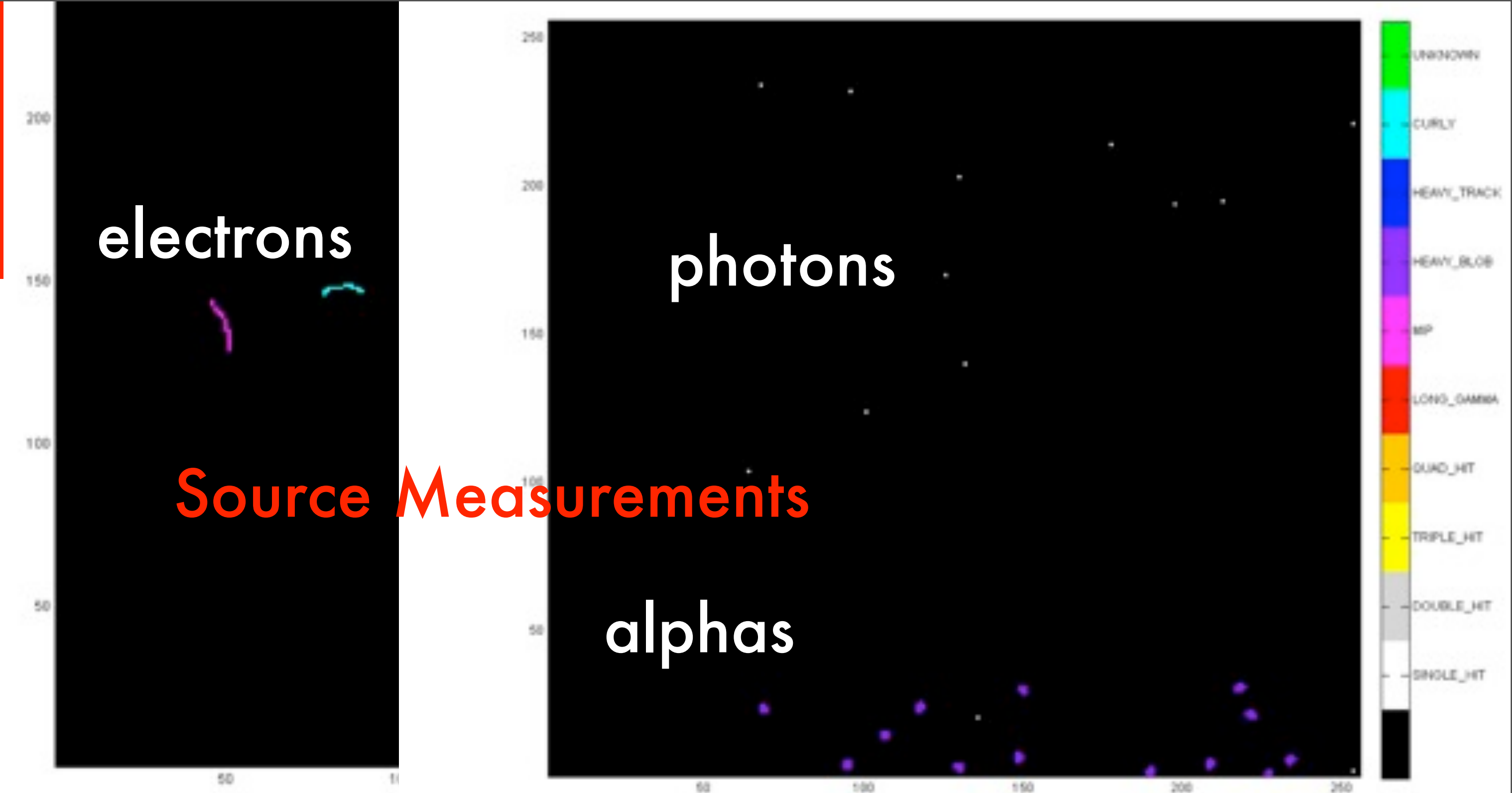
- Looking at the radiation environment a little further away from the central detector
- Close to sensitive electronics
- Important to understand the flux within the CMS cavern
- Also important to understand the particle type and energy
- In particular, neutrons are a major cause of radiation damage and single event upsets
- Validate simulations throughout the CMS cavern



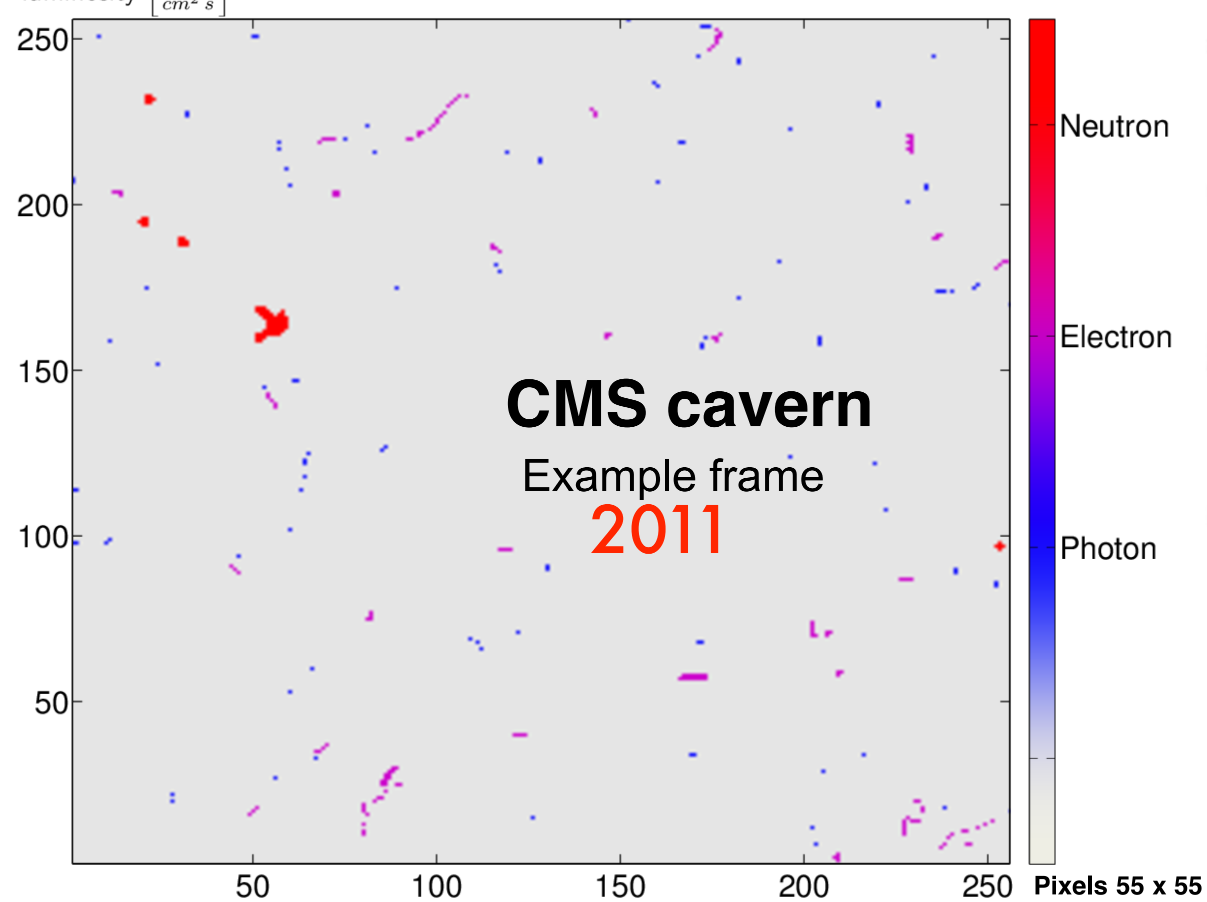
- There are a couple of Medipix neutron cameras installed
- Dedicated devices prepared by IEAP CTU in Prague
- There is a similar larger installation in ATLAS
- Medpix Neutron Cameras are pixelated silicon devices which have several conversion layers applied to have sensitivity to different particle types.
- Analysis of deposits in each layer gives information on particle type: electron, photons, neutrons, ...
  - 6LiF and Polyethylene layers to convert thermal (1%) and fast neutrons (0.2%)

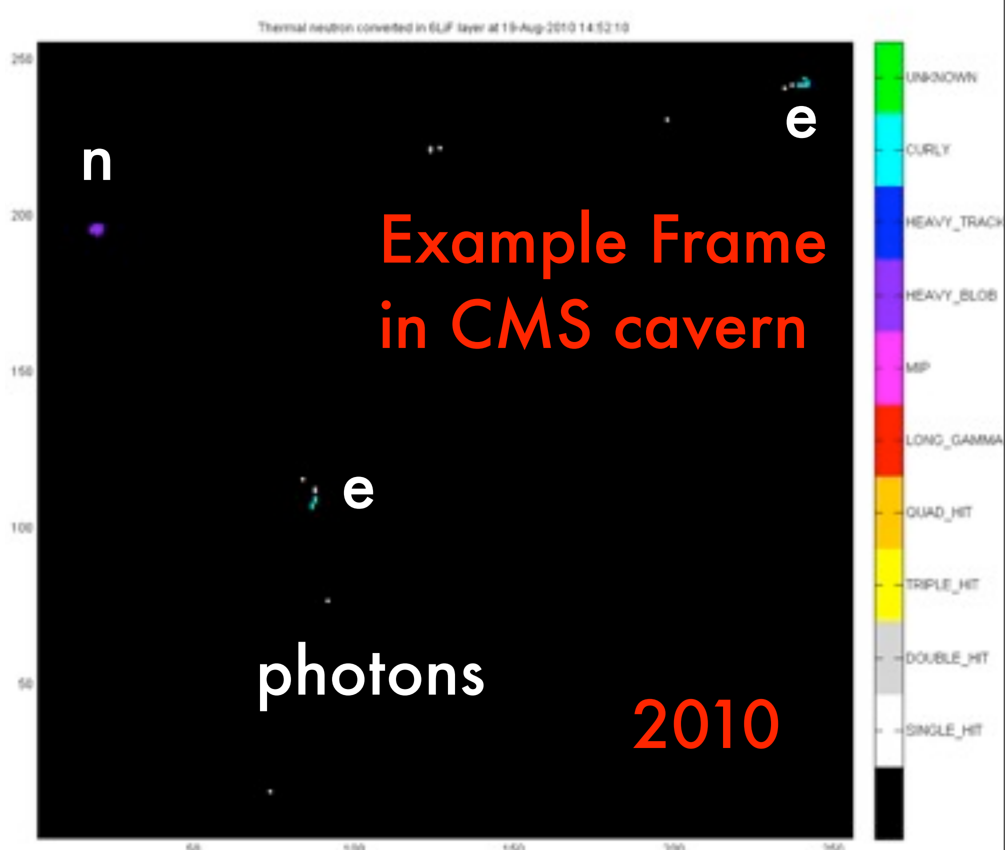
Particle Identification in the CMS Cavern





- Main discriminant is shape of the cluster
- Scales with luminosity





Particle Identification in the CMS Cavern

- Using the spectra predicted from the simulations as input to the efficiency calculations, the flux at the edge of the CMS cavern can be measured
- Measurements agree very well with the simulations for all measured particle types
- Confirmation that radiation effects in the CMS experimental cavern are dominated by luminosity, not backgrounds
- Checked in 2010 and 2011 Data
- This is a nice validation of the simulations
- A similar device inside the electronics areas gives validation of the cavern shielding
- Other devices (LHC-RADMON, Passives, Proportional Counters) exist to provide other validation points

Particle	Measured Flux $\left[\frac{particles}{cm^2\,s} / \frac{10^{30}}{cm^2\,s}\right]$	Simulated Flux (7 TeV) $\left[\frac{particles}{cm^2\,s} / \frac{10^{30}}{cm^2\,s}\right]$	$\frac{\text{Measured Flux}}{\text{Simulated Flux}}$ [%]
neutrons (< 100 keV)	0.11	0.1017(14)	105
neutrons (100 keV - 20 MeV)	0.071	0.0659(07)	108
neutrons (> 20 MeV)	-	0.0181(03)	-
neutrons (all without neutrons > 20 MeV)	0.178	0.1858(12)	96
charged hadrons	-	0.000378(44)	-
electron	0.0023	0.0023(01)	100
photon	0.15	0.1354(19)	111
all (without neutrons > 20 MeV)	0.33	0.3260(23)	101

Summary

- Beam monitoring is very important for experimental protection and optimisation of conditions
  - Monitoring diagnostics to help reduce beam losses and increase number of collisions
  - Also in terms of having a validation of the simulated radiation field

- By example, an overview of how this is done for the CMS experiment at the LHC
- A glimpse of some of the early results on this