PARTICLE COLLIDER INTERACTION REGIONS

Backgrounds and Machine-Detector Interface

Lecture 2: Hadron Colliders

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Lecture 2

Hadron Collider Backgrounds and MDI

OUTLINE

- Backgrounds at Hadron Colliders
- Machine-Induced Backgrounds
  - Tertiary beam halo
  - Beam-gas interactions
  - Missteered beam
- Operational Cases
- Accidental Cases


LHC

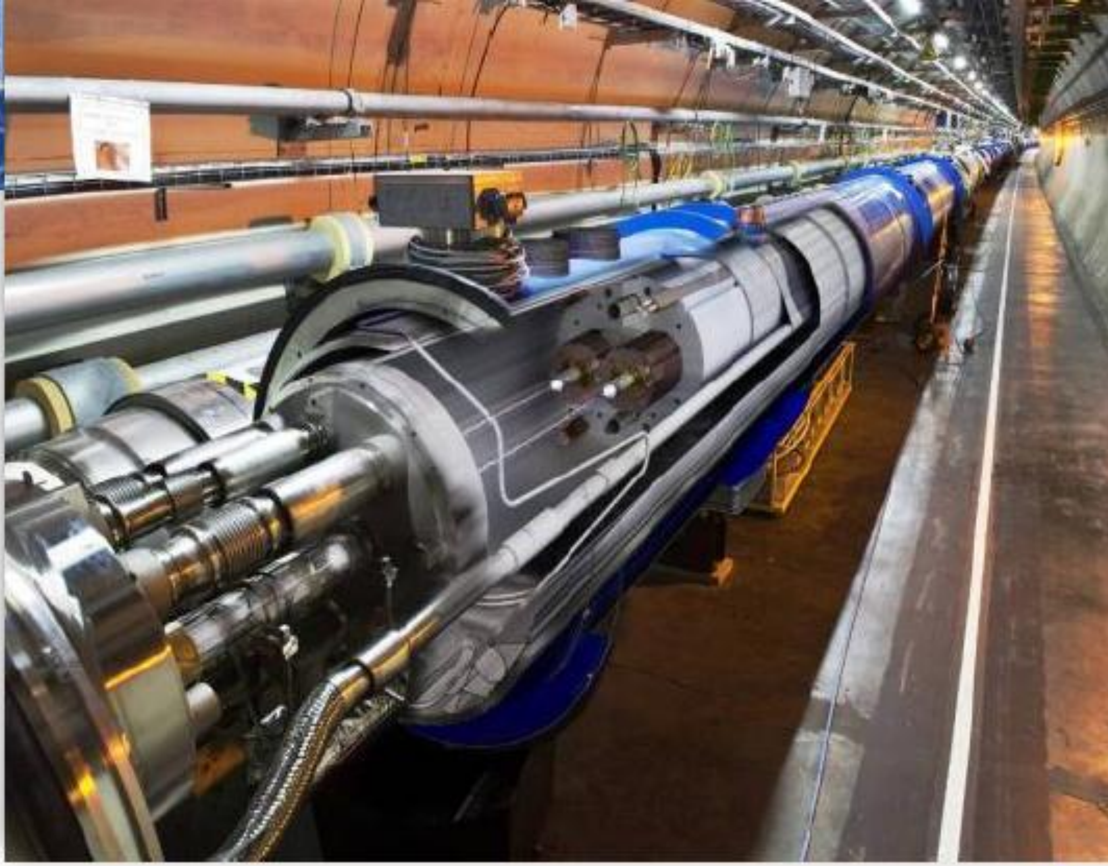
INTRODUCTION (1)

The overall detector performance at colliders is strongly dependent on the background particle rates in detector components. At hadron colliders (LHC and Tevatron), particles originating from the interaction point (IP) are thought to be the major source (>99%) of background and radiation damage in the detectors at nominal parameters and with a well tuned machine.

INTRODUCTION (2)

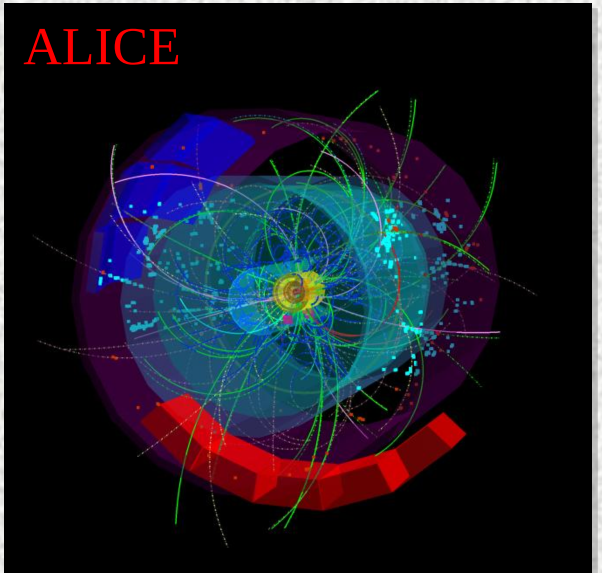
Beam loss in the IP vicinity is the second source of background, but minor at nominal conditions. Particle fluxes generated by such beam interactions are called **machine-induced backgrounds (MIB).** The relative importance of this component can be comparable to the first one at early operation of the LHC because MIB is mostly related to beam intensity and not luminosity, and tuning of the LHC will require substantial time and efforts. These facts are confirmed by the Tevatron experience.

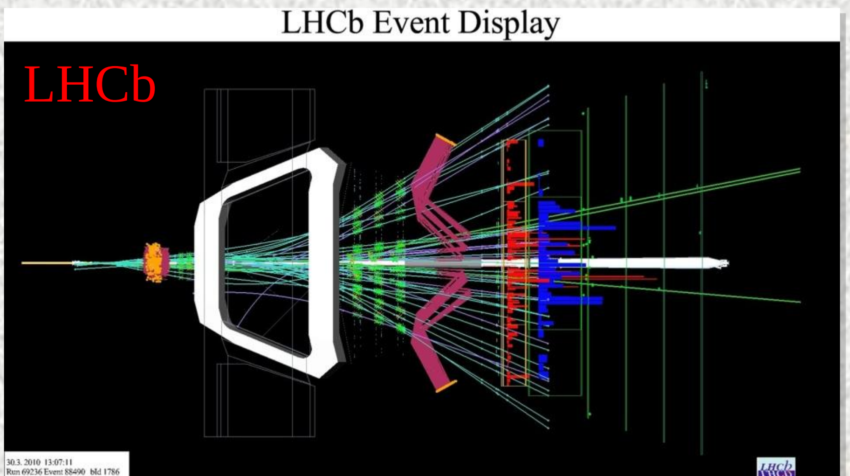
What is special with LHC ?

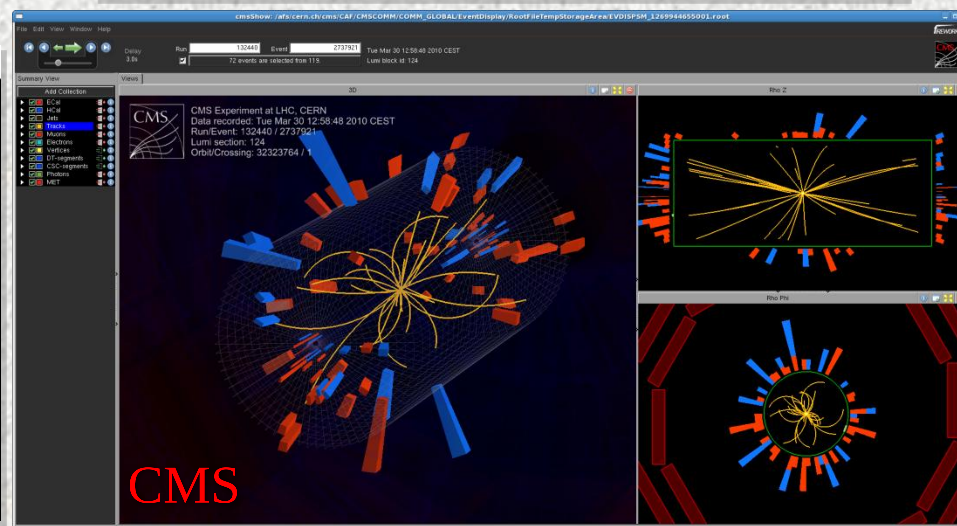


- The highest field accelerator magnets: 8.3 T (ultimate: 9 T)
- Proton-Proton machine : Twin-aperture main magnets
- The largest superconducting magnet system (~8000 magnets)
- The largest 1.9 K cryogenics installation (superfluid helium)
- The highest currents (up to 13 kA) controlled with high precision, few ppm
- A sophisticated and ultra-reliable magnet quench protection system
- 350 MJ beams to steer, collimate, squeeze and dump

LHC: First collisions at 7 TeV on 30 March 2010







Beam Halo and Beam Losses (1)

Even in good operational conditions in an accelerator, some particles leave the beam core – due to various reasons - producing a beam halo. Particle fluxes, generated in showers developed at halo interactions with limiting apertures, are responsible for MIB rates and radiation loads in accelerator and detector components. A multi-stage collimation system reduces these rates at critical locations by a factor of $>10^3$ at the Tevatron and LHC.

Beam Halo and Beam Losses (2)

In addition to these slow losses, there is a probability of fast single-pass losses, caused, e.g., by an abort kicker prefire, when a certain number of bunches can make it through an unprotected section of the ring and be lost in front of the detector. Impact on the machine and collider detectors can be quite severe. Tertiary collimators - as the last line of defense for slow and fast beam losses in the IP vicinity - are mandatory in the LHC, as proven at the Tevatron.

Three Sources of MIB

Compared to the luminosity-driven backgrounds at the IPs, machine-induced backgrounds (MIB) are less studied, their characteristics vary in a broader range, and – at a low luminosity – they can be a serious issue. The collimation system takes care of "slow" losses with a very high efficiency. But still three following components form the MIB at the detectors (considering LHC specifics):

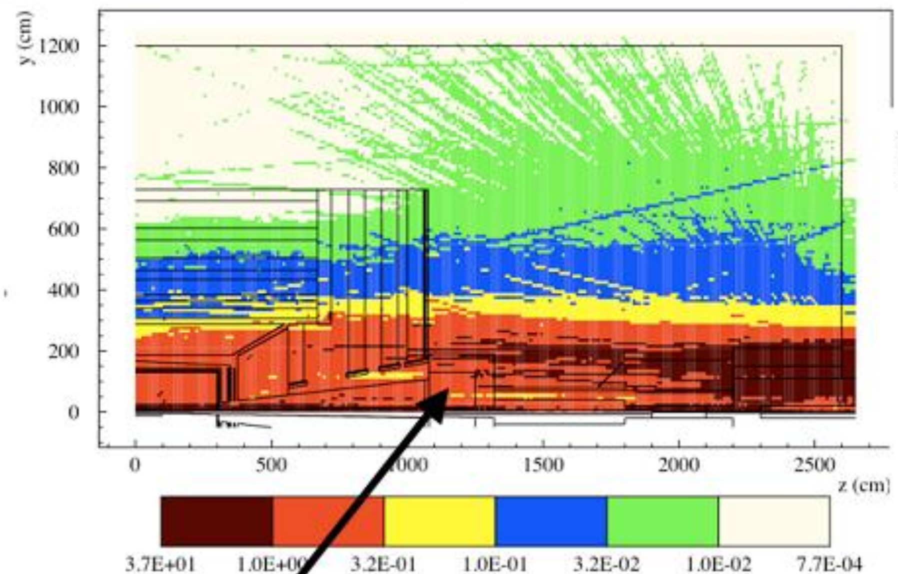
1. **Tertiary beam halo** generated in the IP3 and IP7 collimation systems ("collimation tails").
2. **Beam-gas:** products of beam-gas interactions in straight sections and arcs upstream of the experiments and after the cleaning insertions.
3. **"Kicker prefire":** any remnants of a missteered beam uncaptured in the IP6 beam dump system.

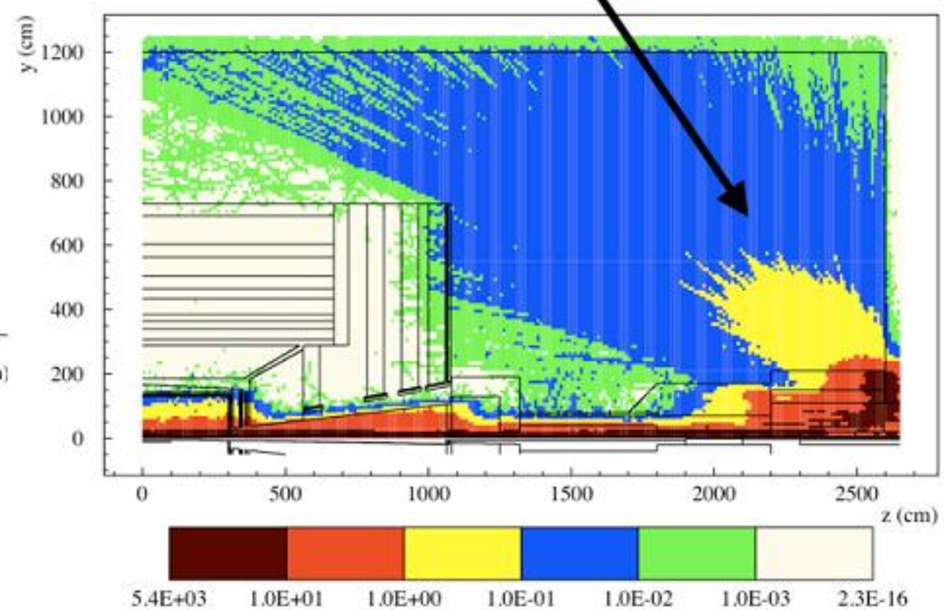
First Complete Studies of Machine Backgrounds at LHC

First complete study in 1996 by Mokhov, Drozhdin and Huhtinen: NIM A 381 (1996) 531

Introduced the concept of "interface plane" at ~26m (here detector simulations can take over from machine)

request to block tunnel entry (to stop hadron & Em halo)
Request to never have beam without TAS present





muons not an occupancy issue
-(compared to pp-background @ 1E34)

Effect on CMS and IP5 SC magnets of a kicker prefire studied first by MDH in 1999

Beam Losses in IP1/IP5 at 7 TeV

1. Betatron cleaning in IP7 for BEAM1 and BEAM2

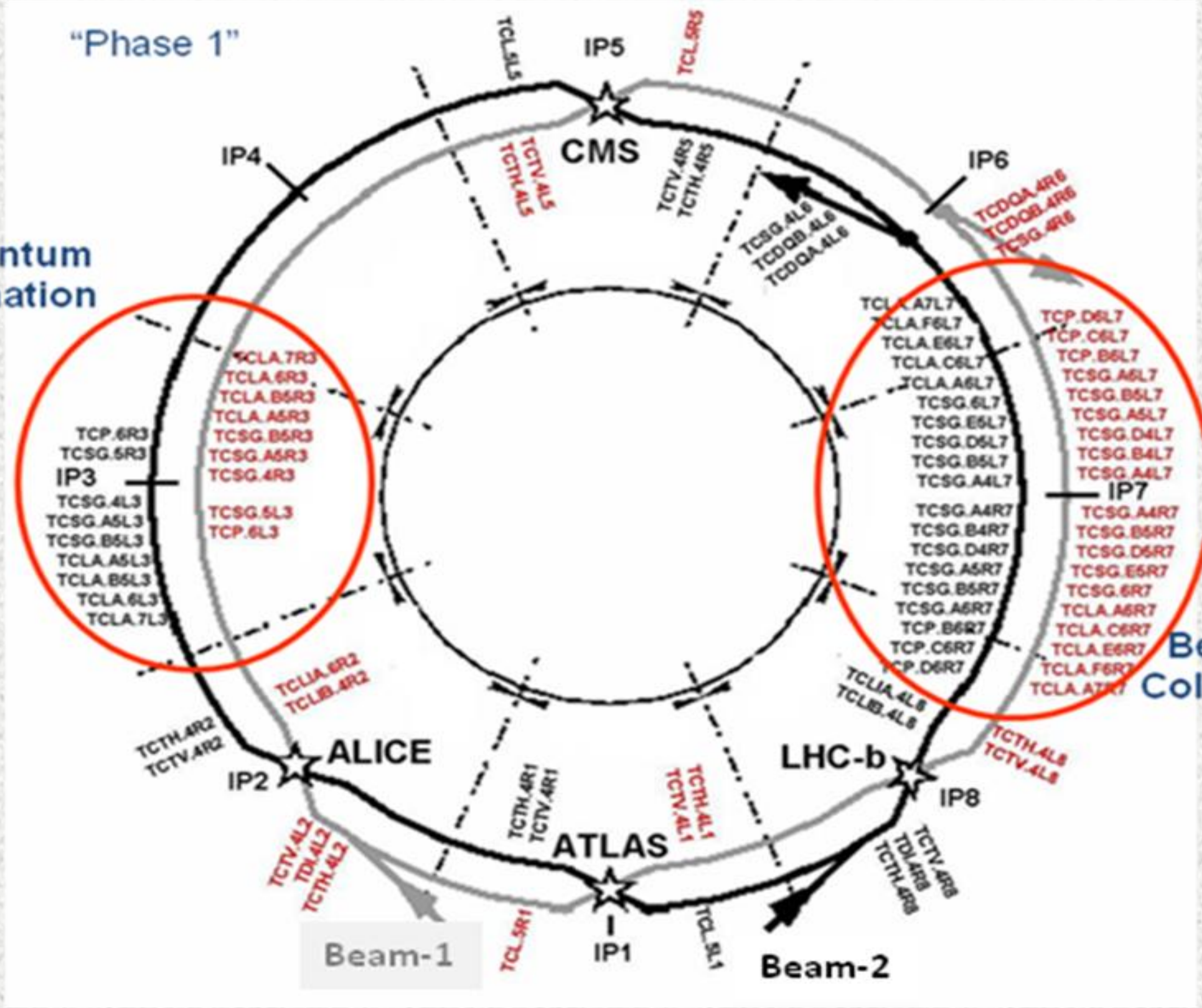
- *Nominal 10-hr beam life time: 8.3e9 p/s*
- *Transient 0.22-hr beam life time: 3.78e11 p/s*

   This results in BEAM2 loss rates on IP5 TCTs of 2.61e6 p/s and 1.19e8 p/s, respectively. Plus momentum cleaning.

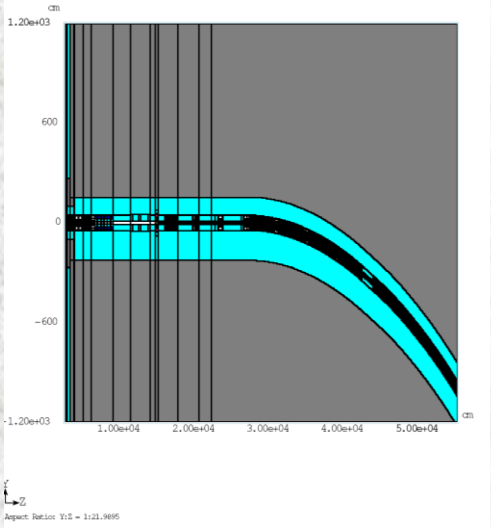
2. Inelastic and elastic nuclear interactions of the beam with gas in the beam pipe in a 550-m region upstream IP1/IP5, 2808 bunches nominal: pressure map → nuclear interaction distribution; 3.07e6 p/s total in the region.

3. Elastic nuclear and large-angle Coulomb interactions of the multi-pass beam with gas in the beam pipe of the entire LHC ring; 1.154×10^{8} per second in the ring for each of the two beams.

LHC Layout and Collimation



MIB in IP1/IP5: MARS15 Modeling



- Machine, interface and related detector elements in ± 550 m from IP1 and IP5: 3-D geometry, materials, magnetic fields, tunnel and rock outside (up to 12 m laterally).
- Tungsten tertiary collimators TCTV and TCTH at 145.34 and 147.02 m from IP, respectively, aligned wrt BEAM2 coming to IP5 and BEAM1 coming to IP1.

- First source: tails from betatron cleaning in IP7 – files of proton hits in TCTs for BEAM1 and BEAM2 calculated with SixTrack.
- Second source: beam-gas interactions of BEAM2 at 0 to 550-m from IP5 using gas pressure maps.
- Third source: on TCT from multi-turn STRUCT runs for both beams for nuclear elastic interactions.

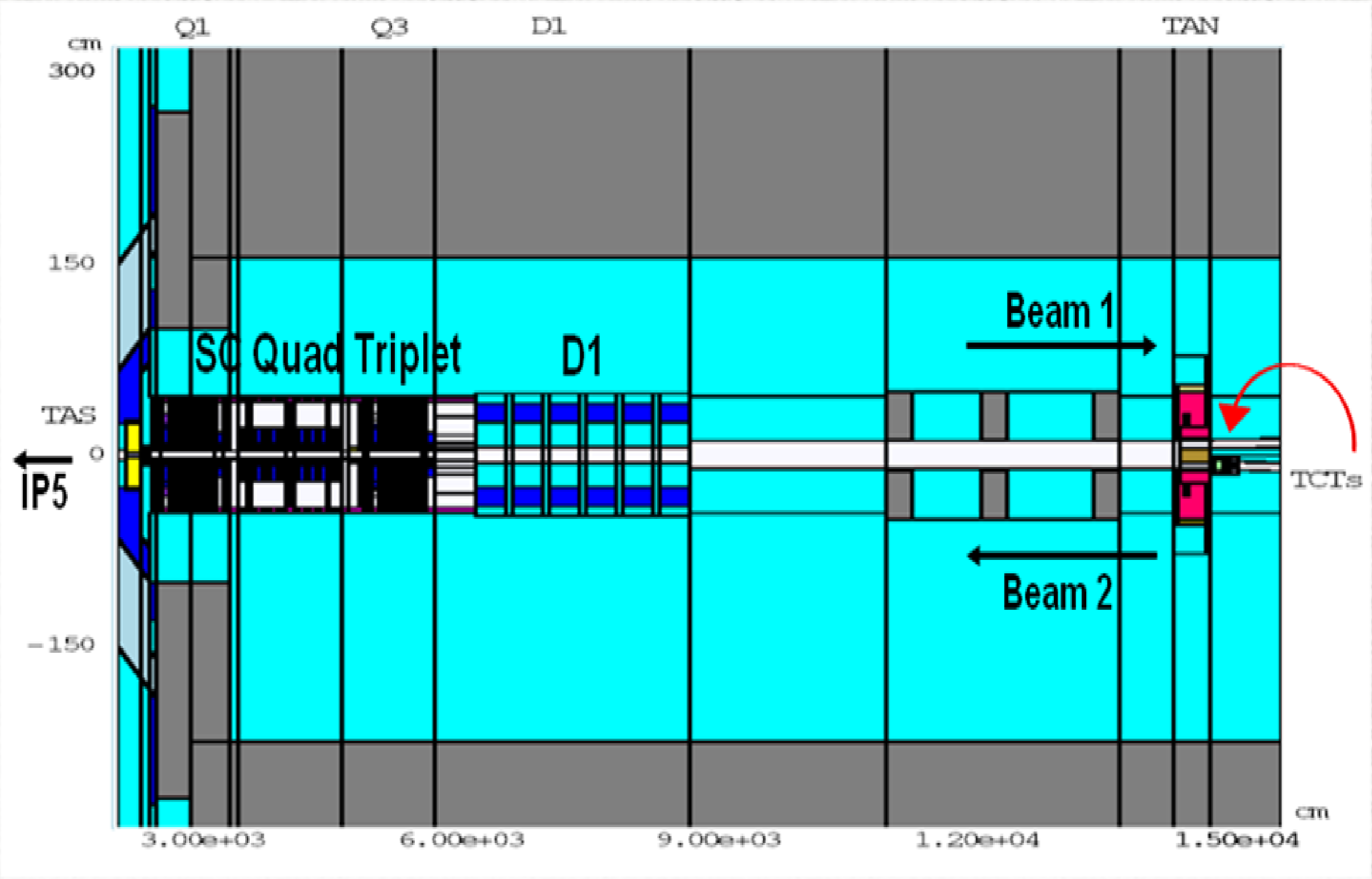
- MARS15 calculations: power density and dynamic heat loads in inner triplet quads, absorbed and residual doses in the entire region, and particle source at z=22.6 m for runs by CMS and ATLAS teams.

Tertiary Beam Halo (1)

The first term of MIB for the experiments are protons escaping the betatron and momentum cleaning insertions (IP7 and IP3, respectively) and being intercepted by the tertiary collimators TCT. This term, related to the inefficiency of the main collimation system, is called “tails from collimators” or “tertiary beam halo”.

The TCTs are situated between the neutral beam absorber (TAN) and D2 separation dipole at about 148m on each side of IP1 and IP5. It is noted that most of protons coming from IP3 and IP7 would be lost in the triplet (closer to the experiment) if they were not intercepted by the TCTs.

IP5 Interaction Region

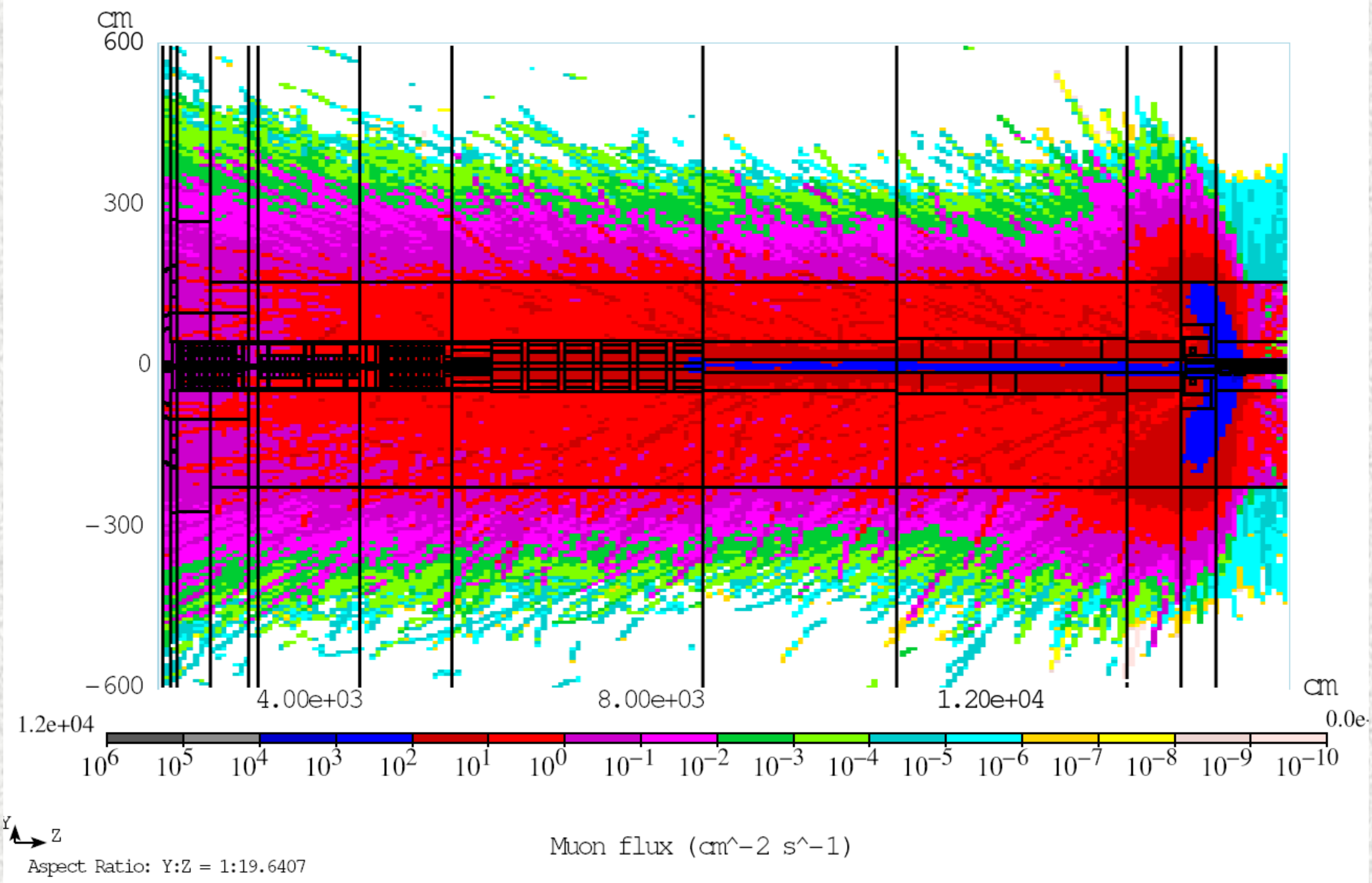


Tertiary Beam Halo (2)

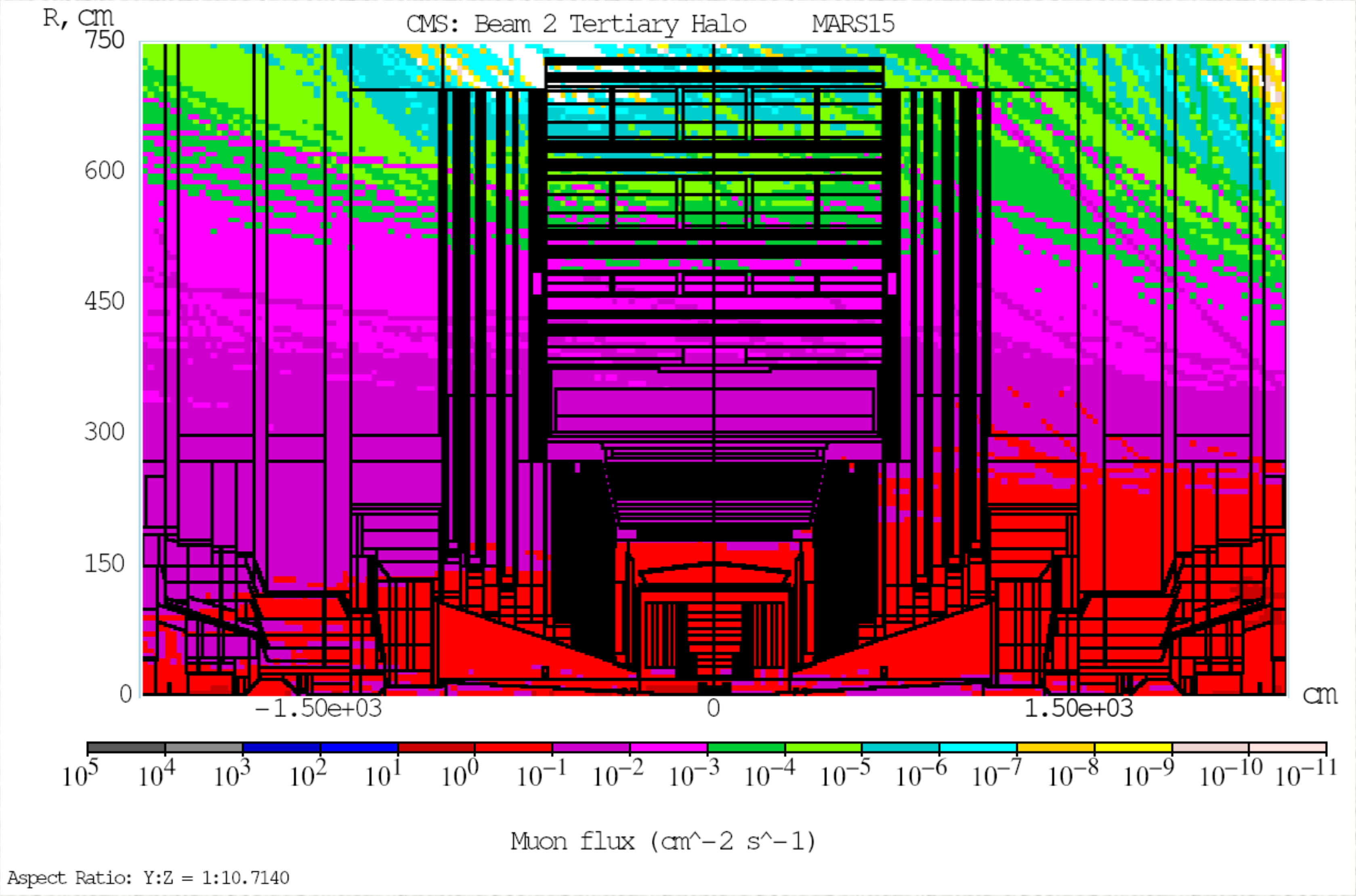
Assuming an ideal machine (no alignment and magnet errors) at 7 TeV and the high-luminosity insertions (IP1 and IP5) squeezed to $\beta^* = 0.55$m, we only take into account the contribution from the betatron cleaning in IP7 at the rate of 8.3×10^9 p/s for a 10-hr beam lifetime and nominal intensity. The collimators were set to the nominal settings, in this case 8.3σ for the tertiary collimators, to fully protect the triplet magnets.

The resulting loss rates on the TCTs are 2.61×10^6 p/s and 4.28×10^6 p/s for Beam-2 approaching IP5 and Beam-1 approaching IP1, respectively. Corresponding loss rates on the other sides of these insertions are about 10% of those. 95% of muons illuminating ATLAS and CMS in a radius of 3m are generated at $50<z<148$m from the IP. Note that the above rates are ~45 times higher for the transient 0.22-hr beam lifetime. Contributions from the momentum cleaning are thought to be substantially lower.

Tertiary Halo: Muon Flux Isocontours in IP5



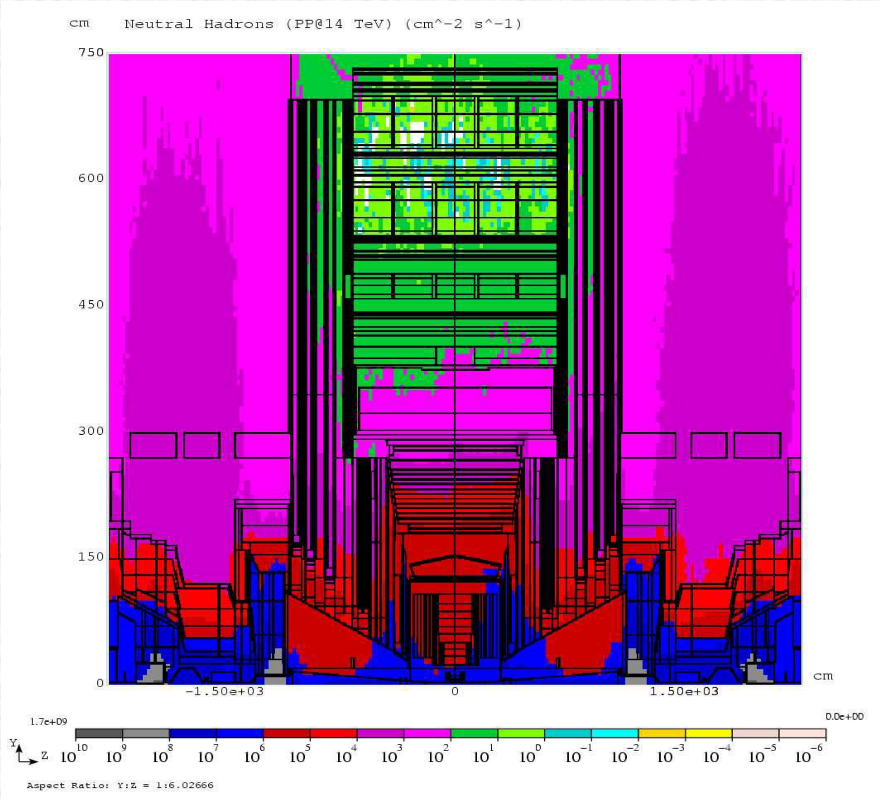
Muon Flux in CMS Induced by Beam2 Tertiary Halo



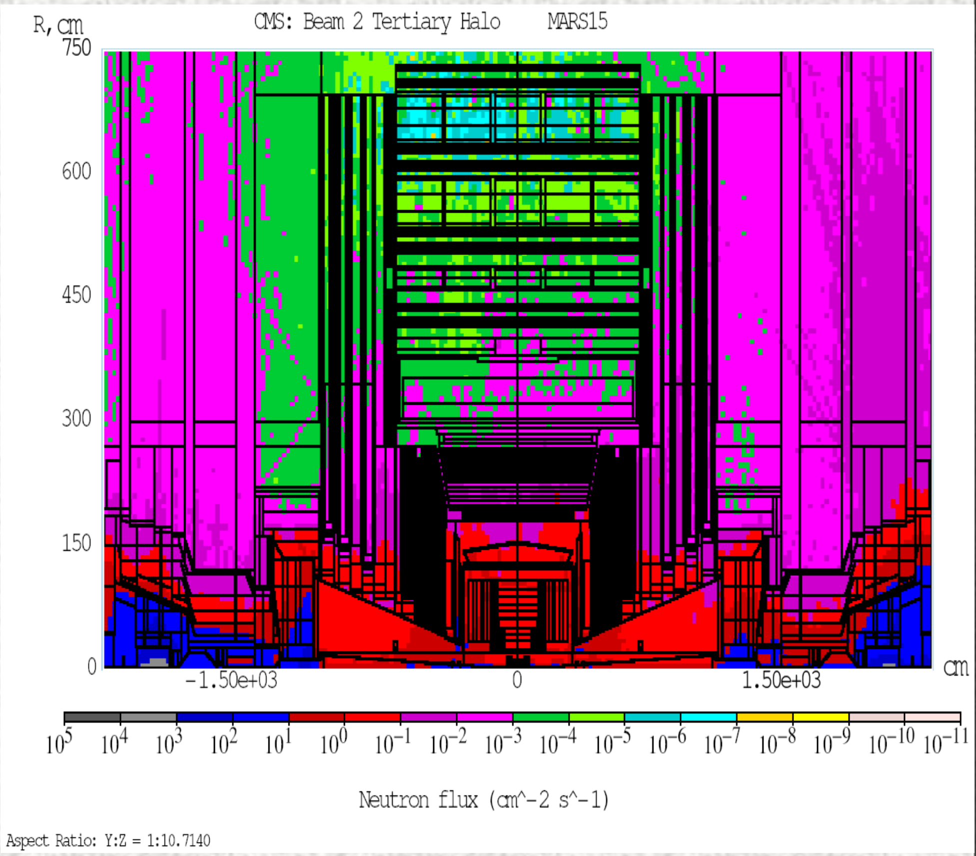
MIB vs pp: Neutron Flux in CMS

LHC, 7x7 TeV, 10^{34} cm^{-2}s^{-1}

pp



Tertiary halo, Beam2



Barrel Si tracker at r=4 cm: $\Phi_n(pp) \approx 10^5\ \Phi_n(MIB_{total})$, but can differ by only a factor of 10 or so at startup conditions

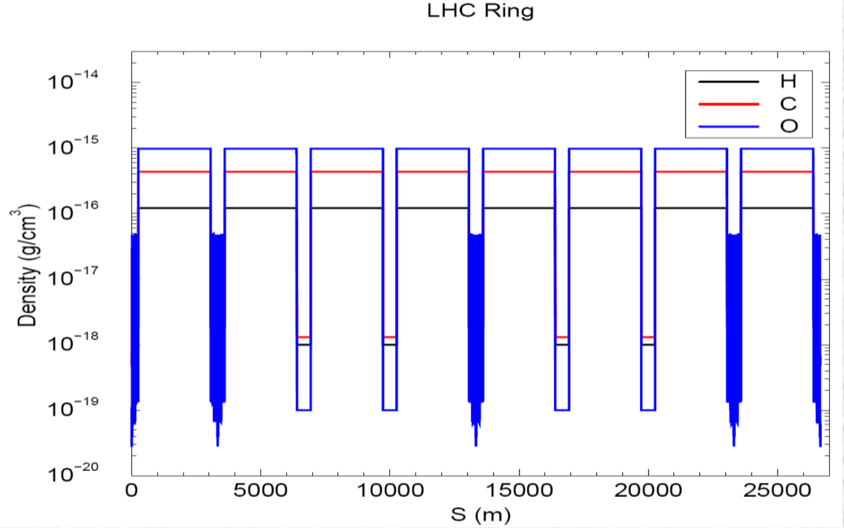
Beam-Gas Interactions (1)

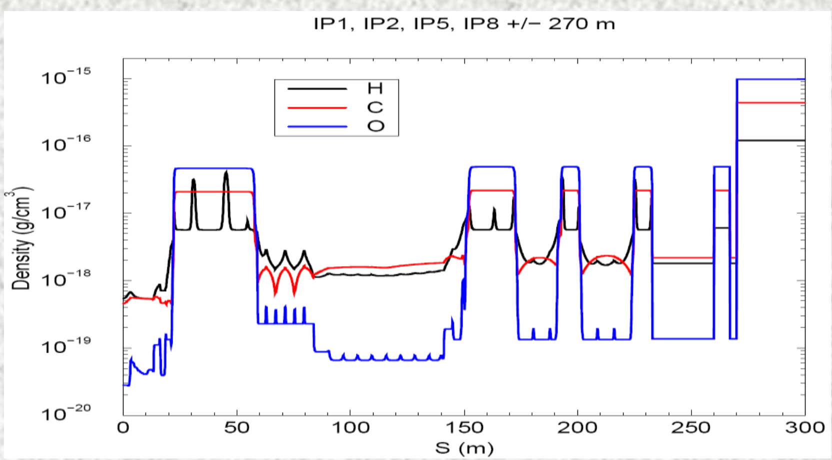
Beam-gas interactions comprise the second term of MIB. Products of beam-gas interactions in straight sections and arcs upstream of the experiments and not intercepted by the collimation system have a good chance to be lost on limiting apertures in front of the collider detectors. The main process of beam-gas interaction, multiple Coulomb scattering, results in slow diffusion of protons from the beam core causing emittance growth. These particles increase their betatron amplitudes gradually during many turns and are intercepted by the main collimators before they reach other limiting apertures.

Similar behaviour takes place for small-angle elastic nuclear scattering. In inelastic nuclear interactions, leading nucleons and other secondaries are generated at angles large enough for them to be lost within tens or hundreds of meters of the LHC lattice after such interactions. The rate of beam-gas interactions is proportional to the beam intensity and residual gas pressure in the beam pipe. Longitudinally it follows the pressure maps .

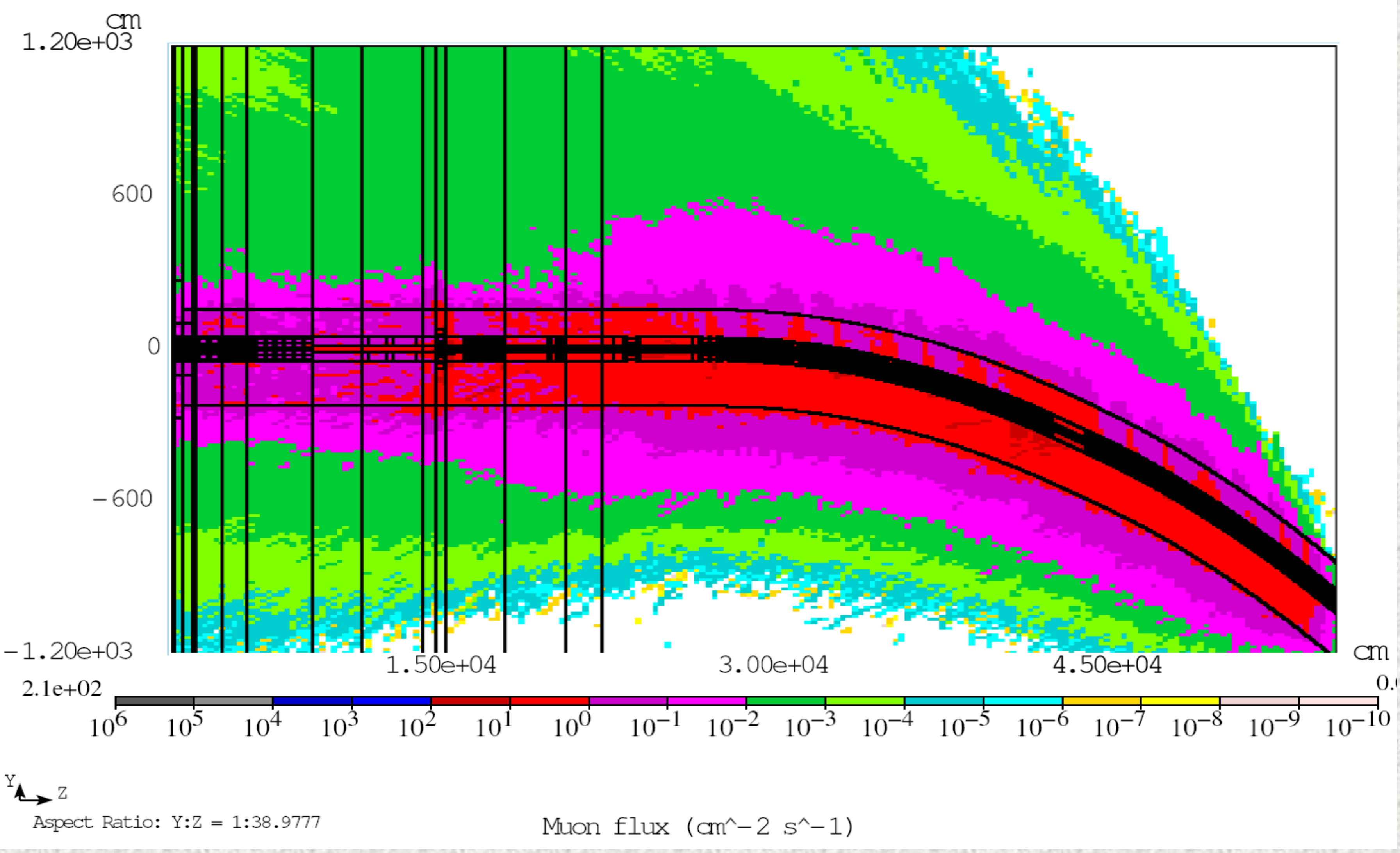
Beam-Gas Interactions (2)

Detailed studies have shown that inelastic and large-angle elastic nuclear interactions in the 550-m regions upstream of IP1 and IP5 are mostly responsible for the beam-gas component of MIB. The total number of elastic and inelastic nuclear interactions in these regions for each of the beams coming to IP1 and IP5 is 3.07×10^6 p/s. Despite a high gas pressure – and beam-gas interaction rate – in the arcs, most muons coming to ATLAS and CMS are generated in ±400-m regions around IP1 and IP5. The others are absorbed/scattered in the magnets and rock (especially that tangent to the orbit).



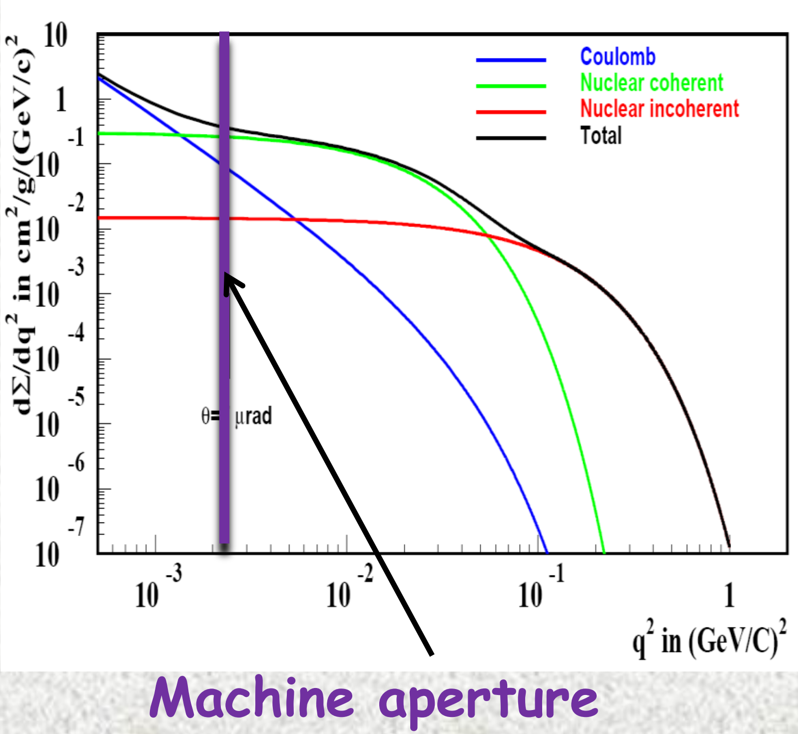


Beam-Gas: Muon Flux Isocontours in IP5



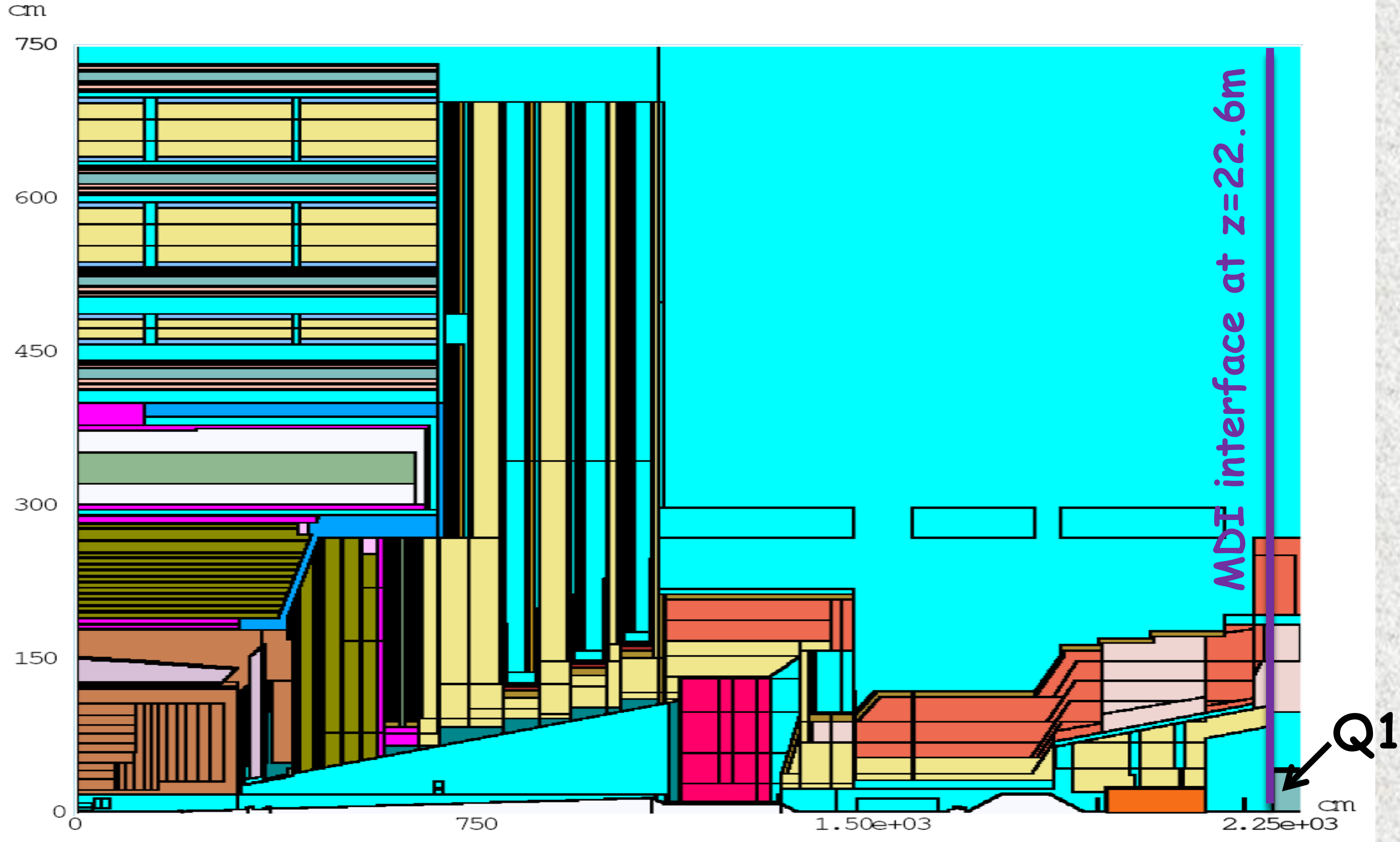
Beam-Gas Elastic Interactions

For the nominal beam current of 0.6 A, one gets 1.154×10^{8} nuclear elastic and Coulomb interactions (with a kick > 7 μrad) per second in the ring for each of the two beams. Multi-turn modeling of these interactions is performed separately for Beam 1 and Beam 2 with the STUCT code, with all the apertures included. The Beam 2 loss rates (MHz) are 35.78 (IP7), 3.07 (TCT.R5), 7.19 (TCT.L1) and 2.08 (rest of the ring). **Run MARS starting TCT.**



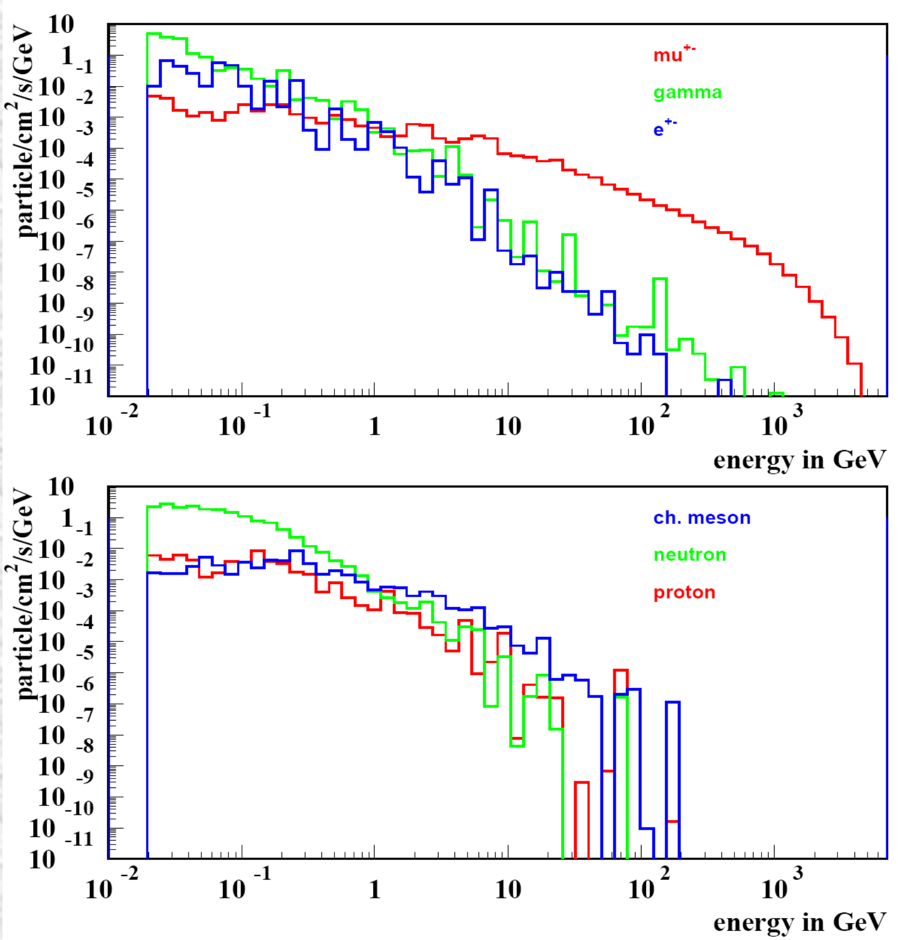
The contributions to the proton loss rate on the tertiary collimators from the incoherent (quasi-elastic), coherent and Coulomb scattering processes in the ring are 46, 52.6 and 1.4 percent, respectively, not very different for Beam 1 and 2 as well as for IP1 and IP5.
Losses on TCT: H, C and O contribute 17, 29 and 54 %, respectively.

CMS Detector at IP5



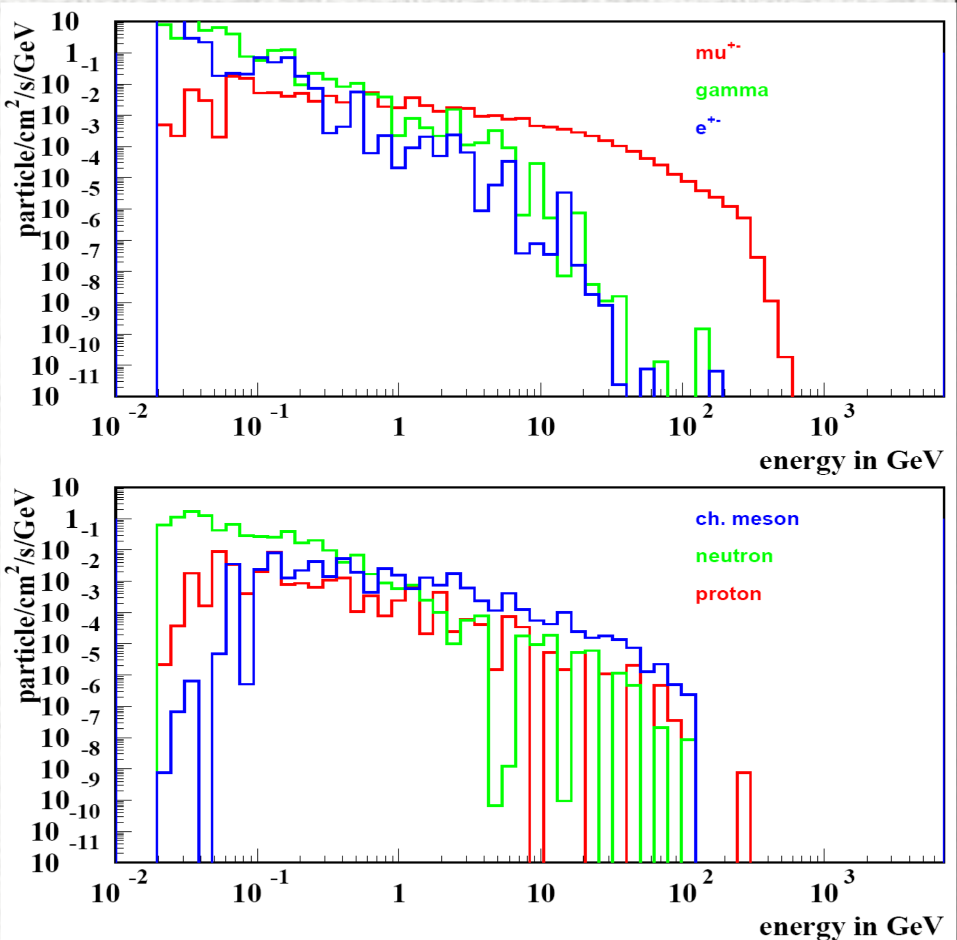
MIB Particle Spectra at 22.6m of IP5 MDI

"Inelastic" beam-gas < 550 m



Energy spectra at CMS (1.7 < r < 100 cm): beam-gas, MARS15

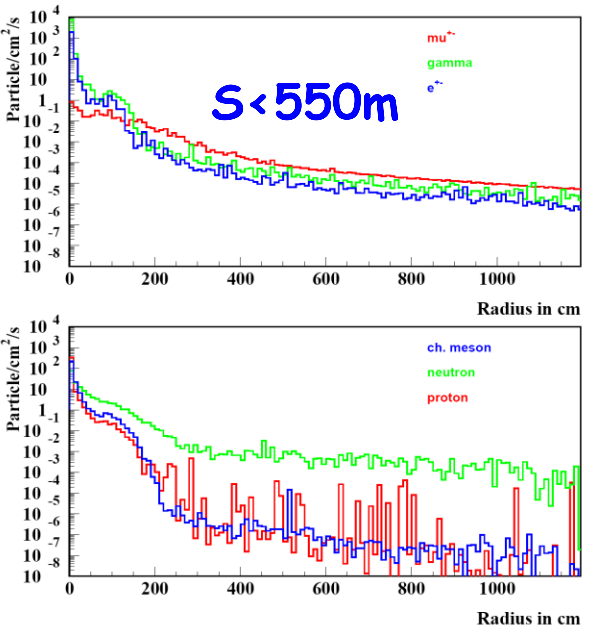
Tertiary beam halo



Energy spectra at CMS (1.7 < r < 100 cm): beam-halo, MARS15

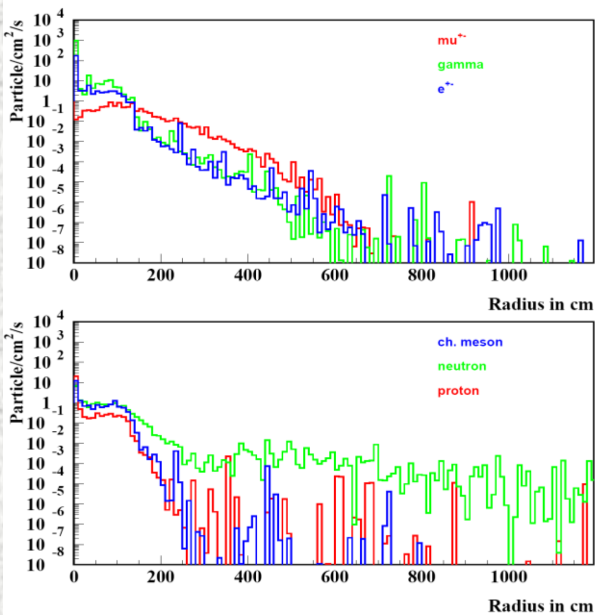
Radial Distributions at 22.6m of IP5 MDI

"Inelastic" beam-gas



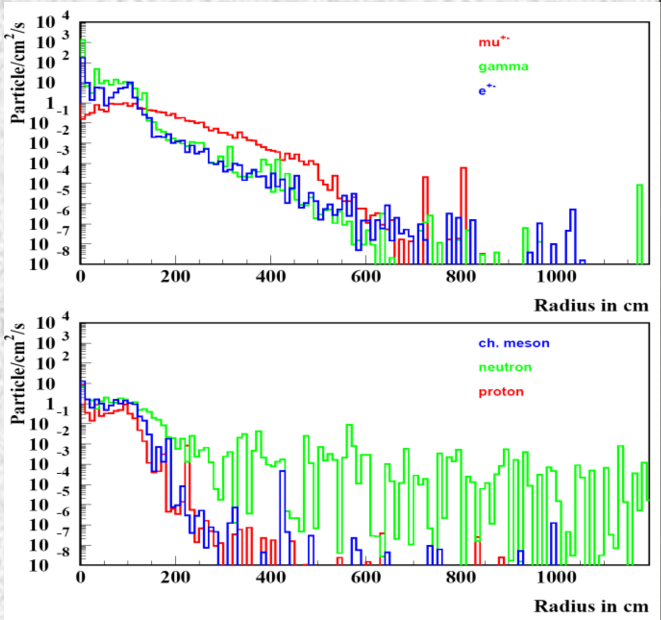
Radial distributions at CMS (E > 0.02 GeV): beam-gas, MARS15

Elastic beam-gas



Radial distr. at CMS (E > 0.02 GeV): bgas elastic, MARS15

Tertiary beam halo

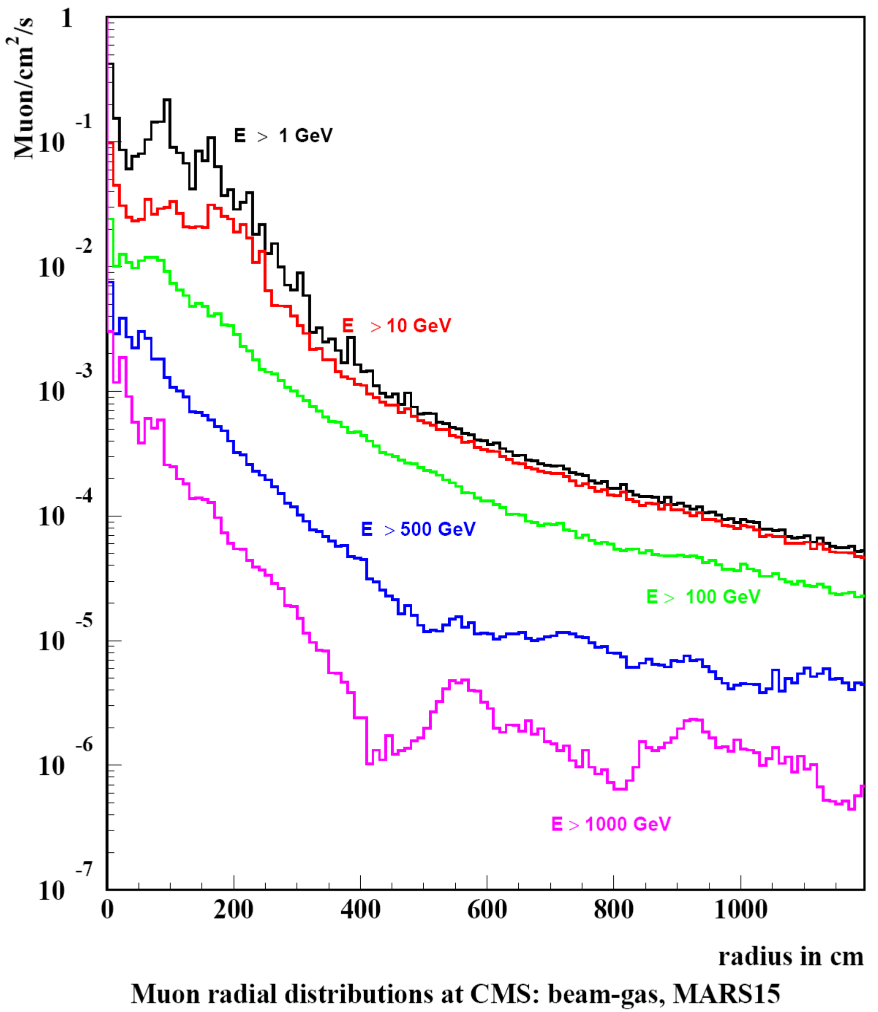


Radial distributions at CMS (E > 0.02 GeV): beam-halo, MARS15

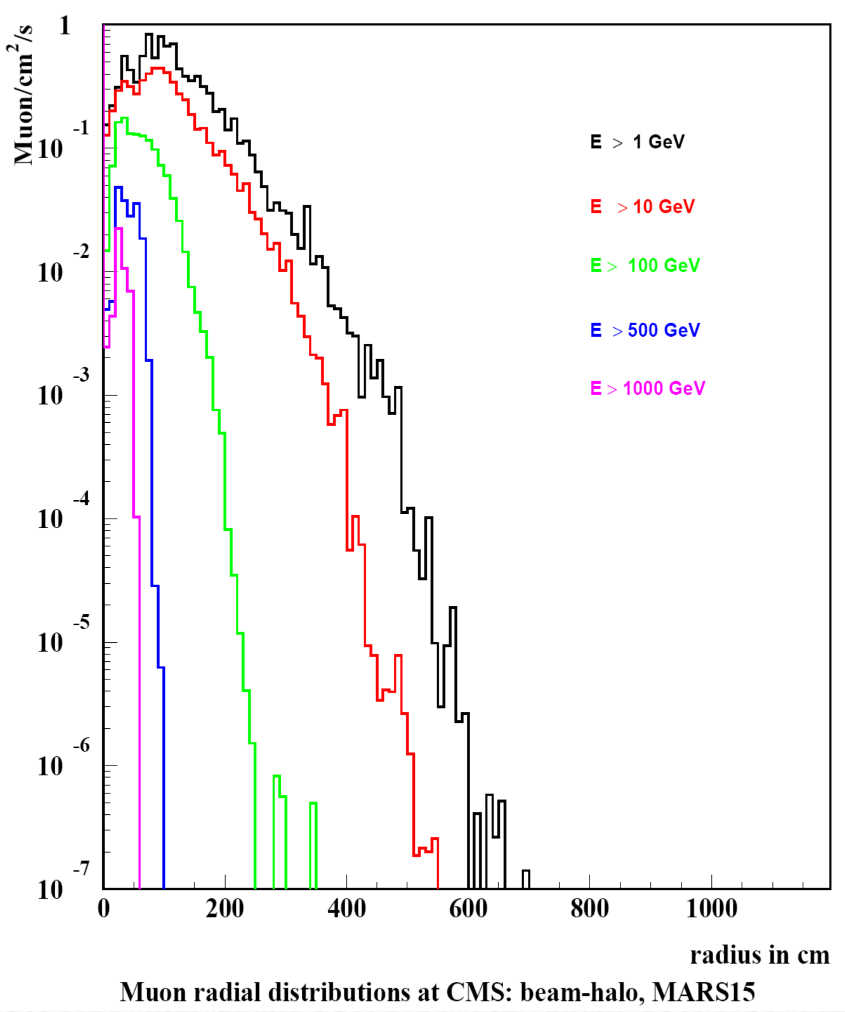
Quite similar: TCT as a point-like source at z=148m

Muon Radial Distributions at 22.6m of IP5 MDI

"Inelastic" beam-gas < 550 m

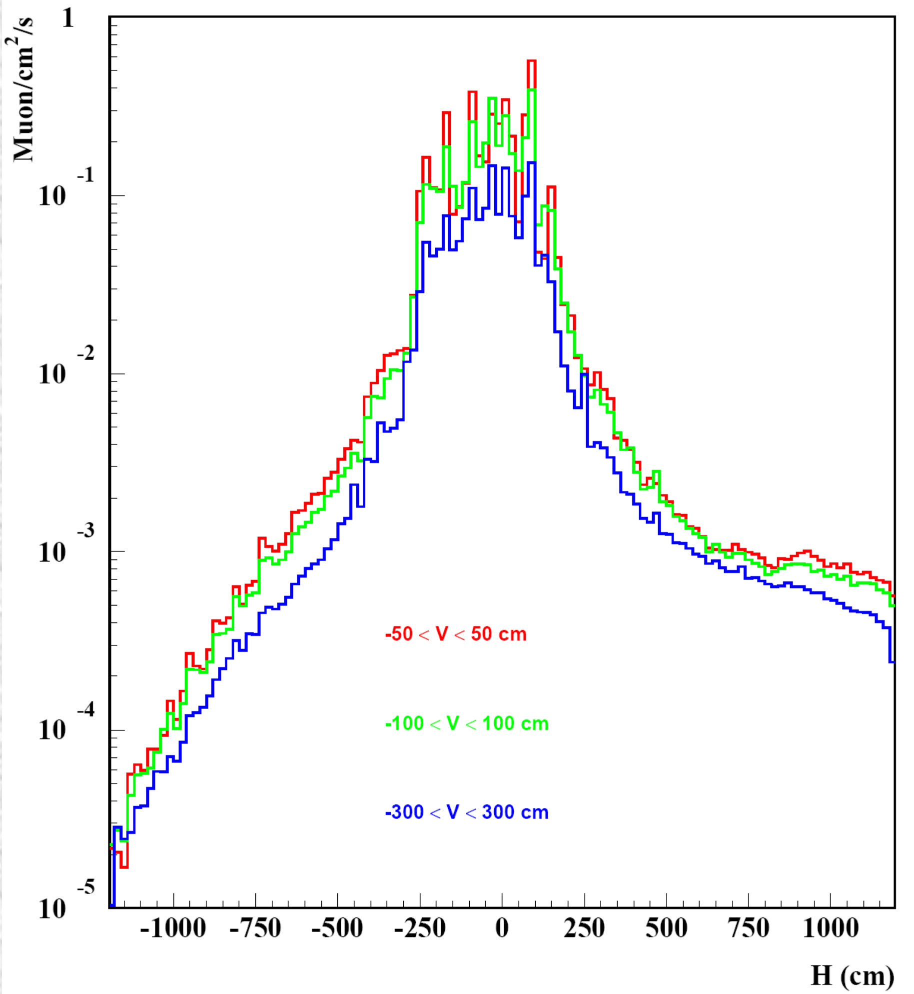


Tertiary beam halo



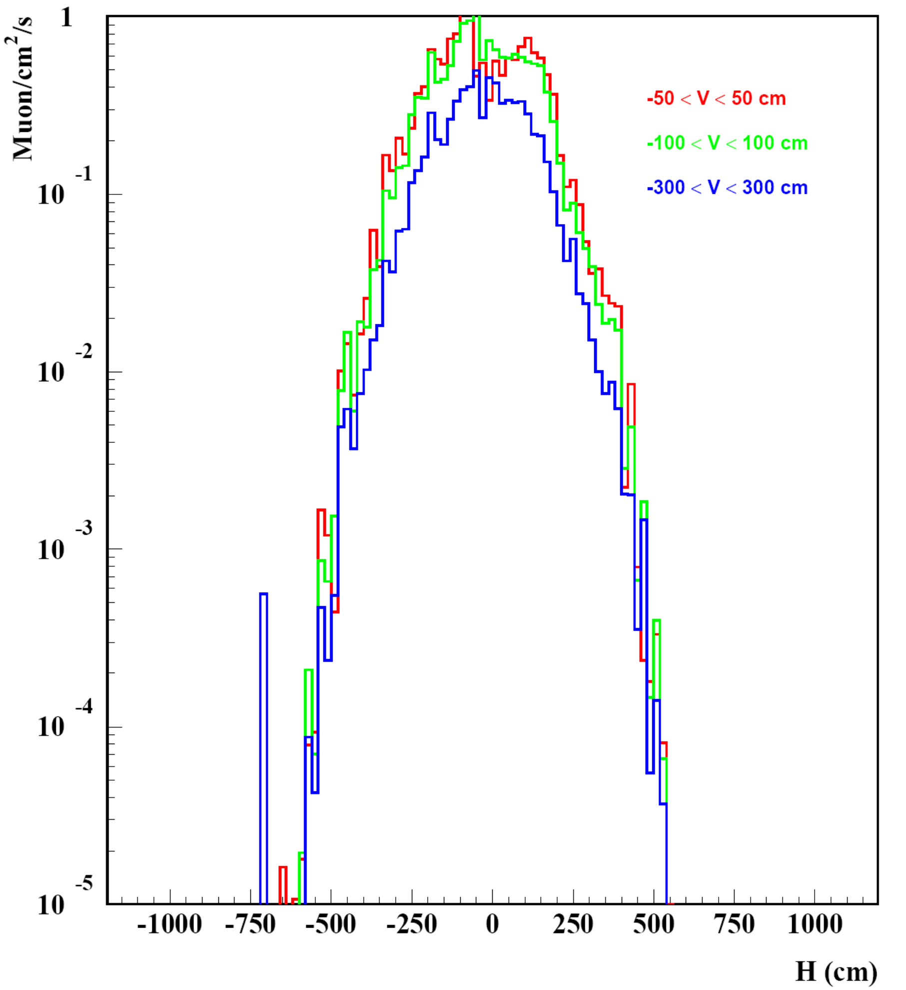
Muon Distributions in Orbit Plane

"Inelastic" beam-gas < 550 m



Muon horizontal distributions at CMS (E > 1 GeV): beam-gas, MARS15

Tertiary beam halo



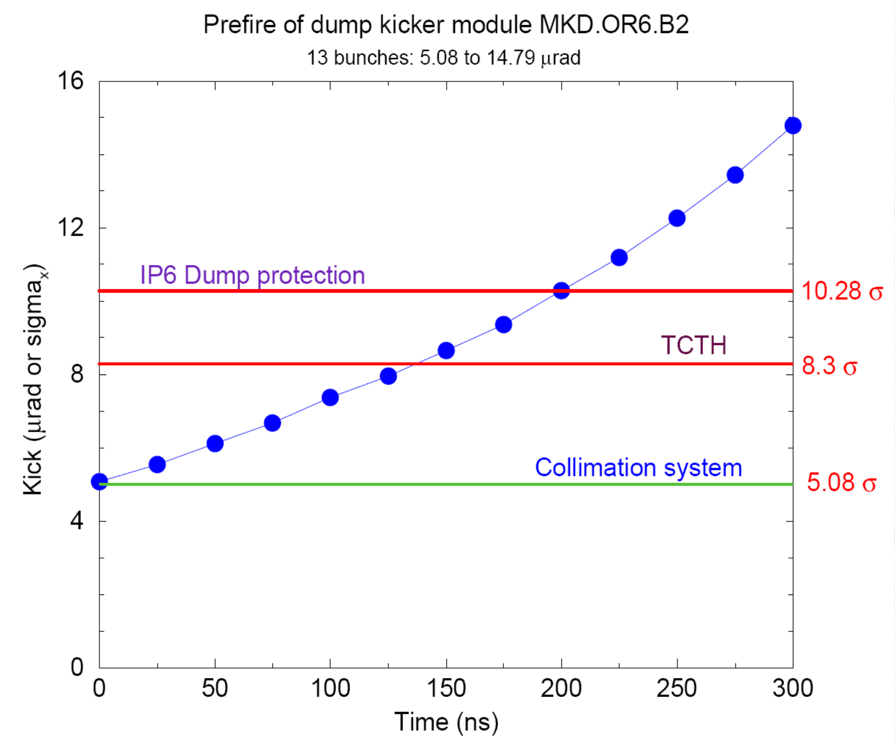
Muon horizontal distributions at CMS (E > 1 GeV): beam-halo, MARS15

Kicker Prefire (1)

These irregular fast losses are caused by machine failures, such as irregular dumps. The impact on the machine and collider detectors – without a multi-component protection system in IP6 - can be disastrous. The worst design case is a dump kicker module prefire. If such an event is detected, the remaining 14 modules will be fired within 700ns to dump the beam. Since the dump kicker modules need a certain time to reach their nominal strength (~3μs), a certain number of bunches will be deflected before they are extracted at the end of one turn.

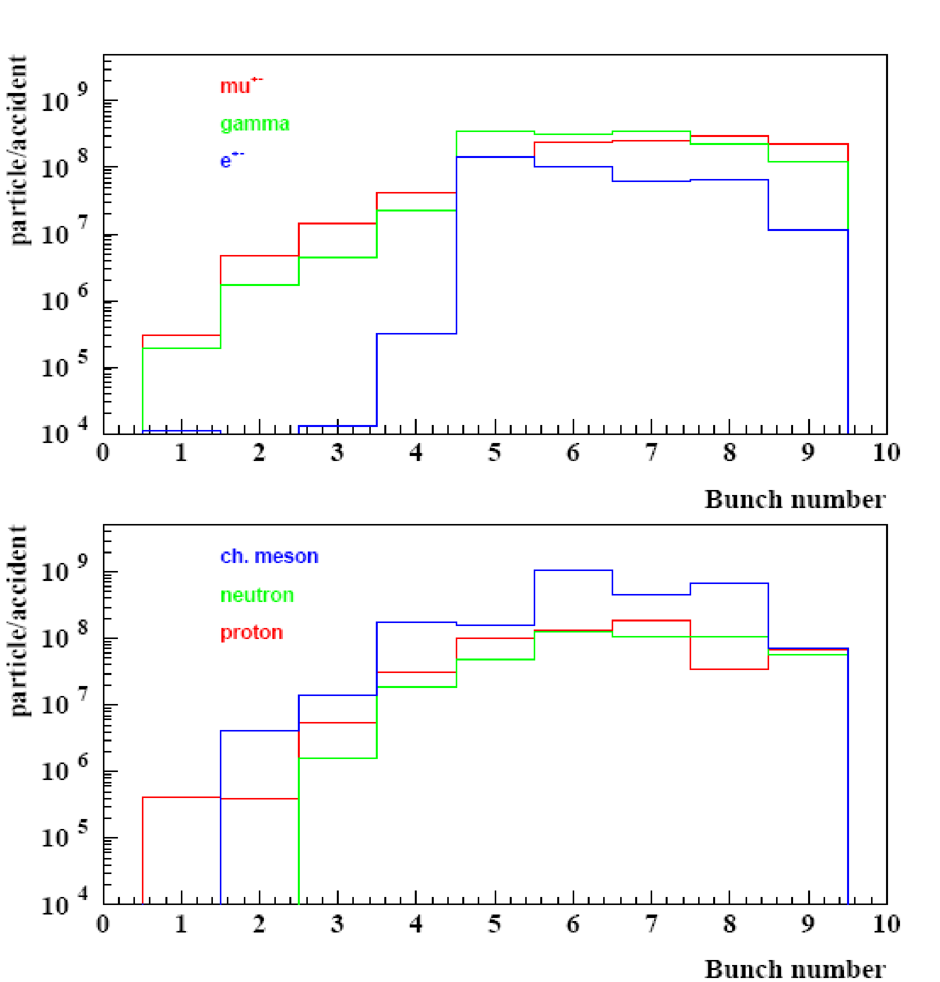
Kicker Prefire (2)

Assuming a $\pi/2$ phase advance between the pre-firing kicker magnet and the TCT tertiary horizontal collimator in front of IP5 (worst case). This results in maximum deflection of the beam at the location of the TCT. Furthermore it is assumed that the dump protection is misaligned so that protons with a betatron amplitude between 8.3σ (nominal setting of the collimator at 7TeV and β^* = 0.55m in IP5) and 10σ will hit the TCTs. Run MARS from TCT again.

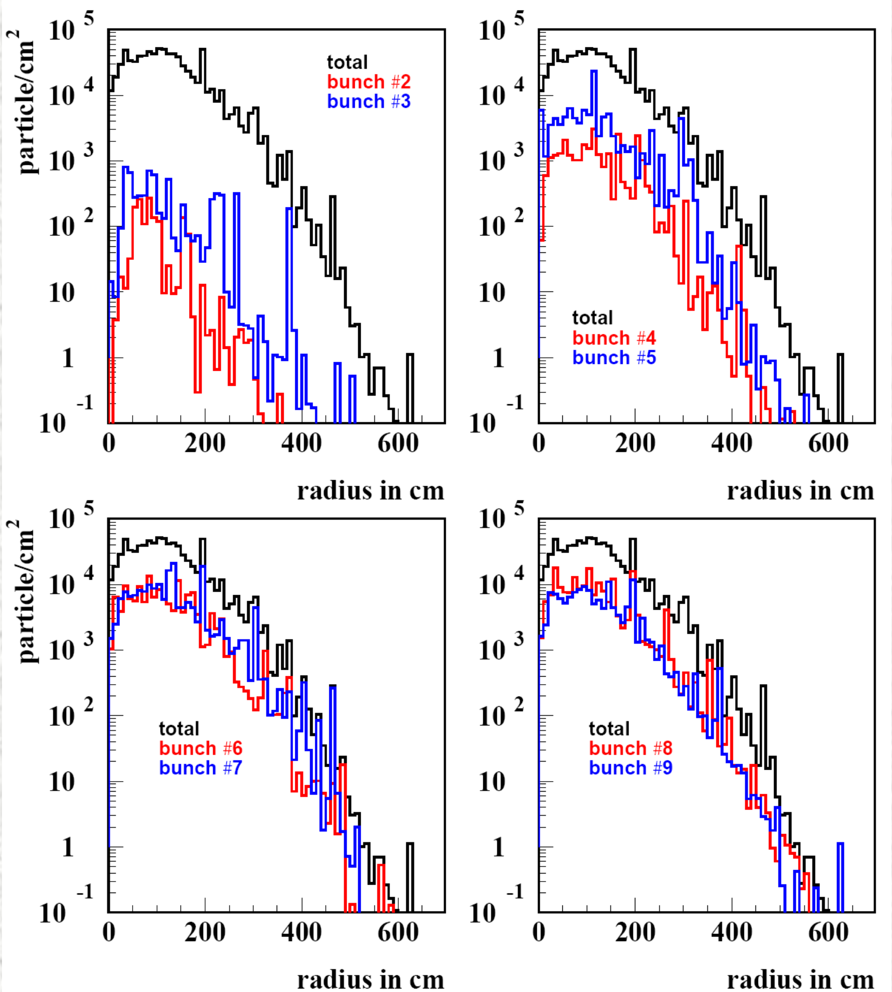


Some protons of 8 mis-steered bunches of Beam 2, separated by 25 ns and each of 1.15×10^{11} protons, can hit the IP5's TCT. The total amount of protons deposited on the TCT is of the order of 2 to 2.5 full bunches.

Kicker Prefire: Bunch Loss in IP5 and Muons on CMS



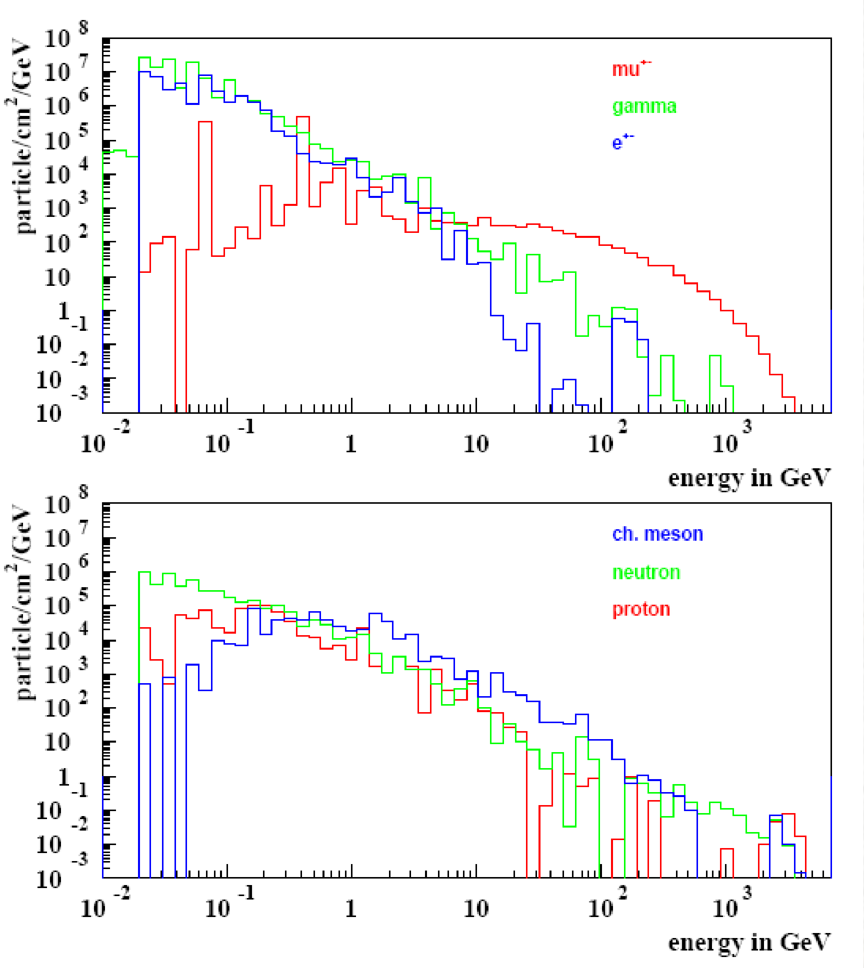
Number of particles with E > 1 GeV at CMS (0 < r < 100 cm)



Radial distributions of muons at CMS (E > 1 GeV)

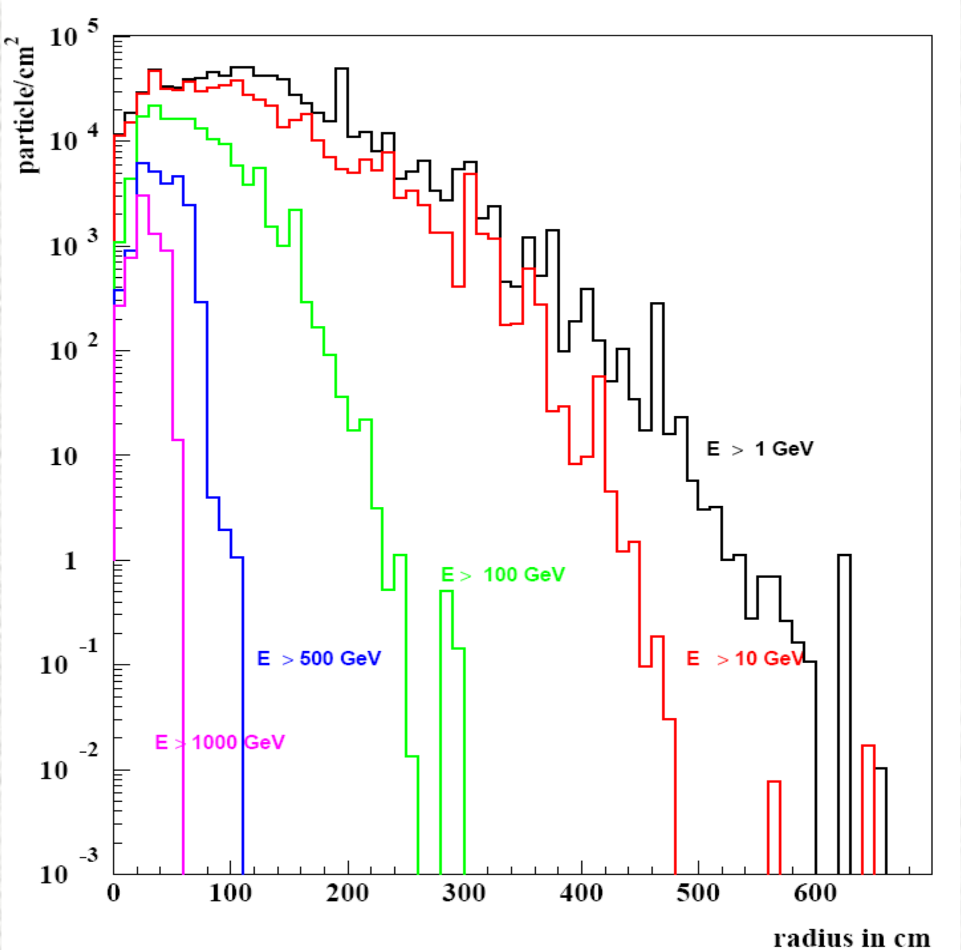
Kiscker Prefire: Particle Distributions at 22.6m

Particle spectra



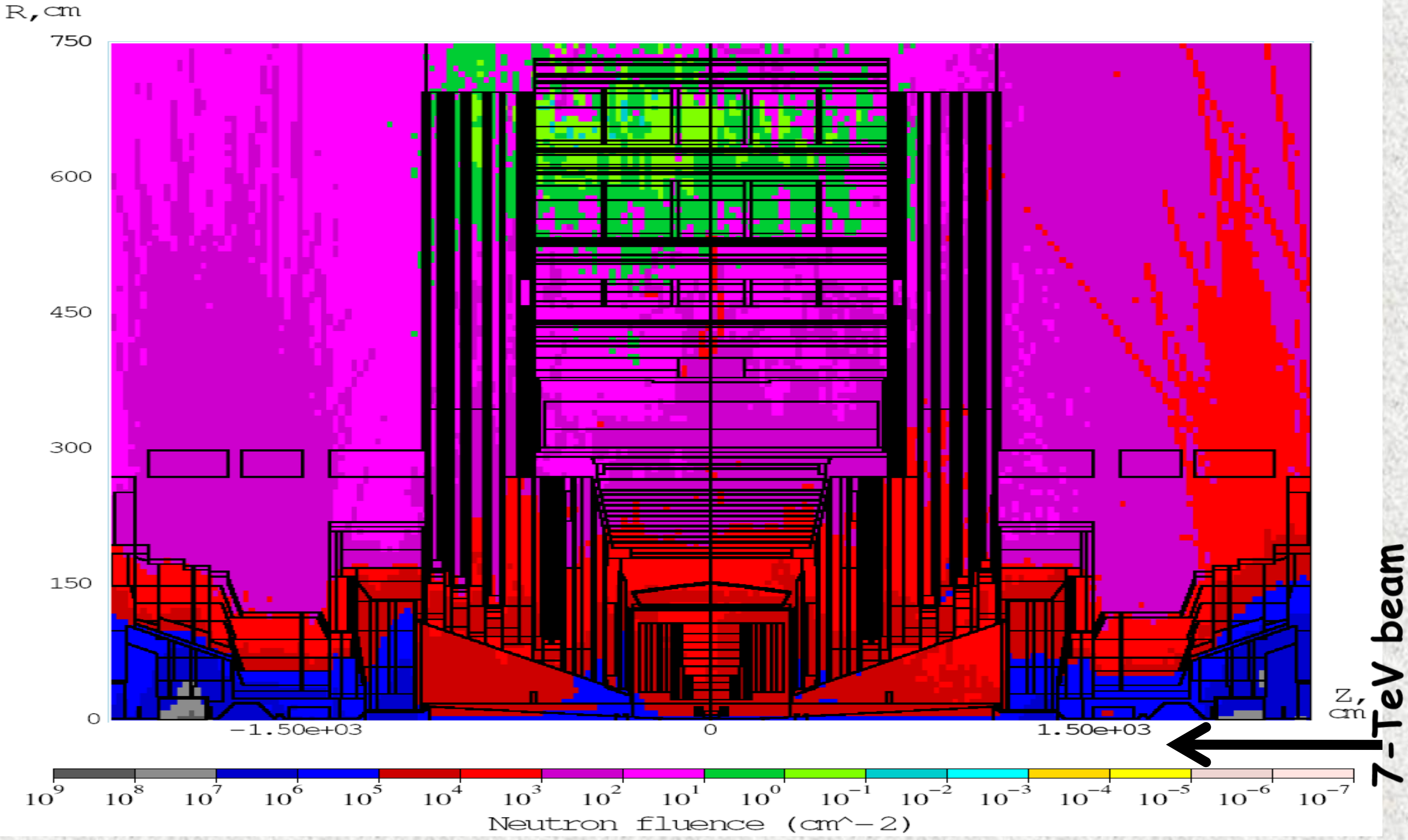
Energy distributions of particles at CMS (1.7 < r < 100 cm)

Muon radial distributions

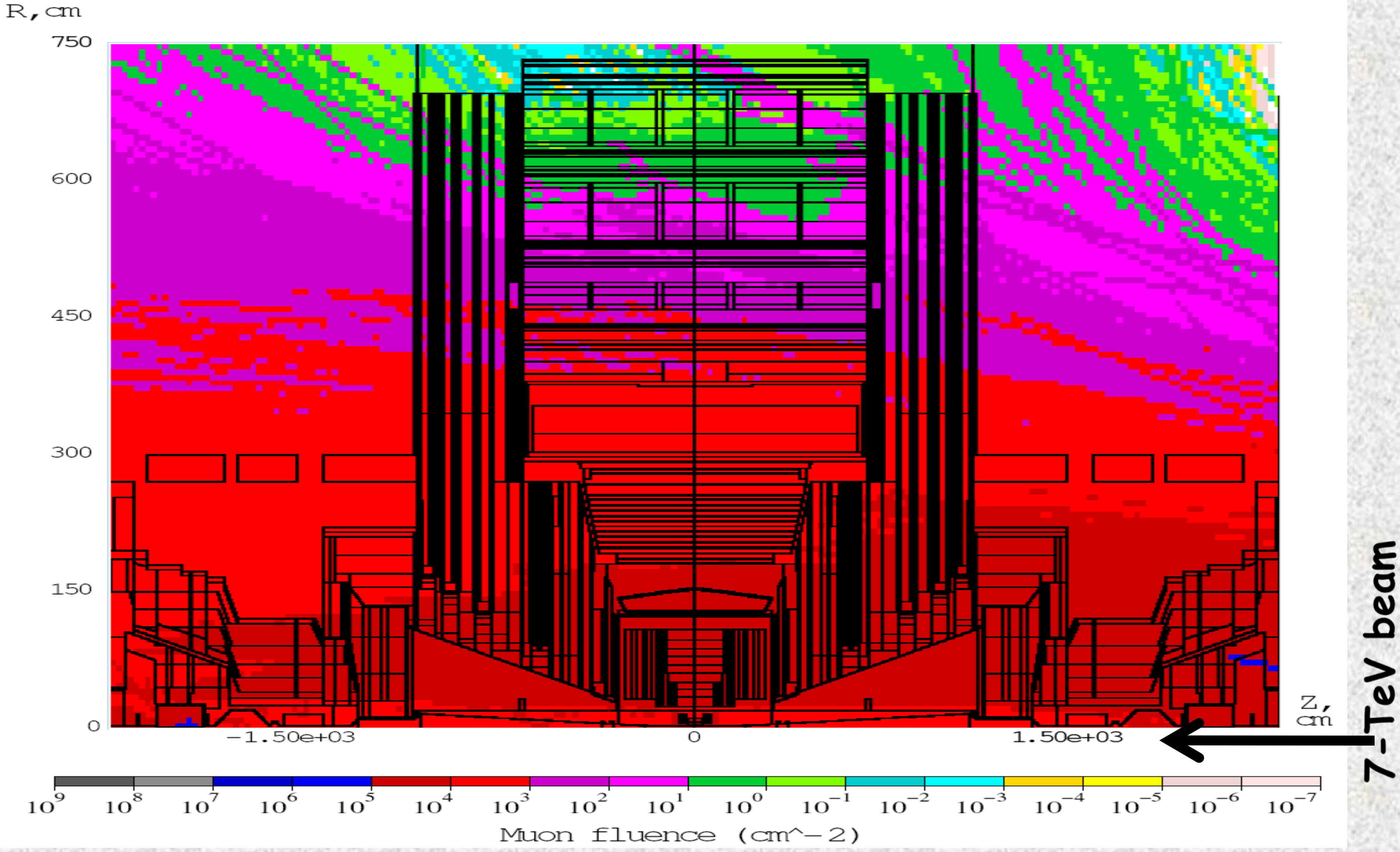


Radial distributions of muons at CMS

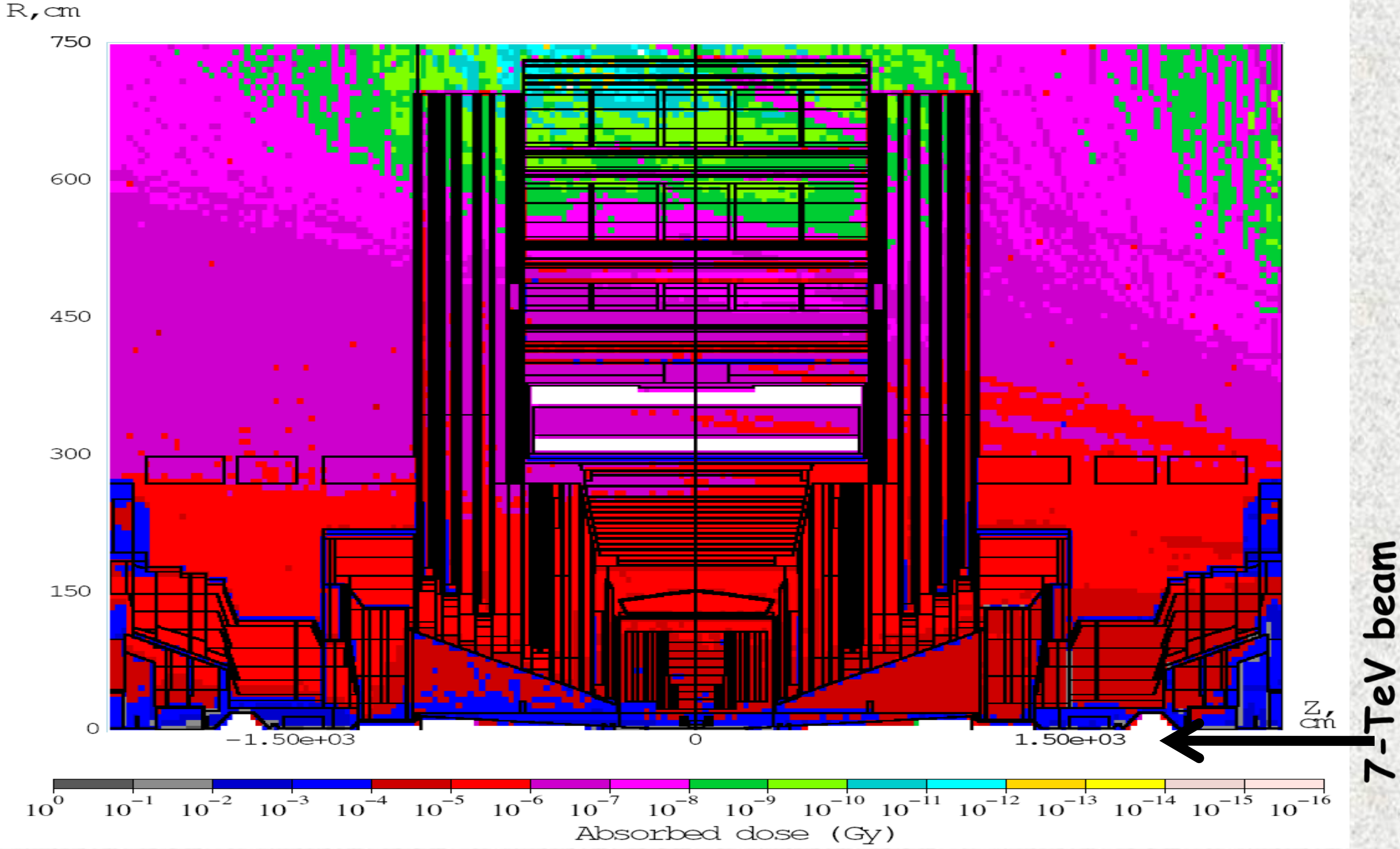
Kicker Prefire: Neutron Fluence



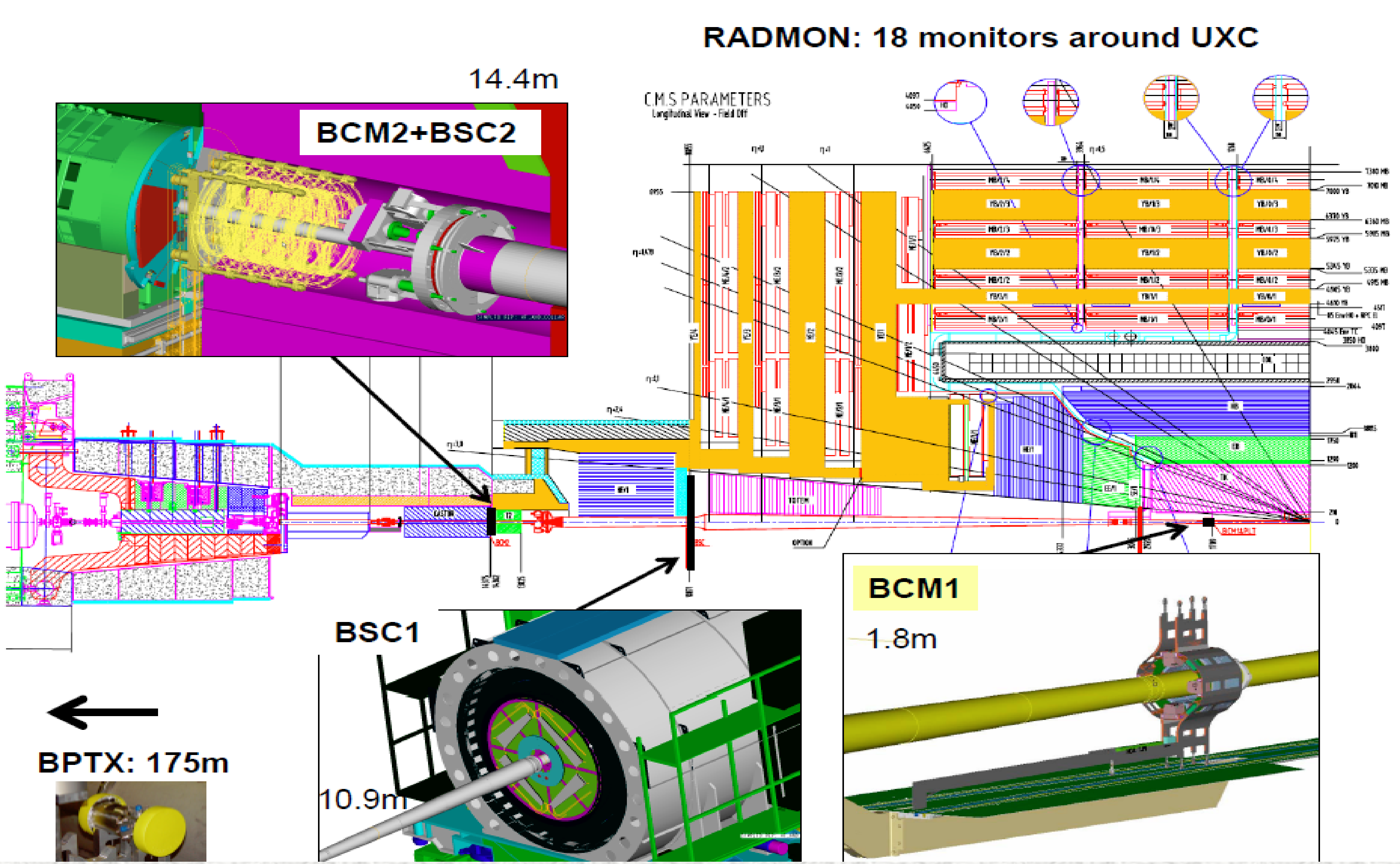
Kicker Prefire: Muon Fluence



Kicker Prefire: Absorbed Dose



Monitoring Beam Loss in CMS Detector



Monitoring Beam Loss in CMS Detector (2)

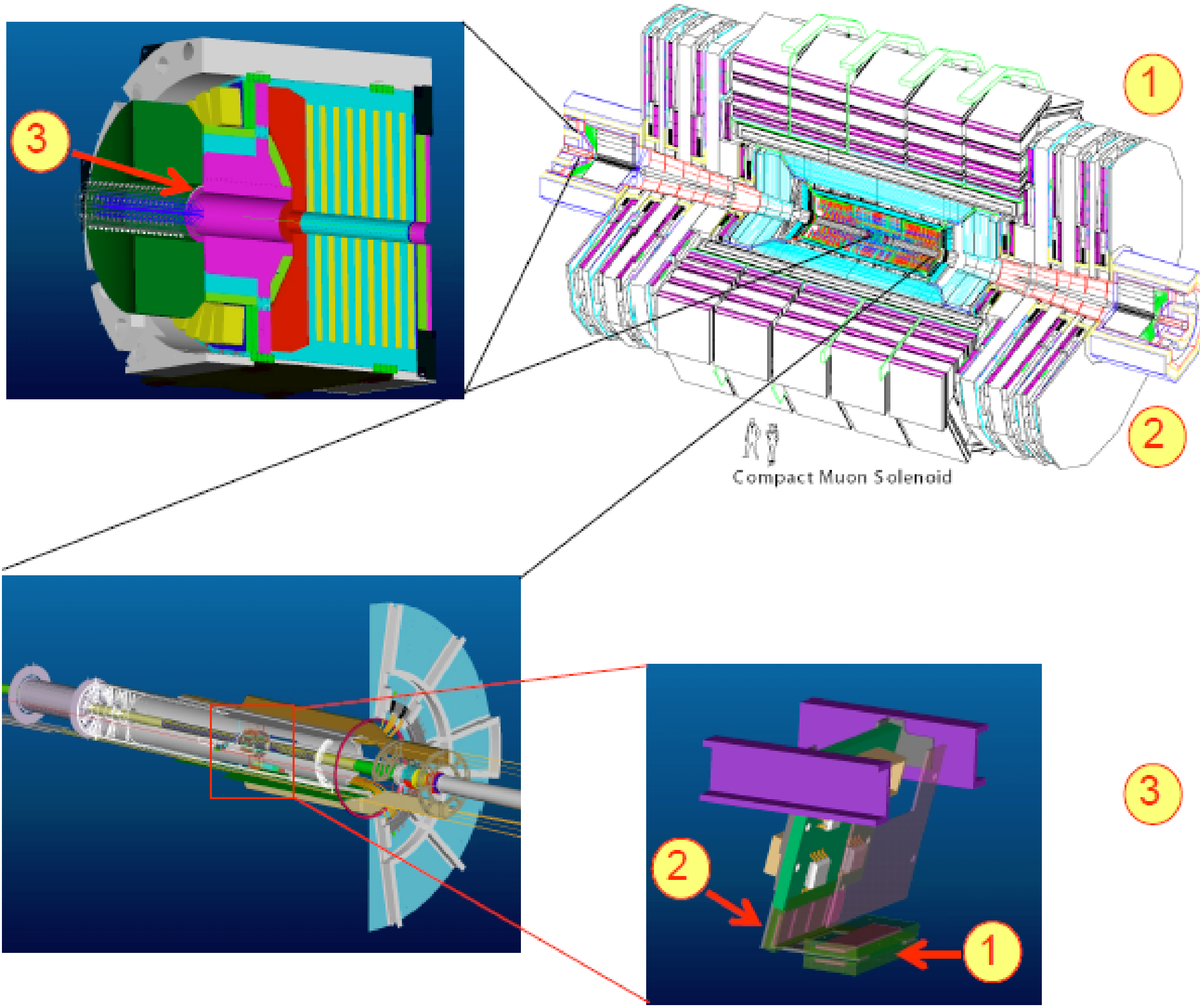
BRM Subsystem Summary

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 (FESA)
BCM2 Diamonds	At rear of HF 14.4m	40 us	Protection	Standard LHC (FESA)
BCM1L Diamonds	Pixel Volume 1.8m	Sub orbit ~ 5us	Protection	CMS + Standard LHC (FESA)
BSC Scintillator	Front of HF 10.9m	Bunch by bunch	Monitoring	CMS Standalone
BCM1F Diamonds	Pixel volume 1.8m	Bunch by bunch	Monitoring + protection	CMS Standalone

Increasing time resolution

All online systems running when machine operational and possibility of beam in LHC
Systems are independent of CMS DAQ

BCM: Beam Conditions Monitors



CMS BCM Units

1 **BCM1L: Leakage current monitor**
Location: z=±1.8m, r=4.5cm
4 stations in φ, 8 sensors total
Sensor: 1cm^2 PCVD Diamond
Readout: 200kHz / 5us
No front end electronics

2 **BCM1F: Fast BCM unit**
Location: z=±1.8m, r=4.3cm
4 stations in φ, 8 sensors total
Sensor: Single Crystal Diamond
Electronics: Analog+ optical
Readout: bunch by bunch (Asynch)

3 **BCM2: Leakage current monitor**
Location: z=± 14.4m, r=29cm, 5cm
8 stations in φ, 24 sensors total
Sensor: 1cm^2 PCVD Diamond
Readout: 25kHz / 40 us
16 Sensors shielded from IP
Off detectors electronics

2 Sensor Locations, 3 Monitoring Timescales