Muon Collider Detector Backgrounds and Machine-Detector Interface

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OUTLINE

- Background Sources
- Detector Performance and Limits
- Background Studies of Last Decade
- New Wave: 2009 Lattice, Detector and MDI
- Magnet and Shielding Constraints
- MARS15 Modeling in IR and Detector
- Background Loads in Detector
- IP versus Machine Backgrounds
- MDI Issues and Work to Do

INTRODUCTION

The high physics potential of a Muon Collider (MC) is reached only if a high luminosity of $\mu^+\mu^-$ collisions in the TeV range is achieved (~10^{34} cm^{-2} s^{-1}). The overall detector performance in this domain is strongly dependent on the background particle rates in various sub-detectors. The deleterious effects of the background and radiation environment produced by the beam in the ring are very important issues in the Interaction Region (IR) and detector design.

Sources of Background at Muon Colliders

1. **IP $\mu^+\mu^-$ collisions:** Production x-section 1.34 pb at $\sqrt{S}$ = 1.5 TeV.

2. **IP incoherent e^+e^- pair production:** x-section 10 mb which gives rise to background of 3×10^4 electron pairs per bunch crossing.

3. **Muon beam decay backgrounds:** Unavoidable bilateral detector irradiation by particle fluxes from beamline components and accelerator tunnel – ***major source at MC***.

4. **Beam halo:** Beam loss at limiting apertures; unavoidable, but is taken care with an appropriate collimation system far upstream of IP.

Muon Collider Background and MDI Studies

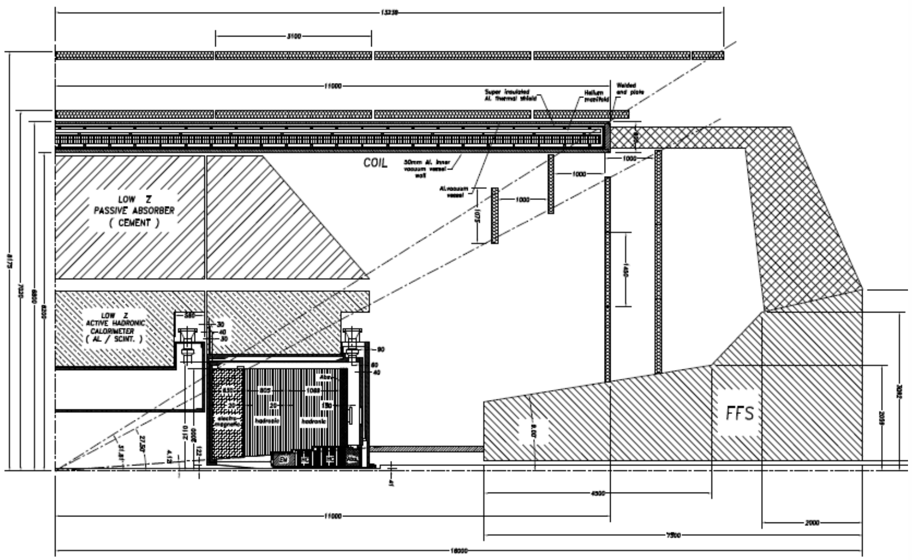
- Incoherent pair production was described by I. Ginzburg (1996) and modeled by I. Stumer.
- Beam decay induced background studies were based on MARS13 (N. Mokhov) and GEANT3 (IS) simulations of 1995-1997 along with MDI optimization by B. Palmer, B. Foster, C. Johnstone, NM and IS. Presented and discussed at Muon Collider Workshops. Documented in Proceedings of those workshops, in Snowmass-96 Feasibility Study and in PRSTAB, vol. 2, 081001 (1999) pp. 1-73.
- Scraping muon beam halo was studied by A. Drozhdin, NM and CJ in 1998-1999.
- New wave in 2009: lattice and background.

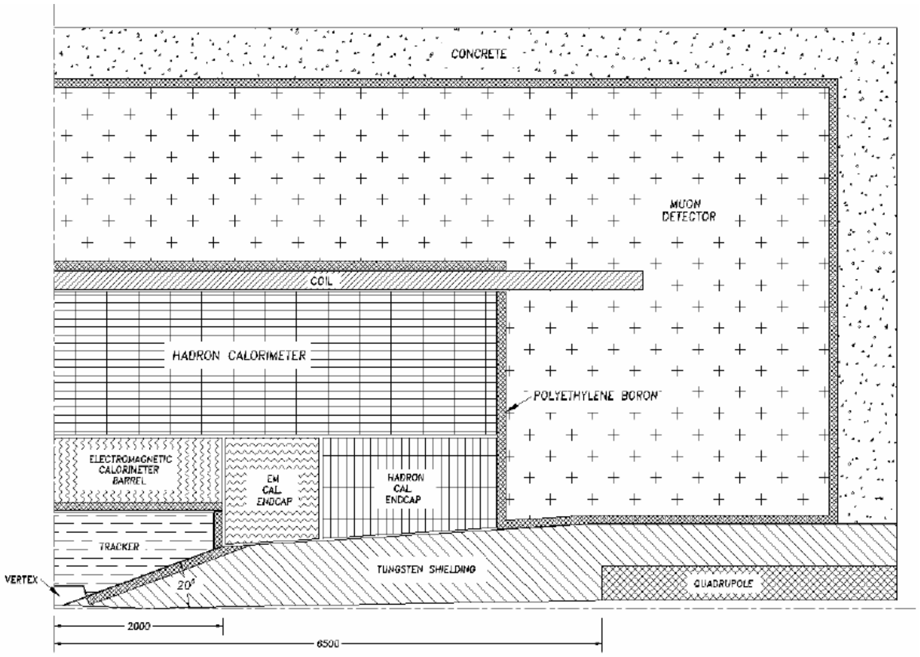
DETECTOR PERFORMANCE

Backgrounds affect collider detector performance in three major ways:

- Detector component radiation aging and damage.
- Reconstruction of background objects (e.g., tracks) not related to products of $\mu^+\mu^-$ collisions.
- Deterioration of detector resolution (e.g., jets energy resolution due to extra energy from background hits).

1996 Strawman MC Detector Concepts





Muon Beam Decays: Major Source of Backgrounds

Contrary to hadron colliders, almost 100% of background and radiation problems at MC arise in the lattice. **Muon decays is the major source**. The decay length for 0.75-TeV muons is λ_D = 4.7×10^6 m. With 2e12 muons in a bunch, one has 4.28×10^5 decays per meter of the lattice in a single pass, and 1.28×10^{10} decays per meter per second for two beams.

Electrons from muon decay have mean energy of approximately 1/3 of that of the muons. At 0.75 TeV, these 250-GeV electrons, generated at the above rate, travel to the inside of the ring magnets, and radiate a lot of energetic synchrotron photons towards the outside of the ring.

Electromagnetic showers induced by these electrons and photons in the collider components generate intense fluxes of muons, hadrons and daughter electrons and photons, which create high background and radiation levels both in a detector and in the storage ring.

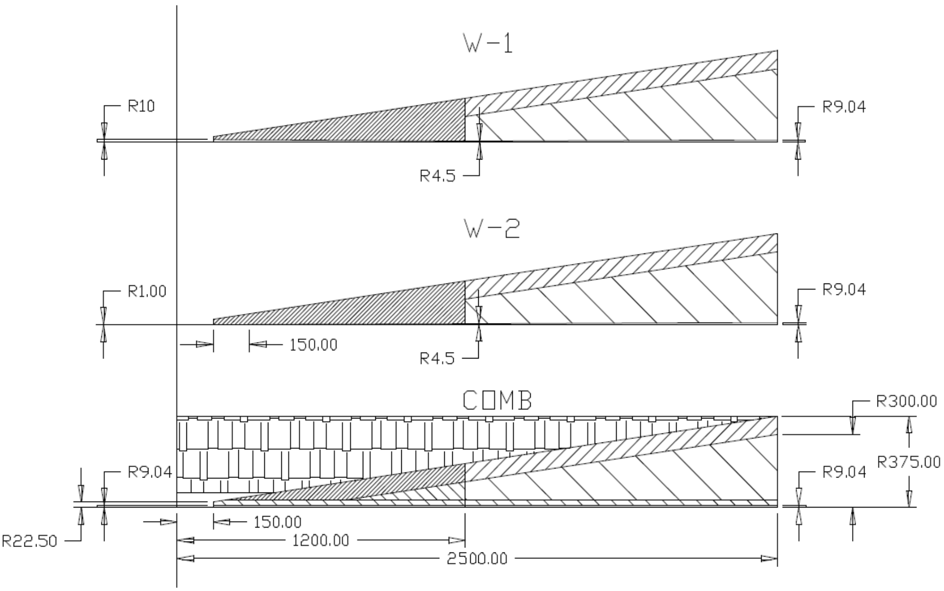
The primary concern is muon decays in the interaction region (IR).

Collimating Nozzles at IP

Due to the very high energy of electrons and photons in the large aperture, the whole triplet is a source of backgrounds in the detector. As calculated, electron and photon fluxes and energy deposition density in detector components are well beyond current technological capabilities if one applies no measures to bring these levels down.

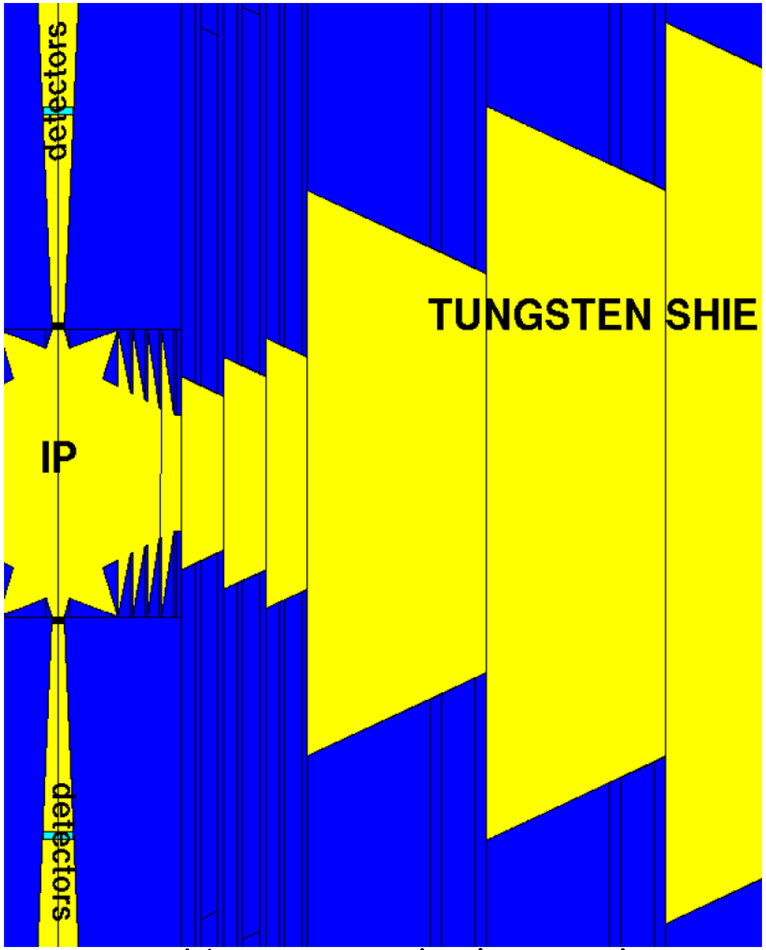
As was found, the most effective collimation includes a limiting aperture about one meter from the IP, with an interior conical surface which opens outward as it approaches the IP. These collimators have the aspect of two nozzles spraying electromagnetic fire at each other, with the charged component of the showers being confined radially by the solenoidal magnetic field and the photons from one nozzle being trapped (to whatever degree possible) by the conical opening in the opposing nozzle.

Nozzle Concepts



Background reduction 30 to 500 times

R=4cm



4m

Detector is not connected by a straight line with any surface hit by decay electrons in forward or backward directions

BACKGROUND TOLERABLE LIMITS

Calorimeter, tracker and vertex detectors: in smallest element, ***occupancy*** ≤ 1%.

To avoid ***pattern recognition*** problem in tracker, hit density from charged particles should be ≤ 0.2 hit/cm^2/bunch.

Muon system: the RPCs (sensitive media) need 1 ms to re-charge a 1 cm^2 area around the avalanche, therefore, the hit rate in excess of 100 Hz/cm^2 would result in an unmanageable dead time. With typical 80 sensitive layers in a Muon Endcap, it corresponds to a muon flux at its entrance of about 1 μ/cm^2/s.

Spreading Decay Electrons Along IR

SC sweep dipoles with tungsten catchers between IR elements : another factor of seven background reduction.

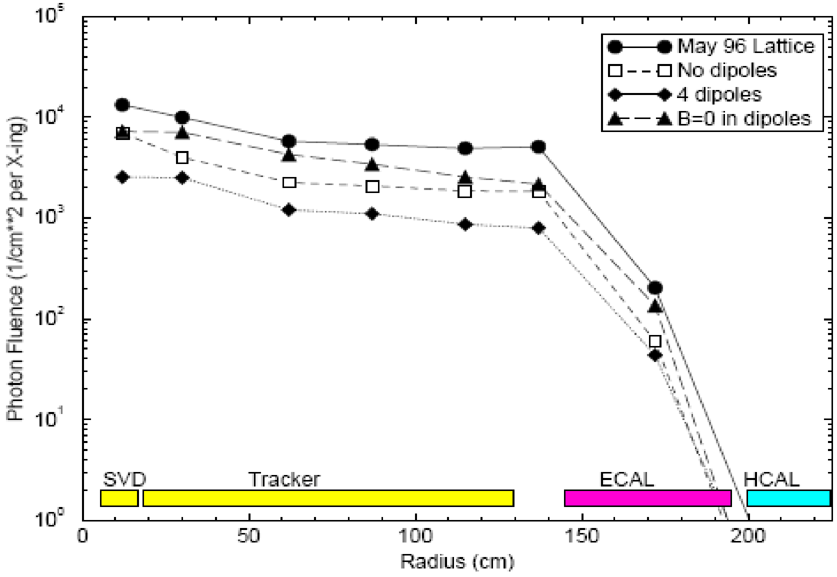


Figure 7: Radial dependence of photon fluence in the ± 1.2 m central detector region around the IP per 2×2 TeV $\mu^+\mu^-$ bunch crossing for different IR scenarios due to muon beam decays.

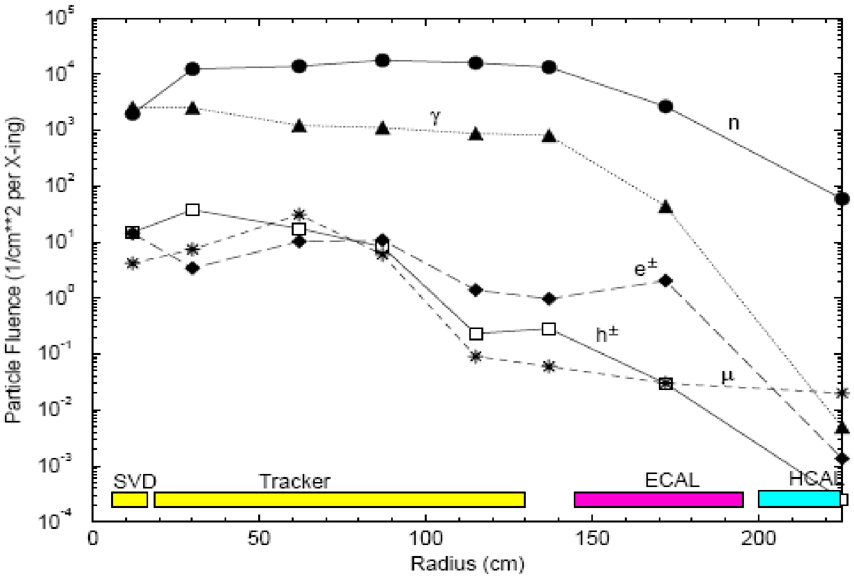


Figure 8: Radial dependence of particle fluence in the ± 1.2 m central detector region around the IP per 2×2 TeV $\mu^+\mu^-$ bunch crossing for the best IR configuration considered.

Helps suppress Bethe-Heitler muons which cause significant fluctuations in transverse energy and missing transverse energy due to energy spikes in deep inelastic interactions of such muons.

TEMPORAL ASPECTS

Temporal considerations in the IP and machine background analysis are of a primary importance. Integrated levels determine radiation damage, aging and radio-activation of detector components as well as the radiation environment in the experimental hall, accelerator tunnel and their surroundings. High instantaneous particle fluxes complicate track reconstruction, cause increased trigger rates and affect detector occupancy.

One can define the ***instantaneous*** or ***effective*** luminosity - which determines the detector performance – for the amount of radiation in the detector active element over the drifting/integration time Δt_d ("sensitivity window") or the bunch train length, whichever is smaller. For detector elements most susceptible to occupancy problem Δt_d is 40 - 300 ns.

Occupancy for 0.3 x 0.3 mm Si-pads

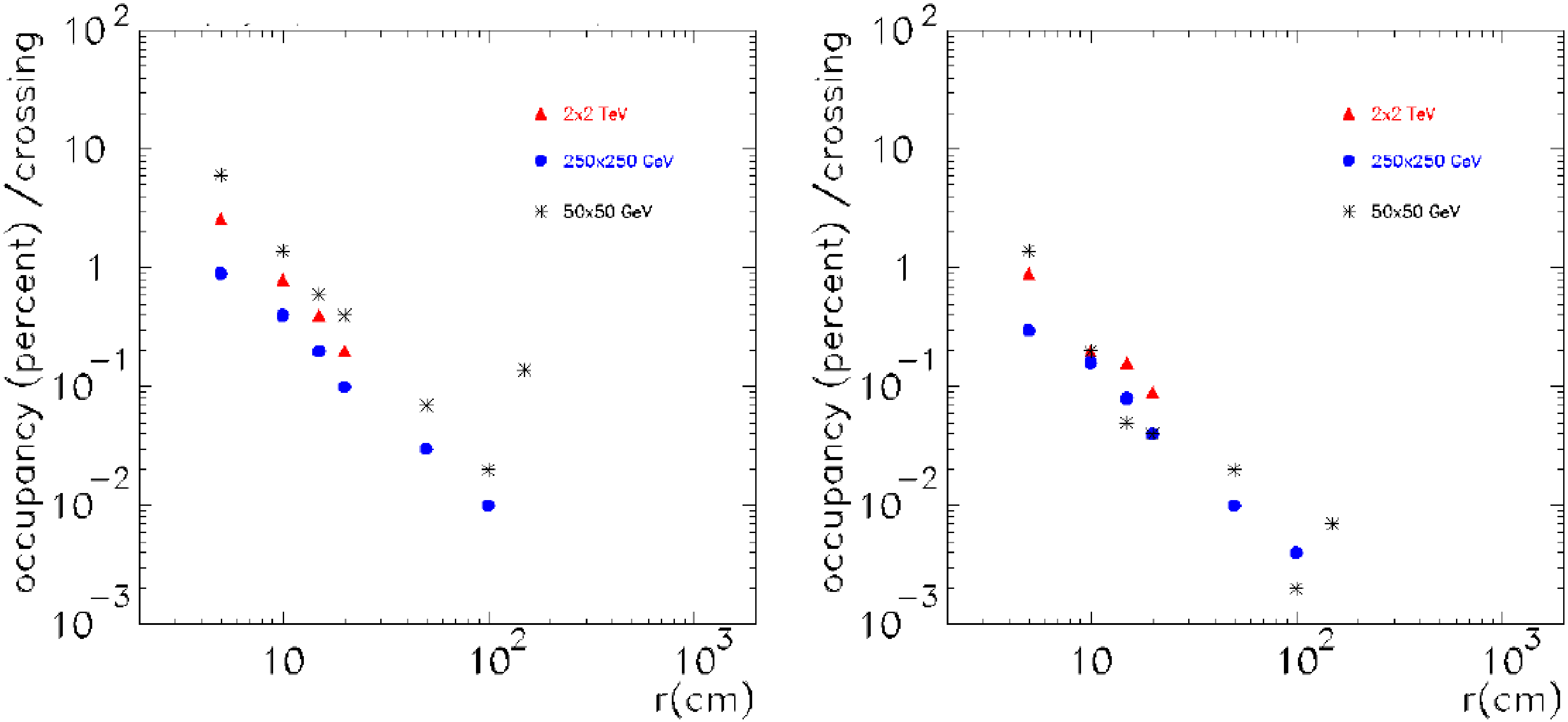


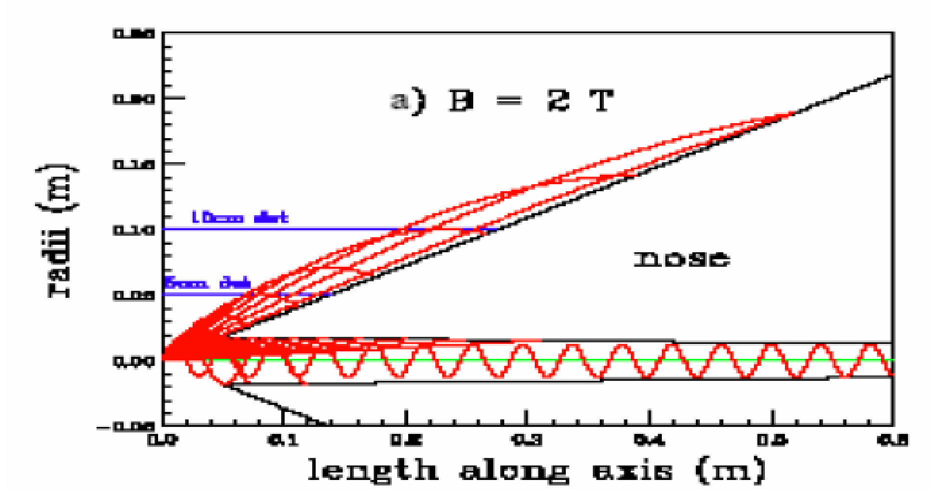
FIG. 64. Occupancy for 300 $\mu m \times 300 \mu m$ silicon pads, as a function of the radius for the three energies studied. Left figure shows the total occupancy and the right figure shows the occupancy from hits resulting from charged particles.

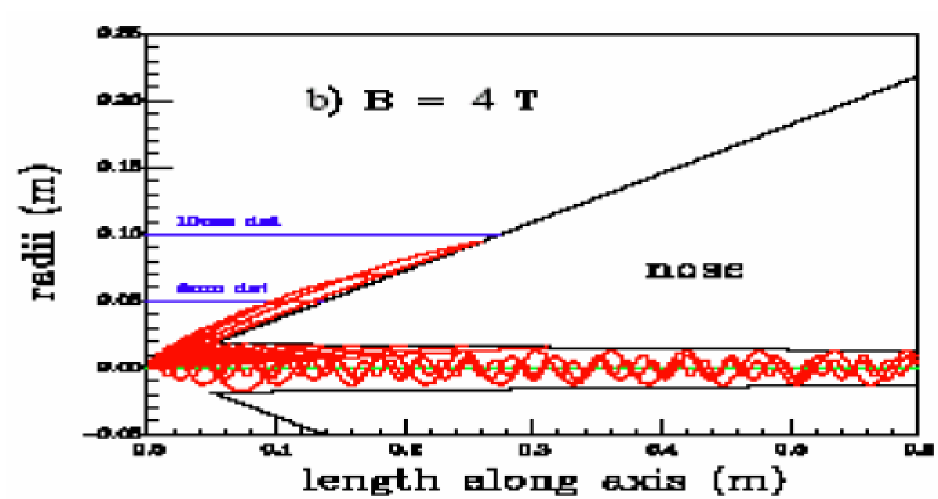
With the best shielding configuration, estimated lifetime of Si detectors is several years

Incoherent Pair Production

Incoherent pair production from $\mu^+\mu^- \rightarrow \mu^+\mu^- e^+e^-$ can be significant for high energy muon colliders.

- Estimated cross section of 10 mb giving 3×10^4 electron pairs per bunch crossing.
- The electron pairs have small transverse momentum, but the on-coming beam can deflect them towards the detector.
- Figures show examples of electron pairs tracked near the detector in the presence of the detector solenoid field.
- With a 2 Tesla field, only 10% of electrons make it 10 cm into the detector. With 4 Tesla field no electrons reach 10 cm.

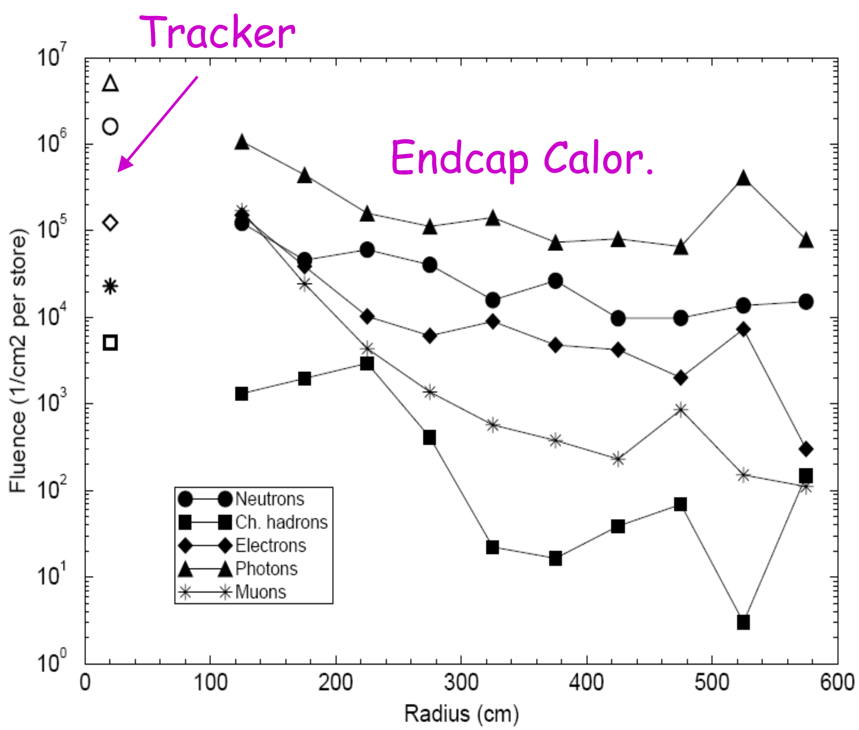




MUON BEAM HALO

We have shown that detector backgrounds originating from beam halo can exceed those from decays in the vicinity of IP. Only with a dedicated beam cleaning system far enough from IP can one mitigate this problem.

Muons injected with large momentum errors or betatron oscillations will be lost within the first few turns. After that, with active scraping, the beam halo generated through beam-gas scattering, resonances and beam-beam interactions at the IP reaches equilibrium and beam losses remain constant throughout the rest of the cycle.



Particle fluxes in detector for 2-TeV beam halo loss (1% per store) at 200m from IP

SCRAPING MUON BEAM HALO

We have designed two beam scraping schemes for MC:

• For TeV domain, extraction of beam halo with electrostatic deflector reduces loss rate in IR by three orders of magnitude; efficiency of an absorber-based system is much-much lower.

• For 50-GeV muon beam, a five meter long steel absorber does an excellent job, eliminating halo-induced backgrounds in detectors.

2009 Muon Collider Tentative Parameters

√s (TeV)	1.5	3
Av. Luminosity / IP (10^{34}/cm^2/s)	0.8	3.4
Max. bending field (T)	10	14
Av. bending field in arcs (T)	6	8.4
Circumference (km)	3	4.5
No. of IPs	2	2
Repetition Rate (Hz)	15	12
Beam-beam parameter/IP	0.1	0.1
β^* (cm)	1	0.5
Beam size @ IP (μm)	6	3
Bunch length (cm)	1	0.5
No. bunches / beam	1	1
No. muons/bunch (10^{12})	2	2
Norm. Trans. Emit. (μm)	25	25
Energy spread (%)	0.1	0.1
Norm. long. Emit. (m)	0.07	0.07
Total RF voltage (MV) at 800MHz	80	900
μ+ in collision / 8GeV proton	0.008	0.007
8 GeV proton beam power (MW)	4.8	4.3

$$\langle \mathcal{L} \rangle = f_0 \frac{n_b N_\mu^2}{4\pi\varepsilon_\perp \beta^*} h \times \frac{1}{2} \tau f_{rep} \sim \frac{P_\mu \xi}{C\beta^*} h \tau$$

P_μ – average muon beam power (~ γ)

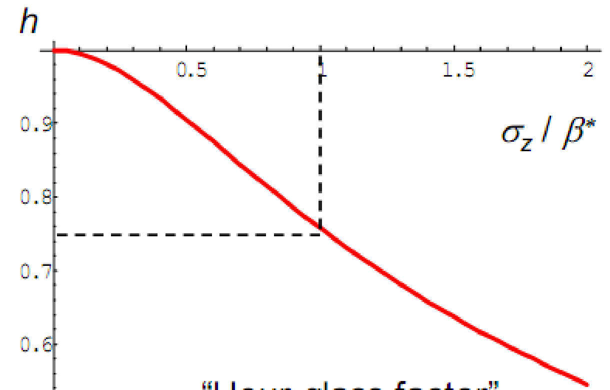
$$\xi = \frac{r_\mu N_\mu}{4\pi\gamma\varepsilon_\perp}$$ – beam-beam parameter

$\gamma\varepsilon_\perp$ – normalized emittance

C – collider circumference (~ γ if B=const)

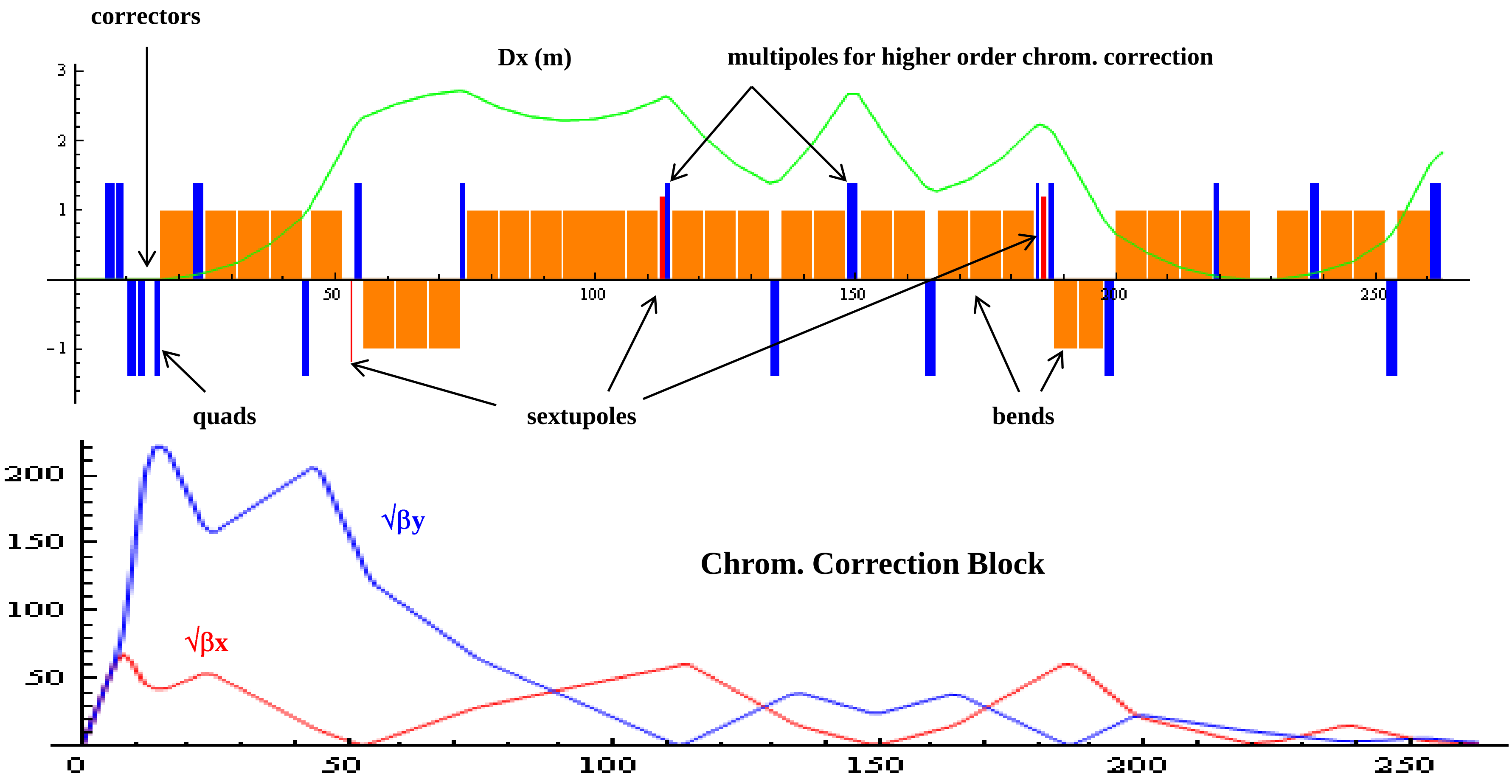
τ – muon lifetime (~ γ)

β^* – beta-function at IP



"Hour-glass factor"

IR Design by E.Gianfelice-Wendt & Y.Alexahin (2009)



See talk by Yuri Alexahin on Wednesday

Requirements/Issues

- Dipoles in IR do an excellent job in spreading decay electrons thus reducing backgrounds in detector; split them in 2-3 m modules with a thin liner inside and tungsten masks in interconnect regions.
- Full aperture $A = 10\ \sigma_{max} + 2$cm
- Maximum tip field in quads = 10T (G=200T/m for A=10cm)
- B = 8T in large-aperture dipoles, = 10T in the arcs
- IR quad length < 2m (split in parts if necessary) with minimal or no shielding inside
- Serious quadrupole, dipole and interconnect technology and design constraints (see talk by A. Zlobin on Thursday)

IR Magnet Constraints

- Quadrupoles: on limits of current state-of-the-art Nb_3Sn technology.
- Dipoles:
  - ➢open midplane – field quality and stresses are a big issue!
  - ➢traditional (cosθ) - may be OK if short, with modest liner, and masks/catchers in interconnect regions.
- Magnet interconnects: up to 50 cm for end parts, multipole correctors and masks.

Tungsten Cone in BCH_2 Shell

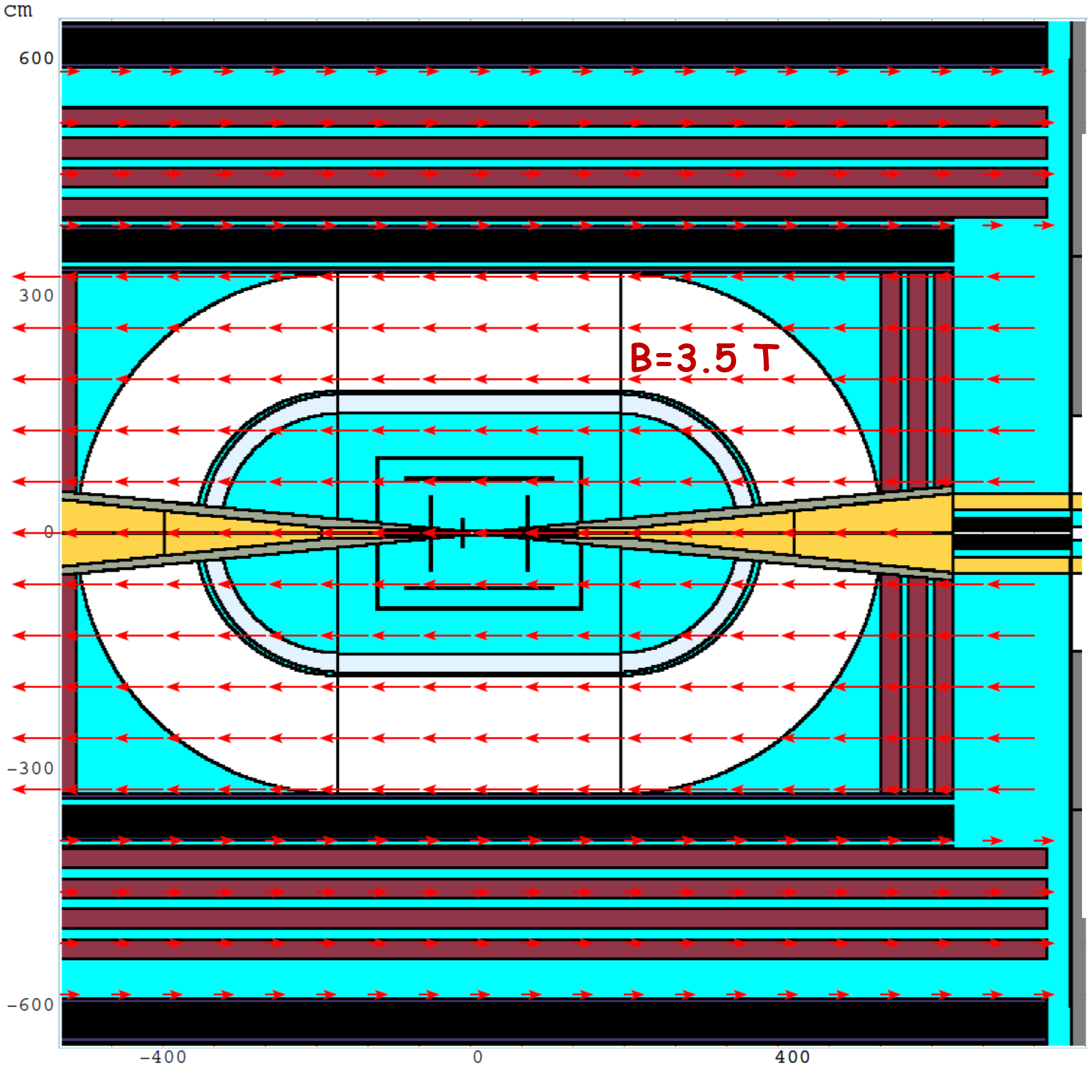
1. **Minimize it** as much as possible (20^0 to 6-9^0) because of serious limitations on possible physics:
   - Top production in forward regions as CoM energy goes up
   - Asymmetries are more pronounced in forward regions
   - Z' => ttbar
   - Final states with many fermions (like ordinary SM tt events) are hardly ever contained in the central detector

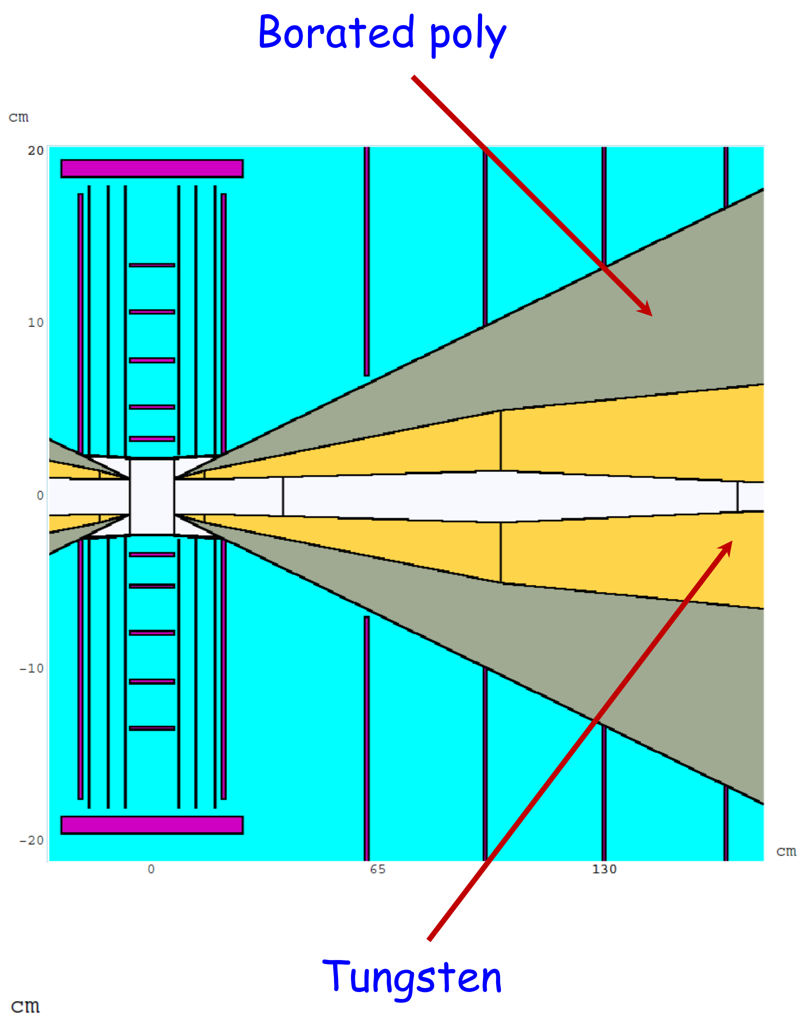
2. **Instrument it**:
   - Forward calorimeter
   - Lumi-cal a'la ILC – 40-140 mrad for precise measurement of the integrated luminosity ($\Delta L/L \sim 10^{-3}$)
   - Beam-cal at smaller angles for beam diagnostics

MARS15 Modeling

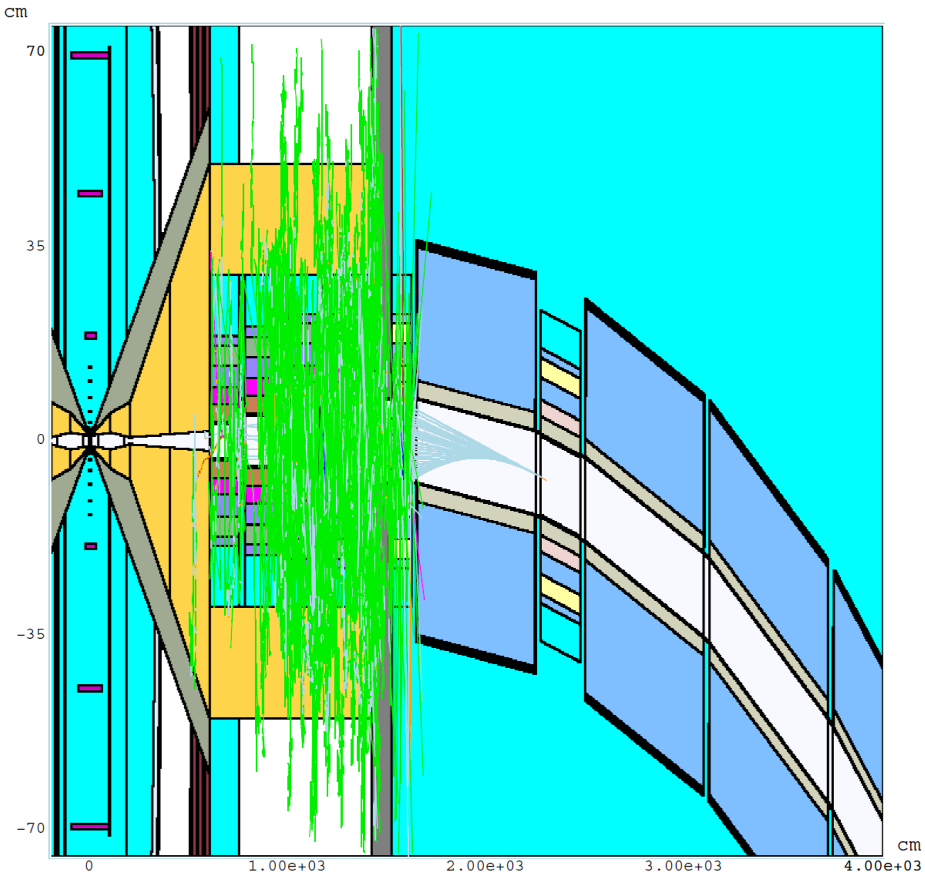
- 250-m segment of EGW-YA lattice implemented in MARS15 model in two versions, with cosθ and open midplane dipoles.
- Model includes rather detailed magnet geometry, materials, magnetic fields (maps and simplified descriptions), tunnel, soil outside and a simplified experimental hall plugged with a concrete wall.
- It includes 4th concept ILC detector with B_z=3.5 T and tungsten nozzle in a BCH_2 shell (about 6^o cone), starting at ±6cm from IP with R=1 cm at this z.
- 750-GeV bunch of 2×10^{12} μ^- approaching IP is forced to decay at -10 to 200 m at 4.28×10^5 per meter rate.
- Cutoff energy is optimized for materials & particle types, varying from 2 GeV at ≥100 m to 0.025 eV in the detector.

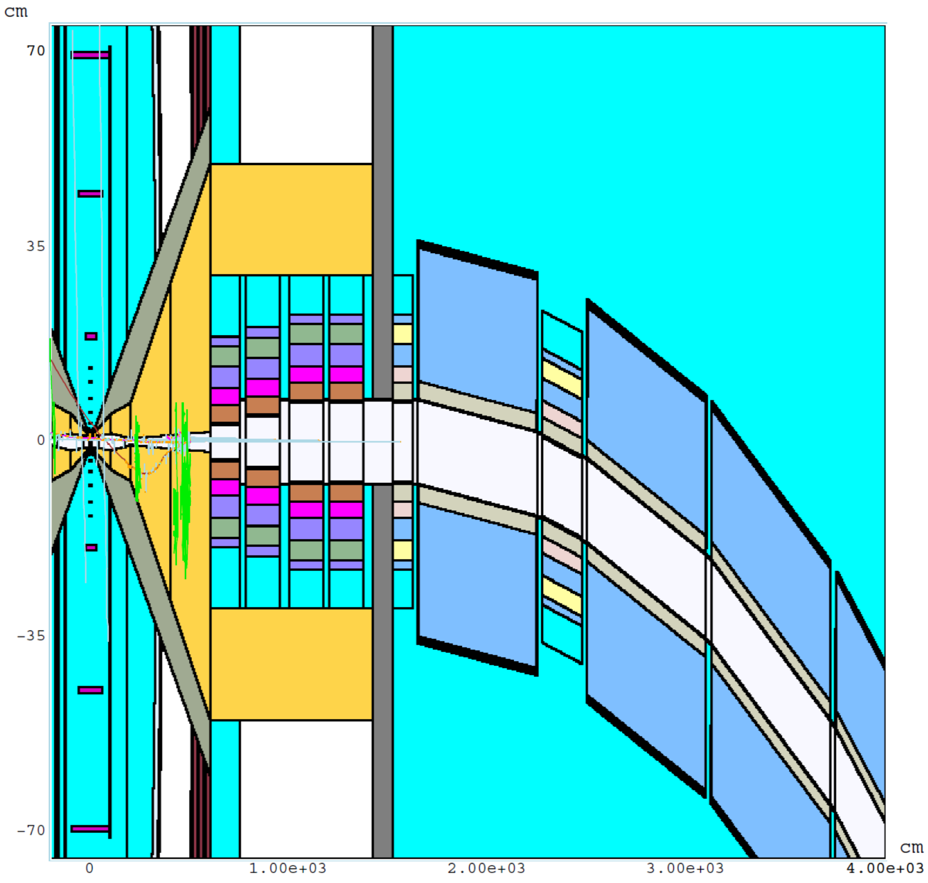
4th Concept Detector at MC: MARS15 Model



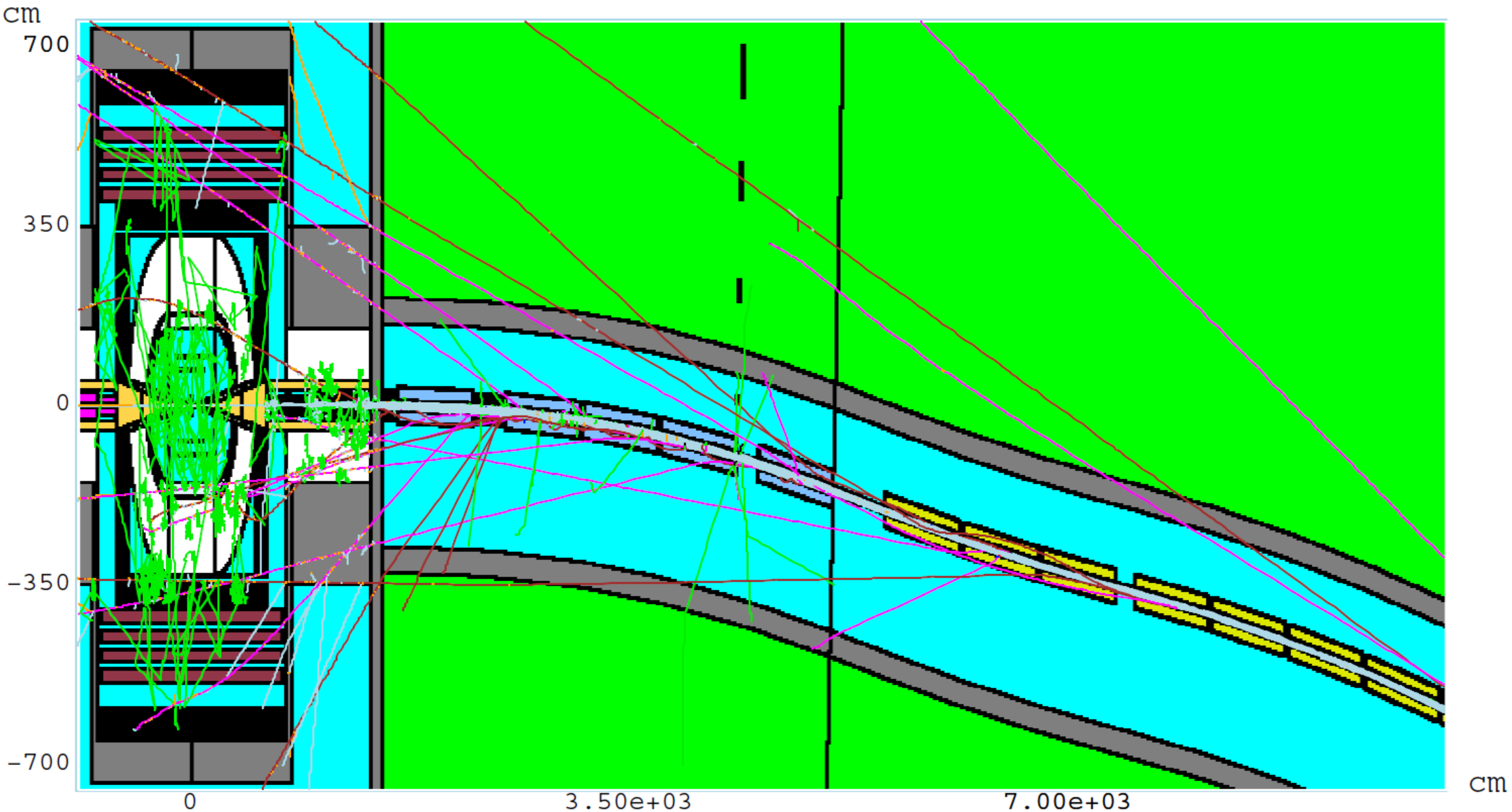


Two Decay Events

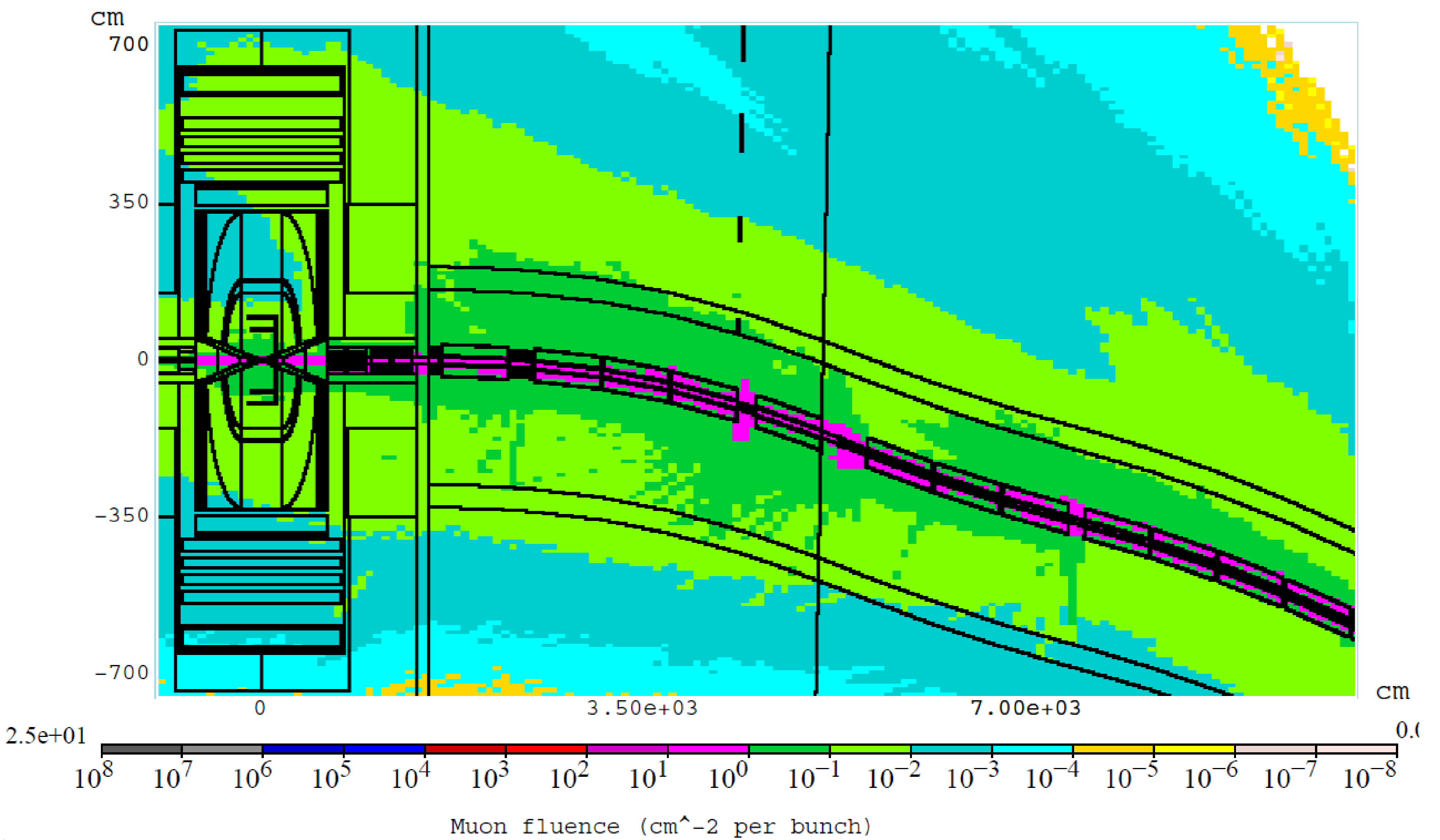




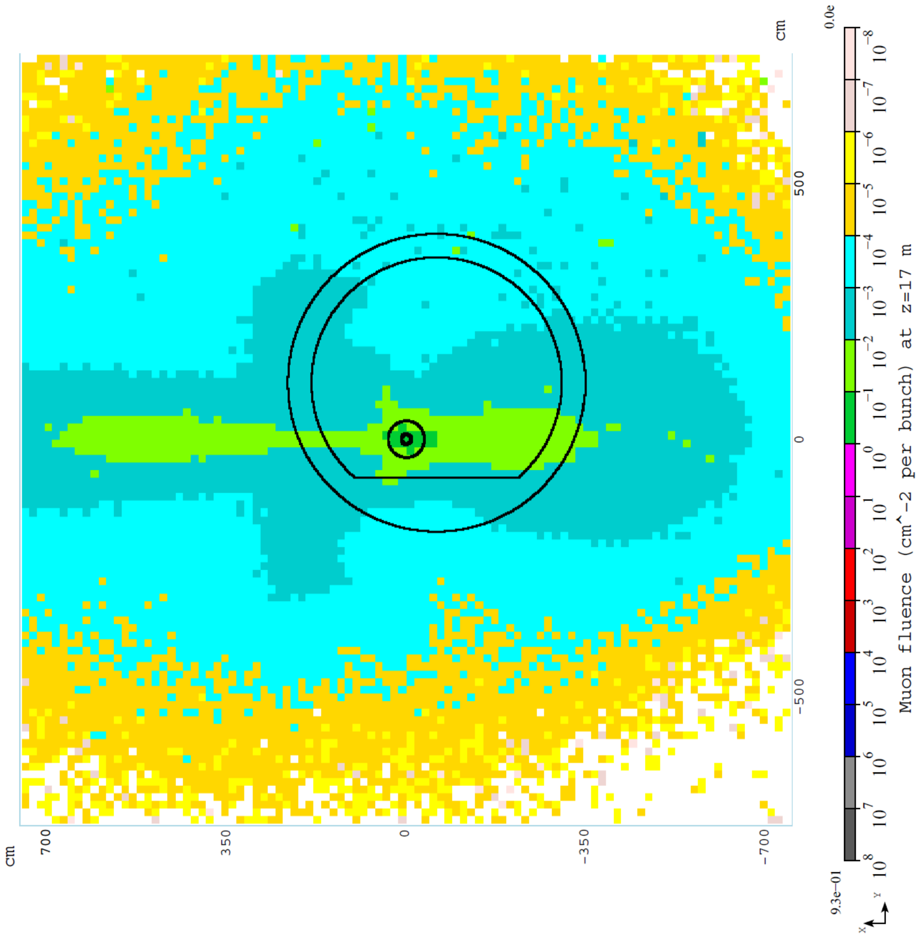
Tracks in IR

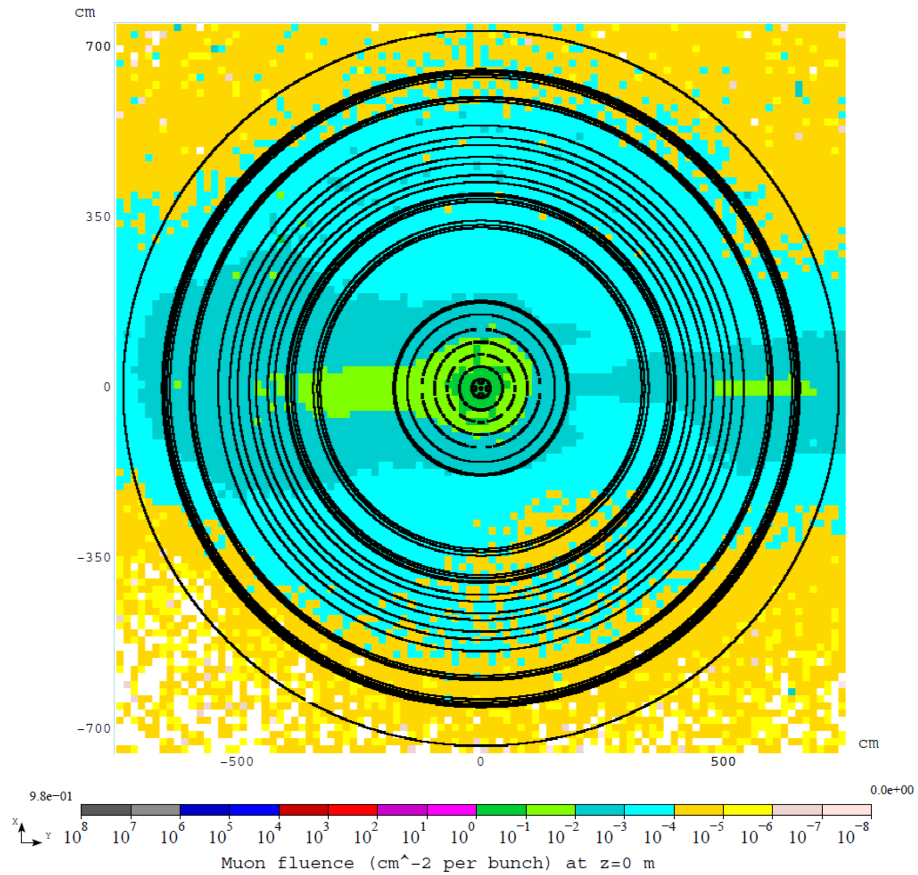


Muon Fluence in Orbit Plane

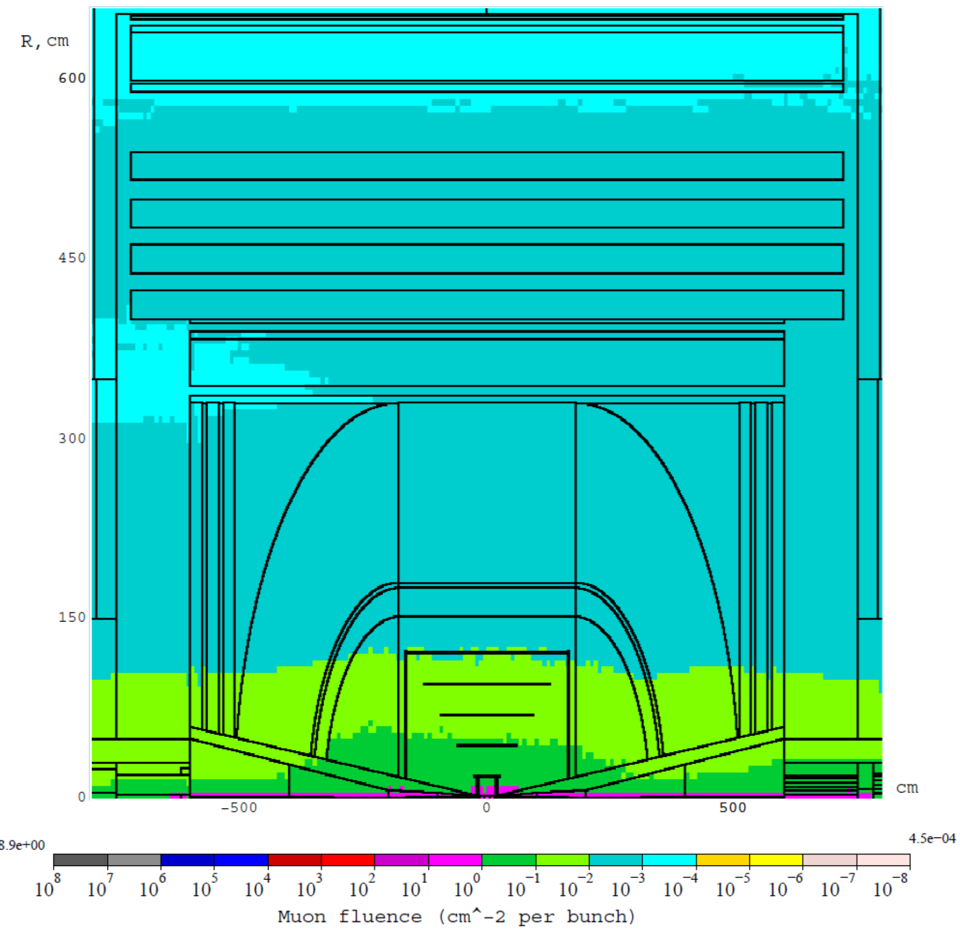


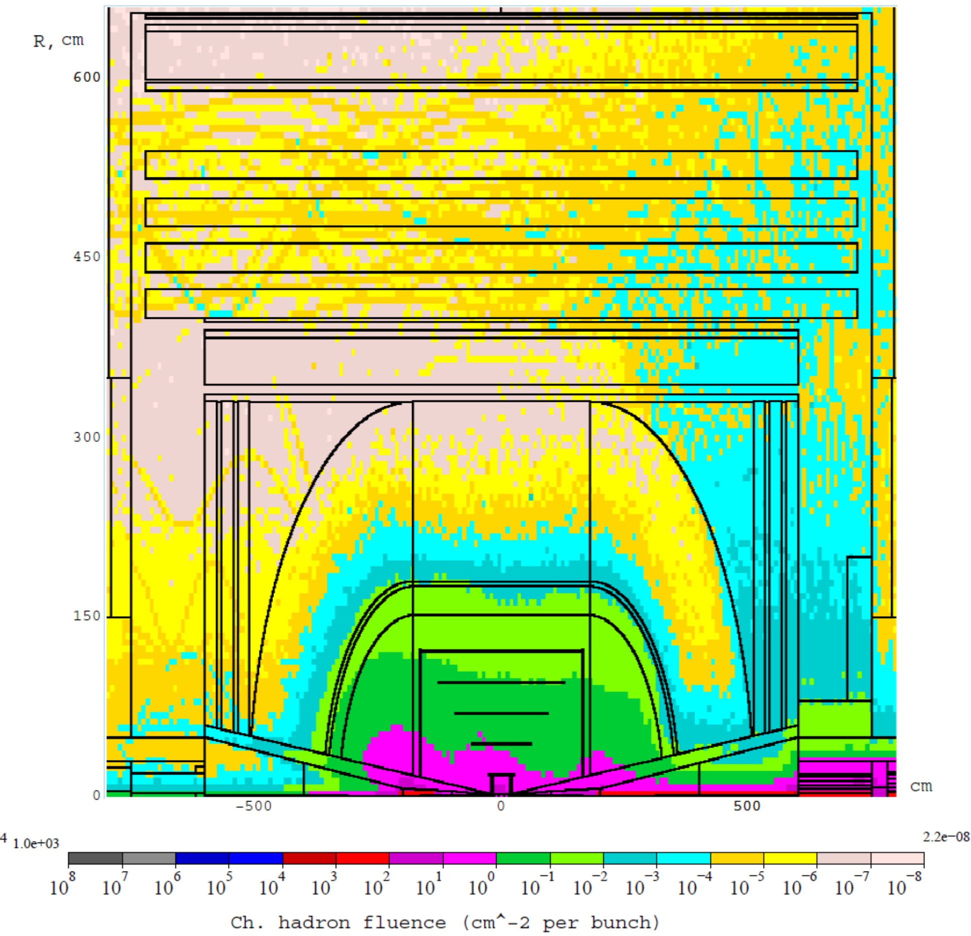
Muon Fluence at z=17 m and z=0



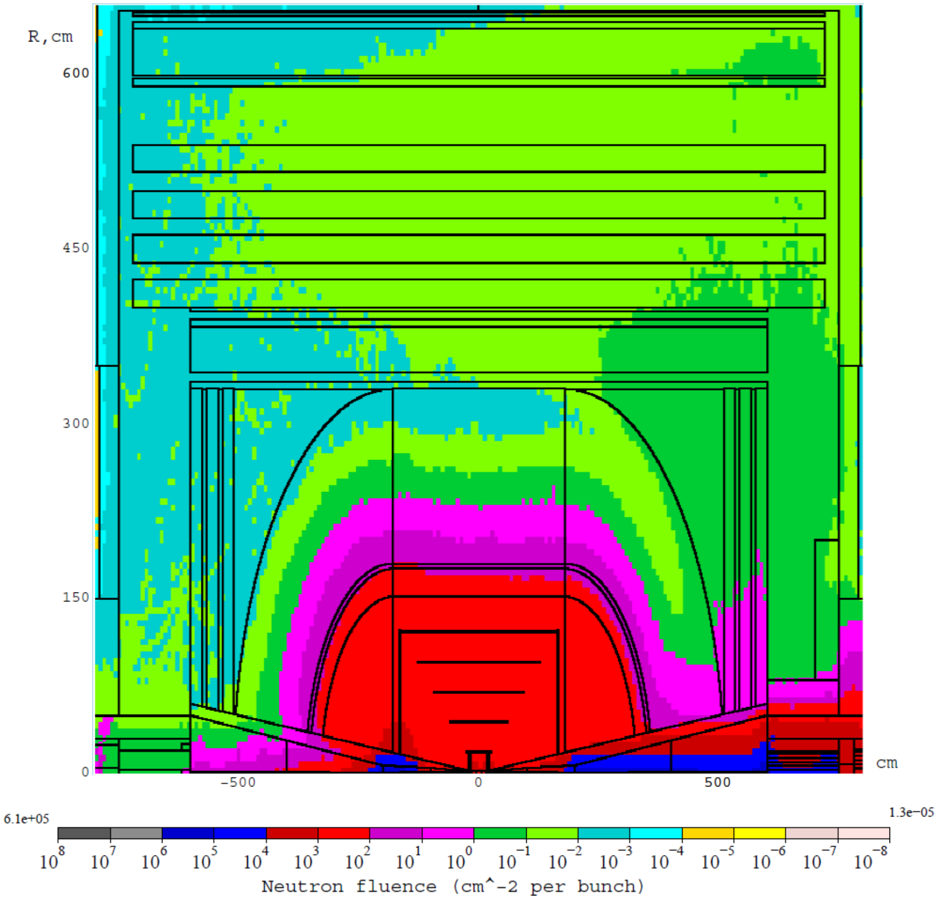


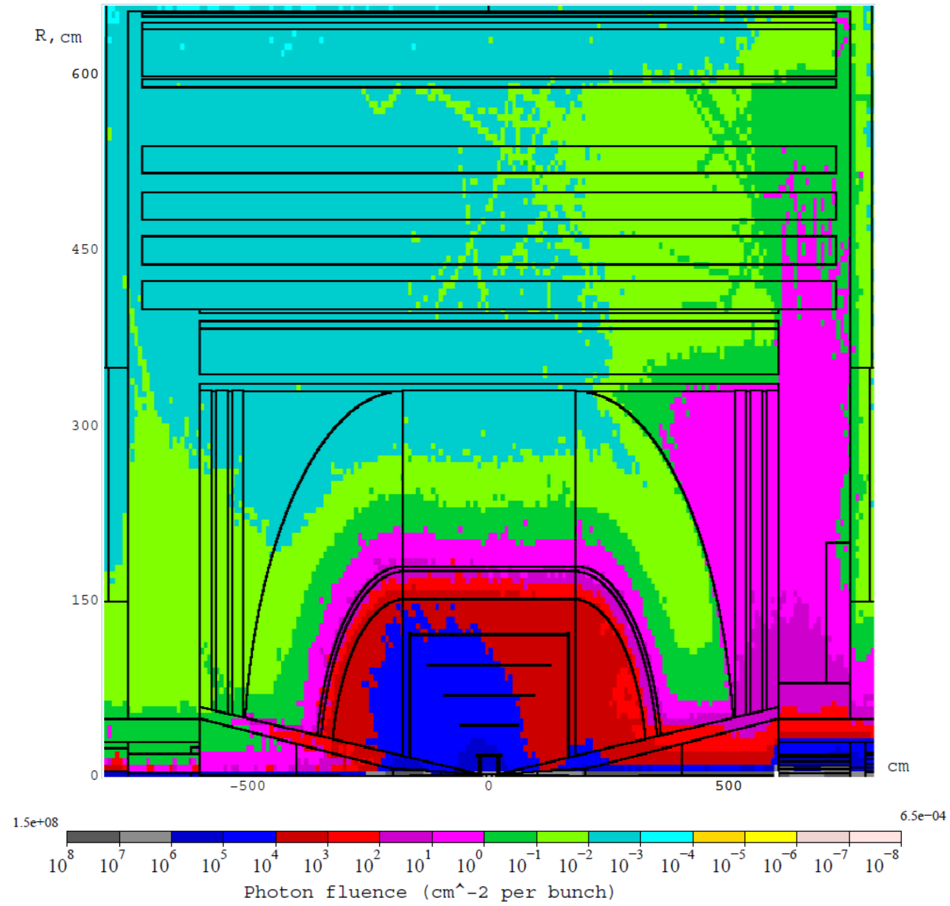
Muon and Charged Hadron Fluence



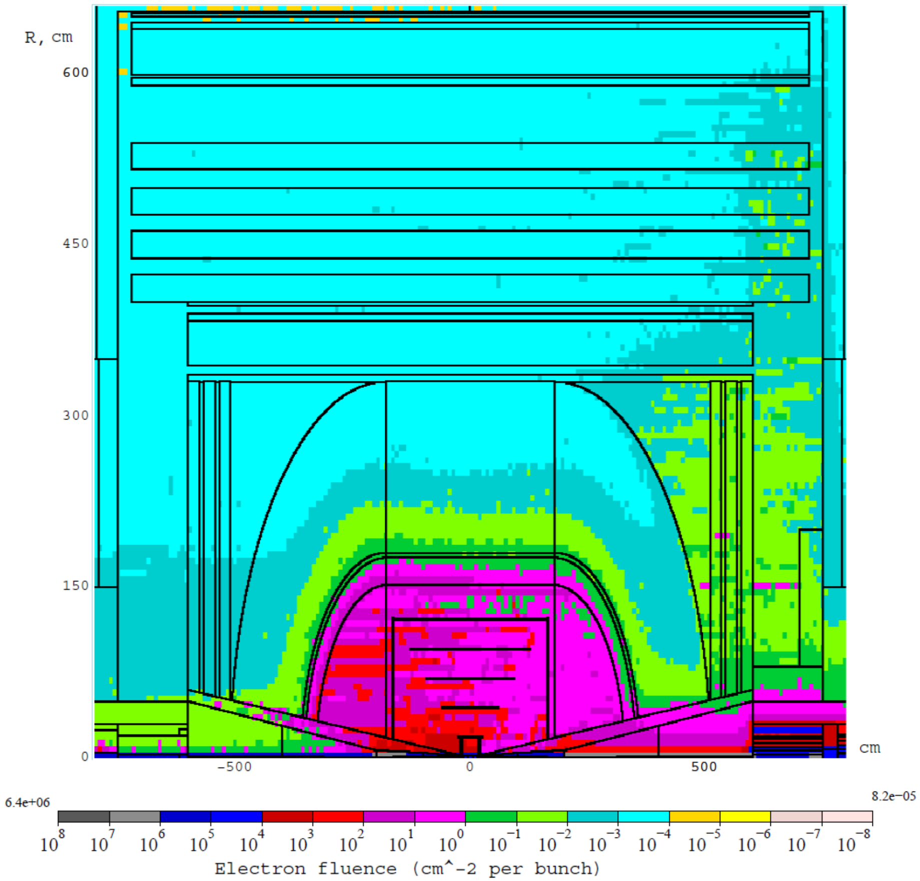


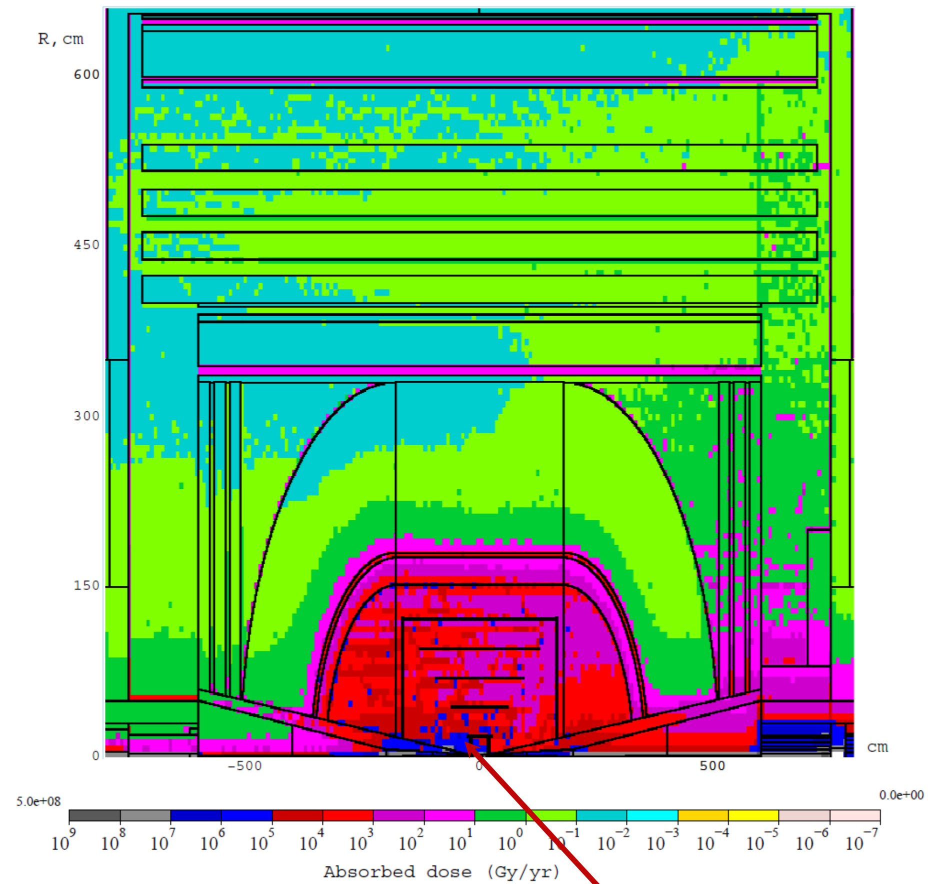
Neutron and Photon Fluence





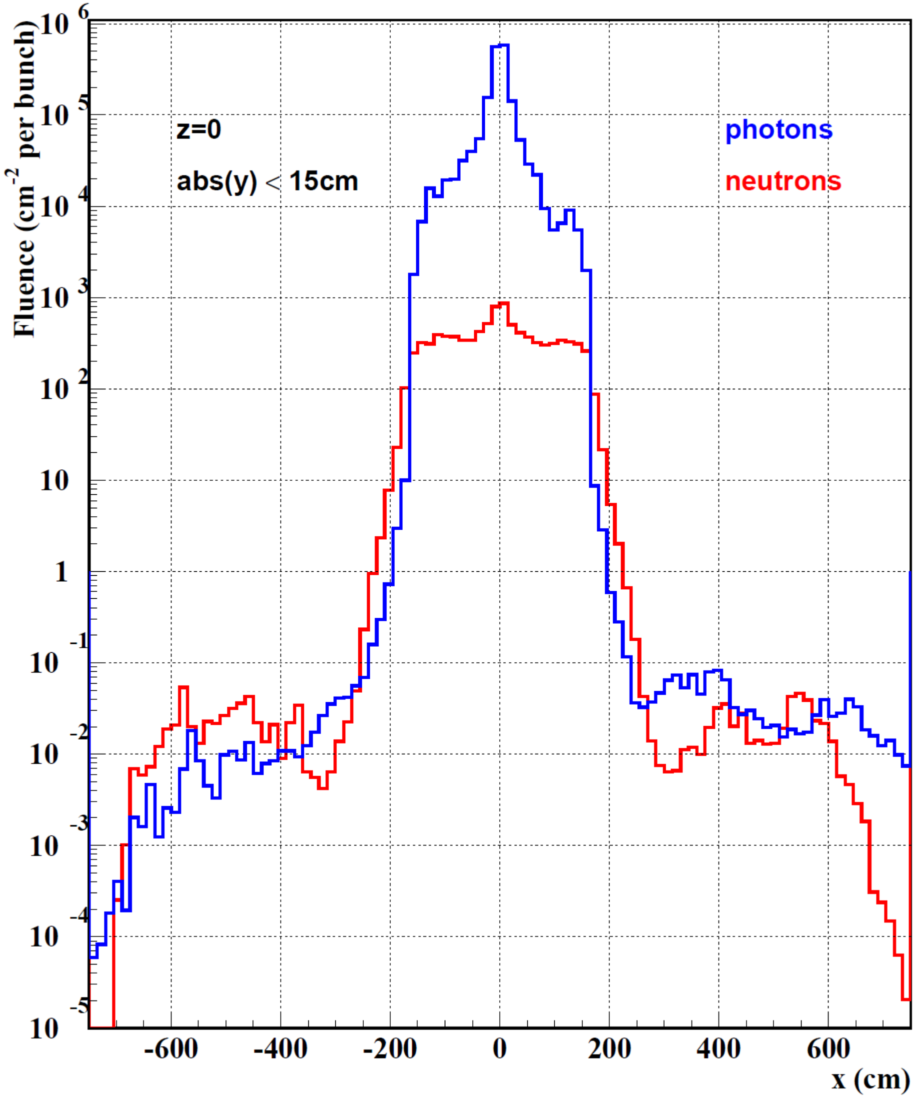
Electron Fluence and Total Dose per Year

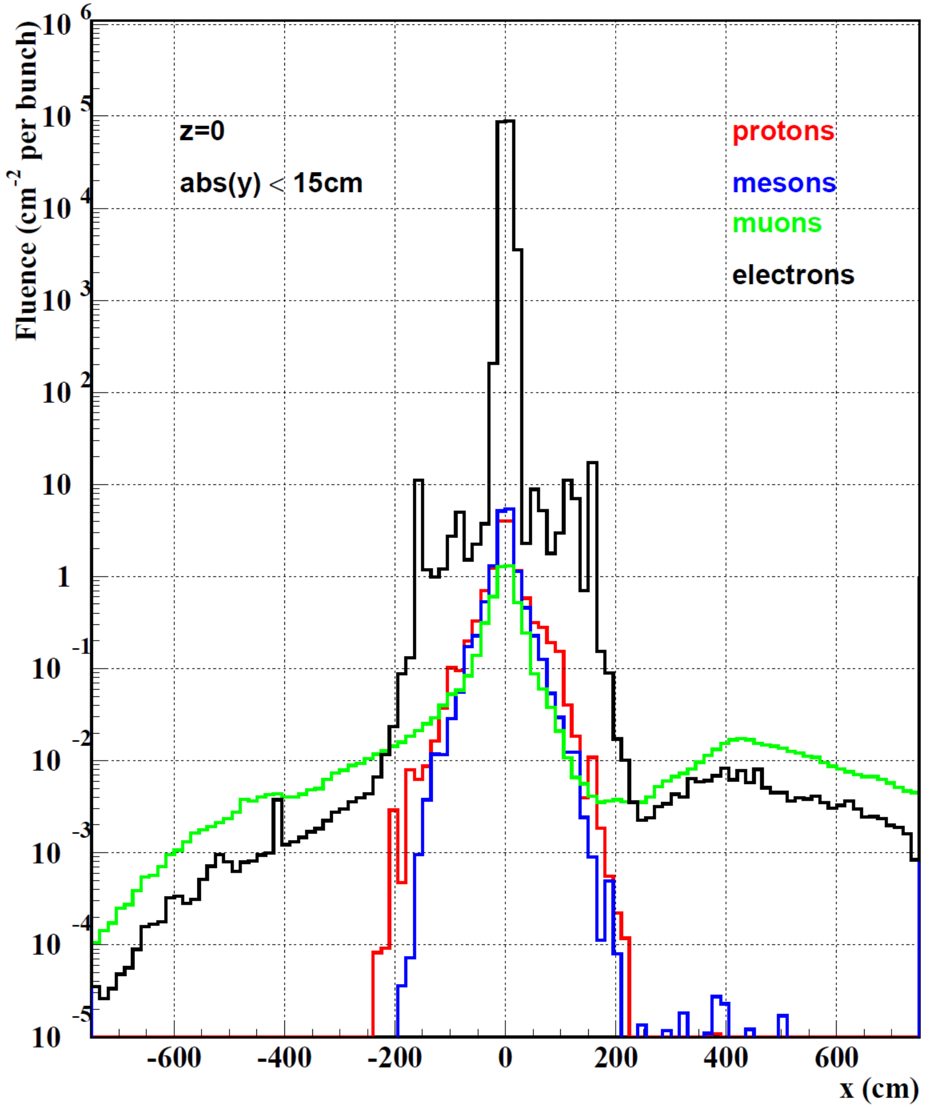




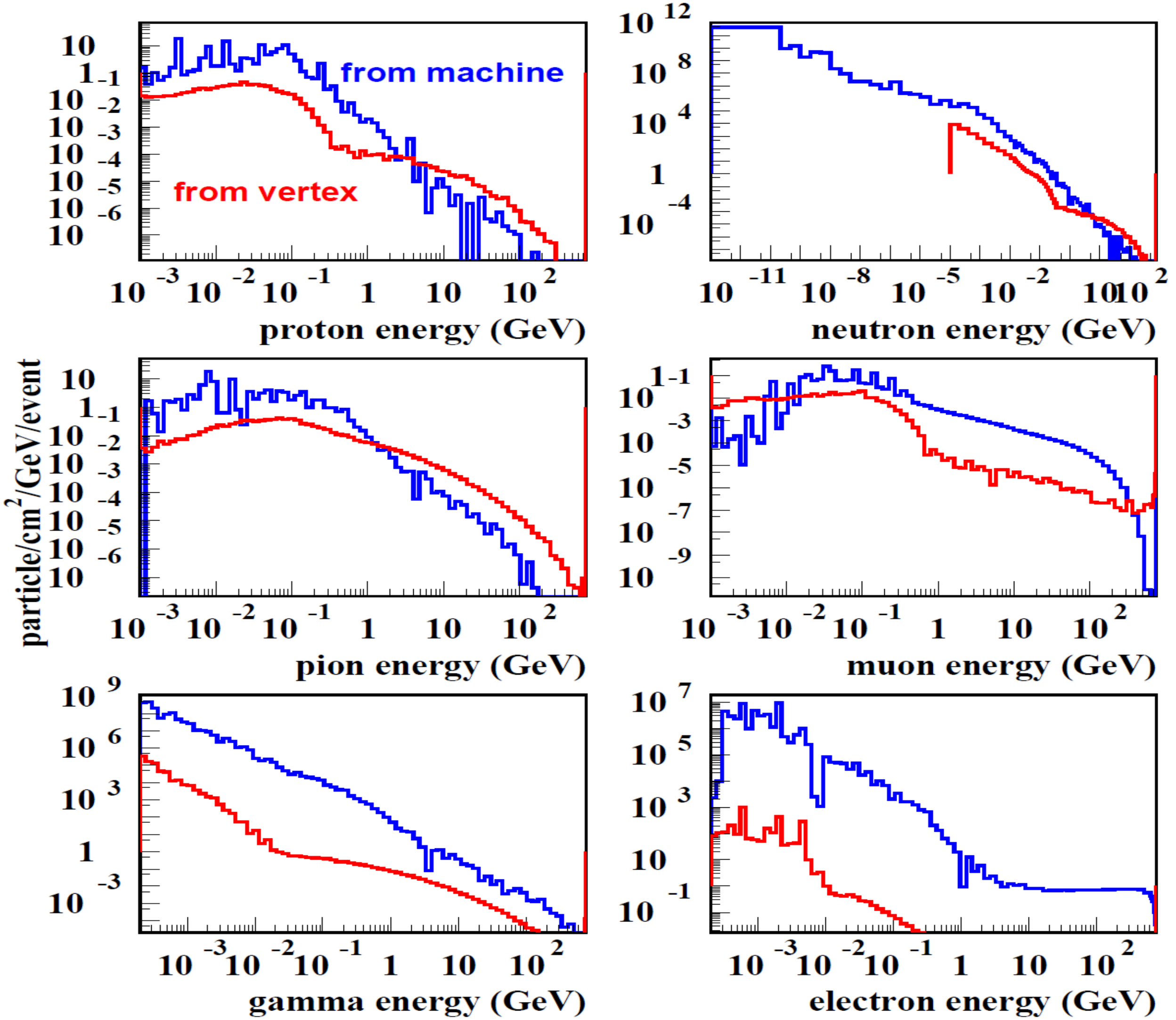
~1 MGy/yr for 2 beams

Particle Fluence in Horizontal Plane at z=0



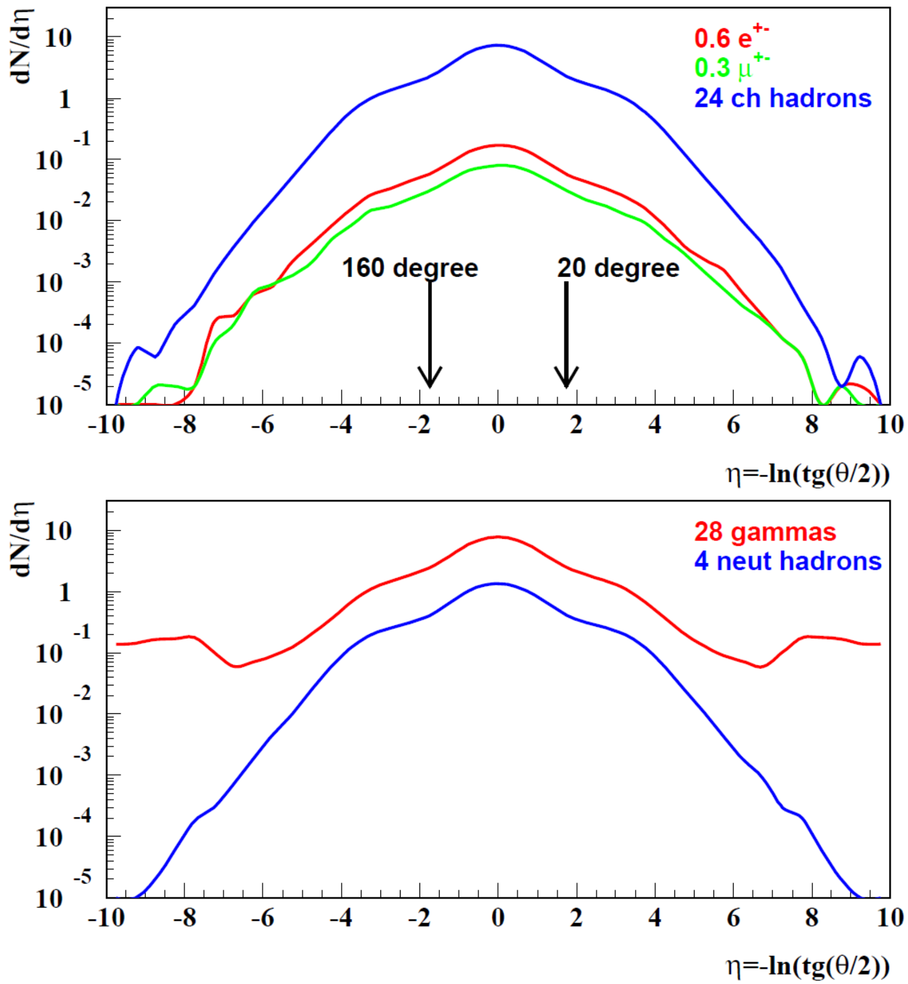


Machine vs Vetrex Backgrounds in Tracker

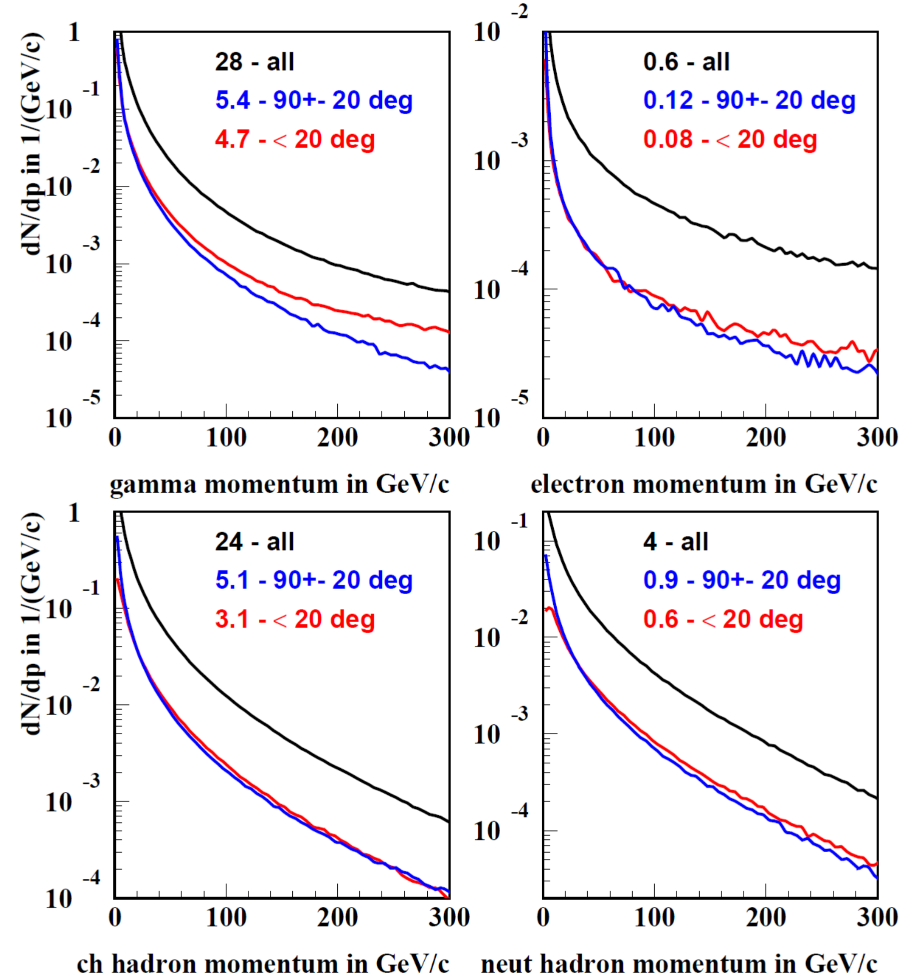


Energy spectra in tracker (+-46x46x5cm3)

Rapidity and Momentum Spectra from $\mu^+\mu^-$ Collision



$\mu^+ \mu^- \rightarrow \gamma^*/Z^0$ at 1500 GeV (1.34 pb)



$\mu^+ \mu^- \rightarrow \gamma^*/Z^0$ at 1500 GeV (1.34 pb)

PYTHIA calculations by S. Striganov, talk tomorrow

MDI Issues and Work to Do (1)

1. It is found only a weak dependence of background rates on magnet technology, but…
2. 8-10 T magnets: open midplane versus conventional $\cos\theta$ dipoles, field quality, stress issues, protection (splitting them in ~3m long pieces with masks in between and modest high-Z liners). Look at alternative technologies (permanent magnets etc.). Quadrupole technology and protection is a special issue.
3. Add their realistic geometry and magnetic field maps to the MARS model.
4. Interconnect regions: 40-50 cm needed, seems OK for optics, backgrounds and neutrino radiation for 750-GeV muon beams; need to keep them as short as possible with energy going up.

MDI Issues and Work to Do (2)

5. Investigate/model a 50-T IR solenoid option.
6. Further optimize the nozzle: increase its current 6-degree cone not sacrificing physics; consider its instrumentation (Lumical and other ILC experience).
7. Investigate if such an optimal cone confines incoherent pairs with the detector 3.5-T field.
8. Model detector response to physics signal in presence of IP and machine backgrounds.
9. Revisit beam scraping schemes for 0.75 and 1.5-TeV muon beams.