PARTICLE COLLIDER INTERACTION REGIONS

Backgrounds and Machine-Detector Interface

Lecture 3: Muon Colliders

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Lecture 3

Muon Collider Backgrounds and MDI

OUTLINE

- Muon Collider
- Background Sources
- Lattice, Ring and IR Magnets
- Backgrounds in Detector and Mitigation
- Physics Events in Background Environment
- Neutrino Hazard

Muon Collider Motivation

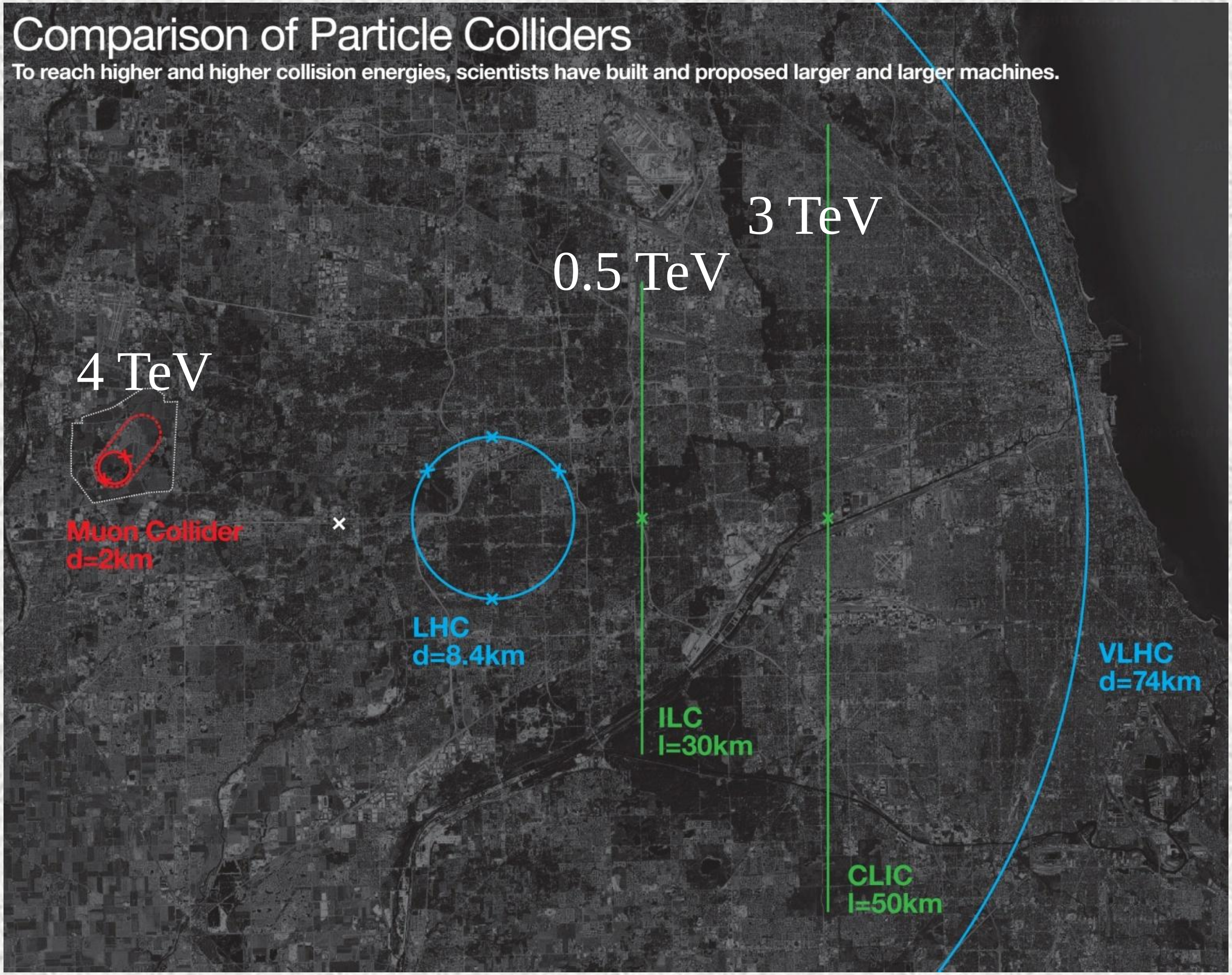
If we can build a multi-TeV muon collider it's an attractive option because muons don't radiate as readily as electrons (m_m / m_e ~ 207):

- **COMPACT**
  - Fits on laboratory site
- **MULTI-PASS ACCELERATION**
  - Cost Effective (e.g. 10 passes → factor 10 less linac)
- **MULTIPASS COLLISIONS IN A RING (~1000 turns)**
  - Relaxed emittance requirements & hence tolerances
- **NARROW ENERGY SPREAD**
  - Precision scans & kinematic constraints
- **TWO DETECTORS (2 IPs)**
- **ΔT_{bunch} ~ 10 μs**
  - Lots of time for readout; Backgrounds don't pile up
- **$(m_\mu/m_e)^2$ = ~40000**
  - Enhanced s-channel rates for Higgs-like particles

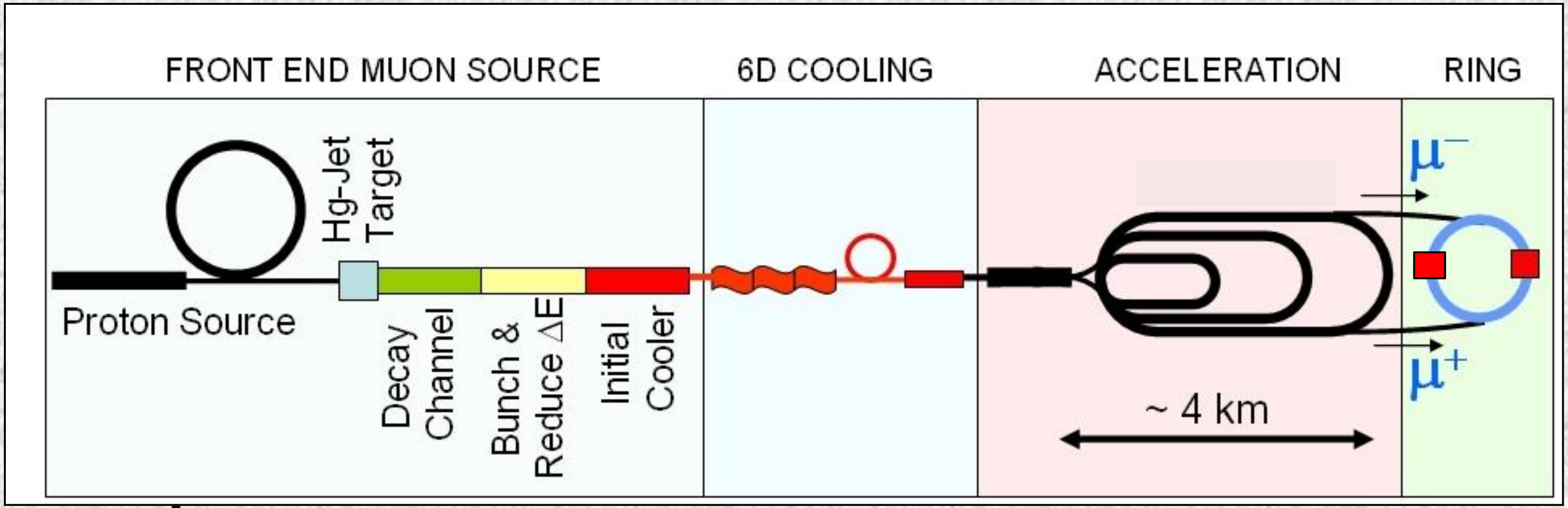
COST

PHYSICS

Muon Colliders are Compact



Muon Collider Schematic



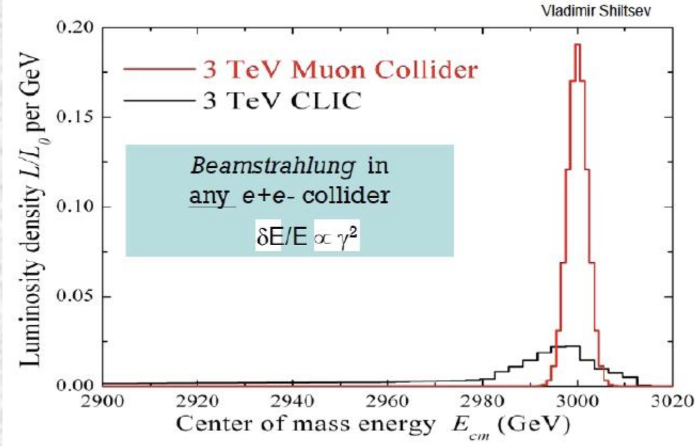
Proton source: Upgraded PROJECT X (4 MW, 2±1 ns long bunches)

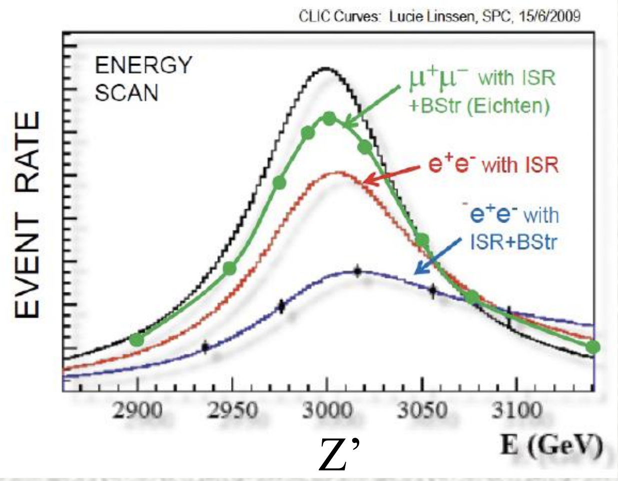
10^{21} muons per year that fit within the acceptance of an accelerator

$\sqrt{s}$ = 1.5 to 4 TeV
Circumference 2.5-5km
$\mathcal{L} = (1\text{-}3)\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$
μ/bunch = 2×10^{12}
$\sigma(p)/p$ = 0.1%
β^* = 5mm
Rep rate 6-12 Hz

Muon Collider: Physics and Detectors

- The overall physics goals of a future lepton collider are similar for ILC/CLIC/MC.
- A coordinated program of detector research is appropriate. The 5 Labs have proposed this to DOE.
- The MC physics effort is in the early stages. Needs much more work to scope out the potential.
- The physics and backgrounds are significantly different for a 500-GeV ILC and a multi-TeV CLIC/MC. For a MC there are additional backgrounds due to muon decays.





Detector Backgrounds

- Muon Collider (MC) detector performance is strongly dependent on the background particle rates in various sub-detectors.

- Deleterious effects of the background and radiation environment produced by muon decays is one of the fundamental issues in the feasibility study of MC ring, Interaction Region (IR) and detector.

Sources of Background at Muon Colliders

1. **IP $\mu^+\mu^-$ collisions:** Production x-section 1.34 pb at $\sqrt{S}$ = 1.5 TeV (negligible compared to #3).
2. **IP incoherent e^+e^- pair production:** x-section 10 mb which gives rise to background of $3{\times}10^4$ electron pairs per bunch crossing (manageable with the nozzle)
3. **Muon beam decays:** Unavoidable bilateral detector irradiation by particle fluxes from beamline components and accelerator tunnel – **major source** at MC: For 0.75-TeV muon beam of 2×10^{12}, 4.28×10^5 dec/m per bunch crossing, or 1.28×10^{10} dec/m/s for 2 beams.
4. **Beam halo:** Beam loss at limiting apertures; severe, can be taken care of by an appropriate collimation system far upstream of IP (**see Lecture 4**).

Muon Decay

Muon decay length

$$\lambda_D = \frac{c\ \tau_\mu\ p}{m_\mu},$$

where $c\tau_\mu = 658.654$ m, $m_\mu = 0.105658389$ GeV/c^2

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 $\lambda_D = 4.7\times10^6$ 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.

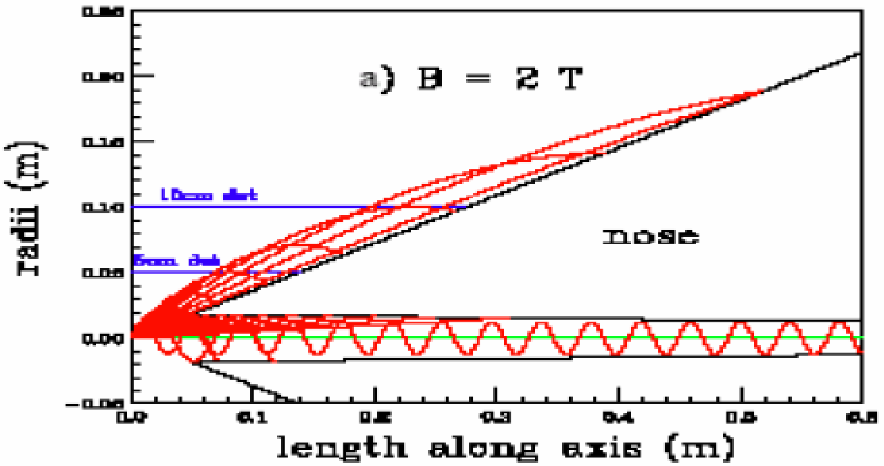
Electrons from muon decay have mean energy of approximately 1/3 of that of the muons. At 0.75 TeV, these 250-GeV electrons, generated at the above rate, travel to the inside of the ring magnets, and radiate a lot of energetic synchrotron photons towards the outside of the ring.

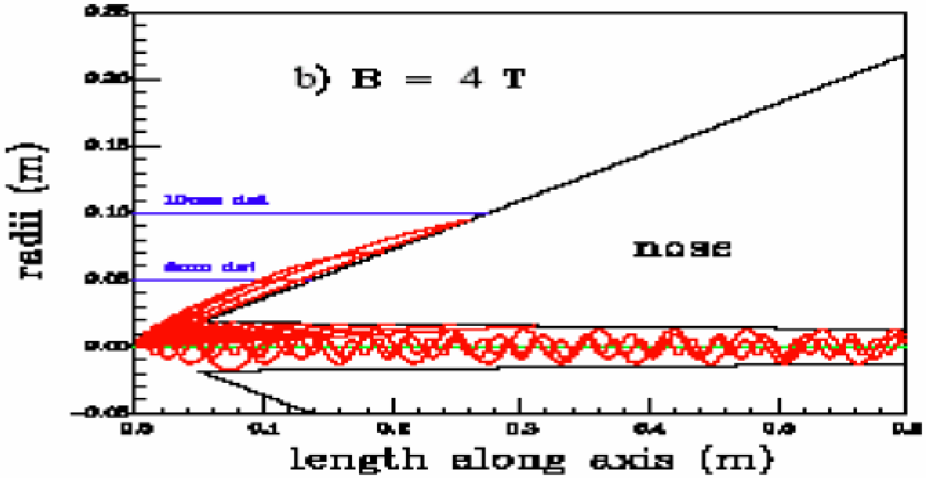
Electromagnetic showers induced by these electrons and photons in the collider components generate intense fluxes of muons, hadrons and daughter electrons and photons, which create high background and radiation levels both in a detector and in the storage ring at the rate of **0.5-1 kW/m** (to be compared to a good practice number of a few W/m). **The primary concern is muon decays in the interaction region (IR).**

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.





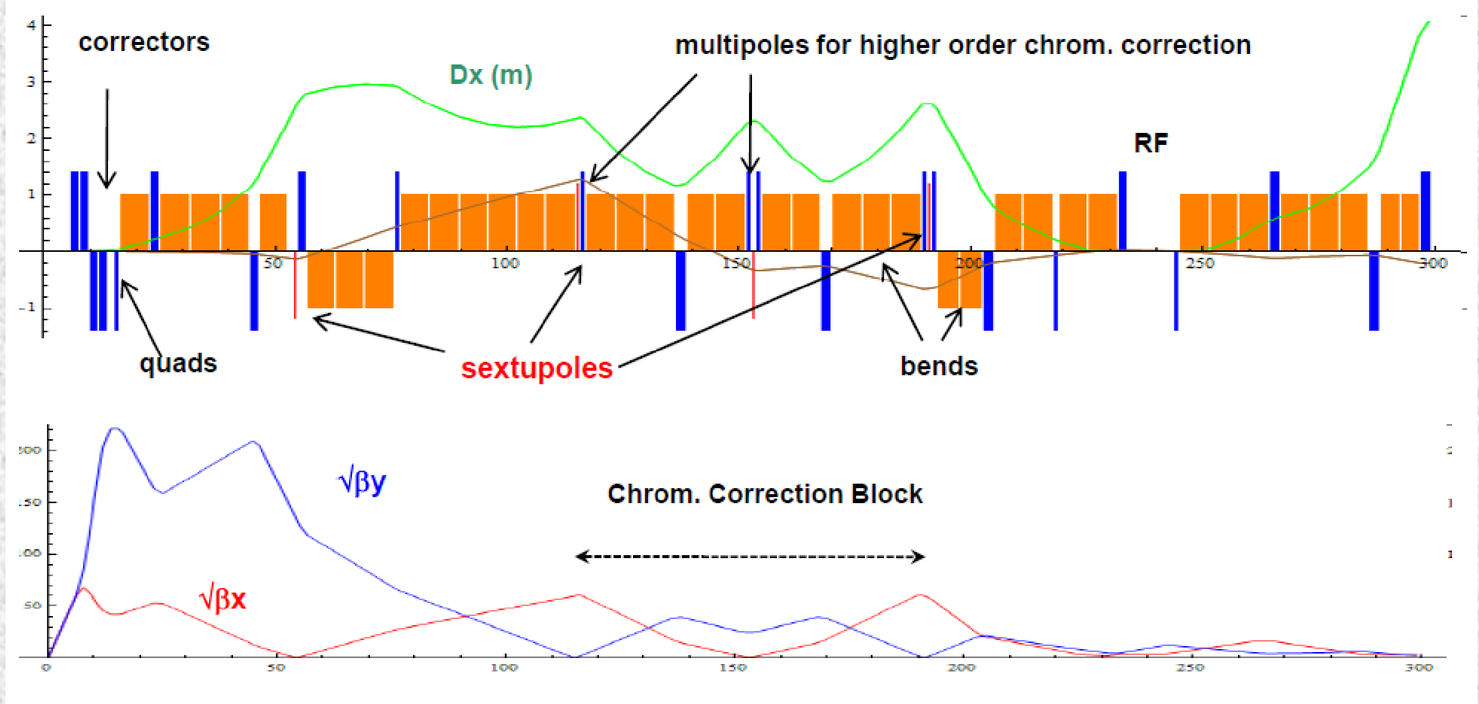
New Wave: 2009-2010

- Compact lattice:
  C=2.5 km with B = 10 T
- Consistent IR design
- Realistic IR magnets
- Full MARS modeling of MDI
- Detector: fast and full simulators

Muon Collider Parameters

E_{cms}	TeV	1.5	4
f_{rep}	Hz	12	6
n_b		1	1
Δt	μs	10	27
N	10^{12}	2	2
$\varepsilon_{x,y}$	μm	25	25
L	$10^{34}\ cm^{-2}s^{-1}$	1	4

IR & Chromatic Correction Section



8-T dipoles in IR to generate large D at sextupoles to compensate chromaticity and sweep decay products; momentum acceptance 1.2%; dynamic aperture sufficient for transverse emittance of 50 μm; under engineering constraints.

Iterative studies on lattice and MDI with magnet experts: High-gradient (field) large-aperture short Nb_3Sn quads and dipoles.

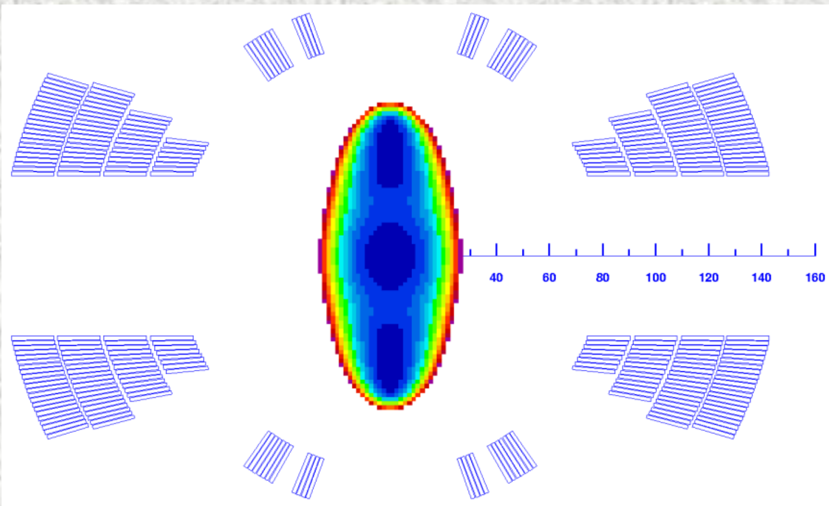
Magnet Requirements/Issues

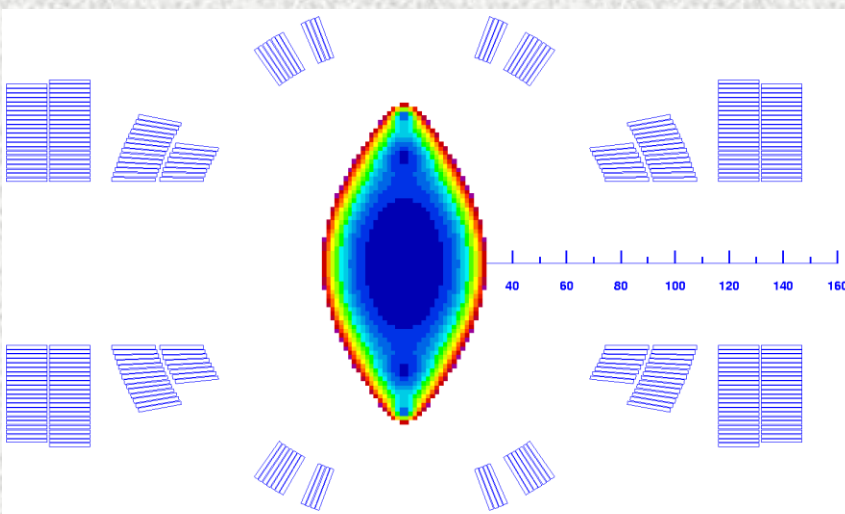
- Dipoles in IR do an excellent job in spreading decay electrons thus reducing backgrounds in detector; split them in 2-3 m modules with a thin liner inside and tungsten masks in interconnect regions.
- Full aperture A = 10 σ_{max} + 2cm
- Maximum tip field in quads = 10T (G=200T/m for A=10cm)
- B = 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

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 (but neutrino hazard!).

IR BE1 Open-Midplane Dipole





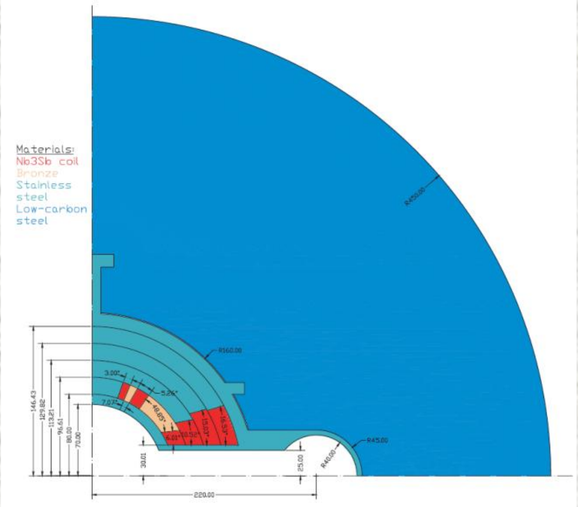
- One of the most challenging magnets in the list: large midplane gap and unusual aperture requirements
- Same concept as for the ring dipole, but field quality optimized for the vertically elongated beam
- Two double-shells or shell/block hybrid
- B_{op} ~ 8T with ~22% margin at 4.5K in either case.
- Midplane gap:

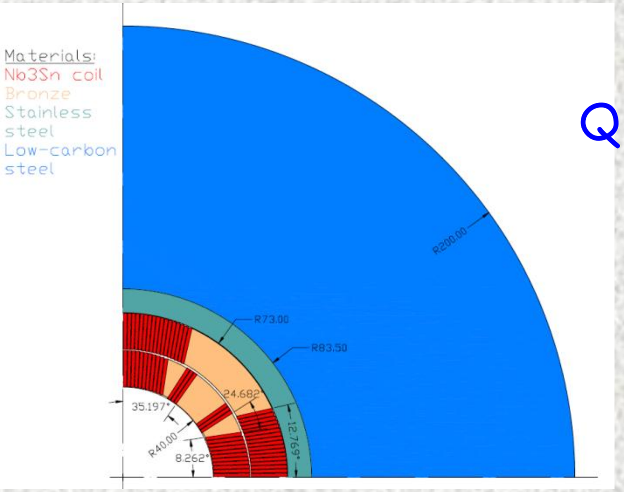
  Coil-coil – 60mm

  Clear – 50mm

New IR Magnet Design and Implementation in MARS

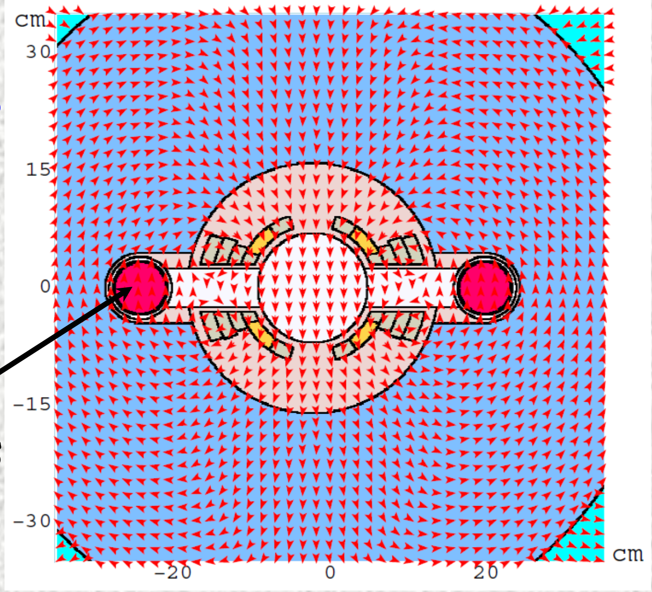
BE1: VK



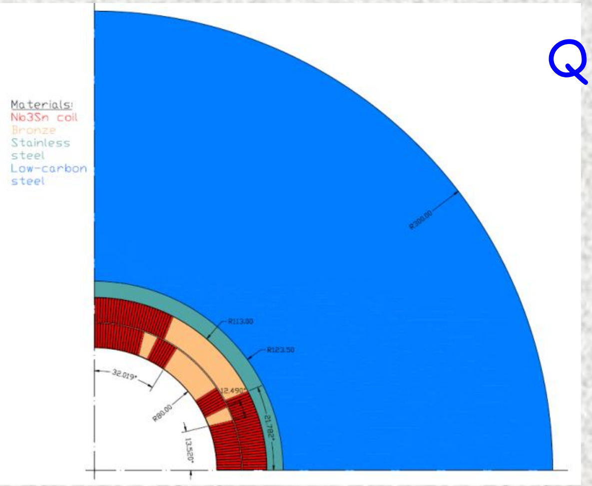


Q1: ID 80mm,
G=250 T/m

BE1: MARS



Tungsten rods cooled by LN2



Q3: ID 160mm,
G=130 T/m

Detector Performance

Backgrounds affect collider detector performance in three major ways:

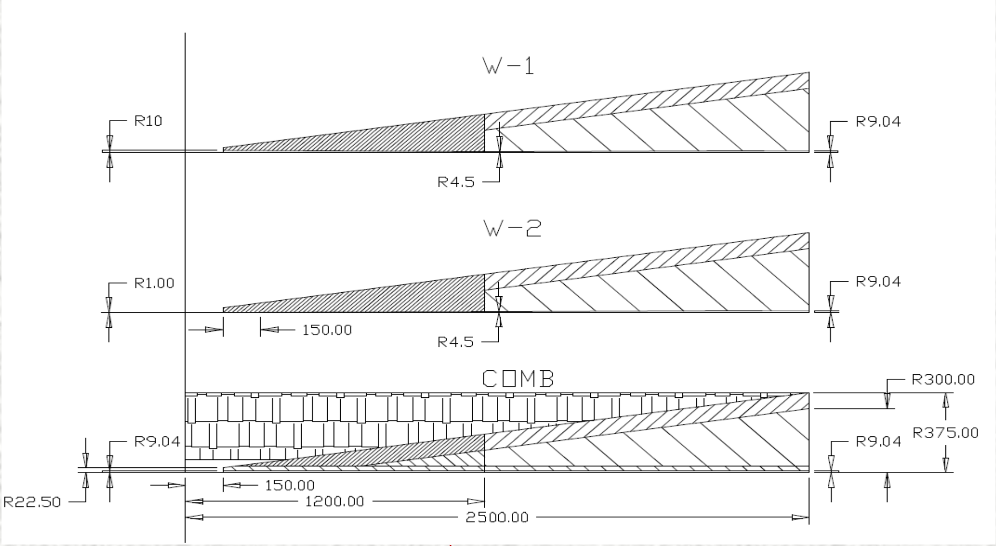
- Detector component radiation aging and damage.
- Reconstruction of background objects (e.g., tracks) not related to products of $\mu^+\mu^-$ collisions.
- Deterioration of detector resolution (e.g., jets energy resolution due to extra energy from background hits).

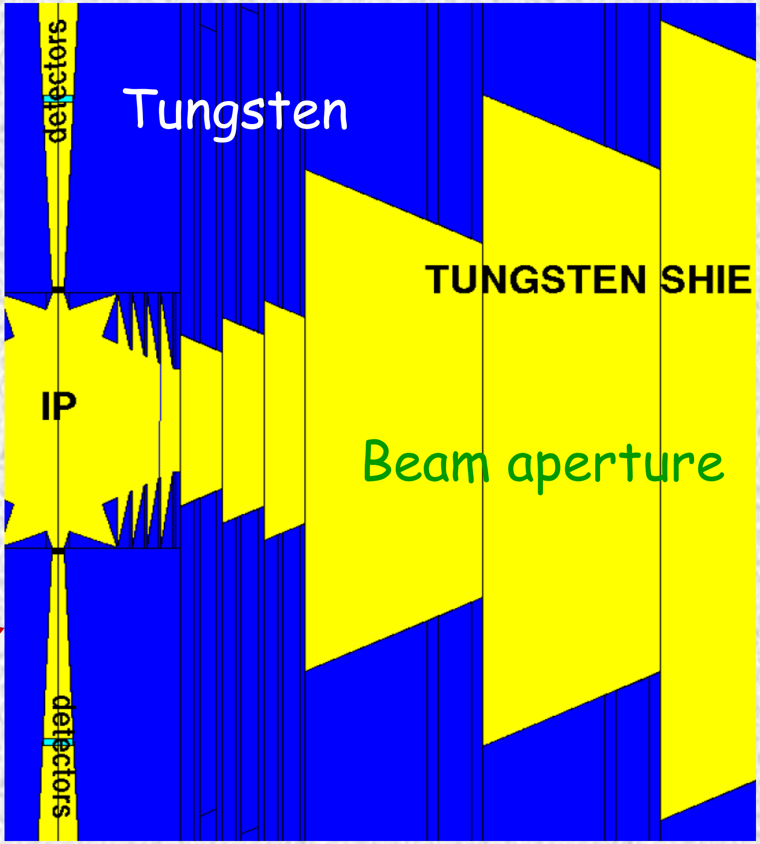
Suppressing Backgrounds: 1. Nozzle at IP (1)

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

As was found, the most effective way 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 charged component of the showers being confined radially by solenoid magnetic field and photons from one nozzle being trapped (to whatever degree possible) by the conical opening in the opposing nozzle.

Suppressing Backgrounds: 1. Nozzle at IP (2)

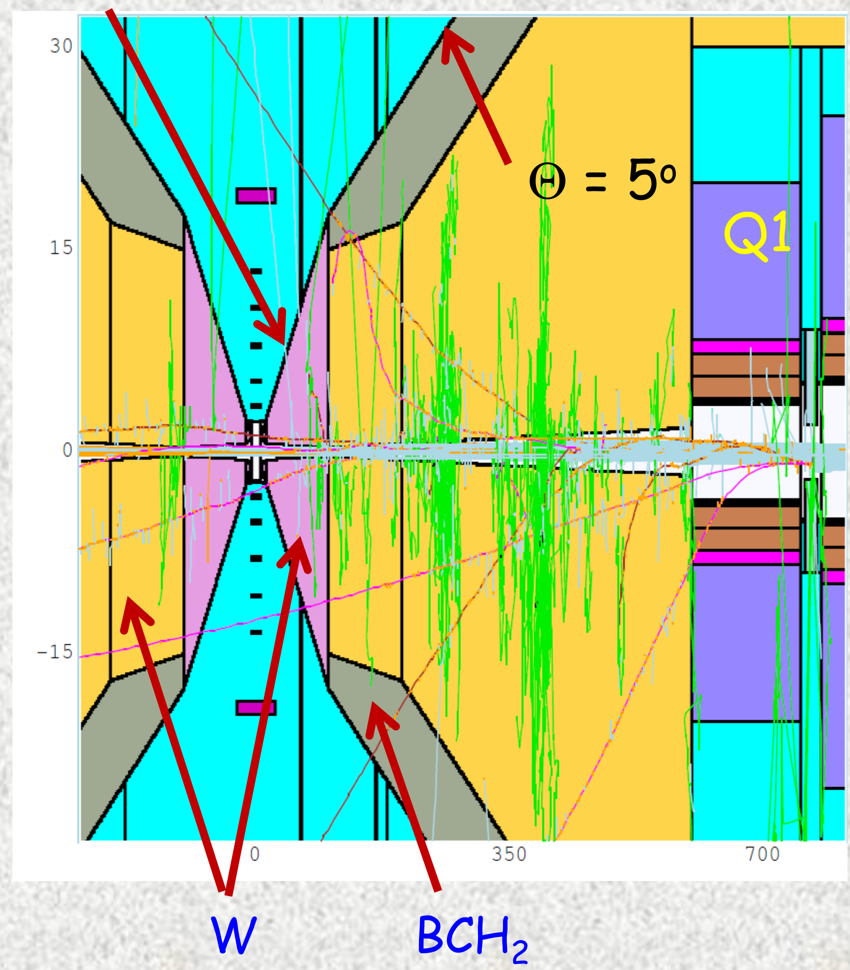




Machine background reduction up to 500 times. Also can fully confine incoherent pairs if B > 3 T

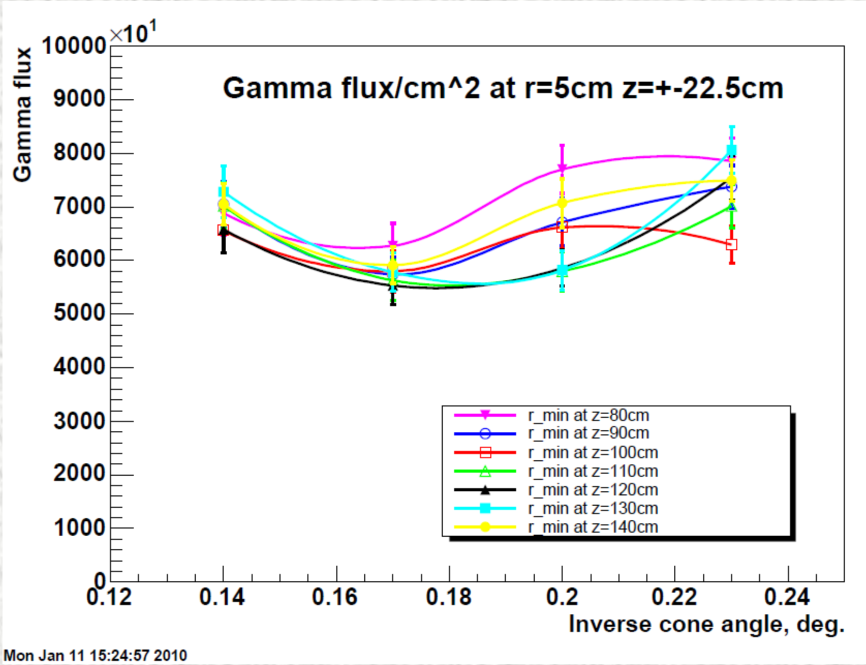
Tungsten Nozzle in BCH_2 Shell

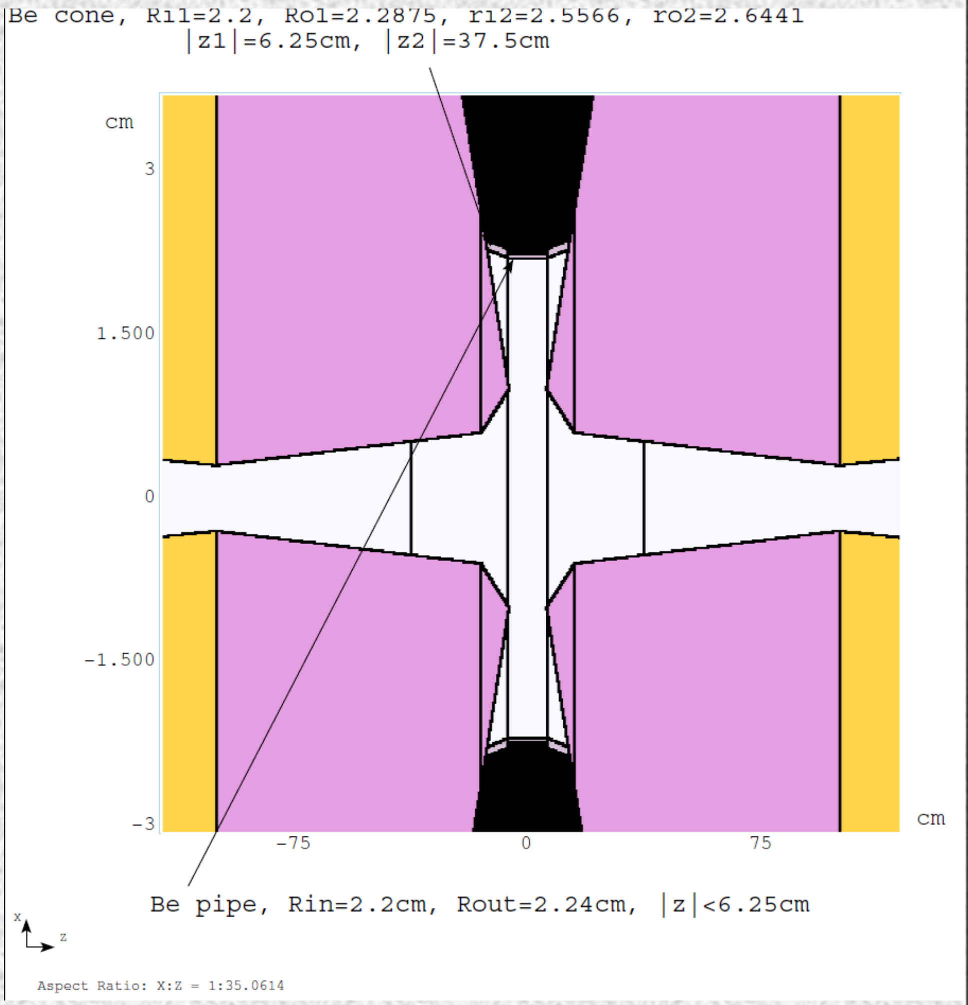
$\Theta = 10^o$ $6 < z < 600$ cm $x:z = 1:17$



1. **Minimize it** ($20^0 \rightarrow 10^0$)
   - Top production in forward regions as CoM energy goes up
   - Asymmetries are more pronounced in forward regions
   - Z' → ttbar
   - Final states with many fermions (e.g. 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 int. luminosity ($\Delta L/L \sim 10^{-3}$)
   - Beam-cal at smaller angles for beam diagnostics

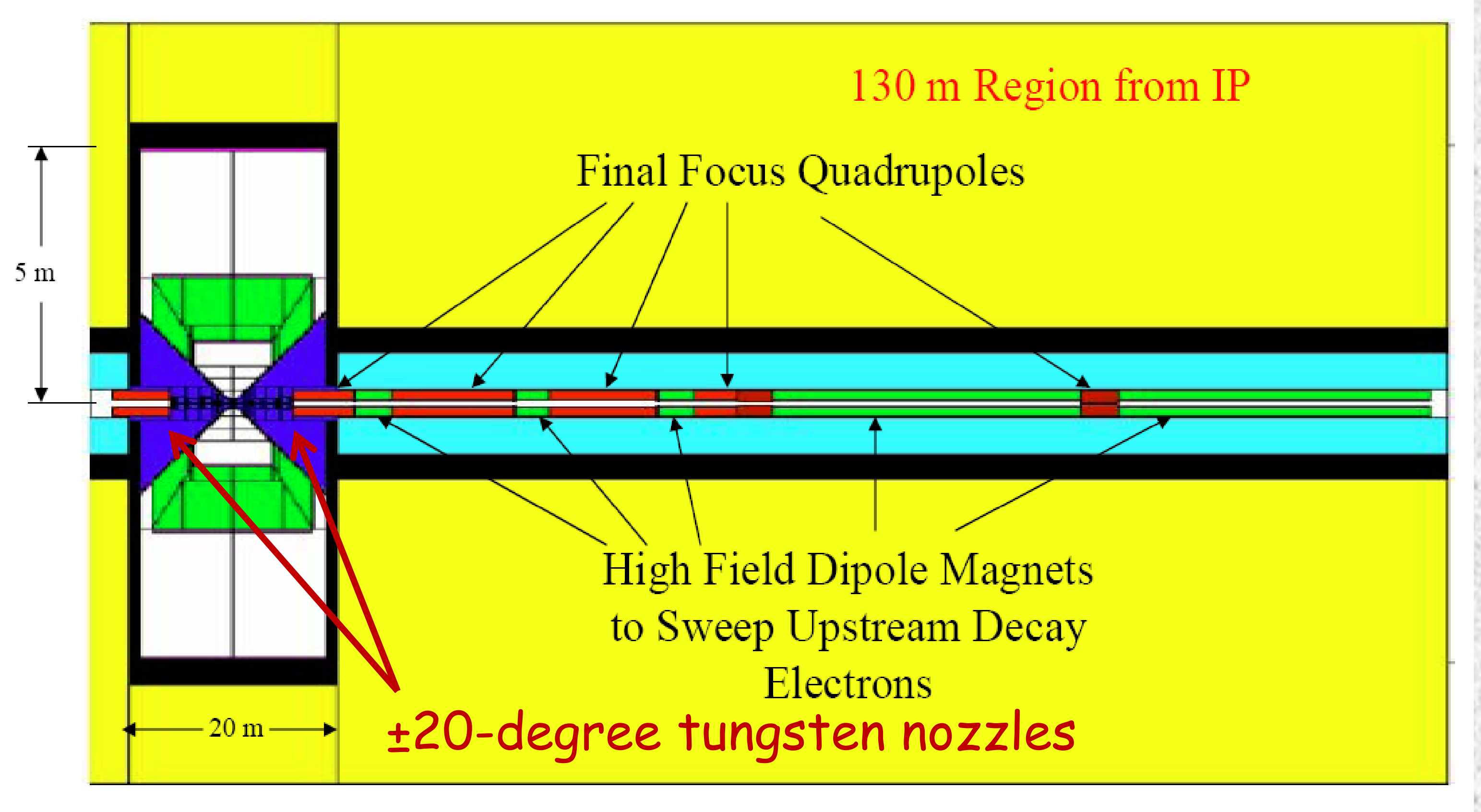
Nozzle Optimization





Optimum: z~120 cm
with r=3.6mm at this z

Suppressing Backgrounds: 2. Dipoles in IR

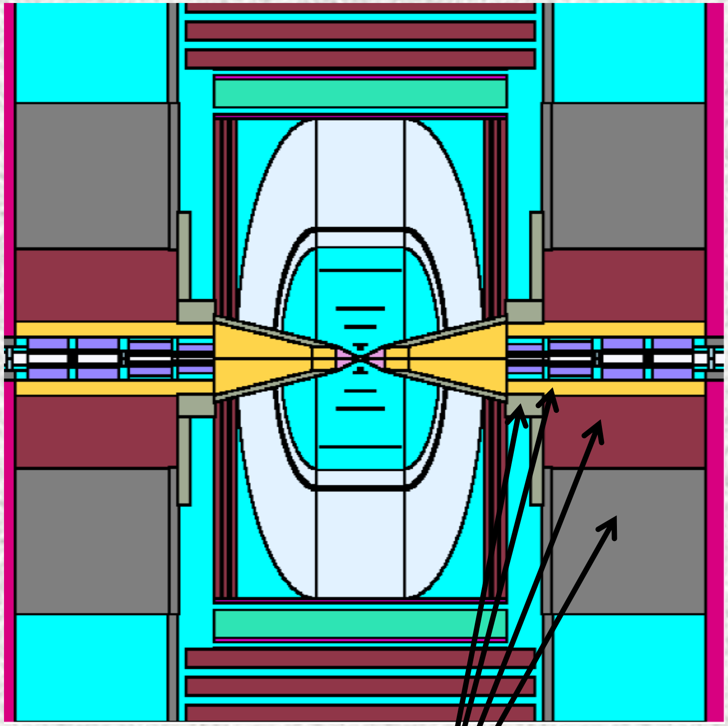


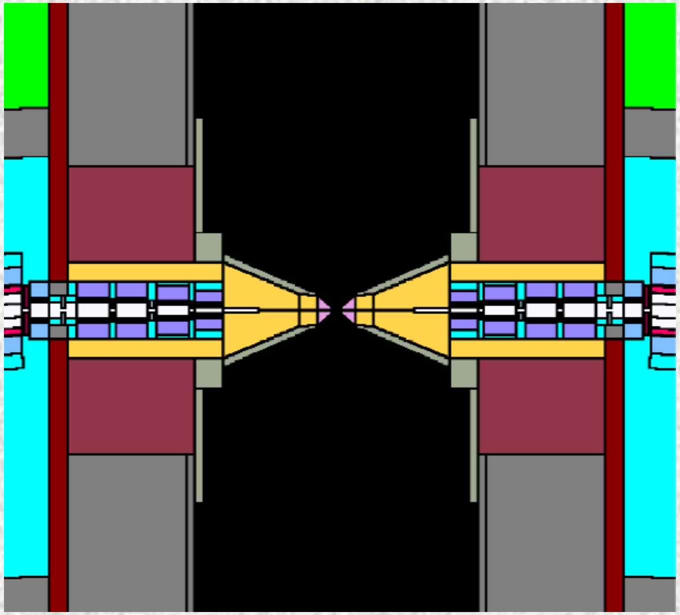
~10T dipoles in IR with tungsten masks in between: further substantial reduction in loads on central detectors; also help reduce Bethe-Heitler muon flux at large radii

MARS15 Modeling

- Segment of the lattice $|S| < S_{max}$, where $S_{max} = 250$ m, implemented in MARS15 model with Nb_3Sn quads and dipoles with masks in interconnect regions.
- Detailed magnet geometry, materials, magnetic fields maps, tunnel, soil outside and a simplified experimental hall plugged with a concrete wall.
- Detector model with $B_z = 3.5$ T and tungsten nozzle in a BCH_2 shell, starting at ±6 cm from IP with R = 1 cm at this z.
- 750GeV bunches of 2×10^{12} μ^- and μ^+ approaching IP are forced to decay at $|S| < S_{max}$, where S_{max} = 75 to 250 m at 4.28×10^5 / m rate.
- Cutoff energies optimized for materials & particle types, varying from 2 GeV at ≥100 m to 0.025 eV in the detector.

Detector Model and Source Term

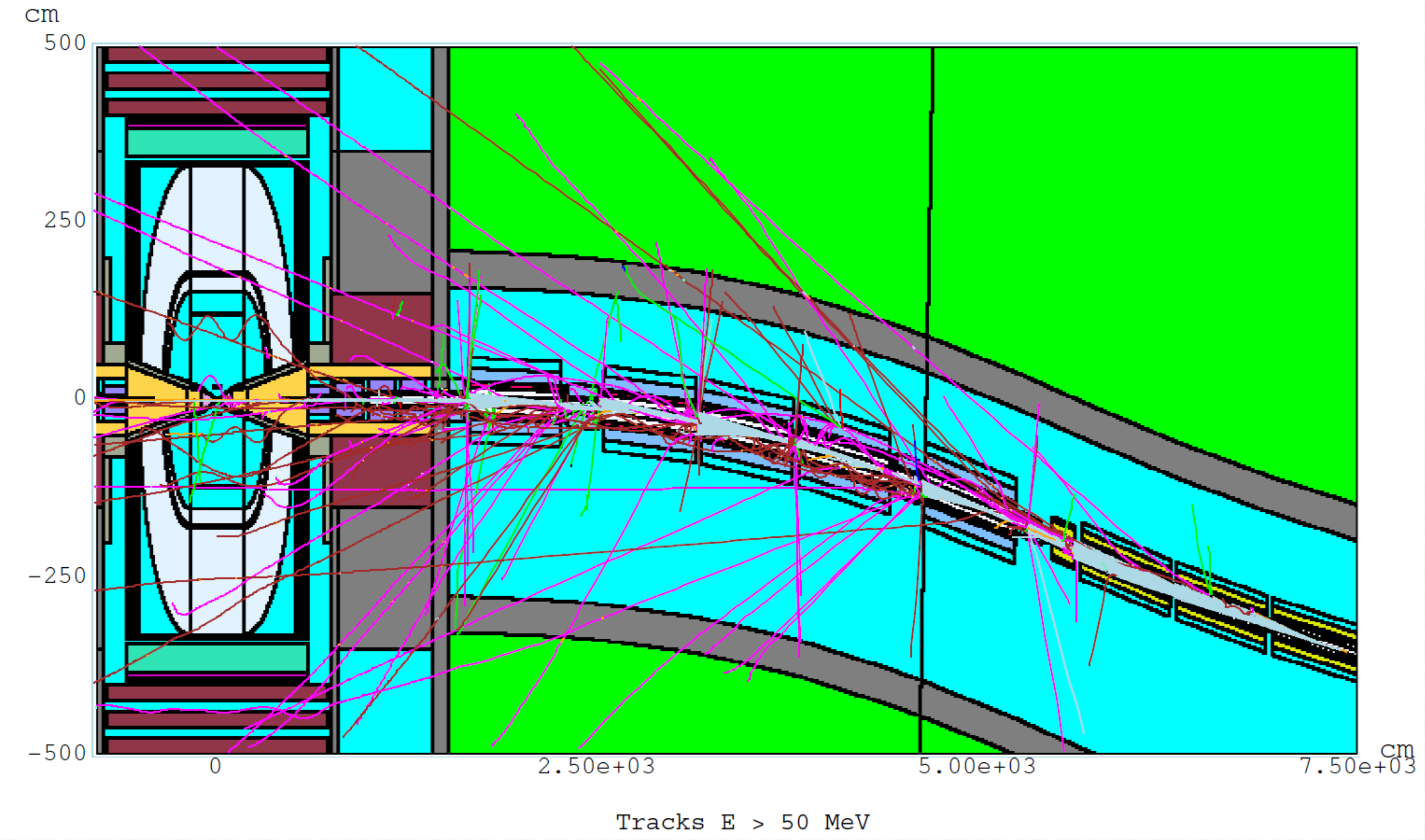




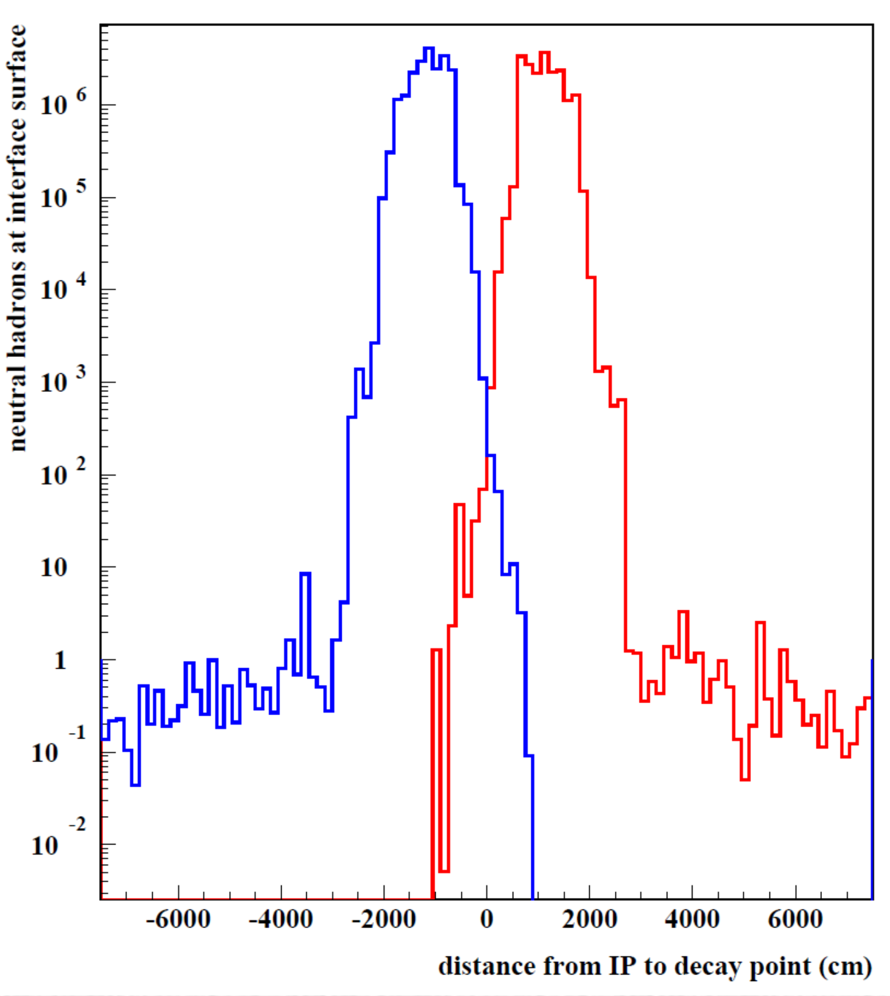
Sophisticated shielding: W, iron, concrete & BCH_2

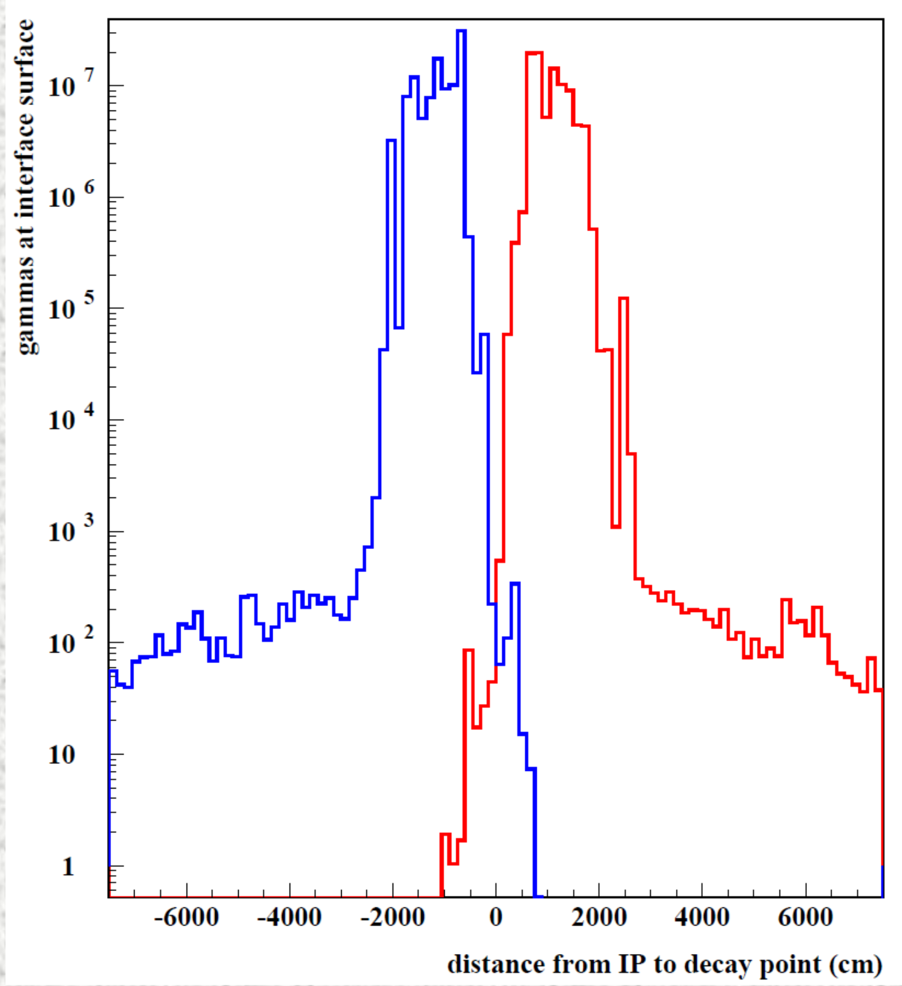
Source term at black hole to feed detector simulation groups: ILCRoot (INFN), Fast MC (FNAL) and lcsim

Particle Tracks in IR



Source Tagging: Neutrons and Photons (1)

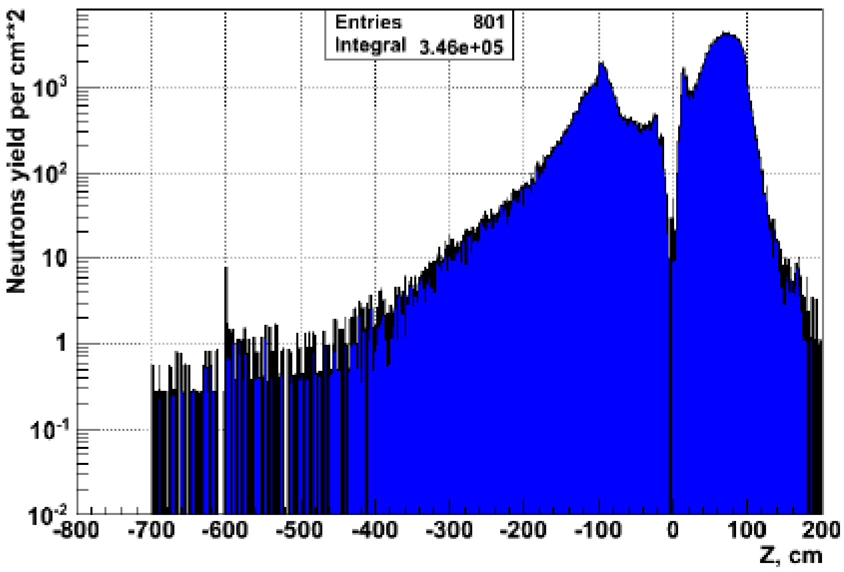




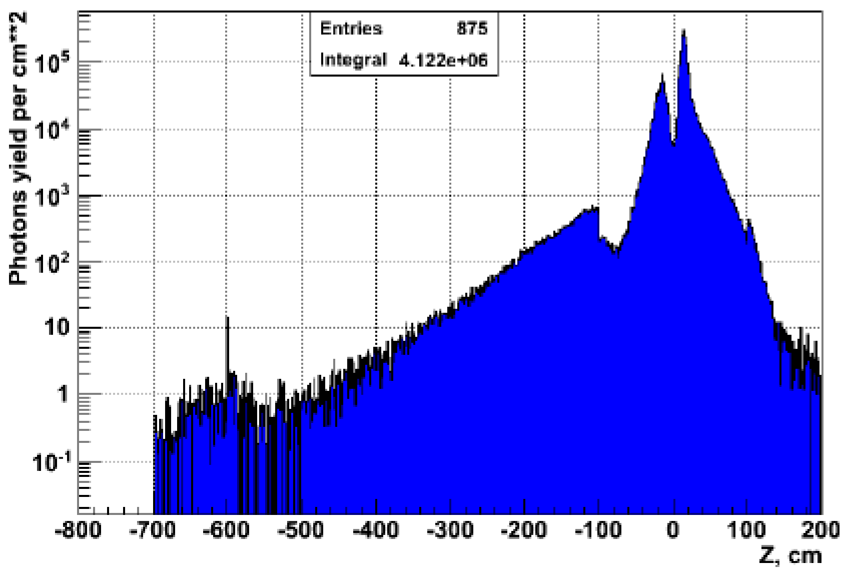
Source Tagging: Neutrons and Photons (2)

- Absolute yields per cm**2 of the nozzle outer surface

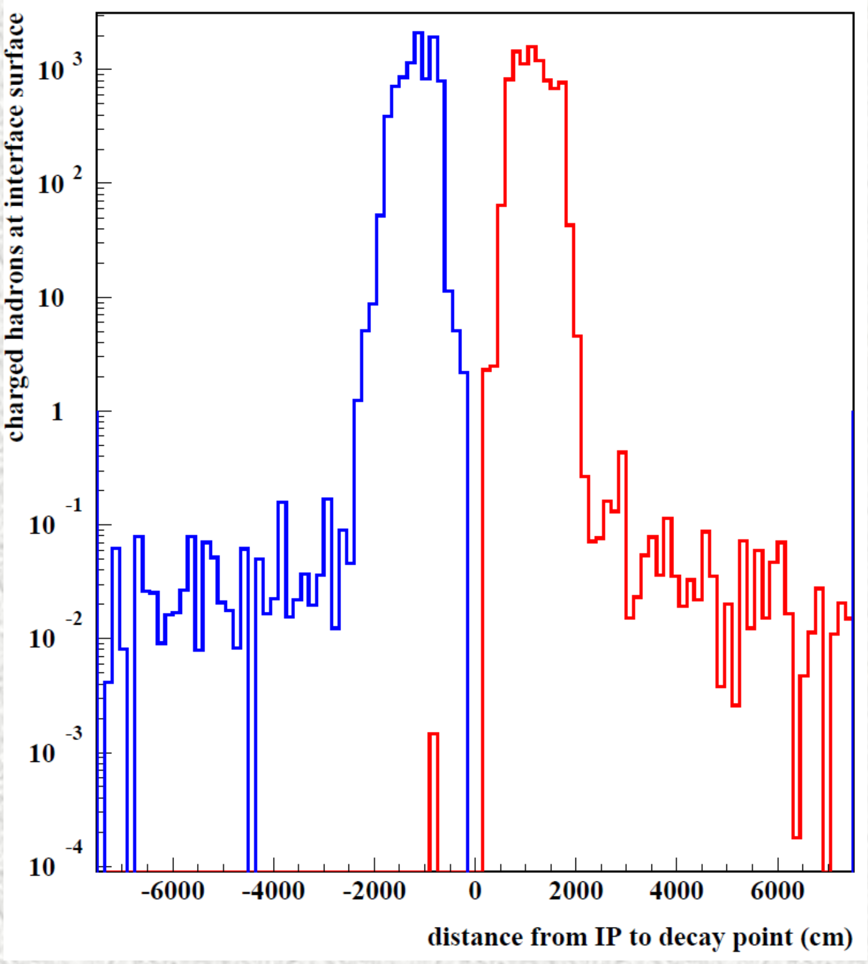
Neutrons

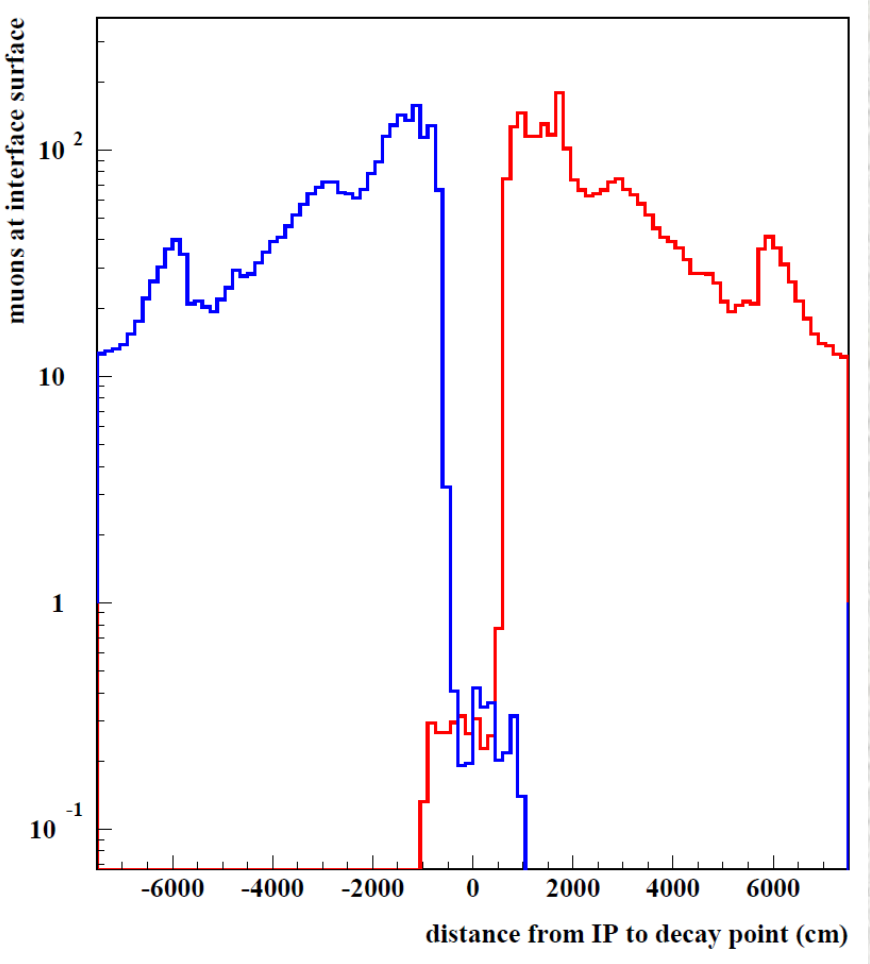


Photons

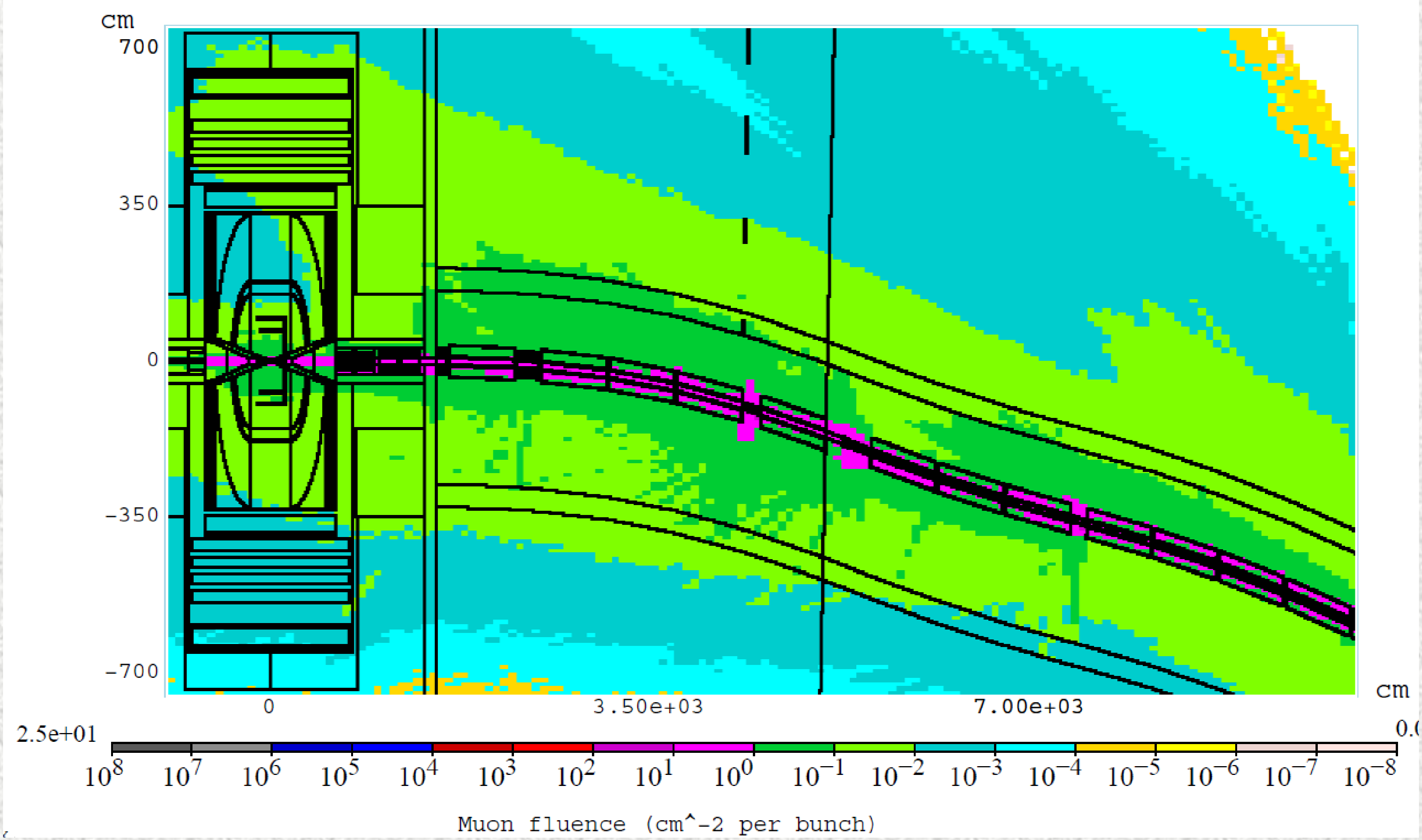


Source Tagging: Charged Hadrons & Muons

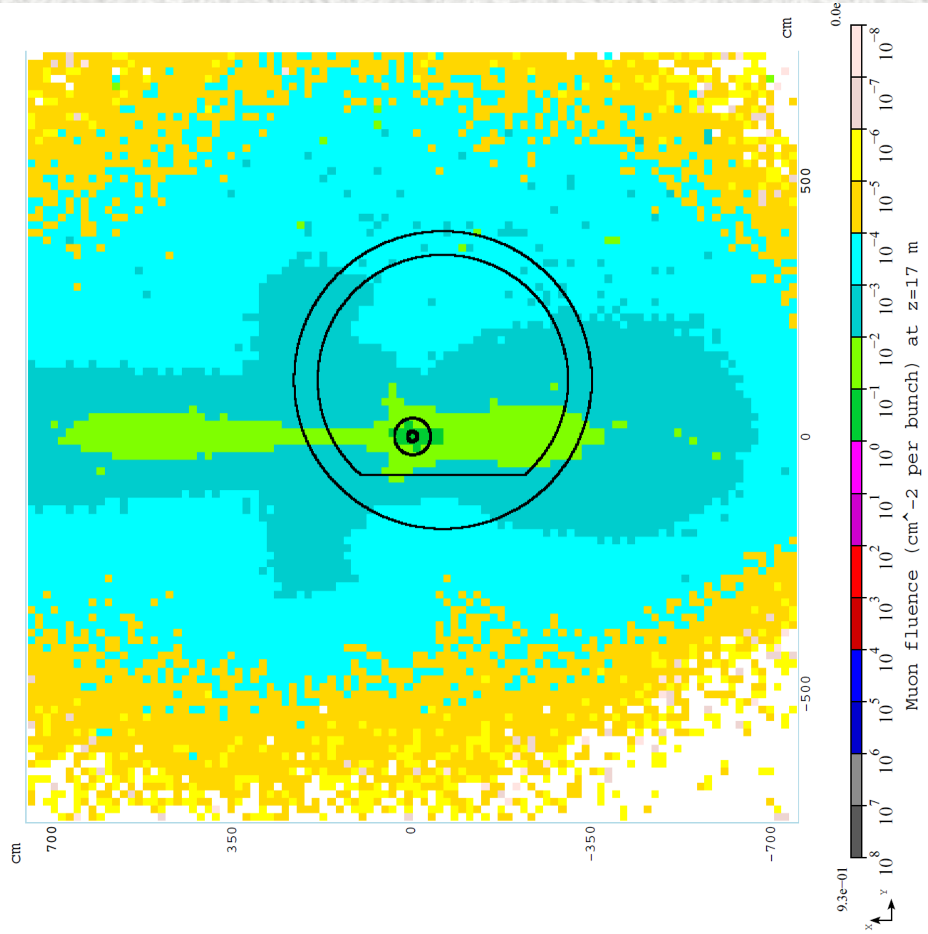


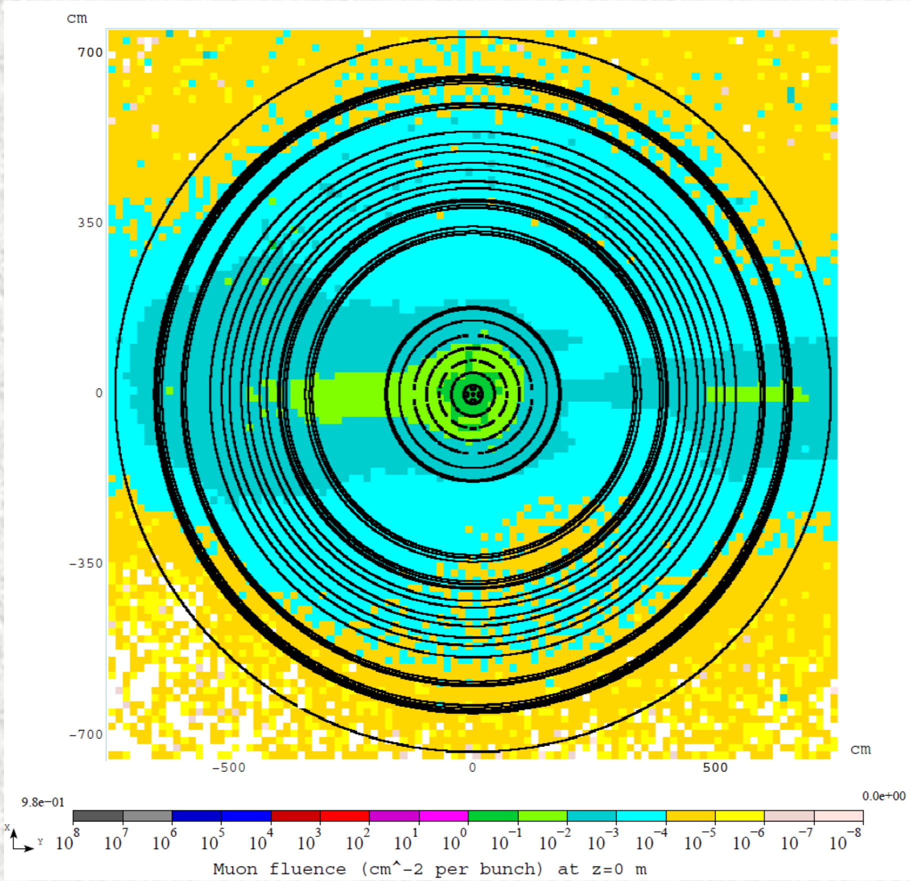


Muon Fluence in Orbit Plane



Muon Fluence at z=17 m and z=0



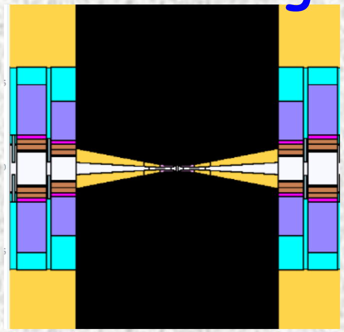


Load to Detector: Two Nozzles

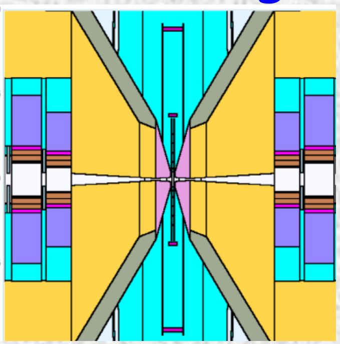
Number of particles per bunch crossing entering detector, starting from MARS source term for S_{max}=75m

Particle	Minimal 0.6-deg	10-deg
Photon	1.5×10^{11}	1.8×10^{8}
Electron	1.4×10^{9}	1.2×10^{6}
Muon	1.2×10^{4}	3.0×10^{3}
Neutron	5.8×10^{8}	4.3×10^{7}
Charged hadron	1.1×10^{6}	2.4×10^{4}

0.6-deg



10-deg



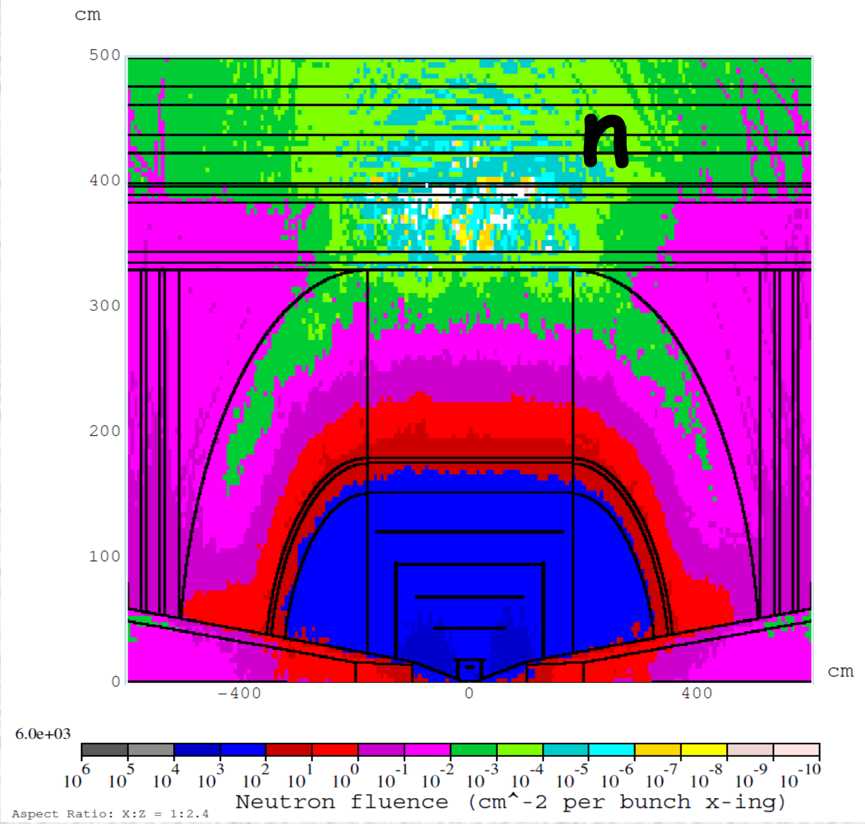
X:Z=1:20

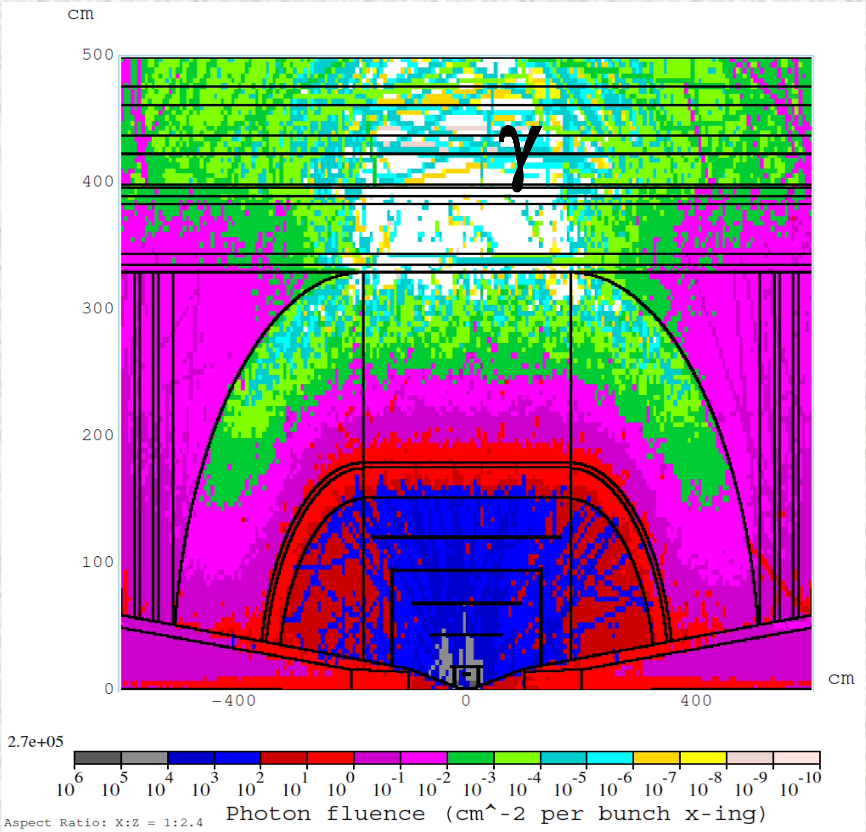
No time cut applied, can help substantially

Neutron and Photon Fluence

Fluence per bunch crossing, starting from MARS source term for S_{max} = 75 m. Compared to best 20-deg '96 configuration, peak values are down 5-10 times for all particles but photons.

Neutron peak/yr = 0.1xLHC@10^{34}





Vertex Detector Hit Density

Layer of Silicon at a radius of 10 cm (earlier results) per bunch x-ing:

750 photons/cm^2	$\rightarrow$ 2.3 hits/cm^2
110 neutrons/cm^2	$\rightarrow$ 0.1 hits/cm^2
1.3 charged tracks/cm^2	$\rightarrow$ 1.3 hits/cm^2
TOTAL	3.7 hits/cm^2

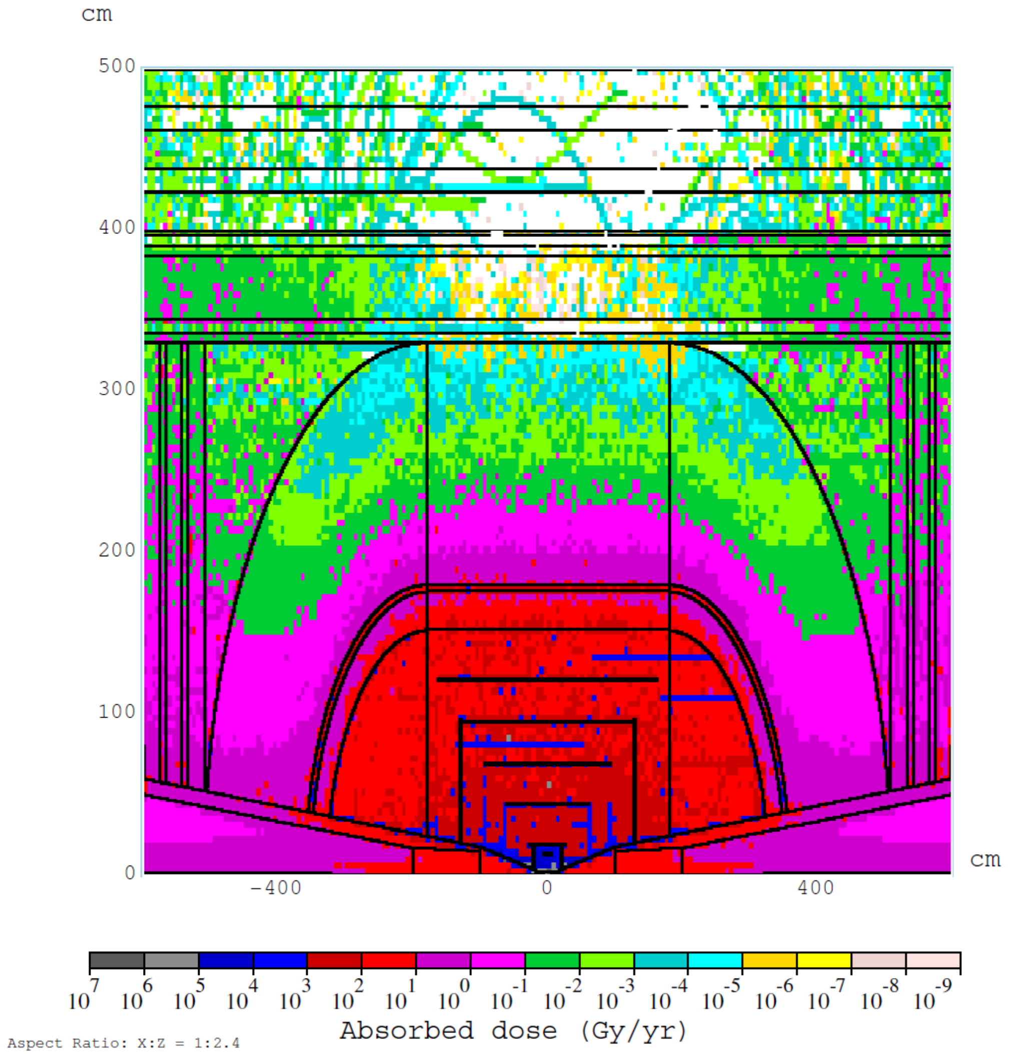
$\rightarrow$ 0.4% occupancy in 300x300 μm^2 pixels (10 times better with nowadays 50x50 μm^2)

At 5cm radius: 13.2 hits/cm^2 $\rightarrow$ 1.3% occupancy (again, better with current technologies)

- **For comparison with CLIC**
  - At r = 3cm hit density about ×2 higher than at 5cm $\rightarrow$ ~20 hits/cm^2 $\rightarrow$ 0.2 hits/mm^2 per bunch x-ing (MC) vs ~1 hit/mm^2/bunch train (CLIC)
  - Shielding cone: 10^o (MC) vs 7-9^o (CLIC)
  - Bunch crossing time: CLIC 0.5ns (signal formation in Si much longer)

    MC: 10μs (lots of time for readout, backgrounds don't pile up)

Absorbed Dose (vs LHC)

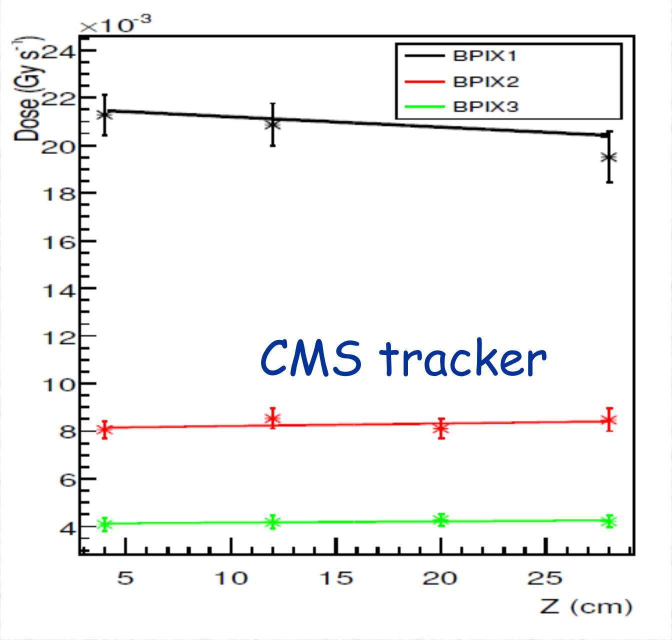


Total absorbed dose in Si

<u>Peak at r=4 cm:</u>

MC: 0.1 MGy/yr

CMS: 0.2 MGy/yr @10^{34}



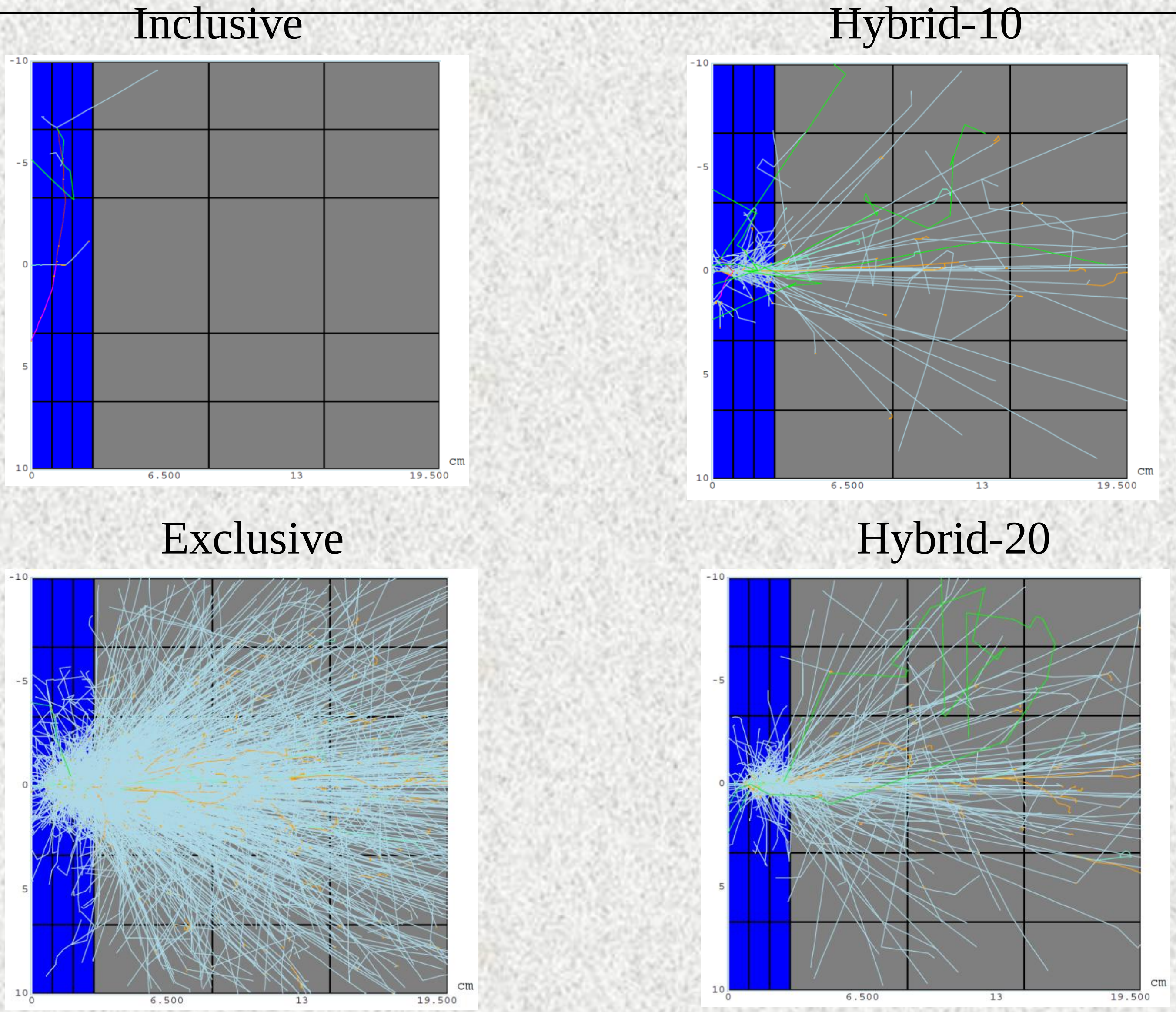
Reducing Weight Fluctuations: Key for Detector Modeling

Statistical weight spread has been substantially reduced recently. Internal MARS weight fluctuations came predominantly from modeling of low-energy electromagnetic and hadronic showers as well as from photo- and electro-nuclear hadron and muon production algorithms.

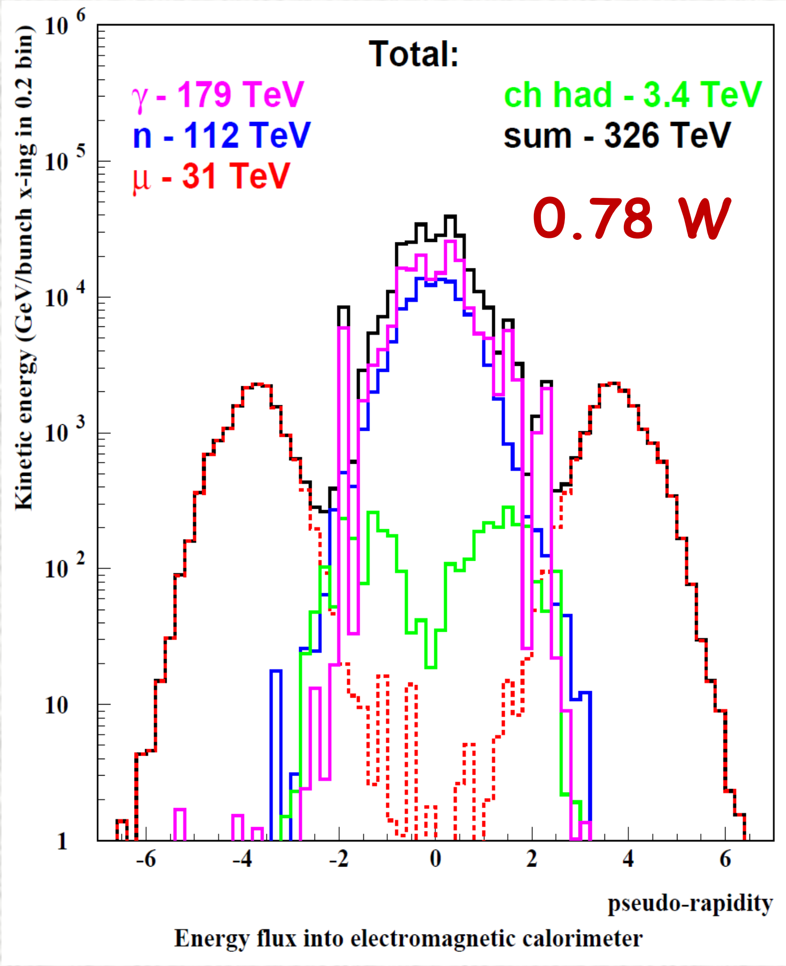
These are now user-controlled by material-dependent switches between exclusive, inclusive and hybrid modes.

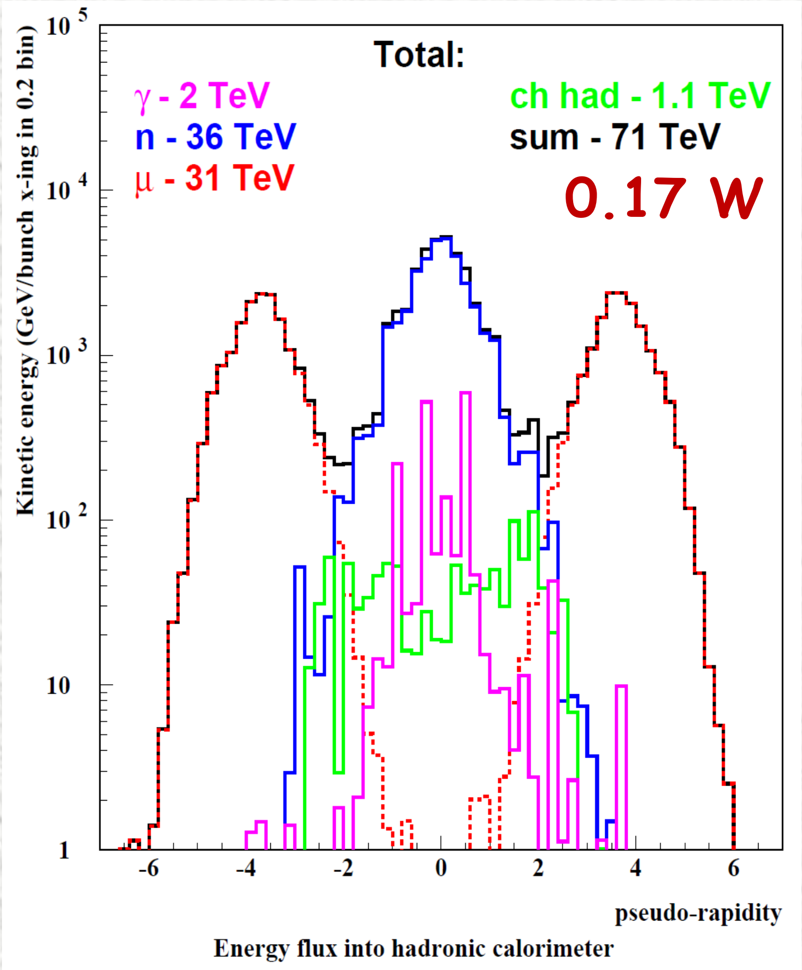
Example: EMS

One 10-GeV e^+ on 3cm W + 17cm concrete



Energy Flux into Ecal and Hcal vs Rapidity





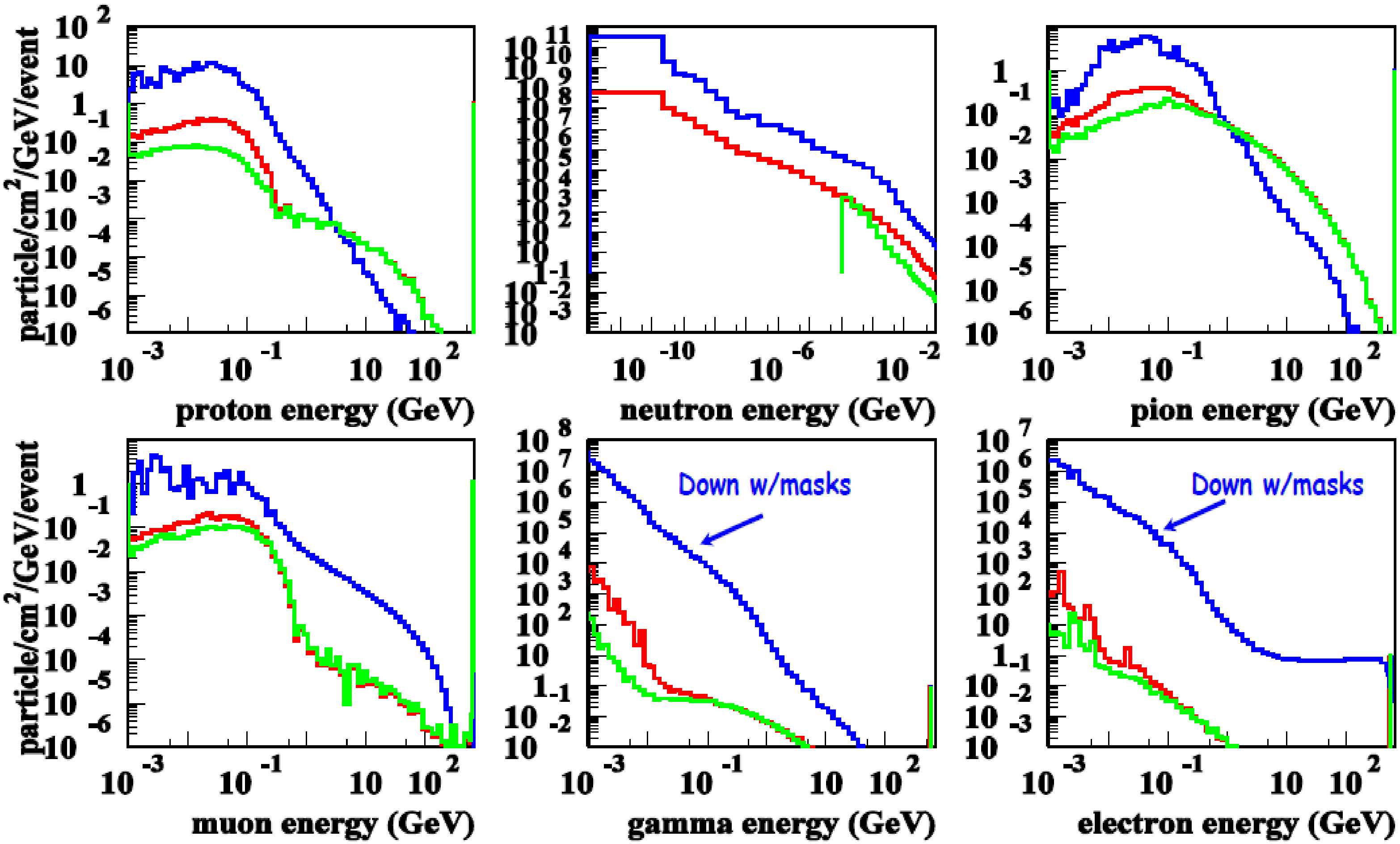
Peak: ~1 GeV / 2x2 cm^2 cell with σ_E ~ 30 MeV

Peak: ~1.5 GeV / 5x5 cm^2 cell with σ_E ~ 80 MeV

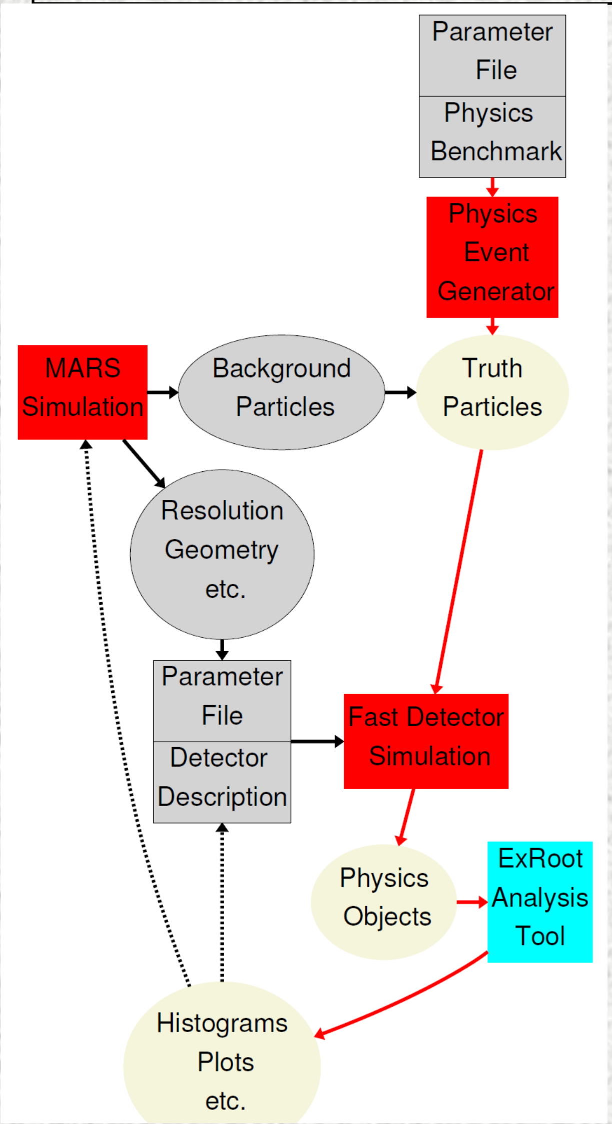
Machine vs IP Backgrounds in Tracker

Energy spectra in tracker (+-46x46x5cm)

Blue lines - from machine, red lines - Z0 events, green lines - Higgs events



Detector Modeling



Develop an initial physics and detector report by the end of 2011. Allows input to the design parameters of the MAP study:

- Set requirements on luminosity, energy, acceptable background rates and suggest feasible methods of attaining these levels.
- Evaluate the impact of polarized beams, energy spread, and detector fiducial volume.
- Compare physics opportunities to CLIC and take account of the substantial running of LHC after luminosity upgrade.
- Possible synergy with the ILC/CLIC and LHC detector R&D.

Using existing framework (ILCroot, lcsim) do detailed simulations to identify further needs for detector development.

Physics Event Reconstruction: First Serious Attempt with ILCroot (1)

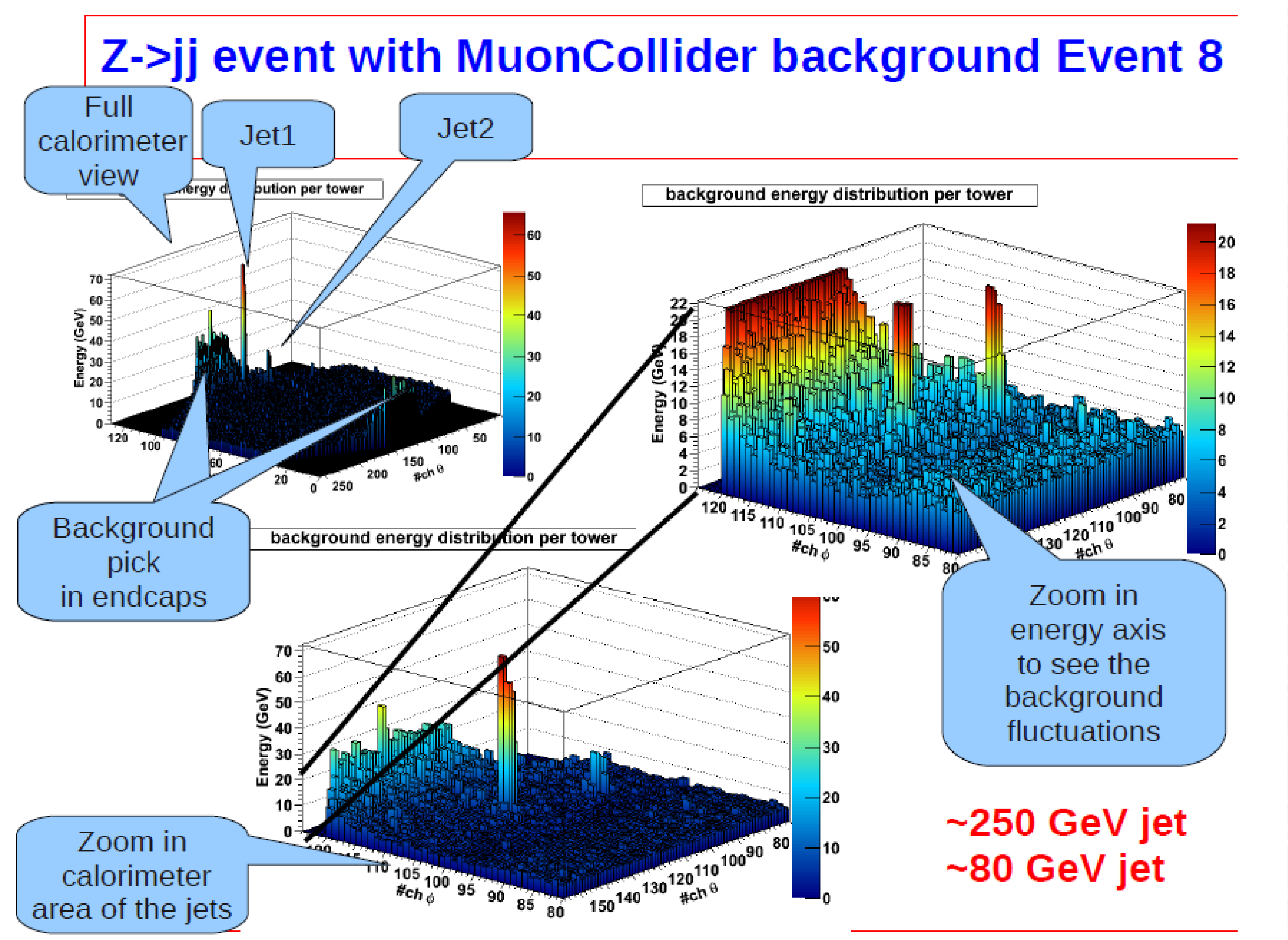
ILCroot: **root I**nfrastructure for **L**arge **C**ollider

- Software architecture based on ROOT, VMC & Aliroot
- Uses ROOT as infrastructure

  All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)

  Extremely large community of users/developers
- Include an interface to read MARS output to handle the MuonCollider background
- Single framework, from generation to reconstruction through simulation. Don't forget analysis!!!
- It is Publicly available at FNAL on ILCSIM since 2006

Physics Event Reconstruction: First Serious Attempt with ILCroot (2)

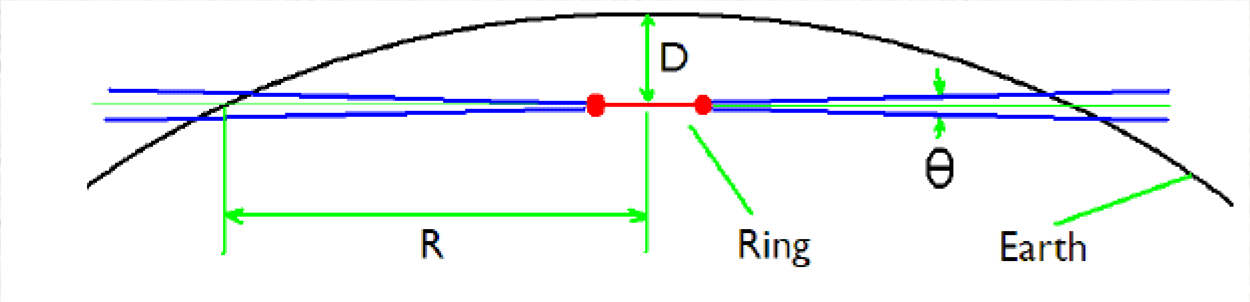


Physics Event Reconstruction: First Serious Attempt with ILCroot (3)

Physics and background: some comment

- Jets develop in 16 – 25 towers; mean energy 150 GeV
- Background in barrel:mean energy 5 GeV RMS 0.6 GeV
  Jet energy fluctuation after background pedestal cut
  2.5 – 3 GeV
- Background in endcap > 20°: mean energy 5 GeV RMS 1. GeV
  Jet energy fluctuation after background pedestal cut
  5 – 6 GeV
- Background in endcap < 20°: mean energy 12 GeV RMS 5. GeV
  Jet energy fluctuation after background pedestal cut
  20 – 25 GeV

Neutrino Radiation



- With $\mathcal{L} \sim E^2$ $\rightarrow$ $$\text{Radiation} \propto \left(\frac{\beta^*}{\Delta\nu\, B_{\text{ring}}}\right) \frac{\gamma^4}{D}$$

- OK at $\sqrt{s}$ = 1 TeV
- OK at $\sqrt{s}$ = 3 TeV if D = 200m
- Severe above 3 TeV
- Mitigation: depth, wobble beam, lower β^*, higher B_{ring} , short straits/drifts