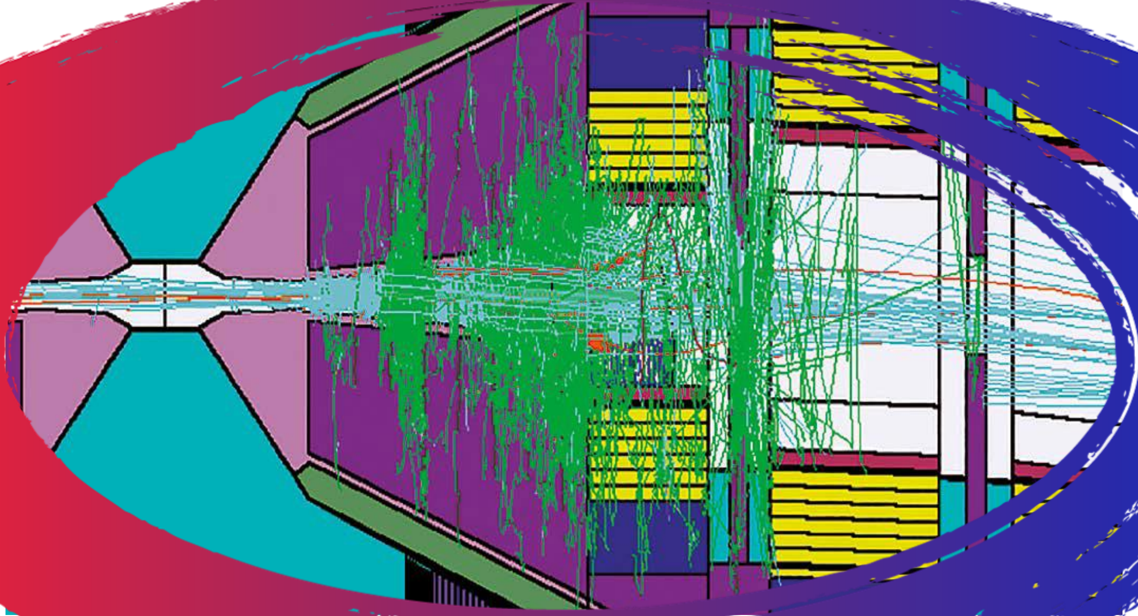
International
MUON Collider
Collaboration

MDI MARS Optimization for 0.125 to 6 TeV Muon Colliders



Nikolai Mokhov, Fermilab, May 20, 2021

Outline

- Introduction
- MDI Basics with 1.5-TeV MC as an Example
- 125-GeV Higgs Factory MC
- Multi-TeV MC

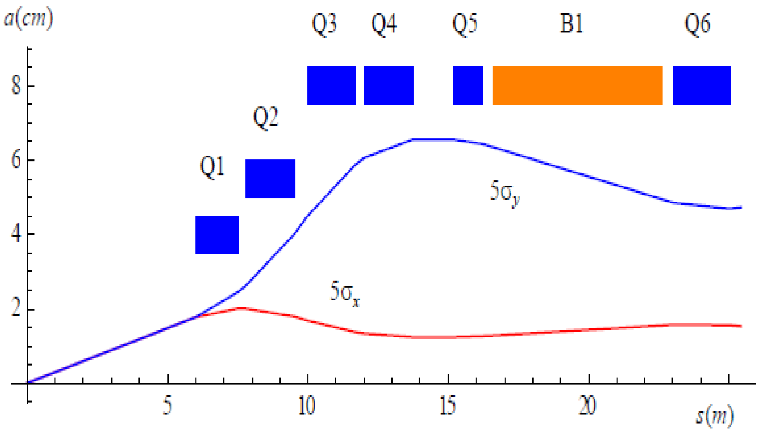
Introduction

The physics goals of a Muon Collider (MC) can only be achieved with self-consistent designs of the ring, IR, high-field SC magnets, MDI and detector.

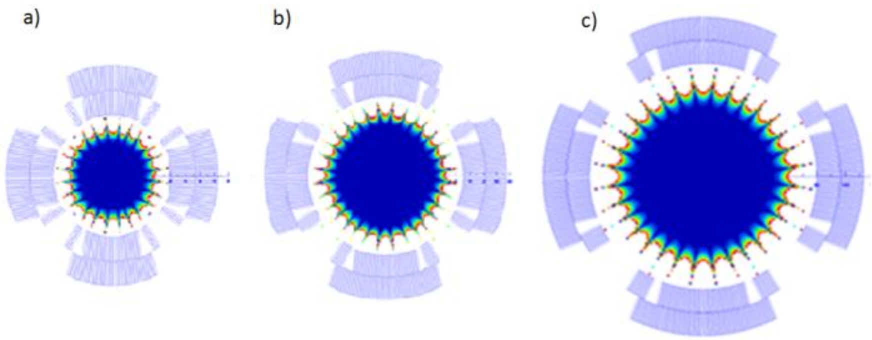
Our results of 1994 through 2014 from realistic simulations for $\sqrt{S}$ =1.5-TeV MC ($4x10^{33}$ cm^{-2} s^{-1}) and $\sqrt{S}$ =125-GeV ($8x10^{31}$ cm^{-2} s^{-1}) HF MC have shown that with adequate protection implemented, heat loads in SC magnets and background rates in the detector can be suppressed by several orders of magnitude.

The study's success at Fermilab was a result of coherent dedicated efforts on the lattice design (led by Yuri Alexahin), high-field large-aperture SC magnet design (led by Sasha Zlobin), mitigating of deleterious impact of muon decay products on IR and detector components with thoroughly optimized in MARS simulations protective measures (led by Nikolai Mokhov), and hit reduction techniques in detector explored in MARS15 + ILCRoot + Geant4 simulations (led by Vito Di Benedetto & C. Gatto).

IR Lattice & Magnet Design for 1.5-TeV MC



Beam sizes and aperture of the FF magnets
$a \geq 5\sigma_{max} + 1$ cm, B=8T in dipole.
L_B = 1.5 to 1.7 m in quads and 6 m in B1

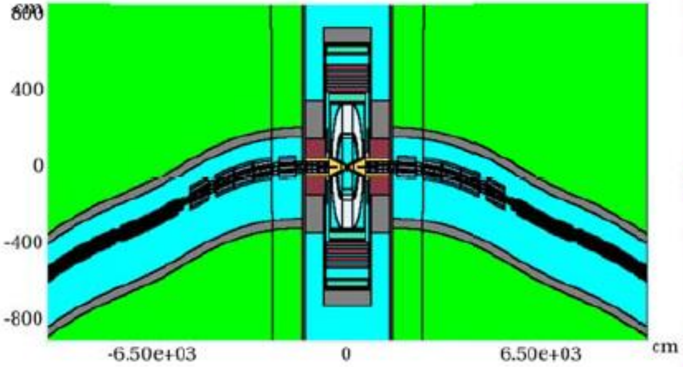


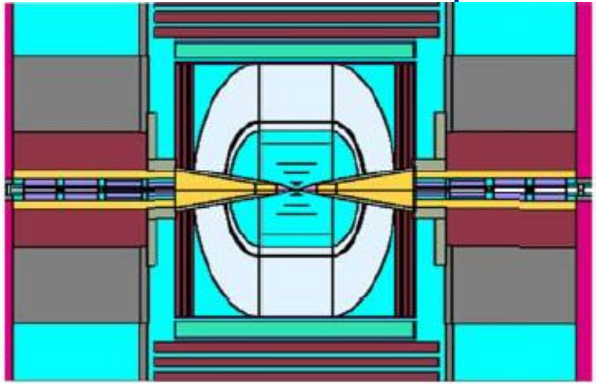
Cross-sections and good-field regions ($|\delta B/B| < 10^{-4}$) of Q1, Q2 and Q3-Q5 quads with G = 250, 187 and -130 T/m, respectively

Sources of Beam-Induced Backgrounds

There are three sources of beam-induced backgrounds (BIB) and radiation loads in MC: **incoherent e^+e^- pair production at the IP, beam halo loss on limiting apertures and muon beam decays.**

At 1.5-TeV MC, σ_{prod}=1.34 pb. The 1st source, with 10-mb X-section, gives rise to BIB in detector of 3×10^4 e^+e^- pairs per bunch crossing. It can be confined with the appropriate design of the MDI assisted by the high solenoidal field of the detector. The 2nd source is taken care of by beam halo extraction far upstream of IR.



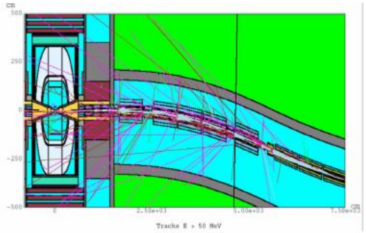


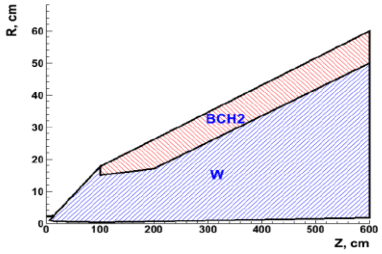
Muon Decays as the Major Source of BIB

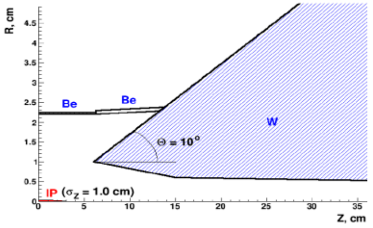
For the 0.75-TeV beam, with 2×10^{12} muons in a bunch, one has **4.28×10^5 decays per meter of the lattice in a single pass**. Electrons from muon decays have mean energy of approximately 1/3 of that of the muons. These ~250-GeV electrons, generated at the above rate, travel to the inside of the ring magnets, and radiate a lot of energetic synchrotron photons tangent to the electron trajectory.

Induced EMS create high background and radiation loads both in the detector and in the ring at the rate of 0.5-1 kW/m (compared to a few W/m in hadron colliders). **Without mitigation measures, the quench stability, cryogenic issues in superconducting magnets, background loads to a detector and neutrino-induced hazard would kill the idea of a high-energy muon collider.**

Findings from 1994-2011 Studies on 1.5-TeV MC







- High-field SC dipoles in IR and a dipole component in IR quads, along with tungsten liners inside magnets and masks in interconnect regions, provide substantial reduction of backgrounds.
- W-nozzles, starting a few cm from IP with 10-20-deg outer angle, are a very effective way (~1/500) of further BIB suppression [Foster & NM (1994)]. These nozzles can also fully confine incoherent pairs if the magnetic field of the detector solenoid is about 4 T.
- With such an IR design, the major source of BIB in a MC detector is muon decays in the IR itself, i.e. the region confined to about ±25 m from the IP.
- Time gates would allow substantial mitigation of remaining background rates in a MC detector.
- There are ways to mitigate neutrino hazard (NM et al), but they put additional constraints on the IR and MDI designs.

1.5-TeV MC MARS MDI Details

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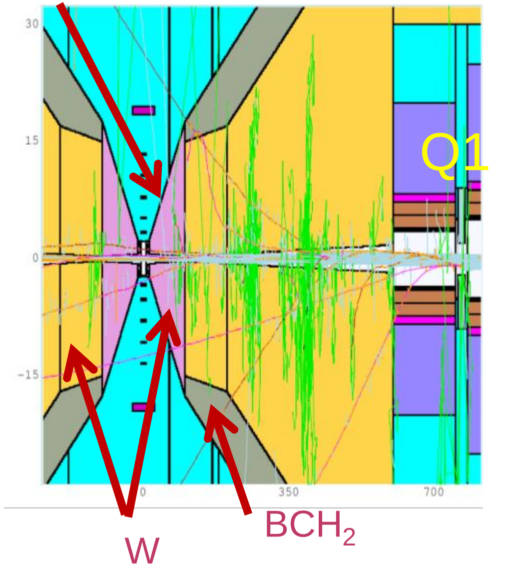
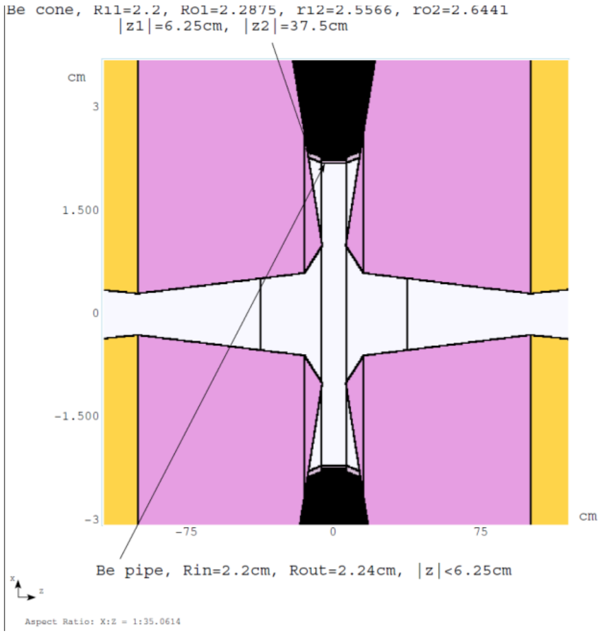
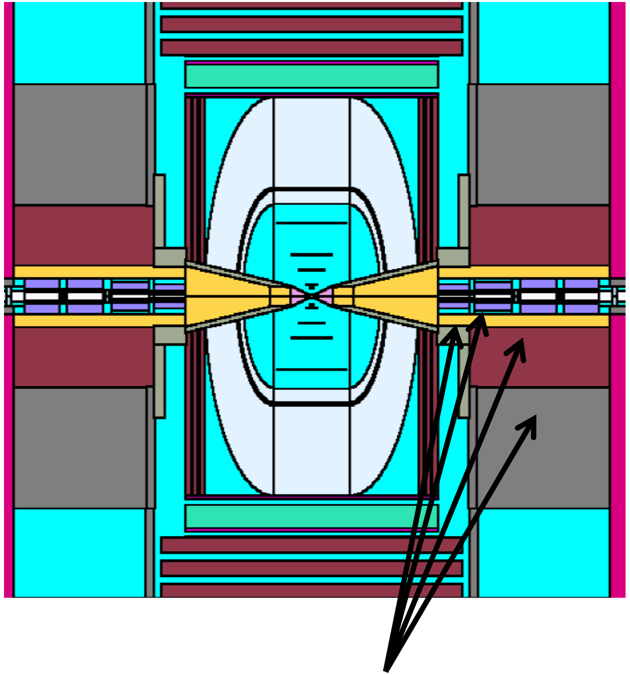
Θ = 10°, 6 < z < 600 cm, x:z = 1:17



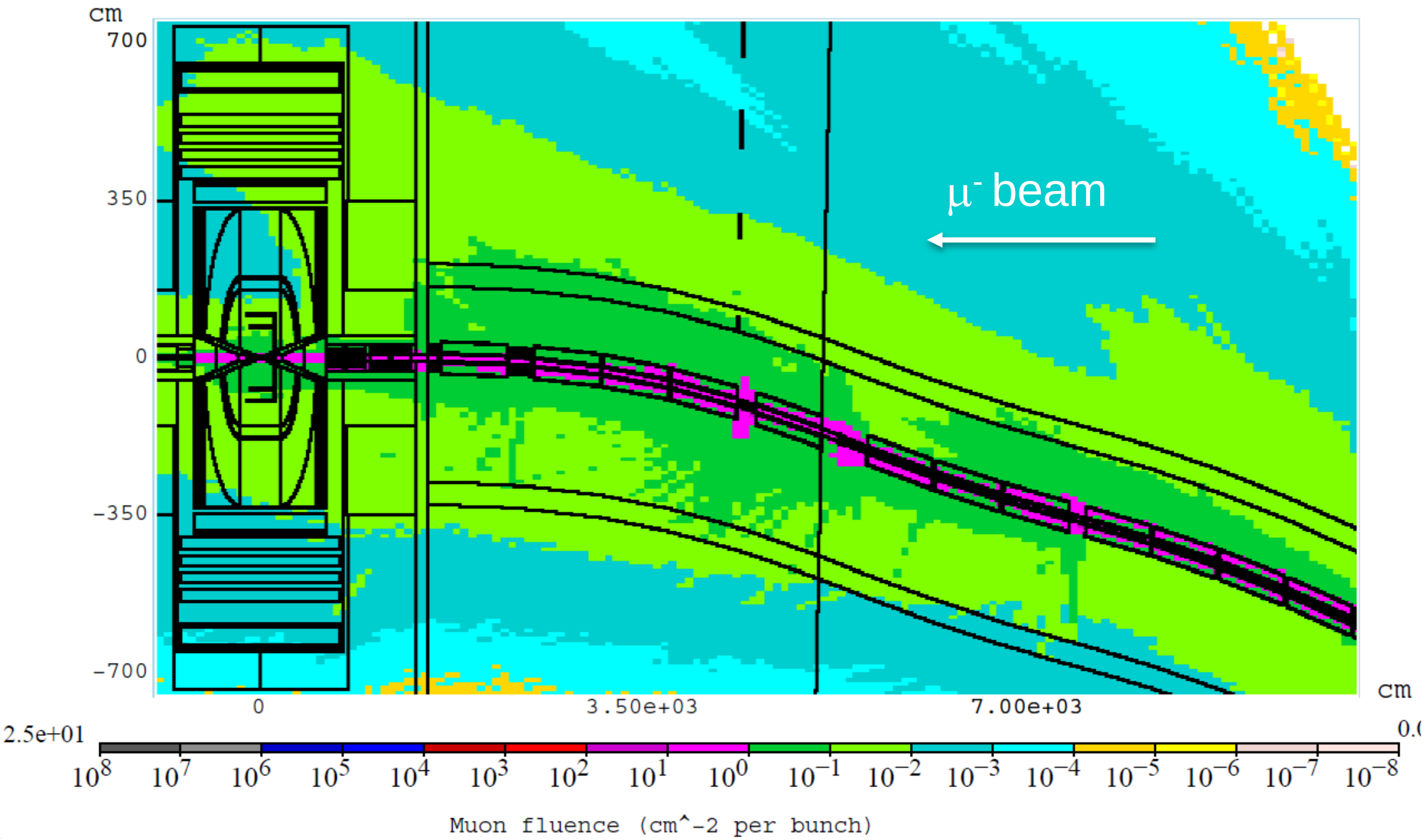




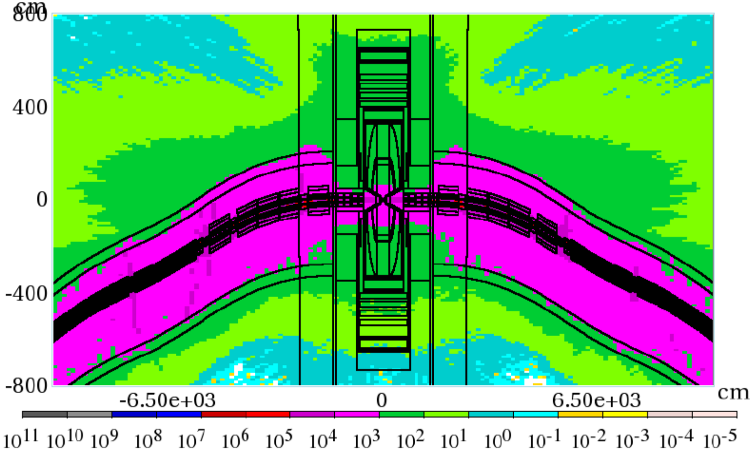
Sophisticated shielding (**SS**): W, iron, concrete & BCH_2

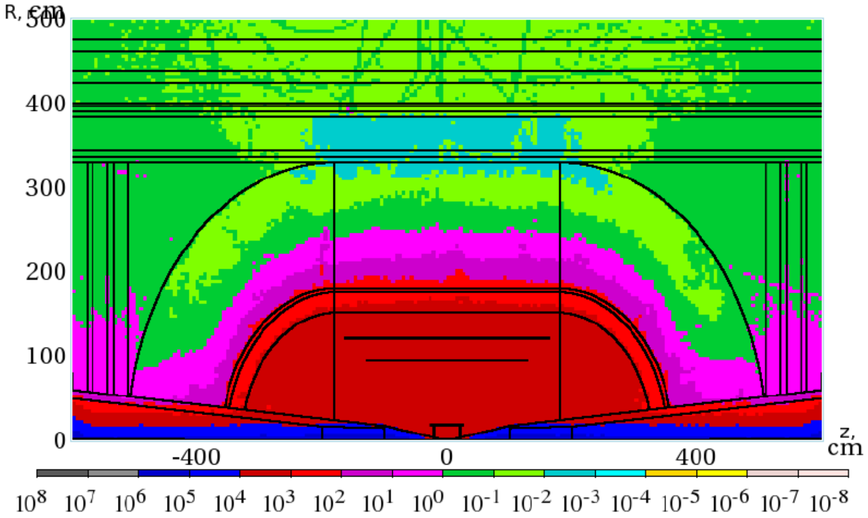
Optional source term scoring at Black Hole: the outer surface Of the Be pipe and nozzle as well as the IP side of the SS surface

Muon Fluence in Orbit Plane



μ and *n* BIB in the 1.5-TeV MC Detector

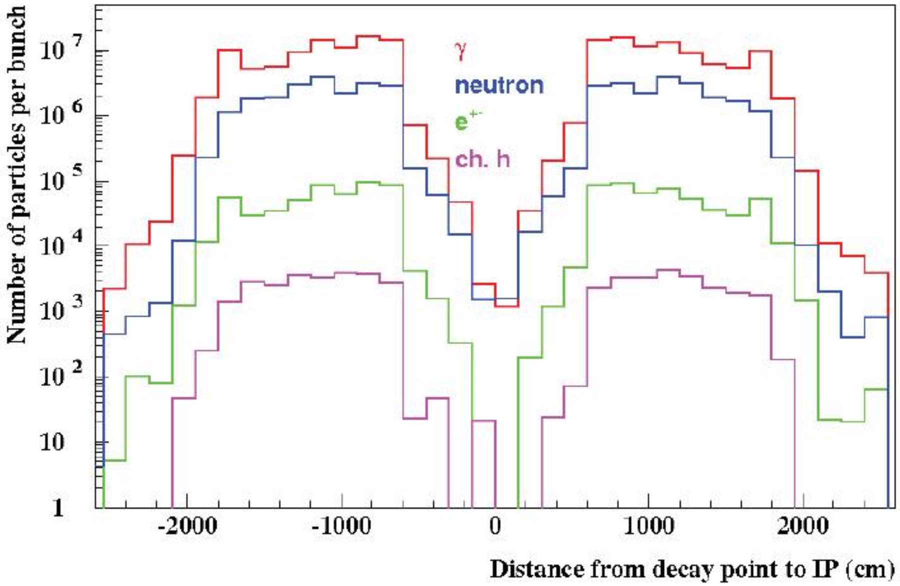


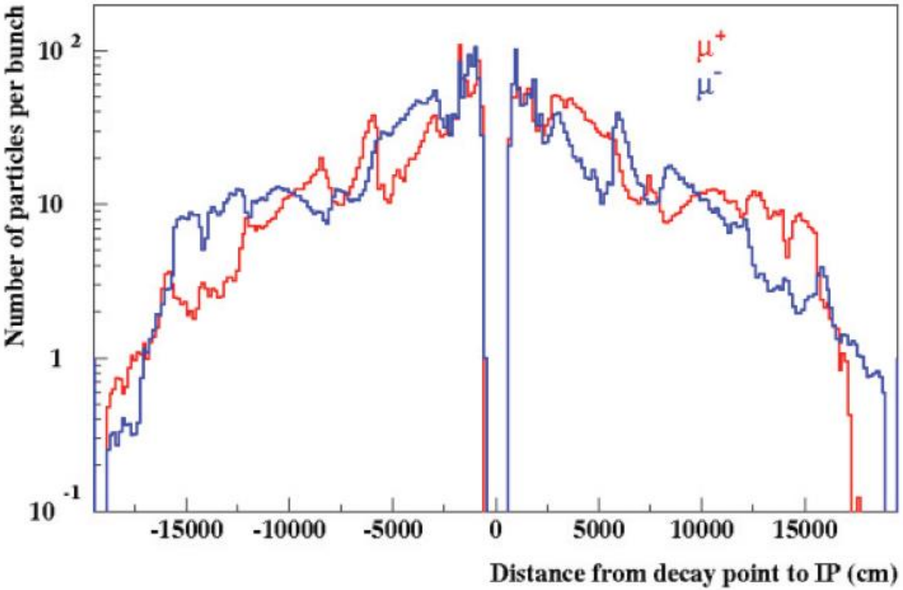


Muon flux map in IR.
Muons – with energy of tens and hundreds GeV – illuminate the whole detector. They are produced as Bethe-Heitler pairs by energetic photons in EMS originated by decay electrons in lattice components.

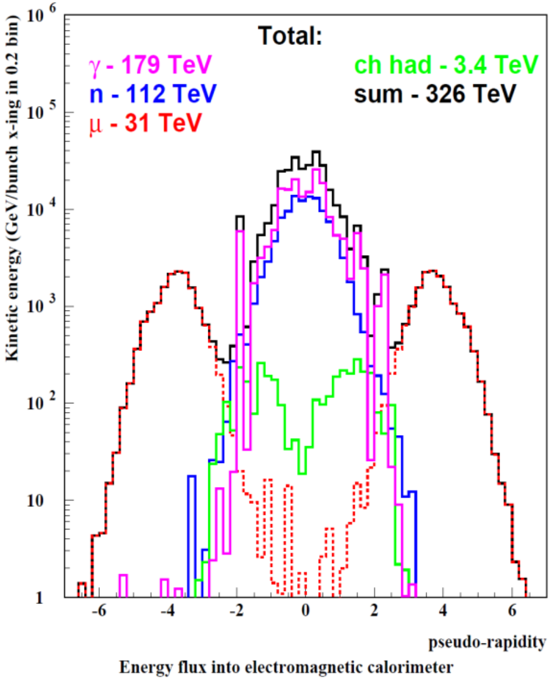
Neutron fluence map inside the detector.
Maximum neutron fluence and absorbed dose in the innermost layer of the Si tracker for a one-year operation are at a 10% level of that in the LHC detectors at the nominal luminosity. High fluences of photons and electrons in the tracker and calorimeter exceed those at LHC.

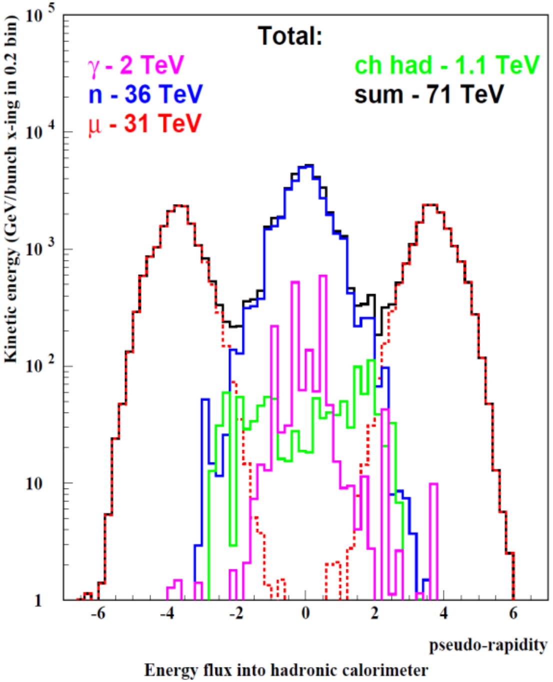
Decay Origin of BIB Entering MDI $\sqrt{S} = 1.5$ TeV





Energy Flux into Ecal and Hcal vs Rapidity

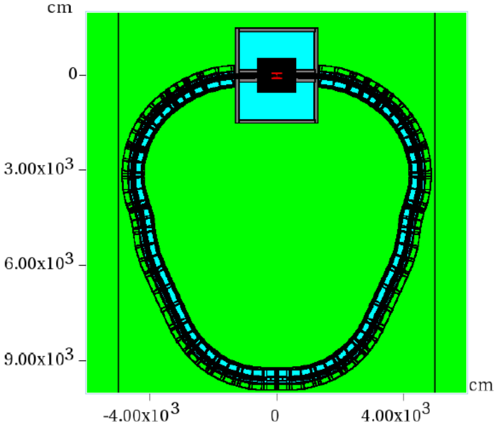




Peak: ~1 GeV / 2x2 cm^2 cell with σ_E ~ 30 MeV

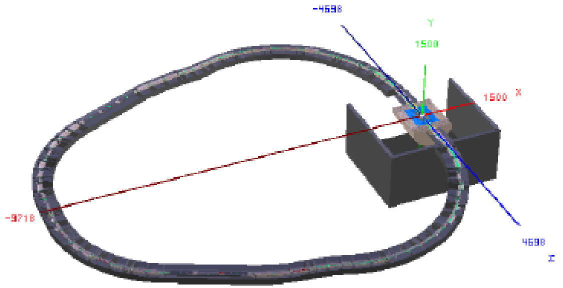
Peak: ~1.5 GeV / 5x5 cm^2 cell with σ_E ~ 80 MeV

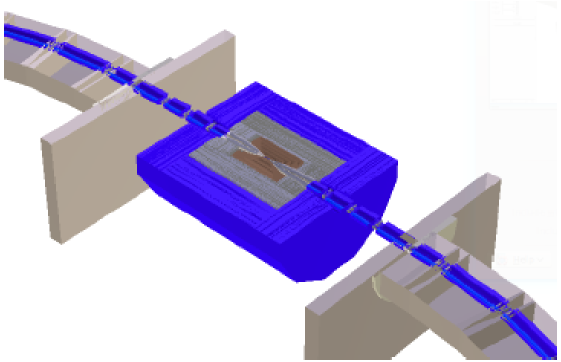
$\sqrt{S} = $ 125-GeV Higgs Factory MARS15 Model



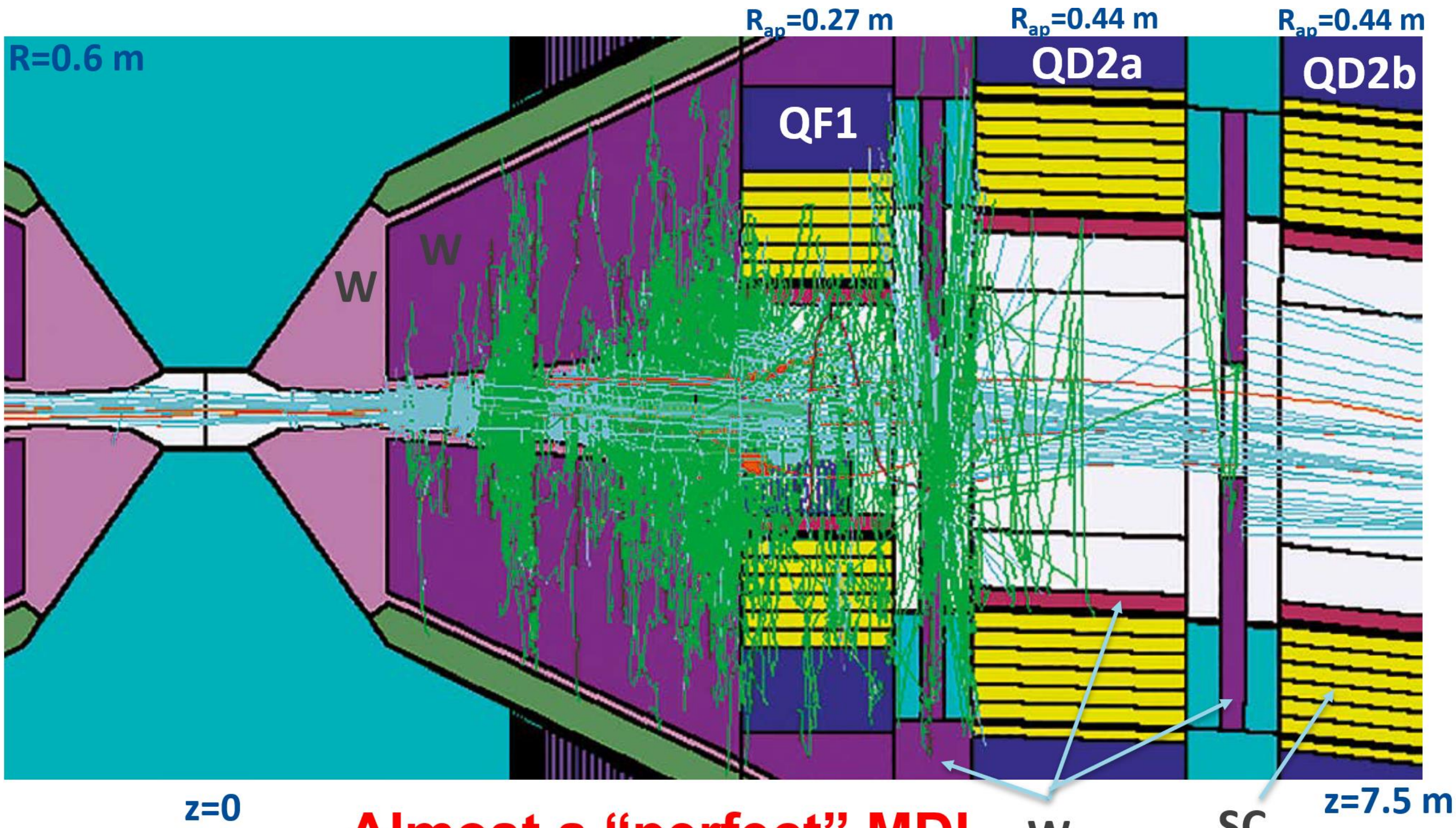
HF Muon Collider with IR, MDI and **SID-like detector with SVD and tracker model based on that of the CMS detector upgrade.** The circumference is about 300 m. Simplified tunnel and detector hall geometry.

λ_D =3.9·10^5 m. With 2·10^{12} muons per bunch, this results in 10^7 decays per meter in a single pass. The HF ring is designed for 1000 to 2000 turns per a store with 30 stores per sec. This provides the average luminosity of 8x10^{31} cm^{-2} s^{-1} compared to ~4x10^{33} cm^{-2} s^{-1} at 1.5TeV MC.





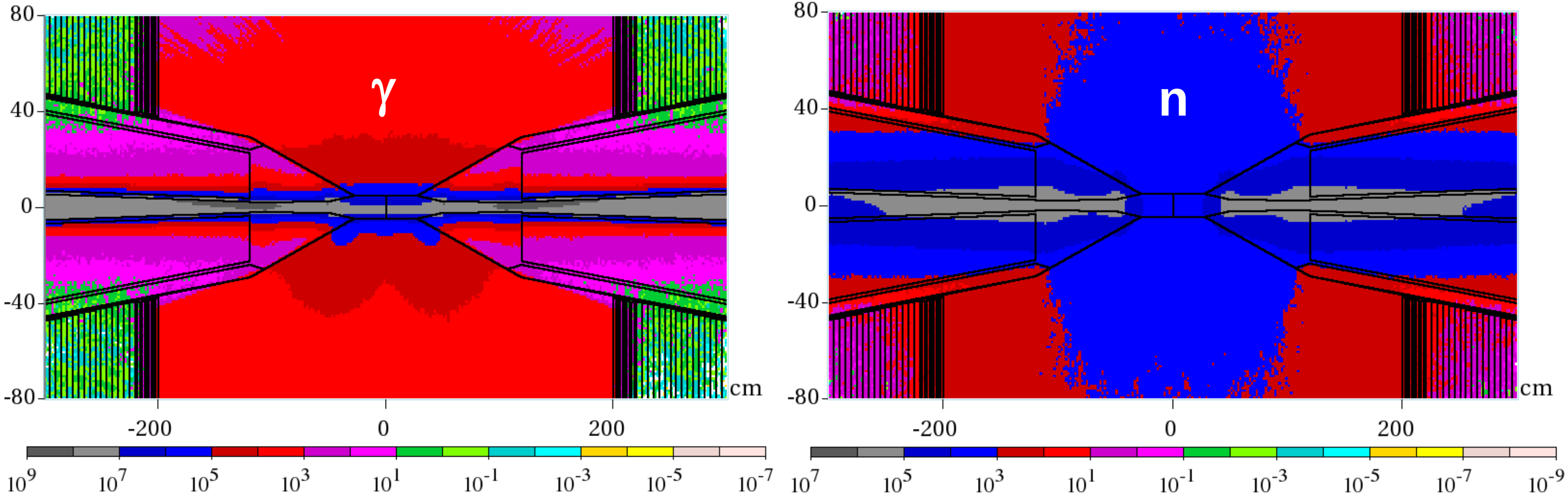
125-GeV Higgs Factory Thoroughly Optimized MDI



Almost a "perfect" MDI

Nikolai Mokhov, Fermilab, May 20, 2021

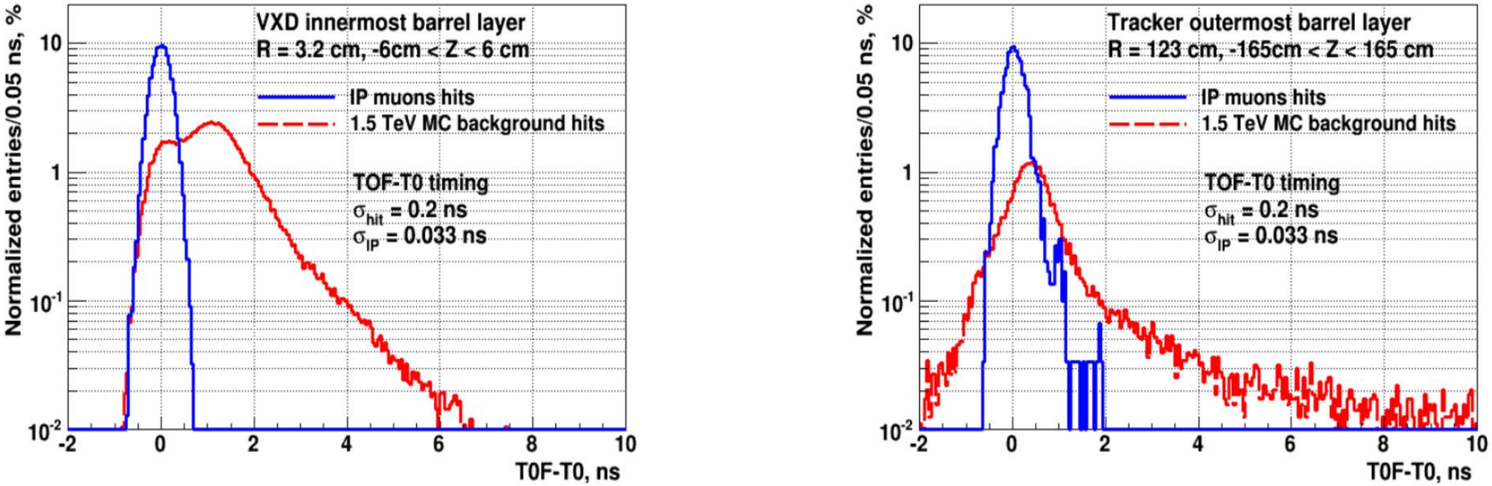
HF MC: γ and *n* Fluences (cm^{-2} per BX)



In central detector, the photon fluence is noticeably larger than in the LHC detectors while for neutrons it is much lower

BIB Rejection in VXD and Tracker at $\sqrt{s} = 1.5$ TeV

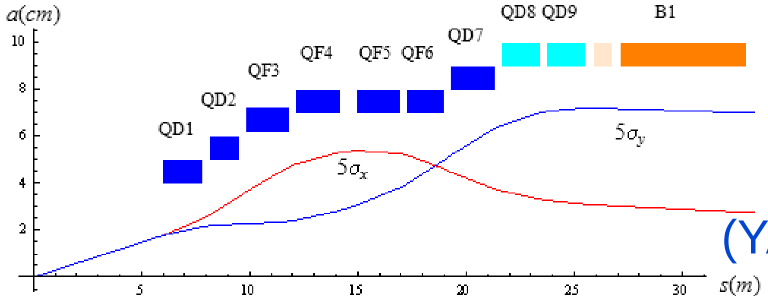
1. **Timing**: Use TOF-T0 where T0 is the time of flight of IP photon from IP to the point with IP muon or BIB particle hit coordinates.



2. **Energy deposition cut:** a modest improvement
3. **Double-layer criteria**: a single layer replaced with two sublayers being 1 – 2 mm apart and located in a strong magnetic field (B ~ 4 T): → The soft tracks from the BIB hits in one sublayer do not reach the second sublayer while IP physics charged tracks produce hits in both sublayers
4. **Directionality**

3 TeV IR and MDI

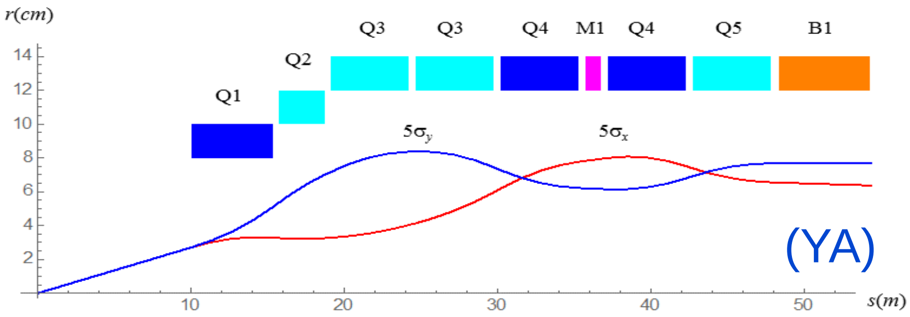
Preliminary lattice ($\beta^* = 5$mm) and magnet parameters were designed under SC magnet, detector and neutrino-induced protection constraints: e.g., quads with inner radii R > $5\sigma_{max}$+ 2cm allowing for W-liners, some defocusing quads (cyan) with 2-T dipole component, maximal quad length < 2 m, short interconnect regions with W-masks, and knowledge on nozzle from the lower energy experience. Quads with abs(G) = 90 to 250 T/m, 8-T dipoles, and coil apertures as large as 18 cm (AZ).



(YA)

6 TeV IR and MDI

Several LOIs were submitted to Snowmass, a kind of a pre-feasibility study to address design of a lattice for the average luminosity of 10^{35} cm^{-2}s^{-1} with β^*=3 mm, high-field / high-gradient superconducting magnets with the coil apertures as large as 25 cm in IR and 15 cm in the arcs, abs(G) = 78 to 200 T/m, 8-T dipoles with hybrid multilayer coils made of HTS and LTS with the stress management (AZ), optimized MDI with tungsten liners, masks, nozzles etc, detector BIB mitigation techniques as well as appropriate measures to mitigate neutrino hazard.



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Thank you for attention

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