1.5 TeV Muon Collider background rejection in ILCroot Si VXD and Tracker

(summary report)

N. Terentiev*
(Carnegie Mellon U./Fermilab)

V. Di Benedetto, C. Gatto
(INFN)
A. Mazzacane, N. Mokhov, S. Striganov
(Fermilab)

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Outline

- **Latest MARS 1.5 TeV Muon Collider background data**
- **ILCroot simulation of VXD/Tracker hits in four different double layer geometries**
- **Background rejection techniques in Si VXD and Tracker (on the hit level)**
  - timing
  - energy deposition
  - double layer method
  - results for IP efficiency and MARS background surviving fraction when all criteria combined
- **Conclusions/Summary/End of work comments**

- **Latest MARS background simulation data (July 2014) for 750+750 GeV $\mu^+ \mu^-$ beams with $2*10^{12}$ μ/BX each**

(N. Mokhov, S. Striganov, www-ap.fnal.gov/~strigano/mumu/2014)

- files **mupl-1e3x500-26m-lowth-excl, ~7.27M** background particles, μ^+ beam
  mumi-1e3x500-26m-lowth-excl, ~7.31M background particles, μ^- beam
- new geometry of muon collider magnets
- no weight fluctuation in interactions, intrinsic weight = 1
- new low energy electron-photon modules in the MARS code
- time of flight new calculations

- **Lower thresholds in MARS data**

(see energy distributions in backup slides)

– **100 keV** threshold for **γ, $e^\pm$, $\mu^\pm$** and charged hadrons (before – **200 keV** for **γ, $e^\pm$, 1 MeV** for **$\mu^\pm$** and hadrons)

– **0.001 eV** for **n** (before – **100 keV**)

MARS 1.5 TeV Muon Collider background

- **MARS particle yields for 1.5 TeV Muon Collider and 10^0 shielding cone**
  - **~4.5%** muon decays were simulated on the **26m** beam length, yielding total of **14.6M** background particles per BX
  - it gives statistical weight **~22.3** which is taken into account in ILCroot simulation (for given MARS particle its momentum is smeared azimuthally 22-23 times to get 100%)
  - correspondingly, **total yield/BX ~ 3.24e+08** particles go into detector in ILCroot simulation (before **~2.2e+08**)
  - MARS particles coordinates, time and momenta are given on the surface of detector side of the shielding cone and beam pipe (see backup slides)

- **MARS particle yields (by ID) for 1.5 TeV Muon Collider and 10^0 shielding cone**

	γ	n	$e^{\pm}$	p, $\pi^{\pm}$	$\mu^{\pm}$
Yield/BX	**1.72e+08**	**1.51e+08**	**1.50e+06**	**6.04e+04**	**0.28e+04**
Yield/BX with hits, %	**3.8**	**1.7**	**19.3**	**64.4**	**84.9**

  - increased neutron yield due to new low kinetic energy threshold (before ~ 0.40e+08)
  - some charged particles are out of VXD/Tracker acceptance or do not reach VXD/Tracker layers in magnetic field due to their low momentum
  - overall fraction of MARS background particles making hits in VXD and Tracker is **2.9%** (for 75 μ thick Si sublayers in VXD and 200 μ thick Si sublayers in Tracker, 3.5T magnetic field)

ILCroot status and data

- **ILCrootMuCv4-1-1, July 2014 release by Vito Di Benedetto**
  - minor changes in the code since ILCroot4MuC
  - the same versions GEANT4 v9.6.01 and ROOT v5.34.05
- **ILCrootMuCv4-1-1 with VXD and Tracker double layer geometry for 1.5 TeV MC new MARS background and IP muons simulation**
  - new physics list QGSP_BERT_HP_LIV (better EM description)
  - simulation was limited to hits in VXD and Tracker only, the rest of detectors as material

- **ILCrootMuCv4-1-1 with VXD and Tracker double layer geometry for 1.5 TeV MC new MARS background and IP muons simulation (cont'd)**
  - 75μ, 100μ and 200μ Si sub-layers in VXD and Tracker layers
  - four geometry layouts for VXD and Tracker to study timing, energy deposition and double layer background rejection:
    - 1 mm and 2 mm space between two sub-layers in layer
    - 3.5T and 7.0T magnetic fields in detector
    - pictures are for 1mm and 3.5T geometry layout
  - IP muons with P = 0.2 - 10 GeV/c
  - ILCroot simulation was made on Fermi Grid

ILCroot status and data

- **ILCroot output files with tracks (Kinematics.root) and hits (CLICCT.Hits.root) were converted into ROOT TNtuple simple tree ntuples Kinematics2ntuple.root and CLICCTHits2ntuple.root in stand-alone conversion code on Fermi Grid**
  - original formats were extended to add more information about tracks and hits
  - ROOT ntuples were joined to Kinematics2ntuple_hadd.root (~9.4 Gb) and CLICCTHits2ntuple_hadd.root (~27 Gb) for each geometry set
  - these files were inputs for stand-alone analysis code (compiled C++ in ROOT) to define and apply timing, energy deposition and double layer cuts and get IP muon hits efficiency and MARS background hits surviving fraction
  - the study was limited to VXD barrel and Tracker barrel layers

Background rejection techniques in Si VXD and Tracker

- **Simulation and analysis on the hit level**
  - the hit level study provides basis for choice of future front-end
- **A hit in GEANT4**
  - “a snapshot of the physical interaction of a track in the sensitive region of a detector”, defined for each step of the particle tracking
  - has X,Y,Z ,Time and P components (at begin and end of the step), ID of the particle, energy deposition in the step etc.
  - ILCroot keeps detailed information about hits including status of the track (in, out or stopped in sensitive volume)
- **Define the hit cluster as a group of hits for given track in given sensitive volume (Si sub-layer) ended by final hit when track left the volume or stopped in it**
  - use it to sum energy deposition per hit cluster
  - for cluster timing and position parameters use average over hits
  - to estimate group of pixels crossed by the track in hit cluster

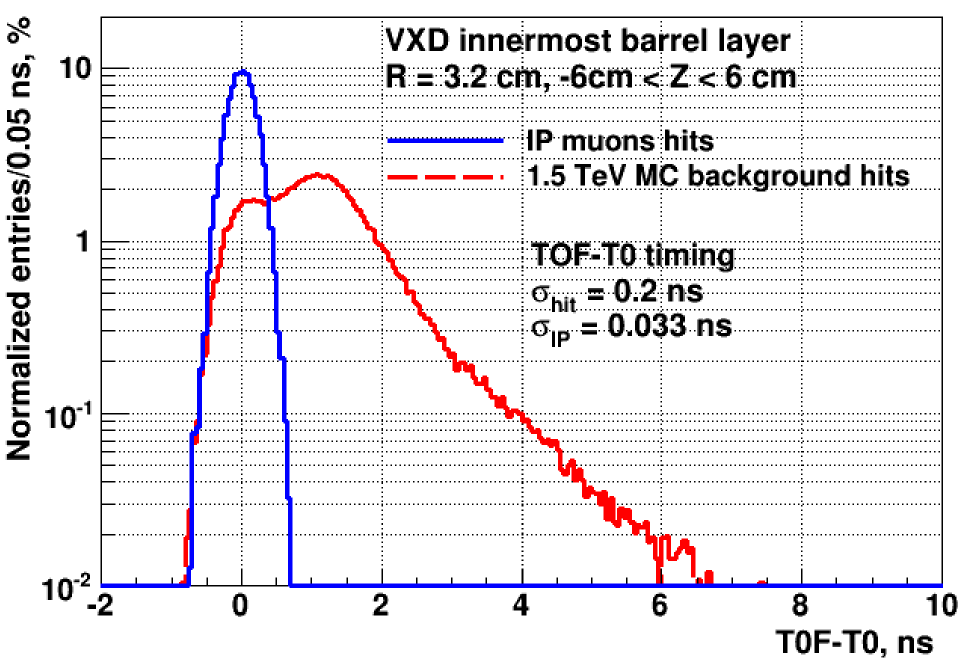
Background rejection techniques in Si VXD and Tracker

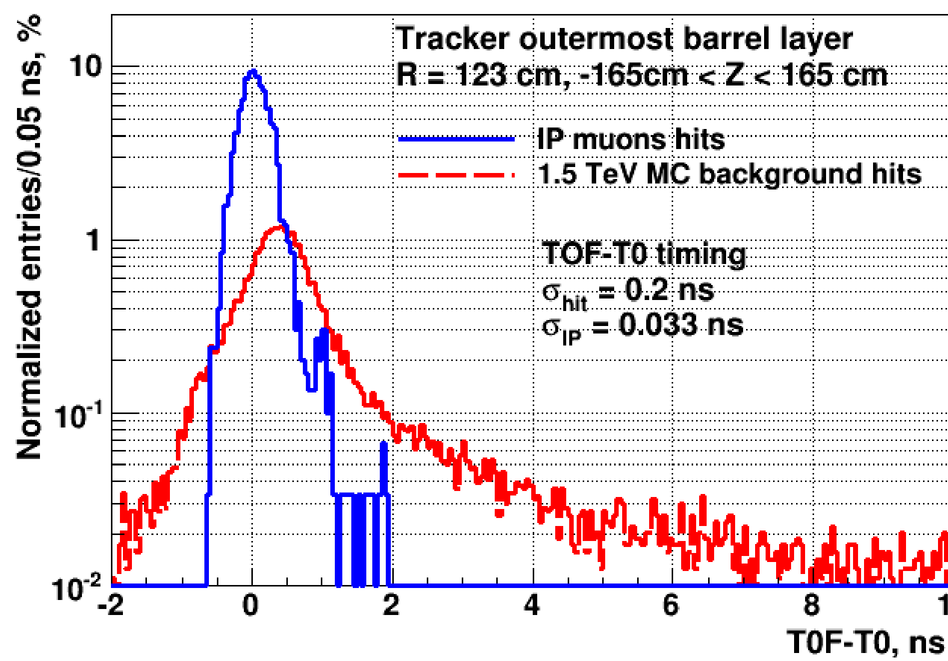
- **List of background rejection techniques**
  - **timing**, requires 100-200 ps time resolution and ~1 ns timing gate width in front-end electronics to distinguish TOF (time of flight) of IP particles hits from TOF of muon collider machine background particles hits
  - **energy deposition threshold,** for Landau peak for IP particles crossing Si sub-layer vs. wide energy deposition distribution for secondary e- produced by background photons and neutrons in any point of the sub-layer, can be applied in a trigger level software or/and offline tracking
  - **double layer** geometry 2D criteria to reject space random neutral background hits and preserve IP charged track correlated hits in both sub-layers (in the trigger software or/and offline tracking)

Background rejection techniques in Si VXD and Tracker

- **Timing**
  - MARS gives time of flight of background particles (with respect to bunch crossing BX) calculated on the detector side surface of the shielding cone
  - GEANT4 in ILCroot is tracking these particles through the detector, takes into account MARS time of flight and provides timing (TOF) for each hit in sensitive volume (with respect to the bunch crossing BX)
  - in analysis use instead TOF-T0 where T0 – time of flight of IP photon from interaction point IP (X=0,Y=0,Z=0) to the point with IP muon or MARS background particle hit coordinates in sub-layer
  - this compensates the different TOF for IP particles making hits in different layers of VXD and Tracker at different R and Z coordinates of the hit

- **Timing (cont'd)**
  - the TOF-T0 of the IP muon hit cluster and MARS background hit cluster was smeared with Gaussian time resolution of 200 ps
  - IP TOF-T0 distribution is fitted by Gaussian to determine start and width of the timing gate for given IP efficiency (97%)
  - MARS background timing is different from layer to layer, therefore different rejection if keep one and the same IP efficiency

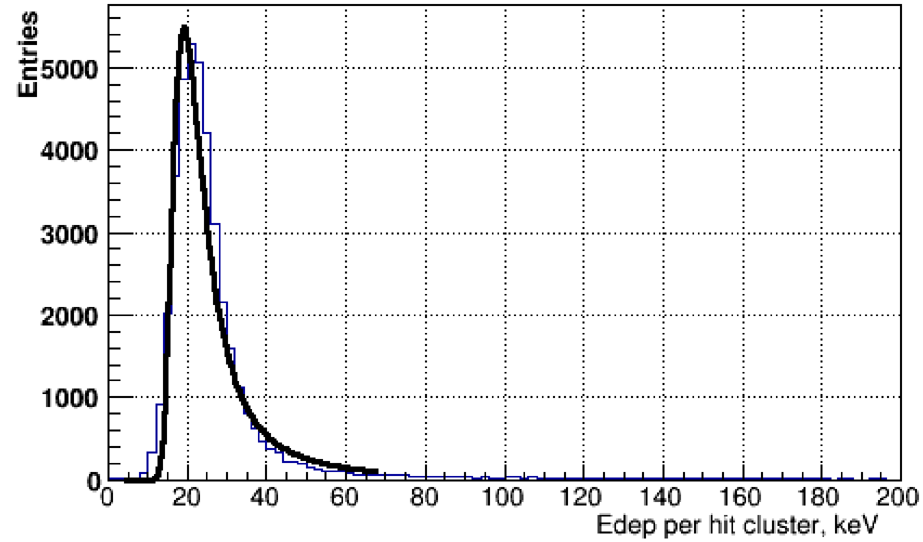


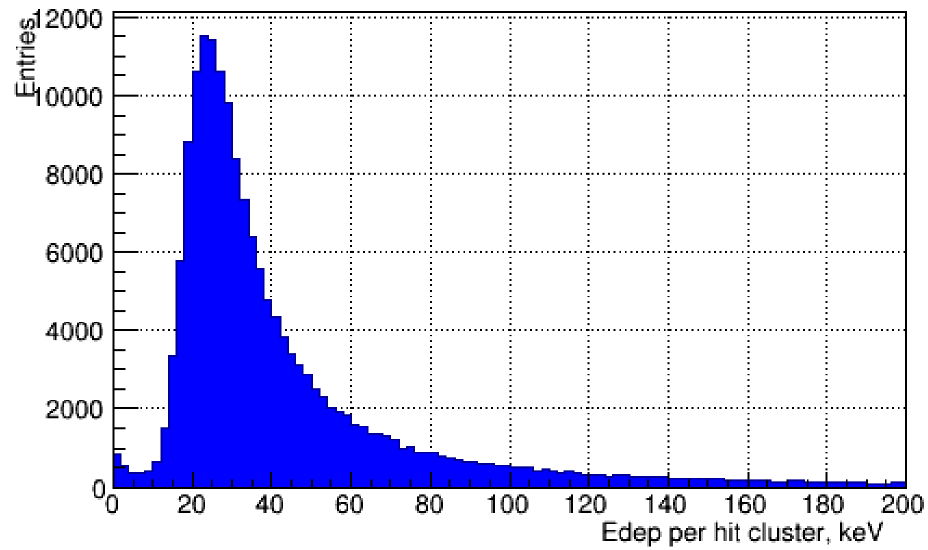


Background rejection techniques in Si VXD and Tracker

- **Energy deposition**
  - Edep - sum of energy depositions in all hits of the hit cluster for given track in given sub-layer
    - Edep resolution was introduced (Gaussian σ_{res} = 2 keV for VXD and 5.6 keV for Tracker) as 1/10 of Landau peak position at Z=0 cm
    - fit Edep distribution for IP muons with Landau function and define Edep cut (threshold) as (Landau peak position – 2.2*σ) where σ is the fit parameter
    - corresponding IP muon track hit cluster efficiency per sub-layer with Edep higher than the threshold is ~96-98%
    - Edep threshold depends on sub-layer thickness (75μm or 200 μm) and Z-position of the IP hit in the sub-layer (θ angle)
    - find surviving fraction of MARS background hit clusters having Edep higher than the threshold, per sub-layer

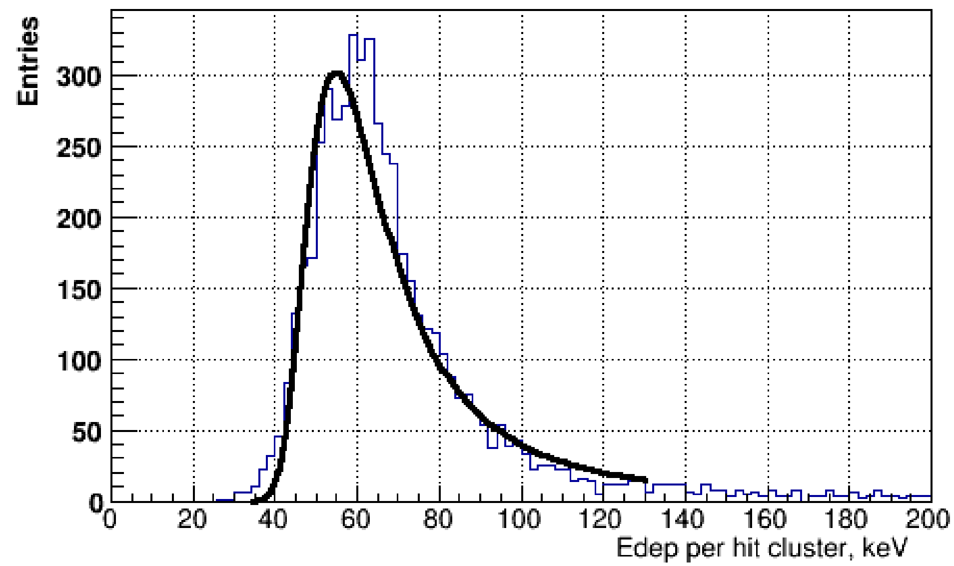
- **Energy deposition for IP muons and MARS background in the VXD innermost barrel sub-layer (75 µm)**
  - IP muon
    - Landau peak **~20** keV at Z=0
    - Edep threshold **~14** keV, IP efficiency ~**97%** per sub-layer
  - MARS background (all Z)
    - mostly MARS e+,e-



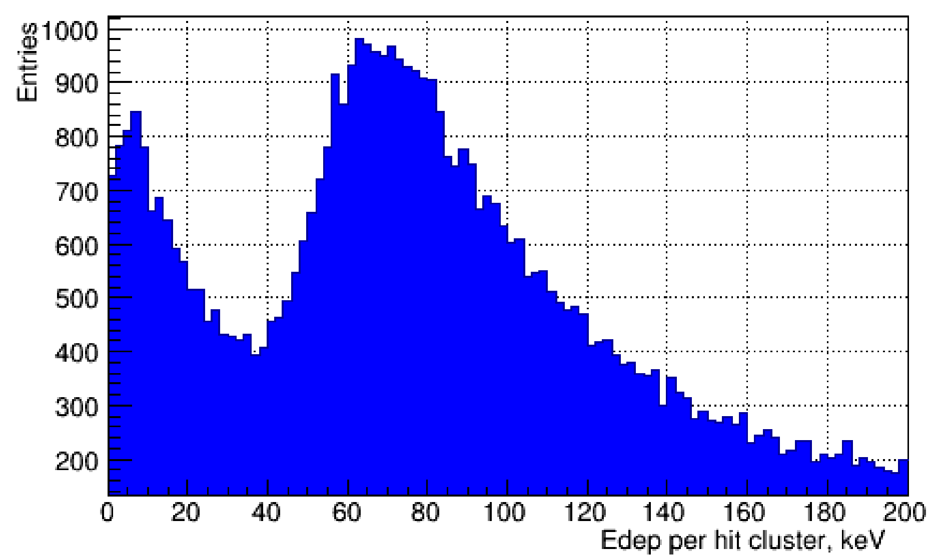


Background rejection techniques in Si VXD and Tracker

- **Energy deposition for IP muons and MARS background in the Tracker outermost barrel sub-layer (200 µm)**
  - IP muon
    - Landau peak **~56** keV at Z=0
    - Edep threshold **~42** keV, IP efficiency ~**98%** per sub-layer



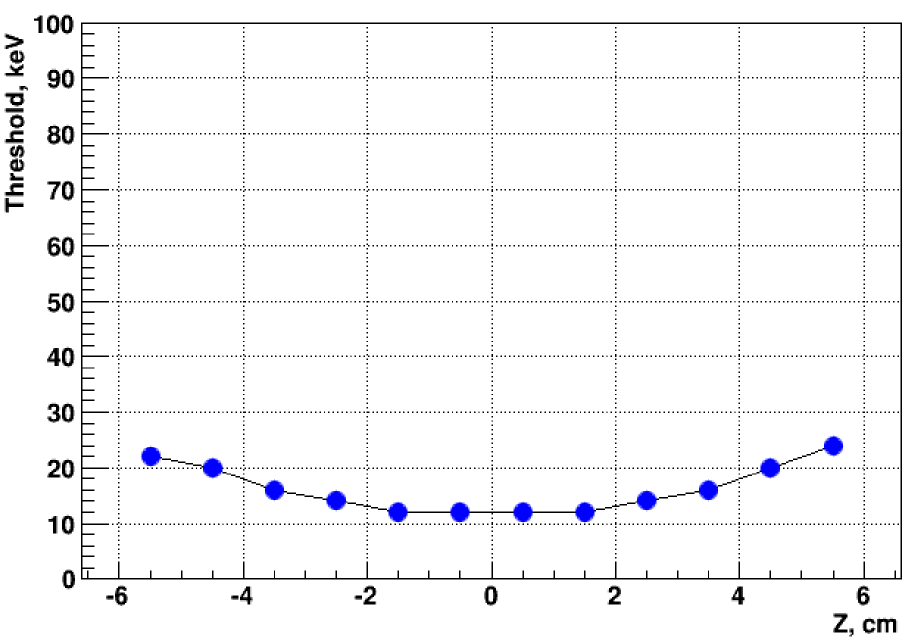
  - MARS background (all Z)
    - mostly e- from n and g interacted in any point of Si layer
    - the second peak is for particles crossing sub-layer



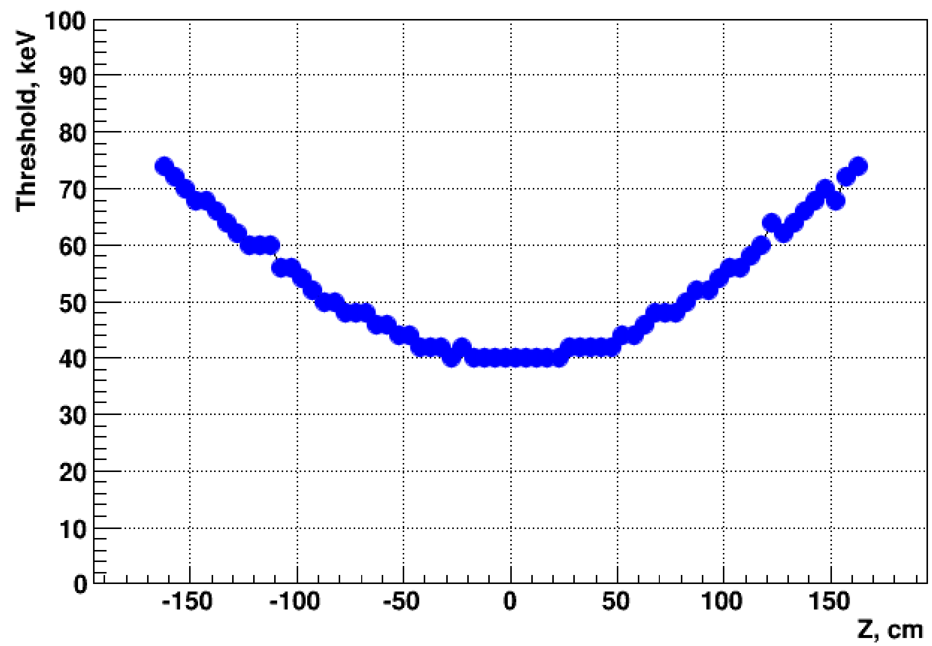
Background rejection techniques in Si VXD and Tracker

- **Edep threshold for IP hit clusters depends on:**
  - sensitive volume thickness (75 µm for VXD barrel and 200 µm for Tracker barrel sub-layers)
  - and IP muon track polar angle (~Z position of the track in the VXD or Tracker barrel sub-layers)

Innermost barrel VXD layer



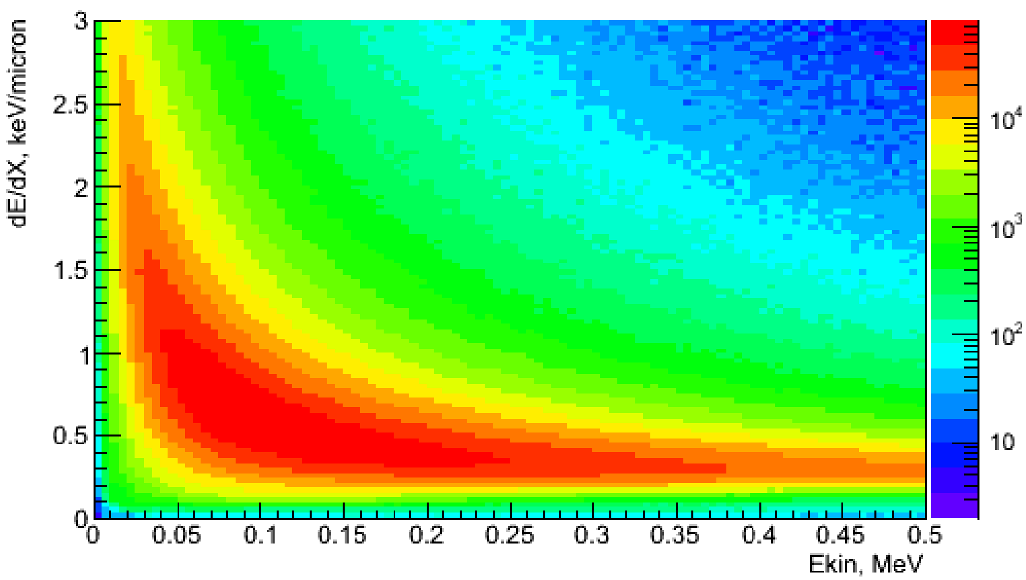
Outermost barrel Tracker layer



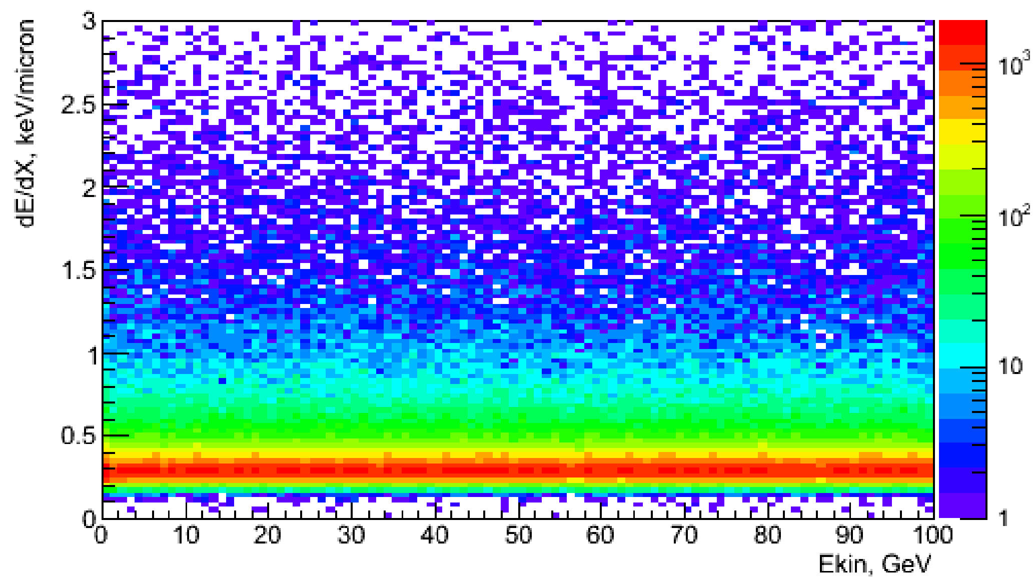
Background rejection techniques in Si VXD and Tracker

- **$Edep_{thr}$ for the hit clusters does not provide good rejection of the muon collider background**
  - large dE/dX at the end of range for low energy e- coming from background photon and neutron interactions, exceeds dE/dX of IP muons crossing sub-layer (data for all barrel layers)
  - expect modest improvement if using likelihood-ratio test instead of threshold

e- from background g and n

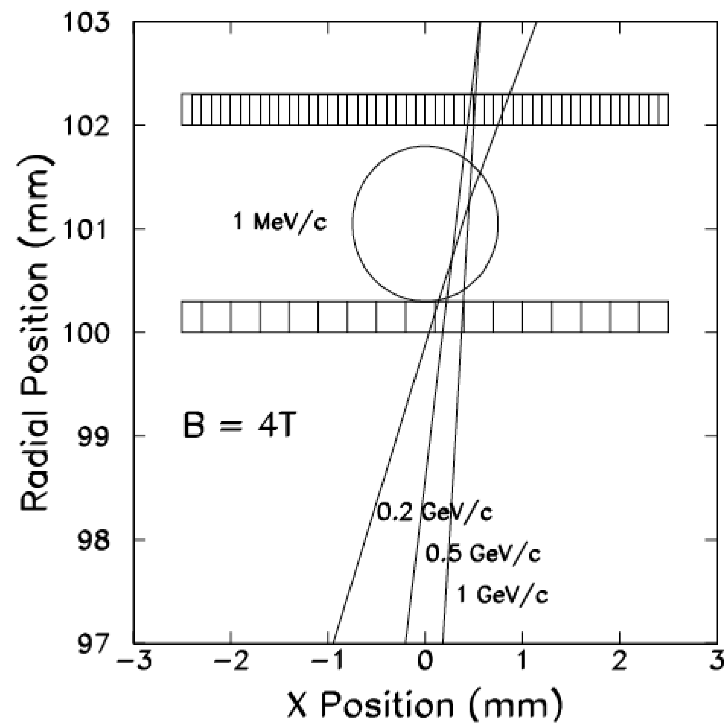


IP muons

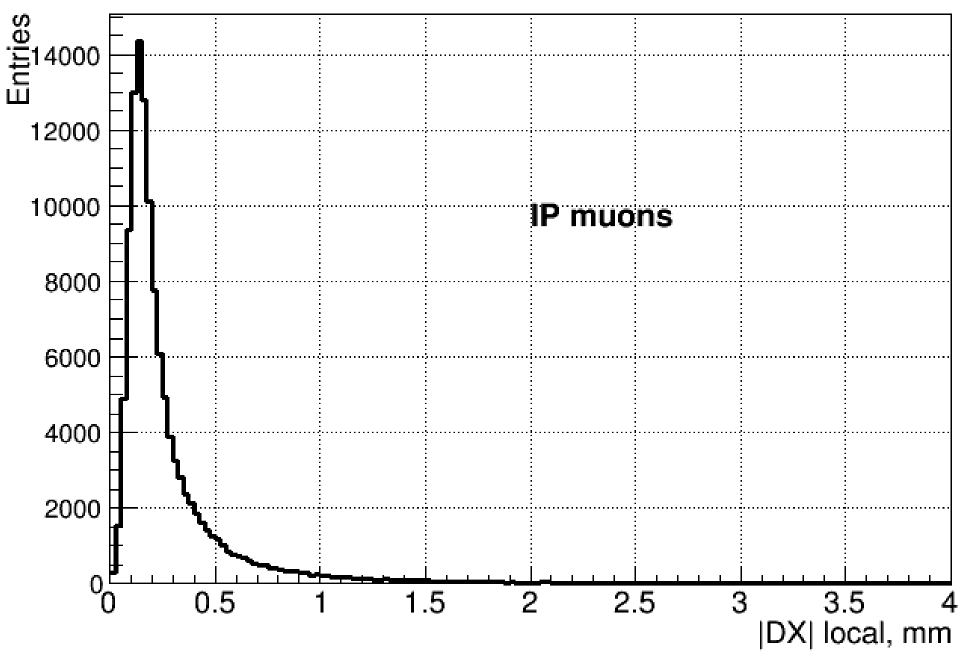


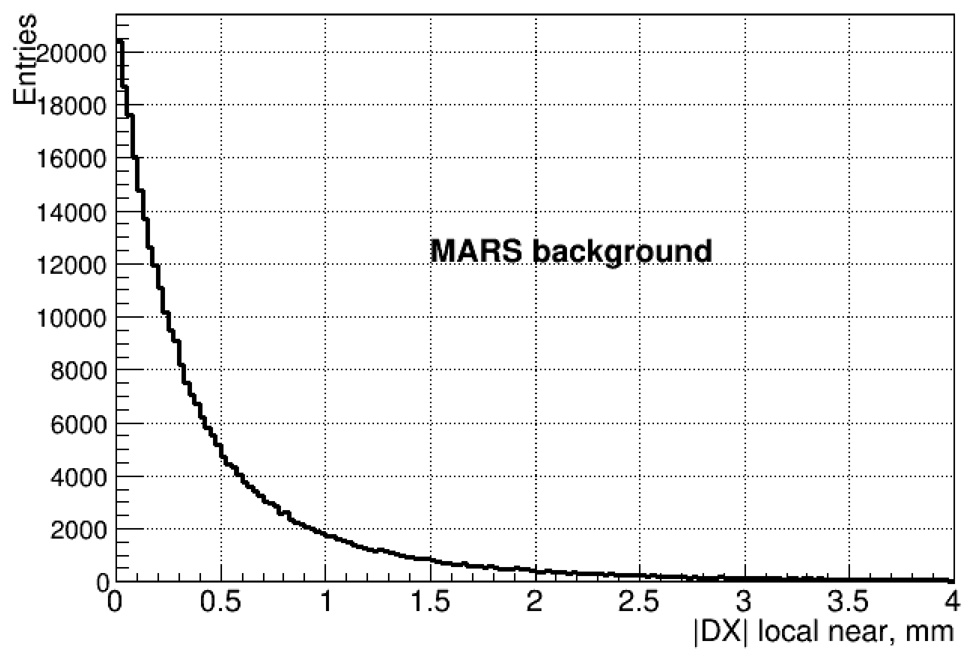
Background rejection techniques in Si VXD and Tracker

- **Double layer criterion - a stacked layer design to reduce random neutral background occupancy based on inter-layer correlations**
  - suggested by J. Chapman and S. Geer for the muon collider in 1996
  - a single layer replaced with two layers being 1-2 mm apart
  - soft MeV tracks from background hit in one layer do not reach the second layer (B=4T)
  - IP physics charged track makes hits in both layers
  - readout takes AND of appropriate pixel pairs in both layers suppressing background hits



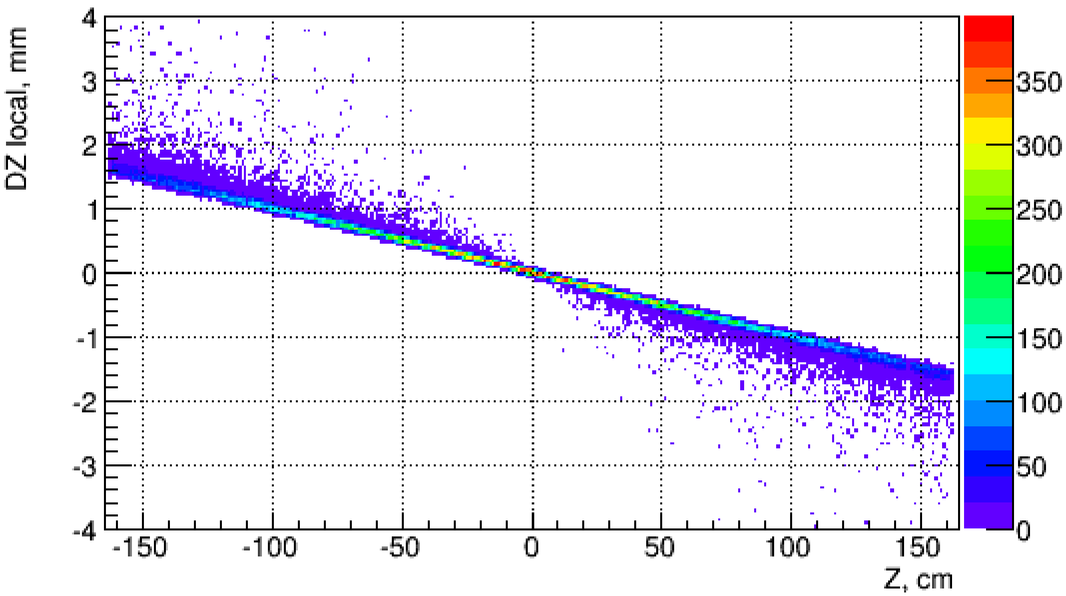
- **Double layer criteria**
  - instead of AND of pixel pairs use cuts on difference of hit clusters coordinates (local X and Z) in both sublayers
  - smear hit cluster local Z and X coordinates in each sub-layer with Gaussian σ_{res} = 6 μm for VXD and σ_{res} = 15 μm for Tracker
  - |DX| local for IP muons and |DX| local nearest for MARS (outmost Tracker barrel layer, “1mm, 3.5T” geometry)



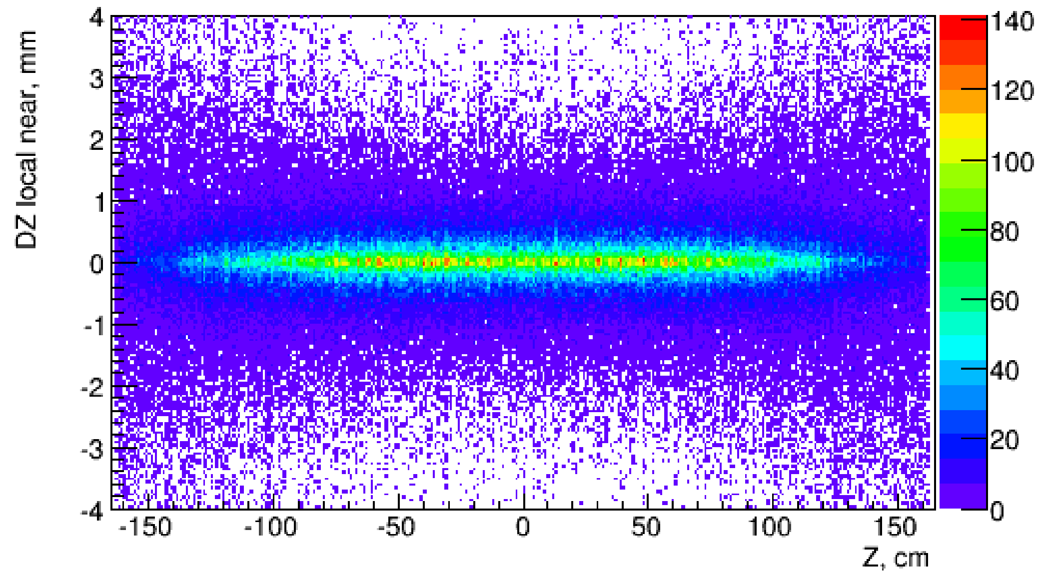


- **Double layer criteria (cont'd)**
  – DZ local vs. Z for IP muons and DZ local nearest vs. Z for MARS (outmost Tracker barrel layer, "1mm, 3.5T" geometry)
  – use two sides cuts for DZ local to select IP muons and reduce MARS background
  – cuts depend on Z and layer

IP muons



MARS background

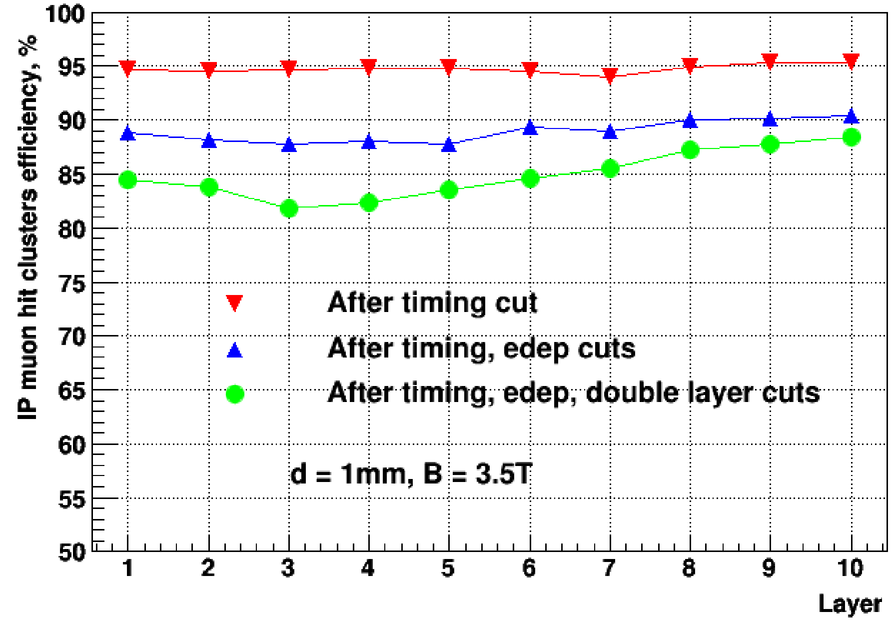


Background rejection techniques in Si VXD and Tracker

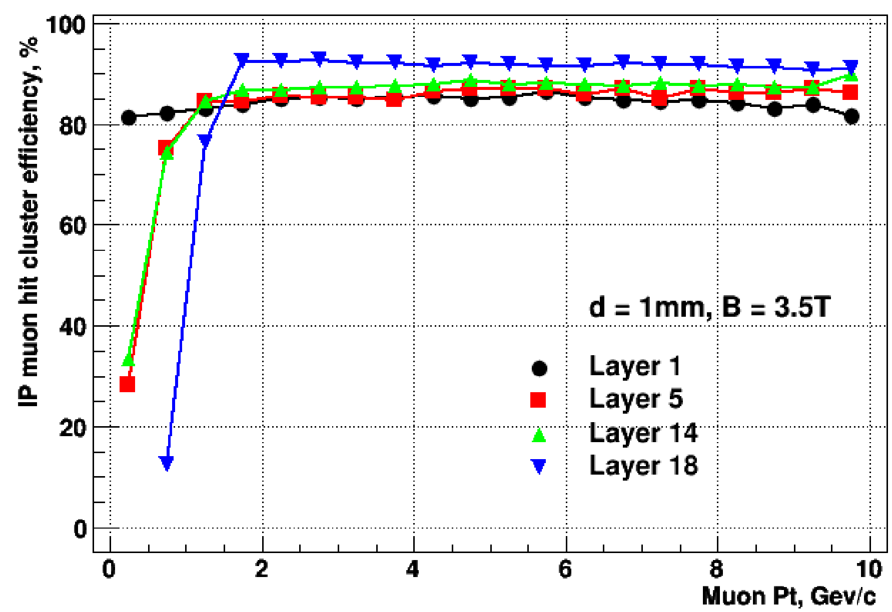
- **Summary of used resolutions in VXD and Tracker barrel sub-layers**
  - 0.2 ns for timing
  - 2 keV (VXD) and 5.6 keV (Tracker) for energy deposition as 1/10 of Landau peak position at Z=0
  - 6 μm (VXD) and 15 μm (Tracker) for X,Z in double layer method
- **Summary of used cuts in VXD and Tracker barrel sub-layers**
  - require IP muon hit cluster efficiency ~97% per sublayer for each cut
  - timing gate width 0.9 ns (VXD) and 0.9 ns – 1.2 ns (Tracker)
  - energy deposition threshold, depends on Z and layer
  - |DX| local cut, depends on layer and geometry, 0.2 - 2.9 mm
  - DZ local two sides cut, depends on Z, layer and geometry

Results for IP efficiency and MARS surviving fraction

- **IP muon hit clusters efficiency (both sublayers) vs. layer**
  (Layers 1-5 are VXD barrel, 6-10 are Tracker barrel)

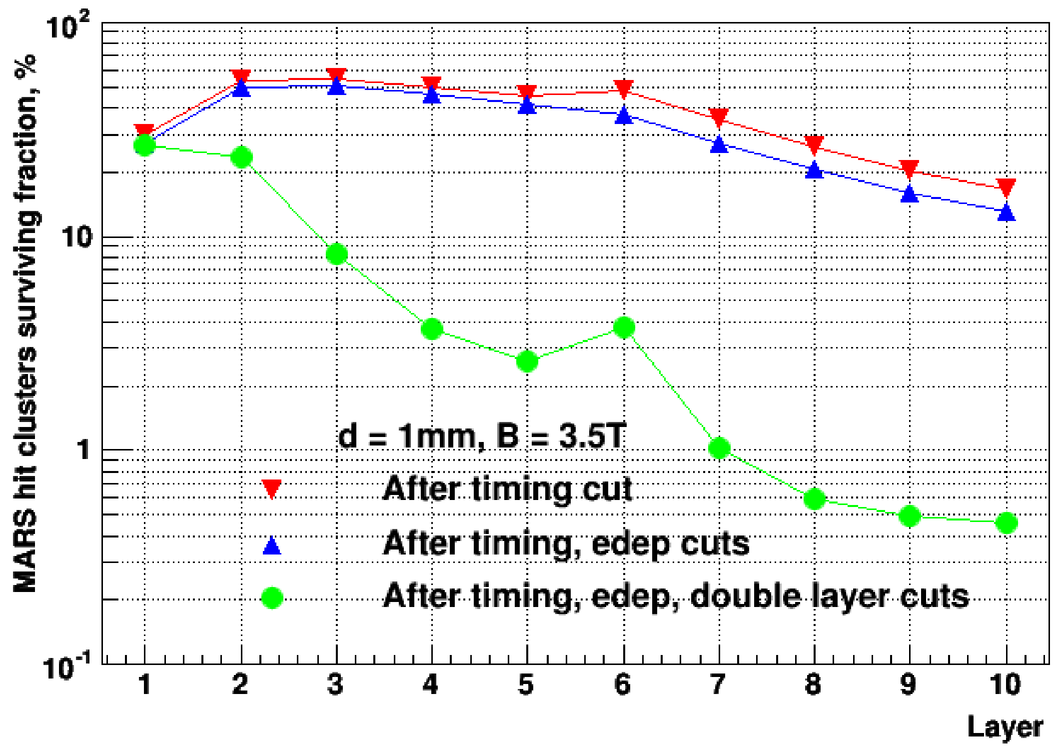


- **IP muon hit clusters efficiency (both sublayers) vs. Pt**
  (Layers 1,5 - VXD barrel, Layers 14(6),18(10) - Tracker barrel)



- Require muon track to have one hit cluster in each sublayer of given layer

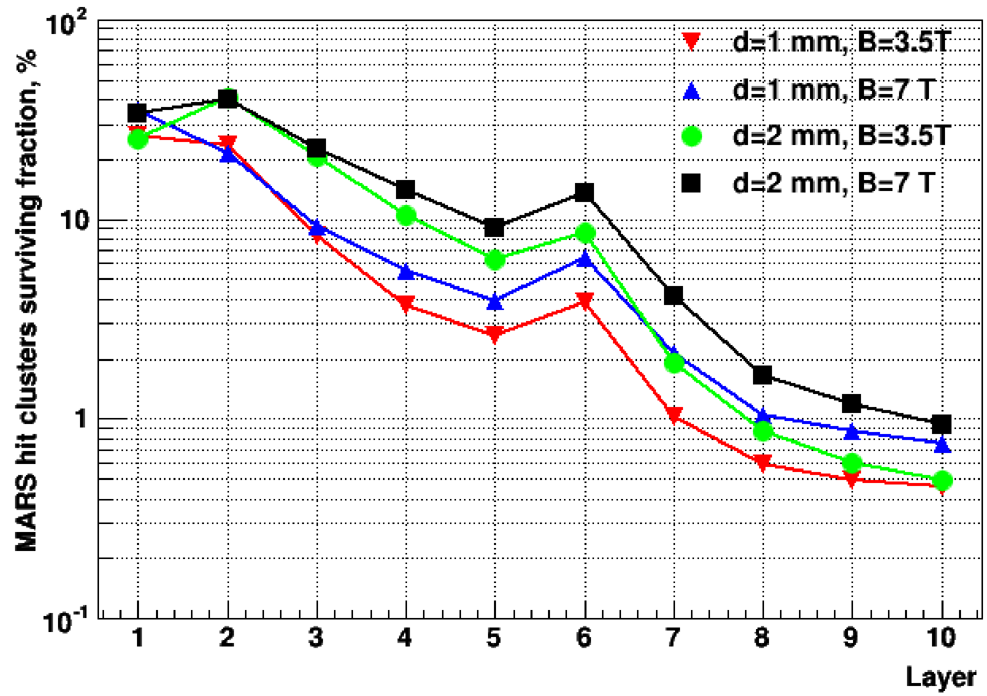
- **MARS hit clusters surviving fraction per sub-layer vs. cuts and layer** (1-5 VXD barrel, 6-10 Tracker barrel) in 1mm, 3.5T geometry



  - most of rejection comes from timing and double layer cuts
  - rejection ~4-200 depending on layer
  - high suppression of background in Tracker outer layers is due to lower hit clusters density and suggests using out-in tracking algorithm

Results for IP efficiency and MARS surviving fraction

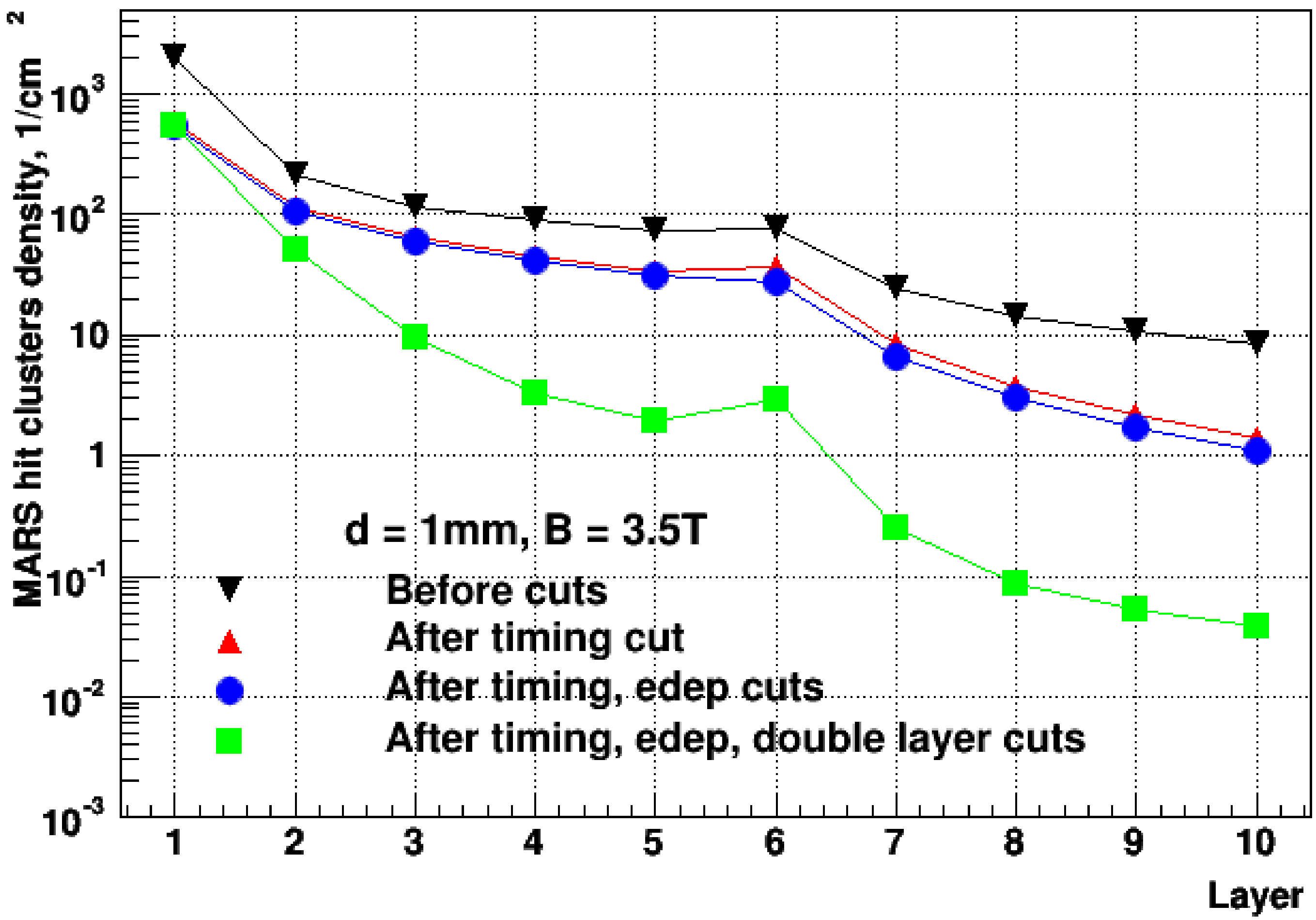
- **MARS hit clusters surviving fraction per sub-layer after all cuts in different geometries** (1-5 VXD barrel, 6-10 Tracker barrel)
  - background surviving fraction goes up with increasing sublayer space and magnetic field due to loosing double layer cuts (if to keep the same IP efficiency)



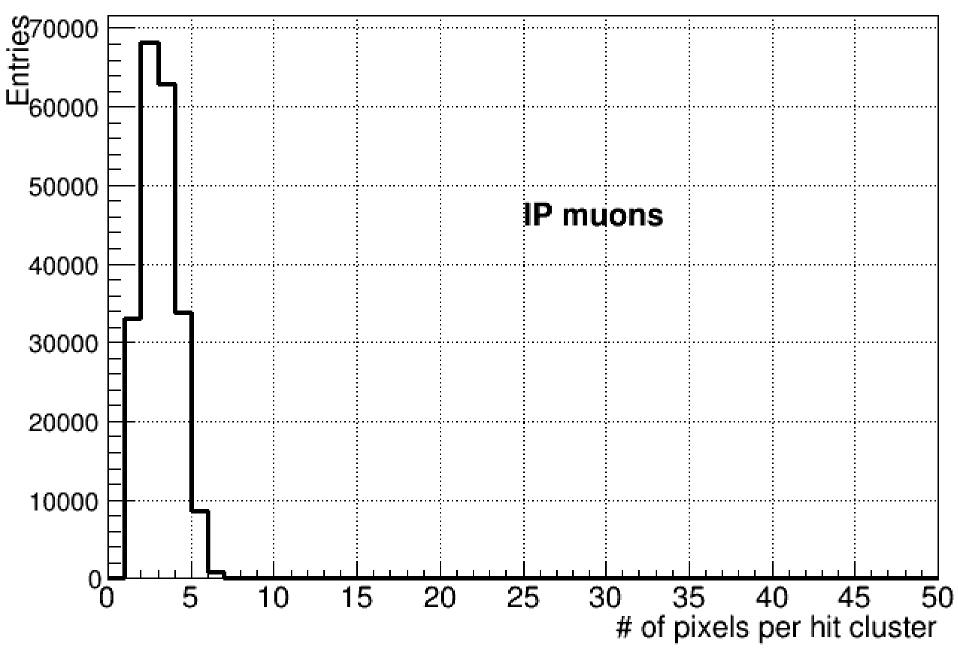
  - overall MARS surviving fraction in barrel VXD and Tracker ~3% in 1mm geometries, ~4-5% in 2 mm geometries at IP efficiency of ~85%
  - comparison of 3.5T and 7.0T geometries is not 100% justified (using the same MARS file with 3.5T field in the shielding cone)

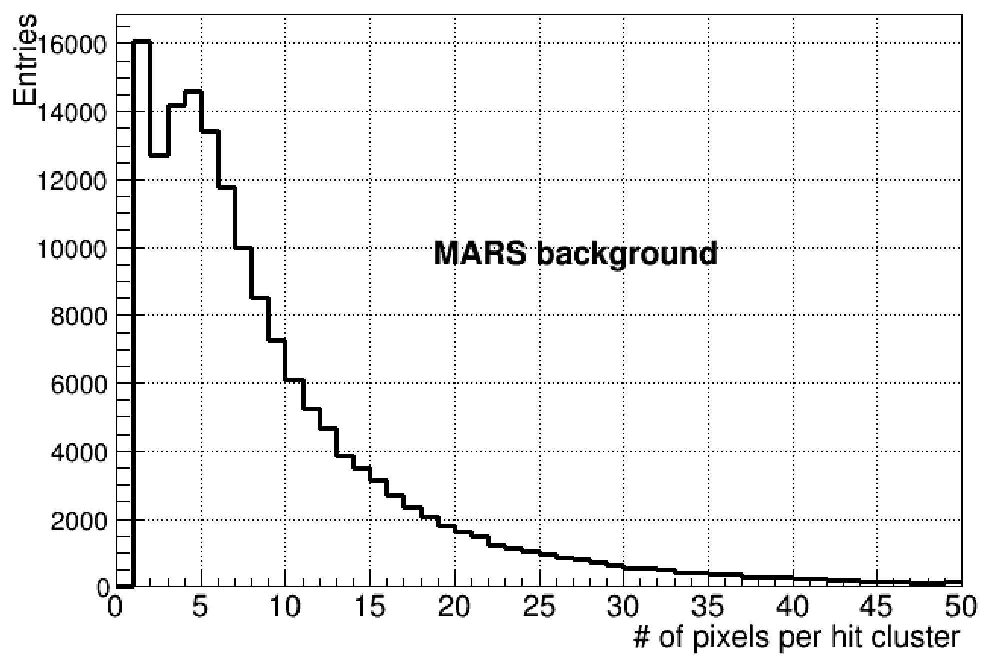
Results for IP efficiency and MARS surviving fraction

- **MARS hit clusters density per sub-layer vs. cuts and layer in 1mm, 3.5 T geometry**
  (1-5 are VXD barrel, 6-10 are Tracker barrel)



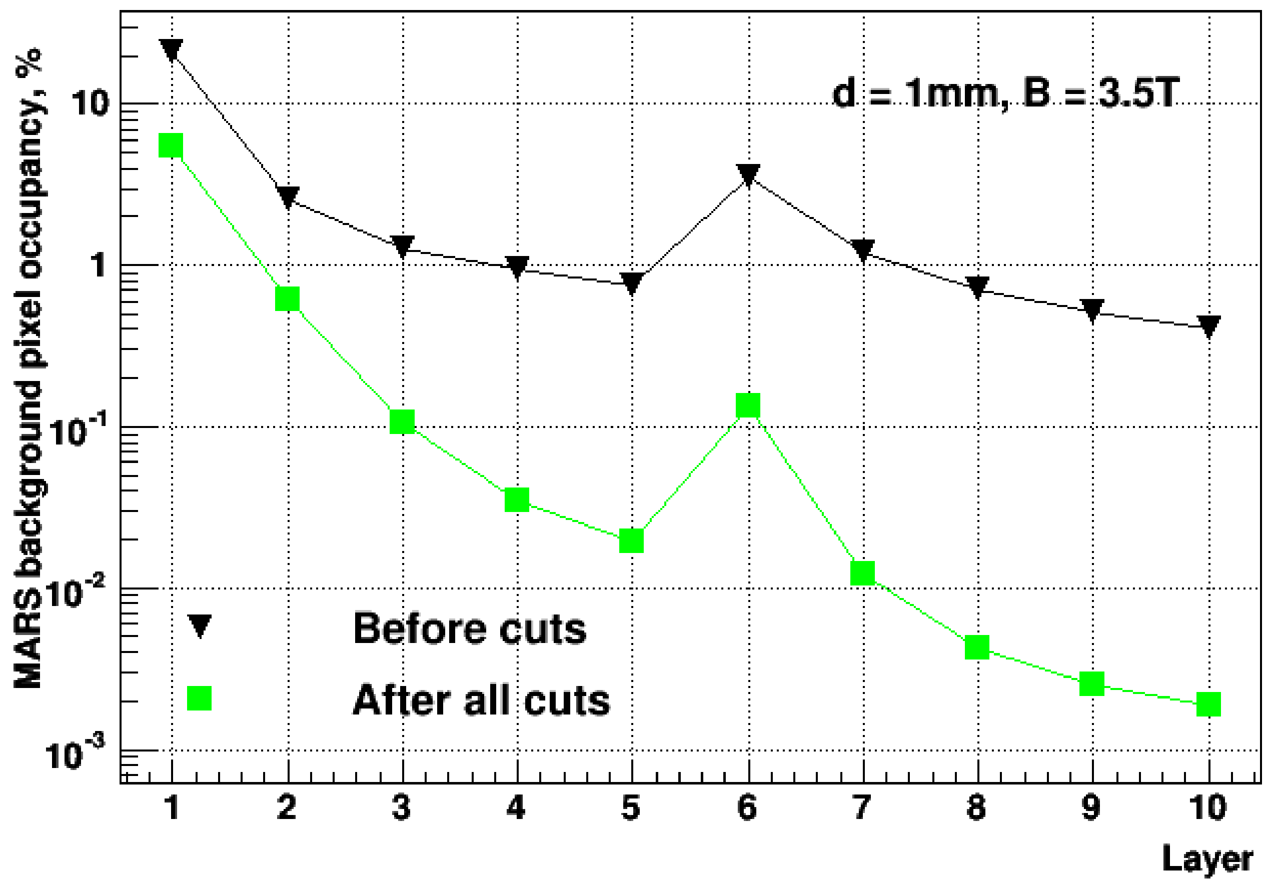
- **IP and MARS background pixel estimates per sub-layer in 1mm, 3.5T geometry**
  - pixels are simulated in the analysis code, not in ILCroot
  - use as an example 20 μ for VXD and 50 μ for Tracker barrels
  - count only pixels crossed by track (pictures - VXD barrel layer 3)
  - # of pixels per cluster – one more way to suppress background?





Results for IP efficiency and MARS surviving fraction

- **MARS background pixel occupancy per sub-layer vs. layer** (1-5 VXD barrel, 6-10 Tracker barrel) **in 1mm, 3.5T geometry**
  - count pixels crossed by track + adjacent pixels



Conclusions

- **The new MARS 1.5 TeV muon collider background data were simulated on the hit level in ILCroot framework with four double layer geometries (1 - 2mm, 3.5 - 7T magnetic field) in Si VXD and Tracker layers.**

- **Stand-alone ROOT based code was prepared and used to study Si VXD and Tracker barrels response to MARS background and develop background suppression criteria (timing, energy deposition and double layer) on the hit level.**

Conclusions (cont'd)

- **The maximum suppression of the background was achieved in 1 mm double layer geometry with 3.5T magnetic field**
  - rejection ~4-200 depending on layer
  - ~26% surviving MARS background hit clusters fraction in the innermost VXD layer and
    ~0.5% in the outermost Tracker layer.
  - high suppression of background in Tracker outer layers suggests using out-in tracking algorithm
  - the surface density of MARS surviving hit clusters
    ~540 cm^{-2} for innermost VXD barrel layer and
    ~0.04 cm^{-2} for outmost Tracker barrel layer.
- **The overall MARS background surviving fraction in all barrel layers of VXD and Tracker at IP muon efficiency ~85% per layer**
  - ~3% in 1mm geometries and
  - 4-5% in 2 mm geometries

Summary/End of work comments

- **The ILCroot framework version dedicated to Muon Collider Detectors study was developed** (V. Di Benedetto, C. Gatto, A. Mazzacane).

- **It was used to study detector response to physics events in the presence of MARS background for 1.5 TeV Muon Collider and Higgs Factory Muon Collider**
  - with use of timing background suppression criteria in calorimetry (V. Di Benedetto) and tracking (A. Mazzacane)
  - on the hit level in VXD and Tracker for MARS background (N. Terentiev)

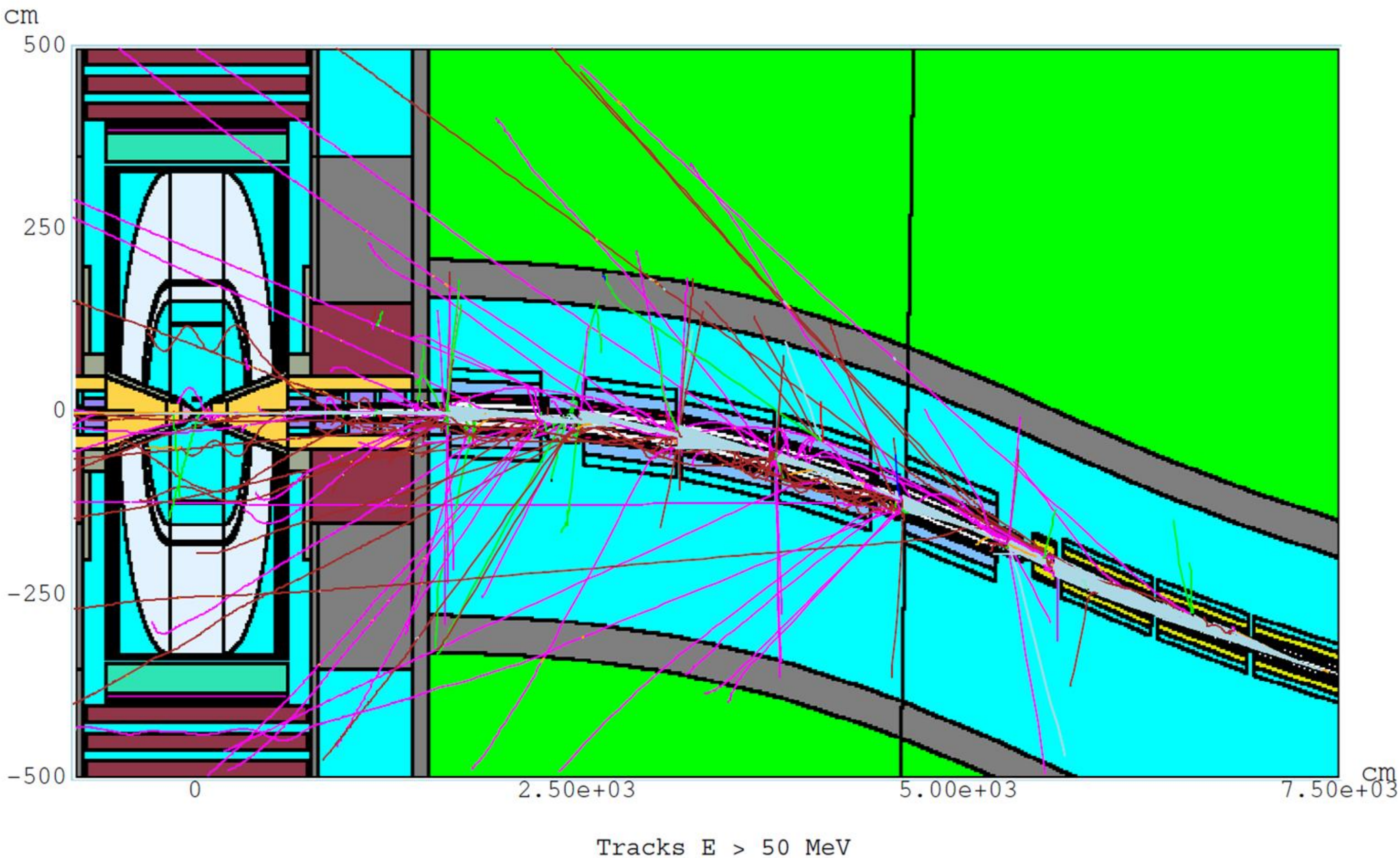
- **The new MARS 1.5 TeV muon collider background data were simulated on the hit level in ILCroot framework with four double layer geometries (1 - 2mm, 3.5 - 7T magnetic field) in Si VXD and Tracker layers.**

Summary/End of work comments (cont'd)

- **All four background rejection criteria (timing, energy deposition, double layer |DX| local and DZ local) were implemented to estimate per layer IP muon track efficiency and MARS background hit cluster surviving fraction in barrel layers of VXD and Tracker.**
  - the most effective are timing and double layer criteria

- **End of work comments**
  - it was recognized that remarkable progress has been made by the Muon Collider Detector/MDI teams at Fermilab (and SLAC) during last years
  - there is a strong need to continue this work

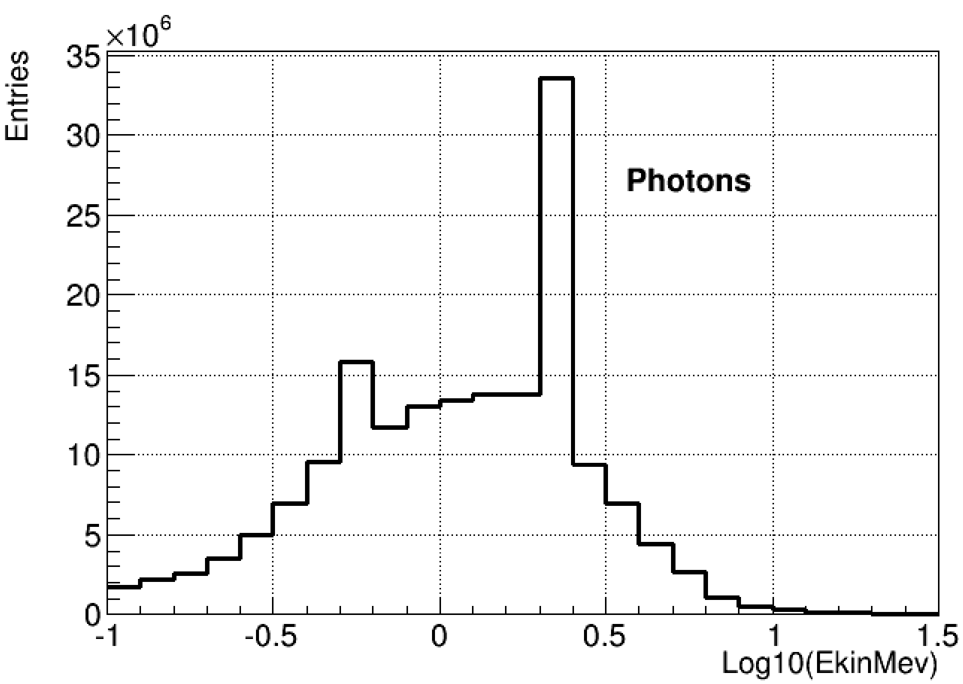
- **MARS background particle tracks near the detector, 750+750 GeV Muon Collider**

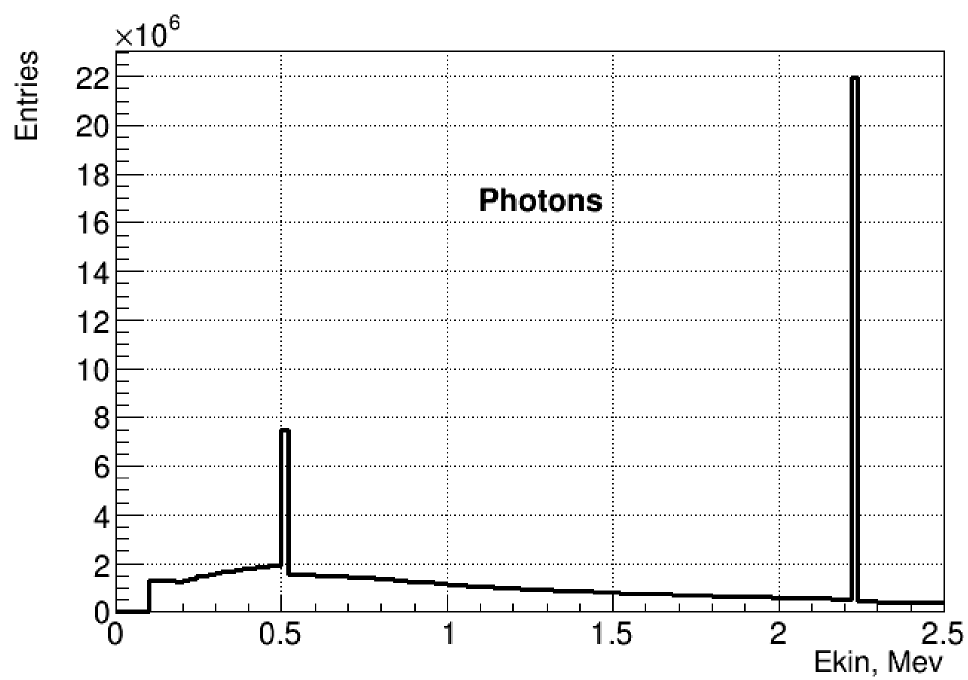


- **Kinetic energy distributions for MARS photons**
  - two delta peaks:

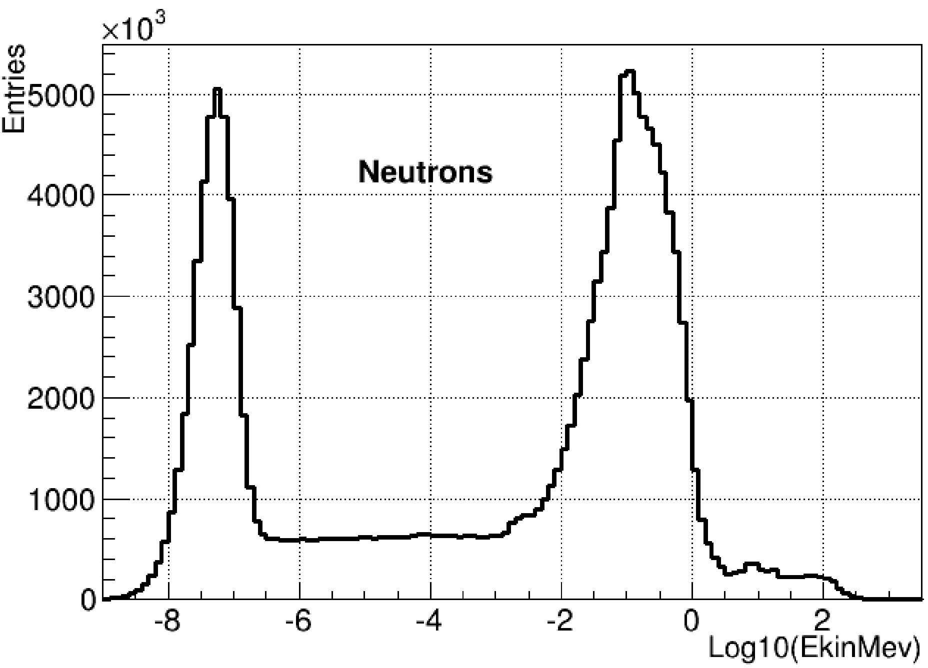
0.511 MeV from e+ annihilation at rest e+ e- -> ɣ ɣ

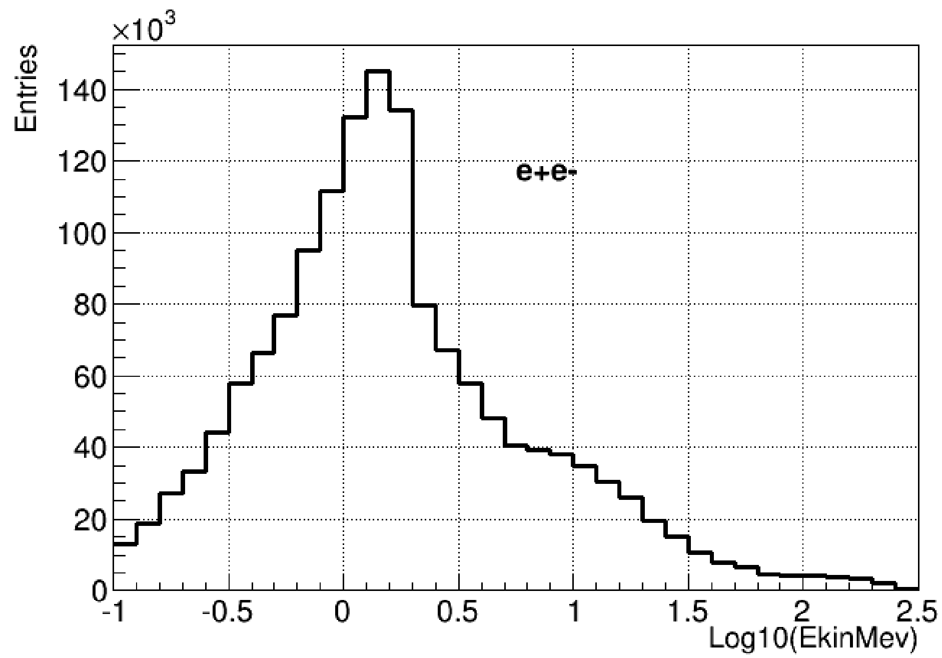
2.224 MeV from n+p -> d+ɣ reaction of neutrons on hydrogen in borated polyethylene of the shielding cone





- **Kinetic energy distributions for MARS neutrons and e+e-**

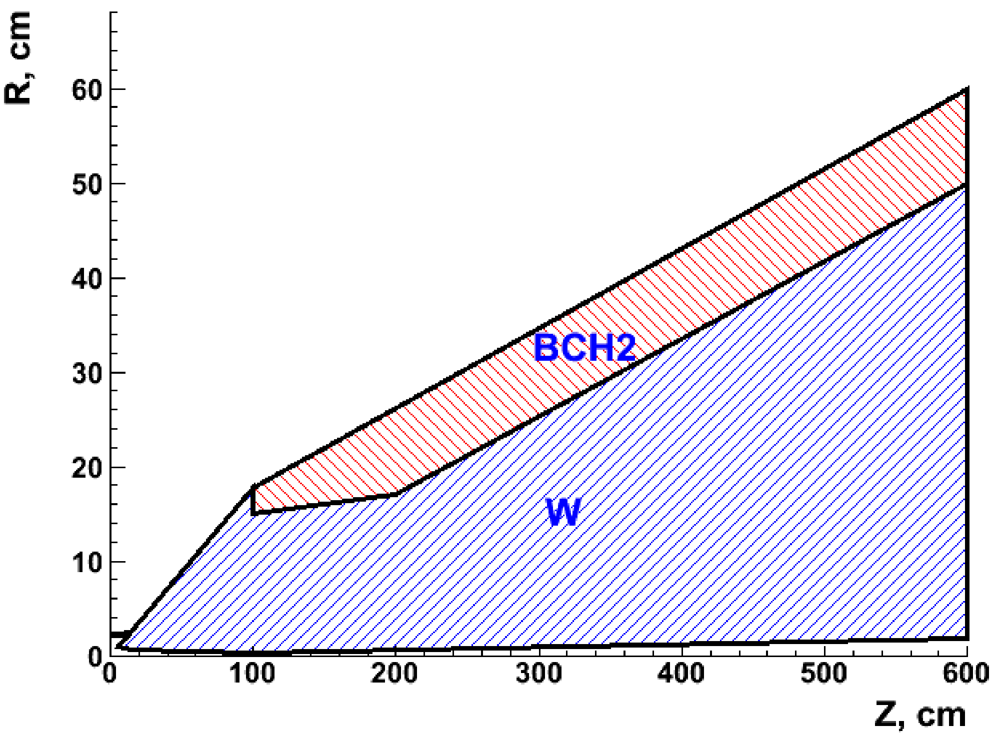


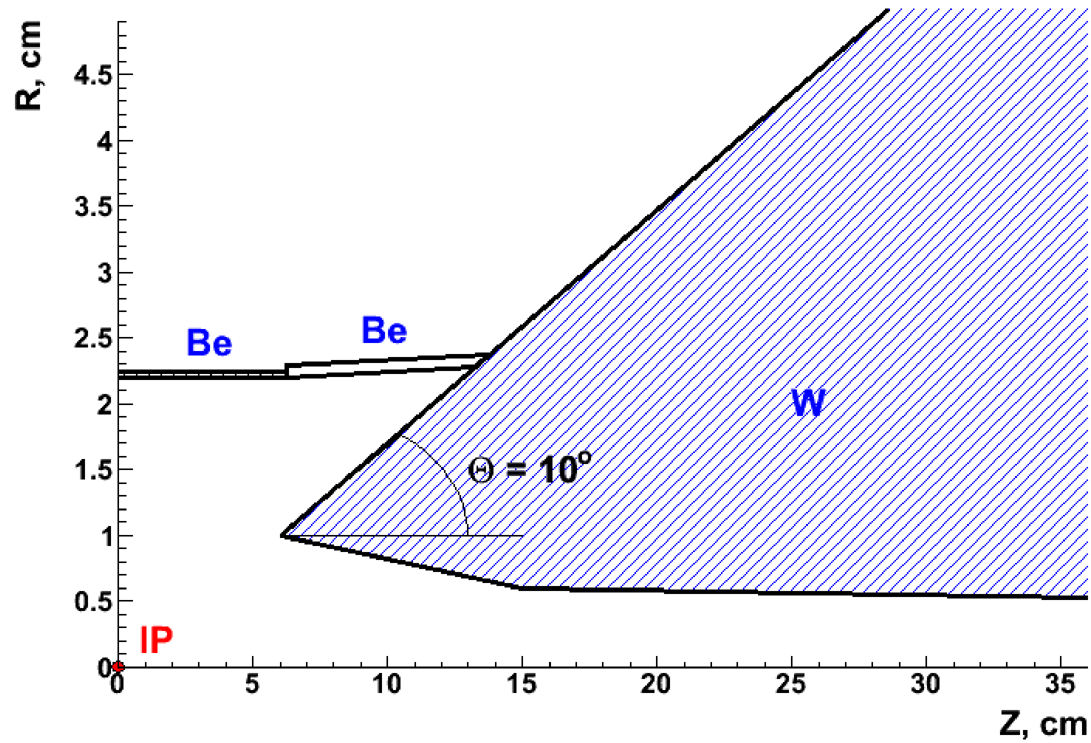


- **10^0 shielding nozzle geometry for 1.5 TeV Muon Collider**

General (RZ) view

Zoom in near IP





W – tungsten

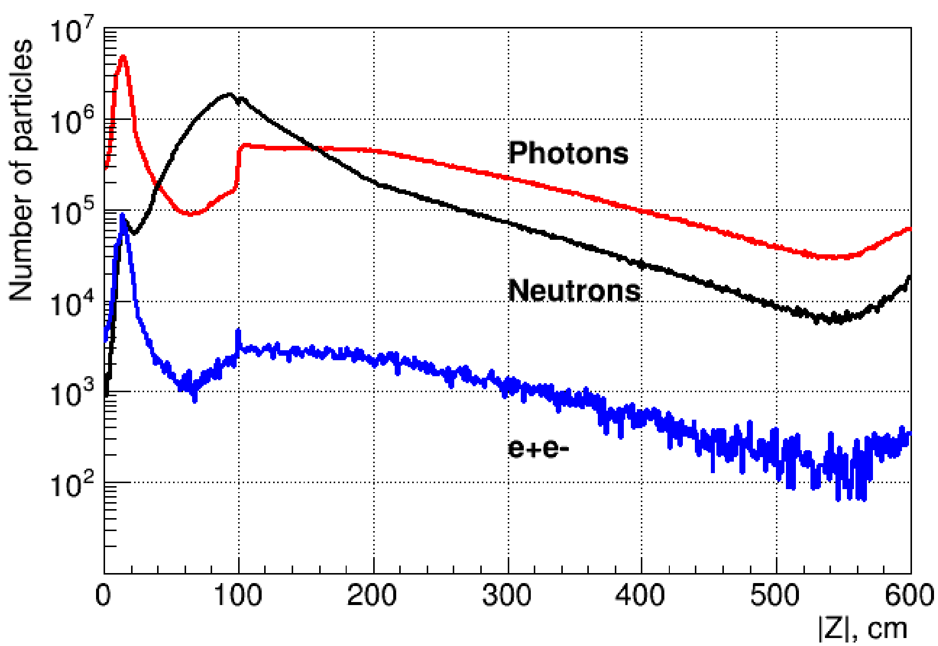
Be – beryllium

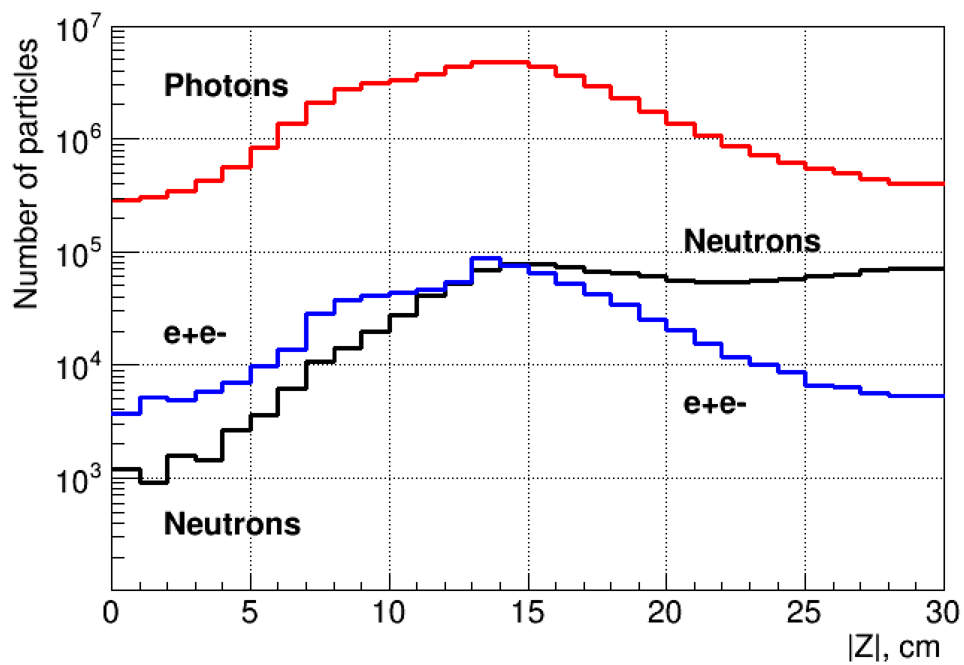
BCH2 – borated polyethylene

- **|Z| coordinate of the MARS background particle on the surface of 10^0 shielding nozzle geometry for 1.5 TeV Muon Collider**

General (RZ) view

Zoom in near IP





Backup slides

- **The ILCRoot - software Infrastructure for Large Colliders based on ROOT and Alice's Aliroot with add-ons for Muon Collider studies**
  - "Detector and Physics studies for a 1.5 TeV Muon Collider Experiments", V. Di Benedetto, December 5, 2014, MAP 2014 Winter Meeting, SLAC, (indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=8959)
  - "Recent developments on ILCroot", V. Di Benedetto, May 18, 2011, Fermilab (indico.fnal.gov/getFile.py/access?contribId=1&resId=0&materialId=slides&confId=4455)
  - "Muon Collider Detector Studies in ILCroot", C. Gatto, Sep. 28, 2011, Granada (ilcagenda.linearcollider.org/contributionDisplay.py?contribId=27&sessionId=33&confId=5134)
  - "Detector and Physics Studies for High Energy Lepton Colliders with ILCroot Simulation Framework", A. Mazzacane, Dec. 1, 2011, Fermilab, (beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=4019)

Backup slides

ILCroot: root Infrastructure for Large Colliders

- Software architecture based on root, VMC & Aliroot
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
  - Extremely large community of users/developers
- Re-allignement with latest Aliroot version every 1-2
- It is a simulation framework and an Offline Systems:
  - Single framework, from generation to reconstruction and analysis!!
  - It naturally evolves into the offline systems of your experiment
  - Six MDC have proven robustness, reliability and portability
- *It is Publicly available at FNAL on ILCSIM since 2006*

The Virtual Montecarlo (VMC) Concept

- Virtual MC provides a virtual interface to Monte Carlo
- It allows to run the same user application with all supported Montecarlo's
- The real Monte Carlo (Geant3, Geant4, Fluka) is selected and loaded at run time

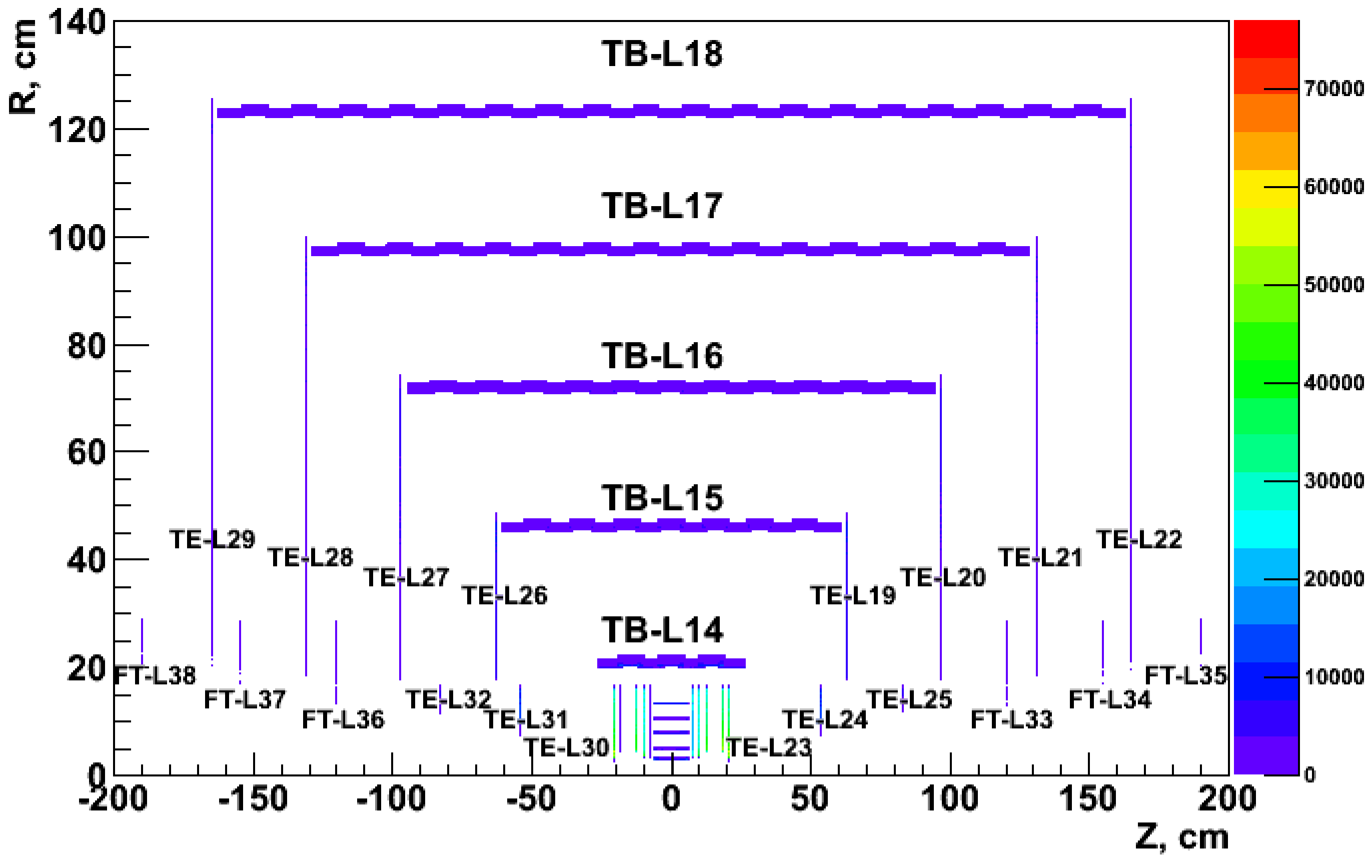
MARS + ILCroot (Oct. 2009)
Dedicated ILCroot framework for MUX Physics and background studies

(in collaboration with N. Mokhov group)

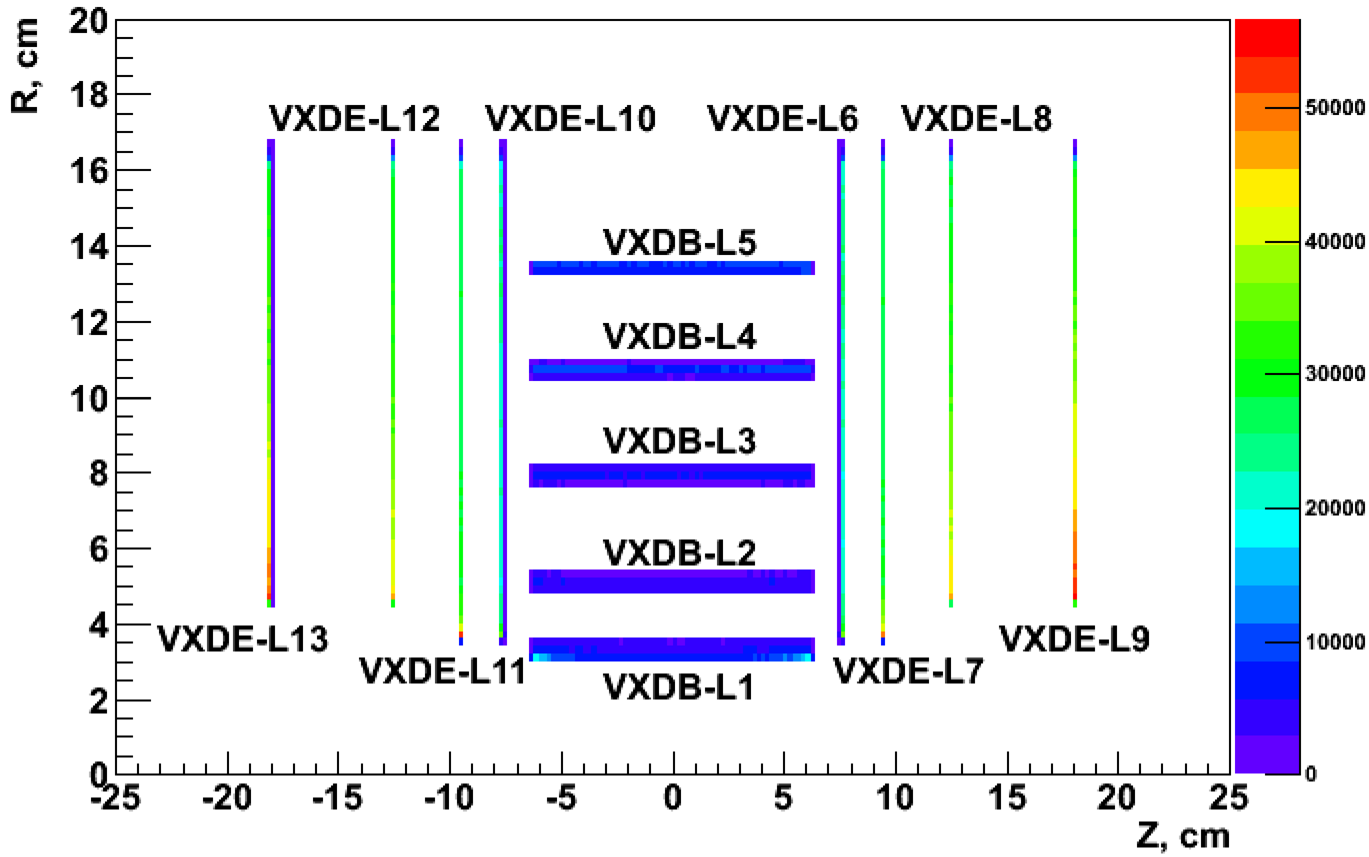
- **The ingredients:**
  - Final Focus descripted in MARS & ILCroot
  - Detector description in ILCroot
  - MARS-to-ILCroot interface (Vito Di Benedetto)
- **How it works**
  - The interface (ILCGenReaderMARS) is a *TGenerator* in ILCroot
  - MARS output is used as a config file
  - ILCGenReaderMARS creates a STDHEP file with a list of particles entering the detector area at z = 7.5m
  - MARS weights are used to generate the particle multiplicity for G4
  - Threshold cuts are specified in Config.C to limit the particle list fed to G4
  - Geant4 takes over at 7.5m
  - Events are finally passed through the usual simulation (G4)-> digitization->reconstruction

Backup slides

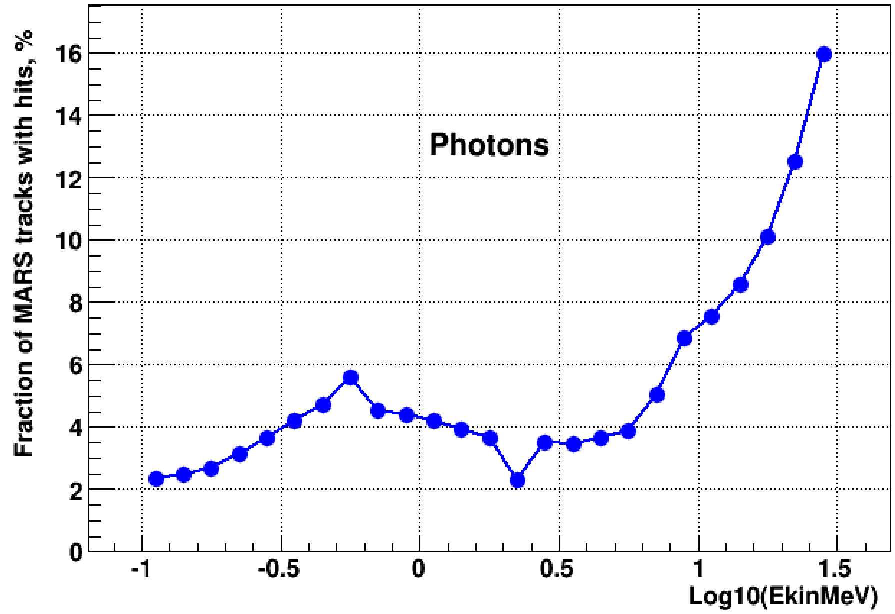
- **Hit R vs. Z for ILCRoot VXD and Tracker detector layers**
  - TB – Tracker Barrel, TE – Tracker Endcap, FT – Forward Tracker

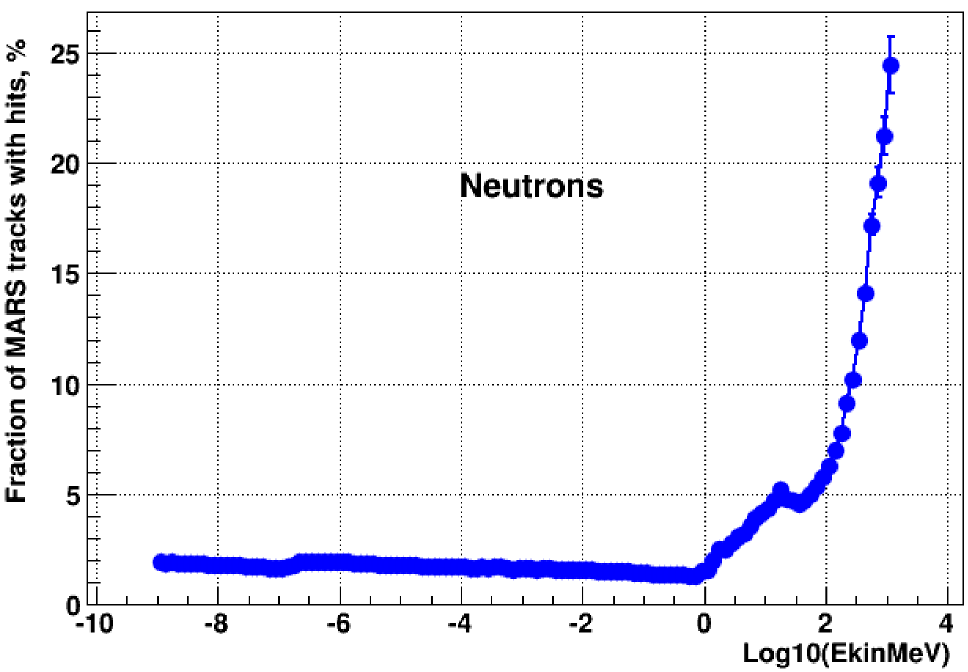


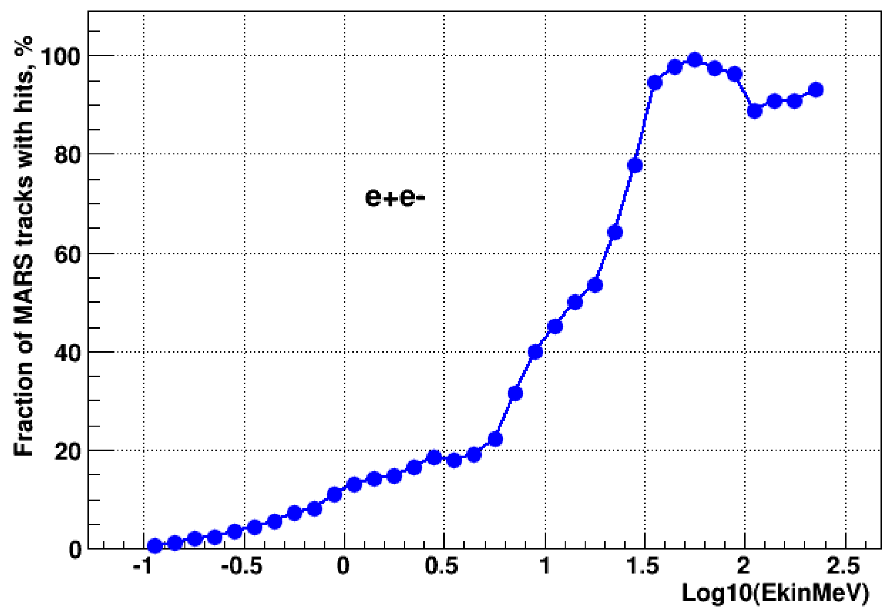
- **Hit R vs. Z for ILCRoot vertex detector (VXD) layers**
  - VXDB – VXD Barrel, VXDE – VXD Endcap



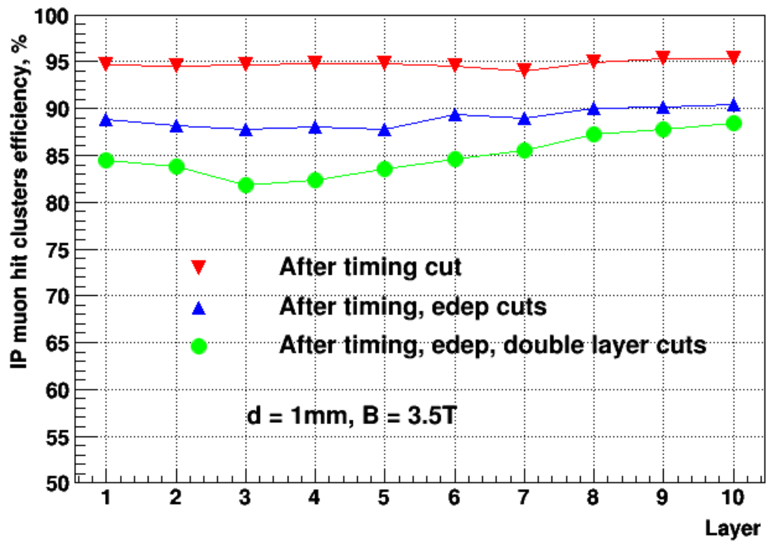
- **Fractions of MARS particles making at least one hit in layers of VXD /Tracker vs. kinetic energy**

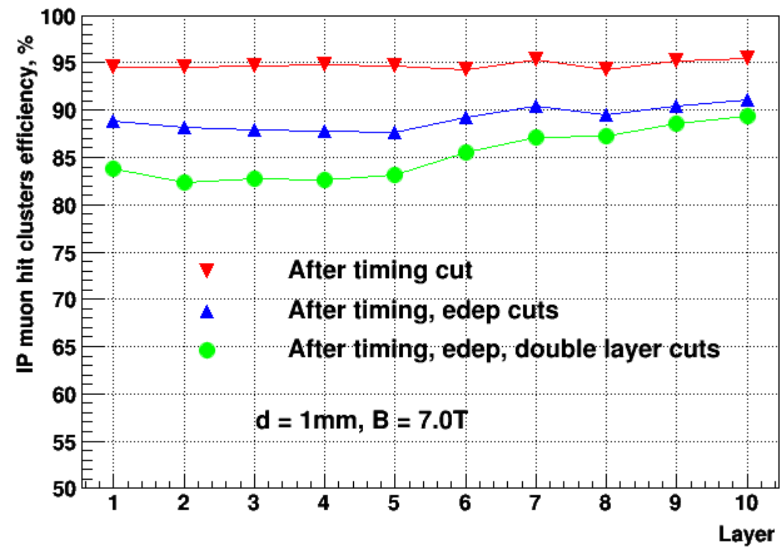


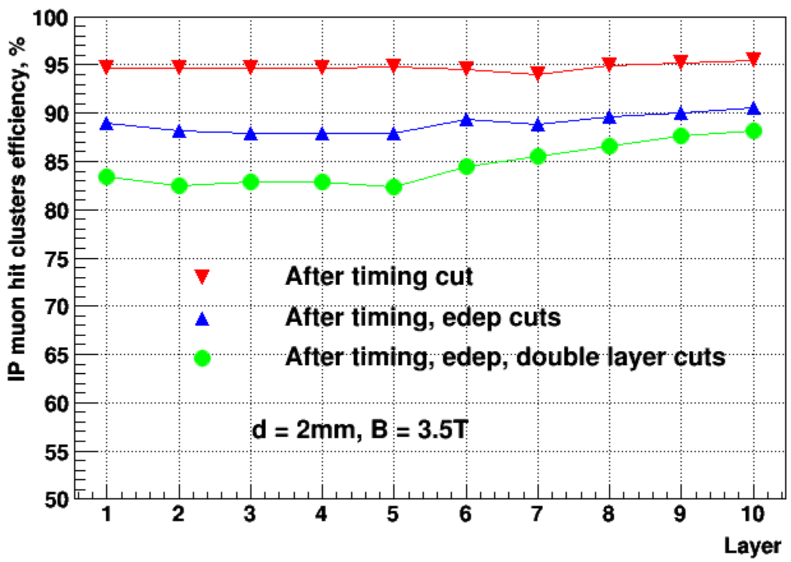


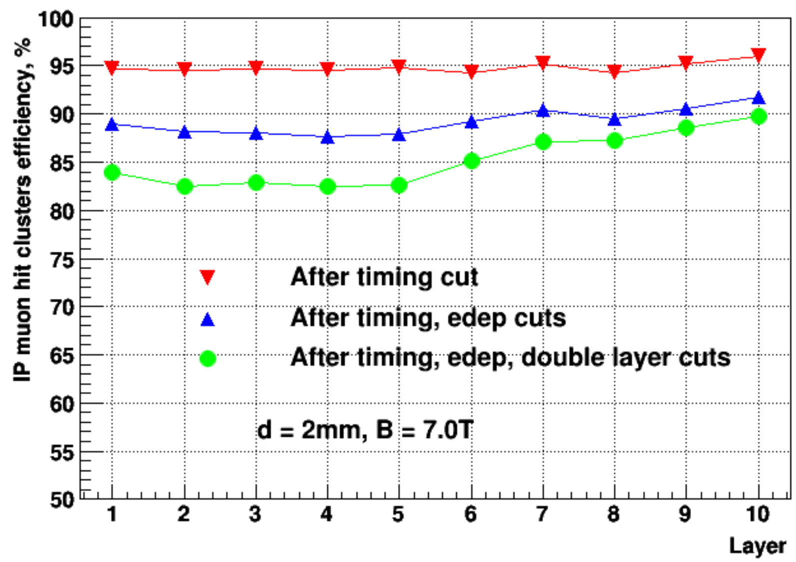


- **IP muon hit clusters efficiency (both sublayers) vs. layer** (1-5 are VXD barrel, 6-10 are Tracker barrel) in all geometries

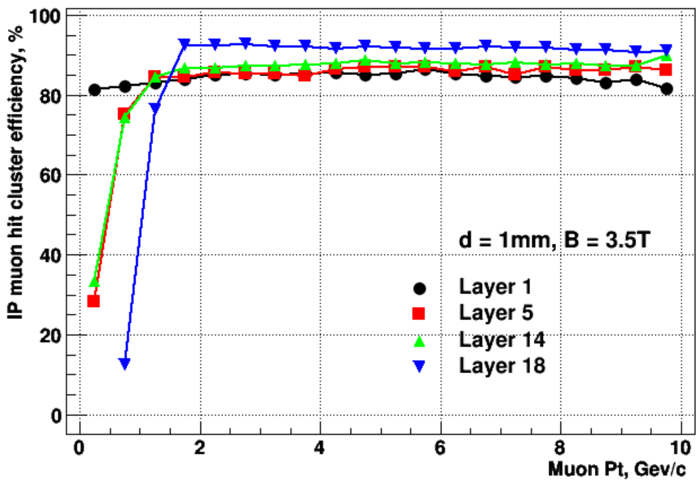


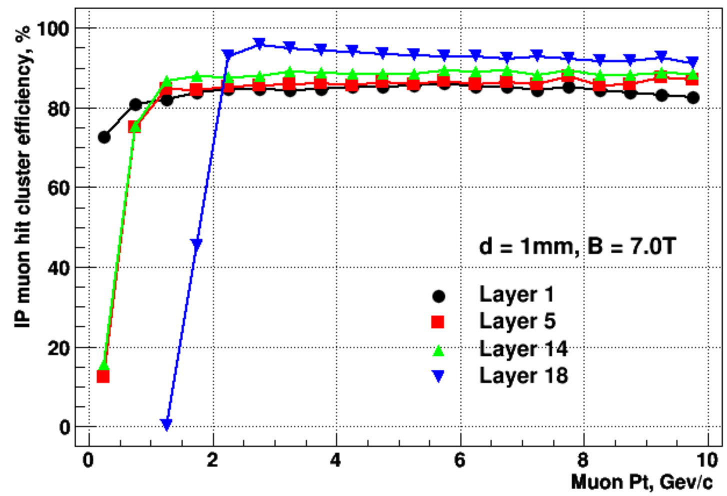


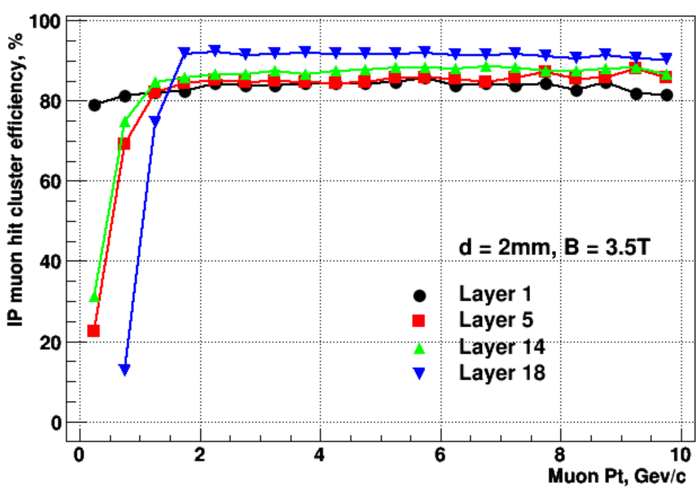


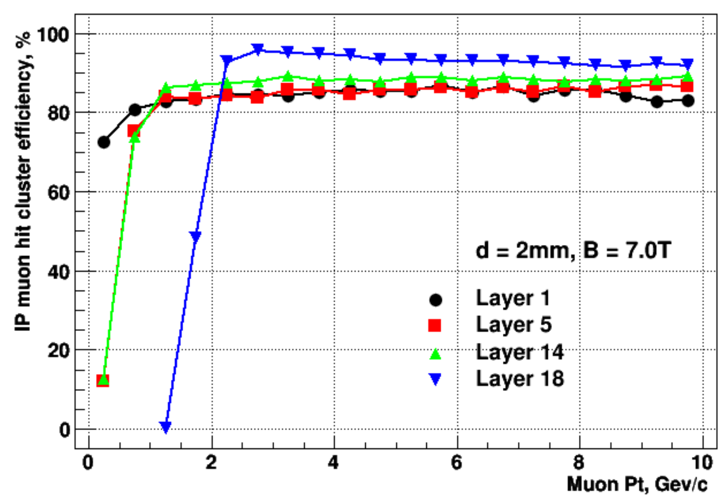


- **IP muon hit clusters efficiency (both sublayers) vs. Pt** (Layers 1,5 - VXD barrel, Layers 14(6),18(10) - Tracker barrel) in all geometries

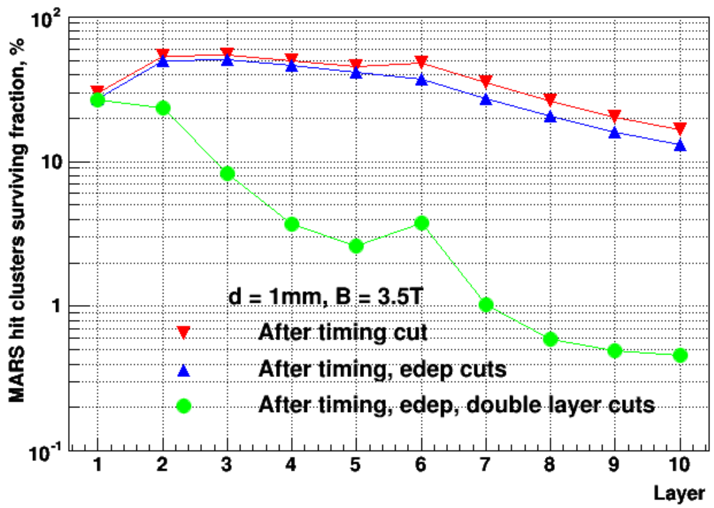


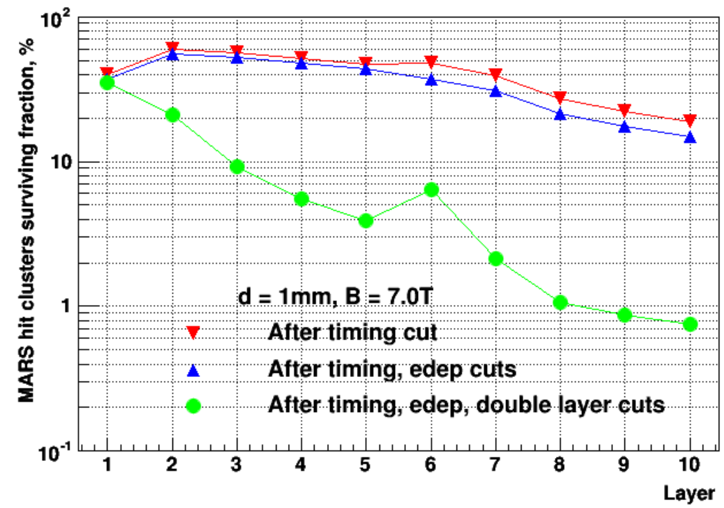


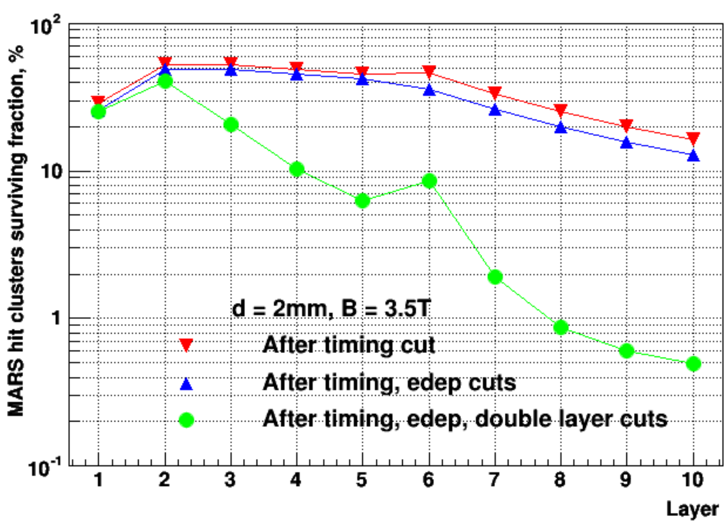


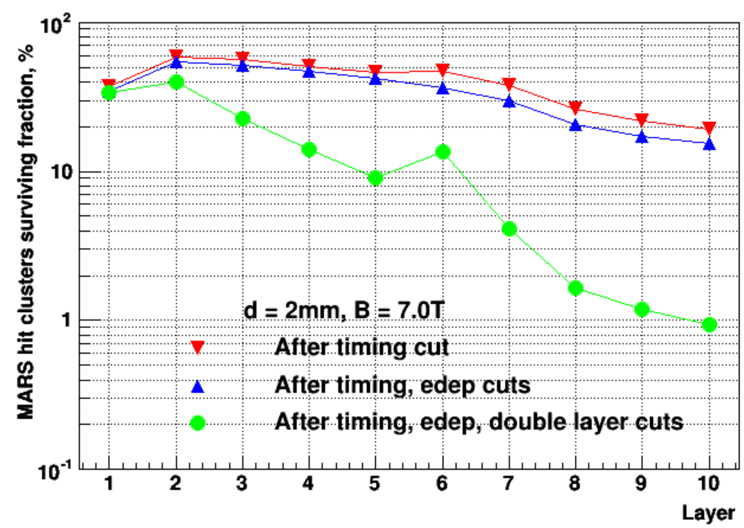


- **MARS hit clusters surviving fraction per sub-layer vs. cuts and layer** (1-5 are VXD barrel, 6-10 are Tracker barrel) in all geometries

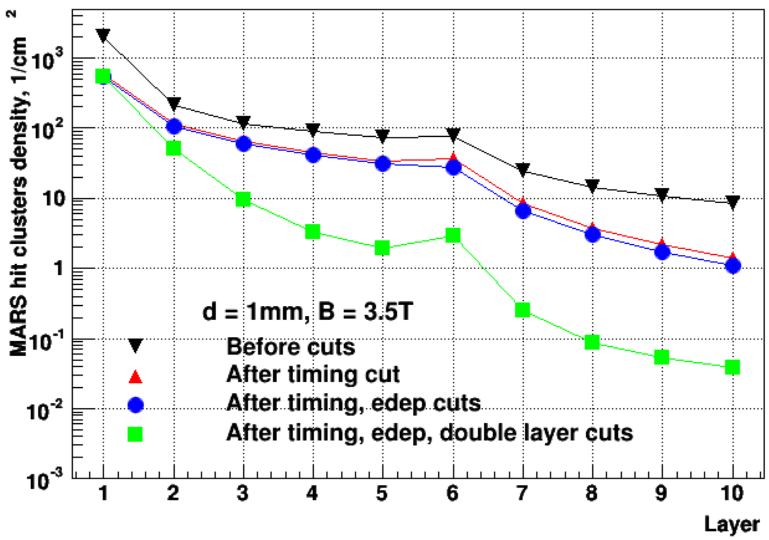


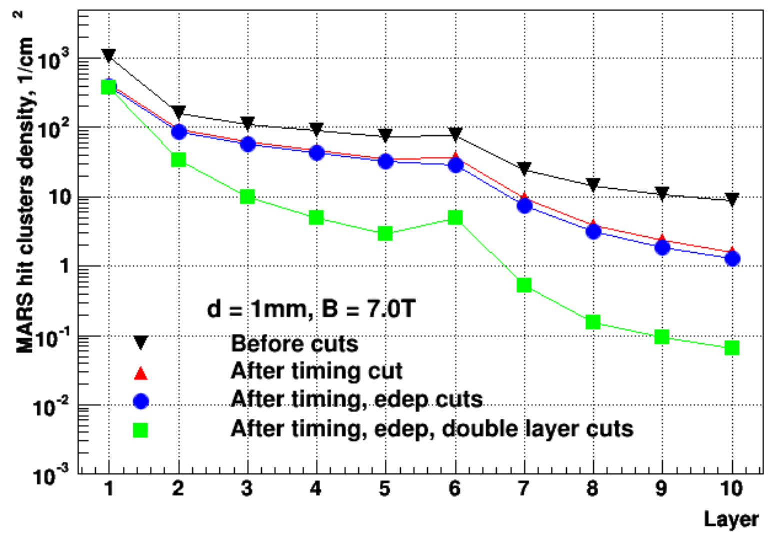


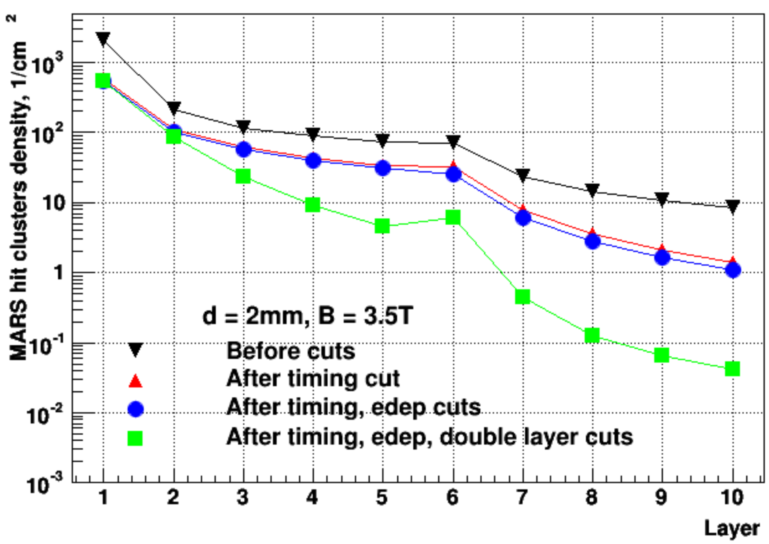


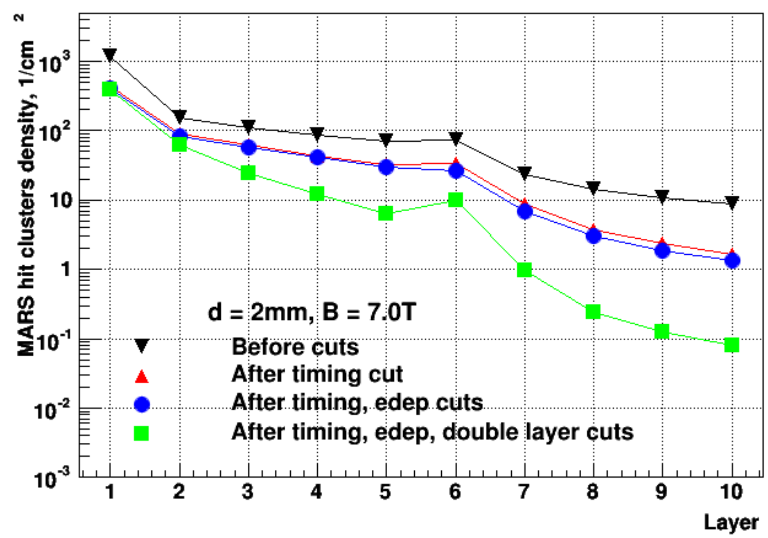


- **MARS hit clusters density per sub-layer vs. cuts and layer**
  (1-5 are VXD barrel, 6-10 are Tracker barrel), all geometries









Backup slides

- **MARS background pixel occupancy per sub-layer vs. layer** (1-5 are VXD barrel, 6-10 are Tracker barrel), all geometries