Detector and Physics studies for a 1.5TeV Muon Collider Experiment

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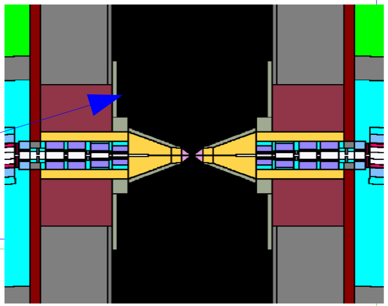
Outline

- Background and detector+MDI simulations
  - MARS and ILCroot frameworks.
- Baseline detector for Muon Collider studies
  - Si vertex and central tracker detector.
  - ADRIANO Dual-readout calorimeter.
- Machine background overview @ 1.5 TeV
  - Partiles species, time/momentum distributions...
- Rejection strategy in calorimeter and tracker
  - Time cuts, energy subtraction and region of interests.
- Study of H/A at 1.5TeV Muon Collider
  - Invariant mass reconstruction.
- Results of H/A invariant mass with fully simulated machine background.
- Conclusions and Remarks

MARS and ILCroot Frameworks

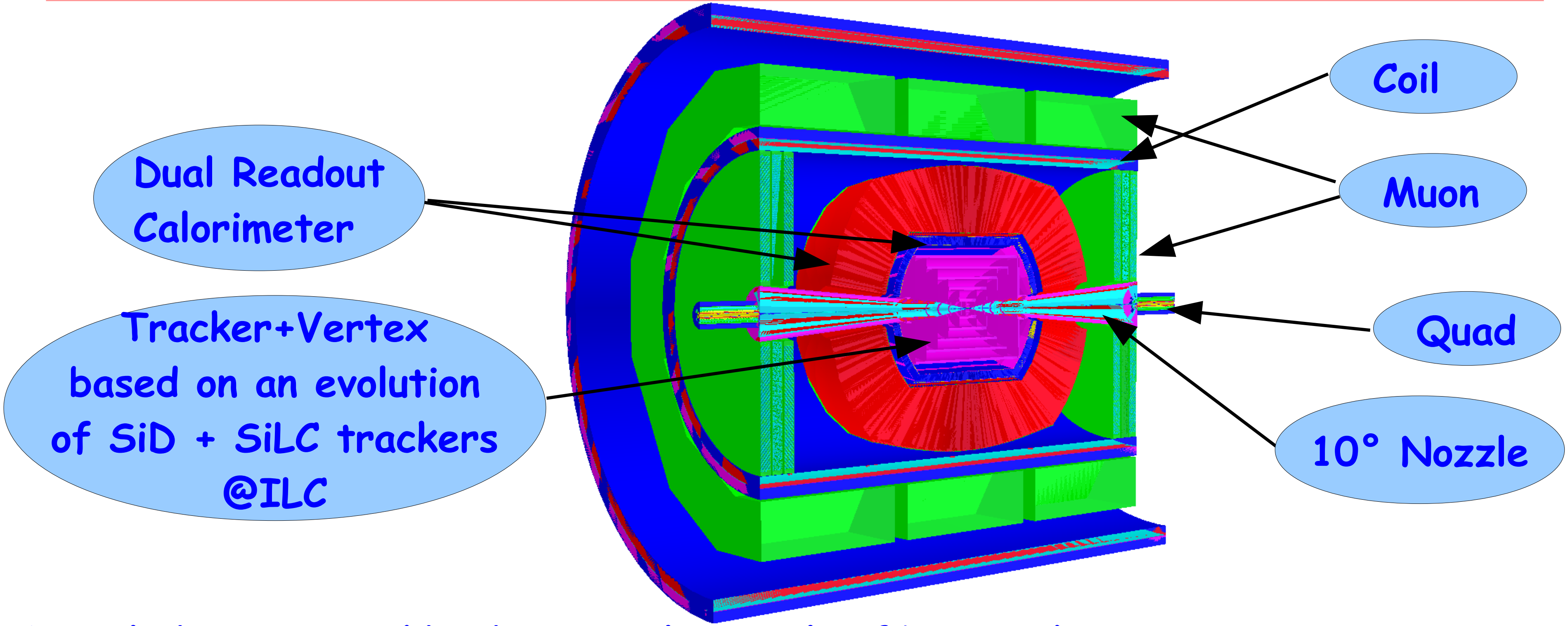
- MARS – is the framework for simulation of particle transport and interactions in accelerator, detector and shielding components.
- New release of MARS15 is available since February 2011 at Fermilab (N. Mokhov, S. Striganov, see www-ap.fnal.gov/MARS).
- Background simulation in the studies shown in this presentation is provided at the surface of MDI (10° nozzle + walls).



- ILCroot is a 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.
- Include an interface to read MARS output to handle the MuonCollider background.
- It is a simulation framework and an offline system:
  - Single framework, from generation to reconstruction and analysis!!!
  - VMC allows to select G3, G4 or Fluka at run time (no change of user code).
- Widely adopted within HEP community (4th Concept@ILC, LHeC, T1015, SiLC, ORKA, MuC).
- It is available at FNAL since 2006.

Extensive and detailed studies are presented in this talk

Muon Collider Detector baseline

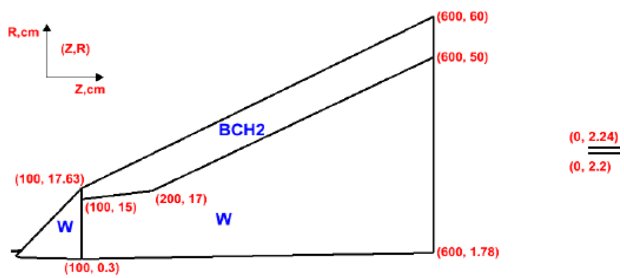


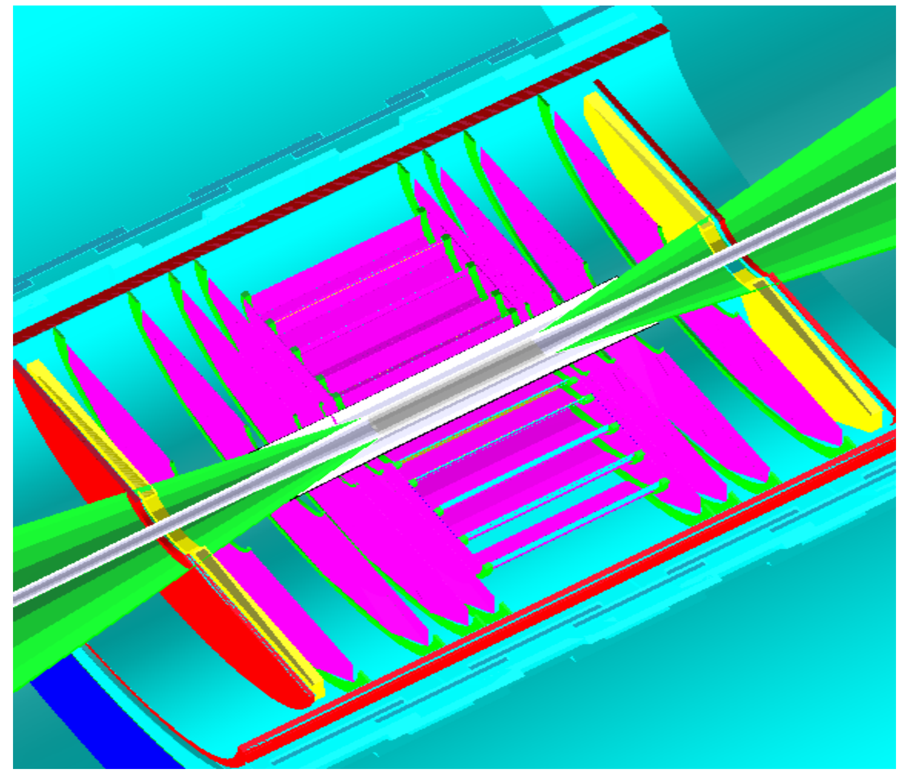
- Detailed geometry (dead materials, pixels, fibers ...)
- Detailed magnetic field map (Includes the magnetic field of the last MDI quad).
- Full simulation: hits-sdigits-digits. Includes noise effect, electronic threshold and saturation, pile up...
- Tracking Reconstruction with parallel Kalman Filter.
- Light propagation and collection for photon detectors.
- Jets reconstruction implemented.

Vertex Detector (VXD) 10°Nozzle and Beam Pipe

VXD

- 75 μm thick Si layers in the barrel
- 100 μm thick Si layers in the endcappixel
- 20 μm x 20 μm Si pixel Si pixel
- Barrel : 5 layers subdivided in 12-30 ladders
- R_{min}~3 cm R_{max}~13 cm L~13 cm
- Endcap : 4 + 4 disks subdivided in 12 ladders
- Total length 42 cm
- Single/double layer version available.





NOZZLE

- W - Tungsten
- BCH2 – Borated Polyethylene
- Starting at ±6 cm from IP with R = 1 cm at this z

PIPE

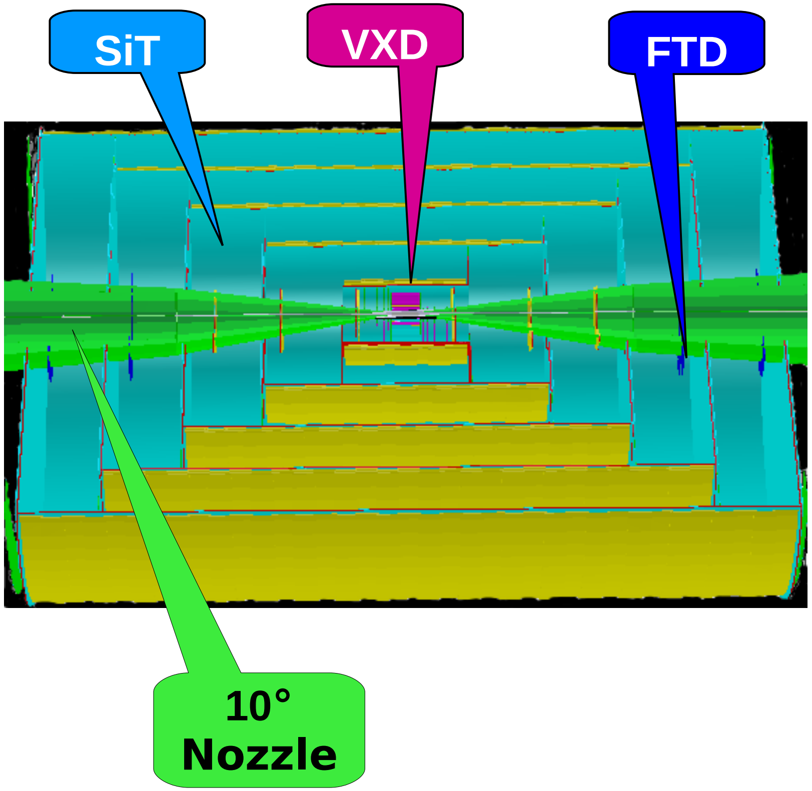
- Be – Berylium 400 μm thick
- 12 cm between the nozzles

ILCroot Simulation

Silicon Tracker (SiT) and Forward Tracker Detector (FTD)

SiT

- 200 μm thick Si layers
- 50 μm x 50 μm Si pixel (or Si strips or double Si strips available)
- Barrel : 5 layers subdivided in staggered ladders
- Endcap : (4+3) + (4+3) disks subdivided in ladders
- R_{min}~20 cm R_{max}~120 cm L~330 cm
- Single/double layer version available.



FTD

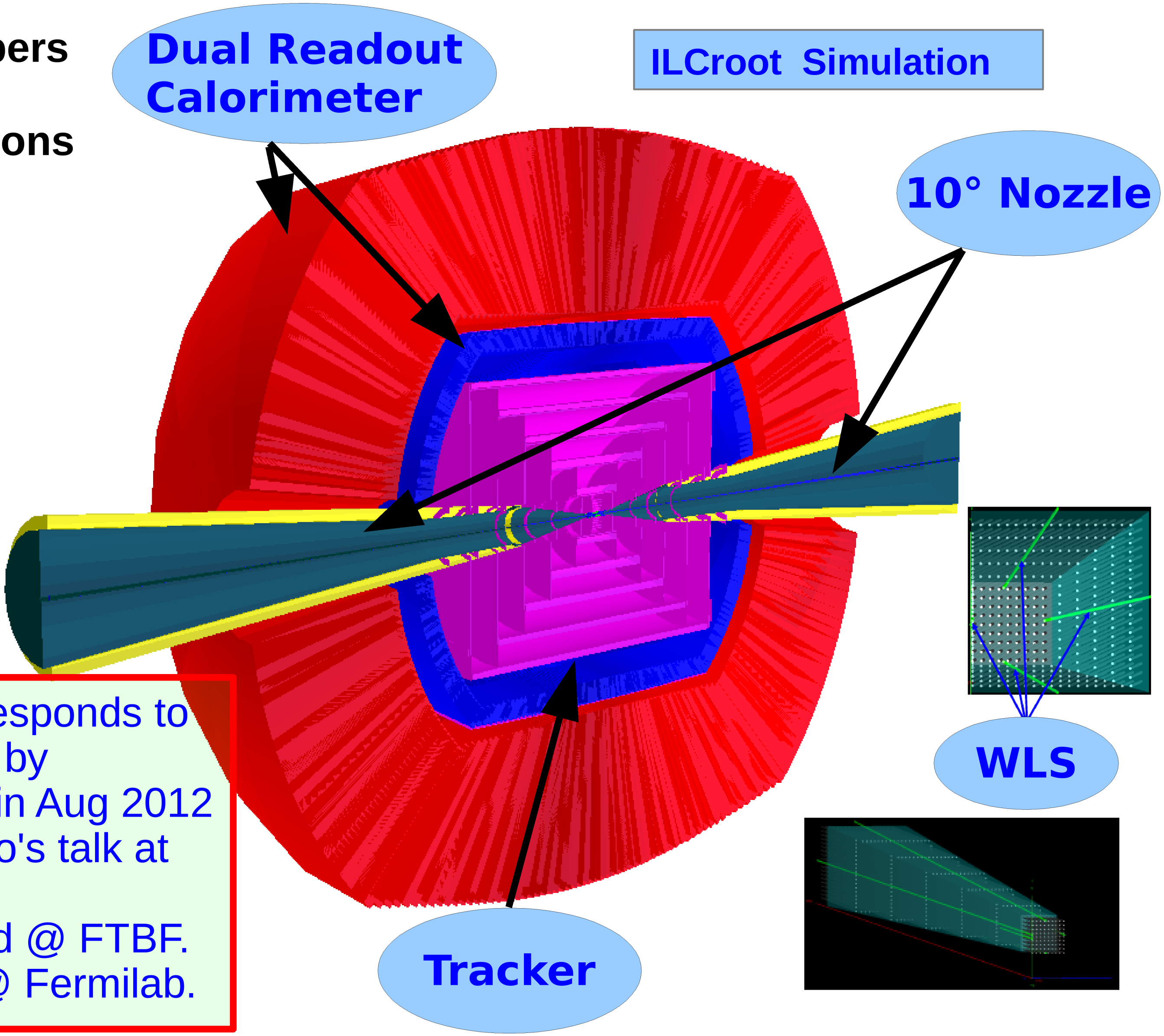
- 200 μm thick Si layers
- 50 μm x 50 μm Si pixel
- Endcap : 3 + 3 disks
- Distance of last disk from IP = 190 cm

- Silicon pixel for precision tracking amid up to 10^5 hits
- Tungsten nozzle to suppress the background

ILCroot Simulation

Dual Readout Projective Calorimeter

- **Lead glass + scintillating fibers**
- **~1.4° tower aperture angle**
- **Split into two separate sections**
- **Front section 20 cm depth**
- **Rear section 160 cm depth**
- **~ 7.5 λ_{int} depth**
- **>100 X_0 depth**
- **Fully projective geometry**
- **Azimuth coverage down to ~8.4° (Nozzle)**
- **Barrel: 16384 towers**
- **Endcaps: 7222 towers**



- All simulation parameters corresponds to ADRIANO prototype #9 tested by Fermilab T1015 Collaboration in Aug 2012 @ FTBF (see also T1015 Gatto's talk at Calor2012)
- Several more prototypes tested @ FTBF.
- New test beam ongoing now @ Fermilab.

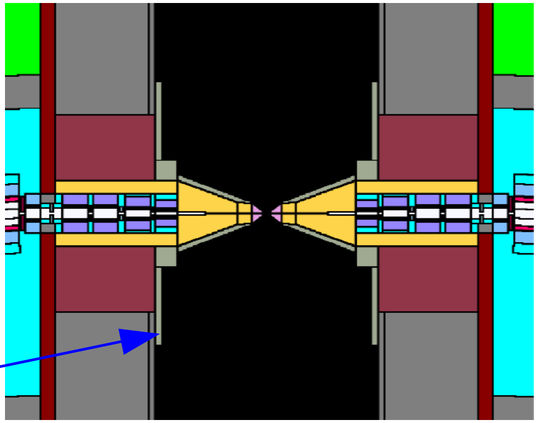
Sources of Background and Dynamic Heat Load

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 3×10^4 electron pairs per bunch crossing (manageable with nozzle & detector B)
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 decay/m per bunch crossing, or 1.28×10^{10} dec/m/s for 2 beams; 0.5 kW/m.
4. **Beam halo:** Beam loss at limiting apertures; severe, can be taken care of by an appropriate collimation system far upstream of IP.

TIPP2011, Chicago, June 9-14, 2011 Detector Backgrounds at Muon Colliders - N. Mokhov, S. Striganov 6

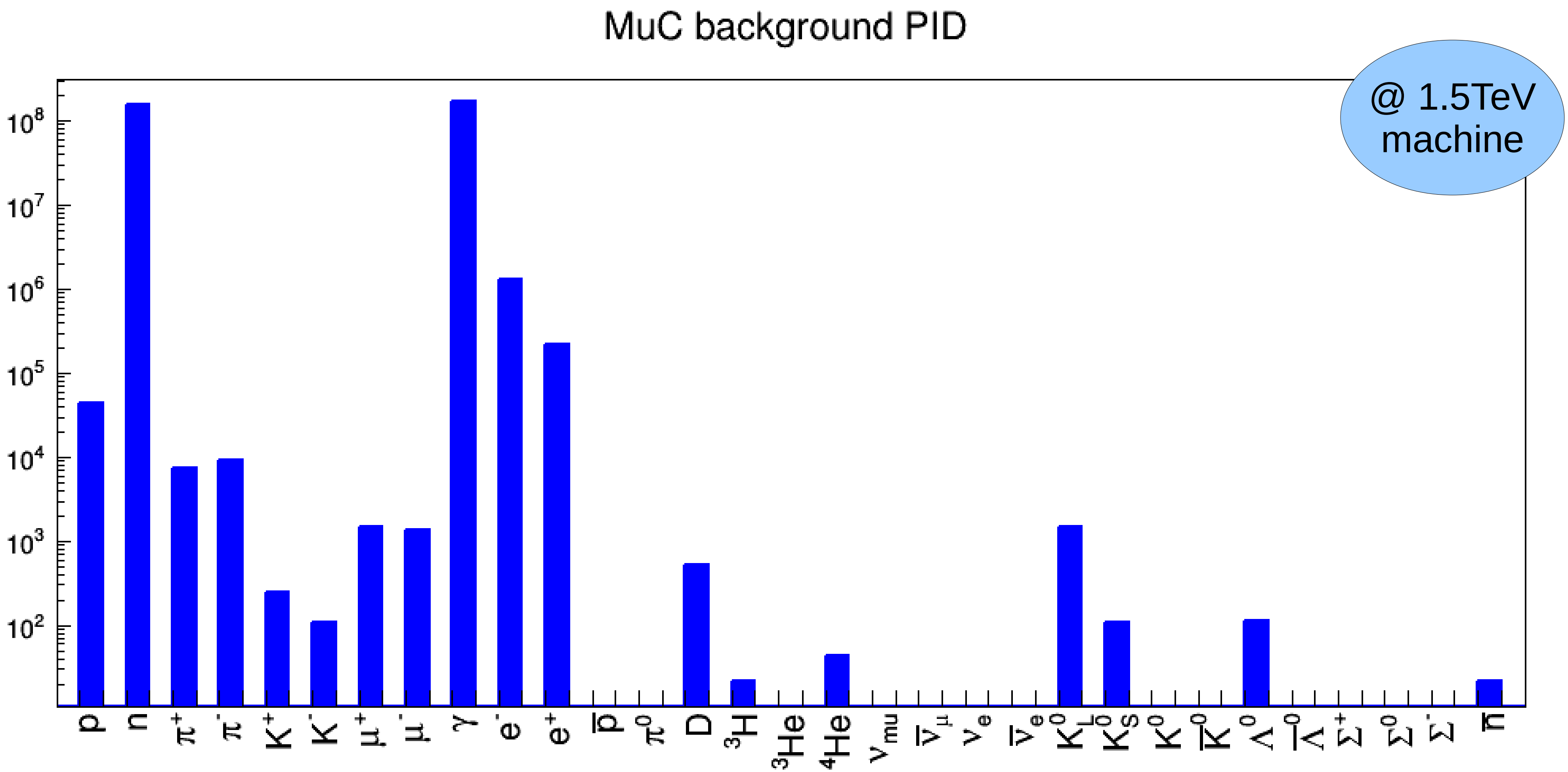
Mars Background Event @1.5 TeV

- New MARS event generated on July 2014:
  - Fix on time-of-flight of particles.
  - Thresholds: 100 keV for μ^+, μ^-, e^+, e^-, γ and charged hadrons; 10^{-3} eV for n.
  - Significant changes in MARS physics modules.
  - New geometry of magnets.
  - No weight fluctuations.
  - Only statistical weight=22.24 for all particles.
- Origin of the particles: MDI surface.



- Particle in a MARS event ~3×10^8.
- Background particles for μ^+ and μ^- within ± 25 m have fixed statistical weight of "22.24"
  - 76% with weight 22 and 24% with weight 23.

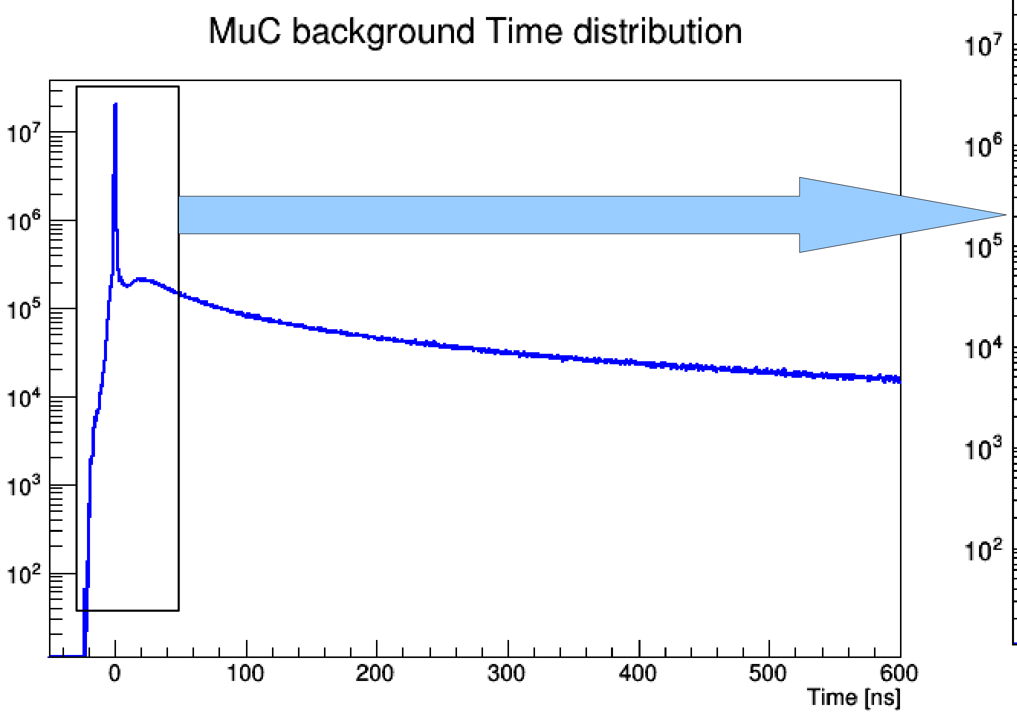
MuC background: Particle's abundance

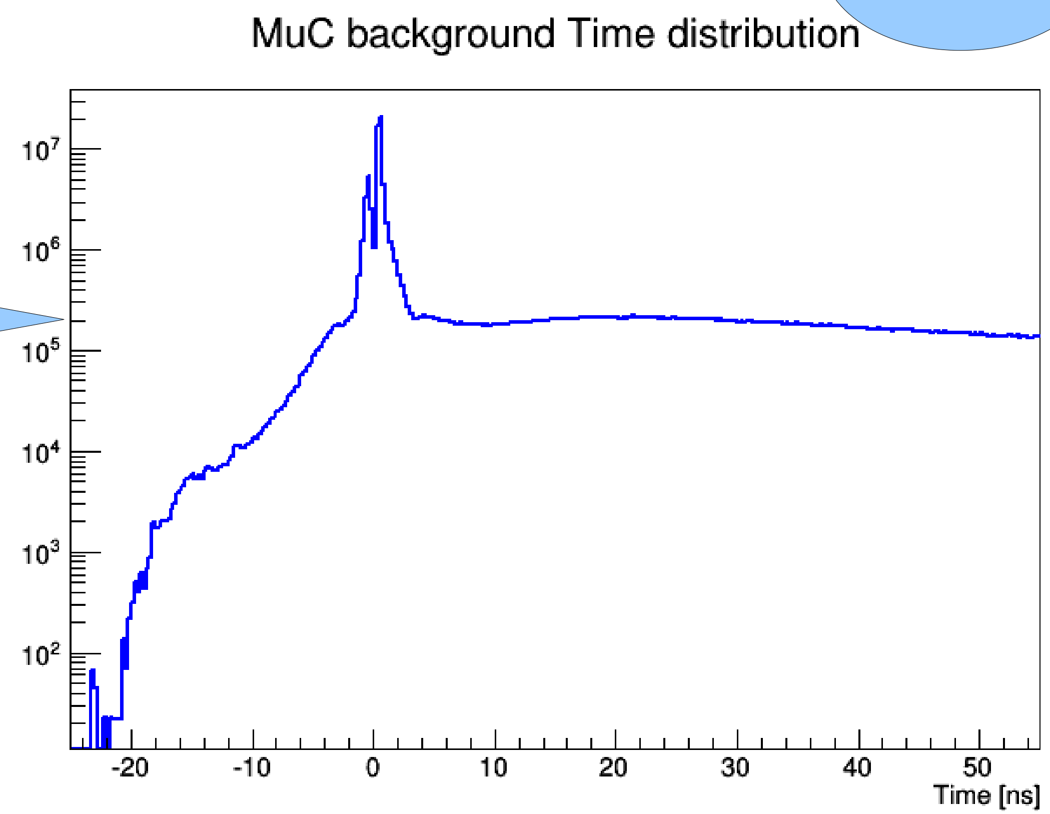


- Most of the background consists of neutrons and gammas.
- then electrons, positrons and protons...

MuC background: Time distribution

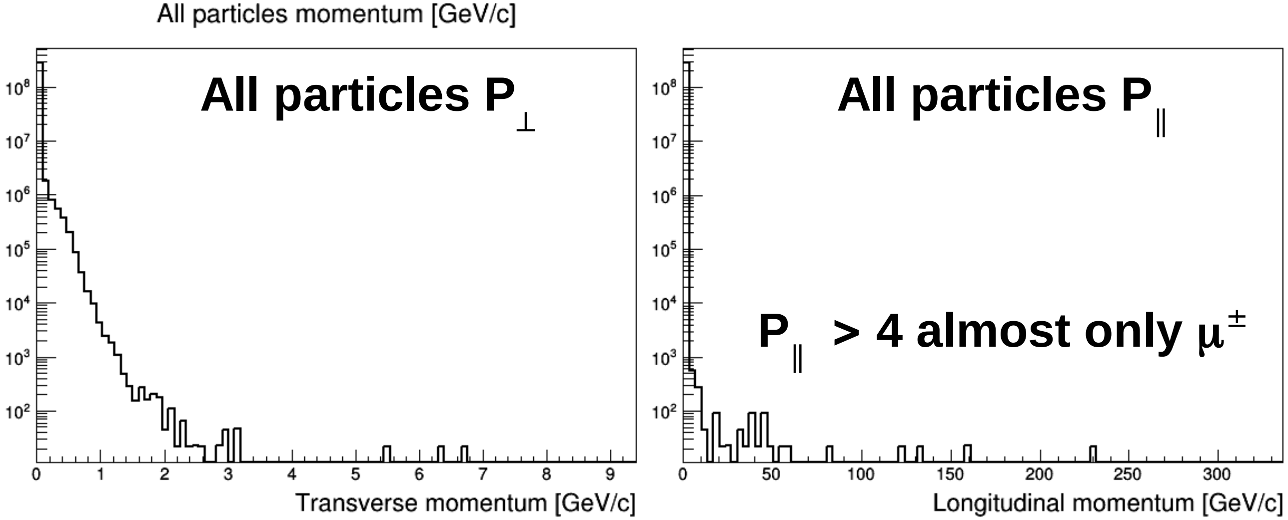
@ 1.5TeV machine





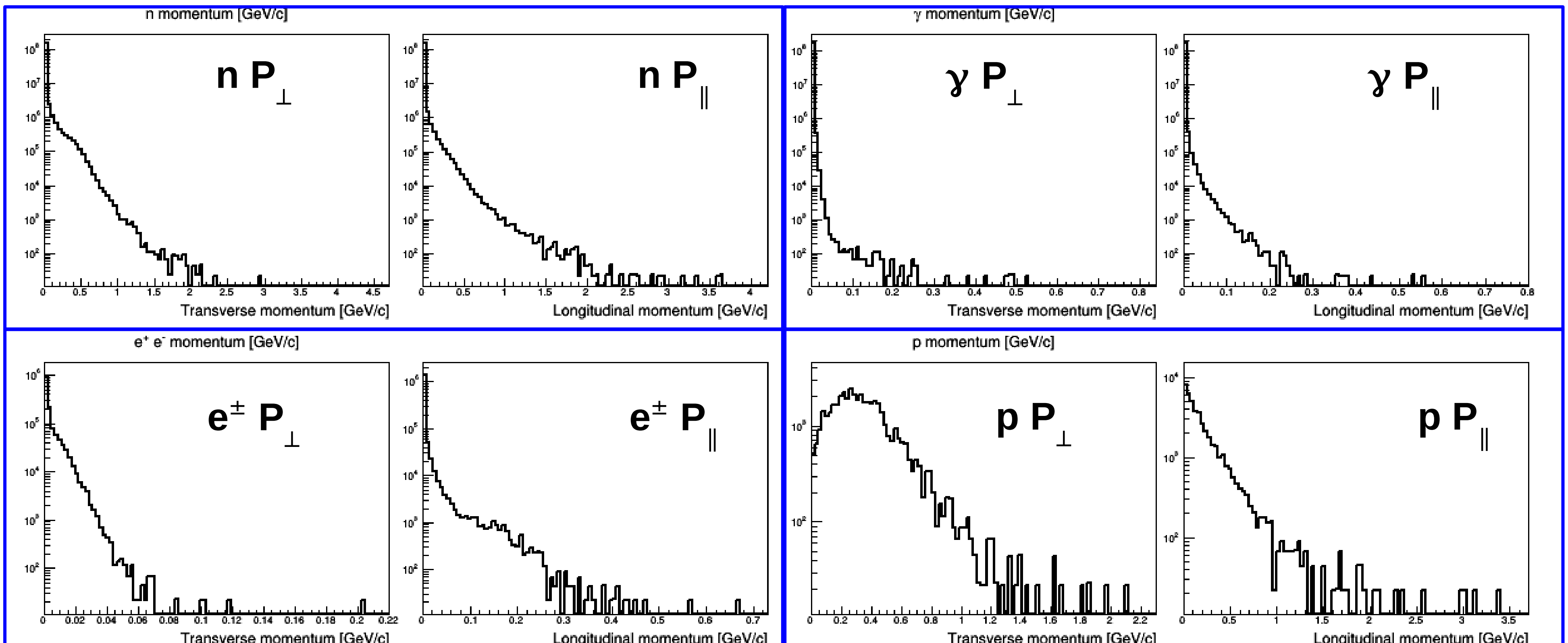
- Time distribution of the MuC background:
  - There is a huge peak around t=0ns, mostly due to gammas and e^+/e^-.
  - There is a long tail almost constant, mostly due to neutrons.

MuC background: Momentum distribution



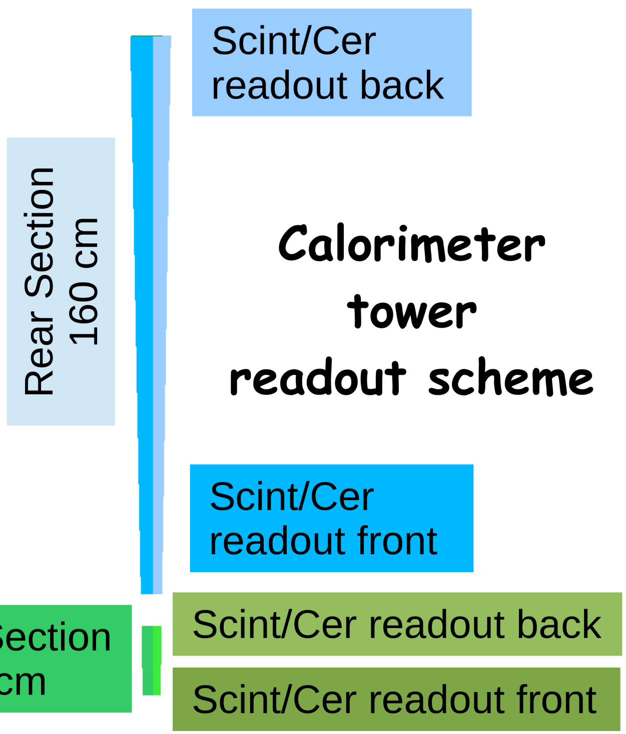
@ 1.5TeV machine

- Momentum distribution of the background.
- Most of the background consist of soft particles.



ADRIANO waveform of the MuonCollider background

Calorimeter is split into a rear (160cm) and front (20 cm) section



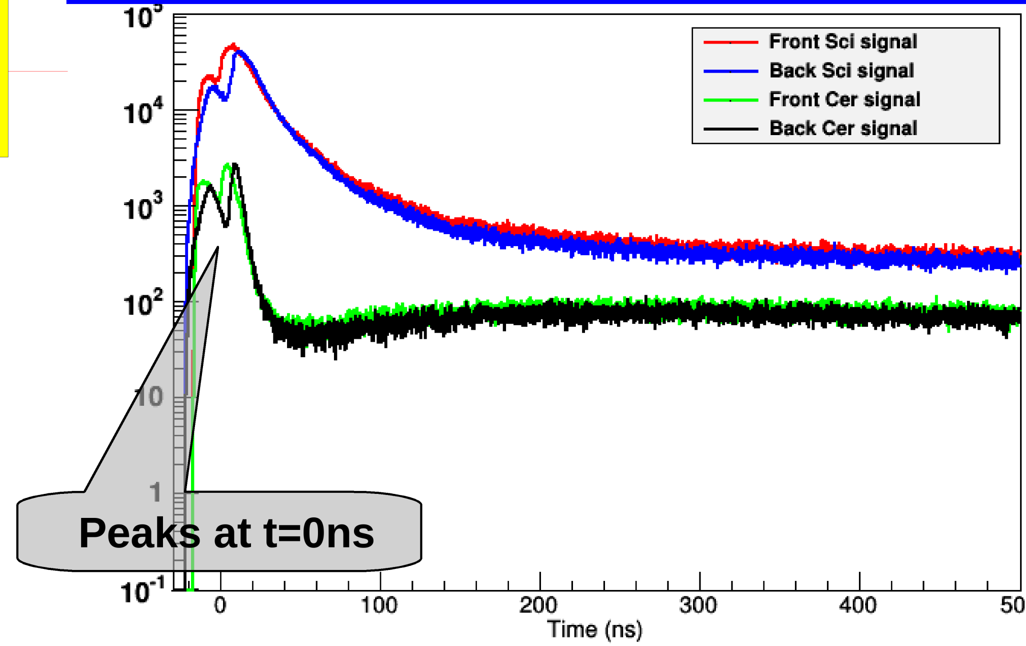
- **Light propagation in fibers and lead glass is implemented in ILCroot**
- **Time bin in calorimeter 25 ps**

Time 0s ≡ time when IP γ reaches the calorimeter.

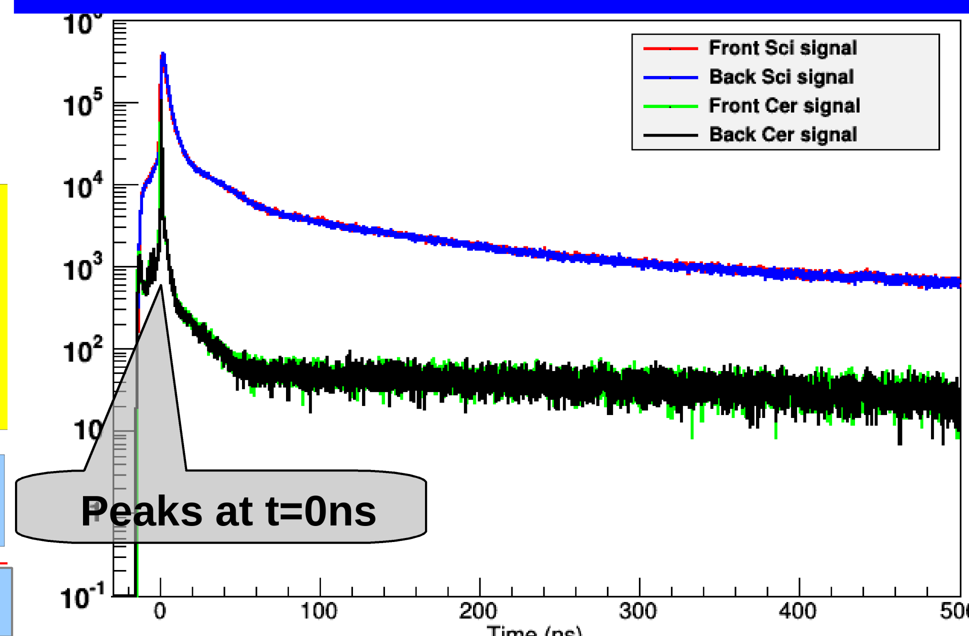
V. Di Benedetto

ILCroot Simulation

Rear Section



Front Section

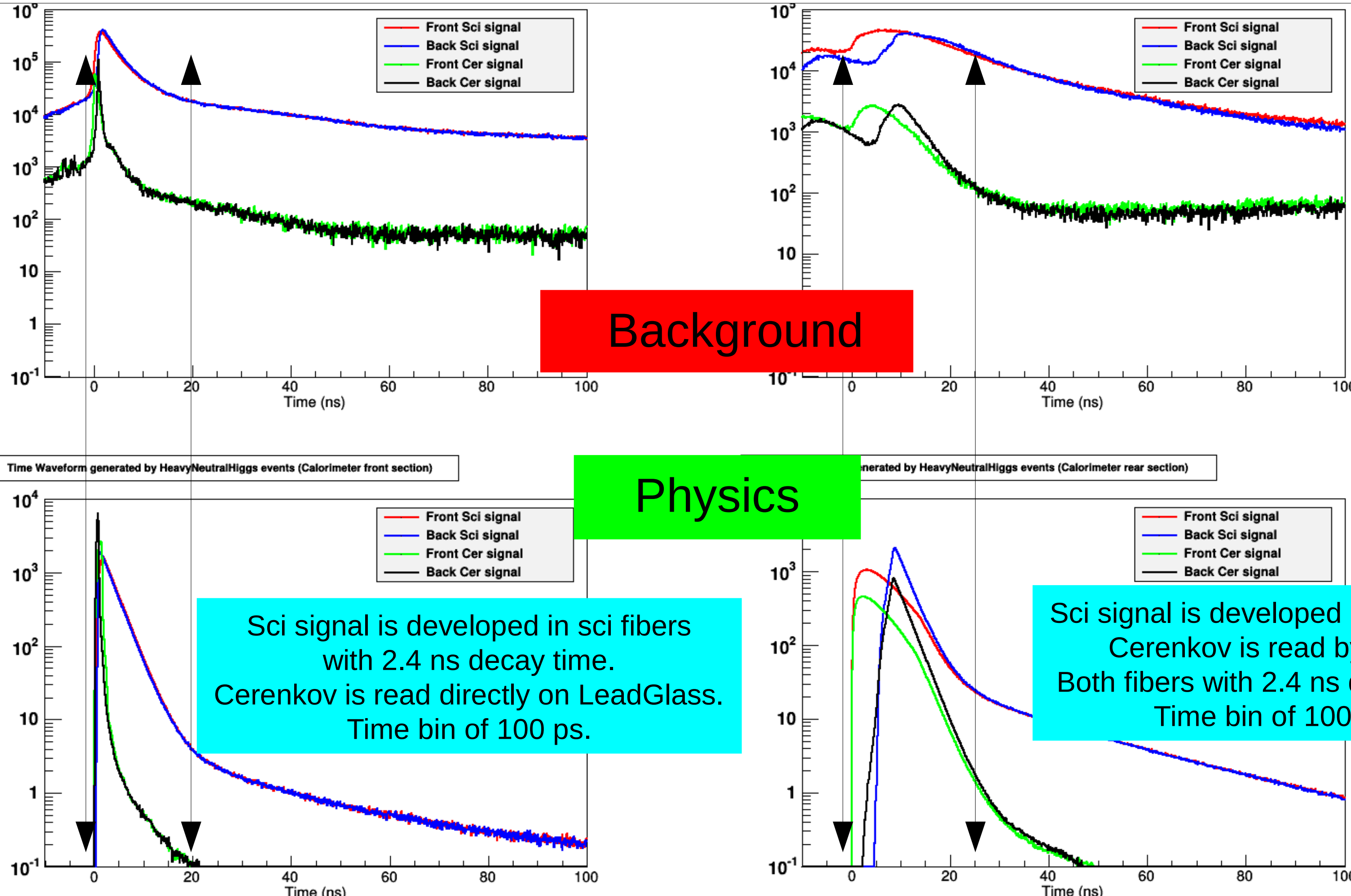


ADRIANO waveform of the MuonCollider background vs H/A events (time < 100 ns)

Front section has a background signal peak ~x10 compared to rear section

Front Section

Rear Section



Time 0s ≡ time when IP γ reachs the calorimeter.

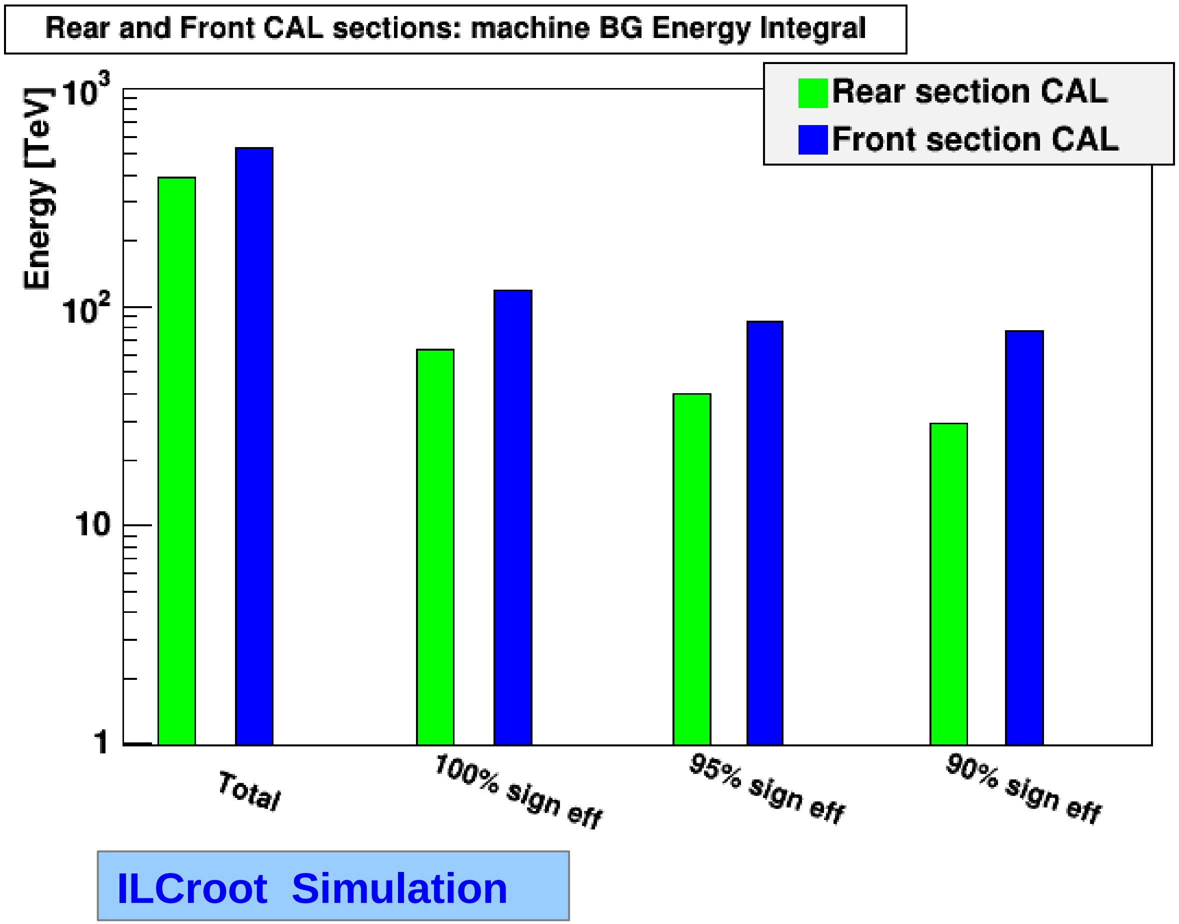
ILCroot Simulation

- Time can't be the only key to suppress machine background in calorimeter

Integral of the energy of the background measured in the two calorimeter sections

- Applied three different time gates to obtain 100%, 95% and 90% signal efficiency.

BG energy	Front Section	Rear Section
Total	532 TeV	386 TeV
100% sign eff	118 TeV	63 TeV
95% sign eff	85 TeV	40 TeV
90% sign eff	77 TeV	29 TeV



- Relevant fraction of the BG is in the front section calorimeter (>70% @ 90% signal efficiency).

- With 90% signal efficiency the rejection of the BG is:
  ~86% in front section
  ~93% in rear section

Machine background suppression strategy in the Calorimeter

Time gate for each section				
	Front Section		Rear Section	
	Scint	Cer	Scint	Cer
front	6.5 ns	1.5 ns	15. ns	11.5 ns
back	6.5 ns	1.0 ns	11.0 ns	8.0 ns
Signal efficiency	90%		90%	
BG suppression	85.5%		92.5%	

BG energy	Front Section	Rear Section
Total	532 TeV	386 TeV
100% sign eff	118 TeV	63 TeV
95% sign eff	85 TeV	40 TeV
90% sign eff	77 TeV	29 TeV

ILCroot Simulation

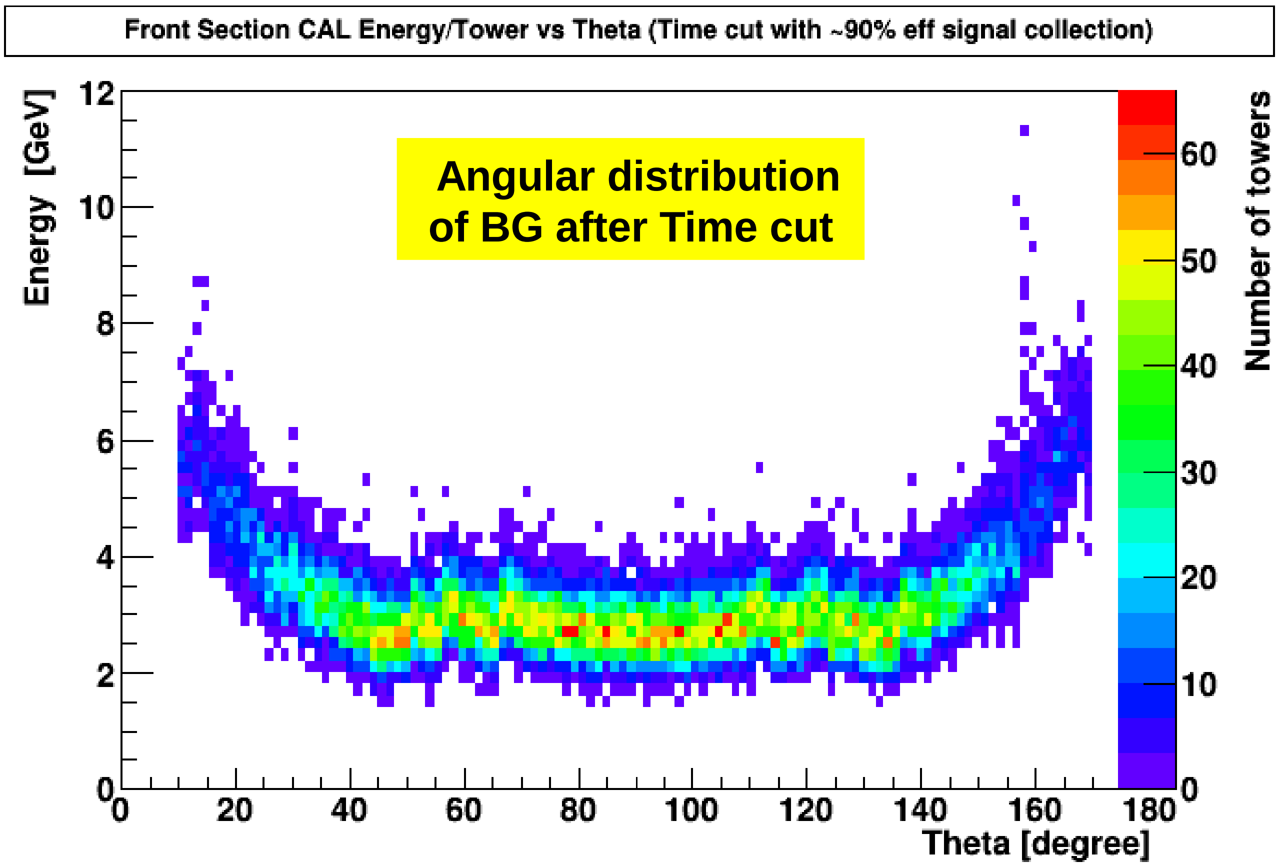
- Applied time gate with fix width:
  - configuration with 90% signal efficiency.
  - The fixed width time gate with start and stop theta dependent according to the distance of the tower from the IP.
- Selected Region of Interest (RoI), i.e. regions where the energy is 2.5 σ above the expected background level.

See next slide

- Applied energy subtraction:
  - Used mean value of the expected background in the RoI as energy subtraction.
  - Used mean value + 5σ of the expected background in other regions.
- Applied energy compensation to recover 100% of the signal.

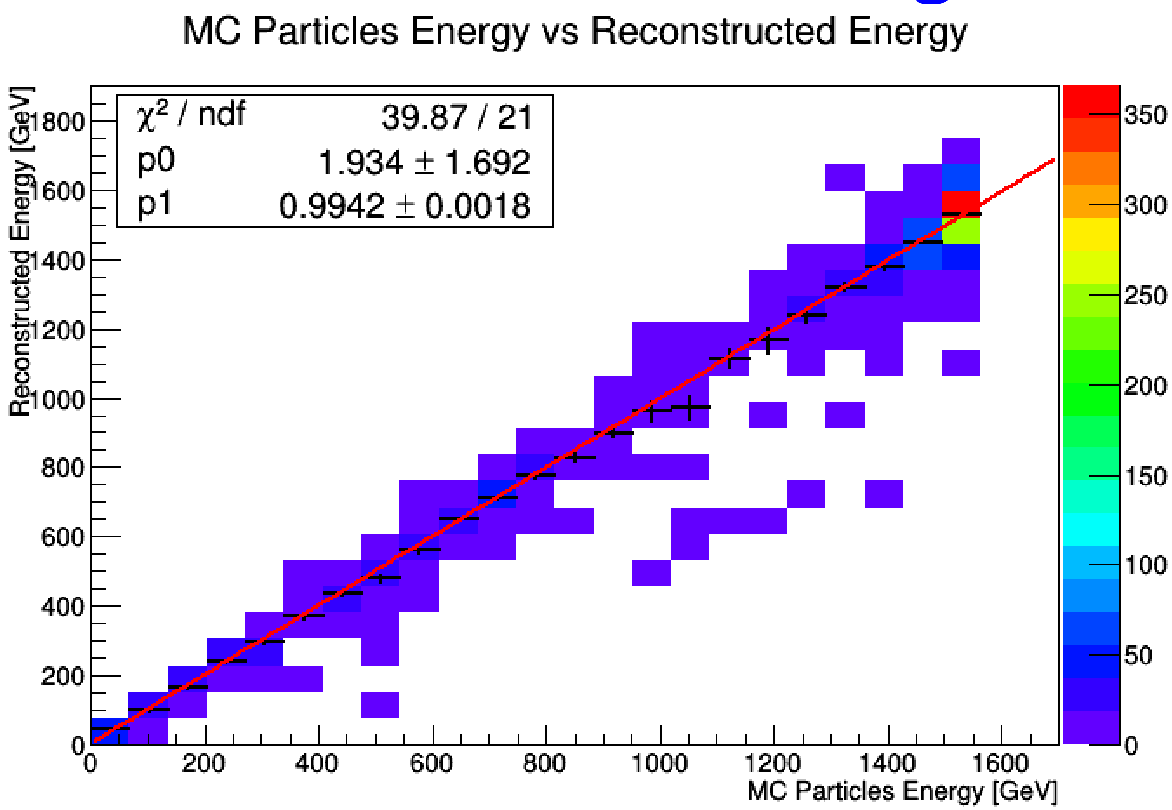
Machine background suppression strategy in the Calorimeter cont'd

- Used the "profile" of the energy distribution vs theta to evaluate the "mean" value used as "Energy subtraction".
- This approach is more effective for the forward/endcap regions.



ILCroot Simulation

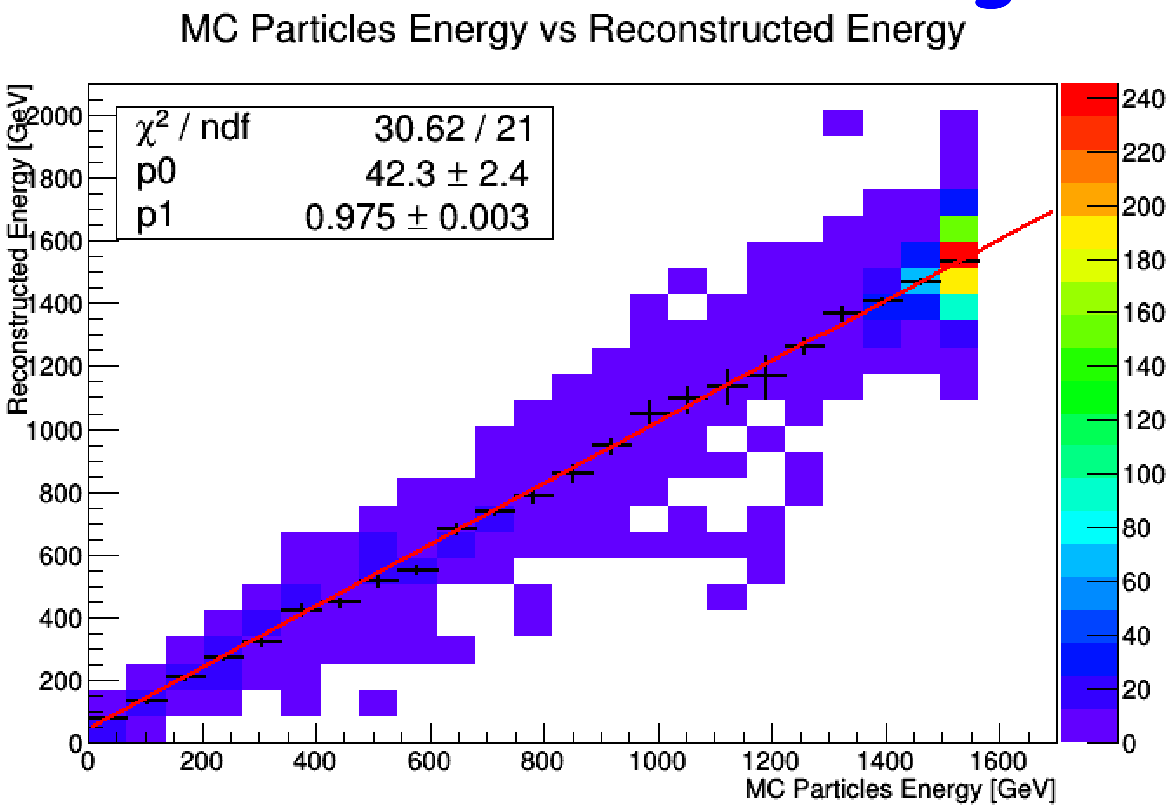
MC truth energy vs Calorimeter energy: No Background



- Selected H/A events with small neutrinos and muons component.
- Only time gate + energy recover applied.
- The calorimeter response seems good.

ILCroot Simulation

MC truth energy vs Calorimeter energy: With background

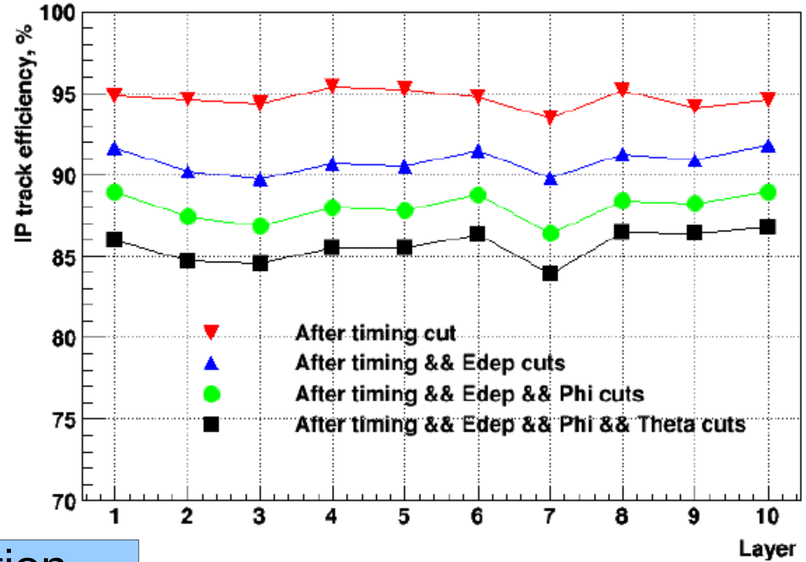


- Selected H/A events with small neutrinos and muons component.
- Added BG in calorimeter then subtracted.
- Time gate + energy recover applied.
- The calorimeter response is deteriored, but there is still room for improvements.

ILCroot Simulation

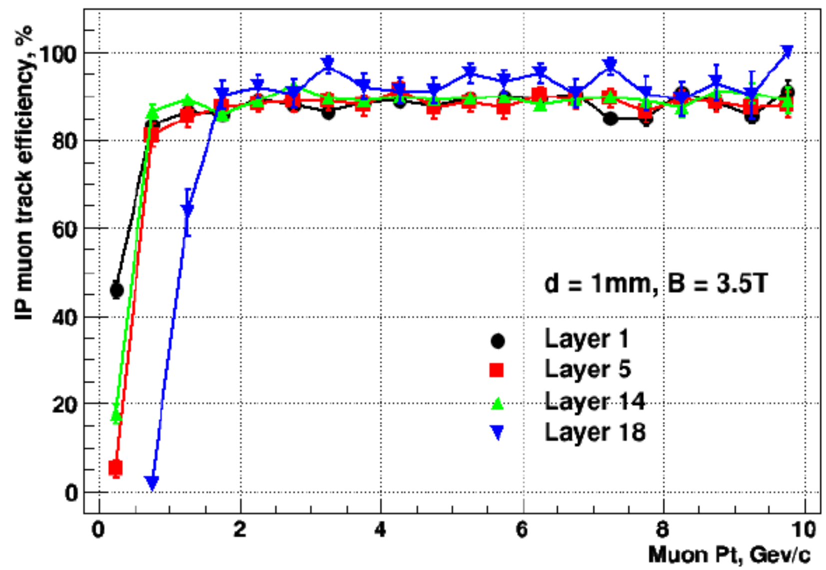
Results for IP efficiency and MARS surviving fraction

- **IP muon tracks efficiency vs. cuts and layer (1-5 are VXD barrel, 6-10 are Tracker barrel)**
  - overall IP efficiency ~85%



0.2 ns time resolution

- **IP muon tracks efficiency vs. Pt (1,5 are VXD barrel, 14(6),18(10) are Tracker barrel)**

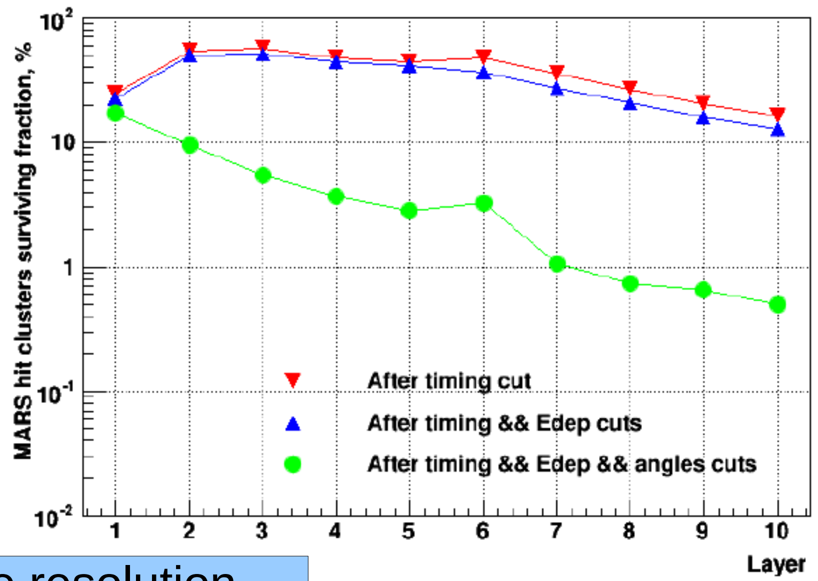


For more details see Terentiev talk

N. Terentiev (CMU/Fermilab) MAP 2014 Winter Workshop 3-7 December, 2014 SLAC 18

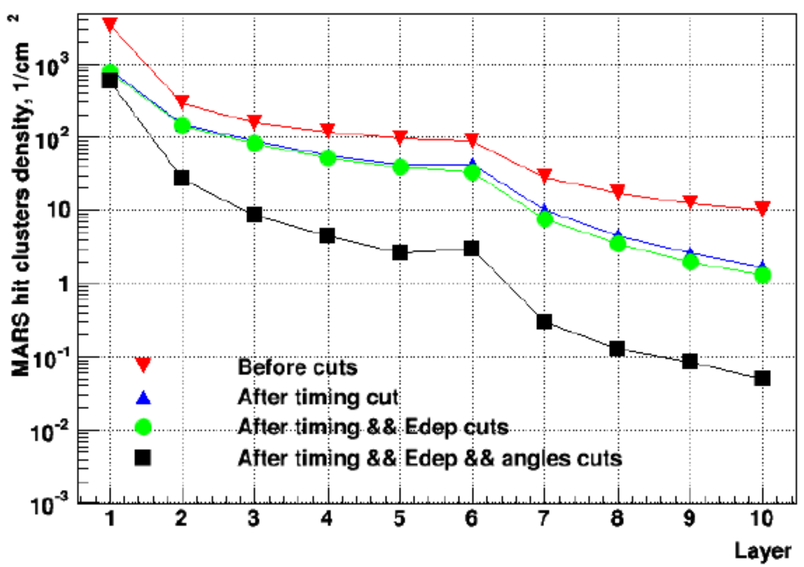
Results for IP efficiency and MARS surviving fraction

- **MARS hit clusters surviving fraction per sub-layer vs. cuts and layer (1-5 are VXD barrel, 6-10 are Tracker barrel)**
  - overall MARS surviving fraction ~2.7%



0.2 ns time resolution

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



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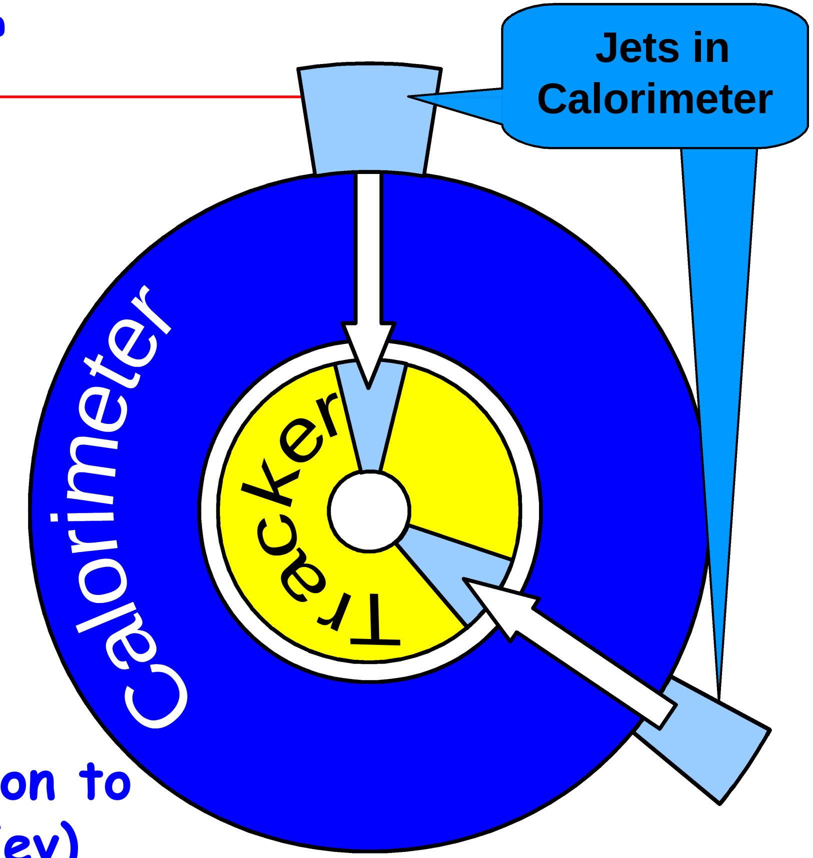
Machine background suppression strategy in the Tracker

Time resolution	0.1 ns	0.2 ns	0.5 ns
IP muon efficiency=95%			
Gate width	0.43 ns	0.80 ns	1.97ns
Gate start	-0.22 ns	-0.40 ns	-0.99ns
MARS single layer hits eff.	12.3%	21.7%	36.6%
MARS single layer hits eff. with RoI		~0.2%	

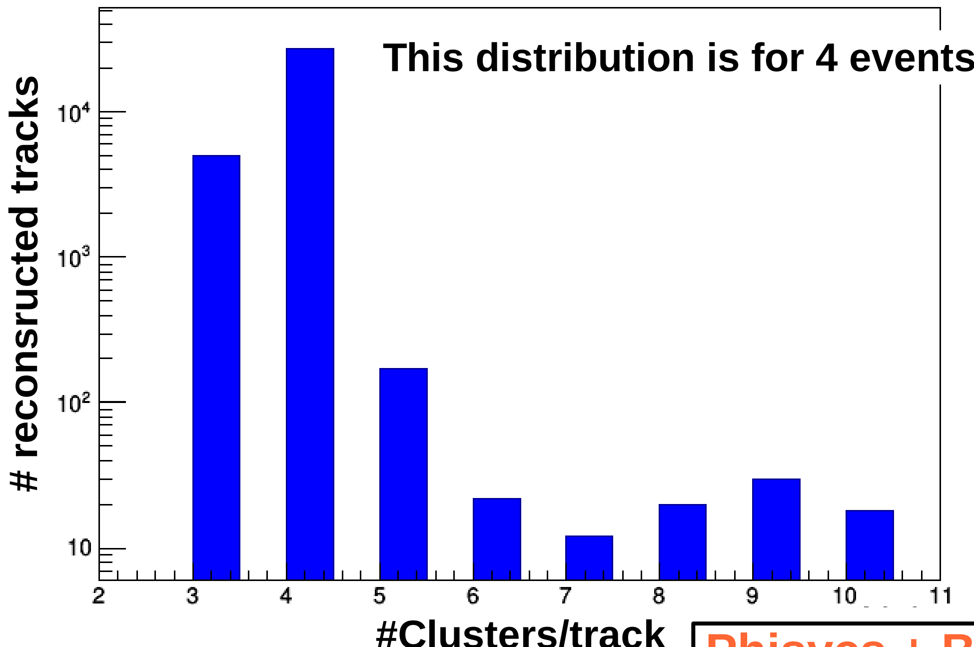


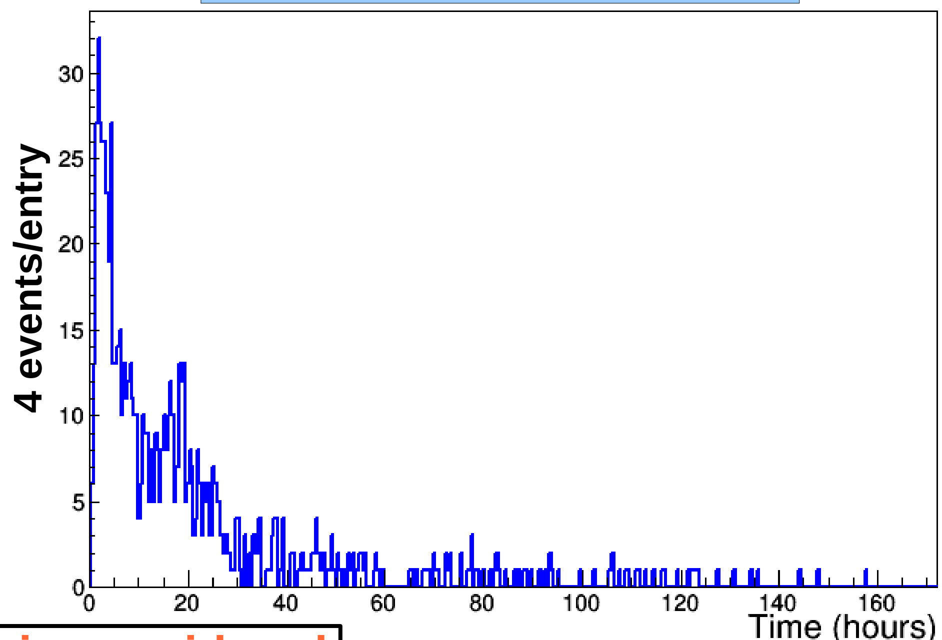
- Applied time gate cut with 0.2ns time resolution to hits in the tracker (as provided by N. Terentiev).
- Still huge background in the tracker after time cut.
- Selected Region of Interest (RoI) in the tracker, corresponding to regions in the calorimeter with energy above the background threshold.
- Digitization and reconstruction only in the RoI.

ILCroot Simulation

Machine background suppression strategy in the Tracker cont'd

ILCroot Simulation



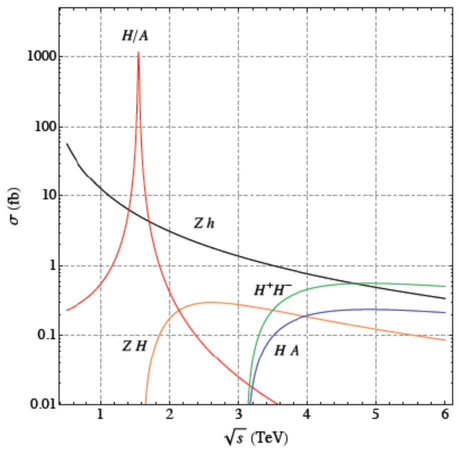


Phisycs + BG is considered

- Average Heavy Higgs event (see next slide) has ~10^2 charged tracks, with BG more than 10^4 reconstructed tracks.
- Nedeed from few hours up to few days to reconstruct an event with the parallel Kalman filter.
- Only tracks reconstructed with more than 4 clusters are taken into account.

The Muon Collider as a H/A factory: From theory

- Heavy Neutral Higgses (H/A) and charged Higgses ($H^{\pm}$) are a simple possibility of New Physics beyond the Standard Model.
- H/A are likely to be difficult to find at the LHC, and at e+ e- colliders are produced in association with other particles, such as Z, since the electron Yukawa coupling is too small for s-channel production.
- The H and A can be produced as s-channel resonances at a Muon Collider.



H/A production in the Natural Supersymmetry model compared with Z^0h, Z^0H and heavy Higgs pair production.

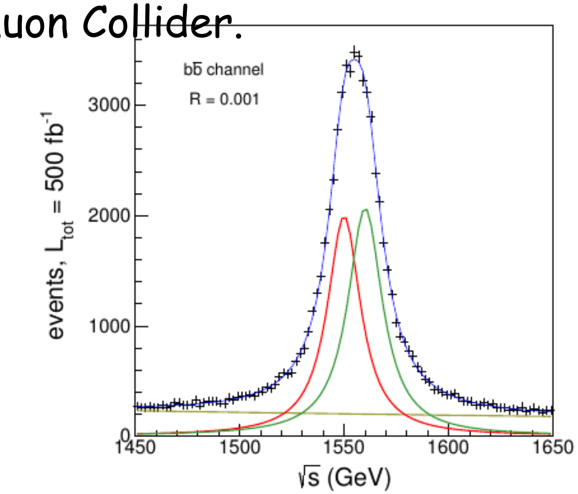
(Eichten and Martin arXiv:1306.2609).

One Resonance

Mass(GeV)	Γ(GeV)	$\sigma_{\rm peak}$ (pb)
1555 ± 0.1 GeV	24.2 ± 0.2	1.107 ± 0.0076
$\chi^2/\mathrm{ndf} = 363/96$		$c_1 = 0.0354 \pm 0.0006$

Two Resonances

Mass(GeV)	Γ(GeV)	$\sigma_{\rm peak}$ (pb)
1550 ± 0.5 GeV	19.3 ± 0.7	0.6274 ± 0.0574
1560 ± 0.5 GeV	20.0 ± 0.7	0.6498 ± 0.0568
$\chi^2/\mathrm{ndf} = 90.1/93$		$c_1 = 0.040 \pm 0.0006$



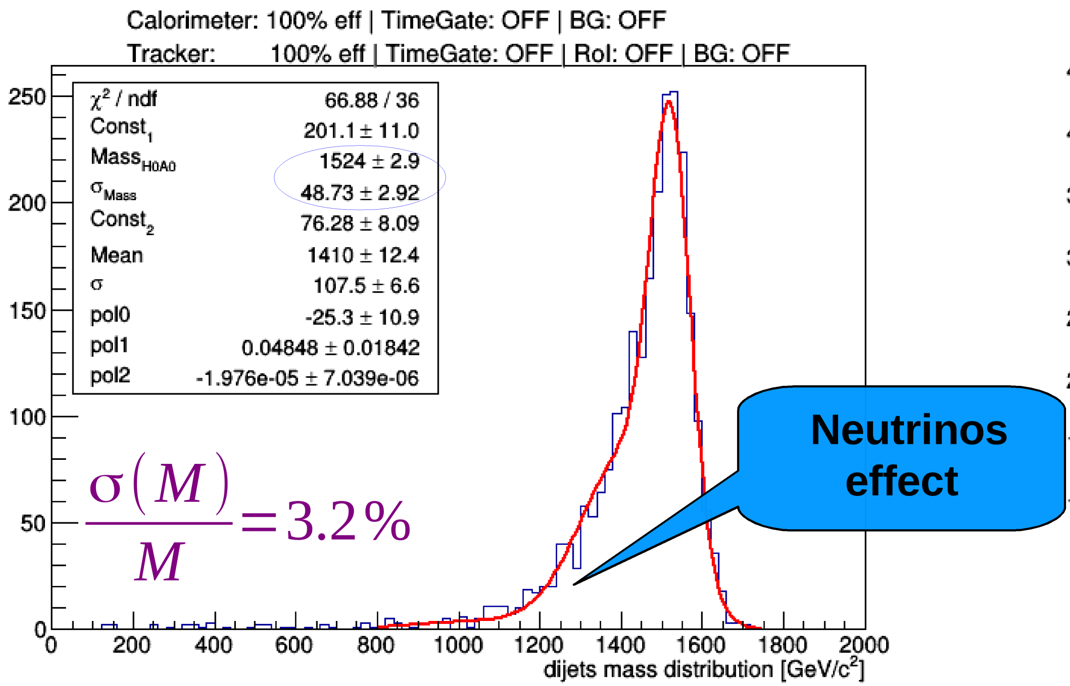
Pseudo-data (in black) along with the fit result in the bb channel. The peak signal is more than an order of magnitude larger than the physics background.

$$\sigma_B(\sqrt{s}) = c_1 \frac{(m_H m_A)}{s(\mathrm{in\ TeV}^2)}$$

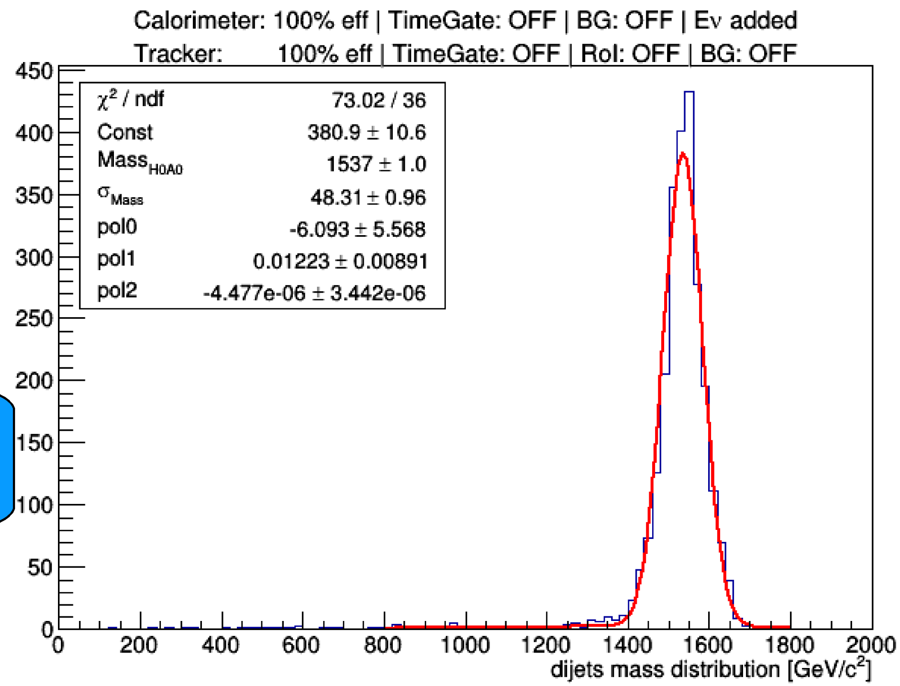
- Fully simulated with track and calorimeter reconstruction in ILCroot framework 4000 H/A events generated by Pythia at $\sqrt{s}$ = 1550 GeV with a Gaussian beam energy smearing (R=0.001) (A. Martin).
- In these studies, considered the $b\bar{b}$ decay of the H/A which is the channel with the largest BR (64%).
- Applied a perfect b-tagging (using information from MonteCarlo truth).
- Reconstructed 2 jets applying PFA-like jet reconstruction developed for ILC benchmark studies.

The Muon Collider as a H/A factory: From reconstruction

Time gate OFF – BG OFF



Time gate OFF – BG OFF
Neutrino component included



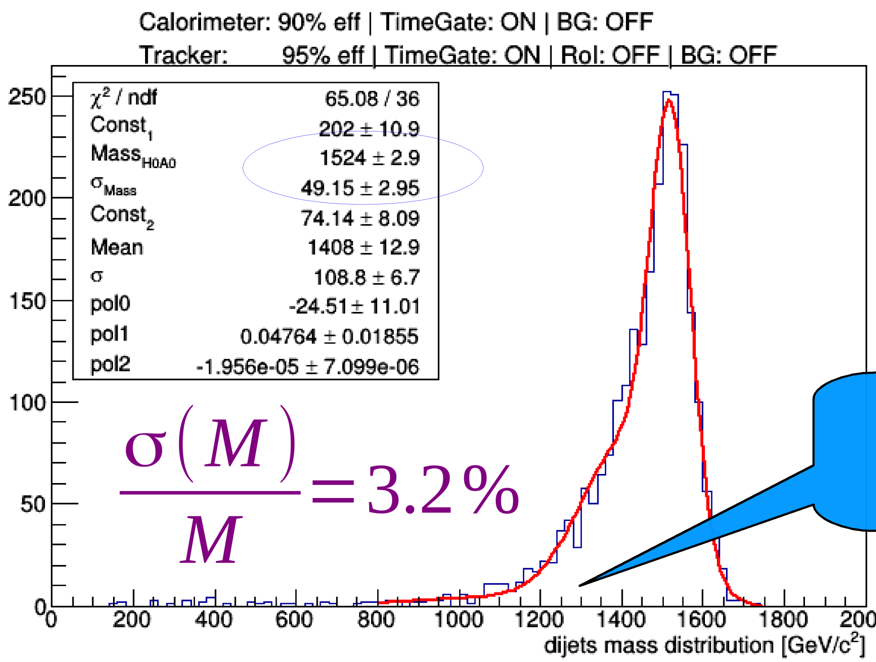
- *H/A mass reconstruction in a clean environment.*
- *Significant neutrino component.*

ILCroot Simulation

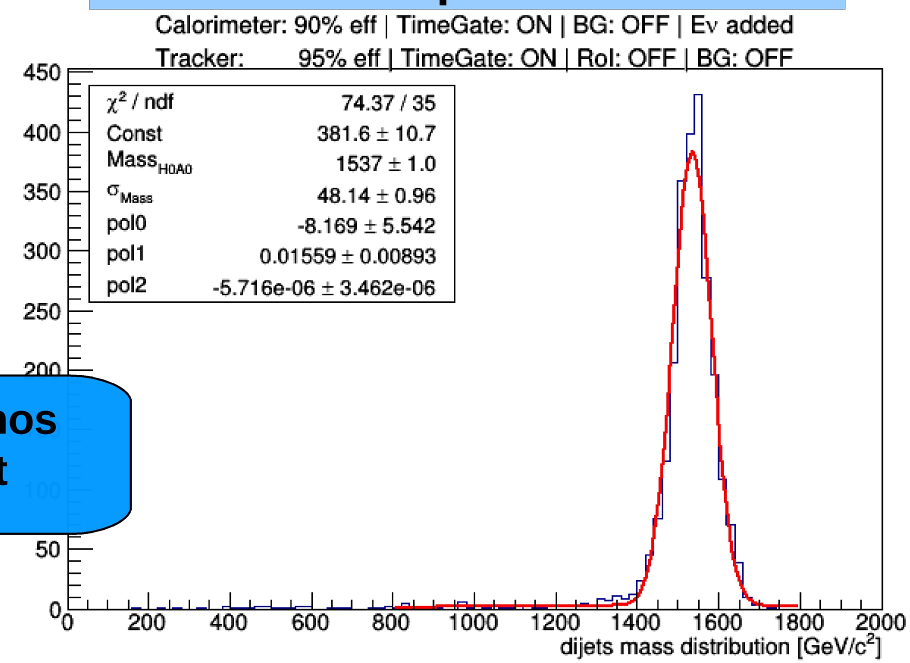
The Muon Collider as a H/A factory: After time cut

ILCroot Simulation

Time gate ON – BG OFF



Time gate ON – BG OFF
Neutrino component included

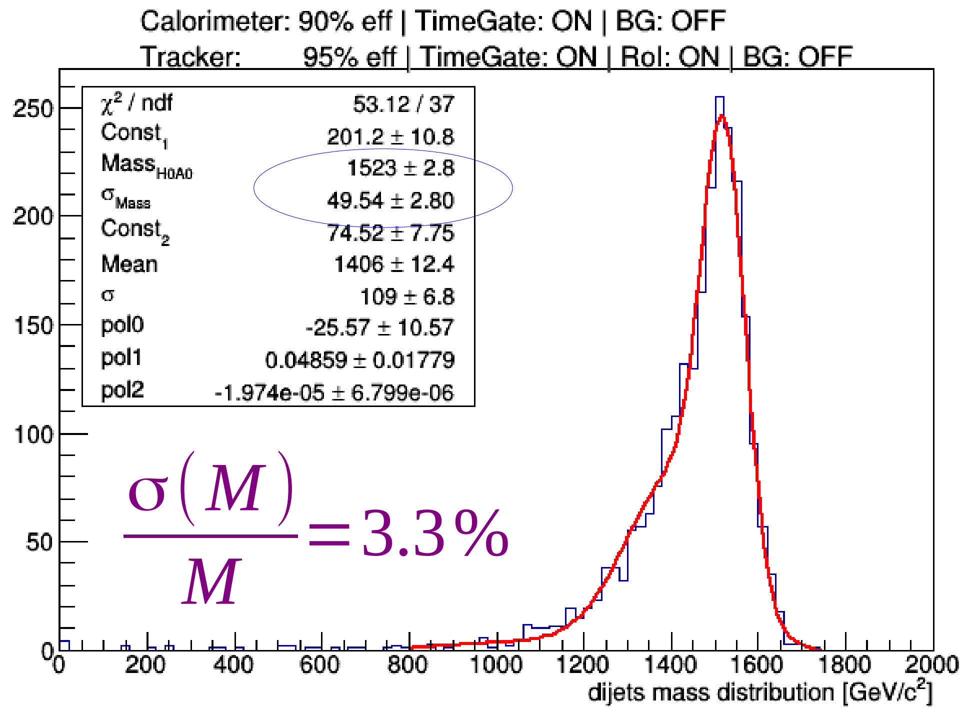


Neutrinos effect

- Applied time gate cut in the tracker (Tracker single layer hit efficiency: 95%.)
- Applied time gate cut in the calorimeter (Calorimeter efficiency: 90%).
- Applied calorimeter energy recovery.
- No background added.
- No degradation in the H/A mass resolution after applying time gate cut.

The Muon Collider as a H/A factory: After cuts and selected RoI (BG OFF)

Time gate & RoI ON – BG OFF

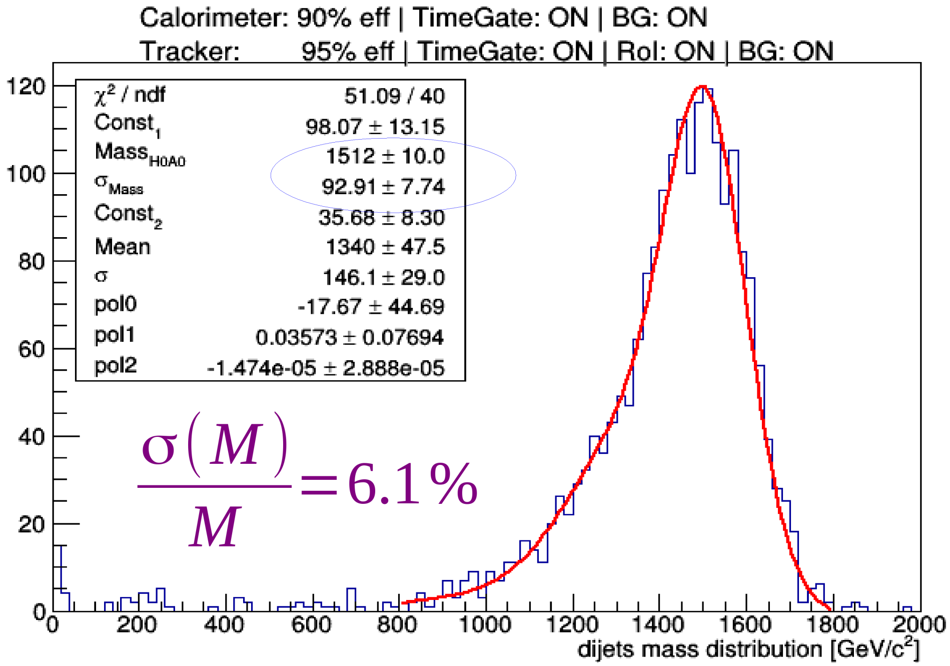


- Added selection of RoI.
- No background added.
- No degradation in the H/A mass resolution, also after applying RoI selection.

ILCroot Simulation

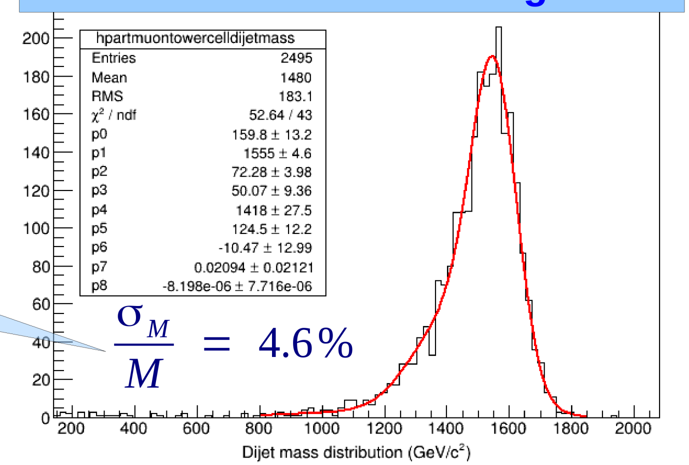
The Muon Collider as a H/A factory: Final result (BG ON)

Time gate & RoI ON – BG ON



- *Merged signal and BG.*
- *Applied time gate cut in calorimeter and tracker.*
- *Applied energy recovery in the calorimeter.*
- *Selected RoI in the tracker.*
- *Significant degradation in the H/A mass resolution.*
- *There are still improvement to apply in tracker and calorimeter.*

YES Time Gate YES Background



With previous backgroud
it was 4.6%

ILCroot Simulation

Conclusions

- Large background is expected in the detector for a Muon Collider experiment.
- Sophisticated shielding have been proposed to suppress the machine background.
- MARS15 simulation shows a reduction of the machine background of few orders of magnitude (depends on the nozzle angle).
- The baseline detector configuration for a Muon Collider has been developed in ILCroot framework and studies on the performance are well advanced.
- Full simulation and reconstruction of Si-tracker detectors and ADRIANO dual-readout calorimeter are implemented in ILCroot framework (thanks to previous and detailed studies at ILC).
- Both ad-hoc tracking and calorimetry simulation implemented in the current software framework.
- The background is very nasty, even with a 10° nozzle, but it has been shown it is not impossible to reach the physics goal at a Muon Collider experiment.

Conclusions (cont'd)

- Current studies with the new MARS background event show that timing cut is not enough to reduce the background and new strategies have been developed.
- Results presented in this talk show that it is not impossible to reduce the background into the detector.
- We are close enough to have an adequate configuration for a MuonCollider detector.
- More R&D is needed for the development of new detector technologies in parallel with accelerator R&D.

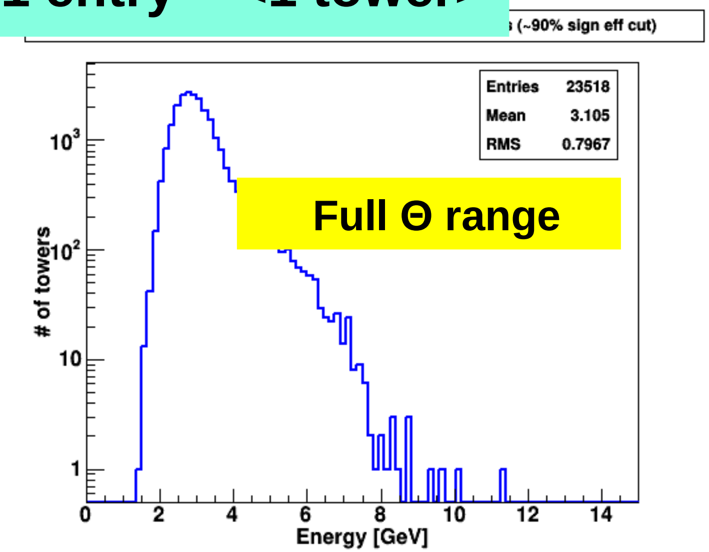
Remarks

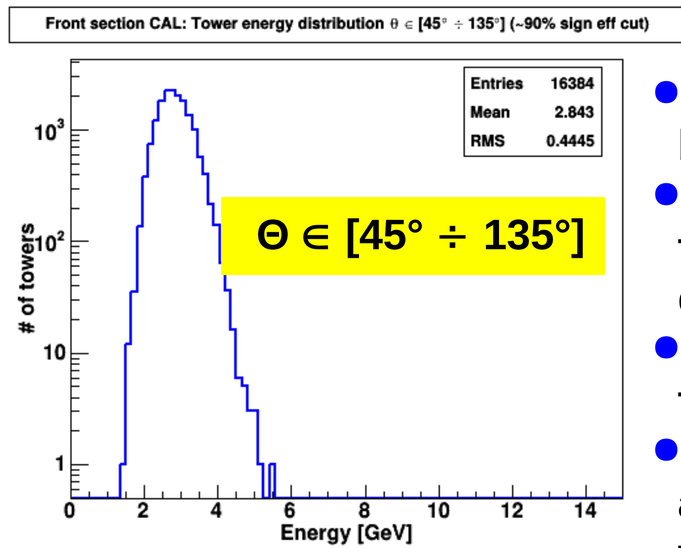
- Tremendous effort made by few people to obtain those results.
- Great potential to increase the number of studies and show capabilities of a MuonCollider experiment.
- All the software machinery (genaration, reconstruction and analysis) is in place and optimized for detailed studies at a MuonCollider.
- All detector and Physics studies can be done with minimal human resources.
- It would be a shame if this is the end of the story.

Back-up slides

Energy distribution of background for different theta ranges after Time cut

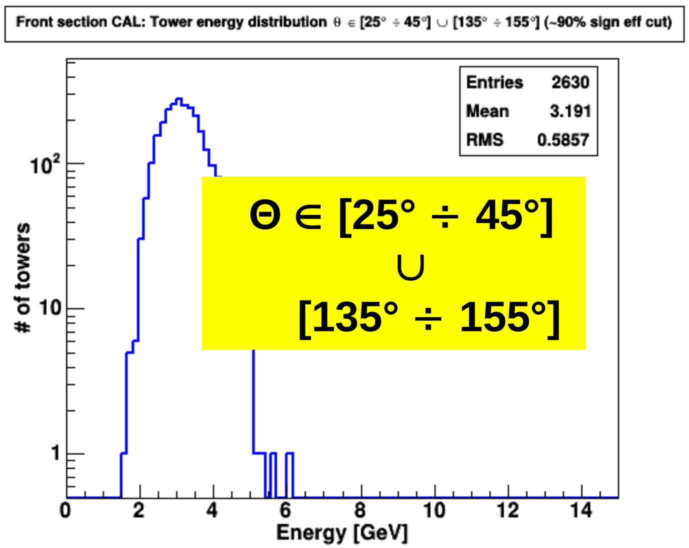
1 entry = <1 tower>

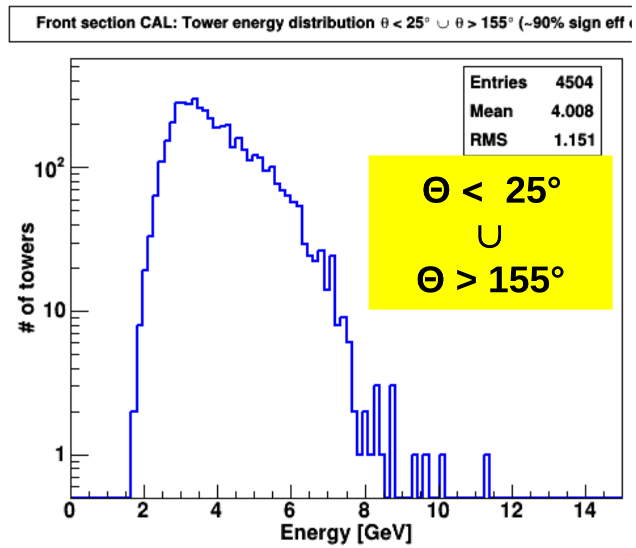


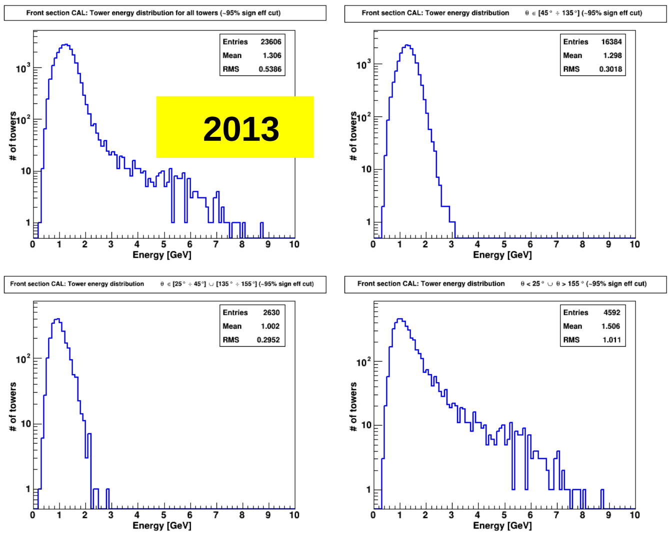


Front Section

- Energy distribution has a broad range.
- In barrel and mid endcap the energy distribution is quite narrow.
- Forward endcap can be tricky to deal with.
- Improved BG time cut algorithm reduces the tail in the forward endcap compared to 2013.

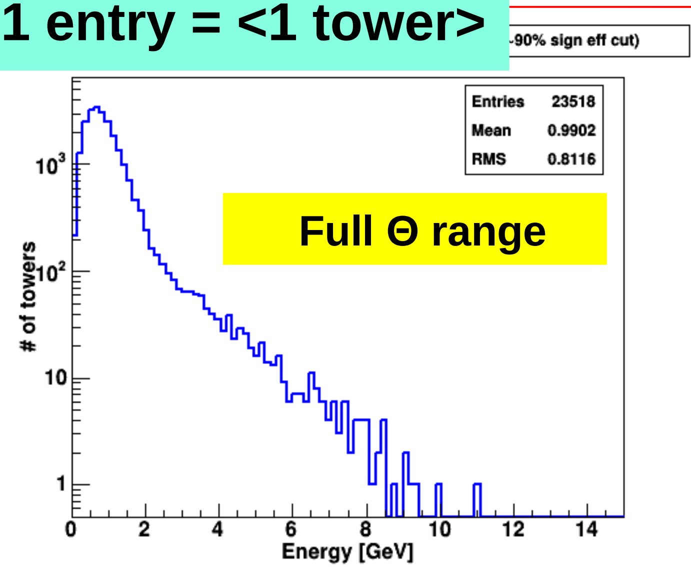


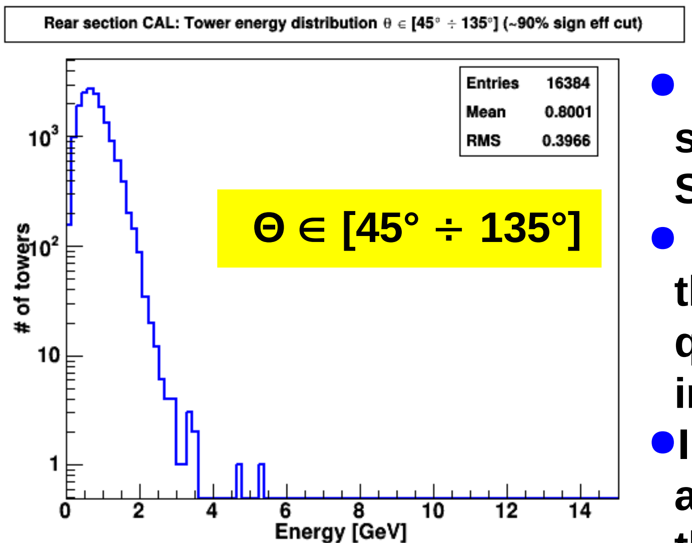


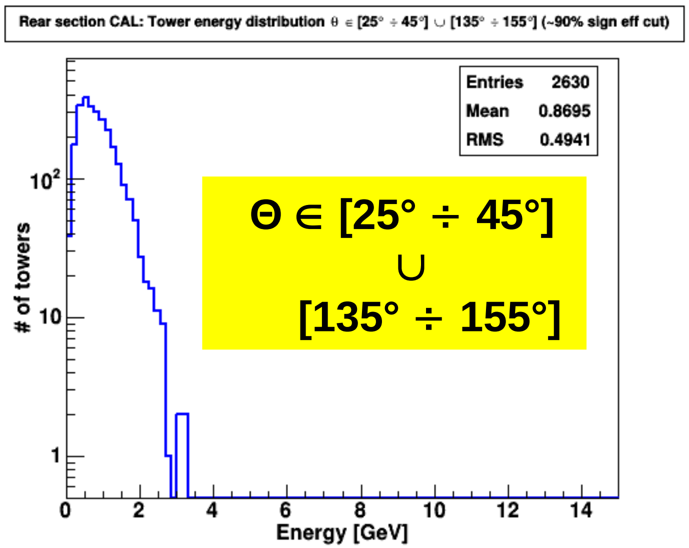


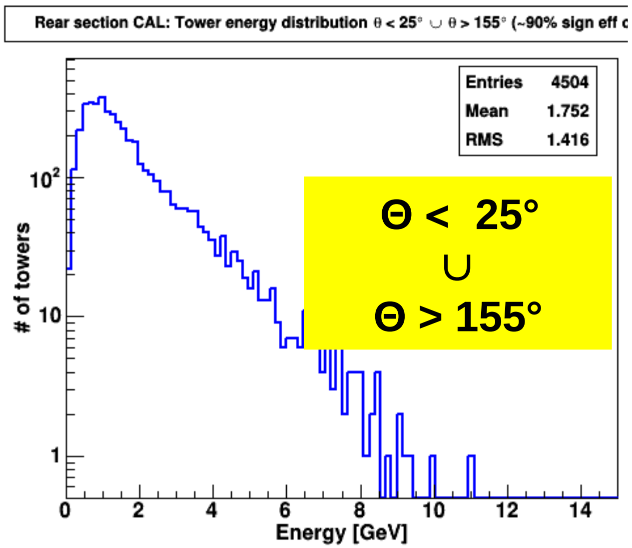
Energy distribution of background for different theta ranges after Time cut

1 entry = <1 tower>



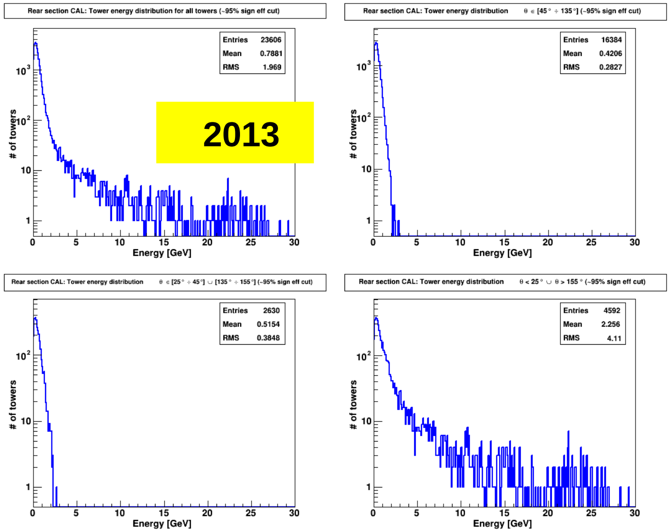




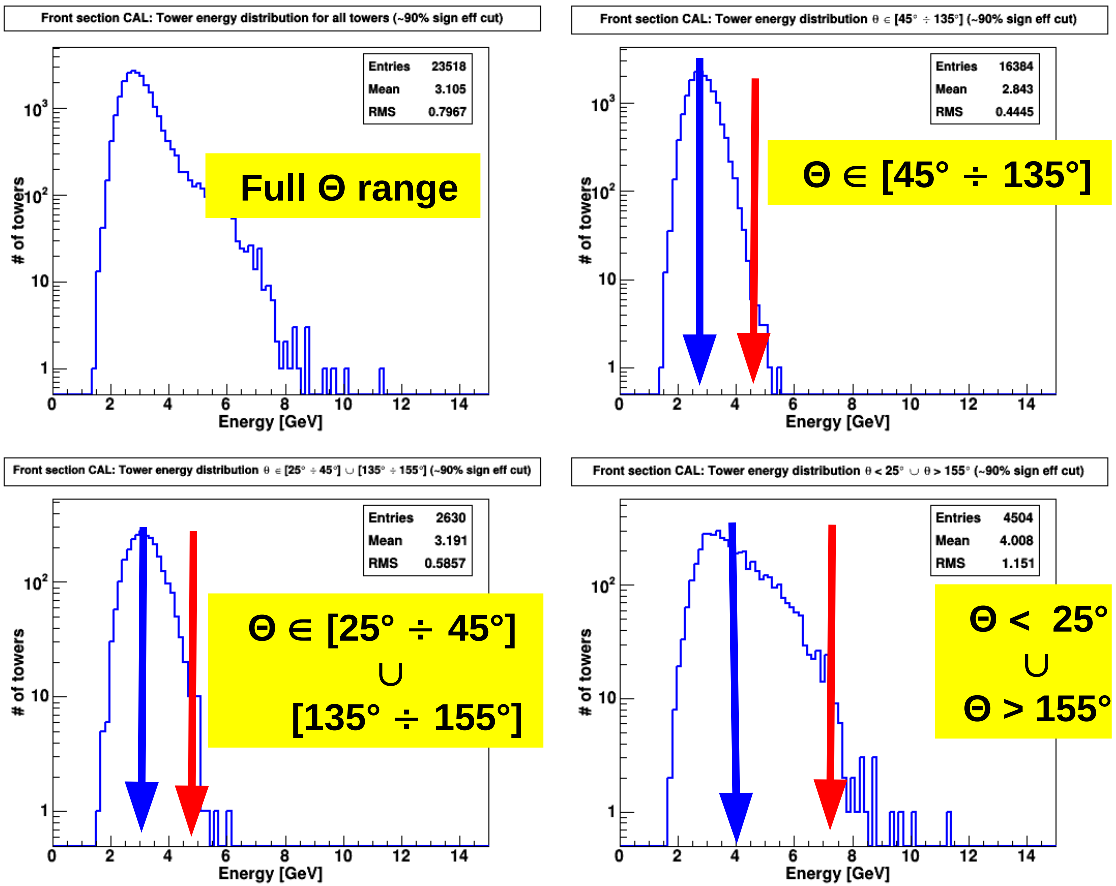


Rear Section

- Energy distribution has a similar range than in Front Section.
- In barrel and mid endcap the energy distribution is quite narrow and lower than in Front Section.
- Improved BG time cut algorithm reduces the tail in the forward endcap compared to 2013.



Machine background soppression strategy
Front Section calorimeter as an example

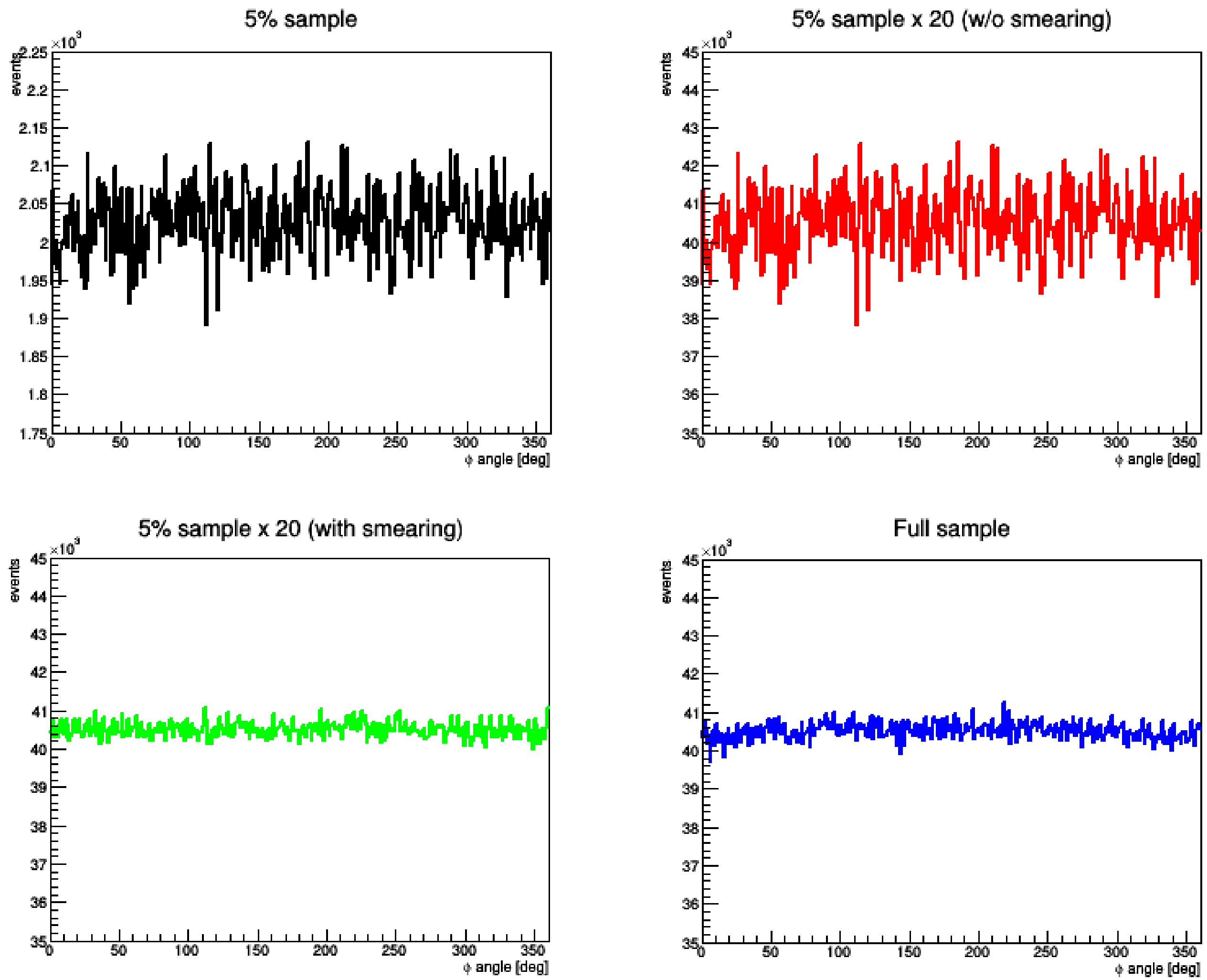


Soft energy cut
Hard energy cut

- First approach to remove machine background.
- Use the "mean" value of the energy distribution as "Energy subtraction" (soft cut).
- This has a concern.
  - This way remove completely the background from about half of calorimeter towers.
  - The other towers mantain an average energy due to the background of the order of the RMS of the energy distribution.
  - The remnant background energy in the calorimeter is about

    10^4 towers X 0.4GeV/tower = 4 TeV !
- It is needed an hard cut to remove quite completely the background.
  - This can have effect on Physics.
- Forward endcap can be tricky to deal with.

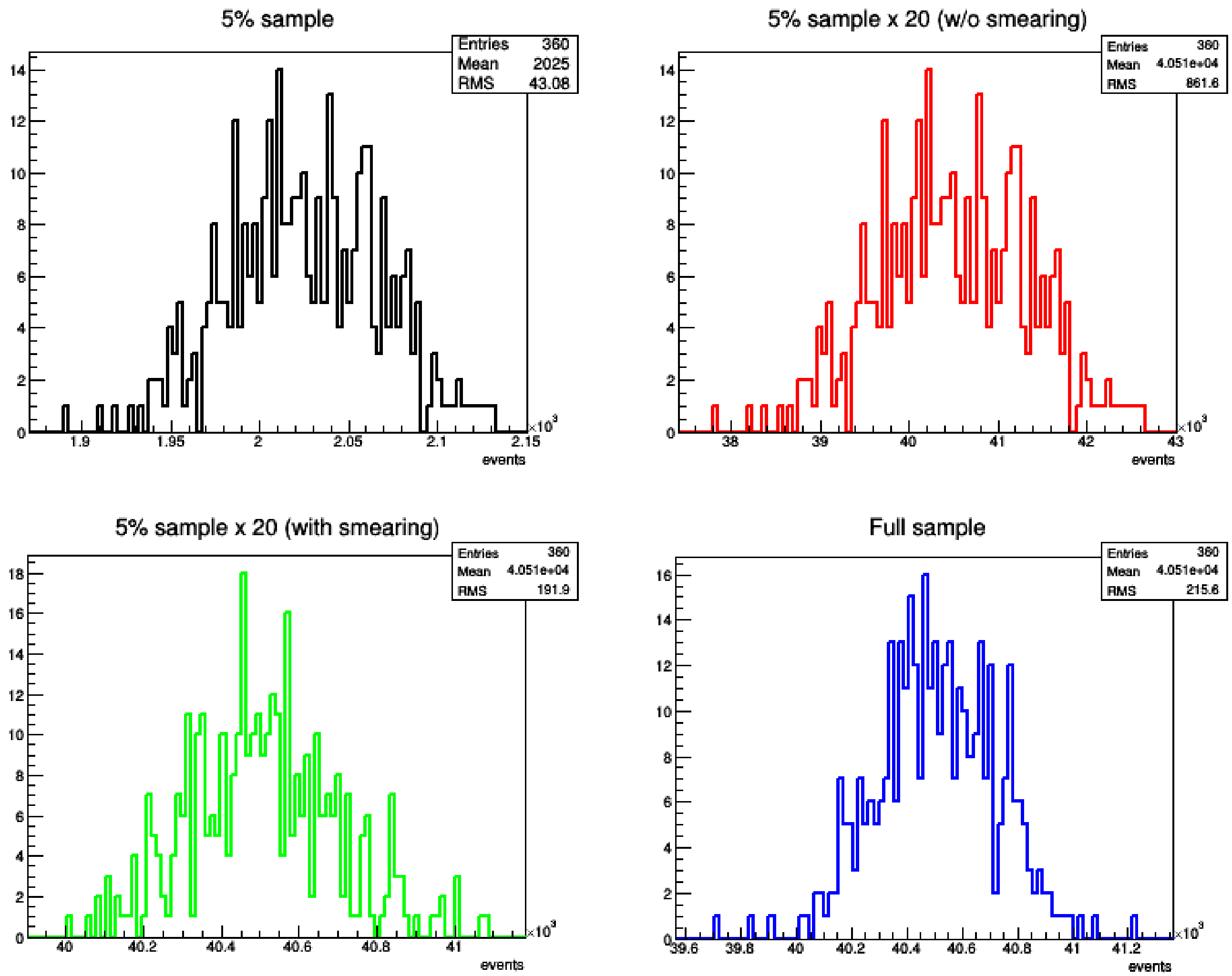
MuC background
Φ distribution of momentum



- This is a test to verify that it is appropriate to smear the particle momentum.
- Extract a sample of 5% from the background (black plot).
- We can just multiply each element of this sample by 20 to get the full sample (red plot).
- Or smear 20 times each element according to some simmetry (green plot).
- The blue plot is the original full sample.

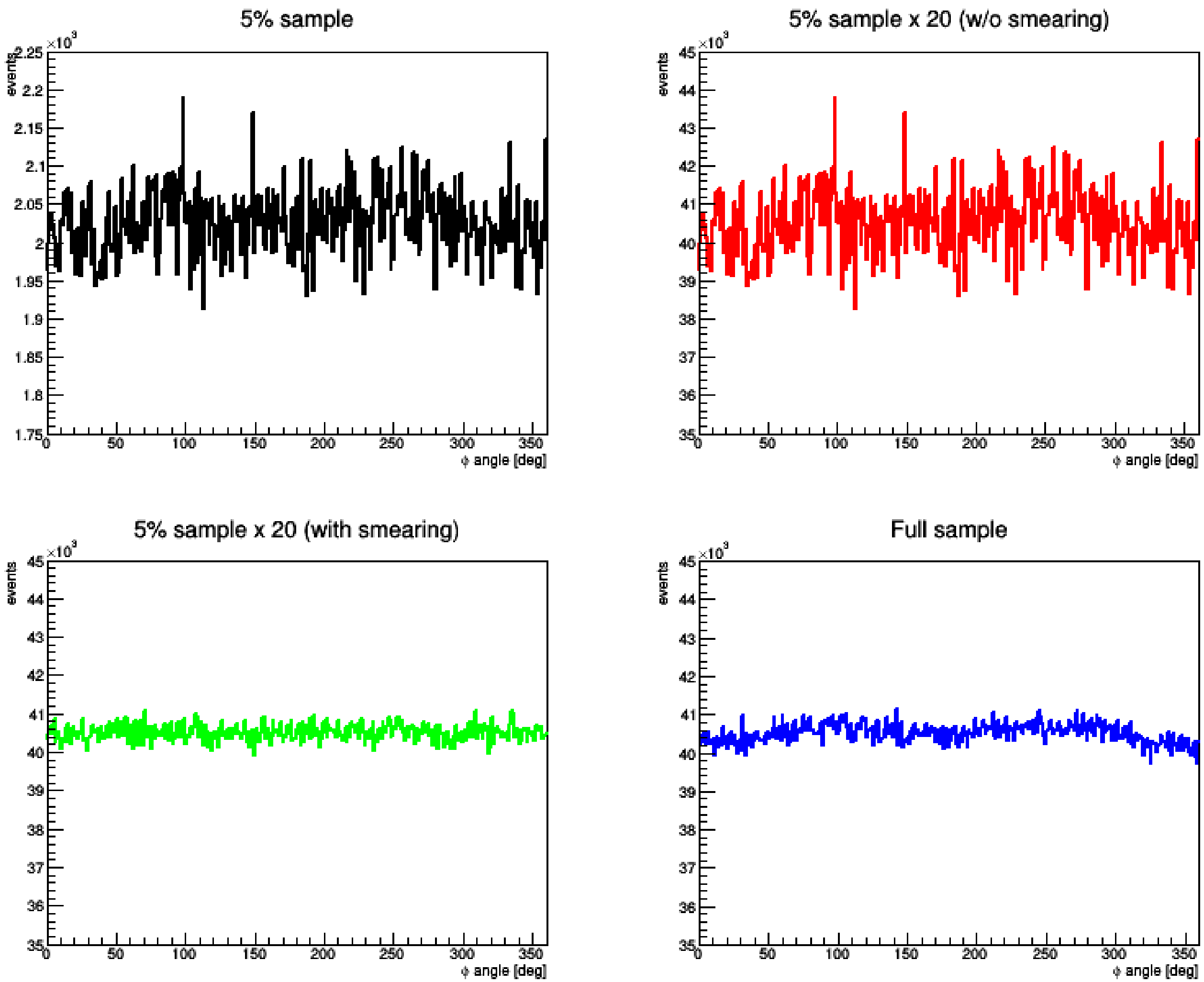
- This exercise shows that smeared distribution is more similar to the original distribution.

MuC background
Φ distribution of momentum



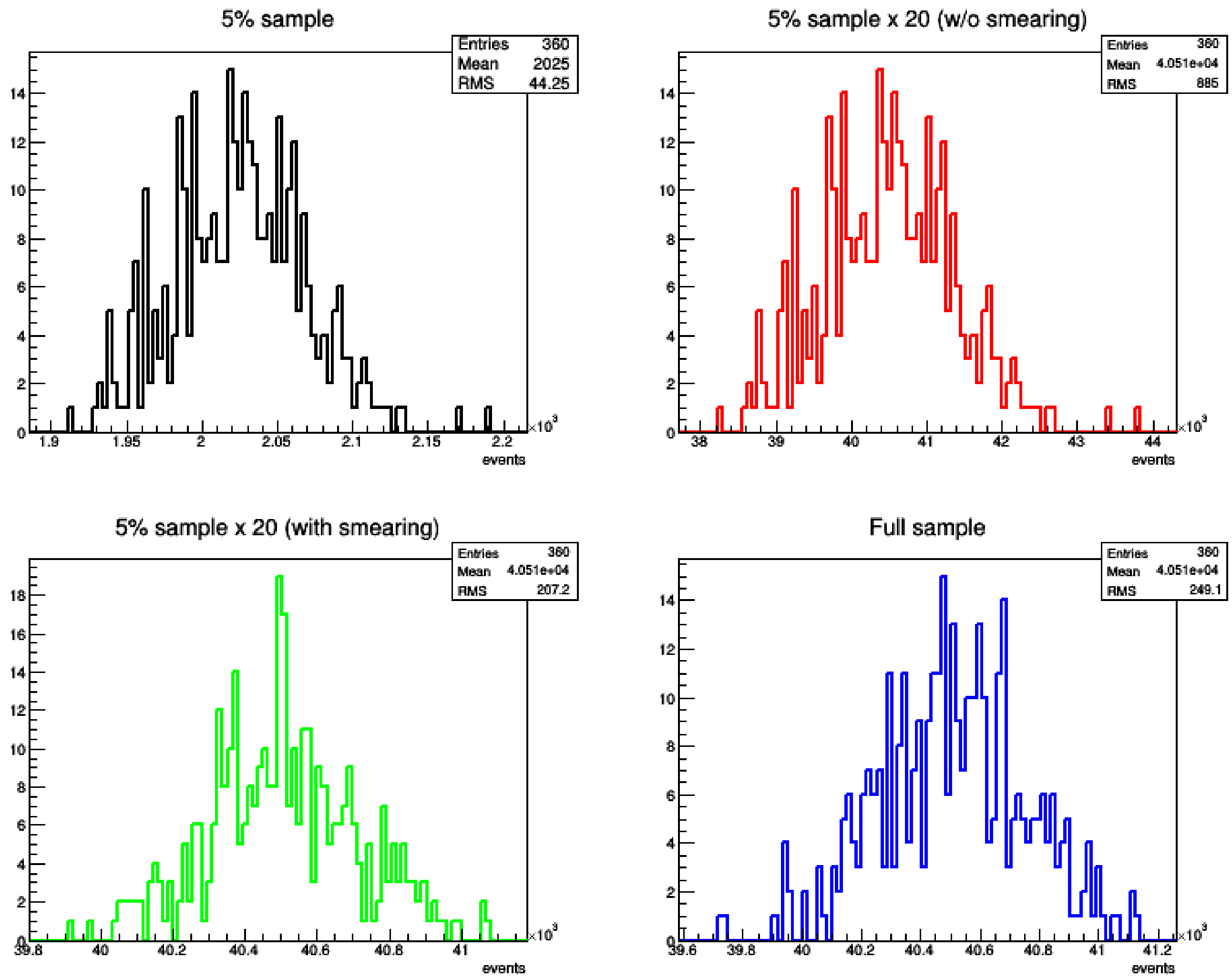
- **These distribution are the projection of the previous distribution on the “y” asis.**
- **Here it is easy to see the “dispersion” of the distributions from the mean value (RMS).**
- **Smeared distribution (green) is more similar to the original distribution (blue) than the distribution weighted without smearing (red).**

MuC background
Φ distribution of vertex



- Also the vertex distribution behaves the same way than the momentum distribution.
- The smeared distribution (green) is more similar to the original distribution (blue) than the distribution weighted without smearing (red).

MuC background
Φ distribution of vertex



- **Also the vertex distribution behave the same way than the momentum distribution.**
- **The RMS of the smeared distribution (green) is more similar to the RMS of original distribution (blue) than the RMS of the distribution weighted without smearing (red).**

The Muon Collider as a H/A factory: "Reality" (cont'd)

Jet Reconstruction Strategy

Assume the jet made of 2 non-overlapping regions

Core: region of the calorimeter with overlapping showers

Outliers: hit towers separated from the core

Measure the Jet axis

using information from the tracker detectors

Measure the Core energy

using information from the calorimeter

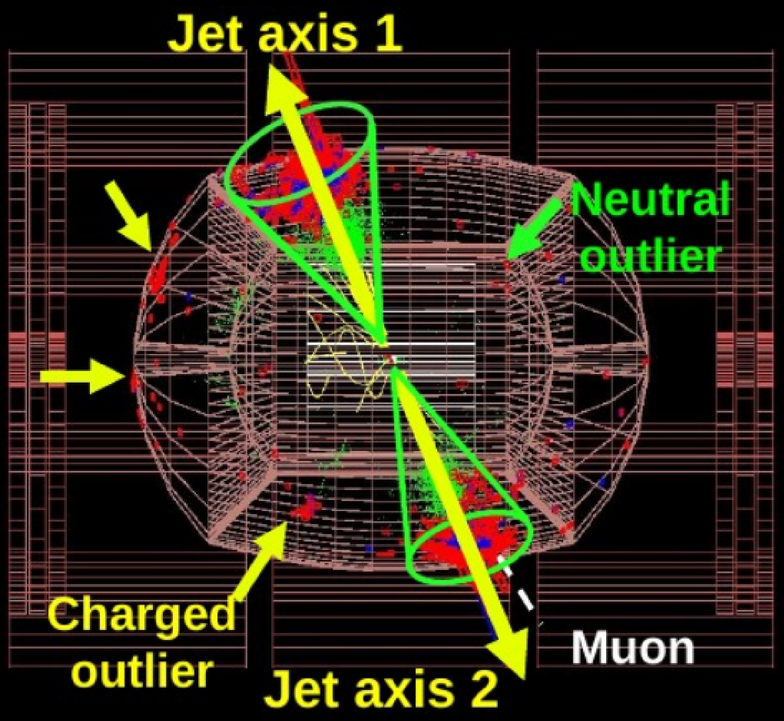
Reconstruct Outliers individually

using tracking and/or calorimetry

depending on the charge of the particle

Add Muons escaping from calorimeter

using muon spetrometer



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ILCroot Simulation