Muon Collider – Archeology

Ronald Lipton

Some History

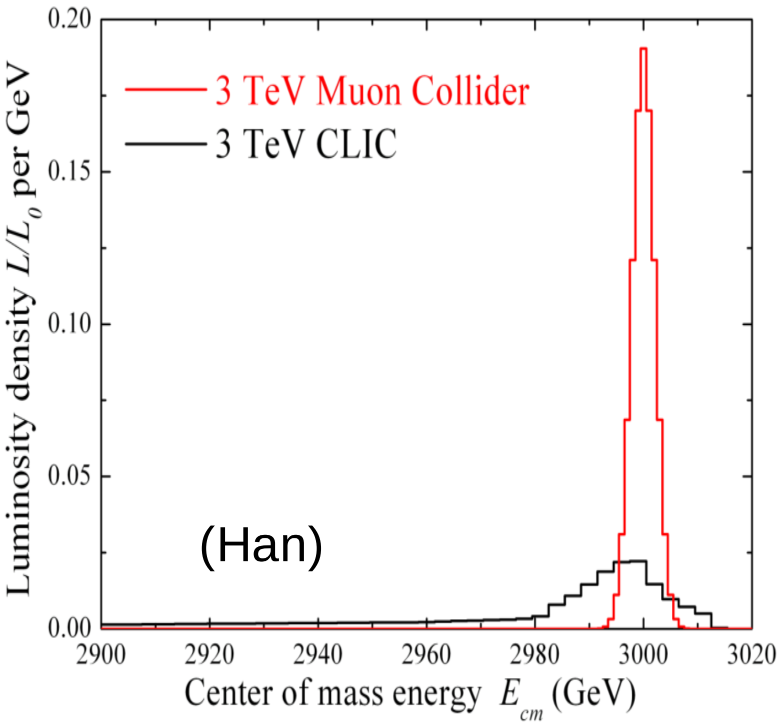
A focused accelerator R&D program, MAP, was launched in 2010 to study the feasibility of a muon-based collider program

- There were a number of earlier studies
- A *small* detector conceptual study was also launched to study the physics potential and associated detector issues

- Snowmass studies were based on a simulation of a 1.5 TeV muon collider, with parametric studies of a Higgs factory.
- As a result of the 2013/14 US P5 process the MAP program was terminated
  - This also led to a termination of physics studies

Most of this work was done by Vito Di Benedetto, Anna Mazzacane, Alex Conway, and Nikolai Terentiev with support from the MARS team and Hans Wentzel as well as Estia Eichten and Chris Hill

Study Thrusts



Much of the muon collider physics overlap with CLIC AND ILC

- We used CLIC and ILC studies as a starting point

The detector environment is very different.

- We tried to understand techniques for handling the background and how the backgrounds might affect the physics reach.

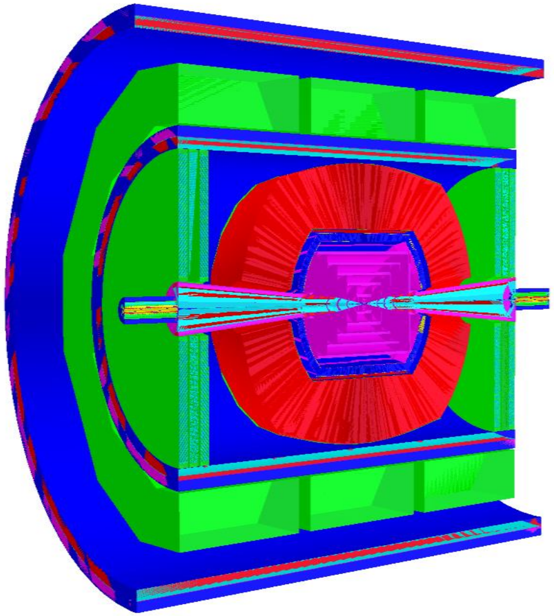
There are some areas where the muon collider has unique advantages – we tried to understand those areas

- Narrow beam energy spread (lower brem) can enable precision physics
- Muon Collider has x 40,000 higher coupling for s-channel Higgs
- Other s-channel resonances (A')
- Precise (~4 MeV) Higgs mass measurement
  - Enabled by precise beam energy measurement by g-2 precession (Raja & Tollestrup)

Detector Model

Detector was based on ILC concepts (SiD, ILD, 4th)

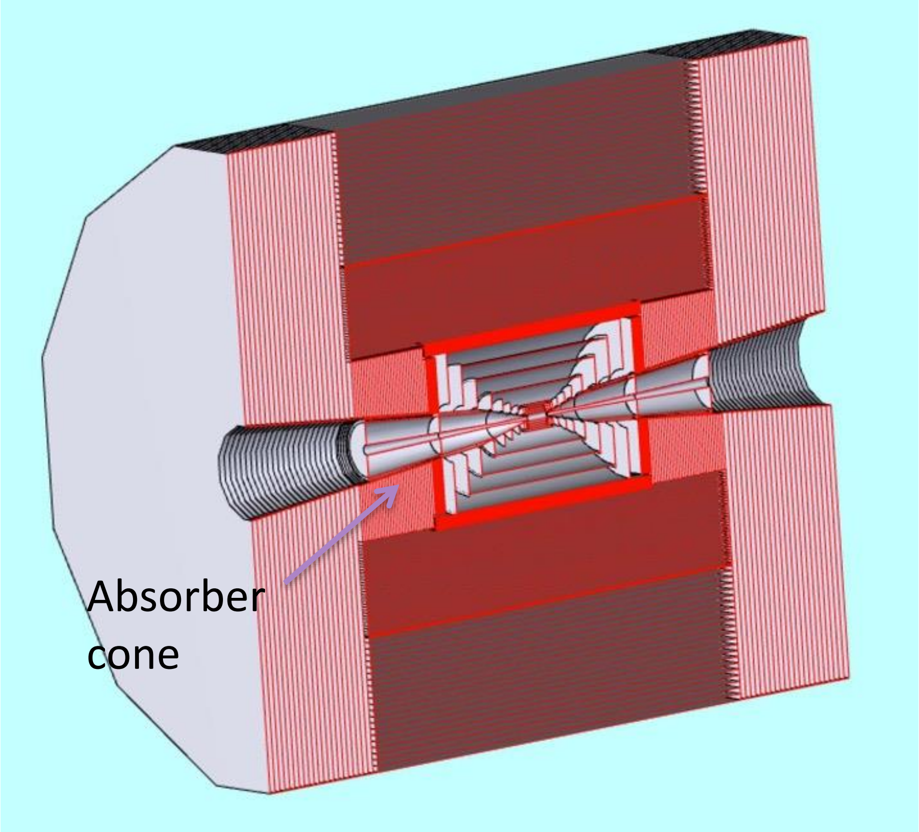
- My own background was work on the SID vertex and tracker design
- Fine pitch pixelated vertex and forward detectors (~20 μm) based on SiD
- More coarsely (50 μm) pixelated tracker
  - Both with sub-ns timing resolution
- Dual readout (scintillator/Cerenkov) calorimeter to optimize hadronic shower resolution
  - Based on existing "Adriano" design with realistic parameters – not optimized for timing
  - Between 1 and 12 ns timing gates



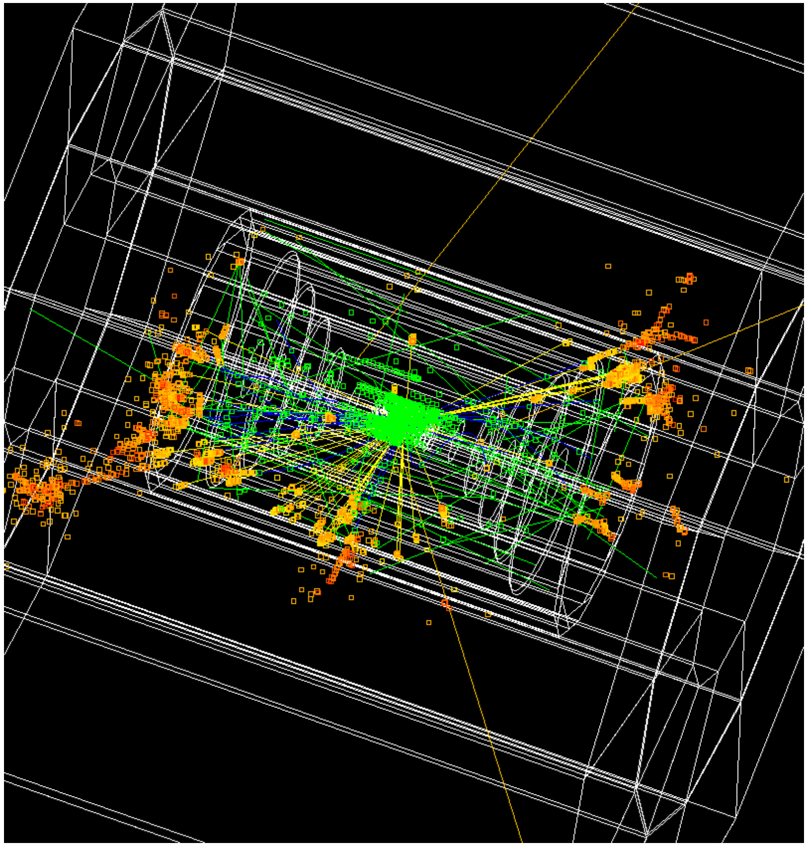
ILCROOT Detector Model

Detector Model based on ILC SiD concept

LCSIM Detector Model



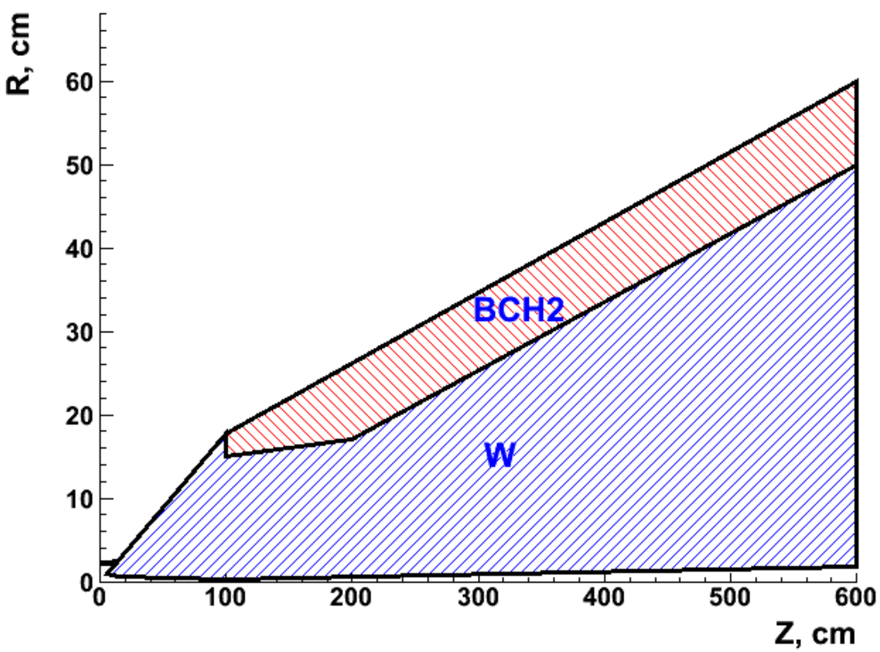
Full Simulation



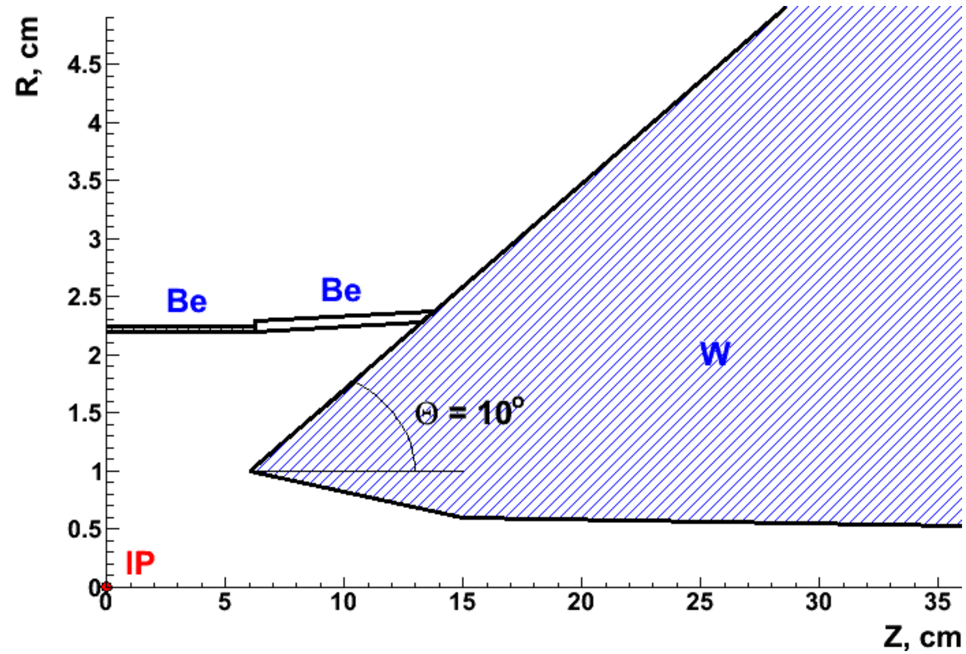
The Nose (google Gogol)

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

General (1/2 RZ) view



Zoom in beam pipe



W – tungsten

Be – beryllium

BCH2 – borated polyethylene

Backgrounds

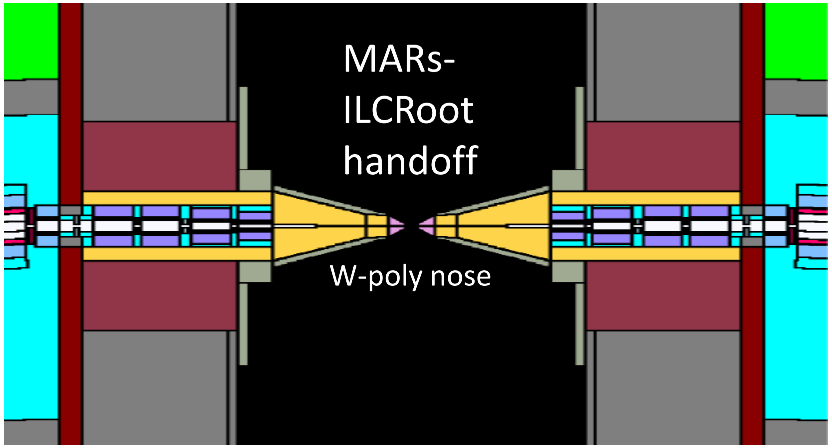
From the detector side the central issue in a muon collider are backgrounds due to muon beam decays.

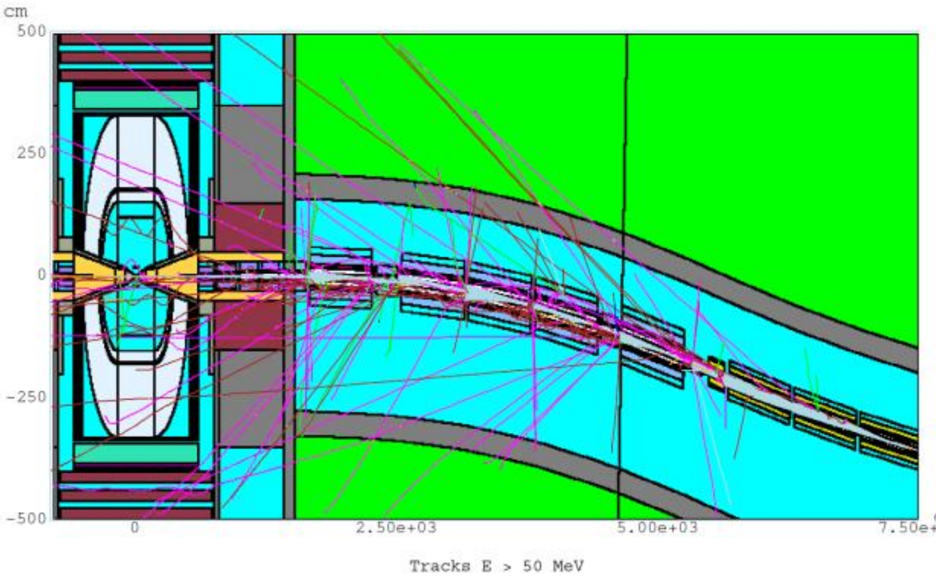
- For a 0.75-TeV muon beam of 2×10^{12}/bunch
  - 4.28×10^{5} decays/m per bunch crossing
  - 0.5 kW/m.

Recalculated with a timing bug fixed in 2014

- 3.24×10^{8} particles into detector per crossing
  - 100 keV threshold for γ, $e^{\pm}$, $\mu^{\pm}$ and charged hadrons
  - 0.001 eV for n

MARS simulations



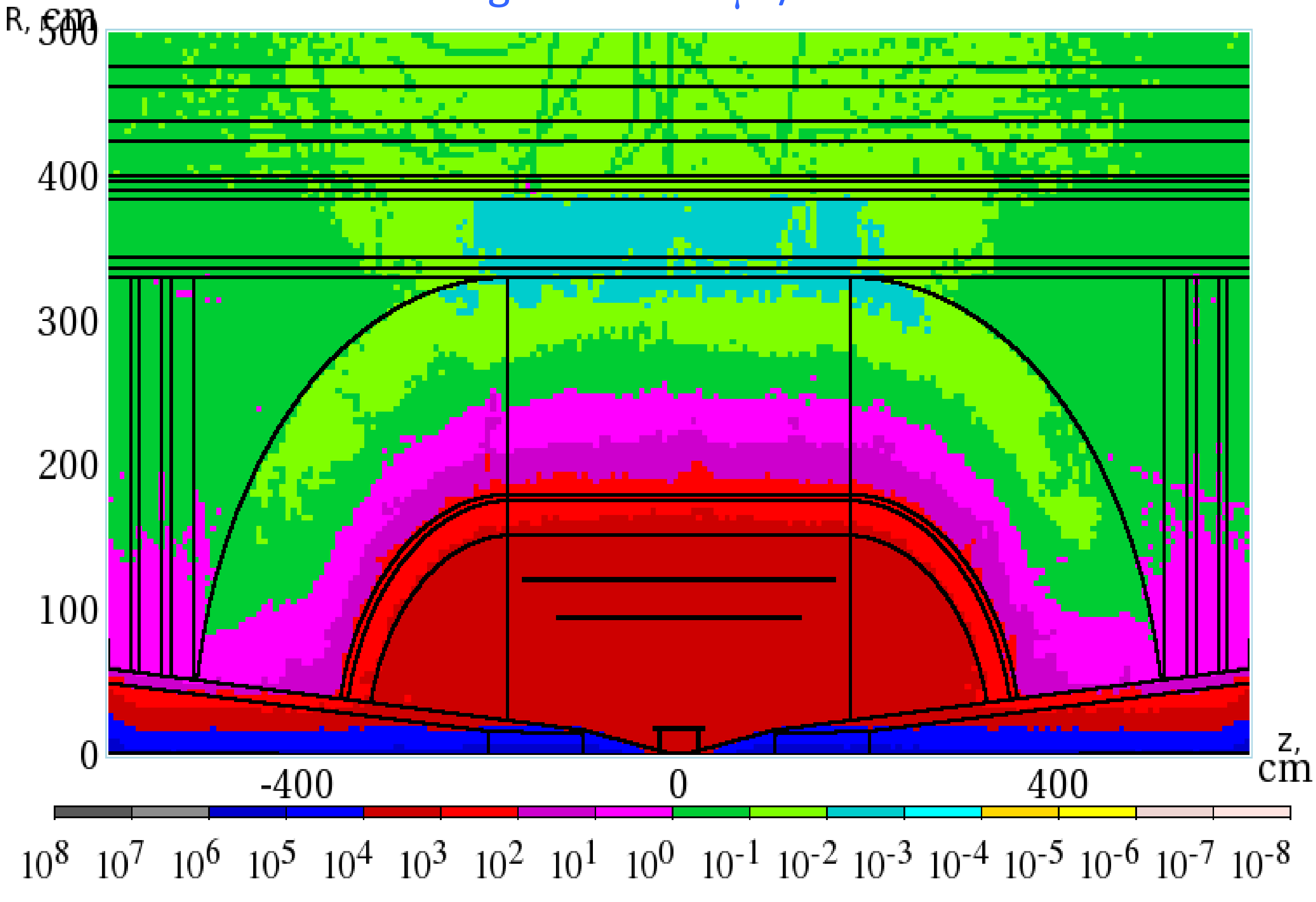


Fermilab

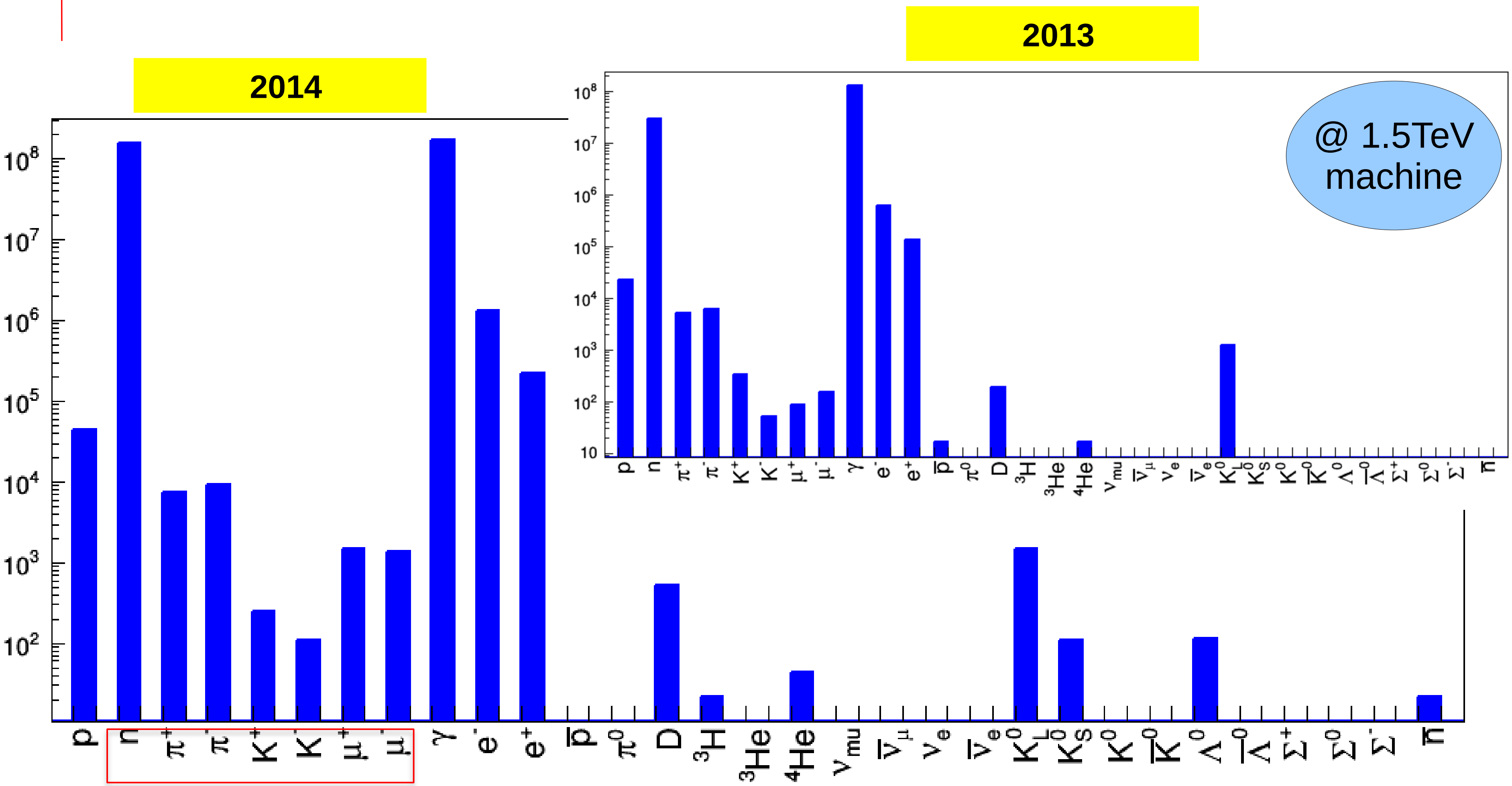
Overall Background – 1.5 TeV

Detectors must be rad hard
Dominated by neutrons – smaller radial dependence

Non-ionizing background ~ .1 x LHC
But crossing interval 10μs/25 ns 400 x



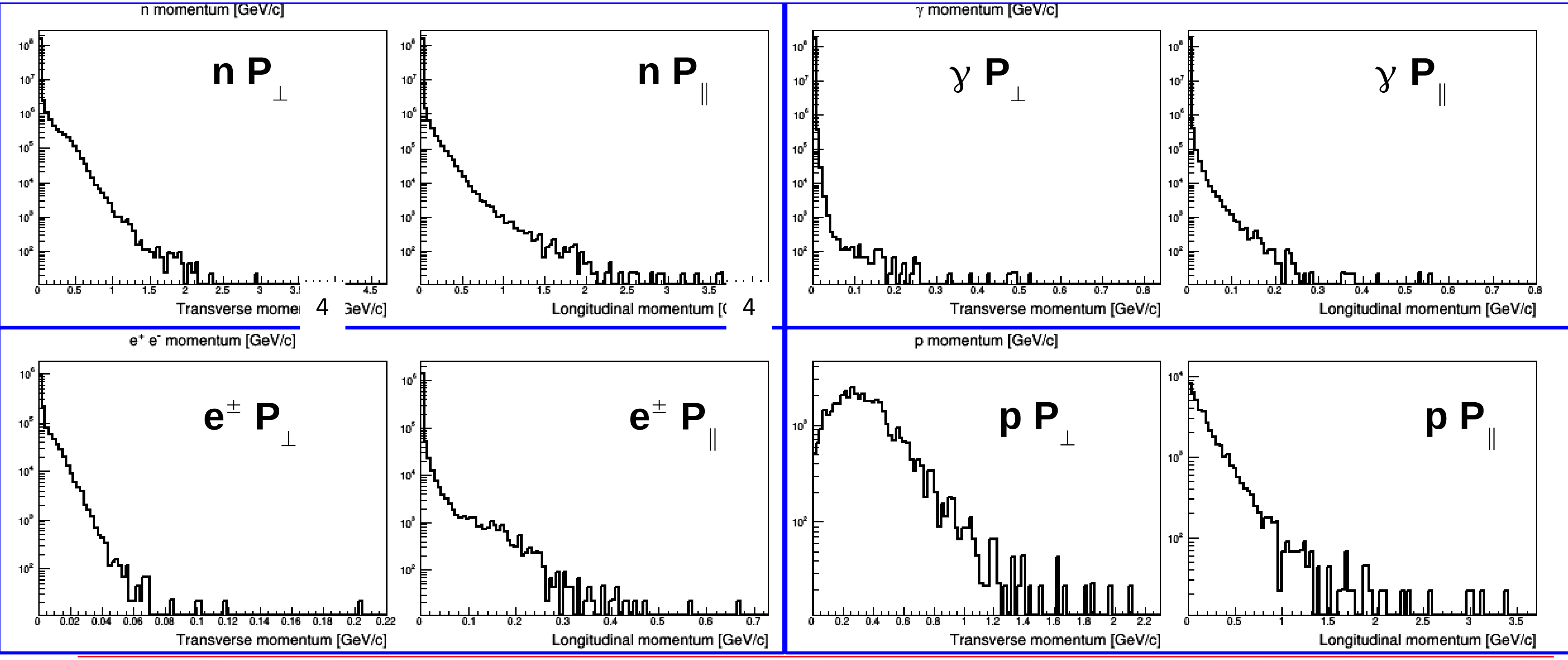
Background Distributions



Mostly neutrons, photons and conversions

Background Energy Distributions

Generally soft

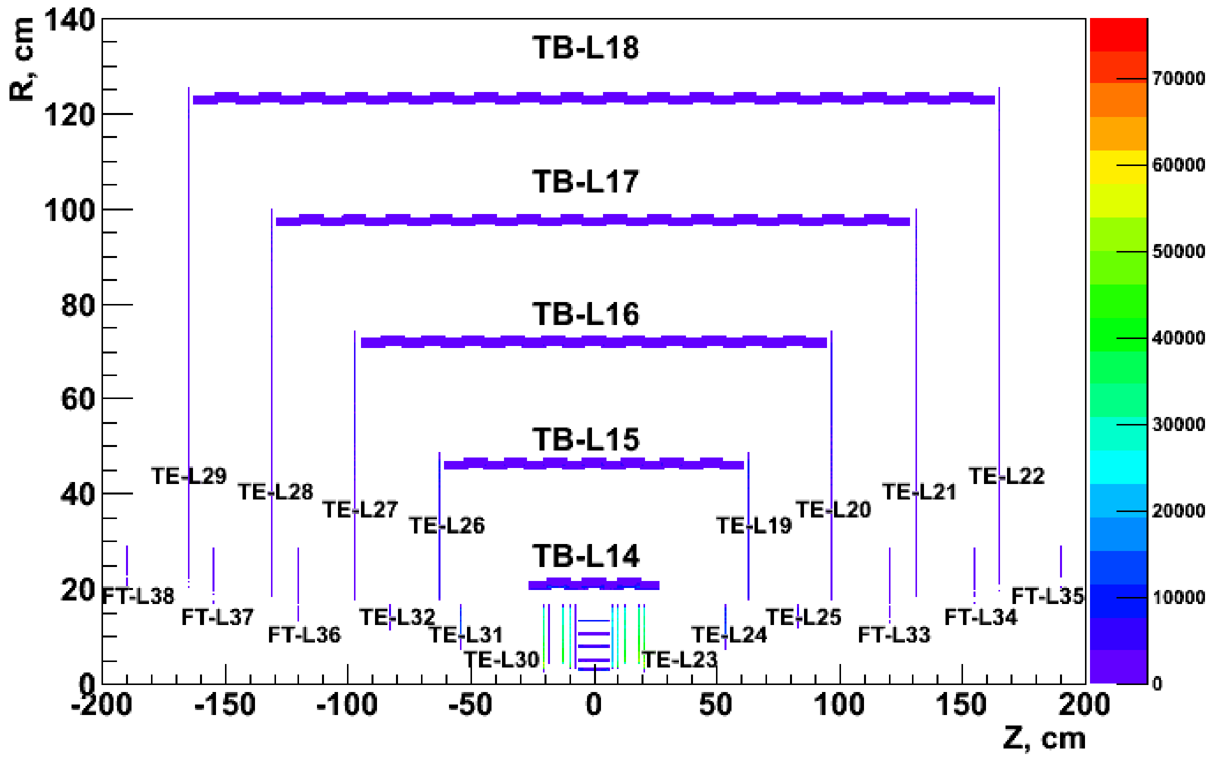


Attacking the Background

- Timing and energy discrimination will be crucial in limiting the background in a Muon Collider
  - Initial studies were conservative, assuming ns-level timing. ~30 ps timing now appears practical
  - TOF corrections are crucial to ID vertex tracks
- We concentrated on understanding the time resolution required and how it may affect the detector mass and resolution for physics objects
- Overall, the R&D was synergistic with CLIC, which requires ns level resolutions, and LHC which is looking at fast timing for background reduction, and intensity frontier experiments, which may require 10’s of ps resolutions

Tracker

- Hit R vs. Z for ILCRoot VXD and Tracker detector layers
  - Essentially a copy of the SiD tracker
  - TB – Tracker Barrel, TE – Tracker Endcap, FT – Forward Tracker

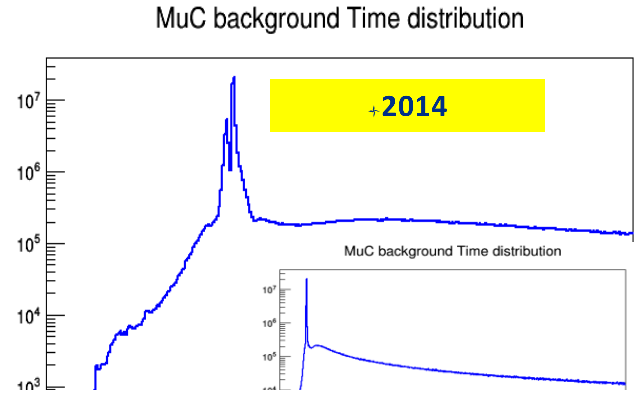


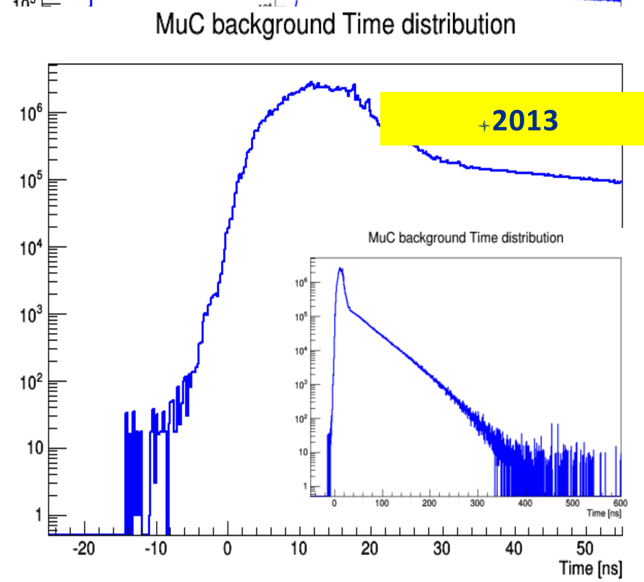
(N. Terentiev)

Background Cuts

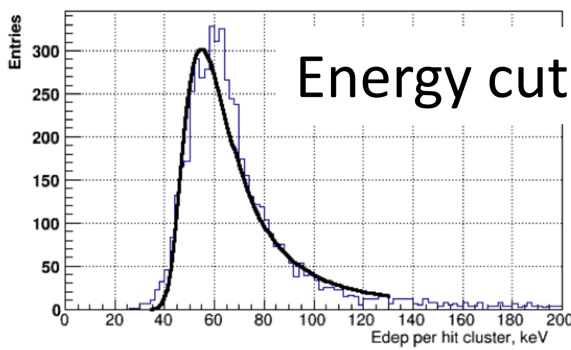
- We had relied heavily on timing for background rejection
- A timing bug in MARS meant we had to revise physics analyses after Snowmass
  - The peak level in the tracker at t=0 is about 4 orders of magnitude higher than before
  - The effects in the calorimeter are less dramatic
- Cuts
  - Timing with respect to muon
  - Energy deposition
  - Angle offsets

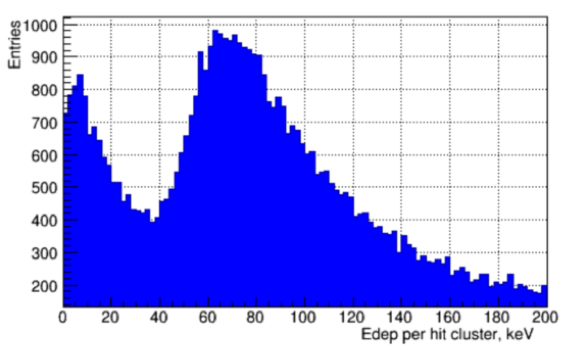
Time cuts

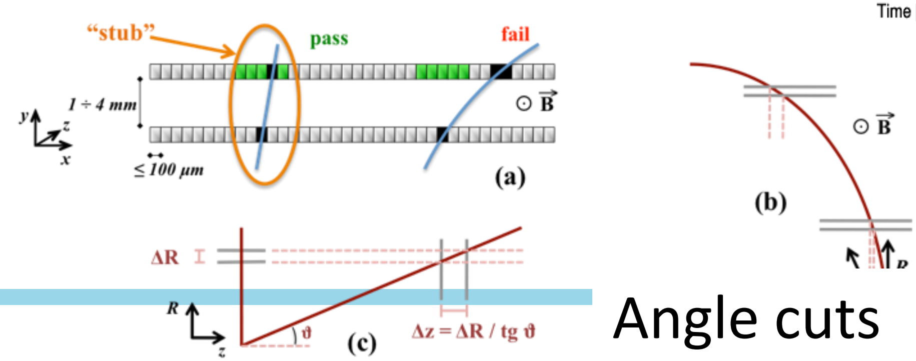




Energy cuts



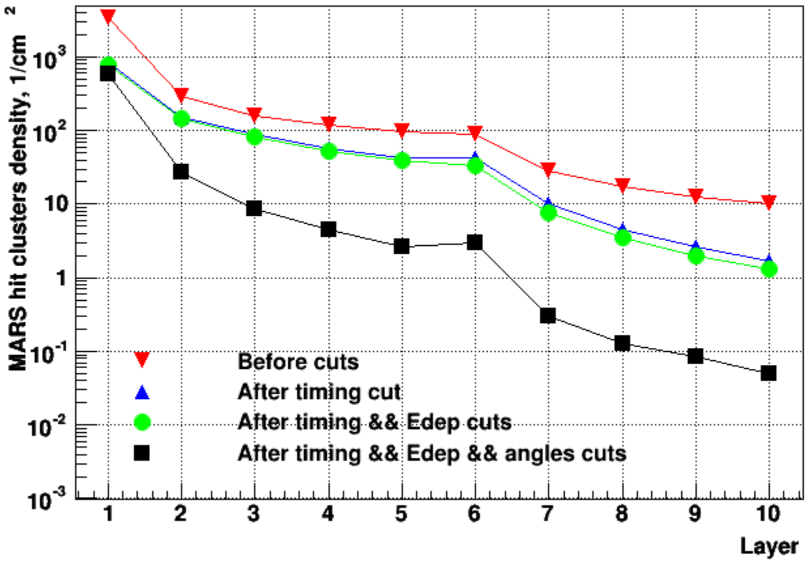




Angle cuts

lab

Tracker Cuts (N. Terentiev)



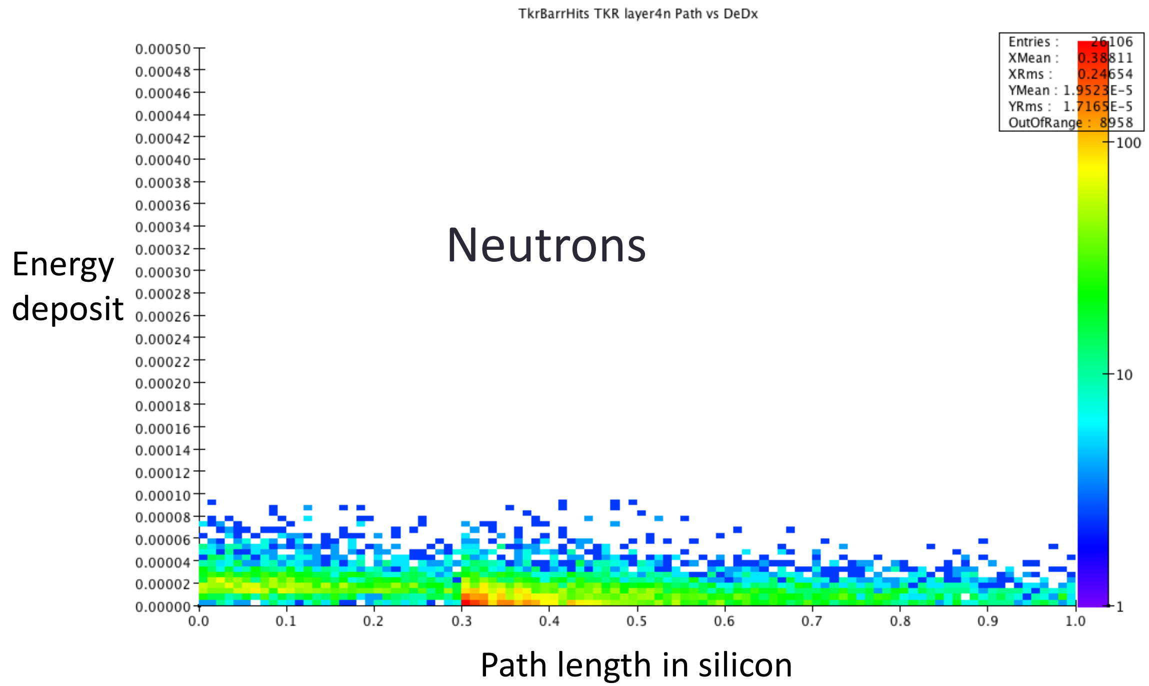
- VXD and Tracker cuts
  - timing gate width 0.9 ns (VXD) and 0.9 ns -
  - energy deposition, Z, layer dependent
  - Delta Phi
  - Delta Theta, depends on Z and layer
- At IP muon efficiency ~85%
  - MARS background fraction is ~17% in the innermost VXD layer
  - ~0.5% in the outermost Tracker layer
  - The density of MARS surviving hit clusters is ~580 cm^{-2} for innermost VXD barrel layer and ~0.05 cm^{-2} for outmost Tracker barrel layer.
- An additional calorimeter ROI cut had to be used for the physics analysis

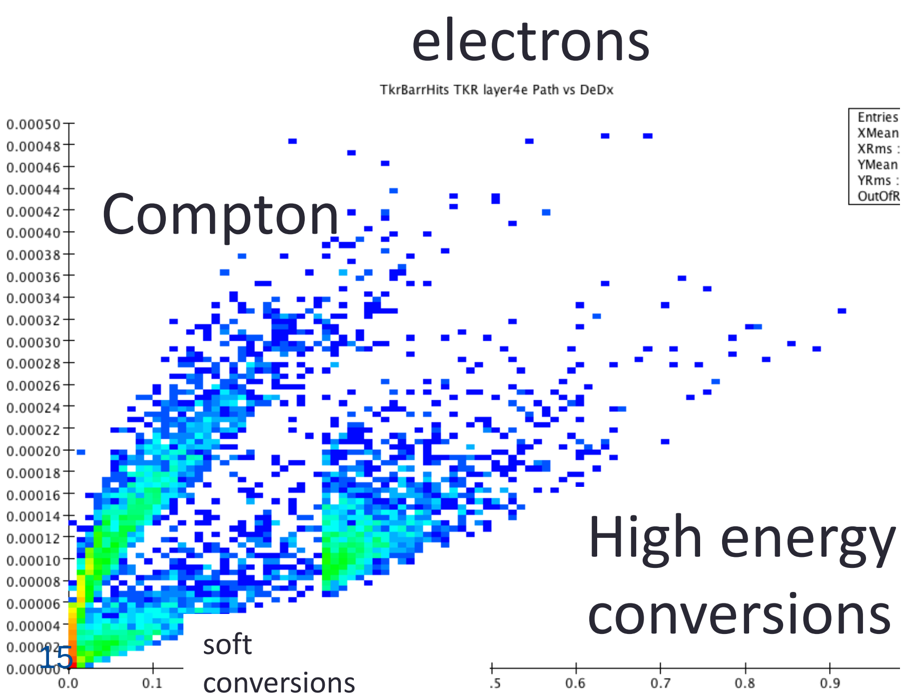
I think we can do much better than this study indicates

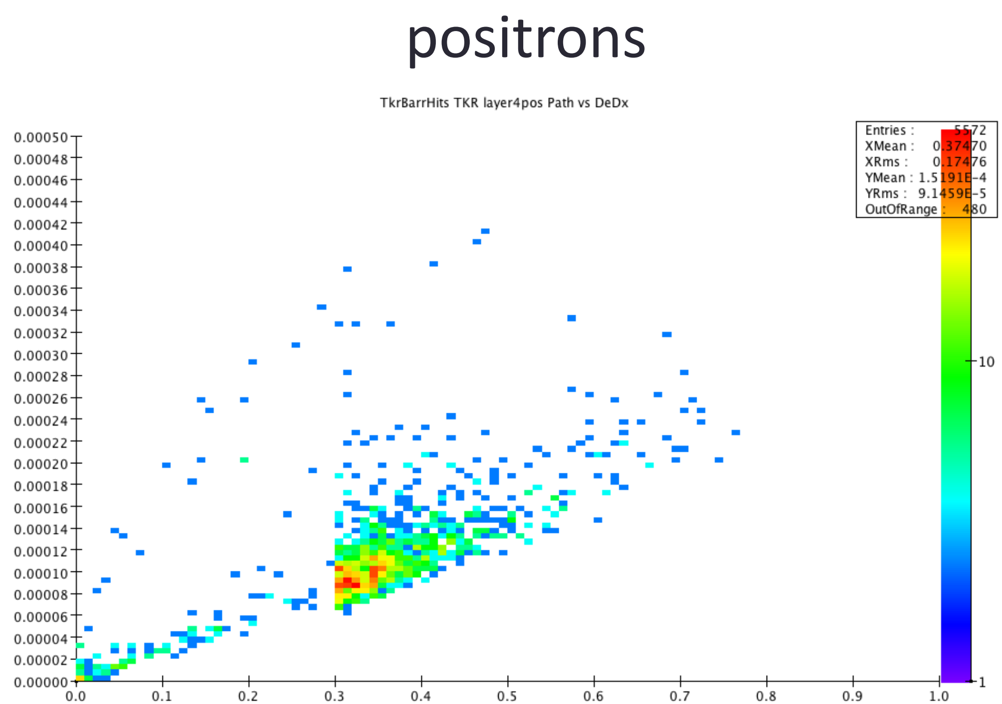
Needed – small pixels, fast (50ps) timing, fast correlation of hits in ϕ and θ

Energy deposits in Silicon layers (RL)

- Substantial background rejection by pulse shape is possible







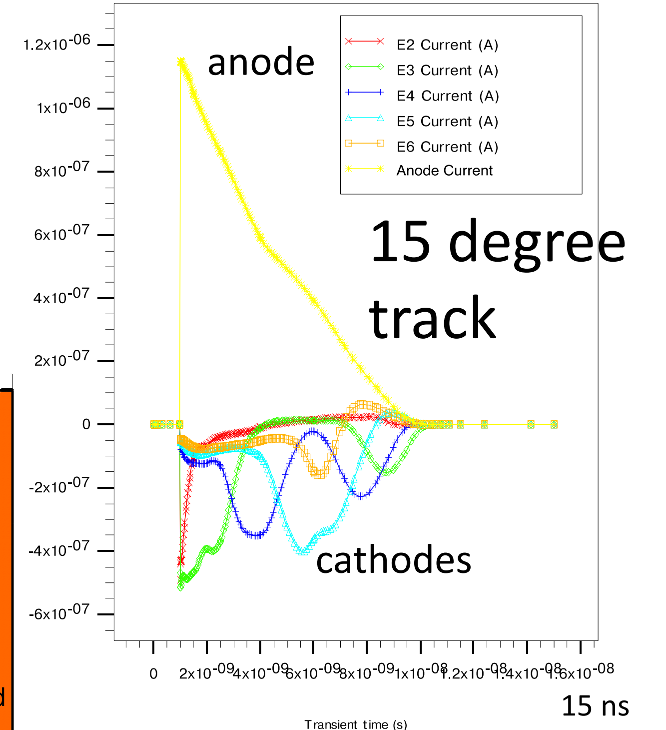
More sophisticated approaches to tracking

There have been substantial developments in tracking, 3D electronics fast timing and device engineering that should enable MUCH more sophisticated track pulse shape discrimination.

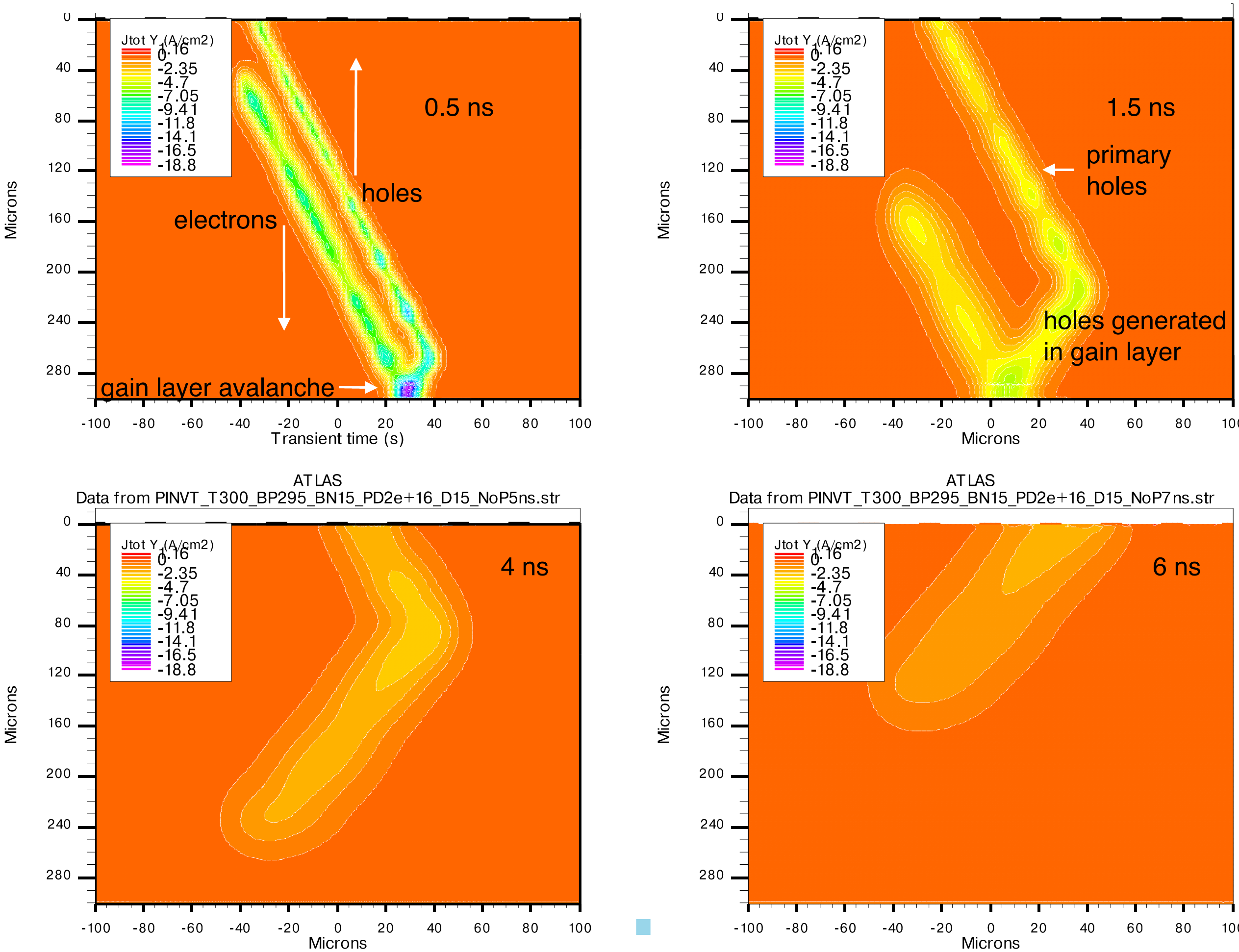
- LGADs to provide internal amplification and fast timing
  - AC LGADs add position resolution and fill factor
- 3D electronics to provide low capacitance small pixels with sophisticated processing
- Substrate engineering to manipulate charge within a detector
  - Much of the neutron background can be eliminated with pulse height and shape discrimination
  - Compton electrons can be addressed by pulse shape cuts
- MAPs for low cost, low mass fine pixel devices.

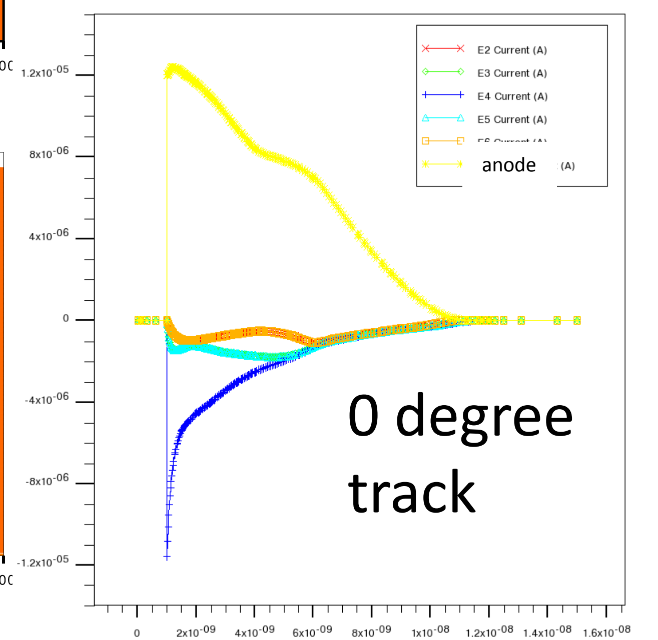
Example:Double Sided LGAD

Use anode for timing, cathodes for pulse shape discrimination



15 degree track detector internal current distributions



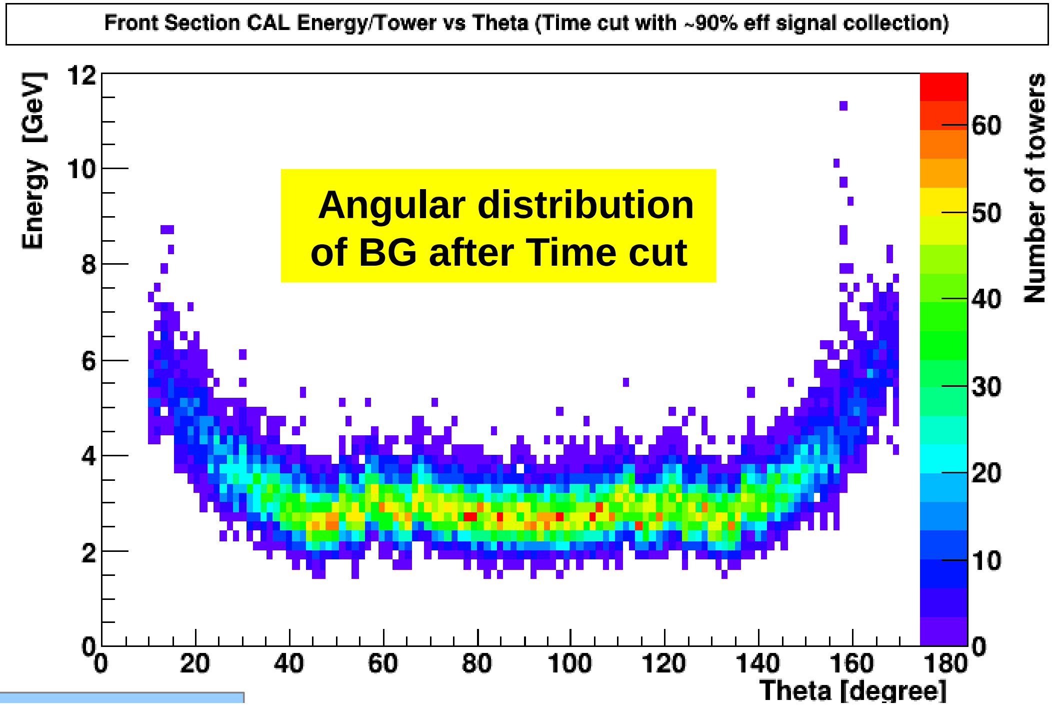


Calorimeter Backgrounds

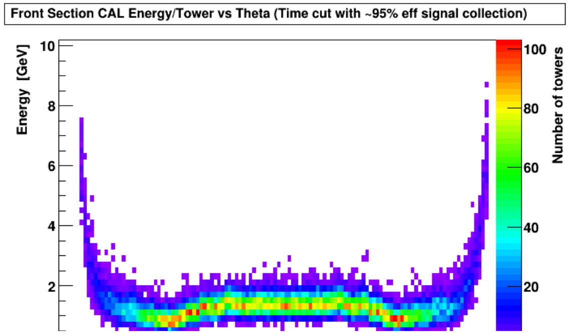
- Much of the calorimeter background is soft and electromagnetic
  - High occupancy in the first few radiation lengths
  - 2014 study used a time cut and front/back segmentation
  - Background pedestal was subtracted.

forward endcap region.

2014



2013



Time Development of Hadron Showers

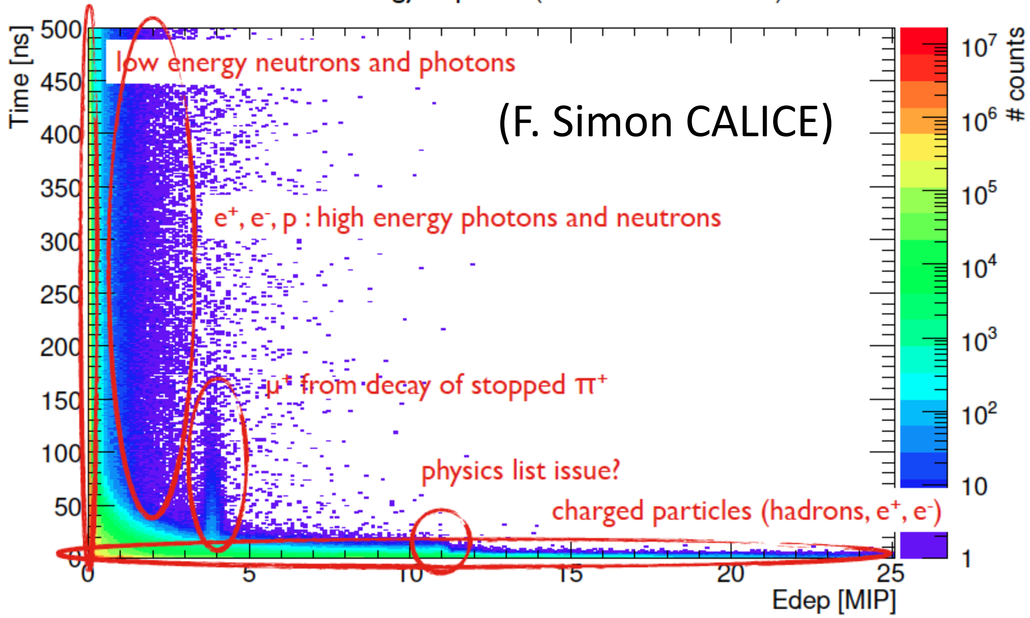
The problem of hadron calorimetry at CLIC and a Muon Collider is interesting…

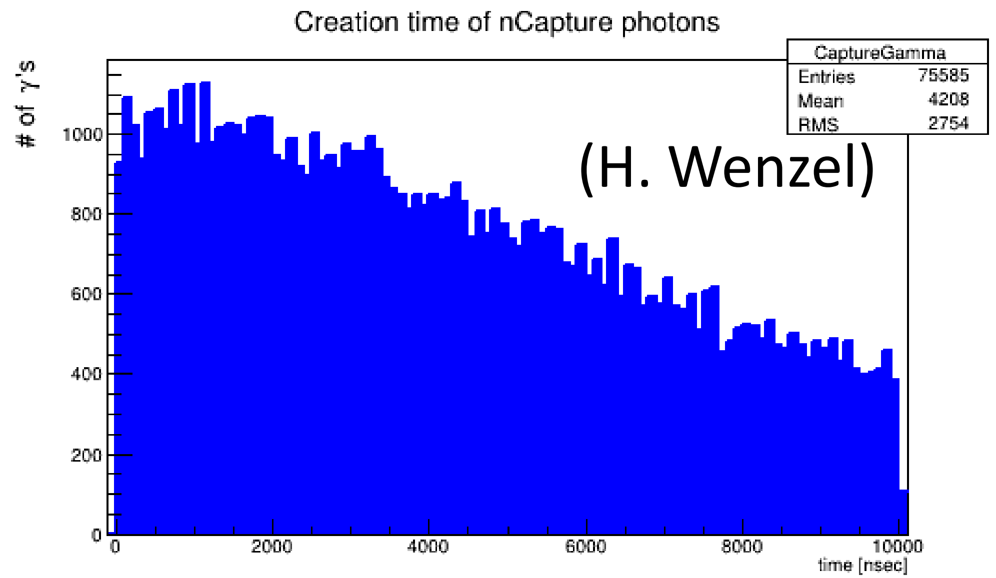
- Hadron showers take time to develop – nuclear processes can take more than the ns time scale we would like for μC

n→ thermalize → neutron Capture → γ → visible Energy

(mean Time: 4.2 μ sec)

- Geant4 simulation of a 30 layer Scintillator-W calorimeter (QGSP_BERT)
  - Time distribution of energy deposits (no detector effects!)





EM Calorimeter

I have not thought about this too much

Original studies used a dual-readout scheme - can this be improved?

- A CMS HGC/Calice design for the EM section with finer sampling seems to make sense
- Use deeper layers to define shower position
  - Fit to shower longitudinal and transverse shapes to remove background pedestal
  - Pointing of showers
- Some energy in a hadronic shower is delayed – how do time cuts affect this?

Fermilab

Last Slide

Given the time I have not had time to describe the physics studies. There were parametric studies of a Higgs factory, self coupling, width measurement, and full simulation of H/A with background at 1.5 TeV (huge effort)

- Some slides are attached

The Muon Collider has great potential

- There is a great deal of work needed to understand how to most effectively cope with decay backgrounds and take full advantage of the proposed machines.

We barely scratched the surface.

The Muon Collider is an exciting experimental and accelerator problem that may ultimately provide the breakthrough we need to progress beyond the standard model.

Physics studies - Higgs Factory

S-channel Higgs production affords the most precise measurement of the muon Higgs-Yukawa coupling, g_μ,

- precision $\delta g_\mu / g_\mu$ ~ (few)%.

The s-channel Higgs production affords the best mass measurement of the Higgs boson

- precision of ~(few) x10^{-6} with a luminosity of 10^{32} $cm^{-2}s^{-1}$.

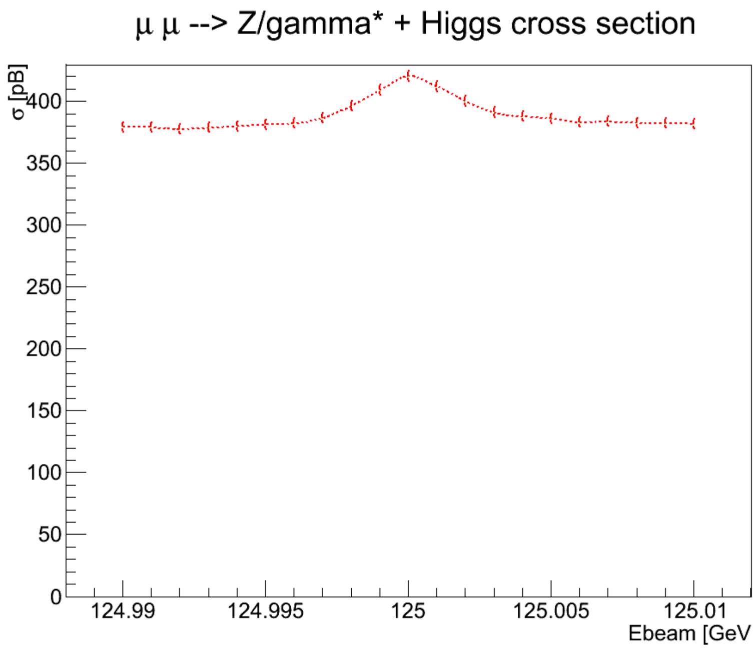
It affords the best *direct* measurement of the Higgs boson width to a

- precision of a few percent

(Analysis by Alex Conway with advice from Chris Hill, Estia Eitchen, RL)

Higgs Factory S/B

Higgs production in an S-channel factory still has significant SM background.



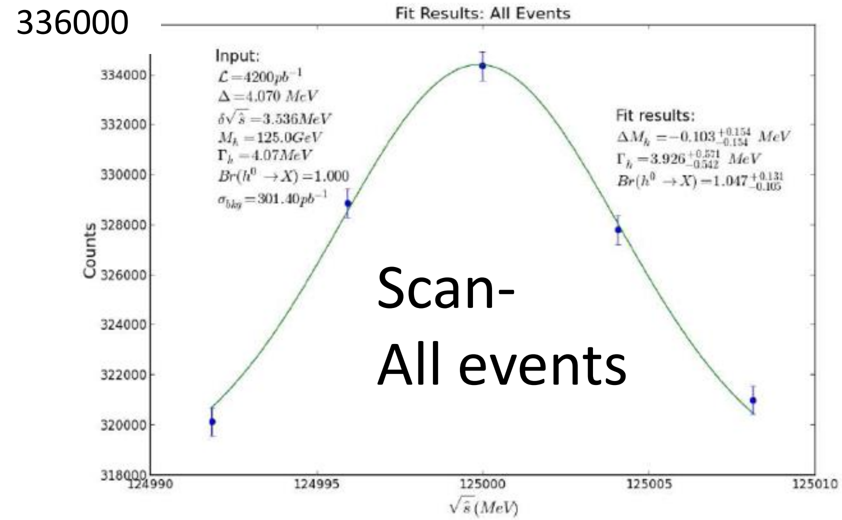
Decay Mode	Bkgr.	h	
	σ (pb)	BR	σ (pb)
$u\overline{u}, d\overline{d}, s\overline{s}$	56.0	0.0003	0.01
$c\overline{c}$	20.3	0.029	1.1
$b\overline{b}$	57.2	0.577	9.6
e^+e^-	9.2	—	—
$\mu^+\mu^-$	4.8	—	—
$\tau^+\tau^-$	9.2	0.063	2.4
$\nu_\ell \overline{\nu_\ell}$	75.2	—	—
gg	—	0.086	3.2
$\gamma\gamma$	27.6	0.002	0.07
WW^*	0.001	0.215	8.0
Z^0Z^0	—	0.026	0.97
Total:	259.6	1.0	25.5

cross sections are calculated as the peak value of the peak Breit-Wigner convoluted with a Gaussian of width 3.54 MeV to simulate the effect of beam smearing. The inclusion of initial state radiation effects and full one loop corrections further reduces the cross sections for Higgs production by a factor of 0.53; resulting in a total Higgs cross section of 13.6 pb.

Higgs Mass and Width

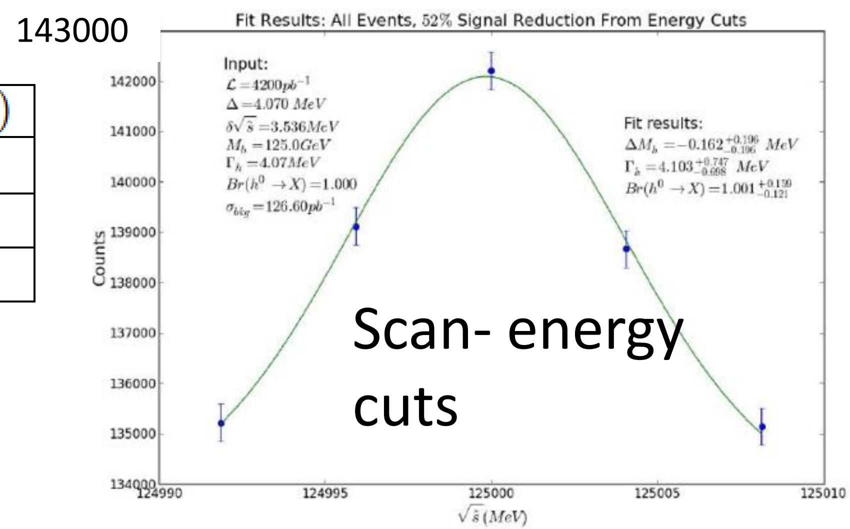
Fitted values of Higgs decay width, mass and branching ratio from simulated data. Mass values are the difference between the measured mass and the true mass of 126 GeV. Total integrated luminosity was 4.2 fb^{-1}

Channel		$\Gamma_{H\to X}(MeV)$	$\Delta M_H(MeV)$	$Br(h\to X)$
Total	Raw	3.9 ± 0.6	-0.10 ± 0.15	1.05 ± 0.13
	Cut	4.1 ± 0.7	-0.16 ± 0.19	1.0 ± 0.16
$b\bar{b}$	Raw	4.3 ± 0.5	0.1 ± 0.1	0.55 ± 0.05
	Cut	3.7 ± 0.4	-0.08 ± 0.1	0.60 ± 0.05
WW^*	Raw	$---$	$---$	$---$
	Cut	3.9 ± 0.2	0.06 ± 0.07	0.22 ± 0.01
$\tau^+\tau^-$	Raw	3.5 ± 2.0	0.00 ± 0.5	0.07 ± 0.05
	Cut	4.5 ± 1.5	-0.1 ± 0.4	0.06 ± 0.02



Channel	δM_H (MeV)	$\delta\Gamma_H$ (MeV)	$\delta Br(h\to X)$
$b\bar{b}$	0.1	0.4	0.05
WW^*	0.07	0.2	0.01
Combined	0.06	0.18	—

Accuracy of fitted parameters



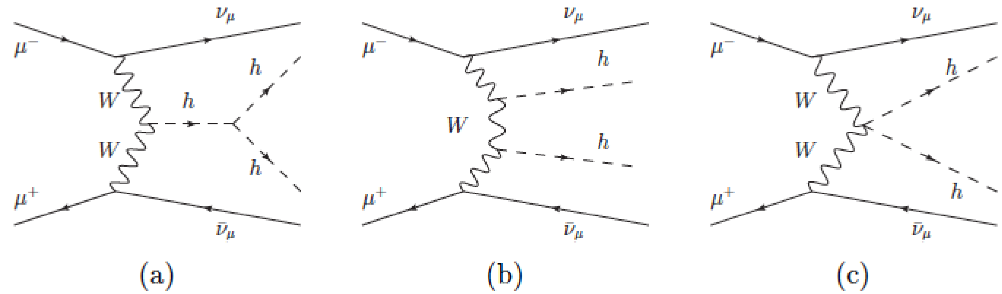
High Energy Collider Higgs Self-Coupling

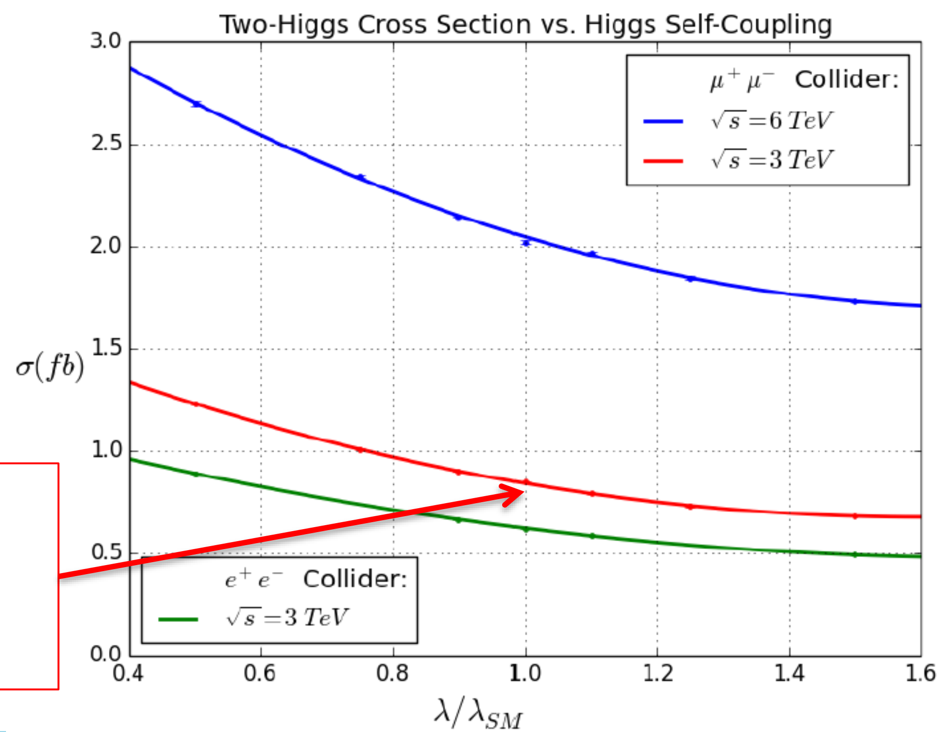
Measurement of the Higgs trilinear self-coupling is a direct probe of the shape of the Higgs potential and a crucial test of the Standard Model.

All future high energy accelerators are likely to address this measurement.

- A high energy (6 TeV) Muon collider would have the advantage of both higher luminosity and larger cross section
- CLIC may have larger acceptance

Study the tradeoffs …

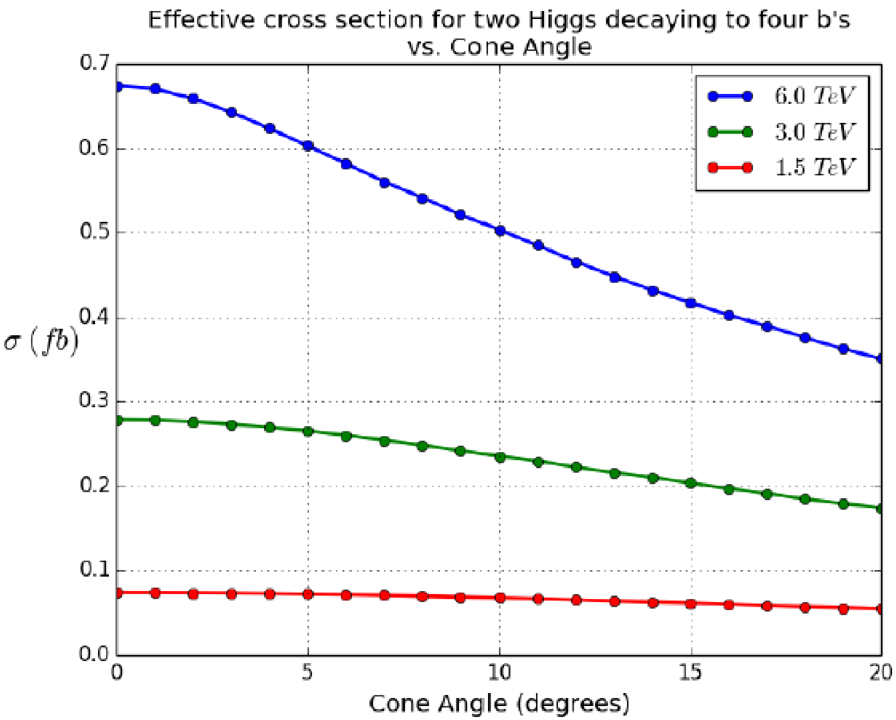




Variation of σ with λ provides the sensitivity

For now we take the CLIC analysis and scale the results to the event yield correcting for events lost to the cone.

- Losses due to the cone cut increase with E_{cm}, but the 6 TeV has about 2x the cross section for cone angles between 10 and 20 degrees



HH->4b, all 4 bs accepted

Tomas Lastovicka and Jan Strube. Measurement of the trilinear higgs self-couping at clic. Accessed online September 3, 2013at http://ilcagenda.linearcollider.org/getFile.py/access?contribId=66&sessionId=3&resId=0&materialId=slides&confId=5840.

Results obtained by scaling CLIC results – note that the values can be improved by utilizing polarization

	CLIC 3TeV	MuCo 3TeV	MuCo 6TeV
Cross Section (fb)	0.59	0.85	2.0
Avg. Luminosity ($10^{34} cm^-2 s^-1$)	5.4	4.4	12
Total Events per $10^7 s$	319	374	2400
Total Events per $3.7 \times 10^7 s$	1180	1380	8880
Acceptance	0.26	0.24	0.16
Total Accepted Events (N_{acc})	306	332	1420
$\sqrt{N_{acc}}/N_{acc}$	0.057	0.055	0.026
$\delta\sigma/\sigma$	0.1	0.1	0.05
R	1.52	1.53	2.08
$\delta\lambda/\lambda$	0.15	0.15	0.1

HL-LHC – evidence
ILC (20yr) – 13%
3 TeV CLIC (polarization) – 10%

Summary

- The physics reach of a Muon collider has tantalizing promise, with many unknowns
- It is challenging for both accelerator and detector technologies
  - An opportunity to explore and expand limits
- The utility of such a machine depends on the physics context
  - Precision physics > 3 TeV
  - Precision Higgs mass studies
  - Z'
  - ?
- A clear understanding of the capability of such a machine would take a significant focused effort for several years (CLIC example)

Summaries MAP 2014 winter meeting: https://indico.fnal.gov/event/8959/other-view?view=standard
Talks by Di Benedetto, Terentiev, and Lipton