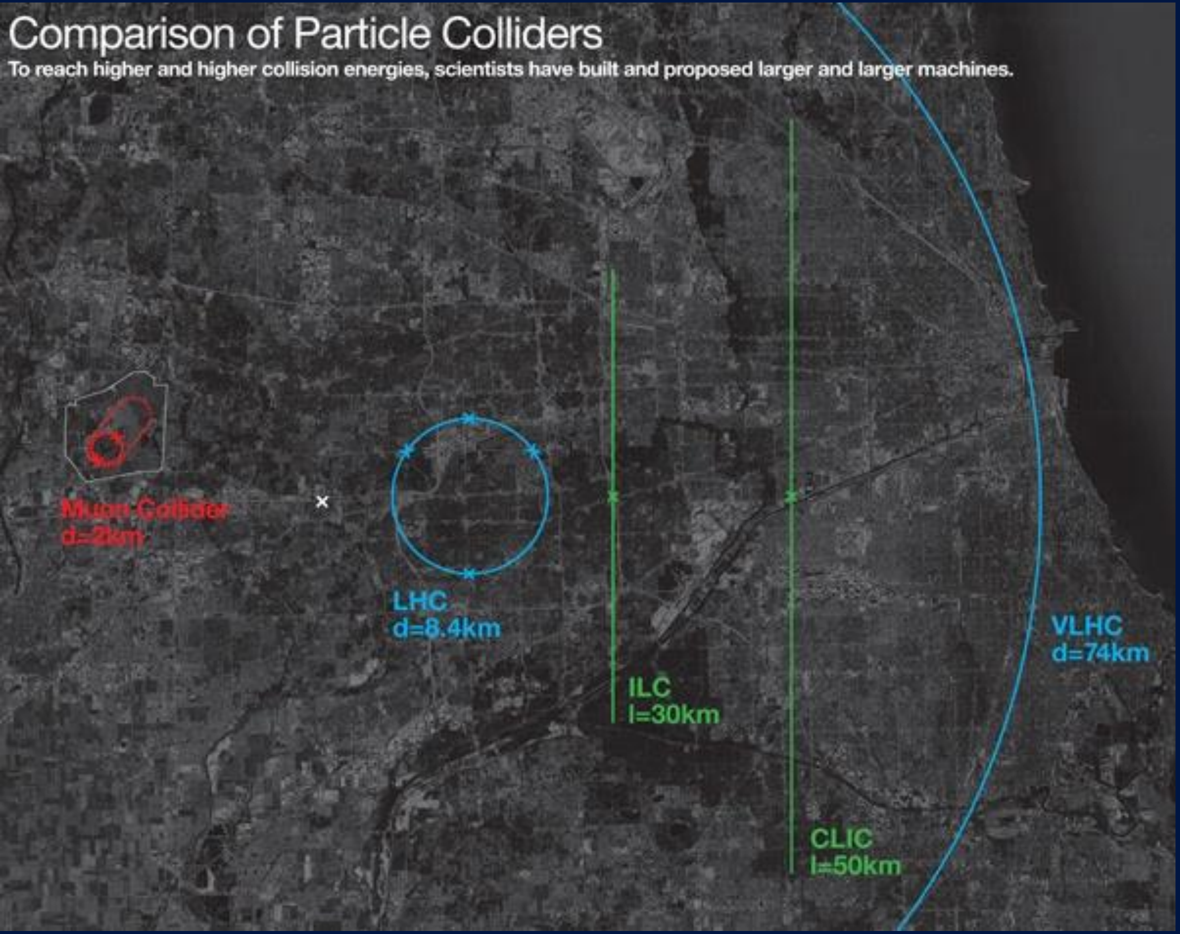
Muon Collider: Plans, Progress and Challenges

Ronald Lipton, Fermilab



Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.

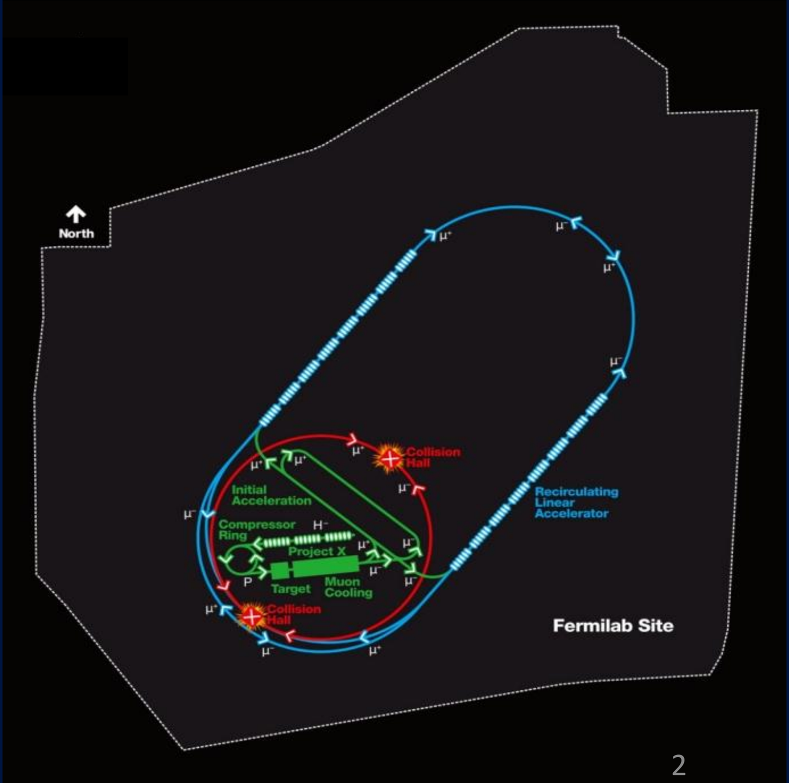
Outline

- Muon Collider Concept
- Muon Accelerator Program
- Machine Detector Interface Studies
- Physics and detector studies
- Future plans and outlook

Muon Collider Study Motivation

- Because muons don't radiate as readily as electrons (m_μ / m_e ~ 207) a muon collider can be circular rather then linear
- Compact
  - Fits on laboratory site
- Multi-pass acceleration
  - Cost effective operation & construction
- Multipass collisions in a ring (~1000 turns)
  - Relaxed emittance requirements & hence relaxed tolerances

A 4 TeV Muon Collider would fit on the Fermilab Site

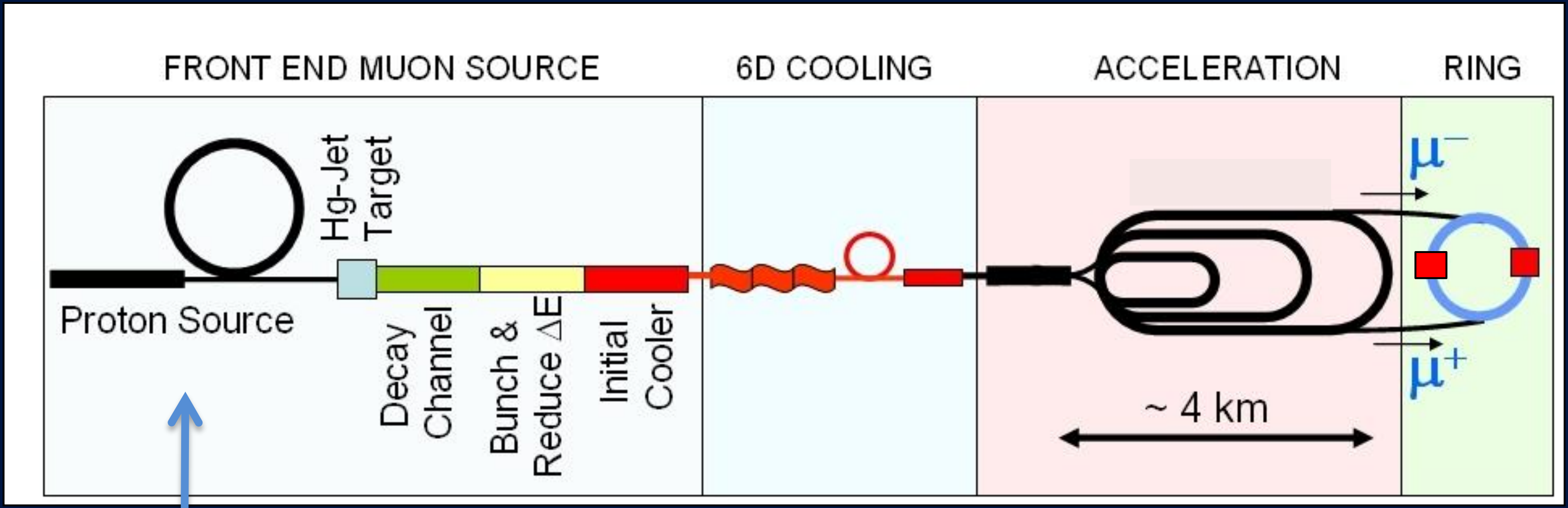


Much of the material in this talk from June Workshop in Telluride

Challenges

- Muons decay ⍰ A 1.5 TeV muon travels 9,300 km in one lifetime (~2000 turns in MuCol ring). Everything must be done fast *and* we must deal with the decay electrons.
- Muons are produced as tertiary particles. To make enough of them we must start with a MW scale proton source & target facility.
- Muons are born within a large phase-space. For a MC we must cool them by O(10^6) before they decay ⍰ New cooling techniques (ionization cooling) must be demonstrated, and it requires components with demanding performance (NCRF in magnetic channel, high field solenoids.)
- After cooling, beams still have relatively large emittance

Muon Collider Schematic



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

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

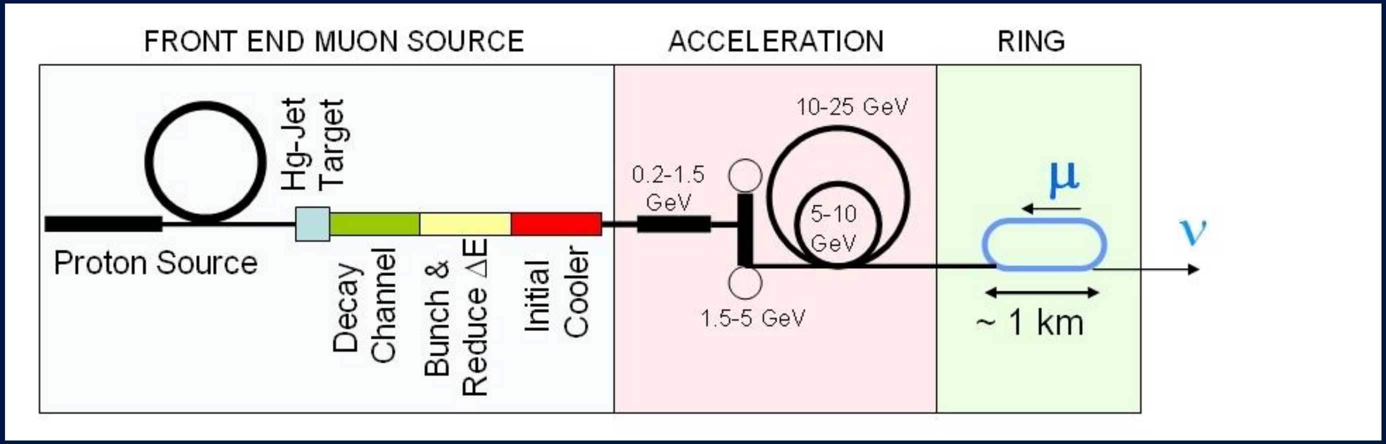
$\varepsilon_{\perp N}$=6000 μm
$\varepsilon_{//N}$=25 mm

$\sqrt{s}$ = 3 TeV
Circumference = 4.5km
$\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
μ/bunch = 2×10^{12}
σ(p)/p = 0.1%
$\varepsilon_{\perp N}$ = 25 μm, $\varepsilon_{//N}$=70 mm
β* = 5mm
Rep Rate = 12Hz

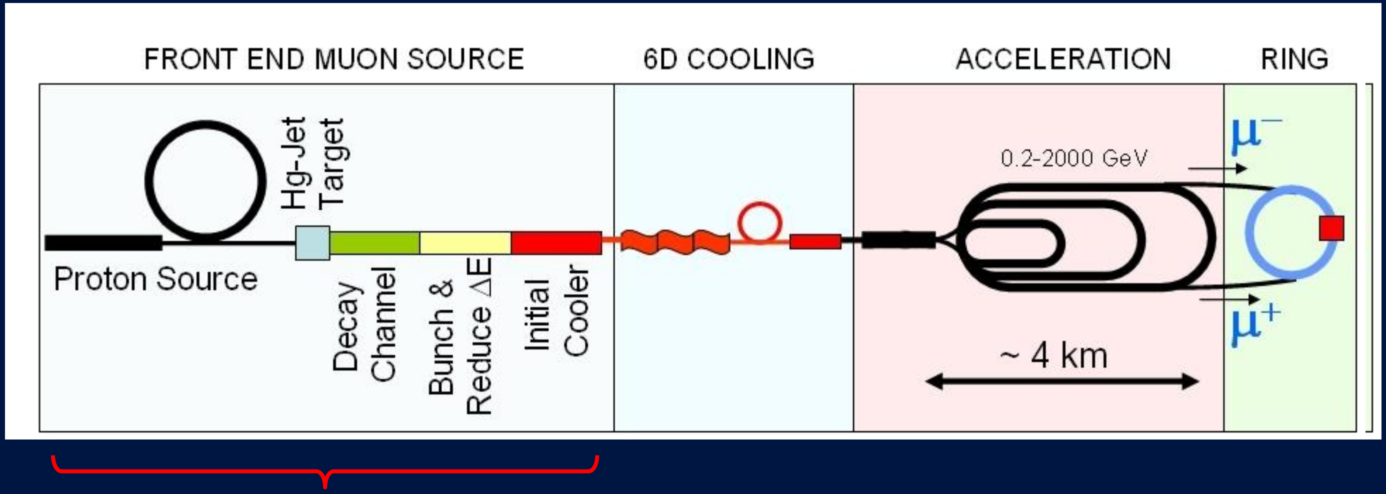
Ronald Lipton 8/11/2011

(Geer)

Neutrino Factory c.f. Muon Collider



NEUTRINO FACTORY



MUON COLLIDER

In present MC baseline design, Front End is same as for NF

(Geer)

Muon Accelerator Program

- Oct 1, 2009 letter from DOE-OHEP to FNAL Director:

> "*Our office believes that it is timely to mount a concerted national R&D program that addresses the technical challenges and feasibility issues relevant to the capabilities needed for future Neutrino Factory and multi-TeV Muon Collider facilities. ...* "

- Letter requested a new organization for a national Muon Collider & Neutrino Factory R&D program, hosted at FNAL.

- **M**uon **A**ccelerator **P**rogram organization is now in place & functioning: >200 participants from 15 institutions:
  - ANL, BNL, FNAL, JLab, LBNL, ORNL, SLAC, Cornell, IIT, Princeton, UCB, UCLA, UCR, U-Miss, U. Chicago
  - http://map.fnal.gov/

Accelerator Challenges

- Ionization Cooling
  - Very high field (40T) high temp superconducting magnets
  - 6 dimensional cooling
- RF breakdown in magnetic fields
- Neutrino radiation (< 10% x DOE limit at site boundary?)
  - Probably OK at 1.5 TeV, harder at 3 TeV
  - Must limit length of straight sections (~ meters) – go deeper?
- Magnet shielding from beam decay heat loads

Are any of these deadly to the Muon Collider concept? – MAP should be able to tell us.

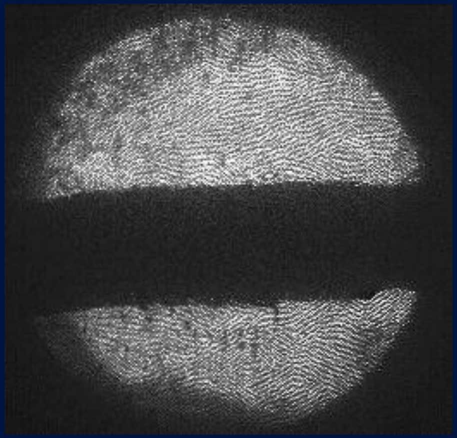
- More details from M. Zisman talk yesterday

MC Ring Parameters (Y Alexahin + RL modifications

				CLIC
C of m Energy	1.5	3	TeV	3
Luminosity	1	2 (4)	10^{34} cm^{2}sec^{-1}	2
Beam-beam Tune Shift	0.087	0.087		
Muons/bunch	2	2	10^{12}	
Total muon Power	7.2	11.5	MW	14
Ring $<$bending field$>$	6.04	8.4	T	
Ring circumference	2.6	4.5	km	
β^* at IP $= \sigma_z$	10	10 (5)	mm	4/.07 mm
rms momentum spread	0.1	0.1	%	29
Wall Power	147	159	MW	~415
Beam Size at IP	4	4	μm	0.001
Repetition Rate	15	12 (15)	Hz	
Proton Driver power	4	3.2 (4)	MW	
Muon Trans Emittance	25	25	pi mm mrad	660/20 nm
Muon Long Emittance	72,000	72,000	pi mm mrad	

Muon Accelerator R&D

Merit at CERN - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid, & hit with a 115 KJ / pulse beam.

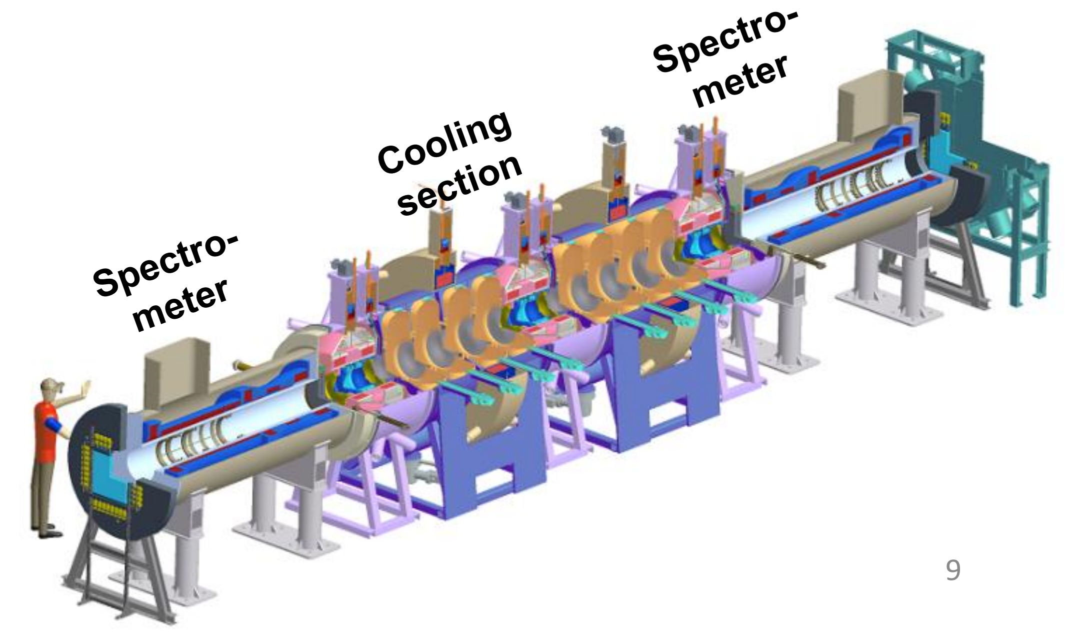


Hg jet in a 15 T solenoid
Measured disruption length = 28 cm

Muon Ionization Cooling Experiment (MICE) AT RAL

- Tests short cooling section, in muon beam, measuring single muons before & after the cooling section.
- Learn about cost, complexity, & engineering issues associated with cooling channels.
- Vary RF, solenoid & absorber parameters & demonstrate ability to simulate response of muons

To be completed ~2014



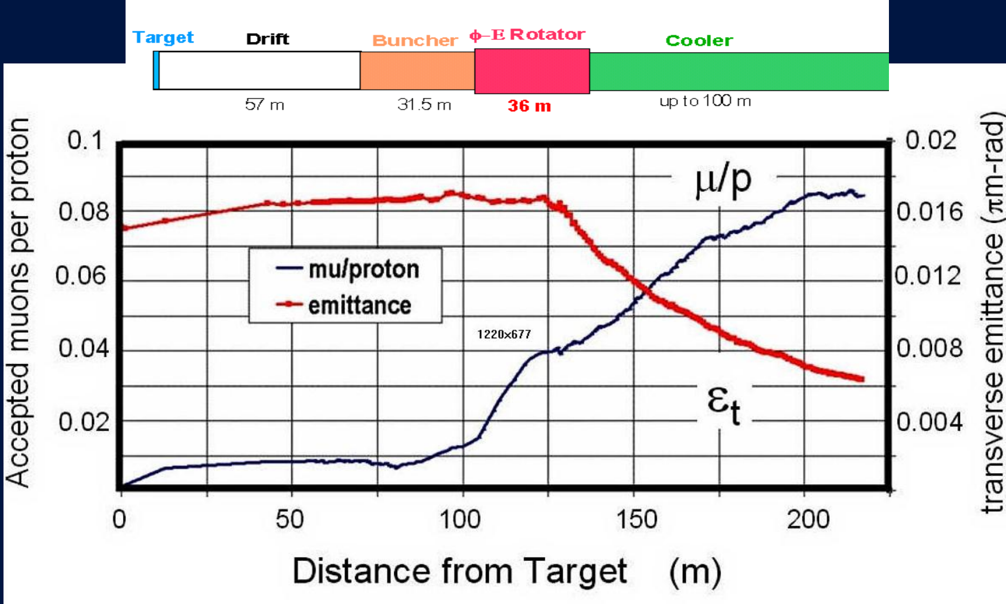
Front End and Cooling Channel Design

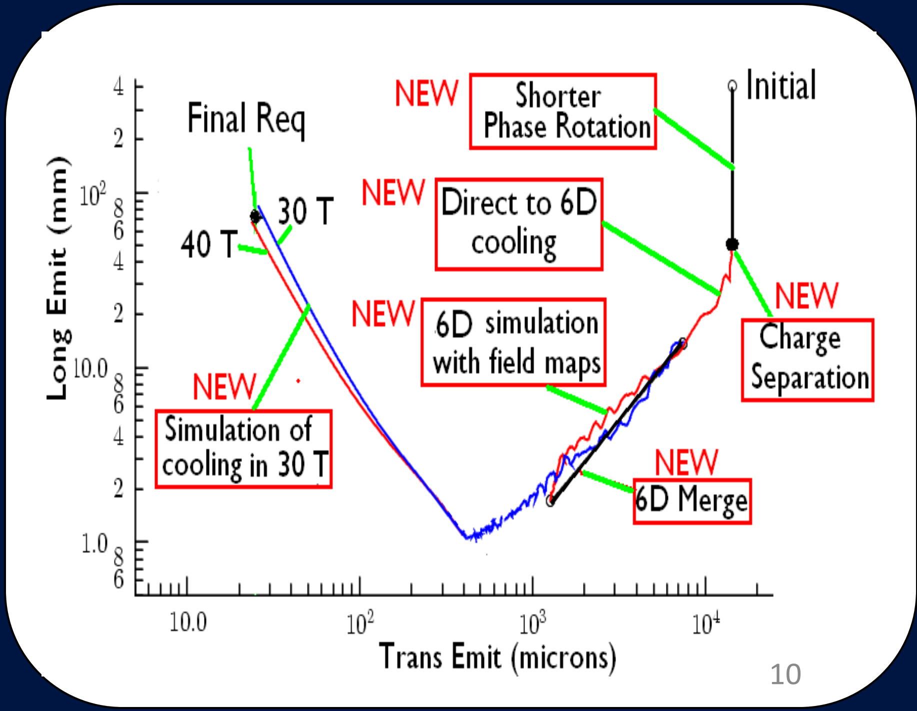
Front End

- With a 4MW proton source, this will enable O(10^{21}) muons/year to be produced, bunched, cooled & fit within the acceptance of an accelerator

Cooling Channel

- Perhaps the most challenging piece of MC design. Requires ideas & detailed design work to identify a set of hardware that can do the job.





Ring and Magnet
Mucool

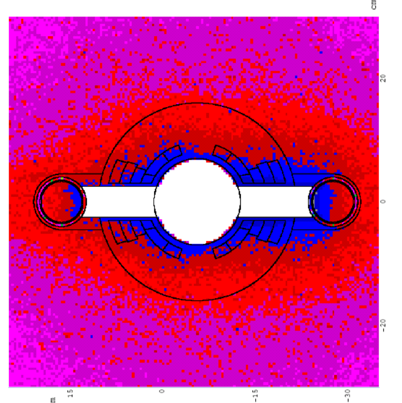
Ring and Magnet

- Lattice design for 1.5 TeV Collider exists, & 3 TeV ring progressing.
- Requires lattice, magnet & MARS simulation
- Studying open mid-plane magnet design (radiation & heat loads, field non-uniformity & affect on lattice performance)

MuCool Test Area

- Built at end of FNAL Linac for ionization cooling testing
- 5 T magnet, RF power at 805 MHz & 201 MHz, clean room, LH_2 handling capability, 400 MeV beam from linac.
- Study RF breakdown in magnetic fields → critical R&D at MTA

First beam in MTA 28 February 2011



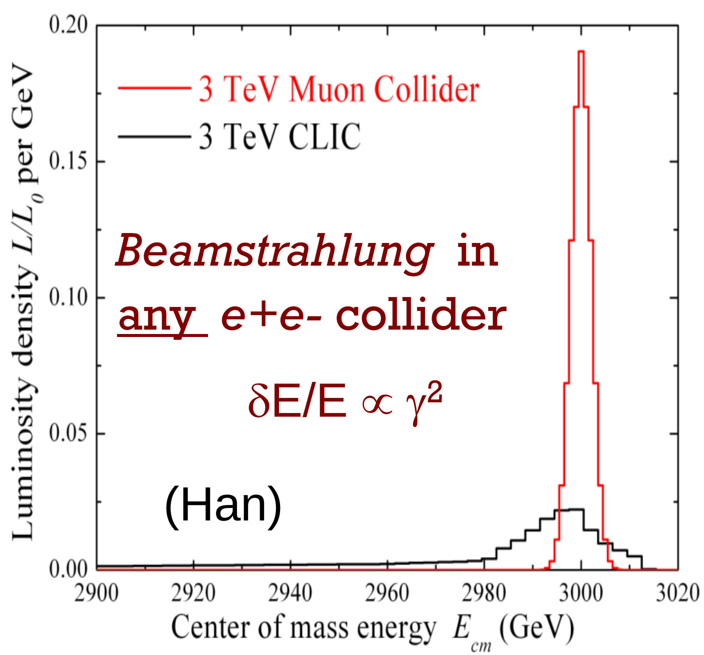
MARS energy deposition map for 1.5 TeV collider dipole

Physics and Detector

- Although there is a revived muon accelerator effort, there has been little corresponding detector effort which could study the large beam-related backgrounds with modern simulation tools and detector technologies
- Beginning such an effort is crucial to understanding the physics reach of such a device and beginning a program to explore detector development for the muon collider environment.
- It is also crucial for community buy-in
- This effort was commissioned at the Muon Collider 2011 meeting in Telluride at the end of June.

Physics Environment

- Narrow beam energy spread
  - Precision scan
  - Kinematic constraints
- 2 Detectors
- ΔT_{bunch} ~ 10 μs
  - Lots of time for readout
  - Backgrounds don't pile up
- $(m_\mu/m_e)^2$ = ~40000
  - Enhanced s-channel rates for Higgs-like particles
- Multi-TeV lepton collider cross sections dominated by fusion

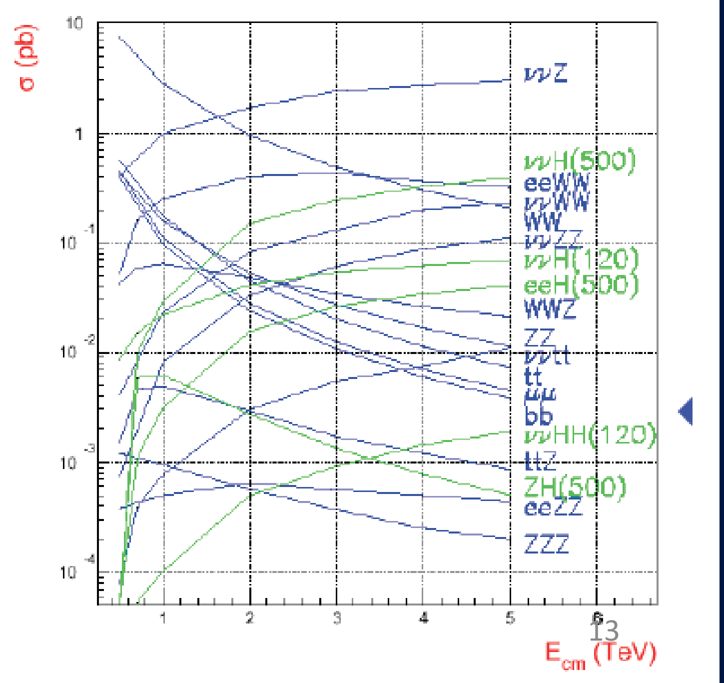


Beamstrahlung in <u>any</u> e+e- collider

$\delta E/E \propto \gamma^2$

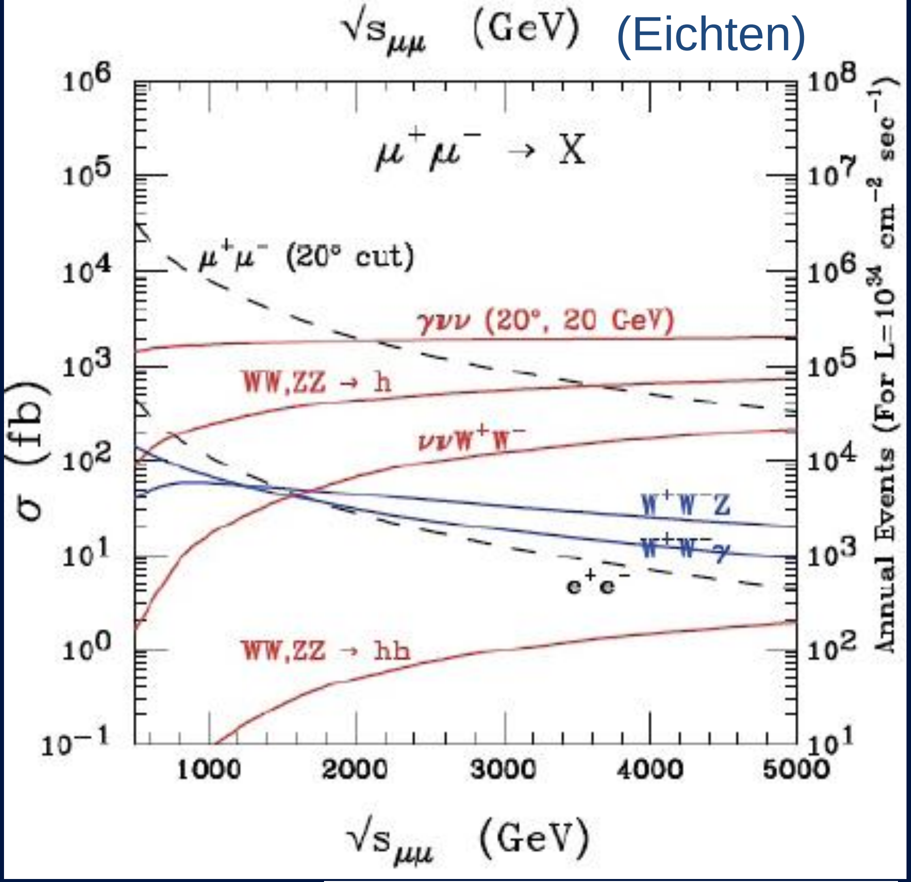
(Han)

CLIC (or MC e<->μ)

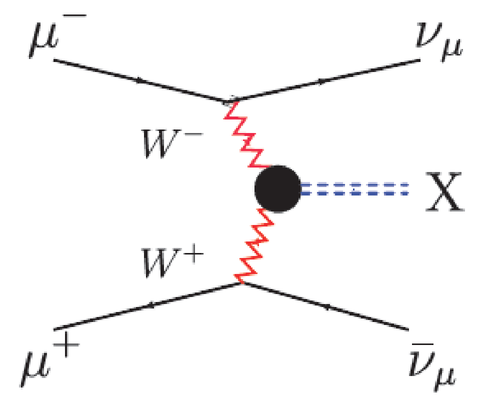


Luminosity Goals for High Energy Muon Collider

- L~10^{34} at 3 TeV provides ~ 965 events/unit R
  - Much of the yield is in fusion reactions
  - Need to resolve W, Z jets
  - Large missing energies
- Physics environment similar to CLIC with lower beamstrahlung, higher decay backgrounds, lower polarization and central 10 degrees obscured by “the nose”



(Eichten)



$$\sigma(s) = C\ln\left(\frac{s}{M_X^2}\right) + \cdots$$

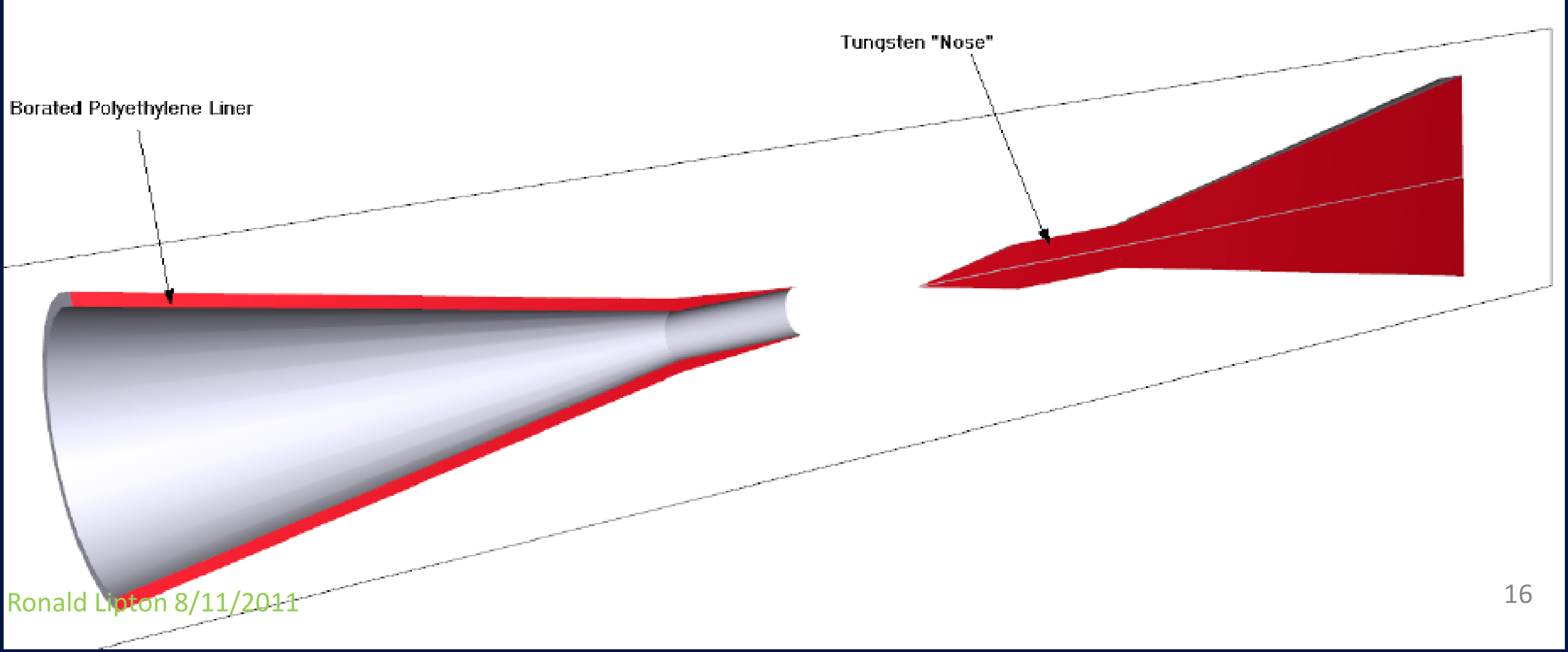
For Experimenters - It’s All About the Background

Experiments at the Muon Collider will endure very harsh background environments. The first order of business in evaluating physics capabilities is to understand and simulate the machine backgrounds.

- IP $\mu^+\mu^-$ collisions – real physics: Production x-section 1.34 pb at $\sqrt{S}$ = 1.5 TeV.
- IP incoherent e^+e^- pair production: of 3×10^4 electron pairs per bunch crossing
- Muon beam decays: For 0.75-TeV muon beam of $2\text{x}10^{12}$, $4.28\text{x}10^5$ dec/m per bunch crossing, or $1.28\text{x}10^{10}$ dec/m/s for 2 beams; 0.5 kW/m.
- Beam halo: Beam loss at limiting apertures; severe, can be taken care of by an appropriate collimation system far upstream of IP.

The Nose

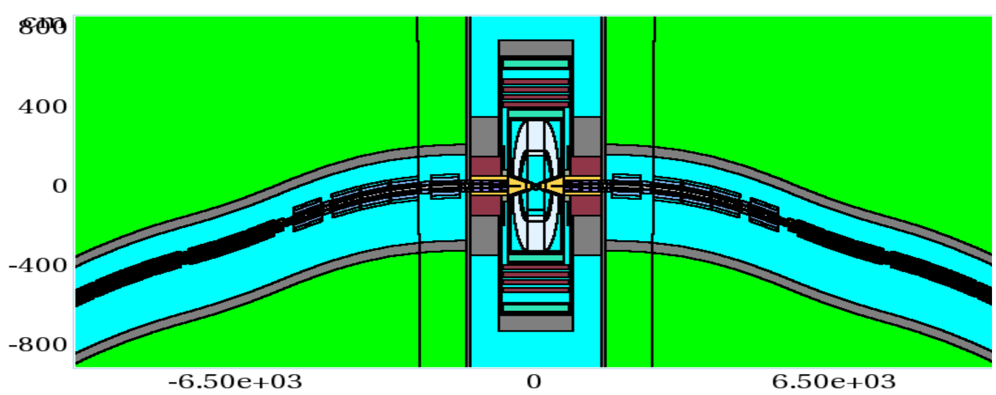
- Ivan Yakovlevitch … glanced into the roll's middle. To his intense surprise he saw something glimmering there .. He stuck in his fingers, and pulled out — a nose! .. .A nose! Sure enough a nose! Yes, and one familiar to him, somehow! Oh, horror spread upon his features! - “The Nose” Gogol (from google)
- A 10 degree tungsten/borated poly “noise”surrounds the beam pipe to absorb the e-m backgrounds 100-1000x background reduction.

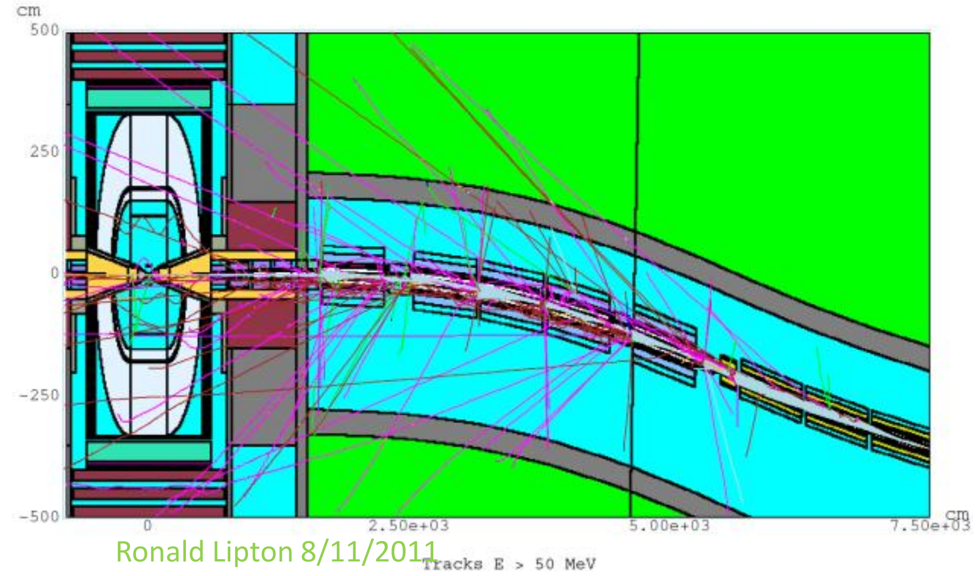


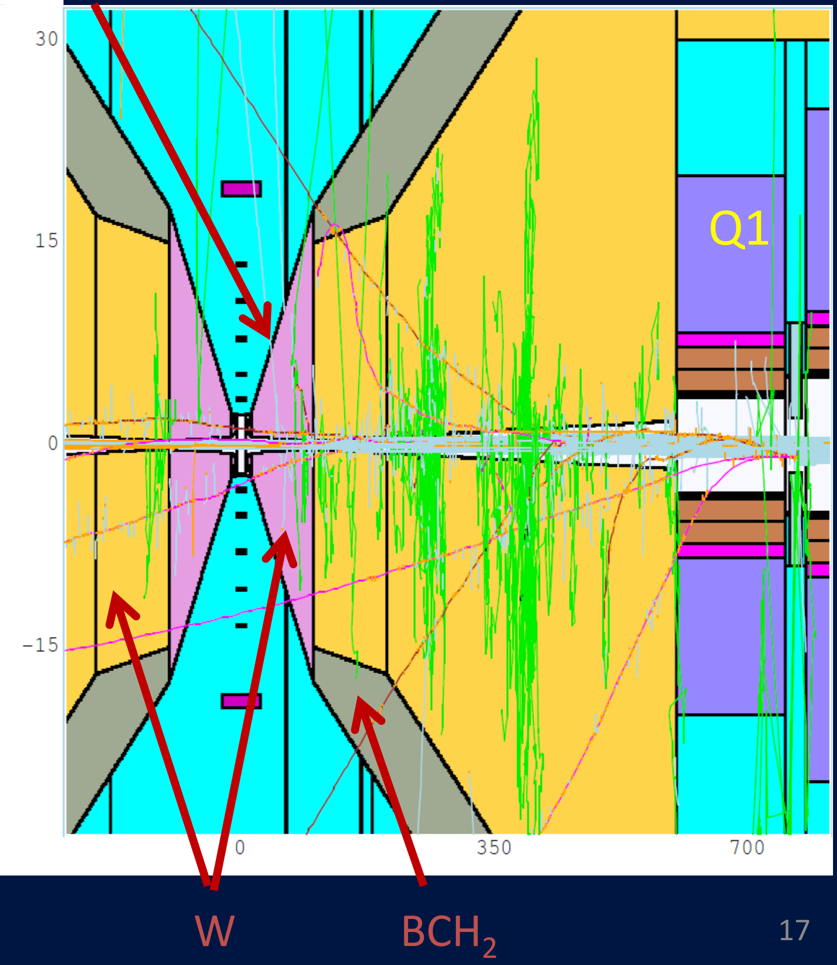
Machine Detector Interface Model

There has been excellent progress in modeling the intense decay backgrounds . Accurate background simulations are now available from MARS and G4beamline

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

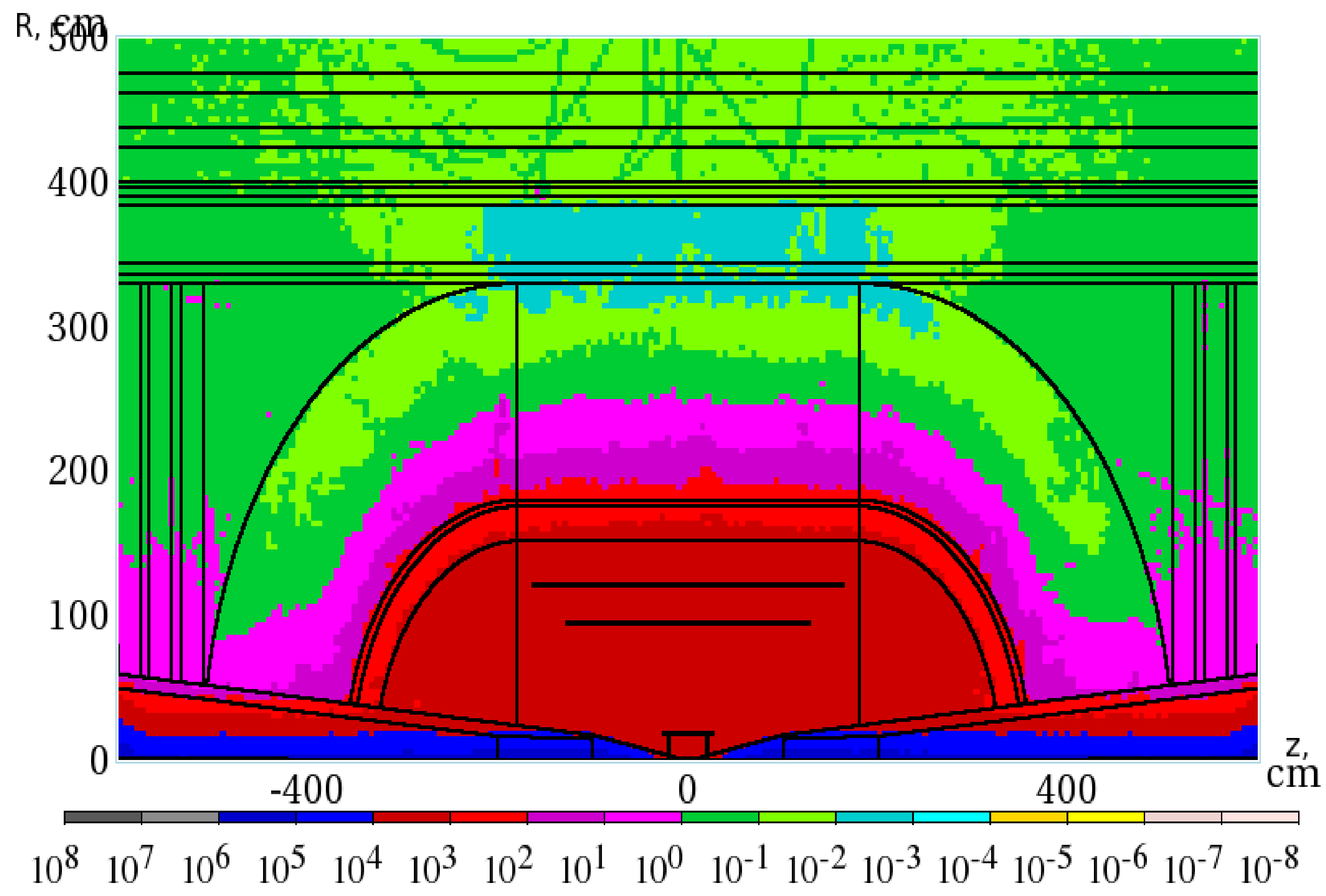






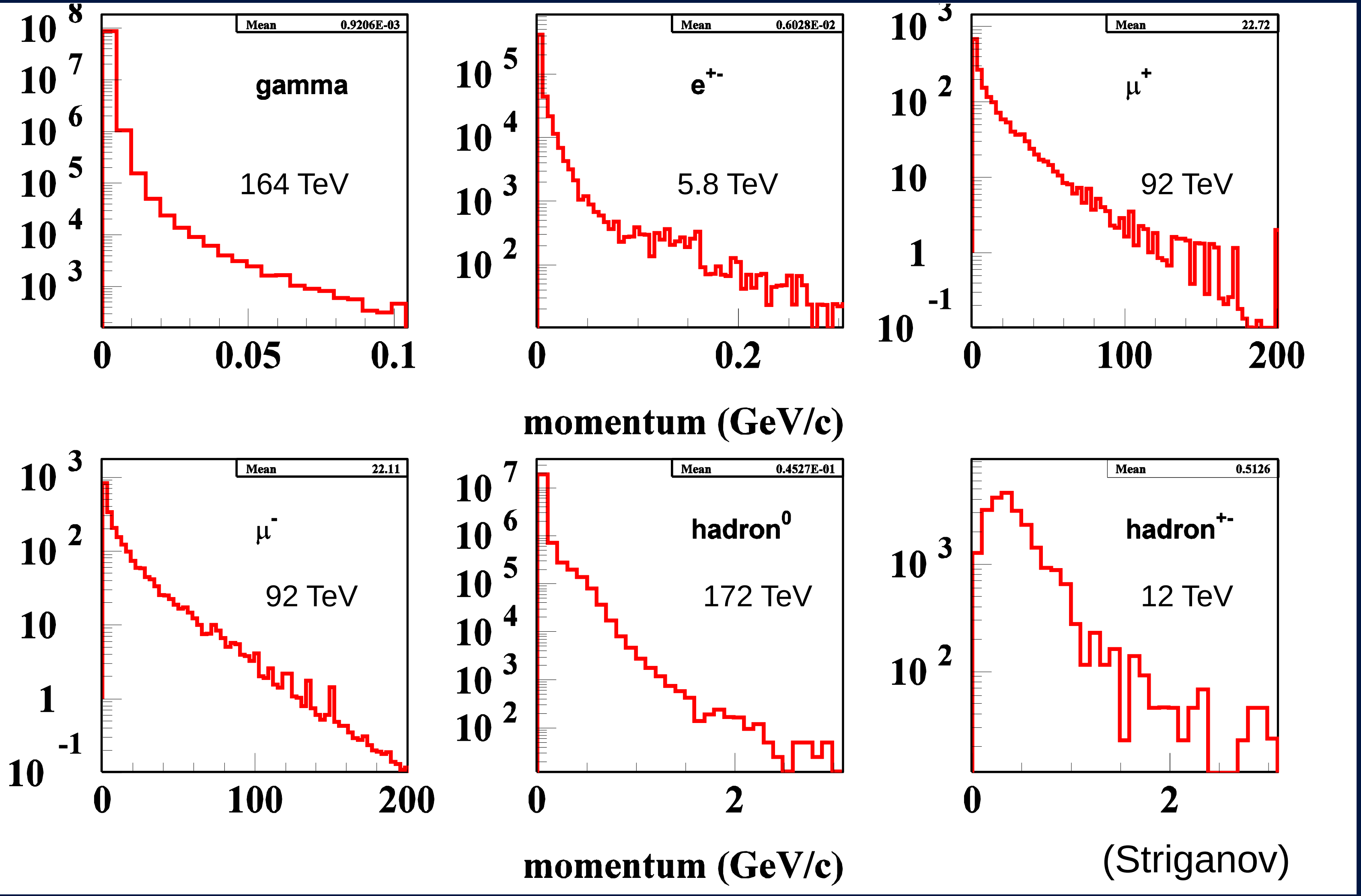
Neutron Background

Non-ionizing background ~ 0.1 x LHC
But crossing interval 10μs/25 ns 400 x



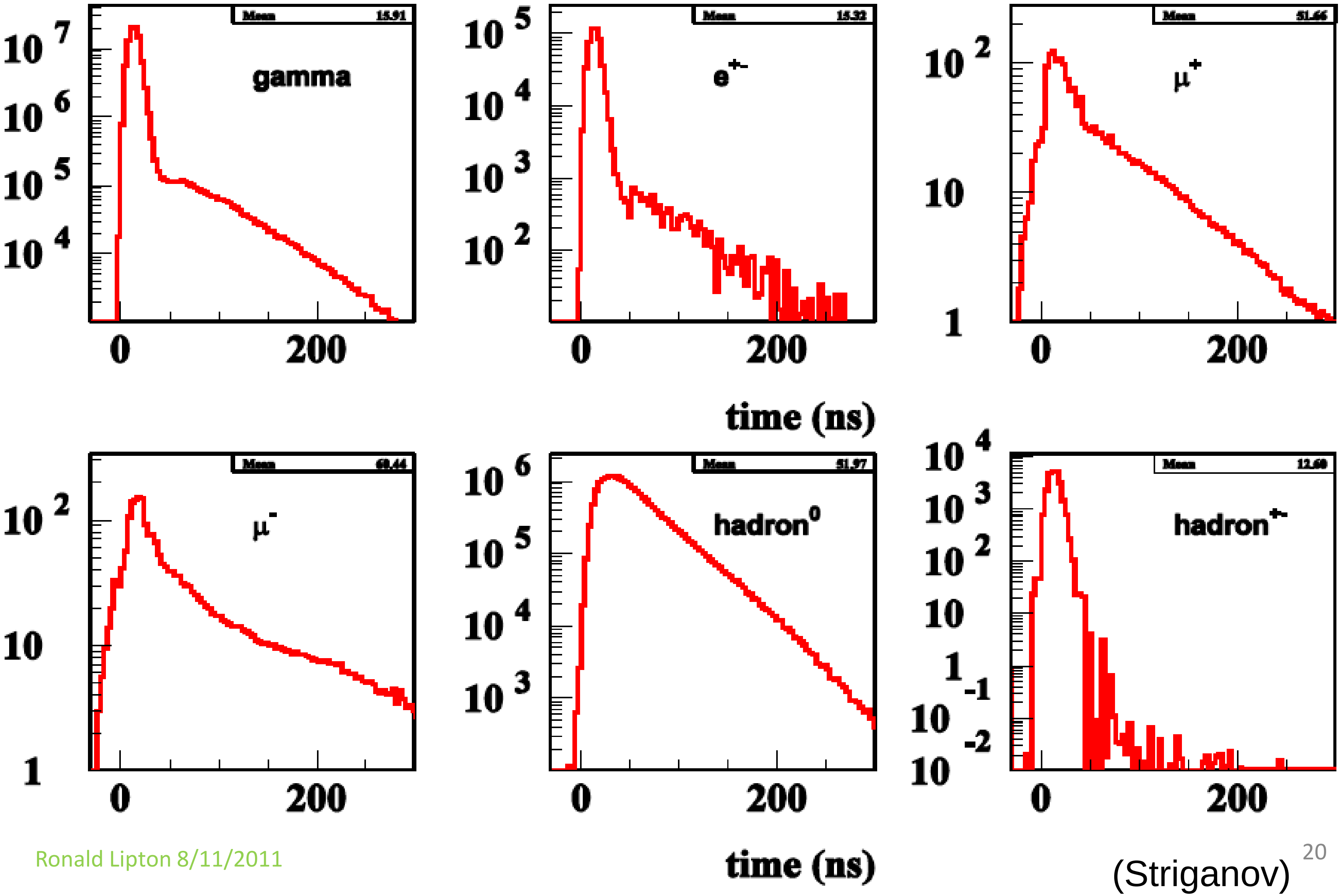
Neutron fluence (cm^-2 per bunch x-ing)

Much of the Background is Soft



(Striganov)

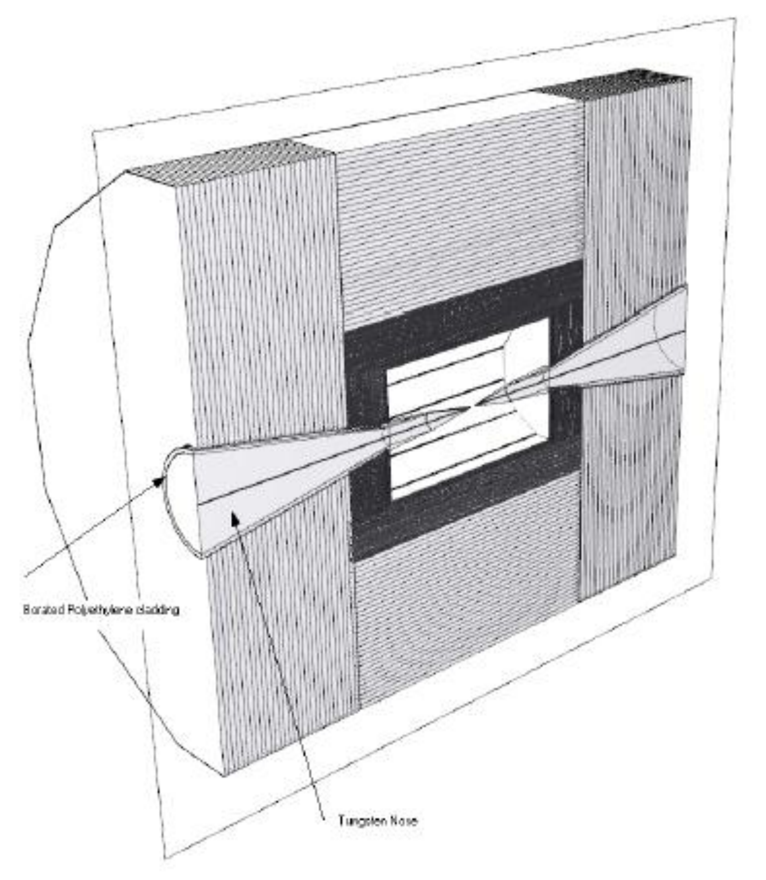
And Out of Time



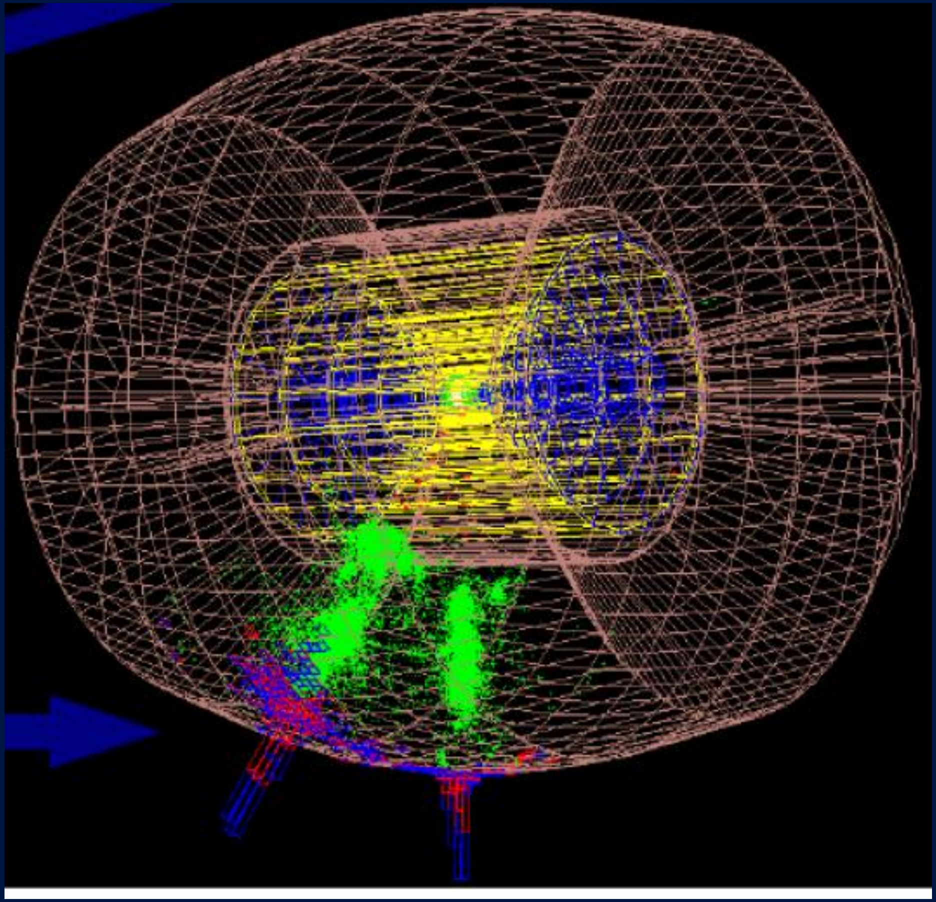
(Striganov)

Detector Models based on ILC (SiD, ILD, 4^{Th})

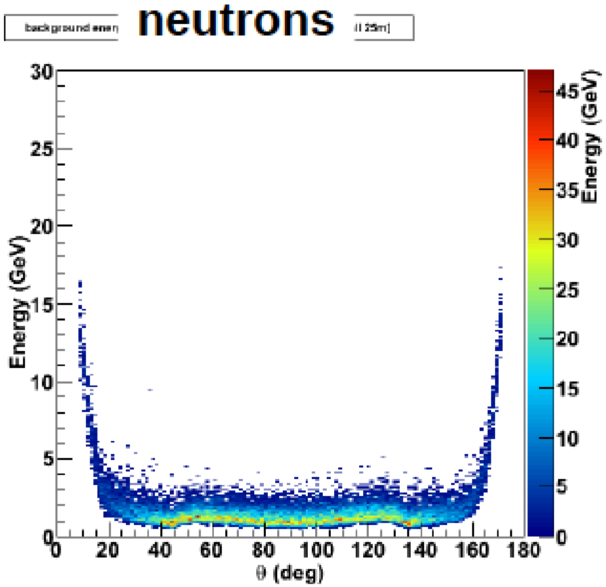
LCSIM Detector Model

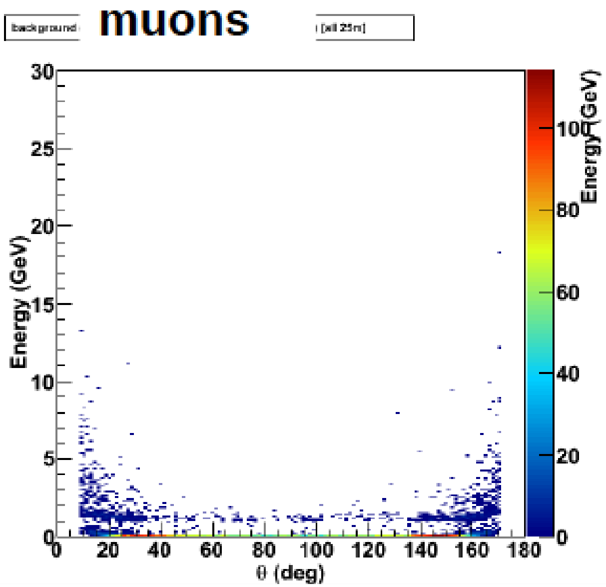


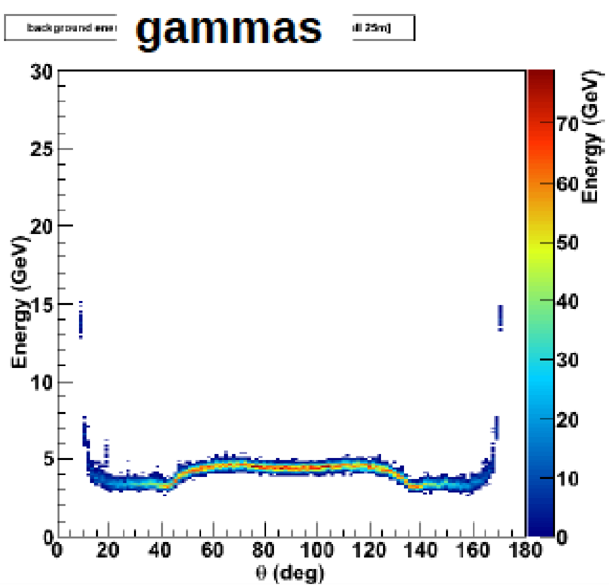
ILCROOT Detector Model

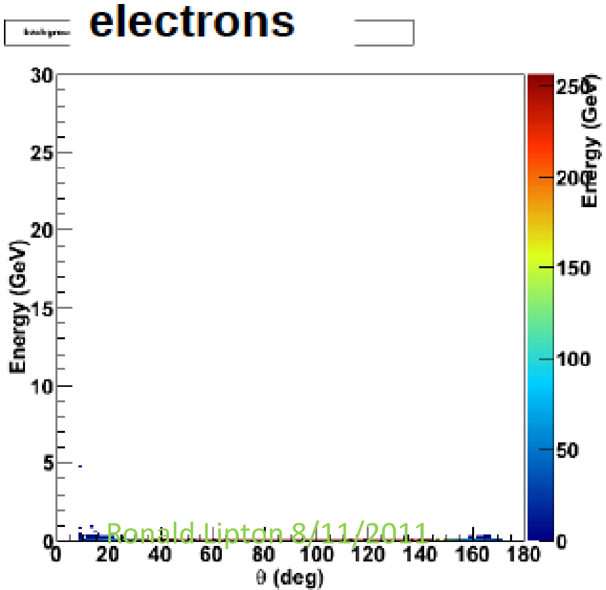


ILCROOT Background Studies (Dual Readout Calorimeter)

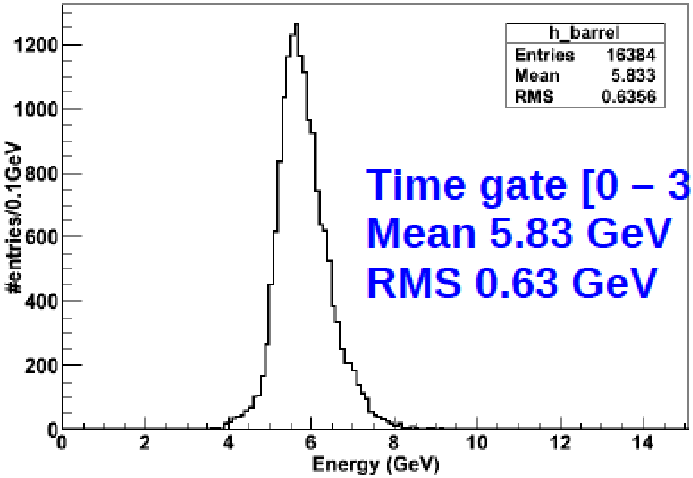

neutrons


muons


gammas


electrons

Central barrel 4x4 cm em+had cell



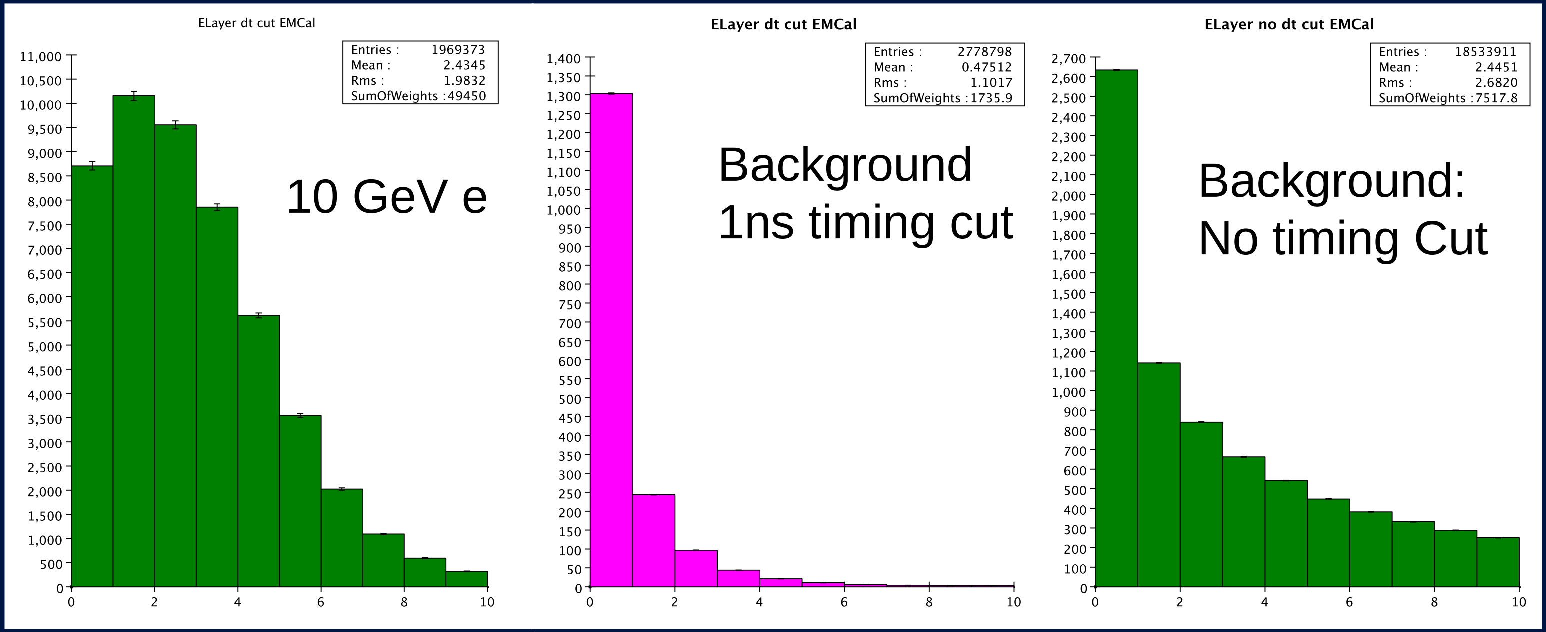
Time gate [0 – 300] ns
Mean 5.83 GeV
RMS 0.63 GeV

(DiBenedetto)

LCSIM Background Studies

An example of background reduction utilizing timing

ECal:
Tungsten,
10 x 1cm
layers
1x1x1cm
cells



EM cal layer

Reduction:
Electromagnetic – 23% of energy survives a 1 ns timing cut
6% of that energy is beyond 1st EM cell

Hadronic- 0.95% of energy survives a 1 ns cut

Ronald Lipton 8/11/2011

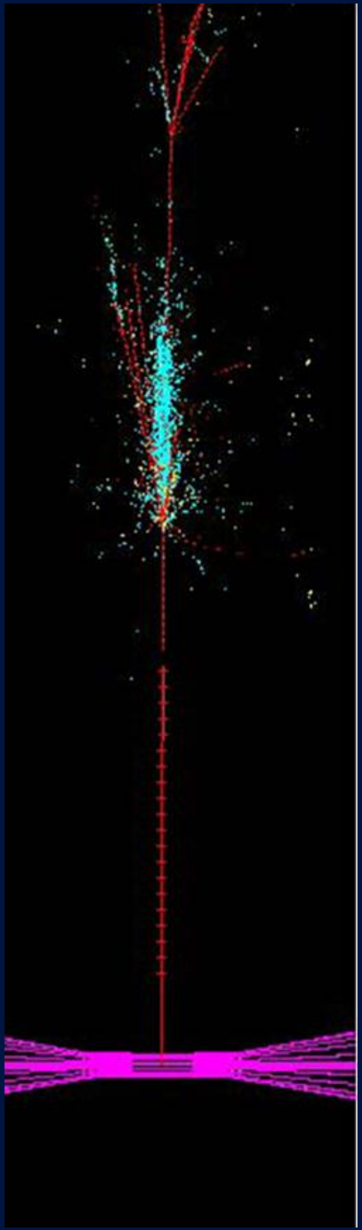
A Compensatable Muon Collider Calorimeter

(R. Raja, Fermilab)

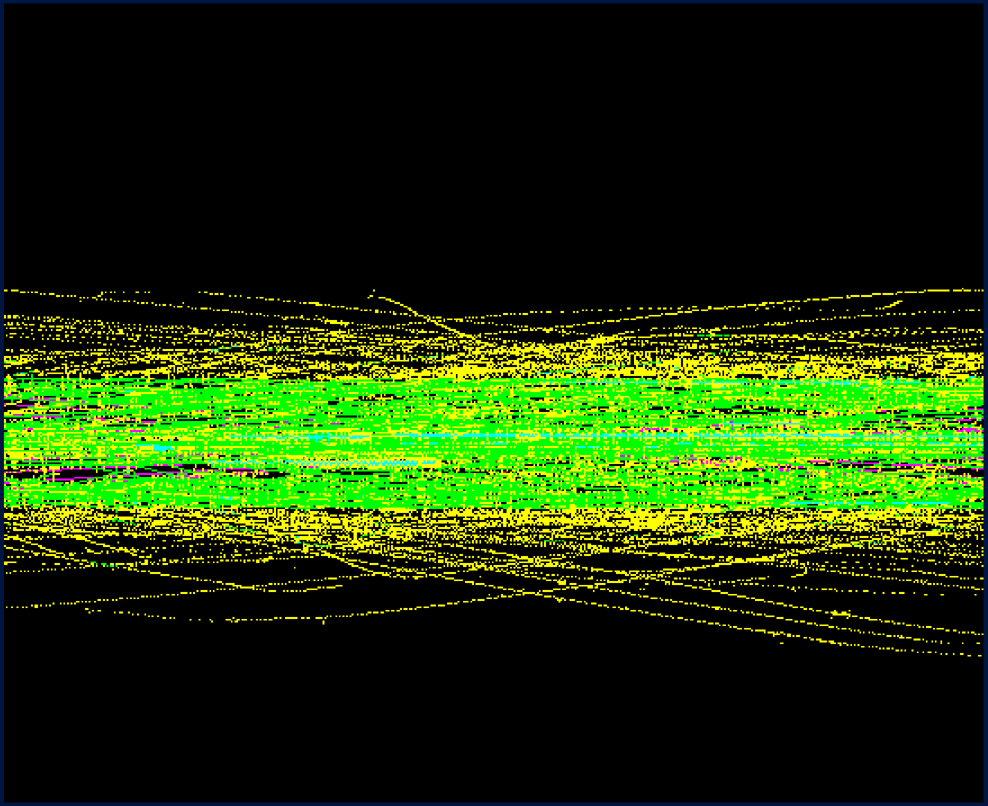
- Pixelated calorimeter with “travelling trigger”
- Each pixel is triggered by a 2 ns gate.
- The beginning of the gate coincides with the time taken for light to travel from IP to the pixel.
- End of trigger = t light + 2 ns. The 2ns gate is chosen to make sure that each pixel can respond to 1 MIP particle going through it and say yes or no.
- Each pixel will have a different start and end gate.
- $3\mathrm{x}10^{-2}$ - $4\mathrm{x}10^{-4}$ background rejection

Hadron EM separable by pattern recognition— Software compensation possible

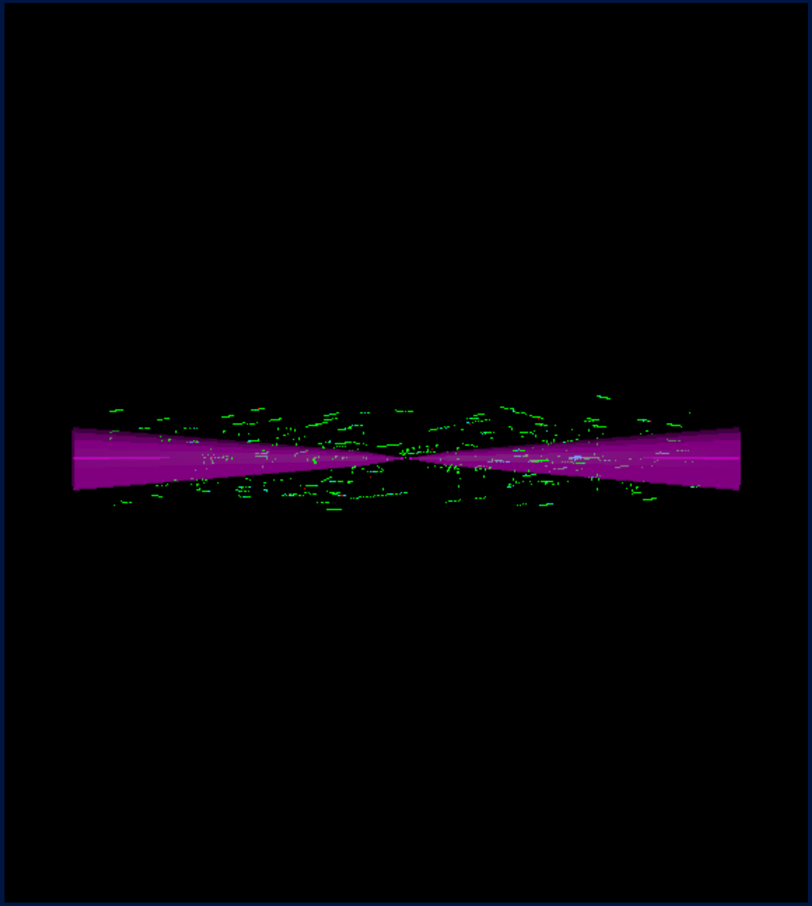
100 GeV pion in pixel calorimeter



Background Muon Segments (Raja)



Without Travelling Trigger

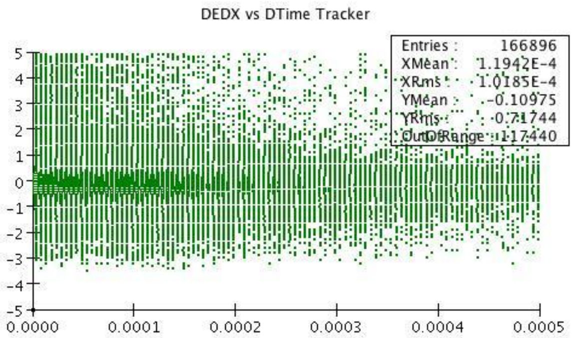


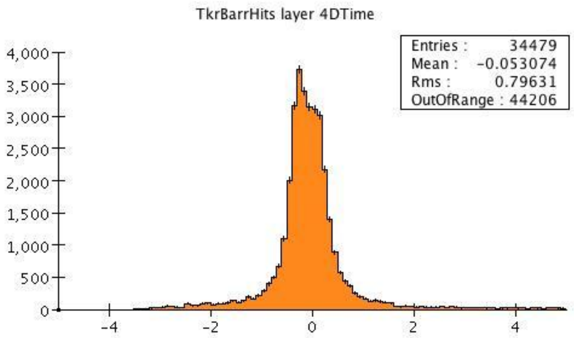
With Travelling Trigger

Track Information (LCSIM)

- Tracking can benefit from precise timing, low occupancy in a pixelated silicon detector.

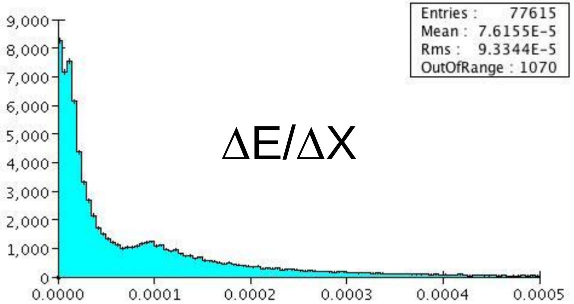
ΔT





ΔE/ΔX

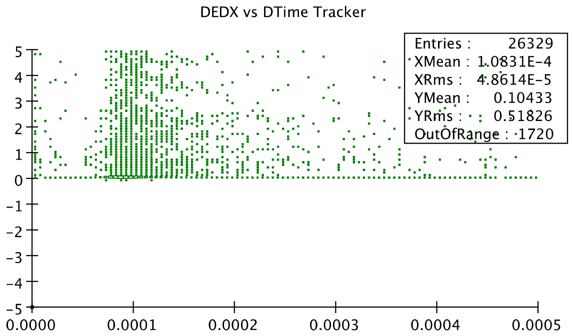
ΔT +/- 5 ns

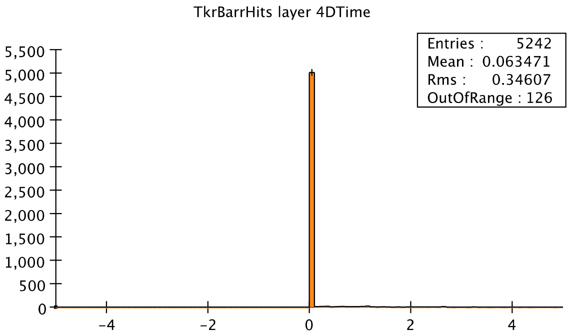


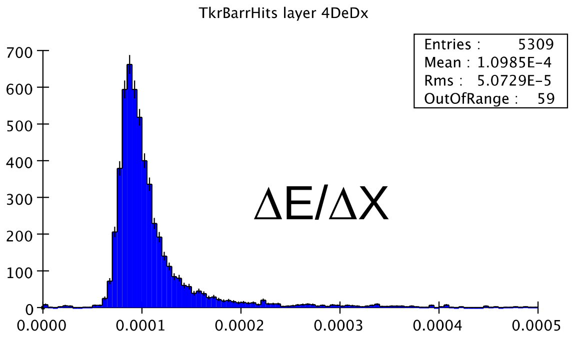
ΔE/ΔX

Background

ΔT







ΔE/ΔX

ΔT +/- 5 ns

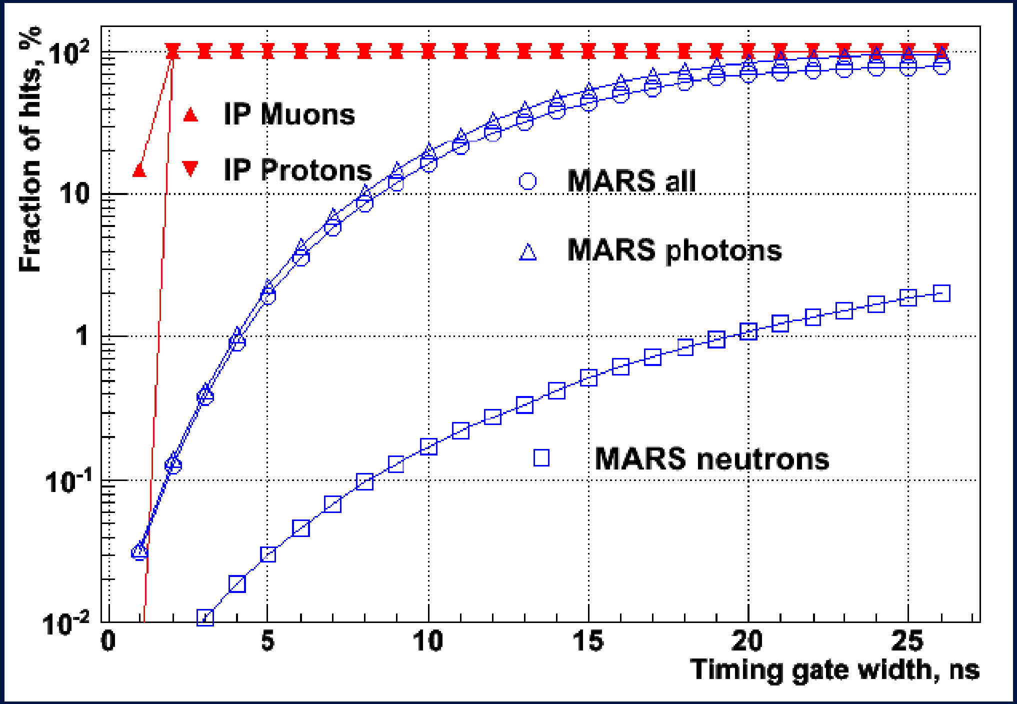
Single Muon

ILCROOT Tracking Studies

Recently demonstrated track finding in a full background event

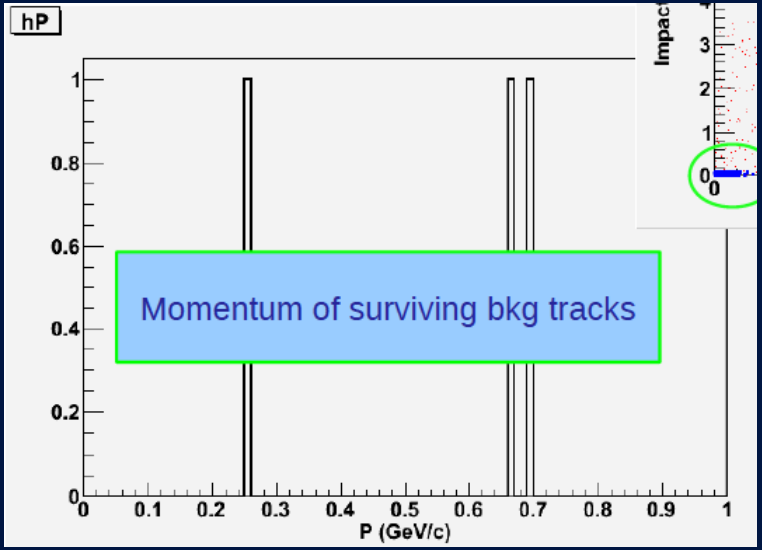
- Cuts on IP, DEDX, and $\Delta T = T_{coll} - TOF$

Timing Cut	Reconstructed tracks
None	Cannot run reconstruction
7 ns around T_{coll}	475
3 ns ΔT	11
1 ns ΔT	3



- Dominated by neutrons and photons
- This is not energy weighted, many are soft tracks

(Terentiev)



(Mazzacane)

What we have learned so far

- Precise timing and pixelated detectors will be crucial
  - Tracking seems possible in such a detector
  - Calorimetery is more challenging (and expensive), but progress is being made on imaging calorimeter concepts
- Tracking detectors will resemble LHC detectors (higher mass) more than ILC detectors
- Machine
  - Any significant polarization (>10%) will come at the cost of luminosity
  - “Local” energy scans not difficult – large energy variations have not been carefully studied

Collaboration on Lepton Collider R&D

- Laboratory “White Paper” on Lepton Colliders last summer established the goals of future cooperative efforts:
  - Establish the requirements of detector systems so the physics can be extracted, taking into account the very different operating conditions at each machine.
  - Provide feedback to the machine design to further optimize the physics potential.
  - Propose necessary detector and other R&D to verify detector technologies.
  - Compare the physics potential of these machines and carry out a cost-benefit analysis.
  - Coordinate the detector and physics program.
- First joint effort was to submit a unified proposal to the “Collider Detector R&D” program (program not funded in FY2011);\:
  - Included support for Muon Collider simulation at FNAL and SLAC
  - Muon Collider detector R&D would come later

Plans

- Summer 2011 – Spring 2012
  - Studies of toy detectors in full background – establish performance envelopes
  - Parameterize backgrounds to enable faster physics simulation
  - Initial physics study including full background simulation

Iterate both the shielding and detector designs based on results of simulation studies.

- 2012-2013 Define detector requirements, and identify needed detector R&D, begin studies to establish a long-term simulation and analysis environment.
- 2014- 2015 Detector R&D + simulation studies to establish likely detector performance
- 2015-2017 Define overall detector design, complete studies for the design feasibility report.

Conclusions and Comments

- Muon Accelerator Project is up and running – making substantial progress
- We are beginning a renewed physics and detector program to study the 1.5-3 TeV Muon Collider environment
- We have a strong foundation – reliable MARS simulation of backgrounds integrated into GEANT-based detector models.

As a field we need to be in a position to make an informed decision about the tradeoffs of alternate approaches.

We need to understand the options if physics points to a multi-TeV lepton collider. CLIC is a strong possibility, but not a “no brainer”, especially as the required energy increases.

There are strong overlaps of interest of Muon Collider with CLIC in physics, fast timing, detector design, and simulation.

Remaining backgrounds-Calorimeter (Raja)

Both beams	**Total**	**Theorem1 < 2ns**	**fraction**	***Energy***	**Energy in time**	**Overall reduction**
	Raw Number			***GeV***	**GeV**	
EM	**1.98E+08**	**2.43E+06**	**1.23E-02**	**1075.3**	**453.9**	**5.18E-03**
MUONS	**2.89E+03**	**5.77E+02**	**2.00E-01**	**585.3**	**12.5**	**4.27E-03**
MESONS	**1.97E+04**	**2.99E+03**	**1.51E-01**	**302.9**	**56.9**	**2.84E-02**
BARYONS	**4.59E+07**	**4.41E+05**	**9.62E-03**	**9444**	**432.8**	**4.41E-04**

Tracking also works well with travelling gate trigger