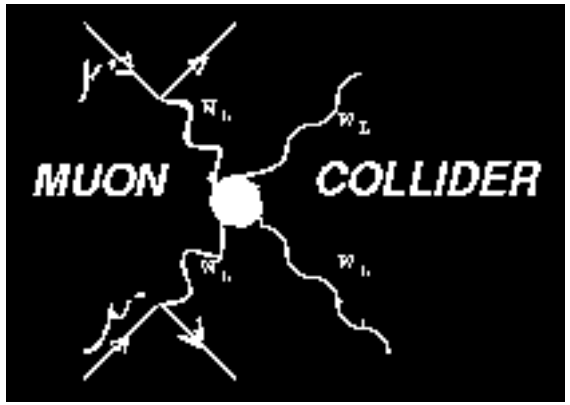


Muon Collider Forum

Kevin Black (UW-Madison)

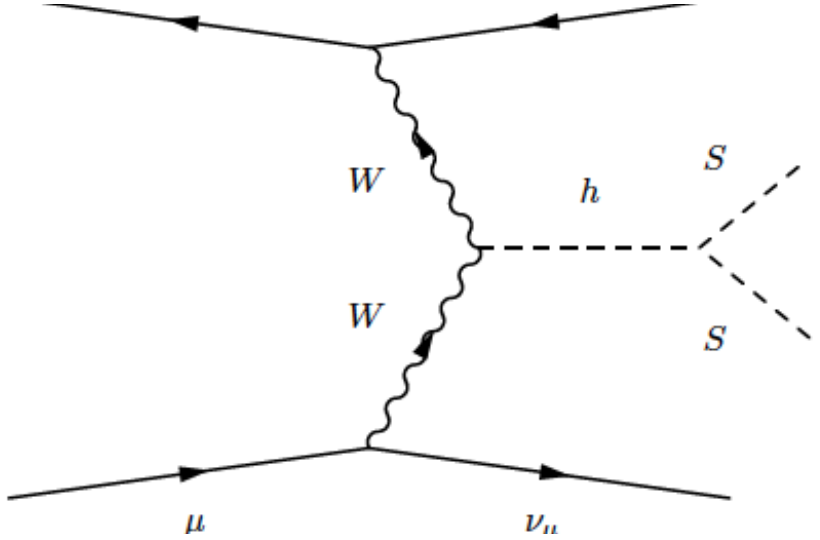
Sergo Jindariani (FNAL)

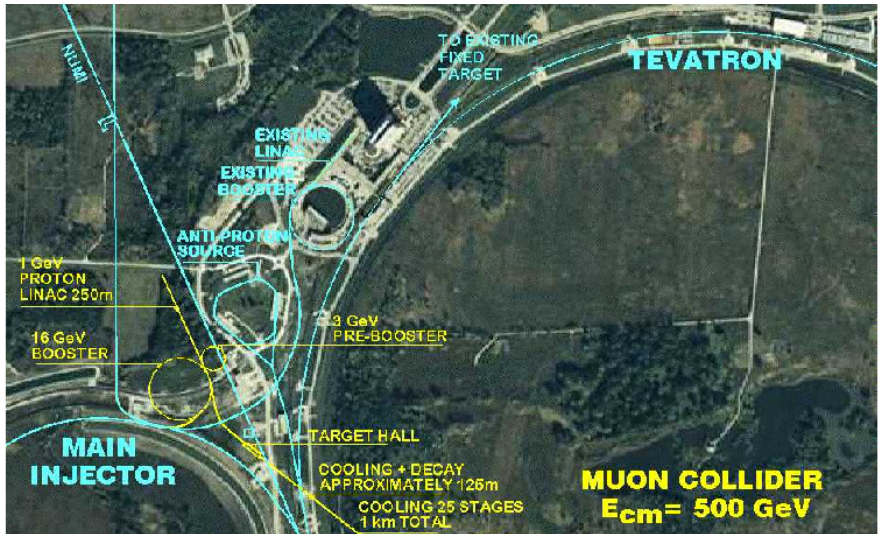
WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Fermilab

Why a muon collider?

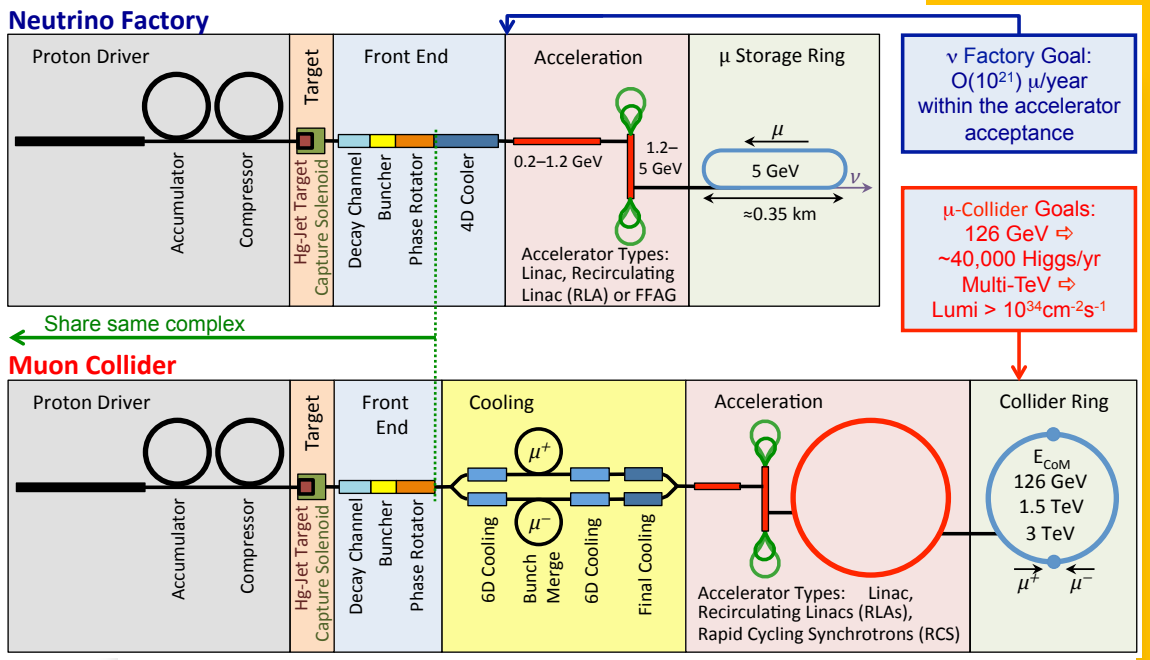
- Many desirable features as $m_\mu/m_e = 207$ which implies much less synchrotron radiation as is proportional to m^{-4}
  - we expect much smaller beam spread (i.e $\Delta p/p \sim 10^{-4}$) allowing precise energy scans for mass and width measurements
  - Multi-TeV collider possible with much smaller footprint (i.e. fitting into existing facilities)
- VBF cross-sections grow as log(s/M) as compared to s-channel 1/s and on multi-TeV scale it becomes a “vector-boson collider” which is very attractive for the continued exploration of EW scale

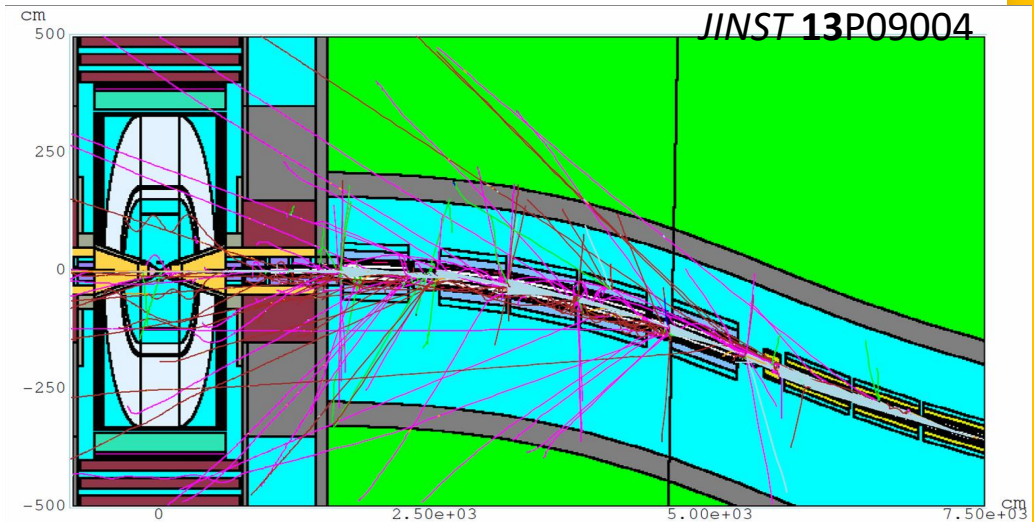




Challenges of a muon collider

- Muons Decay! Unlike electrons , protons , and heavy nuclei which have a long history of success a muon collider has never been constructed
- Conventional production schemes :
  - Proton driver : low energy muons with high emittance requires fast acceleration and both fast and sophisticated cooling mechanisms
  - LEMMA : needs R&D to provide competitive luminosity for physics
- Beam Halo
  - $\mu^- \rightarrow e^- \nu_\mu \nu_e$ causing beamstralung, incoherent electron production, muon pair production in EM showers which then end up either in the detector or producing particles due to decays or additional interaction
- Neutrino halo
  - High flux of neutrino decay along accelerator path causes neutrino radiation away from complex . One solution is to limit the length of straight section which places additional complications and limitations on the accelerator lattice and luminosity.

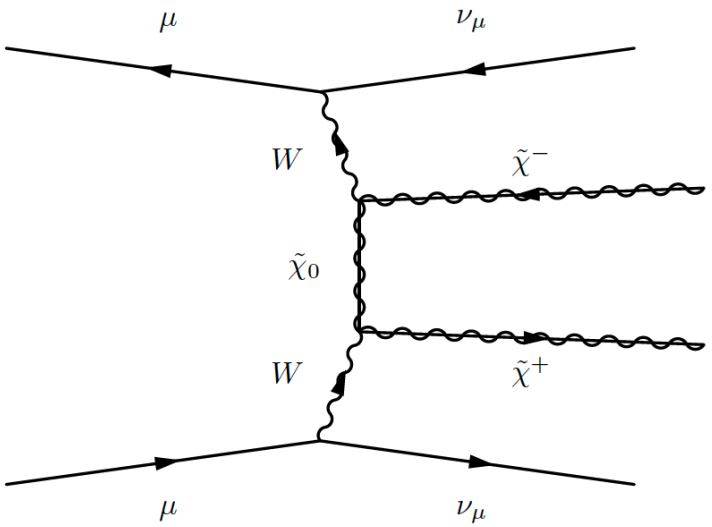


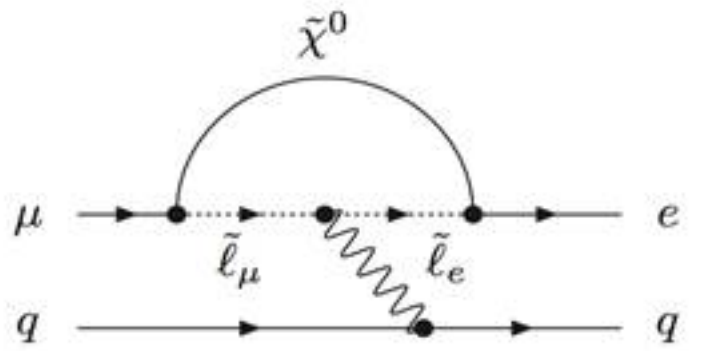


Benedetto, Gatto, Mazzacane, Mokhov, Striganov, Terentiev

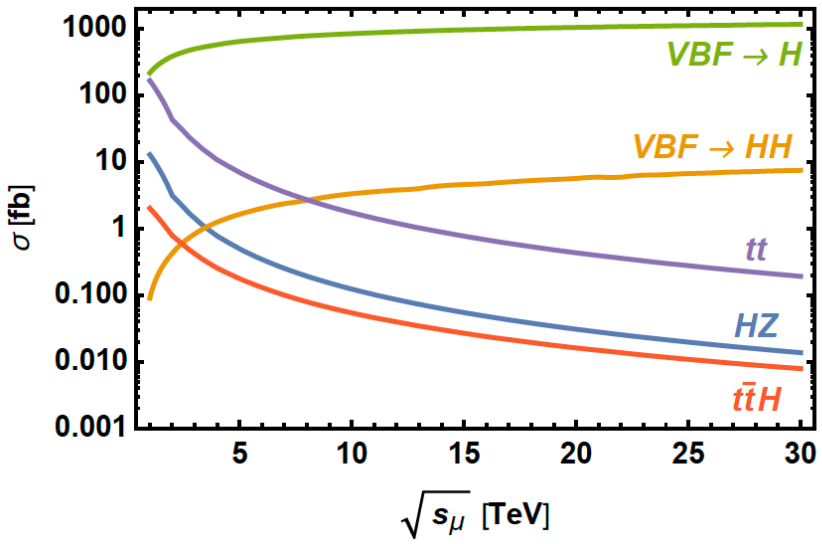
Physics Topics

- `One Ring to Rule them All' or All-in-One Idea
- Mostly will restrict to Energy Frontier Topics but note that a muon collider would be also include topics in the Intensity Frontier
  - Neutrino factory with O(10^{21}) muons/year within accelerator acceptance
  - Allow study of rare processes such as μ–>e, μN–>eN conversion, g-2, etc
- Areas of interest
  - Precision Higgs mass, width, coupling measurements
  - DiHiggs Production and self coupling
  - Direct searches for BSM physics at the EW scale and beyond (SUSY, composite Higgs, new interactions, etc)
  - Dark Matter Searches
  - Precision EW

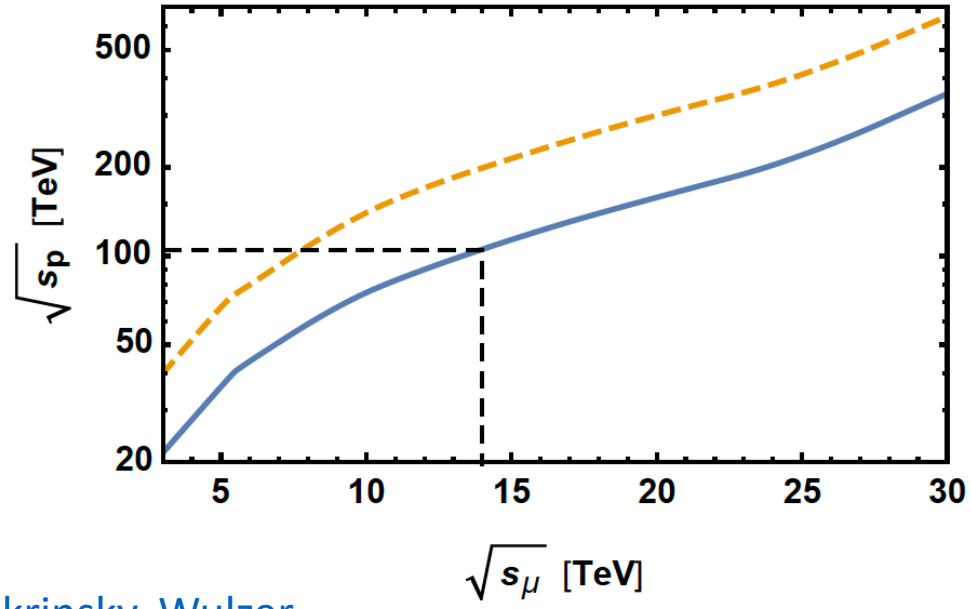




Comparisons with hadron machines



- Lepton collider advantage available energy as compared to falling parton distribution of proton machines
- Note large and growing VBF production ~few TeV
- Some process dependence (i.e dashed orange line assumes comparable Feynman amplitudes while solid blue line x10 times larger strong production)
- Hence many statements at comparing ~14 TeV muon collider to proposed ~100 TeV pp collider as a reference point



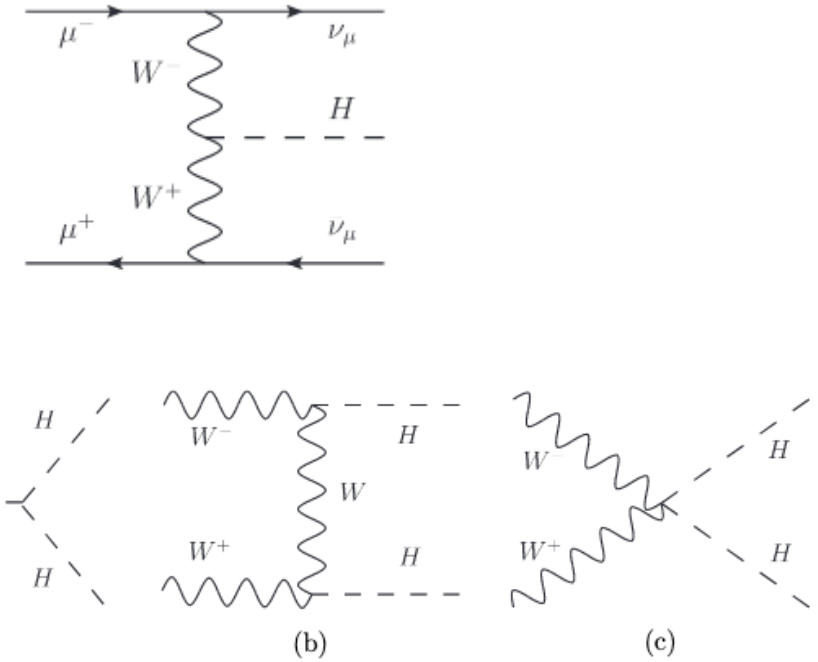
Delahaye, Diemoz, Long, Mansoulie, Pastrone, Rivkin, Schulte, Skrinsky, Wulzer

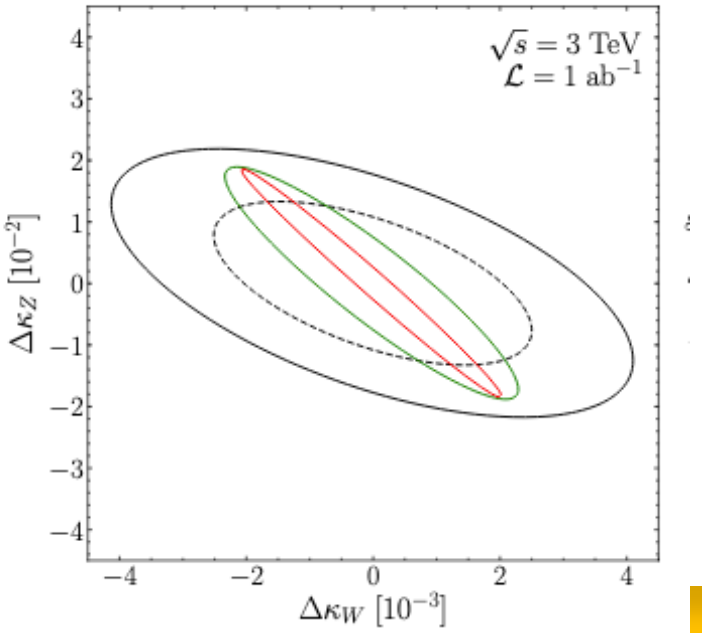
Past and Present

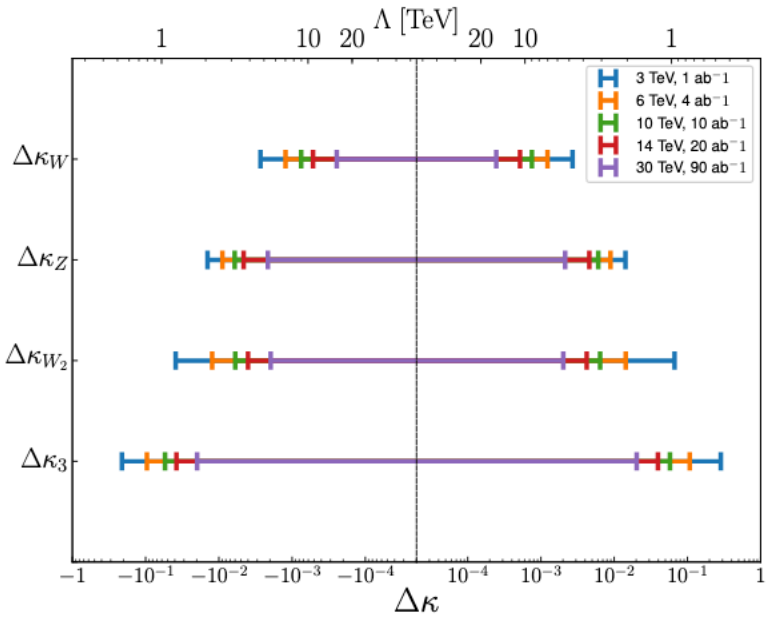
- Muon accelerator program : https://map.fnal.gov/
- Muon Accelerators for Particle Physics: https://iopscience.iop.org/journal/1748-0221/page/extraproc46
- International Muon Ionization Cooling Experiment: http://mice.iit.edu/
- Many new articles on arXiv, in particular hep-ph, Muon Collider ArXiv
- Recent workshop PITT PACC: Muon Collider Physics

Electroweak Coupling Study:HVV, HHVV, HHH

Han, Liu, Low, Wang

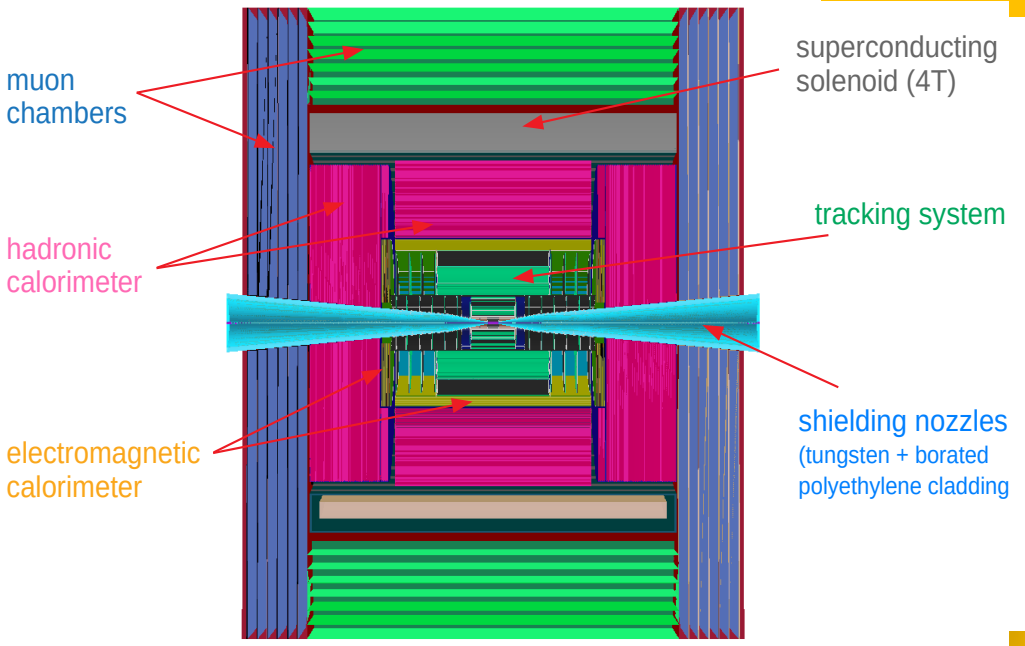






Summary of Higgs VB and self-coupling precision estimates

GEANT Simulation



- From muon collaboration, take CLIC detector with some modifications for muon collider
- **ILCSoft** which will be part of the Future Collider Framework, Key4hep, is used
- Detector frozen for $\sqrt{s}$ **=1.5 TeV** studies

- Full Event Simulation -> runs but large memory footprint and long processing time with beam induced background

Vertex Detector (VXD)
- 4 double-sensor barrel layers 25x25μm^2
- 4+4 double-sensor disks 25x25μm^2

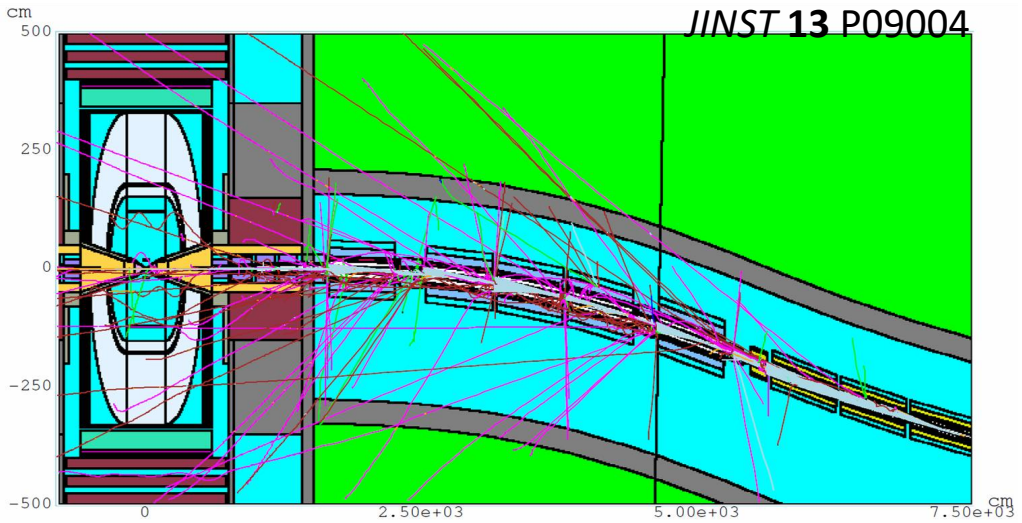
Inner Tracker (IT)
- 3 barrel layers 50x50μm^2
- 7+7 disks ”

Outer Tracker(OT)
- 3 barrel layers 50x50μm^2
- 4+4 disks ”

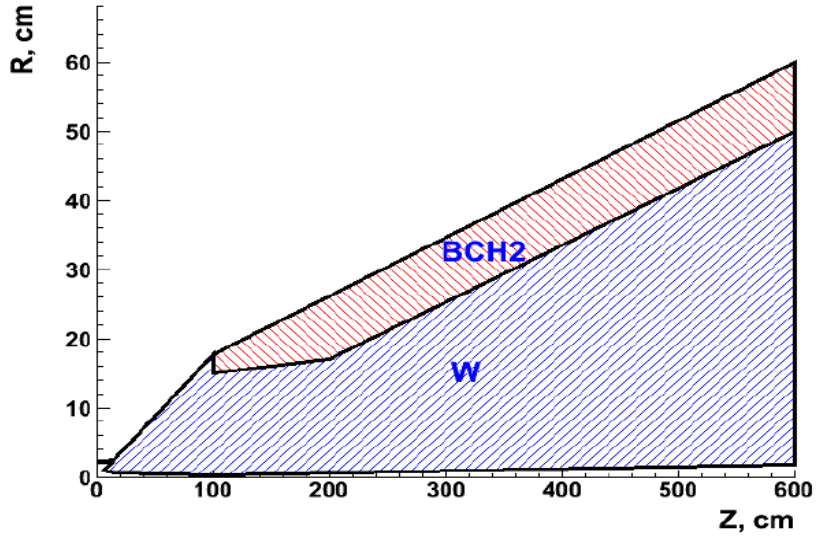
Electromagnetic Calorimeter (ECAL)
- 40 layers W absorber and silicon pad sensors, 5x5 mm^2

Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm^2

Beam Induced Background



JINST **13** P09004

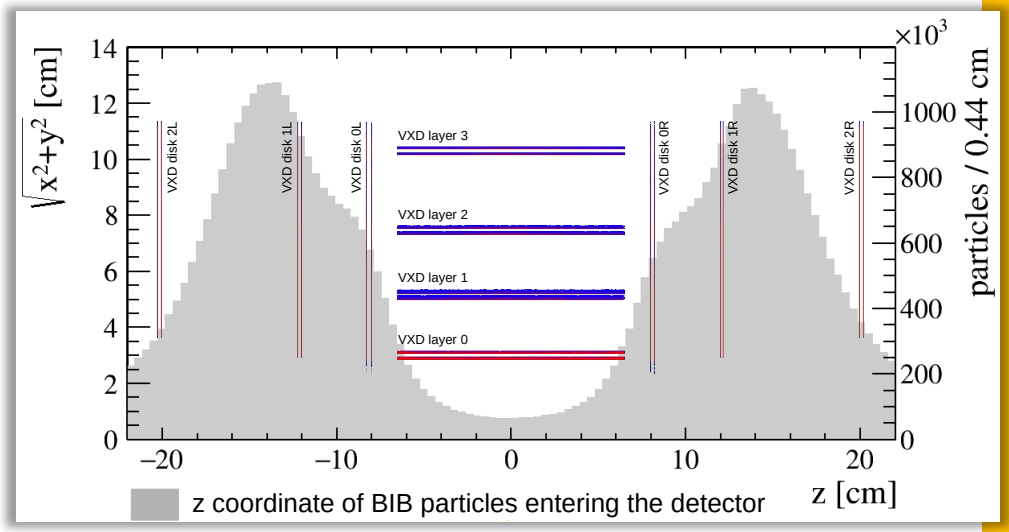


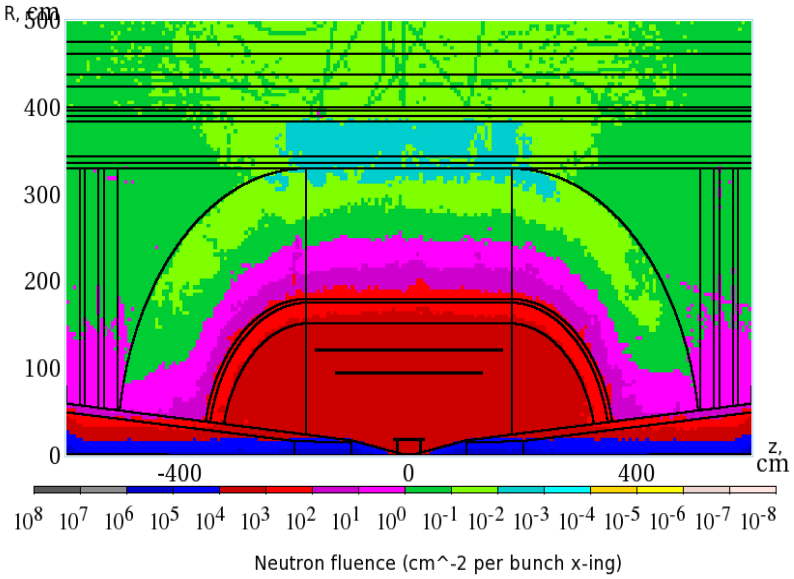
beam energy [GeV]	62.5	750
μ decay length [m]	3.9×10^5	4.7×10^6
μ decays/m per beam	5.1×10^6	4.3×10^5
photons ($E^{kin}_{\mathrm{ph.}} > 0.2$ MeV)	3.4×10^8	1.6×10^8
neutrons ($E^{kin}_{\mathrm{n}} > 0.1$ MeV)	4.6×10^7	4.8×10^7
electrons ($E^{kin}_{\mathrm{el.}} > 0.2$ MeV)	2.6×10^6	1.5×10^6
charged hadrons ($E^{kin}_{\mathrm{ch.had.}} > 1$ MeV)	2.2×10^4	6.2×10^4
muons ($E^{kin}_{\mathrm{mu.}} > 1$ MeV)	2.5×10^3	2.7×10^3

Benedetto, Gatto, Mazzacane, Mokhov, Striganov, Terentiev

Inner Tracker

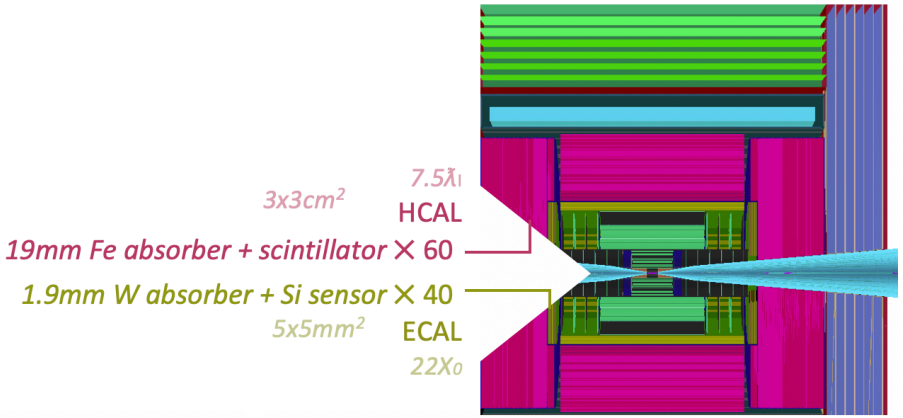
- BIB (Beam Induced Background) is dominated by neutron and photons
- Most inner tracker and calorimeter hits induced from BIB interactions
- Will require high bandwidth and complex reconstruction
- Applying filtering of data both on and offline to make reconstruction viable
- Large bunch crossing interval implies consideration of a triggerless DAQ system (~bunch crossing time of 20-30 ps)
- To achieve ~1% occupancy would require without timing ~20 micron pixels and imply ~ 5 billion pixels with timing resolution of order 20 ps ~ 1 billion pixels.





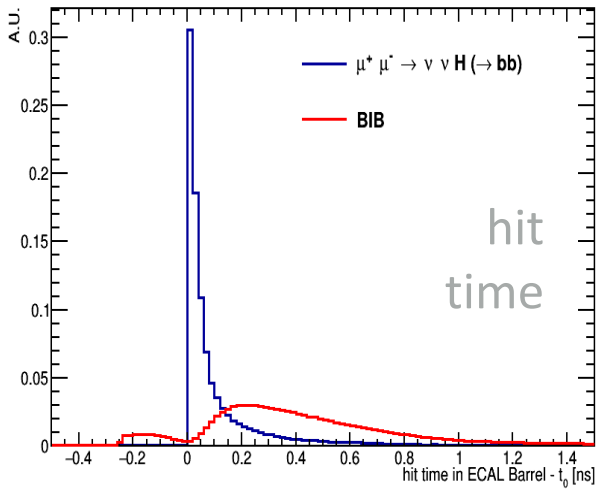
Lucchesi, Jindariani, et al..

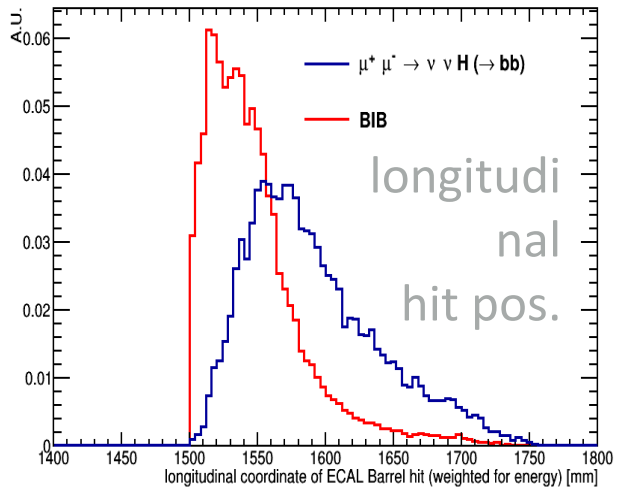
Calorimeter Considerations



- BIB is dominated by neutron and photons
- Currently assumes CLIC calorimeter
- A high granularity calorimeter with precise timing information would allow for a particle flow like algorithm to remove BIB hits
- Similar to phase-2 CMS HG-CAL

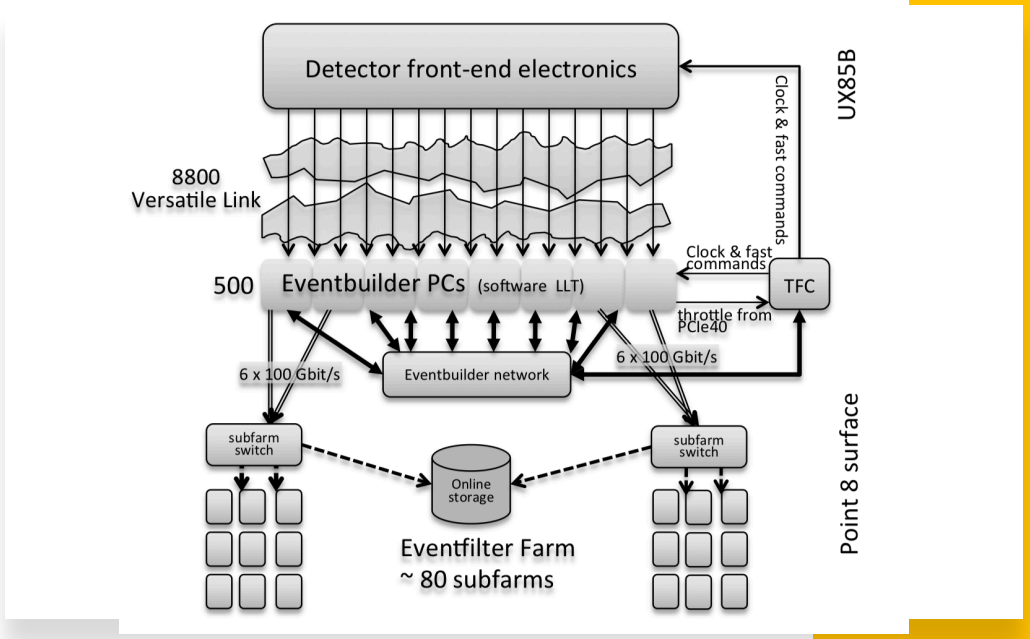
Lucchesi, Jindariani, et al..



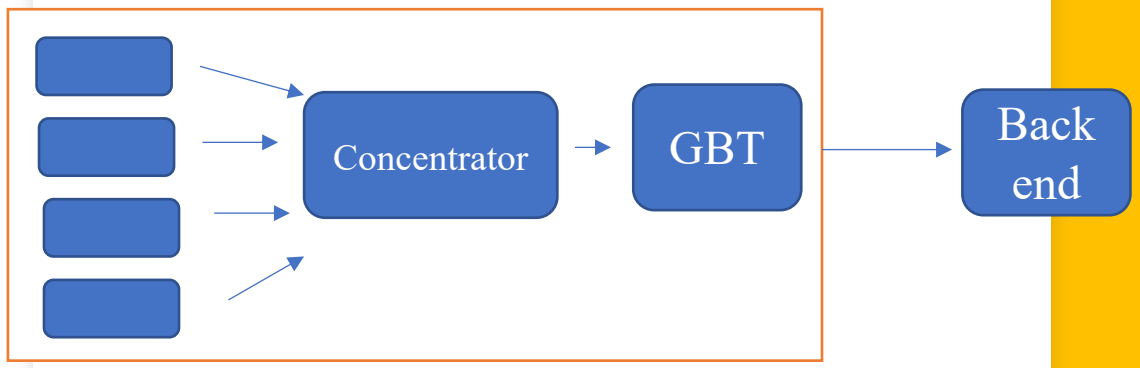


DAQ/Trigger Considerations

- Assume data volume is tracker dominated.
- Total number of hits per event ~10M (less with timing-based filtering)
- Total tracker data rate: 10M*32bits*100 kHz ~ 30 Tbps
- E.g. tracker readout system could consist of <100 readout boards running 25G Links
- Currently assuming LHCb triggerless DAQ readout as baseline
- Timing information, fast pt reconstruction, other handles may be needed



Lucchesi, Jindariani, et al..



What should be our collective goal for snowmass?

- The muon collider case is compelling on basic principles
- Less ‘on-shell’ than next pp or ee machine
  - One can argue that effectively ILC , FCC-ee/hh would be scaling up existing machines with long history of success (modulo politics, money, and foreseeable future machine/detector developments)
  - i.e could in principle start breaking ground
- Need to revitalize case for R&D
  - Move from generator level studies to quasi-realistic full simulation
  - In particular, show that physics could be extracted under assumed and safety factor beam-induced background conditions
- Build on recent momentum and enthusiasm
- Show that muon collider offers superior physics program that is linked to an R&D program for a machine and detectors that could be built
- Converge on a set of realistic assumptions for luminosity/energy (of course pie in the sky thinking also interesting)
- **Aim to showcase the power of the broad physics program by producing same level of comprehensive sets of studies developed by ILC, FCC community in a relatively short time**

What can this forum offer

- Generally ,the spirit of of Snowmass is to let as many flowers as possible blossom and to let as many different ideas come to fruition
- Currently the plan is not to have a separate muon collider summary paper but rather that different studies of different physics topics will be accumulated by current energy frontier groups
- Forum serves as a place for discussion of ideas, collection of useful tools (i.e ILC software instructions, beam induced background technicalities, common muon collider Delphis settings, and to help with Monte Carlo production for studies)
- Also, useful to keep track of what is being studied so that newcomers can be aware of areas that are not covered or being studied to maximize our collective output