Muon Collider Detector Performance for Higgs Self-Coupling Measurements

Snowmass EF01 Muon Collider Jamboree

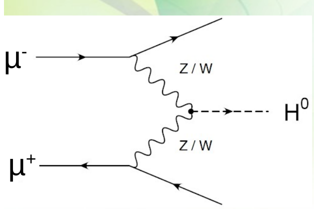
Max Swiatlowski
TRIUMF

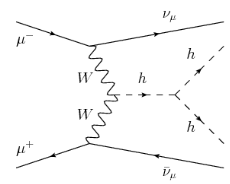
With inputs and on behalf of many!

ATLAS
EXPERIMENT

LOIs Covered

Study of Higgs couplings and self-couplings precision





Lorenzo Sestini (INFN Padova)
LoI proponents:
C. Aimè, F. Balli, N. Bartosik, L. Buonincontri, M. Casarsa, M. Chiesa, F. Collamati, C. Curatolo, D.Lucchesi, B. Mele, F. Maltoni, B. Mansoulié, A. Nisati, N. Pastrone, F. Piccinini, C. Riccardi, P. Sala, P. Salvini, L. Sestini, I. Vai, D. Zuliani

Higgs and Electroweak Physics at the Muon Collider: Aiming for Precision at the Highest Energies

Aram Apyan[1], Jeff Berryhill[1], Pushpa Bhat[1], Kevin Black[2], Elizabeth Brost[3], Anadi Canepa[1], Sridhara Dasu[2], Dmitri Denisov[3], Karri DiPetrillo[1], Zoltan Gesce[1], Tao Hann[4], Ulrich Heintz[5], Rachel Hyneman[6], Young-Kee Kim[7], Da Liu[8], Mia Liu[9], Zhen Liu[10], Ian Low[11,12], Sergo Jindariani[1], Chang-Seong Moon[13], Isobel Ojalvo[14], Meenakshi Narain[5], Maximilian Swiatlowski[15]*, Marco Valente[15], Lian-Tao Wang[7], Xing Wang[16], Hannsjörg Weber[1], David Yu[5]

[1]Fermi National Accelerator Laboratory, [2]University of Wisconsin, Madison, [3]Brookhaven National Laboratory, [4]University of Pittsburgh, [5]Brown University, [6]SLAC National Accelerator Laboratory, [7]Enrico Fermi Institute, University of Chicago [8]University of California, Davis, [9]Purdue University, [10]University of Maryland, [11]Northwestern University, [12]Argonne National Laboratory, [13]Kyungpook National University, [14]Princeton University, [15]TRIUMF, [16]University of California, San Diego

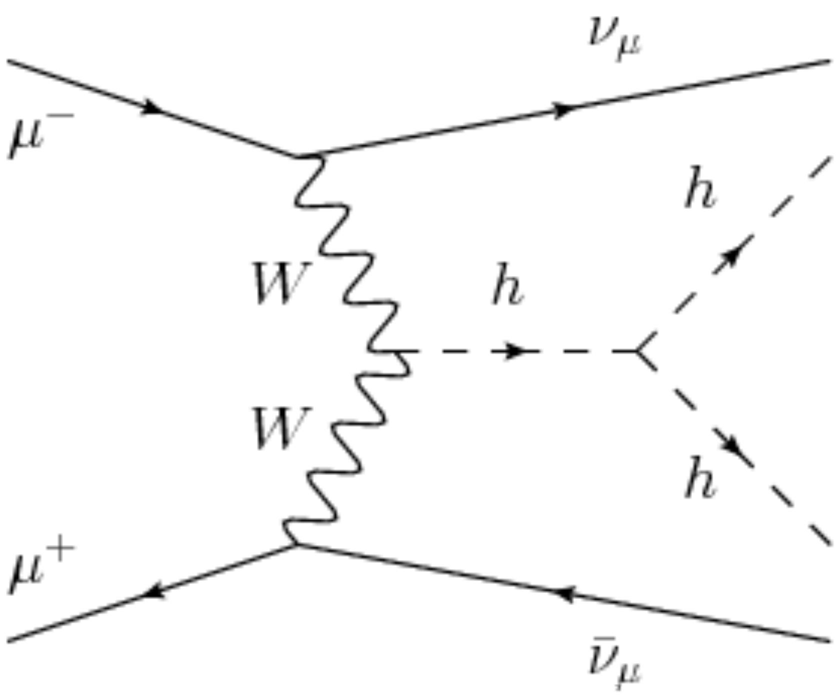
Muon Collider: solidifying the physics case.

Elizabeth Brost, Dmitri Denisov *(BNL)*
Ulrich Heintz, Meenakshi Narain, David Yu *(Brown University)*
Katherine Pachal *(Duke University)*
Artur Apresyan, Doug Berry, Anadi Canepa, Karri DiPetrillo, Zoltan Gecse, Allie Hall, Christian Herwi
Sergo Jindariani*, Ron Lipton, Nikolai Mokhov, Kevin Pedro, Hannsjoerg Weber *(Fermilab)*
Swapan Chattopadhyay *(Fermilab/Northern Illinois University)*
Lawrence Lee *(Harvard University)*
Nazar Bartosik, Nadia Pastrone *(INFN Torino)*
Massimo Casarsa *(INFN Trieste)*
Andrew Ivanov *(Kansas State University)*
Chang-Seong Moon *(Kyungpook National University)*
Simone Pagan Griso, Elodie Resseguie *(LBNL)*
Isobel Ojalvo *(Princeton University)*
Mia Liu *(Purdue University)*
Tova Holmes, Stefan Spanier *(Tennessee)*
Maximilian Swiatlowski, Marco Valente *(TRIUMF)*
Young-Kee Kim, Lian-Tao Wang *(University of Chicago)*
Alexx Perloff *(University of Colorado)*
Laura Buonincontri, Donatella Lucchesi, Lorenzo Sestini *(University and INFN of Padova)*
Cristina Riccardi, Ilaria Vai *(University and INFN of Pavia)*
Scarlet Norberg *(University of Puerto Rico)*
Kevin Black, Sridhara Dasu *(University of Wisconsin)*

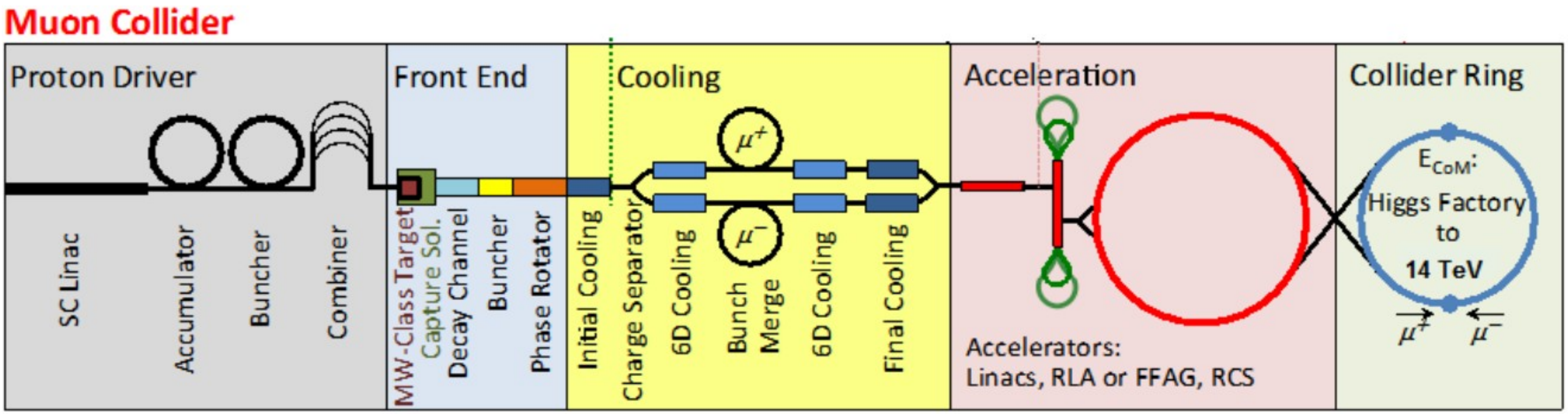
- Covering today work from several groups and LOIs
- We are all already collaborating together: **thank you** to the MuonCollider collaboration for offering simulation, code, etc.
    - Most results today come from their work

What Do We Need?

- Thanks to the overview from Lorenzo, we know what we need to measure the Higgs self-coupling at a muon collider:
  - Signal rate is fairly low, so use highest BR decays: **need good jet reconstruction and b-tagging**
  - Production is mostly via VBF, where muons become neutrinos: **need good missing energy reconstruction**
  - Cross-section goes up with energy, especially for quartic coupling: **need high energy accelerator**



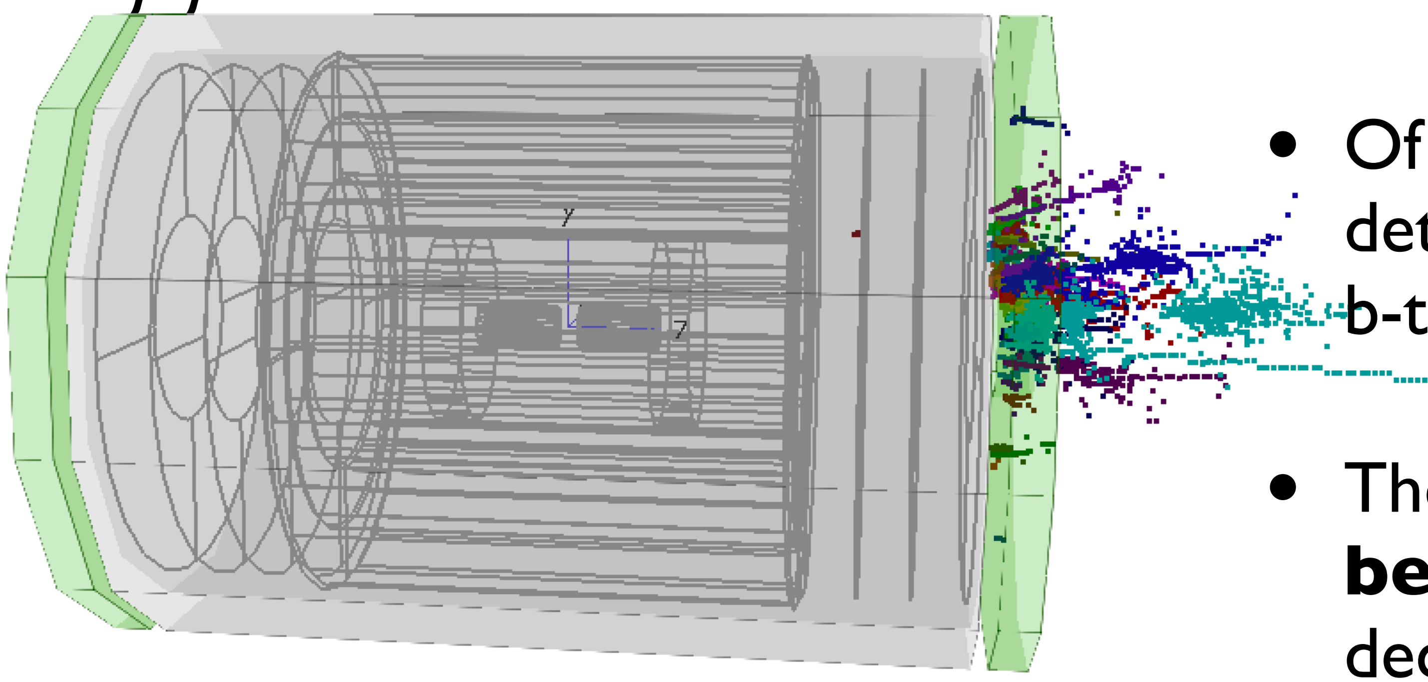
Accelerator Design



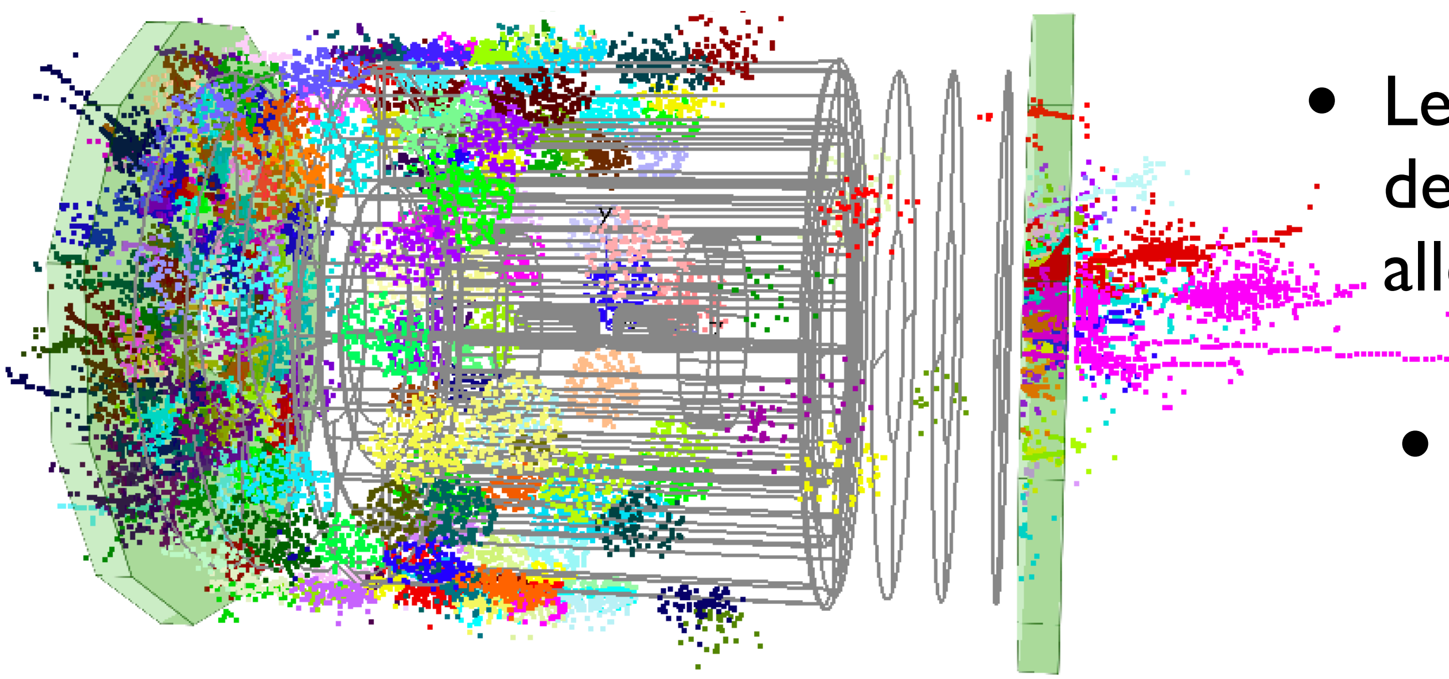
- Robust designs for accelerator exist for Higgs factory (125 GeV) and $\sqrt{s} = 1.5$ TeV
  - MAP collaboration had advanced conceptual design for up to $\sqrt{s} = 6$ TeV, and we are now studying up to $\sqrt{s} = 14$ TeV
- Design calls for bunched beam with 10 μs spacing: 100 kHz collision rate

The Challenge

$\mu\mu \to H\nu\nu \to bb\nu\nu$

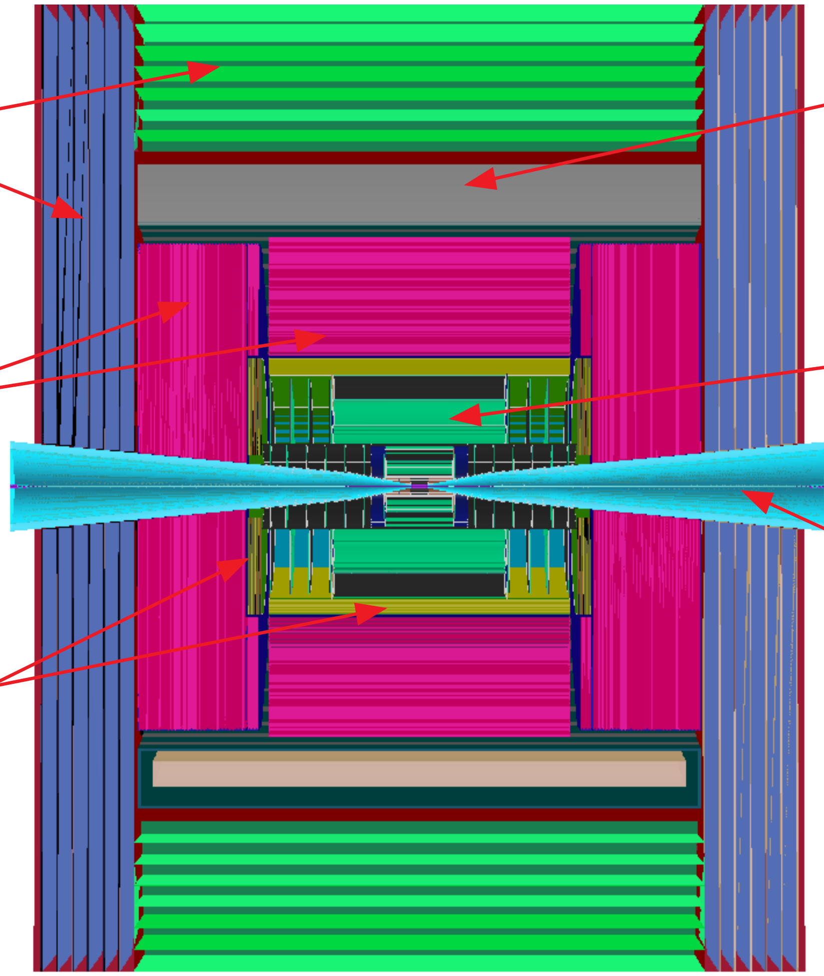


- Of course, we know how to make detectors that can measure jets and do b-tagging
- The muon-collider adds a new challenge: **beam induced background** from decays of muons in the beam
- Leads to a huge background: what detector considerations can help alleviate this?
  - Background worse for Higgs factory compared to high energy machine: faster rate of decays for muon beam



$\mu\mu \to H\nu\nu \to bb\nu\nu$ + 0.03% BIB

The 'Baseline' Detector



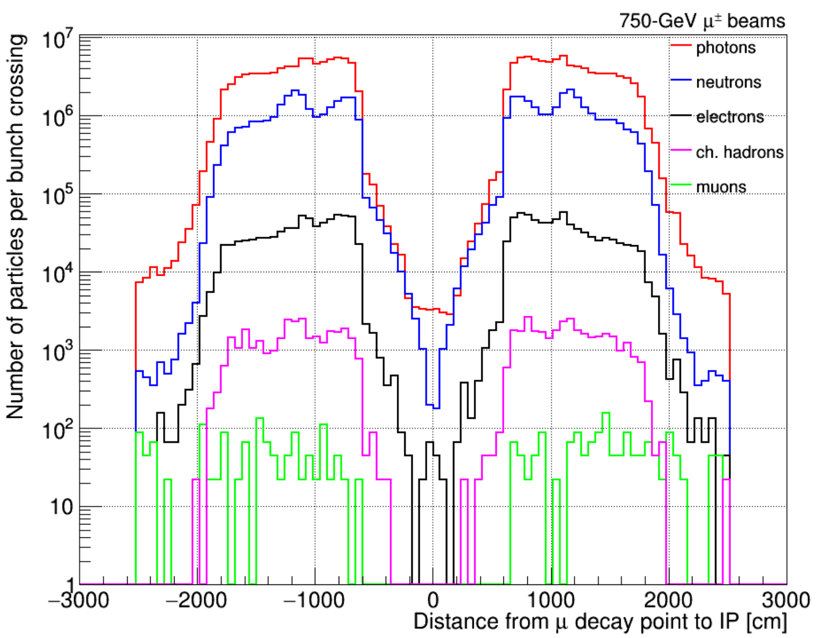
Vertex Detector	Inner Tracker	Outer Tracker	ECal	HCal
4 layers	3 layers (barrel) 7 disks	3 layers 4 disks	40 layers W + silicon	60 layers steel + plastic
$25 \times 25 \mu m^2$	$50 \times 50 \mu m^2$	$50 \times 50 \mu m^2$	$5 \times 5 mm^2$	$30 \times 30 mm^2$

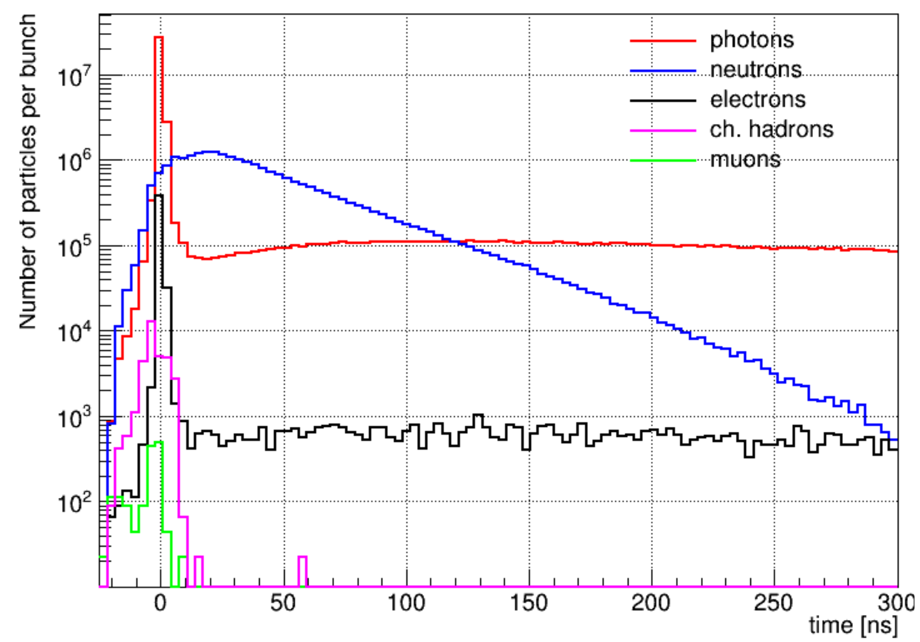
- A full simulation (including BIB!) baseline detector, developed by the MuonCollider Collaboration, is the basis for all our studies
- The detector is mostly based on the CLIC design: emphasizing tracking and particle flow calorimetry
- Tungsten+polyethylene 'nozzle' used to (partly) shield detector from beam

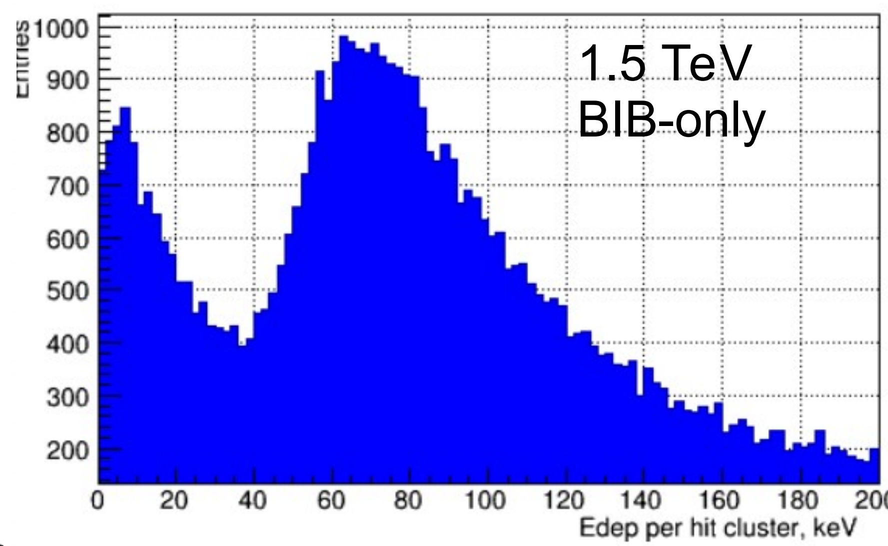
Simulation Status

- Simulation implemented in ILCSoft framework
  - Tutorials available and documentation available
- Detector optimized for $\sqrt{s} = 1.5$ TeV: full simulation works without issues
- BIB implementation available, but leads to extremely long reconstruction (mostly in tracking)
  - Optimization underway: improvements converging
- Jet reconstruction (via Pandora PFlow algorithm) working
  - BIB mitigation using energy cuts in place: optimization of PFlow underway
- B-tagging under study: in progress, almost ready
- Full simulation largely ready to be used!
  - Fast simulation underway: 'target' performance card, and 'degraded'

BIB Characteristics



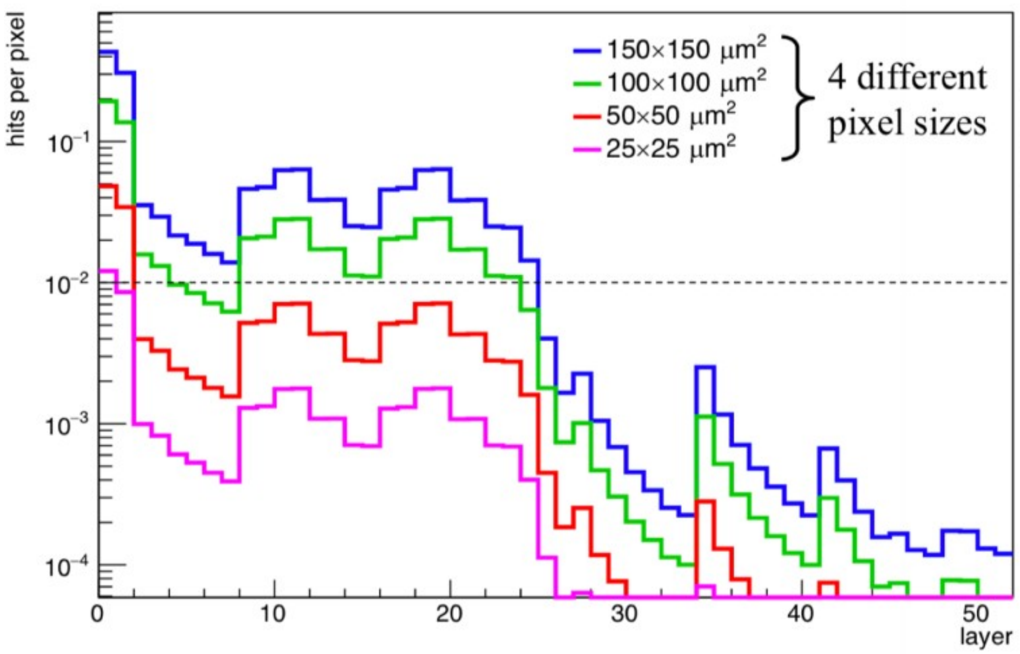




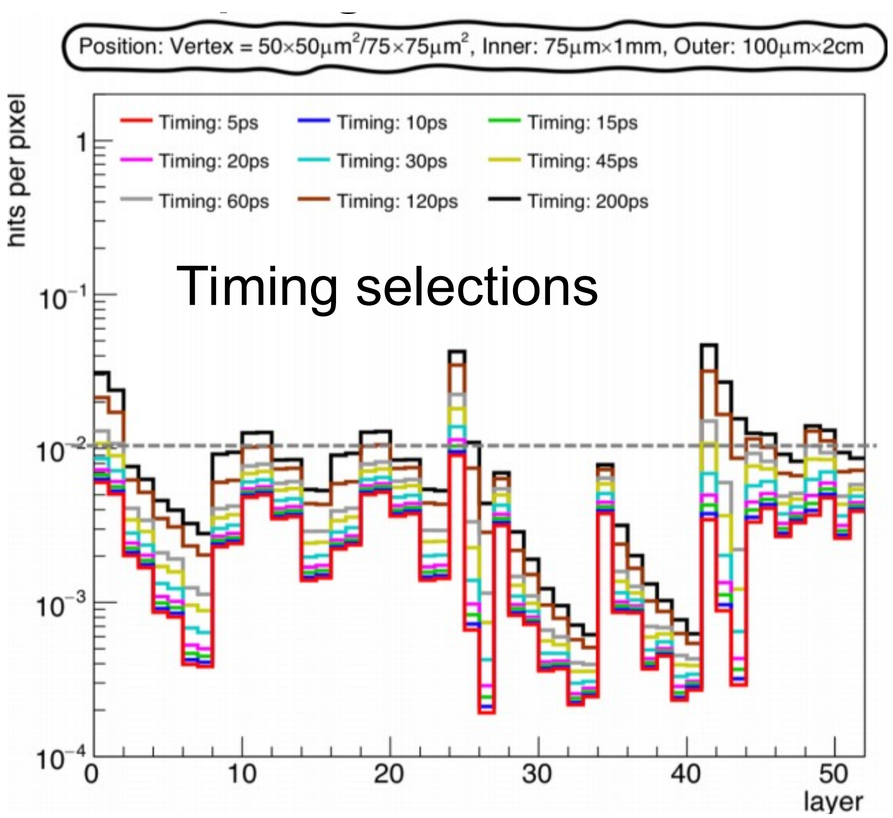
- Here, show characteristics of BIB particles and their origin for 750 GeV beams
- Photon and neutron component is the largest
  - **Timing** and **directionality** can be critical for reduction of background
  - **Energy cuts** can also be utilized: most BIB interactions are very soft
    - Partly due to the ‘nozzle’: absorbs primaries, softens high energy particles

Tracking Design

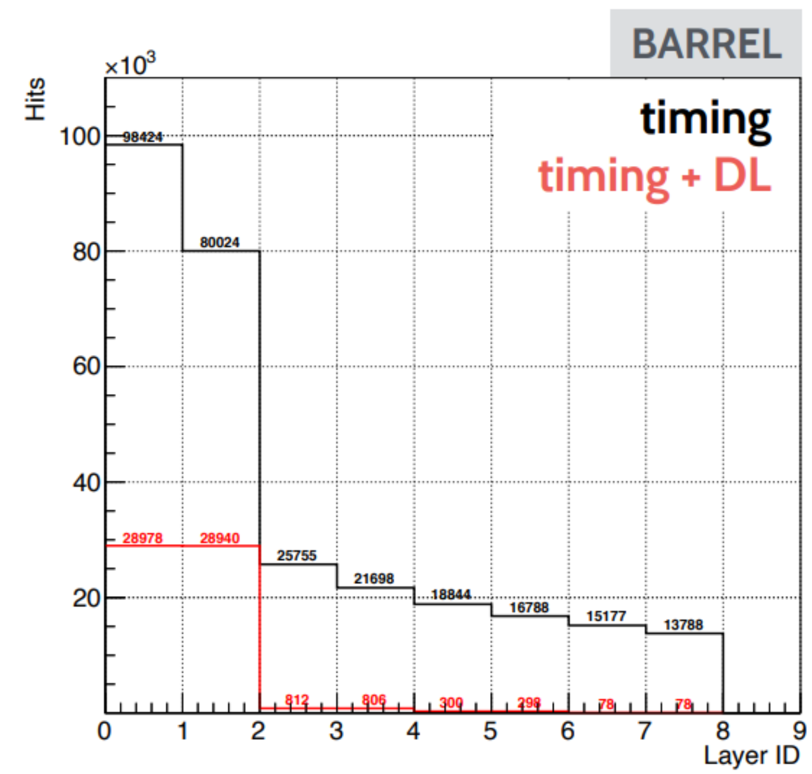
Occupancy studies → pixel pitch



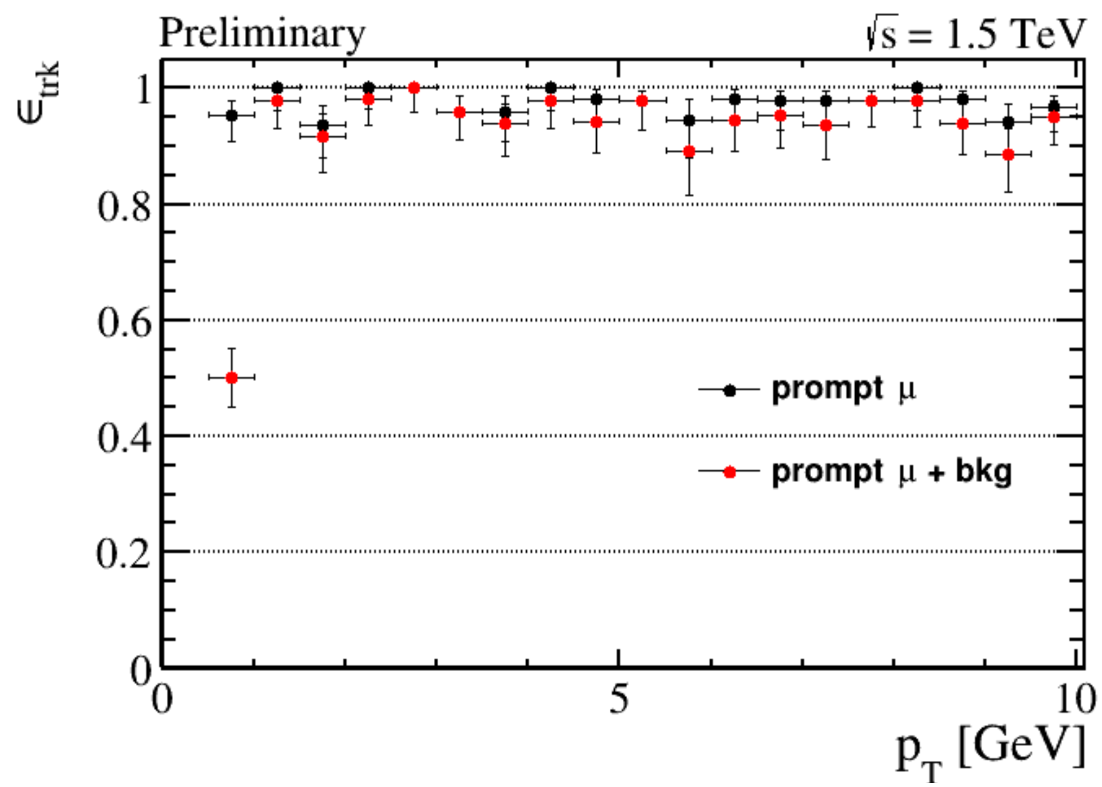
Vertex (25×25 μm²): 4.6 billion pixels
Inner (150×150 μm²): 0.9 billion pixels
Outer (150×150 μm²): 5.1 billion pixels

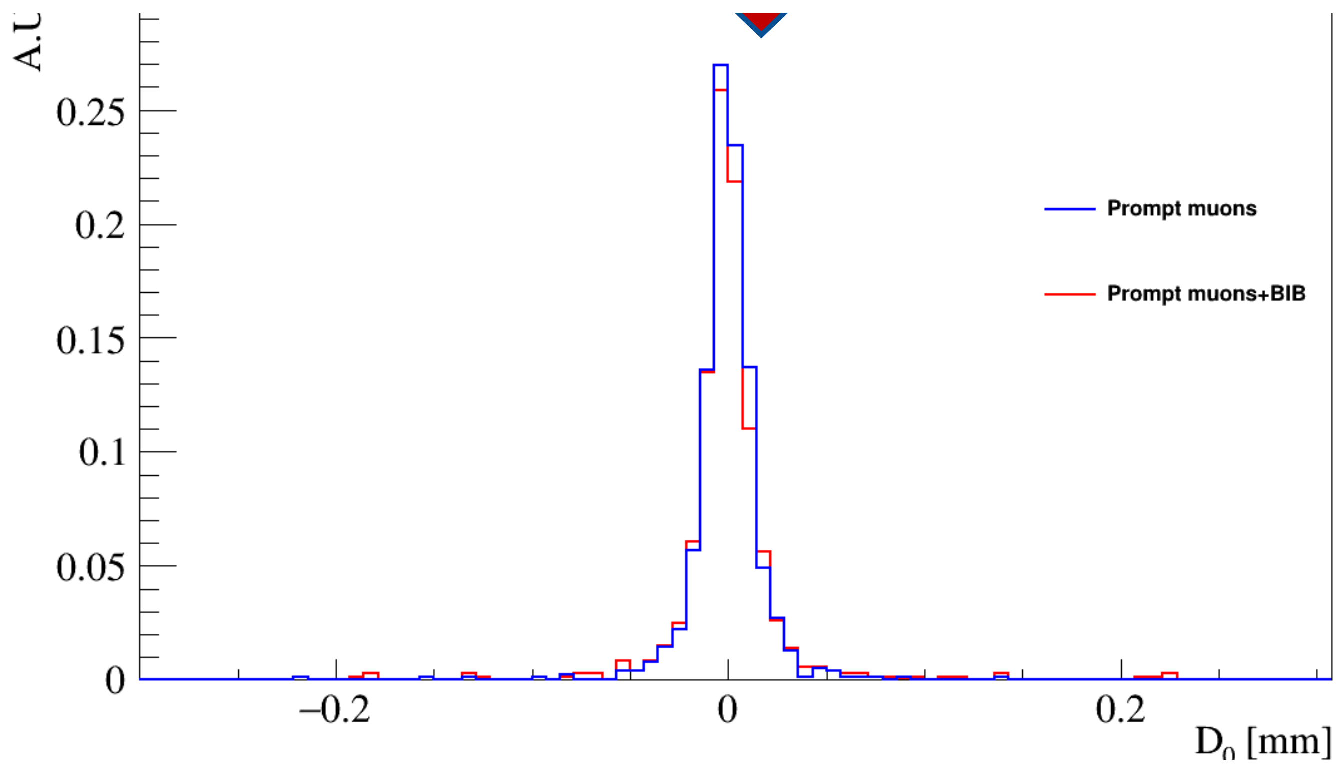


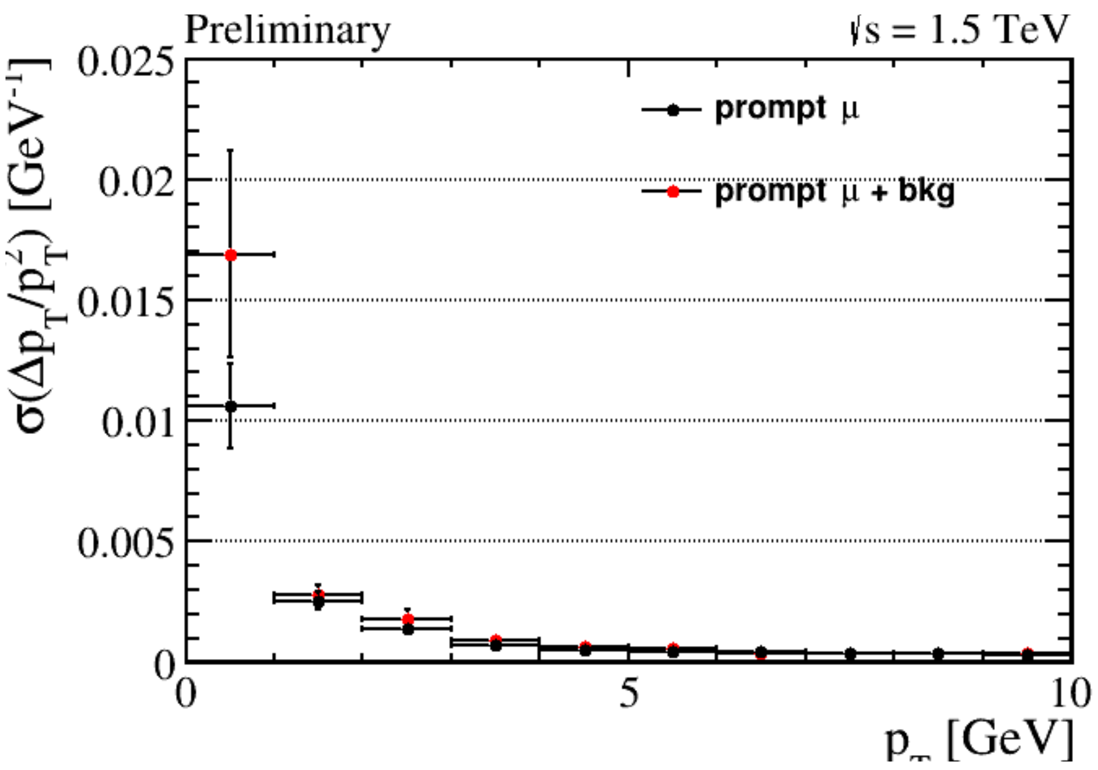
- Tracking critical for **jet reconstruction** and **b-tagging**
- Occupancy is a large problem: can be reduced substantially with timing cuts
- CMS-style 'double layer' readout with directional discrimination can also substantially lower occupancy



Tracking Performance

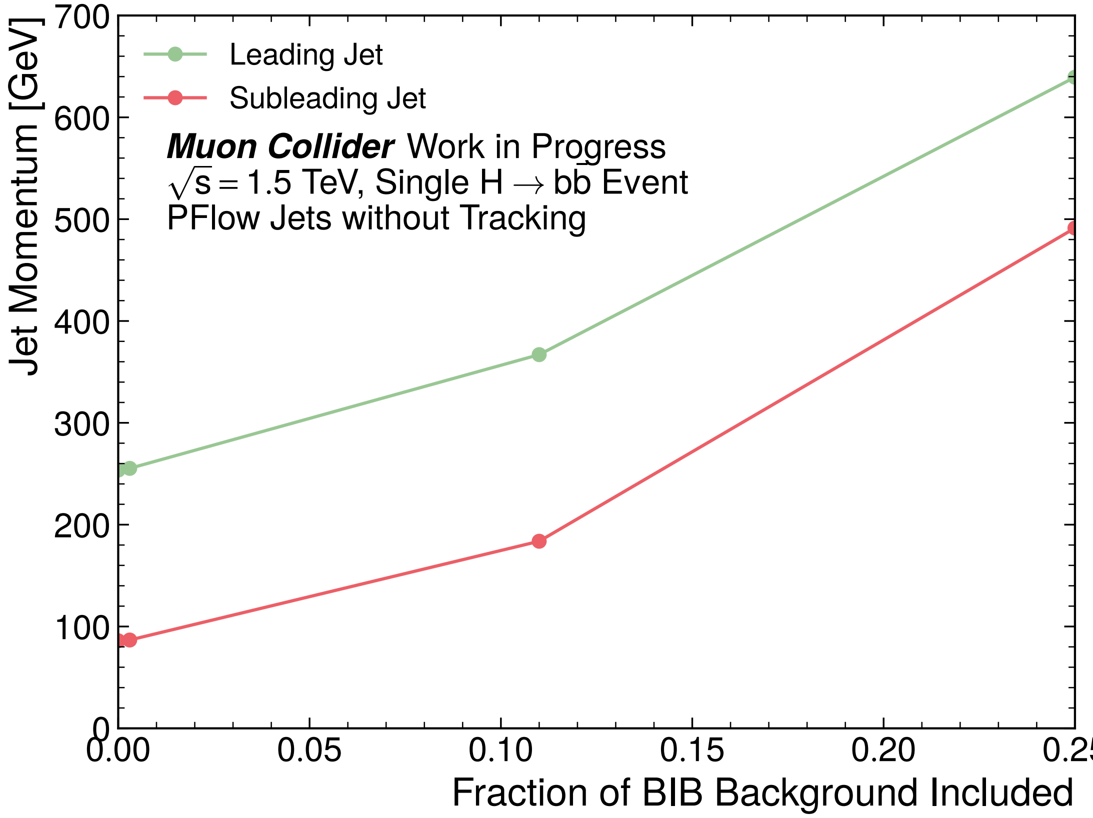


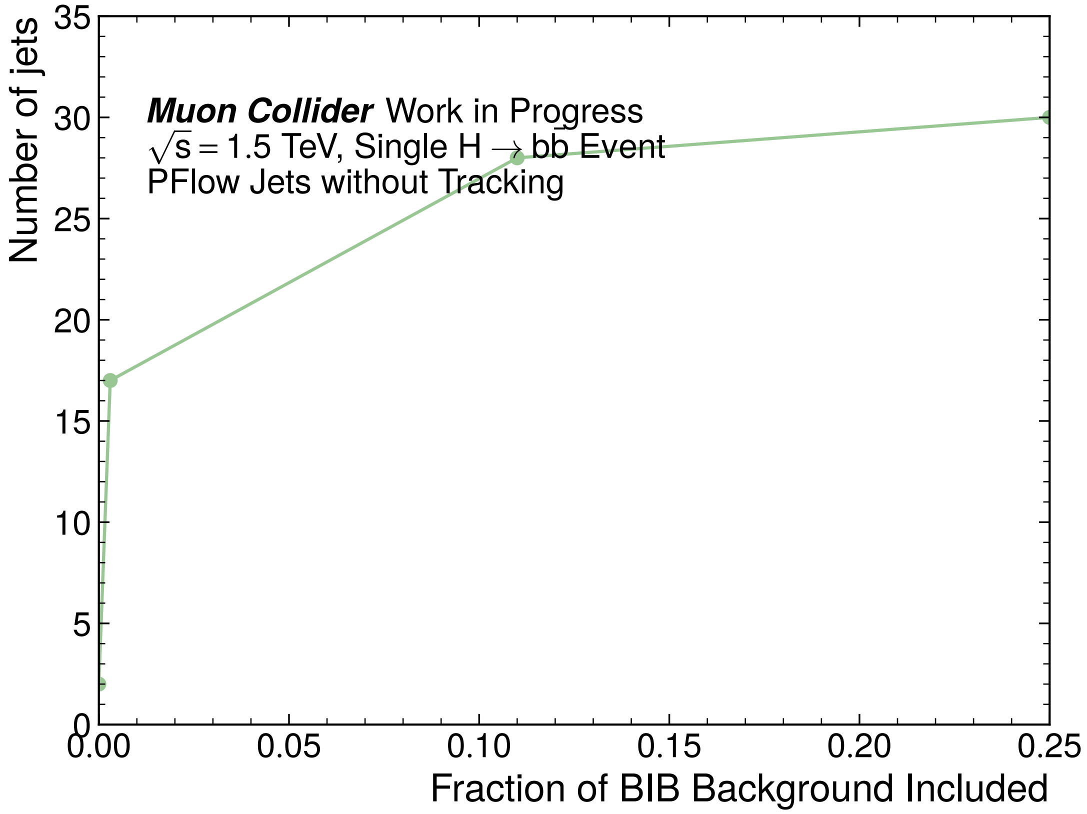




- With some basic hit suppression and track level cuts, get good track efficiency and low fake rate
  - Next question: how much of this can be done ‘on detector’ to reduce read out burden?

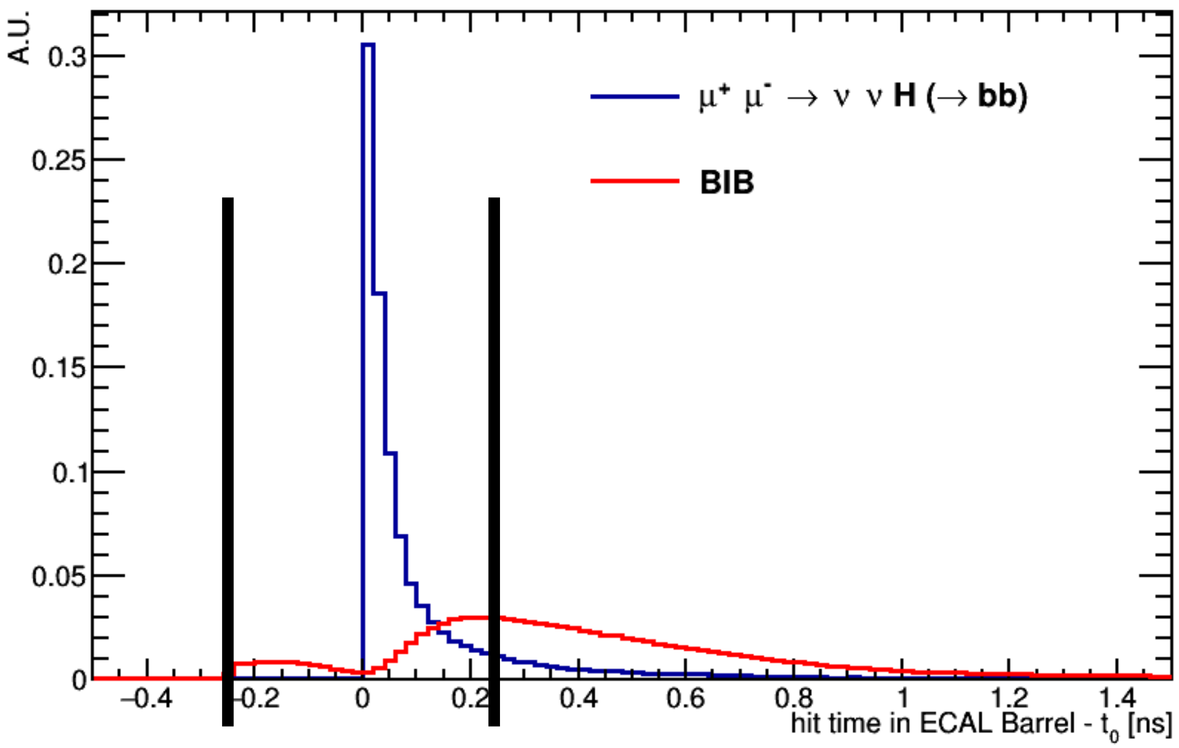
Jet Performance



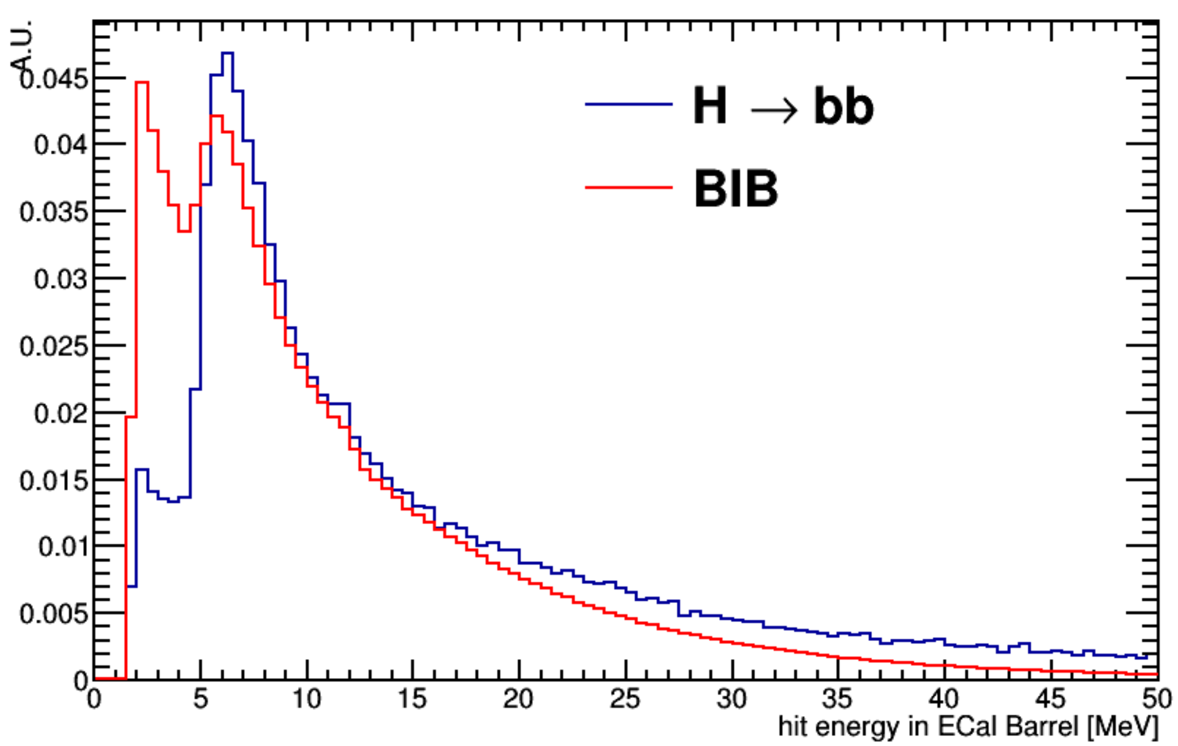


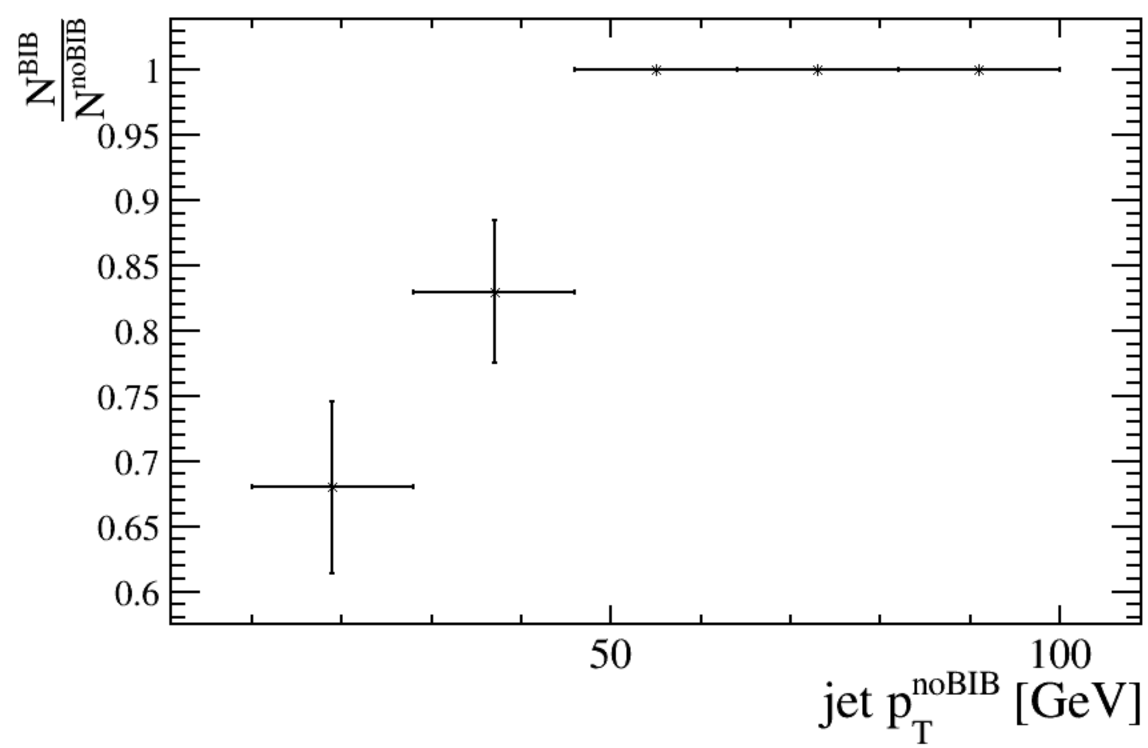
- Here, run jet reconstruction (without tracking) using ~default CLIC reconstruction and up to 25% of BIB
- Two critical observations:
  - Jet momentum increases dramatically: 250 GeV → 650 GeV
  - Number of jets increases dramatically: 2 → 30
    - Most are higher energy than the 'real' jets in the event! Very different from LHC

Mitigating BIB in Jets

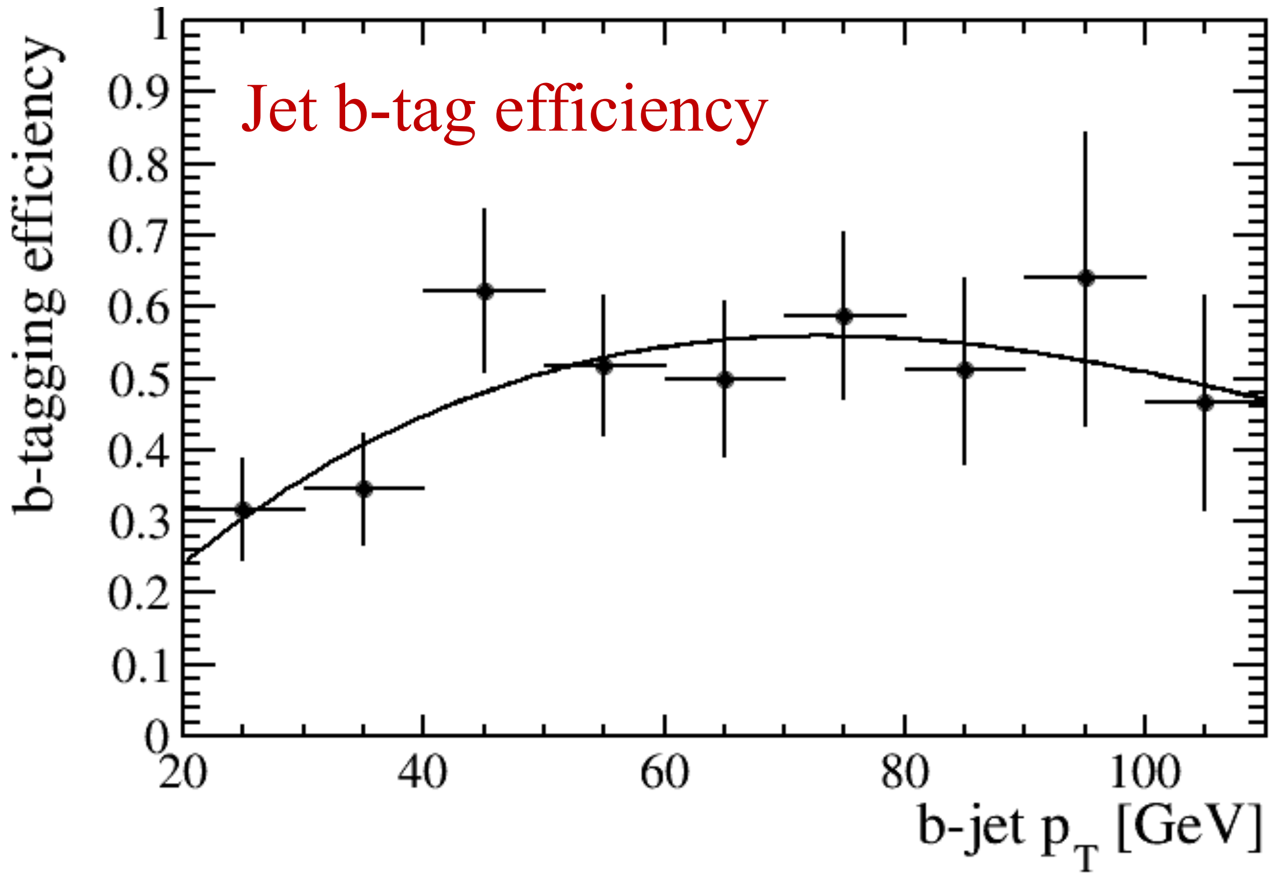


- However, there are obvious timing and energy cuts than can be used to suppress the BIB
- Here, still Calo only: PFlow with tracking results also in progress and very promising!
  - Should be able to have good efficiency with good resolution: not as good as CLIC, but starting to be comparable



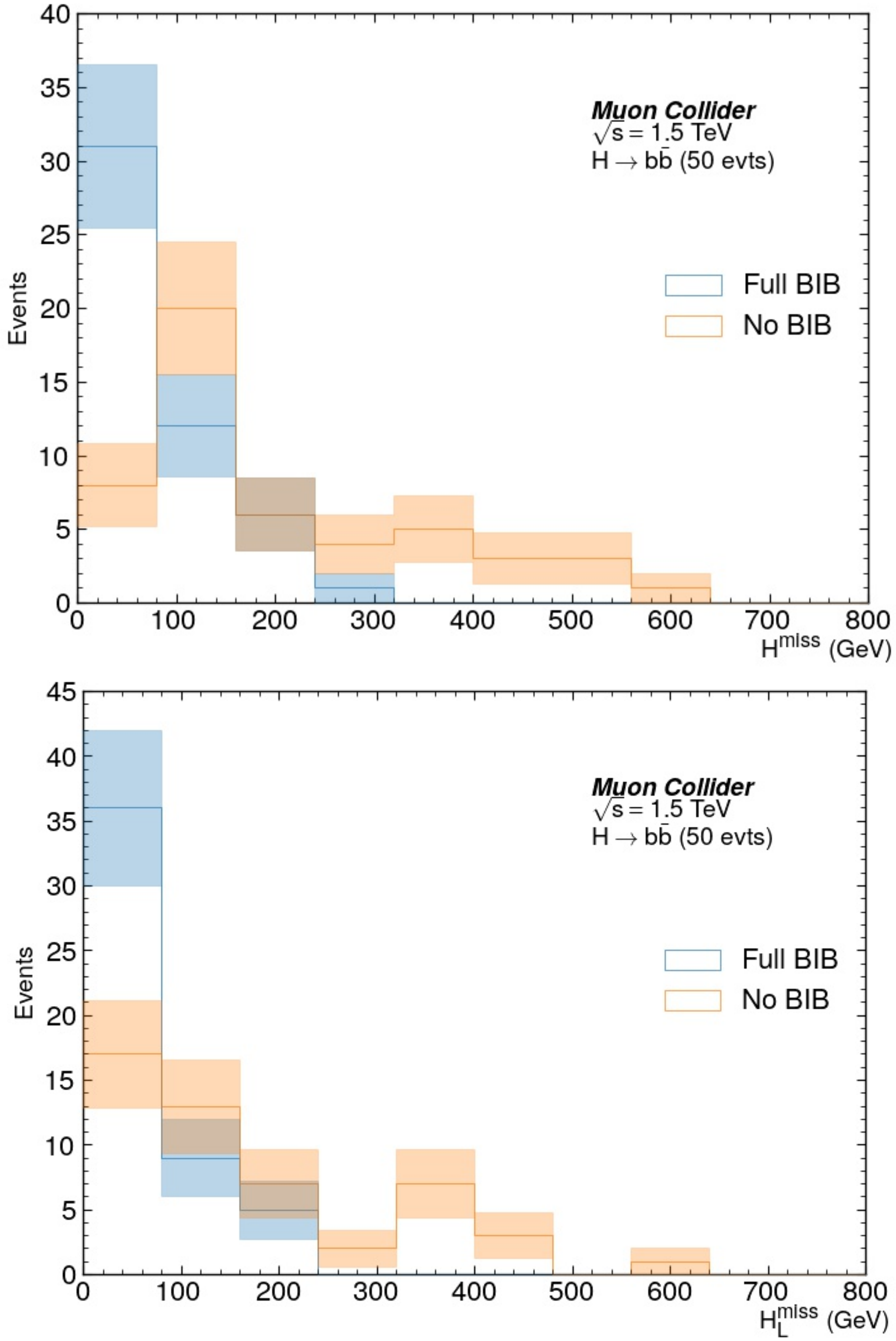


B-Tagging



- The older “MAP” framework had simple b-tagging implemented, with decent b-tagging based on SV finding
- CLIC’s BDT-based b-tagging being implemented now: good progress
  - With good tracking and low fakes already seen, should be powerful

Missing (Transverse?) Energy



- Missing energy critical for VBF selection: forward neutrinos can be useful for background rejection
- Unfortunately, BIB has large smearing effect on the longitudinal component — leads to smearing of the "total" missing energy as well
  - Update to tracking PFlow may help?
  - But transverse-only missing energy may be more useful
  - More studies in progress

Trigger and DAQ

- Raw DAQ rate, if all hits read out of tracker, is 10x rate of the HL-LHC
    - Can this be reduced on-detector?
- 100 kHz collision rate is low, and could enable trigger-less readout
    - Could be an advantage compared to FCC-hh?

Why a Muon Collider for Higgs Self Coupling?

- The muon collider may be an effective way to get to high-energy collisions
  - Some Higgs properties, like the self-coupling and quartic coupling, absolutely require these high energies
- The experimental environment of the muon collider is unique and challenging
  - But the work of MAP, and our initial studies, are very promising: seems like mitigating the BIB is mostly feasible
  - A muon collider can provide an environment 'in between' FCC-hh and electron machines: high energy like FCC-hh, but much cleaner!
- Snowmass is a great opportunity to develop this idea: lots of collaborating groups and interest, and great potential for a new approach to shake up the future