The MAIA Detector for a 10 TeV Muon Collider

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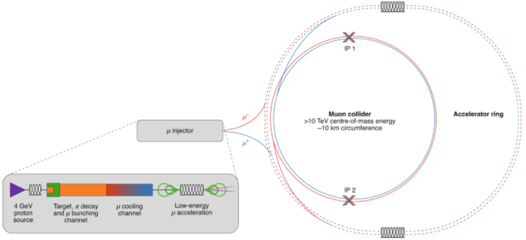
November 12, 2024

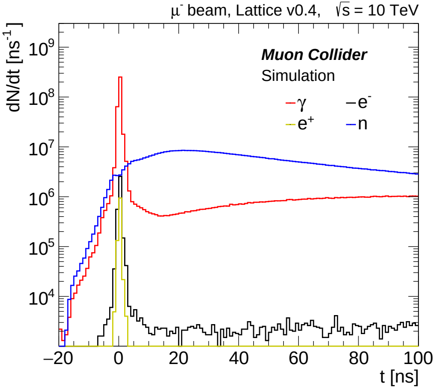
Introduction

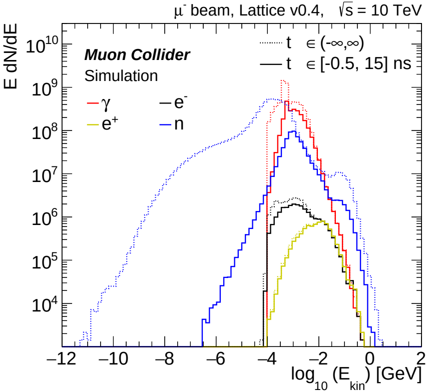
- Can we build a detector for a $10\,\mathrm{TeV}$ muon collider?
  - Colliding fundamental particles (like electrons) with much less synchrotron radiation (like protons) offers **compact, efficient way** to reach high energies.
  - Muons are unstable: **many challenges**, lots of accelerator and detector R&D needed!
  - Detailed studies done with a $\sqrt{s} = 1.5$ or $3\,\mathrm{TeV}$ detector design: based on CLIC, with addition of tungsten "shielding nozzles" to suppress large beam-induced background (**BIB**).
  - To maximize physics potential, important for muon collider to reach $\sqrt{s} = 10\,\mathrm{TeV}$.
- **MAIA** (Muon Accelerator Integrated Apparatus) is one $10\,\mathrm{TeV}$ detector under study.
- This talk:
  - Overview of the MAIA detector design.
  - Tracker design and performance.
  - Calorimeter design and performance.
  - Conclusion and outlook.
- Note: plan to show latest results publicly at US CPAD workshop next week.



Studies with Beam Induced Background

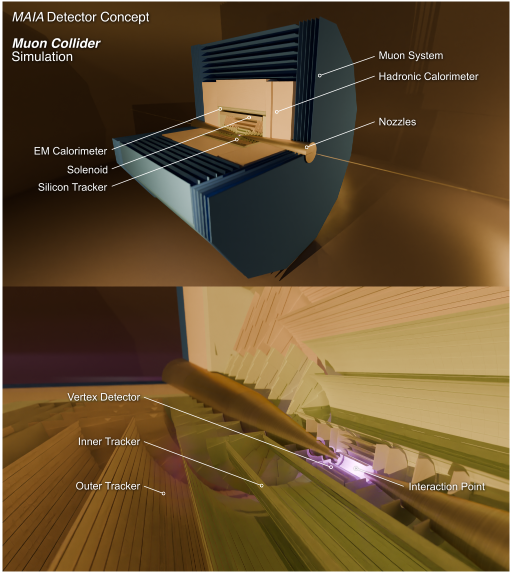
- MAIA performance evaluated using updated FLUKA 10 TeV BIB:
  - Simulation performed by randomly sampling and combining FLUKA "sub-events" (1/10 of bunch crossing) to ensure statistical independence, and then overlaying during digitization.
  - BIB kinematics very similar to $3\,\mathrm{TeV}$; but MDI, nozzle optimization **extremely** important.
  - See Kiley Kennedy's USMCC talk on MDI for more details (will also be presented at CPAD).



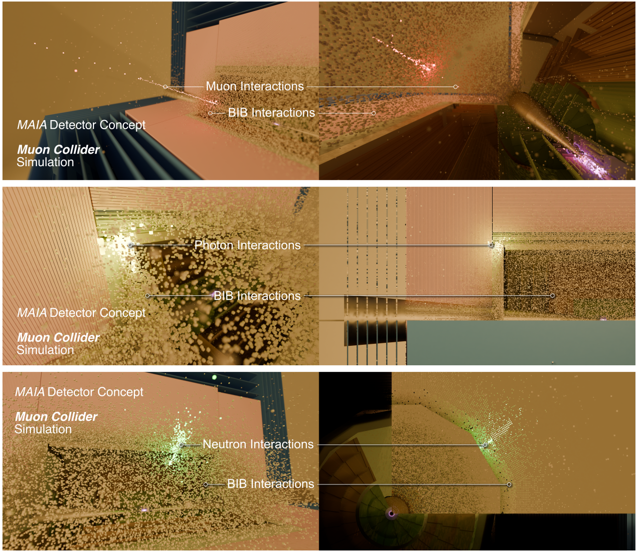


MAIA Detector Concept

- Evolution of $3\,\mathrm{TeV}$ CLIC detector; still using tungsten shielding nozzles to mitigate BIB.
- Solenoid moved to sit **inside calorimeters**:
  - Field strength increased from **3.57 to 5** T.
  - Smaller overall (265 vs $344\,\mathrm{mm}$ in barrel).
  - **Shields calorimeters** from the effect of BIB.
- Silicon tracker partially **reoptimized**:
  - Vertex detector used double-sided vertex layers to select hits; requires extra material and power, mildly inefficient for displaced tracks.
  - Greatly improved ACTS-based track finding allowed removing **all but innermost** doublet.
- Calorimeter **depth increased**:
  - Silicon-tungsten EM calorimeter: $40 \to 50$.
  - Iron-scintillator hadronic calorimeter: $60 \to 75$.



MAIA Performance Studies

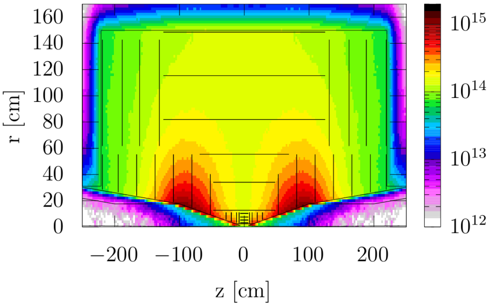


- Detector performance evaluated using **single particle** samples:
  - Muons for the tracker: flat in p_T.
  - Photons the ECal: flat in E.
  - Neutrons for the HCal: flat in E.
  - Uniformly distributed in $0 < \phi < 2\pi$, $8^\circ < \theta < 172^\circ$.
- BIB overlay applied; reconstruction performed using key4hep-based MuonColliderSoft framework.
- Reco uses **Pandora** particle flow:
  - Track-to-cluster association found to be suboptimal for muon collider.
  - Work needed before we can study other objects (electrons, taus).

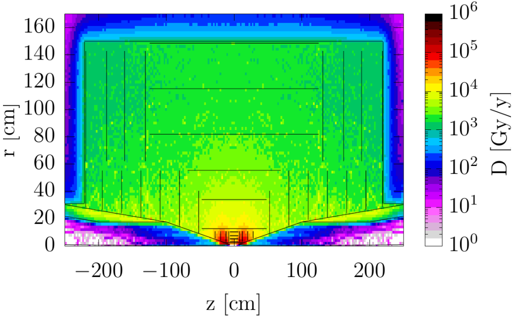
Expected Radiation Damage

- Radiation at $10\,\mathrm{TeV}$ **comparable to HL-LHC** and previous $3\,\mathrm{TeV}$ muon collider studies; much lower than FCC-hh (10^{18} $1\,\mathrm{MeV\text{-}n_{eq}/cm^2}$) (2209.01318, 2105.09116)

1 MeV neutron equivalent in Silicon [n cm^{-2} y^{-1}]



Total ionizing dose

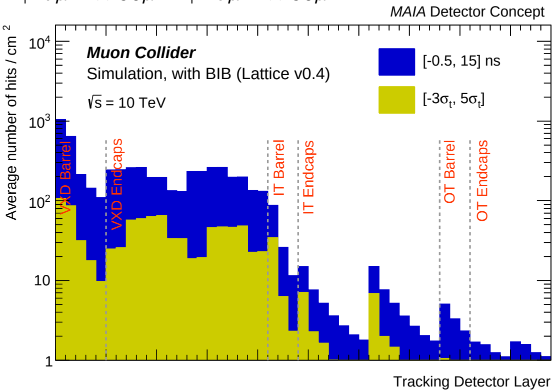


	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider ($3\,\mathrm{TeV}$)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider ($10\,\mathrm{TeV}$)	20	0.2	3×10^{14}	10^{14}

MAIA Tracker Layout and Occupancy

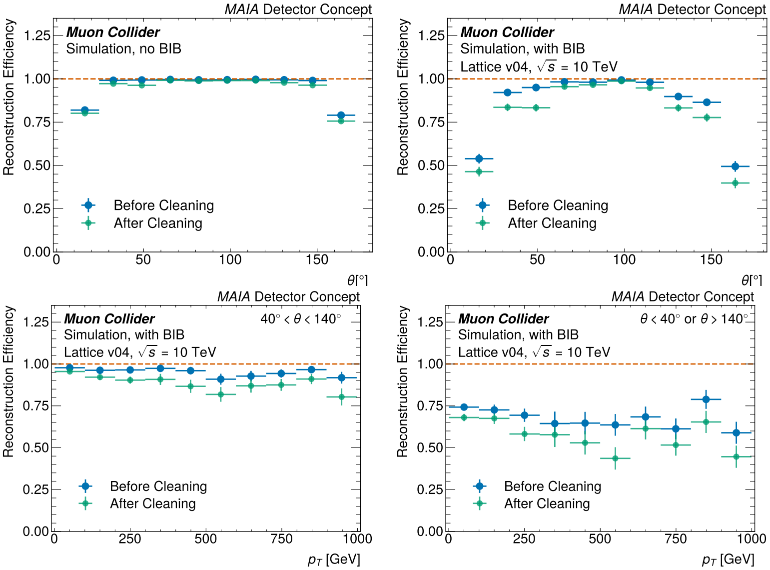
	Vertex Detector	Inner Tracker	Outer Tracker
Sensor Type	pixels	macropixels	microstrips
Layers, Barrel (Endcap)	4 (4)	3 (7)	3 (4)
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
Sensor Thickness	$50\mu m$	$100\mu mm$	$100\mu mm$
Time Resolution	30ps	60ps	60ps
Spatial Resolution	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu m$	$7\mu m \times 90\mu m$

- Very high hit densities in vertex layers:
  - Up to 1600 $\mathrm{hits/cm^2}$ in innermost (but collisions 1000x less frequent than LHC).
  - Compare to HL-LHC LGADs: same resolution but 1mm $\times$ 1mm granularity.
- $[-3\sigma, 5\sigma]$ beam crossing timing window eliminates much of the BIB:
  - Window cut also eliminates z-dependence from nozzle in barrel.
  - Incoherent e^+e^- pairs may lead to additional flux; **not included**.



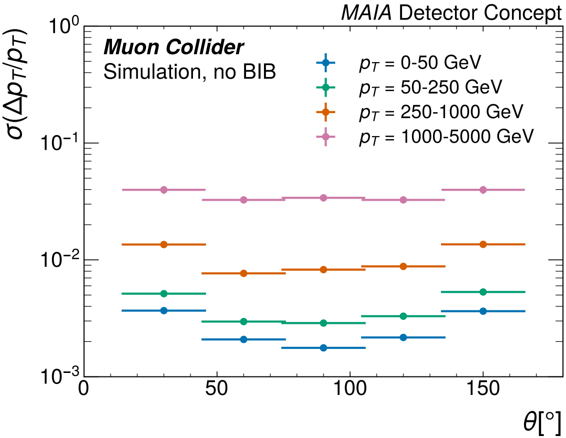
Tracking Efficiency

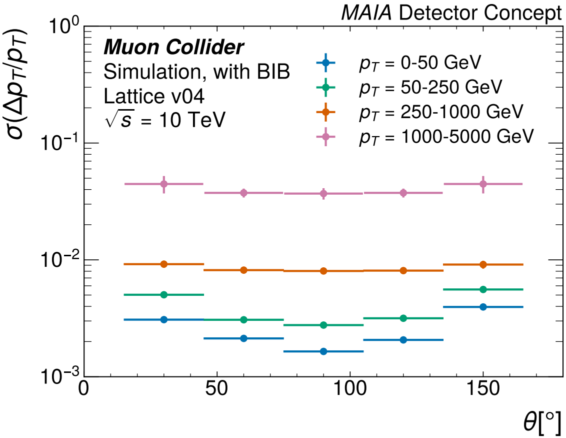
- Efficiency quite high with BIB, at least in the barrel:
  - Only about 3.5% lower overall wrt without BIB.
  - Noticeably worse in forward region: **future work** to optimize!
  - Stays relatively high as function of p_{T}.
- Track cleaning applied to reject BIB fakes:
  - $p_{\mathrm{T}} > 1\,\mathrm{GeV}$
  - $N_{\mathrm{hits}} > 5$
  - $|d_0| < 0.1\,\mathrm{mm}$
  - $\chi^2/\mathrm{DOF} < 3.$
  - Needs reoptimization for heavy flavour!



Track p_T Resolution

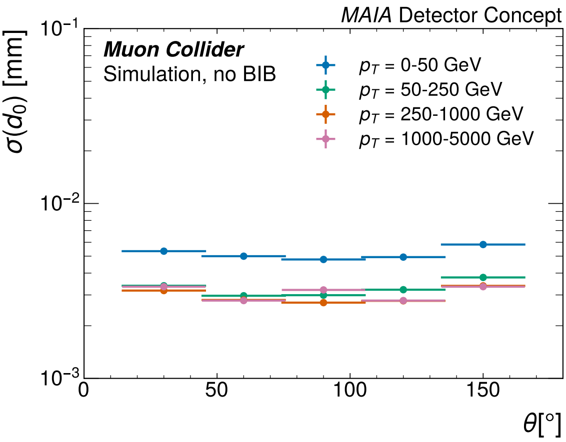
- Track p_T resolution shown as function of different p_T ranges, with/without BIB.
- Momentum resolution ranges from a few percent to up to 5% for 1-5 TeV tracks.
- Resolution **does not degrade** in the presence of BIB.

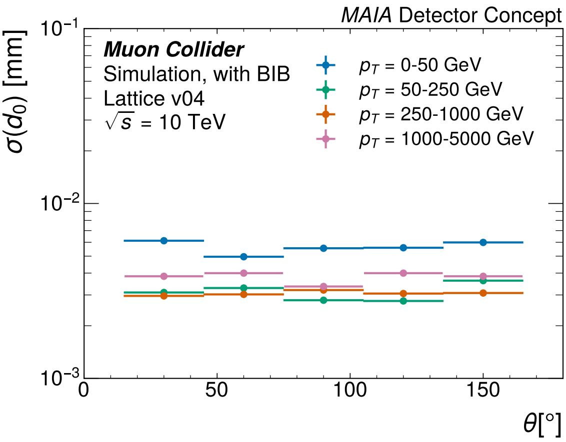




Track d_0 Resolution

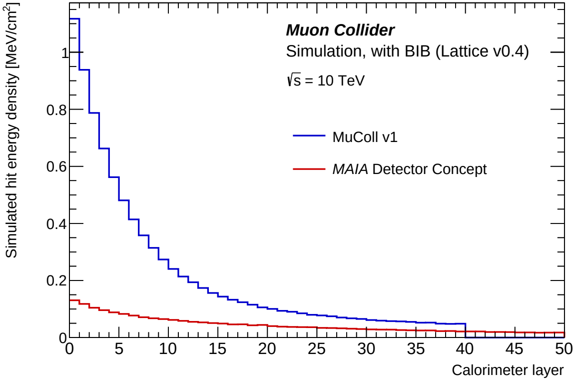
- d_0 resolution also stays stable in the presence of BIB.
- Consistently found to be below $10\,\mu\mathrm{m}$; roughly stable as function of p_T and θ.



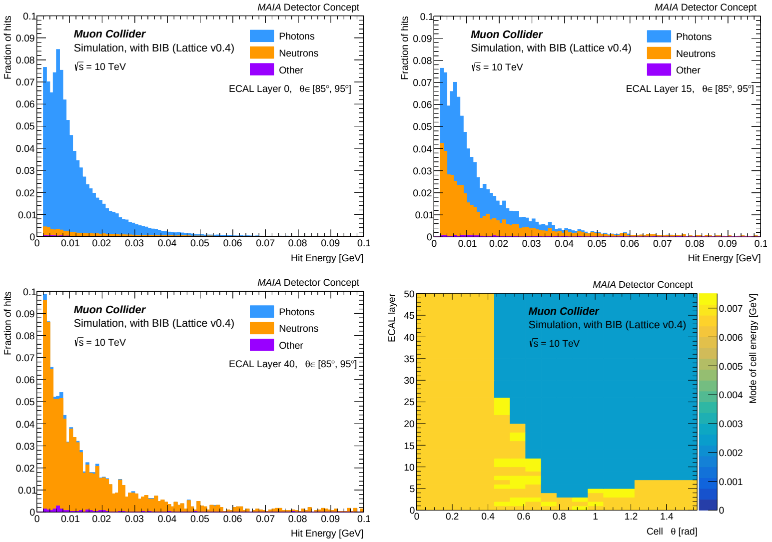


	ECAL	HCAL
Cell type	Silicon - Tungsten	Iron - Scintillator
Cell Size	5.1mm × 5.1mm	30.0mm × 30.0mm
Sensor Thickness	0.5mm	3.0mm
Absorber Thickness	2.2mm	20.0mm
Number of layers	50	100

- Current proposals comparable to existing calorimeter technology:
  - ECal very similar to CMS high granularity calorimeter upgrade.
  - HCal similar to ATLAS TileCal (10x smaller sensors).
- Impact of solenoid shielding:
  - Approximately $4X_0$ worth of material.
  - Reduces incoming BIB flux by a factor of **10** compared to previous design.



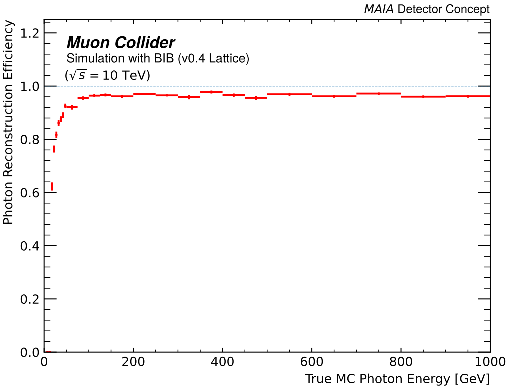
Variable Cell Thresholds

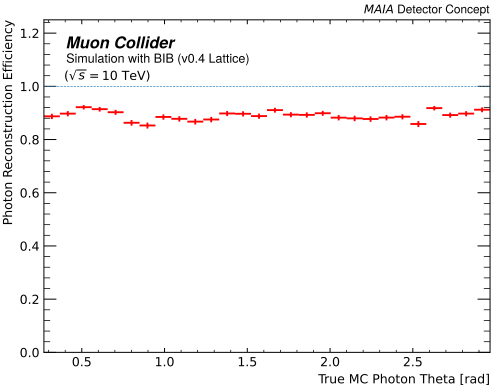


- BIB in the ECAL:
  - Lower layers dominated by **photons**.
  - Layers further away mainly **neutrons**.
  - **Very low energy**, soft, diffuse: hard to reconstruct.
- High cell thresholds needed for BIB:
  - Derive **cell-dependent** thresholds from BIB.
  - Higher thresholds to reject photons.
  - Strong handle at reducing fakes; at cost of worse resolution.

Photon Efficiency

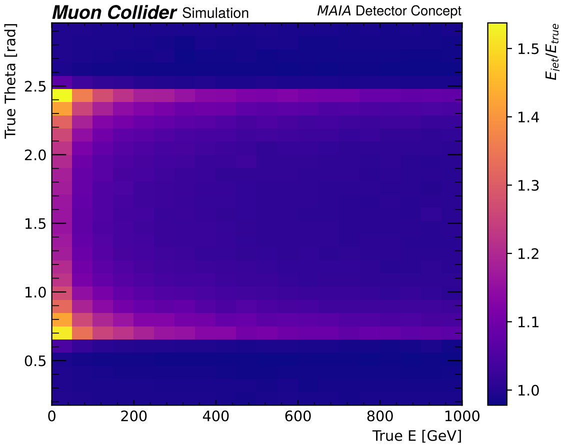
- Photons reconstructed by Pandora cone-clustering of cells with timing b/w -0.5 to 10 ns.
- Efficiency measured by $\Delta R < 0.1$ matching reco photons with $p_{\mathrm{T}} > 5\,\mathrm{TeV}$ to truth.
- Very high (95%) above $100\,\mathrm{GeV}$, but drops down to 60% for a 10-$20\,\mathrm{GeV}$ photon.





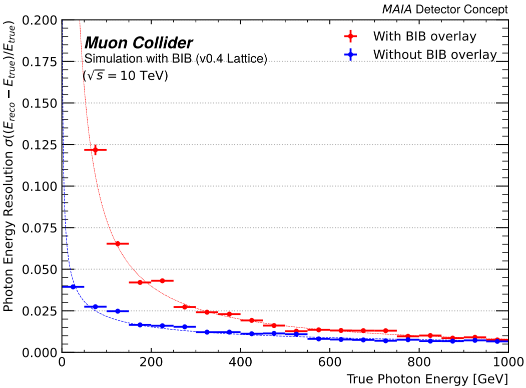
Electromagnetic Calorimeter Response

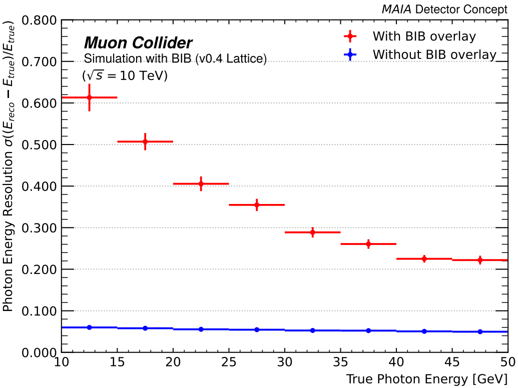
- Measuring energy resolution requires characterizing calorimeter **response function**:
  - Determined by studying photons **without** BIB, using jets as proxy for photons instead of Pandora objects.
  - Binned in photon energy and θ.
  - Low-energy photons at edge of detector acceptance show largest discrepancy.
- **Correct** energy resolution using measured response to account for these effects.



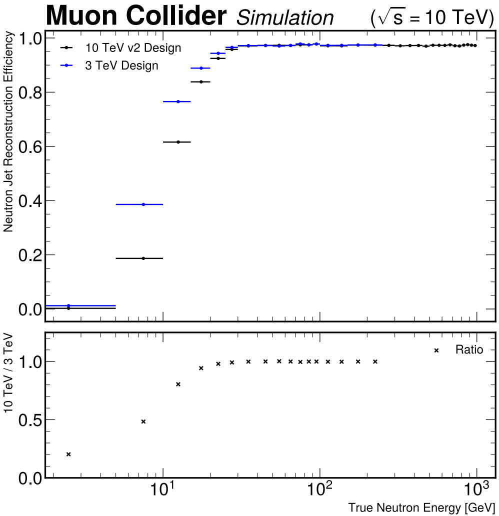
Photon Energy Resolution

- Without BIB, energy resolution stays stable at around 6%: no impact from shielding!
- With BIB, Pandora issues cause high contamination below $50\,\mathrm{GeV}$: drops as low as 60%.
- More detailed BIB mitigation (taking **cell timing** into account) could help mitigate this.





Hadronic Calorimeter Performance



- HCal performance **still work in progress**:
  - In the past: showed very poor reconstruction efficiency for neutrons.
  - This turned out to be due to a typo in a steering file: HCal deposits in the barrel were **not getting processed**.
  - With that fixed: efficiency looks great, quite comparable to 3 TeV detector.
- Resolution studies with BIB still not finalized:
  - Similar calibration strategy as ECal: derive response function from simulation w/o BIB.
  - Hope to have these results **very soon**.
- Will update paper draft once they are ready.

Future Work

- Presented an initial look at the MAIA detector design and performance studies.
- Many areas for future work:
  - **Muon system**: far enough away to not be impacted by BIB, but can a next-gen HCal replace this altogether?
  - **Forward region**: clear issues, especially tracker layout needs reoptimizing.
  - **Nozzle geometry**: aim to increase η coverage without affecting BIB rejection.
  - **Magnet feasibility**: how practical is the proposed $5\,\mathrm{T}$ field?
  - **Trigger system**: aiming for triggerless readout, more detailed studies needed.
  - **Particle flow**: better algorithms needed for additional objects!

MAIA: A new detector concept for a 10 TeV muon collider

Charles Bell,[1] Daniele Calzolari,[2] Christian Carli,[2] Karri Folan Di Petrillo,[3] Micah Hillman,[1] Tova R. Holmes,[1] Sergo Jindariani,[4] Kiley E. Kennedy,[5] Ka Hei Martin Kwok,[4] Anton Lechner,[2] Lawrence Lee,[1] Thomas Madlener,[6] Federico Meloni,[6] Isobel Ojalvo,[5] Priscilla Pani,[6] Rose Powers,[5] Benjamin Rosser,[3] Leo Rozanov,[3] Kyriacos Skoufaris,[2] Elise Sledge,[7] Alexander Tuna,[1] and Junjia Zhang[5]

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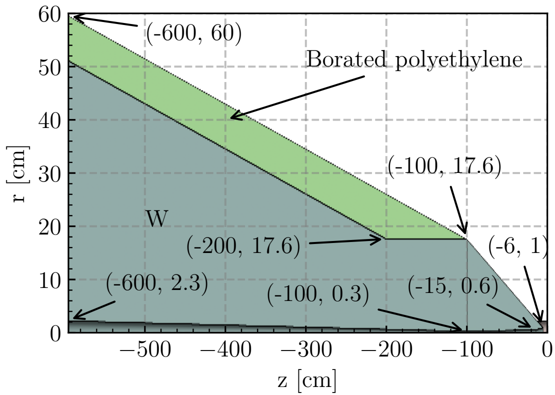
(Dated: November 10, 2024)

Conclusion and Paper Status

- Thanks to Alex Cerri and Kevin Black for providing comments on the paper draft!
- We'll consider and implement editorial suggestions. Some responses to questions:
- Why is tracking efficiency preferentially lost at high p_T after cleaning?
  - Higher momentum muons are more likely to radiate; cleaning is also quite strict.
- Are other sources of BIB (e.g. neutrino interactions) relevant?
  - Decay electrons interacting are by far the dominant component of the BIB.
- Is there a reason to limit ourselves to $O(10\,\mathrm{ps})$ resolution? Would $O(1\,\mathrm{ps})$ help?
  - Wanted to be conservative in establishing baseline performance; definitely want to study effect of improved resolution in the future.
- Why a $5\,\mathrm{T}$ magnetic field specifically?
  - Based on a scan considering incoherent pairs effects (omitted in these studies).
- 80% tracking efficiency seems quite low– is it a good idea to quote that number?
  - Cumulative efficiency including (suboptimal) endcaps; we can avoid quoting this number.

Backup

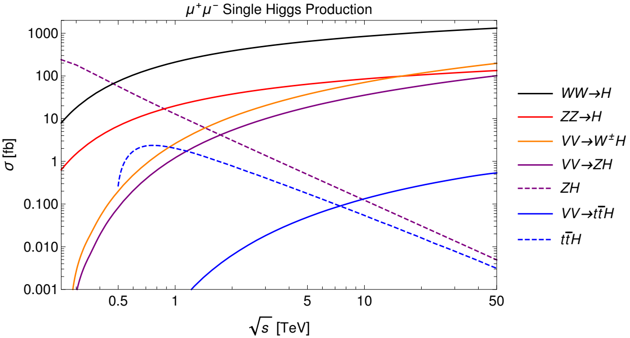
Tungsten Shielding Nozzles



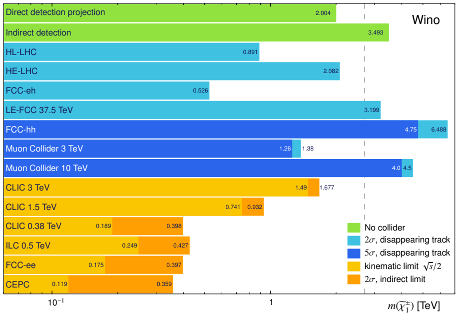
- Current nozzle geometry:
  - Restricts forward region to $|\eta| < 2.44$ (10°).
  - Dark green at bottom of figure is cavity for muon beam pipe.

The Case for 10 TeV

- $\sqrt{s} = 10\,\mathrm{TeV}\ \mu^+\mu^-$ **approximately comparable** to $100\,\mathrm{TeV}\ pp$ collider:
  - Can nail down shape of the Higgs potential, achieve strong Higgs precision (2206.08326).
  - 5σ discovery potential for some minimal WIMP dark matter models at correct thermal target.
- Muon colliders **become VBF colliders**: notion of "electroweak PDF" emerges.
  - s-channel interactions (dashed lines) fall with $\sqrt{s}$; electroweak interactions become dominant.



M. Forslund, P. Meade (10.1007/JHEP08(2022)185)



R. Capdevilla et al. (10.1007/JHEP06(2021)133)

Existing 3 TeV Detector Design

- Existing detector concept **based on CLIC** with addition of **shielding nozzles** to reduce BIB.

hadronic calorimeter

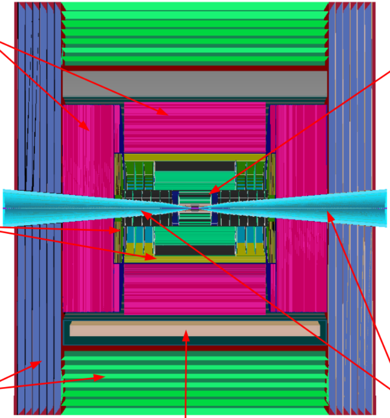
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

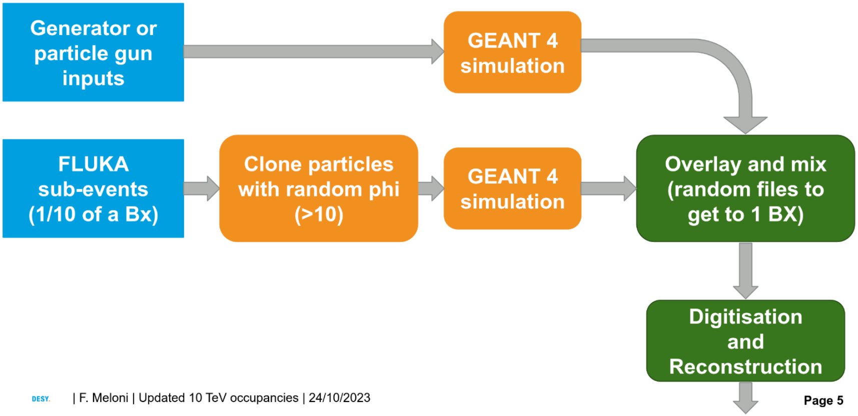
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

IMCC: Muon Collider Detector (CERN)

BIB Overlay and Subevent Mixing

- See Nazar's talk for details on BIB overlay and simulation.
- For 10 TeV studies, we're now using new pipeline with FLUKA **subevent mixing**:
  - Simulating the BIB contributions in FLUKA is **computationally expensive**.
  - Overlays statistically independent; reduced effects due to lack of BIB statistics.



Expected Tracker Occupancies