The MAIA Detector for a 10 TeV Muon Collider

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October 14, 2025



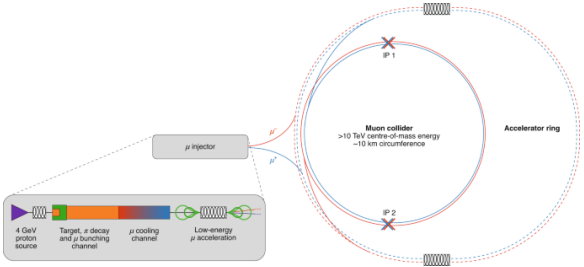
THE UNIVERSITY OF CHICAGO





Introduction and Outline

- I (mostly) work on ATLAS; topics I won't cover today:
  - Higgs boson decay to invisible particles
  - Long-lived particles (displaced vertices and $E_{\mathrm{T}}^{\mathrm{miss}}$, displaced taus)
  - ATLAS track trigger upgrade for HL-LHC
  - Front-end electronics for HL-LHC Inner Tracker Strip detector



- This talk: can we build a detector for a $10\,\mathrm{TeV}$ **muon collider**?
  - Introduction to muon colliders.
  - Accelerator and detector R&D needs.
  - Overview of **MAIA** (Muon Accelerator Instrumented Apparatus) detector.
  - MAIA performance studies, including **new** results for European Strategy.
  - Opportunities and plans for future work.

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Muon Colliders

Existing Collider Technologies

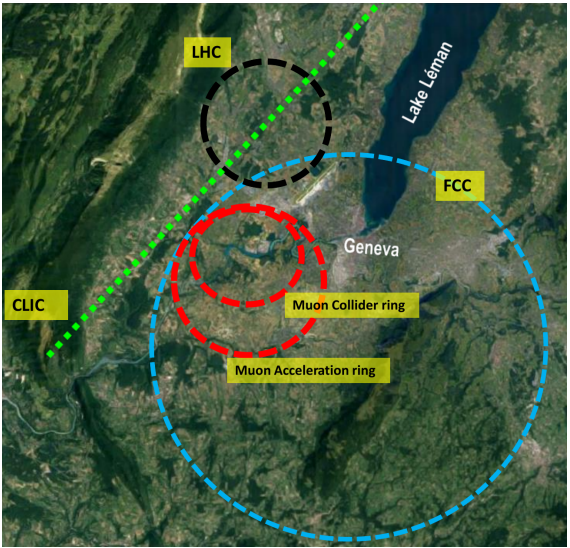


CERN-MI-0807031

- Electron/positron colliders:
  - **Fundamental** particles.
  - Maximum energy limited by **synchrotron radiation**, energy loss $\propto 1/m^4$.
  - Electrons are light: $0.511\,\mathrm{MeV}$
- Proton colliders:
  - $\sim$**2000 times** heavier than electrons ($938\,\mathrm{MeV}$).
  - Compare $13.6\,\mathrm{TeV}$ LHC vs $209\,\mathrm{GeV}$ LEP in **same tunnel**.
  - **Composite** particles: messy collisions, beam energy divided across many partons.

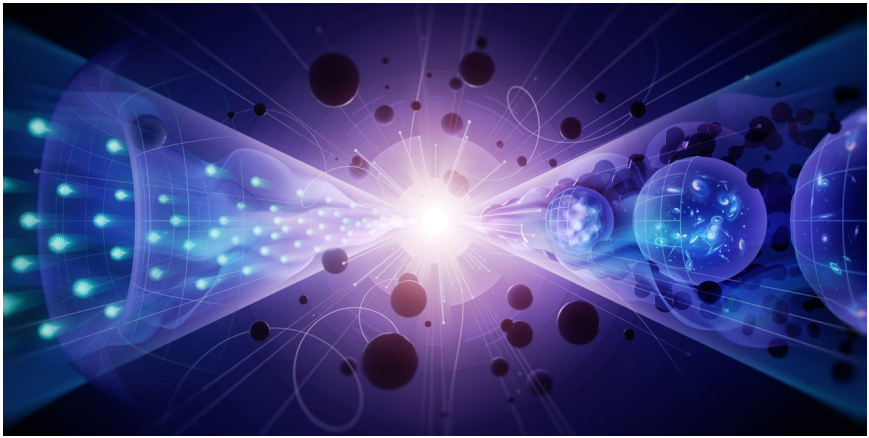
Why Collide Muons?

- Muons: best of both worlds?
  - **200x** heavier than electrons.
  - Like electrons, **fundamental** particle: all beam energy goes into collision.
  - $10\,\mathrm{TeV}$ muon collider roughly **equivalent** to $100\,\mathrm{TeV}$ proton collider (FCC).
  - But much smaller footprint, close to LHC.
- ...except they are **unstable**: $2.2\,\mu\mathrm{s}$ lifetime.
- Lots of R&D needed!
- International Muon Collider Collaboration (IMCC) and US Muon Collider Collaboration (USMCC) created.



2024 IMCC Annual Meeting

The P5 and NAS Reports



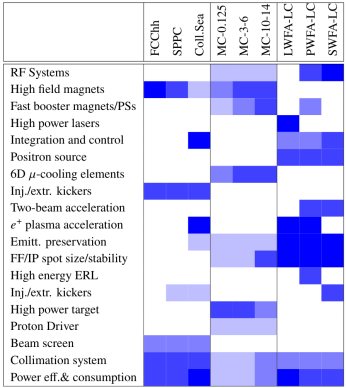
- $10\,\mathrm{TeV}$ "parton" center of mass energy collider R&D strongly endorsed by 2023 US Particle Physics Project Prioritization Panel report: "muon shot".
- Muon collider specifically recommended by 2025 National Academies Report.

Snowmass Implementation Task Force

- Smaller footprint leads to **lower cost** and **power** compared to hadron collider alternatives.
- Technical readiness and risk evaluated in detail during 2021 Snowmass process.

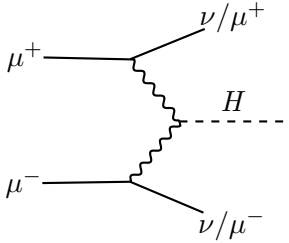
Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPC	125 (75-125)	13 (26)	>10	>25	30-80	~400

Snowmass ITF Report (2208.06030)

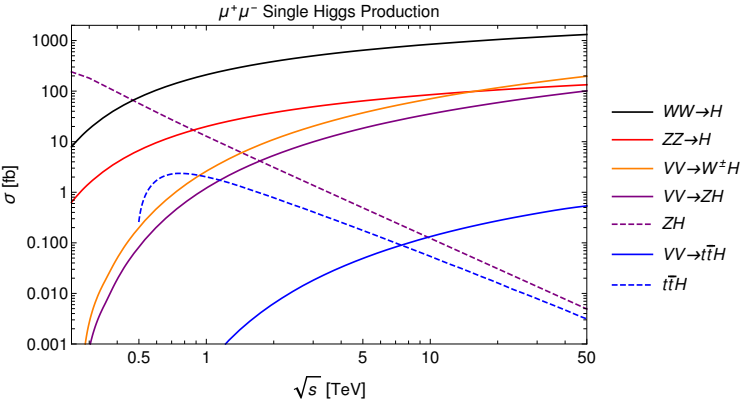


The Case for 10 TeV

- LHC had "no-lose theorem": either find light Higgs with $m < 1\,\mathrm{TeV}$ **or** BSM physics.
- **No such guarantee** for future colliders at present!



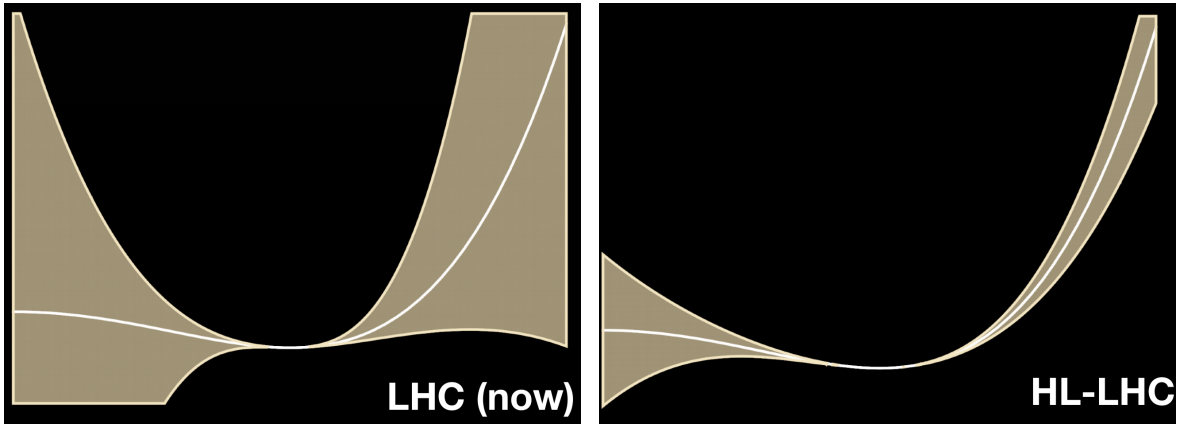
- So why 10 TeV?
  - Muon collider becomes **electroweak** collider.
  - VBF/VBS becomes dominant over s-channel.
  - "Electroweak PDF"



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

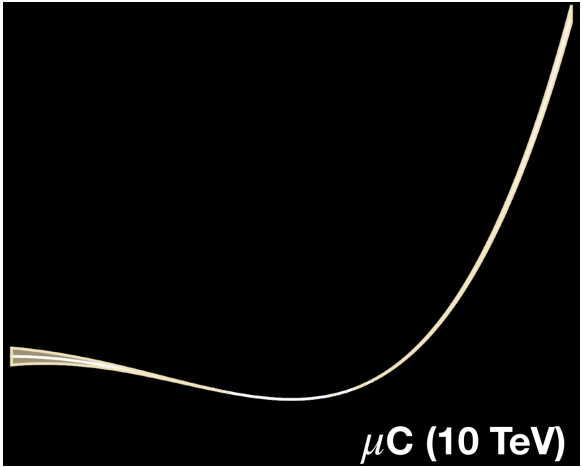
Higgs Potential

- Higgs looks Standard Model like, but **shape of potential** uncertain even after HL-LHC!



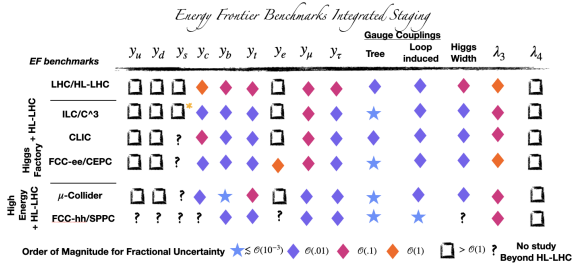
Nathaniel Craig

Higgs Couplings at a Muon Collider



Nathaniel Craig

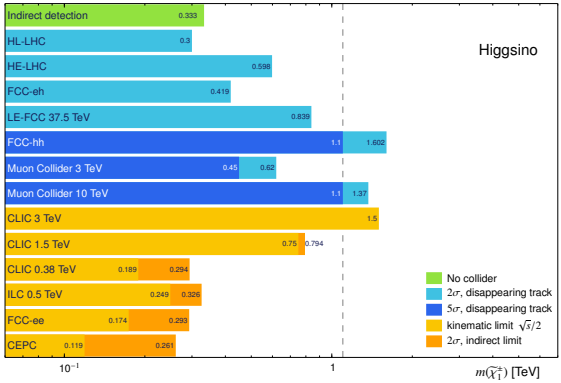
- 10 TeV muon collider will constrain potential shape to $O(1)\%$.
- Constraints on couplings **comparable** between muon collider, FCC-hh.

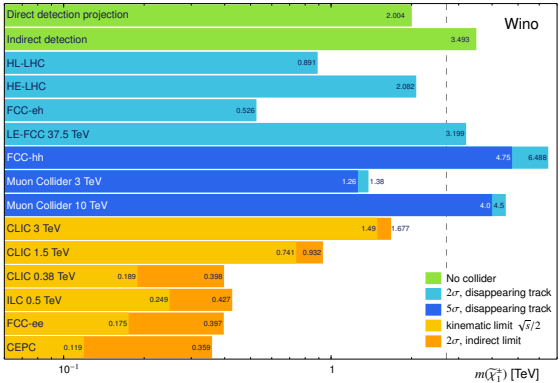


Snowmass Energy Frontier Report (2211.11084)

Dark Matter at Future Colliders

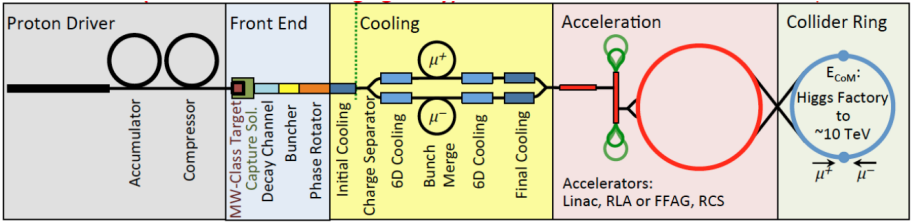
- Simplest WIMPs: "minimal dark matter" (0903.3381, 2203.07351):
  - No new interaction; add new scalar or fermionic multiplet charged under $SU(2)_L \times U(1)_Y$.
  - SUSY examples: doublet (Higgsino), triplet (Wino); higher order multiplets possible.
  - **Not excluded**; $10\,\mathrm{TeV}$ collider can reach relic density at 5σ for Higgsino/Wino-like DM.





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

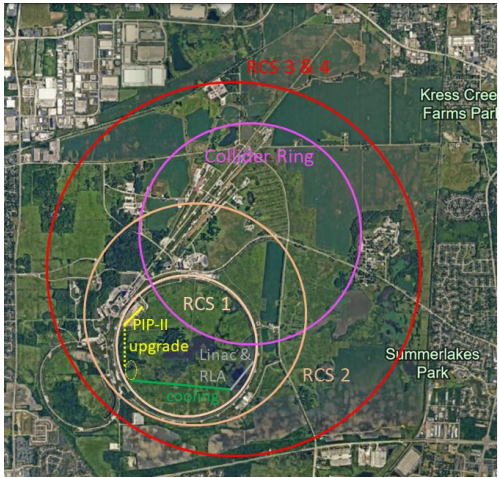
How to Collide Muons

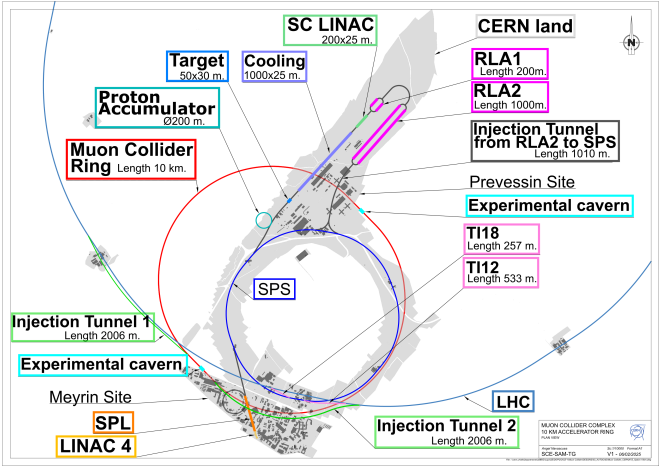


- Main muon collider challenges all **accelerator** related:
  - 1-4 MW target for proton driver: alternatives to liquid mercury needed.
  - 6D ionization cooling: must focus beam as quickly as possible, reduce transverse emittance.
  - Fast ramping magnets to inject, accelerate beam: need $1000\,\mathrm{T/s}$, plus $16\,\mathrm{T}$ DC magnet.
  - Collider ring: 12-16 T large aperture dipoles, 15-20 T quadrupoles; **similar to FCC-hh**.
  - Neutrino radiation flux from decaying muons.
- Baseline design from US Muon Accelerator Program, updated by IMCC (2303.08533)

Siting Options

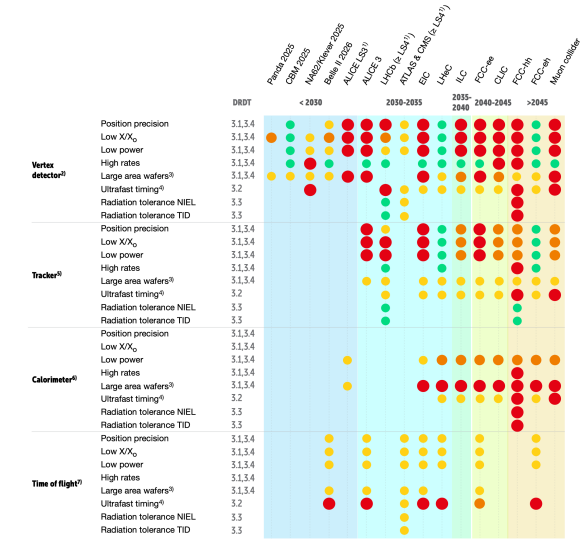
- Options for Fermilab or CERN: fit **on current land**, reuse **existing** accelerators.

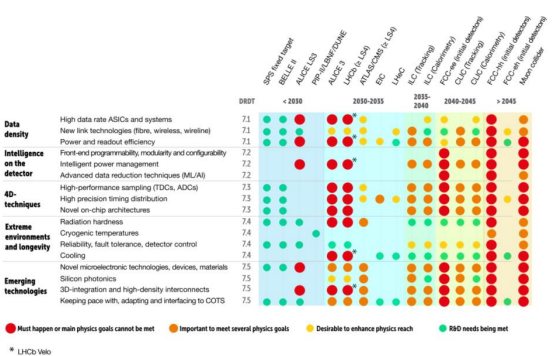




IMCC 2025 ESPPU Input

Detector Challenges





* LHCb Velo

- ECFA Roadmap for future colliders:
  - Many common needs with e^+e^-, pp: work can benefit multiple projects!
- What is unique about muon colliders?
  - **Beam induced background** (BIB) from muon decay: huge challenge!

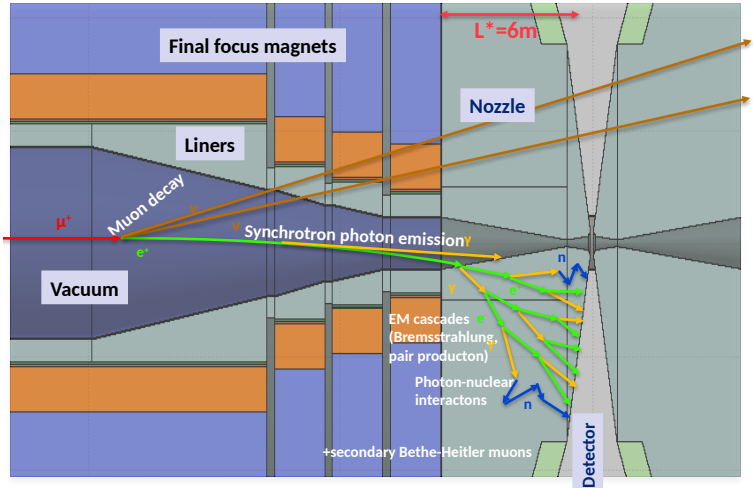
Beam Induced Background

- Only **one bunch** per beam.
- $30\,\mu$s collisions, 10^3 **slower** than LHC.
- Time dilation: muon lab frame lifetime $\propto E$.
- Decay rate $\propto 1/E$ in $20\,\mathrm{m}$.
- Energy of decays **does not depend** on E, but is huge.

$$\tau'_\mu = (21\,\mathrm{ms})\left(\frac{E}{1\,\mathrm{TeV}}\right)$$

$$f \approx (6.4\times10^{-6})\left(\frac{1\,\mathrm{TeV}}{E}\right)$$

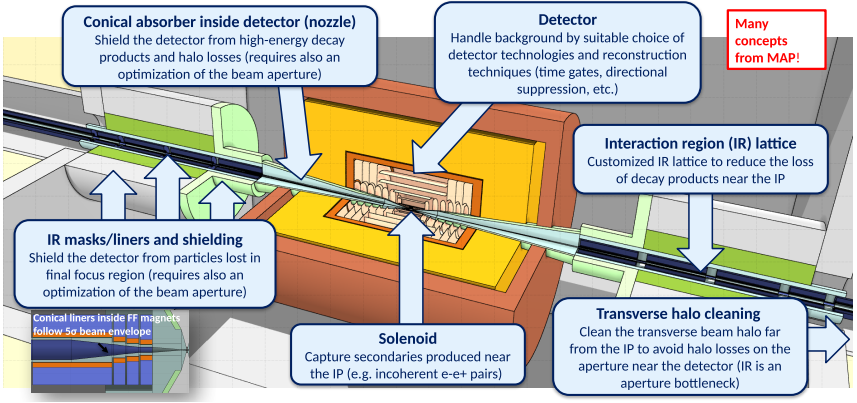
$$E_{\mathrm{decay}} = (13\,\mathrm{EeV})\left(\frac{n_\mu/\mathrm{bunch}}{2\times10^{12}}\right)$$



Daniele Calzolari

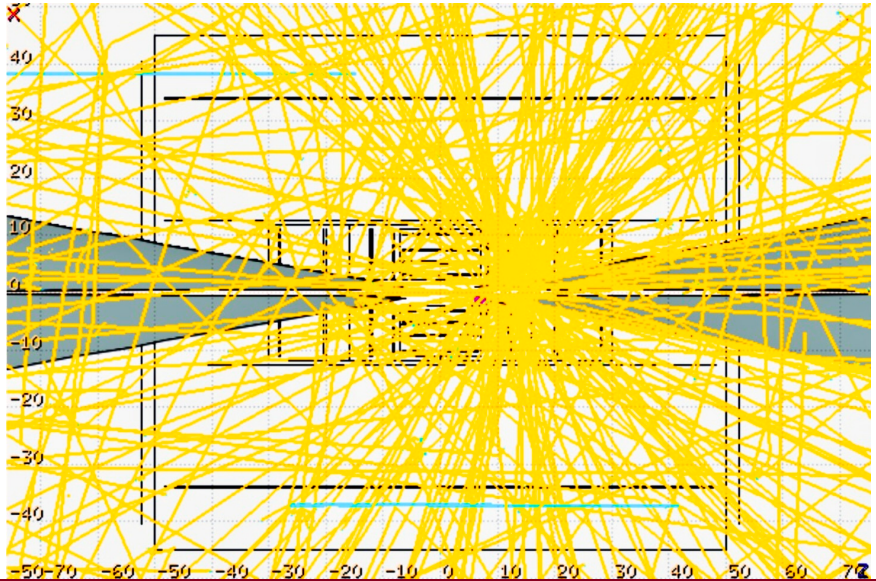
Machine-Detector Interface

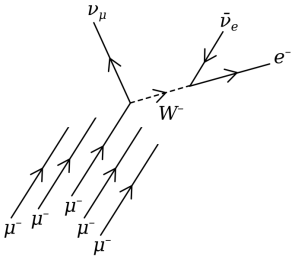
- Must shield detector from the huge beam induced background energy:
  - Optimize accelerator lattice, final focusing region to **bend particles** away.
  - Near detector, surround beam pipe in **tungsten nozzles**; particles from decays will shower.
  - Machine-detector interface **completely determines** BIB that reaches the detector.



Daniele Calzolari

BIB after Shielding

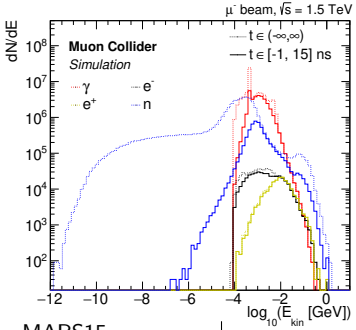


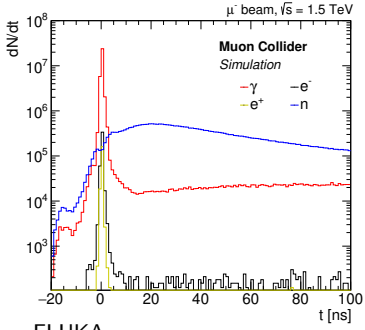


- Photons
- Electrons
- Positrons
- **0.0003%** of one BIB event!

BIB Simulation: $1.5\,\mathrm{TeV}$

- BIB simulations done using MARS15 and FLUKA (2303.08533, 2209.01318):
  - Good agreement!
  - $750\,\mathrm{GeV}$ beam used for both $\sqrt{s} = 1.5,\, 3\,\mathrm{TeV}$.
  - Clearly see potential of **timing** to kill BIB.

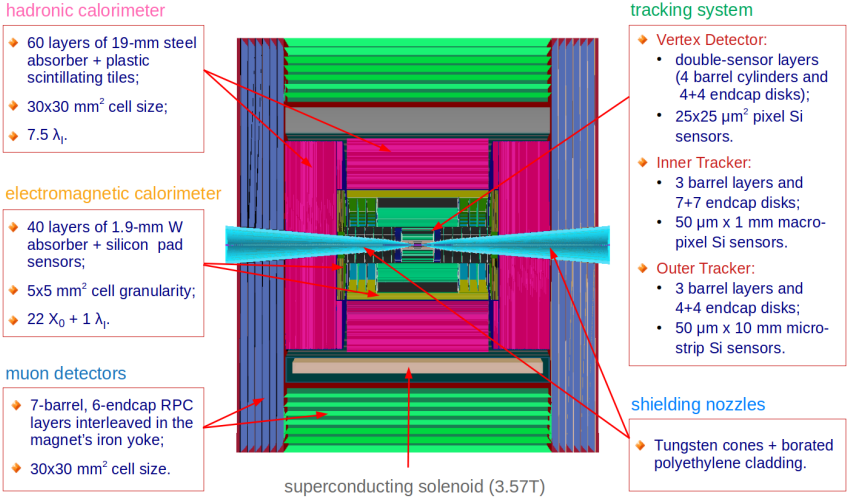




Simulation Source	MARS15		FLUKA		
Beam Energy [GeV]	62.5	750	750	1500	5000
Muon decay length [m]	3.9×10^5	46.7×10^5	46.7×10^5	93.5×10^5	311.7×10^5
(Muon decays/m)/beam	51.3×10^5	4.3×10^5	4.3×10^5	2.1×10^5	0.64×10^5
γ/BX ($E_\gamma > 0.1$ MeV)	170×10^6	86×10^6	51×10^6	70×10^6	116×10^6
n/BX ($E_n > 1$ MeV)	65×10^6	76×10^6	110×10^6	91×10^6	89×10^6
$e^\pm$/BX ($E_e > 0.1$ MeV)	1.3×10^6	0.75×10^6	0.86×10^6	1.1×10^6	0.95×10^6
$h^\pm$/BX ($E_h > 0.1$ MeV)	0.011×10^6	0.032×10^6	0.017×10^6	0.020×10^6	0.034×10^6
$\mu^\pm$/BX ($E_\mu > 0.1$ MeV)	0.0012×10^6	0.0015×10^6	0.0031×10^6	0.0033×10^6	0.0030×10^6

1.5/3 TeV Detector Design

- Existing detector **based on CLIC**, used for Snowmass studies; **must be updated** to 10 TeV.

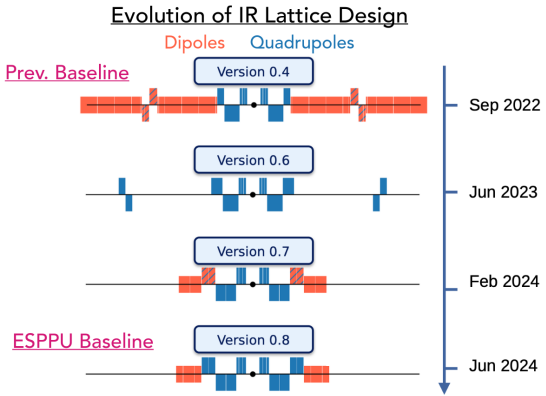


IMCC: Muon Collider Detector (CERN)

10 TeV Lattice and MDI

- Accelerator lattice design also must be updated for $10\,\mathrm{TeV}$:

- Lattice needs to meet key challenges:
  - Very small $\beta^* = 1.5$ (beam size at IP).
  - Large relative energy spread.
  - Short bunch length ($\sigma_z = 1.5$).
  - Radiation damage to magnets from BIB.
  - Limited straight sections to mitigate **neutrino radiation**.
- Current target: collider lifetime of **5-10 years**; aim to collect $10\,\mathrm{ab}^{-1}$ in 5 years.
- Studies performed with two designs:
  - v0.4: initial design (2502.00181).
  - v0.8: **more realistic**, now baseline for 2025 European Strategy.

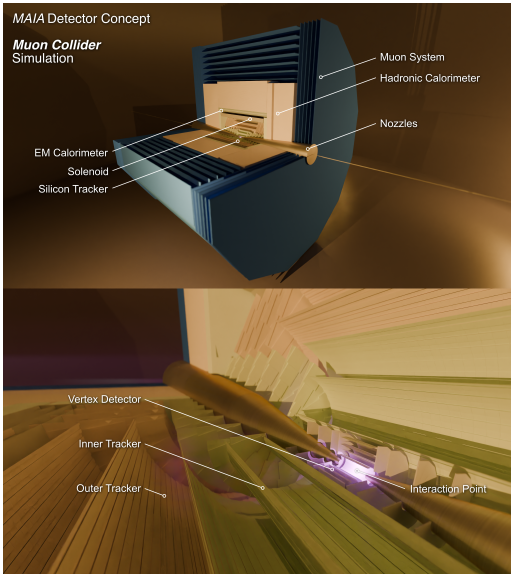


Kiley Kennedy (CPAD 2024), Marion Vanwelde

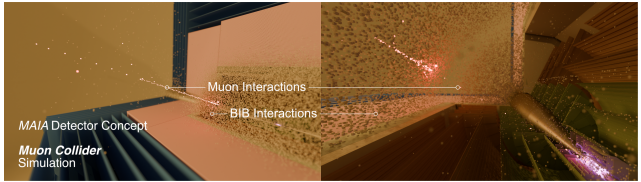
MAIA Detector

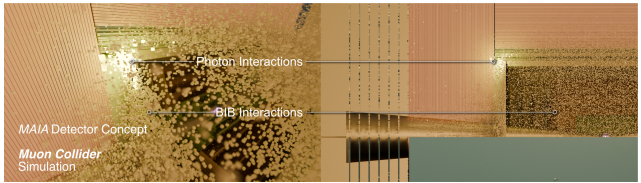
MAIA Detector Concept

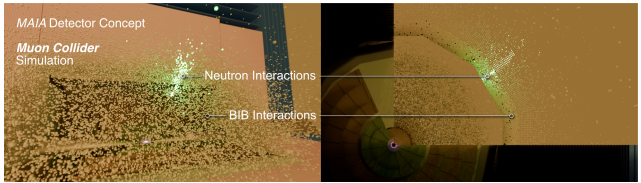
- Evolution of $3\,\mathrm{TeV}$ CLIC detector.
- Solenoid moved to sit **inside calorimeters**:
  - Field strength increased from **3.57 to 5** T.
  - Smaller overall (265 vs $344\,\mathrm{mm}$ in barrel).
  - **Shields calorimeters** from the effect of BIB.
- Silicon tracker partially **reoptimized**:
  - 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



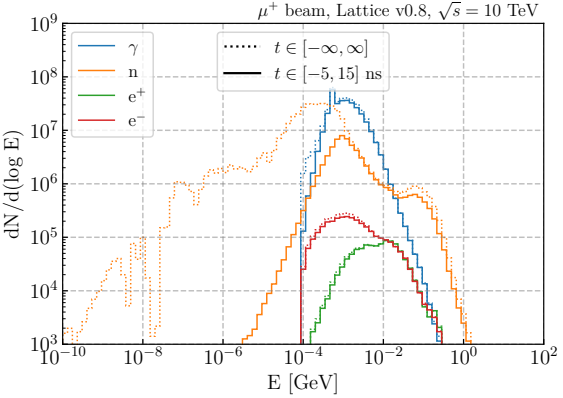


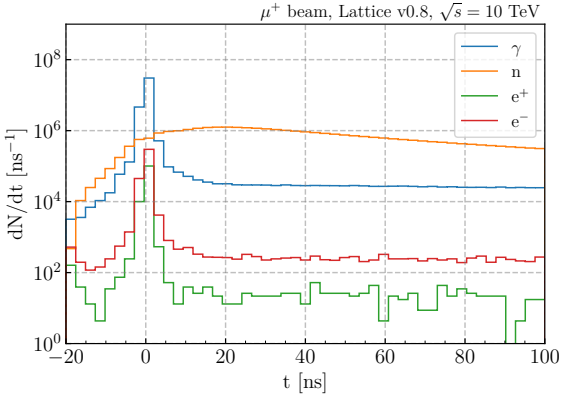


- Detector performance evaluated using **single particle** samples:
  - Muons for the tracker: flat in p_{T}.
  - Photons the ECal: flat in E.
  - Neutrons for the HCal: flat in E.
  - Uniformly distributed in $0 < \phi < 2\pi$, $8^{\circ} < \theta < 172^{\circ}$.
- BIB overlaid during digitization.
- Reconstruction 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).

Studies with Beam Induced Background

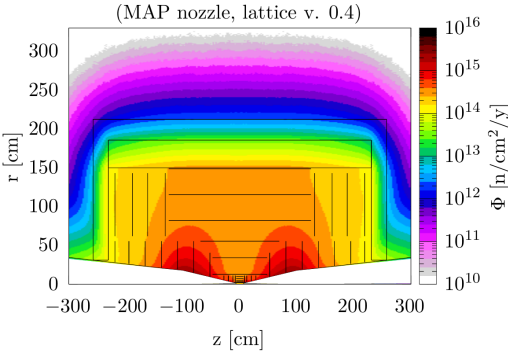
- MAIA performance evaluated using updated FLUKA 10 TeV BIB:
  - BIB kinematics very similar to $3\,\mathrm{TeV}$; but MDI, nozzle optimization **extremely** important.
  - FLUKA only reports particle flux **entering** detector at nozzle surface.

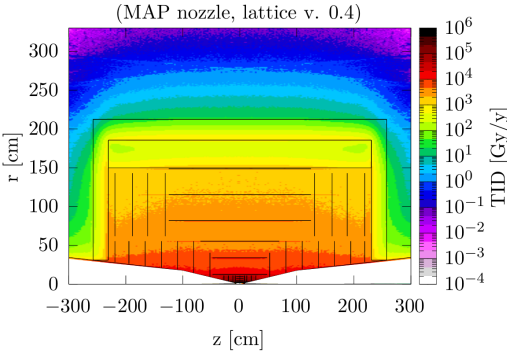




Expected Radiation Damage

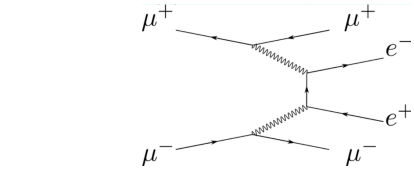
- Radiation at $10\,\mathrm{TeV}$ **comparable to HL-LHC** and previous $3\,\mathrm{TeV}$ muon collider studies; much lower than FCC-hh ($10^{18}\ 1\,\mathrm{MeV\text{-}n_{eq}/cm^2}$) (2209.01318, 2105.09116)



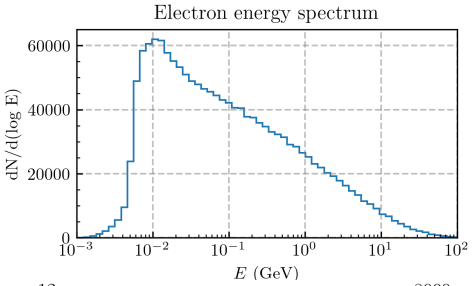


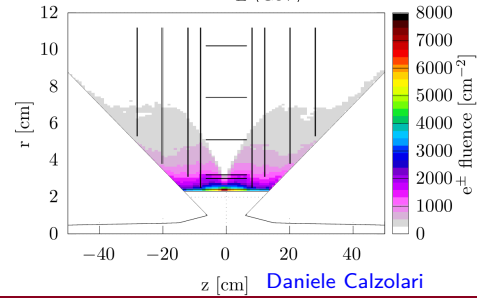
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider ($3\,\mathrm{TeV}$)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider ($10\,\mathrm{TeV}$)	20	0.2	3×10^{14}	10^{14}

Other Sources of BIB



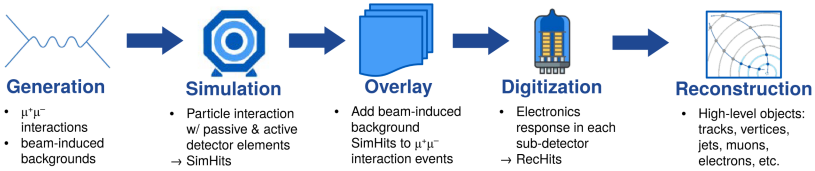
- Muon decays are **main** source of BIB.
- Second largest effect: **incoherent** e^+e^- pairs:
  - Muons radiate photons, which then interact.
  - Not previously included; now modelled using GUINEA-PIG generator.
  - Around 20-30% more BIB, **more energetic**.
- Other sources:
  - Beam instabilities; muon Bhabha scattering; beamstrahlung; beam-gas interactions; magnetic field misalignment; etc.
  - Most components expected to be small.



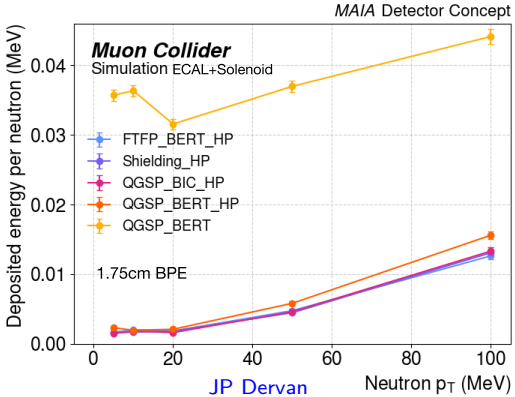


Daniele Calzolari

BIB Simulation and Reconstruction



- BIB simulation **extremely** expensive:
  - One bunch crossing takes a month...
  - Simulate tenths of BX, randomly sample and combine to create independent pseudo-events.
  - Ideas for **use of ML** to speed things up.
- Important to use the **right physics list**!
  - (Old) default `QGSP_BERT` has poor modeling of low energy neutrons: large fraction of BIB.
  - Newer physics lists: many fewer neutrons make it to ECAL.

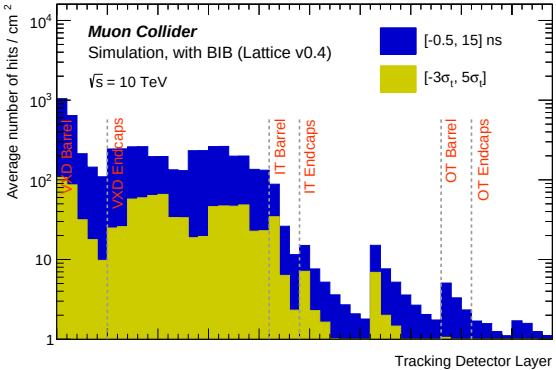


MAIA Tracker Layout and Occupancy

	Vertex Detector	Inner Tracker	Outer Tracker
Sensor Type	pixels	macropixels	macropixels
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	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu m$	$7\mu m \times 90\mu m$

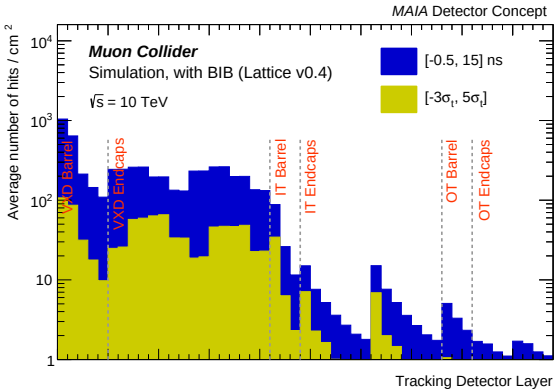
- Very high hit densities in vertex layers:
  - Up to 1600 $\mathrm{hits/cm^2}$ in innermost (v4).
  - Compare to HL-LHC LGADs: same resolution but 1mm $\times$ 1mm granularity.
- $[-3\sigma, 5\sigma]$ beam crossing timing window eliminates much of the BIB:
  - Incoherent e^+e^- pairs may lead to additional flux; **not included**.

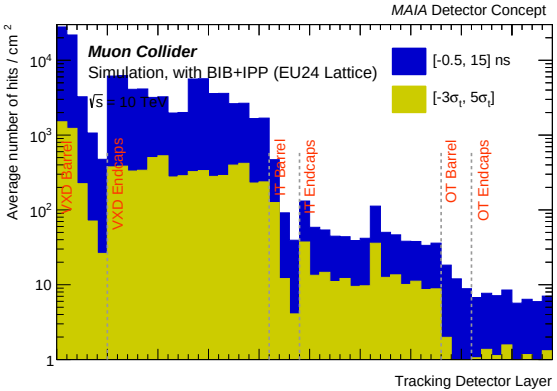
MAIA Detector Concept



Updated Tracker Occupancy

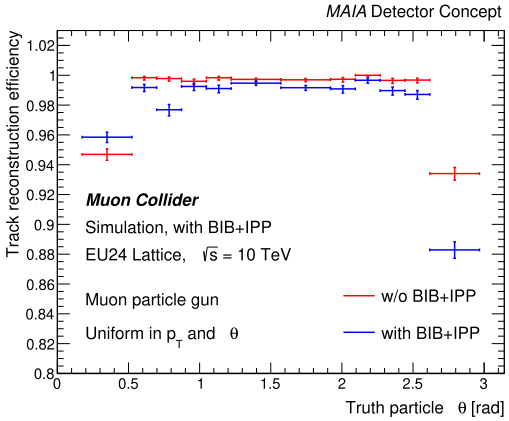
- **Order of magnitude more BIB** in tracker using lattice v0.8 vs v0.4.
  - Not due to addition of incoherent e^+e^- pairs: only $\sim 20\%$ of the first layer.
  - Only 2x increase of BIB in FLUKA: but that only counts particles **entering** detector.
  - Significant negative impact on reconstruction time when running BIB simulation.

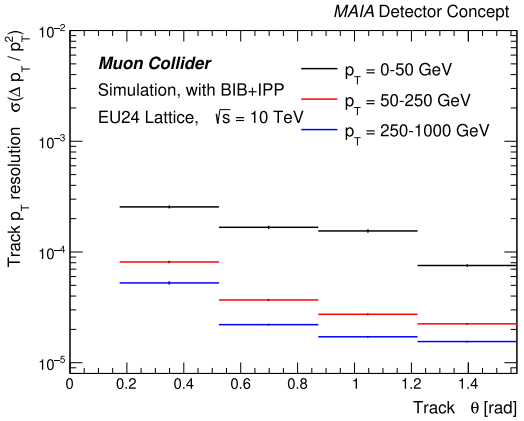




Tracker Performance

- Track reconstruction efficiency quite high for single muons, at least in **barrel**.
- p_{T} resolution shown as function of different p_{T} ranges, with BIB:
  - **Does not degrade** in the presence of BIB; generally good even for $1 + \mathrm{TeV}$ tracks.
  - Impact parameter resolution also excellent, consistently found to be below $10\,\mu\mathrm{m}$.

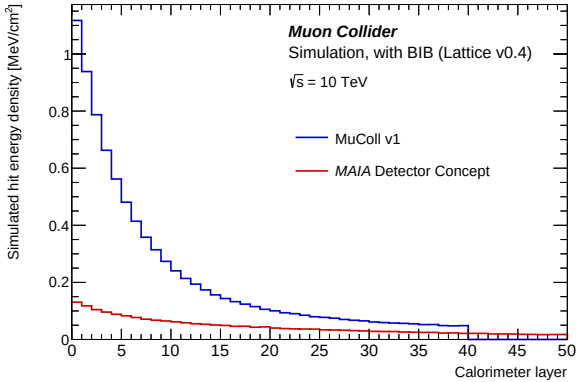




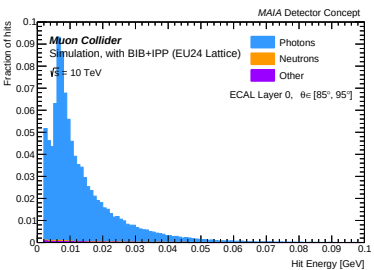
Calorimetry

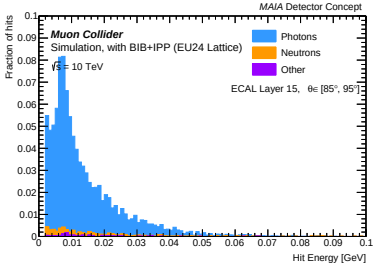
	ECAL	HCAL
Cell type	Silicon - Tungsten	Iron - Scintillator
Cell Size	5.1mm × 5.1mm	30.0mm × 30.0mm
Sensor Thickness	0.5mm	3.0mm
Absorber Thickness	2.2mm	20.0mm
Number of layers	50	100

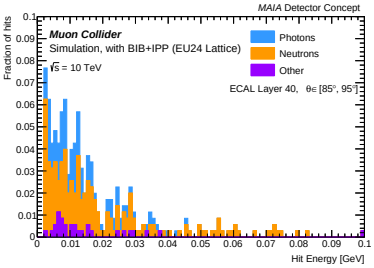
- Current proposals comparable to existing calorimeter technology:
  - ECal very similar to CMS high granularity calorimeter upgrade.
  - HCal similar to ATLAS TileCal (10x smaller sensors).
- Impact of solenoid shielding (v4):
  - Approximately $4X_0$ worth of material.
  - Reduces incoming BIB flux by a factor of **10** compared to previous design.

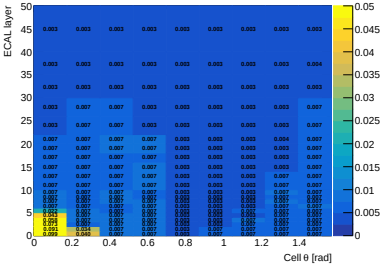


Variable Cell Thresholds





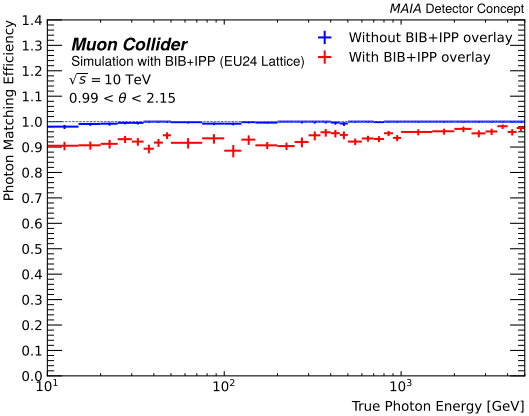


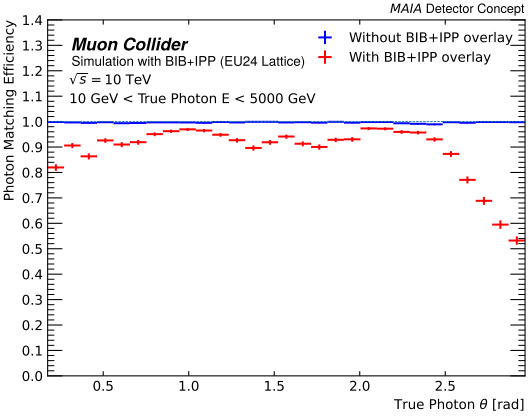


- BIB in the ECAL:
  - Lower layers dominated by **photons**.
  - **Very low energy**, soft, diffuse: hard to reconstruct.
- High cell thresholds needed for BIB:
  - Derive **cell-dependent** thresholds from BIB.
  - Higher thresholds to reject photons.
  - Strong handle at reducing fakes; at cost of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

Photon Efficiency

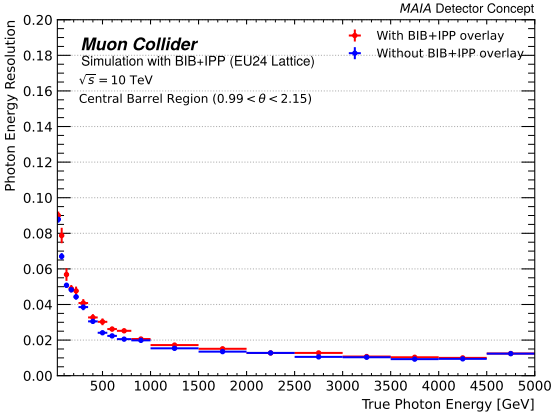
- Photons reconstructed by Pandora cone-clustering of cells with timing b/w -0.5 to 10 ns.
- Efficiency measured by $\Delta R < 0.1$ matching reco photons with $p_{\mathrm{T}} > 5\,\mathrm{TeV}$ to truth.
- Inefficiency in forward region; **asymmetry** suspicious, currently being investigated.

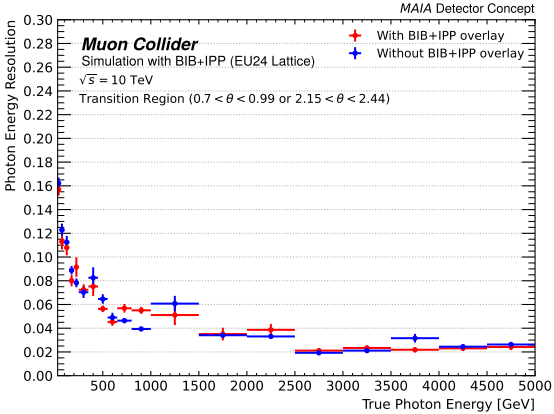




Photon Energy Resolution

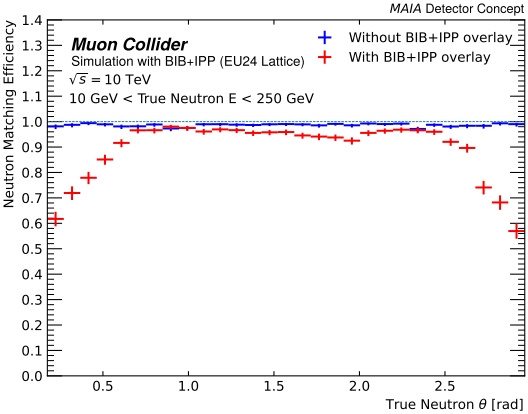
- Compare energy resolution with and without BIB in the barrel, transition regions:
  - Using response function derived from true vs reco photons without BIB.
  - Photon reconstruction in endcap still needs optimization.

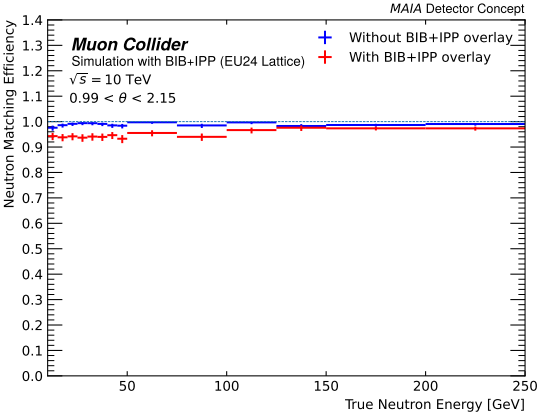




Neutron Efficiency

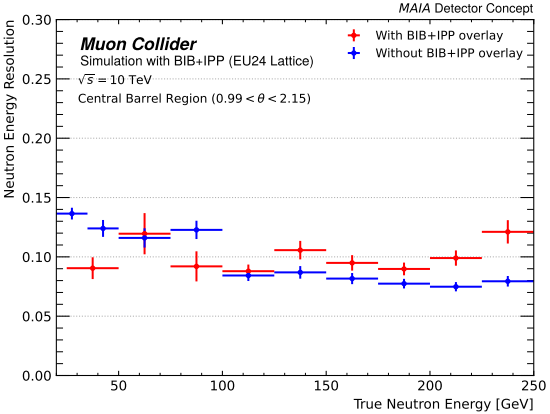
- Identify neutrons using Pandora; match to truth particles within $\Delta R = 0.4$.
- Very high efficiency in barrel; noticeably worse in forward region with BIB.
- Have started looking at **jet** reconstruction for higher energy hadronic particles.

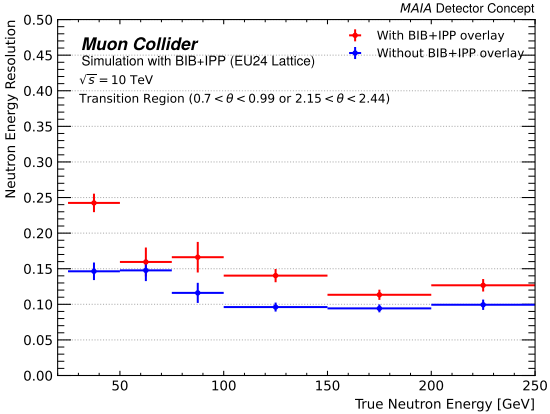




Neutron Resolution

- In high-efficiency barrel and transition regions: good resolution even with BIB.
- Significant improvement over initial MAIA studies (2502.00181).

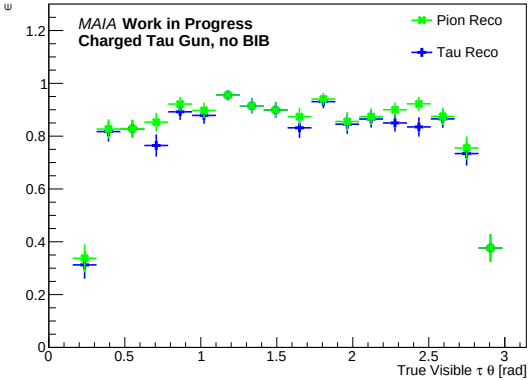




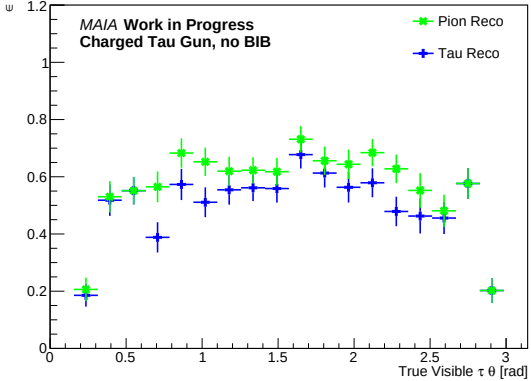
Tau Reconstruction

- Studies of more complex object reconstruction underway: currently still **without BIB**:
  - Progress made in understanding and adapting Pandora to muon collider environment.
  - Starting to study taus thanks to **improved pion reco** (Ethan Martinez, Gregory Penn).

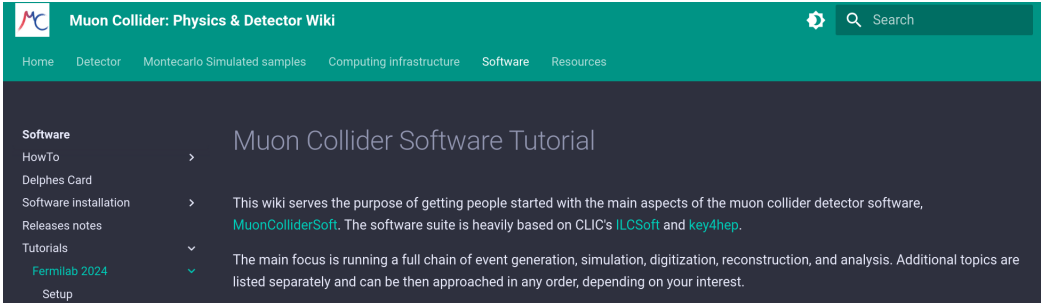
1-Prong (0 Neutrals) Reconstruction Efficiency



3-Prong (0 Neutrals) Reconstruction Efficiency



Getting Involved



- For detector design studies, we have run **software tutorials**:
  - Available at `https://mcd-wiki.web.cern.ch/software/tutorials/fermilab2024/`
  - MAIA instructions: `https://mcd-wiki.web.cern.ch/software/howto/maia/`
- Contact info for USMCC: `https://www.muoncollider.us/`.

Conclusion

- Presented initial look at MAIA detector design; many areas for future work:
  - **Muon system**: not impacted by BIB.
  - **Forward region**: needs optimization.
  - **Nozzle geometry**: increase η coverage w/o 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!
  - **Luminosity measurements**: best strategy unclear.
- Thanks for your attention!



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]

[1] *University of Tennessee, Knoxville, TN, USA*

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[3] *University of Chicago, IL, USA*

[4] *Fermi National Accelerator Laboratory, IL, USA*

[5] *Princeton University, NJ, USA*

[6] *Deutsches Elektronen-Synchrotron DESY, Germany*

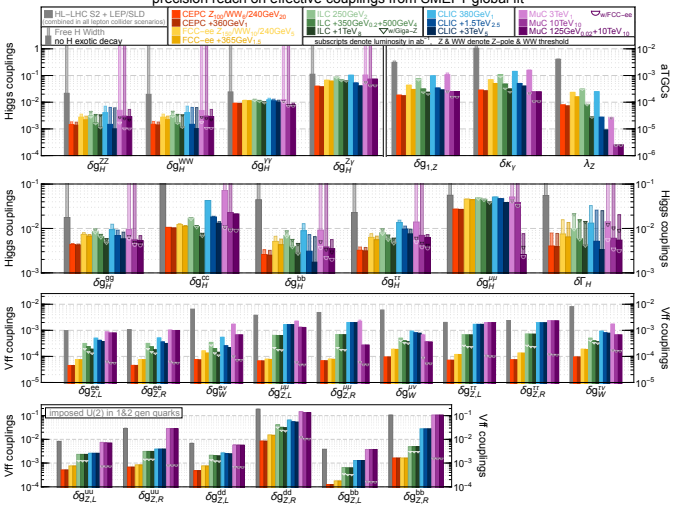
[7] *California Institute of Technology, CA, USA*

(Dated: November 10, 2024)

arXiv:2502.00181

Backup

SMEFT Couplings and Future Colliders

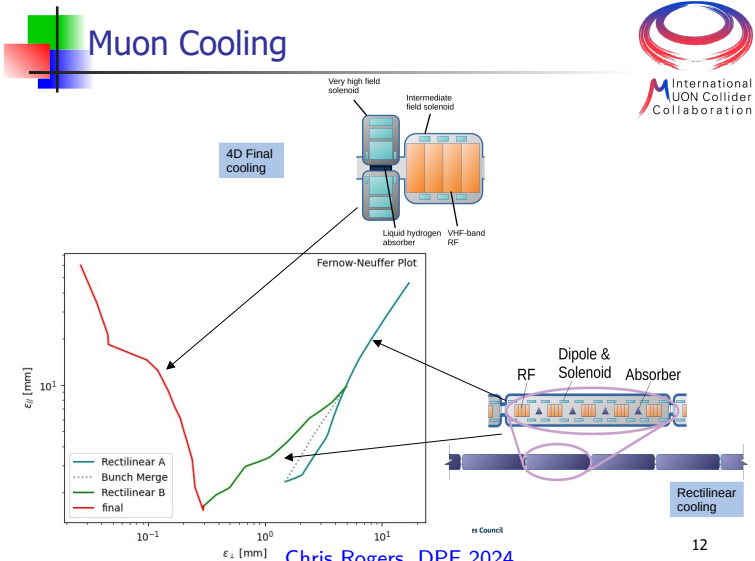


Snowmass Energy Frontier Report (2211.11084)

6D Ionization Cooling

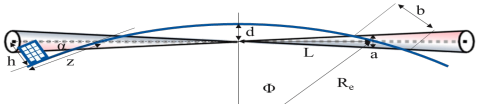
$$L = \frac{N_+ N_- n_c f}{4\pi \sigma_x \sigma_y}$$

- Luminosity depends on **bunch size**; must focus beam to maximize!
- Normal methods **too slow**.
- Basic idea for fast cooling:
  - Chain of cells, each reduce emittance $\sim 10\%$.
  - Trade longitudinal for transverse emittance to reach final target.
  - Design for **demonstrator** underway: workshop at FNAL last October.

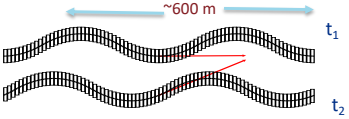


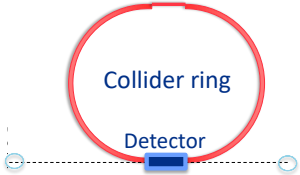
Neutrino Flux Mitigation

Aim to have **negligible impact from arcs** (<10 μSv/year). For comparison airline flight 3 μSv/hour



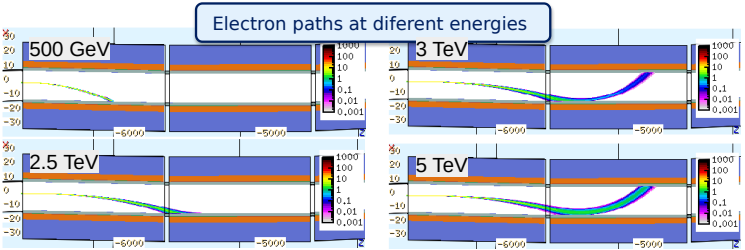
- Arcs:
  - 3 TeV at 200m depth – acceptable
  - 10 TeV needs 200m + "wobble" the beam
- The straights may require acquisition of small land





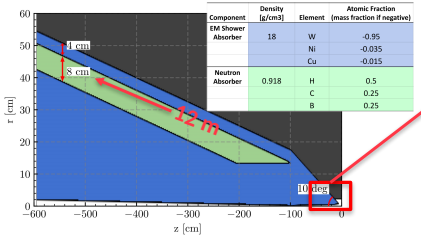
- Need to further develop the mitigation strategy, investigate impacts on the beam dynamics, … and study opportunities with high energy neutrino beams

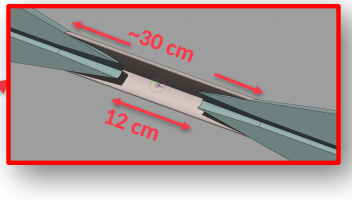
Ongoing MDI Studies



- $100\,\mathrm{m}$ drift before dipole in final focusing region.
  - Electrons from muon decays can accumulate.
  - Synchrotron radiation also problem!
  - Studying impact on **power**, **radiation damage**.

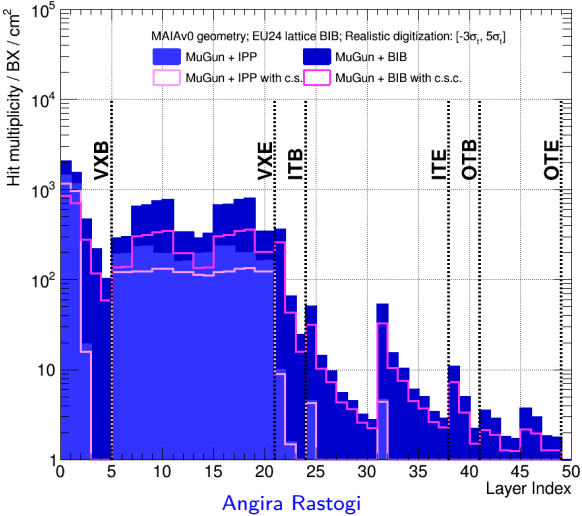
- **Optimized** nozzle placement: $6\,\mathrm{cm}$ from IP.
  - INERMET180 tungsten alloy (EM showers).
  - Borated polyethylene to absorb neutrons.
  - New default design.





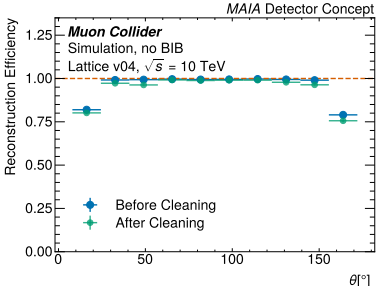
Tracker Digitization

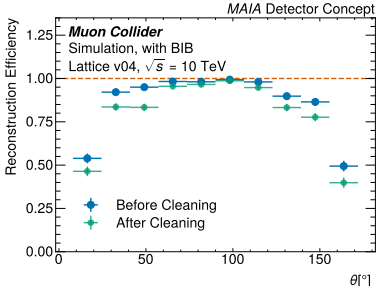
- Important caveat: not currently using **realistic** tracker digitization.
  - Actual rates can be reduced significantly using cluster shape information, other variables to quickly reject BIB.
  - Adding to simulation can speed up processing time for studies.
  - Implementing in **front end**: fast rejection of BIB on detector.
- See talks on smart pixels, fast timing on Thursday for more on this idea!

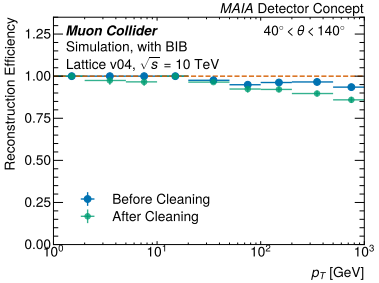


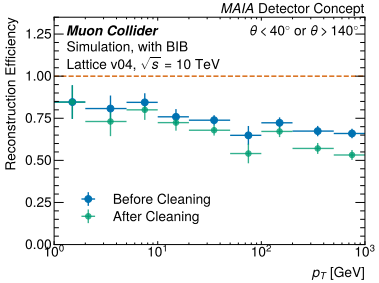
Tracking Efficiency

- Efficiency quite high with BIB, at least in the barrel:
  - Only about 3.5% lower.
  - Noticeably worse in forward region: **future work** to optimize!
- Track cleaning applied to reject BIB fakes:
  - $p_T > 1\,\mathrm{GeV}$
  - $N_{\mathrm{hits}} > 5$
  - $|d_0| < 0.1\,\mathrm{mm}$
  - $\chi^2/\mathrm{DOF} < 3.$
  - Needs reoptimization for heavy flavour!



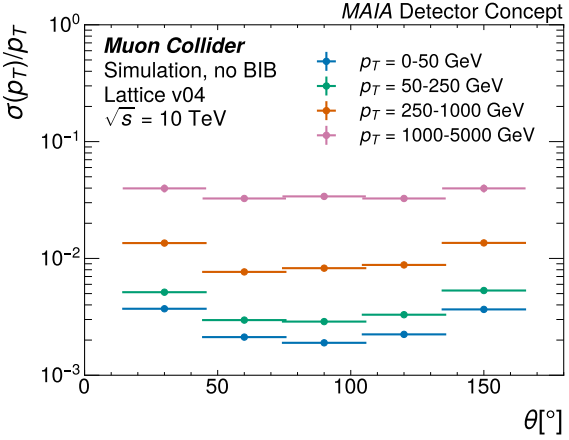


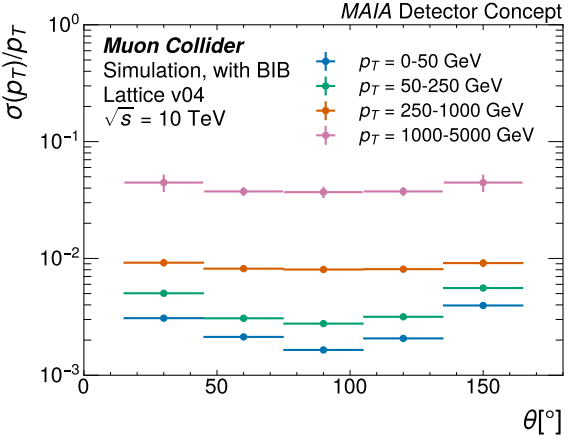




Track p_T Resolution

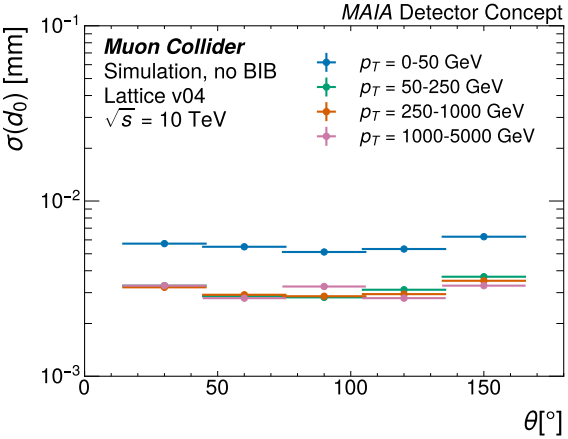
- Track p_T resolution shown as function of different p_T ranges, with/without BIB.
- Momentum resolution ranges from a few percent to up to 5% for 1-5 TeV tracks.
- Resolution **does not degrade** in the presence of BIB.

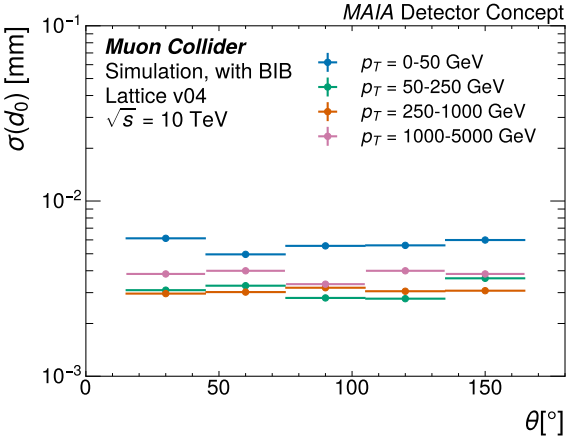




Track d_0 Resolution

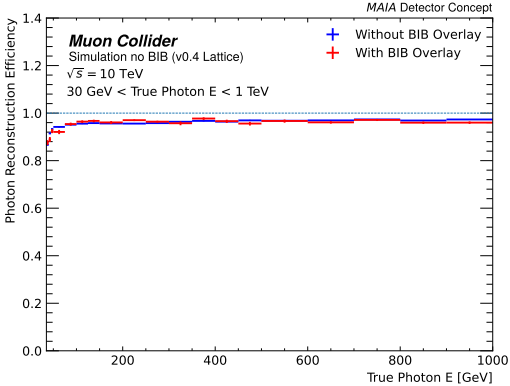
- d_0 resolution also stays stable in the presence of BIB.
- Consistently found to be below $10\,\mu\mathrm{m}$; roughly stable as function of p_T and θ.

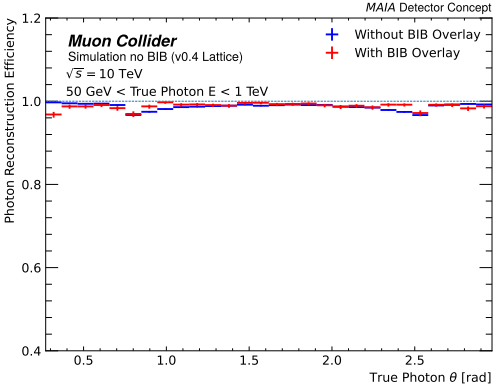




Photon Efficiency

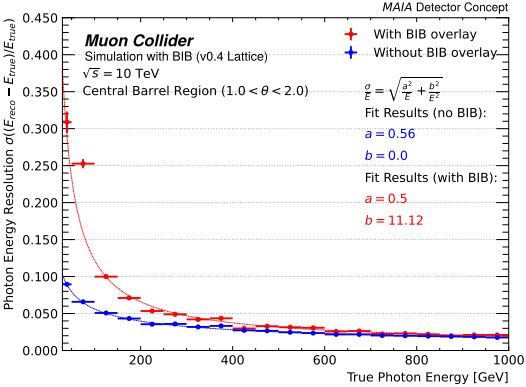
- Photons reconstructed by Pandora cone-clustering of cells with timing b/w -0.5 to 10 ns.
- Efficiency measured by $\Delta R < 0.1$ matching reco photons with $p_{\mathrm{T}} > 5\,\mathrm{TeV}$ to truth.
- Very high (95%) above $100\,\mathrm{GeV}$, but drops down to 60% for a 10-$20\,\mathrm{GeV}$ photon.

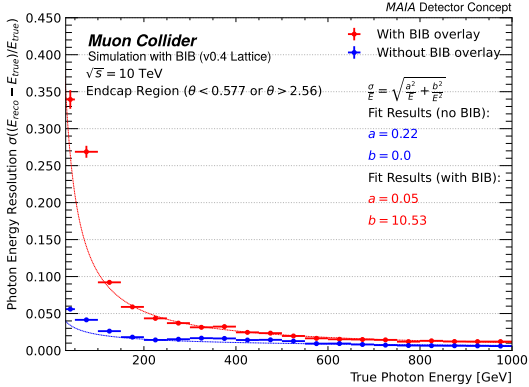




Photon Energy Resolution

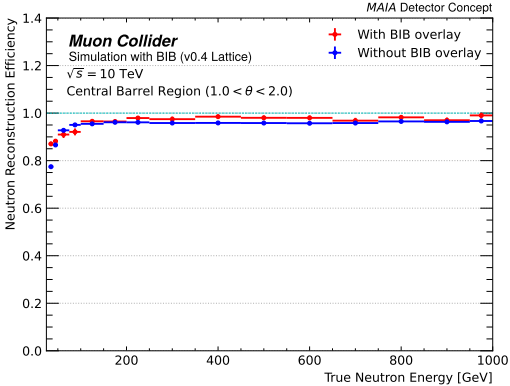
- Compare energy resolution with and without BIB in the barrel vs endcap regions:
  - Using response function derived from true vs reco photons without BIB.
  - Performance noticeably **worse** in barrel (and transition region) due to shielding.
- More detailed BIB mitigation (**cell timing**) could improve resolution below $50\,\mathrm{GeV}$.

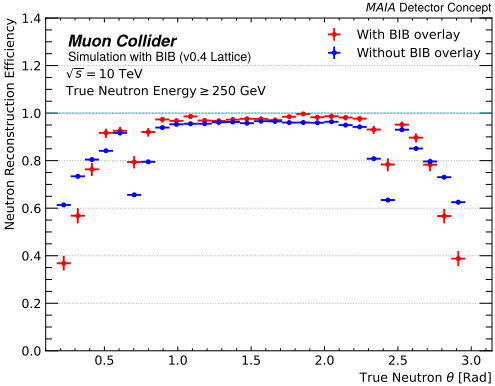




Neutron Efficiency

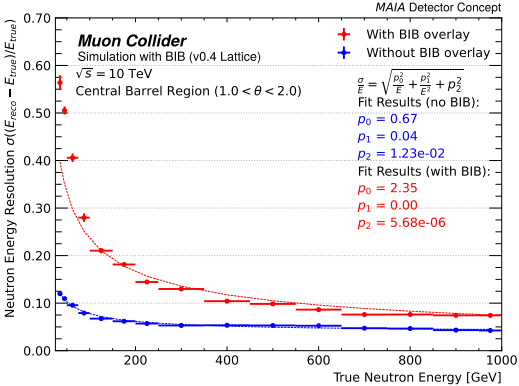
- Identify neutrons using $\Delta R = 0.1$ cone; require at least one tagged neutron in cone.
- Veto objects with $E < 20\,\mathrm{GeV}$ due to high Pandora fake rate from BIB.
- Very high efficiency in barrel; noticeably worse in transition, forward regions.

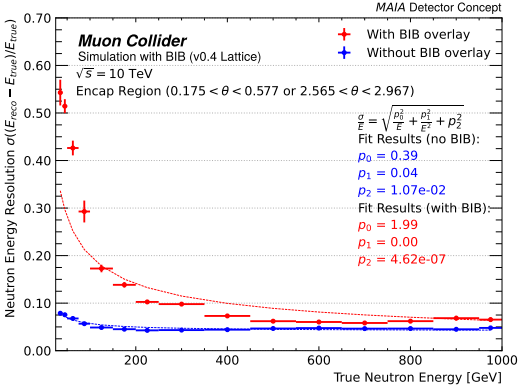




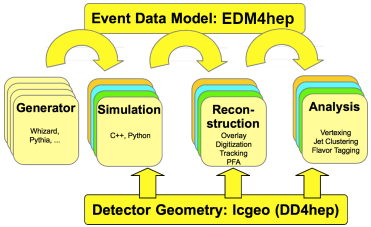
Neutron Resolution

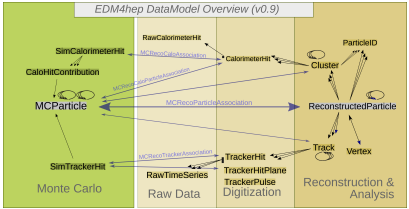
- HCal response measured without BIB: found to be close to unity everywhere, not used.
- Neutron energy resolution more consistent across all regions.





Reconstruction Studies and Computing

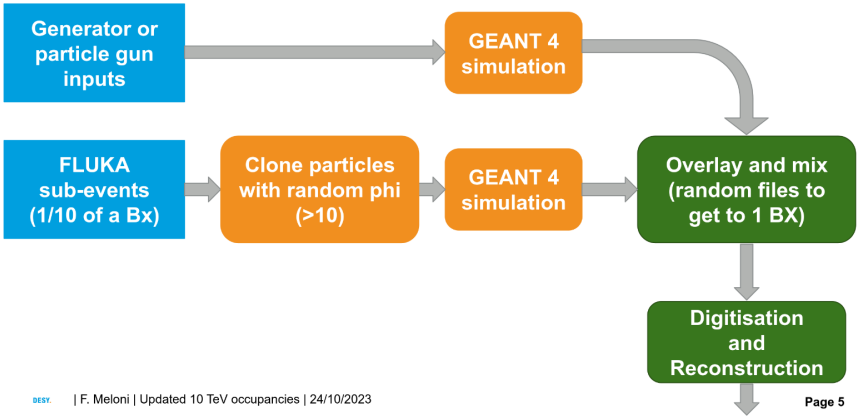




- Studies underway to assess performance with new detector and new BIB.
- IMCC software based on ILCSoft/Key4HEP:
  - **Common framework** for future collider R&D: shared with FCC, ILC, CLIC, C3, etc.
  - Integrates many other packages; Pandora particle flow, ACTS tracking, Gaudi, etc.
  - Output LCIO and EDM4hep ntuples, easy to analyze with ROOT or uproot.
- Variety of signatures (electron, muon, photon, tau, pion, jet) being studied:
  - Monte Carlo samples simulated using DD4hep and reconstructed with Marlin.
  - See recent tutorial:
    `https://mcd-wiki.web.cern.ch/software/tutorials/fermilab2024/setup/`.

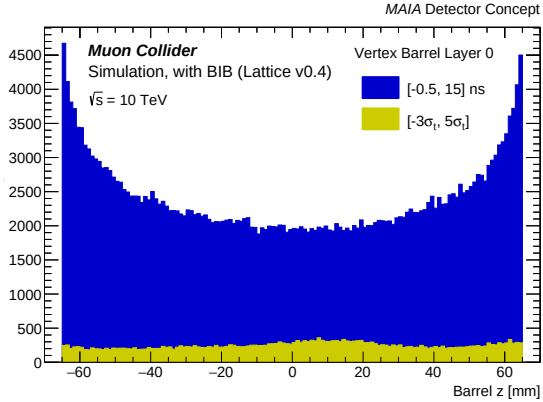
BIB Overlay and Subevent Mixing

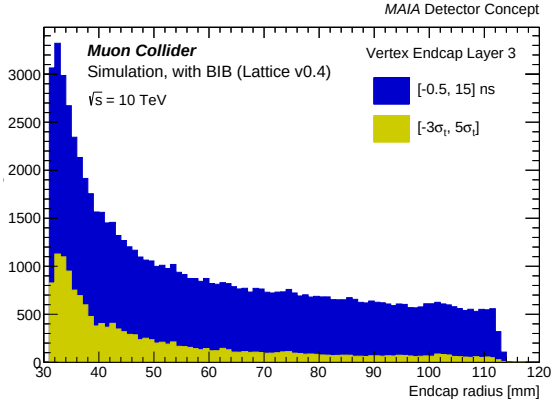
- For 10 TeV studies, now using new pipeline with FLUKA **subevent mixing**:
  - Simulating the BIB contributions in FLUKA is **computationally expensive**.
  - Overlays statistically independent; reduced effects due to lack of BIB statistics.



Expected Tracker Occupancies

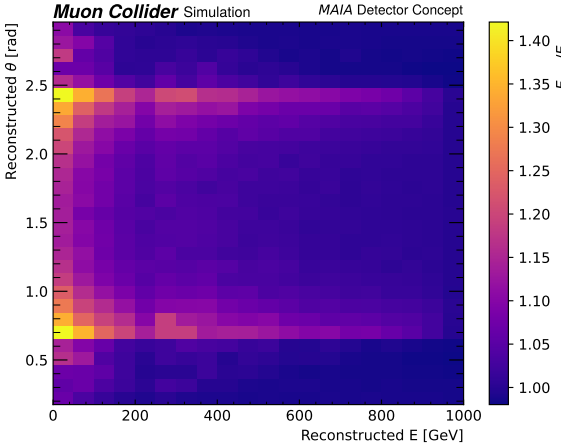
- Timing window cut also eliminates z-dependence from nozzle in barrel.





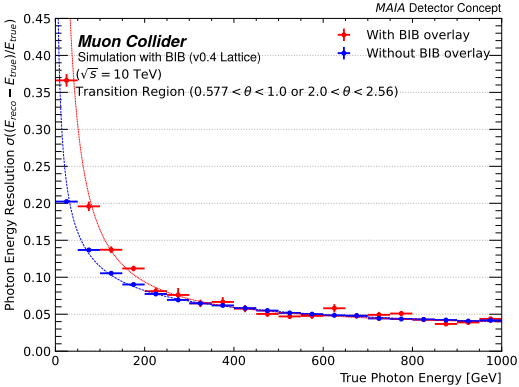
Electromagnetic Calorimeter Response

- Measuring energy resolution requires characterizing calorimeter **response function**:
  - Determined by studying photons **without** BIB.
  - 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.



ECAL Resolution Fits

- Fit results for barrel, endcap, transition region.



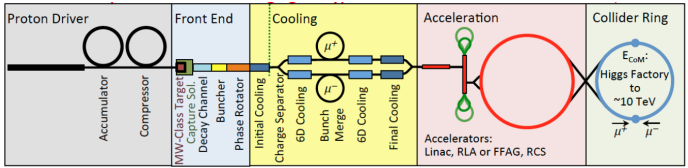
Fit Params	Stochastic	Noise	Constant
No BIB	0.559	0.0	0.0
BIB	0.648	8.537	0.001

Fit Params	Stochastic	Noise	Constant
No BIB	0.184	0.0	0.0
BIB	0.213	8.219	0.0

Fit Params	Stochastic	Noise	Constant
No BIB	1.131	0.0	0.018
BIB	0.773	14.20	0.028

Accelerators and Beam Induced Background

- Main muon collider challenges: accelerator related:
  - Targetry; alternatives to liquid mercury.
  - 6D ionization cooling to focus beam.
  - Fast ramping magnets for acceleration.
  - Neutrino radiation mitigation.
  - Work underway on all these areas.
- **Machine-detector interface** extremely important:
  - Decaying muons: large **beam-induced background** (BIB) in our detectors.
  - **Only two bunches**, collisions at $O(10\,\mu s)$.
  - Need accelerator/detector experts to collaborate!



Tentative target parameters
Scaled from MAP parameters

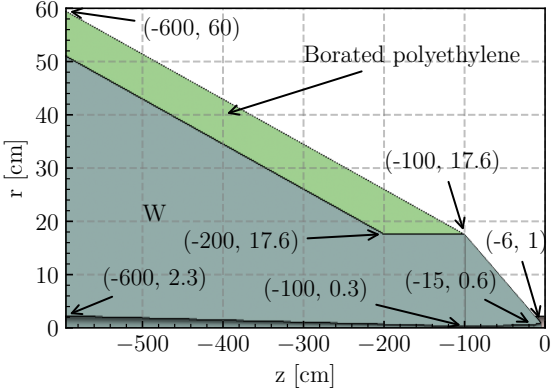
Comparison:
CLIC at 3 TeV: 28 MW

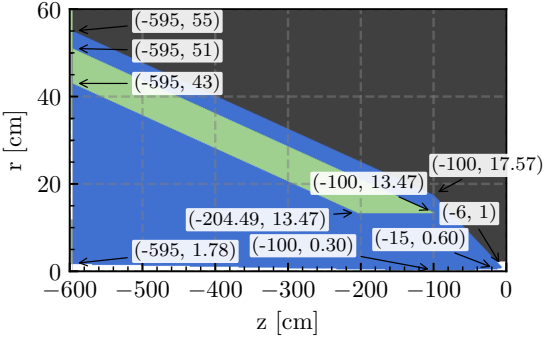
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	μm	25	25	25
$\sigma_{x,y}$	μm	3.0	0.9	0.63

IMCC, 2201.07895

Nozzle Optimization

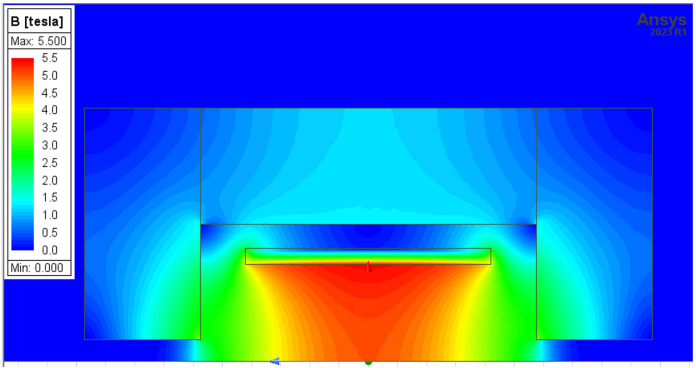
- Part of MDI: optimized nozzle placement to further reduce BIB.
- Mostly tungsten, borated polyethylene in green. Left: v0.4, right: v0.8 nozzle.
- Restricts forward region to $|\eta| \lesssim 2.44$ (10°).





Realistic Magnetic Field

- Tracking studies have all assumed a **uniform** magnetic field so far.
- In reality, field is non-uniform; size/shape/space for solenoid hugely important.
- IMCC Magnet workshop held last October; further discussion at the annual meeting.

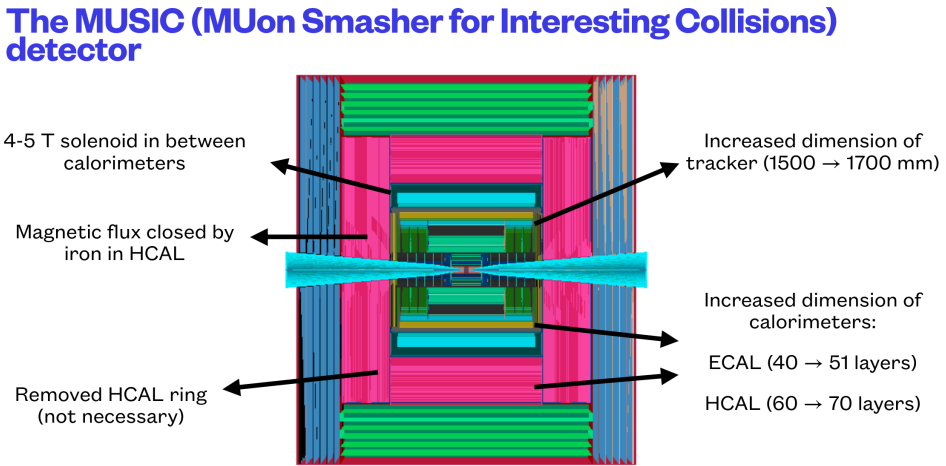


Andrea Bersani

- First look from magnet experts at our design:
  - "Shamefully preliminary"; layout may not be perfect.
  - Distance of solenoid from iron (HCAL) influences field.
  - Endcap may be **too far away**; optimize design?
  - Discussion that 5 TeV may be too high; maybe lower is okay?
- Want to start simulations with realistic field map!

Alternate Design: MUSIC

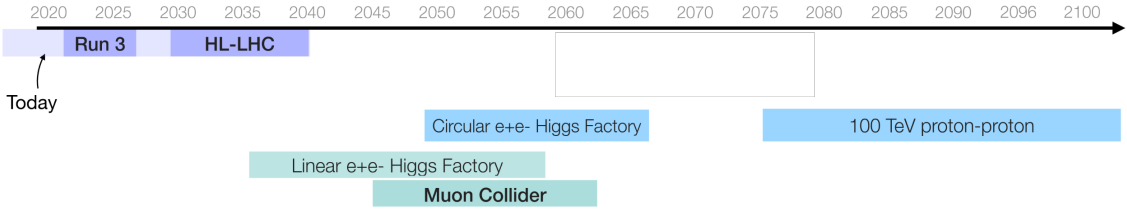
- Other designs being studied! This one: solenoid **between** calorimeters (Davide Zuliani):



Accelerator R&D Needs

	Target	Status	Notes	Future work
Pulse compression	1-3 ns	SPS does O(1) ns	Need higher intensity. O(30) ns loses only factor 2 in the produced muons.	Refine design, including proton acceleration. Accumulation and compression of bunches.
High-power targets	2 MW	2 MW	Available for neutrino and spallation neutrons. Aim for 4 MW to have margin.	Develop target design for 2 MW, O(1) ns bunches create larger thermal shocks. Prototype in 2030s.
Capture solenoids	15 T	13 T	ITER central solenoid.	Study superconducting cables and validate cooling. Investigate HTS cables.
Cooling solenoids	50 T	30-40 T	30 T leads to a factor 2 worse transverse emittance with respect to design.	Extend designs to the specs of the 6D cooling channel. Demonstrator.
RF in magnetic field	>50 MV/m	65 MV/m	MUCOOL published results. Requires test in non-uniform B.	Design to the specs of 6D cooling. Demonstrator.
6D cooling	10^{-6}	0.9 (1 cell)	MICE result (no re-acceleration). Emittance exchange demonstrated at g-2.	Optimise with higher fields and gradients. Demonstrator.
RCS dynamics	-	-	Simulation. 3 TeV lattice design in place.	Develop lattice design for a 10 TeV accelerator ring.
Rapid cycling magnets	2 T/ms 2 T peak	2.5 T/ms 1.81 T peak	Normal conducting magnets. HTS demonstrated 12 T/ms, 0.24 T peak.	Design and demonstration work. Optimise power management and re-use.
Ring magnets aperture	20 T quads	12-15 T (Nb3Sn)	Need HTS or revise design to lower fields.	Design and develop larger aperture magnets, 12-16 T dipoles and 20 T HTS quads.
Collider dynamics	-	-	3 TeV lattice in place with existing technology.	Develop lattice design for a 10 TeV collider.
Neutrino radiation	10 μSv/year	-	3 TeV ok with 200 m deep tunnel. 10 TeV requires a mover system.	Study mechanical feasibility of the mover system impact on the accelerator and the beams.
Detector shielding	Negligible	LHC-level	Simulation based on next-gen detectors.	Optimise detector concepts. Technology R&D.

Future Colliders Timeline



Karri DiPetrillo, Fermilab P5 Townhall