Detector R&D Towards a 10 TeV Muon Collider

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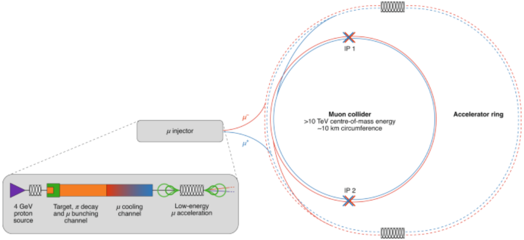
Introduction

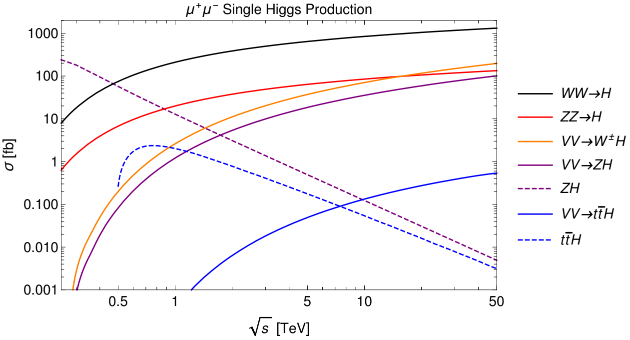
- Significant community interest in muon colliders emerged during Snowmass, European Strategy processes:
  - Colliding fundamental particles (like electrons) with much less synchrotron radiation (like protons) offers **compact, efficient way** to reach high energies.
  - Muons are unstable: **many challenges**, lots of accelerator and detector R&D needed!
- Work is underway on both areas, both in the US and internationally:
  - CERN has formed the International Muon Collider Collaboration to coordinate activities.
  - Informal organization created in the US (pending outcome of P5).
  - US Muon Collider R&D Coordination Panel formed to provide input to P5 for both accelerator and detector needs.

- This talk:
  - Brief outline of **detector** R&D efforts.
  - Overview of updated 10 TeV detector concept.
  - Preliminary performance results.
  - Opportunities for future R&D.

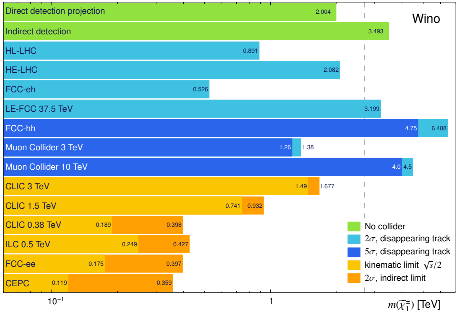


The Case for 10 TeV

- $\sqrt{s} = 10\,\text{TeV}\ \mu^+\mu^-$ **approximately comparable** to $100\,\text{TeV}\ pp$ 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.



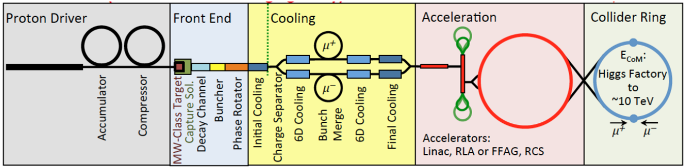
M. Forslund, P. Meade (10.1007/JHEP08(2022)185)



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

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

Existing Detector Design

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

hadronic calorimeter

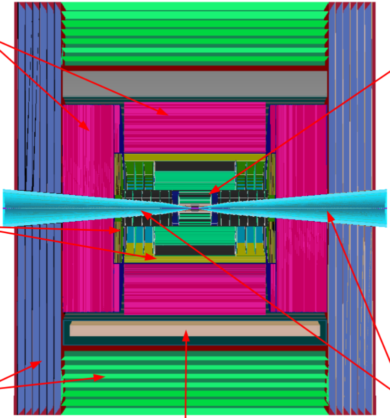
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.

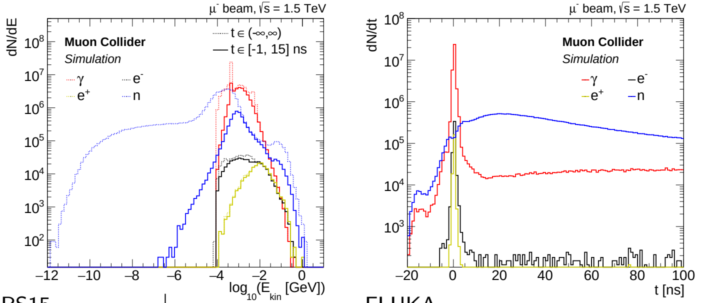
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

IMCC: Muon Collider Detector (CERN)

Existing BIB Simulation

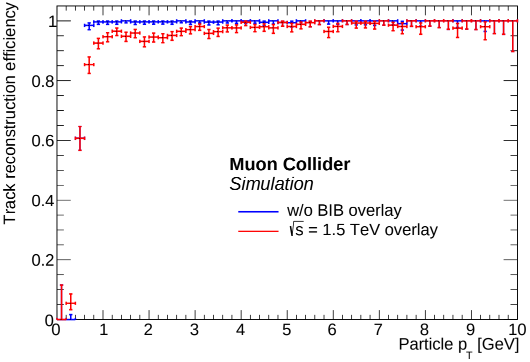
- BIB simulations done using MARS15 and Fluka (2303.08533, 2209.01318):
  - Generally good agreement!
  - $750\,\mathrm{GeV}$ beam energy used for both $\sqrt{s} = 1.5,\ 3\,\mathrm{TeV}$.
  - Clearly see potential of **timing** to kill low-energy BIB.

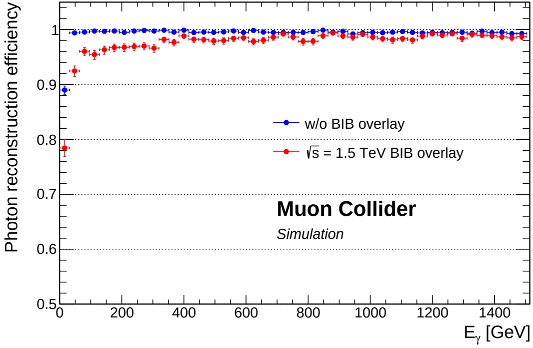


Simulation Source	MARS15		FLUKA		
Beam Energy [GeV]	62.5	750	750	1500	5000
MDI Optimization	yes	yes	yes	no	no
Muon decay length [m]	3.9×10^5	46.7×10^5	46.7×10^5	93.5×10^5	311.7×10^5
(Muon decays/m)/beam	51.3×10^5	4.3×10^5	4.3×10^5	2.1×10^5	0.64×10^5
γ/BX ($E_\gamma > 0.1$ MeV)	170×10^6	86×10^6	51×10^6	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

Existing Performance Studies

- This $1.5/3\,\mathrm{TeV}$ detector design has been studied extensively during Snowmass:
  - Work based on existing designs and concepts from MAP/MICE.
  - Many results collected by the Muon Collider Forum and IMCC.
  - Potential for new R&D to surpass existing (LHC-level) reconstruction performance.





Challenges for 10 TeV Detectors

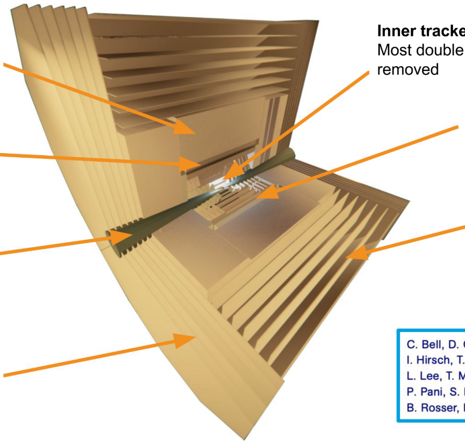
- Existing detector design shown to work, but for $\sqrt{s} = 1.5$ or $3\,\text{TeV}$.
- What changes at $10\,\text{TeV}$? Beam is more energetic, but also more relativistic:
  - BIB energy expected to be **independent** of $\sqrt{s}$, but there may be other differences.
  - Need $5\,\text{T}$ magnetic field; detector size overall needs to grow with energy.
  - Thicker calorimeters to fully contain showers; higher granularity trackers at large-r.
- Studies underway towards different 10 TeV concepts:
  - Ranging from simple evolution of 3 TeV layout to ideas for alternate B field configurations
  - Our approach: move from "CMS-like" to "ATLAS-like" magnet system.
  - Place solenoid **inside the detector** around the tracker; use to **shield calorimeters** from BIB.
  - Calorimeter layers now outside magnet, further from interactions: need to study performance.

B	3.57 T	5 T
Thickness	344 mm	265 mm
R	3821 mm	1500 mm

10 TeV Detector Design

- Concept developed at KITP workshop at Santa Barbara in February.
- Layout implemented in DD4hep; IMCC software used for simulations over past year.

- Reoptimized tracker: no need for double-sided vertex layers.
- Use silicon pixels for vertex, inner tracker; strips for outer tracker.
- Vertex: $30\,\mathrm{ps}$ timing, 5x5 $\mu\mathrm{m}$ spatial resolution.
- Inner and outer trackers: $60\,\mathrm{ps}$ timing, 7x90 $\mu\mathrm{m}$ spatial resolution.

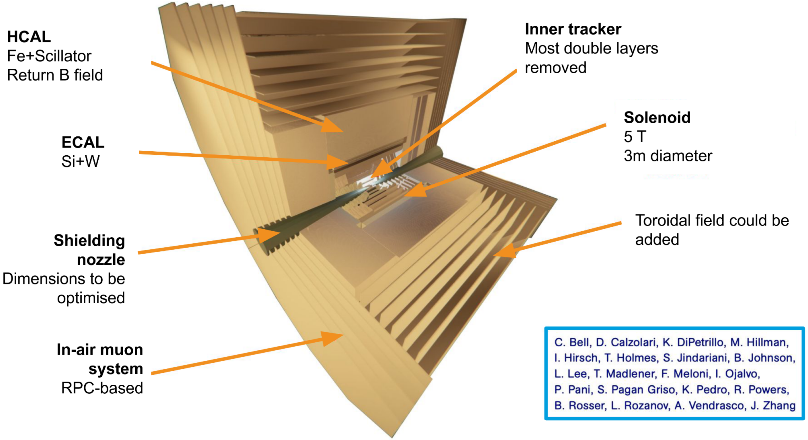


C. Bell, D. Calzolari, K. DiPetrillo, M. Hillman, I. Hirsch, T. Holmes, S. Jindariani, B. Johnson, L. Lee, T. Madlener, F. Meloni, I. Ojalvo, P. Pani, S. Pagan Griso, K. Pedro, R. Powers, B. Rosser, L. Rozanov, A. Vendrasco, J. Zhang

10 TeV Detector Design, Continued

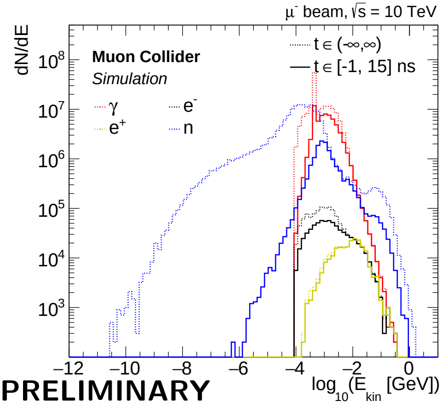
- Design continuing to evolve rapidly, lots of R&D still to do!

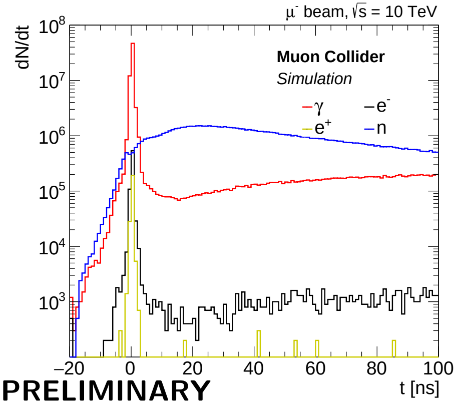
- Calorimeters: $100\,\mathrm{ps}$ timing resolution.
- ECAL energy resolution target: $10\%/\sqrt{E}$.
- HCAL jet energy resolution: $35\%/\sqrt{E}$.
- Optimize depth: $40 \to 50$ ECAL layers, $60 \to 75$ HCAL layers.
- Simplified muon system (no magnet yoke).



Simulating BIB at 10 TeV

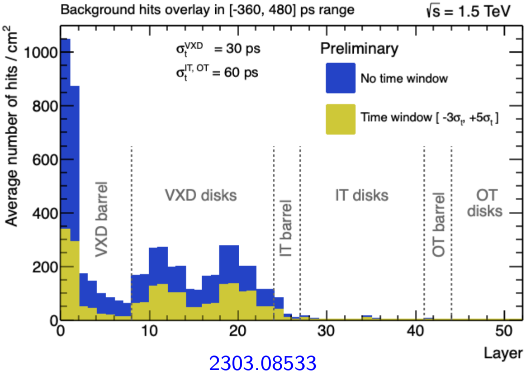
- Generate **new BIB** at $\sqrt{s} = 10\,\mathrm{TeV}$ using **Fluka**:
  - Timing, energy distribution shapes very consistent with lower-energy results.
  - **Preliminary results**: look promising, collaboration with accelerator physicists ongoing.



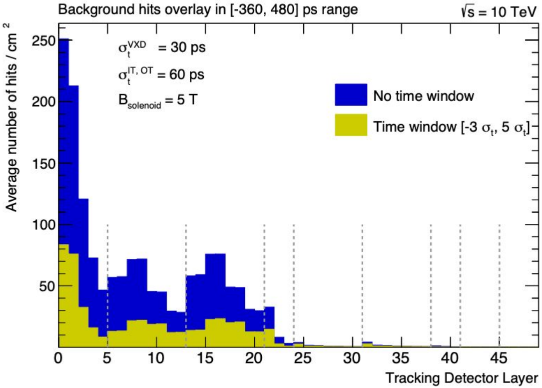


Tracker Occupancy

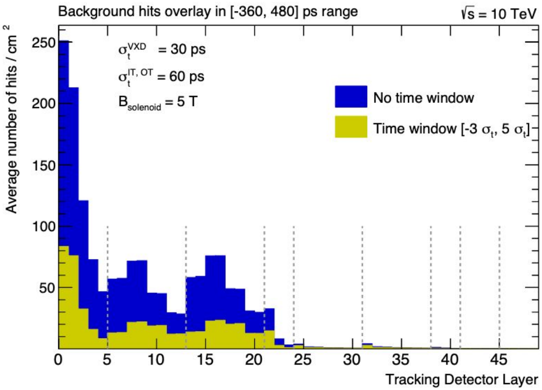
- 30-60 ps timing resolution critical to reduce hit occupancy in innermost tracking layers.
- Shapes agree between 1.5, 10 TeV simulations, but average number of hits 4x smaller:
  - Accelerator lattice, nozzle shape have been reoptimized; this will lead to changes.
  - Still investigating potential differences, but effect illustrates importance of MDI.

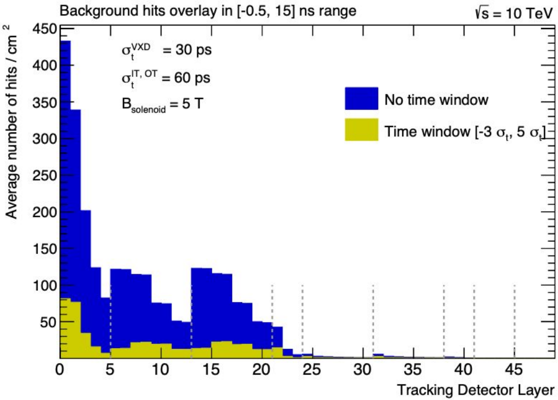


2303.08533



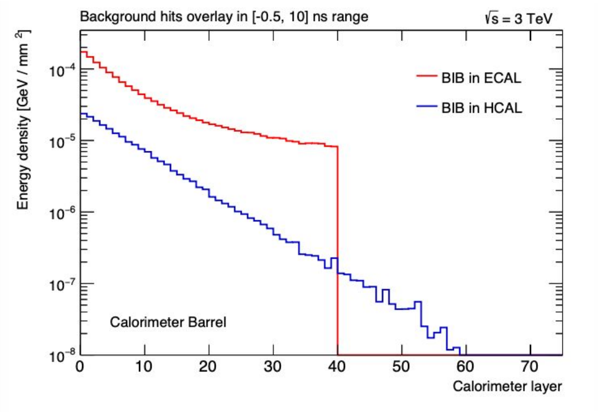
- Slight bias in these results due to $< 1\,\mathrm{ns}$ time window.
- Relaxing the time window: higher occupancies overall but shapes more or less unchanged.

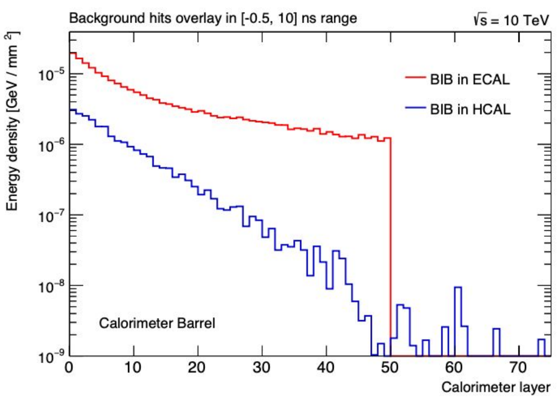




BIB in the Calorimeters

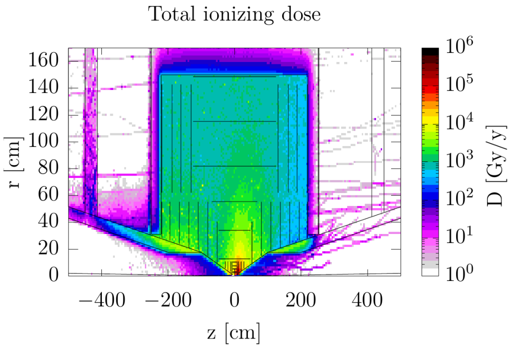
- Energy density in both calorimeters also has same shape between beam energies.
- **Order of magnitude** lower in our $10\,\mathrm{TeV}$ design: shows impact of solenoid shielding!

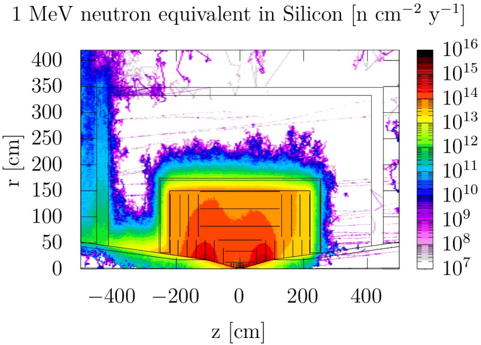




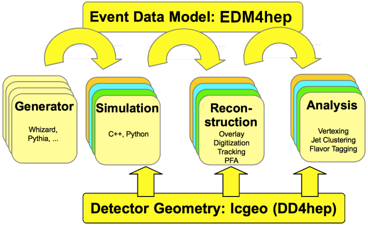
Radiation Damage

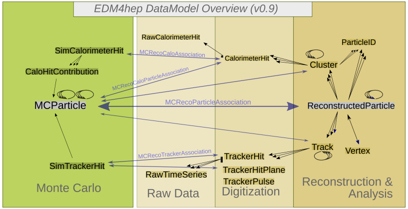
- Radiation at $10\,\mathrm{TeV}$ **comparable to HL-LHC** and previous $3\,\mathrm{TeV}$ muon collider studies; much lower than FCC-hh ($10^{18}\ 1\,\mathrm{MeV}\text{-}n_{eq}/\mathrm{cm}^2$) (2209.01318, 2105.09116)





	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}

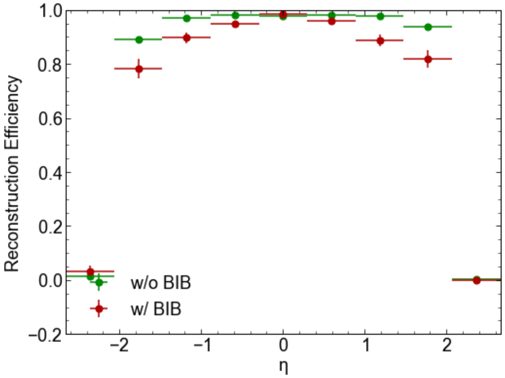


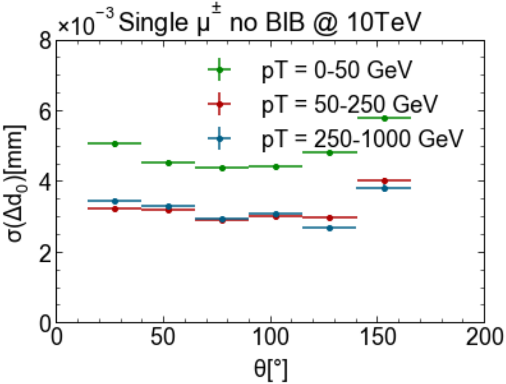


- Studies underway to assess object reconstruction performance with this detector.
- IMCC software based on ILCSoft/Key4HEP:
  - **Common framework** for future collider R&D: shared with FCC, ILC, CLIC, C3, etc.
  - Integrates many other packages; Pandora particle flow, ACTS tracking, Gaudi, etc.
  - 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.
  - During reco, BIB from Fluka can be sampled, overlaid: **computationally expensive!**
  - Some **preliminary results** presented today for **tracking** and **calorimetry**.

Tracking Performance

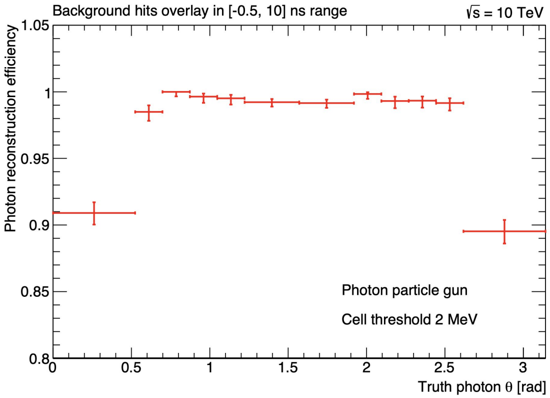
- Track reconstruction powered by ACTS; studied using single muon samples.
- 3.5% efficiency loss from addition of BIB, but overall tracking still seems to work!
- Initial results promising, but more studies needed (especially in forward region).

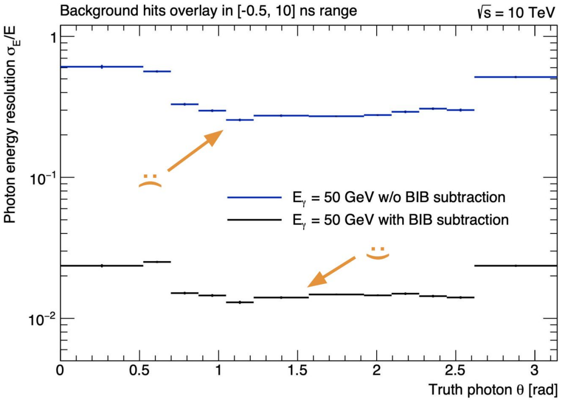




Electromagnetic Calorimeter Performance

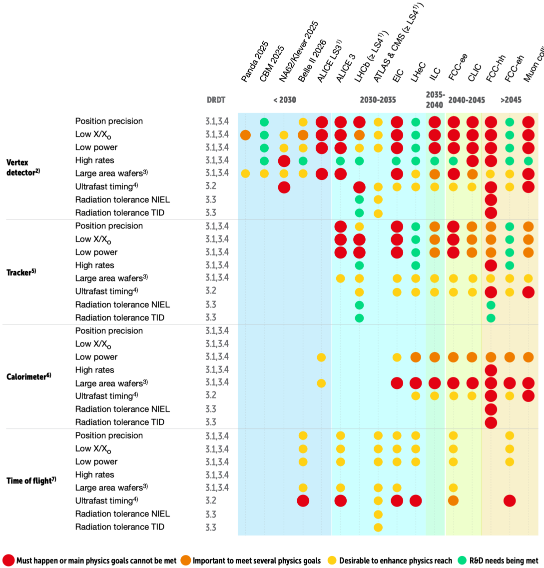
- Photon reconstruction efficiency very high even with addition of $5\,\mathrm{T}$ solenoid.
- Energy resolution not ideal due to high cell thresholds, but can be improved:
  - **BIB subtraction**: digitize with $50\,\mathrm{keV}$ thresholds, then remove average BIB when clustering.
  - Leads to **order-of-magnitude** improvement in resolution for $50\,\mathrm{GeV}$ photons!





Future R&D Opportunities

- From Tuesday: lots of overlap in detector needs for **any** future collider:
  - As shown in ECFA Detector Roadmap.
  - Many common needs with e^+e^-, pp: work can benefit multiple projects!
- Some areas of particular importance:
  - **Timing** critical for BIB reduction.
  - Dedicated **forward detectors** for muon tagging: distinguish VBF processes.
  - **Nozzle optimization** and mechanics.
  - Radiation hardened readout electronics with **on-detector intelligence**.
  - **Solenoid design**: need to develop and retain expertise for high-field magnets (discussed in RDC10 on Thursday).



Conclusion and Acknowledgements

- 10 TeV detector R&D for a muon collider is underway, but there's still lots to do!
  - Have gone from design concept to simulations and studies in **less than a year**.
  - Plan to write a paper describing this initial design soon.
  - Collaboration between **accelerator and detector** experts critical in studying muon colliders.
- This effort has been a joint effort with contributions by many people, including:
  - Federico Meloni, Thomas Madlener, Priscilla Pani (DESY); Daniele Calzolari (CERN).
  - Karri DiPetrillo, Ben Rosser, Leo Rozanov, Isaac Hirsch, Noah Virani (Chicago).
  - Tova Holmes, Larry Lee, Ben Johnson, Micah Hillman, Adam Vendrasco (Tennnessee).
  - Sergo Jindariani, Kevin Pedro, (FNAL); Rose Powers (Yale).
  - Simone Pagan Griso (LBNL); Isobel Ojalvo, Junjia Zhang (Princeton).
- Thanks for your attention!

Backup

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.

ECFA Roadmap

- ECFA roadmap tables for **electronics** and **integration**; again emphasizing commonality between needs for future facilities.