Detector Simulations for a 10 TeV Muon Collider

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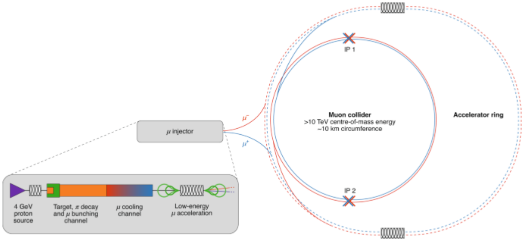
Introduction

- Can we build a detector for a $10\,\mathrm{TeV}$ muon collider?
  - Main accelerator challenge: mitigating **beam induced background** (BIB).
  - Tightly coupled to accelerator design and machine-detector interface (MDI).
- Design exists for a $\sqrt{s} = 1.5$ or $3\,\mathrm{TeV}$ detector, studied extensively during Snowmass:
  - Detector R&D efforts underway both in the US and internationally (IMCC).
  - Now studying an initial concept for a $10\,\mathrm{TeV}$ detector with updated BIB simulation.

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



Existing Detector Design

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

hadronic calorimeter

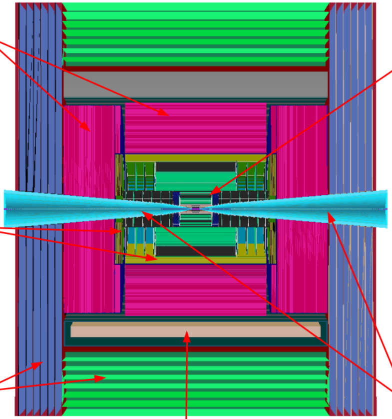
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.

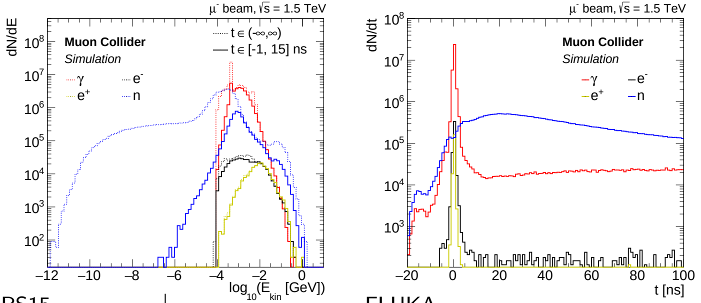
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

IMCC: Muon Collider Detector (CERN)

Existing BIB Simulation

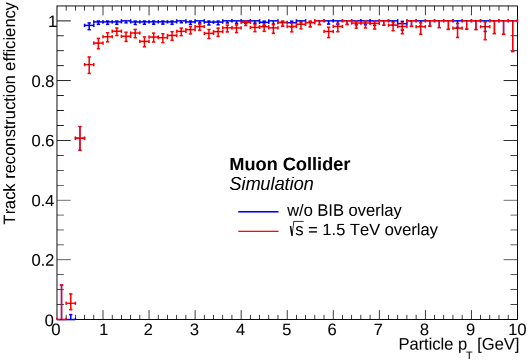
- BIB simulations done using MARS15 and Fluka (2303.08533, 2209.01318):
  - Generally good agreement!
  - $750\,\text{GeV}$ beam energy used for both $\sqrt{s} = 1.5,\ 3\,\text{TeV}$.
  - Clearly see potential of **timing** to kill low-energy BIB.

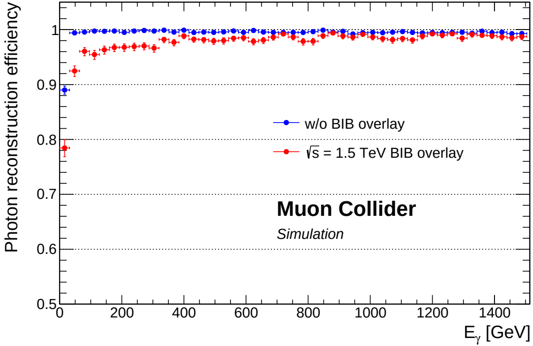


Simulation Source	MARS15		FLUKA		
Beam Energy [GeV]	62.5	750	750	1500	5000
MDI Optimization	yes	yes	yes	no	no
Muon decay length [m]	3.9×10^5	46.7×10^5	46.7×10^5	93.5×10^5	311.7×10^5
(Muon decays/m)/beam	51.3×10^5	4.3×10^5	4.3×10^5	2.1×10^5	0.64×10^5
γ/BX ($E_\gamma > 0.1$ MeV)	170×10^6	86×10^6	51×10^6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

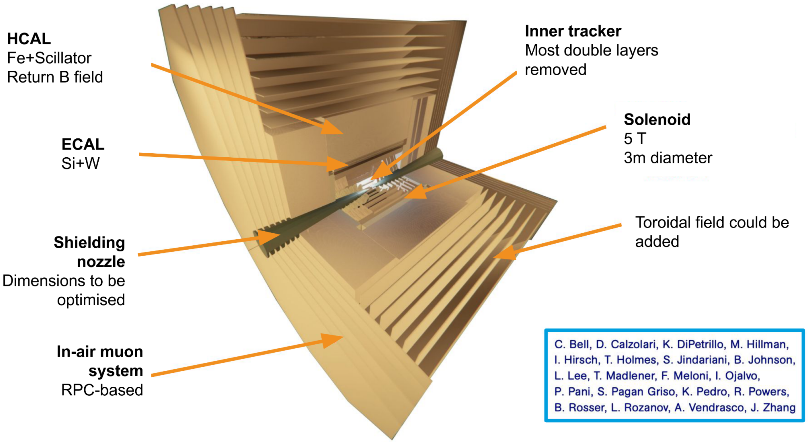
- Existing detector design shown to work, but for $\sqrt{s} = 1.5$ or $3\,\mathrm{TeV}$.
- What changes at $10\,\mathrm{TeV}$? Beam is more energetic, but also more relativistic:
  - BIB energy expected to be **independent** of $\sqrt{s}$, but there may be other differences.
  - Need $5\,\mathrm{T}$ 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.



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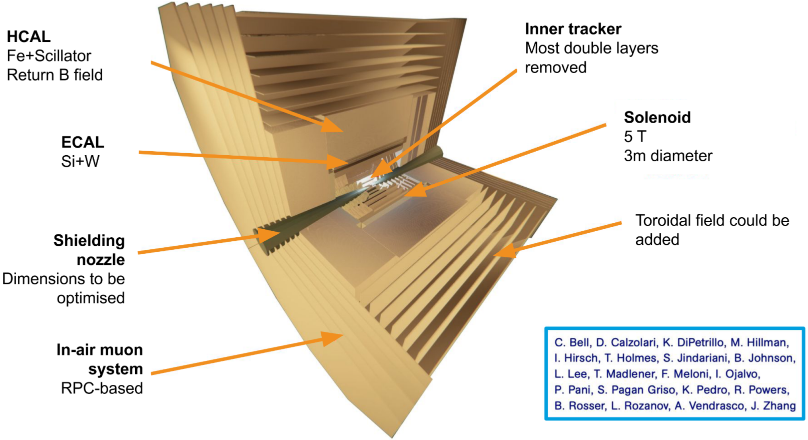
10 TeV Detector Design, Continued

- 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: $40 \rightarrow 50$ ECAL layers, $60 \rightarrow 75$ HCAL layers.
- Simplified muon system (no magnet yoke).



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Machine Detector Interface: BIB Simulation

- **Machine-detector interface** extremely important for muon colliders:
  - Detector design must be done in close collaboration with accelerator and MDI designers.
  - Accelerator lattice and MDI design **completely determines** BIB that reaches the detector.
  - For detector: can **optimize geometry** or **improve reconstruction** algorithms to reduce BIB.
- **Dedicated IMCC workflow** to share simulated data, allow experts to provide feedback.

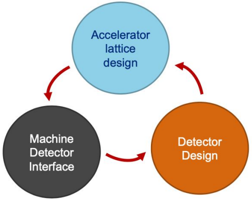
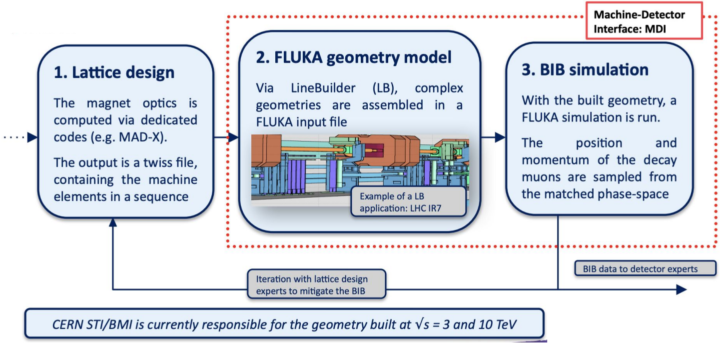


Diagram credit: S. Jindariani

STATUS

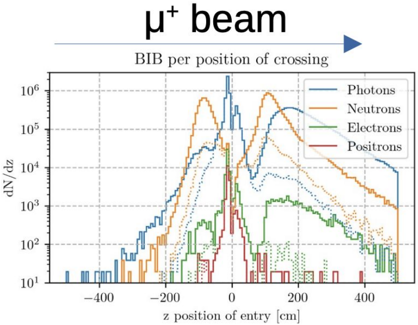
$\sqrt{s}$	IP design	MDI	Detector
3 TeV	✔	1.5 TeV BIB	✔
10 TeV	ongoing	ongoing	ongoing

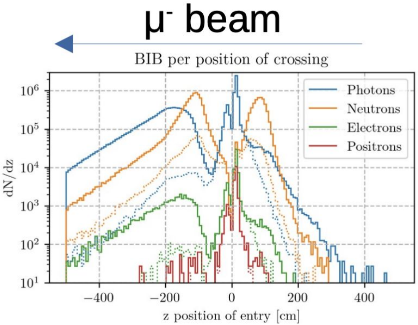


Slide credit: D. Calzolari

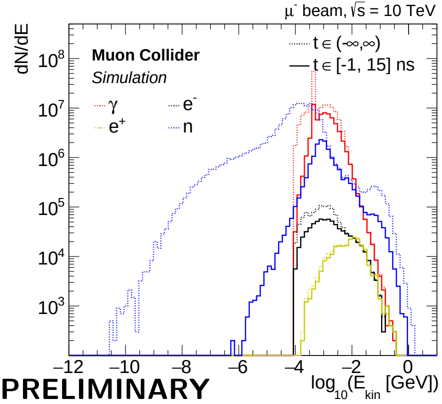
FLUKA BIB Simulation at 10 TeV

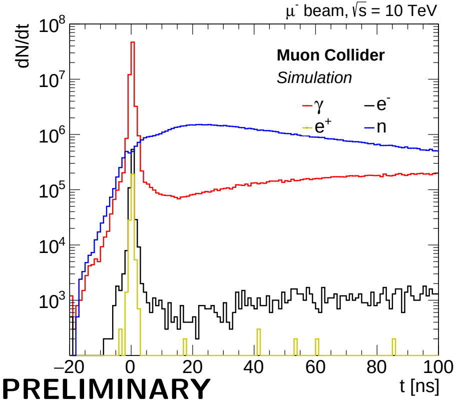
- High-statistics ($\sim 1/10$ of a BX) inputs available for both μ^+ and μ^- beams at $10\,\mathrm{TeV}$.
- Kept machine lattice fixed to initial design (will be updated once new designs are mature).
- Available from IMCC on demand (soon to be distributed through Zenodo).





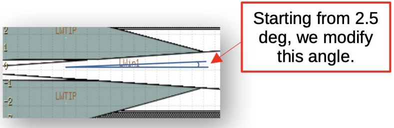
- Timing, energy distribution shapes very consistent with lower-energy results.
- **Preliminary results**; collaboration with accelerator physicists ongoing!

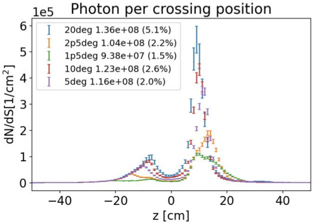


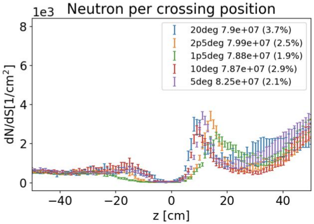


Work on MDI: Nozzle Optimization

- The nozzle is the most important element in the BIB mitigation
- A simple parametric scan proved effective in altering the nozzle shape to mitigate the BIB multiplicity
- In collaboration with Physics and Detector performance working group, we need to identify fundamental parameters to perform a systematic study



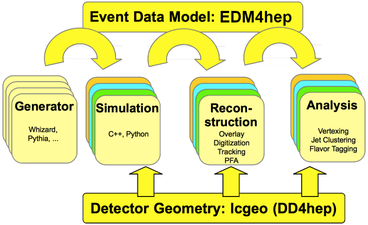


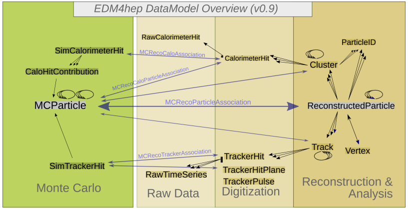


Slide credit: D. Calzolari

- Strive to **reduce nozzle size** in order to **maximize physics acceptance**:
  - Nozzles limit detector capabilities in the forward region: essential for lots of physics.
  - Better detector reconstruction might allow us to **tolerate more BIB** and reduce nozzles.

Reconstruction Studies and Computing

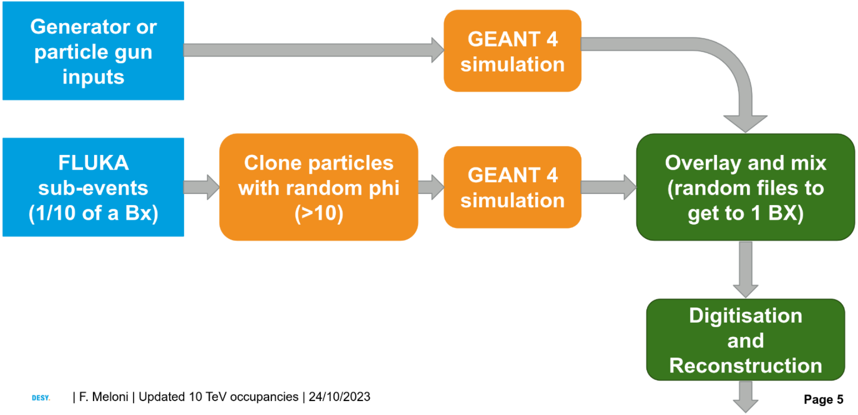




- Studies underway to assess performance with new detector and new BIB.
- IMCC software based on ILCSoft/Key4HEP:
  - **Common framework** for future collider R&D: shared with FCC, ILC, CLIC, C3, etc.
  - Integrates many other packages; Pandora particle flow, ACTS tracking, Gaudi, etc.
  - Output LCIO 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.
  - Some **preliminary results** presented today for **tracking** and **calorimetry**.

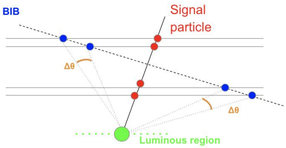
Overlays: Keeping Events Statistically Independent

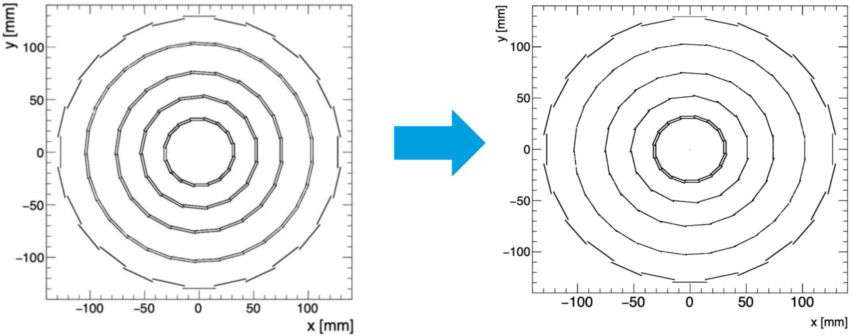
- During reco, BIB from FLUKA can be sampled and overlaid on to Monte Carlo:
  - Simulating the BIB contributions in FLUKA is **computationally expensive**.
  - New pipeline developed based on random FLUKA sub-event mixing.
  - Strongly reduced effects due to lack of BIB statistics (mostly seen in calorimetry).



New Tracker Layout

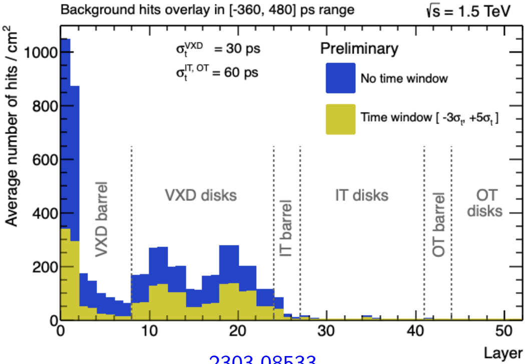
- Previous detector design relied on double layers to select hits from track stubs:
  - Introduce **inefficiencies for displaced tracks** (already Bs, even before considering BSM).
  - Additional layers mean additional **detector material** and **power dissipated**.
- Greatly improved tracking software (now based on ACTS library) made double layers redundant: removed **all but one** in vertex detector.





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.



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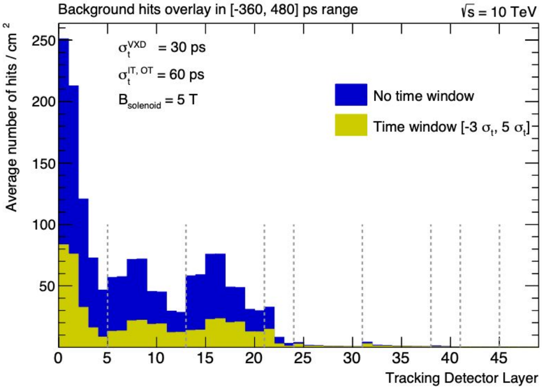
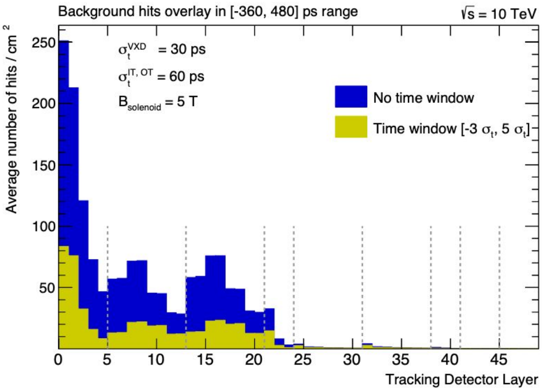
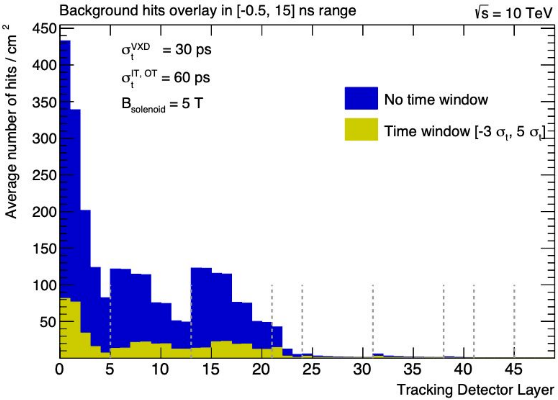


Tracker Occupancy, Continued

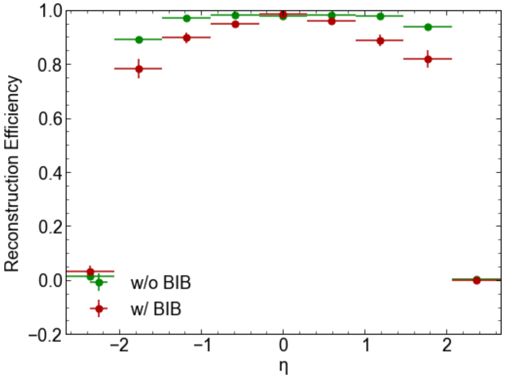
- Slight bias in these results due to $< 1\,\mathrm{ns}$ time window.
- Relaxing the time window: higher occupancies overall but shapes more or less unchanged.

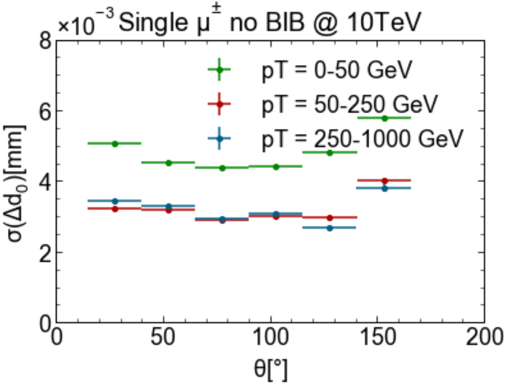




Preliminary Tracking Performance

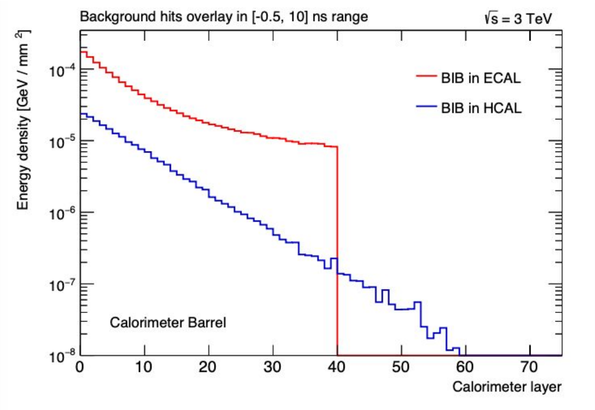
- Track reconstruction with new detector layout studied using single muon samples.
- 3.5% efficiency loss from addition of BIB, but overall tracking still seems to work!
- Initial results promising, but more studies needed (especially in forward region).

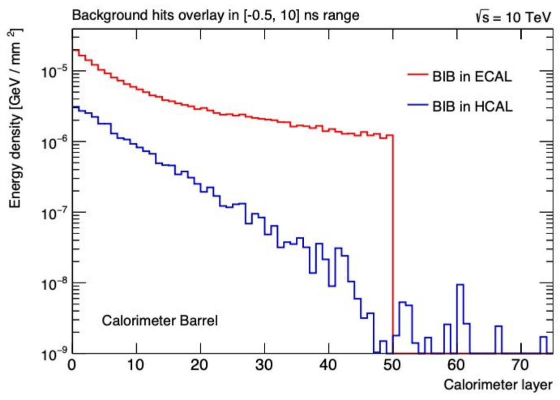




BIB in the Calorimeters

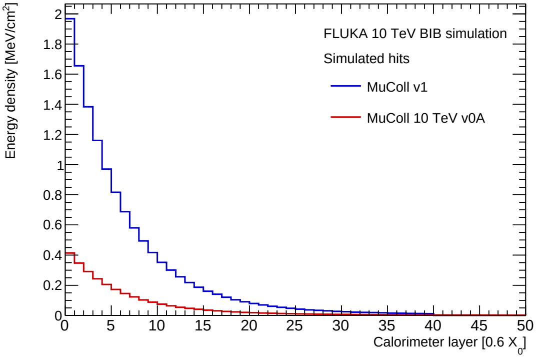
- Energy density in both calorimeters also has same shape between beam energies.
- **Order of magnitude** lower in our $10\,\mathrm{TeV}$ design: shows impact of solenoid shielding!

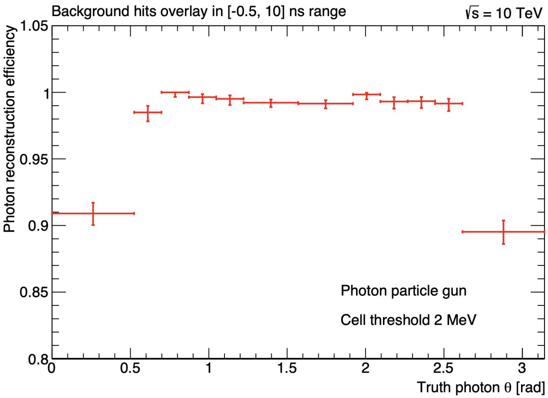




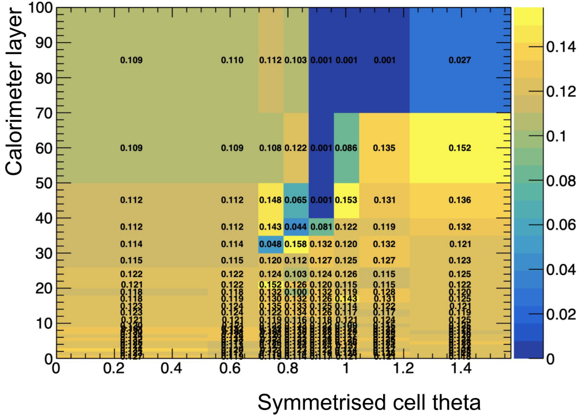
Preliminary Calorimeter Performance

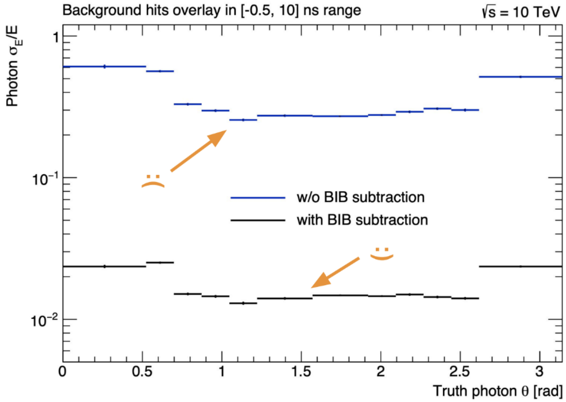
- Despite reduced energy density: still overall high photon reconstruction efficiency.





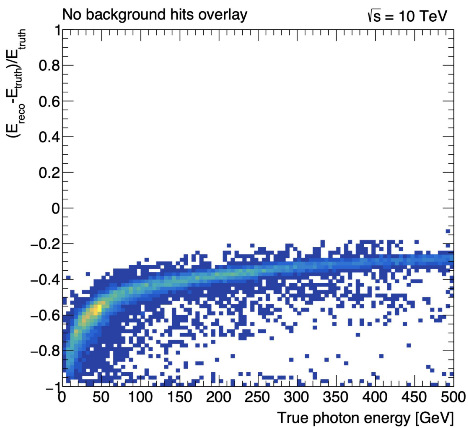
- Calorimeter energy resolution not ideal: high cell thresholds ($2\,\mathrm{MeV}$) needed for BIB.
  - Expected BIB distribution in cells can be used to derive position-dependent thresholds.
  - Strongly reduced BIB-induced fake objects (e.g. less than 1 BIB photon per event!)
  - Leads to **order-of-magnitude** improvement in resolution for $50\,\mathrm{GeV}$ photons!

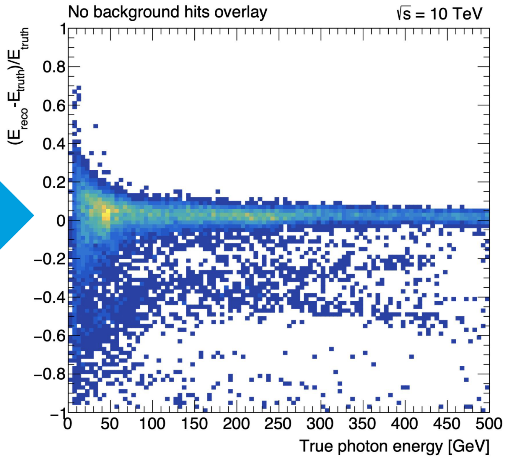




BIB Subtraction, Continued

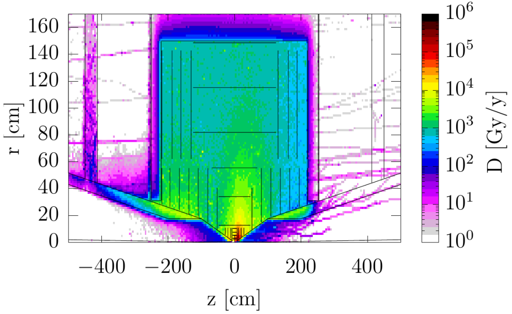
- Applying these thresholds induces a **nonlinearity**: however this can be corrected.
- Example of the type of advanced reconstruction that can make a huge difference!

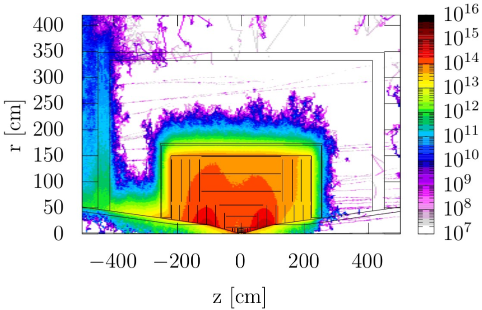




Radiation Damage

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

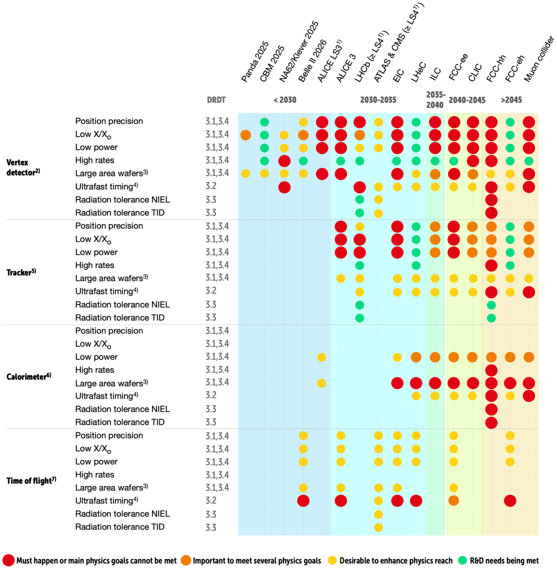




	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider ($3\,\mathrm{TeV}$)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider ($10\,\mathrm{TeV}$)	20	0.2	3×10^{14}	10^{14}

Future R&D Opportunities

- From CPAD, ECFA: 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 and luminosity measurements.
  - **Nozzle optimization** and mechanics.
  - Radiation hardened readout electronics with **on-detector intelligence**.
  - **Solenoid design**: need to develop and retain expertise for high-field magnets.



Conclusion and Acknowledgements

- Collaboration between **accelerator and detector** experts critical for muon colliders.
- 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.
- 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).

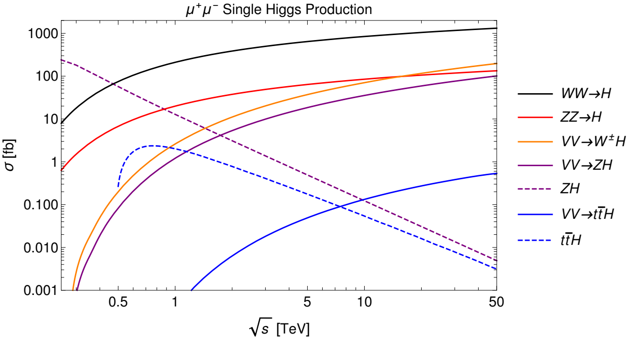
Topics for Discussion

- Better version of the Delphes card:
  - 2 cards with a conservative and aspirational set of parameters.
- Luminosity measurements and the associated uncertainty is another interesting topic.
- Incoherent e^+e^- and whether this is important or not.
- **What else do theorists need from experimentalists to improve studies?**

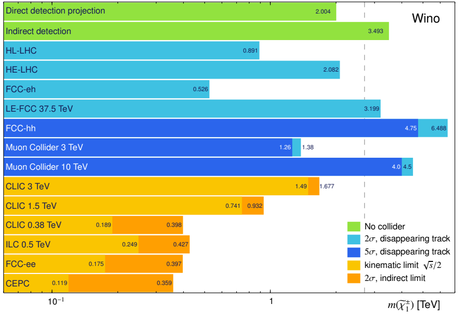
Backup

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.



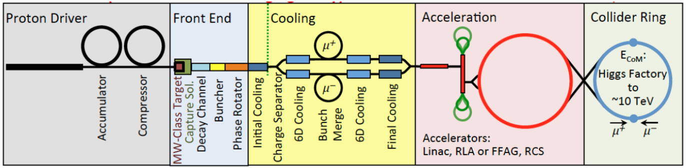
M. Forslund, P. Meade (10.1007/JHEP08(2022)185)



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

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

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.