Detector R&D Towards a 10 TeV Muon Collider

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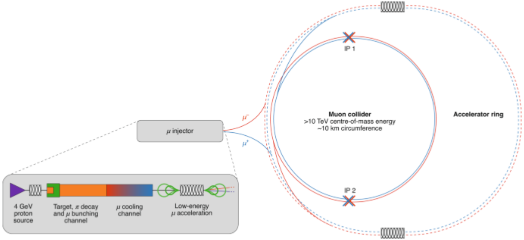
Introduction

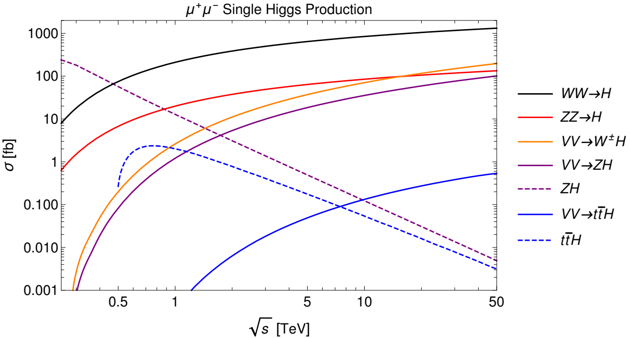
- Significant community interest in muon colliders emerged during the Snowmass and European Strategy processes:
  - Colliding fundamental particles (like electrons) with much less synchrotron radiation (like protons) offers **compact, efficient way** to reach high energies.
  - Muons are unstable: **many 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).

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

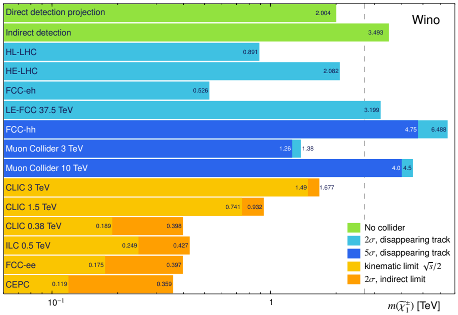


The Case for 10 TeV

- $\sqrt{s} = 10\,\text{TeV}\ \mu^+\mu^-$ **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

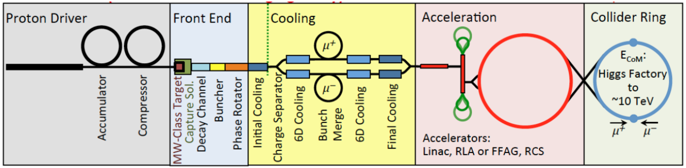
- Main muon collider challenges: accelerator related:
  - Targetry; alternatives to liquid mercury.
  - 6D ionization cooling to focus beam.
  - Fast ramping magnets for acceleration.
  - Neutrino radiation mitigation.
  - Work underway on all these areas.
- **Machine-detector interface** extremely important:
  - Decaying muons: large **beam-induced background** (BIB) in our detectors.
  - 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

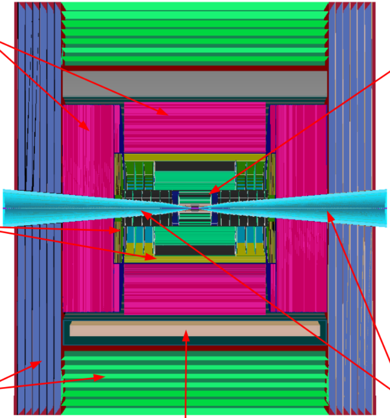
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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)

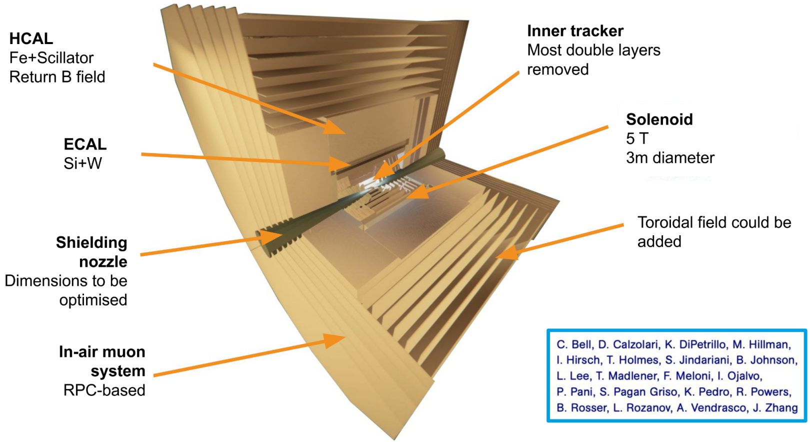
Challenges for 10 TeV Detectors

- 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.
  - Extra material potentially reduces calorimeter performance, need to study impact.

10 TeV Detector Design

- Concept developed at KITP workshop at Santa Barbara in February.
- Layout implemented in DD4hep; ILCSoft-based IMCC software stack used for simulations.

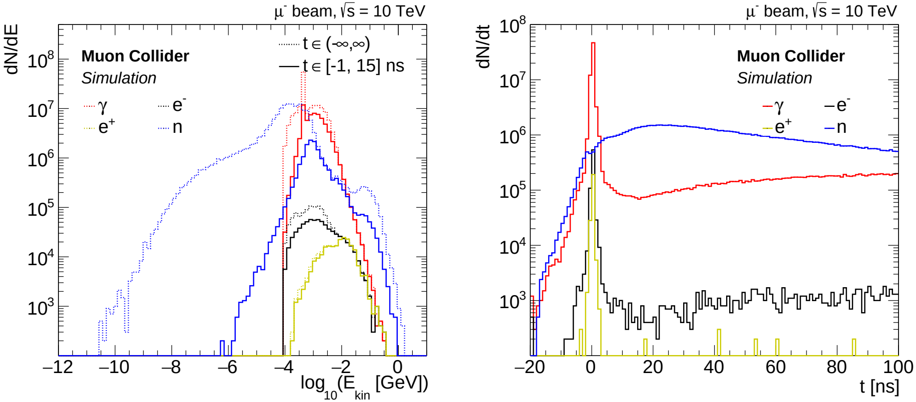
- Simplified muon system (no magnet yoke).
- Reoptimized calorimeter depth.
- Reoptimized tracker layout.
- Design evolving rapidly, lots of R&D still to do.



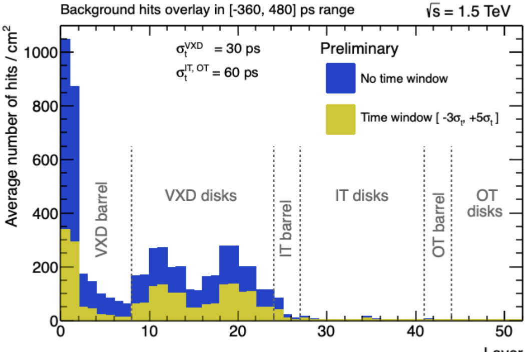
C. Bell, D. Calzolari, K. DiPetrillo, M. Hillman, I. Hirsch, T. Holmes, S. Jindariani, B. Johnson, L. Lee, T. Madlener, F. Meloni, I. Ojalvo, P. Pani, S. Pagan Griso, K. Pedro, R. Powers, B. Rosser, L. Rozanov, A. Vendrasco, J. Zhang

Simulating BIB at 10 TeV

- BIB simulations done using MARS15 and Fluka: excellent agreement seen.
- Preliminary 10 TeV BIB generated with Fluka:
  - Mostly low energy (below $1\,\mathrm{GeV}$); significant fraction removable using **precision timing**.



- 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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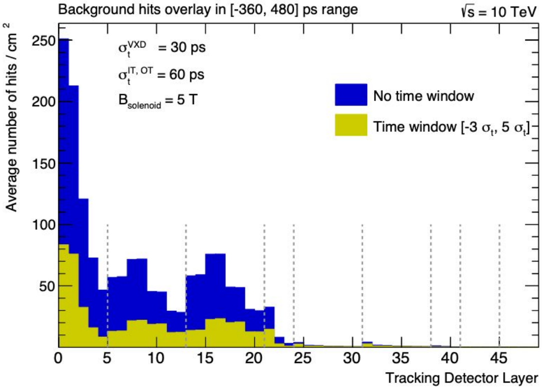
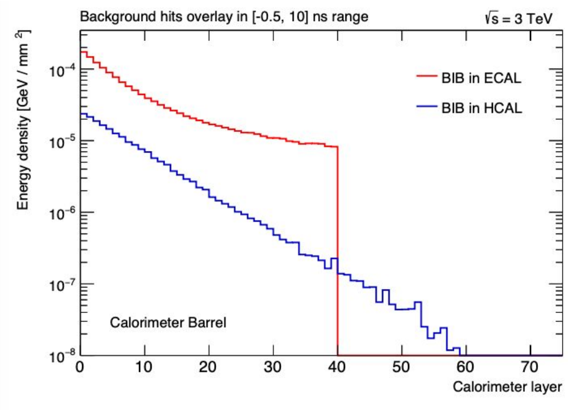
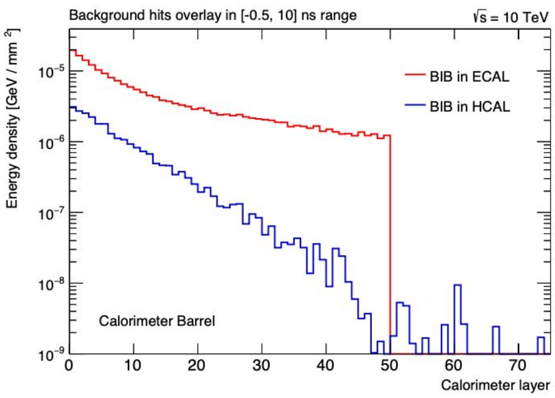


BIB in the Calorimeters

- 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!





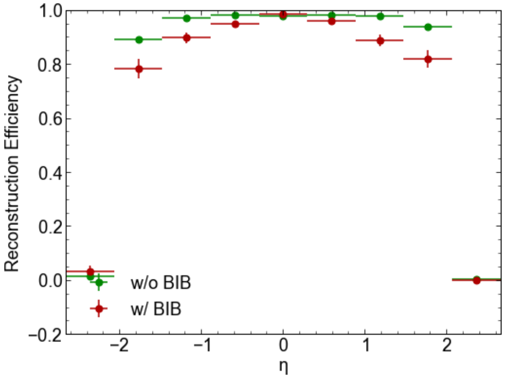
Reconstruction Studies

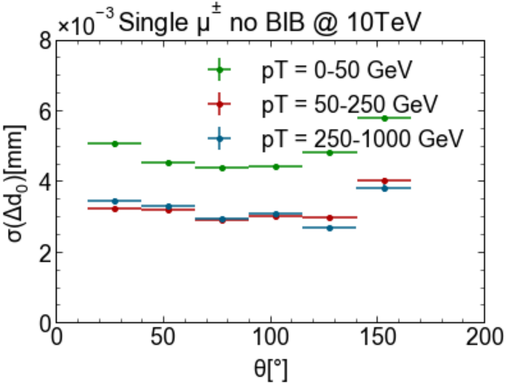
- Studies underway to assess object reconstruction performance with this detector:
  - Variety of signatures (electron, muon, photon, tau, pion, jet) being studied.
  - Monte Carlo samples simulated using DD4hep and reconstructed with Marlin.
  - During reconstruction, BIB from Fluka can be sampled and overlaid.
- Some **preliminary results** presented today for **tracking** and **calorimetry**.

TODO: Are there any other preliminary plots (tau/electron/pion) that we could show here? Can add more slides too.

Tracking Performance

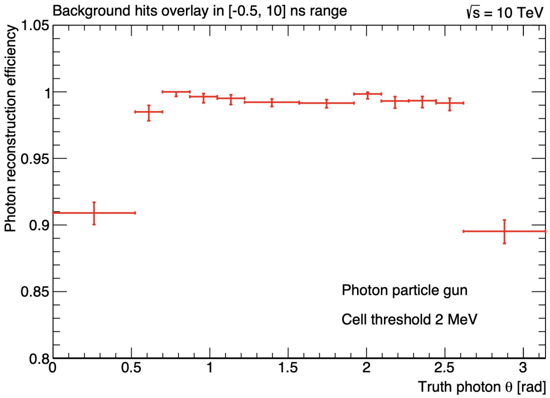
- Track reconstruction powered by ACTS; studied using single muon samples.
- 3.5% efficiency loss from addition of BIB, but overall tracking still seems to work!
- Initial results promising, but more studies needed (especially in forward region).

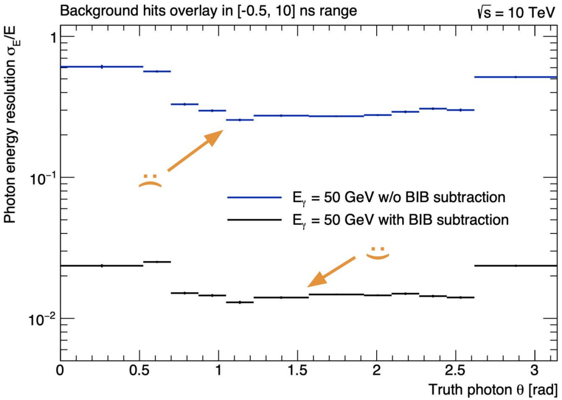




Electromagnetic Calorimeter Performance

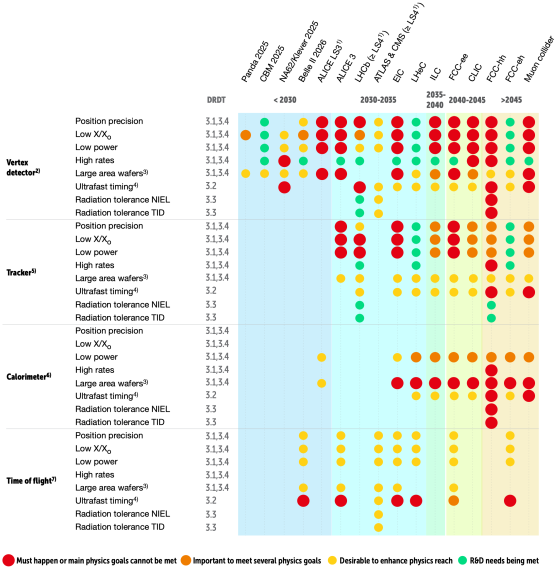
- Photon reconstruction efficiency very high even with addition of $5\,\mathrm{T}$ solenoid.
- Energy resolution not ideal due to high cell thresholds, but can be improved:
  - **BIB subtraction**: digitize with $50\,\mathrm{keV}$ thresholds, then remove average BIB when clustering.
  - Leads to **order-of-magnitude**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



Conclusion