# Detector concepts/requirements for a Muon Collider

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# Detector requirements for a muon collider

- The requirements for the detector specifications from physics are similar to those of other multi-TeV machines to reconstruct:
  - boosted low-$p_T$ physics objects from Standard Model processes;
  - central energetic physics objects from decays of possible new massive states;
  - less conventional experimental signatures: disappearing tracks, displaced leptons, displaced photons or jets, ...
- Constraints from the machine design: final focusing quadrupoles at $\pm 6$ m from the interaction point.
- Machine background conditions.

Ultimately, the detector design, the technological choices, and the development of the event reconstruction algorithms will be driven by the high levels of machine-induced background.

# Unique background conditions

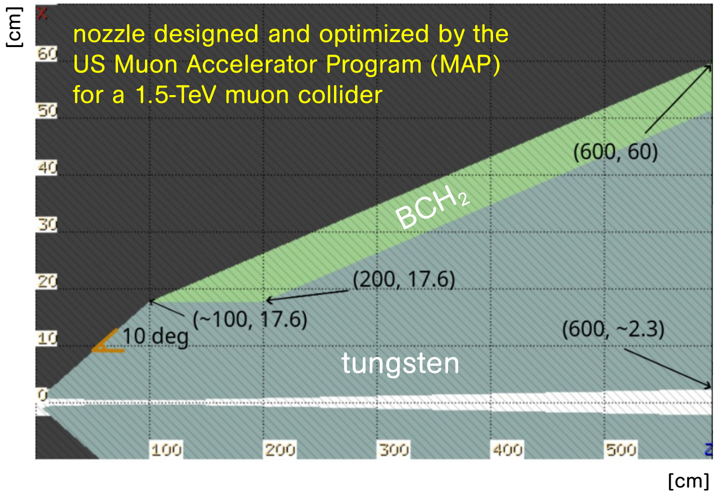
| | Description | Relevance as background |
|---|---|---|
| **Muon decay** | **Decay of stored muons around the collider ring** | **Dominating source** |
| **Synchrotron radiation by stored muons** | Synchrotron radiation emission by the beams in magnets near the IP (including IR quads → large transverse beam tails) | **Small** |
| **Muon beam losses on the aperture** | Halo losses on the machine aperture, can have multiple sources, e.g.:<br>• Beam instabilities<br>• Machine imperfections (e.g. magnet misalignment)<br>• Elastic (Bhabha) μμ scattering<br>• Beam-gas scattering (Coulomb scattering or Bremsstrahlung emission)<br>• Beamstrahlung (deflection of muon in field of opposite bunch) | **Can be significant** (although some of the listed source terms are expected to yield a small contribution like elastic μμ scattering, beam-gas, Beamstrahlung) |
| **Coherent $e^-e^+$ pair production** | Pair creation by real* or virtual photons of the field of the counter-rotating bunch | **Expected to be small** (but should nevertheless be quantified) |
| **Incoherent $e^-e^+$ pair production** | Pair creation through the collision of two real* or virtual photons emitted by muons of counter-rotating bunches | **Significant** |

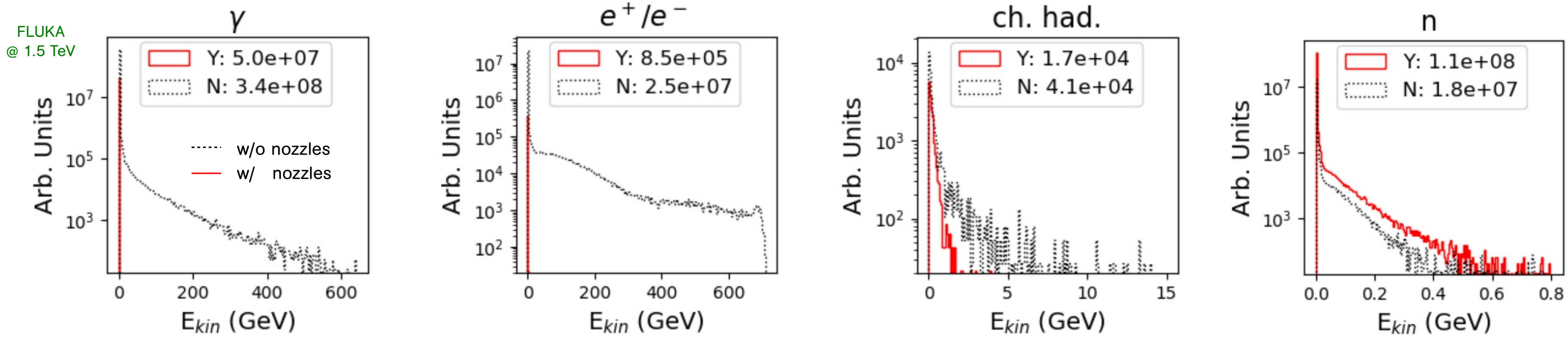
from yesterday's presentation by D. Calzolari

- The detector studies presented here take into account only the dominant background from muon decays
  → beam-induced background (BIB).

# MDI: the detector's first line of defense

- The machine-detector interface (MDI) includes two conical tungsten shields ("nozzles") coated with borated polyethylene:
  - in combination with an appropriate configuration of the interaction region magnets, the nozzles significantly reduce the background particle flux into the detector.

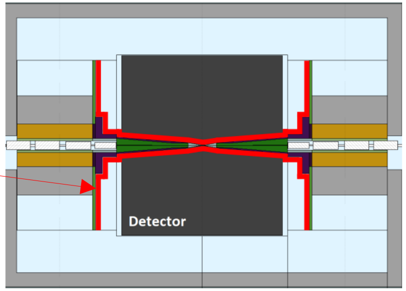


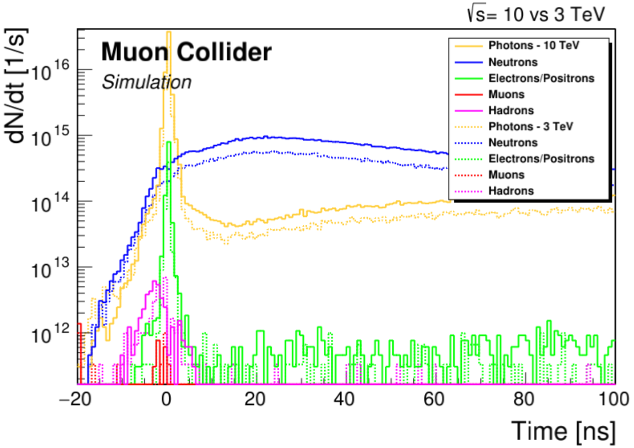

F. Collamati et al., 2021 JINST 15 P11009

# BIB particles entering the detector volume

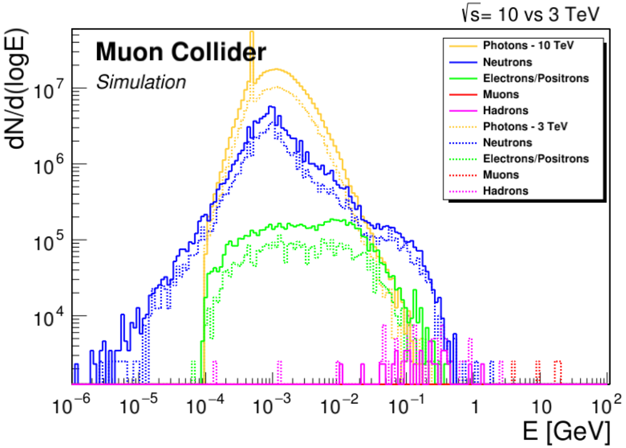
- The BIB samples are generated with FLUKA, which transports the background particles up to the detector envelope
  - → details in D. Calzolari's presentation.
- On average, $\sim 10^8$ BIB particles enter the detector volume at every bunch crossing: mostly photons, neutrons, electrons/positrons, and charged hadrons.




time of arrival w.r.t. bunch crossing

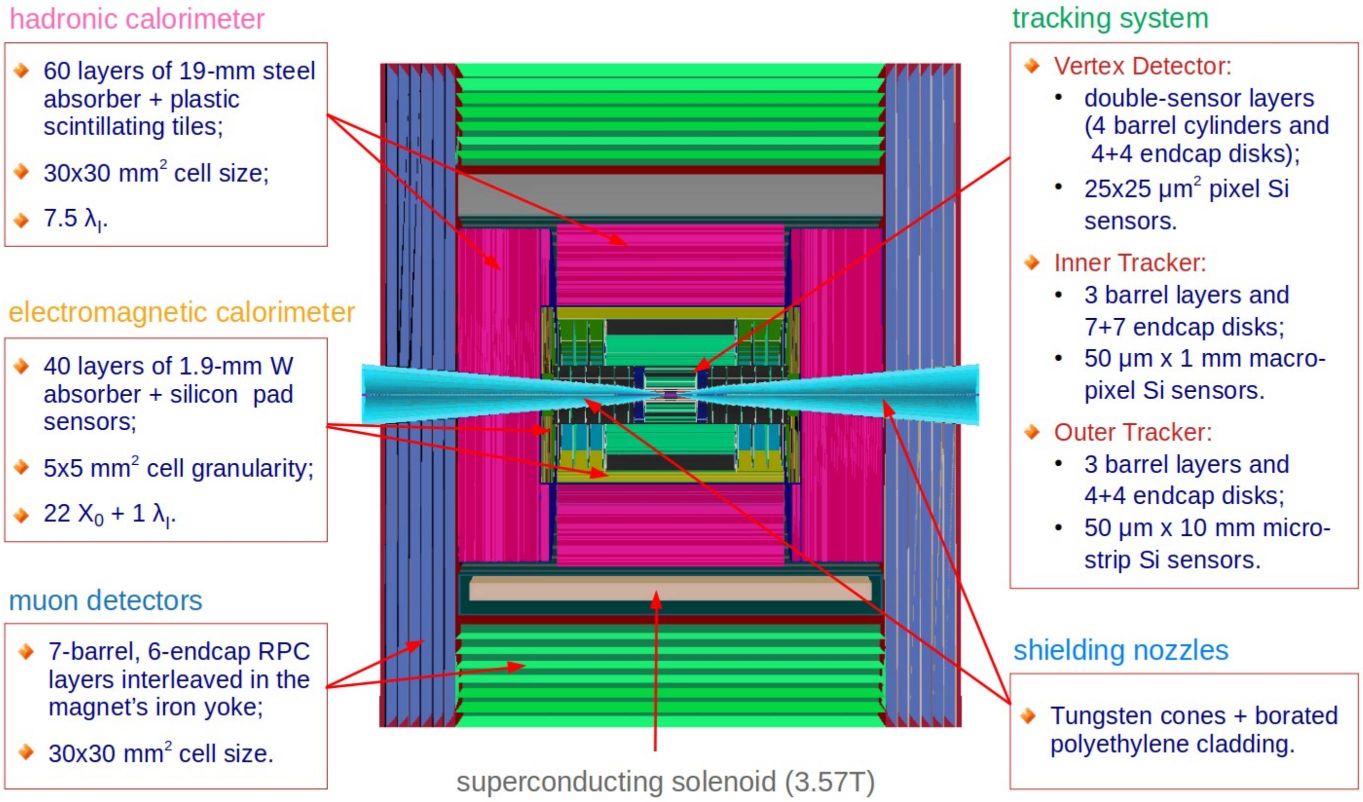



energy spectra for -1 < T < 15 ns w.r.t bunch crossing




- For the time being, using the same1.5-TeV nozzles for both 3 and 10 TeV samples
  - → beam-induced background characteristics in the detector mainly determined by the nozzles.

# Detector concept for $\sqrt{s}$ = 3 TeV



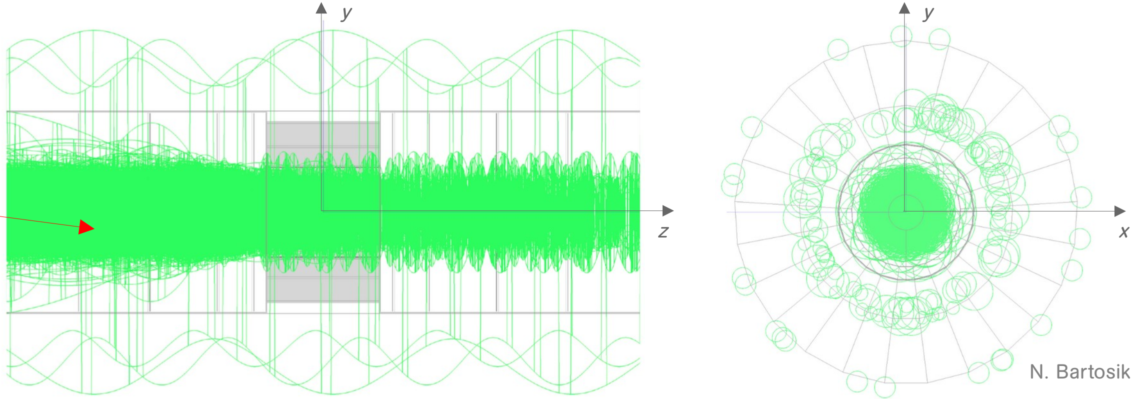

- The detector model for 3-TeV studies is based on CLIC's detector concept + the MDI and the vertex detector designed by the US Muon Accelerator Program (MAP).
- The simulation and reconstruction software is derived from CLIC's iLCSoft (transition to the Key4hep framework in progress)
  → github.com/MuonColliderSoft.
- The propagation of the BIB particles in the detector and their interactions with the detector materials are handled by GEANT4.

The following full-simulation detector studies with BIB focus on $\sqrt{s}$ = 3 TeV, but the findings and results also apply to the 10 TeV case because of the similarity in the BIB characteristics.

# Tracking system

- In the tracking system, the BIB produces a huge amount of spurious hits (mostly from very low-$p_T$ electrons looping inside the tracker volume)
  - → track finding is very challenging due due to the number of hit combinations.

charged BIB particles in the muon collider tracker (generator level)



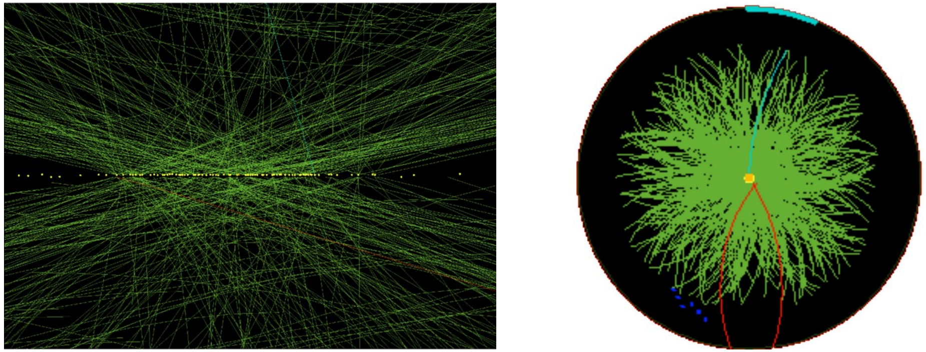

N. Bartosik

Muon Collider Detector

| Detector Reference | Hit Density [mm$^{-2}$] MCD | ATLAS ITk | ALICE ITS3 |
|---|---|---|---|
| Pixel Layer 0 | 3.68 | 0.643 | 0.85 |
| Pixel Layer 1 | 0.51 | 0.022 | 0.51 |

C. Accettura et al., Eur. Phys. J. C 83 (2023) 864

event with 78 pileup vertices at CMS

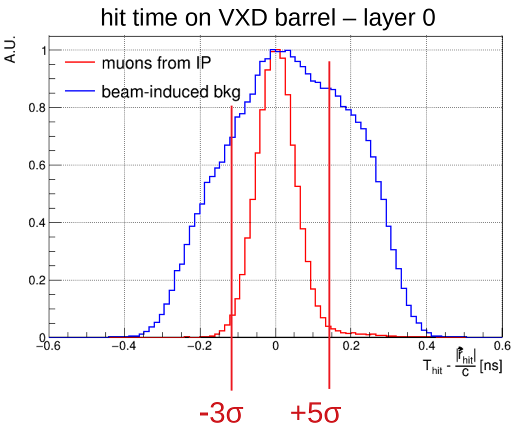


Higher hit occupancies than at HL-LHC detectors are expected, but the crossing rate at the muon collider is ~30-70 kHz vs 40 MHz at LHC.

# BIB mitigation in the tracking system

- Key features of the tracking system to deal with the BIB:
  - optimized detector layout;
  - high granularity;
  - precise timing;
  - directional information;
  - characteristics of the detector response (pulse shape and pixel cluster size).

high-precision timing



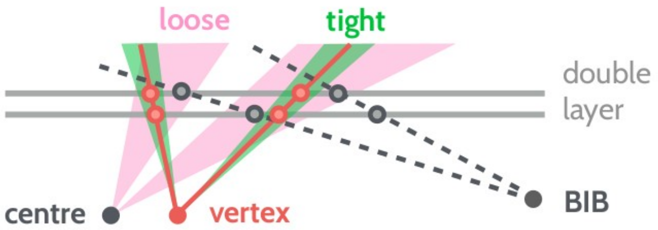

## Ongoing R&D (DRD3)

- Silicon LGAD sensors for 4D tracking up to very high fluence:
  - V. Sola et al., Nucl. Instrum. Meth. A 1040 (2022) 167232.

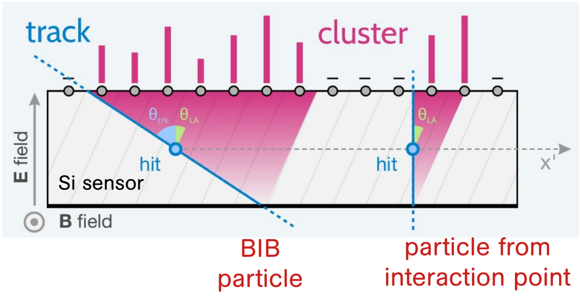
prototype with new LGAD design funded by INFN-CSN5 and AIDAinnova grants

Project funded also by an EU ERC Consolidator Grant.

incoming direction of the particle



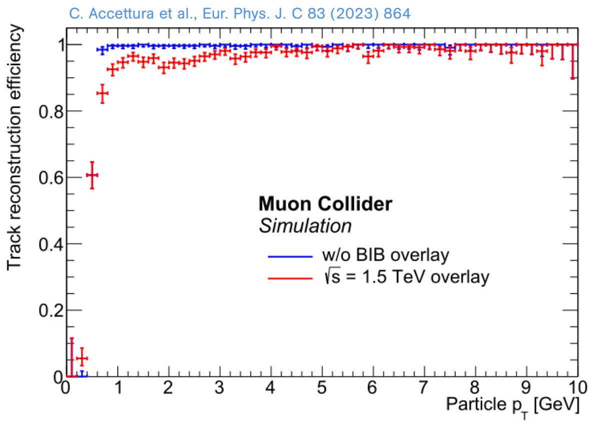

shape and size of pixel clusters

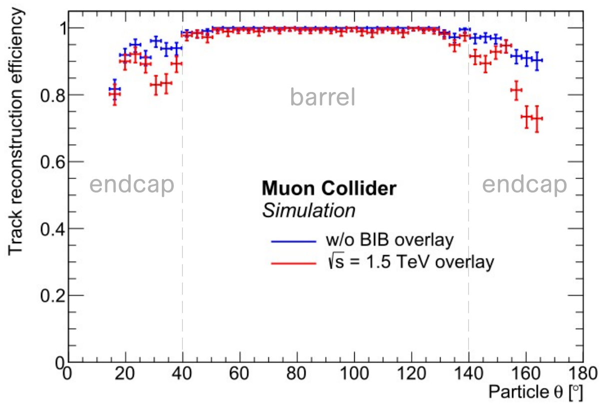


# Track reconstruction performance

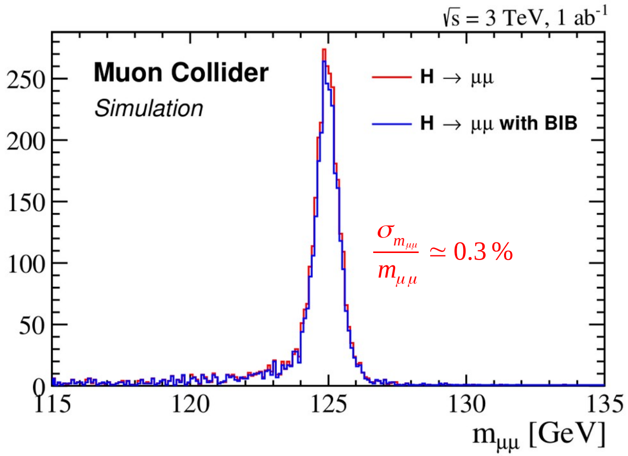
- In the presence of the BIB, the reconstruction algorithms for all the physics objects had to be revisited or fine-tuned.
- Detector performance assessed with single particle samples and benchmark physics channels.

single muon samples



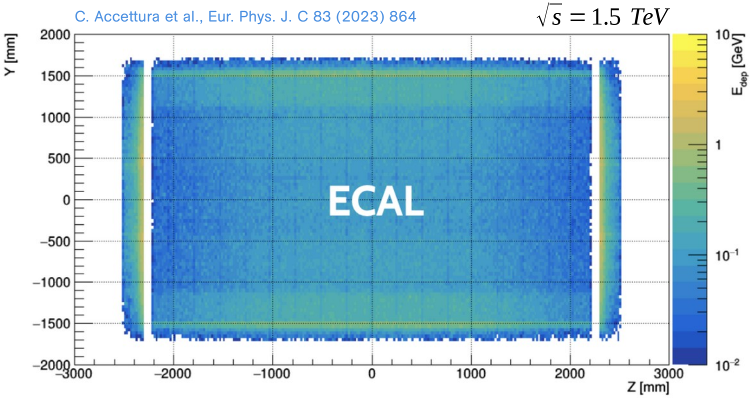




$\mu\mu \rightarrow H\nu\bar{\nu} \rightarrow \mu\mu\nu\bar{\nu}$

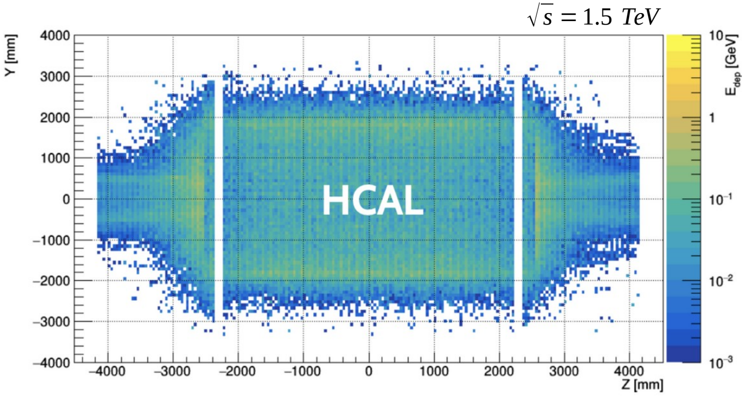


# Calorimeters

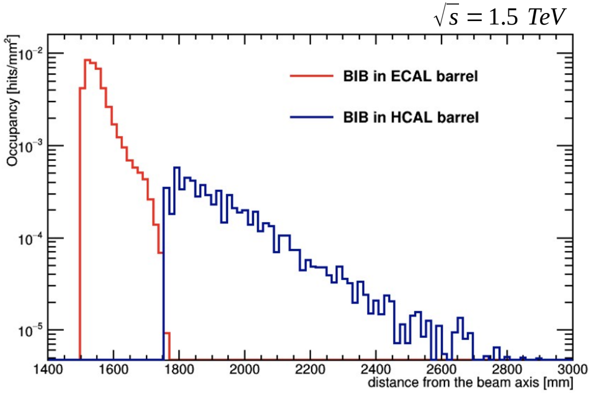
BIB energy in the electromagnetic calorimeter




BIB energy in the hadronic calorimeter




density of BIB hits vs calorimeter barrel depth

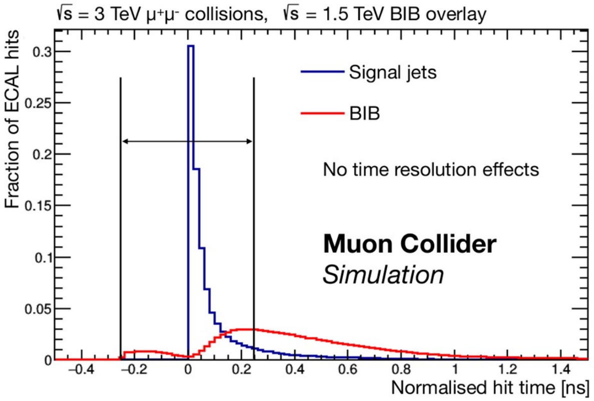



- In calorimeters, expected an approximately uniform deposition of energy by BIB particles.
- ECAL:
  - estimated a flux of 300 particles per cm$^2$ through the ECAL surface at every bunch crossing:
  - $\sim$96% photons and $\sim$4% neutrons;
  - average photon energy: 1.7 MeV.
- HCAL:
  - expected a $\sim$10 times lower hit occupancy due to the BIB than in the ECAL;
  - $\sim$99% neutrons.

# BIB mitigation in the calorimeters

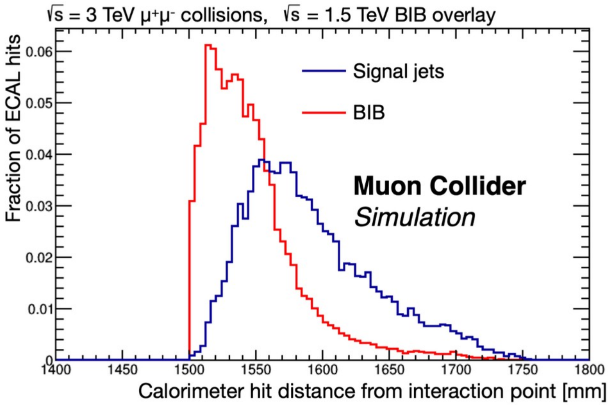
- Key calorimeter features to mitigate the BIB effects:
  - high granularity;
  - fine longitudinal segmentation;
  - resolution on the particle time of arrival of ~100 ps.

time of ECAL barrel hits



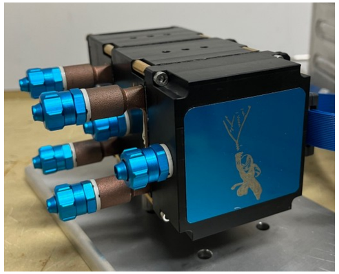

C. Accettura et al., Eur. Phys. J. C 83 (2023) 864

shower profile of signal jets vs bkg




Ongoing R&D (DRD6)

- Semi-homogeneous electromagnetic calorimeter based on lead fluoride crystals (CRILIN):
  - S. Ceravolo et al., Nucl. Instrum. Meth. A 1047 (2023) 167817.



2-layer 3x3-crystal CRILIN prototype funded by INFN

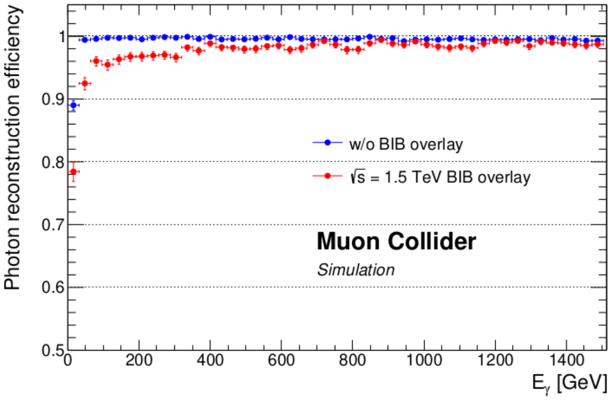
- Hadronic calorimeter based on Micro-Pattern Gaseous Detectors:
  - C. Aruta et al., Nucl. Instrum. Meth. A 1047 (2023) 167731.

Funding from the Italian Ministry for Universities and Research ("PRIN") to build an integrated ECAL-HCAL prototype.

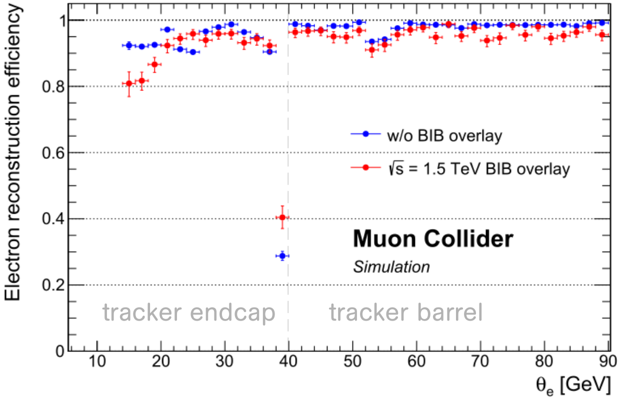
# e.m. object reconstruction performance

single photon sample

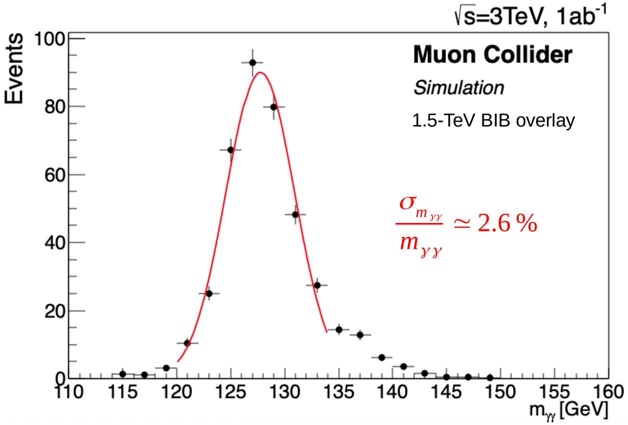
C. Accettura et al., Eur. Phys. J. C 83 (2023) 864




single electron sample

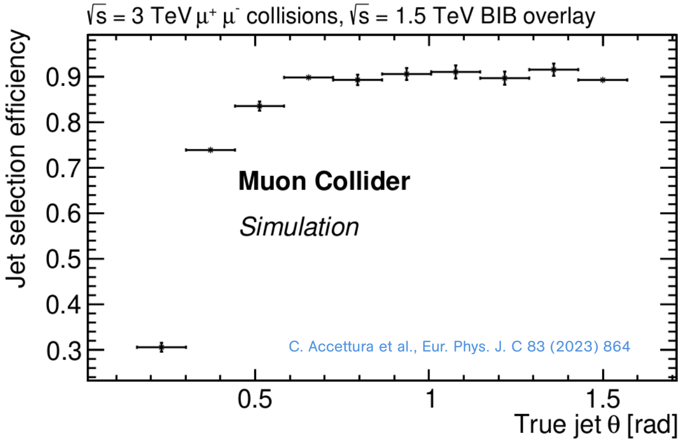



$\mu\mu \to H\nu\bar{\nu} \to \gamma\gamma\nu\bar{\nu}$

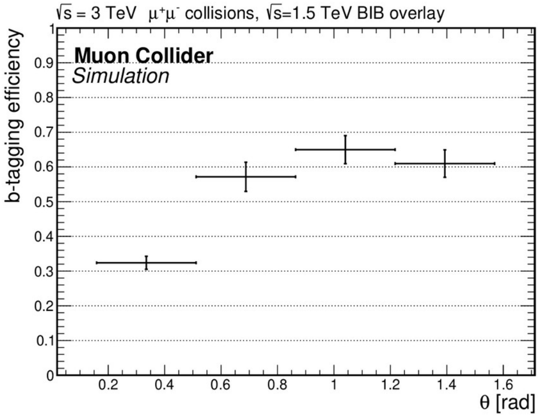


# Jet reconstruction performance

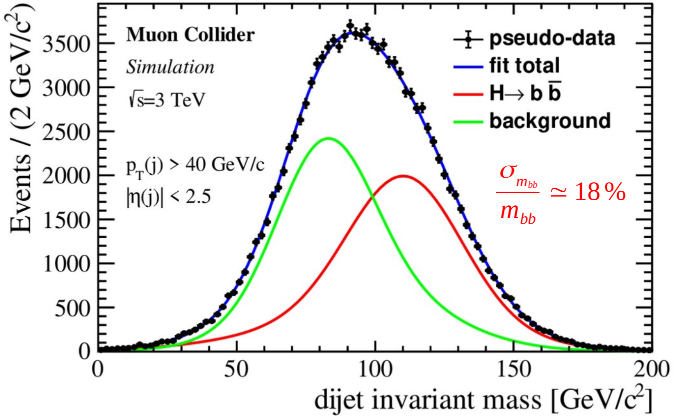
dijet samples




$b\bar{b}$ sample




$\mu\mu \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$



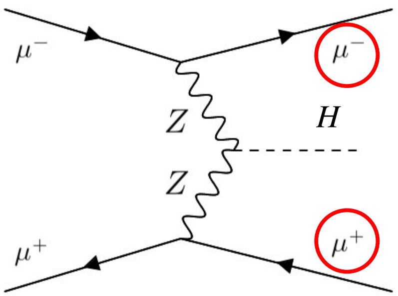

- To reduce contamination from BIB hits, the energy thresholds for ECAL and HCAL hits have been set to 2 MeV.
- Despite crude background mitigation measures, simple calibration procedures, and non-optimized reconstruction algorithms, the performance of the 3 TeV detector in reconstructing the main physics objects is already satisfactory.

# Muon system

- In the muon system, significant BIB effects only in the endcap regions close to the beamline:
  - required good spatial resolution and possibly sub-ns time resolution.

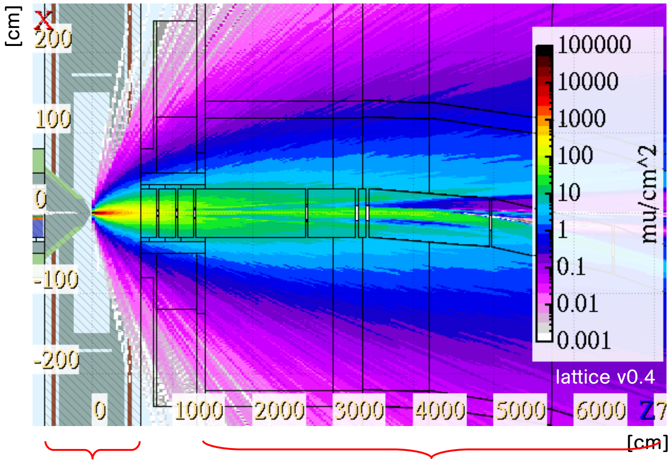
- Under investigation the possibility of detecting the forward-scattered muons associated with the ZZ-fusion production process:
  - exploit the specific ZZ-fusion signature;
  - possibly help with the luminosity measurement.

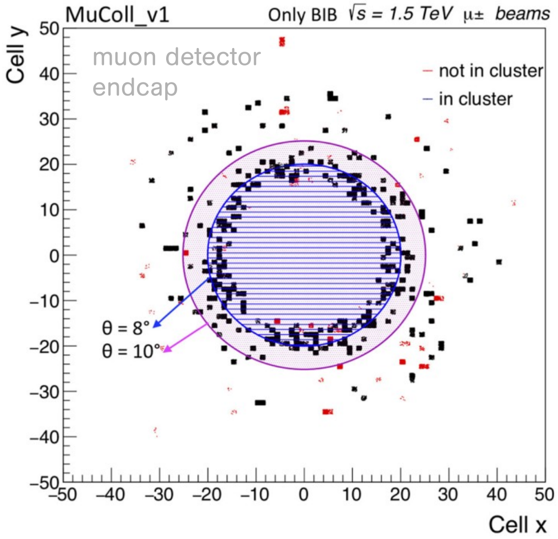
$\mu^-\mu^+ \rightarrow H\ \mu^-\mu^+$ at 3TeV




forward-muon fluence

D. Calzolari




## Ongoing R&D (DRD1)

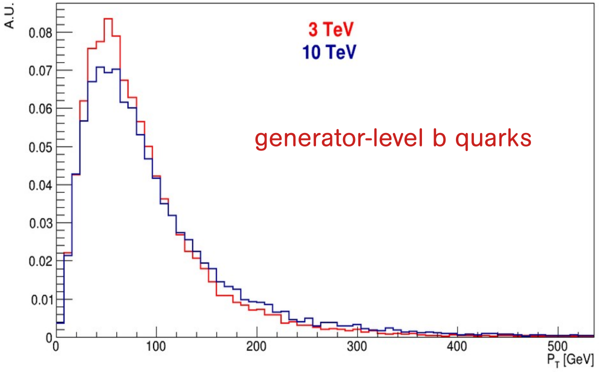
- Muon detector based on PicoSec Micromegas:
  - C. Aimè et al., 2024 JINST 19 C03052.

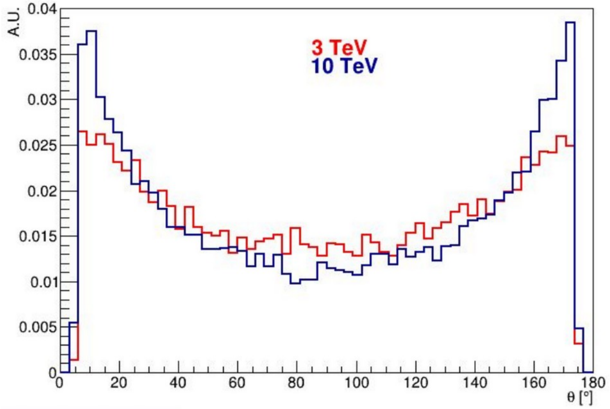
# Towards the update of the European Strategy

- Basic plan for the next update of the European Strategy for Particle Physics is to assess the detector performance on a set of representative physics channels with a detailed detector simulation that includes the machine background.

- Focus on benchmark processes with low- and high-$p_T$ physics objects:
  - At $\sqrt{s}$ = 3 TeV (results to be submitted to JHEP):
    - production cross sections of Higgs boson into $b\bar{b}$, WW*, ZZ*, $\gamma\gamma$, $\mu\mu$
      - → Higgs properties at 3 and 10 TeV very similar, conclusions on the detector requirements apply also for 10 TeV;
    - double Higgs production and Higgs trilinear self-coupling in the channel $HH \rightarrow b\bar{b}b\bar{b}$.
  - At $\sqrt{s}$ = 10 TeV:
    - Higgs boson self-couplings in as many decay channels as possible;
    - Z' boson production.

$\mu\mu \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$ at $\sqrt{s}$ = 3 and 10 TeV

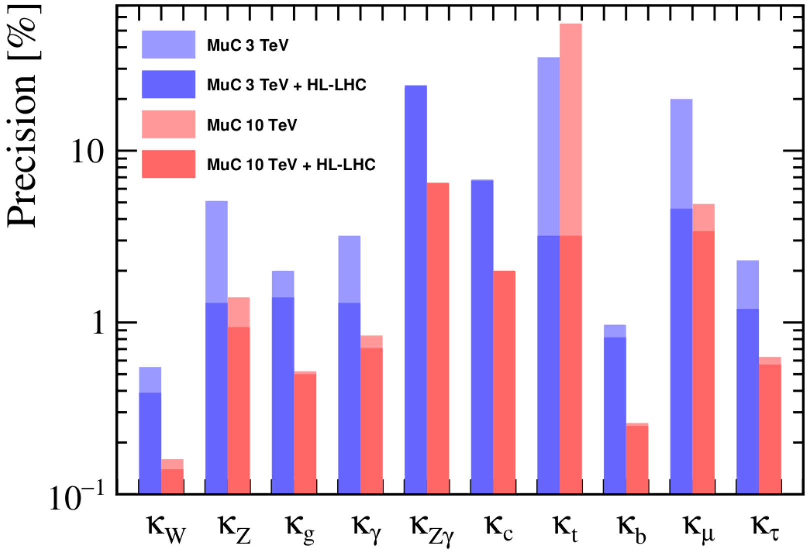


# Expected performance on Higgs couplings

- Higgs boson couplings to fermions and bosons are extracted from a global fit to the Higgs boson production cross sections:
  - the set of channels of full-simulation studies at 3 TeV is not yet complete for a global fit;
  - the muon collider potential at 3 TeV (1 ab$^{-1}$) and 10 TeV (10 ab$^{-1}$) is evaluated with a parametric detector simulation (partially tuned on the detailed detector simulation at 3 TeV) by M. Forslund and P. Meade and JHEP 08 (2022) 185.

M.C., D. Lucchesi, L. Sestini arXiv:2311.03280



# Higgs boson self-couplings

- A precise measurement of the Higgs boson self-couplings $\lambda_3$ and $\lambda_4$ would allow to constraint the shape of the Higgs potential:

$$V(h) = \frac{1}{2} m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$

- At 3 TeV sensitivity study with full simulation on $\lambda_3$ using the channel $\mu\mu \to HH\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$:

$$\frac{\Delta\lambda_3}{\lambda_3} \sim 20-30\% \quad (1\ \mathrm{ab}^{-1} \text{ with 1 experiment})$$

CLIC at 3 TeV with 2 $ab^{-1}$ and $e^-$ beam polarization ($b\bar{b}b\bar{b}$ + $b\bar{b}WW^* \to b\bar{b}q\bar{q}'\bar{q}q'$): 22%

H. Abramowicz et al., Eur. Phys. J. C 77, 475 (2017)

  - in line with a parametric study by T. Han et al., Phys. Rev. D 103 (2021) 013002:

$$\frac{\Delta\lambda_3}{\lambda_3} = 25\% \quad (1\ \mathrm{ab}^{-1} \text{ with 1 experiment}).$$

- But the full potential of the muon collider emerges at higher energies:
  - at 10 TeV the same parametric study by T. Han et al. estimates:

$$\frac{\Delta\lambda_3}{\lambda_3} = 5.6\% \quad (10\ \mathrm{ab}^{-1} \text{ with 1 experiment}).$$

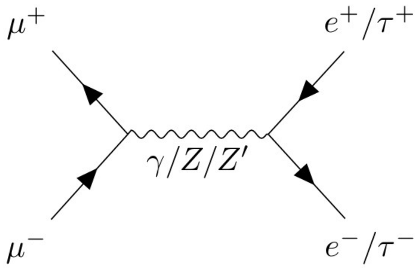
**Quartic self-coupling**

- Phenomenological study by M. Chiesa et al., JHEP 09 (2020) 098:
  - at 10 TeV assuming 20 $ab^{-1}$:
    $\Delta\lambda_4/\lambda_4 \sim 50\%$.

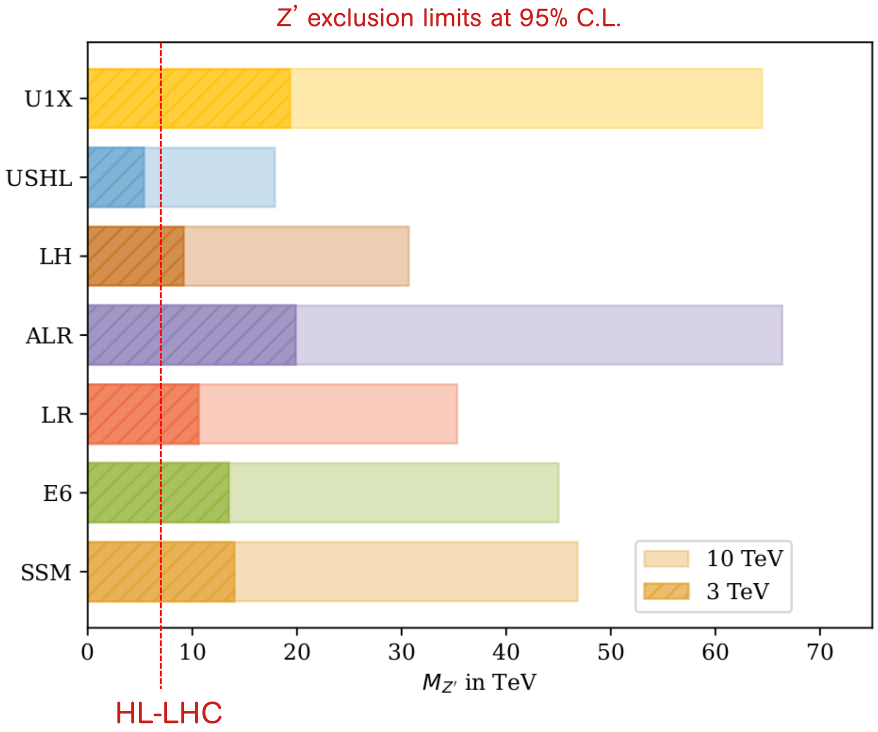
# Example of Z' searches

- New Z' bosons can be probed directly up to $M_{Z'} \sim \sqrt{s}$, but indirect searches extend much beyond:
  - example of a phenomenological study exploring the reach of a muon collide for additional neutral gauge bosons that couple to the standard model: K. Korshynska et al., arXiv:2402.18460.

- Indirect discovery potential for a new Z' boson coupled to the standard model in the final states ee and $\tau\tau$:




  - assumed 1 $ab^{-1}$ at $\sqrt{s}$ = 3 TeV and 10 $ab^{-1}$ at $\sqrt{s}$ = 10 TeV;
  - off-peak analysis based on observables of the final state leptons.

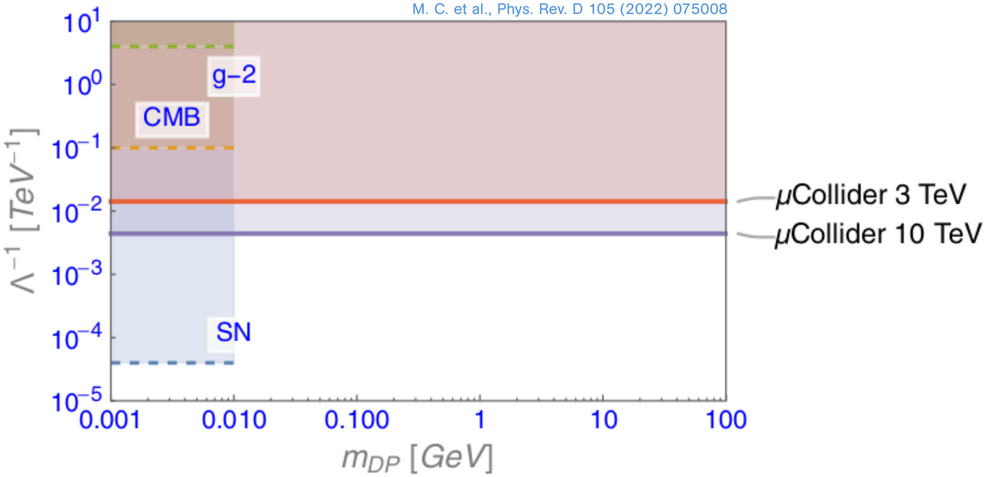


# Example of dark matter searches

- Higgs boson couplings represent a guaranteed result, but the muon collider physics program is much broader.

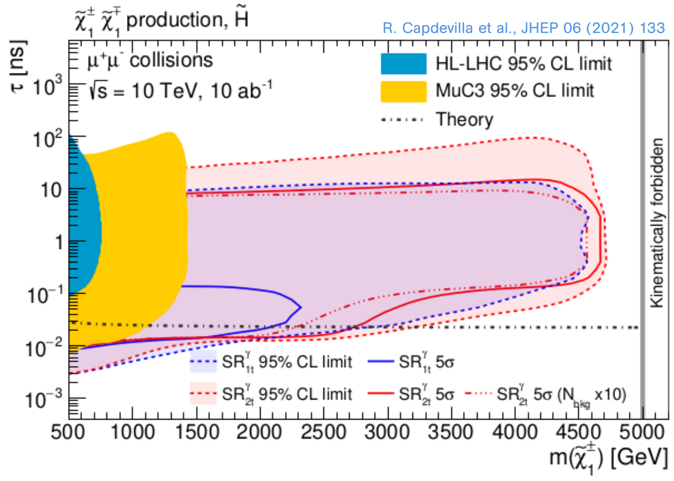
- Search for a dark photon (DP) or an ALP produced in association with a photon at $\sqrt{s}$ = 3 TeV (1 ab$^{-1}$) and $\sqrt{s}$ = 10 TeV (10 ab$^{-1}$) in events with a single monochromatic photon.

95% CL limits on DP effective coupling to muons



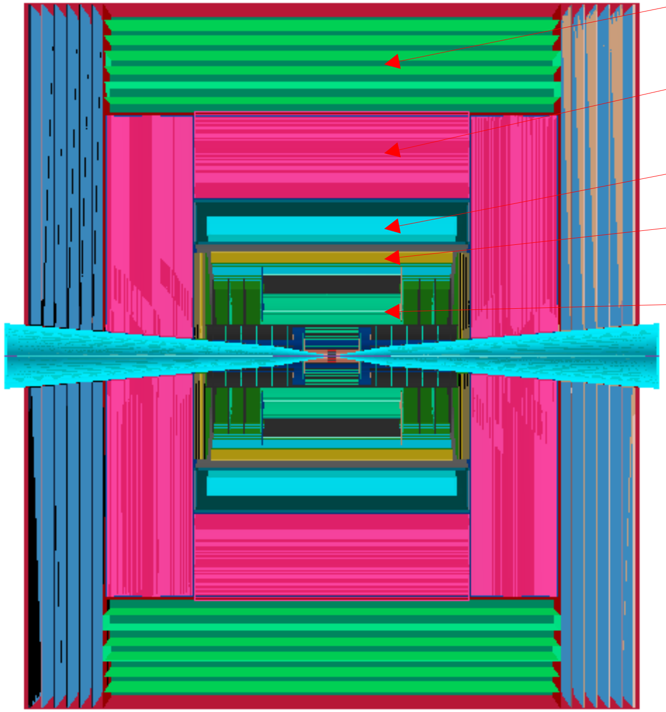

- Search for wino and higgsino dark matter at $\sqrt{s}$ = 3 TeV (1 ab$^{-1}$) and $\sqrt{s}$ = 10 TeV (10 ab$^{-1}$) with the disappearing track signature.

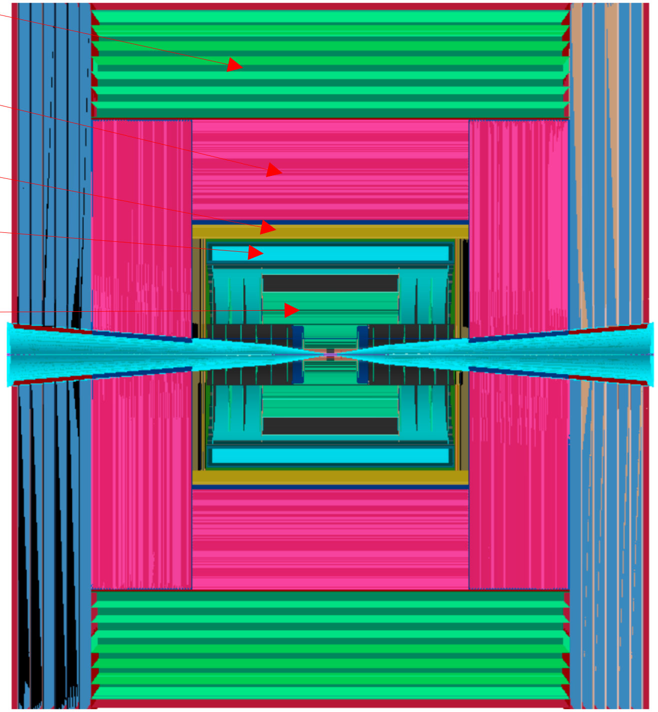
expected sensitivity as a function of chargino m and τ



# Detector concepts for 10 TeV collisions

- Two detector concepts are currently under development with different layouts.
  - key features being optimized: tracker radius, magnetic field intensity, calorimeter depth.



# Summary

- The effects of beam-induced background in the detector have been thoroughly studied with a detailed detector simulation and mitigation measures are in place to keep them under control.

- Full-simulation studies at 3 TeV are concluded and results will be soon published.

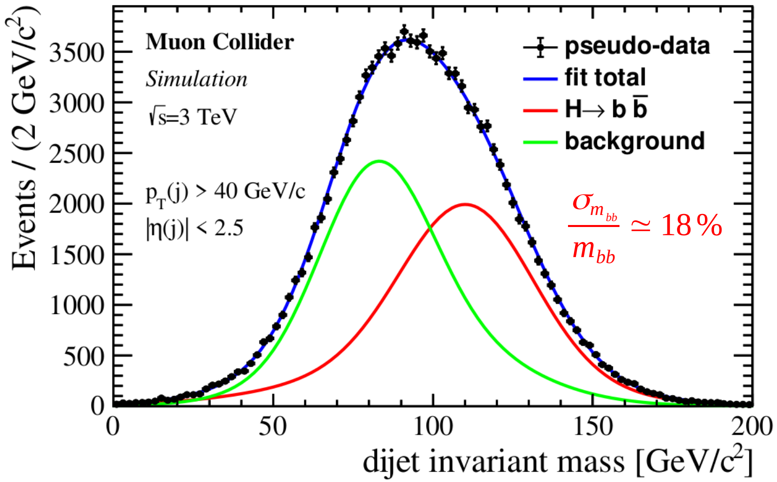
- The full-simulation studies point the way for the detector R&D (some R&D's already well advanced).

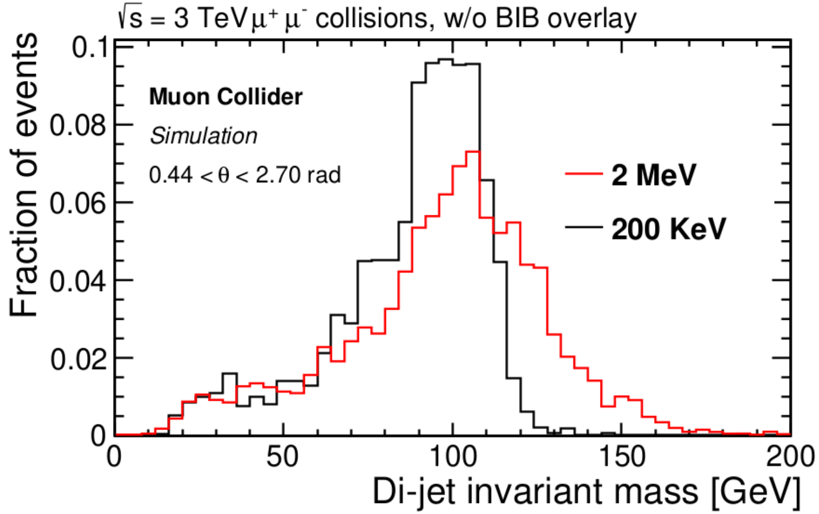
- The goals for the European Strategy update are a detector concept for 10 TeV collisions and the muon collider reach for representative physics cases.

# Backup

# $b\bar{b}$ mass resolution vs hit energy threshold

$\mu\mu \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$




- Hadronic jets are reconstructed using also low-energy objects: the energy threshold of 2 MeV for the calorimeter hits affects the energy resolution.

# Full sim vs parametric sim at 3 TeV

| | Full sim | | Fast sim | |
|---|---|---|---|---|
| Cross sections resolution | H->WW | 2.9% | H->WW | 1.7% |
| | H->ZZ | 17% | H->ZZ | 11% |
| | H->bb | 0.75% | H->bb | 0.76% |
| | H->μμ | 38% | H->μμ | 40% |
| | H->γγ | 8.9% | H->γγ | 6.1% |
| | HH->4b | 30% | | |
| Couplings resolution | $g_{HWW}$ | 0.9% | $g_{HWW}$ | 0.55% |
| | $g_{HZZ}$ | 8.2% | $g_{HZZ}$ | 5.1% |
| | $g_{Hbb}$ | 0.8% | $g_{Hbb}$ | 0.97% |
| | $g_{H\mu\mu}$ | 19% | $g_{H\mu\mu}$ | 20% |
| | $g_{H\gamma\gamma}$ | 4.5% | $g_{H\gamma\gamma}$ | 3.2% |
| | $\lambda_3$ | 20% | $\lambda_3$ (95% CL) | 25% |

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# Higgs boson couplings at future colliders

S. Dawson et al., Report of the Topical Group on Higgs Physics for Snowmass 2021: The Case for Precision Higgs Physics, arXiv:2209.07510

| Higgs Coupling (%) | HL-LHC | ILC250 + HL-LHC | ILC500 +HL-LHC | ILC1000 + HL-LHC | FCC-ee + HL-LHC | CEPC240 + HL-LHC | CEPC360 +HL-LHC | CLIC380 + HL-LHC | CLIC3000 +HL-LHC | $\mu$(10TeV) + HL-LHC | $\mu$125 +HL-LHC | FCC-hh +FCCee/FCCeh |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $hZZ$ | 1.5 | .22 | .17 | .16 | .17 | .074 | .072 | .34 | .22 | .33 | 1.3 | .12 |
| $hWW$ | 1.7 | .98 | .20 | .13 | .41 | .73 | .41 | .62 | 1 | .1 | 1.3 | .14 |
| $hb\bar{b}$ | 3.7 | 1.06 | .50 | .41 | .64 | .73 | .44 | .98 | .36 | .23 | 1.6 | .43 |
| $h\tau^+\tau^-$ | 3.4 | 1.03 | .58 | .48 | .66 | .77 | .49 | 1.26 | .74 | .55 | 1.4 | .44 |
| $hgg.$ | 2.5 | 1.32 | .82 | .59 | .89 | .86 | .61 | 1.36 | .78 | .44 | 1.7 | .49 |
| $hc\bar{c}$ | - | 1.95 | 1.22 | .87 | 1.3 | 1.3 | 1.1 | 3.95 | 1.37 | 1.8 | 12 | .95 |
| $h\gamma\gamma$ | 1.8 | 1.36 | 1.22 | 1.07 | 1.3 | 1.68 | 1.5 | 1.37 | 1.13 | .71 | 1.6 | .29 |
| $h\gamma Z$ | 9.8 | 10.2 | 10.2 | 10.2 | 10 | 4.28 | 4.17 | 10.26 | 5.67 | 5.5 | 9.8 | .69 |
| $h\mu^+\mu^-$ | 4.3 | 4.14 | 3.9 | 3.53 | 3.9 | 3.3 | 3.2 | 4.36 | 3.47 | 2.5 | .6 | .41 |
| $ht\bar{t}$ | 3.4 | 3.12 | 2.82 | 1.4 | 3.1 | 3.1 | 3.1 | 3.14 | 2.01 | 3.2 | 3.4 | 1.0 |
| $\Gamma_{tot}$ | 5.3 | 1.8 | .63 | .45 | 1.1 | 1.65 | 1.1 | 1.44 | .41 | .5 | 2.7 | |

# Higgs self-coupling $\lambda_3$ at future colliders

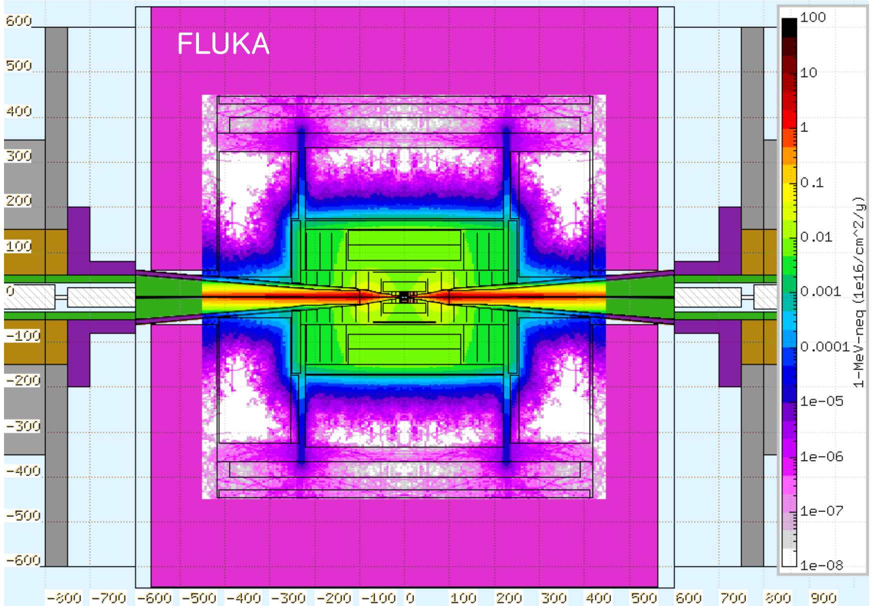
S. Dawson et al., Report of the Topical Group on Higgs Physics for Snowmass 2021: The Case for Precision Higgs Physics, arXiv:2209.07510

| collider | Indirect-$h$ | $hh$ | combined |
|---|---|---|---|
| HL-LHC [78] | 100-200% | 50% | 50% |
| $\text{ILC}_{250}/\text{C}^3$-250 [51, 52] | 49% | — | 49% |
| $\text{ILC}_{500}/\text{C}^3$-550 [51, 52] | 38% | 20% | 20% |
| $\text{CLIC}_{380}$ [54] | 50% | — | 50% |
| $\text{CLIC}_{1500}$ [54] | 49% | 36% | 29% |
| $\text{CLIC}_{3000}$ [54] | 49% | 9% | 9% |
| FCC-ee [55] | 33% | — | 33% |
| FCC-ee (4 IPs) [55] | 24% | — | 24% |
| FCC-hh [79] | - | 3.4-7.8% | 3.4-7.8% |
| $\mu$(3 TeV) [64] | - | 15-30% | 15-30% |
| $\mu$(10 TeV) [64] | - | 4% | 4% |

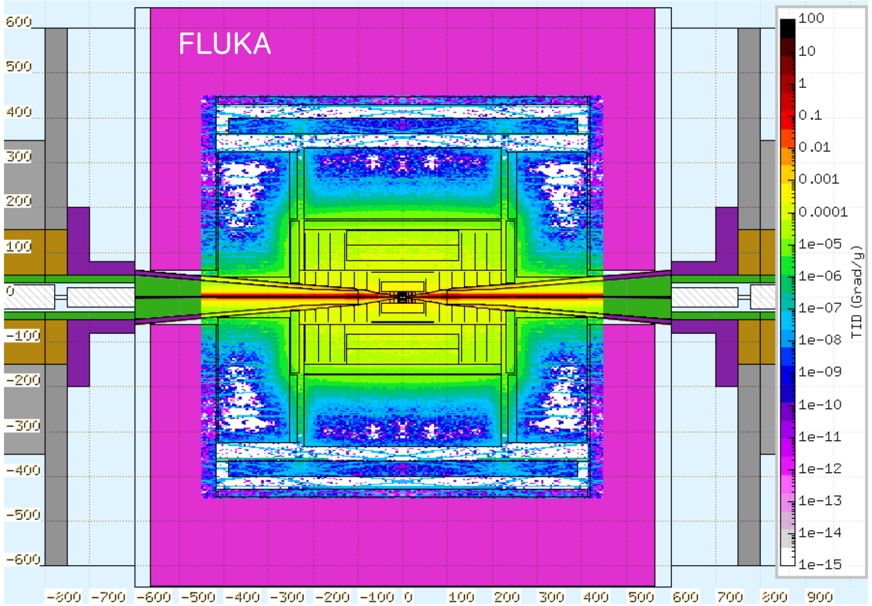
# Radiation environment

C. Accettura et al., Eur. Phys. J. C 83 (2023) 864

1-MeV neutron equivalent fluence per year




total ionizing dose per year




Assumptions:

- collision energy: 1.5 TeV;
- collider circumference: 2.5 km;
- beam injection frequency: 5 Hz;
- days of operation per year: 200.

| | Maximum Dose (Mrad) | | Maximum Fluence (1 MeV-neq/cm$^2$) | |
|---|---|---|---|---|
| | R= 22 mm | R= 1500 mm | R= 22 mm | R= 1500 mm |
| Muon Collider | 10 | 0.1 | $10^{15}$ | $10^{14}$ |
| HL-LHC | 100 | 0.1 | $10^{15}$ | $10^{13}$ |

Radiation hardness requirements are similar to what expected at HL-LHC.