



Detector performance and physics reach at a muon collider

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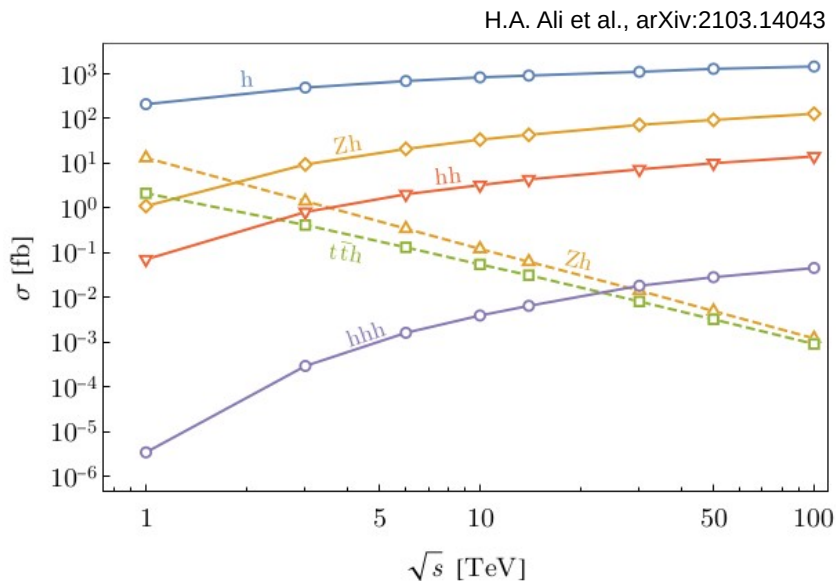
for the International Muon Collider Collaboration

*30th International Symposium on Lepton Photon Interactions at High Energies
Online Event @ The University of Manchester, UK
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- Advantages and Physics potential of a multi-TeV muon collider.
- Technological and experimental challenges of colliding muons:
 - ▶ the beam induced background in the detector.
- Overview of preliminary detector performance studies and physics results.
- Summary.

Advantages of muon collisions

- A muon collider can push the advantages of leptonic collisions into the multi-TeV energy range, thanks to synchrotron radiation losses smaller by a factor of $(m_\mu/m_e)^4$ w.r.t. to circular electron-positron colliders:
 - ▶ the full energy carried by the colliding particles is available in the hard-scattering process;
 - ▶ leptonic collisions produce cleaner final states.
- Moreover:
 - ▶ no significant beam-strahlung effects like in electron-positron linear colliders: a beam energy spread $dE/E < 10^{-3}$ is expected for $\sqrt{s} = 3$ to 14 TeV;
 - ▶ at the highest collision energies, a muon collider is the most power-efficient machine, i.e. it's the cheapest to operate;
 - ▶ a muon collider is a compact circular collider, the accelerator facility features a relatively small footprint, i.e. with a reduced environmental impact.
- The new International Muon Collider Collaboration is focusing on the baseline designs of a 3 TeV and a 10+ TeV machine with instantaneous luminosities of about $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and $4 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$, respectively.



J. de Blas et al., arXiv:1905.03764

κ_{-0} fit	HL-LHC	LHeC	HE-LHC S2 S2'	ILC 250 500 1000	CLIC 380 1500 3000	CEPC	FCC-ee 240 365	FCC-ee/ eh/hh	$\mu^+\mu^-$ 10000
κ_W [%]	1.7	0.75	1.4 0.98	1.8 0.29 0.24	0.86 0.16 0.11	1.3	1.3 0.43	0.14	0.06
κ_Z [%]	1.5	1.2	1.3 0.9	0.29 0.23 0.22	0.5 0.26 0.23	0.14	0.20 0.17	0.12	0.23
κ_g [%]	2.3	3.6	1.9 1.2	2.3 0.97 0.66	2.5 1.3 0.9	1.5	1.7 1.0	0.49	0.15
κ_γ [%]	1.9	7.6	1.6 1.2	6.7 3.4 1.9	98* 5.0 2.2	3.7	4.7 3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	—	5.7 3.8	99* 86* 85*	120* 15 6.9	8.2	81* 75*	0.69	1.0
κ_c [%]	—	4.1	— —	2.5 1.3 0.9	4.3 1.8 1.4	2.2	1.8 1.3	0.95	0.89
κ_t [%]	3.3	—	2.8 1.7	— 6.9 1.6	— — 2.7	—	— —	1.0	6.0
κ_b [%]	3.6	2.1	3.2 2.3	1.8 0.58 0.48	1.9 0.46 0.37	1.2	1.3 0.67	0.43	0.16
κ_μ [%]	4.6	—	2.5 1.7	15 9.4 6.2	320* 13 5.8	8.9	10 8.9	0.41	2.0
κ_τ [%]	1.9	3.3	1.5 1.1	1.9 0.70 0.57	3.0 1.3 0.88	1.3	1.4 0.73	0.44	0.31

$$\kappa_i = \frac{g_i}{g_i^{SM}}$$

H.A. Ali et al.,
arXiv:2103.14043

- Leptonic collisions at \sqrt{s} energies of several TeV would enable a novel unprecedented physics program:

- ▶ precise measurements in the Higgs sector:
 - ◆ Higgs couplings to fermions and bosons;
 - ◆ trilinear and quartic H self-couplings (λ_3, λ_4)

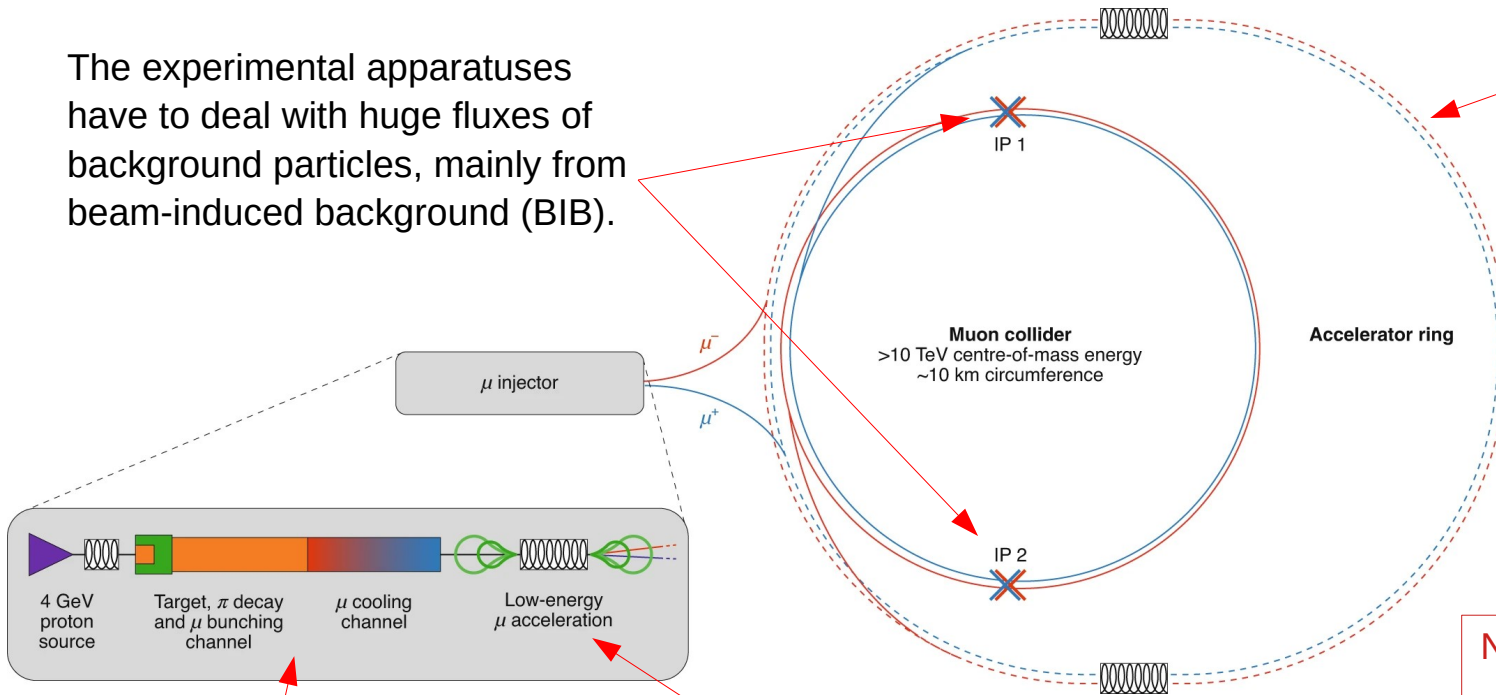
→ determination of the Higgs potential:

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

- ▶ high-precision measurements of known Standard Model processes in a yet unexplored multi-TeV energy range;
- ▶ direct and indirect searches for new phenomena beyond the Standard Model.

- The muon collider complex has to produce, accelerate and collide bright beams of short-lived particles ($\tau_\mu = 2.2 \mu\text{s}$).

The experimental apparatuses have to deal with huge fluxes of background particles, mainly from beam-induced background (BIB).



High levels of machine background: all machine elements need to be properly shielded (a 750-GeV beam with 2×10^{12} μ /bunch is expected to radiate on average 0.5 kW/m).

Neutrino-induced radiation

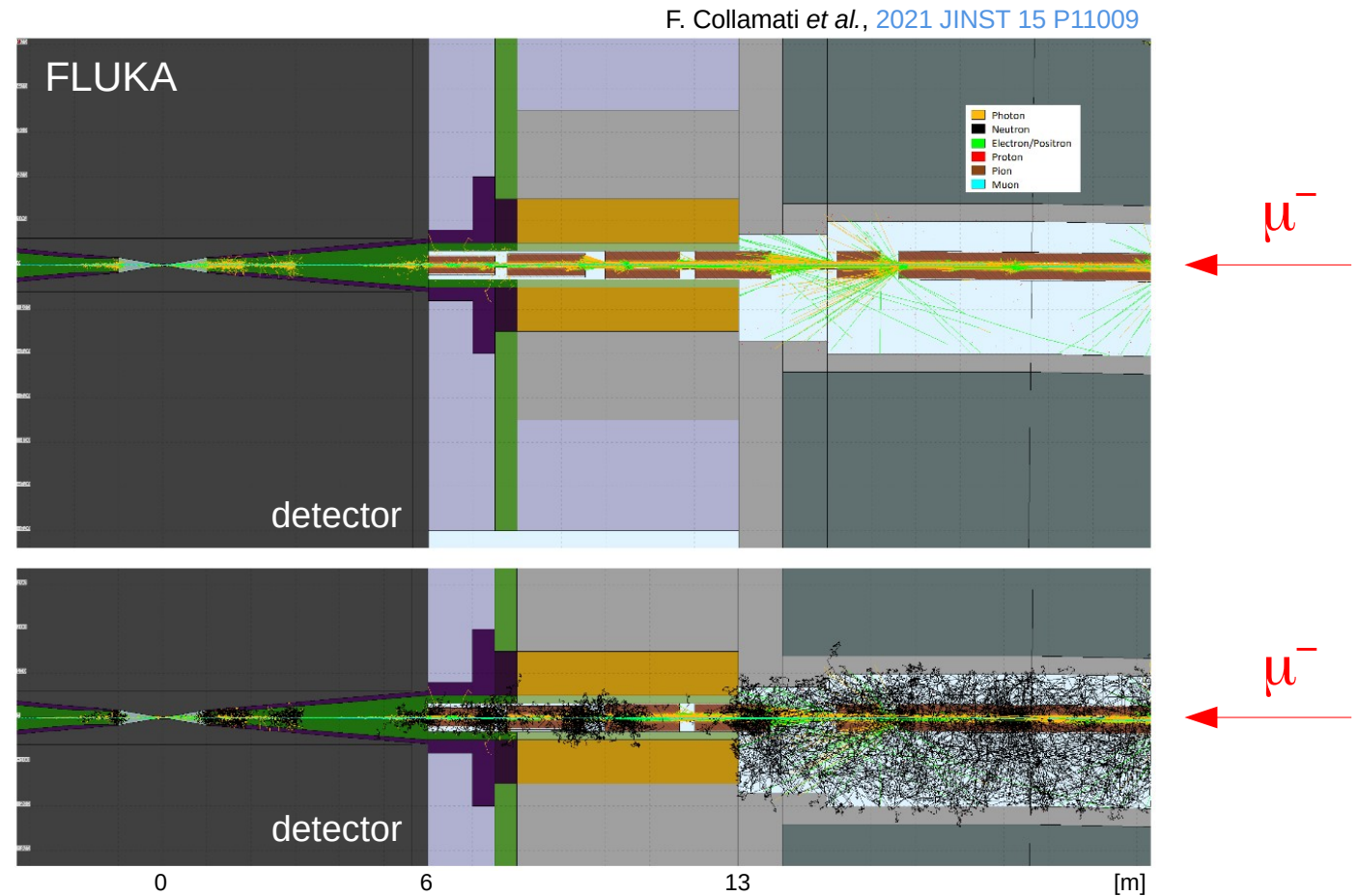
Intense and highly collimated neutrino beams, emerging at the earth surface even very far from the muon collider complex, may be responsible for a severe ionization radiation hazard for the population and the environment.

The muon beam production and “cooling”, i.e. the reduction of the initial transverse phase-space volume by more than $O(10^5)$, represent the crucial stage of the facility.

Muon beams must be prepared and accelerated as quick as possible to exploit the relativistic time dilation in the lab system (for a 5 TeV beam $t_\mu = 105$ ms in the lab).

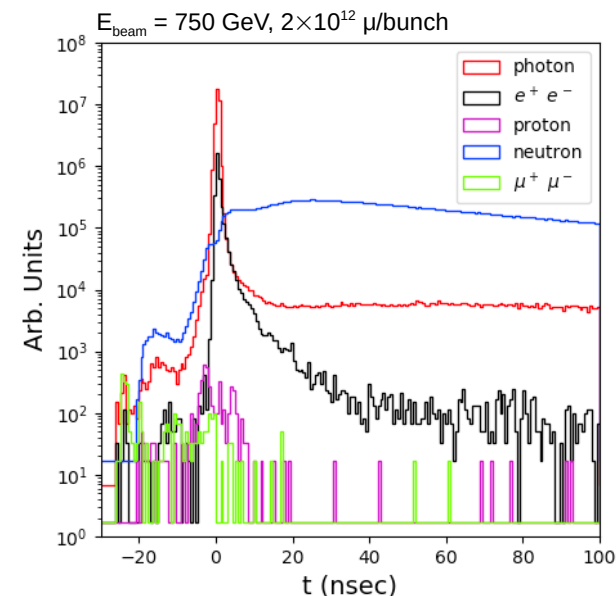
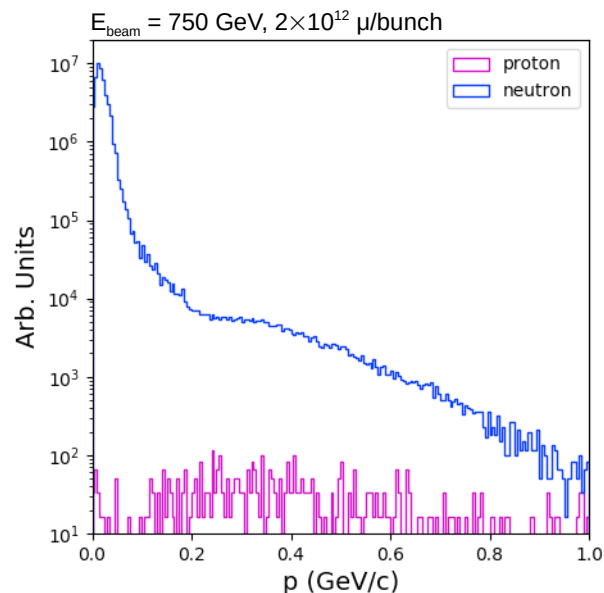
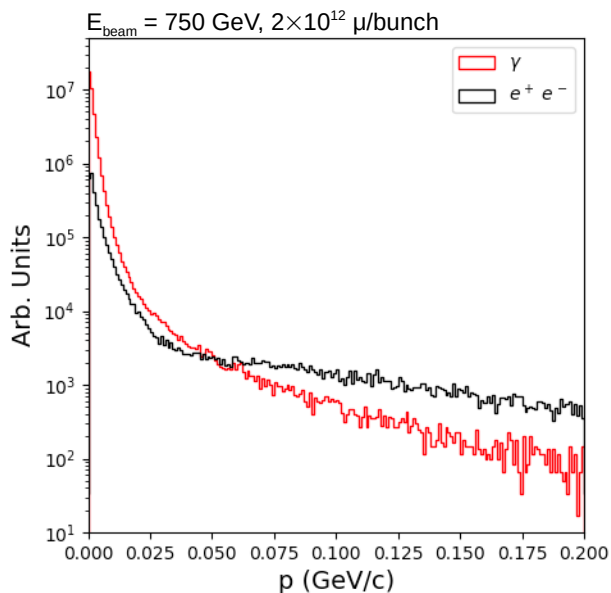
The beam-induced background

- The particles generated in the interactions of the decay products of the circulating muons with the machine elements represent the dominant contribution to the machine background in the detector.



BIB in the detector

- Available BIB FLUKA samples for machines operating at $\sqrt{s} = 1.5$ and 3 TeV, 10 TeV machine currently under study.
- For $\sqrt{s} = 1.5$ TeV, $O(10^8)$ BIB particles enter the detector at every bunch crossing ($f_{BX} \sim 100$ kHz):
 - ▶ mostly photons ($\sim 10^7$), neutrons ($\sim 10^7$), electrons/positrons ($\sim 10^6$), charged hadrons ($\sim 10^4$), muons ($\sim 10^3$);
 - ▶ soft momentum spectra: $\langle p_\gamma \rangle \sim 2$ MeV, $\langle p_e \rangle \sim 6$ MeV,
 $\langle p_{n,p} \rangle \sim 500$ MeV, $\langle p_\mu \rangle \sim$ tens of GeV;
 - ▶ asynchronous time of arrival to the detector w.r.t. the bunch crossing.



hadronic calorimeter

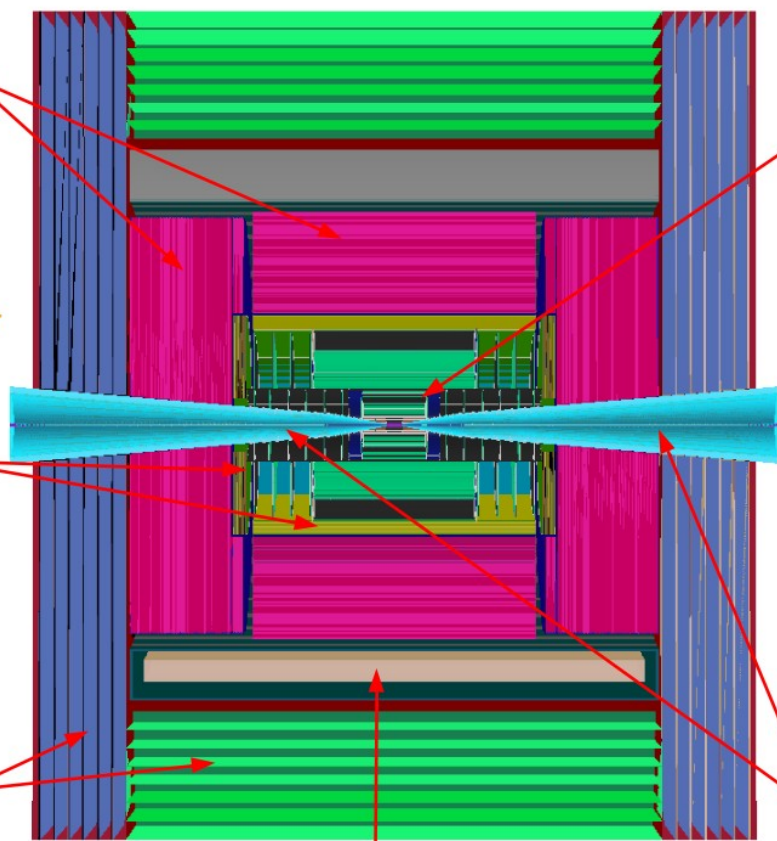
- ◆ 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- ◆ 30x30 mm² cell size;
- ◆ 7.5 λ_I .

electromagnetic calorimeter

- ◆ 40 layers of 1.9-mm W absorber + silicon pad sensors;
- ◆ 5x5 mm² cell granularity;
- ◆ 22 X_0 + 1 λ_I .

muon detectors

- ◆ 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- ◆ 30x30 mm² cell size.



superconducting solenoid (3.57T)

tracking system

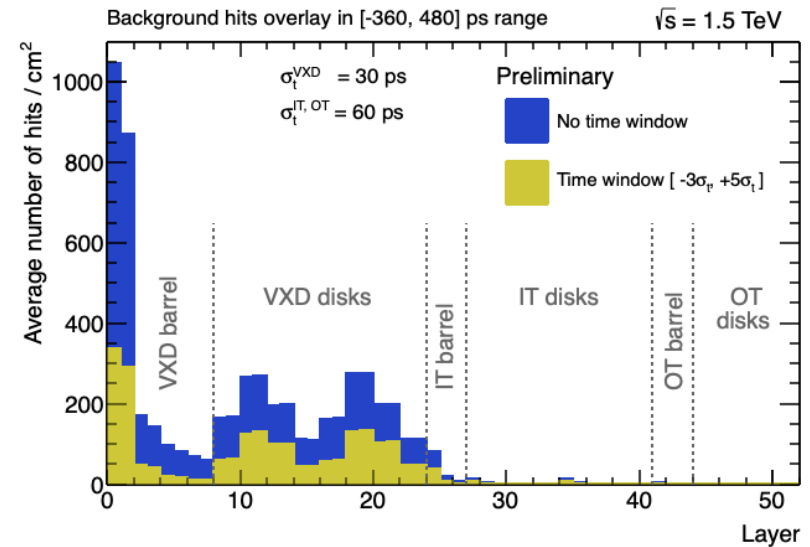
- ◆ **Vertex Detector:**
 - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
 - 25x25 μm^2 pixel Si sensors.
- ◆ **Inner Tracker:**
 - 3 barrel layers and 7+7 endcap disks;
 - 50 μm x 1 mm macro-pixel Si sensors.
- ◆ **Outer Tracker:**
 - 3 barrel layers and 4+4 endcap disks;
 - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

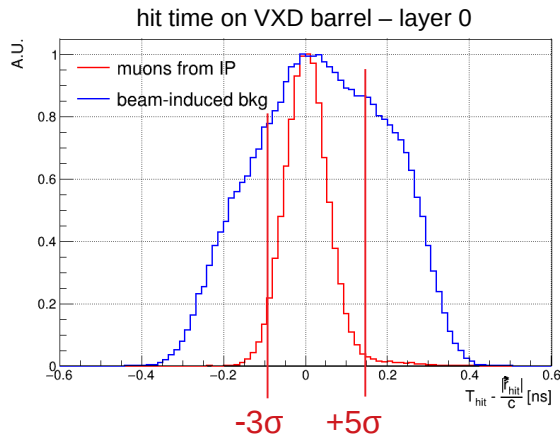
- ◆ Tungsten cones + borated polyethylene cladding.

● Based on CLIC's concept + the MDI and vertex detector designed by the US Muon Accelerator Program.

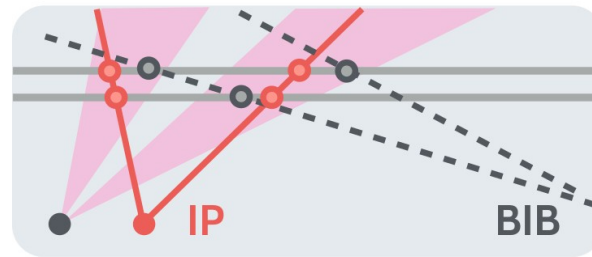
- The closest detector to the beamline and the most affected by BIB:
 - ▶ a huge amount of spurious hits is produced that make the detector operation and track finding very difficult.
- Most powerful handles to filter the spurious hits upstream and mitigate the BIB effects:



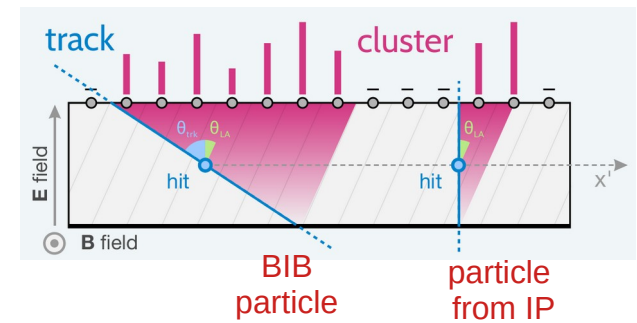
high precision timing



incoming direction of the particle



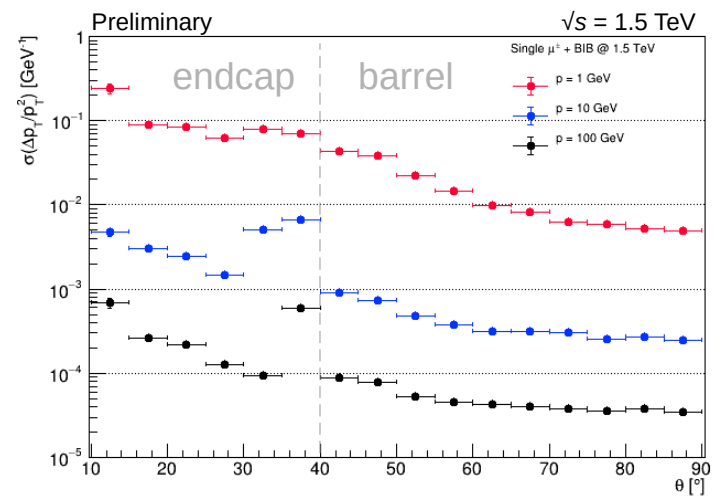
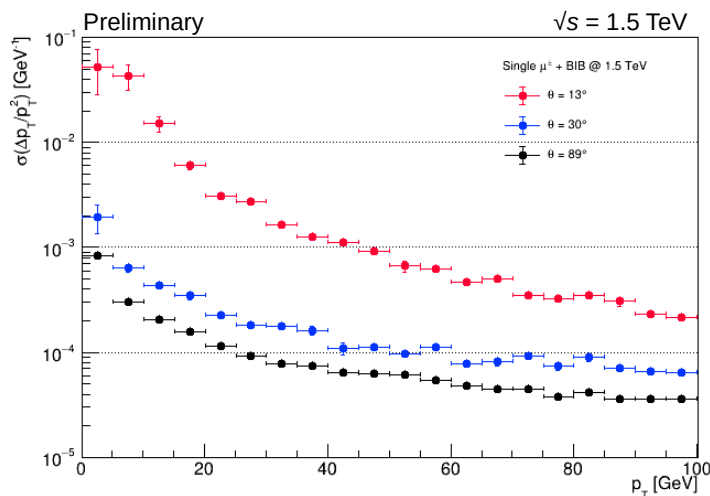
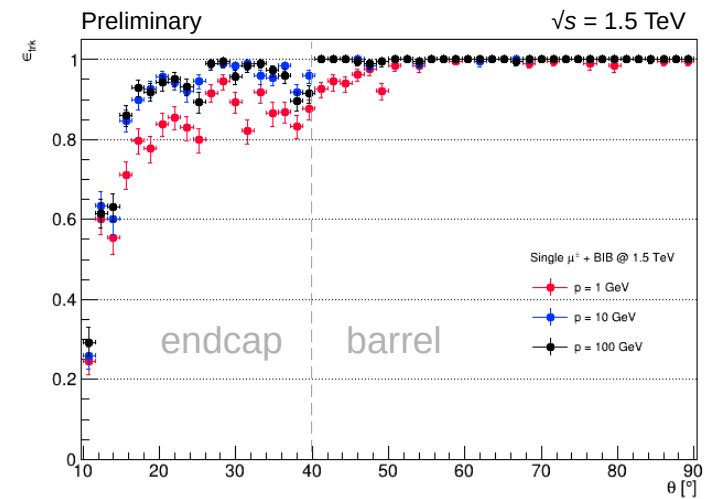
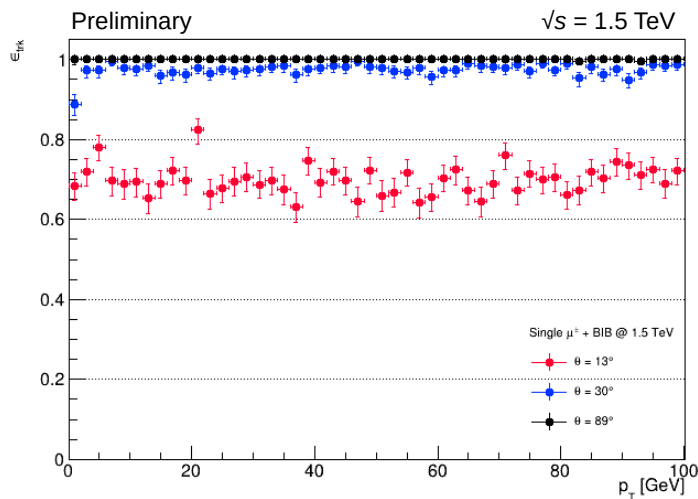
shape of pixel clusters



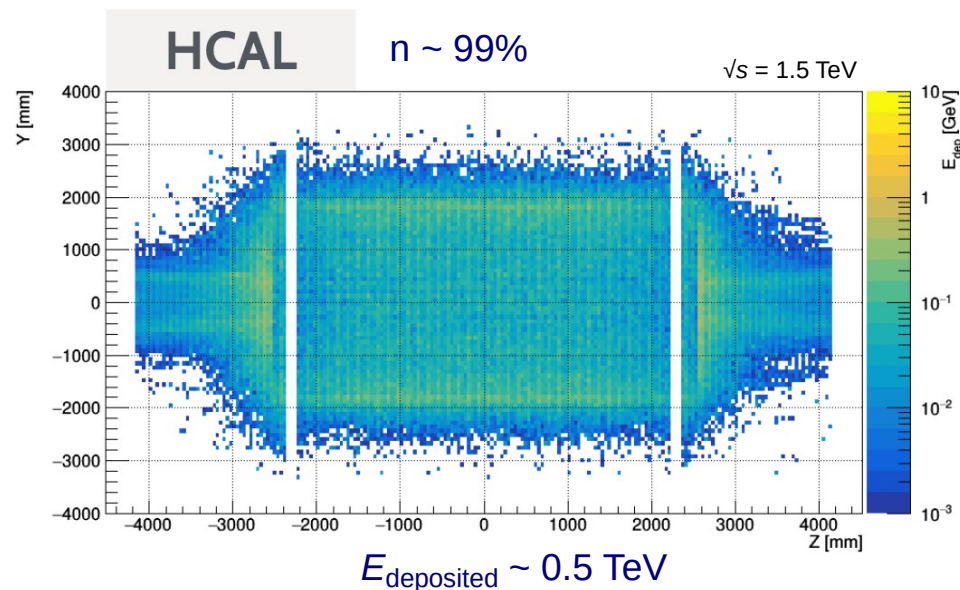
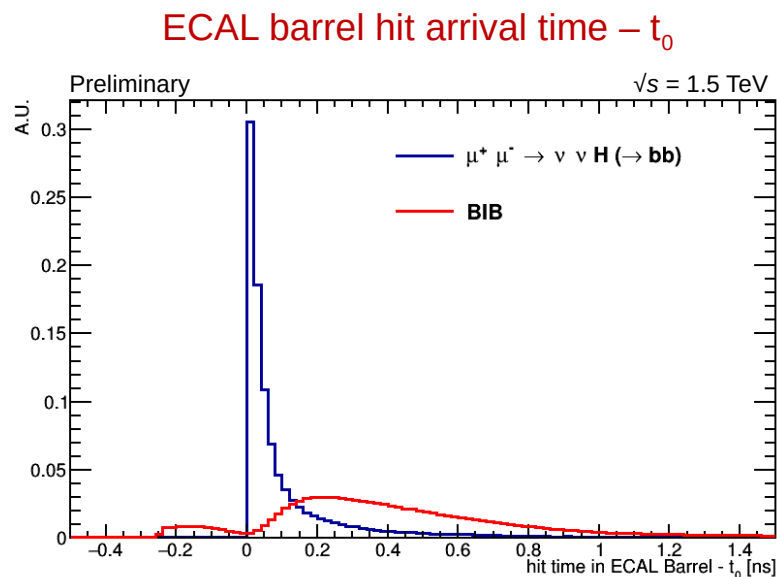
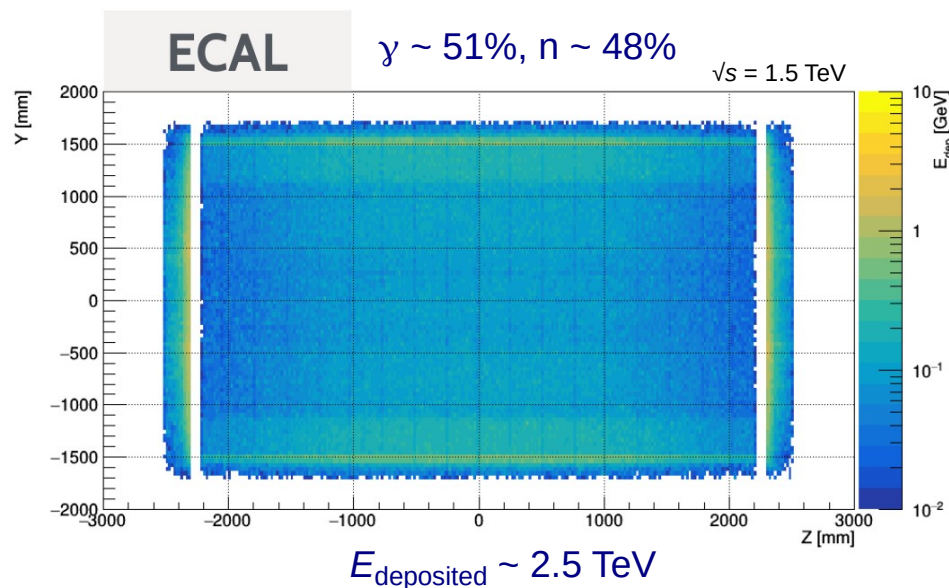
■ N. Bartosik, "The challenge of track reconstruction at a multi-TeV muon collider" in Future Experiments and Facilities: Poster Session.

- Single muons + BIB @ 1.5 TeV:

- ▶ tracks reconstructed with hits in a region-of-interest (ROI) cone around the muon direction.

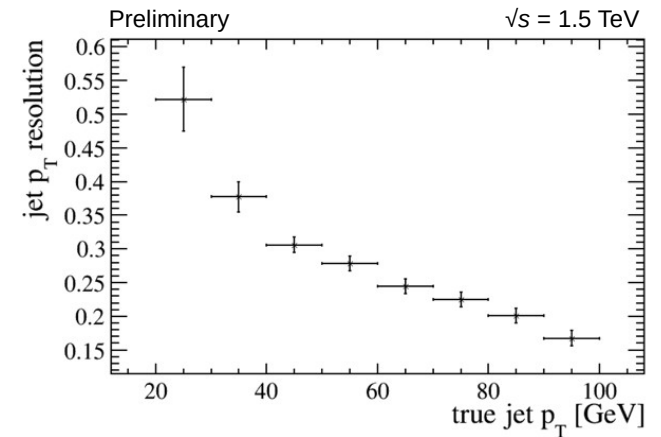
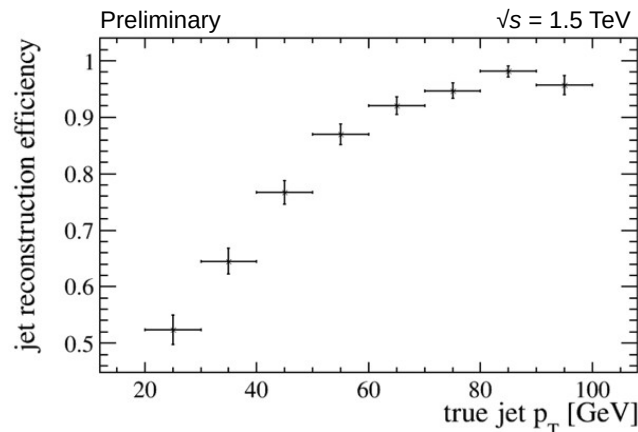


- Energy deposited by BIB (mostly photons and neutrons) in the electromagnetic and hadronic calorimeters is \sim uniformly distributed.
- Timing, very high granularity, fine longitudinal segmentation and state-of-the-art background-subtraction and Particle Flow algorithms needed to cope with BIB.

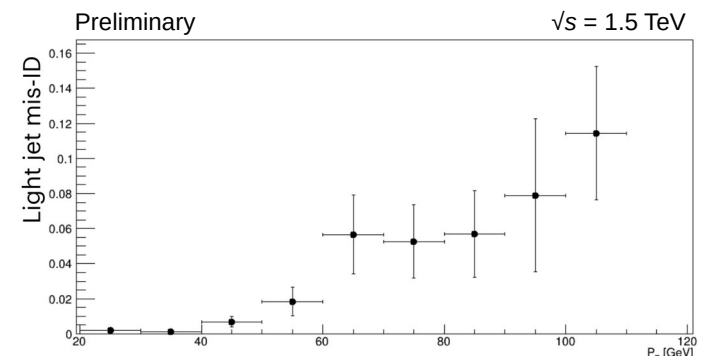
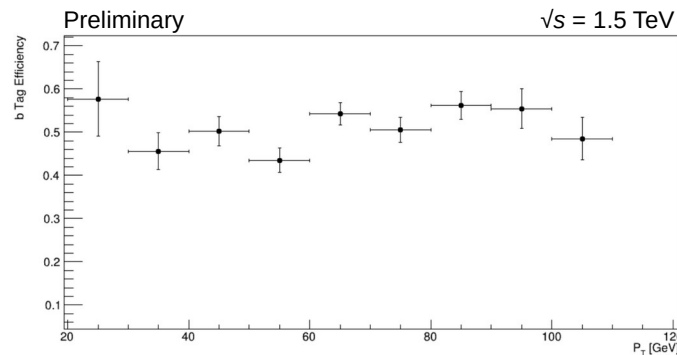


Jet reconstruction performance

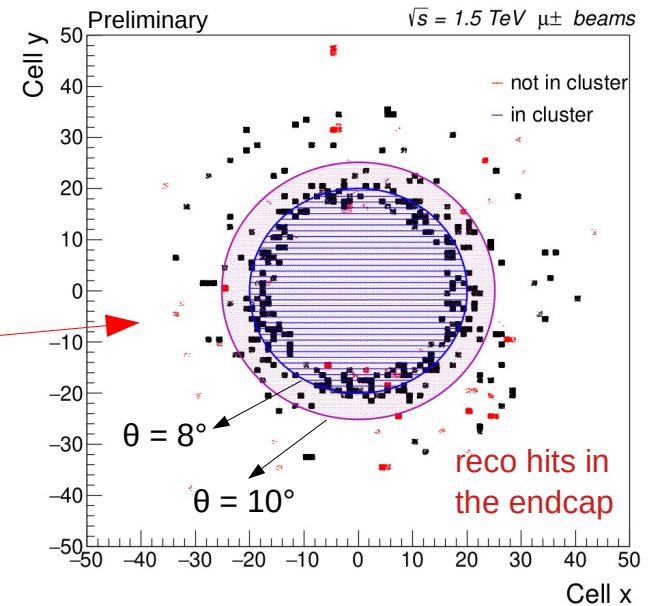
- $b\bar{b}$ -dijet events + BIB @ 1.5 TeV:
 - ▶ average BIB energy subtracted in ECAL barrel like for underlying events;
 - ▶ ROI tracking around jet direction (estimated with calorimeter info only);
 - ▶ full jet reconstruction (k_t algorithm with $R = 0.5$).



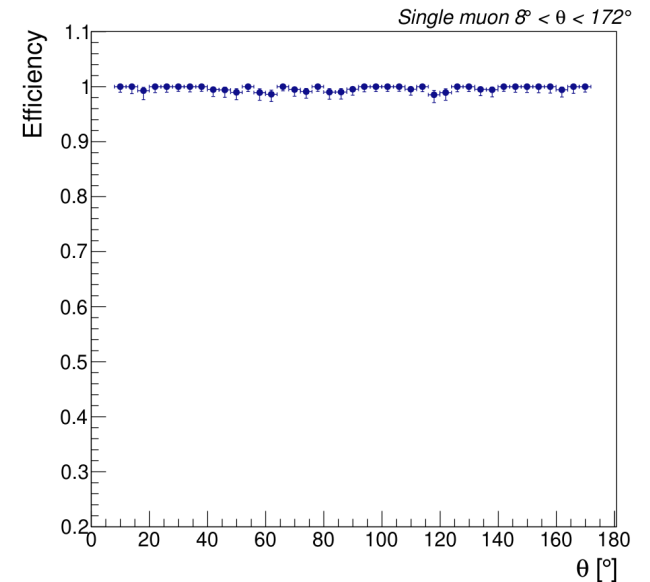
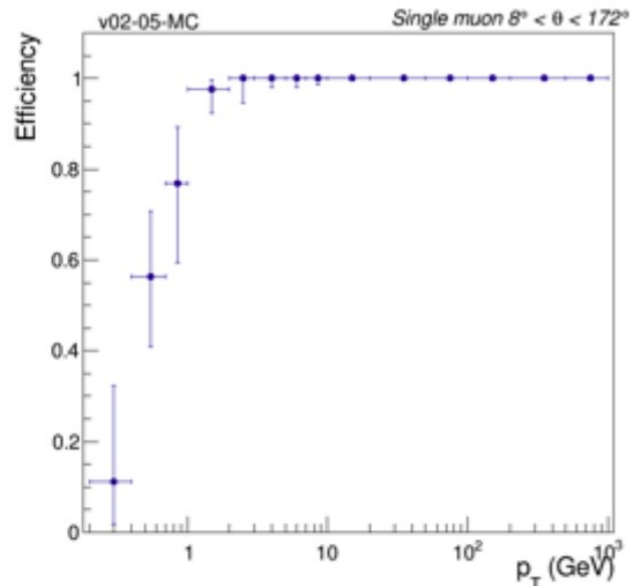
- B-tagging based on identification of secondary vertices inside the jet cones (to be optimized).



- The muon detectors, installed in the outermost region of the detector, are only marginally affected by the beam-induced background.
- Bigger effects in the endcap regions closer to the beamline.



reconstruction efficiency for single muons



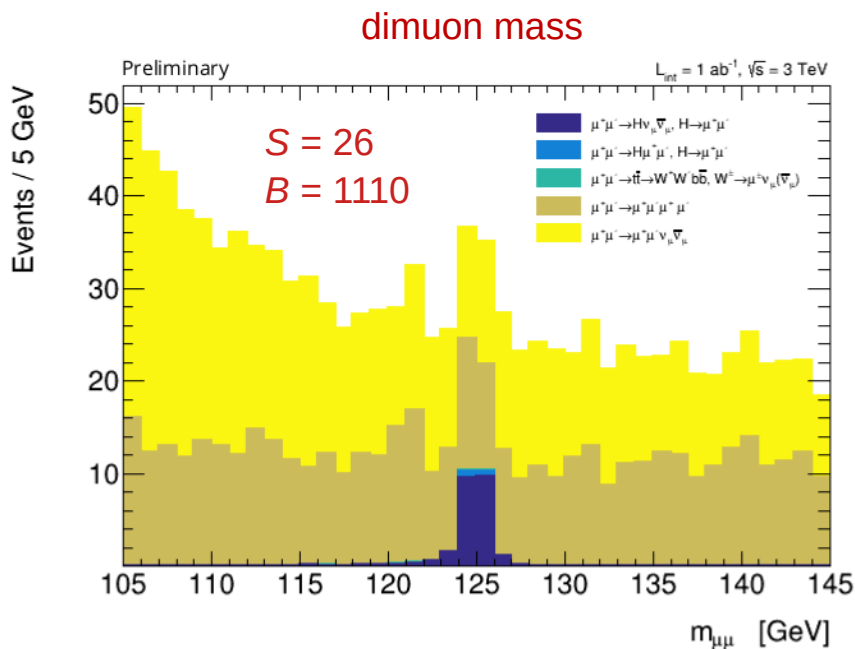
■ C. Aimè, "Reconstructing muons at a Muon Collider" in Future Experiments and Facilities: Poster Session.

- Extensive campaign of studies underway to assess the muon collider reach in the Higgs sector. The preliminary results focus on a 3 TeV machine:

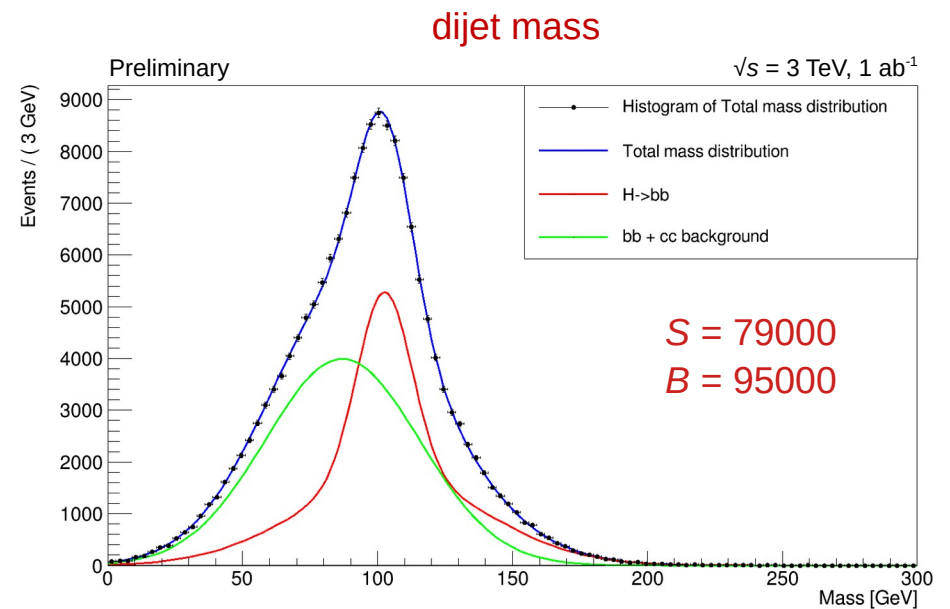
- ▶ Higgs couplings to fermions and vector bosons:

$$H \rightarrow b\bar{b}, c\bar{c}, ZZ, W^+W^-, \mu^+\mu^-;$$

- ▶ determination of the Higgs trilinear self-coupling from $HH \rightarrow b\bar{b}b\bar{b}$.



$$\frac{\Delta \sigma_{H \rightarrow \mu\mu}}{\sigma_{H \rightarrow \mu\mu}} \sim 38\%$$



$$\frac{\Delta \sigma_{H \rightarrow bb}}{\sigma_{H \rightarrow bb}} \sim 0.8\%$$

■ A. Montella, "H → μμ at a 3-TeV muon collider" in Future Experiments and Facilities: Poster Session.

Trilinear Higgs self-coupling

● $HH \rightarrow b\bar{b}b\bar{b}$ @ 3 TeV ($L_{\text{int}} = 1.3 \text{ ab}^{-1}$):

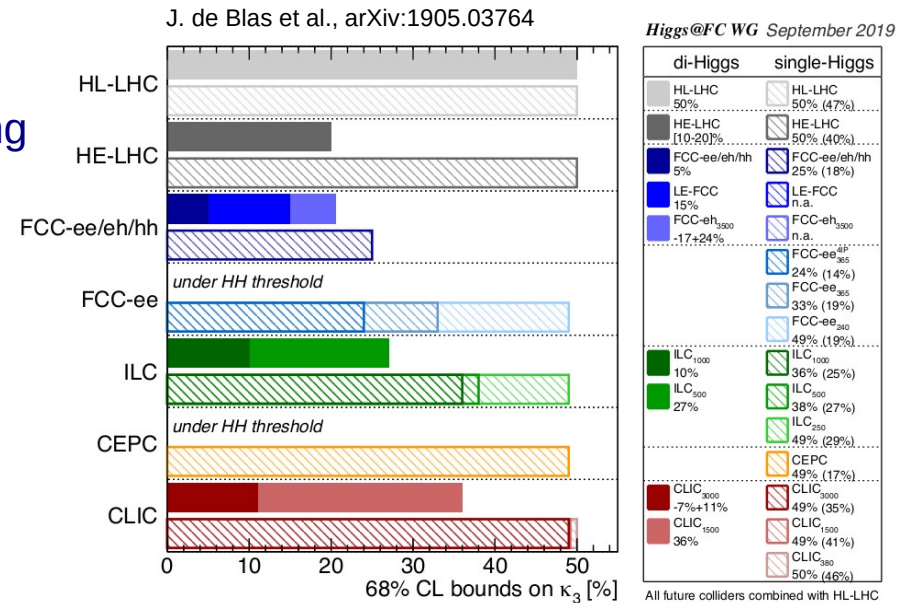
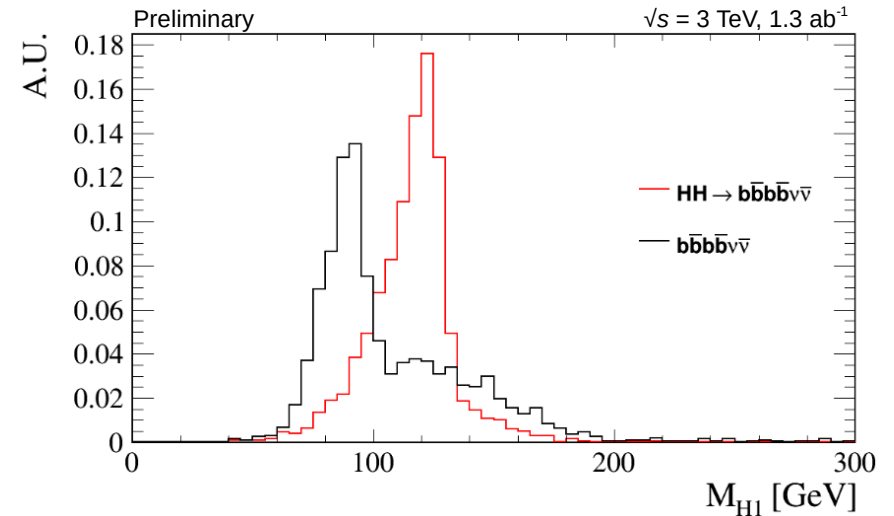
- ▶ H candidates built pairing b jets;
- ▶ b -tagging efficiency estimated with BIB and used to weight events;
- ▶ BDT to separate signal and bkg events ($S = 65, B = 560$)
- ➔ cross-section sensitivity:

$$\frac{\Delta \sigma_H}{\sigma_H} \sim 30\%$$

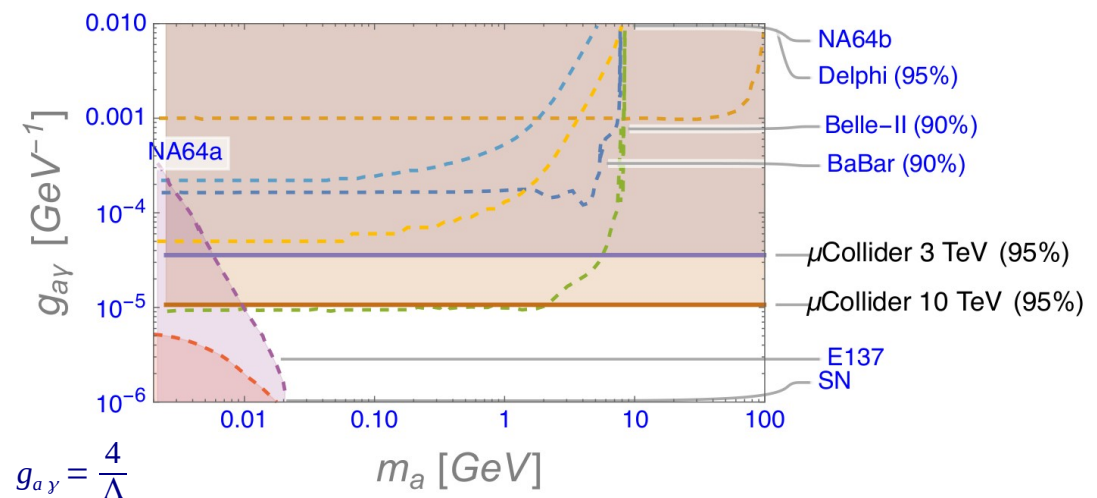
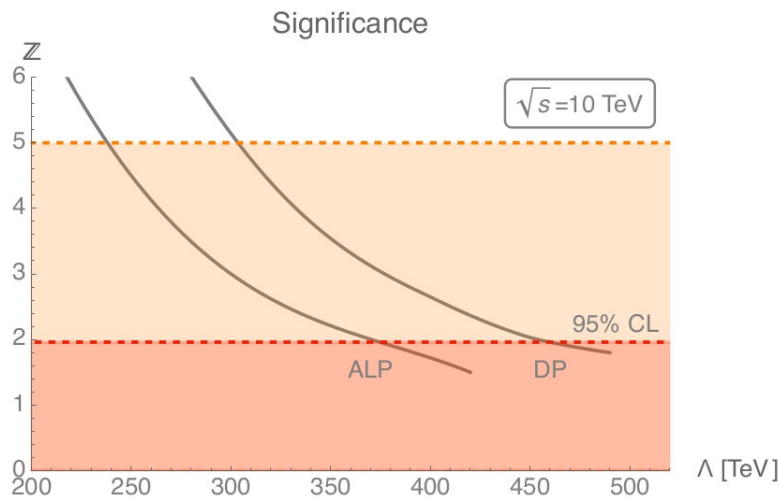
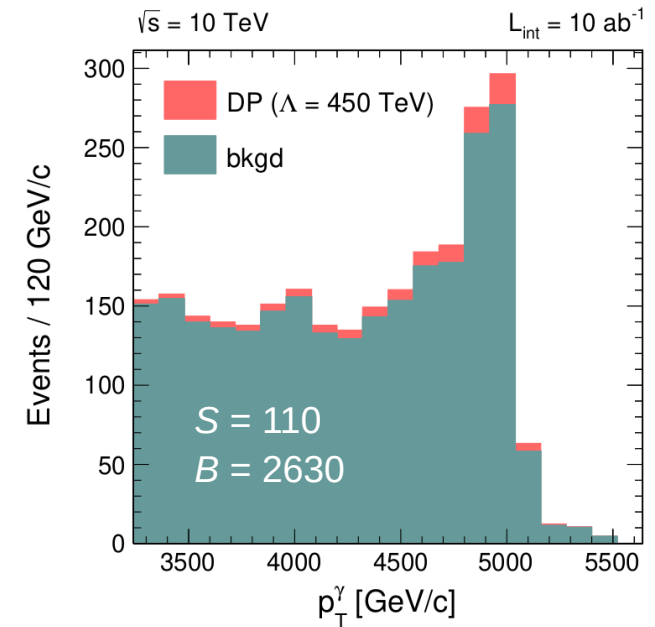
- ▶ first preliminary estimate of sensitivity to the trilinear Higgs self-coupling, disentangling the trilinear contribution from all elementary processes contributing to the channel HH :

$$\frac{\Delta(\lambda_3/\lambda_3^{SM})}{\lambda_3/\lambda_3^{SM}} \sim 20\%$$

leading Higgs candidate



- Search for the associated production of a dark photon (*DP*) or an axion-like particle (*ALP*) with a photon at $\sqrt{s} = 3 \text{ TeV}$ (1 ab^{-1}) and $\sqrt{s} = 10 \text{ TeV}$ (10 ab^{-1});
 - ▶ at high energies the production cross sections depend on a single effective energy scale: $\sigma \propto 1/\Lambda^2$;
 - ▶ *DP* and *ALP* assumed not-detectable
 - ➔ experimental signature is a single monochromatic photon;
 - ▶ BIB effects not included.



Summary

- A multi-TeV muon collider represents a unique machine, which can give access to an unexplored energy regime of leptonic collisions and enable an extraordinary and novel physical program.
- The exploitation of the full muon collider potential will crucially rely on the capacity of the experiments to tame the beam-induced background. Preliminary full-simulation studies prove that this is attainable.
- An extensive campaign of studies is underway to assess both the detector requirements and performance and the physics reach of a 3 TeV and a 10 TeV muon collider.