Prospects of a future multi-TeV muon collider

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Outline

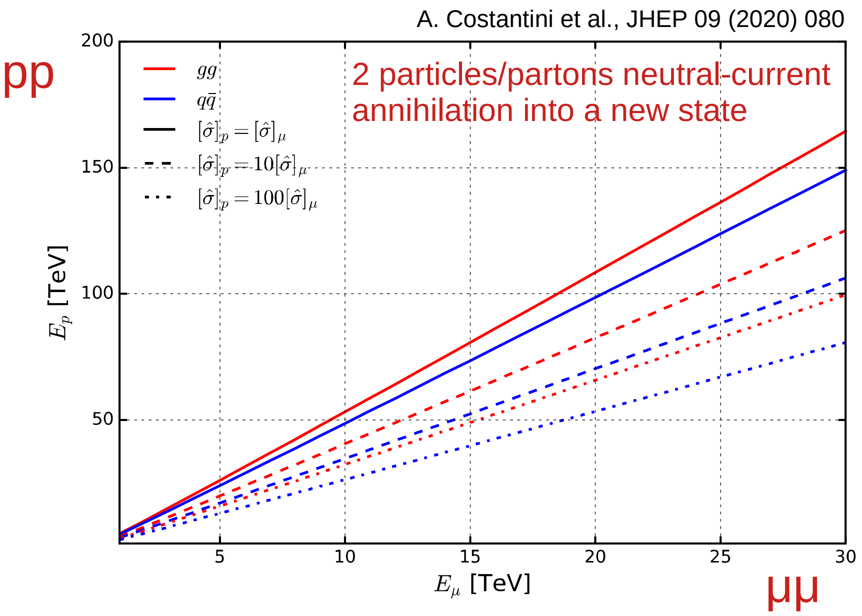
- Muon collider potential and advantages.
- Experimental and technological challenges.
- Beam-induced background.
- Full simulation studies.
- Conclusions.

Muon collider potential

An ideal machine

- A muon collider has the capability to push the leptonic collisions into the multi-TeV energy range: synchrotron radiation effects are smaller by a factor of about $(m_\mu/m_e)^4$ w.r.t. to electron-positron colliders.

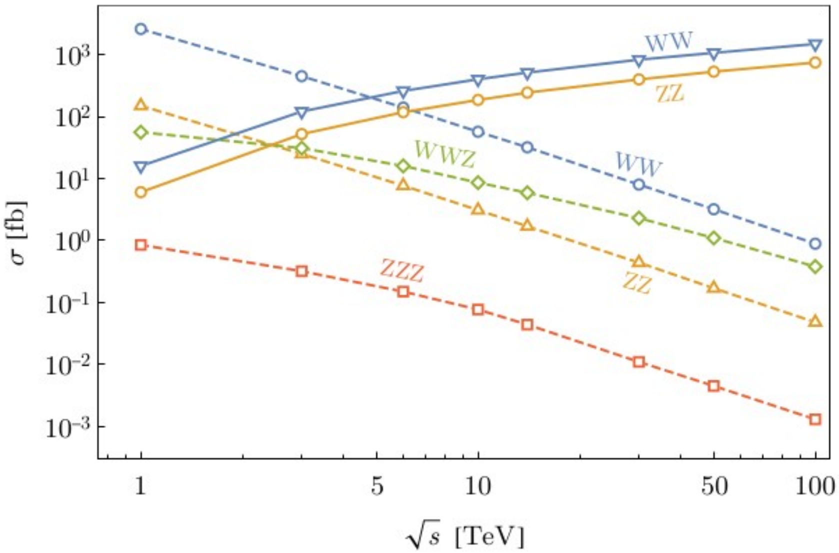
- As a fundamental particle, the muon's full energy is available in the hard-scattering process, with cleaner final states w.r.t. hadronic collisions:

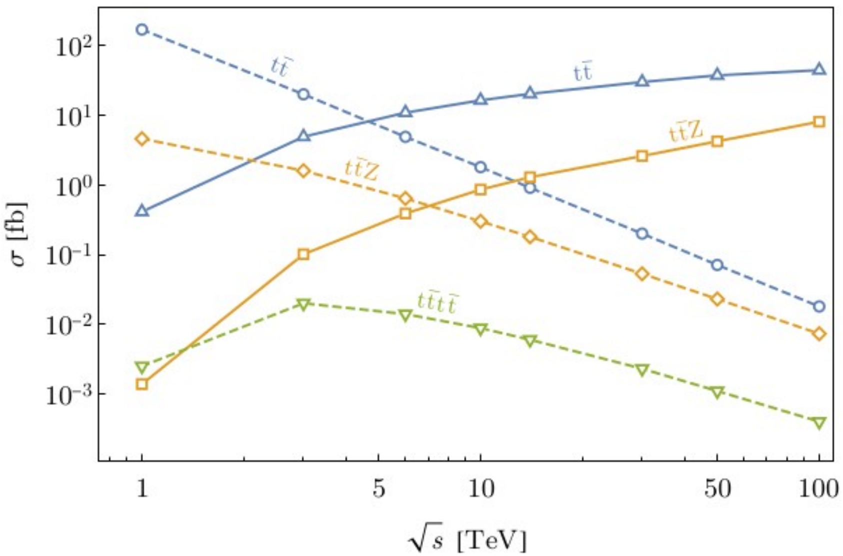


- This would open the way to an unprecedented and vast Physics program.

Standard Model

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





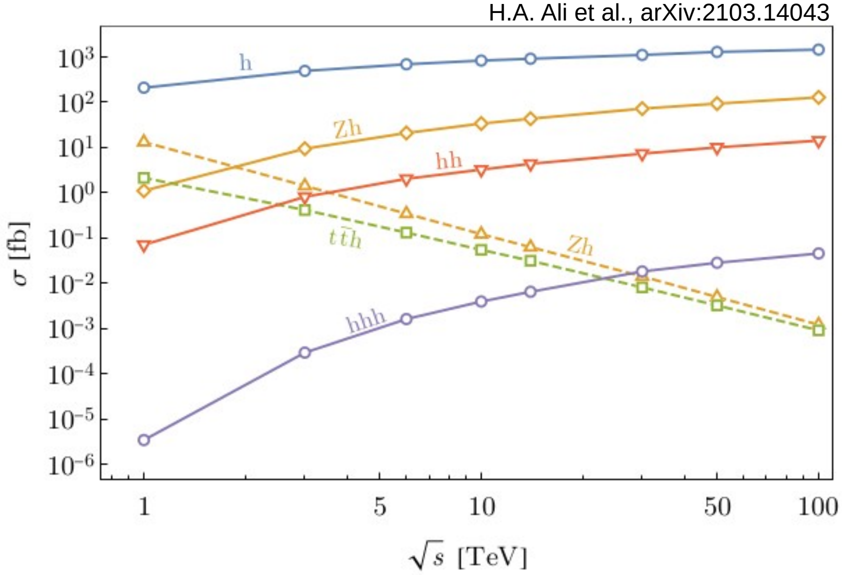
- High-precision measurements of known Standard Model processes in an unexplored multi-TeV energy regime.

20 ab^{-1} @ 14 TeV

process	expected yield [$\times 10^3$]
WW	11240
ZZ	5240
WWZ	1130
ZZZ	240
tt	440
ttZ	30

Higgs sector

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

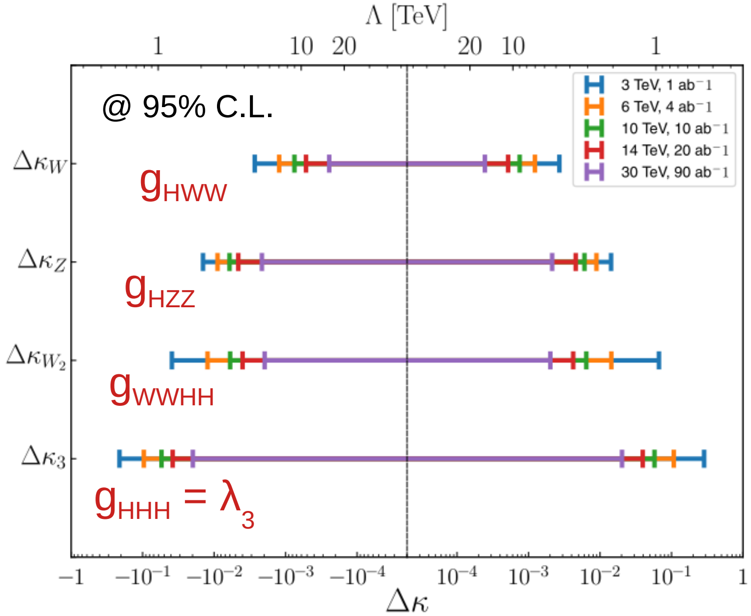


20 ab^{-1} @ 14 TeV

process	expected yield [× 10³]
H	18800
ZH	900
HH	88
ttH	3
HHH	0.14

- Precise measurements in the Higgs sector:
  - H couplings to fermions and bosons;
  - trilinear and quartic H self-couplings (λ_3, λ_4)
    ➔ determination of the Higgs potential:

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



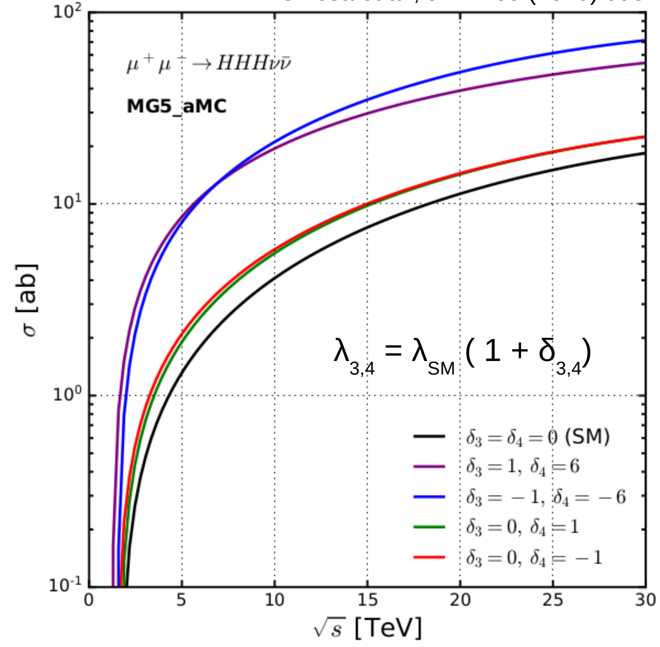
T. Han et al., Phys. Rev. D 103, 013002 (2021)

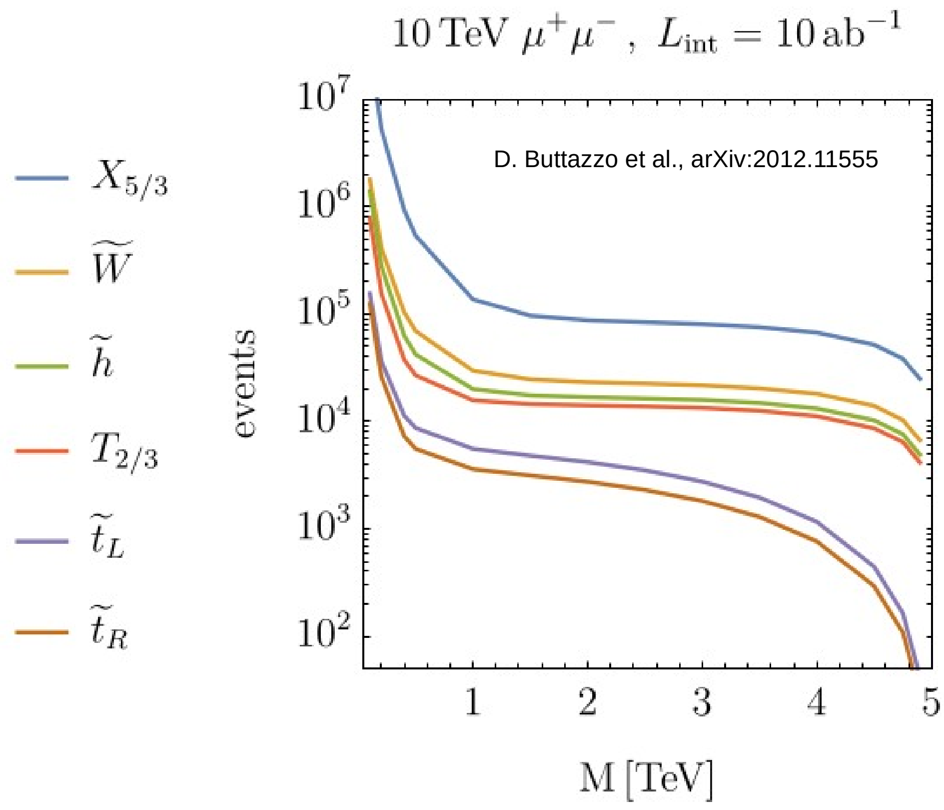
Beyond the Standard Model

- Indirect searches:
  for example, probing the trilinear and quartic Higgs self-couplings for deviations from the SM value.

- Direct searches:
  for example, searching for EW pair production of new heavier states.

M. Chiesa et al., JHEP 09 (2020) 098

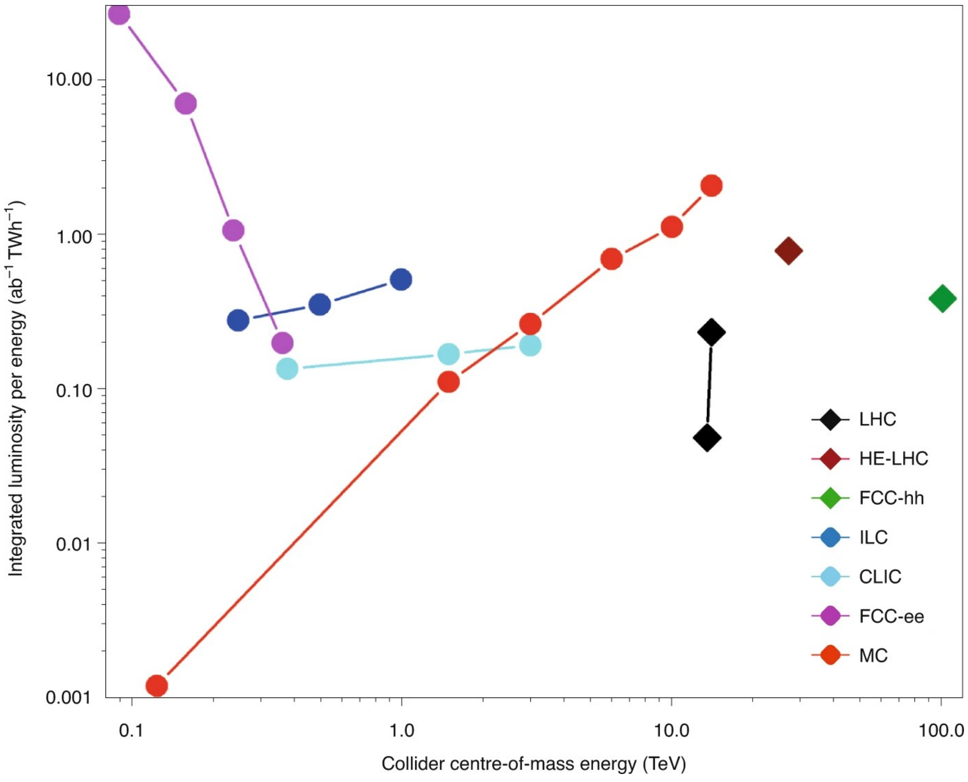




An important point: the costs!

- At the highest collision energies a muon collider is the most power-efficient machine.
- No severe beam-strahlung effects: beam energy spread *dE/E* < 10^{-3} (for 3 to 14 TeV).
- A muon collider facility may be built with a relatively small footprint.

K.R Long et al., Nat. Phys. 17, 289-292 (2021)



Muon collider challenges

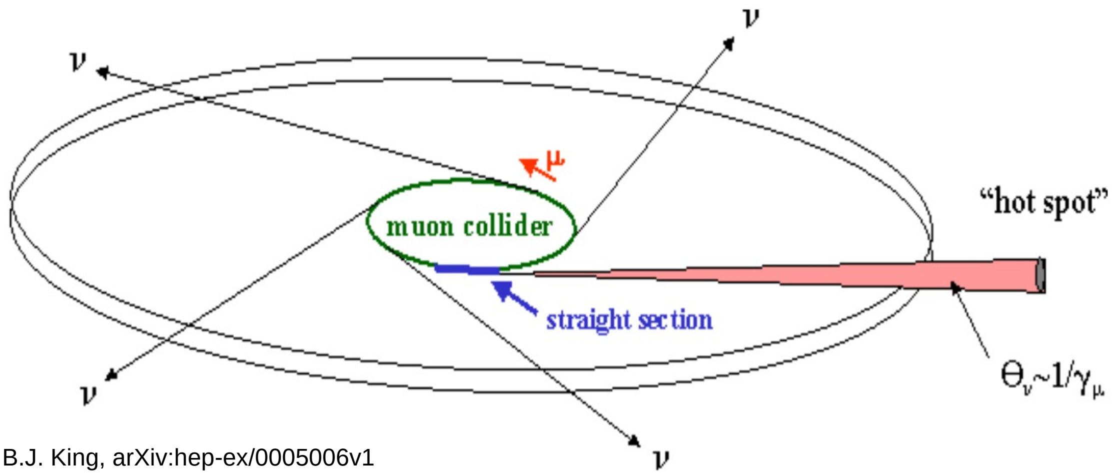
The other side of the coin

- Unfortunately, such a tremendous physical potential is not coming for free.
- Muons are unstable particles (τ_μ = 2.2 μs):

$$\mu^- \rightarrow e^- \; \bar{\nu}_e \; \nu_\mu$$

- Fortunately, the relativistic time dilation in the lab system gives enough time to properly prepare, accelerate and bring to collision μ^- and μ^+ beams (for a 5 TeV beam t_μ = 105 ms in the lab).
- The products of muon decays represent a dominant source of machine background: the electrons and the photons radiated by them interact with the machine elements producing a pervasive flux of secondary and tertiary particles at every stage of the beam life-cycle.
- All the machine elements and the experimental apparatuses 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



B.J. King, arXiv:hep-ex/0005006v1

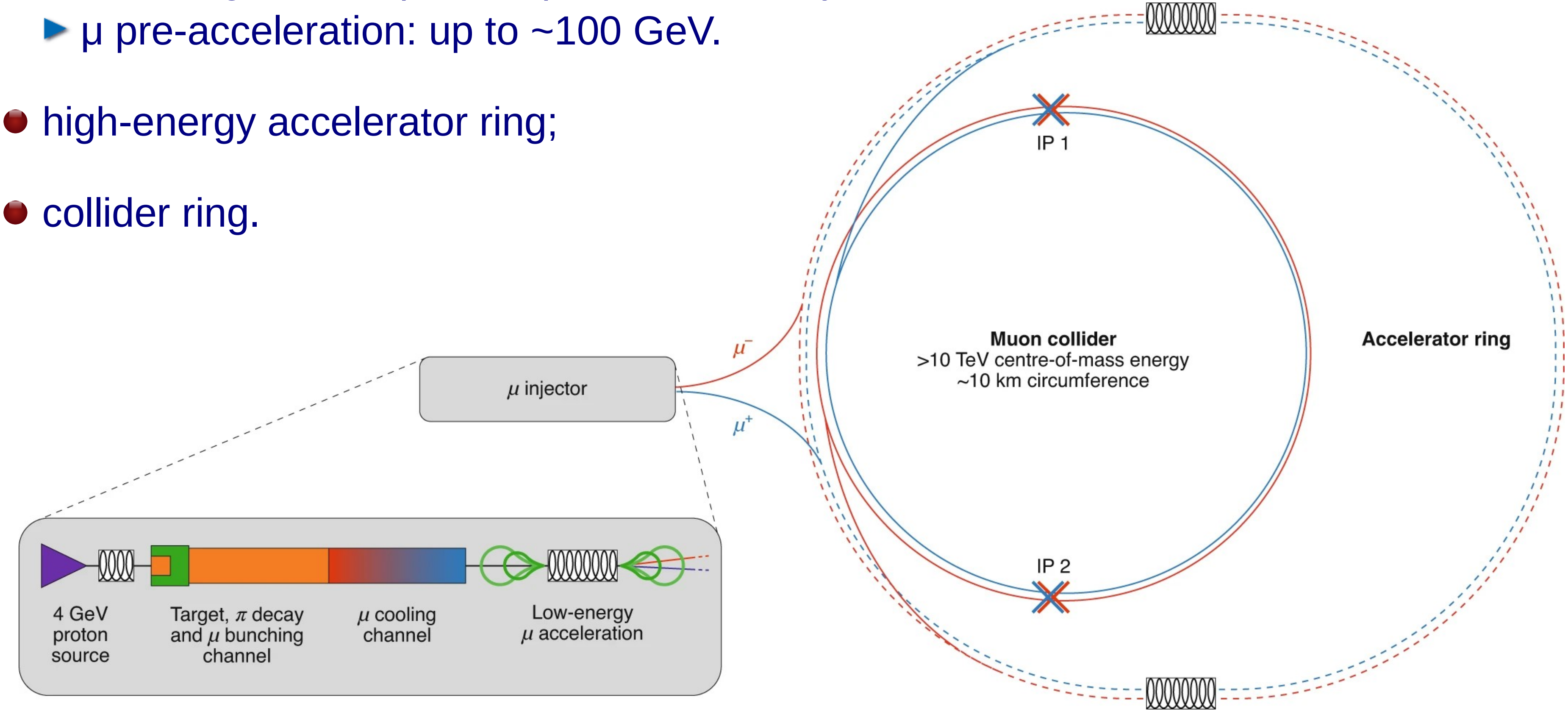
$$\theta_\nu \sim \frac{10^{-4}}{E_\mu [TeV]}$$

$$\langle dose \rangle \sim \frac{E_\mu^3}{depth}$$

- Ultimately, the most stringent constraint on the maximum muon collider energy is set by the acceptable level for the neutrino-induced radiation.
- Intense and highly collimated ν beams, emerging on 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.
- At CERN a team is studying the orography of the area to assess the impact of a muon collider in the LHC tunnel and considering mitigation measures to keep the radiation field well below safety levels (the legal limit is 0.1 mSv/year).
- Preliminary studies done by the US Muon Acceleration program show that $\sqrt{s}$ = 3 TeV is safe, $\sqrt{s}$ = ~10 TeV can be reached with mitigation measures in place.

Muon collider main components

- Injector:
  - μ source: muons are produced as tertiary particles from decay of pions created by a proton beam impinging a target;
  - μ cooling: muons phase space reduced by ~10^5;
  - μ pre-acceleration: up to ~100 GeV.
- high-energy accelerator ring;
- collider ring.



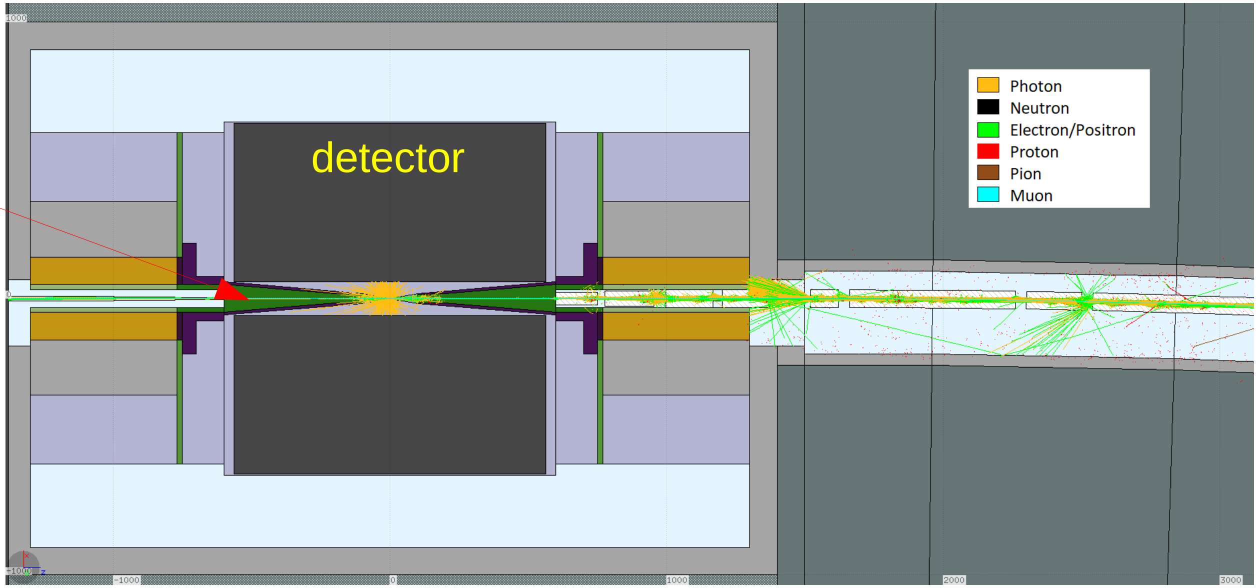
Beam-induced background

Beam-induced background

- The amount and characteristics of the beam-induced background (BIB) reaching the detector depend on the collider energy, the machine optics and lattice elements, and the machine-detector interface (MDI).
- To study the BIB effects on the detector response and optimize the MDI a full simulation based on FLUKA has been set up that integrates the full machine design.
- Previously, extensive studies were conducted by the US Muon Accelerator Program with MARS15 package for machines operating at $\sqrt{s}$ = 125 GeV and 1.5 TeV.

FLUKA model

tungsten shielding cones ("nozzles"), designed by MAP



μ^- beam

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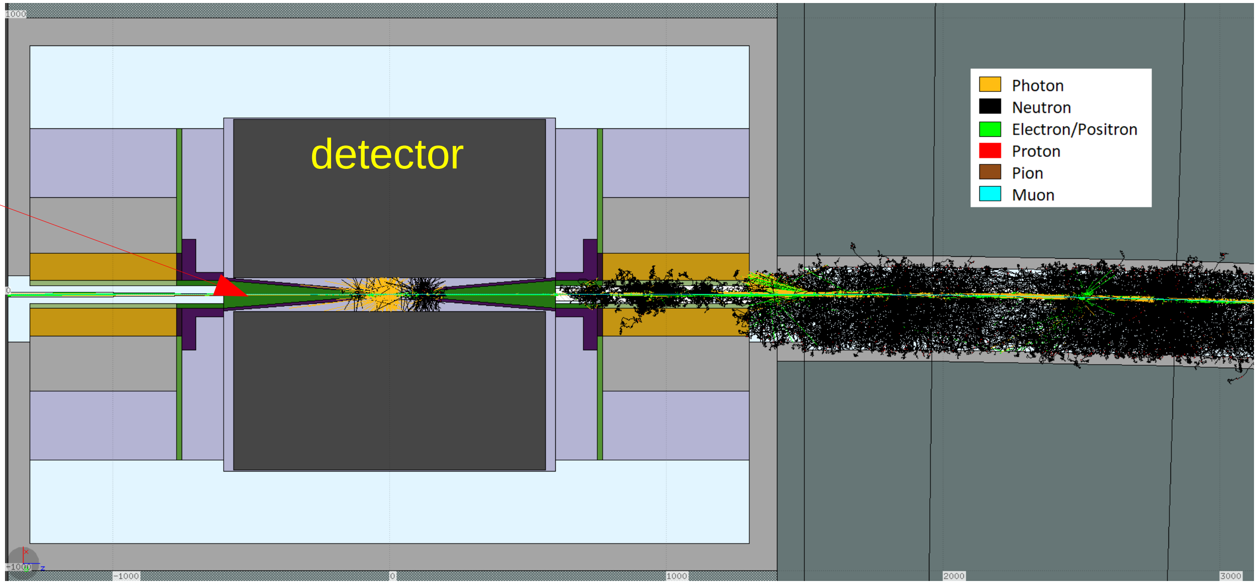


μ^- beam

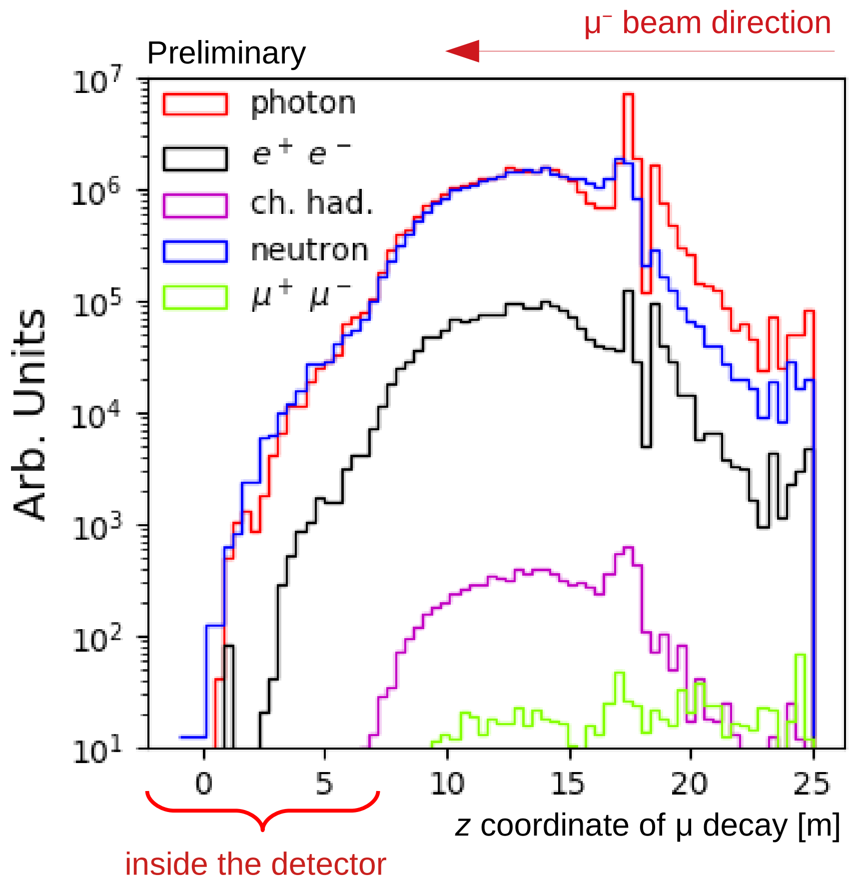
Beam-induced bkg composition

- BIB particles entering the detector at every bunch crossing:
  - bkg particles originating from muons decayed tens of meters upstream the interaction region (IR) may eventually reach the detector;
  - for 750-GeV beams main contribution from μ's decaying within | z | < 25 m around the IR.

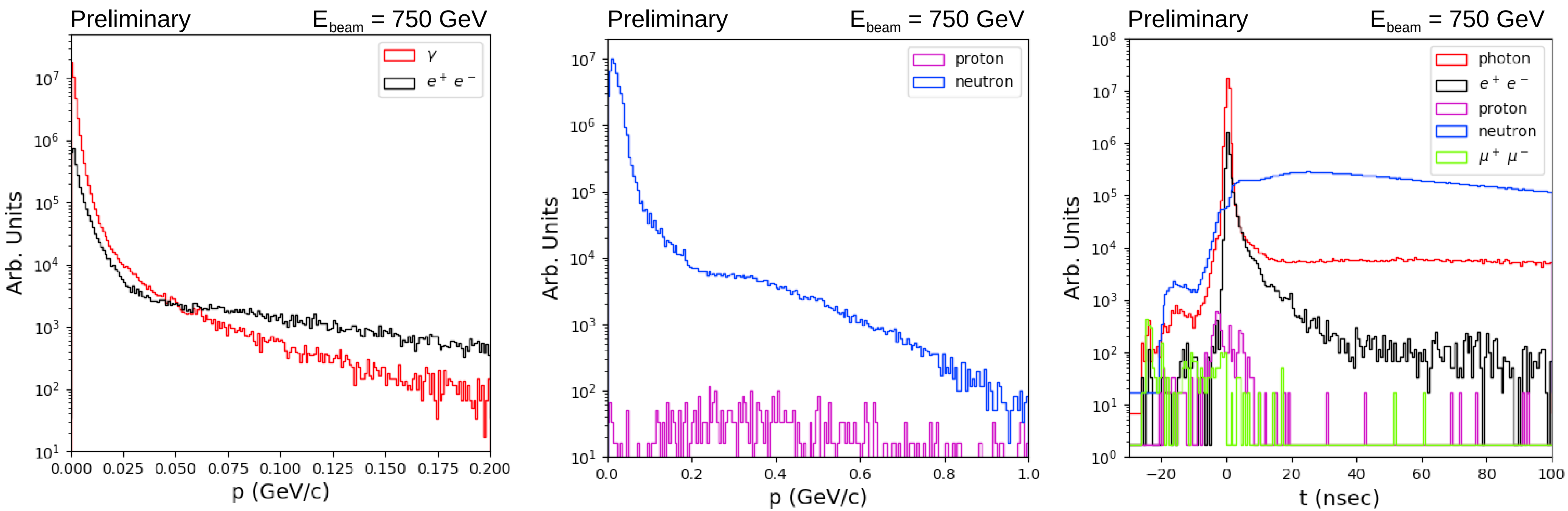
beam energy	= 750 GeV
μ / bunch	= 2×10^{12}
μ decays / m	= 4.3×10^{5}
μ decay length	= 4.7×10^{6} m

Preliminary

particle species	energy cutoff	estimated yield per BX [$\times 10^3$]
photons	$E_\gamma > 0.2$ MeV	42410
neutrons	$E_n > 0.1$ MeV	33300
electrons/positrons	$E_e > 0.2$ MeV	2060
charged hadrons	$E_h > 1$ MeV	9
Bethe-Heitler muons	$E_\mu > 1$ MeV	0.9



BIB particles characteristics



- Relatively soft momentum spectra:
  - electromagnet component: $\langle p_\gamma \rangle$ ~ 2 MeV, $\langle p_e \rangle$ ~ 6 MeV;
  - hadronic component: $\langle p_{n,p} \rangle$ ~ 500 MeV;
  - muons: $\langle p_\mu \rangle$ ~ tens of GeV.
- Time of arrival to the detector asynchronous w.r.t. bunch crossing.

Full simulation studies

Detector model

hadronic calorimeter

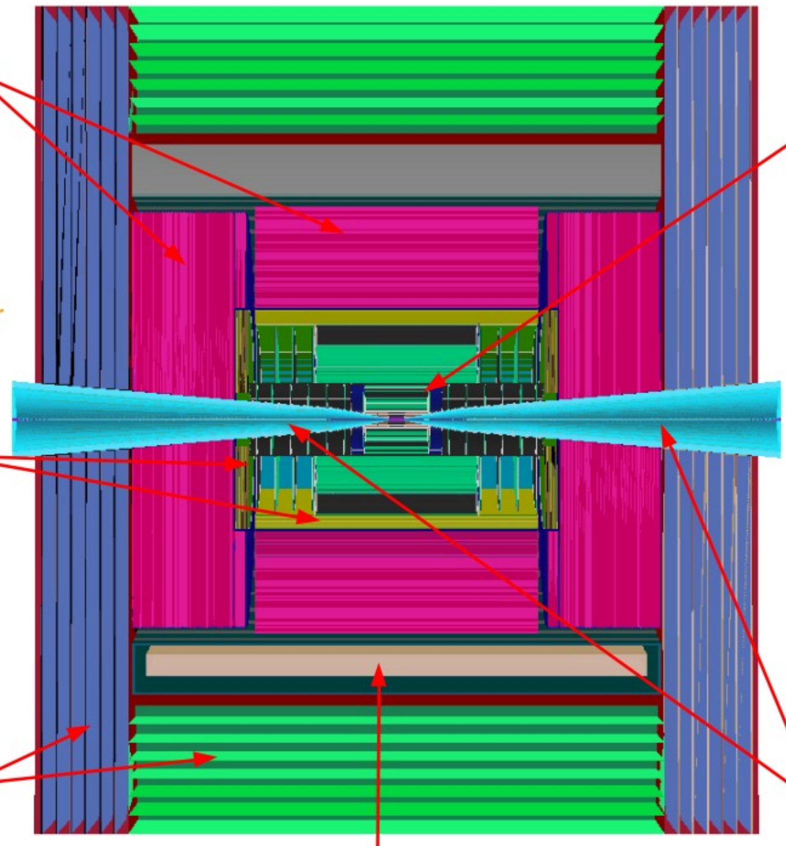
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.

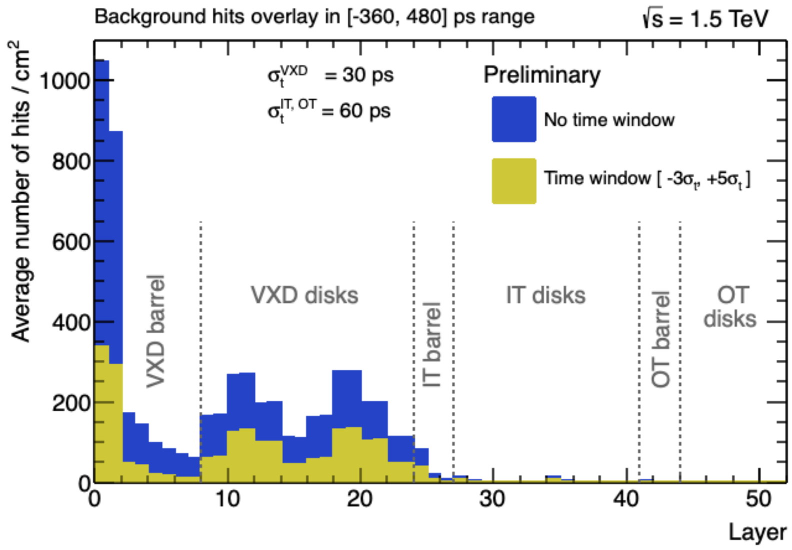
shielding nozzles

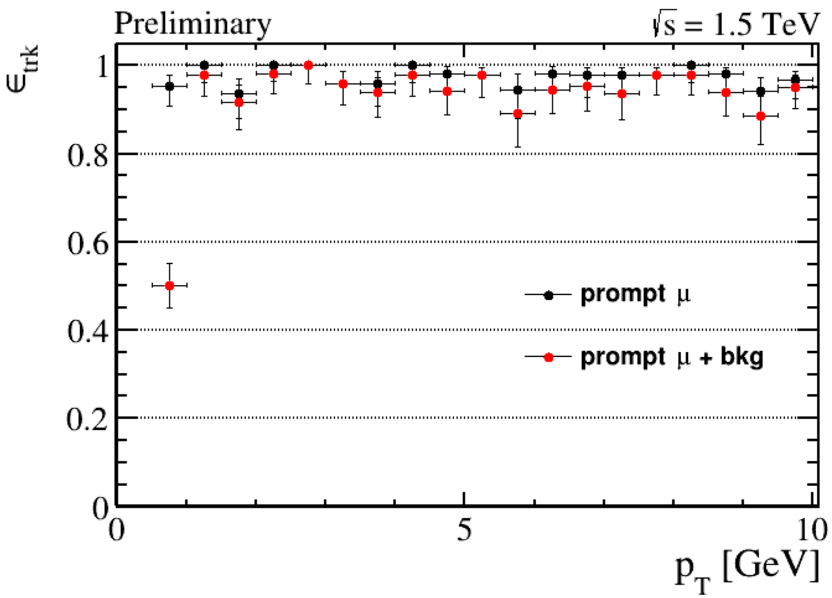
- Tungsten cones + borated polyethylene cladding.

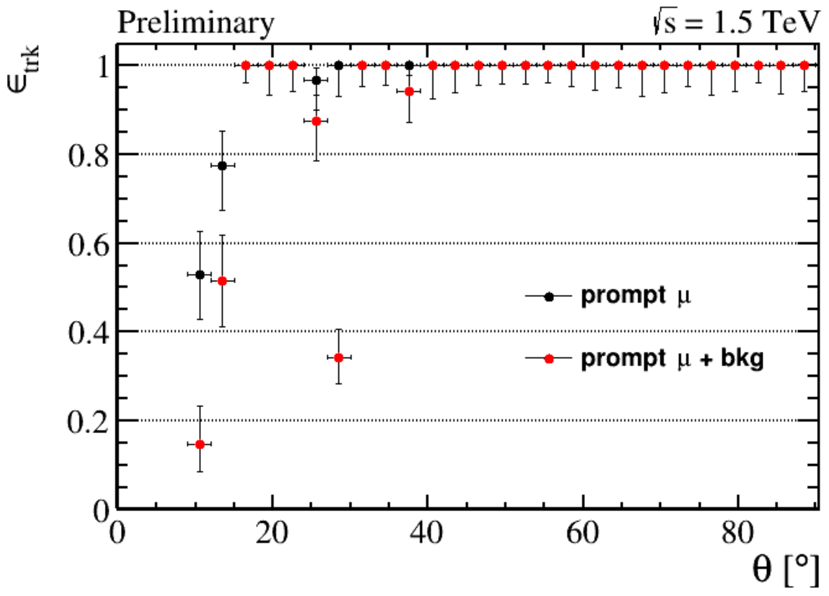
- Based on CLIC's model + the MDI and vertex detector designed by MAP.

Tracking system

- The closest detector to the beamline, the effect of BIB could be severe if not mitigated.
- Most powerful handles:
  - high-precision timing;
  - double-layer pointing;
  - pixel cluster shape.
- Tracking optimization under way.

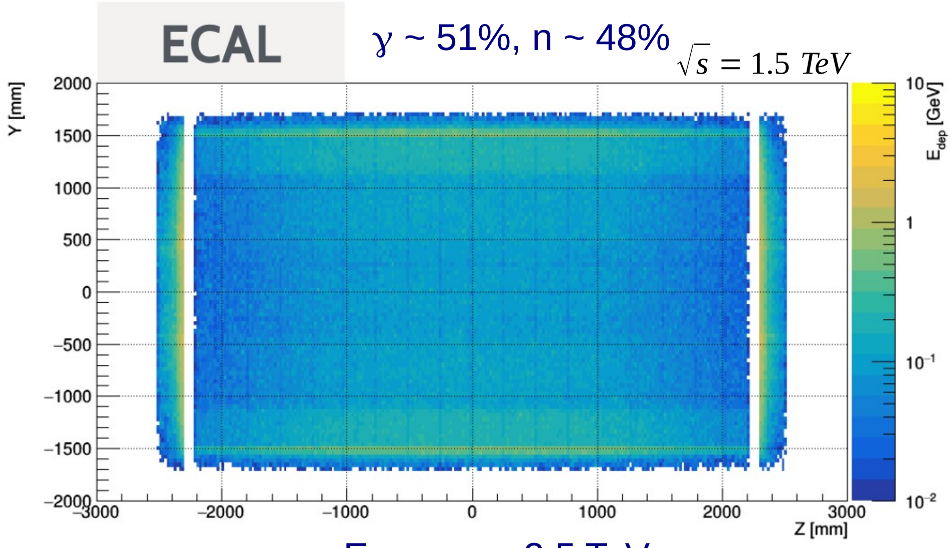






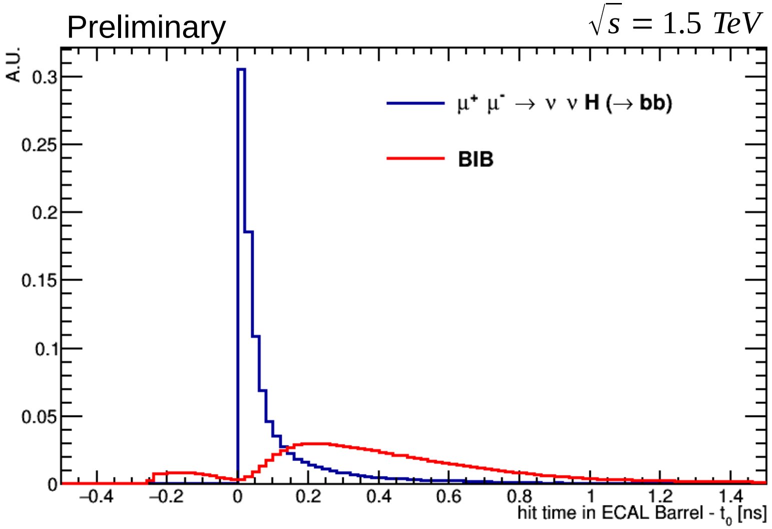
Calorimeters

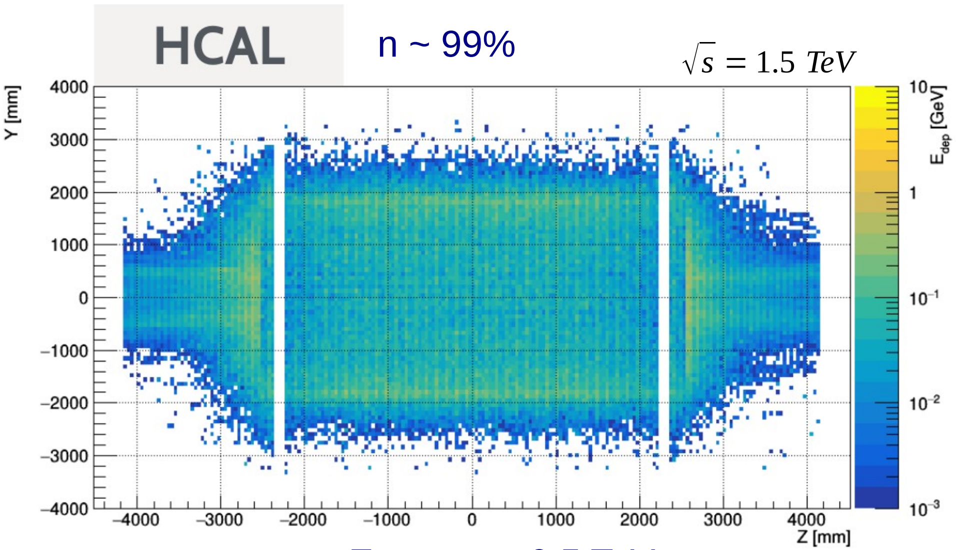
- BIB is ~uniformly distributed in the electromagnetic and hadronic calorimeters.
- Timing, very high granularity and fine longitudinal segmentation needed to cope with BIB.
- Ongoing study of a jet reconstruction algorithm based on Particle Flow, which takes into account the BIB.



$E_{deposited}$ ~ 2.5 TeV

ECAL barrel hit arrival time – t_0

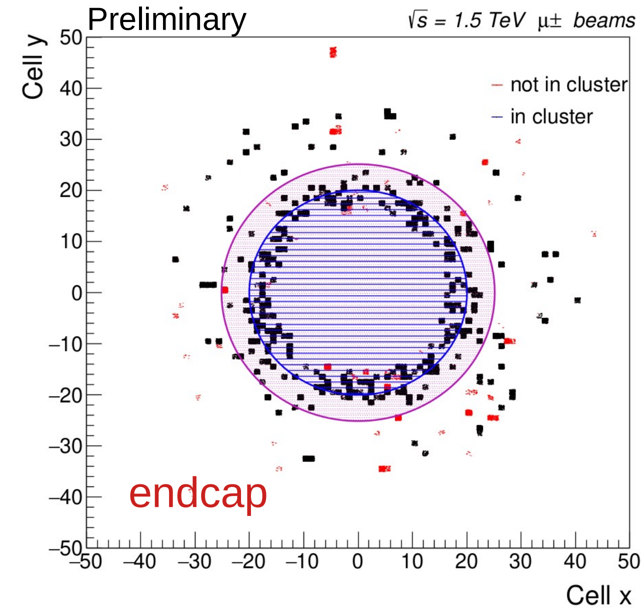




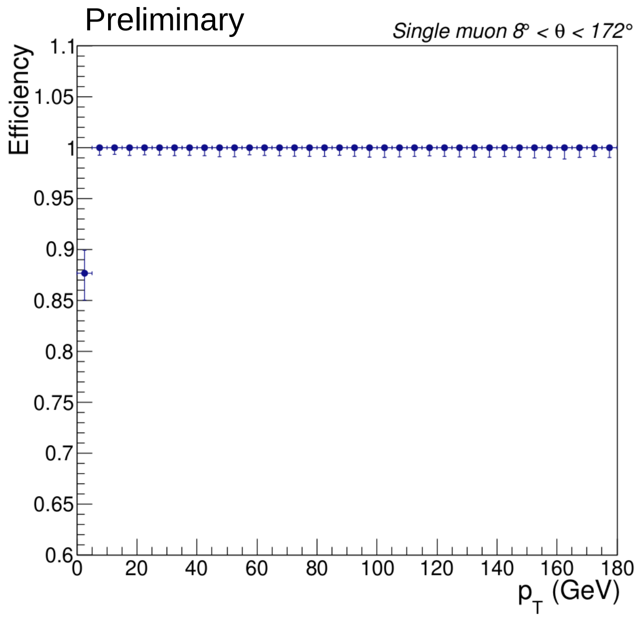
$E_{deposited}$ ~ 0.5 TeV

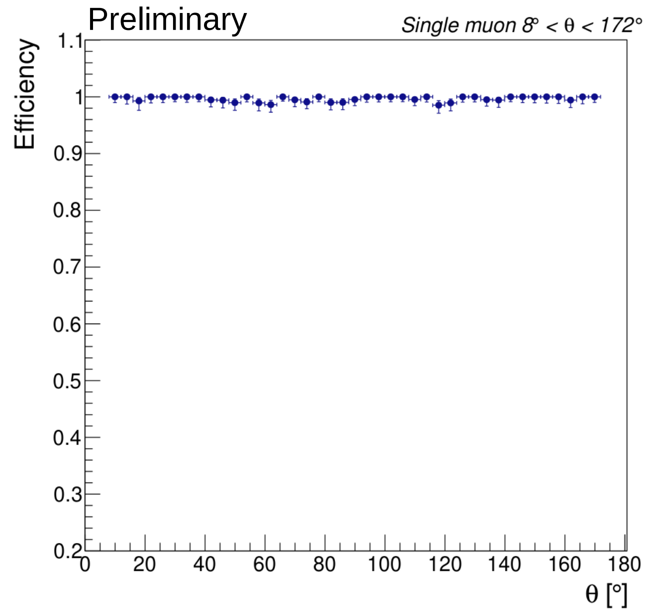
Muon detectors

- The muon RPCs, 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.

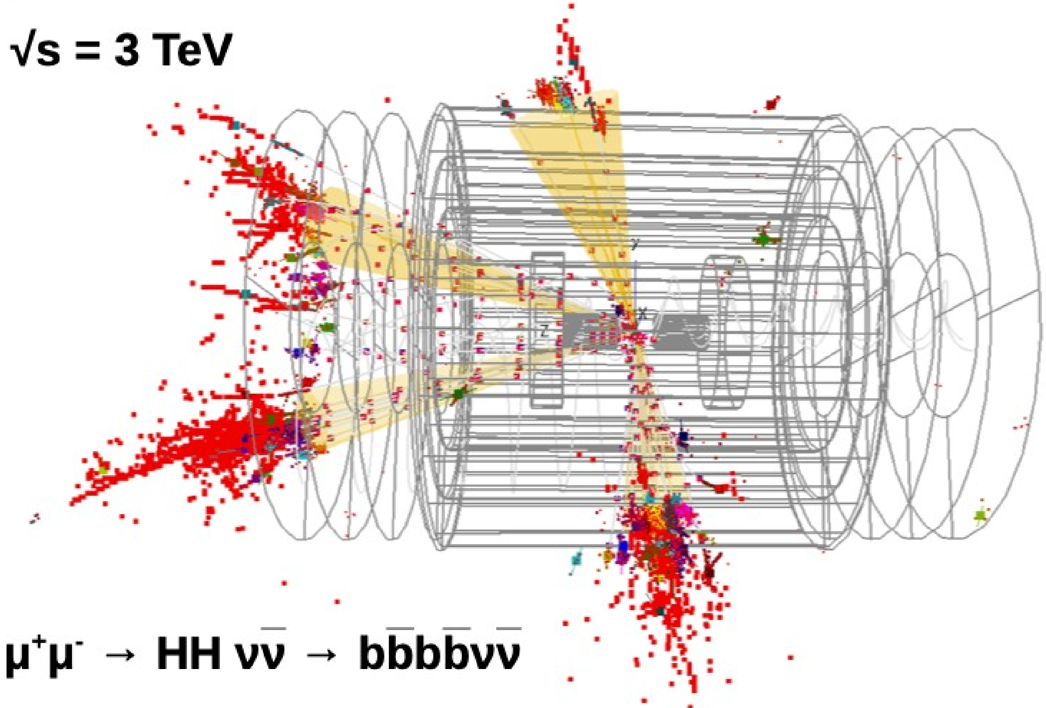


reconstruction efficiecy for single muons

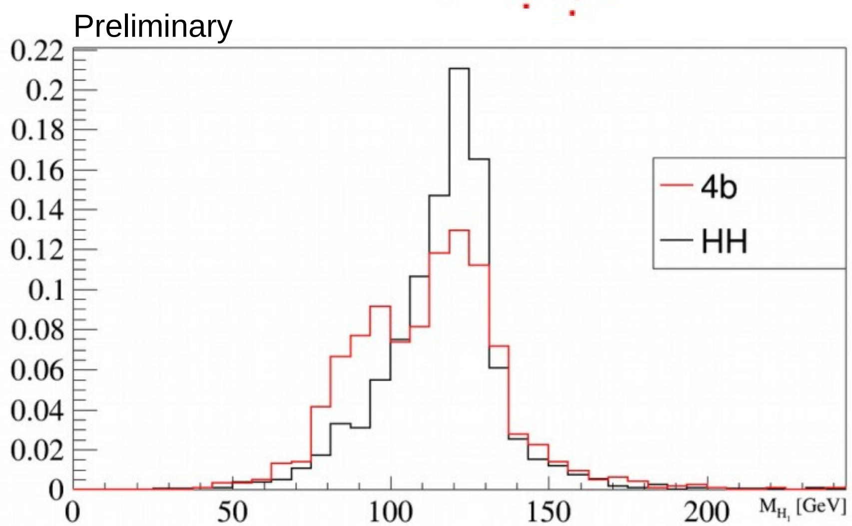


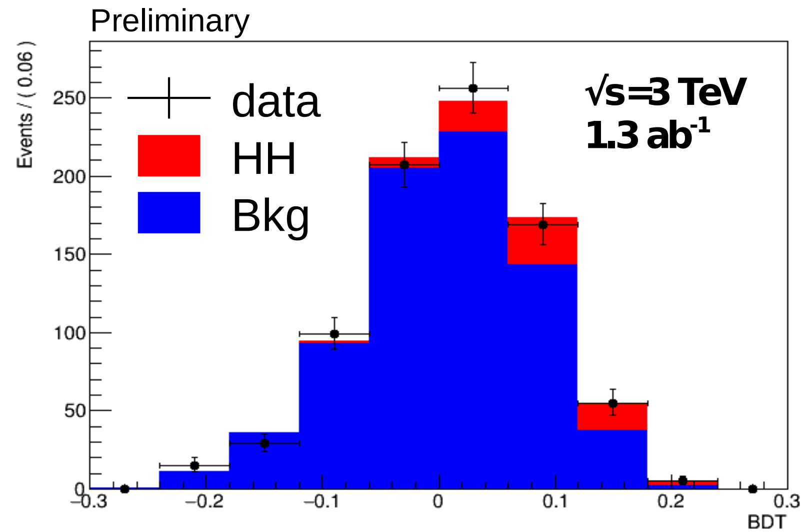


First full-sim Physics studies



- Towards a measurement of the production cross section σ_{HH} (gateway to the trilinear Higgs self-coupling), first estimate of the HH yield at $\sqrt{s}$ = 3 TeV.
- Signal-background discrimination with a Boosted Decision Tree.
- Signal yield from a fit to the BDT output:
  S = 67 ± 22.
- New results for APS!





Conclusions

- The muon collider project is going to present unprecedented technological and experimental challenges along the way, but the final reward will be an extraordinary and unique physical potential.

- The first step has been taken: an International Muon Collider Collaboration is been formed with the objective of assessing the potential of a muon collider and identifying an R&D path to demonstrate the feasibility of such a collider for the next update of the European Strategy for Particle Physics.

https://muoncollider.web.cern.ch

"A journey of a thousand miles begins with a single step." (Lao-Tzu)