Dark Matter Studies in Accelerator Physics
3rd DMNet international symposium
26-28 September 2023
Palazzo Moroni, Padua, Italy

DMNet

INFN Istituto Nazionale di Fisica Nucleare

INFN PADOVA

Dipartimento di Fisica e Astronomia Galileo Galilei

International MUON Collider Collaboration

MuCol

aMUSE

Future muon collider physics prospects

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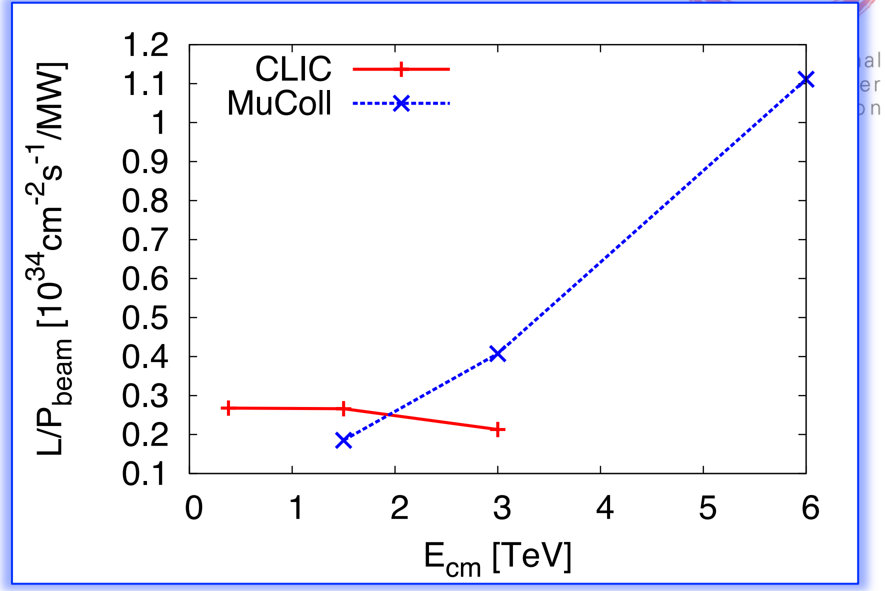
Muon Collider: a new concept machine

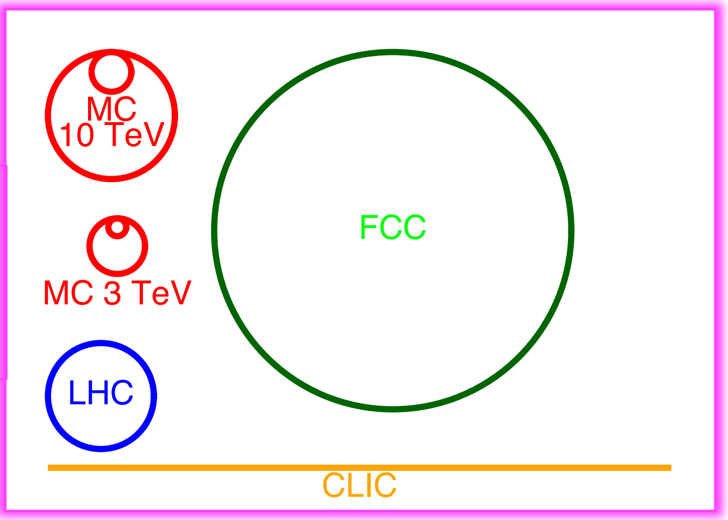
Muons do not suffer synchrotron radiation in this energy range

High center of mass energy & high luminosity & power efficient: luminosity increase per beam power



Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	2	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	$N_{\pm}$	1×10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Total beam power	$P_- + P_+$	MW	5.3	14	20
Longitudinal emittance	ε_l	MeV m	7.5	7.5	7.5
Transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.1
IP beta-function	$\beta^*_{\perp}$	mm	5	1.5	1.1
IP beam size	$\sigma_{\perp}$	µm	3	0.9	0.6

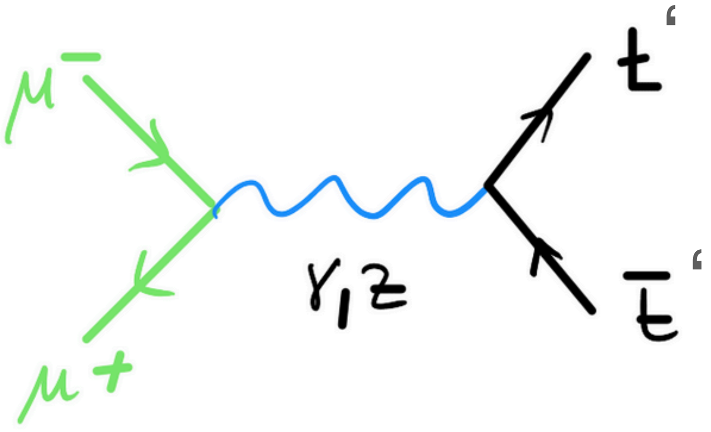
Compact: cost effective & sustainable



Physic processes: two colliders in one

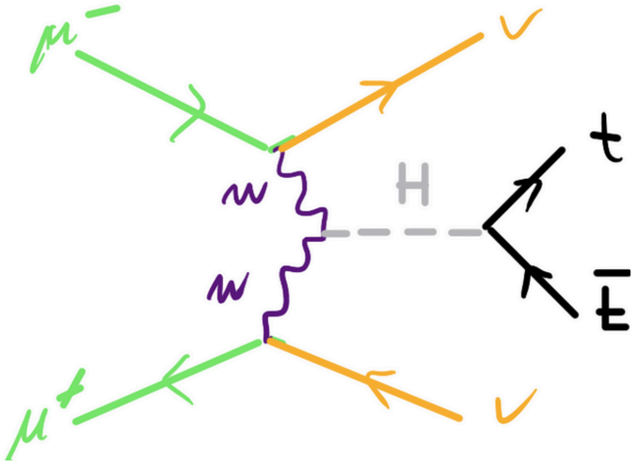
F. Maltoni
"Physics Overview" Annual Meeting IMCC

Multi-TeV muon collider opens a completely new regime :



$$\sigma \sim \frac{1}{s}$$

Energetic final states
(heavy particle or very boosted)



$$\sigma \sim \frac{1}{M^2} log^n \frac{s}{M}$$

Standard Model coupling measurements
Discovery light and weakly interacting particles

Different physics can be probed in the two channels

Muon Collider: luminosity, energy and physics

F. Maltoni
"Physics Overview" Annual Meeting IMCC

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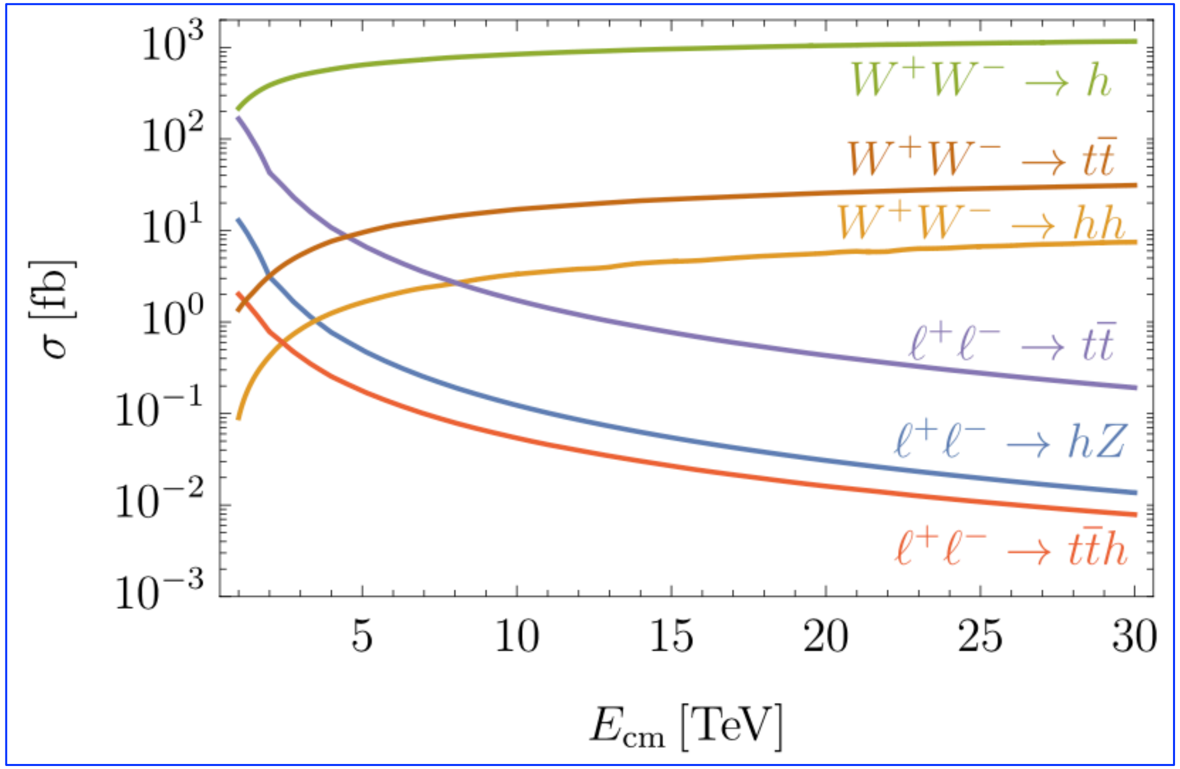
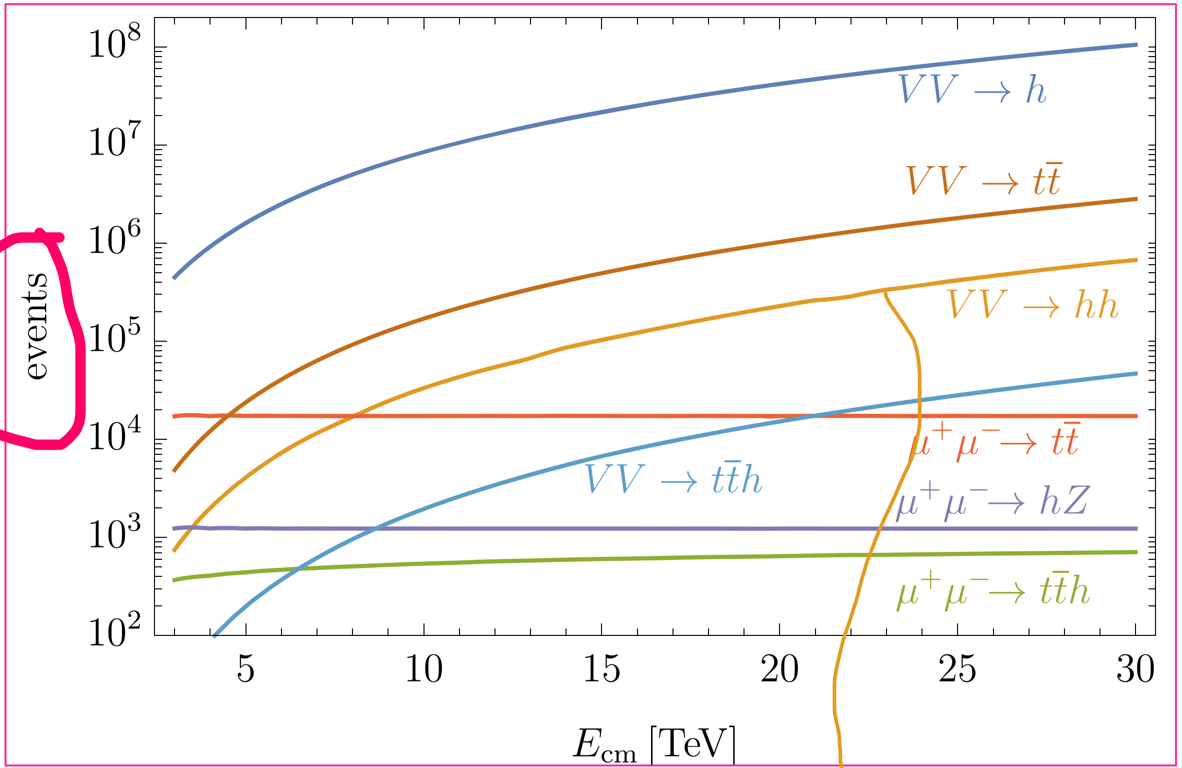
$$\mathcal{L} = 10ab^{-1}\left(\frac{E_{cm}}{10\ TeV}\right)^2$$

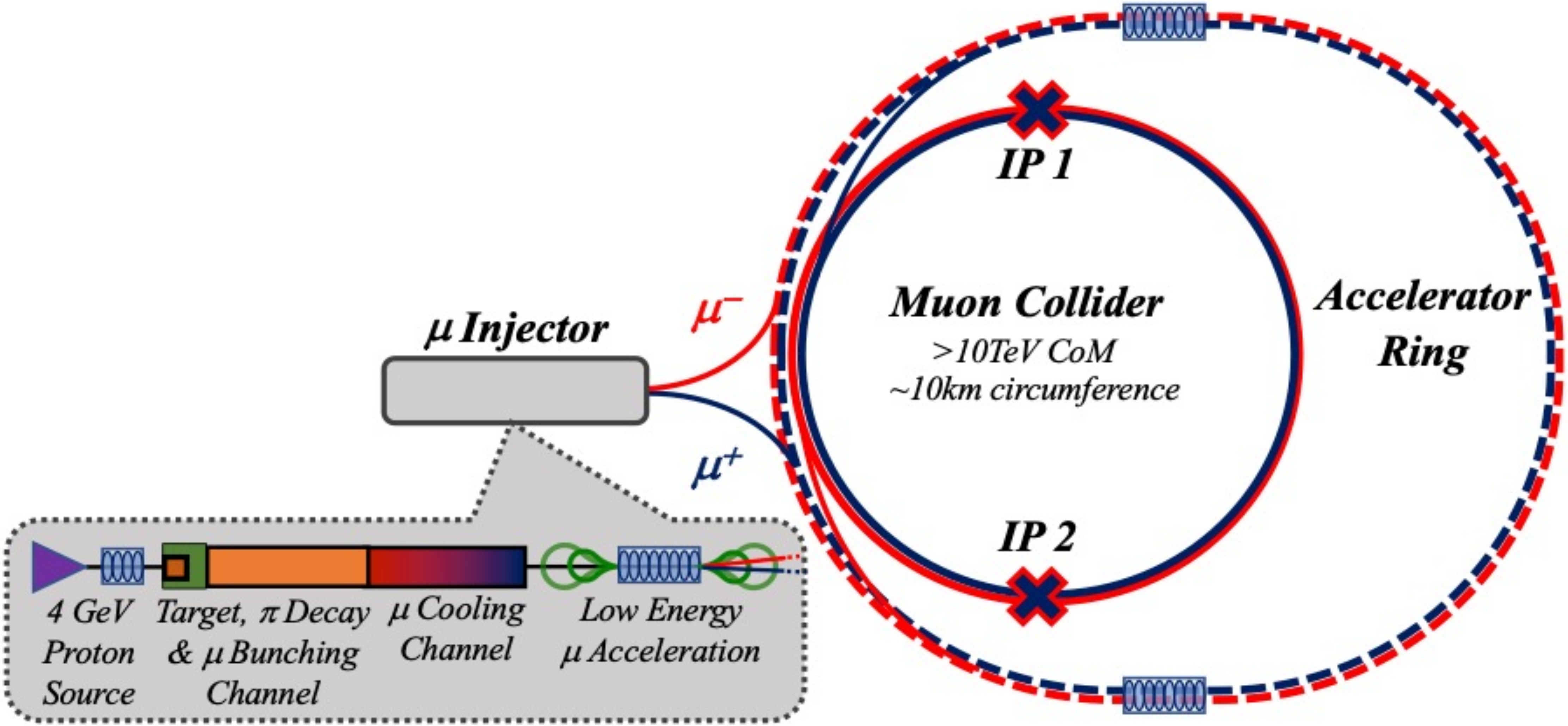




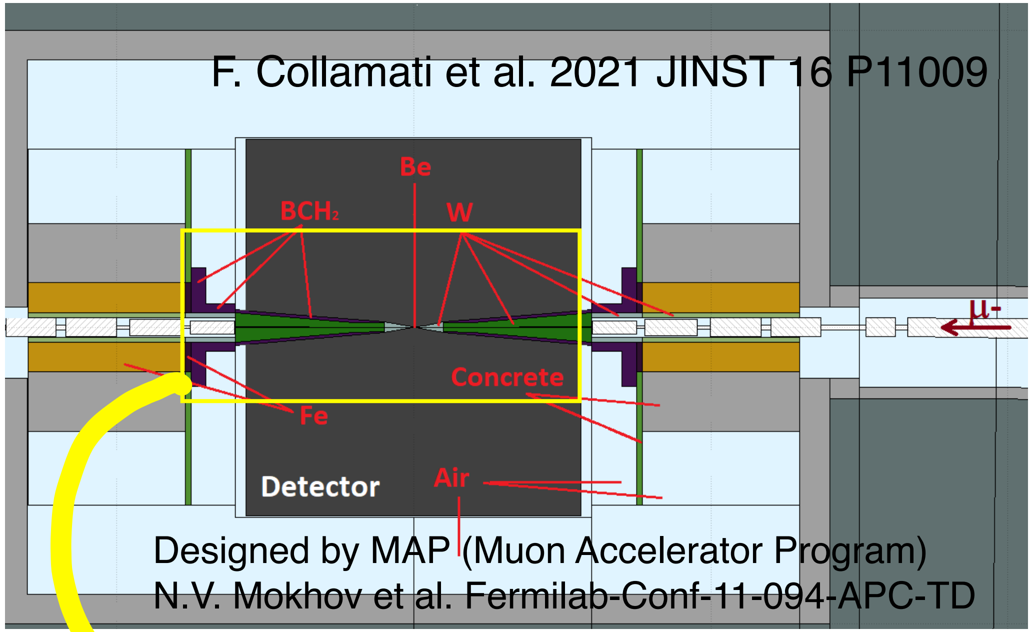
Possibility to determine Higgs potential

Integrated luminosity: $\sqrt{s} = 3$ TeV 1 ab^{-1} 5 years one experiment
$\sqrt{s} = 10$ TeV 10 ab^{-1} 5 years one experiment

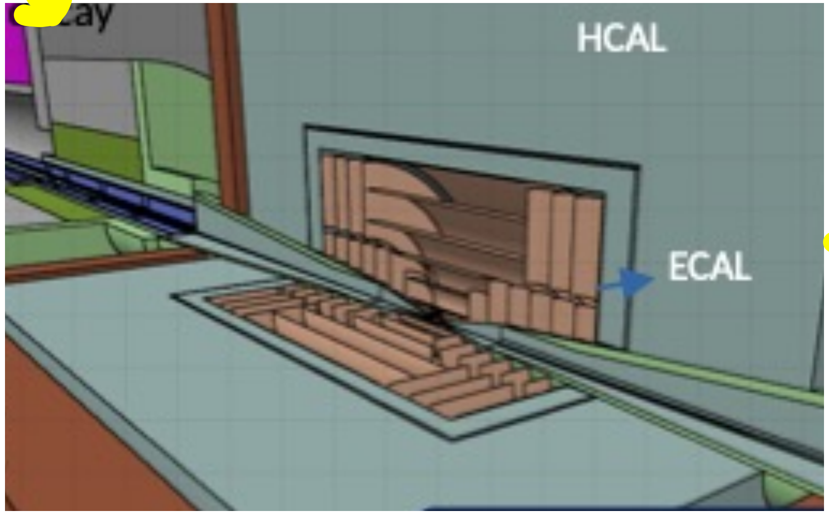
Muon Collider Facility

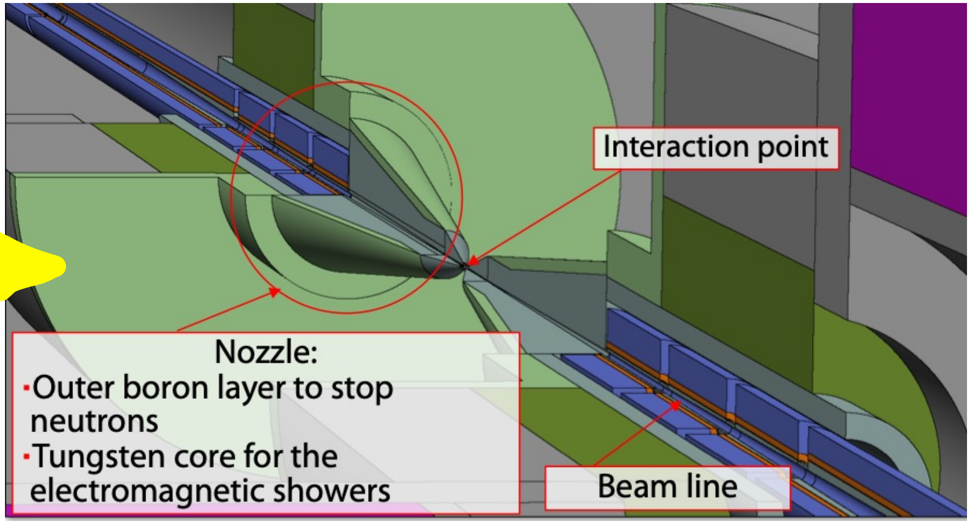


Beam-Induced Background sources in the detector region



- Muon decay along the ring, $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ produces huge fluxes of particles arriving on the detector.
- Introduction of conical-shaped absorbers, nozzles, eliminate the high energy component of particles





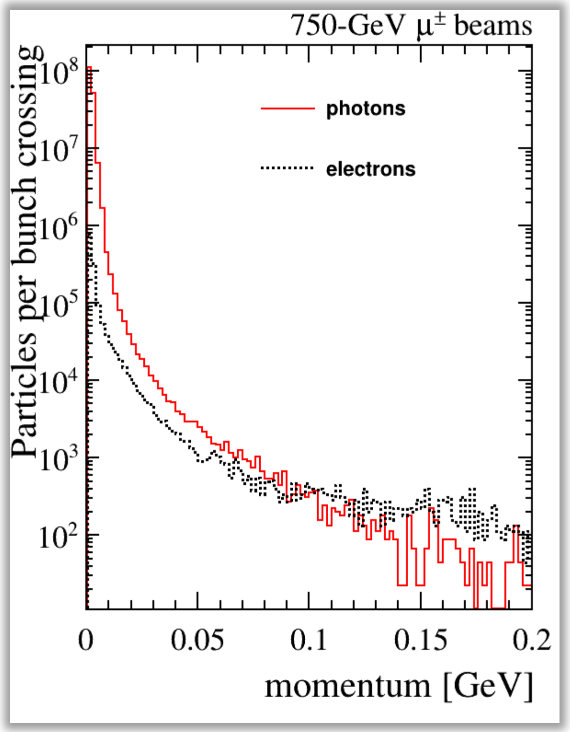
D. Calzolari [IMCC Ann. meeting Orsay 2023]

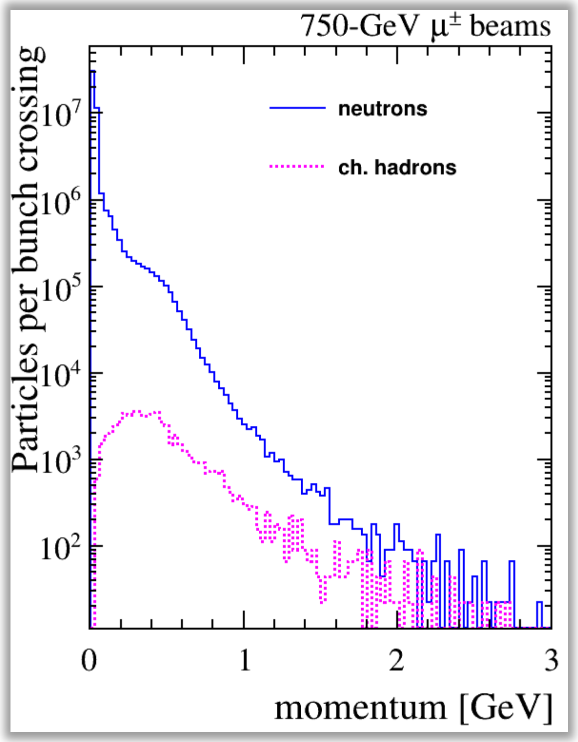
Survived beam-Induced background (BIB) properties

Particles arriving on the detector with the nozzle:

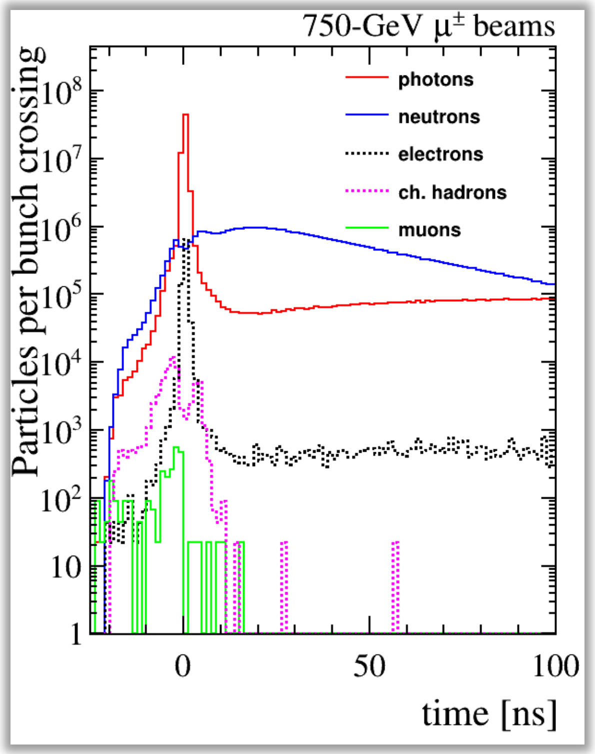
- Muon beam 0.75 TeV, IR designed by MAP
- BIB generated with MARS15

N. Bartosik *et al* 2020 *JINST* **15** P05001





Low momentum particles



Detector read-out window [-1ns,15ns]

Partially out of time vs beam crossing t_0

Despite the nozzles, huge number of particles arrives on the detector

First detector concept

$\sqrt{S} = 3$ TeV

hadronic calorimeter

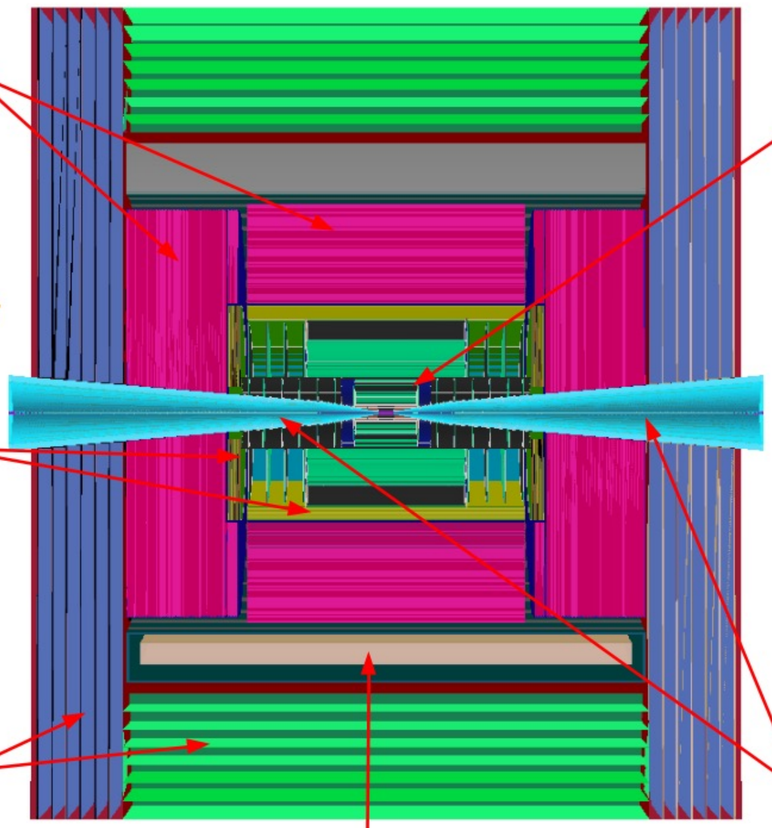
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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

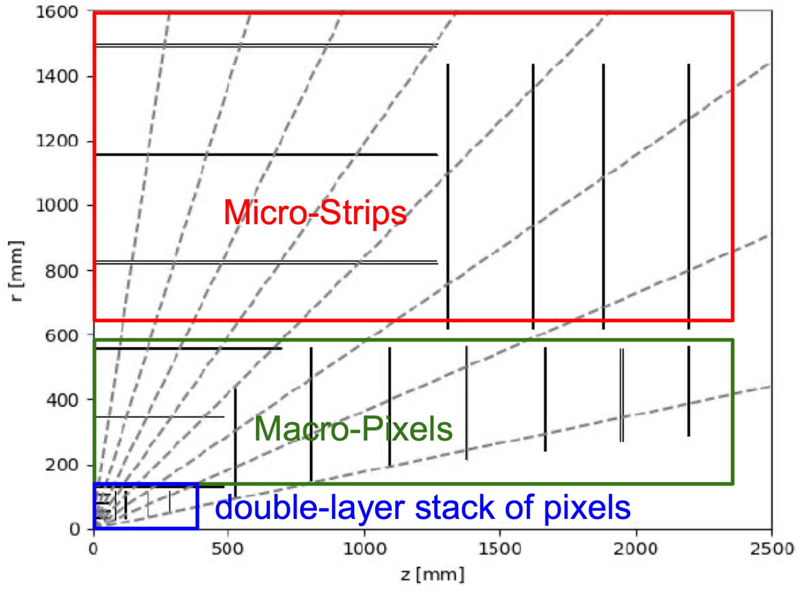
- Tungsten cones + borated polyethylene cladding.

BIB affects:

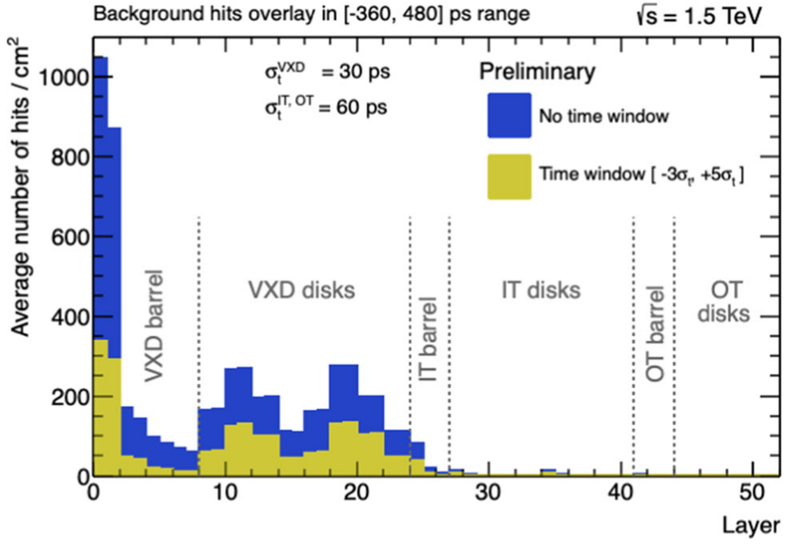
- tracker system
- ECAL
- Forward muon

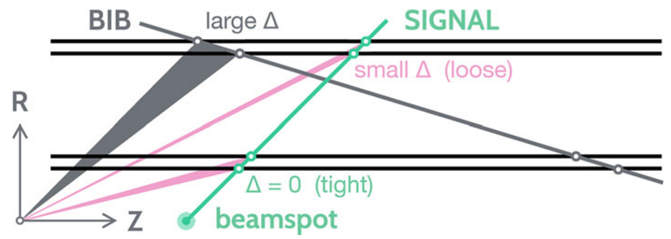
Detector for $\sqrt{S} = 10$ TeV in progress together with BIB

Track reconstruction performance

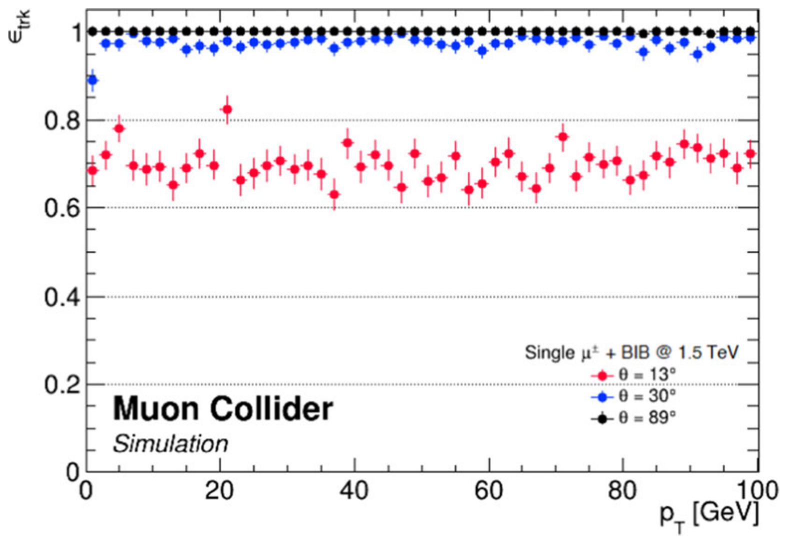


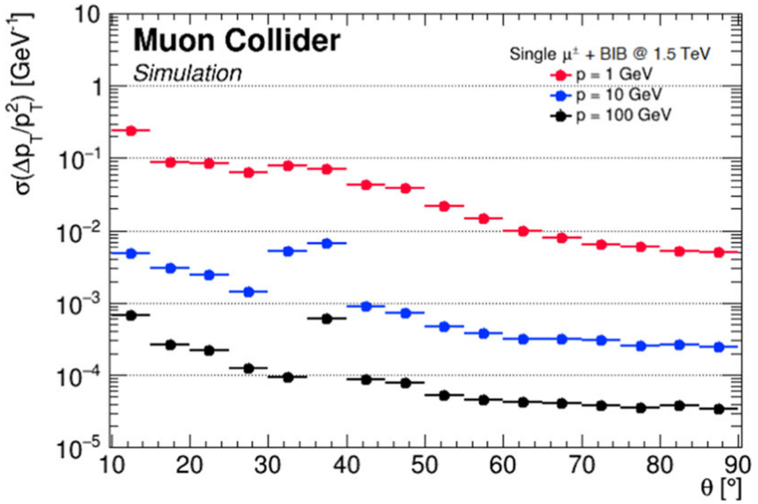
Tight timing requirements reduce occupancy due by BIB hits





double layers filtering reduce BIB hits but bias secondary tracks efficiency





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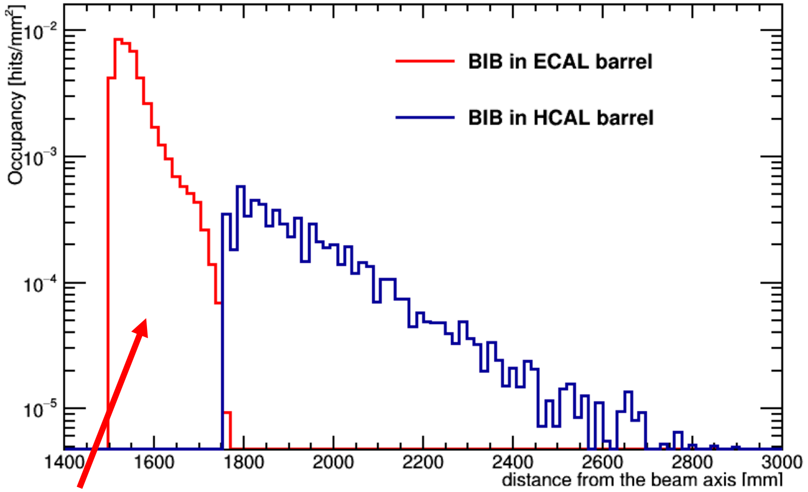
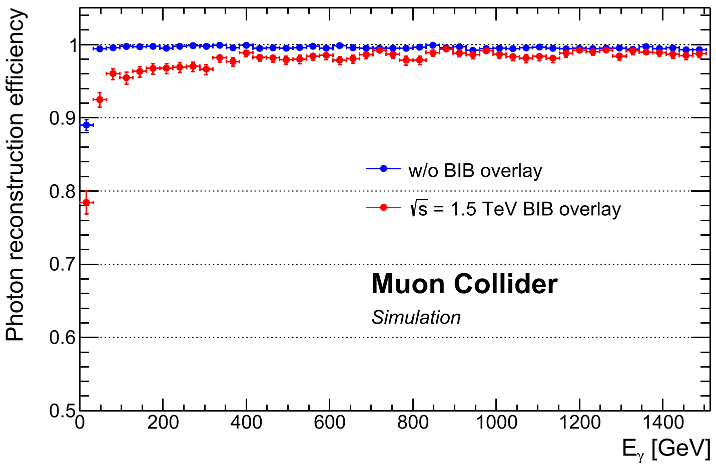
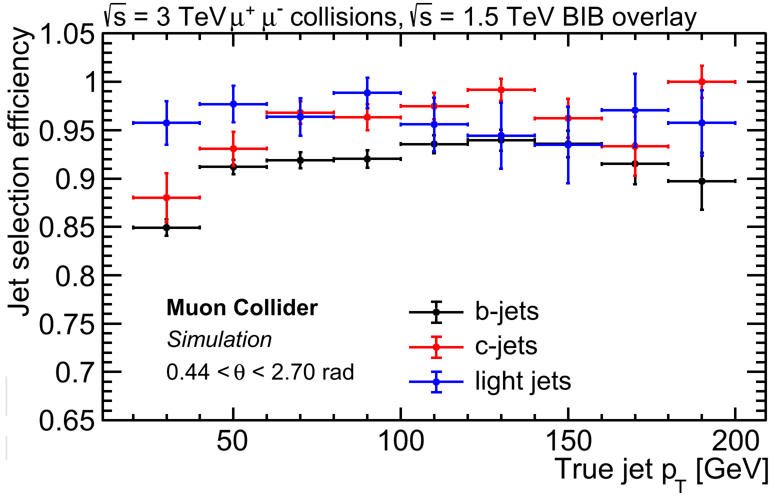
Photon/electron & jets reconstruction performance

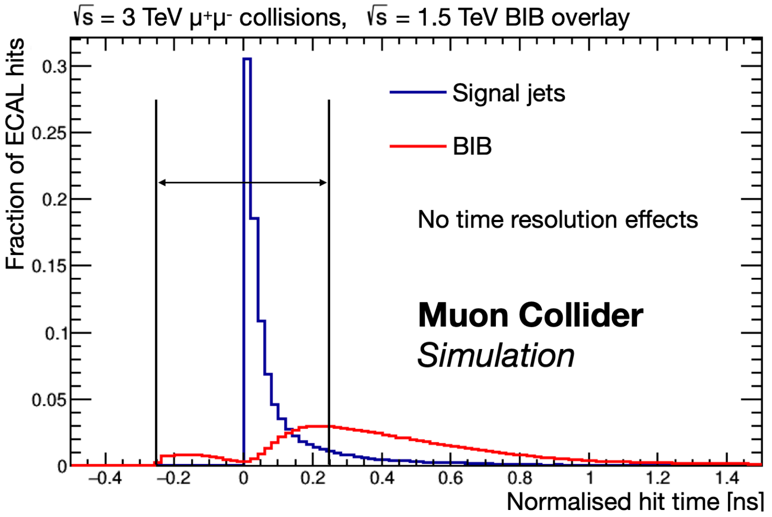


High level of BIB

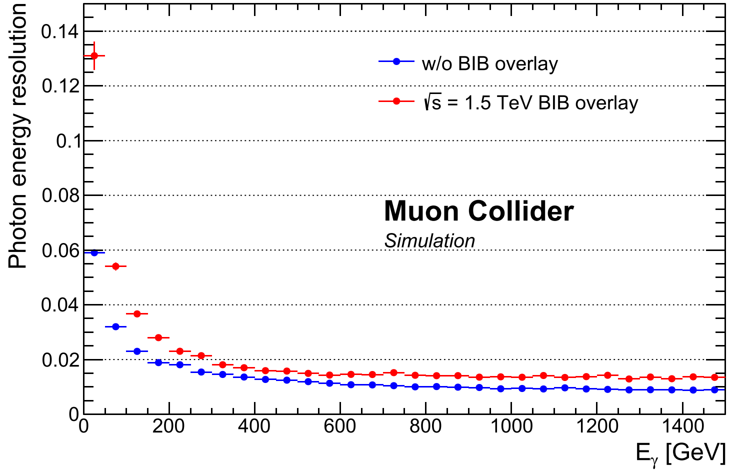
$E_{hit} > 2$ MeV

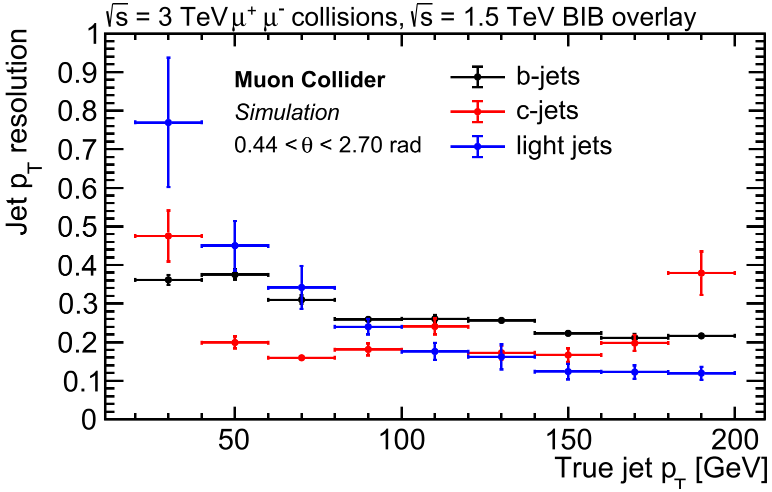






time information helps





Global assessment of dark matter searches at muon collider is still to be done.

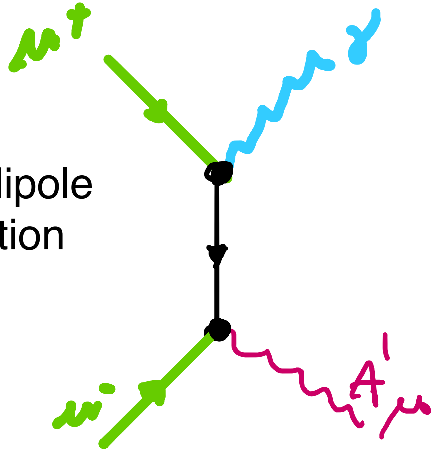
I picked up few examples, personal choice.

Dark photon and Axion-Like Particle

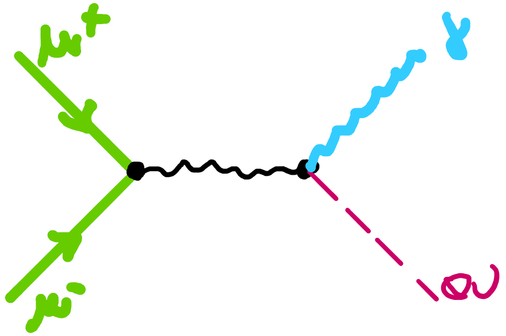
M. Casarsa, et al. *Monochromatic single photon events at the muon collider*
Phys. Rev. D 105(7), 7153 075008 (2022)

Model

magnetic-dipole
like interaction

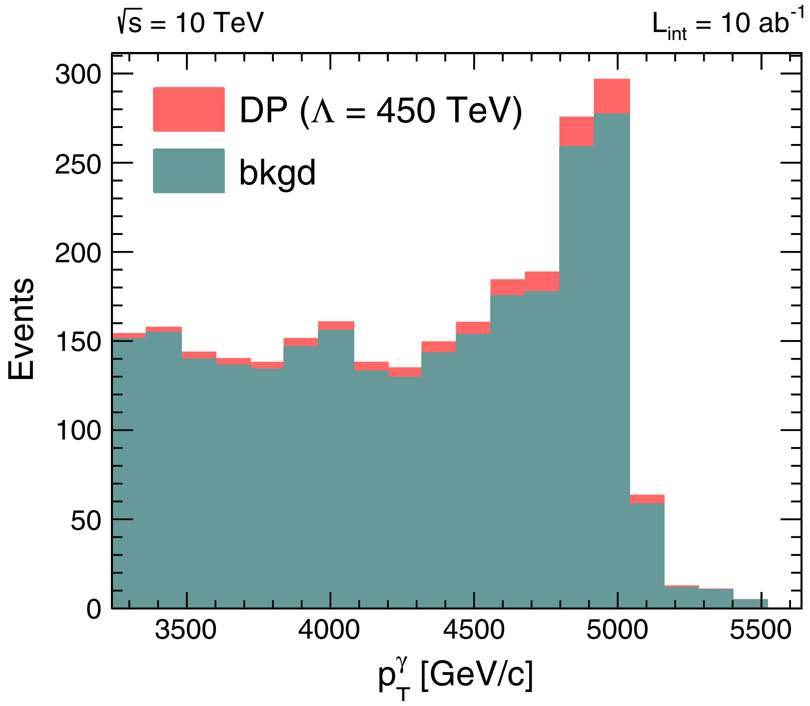


portal operator
function $\partial_\mu a$



Signature: monochromatic photon

Both depending on
interaction scale Λ



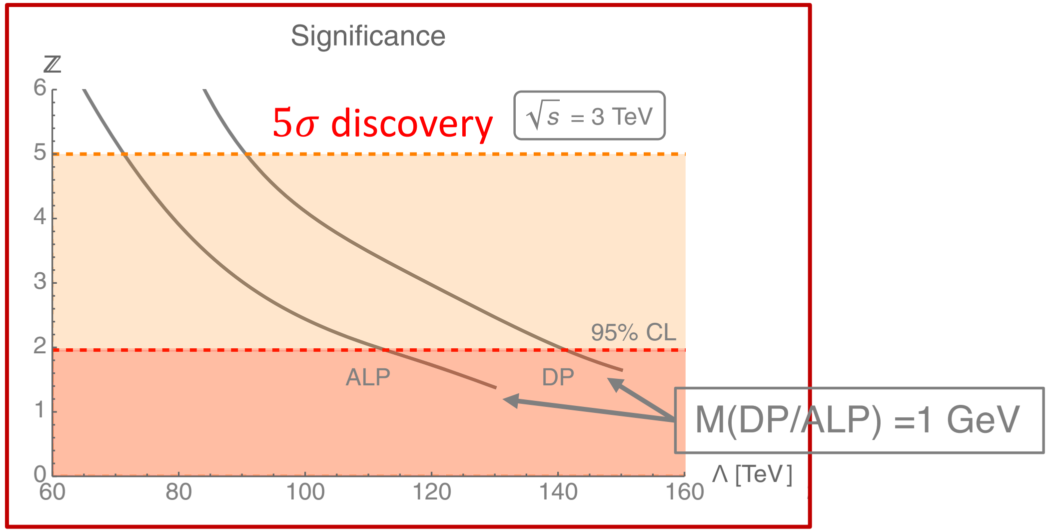
Full detector simulation including BIB

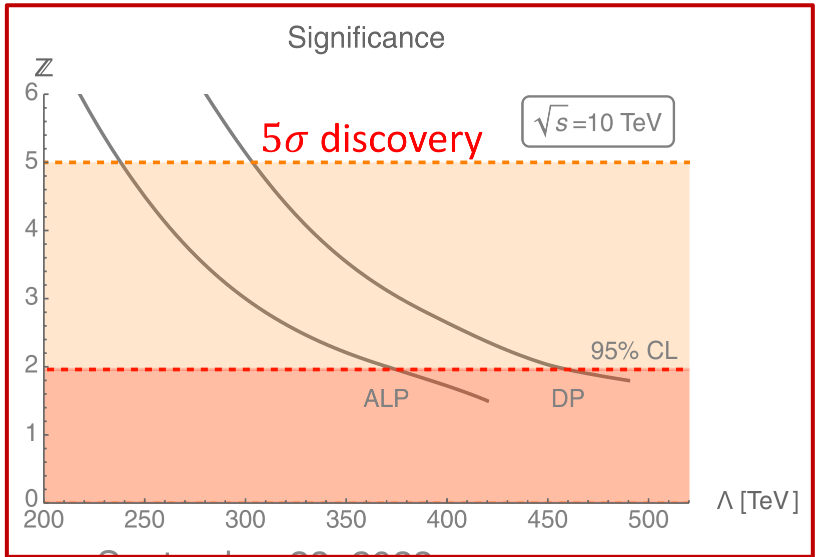
Dominant background $\mu^+\mu^- \rightarrow \gamma\nu\bar{\nu}$

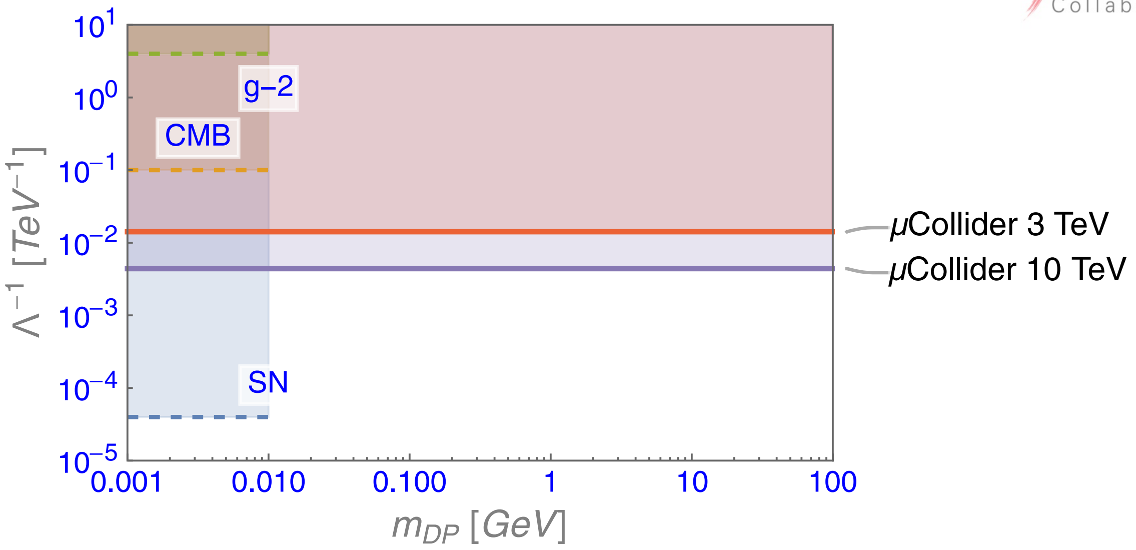
Event requirements:
$40.4^o < \theta_{\mu^-} < 139.6^o$
$E_\gamma > 1450(4800)$ GeV for $\sqrt{s} = 3(10)$ TeV
(Maximize $S/\sqrt{S+B}$)

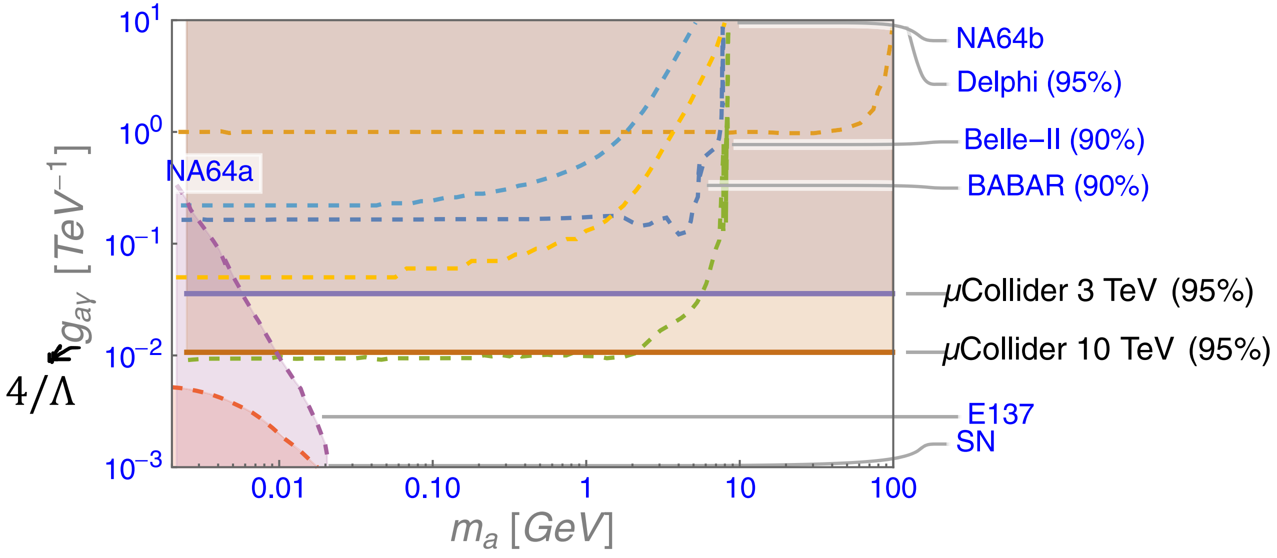
Dark photon and Axion-Like Particle results

M. Casarsa, et al. *Monochromatic single photon events at the muon collider*
Phys. Rev. D 105(7), 7153 075008 (2022)



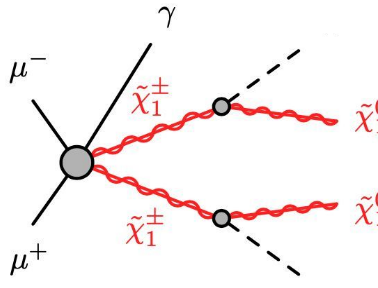






Disappearing Tracks (DT)

R. Capdevilla et al., *Hunting wino and higgsino dark matter at the muon collider with disappearing tracks.* [JHEP 06, 133 (2021)]



Model: pure case of MSSM, wino ($\widetilde{W}$) or higgsino ($\widetilde{H}$)

Low energy spectrum: chargino, $\tilde{\chi}^\pm$,+1(2) neutral particle(s) for $\widetilde{W}\,(\widetilde{H})$

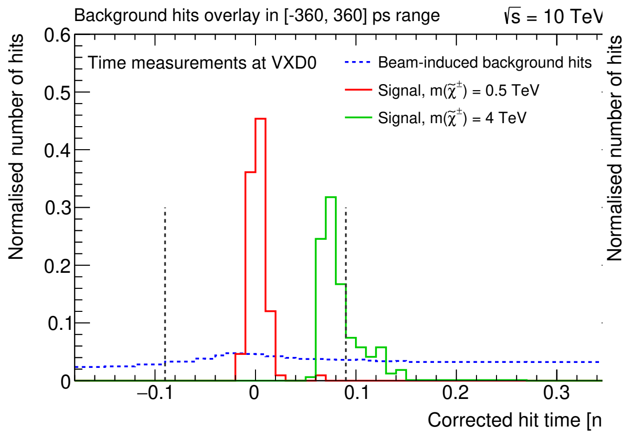
Full detector simulation including BIB

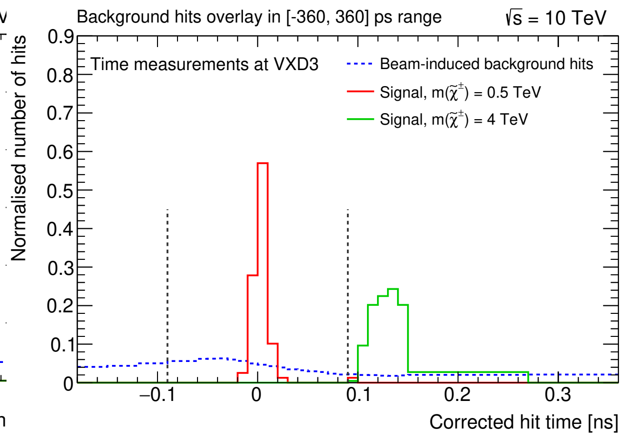
Default tracks reconstruction:

- $30 < \theta < 150$ due to BIB
- $d_0 < 0.05$ mm

Special tuning for DT:

- hit arrival time





- No hits starting from Inner Tracker

Event selection

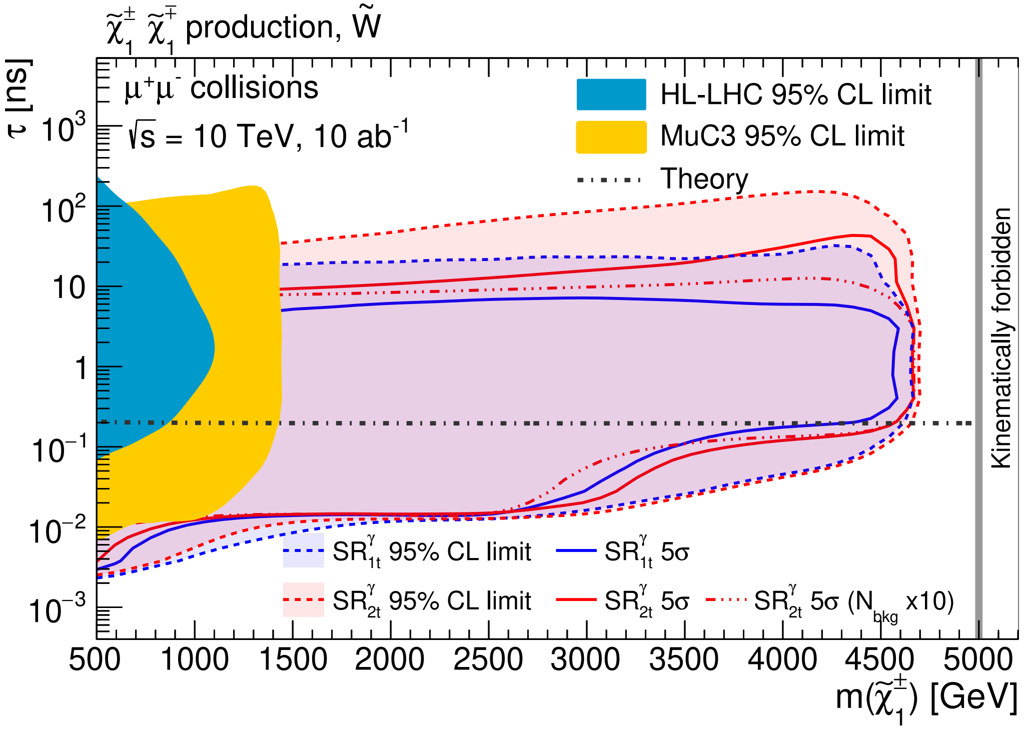
Requirement / Region	$\mathrm{SR}_{1t}^{\gamma}$	$\mathrm{SR}_{2t}^{\gamma}$
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	—	> 10
Tracklet pair Δz [mm]	—	< 0.1
Photon energy [GeV]	> 25	> 25

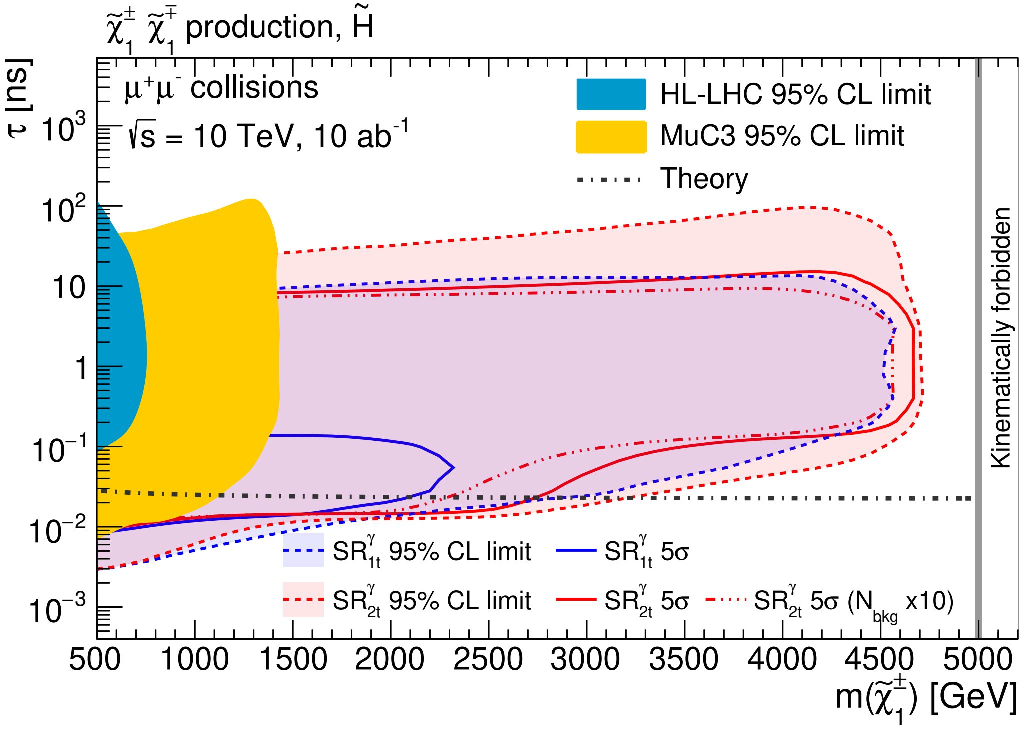
Physics background:

- hadron scattering negligible
- photon bremsstrahlung included

Disappearing tracks results

R. Capdevilla et al., *Hunting wino and higgsino dark matter at the muon collider with disappearing tracks.*
[JHEP 06, 133 (2021)]





- Lifetime coverage determined by tracking detector configuration and track reconstruction

Mono-X searches model

T. Han, et al. *WIMPs at high energy muon colliders* Phys. Rev. D 103(7), 075004 (2021).

$\mu^+\mu^- \rightarrow \chi\chi + X$

Standard Model particle: $\gamma, W, Z, \mu^{\pm}, \mu\mu$

DM particle or generic DM *n*-plet state

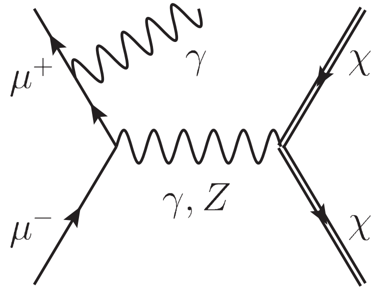
Electroweak multiplet $(1, n, Y)$ under $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ dimension $n \leq 7$

Notation:

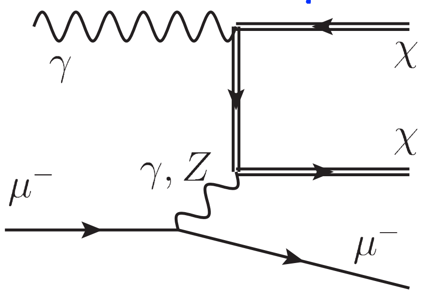
- Odd n: Dirac $\rightarrow (1, n, \varepsilon)$ ε: small hypercharge Majorana $\rightarrow (1, n, 0)$
- Even n: $Y = \frac{1}{2} \rightarrow$ neutral lightest eigenstate

Not complete signals diagrams examples

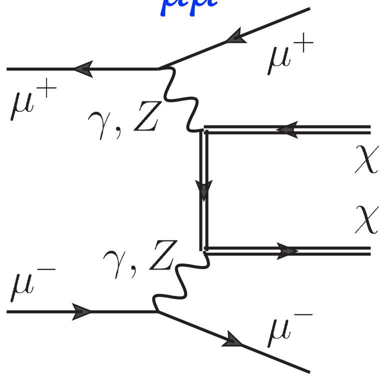
mono- γ



mono- μ

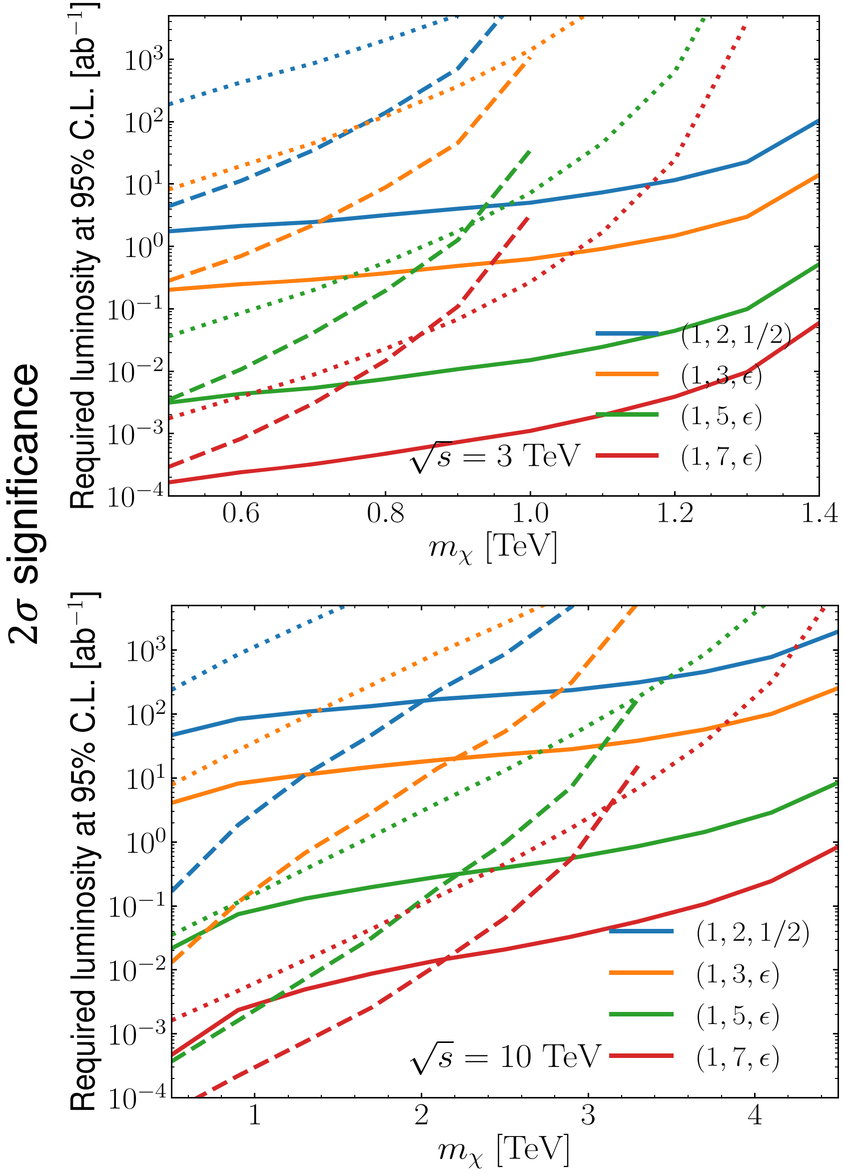


$\mu\mu$



Mono-X results

T. Han, et al. *WIMPs at high energy muon colliders* Phys. Rev. D 103(7), 075004 (2021).



mono- γ

mono- μ

$\mu\mu$

$(1, n, Y)$	Thermal target
$(1, 2, 1/2)$	1.1 TeV
$(1, 3, \varepsilon)$	2.0 TeV
$(1, 5, \varepsilon)$	6.6 TeV
$(1, 7, \varepsilon)$	16 Tev

Detector coverage: $10^o < \theta < 170^o$
No BIB considered
$m^2_{missing} \equiv p_{\mu+} + p_{\mu+} - p_\gamma > 4m^2_\chi$

mono- γ
Main background: low energy ISR photon
$E_\gamma > 50$ GeV

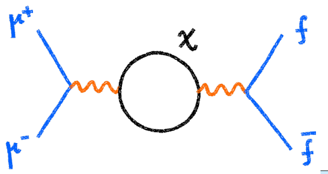
mono- μ
Dominant backgrounds: $\gamma\mu^- \to \mu^-\nu\bar{\nu}$,
$\gamma\mu^\pm \to \gamma\mu^\pm$
$E_\mu > 0.71, 2.3$ GeV ($\sqrt{s} = 3{,}10$ TeV)
$10^o < \theta_{\mu^-} < 90^o, 90^o < \theta_{\mu^+} < 170^o$

$\mu\mu$
Dominant background: $\mu^+\mu^- \to \mu^+\mu^-\nu\bar{\nu}$
$m_{\mu^+\mu^-} > 300$ GeV

Weakly Interacting Massive Particles (WIMP) in standard model measurements

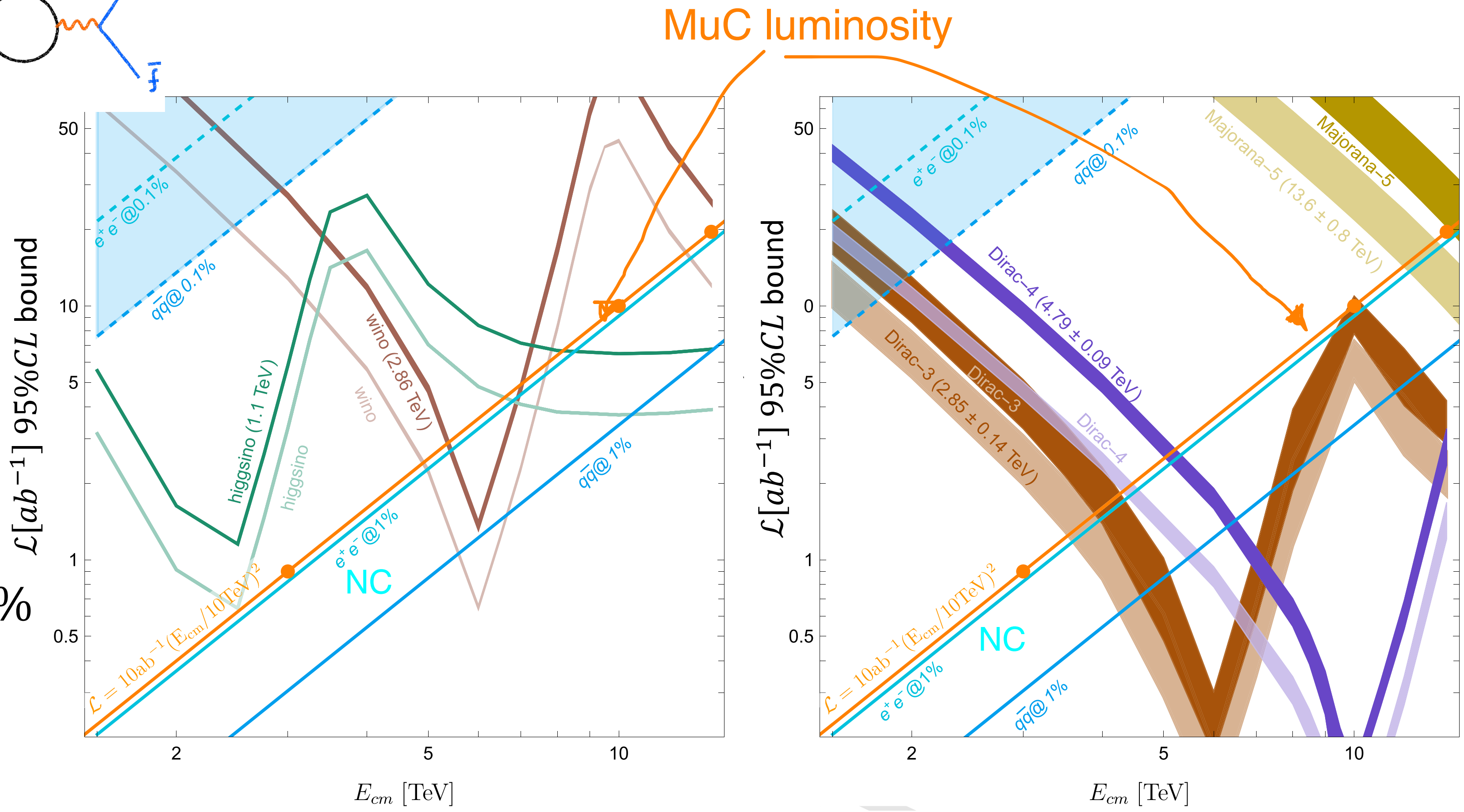
R. Franceschini, X. Zhao, *Going all the way in the search for WIMP dark matter at the muon collider through precision measurements.*
[Eur. Phys. J. C 83(6), 552 (2023)]

- Interference SM-DM
  $\mu^+\mu^- \to f'\bar{f} + X$
  $\mu^+\mu^- \to Zh/W^+W^- + X$



- SM syst. uncert. 0.1% - 1%
- Observables: $\sigma, d\sigma/d\cos\theta$

- $t\bar{t}, W^+W^-$: hadronic and semileptonic decay
- $HZ, H \to b\bar{b}\ Z \to \ell^+\ \ell^-$
- qq: u, d, s, c, b $\varepsilon_{tagging} = 100\%$
- $e^+e^-, \mu^+\mu^-$: 100% efficiency
- $\tau^+\tau^-$: 50% efficiency
- Particles $8^o < \theta < 172^o$

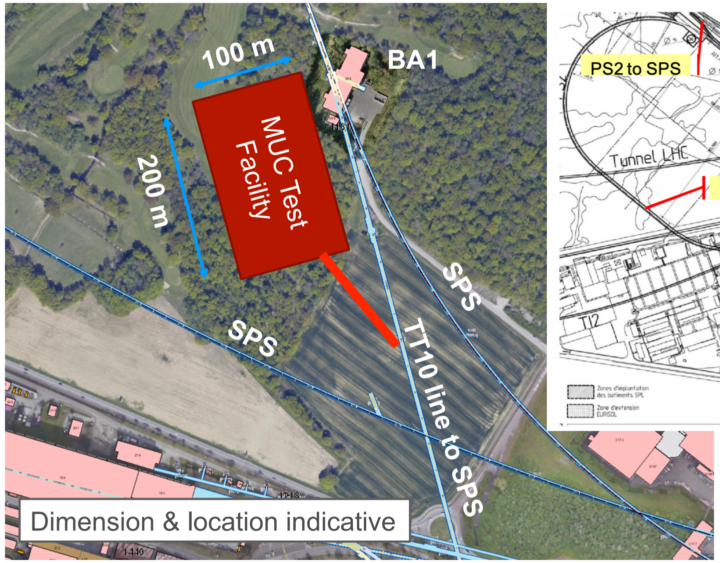


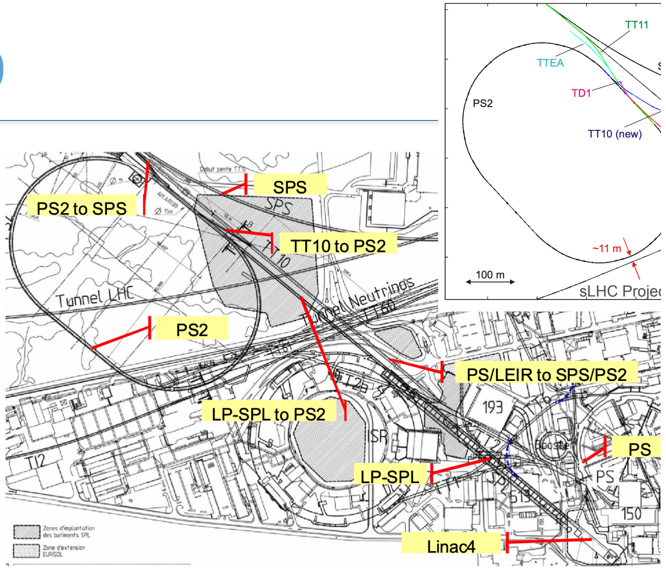
Dark/light curves unpolarized/polarized beams (30%)
WIMP thermal mass for each process in ()

You may think that measurements at Muon Collider are far in time…
… true but we are asking the community to support the construction of a demonstrator facility.

Demonstrator facility needed:
- muon cooling system for 6D cooling principle at low emittance including re-acceleration
- high gradients and relatively high-field solenoids
- high-power target

Possibility around TT10



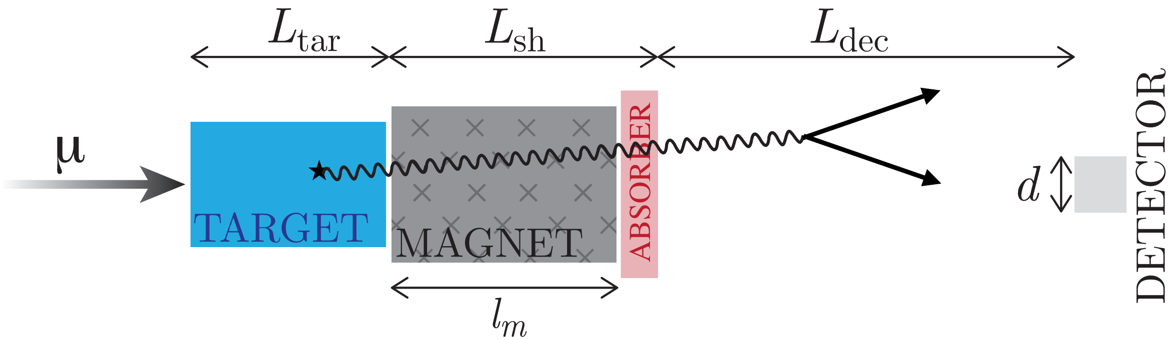


M. Benedikt, LHC Performance Workshop, Chamonix
CERN-AB-2007-061

Not only technology demonstrator
Physics measurements may be possible

C. Cesarotti, et al. *Probing New Gauge Forces with a High-Energy Muon Beam Dump* Phys. Rev. Lett. 130, 7 071803 2023

Dark photon search



… and that’s all I have.
I conclude:

First detector concept at Muon Collider has physics object reconstruction performance already sufficient to explore several model of DM.

The situation (of DM searches) at colliders is changed dramatically by the possibility to build high energy muon collider.

(R. Franceschini, X. Zhaob Eur. Phys. J. C 83(6), 552 (2023))

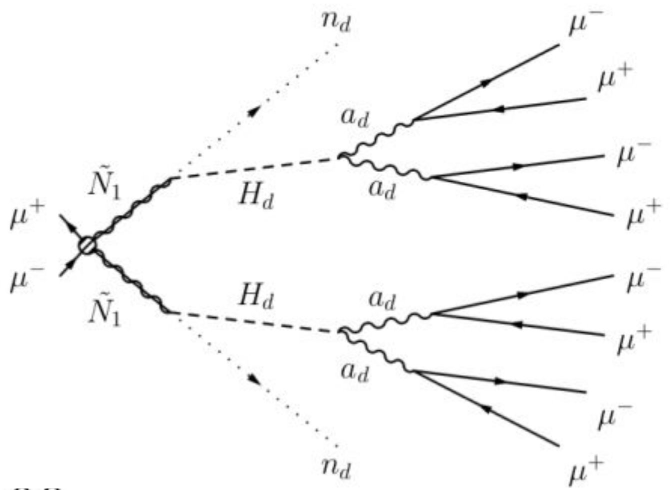
Demonstrator can enable physics measurements well before the final machine.

International MUON Collider Collaboration

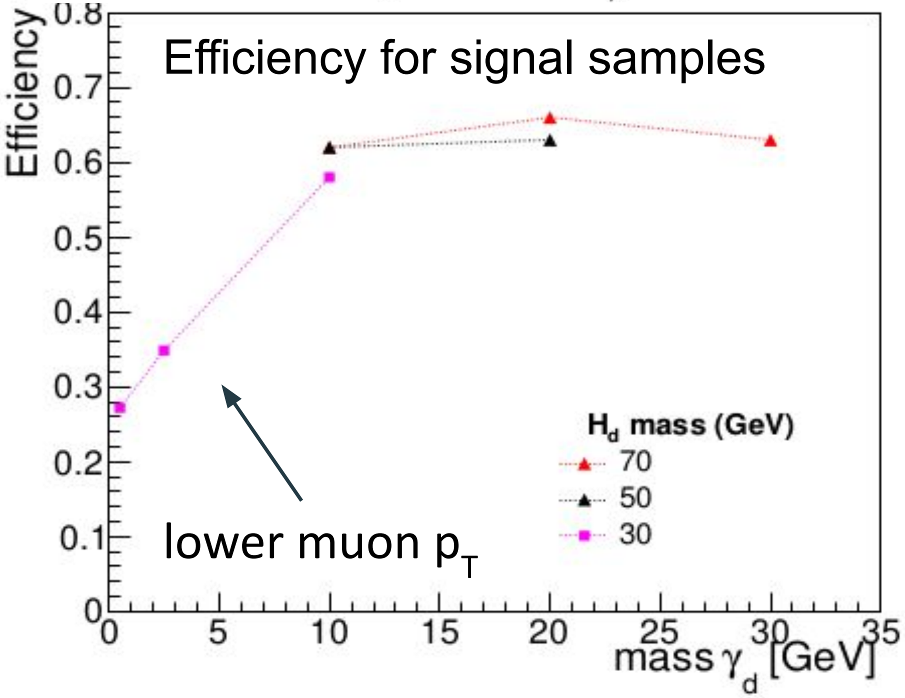
Additional Slides

Preliminary study of dark SUSY at $\sqrt{s}$=3 TeV

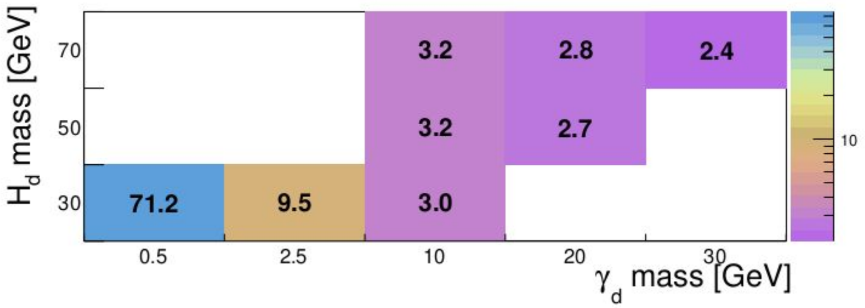
C.Aimè et al. *Dark-SUSY channels to study muon reconstruction performance at the Muon Collider* [EPS-2021](EPS-2021)



- Lightest MSSM neutralino → dark Higgs → dark photons
- Final state: 8 μ
- Background 8 μ negligeable
- Background 8 $\mu + \nu$ impossible to generate, under study
- Full simulation of the detector, BIB negligeable effect

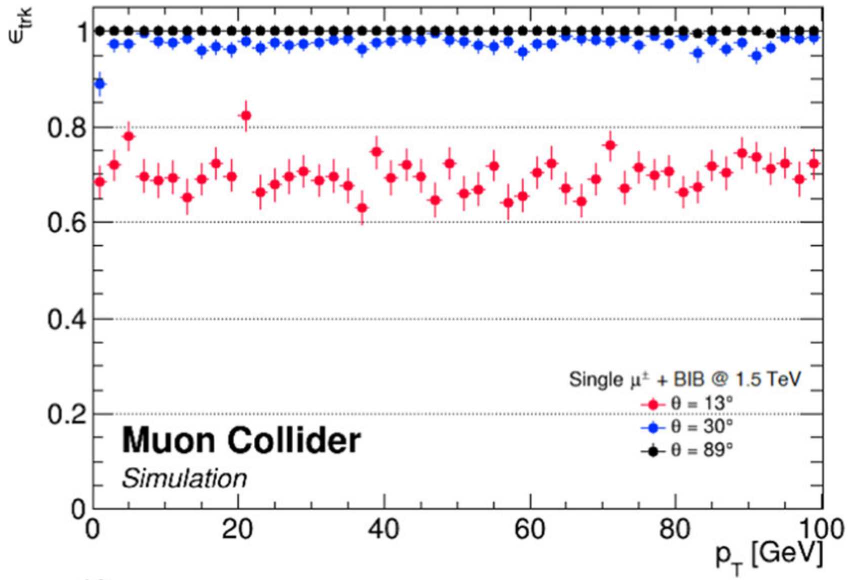


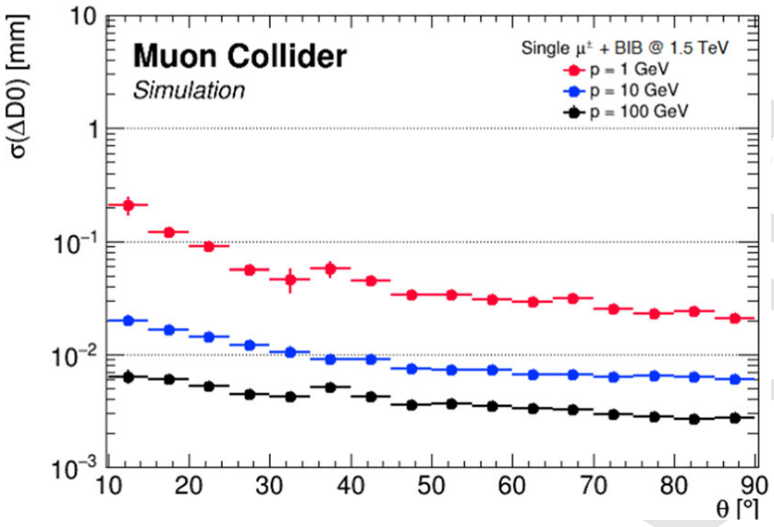
Signal yield for 1 ab^{-1}



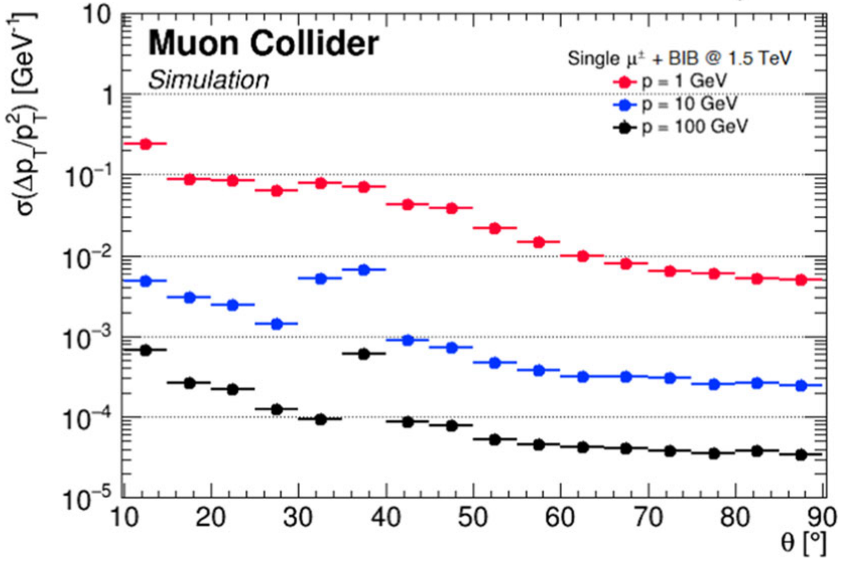
Limits under evaluation

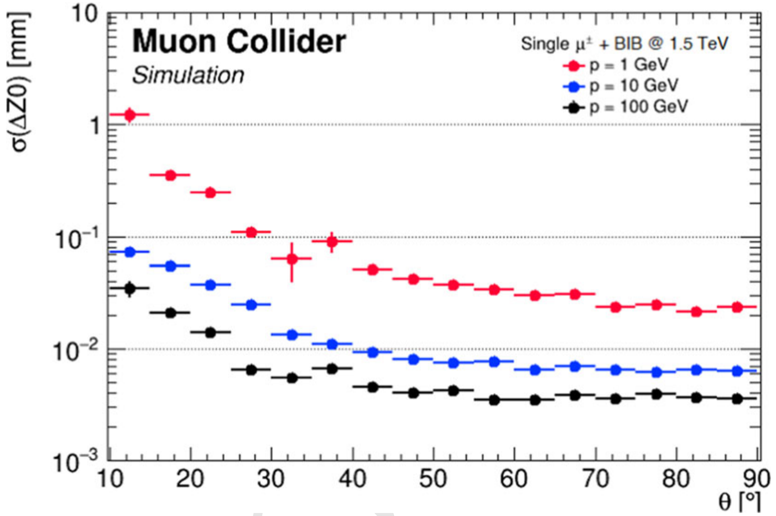
Track reconstruction performance



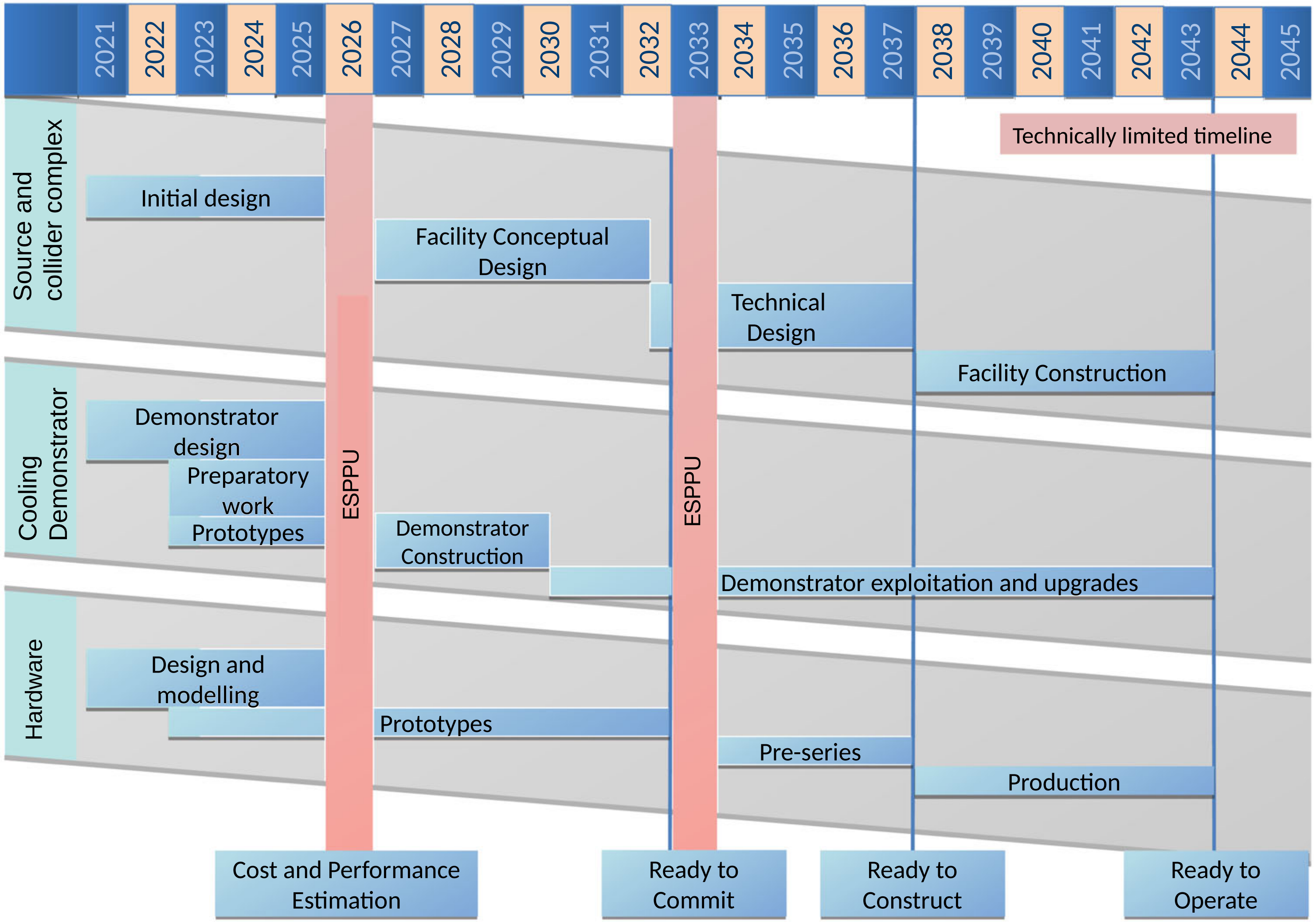


Track efficiency affected by BIB

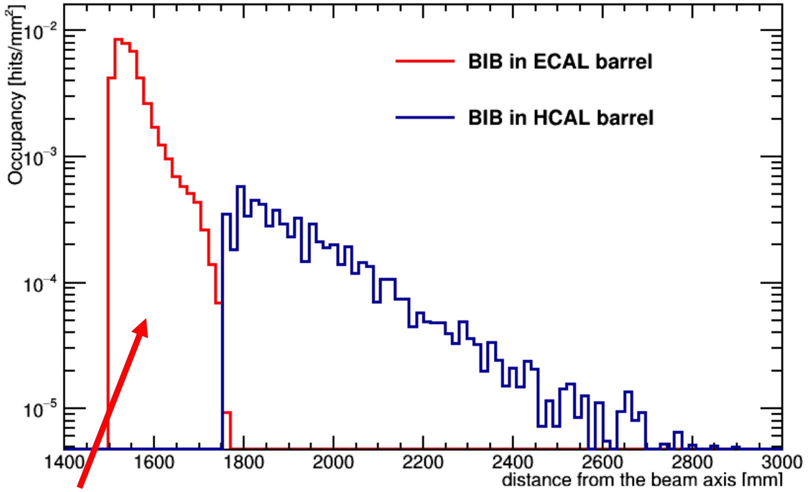




Technically limited timeline

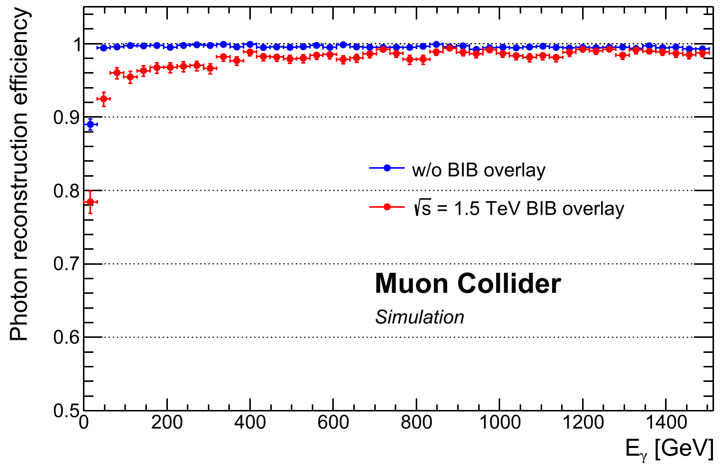


Photon & electron reconstruction performance

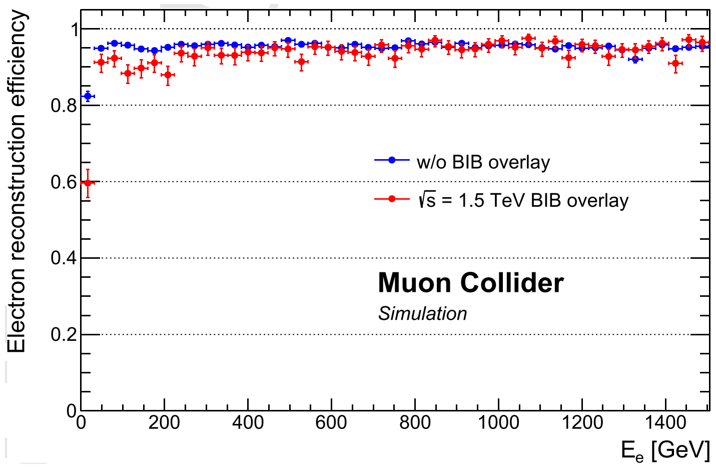


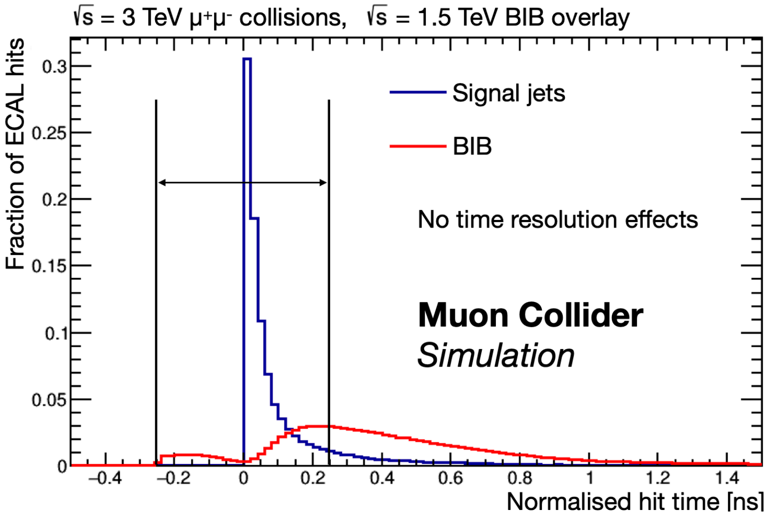
High level of BIB

E_{hit}> 2 MeV

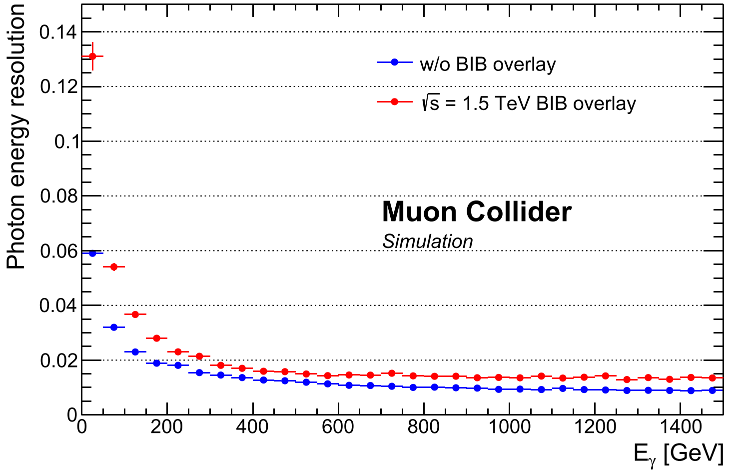


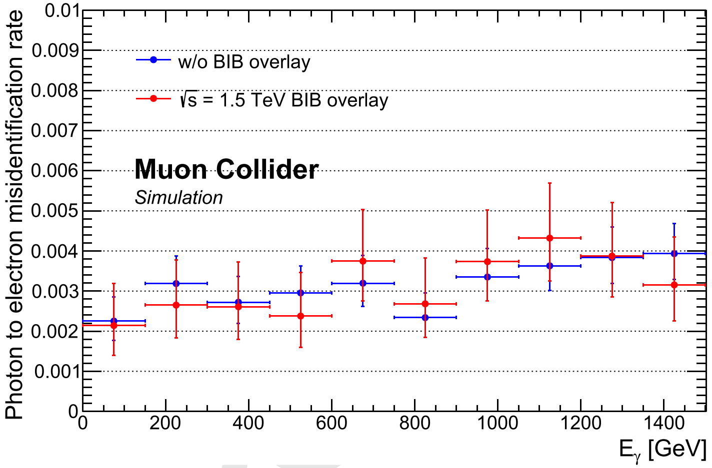
E_{hit}> 5 MeV



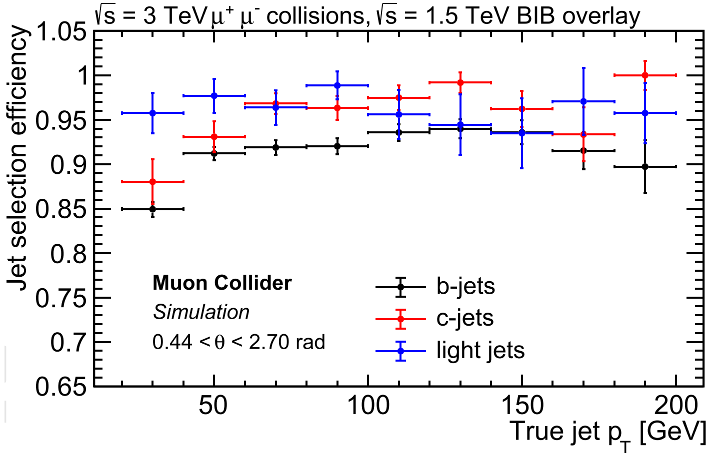


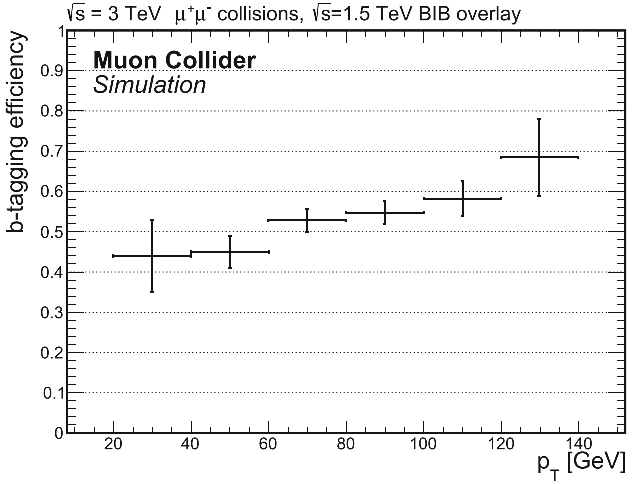
time information helps

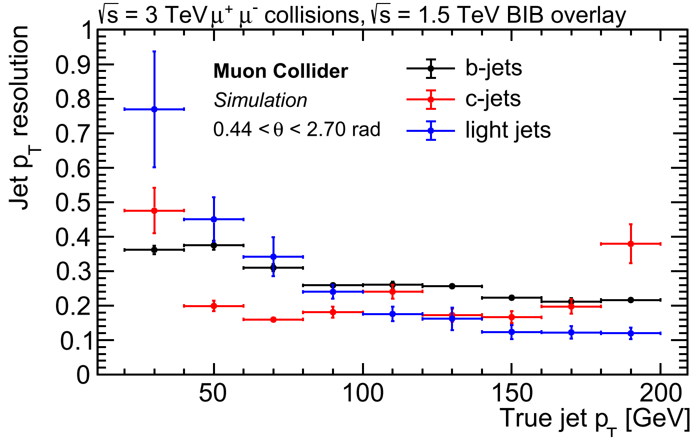


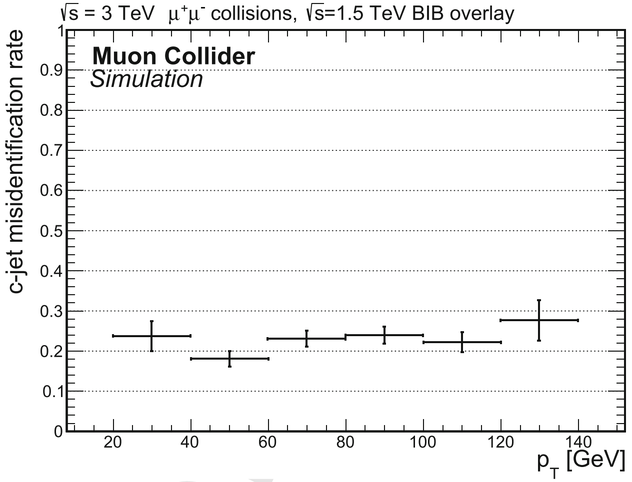


Jet reconstruction performance

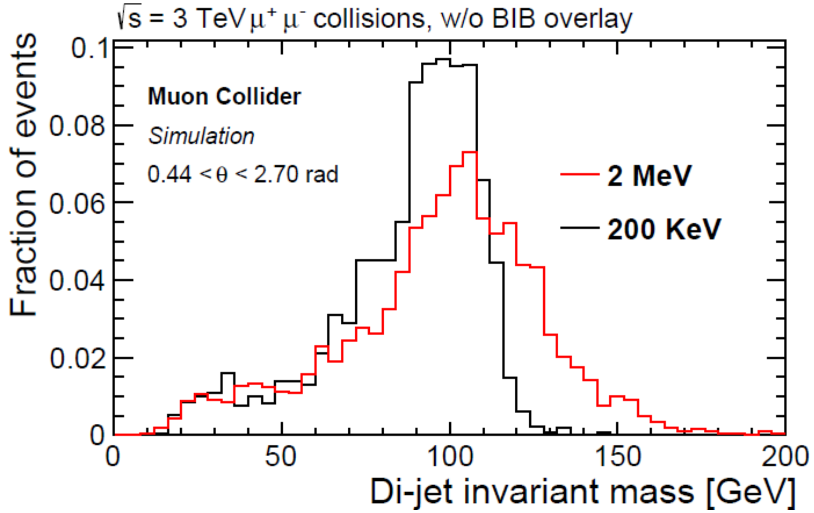






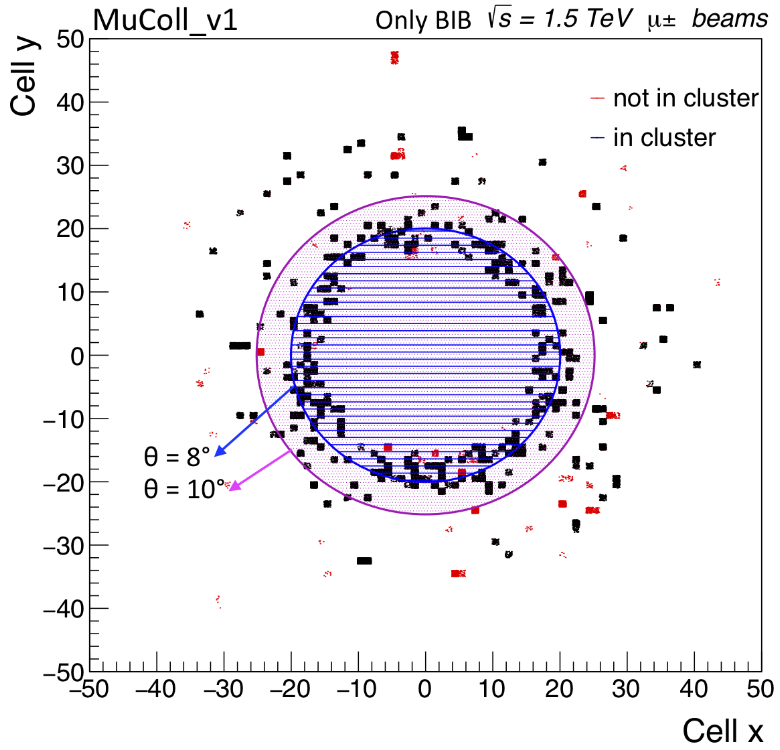


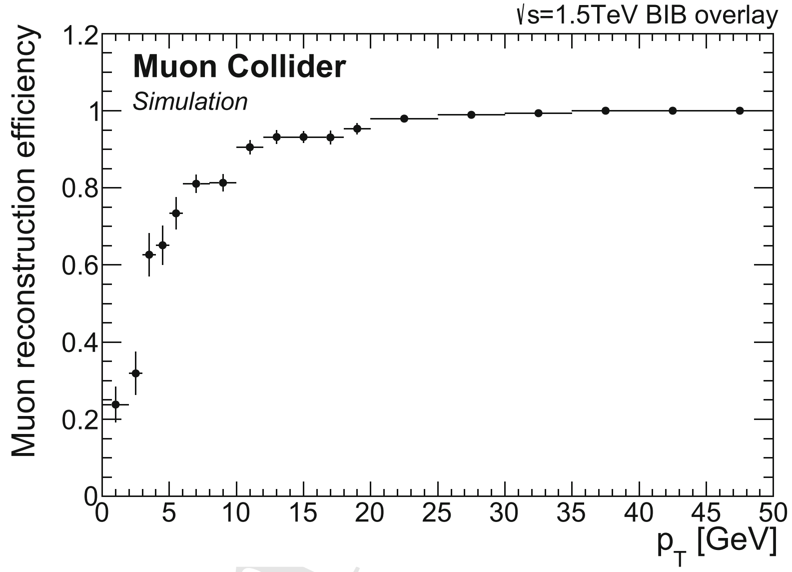
Bias due to E_{hit}> 2 MeV

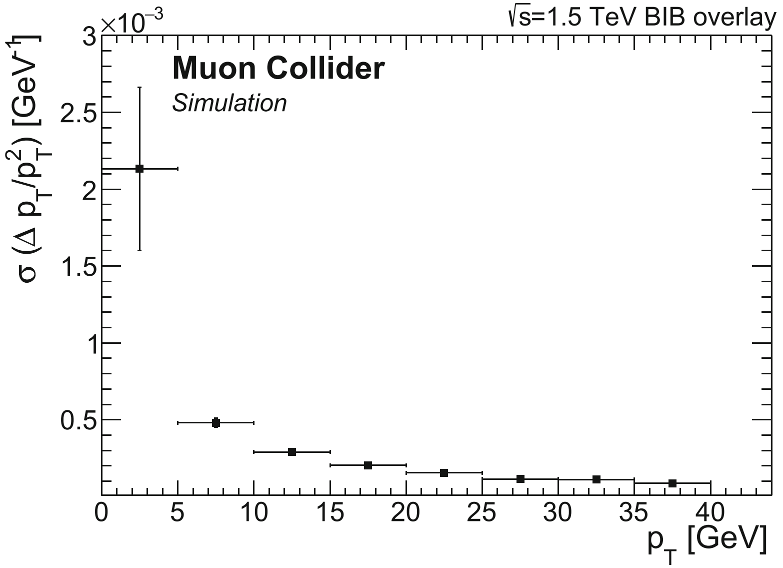


Muon reconstruction performance

BIB: mainly neutrons & photons
Affects endcap around the beamline
Not important as for tracker and ECAL

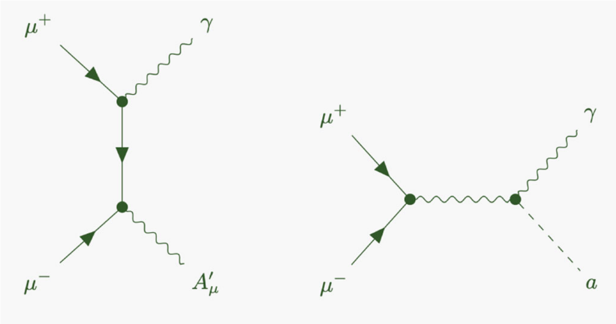






Dark photon and Axion-Like Particle

M. Casarsa, et al. *Monochromatic single photon events at the muon collider*
Phys. Rev. D 105(7), 7153 075008 (2022)



Full detector simulation including beam-induced background

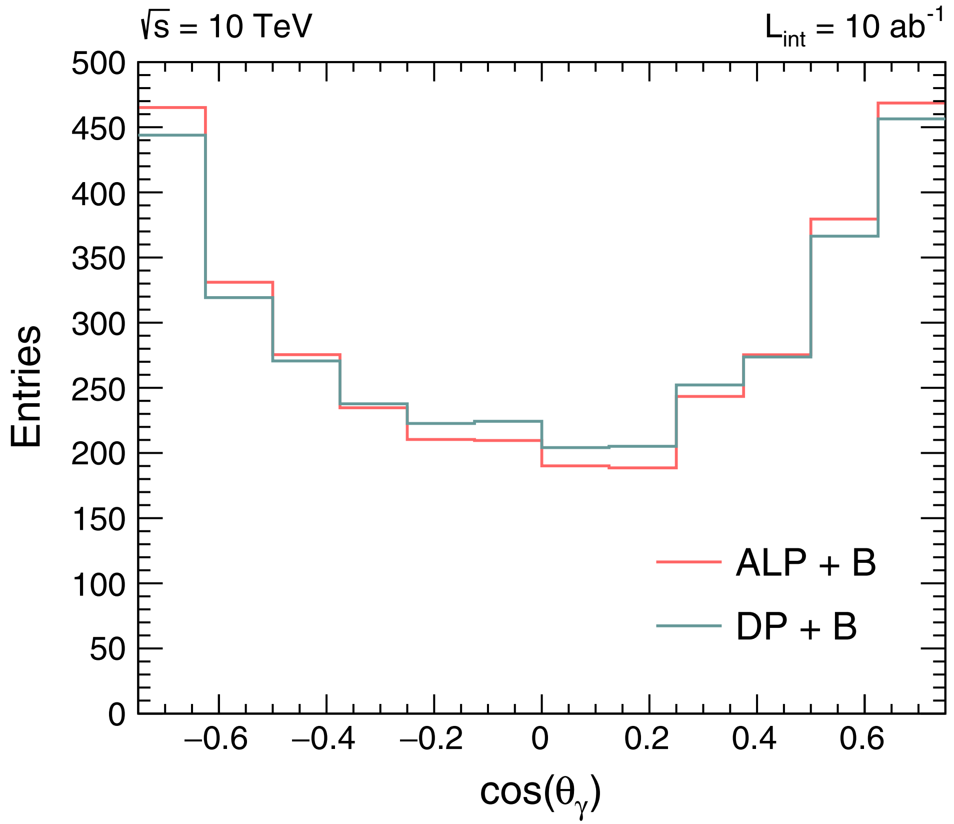
Dominant background

$\mu^+\mu^- \rightarrow \gamma\nu\bar{\nu}$

Event requirements:

$10^o < \theta_{\mu^-} < 90^o$

$E_\gamma > 1450(4800)$ GeV for $\sqrt{s} = 3(10)$ TeV



Separation of dark photon from ALP done by using angular distribution