Hunting for Inert Triplet Scalars at a Muon Collider

μ^+ μ^-

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Based on:
P. Bandyopadhyay, S. Parashar, C. Sen, J.H. Song. *JHEP 07 (2024) 253*

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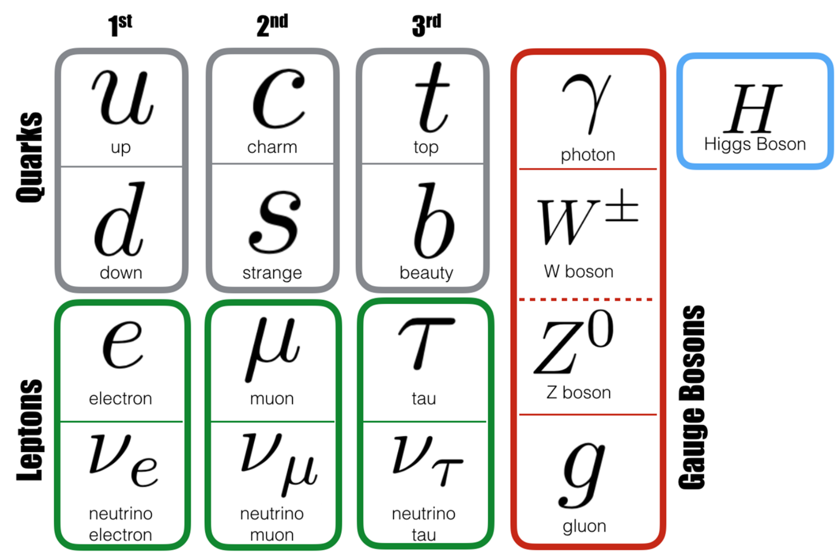
The (not very) Standard Model

- A unification of strong, weak and EM interactions within the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$

- Discovery of the Higgs boson in 2012 completed the model.

- Still plagued by observations that require explanation.

- Cannot explain Dark Matter, neutrino mass, etc etc.



We need to venture
Beyond the Standard Model (BSM)!

The Inert Triplet Model (ITM)

Extend the SM scalar sector with an $SU(2)$ triplet with $Y = 0$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \mathcal{T} = \frac{1}{2}\begin{pmatrix} T^0 & \sqrt{2}T^+ \\ \sqrt{2}T^- & -T^0 \end{pmatrix}$$

scalar potential

$$V(\Phi, \mathcal{T}) = \mu_h^2 \Phi^\dagger \Phi + \mu_T^2 Tr(\mathcal{T}^\dagger \mathcal{T}) + \lambda_h |\Phi^\dagger \Phi|^2 + \lambda_T (Tr|\mathcal{T}^\dagger \mathcal{T}|)^2 + \lambda_{hT} (\Phi^\dagger \Phi) Tr(\mathcal{T}^\dagger \mathcal{T})$$

$\mathcal{T}$ is odd under a discrete Z_2 symmetry, all SM fields are even => T^0 does not get a vev.

After EWSB: Scalar mass spectrum => $M_h^2 = 2\lambda_h v^2, \quad M_{T^0}^2 = M_{T^\pm}^2 = \frac{1}{2}\lambda_{hT} v^2 + \mu_T^2.$

At tree-level, T^0, $T^\pm$ are degenerate: at one-loop level, $M_{T^\pm} - M_{T^0} \sim 166\,\mathrm{MeV}$

This means T^0 is the lightest inert particle: Dark Matter (DM) candidate!

Small mass splitting leads to long lifetimes => displaced decays.

$$T^\pm \to T^0 \pi^\pm \quad BR \sim 97.7\%,$$
$$T^\pm \to T^0 e^\pm \nu_e \quad BR \sim 2\%,$$
$$T^\pm \to T^0 \mu^\pm \nu_\mu \quad BR \sim 0.25\%,$$

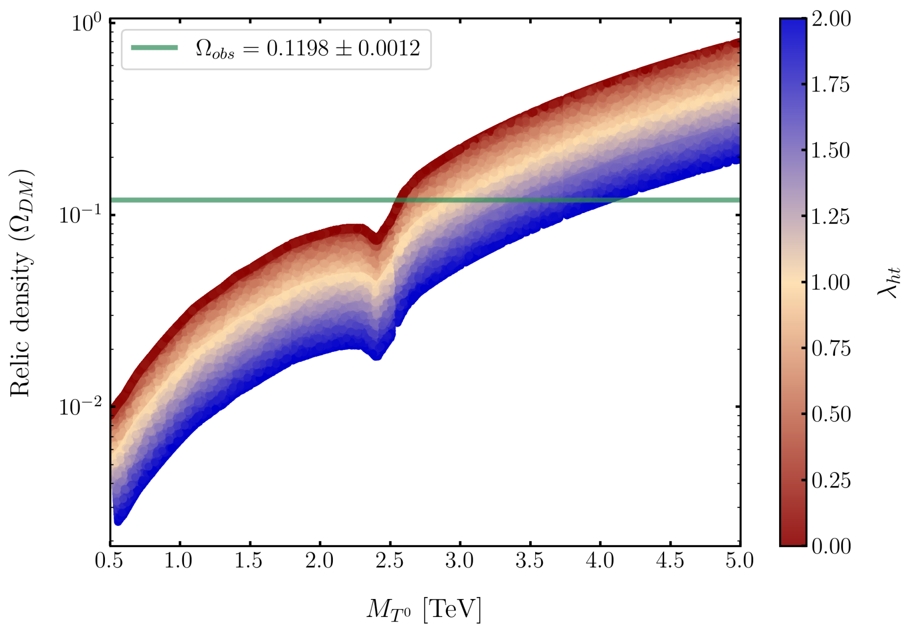
Proper lifetime ~ 0.19 ns

Rest mass decay length ~ 5.7 cm

Cirelli *et al,* Nucl. Phys. B 753 (2006) 178-194

DM constraints and Collider Benchmarks

DM Relic density



Benchmarks for Collider Study

BP	M_{T^0} [TeV]	λ_{ht}	$\Omega_{\rm DM}$	$\Omega_{\rm DM}/\Omega_{obs}$
BP1	1.21	0.026	0.037	0.312
BP2	1.68	0.0	0.063	0.525
BP3	3.86	1.861	0.119	1.000

Relic-satisfying points between 2.5 – 3.8 TeV are excluded by Fermi-LAT data.

From a purely collider perspective, a discovery projection is performed independently, later.

Why a muon collider?

- Production rates of TeV scale particles such as ours are very small at the 14 TeV LHC. 100 TeV FCC: too much background.
- Muons are fundamental particles: all of the centre-of-mass (COM) energy is available for collision.

Accettura et al, *Towards a Muon Collider,* 2303.08533

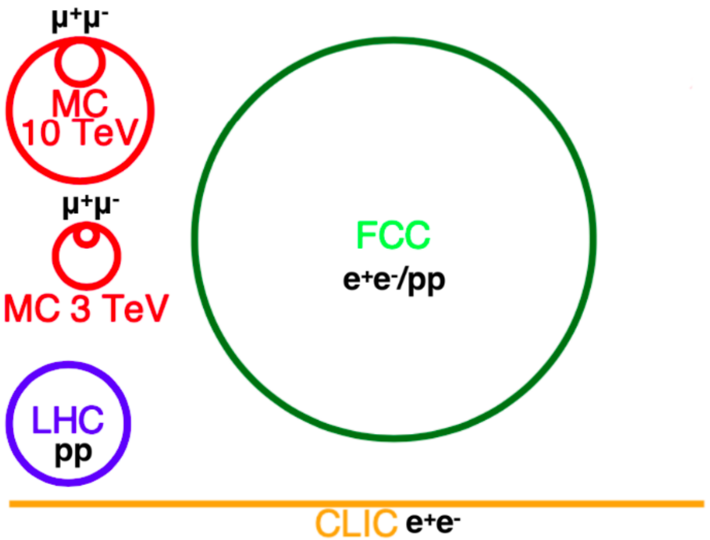
- Less background from QCD processes: hadronically clean environment: higher precision.
- Aimed to be a high-precision, high-luminosity discovery machine for BSM particles.
- $E_{CM}\ (\sqrt{s})$ and luminosity goals:

3 TeV → 1 /ab

6 TeV → 4 /ab

10 TeV → 10 /ab

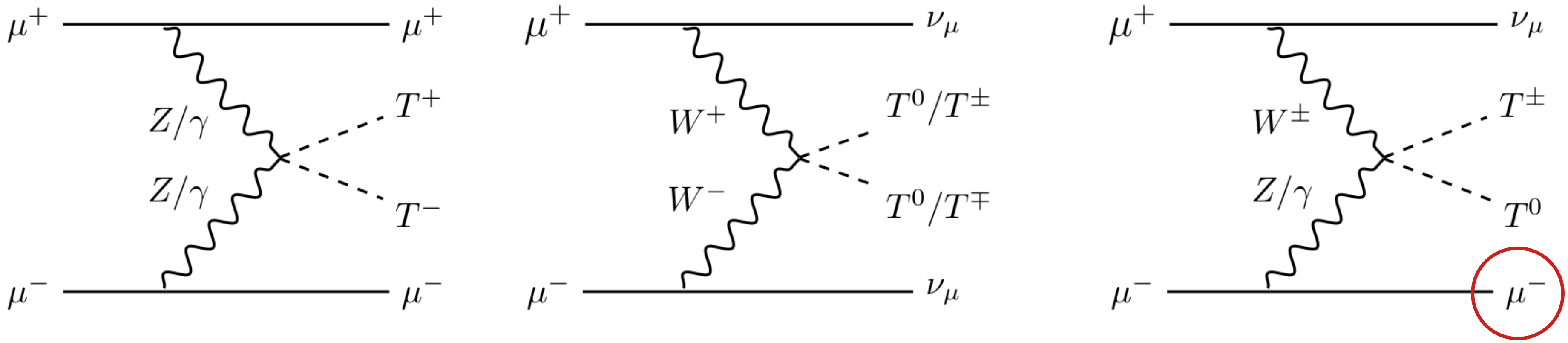
Centre-of-mass energies for our analysis



L. Sestini, EPS HEP2023

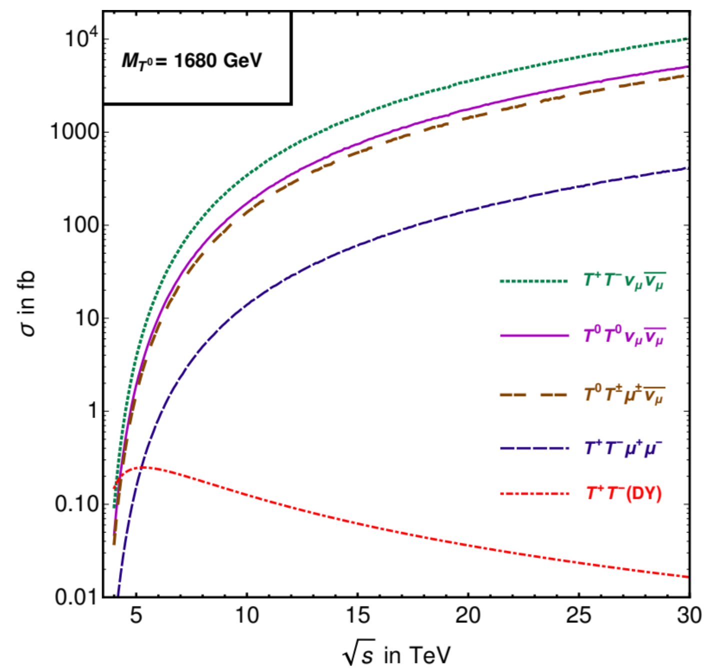
Al Ali et al, *The Muon Smasher's Guide,* Rept.Prog.Phys. 85 (2022) 8, 084201

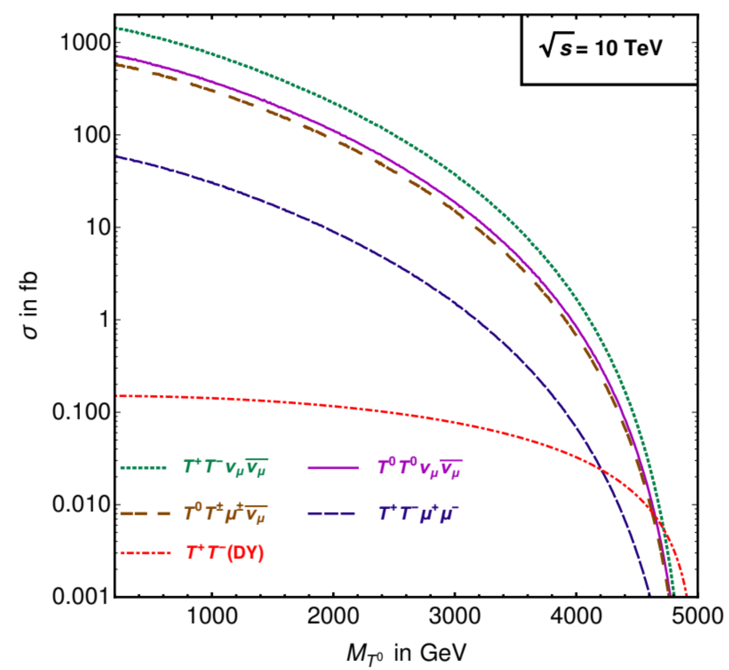
Production of ITM scalars from VBF at a muon collider



spectator muons with high energy and very forward

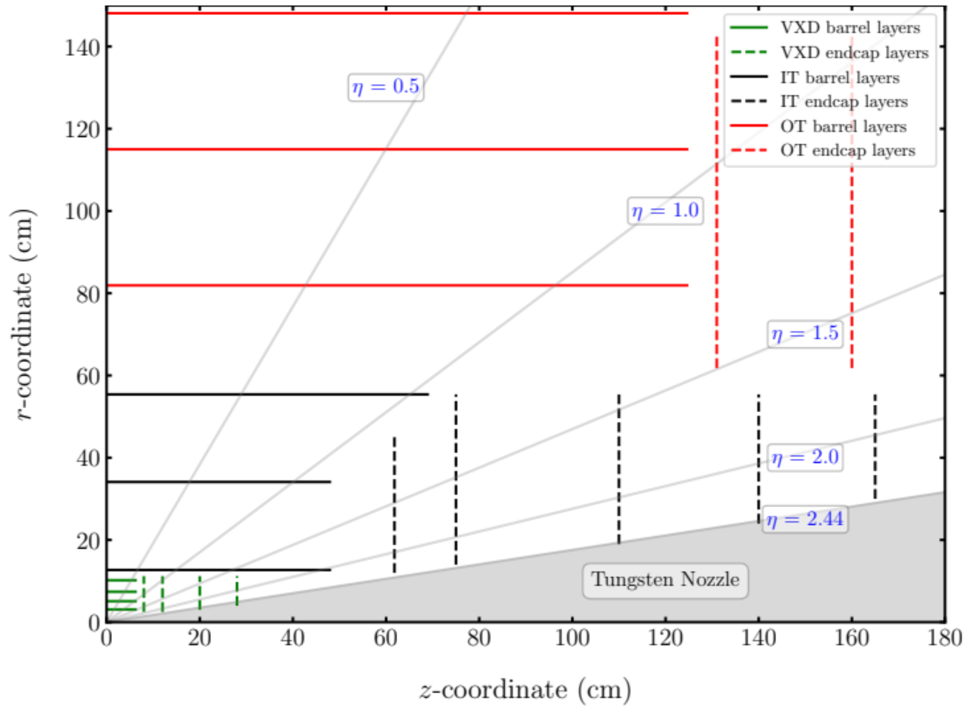
- At higher energies, muon colliders are essentially vector boson fusion (VBF) machines, as cross-sections grow $\propto \log^n(s/M_V^2)$





Muon collider detector

- Less SM QCD backgrounds, but muon collider suffers from Beam Induced Backgrounds (BIB): swarm of soft photons, leptons and charged hadrons coming from beam muons decaying in flight.
- BIB is mostly in the forward directions with $|\eta| \geq 2.5$: Tungsten nozzles to be installed so they can be absorbed.Tracking system and calorimeter coverage upto $|\eta| < 2.5$ only.
- VBF spectator muons are high-energy and highly forward: can pass through nozzles, can be detected at dedicated forward muon facility.



Simulated Detector Performance at the Muon Collider, International Muon Collider Collaboration, arXiv: 2203.07964 [hep-ex]

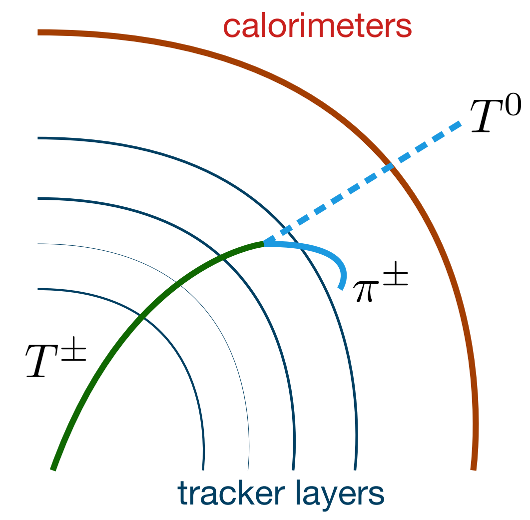
Final states for model signature

- Displaced decay of $T^{\pm} \to T^0 \pi^{\pm}$ gives very soft pions: difficult to detect due to BIB.
- Invisible decay product → Disappearing charged track (DCT) for $T^{\pm}$
- High-energy VBF muons with high pseudorapidity: Forward muons : can be tagged
- VBF spectator neutrinos are not detectable.
- Summary: four possible final states from two VBF signal processes:

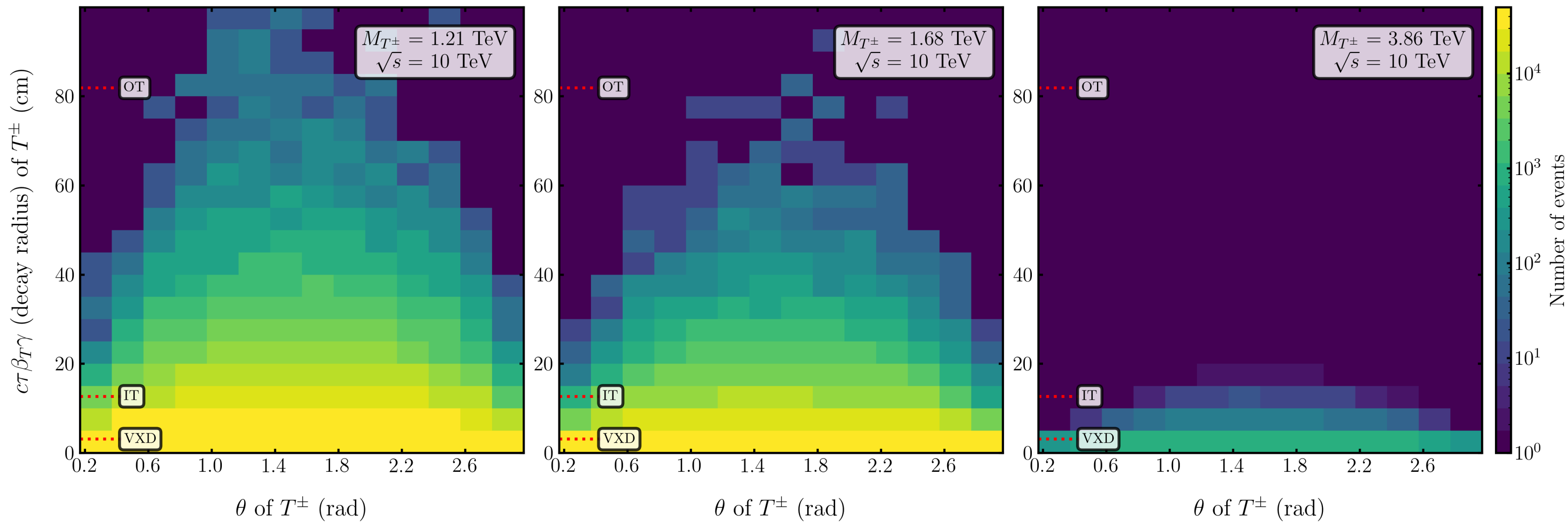
FS1: 1 DCT + 1 Forward muon + MET $\Longleftarrow T^{\pm}T^0\mu^{\pm}\nu, \quad T^+T^-\mu^+\mu^-;$
FS2: 2 DCT + 2 Forward muons + MET $\Longleftarrow T^+T^-\mu^+\mu^-;$
FS3: 1 DCT + 2 Forward muons + MET $\Longleftarrow T^+T^-\mu^+\mu^-;$
FS4: 2 DCT + 1 Forward muon + MET $\Longleftarrow T^+T^-\mu^+\mu^-.$

Analysis strategy:

- Generate VBF signal events with `MadGraph5`
- Use the `delphes_card_MuonColliderDet.tcl` to simulate the detector.
- To take care of $T^{\pm}$ tracking efficiencies against fake tracks from BIB, use the explicit map provided by Capdevilla et al in JHEP 06 (2021) 133.
- Veto out calorimeter hits + Track p_T > 300 GeV : Negligible SM bkg, only fake tracks from BIB.

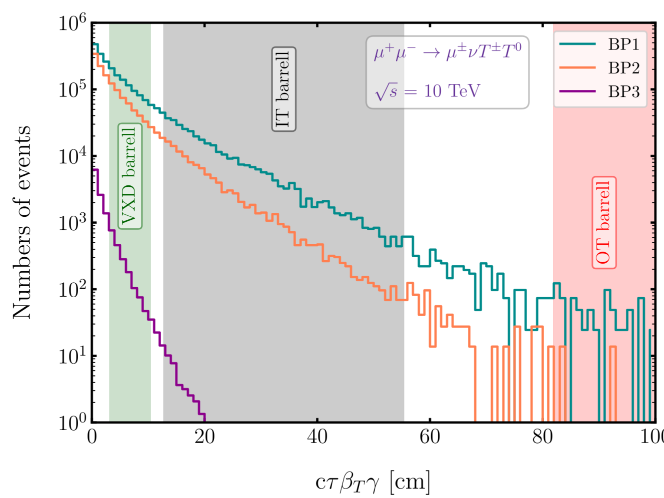


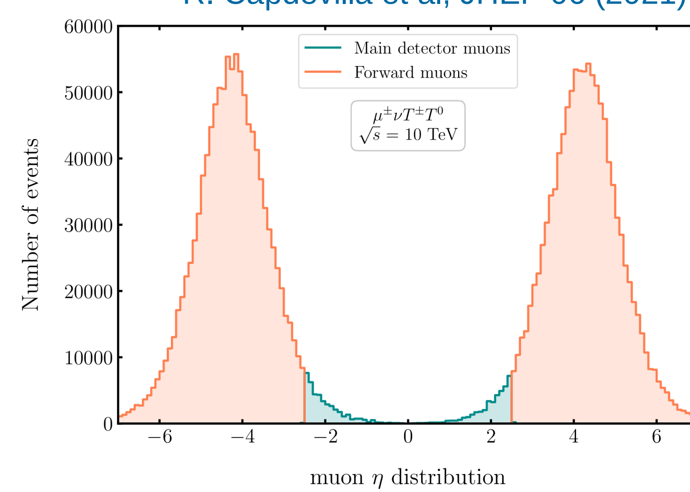
Signal kinematics



More BIB in forward regions and early tracker layers → less tracking efficiency

R. Capdevilla et al, JHEP 06 (2021) 133

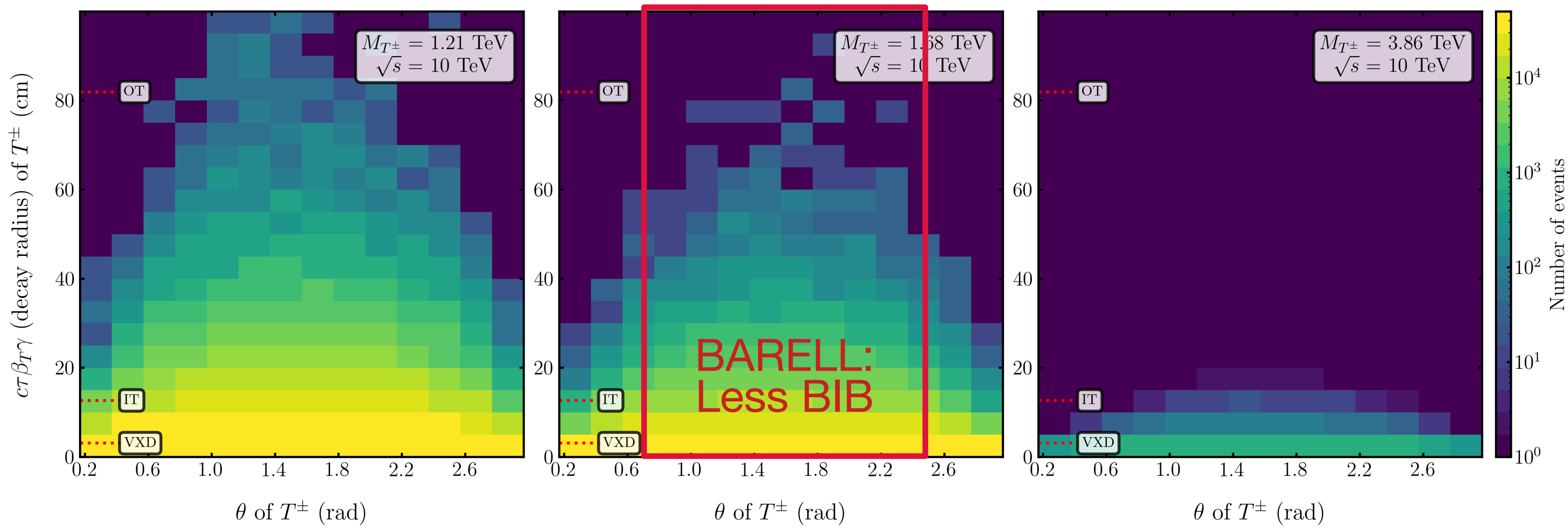




Selection criteria for DCT:
0.7 rad < θ < 2.44 rad (barrell)
5.1 cm < decay radius < 148.1 cm

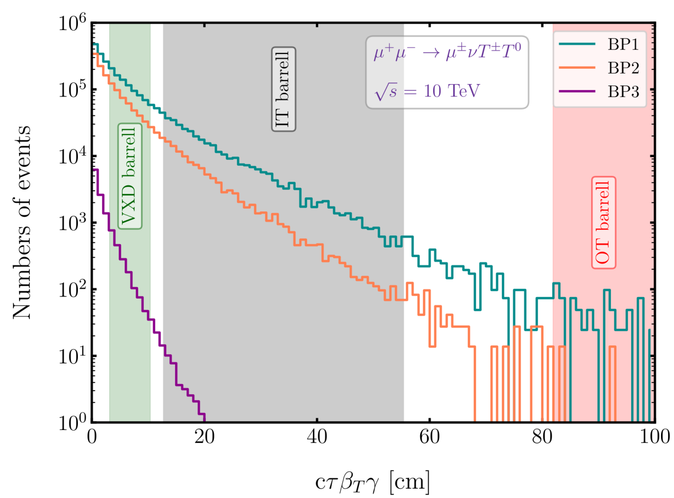
Selection criteria for Forward $\mu^\pm$
2.5 $\leq |\eta| \leq$ 7.0
$p_{\mu_F} \geq$ 300 GeV.

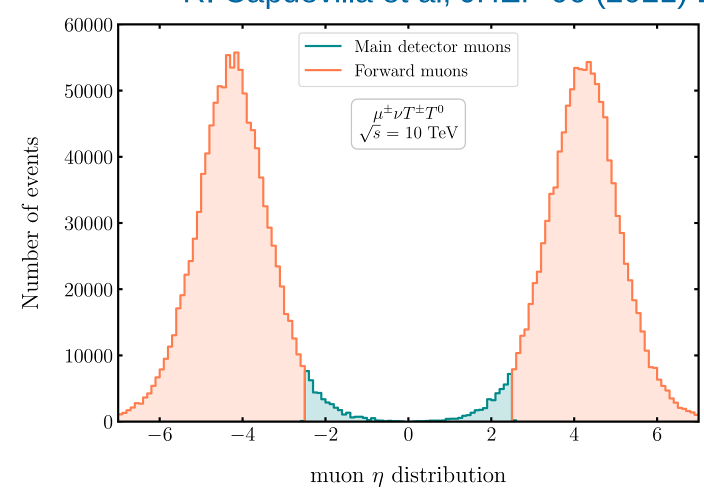
Signal kinematics



More BIB in forward regions and early tracker layers → less tracking efficiency

R. Capdevilla et al, JHEP 06 (2021) 133





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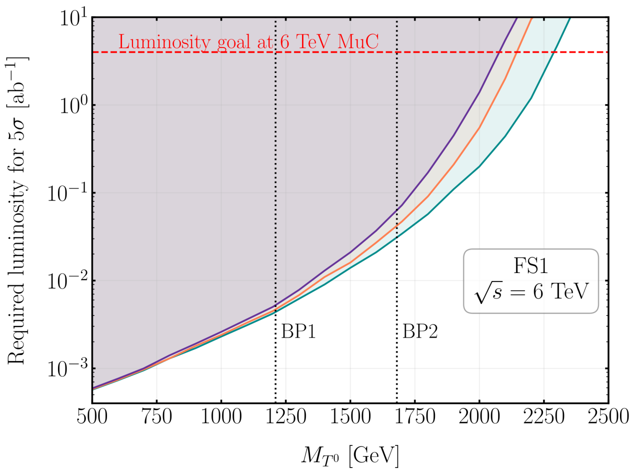
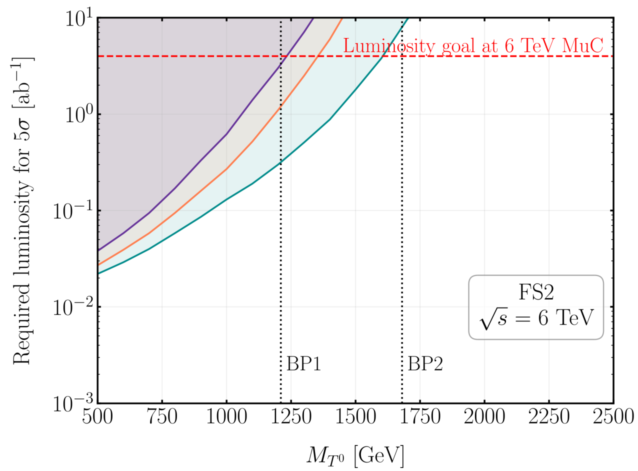
$2.5 \leq |\eta| \leq 7.0$
$p_{\mu_F} \geq$ 300 GeV.

Discovery projections: 6 TeV Muon Collider

1 DCT + 1 Forward muon



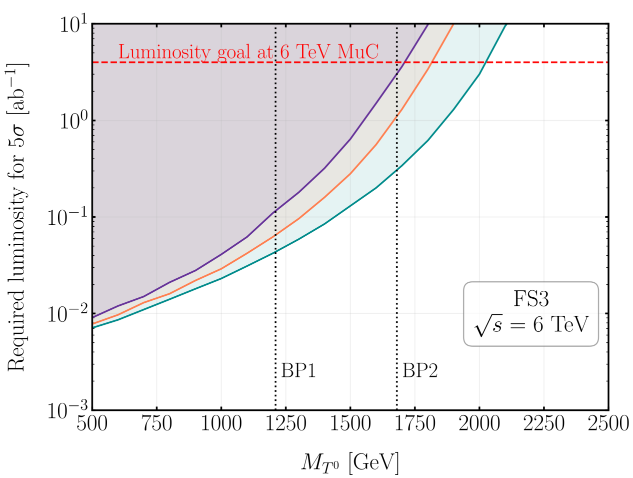
2 DCT + 2 Forward muon



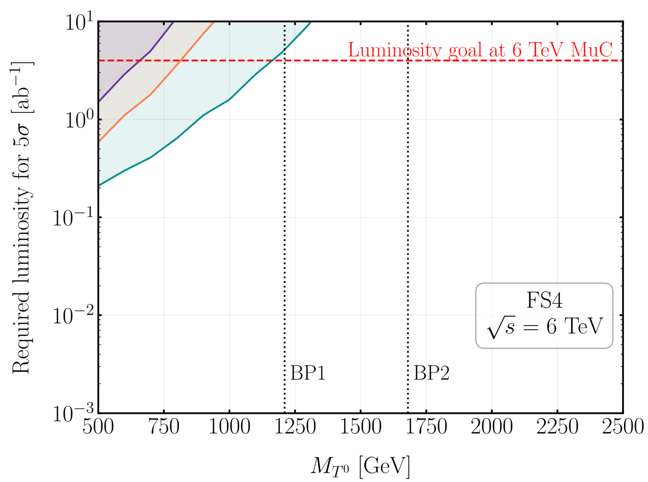
FS1 and FS3 can probe well beyond BP2 masses, with Forward muon tagging. BP3 is beyond kinematic reach.

Forward muon tagging enhances performance.

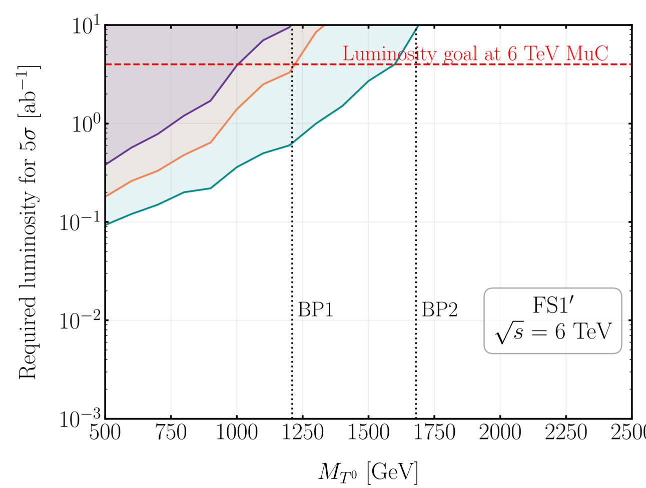
1 DCT + 2 Forward muon



2 DCT + 1 Forward muon

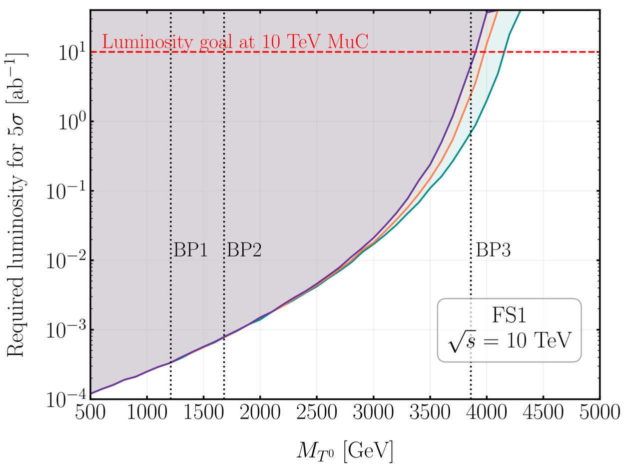


1 DCT + 1 main detector muon

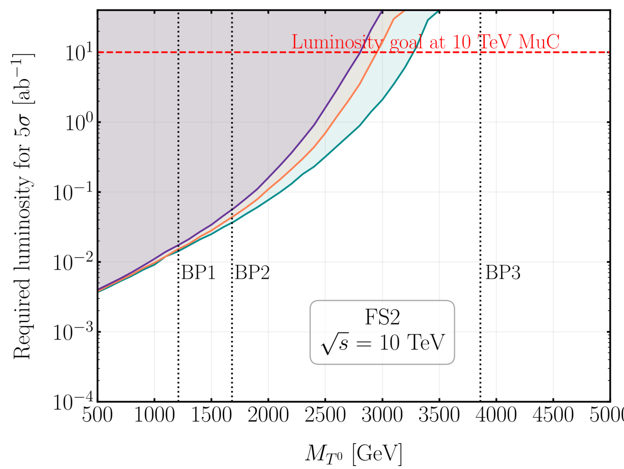


Discovery projections: 10 TeV Muon Collider

1 DCT + 1 Forward muon



2 DCT + 2 Forward muon

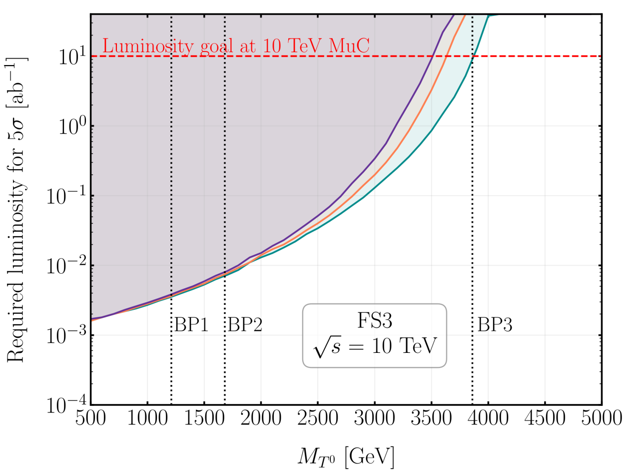


FS1 and FS3 can probe masses of all three BPs with the luminosity goal.

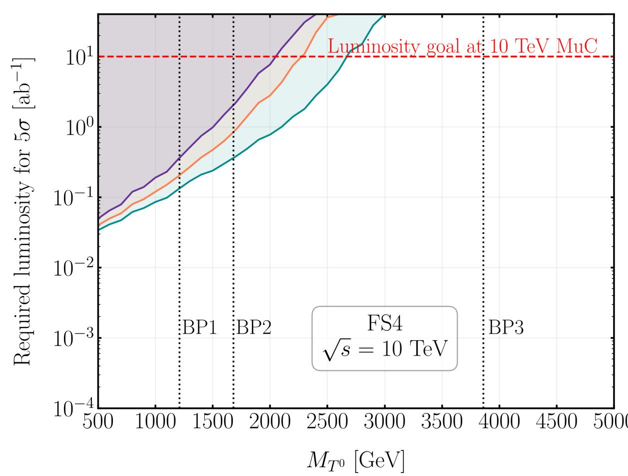
Maximum reach of 4.2 TeV (3.2 TeV) with (without) Forward muons.

10 backgrounds | 200 backgrounds | 600 backgrounds

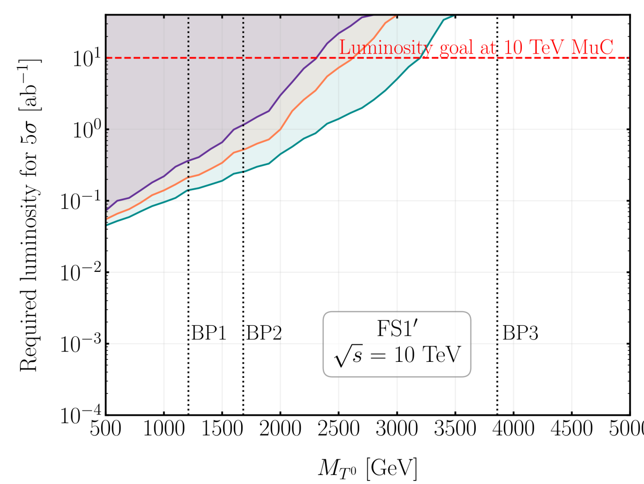
1 DCT + 2 Forward muon



2 DCT + 1 Forward muon



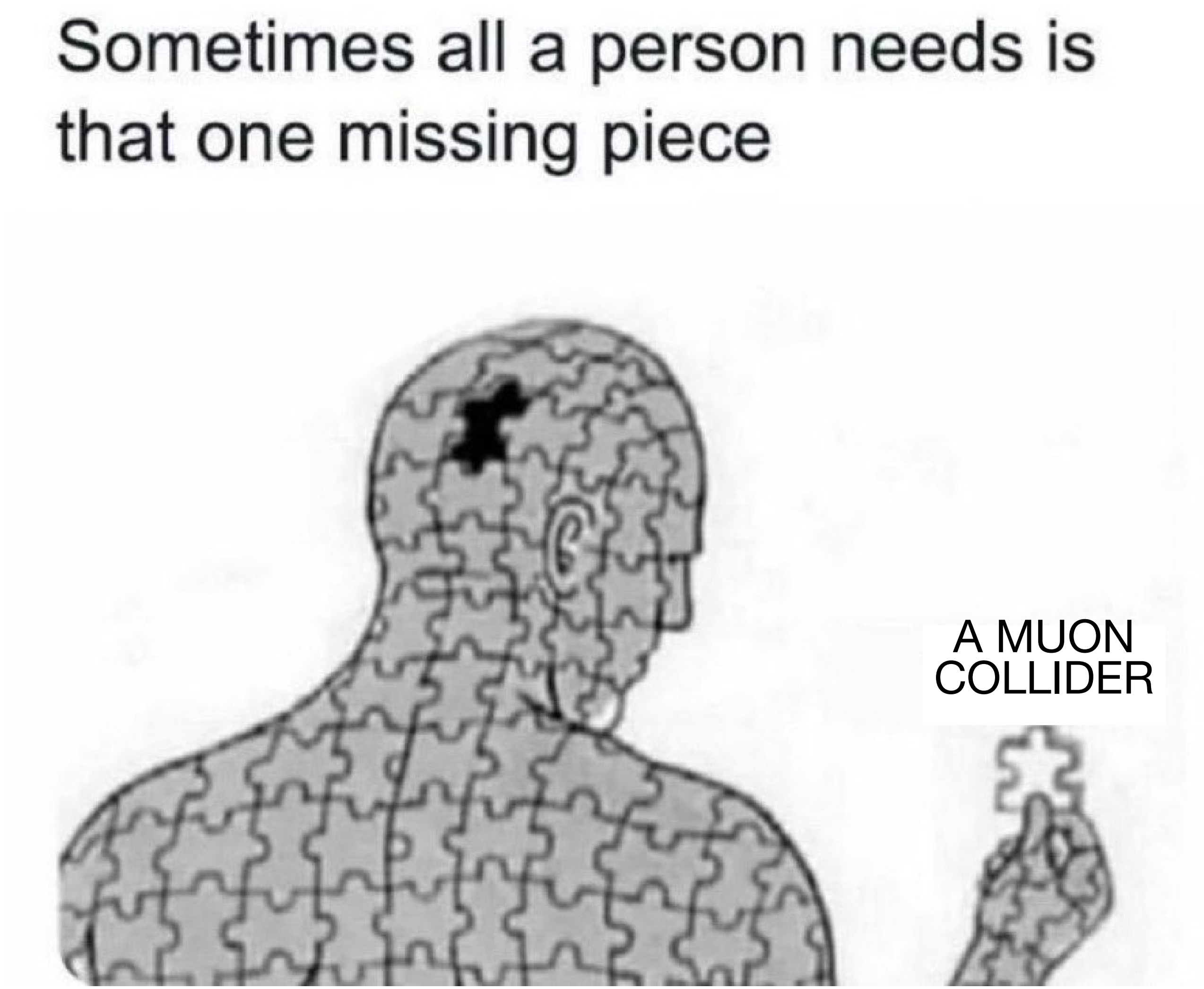
1 DCT + 1 main detector muon



Summary

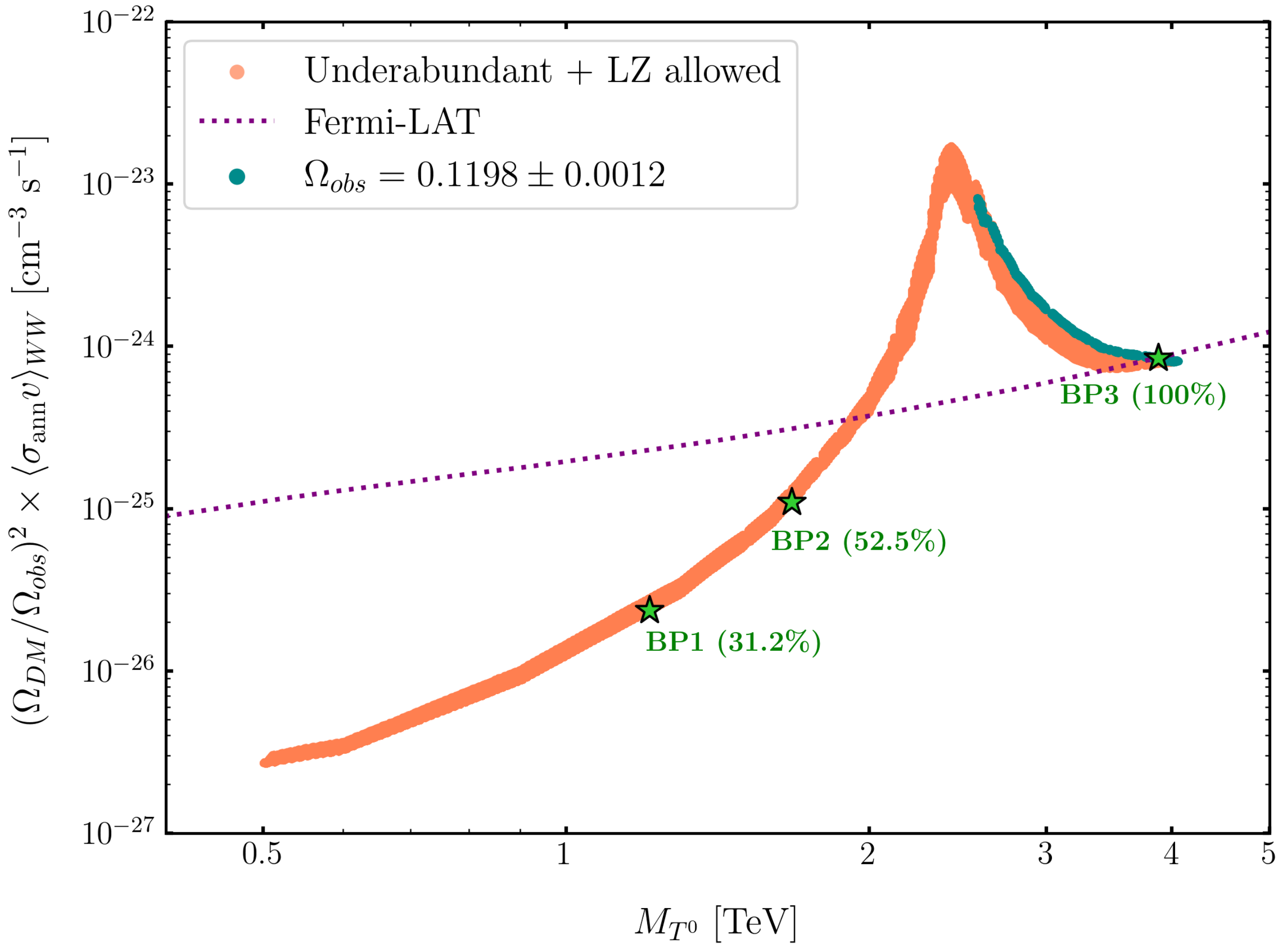
- Extending the Standard Model with inert multiplets often lead to a Dark Matter candidate, and provides long-lived particle signatures at the colliders.
- For the inert triplet model (ITM), the neutral component of the hypercharge-less scalar triplet becomes the DM, and the charged component is heavier by ~166 MeV.
- This small splitting leads to disappearing track signature for the charged scalars.
- TeV-scale charged scalars can be produced copiously via VBF at a multi-TeV muon collider.
- Final states consisting of disappearing tracks and Forward muons from VBF can probe the model over a large range of TeV masses, against the fake tracks from BIB.

Thank you.


Sometimes all a person needs is
that one missing piece
A MUON
COLLIDER

Backup slides

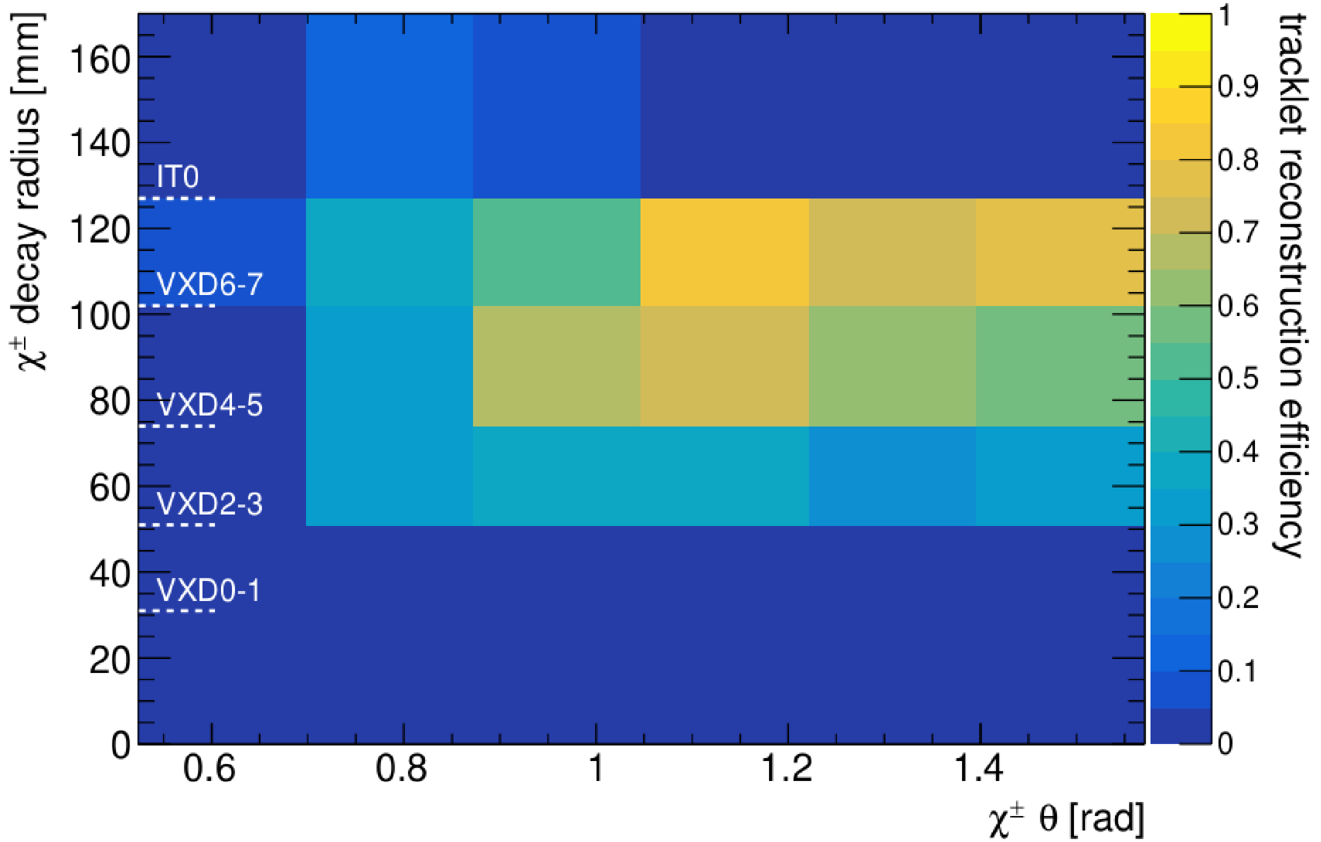
Fermi-LAT exclusion of ITM



Tracklet reconstruction efficiencies

Model-independent tracklet efficiency map taken from Capdevilla et al, JHEP 06 (2021) 133. Here, tracklets are defined as DCTs that vanish before reaching the inner tracker, and efficiencies are calculated based on BIB hits.

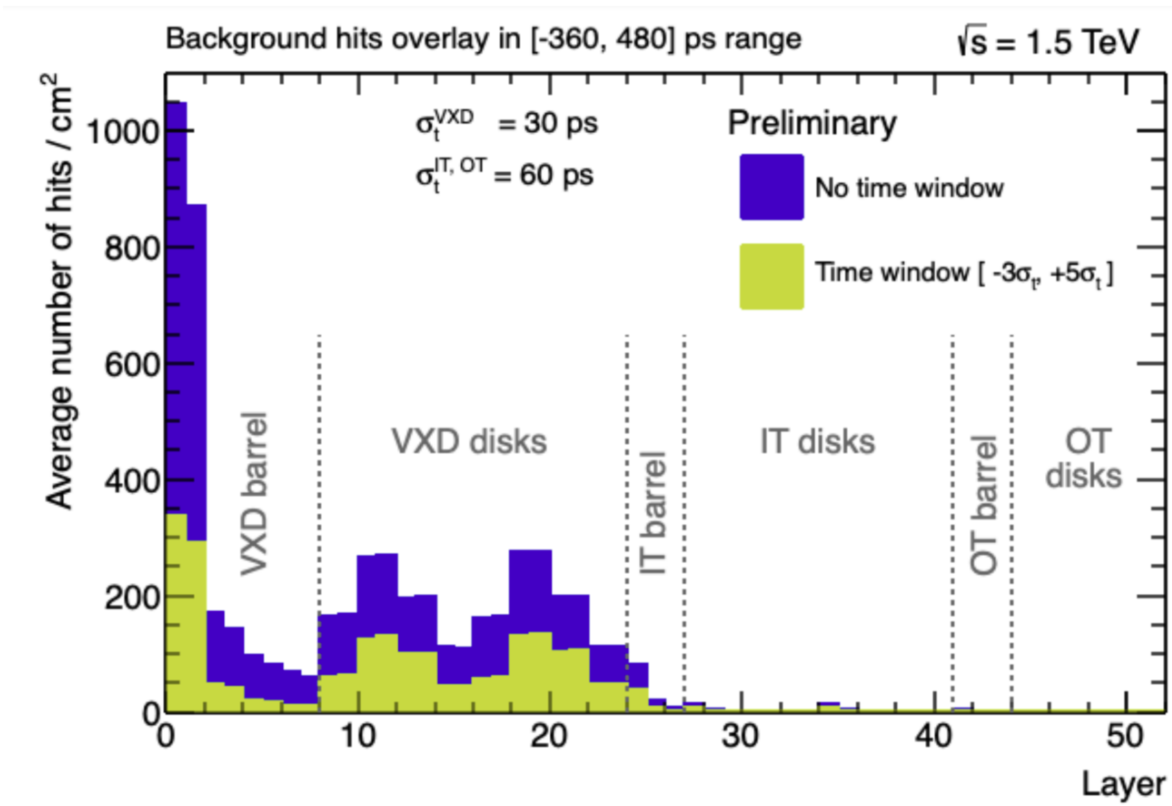
For DCTs inside IT and OT, VXD final layer efficiencies can be conservatively assumed, as BIB hits remain in the same order in the barrell regions.



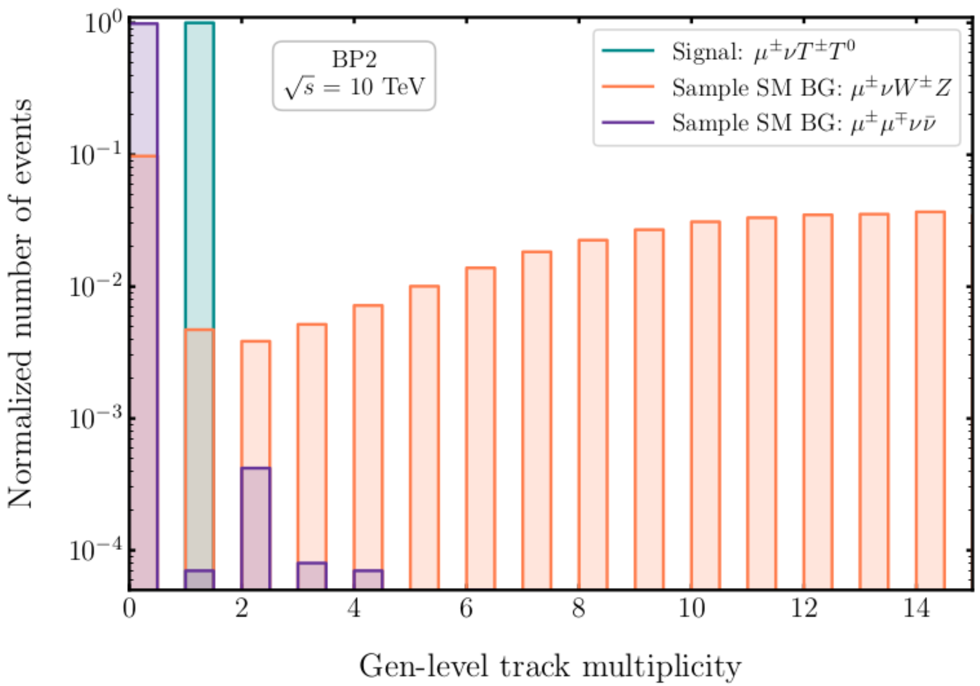
BIB hits

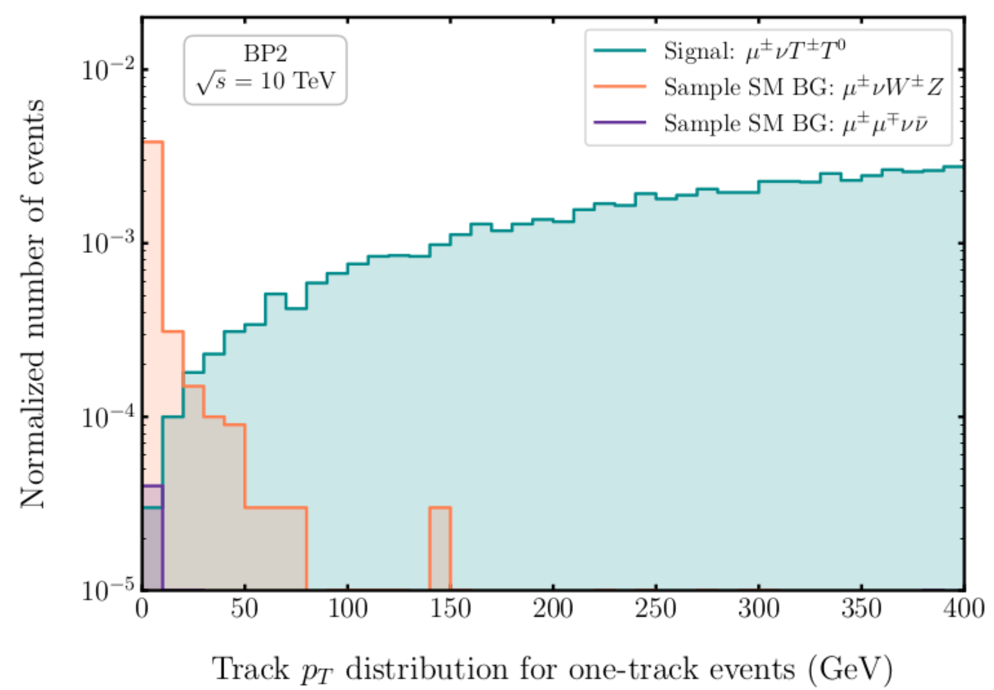
1.5 TeV BIB overlay is currently used as a reference even for the 10 TeV detector.
10 TeV BIB is expected to be even lesser in the barrell regions, allowing less fake tracks.

Simulated Detector Performance at the Muon Collider, International Muon Collider Collaboration, arXiv: 2203.07964 [hep-ex]



SM BG rejection





Displaced pions

- Even though the idea of displaced pion tracks sound enticing, their softness prohibit their tracks from being reconstructed.