Discovering Minimal Dark Matter at Future Muon Colliders

DPF-PHENO

University of Pittsburgh / Carnegie Mellon University

May 13, 2024

Rodolfo Capdevilla
Fermilab

Federico Meloni, DESY

Rosa Simoniello, CERN

Jose Zurita, U. Valencia

***RC**, Federico Meloni, Jose Zurita, ArXiv: 2405.xxxxx*
***RC**, Federico Meloni, Rosa Simoniello, Jose Zurita, JHEP **06** (2021) 133*

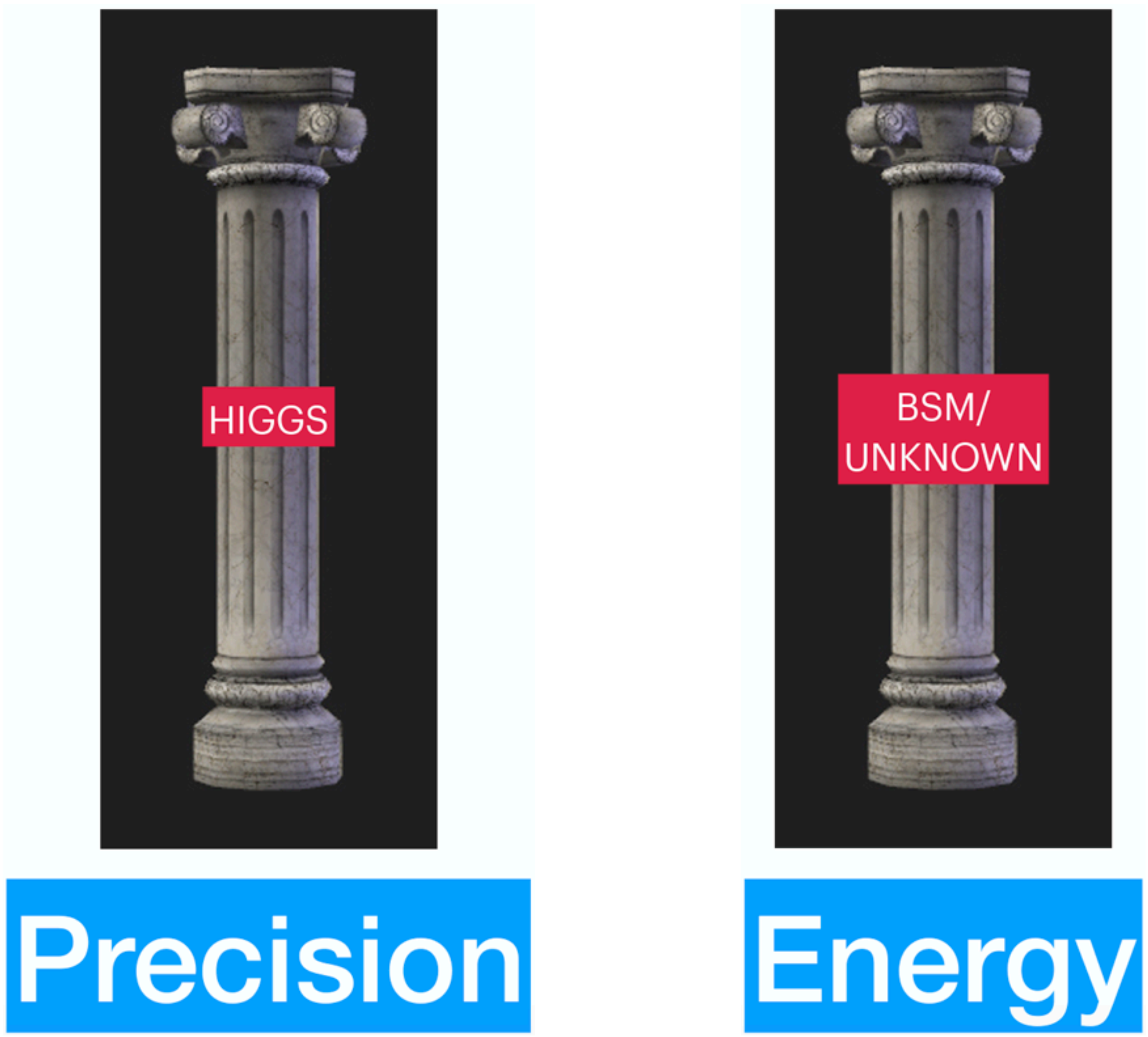
Outline

1. Introduction
2. Minimal Dark Matter
    - Properties
    - Projections
3. Soft Tracks
    - Signal Regions
    - Backgrounds
4. Results
    - The Importance of the 3TeV MuC!

1. Introduction

- Pillars for the Energy Frontier:

Foundational Physics Cases



Patrick Meade

Higgs:

Is there a more fundamental description of EWSB?
What mechanism sets the scale and stabilizes the Higgs mass?
…

BSM:

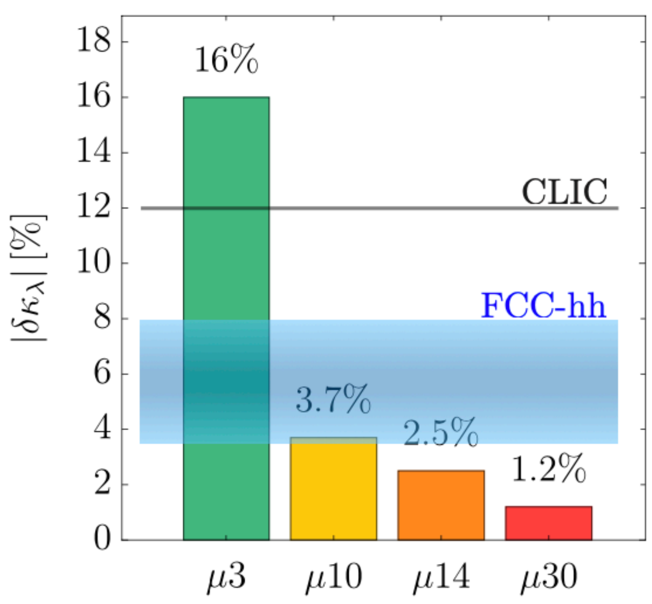
What is the nature of Dark Matter?
What is the mechanism for Baryogenesis?
What is the mechanism for neutrino masses?
The unknown! How can nature surprise us?
…

1. Introduction

- MuC strong candidate for both:

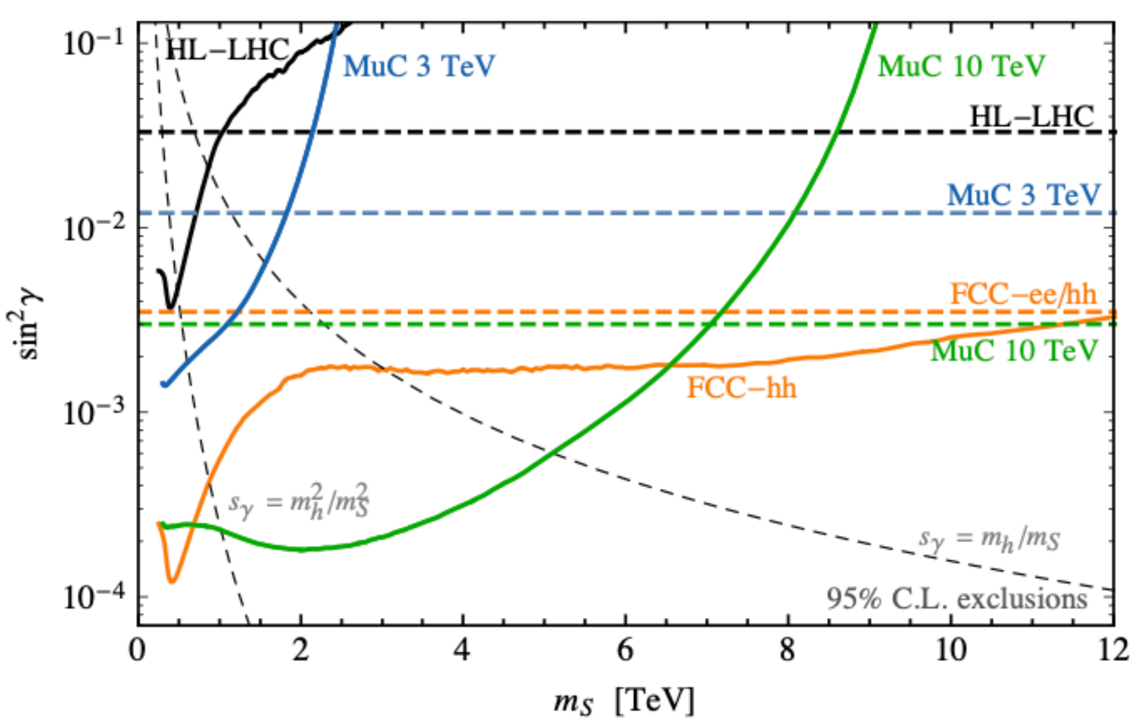
Higgs/Precision

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 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

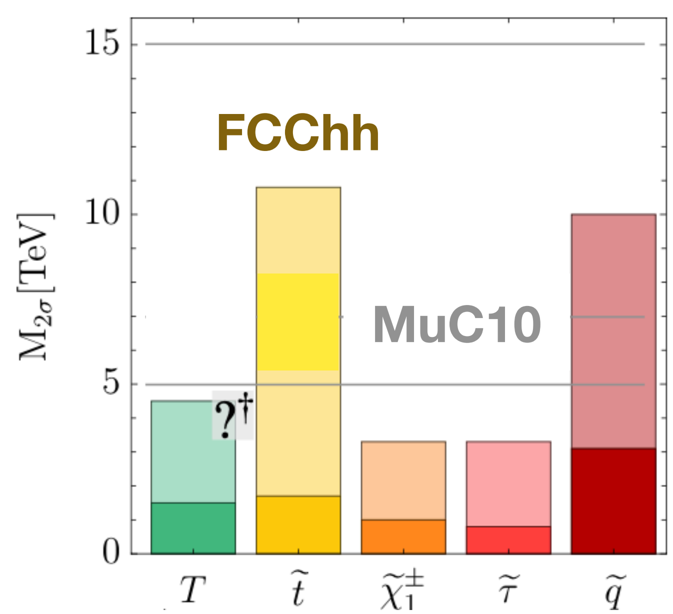


H. Al Ali et al., Muon Smasher's guide + Delphes

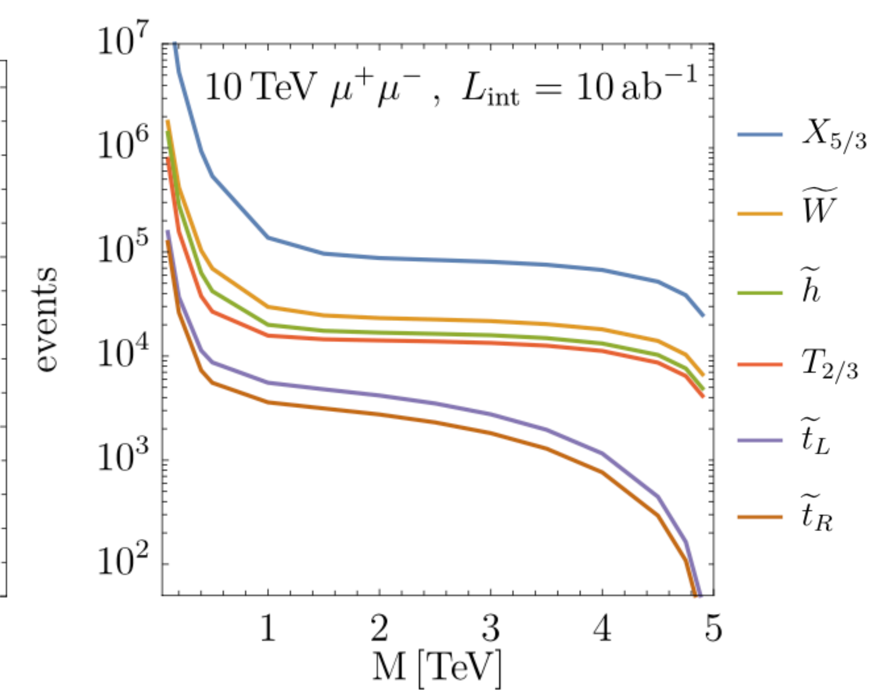
BSM/Unknown



H. Al Ali et al., Muon Smasher's guide



D. Buttazzo,
R. Franceschini,
A. Wulzer,
JHEP 05 (2021) 219



R. K. Ellis et al.,
arXiv:1910.11775

Outline

1. Introduction

2. Minimal Dark Matter

- **Properties**
- Projections

3. Soft Tracks

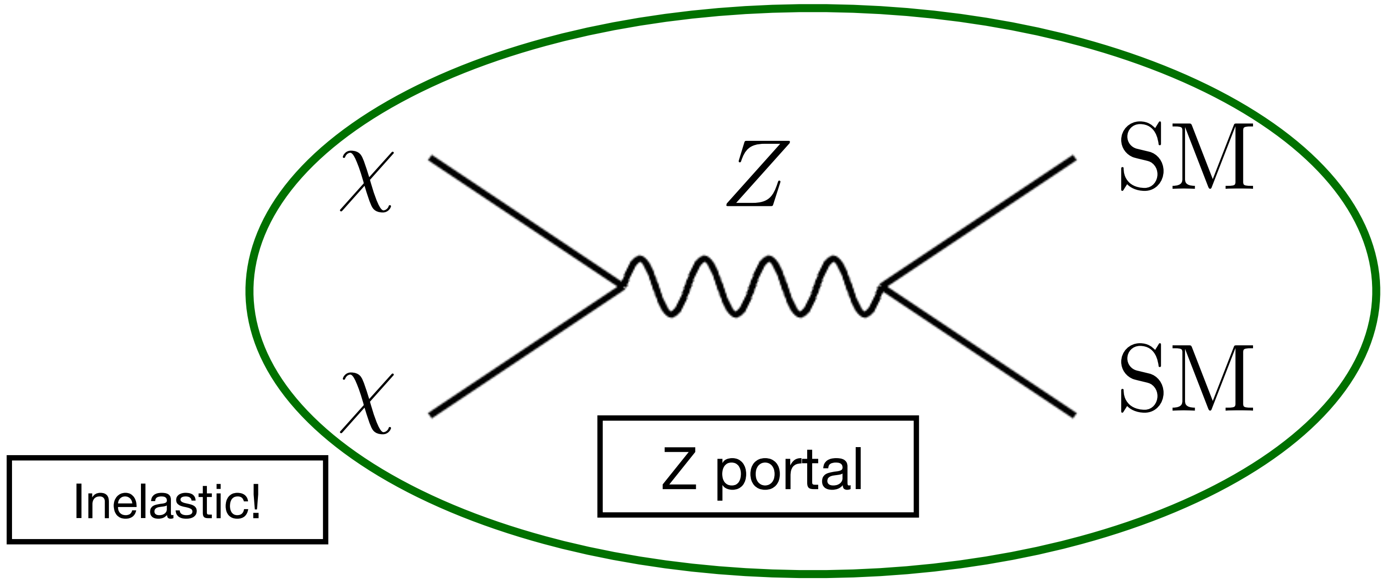
- Signal Regions
- Backgrounds

4. Results

- The Importance of the 3TeV MuC!

2. Minimal Dark Matter

- The Model:



Cirelli, Fornengo, Strumia, Nucl. Phys. B 753 (2006) 178-194
Cirelli, Strumia, New J. Phys. 11 (2009) 105005
Hisano, Ishiwata, Nagata, Takesako, JHEP 07 (2011) 005
Low, Wang, JHEP 08 (2014) 161
DelNobile, Nardecchia, Panci, JCAP 04 (2016) 048
Baumgart et al., JHEP 01 (2019) 036

EW multiplets

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\chi_{\tilde{H}} = \begin{pmatrix} \chi^+_{\tilde{H}} \\ \chi^0_{\tilde{H}} \end{pmatrix}$$

$(\mathbf{1}, \mathbf{2}, 1/2)$
Higgsino-like

$$\chi_{\tilde{W}} = \begin{pmatrix} \chi^+_{\tilde{W}} \\ \chi^0_{\tilde{W}} \\ \chi^-_{\tilde{W}} \end{pmatrix}$$

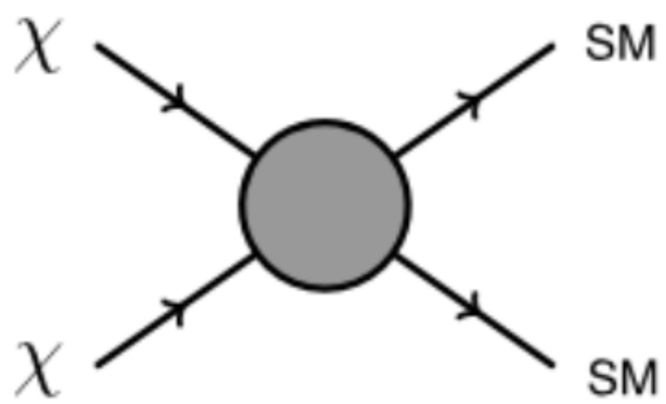
$(\mathbf{1}, \mathbf{3}, 0)$
Wino-like

Neutral component = DM

2. Minimal Dark Matter: Properties

- DM Freeze Out:

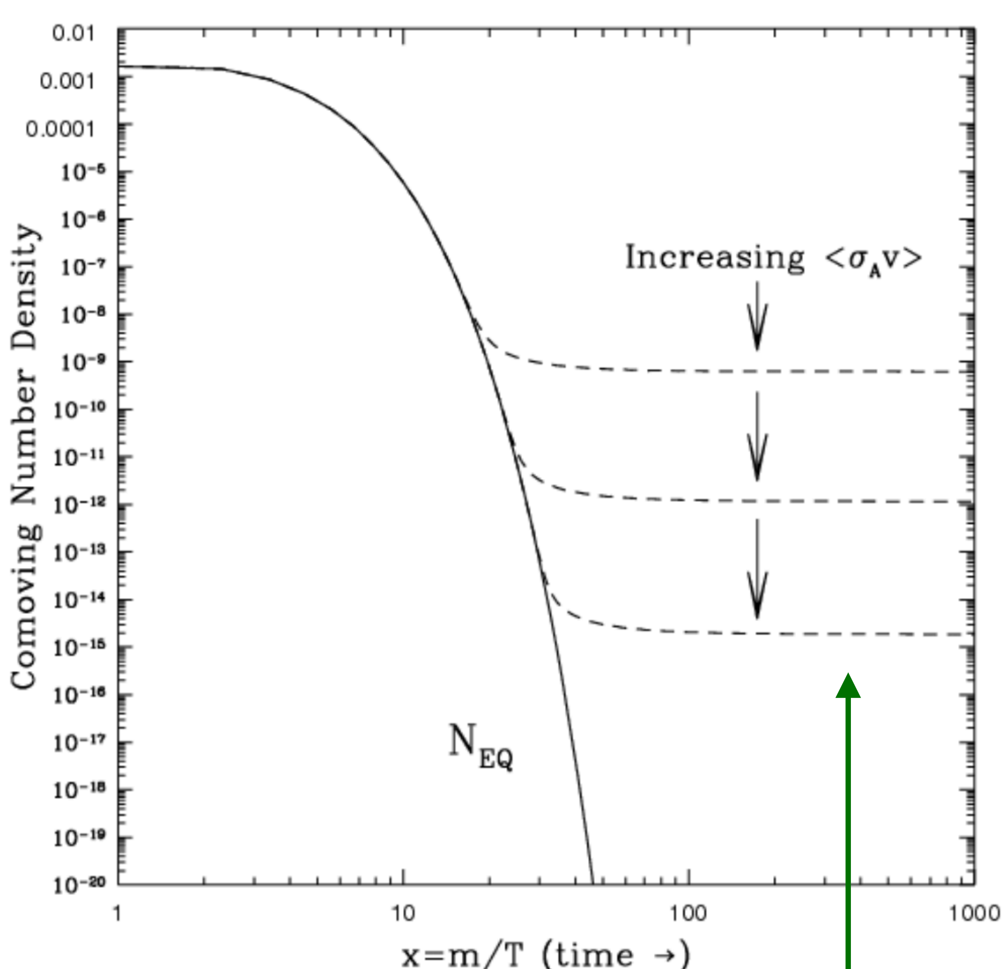
Annihilation in the early Universe



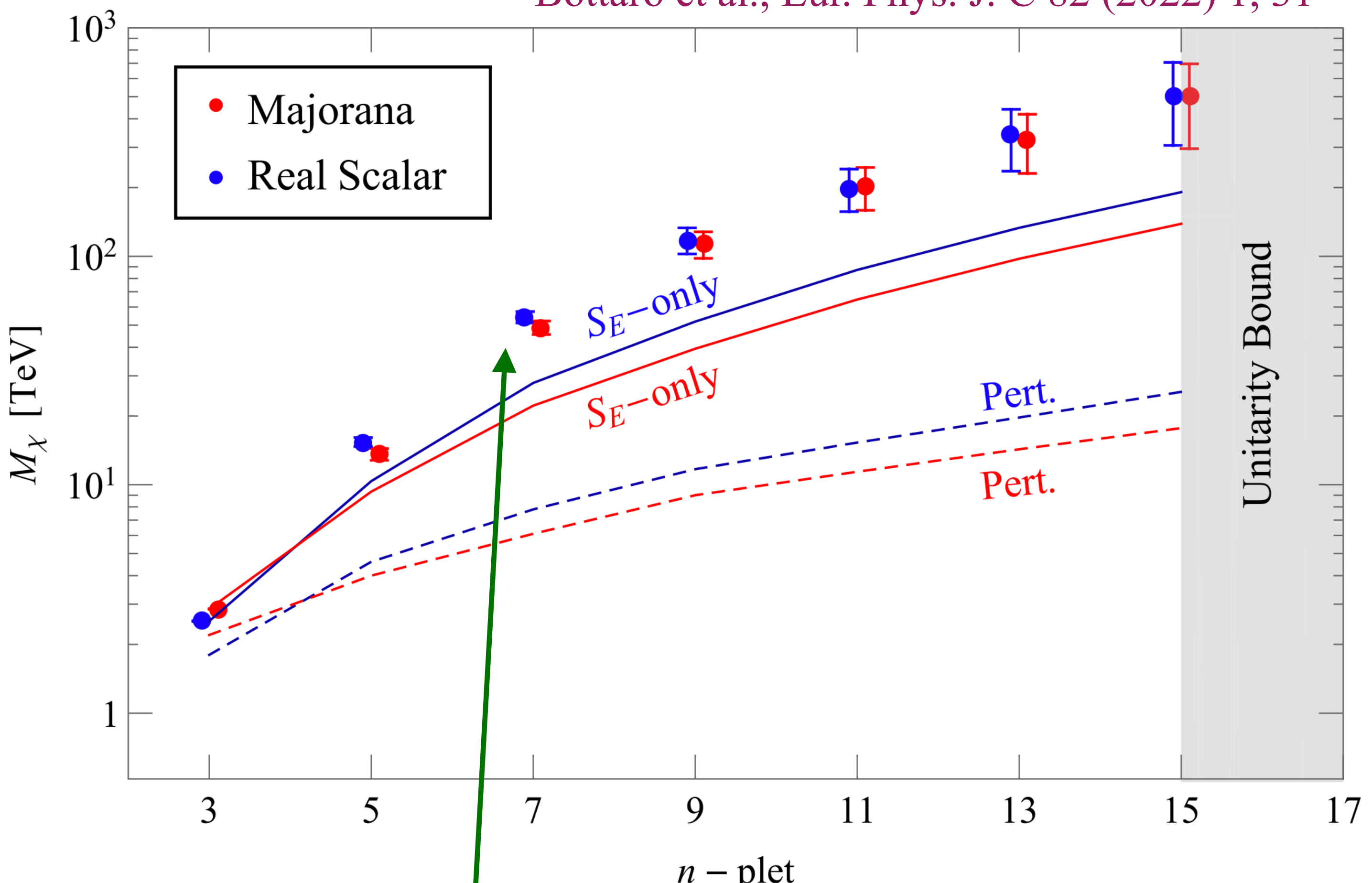
Cirelli, Fornengo, Strumia, Nucl. Phys. B 753 (2006) 178-194

$$\langle \sigma v \rangle \sim \frac{g_2^4 n^4 + 8 g_2^2 g_Y^2 Y^2 n^2}{64\pi M^2 g_\chi}$$

(**Scalar Large n**)



Bottaro et al., Eur. Phys. J. C 82 (2022) 1, 31



More annihilation requires heavier DM

Mass for which n-plet represents 100% of DM

Rodolfo Capdevilla, Fermilab

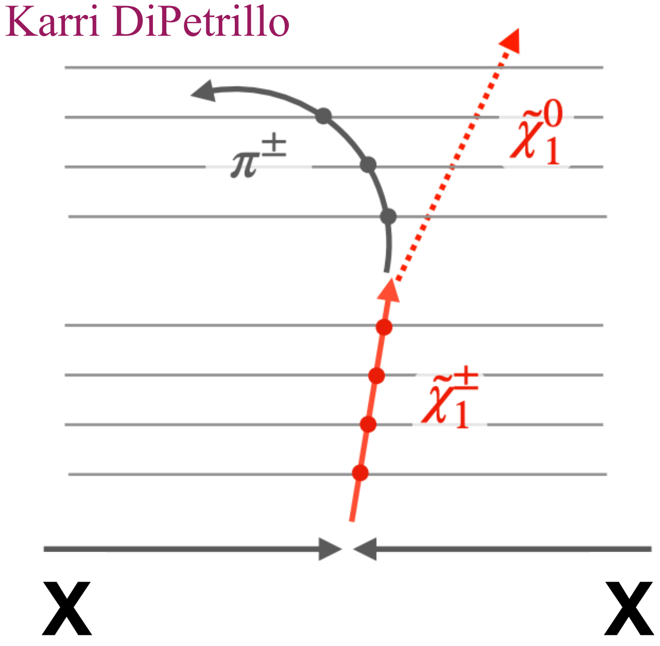
2. Minimal Dark Matter: Properties

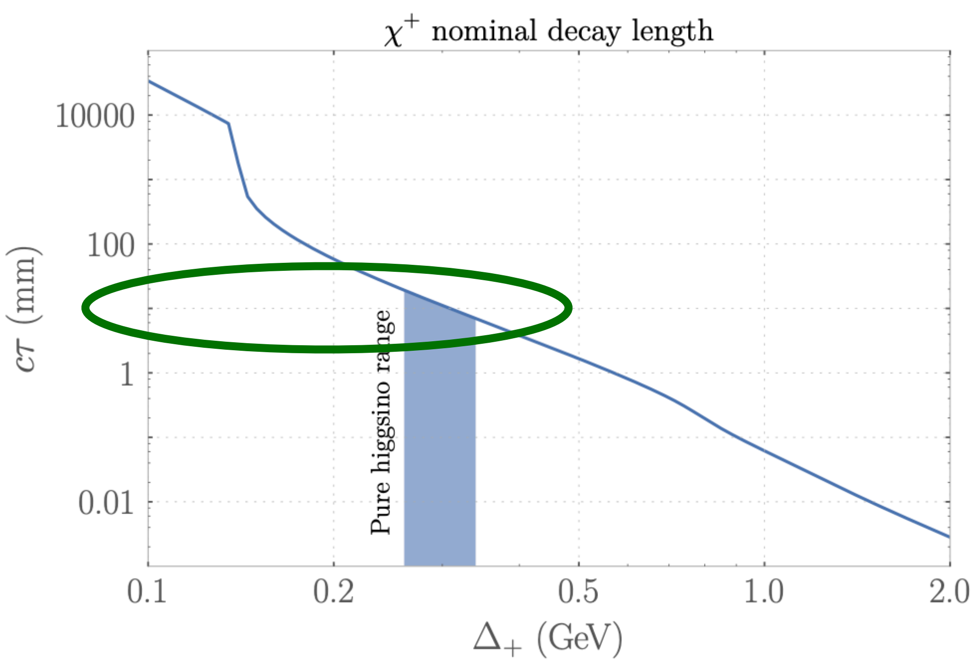
- Lifetime:

$$\Delta m = m_{\chi^+} - m_{\chi^0} > 0$$

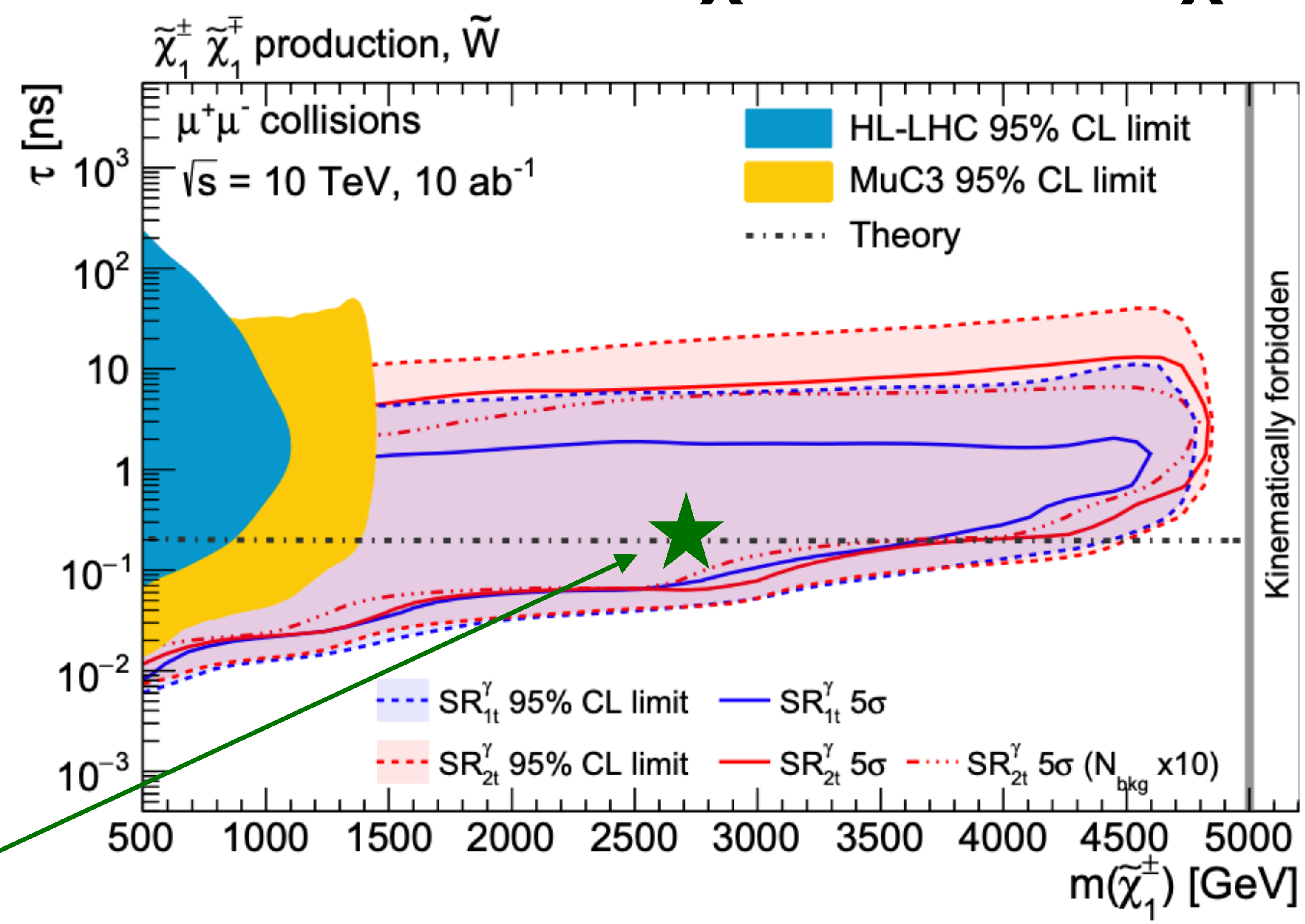
Small mass splitting (from loops) → *Long lifetime Disappearing Tracks (DT)*

Karri DiPetrillo





R. Mahbubani, P. Schwaller, J. Zurita, JHEP 06 (2017) 119



Capdevilla, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133

Thermal target mass 2.7 TeV

Outline

1. Introduction

2. Minimal Dark Matter

- Properties
- **Projections**

3. Soft Tracks

- Signal Regions
- Backgrounds

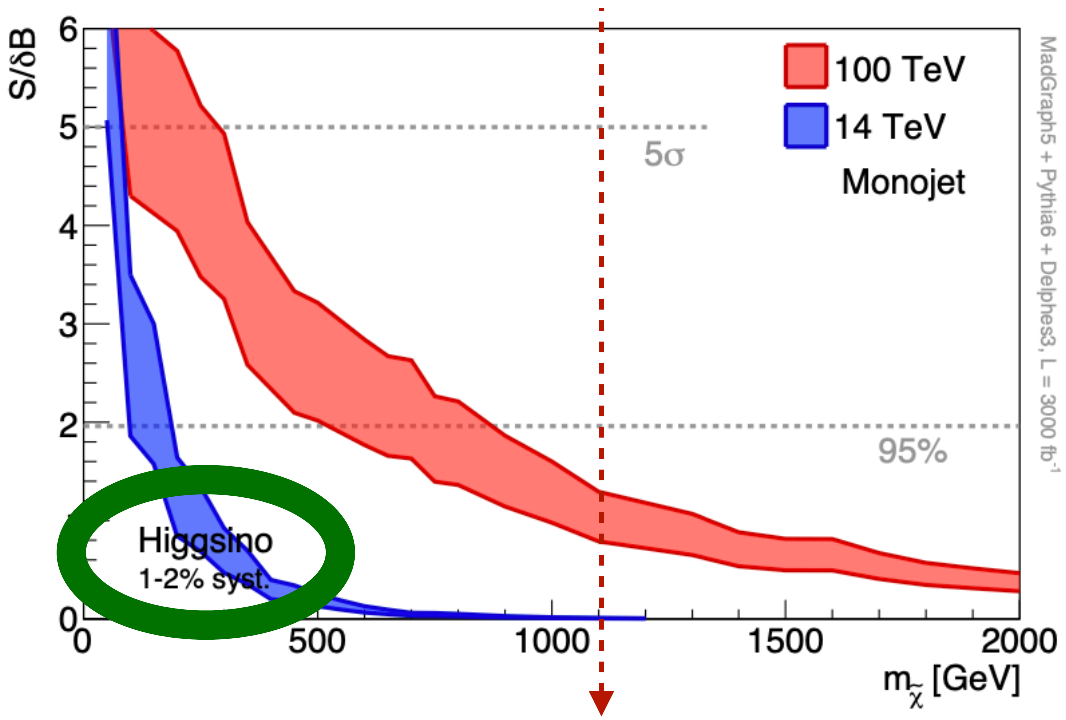
4. Results

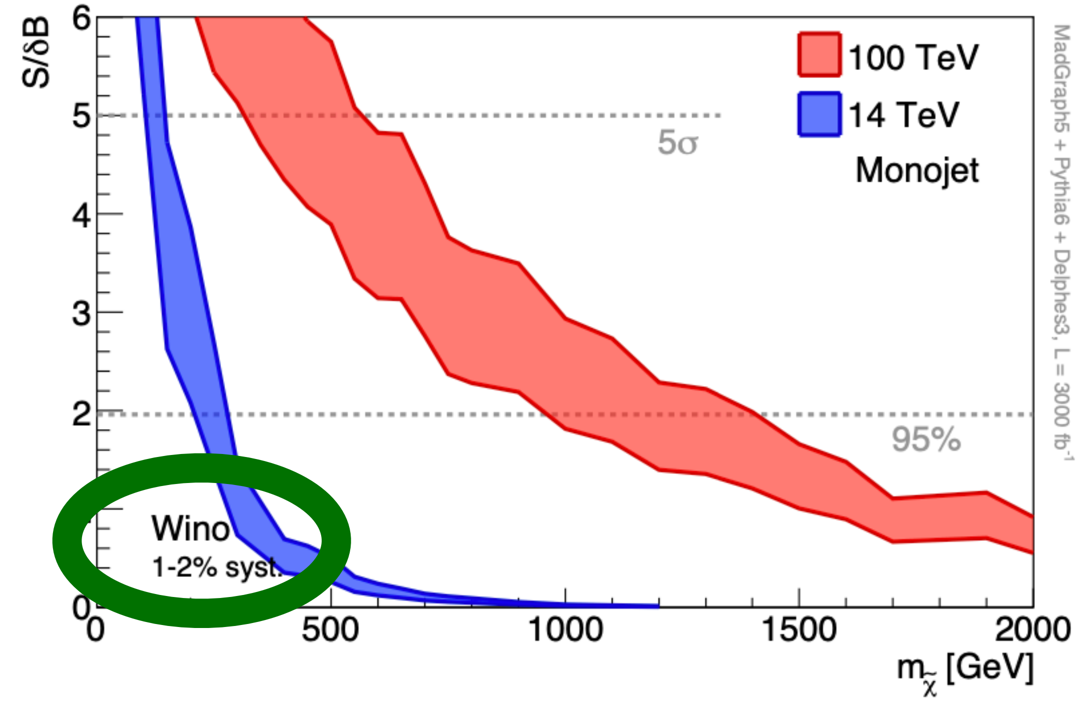
- The Importance of the 3TeV MuC!

2. Minimal Dark Matter: Projections

- Hadron colliders

M. Low, L. Wang, JHEP 08 (2014) 161

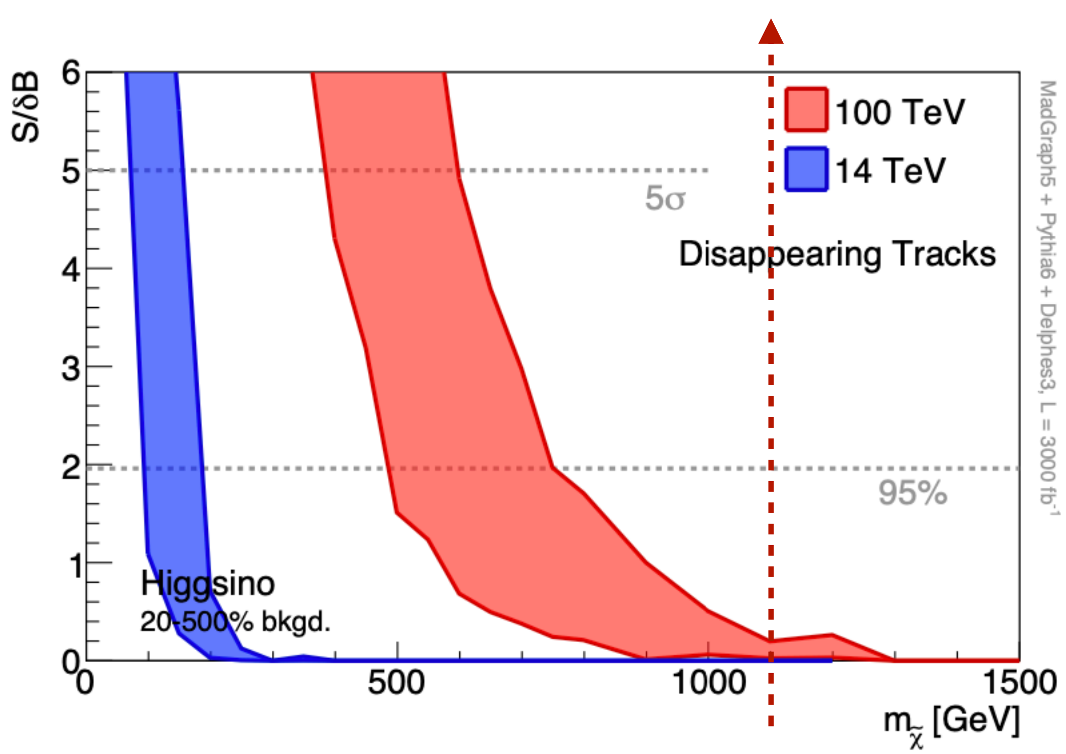


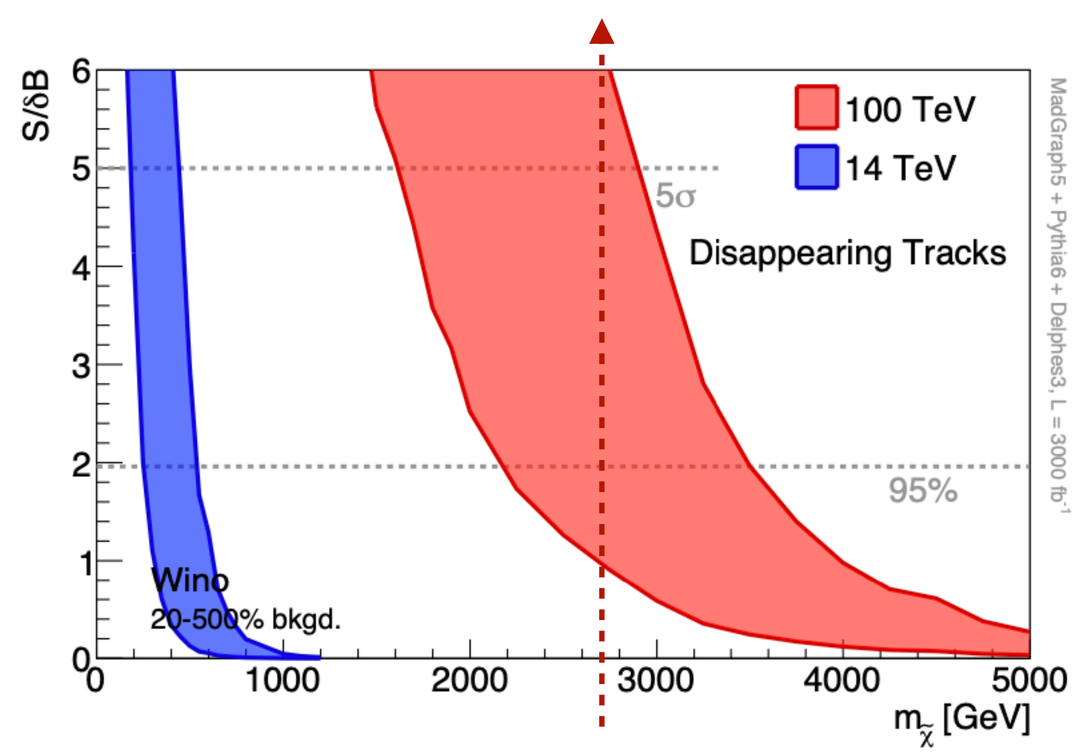


Thermal Target! $\sim 1.1\,\mathrm{TeV}$

$\sim 2.7\,\mathrm{TeV}$

In more recent studies FCChh can reach the thermal target!

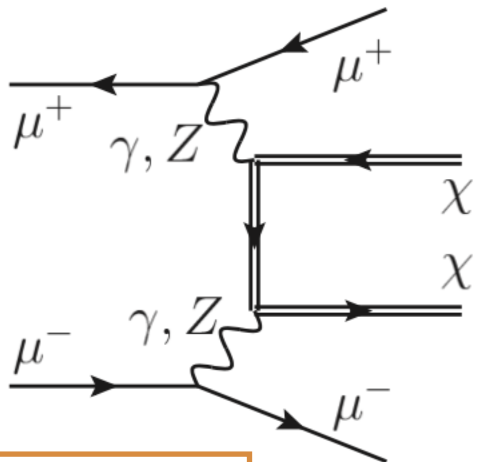




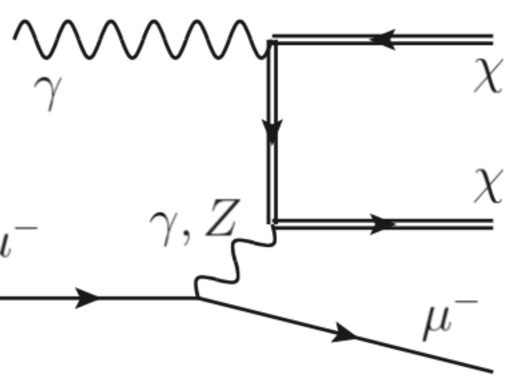
2. Minimal Dark Matter: Projections

- Muon colliders

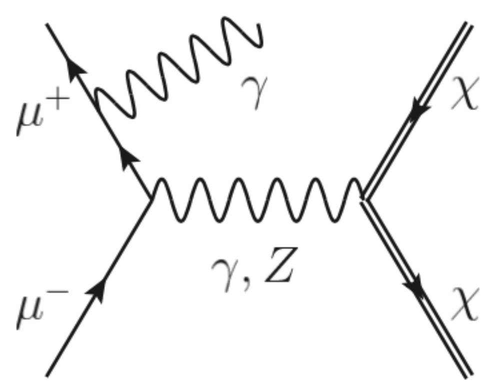
T. Han, Z. Liu, L. Wang, X. Wang,
Phys. Rev. D 103 (2021) 7, 075004



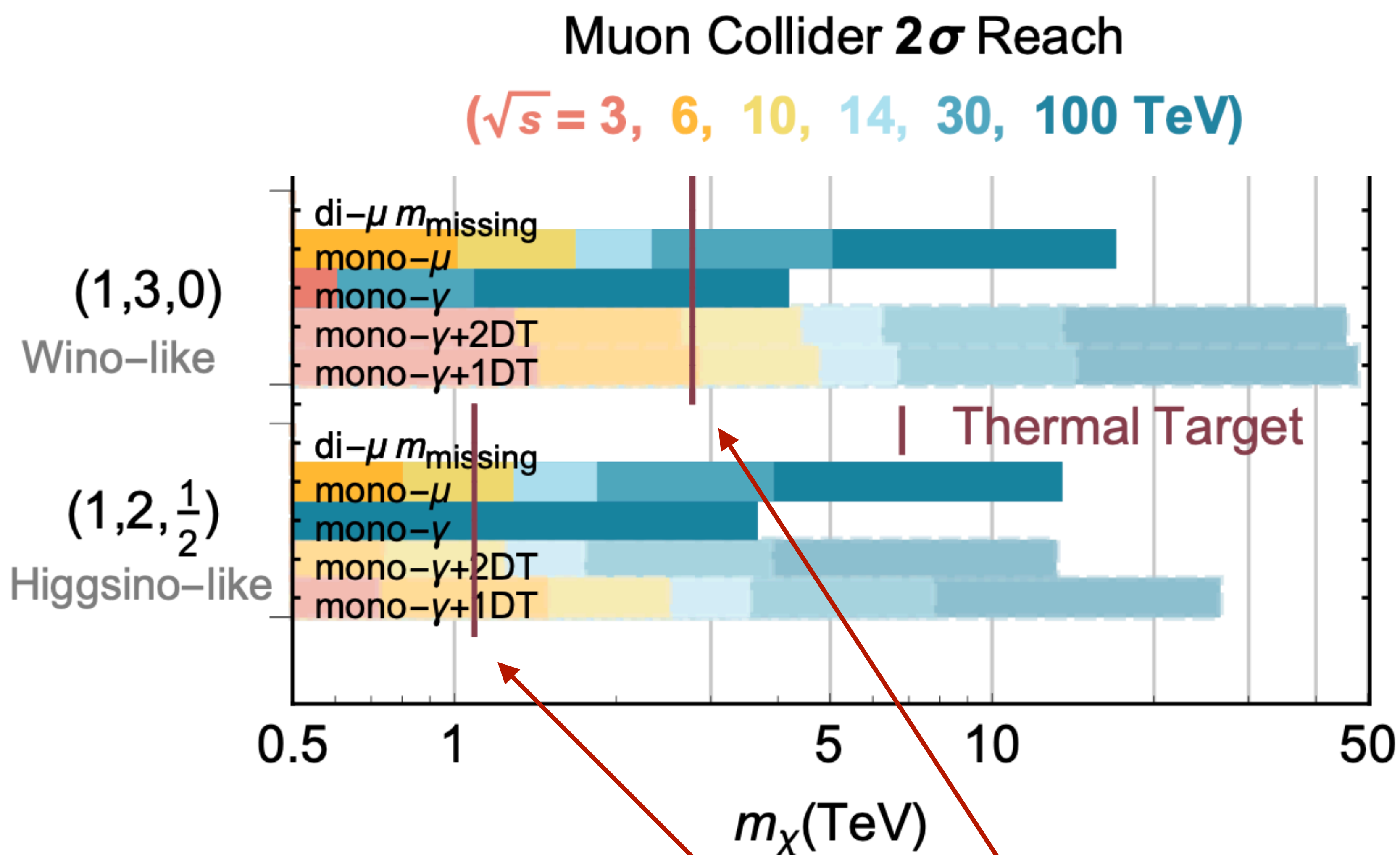
di-muon + MET



mono-muon



Mono-photon



The 10 TeV MuC can reach the thermal target (?)

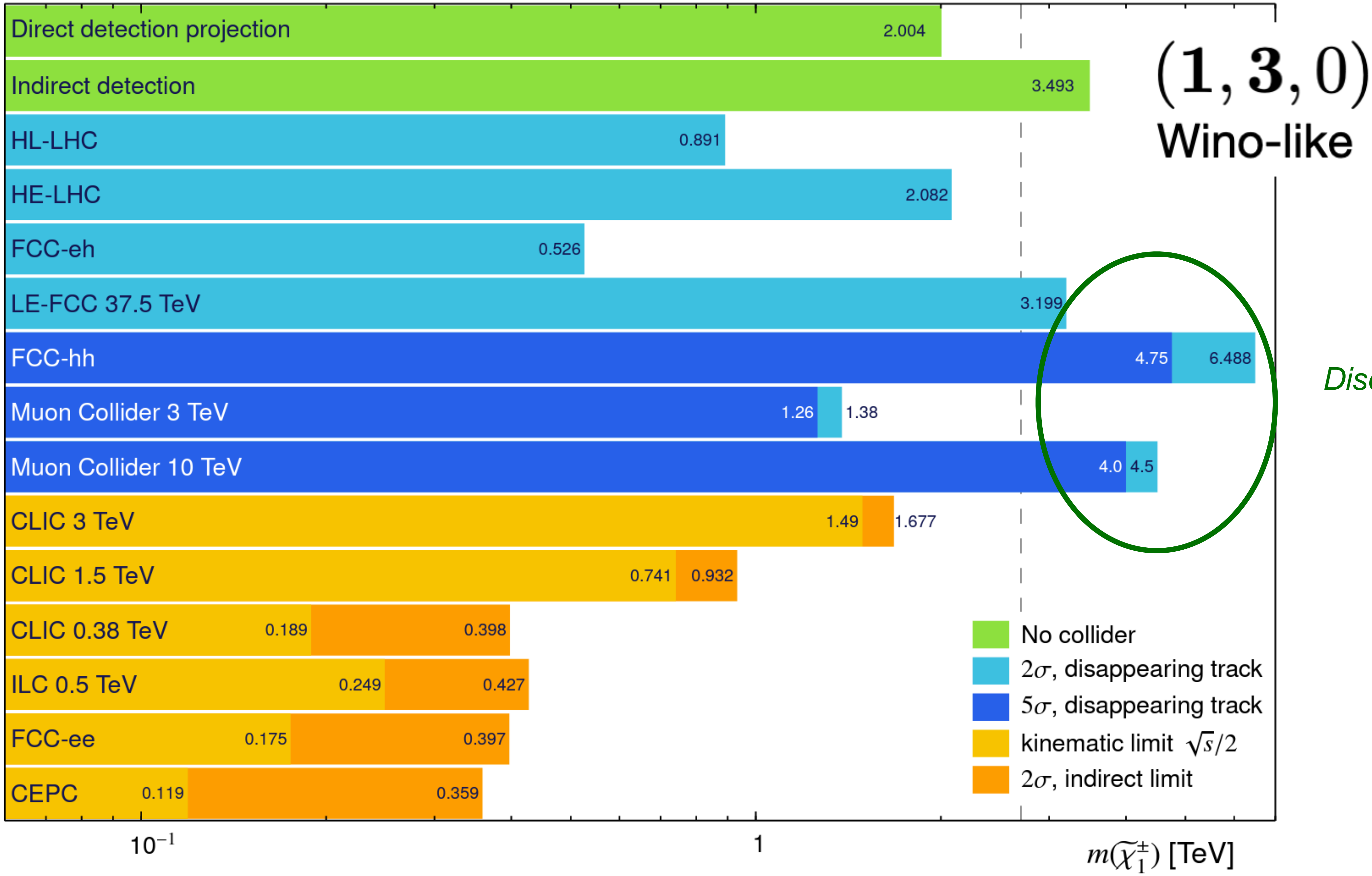
Need DT

BIB impact?

2. Minimal Dark Matter: Projections

- Triplet MDM:

Capdevilla, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133



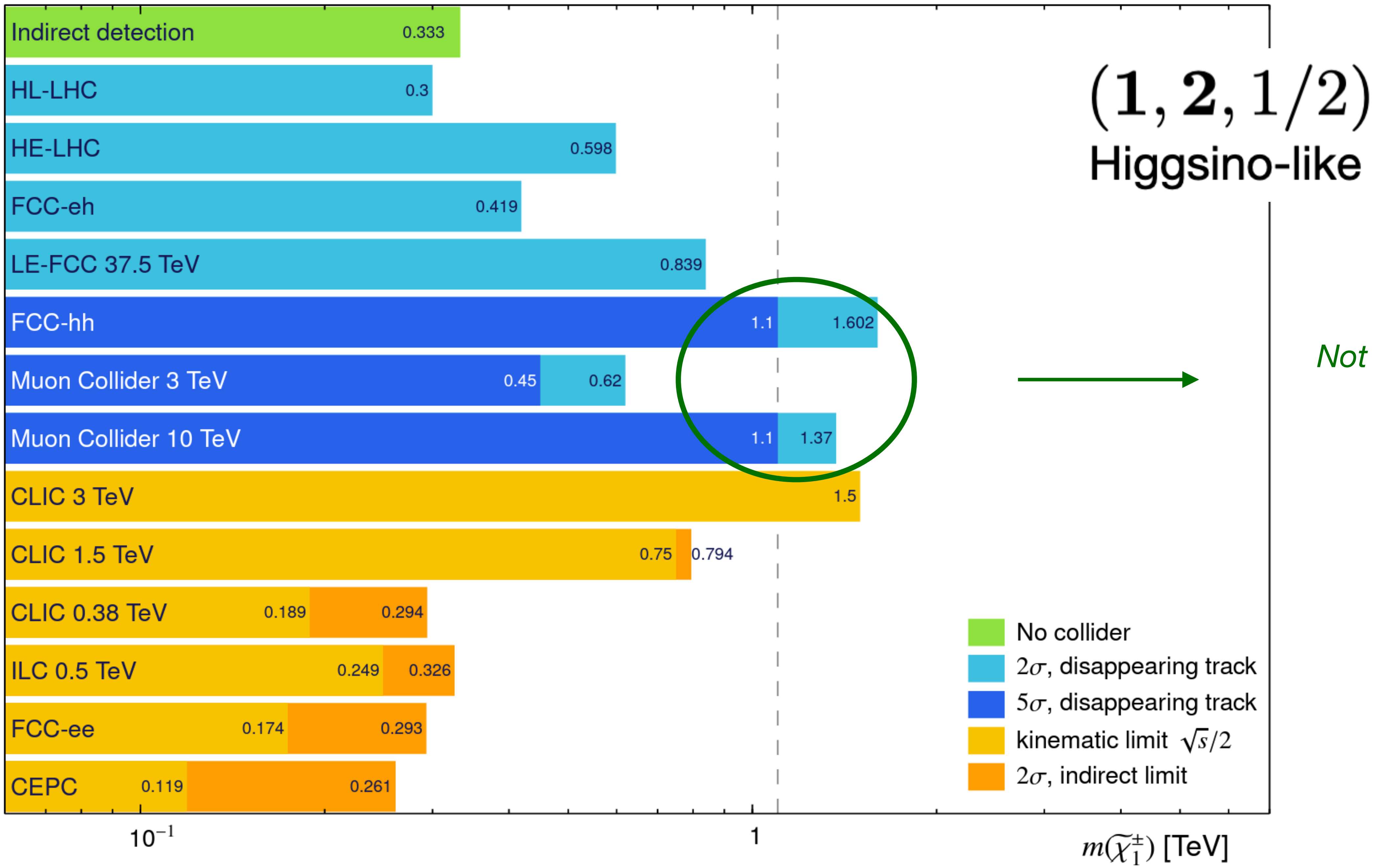
Discovery potential from DT

Rodolfo Capdevilla, Fermilab

2. Minimal Dark Matter: Projections

- Doublet MDM:

Capdevilla, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133



Not clear discovery potential…

Outline

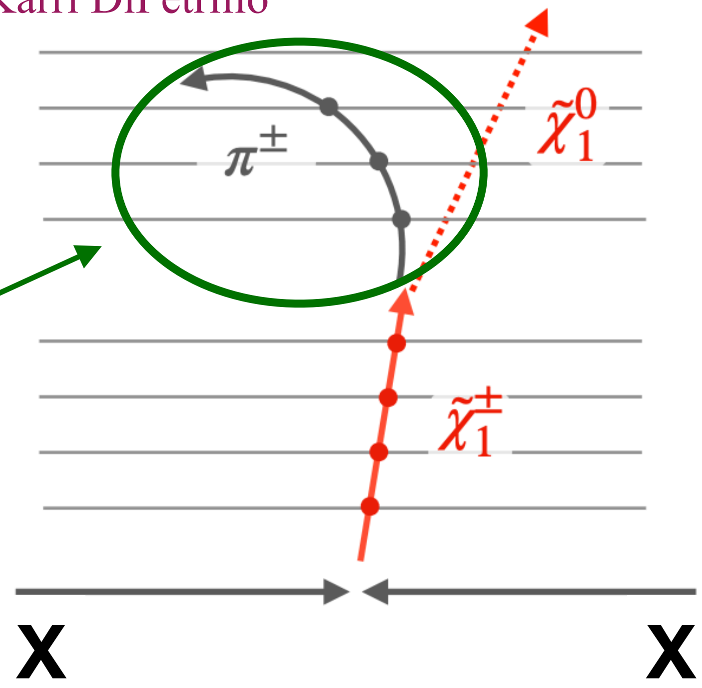
3. Soft Tracks

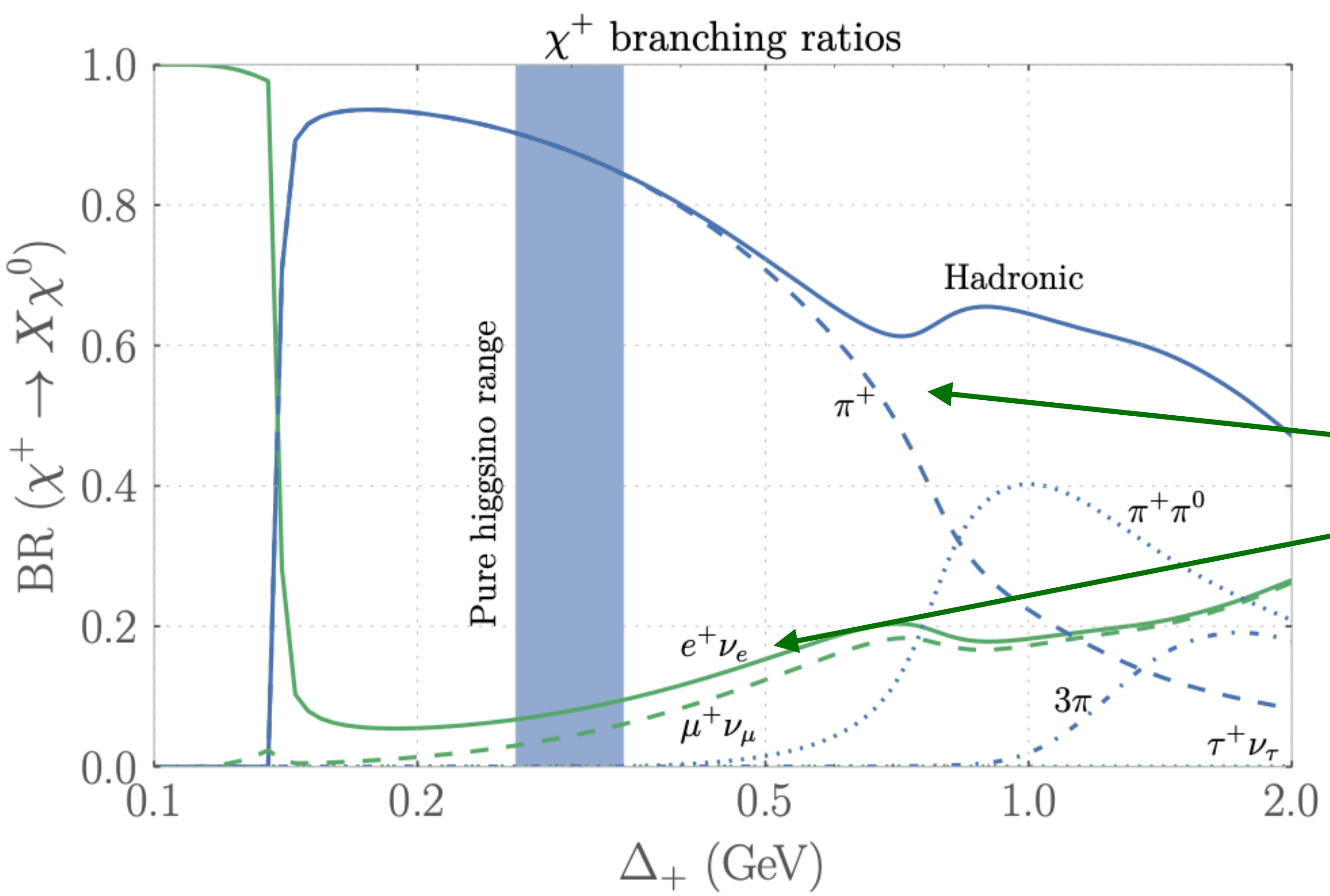
- Definition:

$$\Delta m = m_{\chi^+} - m_{\chi^0} > 0$$

Small mass splitting (from loops) → *Long lifetime / Disappearing Tracks / Soft Tracks (ST)*

Karri DiPetrillo





Soft pions
Soft muons = *ST*
Soft electrons

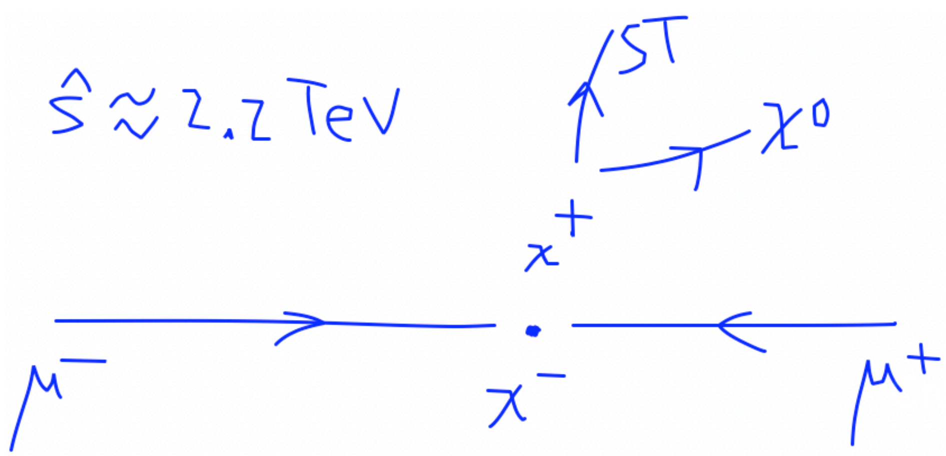
R. Mahbubani, P. Schwaller, J. Zurita, JHEP 06 (2017) 119

3. Soft Tracks: Signal Region

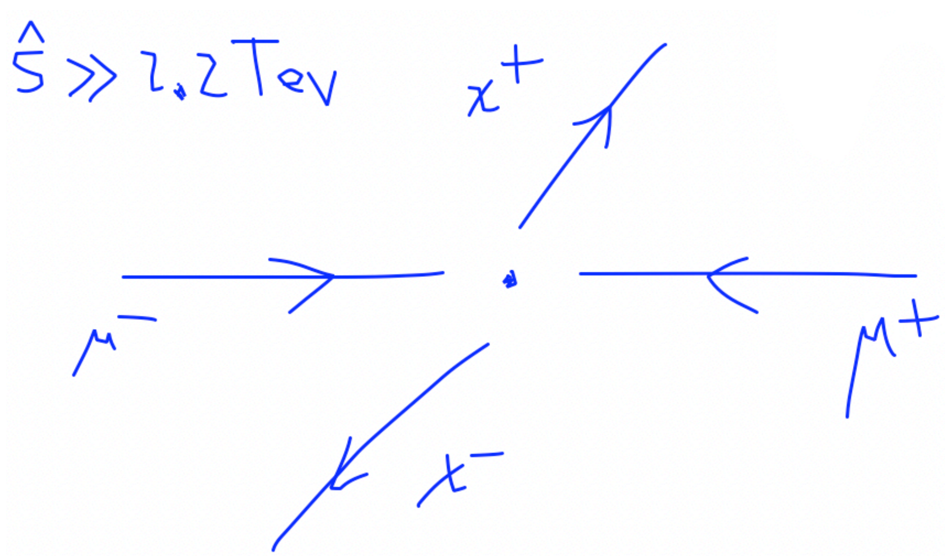
Thermal Higgsino
(doublet MDM)

Very small gap!

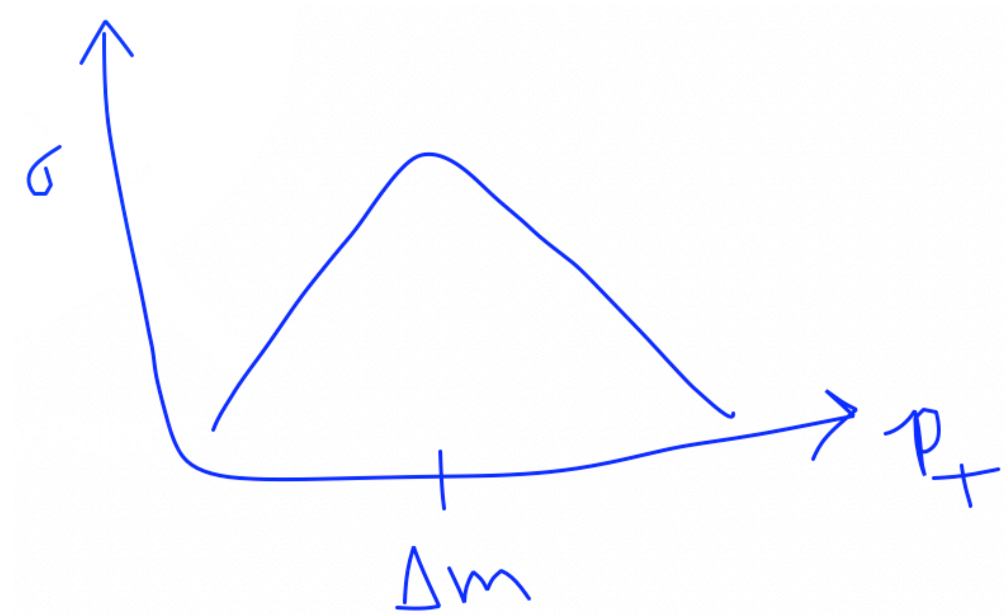
$$m_\chi = 1.1\,\mathrm{TeV}$$
$$\Delta m \sim 0.3\,\mathrm{GeV}$$



Threshold production



Boosted production

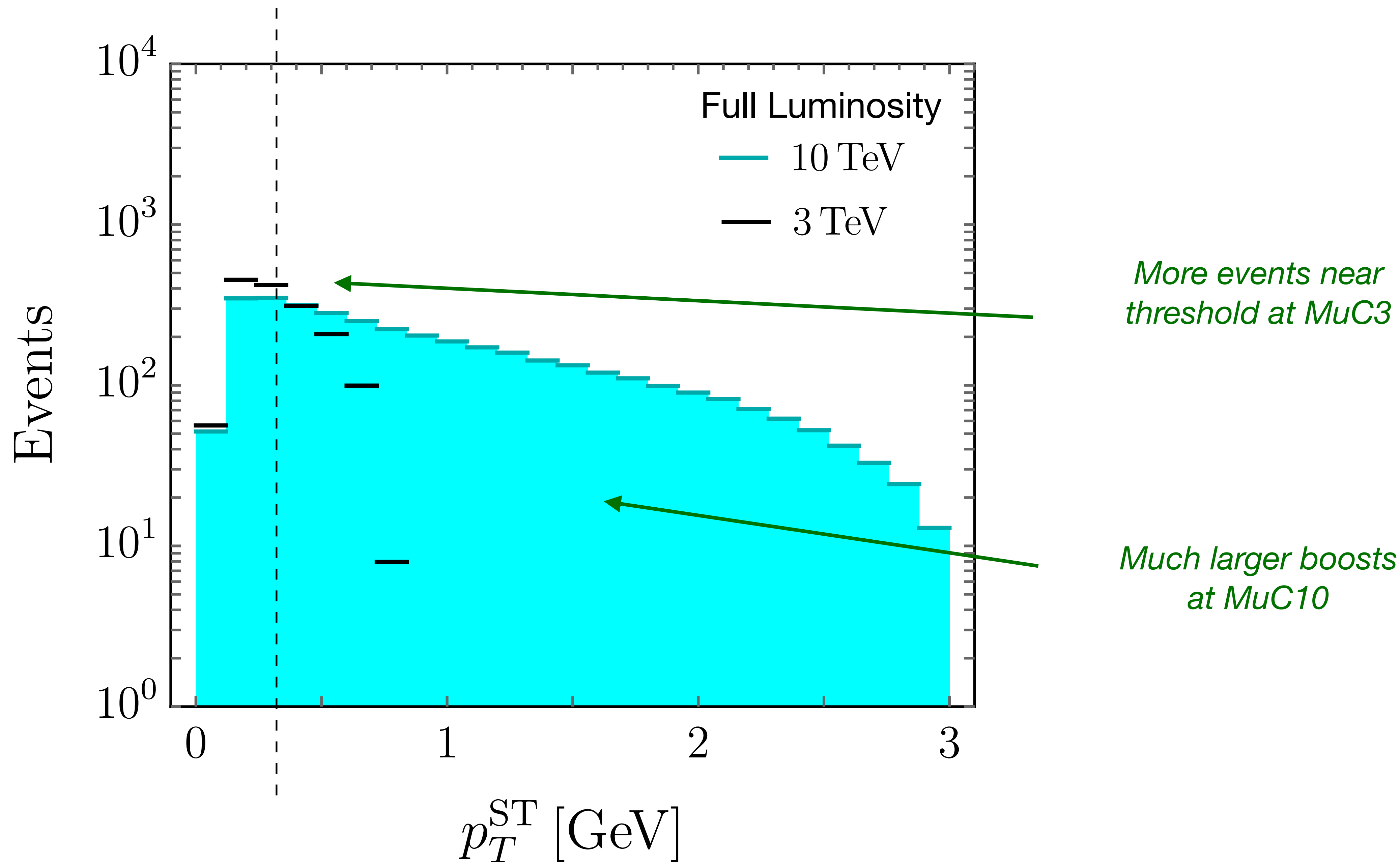


Rodolfo Capdevilla, Fermilab

3. Soft Tracks: Signal Region

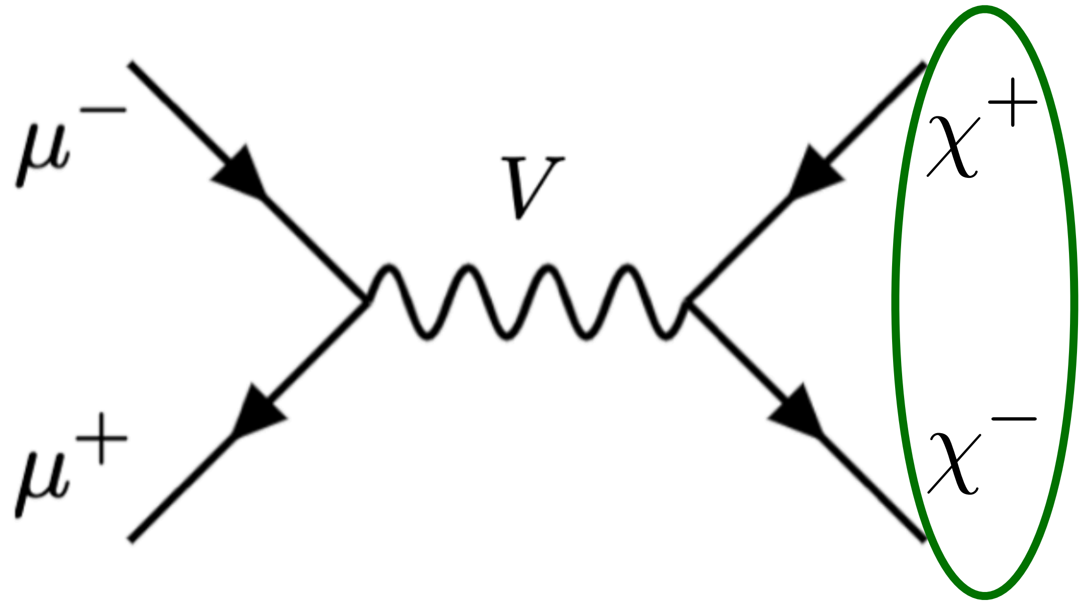
Thermal Higgsino
(doublet MDM)

$$m_\chi = 1.1\,\text{TeV}$$
$$\Delta m \sim 0.3\,\text{GeV}$$

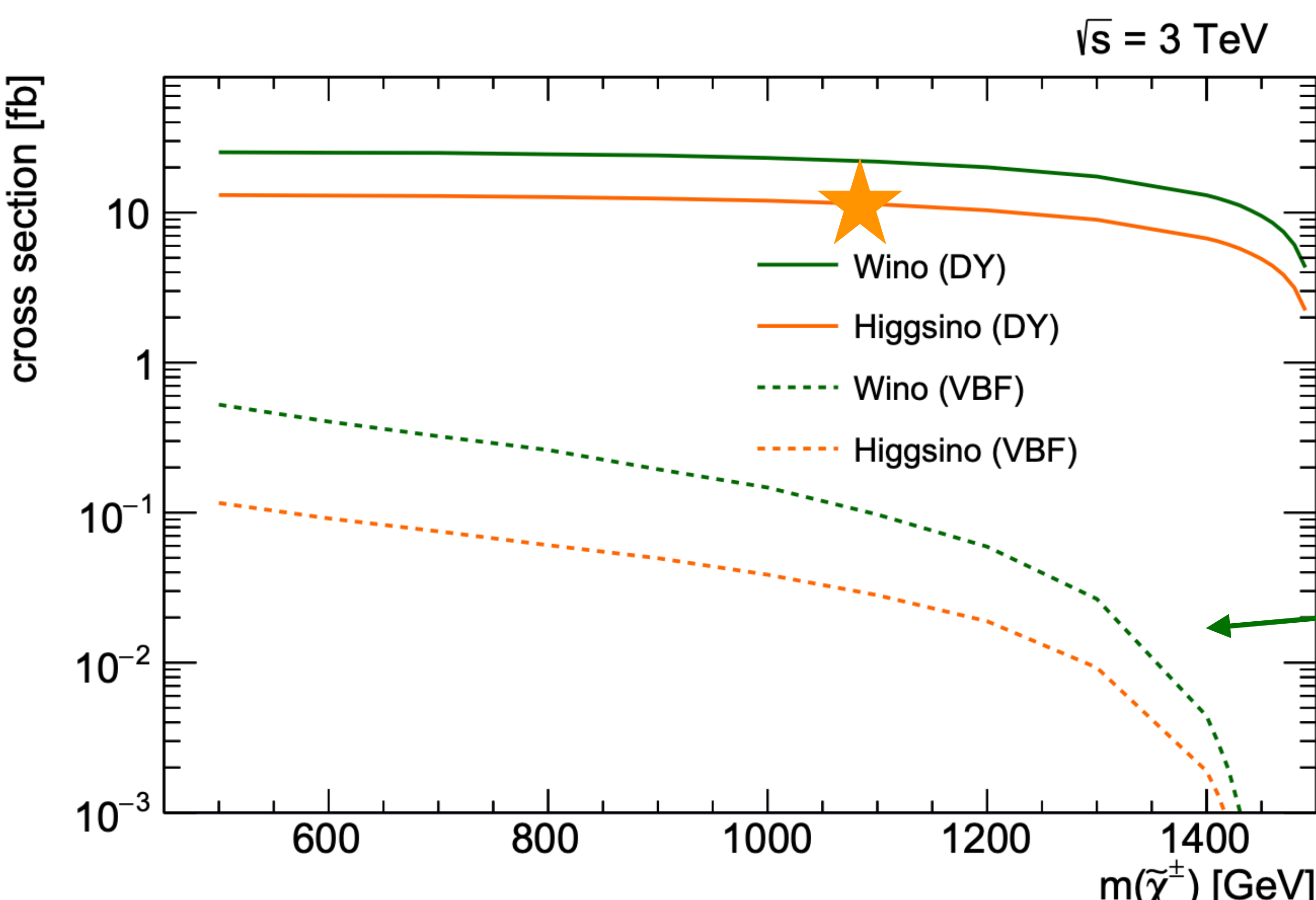


3. Soft Tracks: Signal Region

- Drell-Yan:



0-2 ST



Drell-Yan-like process dominates ST production

VBF processes are subdominant (For signal)

Capdevilla, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133

3. Soft Tracks: Signal Region

- Signal Regions:

Thermal Higgsino (doublet MDM)

MuC 3 TeV

$1\text{ST}\,0\gamma$ 14%	$1\text{ST}\,1\gamma$ 2%
$2\text{ST}\,0\gamma$ 75% $\sigma_T = 12.53(3)$ fb	$2\text{ST}\,1\gamma$ 9%

About 1k signal events in this signal region

MuC 10 TeV

$1\text{ST}\,0\gamma$ 7%	$1\text{ST}\,1\gamma$ 2%
$2\text{ST}\,0\gamma$ 65% $\sigma_T = 1.7996(36)$ fb	$2\text{ST}\,1\gamma$ 20%

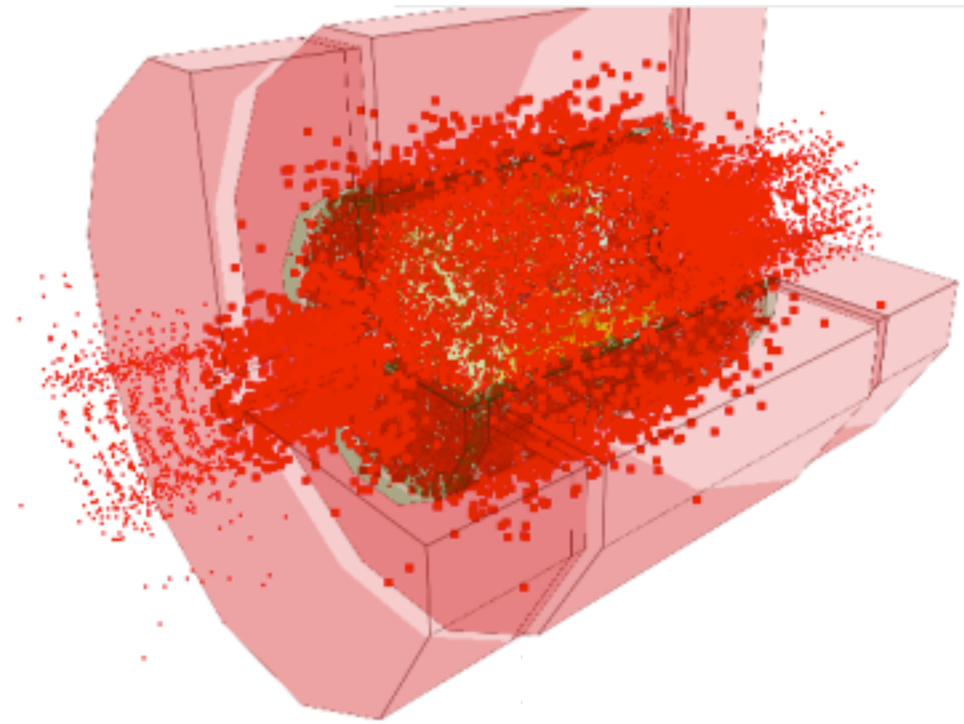
Outline

1. Introduction
2. Minimal Dark Matter
   - Properties
   - Projections
3. **Soft Tracks**
   - Signal Regions
   - **Backgrounds**
4. Results
   - The Importance of the 3TeV MuC!

Rodolfo Capdevilla, Fermilab

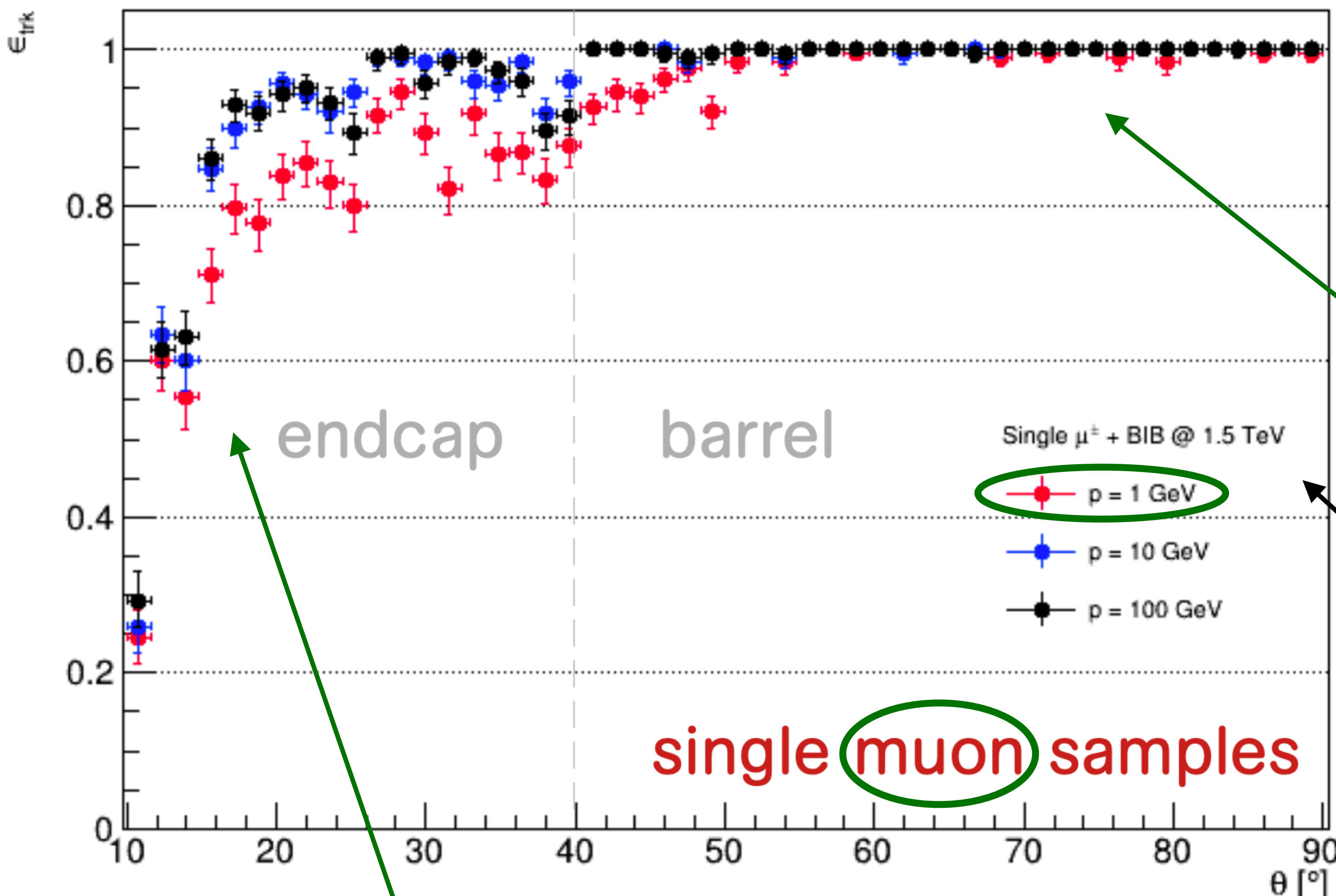
3. Soft Tracks: Backgrounds

Sestini and Casarsa



- BIB: Track Reconstruction

C. Accettura et al., Eur. Phys. J. C **83** (2023) 9, 864



Central angular region:

Small probability of missing a track immersed in the BIB

Forward/backward angular regions:

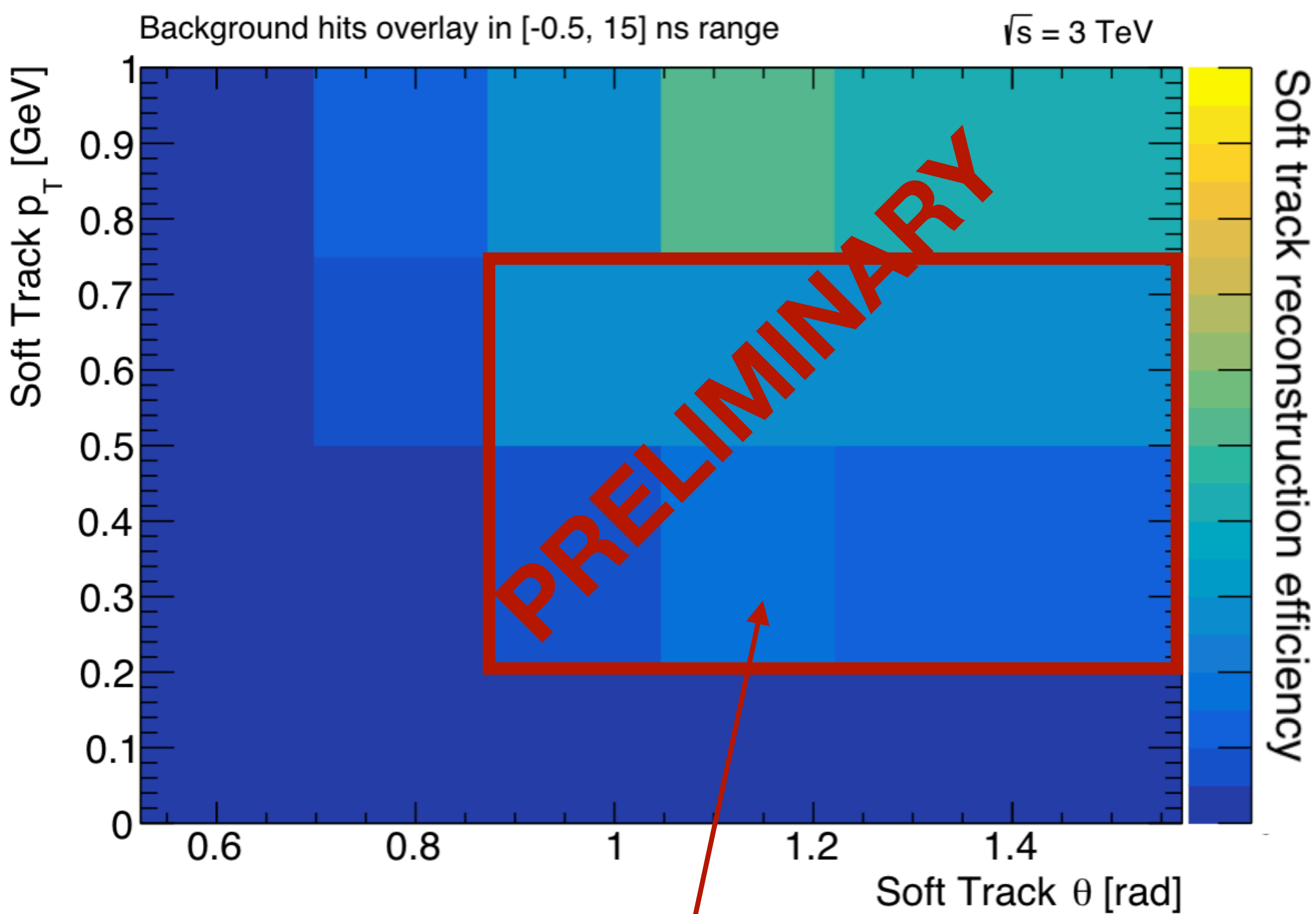
Large probability of missing a track immersed in the BIB

BIB Data from the MAP collaboration

N.V. Mokhov, S.I. Striganov, Phys. Procedia 37 (2012)

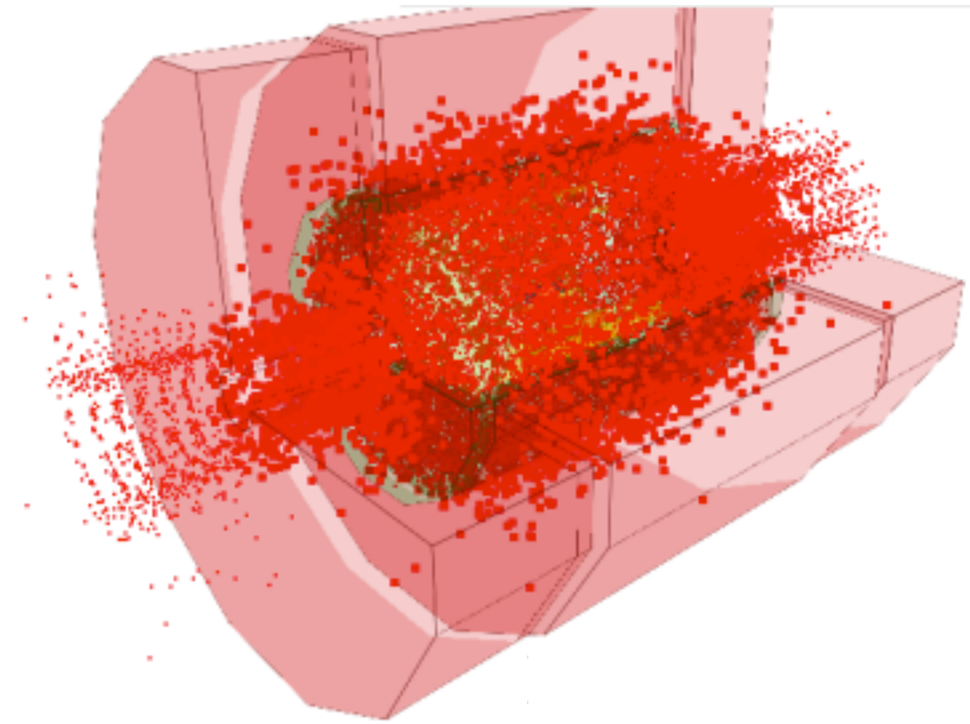
3. Soft Tracks: Backgrounds

- BIB: Track Reconstruction



Order 10-30% reconstruction efficiency in the signal region

Sestini and Casarsa



Soft Track

$$60^\circ \leq \theta_{\mathrm{ST}} \leq 120^\circ$$

$$0.2 \leq p_T^{\mathrm{ST}} \leq 0.75\,\mathrm{GeV}$$

Photons

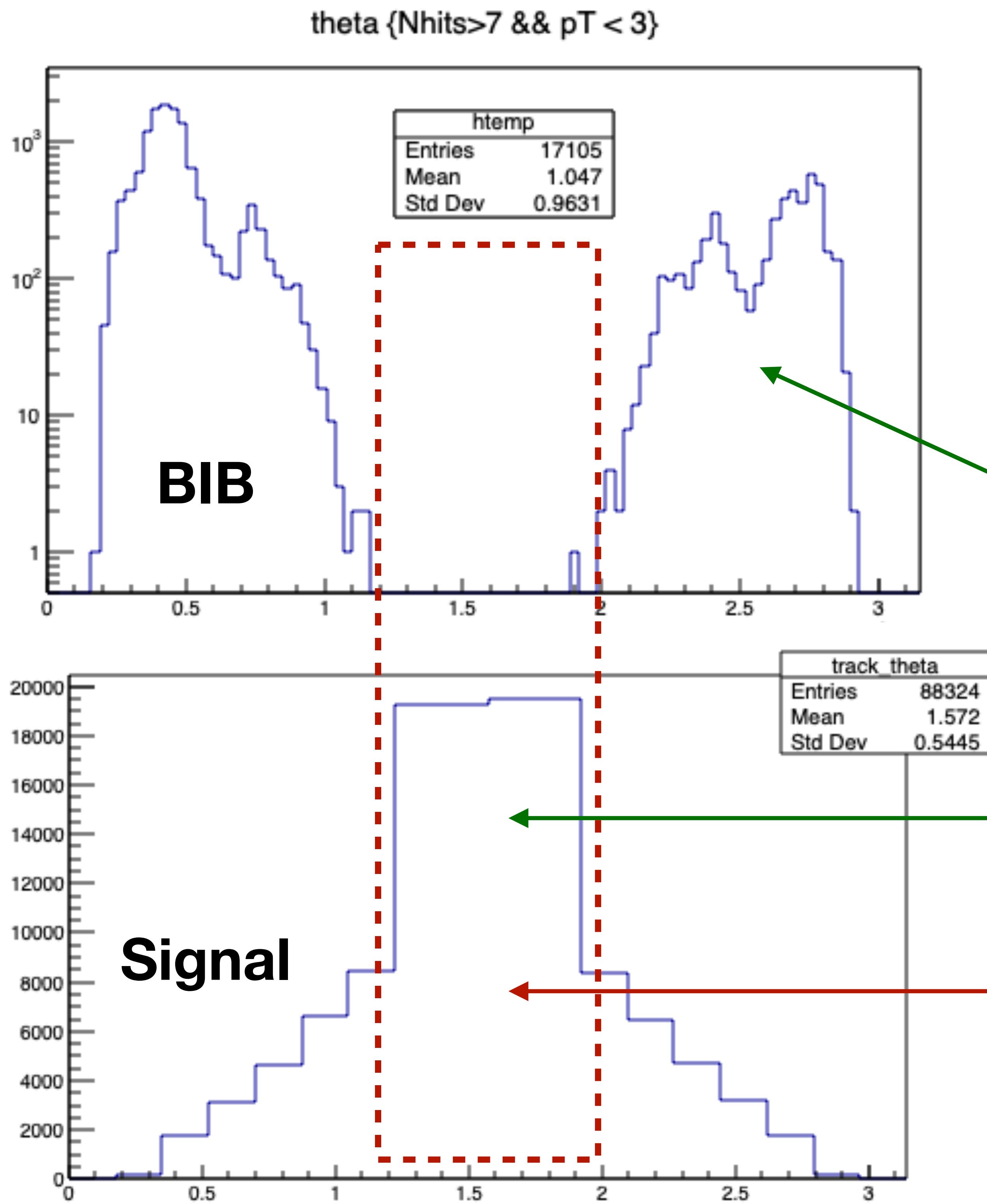
$$10^\circ \leq \theta_\gamma \leq 170^\circ$$

$$p_T^\gamma \geq 40\,\mathrm{GeV}$$

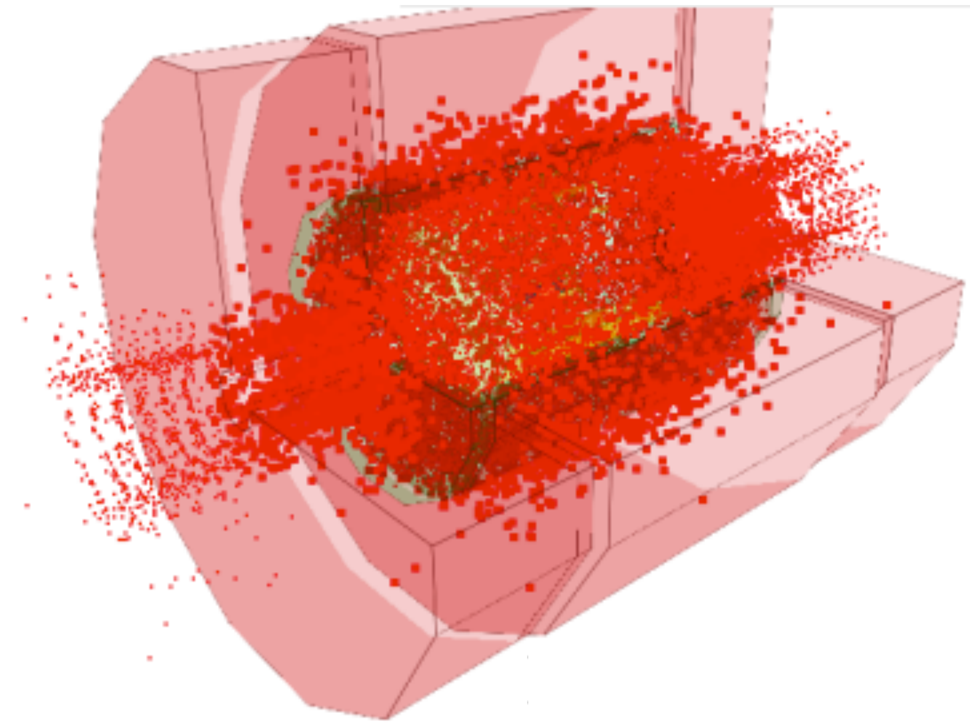
3. Soft Tracks: Backgrounds

Sestini and Casarsa

- BIB: Fake Tracks



θ_{ST}



The BIB fake tracks want to be forward/backward

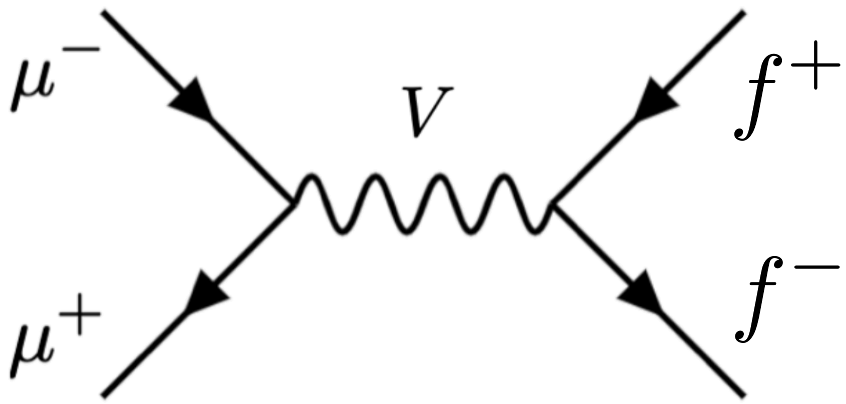
The signal wants to be central

This is why:

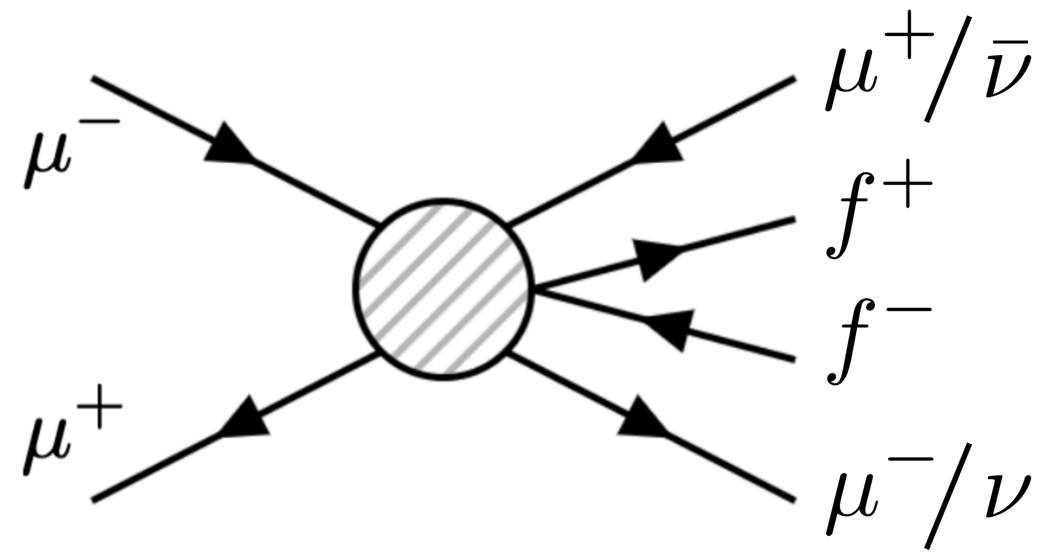
$$60^\circ \leq \theta_{\mathrm{ST}} \leq 120^\circ$$

3. Soft Tracks: Backgrounds

- ST from Leptons/Hadrons: $f = \ell, \tau, j$



DY-like process is subdominant



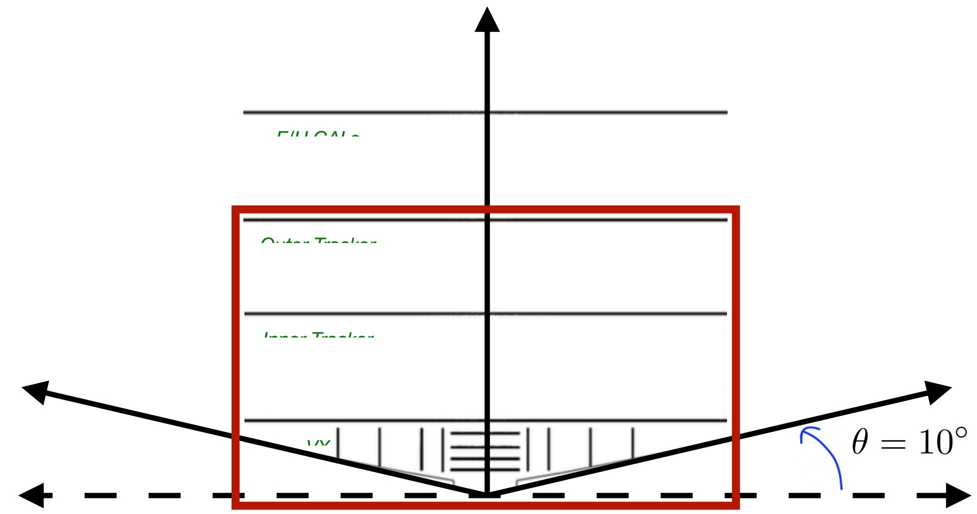
VBF and Bhabha-like processes dominate background production

$\mu^+\mu^- \to \gamma + \mathrm{X}\ (+Z \to \nu\nu)$		
X	$\sigma(\gamma\mathrm{X})$ [fb]	$\sigma(\gamma\mathrm{X}Z)$ [fb]
$\ell^+\ell^-\nu_\ell\bar{\nu}_\ell$	242.0	2.828
$\ell^+\ell^-\mu^+\mu^-$	60.45	0.012
$e^+\nu_e\mu^-\bar{\nu}_\mu$ + CP	226.6	2.710
$\tau^+\tau^-\nu_\ell\bar{\nu}_\ell$	6.493	0.058
$\tau^+\tau^-\mu^+\mu^-$	30.86	0.006
$\tau^+\nu_\tau\mu^-\bar{\nu}_\mu$ + CP	226.2	2.722
$jj\nu_\ell\bar{\nu}_\ell$	104.5	0.904
$jj\mu^+\mu^-$	30.63	0.019
$jj\mu^-\bar{\nu}_\mu$ + CP	1215.	11.57

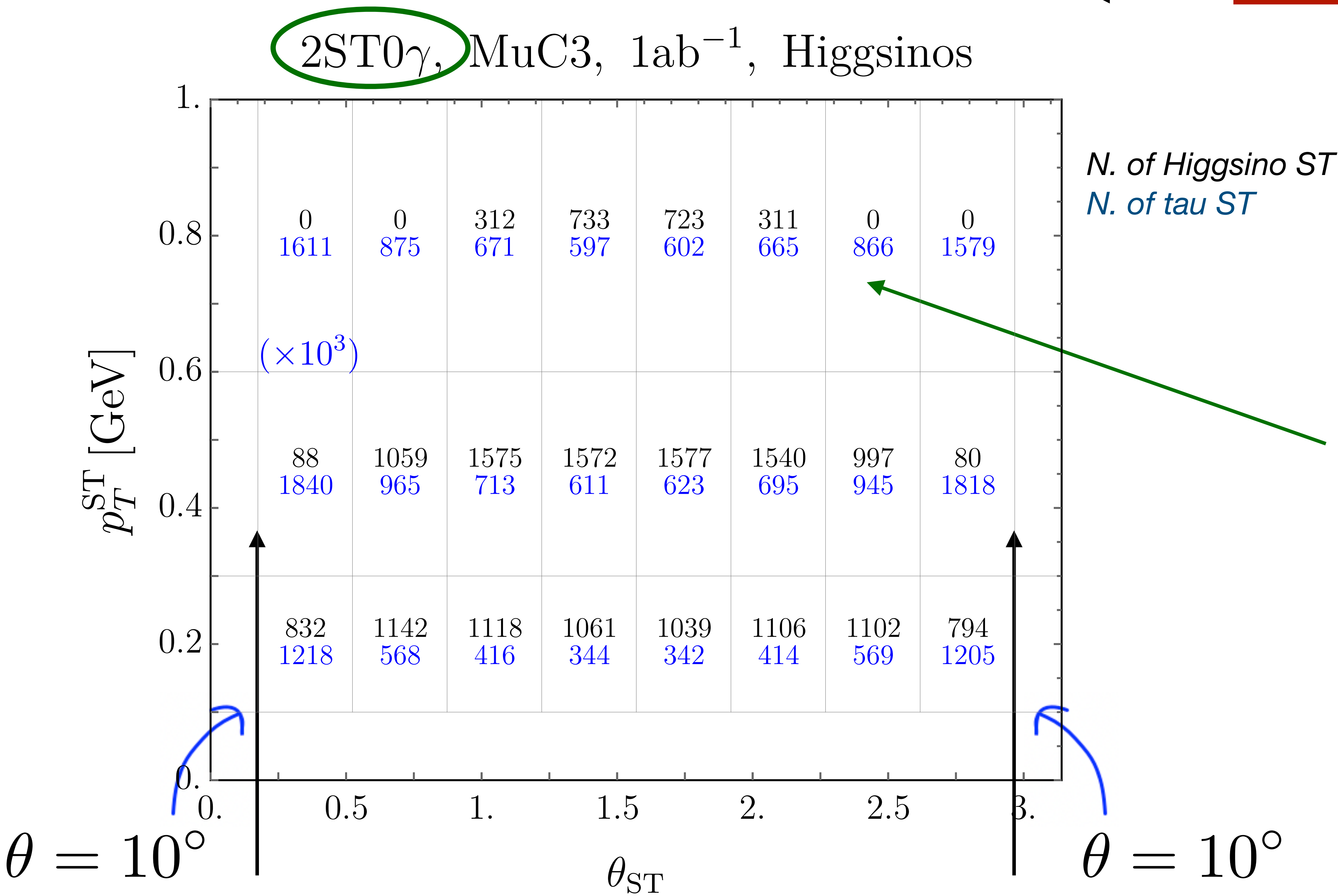
$$p_T^\gamma \geq 20\ \mathrm{GeV}$$
$$|\eta_\gamma| < 2.44$$

$$p_T^\ell \geq 0.1\ \mathrm{GeV}$$
$$p_T^j \geq 0.1\ \mathrm{GeV}$$

3. Soft Tracks: Backgrounds



- Backgrounds:



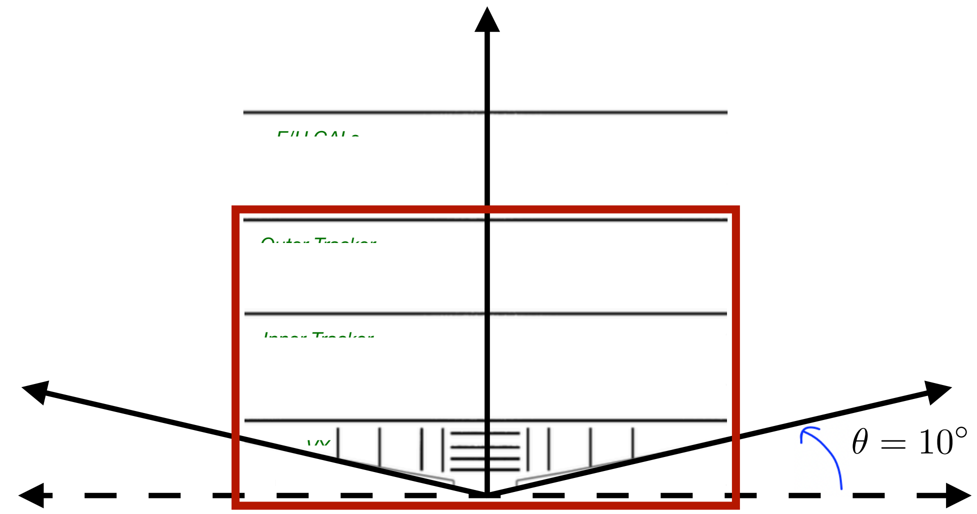
N. of Higgsino ST

N. of tau ST

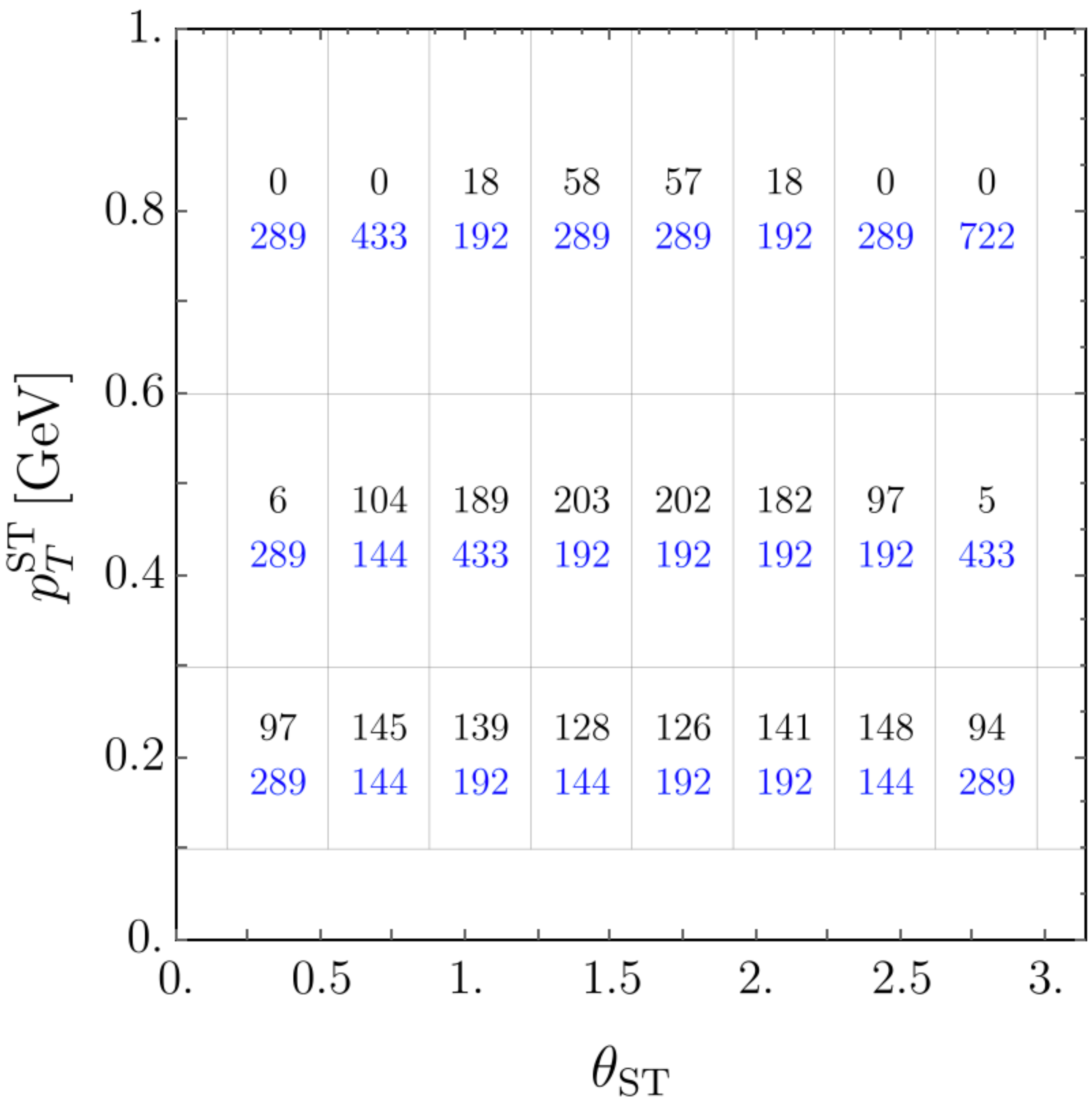
Bad luck!

The signal region with more events is overwhelmed by the background!

3. Soft Tracks: Backgrounds



- Backgrounds:



N. of Higgsino ST

N. of tau ST

$\mathrm{MuC3,\ 1ab^{-1}}$

$\mathrm{2ST1\gamma,\ Higgsinos}$

$p_T^\gamma \geq 10\,\mathrm{GeV}$

$N_{\mathrm{tot}} = 2157$

$N_{\mathrm{tot}} = 6350$

Good luck!

The photon in the event pushes the ST candidates out of the acceptance!!!

This is why:

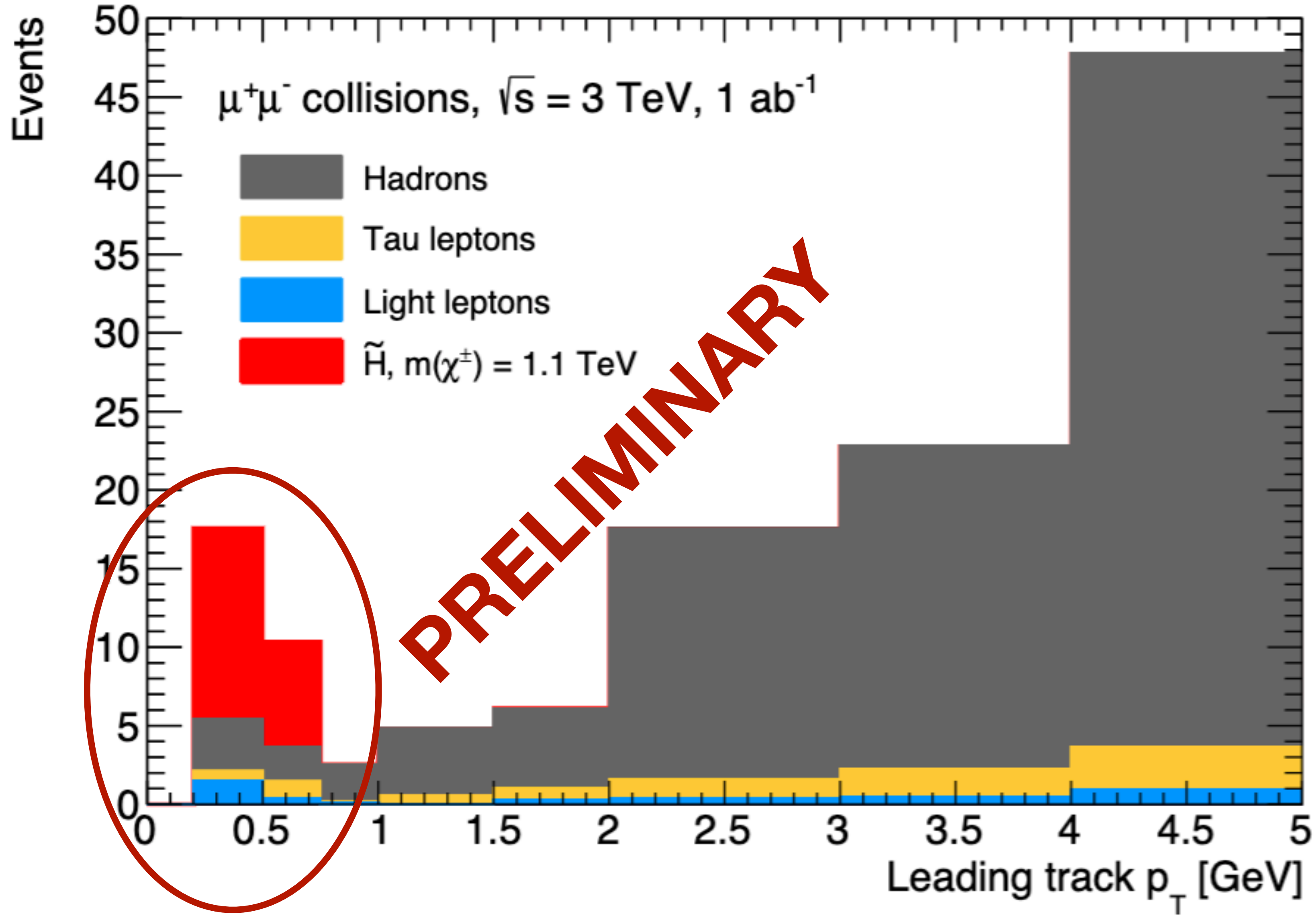
$$p_T^\gamma \geq 40\,\mathrm{GeV}$$

Outline

Rodolfo Capdevilla, Fermilab

4. Results

- The Importance of the 3TeV Collider:



Five sigma for the Thermal Higgsino (Doublet MDM)

Signal region:
2 ST + 1 gamma
0.2 < pT < 0.75 GeV

Vetoes:
Hard tracks
Heavy neutrals

Photon pT above 40 GeV

Fakes:

Random ECAL hits from the BIB that can mimic a photon

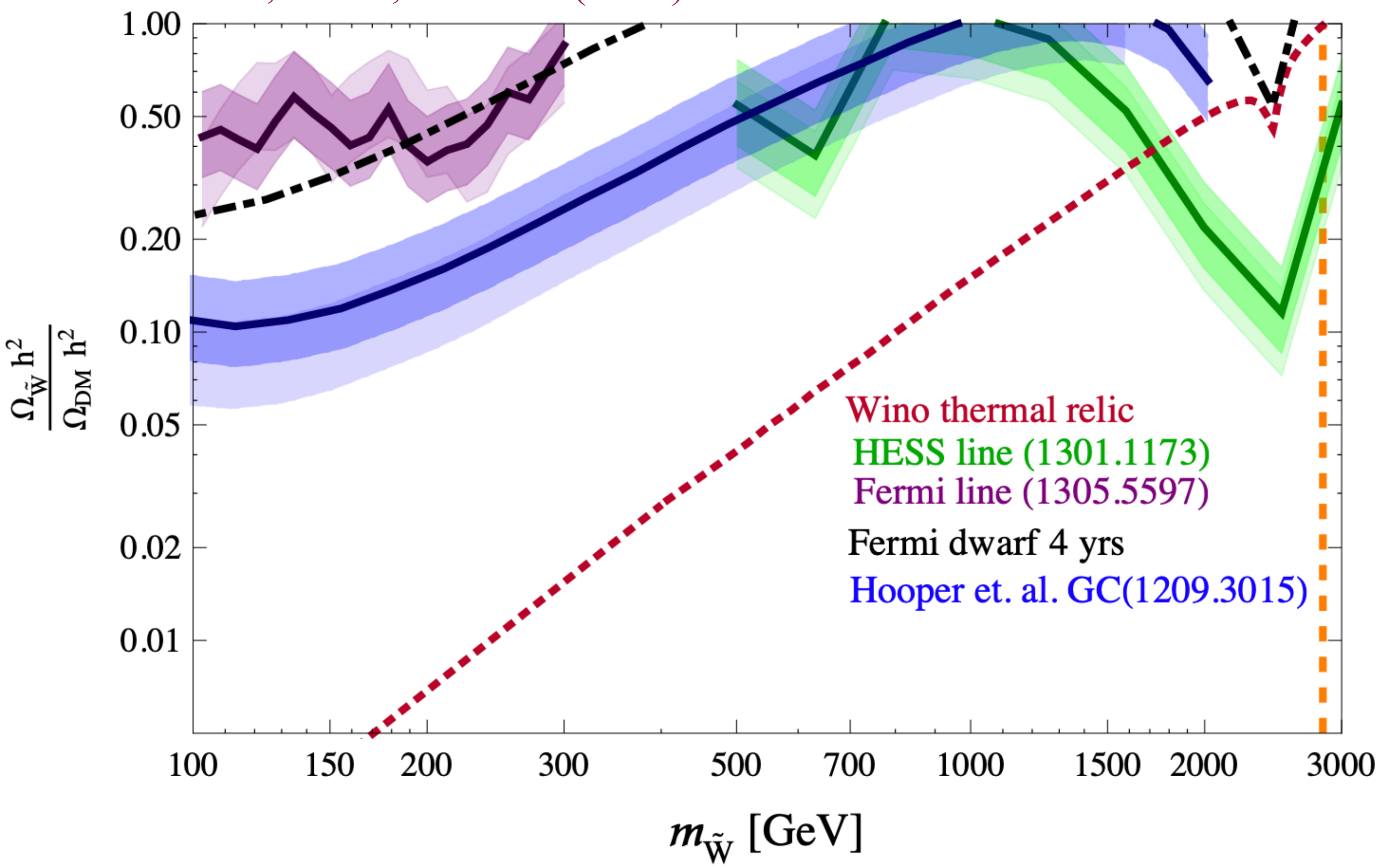
Incoherent pair production via synchrotron

4. Results

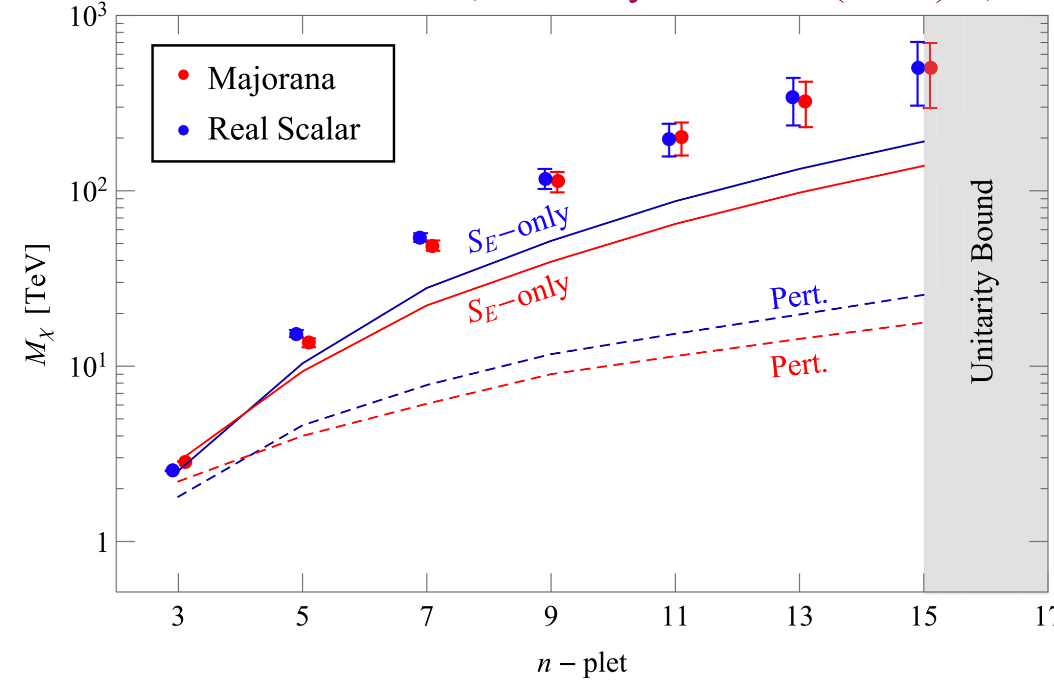
- The Importance of the 3TeV Collider:

Not just the Higgsino (doublet MDM)

Fan, Reece, JHEP 10 (2013) 124

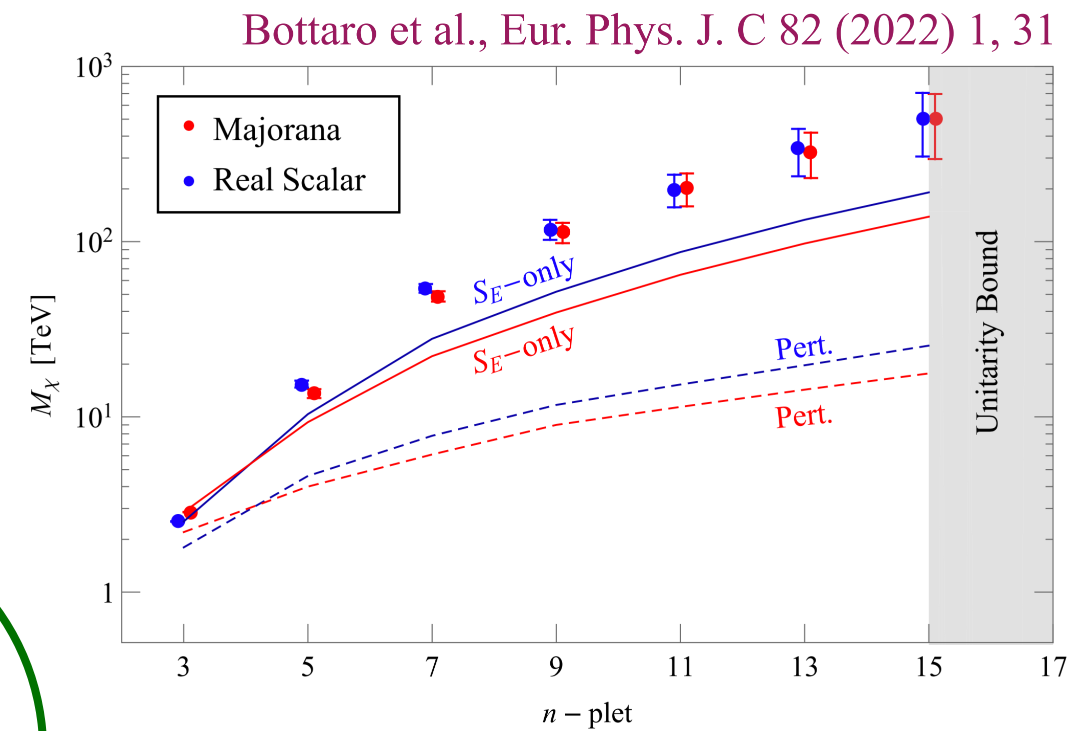


Bottaro et al., Eur. Phys. J. C 82 (2022) 1, 31

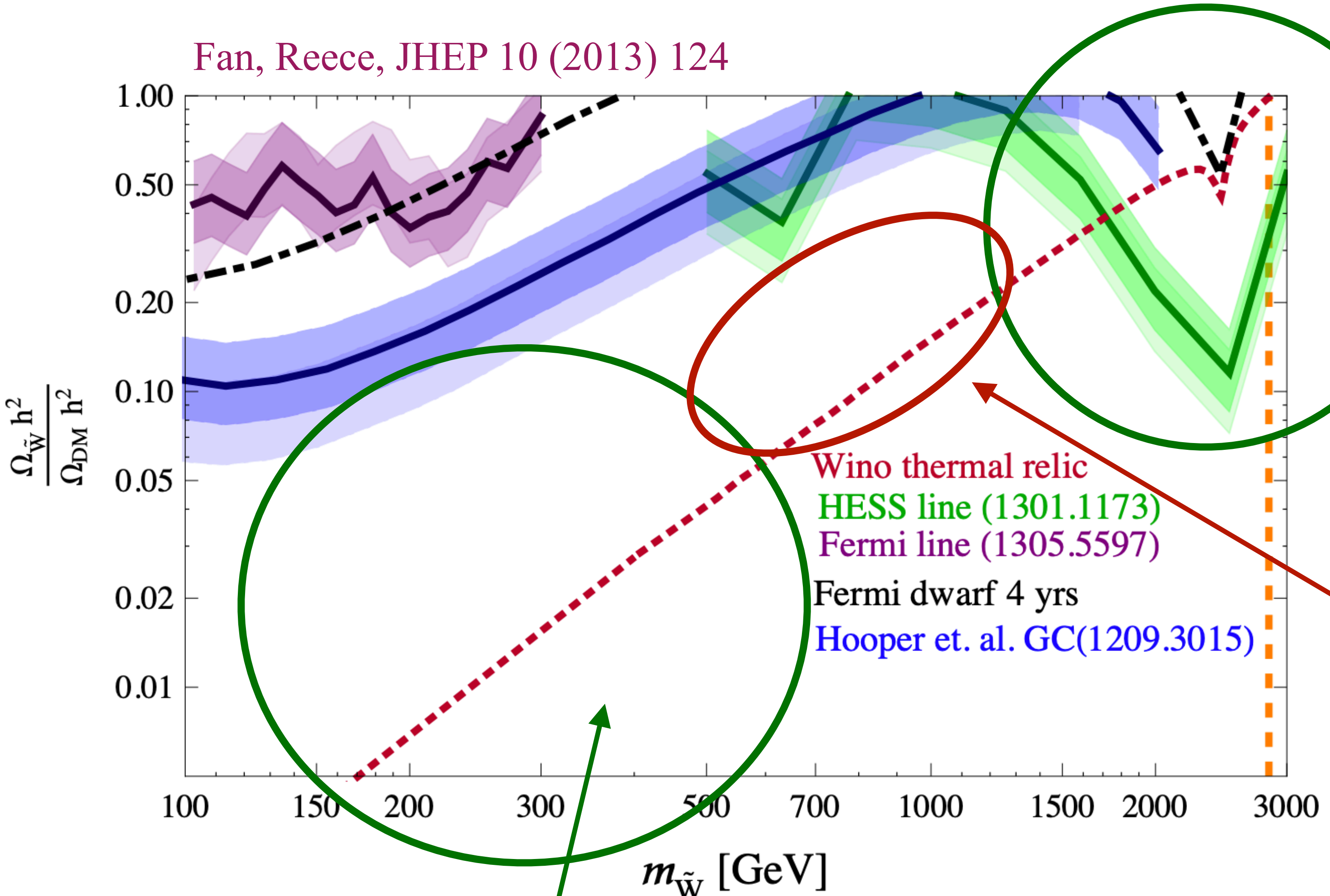


4. Results

- The Importance of the 3TeV Collider:



Not just the Higgsino (doublet MDM)



Indirect detection reach

MuC?

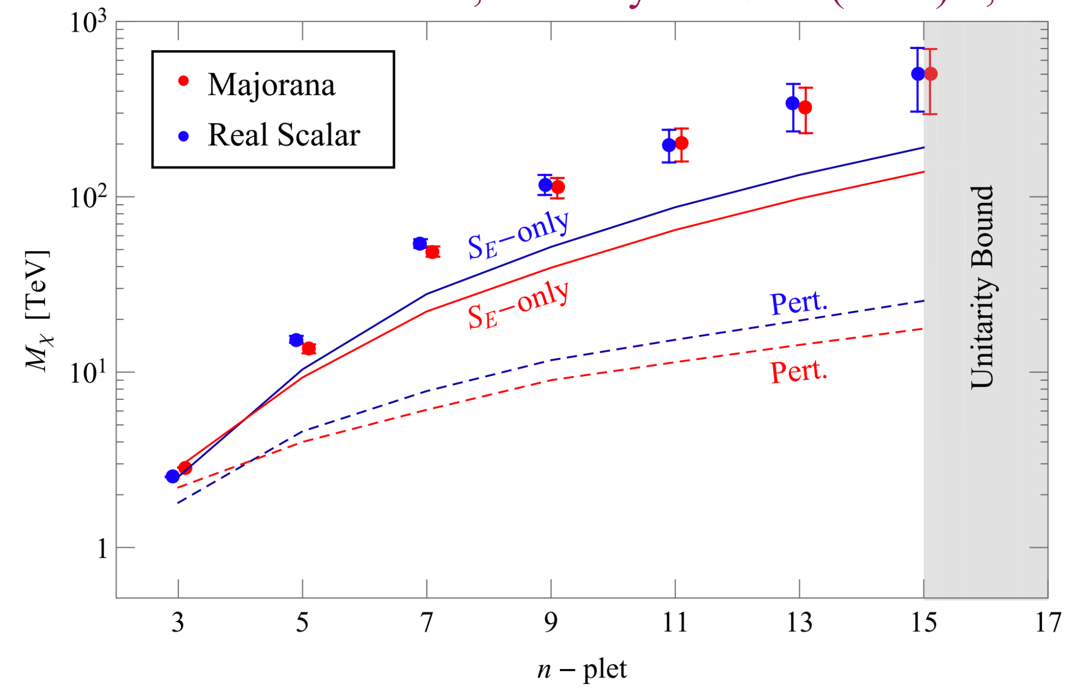
HL-LHC reach

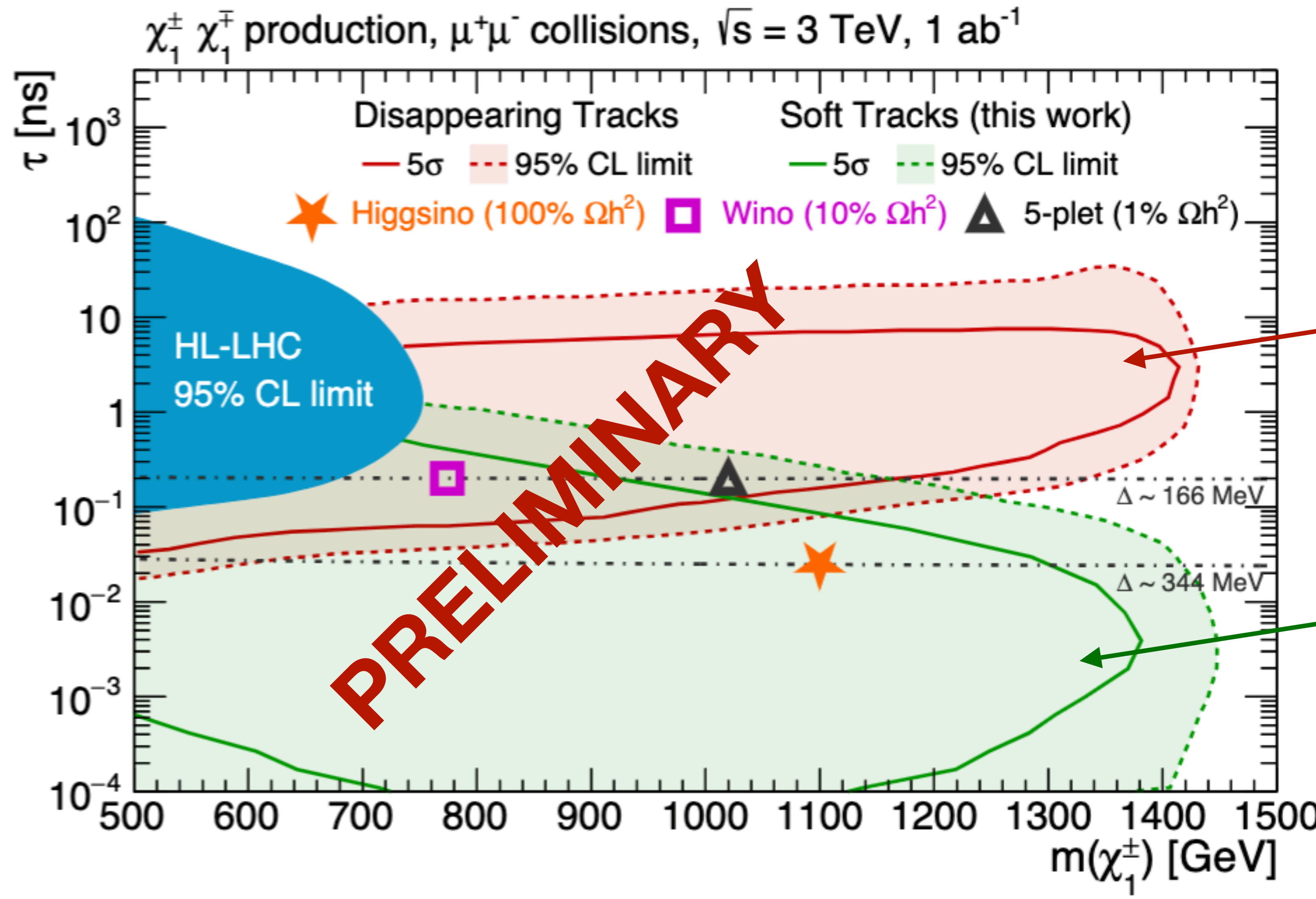
4. Results

- The Importance of the 3TeV Collider:

Not just the Higgsino (doublet MDM)

Bottaro et al., Eur. Phys. J. C 82 (2022) 1, 31





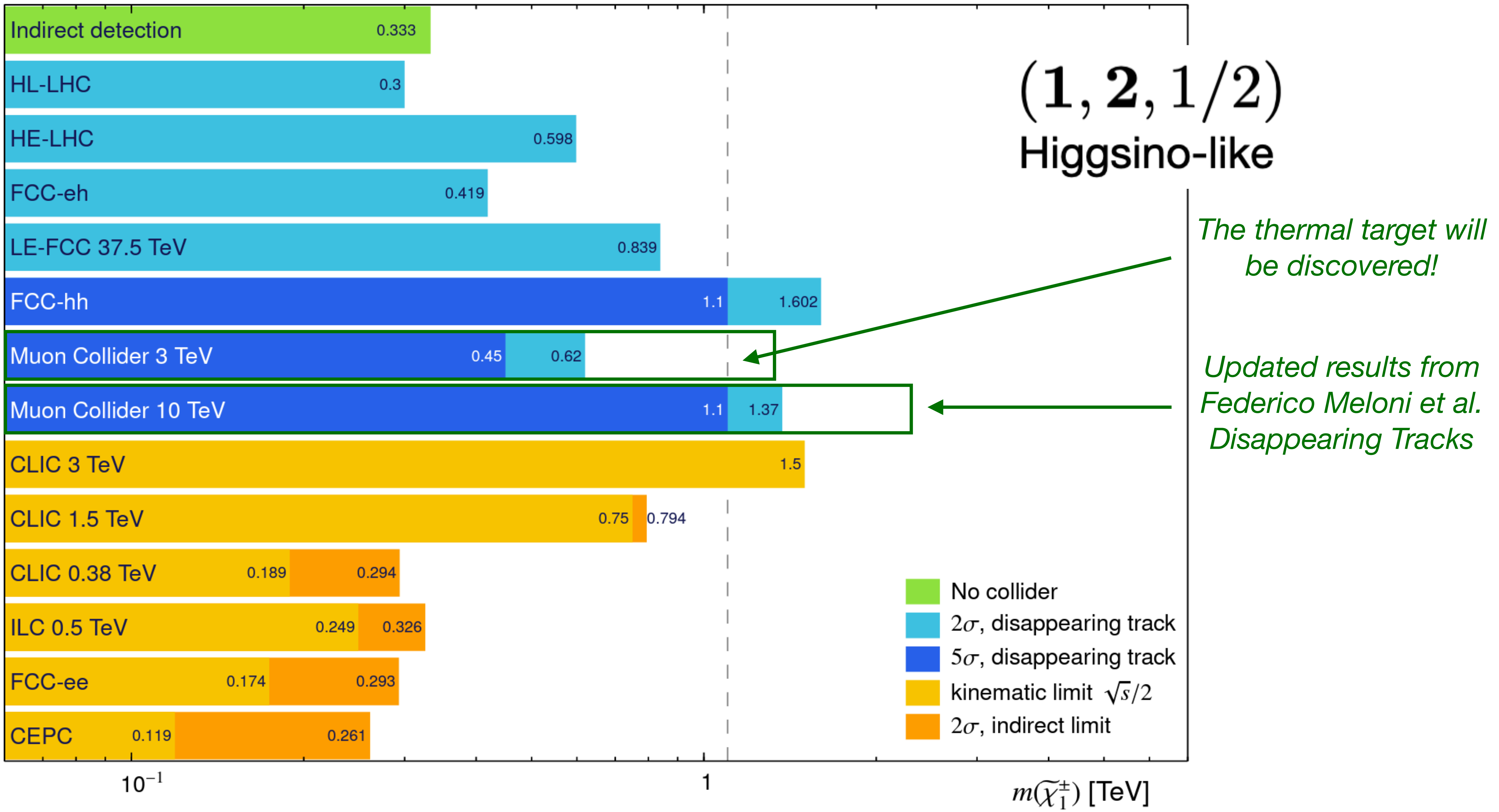
Previous result from DT

NEW result from ST

Rodolfo Capdevilla, Fermilab

4. Results

- Projections:



Rodolfo Capdevilla, Fermilab

Outline

1. Introduction
2. Minimal Dark Matter
   - Properties
   - Projections
3. Soft Tracks
   - Signal Regions
   - Backgrounds
4. Results
   - The Importance of the 3TeV MuC!

Summary

1. Minimal Dark Matter models constitute high motivated targets for future colliders. Small multiplets (doublets/triplets) have thermal masses at the reach of foreseeable MuC. Larger multiplets (5-plet and above) that can explain 1-10% of the DM in the Universe also falls into the multi-TeV rage that can be discovered at MuC.

2. Soft Track searches will be possible at the Muon Collider. Using this technique **the 3TeV Muon Collider has the potential of discovering the thermal Higgsino-like minimal Dark Matter candidate.** This result suggest that the 3TeV Muon collider is not only a stage to the 10TeV machine but it is also a powerful discovery machine.

3. The Muon Collider program (3 -> 10 TeV) will be able to discover and characterize minimal WIMPs. A combination of Disappearing Track and Soft Track searches will allow us to determine the mass of the thermal relic, as well as the mass gap between this particle and its companion charged state.

Thank You!

Discovering Minimal Dark Matter at Muon Colliders

- Minimal Dark Matter models extend the Standard Model by incorporating a single electroweak multiplet, with its neutral component serving as a candidate for the thermal relic dark matter in the Universe. These models predict TeV-scale particles with sub-GeV mass splittings Δ. Collider searches aim at producing the charged member of the electroweak multiplet which then decays into dark matter and a charged particle. Traditionally, these searches involve signatures of missing energy and disappearing tracks. Due to the small size of Δ, the transverse momentum of this charged particle is too soft to be resolved at hadron colliders. In this talk, I show that a Muon Collider is capable of detecting these soft charged decay products, providing a means to discover TeV thermal relics with an almost degenerate charged companion. Our technique also facilitates the determination of Δ, allowing for a comprehensive characterization of the dark sector. Our results indicate that a 3 TeV muon collider will have the capability to discover the highly motivated thermal Higgsino-like dark matter candidate as well as other scenarios of Minimal Dark Matter featuring larger multiplets whose neutral component corresponds to a fraction of the total dark matter in the Universe. This study highlights the potential of a muon collider to make significant discoveries even at its early stages of operation.