Soft Tracks for Higgsino Discovery

IMCC and MuCol Annual Meeting

CERN

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***RC**, Federico Meloni, Jose Zurita, ArXiv: 2403.xxxxx*
***RC**, Federico Meloni, Rosa Simoniello, Jose Zurita, JHEP **06** (2021) 133*

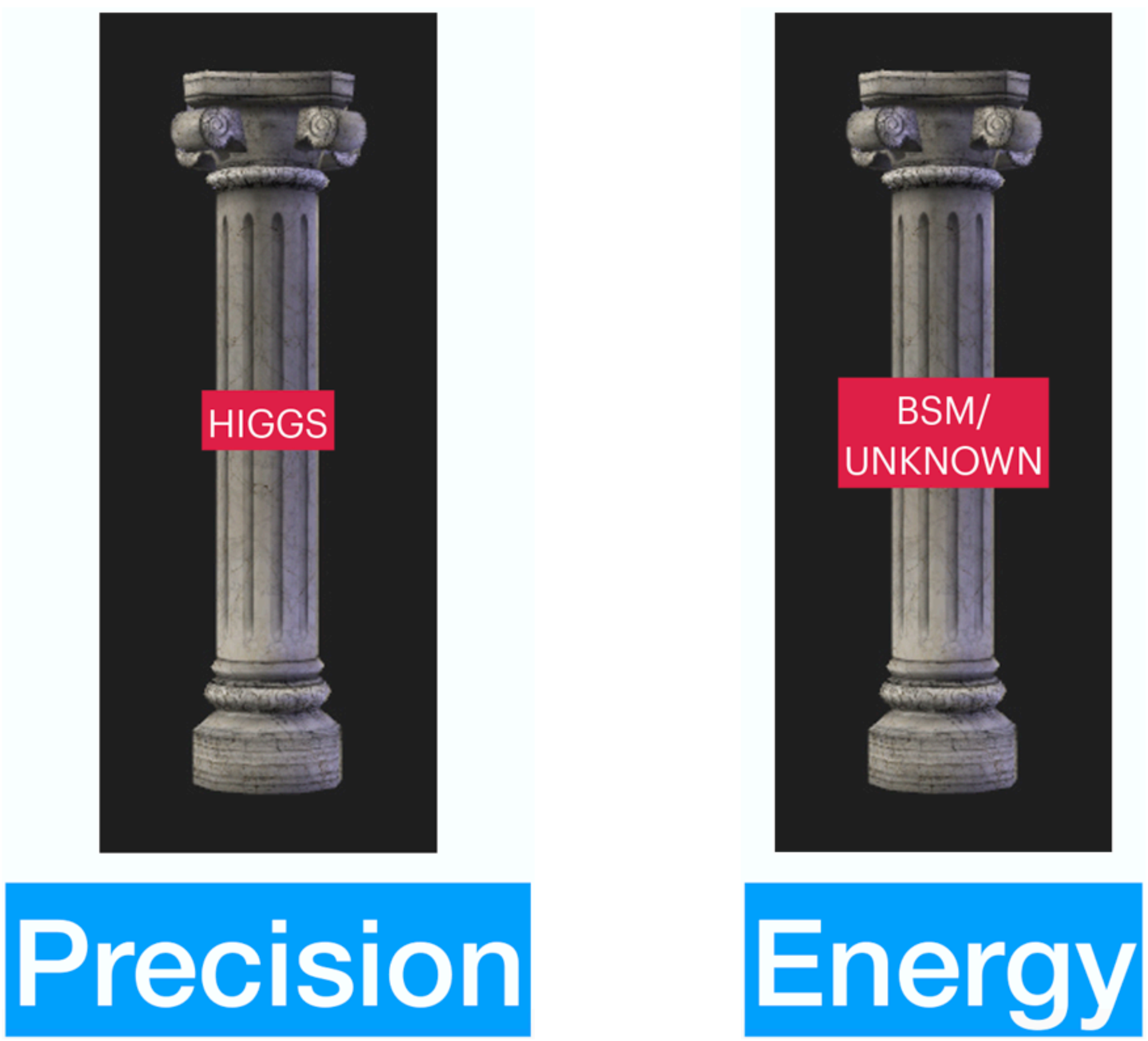
Outline

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



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?
…

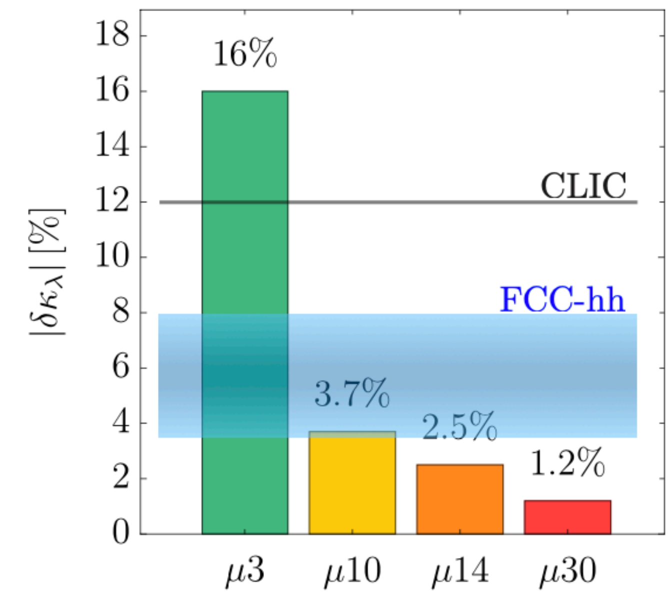
From Patrick Meade's talks!

1. Introduction

- MuC strong candidate for both:

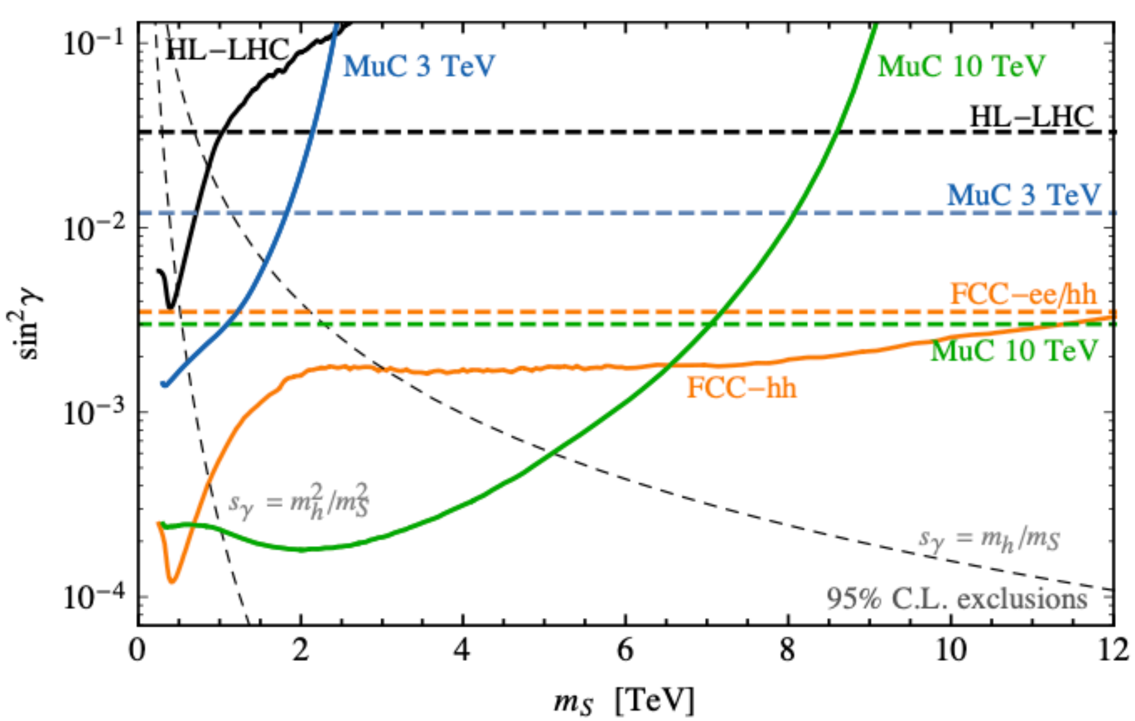
Higgs/Precision

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

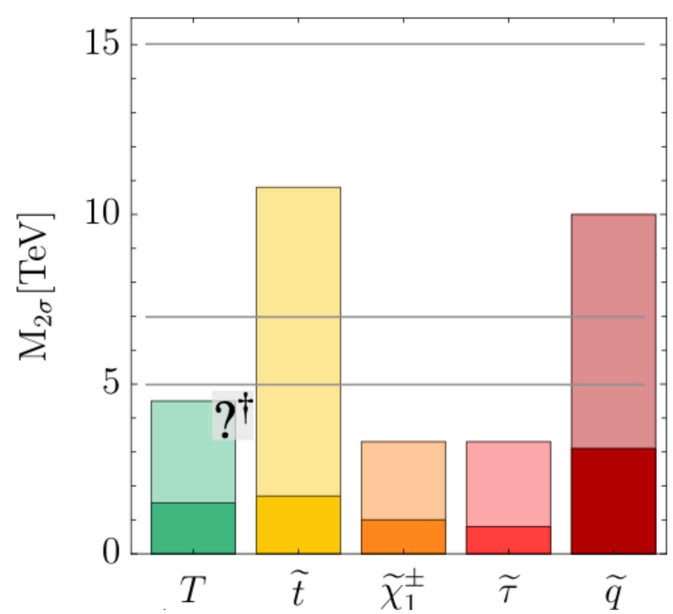


H. Al Ali et al., Muon Smasher's guide + Delphes

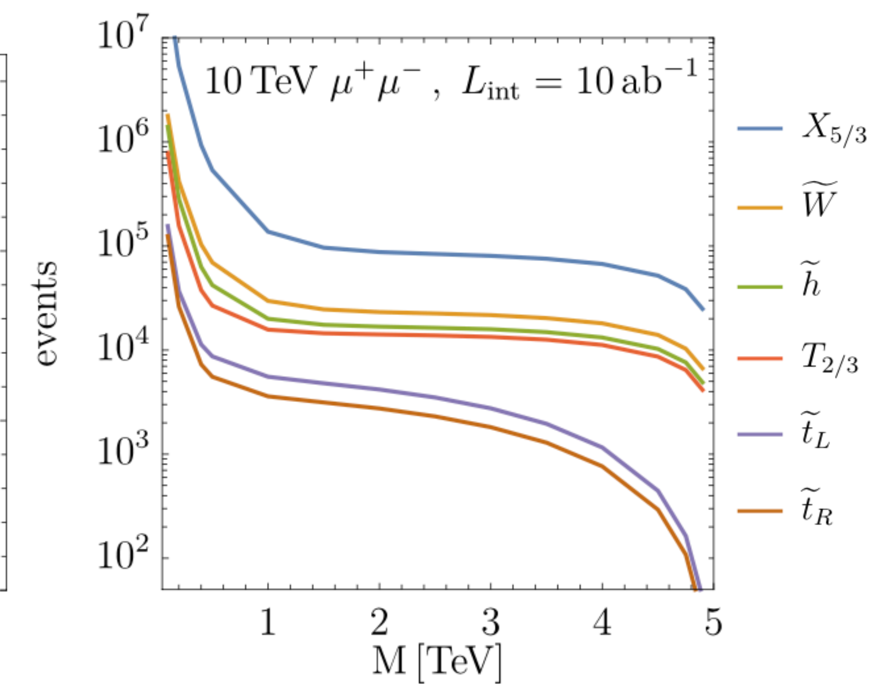
BSM/Unknown



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

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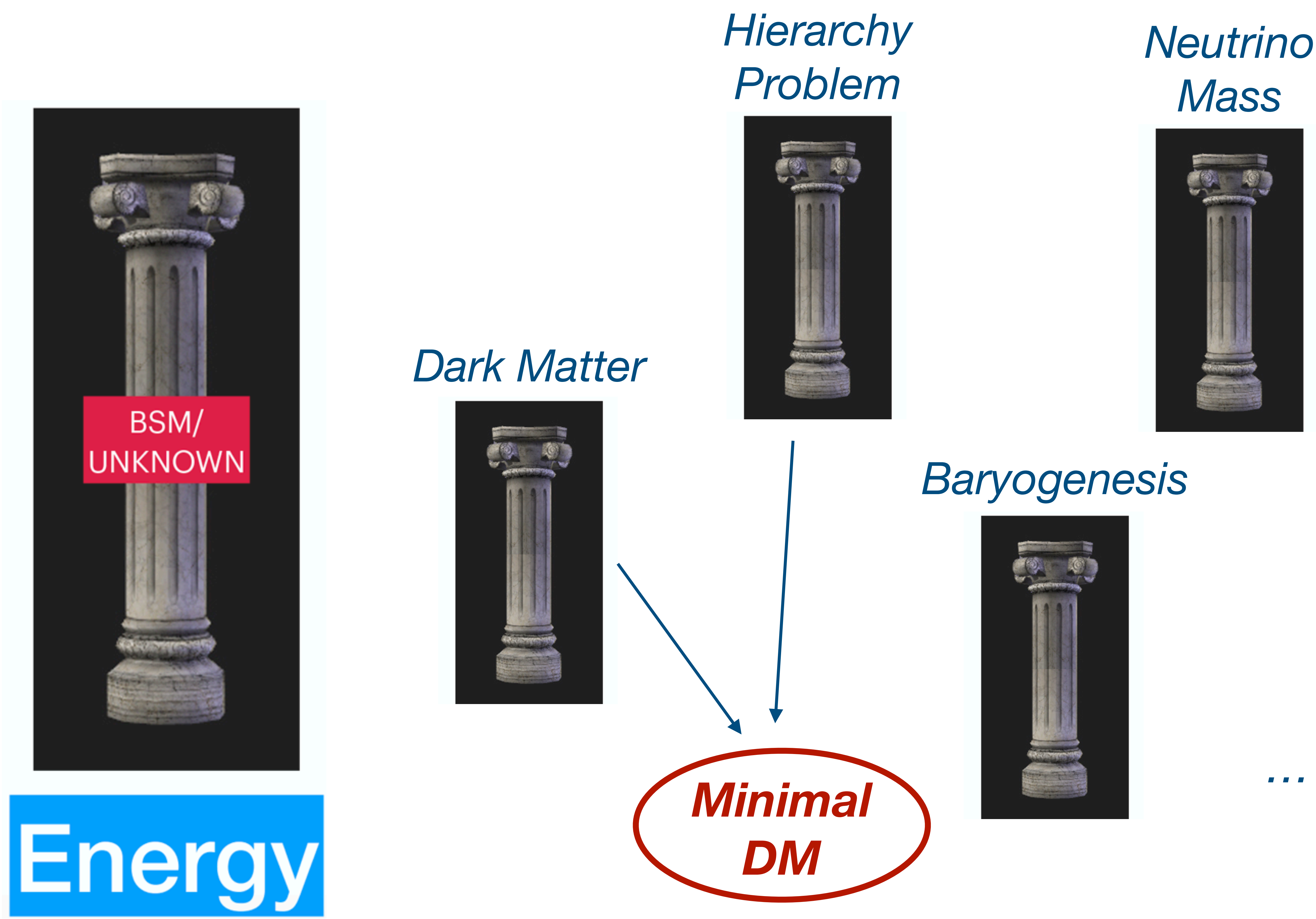
Outline

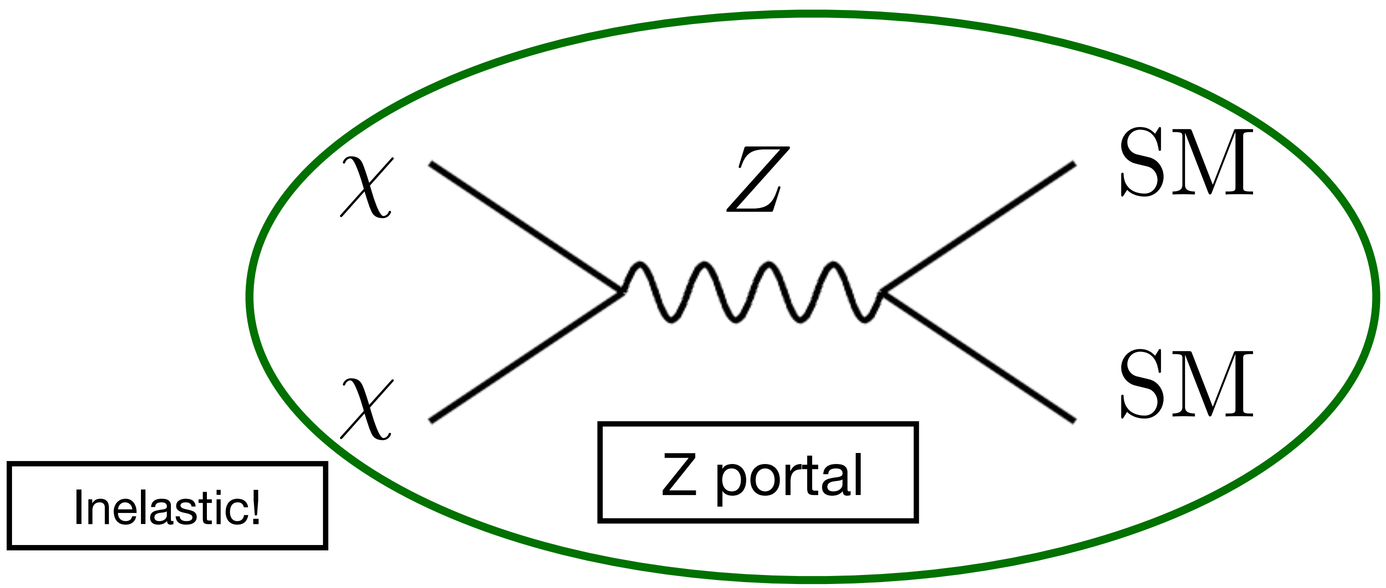
2. Minimal Dark Matter



Rodolfo Capdevilla, Fermilab

2. Minimal Dark Matter: Properties

- 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

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

$(\mathbf{1}, \mathbf{3}, 0)$

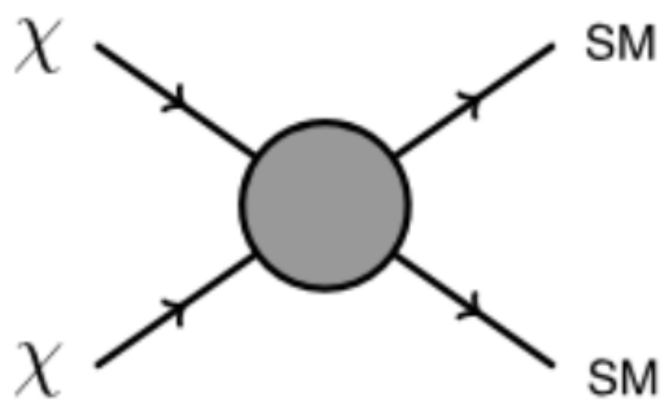
Wino-like

Neutral component = DM

2. Minimal Dark Matter: Properties

- DM Freeze Out:

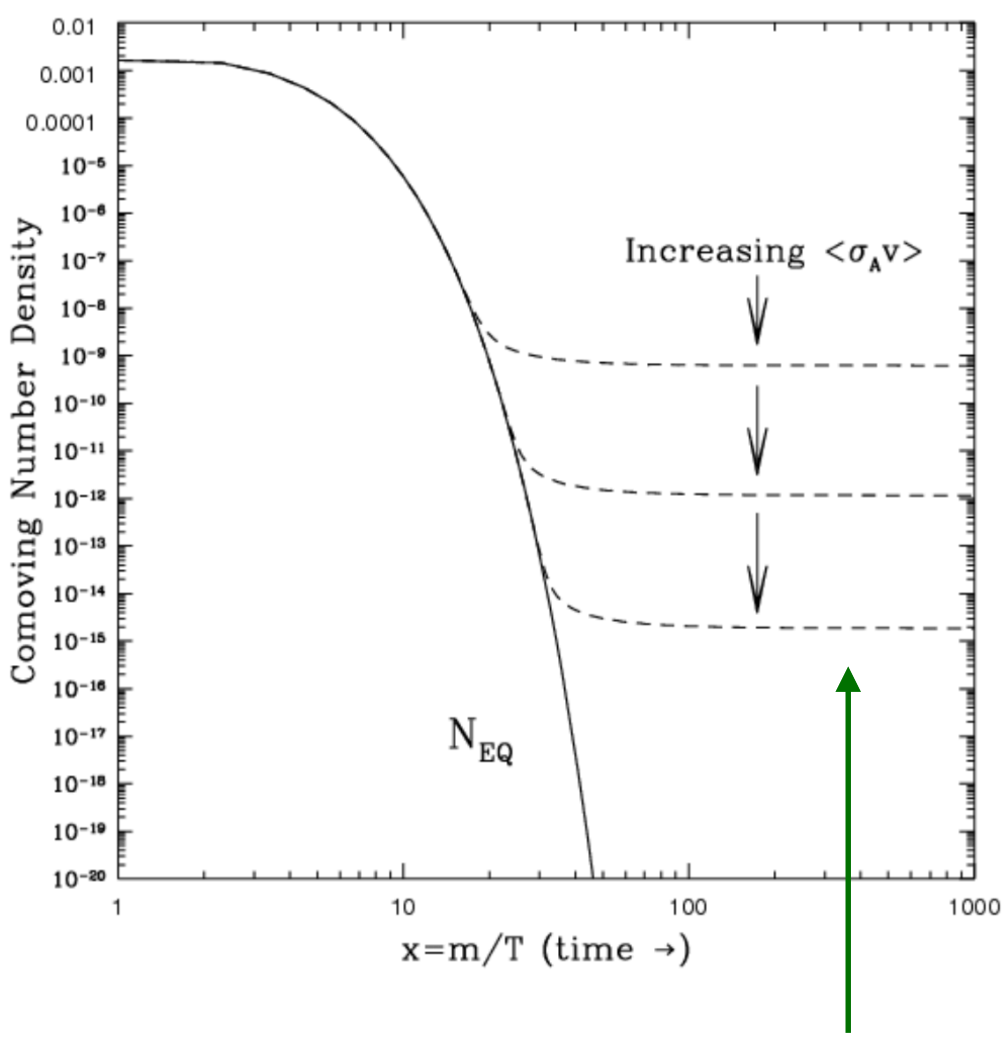
Annihilation in the early Universe



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

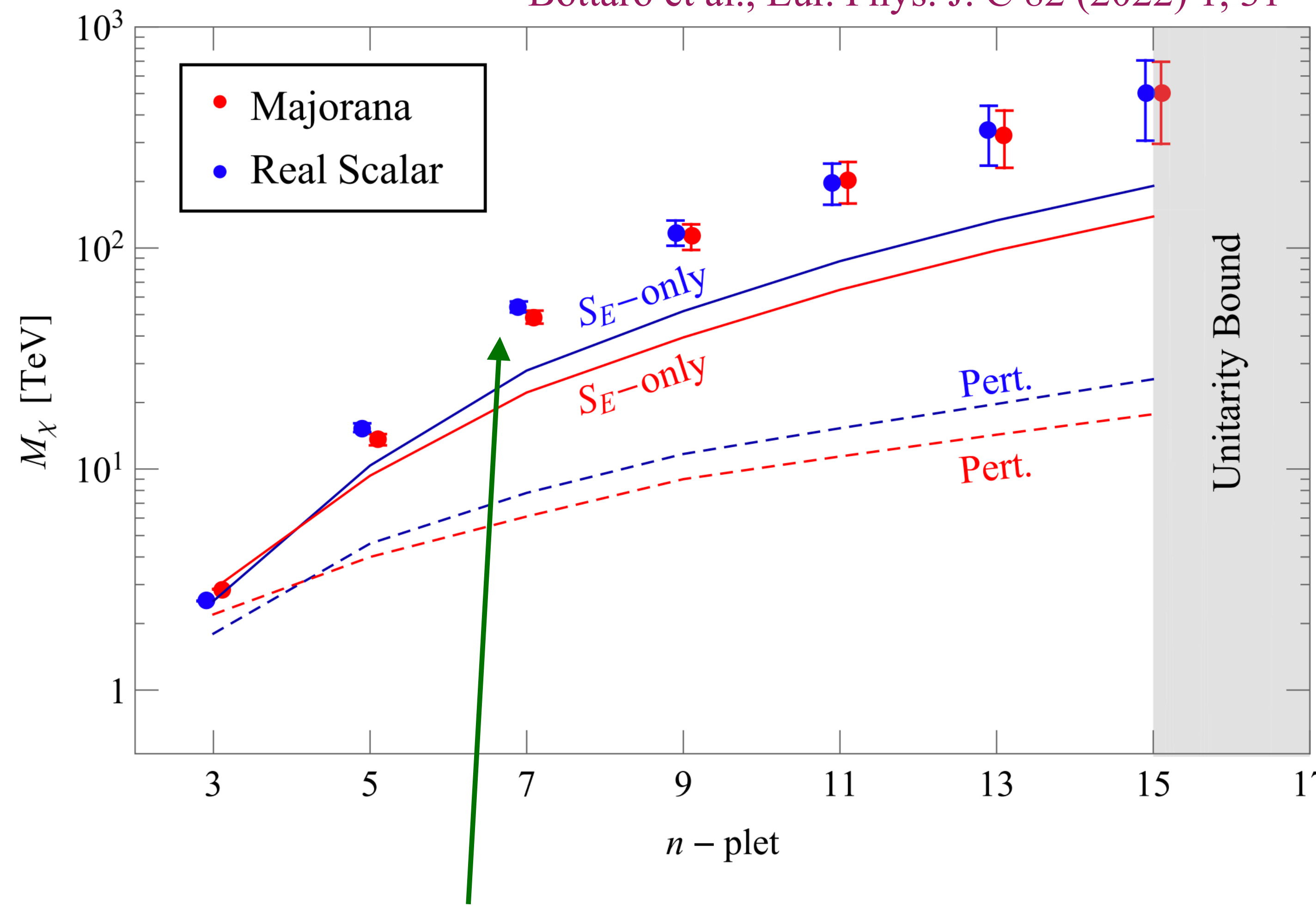
$$\langle \sigma v \rangle \sim \frac{g_2^4 n^4 + 8 g_2^2 g_Y^2 Y^2 n^2}{64 \pi M^2 g_\chi}$$

(**Scalar Large n**)



More annihilation requires heavier DM

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



Mass for which n-plet represents 100% of DM

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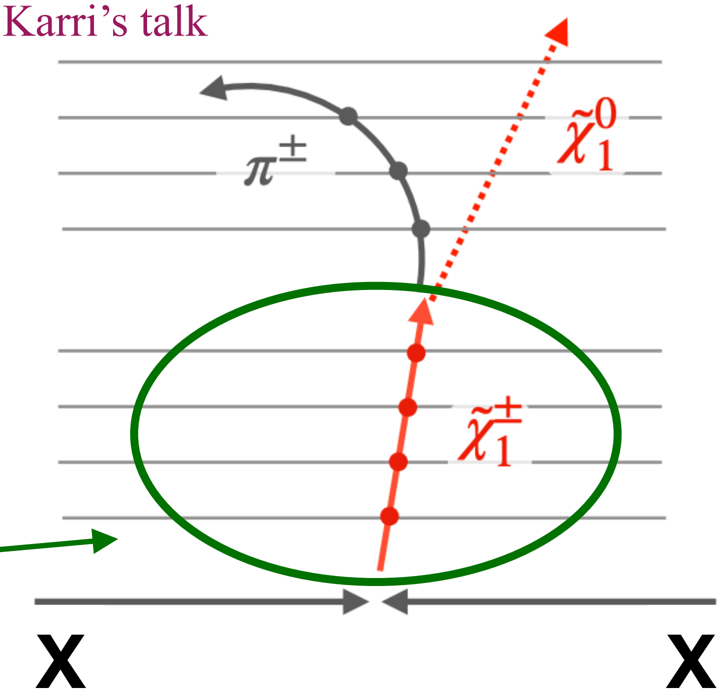
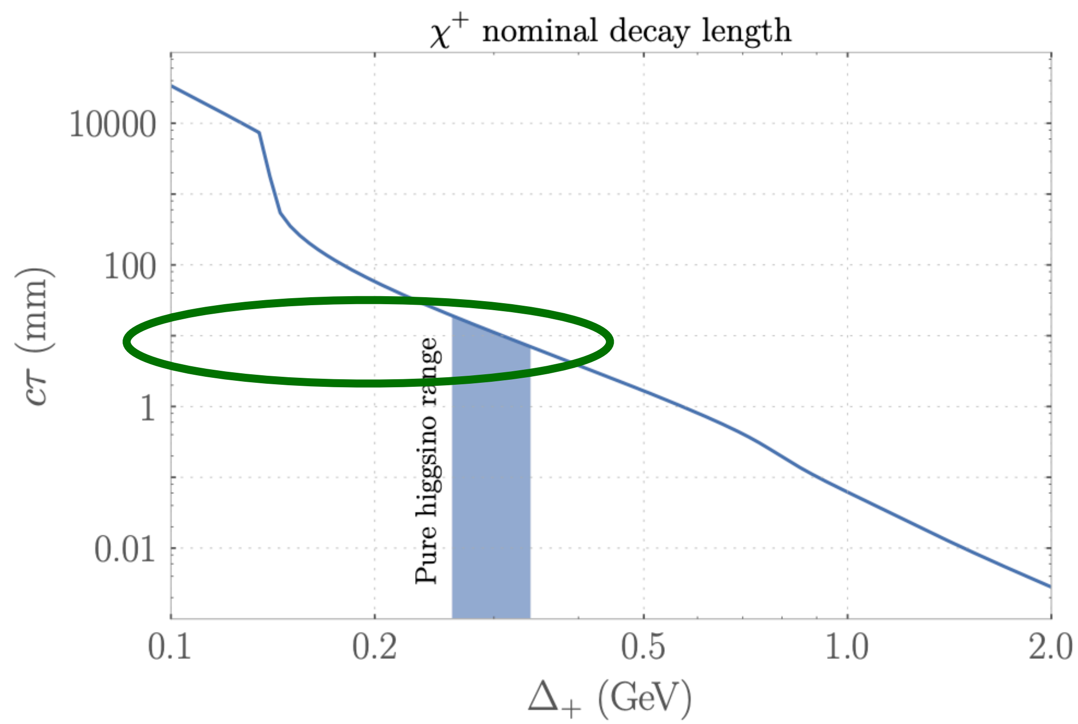
2. Minimal Dark Matter: Properties

- Lifetime:

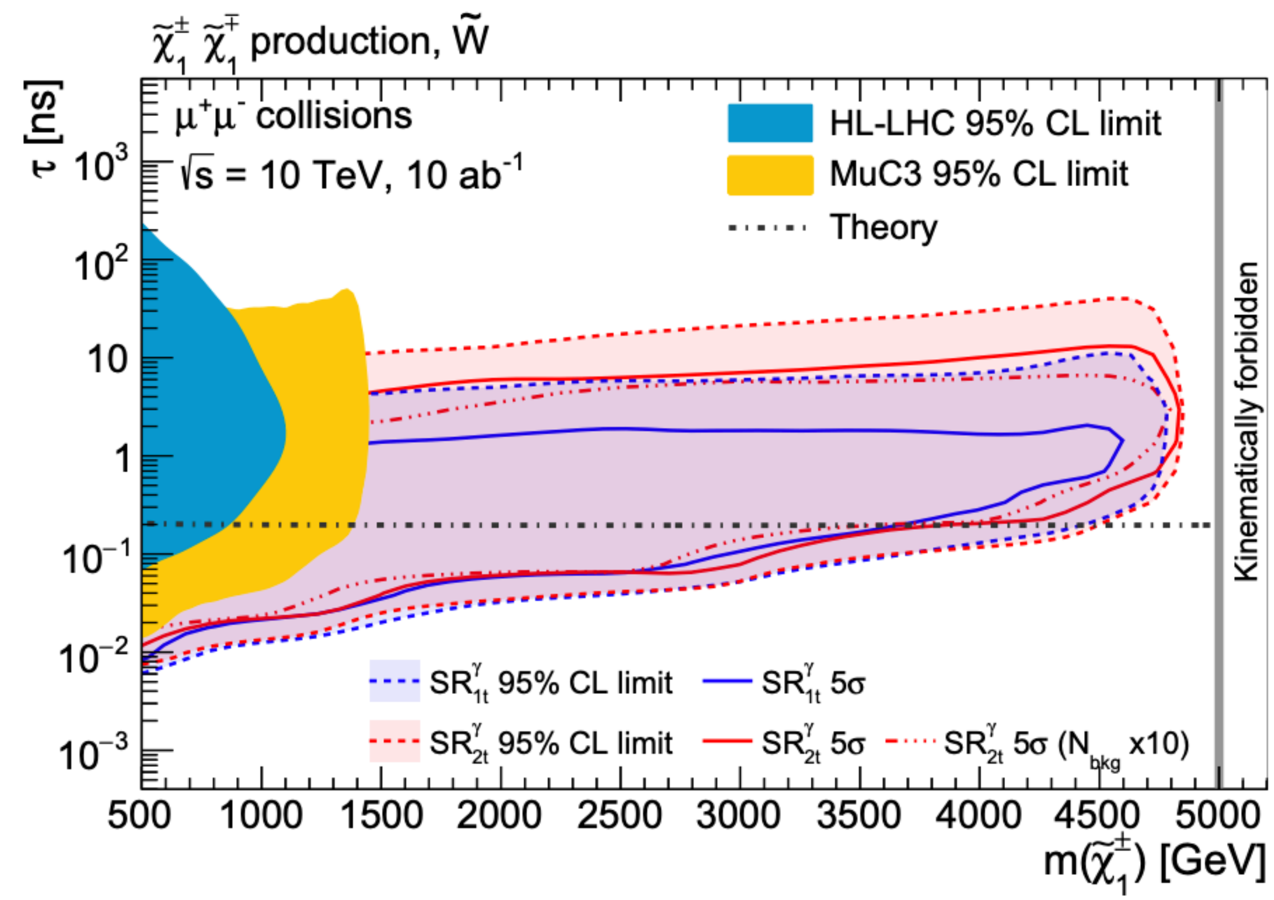
$$\Delta m = m_{\chi^+} - m_{\chi^0} > 0$$

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





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

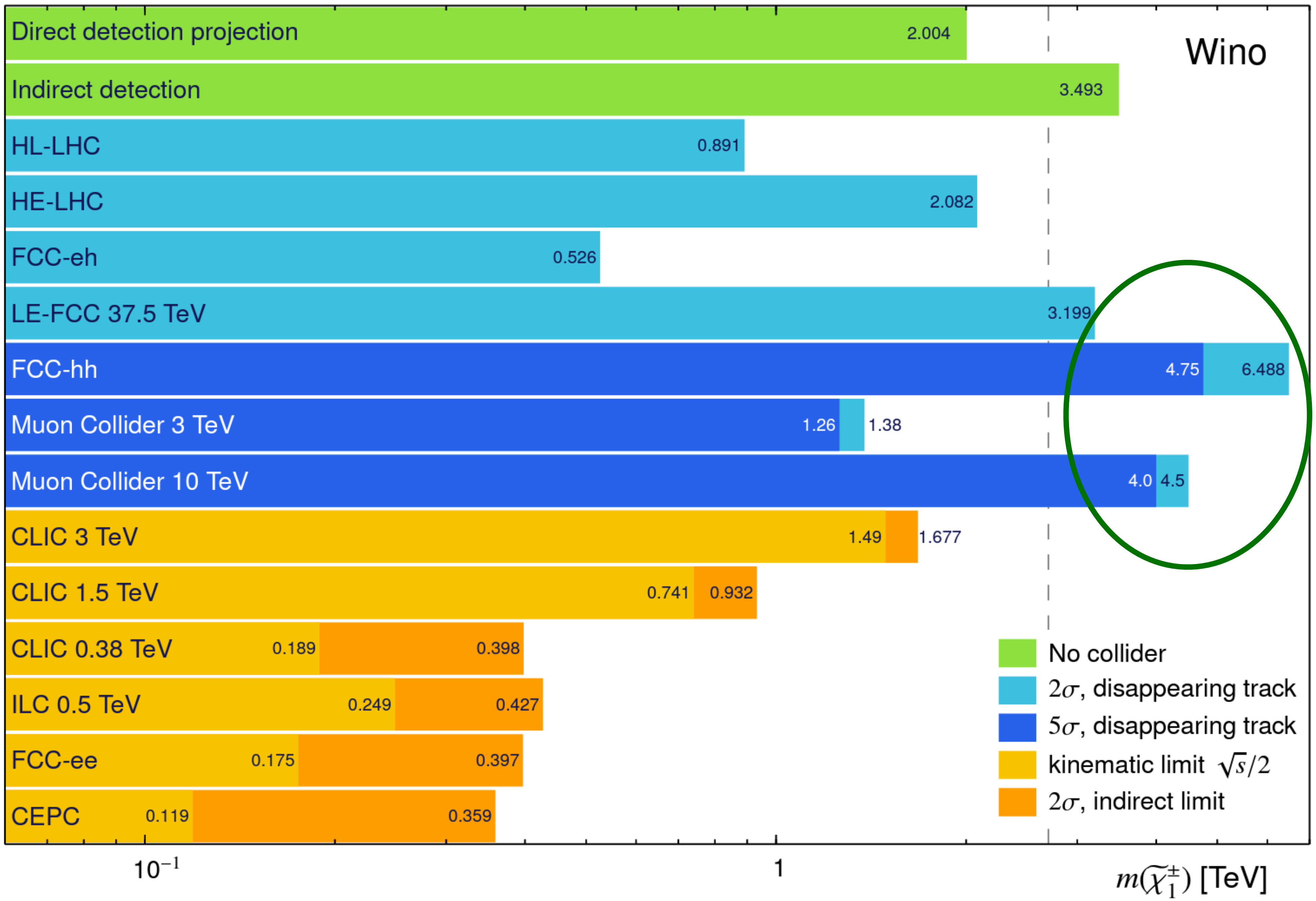


Capdevilla, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133

2. Minimal Dark Matter: Projections

- Triplet MDM:

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

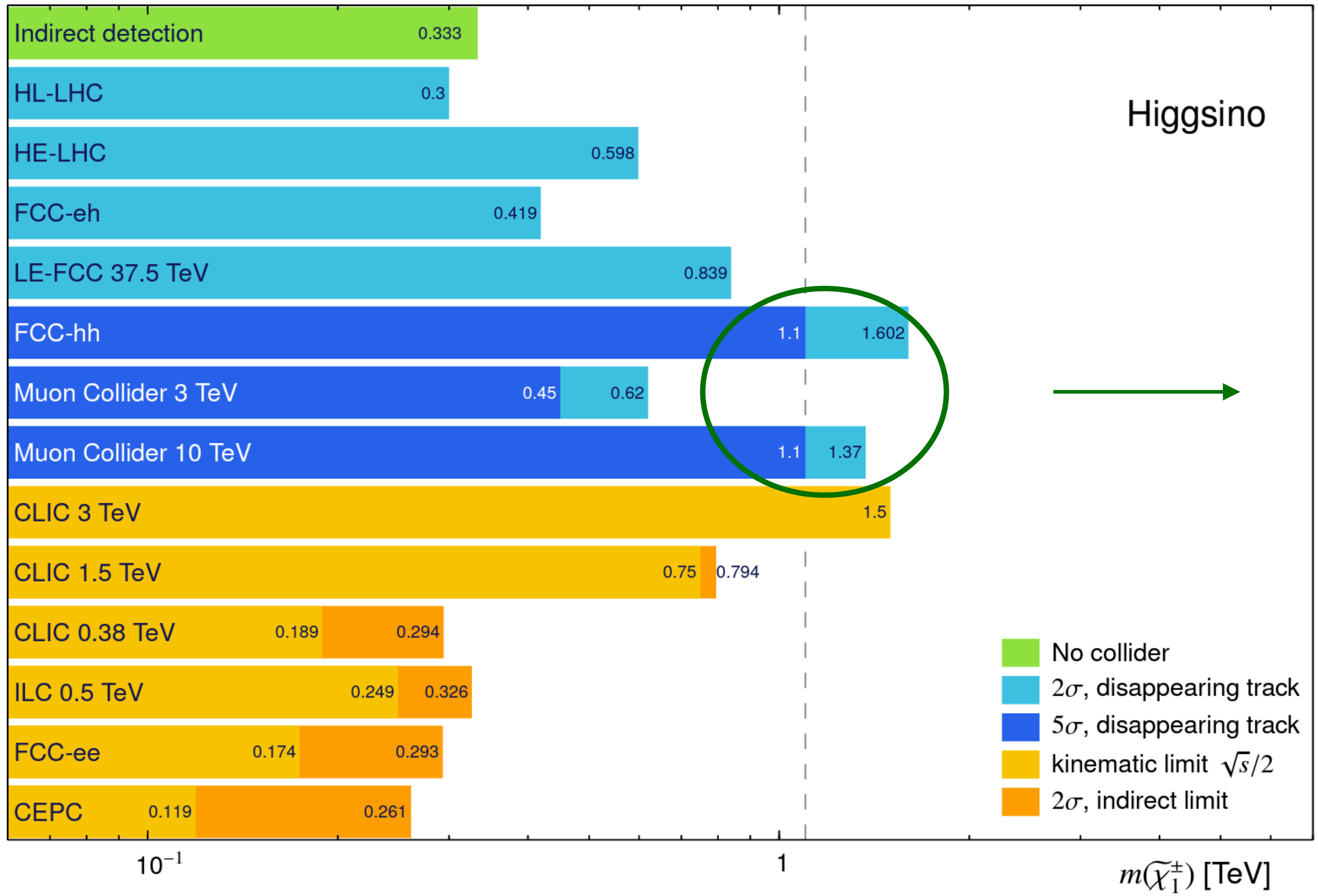


Discovery potential from DT

2. Minimal Dark Matter: Projections

- Doublet MDM:

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



Not clear discovery potential…

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    - **Signal Regions**
    - **Backgrounds**
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    - The Importance of the 3TeV MuC!

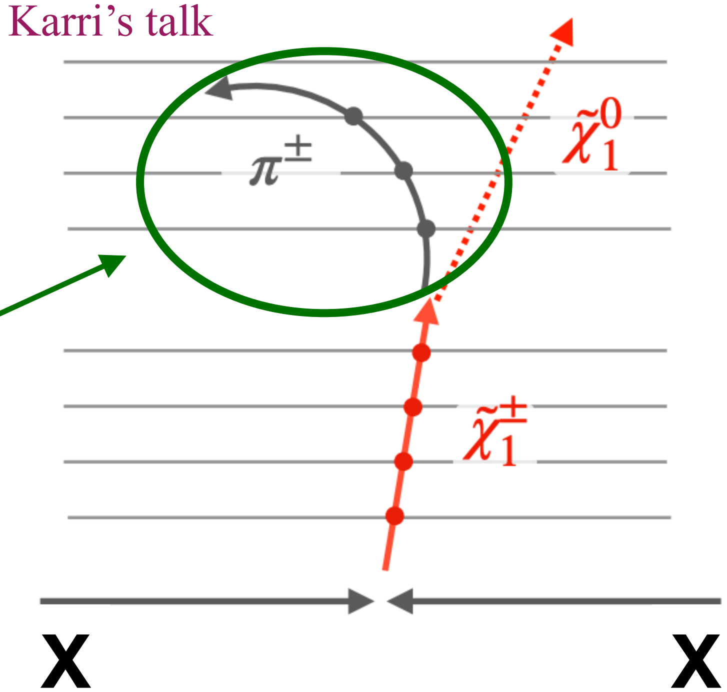
3. Soft Tracks

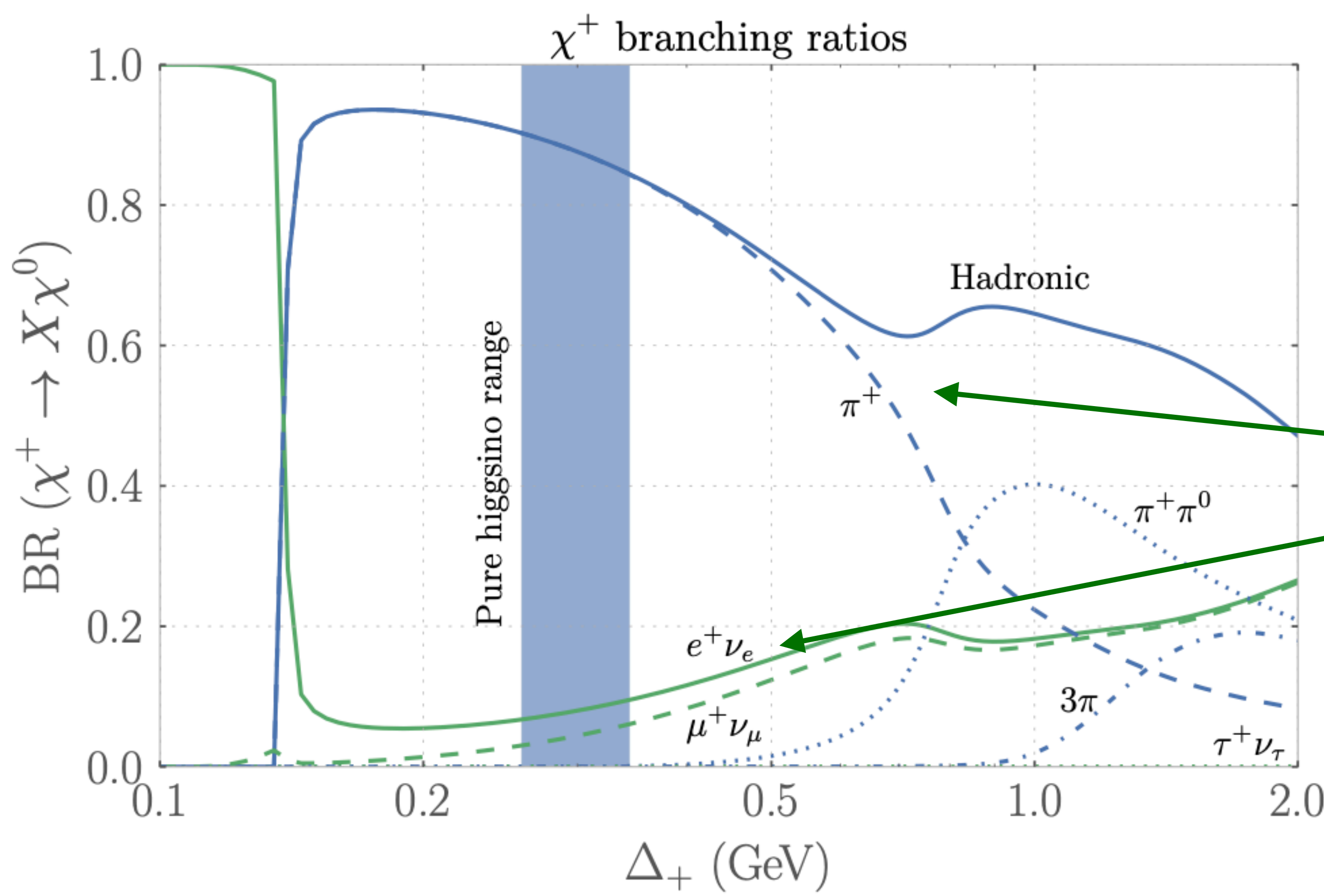
- Definition:

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

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

Karri's talk





Soft pions
Soft muons
Soft electrons = *ST*

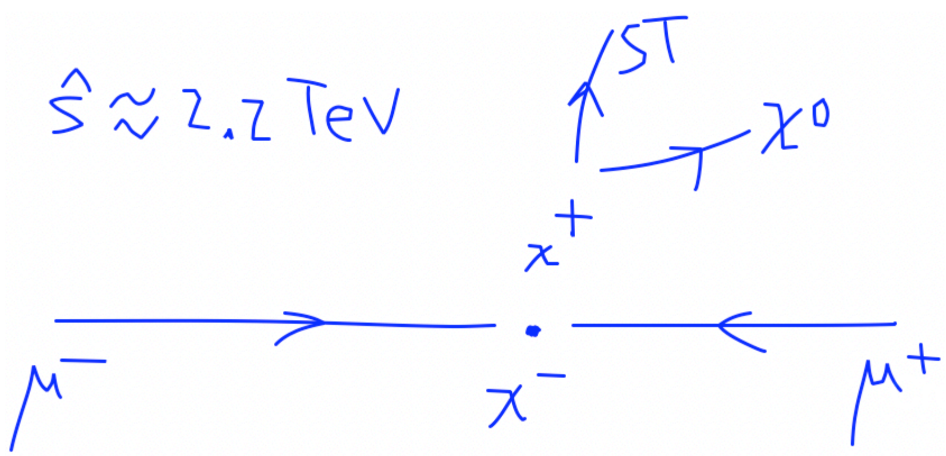
R. Mahbubani, P. Schwaller, J. Zurita, JHEP 06 (2017) 119

3. Soft Tracks: Signal Region

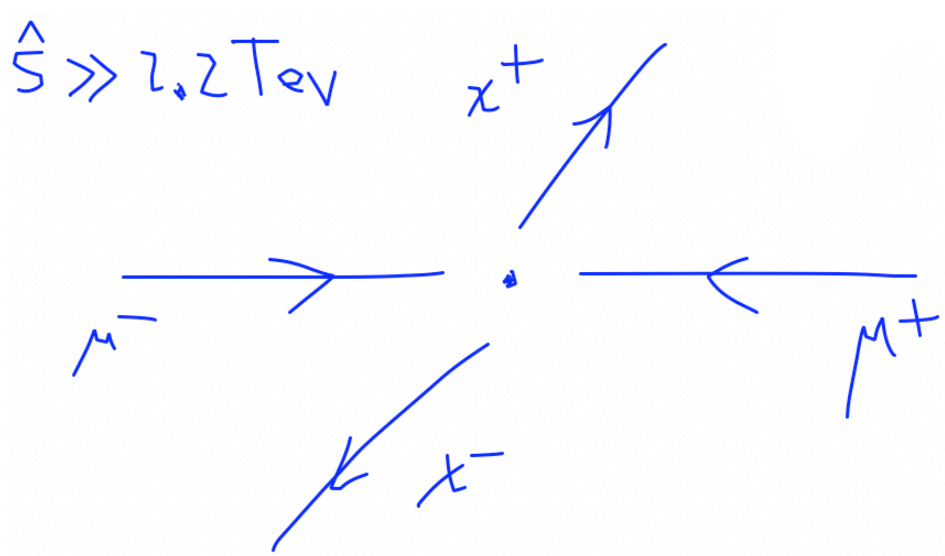
Thermal Higgsino
(doublet MDM)

Very small gap!

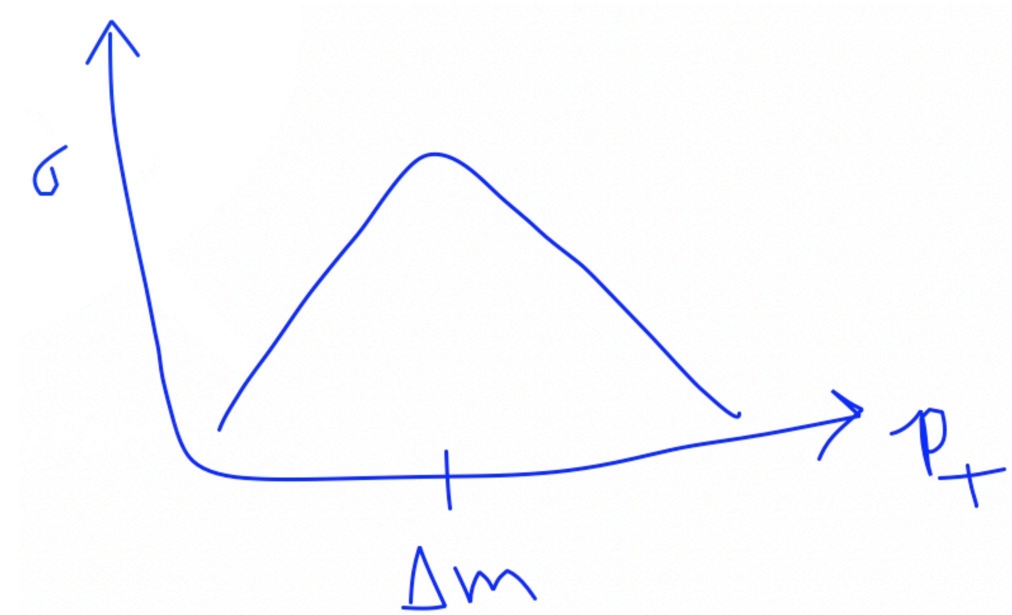
$$\Delta m \sim 0.3\,\mathrm{GeV}$$



Threshold production



Boosted production

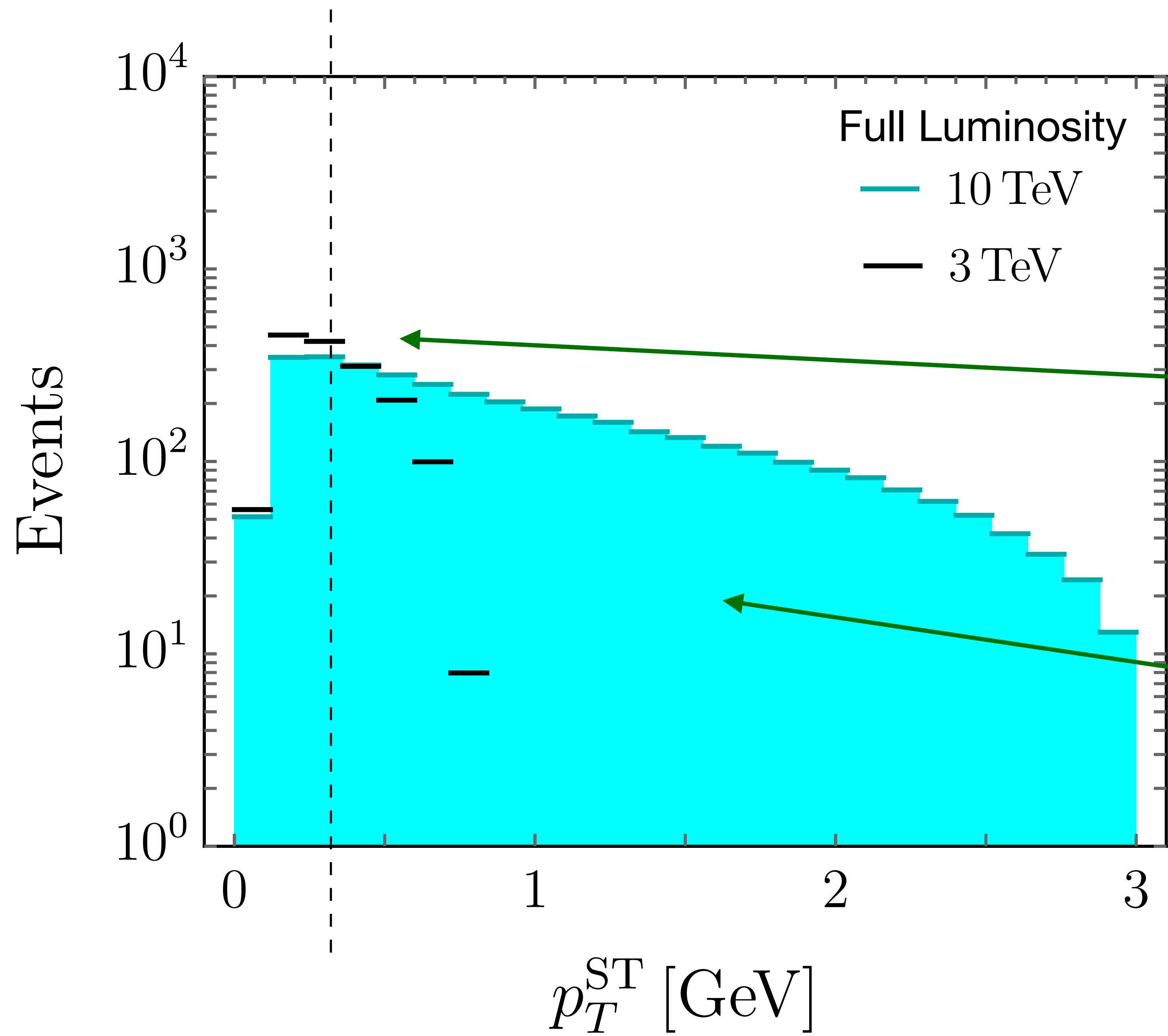


Rodolfo Capdevilla, Fermilab

3. Soft Tracks: Signal Region

Thermal Higgsino (doublet MDM)

$$\Delta m \sim 0.3\,\mathrm{GeV}$$

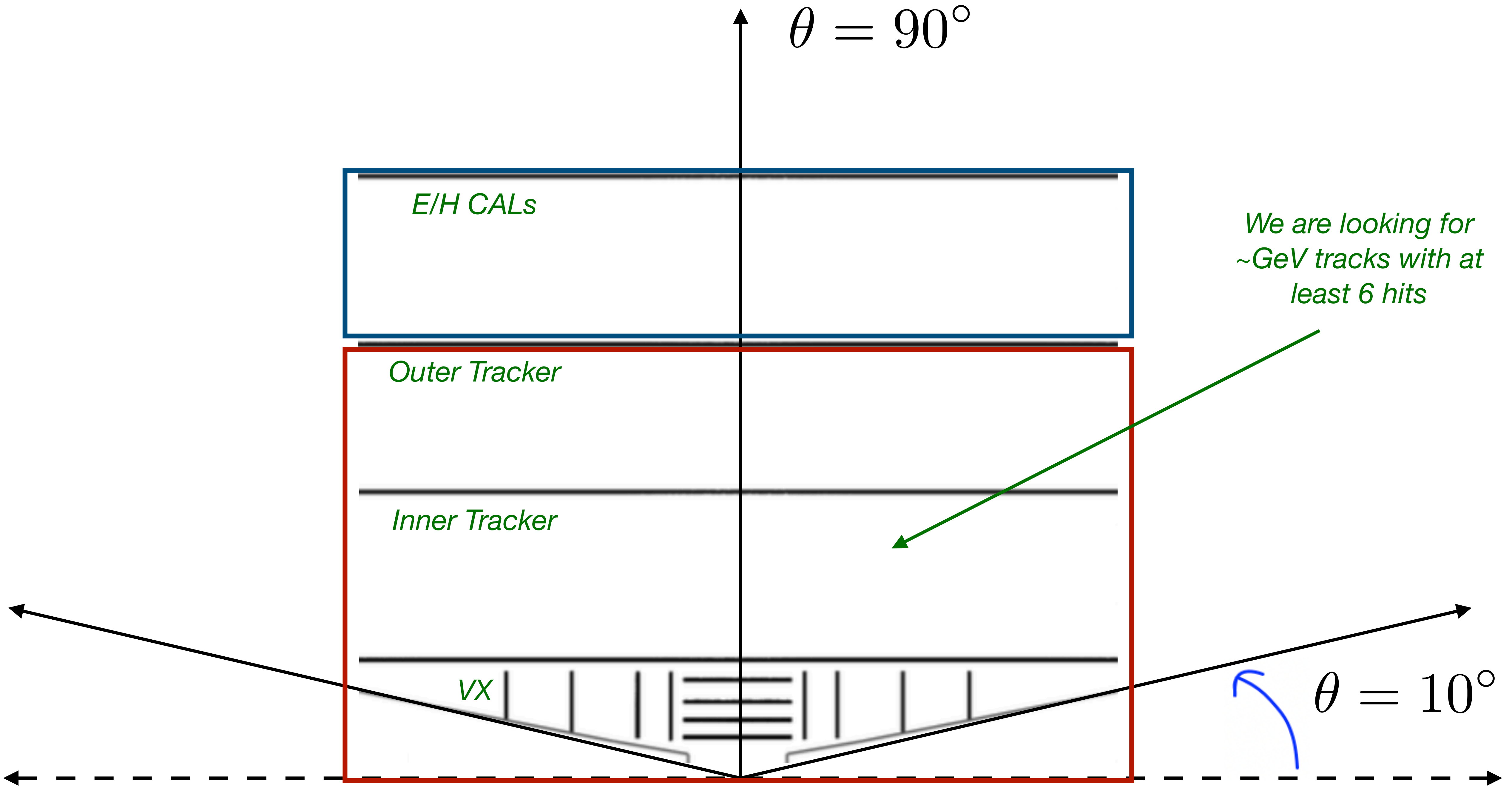


More events near threshold at MuC3

Much larger boosts at MuC10

3. Soft Tracks: Signal Region

- Definition of a ST:



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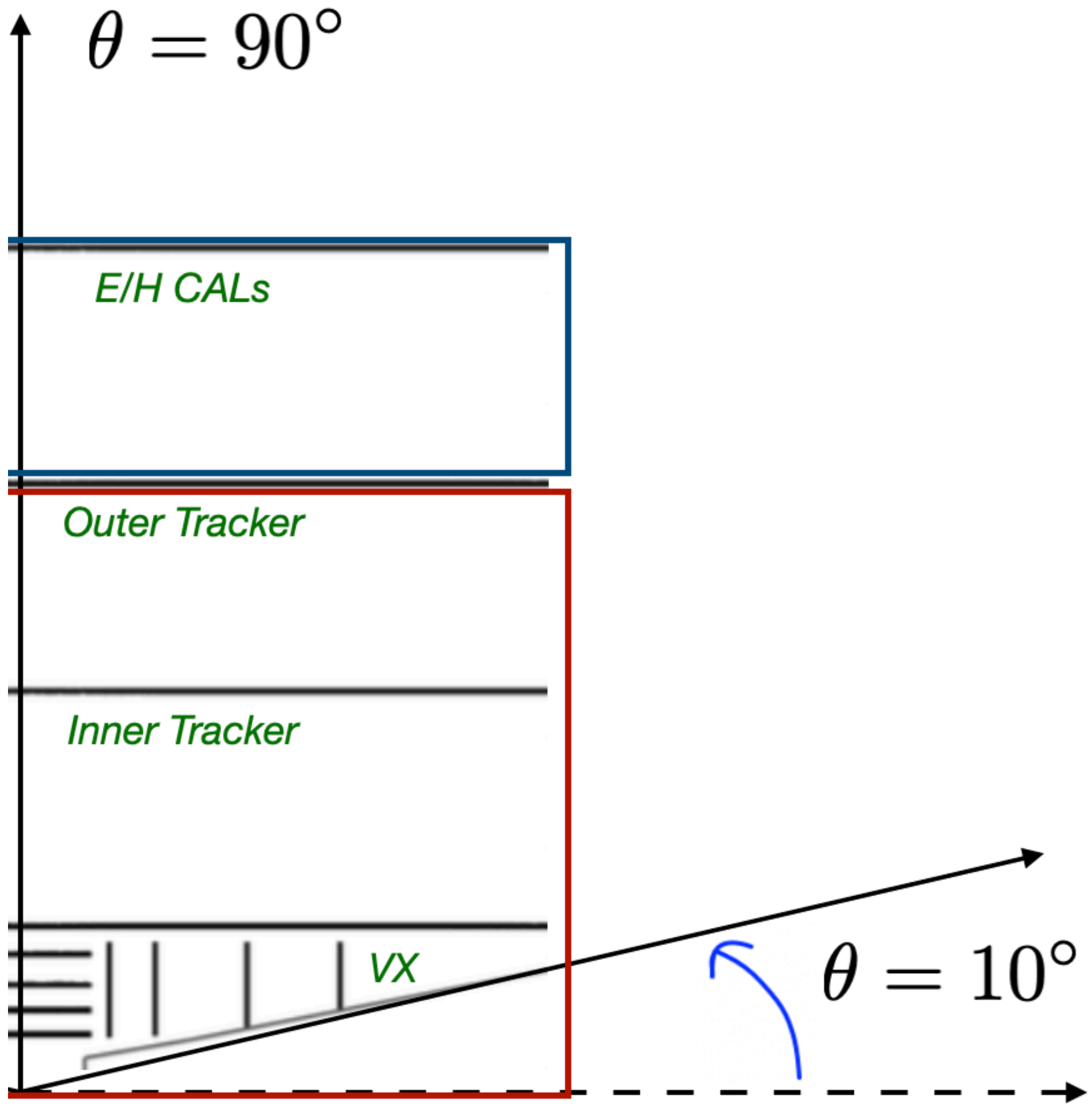
3. Soft Tracks: Signal Region

Thermal Higgsino (doublet MDM)

- Definition of a ST:



Soft Track

$\ell^\pm$ *(Leptons)* $h^\pm$ *(Hadrons)*

$10^\circ < \theta < 170^\circ$

$0.1 < p_T < 1$ GeV   MuC3

Heavy Neutrals

$E > 10\,\text{GeV}$

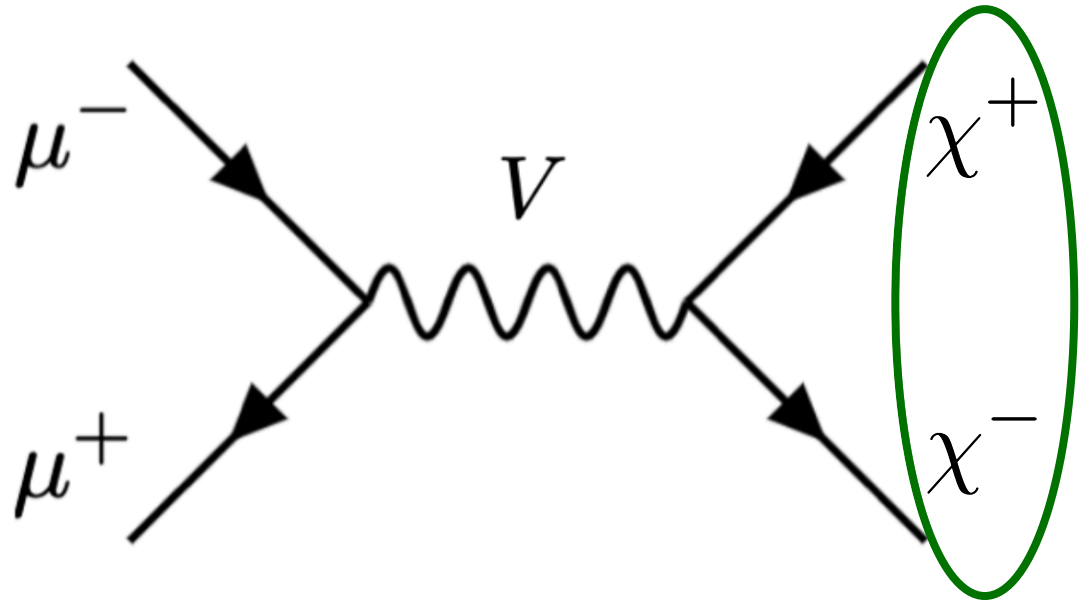
Photons

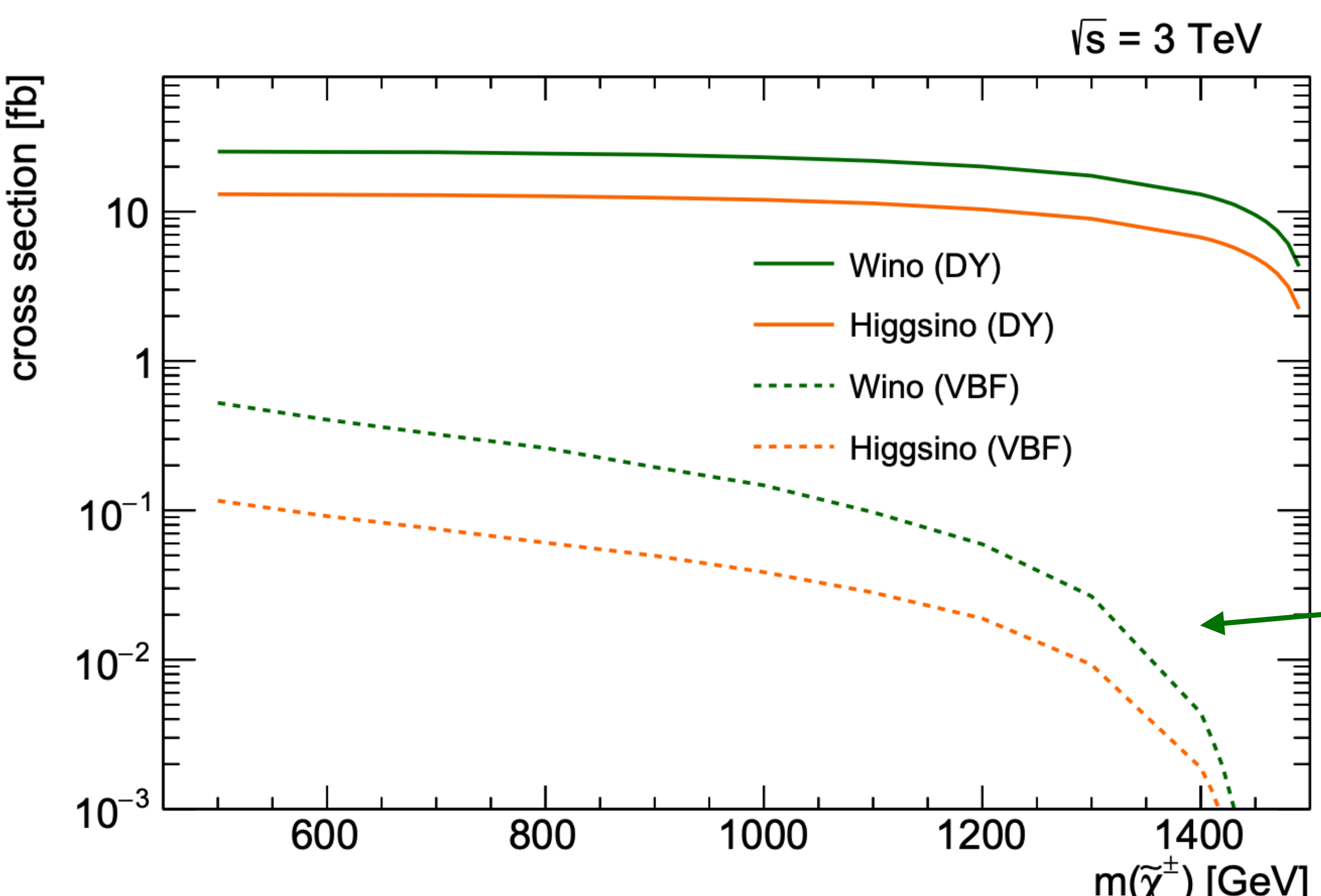
$10^\circ < \theta < 170^\circ$

$p_T > 10\,\text{GeV}$

3. Soft Tracks: Signal Region

- Drell-Yan:





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

Drell-Yan-like process dominates ST production

VBF processes are subdominant (For signal)

3. Soft Tracks: Signal Region

- Signal Regions:

Thermal Higgsino
(doublet MDM)

MuC 3 TeV

1ST 0γ 14%	1ST 1γ 2%
2ST 0γ 75% $\sigma_T = 12.53(3)$ fb	2ST 1γ 9%

About 1k signal events in this signal region

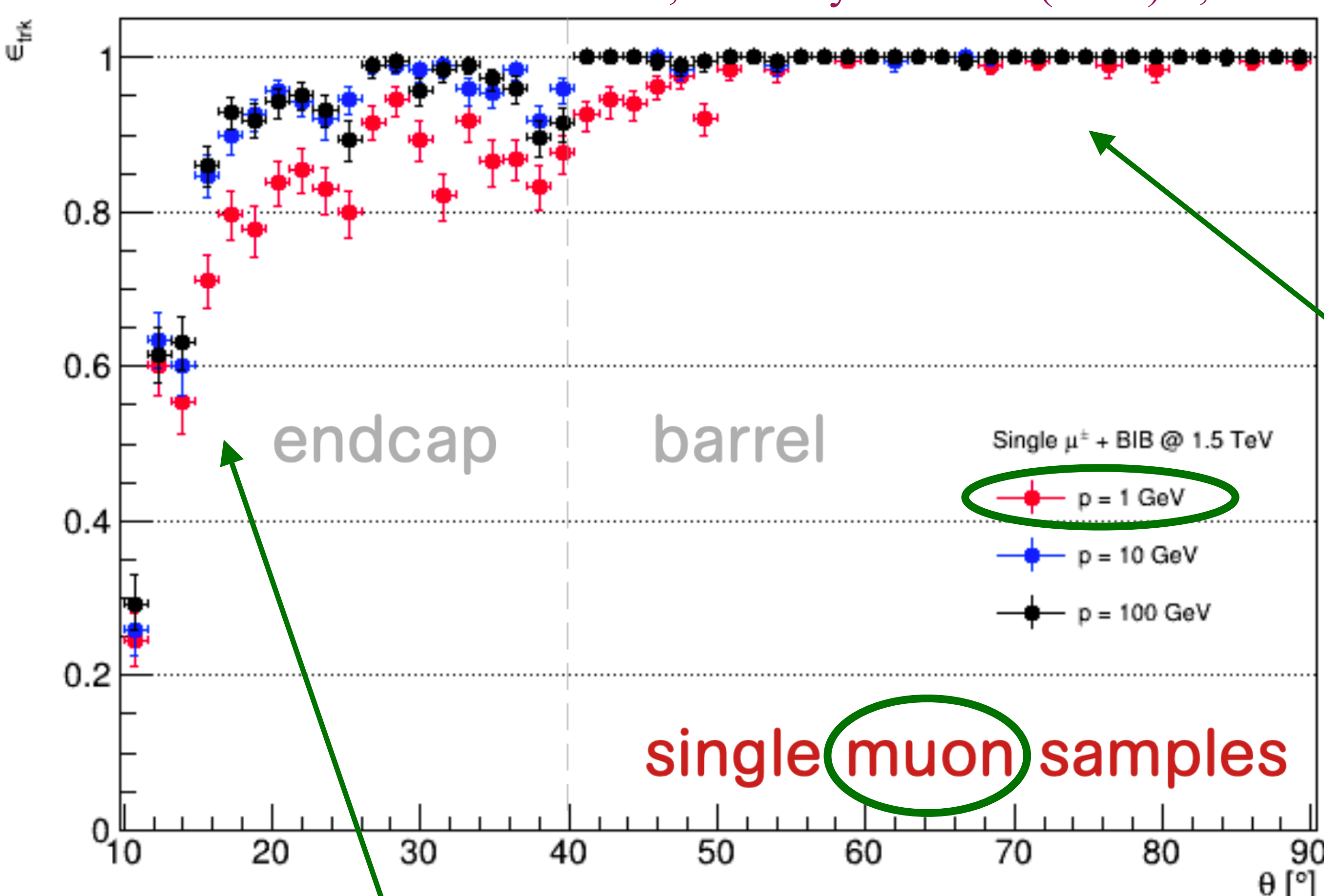
MuC 10 TeV

1ST 0γ 7%	1ST 1γ 2%
2ST 0γ 65% $\sigma_T = 1.7996(36)$ fb	2ST 1γ 20%

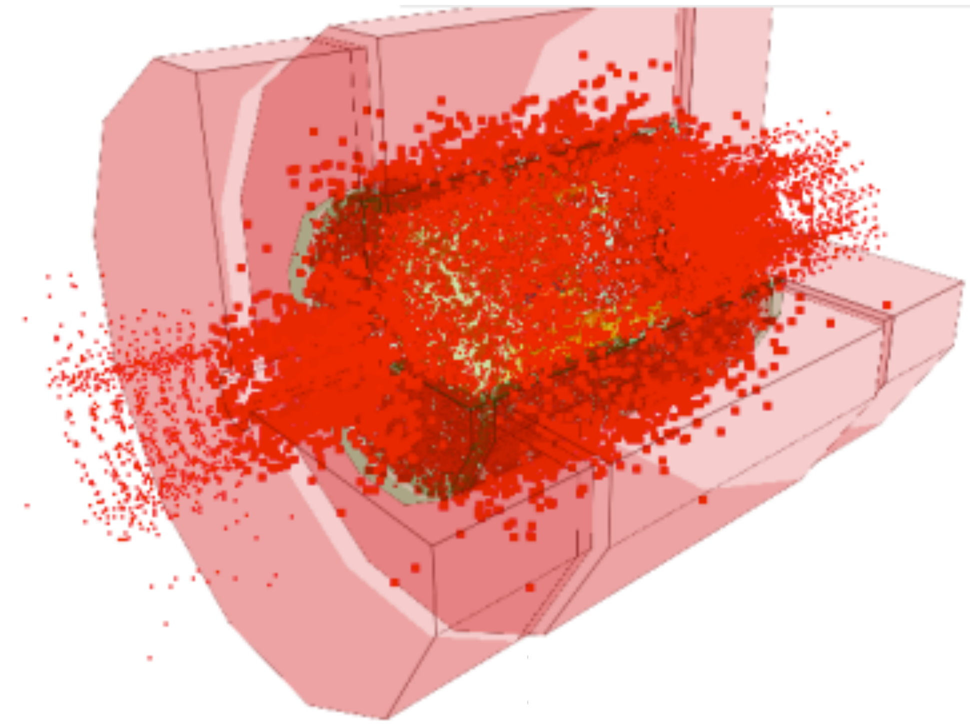
3. Soft Tracks: Backgrounds

- BIB: Track Reconstruction

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



Sestini and Casarsa



Central angular region:

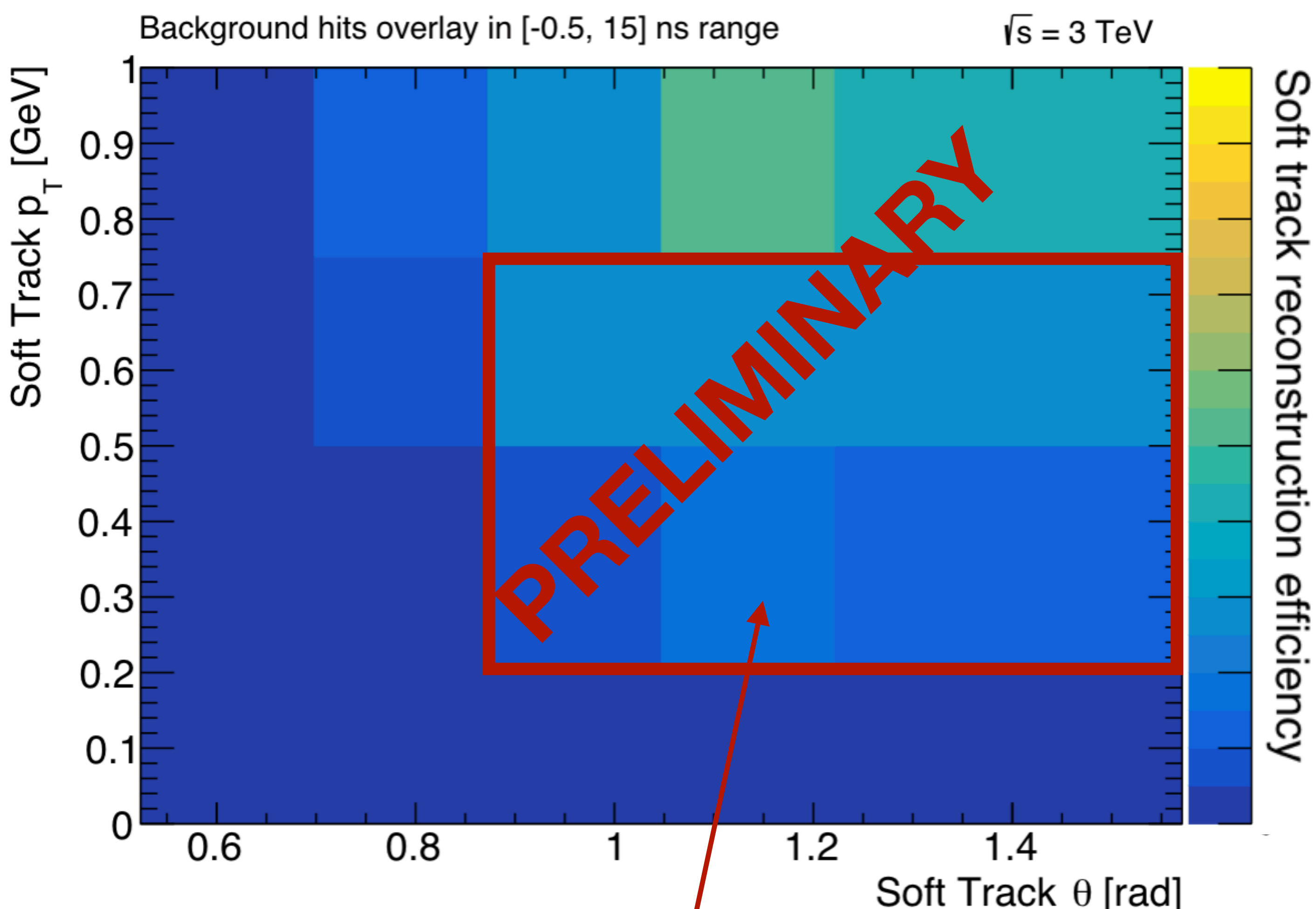
Small probability of missing a track immersed in the BIB

Forward/backward angular regions:

Large probability of missing a track immersed in the BIB

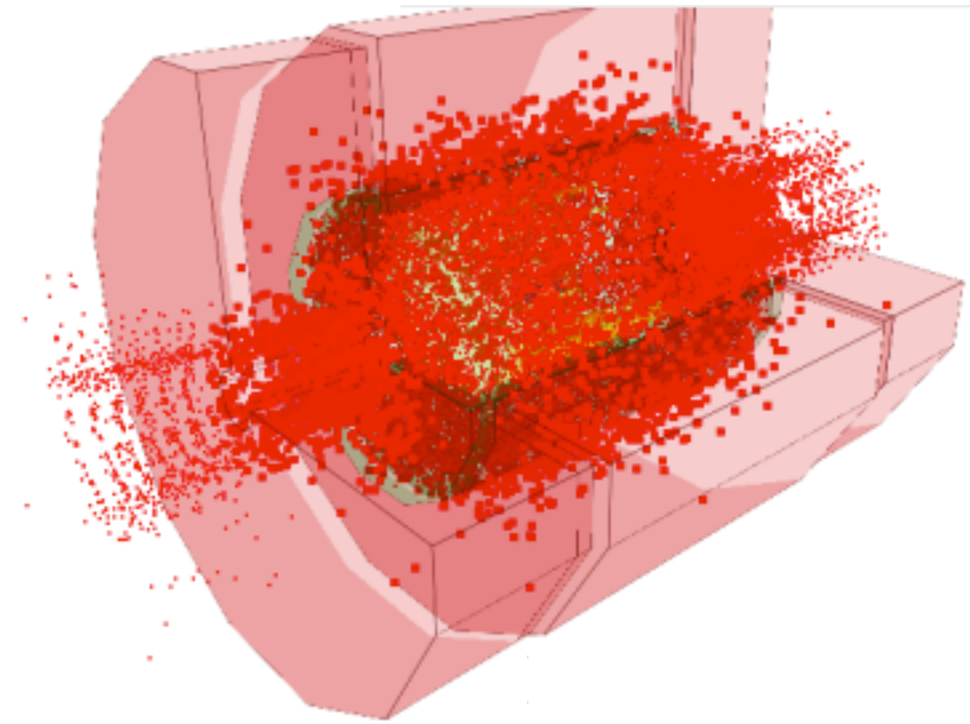
3. Soft Tracks: Backgrounds

- BIB: Track Reconstruction



Order 10-30% reconstruction efficiency in the signal region

Sestini and Casarsa



Soft Track

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

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

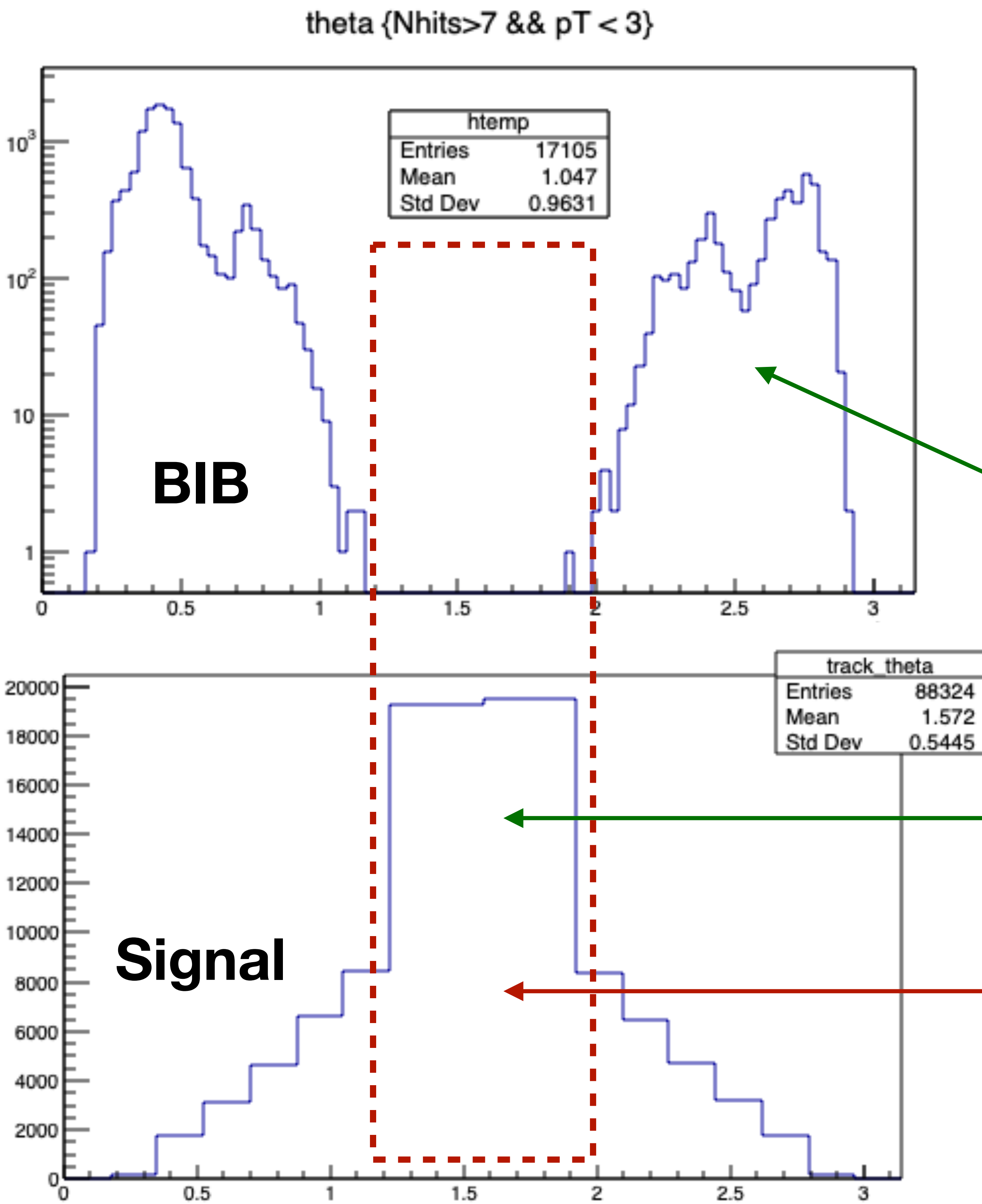
Photons

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

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

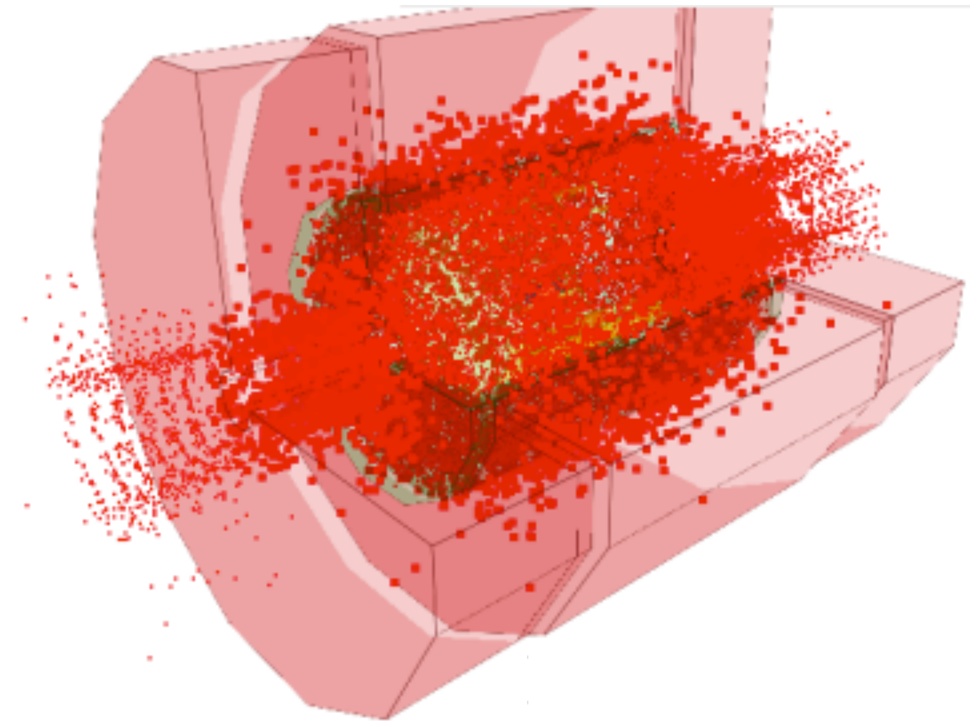
3. Soft Tracks: Backgrounds

- BIB: Fake Tracks



θ_{ST}

Sestini and Casarsa



The BIB fake tracks want to be forward/backward

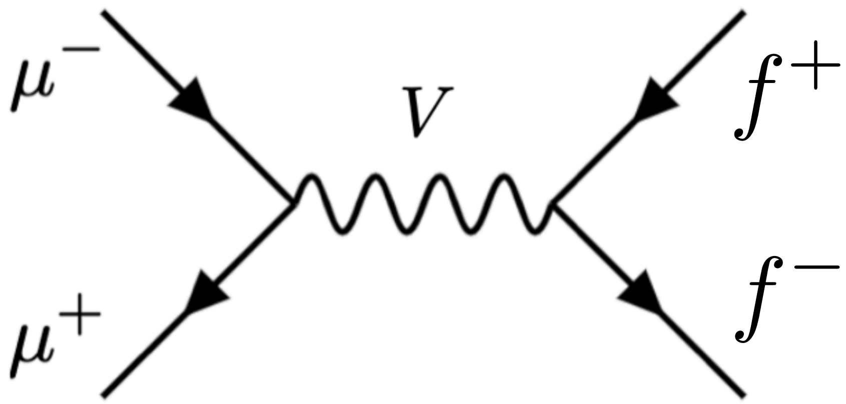
The signal wants to be central

This is why:

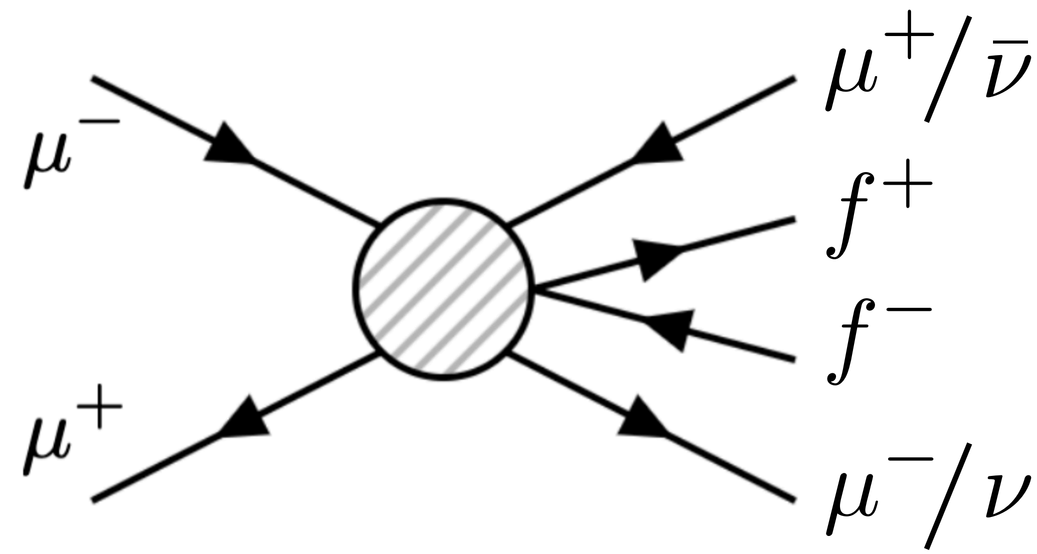
$$60^\circ \leq \theta_{\mathrm{ST}} \leq 120^\circ$$

3. Soft Tracks: Bakcgrounds

- 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

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

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

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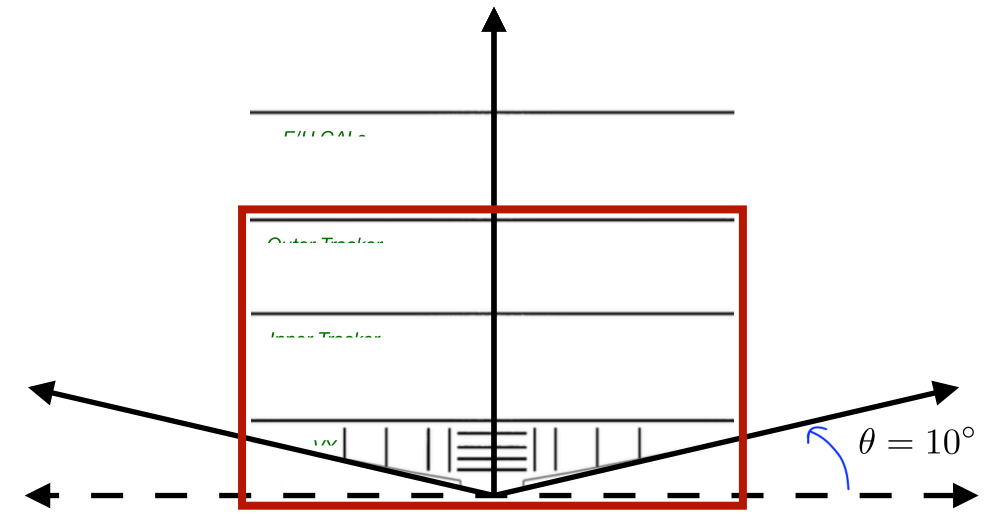
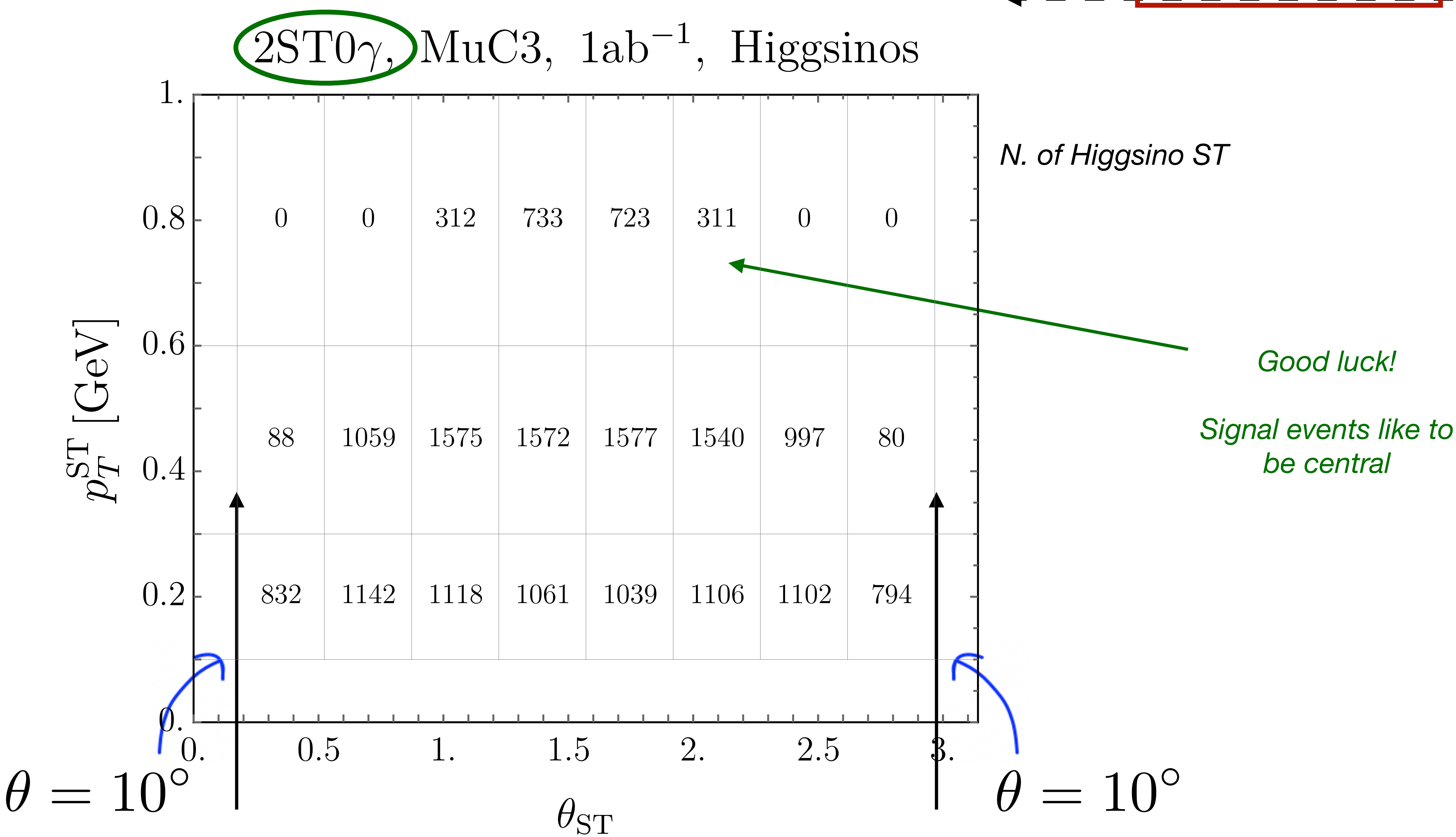
3. Soft Tracks

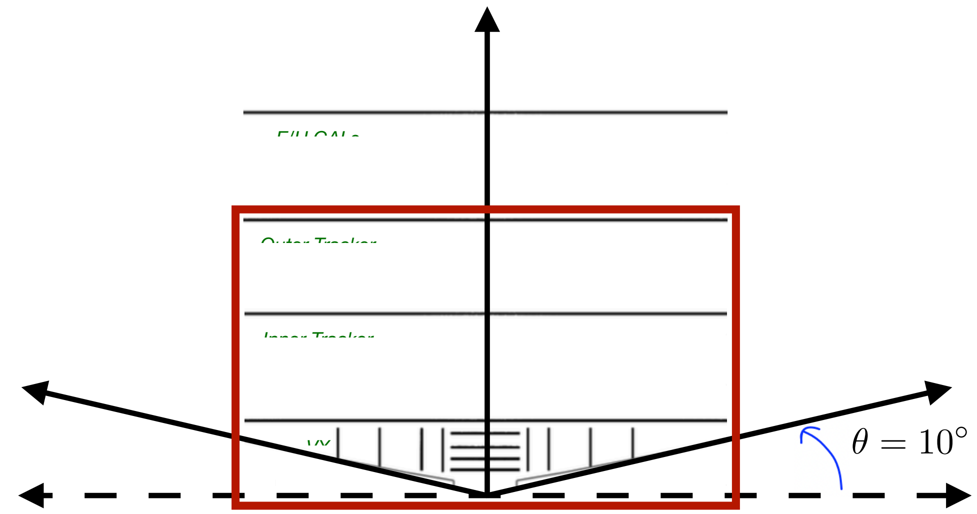
- Backgrounds:

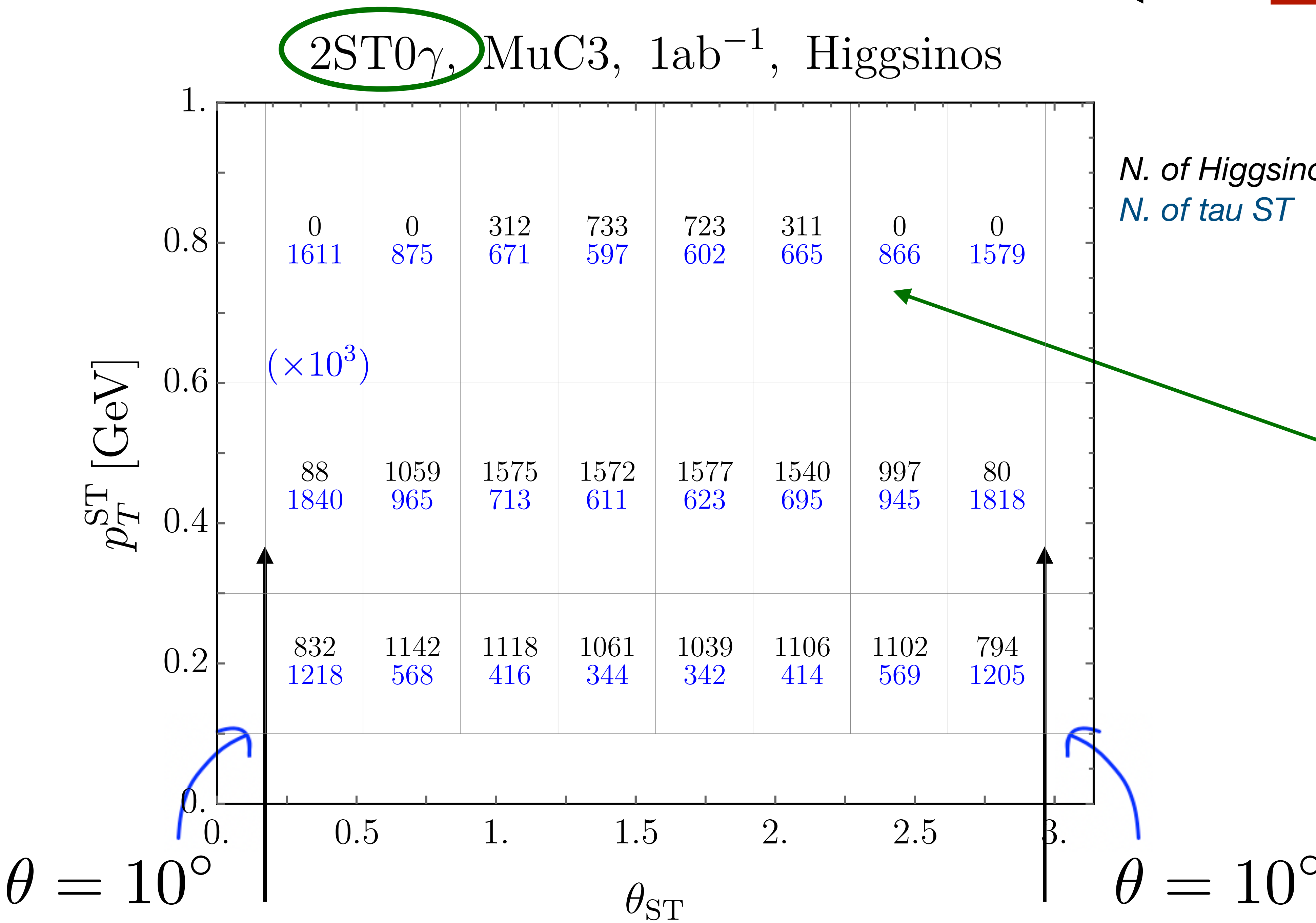




3. Soft Tracks

- Backgrounds:





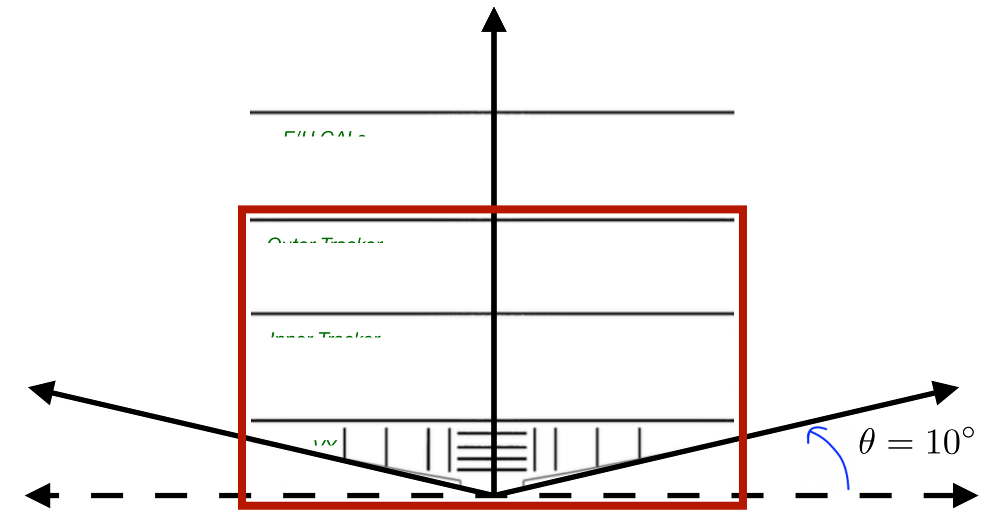
N. of Higgsino ST

N. of tau ST

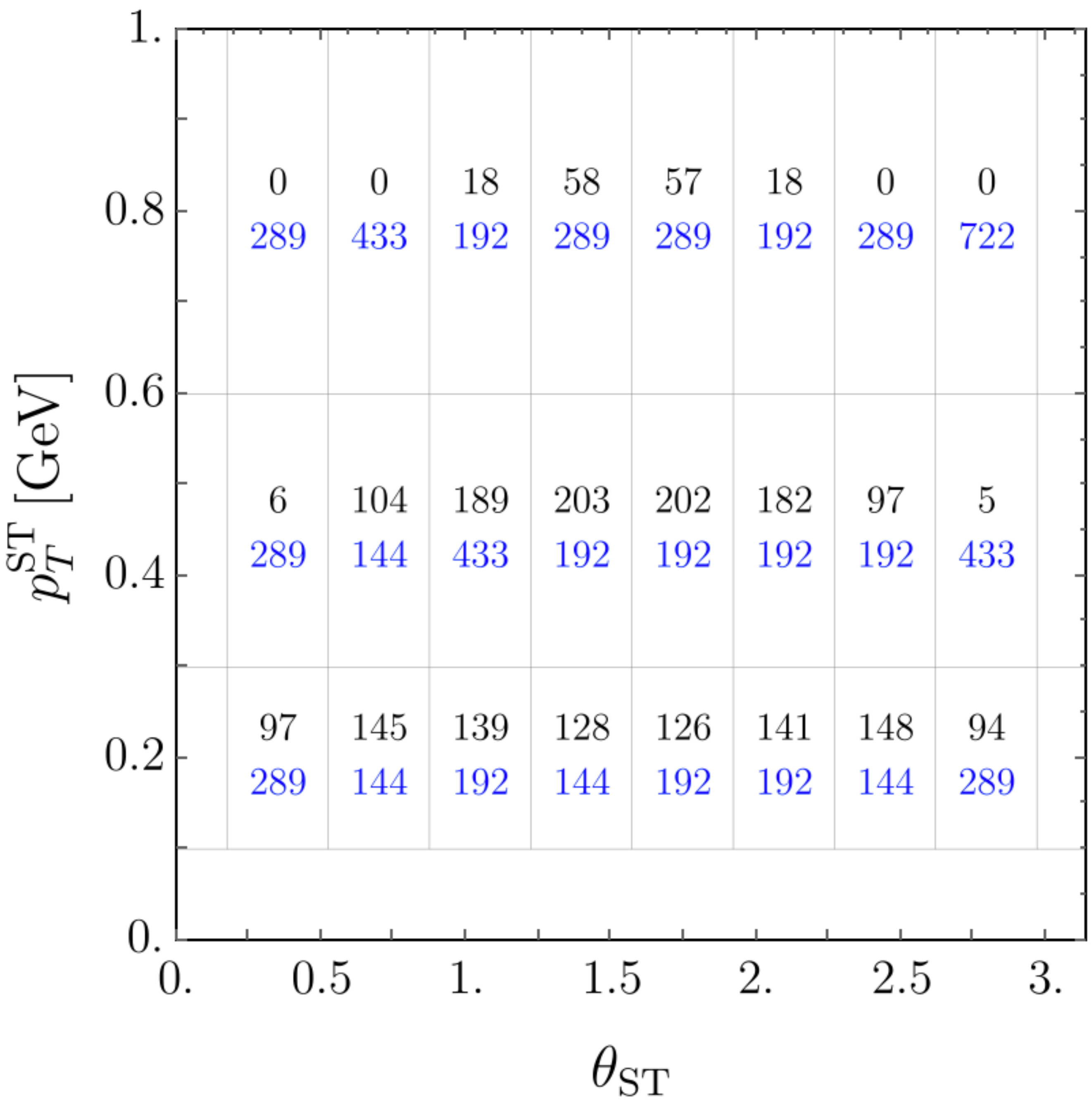
Bad luck!

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

3. Soft Tracks



- Backgrounds:



N. of Higgsino ST

N. of tau ST

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

$2\mathrm{ST}1\gamma$, 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:

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

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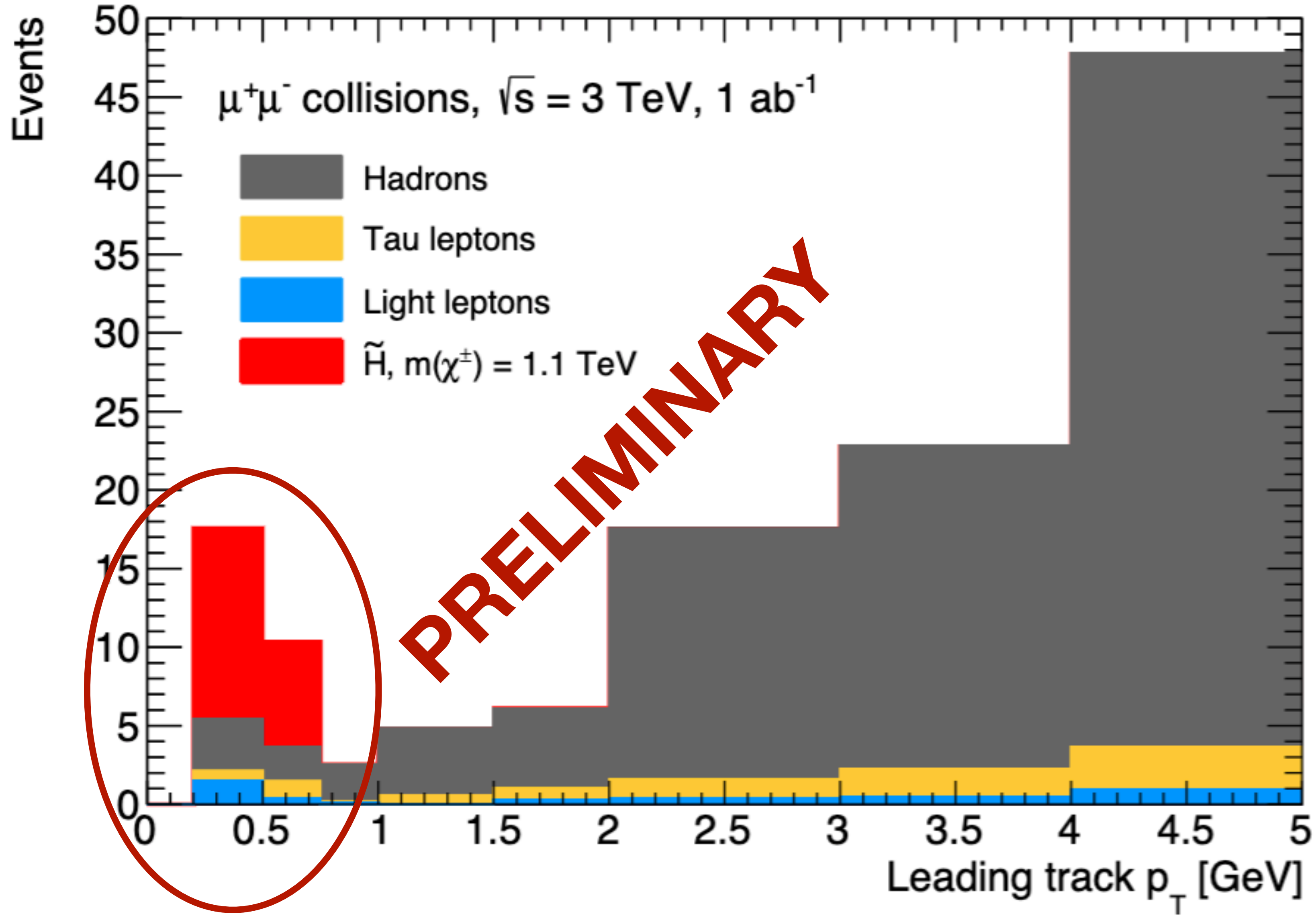
    - **The Importance of the 3TeV MuC!**

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:

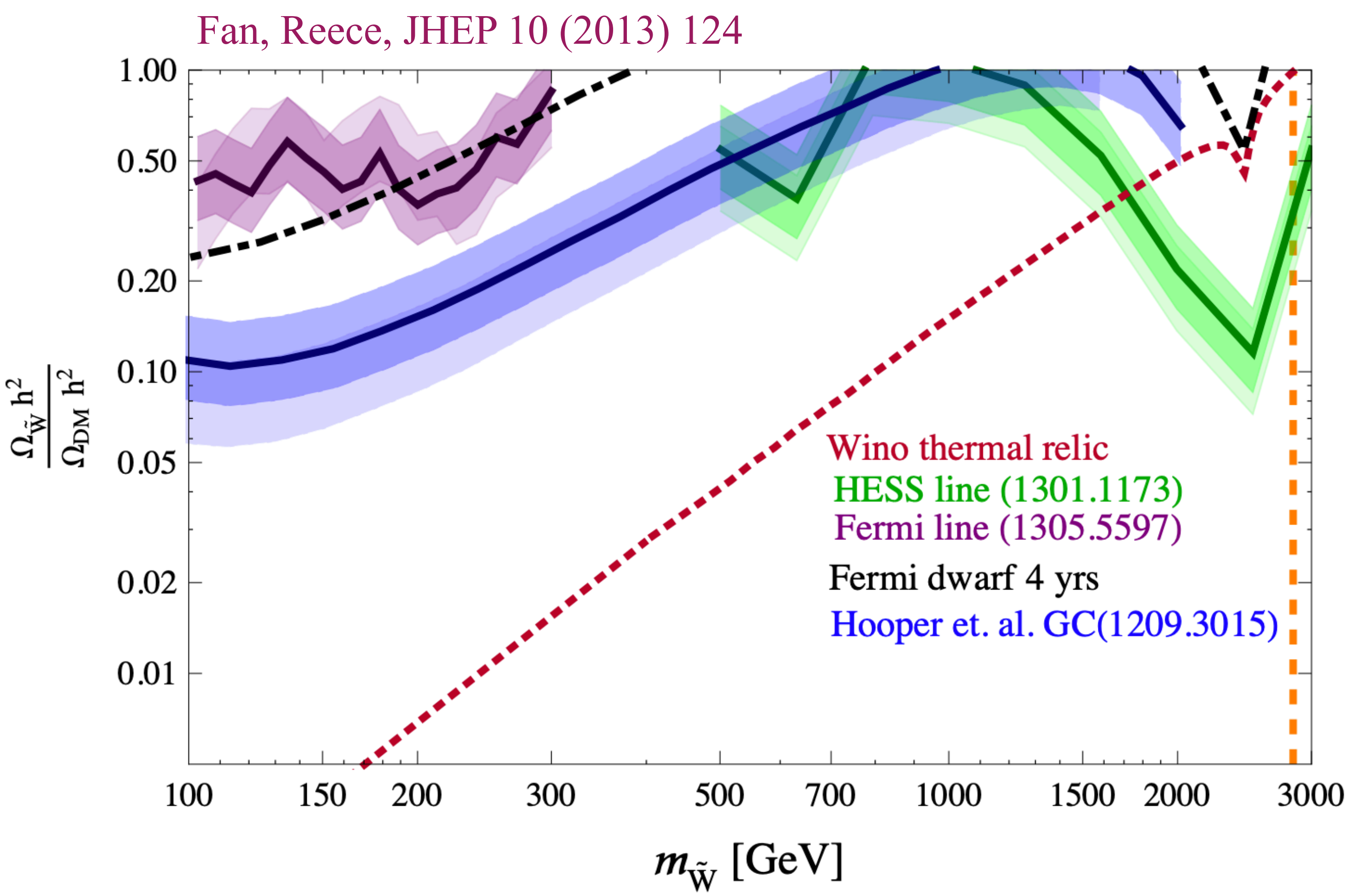
Pairs of ST along with an uncorrelated photon

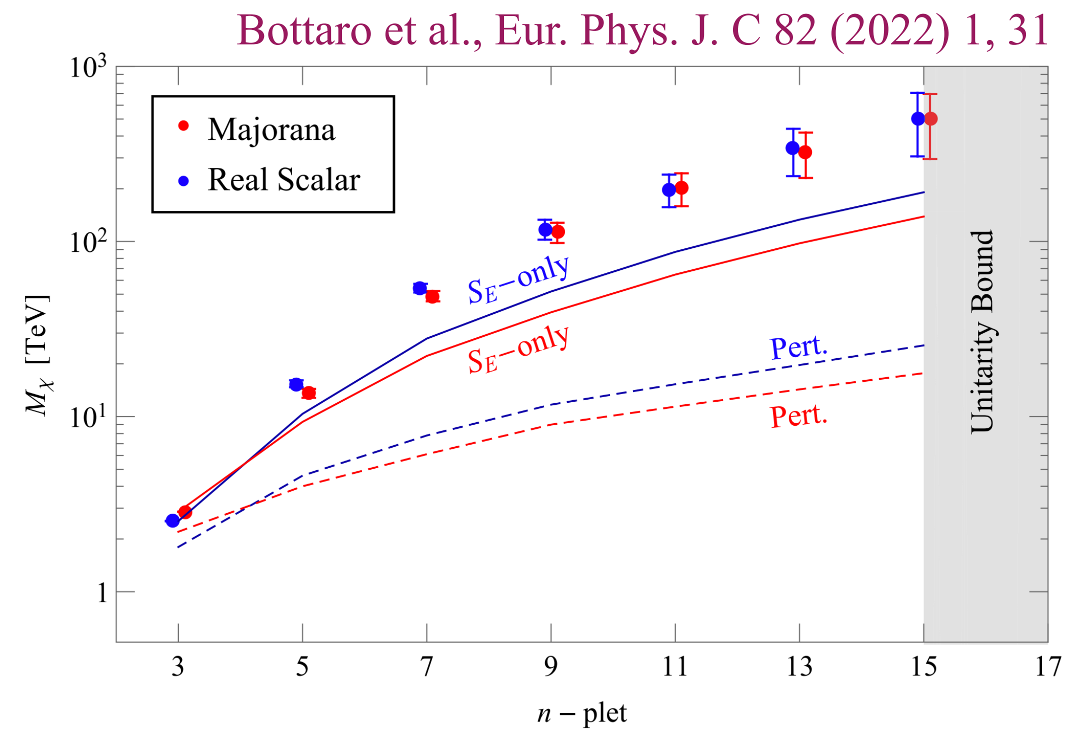
Random ECAL hits from the BIB that can mimic a photon

4. Results

- The Importance of the 3TeV Collider:

Not just the Higgsino (doublet MDM)

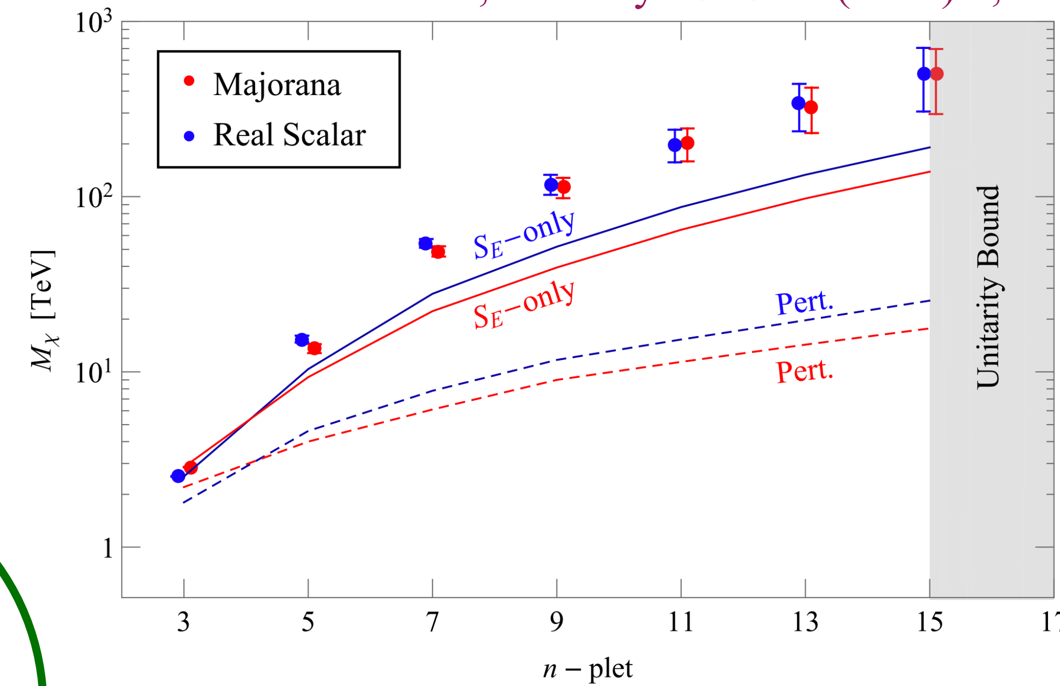




4. Results

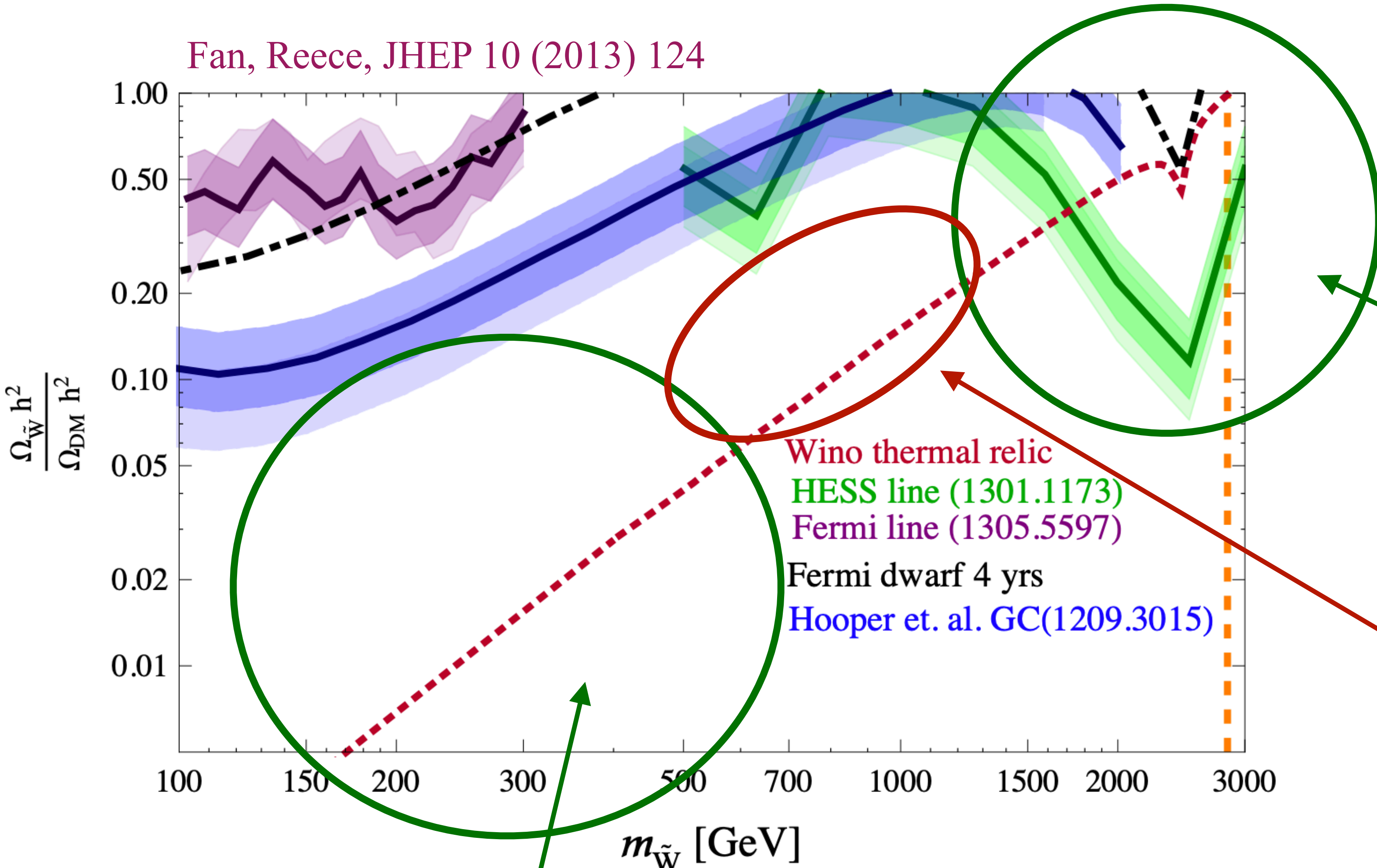
- The Importance of the 3TeV Collider:

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



Not just the Higgsino (doublet MDM)

Fan, Reece, JHEP 10 (2013) 124



Indirect detection reach

MuC?

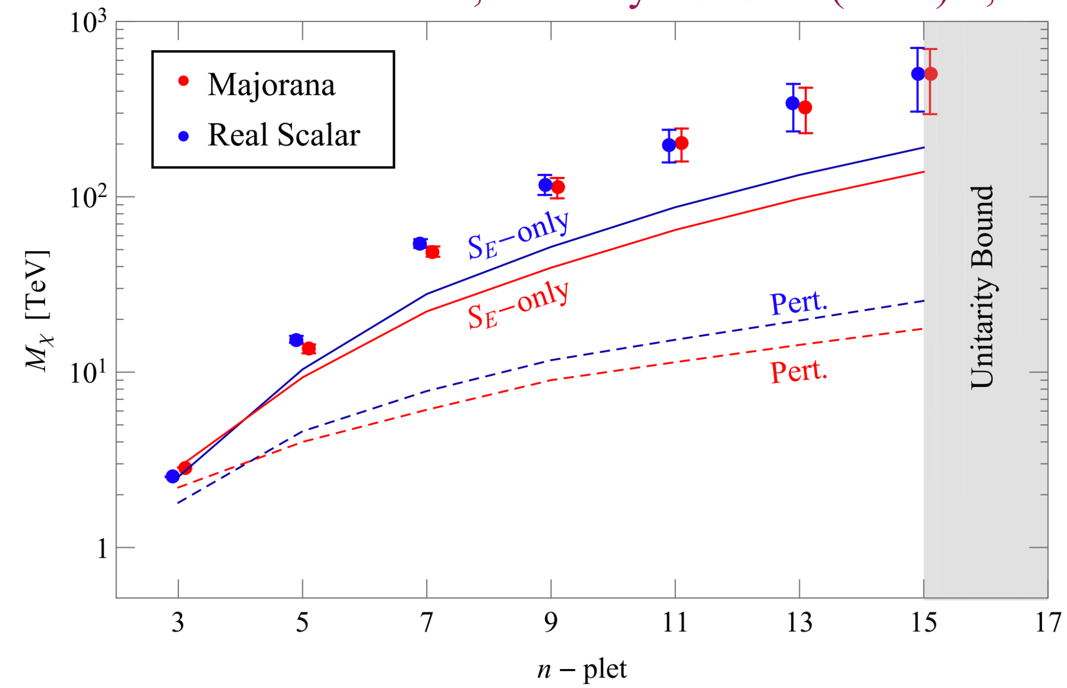
HL-LHC reach

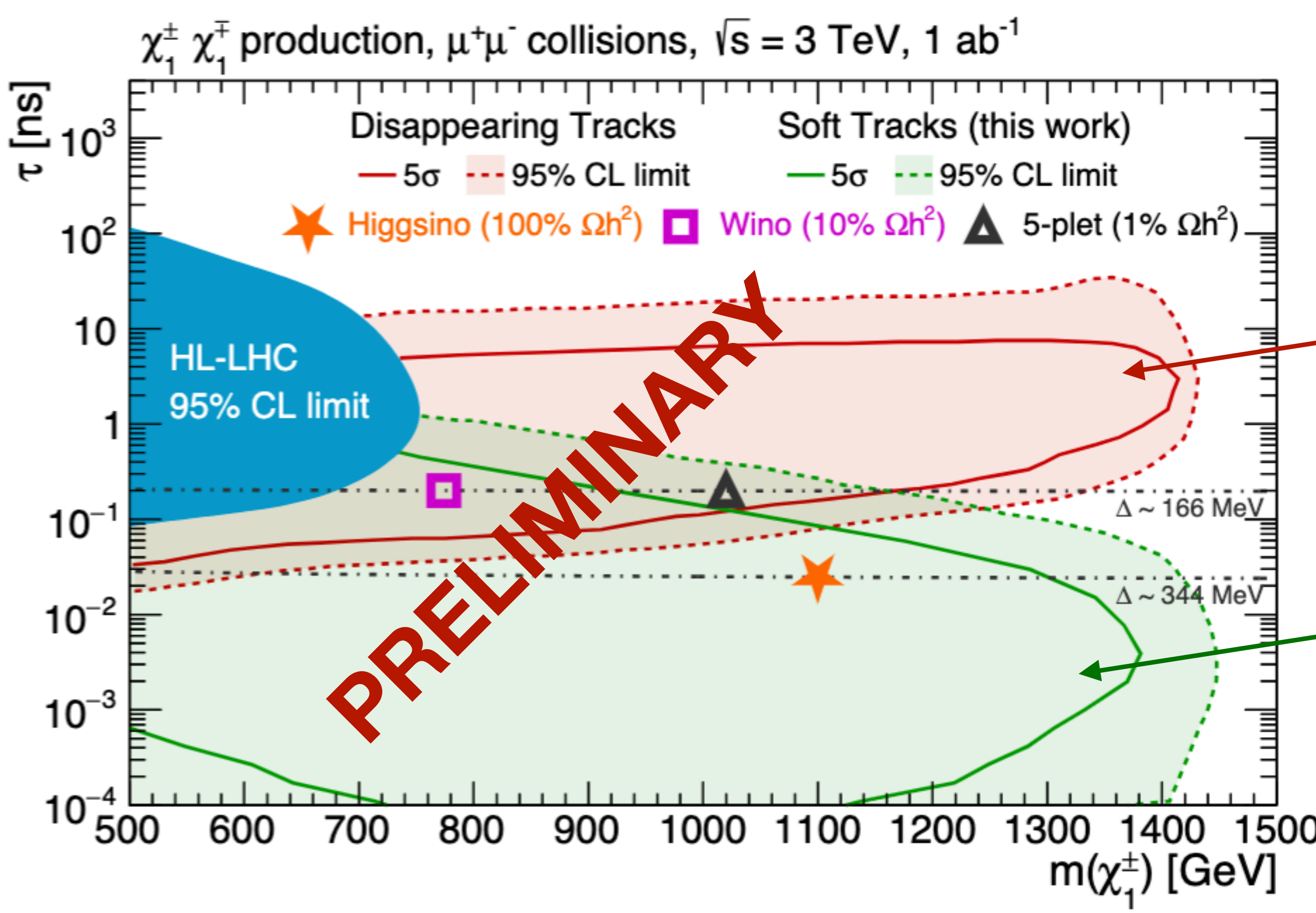
4. Results

- The Importance of the 3TeV Collider:

Not just the Higgsino (doublet MDM)

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



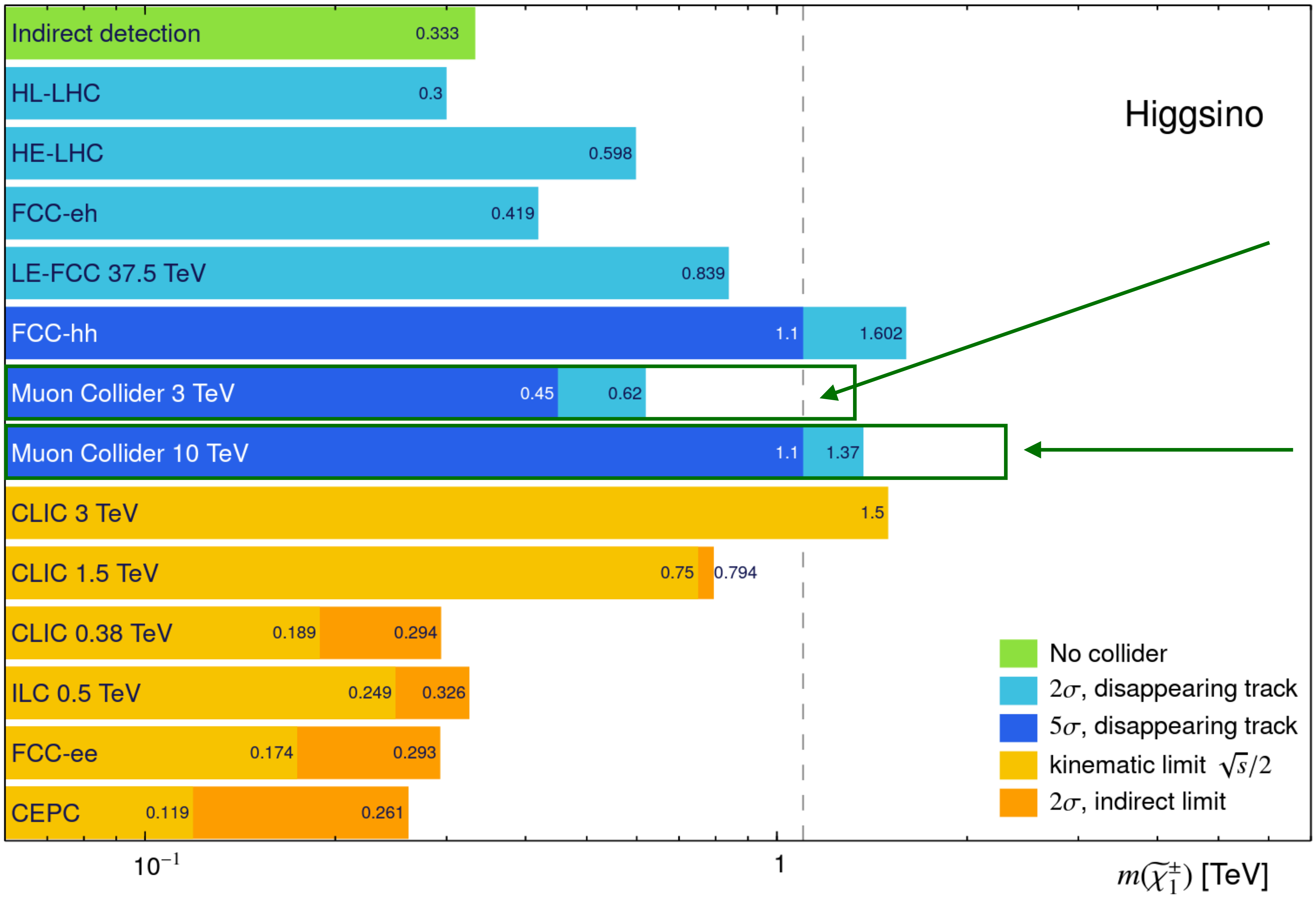


Previous result from DT

NEW result from ST

4. Results

- Projections:



The thermal target will be discovered!

Updated results from Federico et al. Disappearing Tracks

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!