Road to Minimal WIMPs

Particle Physics Seminar

UC Davis

Oct 14, 2024

Rodolfo Capdevilla
Fermilab

***RC**, Federico Meloni, Jose Zurita, arXiv:2405.08858*
***RC**, Federico Meloni, Rosa Simoniello, Jose Zurita, JHEP **06** (2021) 133*

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

- **Minimal WIMPs:**

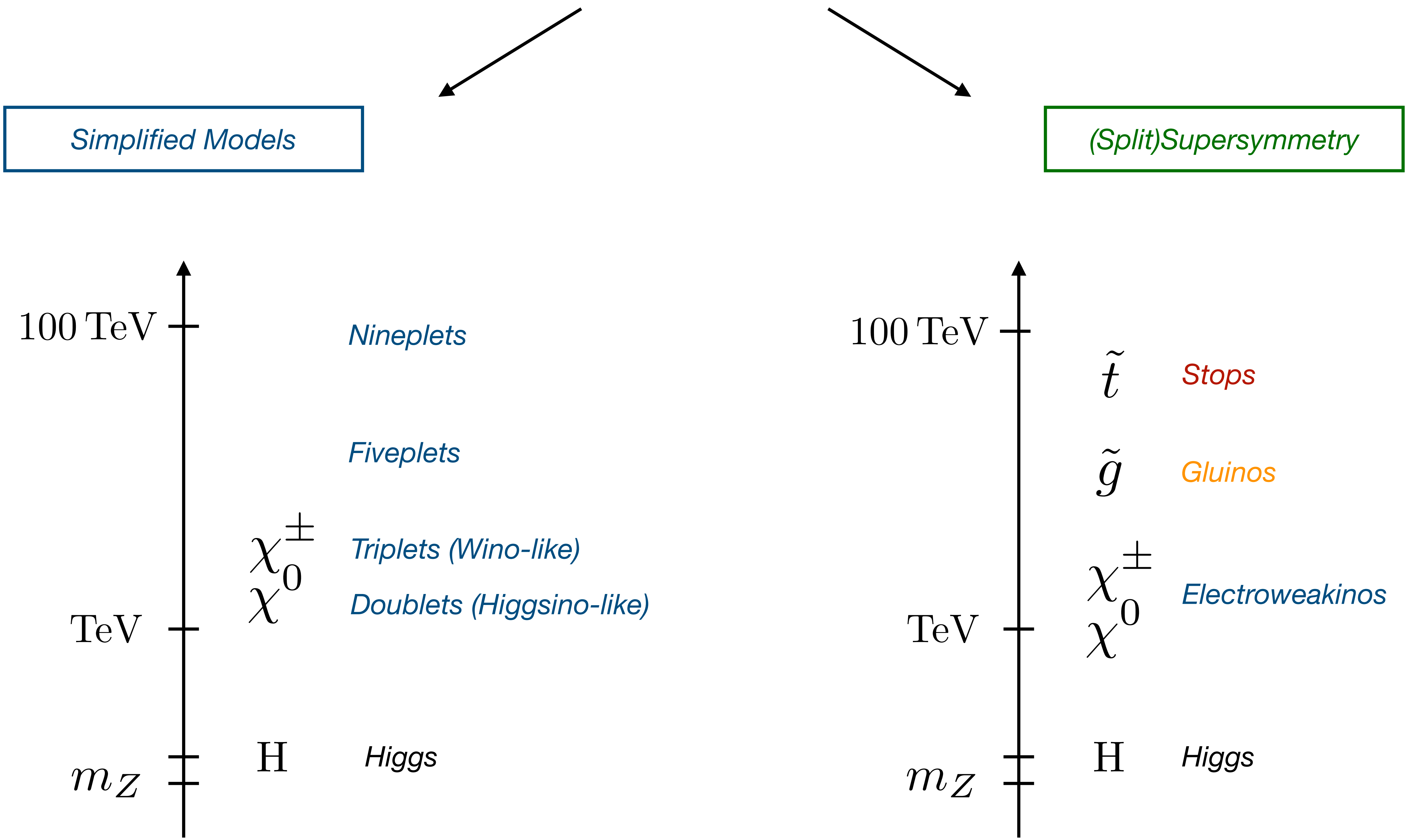
Minimal Dark Matter
Electroweak Interacting Dark Matter
Minimal WIMPs

$$\chi_{\mathbf{2}} \equiv \chi_{\tilde{H}} = \begin{pmatrix} \chi^+_{\tilde{H}} \\ \chi^0_{\tilde{H}} \end{pmatrix}, \qquad \chi_{\mathbf{3}} \equiv \chi_{\tilde{W}} = \begin{pmatrix} \chi^+_{\tilde{W}} \\ \chi^0_{\tilde{W}} \\ \chi^-_{\tilde{W}} \end{pmatrix} \ldots \qquad \chi_{\mathbf{5}} \ldots \qquad \chi_{\mathbf{9}} \ldots$$

Doublets (Higgsino-like) — *Triplets (Wino-like)* — *Fiveplets…* — *Nineplets…*

- **Minimal WIMPs:**

Minimal Dark Matter
Electroweak Interacting Dark Matter
Minimal WIMPs

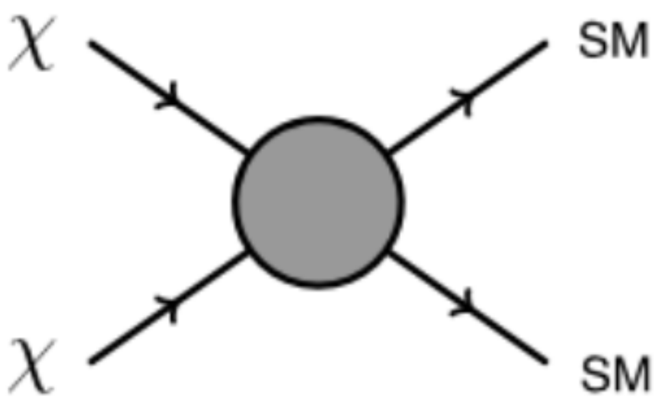


Outline

1. Introduction
2. Minimal WIMP Searches
   - Direct Detection
   - Indirect Detection
   - LHC
3. Future p/e Colliders
4. Muon Collider
   - Disappearing Tracks
   - Soft Tracks

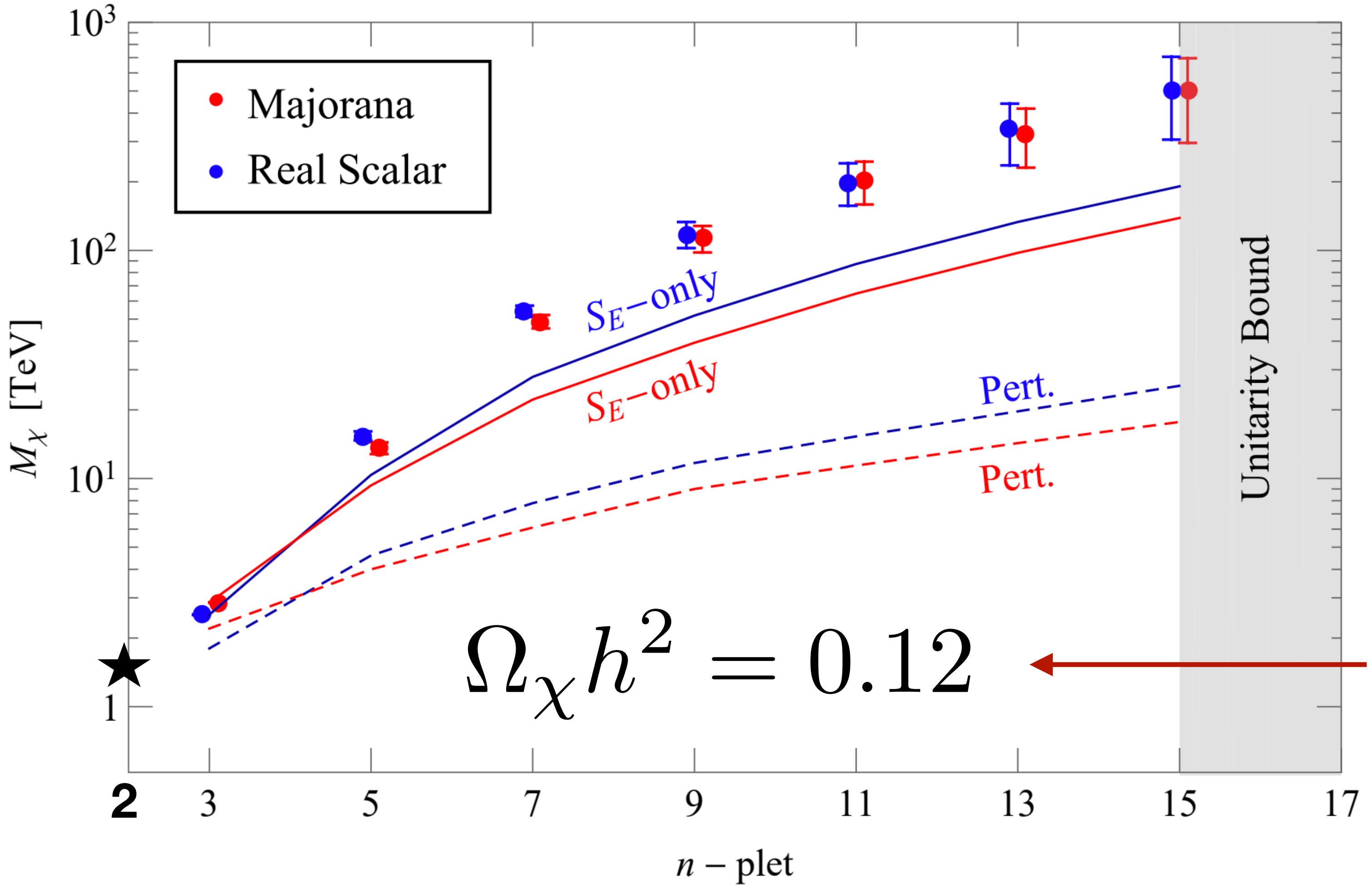
Summary

- **Mass:**



$$\langle \sigma v \rangle \sim \frac{g^4 n^3 + 8 g^2 g_Y^2 Y^2 n}{128 \pi M_\chi^2}$$ (Majorana Large n)

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



(Thermal Target)

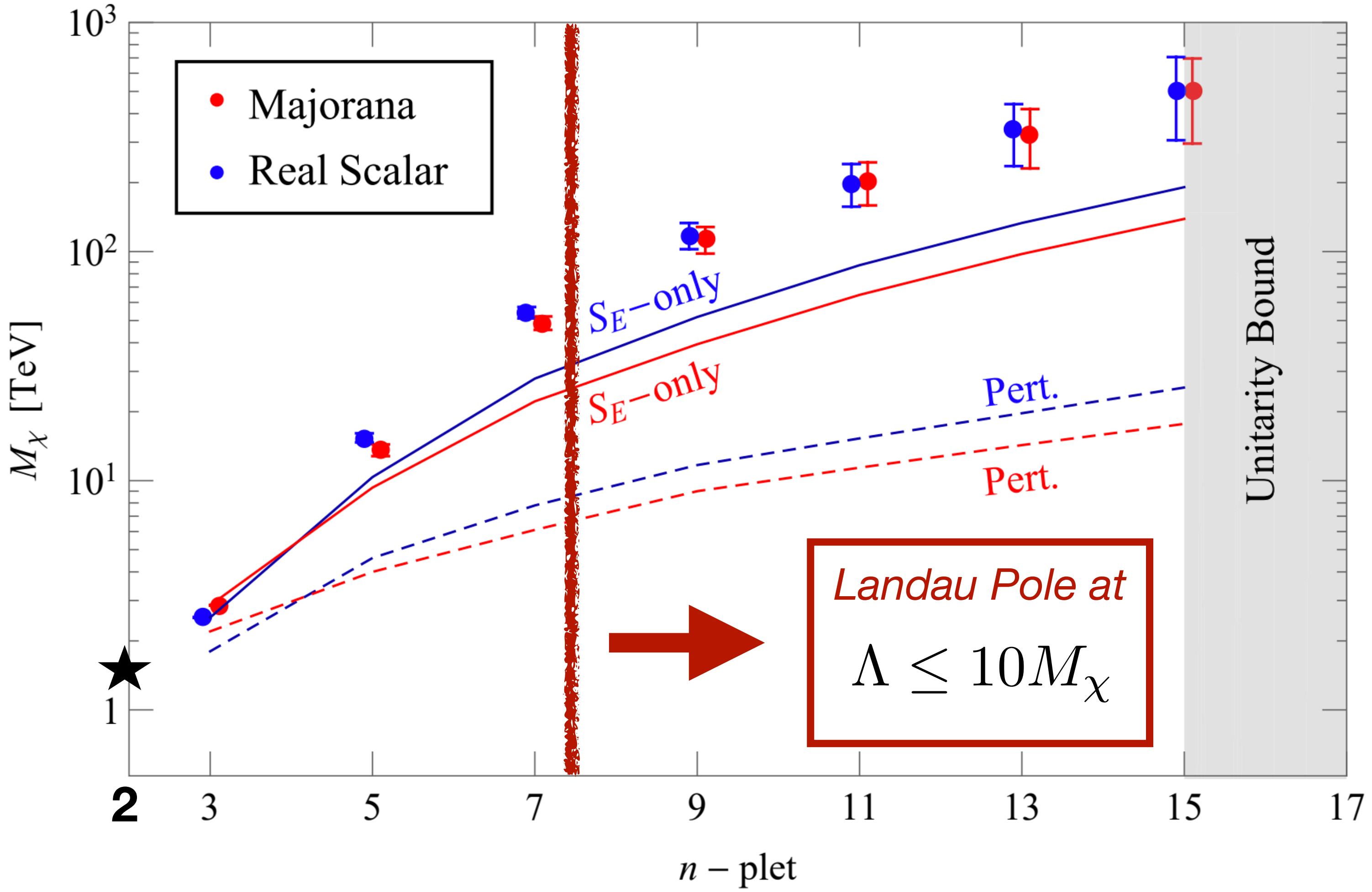
Bottaro et al., Eur. Phys. J. C 82 (2022) 1, 31

- **Mass:**

Very large multiplets become less motivated

A good target can be:

- *EW multiplets:* ***2***, ***3***, *…*, ***7***
- *Masses:* *1-50 TeV*



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

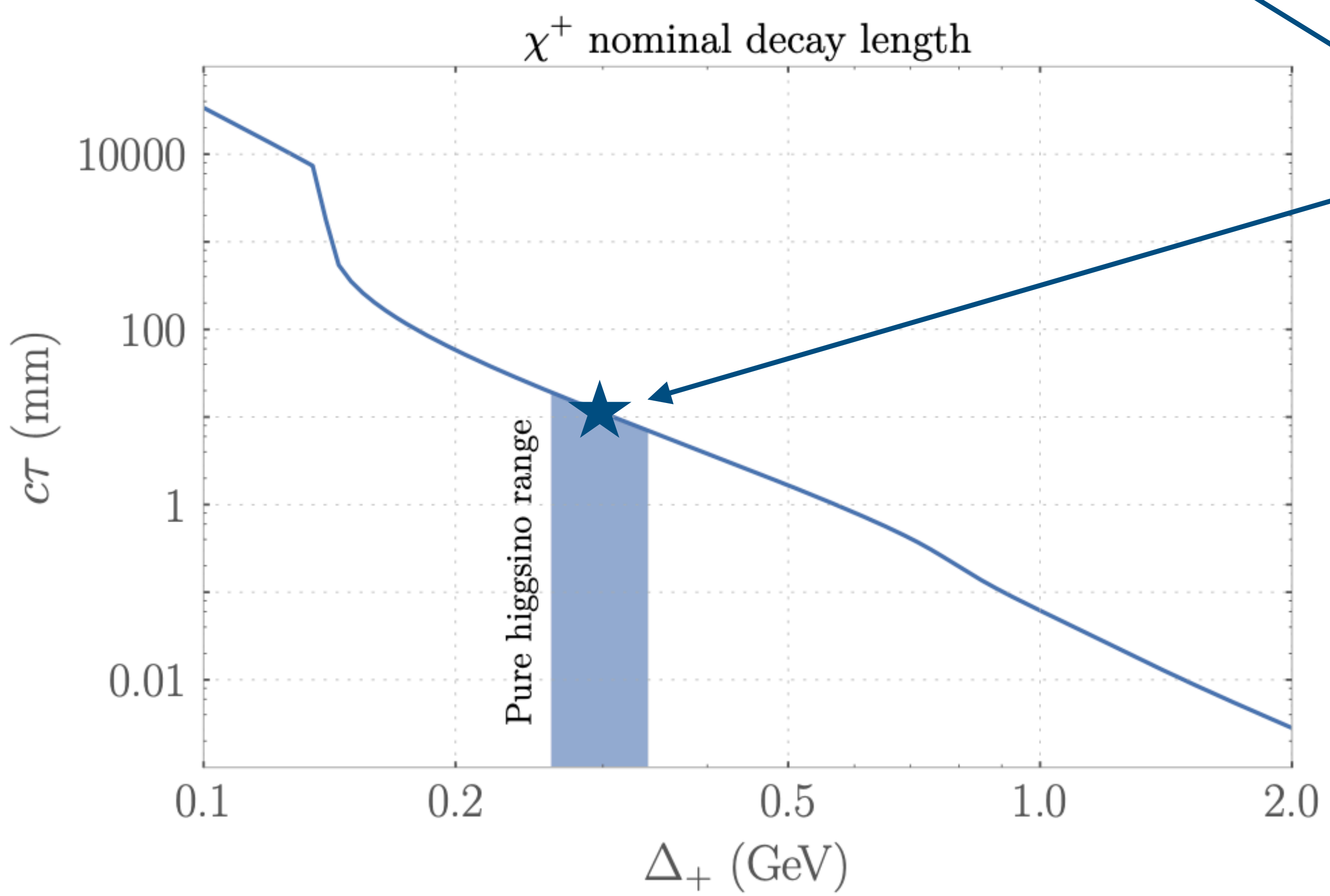
- **Lifetime**

For a given multiplet

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

Loop effects generate chargino-neutralino splitting

$$\Delta M = M_{\chi^{\pm}} - M_{\chi^{0}} > 0$$



Macroscopic decay length!

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

- **Thermal Targets**

$$\chi_{\mathbf{2}} \equiv \chi_{\tilde{H}} = \begin{pmatrix} \chi^{+}_{\tilde{H}} \\ \chi^{0}_{\tilde{H}} \end{pmatrix}, \quad \chi_{\mathbf{3}} \equiv \chi_{\tilde{W}} = \begin{pmatrix} \chi^{+}_{\tilde{W}} \\ \chi^{0}_{\tilde{W}} \\ \chi^{-}_{\tilde{W}} \end{pmatrix} \ldots \quad \chi_{\mathbf{5}} \ldots \quad \chi_{\mathbf{9}} \ldots$$

	Doublets (Higgsino-like)	Triplets (Wino-like)	Fiveplets…	Nineplets…
Mass:	1.1 TeV	2.7 TeV	14 TeV	
Lifetime:	0.02 ns	0.2 ns	0.2 ns	

Outline

1. Introduction

2. Minimal WIMP Searches

- Direct Detection
- Indirect Detection
- LHC

3. Future p/e Colliders

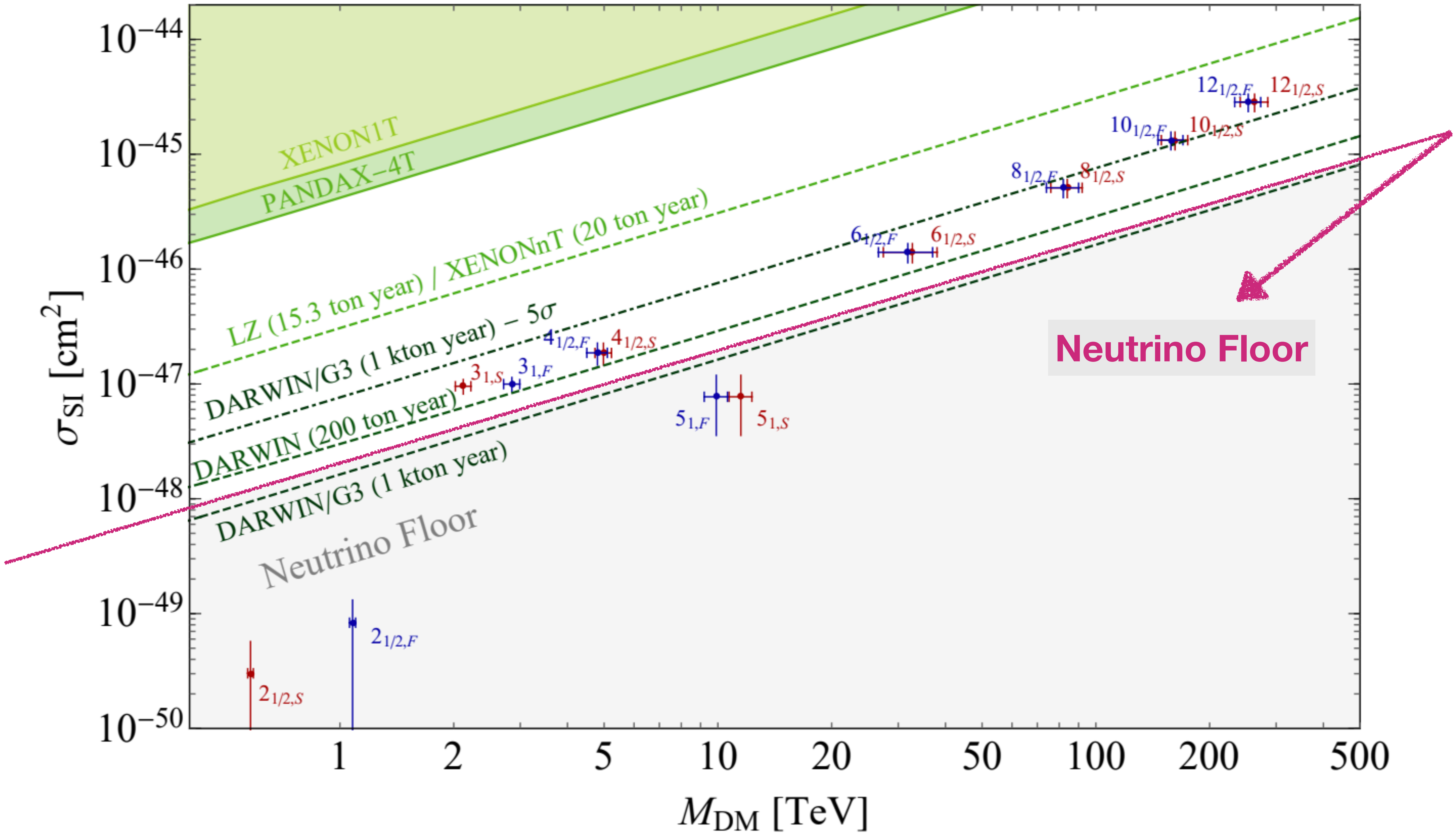
4. Muon Collider

- Disappearing Tracks
- Soft Tracks

Summary

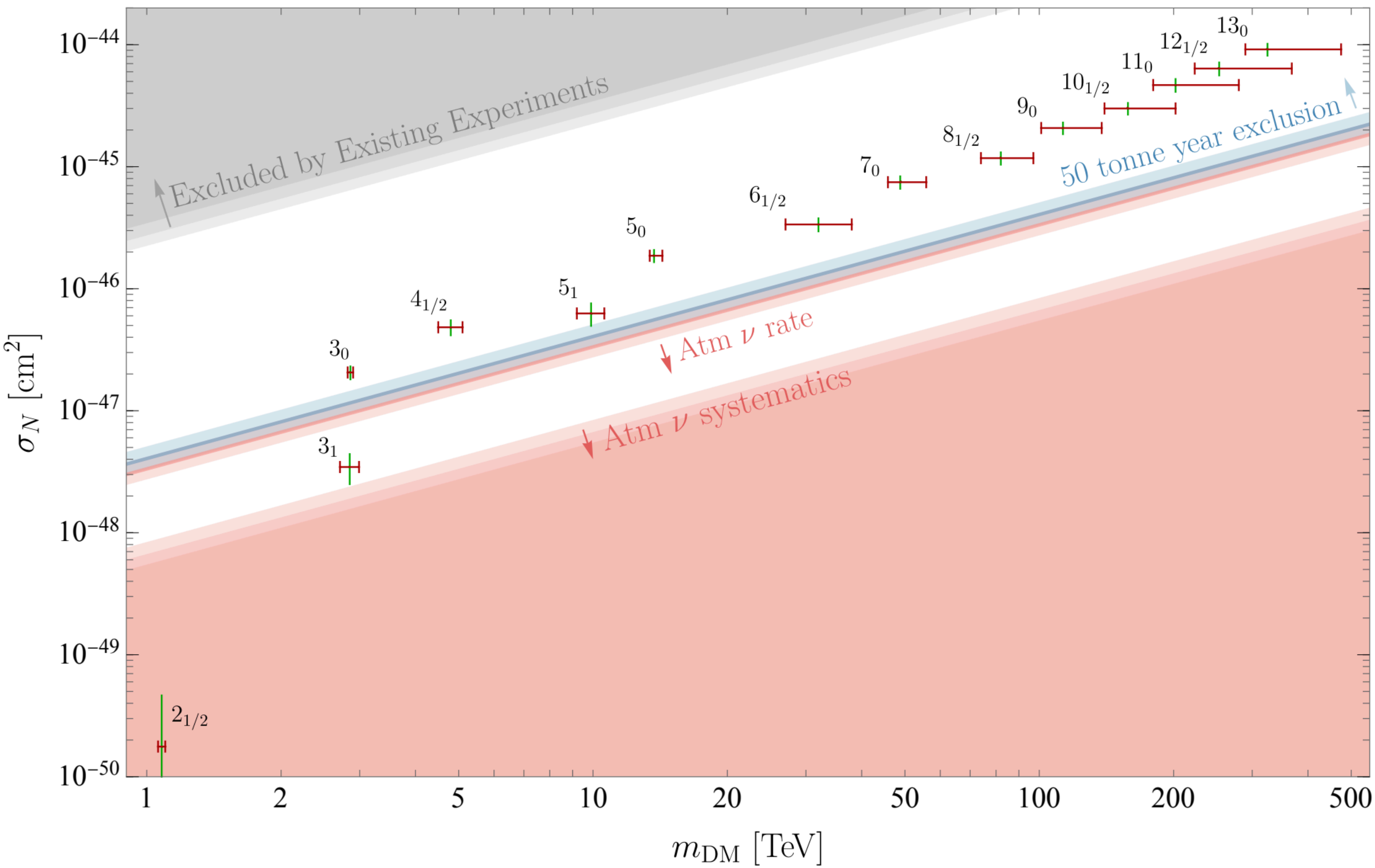
- **Direct Detection (DD)**

Bottaro, Buttazzo, Costa, Franceschini, Panci, Redigolo, Vittorio, Eur. Phys. J. C 82 (2022) 11, 992



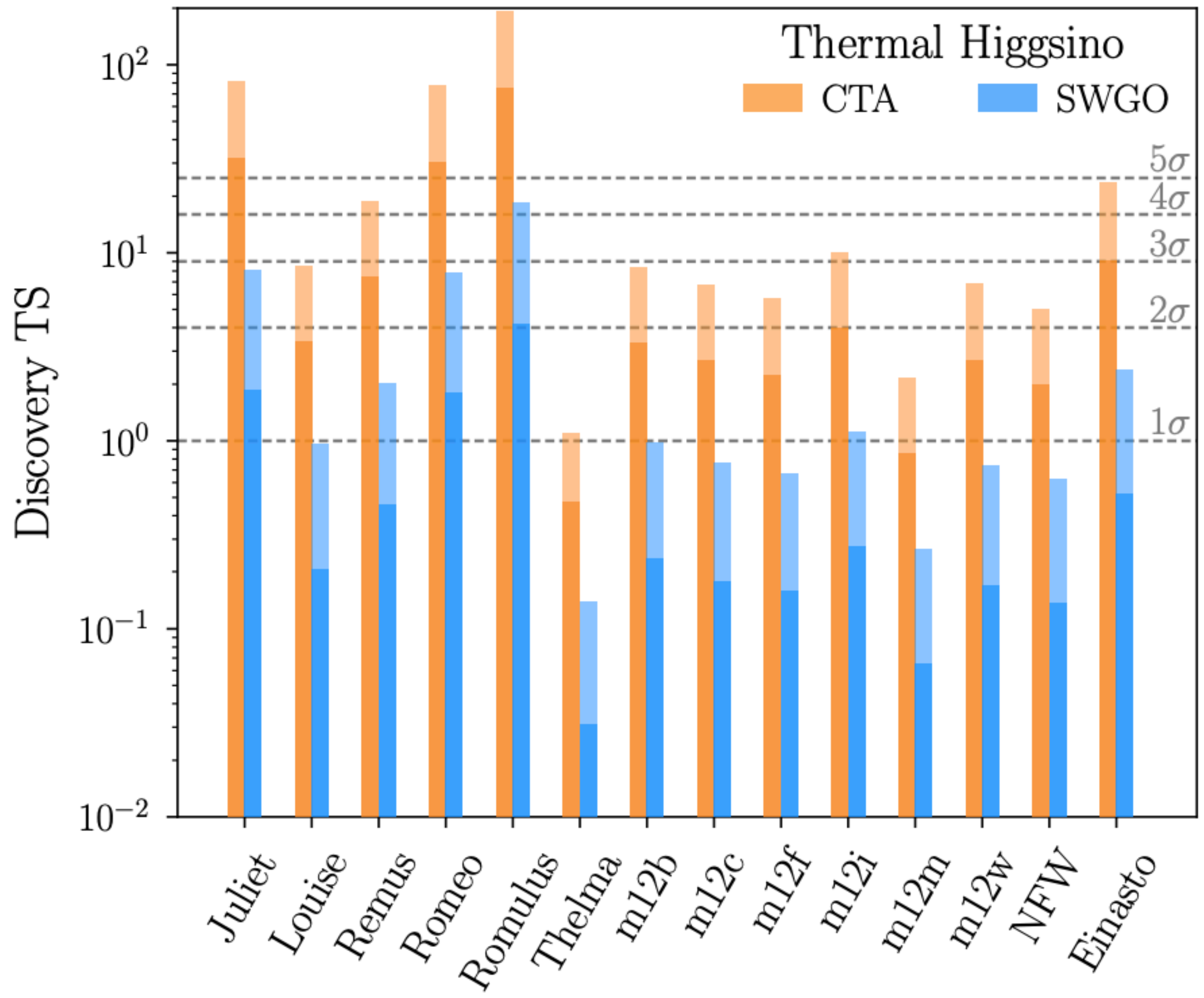
- **Direct Detection (DD)**

I. Bloch, S. Bottaro, D. Redigolo, L. Vittorio, ArXiv:2410.02723



- **Indirect Detection (ID)**

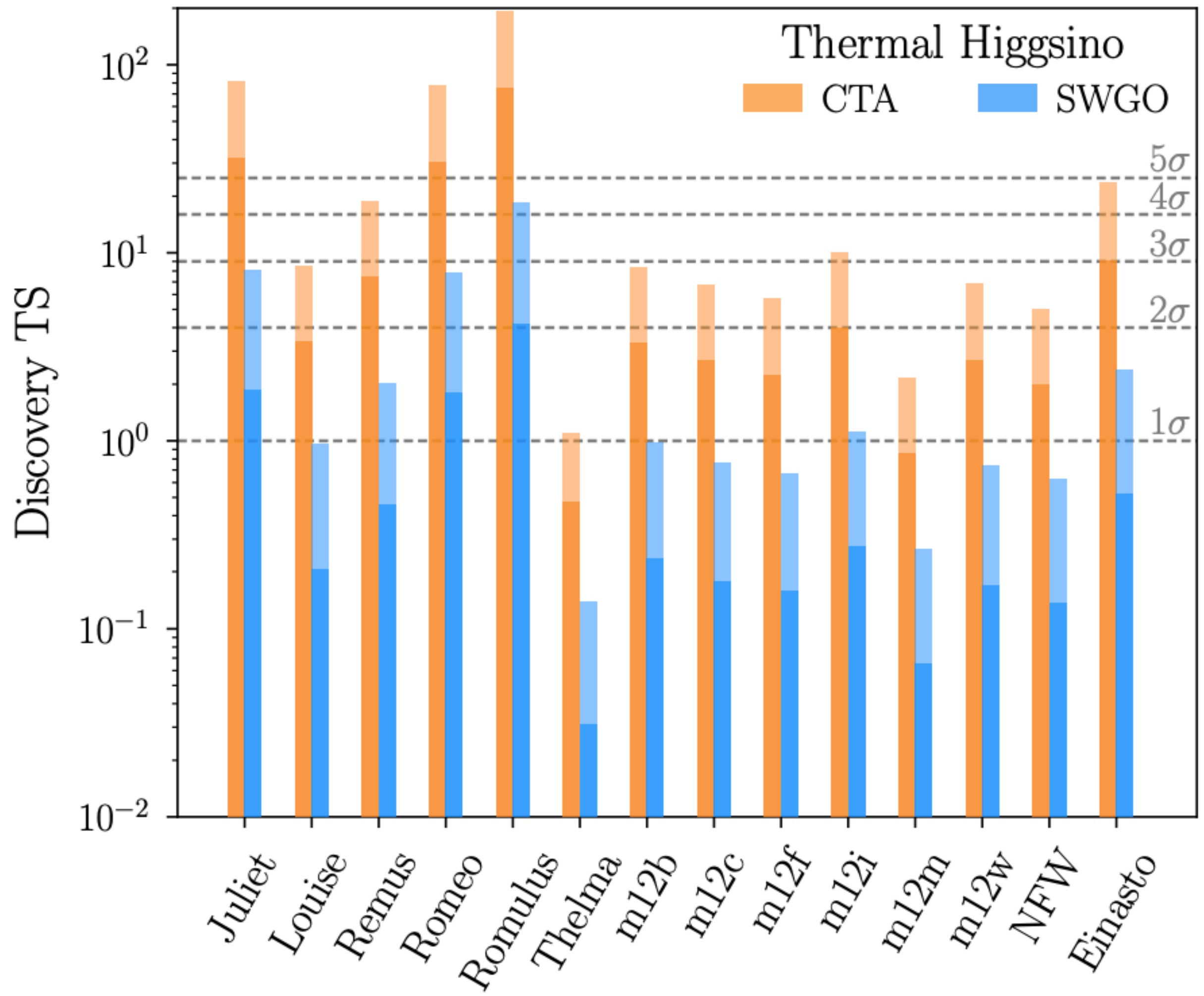
Doublet



Nicholas L. Rodd, Benjamin R. Safdi, Weishuang Linda Xu,
Phys. Rev. D 110 (2024) 4, 043003

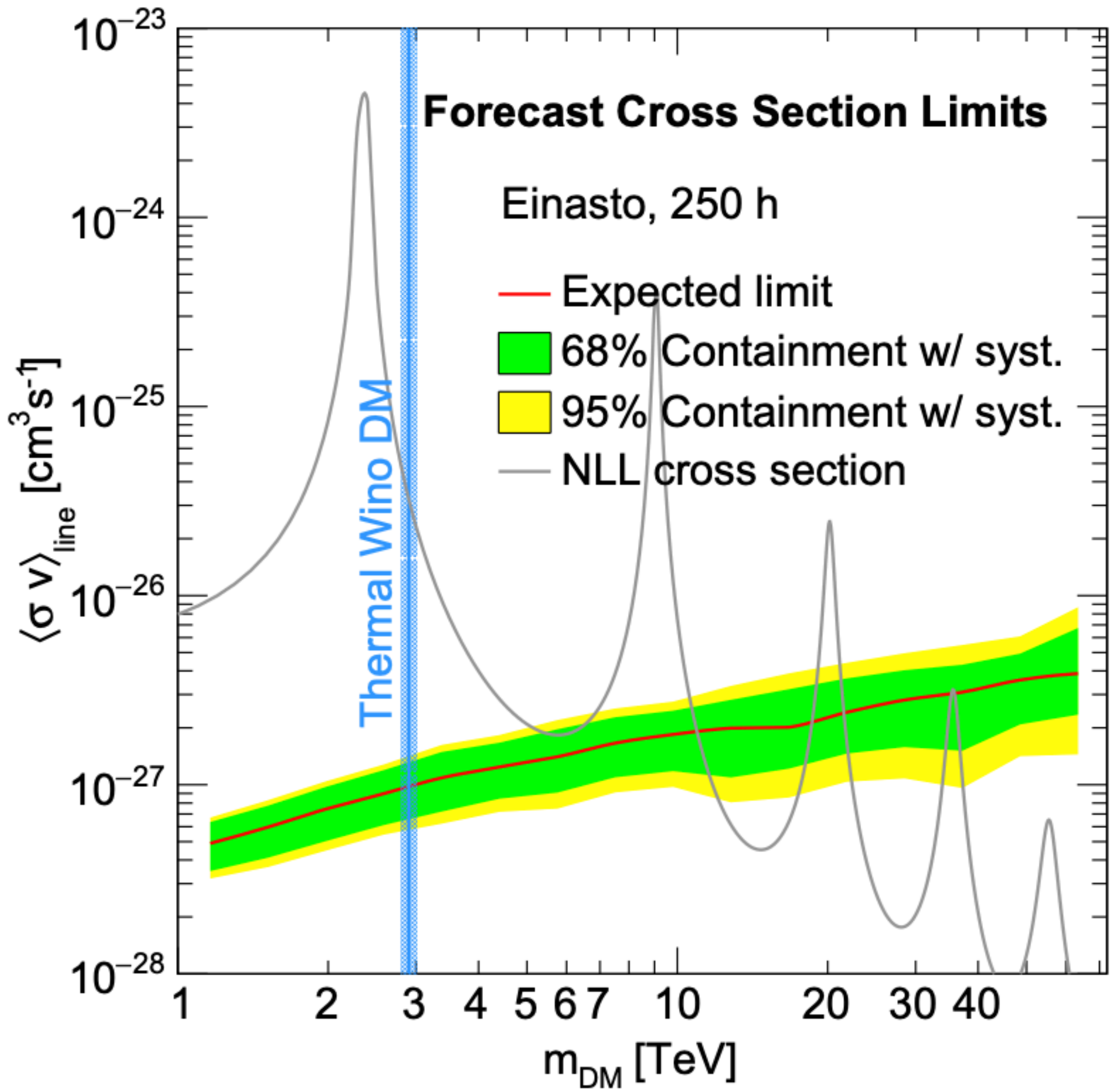
- **Indirect Detection (ID)**

Doublet



Nicholas L. Rodd, Benjamin R. Safdi, Weishuang Linda Xu, Phys. Rev. D 110 (2024) 4, 043003

Triplet



Rinchiuso et al., Phys. Rev. D 98 (2018) 12, 123014
Cohen, Lisanti, Pierce, Slatyer, JCAP 10 (2013) 061

Outline

1. Introduction
2. Minimal WIMP Searches
   - Direct Detection
   - Indirect Detection
   - LHC

3. Future p/e Colliders

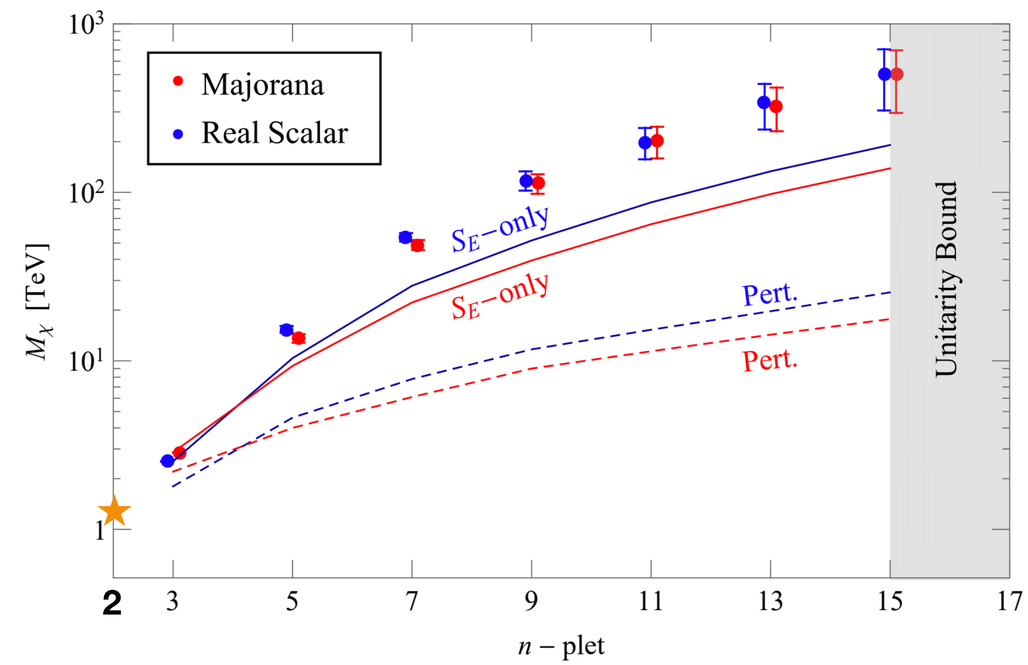
4. Muon Collider
   - Disappearing Tracks
   - Soft Tracks

Summary

- **Towards the Thermal Targets:**

  - *Electroweak states*
  - *1-100 TeV masses*
  - *100% of Dark Matter*

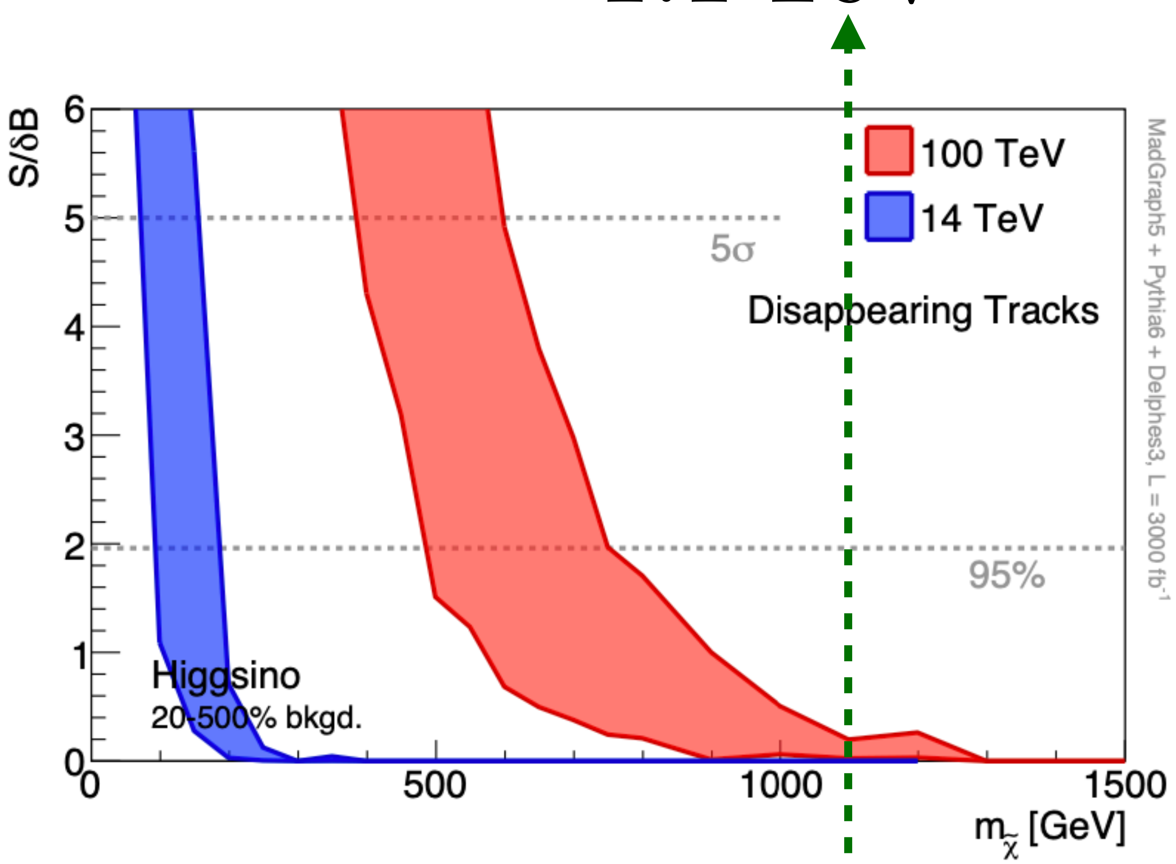
A task for future colliders!



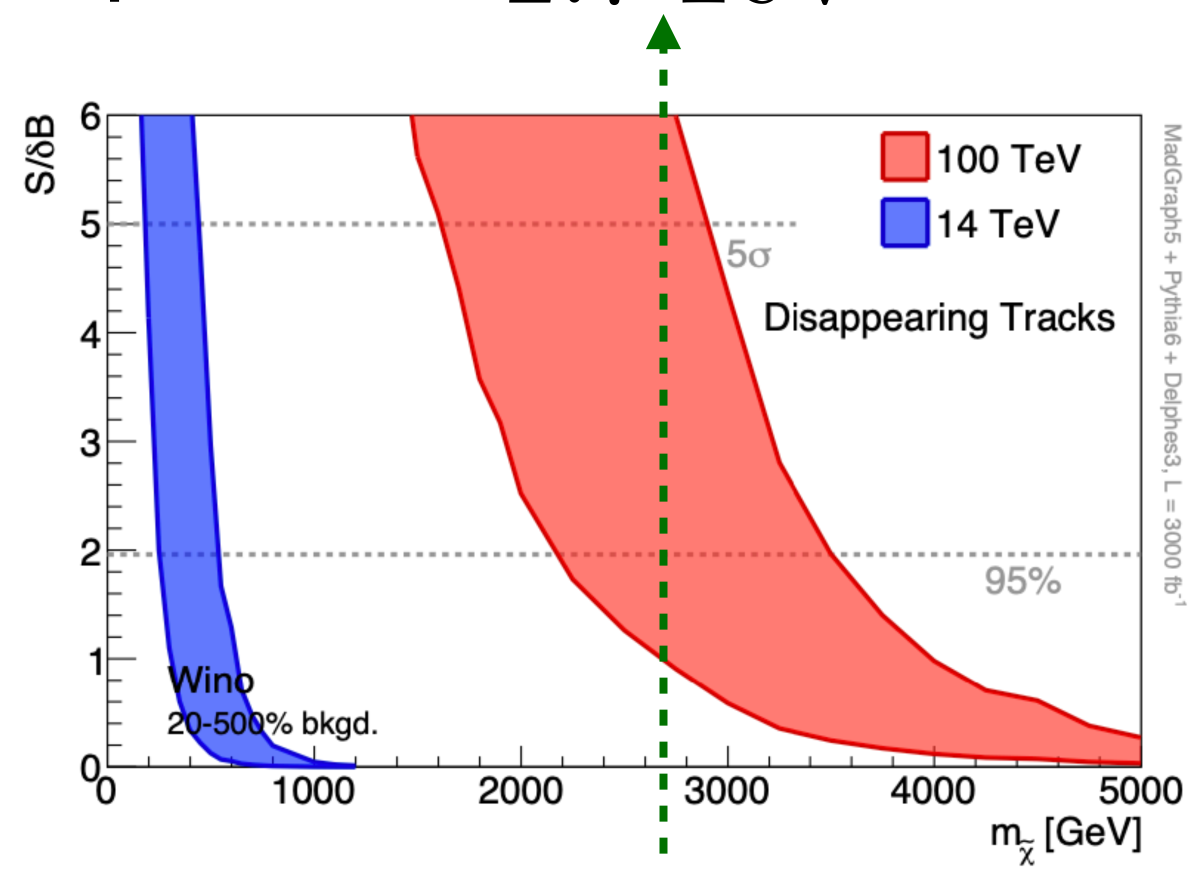
- **pp (100 TeV):**

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

Doublet $\sim 1.1\,\text{TeV}$



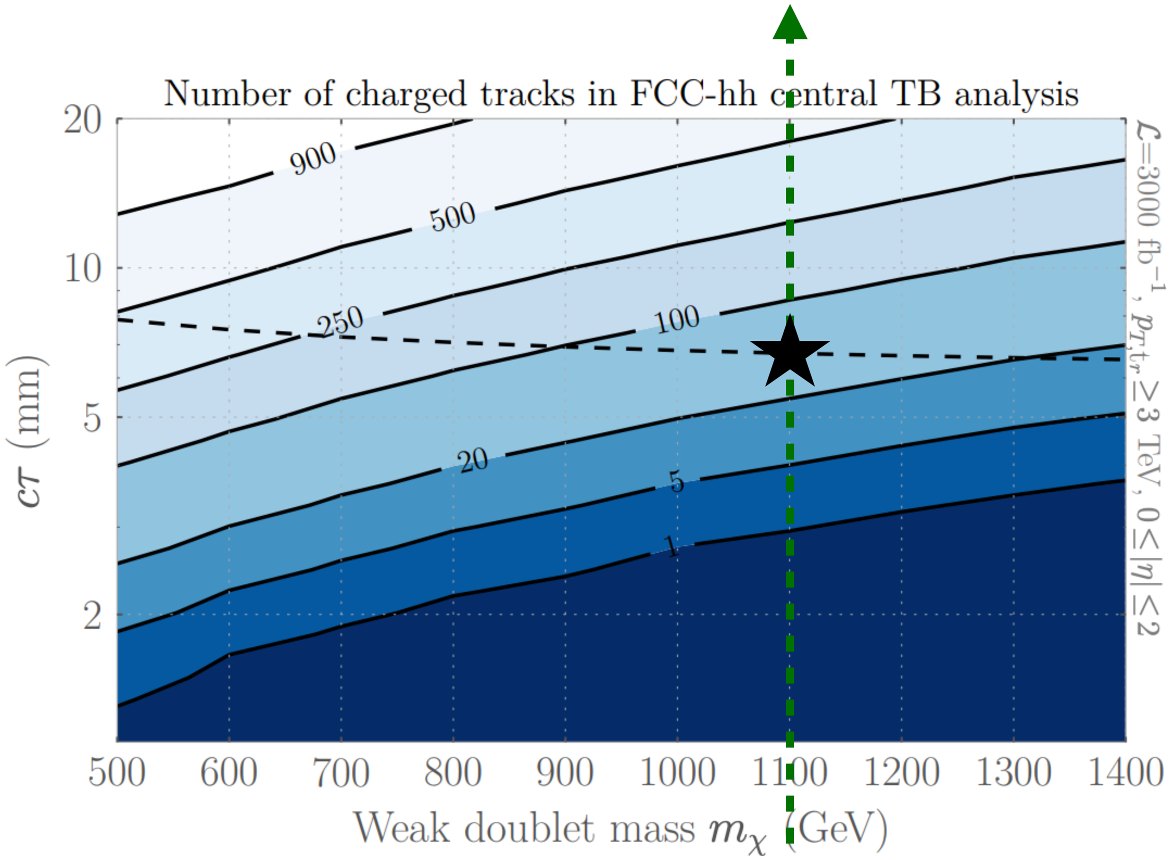
Triplet $\sim 2.7\,\text{TeV}$



Thermal Target!

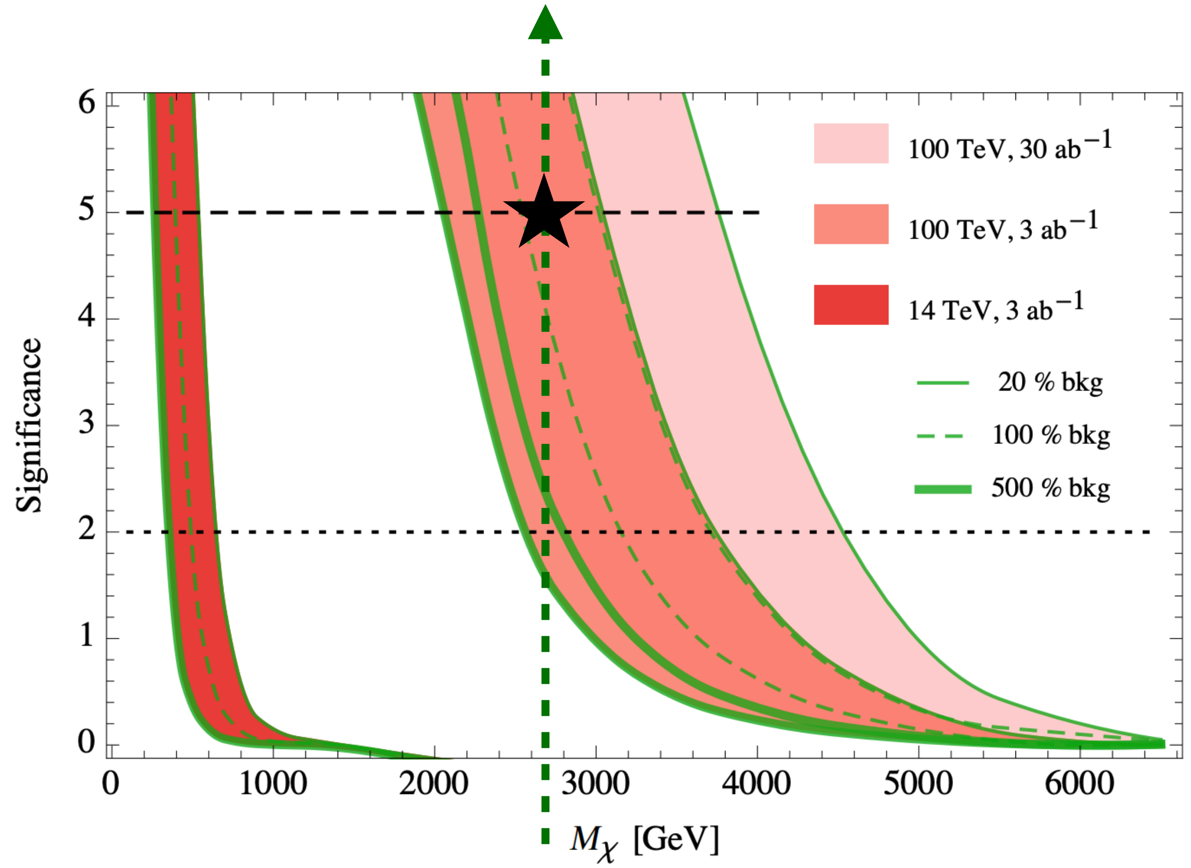
- **pp (100 TeV):**

Doublet $\sim 1.1\,\text{TeV}$



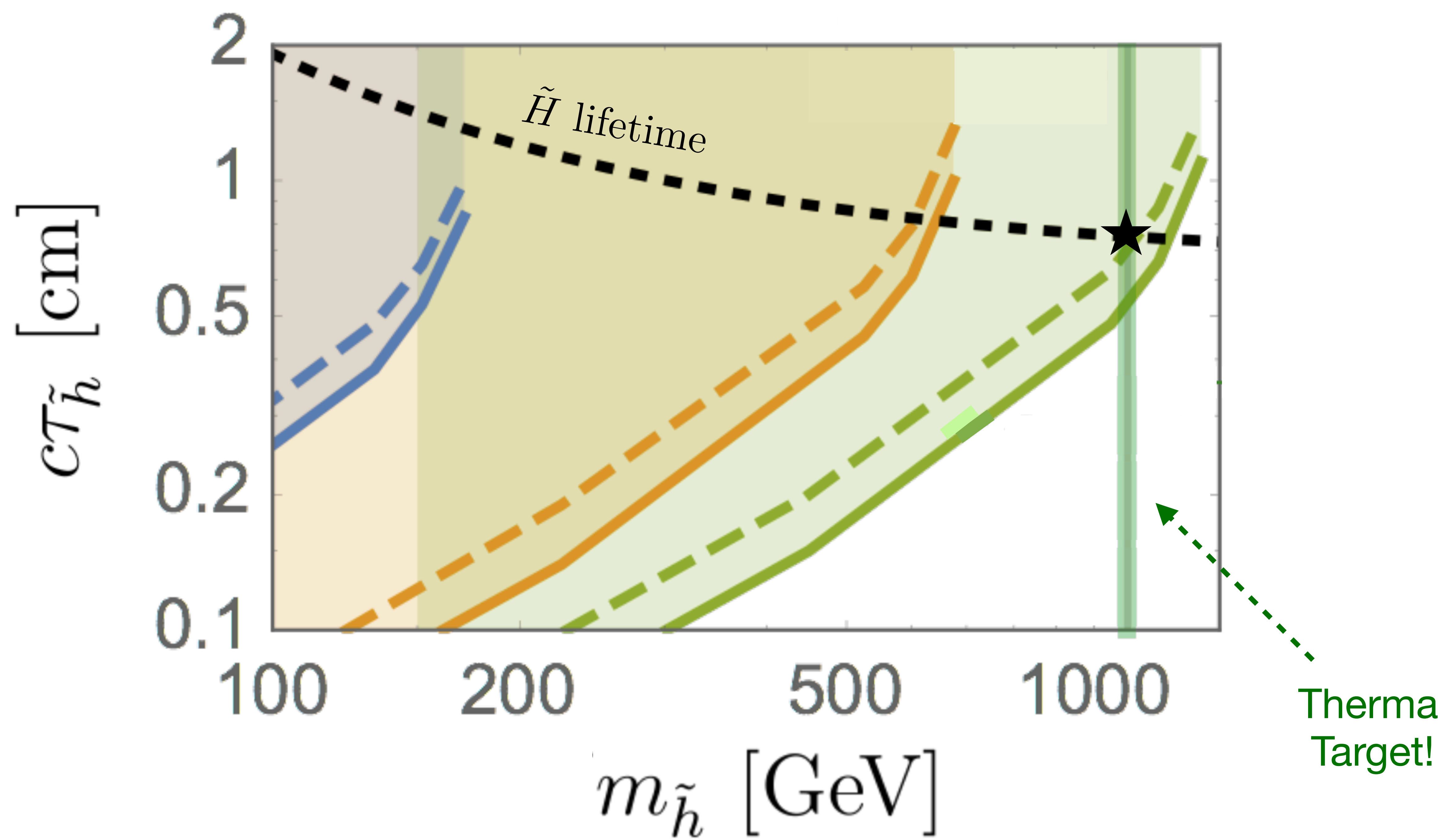
R. Mahbubani, P. Schwaller, J. Zurita, JHEP 06 (2017) 119

Triplet $\sim 2.7\,\text{TeV}$



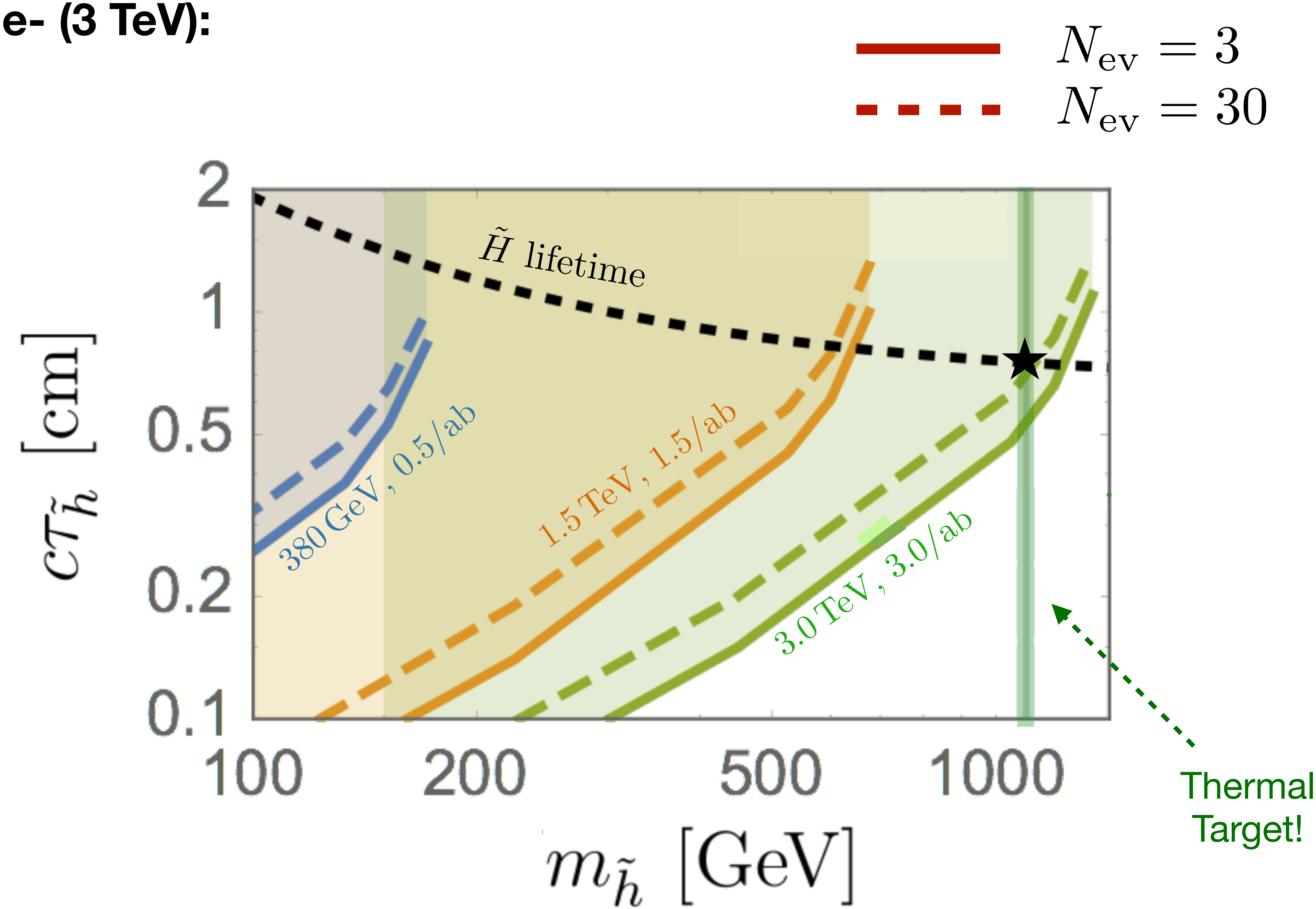
M. Cirelli, F. Sala, M. Taoso, JHEP 10 (2014) 033

- **e+e- (3 TeV):**



CLIC Collaboration, CERN Yellow Rep. Monogr. 3 (2018)

- **e+e- (3 TeV):**



CLIC Collaboration, CERN Yellow Rep. Monogr. 3 (2018)

Outline

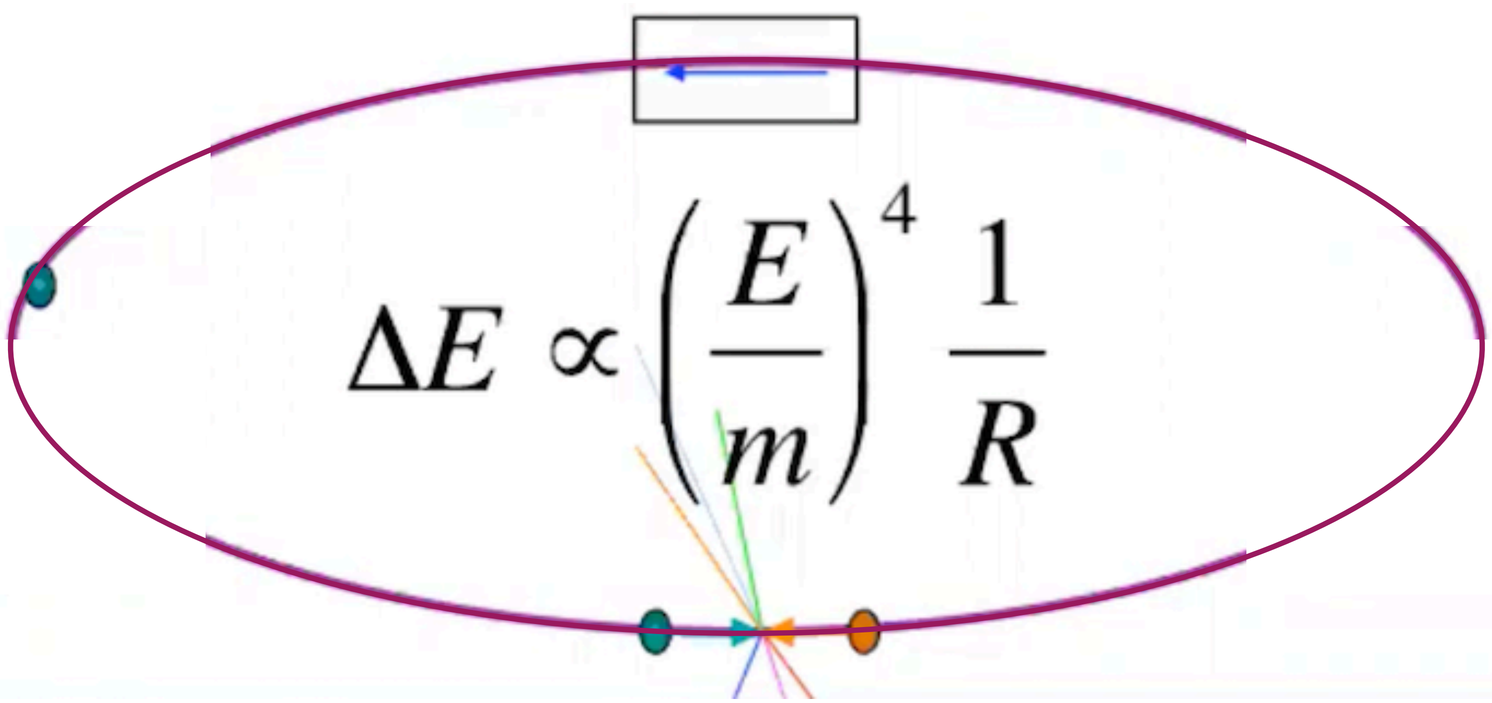
1. Introduction
2. Minimal WIMP Searches
   - Direct Detection
   - Indirect Detection
   - LHC
3. Future p/e Colliders
4. **Muon Collider**
   - Disappearing Tracks
   - Soft Tracks

Summary

- **Muon Colliders:**

Advantages of circular lepton colliders:

(i) Multi-pass! (recycle beam; lumi, power)
(ii) All CoM energy is available
(iii) Clean (from huge hadronic backgrounds!)

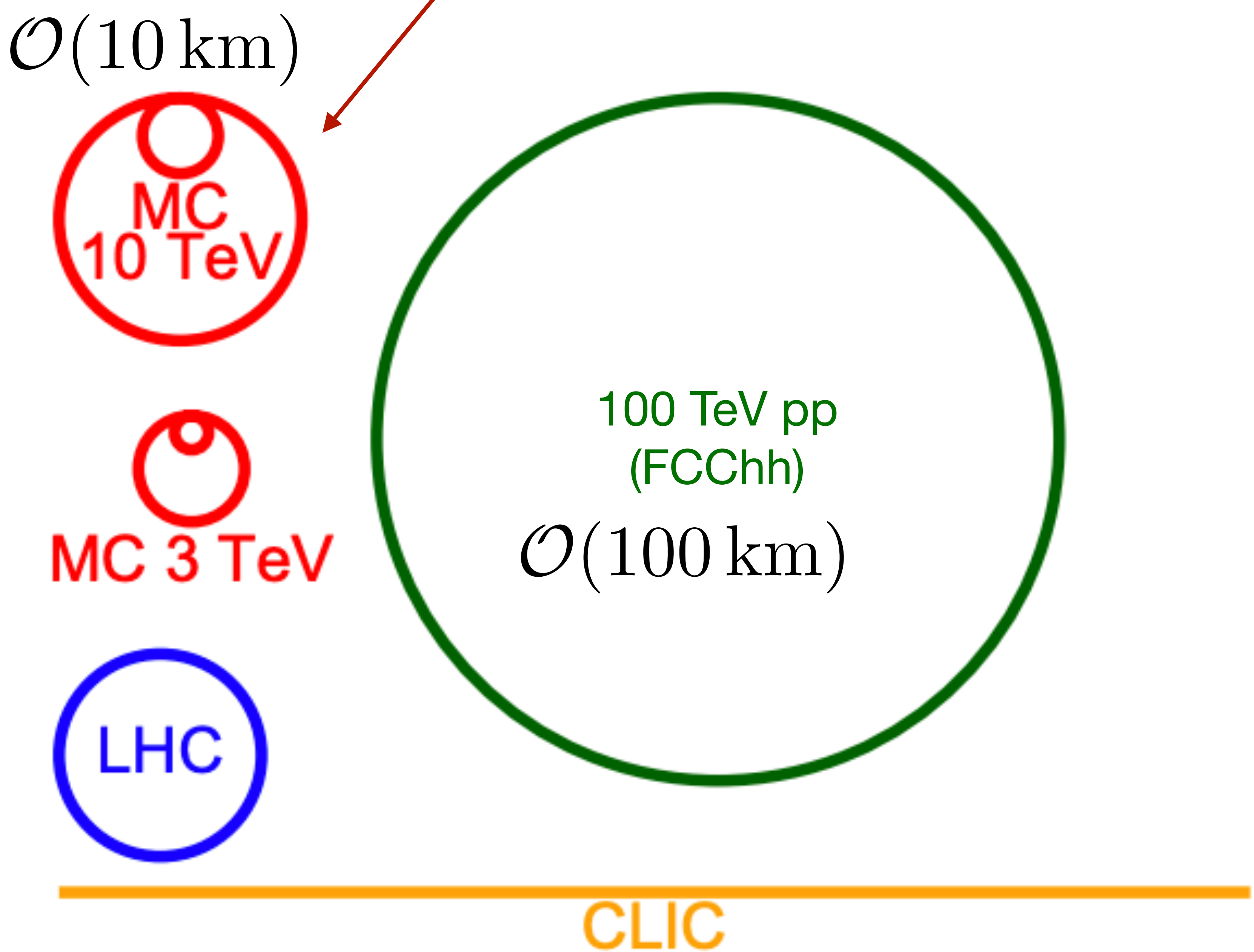


$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

- **Muon Colliders:**

MuC allows us to reach 10 TeV c.o.m. collisions with ~10 km ring!

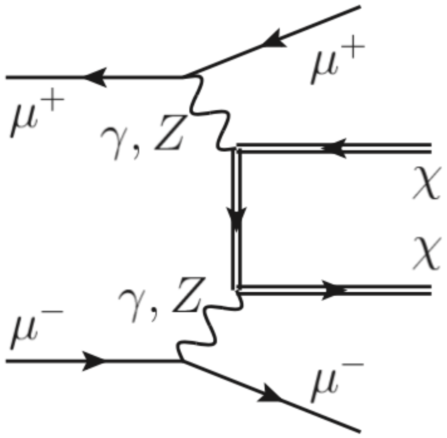
P5 Report: “This is our muon shot”



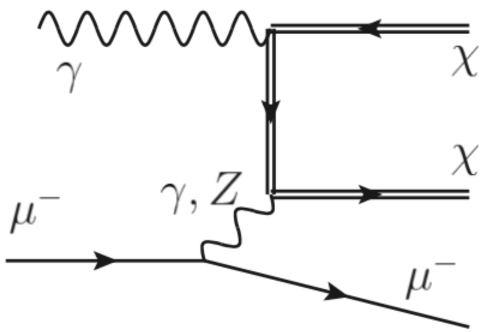
- **Muon Colliders:**

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

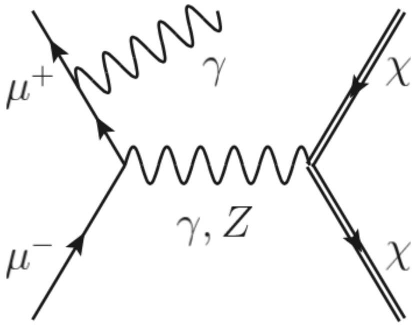
di-muon + MET



mono-muon



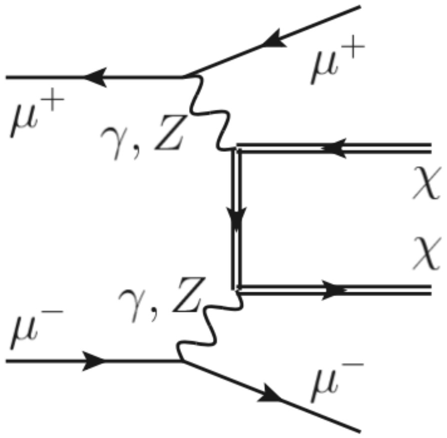
Mono-photon



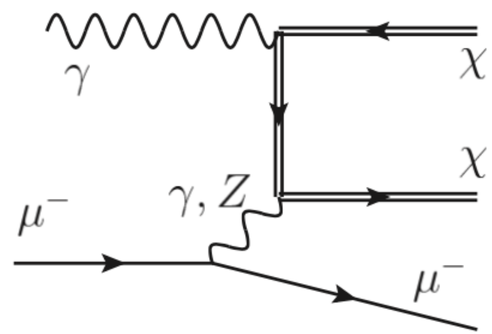
T. Han, Z. Liu, L. Wang, X. Wang, Phys. Rev. D 103 (2021) 7, 075004

- **Muon Colliders:**

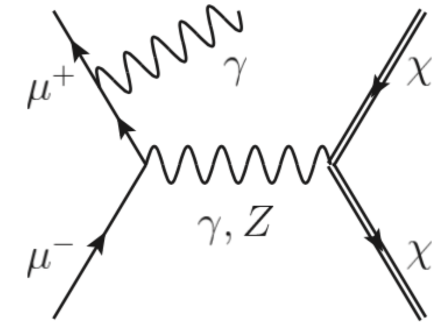
di-muon + MET

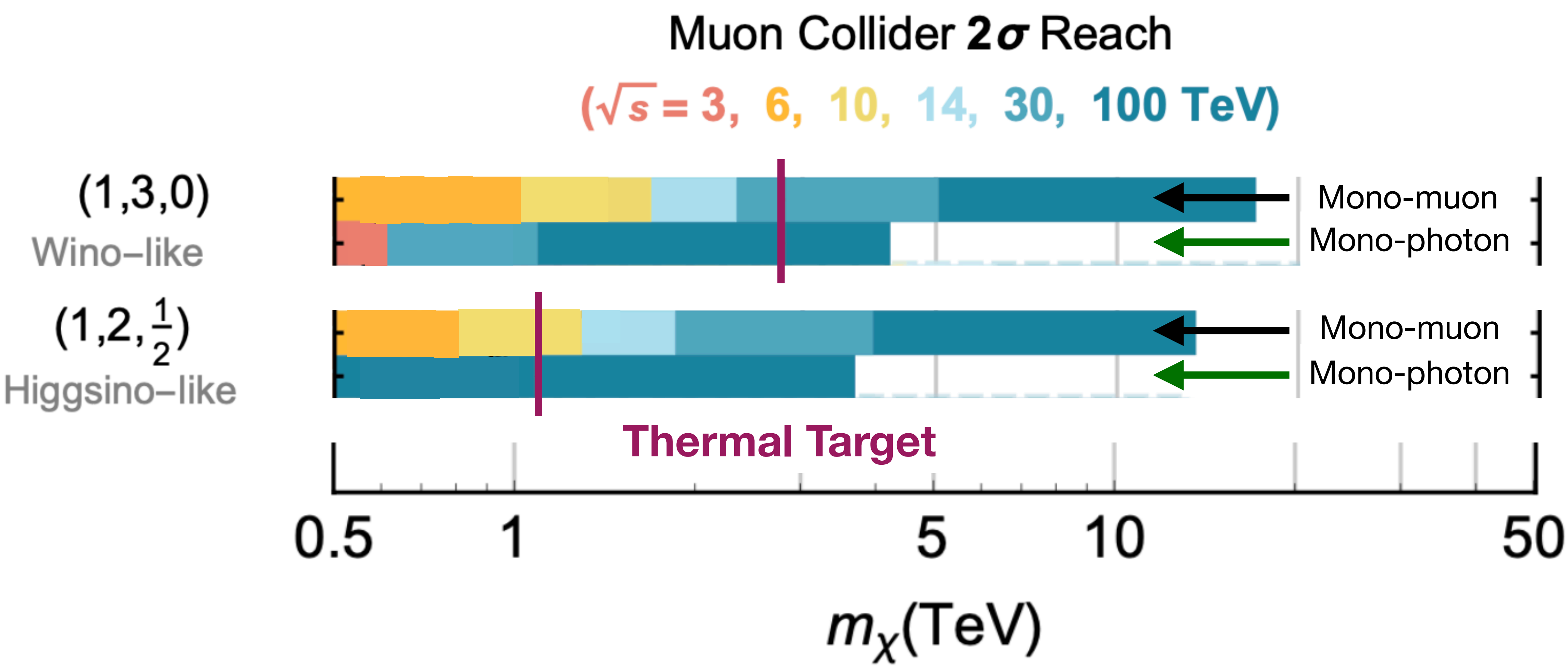


mono-muon



Mono-photon

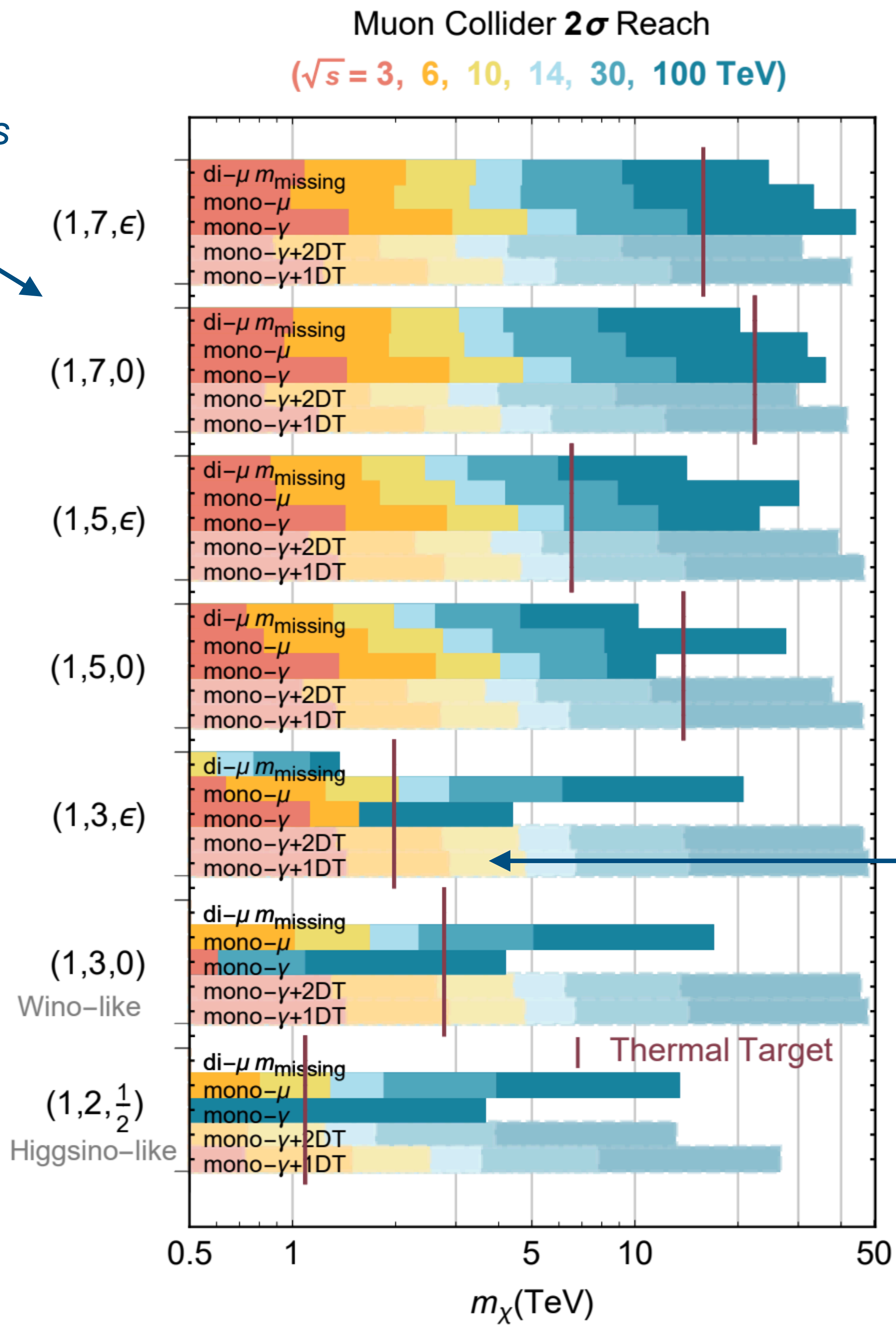


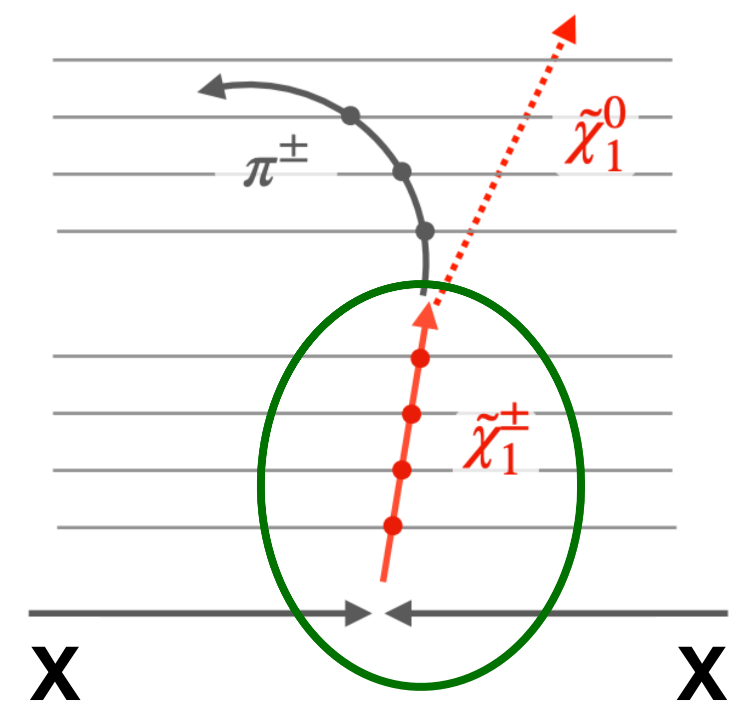


- **Muon Colliders:**

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

Lager multiplets



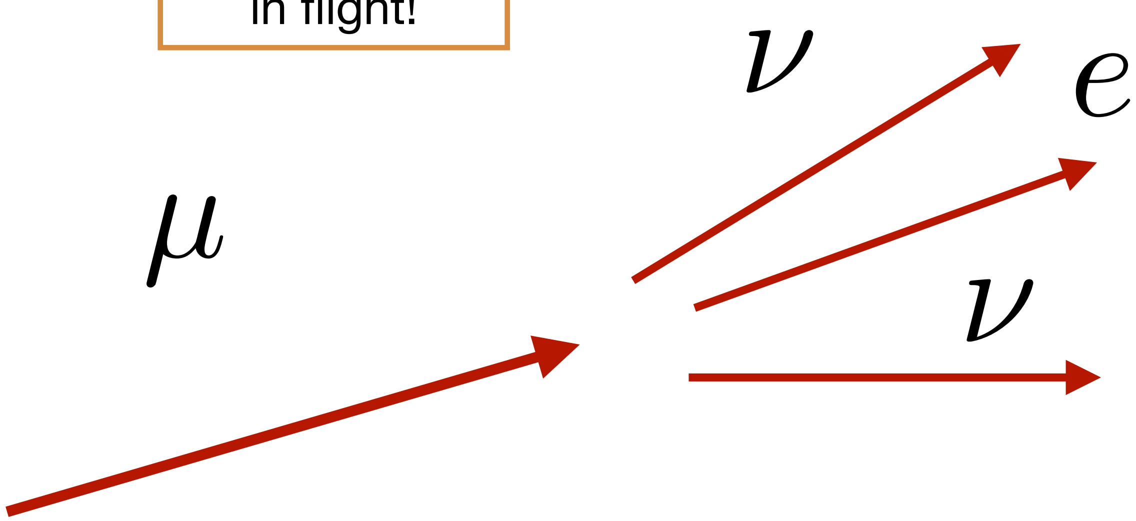


Disappearing Tracks!

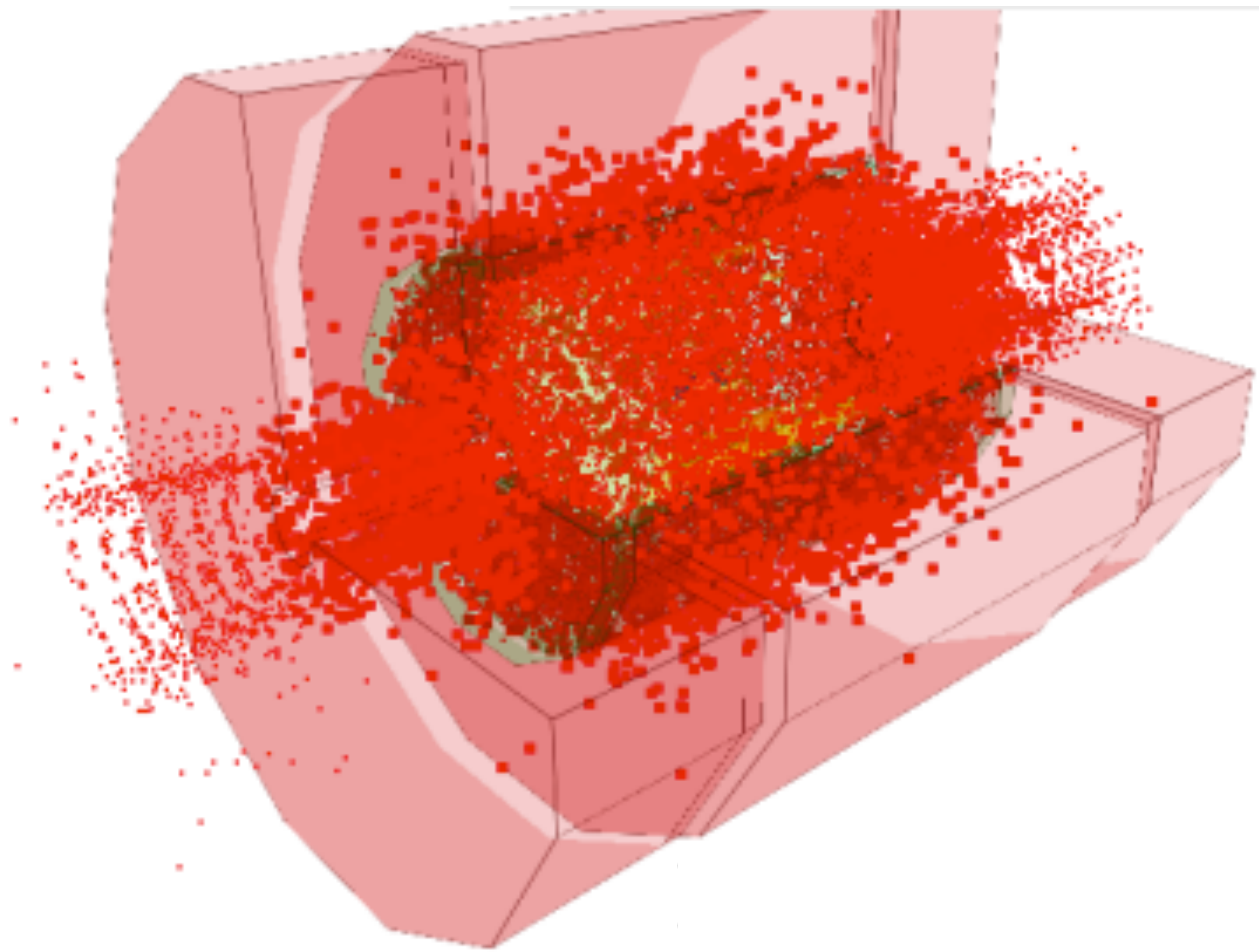
Rodolfo Capdevilla, Fermilab

- **Muon Colliders:**

Muons decay in flight!

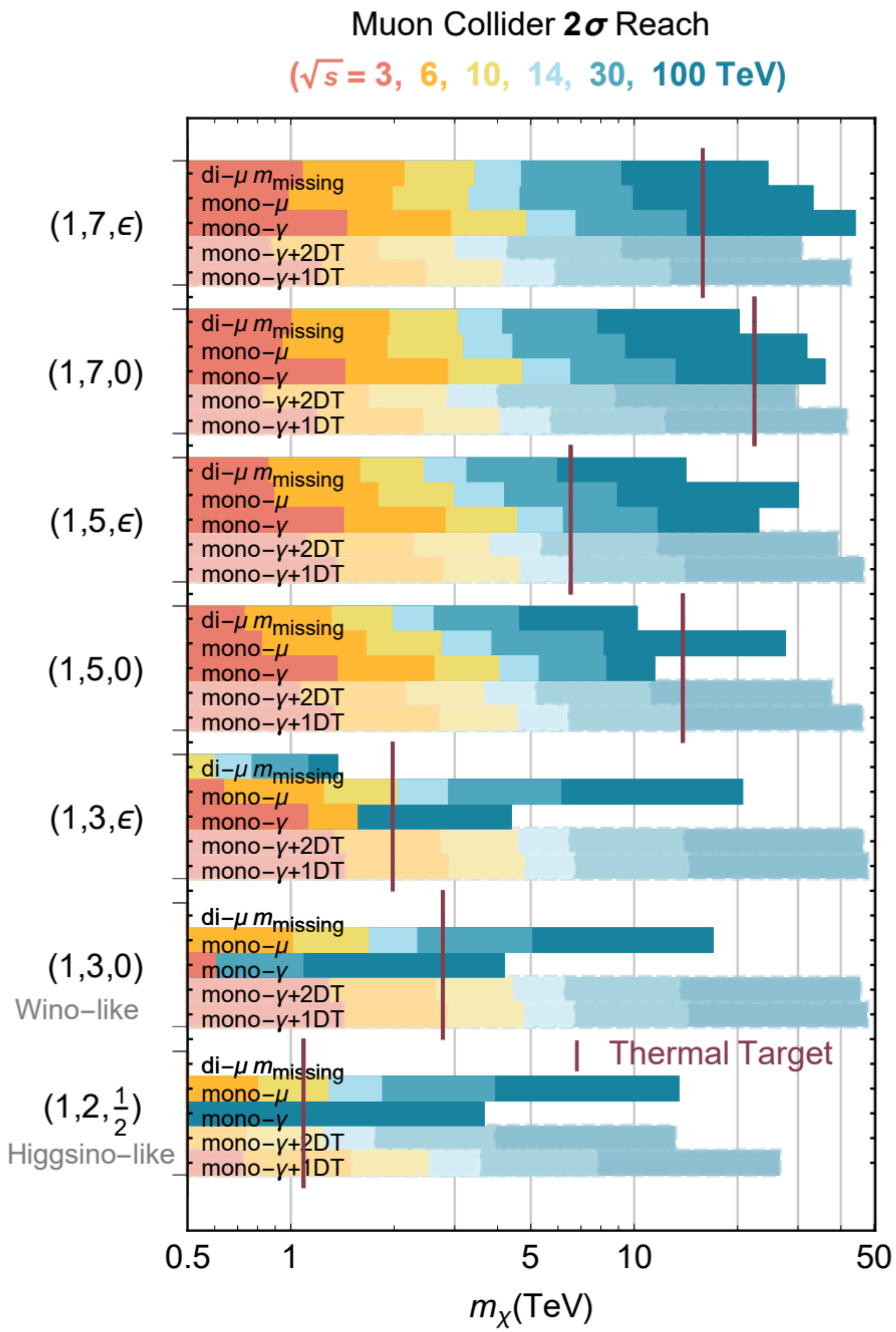


Sestini and Casarsa



- **Muon Colliders:**

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



How about **full detector simulation**?

How about the **BIB**?

Outline

1. Introduction
2. Minimal WIMP Searches
   - Direct Detection
   - Indirect Detection
   - LHC
3. Future p/e Colliders
4. Muon Collider
   - **Disappearing Tracks**
   - Soft Tracks

Summary

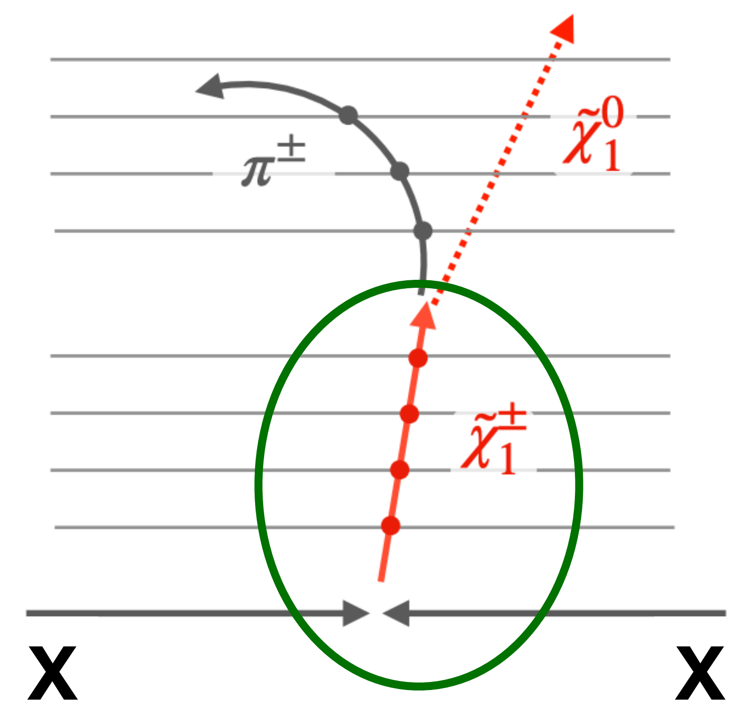
- **Full Detector Simulation + BIB:**

DESY 21-019   IFIC/21-03

Hunting wino and higgsino dark matter at the muon collider with disappearing tracks

Rodolfo Capdevilla,[a,b] **Federico Meloni,**[c] **Rosa Simoniello,**[d] **Jose Zurita**[e]

[a] *Department of Physics, University of Toronto, Canada*
[b] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada*
[c] *Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*
[d] *CERN, Geneva, Switzerland*
[e] *Instituto de Física Corpuscular, CSIC-Universitat de València, Valencia, Spain*



Disappearing Tracks

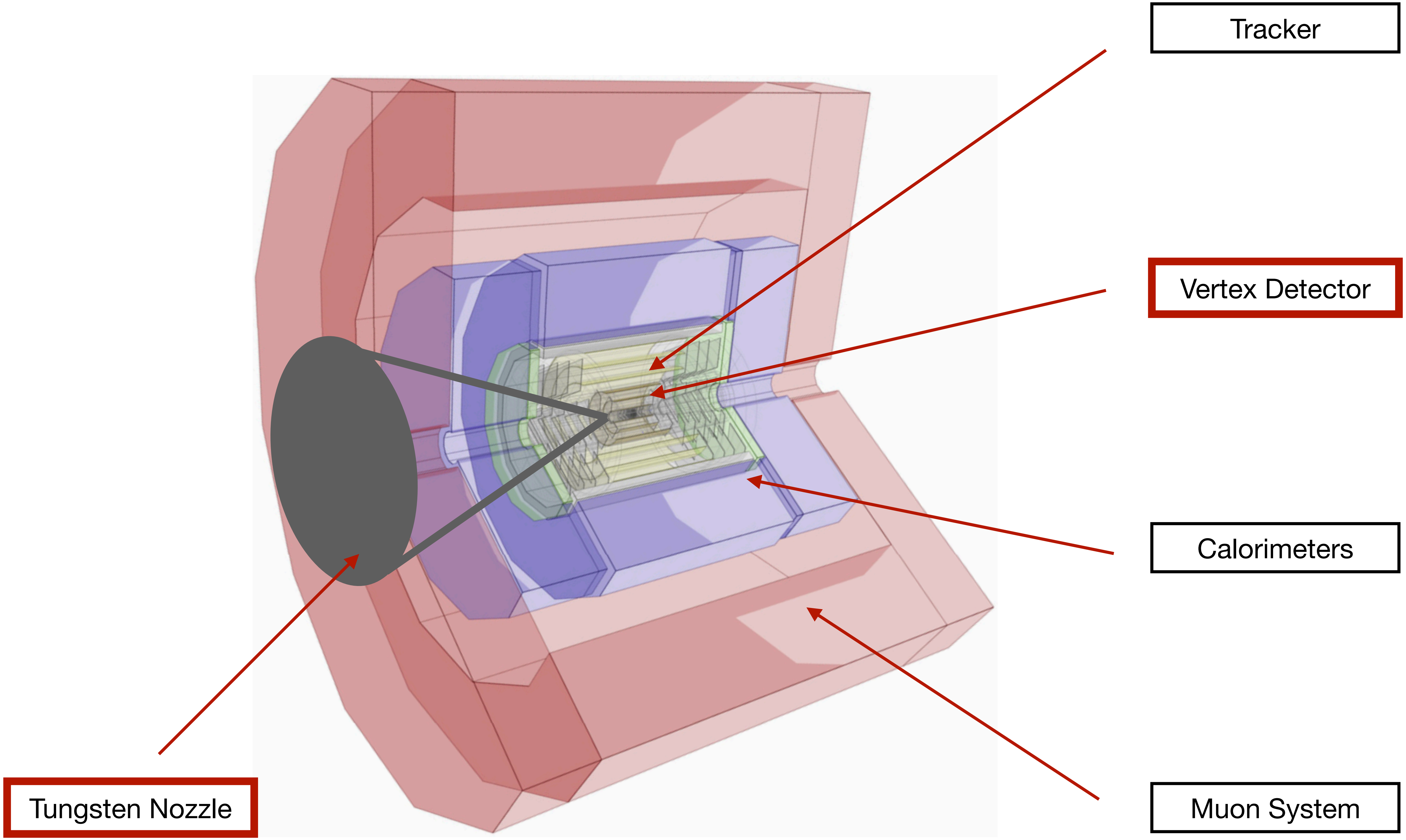
__RC__, Federico Meloni, Rosa Simoniello, Jose Zurita, JHEP __06__ (2021) 133

Federico Meloni, DESY

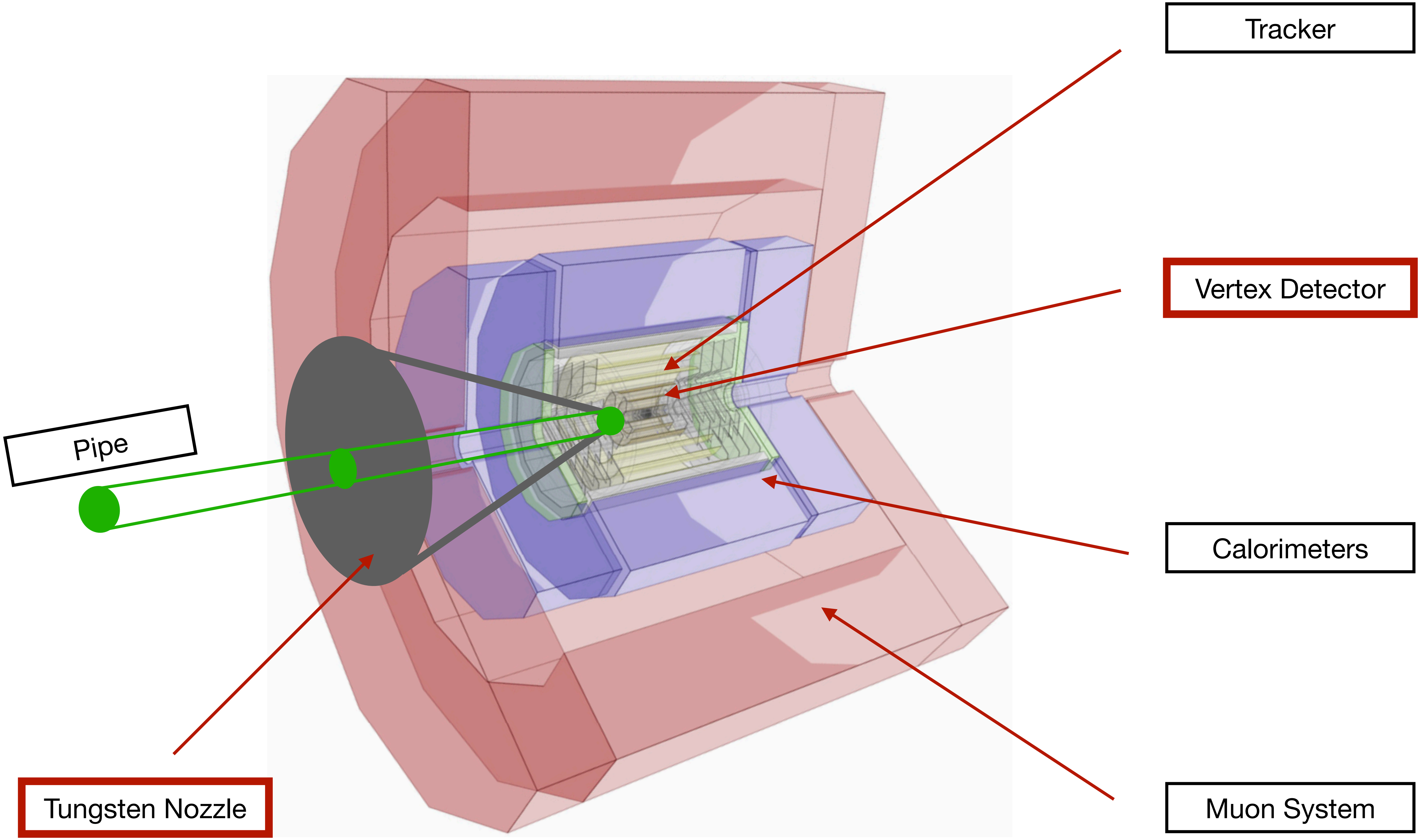
Rosa Simoniello, CERN

Jose Zurita, U. Valencia

- **Design Adapted from CLIC:**

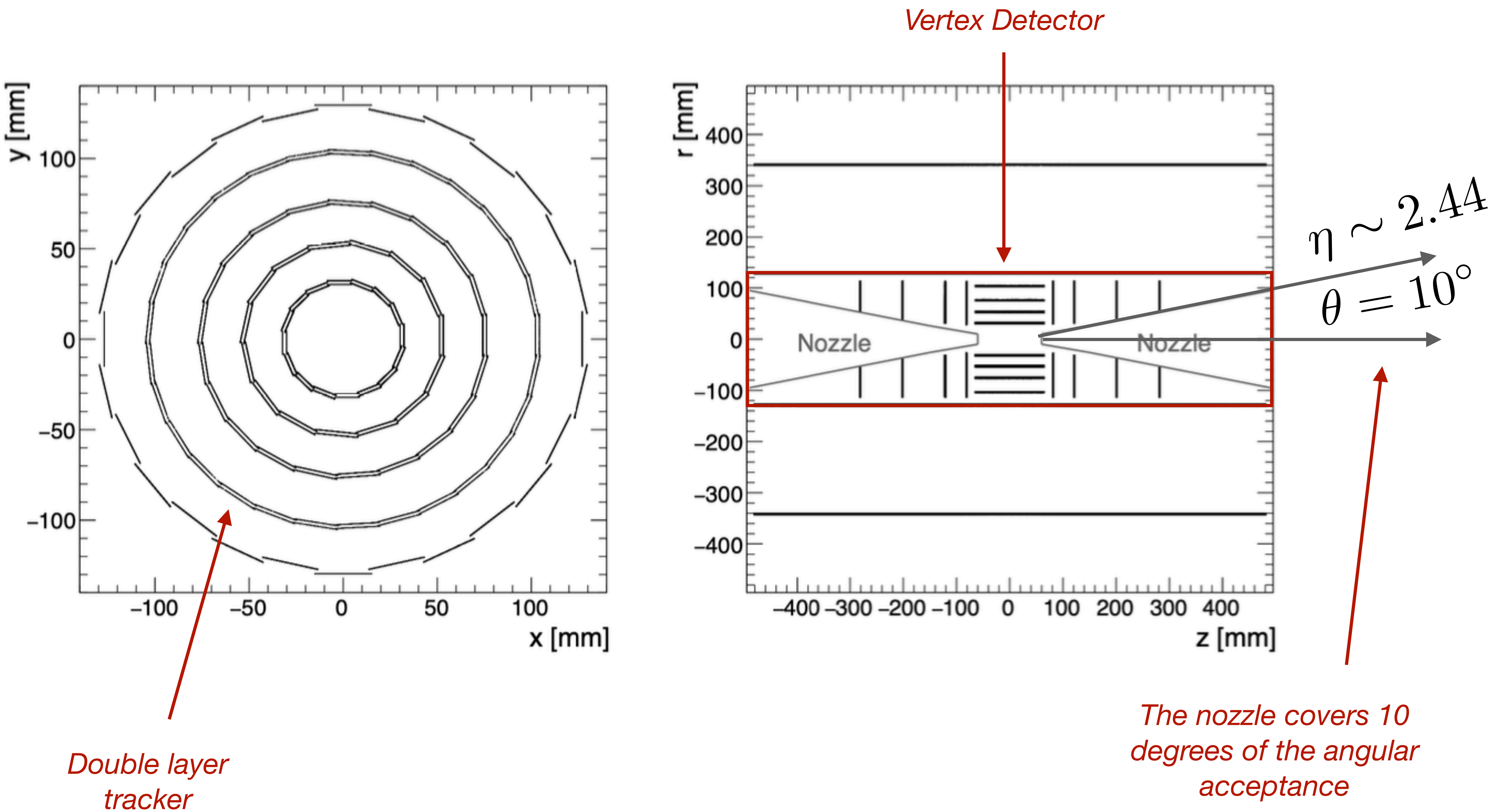


- **Design Adapted from CLIC:**

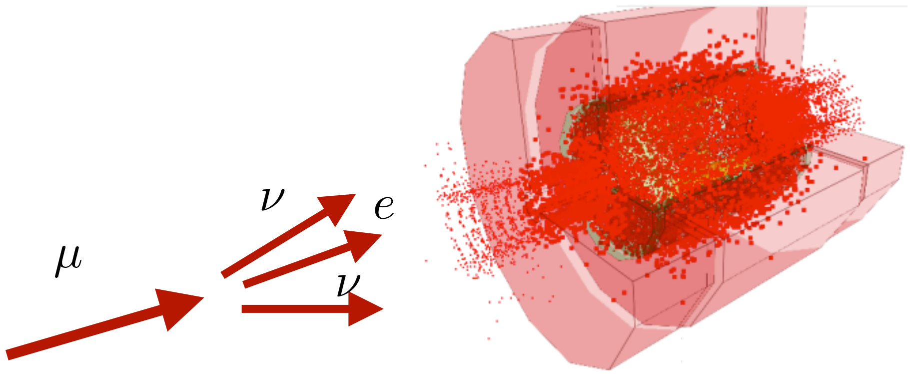


Rodolfo Capdevilla, Fermilab

- **Focus on the Vertex Detector:**

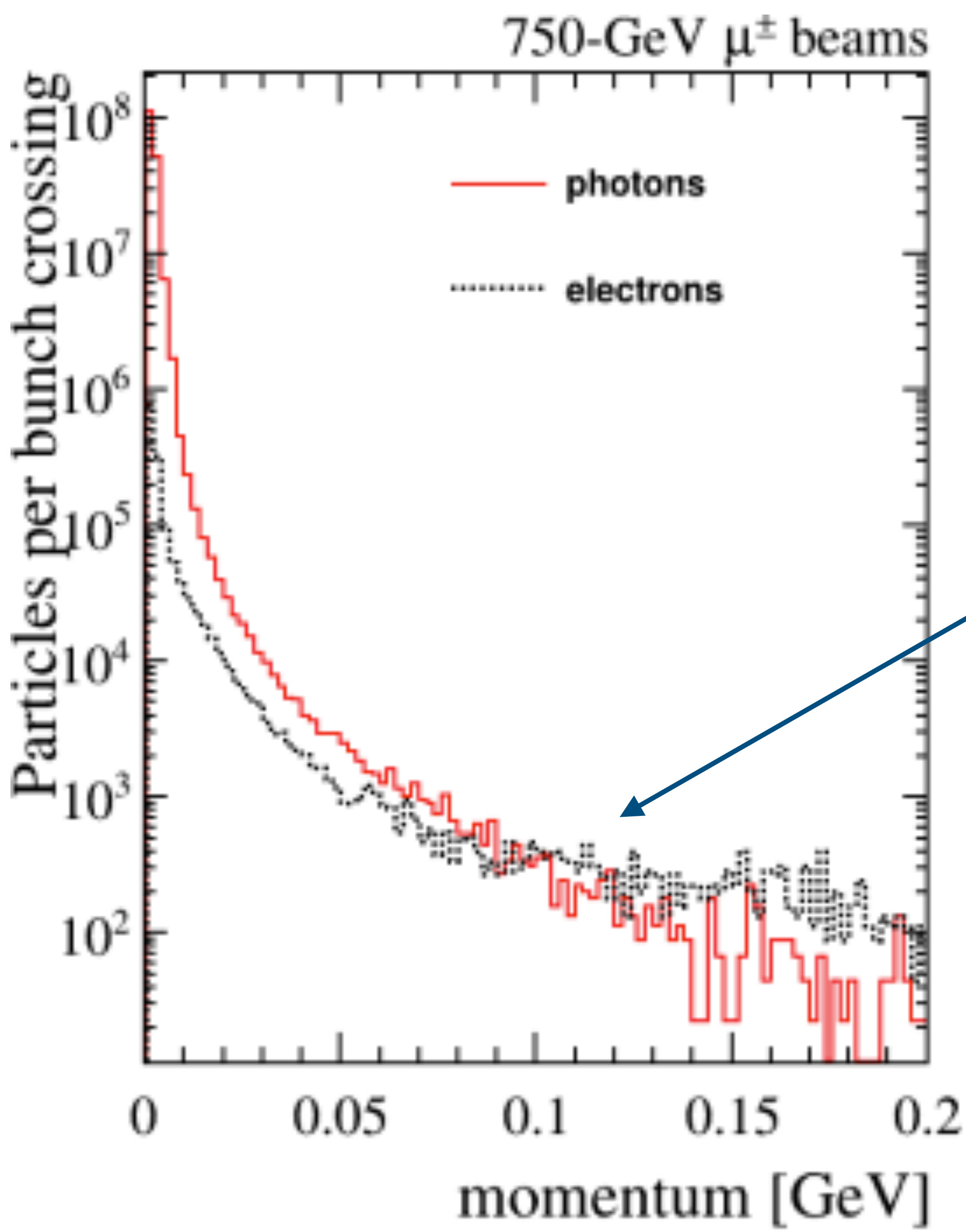


- **BIB:**



1. Soft
2. Arrives late
3. Mostly forward

N. Bartosik et al., 2020 JINST 15 P05001



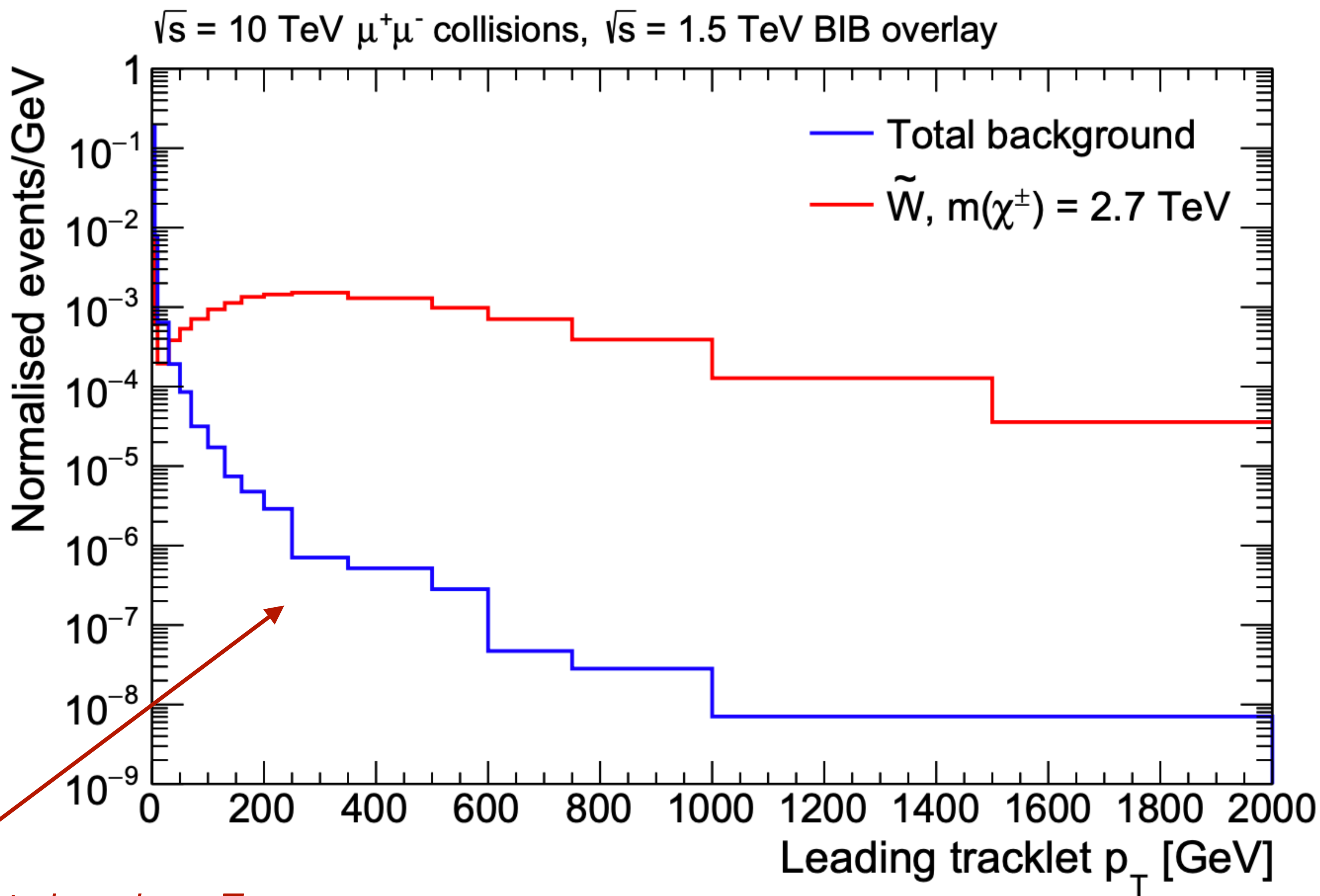
BIB is mainly composed of photons and electrons with a rapidly falling momentum distribution

- **Removing the BIB:**

1. Soft

2. Arrives late

3. Mostly forward



BIB tracklets tend to have low pT

Rodolfo Capdevilla, Fermilab

- **BIB:**

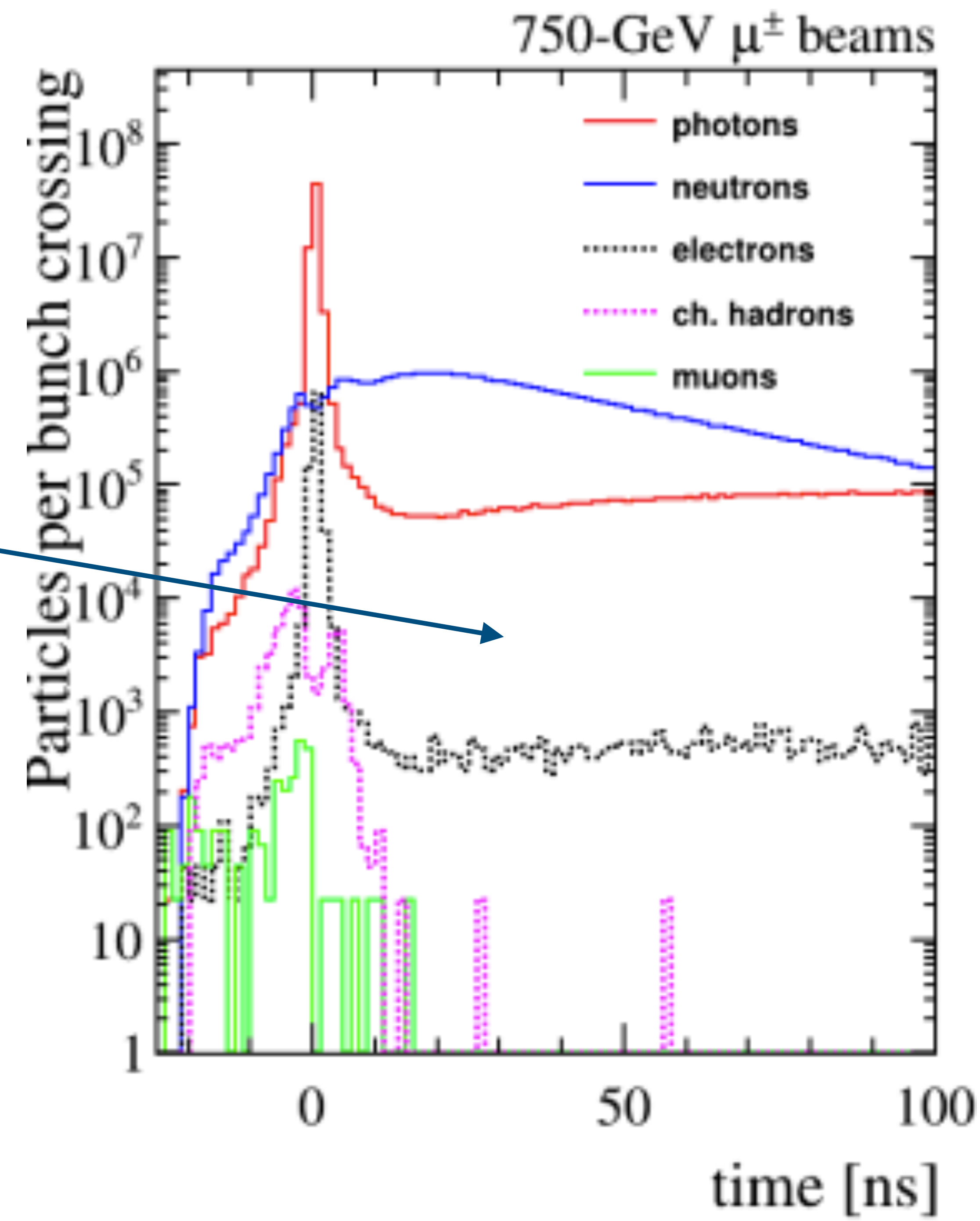
1. Soft

2. Arrives late

3. Mostly forward

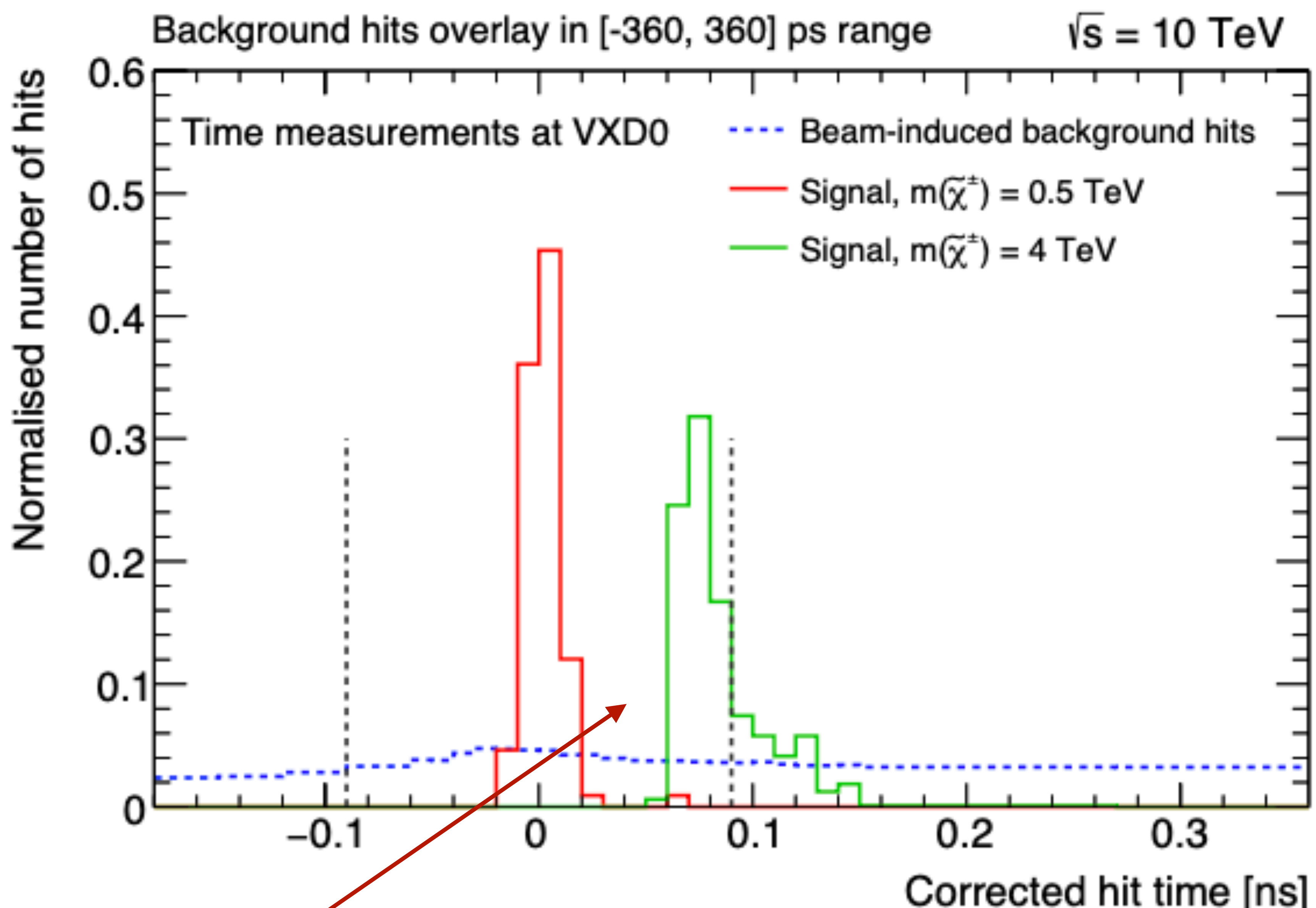
N. Bartosik et al., 2020 JINST 15 P05001

The BIB spreads over a wide range of time



- **Removing the BIB:**

1. Soft
2. Arrives late
3. Mostly forward



For a given mass we choose the appropriate time window!

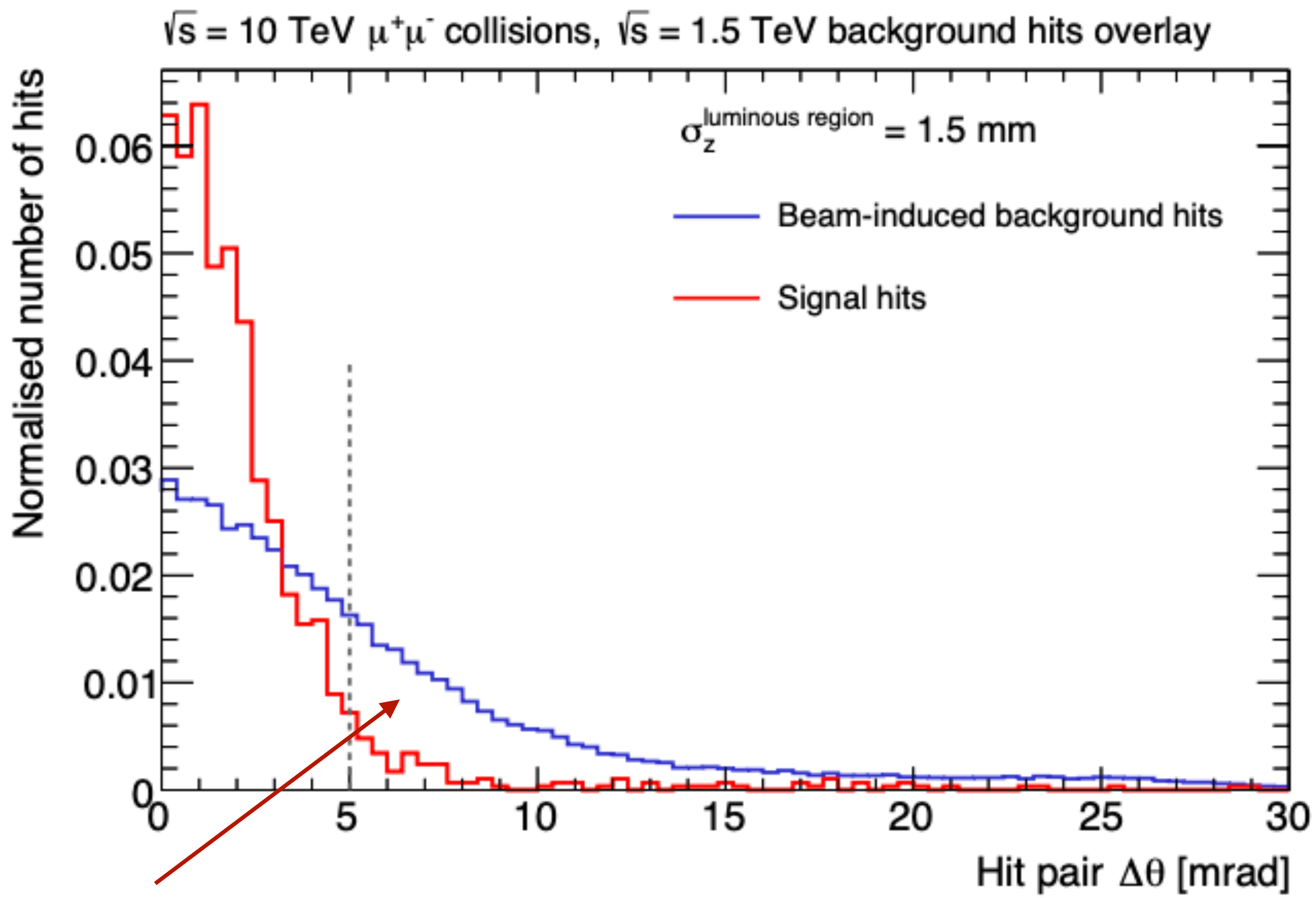
Rodolfo Capdevilla, Fermilab

- **Removing the BIB:**

1. Soft

2. Arrives late

3. Mostly forward



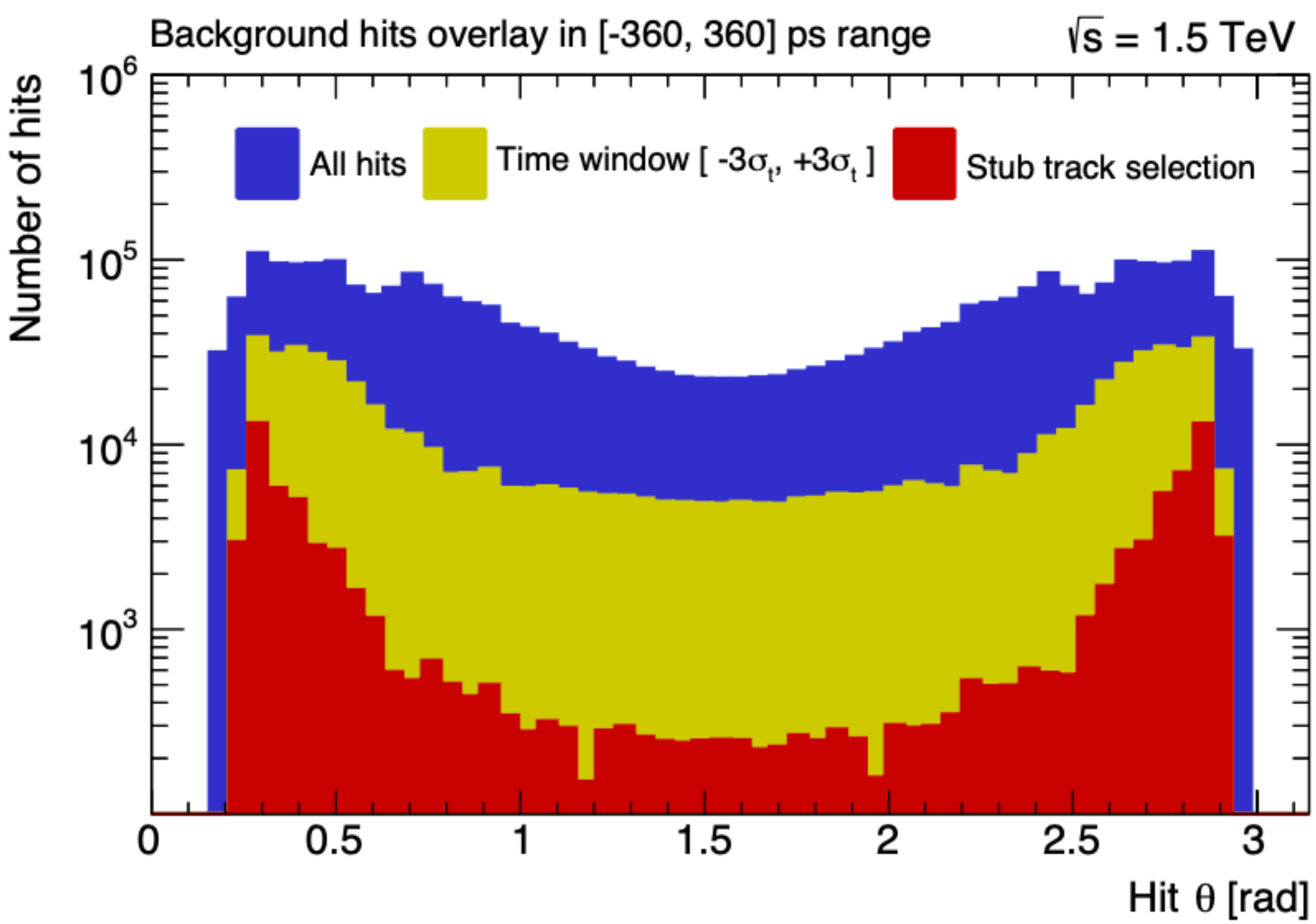
Angle between consecutive tracking layers

- **Removing the BIB:**

1. Soft
2. Arrives late
3. Mostly forward

	SR^{γ}_{1t}	SR^{γ}_{2t}
Total background	187.8 ± 0.6	0.16 ± 0.05
$\tilde{W}$, 2.7 TeV, $\tau = 0.2$ ns	313 ± 5	168 ± 2
$\tilde{H}$, 1.1 TeV, $\tau = 0.02$ ns	53.0 ± 0.7	3.92 ± 0.05

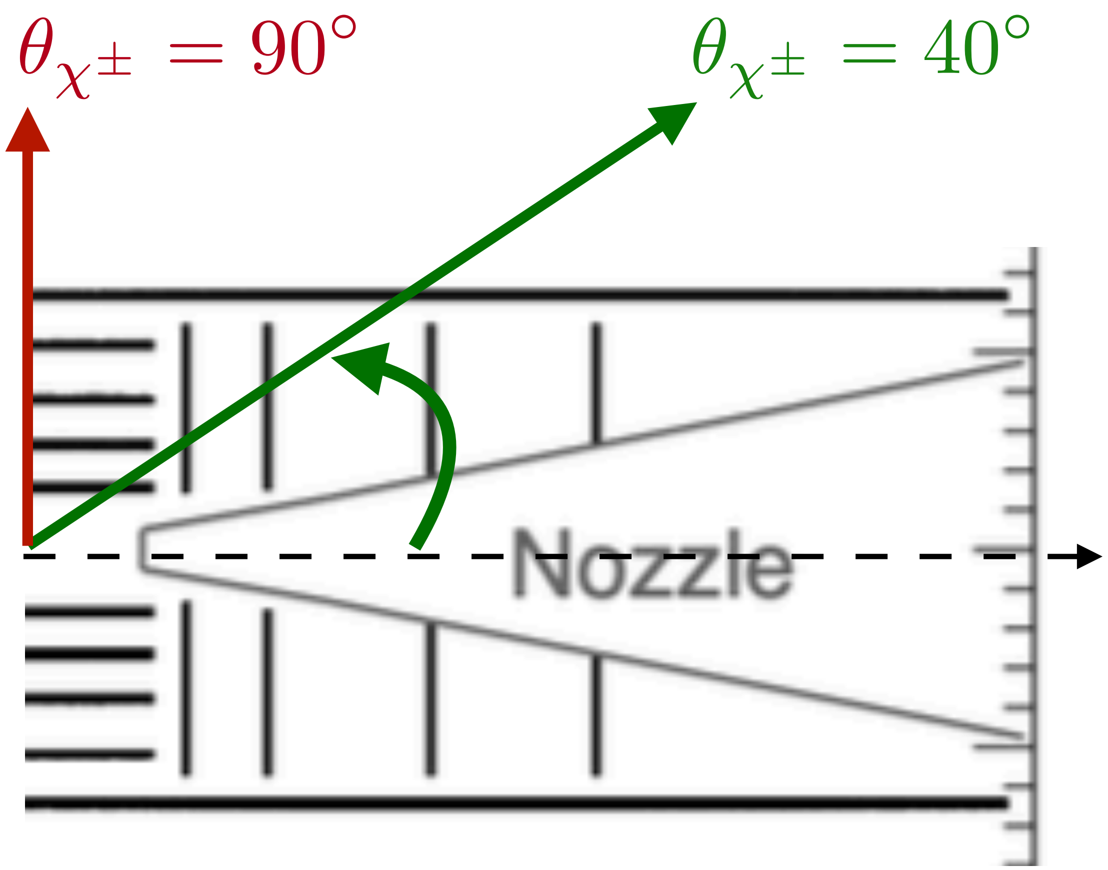
Three orders of magnitude background suppression

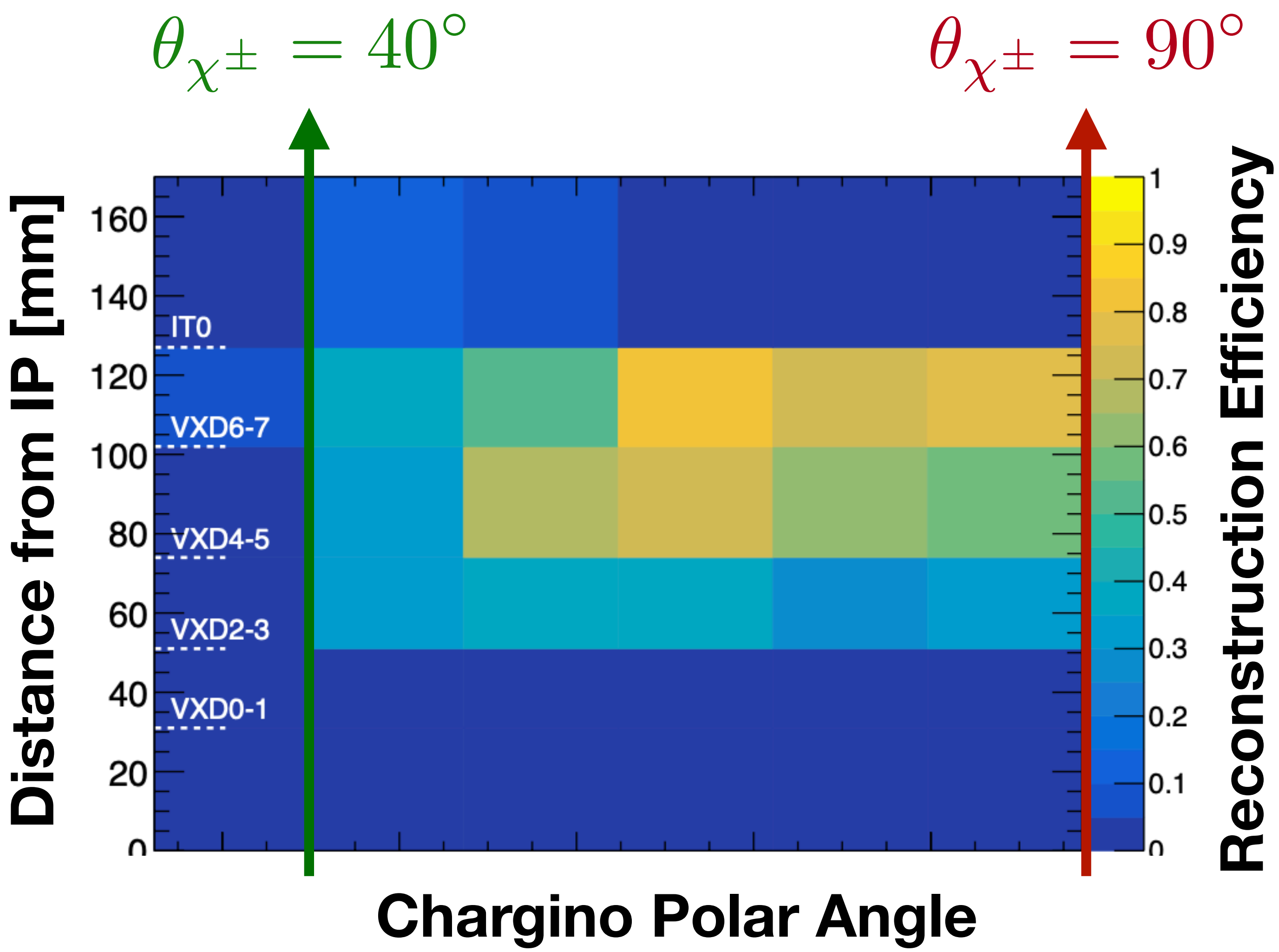


Requirement / Region	SR^{γ}_{1t}	SR^{γ}_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
Photon energy [GeV]	> 25	> 25

- **Efficiency:**

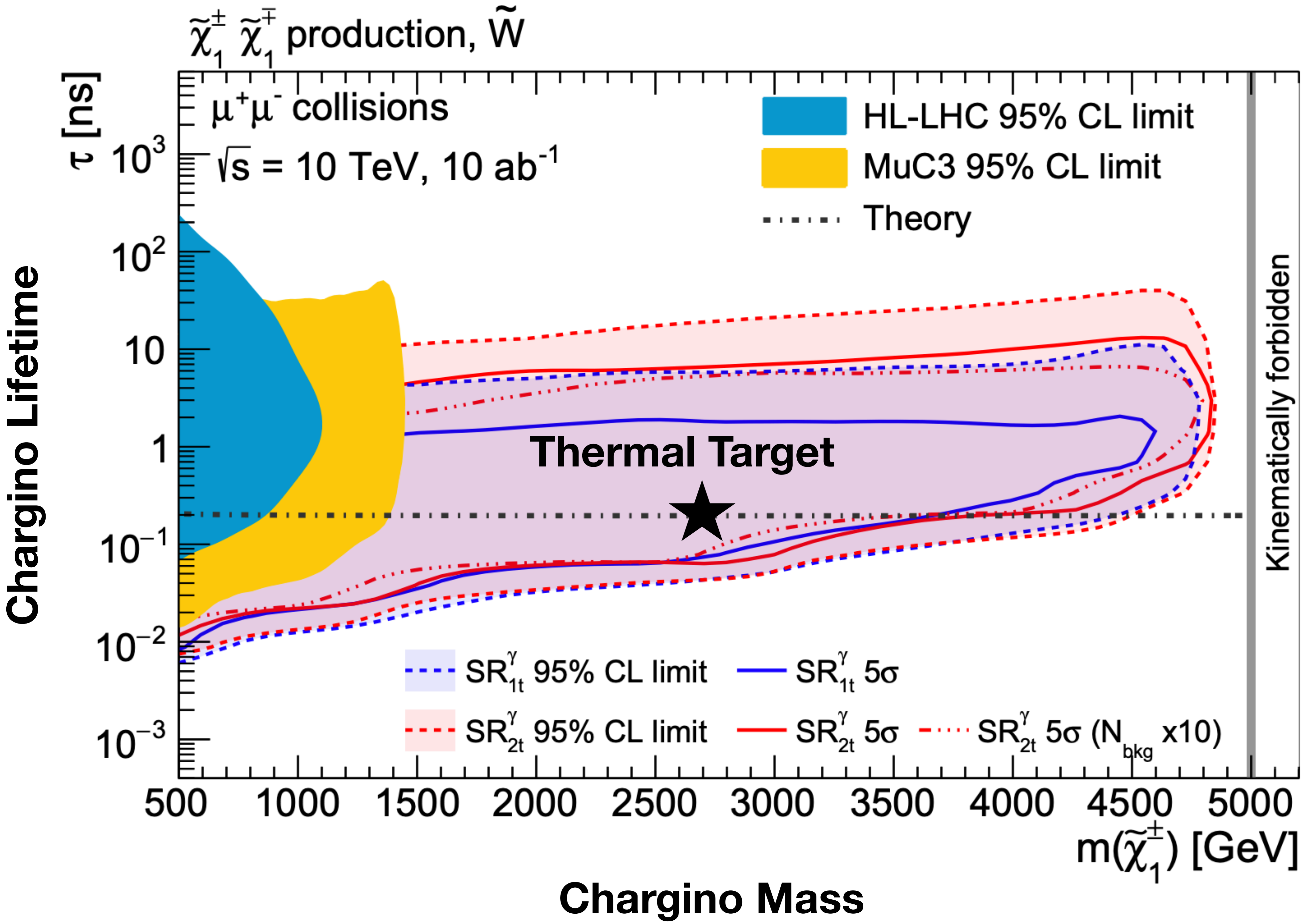
Good signal efficiency ~30-80%





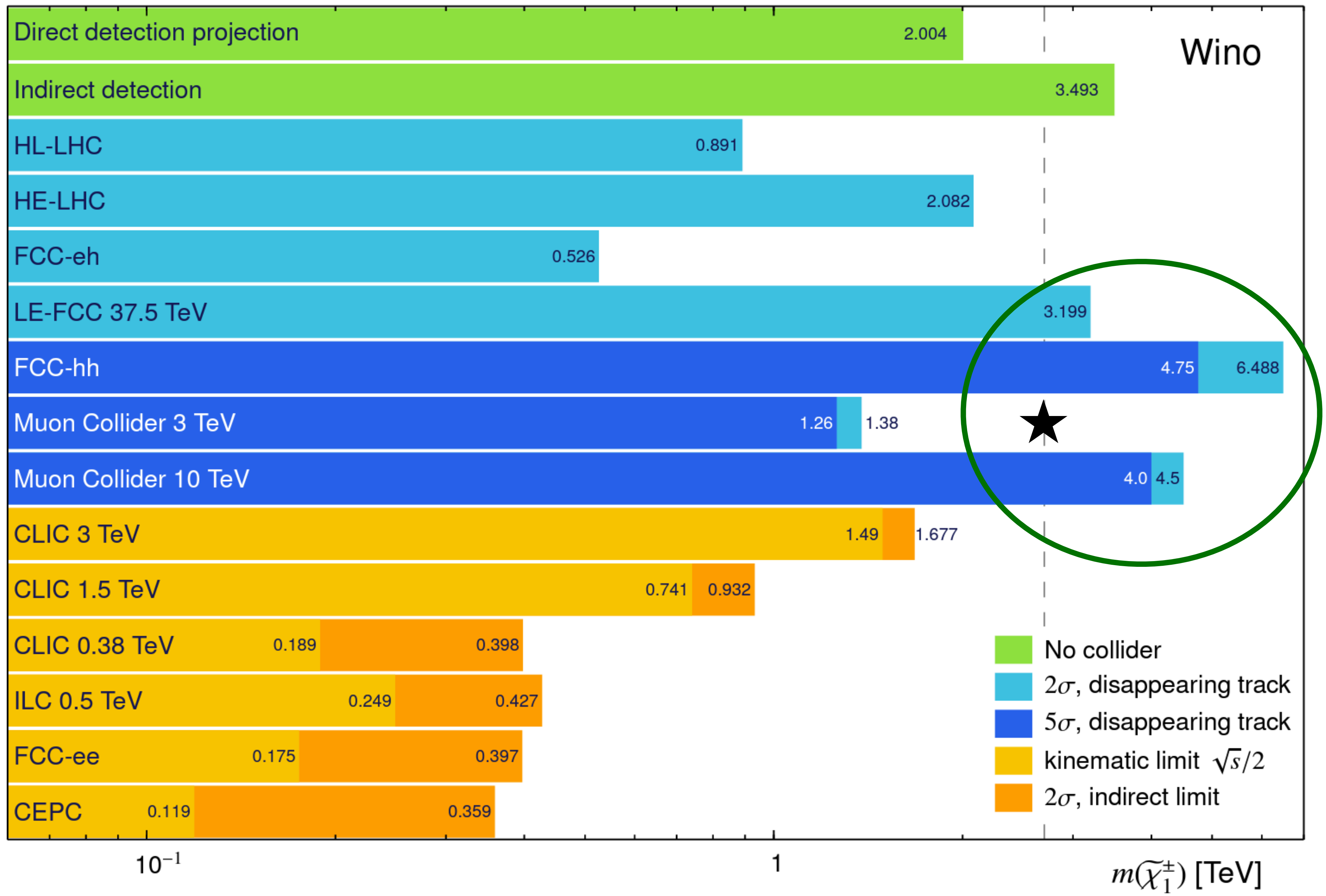
Rodolfo Capdevilla, Fermilab

- **DT Reach: Wino**



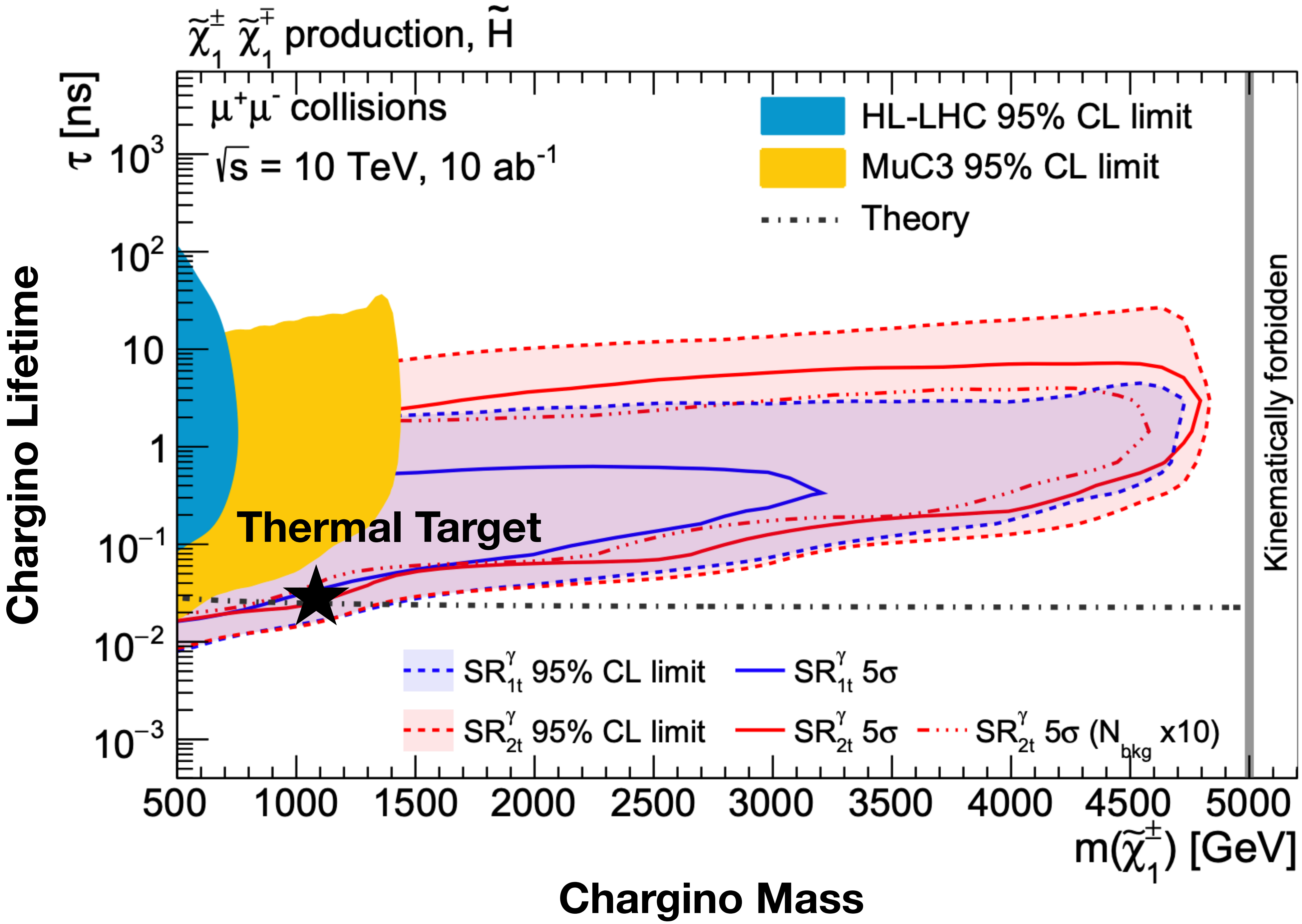
- **DT Reach: Wino**

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



Discovery potential from DT

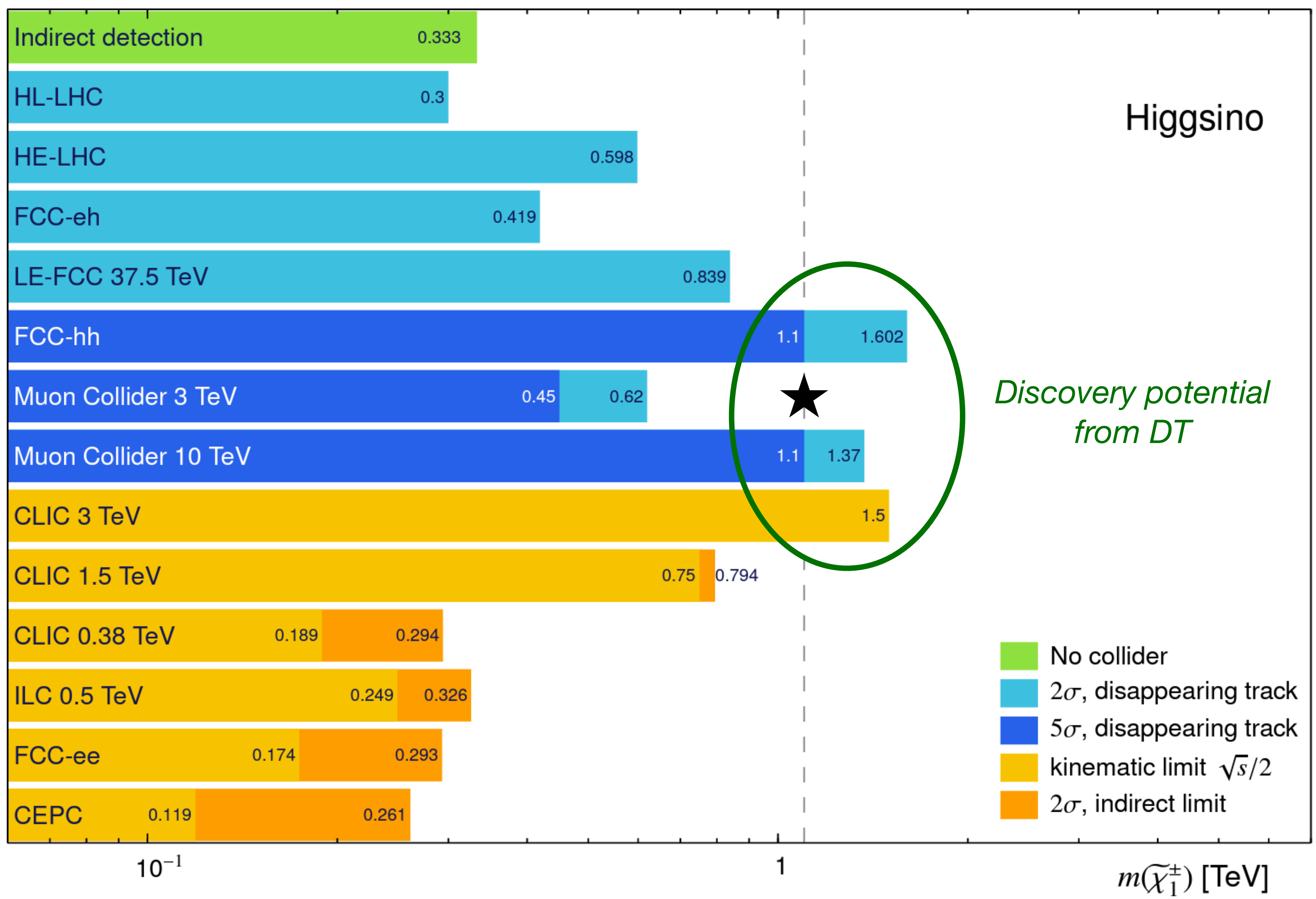
- **DT Reach: Higgsino**



Rodolfo Capdevilla, Fermilab

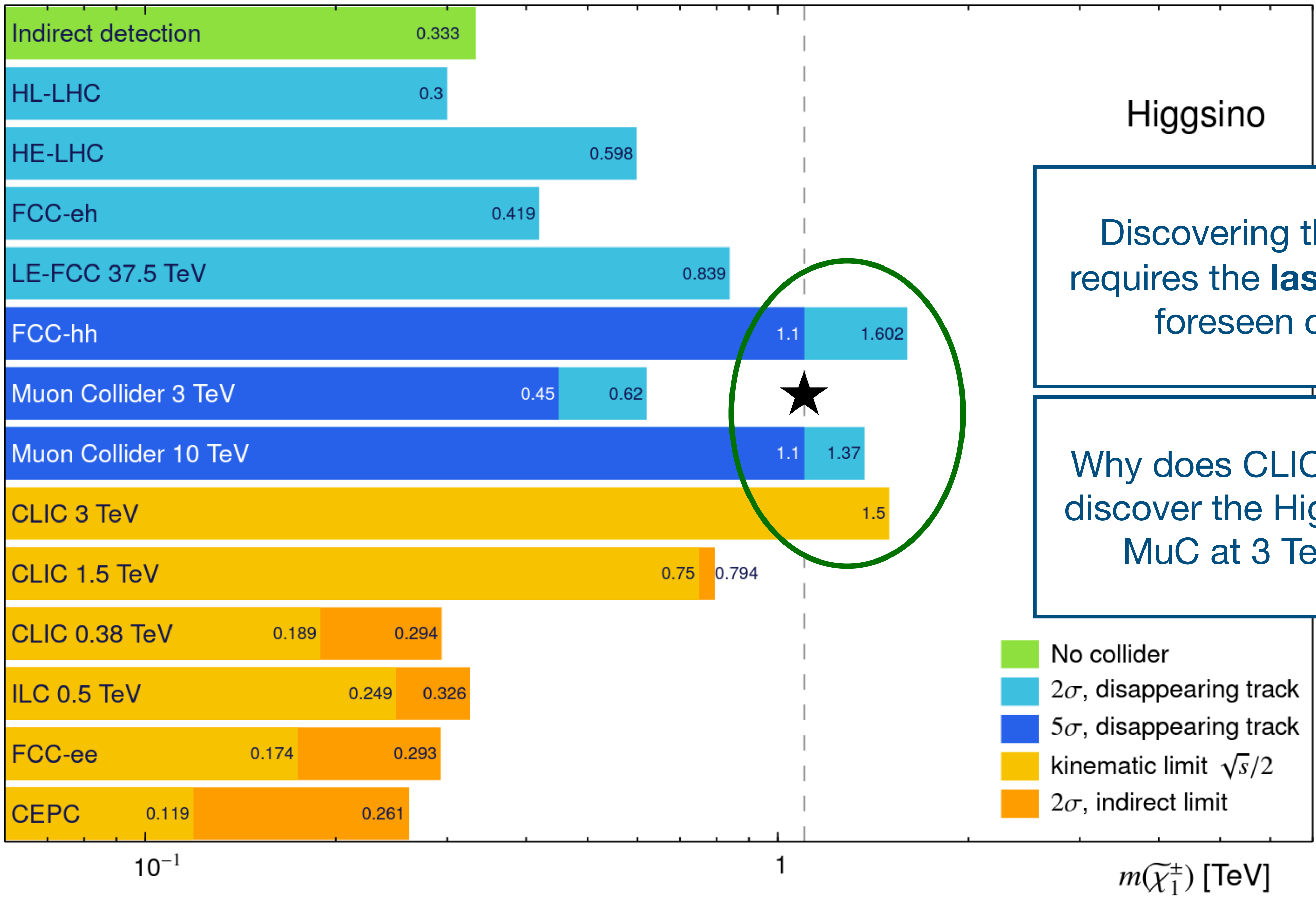
- **DT Reach: Higgsino**

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



- **DT Reach: Higgsino (can we do better?)**

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



Discovering the Higgsino requires the **last** stage of the foreseen colliders!

Why does CLIC at 3 TeV can discover the Higgsino but the MuC at 3 TeV cannot?

- **DT Reach: Higgsino (can we do better?)**

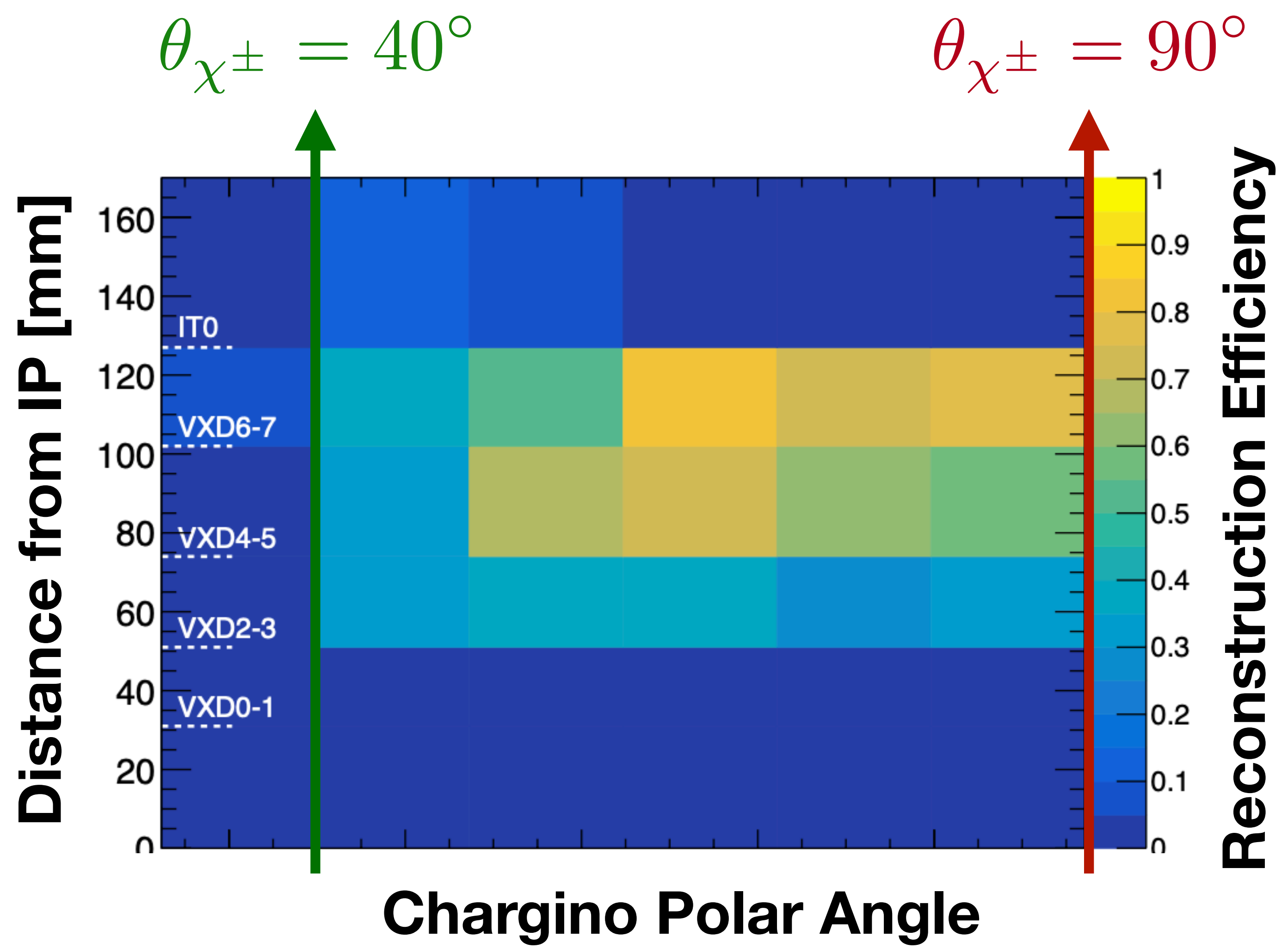
Why does CLIC at 3 TeV can discover the Higgsino but the MuC at 3 TeV cannot?

Doublets (Higgsino-like)

$$\chi_2 \equiv \chi_{\tilde{H}} = \begin{pmatrix} \chi^+_{\tilde{H}} \\ \chi^0_{\tilde{H}} \end{pmatrix}$$

Mass = 1.1 TeV

Lifetime = 0.02 ns



Rodolfo Capdevilla, Fermilab

Outline

1. Introduction
2. Minimal WIMP Searches
    - Direct Detection
    - Indirect Detection
    - LHC
3. Future p/e Colliders
4. Muon Collider
    - Disappearing Tracks
    - **Soft Tracks**

Summary

- **A New Search Strategy: Soft Tracks!**

FERMILAB-PUB-23-0832-T DESY-24-069 APS/123-QED

Discovering Electroweak Interacting Dark Matter at Muon Colliders using Soft Tracks

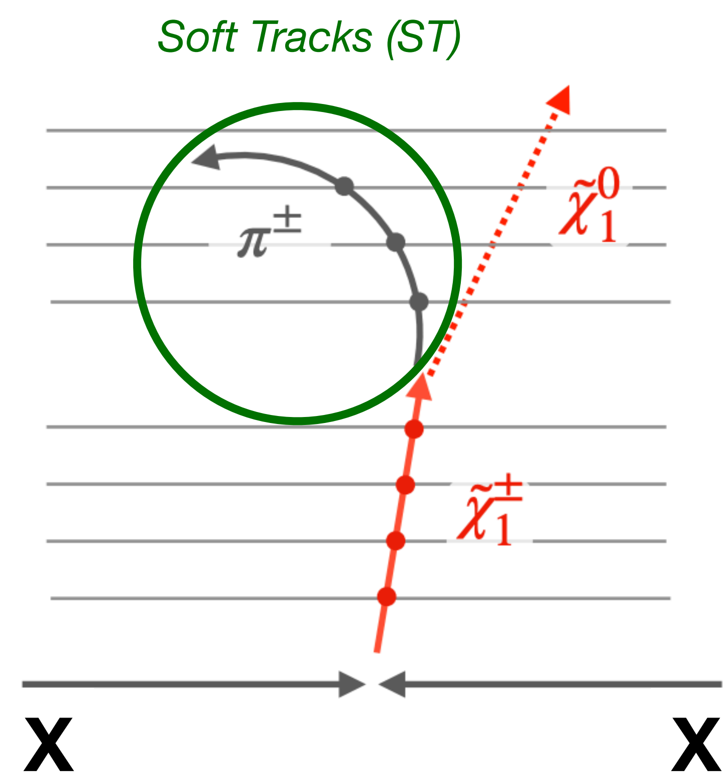
Rodolfo Capdevilla,[1] Federico Meloni,[2] and Jose Zurita[3]

[1] *Particle Theory Department, Fermi National Accelerator Laboratory , Batavia, IL 60510, USA**
[2] *Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*†
[3] *Instituto de Física Corpuscular, CSIC-Universitat de València, Valencia, Spain*‡

(Dated: May 16, 2024)

Focus on:

1. **Higgsino Thermal Target**
2. **Muon Collider 3 TeV**



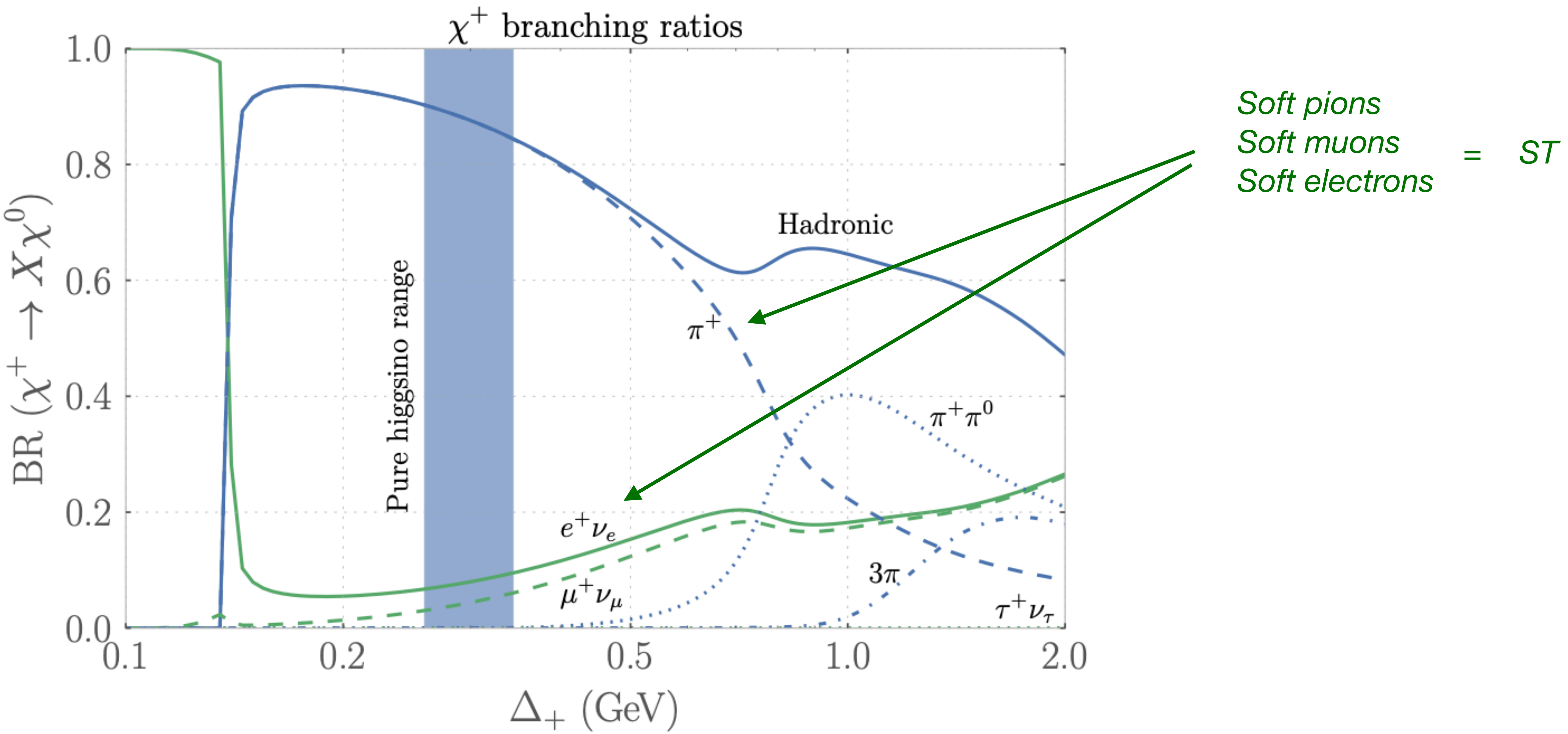
Federico Meloni, DESY

Jose Zurita, U. Valencia

***RC**, Federico Meloni, Jose Zurita, arXiv:2405.08858*

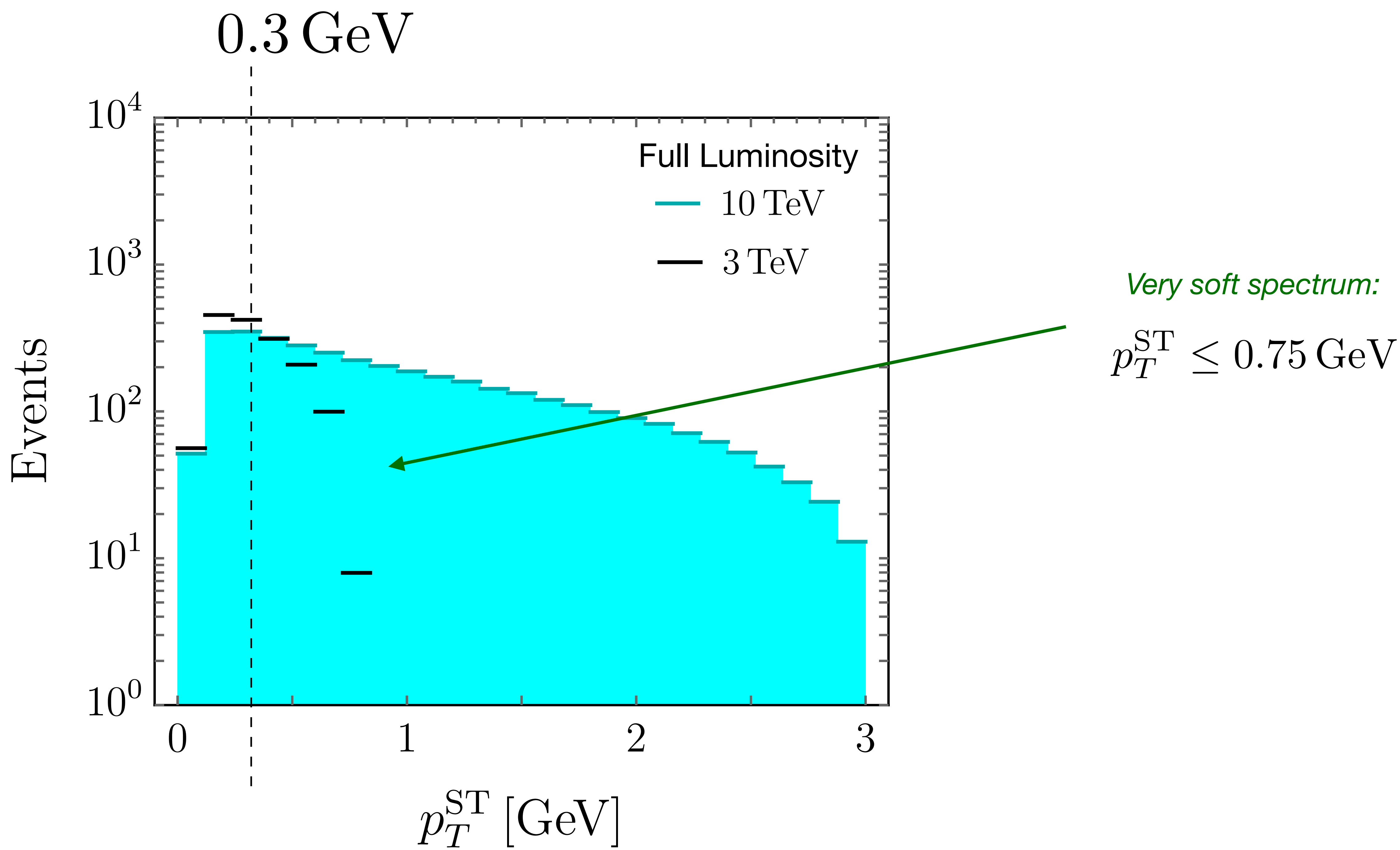
- **Focus on Higgsinos:**

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



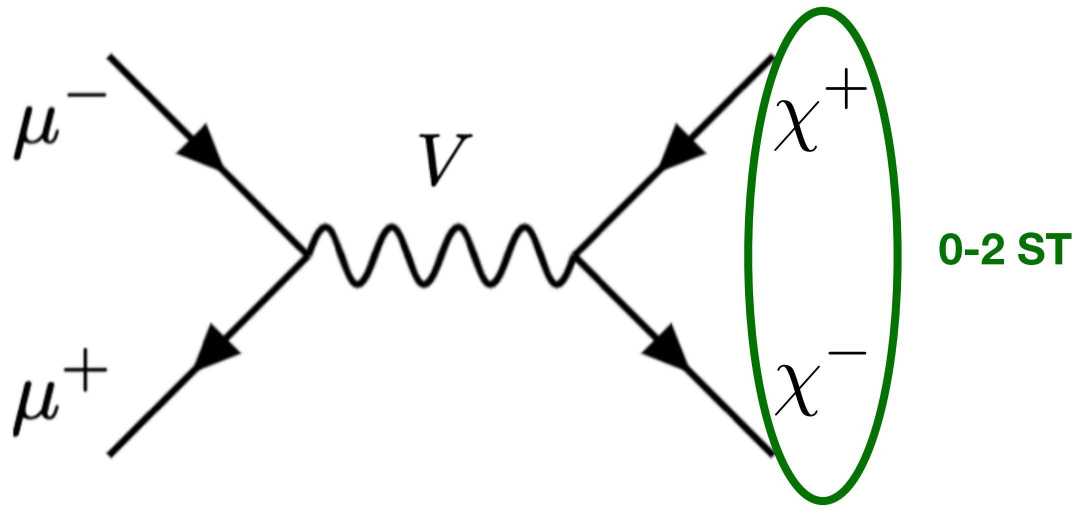
R. Mahbubani, P. Schwaller, J. Zurita, JHEP 06 (2017) 119

- **Focus on the 3 TeV Collider:** $\mathcal{L} = 1\,\mathrm{ab}^{-1}$

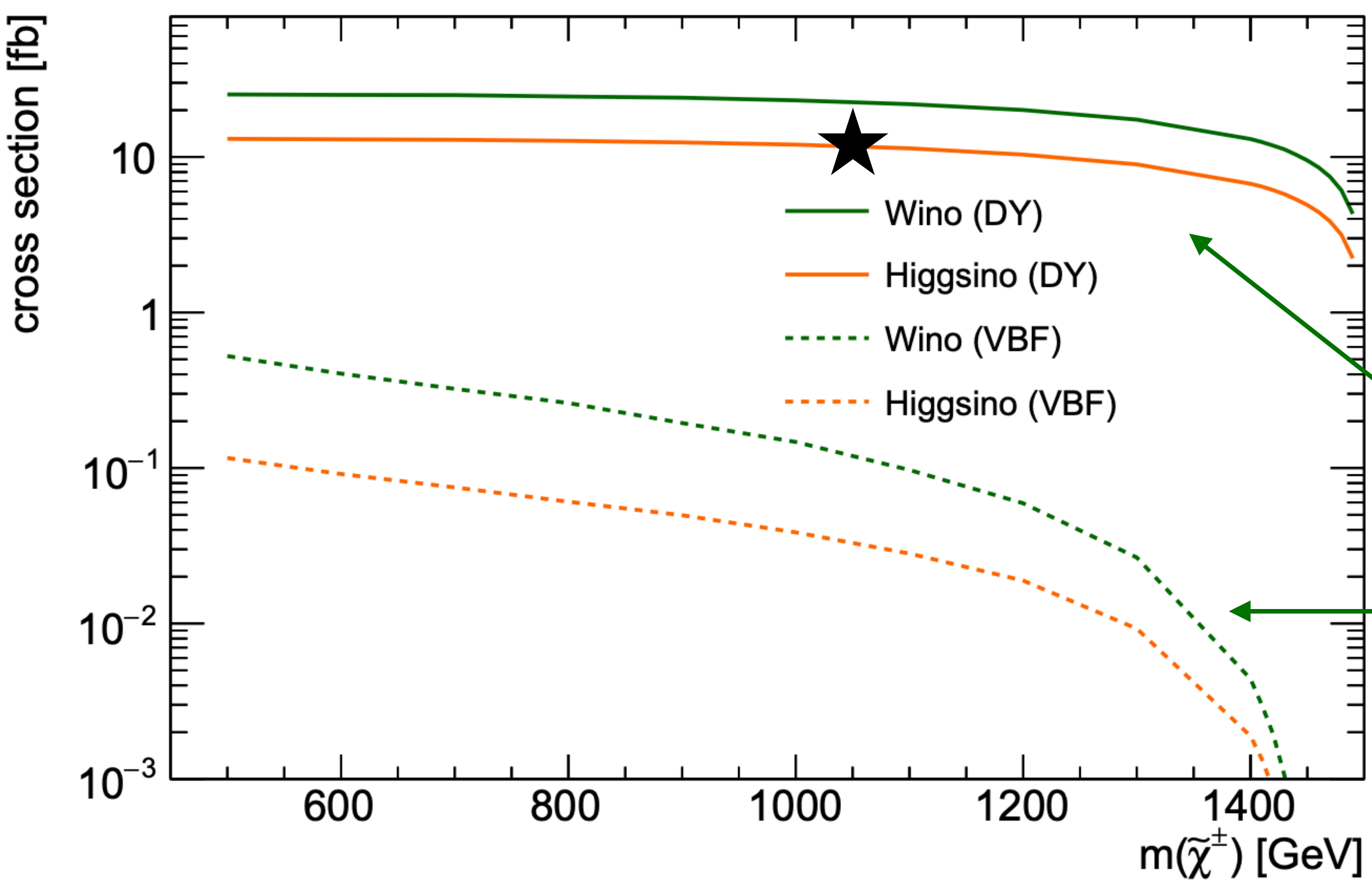


Rodolfo Capdevilla, Fermilab

- **Signal Events:**



MuC 3 TeV



xsec = 10 fb
Lumi = 1/ab
Nevents = 10,000

s-chanel neutral current process dominates signal production over VBF

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

- **Signal Events:**

MuC 3 TeV

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

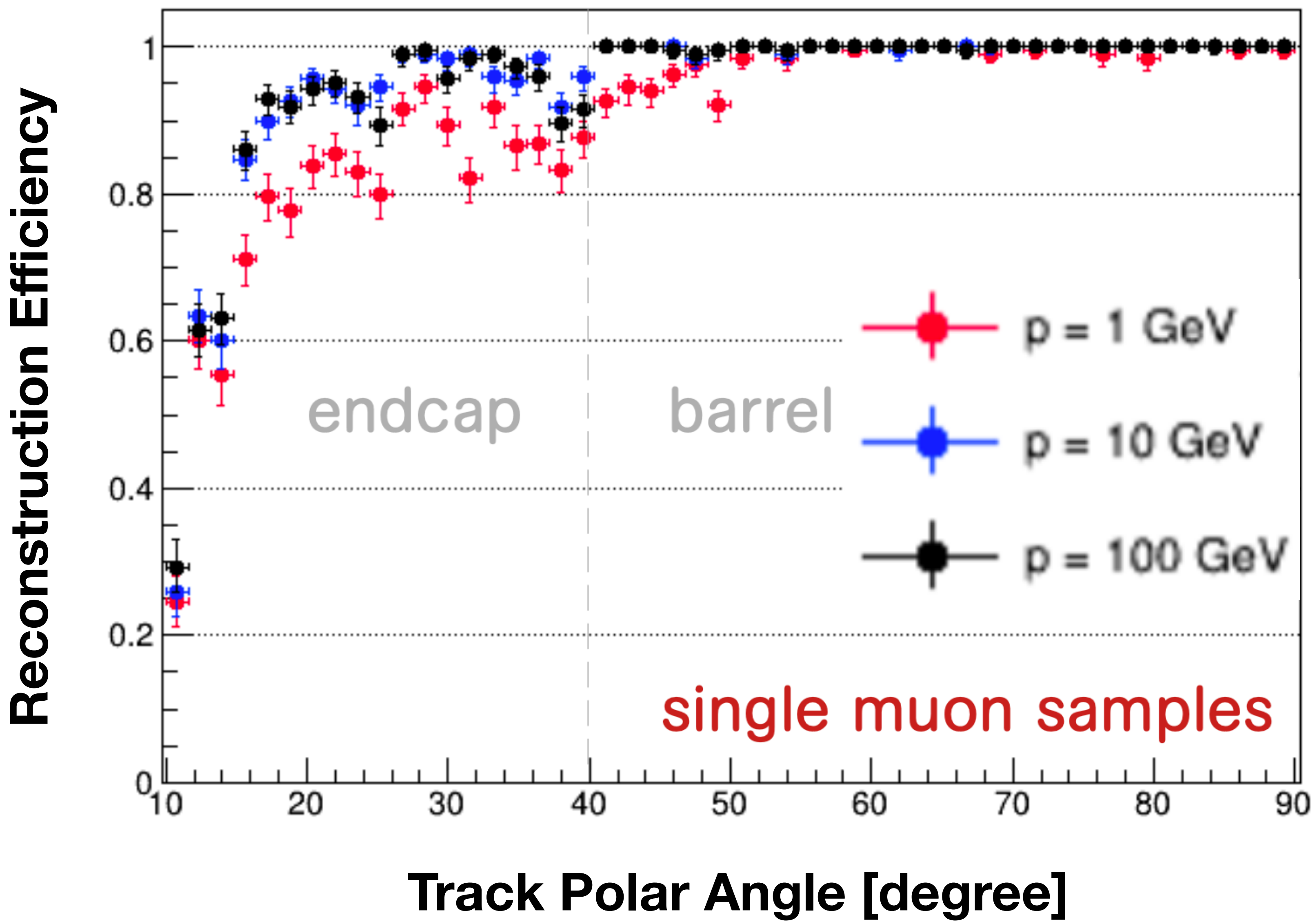
*About **1,000** signal events in this signal region*

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

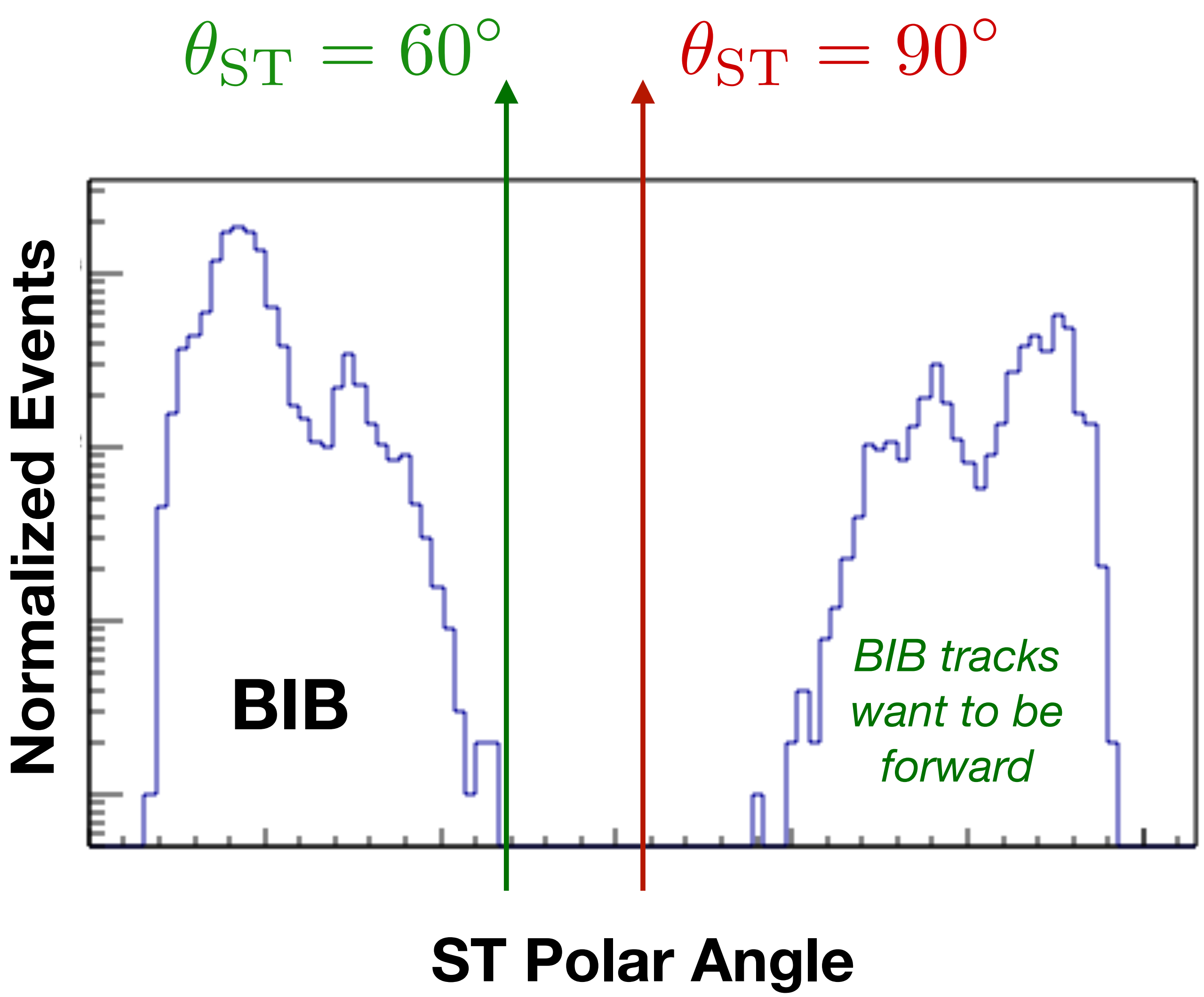
- **Backgrounds: BIB (efficiency)**

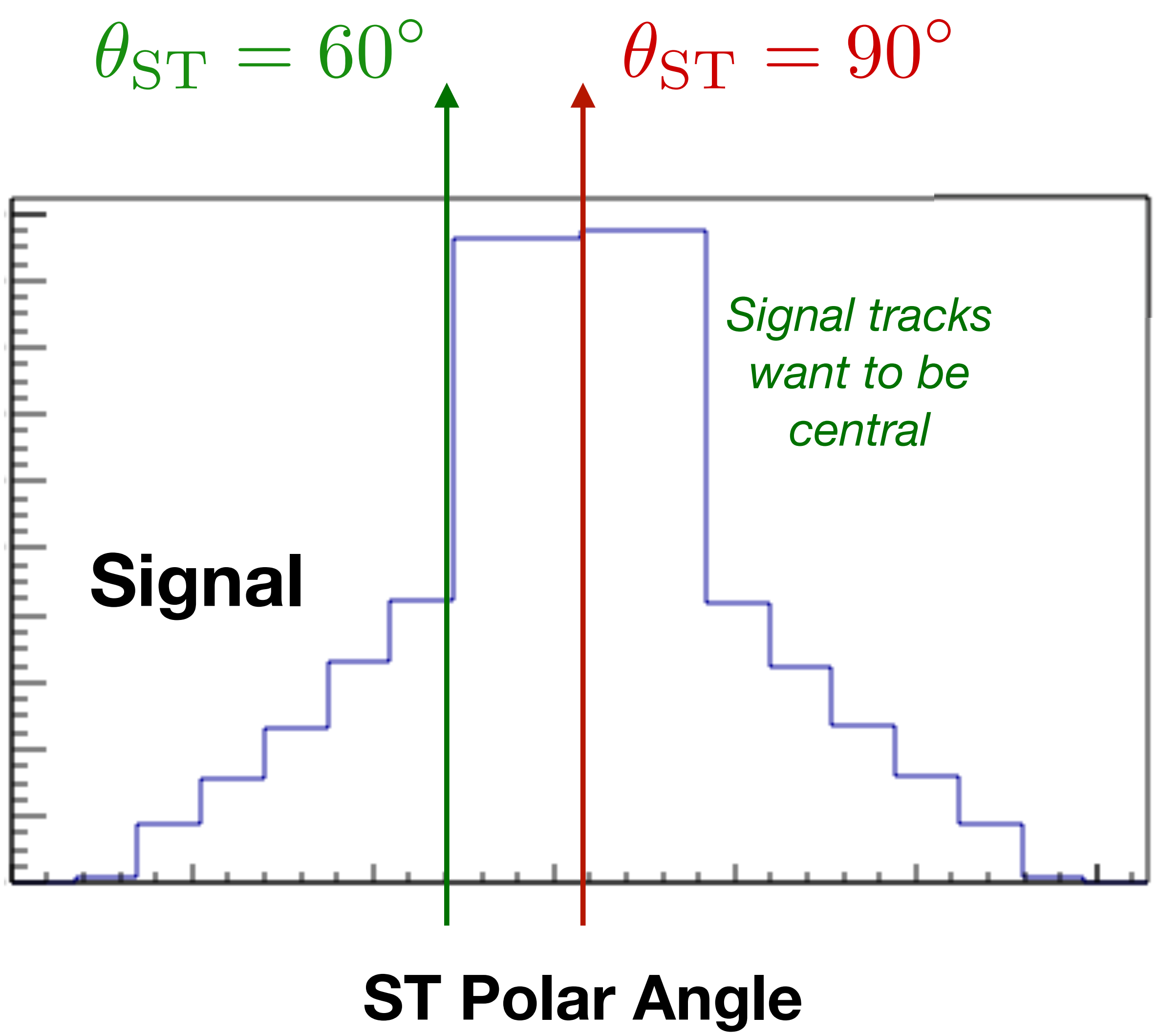
BIB Data from the MAP collaboration

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



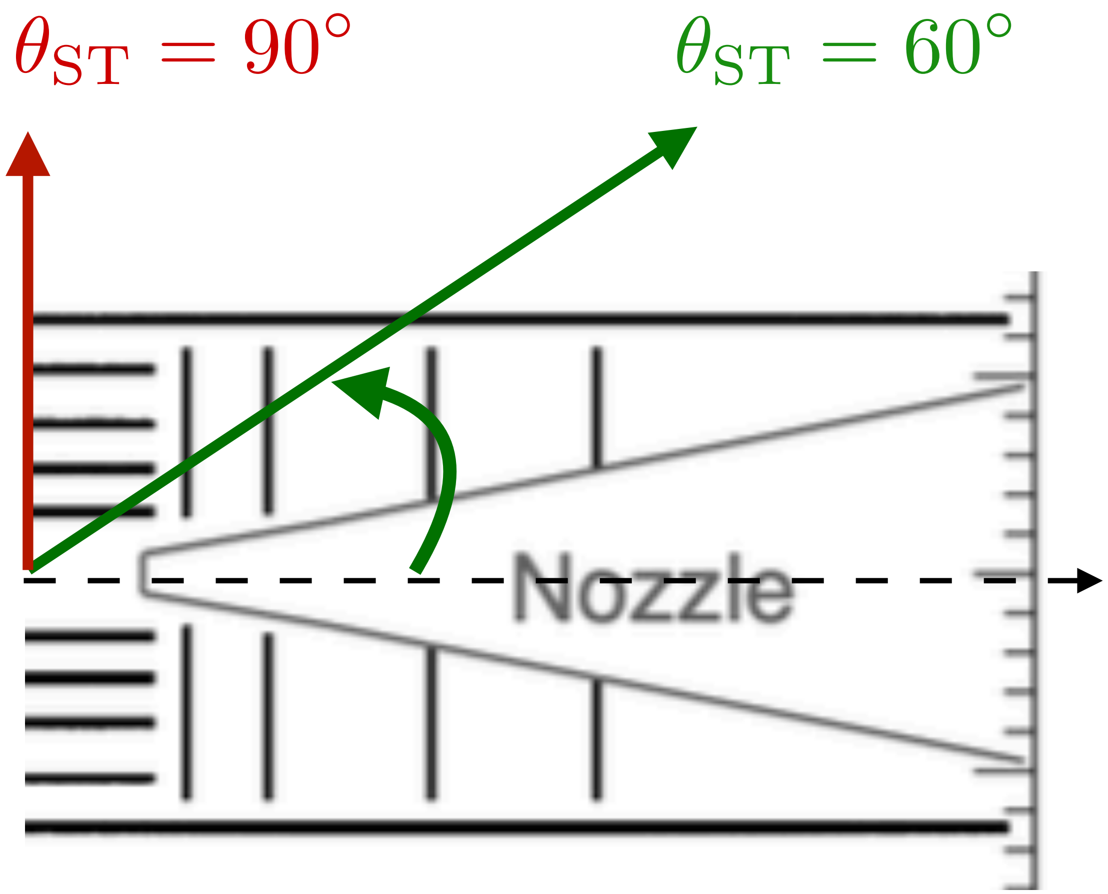
- **Backgrounds: BIB (fake tracks)**

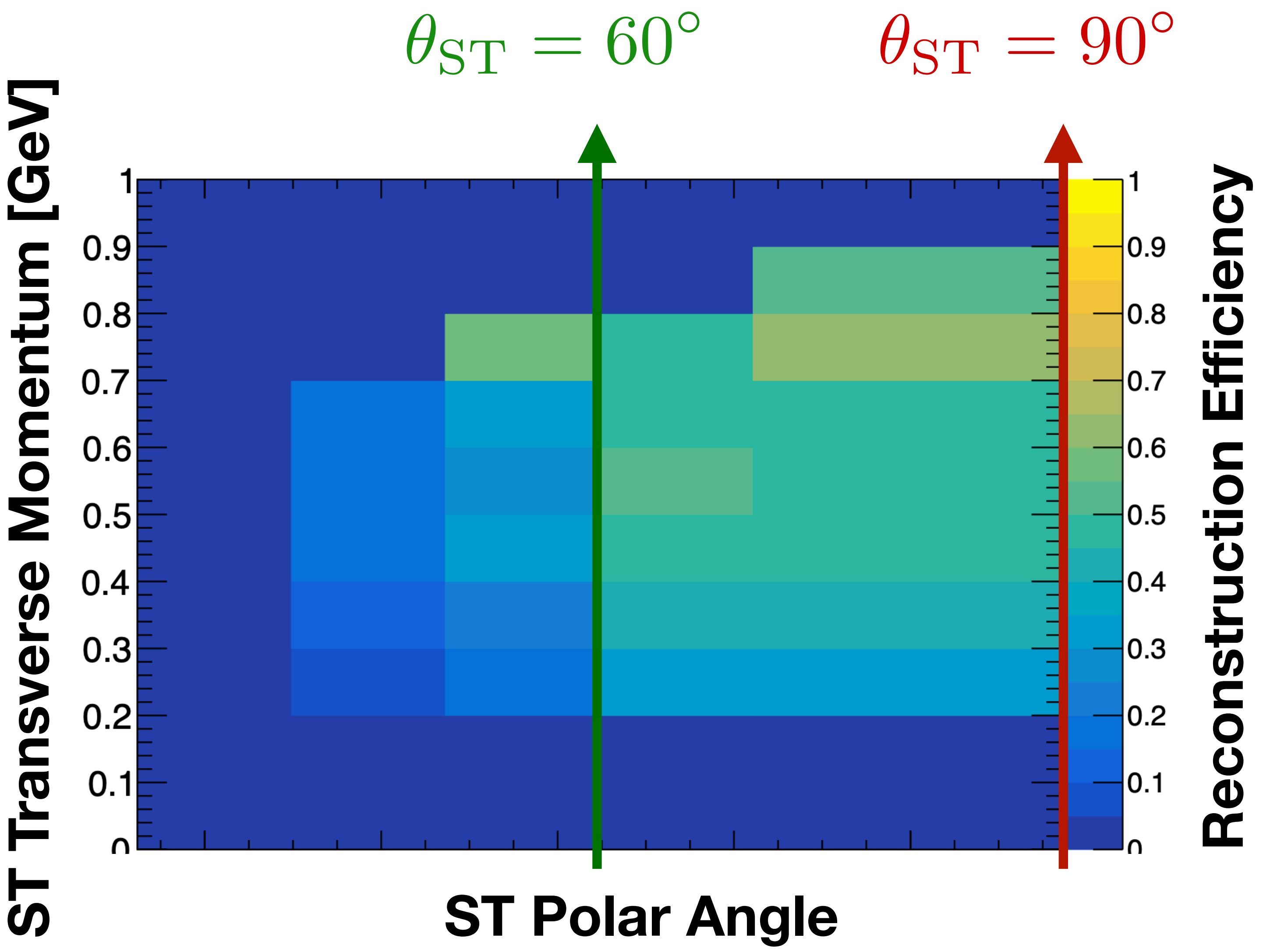




- **Efficiency:**

Decent reconstruction efficiency ~30-60%



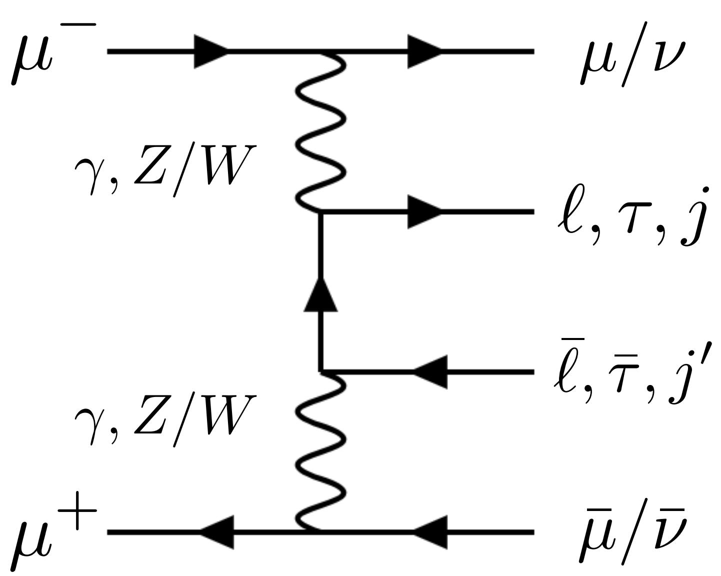


Rodolfo Capdevilla, Fermilab

- **Background Processes:**

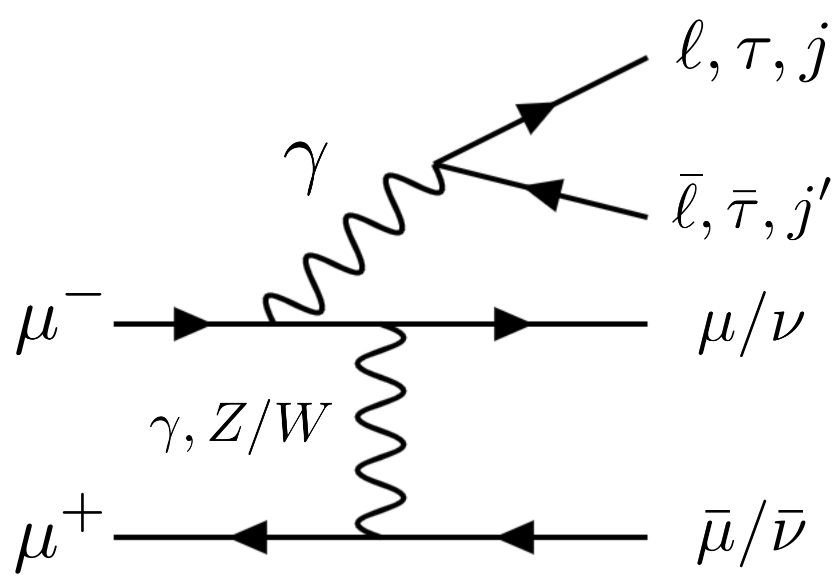
VBF & Bhabha-like processes
dominate background production

Vector Boson Fusion



Soft Tracks

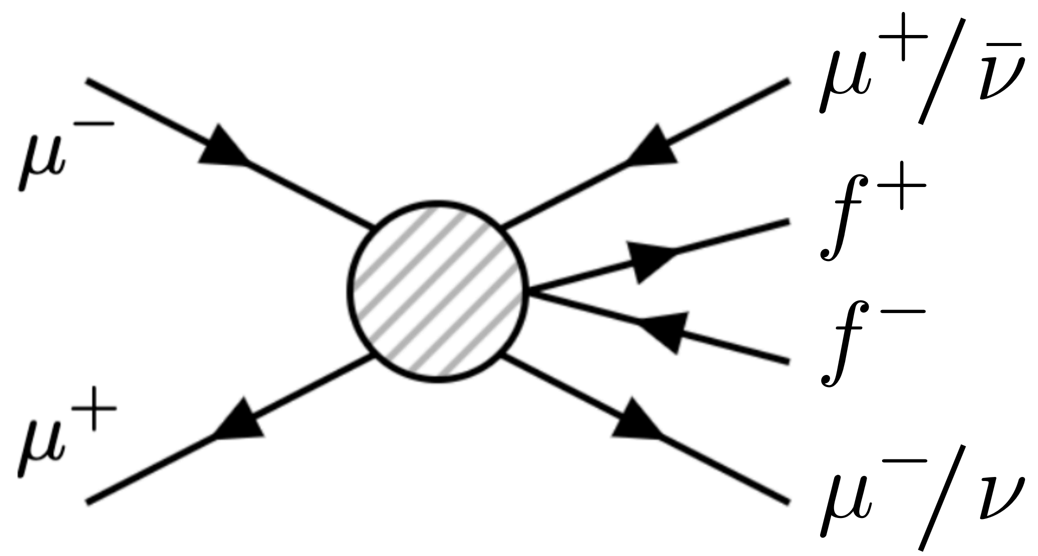
Bhabha-Like Scattering



Soft Tracks

- **Background Processes:**

VBF & Bhabha-like processes dominate background production



$$f = \ell, \tau, j$$

$\mu^+\mu^- \to \gamma + \text{X} \; (+Z \to \nu\nu)$		
X	$\sigma(\gamma\text{X})$ [fb]	$\sigma(\gamma\text{X}Z)$ [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

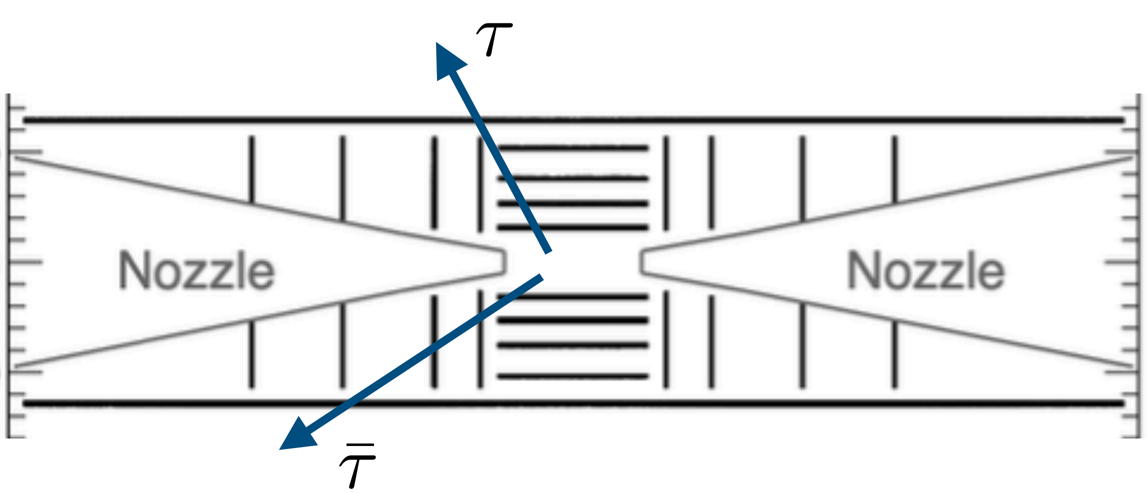
$$p_T^\gamma \geq 20 \text{ GeV}$$
$$|\eta_\gamma| < 2.44$$

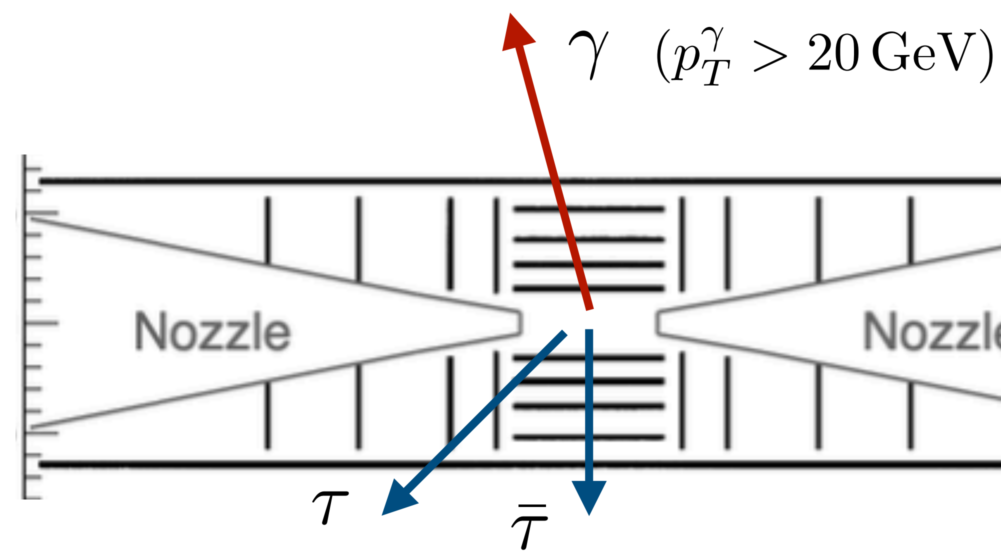
$$p_T^\ell \geq 0.1 \text{ GeV}$$
$$p_T^j \geq 0.1 \text{ GeV}$$

Compare with the ~1fb signal

- **The Importance of the Photon:**

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



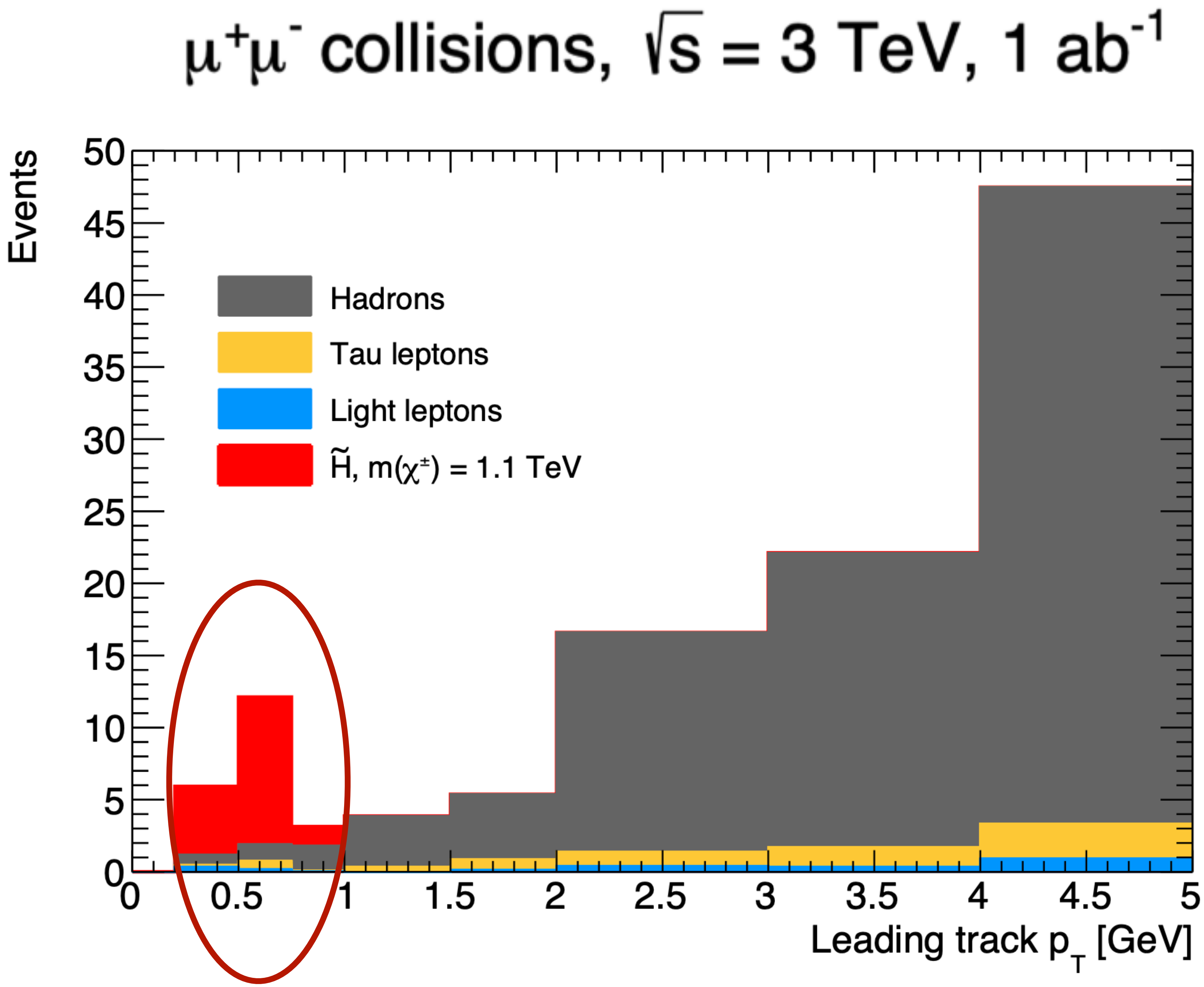


$$N_{\text{signal}} \sim 9000$$
$$N_{\text{background}} \sim 10^3 \times N_{\text{signal}}$$

$$N_{\text{signal}} \sim 2000$$
$$N_{\text{background}} \sim 6000$$

Note: Considering di-tau production using the improved Weizsäcker-Williams approximation for the photon PDF.

- **Projection:**



Five sigma+ for the Thermal Higgsino (Doublet MDM)

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

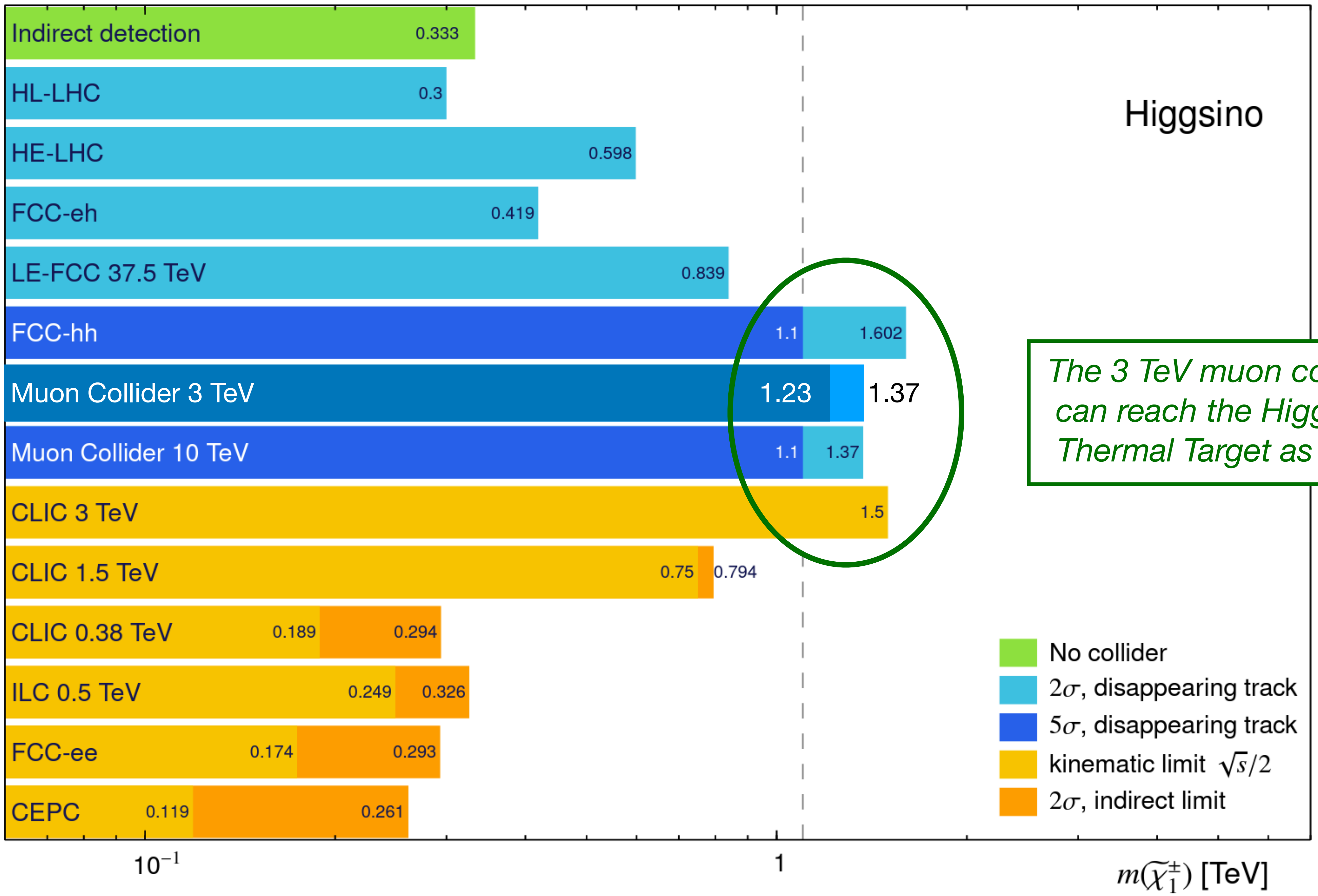
Photon pT above 40 GeV

Fakes:

Pairs of ST along with an uncorrelated photon

Random ECAL hits from the BIB that can mimic a photon

- **Projection:**



The 3 TeV muon collider can reach the Higgsino Thermal Target as well.

Outline

1. Introduction
2. Minimal WIMP Searches
   - Direct Detection
   - Indirect Detection
   - LHC
3. Future p/e Colliders
4. Muon Collider
   - Disappearing Tracks
   - Soft Tracks

Summary

- **Thermal Targets**

$$\chi_{\mathbf{2}} \equiv \chi_{\tilde{H}} = \begin{pmatrix} \chi^{+}_{\tilde{H}} \\ \chi^{0}_{\tilde{H}} \end{pmatrix}, \quad \chi_{\mathbf{3}} \equiv \chi_{\tilde{W}} = \begin{pmatrix} \chi^{+}_{\tilde{W}} \\ \chi^{0}_{\tilde{W}} \\ \chi^{-}_{\tilde{W}} \end{pmatrix} \ldots \quad \chi_{\mathbf{5}} \ldots \quad \chi_{\mathbf{9}} \ldots$$

	Doublets (Higgsino-like)	*Triplets (Wino-like)*	*Fiveplets…*	*Nineplets…*
Mass:	1.1 TeV	2.7 TeV	14 TeV	
Lifetime:	0.02 ns	0.2 ns	0.2 ns	

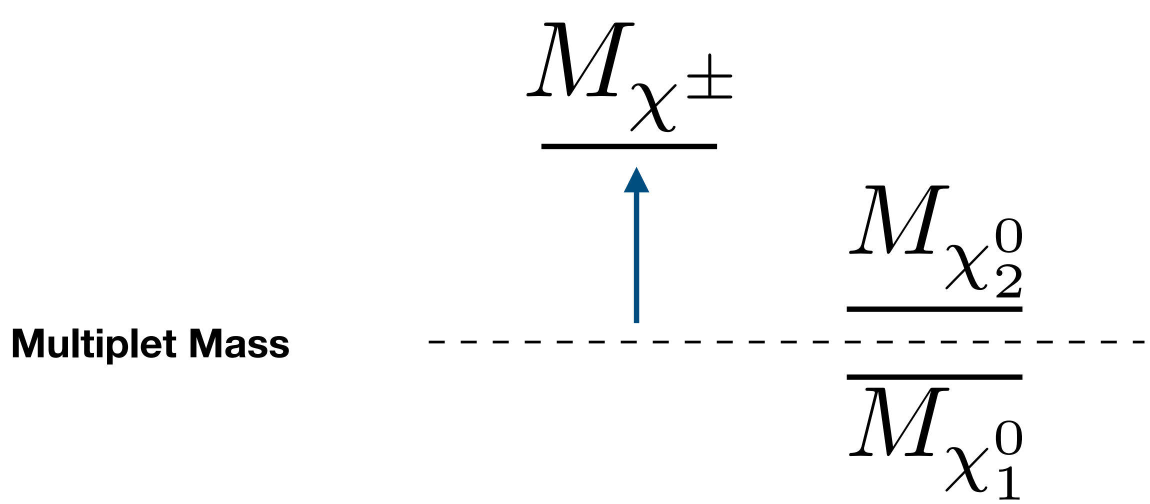
• Lifetime

For a given multiplet

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

Loop effects generate chargino-neutralino splitting

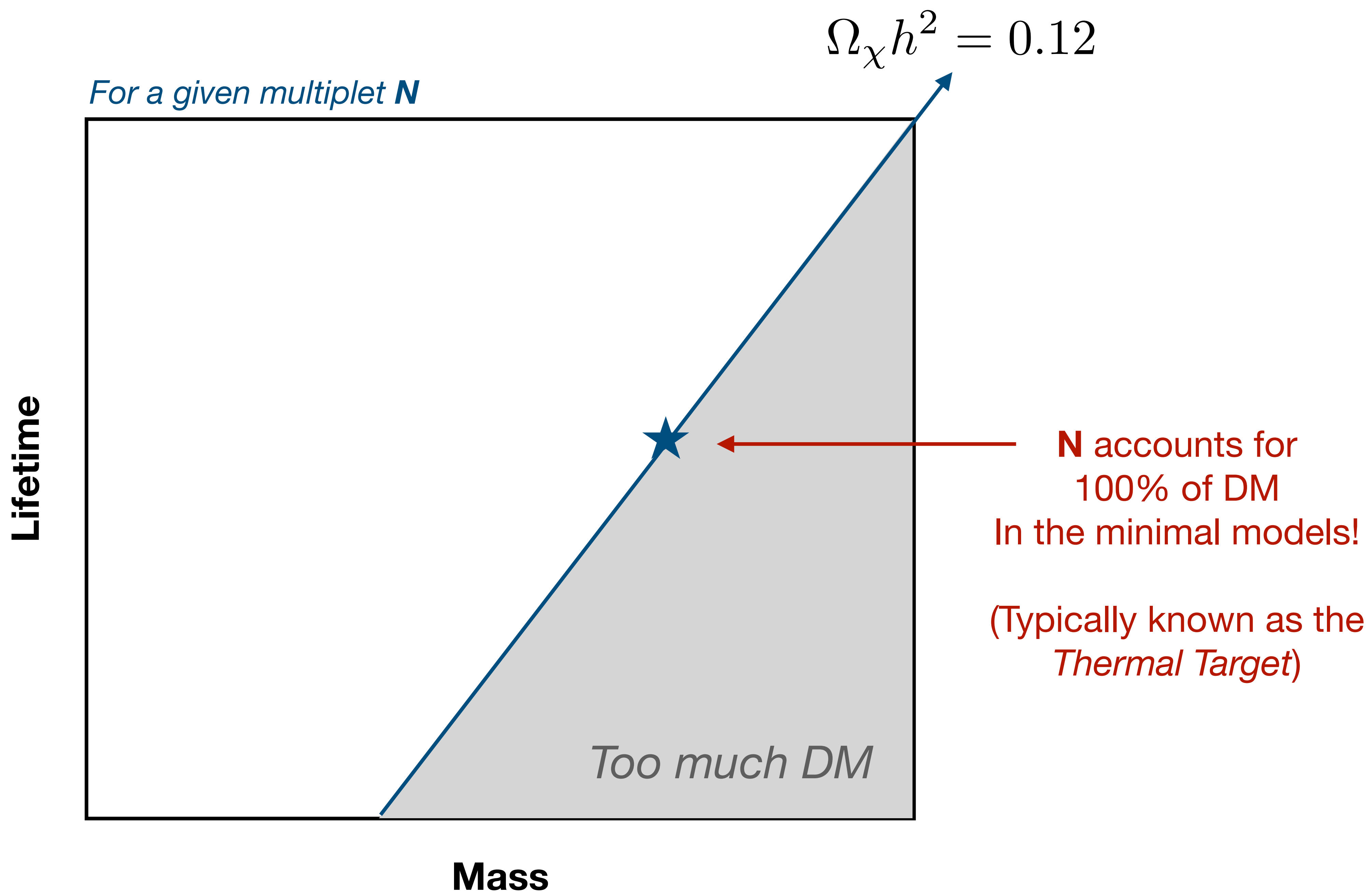
$$\Delta M = M_{\chi^{\pm}} - M_{\chi^{0}} > 0$$



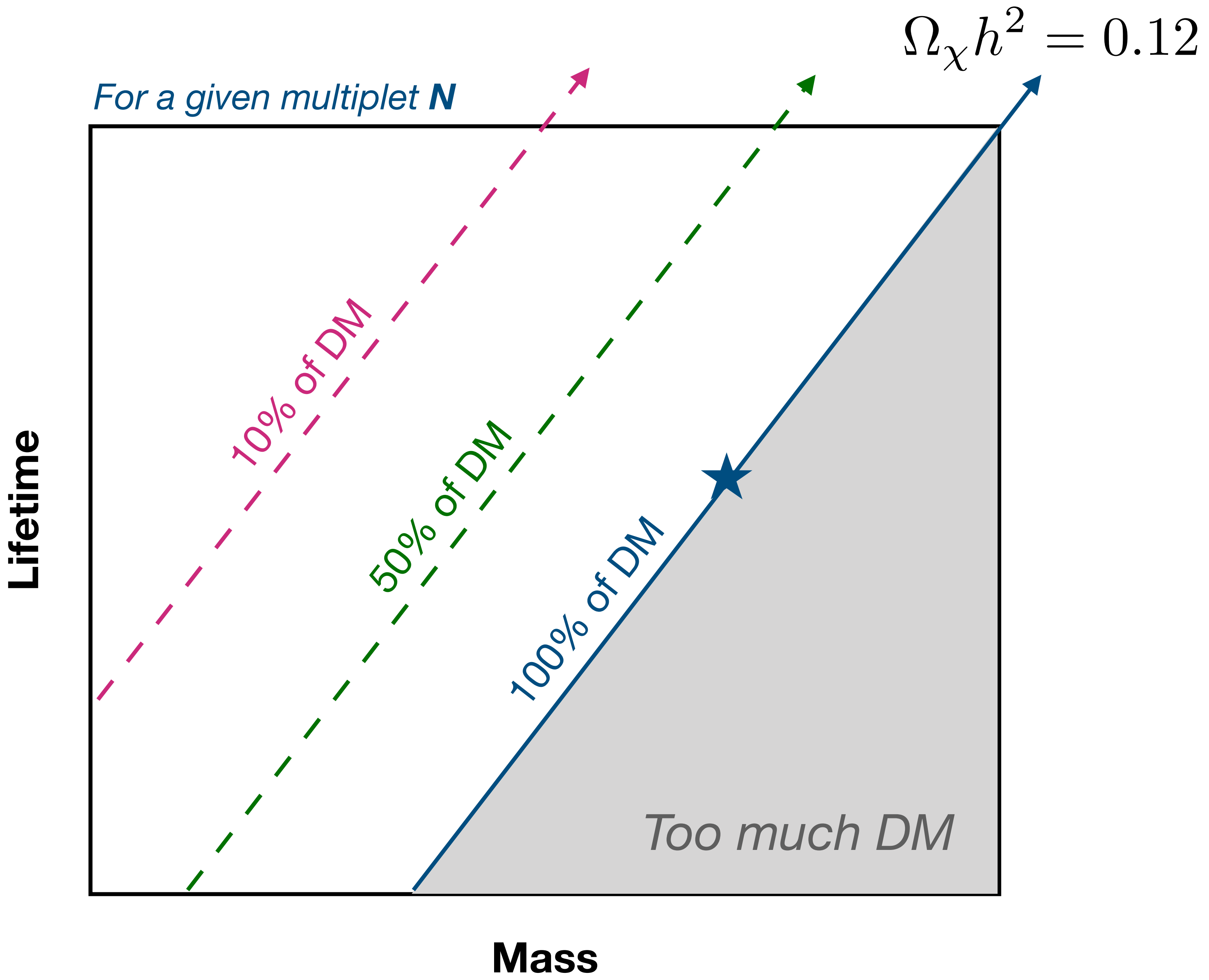
"Neutralino mixing" is important to evade DD constraints

"Neutralino mixing" is important to evade DD constraints

- **Target Parameter Space:**



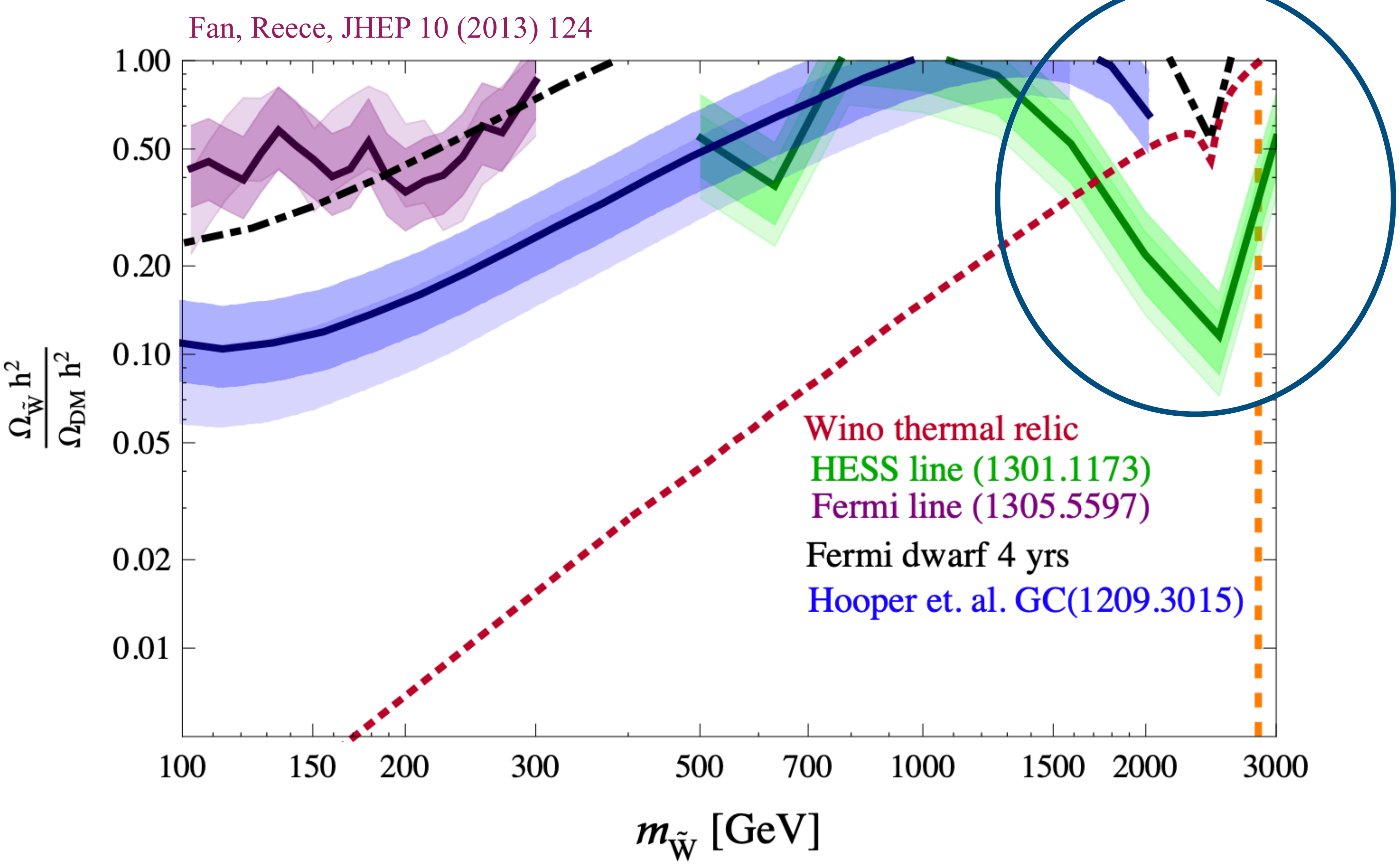
- **Target Parameter Space:**



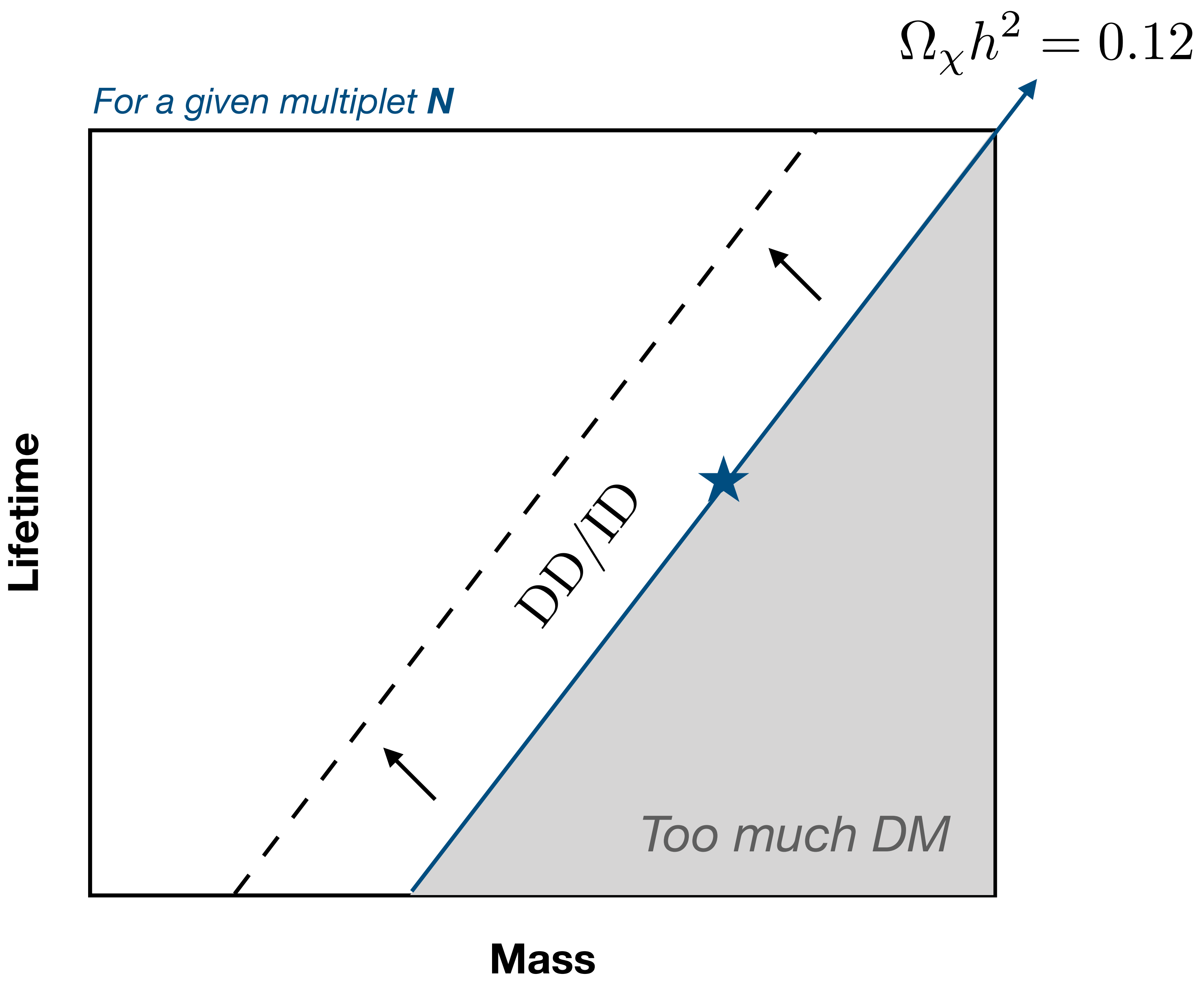
Rodolfo Capdevilla, Fermilab

- **Indirect Detection (ID)**

Bounds weaken as the mass decreases



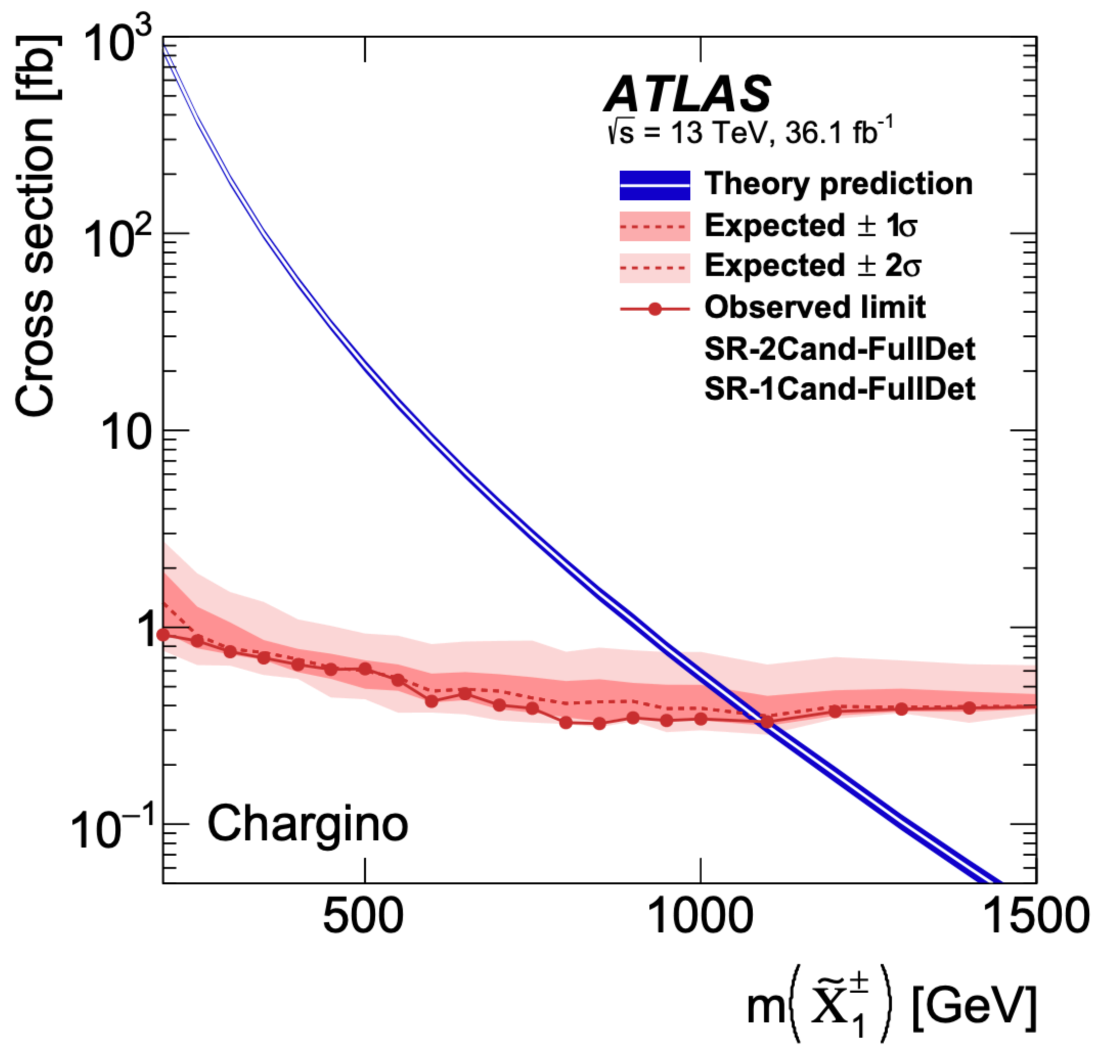
- **Target Parameter Space:**



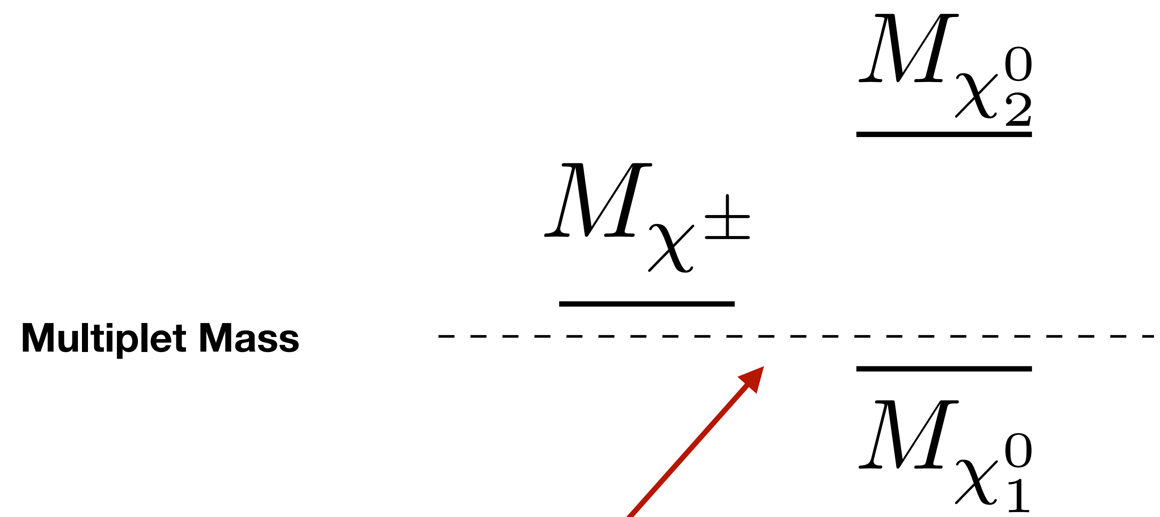
- **LHC:**

HSCP

Heavy Stable (50ns) Charged Particle



ATLAS Collaboration, Phys. Rev. D **99** (2019) 9, 092007

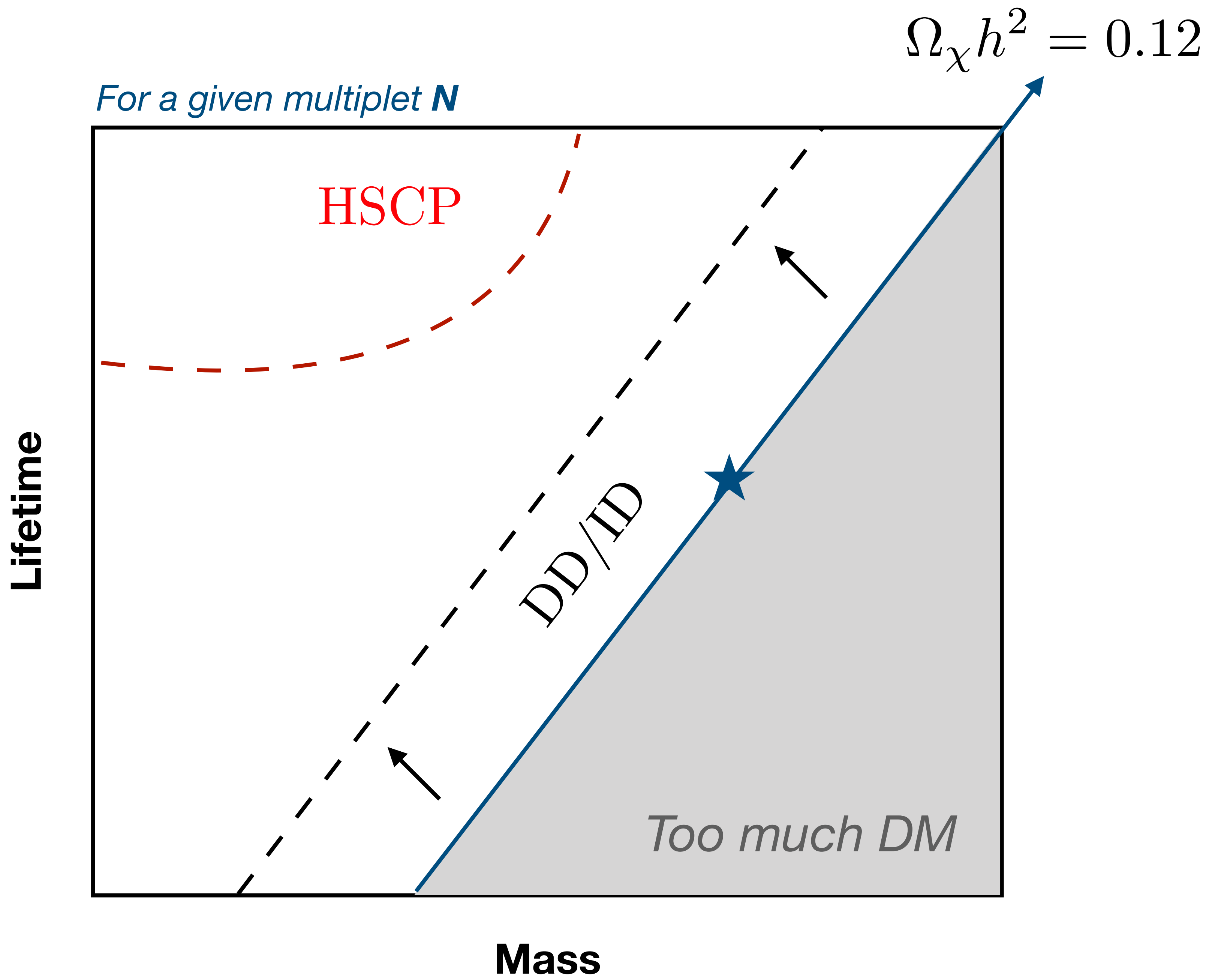


Very small chargino-neutralino mass gap:

- **LHC:**

HSCP

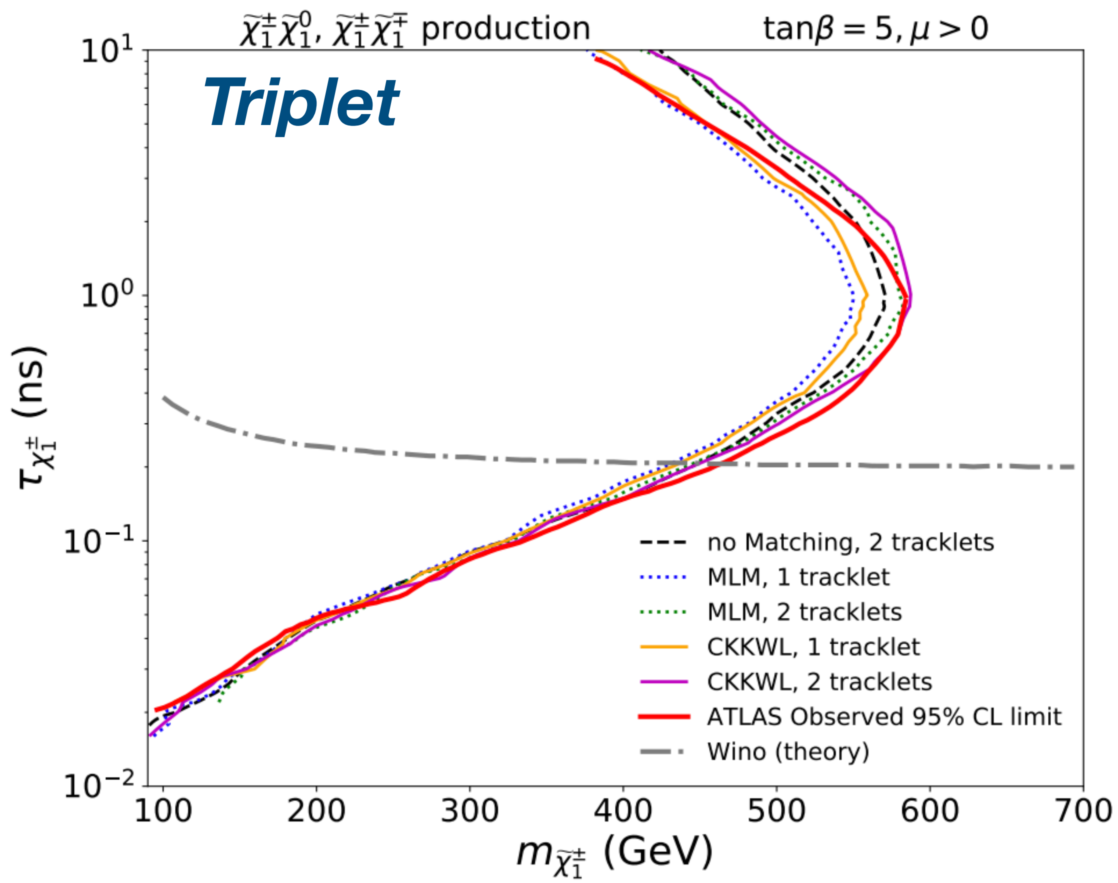
Heavy Stable (50ns)
Charged Particle



- **LHC:**

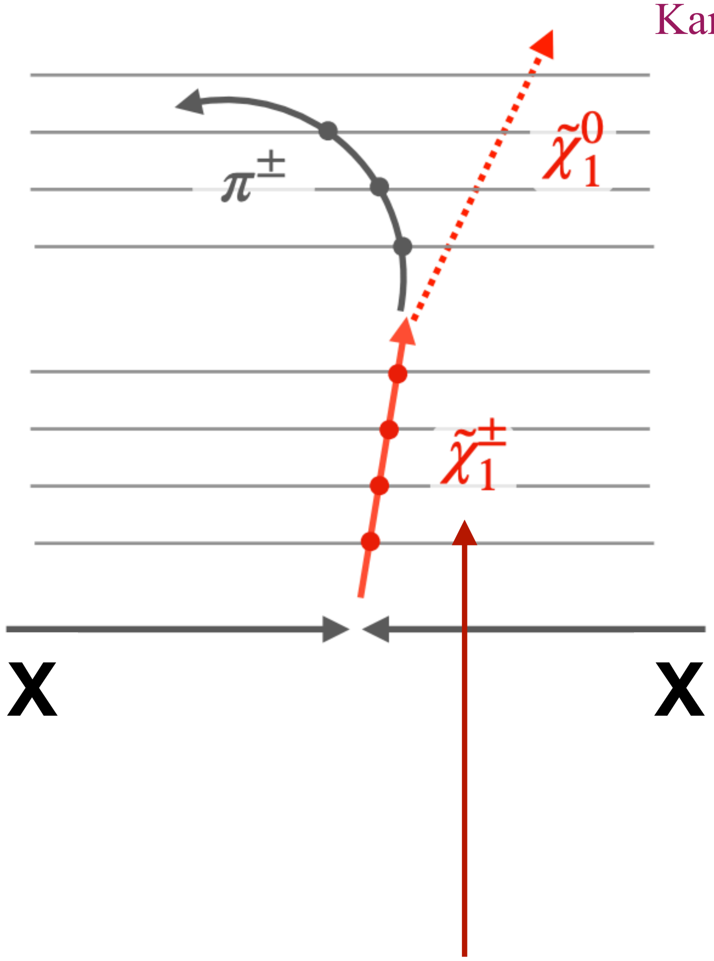
DT

Disappearing Tracks



A. Belyaev et al., Phys. Rev. D **103** (2021) 9, 095006

Karri DiPetrillo

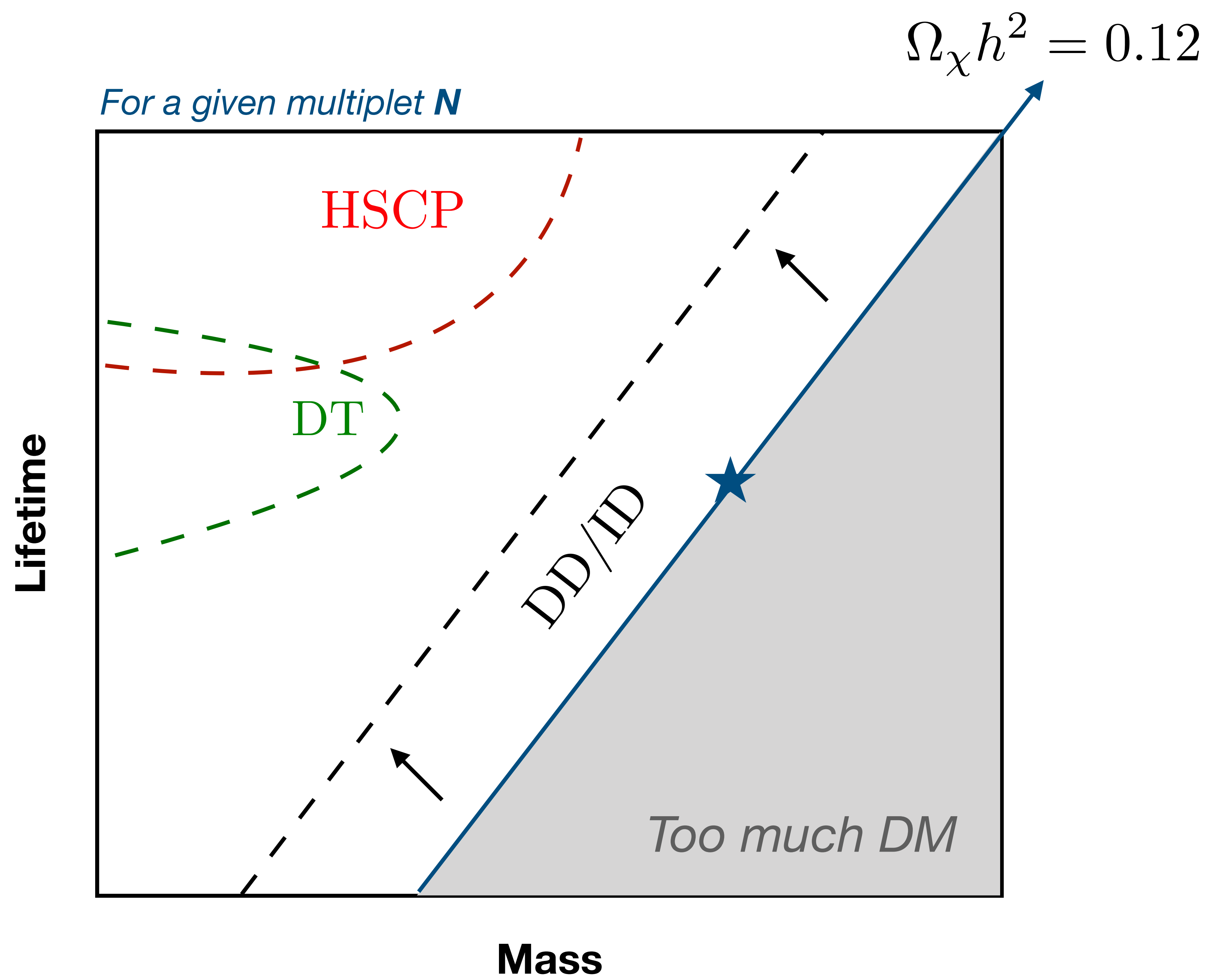


Chargino has a long lifetime due to small mass gap!

- **LHC:**

DT

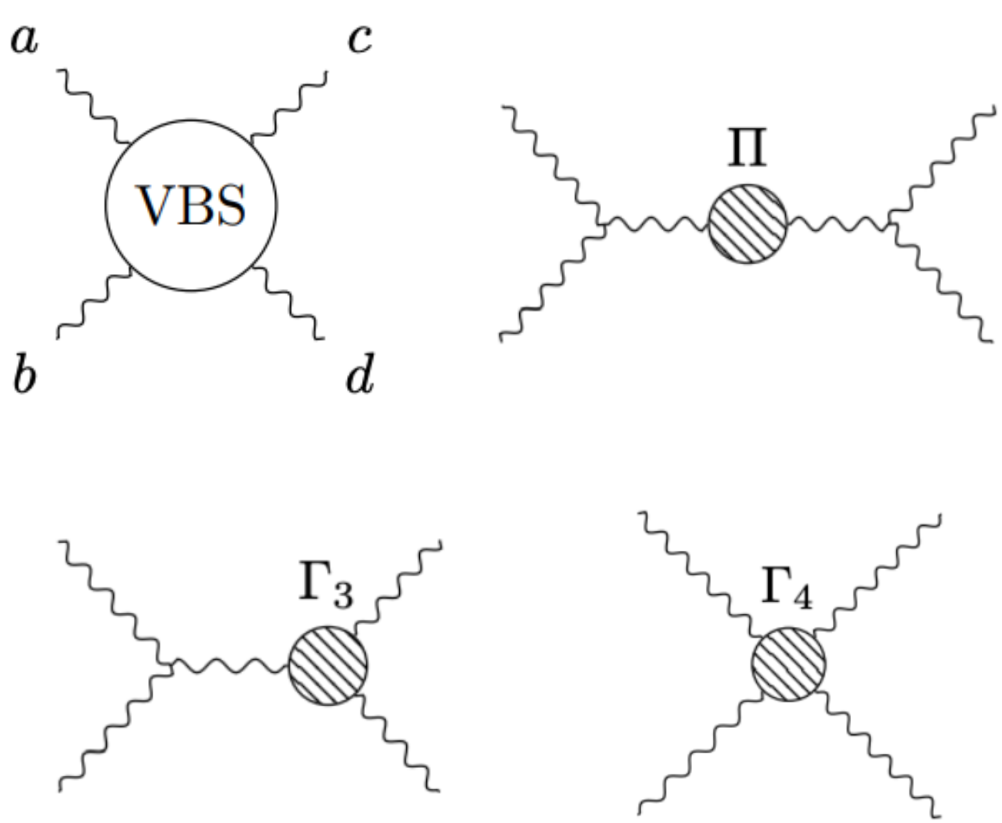
Disappearing Tracks

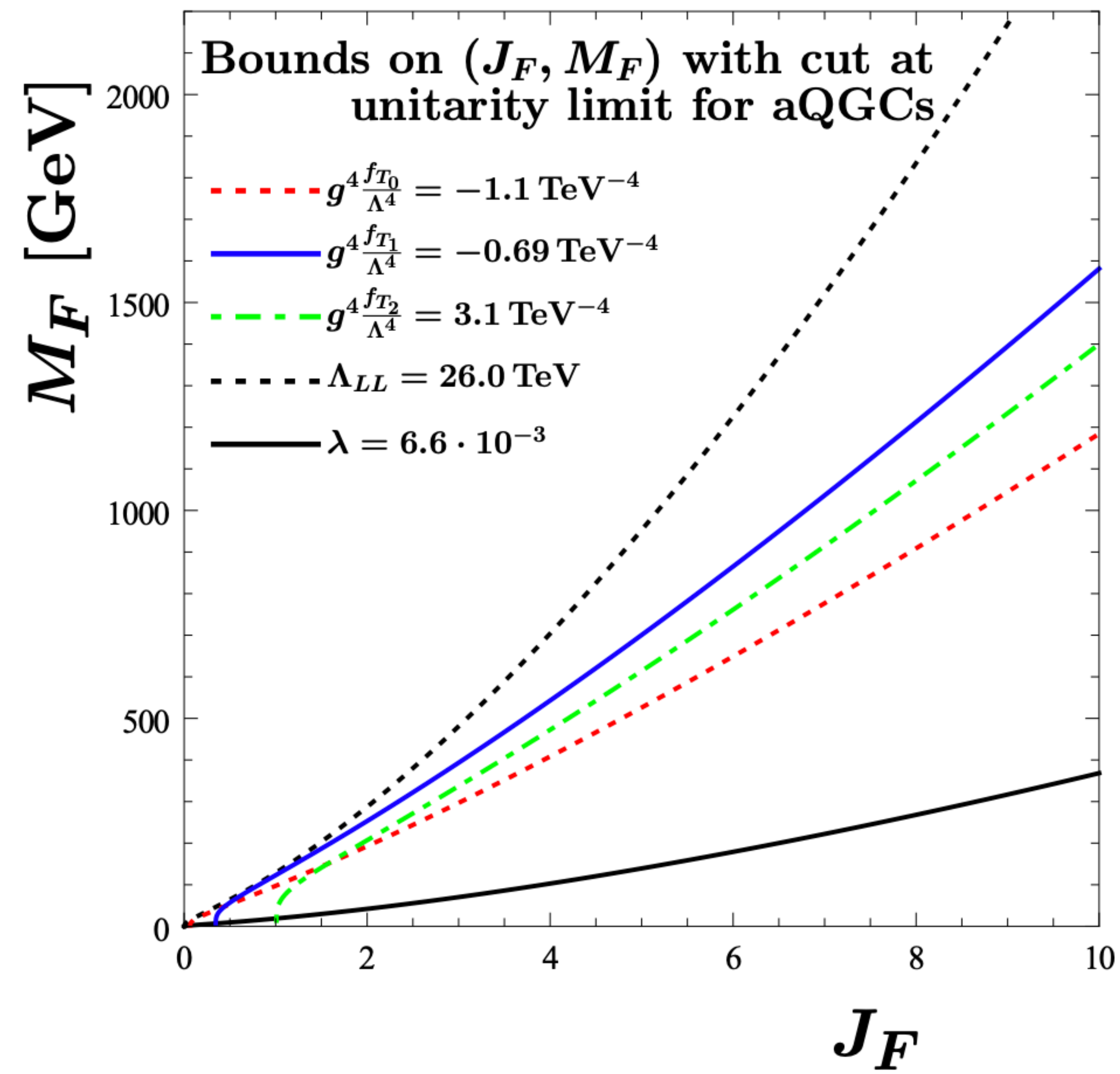


- **LHC:**

VBS

Vector Boson Scattering



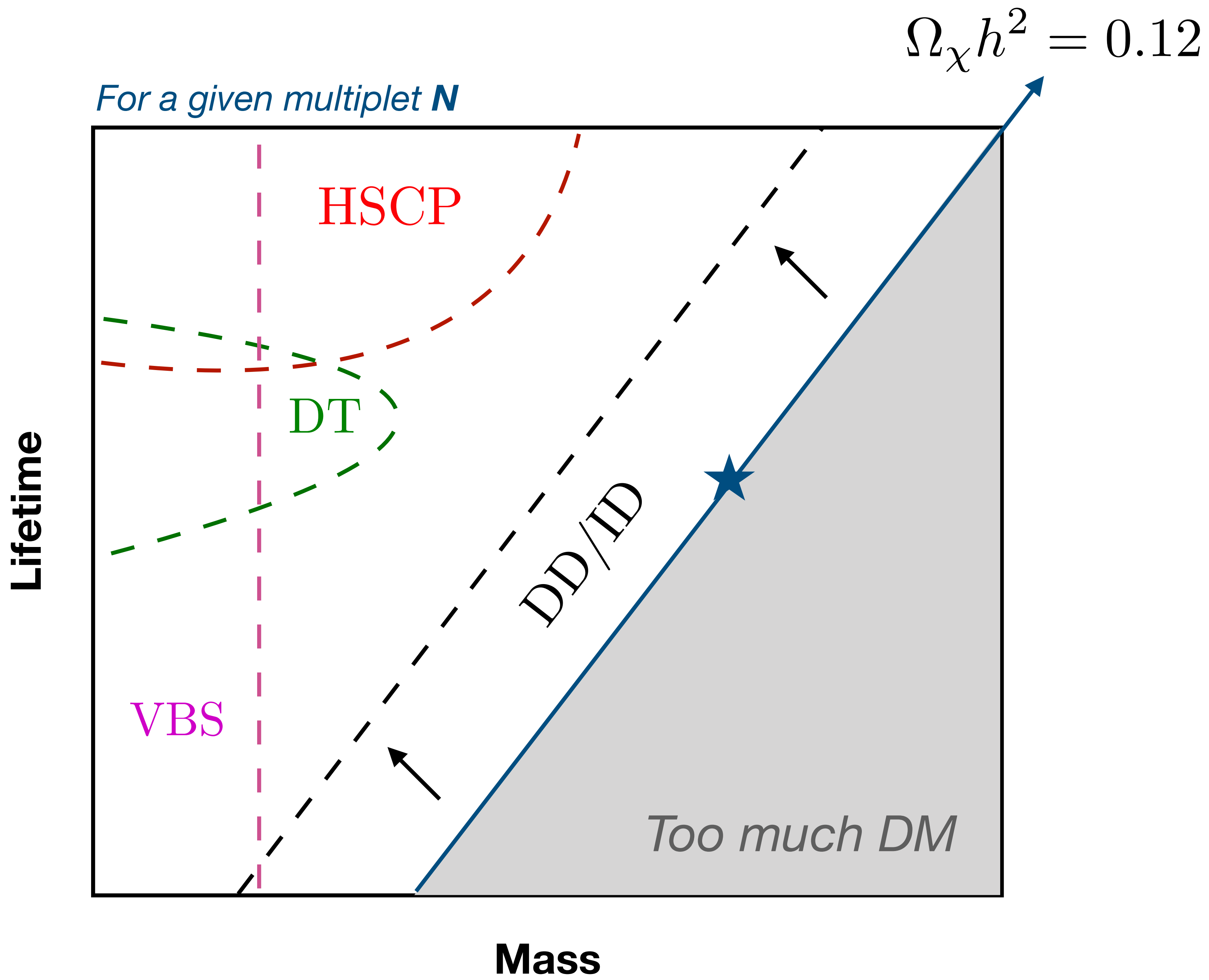


J. Lang et al., Eur. Phys. J. C 81 (2021) 7, 659

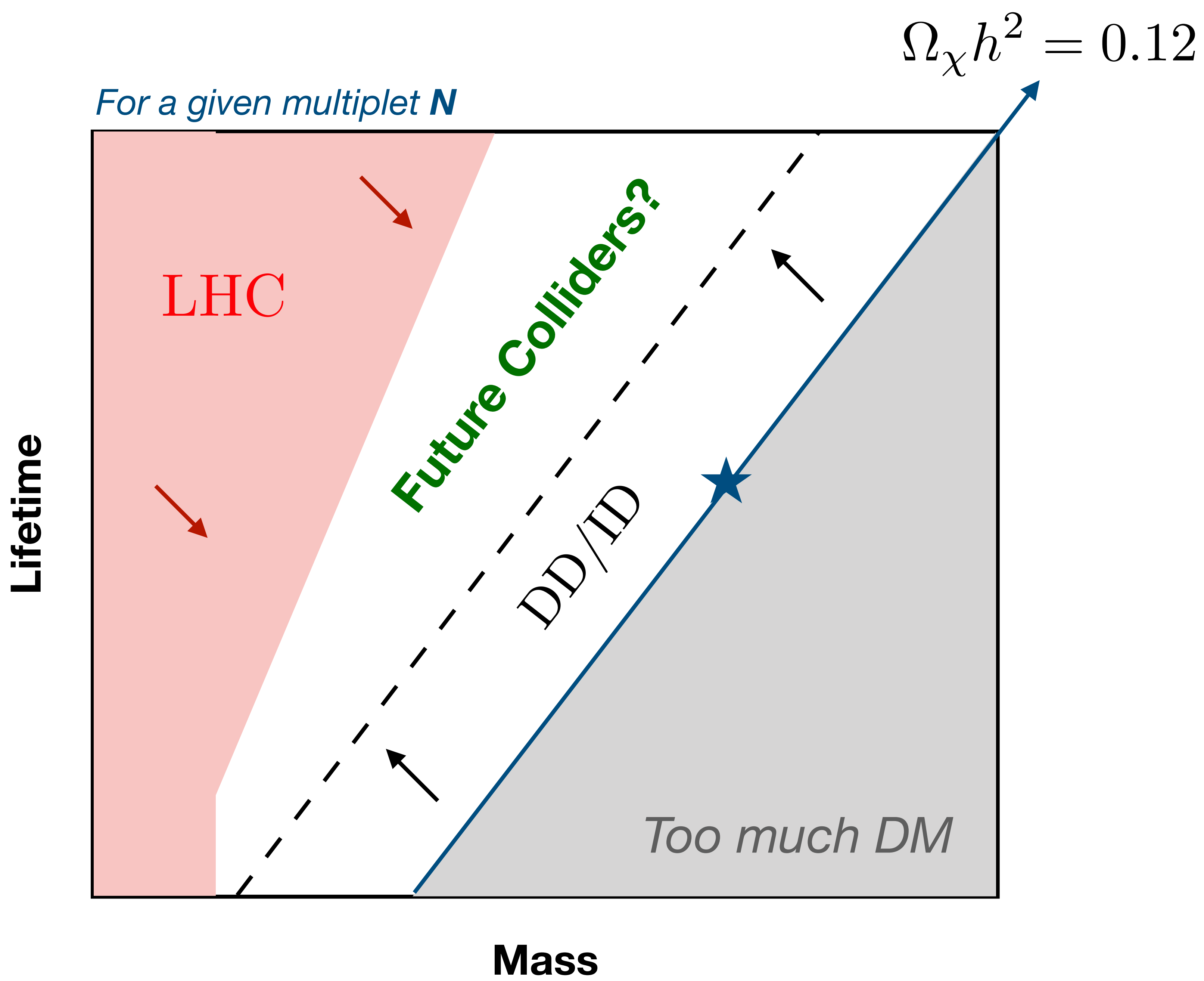
- **LHC:**

VBS

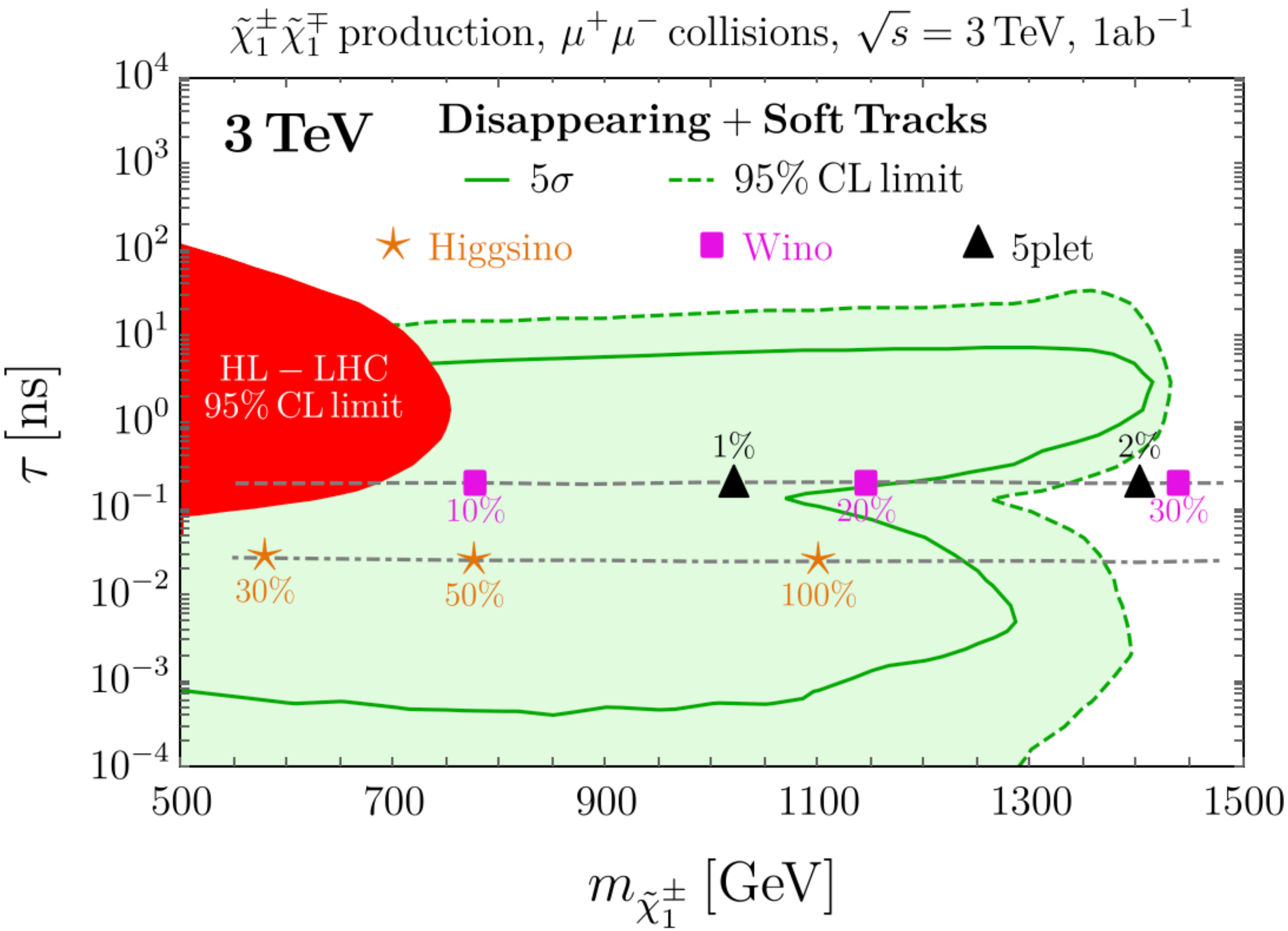
Vector Boson Scattering

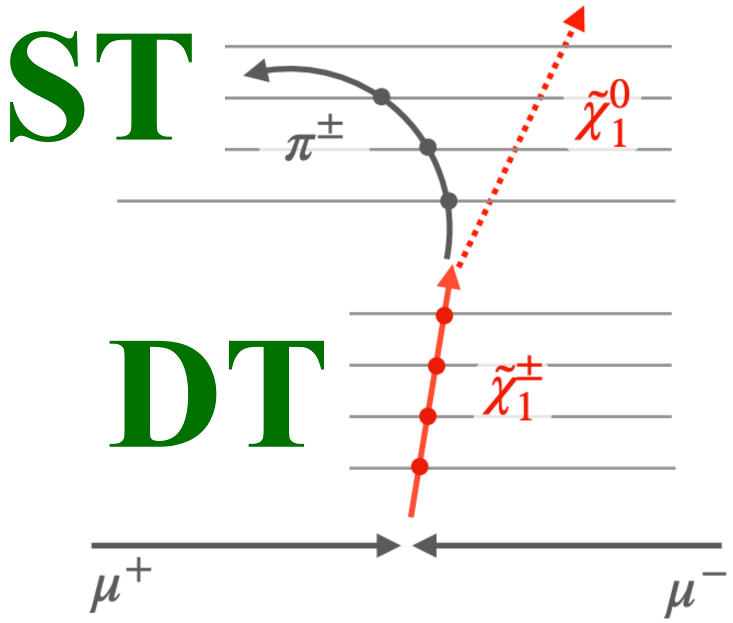


- **Road to Minimal WIMPs?**



- **Road to Minimal WIMPs:**



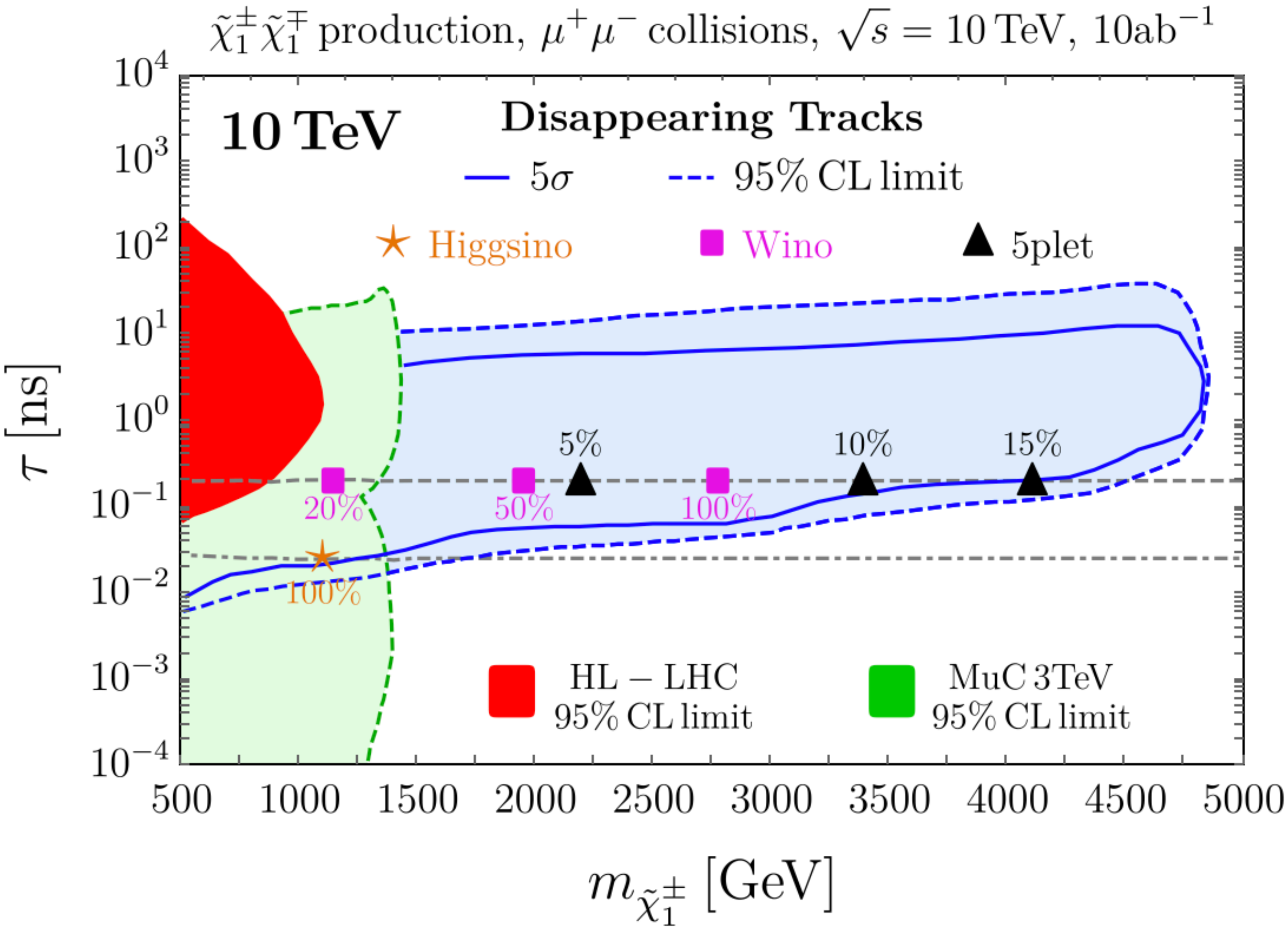


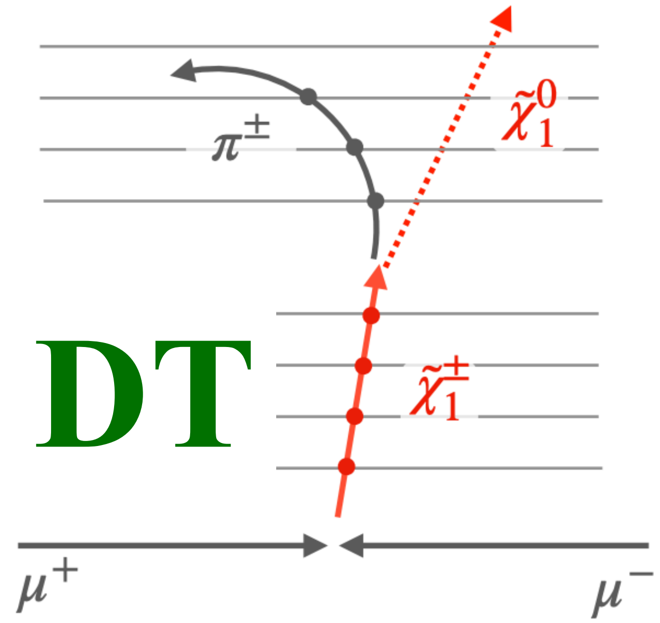
The 3 TeV collider:

Doublets	100% of DM
Triplet	20% of DM
Fiveplet	1% of DM

RC, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133
RC, Meloni, Zurita, arXiv:2405.08858

- **Road to Minimal WIMPs:**





The 3 TeV collider:

Doublets	100% of DM
Triplet	100% of DM
Fiveplet	10% of DM

RC, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133
RC, Meloni, Zurita, arXiv:2405.08858

Summary

1. Minimal WIMPs constitute highly motivated targets for BSM physics. **Doublets/Triplets** that account for **100% of DM** in the Universe as well as **5-plets** that can account for **~10% of DM** fall into the multi-TeV rage, reachable at future colliders.

2. In our ***Road to Minimal WIMPs***, the LHC plays an important role. Searches for HSCP, DT, VBS cover important portions of the lifetime/mass parameter space.

3. The **Muon Collider** program (3 -> 10 TeV) could discover and characterize minimal WIMPs. **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.

4. These studies with full detector simulation and BIB overlay require the collaboration between **theorists and experimentalists.** Preliminary studies with new detector designs and new BIB data show improvements with respect to the results shown in this talk.

Thank You!