WIMP DM at muon colliders

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Muon Collider Physics and Detector Workshop. June 3, 2021

Probing WIMP dark matter is a main physics goal for high energy colliders.

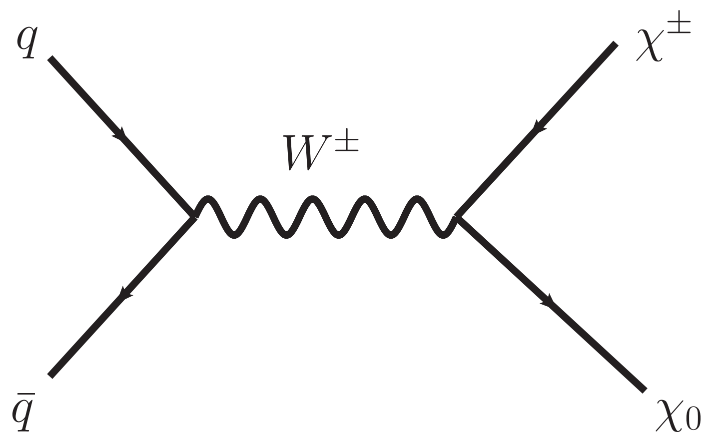
A main part of the physics studies for future colliders.

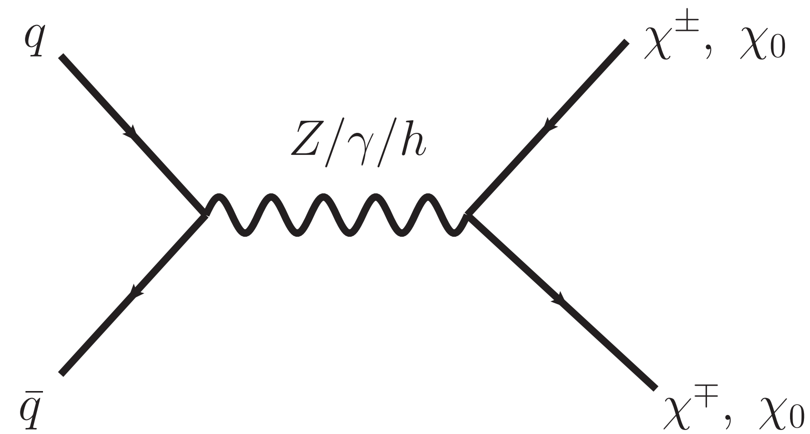
My talk:

- Reach of muon collider for simple(st) WIMP dark models.
  - Overview + inclusive searches.
- A few directions for further studies.

Simplest WIMP

DM part of a EW multiplet





- Simplicity: there is no additional new mediator.
  - Mediated by W/Z/h.
- In SUSY, there are two such examples
  - Higgsino: doublet. Wino: triplet.

DM part of a EW multiplet

"Minimal dark matter", Cirelli, Fornengo and Strumia, hep-ph/0512090, 0903.3381

$$\text{DM} \in (1,\, n,\, \text{Y}) \;\text{ of }\; \text{SU(3)}_\text{C} \times \text{SU(2)}_\text{L} \times \text{U(1)}_\text{Y}$$

- Consider first the fermionic mulitplets.
  - Only couplings at the renormalizable level are the gauge interactions.
  - The only free parameter at this level is the mass, m_χ.
  - Very predictive.

DM part of a EW multiplet

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$$\text{DM} \in (1, n, \text{Y}) \text{ of } \text{SU(3)}_\text{C} \times \text{SU(2)}_\text{L} \times \text{U(1)}_\text{Y}$$

- n odd. Fermionic.
  - n>7, Landau pole close to M_{DM} .
  - After EWSB, mass splitting (minimally) generated at 1-loop.
  - Choose Y=0. Lightest member electric neutral. Potential DM candidate.
  - n ≥ 5, can have operators which decays the DM. Can be avoided if additional symmetry are imposed (or introduce a tiny hypercharge.)

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– n even. Fermionic

- Choose Y=(n-1)/2 ensures lightest member is neutral.
- Direct detection rules out the minimal case due to tree level Z exchange.
    - Can be avoided to introduce a small splitting, $\delta m > 10^2$ keV, of the neutral states (for example, from a dim-5 operator). Not quite minimal, but still viable.
- Famous example: Higgsino $(1,2)_{1/2}$

DM part of a EW multiplet

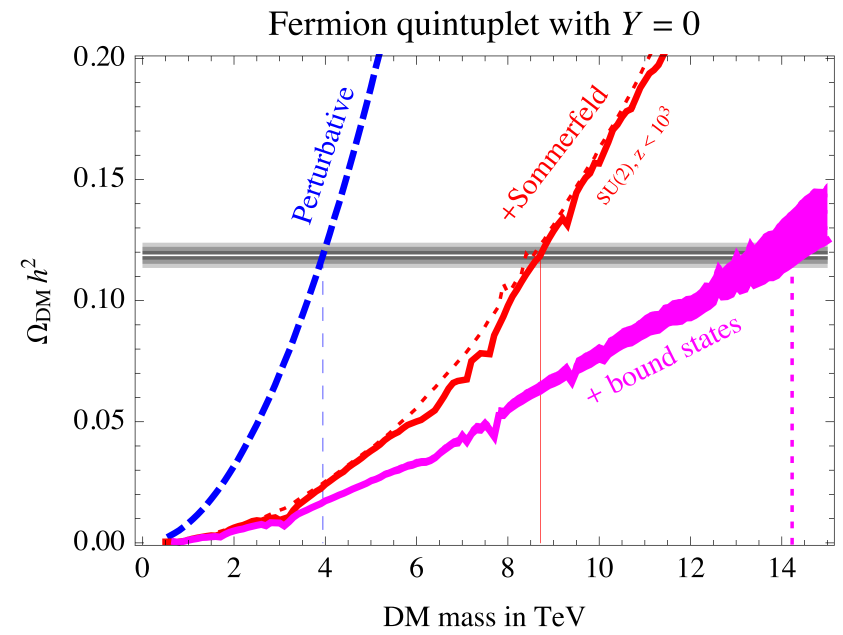
"Minimal dark matter", Cirelli, Fornengo and Strumia, hep-ph/0512090, 0903.3381

$$\text{DM} \in (1, n, \text{Y}) \text{ of } \text{SU}(3)_\text{C} \times \text{SU}(2)_\text{L} \times \text{U}(1)_\text{Y}$$

- Scalar (real and complex)
  - In principle interesting as well.
  - Minimal mass splitting, stability discussion parallel to that of the fermionic multiplets.
  - Addition couplings of the form $H^\dagger H X^\dagger X$. More parameters involved in a full analysis.
- As a first step, we will focus on fermionic candidates here.

Thermal targets

Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3,ϵ)	Dirac	2.0 TeV
(1,5,0)	Majorana	14 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV $\to$ 40 TeV
(1,7,ϵ)	Dirac	16 TeV

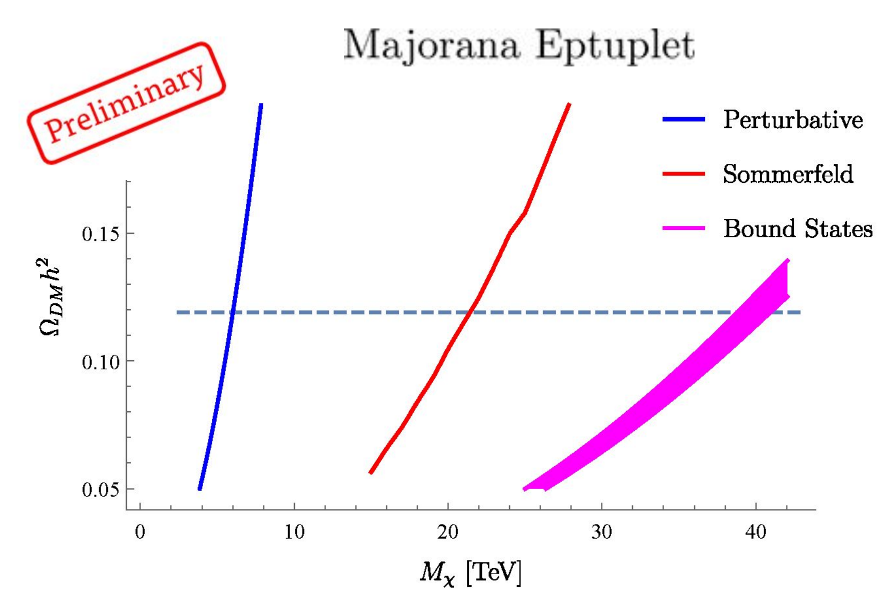


Mitridate, Redi, Smirnov, Strumia, 1702.01141

Reach up to thermal target

≈

complete coverage for WIMP candidate

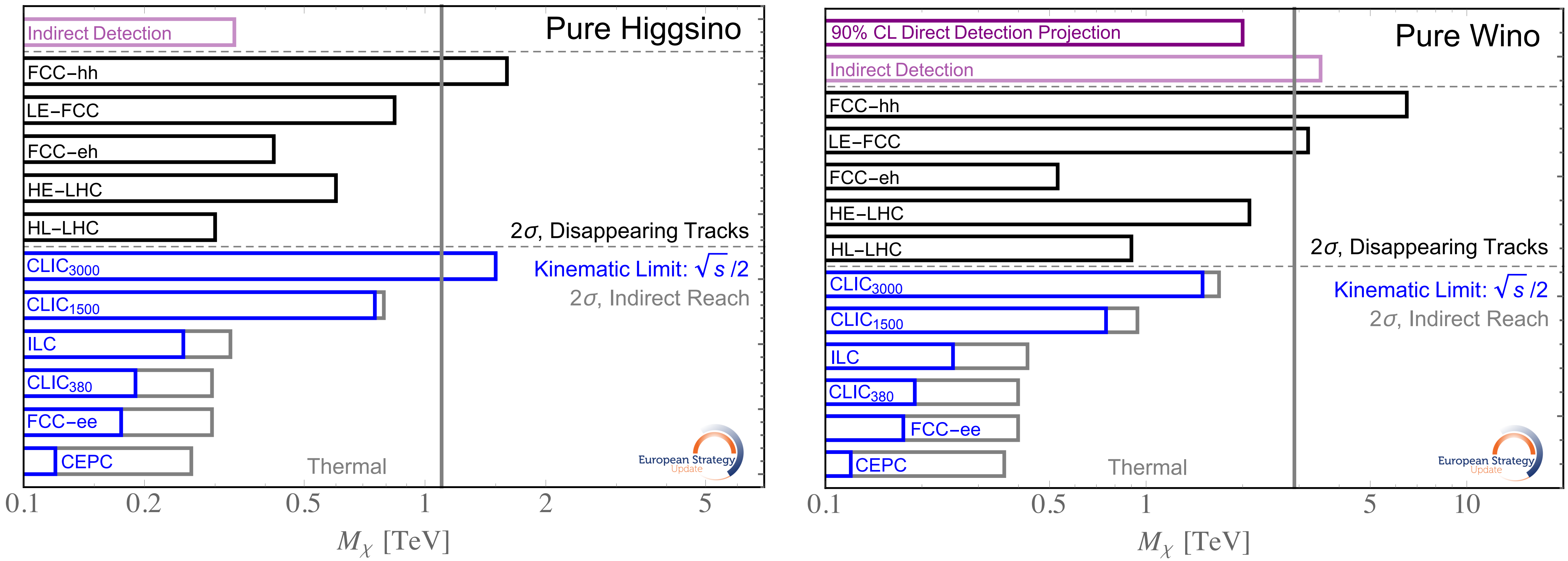


Bottaro, 2nd muon collider physics potential meeting

Two classes of signals at colliders

- Production of dark matter particle.
  - Inclusive search for X+MET
    - e.g. mono-jet at hadron colliders.
- Small EW induced mass splitting, charged member long-lived
  - Disappearing track

Search at future colliders



100 TeV pp collider is needed
to cover the EW doublet (Higgsino) and triplet (wino) DM.

Not enough to cover the higher dim multiplets.

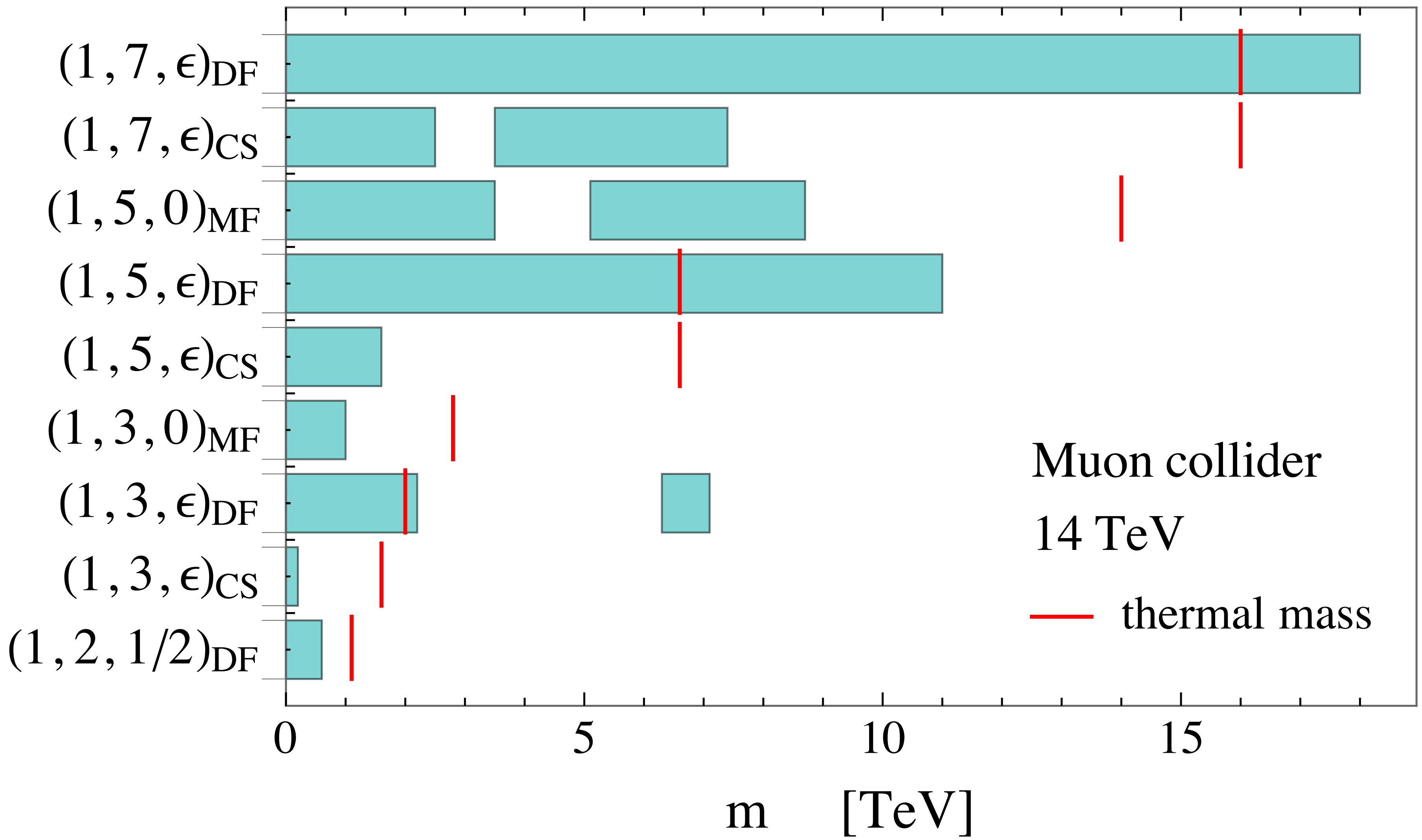
At muon colliders

Naive expectation: reach dark matter mass $m_\chi \approx 1/2\ E_{CM}$

Well, almost. But not so easy.

From precision measurement

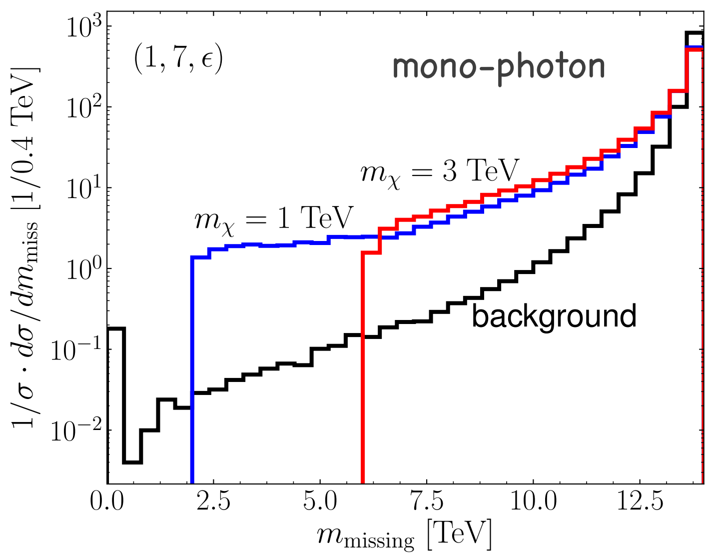
Di Luzio, Grober, Panico, 1810.10993



Virtual effect to Drell-Yan processes

Inclusive missing mass searches

Missing mass: $m^2_{\rm missing} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\rm obs})^2 \qquad m^2_{\rm missing} > 4m_\chi^2$



Useful for background suppression, especially for large dark matter mass

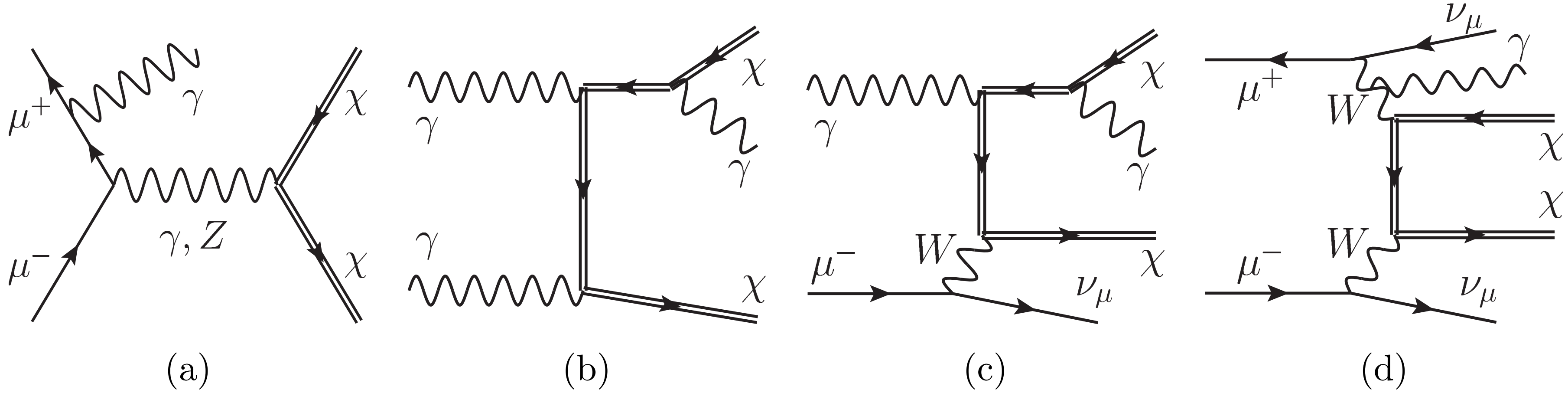
Missing mass + X: X= photon, muon, W/Z, etc

Similar to the X+MET searches at hadron colliders. But in a cleaner environment

Mono-photon channel

Signal:

Drell-Yan　　　　　　　　　　　　　　　　VBF



Dominated by the production of charged members of the multiplet.

Consider the delayed decay and the decay products from, e.g.,

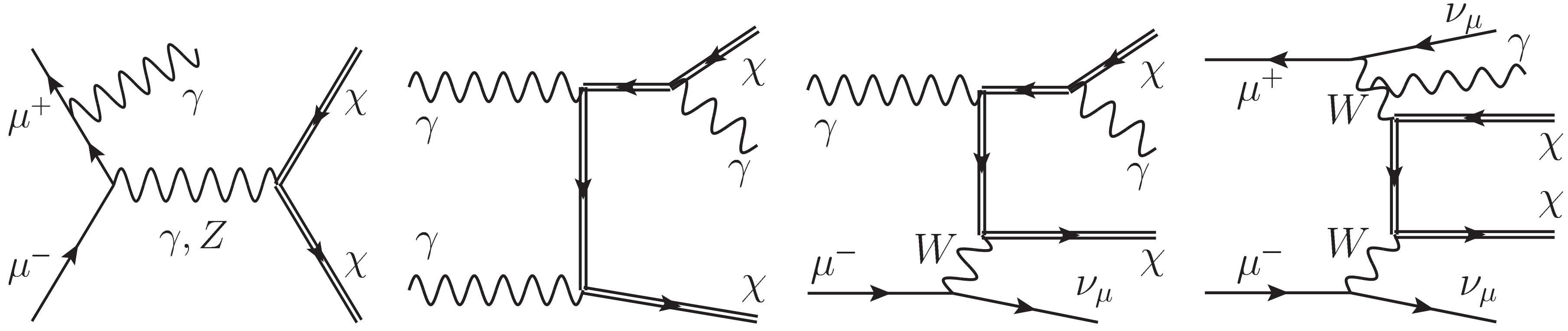
$$\chi^{\pm} \rightarrow \chi_0 + \text{soft particles}$$

as invisible here. (More on this later)

Mono-photon channel

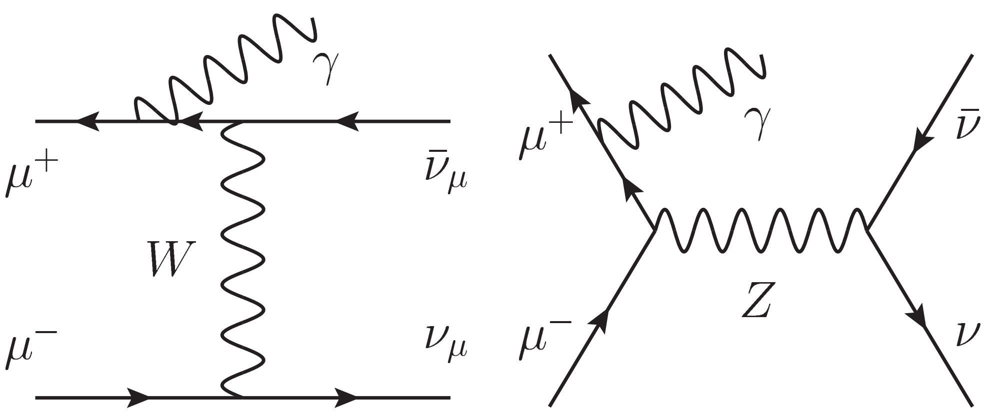
Drell-Yan VBF

Signal:



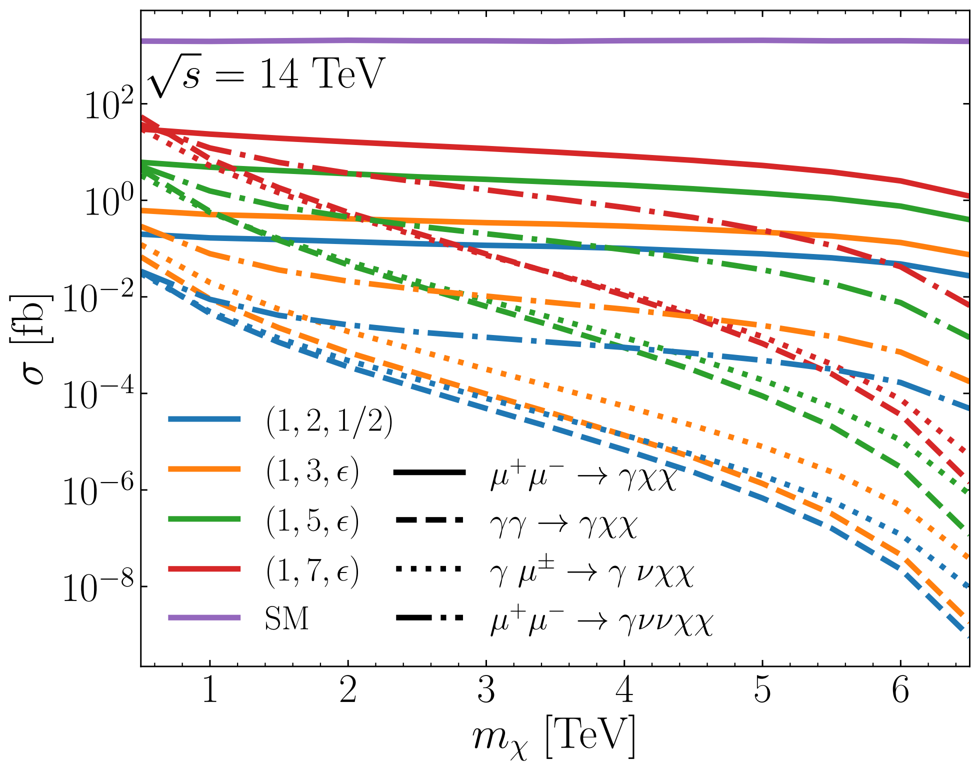
(a) (b) (c) (d)

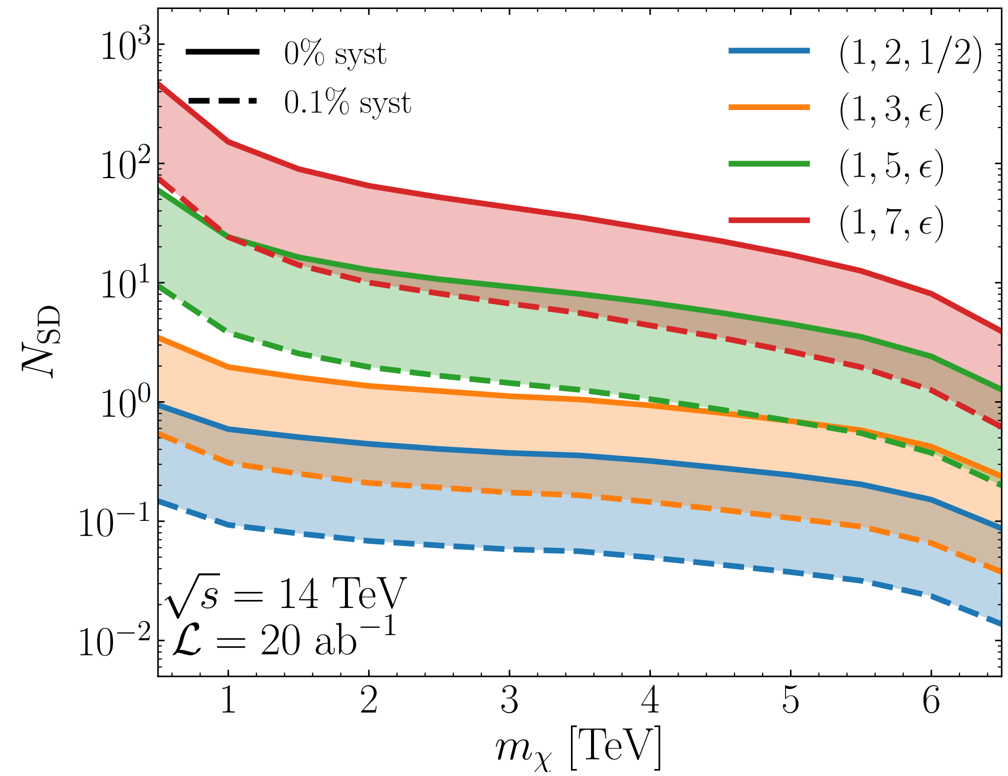
Background:



(a) (b)

Signal significance





$$\mathrm{N_{SD}} = \frac{S}{\sqrt{S + B + (\epsilon_S S)^2 + (\epsilon_B B)^2}}$$

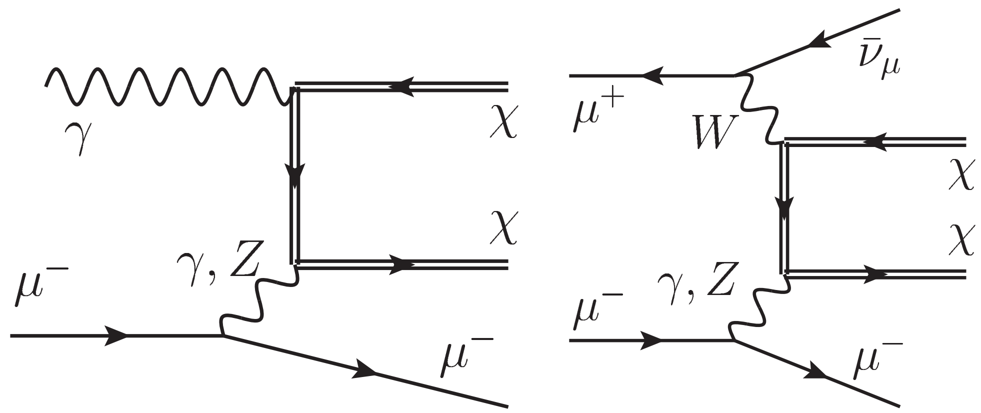
$B \approx 10^{2\div 3} \times S.$

Signal significance is dominated by the systematics.
Good reach if one can control the systematics to the level of 10^{-3}

Mono-muon

A signal unique to muon collider

Signal:



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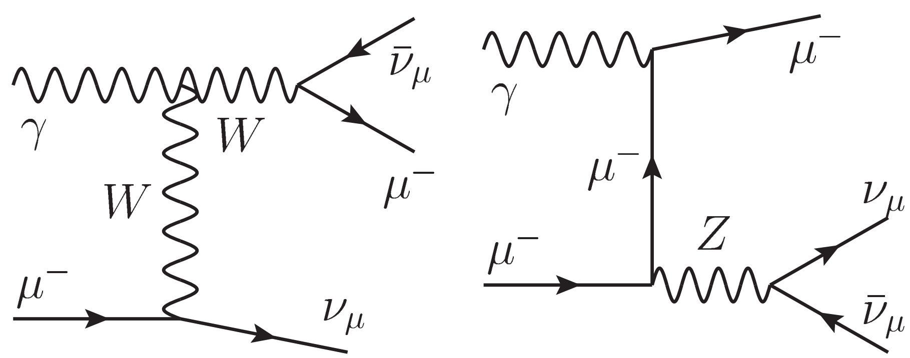
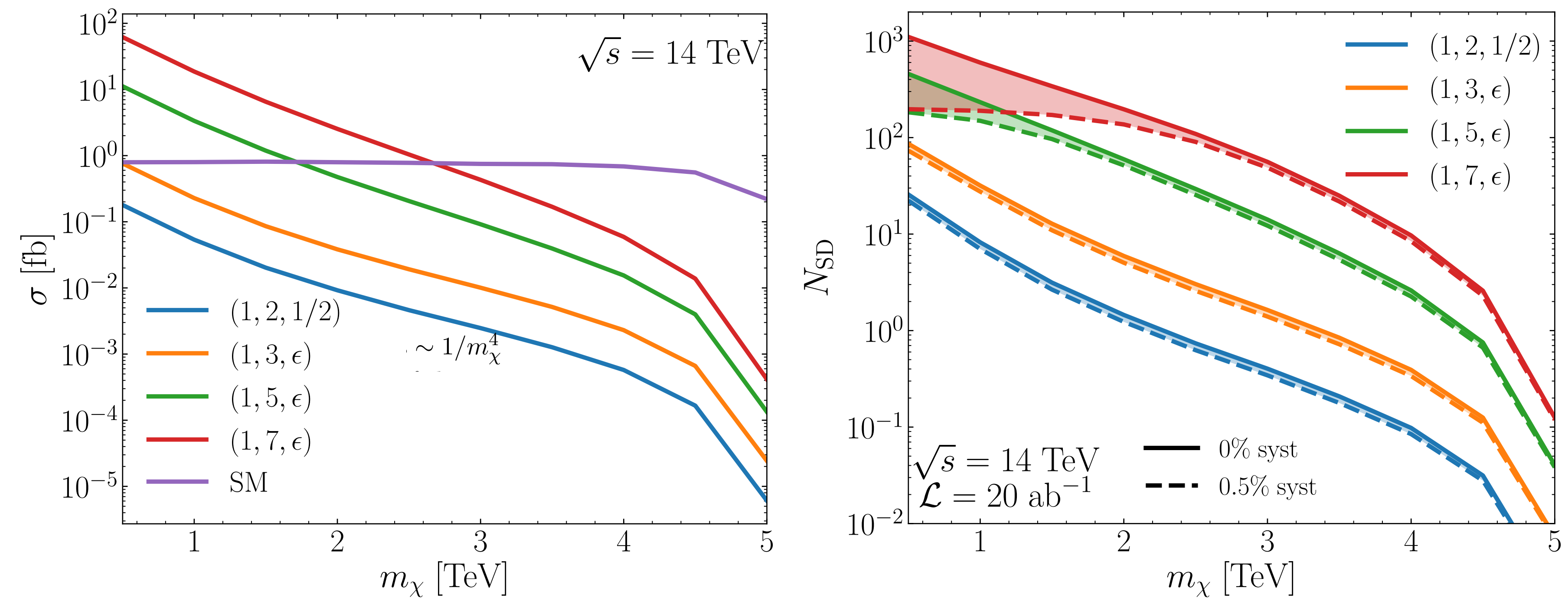
Background:



(a) (b)

Signal significance

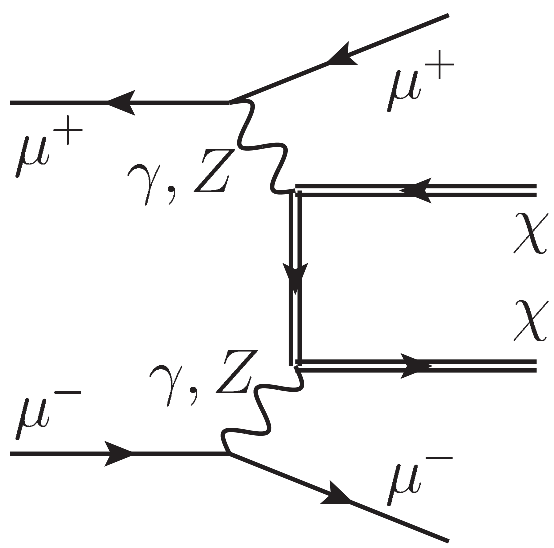


VBF-like signal. Falls off like m_χ^{-4} .

S is comparable to B. Less susceptible to systematics

VBF

Signal:



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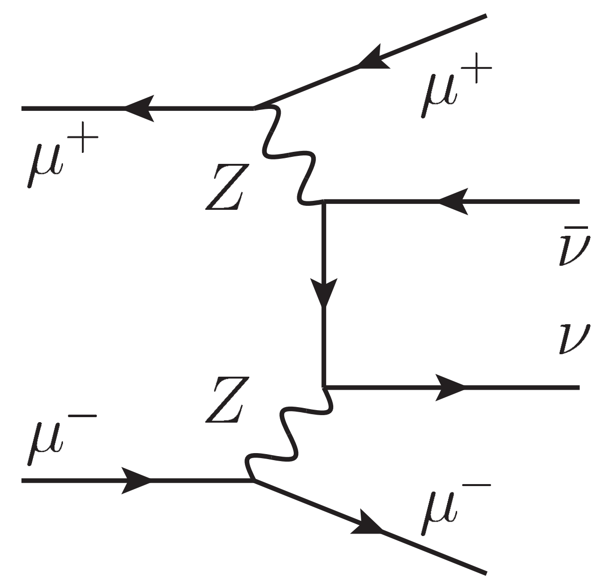
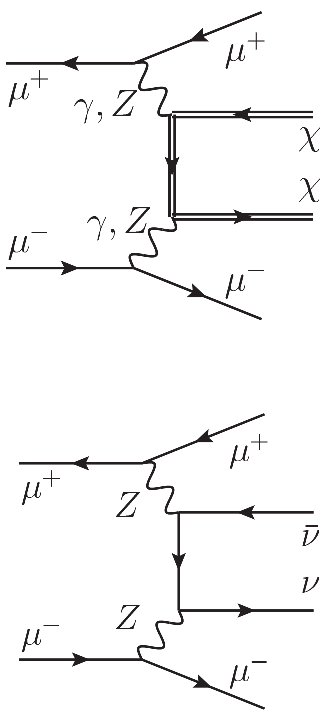
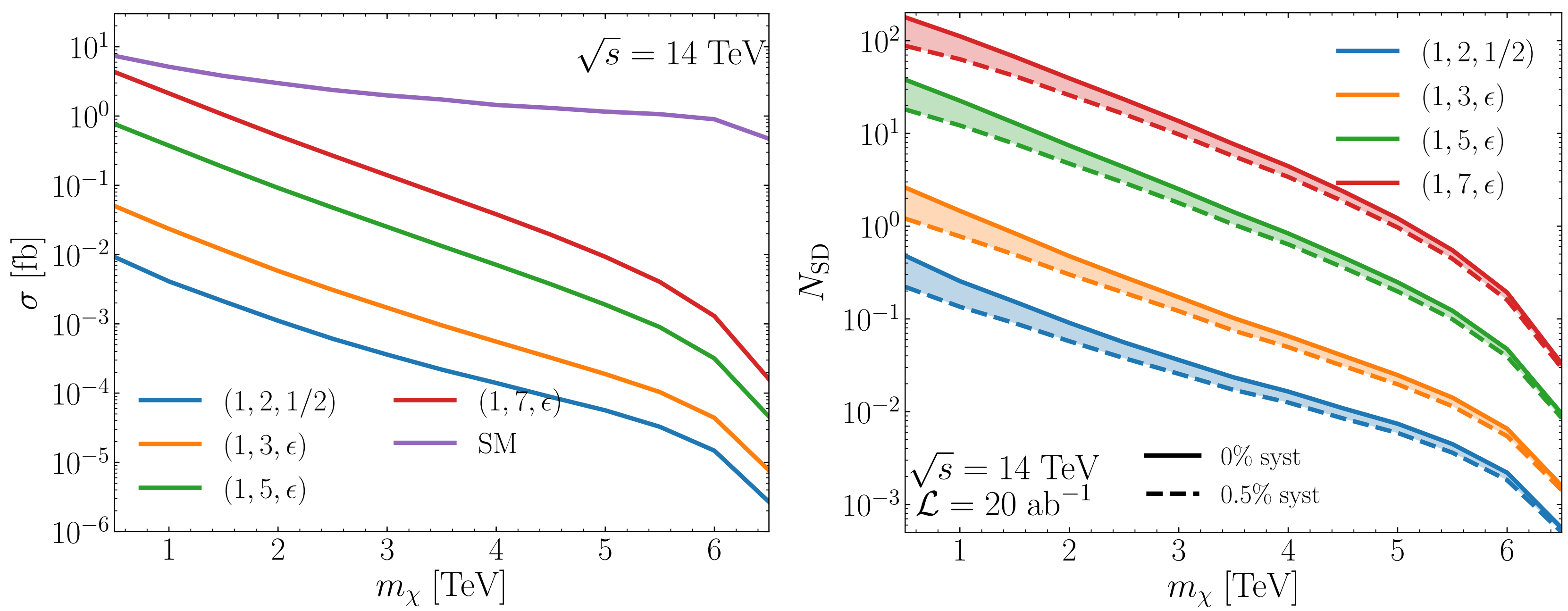


Imposing selection cuts:

$$m_{\mu^+\mu^-} > 300 \text{ GeV}, \quad m_{\text{missing}} = (p^{\text{in}}_{\mu^+} + p^{\text{in}}_{\mu^-} - p^{\text{out}}_{\mu^+} - p^{\text{out}}_{\mu^-})^2 > 4m_\chi^2.$$

Signal significance





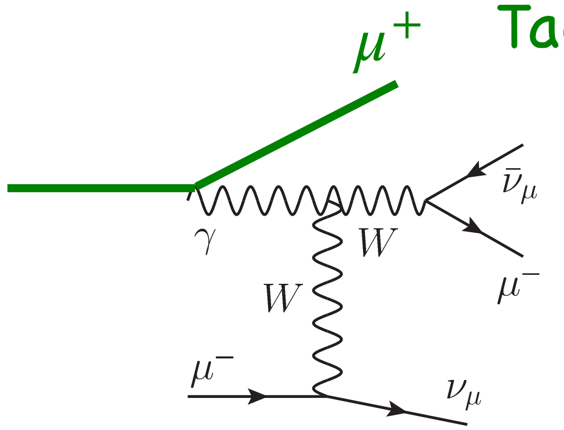
(a) (b)

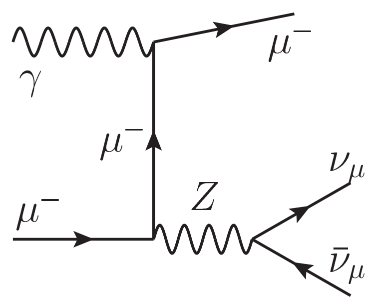
Need to tag two forward muons (angular acceptance).
Only neutral channel contribute.

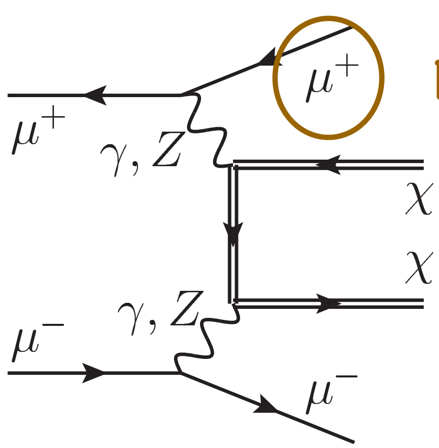
Lower signal significance comparing to mono-muon

Benefits of better angular coverage

Tag this muon, suppress mono-muon bkgd.







Easier to catch this. Enhance signal rate.

Effect scales like: $1/p_T^{\mu 2} \propto 1/\theta_{\rm cut}^2$

Disappearing track

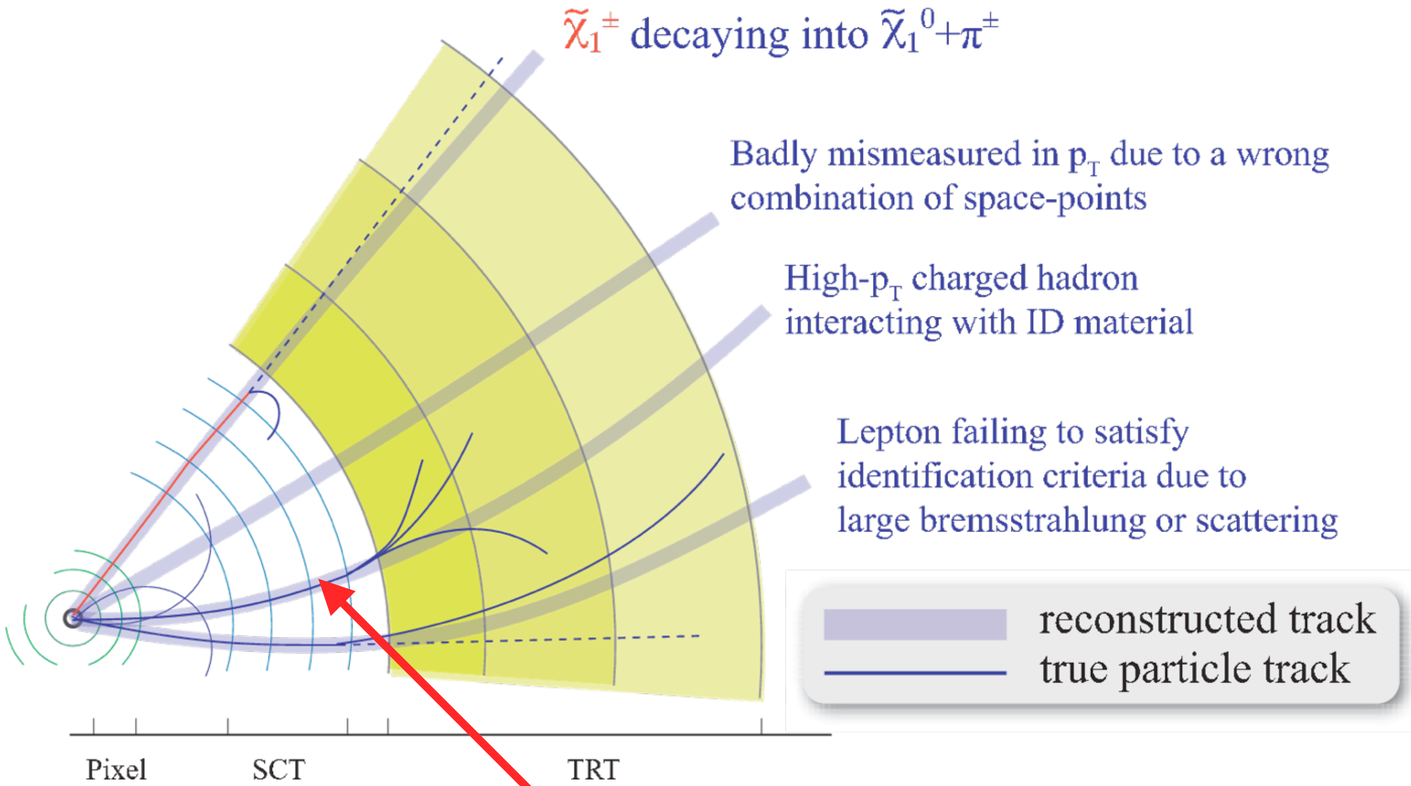


Figure from ATLAS disappearing track search twiki

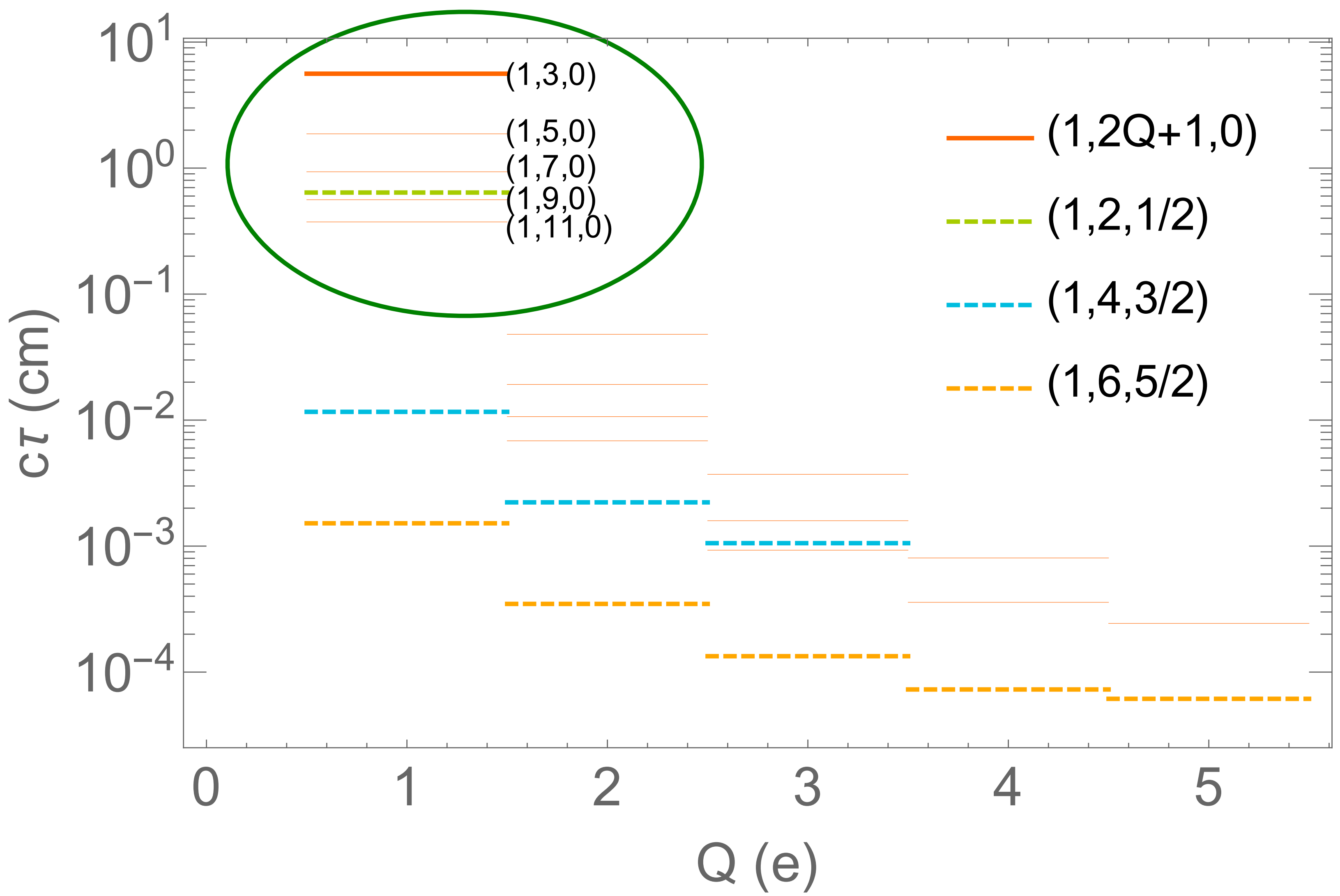
Signal of a sufficiently long-lived charge particle

BIB a significant background.

Detailed study including simulated BIB for Higgsino and wino:
Capdevilla, Meloni, Simoniello, Zurita, 2102.11292

See talk by Jose Zurita

Small mass splitting, long lifetime



$$\Delta m_{Q,Q'} \equiv m_Q - m_{Q'} \simeq (Q-Q')\left(Q+Q'+\frac{2Y}{\cos\theta_W}\right)\delta m$$

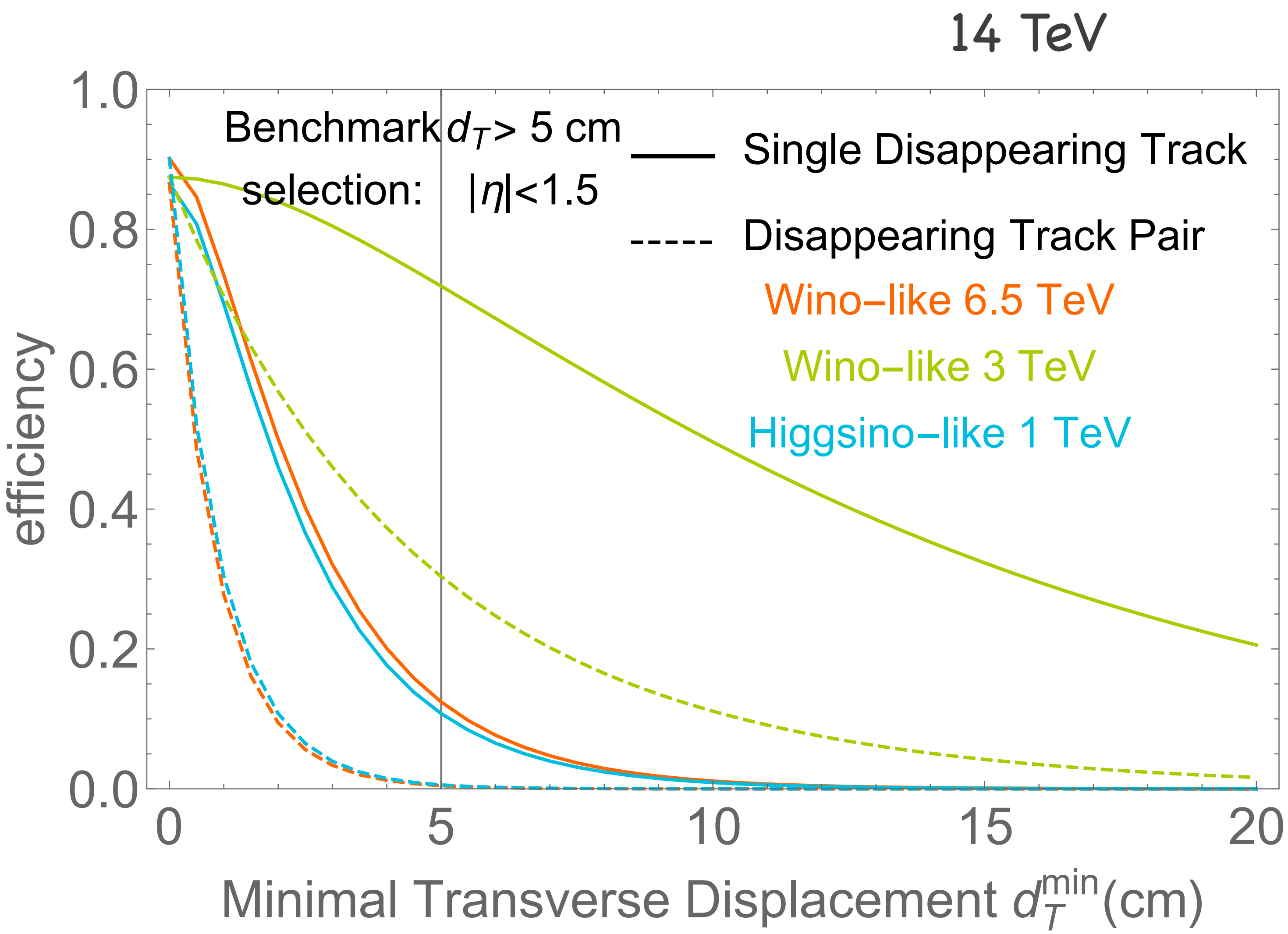
$$\delta m = \frac{g^2}{4\pi} m_W \sin^2\frac{\theta_W}{2} \approx 160\text{–}170\ \mathrm{MeV}$$

Charge ±1 states tends to have macroscopic lifetime.

Best for the triplet (wino)

More challenging for higher (n=odd) mutiplet, and the doublet.

Signal rate



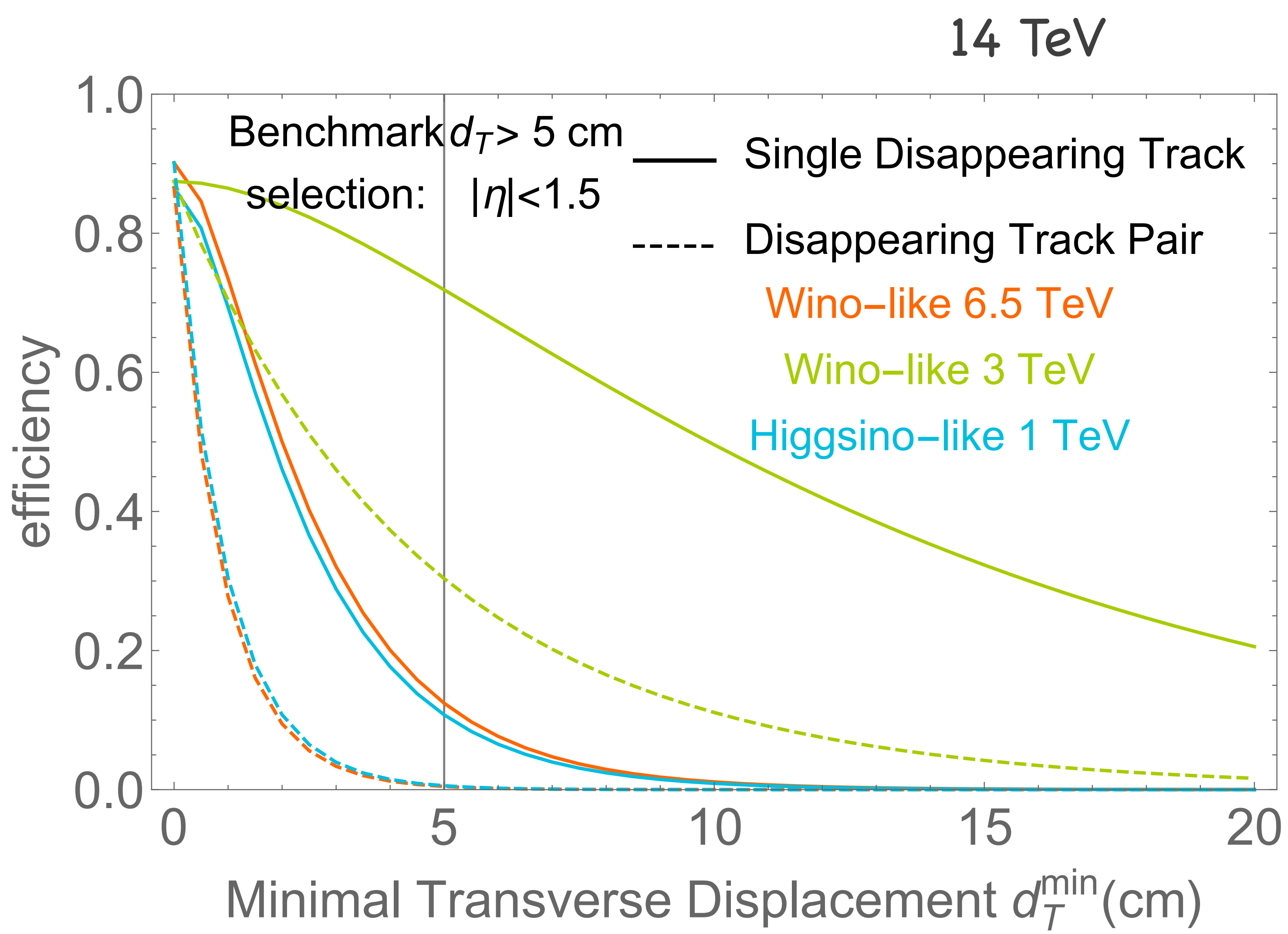
Boost matters.

Heavy WIMP⇔ less boost⇔ lower eff.

Higgsino has shorter lifetime, lower eff.

"survival" probability: $\epsilon_\chi(\cos\theta, \gamma, d_T^{\min}) = \exp\left(\frac{-d_T^{\min}}{\beta_T \gamma c\tau}\right)$ $\beta_T = \sqrt{1 - 1/\gamma^2}\sin\theta$

Signal rate



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As an guestimate of the reach, we take

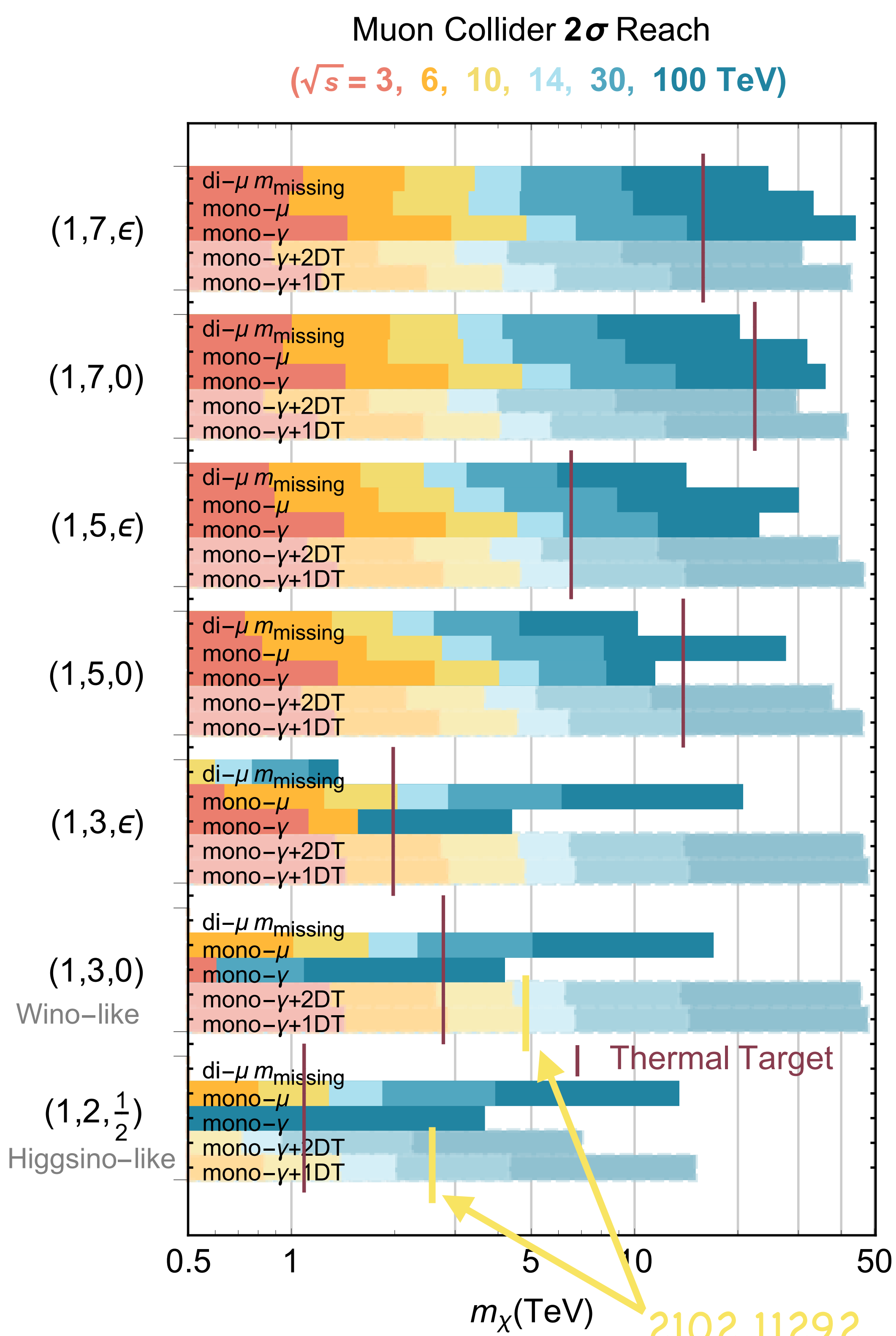
$d_T^{\rm min} = 5$ cm with $|\eta_\chi| < 1.5$

20(50) signal events for 2(5)σ reach.

Reach by channel

Luminosity benchmark:

$$\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\text{TeV}}\right)^2 \times 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$$



T. Han, Z. Liu, X. Wang and LTW, 2009.11287

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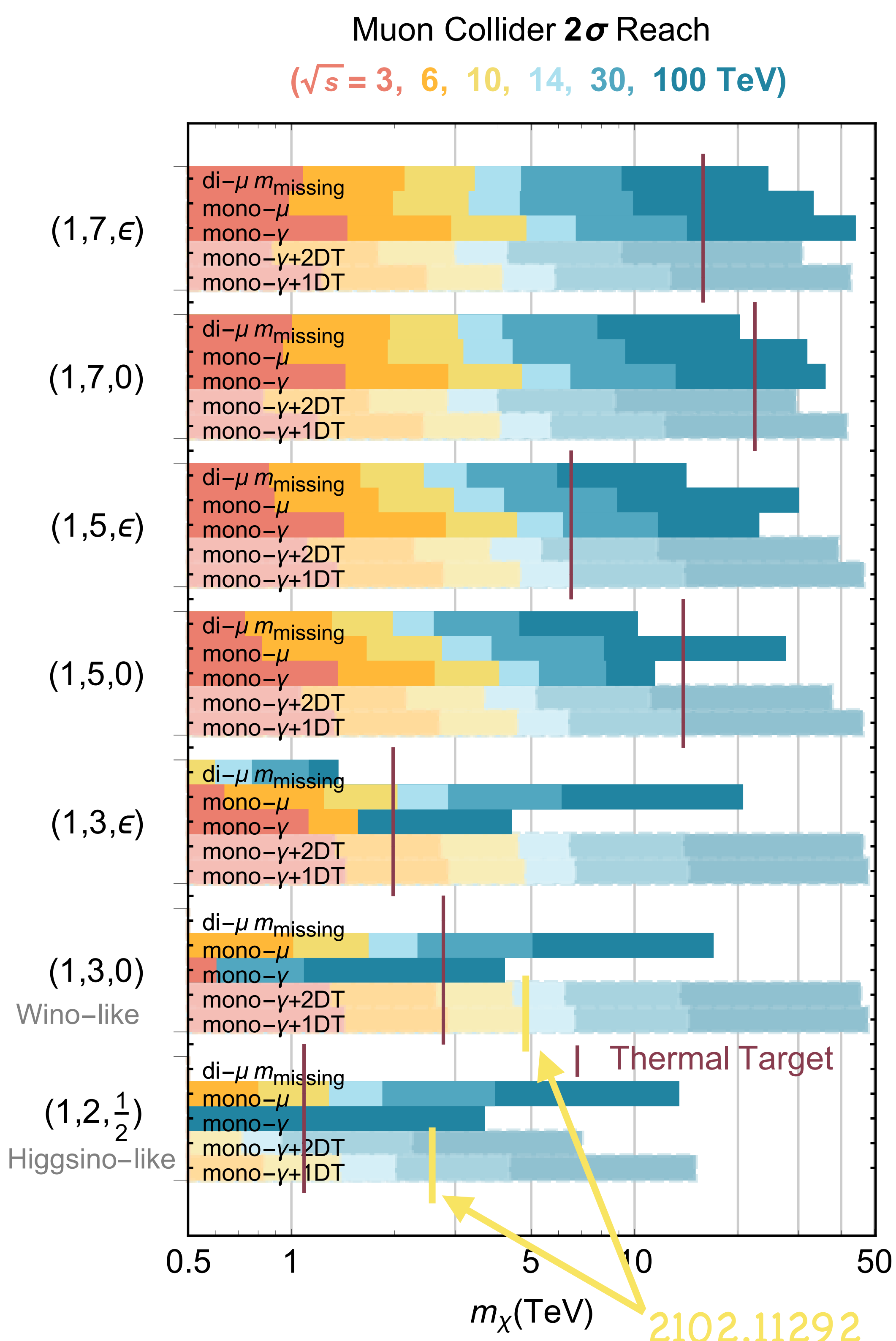

Mono-muon channel, high S/B. Strong for $m_\chi \ll E_{CM}$.

Good reach for lower dim (n≤3) multiplets.

Di-muon can be useful for higher multiplets.

T. Han, Z. Liu, X. Wang and LTW, 2009.11287

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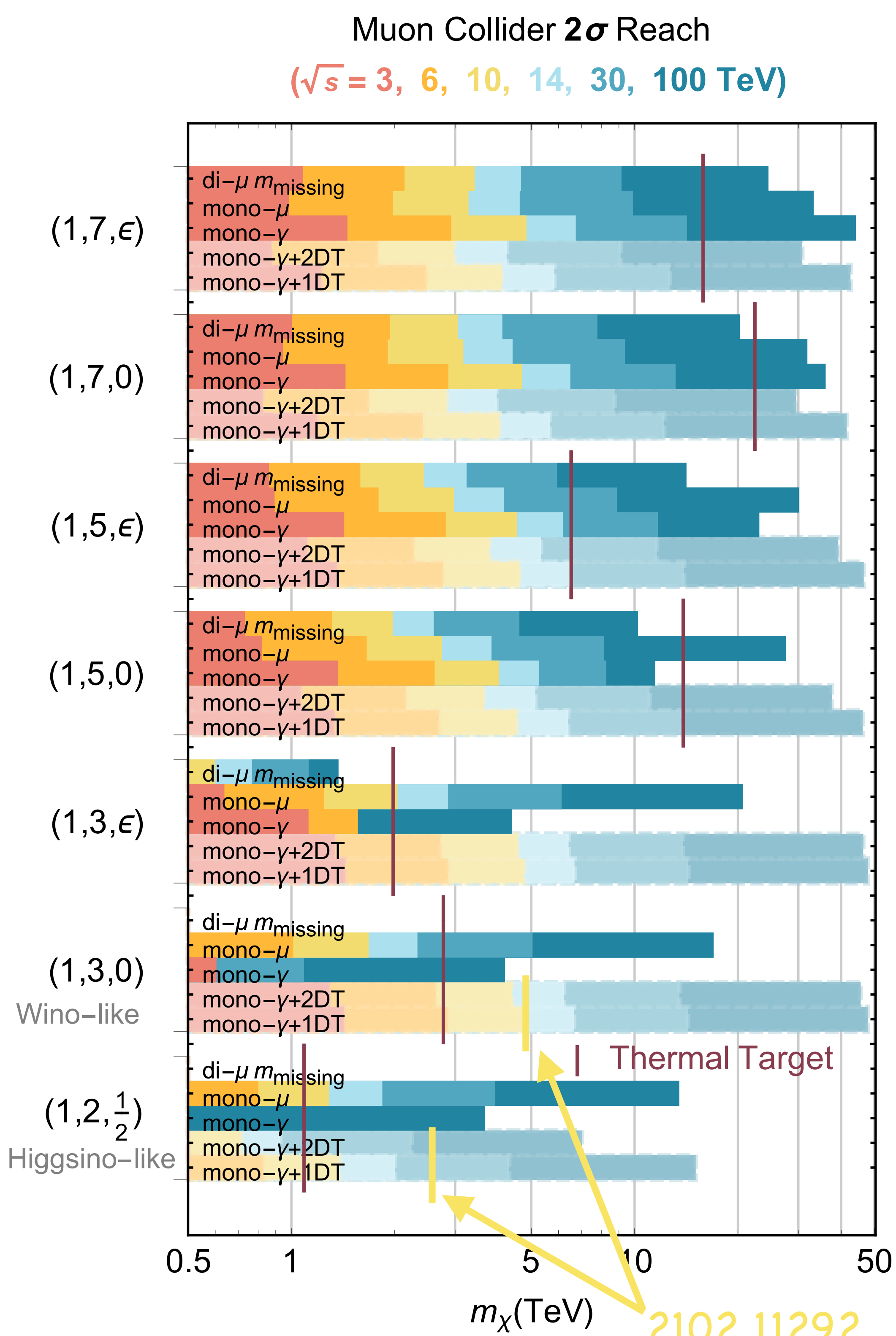

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Mono-photon channel, low S/B, systematics dominated.

Not yet reach $m_\chi \approx 1/2\ E_{CM}$.

Stronger reach for higher dim (n≥5) multiplets, coupling enhancement, higher multiplicity.

T. Han, Z. Liu, X. Wang and LTW, 2009.11287

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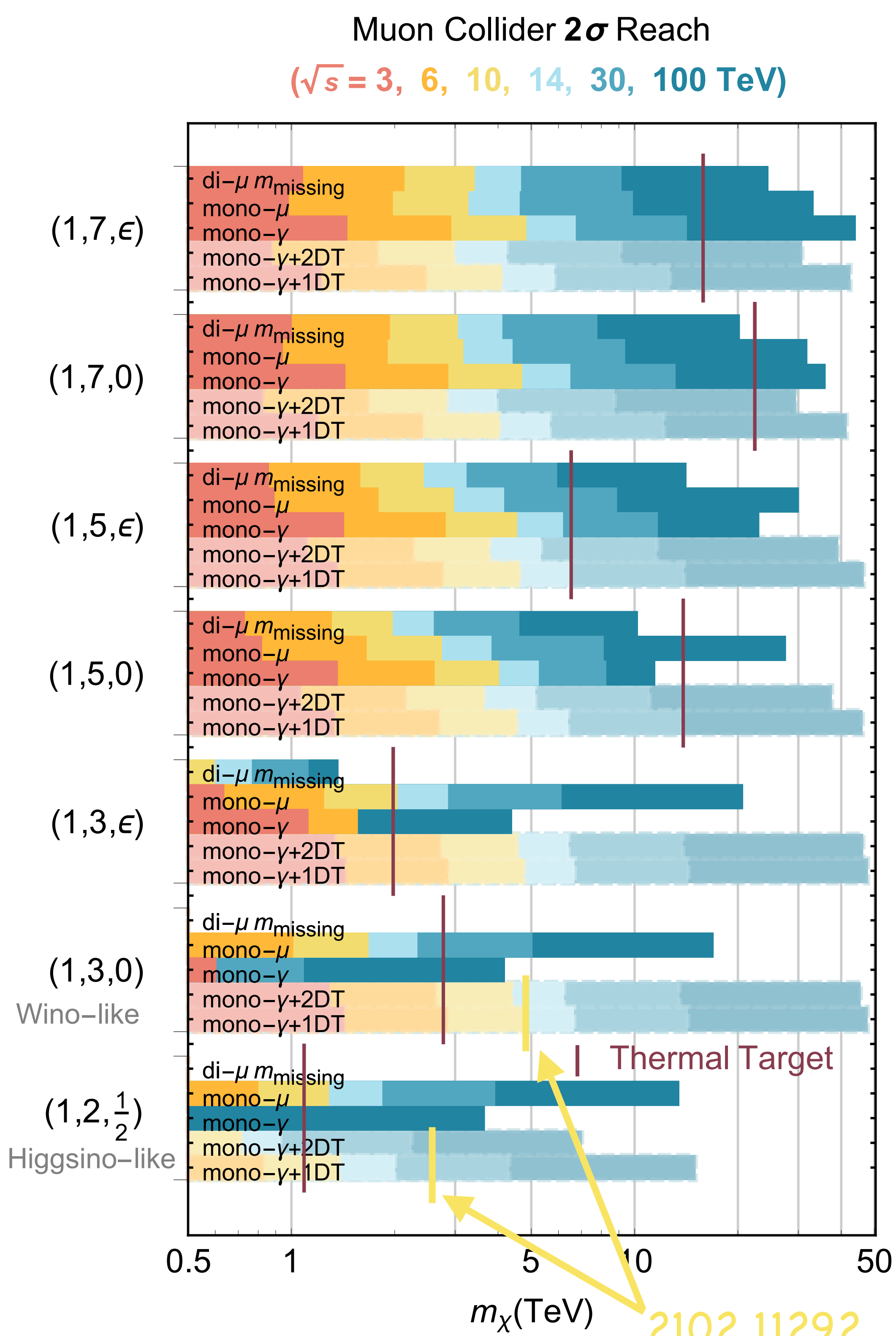

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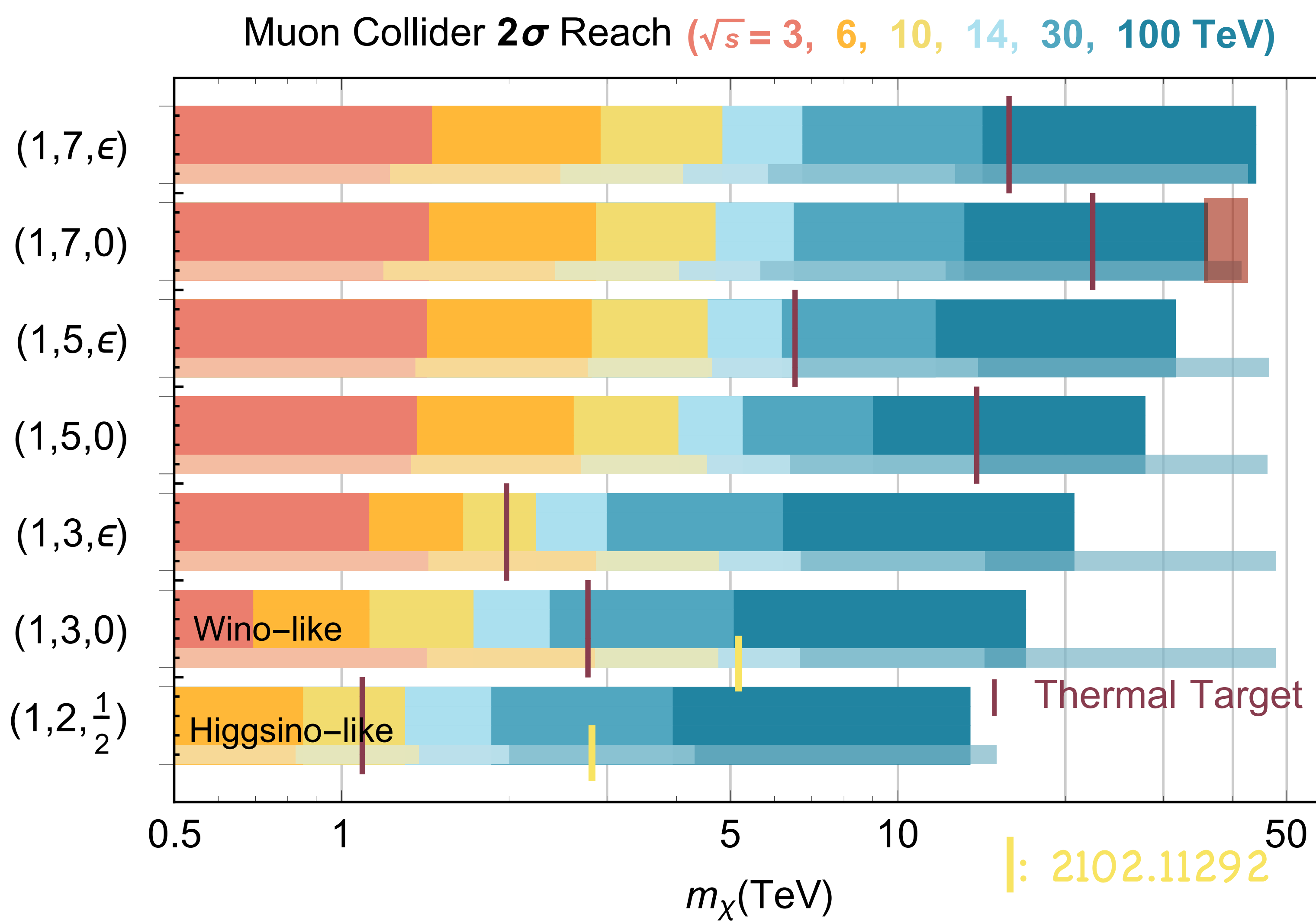
Stronger reach for higher dim ($n \geq 5$) multiplets, coupling enhancement, higher multiplicity.

Disappearing track. Great potential! Not quite reaching $m_\chi \approx 1/2\ E_{CM}$ (close for the triplet), since some boost still needed (particularly for $n \geq 5$)

T. Han, Z. Liu, X. Wang and LTW, 2009.11287

Summary: the reach

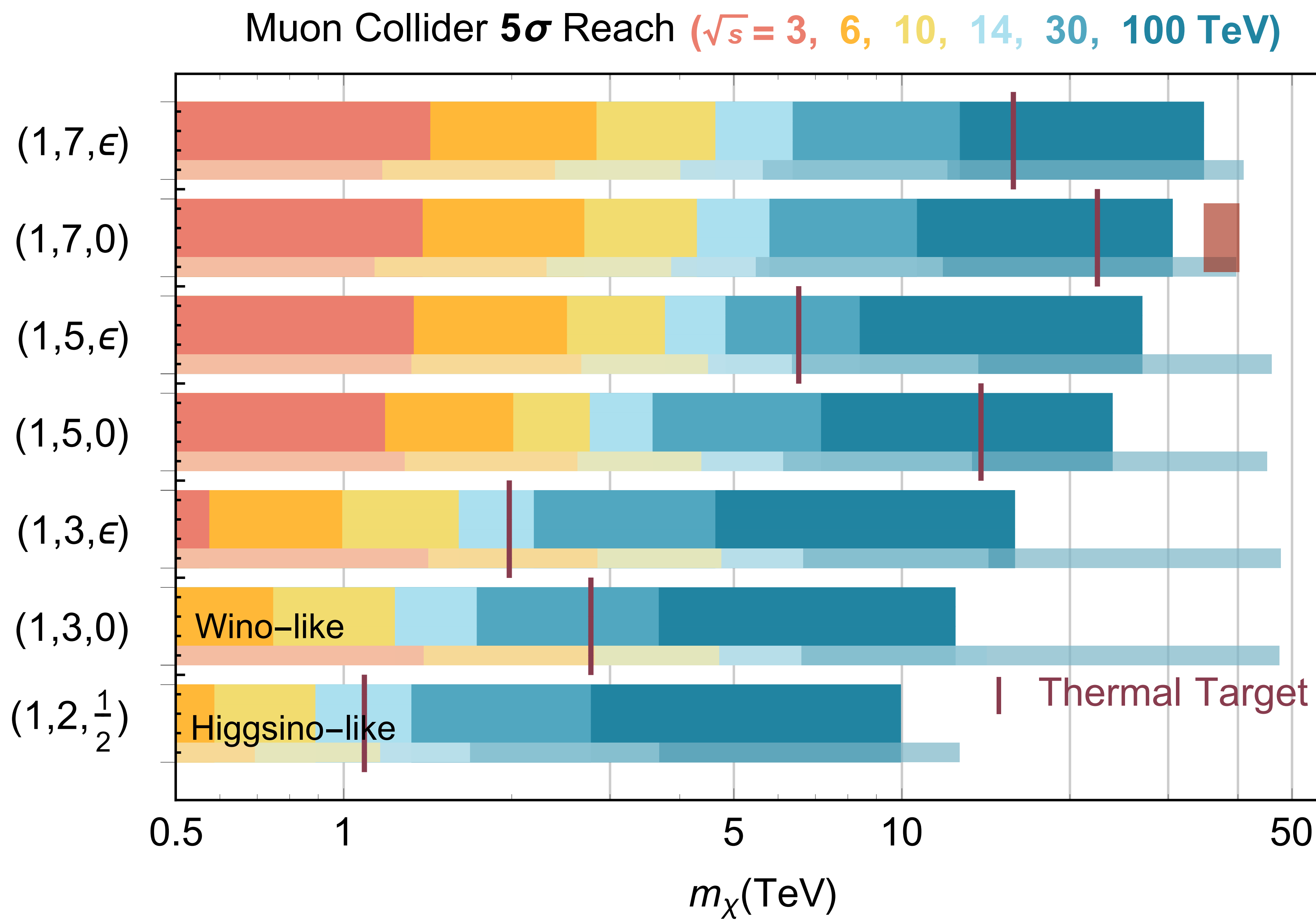


With inclusive signal: E_{CM} ≈ 14 TeV enough to cover n≤3 multiplets.

Higher energy needed to cover higher multiplets.

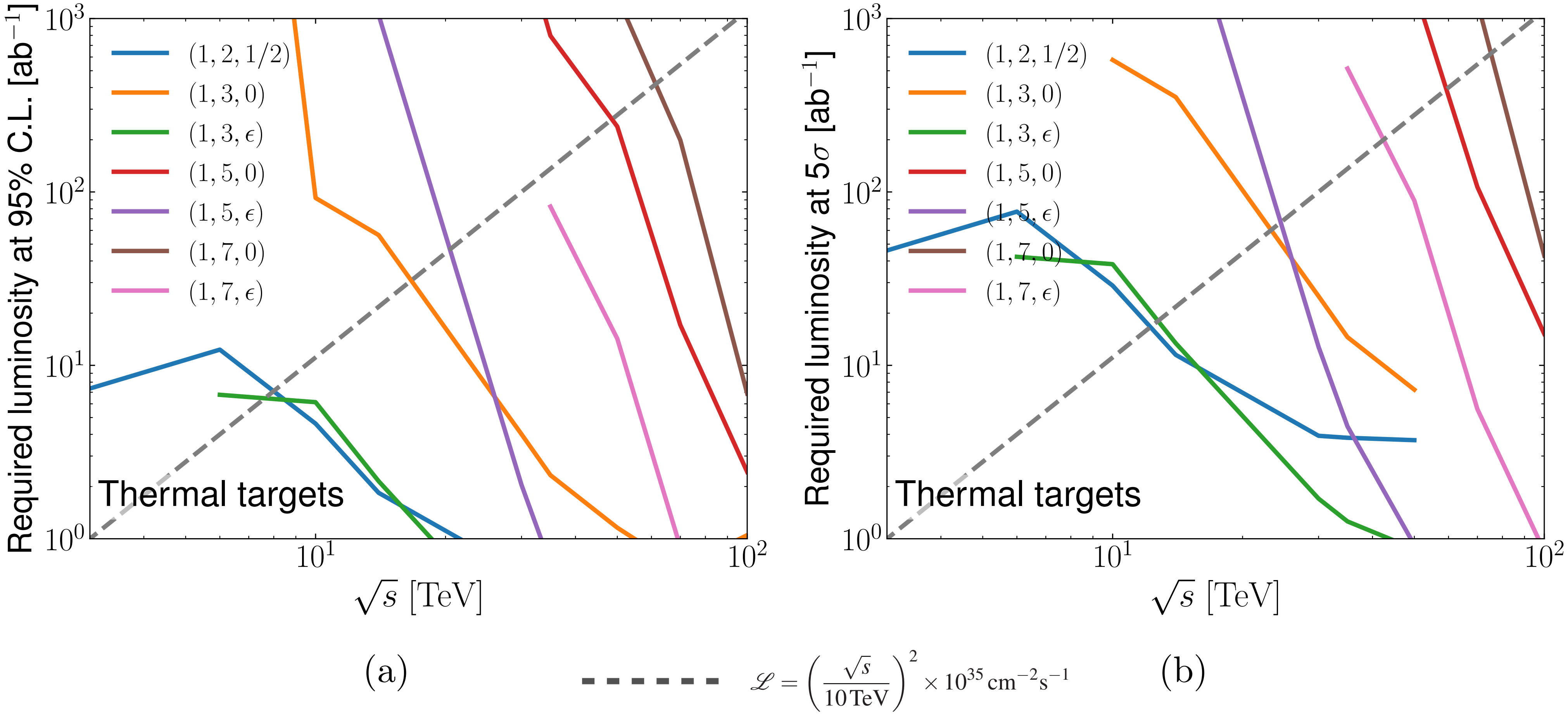
With disappearing track: potential to reach almost $m_\chi \approx 1/2\ E_{CM}$

5σ discovery reach



Luminosity and energy: trade off

Inclusive searches:



(a) (b)

Some examples

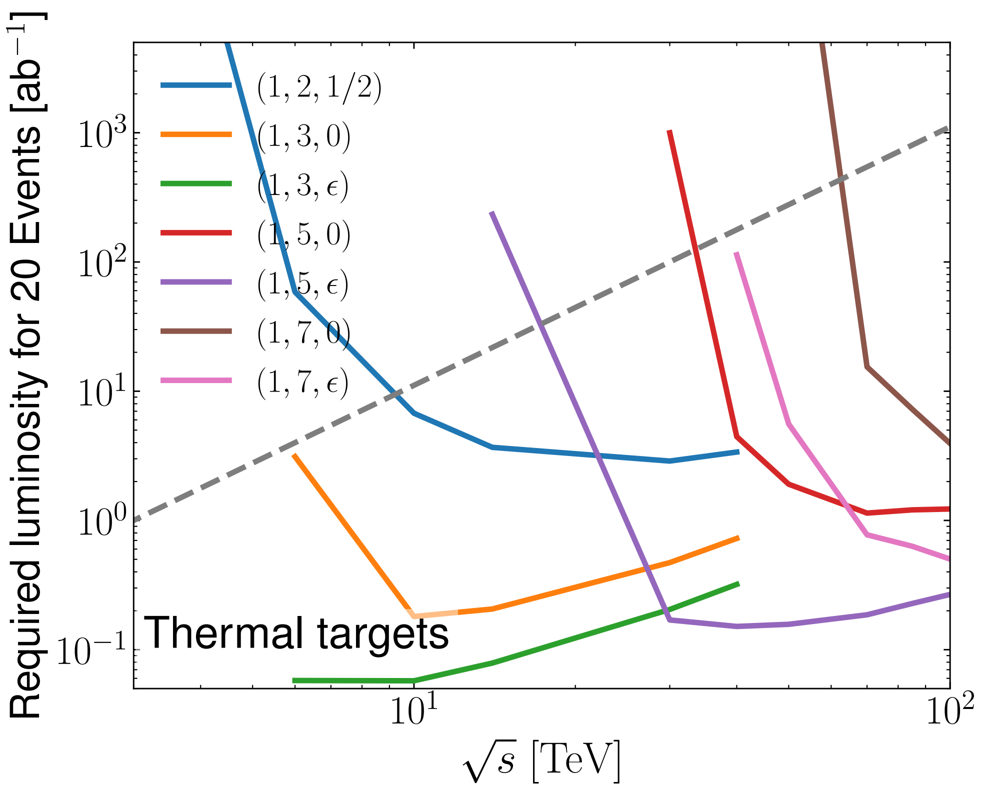
doublet: 5 ab^{-1} at 10 TeV

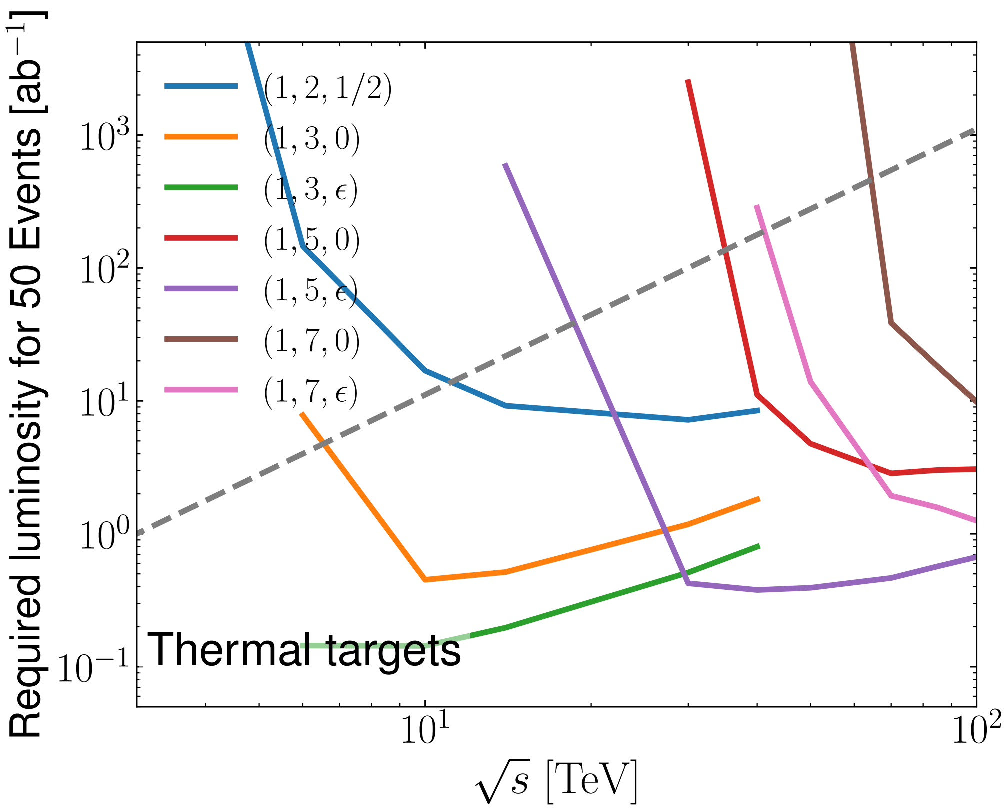
Dirac triplet: 6 ab^{-1} at 10 TeV or 2 ab^{-1} at 15 TeV

Majorana 5-plet: 300 ab^{-1} at 60 TeV or 3 ab^{-1} at 100 TeV

Luminosity and energy: trade off

Disappearing track searches





Some examples

doublet: 10 ab^{-1} at 10 TeV or 3 ab^{-1} at 20 TeV

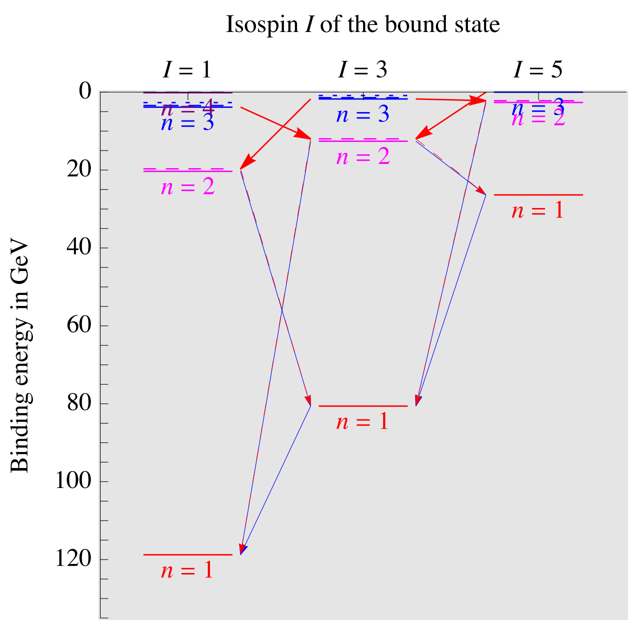
Dirac triplet: < 0.1 ab^{-1} at 6 TeV

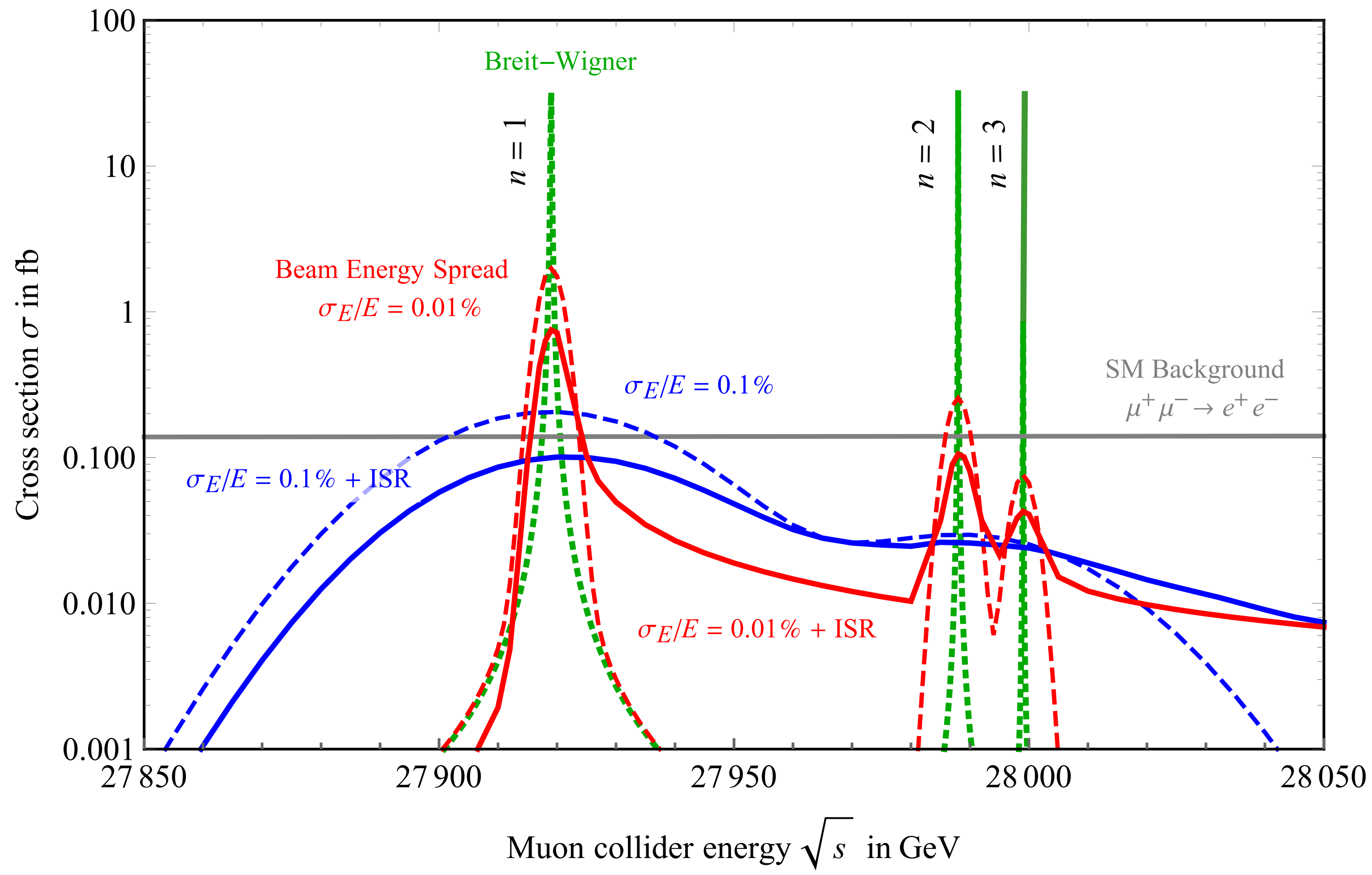
Majorana 5-plet: 100 ab^{-1} at 30 TeV or 1 ab^{-1} at 100 TeV

Dirac 7-plet: 100 ab^{-1} at 40 TeV or 10 ab^{-1} at 50 TeV

More fun with minimal DM

Bottaro, Strumia, Vignaroli, 2103.12766





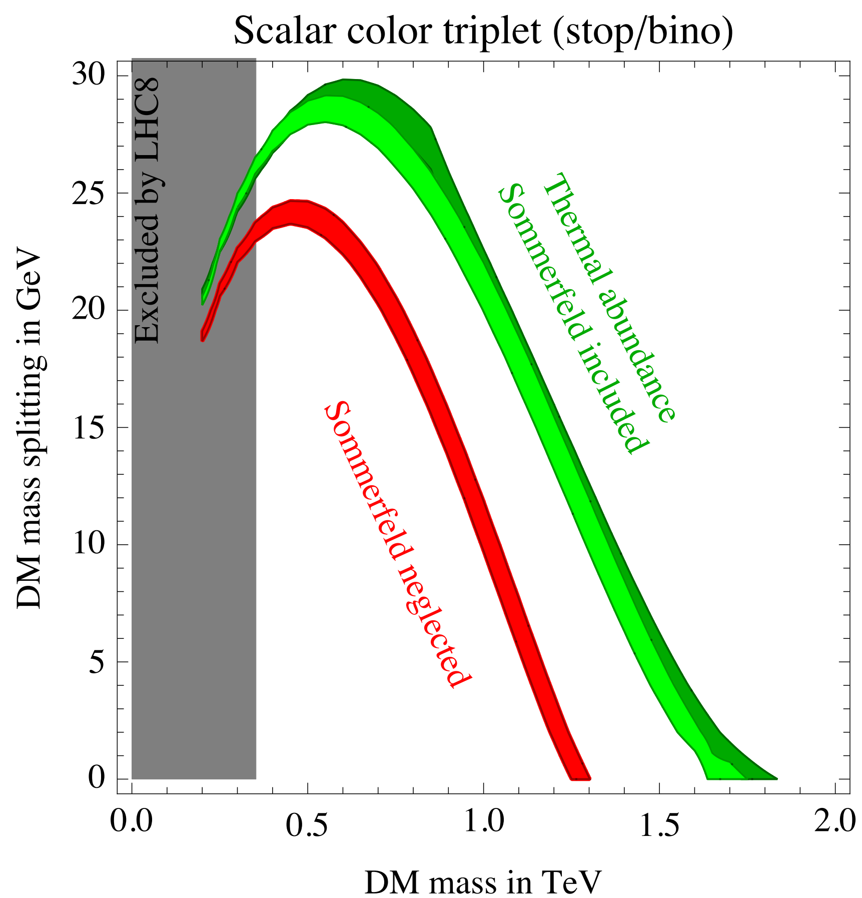
bound states of 14 TeV 5-plet

Beyond simplest model

Further detailed studies could be useful

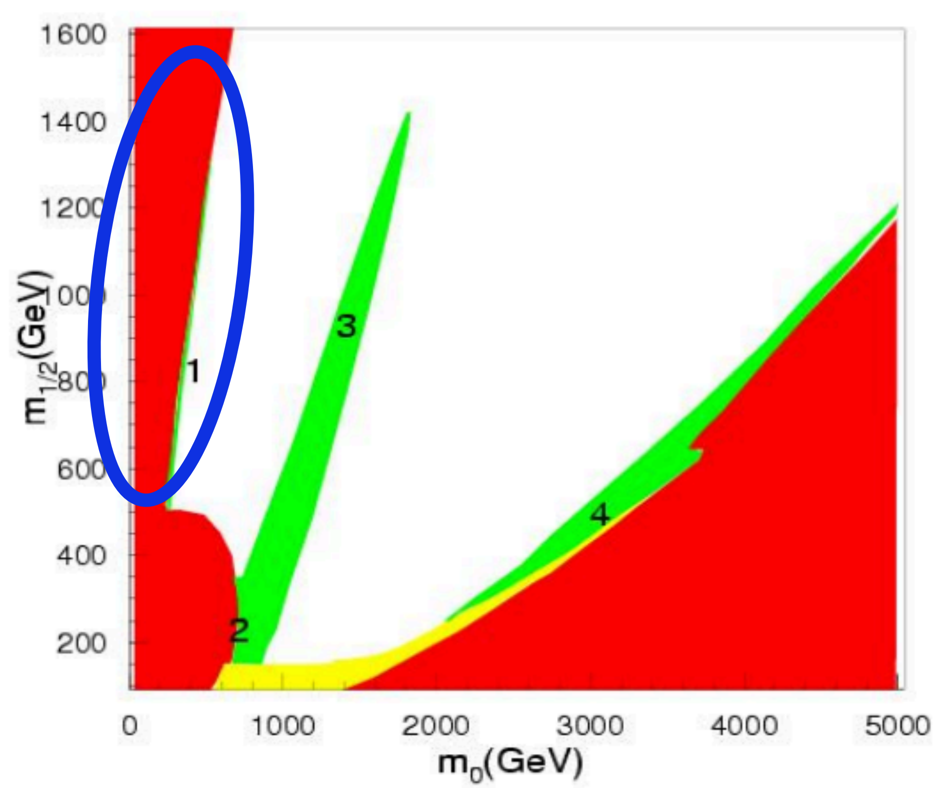
Additional scenarios

- Coannihilation.



De Simone, Giudice, Strumia, 2014

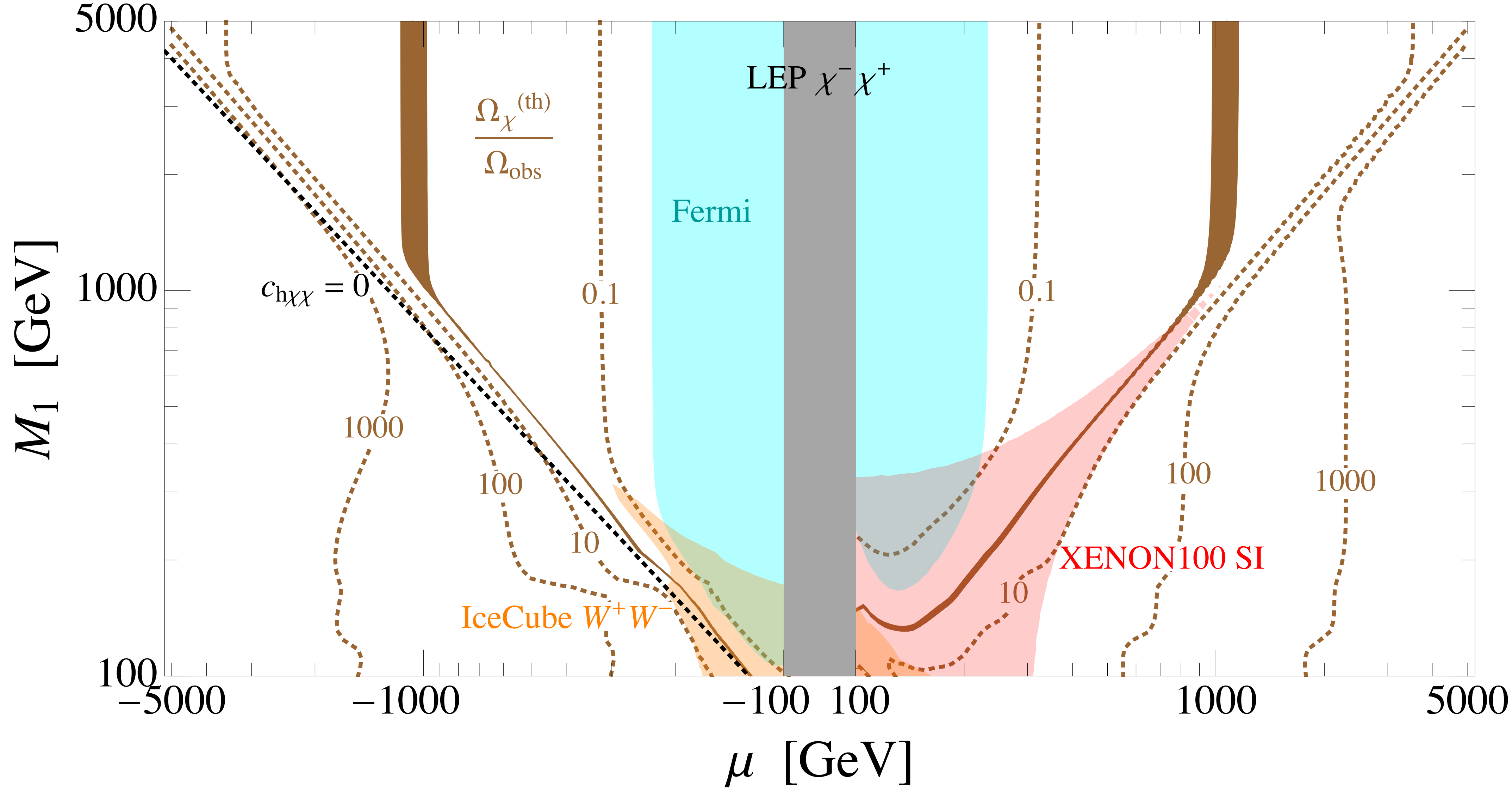
stau coannhilation



Larger (still compressed) mass splitting, no disappearing track. More challenging

Expect to be covered by the inclusive missing mass searches.

Well temper-like

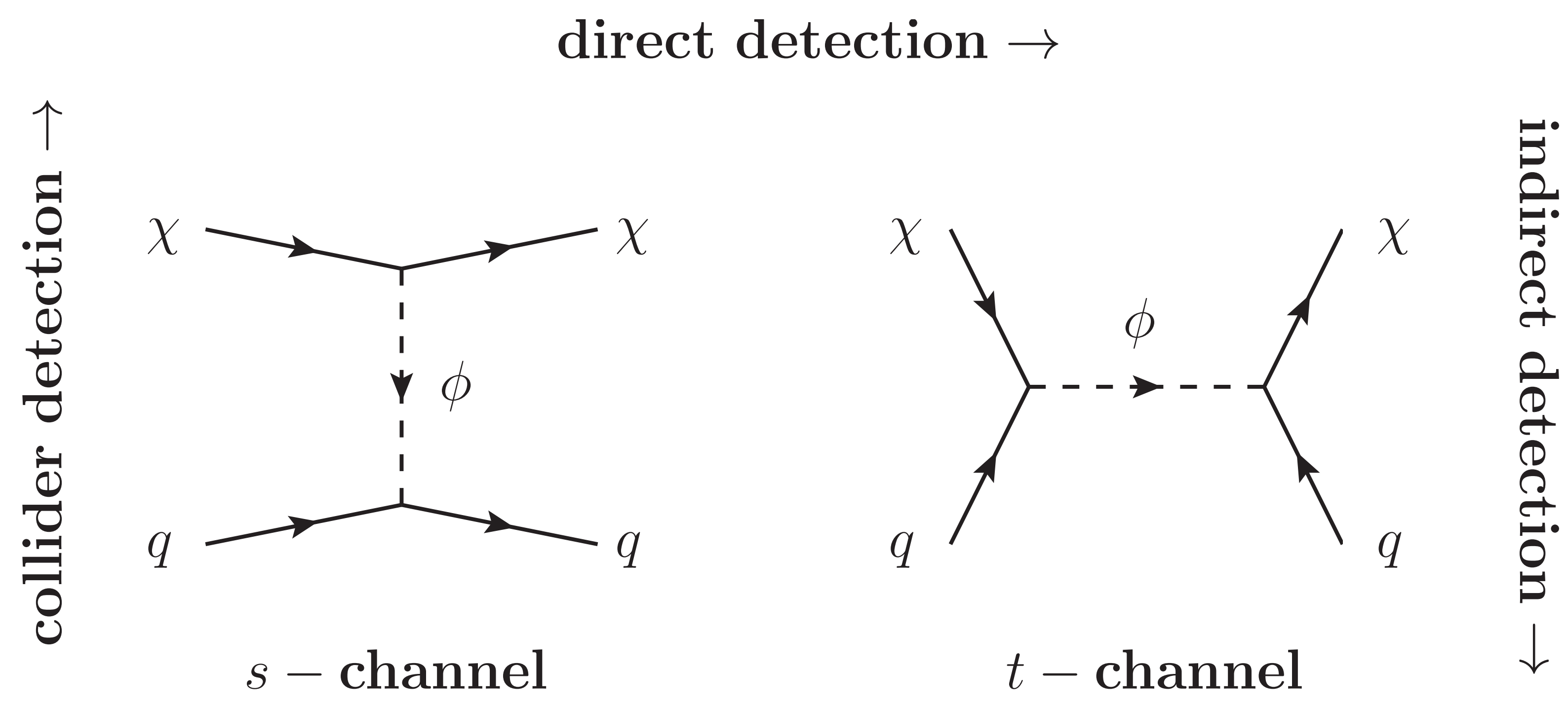


Arkani-Hamed, Delgado, Giudice, 0601041
Cheung, Hall, Pinner, Ruderman, 1211.4873

Probably similar to the other compressed scenarios.

Additional scenarios

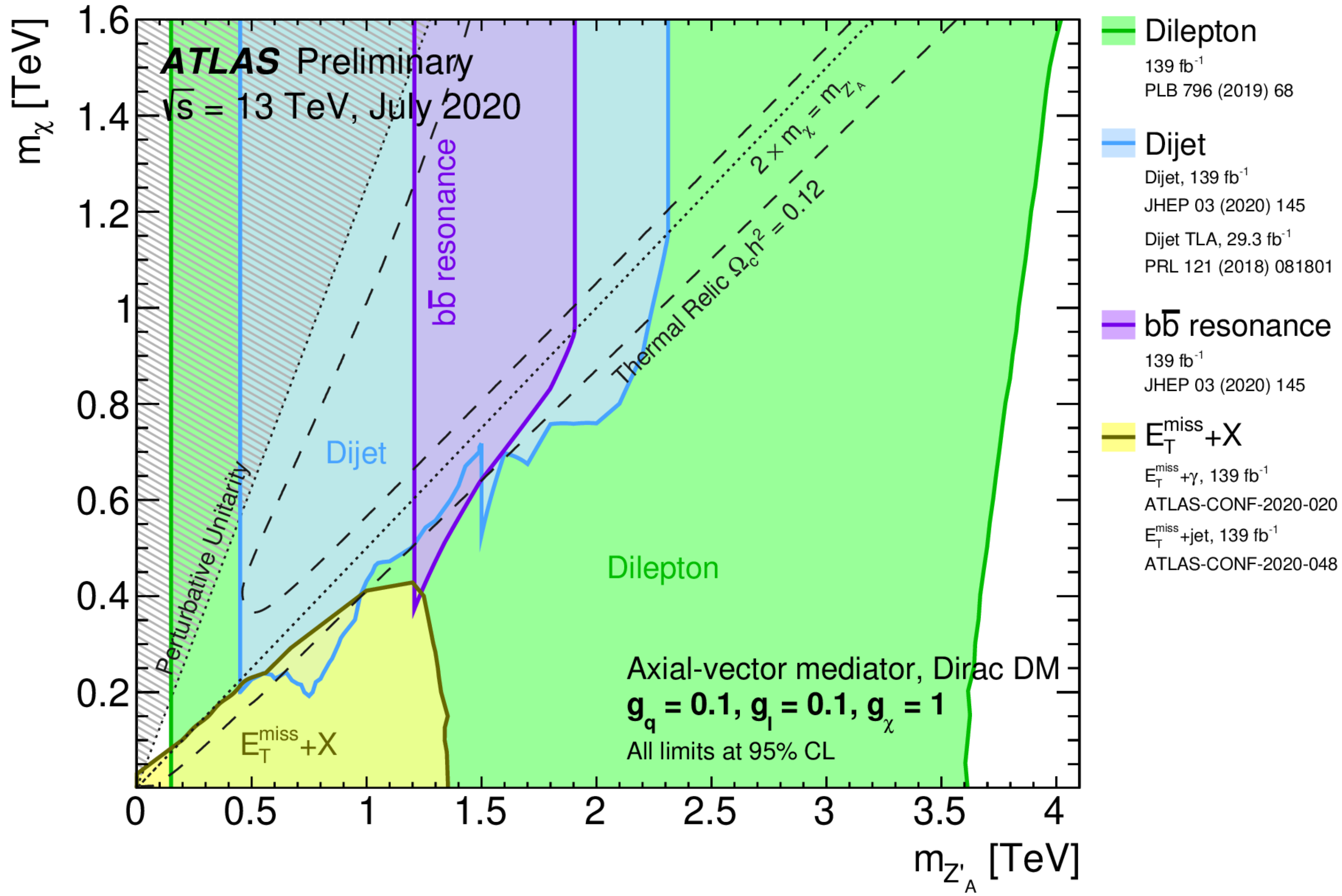
- Simplified models. (More complicated the minimal DM.)



Introducing new mediators between DM and SM.

Muon collider sensitive to mediators which couples to muons.

Search for mediators



Typically, direct search for mediators more sensitive.

Expected to be similar at muon collider.

Inverse problem

- If we discover WIMP, how well we can measure its property and verify it is the WIMP?
  - Mass
  - Spin
  - Coupling
  - ...

Vast (old) literature for LHC, also studies for ILC, CLIC

- Lepton colliders have advantages (simpler kinematics, cleaner).

- Expect muon collider to be effective here as well.

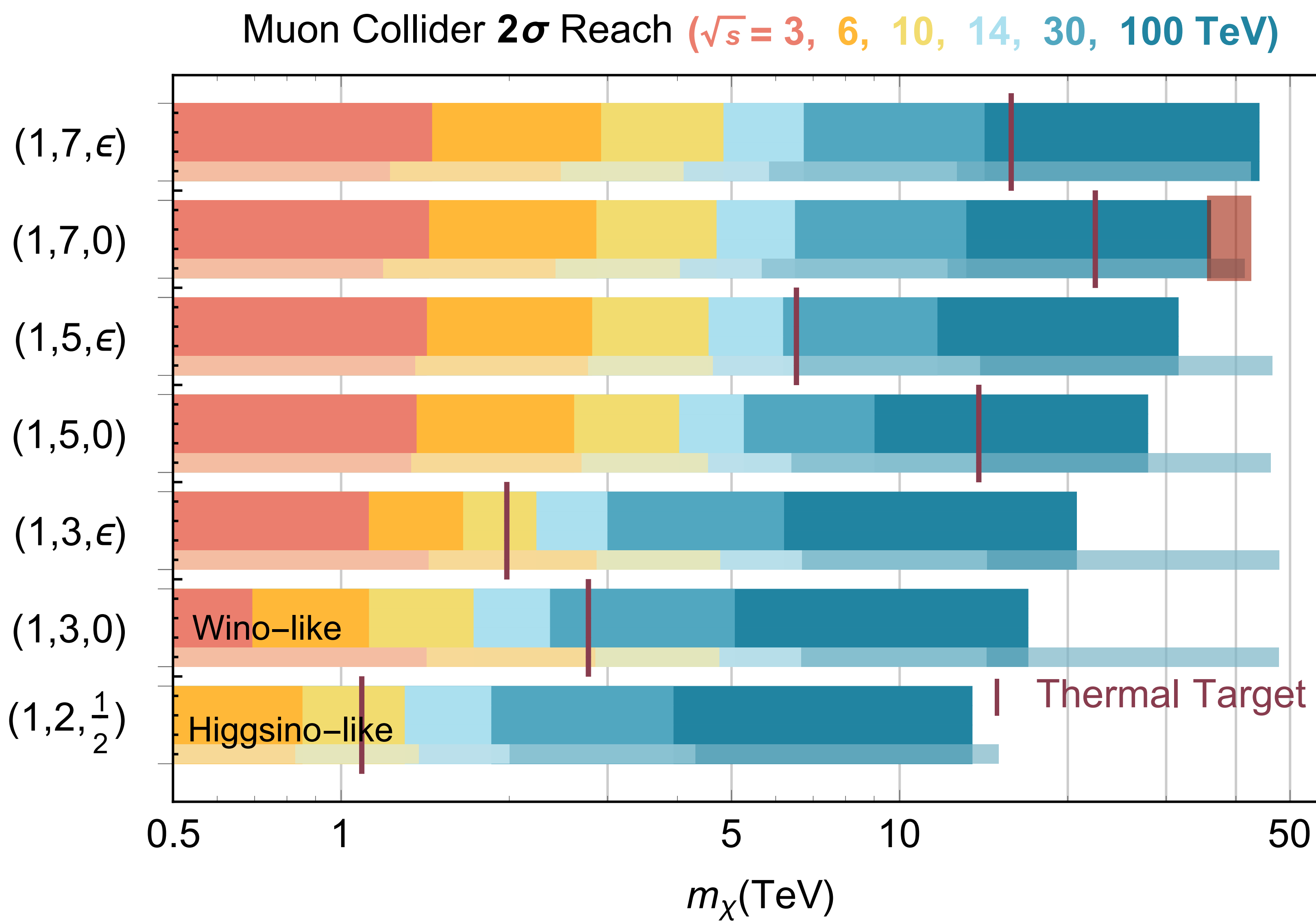
And, of course

- Portals, dark photons, ...

However, in terms of dark matter

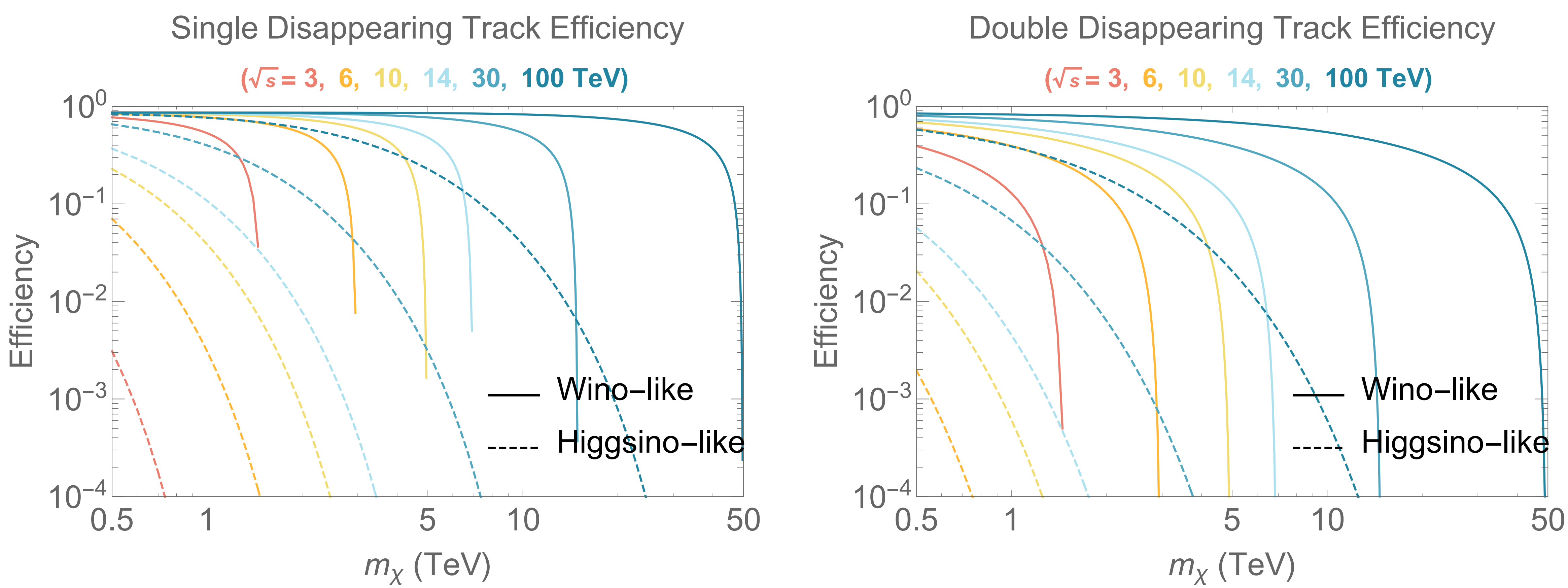
- The best physics case/target for high energy muon collider is to make a decisive statement on the WIMP scenario.

Conclusion



High energy muon collider can play a decisive role in probing WIMP dark matter!

Signal effciencies



Apply disappearing track to Drell-Yan mono-photon signal

Double disp-track signal has lower rate, but better for BIB

As a target/benchmark, use

20(50) signal events for 2(5)σ reach.

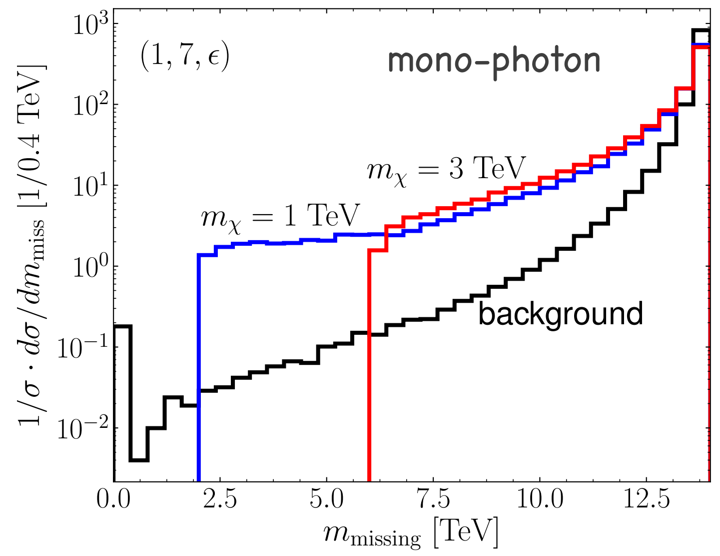
Inclusive missing mass searches

General cuts.

Angular acceptance: $10^\circ < \theta_{\rm obs} < 170^\circ$

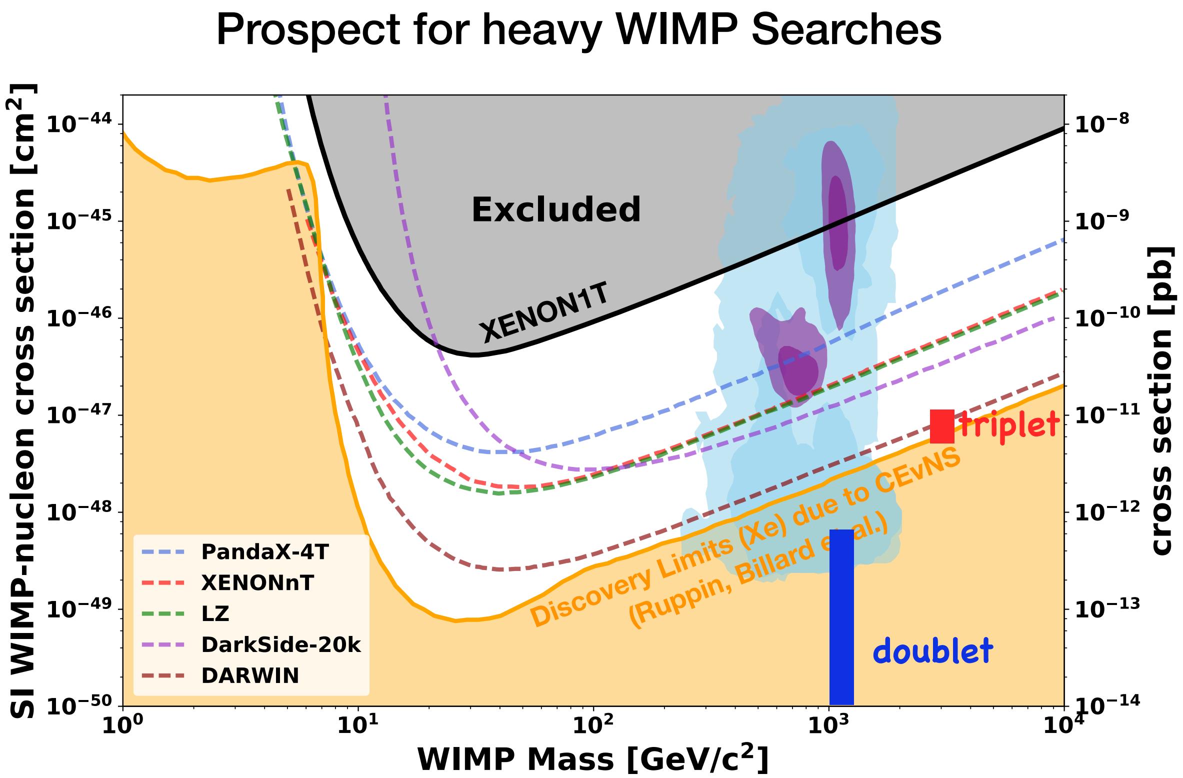
Due to shielding. Better forward coverage can be beneficial. More later.

Missing mass: $m^2_{\rm missing} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\rm obs})^2 \quad m^2_{\rm missing} > 4m_\chi^2$

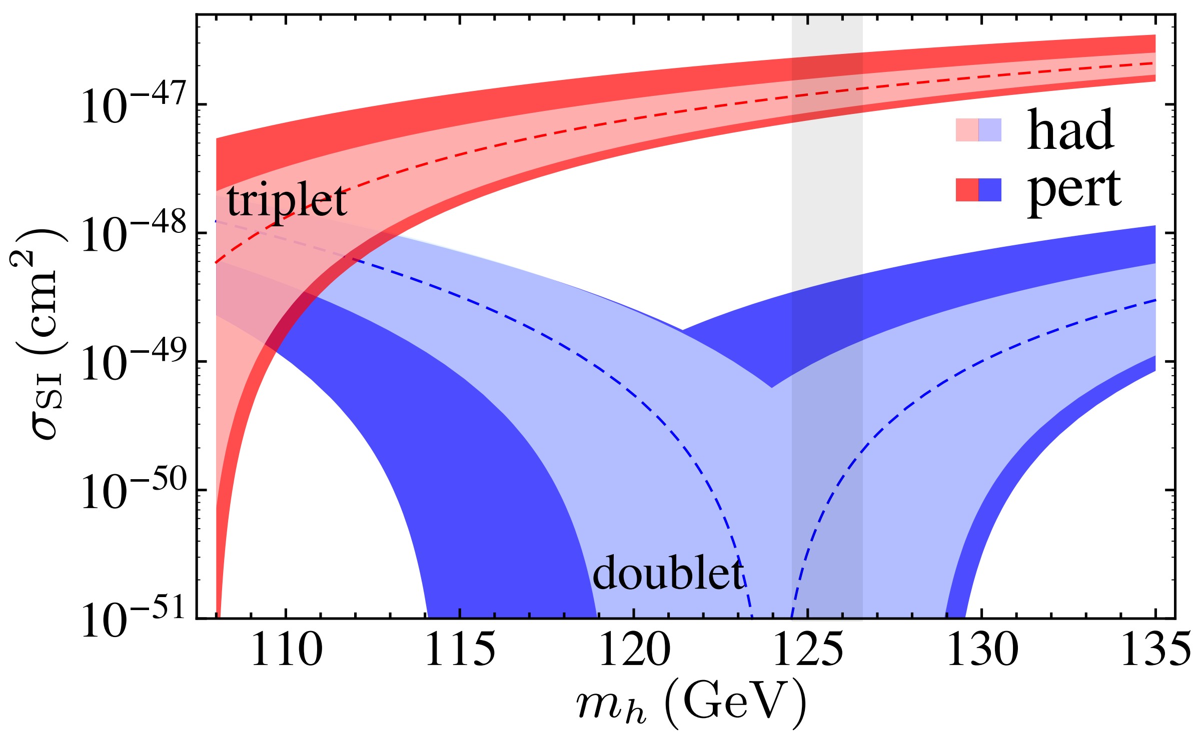


Useful for background suppression, especially for large dark matter mass

Direct detection



Hill and Solon, 1309.4902



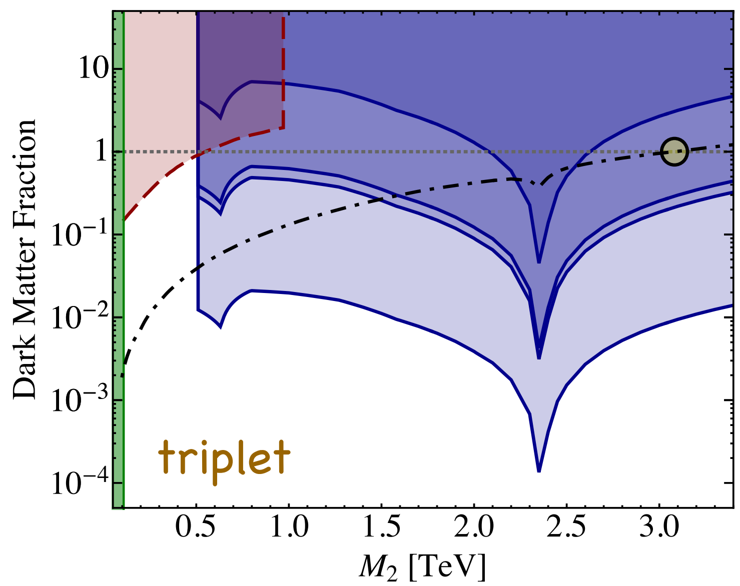
Scattering process loop induced.

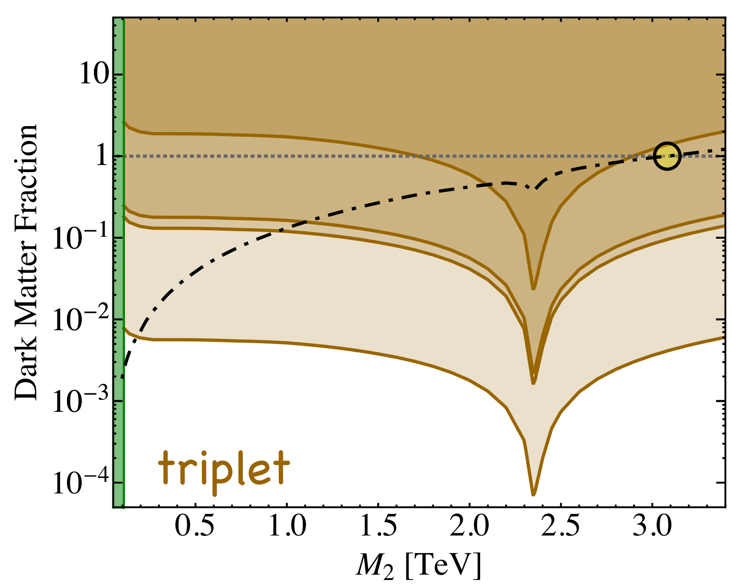
Large cancellation above two classes of diagrams.

Very challenging!

Indirect detection (di-photon ...)

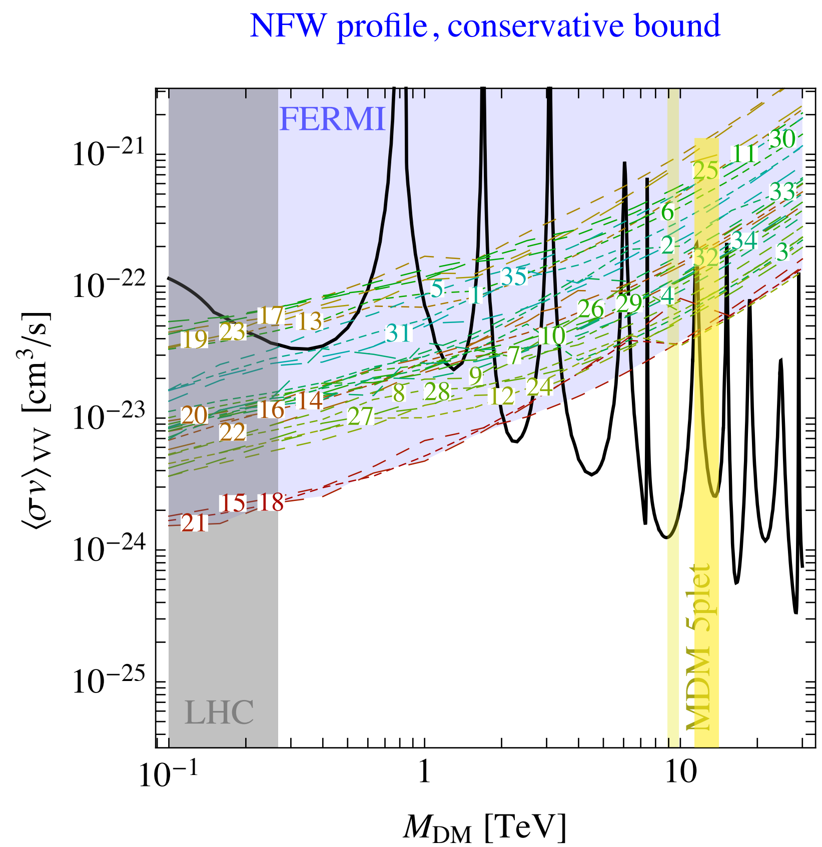
Cohen, Lisanti, Pierce, Slatyer, 1307.4082
Fan, Reece, 1307.4400





Doublet less constrained

Cirelli, Hambye, Panci, Sala and Taoso, 1507.05519

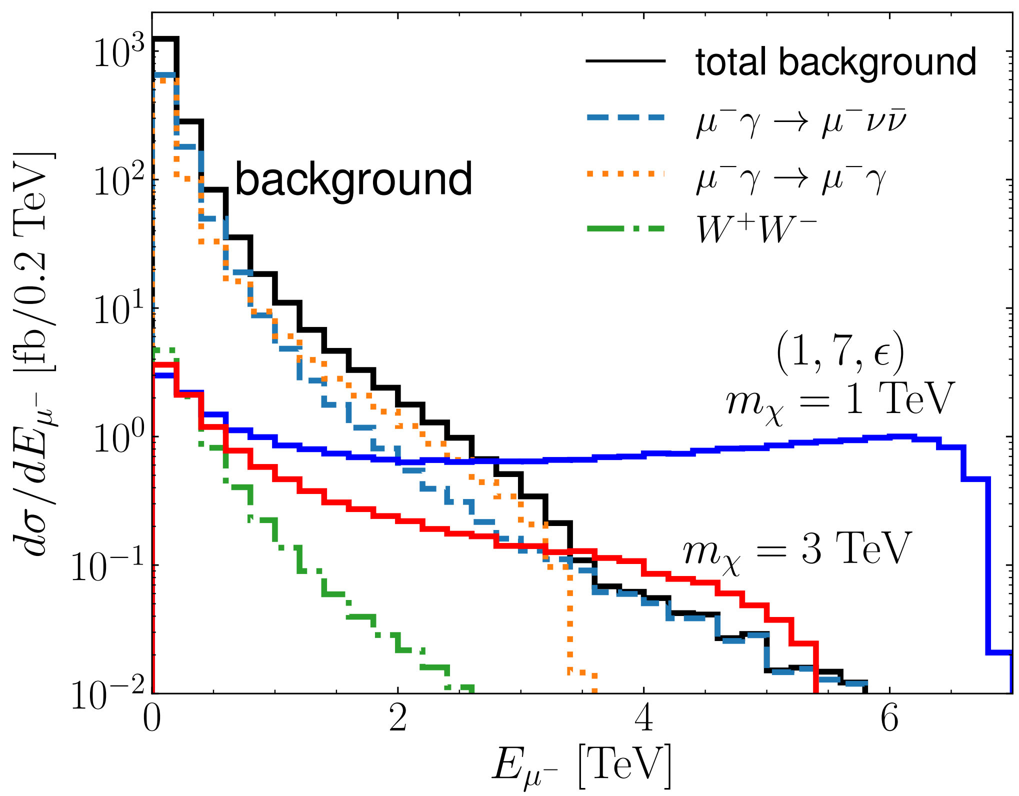


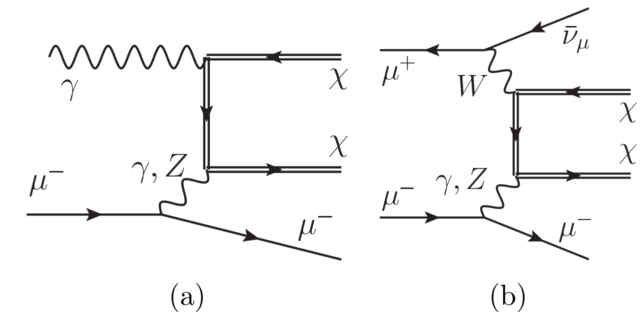
Certain cases constrained
(with large astrophysical uncertainties)

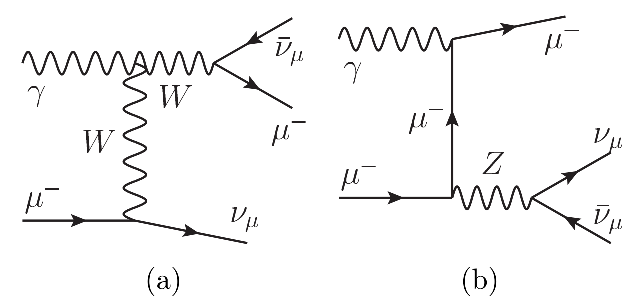
Will improve in the future. Could even see a signal.

Still, important to search/study such particles at a collider.

Some kinematics

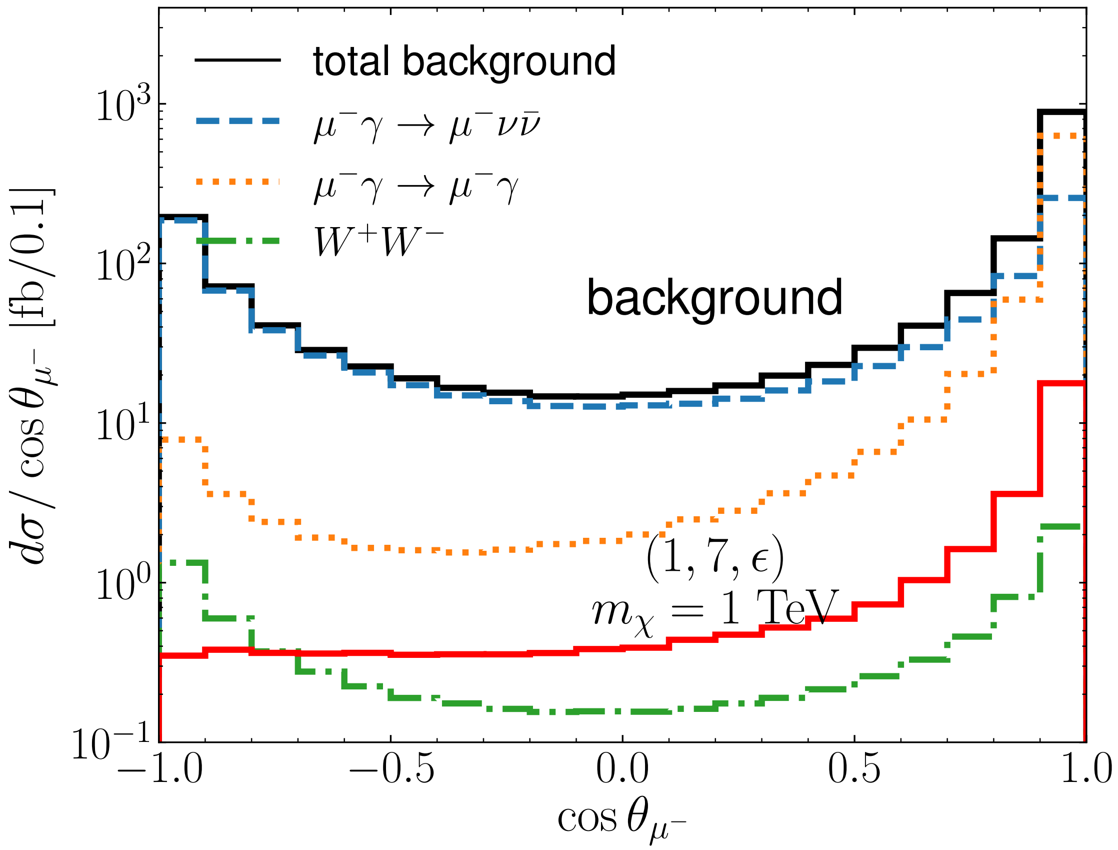


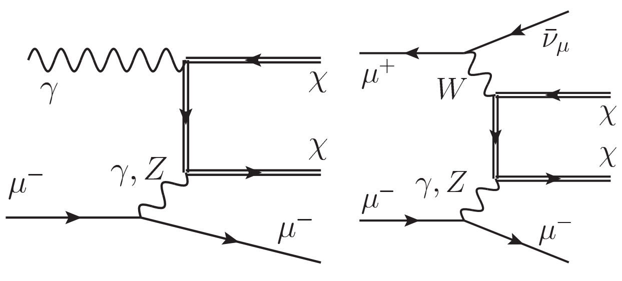


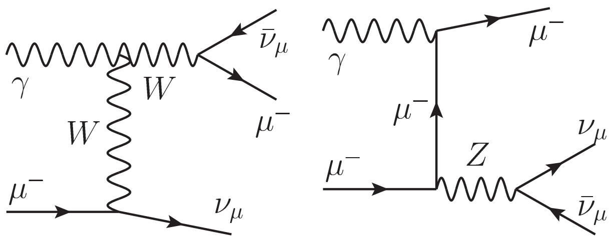


$$E_{\mu^\pm} > 0.71,\ 1.4,\ 2.3,\ 3.2,\ 6.9,\ 22.6\ \text{TeV}, \quad \text{for } \sqrt{s} = 3,\ 6,\ 10,\ 14,\ 30,\ 100\ \text{TeV}$$

Some kinematics

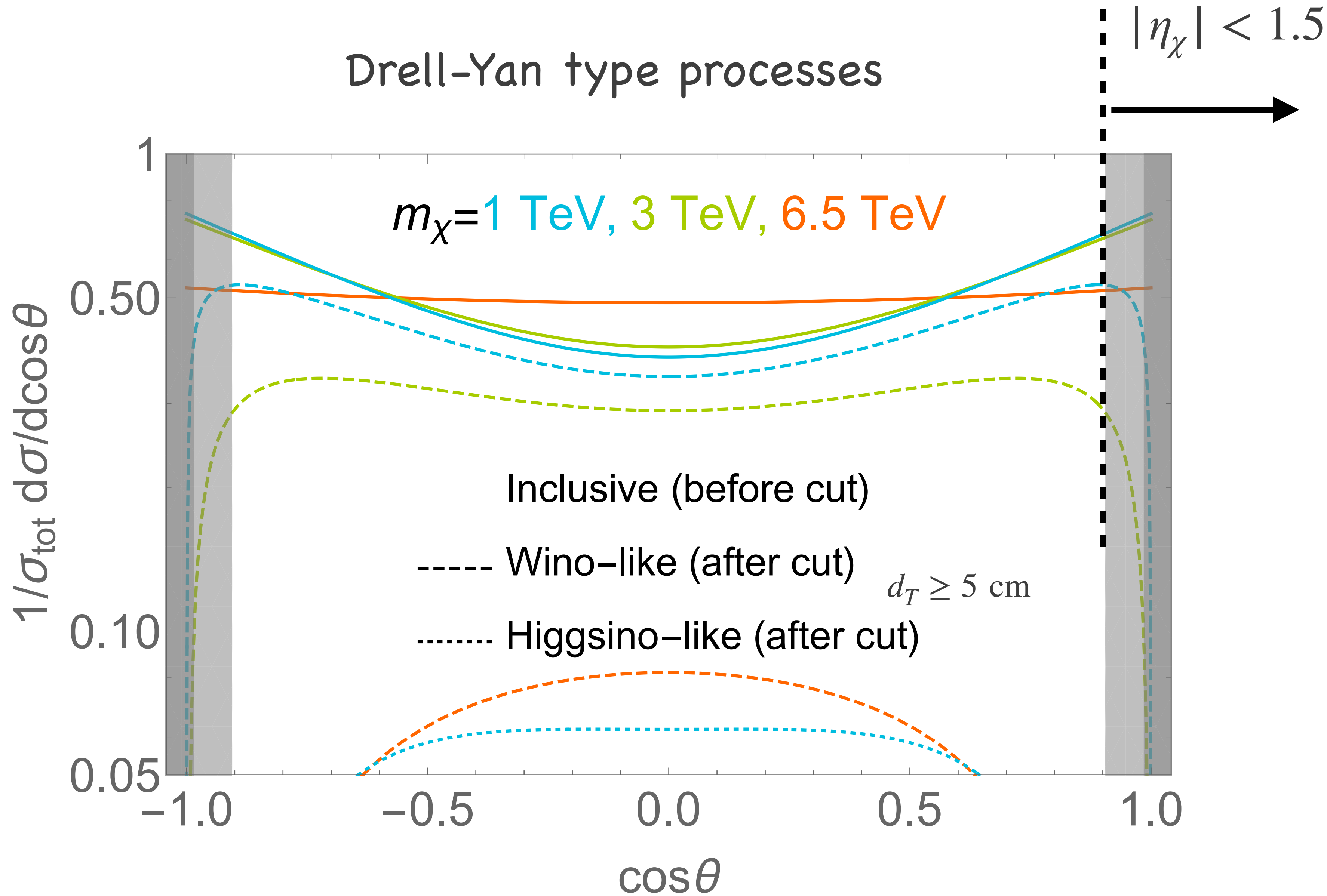




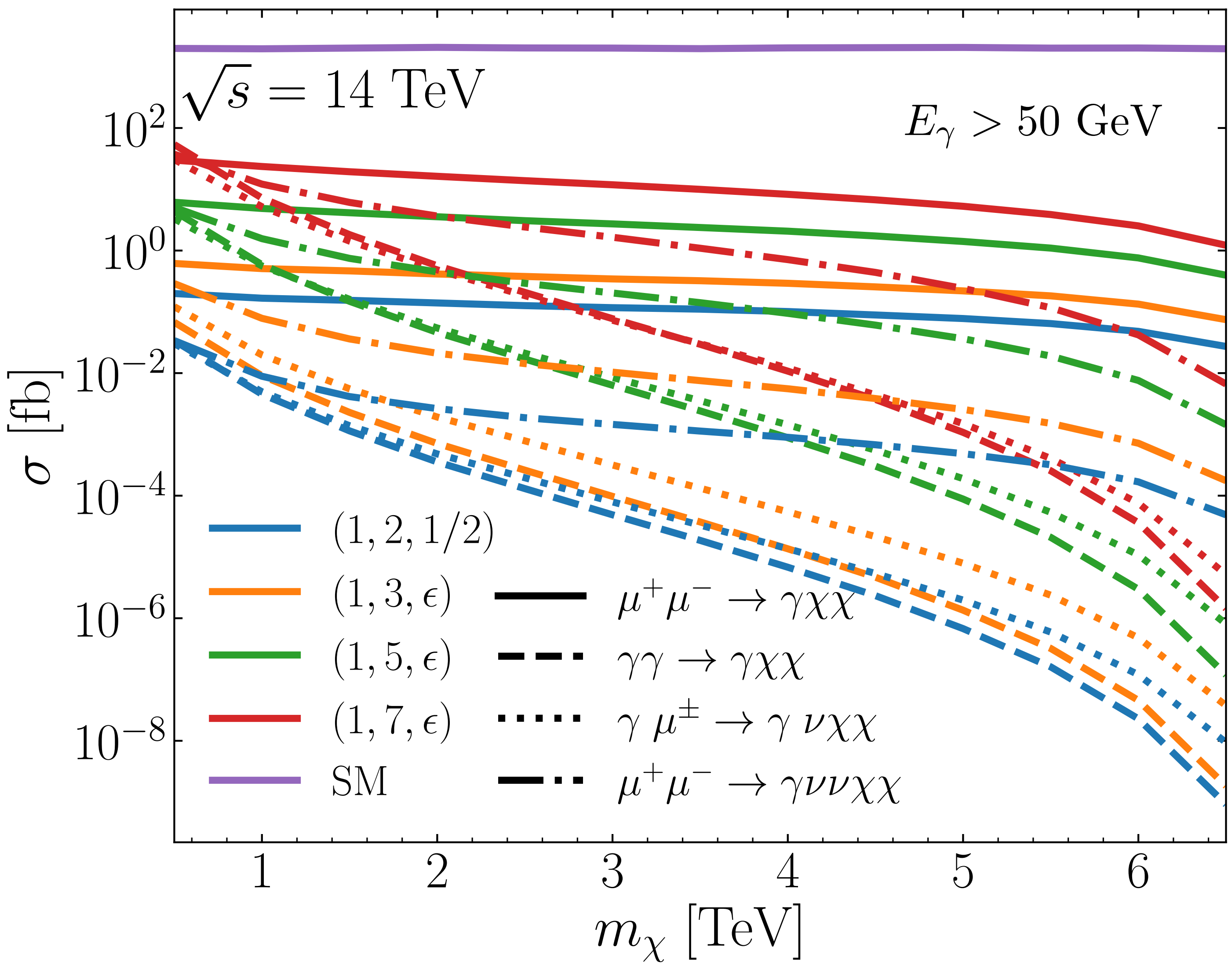


$$10^\circ < \theta_{\mu^-} < 90^\circ, \quad 90^\circ < \theta_{\mu^+} < 170^\circ$$

Angular distribution of the signal



Mono-photon rates



Drell-Yan like process dominate for large m_χ

Higher rate for higher multiplets: larger coupling (charge), higher multiplicity of final states.

FSR photon enhanced for higher multiplets.

VBF like processes falls off like m_χ^{-4}. Useful for $m_\chi \ll E_{CM}$.

Photon initial state treated "pdf"-like, used Effective photon approximation.