WIMP DM at muon colliders

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

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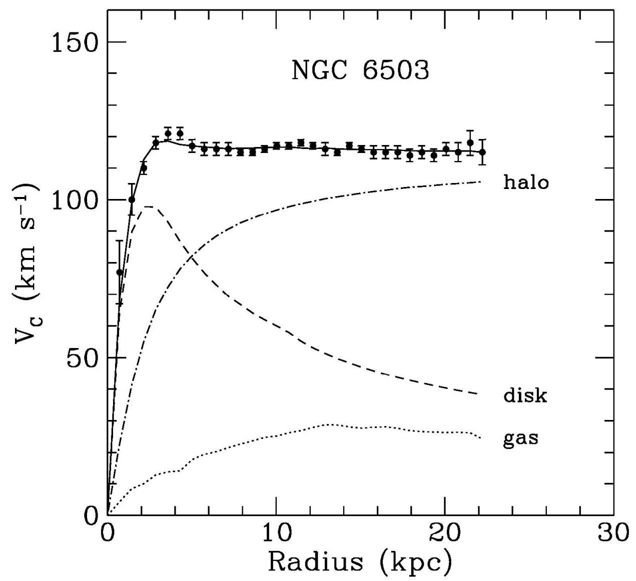
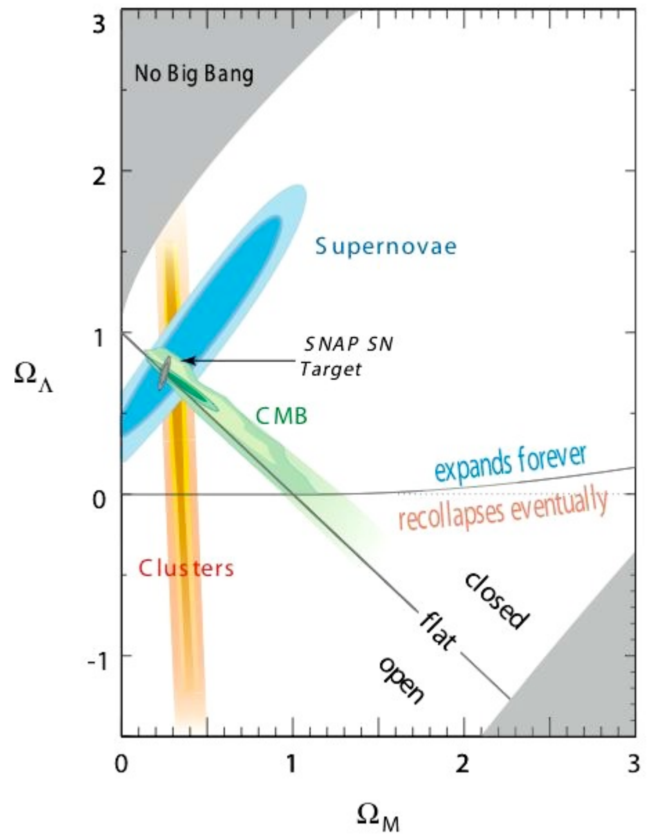
Dark matter

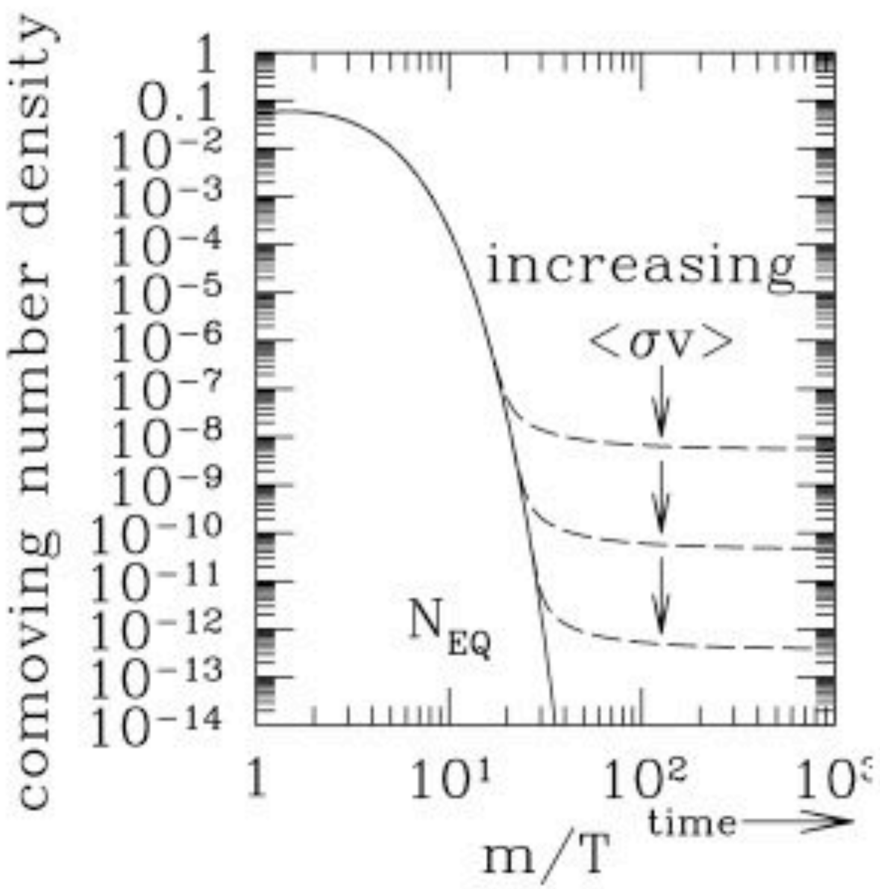


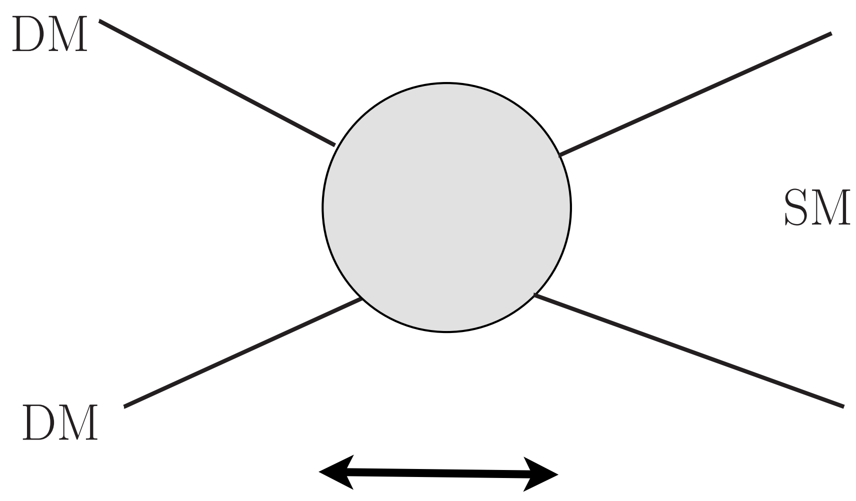


It is there.

Only seen its gravitational interaction.
We have to understand them better.
Collider search is a key approach.

WIMP

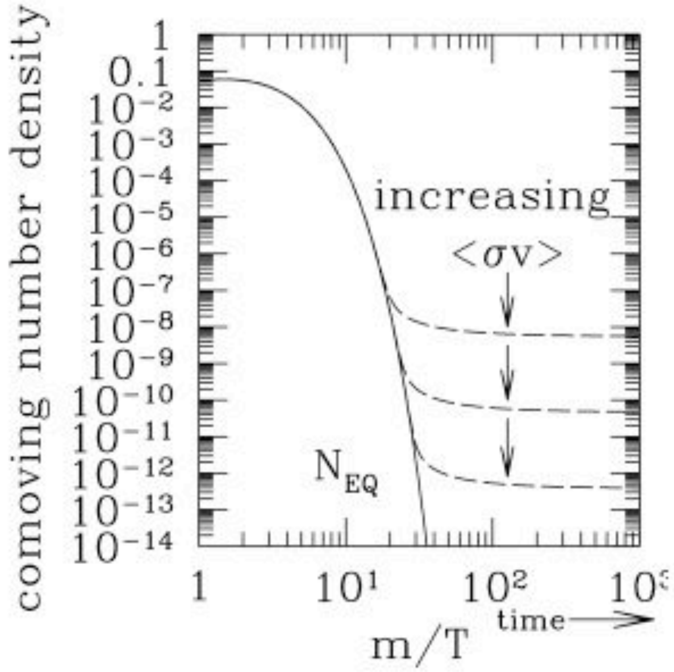


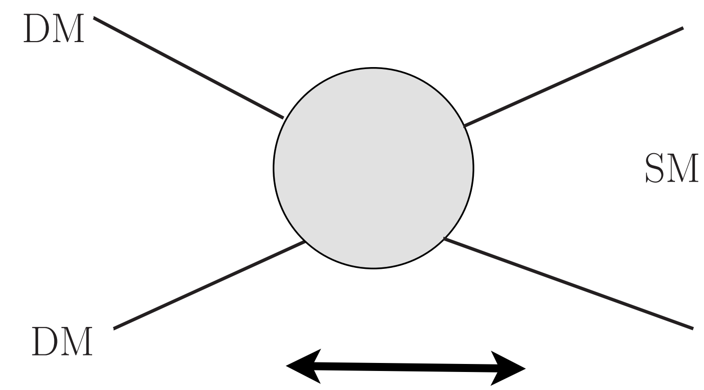


$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- If $g_D \sim 0.1$ $M_D \sim$ 10s GeV - TeV
  - We get the right relic abundance of dark matter.
- Thermal equilibrium: model independence.
- Major hint for weak(±) scale new physics!

WIMP

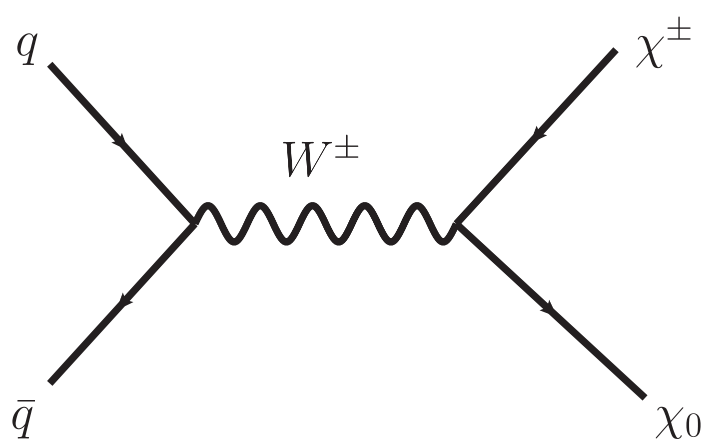


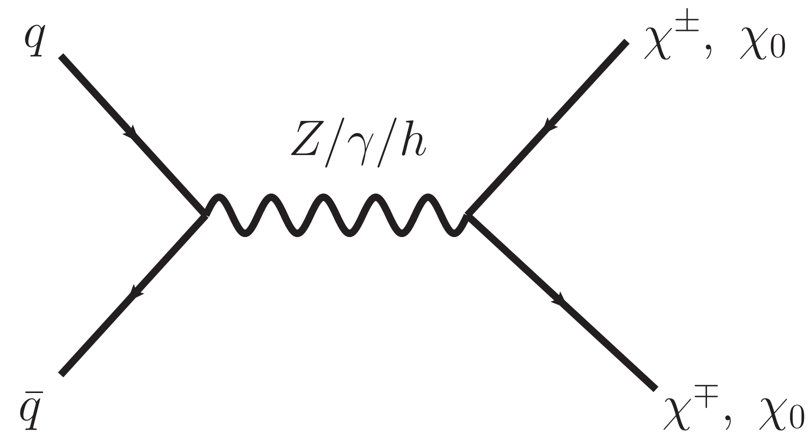


$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

- If the cross section too small, e.g. M_{DM} too large, too much dark matter.
  - Need some contrived mechanism to get rid of DM.
- If the cross section too large, e.g. M_{DM} too small, not enough DM.
  - Can have non-thermal production. Not ideal, but can be plausible.

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

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

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

- 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.)

DM part of a EW multiplet

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

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

- 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-6 operator). Not quite minimal, but still viable.
  - Famous example: Higgsino $(1,2)_{1/2}$

DM part of a EW multiplet

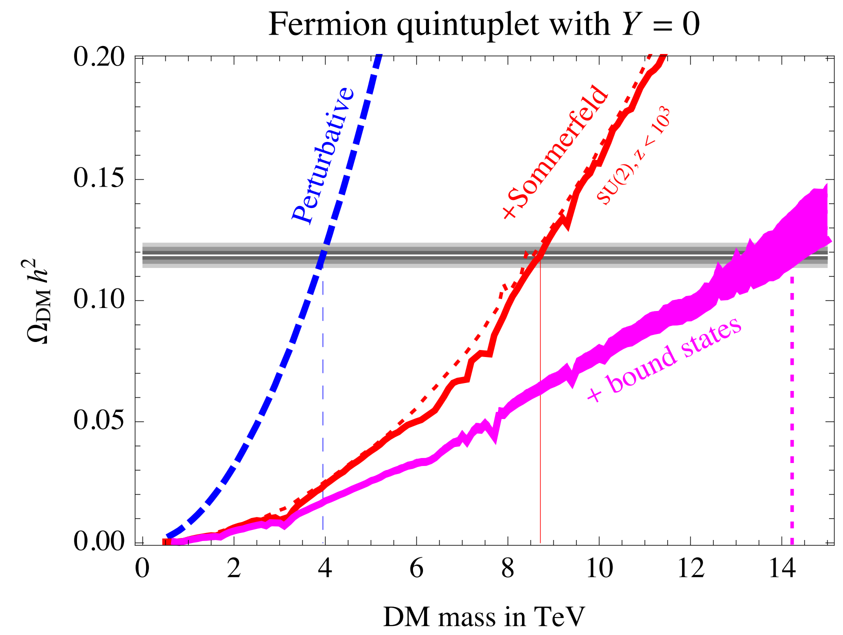
"Minimal dark matter", Cirelli, Fornengo and Strumia, hep-ph/0512090, 0903.3381

$$\text{DM} \in (1,\, n,\, \text{Y}) \text{ of } SU(3)_C \times SU(2)_L \times U(1)_Y$$

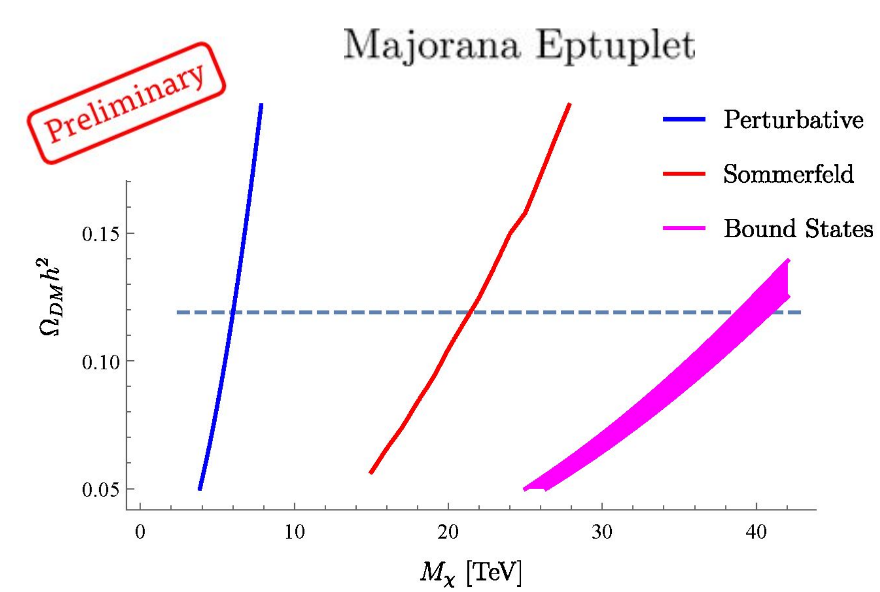
- Scalar (real and complex)
  - In principle interesting as well.
  - Minimal mass splitting, stability discussion parallel to that of the fermionic multiplets.
  - Addition couplings of the form $H^\dagger H X^\dagger X$. More parameters involved in a full analysis.
- As a first step, we will focus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



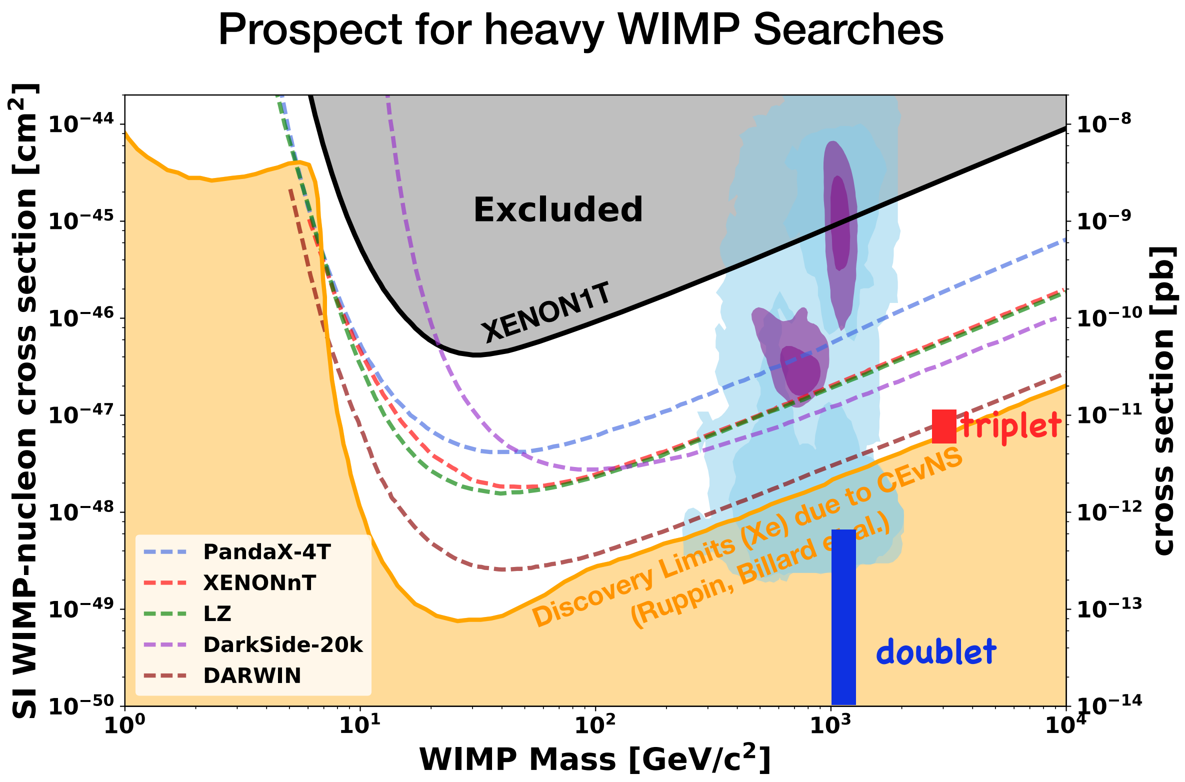
Bottaro, 2nd muon collider physics potential meeting

Reach up to thermal target

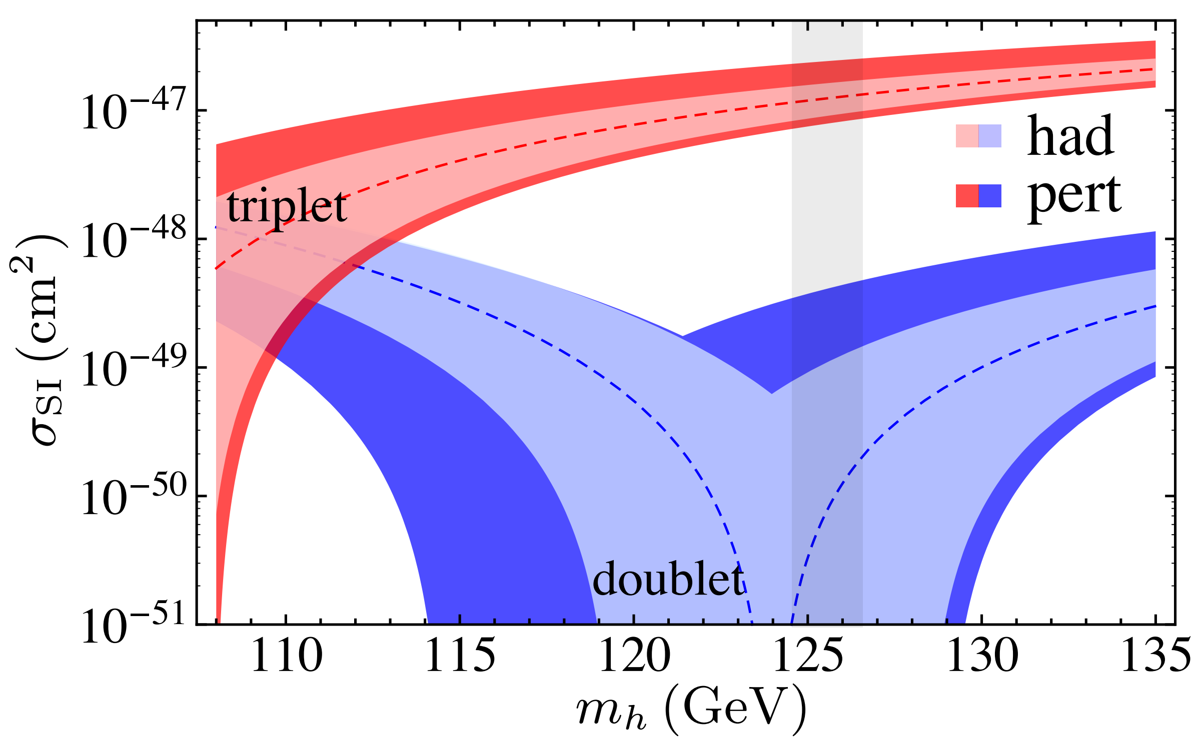
≈

complete coverage for WIMP candidate

Direct detection



Hill and Solon, 1309.4902



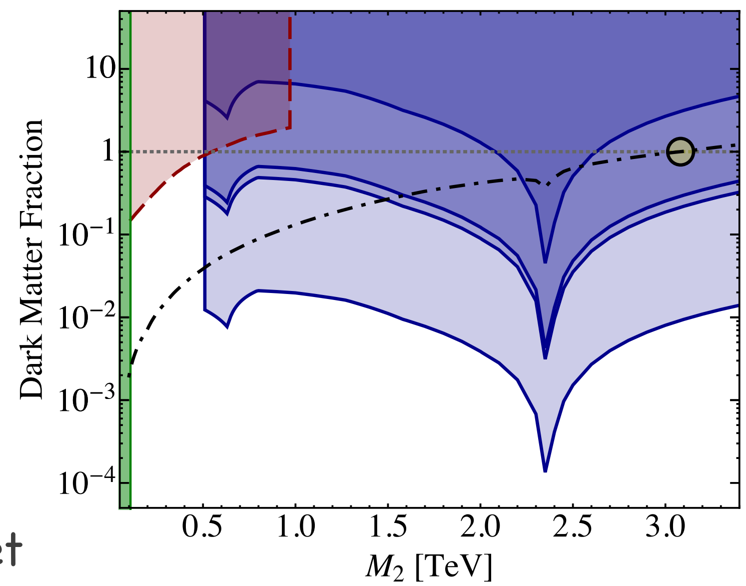
Scattering process loop induced.

Large cancellation above two classes of diagrams.

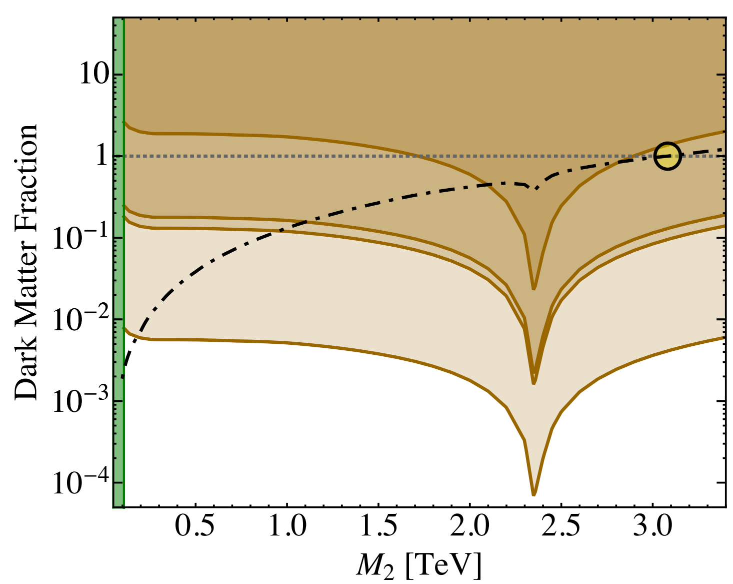
Very challenging!

Indirect detection (di-photon ...)

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

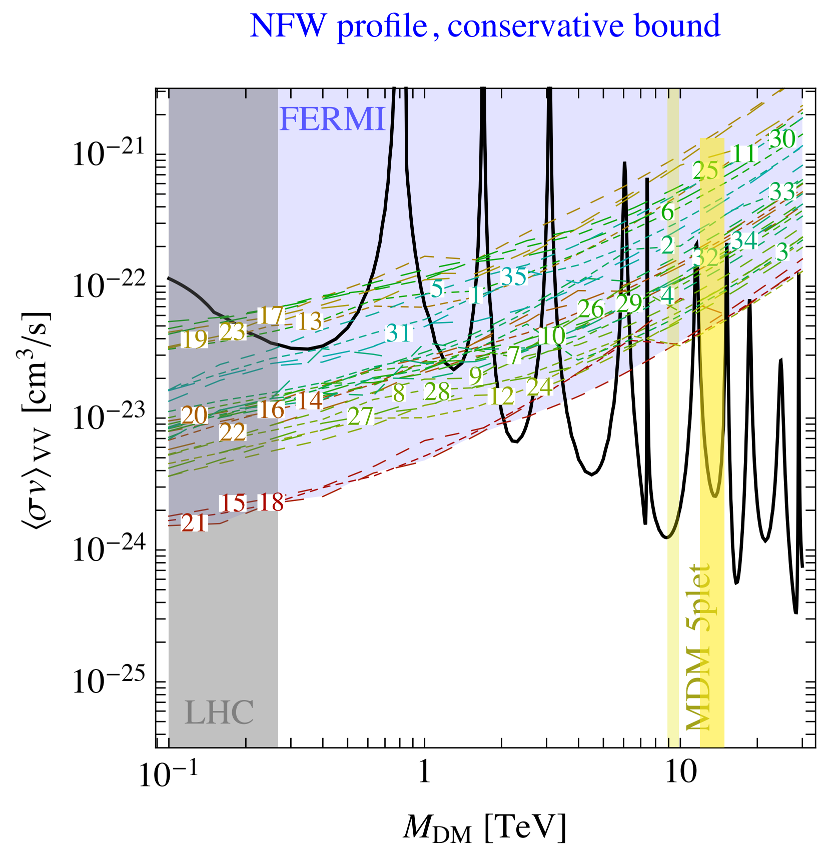


triplet



Doublet less constrained

Cirelli, Hambye, Panci, Sala and Taoso, 1507.05519



Certain cases constrained
(with large astrophysical uncertainties)

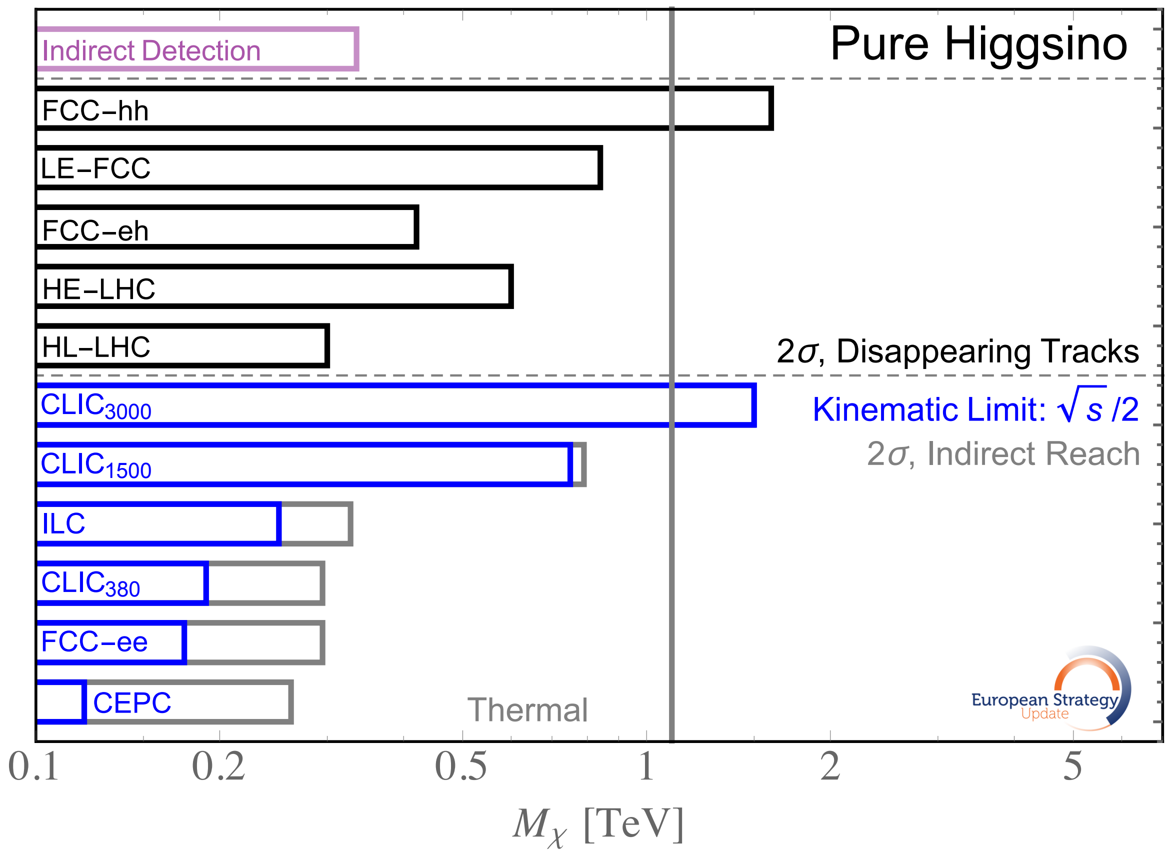
Will improve in the future. Could even see a signal.

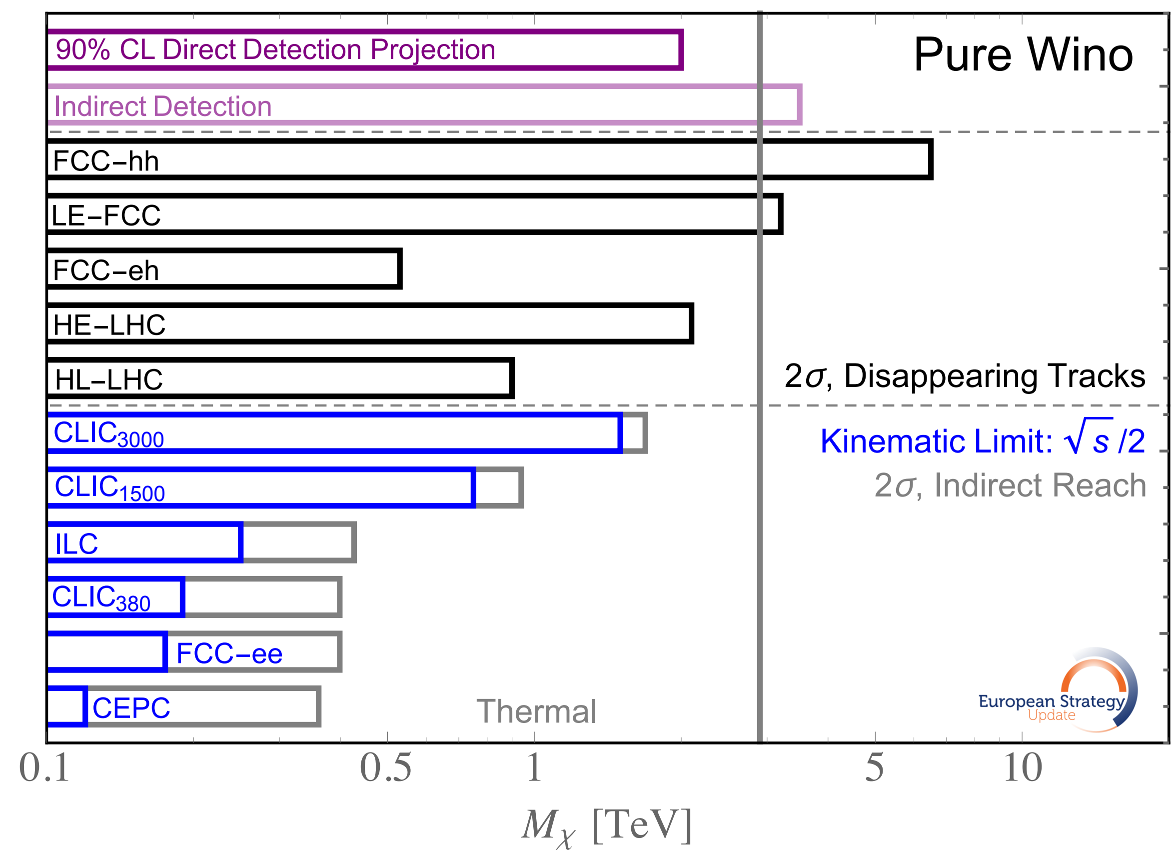
Still, important to search/study such particles at a collider.

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 $m_\chi \approx 1/2\ E_{CM}$

Our result: almost. But not so easy.

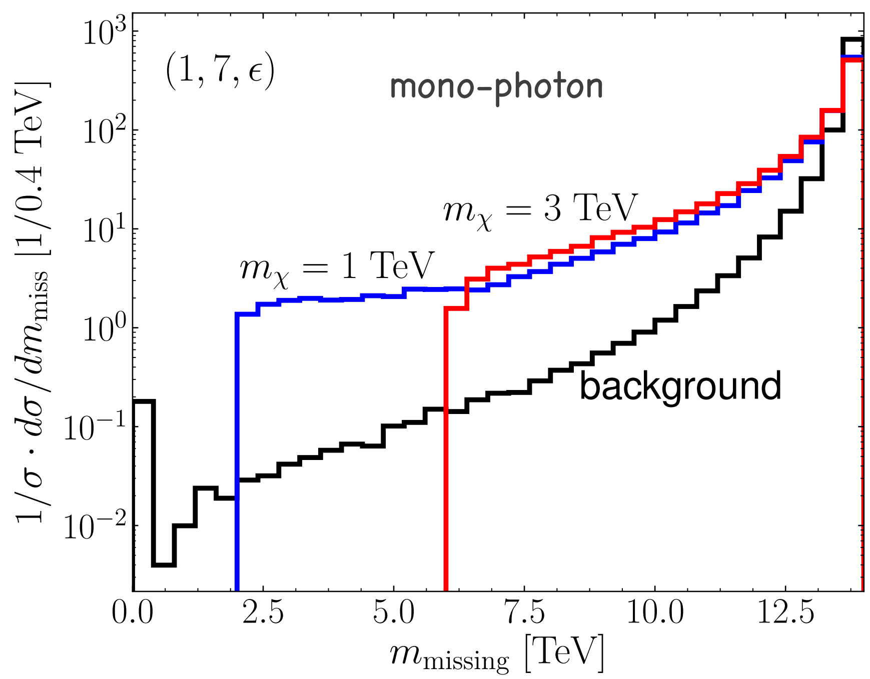
Inclusive missing mass searches

General cuts.

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

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

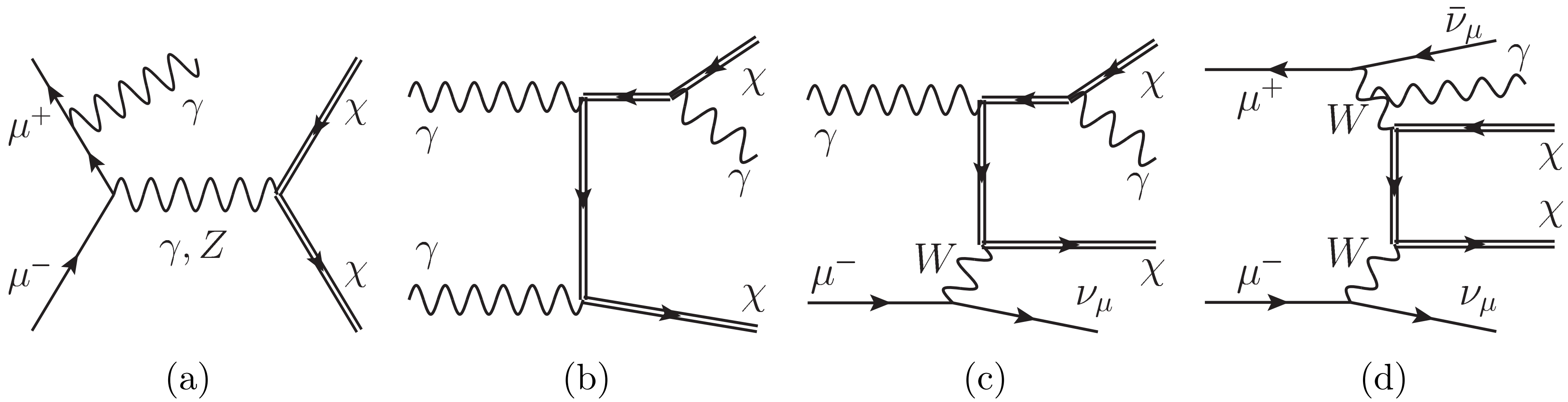
Missing mass: $m^2_{\rm missing} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\rm obs})^2$ $\quad m^2_{\rm missing} > 4m_\chi^2$



Useful for background suppression, especially for large dark matter mass

Mono-photon channel

Signal:



Dominated by the production of charged members of the multiplet.

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

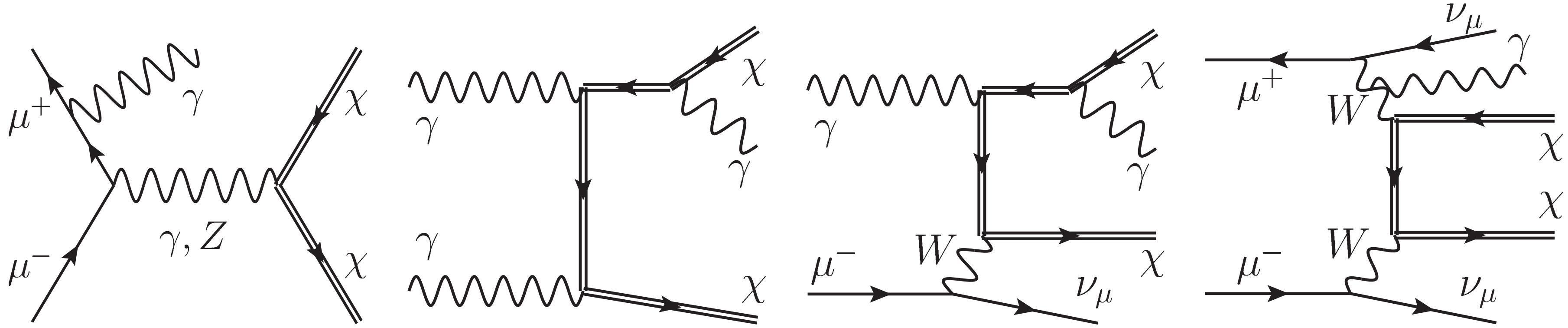
$$\chi^\pm \to \chi_0 + \text{soft particles}$$

as invisible here. (More on this later)

Mono-photon channel

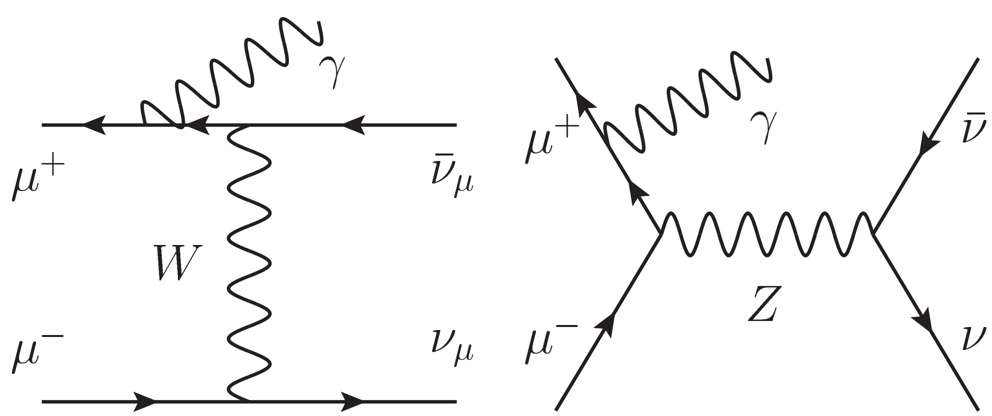
Drell-Yan VBF

Signal:



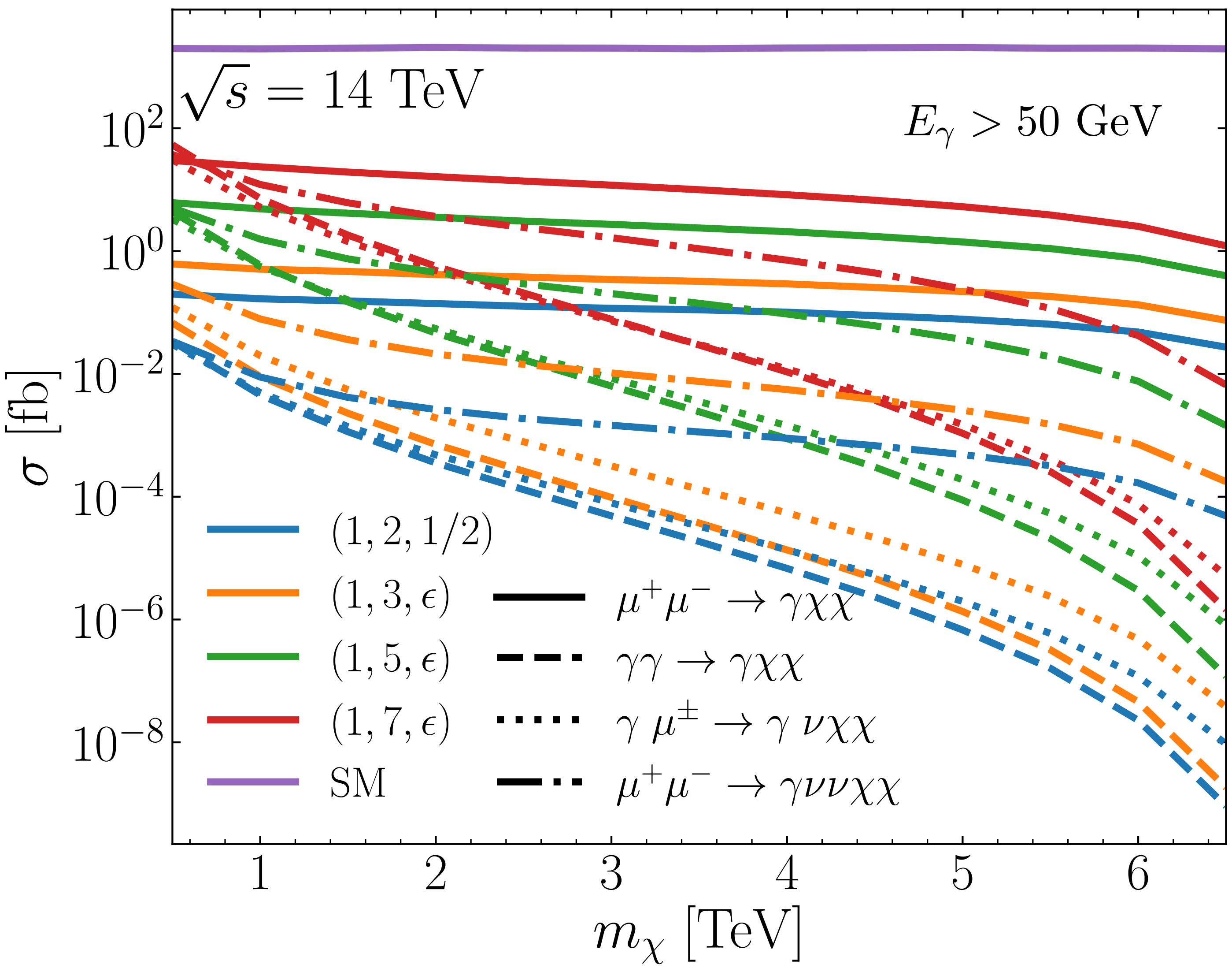
(a) (b) (c) (d)

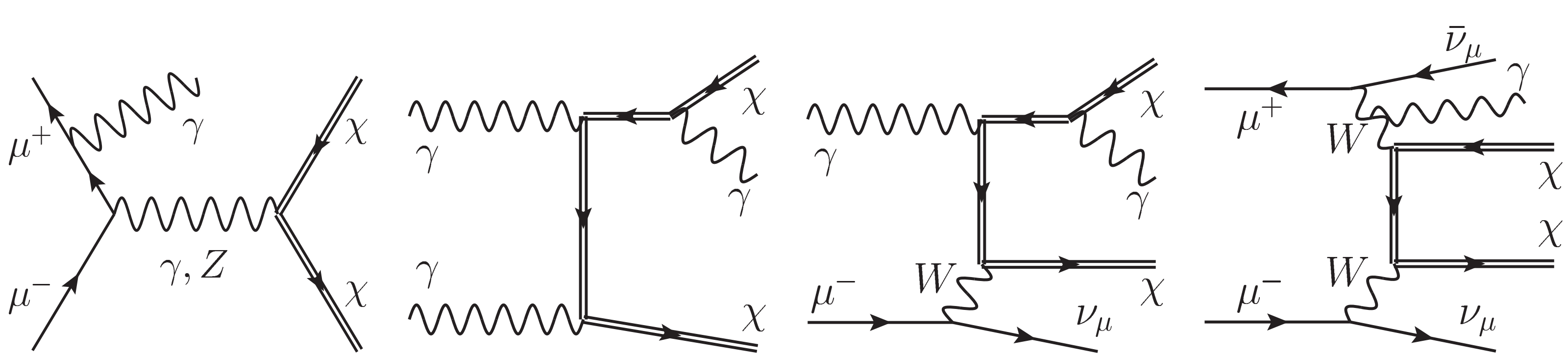
Background:



(a) (b)

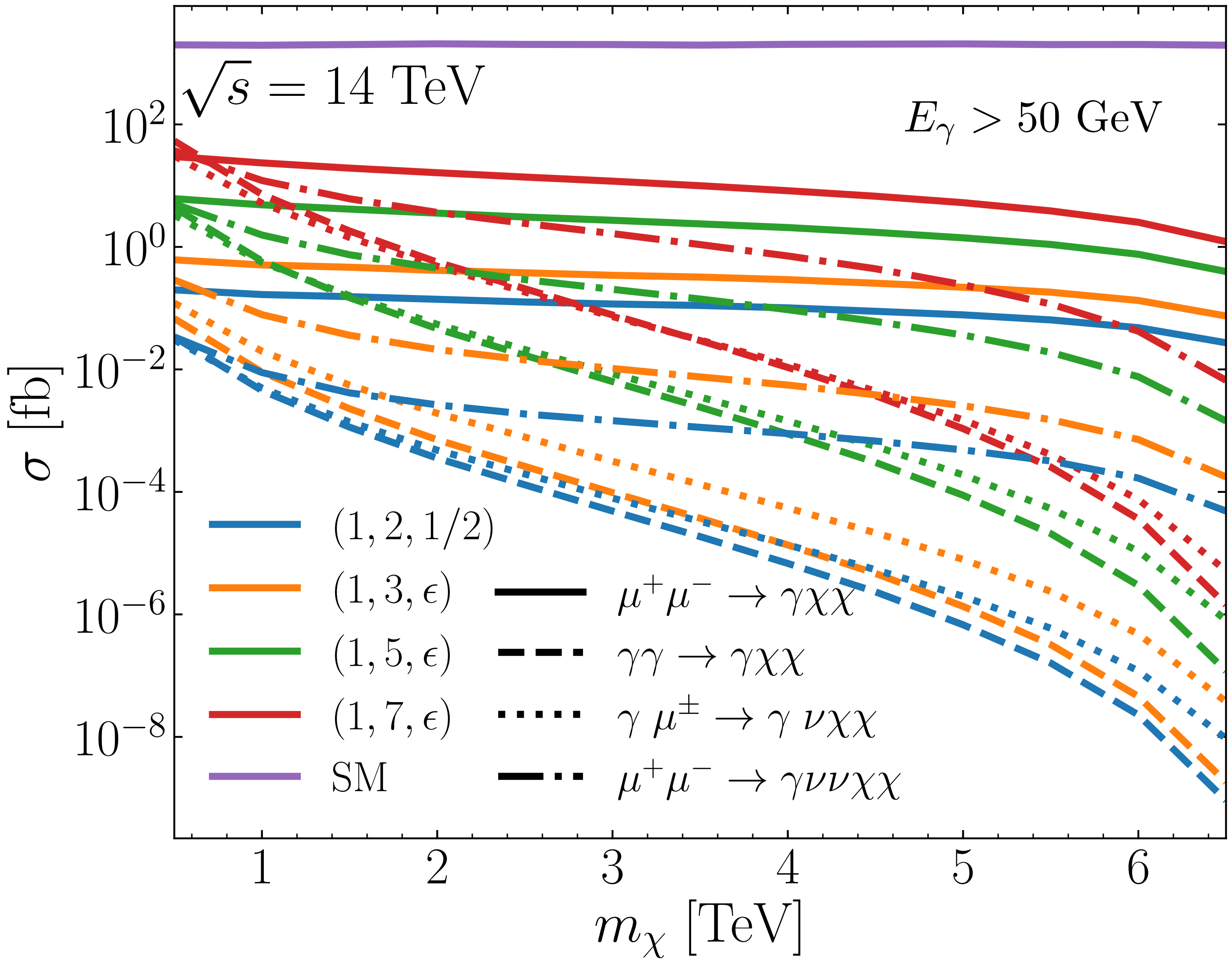
Mono-photon rates



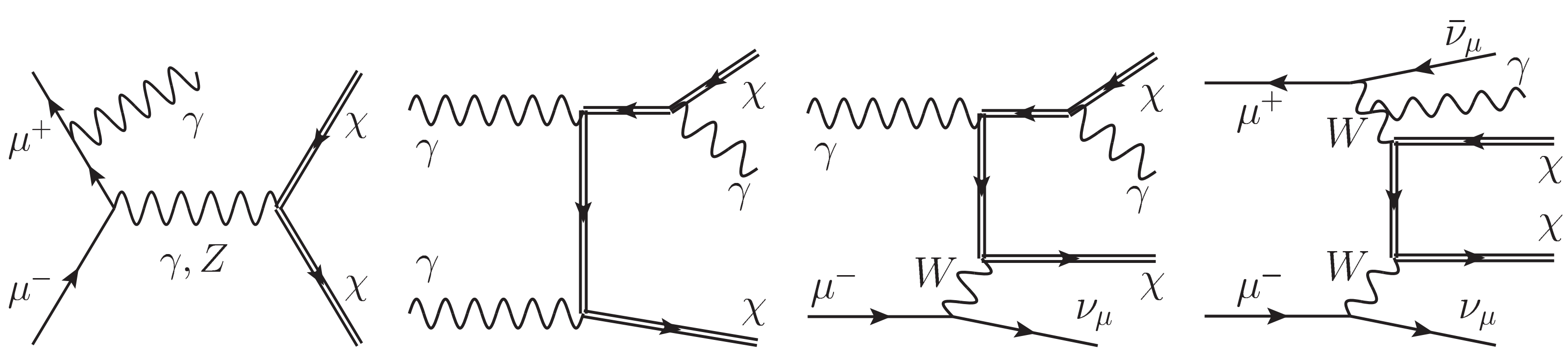


(a) (b) (c) (d)

Mono-photon rates



Drell-Yan like process dominate for large m_χ



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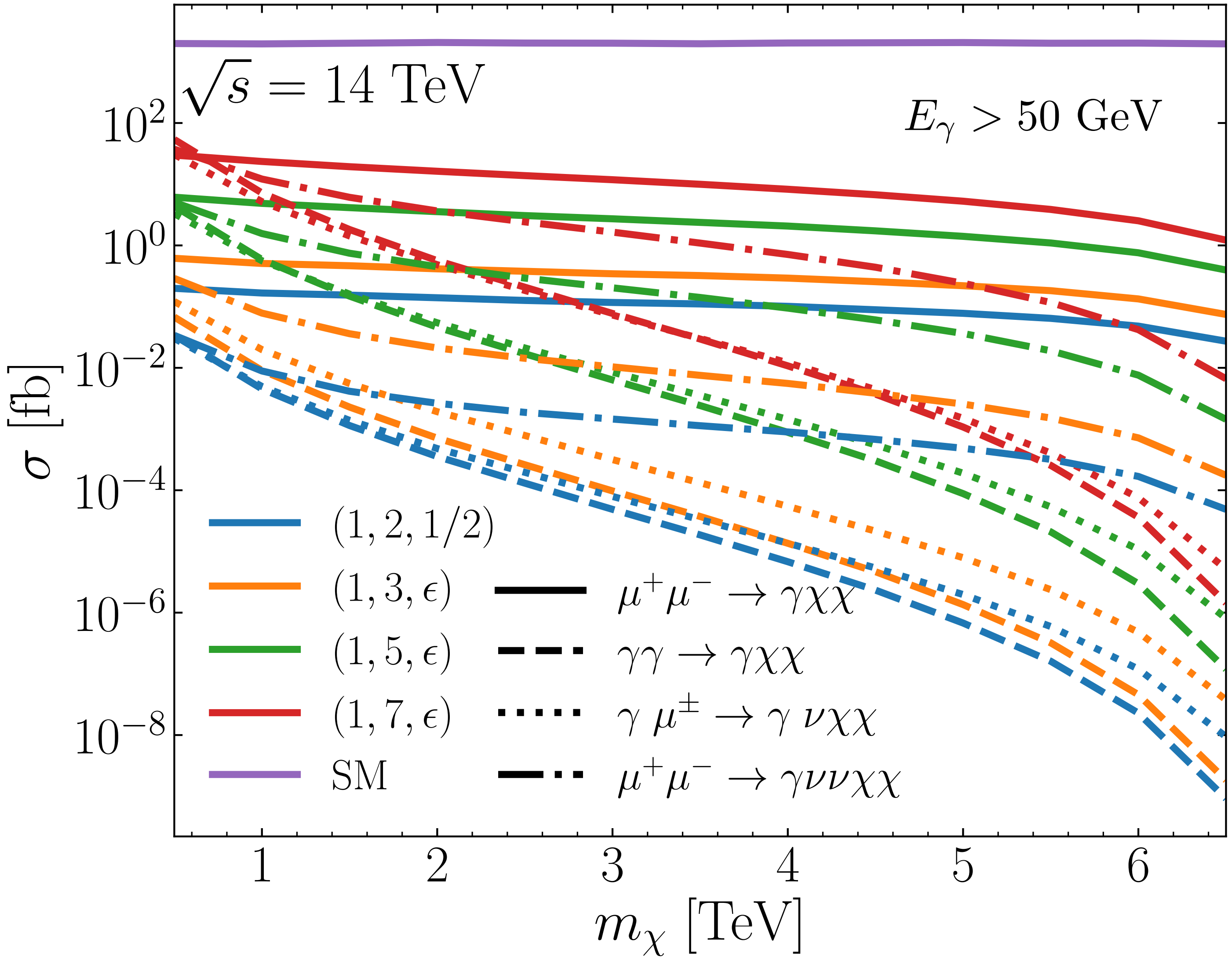
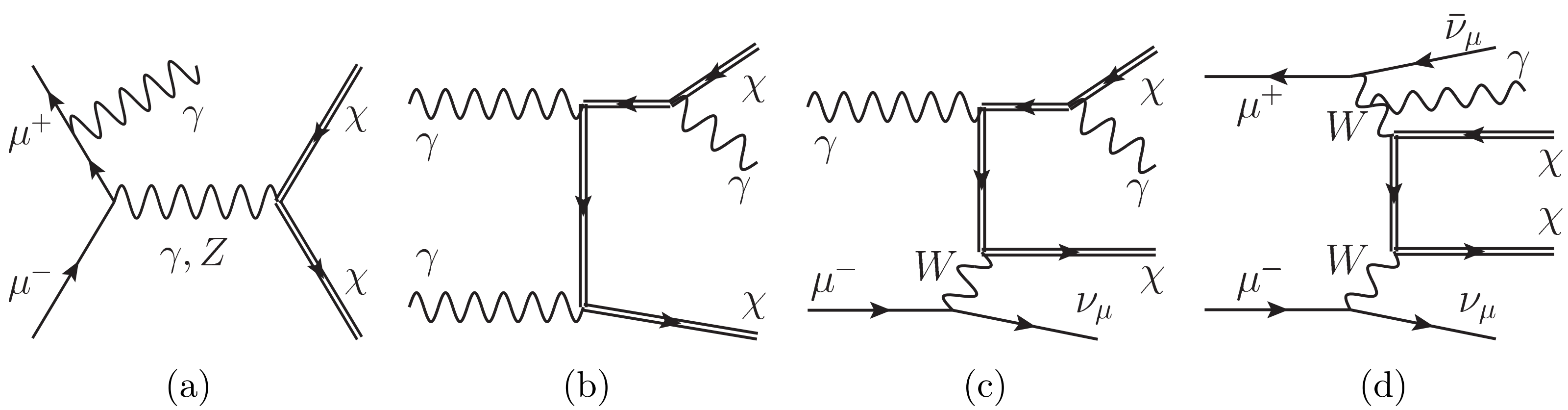
Mono-photon rates

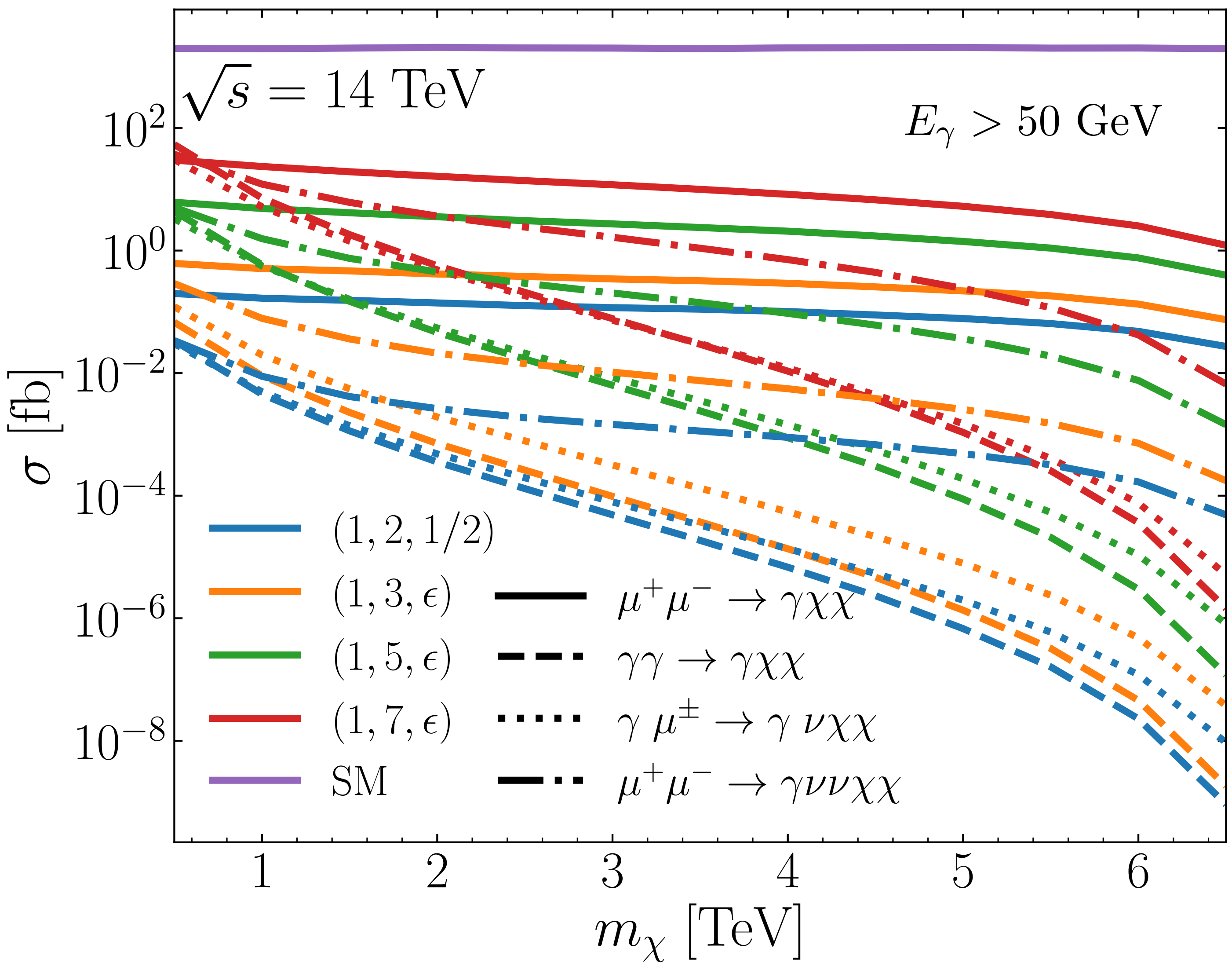


Drell-Yan like process dominate for large m_χ

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



Mono-photon rates



Drell-Yan like process dominate for large m_χ

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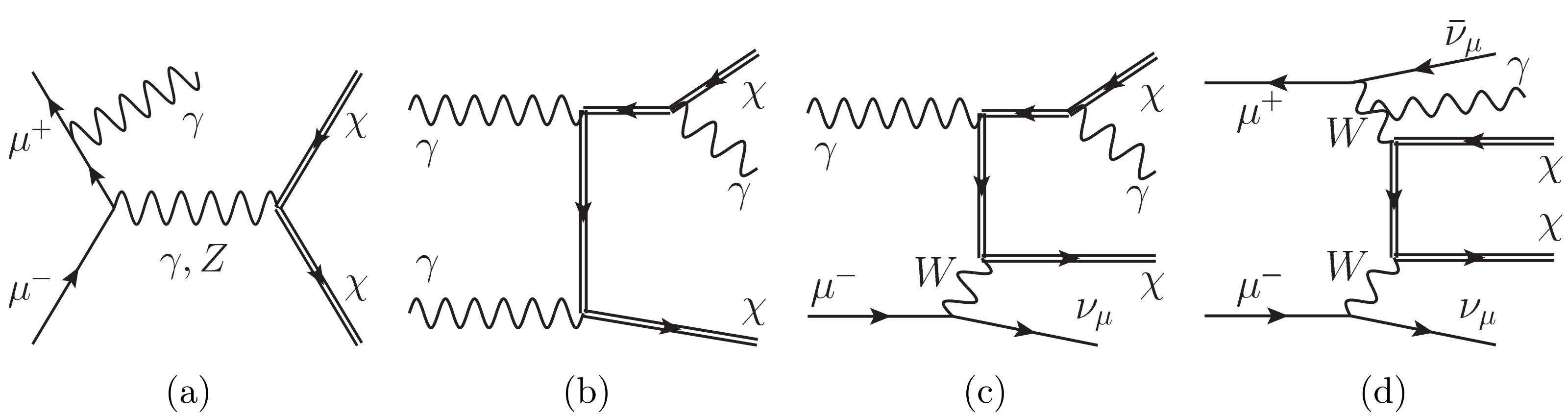
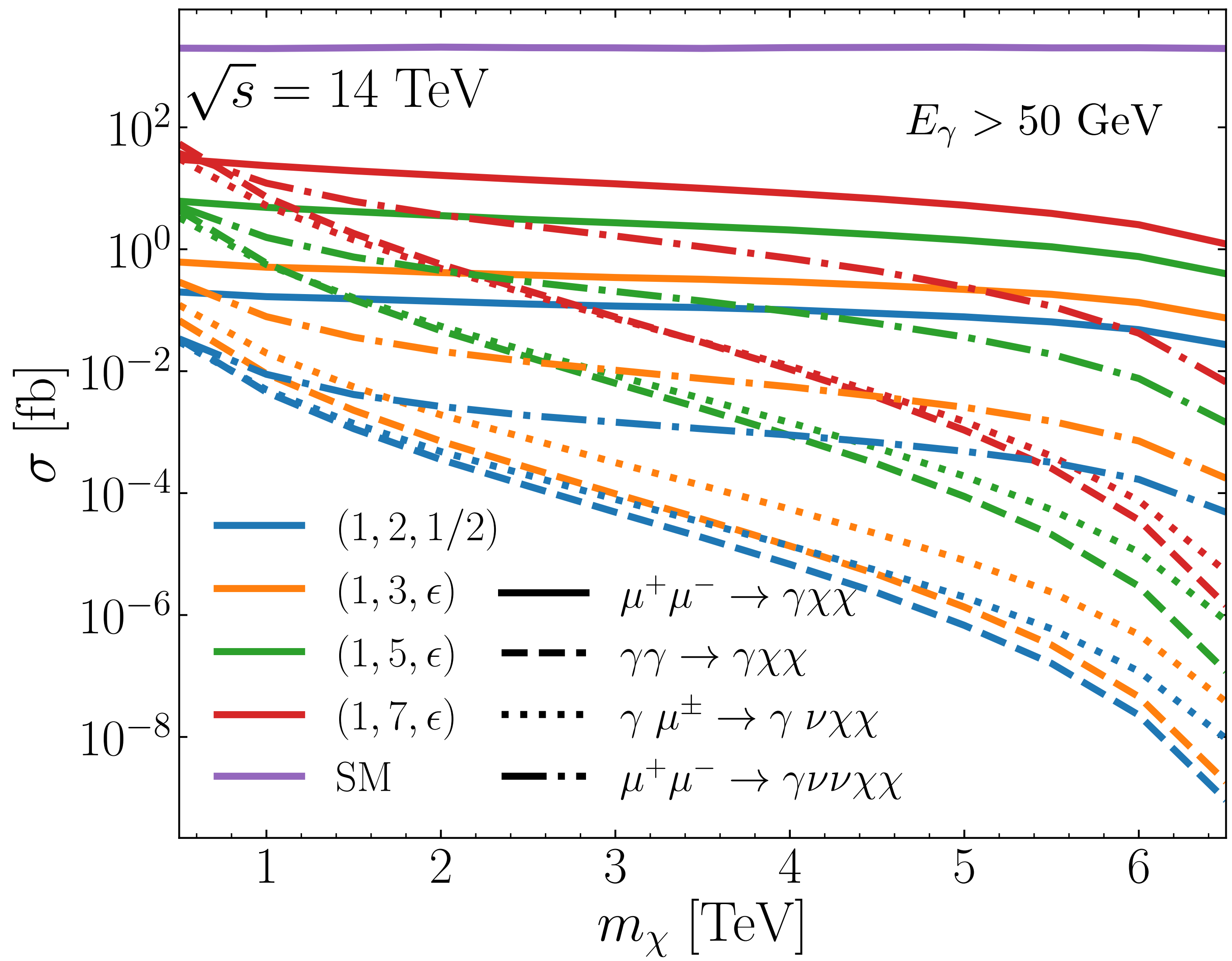
FSR photon enhanced for higher multiplets.



Mono-photon rates



Drell-Yan like process dominate for large m_χ

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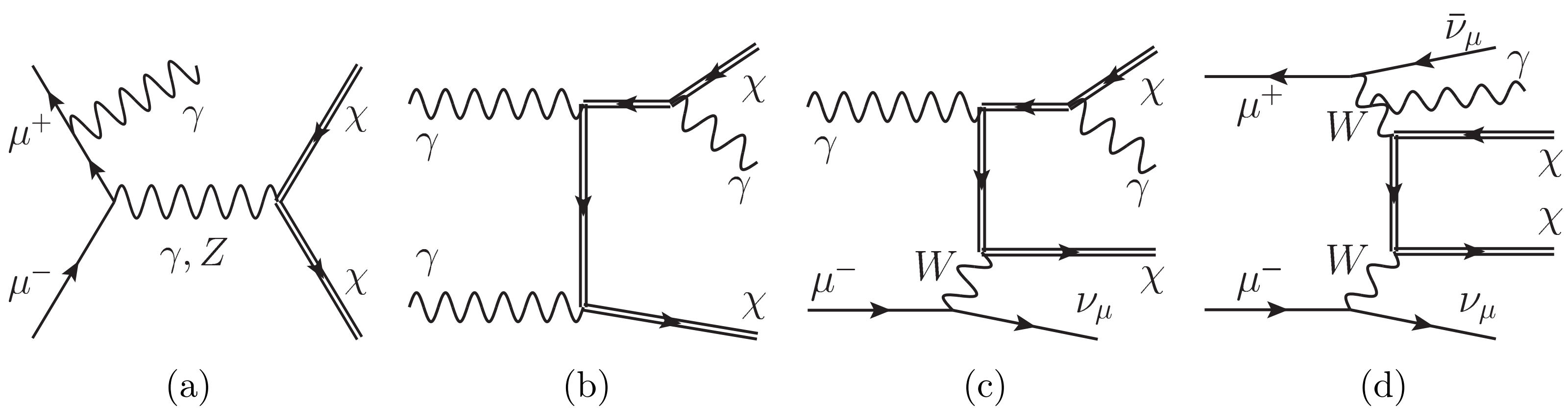
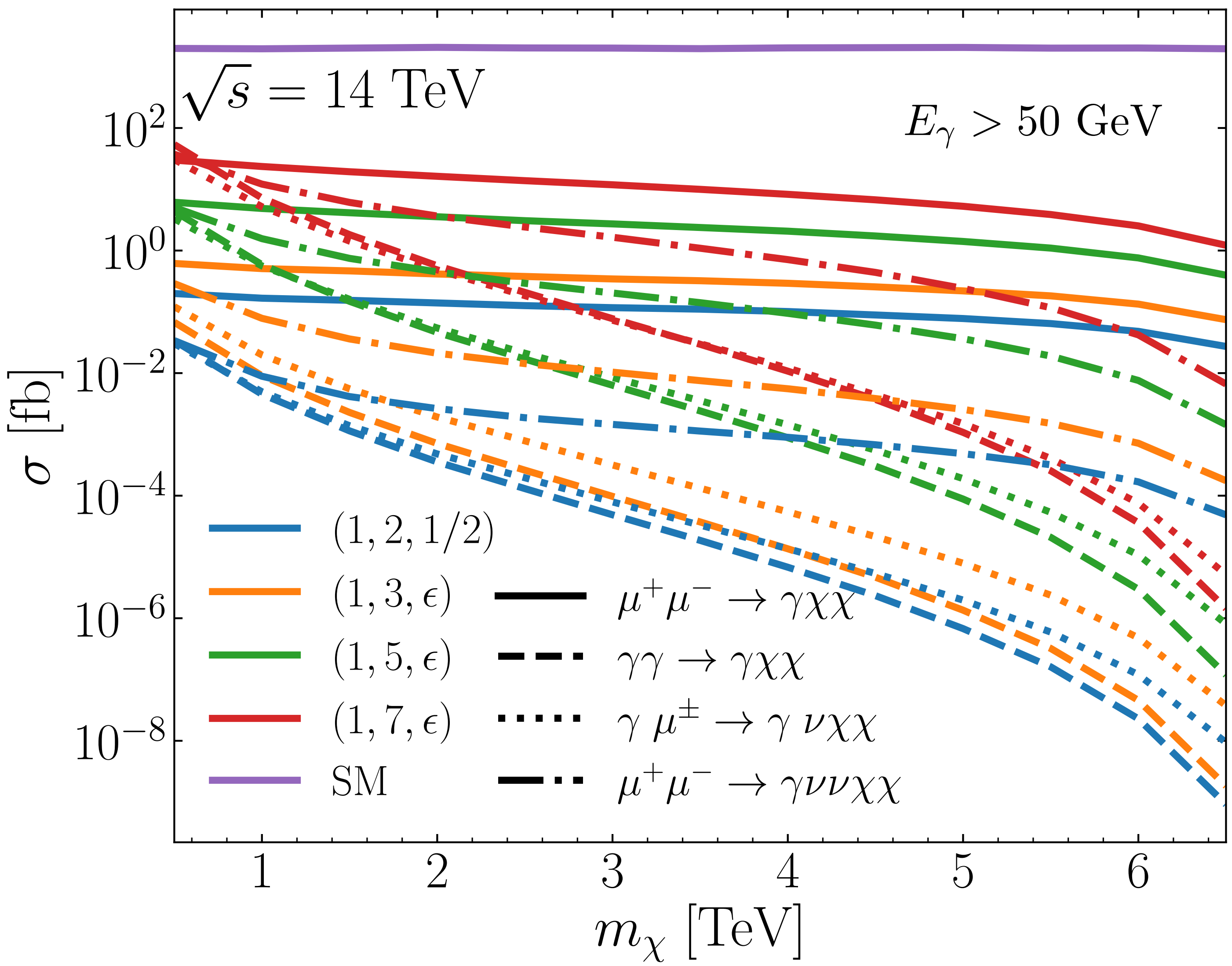
FSR photon enhanced for higher multiplets.

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



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.

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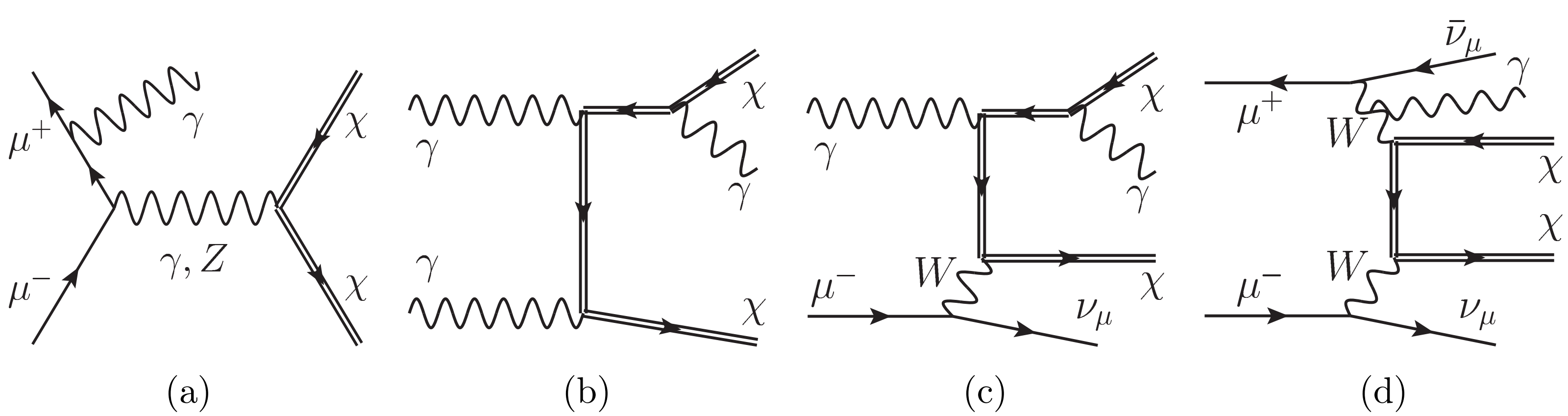
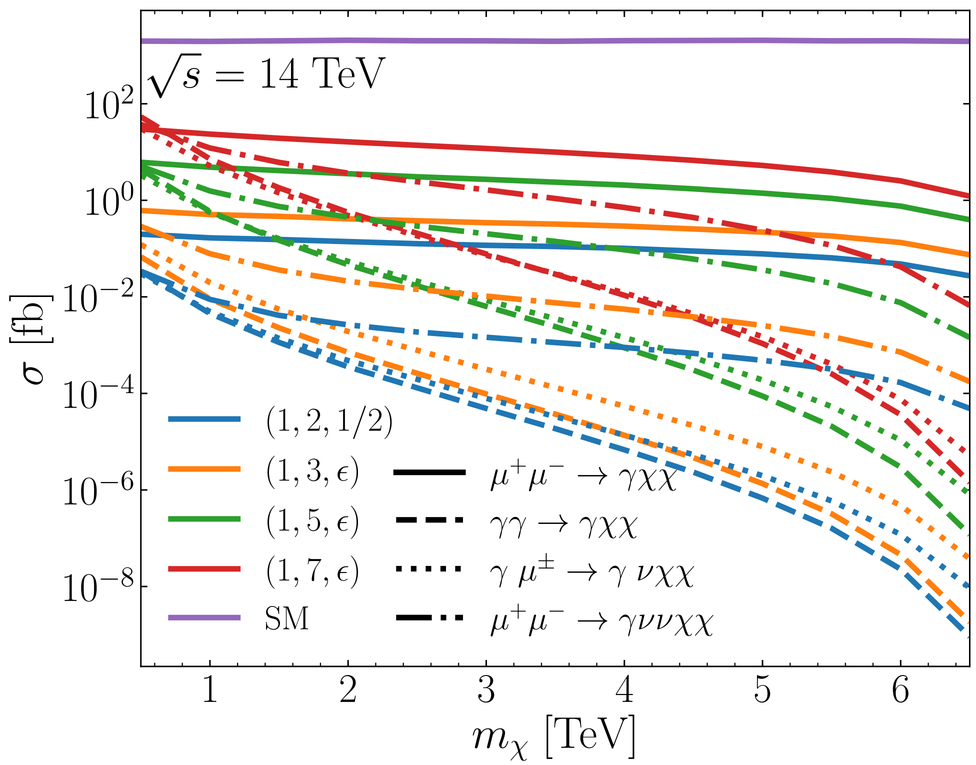
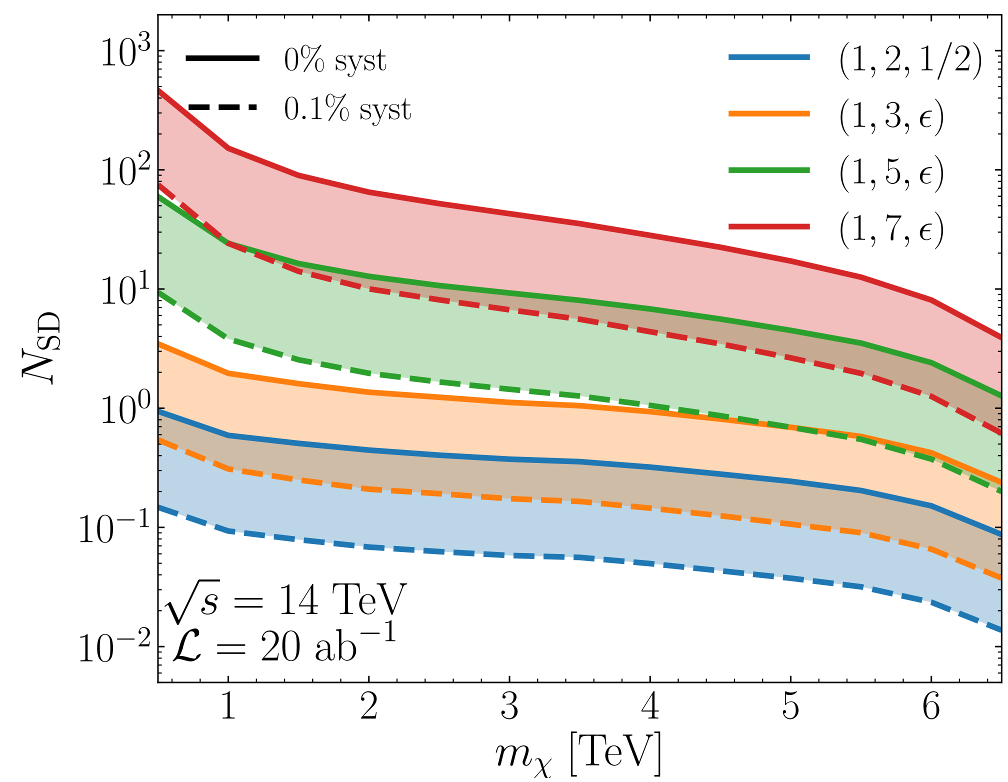
Photon initial state treated "pdf"-like, used Effective photon approximation.



Signal significance





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

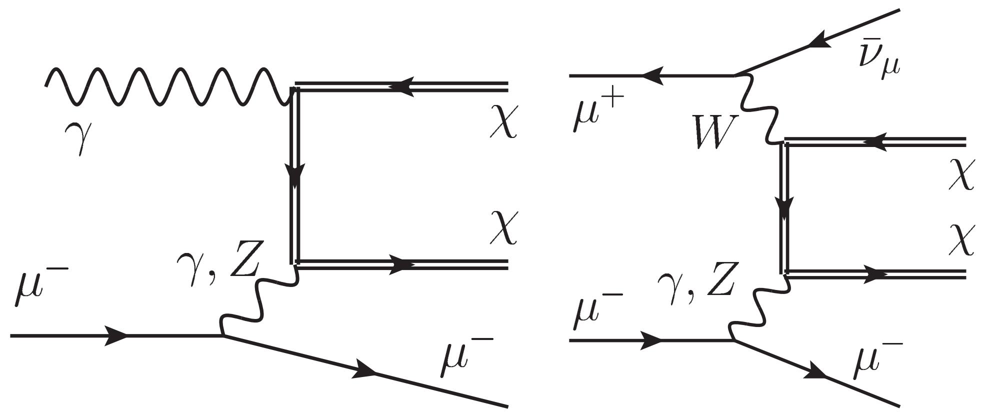
$B \approx 10^{2\div3} \times S.$

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

Mono-muon

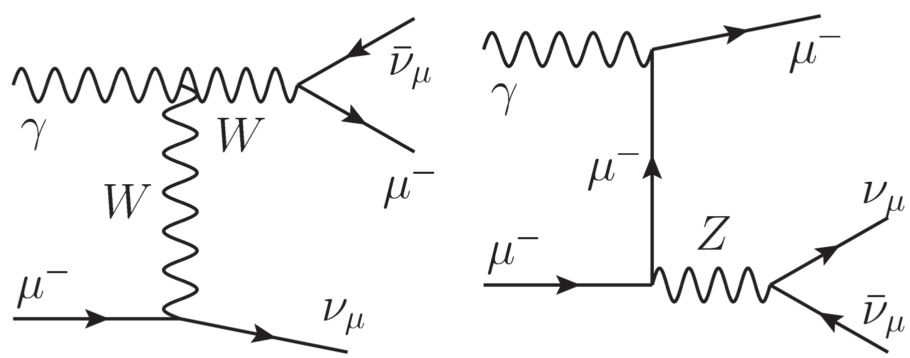
A signal unique to muon collider

Signal:



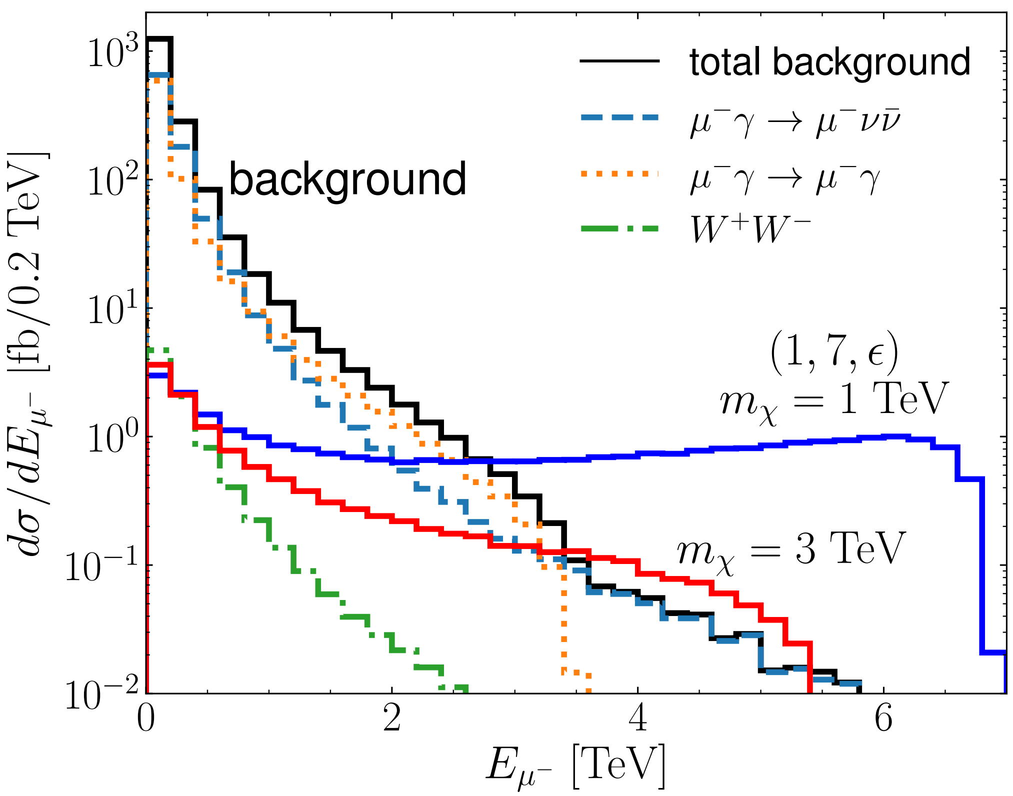
(a) (b)

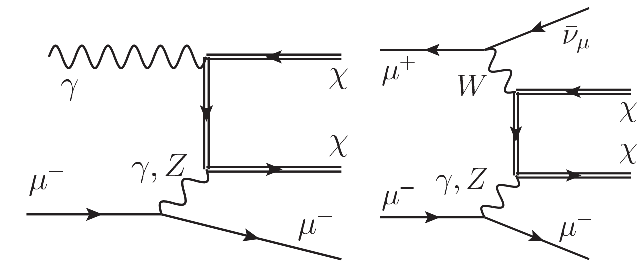
Background:



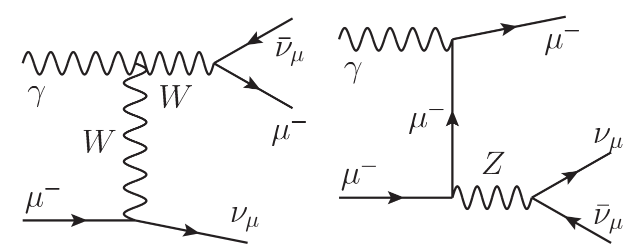
(a) (b)

Some kinematics





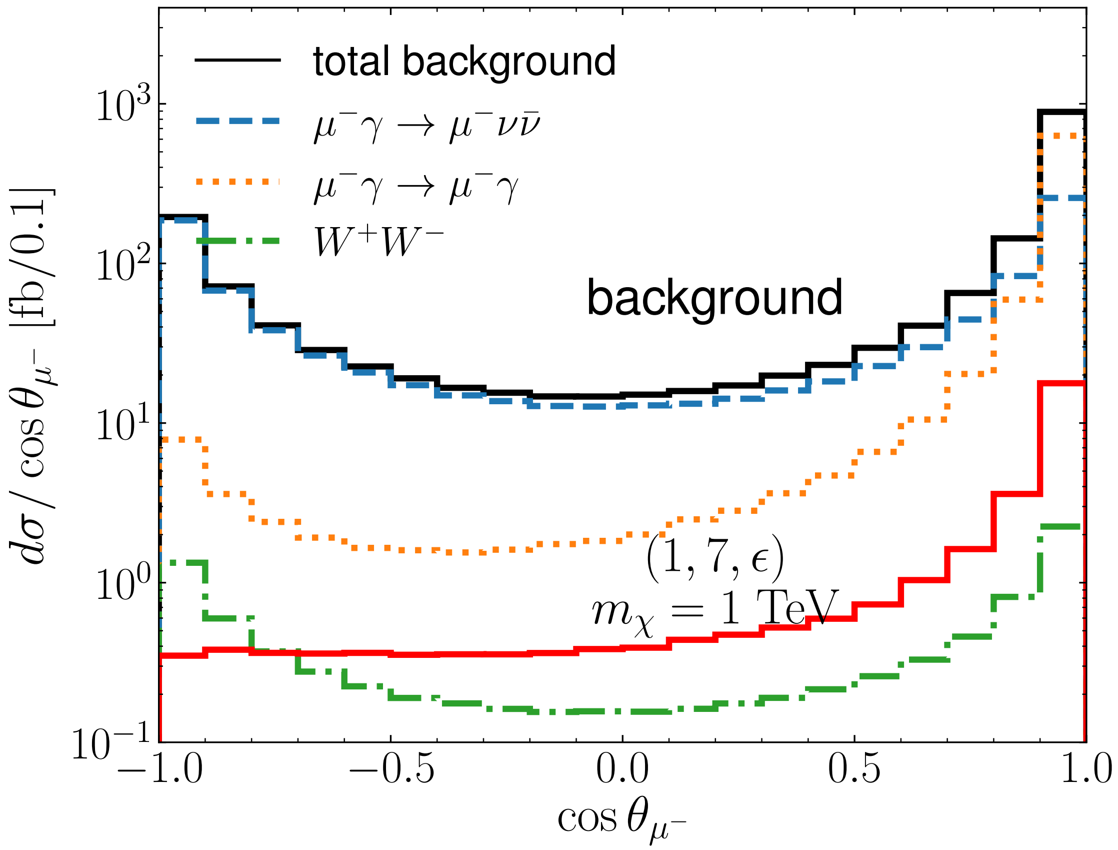
(a) (b)

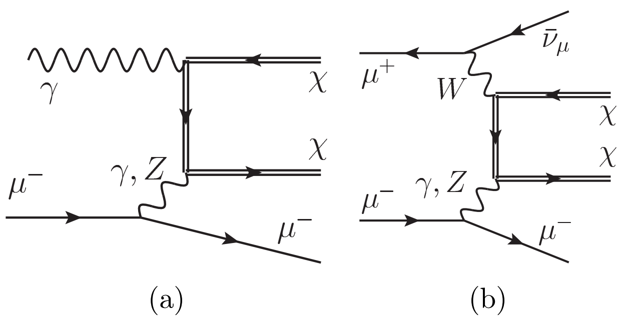


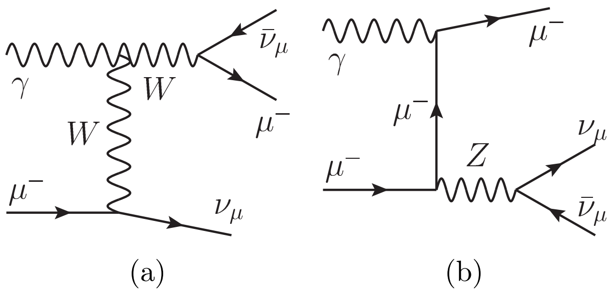
(a) (b)

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

Some kinematics

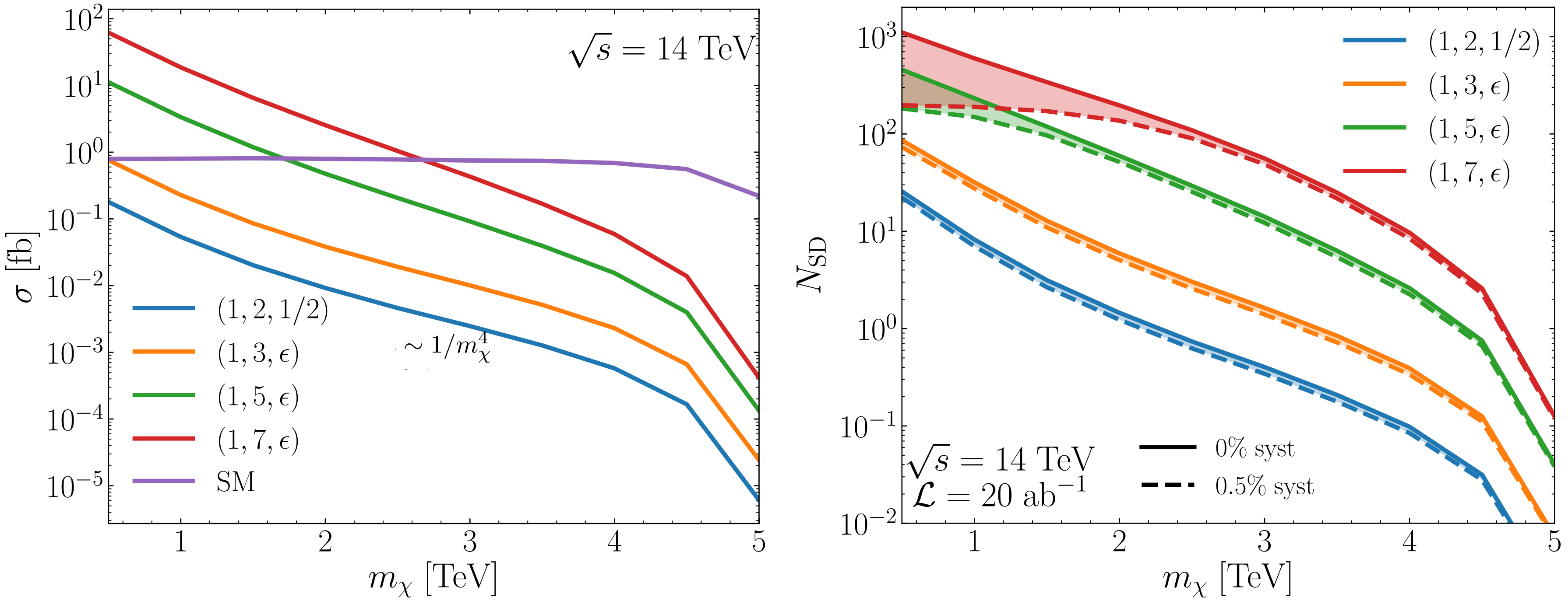






$$10^\circ < \theta_{\mu^-} < 90^\circ, \quad 90^\circ < \theta_{\mu^+} < 170^\circ$$

Signal significance

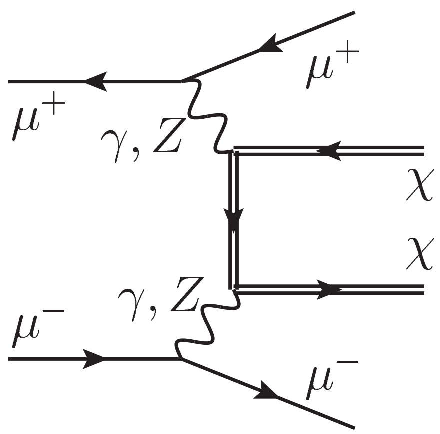


VBF-like signal. Falls off like m_χ^{-4} .

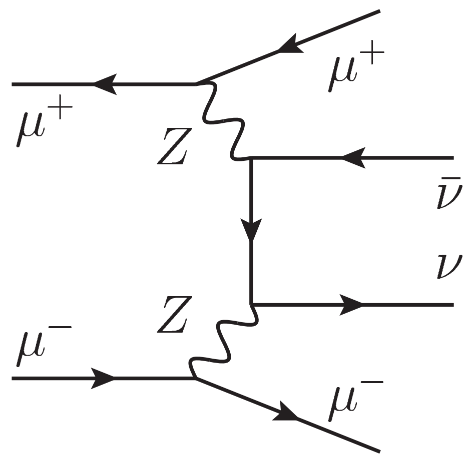
S is comparable to B. Less susceptible to systematics

VBF

Signal:



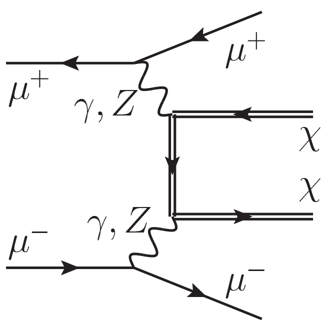
Background:

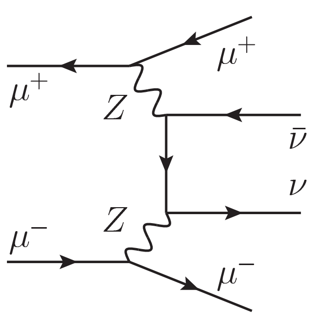


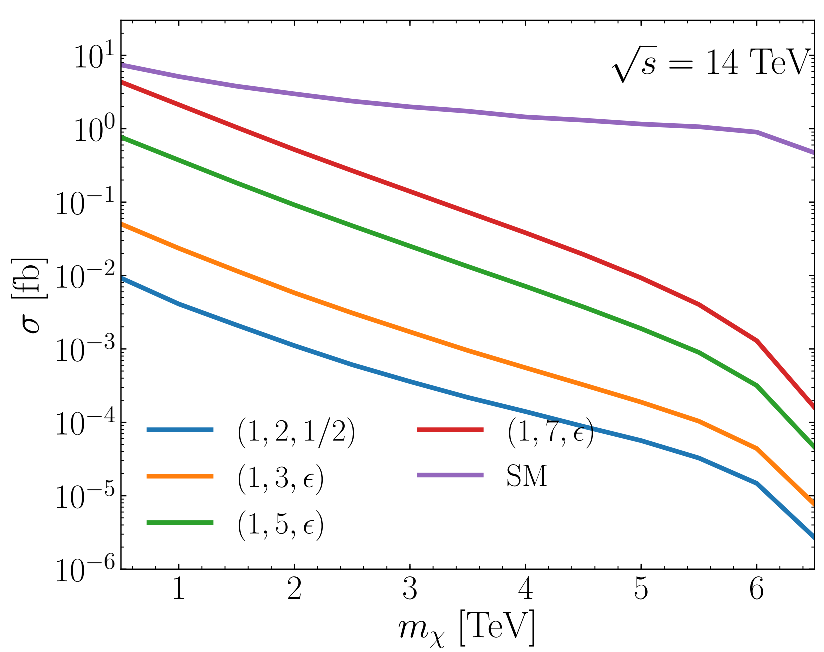
Imposing selection cuts:

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

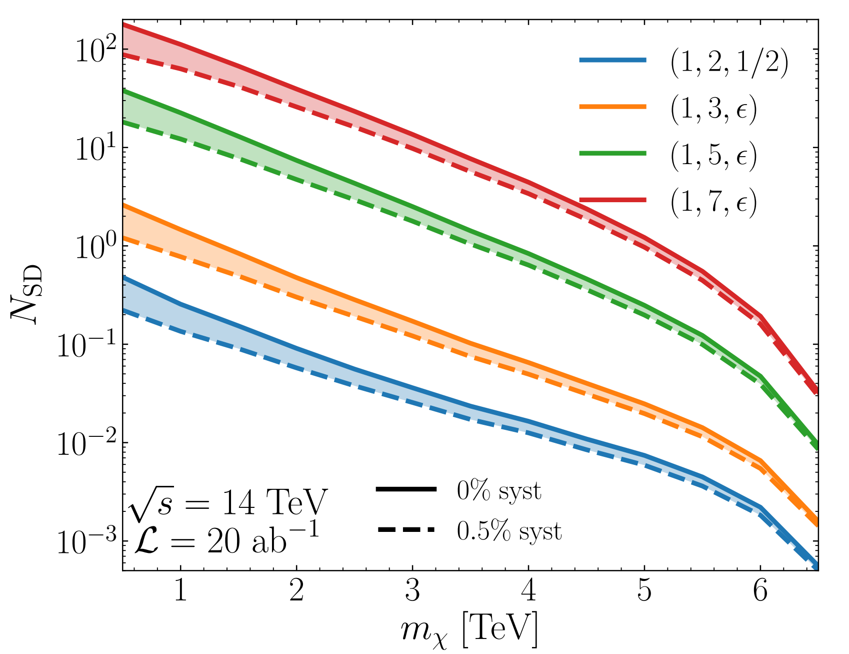
Signal significance







(a)

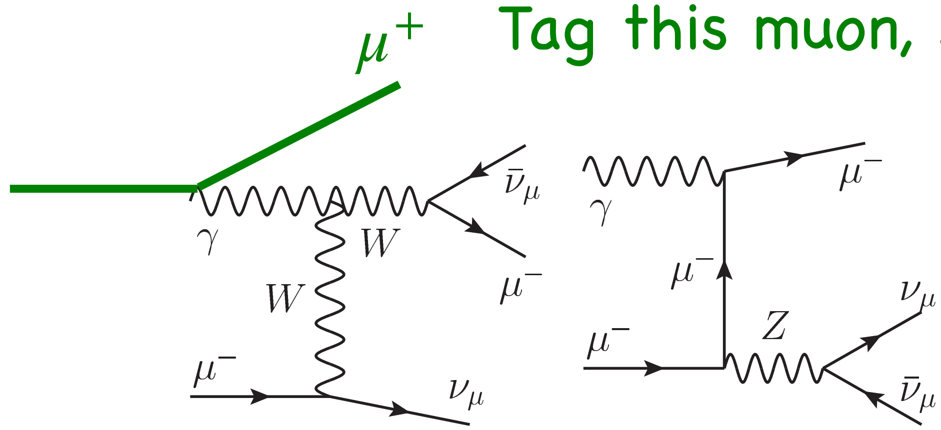


(b)

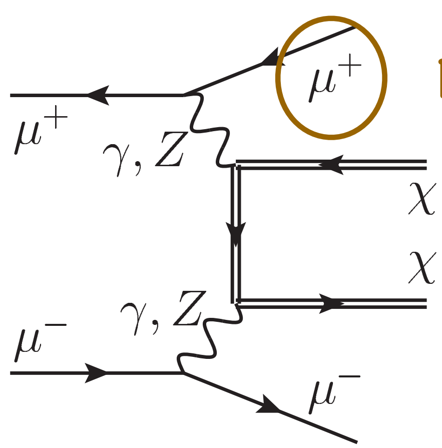
Need to tag two forward muons (angular acceptance).
Only neutral channel contribute.

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

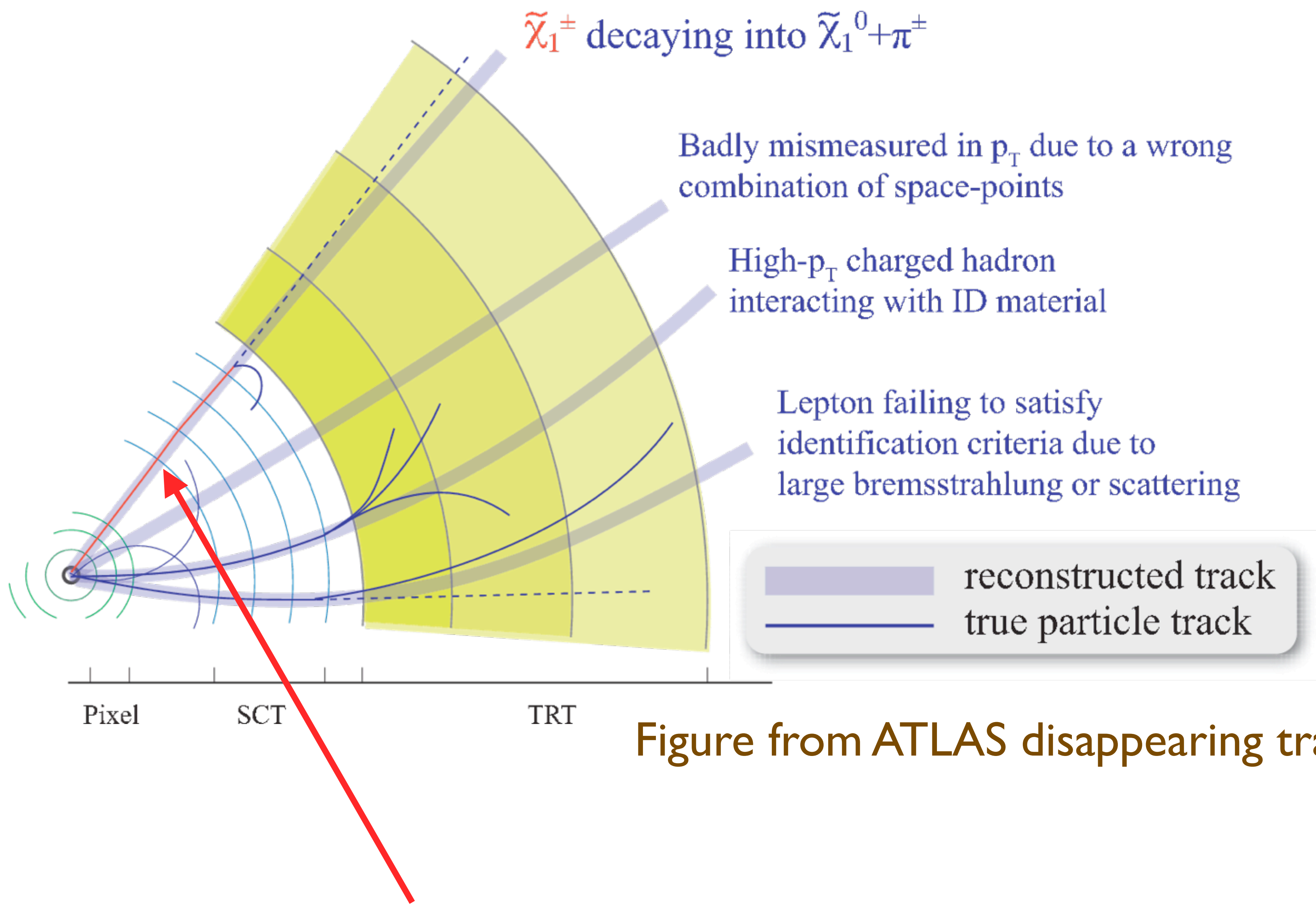


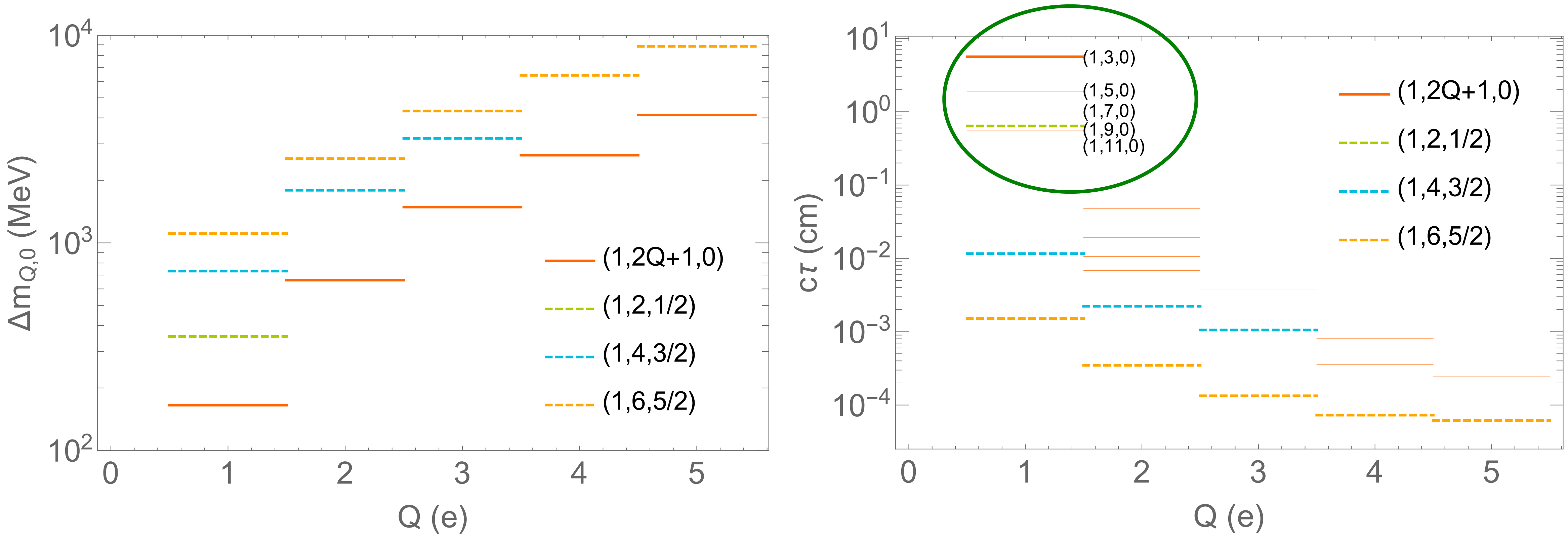
Figure from ATLAS disappearing track search twiki

Signal of a sufficiently long-lived charge particle

More distinct, but harder

- A distinct signal, no "physics" background.
- However, no hard objects. BIB important.
  - A lot of background hits, also a lot of handles (timing, direction, etc.)
  - Dedicated study on-going. talk by F. Meloni at muon collider coll. meeting.
- Here, basic feature of the signal.
  - Setting targets.

Small mass splitting, long lifetime



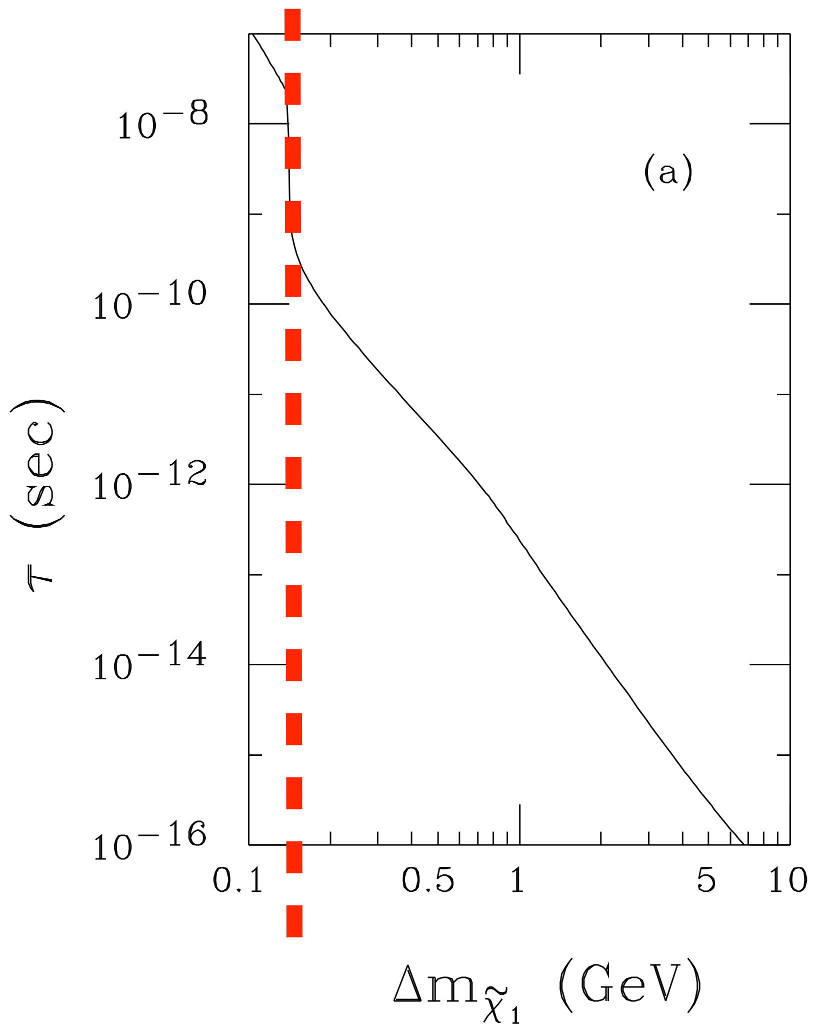
$$\Delta m_{Q,Q'} \equiv m_Q - m_{Q'} \simeq (Q - Q')\left(Q + Q' + \frac{2Y}{\cos\theta_W}\right)\delta m$$

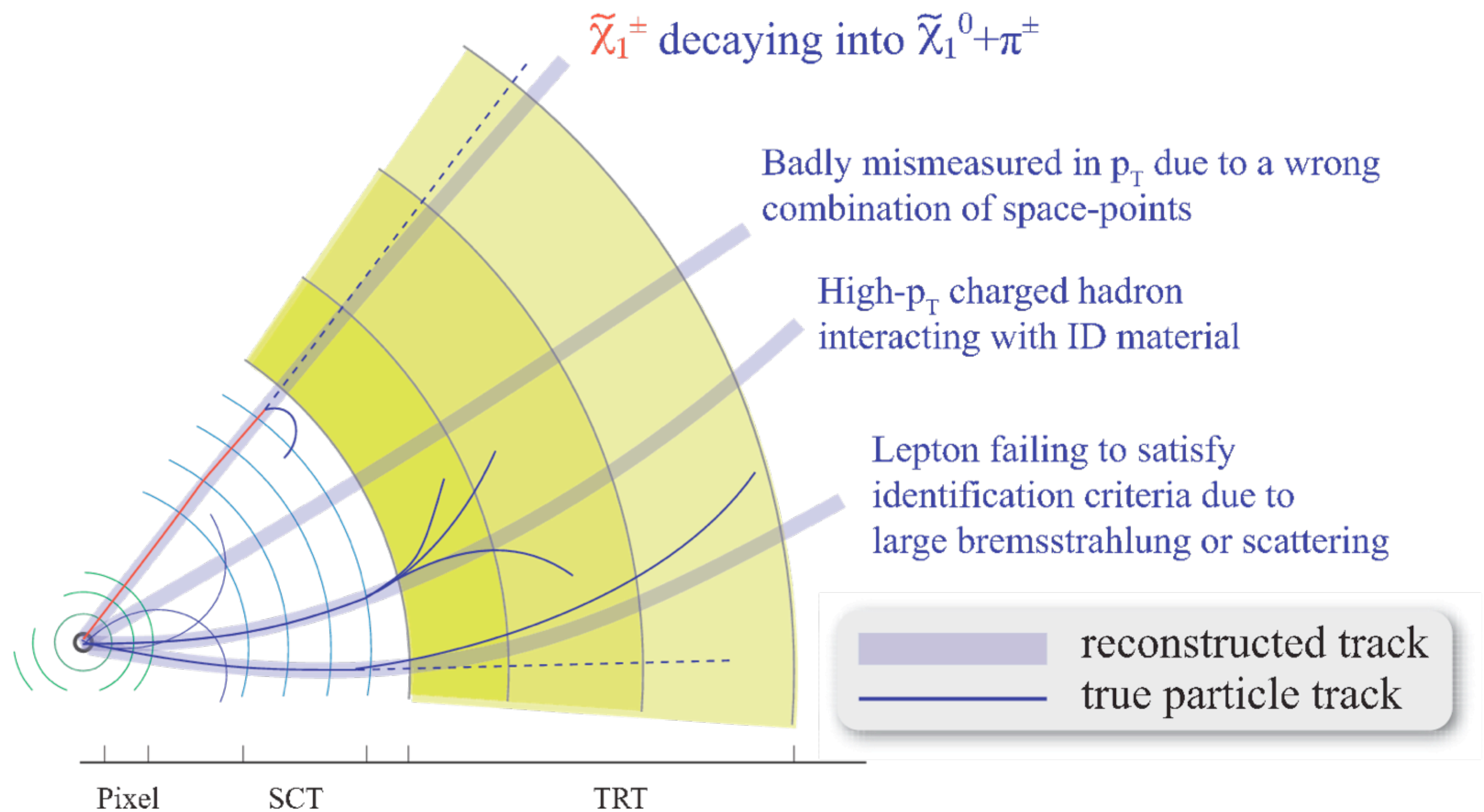
$$\delta m = \frac{g^2}{4\pi} m_W \sin^2\frac{\theta_W}{2} \approx 160\text{–}170\ \mathrm{MeV}$$

Charge ±1 states tends to have macroscopic lifetime.

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

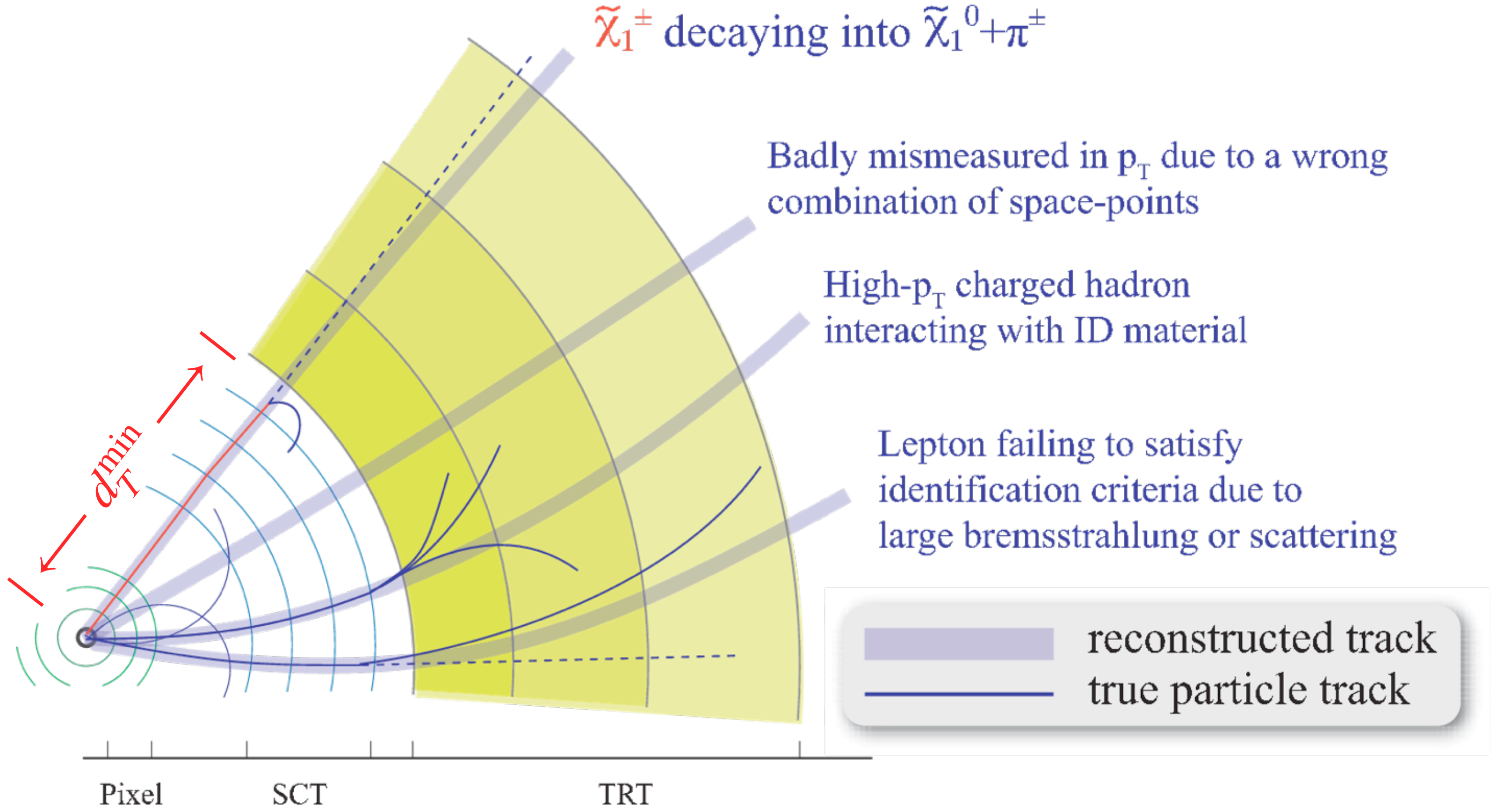
Disappearing track





- Main decay mode $\chi^{\pm} \to \pi^{\pm} + \chi^{0}$
- Charge track ≈ 10(s) cm

Signal acceptance

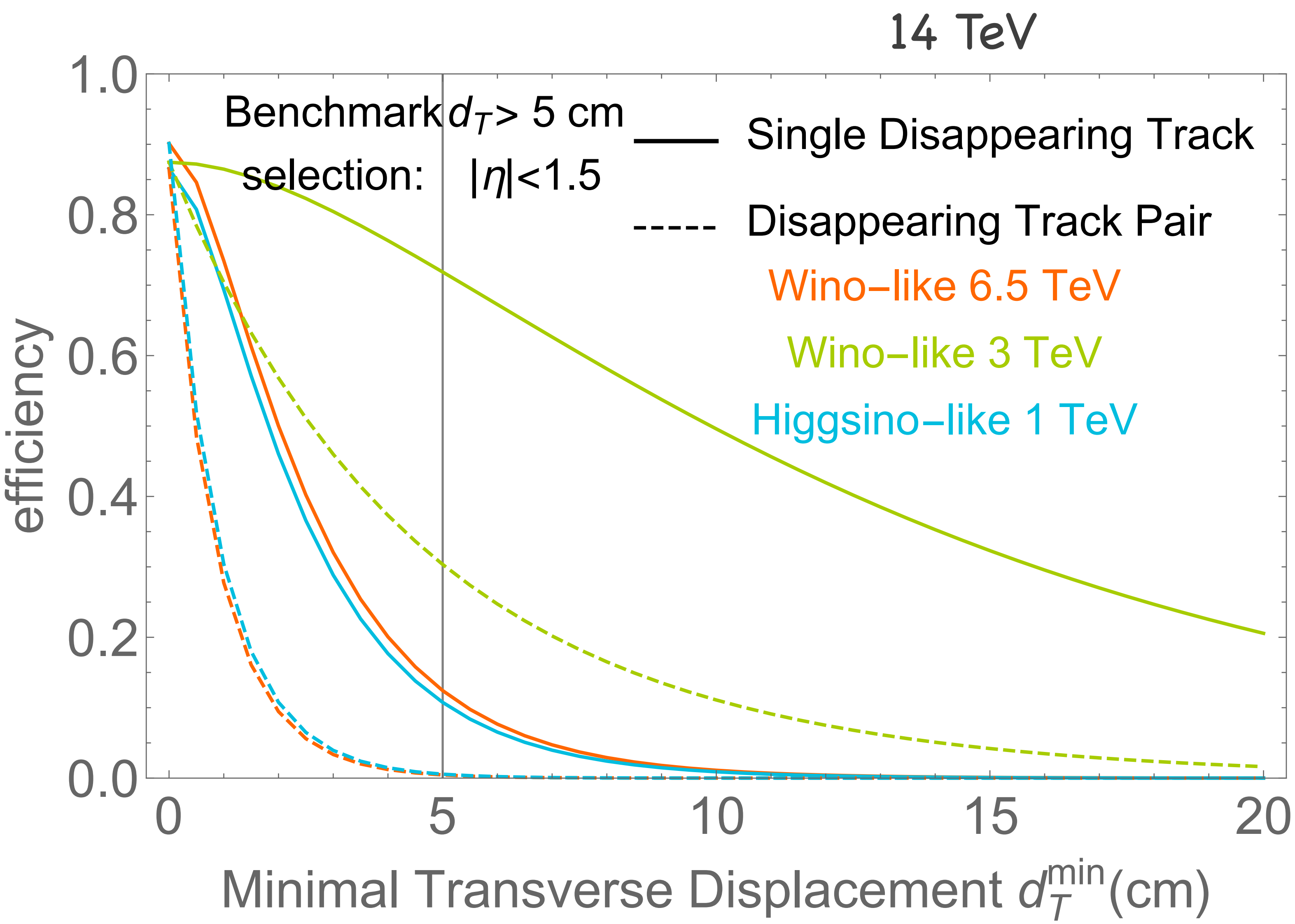


To reconstruct a disappearing track: 2-3 hits needed.

Focusing on the barrel region, endcap further away.

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

Signal rate

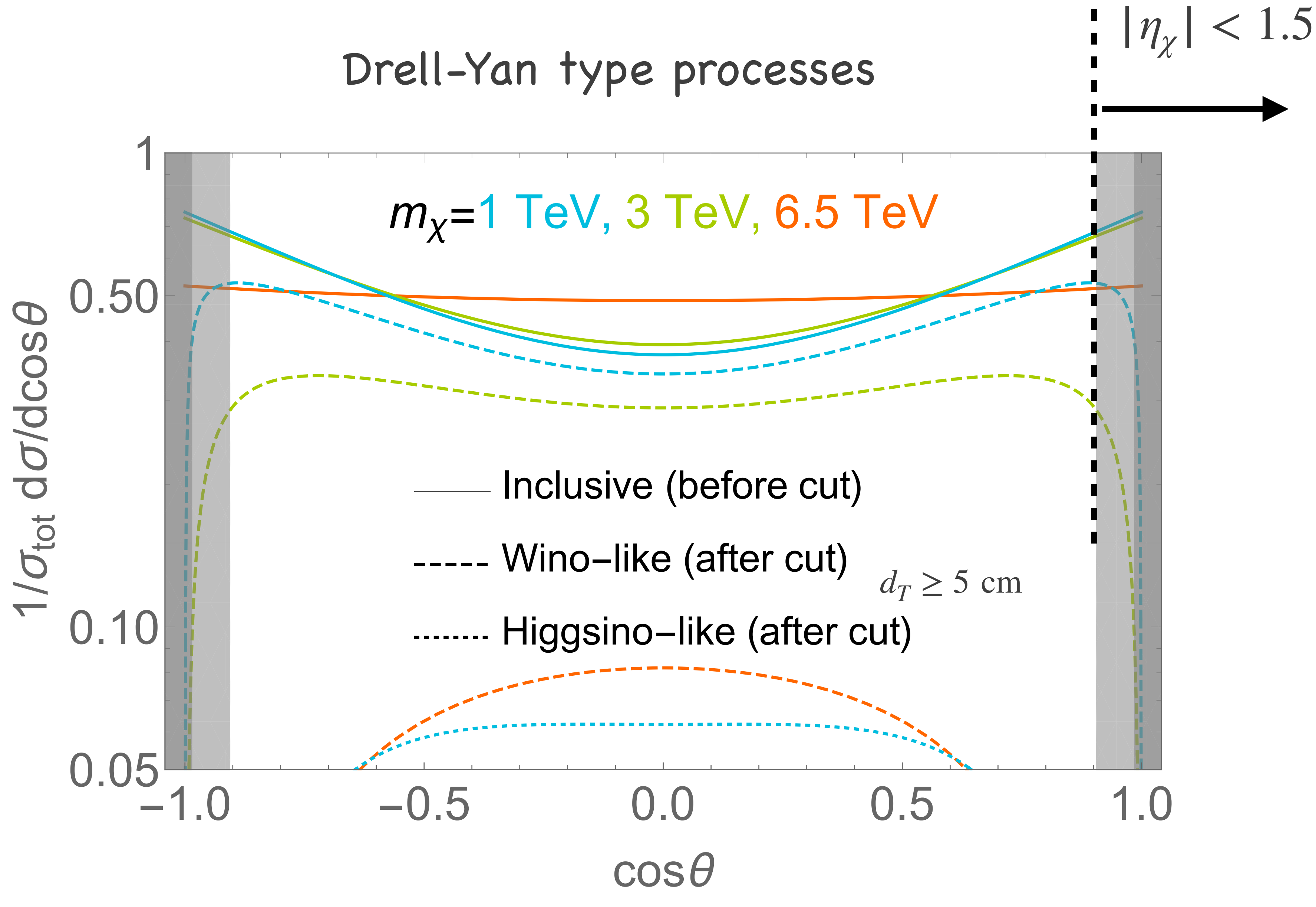


Boost matters

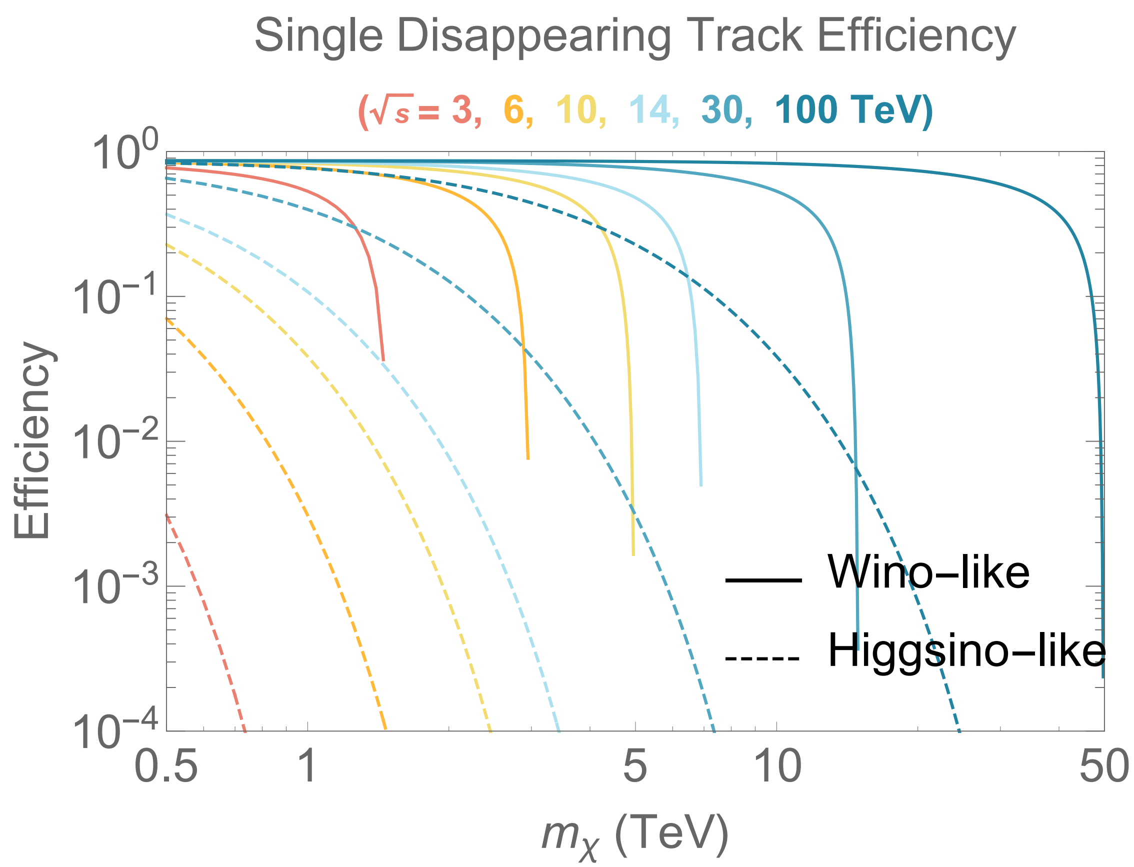
Higgsino has shorter lifetime

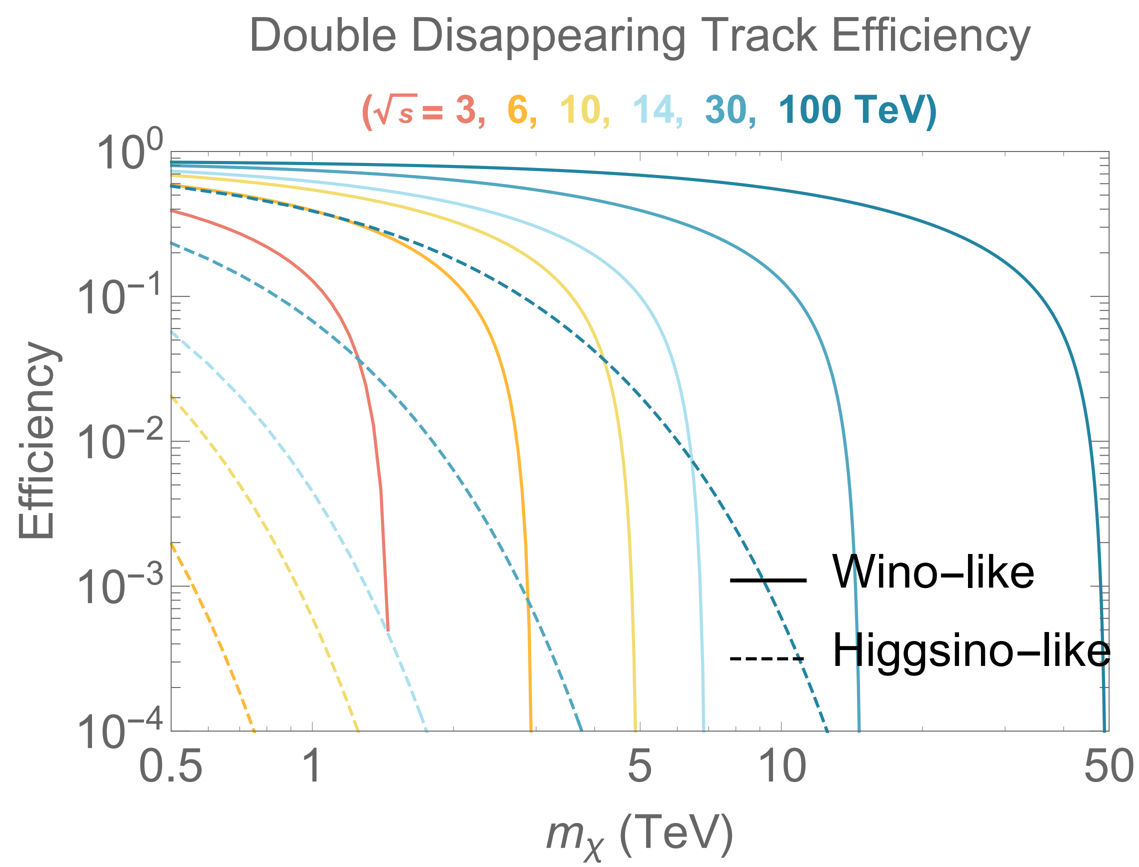
"survival" probability: $\epsilon_\chi(\cos\theta, \gamma, d_T^{\min}) = \exp\left(\frac{-d_T^{\min}}{\beta_T \gamma c\tau}\right)$ $\beta_T = \sqrt{1 - 1/\gamma^2}\sin\theta$

Angular distribution of the signal



Signal effciencies





Apply disappearing track to Drell-Yan mono-photon signal

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

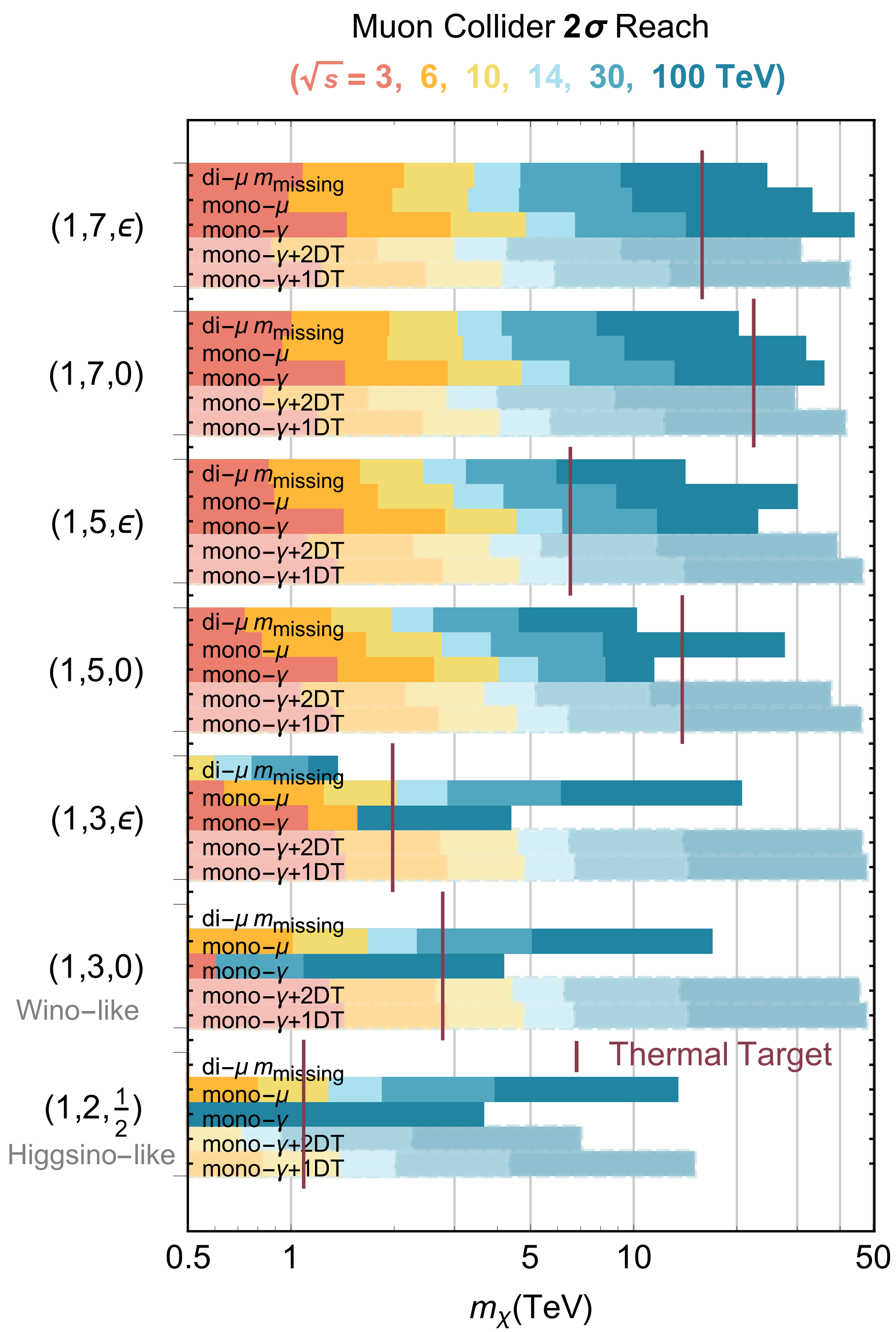
As a target/benchmark, use

20(50) signal events for 2(5)σ reach.

Reach by channel

Luminosity benchmark:

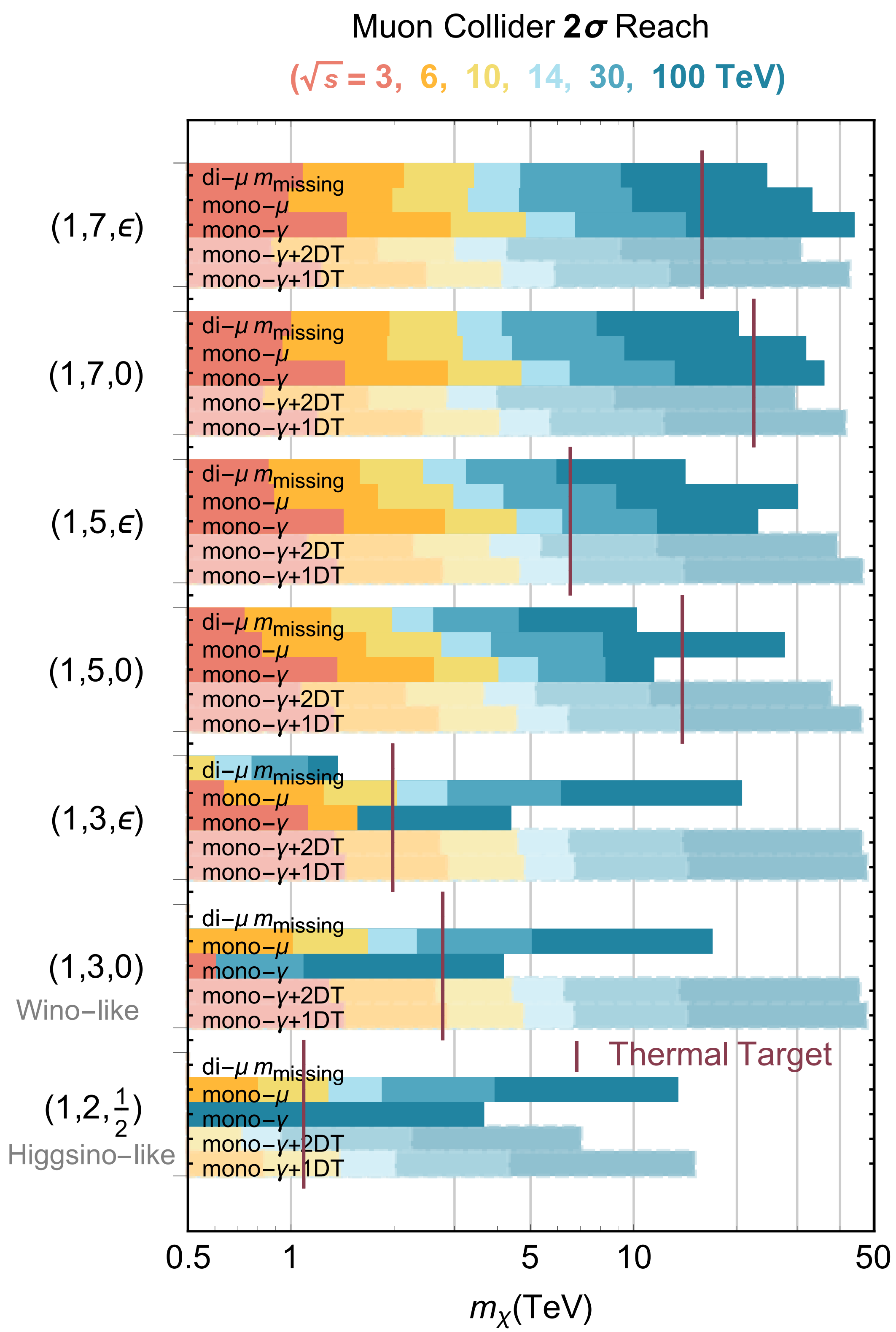
$$\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$



Reach by channel

Luminosity benchmark:

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



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

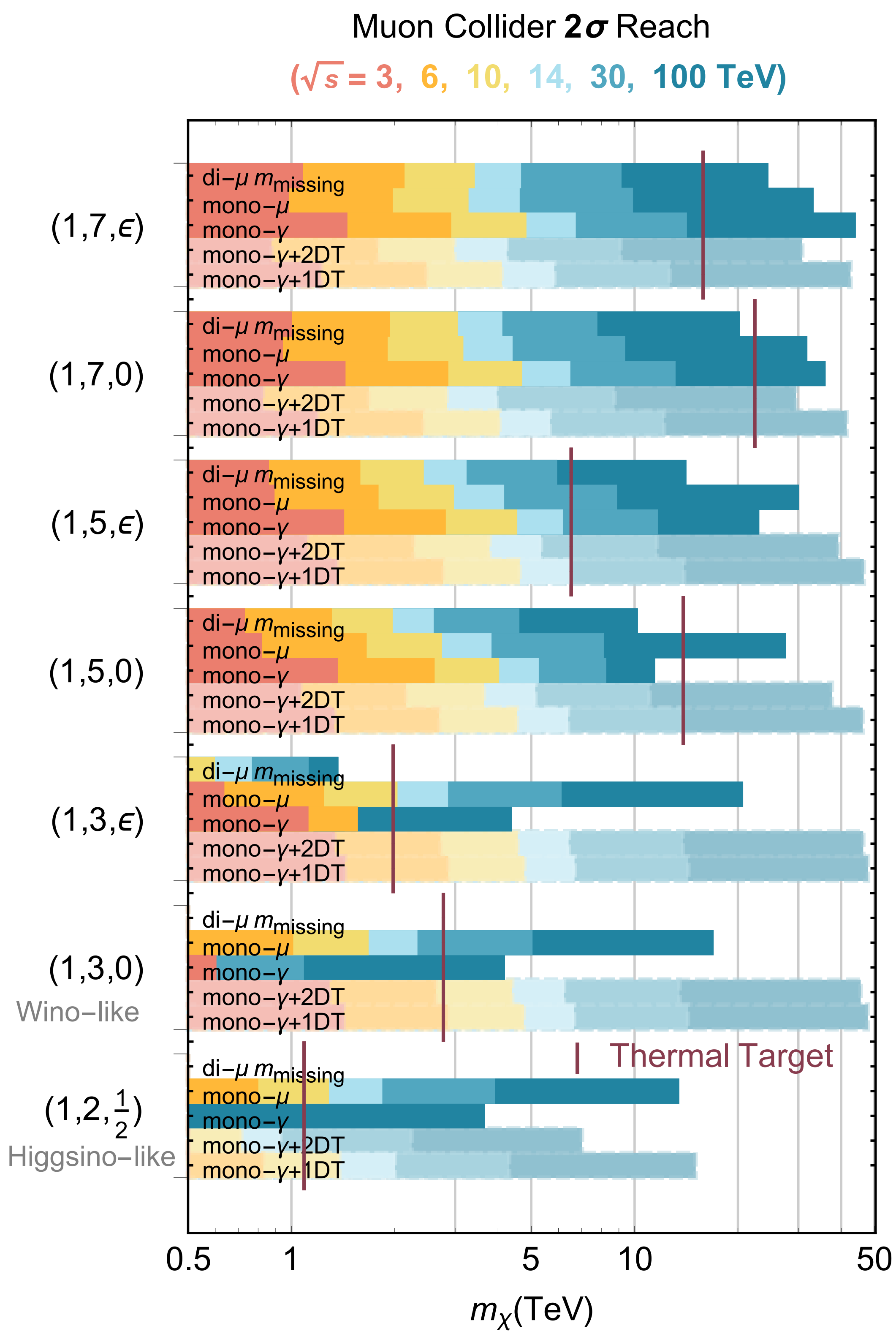
Good reach for lower dim (n≤3) multiplets.

Di-muon can be useful for higher multiplets.

Reach by channel

Luminosity benchmark:

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



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.

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

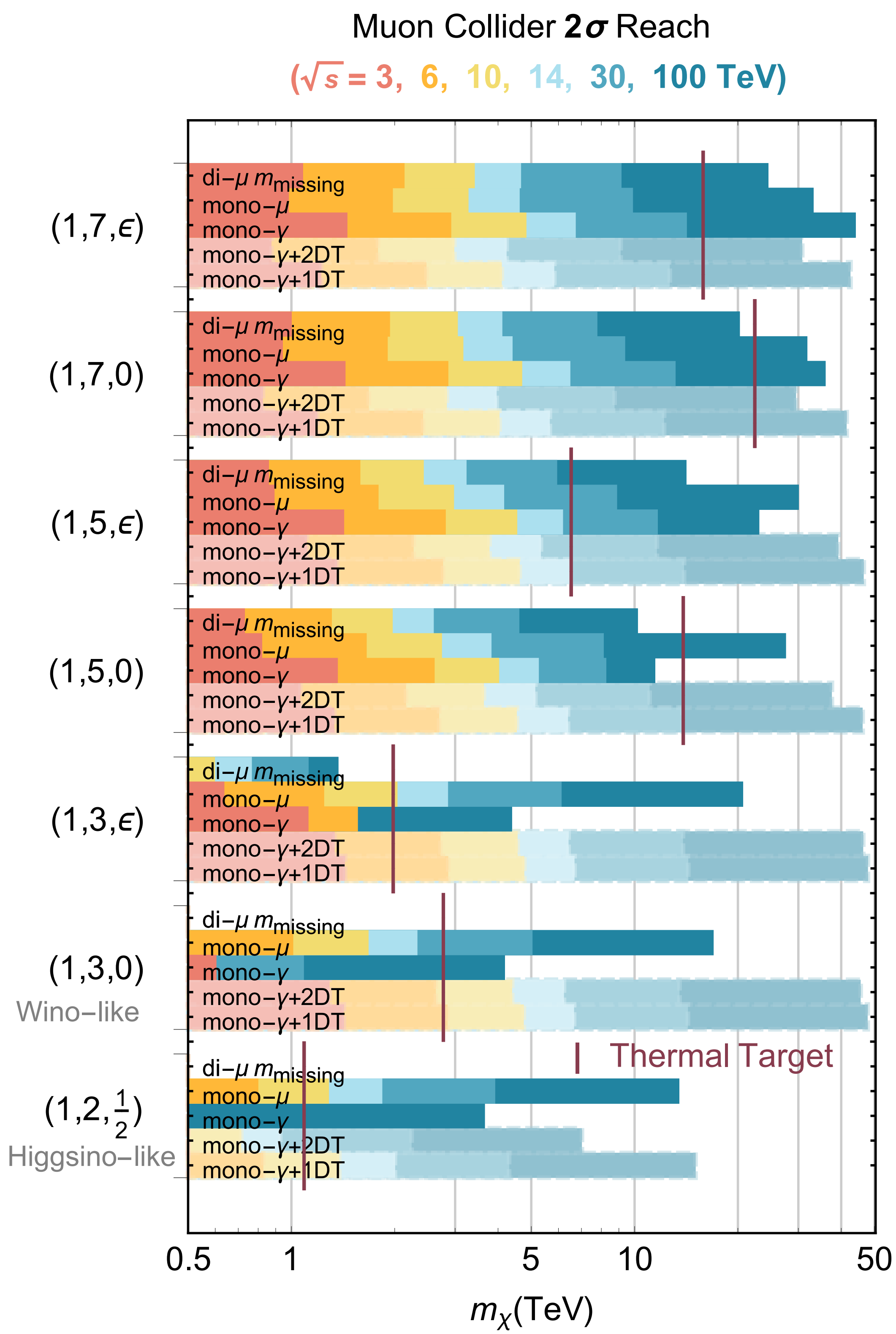
Not yet reach $m_\chi \approx 1/2\ E_{CM}$.

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

Reach by channel

Luminosity benchmark:

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



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

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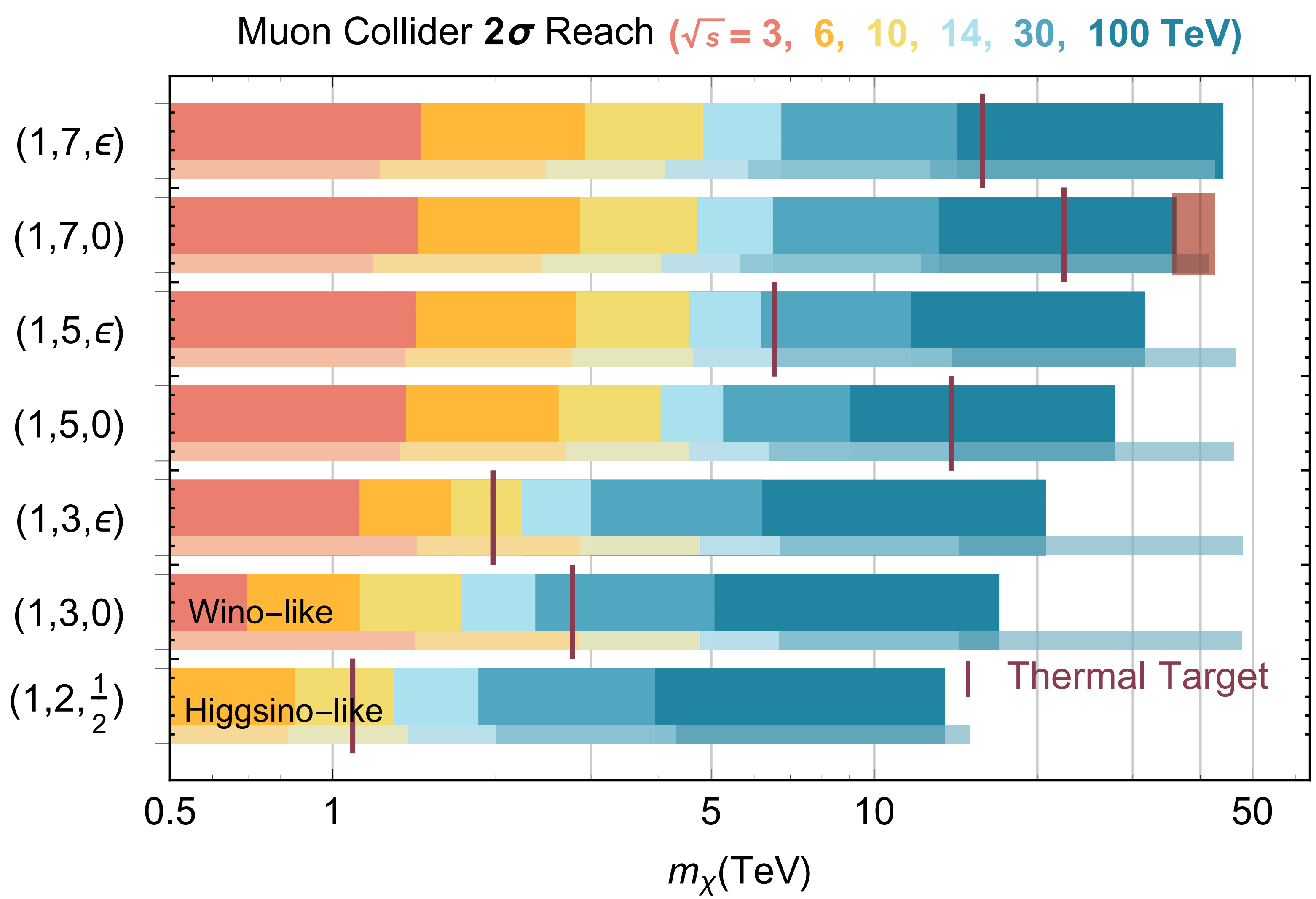
Mono-photon channel, low S/B, systematics dominated.

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

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

Disappearing track. Great potential! However, reach will depend on BIB level. Not quite reach the $m_\chi \approx 1/2\ E_{CM}$ (close for the triplet), since some boost still needed (particularly for n≥5)

Summary: the reach

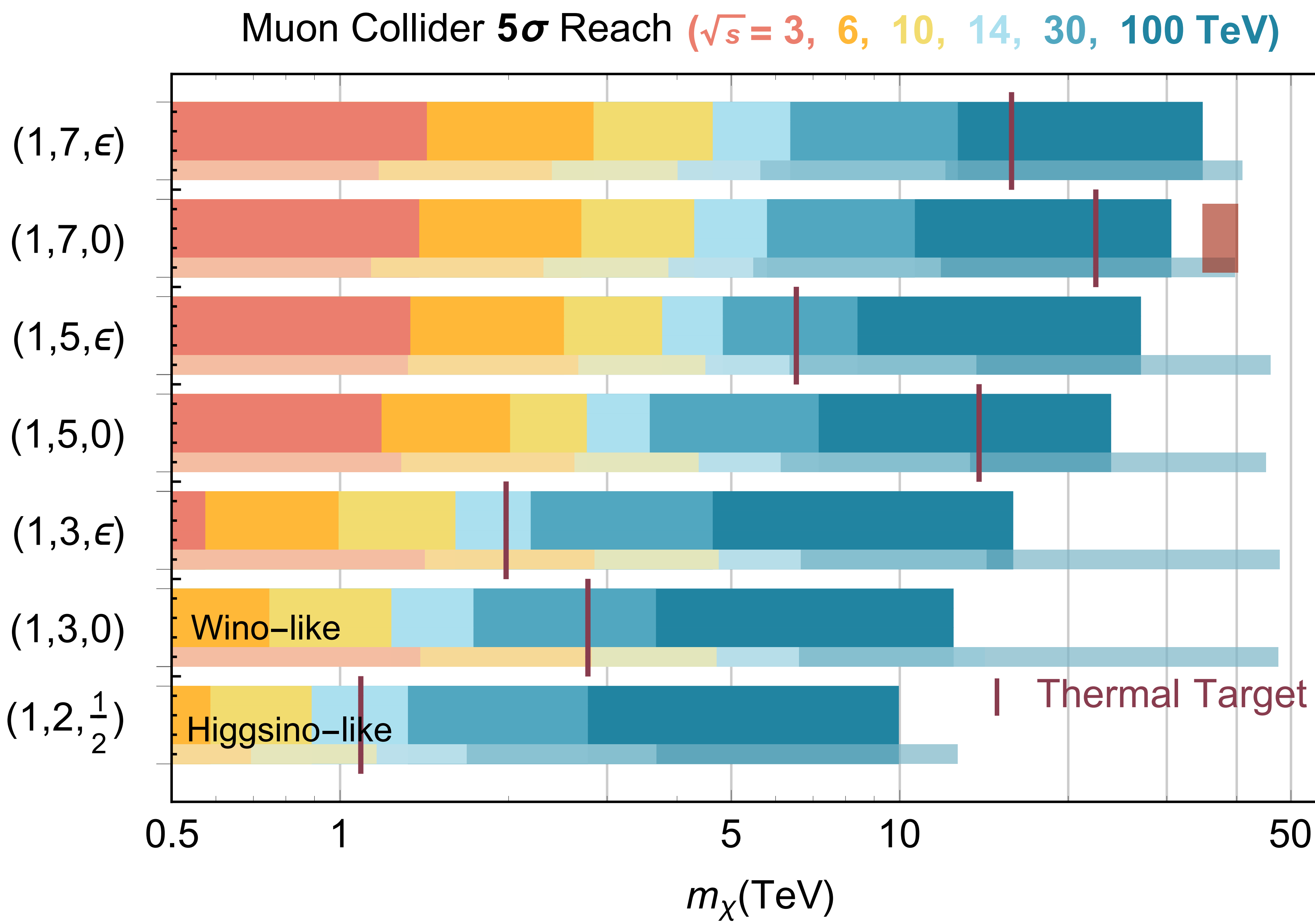


With inclusive signal: E_{CM} ≈ 14 TeV enough to cover n≤3 multiplets.

Higher energy needed to cover higher multiplets.

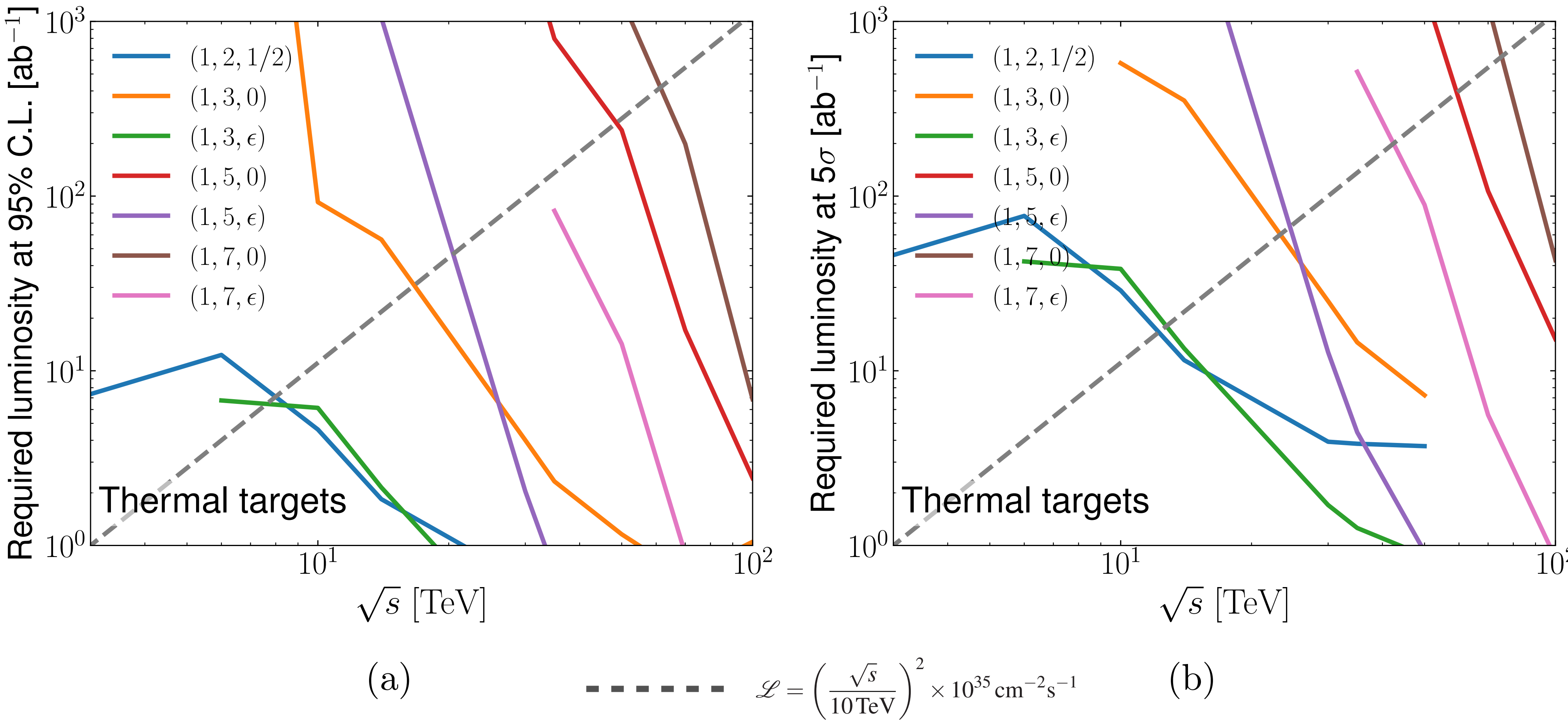
With disappearing track: potential to reach almost $m_\chi \approx 1/2\ E_{CM}$

5σ discovery reach



Luminosity and energy: trade off

Inclusive searches:



Some examples

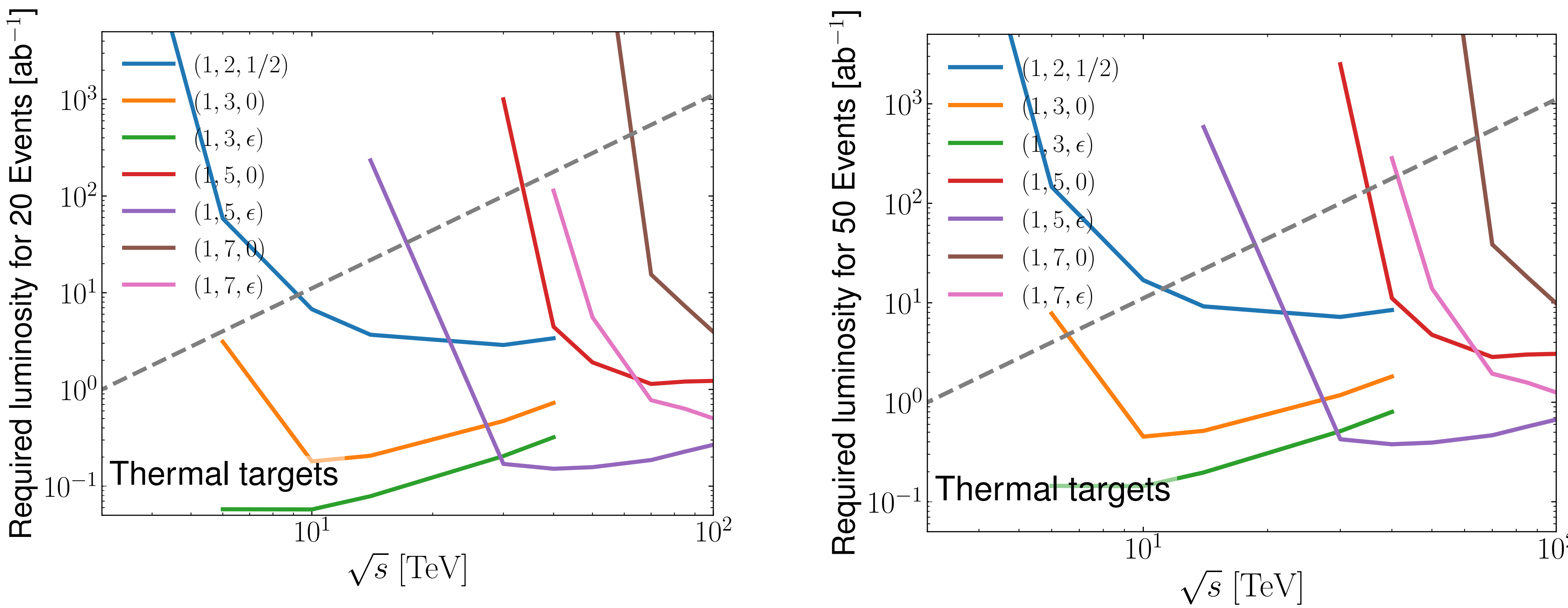
doublet: 5 ab^{-1} at 10 TeV

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

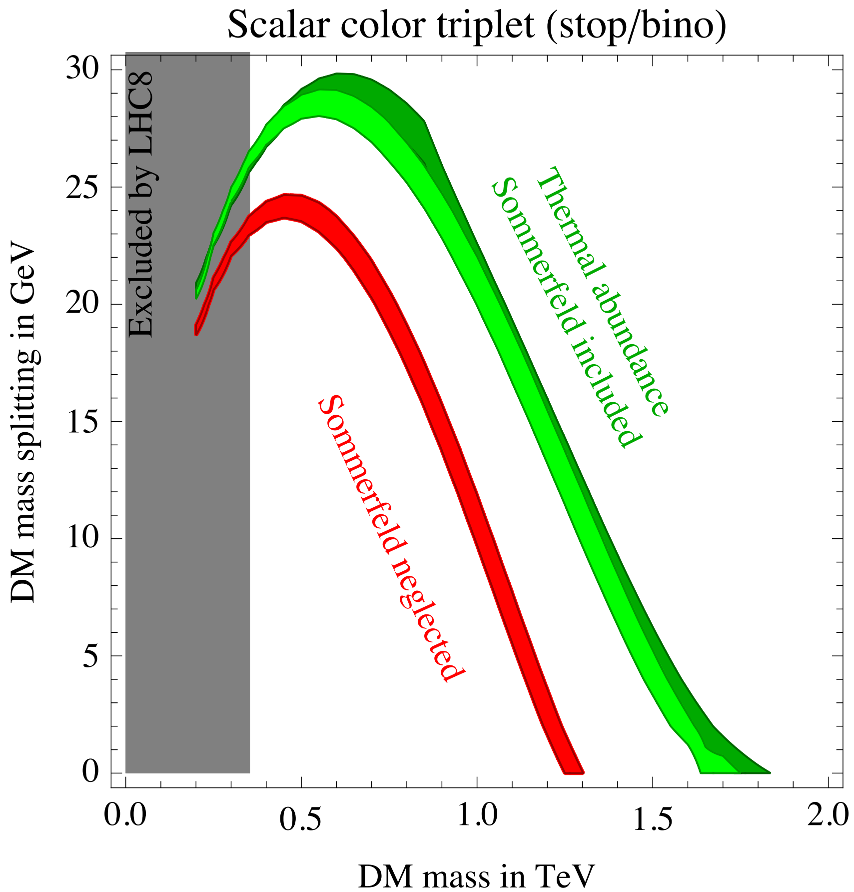
Dirac triplet: < 0.1 ab^{-1} at 6 TeV

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

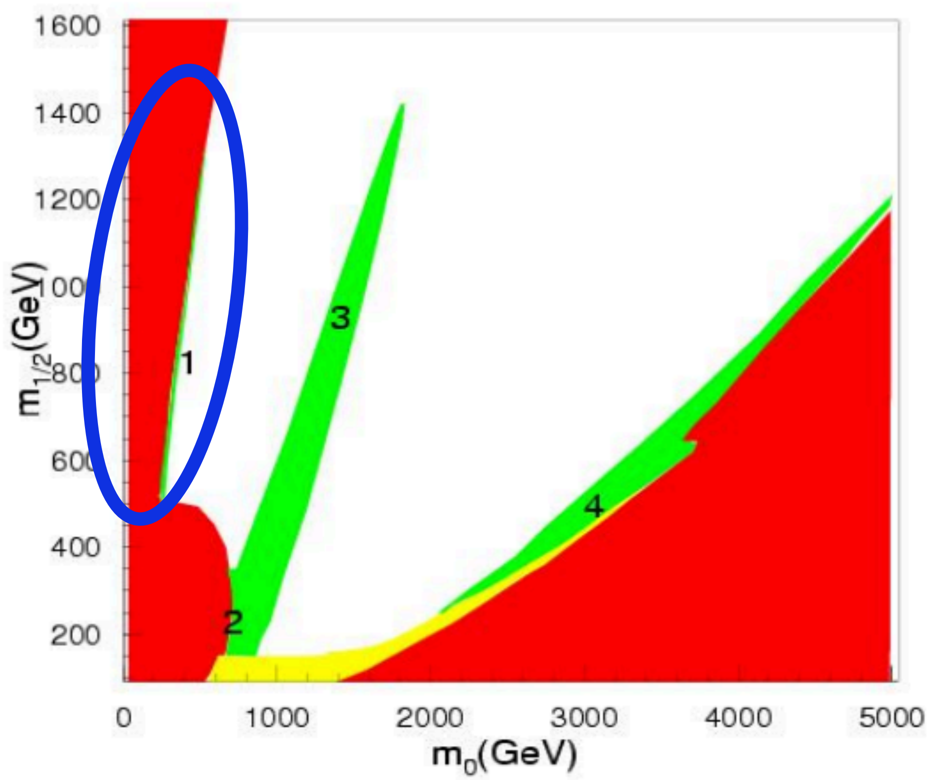
Additional scenarios

- Coannihilation.



De Simone, Giudice, Strumia, 2014

stau coannhilation

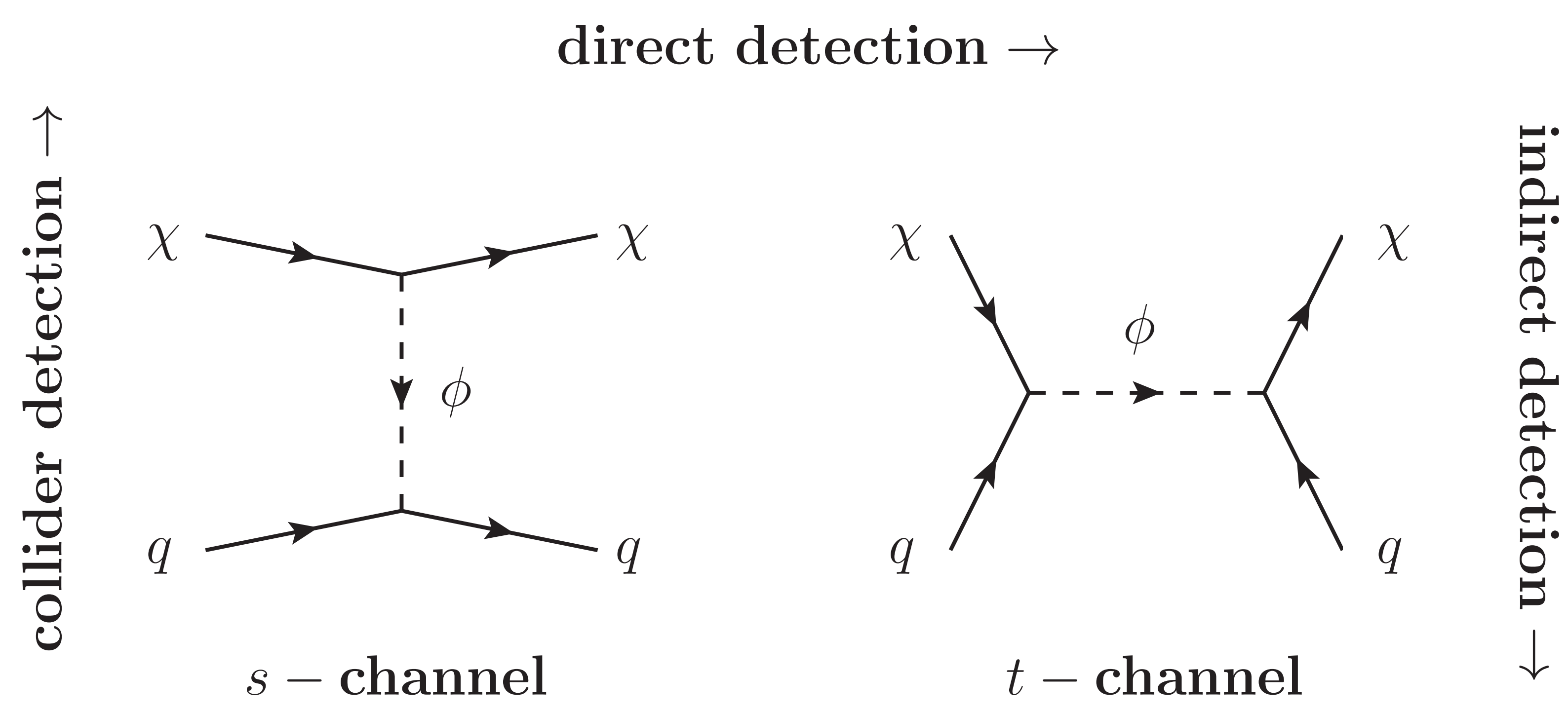


Larger mass splitting, no disappearing track.

Expect to be covered by the inclusive missing mass searches.

Additional scenarios

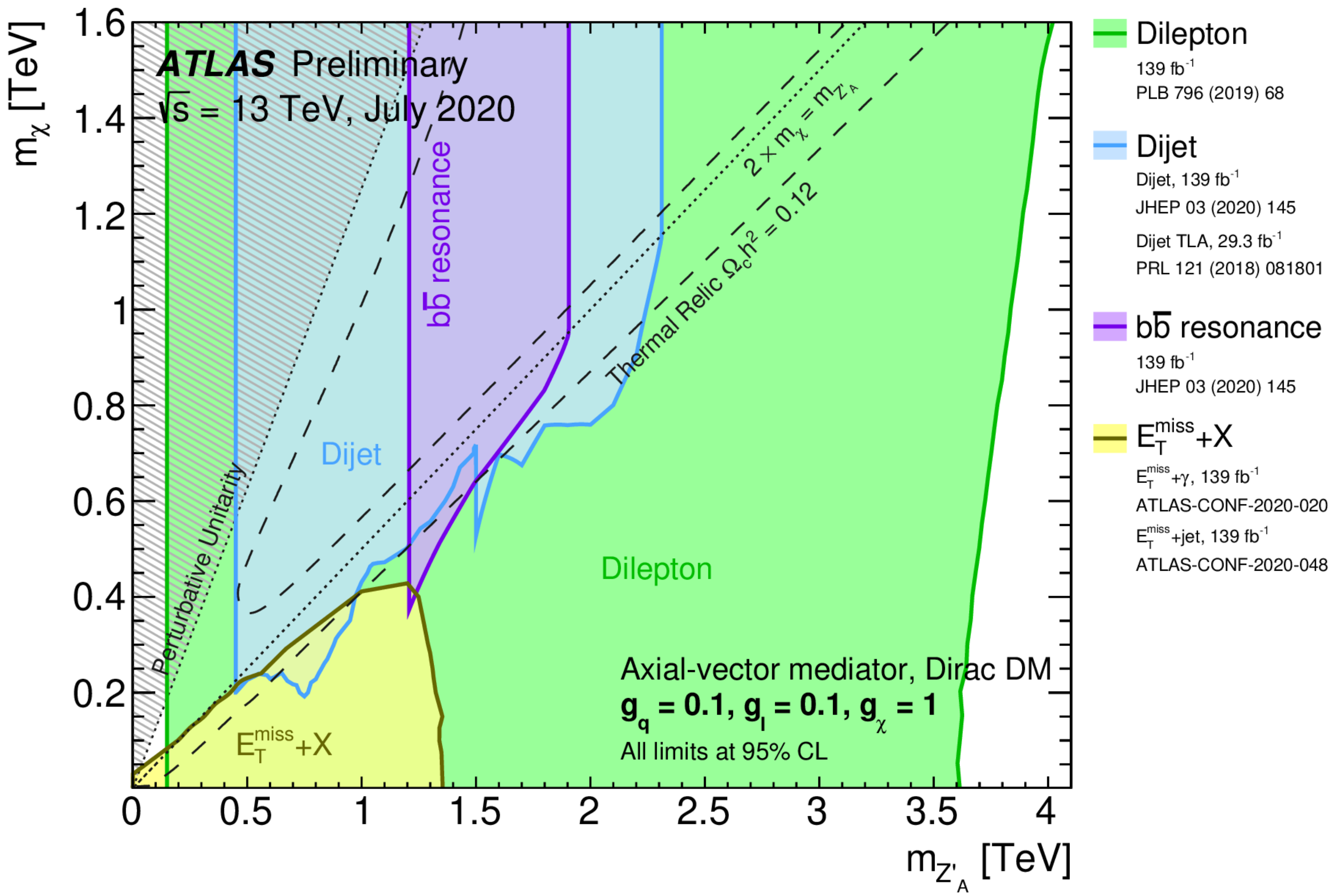
- Simplified models. (Actually more complicated.)



Introducing new mediators between DM and SM.

Muon collider sensitive to mediators which couples to muons.

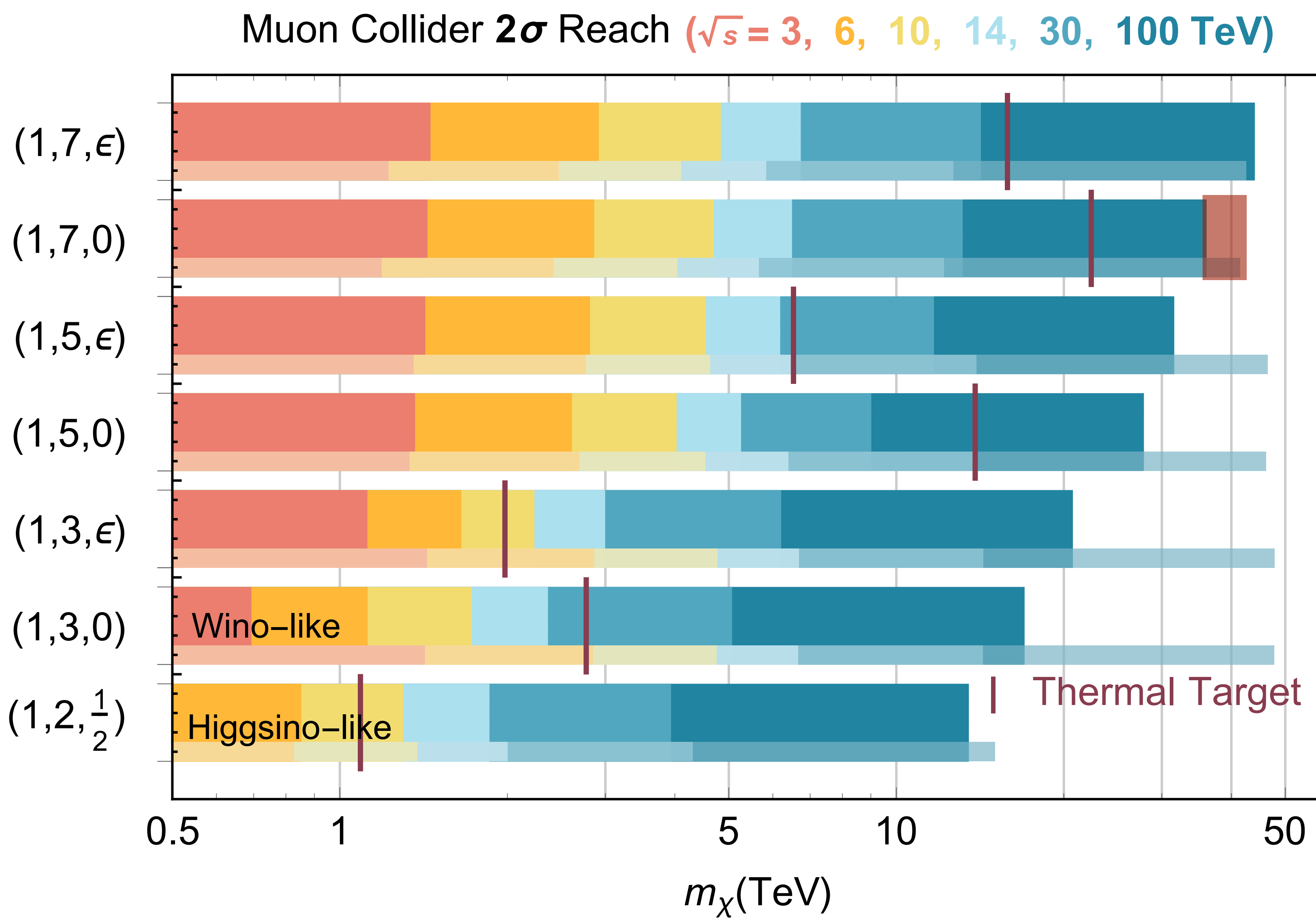
Search for mediators



Typically, direct search for mediators more sensitive.

Expected to be similar at muon collider

Conclusion



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

Muon collider scenarios

D. Schulte, Snowmass AF+EF joint meeting

Muon Collider Parameters

From the MAP collaboration: Proton source

		Higgs			
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\text{ cm}^{-2}\text{s}^{-1}$	1.8	20	40

Higher energies, 30 TeV and even higher, have also been mentioned.

Luminosity benchmark:

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

Marching forward