Community Summer Study
Energy Frontier: Dark Matter Discussion

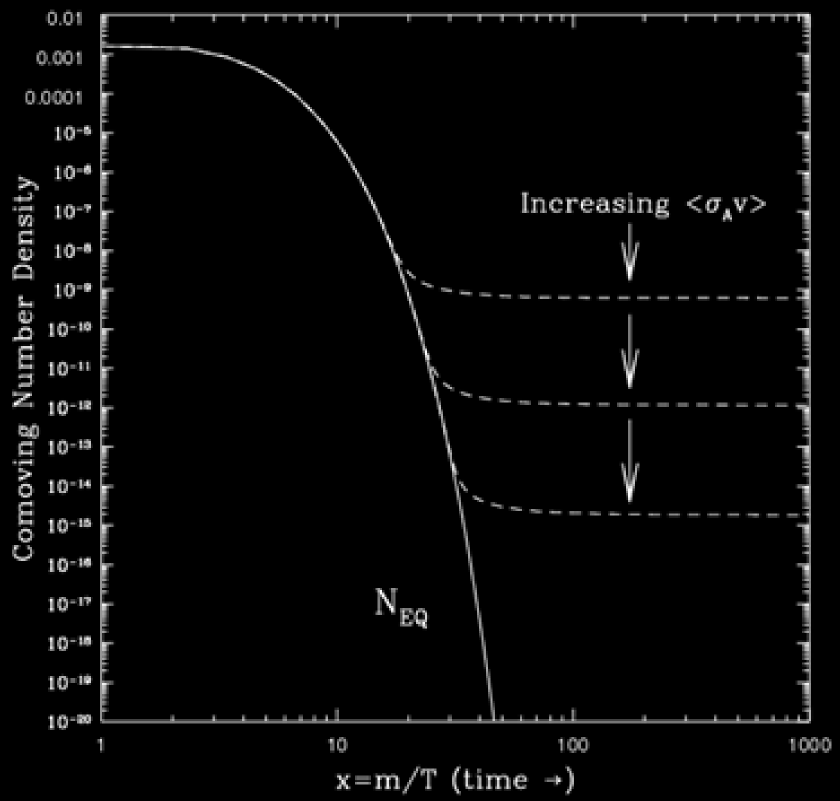
Minimal Dark Matter

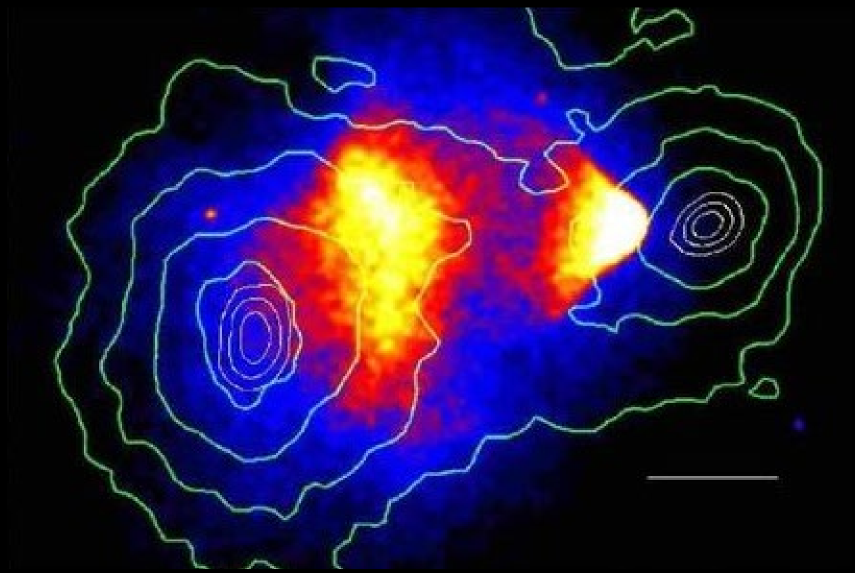
Zhen Liu
University of Minnesota
07/21/2022

WIMP Dark Matter

A **compelling**, **simple**, **predictive** explanation for thermal, cold dark matter.

One **key target** for future **collider** programs.





$$\Omega h^2 \simeq 0.1 \times \left(\frac{2\times 10^{-26}\mathrm{cm}^3/\mathrm{sec}}{<\sigma_{\mathrm{eff}} v>_{\mathrm{freeze-out}}}\right)$$

$$<\sigma_{\mathrm{eff}} v>_{\chi\bar{\chi}\to VV} \simeq \frac{\pi\alpha_\chi^2}{m_\chi^2}$$

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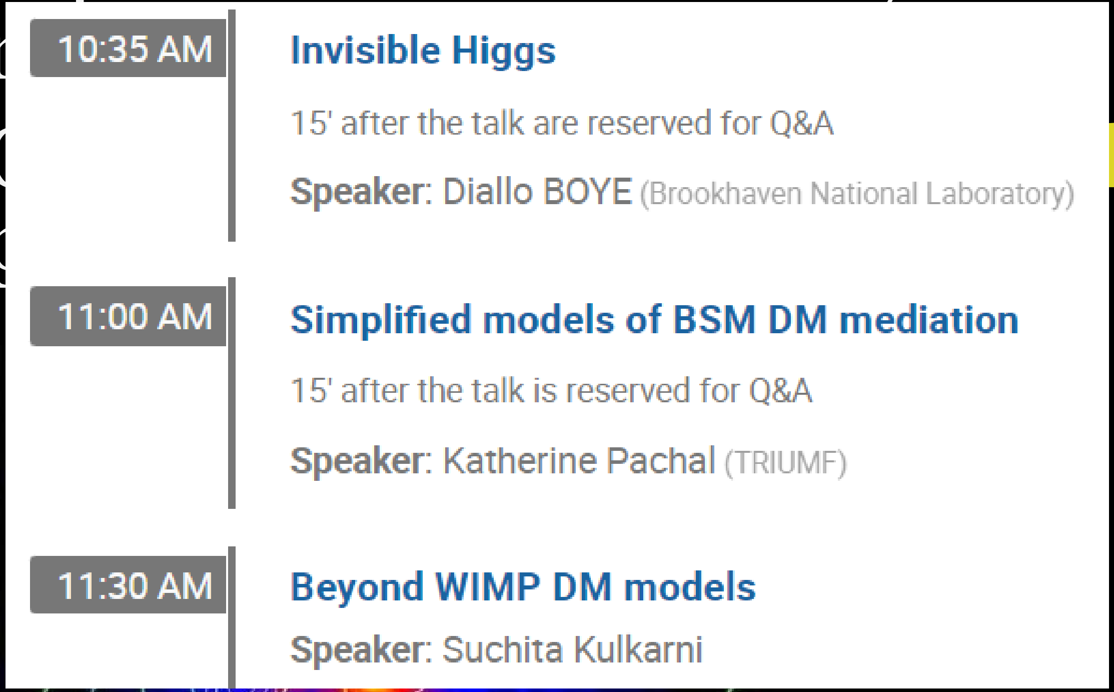
10:35 AM
Invisible Higgs
15' after the talk are reserved for Q&A
Speaker: Diallo BOYE (Brookhaven National Laboratory)

11:00 AM
Simplified models of BSM DM mediation
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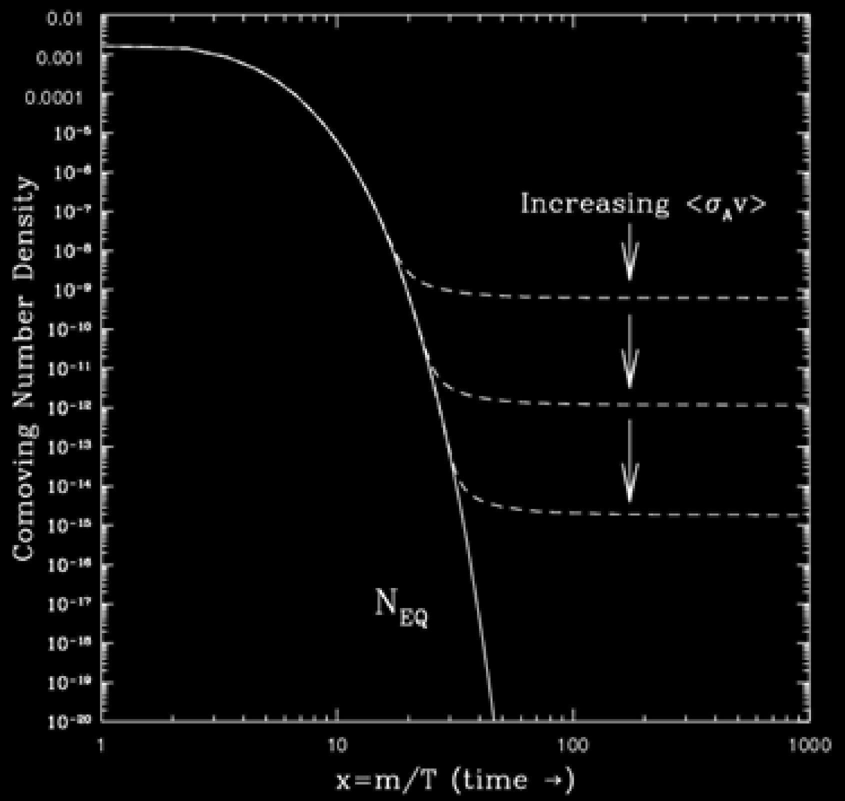
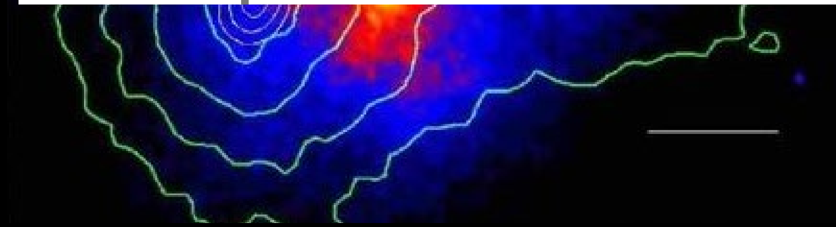
Speaker: Katherine Pachal (TRIUMF)

11:30 AM
Beyond WIMP DM models
Speaker: Suchita Kulkarni





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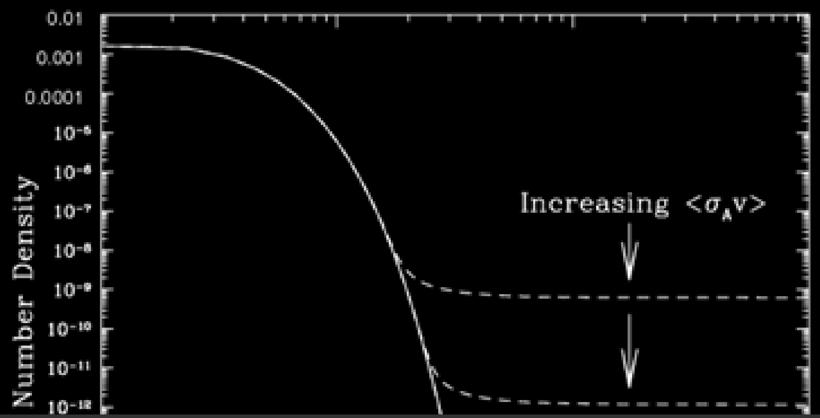

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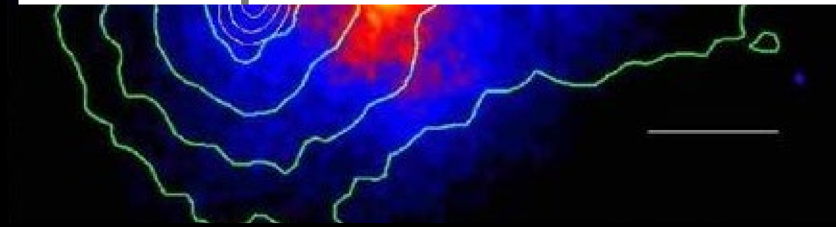
Lots of new research activities in research in non-minimal dark matter and dark sectors, in particular, Long-Lived Particles signatures.
See also in other sessions.



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Heavy DM at Colliders

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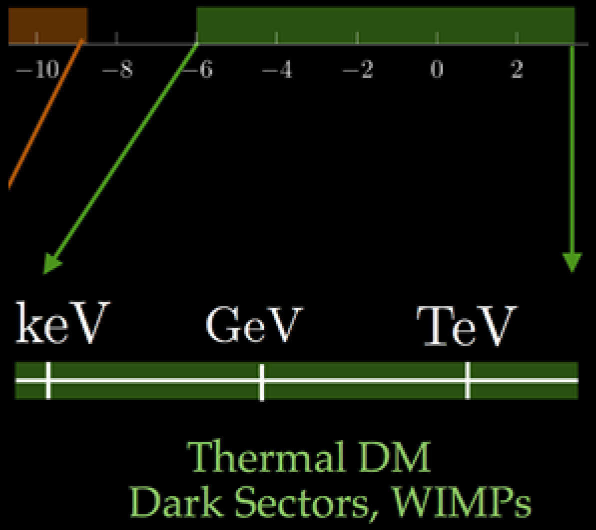
One **key target** for future **collider** programs.

Has a scale

Has an upper bound on the scale



Heavy DM at Colliders

Colliders can (via creative and ambitious efforts)

- Discover
- Test fully this regime
- Reveal their thermal mechanisms
- Check complimentarily and consistently

To search for: DM and its friends

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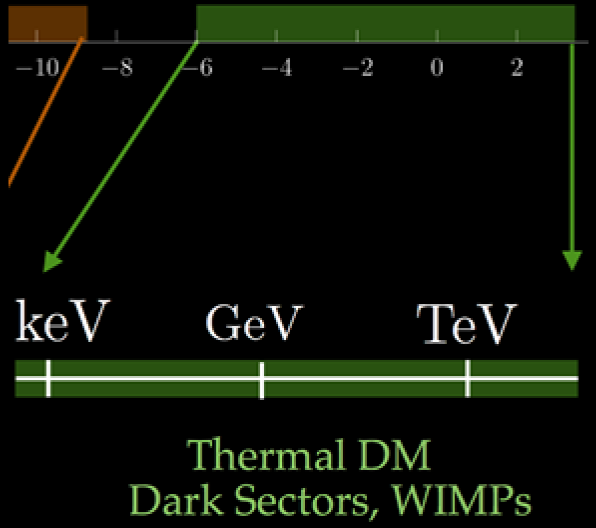

"minimal" scenario

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	11 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	14 TeV
(1,7,ϵ)	Dirac	16 TeV

*Recent work show sevenplet Majorana thermal target as high as 49 TeV

"Nightmare":

Additional considerations:

- Doublet → "Higgsino"
- Triplet → "Wino"
- Use "epsilon" notation to indicate Dirac case
- Even-plet requires non-zero Y (and additional splitting to suppress direct detection)
- Perturbative Unitarity
- Summonfeld and bound-state effect

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"Nightmare":

- High thermal targets
  - 23 TeV for 7-plet Majarona
- Minimal signatures
  - Only missing energy (details next)

Additional considerations:

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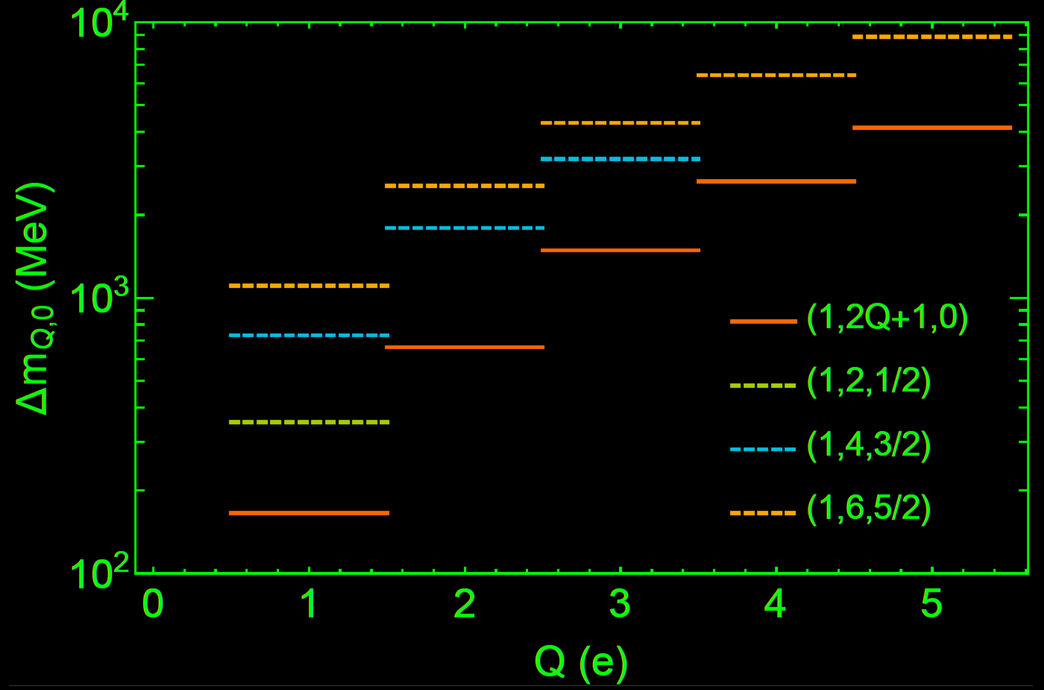
$$< \sigma_{\chi\bar{\chi}\to VV} v > \simeq \frac{g_2^4\, n^4 + 16 Y^4 g_1^4 + 8 g_2^2 g_1^2 Y^2 n^2}{64\pi\, M_\chi^2 g_\chi}$$

Basic Pheno Considerations

"non-trivial" to consider MuC

- Minimal signature



Basic Pheno Considerations

"non-trivial" to consider MuC

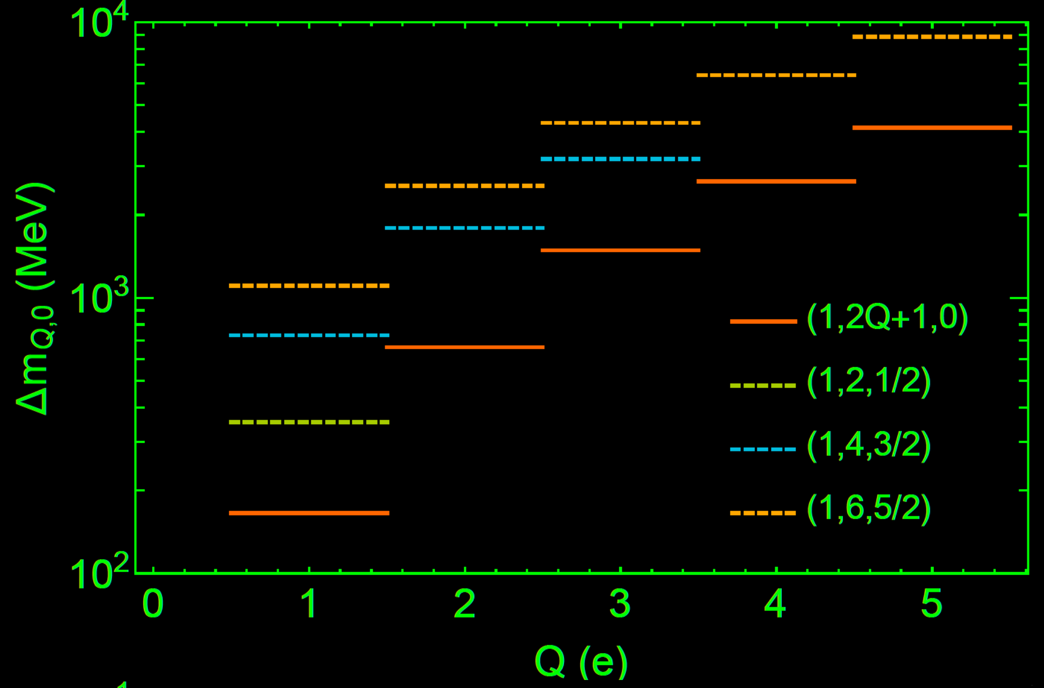
- Minimal signature
  - Mass splitting O(few hundred MeV)
  - Decay products soft
  - Transition between states fast (<mm for most of the cases)
- Missing ET (at LHC)➔Missing Mass (at MuC)

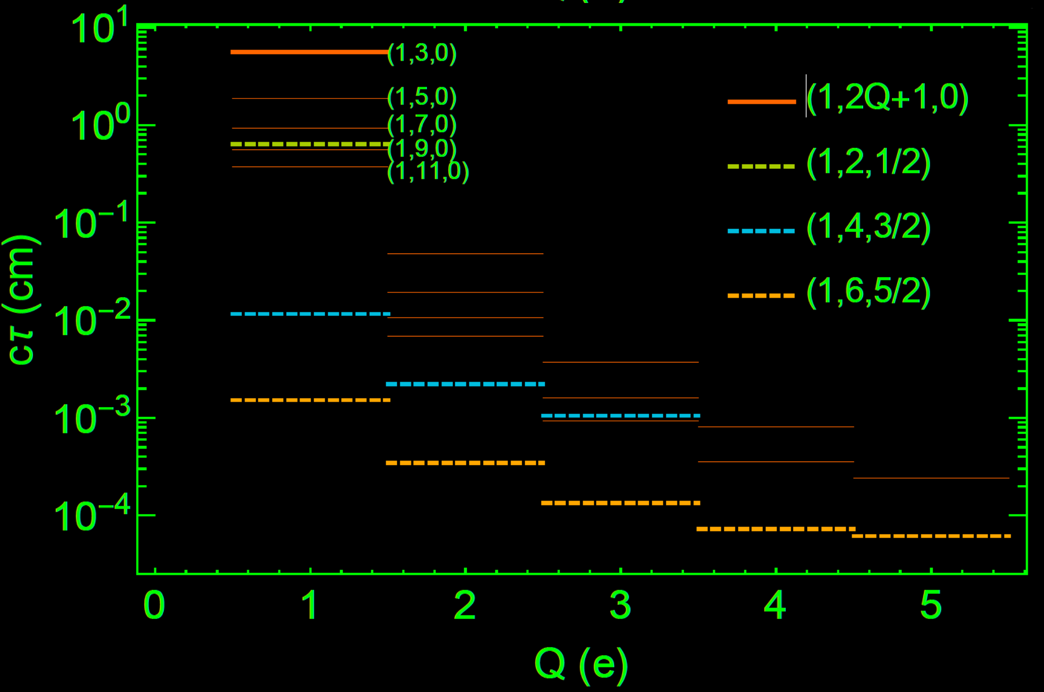
$$m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\text{obs}})^2$$

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

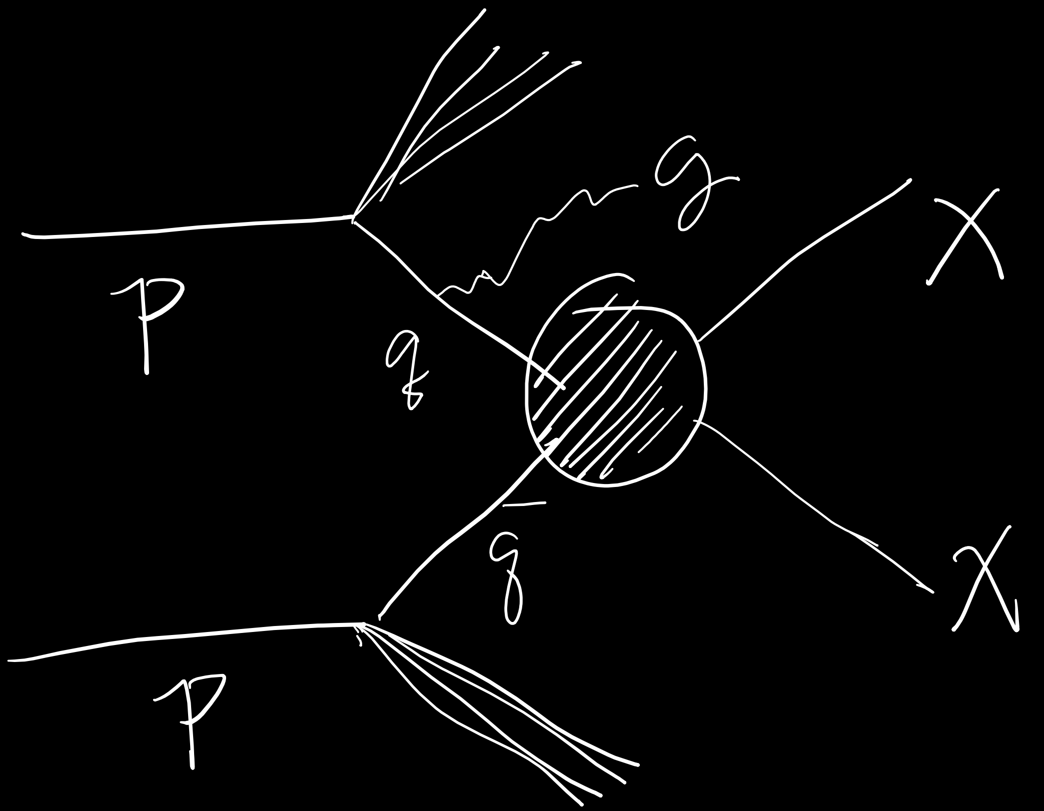
$$\delta m = \frac{g^2}{4\pi} m_W \sin^2\frac{\theta_W}{2} \approx 160\text{–}170 \text{ MeV}$$

$$\kappa_W = \frac{2}{(T - Q + Y)(T + Q - Y + 1)}$$

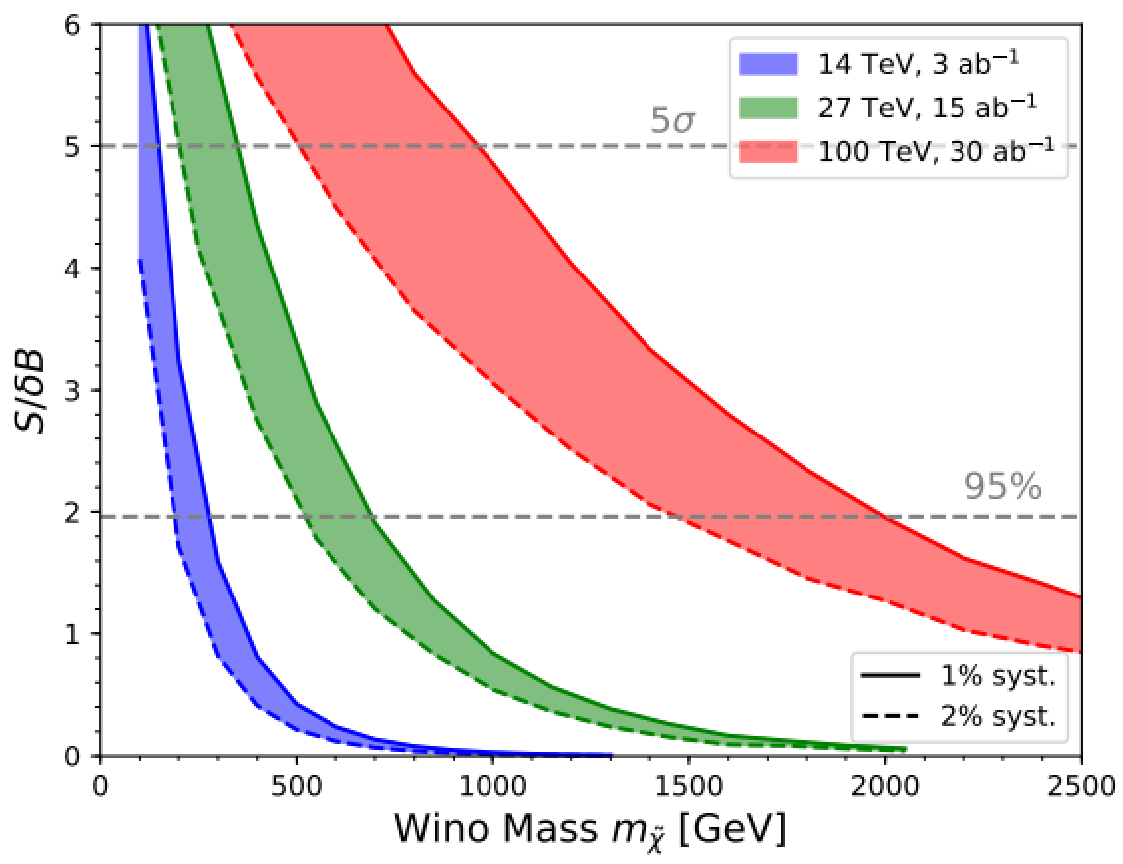


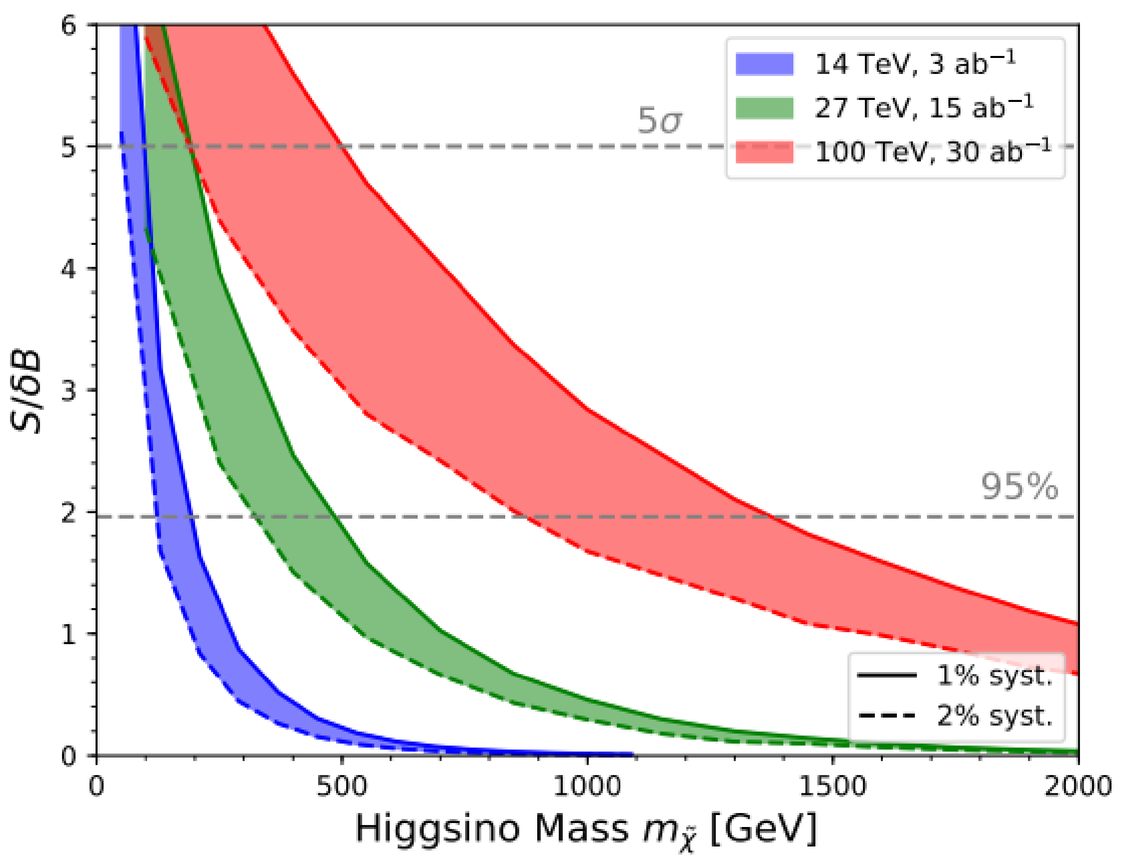


Minimal & Inclusive Signatures: Missing Energy/Momentum



Hadron Collider: Missing Transverse Energy





Band: systematic uncertainty assumptions.

Han, Mukhopadhyay, Wang, 18',
Low, Wang 14'

Lepton Colliders: Pheno Considerations

- Missing ET (at LHC)→Missing Mass (at MuC)
- The interplay between different channels:
  - DY-type dominance but large background
  - VBF-type log-growth but limited available energy
- Photon initial state process important
  - Needs to use photon PDF or Weizsacker-Williams approximation
  - Hacked Madgraph to implement
  - Additional divergences often-appear

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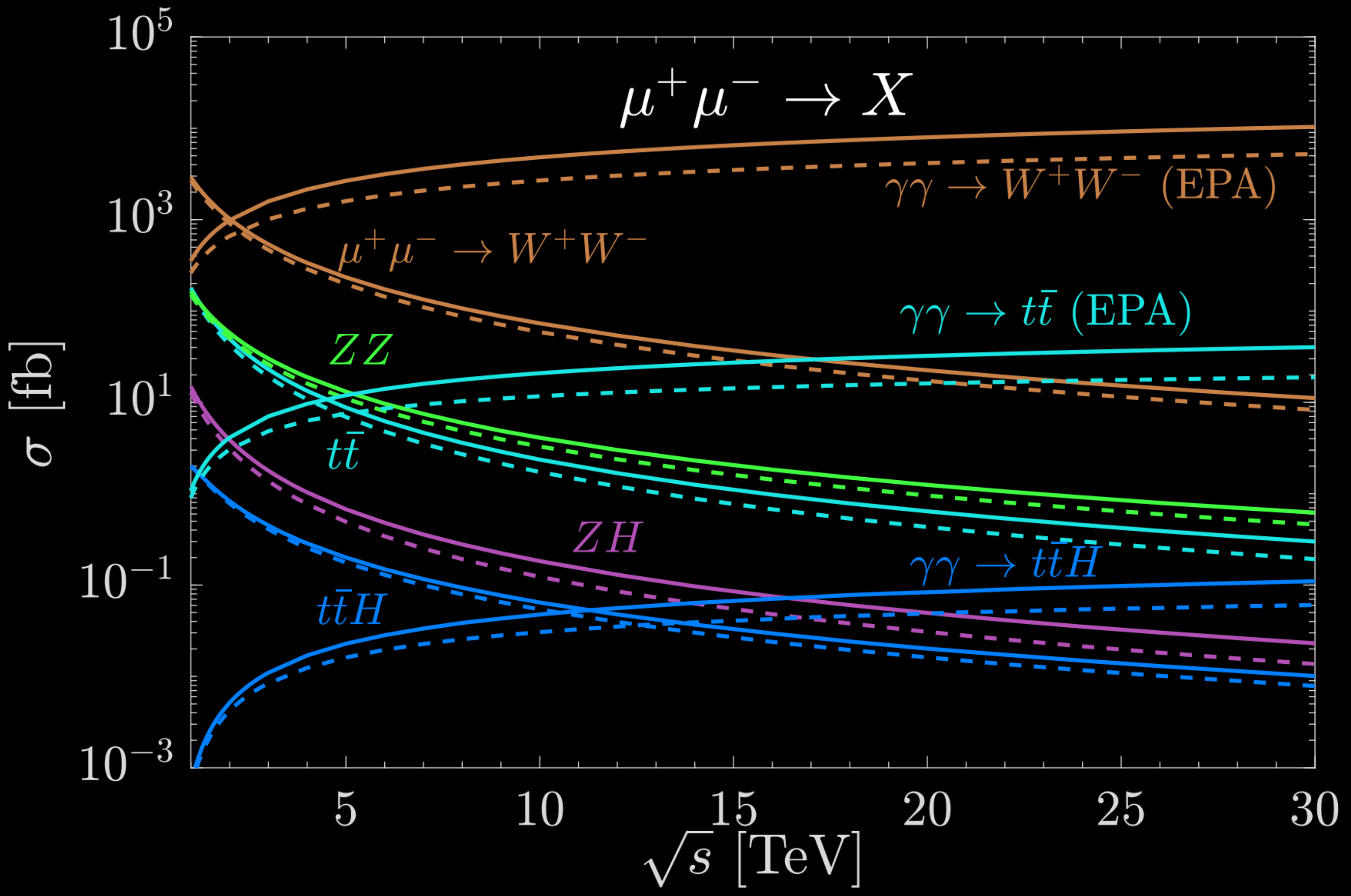
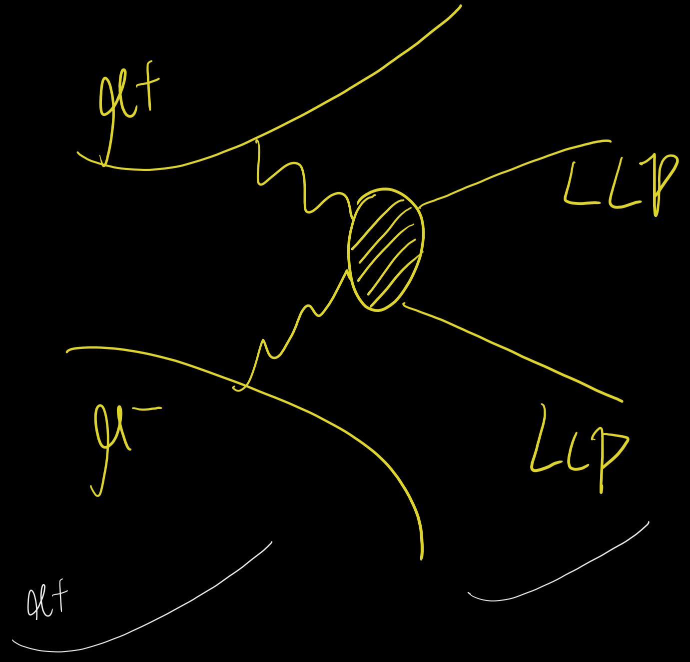
Missing Mass signature:

- Simple and inclusive (hence also most conservative)
- Mono-photon
- VBF-dimuon
- Mono-muon
- Mono-W

High Energy lepton colliders also a Vector Boson Machine



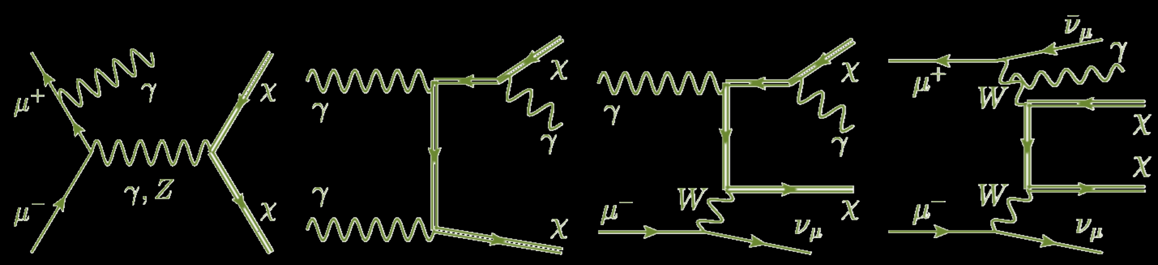
For light (<)(EW-charged) LLPs:
VBF dominants the production.
In particular, there is a logarithmic enhancement and longitudinal enhancement.

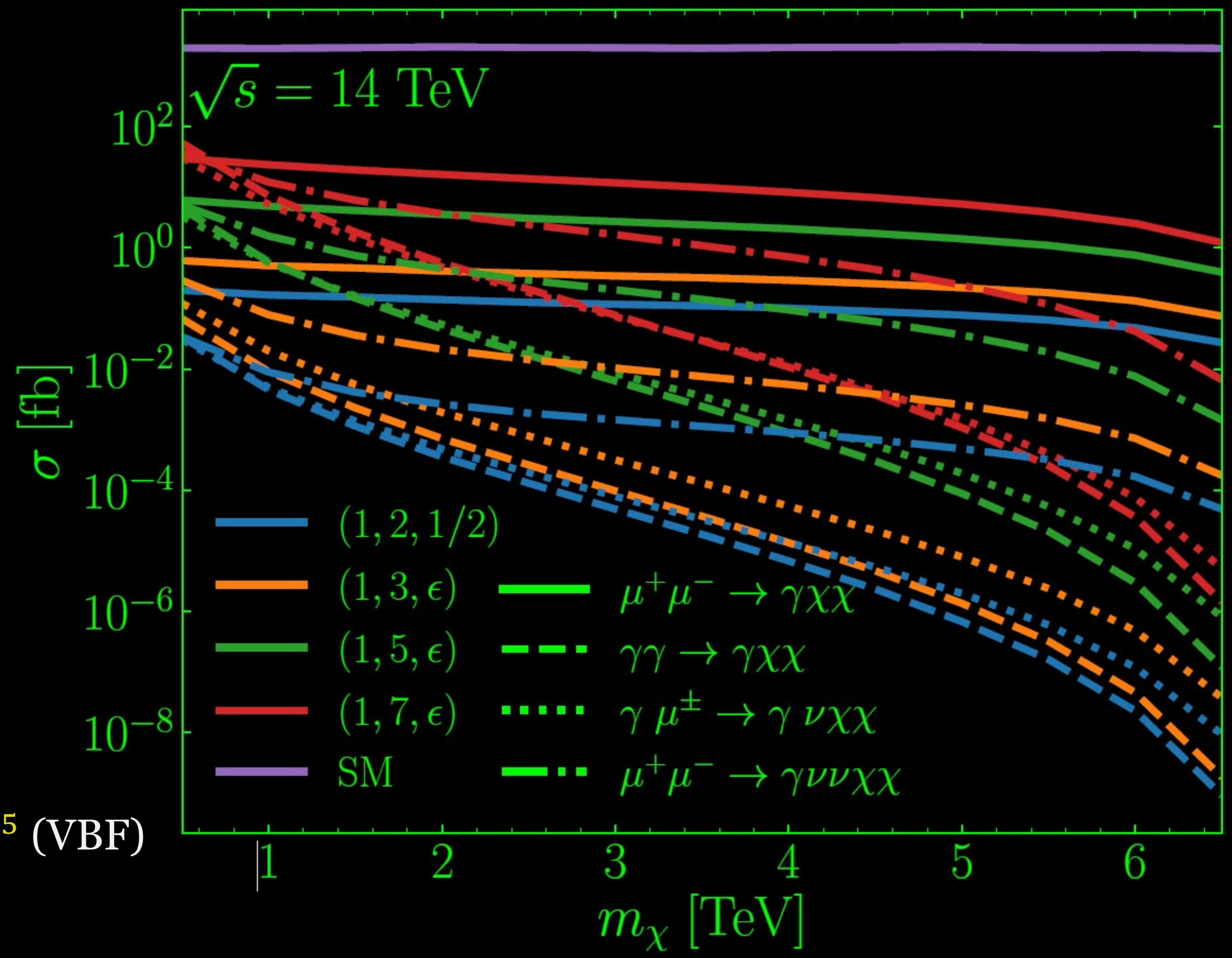


Han, Ma, Xie, [2007.14300]

All combinations of components of the EW multiplet are included, so-long as they respect the underlying gauge symmetries

Mono-Photon





Rate grows with n-plets as roughly $n^{2\sim3}$ (DY) and $n^{4\sim5}$ (VBF)
Doublet and Triplet very hard to probe

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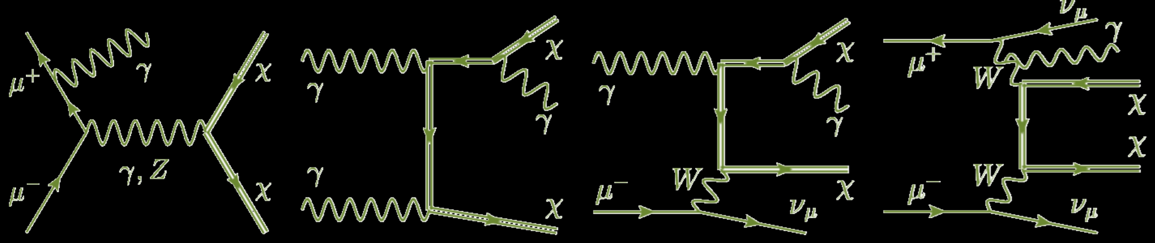

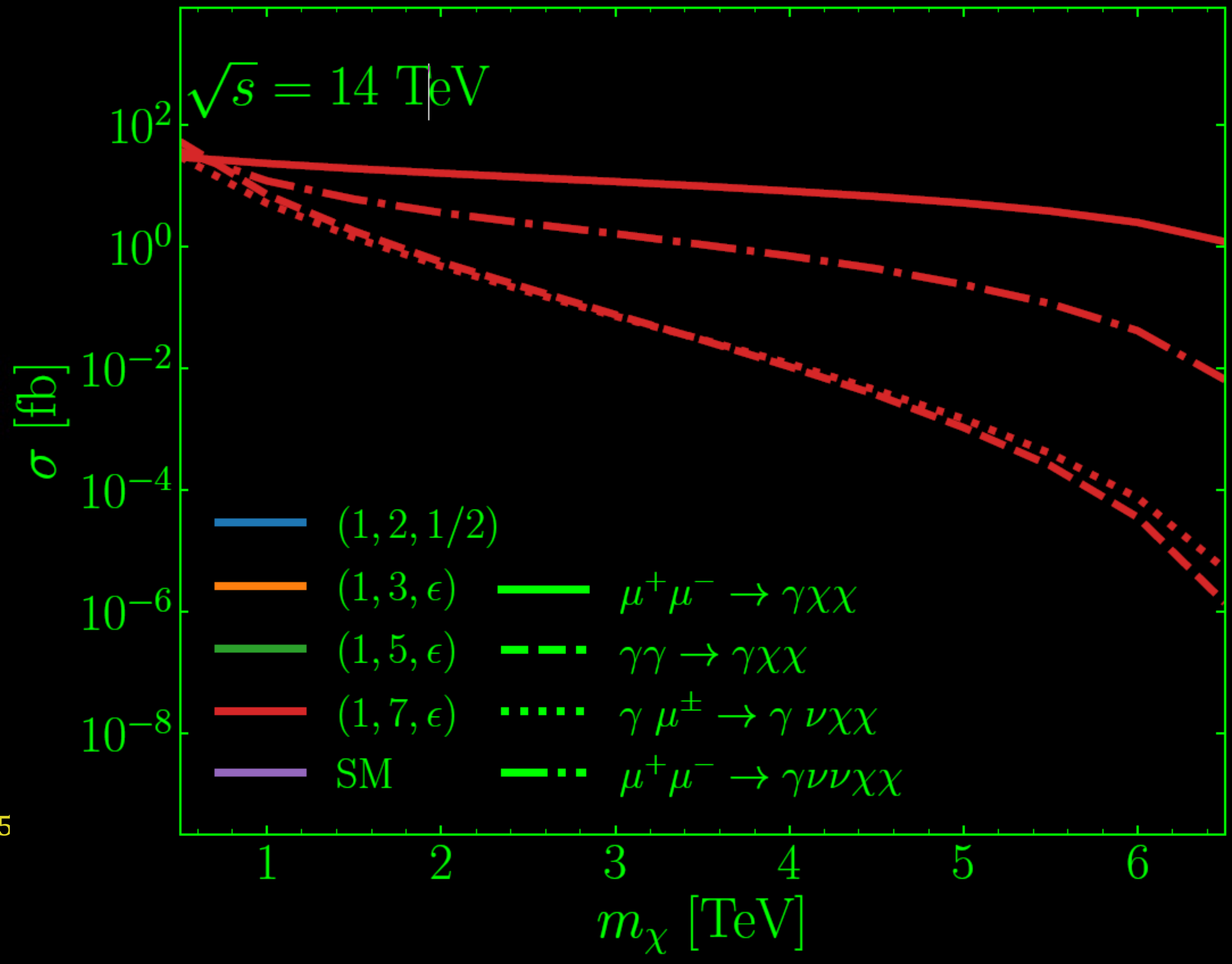

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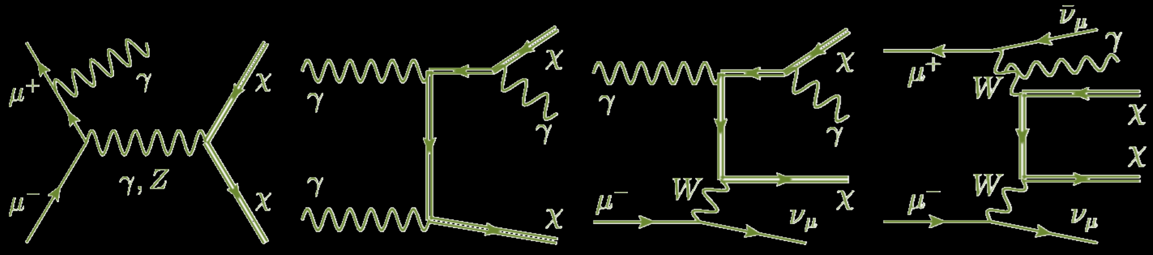

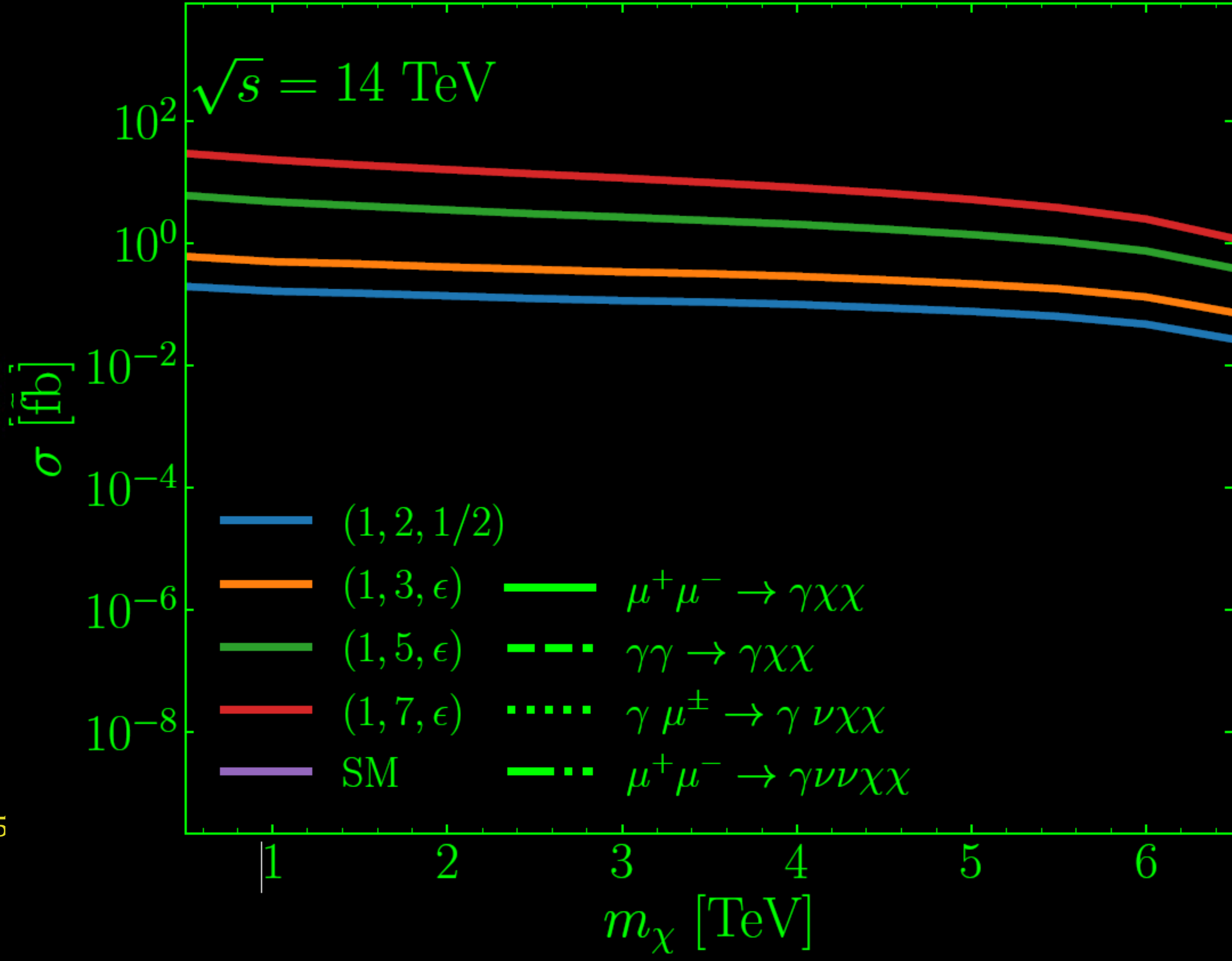

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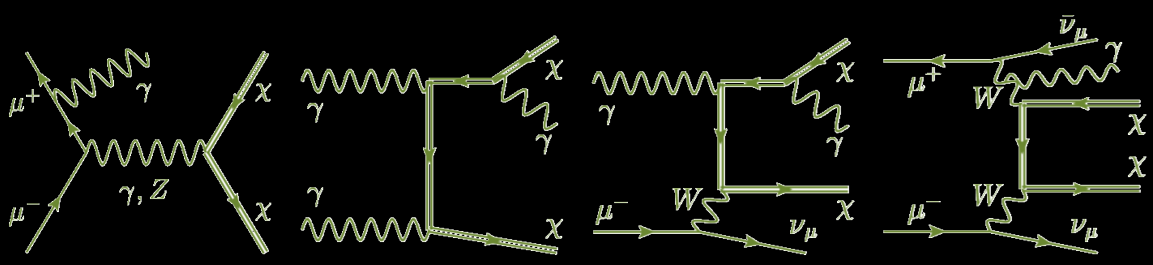

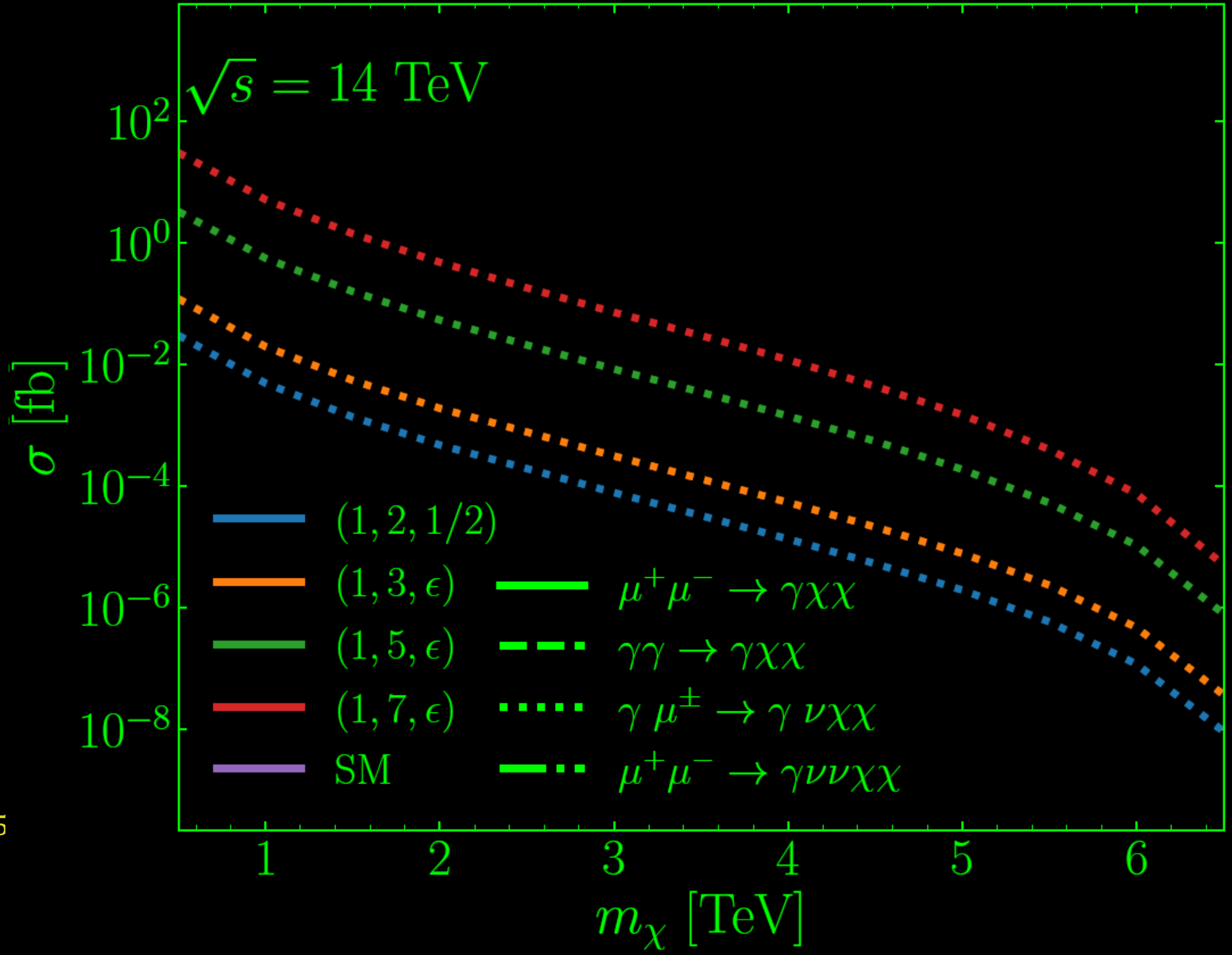

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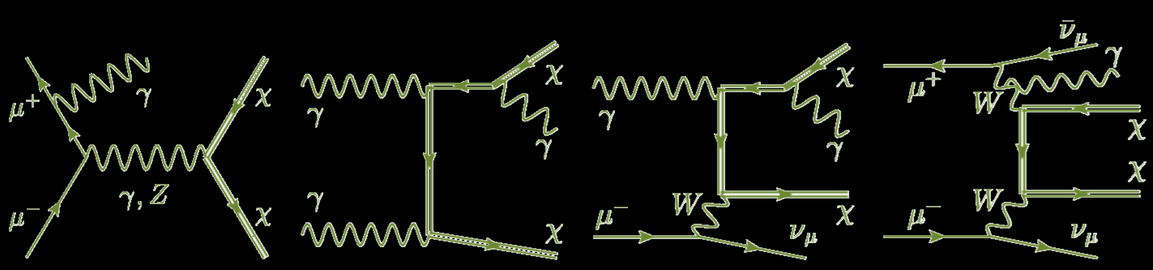

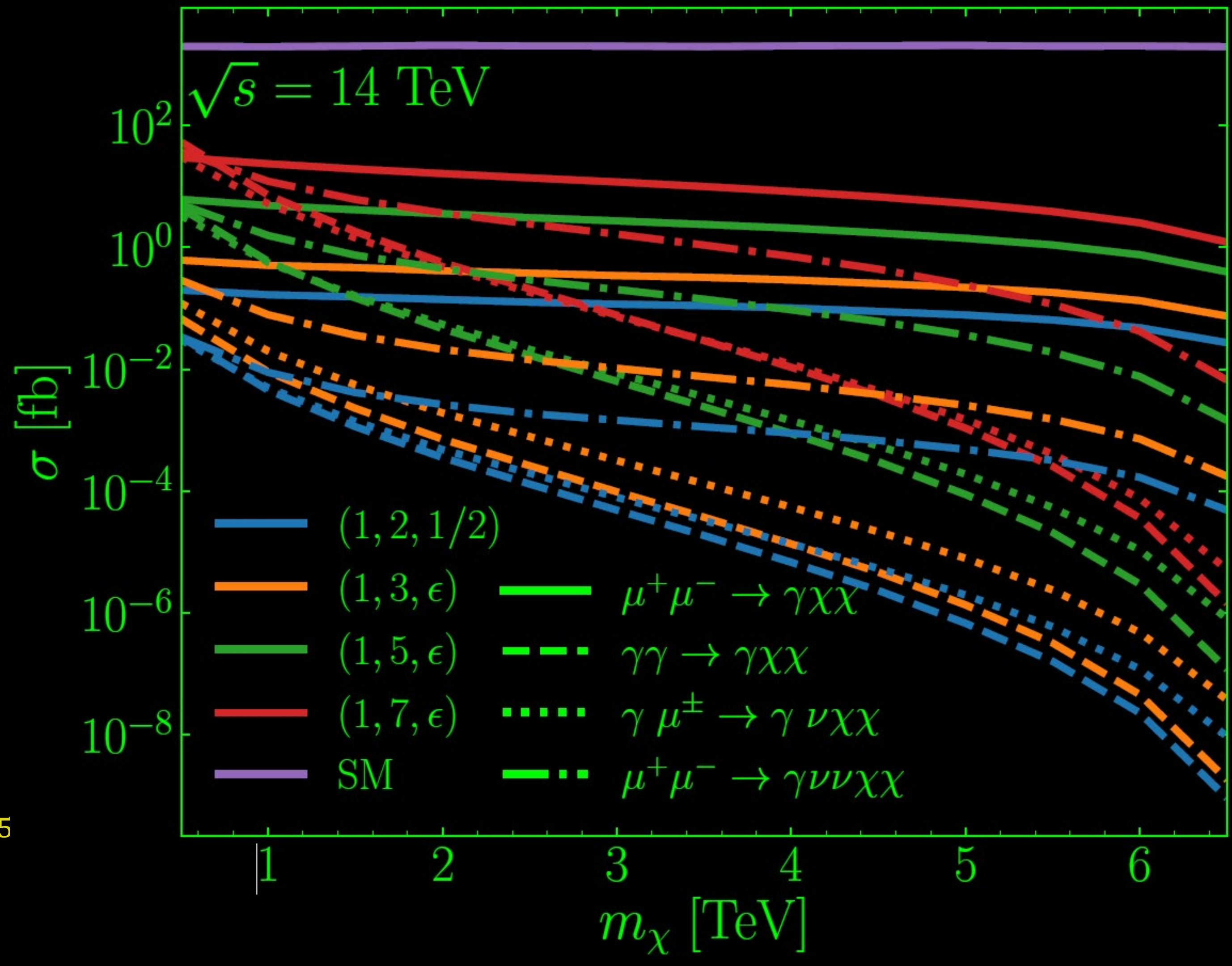

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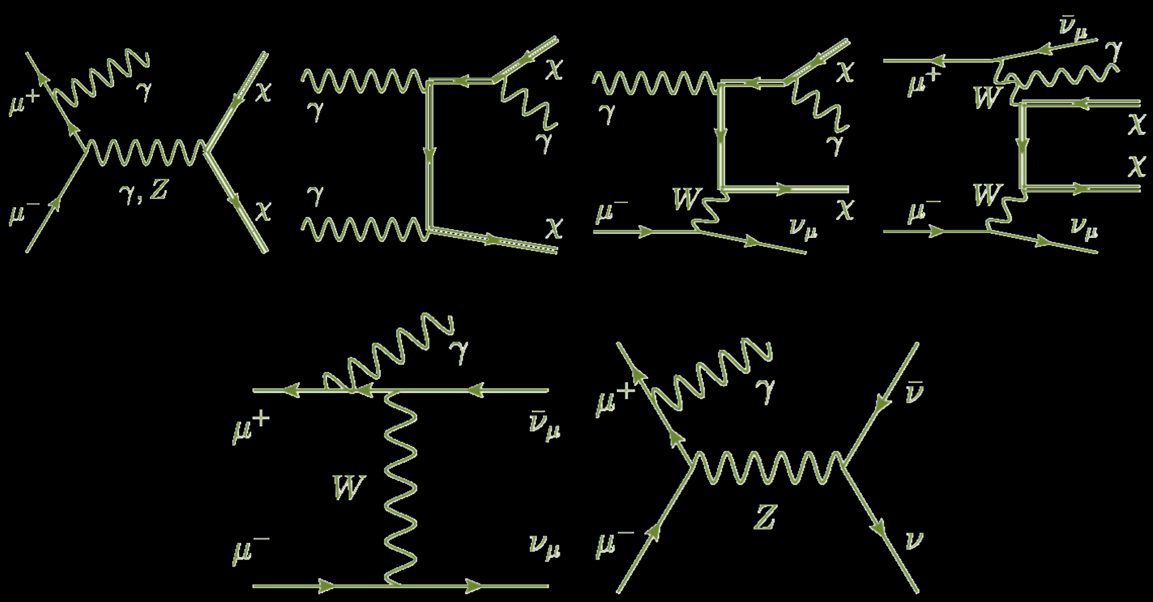

$$10^\circ < \theta_\gamma < 170^\circ$$

$$E_\gamma > 50\ \text{GeV}, \quad m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - p_\gamma)^2 > 4n$$

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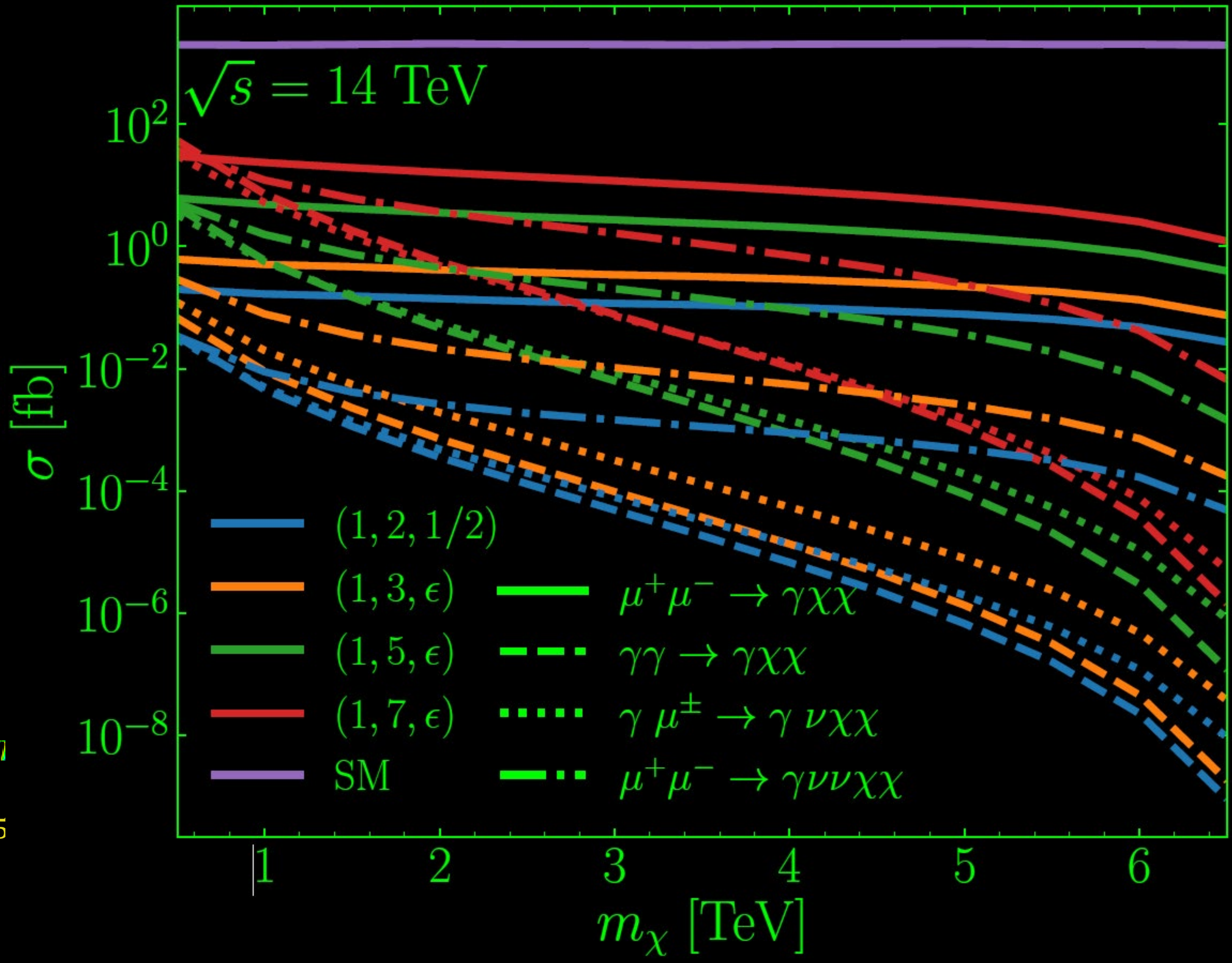
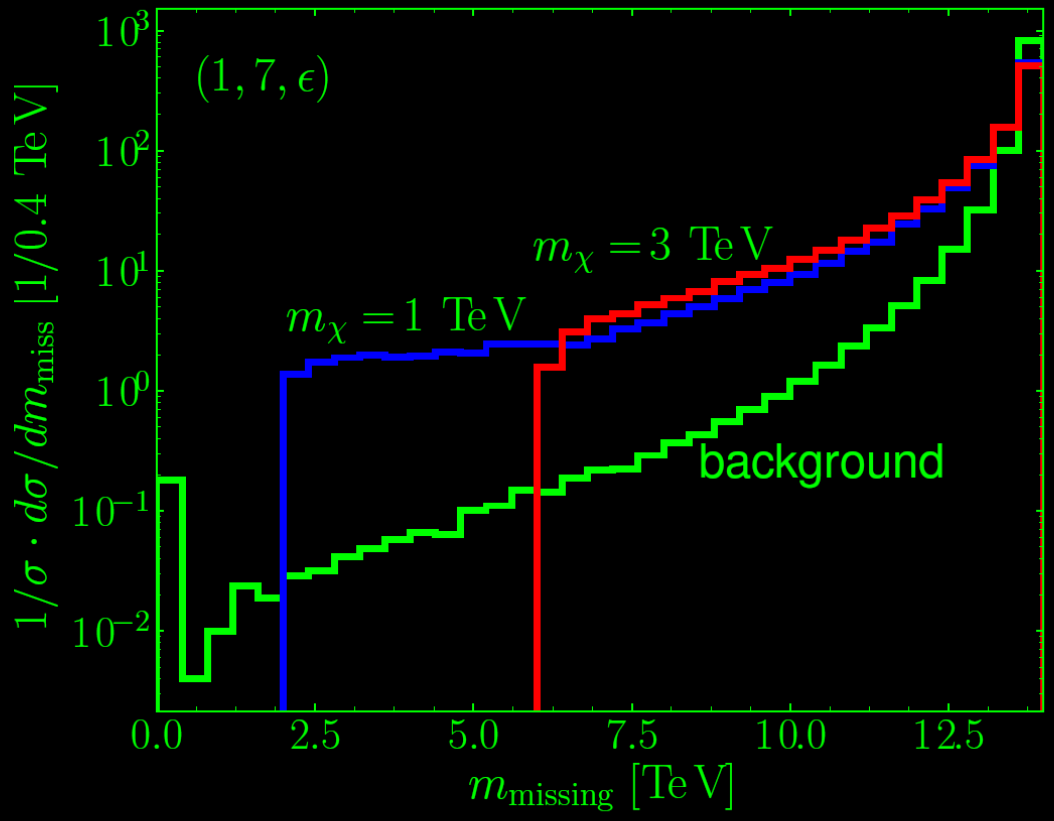
Doublet and Triplet very hard to probe



Mono-photon

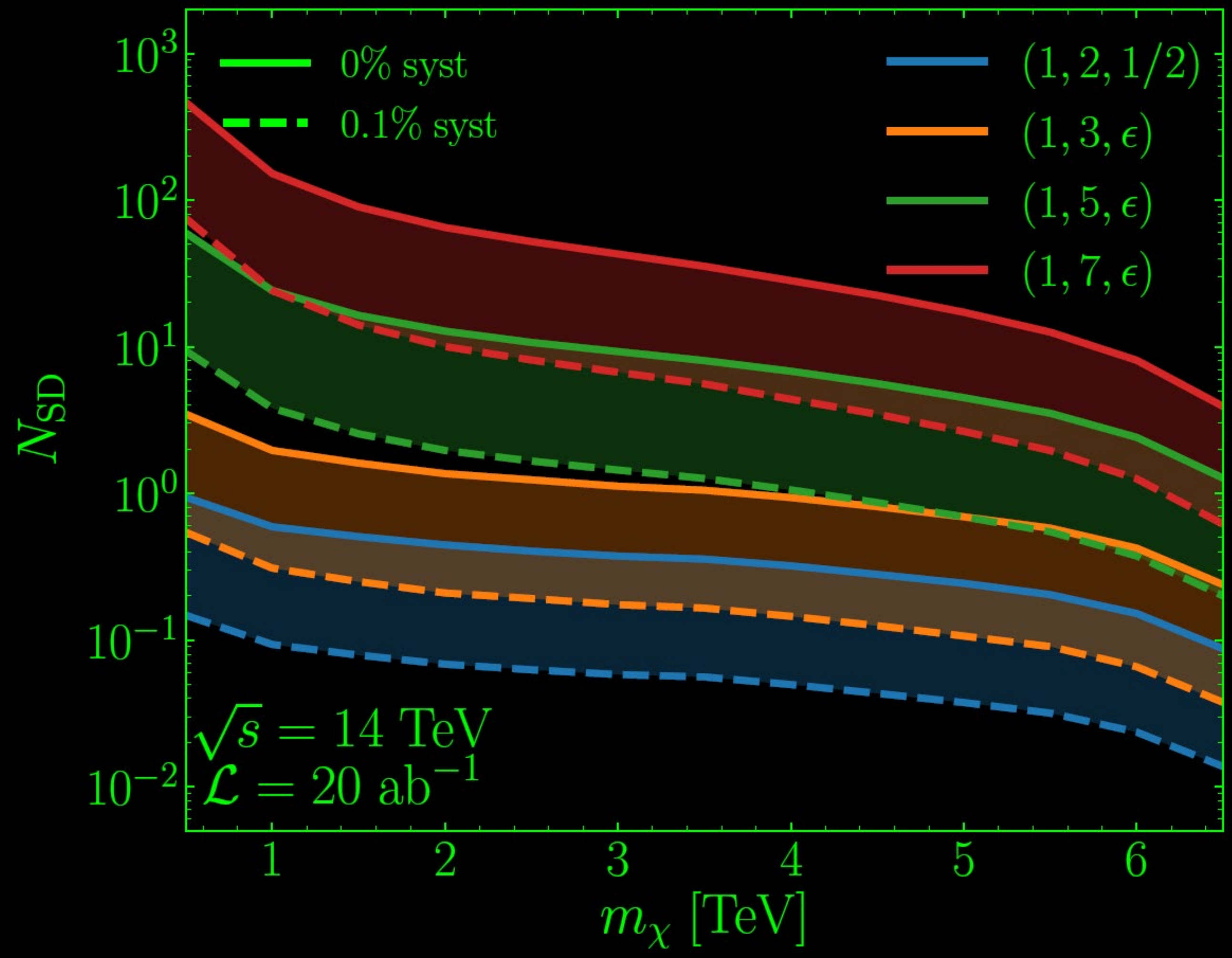
Missing mass:

- Sharp kinematic features
- Signal-background separation
- Signal parameter determination



Signal-background ratio 10^-3

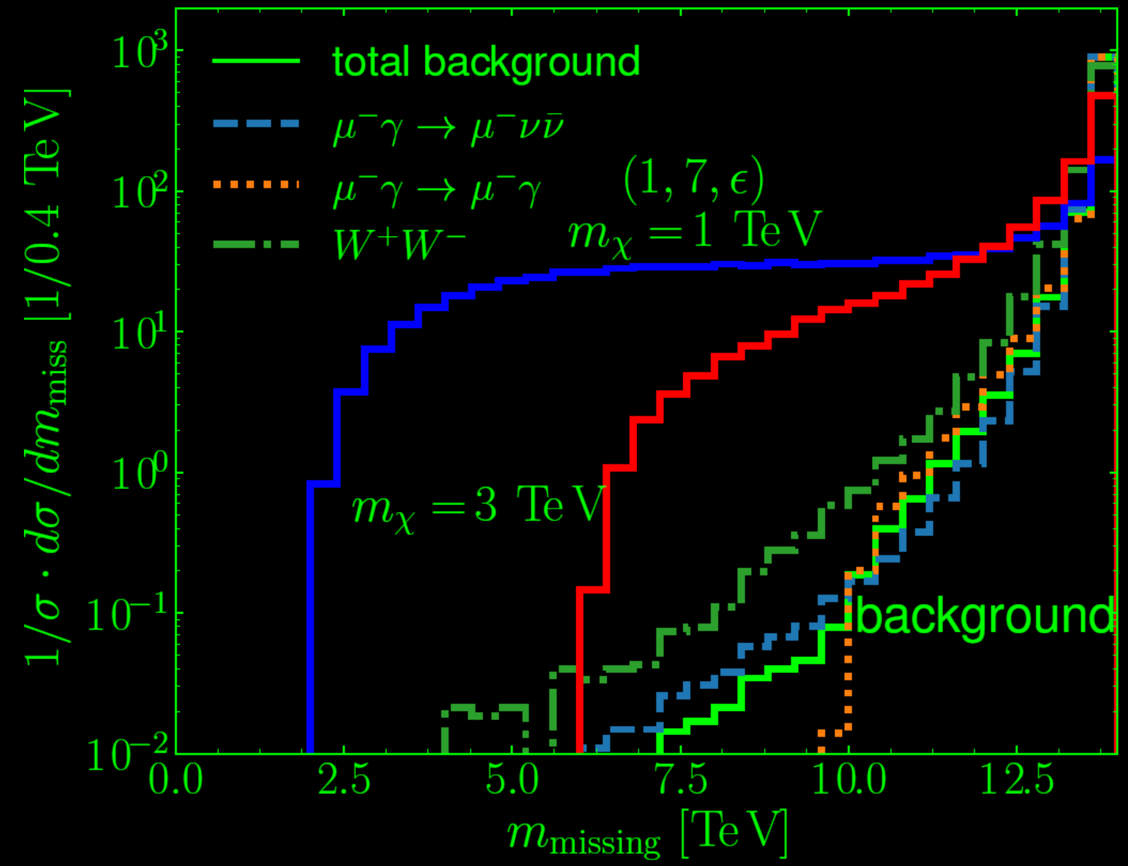
At lepton colliders systematics controlled to this level should be achievable but requires theory & experimental work

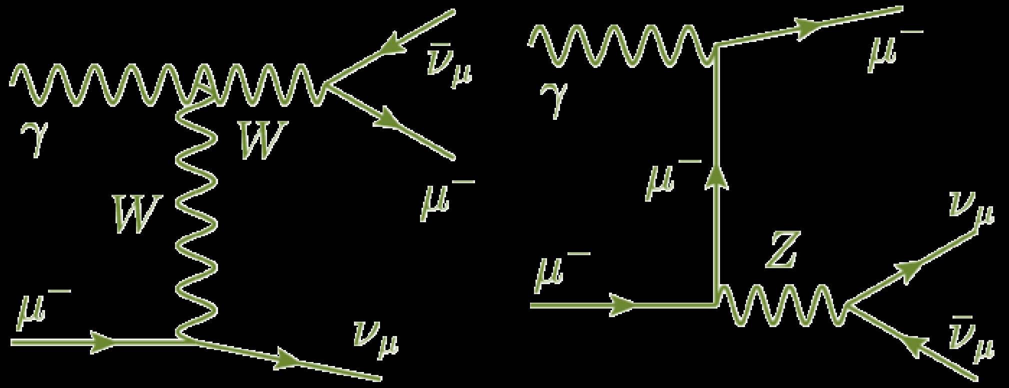


Unique Mono-Muon Channel

Complex background compositions:

from missing a SM particles via various mechanisms





Collinear emissions, missing final state muons, properly calculated using photon PDF

Also includes dominant 2->2 processes with one of them decays forward

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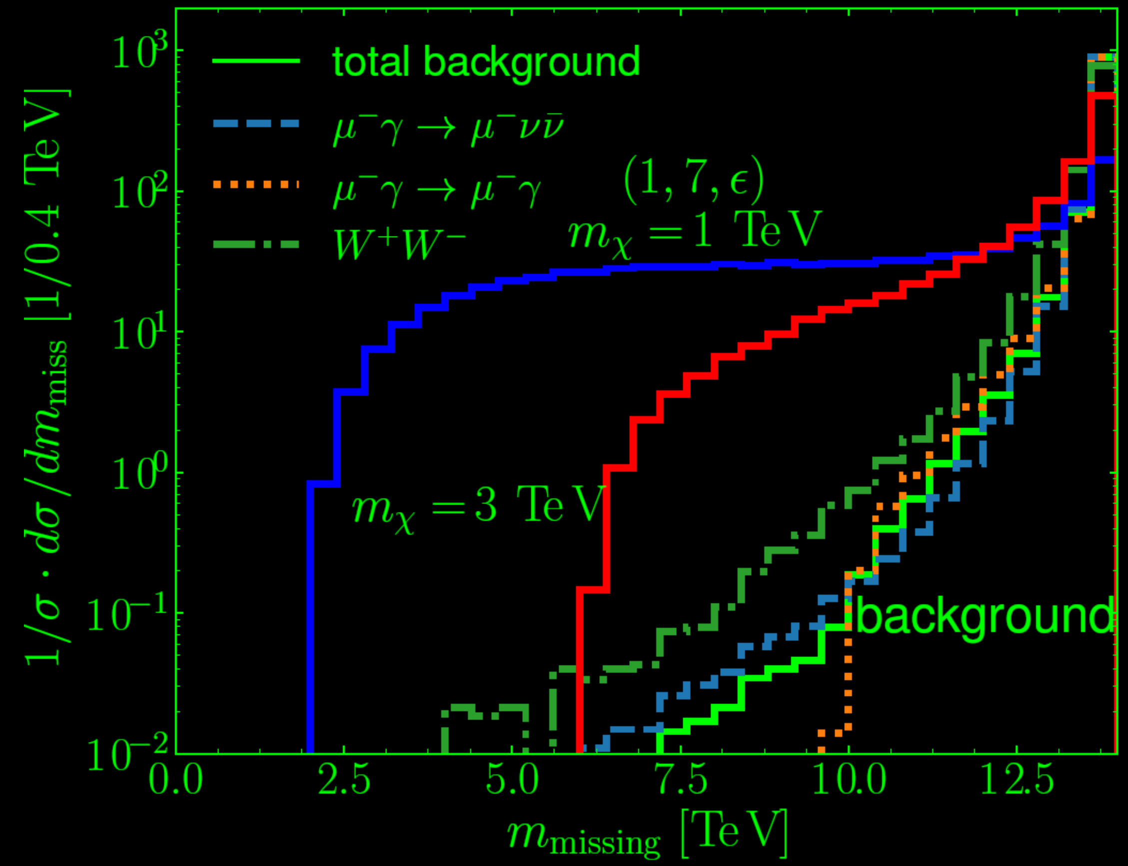

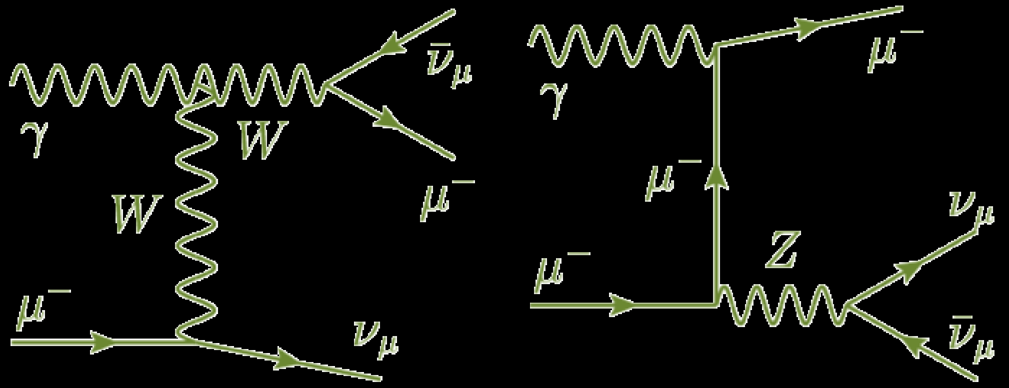

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Also includes dominant 2->2 processes with one of them decays forward

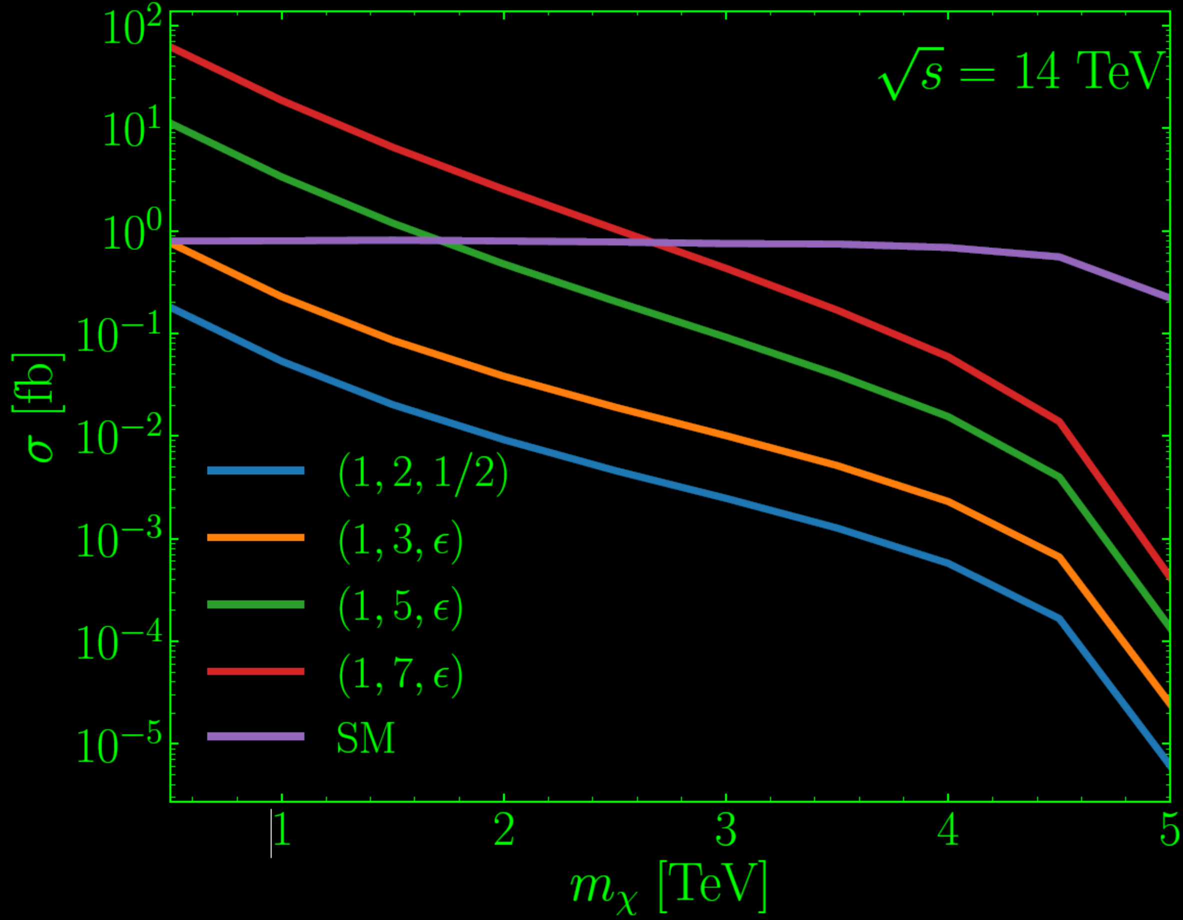
$$10^\circ < \theta_{\mu^-} < 90^\circ, \quad 90^\circ < \theta_{\mu^+} < 170^\circ$$

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

Unique Mono-Muon Channel

Apparent "Charge Violation" channel

(very different from the LHC)



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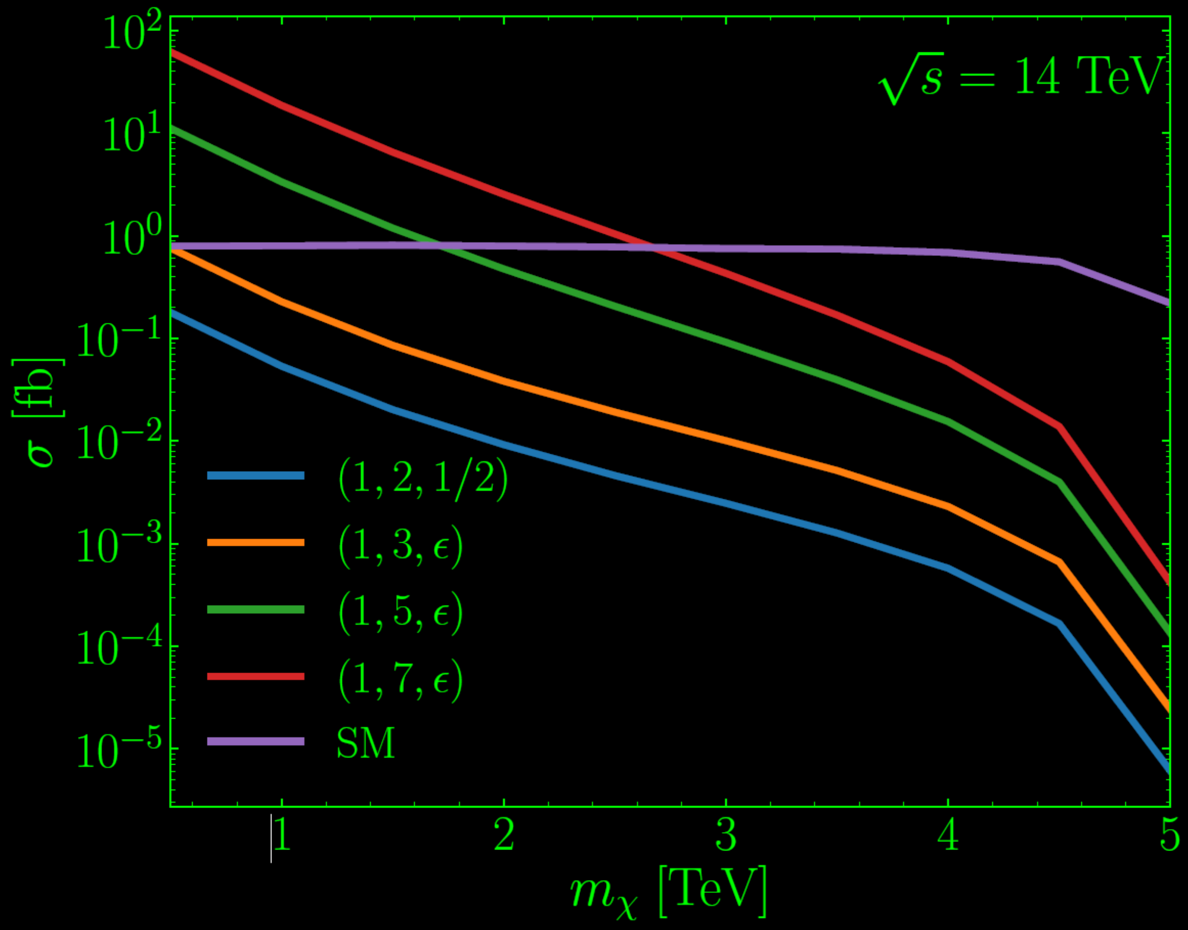
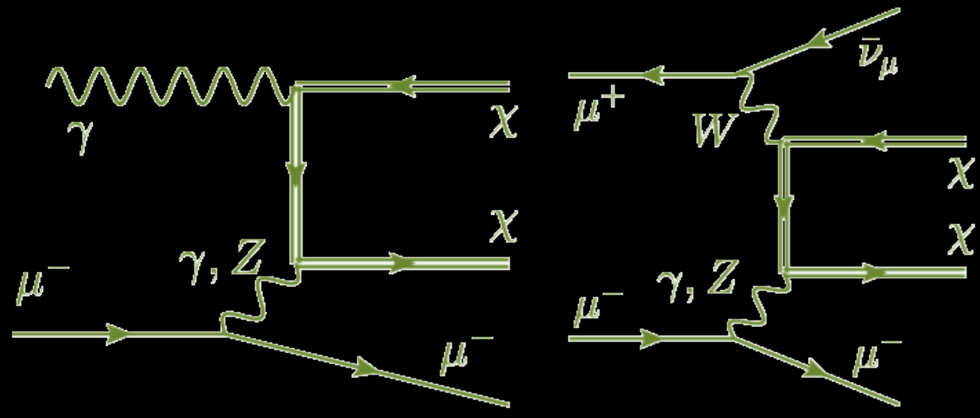


Signature: Energetic mono-muon



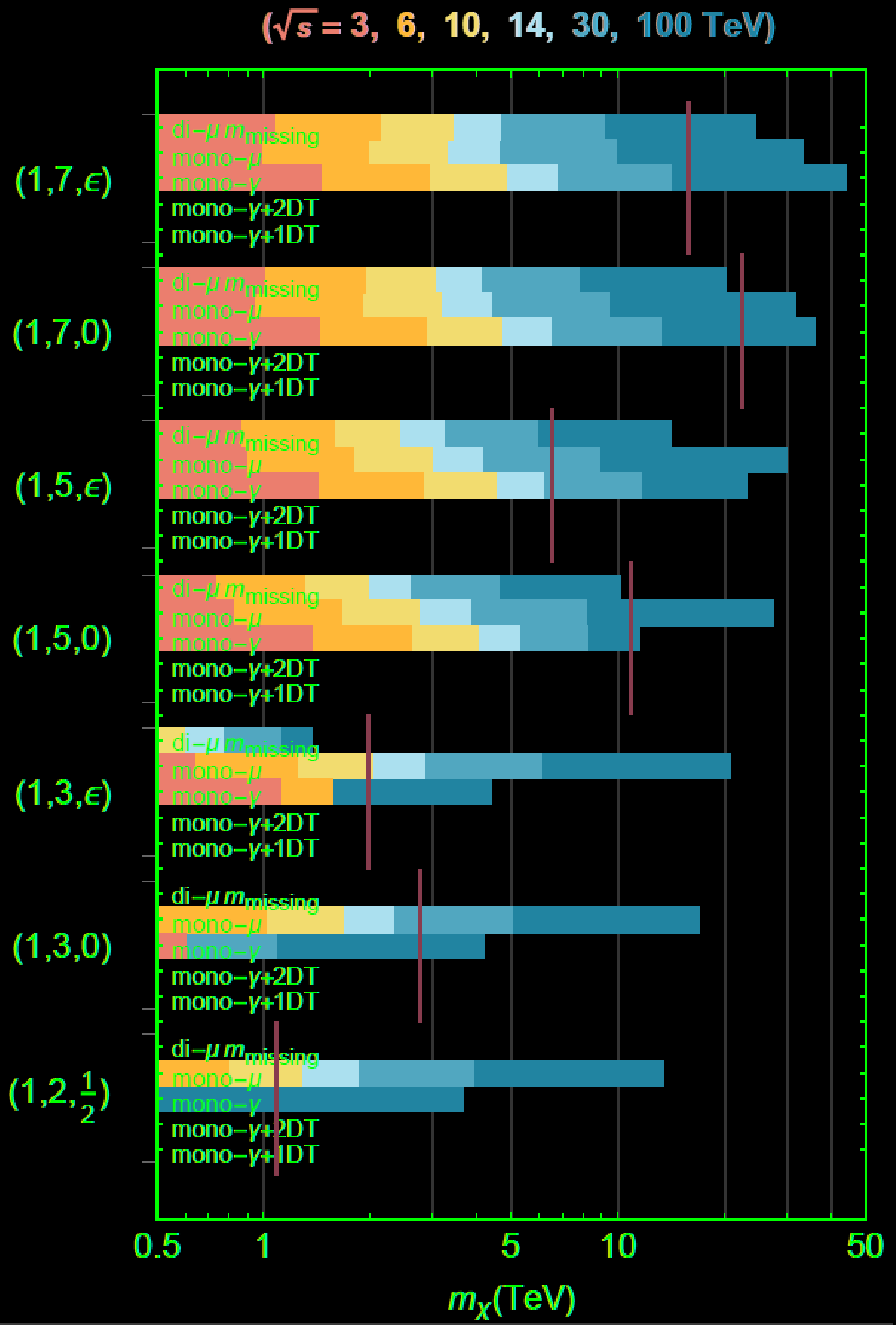
Muon pairs → muon + missing mass

One charge is missed due to the soft (non-reconstructable) decays of the charged states

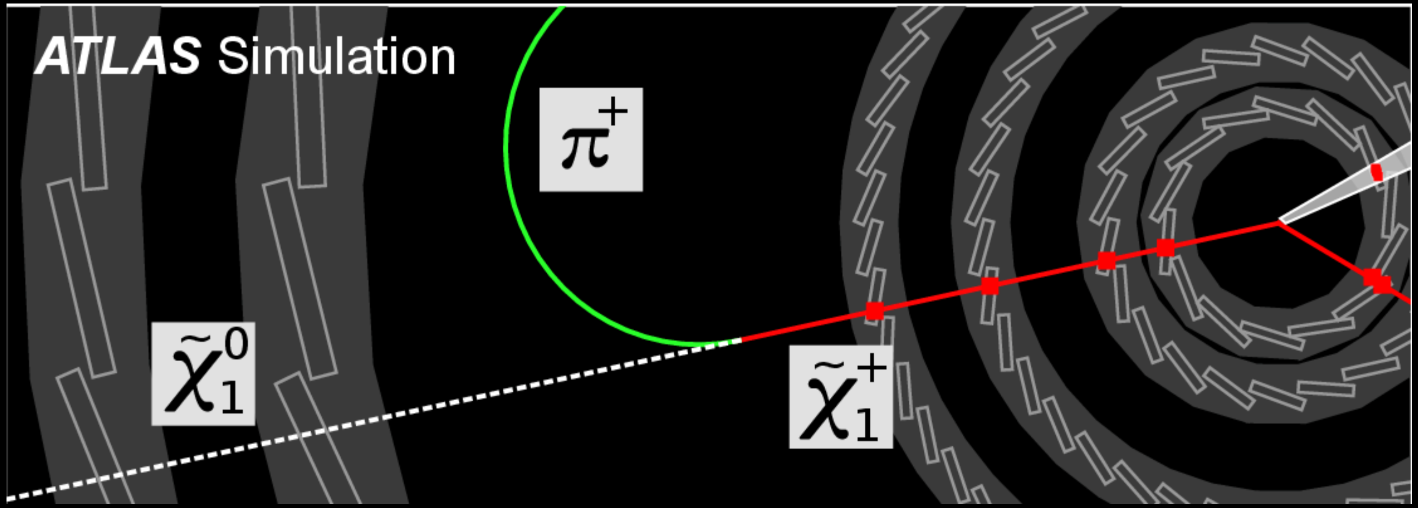
Unique and powerful channel

Summary (by channel)

- Mono-photon powerful for high n-plets
- Mono-muon uniquely powerful low multiplets (Wino and Higgsinos)
- VBF dimuon large room to improve (we conservatively assumed |\eta mu|<2.5, losing lots of signals)



Disappearing Tracks: next to minimal signatures



- Mono-photon+disappearing tracks

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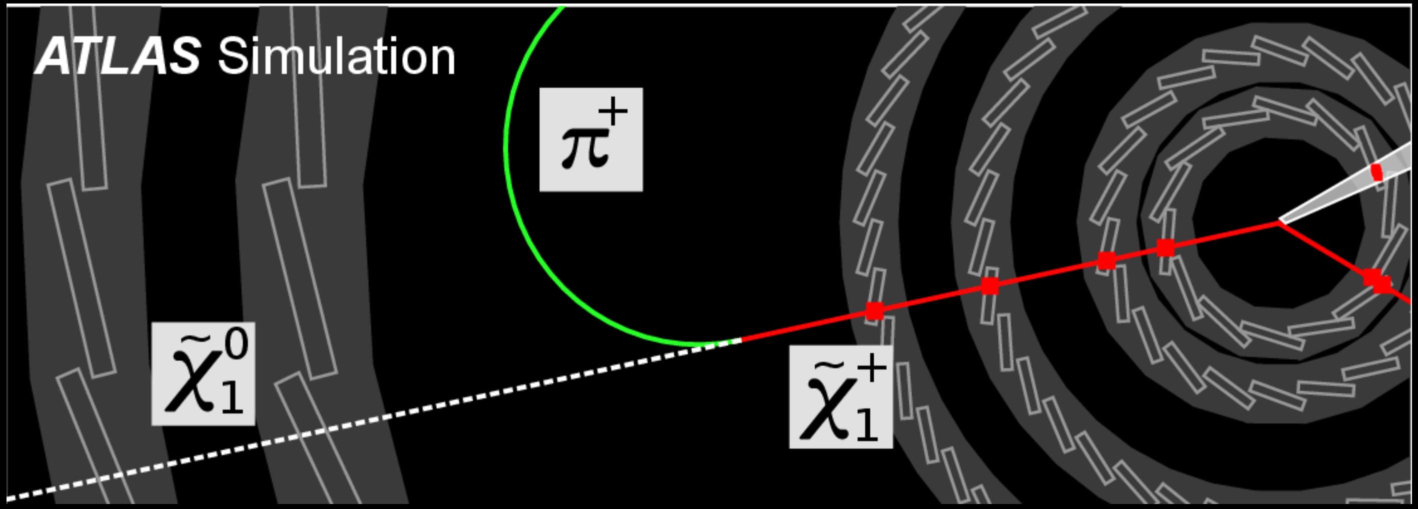

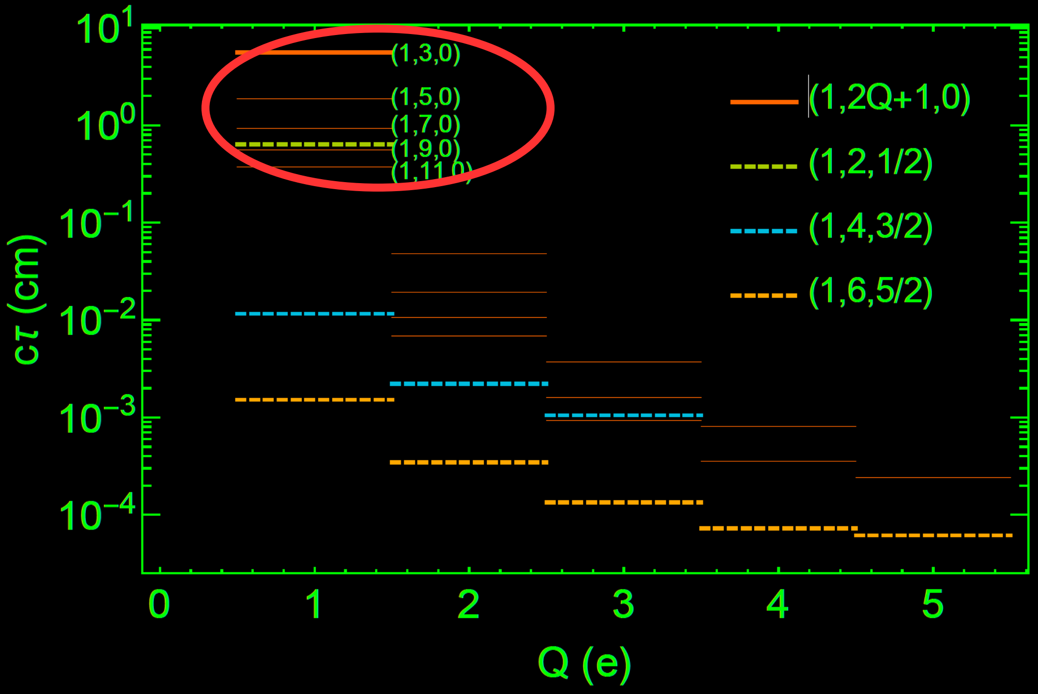

- Only useful for searches using charge 1 states
- Still, all higher charged states will cascade back to charge 1 states promptly
- Use all the production rates of charged states
- Mono-photon+disappearing tracks

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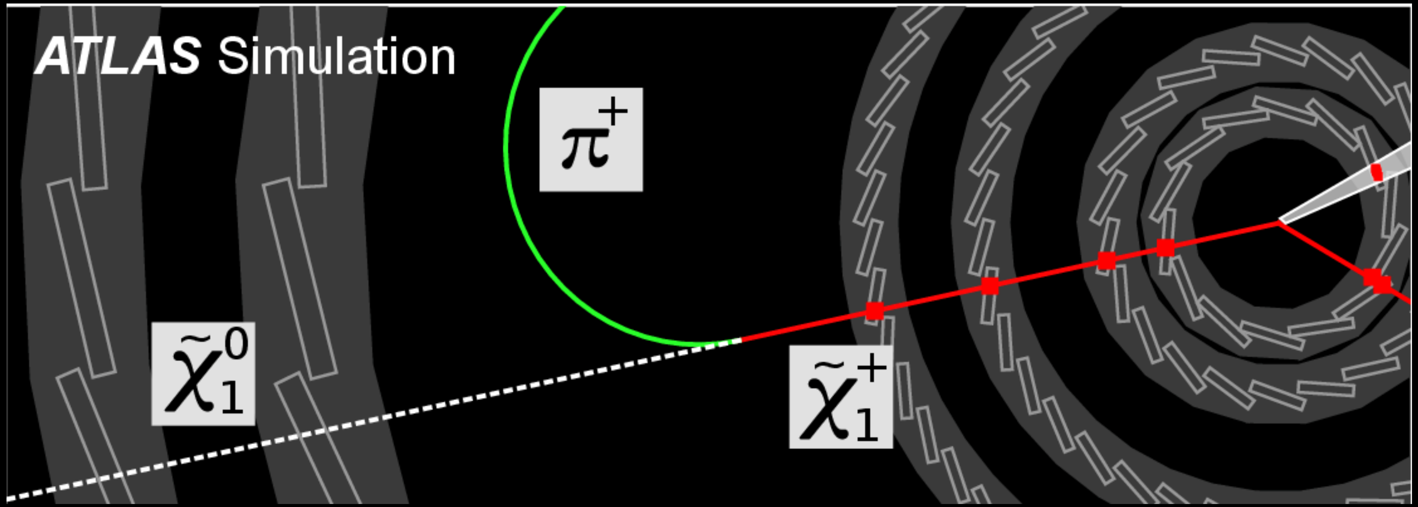

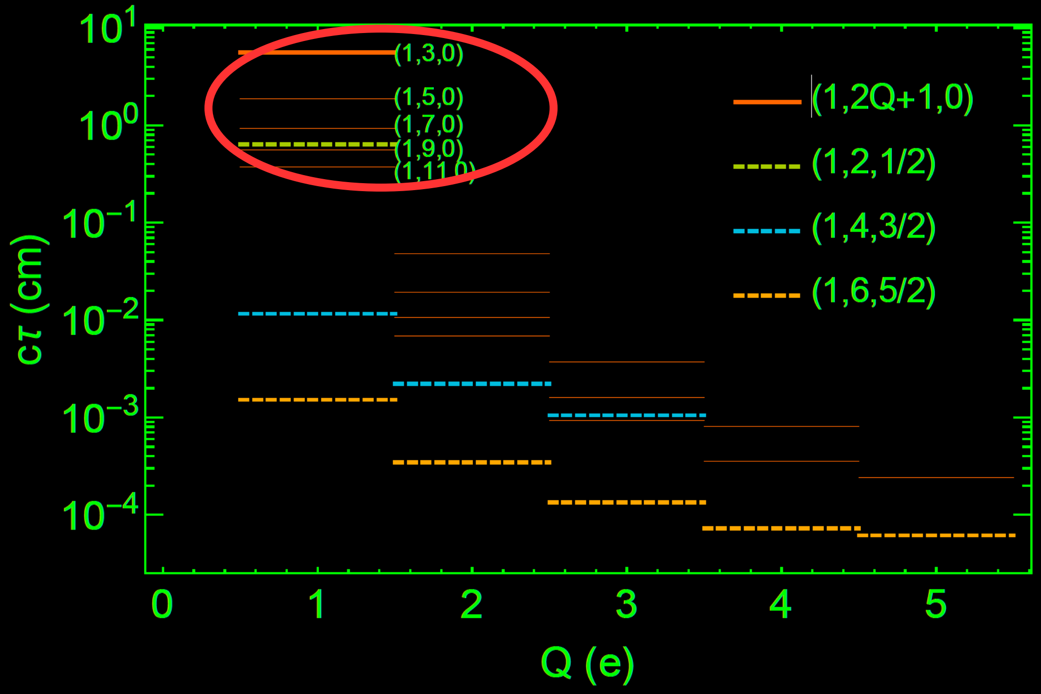

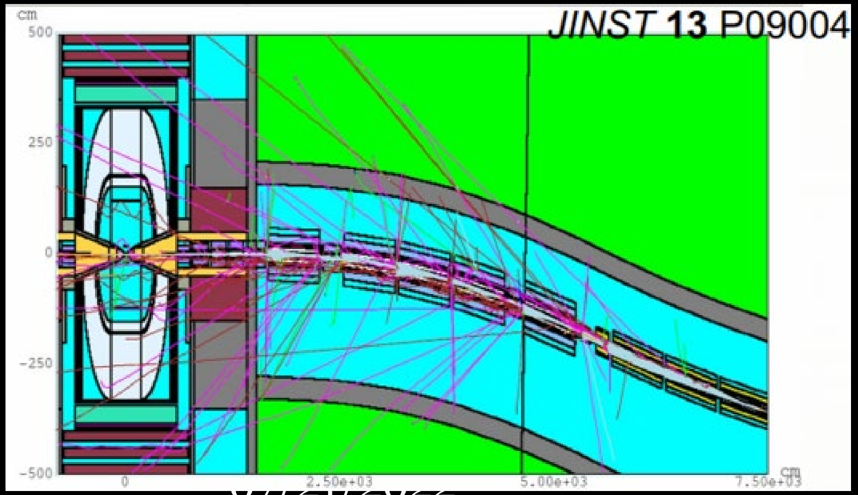

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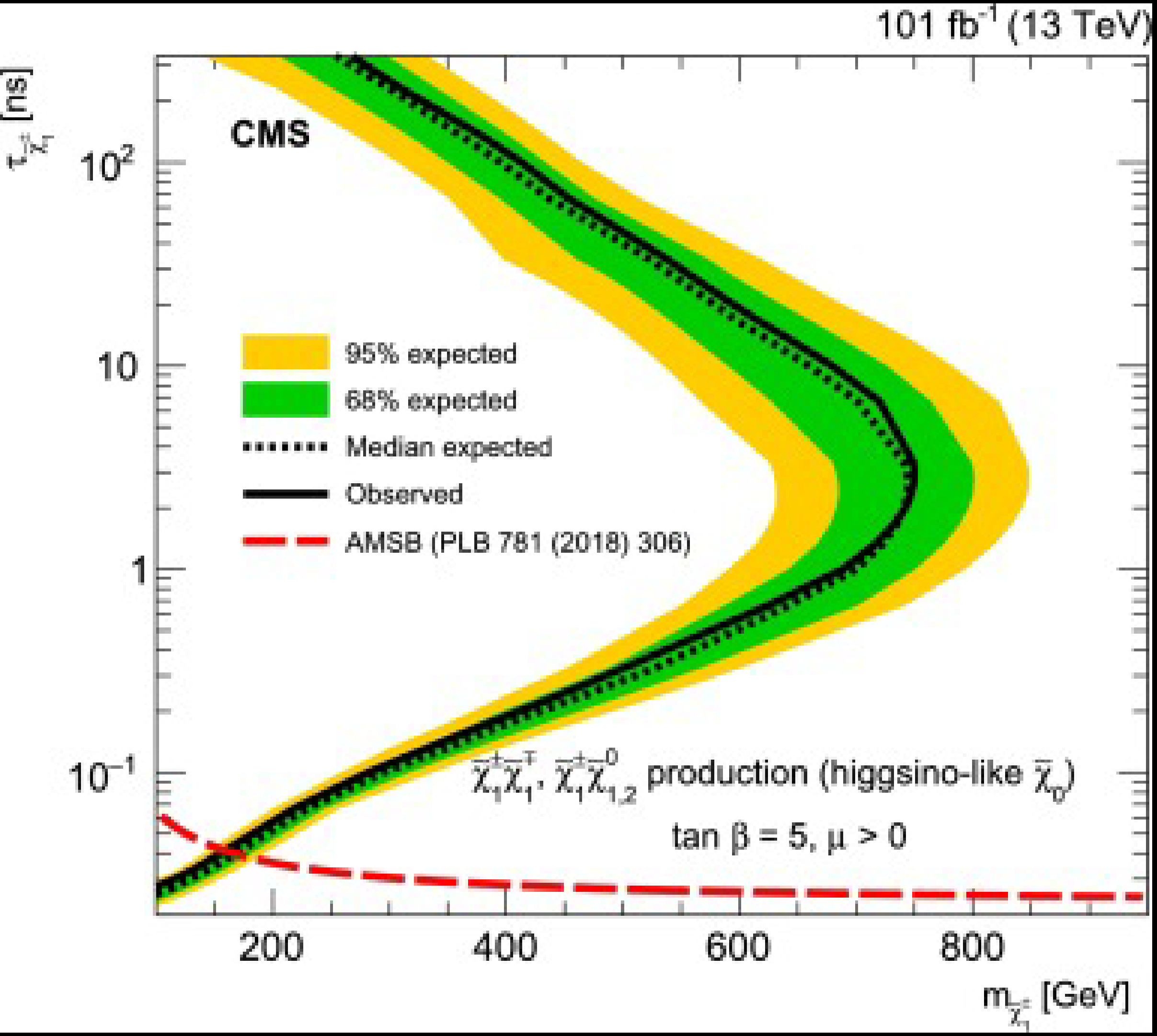
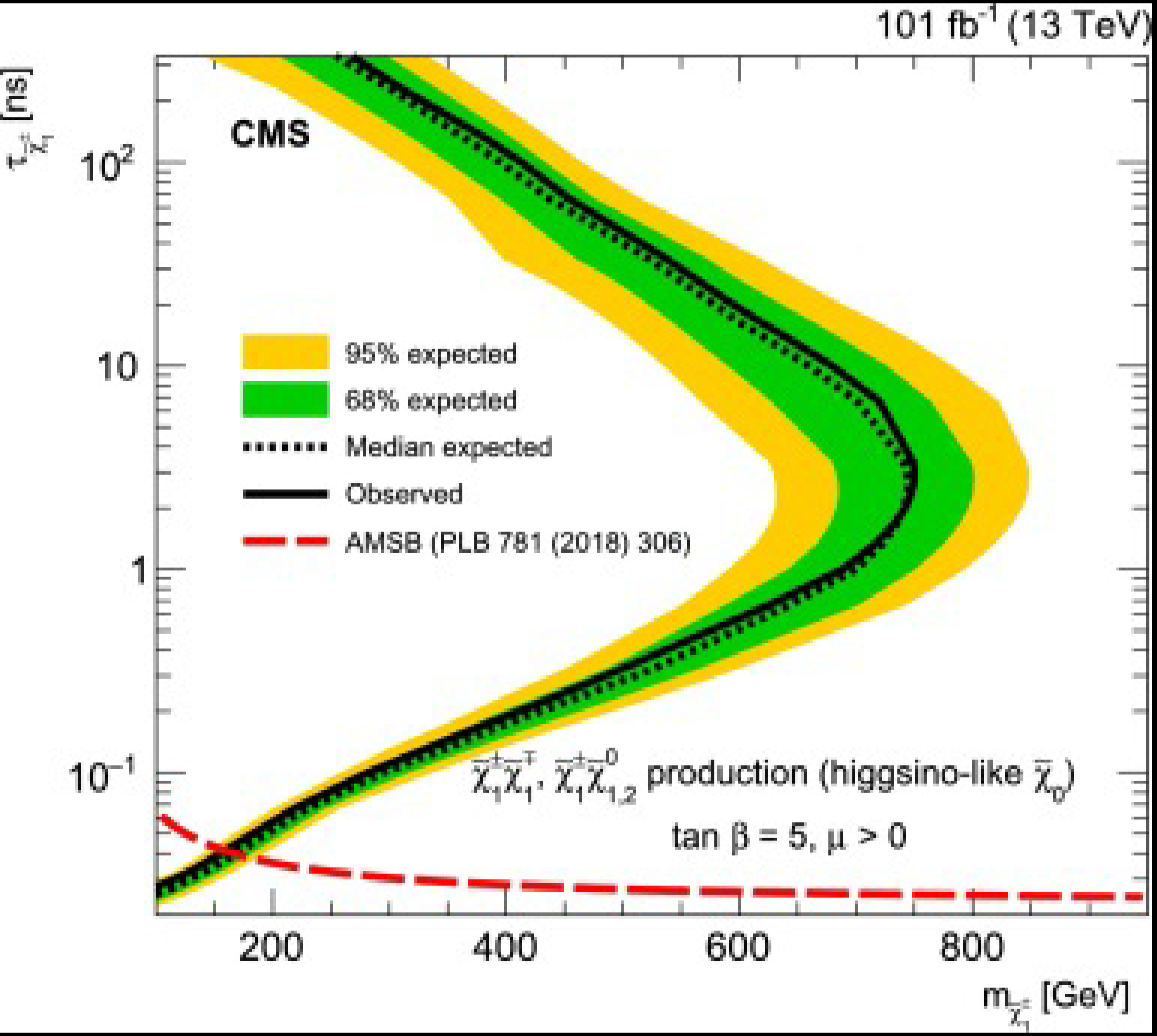
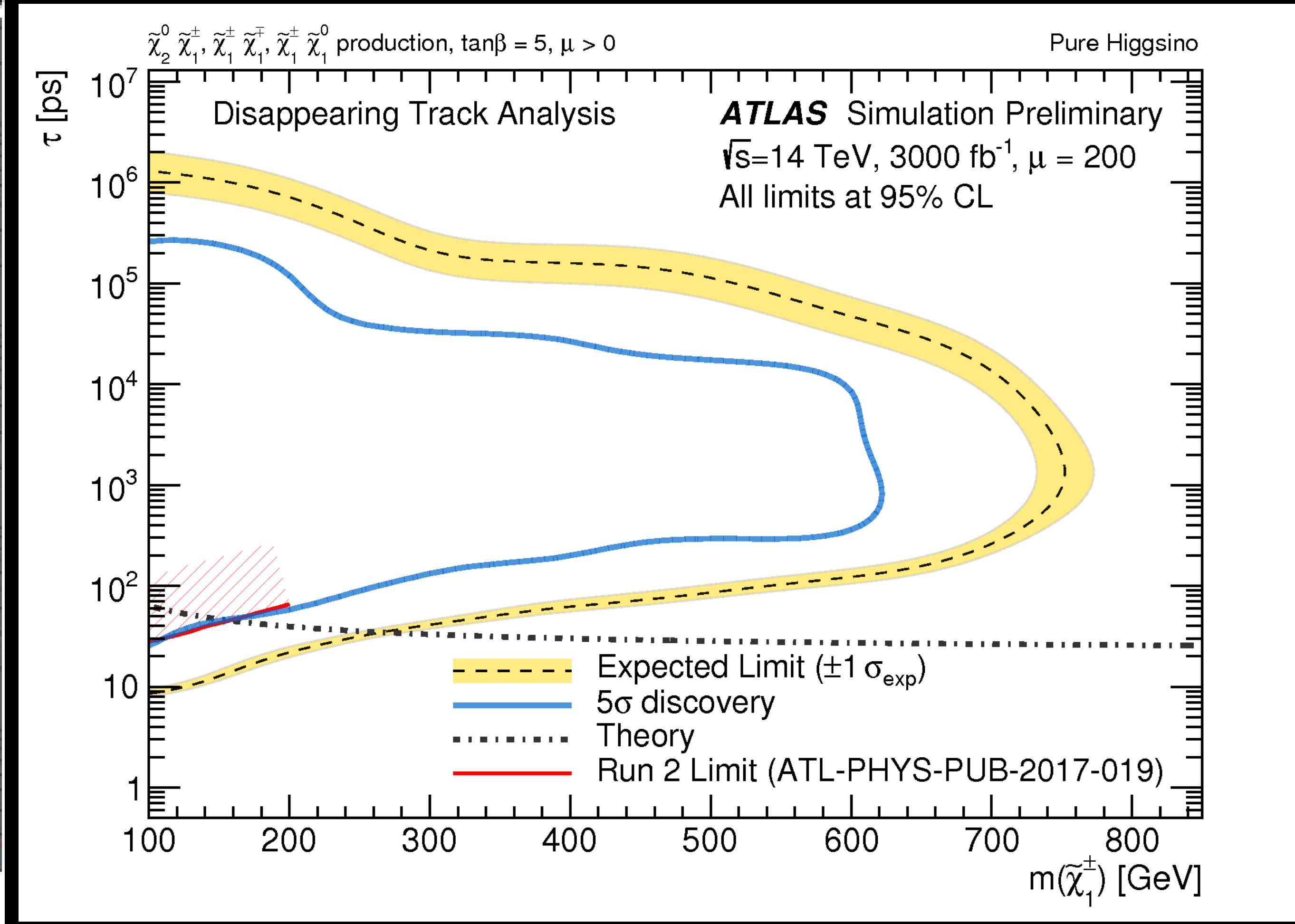
- Mono-photon+disappearing tracks
- Beam Induced Background

Disappearing Track at the LHC



Disappearing Track at the LHC



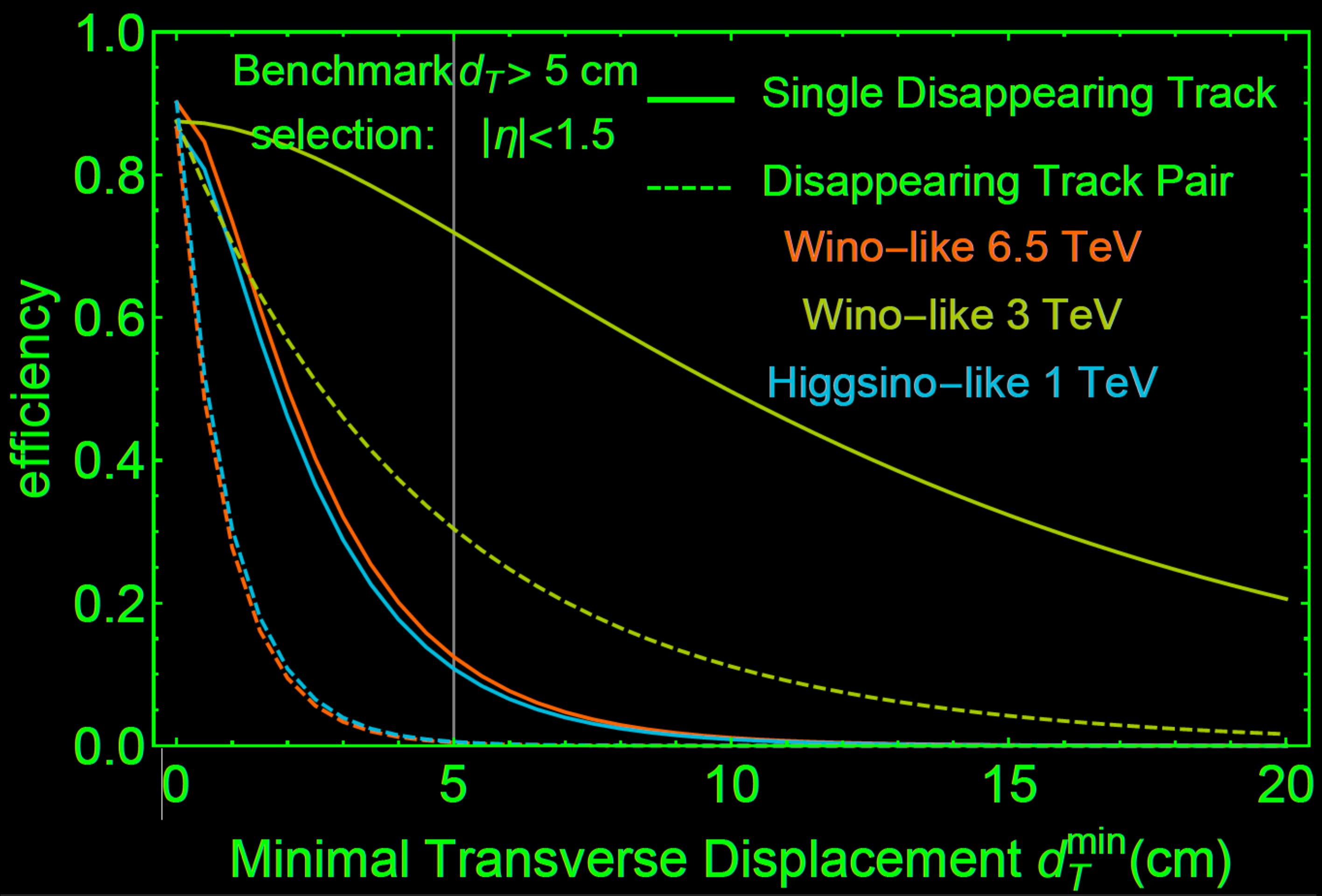


Minimal transverse displacement

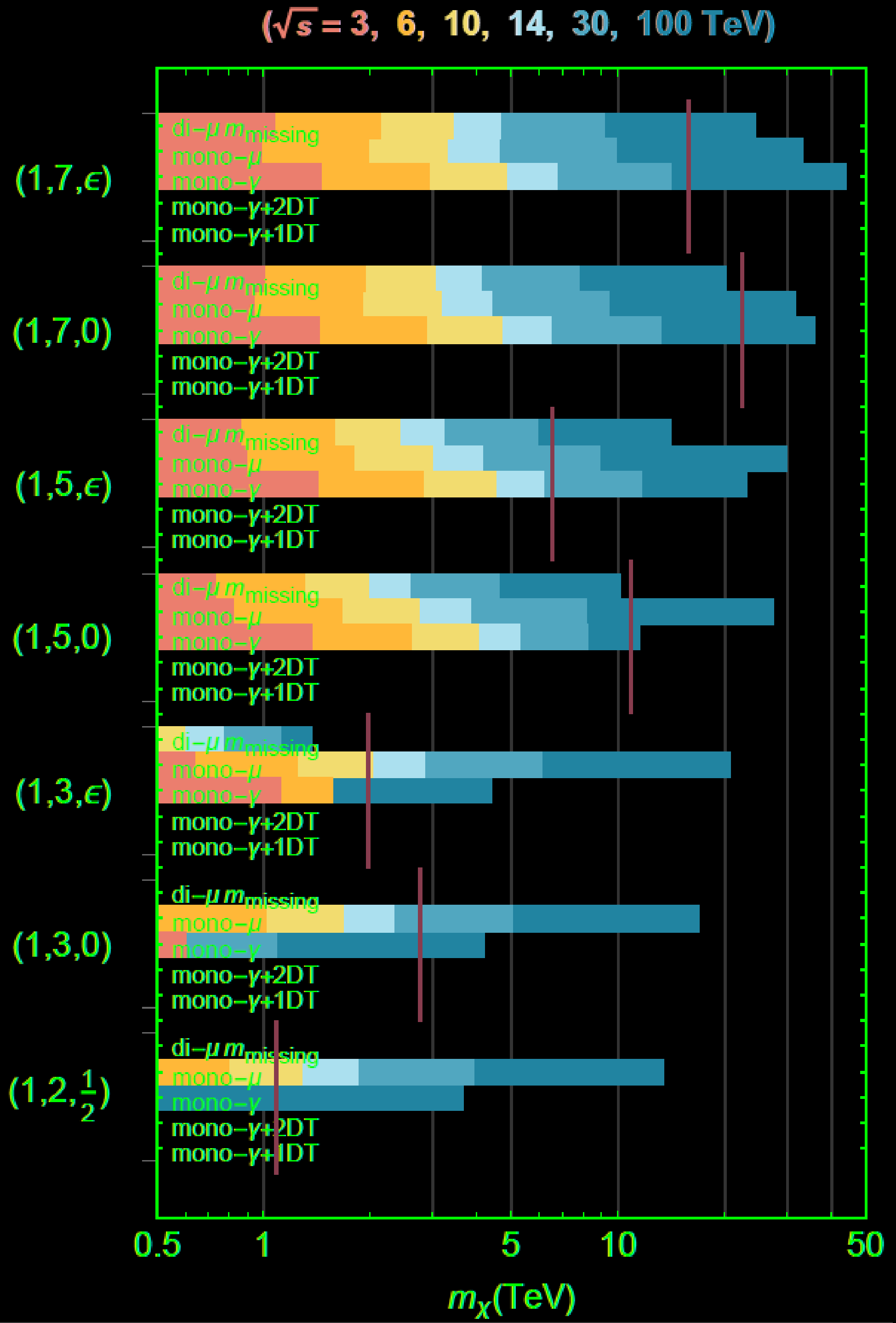
- Only use the central tracks, |eta|<1.5
- Current design have the first layer of pixel detector at 3cm (new discussion about 2cm)
- We assume at least two hits can be measured at 5cm
- Show both pair reconstruction or single reconstruction results
- Requiring 50 signal events for discovery

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

$$\epsilon_\chi(\cos\theta, \gamma, d_T^{\min}) = \exp\left(\frac{-d_T^{\min}}{\beta_T \gamma c\tau}\right)$$



Summary (by channel)



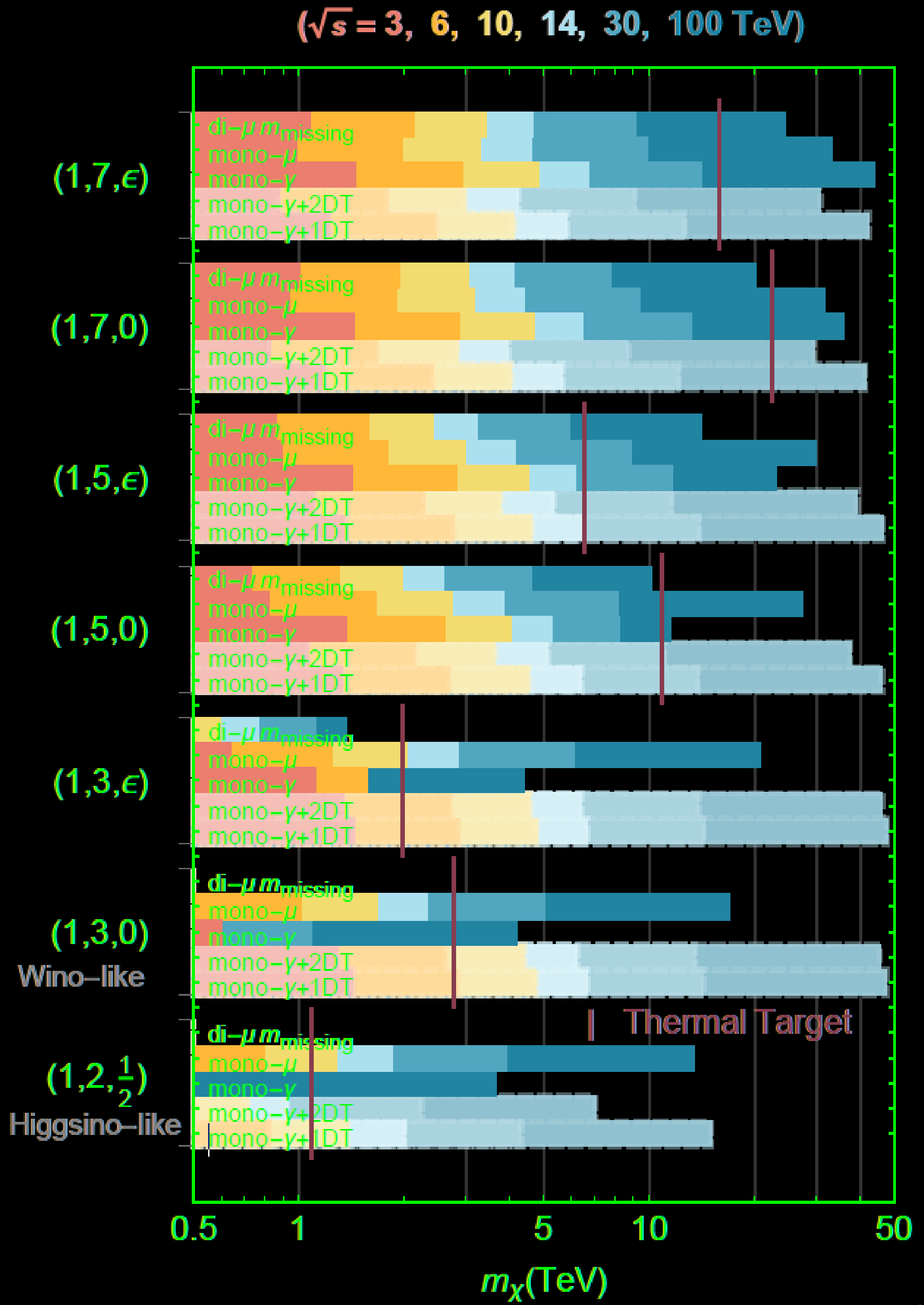
Summary (by channel)

- Disappearing track great potential (can push to the kinematic limit)!

Detector design with a few tracking layers close to IP (interaction point) is critical.

Background mitigation is important.

New ideas in appearing pions also might also help.



See also Capdevilla, Meloni, Simoniello, Zurita, 2102.11292

Required Luminosity for Future colliders

Higgsino (1.1. TeV target):

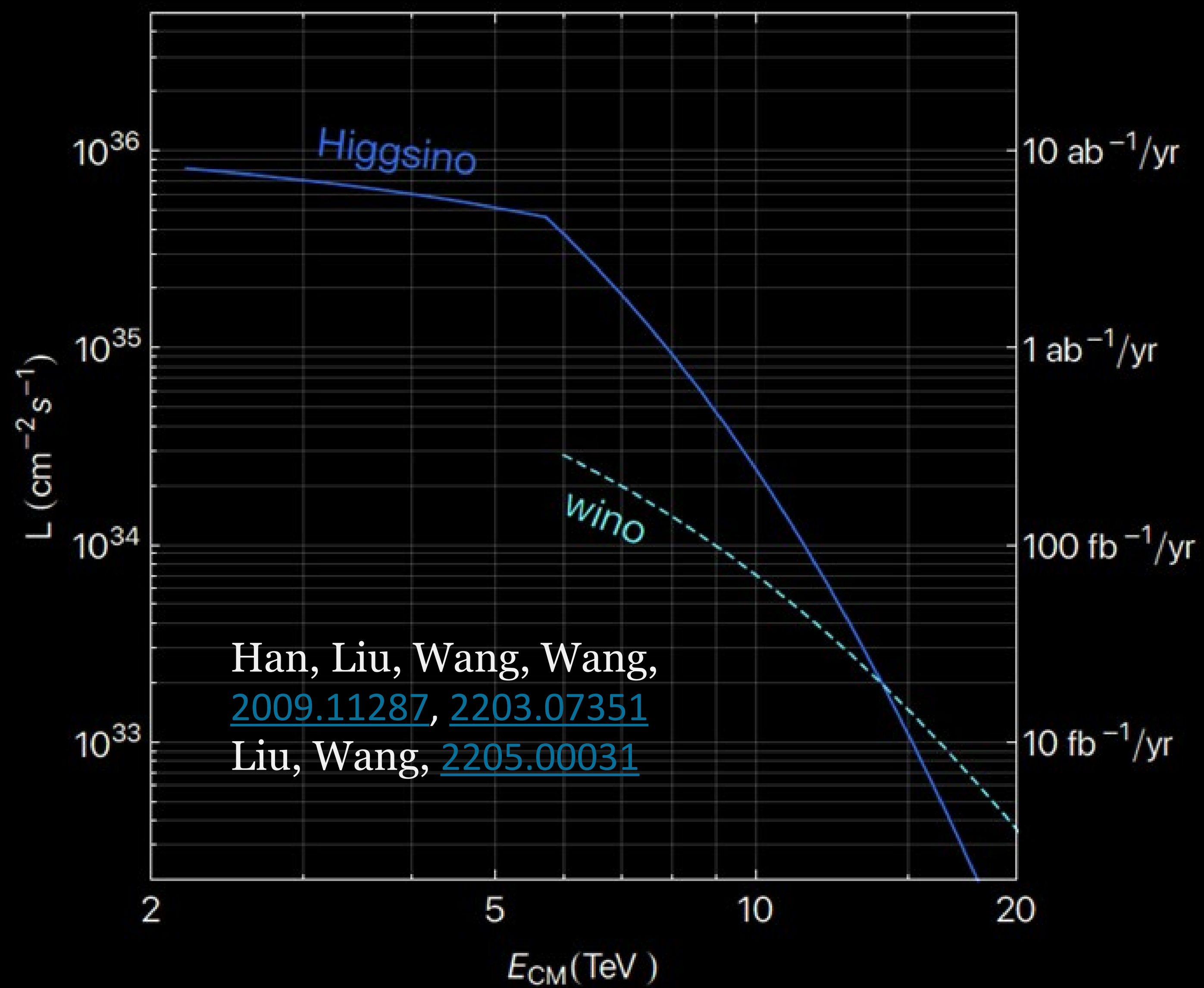
- Missing mass search dominants at low Energy;
- Disappearing track search at high Energy (enough boost);

Wino (~3 TeV target):

- Disappearing track search dominant;

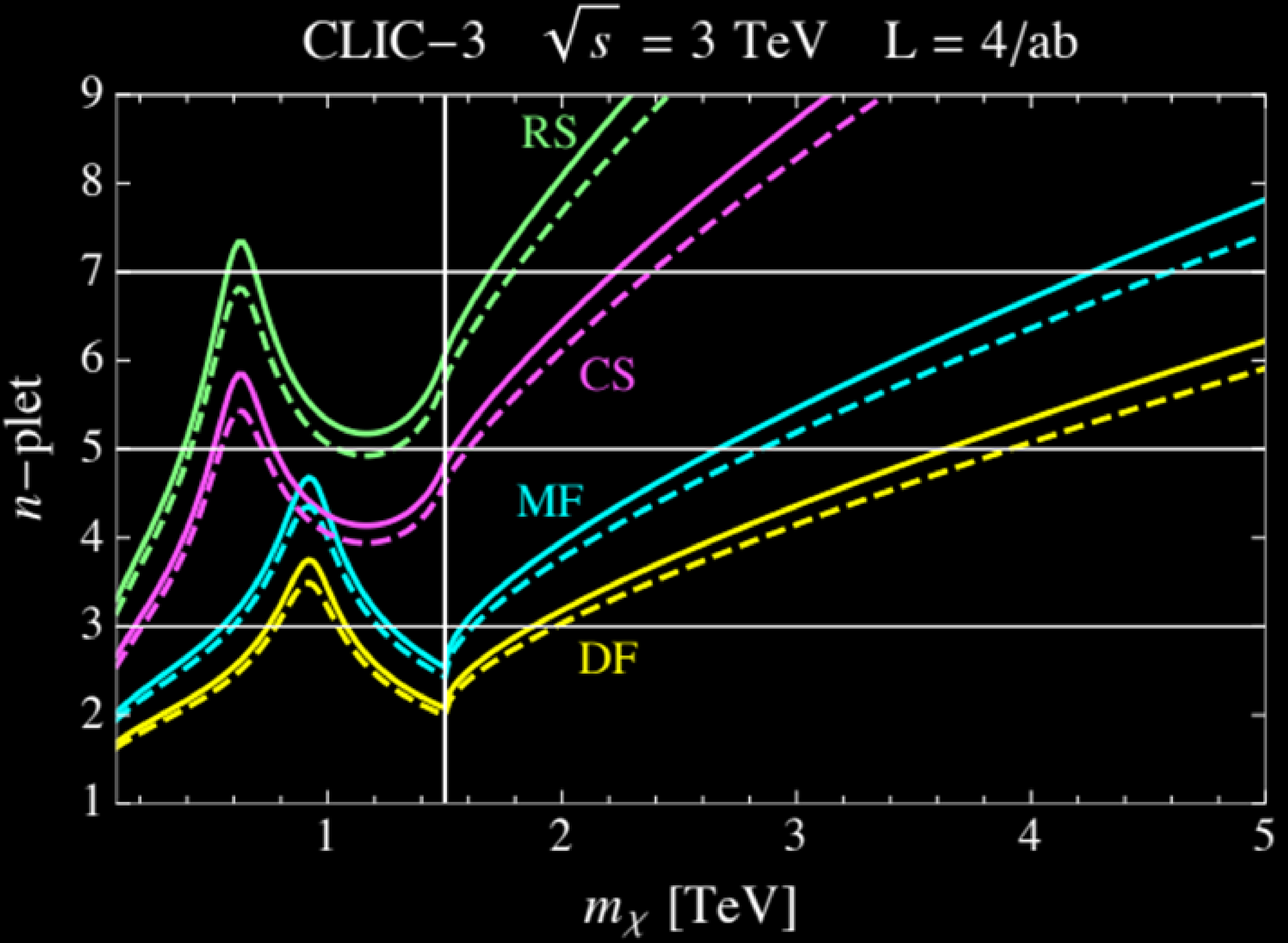
<1 ab^-1 sufficient for discovery at high E

Needed luminosity vs E_{CM} to reach thermal target



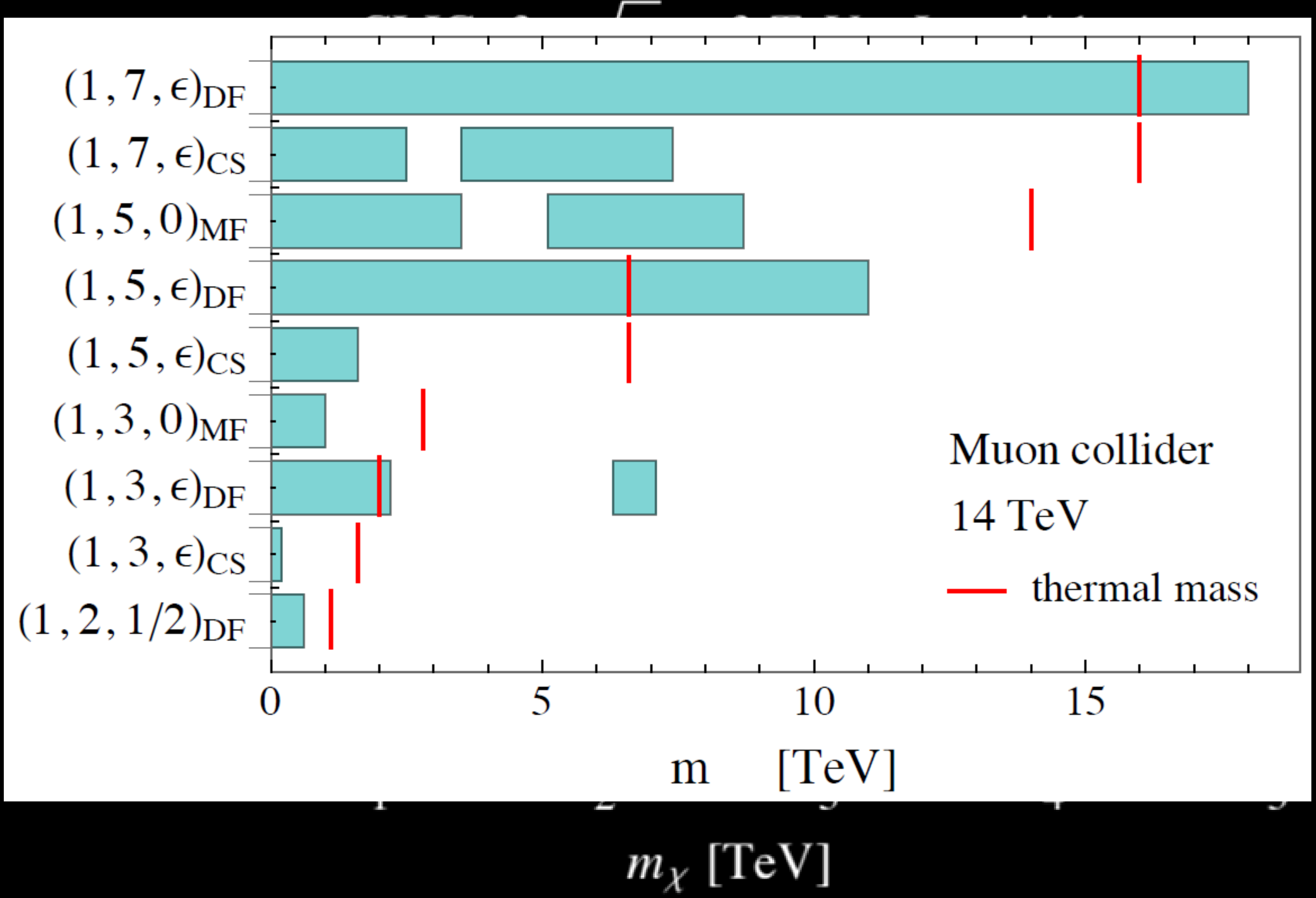
Han, Liu, Wang, Wang, 2009.11287, 2203.07351
Liu, Wang, 2205.00031

Complementarity: Precision EW



Minimal DM also invokes EW precision correction via loop processes (& integrating out) Precision EW (e.g., dileptons) provide new sensitivities.

Complementarity: Precision EW

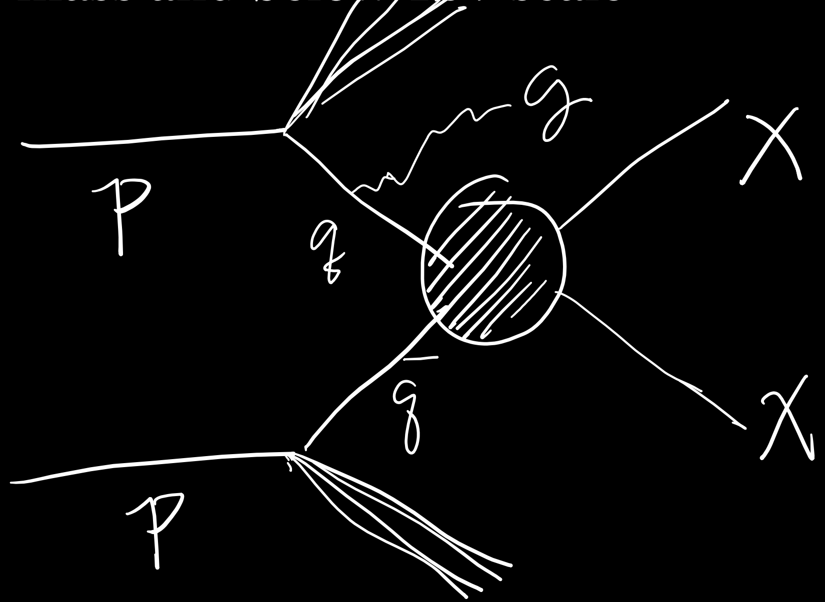


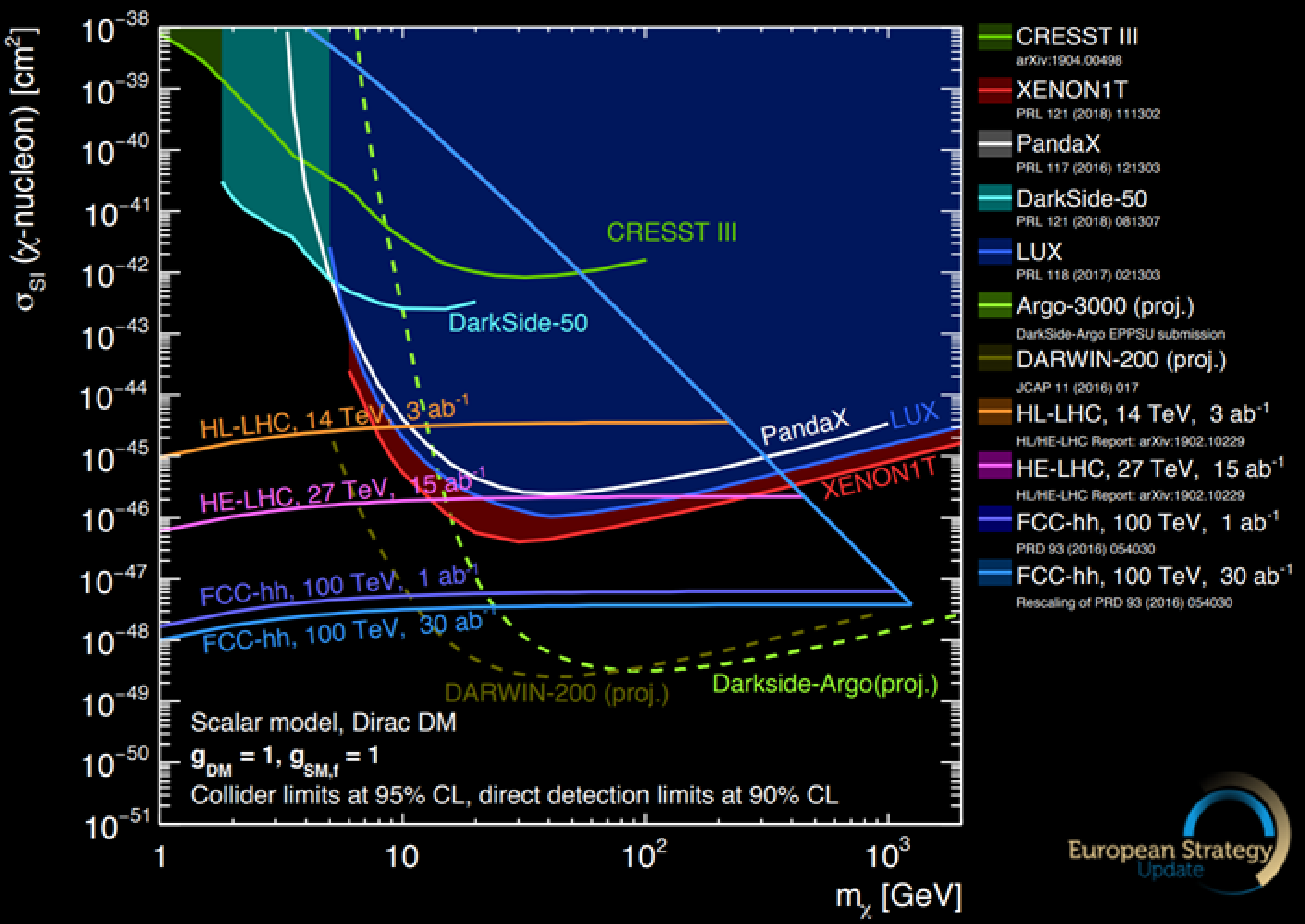
Minimal DM also invokes EW precision correction via loop processes (& integrating out) Precision EW (e.g., dileptons) provide new sensitivities.

Mono-jet (or generic MET searches)

Many possible operators (mediator types and interaction types)
Searching for Missing Transverse Energy is an inclusive strategies

Colliders are to fully cover low mass and below TeV scale

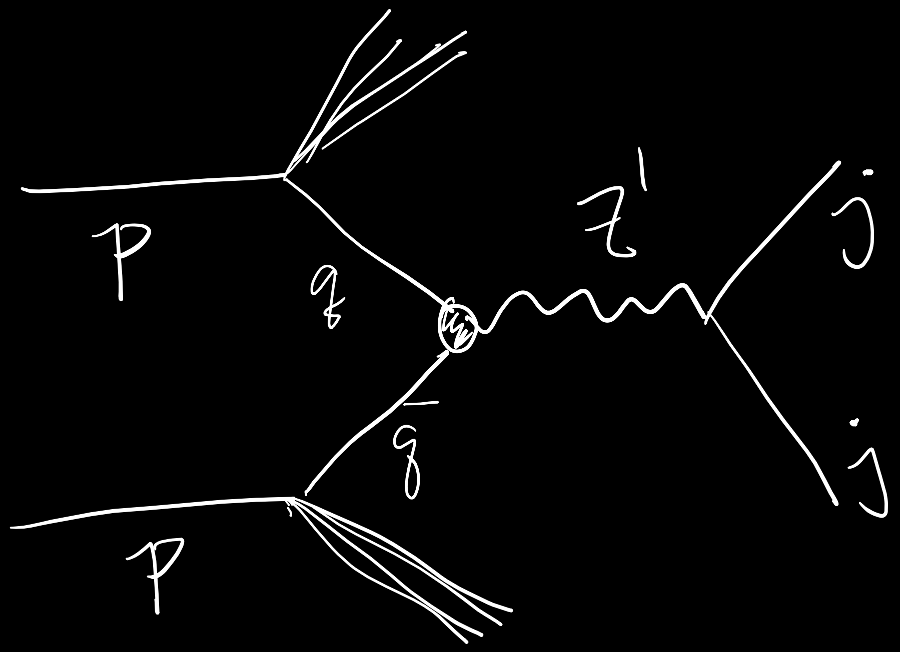


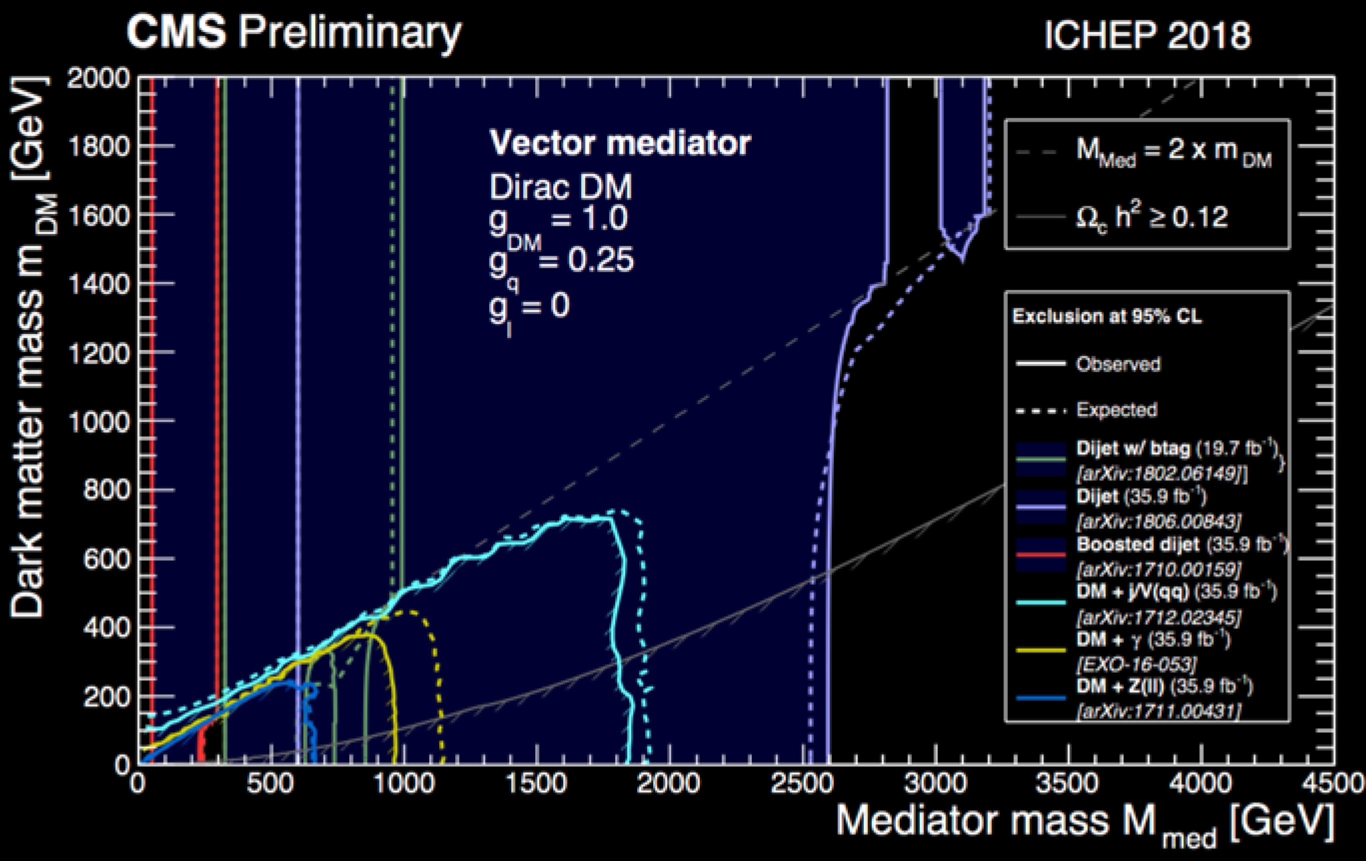


Active Mediator Hunting

Many possible operators (mediator types and interaction types)

Searching for the mediators, e.g., Z', can provide complementary information.





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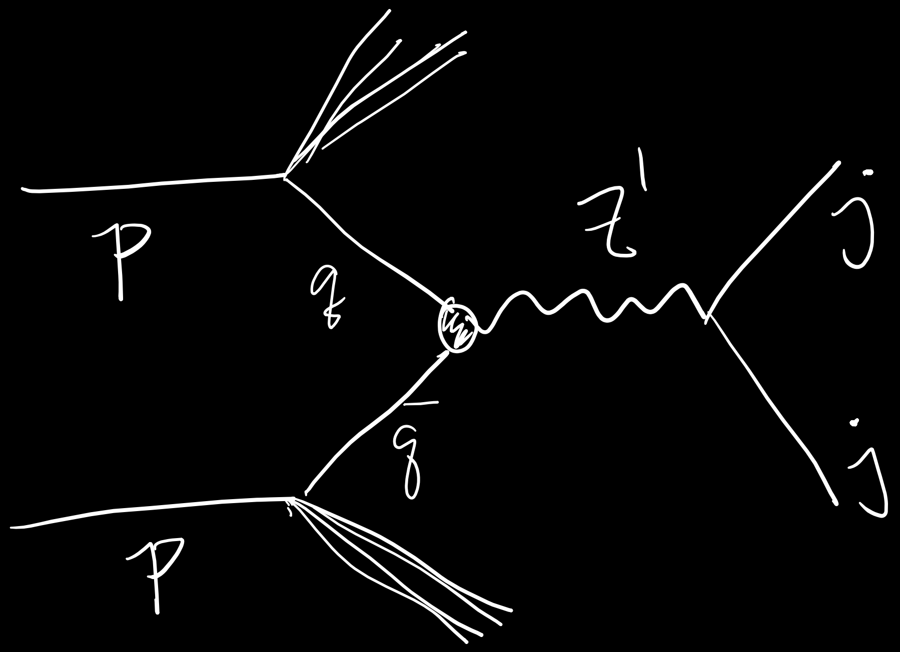
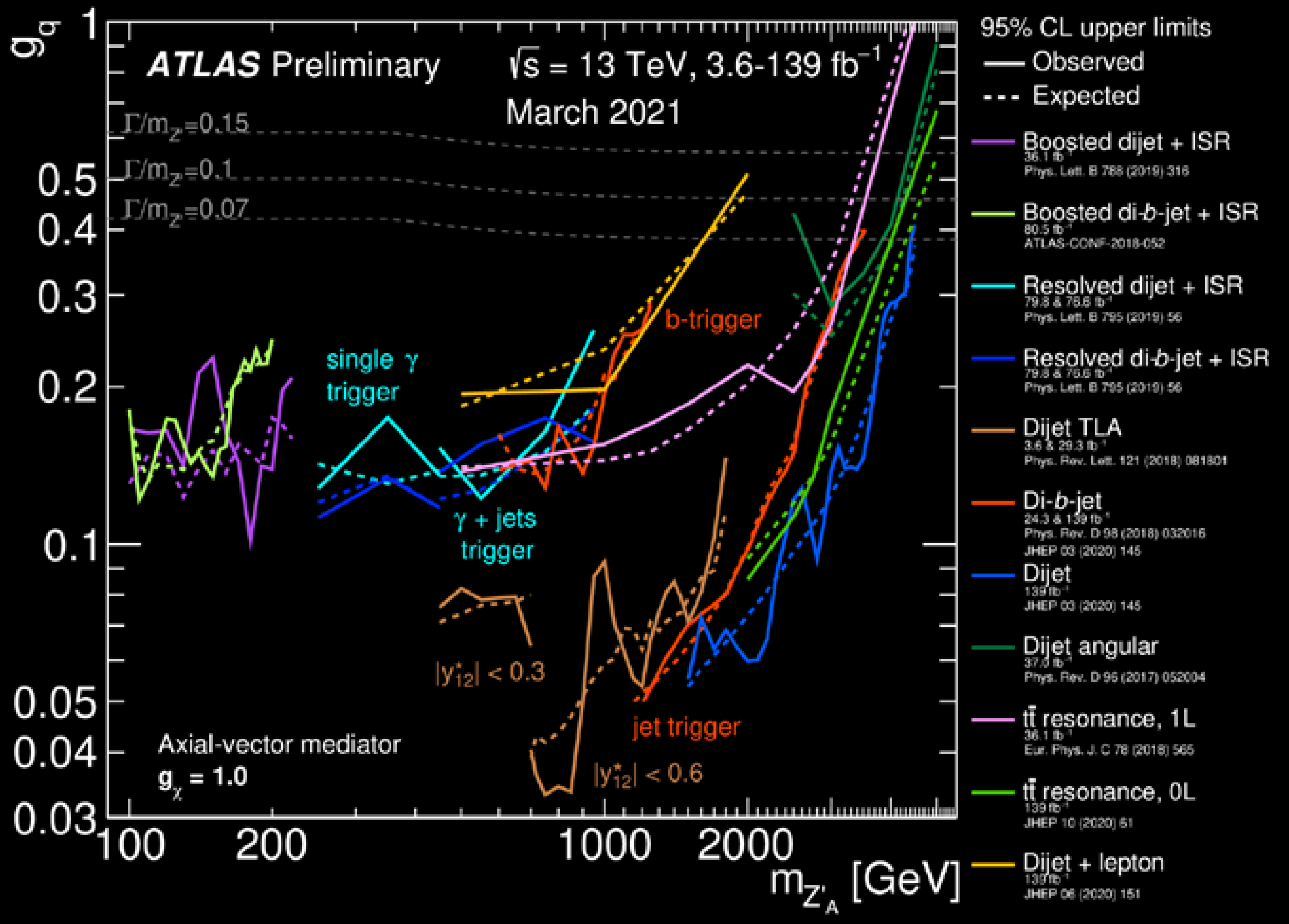


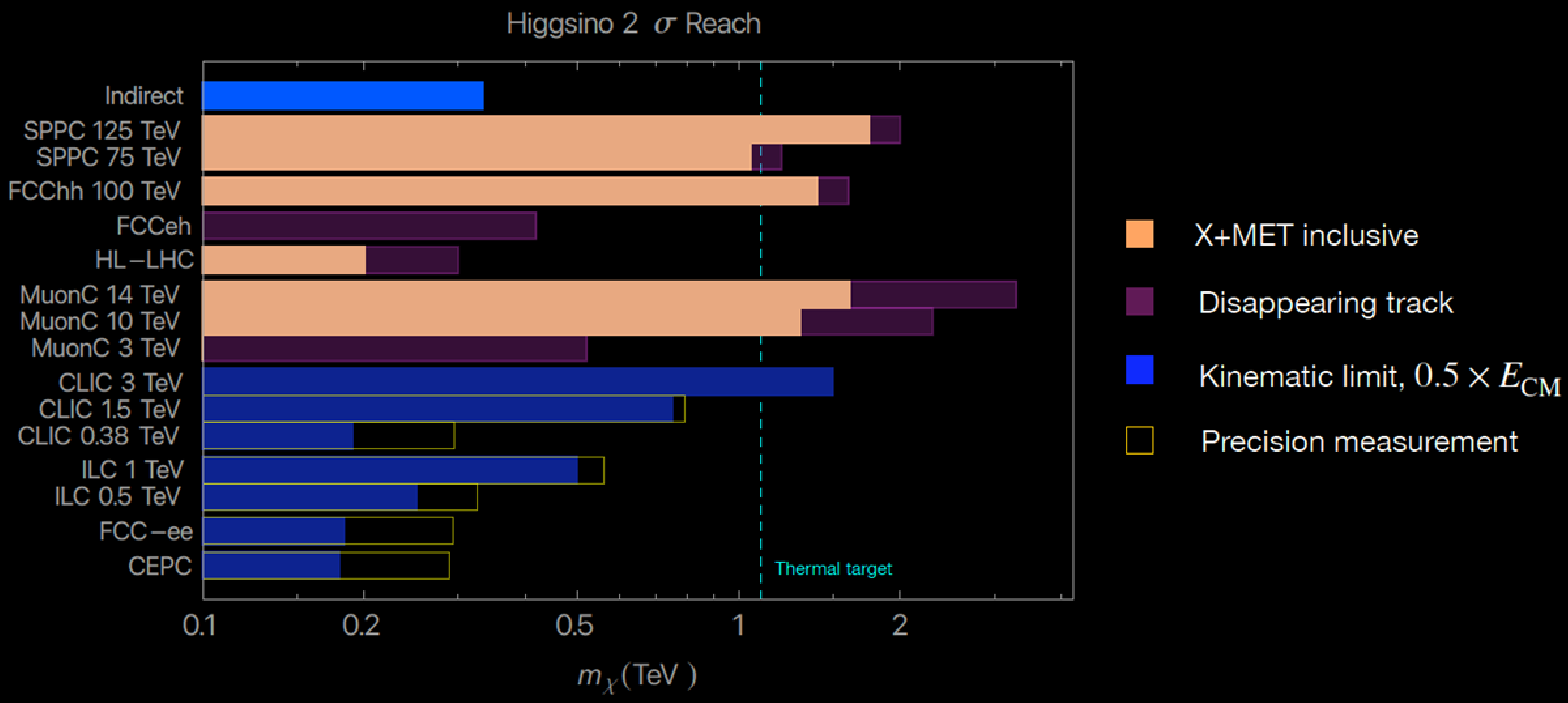


EF BSM report

A comprehensive study & summary for minimal dark matter are provided for

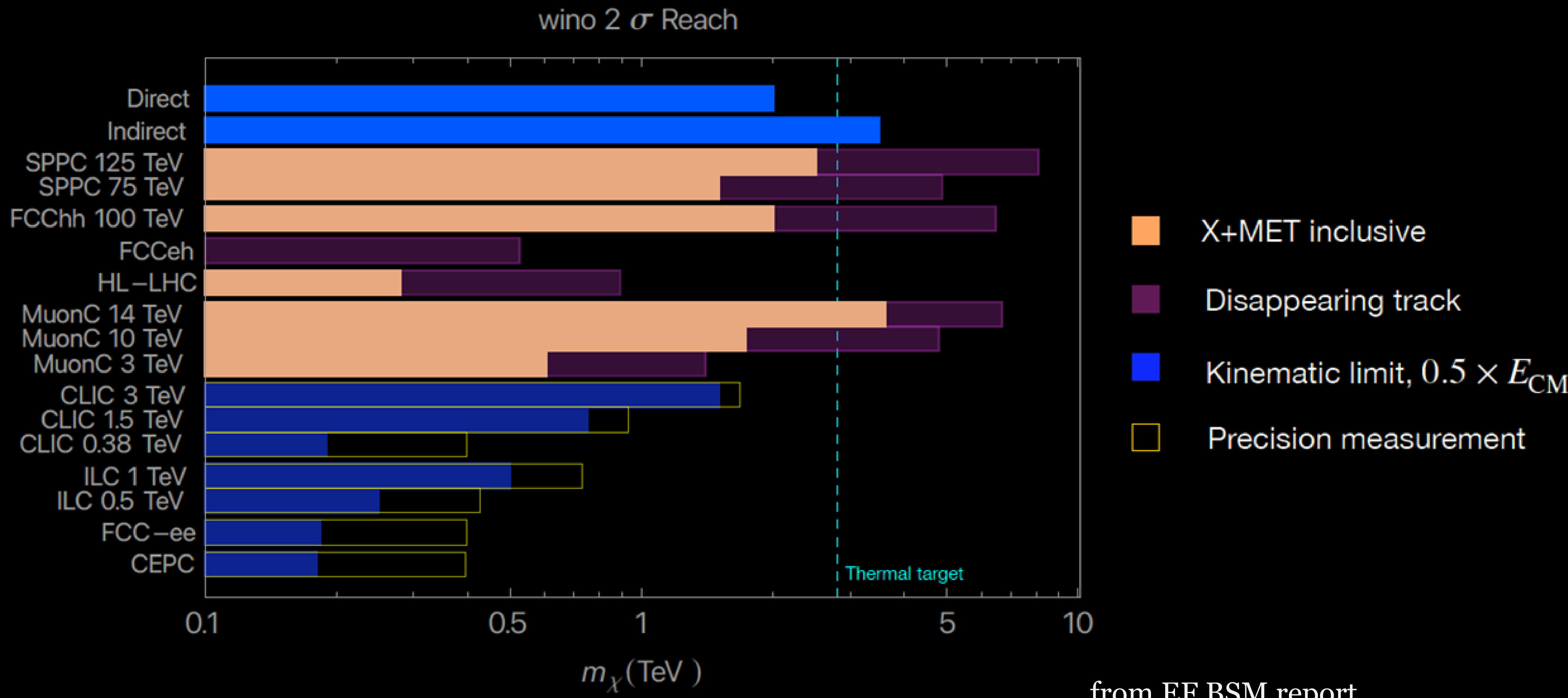
- EW Fermionic Doublet (Higgsinos)
- EW Fermionic Triple (Winos)

Higgsino Summary



from EF BSM report

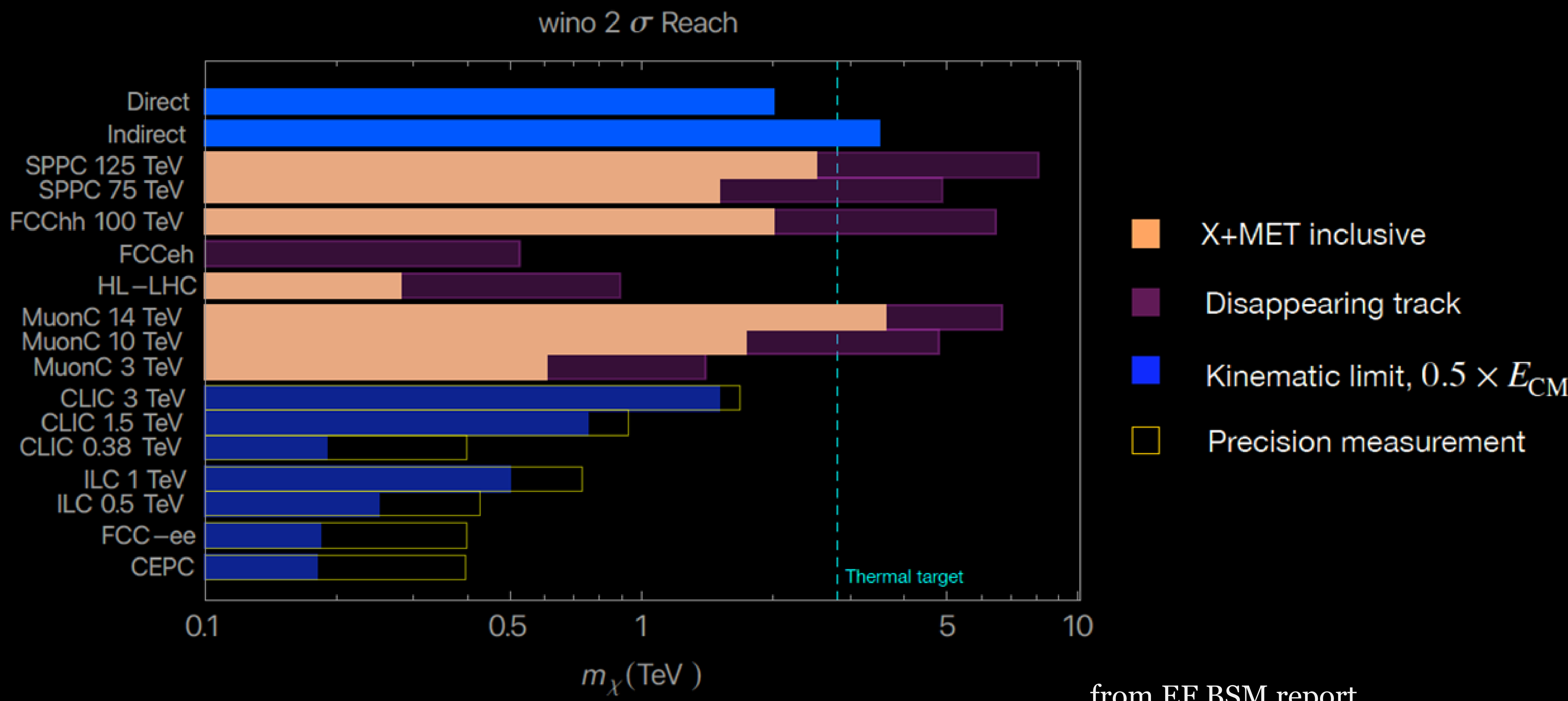
Wino Summary



from EF BSM report

Wino Summary

Thank you!



from EF BSM report