APS April Meeting:
Muon Collider Symposium

WIMPs at High Energy Muon Colliders

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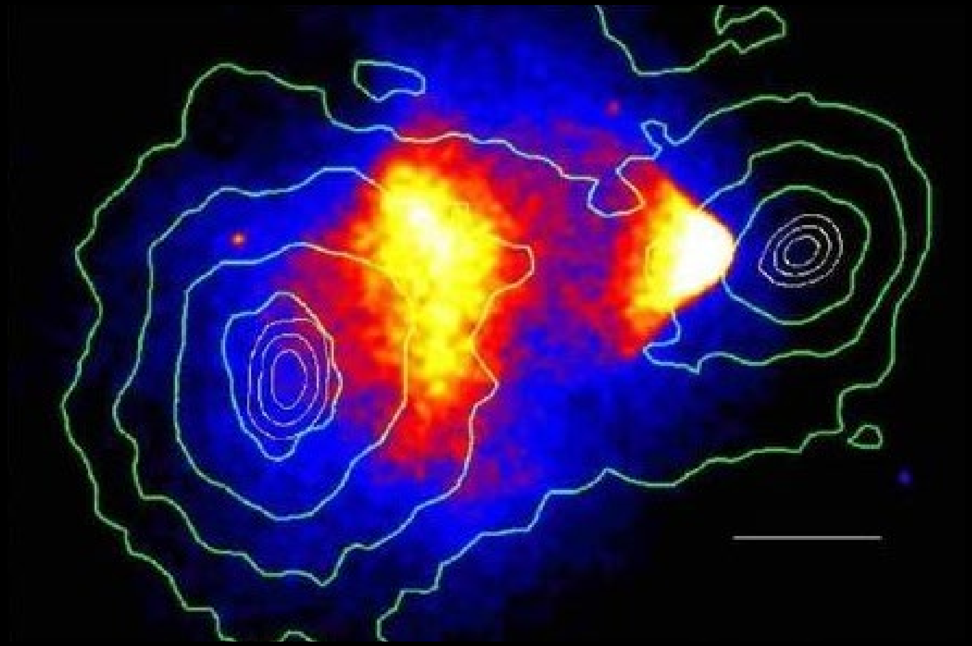
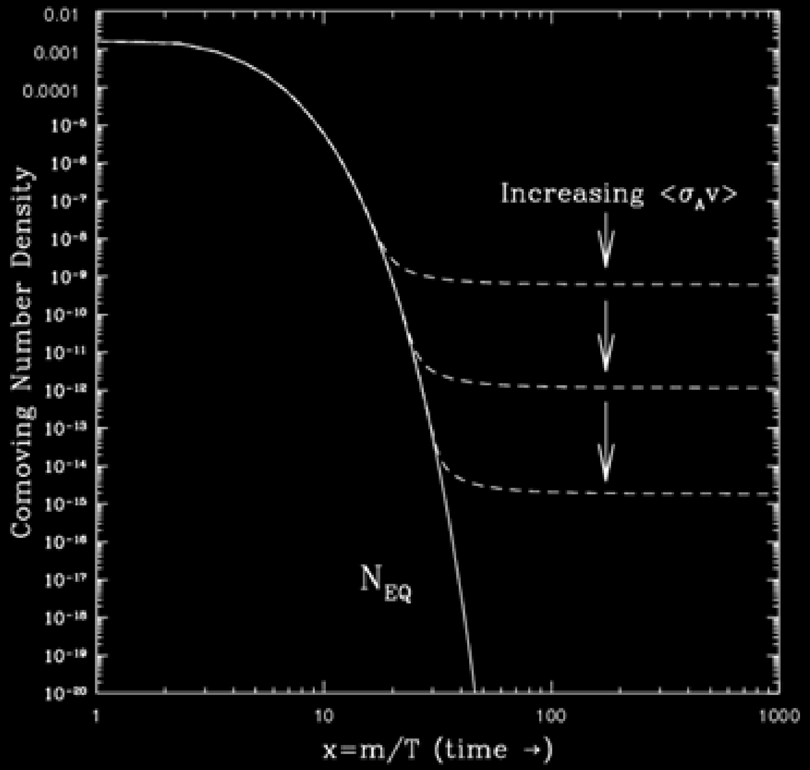
04/17/2021

Han, ZL, Wang, Wang, 2009.11287

WIMP Dark Matter

Compelling, simple, predictive explanation for thermal, cold dark matter





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

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

There is a scale…

Our Approach: work on the "nightmare" scenario

Consider the following "Minimal Dark Matter"*:

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
(1,7,ϵ)	Dirac	16 TeV

"Nightmare":

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

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

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

Basic Pheno Considerations

"non-trivial" to consider MuC

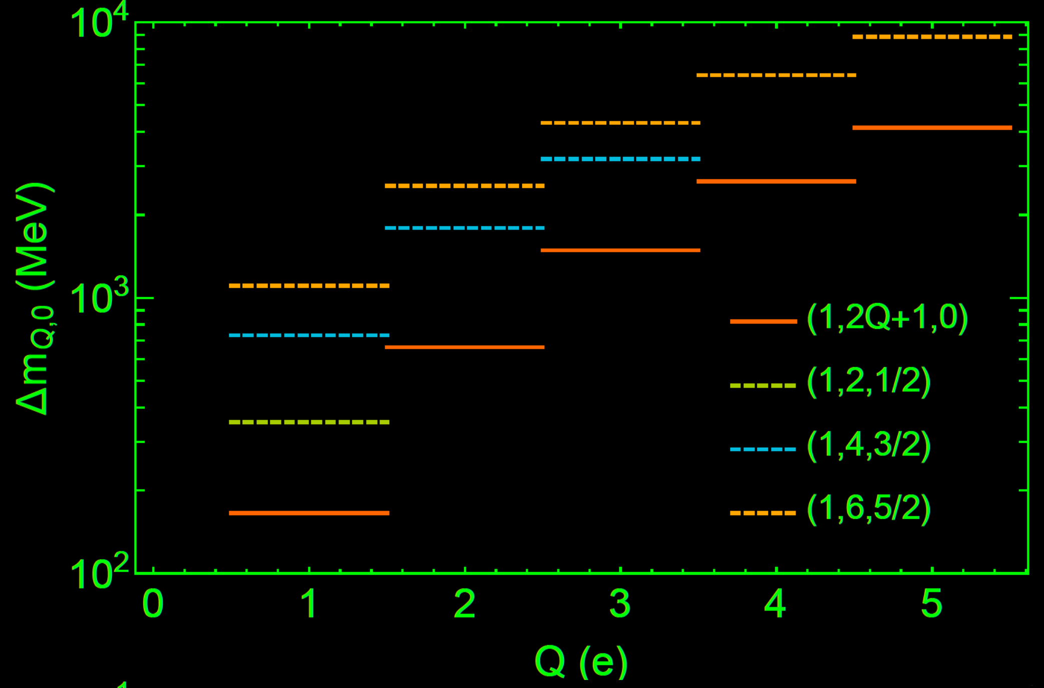
- Minimal signature
  - Mass splitting O(few hundred MeV)
  - Decay products soft
  - Transition between states fast (<mm for most of the cases)
- Missing ET (at LHC)➔Missing Mass (at MuC)

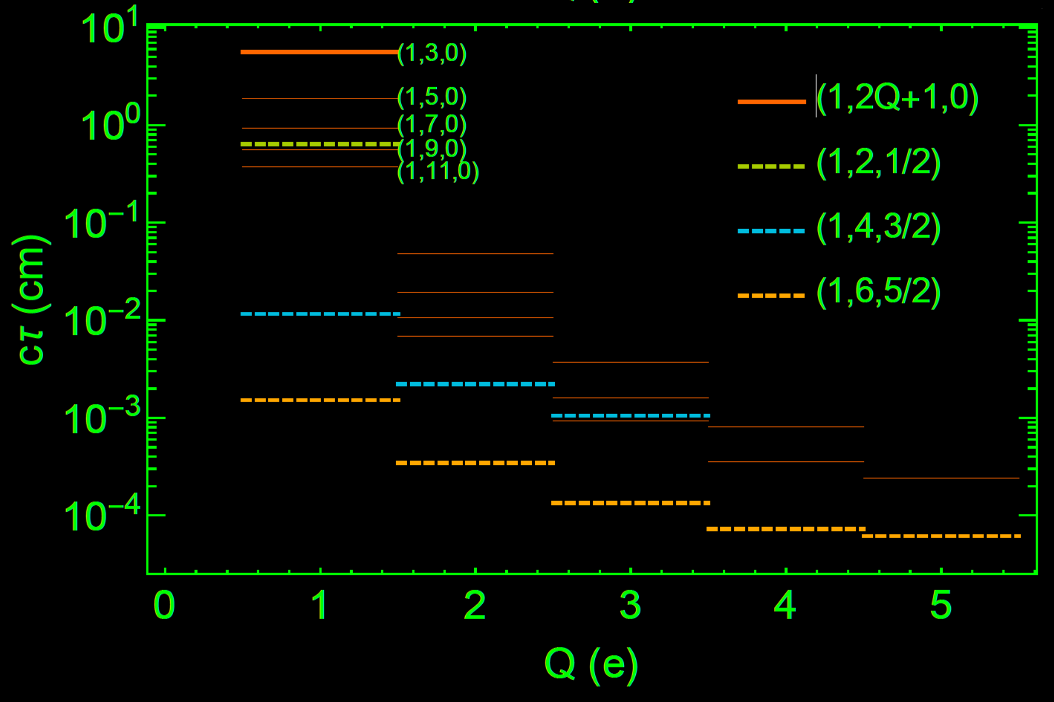
$$m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\text{obs}})^2$$

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

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

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





Basic Pheno Considerations

"non-trivial" to consider muon collider reaches

- 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)
- 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
- Beam induced background (BIB)
  - Affects detector coverage
  - Affects photon, muon threshold
  - Affects disappearing track considerations

Missing Mass signature:

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

Disappearing track signature:

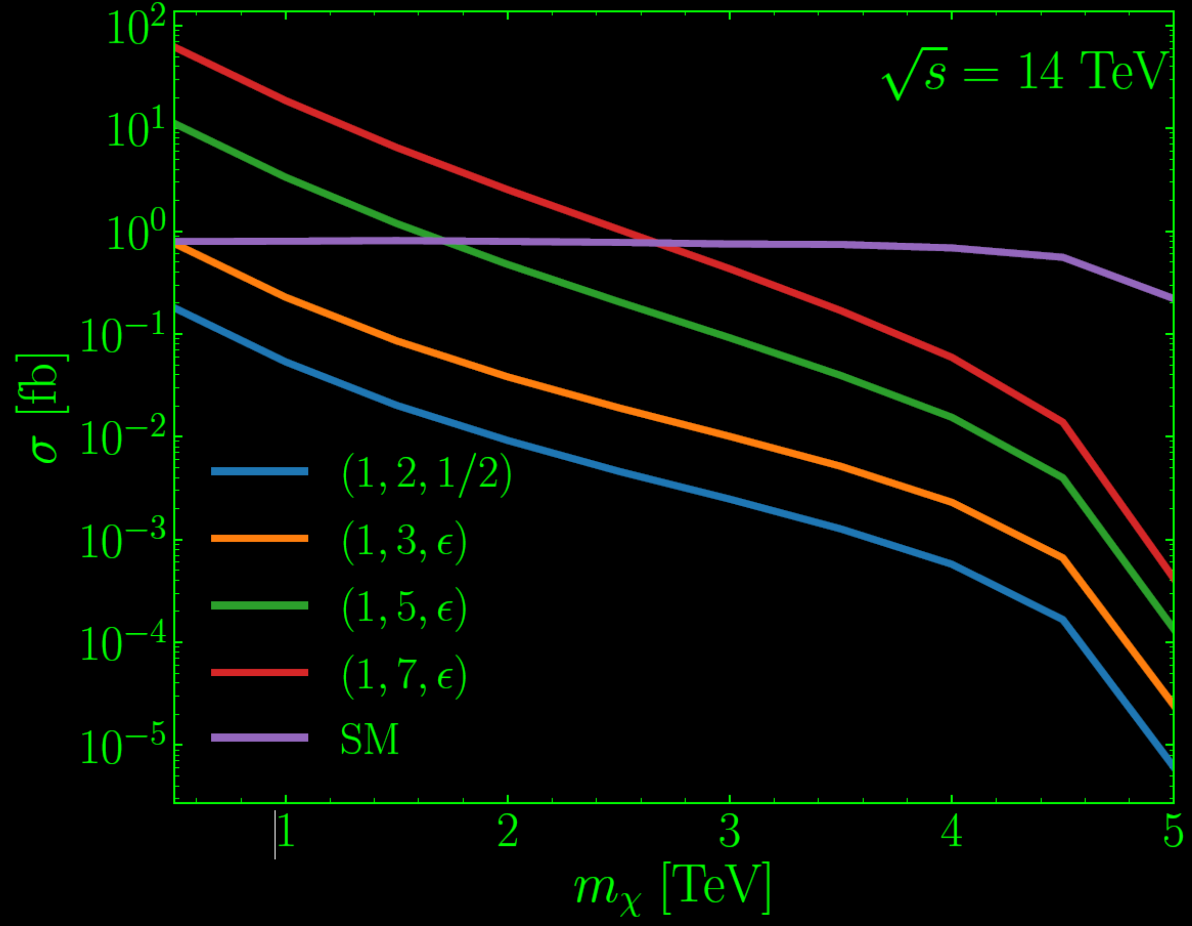
- Exclusive but challenging
- Most useful for Wino and Higgsinos
- Great potential

$$\sqrt{s} = 3,\ 6,\ 10,\ 14,\ 30 \text{ and } 100 \text{ TeV}$$

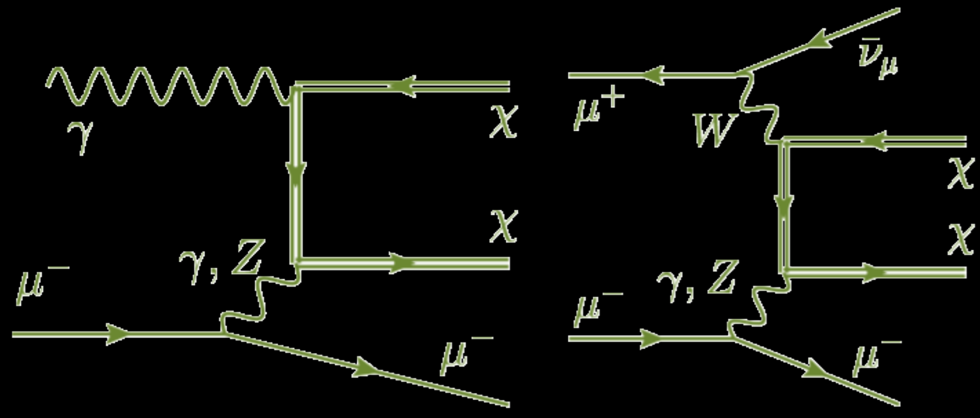
$$\mathcal{L} = 1,\ 4,\ 10,\ 20,\ 90,\ \text{and } 1000 \text{ ab}^{-1}$$

Unique Mono-Muon Channel

Apparent "Charge Violation" channel
(very different from the LHC)



Signature: Energetic mono-muon



Muon pairs → muon + missing mass

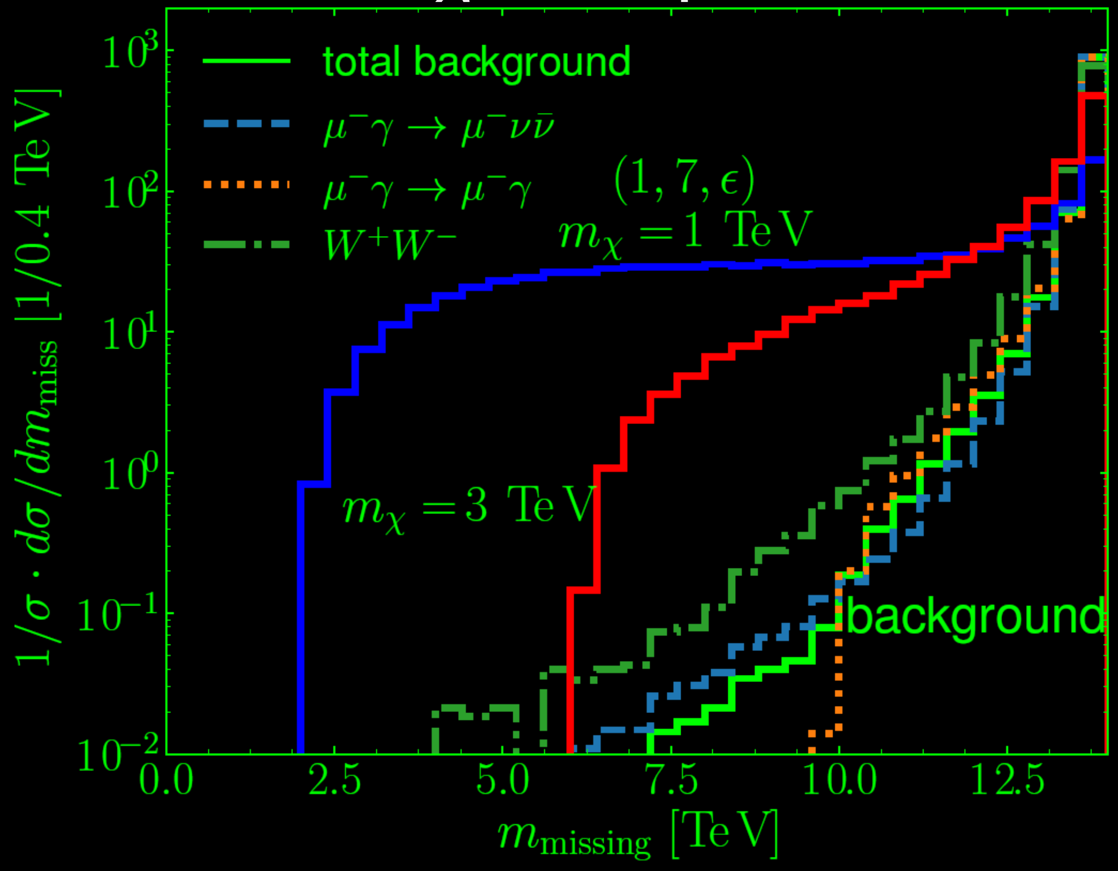
One charge is missed due to the soft (non-reconstructable) decays of the charged states

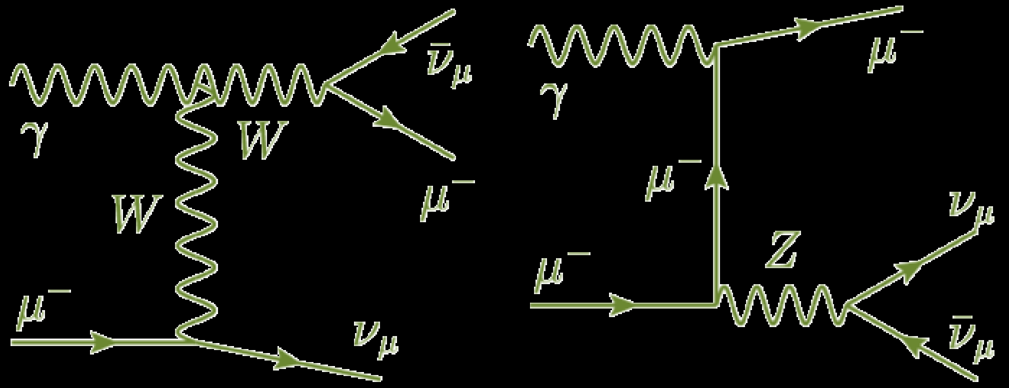
Unique and powerful channel

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

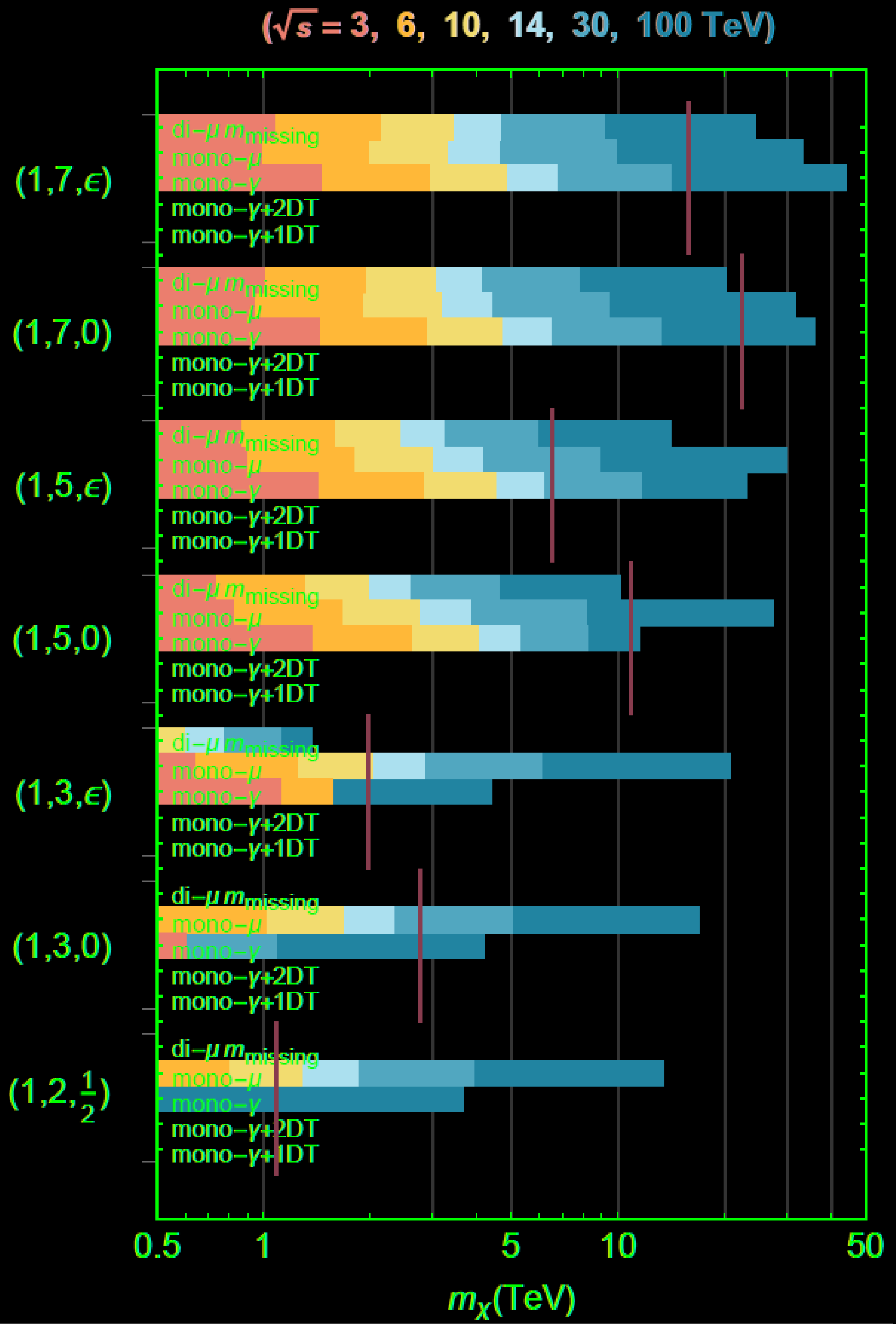
Also includes dominant 2->2 processes with one of them decays forward

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

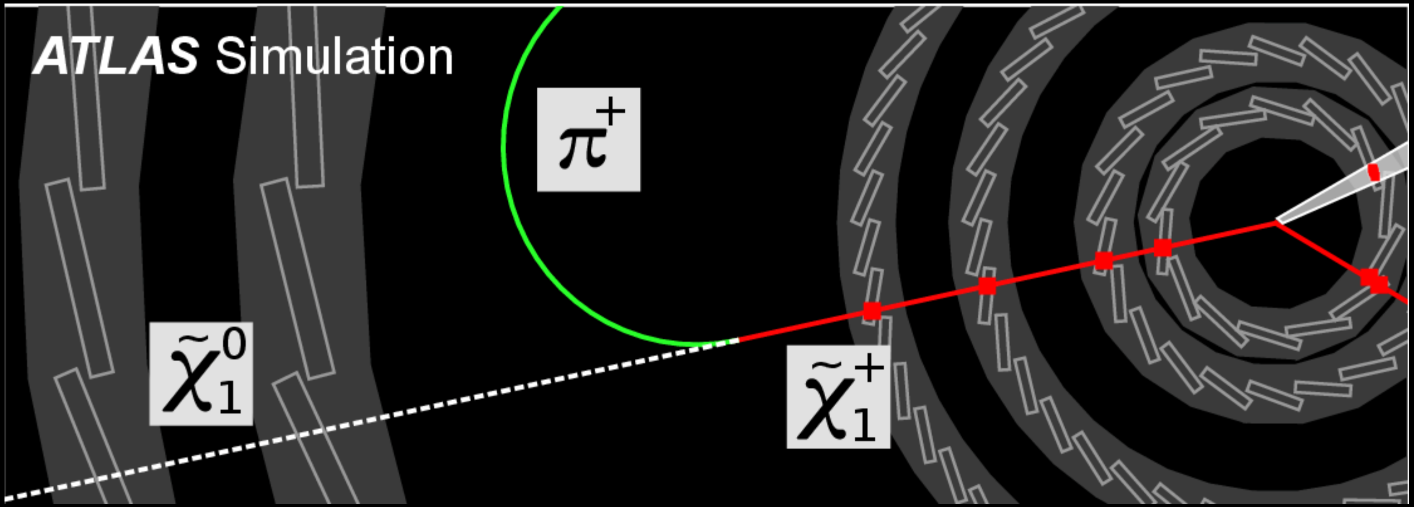
$$E_{\mu^\pm} > 0.71,\ 1.4,\ 2.3,\ 3.2,\ 6.9,\ 22.6 \text{ TeV}, \quad \text{for } \sqrt{s} = 3,\ 6,\ 10,\ 14,\ 30,\ 100 \text{ TeV}$$

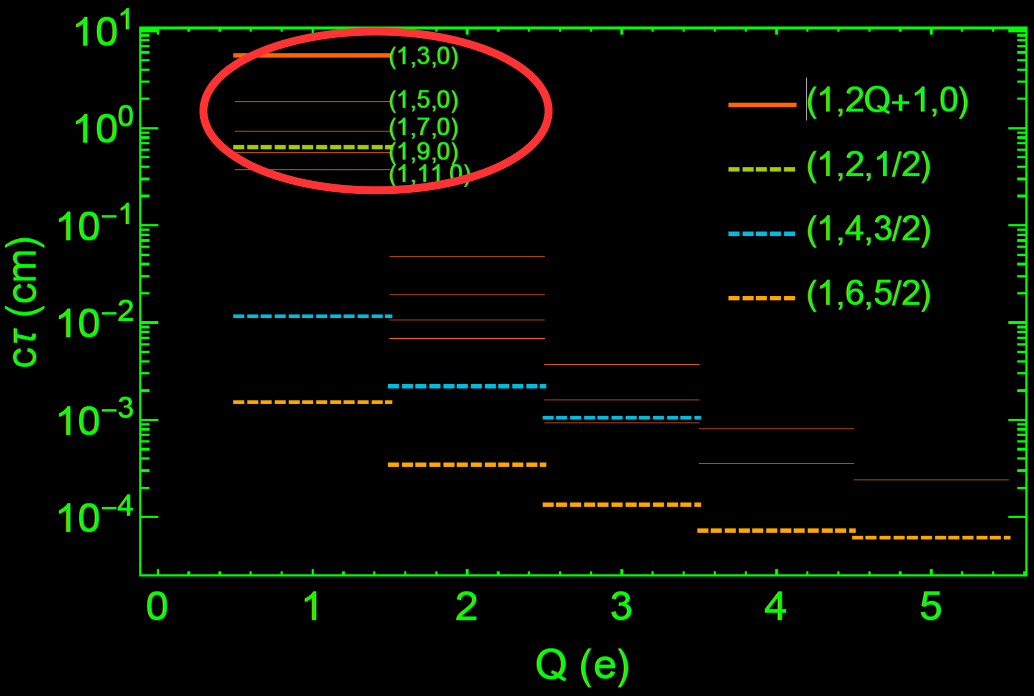
Summary (by channel)

- 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)

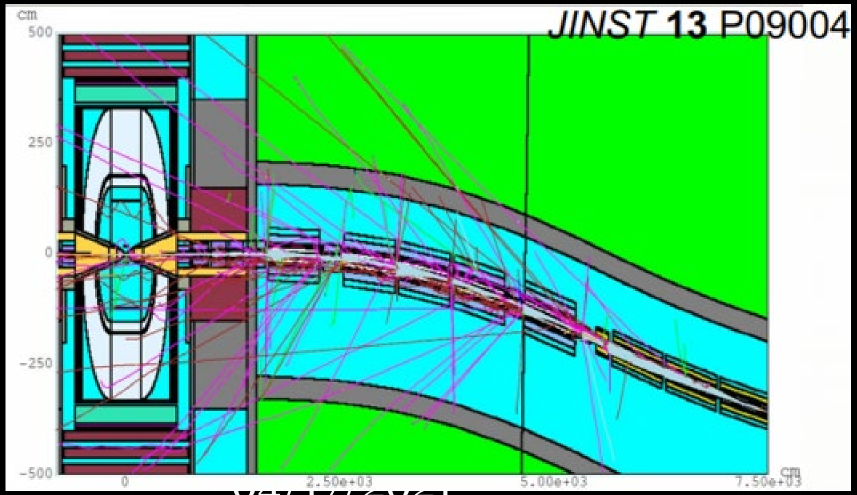


Disappearing Tracks: next to minimal signatures



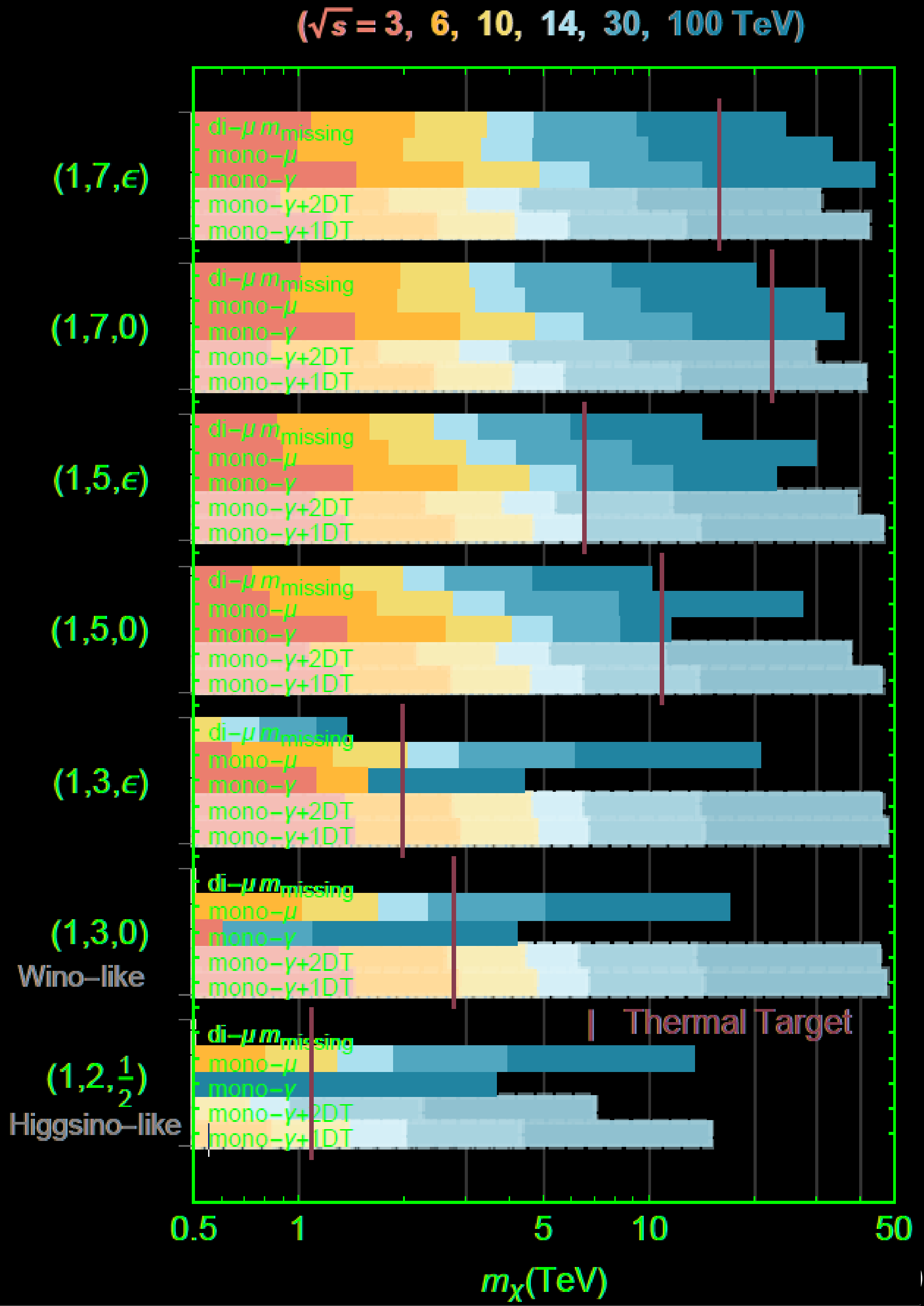


- Only useful for searches using charge 1 states
- Still, all higher charged states will cascade back to charge 1 states promptly
- Use all the production rates of charged states
- Mono-photon+disappearing tracks
- Beam Induced Background



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



See also Capdevilla, Meloni, Simoniello, Zurita, 2102.11292

Thank you!

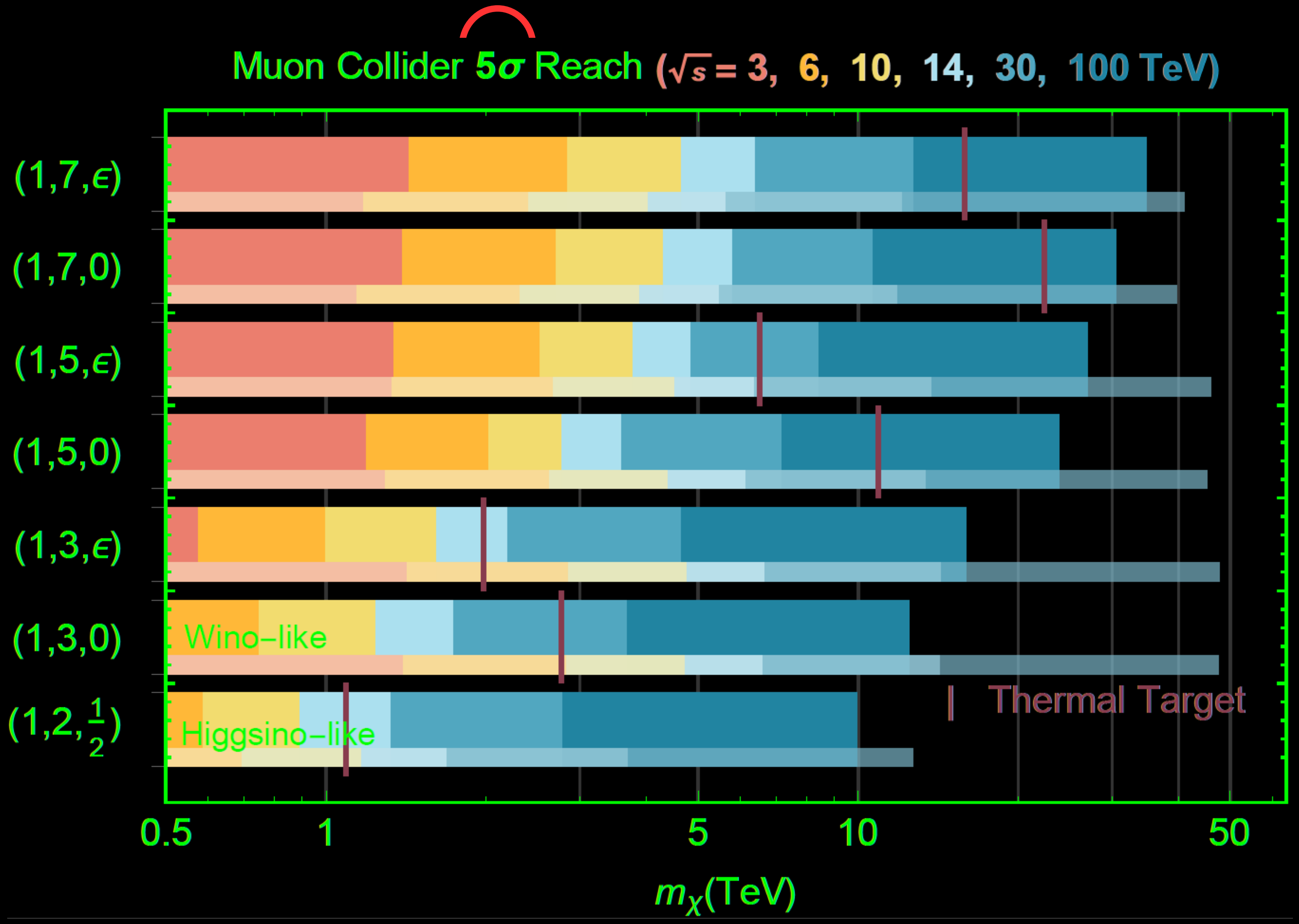
Summary (by energy)

We only combine the missing mass searches (mono-muon, mono-photon, VBF dimuon)

High Energy Muon Collider will cover all of them with different run energies.

Electroweak precision probes for these EW multiplets, mainly useful for the high n-plets.

Collider always provides definitive measures for new particles (even if we discover WIMP DM in e.g., DD).

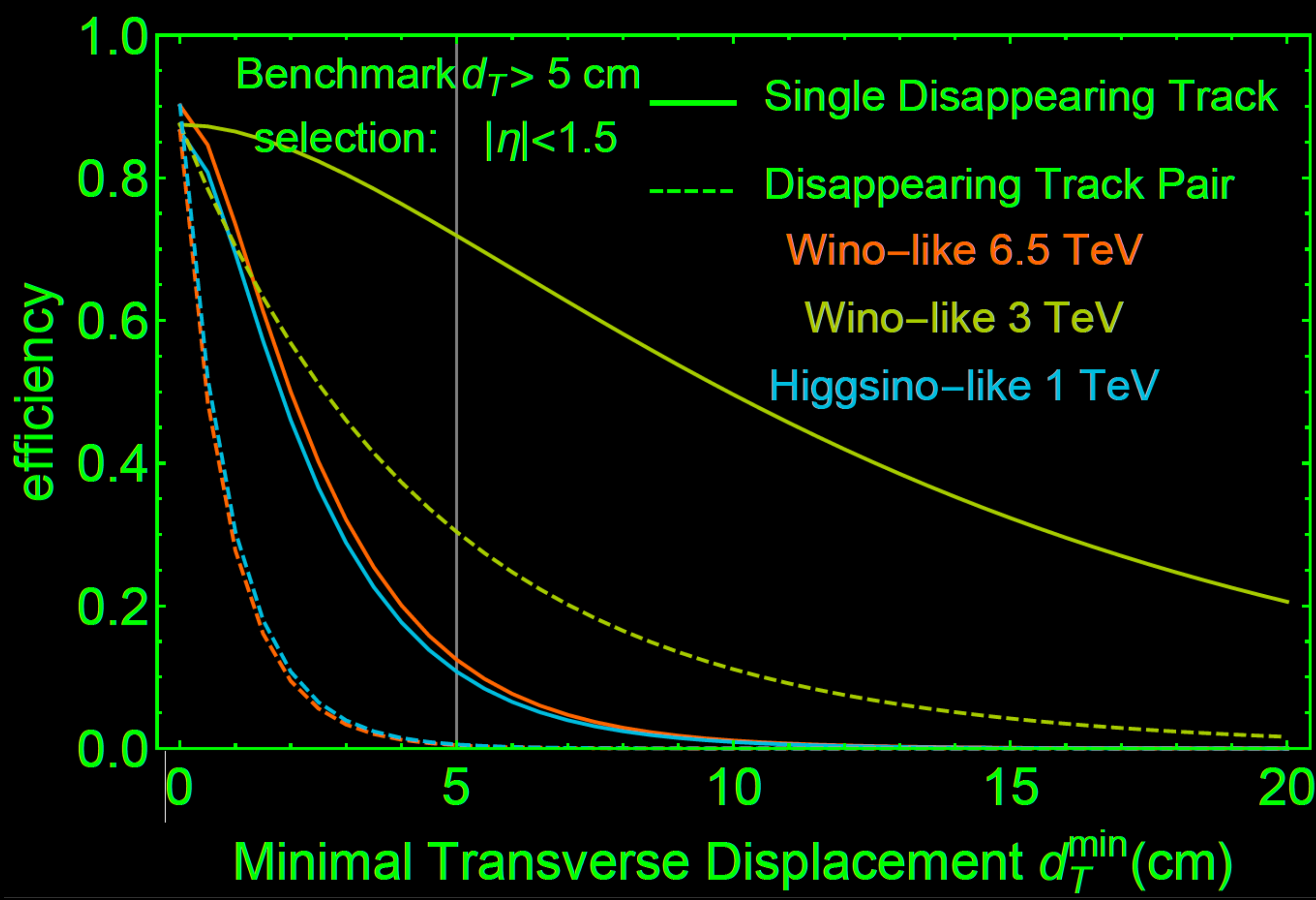


Minimal transverse displacement

- Only use the central tracks, |eta|<1.5
- Current design have 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

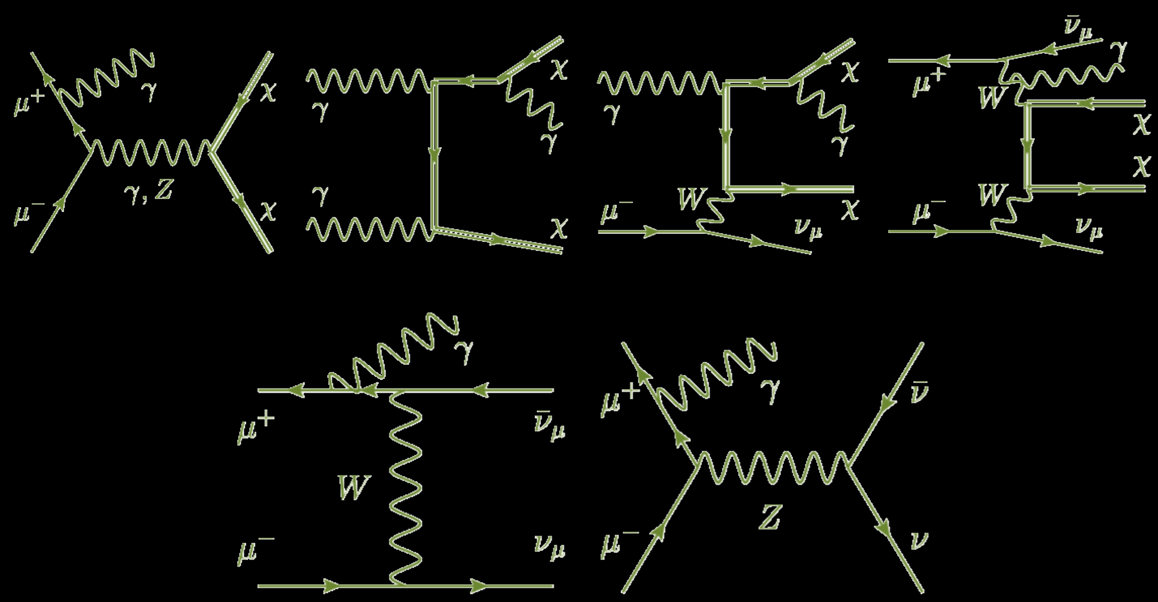
$$d_T^{\rm min} = 5 \text{ cm with } |\eta_\chi| < 1.5$$

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



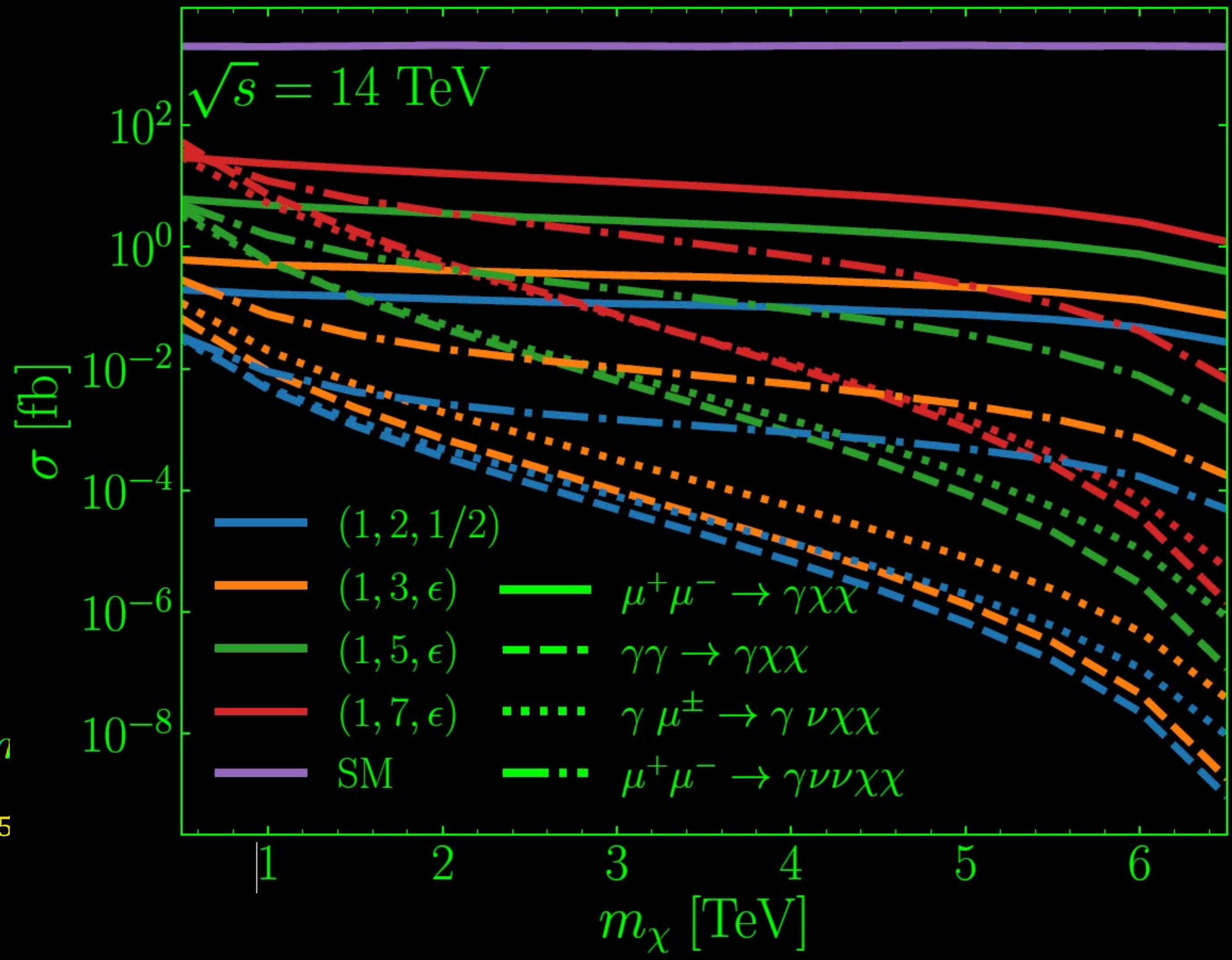
All combinations of components of the EW multiplet are included, so-long as they respect the underlying gauge symmetries

Mono-Photon



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

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



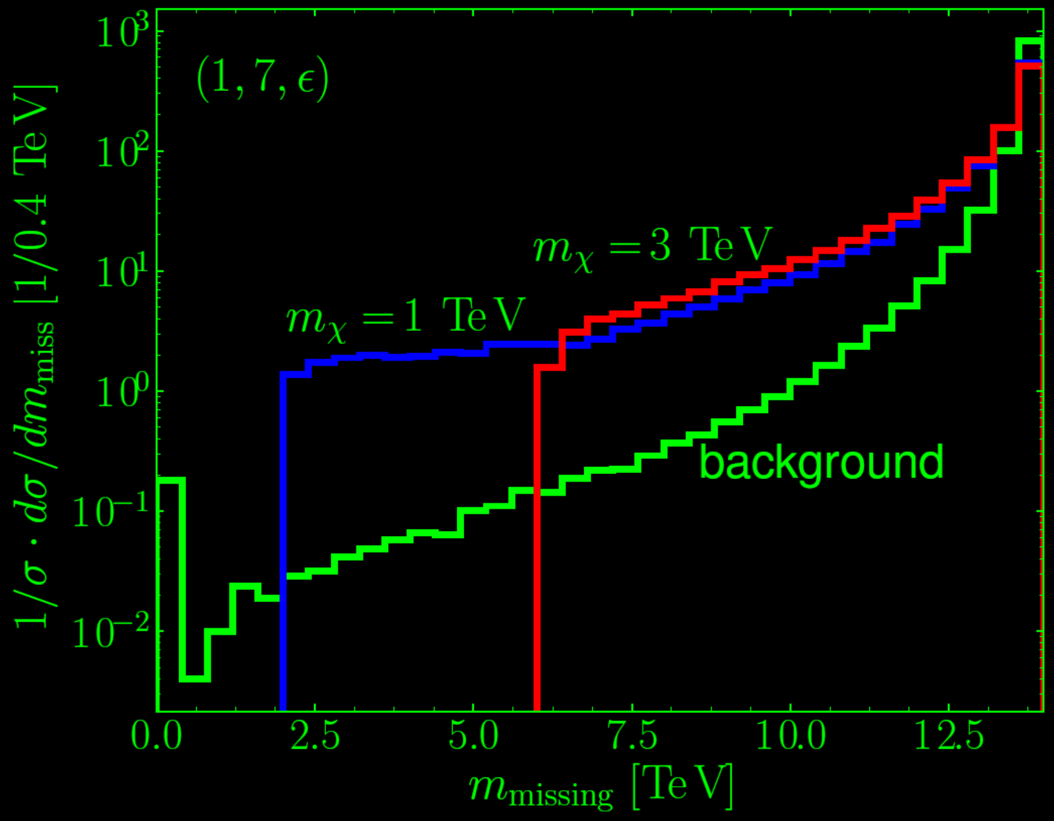
Rate grows with n-plets as roughly $n^{2\sim3}$ (DY) and $n^{4\sim5}$
Doublet and Triplet very hard to probe

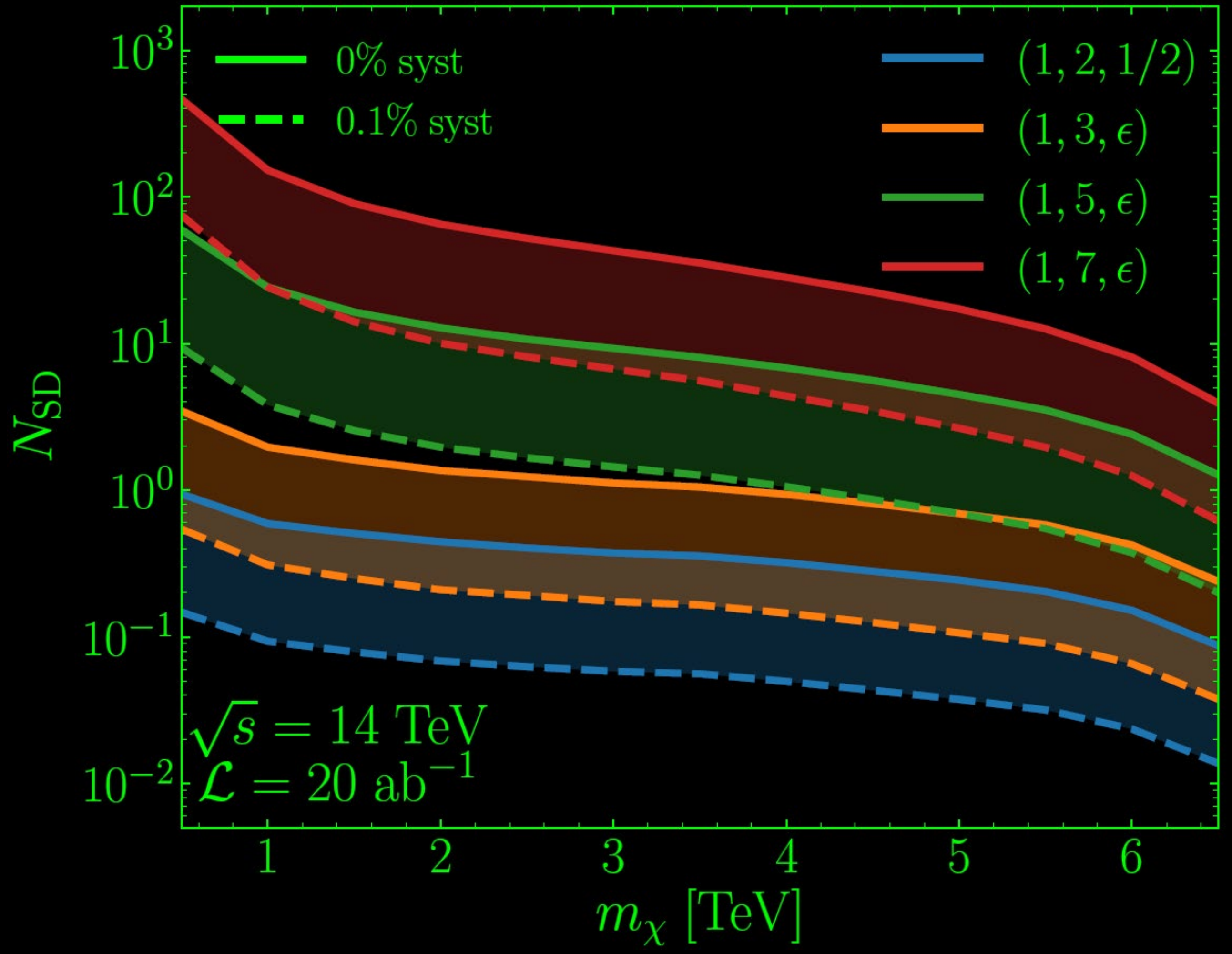
Signal-background ratio 10^-3
At lepton colliders systematics controlled to this level should be achievable but requires theory & experimental work

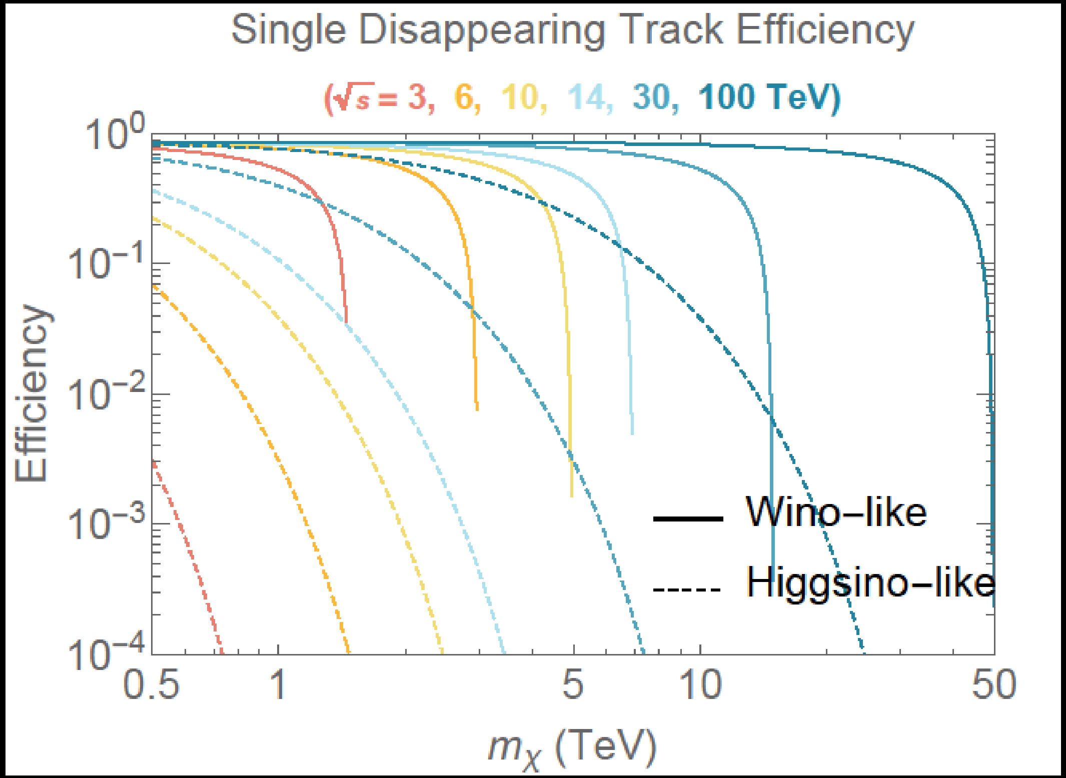
Mono-photon

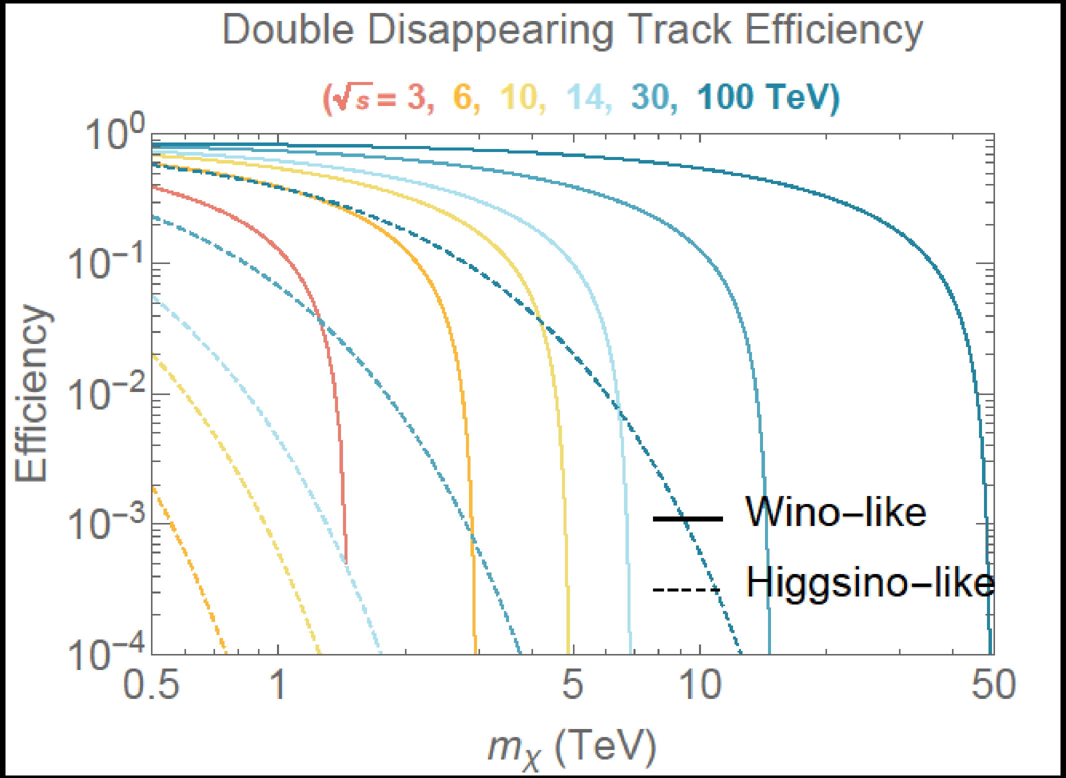
Missing mass:

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

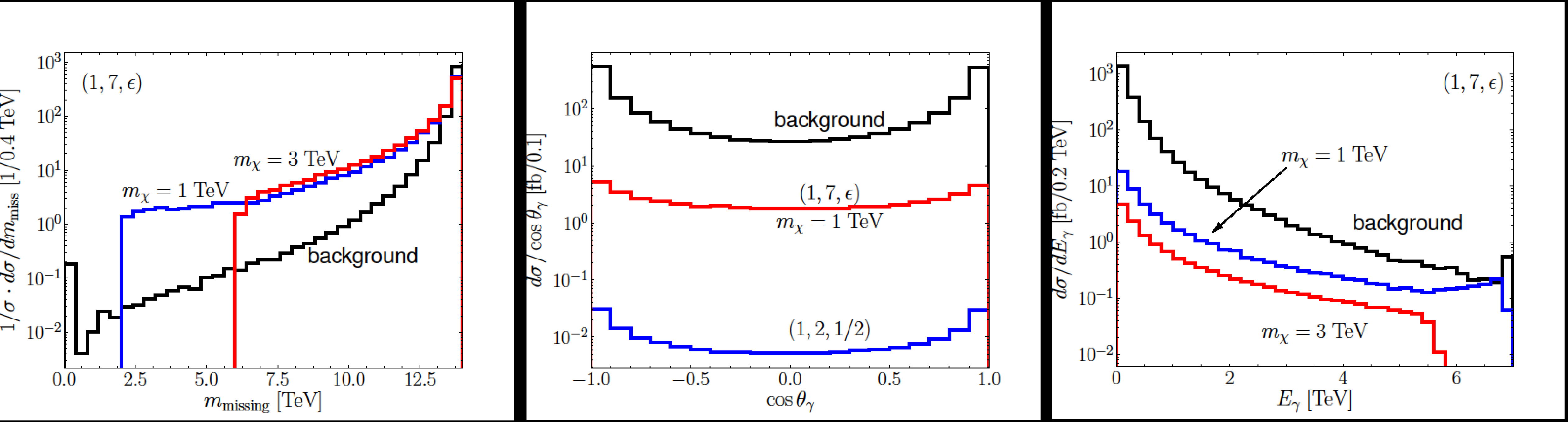




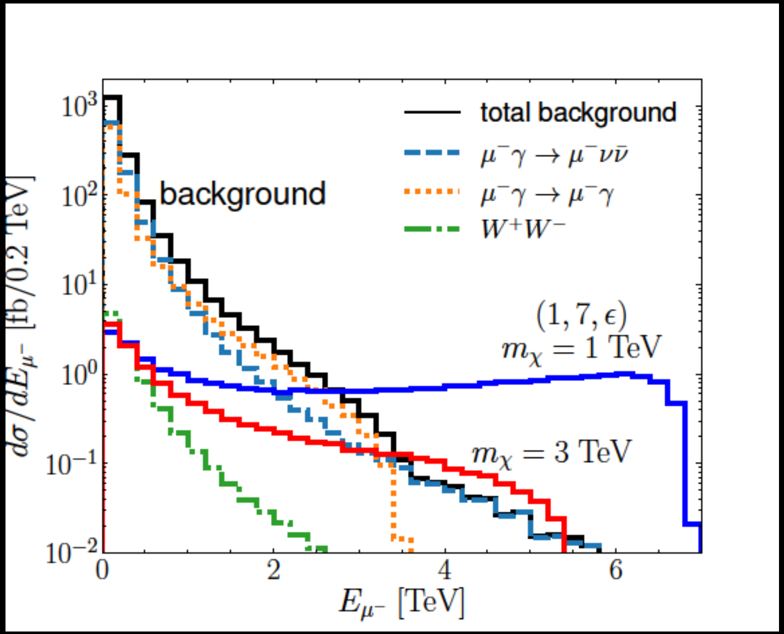

Single Disappearing Track Efficiency
(√s = 3, 6, 10, 14, 30, 100 TeV)
Efficiency
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.5
1
5
10
50
m_χ (TeV)
Wino–like
Higgsino–like

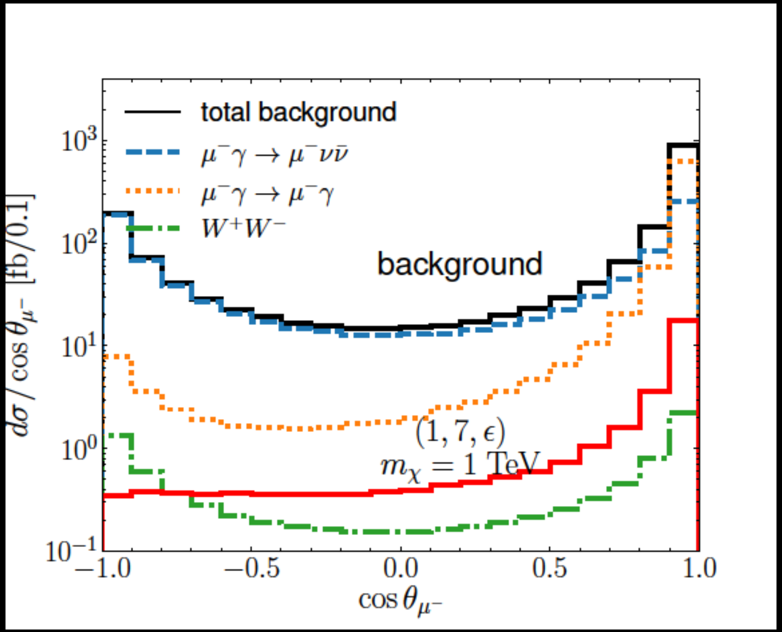

Double Disappearing Track Efficiency
(√s = 3, 6, 10, 14, 30, 100 TeV)
Efficiency
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.5
1
5
10
50
m_χ (TeV)
Wino–like
Higgsino–like

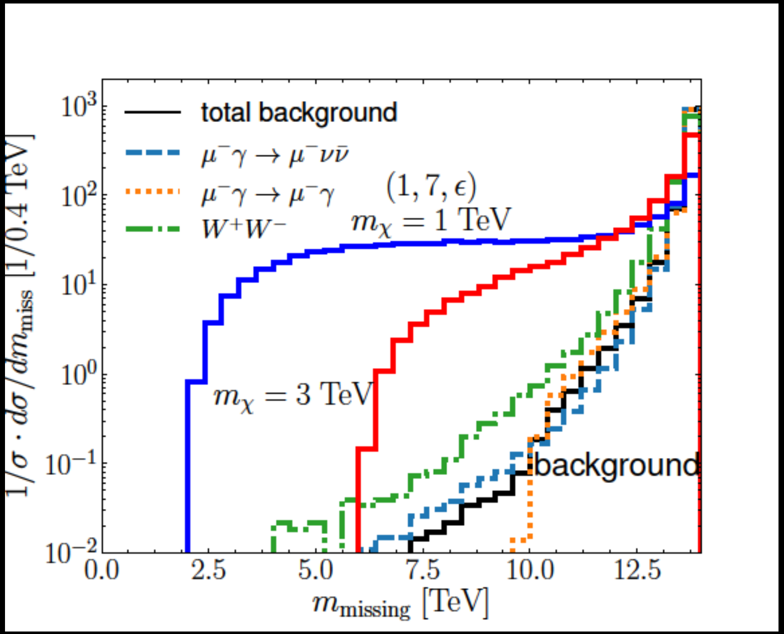
Mono-Photon Kinematics

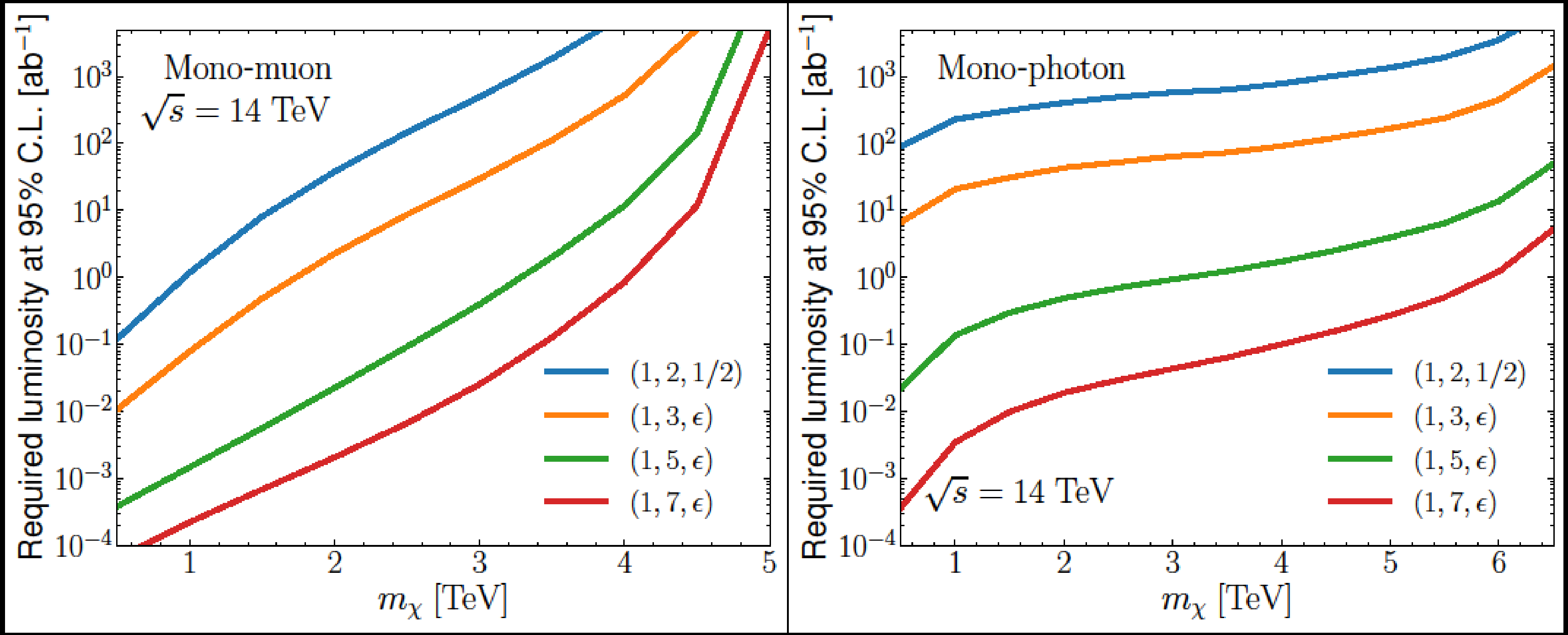


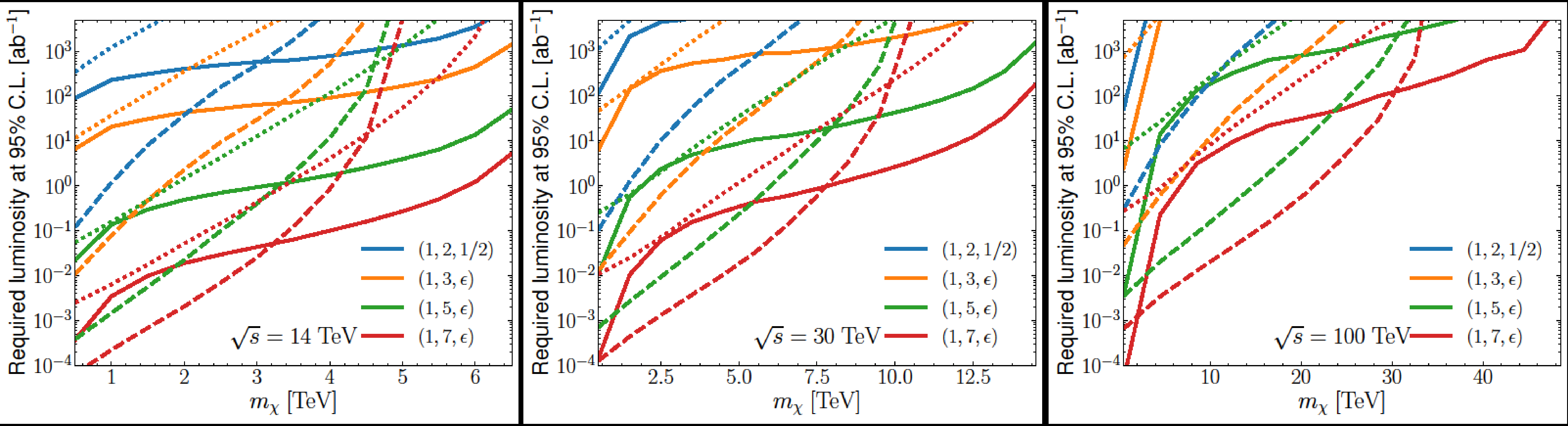
Mono-muon Kinematics

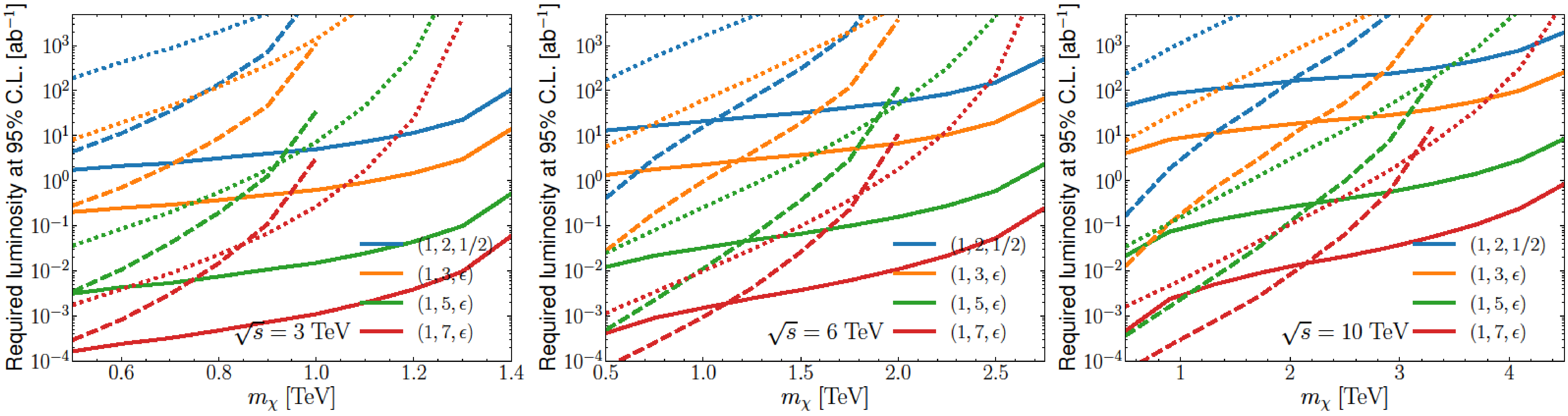


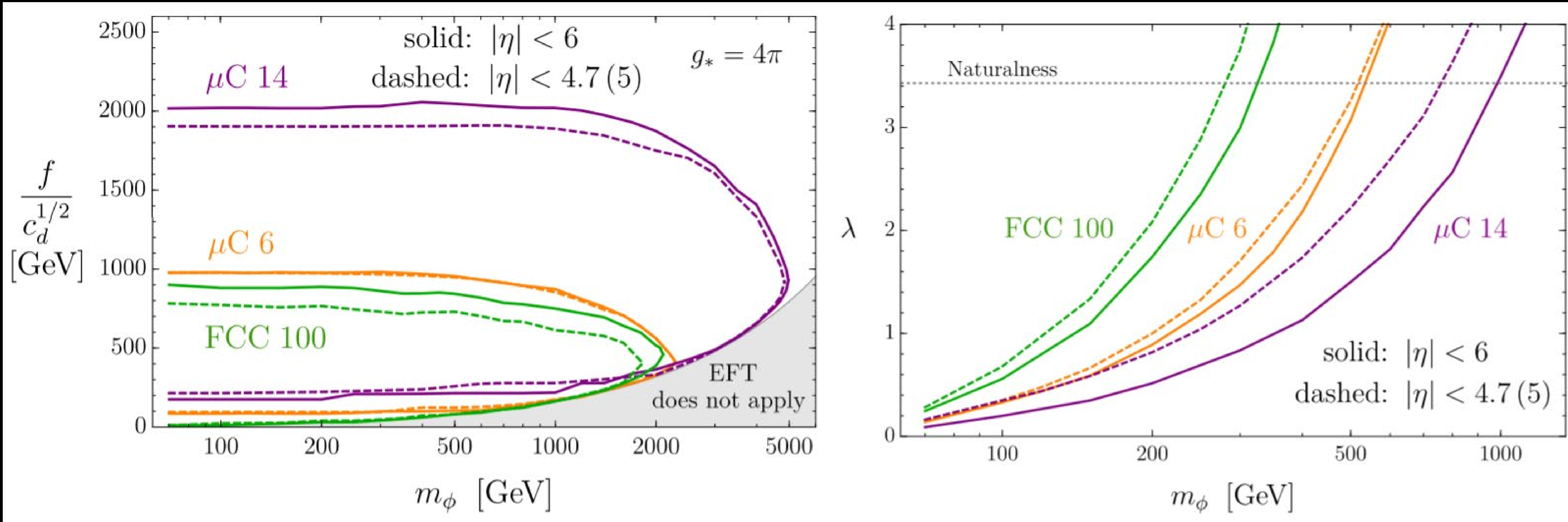




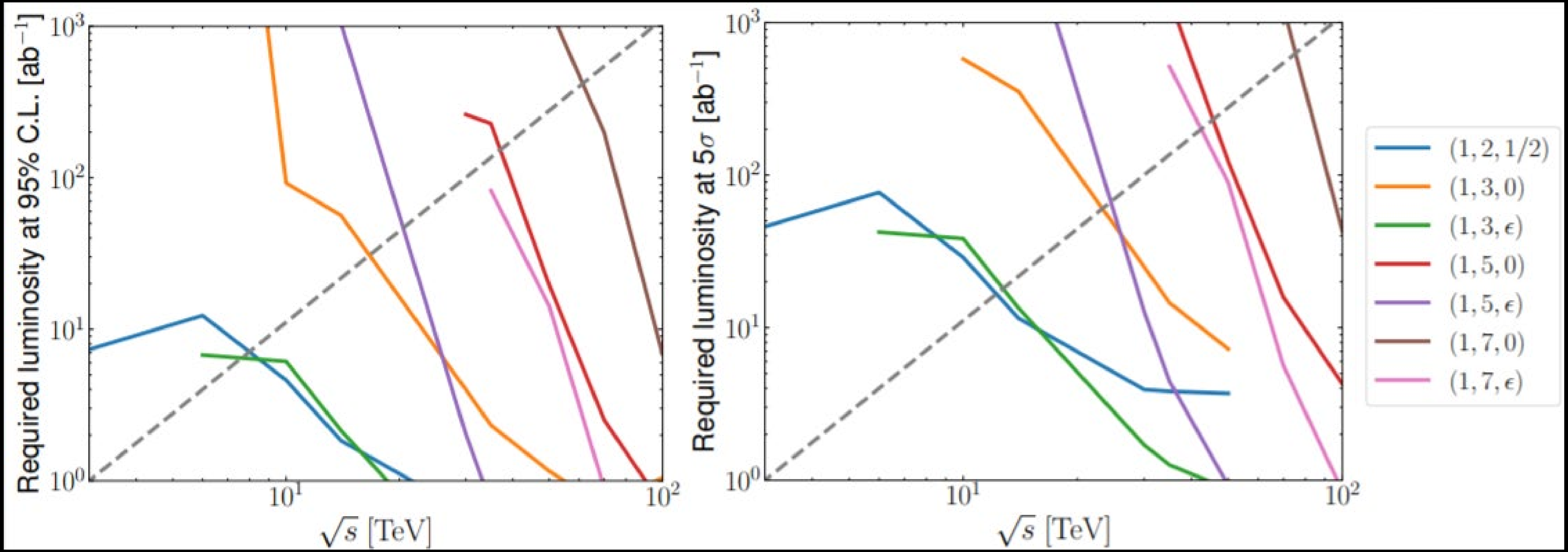

Mono-muon
$\sqrt{s} = 14$ TeV
Required luminosity at 95% C.L. [ab^{-1}]
m_χ [TeV]
(1, 2, 1/2)
(1, 3, ϵ)
(1, 5, ϵ)
(1, 7, ϵ)
Mono-photon
$\sqrt{s} = 14$ TeV
Required luminosity at 95% C.L. [ab^{-1}]
m_χ [TeV]
(1, 2, 1/2)
(1, 3, ϵ)
(1, 5, ϵ)
(1, 7, ϵ)


Required luminosity at 95% C.L. [ab^{-1}]
m_χ [TeV]
$\sqrt{s}$ = 14 TeV
$\sqrt{s}$ = 30 TeV
$\sqrt{s}$ = 100 TeV
(1, 2, 1/2)
(1, 3, ϵ)
(1, 5, ϵ)
(1, 7, ϵ)

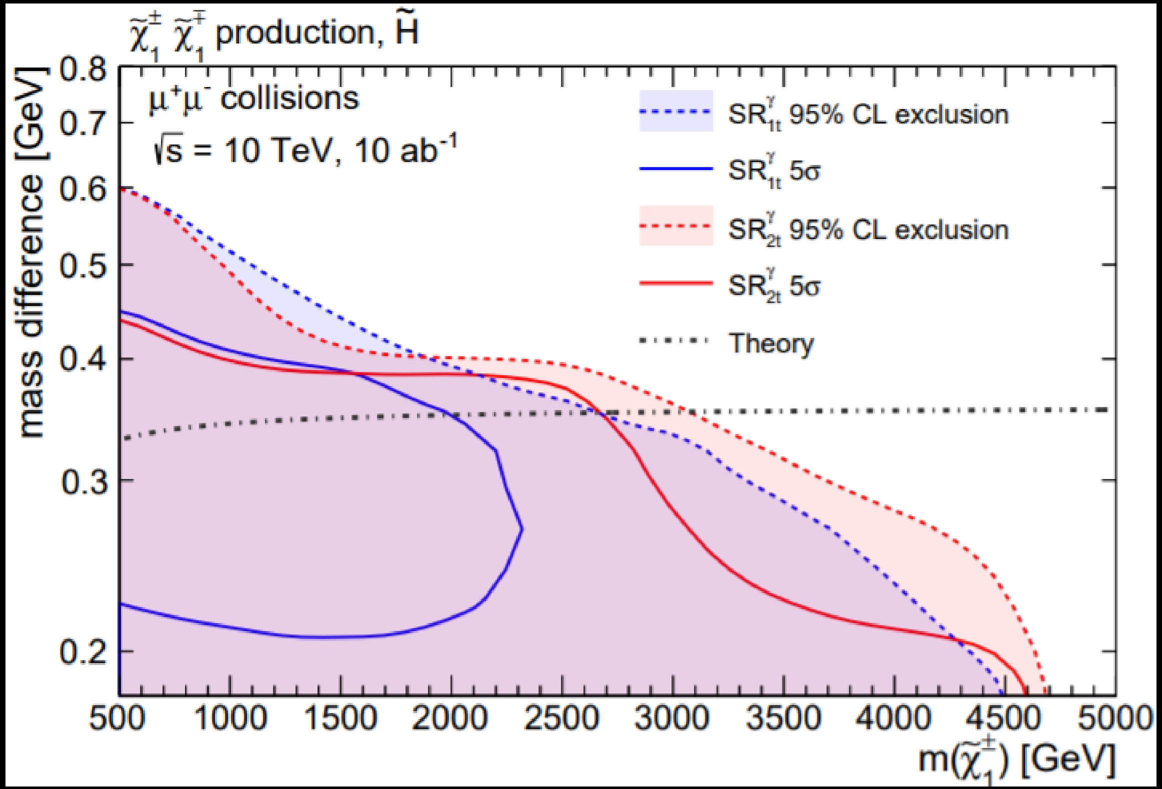

Required luminosity at 95% C.L. [ab^{-1}]
m_χ [TeV]
$\sqrt{s}$ = 3 TeV
$\sqrt{s}$ = 6 TeV
$\sqrt{s}$ = 10 TeV
(1, 2, 1/2)
(1, 3, ϵ)
(1, 5, ϵ)
(1, 7, ϵ)



Ruhdorfer, Salvioni, Weiler, 1910.04170



Required luminosity at 95% C.L. [ab^{-1}]
Required luminosity at 5σ [ab^{-1}]
$\sqrt{s}$ [TeV]
$\sqrt{s}$ [TeV]
10^0
10^1
10^2
10^3
$(1,2,1/2)$
$(1,3,0)$
$(1,3,\epsilon)$
$(1,5,0)$
$(1,5,\epsilon)$
$(1,7,0)$
$(1,7,\epsilon)$



See also Capdevilla, Meloni, Simoniello, Zurita, 2102.11292

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

	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	201 ± 5	199 ± 4
$\tilde{H}$, 1.1 TeV, $\tau = 0.03$ ns	250 ± 4	171.5 ± 2.1