Accidental Dark Matter

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Luca Di Luzio

UNIVERSITÀ DI PISA

INFN

Outline

1. Physics case for new EW multiplets
    - minimal (millicharged) DM
    - accidental matter
2. Indirect probes of new EW multiplets
    - theoretical framework
    - analysis
    - projections @ CLIC & other future colliders

Based on:
LDL, Gröber, Panico - JHEP 1901 (2019) 011 [1810.10993]
de Blas et al - The CLIC Potential for New Physics [1812.02093]

EW matter: who ordered that ?

- BSM frameworks often predict new, light* EW states $\chi \sim (1, n, y)$ [fermion/scalar]

* [100 GeV, few TeV] potential target for (lepton) colliders / no QCD production

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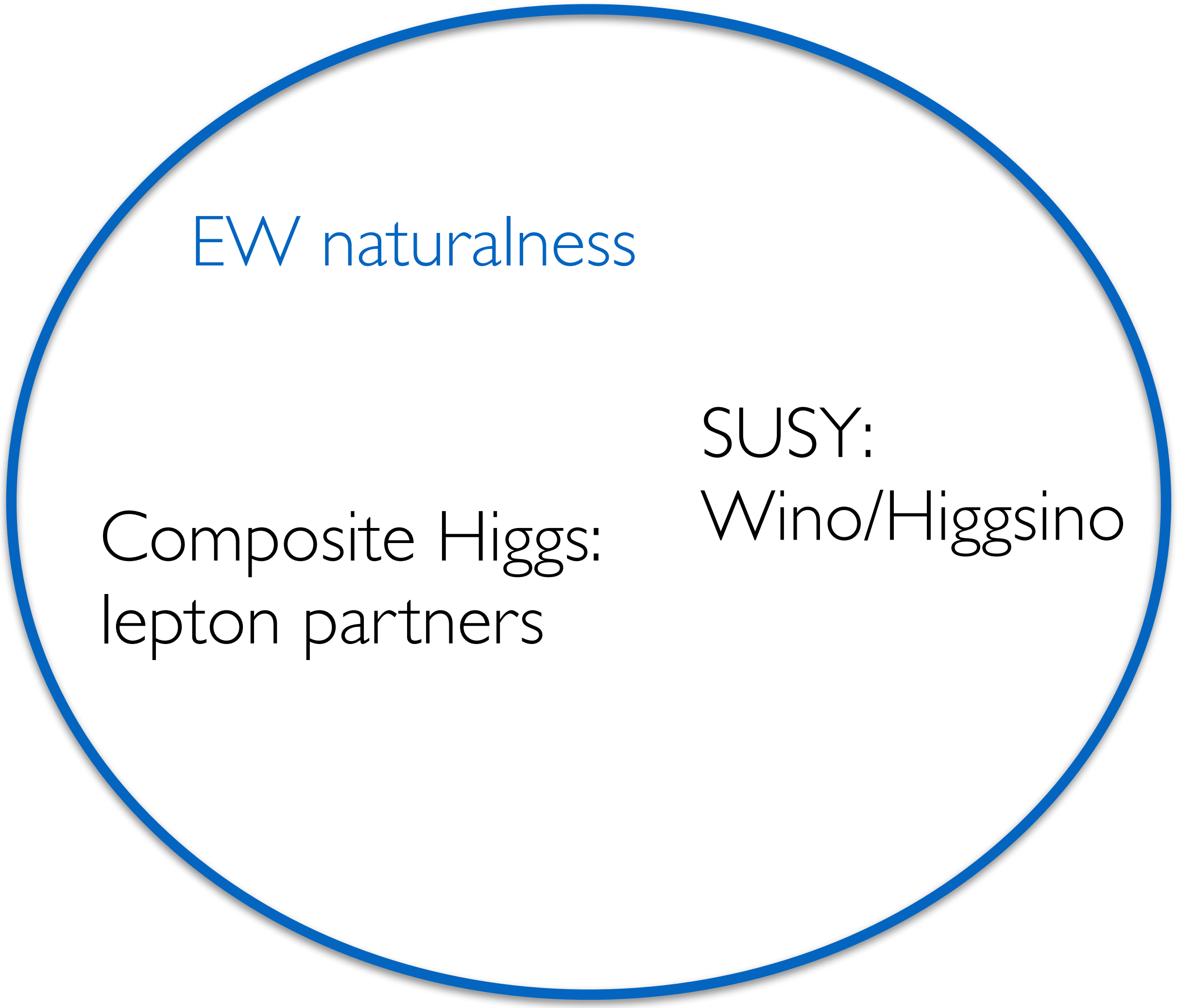

EW naturalness

SUSY:
Wino/Higgsino

Composite Higgs:
lepton partners

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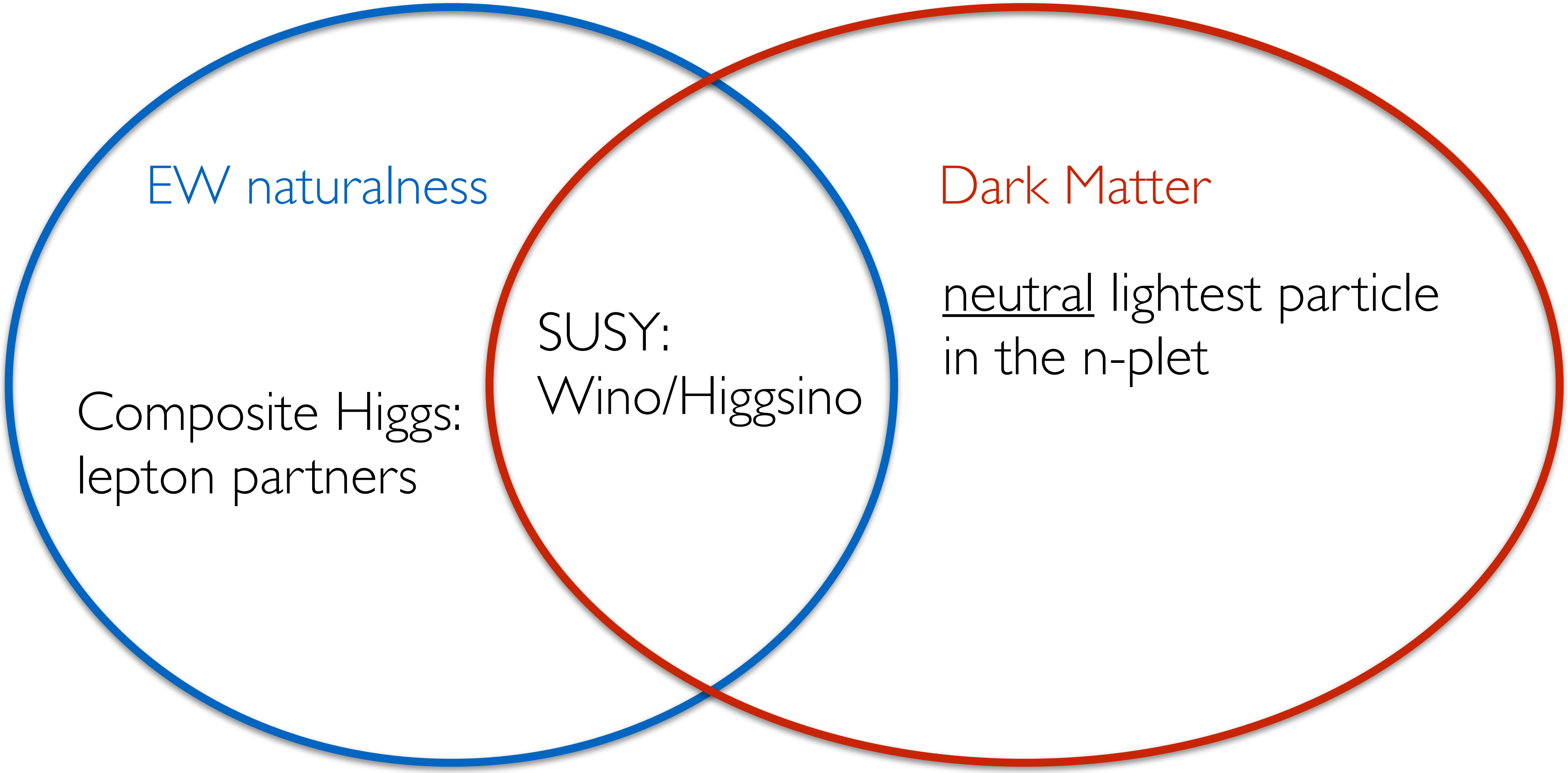

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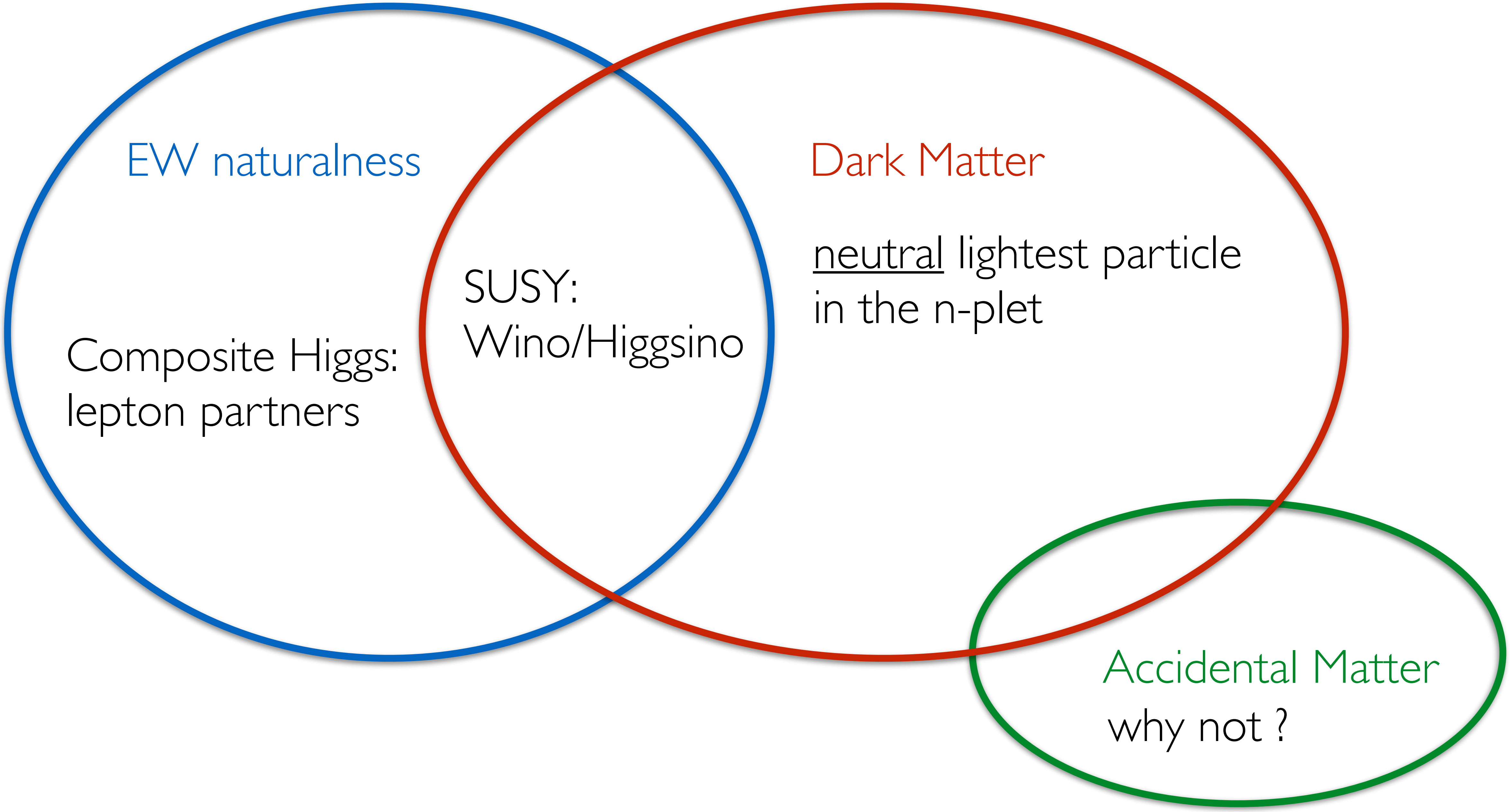

EW naturalness

Composite Higgs:
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Dark Matter

<u>neutral</u> lightest particle
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Accidental Matter
why not ?

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Minimal Dark Matter

- Criteria $\chi \sim (1, n, y)$ [Cirelli, Fornengo, Strumia, hep-ph/0512090, …]

1. $y = 0$ to avoid tree-level Z exchange in DM direct detection
2. Lightest particle in the n-plet is neutral
3. n such that no $\chi \, \mathrm{SM} \, \mathrm{SM}$ interactions at the ren. level (χ accidentally stable)
4. No Landau poles < Planck

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4. No Landau poles < Planck → n < 7 (9) for χ a Majorana fermion (real scalar)

→ 2. and 3. <u>automatically</u> satisfied if n > 3 and χ a fermion (scalars more model dep.)

$$\Delta m_{\text{rad}} = m_{Q+1} - m_Q \approx 166 \text{ MeV} \left(1 + 2Q + \frac{2y}{\cos\theta_W} \right)$$

(radiative mass splitting)

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- Remarkably, only one possibility*

n = 5 Majorana fermion with $m_\chi \simeq 14\ \mathrm{TeV}$ [DM mass fixed by SM gauge interactions]

[*real scalar 7-plet ruled out in LDL, Gröber, Kamenik, Nardecchia, 1504.00359]

Minimal Dark Matter

- Bound state effects <u>crucial</u> for n > 3

[Mitridate, Redi, Smirnov, Strumia, 1702.01141]

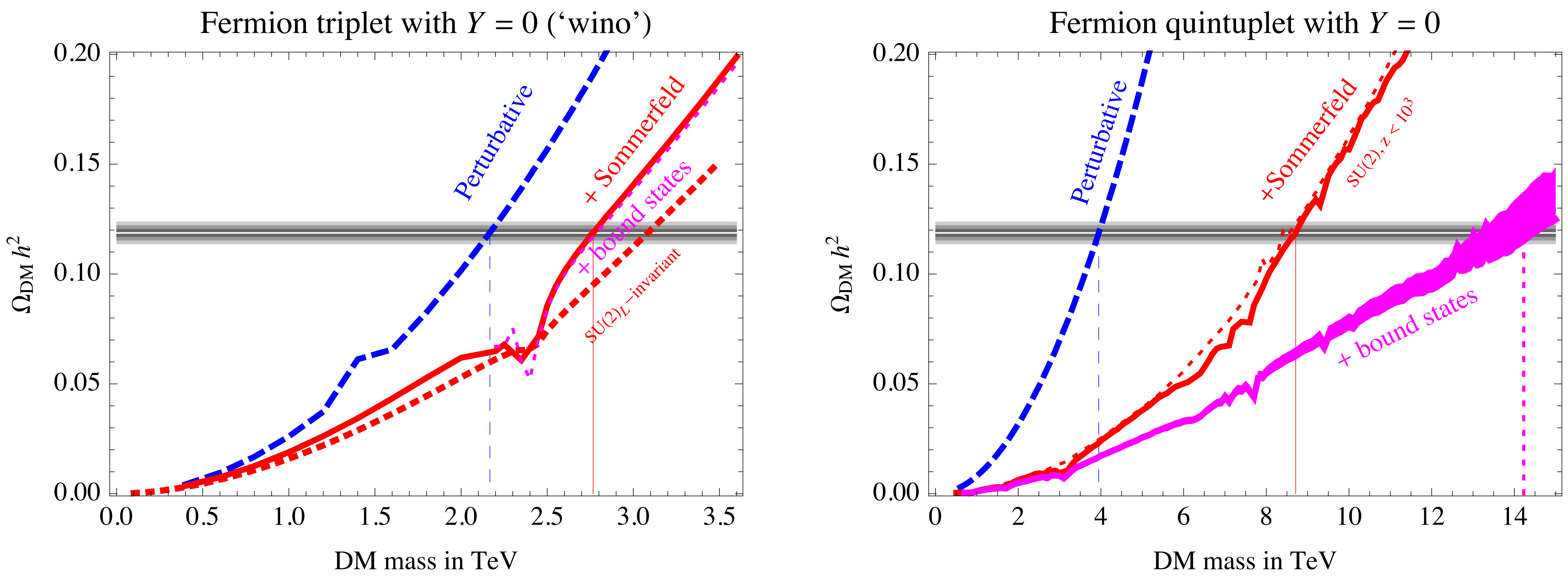


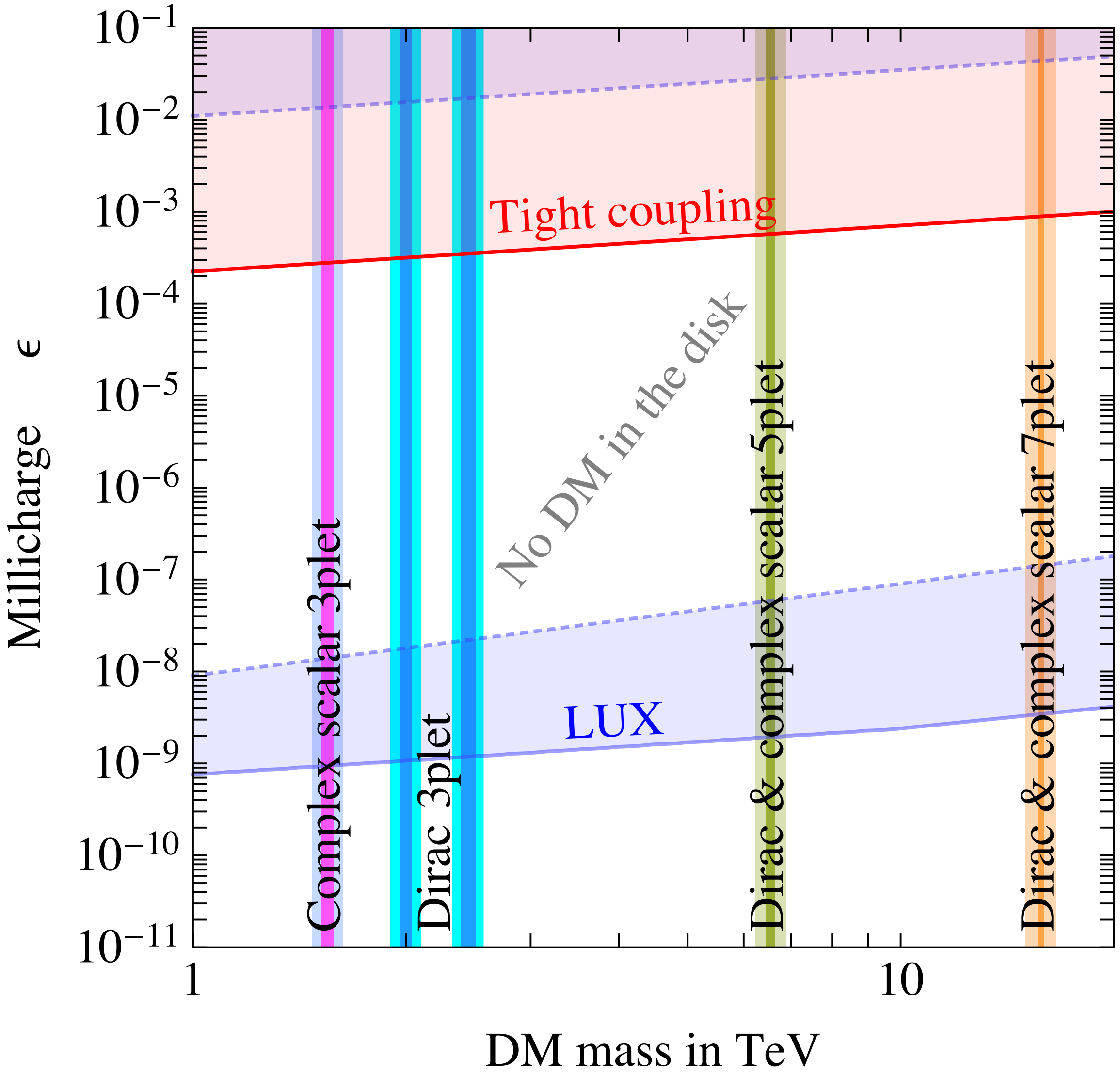
Figure 5: *Thermal relic DM abundance computed taking into account tree-level scatterings (blue curve), adding Sommerfeld corrections (red curve), and adding bound state formation (magenta). We consider DM as a fermion* $\mathrm{SU}(2)_L$ *triplet (left panel) and as a fermion quintuplet (right panel). In the first case the* $\mathrm{SU}(2)_L$*-invariant approximation is not good, but it's enough to show that bound states have a negligible impact. In the latter case the* $\mathrm{SU}(2)_L$*-invariant approximation is reasonably good, and adding bound states has a sizeable effect.*

Minimal (Millicharged) Dark Matter

- A millicharge stabilizes (exactly) the DM: $\chi \sim (1, n, \epsilon)$

- n = 3, 5, 7, … thermal production via gauge interactions (and suppressed Z couplings)

[Del Nobile, Nardecchia, Panci 1512.05353]



→ ϵ bears no effects at colliders

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  - n = 3, 5, 7, … thermal production via gauge interactions (and suppressed Z couplings)

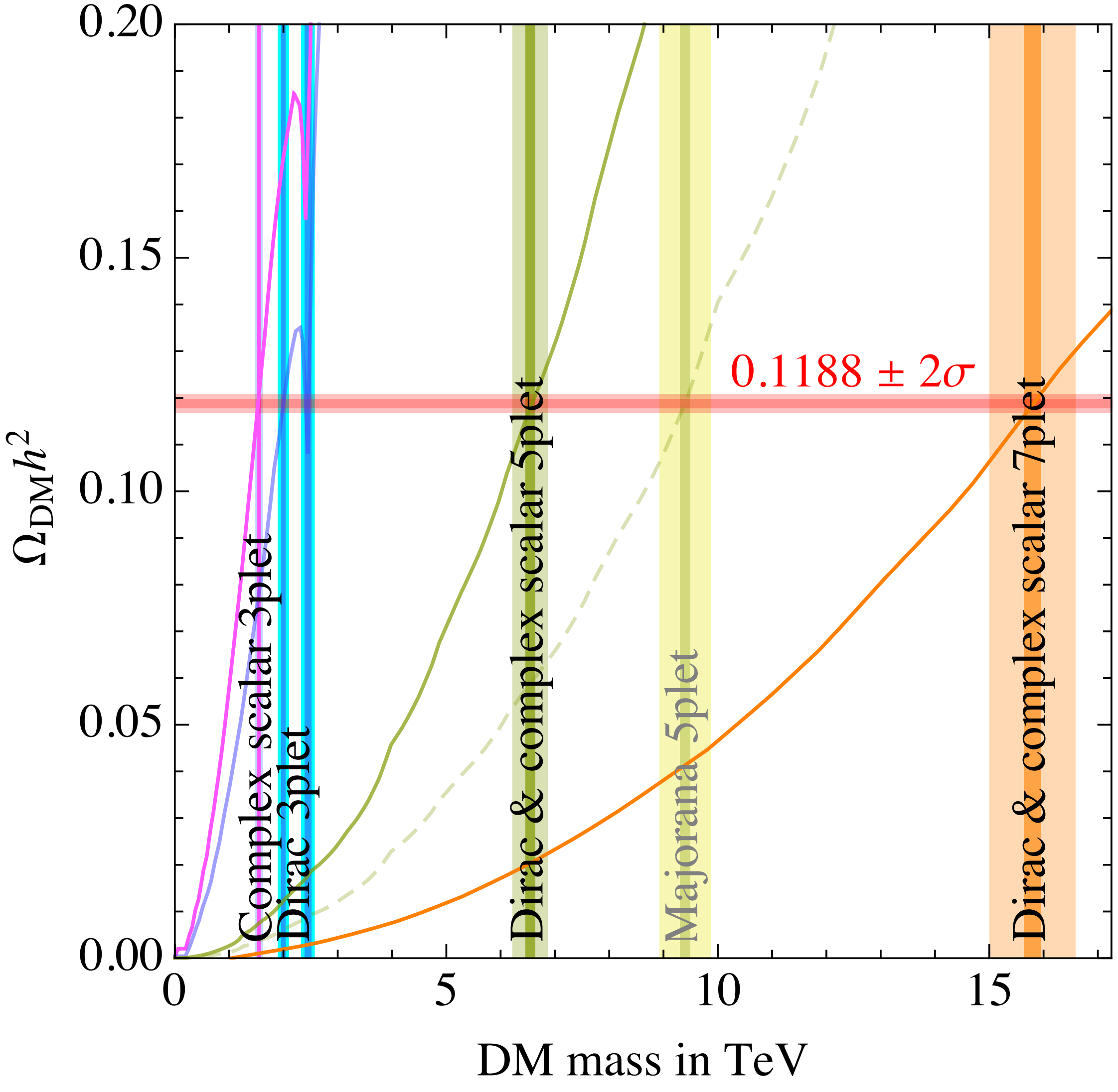
  - mass fixed by relic density

χ / m_χ [TeV]	DM
$(1,2,1/2)^{*}_{\rm DF}$	1.1
$(1,3,\epsilon)_{\rm CS}$	1.6
$(1,3,\epsilon)_{\rm DF}$	2.0
$(1,3,0)^{**}_{\rm MF}$	2.8
$(1,5,\epsilon)_{\rm CS}$	6.6
$(1,5,\epsilon)_{\rm DF}$	6.6
$(1,5,0)^{***}_{\rm MF}$	14
$(1,7,\epsilon)_{\rm CS}$	16
$(1,7,\epsilon)_{\rm DF}$	16

RS = Real Scalar
CS = Complex Scalar
MF = Majorana Fermion
DF = Dirac Fermion

* Higgsino DM
** Wino DM
*** Minimal DM

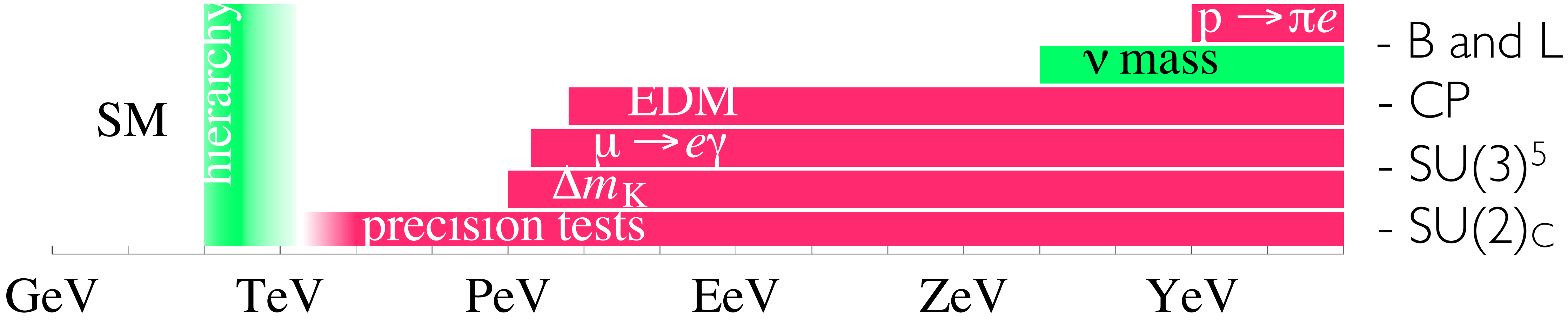
[Del Nobile, Nardecchia, Panci 1512.05353]



Accidental Matter

- Exotic EW multiplets also motivated by the following phenomenological argument:

they automatically preserve the accidental (B, L) and approximate (flavour, etc.) symmetry structure of the SM, and are hence screened from low-energy indirect probes



- B and L
- CP
- $SU(3)^5$
- $SU(2)_C$

Accidental Matter

- Exotic EW multiplets also motivated by the following phenomenological argument:

they ***automatically*** *preserve the accidental (B, L) and approximate (flavour, etc.) symmetry structure of the SM, and are hence screened from low-energy indirect probes*

[LDL, Gröber, Kamenik, Nardecchia, 1504.00359]

Spin	χ	$Q_{\rm LP}$	$\mathcal{O}_{\rm decay}$	$\dim(\mathcal{O}_{\rm decay})$	$\Lambda^{2-\rm loop}_{\rm Landau}\,[\rm GeV]$
0	$(1,1,0)$	0	$\chi H H^\dagger$	3	$\gg m_{\rm Pl}\ (g_1)$
0	$(1,3,0)^\ddagger$	0,1	$\chi H H^\dagger$	3	$\gg m_{\rm Pl}\ (g_1)$
0	$(1,4,1/2)^\ddagger$	-1,0,1,2	$\chi H H^\dagger H^\dagger$	4	$\gg m_{\rm Pl}\ (g_1)$
0	$(1,4,3/2)^\ddagger$	0,1,2,3	$\chi H^\dagger H^\dagger H^\dagger$	4	$\gg m_{\rm Pl}\ (g_1)$
0	$(1,2,3/2)$	1,2	$\chi H^\dagger \ell\ell,\ \chi^\dagger H^\dagger e^c e^c,\ D^\mu \chi^\dagger \ell^\dagger \overline{\sigma}_\mu e^c$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(1,2,5/2)$	2,3	$\chi^\dagger H e^c e^c$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(1,5,0)$	0,1,2	$\chi H H H^\dagger H^\dagger,\ \chi W^{\mu\nu} W_{\mu\nu},\ \chi^3 H^\dagger H$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(1,5,1)$	-1,0,1,2,3	$\chi^\dagger H H H H^\dagger,\ \chi\chi\chi^\dagger H^\dagger H^\dagger$	5	$\gg m_{\rm Pl}\ (g_1)$
0	$(1,5,2)$	0,1,2,3,4	$\chi^\dagger H H H H$	5	$3.5 \times 10^{18}\ (g_1)$
0	$(1,7,0)^\star$	0,1,2,3	$\chi^3 H^\dagger H$	5	$1.4 \times 10^{16}\ (g_2)$
1/2	$(1,4,1/2)$	-1	$\chi^c \ell H H,\ \chi \ell H^\dagger H,\ \chi \sigma^{\mu\nu} \ell W_{\mu\nu}$	5	$8.1 \times 10^{18}\ (g_2)$
1/2	$(1,4,3/2)$	0	$\chi \ell H^\dagger H^\dagger$	5	$2.7 \times 10^{15}\ (g_1)$
1/2	$(1,5,0)$	0	$\chi \ell H H H^\dagger,\ \chi \sigma^{\mu\nu} \ell H W_{\mu\nu}$	6	$8.3 \times 10^{17}\ (g_2)$

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- Particularly challenging if the lightest particle in the n-plet is neutral !

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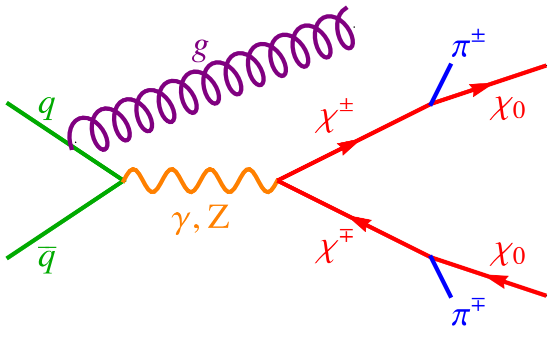
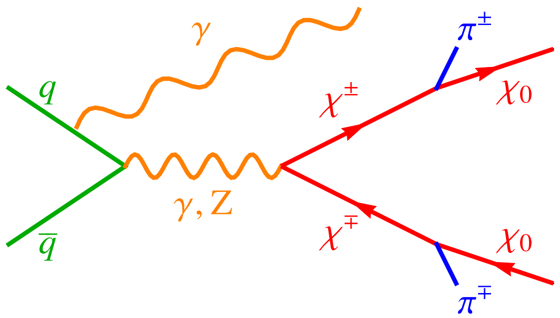
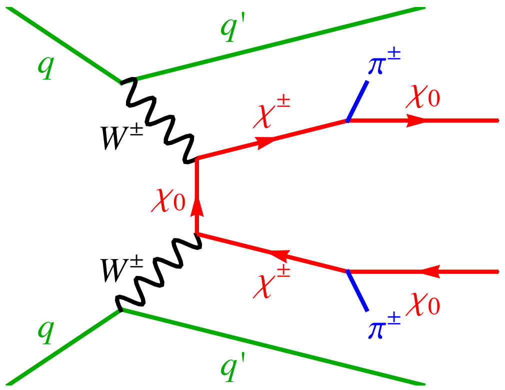
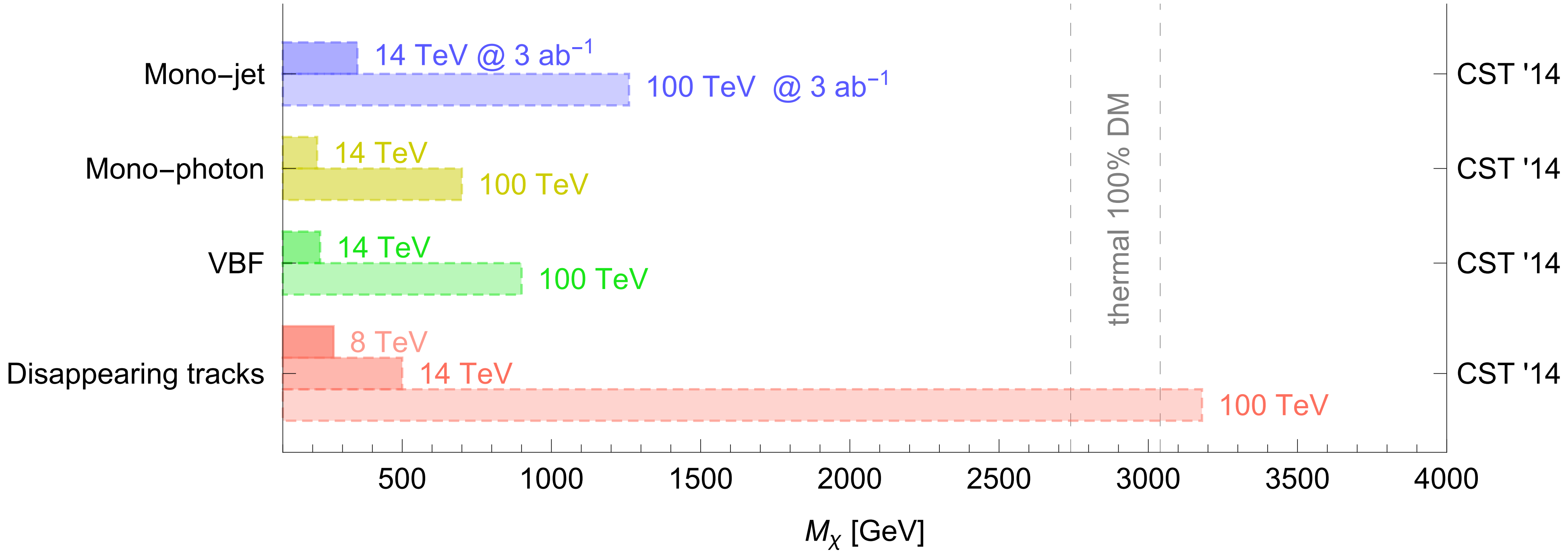
  - Hadron colliders: Mono-x searches + VBF + disappearing tracks







[For "Wino-like DM" see e.g. Cirelli, Sala, Taoso 1407.7058 - DT updates in 1703.05327, 1703.09675, 1812.07831]



Direct searches

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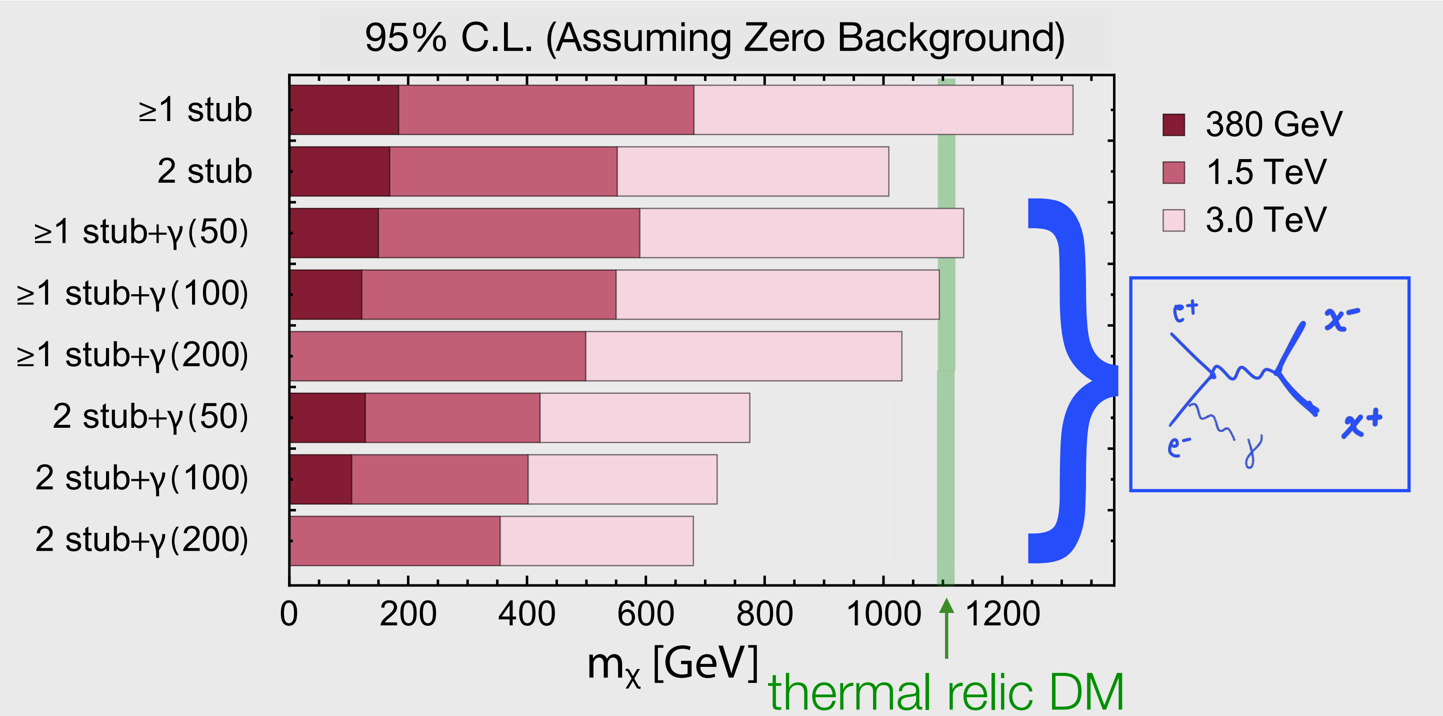

[1812.02093]

[See also talk by R. Franceschini yesterday]

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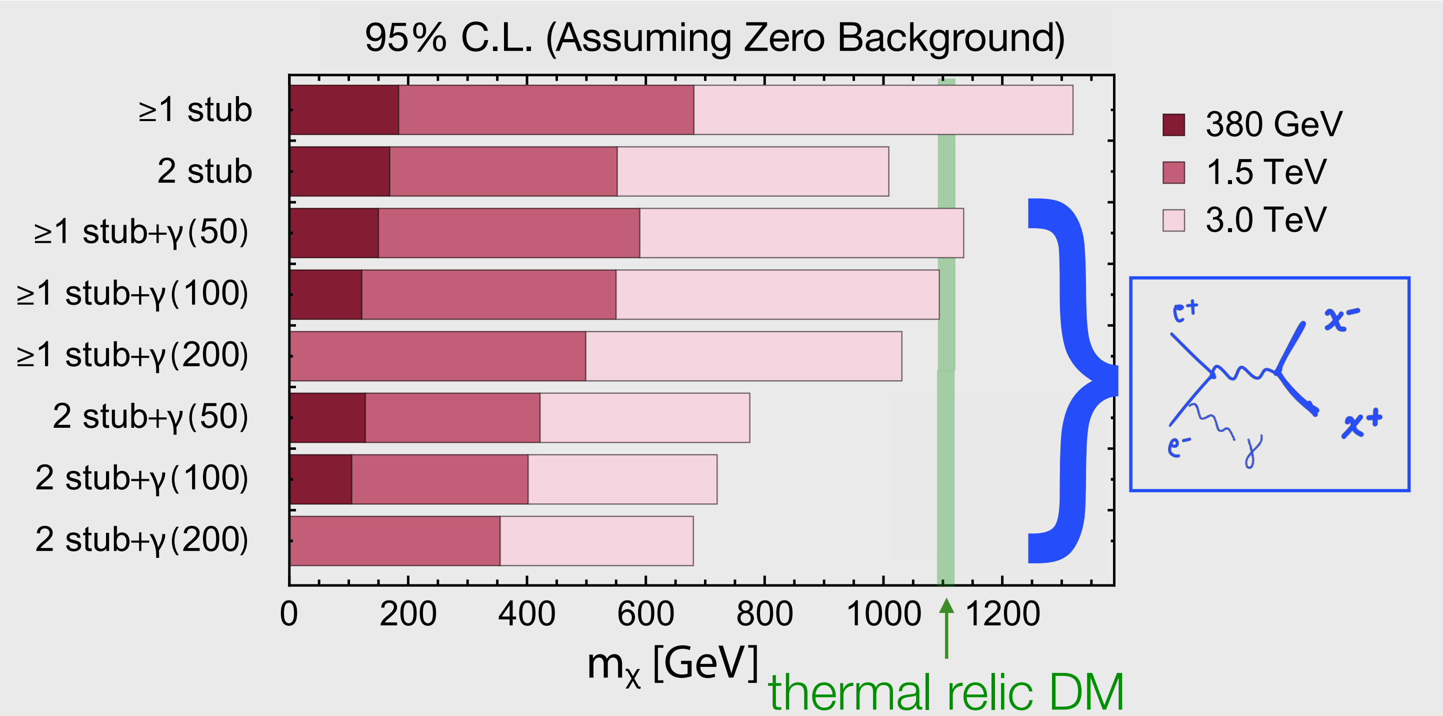

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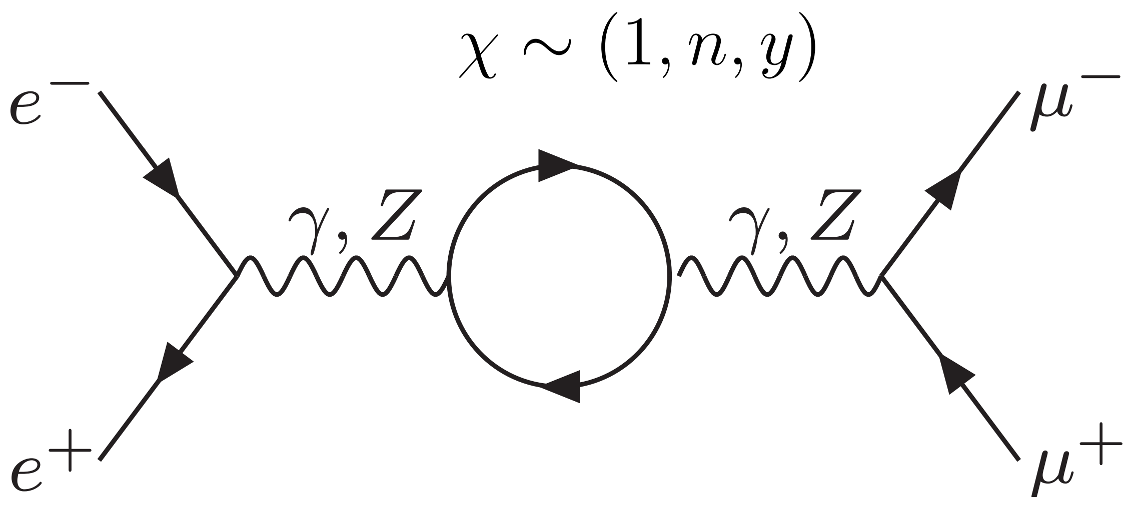
kinematically inaccessible for CLIC direct searches

Indirect probes of new EW states

- Universal corrections to 2 → 2 fermion scattering

[See also Harigaya et al, 1504.03402
Matsumoto et al 1711.05449]



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- Parametrized in terms of EW form factors*

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{g^2 C^{\text{eff}}_{WW}}{8} W^a_{\mu\nu} \Pi(-D^2/m^2_\chi) W^{a\mu\nu} + \frac{g'^2 C^{\text{eff}}_{BB}}{8} B_{\mu\nu} \Pi(-\partial^2/m^2_\chi) B^{\mu\nu}$$

$C^{\text{eff}}_{WW} = \kappa(n^3 - n)/6$ $\kappa = 1/2, 1, 4, 8$ [RS, CS, MF, DF]

$C^{\text{eff}}_{BB} = 2\kappa n y^2$

---

* we neglect mass splitting within the n-plet [ok for n > 3 fermions, not necessarily a good approx for light scalars]

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- Heavy new physics $\sqrt{s} \ll m_\chi$ (EFT limit)

$$\Pi\left(\frac{s}{m^2_\chi}\right) \simeq -\frac{1}{480\pi^2} \frac{s}{m^2_\chi} \quad \longrightarrow \quad S = T = U = 0$$

$$W = \frac{g^2 C^{\text{eff}}_{WW}}{960\pi^2} \frac{m^2_W}{m^2_\chi} \qquad Y = \frac{g'^2 C^{\text{eff}}_{BB}}{960\pi^2} \frac{m^2_W}{m^2_\chi}$$

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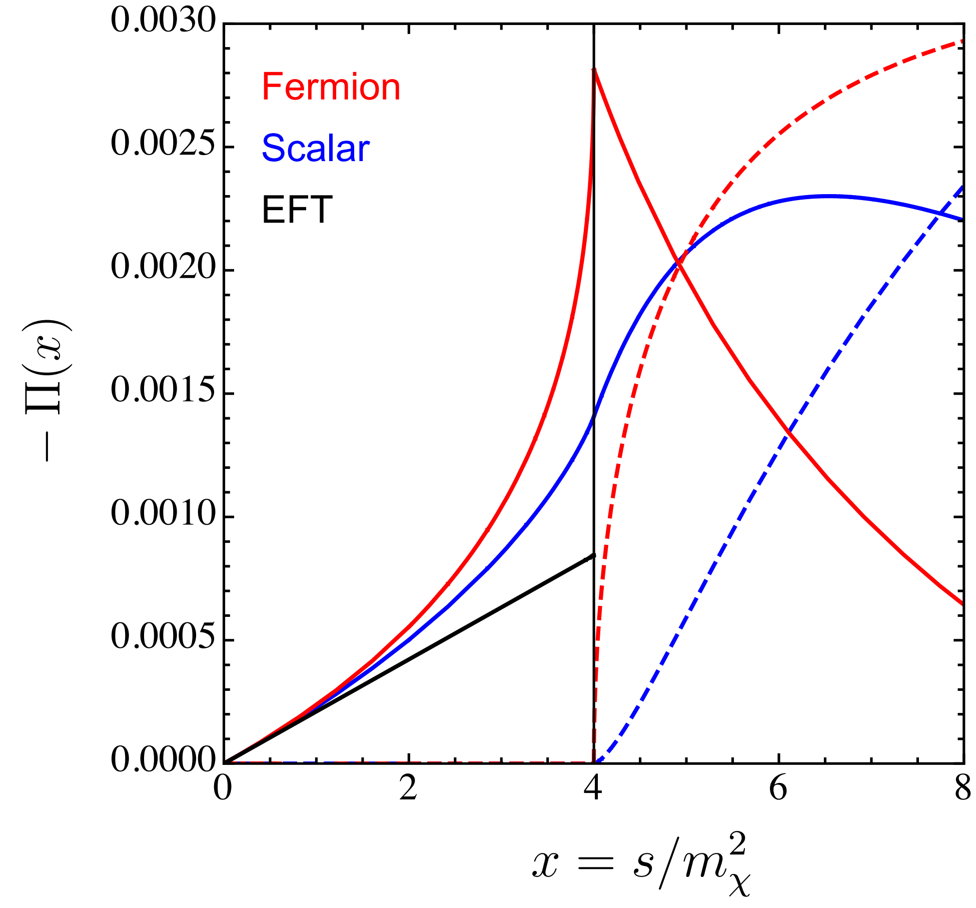
- Full kinematical dependence

$$\Pi(x) = \begin{cases} -\dfrac{8(x-3)+3x\left(\frac{x-4}{x}\right)^{3/2}\log\left(\frac{1}{2}\left(\left(\sqrt{\frac{x-4}{x}}-1\right)x+2\right)\right)}{144\pi^2 x} & \text{(F)} \\ -\dfrac{12+5x+3\sqrt{\frac{x-4}{x}}(x+2)\log\left(\frac{1}{2}\left(\left(\sqrt{\frac{x-4}{x}}-1\right)x+2\right)\right)}{288\pi^2 x} & \text{(S)} \end{cases}$$



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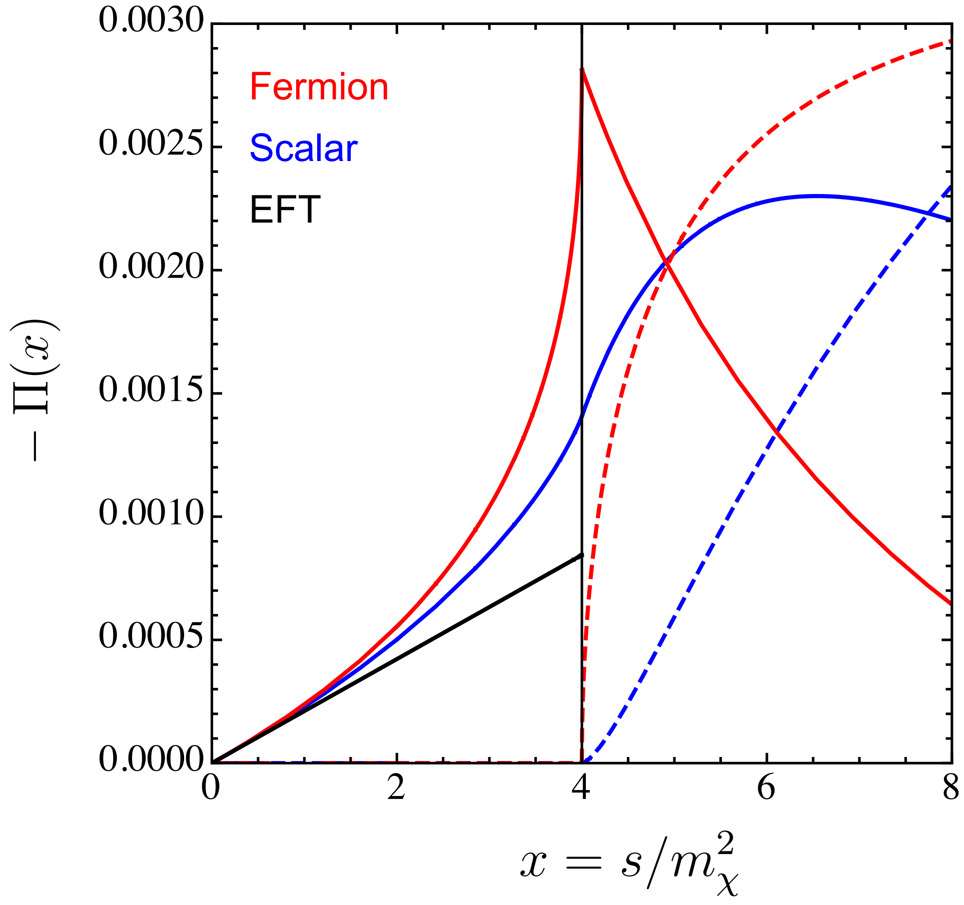
momentum dependence relevant also below threshold for pair production !



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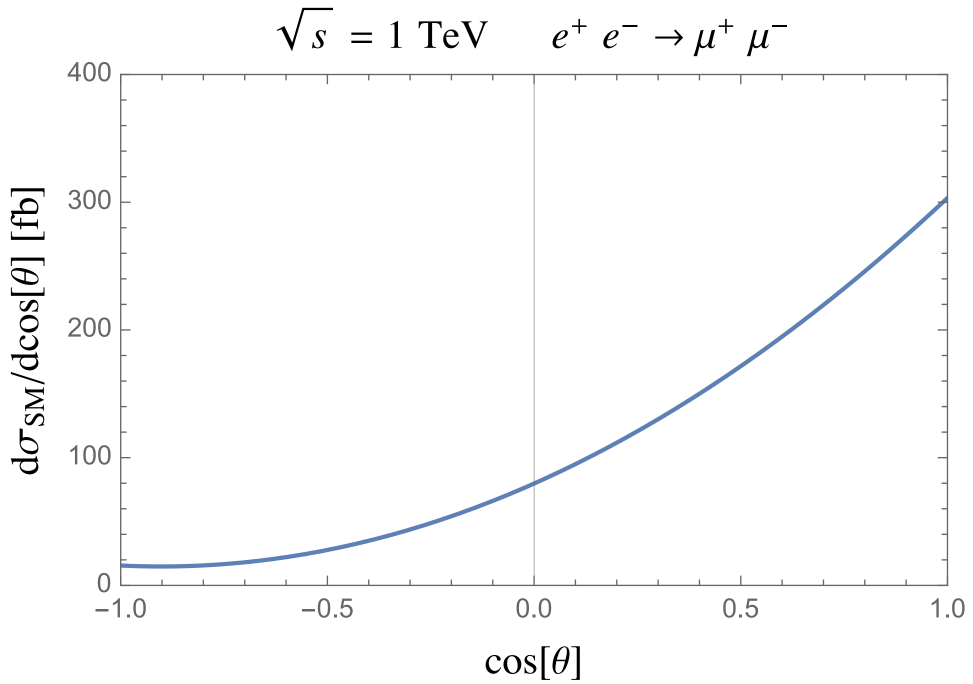
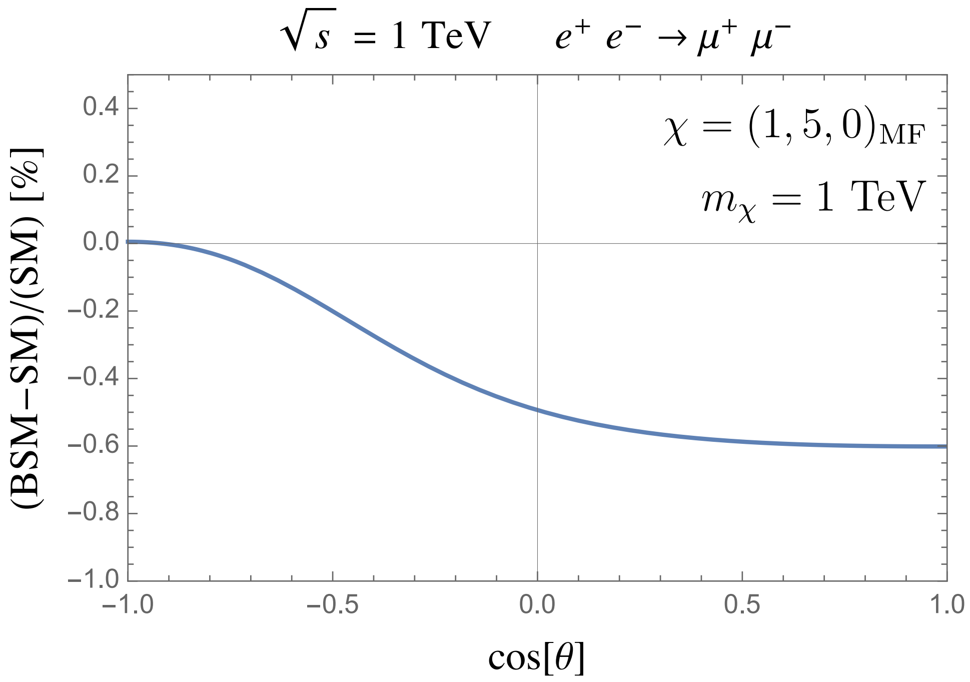
Angular distributions

- Binned likelihood analysis of $e^+e^- \to f\overline{f}$ as a function of $\cos\theta$





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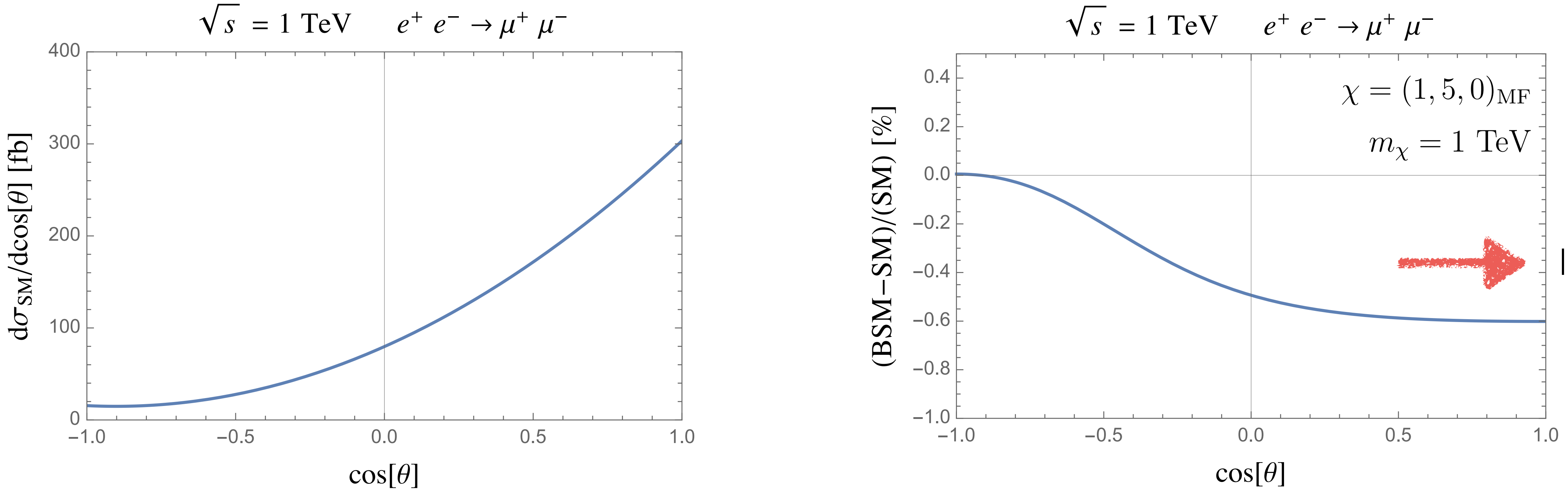

1% BSM effect

$$\frac{\sigma_{\rm BSM} - \sigma_{\rm SM}}{\sigma_{\rm SM}} \simeq \mathrm{Re}\left[\frac{2\,\mathcal{M}_{\rm NLO}}{\mathcal{M}_{\rm LO}}\right] \simeq \frac{\kappa\, g^2 (n^3 - n)}{6}\Pi(1) \simeq -0.68\ \%$$

Angular distributions

- Binned likelihood analysis of $e^+e^- \to f\bar{f}$ as a function of $\cos\theta$

- Details of the analysis

  - $\cos\theta \in [-0.95, 0.95]$ in 10 uniform intervals

  - consider $f = e,\ \mu,\ b,\ c$ final states with detection efficiencies $\varepsilon[e, \mu, b, c] = [1, 1, 0.8, 0.5]$

$$\chi^2 = \sum_{i=1}^{10} \frac{\left(N_i^{\text{SM+BSM}} - N_i^{\text{SM}}\right)^2}{\underbrace{N_i^{\text{SM}}}_{\text{statistical error}} + \underbrace{\left(\epsilon_i N_i^{\text{SM}}\right)^2}_{\text{systematic error}}}$$

  - assume some c.o.m. energy, luminosity, beam polarization [see later]

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  - assume some c.o.m. energy, luminosity, beam polarization [see later]

→ set 95% CL bound on m_χ for $\chi^2 = 3.84$ (1 d.o.f.)

Role of beam polarization

- Cross-section of an e^+e^- polarized beam

$$\sigma_{P_{e^-}P_{e^+}} = \frac{1}{4}\left[(1+P_{e^-})(1+P_{e^+})\sigma_{RR} + (1-P_{e^-})(1-P_{e^+})\sigma_{LL} \right.$$
$$\left. + (1+P_{e^-})(1-P_{e^+})\sigma_{RL} + (1-P_{e^-})(1+P_{e^+})\sigma_{LR}\right]$$

- Higgs program at CLIC prefers $P_{e^-} = -80\%$

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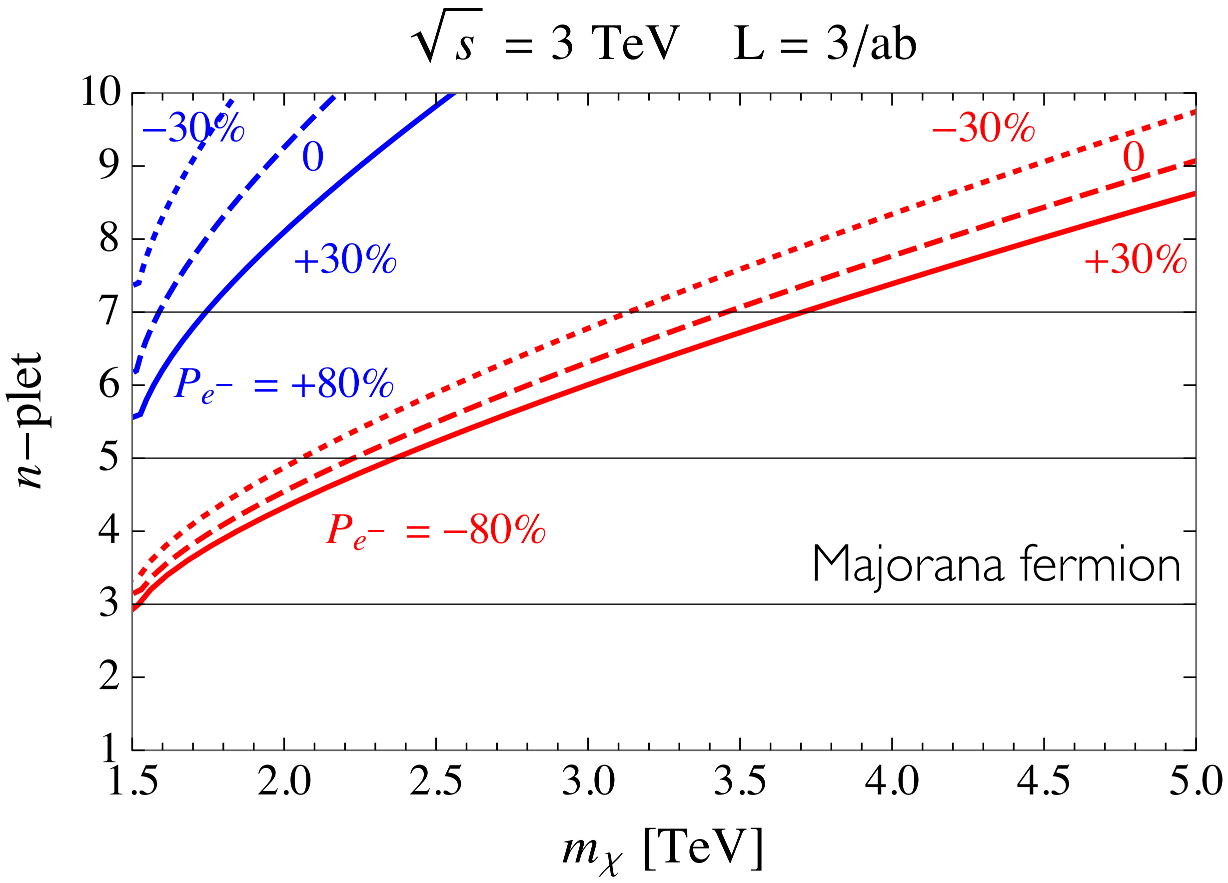

LH e^- polarization beneficial !
(mainly because of higher x-section)

RH e^+ polarization would help a bit
(but not crucial)

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- Two energy benchmarks with $P_{e^-} = -80\%$ (nominal luminosities rescaled by 4/5)

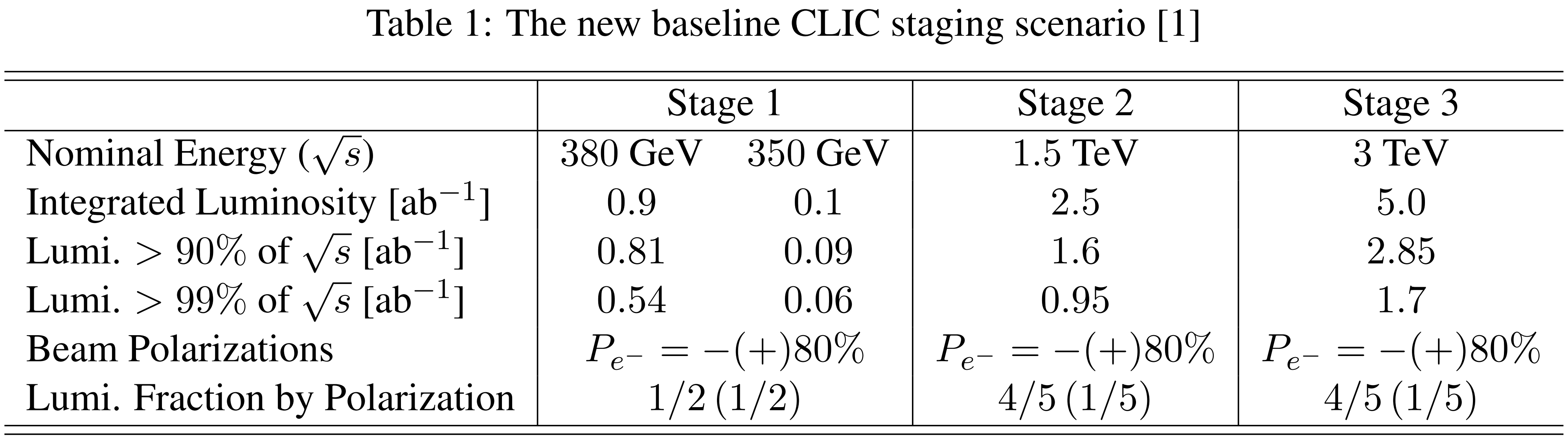


Table 1: The new baseline CLIC staging scenario [1]

	Stage 1		Stage 2	Stage 3
Nominal Energy ($\sqrt{s}$)	380 GeV	350 GeV	1.5 TeV	3 TeV
Integrated Luminosity [ab^{-1}]	0.9	0.1	2.5	5.0
Lumi. $>90\%$ of $\sqrt{s}$ [ab^{-1}]	0.81	0.09	1.6	2.85
Lumi. $>99\%$ of $\sqrt{s}$ [ab^{-1}]	0.54	0.06	0.95	1.7
Beam Polarizations	$P_{e^-} = -(+)80\%$		$P_{e^-} = -(+)80\%$	$P_{e^-} = -(+)80\%$
Lumi. Fraction by Polarization	$1/2\,(1/2)$		$4/5\,(1/5)$	$4/5\,(1/5)$

[See Robson, Roloff 1812.01644]

Projections @ CLIC

[LDL, Gröber, Panico 1810.10993, 1812.02093]

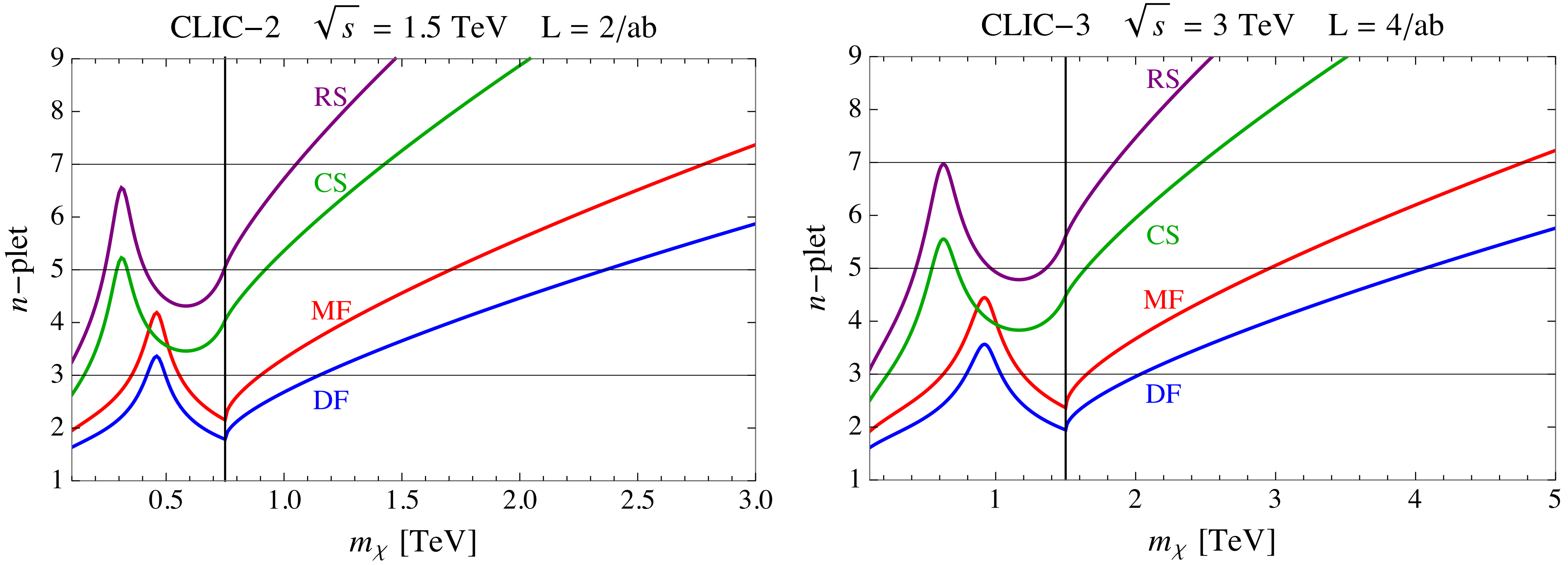
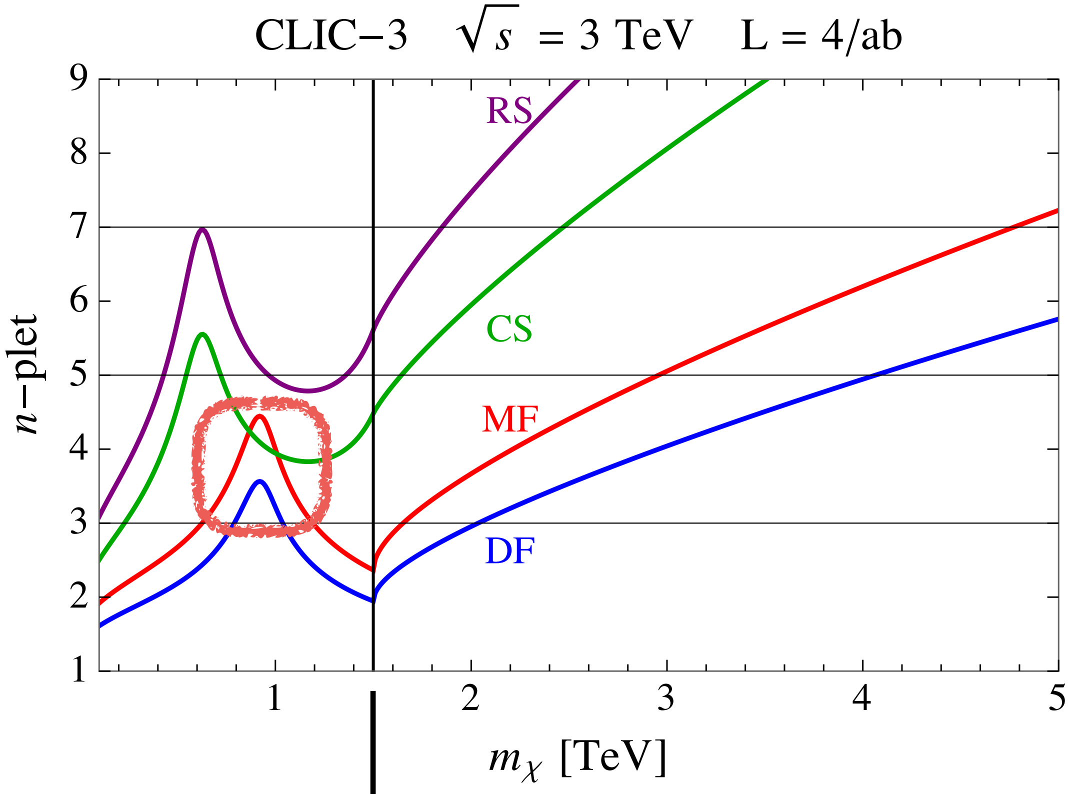


Figure 1: 95% CL exclusion limits for CLIC-2 (left panel) and CLIC-3 (right panel), obtained by combining the $e/\mu/b/c$ channels with 0.3% systematic error and polarization fractions $P_{e^-} = -80\%$ and $P_{e^+} = 0$.

Projections @ CLIC

where does the dip in sensitivity come from ?

[LDL, Gröber, Panico 1810.10993, 1812.02093]



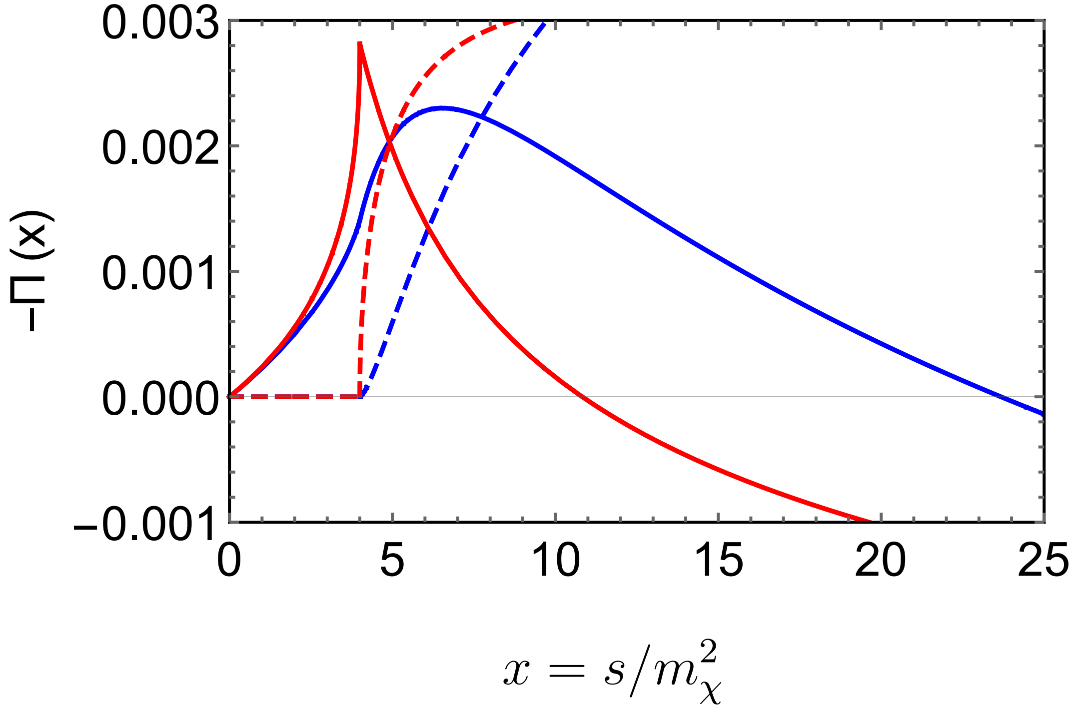
$x = s/m_\chi^2 = 4$ [threshold for pair-production]

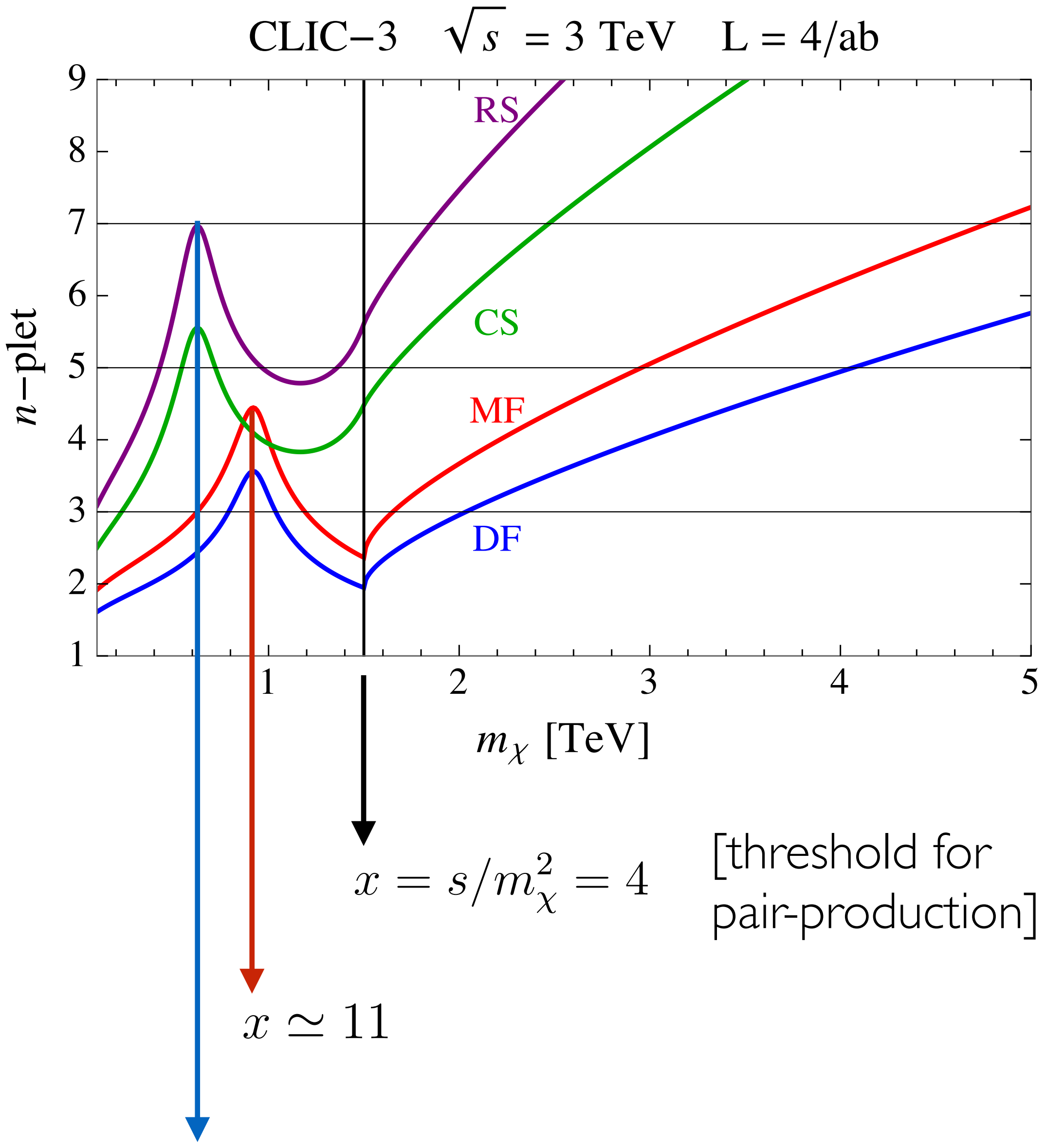
Projections @ CLIC

where does the dip in sensitivity come from ?

[LDL, Gröber, Panico 1810.10993, 1812.02093]

$$\frac{\sigma_{\rm BSM} - \sigma_{\rm SM}}{\sigma_{\rm SM}} \simeq \text{Re}\left[\frac{2\,\mathcal{M}_{\rm NLO}}{\mathcal{M}_{\rm LO}}\right]$$





$x = s/m_\chi^2 = 4$

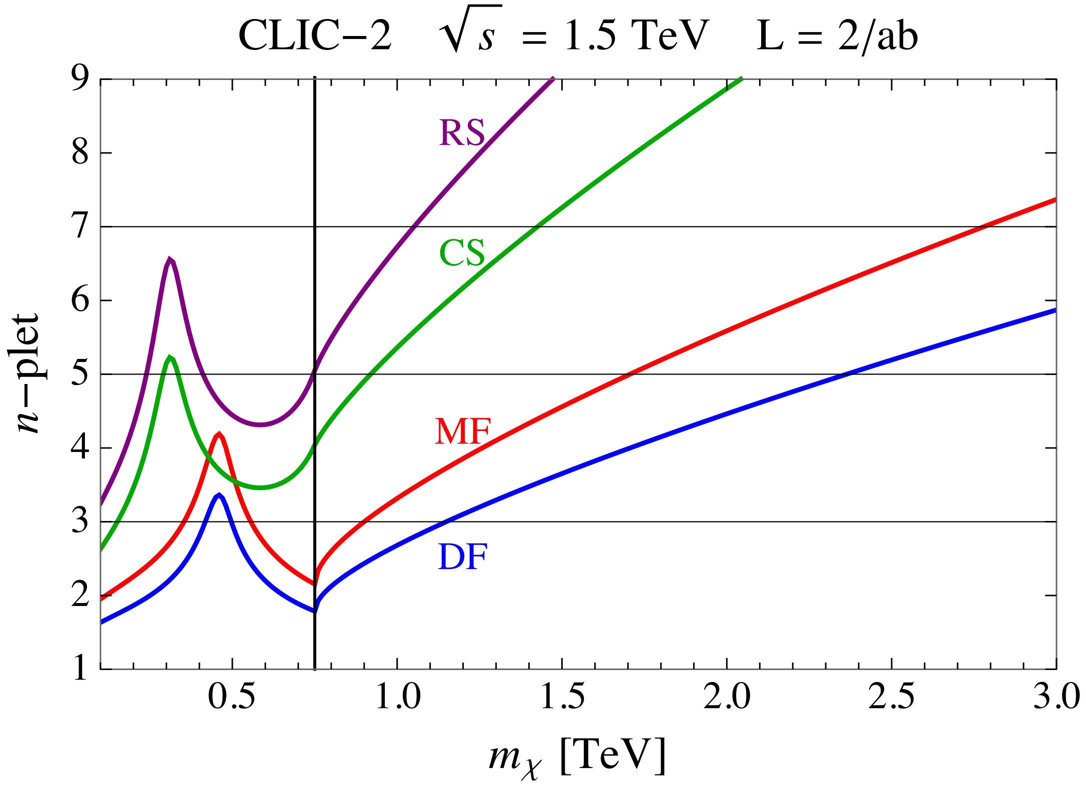
[threshold for pair-production]

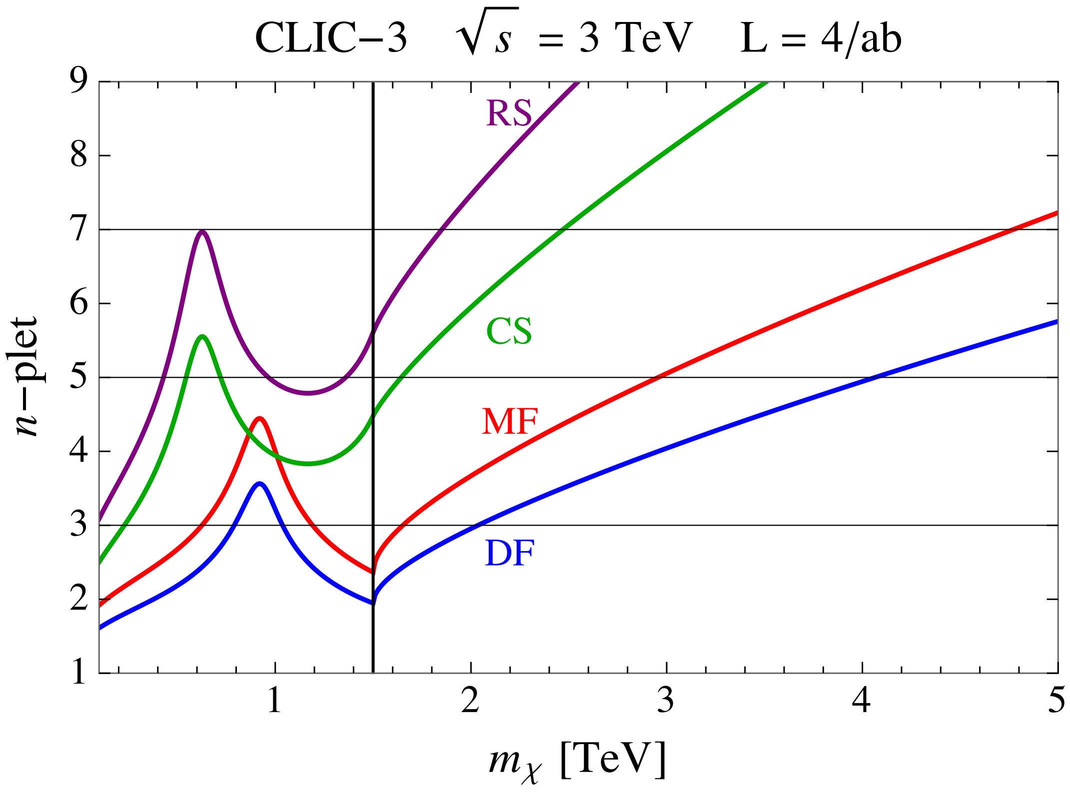
$x \simeq 11$

$x \simeq 25$

Projections @ CLIC

[LDL, Gröber, Panico 1810.10993, 1812.02093]





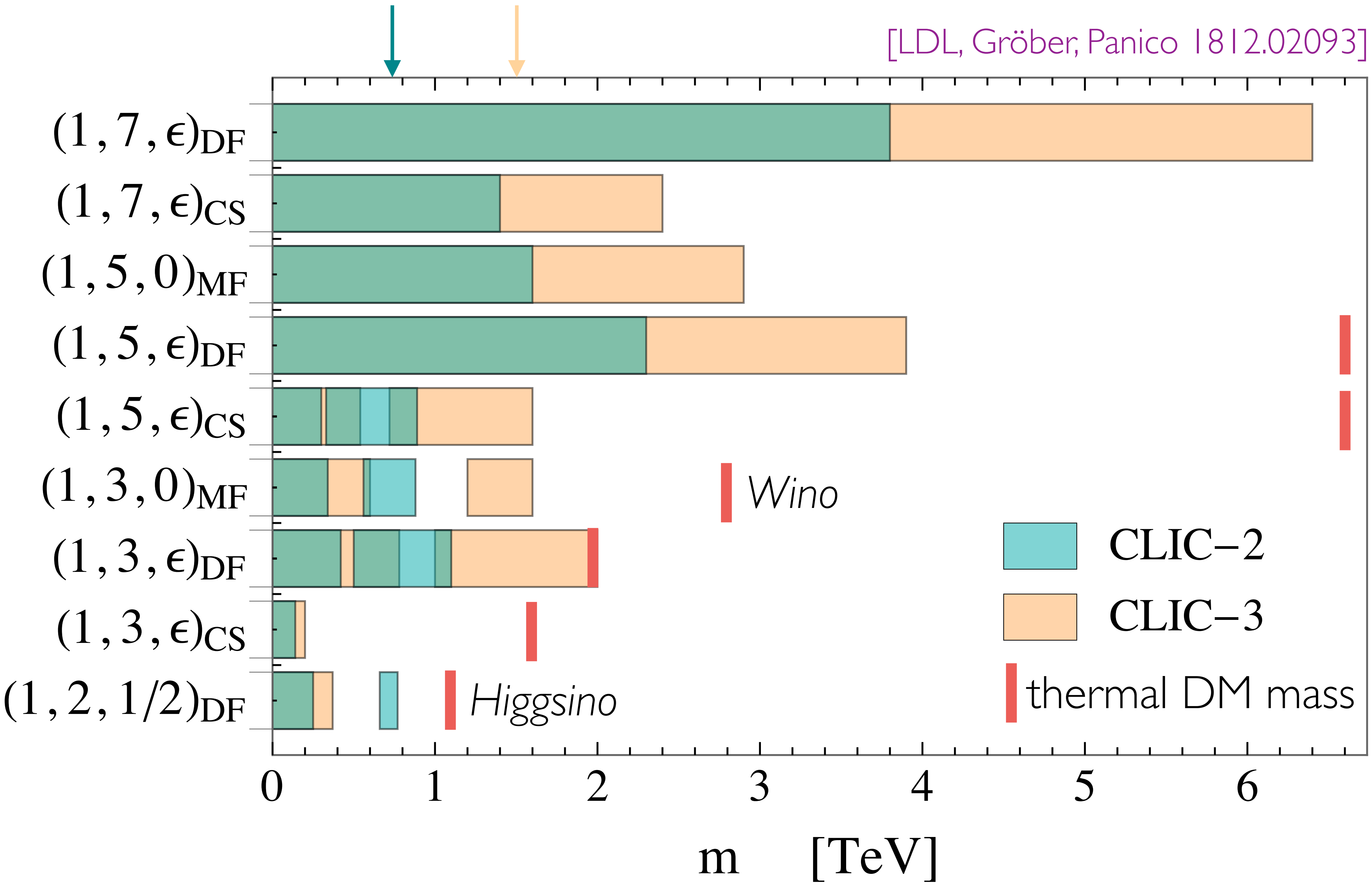
The dip moves for different $\sqrt{s}$ → *non-trivial interplay between CLIC-2 and CLIC-3 in the region above threshold for pair-production*

[how stable is the dip under radiative corrections ?]

Accidental Dark Matter @ CLIC

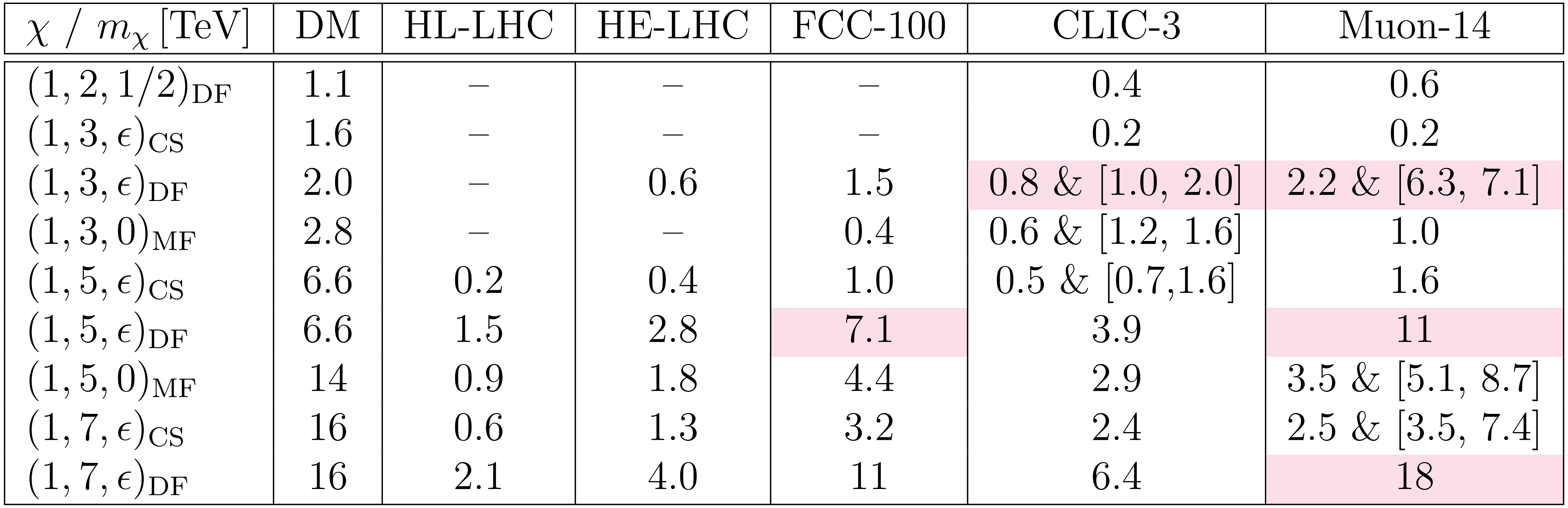
absolute limit from direct searches

[LDL, Gröber, Panico 1812.02093]



Comparison future colliders

[LDL, Gröber, Panico 1810.10993]



χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1,2,1/2)_{\rm DF}$	1.1	–	–	–	0.4	0.6
$(1,3,\epsilon)_{\rm CS}$	1.6	–	–	–	0.2	0.2
$(1,3,\epsilon)_{\rm DF}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1,3,0)_{\rm MF}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1,5,\epsilon)_{\rm CS}$	6.6	0.2	0.4	1.0	0.5 & [0.7,1.6]	1.6
$(1,5,\epsilon)_{\rm DF}$	6.6	1.5	2.8	7.1	3.9	11
$(1,5,0)_{\rm MF}$	14	0.9	1.8	4.4	2.9	3.5 & [5.1, 8.7]
$(1,7,\epsilon)_{\rm CS}$	16	0.6	1.3	3.2	2.4	2.5 & [3.5, 7.4]
$(1,7,\epsilon)_{\rm DF}$	16	2.1	4.0	11	6.4	18

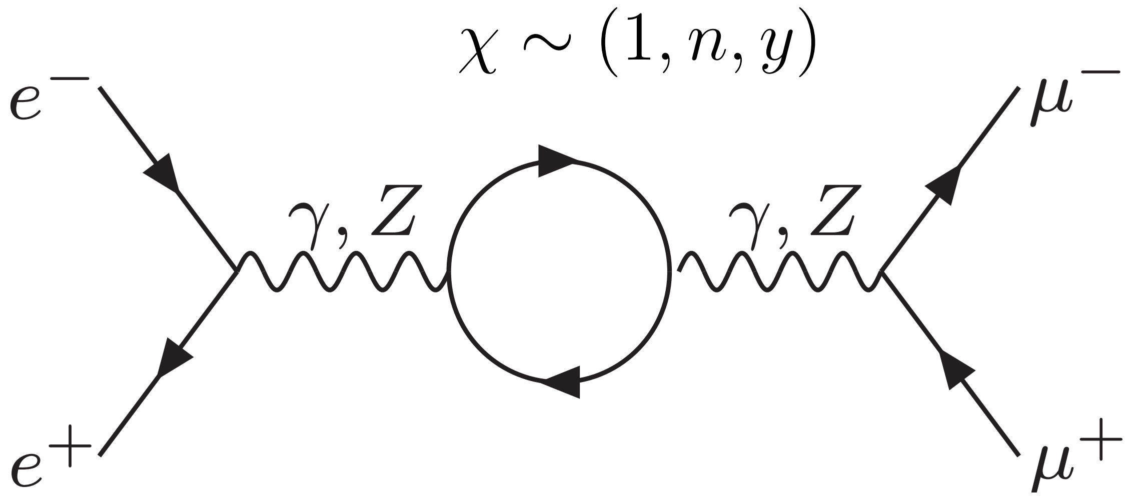
Table 1: *Pure higgsino/wino-like DM and MDM candidates, together with the corresponding masses saturating the DM relic density (second column) and the projected 95% CL exclusion limits from EW precision tests at HL-LHC ($\sqrt{s} = 14$ TeV and $L = 3/ab$), HE-LHC ($\sqrt{s} = 28$ TeV and $L = 10/ab$), FCC-100 ($\sqrt{s} = 100$ TeV and $L = 20/ab$), CLIC-3 ($\sqrt{s} = 3$ TeV and $L = 4/ab$), and Muon-14 ($\sqrt{s} = 14$ TeV and $L = 20/ab$). In the last two columns the numbers in square brackets stand for a mass interval exclusion. The cases where the DM hypothesis could be fully tested are emphasized in light red.*

Conclusions*

- Light EW states motivated by EW naturalness / Dark Matter / …

→ a clear target for future lepton colliders such as CLIC

- Indirect way as a promising approach, complementary to direct searches



* *A special thank to R. Franceschini for triggering this work back in 2017 !*

Conclusions*

- Light EW states motivated by EW naturalness / Dark Matter / …

  → a clear target for future lepton colliders such as CLIC

- Indirect way as a promising approach, complementary to direct searches

- Some directions for the future:

  1. *radiative corrections*
  2. *understand better the region above threshold for pair-production*
  3. *other precision observables ?*

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* *A special thank to R. Franceschini for triggering this work back in 2017 !*

Backup slides

Results HL-LHC

[LDL, Gröber, Panico 1810.10993]

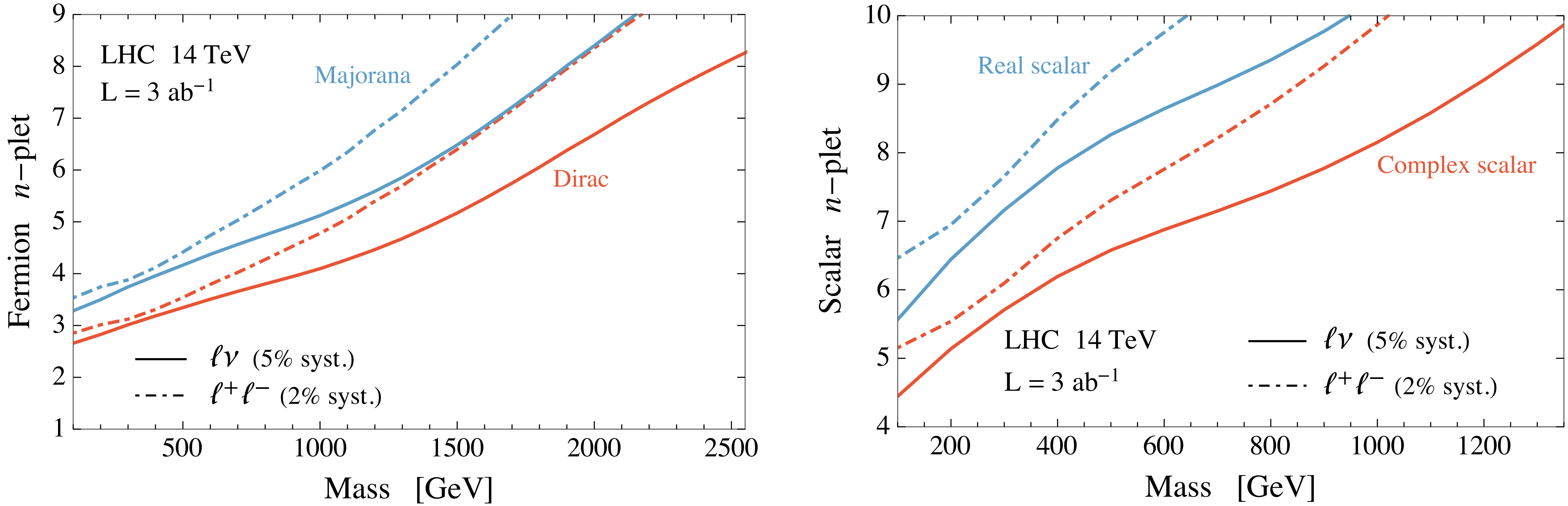

Figure 2: *Expected 95% CL exclusion limits at the HL-LHC. The left and right panels show the bounds on fermion and scalar multiplets respectively. The vertical axis reports the effective n of the multiplet, while the horizontal axis gives the mass of the states in the multiplet, which are assumed to be (almost) degenerate. The solid and dot-dashed lines correspond to the bounds from the $\ell\nu$ and $\ell^+\ell^-$ channels respectively. The blue (red) lines give the bounds for Majorana (Dirac) fermions on the left panel and for real (complex) scalars in the right panel.*

Systematic errors @ CLIC

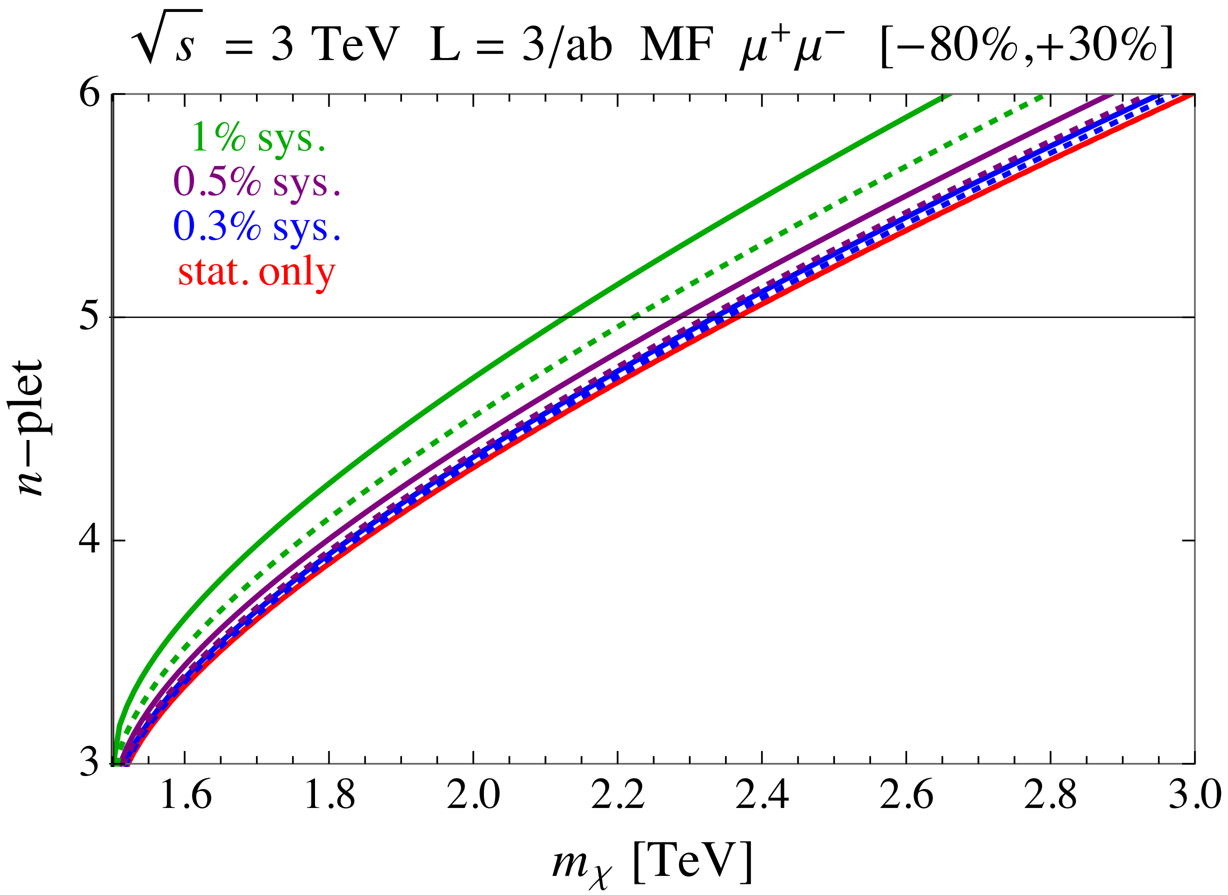

Fig. 77: Impact of systematic error: this plot shows e.g. that the 0.3% systematic error line is almost indistinguishable from the "pure statistical" one. We also superimpose (dotted lines) the exclusions obtained by augmenting the number of bins from 10 to 20 (same colour code for the error treatment as before). We see that increasing the numbers of bins helps for larger systematic errors, but does not matter much for e.g. 0.3% systematics. Hence, in the following we stick to 0.1% systematics with 10 bins.