## Accidental Dark Matter

## CLIC Workshop 2019 - CERN - 24 Jan 2019

## Luca Di Luzio







- 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]*

• BSM frameworks often predict new, light\* EW states  $\chi \sim (1, n, y)$  [fermion/scalar] New EW states charged under SU(2)*<sup>L</sup>* ⇥U(1)*y*, which are generically denoted by their quantum

 $\text{C}\cap\text{product}$ If one further requires that the theory requires that the theory remains weakly coupled up to the Planck scale and \* [100 GeV, few TeV] potential target for (lepton) colliders / no QCD production

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### Minimal Dark Matter *Sezione di Genova, Via Dodecaneso 33, 16159 Genova, Italy* <sup>3</sup>*Faculty of Nuclear Sciences and Physical Engineering,*

• Criteria  $\chi \sim (1,n,y)$ New EW states charged under SU(2)*<sup>L</sup>* ⇥U(1)*y*, which are generically denoted by their quantum *Charles University in Prague, V Holeˇsoviˇck´ach 2, 180 00 Praha 8, Czech Republic*

 $\textsf{Criteria} \quad \chi \thicksim (1,n,y)$  [Cirelli, Fornengo, Strumia, hep-ph/0512090, …]

- 1.  $y = 0$  to avoid tree-level Z exchange in DM direct detection  $\frac{1}{2}$   $\frac{1}{2}$
- 2. Lightest particle in the n-plet is neutral *y* = 0 (1)  $\alpha$  la Peccei-Quinn drives the pattern of Majorana neutrino masses while providing a dynamical providing a dynamical
- existence of large EW multiplets from the standpoint of accidental global symmetries. 3. n such that no  $\chi$  SM SM interactions at the ren. level ( $\chi$  accidentally stable)  $\sigma$ , it such and the  $\lambda$  sin sin interactions of
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### Minimal Dark Matter <sup>0</sup> 1 **Minimal Dark Matter**

• Criteria New EW states charged under SU(2)*<sup>L</sup>* ⇥U(1)*y*, which are generically denoted by their quantum representation. We have  $(1 \text{ mod } 1)$ to ⇢<sup>0</sup> are less general (they depend on the value of ) and not particularly constraining when

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	- existence of large EW multiplets from the standpoint of accidental global symmetries. *y* = 0 (1) 3. n such that no  $\chi$  SM SM interactions at the ren. level ( $\chi$  accidentally stable)
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2. and 3. <u>automatically</u> satisfied if  $n > 3$  and  $\chi$  a fermion (scalars more model dep.) station of <u>adcomatical</u> sucidities in the station of presence of non-trivial Surface of non-

If one further requires that the theory remains weakly coupled up to the Planck scale and

◆

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

### that the gauge quantum numbers of are such that no operators with dimension smaller than  $03/13$ *v*2 GeV Matter

# Minimal Dark Matter

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	- 2. and 3. <u>automatically</u> satisfied if n > 3 and  $\chi$  a fermion (scalars more model dep.)
- $p_0$ spiritual is a *n*<sub>1</sub>, or if  $\theta$  purely radiative as in the case of  $\theta$  and  $\theta$   $\theta$   $\theta$   $\theta$   $\theta$ • Remarkably, only one possibility\*

 $-5$  Maiorana formion with  $m \sim 14$  TeV. CDM mass fixed by SM gauge interactional  $\mathcal{L}$  is a substitution with  $m_{\chi} = 11 \pm 0.1$  [bindings  $\frac{m_{\chi}}{m_{\chi}^2}$  b) or a gauge mitor action  $\mathcal{L}$ n = 5 Majorana fermion with  $m_\chi \simeq 14$  TeV  $\,$  [DM mass <u>fixed</u> by SM gauge interactions]

[\*real scalar 7-plet ruled out in LDL, Gröber, Kamenik, Nardecchia, 1504.00359] If one further requires that the theory remains weakly coupled up to the Planck scale and *<u><u>y yestematic USA</u>*</u> (20259)</u>

# Minimal Dark Matter

• Bound state effects crucial 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  $SU(2)_L$  triplet (left panel) and as a fermion quintuplet (right panel). In the first case the  $SU(2)_L$ -invariant approximation is not good, but it's enough to show that bound states have a negligible impact. In the latter case the  $SU(2)_L$ -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)



# Minimal (Millicharged) Dark Matter

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⇤e↵



 $RS = Real Scalar$ MF = Majorana Fermion  $DF = Dirac$  Fermion rifical fermion termion tests at the contract of the contract of the LHC. In the contract of the contract of the c<br>International second tests and the contract of the contract of the contract of the contract of the contract *for details about center-of-mass energies and luminosities). In the last two columns the numbers*

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



### - mass fixed by relic density [Del Nobile, Nardecchia, Panci 1512.05353]

### *in square brackets stand for a mass interval exclusion. The cases where the DM hypothesis could* L. Di Luzio (Pisa U.) - Accidental Dark Matter 04/13

# 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*



## Accidental Matter not by a concentral lyiatteries. Finally, such the representation of  $\mathcal{A}$  consistent and  $\mathcal{A}$  consistent description of  $\mathcal{A}$

(in particular the SM gauge couplings) remain perturbative up to ⇤e↵. The physical idea • Exotic EW multiplets also motivated by the following phenomenological argument:

new, generic dynamics that will break the accidental symmetries of the SM at scales above the Landau <u>presente and accident</u> in Sect. 2.4, the community in Sect. 2011 in Sect. 2014 structure of the SM, and are hence screened from low-energy indirect probes *they automatically preserve the accidental (B, L) and approximate (flavour, etc.) symmetry* 

[LDL, Gröber, Kamenik, Nardecchia, 1504.00359]

Spin		$Q_{\rm LP}$	$\mathcal{O}_{\text{decay}}$	$\dim(\mathcal{O}_{\mathrm{decay}})$	$\sqrt{\Lambda_{\rm Landau}^{2-loop}[{\rm GeV}]}$
$\bigcap$	(1, 1, 0)	$\bigcap$	$\chi H H^{\dagger}$	3	$\gg m_{\rm Pl}(g_1)$
$\overline{0}$	$(1,3,0)^{\ddagger}$	0,1	$\chi H H^{\dagger}$	3	$\gg m_{\rm Pl}(g_1)$
$\overline{0}$	$(1,4,1/2)^{\ddagger}$	$-1,0,1,2$	$\chi H H^\dagger H^\dagger$		$\gg m_{\rm Pl}(g_1)$
$\overline{0}$	$(1,4,3/2)^{\ddagger}$	0,1,2,3	$\chi H^{\dagger} H^{\dagger} H^{\dagger}$	4	$\gg m_{\rm Pl}(g_1)$
$\Omega$	(1, 2, 3/2)	1,2	$\chi H^{\dagger} \ell \ell$ , $\chi^{\dagger} H^{\dagger} e^c e^c$ , $D^{\mu} \chi^{\dagger} \ell^{\dagger} \overline{\sigma}_{\mu} e^c$	$\overline{5}$	$\gg m_{\rm Pl}(g_1)$
$\overline{0}$	(1, 2, 5/2)	2,3	$\chi^{\dagger} H e^c e^c$	$\overline{5}$	$\gg m_{\rm Pl}(g_1)$
$\Omega$	(1, 5, 0)	0,1,2	$\chi H H H^{\dagger} H^{\dagger}$ , $\chi W^{\mu\nu} W_{\mu\nu}$ , $\chi^3 H^{\dagger} H$	$\overline{5}$	$\gg m_{\rm Pl}(g_1)$
$\overline{0}$	(1, 5, 1)	$-1,0,1,2,3$	$\chi^{\dagger}HHHH^{\dagger}, \ \chi\chi\chi^{\dagger}H^{\dagger}H^{\dagger}$	$5\overline{)}$	$\gg m_{\rm Pl}(g_1)$
$\overline{0}$	(1, 5, 2)	0,1,2,3,4	$\chi$ <sup>†</sup> $HHHH$	$\overline{5}$	$3.5 \times 10^{18}$ ( <i>g</i> <sub>1</sub> )
$\overline{0}$	$(1, 7, 0)^*$	0,1,2,3	$\chi^3 H^{\dagger} H$	$\overline{\partial}$	$1.4 \times 10^{16}$ $(g_2)$
1/2	(1,4,1/2)	$-1$	$\chi^{c}\ell H H$ , $\chi \ell H^{\dagger} H$ , $\chi \sigma^{\mu\nu} \overline{\ell W_{\mu\nu}}$	$\overline{5}$	$8.1 \times 10^{18}$ $(g_2)$
1/2	(1,4,3/2)	$\overline{0}$	$\chi \ell H^{\dagger} H^{\dagger}$	$\overline{5}$	$2.7 \times 10^{15}$ $(g_1)$
1/2	(1, 5, 0)	$\overline{0}$	$\chi \ell H H H^{\dagger}, \; \chi \sigma^{\mu \nu} \ell H W_{\mu \nu}$	6	$8.3 \times 10^{17}$ $(g_2)$

# Direct searches

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

# Direct searches

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



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### Direct searches  $t_{\rm max}$  requires at least one charged studies on with an ISR photon of energy *>* 50 GeV or *>* 100 GeV – are capable of covering higgsino

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	- Lepton colliders: Mono-photon + (short) disappearing tracks ASSUME PURE HIGGSINO LIFETIME



 $cr = 1.2$  cm @ 200 GeV  $\rightarrow$  0.7 cm @ 1 TeV

*[See also talk by R. Franceschini yesterday]*

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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, HE-LHC, FCC-100, CLIC-3 and Muon-14 (see text kinematically inaccessible*  For CLIC direct searches

## *[See also talk by R. Franceschini yesterday]*

### Indirect probes of new EW states of future lepton collider options. Finally in Sect. 6 we briefly compare our bounds on  $\mathcal{L}$  $m$ hes ot new FW states and conclude in  $M$ the collection of some additional results and technical details.

• Universal corrections to  $2 \rightarrow 2$  fermion scattering

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



# Indirect probes of new EW states

● Universal corrections to 2 → 2 fermion scattering [See also Harigaya et al, 1504.03402  $2 \times 1$  Form for search

S<br>Matsumoto et al 1711.05449] [See also Harigaya et al, 1504.03402

• Parametrized in terms of EW form factors\*  $f(x)$  in the event is the event in the event in  $\frac{1}{2}$ • Parametrized in terms of EW form factors\*

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

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

 $\widehat{\mathcal{C}}$  for  $\widehat{\mathcal{C}}$ .  $\mathcal{L}_{BB}$  contribution of  $\mathcal{L}_{BB}$  $C_{BI}^{\text{eff}}$  $\frac{f_{\text{eff}}}{BB} = 2 \kappa n y^2$ 

> $^*$  we neglect mass splitting within the n-plet [ok for n > 3 fermions, not necessarily a good approx for light scalars] *,* (14) n-plet [ok for n > 3 fermions, not necessarily a good approx for light scalars]

#### , where *q* is the external momentum of the external momentum of the gauge boson propagator propagator and  $\alpha$  is the gauge boson propagator  $\alpha$  is the gauge boson propagator and  $\alpha$  is the gauge boson propagator and  $\$ *x* L. Di Luzio (Pisa 2 ⇣⇣q*<sup>x</sup>*<sup>4</sup>  $c$  *i* denta ⌘ *<sup>x</sup>* + 2⌘⌘ the renormalization scale. A useful choice is *µ* = *m*, which ensures that the form factors ⇧*S,F* L. Di Luzio (Pisa U.) - Accidental Dark Matter 07/13

#### Indirect probes of new EW states fermion (MF), Dirac fermion (DF).  $T$  contained  $T$  of  $T$  and  $T$   $\vdash$   $\mathcal{N}$  defined by  $T$ renormalized form factors are (respectively for the case of a scalar and a fermion running in  $T$  to the contribution of  $\mathbb{R}^n$  gauge boson propagators is purely transversal and the MS  $\mathbb{R}^n$ t nrohes ot new FW states are the case of a fermion running in  $\vdash$   $\vdash$   $\vdash$

● Universal corrections to 2 → 2 fermion scattering [See also Harigaya et al, 1504.03402  $m$ ion scatte + 8(*x* 3) + 3*x*  $\overline{1}$ + 8(*x* 3) + 3*x*

Social definition, due to the presence of a new state in the presence of a new state  $\frac{1}{2}$  Matsumoto et al 1711.05449] <u>See also Harigay</u><br>Matsumoto et al a et al, 1504.0340.<br>JRU OF 4401 *<sup>x</sup>* + 2⌘⌘ *<sup>x</sup>*<sup>4</sup> *x* also Hariga<sub>)</sub>  $\overline{1}$ d<br>d ⇣⇣q*<sup>x</sup>*<sup>4</sup> 04.0340  $\overline{a}$ <u>145<del>yi 197</del></u> [See also Harigaya et al, 1504.03402 Matsumoto et al 1711.05449]

• Parametrized in terms of EW form factors\*  $f(x)$  in the event is the event in the event in  $\frac{1}{2}$  $\frac{1}{\sqrt{2}}$ <sup>3</sup>*<sup>x</sup>* log ⇣ *<sup>µ</sup>*<sup>2</sup> <sup>*1</sup>* factors<sup>\*</sup></sup>

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

*WW* = (*n*<sup>3</sup> *n*)*/*6, *C*<sup>e</sup>↵ *BB* = 2*nY* <sup>2</sup>, and = 1*/*2*,* 1*,* 4*,* 8, respectively for being a - Heavy new physics  $\sqrt{s} \ll m_\chi$  (EFT limit)  $\lambda$   $\lambda$  1. vanish for *x* = 0. This choice is henceforth assumed. The behavior of the ⇧*S,F* form factors is  $\sqrt{s} \ll m_{\chi}$  (CFT)

$$
\Pi\left(\frac{s}{m_{\chi}^2}\right) \simeq -\frac{1}{480\pi^2} \frac{s}{m_{\chi}^2}
$$
\n
$$
S = T = U = 0
$$
\n
$$
s^2 \text{C}^{\text{eff}} \quad m^2
$$

$$
W = \frac{g^2 C_{WW}^{\text{eff}} m_W^2}{960\pi^2} \qquad Y = \frac{g'^2 C_{BB}^{\text{eff}} m_W^2}{960\pi^2} \frac{m_\chi^2}{m_\chi^2}
$$

 $\frac{1}{2}$  smaller  $\frac{1}{2}$  for  $\frac{1}{2}$  formal and no concernity of  $\frac{1}{2}$  or  $\frac{1}{2}$ <u>m ' 14 TeV (5)</u><br>The contract of the contract of  $^\ast$  we neglect mass splitting within the n-plet [ok for n  $\geq 3$  fermions, not necessarily a good approx for light scalars]

#### means that indirect searches for multiplets with a mass control multiplets with a mass control of pair product<br>The pair production thresholds with a mass control of pair production thresholds with a mass control of the pa tend to be significantly more sensitive than what the EFT approximation what the EFT approximation would suggest. means that individual of multiplets with a mass control of multiplets with a mass control of the pair production of the pair production of the pair production threshold of the pair production of the pair production of the

## Indirect probes of new EW states Indigact probac of At lepton colliders one can study the modifications of the process *e*<sup>+</sup>*e* ! *ff*, where *f* is a

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	-

$$
\Pi(x) = \begin{cases}\n-\frac{8(x-3)+3x(\frac{x-4}{x})^{3/2}\log\left(\frac{1}{2}\left((\sqrt{\frac{x-4}{x}}-1)x+2\right)\right)}{144\pi^2x} & \text{(F)} \\
-\frac{12+5x+3\sqrt{\frac{x-4}{x}}(x+2)\log\left(\frac{1}{2}\left((\sqrt{\frac{x-4}{x}}-1)x+2\right)\right)}{288\pi^2x} & \text{(S)}\n\end{cases}
$$
\n0.0010\n0.0005



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$$

*y prometrically dependence relevant also* 0.0000 0.0000 0.0000 0.0000 0.0000 0.00 require that potential terms allowed by gauge invariance are subleading. *momentum dependence relevant also below threshold for pair production !*



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# Angular distributions

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



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

#### Angular distributions so that it becomes include that it becomes include the full constructions of the form  $\mathcal{A}$ even below the pair-production threshold.  $\Lambda$  muon collider was recently sources. In particular, the proposal of a low emitted source from positron source from positron  $\mathcal{A}$  is positron source from positron source from  $\mathcal{A}$  is positron source from positron source from positron source fr on a target, LEMMA [21–23], allows to reach centre-of-mass energies above 10 TeV [40]. As

- Binned likelihood analysis of  $e^+e^- \rightarrow f\overline{f}$  as a function of  $\cos \theta$  $\cos \theta$  $3.5$  Description of the analysis of  $\sigma$  of  $\sigma$  and  $\sigma$ a benchmark we choose a luminosity of  $\frac{1}{2}$   $\frac{1}{2}$  and  $\frac{1}{2}$ **c** billinou interference allary situation by factors of 1*/4* as a report of 1*/2* and a higher even allows of the  $\alpha$
- Details of the analysis  $E_{\rm eff}$  for the refer to  $[3]$  for the refer to  $[3]$  formulae. Note that since that since the radiative corrections of  $\alpha$ energy option of p*s* = 30 TeV for various values of the luminosity.<sup>9</sup>
- $\cos \theta \in [-0.95, 0.95]$  in 10 uniform intervals  $\mathcal{S}$  we perform a binned likelihood and the process section of the process sect of the process `<sup>+</sup>` ! *ff* with respect to the cosine of the scattering angle ✓. In particular, we
- ⇧(*x*) (3)  $\frac{d}{dx}$   $\frac{d}{dx}$   $\frac{d}{dx}$   $\frac{d}{dx}$   $\frac{d}{dx}$  of the scattering angle  $\frac{d}{dx}$   $\frac{d}{dx$ sider  $j = e, \mu, v, c$  intarstates with detection enterties  $\varepsilon[e, \mu, v, c] = [1, 1, 0.8, 0.5]$ . - consider  $f = e, \mu, b, c$  final states with detection efficiencies  $\varepsilon[e, \mu, b, c] = [1, 1, 0.8, 0.5]$



uminosity, beam polarization [see later] arizatic |
| L<sub>2</sub> laterl *m*<sup>2</sup> - assume some c.o.m. energy, luminosity, beam polarization [see later] - assume some c.o.m. energy, luminosity, beam polarization [see later]

#### Angular distributions so that it becomes include that it becomes include the full constructions of the form  $\mathcal{A}$ even below the pair-production threshold.  $\Lambda$  muon collider was recently sources. In particular, the proposal of a low emitted source from positron source from positron  $\mathcal{A}$  is positron source from positron source from  $\mathcal{A}$  is positron source from positron source from positron source fr on a target, LEMMA [21–23], allows to reach centre-of-mass energies above 10 TeV [40]. As

- Binned likelihood analysis of  $e^+e^- \rightarrow f\overline{f}$  as a function of  $\cos \theta$  $\cos \theta$  $3.5$  Description of the analysis of  $\sigma$  of  $\sigma$  and  $\sigma$ a benchmark we choose a luminosity of  $\frac{1}{2}$   $\frac{1}{2}$  and  $\frac{1}{2}$ **c** billinou interference allary situation by factors of 1*/4* as a report of 1*/2* and a higher even allows of the  $\alpha$
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*f* = *e, µ, b, c* (3)

*f* = *e, µ, b, c* (2)

- uminosity, beam polarization [see later] arizatic |
| L<sub>2</sub> laterl *m*<sup>2</sup> - assume some c.o.m. energy, luminosity, beam polarization [see later] - assume some c.o.m. energy, luminosity, beam polarization [see later] v luminosity beam polarization [see later]
- $\text{IOf } \chi^2 = 3.84 \text{ (I Q.O.I.)}$ <sup>p</sup>*<sup>s</sup>* ⌧ *<sup>m</sup>* (8)  $\text{Set } 95\% \text{ CL bound on } m_{\text{v}} \text{ for } \chi^2 = 3.84$ **b** set 95% CL bound on  $m_\chi$  for  $\chi^2 = 3.84$  (1 d.o.f.)

## Role of beam polarization beam in terms of the polarization fractions *P<sup>e</sup>* and *Pe*<sup>+</sup> is defined by

• Cross-section of an  $e^+e^-$  polarized beam beam in terms of the polarization fractions *P<sup>e</sup>* and *Pe*<sup>+</sup> is defined by *P <sup>e</sup> P e*+ =

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

where  $L$  stands for instands for instands for instands for the early left-handed if the early left-handed if the  $\mu$ - Higgs program at CLIC prefers  $P_{e^-} = -80\%$ polarization, since this configuration enhances the *e*<sup>+</sup>*e* ! *ff* cross-section. The Higgs program

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*(mainly because of higher x-section)*  $\begin{bmatrix} -50\% & -50\% \\ -50\% & -50\end{bmatrix}$ 

"[*e, µ, b, c*] = [1*,* 1*,* 0*.*8*,* 0*.*5] (4) **The option of a muon collider was recently representation of a muon collider was representation of a muon collider was relative** 

### ⇤SM+ (9) comparison we vary the luminosity by factors of 1*/*4*,* 1*/*2 and 4, and we consider even a higher energy option of ps *a* U, *second of the park in attention of the luminosity.* **L. Di Luzio (Pisa U.) - Accidental Dark Matter** 09/13

## Role of beam polarization beam in terms of the polarization fractions *P<sup>e</sup>* and *Pe*<sup>+</sup> is defined by

• Cross-section of an  $e^+e^-$  polarized beam beam in terms of the polarization fractions *P<sup>e</sup>* and *Pe*<sup>+</sup> is defined by *P <sup>e</sup> P e*+ = <sup>4</sup> [(1 + *<sup>P</sup><sup>e</sup>* )(1 + *<sup>P</sup>e*<sup>+</sup> )*RR* + (1 *<sup>P</sup><sup>e</sup>* )(1 *<sup>P</sup>e*<sup>+</sup> )*LL*

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

where  $L$  stands for instands for instands for instands for the early left-handed instands for instands for the  $\mu$ • Two energy benchmarks with  $P_{e^-} = -80\%$  (nominal luminosities rescaled by 4/5) polarization, since this configuration enhances the *e*<sup>+</sup>*e* ! *ff* cross-section. The Higgs program  $\alpha$ chmarks with  $P_{e^-} = -80\%$  (nominal luminosities rescaled by 4/5)

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

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

s en la componenta de la<br>Encontrada de la componenta de la componen  $TC_{\text{c}}$  option of a muon collider was recently represented to new proposals for muon collider  $T$  $S = \left[ \frac{1}{2} \sum_{i=1}^{n} \frac{1}{2} \sum_{i$ [See Robson, Roloff 1812.01644] a benchmark we choose a 14 Terminosity of 14 Terminosity of 14 Terminosity of *Latin* and *Latin* a luminosity of *Latin a luminosity of 20 ab* comparison we vary the luminosity by factors of 1*/*4*,* 1*/*2 and 4, and we consider even a higher

# Projections @ CLIC



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 CLIC, denoted respectively CLIC-2 (p*s* = 1*.*5 TeV, *L* = 2 ab<sup>1</sup> ) and CLIC-3 (p*s* = 3 TeV, ). To obtain these exclusions we have combined the *e/µ/b/c* channels assuming

where does the dip in sensitivity come from ? [LDL, Gröber, Panico 1810.10993, 1812.02093]



### Projections @ CLIC CLIC, denoted respectively CLIC-2 (p*s* = 1*.*5 TeV, *L* = 2 ab<sup>1</sup> ) and CLIC-3 (p*s* = 3 TeV, ). To obtain these exclusions we have combined the *e/µ/b/c* channels assuming



*x* = *s/m*<sup>2</sup>

<u>(8) - Antonio Alemania, politikar politikar (h. 1888).</u><br>1900 - Antonio Alemania, politikar politikar (h. 1880).

### $\left( \bigcap_{i=1}^{n} |f_{i}|\right)$  have some non-trivial features which can be understood by understood b following the shape of the real part of the form factor above threshold (cf. Fig. 6). ✓ *s* ◆ 1 *s* L. Di Luzio (Pisa U.) - Accidental Dark Matter 10/13

# Projections @ CLIC



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 @ CHC and 5.3 for more discussion. Accidental Dark Matter @ CLIC



# Comparison future colliders

[LDL, Gröber, Panico 1810.10993]

$m_{\chi}$ [TeV]	DM	HL-LHC	HE-LHC	$\mathrm{FCC}\text{-}100$	CLIC-3	$M$ uon-14
$(1,2,1/2)_{\text{DF}}$	1.1				0.4	0.6
$(1,3,\epsilon)_{\mathrm{CS}}$	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
$(1,5,\epsilon)_{\text{CS}}$	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	$3.5 \& [5.1, 8.7]$
$(1,7,\epsilon)_{\mathrm{CS}}$	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\* plets. In Sect. 3 we describe the parametrization of the new physics corrections to the gauge bon clusions<sup>\*</sup>

• Light EW states motivated by EW naturalness / Dark Matter / ...  $m_{\text{in}}$  multiplets with direct searches and conclude in Sect. 7. Appendix and B are devoted to the devoted to the

 $\begin{array}{ccc} \hline \end{array}$ a clear target for future lepton colliders such as CLIC

• Indirect way as a promising approach, complementary to direct searches z<br>2 Physics camplementary to direct searches



\* *A special thank to R. Franceschini for triggering this work back in 2017 !*  $\frac{1}{2}$  for triggoring this work back in 20171 further assumes and work back in 2017. process thank to D Exanceschini for triggering this work hack in 2017 I becial thank to R. Franceschini for triggering this work back in 2017. I

## 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 ?*

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



# Results HL-LHC



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.