Hunting for Charged Resonances and Minimal Dark Matter at a Muon Collider

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Mainly based on: *NV, JHEP 10 (2023) 121*

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Outline

- **Opportunities offered by a multi-TeV Muon Collider** (MuCol)

  in particular to address questions related to two fundamental puzzles in fundamental High-Energy Physics:

  The presence of **New Physics** connected to a more complete understanding of the **EWSB Higgs mechanism**

  and the origin of the **Dark Matter** of the universe
- WIMP Minimal Dark Matter
- MDM bound state production at a MuCol
- Charged resonances at a future Muon Collider
- Outlook

A Future Muon Collider

key point of the strategic plans for the development of particle physics both in Europe (ESPP '20) and in the USA (P5 recommendations '23)

D. Stratakis et al. (Muon Collider), A Muon Collider Facility for Physics Discovery, (2022), arXiv:2203.08033, K. M. Black et al., Muon Collider Forum Report, (2022), arXiv:2209.01318 [hep-ex]; C. Accettura et al., Towards a Muon Collider, (2023), arXiv:2303.08533 [physics.acc-ph].

mu+ mu- in a circular collider with a ring of the size of the LHC, 27 Km (possibly using the LHC ring)

Energy and Luminosity design targets:

$$\sqrt{s} = 1, 3, 10, 30, 50 \text{ TeV} \qquad L = 0.1, 0.9, 10, 90, 250 \ \text{ab}^{-1} \qquad L = 10 \left(\frac{\sqrt{s}}{10\,\text{TeV}} \right)^2 \text{ab}^{-1}$$

Advantages:

- typically higher effective collision energies (hadron colliders pay for PDFs, e+e- for sinchrotron radiation effects)
- lower background (compared to hadron colliders)

Main challenge: short life-time of muons

WIMP Minimal Dark Matter

Cirelli, Fornengo, Strumia,
Nucl.Phys.B 753 (2006) 178-194

The minimal solution to the DM puzzle:

simply add to the SM an EW multiplet

$$\mathscr{L} = \mathscr{L}_{\rm SM} + c \begin{cases} \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X} & \text{when } \mathcal{X} \text{ is a spin 1/2 fermionic multiplet} \\ |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2 & \text{when } \mathcal{X} \text{ is a spin 0 bosonic multiplet} \end{cases}$$

χ is an n-tuplet of the $SU(2)_L$ gauge group, $n=\{1,2,3,4,5, ...\}$

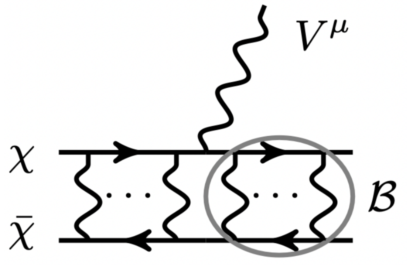
The neutral component is the lightest, is (automatically) stable and is a good DM candidate

Thermal targets

- MDM thermal relic produced via freeze out: the relic abundance is calculable and depends on one parameter: the mass M
- Important corrections that must be taken into account:

  Sommerfeld enhancement (SE), bound state formation (BSF)

When $M \gtrsim M_{W,Z}/\alpha_W$ Coulomb-like attractive potential leads to the formation of MDM bound states

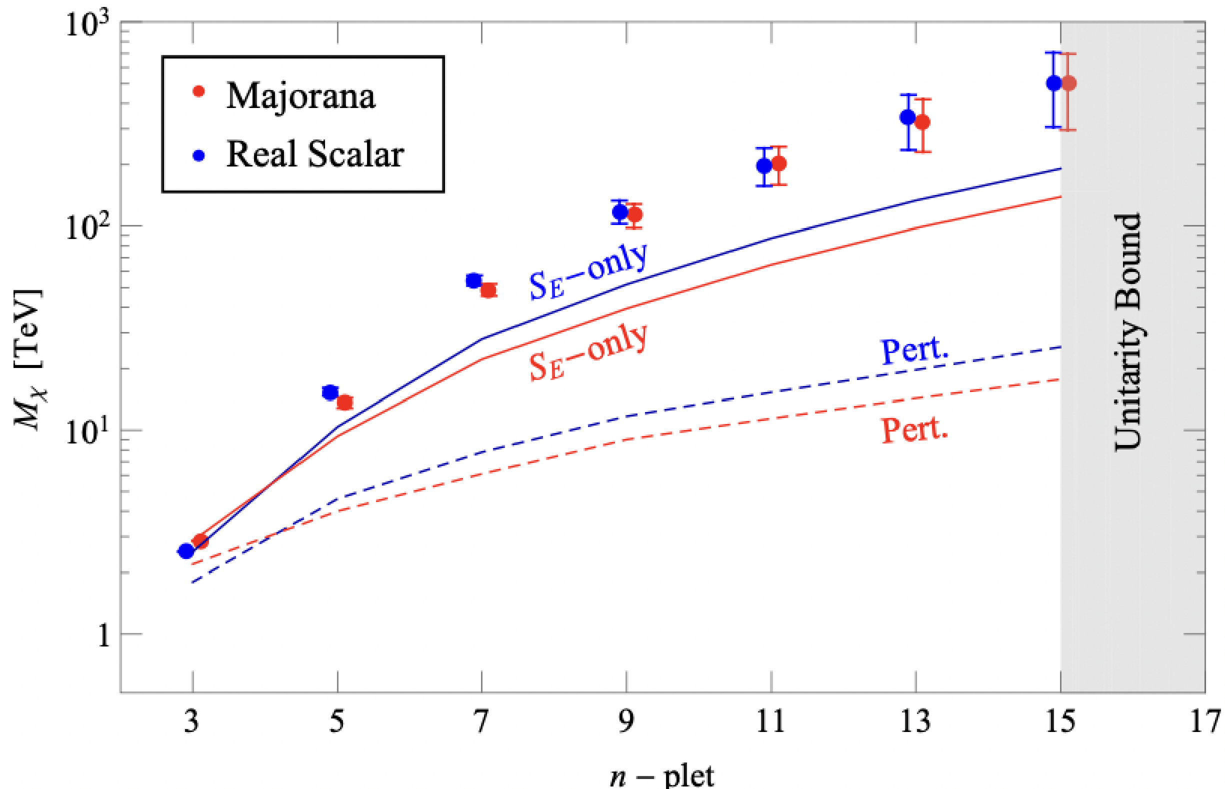


A. Mitridate, M. Redi, J. Smirnov, and A. Strumia, JCAP 05 (2017) 006

Thermal targets

S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, D. Redigolo, and L. Vittorio, Eur. Phys. J. C 82, 31 (2022)

Majorana 5-plet is special, because it can be made **accidentally stable**.
No need of specific UV completion, since the weak coupling stays perturbative up to very high scale, above the Planck scale

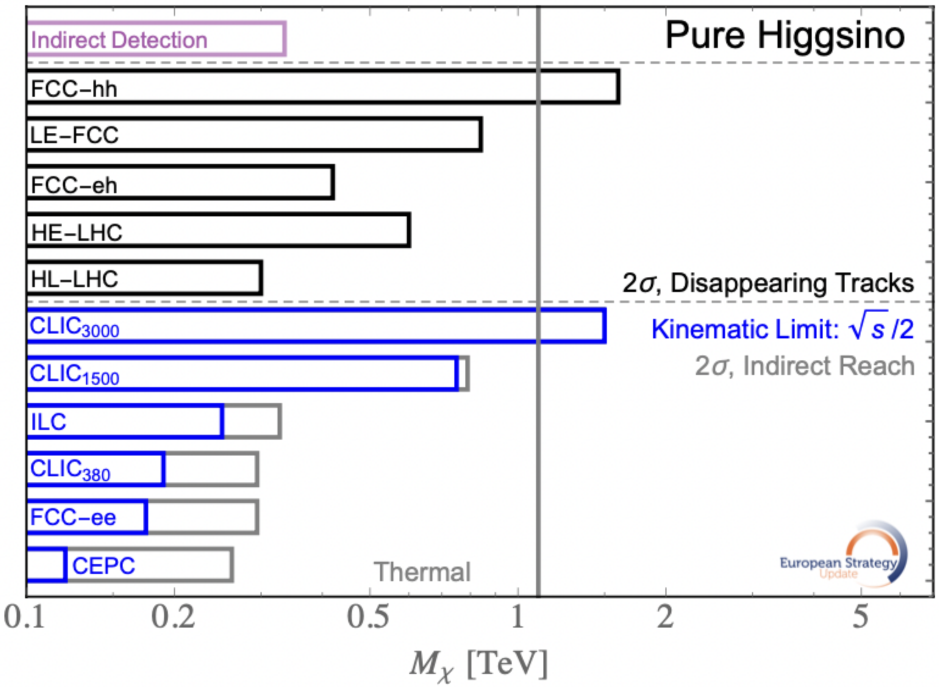


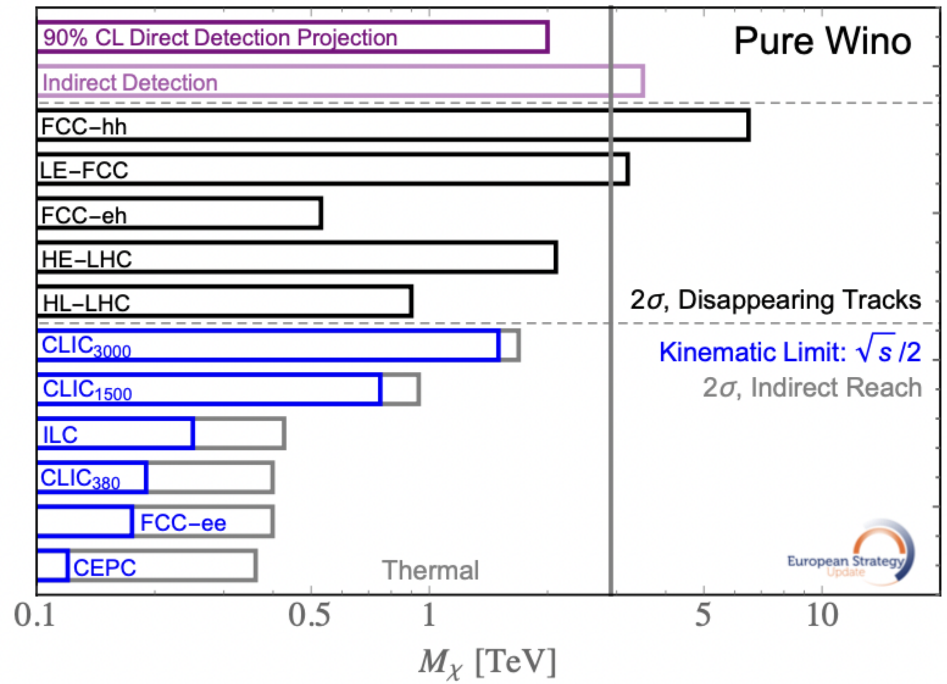
s-wave perturbative unitarity limit

Status of the search for WIMPs

Prospects for HL-LHC and FCC

Physics Brief ng Book - Input for the European Strategy for Particle Physics Update 2020, arXiv:1910.11775v2 [hep-ex]



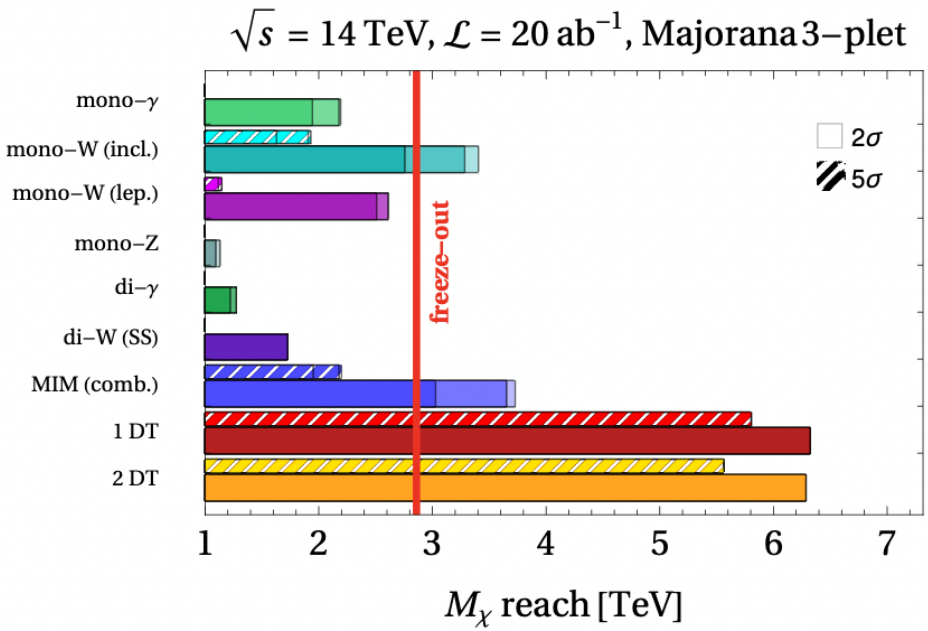


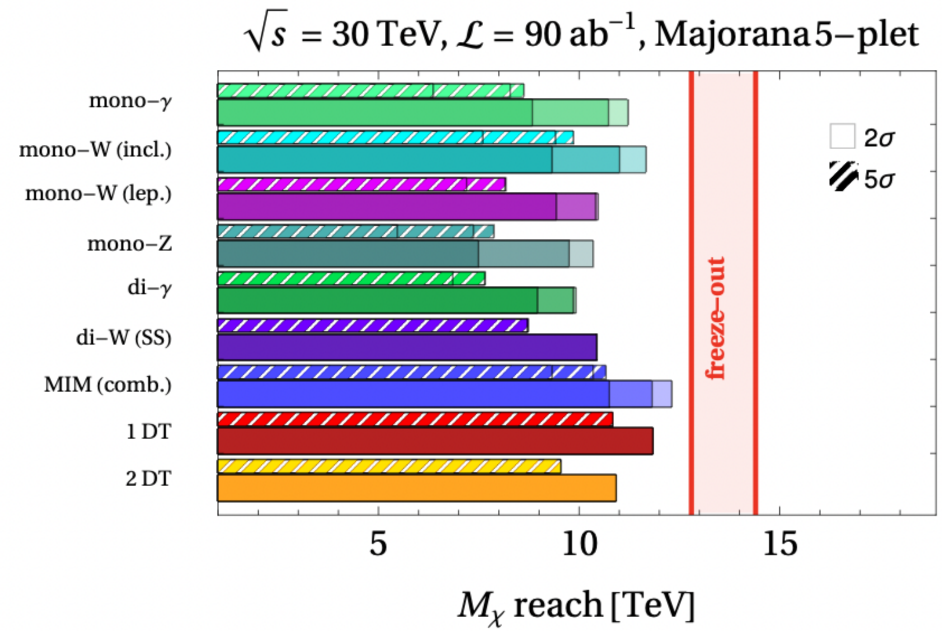
Wino target can be reached at the FCC-hh but no hopes for the 5-plet target

Status of the search for WIMPs

<u>Missing energy, disappearing tracks</u> and precision measurements at a future **muon collider**

Plots from S. Bottaro *et al.*, Eur. Phys. J. C 82, 31 (2022)





(For DT searches see also R. Capdevilla, F. Meloni, R. Simoniello, and J. Zurita, arXiv:2102.11292 [hep-ph])

Status of the search for WIMPs

Even at a Muon Collider it is not possible to test the 5-plet *directly* by "conventional searches": mono-X, MIM, DT, ...

Indirect exclusion is possible by precision measurements with an energy of at least 14 TeV (cfr Franceschini, Zhao, *Eur.Phys.J.C 83 (2023) 6, 552*)

DM direct detection experiments need a long exposure to test the MDM scenario: DARWIN 200 ton/year

New idea →

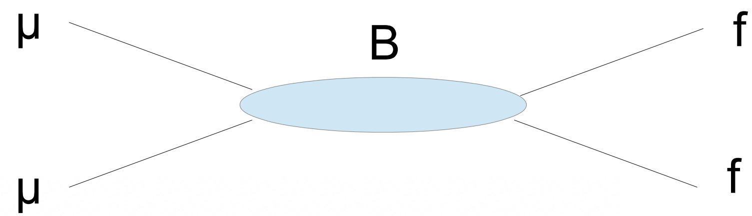
S. Bottaro, A. Strumia, NV, JHEP 06 (2021) 143

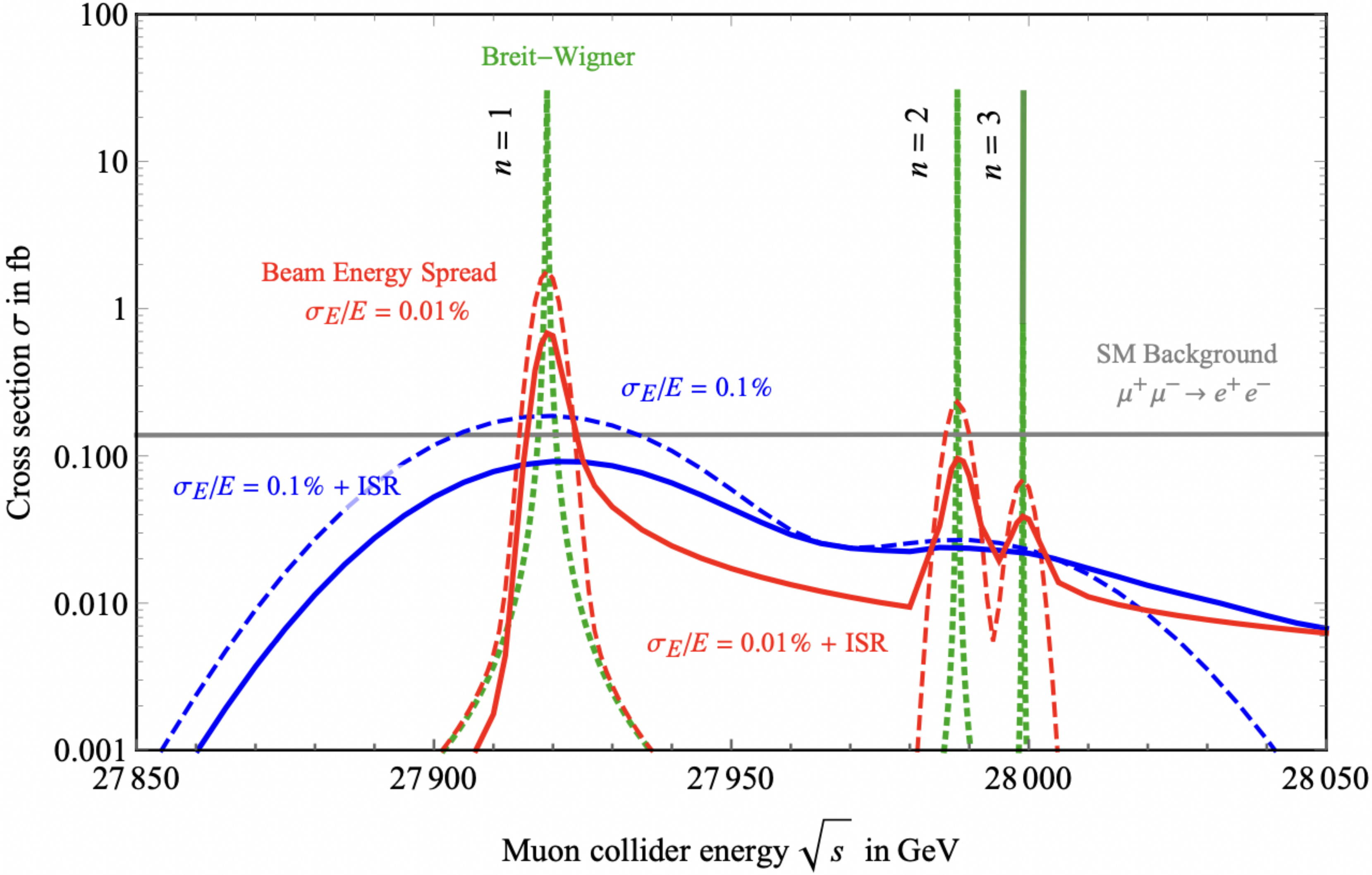
5plets form bound states with mass ~2M and quantum EW numbers as W'/Z' triplets, which couple to SM fermions

A multi-TeV MuCol could produce these states, we could directly search for MDM 5plets

Resonant production at a MuCol

S. Bottaro, A. Strumia, NV, JHEP 06 (2021) 143

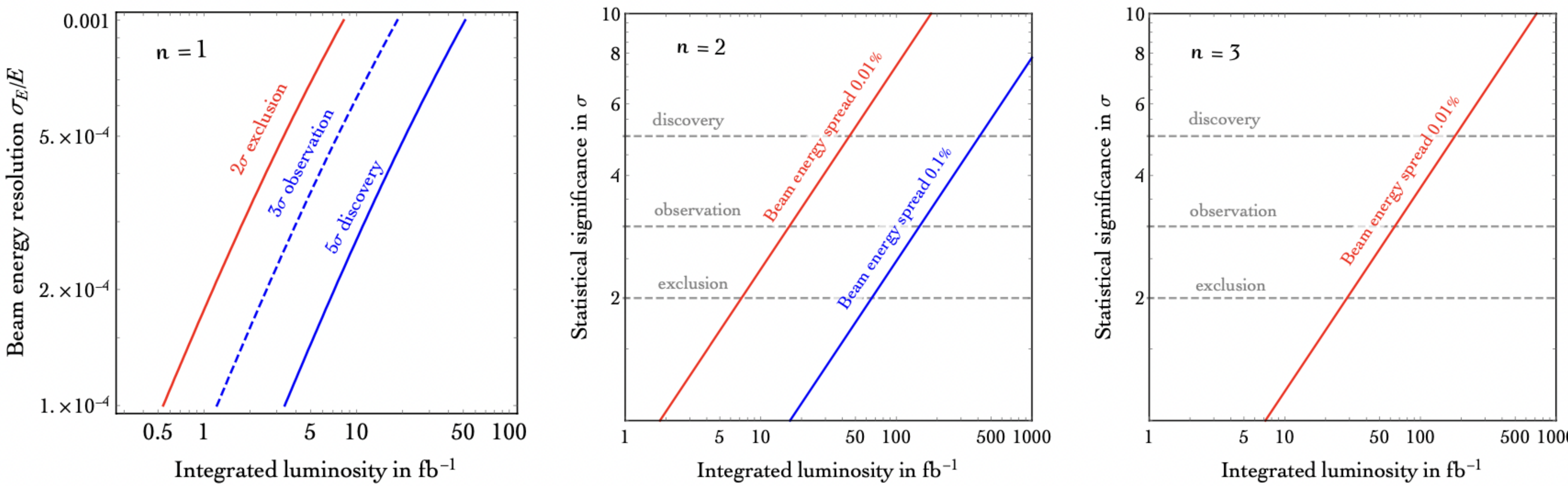




Resonant production at a MuCol

S. Bottaro, A. Strumia, NV, JHEP 06 (2021) 143

Reach



Possibility to discover the 5-plet with just few fb-1 (one day of run)

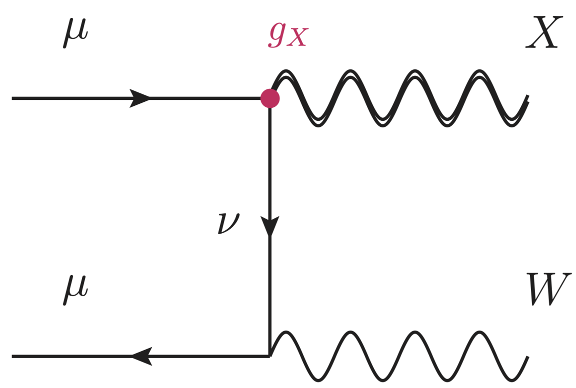
Drawback: on-peak → it is possible to overcome it

W associated production

X generic spin-1 resonance of the SSM
W-prime type

$$\mathcal{L}_{eff}^{W'} = \frac{g_X}{\sqrt{2}} \left[V_{ij}^{CKM} \bar{u}_i \gamma^\mu P_L d_j \right.$$

$$\left. + V_{ij}^{PMNS} \bar{\nu}_i \gamma^\mu P_L \ell_j \right] X_\mu + H.c.$$



MDM bound state can be described by the effective W'
description with:

NV, JHEP 10 (2023) 121

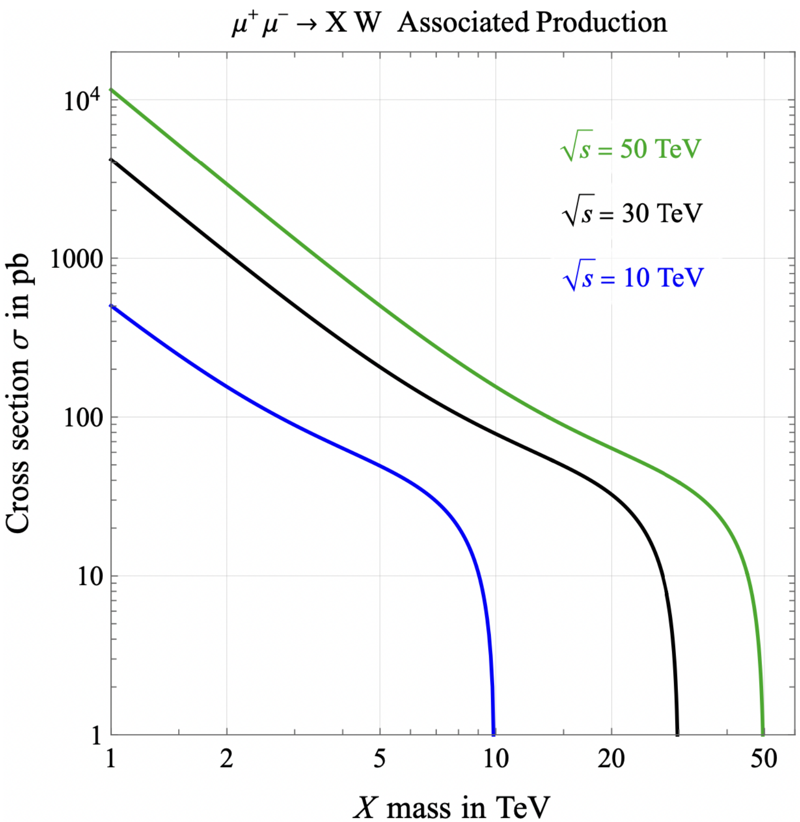
$$g_X = g_{1\, s_3} \simeq 0.014\, g_2$$

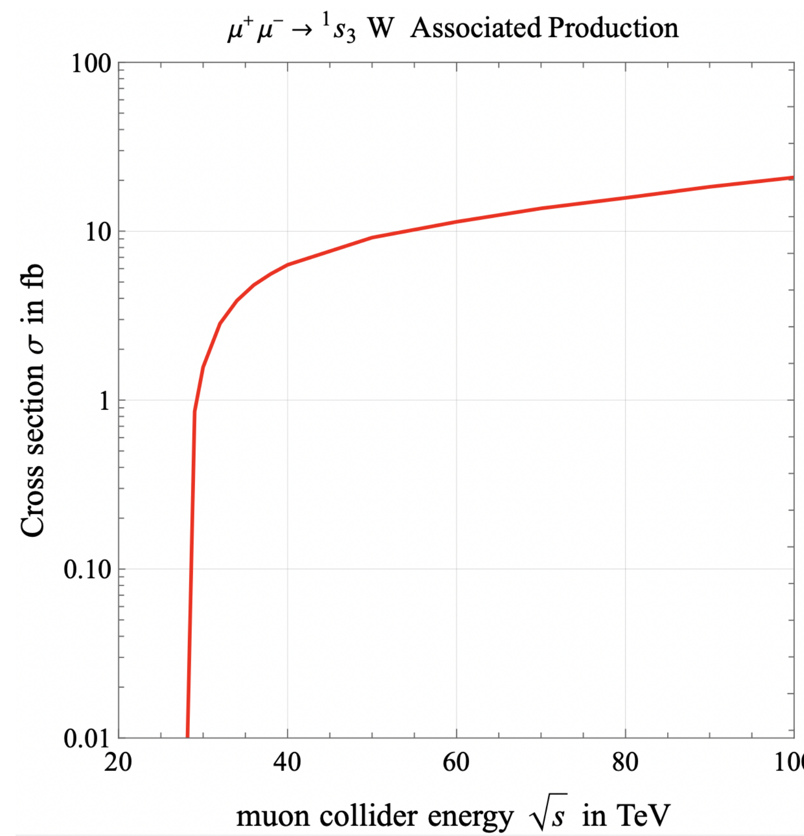
$$\sigma(\mu^+\mu^- \to X^+W^-) = \sigma(\mu^+\mu^- \to X^-W^+) \simeq$$

$$\frac{g_2^2\, g_X^2}{1536\, \pi\, s^2\, m_X^2\, m_W^2} \left[s^2 + 10\, m_X^2 s + m_X^4 + m_W^4 \right.$$

$$\left. + 10\, m_W^2 (s - 5 m_X^2) \right] \sqrt{(s - m_X^2)^2 - 2 m_W^2 (s + m_X^2) + m_W^4}$$

W associated production





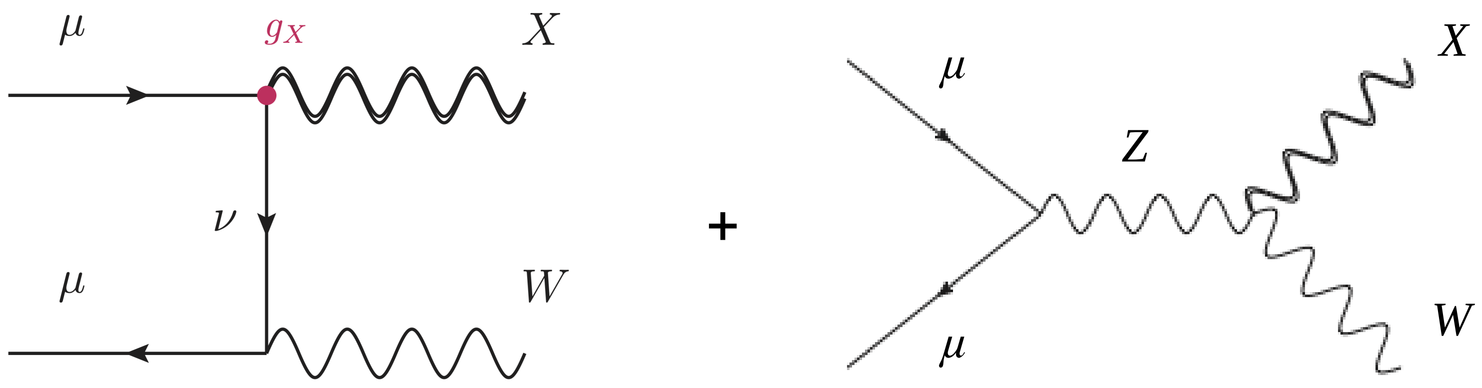
SSM case, $g_X = g_2$

MDM bound state

W associated production

In addition to SSM type resonances and MDM bound states, the associated production channel can also test resonances that emerge from a new strong dynamics (ex. in **Composite Higgs Models**)

In this case, the results we obtain are **conservative**, since will not include a significant contribution to the W associated production process, which is relevant for CHM and anologous strong-dynamics-induced EWSB theories (which have non-suppressed couplings W' VV):



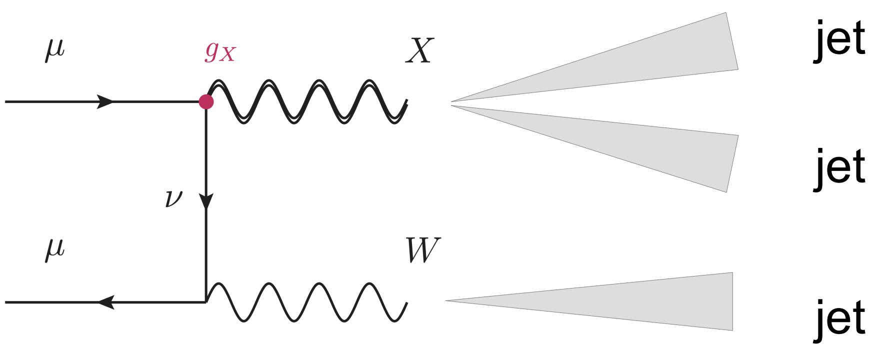
[Recent paper on composite resonances at a MuCol: Liu, Wang, Xie, JHEP 04 (2024) 084]

Search strategy

- Fully hadronic final state

  Acceptance selection

  At least 3 jets with:



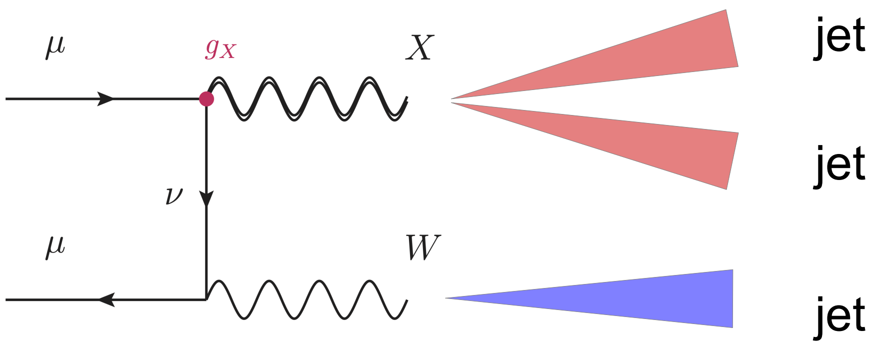
$$p_T\, j > 30\ \mathrm{GeV}\,, \quad |\eta_j| < 2.5\,, \quad \Delta R_{jj} > 0.4$$

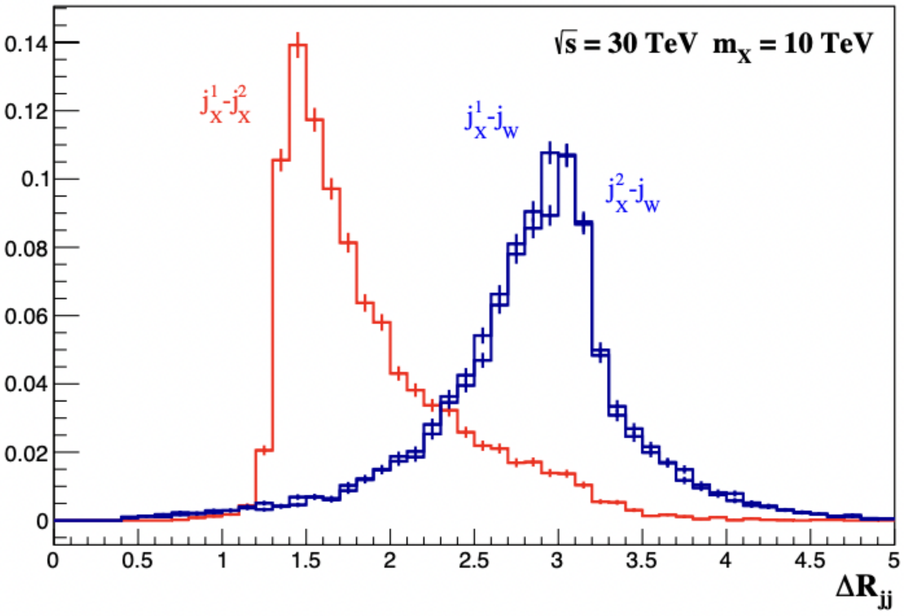
- Background is small, few fb before selection

  mainly given by Z/γ* → jets and (by a smaller component) VV → jets

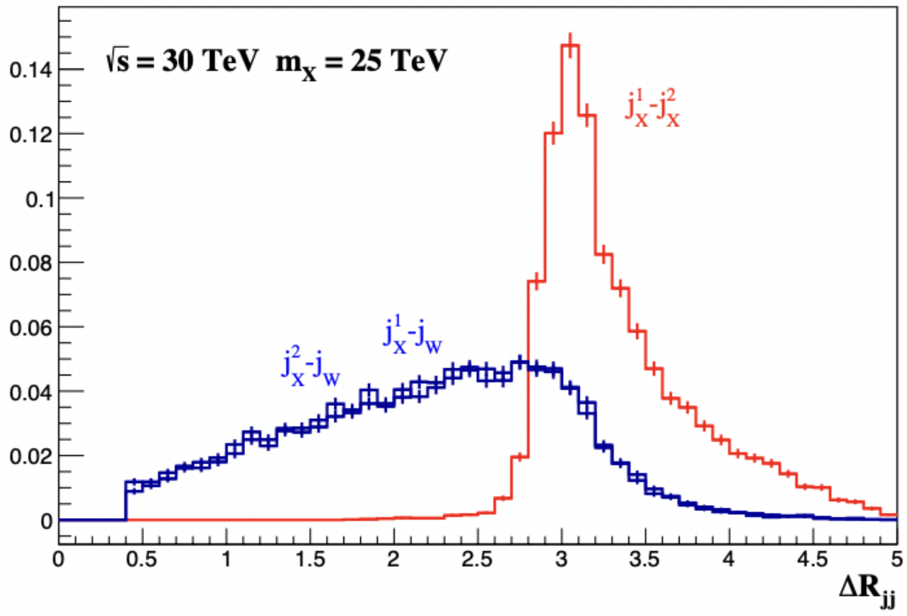
Search strategy

W, X reconstruction





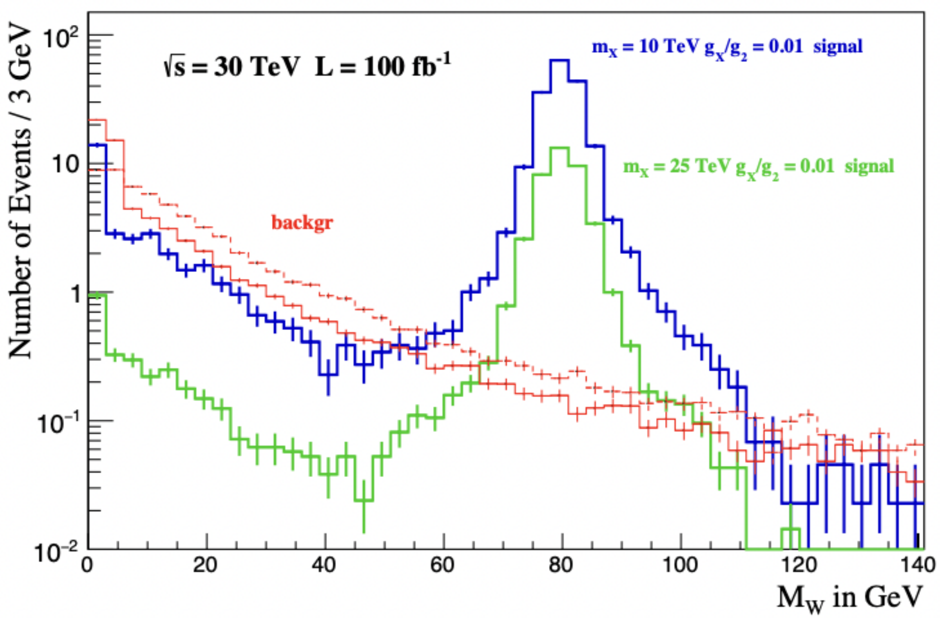
$m_X \leq \sqrt{s}/2$

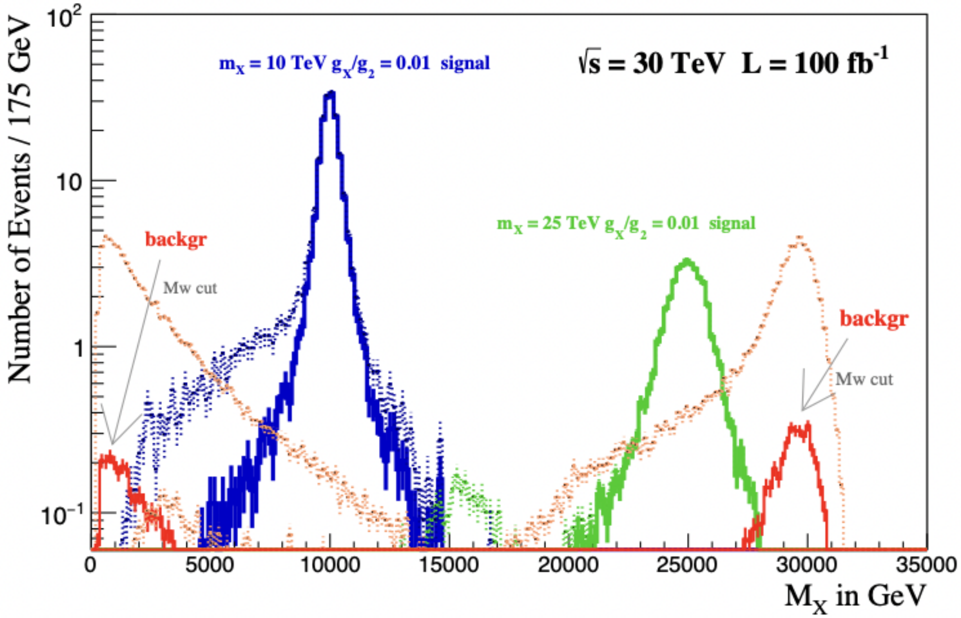


$m_X > \sqrt{s}/2$

Search strategy

W, X reconstruction

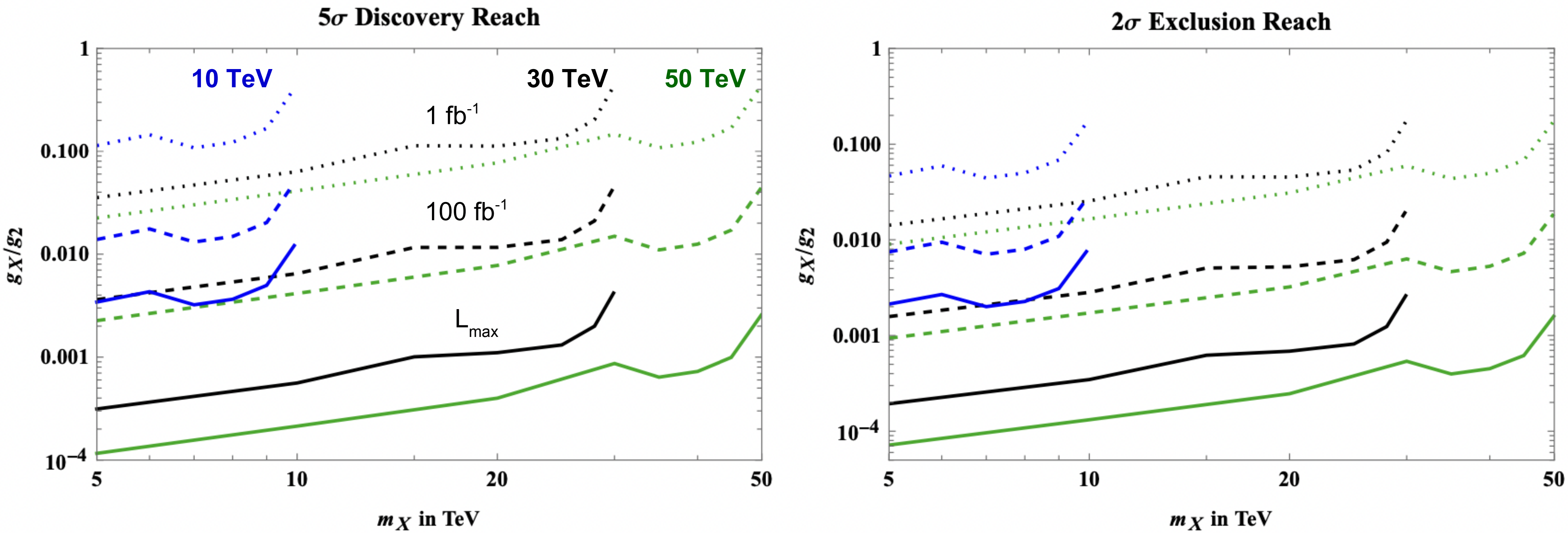




M_W cut:

$$50\,\mathrm{GeV} < M_W < 110\,\mathrm{GeV}$$

W+X Reach

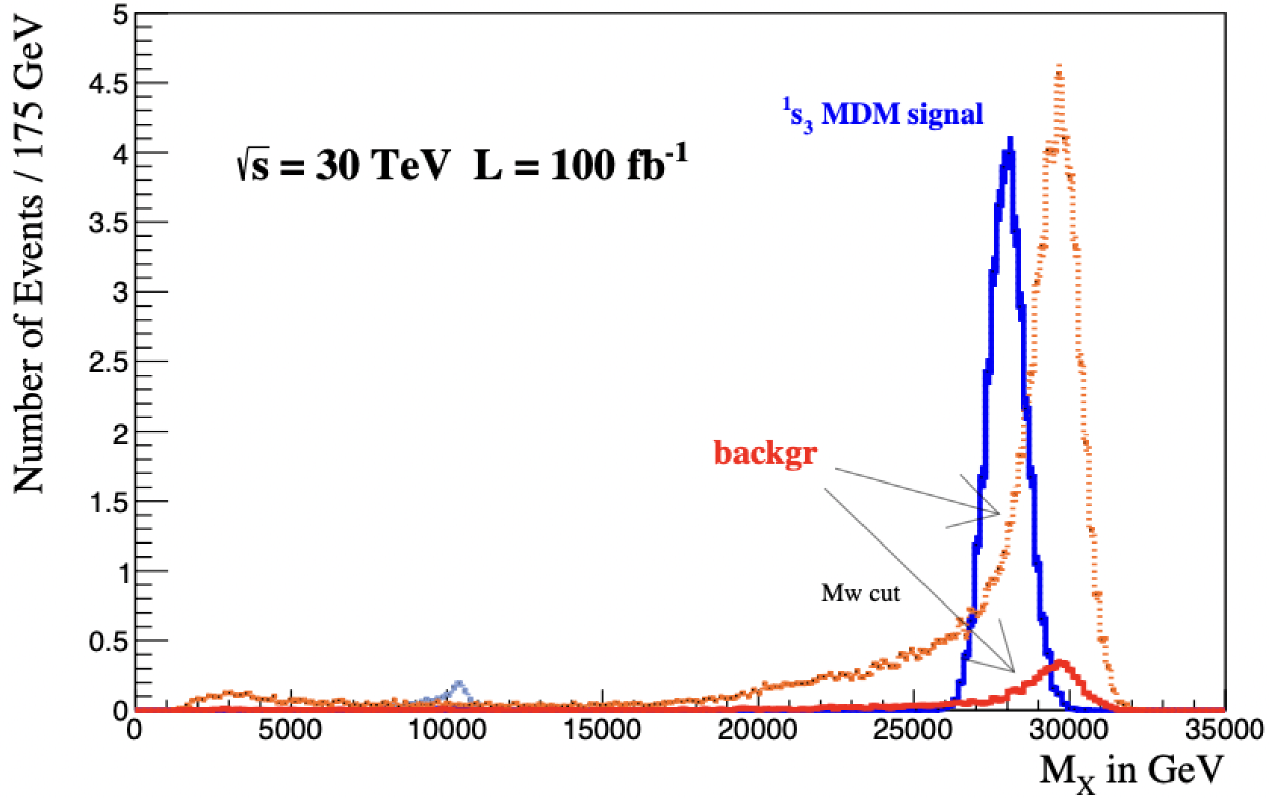


A SSM W-prime ($g_X=g_2$) with a mass up to 9, 28 and 46 TeV can be discovered respectively by a 10, 30 and 50 TeV MuCol with just 50/pb

In general, charged resonances ca be tested up to multi-TeV mass values close to the collision energy, and for **very small couplings** with the SM fermions, of the order of 10^{-3} - 10^{-4} times the SM weak coupling.

➡ **unprecedented level for a direct search** (FCC-hh reach ~1-2 orders of magnitude lower than 10 TeV MuCol reach [CERN Yellow Rep. (2017) 3])

MDM 5-plet buond state in the W associated channel



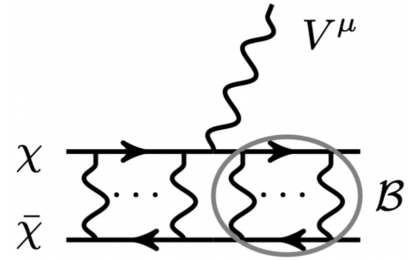
A 5-plet MDM bound state can be excluded with about 34 fb^{-1} and discovered with 210 fb^{-1} by a 30 TeV muon collider

Conclusions

- A multi-TeV muon collider proves to be very efficient not only for the search for new heavy neutral particles, but also for the discovery of charged bosons
- The W associated production allows to directly test charged resonances up to multi-TeV mass values close to the collision energy, and for very small couplings with the SM fermions, of the order of 10^{-3} - 10^{-4} times the SM weak coupling. This marks an unprecedented level of efficiency
- charged bound states of WIMP Minimal Dark Matter (the very special case of a Majorana fermionic 5-plet) can be discovered with low statistics by running above the kinematic threshold, at a center-of-mass energy just slightly above the mass of the MDM bound state:
  - very interesting possibility for the discovery of WIMPs, complementary to the search for the resonant production of the neutral MDM bound state component, which relies on an on-peak search.
  - For 5-plet MDM the proposed search strategy is more efficient than the WIMP searches based on mono-X, missing-mass and disappearing tracks signatures.

Extra slides

MDM bound states



When $M \gtrsim M_{W,Z}/\alpha_W$ Coulomb-like attractive potential

$$V = -\alpha_{\rm eff} \frac{e^{-M_{W,Z}\, r}}{r}$$

$$5 \otimes 5 = 1 \oplus 3 \oplus 5 \oplus 7 \oplus 9$$

$$I = 1 \; (\alpha_{\rm eff} = 6\alpha_2),\; I = 3 \; (\alpha_{\rm eff} = 5\alpha_2),\; \text{and} \; I = 5 \; (\alpha_{\rm eff} = 3\alpha_2)$$

leads to the formation of MDM bound states

$$E_B \approx \frac{\alpha_{\rm eff}^2 M}{4n^2}\left[1 - n^2 y - 0.53 n^2 y^2 \ell(\ell+1)\right]^2 \qquad \text{where} \qquad y \approx \frac{1.74 M_{W,Z}}{\alpha_{\rm eff} M}$$

Calculations (in $SU(2)_L$ symmetric approximation) first performed in A. Mitridate, M. Redi, J. Smirnov, A. Strumia, “Cosmological Implications of Dark Matter Bound States”, JCAP 05 (2017) 006

S. Bottaro, A. Strumia, NV, JHEP 06 (2021) 143

MDM bound states

name	Quantum numbers					Annihilation		Decay	
${}^n_J\ell_I^{PC}$	n	I	S	ℓ	E_B	$\Gamma_{\rm ann}$	into	$\Gamma_{\rm dec}$	into
${}^1_1s_1^{-+}$	1	1	0	0	118 GeV	$3240\,\alpha_2^5 M \approx 1.63\,\text{GeV}$	$V\tilde V$	0	—
${}^1_1s_3^{--}$	1	3	1	0	81 GeV	$15625\,\alpha_2^5 M/48 \approx 0.17\,\text{GeV}$	$f_L\bar f_L + HH^*$	$36\,\alpha_2^6\alpha_{\rm em}M \approx 4.6\,\text{keV}$	${}^1s_1\gamma$
${}^1_1s_5^{-+}$	1	5	0	0	26 GeV	$567\,\alpha_2^5 M/4 \approx 0.07\,\text{GeV}$	VV	$295\,\alpha_2^6\alpha_{\rm em}M \approx 38\,\text{keV}$	${}^1s_3\gamma$
${}^2_1s_1^{-+}$	2	1	0	0	20.3 GeV	$405\alpha_2^5 M \approx 0.2\,\text{GeV}$	$V\tilde V$	$13\,\alpha_2^6\alpha_{\rm em}M \approx 1.7\,\text{keV}$	${}^1s_3\gamma$
${}^2_1s_3^{--}$	2	3	1	0	13 GeV	$15625\,\alpha_2^5 M/384 \approx 21\,\text{MeV}$	$f_L\bar f_L + HH^*$	$(6.9\,\alpha_2 + 0.3\,\alpha_{\rm em})\alpha_2^6 M \approx 3.7\,\text{keV}$	${}^1s_{1+5}V$
${}^2_1s_5^{-+}$	2	5	0	0	2.6 GeV	$567\,\alpha_2^5 M/32 \approx 9\,\text{MeV}$	$V\tilde V$	$28.4\,\alpha_2^6\alpha_{\rm em}M \approx 3.6\,\text{keV}$	${}^1s_3\gamma$
${}^2_Jp_1^{++}$	2	1	1	1	19.7 GeV	$\mathcal{O}(\alpha_2^7 M) \sim \text{keV}$	VV	$20.4\,\alpha_2^4\alpha_{\rm em}M \approx 2.5\,\text{MeV}$	${}^1s_3\gamma$
${}^2_1p_3^{+-}$	2	3	0	1	12 GeV	$\mathcal{O}(\alpha_2^8 M) \sim 10\,\text{eV}$	VVV	$(30.2\,\alpha_2 + 0.3\,\alpha_{\rm em})\,\alpha_2^4 M \approx 15.3\,\text{MeV}$	${}^1s_{1+5}V$
${}^2_Jp_5^{++}$	2	5	1	1	2.2 GeV	$\mathcal{O}(\alpha_2^7 M) \sim \text{keV}$	VV	$4.7\,\alpha_2^4\alpha_{\rm em}M \approx 0.6\,\text{MeV}$	${}^1s_3\gamma$
${}^3_1s_1^{-+}$	3	1	0	0	3.8 GeV	$120\alpha_2^5 M \approx 60\,\text{MeV}$	$V\tilde V$	$0.34\,\alpha_2^4\alpha_{\rm em}M \approx 42\,\text{keV}$	${}^2p_3\gamma$
${}^3_1s_3^{--}$	3	3	1	0	1.7 GeV	$15625\alpha_2^5 M/1296 \approx 6.0\,\text{MeV}$	$f_L\bar f_L + HH^*$	$(0.003 + 0.005)\alpha_2^4\alpha_{\rm em}M \approx 1\,\text{keV}$	${}^2p_{1+5}\gamma$
${}^3_1s_5^{-+}$	3	5	0	0	1.7 MeV	$21\alpha_2^5 M/4 \approx 2.7\,\text{MeV}$	$V\tilde V$	$0.3\alpha_2^4\alpha_{\rm em}M \approx 36\,\text{keV}$	${}^2p_3\gamma$
${}^3_Jd_3^{--}$	3	3	1	2	0.9 GeV	$\mathcal{O}(\alpha_2^9 M) \sim \text{eV}$	$f_L\bar f_L$	$0.4\alpha_2^4\alpha_{\rm em}M \approx 52\,\text{keV}$	${}^2p_{1+5}\gamma$

We are particularly interested in the states that can be directly produced at a MuCol: the isospin triplets
Scalar bound state can be produced via VBF, but with lower cross sections