WIMPs at Muon colliders

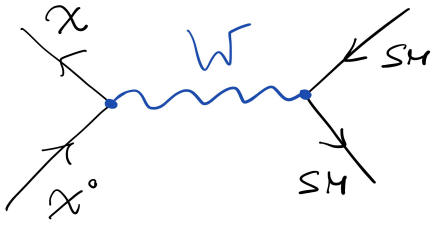
S.Bottaro, D.Buttazzo, M.Costa, R.Franceschini, P.Panci, D.Redigolo, L.Vittorio

2107.09688

Based on: Di Luzio et al. 1810.10993, Han et al. 2009.11287, Capdevilla et al. 2102.11292, Bottaro et al. 2103.12766

Which WIMP?

- **EW** interaction sets abundance: **M** only parameter



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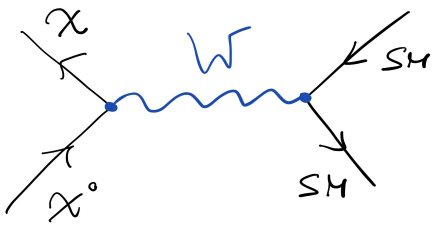
$$T_3 + Y = 0$$



$$(1, n)_0 \left\{ \begin{array}{c} \cdots \\ \chi^+ \\ \chi^0 \\ \chi^- \\ \cdots \end{array} \right.$$

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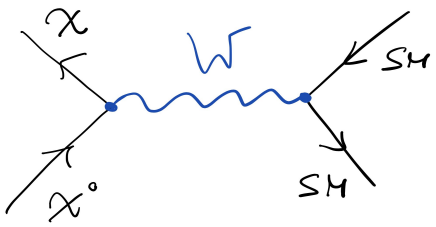

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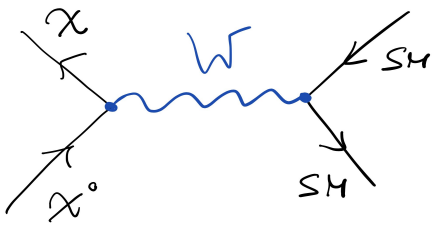

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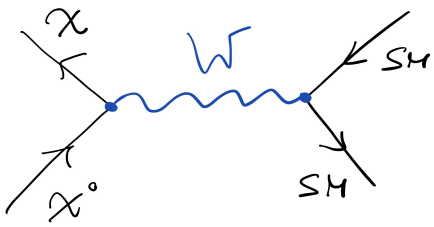

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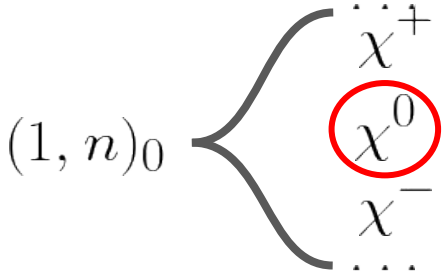

- Real odd-plets **SPECIAL**: IR physics **independent** on completion

- **Computability**: SU(2) Landau Pole >> M ⇒**n≤13**

Computing the DM Relic Abundance

Boltzmann equation: $$\frac{\mathrm{d}Y}{\mathrm{d}x} = -\frac{s(x)}{xH(x)}\langle\sigma v\rangle\left(1 - \frac{x}{3g_*(x)}\frac{\mathrm{d}g_*}{\mathrm{d}x}\right)\left(Y^2(x) - Y_{eq}^2(x)\right)$$

M.Costa (SNS and INFN, Pisa)

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WHICH CROSS-SECTION?

Std. tree-level cross-section: $$\langle\sigma v\rangle_0 = \frac{\pi\alpha_2^2(2n^4 + 17n^2 - 19)}{16 g_\chi M_\chi^2}$$

Correct...

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- Sommerfeld enhancement
- Bound states formation

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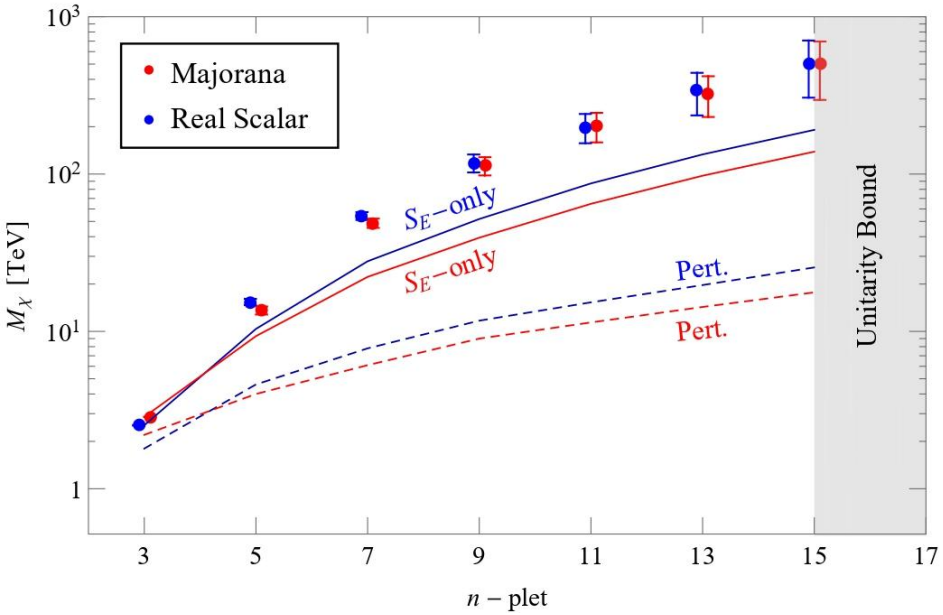
keep in mind for later!

Thermal target results



DM spin	EW n-plet	M_χ (TeV)
Real scalar	3	2.53 ± 0.01
	5	15.4 ± 0.7
	7	54.2 ± 3.1
	9	117.8 ± 15.4
	11	199 ± 42
	13	338 ± 102
Majorana fermion	3	2.86 ± 0.01
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	9	113 ± 15
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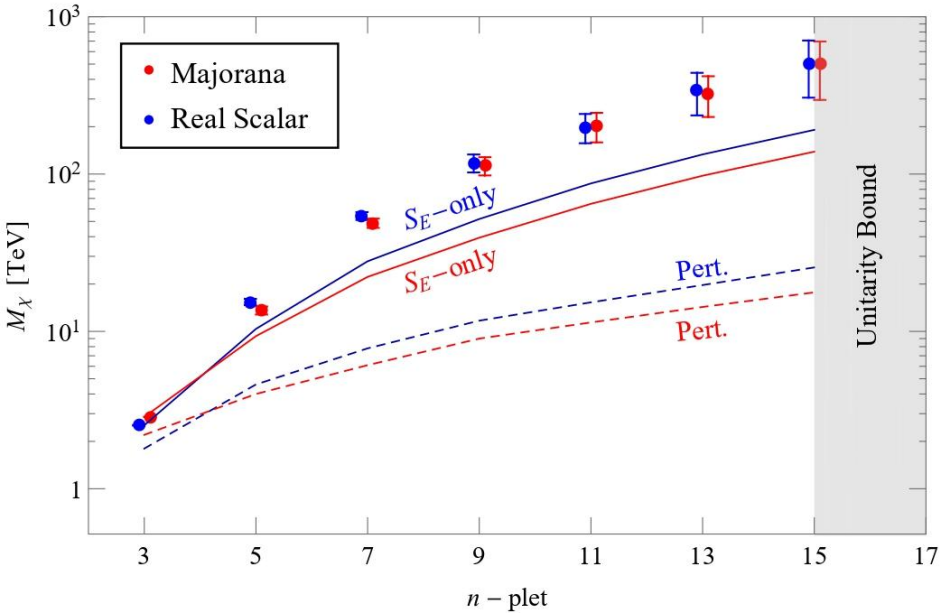

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30-ish TeV collider might probe them

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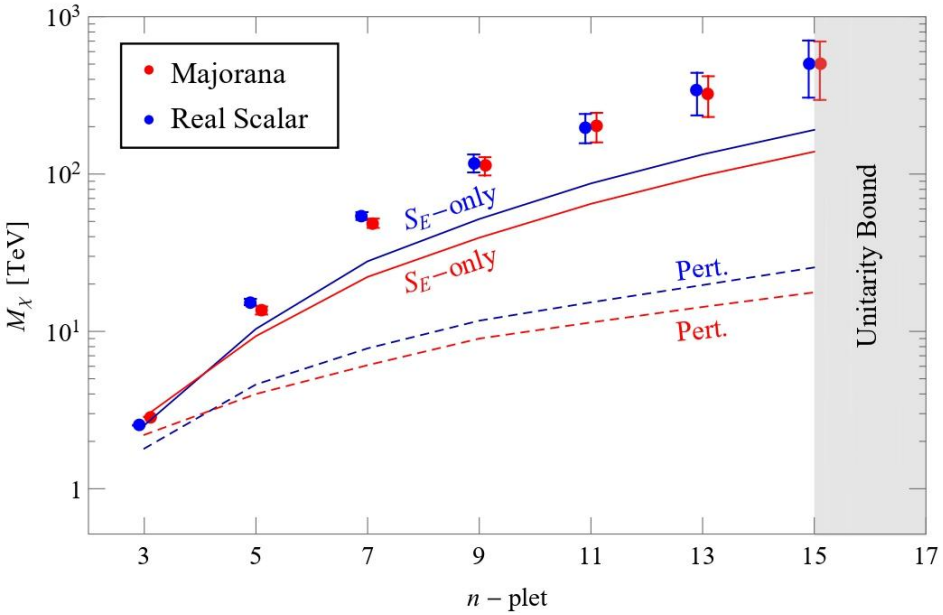

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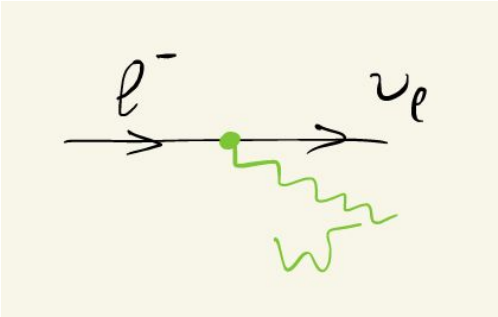
Need at least 100 TeV collider!

WIMPs @ high energy lepton colliders

Why high energy lepton colliders?

- **EW nature of signal** : high energy lepton collider as

  “EW bosons collider”



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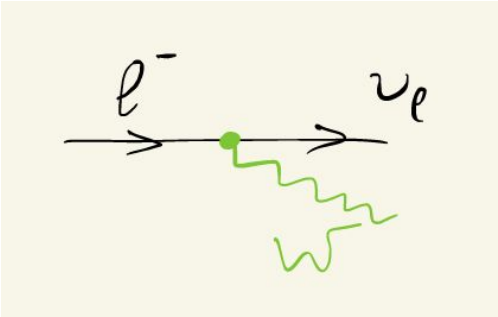

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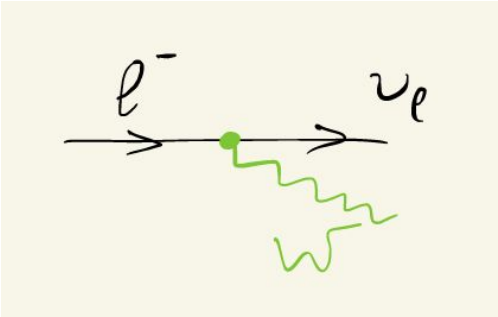
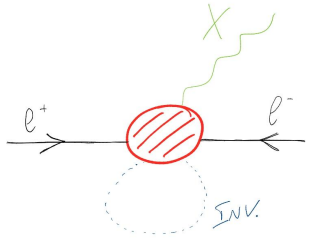
- **More energy in hard cross section**: needed since WIMPs are heavy



How to detect WIMPs @ Muon Collider?

- **Recoils** against invisible objects: **Mono-X,Di-X**

  (monoɣ, monoZ, monoW, monoμ, Diɣ, DiW, Diμ)



Han et al. 2009.11287

Bottaro, MC et al. 2107.09688

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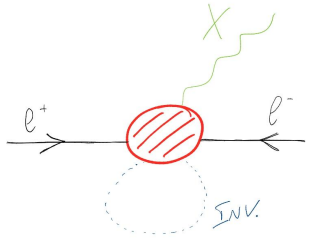

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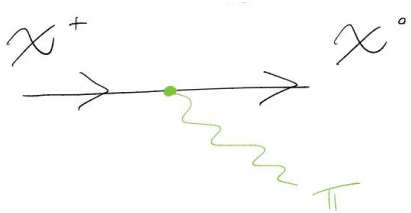
- **Disappearing tracks**: **lifetime robust prediction**



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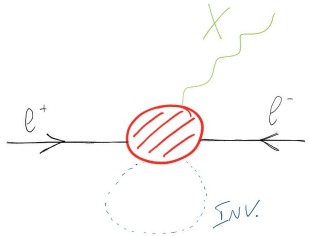

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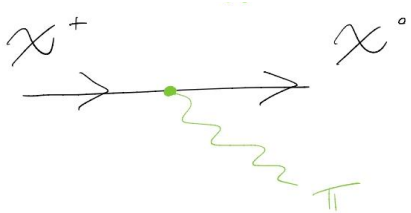

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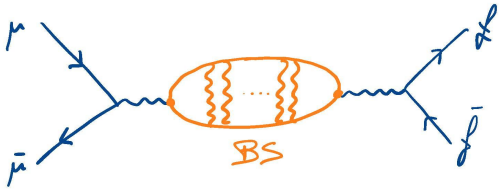
- **Resonances**: **Bound States**

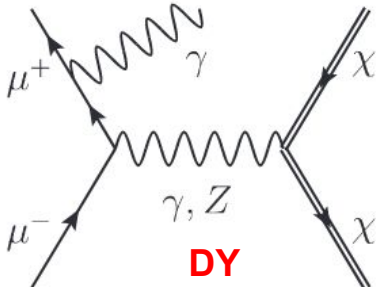
Bottaro et al. 2103.12766



Missing Mass search example: mono-γ

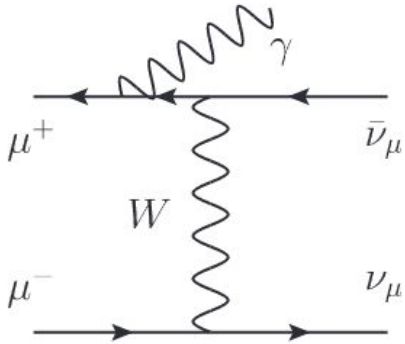
γ

Sig



$$\mu^-\mu^+ \to \gamma\chi^n\chi^{-n}$$

Bkg



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ISR(/FSR)

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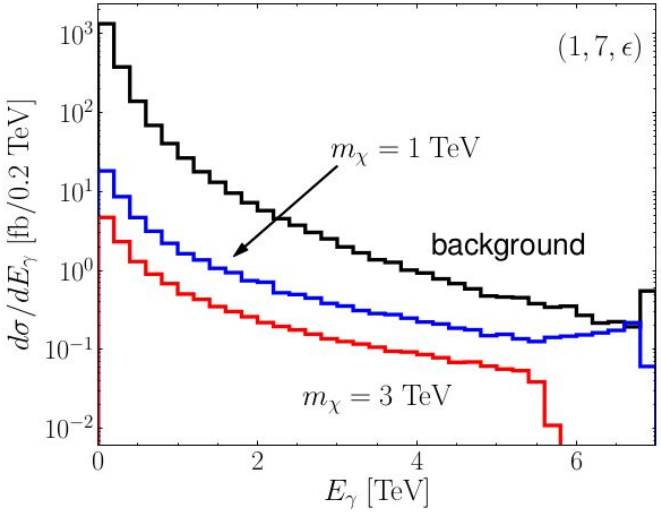
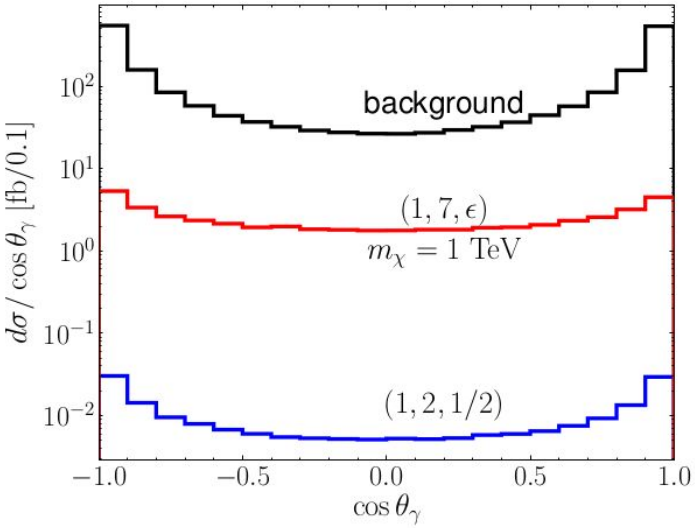
Han et al.2009.11287





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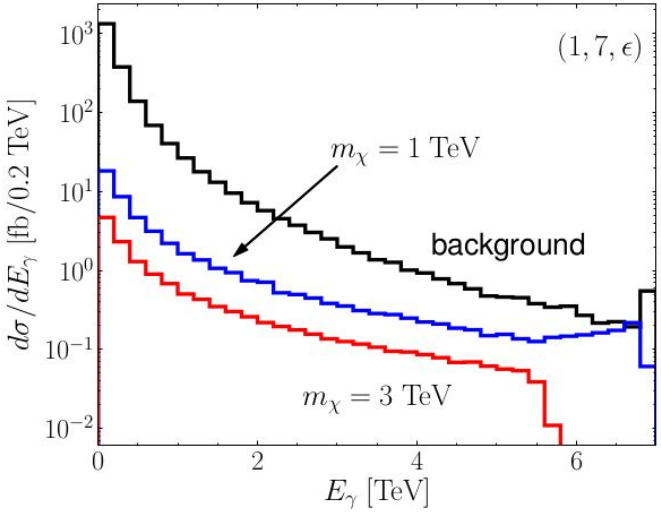
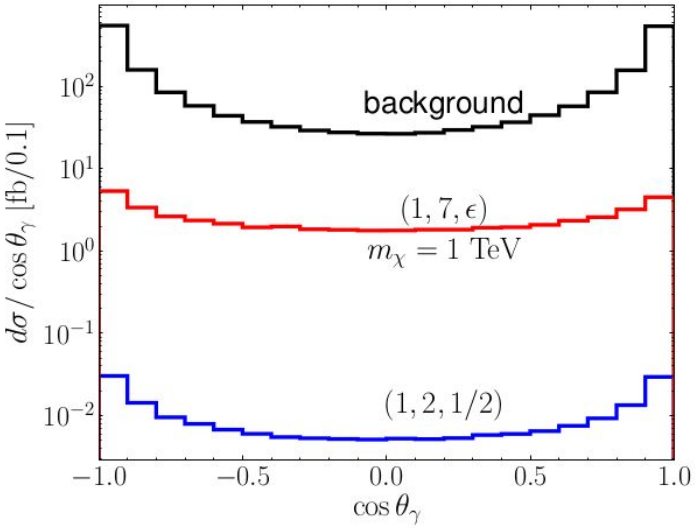


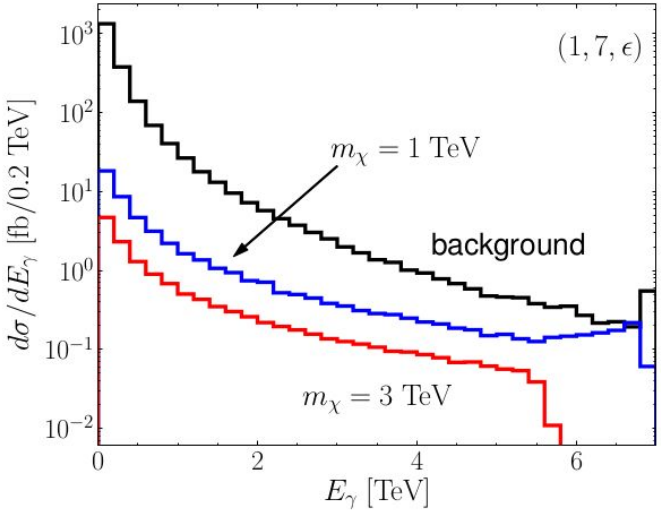


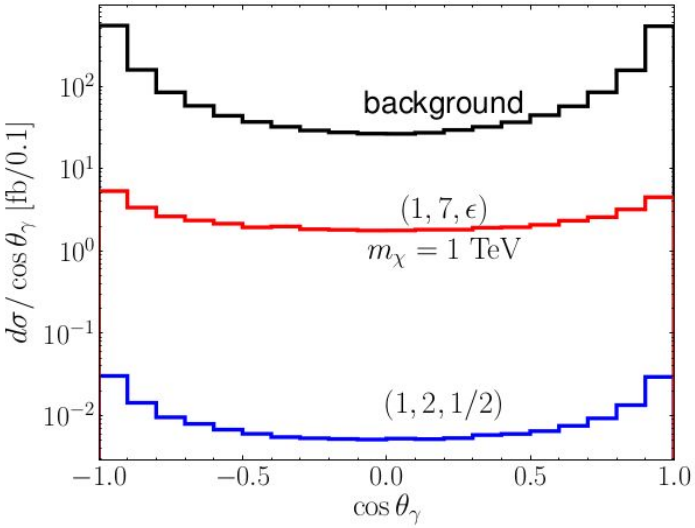
$$\frac{S}{\sqrt{S + B + (\epsilon_S S)^2 + (\epsilon_B B)^2}}$$

S/B<0.1% LOW!

Missing Mass search example: mono-γ

Han et al.2009.11287





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S/B<0.1% LOW!

$$\mathrm{MIM} > 2m_\chi \ , \quad |\eta_\gamma| < \eta_{\gamma\mathrm{cut}} \ , \quad \mathrm{MET} > \mathrm{MET}_{\mathrm{cut}}$$

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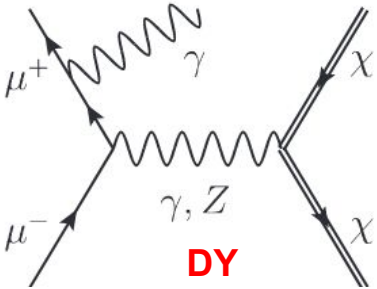
Mono-V

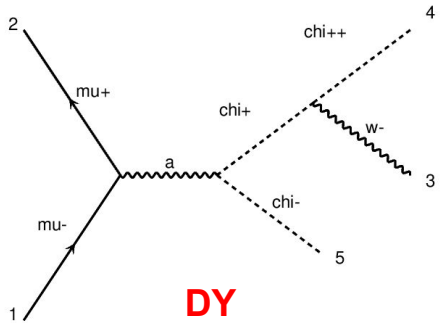
γ/Z

W

Sig

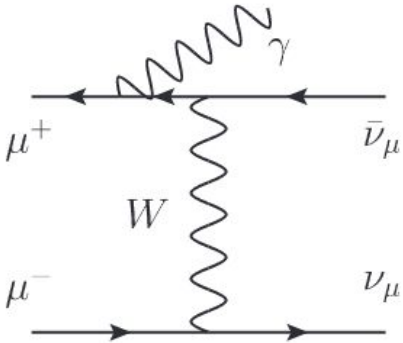


DY

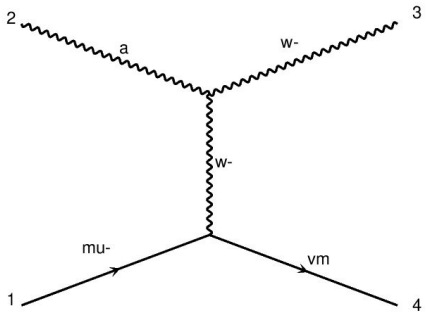


DY

Bkg



ISR(/FSR)

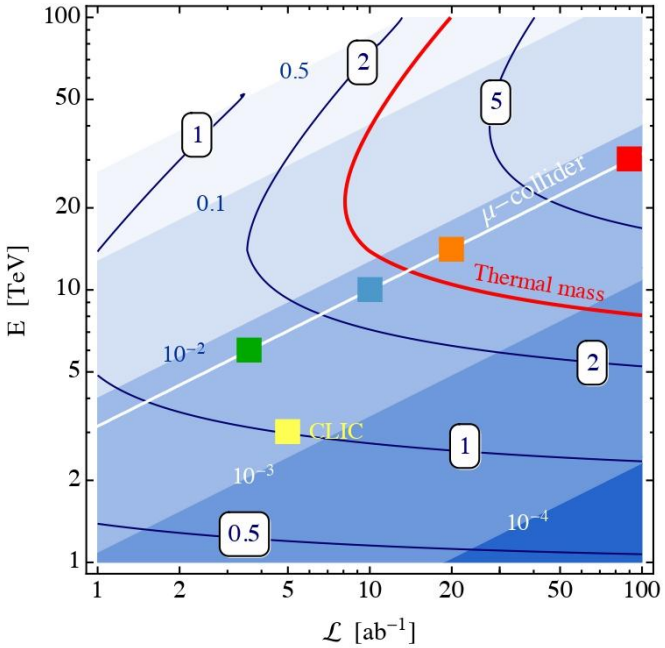


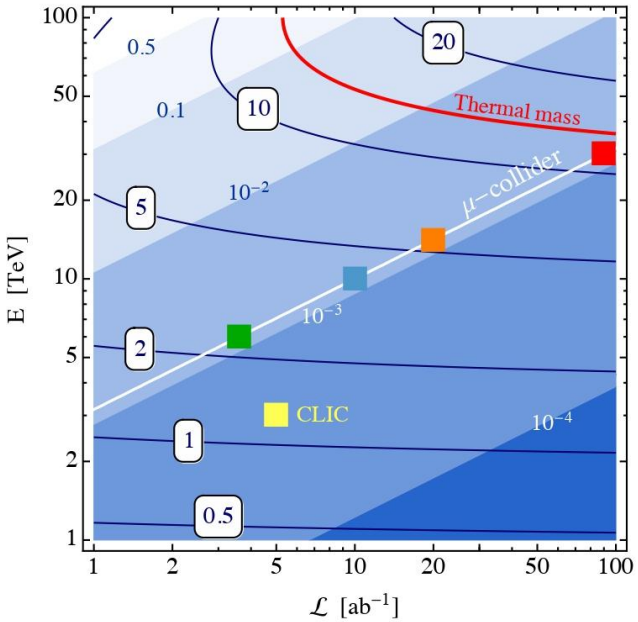
VBF

Lumi vs Energy (Mono-W)

$$\mathcal{L} \simeq 10\ \mathrm{ab}^{-1} \cdot \left(\frac{\sqrt{s}}{10\ \ \mathrm{TeV}}\right)^2$$

3F **ϵ=0%** **5F**





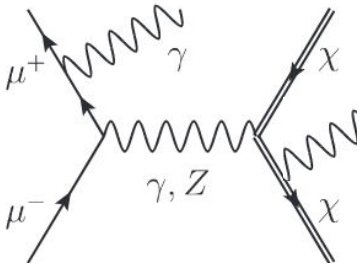
2σ: 12 TeV **2σ: 35 TeV**

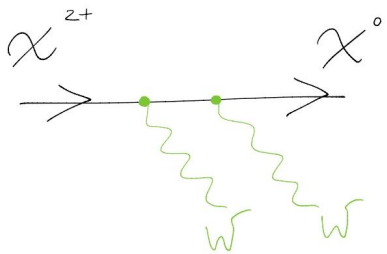
Di-V

Di-γ

Di-W (same sign)

Sig





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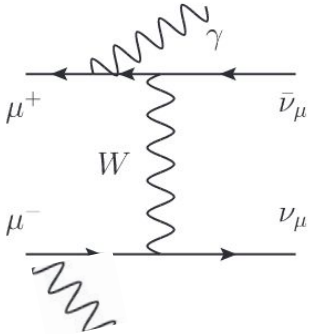


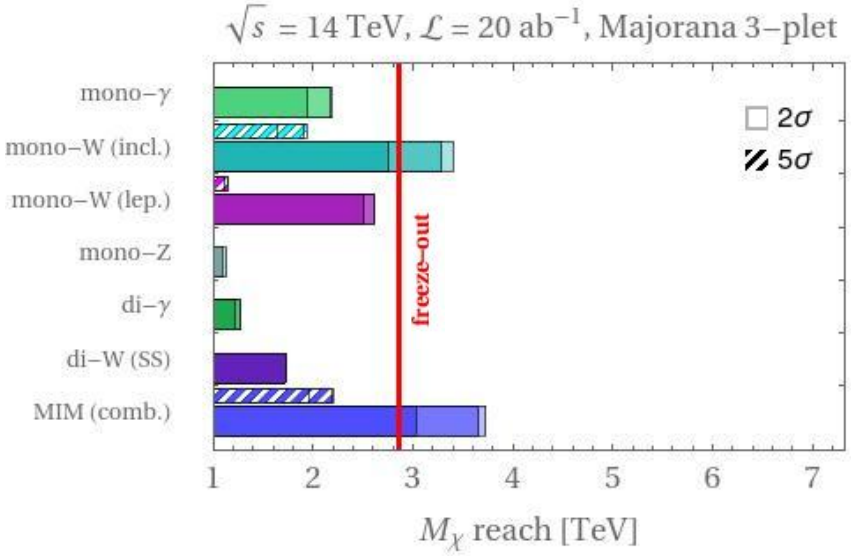
W+W-$\nu\nu$ + mistag

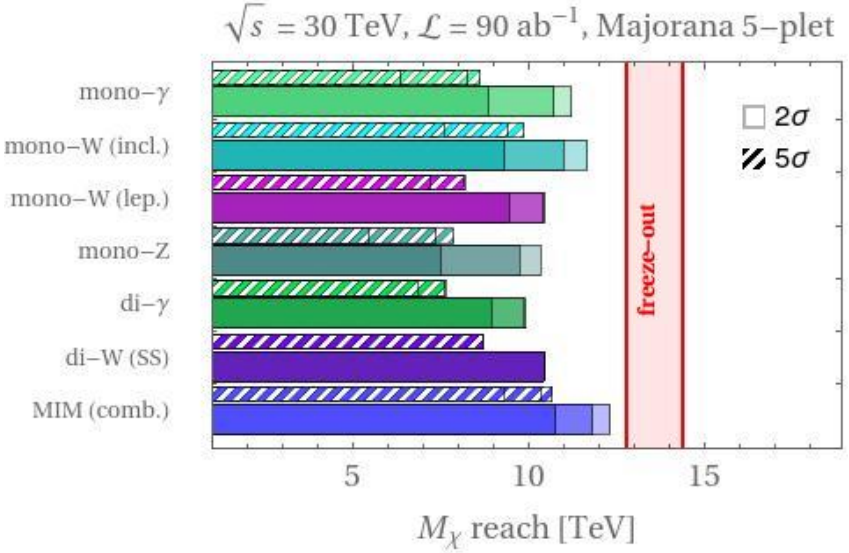
ϵ mistag=0.1%

Exploit high EW charge of signal

Mono-X & Di-X results

ϵ= 0%, 0.1%, 1%





Mono-X: Mono-W best; S/B<0.1%: need strong pT cuts (E/4-ish)
Di-X: Good for 5; S/B up to 1; robust to **ϵ**

M.Costa (SNS and INFN, Pisa)

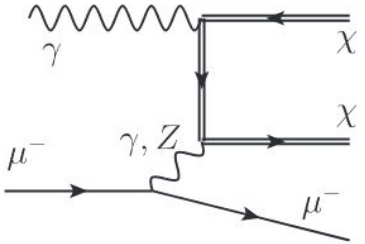
Muon channels

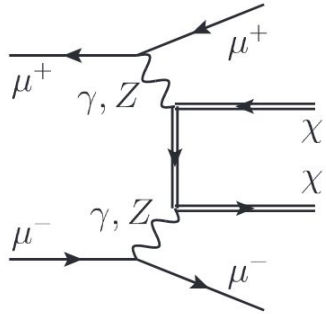
Han et al.
2009.11287

Mono-μ

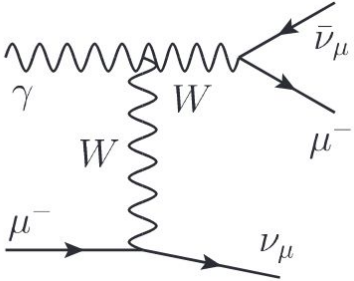
Di-μ

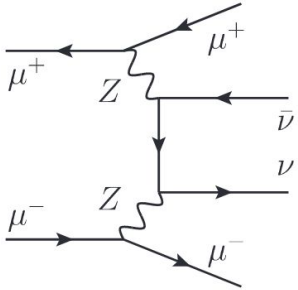
Sig





Bkg



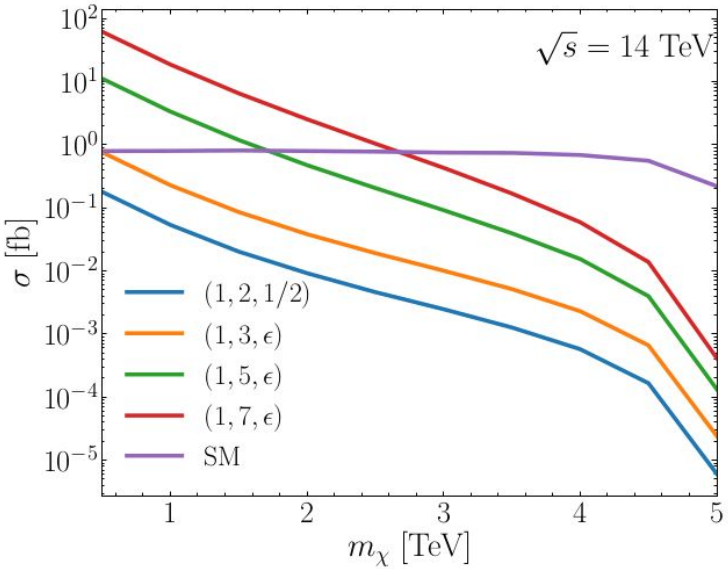


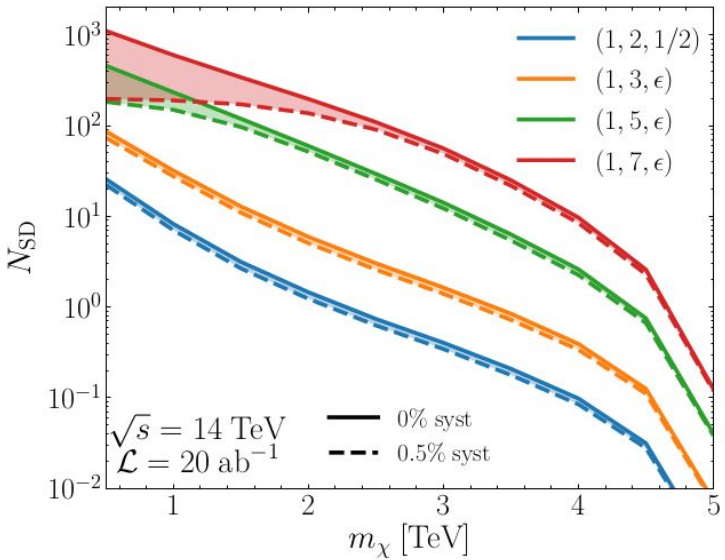
VBF channels

M.Costa (SNS and INFN, Pisa)

Mono-μ results

Han et al.
2009.11287



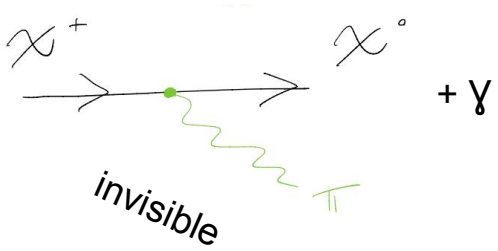


Good at low mass

Disappearing Tracks

Disappearing condition:
decay between 5 cm and 12.7 cm

Sig

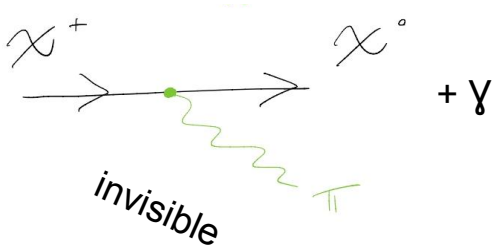


Bkg

BIB hits reconstructed as tracks + γ

Disappearing Tracks

Sig



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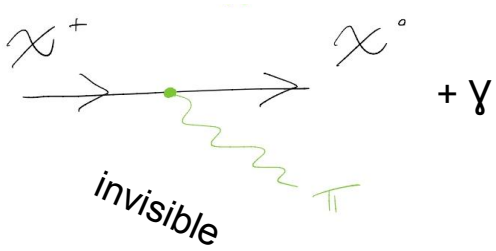
Recast of Capdevilla et.al
2102.11292

For details of analysis:
see next talk by J.Zurita

Disappearing Tracks

Sig



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Recast of Capdevilla et.al
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For details of analysis:
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Bkg BIB hits reconstructed as tracks + γ

Splitting/lifetime FIXED for real WIMPs

$$M_Q - M_0 \simeq \frac{Q^2 \alpha_{\rm em} m_W}{2(1+\cos\theta_W)} \; ; \quad c\tau_{\chi^+} \simeq \frac{120 \text{ mm}}{T(T+1)}$$

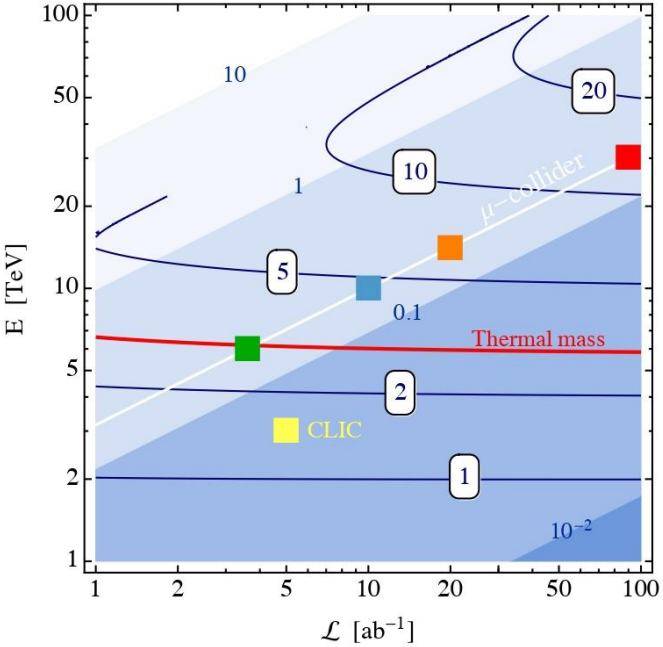
M.Costa (SNS and INFN, Pisa)

Lumi vs Energy (DT)

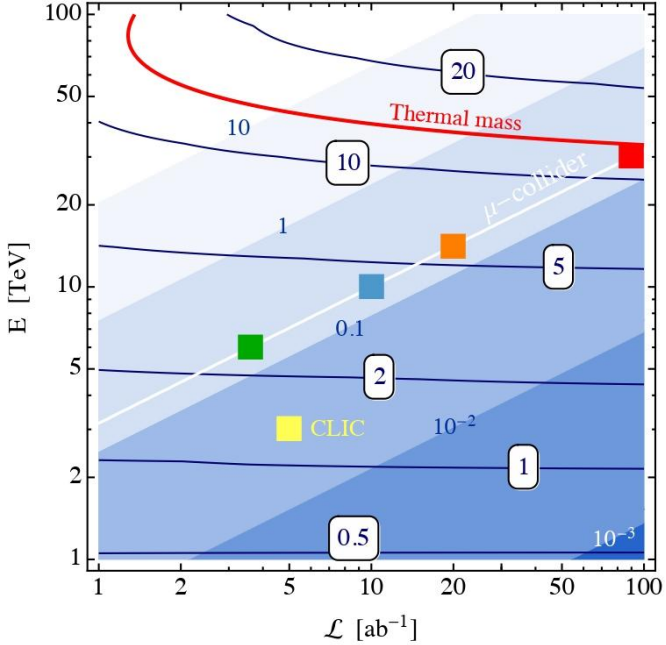
3F

ϵ=0%

5F



2σ: 6 TeV

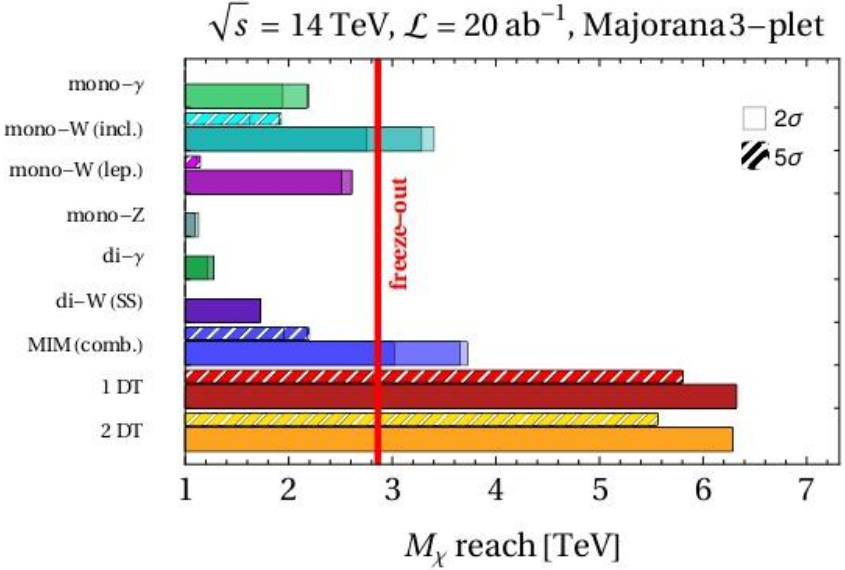


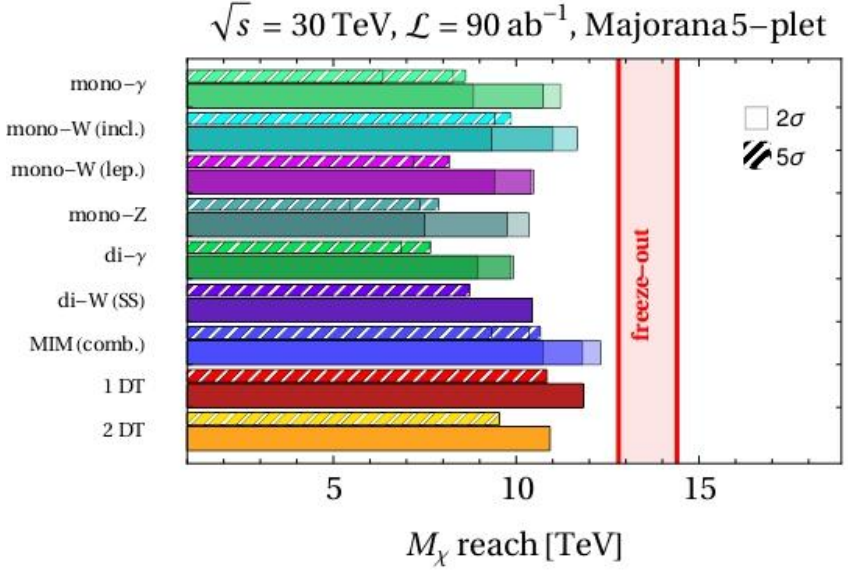
2σ: 35 TeV...

Mono-X & Di-X results

Bottaro, MC et al. 2107.09688c

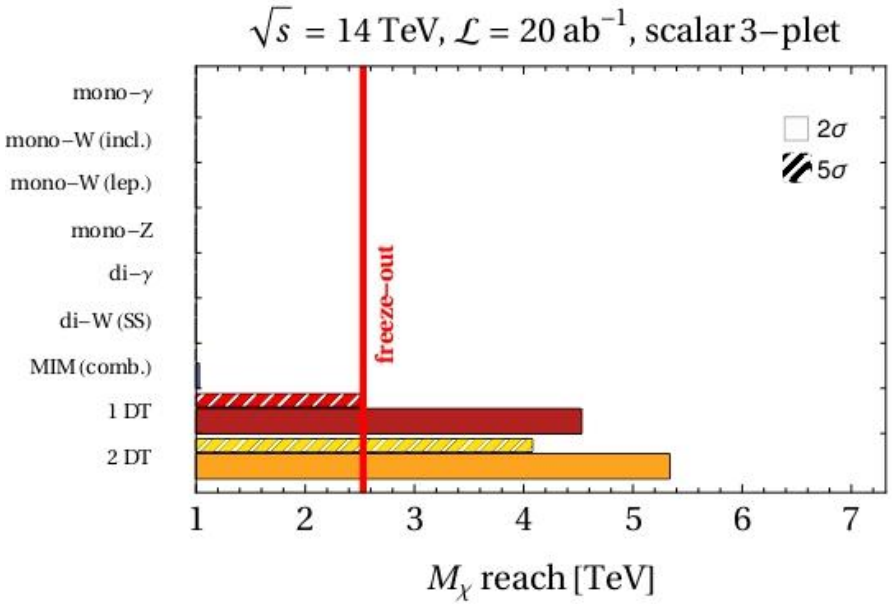
ϵ= 0%, 0.1%, 1%





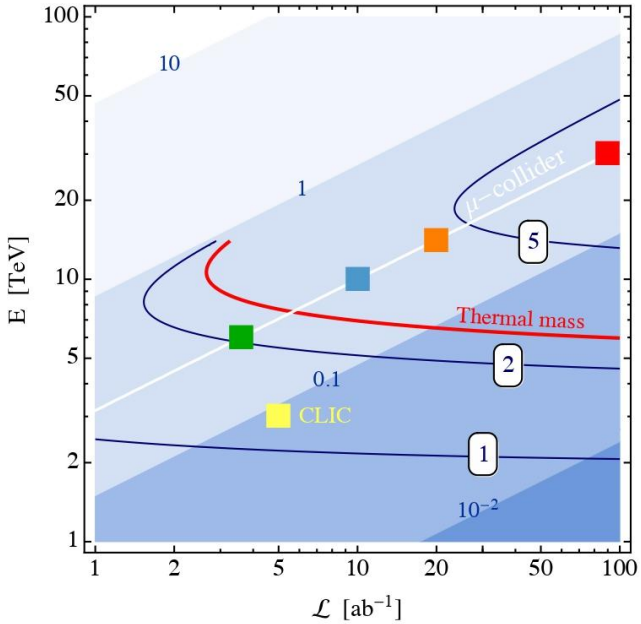
1DT: Good for 3; For 5 comparable to MIM

Scalar WIMPs



3S: DTs only hope

3S (Disappearing Tracks)



2σ: 8 TeV

M.Costa (SNS and INFN, Pisa)

Bound States (5F only)

Bottaro et al. 2103.12766

Peaks in ee cross section

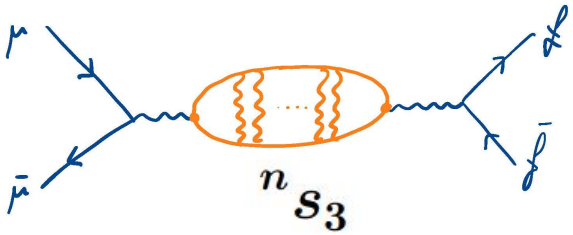
For indirect searches (virtual corrections) in $\mu\mu \to$ee:
Di Luzio et al. 1810.10993

Bound States (5F only)

Bottaro et al. 2103.12766

Peaks in ee cross section

same QN as W's!
s-channel mixing



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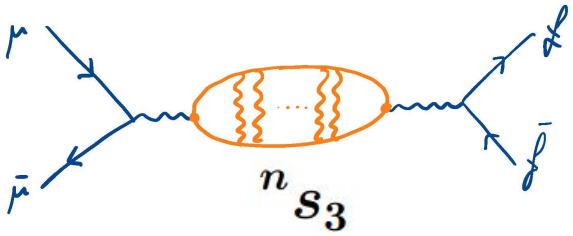

$$\sigma(i_1 i_2 \to B \to f) \approx \mathrm{BW}(s)\sigma_{\mathrm{peak}}$$

Convoluted with Gaussian beam
Energy spread
O(1-10 GeV) vs O(0.1-1GeV) widths

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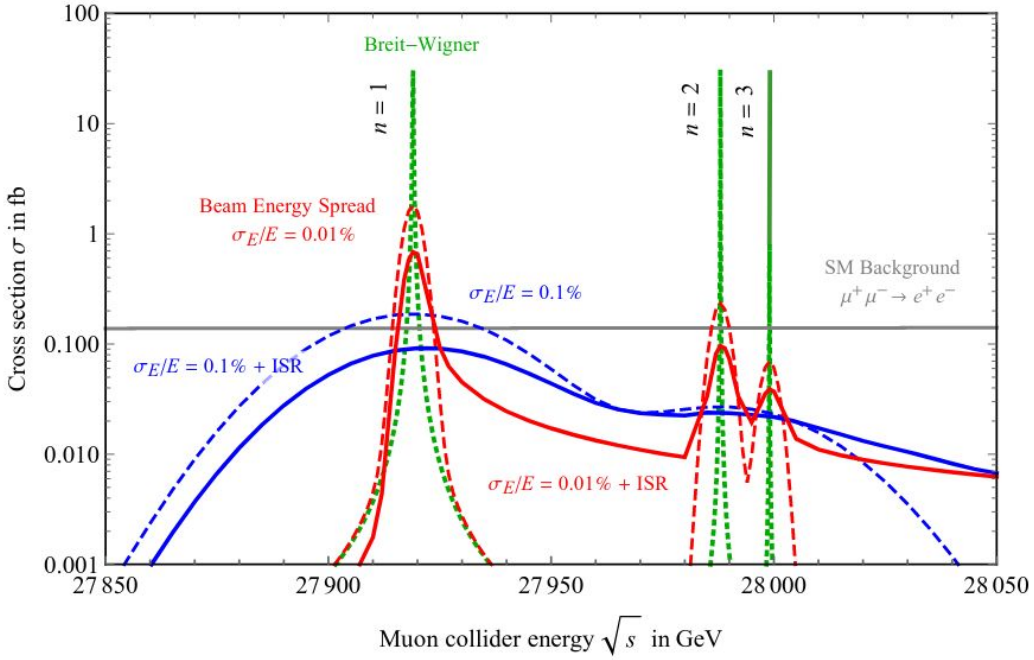
Bottaro et al. 2103.12766



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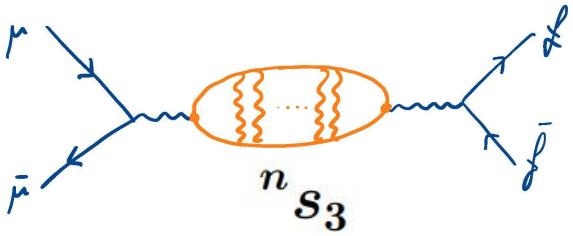

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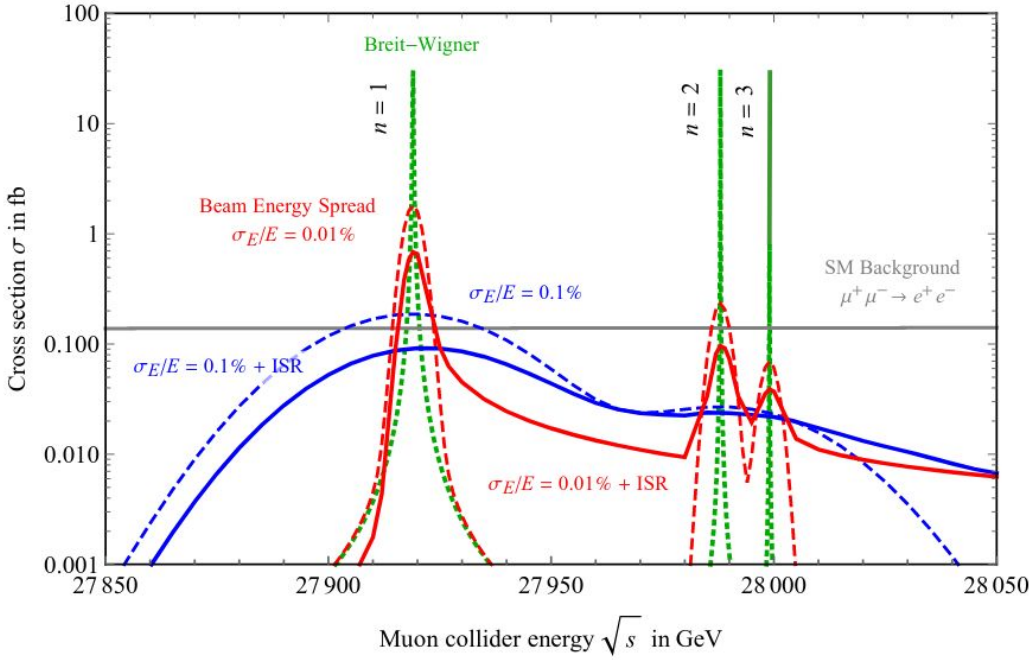

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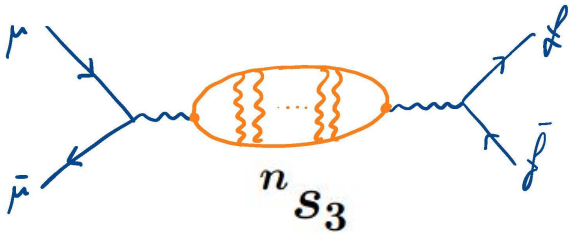

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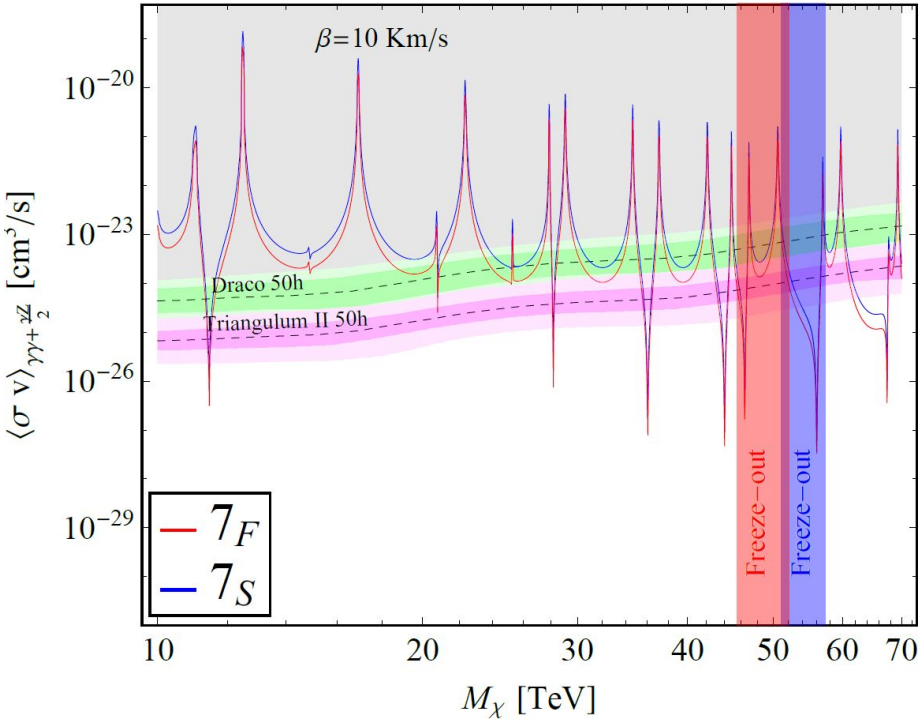
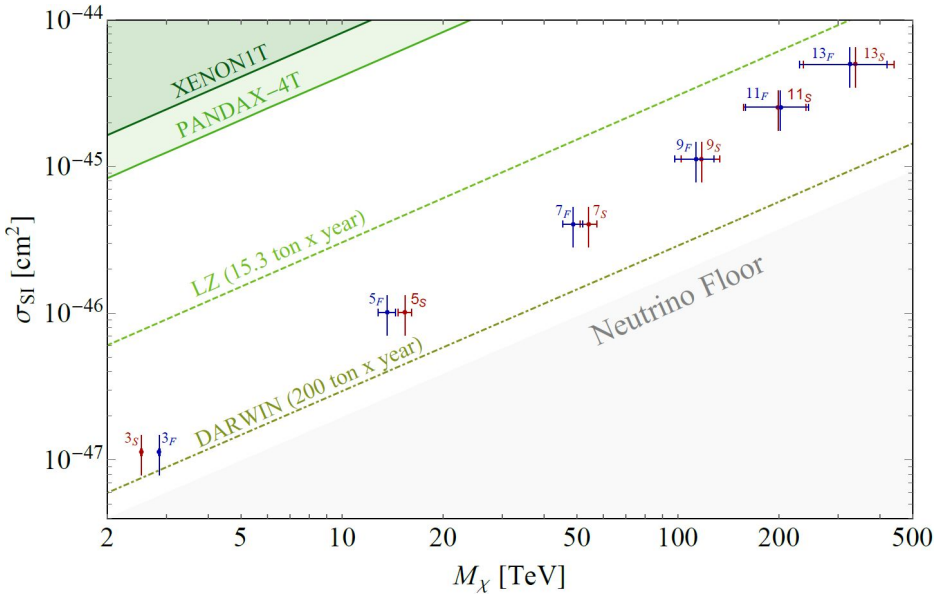
Collider vs ID/DD





recast from Panci et al.
1608.00786

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M.Costa (SNS and INFN, Pisa)

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M.Costa (SNS and INFN, Pisa)

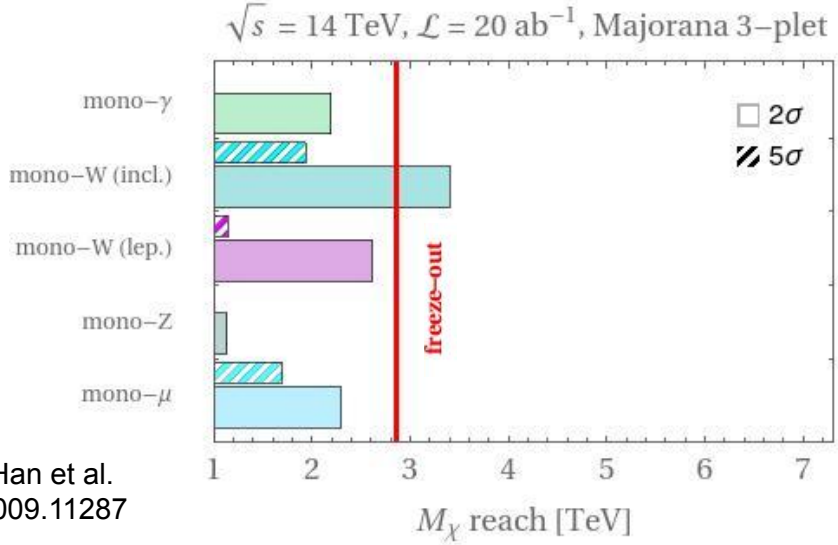
Thanks for the attention!

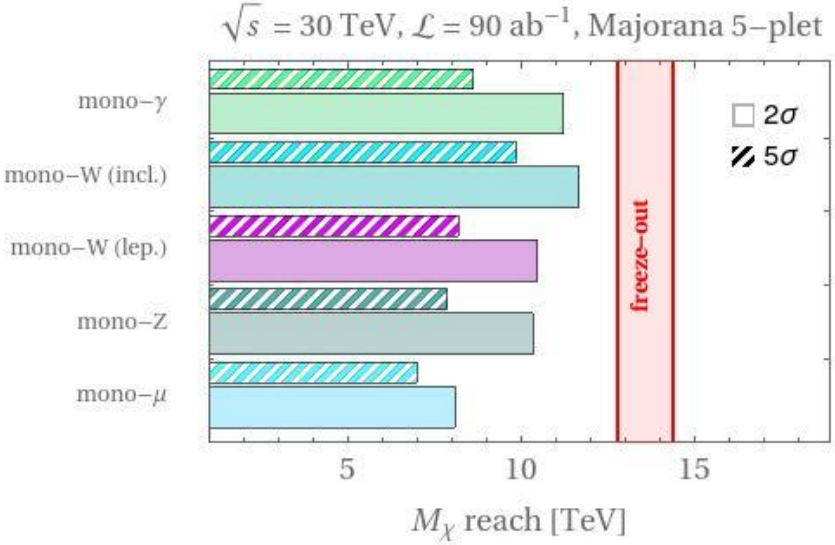
Backup

Mono-X

ϵ=0%

Bottaro, MC et al. 2107.09688



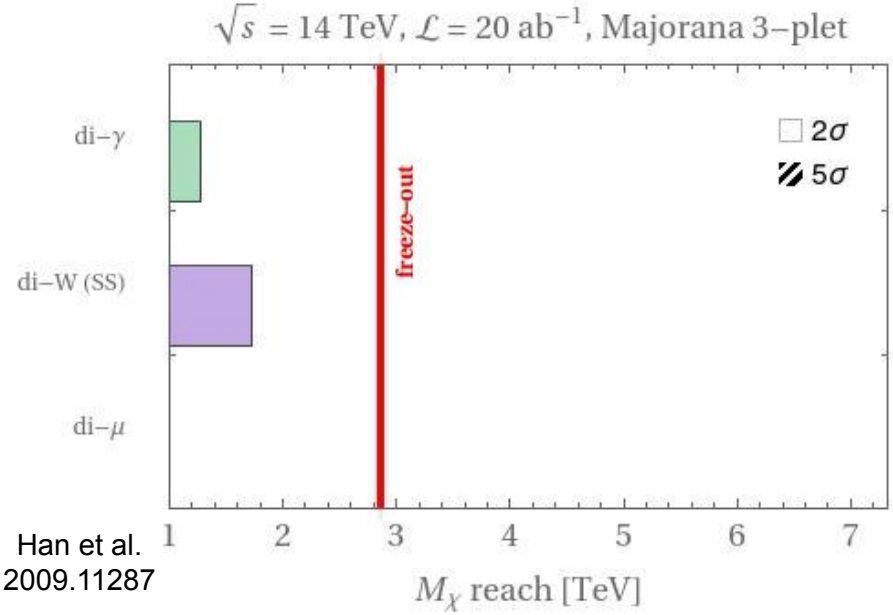


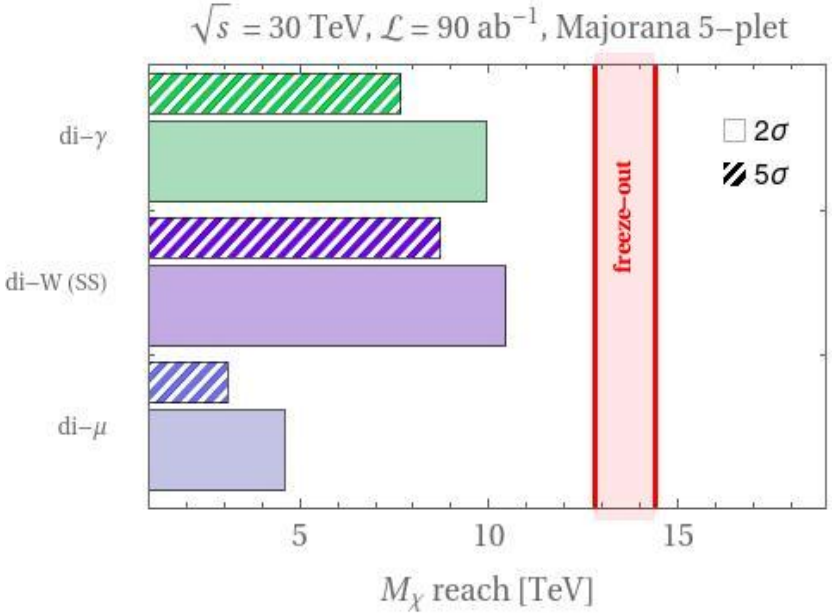
Han et al.
2009.11287

Di-X

ϵ=0%

Bottaro, MC et al. 2107.09688c

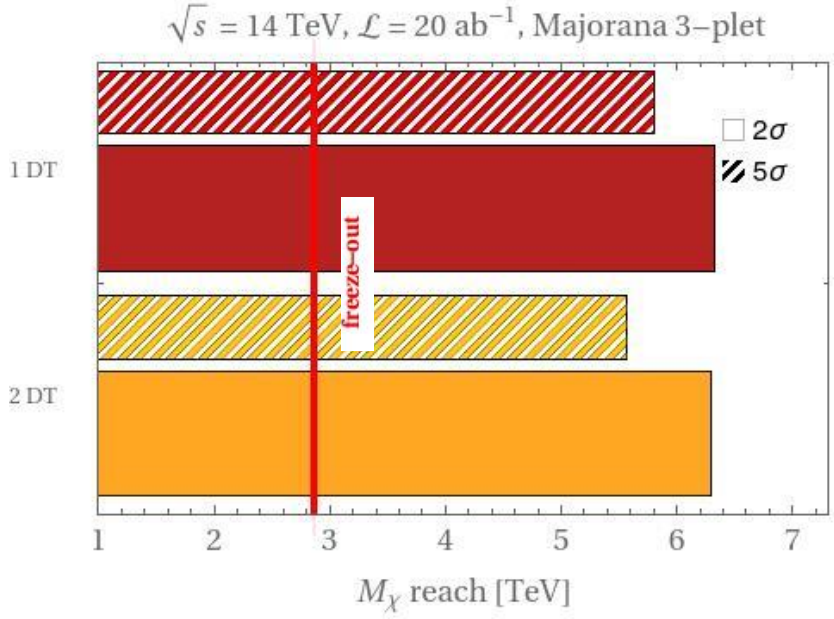


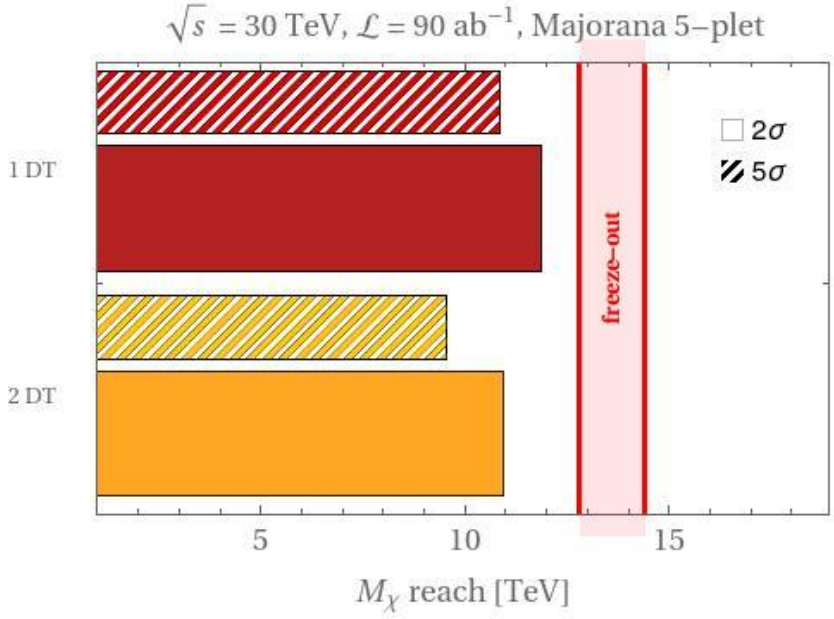


Han et al. 2009.11287

Disappearing Tracks

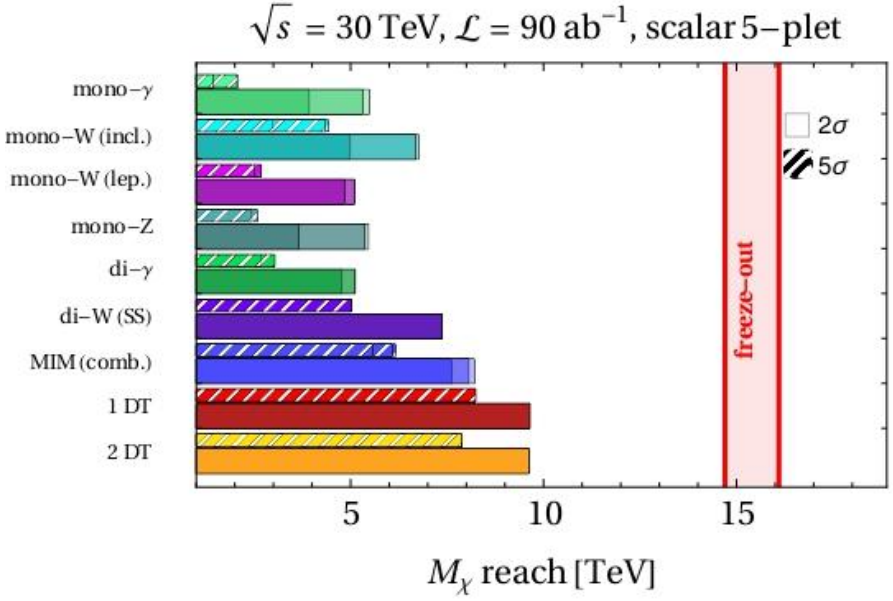
ϵ=0%



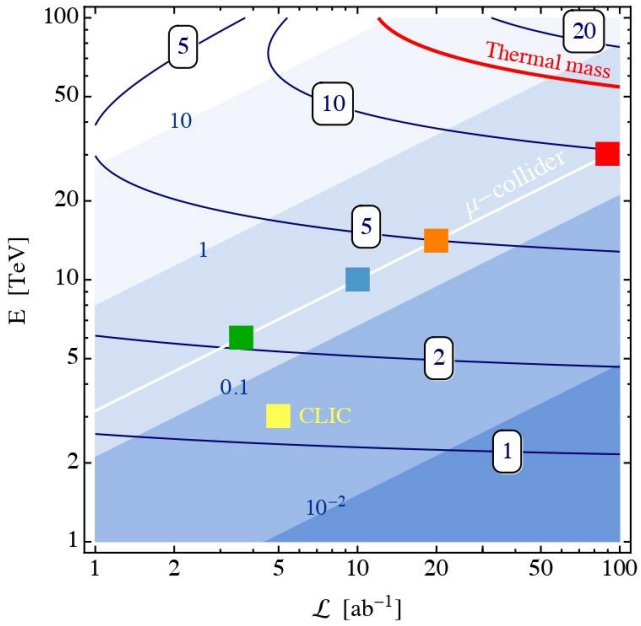


M.Costa (SNS and INFN, Pisa)

Scalar WIMPs



5S (Disappearing Tracks)



2σ: hopeless

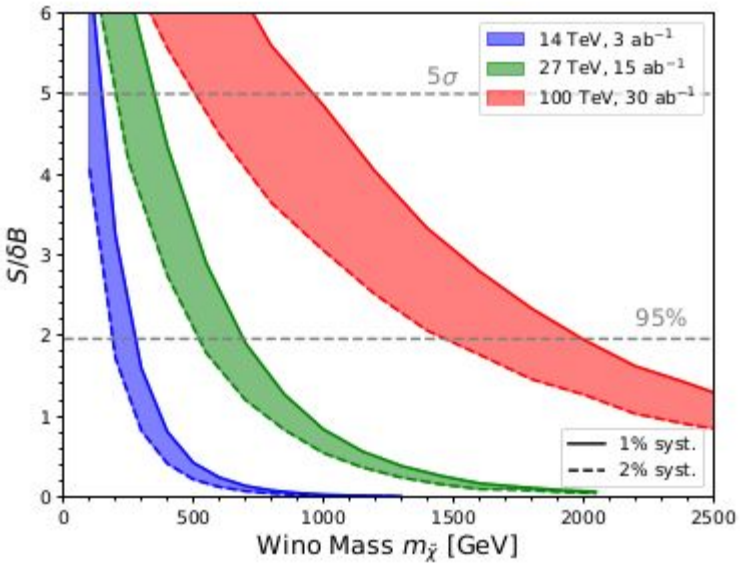
Cuts

			Majorana 3-plet					Majorana 5-plet				
	$\sqrt{s}$	$\epsilon_{\rm sys}$	$\eta_X^{\rm cut}$	$p_{T,X}^{\rm cut}$ [TeV]	$S_{95\%}$	$S_{95\%}/B$	$M_{95\%}$ [TeV]	$\eta_X^{\rm cut}$	$p_{T,X}^{\rm cut}$ [TeV]	$S_{95\%}$	$S_{95\%}/B$	$M_{95\%}$ [TeV]
Mono-γ	3 TeV	0	2.4	0.18	1007	0.004	0.72	2.4	0.0	3038	0.001	1.4
		1‰	2.2	0.24	746	0.006	0.67	1.2	0.0	3683	0.003	1.3
		1%	1.2	0.78	107	0.05	0.58	0.6	0.3	639	0.02	1.1
	14 TeV	0	1.6	2.5	360	0.01	2.2	2.2	0.28	3693	0.001	5.5
		1‰	1.6	2.8	323	0.01	2.2	1.2	0.84	1300	0.004	5.2
		1%	1.0	4.5	108	0.05	1.9	0.8	2.8	331	0.03	4.4
	30 TeV	0	1.2	7.8	174	0.02	4.4	1.6	1.8	1795	0.002	11
		1‰	1.2	7.8	175	0.02	4.4	1.0	2.4	1312	0.004	11
		1%	1.2	8.4	190	0.03	4.0	0.8	6.0	455	0.03	8.8
Mono-W (inclusive)	3 TeV	0	1.6	0.36	842	0.005	0.79	2.2	0.06	5625	0.0007	1.2
		1‰	1.4	0.48	534	0.008	0.78	1.0	0.24	1649	0.004	1.2
		1%	1.0	0.84	172	0.04	0.64	0.6	0.54	515	0.02	1.0
	14 TeV	0	1.6	2.0	819	0.005	3.4	1.8	0.56	5325	0.0008	5.5
		1‰	1.6	2.2	665	0.007	3.3	1.0	1.4	1342	0.004	5.2
		1%	0.8	4.2	155	0.04	2.8	1.2	2.5	635	0.03	4.4
	30 TeV	0	1.4	5.4	696	0.006	6.7	1.8	1.8	3946	0.001	12
		1‰	1.4	5.4	606	0.007	6.7	1.4	2.4	2771	0.003	11
		1%	1.0	9.0	211	0.03	5.2	0.8	5.4	813	0.02	9.3

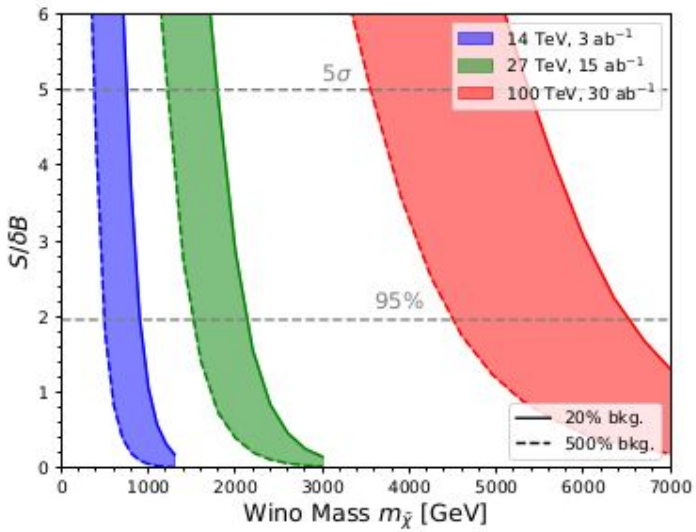
M.Costa (SNS and INFN, Pisa)

FCC-hh prospects

Han et al.
1805.00015



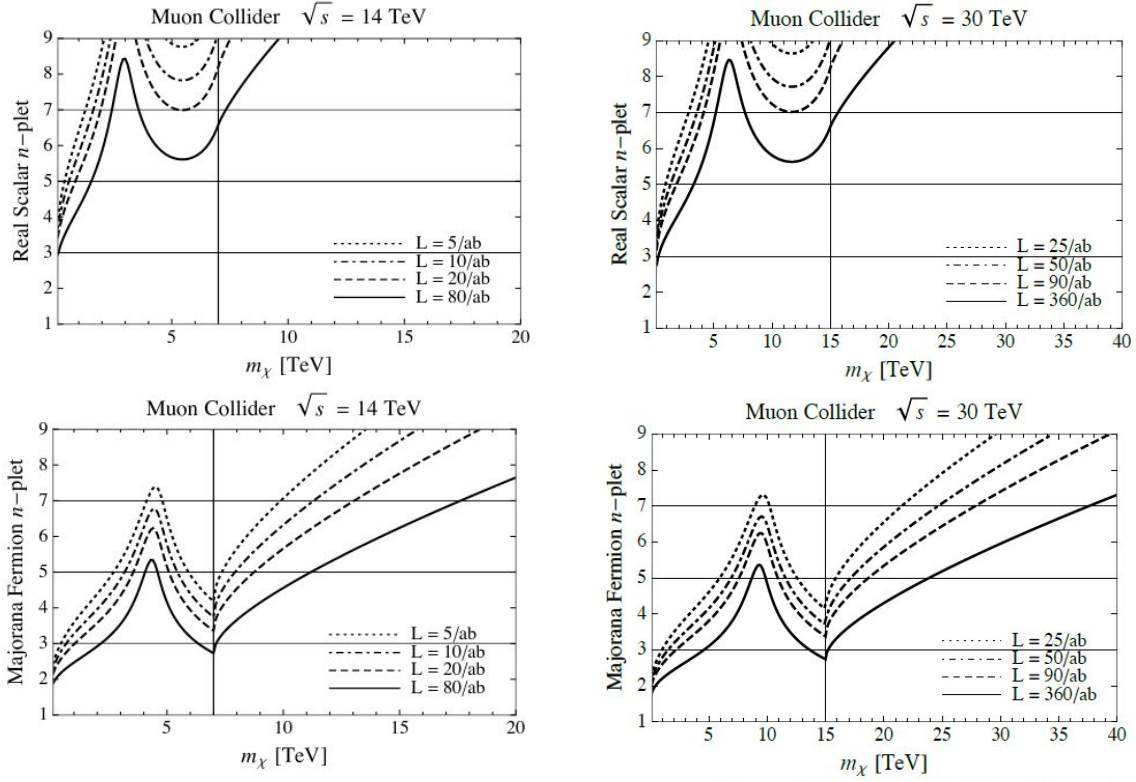
mono-jet



DT

Indirect collider prospects

μμ -> ff corrections

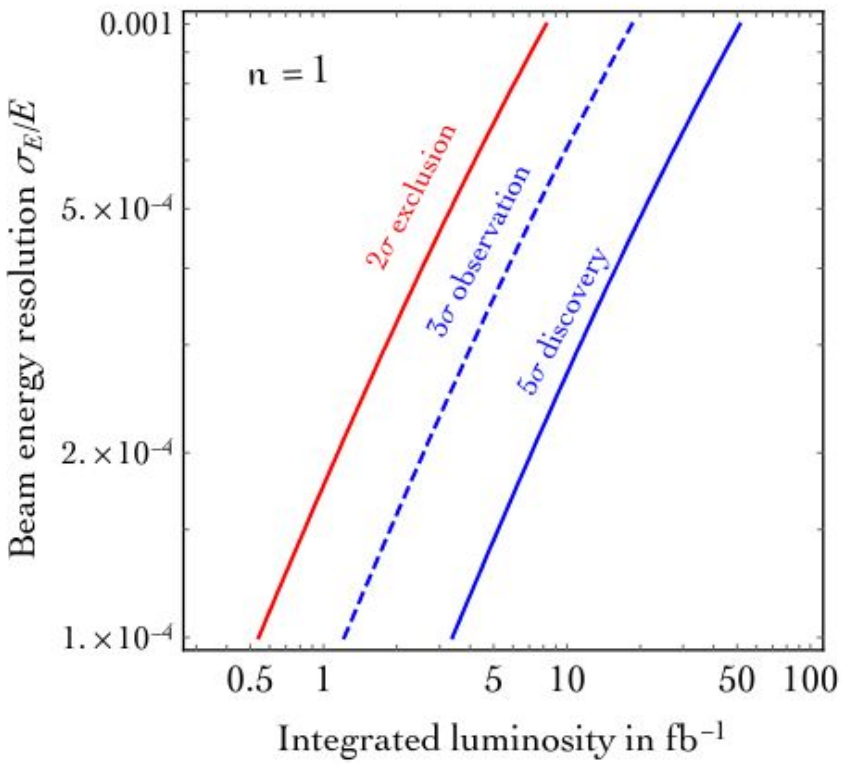


Expected 95% CL exclusion limits

Di Luzio et al. 1810.10993

Integrated luminosity for BS

Bottaro et al. 2103.12766



DT recast

Capdevilla et al.
2102.11292

$$P(\theta, r_{\min}, r_{\max}) = \int_{r_{\min}}^{r_{\max}} \frac{\mathrm{d}r\, \epsilon_{\mathrm{rec}}(r,\theta)}{c\tau\beta\gamma \sin\theta} e^{-r/(c\tau\beta\gamma\sin\theta)},$$

Requirement / Region	$\mathrm{SR}^{\gamma}_{1t}$	$\mathrm{SR}^{\gamma}_{2t}$
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