EW WIMPs at future lepton colliders

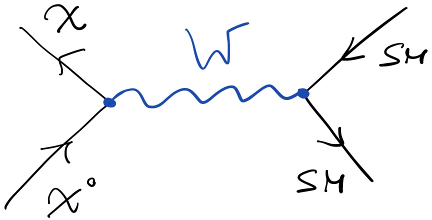
Marco Costa
(Scuola Normale Superiore, INFN Pisa)

based on 2107.09688, 2205.04486

In collaboration with S. Bottaro, D. Buttazzo, R. Franceschini, P. Panci, D. Redigolo, and L. Vittorio

Which WIMP?

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



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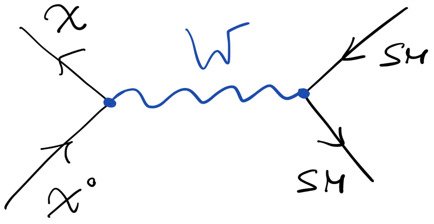
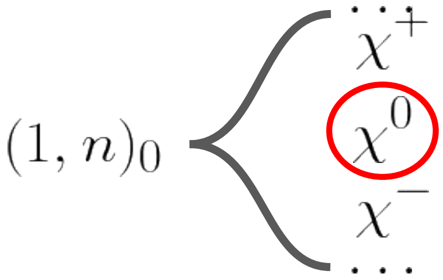
$$T_3 + Y = 0$$





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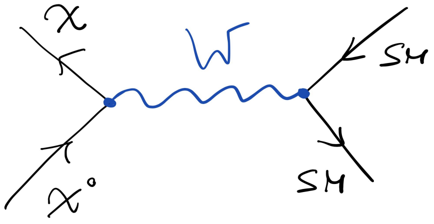
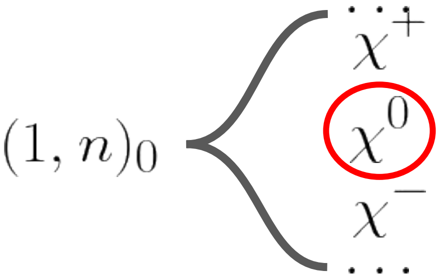
  - even n, **Y=½ , 1** : needs UV physics (mixing partner)





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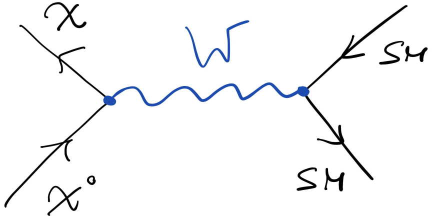

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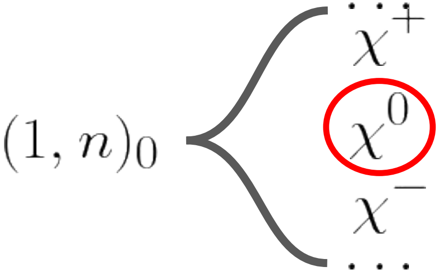

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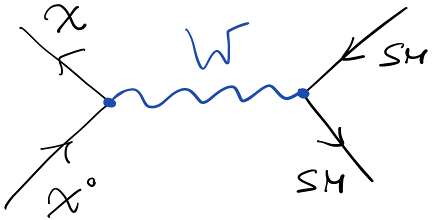

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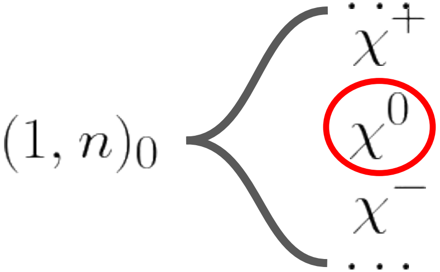

- **Computability**: (perturbative unitarity) ⇒**n≤13**

Thermal target results

DM spin	EW n-plet	M_χ (TeV)
Real scalar $Y=0$	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 $Y=0$	3	2.86 ± 0.01
	5	13.6 ± 0.8
	7	48.8 ± 3.3
	9	113 ± 15
	11	202 ± 43
	13	324.6 ± 94

30-ish TeV collider might probe them

DM spin	n_Y	$M_{\rm DM}$ (TeV)
Dirac fermion	$2_{1/2}$	1.08 ± 0.02
	3_1	2.85 ± 0.14
	$4_{1/2}$	4.8 ± 0.3
	5_1	9.9 ± 0.7
	$6_{1/2}$	31.8 ± 5.2
	$8_{1/2}$	82 ± 8
	$10_{1/2}$	158 ± 12
	$12_{1/2}$	253 ± 20
Complex scalar	$2_{1/2}$	0.58 ± 0.01
	3_1	2.1 ± 0.1
	$4_{1/2}$	4.98 ± 0.25
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Need > 60 TeV collider!

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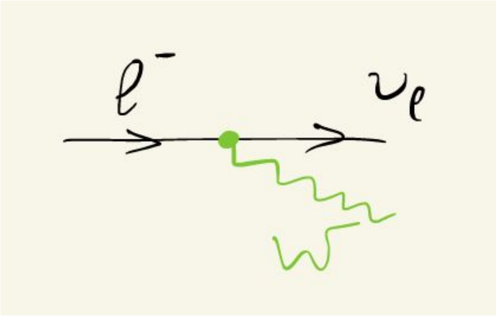
WIMPs @ high energy lepton colliders

Why high energy lepton colliders?

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



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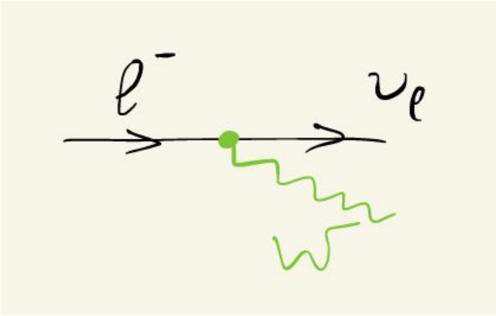

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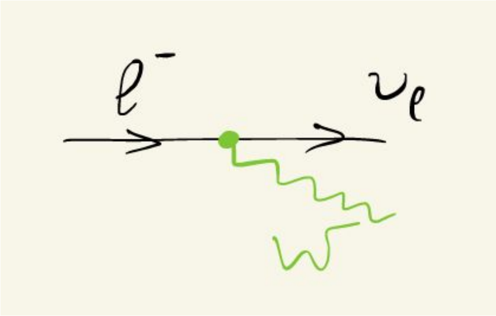
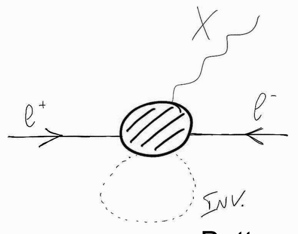
- **More energy in hard cross section**: needed since WIMPs are heavy



How to detect WIMPs @ Muon Collider?

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

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



Han et al. 2009.11287

Bottaro, MC et al.
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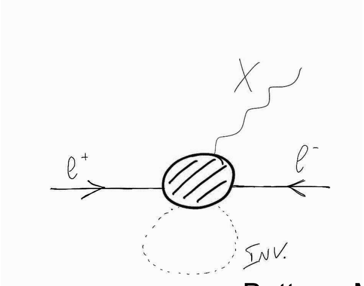

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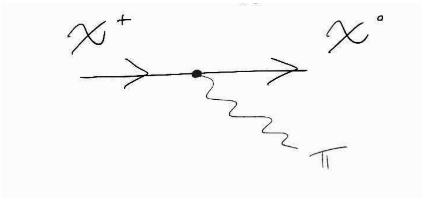

Recast of Capdevilla et al.
2102.11292

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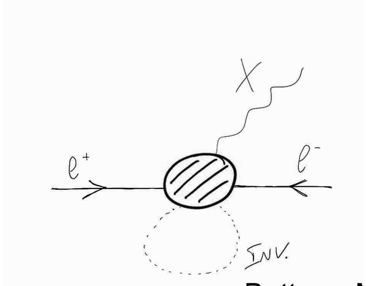

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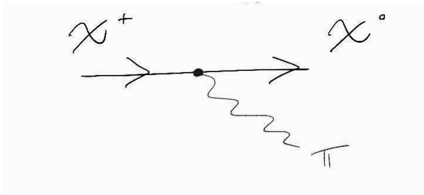

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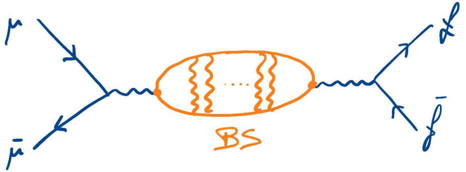
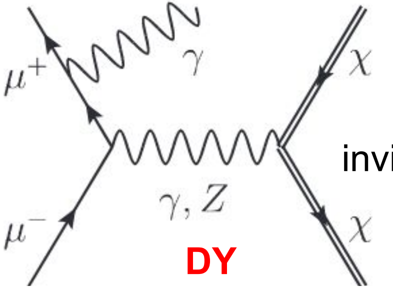
- **Resonances**: **Bound States**



Bottaro et al. 2103.12766

Missing Mass search example: mono-ɣ

Sig



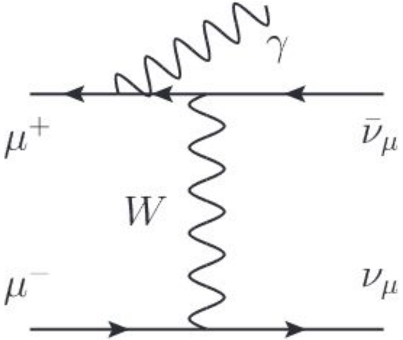
invisible

DY

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

More central
More missing energy

Bkg



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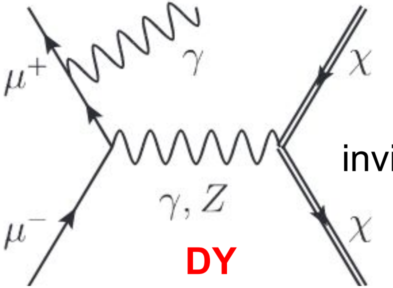

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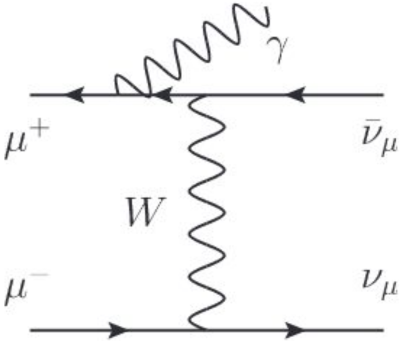

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$$\mu^-\mu^+ \to \gamma\nu\bar{\nu}$$

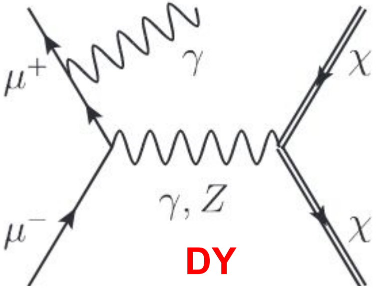
$$\frac{S}{\sqrt{S + B + (\epsilon_S S)^2 + (\epsilon_B B)^2}}$$

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

Mono-V

γ | **W**

Sig



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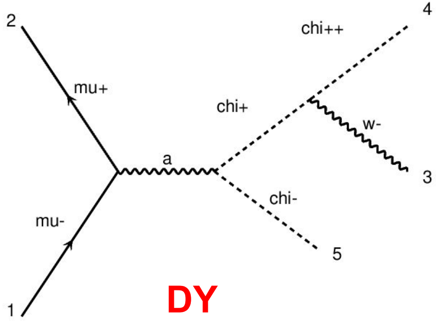

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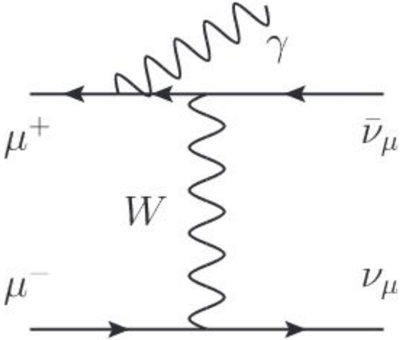

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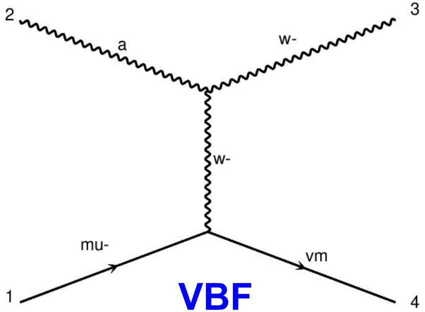
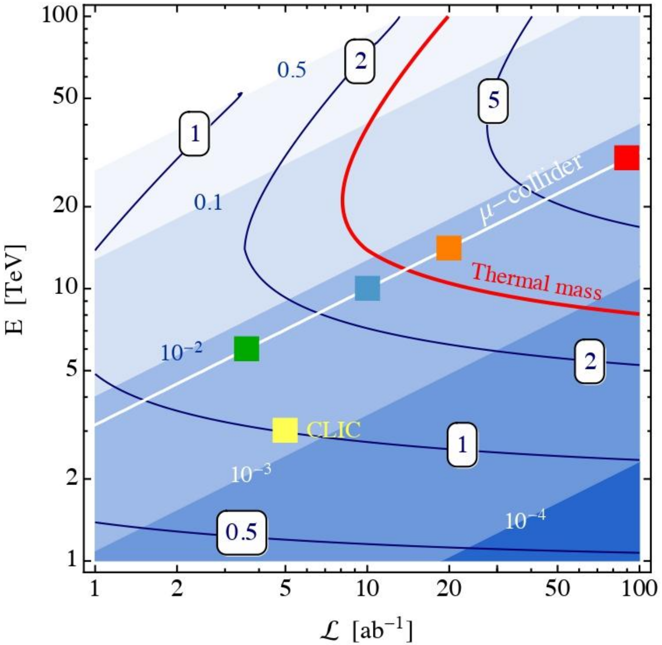


VBF

Lumi vs Energy (Mono-W)

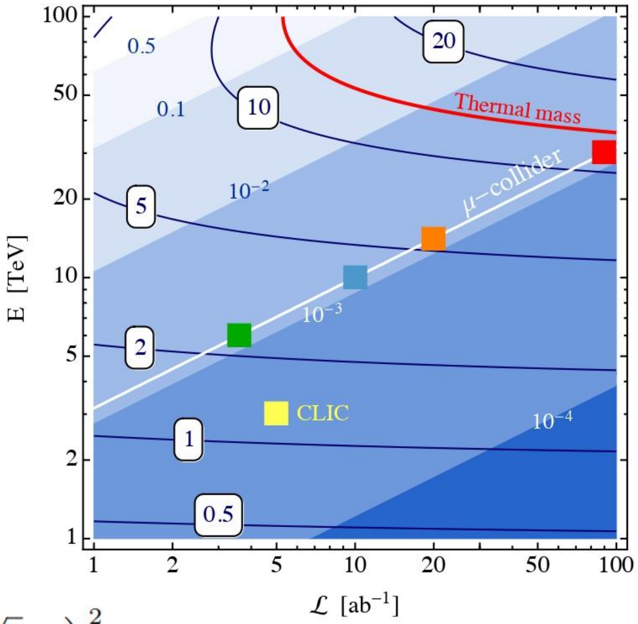
ϵ=0%

3_0F



2σ: 12 TeV

5_0F



2σ: 35 TeV

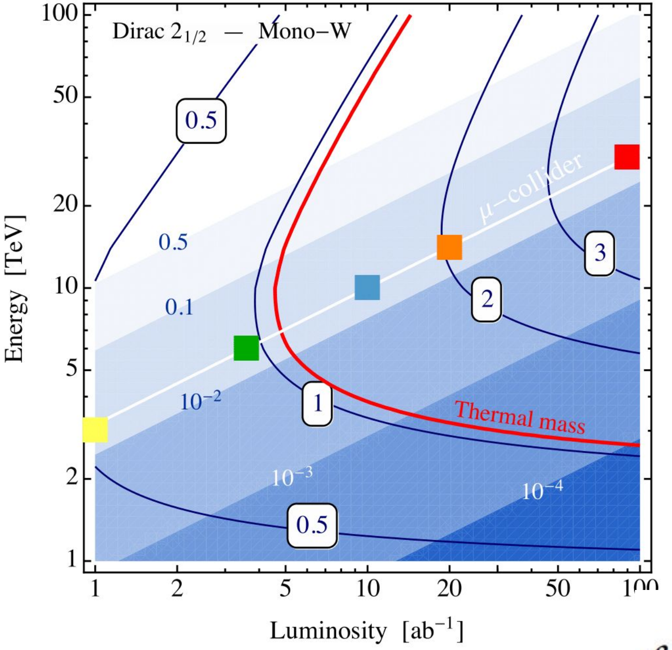
$$\mathcal{L} \simeq 10 \text{ ab}^{-1} \cdot \left(\frac{\sqrt{s}}{10 \text{ TeV}}\right)^2$$

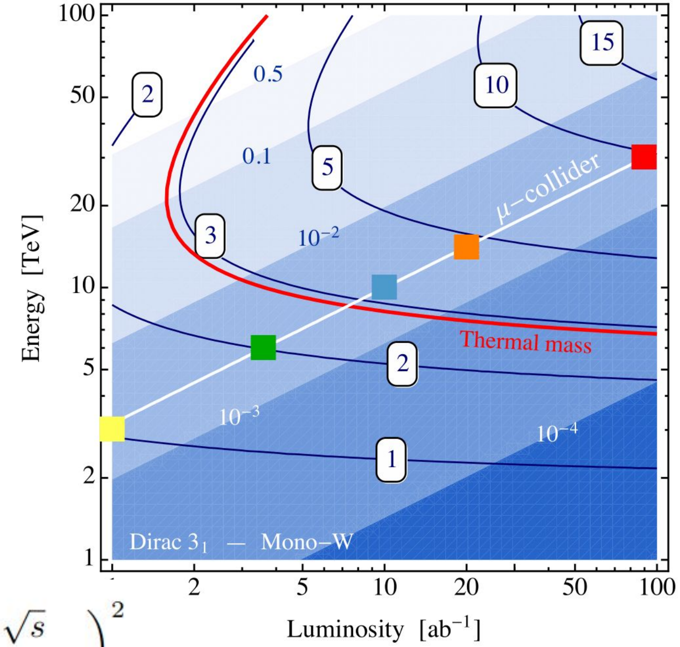
Lumi vs Energy (Mono-W)

$2_{1/2}$F

ϵ=0%

3_1F





2σ: 7 TeV

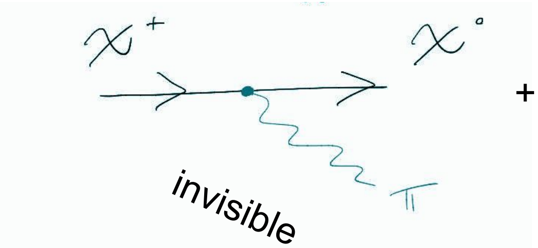
$$\mathcal{L} \simeq 10\ \mathrm{ab}^{-1} \cdot \left(\frac{\sqrt{s}}{10\ \ \mathrm{TeV}}\right)^2$$

2σ: 9 TeV

Tracks

1 or 2 Disappearing ("stub")

Sig



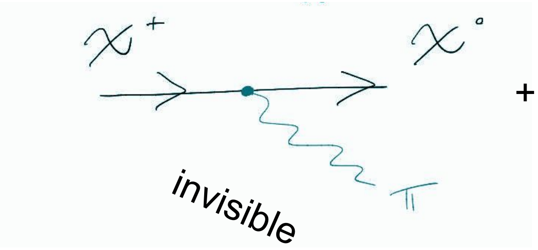
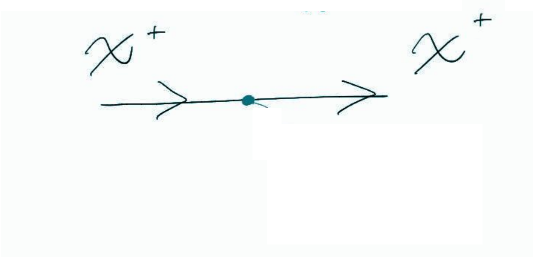
+ γ

Bkg

BIB hits reconstructed as tracks + γ

Disappearing condition:
decay between 5 cm and 12.7 cm

Tracks

	1 or 2 Disappearing (“stub“)	Charged (“long”)
Sig	 + γ	
Bkg	BIB hits reconstructed as tracks + γ	??

Disappearing condition:
decay between 5 cm and 12.7 cm

Long Track condition:
decay after 1m

Understanding Lifetimes

$$\Gamma_{\pi^\pm} = g\left(n, Y, \pm 1\right) \frac{G_F^2 f_\pi^2 |V_{ud}|^2 \delta m_\pm^3}{4\pi} \sqrt{1 - \frac{m_\pi^2}{\delta m_\pm^2}}$$

Understanding Lifetimes

$$\Gamma_{\pi^\pm} = g(n, Y, \pm 1)\,\frac{G_F^2 f_\pi^2 |V_{ud}|^2 \delta m_\pm^3}{4\pi}\sqrt{1 - \frac{m_\pi^2}{\delta m_\pm^2}}$$

gauge

$$\Delta M_Q^{\mathrm{EW}} = \delta_g \left(Q^2 + \frac{2YQ}{\cos\theta_W}\right)$$

$$\delta_g = \alpha_2 M_W \sin^2\frac{\theta_W}{2} \approx 167\ \mathrm{MeV}$$

Understanding Lifetimes

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gauge

UV

$$\Delta M_Q^{\rm EW} = \delta_g \left(Q^2 + \frac{2YQ}{\cos\theta_W} \right)$$

$$\delta_g = \alpha_2 M_W \sin^2\frac{\theta_W}{2} \approx 167\ \mathrm{MeV}$$

$$\mathcal{O}_+ = -\overline{\chi} T^a \chi H^\dagger \frac{\sigma^a}{2} H$$

Vanishes for real candidates

$$c\tau_{\chi^+} \simeq \frac{120\ \mathrm{mm}}{T(T+1)}$$

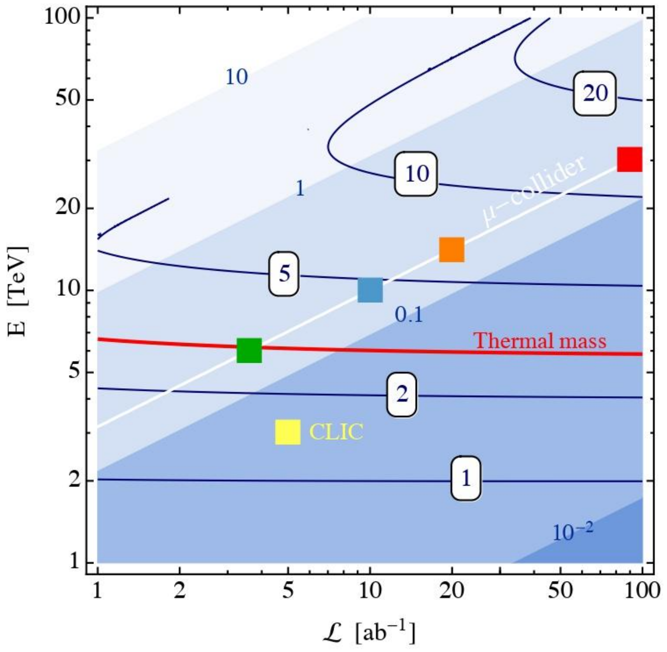
- **6 cm n=3**
- **2 cm n=5**

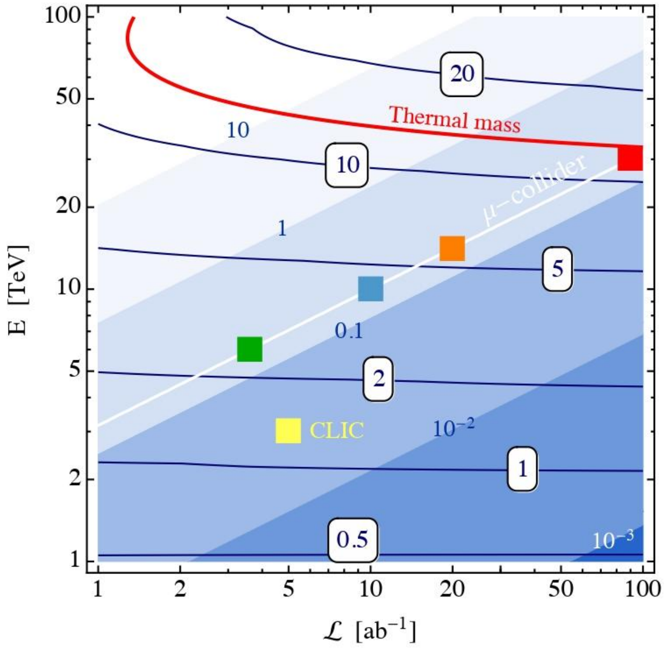
DT Real WIMPs

3_0F

ϵ=0%

5_0F

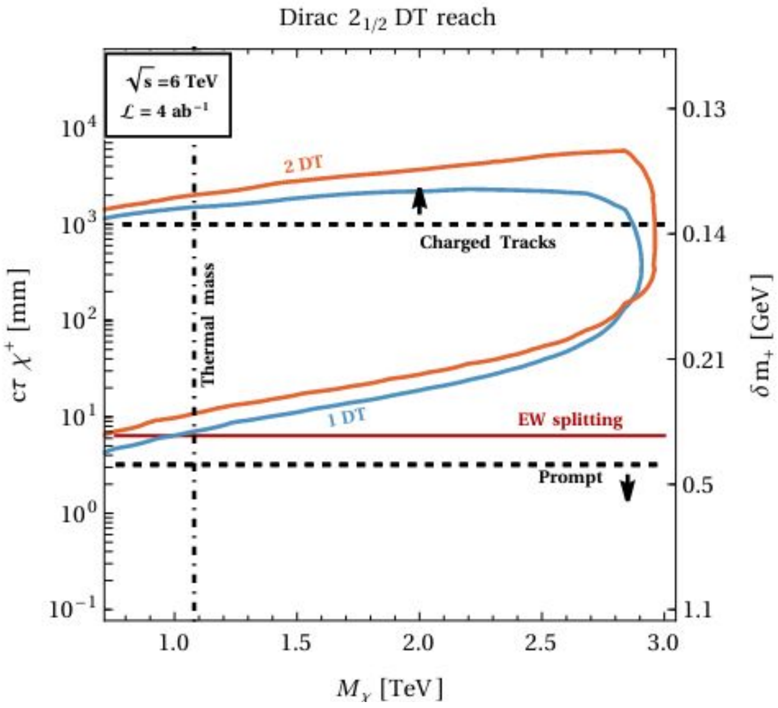


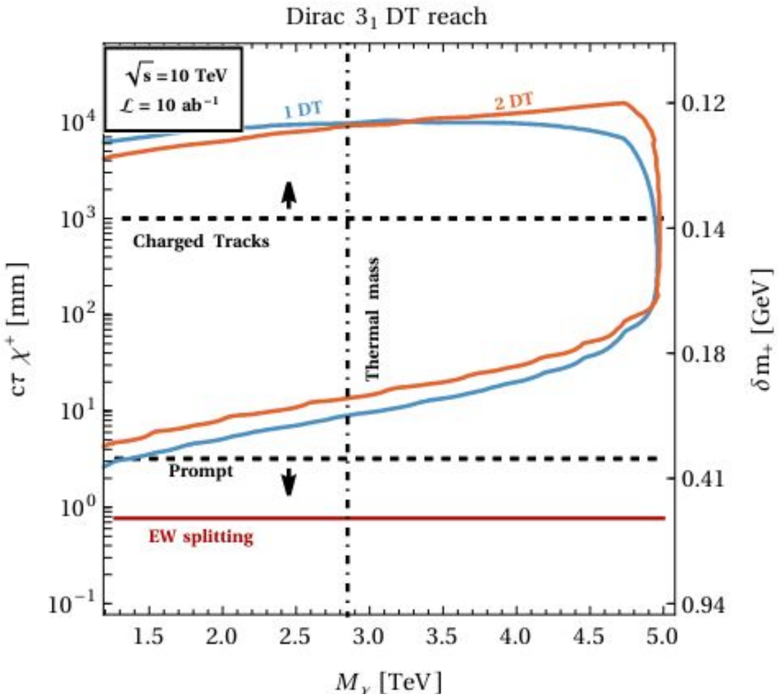


2σ: 6 TeV

2σ: 35 TeV...

Complex DT: $2_{1/2}$, 3_1

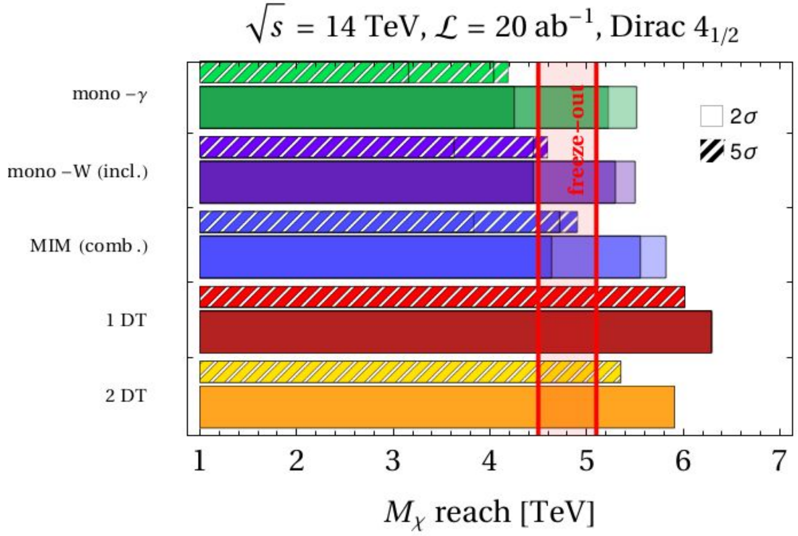


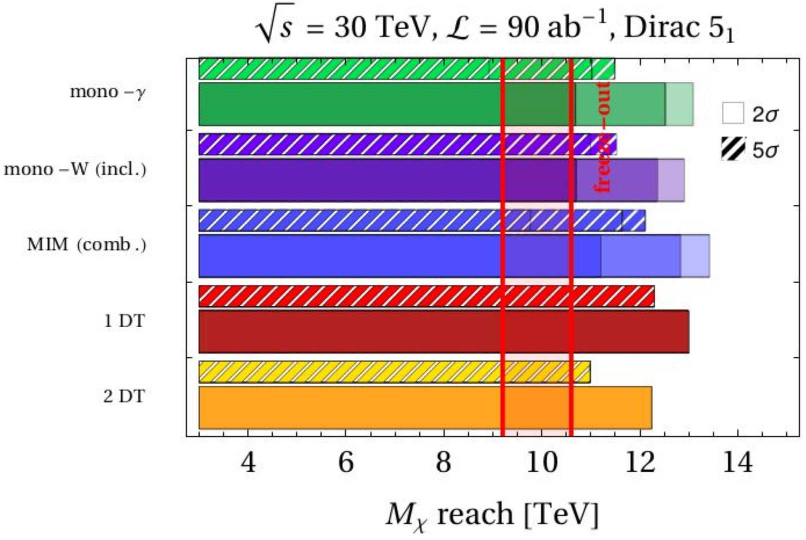


2σ: 6 TeV probe EW splitting (neglecting δm_0) **EW splitting TOO PROMPT**

Complex WIMPs: $4_{1/2}$, 5_1

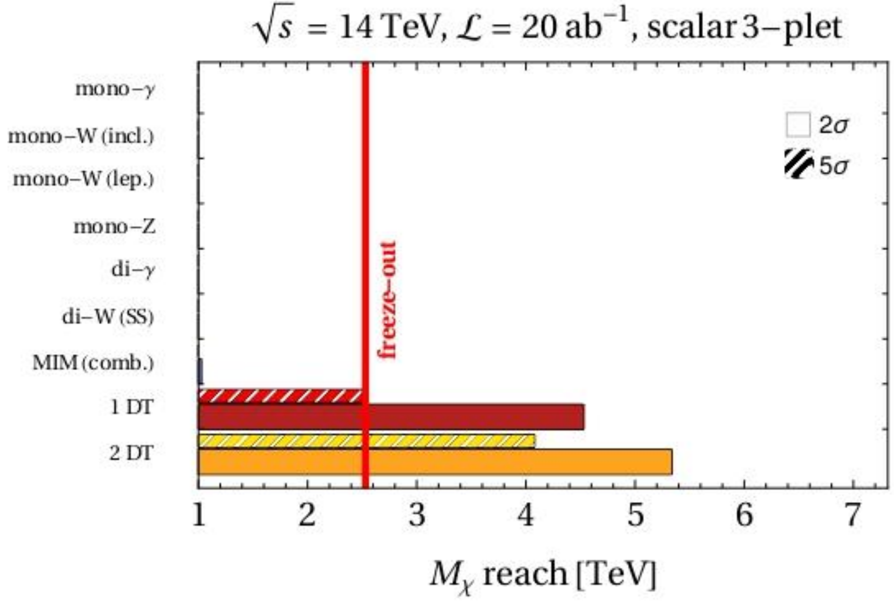
ϵ= 0%, 0.1%, 1%





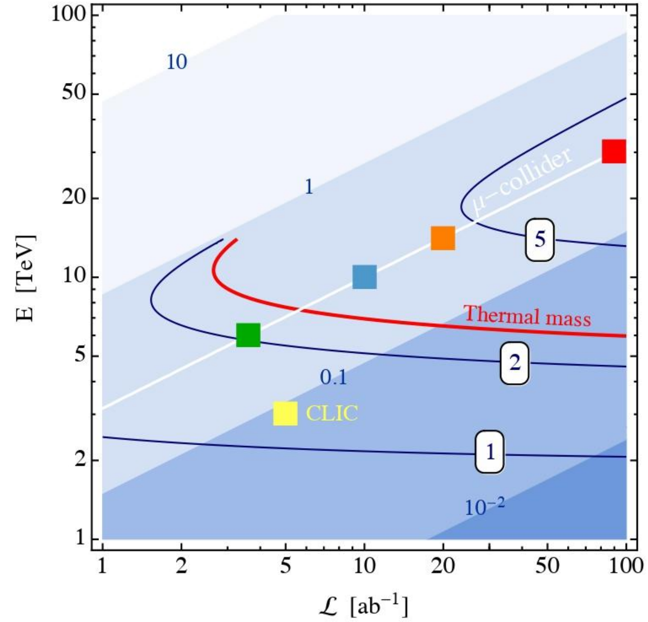
MIM: $4_{1/2}$ @ □ 12 TeV, 5_1 needs **< 30 TeV. DT (EW)** as good

Scalar Real WIMPs



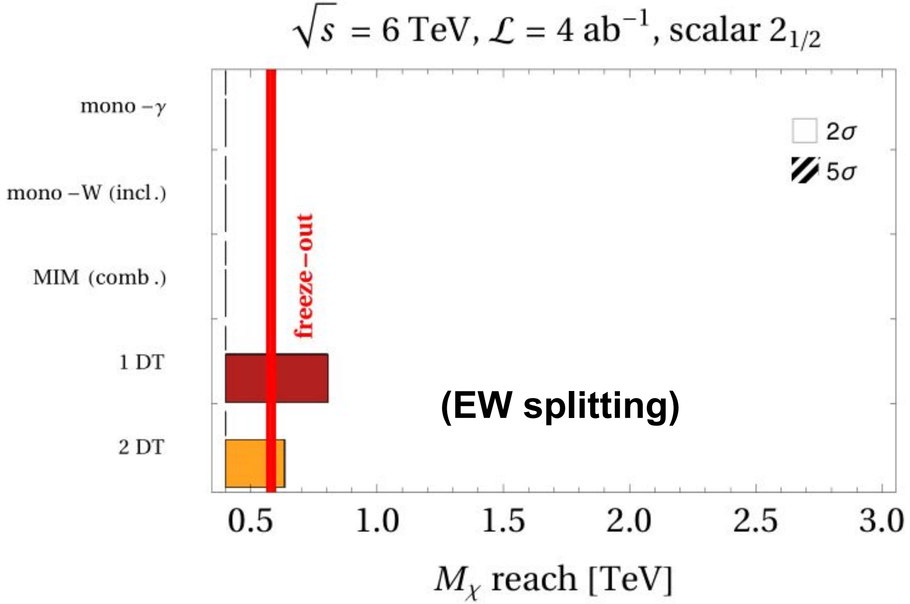
3S: DTs only hope

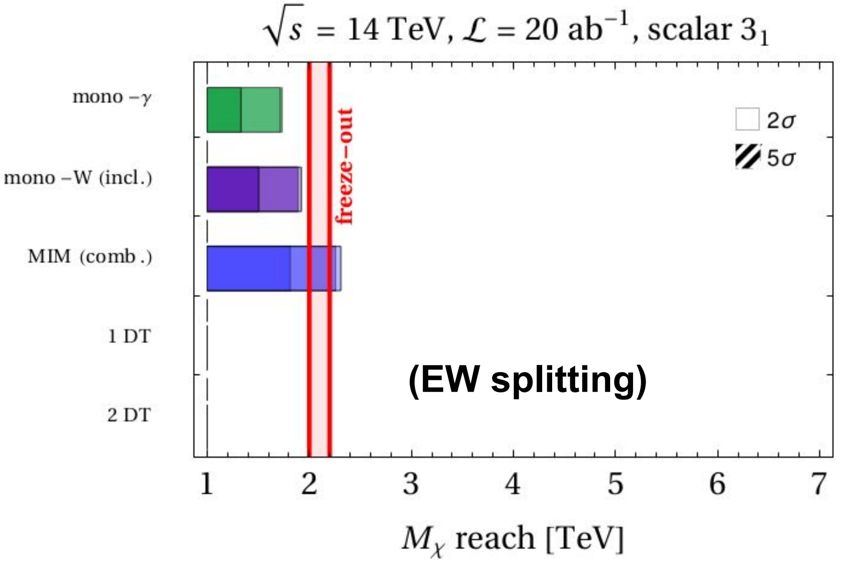
3_0S (Disappearing Tracks)



2σ: 8 TeV

Scalar Complex WIMPs





$2_{1/2}$S: DT only hope, 6 TeV (but MODEL DEPENDENT)

3_1S: MIM 2σ 14 TeV

$4_{1/2}$S: MIM 2σ 30 TeV, DT 14 TeV

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- mono-X 2σ: **$2_{1/2}$F 6 TeV**, **3_0F 12 TeV**, **3_1F 8 TeV**, **$4_{1/2}$F 12 TeV**, **3_1S 14 TeV**
- **DT**: robust for reals. **3_0F** 2σ @ **6 TeV, 3_0S @ 8 TeV** (only chance)
- **DT**: model dependent for complex. Best channel for **$2_{1/2}$S**: 2σ @ **6 TeV** (EW)

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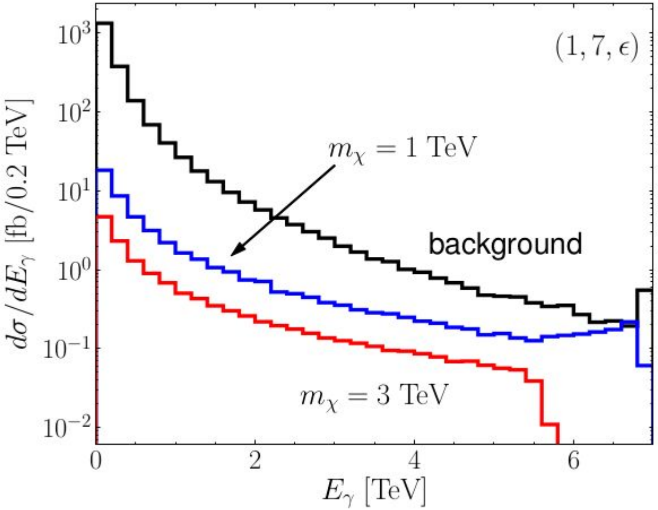
- Only **$2_{1/2}$, $4_{1/2}$, $3_{0,1}$ $5_{0,1}$ (F,S)** kinematically allowed if $\sqrt{s}$ < 30 TeV
- mono-X 2σ: **$2_{1/2}$F 6 TeV**, **3_0F 12 TeV**, **3_1F 8 TeV**, **$4_{1/2}$F 12 TeV**, **3_1S 14 TeV**
- **DT**: robust for reals. **3_0F** 2σ @ **6 TeV, 3_0S @ 8 TeV** (only chance)
- **DT**: model dependent for complex. Best channel for **$2_{1/2}$S**: 2σ @ **6 TeV** (EW)
- **Other**: **30 TeV** or more

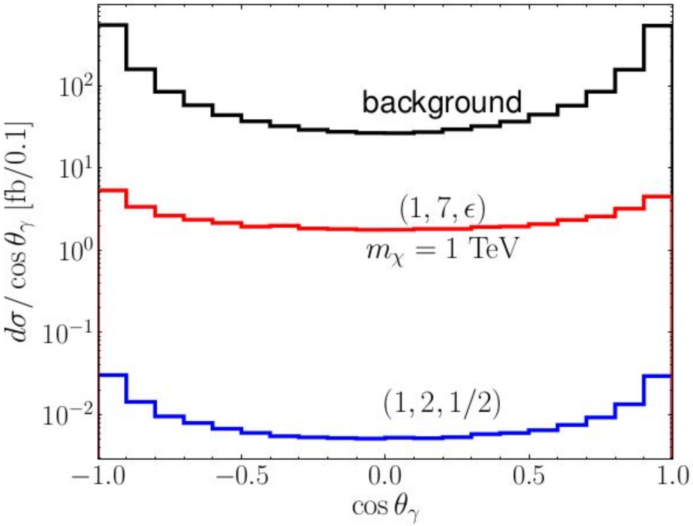
Thanks for the attention!

Backup

Missing Mass search example: mono-ɣ

Han et al.2009.11287





S/B<0.1% LOW!

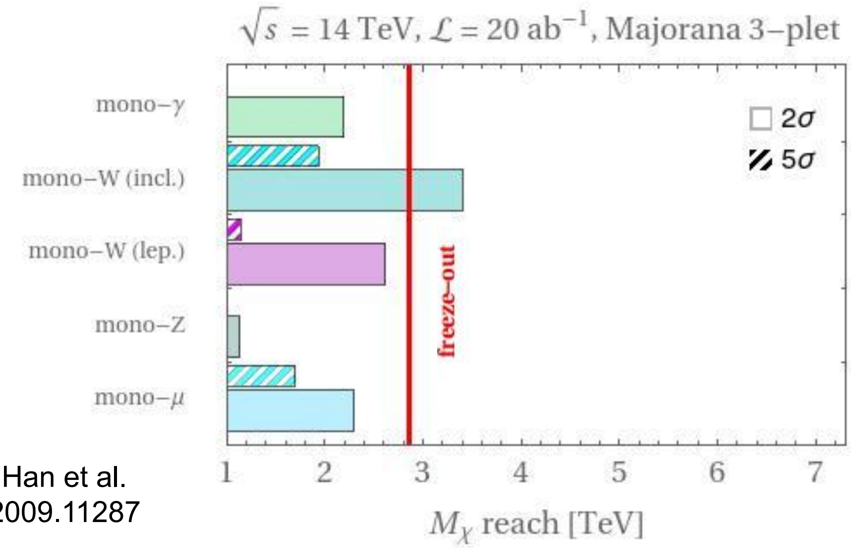
$$\frac{S}{\sqrt{S+B+(\epsilon_S S)^2+(\epsilon_B B)^2}}$$

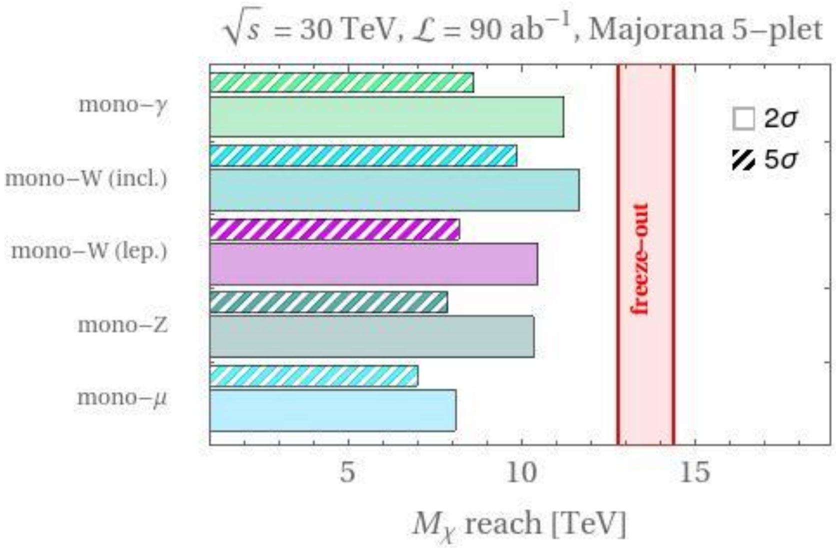
$$\text{MIM} > 2m_\chi\ , \quad |\eta_\gamma| < \eta_{\gamma\text{cut}}\ , \quad \text{MET} > \text{MET}_{\text{cut}}$$

Mono-X

Bottaro, MC et al. 2107.09688

ϵ=0%





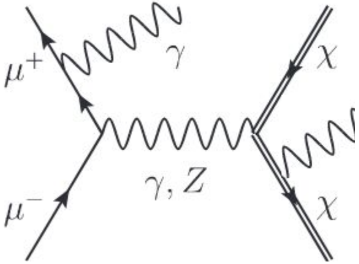
Han et al. 2009.11287

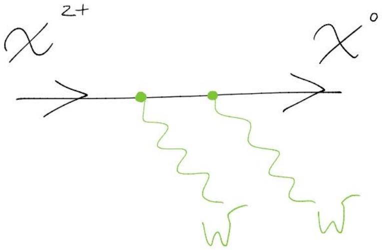
Di-V

Di-ɣ

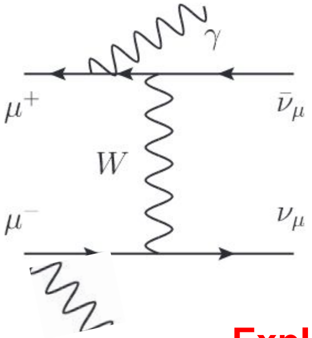
Di-W (same sign)

Sig





Bkg



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

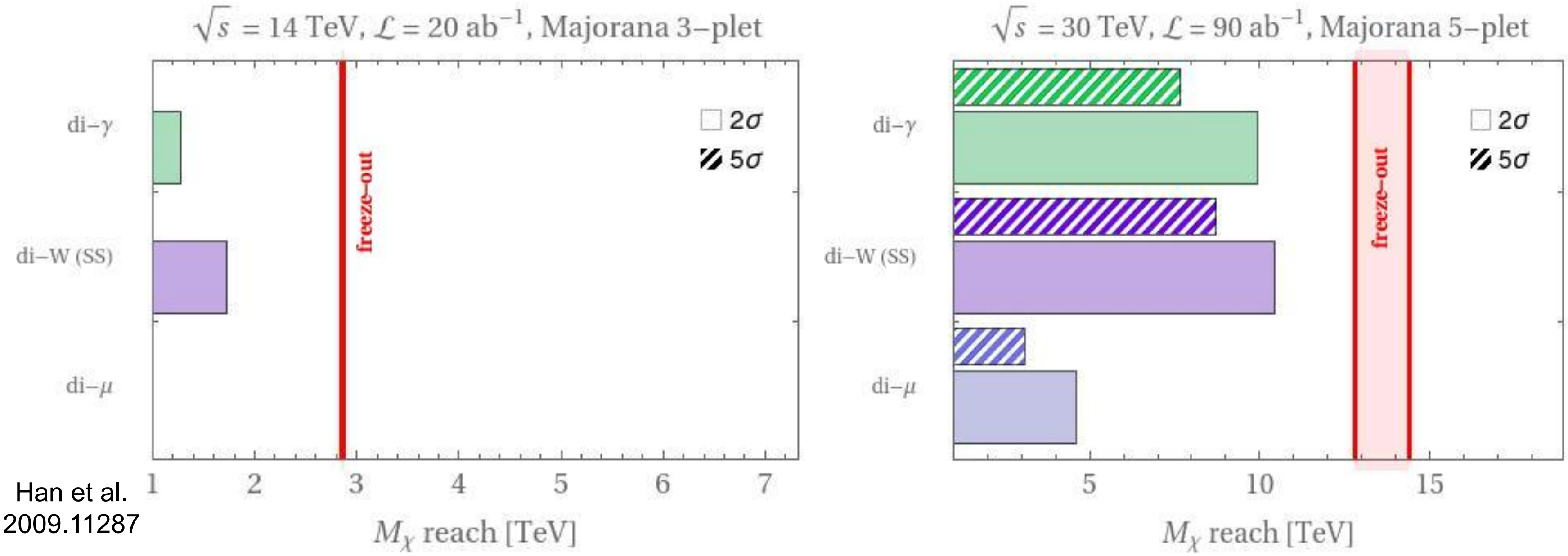
ϵ mistag=0.1%

Exploit high EW charge of signal

Di-X

ϵ=0%

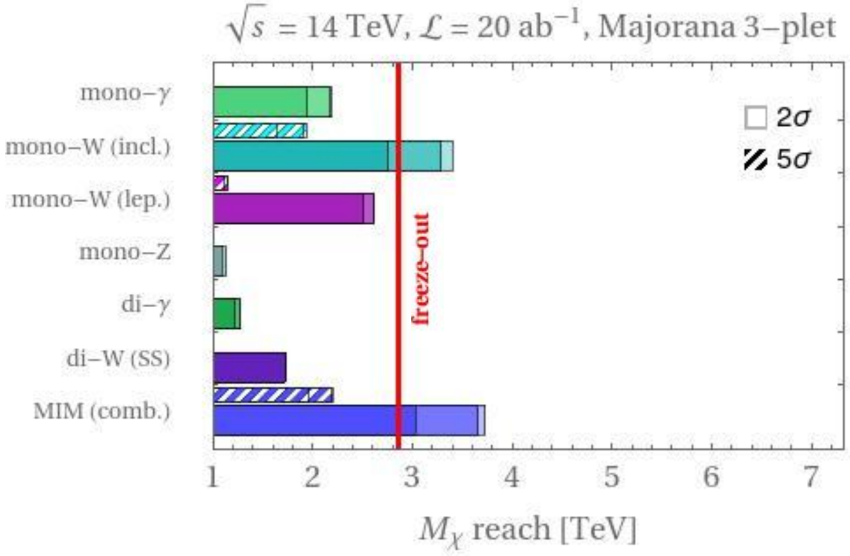
Bottaro, MC et al. 2107.09688

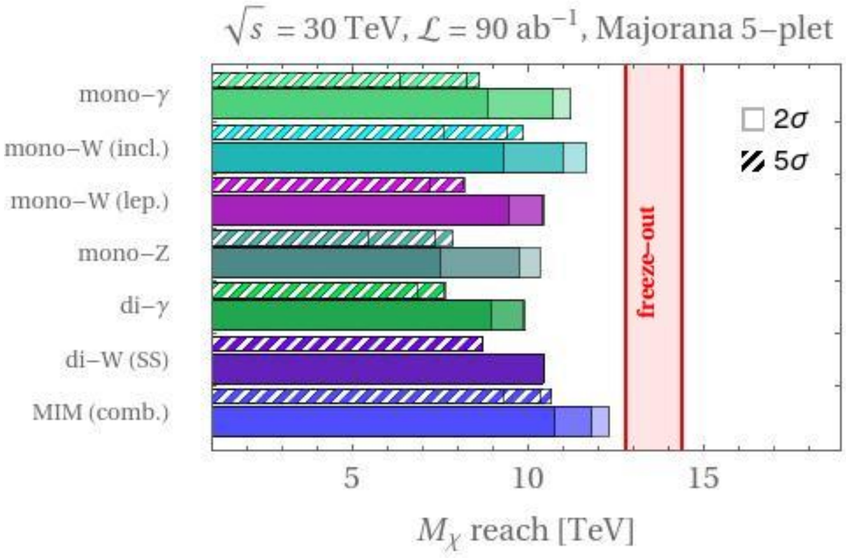


Han et al. 2009.11287

Mono-X & Di-X Real 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

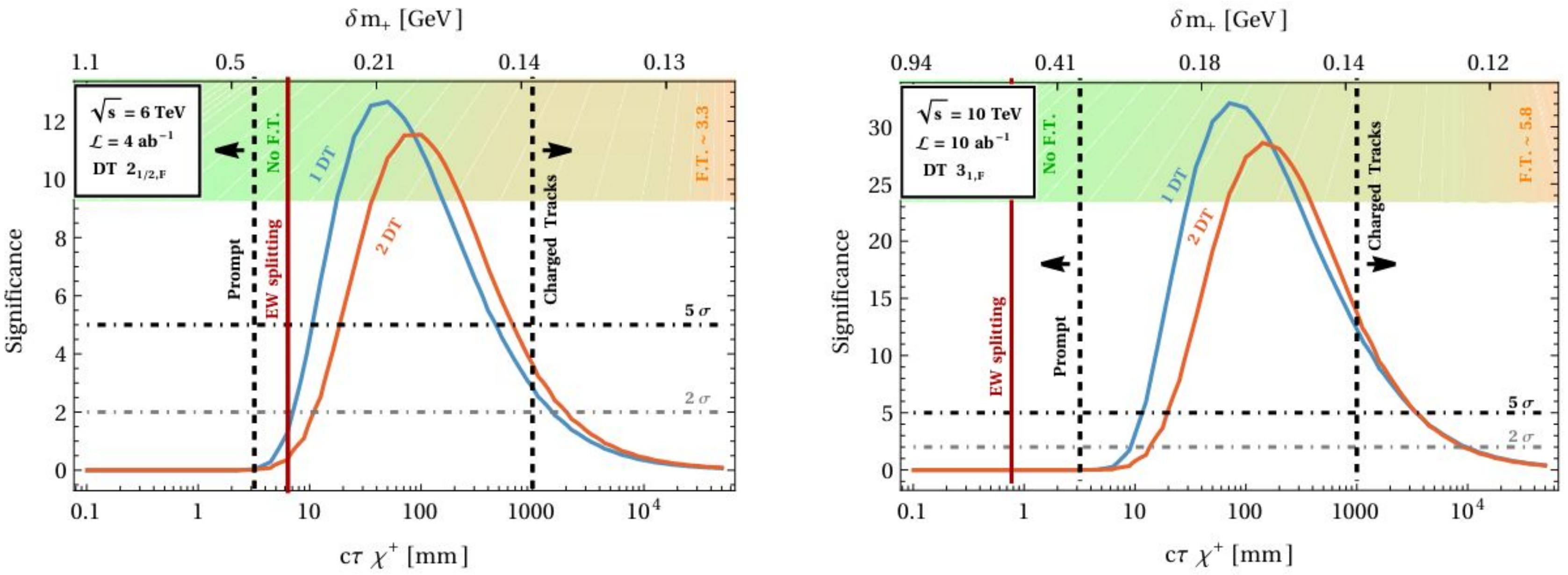
DT recast

Capdevilla et al.
2102.11292

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

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

DT Complex WIMPs

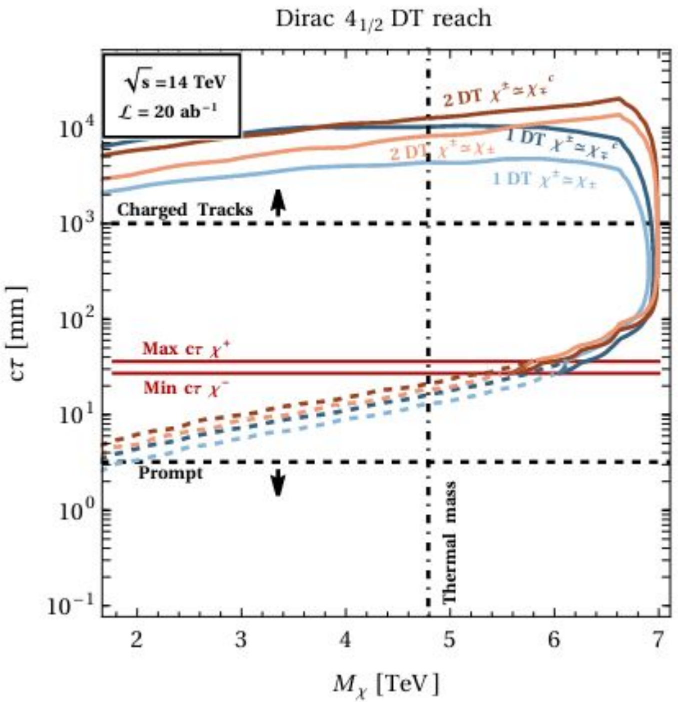


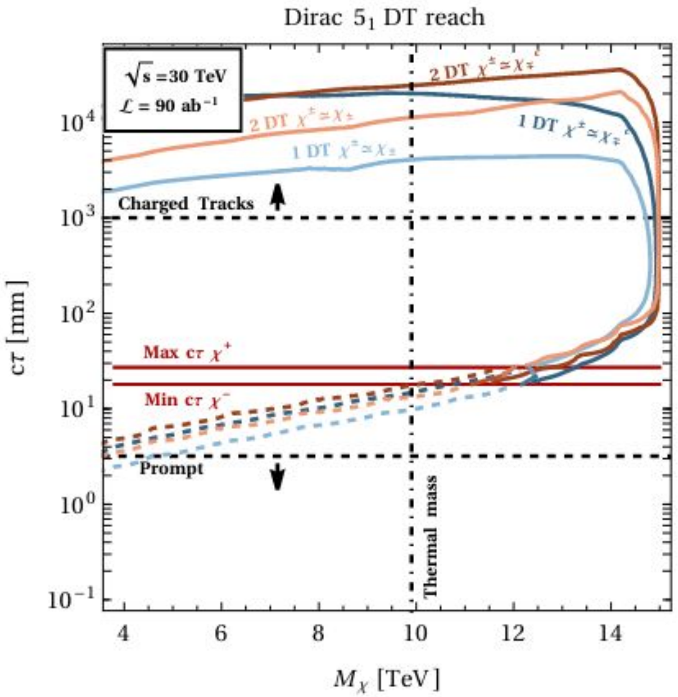
2σ: 6 TeV probe EW splitting

(neglecting δm_0)

EW splitting TOO PROMPT

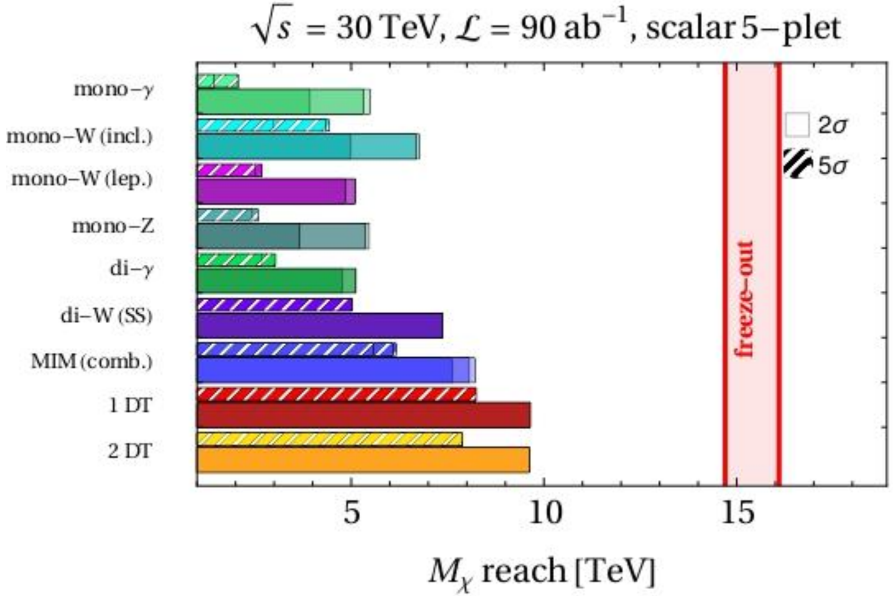
Complex DT full reach



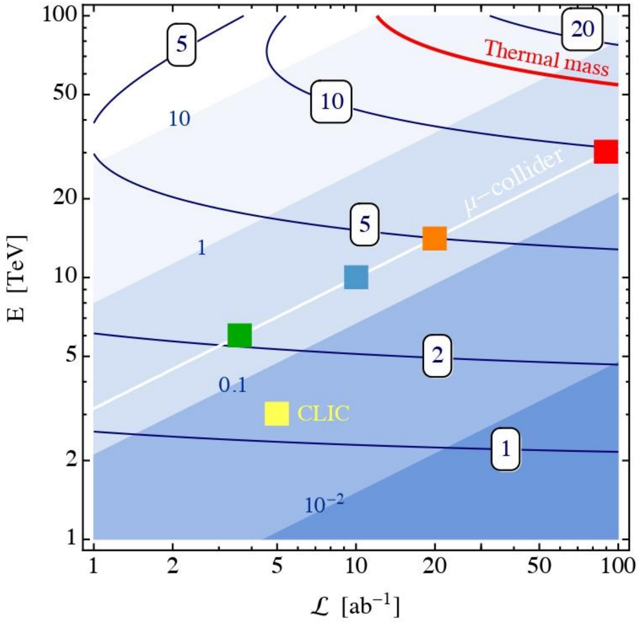


2 charged particles: long lived (solid), short lived (dashed)

5_0S

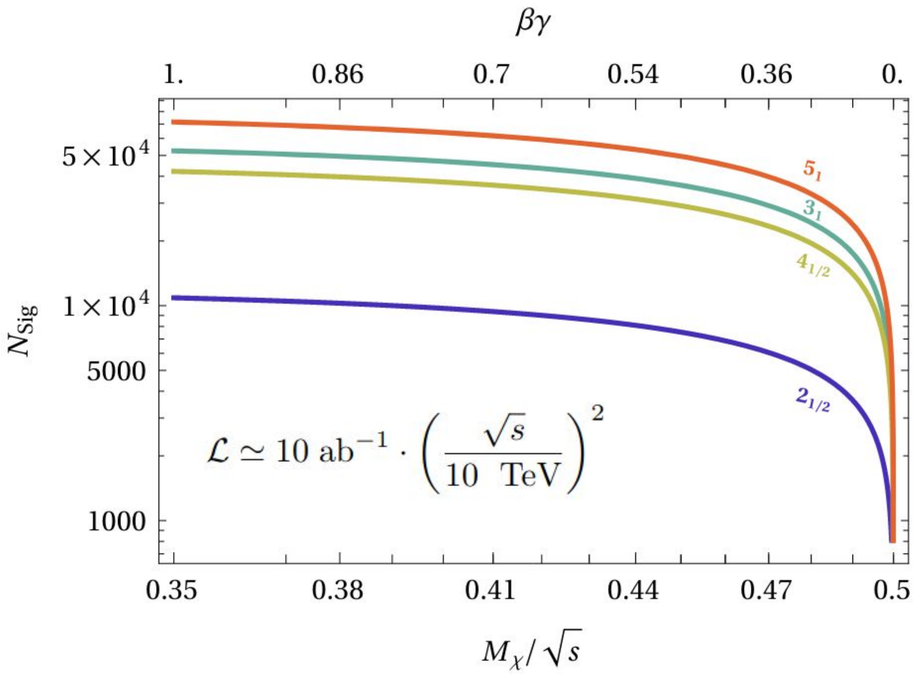


$5S_0$ (Disappearing Tracks)



2σ: hopeless

Charged Tracks

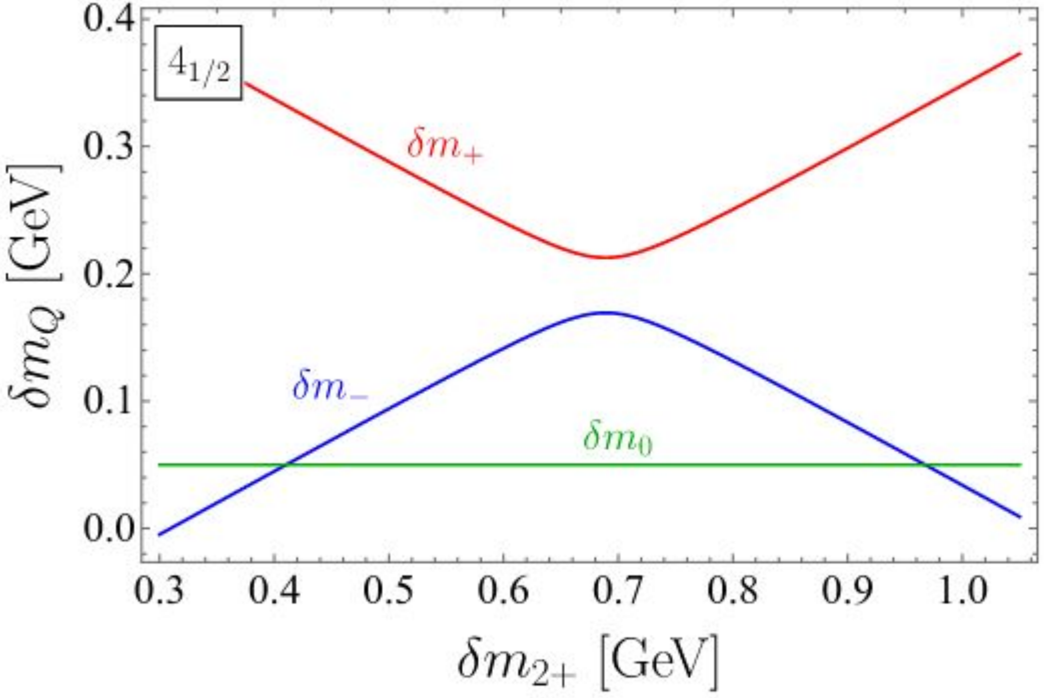


Minimal splitting scenario

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

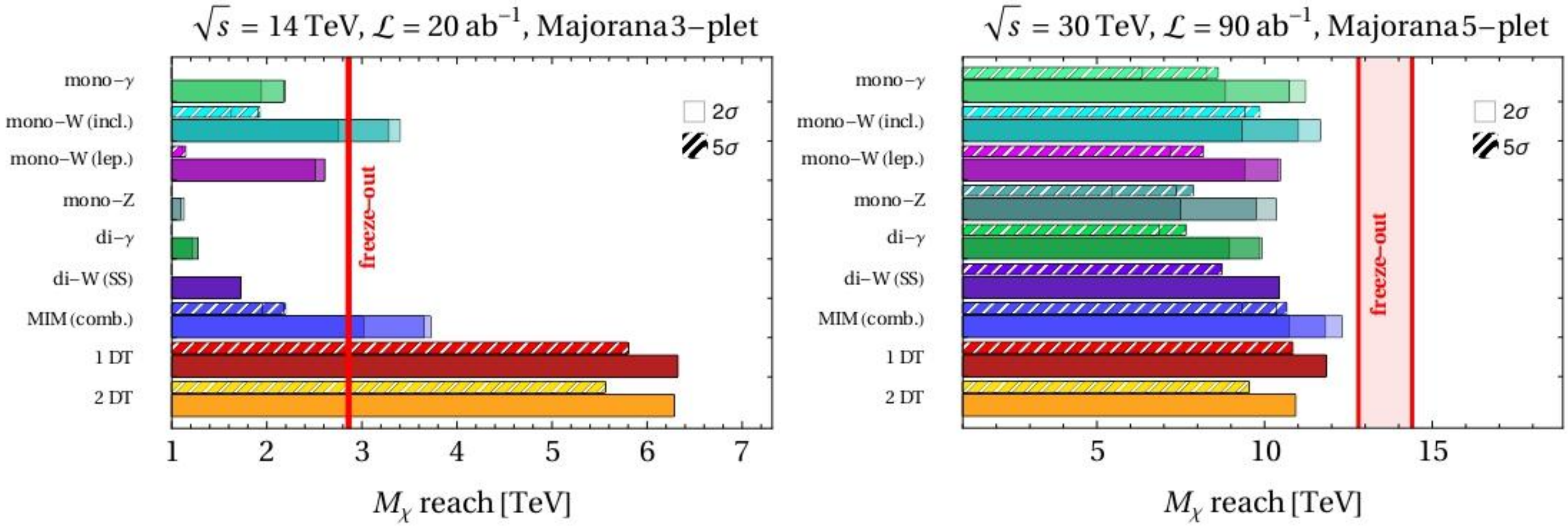
- **Signal:** energy deposition
- Energy loss β dependent
- Need careful bkg estimation
- Longest lived charged particle depends on spectrum, which depends also on neutral splitting

Mixing: $4_{1/2}$, 5_1



Results: Real WIMPs

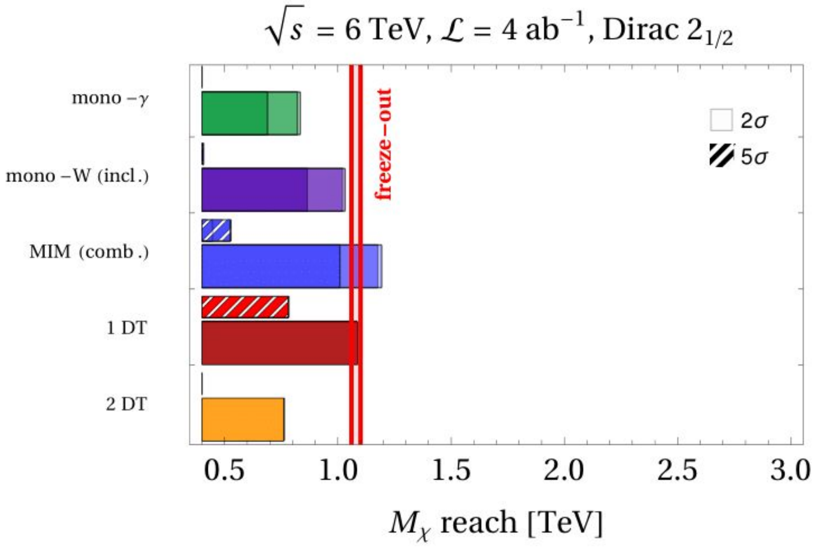
ϵ= 0%, 0.1%, 1%

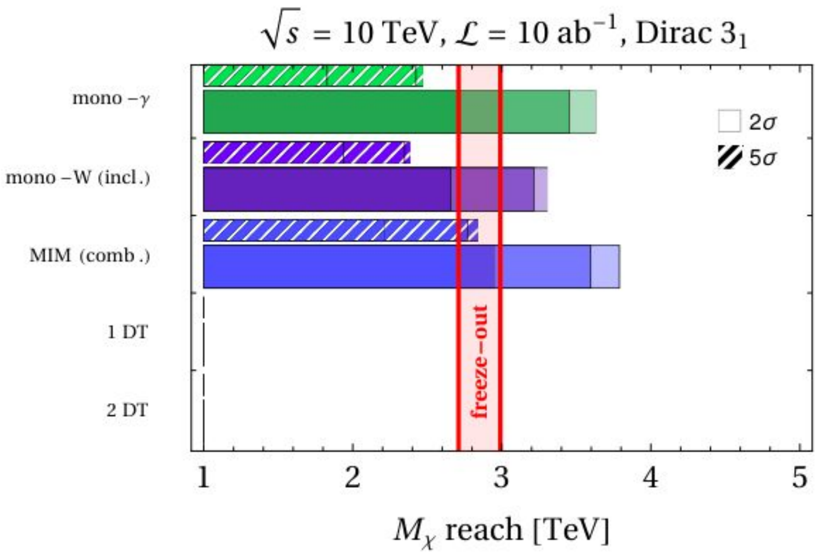


1DT: Good for 3_0; For 5_0 comparable to MIM

Complex WIMPs: $2_{1/2}$, 3_1

ϵ= 0%, 0.1%, 1%





$2_{1/2}$:@**6 TeV** with MIM and DT (EW)

3_1: **10 TeV only MIM** more than enough

Cuts (Reals)

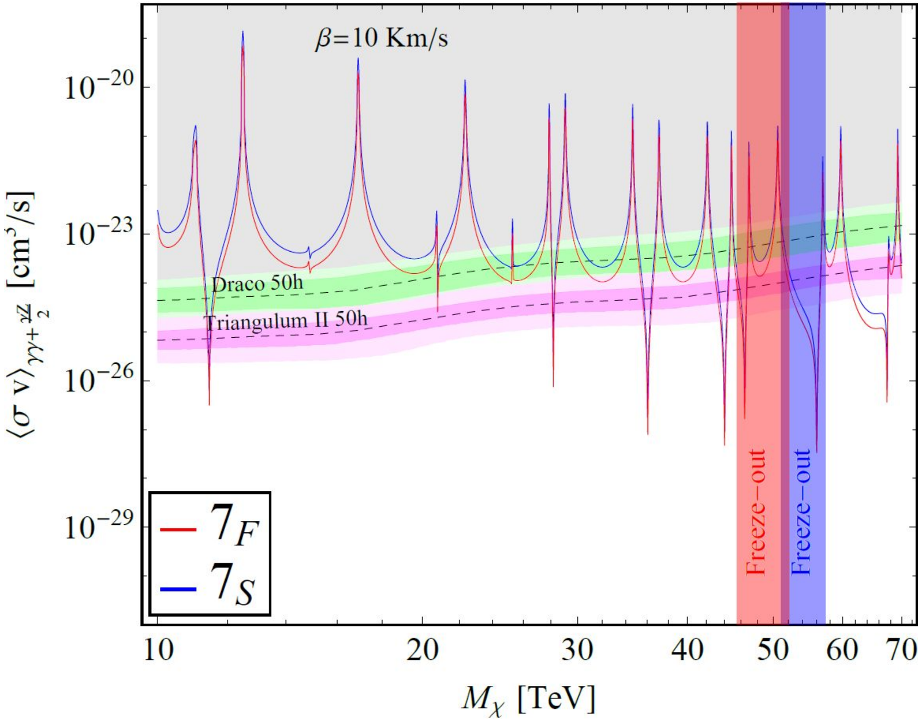
	$\sqrt{s}$	ϵ_{sys}	Majorana 3-plet η_X^{cut}	$p_{T,X}^{cut}$ [TeV]	$S_{95\%}$	$S_{95\%}/B$	$M_{95\%}$ [TeV]	Majorana 5-plet η_X^{cut}	$p_{T,X}^{cut}$ [TeV]	$S_{95\%}$	$S_{95\%}/B$	$M_{95\%}$ [TeV]
Mono-γ	3 TeV	0	2.4	0.18	1007	0.004	0.72	2.4	0.0	3038	0.001	1.4
		1‰	2.2	0.24	746	0.006	0.67	1.2	0.0	3683	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

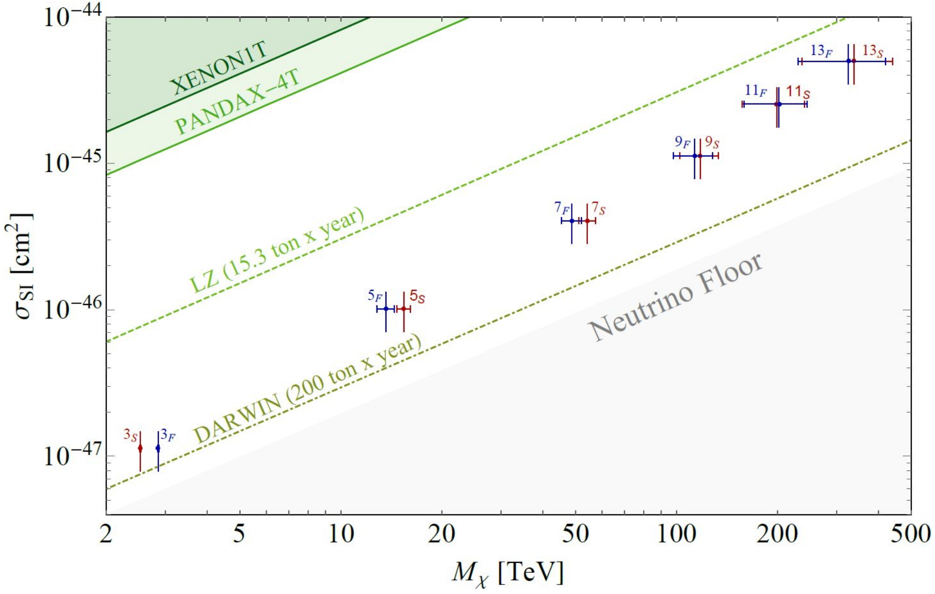
Cuts (Complex)

	$\sqrt{s}$	ϵ_{sys}	Dirac $2_{1/2}$ η_X^{cut}	$p_{T,X}^{cut}$ [TeV]	$S_{95\%}$	$S_{95\%}/B$	$M_{95\%}$ [TeV]	Dirac 3_1 η_X^{cut}	$p_{T,X}^{cut}$ [TeV]	$S_{95\%}$	$S_{95\%}/B$	$M_{95\%}$ [TeV]
Mono-γ	3 TeV	0	2.4	0.24	492	0.01	0.5	2.4	0.01	3181	0.001	1.3
		1‰	1.6	0.54	213	0.02	0.49	1.4	0.12	1217	0.004	1.2
		1%	1.	0.9	94	0.05	0.43	0.6	0.42	353	0.03	0.94
	6 TeV	0	1.8	0.96	296	0.02	0.83	2.4	0.	6895	0.0006	2.5
		1‰	1.4	1.4	282	0.02	0.82	1.4	0.24	1453	0.004	2.2
		1%	1.	1.9	83	0.06	0.69	0.8	1.1	309	0.03	1.7
	10 TeV	0	1.2	3.	101	0.05	1.1	2.	0.2	3159	0.001	3.6
		1‰	1.2	3.	99	0.04	1.1	1.4	0.8	867	0.006	3.5
		1%	0.8	3.8	56	0.08	0.98	1.	2.	348	0.03	2.7
	14 TeV	0	1.2	4.2	107	0.04	1.5	1.8	0.56	2080	0.002	4.9
		1‰	0.8	4.5	110	0.04	1.5	1.6	1.1	991	0.005	4.7
		1%	0.6	5.9	46	0.1	1.3	0.6	2.8	290	0.03	3.7
	30 TeV	0	1.	9.6	107	0.04	3.	1.8	1.8	1423	0.003	10.
		1‰	1.	9.6	107	0.04	3.	1.6	3.	911	0.005	9.6
		1%	0.8	10.	98	0.05	2.7	1.	6.6	309	0.03	7.6
Mono-W (inclusive)	3 TeV	0	1.4	0.6	336	0.01	0.53	2.	0.18	1833	0.002	1.1
		1‰	1.2	0.72	228	0.02	0.52	1.6	0.3	1180	0.004	1.
		1%	0.8	1.	92	0.06	0.47	1.	0.66	345	0.03	0.85
	6 TeV	0	1.4	1.2	361	0.01	1.	2.	0.48	1572	0.003	2.
		1‰	1.4	1.2	351	0.01	1.	1.4	0.72	1051	0.005	2.
		1%	1.	1.8	140	0.04	0.86	0.8	1.2	480	0.03	1.6
	10 TeV	0	1.6	2.	336	0.01	1.5	1.6	1.	1424	0.003	3.3
		1‰	1.6	2.	331	0.01	1.5	1.4	1.2	1065	0.005	3.2
		1%	0.8	3.4	100	0.05	1.3	0.8	2.	429	0.03	2.7
	14 TeV	0	1.2	3.4	298	0.01	2.1	1.6	1.4	1566	0.003	4.6
		1‰	1.2	3.4	322	0.01	2.1	1.4	1.7	1066	0.005	4.4
		1%	0.8	4.8	107	0.05	1.7	0.8	3.6	225	0.03	3.6
	30 TeV	0	1.4	6.6	344	0.01	4.1	1.8	3.	1433	0.003	9.6
		1‰	1.4	7.2	283	0.01	4.1	1.6	4.2	976	0.005	9.3
		1%	0.8	11.	75	0.07	3.4	0.8	8.4	216	0.03	7.5

	$\sqrt{s}$	ϵ_{sys}	Dirac $4_{1/2}$ η_X^{cut}	$p_{T,X}^{cut}$ [TeV]	$S_{95\%}$	$S_{95\%}/B$	$M_{95\%}$ [TeV]	Dirac 5_1 η_X^{cut}	$p_{T,X}^{cut}$ [TeV]	$S_{95\%}$	$S_{95\%}/B$	$M_{95\%}$ [TeV]
Mono-γ	3 TeV	0	2.4	0.01	3026	0.001	1.4	2.4	0.01	2823	0.001	1.5
		1‰	1.4	0.01	4092	0.003	1.3	1.6	0.01	3906	0.003	1.4
		1%	0.6	0.3	517	0.02	1.1	0.4	0.12	1245	0.02	1.2
	6 TeV	0	2.4	0.01	6776	0.0006	2.7	2.4	0.01	6400	0.0006	2.9
		1‰	1.2	0.24	1732	0.004	2.4	1.2	0.01	6084	0.003	2.7
		1%	0.8	0.96	478	0.02	2.	0.6	0.72	697	0.02	2.3
	10 TeV	0	2.4	0.01	7217	0.0008	4.1	2.4	0.01	10886	0.0004	4.7
		1‰	1.2	0.6	1264	0.004	3.8	1.2	0.2	3073	0.003	4.4
		1%	0.8	1.6	424	0.03	3.1	0.4	1.2	531	0.02	3.7
	14 TeV	0	2.2	0.28	3174	0.001	5.5	2.4	0.01	15838	0.0003	6.4
		1‰	1.2	1.1	936	0.005	5.2	1.	0.56	1967	0.003	6.
		1%	0.6	2.8	276	0.03	4.3	0.4	2.	483	0.02	5.1
	30 TeV	0	1.6	1.2	2374	0.002	11.	1.6	0.6	4145	0.001	13.
		1‰	1.2	2.4	1134	0.004	11.	0.8	1.2	2078	0.003	13.
		1%	0.8	6.	356	0.03	8.7	0.6	4.2	671	0.02	11.
Mono-W (inclusive)	3 TeV	0	2.4	0.06	5317	0.0008	1.2	2.4	0.	6314	0.0006	1.3
		1‰	1.2	0.24	1409	0.004	1.2	1.	0.18	1705	0.004	1.3
		1%	0.8	0.54	460	0.02	1.	0.6	0.36	1255	0.02	1.1
	6 TeV	0	2.2	0.12	8969	0.0004	2.4	2.4	0.	16721	0.0002	2.6
		1‰	1.2	0.48	1855	0.003	2.3	1.	0.36	2629	0.003	2.5
		1%	0.8	1.1	467	0.03	2.	0.6	0.72	1010	0.02	2.2
	10 TeV	0	2.	0.4	4213	0.001	4.	2.2	0.2	9661	0.0004	4.4
		1‰	1.4	1.	1202	0.004	3.8	1.2	0.6	2786	0.003	4.2
		1%	0.6	2.	441	0.03	3.2	0.4	1.6	622	0.02	3.7
	14 TeV	0	1.8	0.56	4093	0.001	5.5	2.2	0.28	10846	0.0004	6.1
		1‰	1.2	1.4	1215	0.004	5.3	1.2	0.84	2859	0.003	5.8
		1%	1.	2.8	486	0.02	4.4	0.2	2.5	315	0.03	5.
	30 TeV	0	1.6	2.4	2888	0.002	12.	2.2	0.6	8056	0.0006	13.
		1‰	1.2	2.4	1922	0.003	11.	1.2	2.4	1829	0.003	12.
		1%	1.	6.	627	0.02	9.3	0.4	5.4	395	0.03	11.

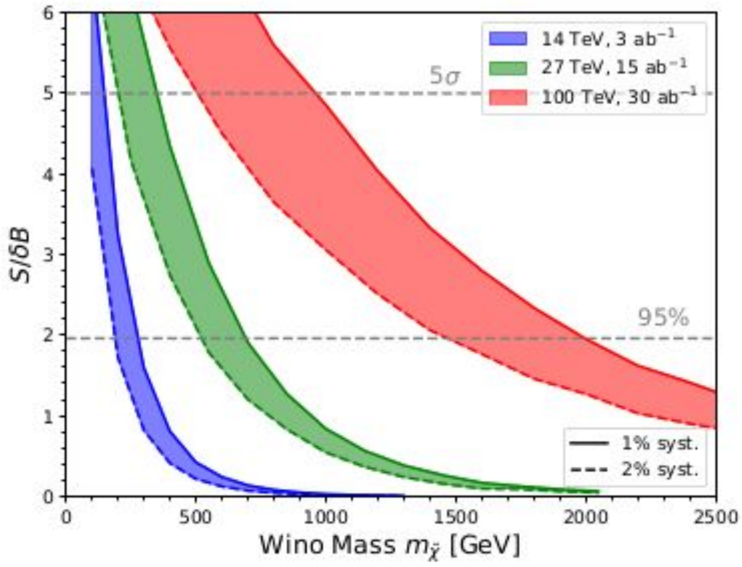
Collider vs ID/DD

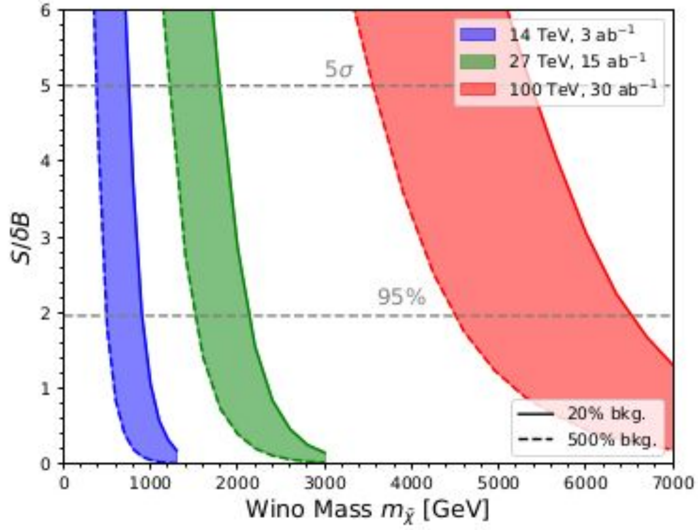




recast from Panci et al. 1608.00786

FCC-hh prospects





Han et al.
1805.00015

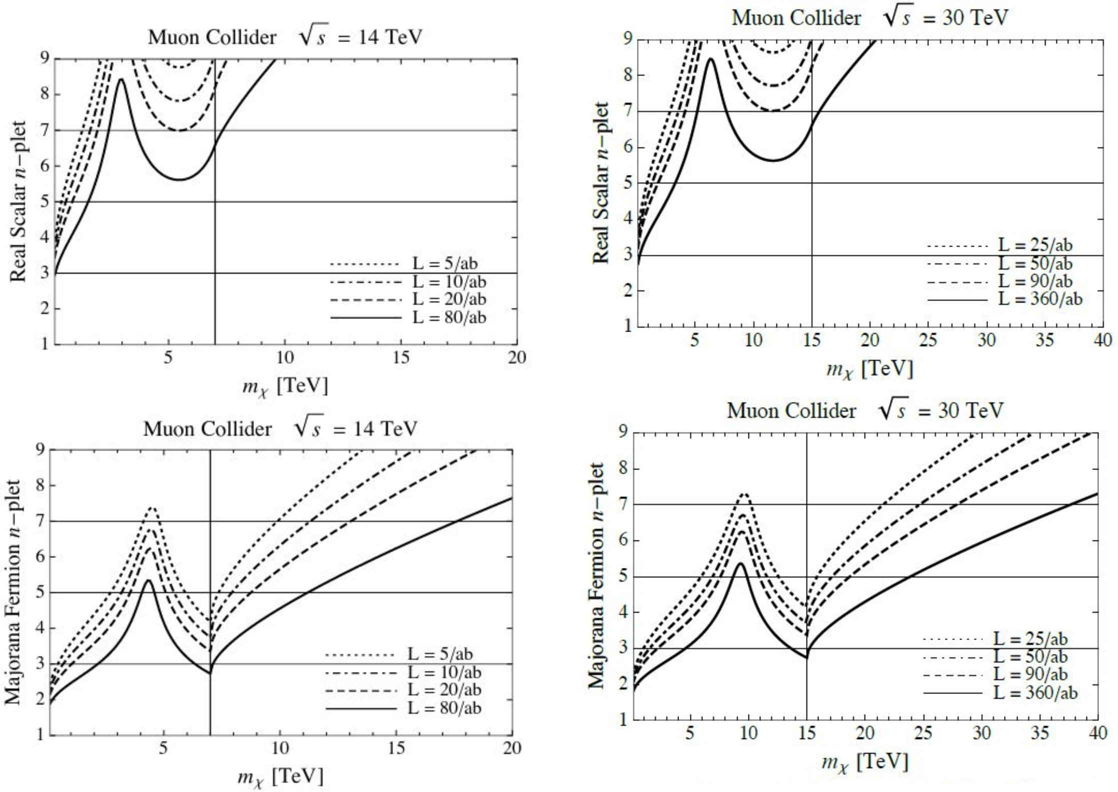
mono-jet

DT

Indirect collider prospects

μμ -> ff
corrections

Expected 95% CL exclusion limits



Di Luzio et al.
1810.10993

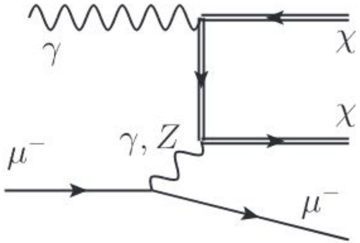
Muon channels

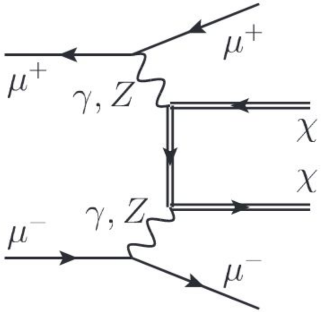
Mono-μ

Di-μ

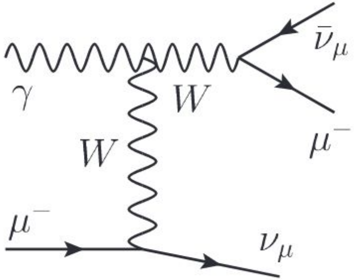
Han et al.
2009.11287

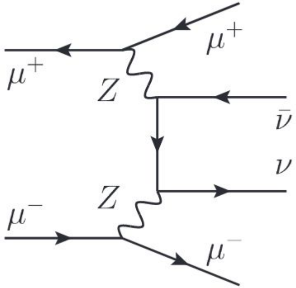
Sig





Bkg

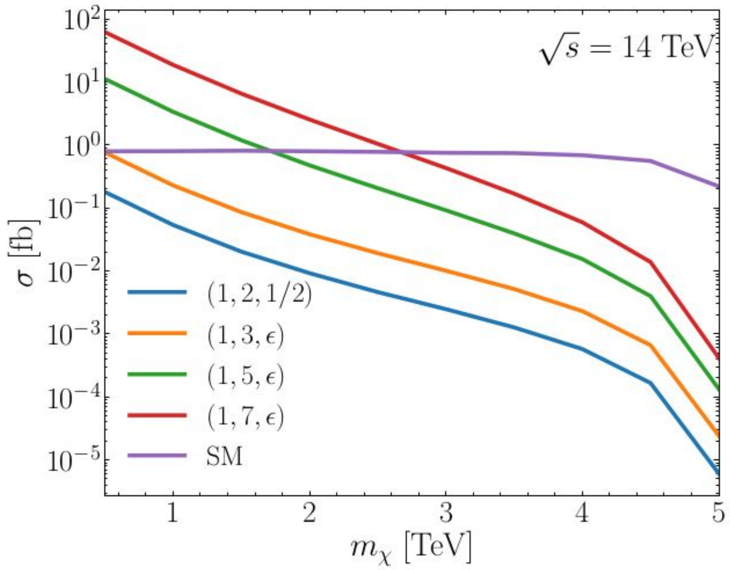


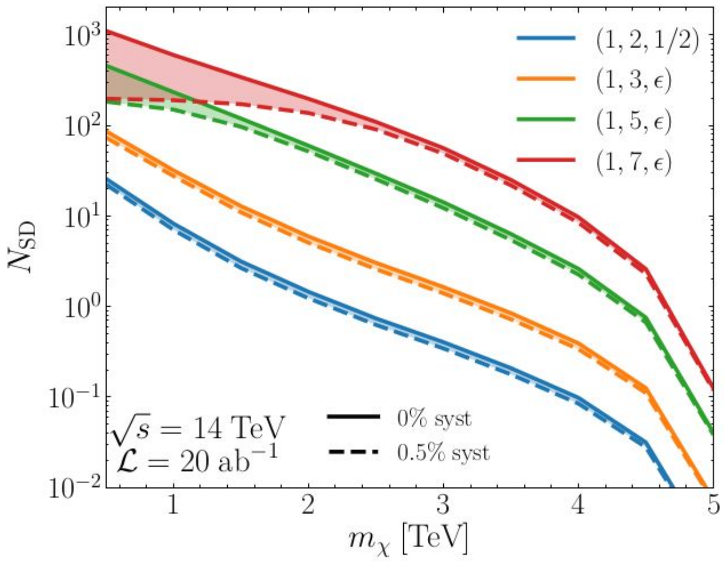


VBF channels

Mono-μ results

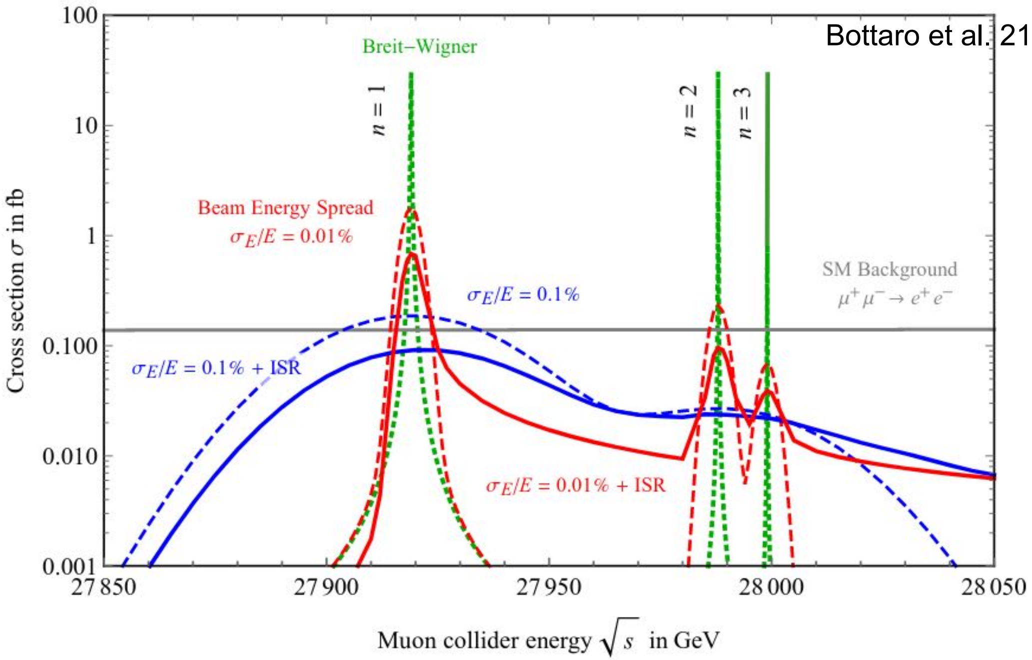
Han et al.
2009.11287





Good at low mass

Bound States (5_0F only)

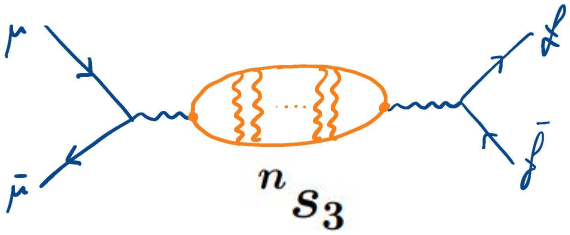


Bottaro et al. 2103.12766

Discovery in 1 day of running!

Peaks in ee cross section

same QN as W's!
s-channel mixing



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

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