CLOSING IN ON
WIMP DM
AT THE MUON COLLIDER

ROBERTO FRANCESCHINI

November 18th 2023 - Pittsburgh

AN ATTEMPT TO A REVIEW

AND WORKS WITH SALVATORE BOTTARO, MARCO COSTA, LUDOVICO VITTORIO, XIAORAN ZHAO AND DARIO BUTTAZZO, PAOLO PANCI, DIEGO REDIGOLO

2107.09688, 2205.04486, 2212.11900

ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN Roma3

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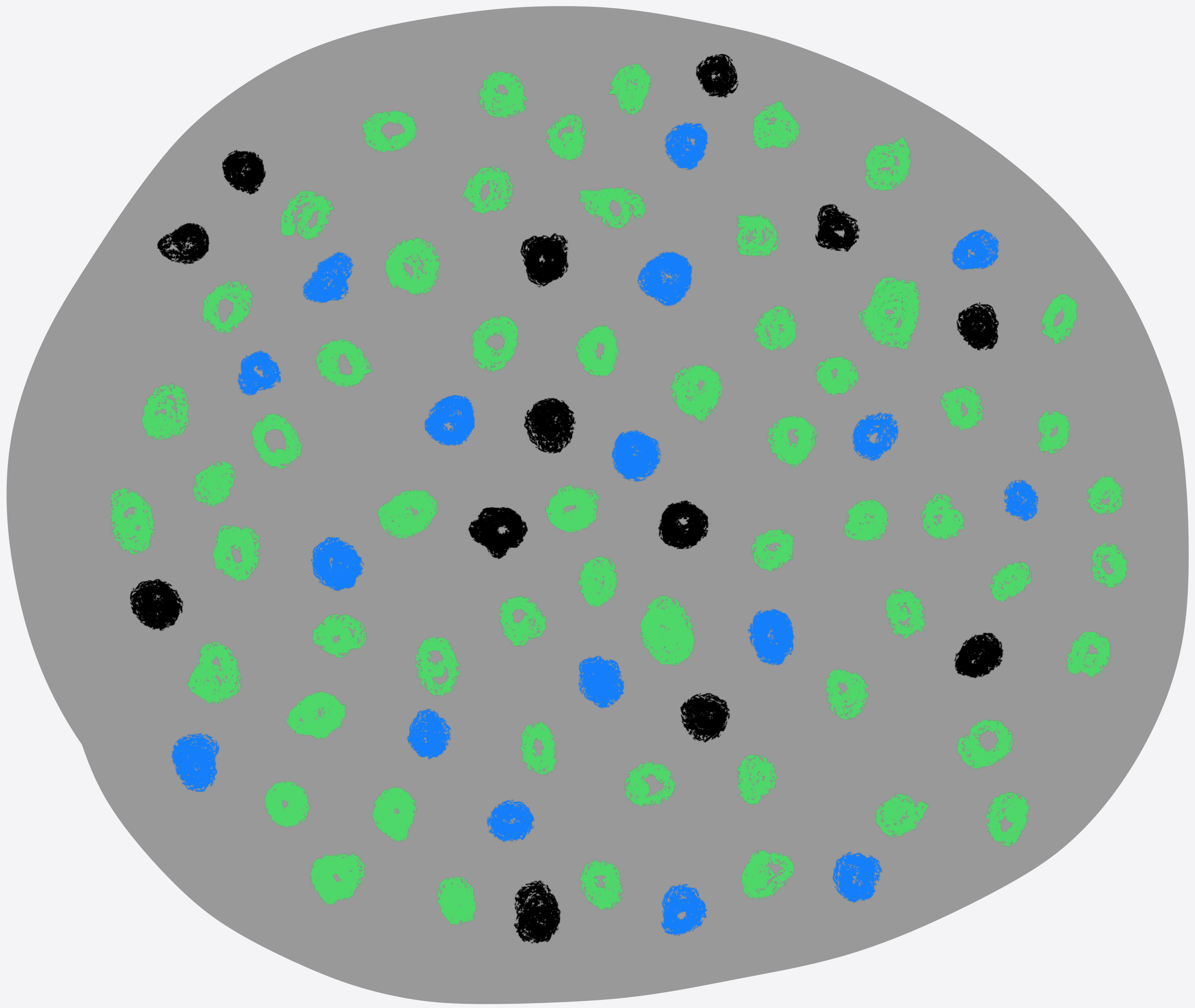
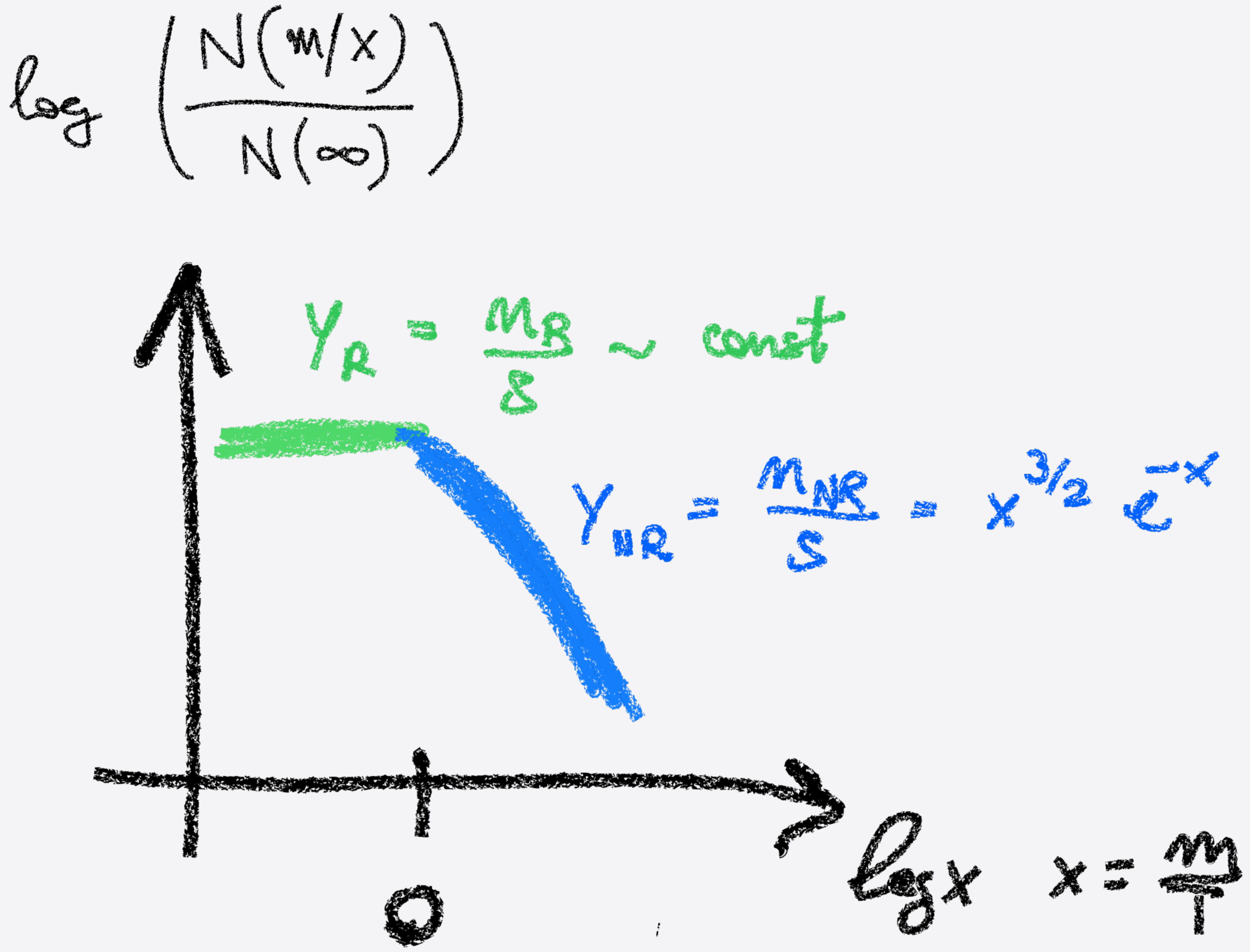
INTRO

A SIMPLEST EXPLANATION FOR ITS PRODUCTION



- SM RELATIVISTIC
- DARK MATTER
- SM NON-RELATIVISTIC



Following equilibrium thermodynamics the number density of a specie can be predicted at all times it is in equilibrium. Once it drops out from equilibrium Y freezes out and the relic density is fixed.

$$\frac{dY}{dx} = \frac{-x\overbrace{\langle \sigma_a v \rangle}^{\sigma_0 \cdot T^k} s}{H(m)}\left(Y^2 - Y_{eq}^2\right)$$

$$= \# \, m M_{pl} \sigma_0 \, x^{-k-2}$$

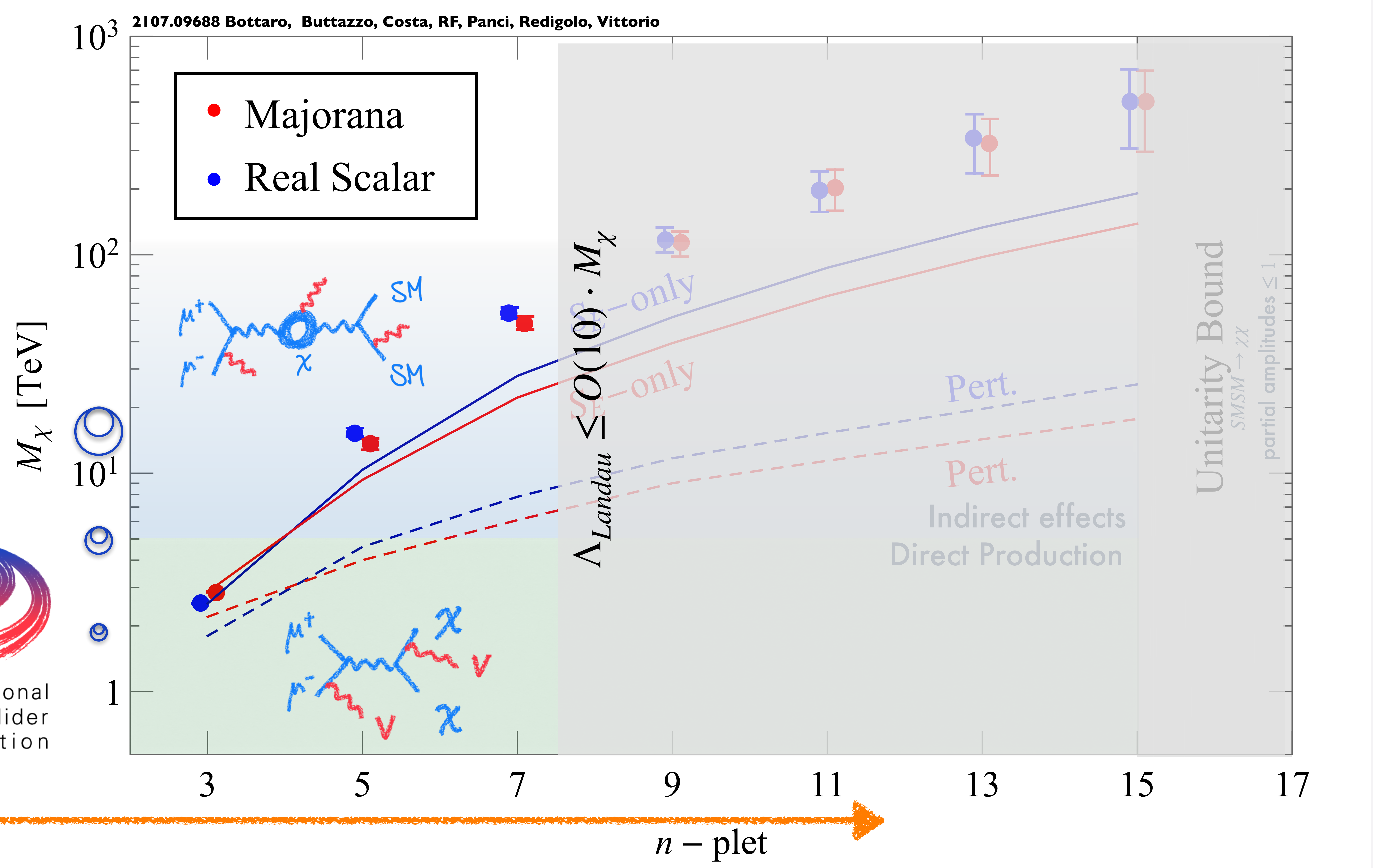
$$Y_\infty = \# \frac{(x_f)^{k+1}}{M_{pl}\, m\, \sigma_0} \sim \# \frac{m}{M_{pl}} (x_f)^{k+1}$$

THE WIMP "CATALOG"

mass of the DM

Following equilibrium thermodynamics the number density of a specie can be predicted at all times it is in equilibrium. Once it drops out from equilibrium Y freezes out and the relic density is fixed.

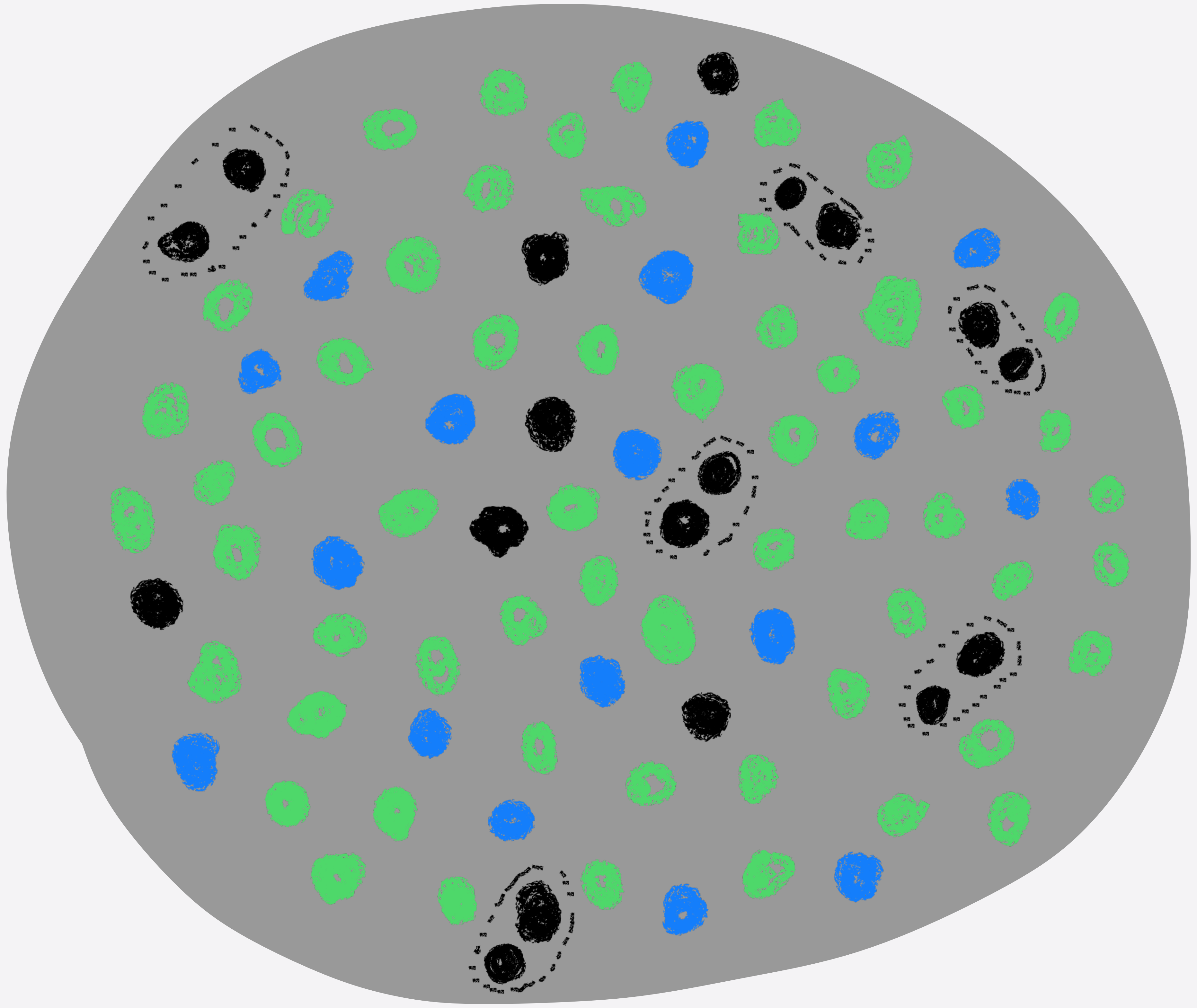
$$\Omega_{nr} \sim \frac{1}{\sigma_{ann}} \sim \frac{M^2}{C_n \cdot g^2}$$



weak charge of the DM

WIMPs are clearly "muon collider material"

A STILL SIMPLE EXPLANATION FOR ITS PRODUCTION



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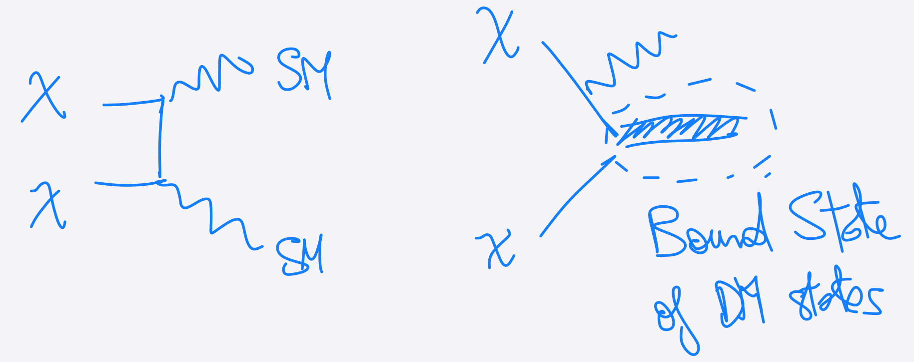
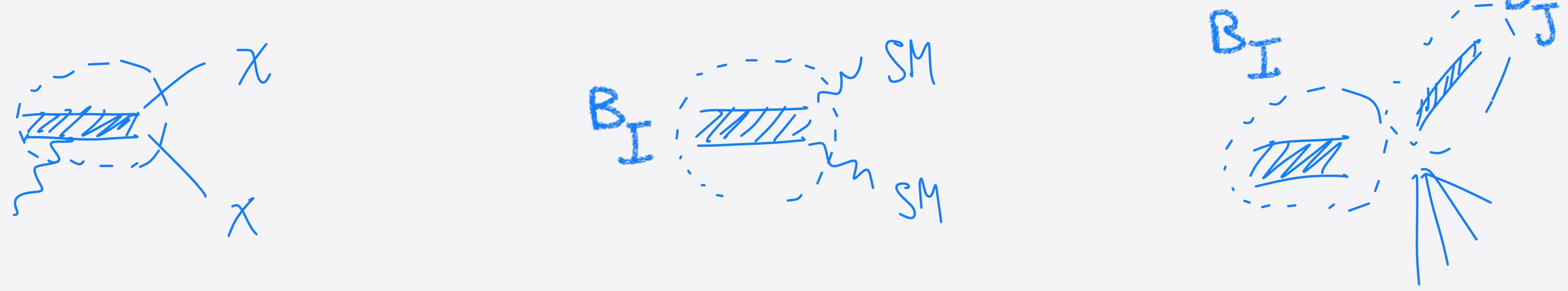
$$z s H(T) \frac{dY}{dx} = -\gamma_a\left(\frac{Y_{DM}^2}{Y_{eq}^2}-1\right) - \sum \gamma_I \left(\frac{Y_{DM}^2}{Y_{DM}^{eq\,2}} - \frac{Y_I}{Y_{eq}}\right)$$



$$s z H \frac{dY_{B_I}}{dx} = \Gamma_{B_I,\text{break}}\left(\frac{Y_{DM}^2}{Y_{eq}^2} - \frac{Y_{B_I}}{Y_{B_I}^{eq}}\right) + \Gamma_{B_I,\text{ann}}\left(1-\frac{Y_{B_I}}{Y_{B_I}^{eq}}\right) + \sum \Gamma_{IJ}\left(\frac{Y_{B_I}}{Y_{B_I}^{eq}} - \frac{Y_{B_J}}{Y_{B_J}^{eq}}\right)$$



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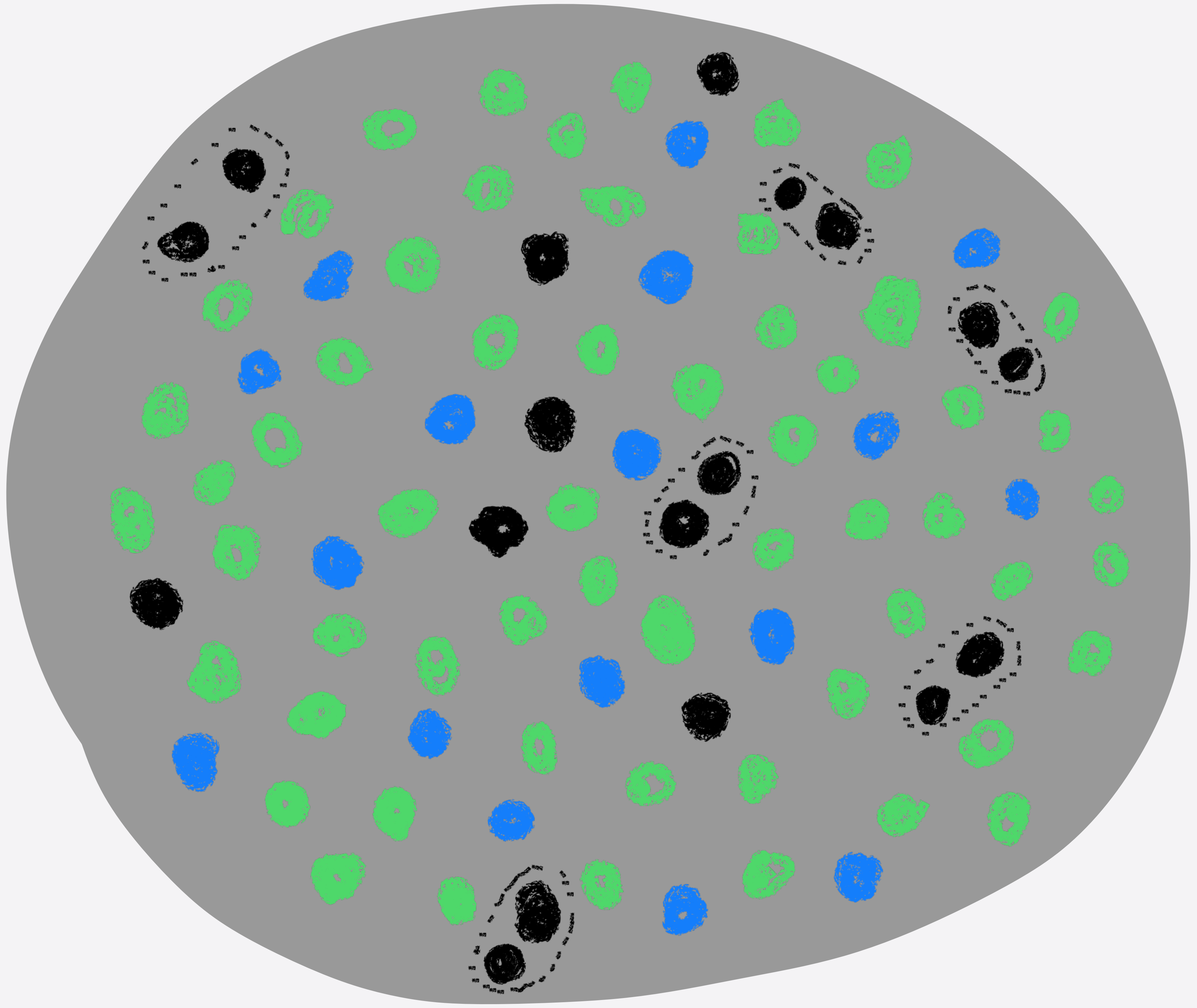

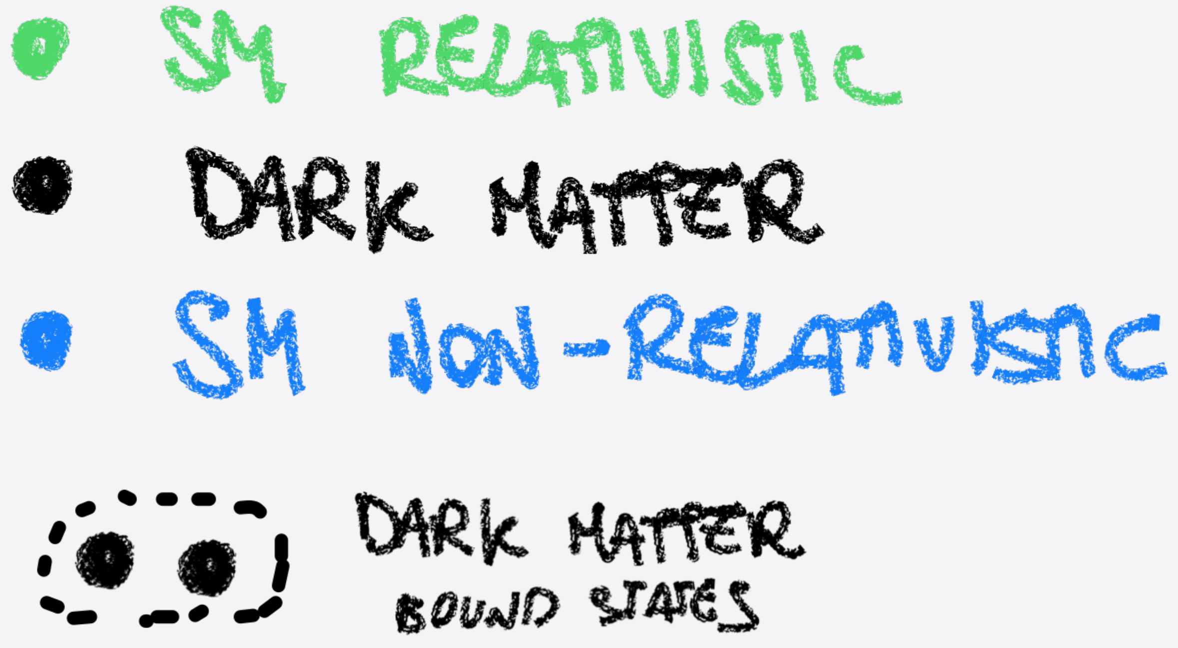

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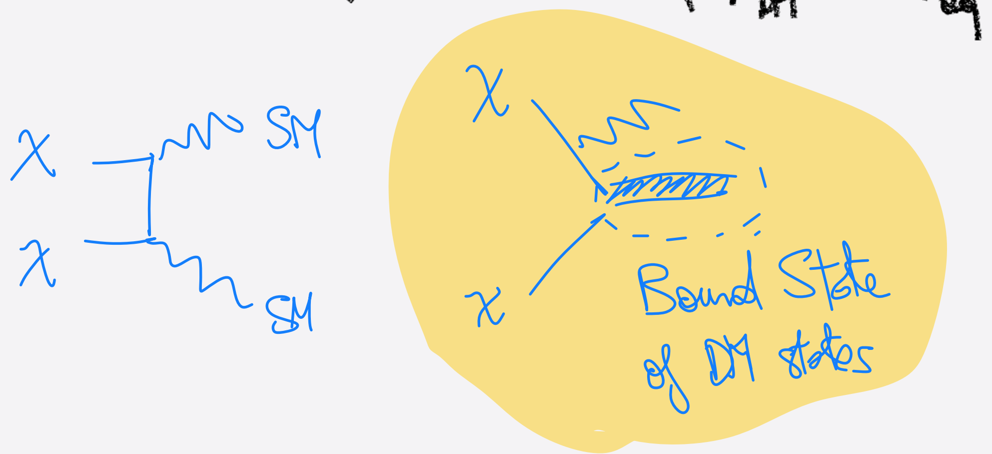

$H \ll \Gamma$

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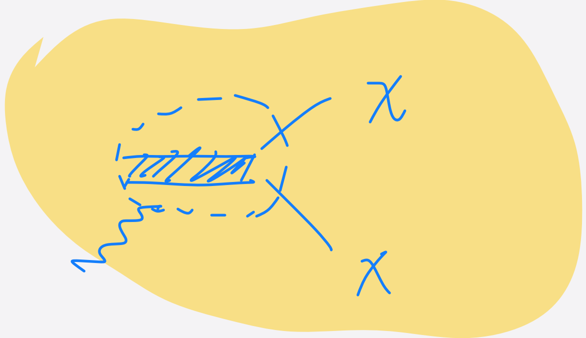

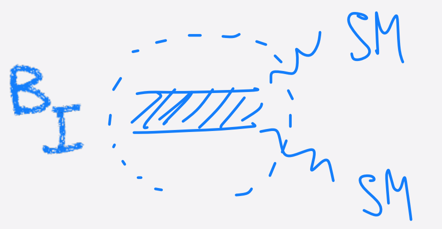

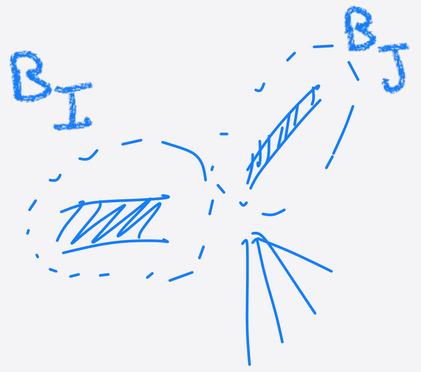

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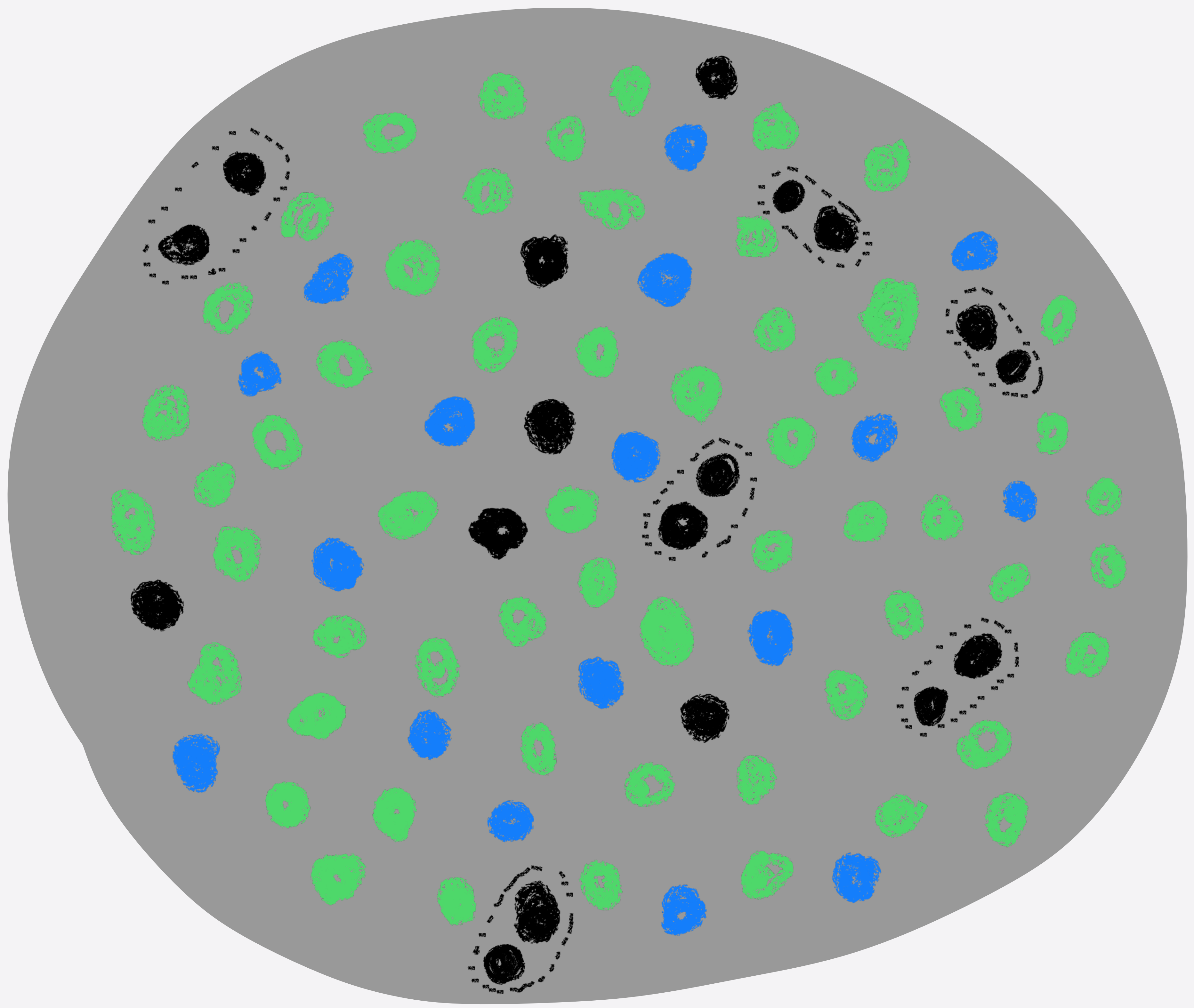
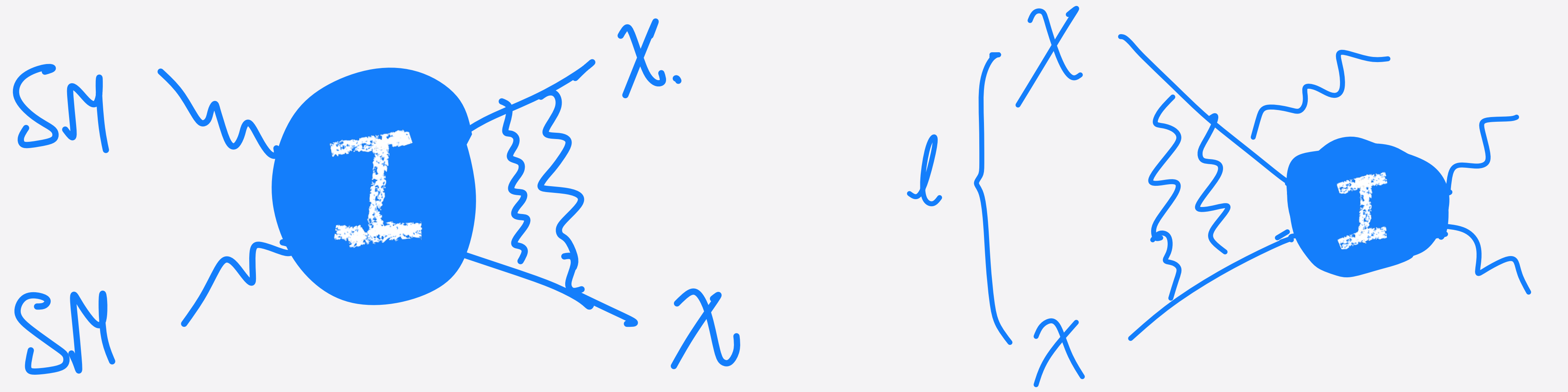


- SM RELATIVISTIC
- DARK MATTER
- SM NON-RELATIVISTIC
- DARK MATTER BOUND STATES

Following equilibrium thermodynamics the number density of a specie can be predicted at all times it is in equilibrium. Once it drops out from equilibrium Y freezes out and the relic density is fixed.

$$x H \frac{dY}{dx} = -\langle \sigma_{eff} v \rangle s \left(Y^2 - Y_{eq}^2 \right)$$

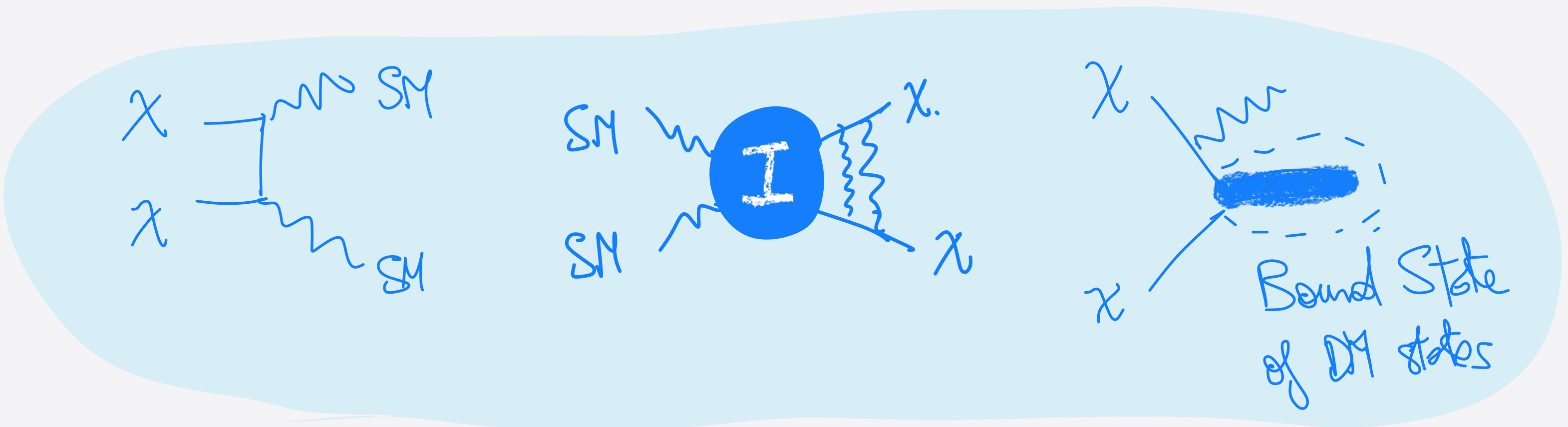
$$\langle \sigma_{eff} v_{rel} \rangle = \sum_I \langle S_E^{(I)} \sigma_{ann}^{(I)} v_{rel} \rangle + \sum_{B_j} \sum_{I\ell} S_E^{(I)} S_{B_j}^{I,\ell} R_{B_j}$$



channel-by-channel Sommerfeld enhancement (resummation)

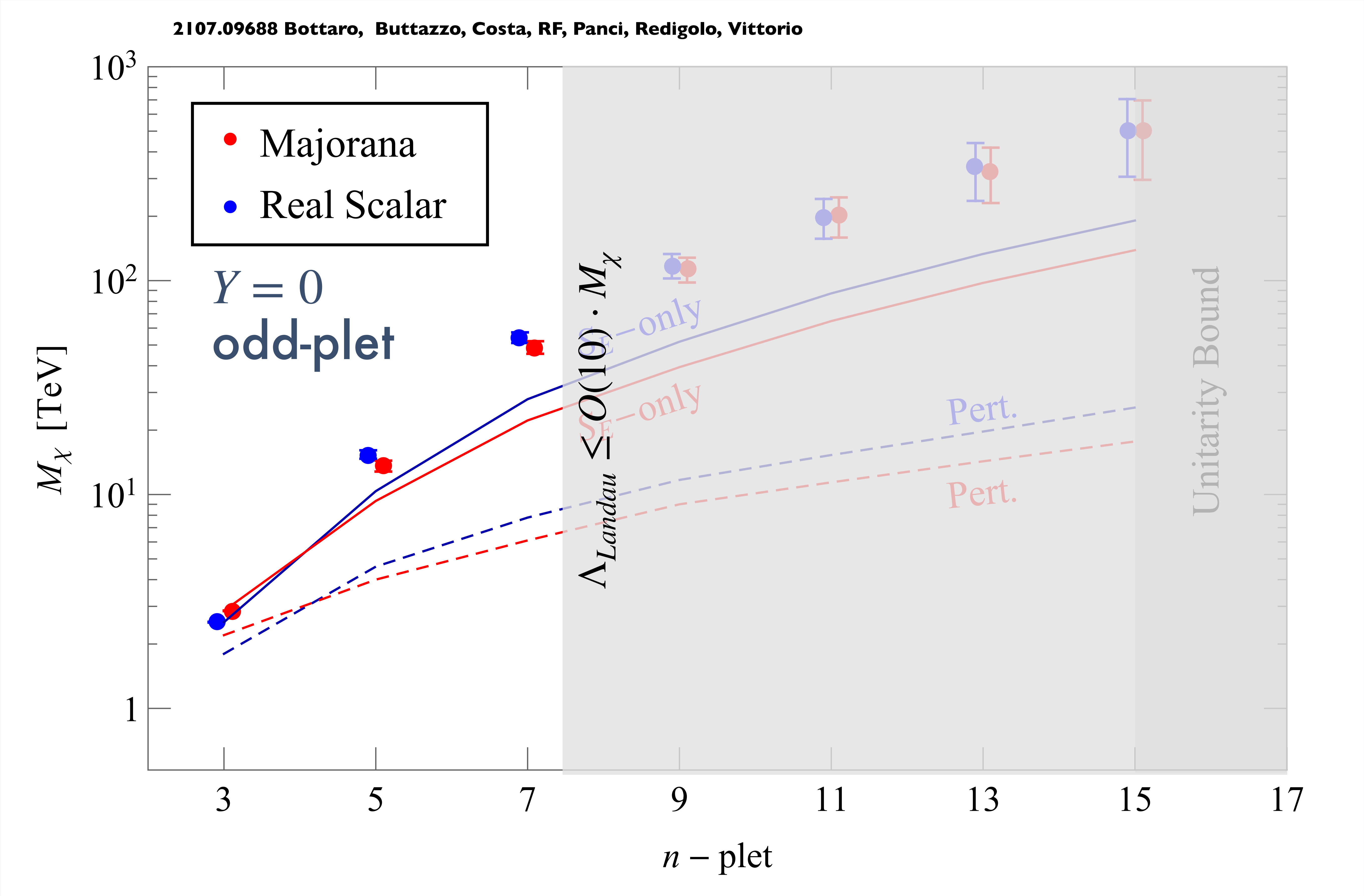
AN "INTERPOLATOR" MODEL

$$\Omega_{nr} \sim \frac{1}{\sigma_{ann}} \sim \frac{M^2}{C_n \cdot g^2}$$



given n the mass is predicted

understood as the maximal mass for that n



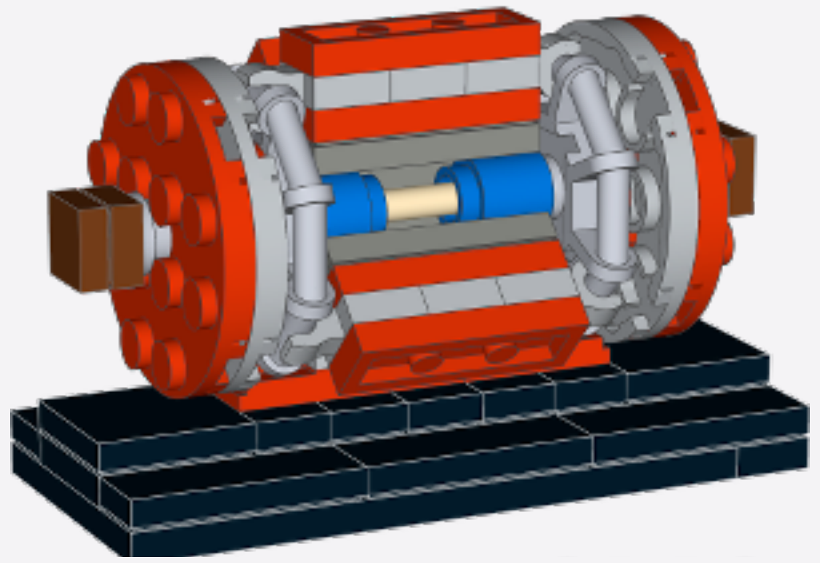
If Dark Matter feels SM weak interactions we can use the general n-plet WIMP to measure how well we are able to test this hypothesis and possibly discover or exclude one or several or the whole category of DM candidates.

AFTER DECADES OF WIMPs WE MIGHT START TO SEE THE END OF THE WAY (!)

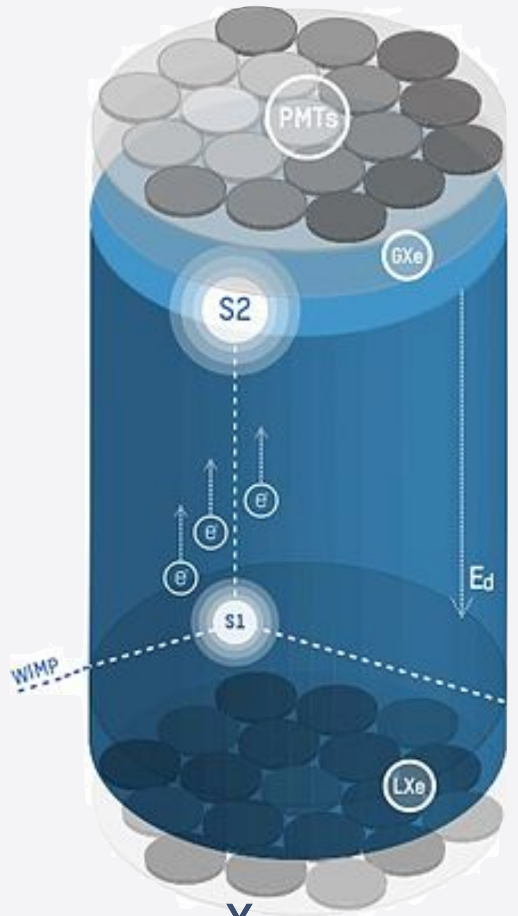
How to thoroughly test it?

- Produce WIMPs in the lab
- Detect a WIMPs from natural source (big-bang)
- Observe WIMPs interactions (annihilation)

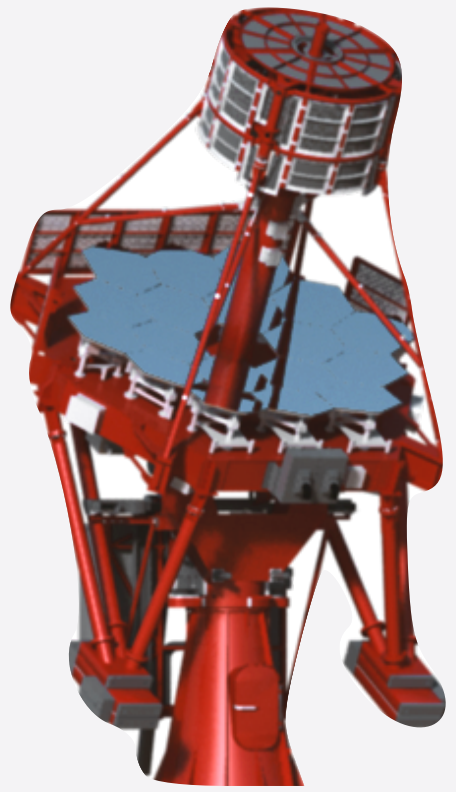
- Future Colliders sensitive to O(100) TeV
- Upcoming nT *Xe* detectors
- Upcoming Cosmic Rays observatories



Future Collider



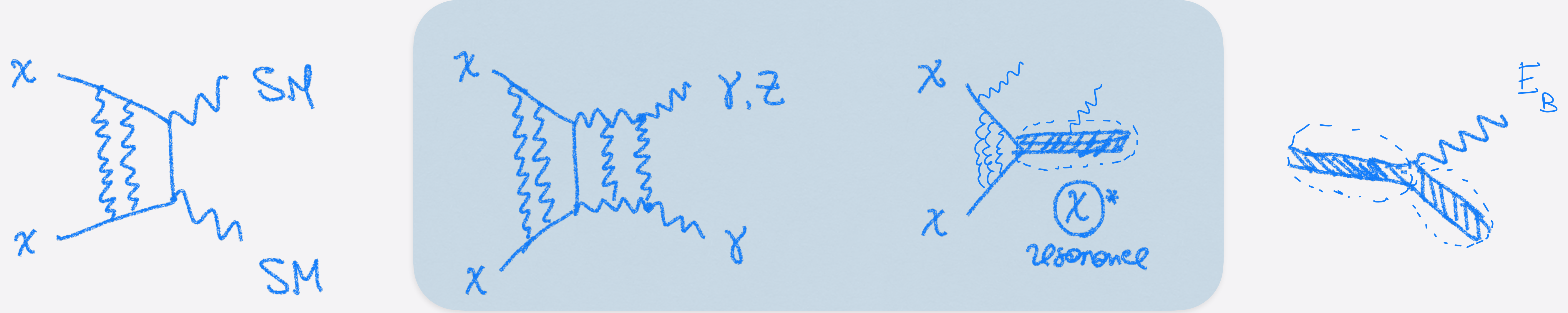
Xenon



CTA

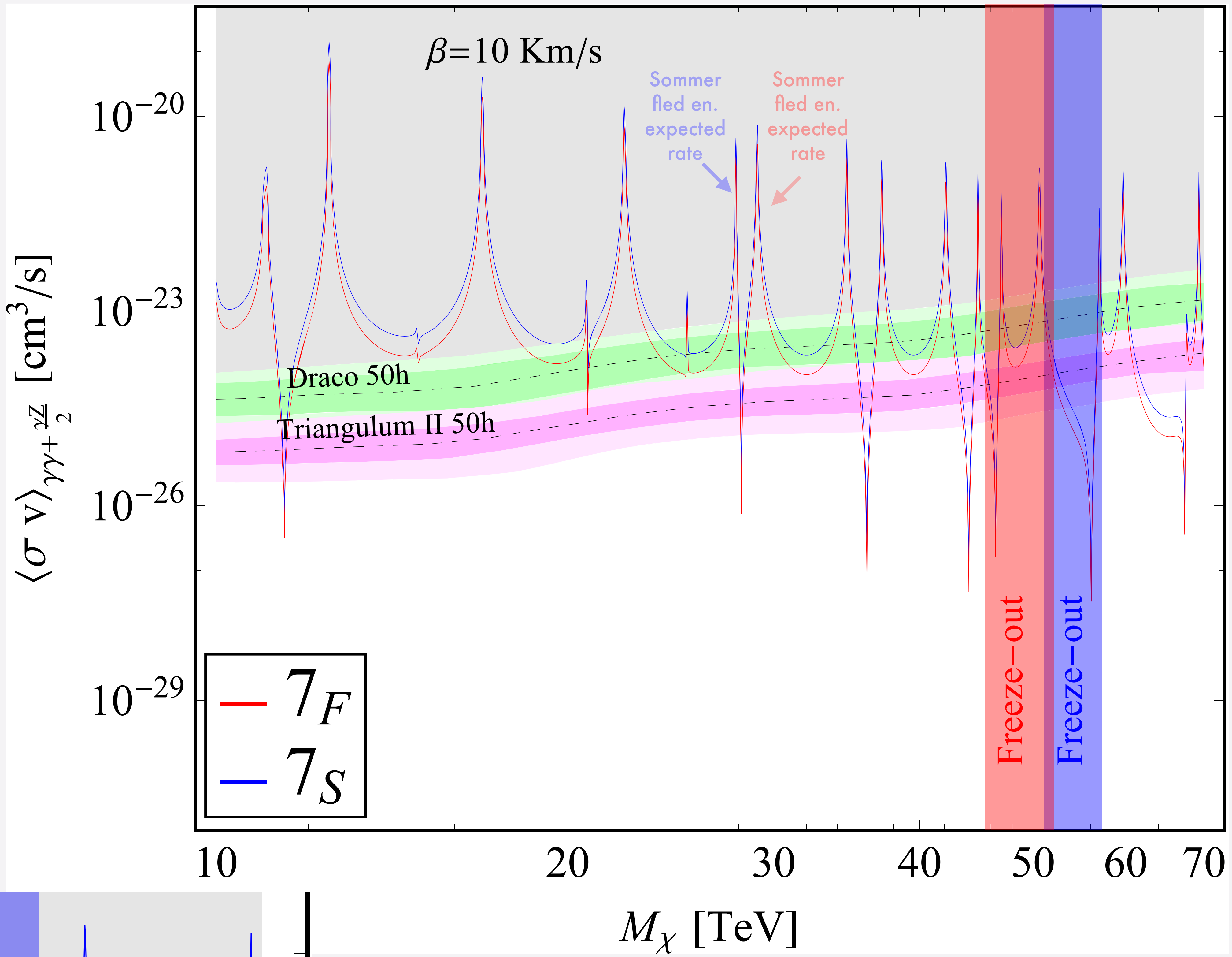
1210.6104

INDIRECT DETECTION

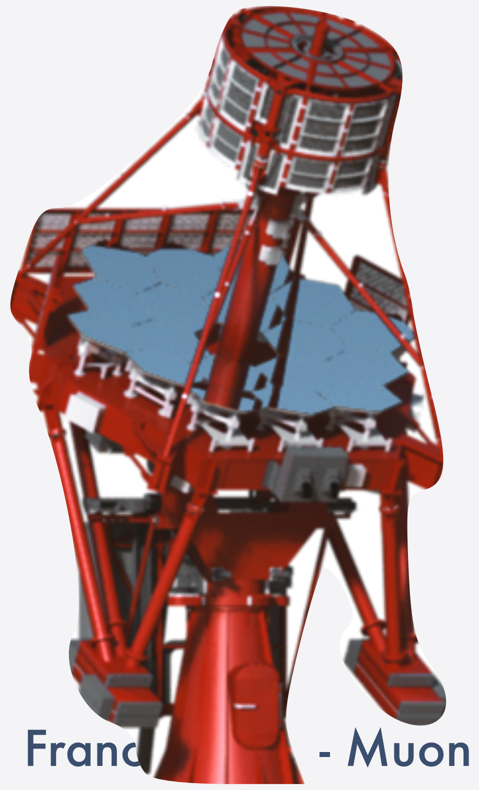


Annihilation in the astrophysical environment result in high-energy SM particle, which can be detector by cosmic rays observatories.

The signature depends on DM mass, possible resonant bound states formation and DM density profile

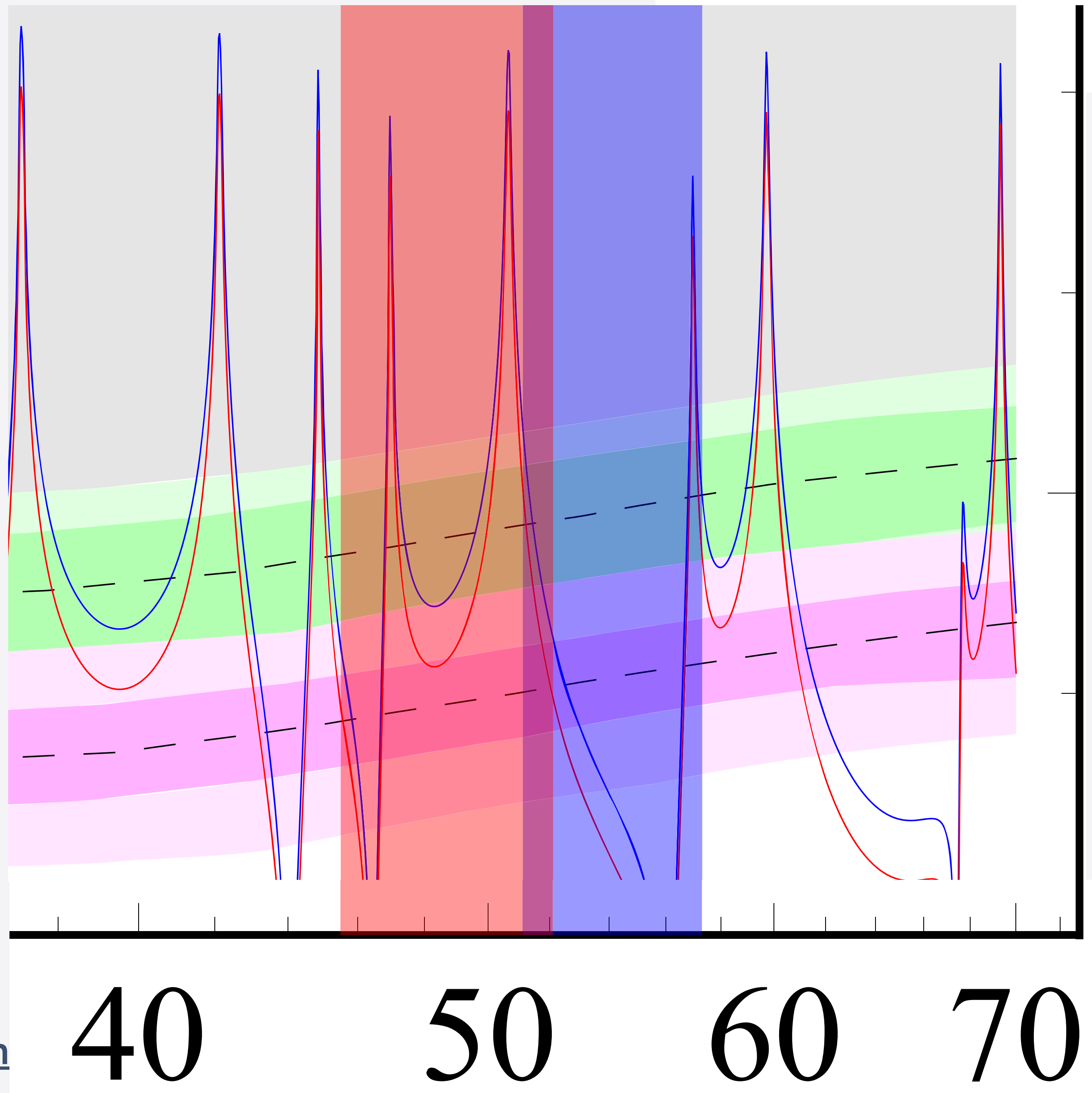


An excess on monochromatic multi-TeV photons would be quite convincing evidence of DM. The model can be even tested by the presence of multiple "lines" from bound states annihilations and lower energy de-excitation



2030s

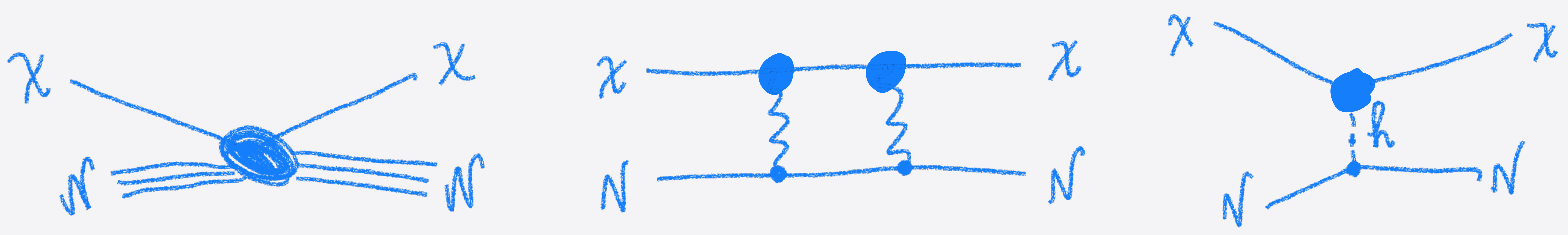
up to 300 TeV, $\frac{\Delta E}{E} \sim 10\,\%$

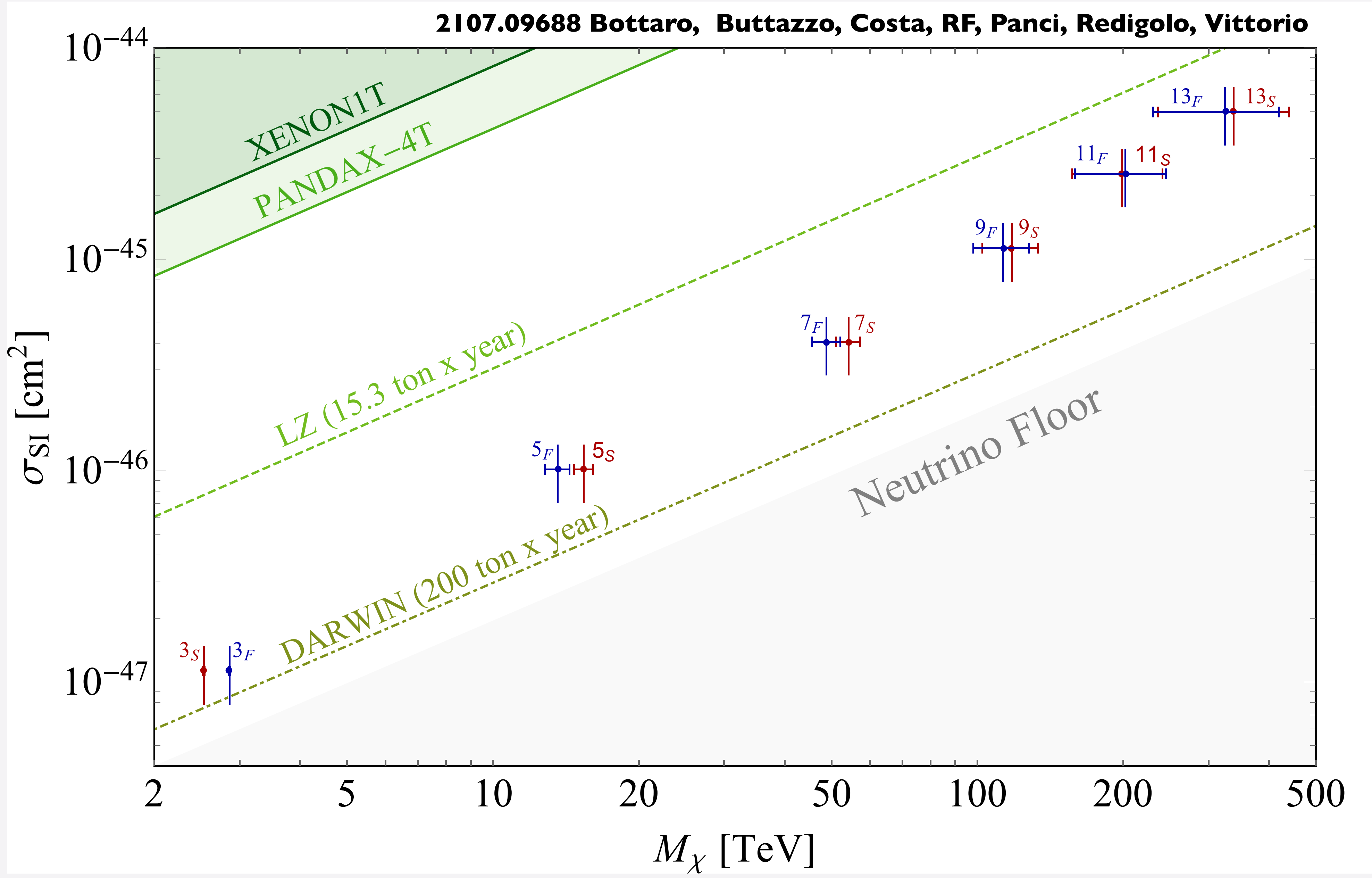


thermal mass "lottery": if the actual mass varies within the current theoretical uncertainty the signal strength changes by orders of magnitude!

1104.0228 - Hisano, Ishiwata, Nagata, Takesako

DIRECT DETECTION



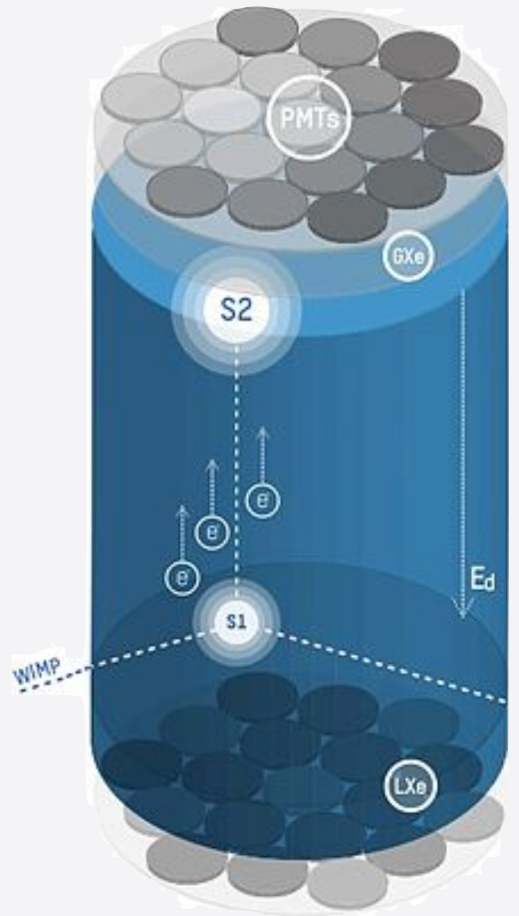


Scattering on SM materials can be detected in ultra-low background experiments

Larger rates for the larger n-plets keep them visible

For such large DM mass the signature does not depend on the DM mass.

An excess would require a "seasonality" check and maybe independent confirmation (many excesses in the past in this type of experiments, though most were at the lowest accessible masses)



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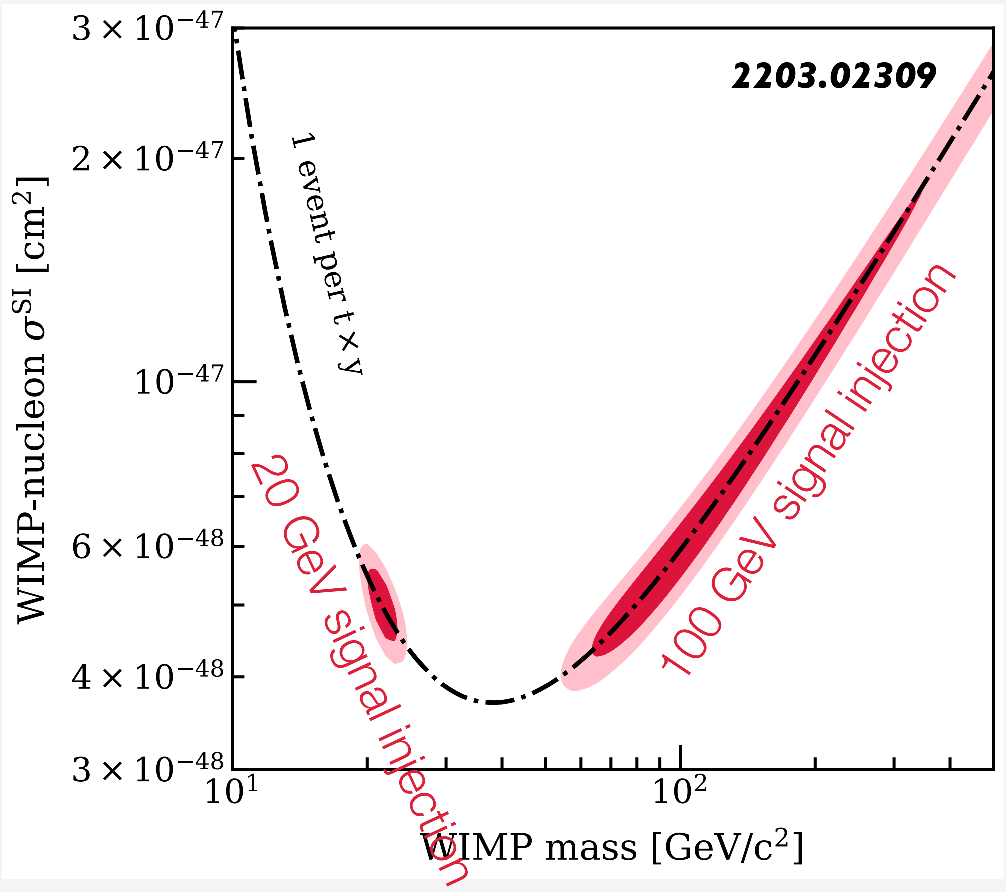
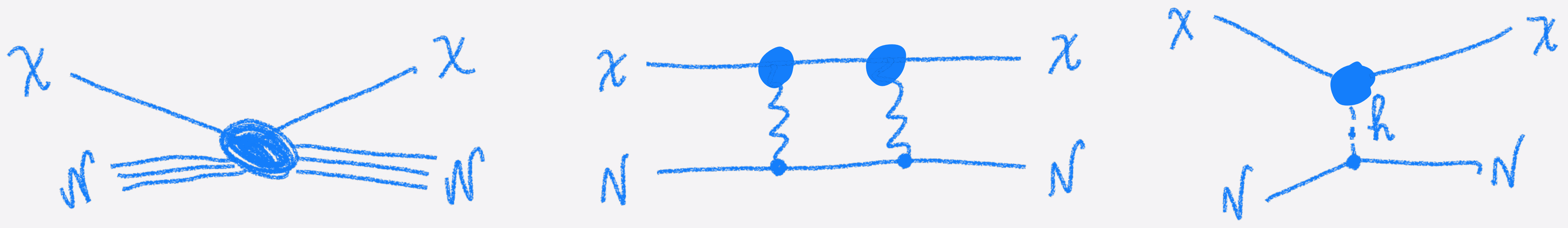
up to O(PeV)



insensitive to χ mass, urgent need for high-energy colliders

DIRECT DETECTION



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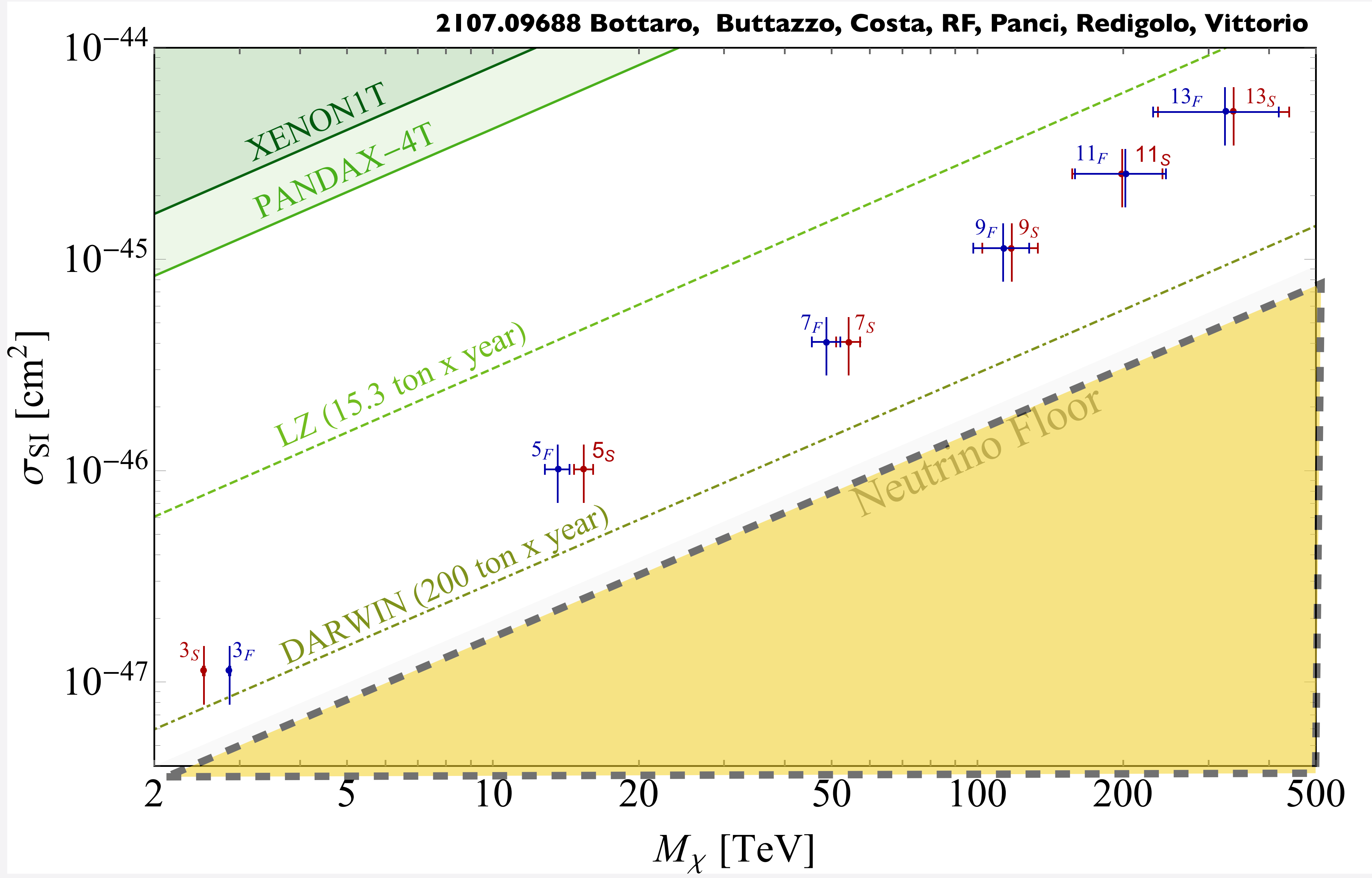

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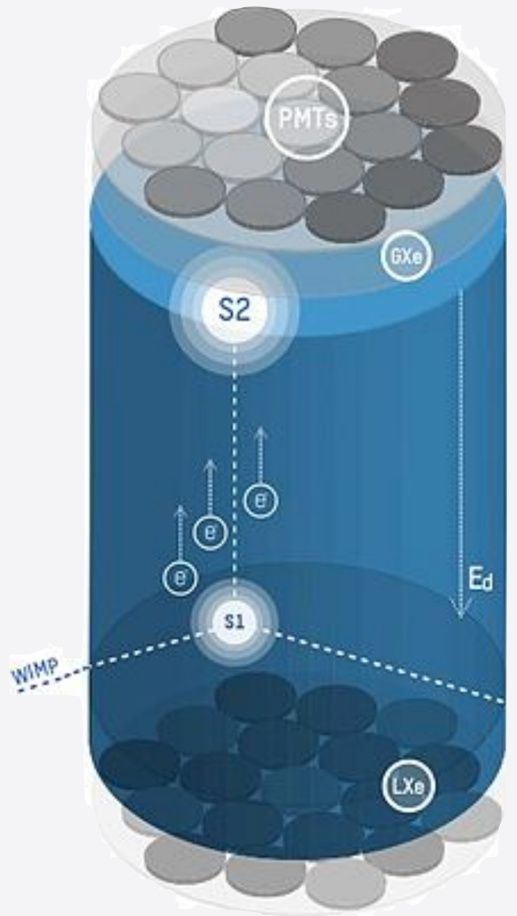

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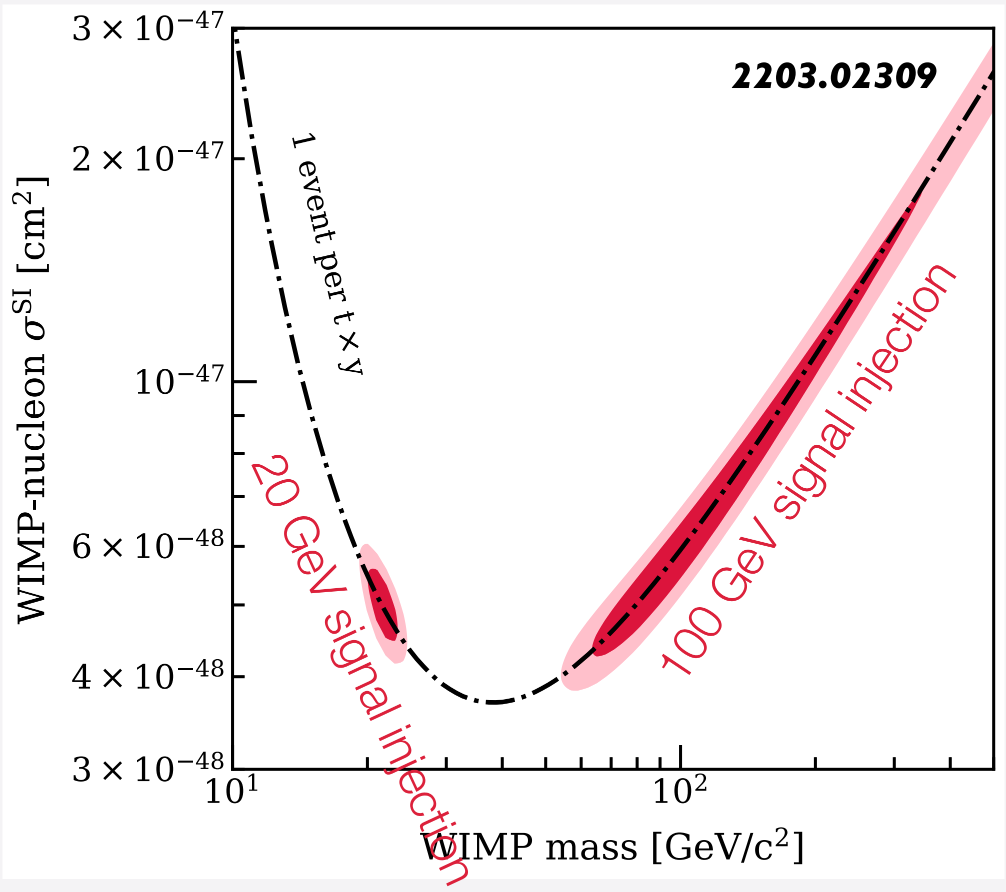

insensitive to χ mass, urgent need for high-energy colliders

(IN)DIRECT DETECTION CIRCA 2030s

- Within 10 years we may have a detection of a WIMPs from natural source (big-bang)
- No detection at Darwin may kill the most minimal case ("odd-plet" $Y=0$)
- Within 10 years we may get indirect observation of WIMPs annihilation
- "No detection" would be harder to interpret, because of possible missing pheno bits (e.g. expected SNR in the astrophysical objects for the actual detector resolution)

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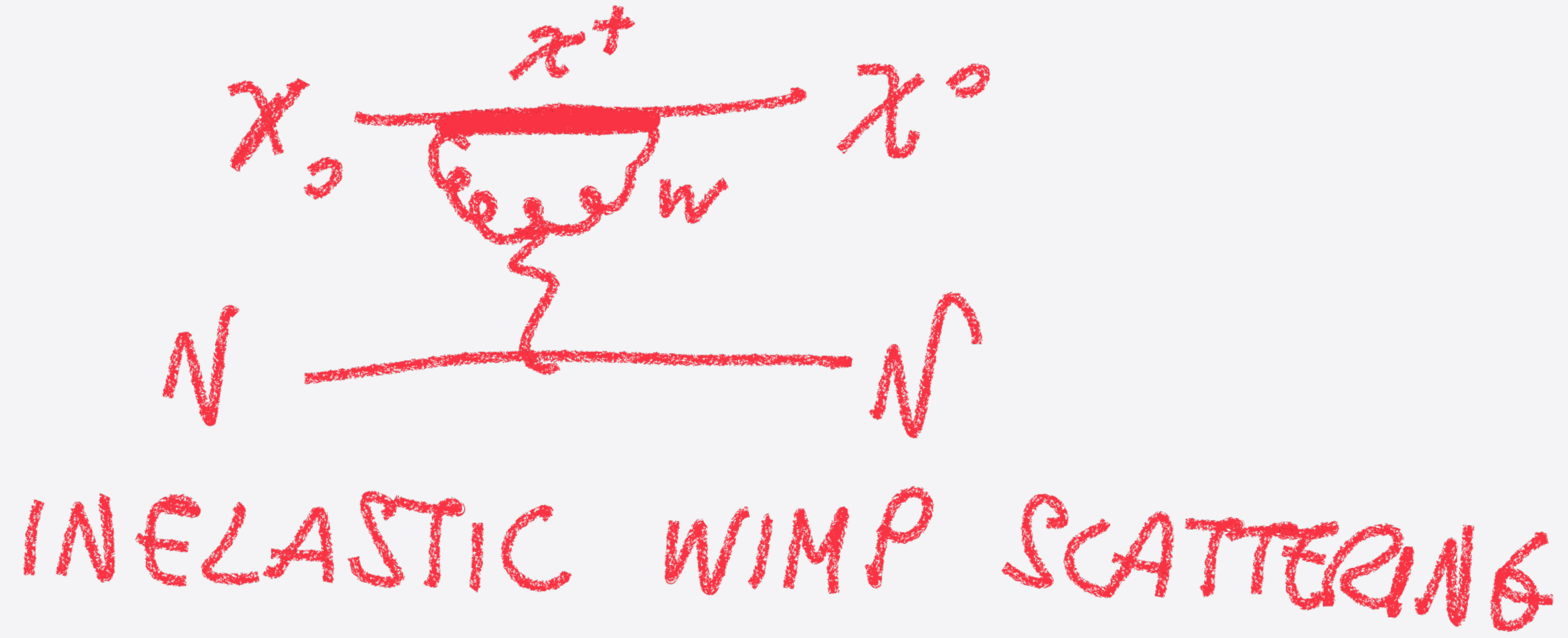

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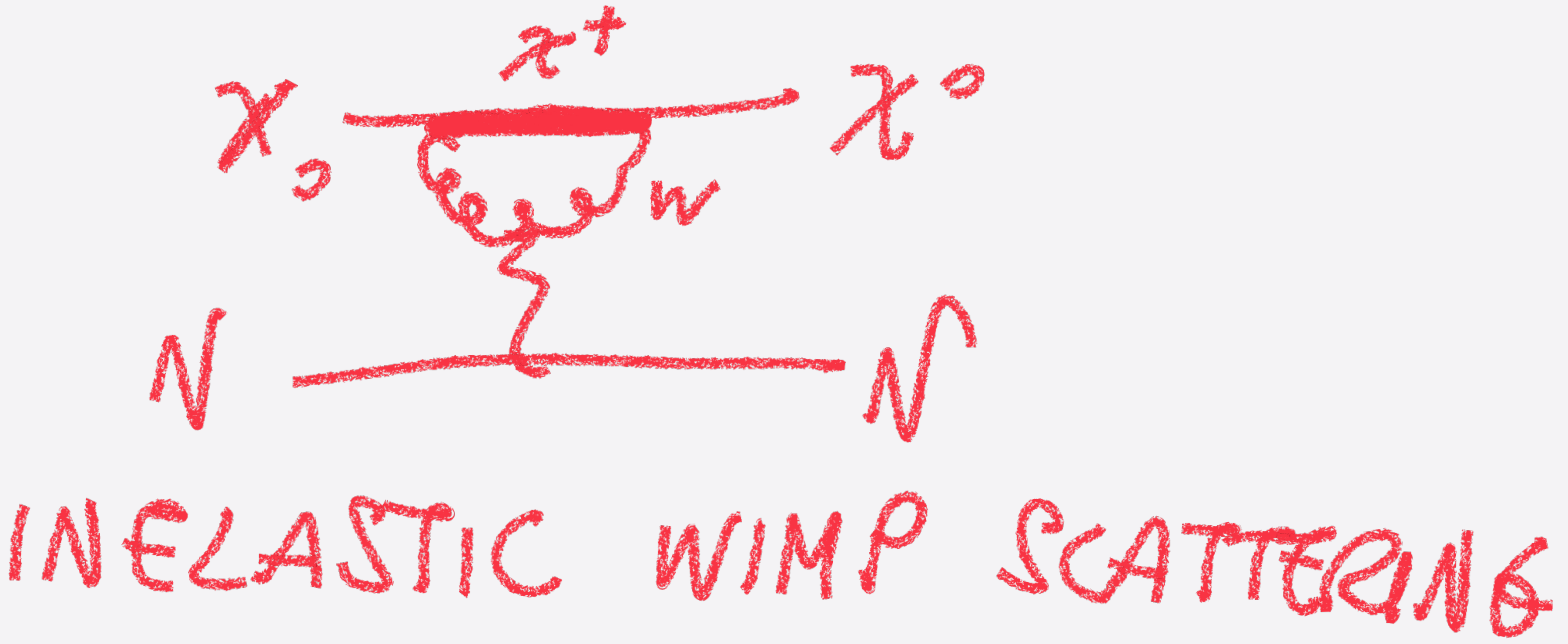

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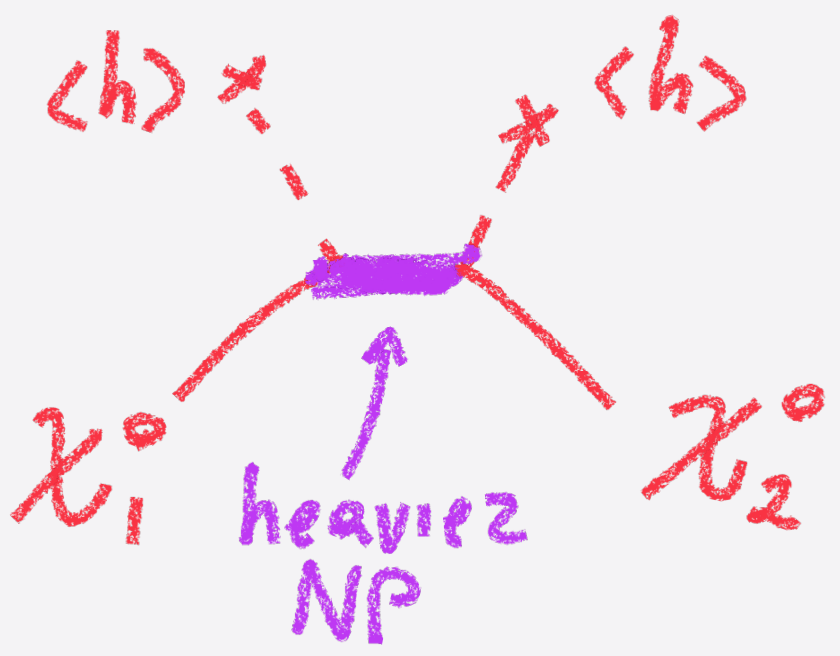

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INELASTIC WIMP SCATTERING

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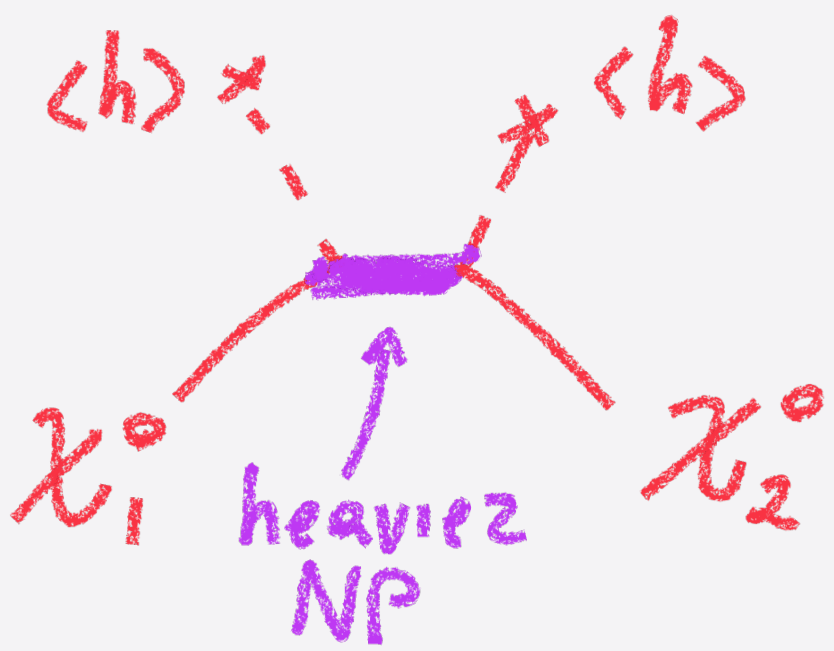
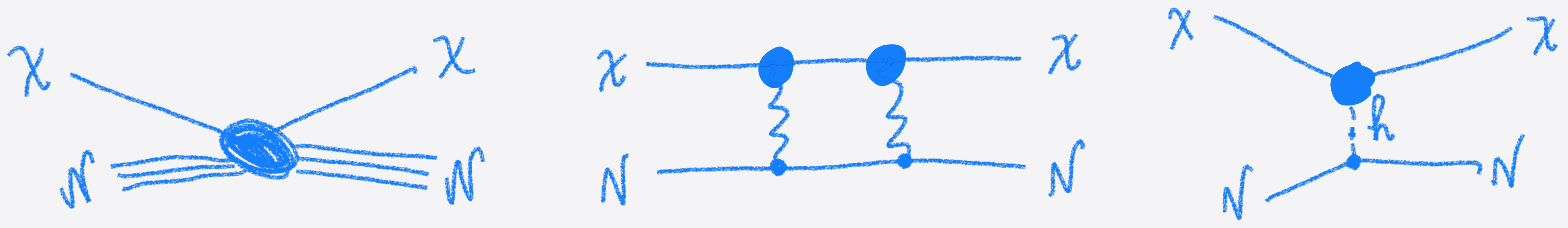


hypercharge offers one extra handle on the mass splitting

DIRECT DETECTION

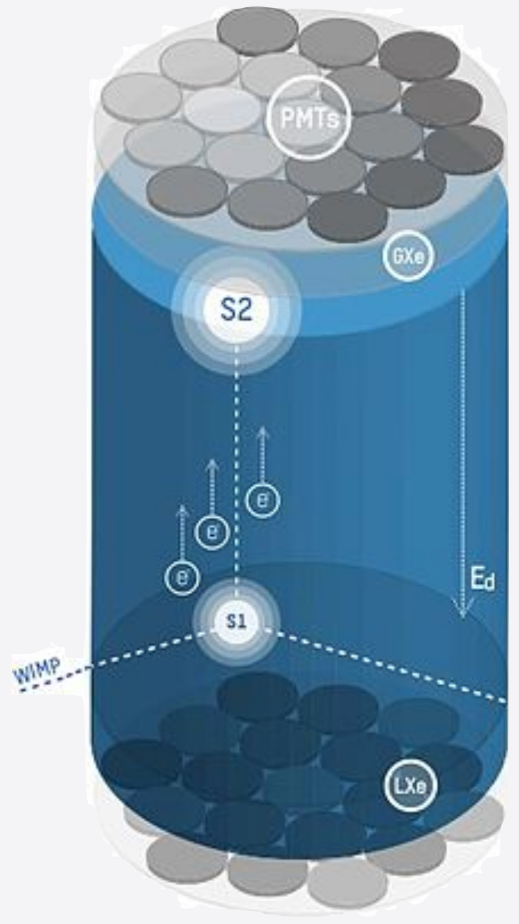
$Y \neq 0$, pure EW Mass-Splitting



Scattering on SM materials can be detected in ultra-low background experiments

Larger rates for the larger n-plets keep them visible

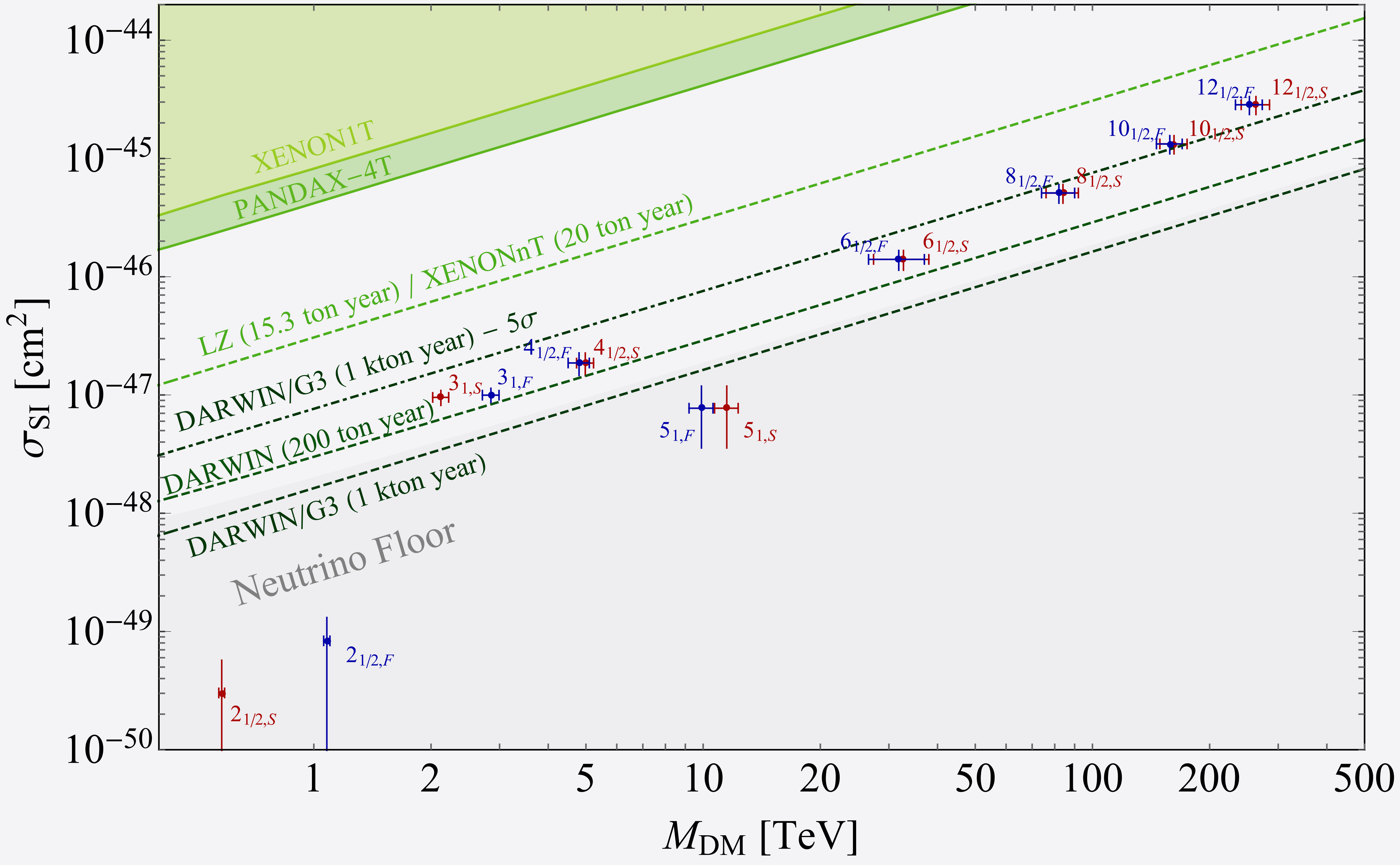
For such large DM mass the signature <u>does not</u> depend on the DM mass.



2030s

up to O(PeV)

2205.04486 Bottaro, Buttazzo, Costa, RF, Panci, Redigolo, Vittorio



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simple $2n$-plet scenarios can evade Direct Detection

DIRECT DETECTION

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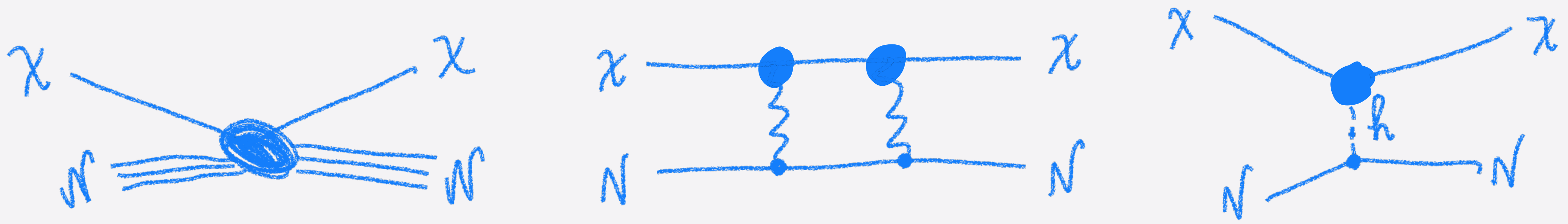

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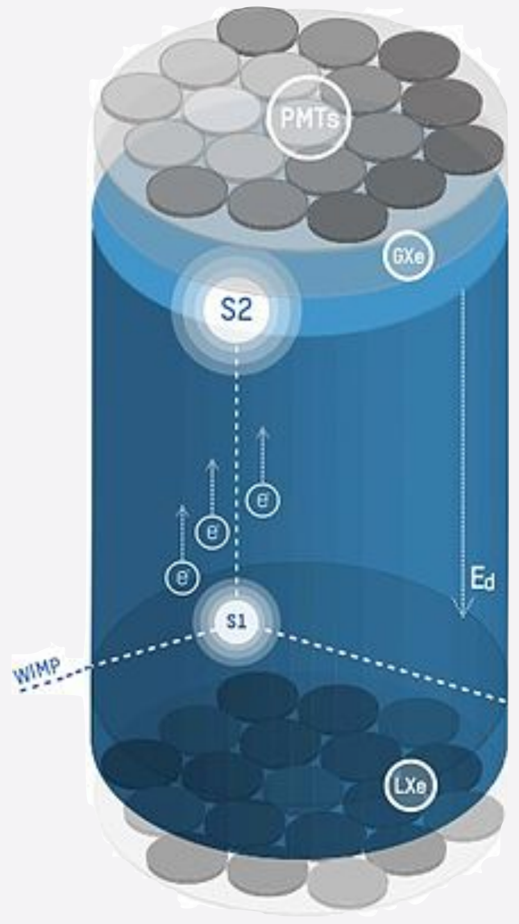

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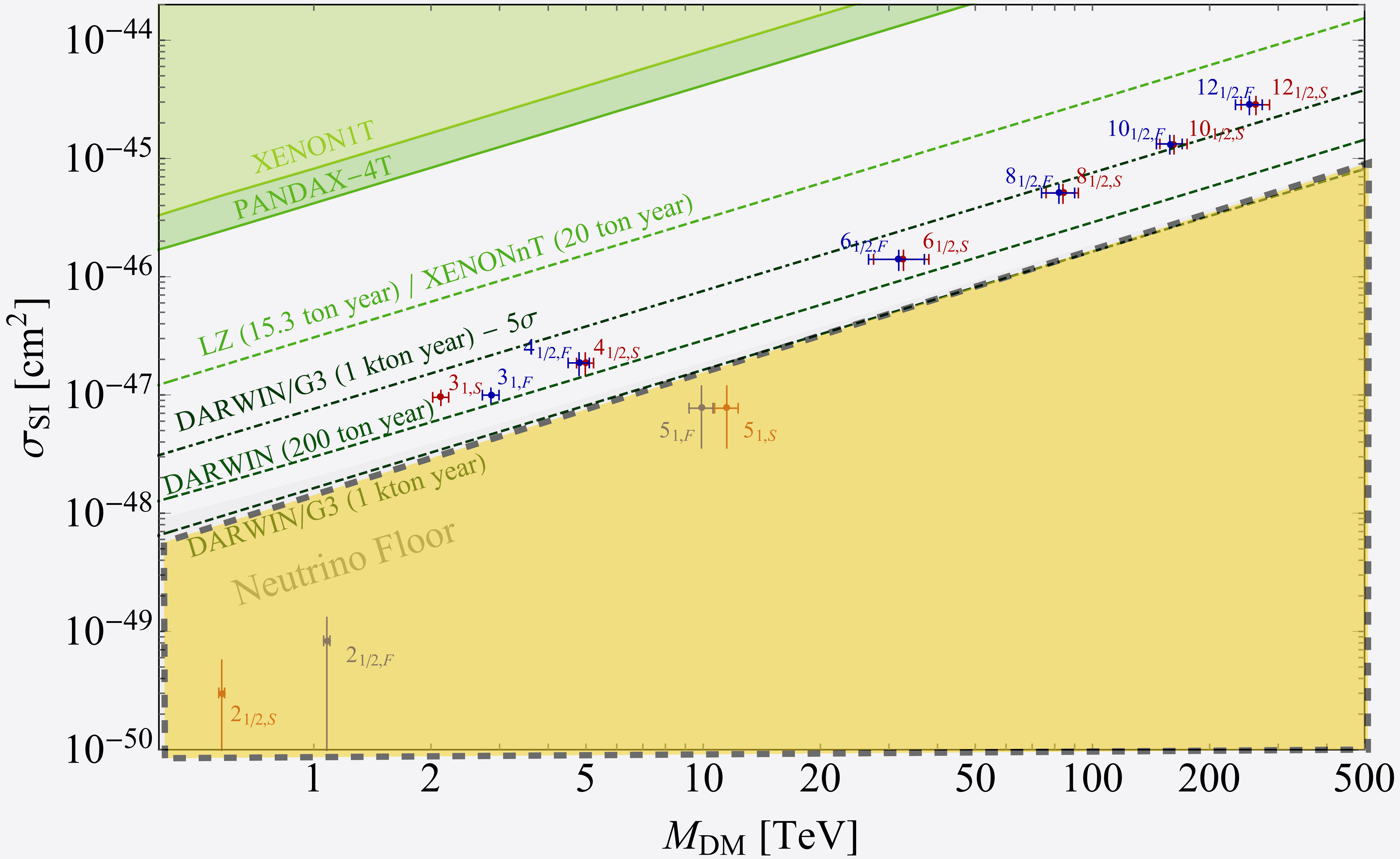

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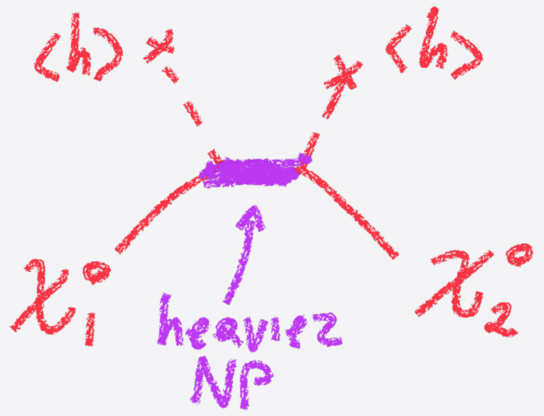
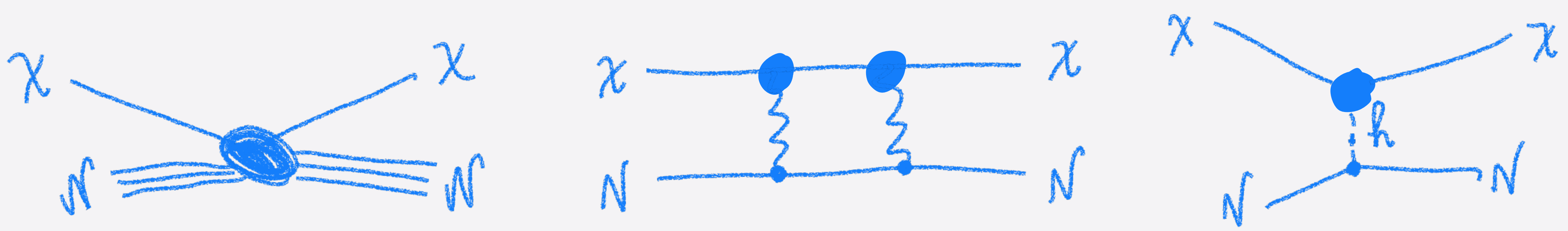
DIRECT DETECTION

$Y \neq 0$, Mass-Splitting from DIM>4





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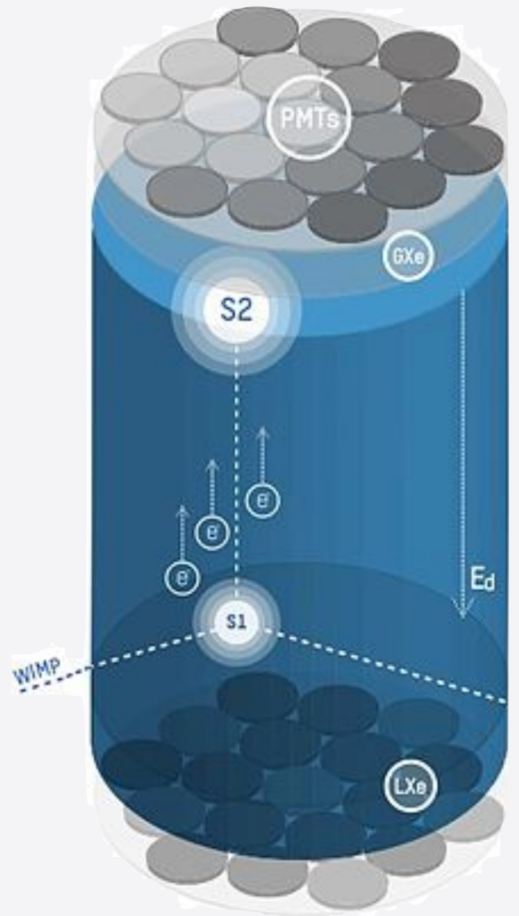
For such large DM mass the signature does not depend on the DM mass.



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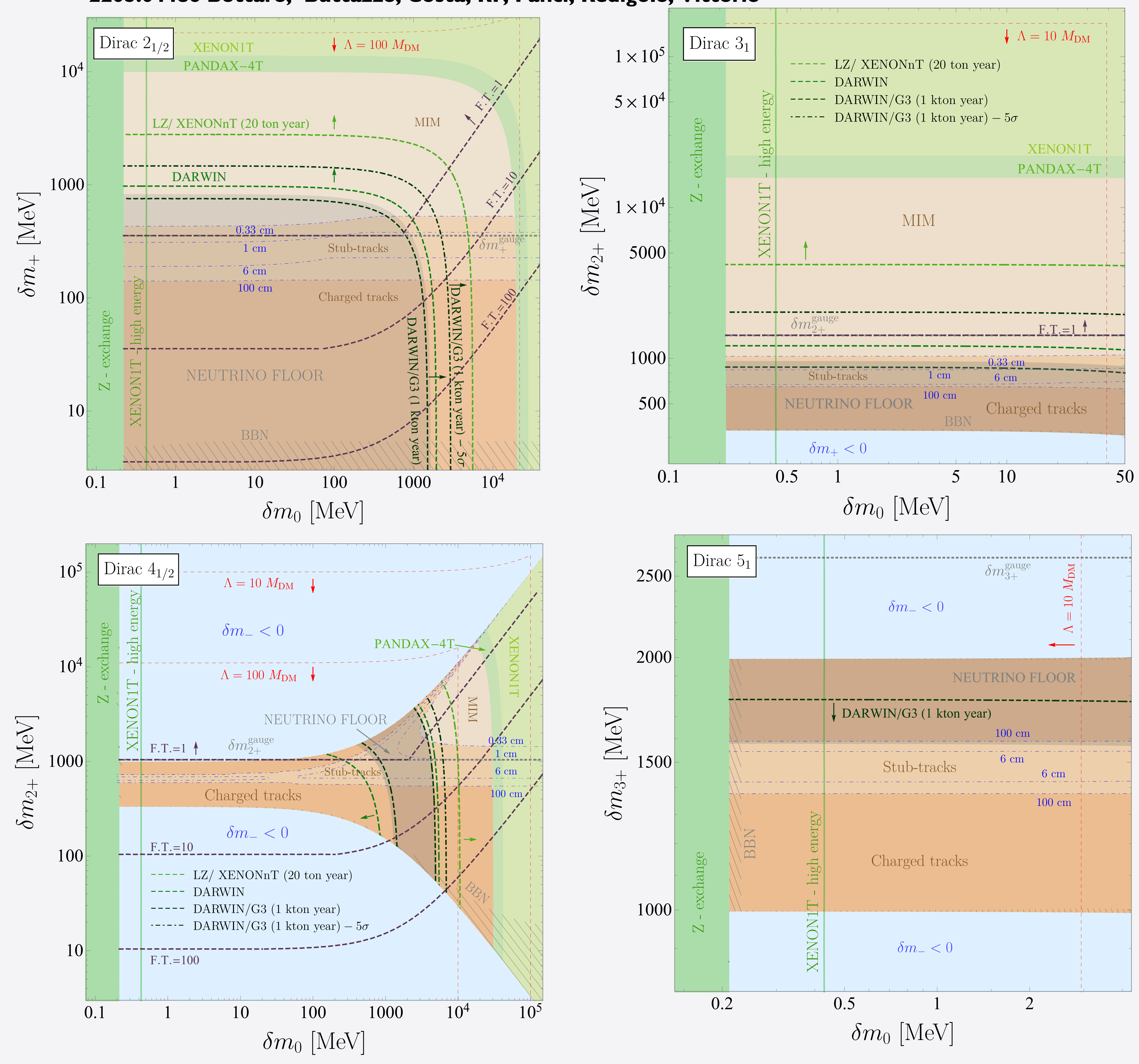
2205.04486 Bottaro, Buttazzo, Costa, RF, Panci, Redigolo, Vittorio



all next-to-simple $2n$-plet scenarios can evade Direct Detection

DIRECT DETECTION

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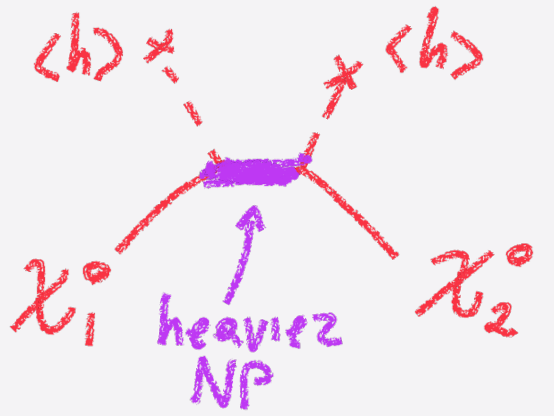
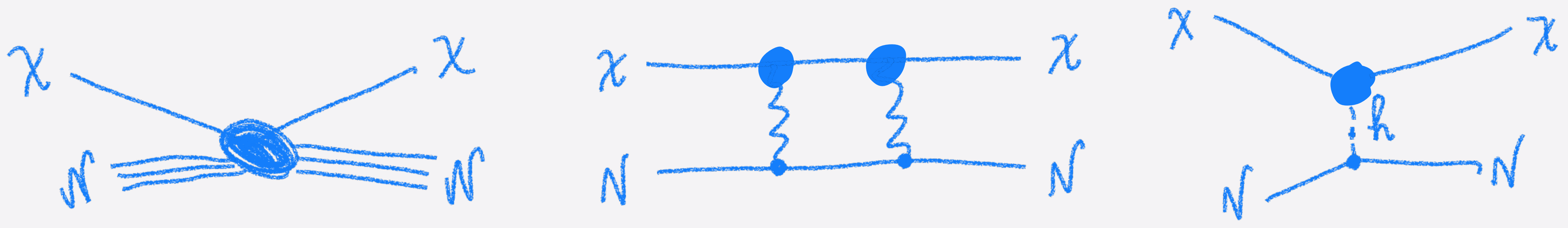
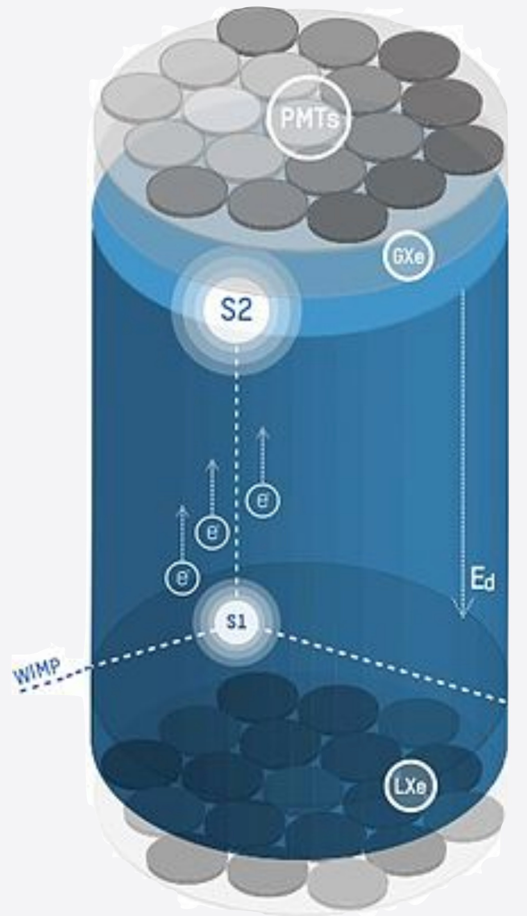




Scattering on SM materials can be detected in ultra-low background experiments

Larger rates for the larger n-plets keep them visible

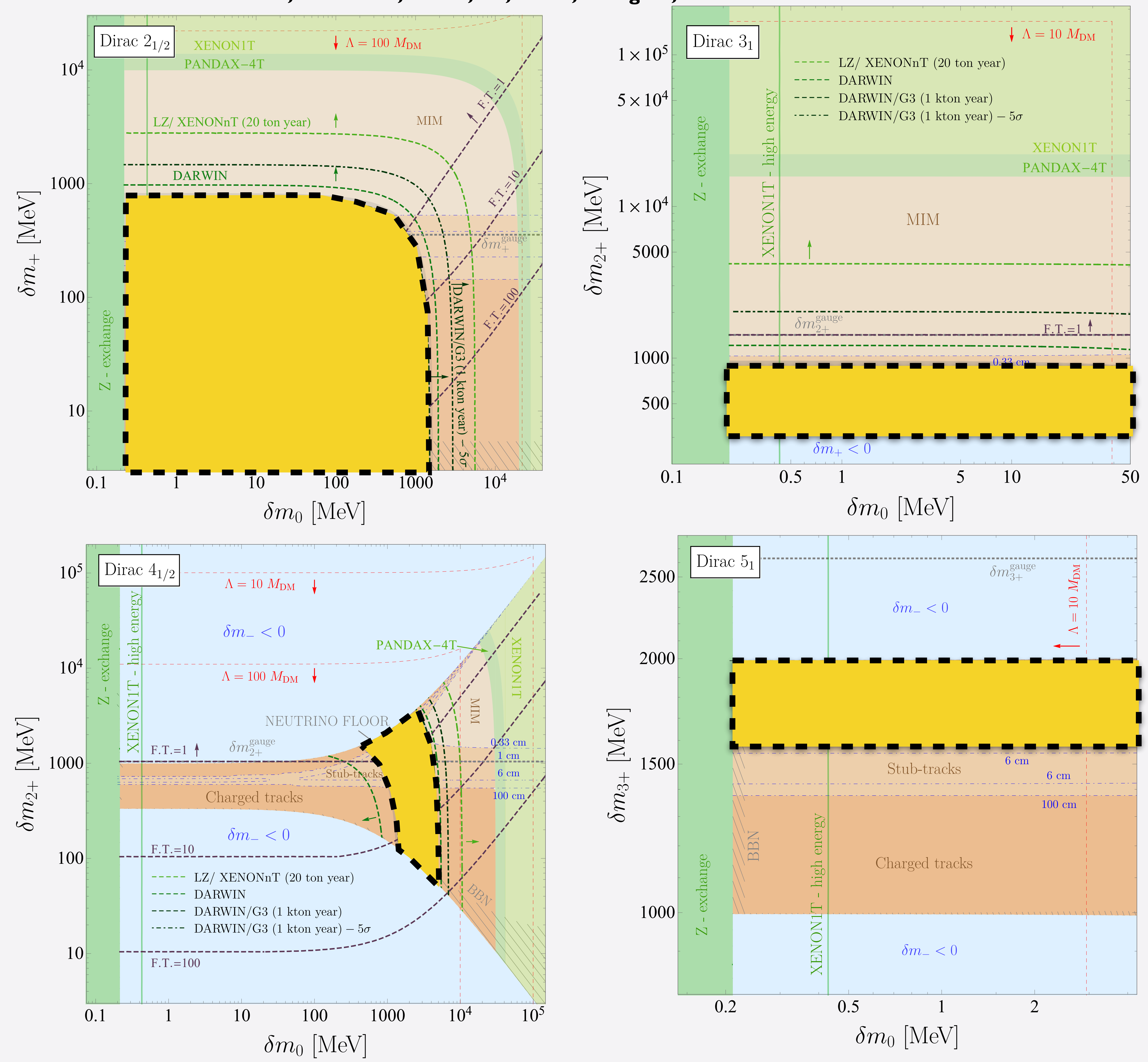
For such large DM mass the signature does not depend on the DM mass.



2030s

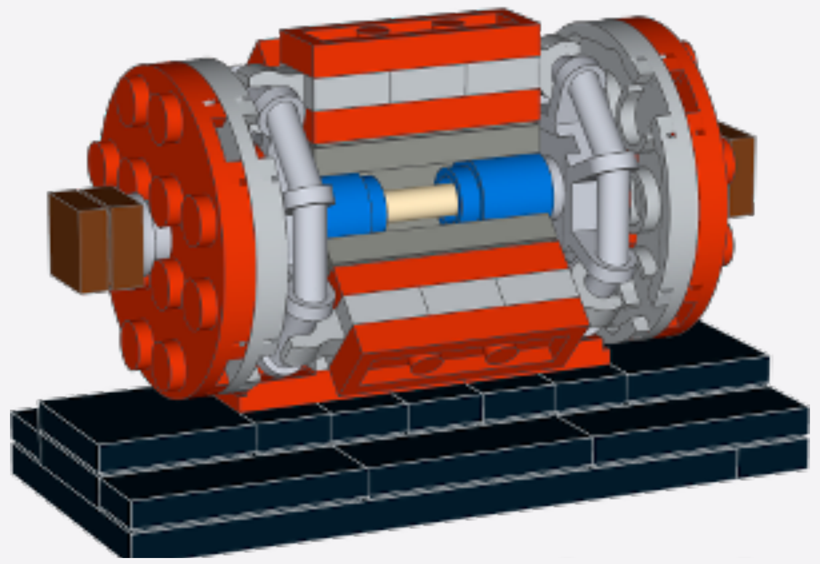
up to O(PeV)

2205.04486 Bottaro, Buttazzo, Costa, RF, Panci, Redigolo, Vittorio



all next-to-simple $2n$-plet scenarios can evade Direct Detection

DIRECT PRODUCTION AT COLLIDERS



2040s

DIRECT SIGNALS AT COLLIDERS

Δm

Wide open spectra		Generic leptons+missing momentum
Co-annihilation		Soft-objects + missing momentum
	GeV	
WIMP-like multiplet Accidental Dark Matter		Short (disappearing) tracks
DM SM singlet pp or $\ell^+\ell^- \to Z' \to \chi\,\chi$	0	Mono-X

Precision Tests

DIRECT SIGNALS AT COLLIDERS

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Precision Tests

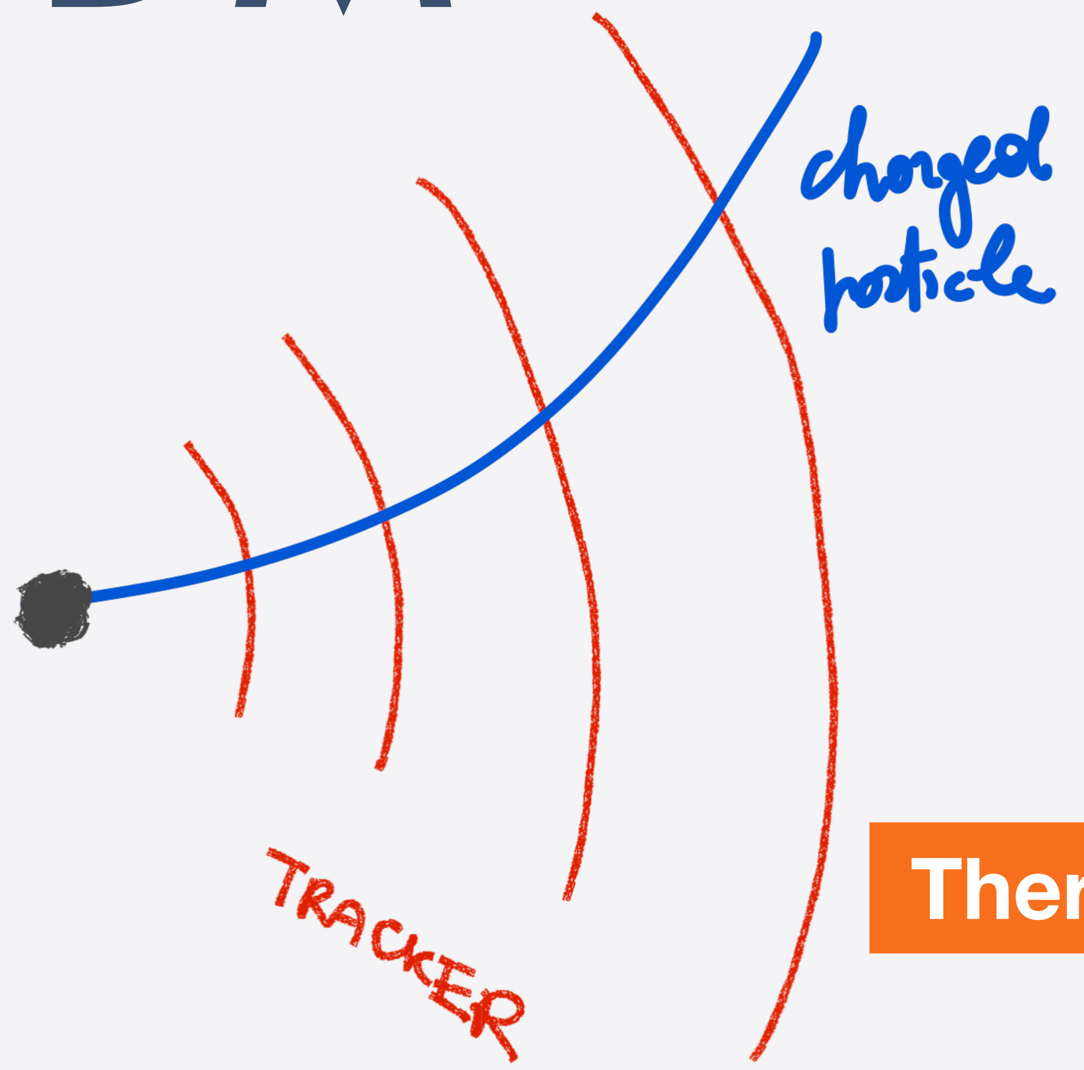
2203.07256 1901.02987 2102.11292 2203.07351

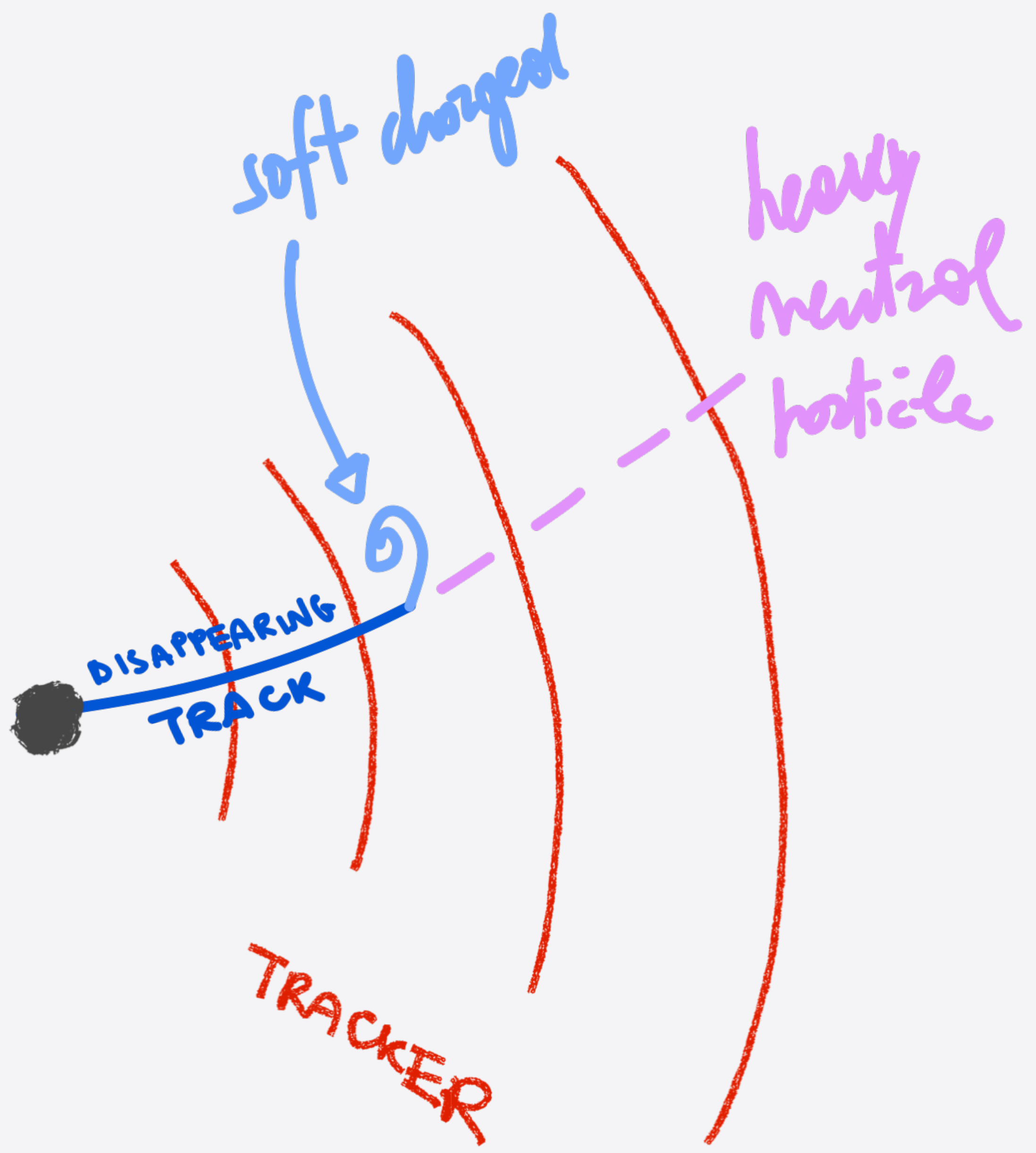
PURE $\tilde{h}$ AND $\tilde{W}$ DM

stub track and soft tracks

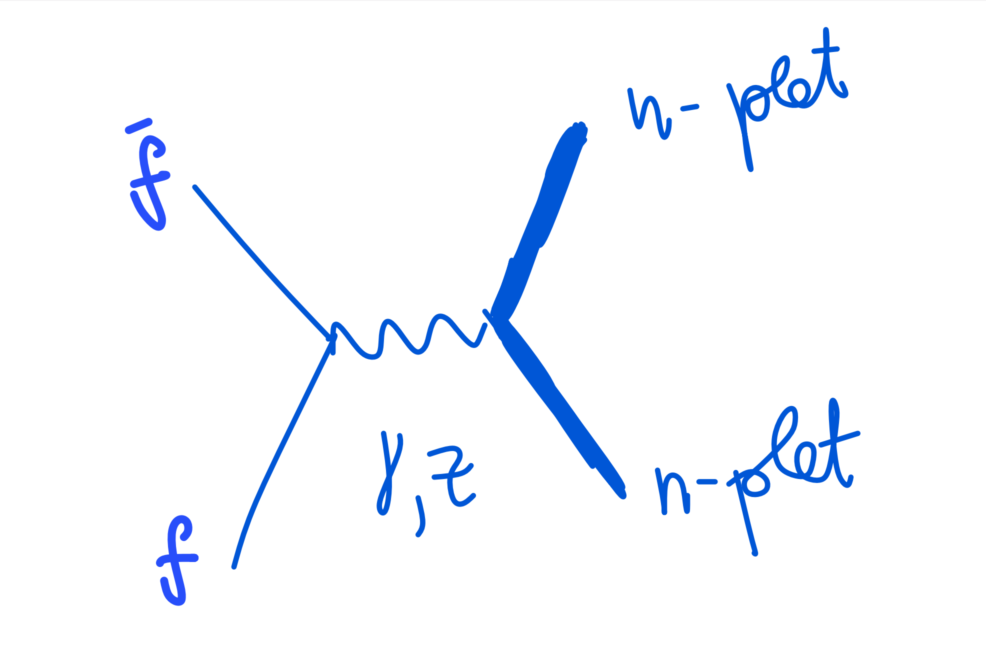
2040s

up to $\mu\mu$ 3-10 TeV

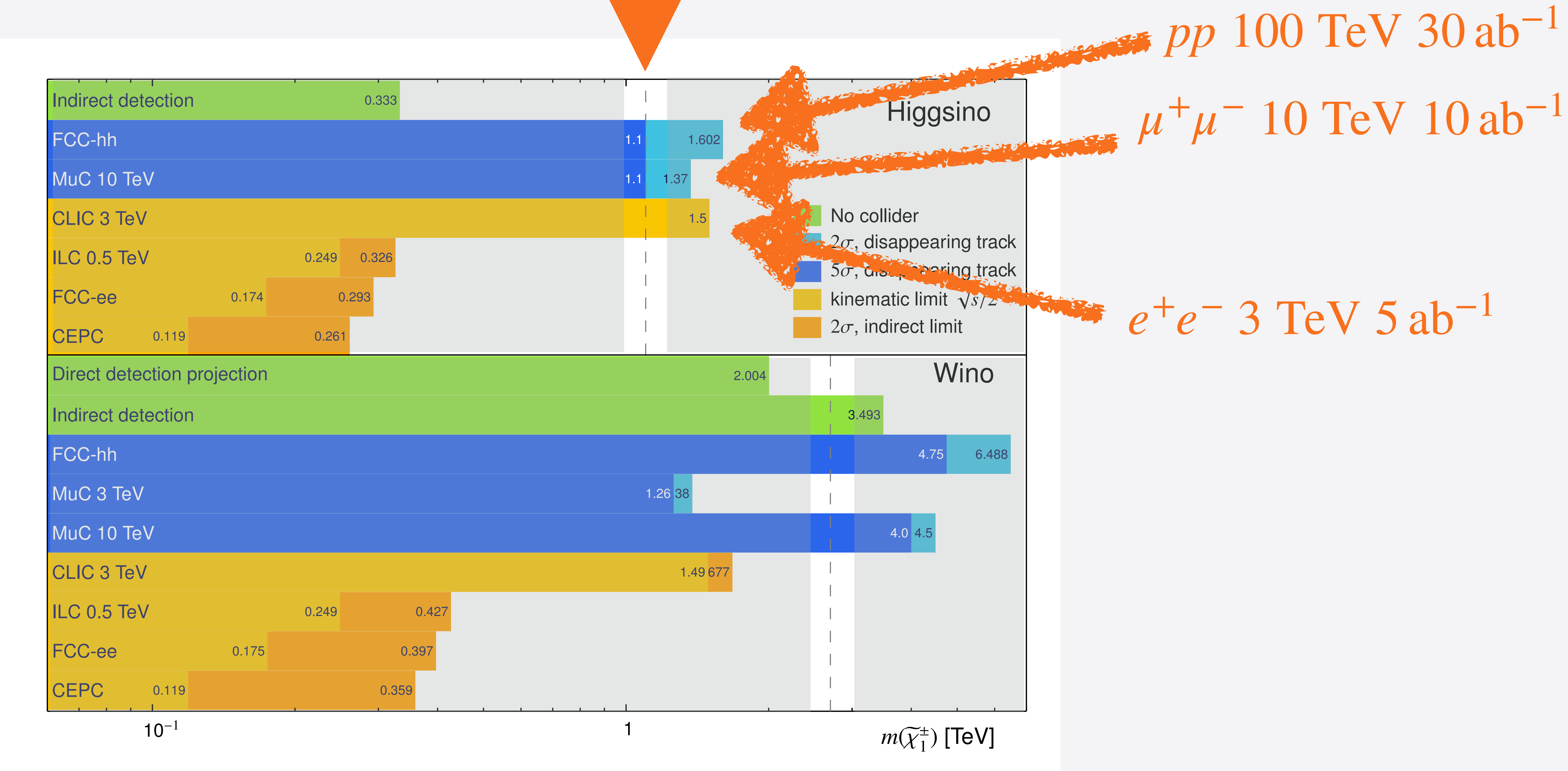




- Heavy n-plet of SU(2)
- Mass splitting $\sim \alpha_W m_W \sim 0.1\text{GeV} - 1\text{GeV}$



Large rates, but needs to light up the detector in a discernible way



2203.07256 1901.02987 2102.11292 2203.07351

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2040s

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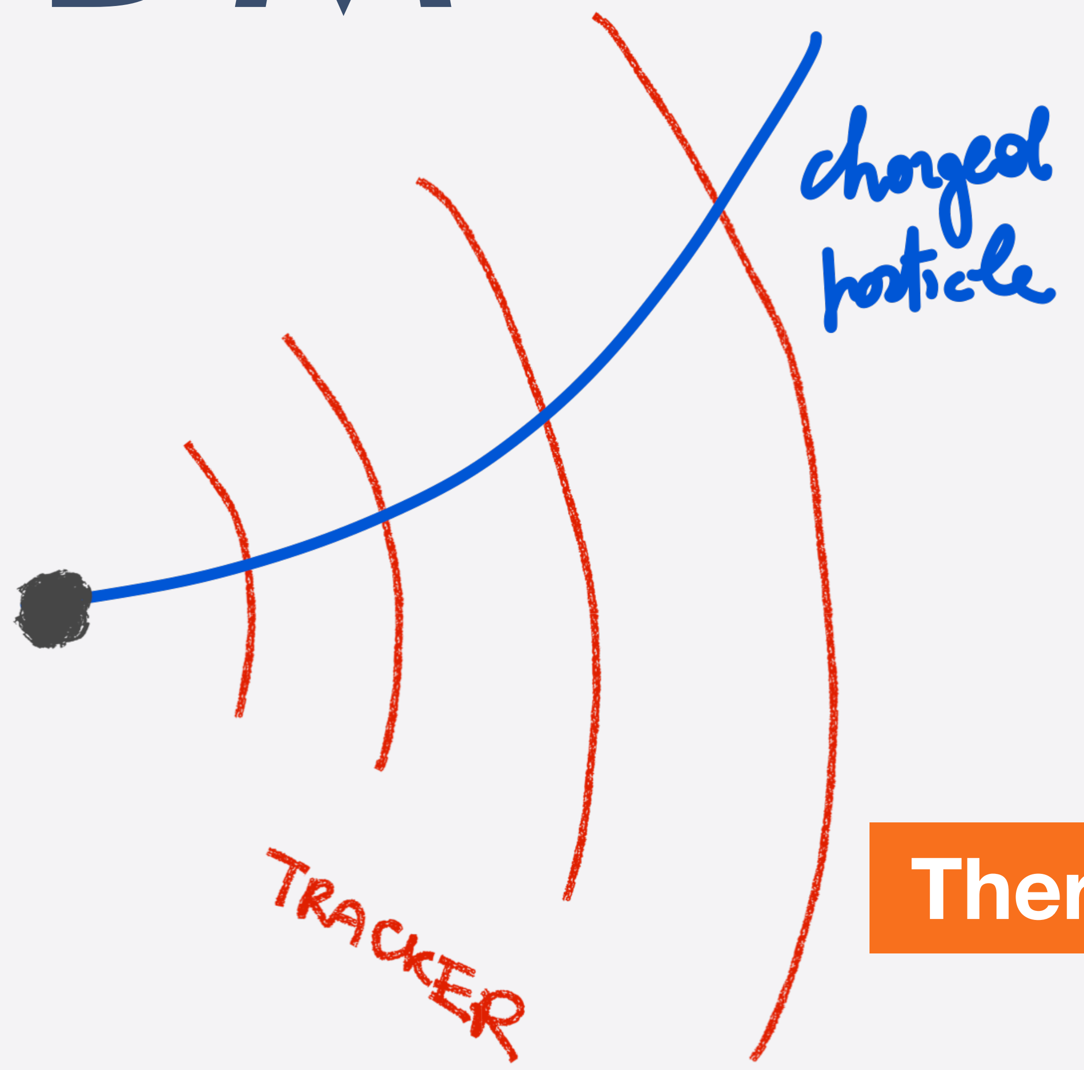

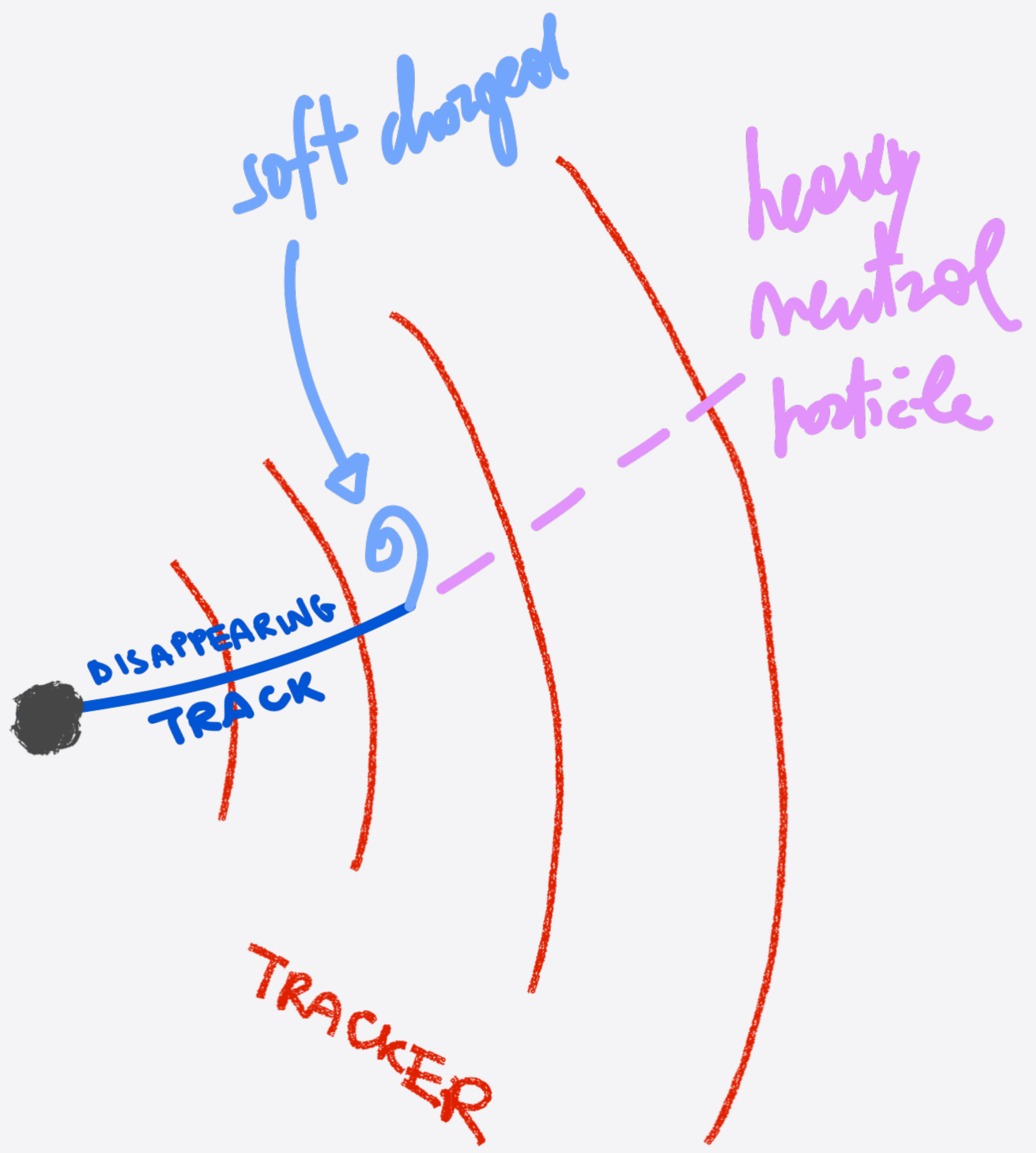

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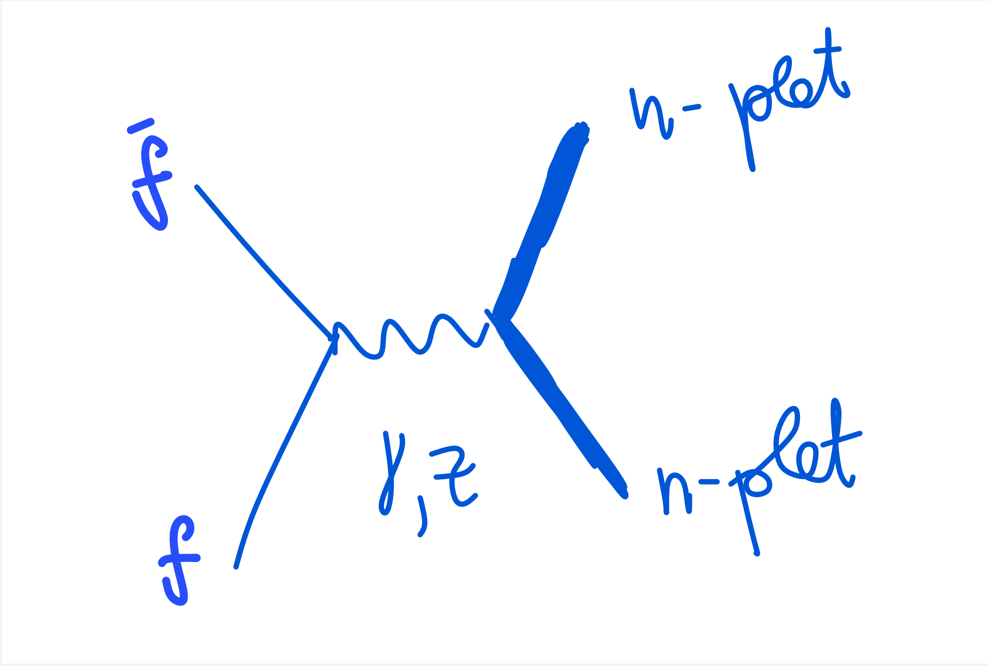

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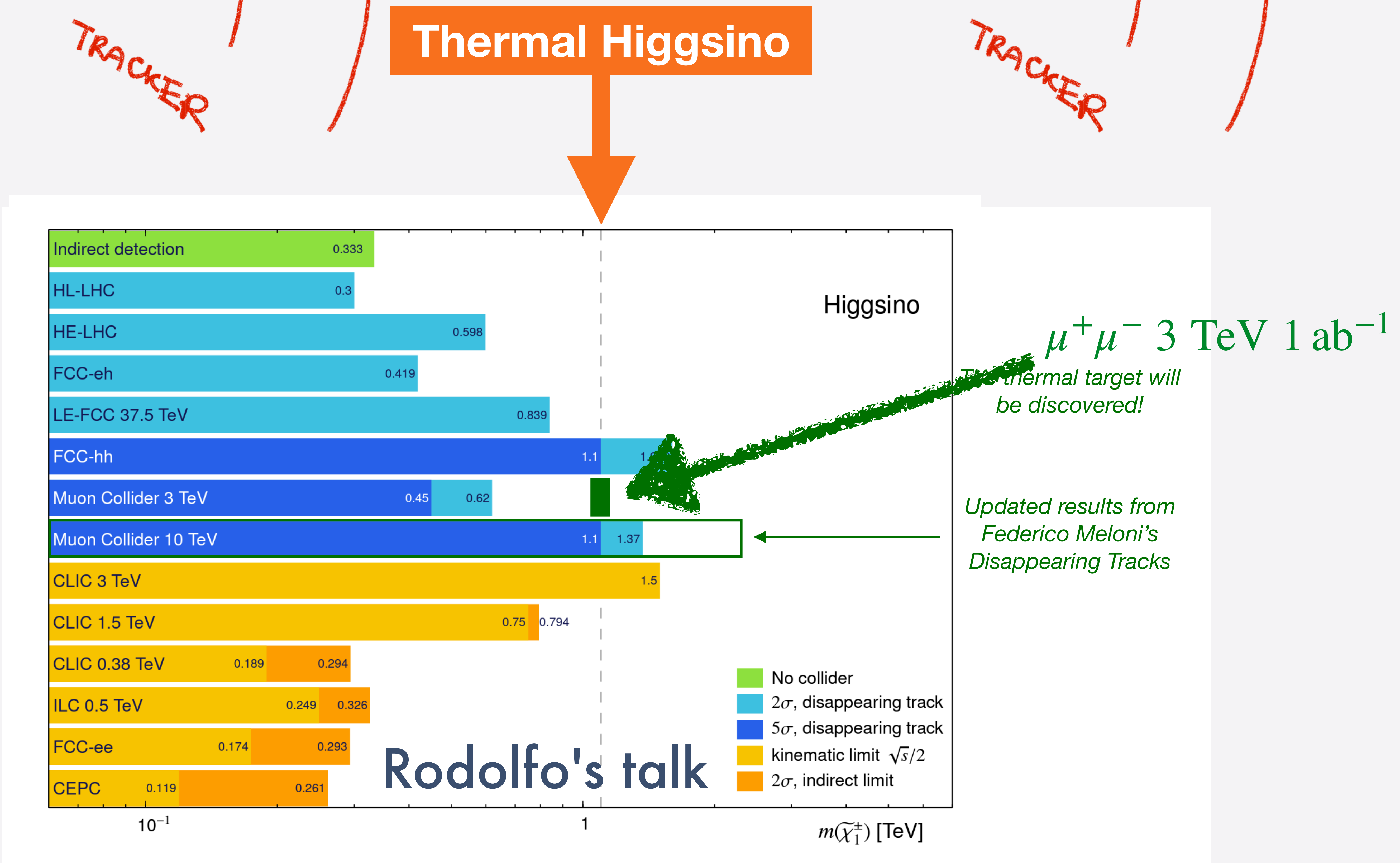

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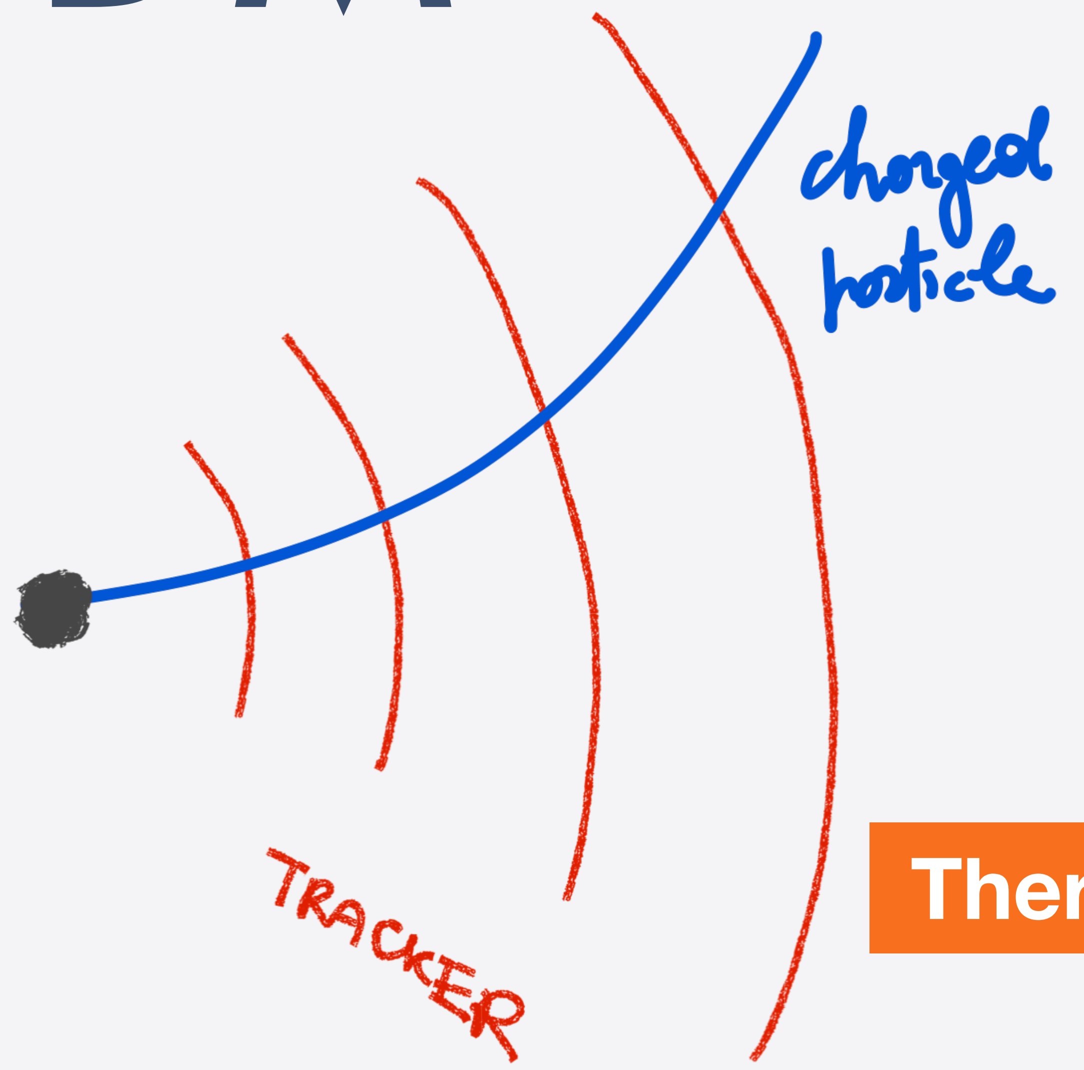

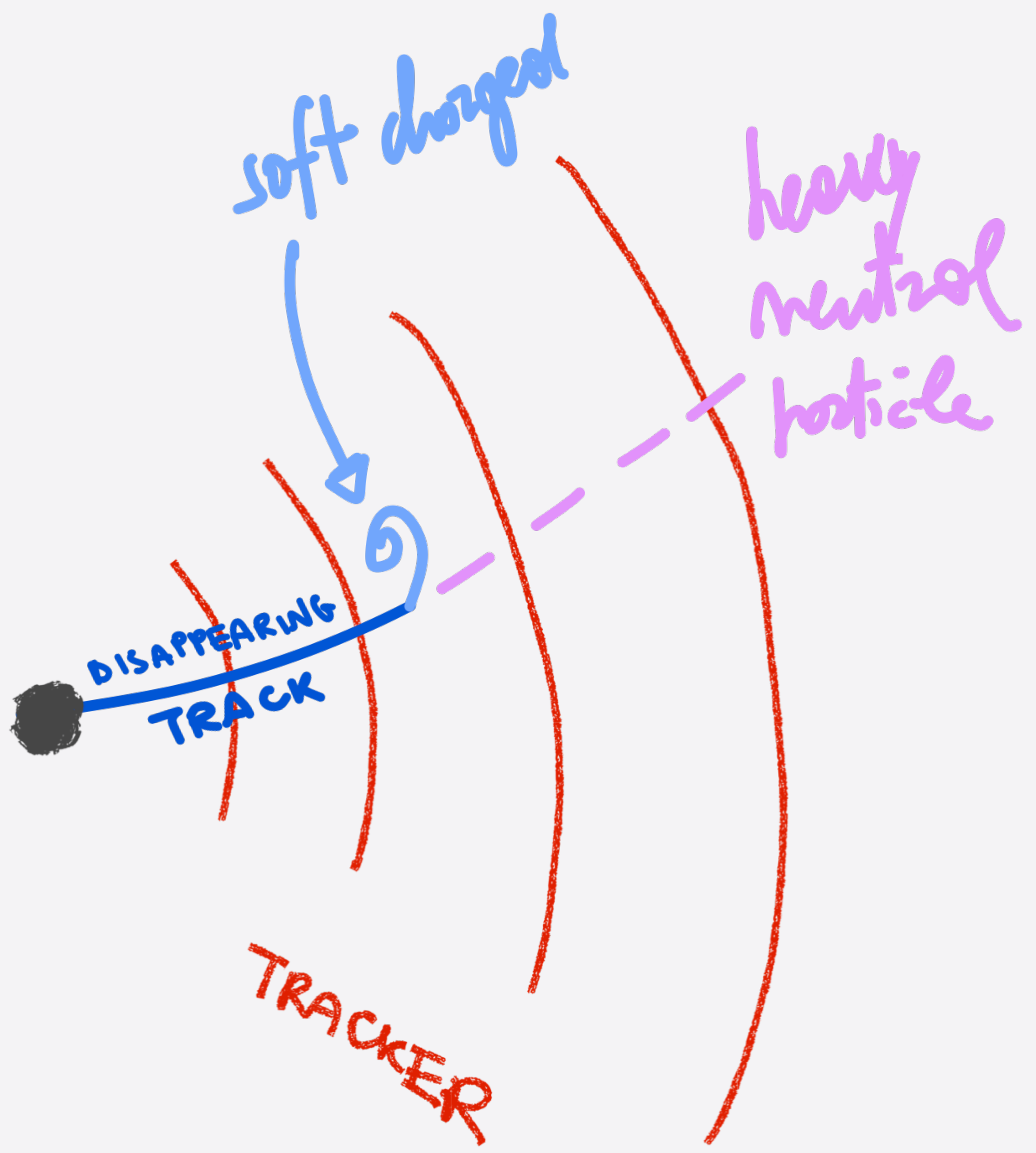

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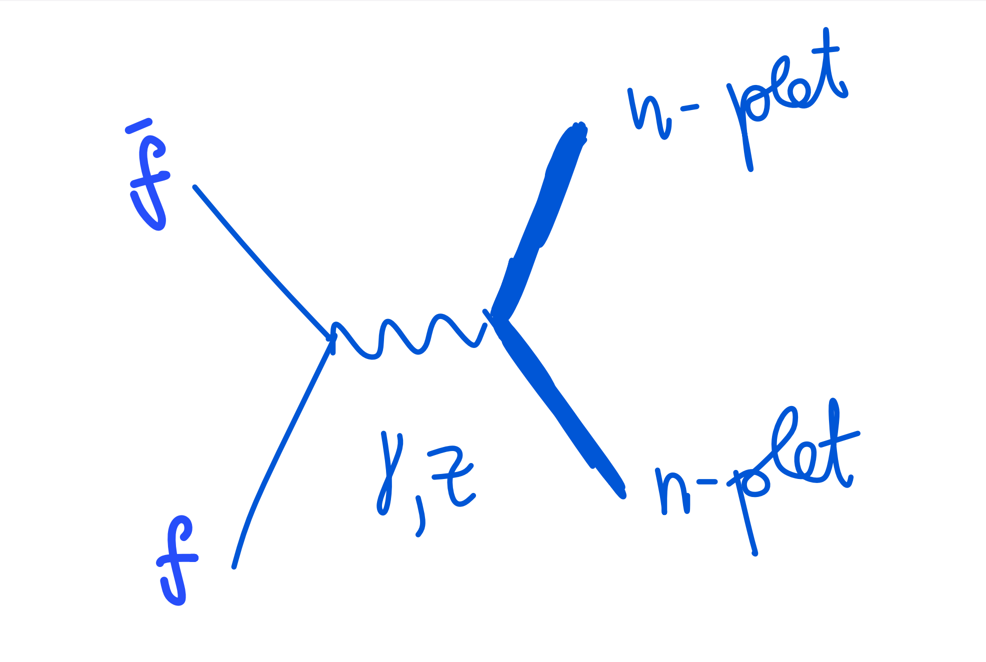
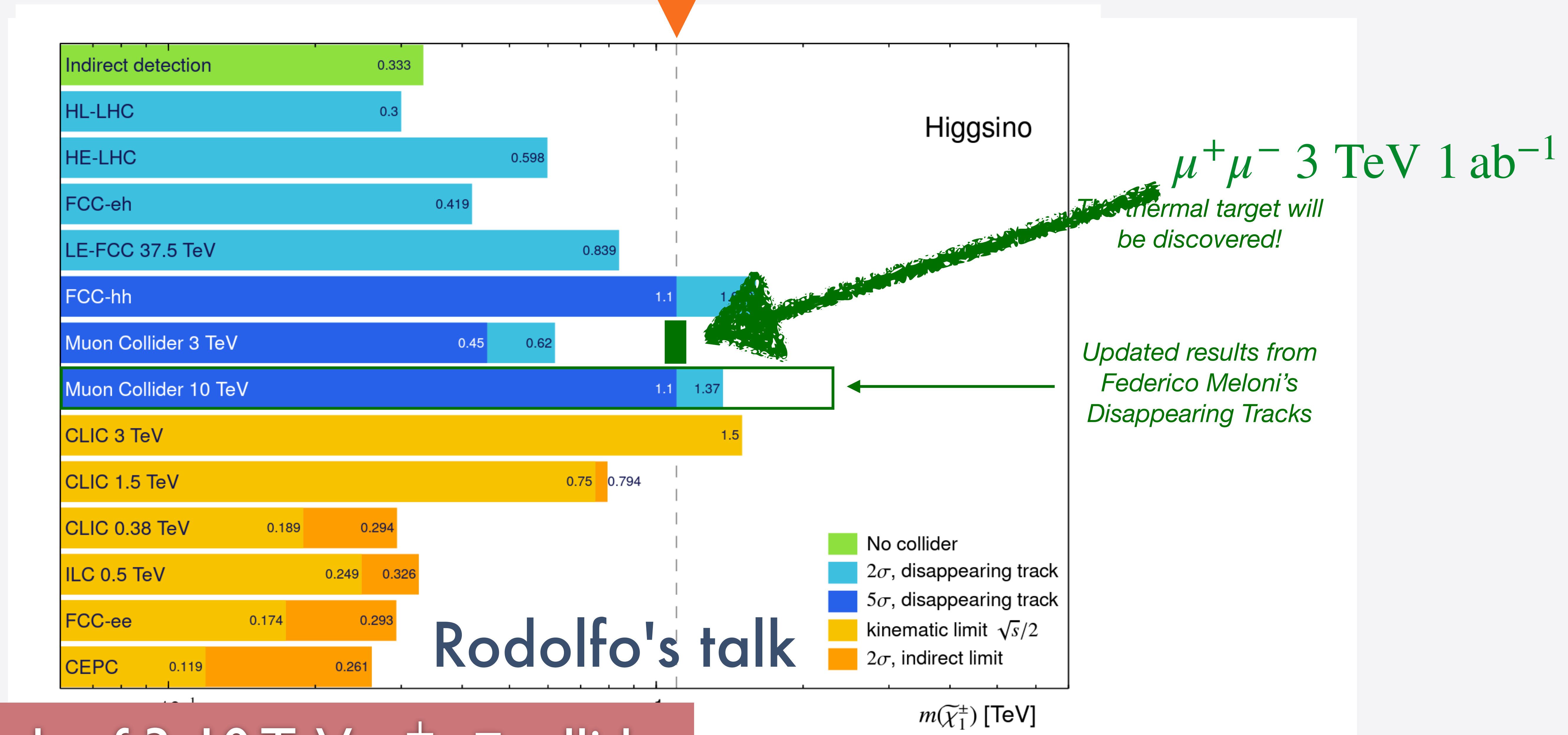


Large rates, but needs to light up the detector in a discernible way

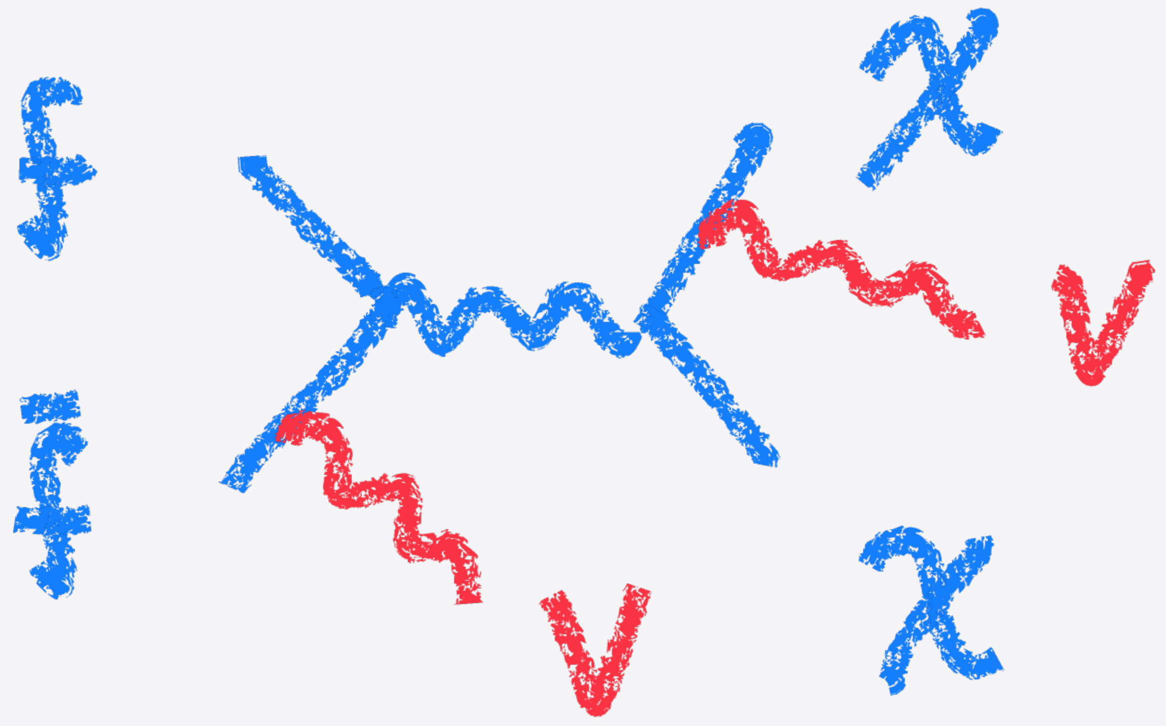
Thermal Higgsino



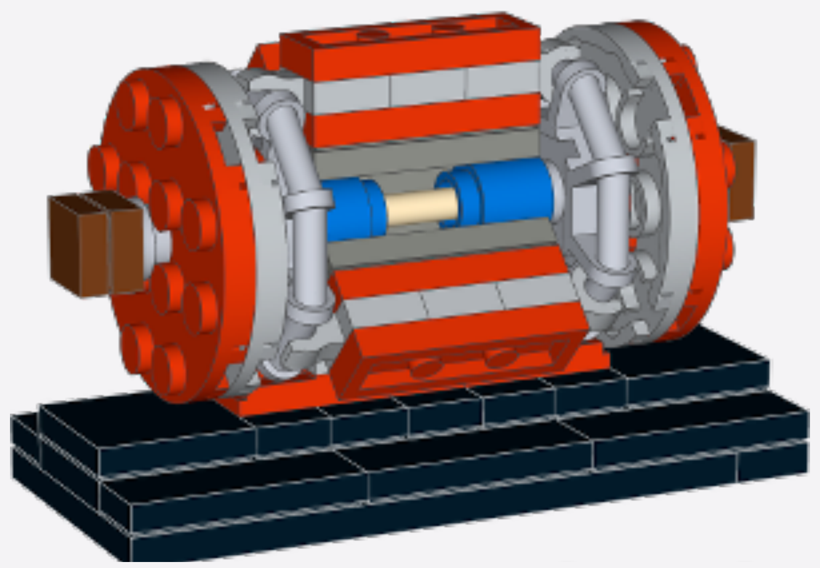
$n = 2$ and $n = 3$ well inside reach of 3-10 TeV $\mu^+\mu^-$ collider

PURE $\tilde{h}$ AND $\tilde{W}$ DM

stub tracks

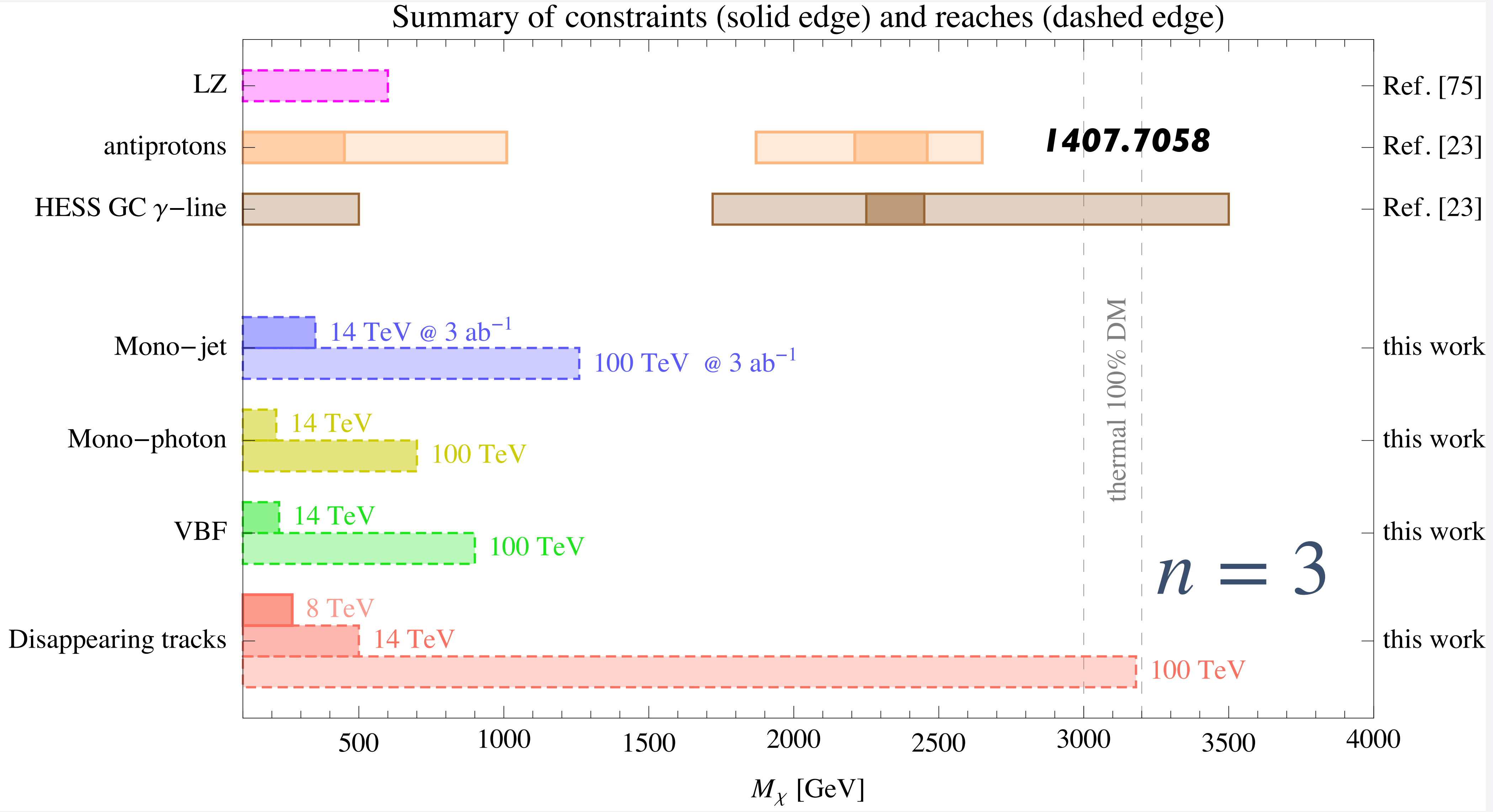


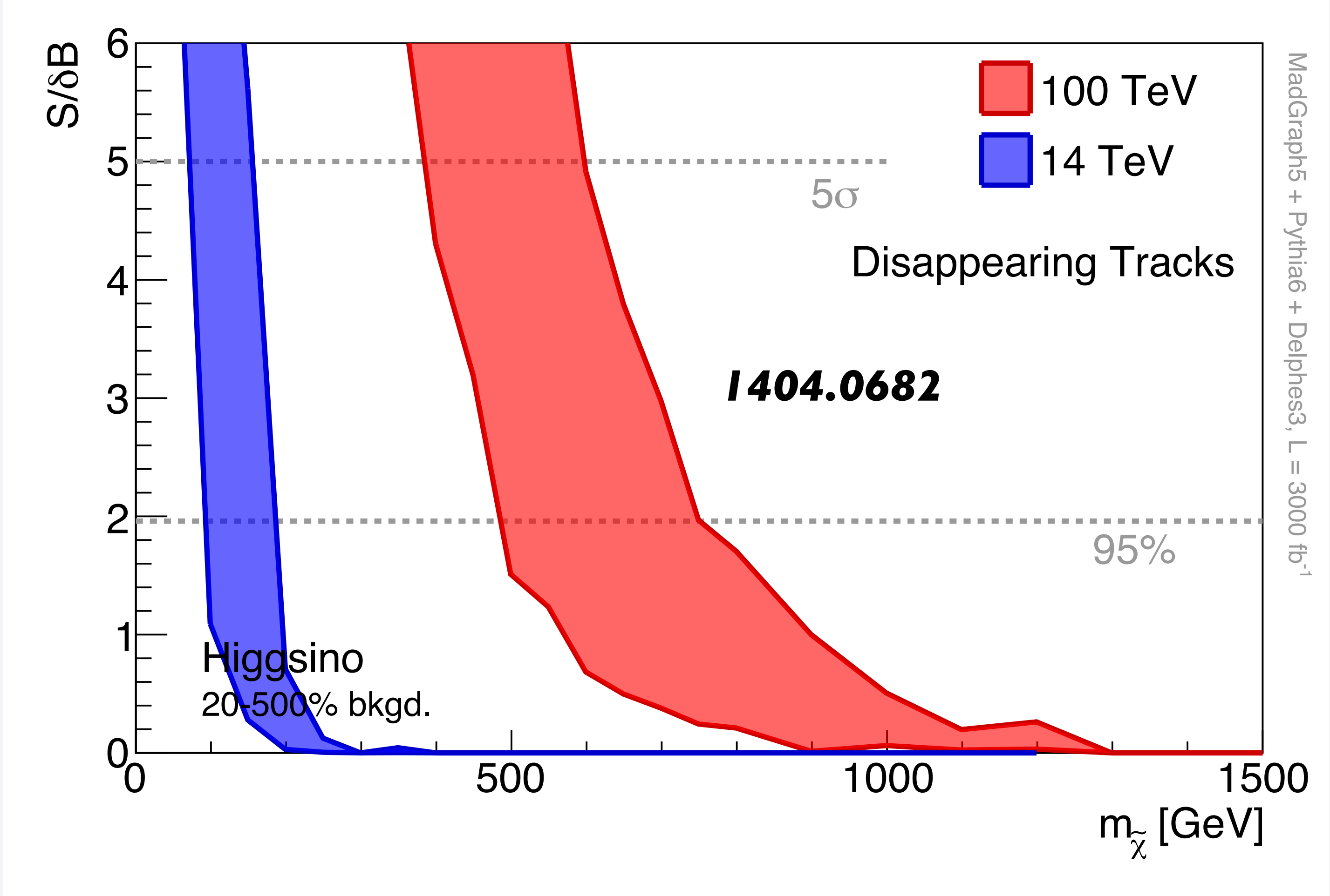
Production of Dark Matter weak multiplet states and observation of the decay products or associated productions



2060s

up to pp 100 TeV





$n = 2$ and $n = 3$ just inside reach of 100 TeV pp collider

DIRECT SIGNALS AT COLLIDERS

Δm

Wide open spectra	Generic leptons+missing momentum	Precision Tests
Co-annihilation	Soft-objects + missing momentum	
GeV		
WIMP-like multiplet Accidental Dark Matter	Short (disappearing) tracks	
DM SM singlet pp or $\ell^+\ell^- \to Z' \to \chi\,\chi$	Mono-X	
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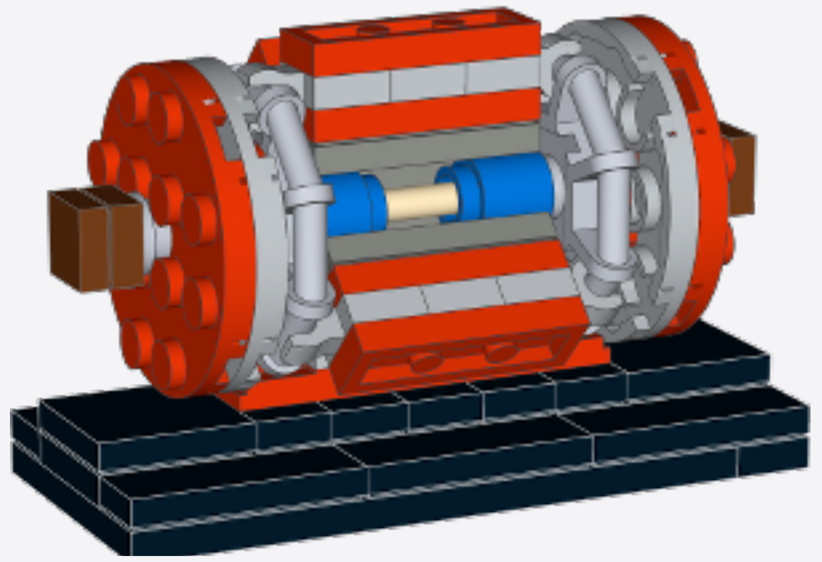
Precision Tests

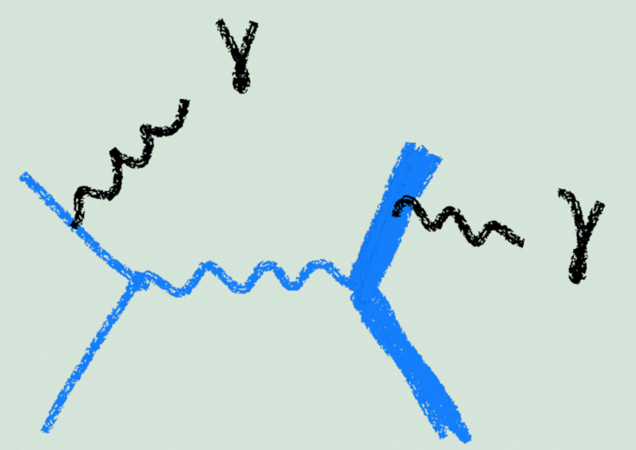
MONO-X

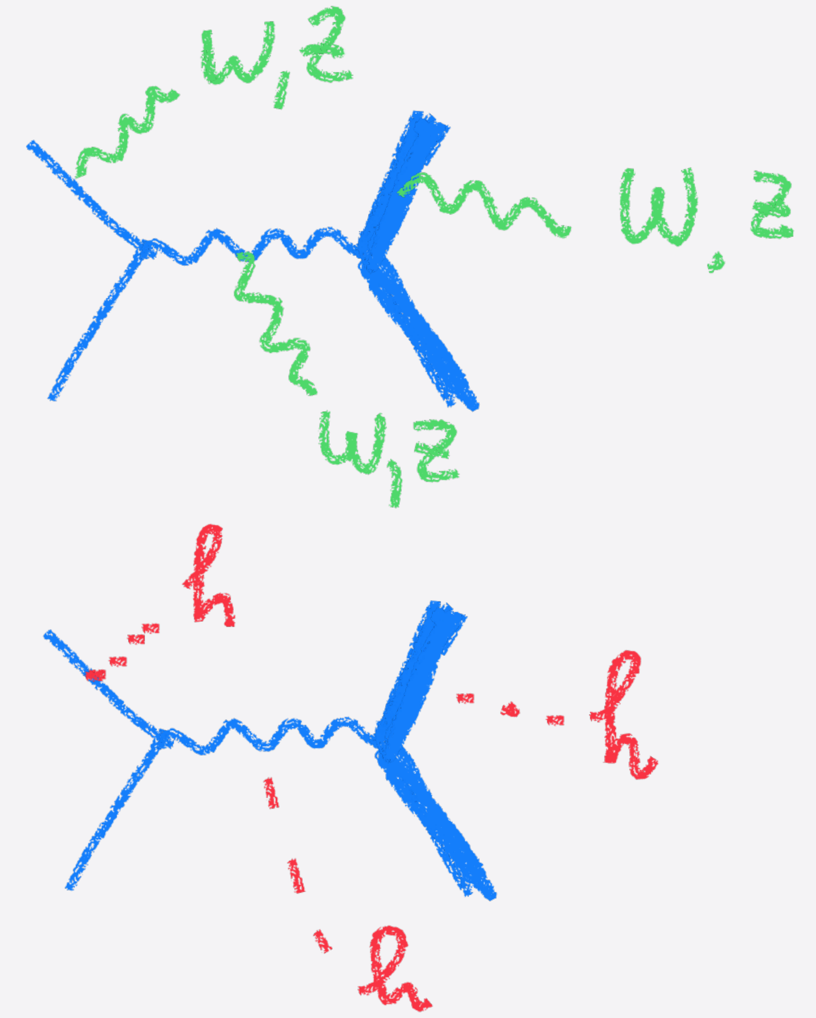


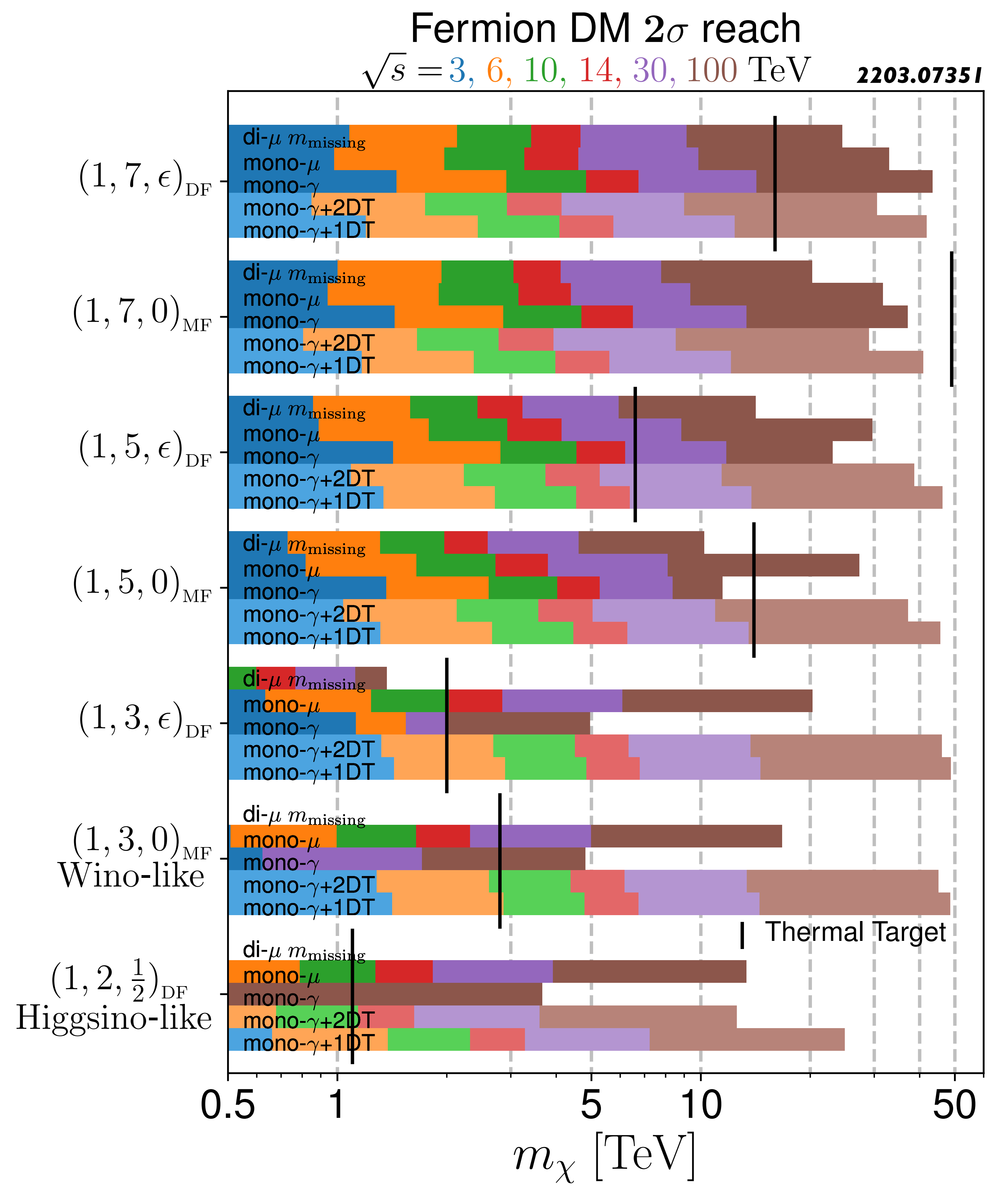
2040s

up to 10+ TeV

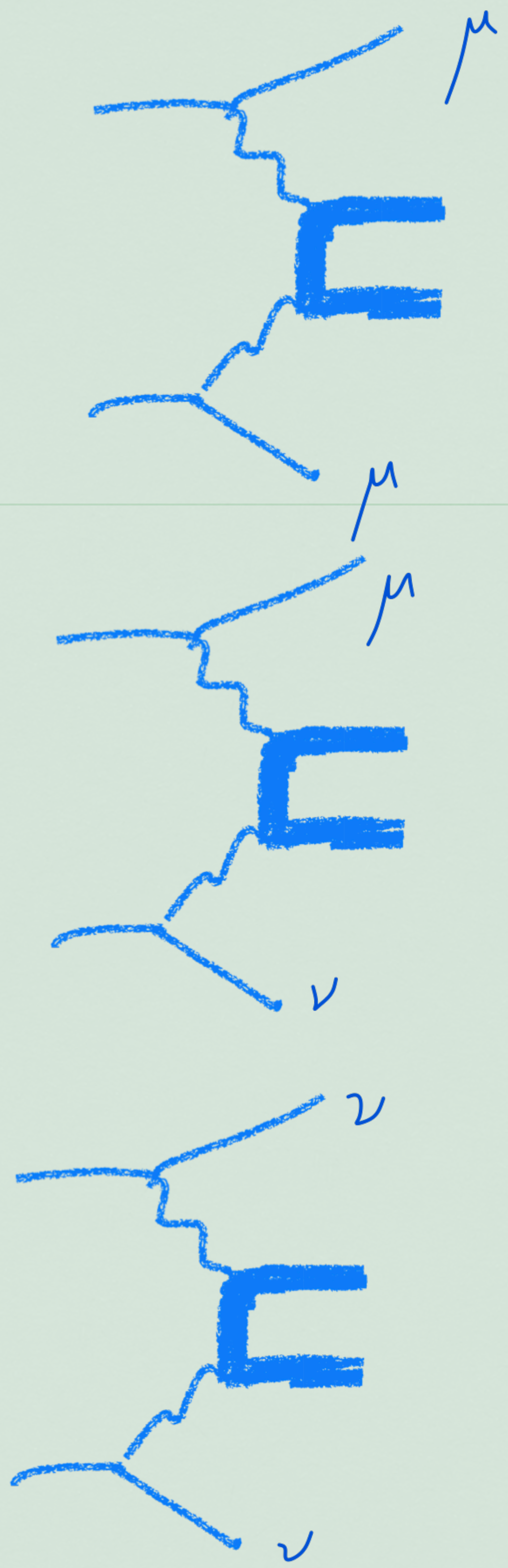
Sensitive up to mass comparable to the center of mass of $\mu^+\mu^-$



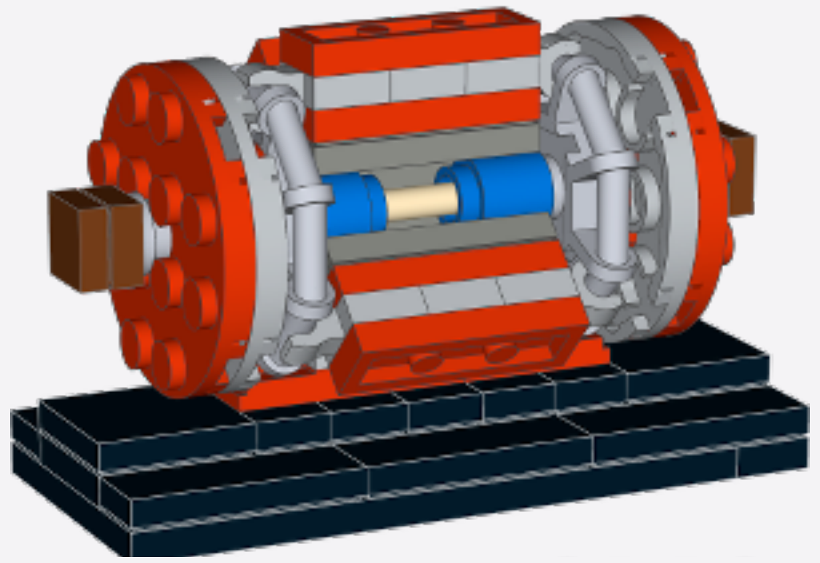




Excellent for low mass compared to the center of mass of $\mu^+\mu^-$



MONO-X



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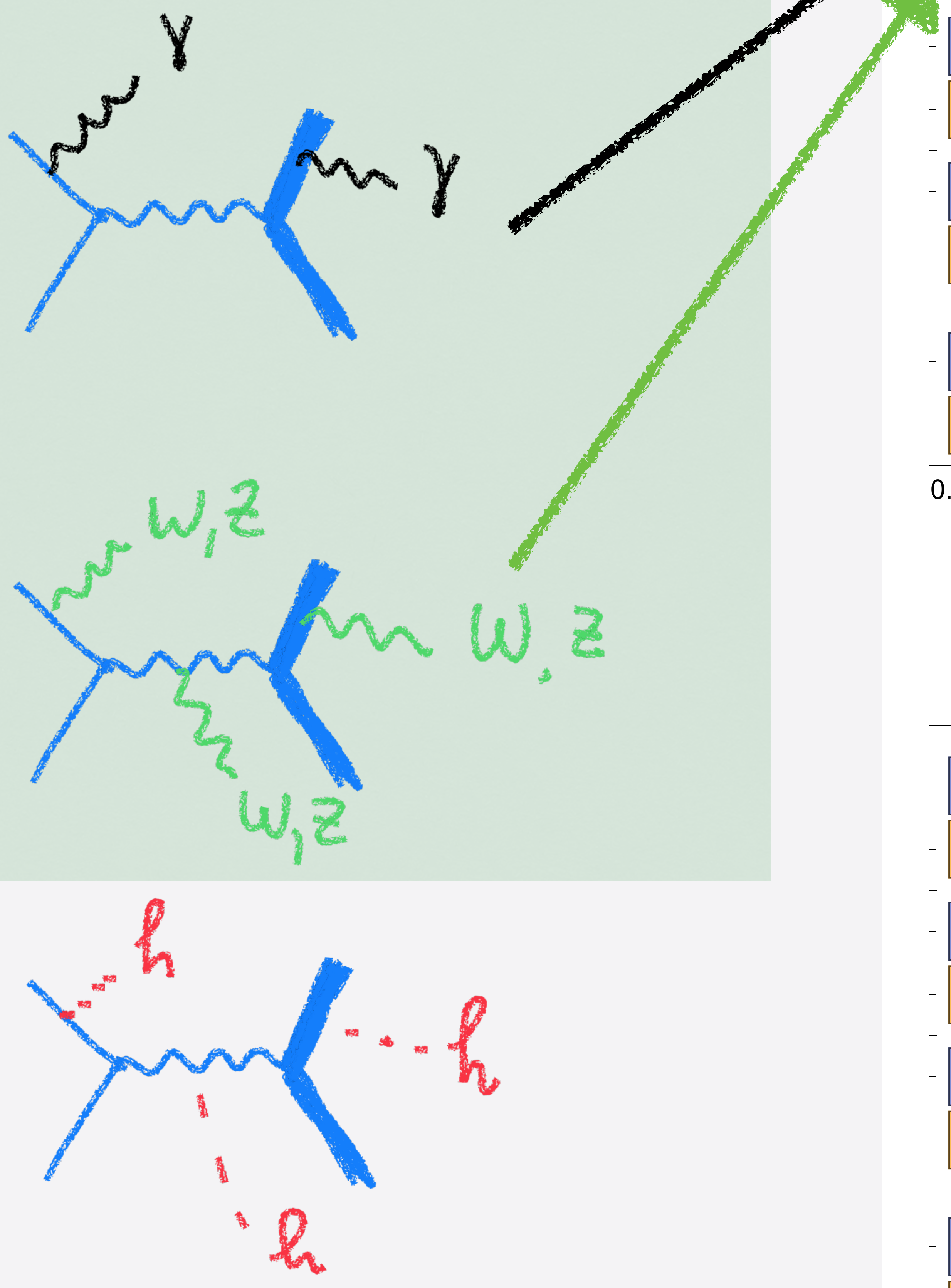

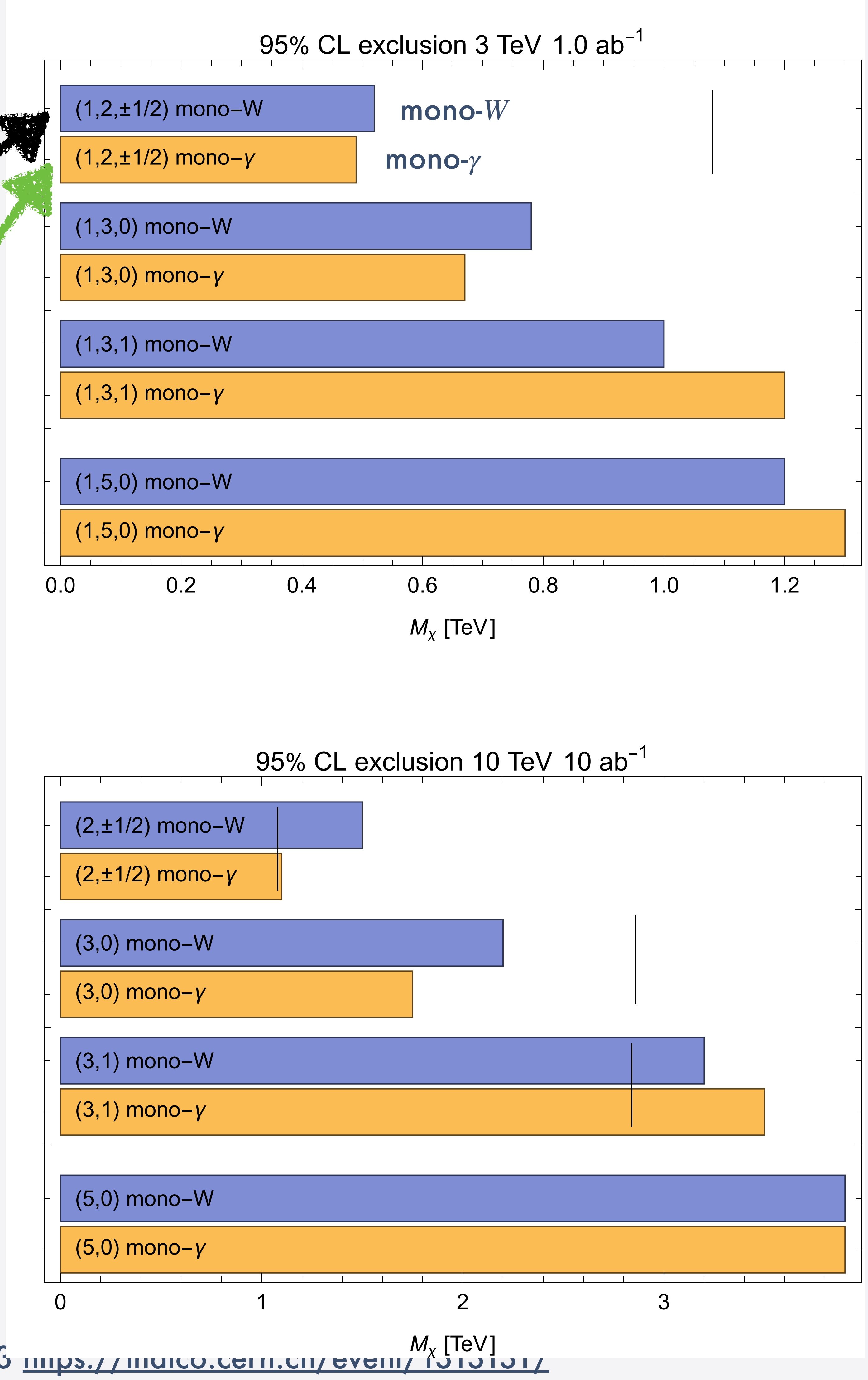

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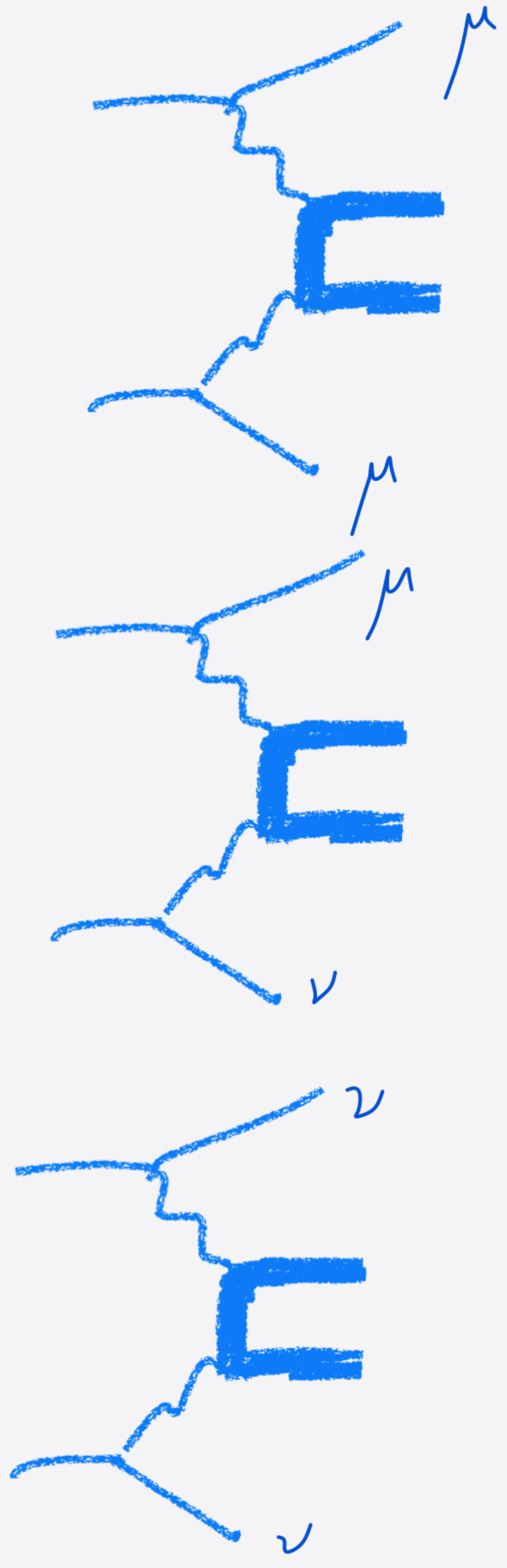
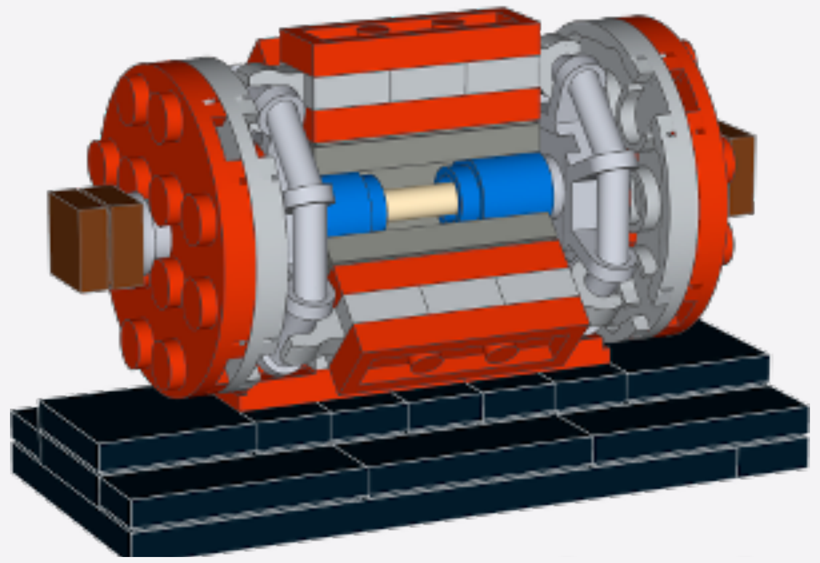


MONO-X



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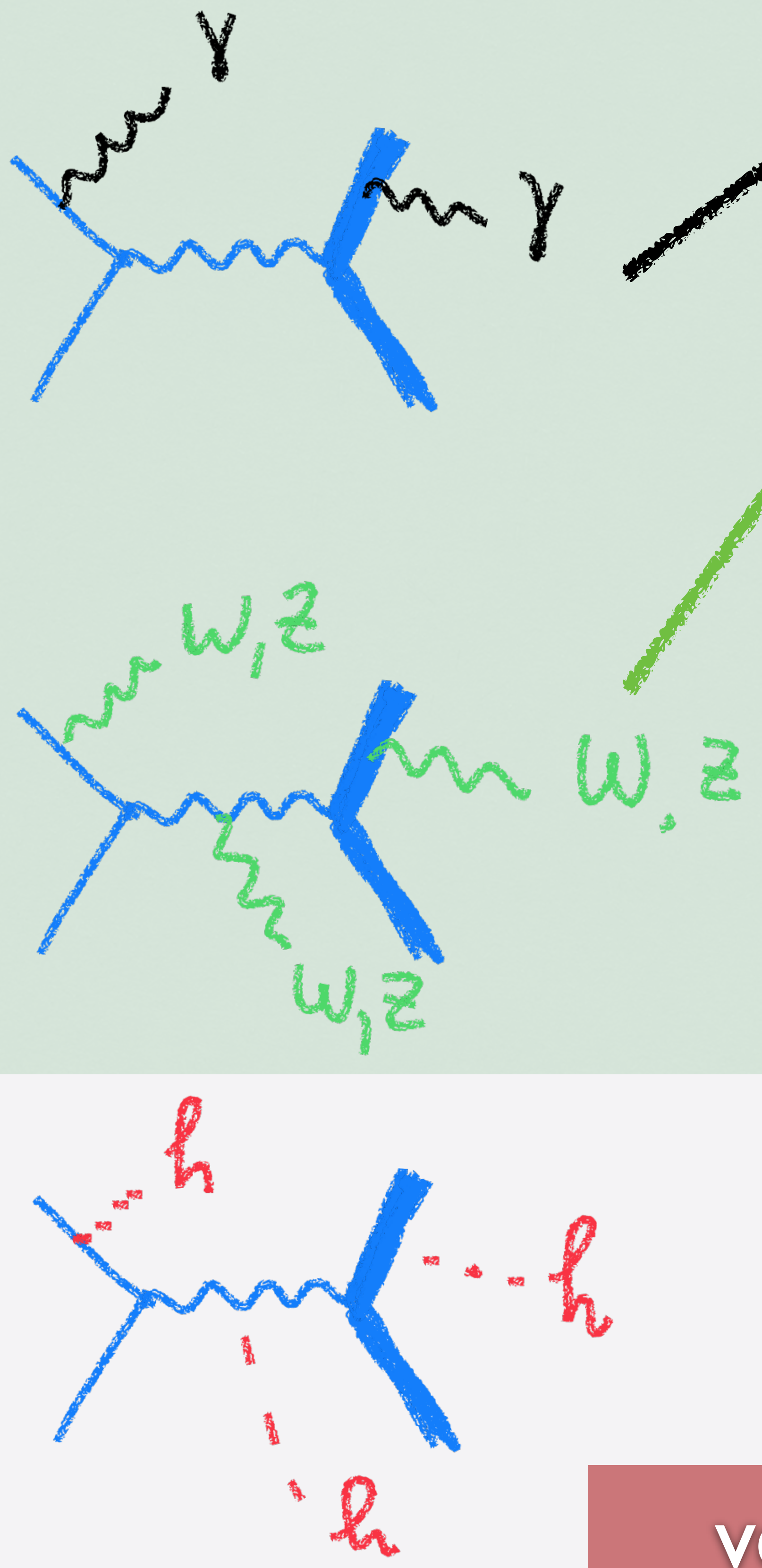

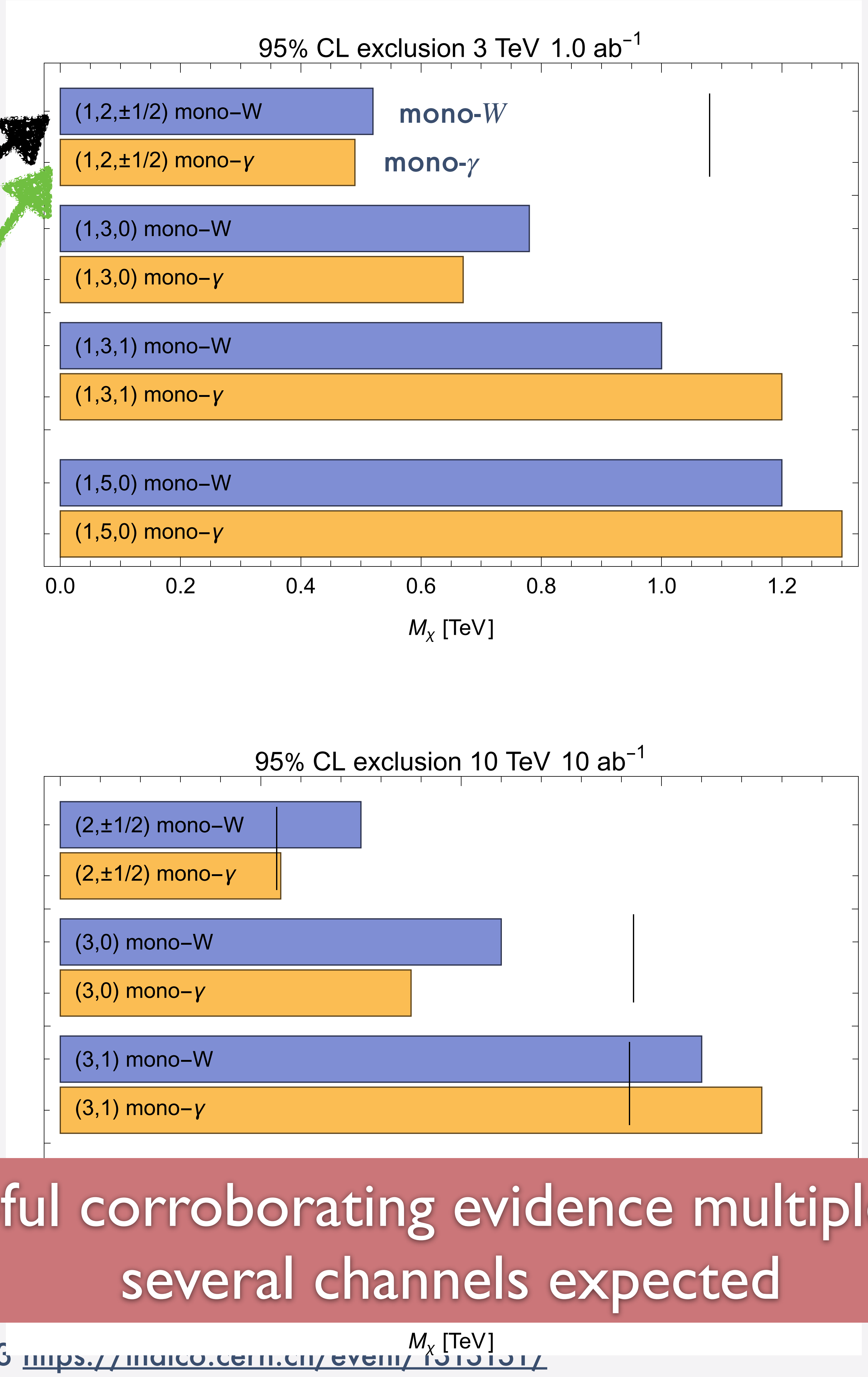

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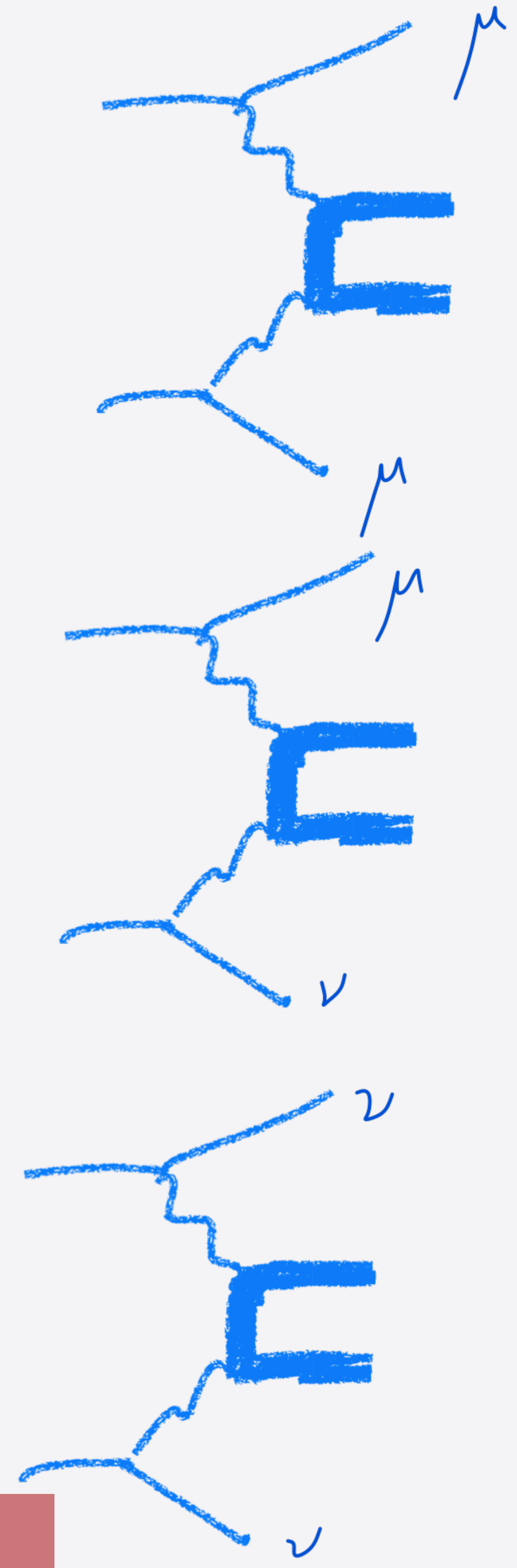
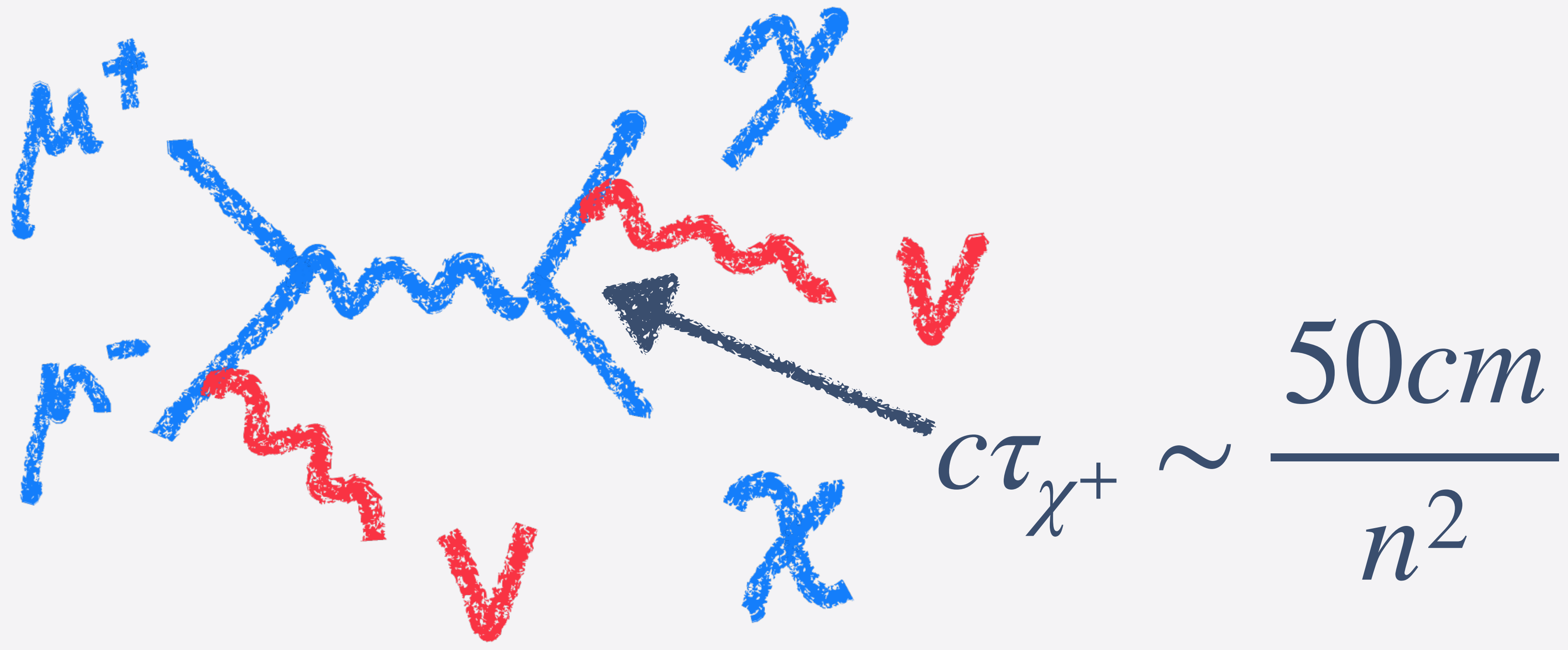


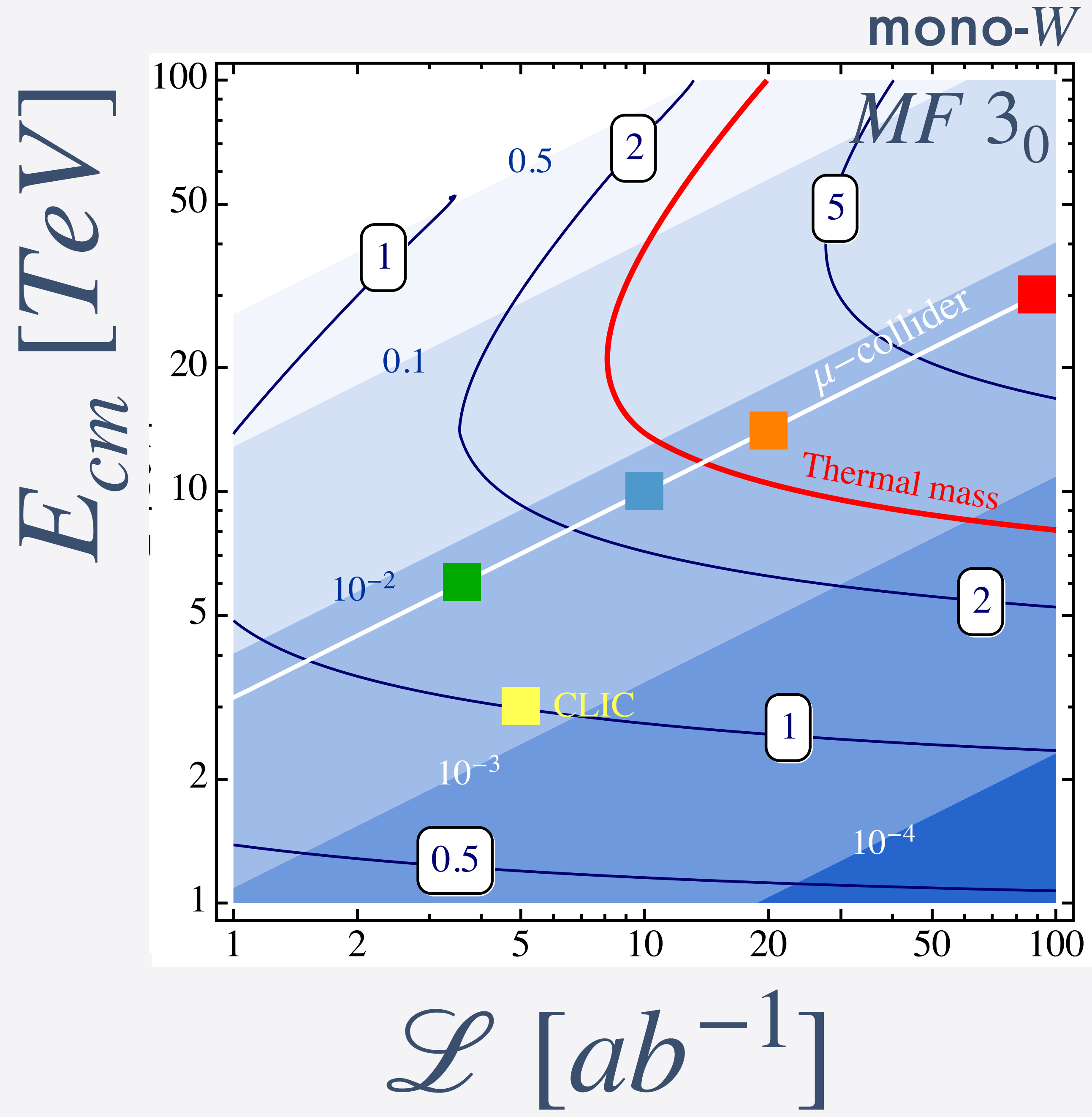
very helpful corroborating evidence multiple signals in several channels expected

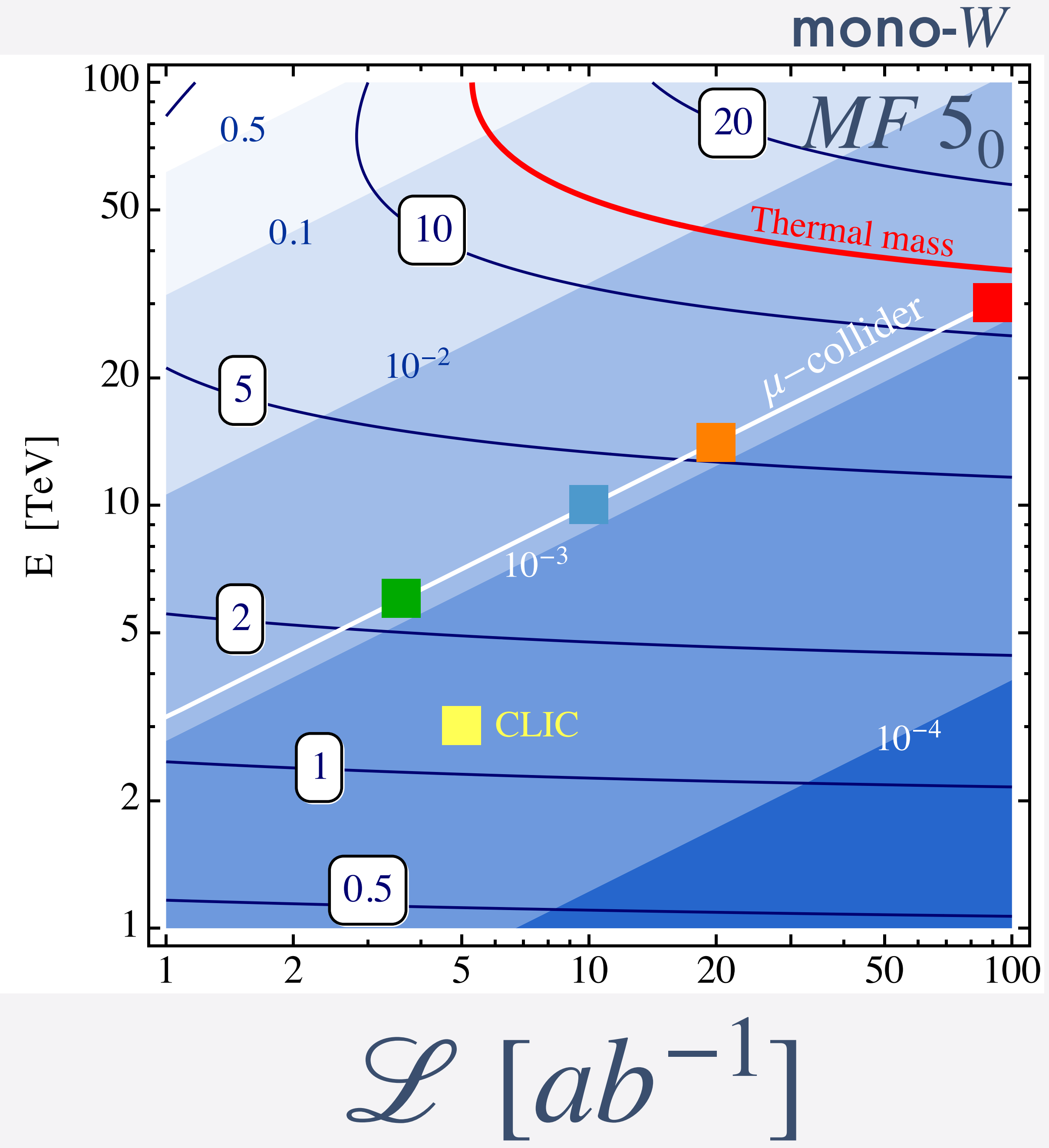
2009.11287, 2107.09688, 2205.04486 Han, Liu, Wang, Wang, Bottaro, Buttazzo, Costa, RF, Panci, Redigolo, Vittorio

DIRECT PRODUCTION



Production of Dark Matter weak multiplet states and observation of the decay products or associated productions





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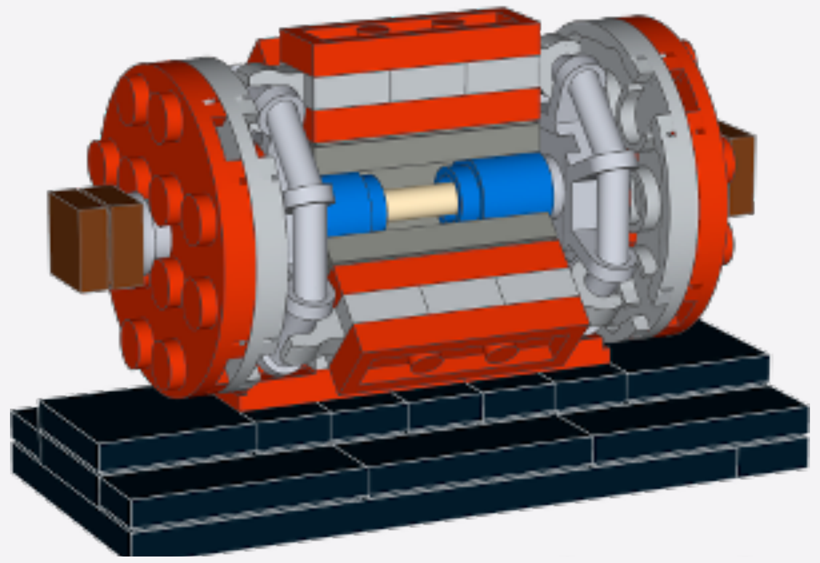
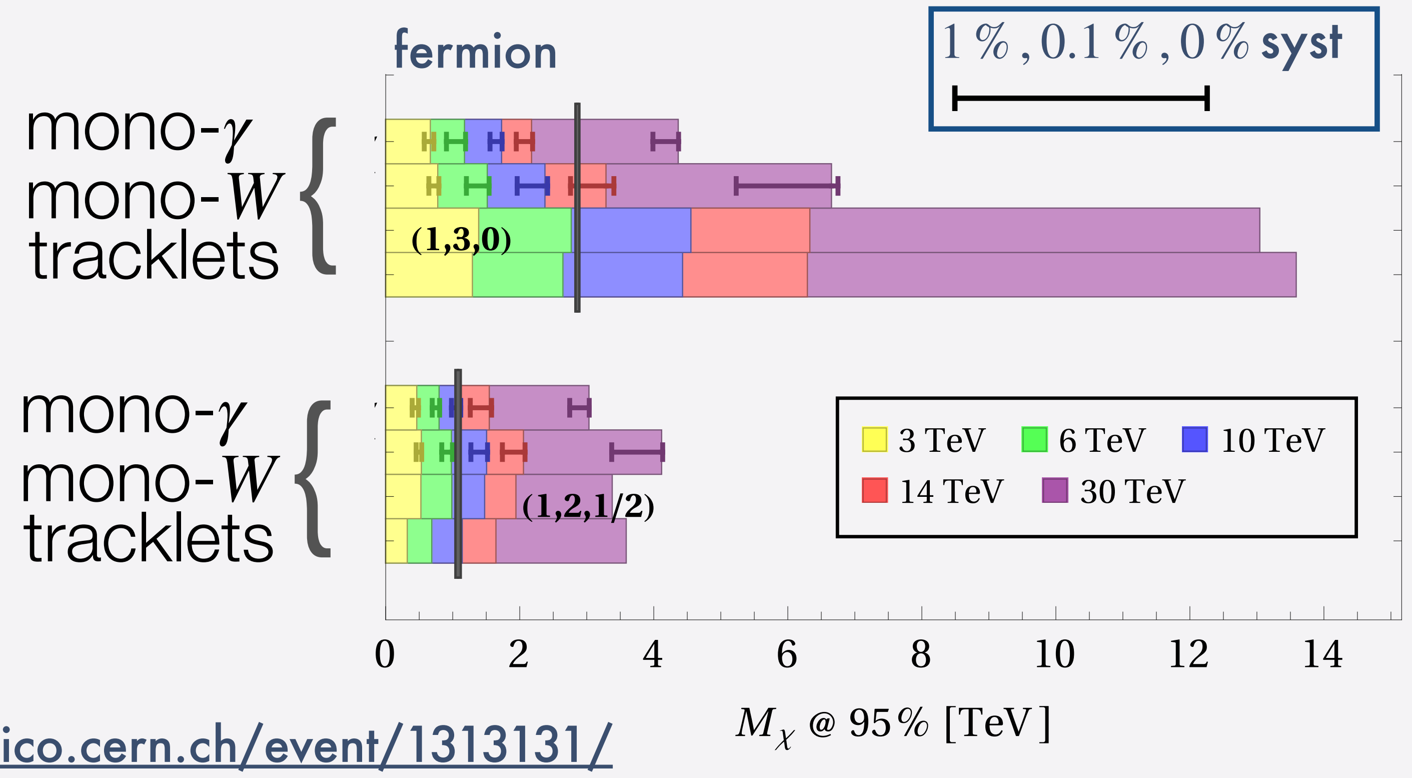
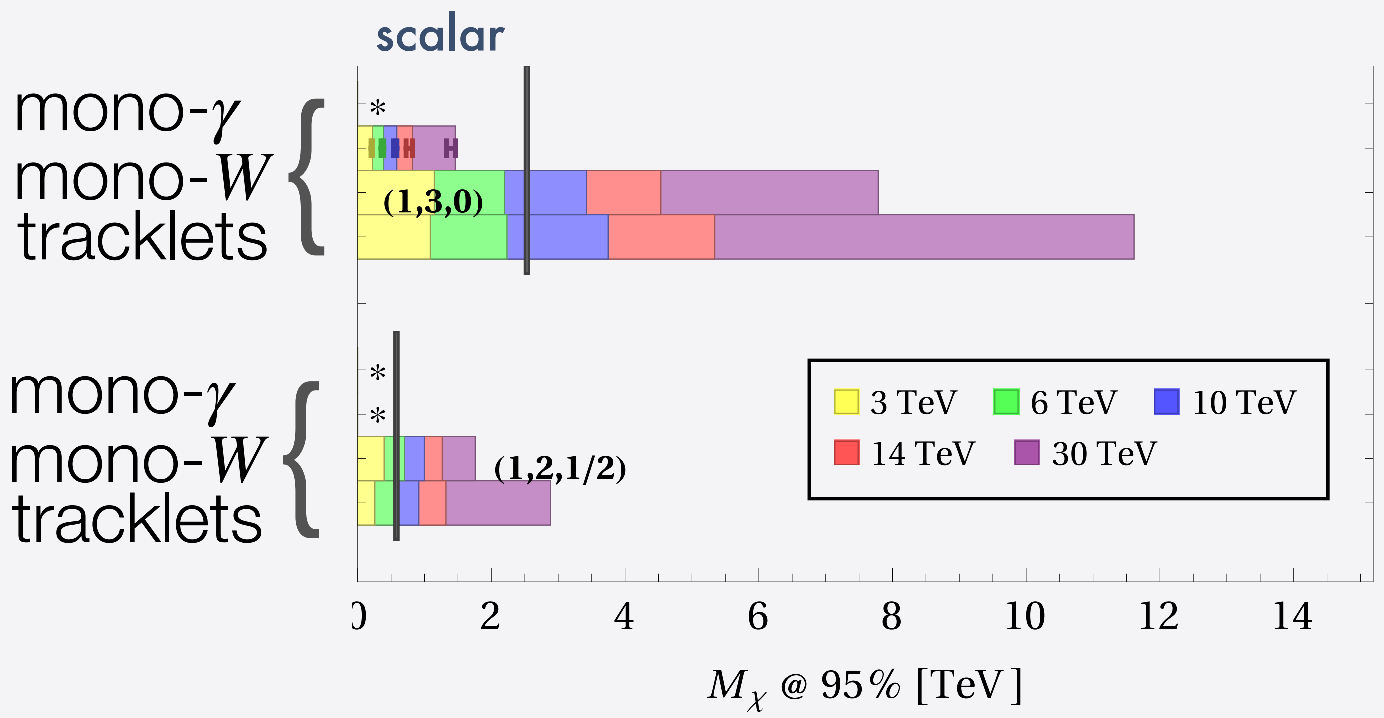


2040s

up to 10+ TeV





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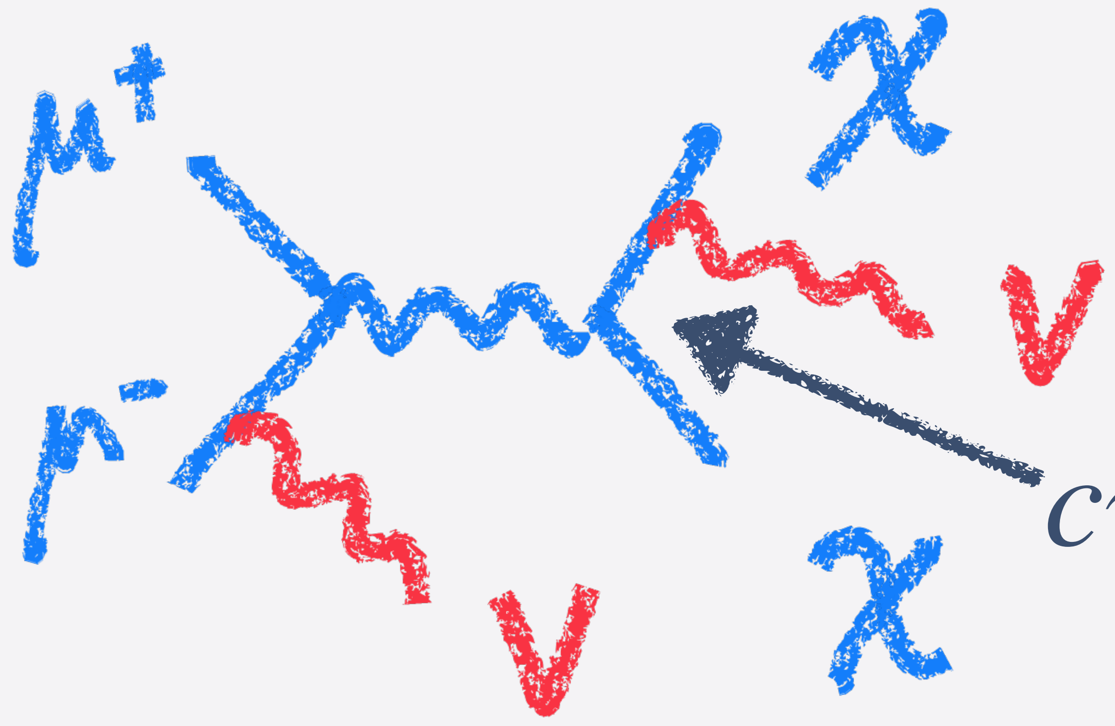
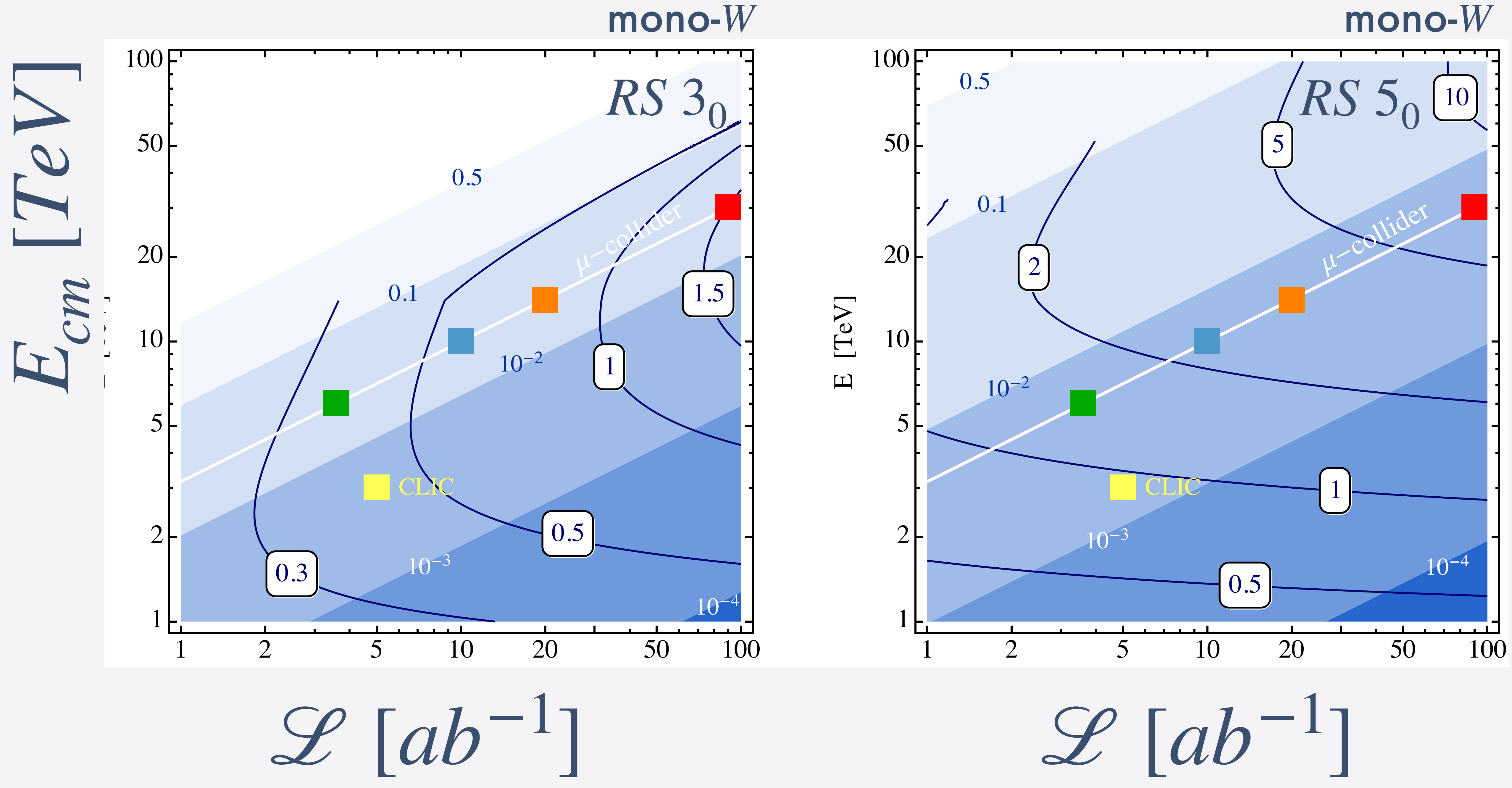


$$c\tau_{\chi^+} \sim \frac{50cm}{n^2}$$

Production of Dark Matter weak multiplet states and observation of the decay products or associated productions



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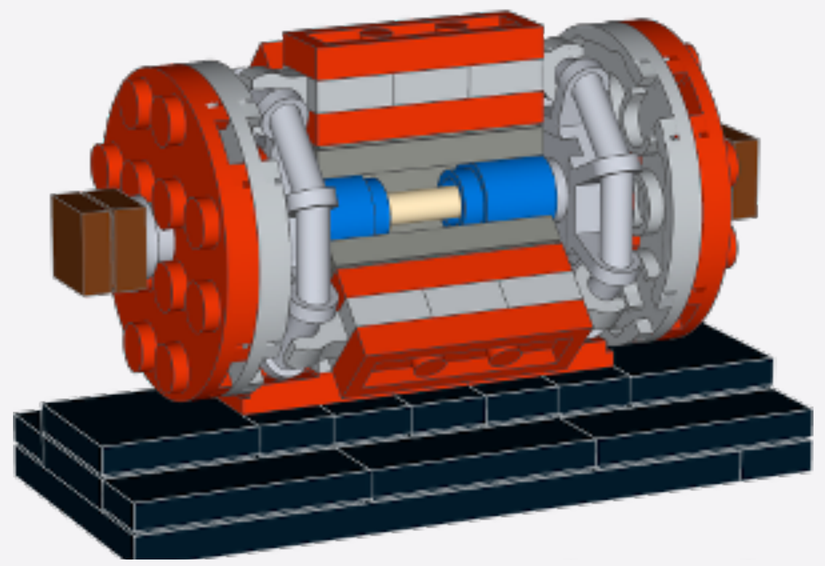

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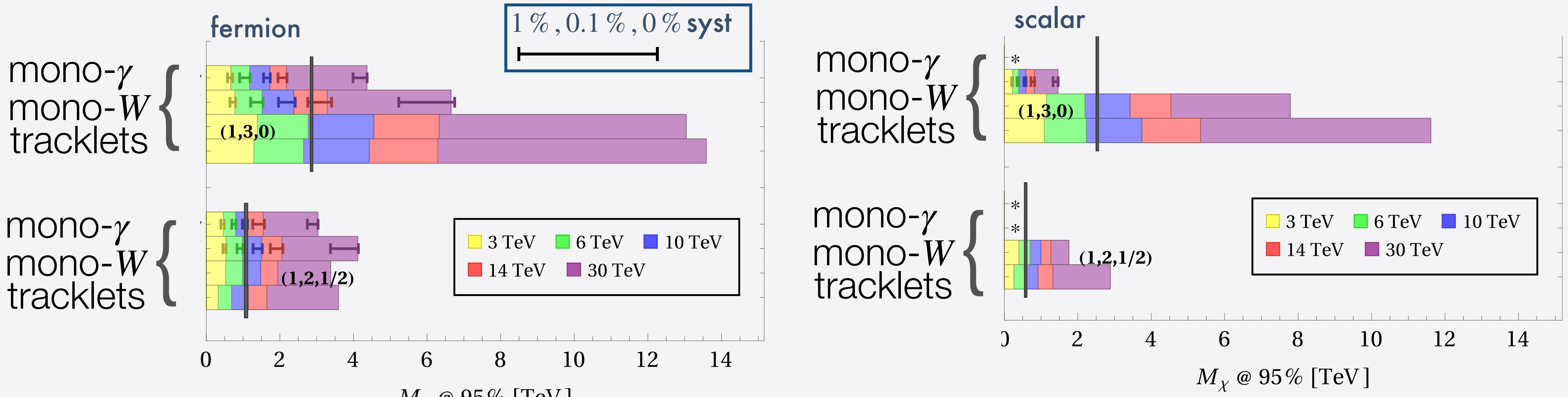
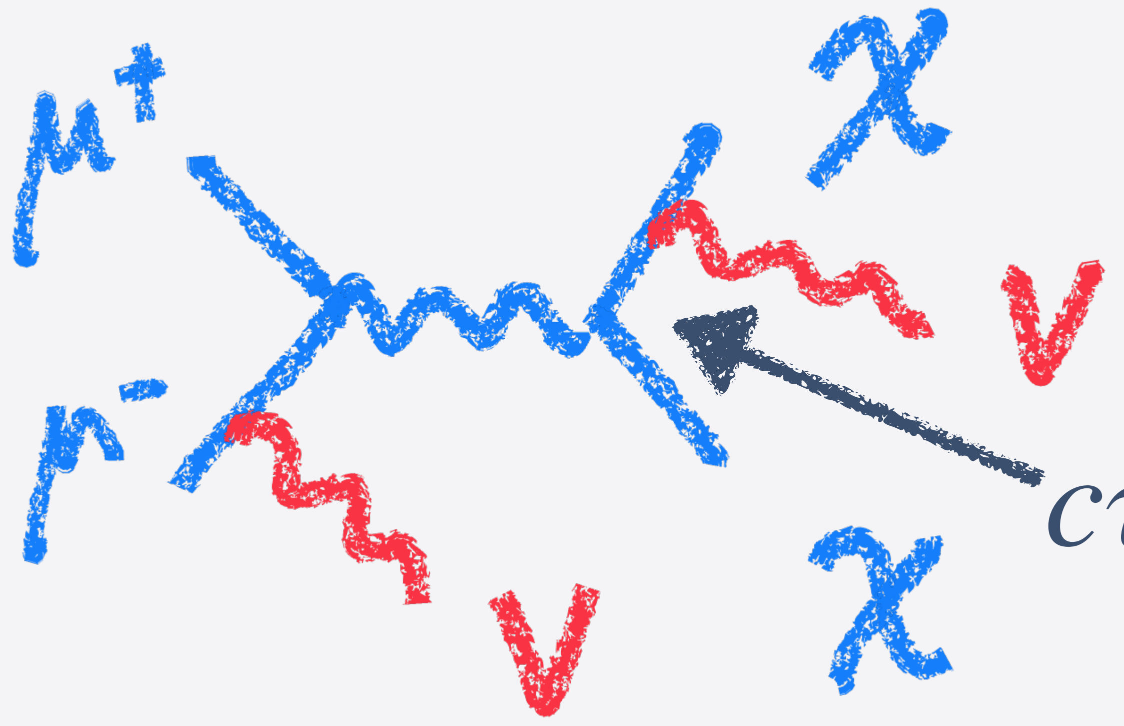


DIRECT PRODUCTION



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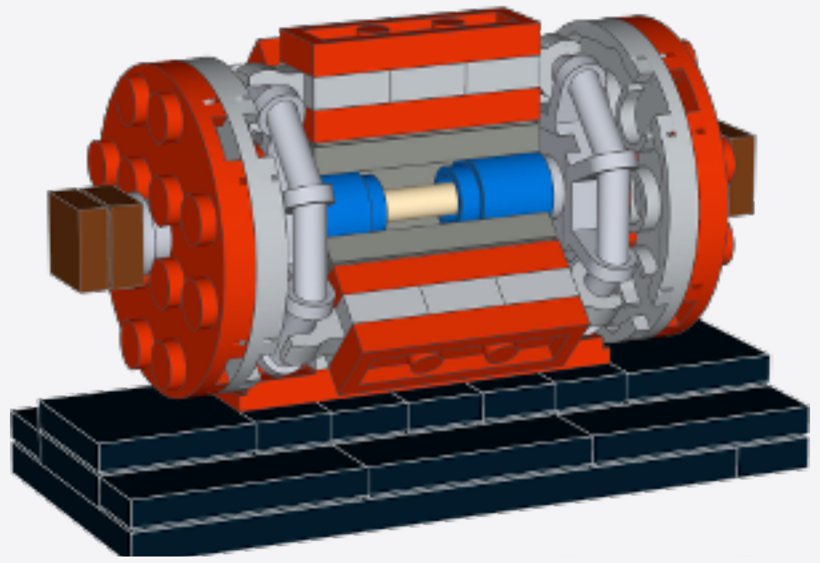

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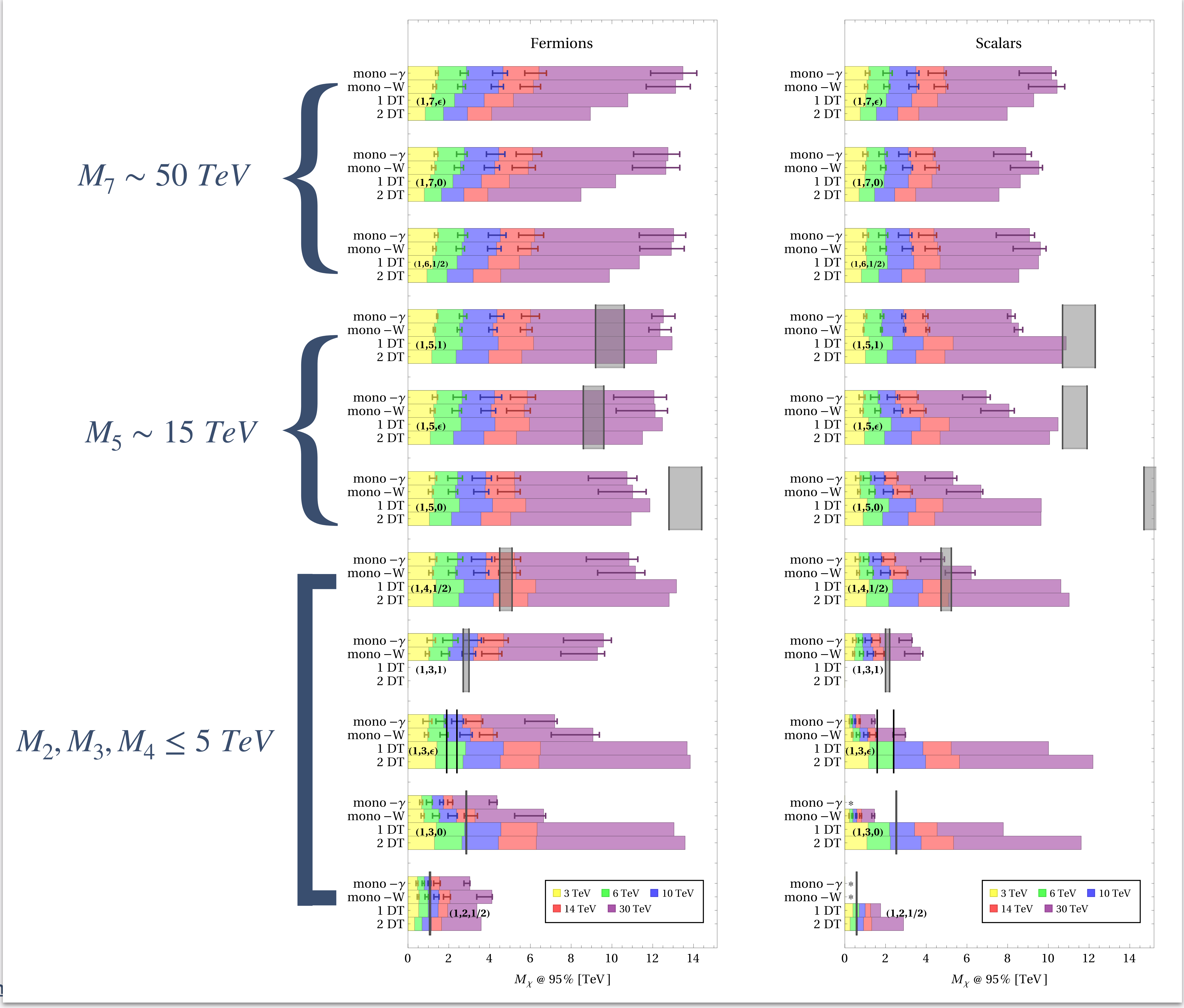

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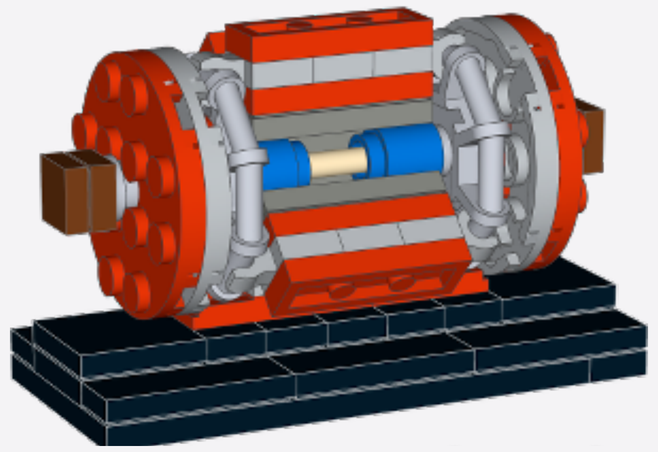
Precision Tests

VIRTUAL* PRODUCTION

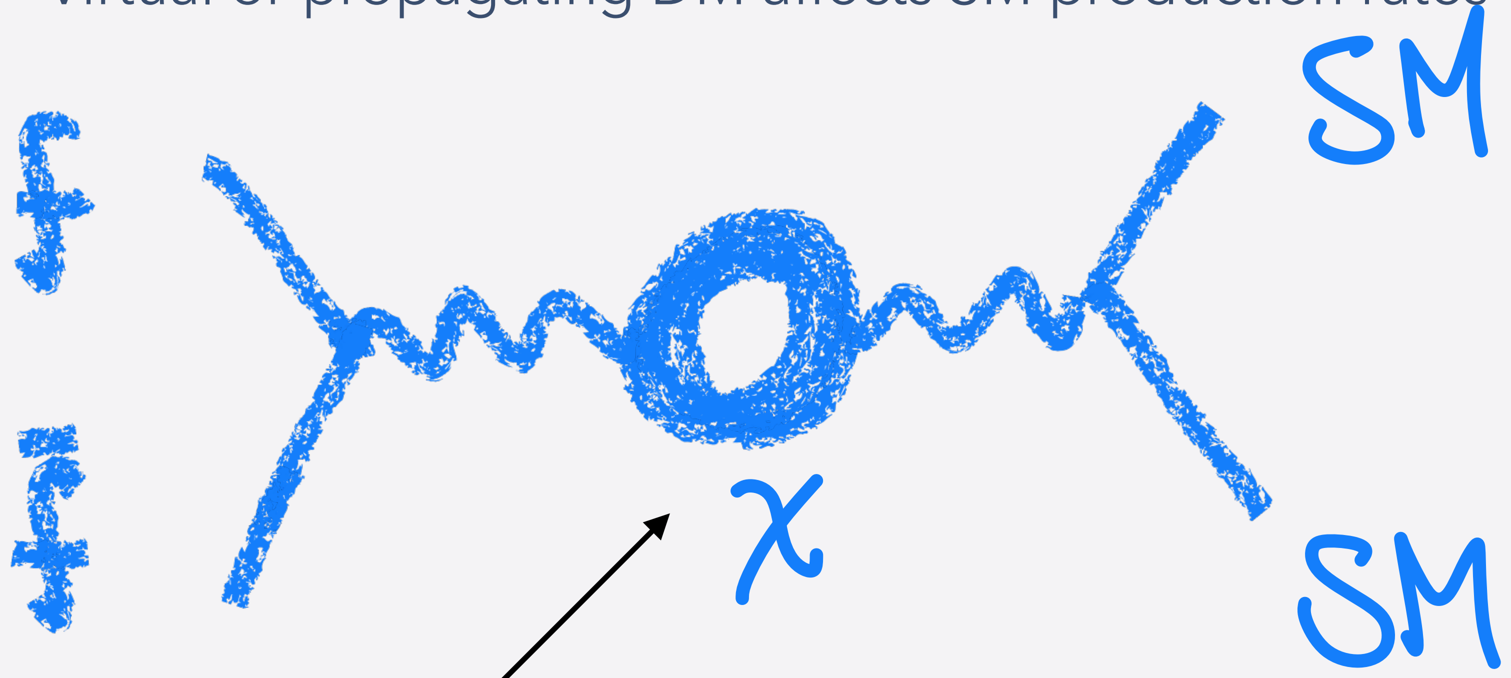
s-channel and t-channel



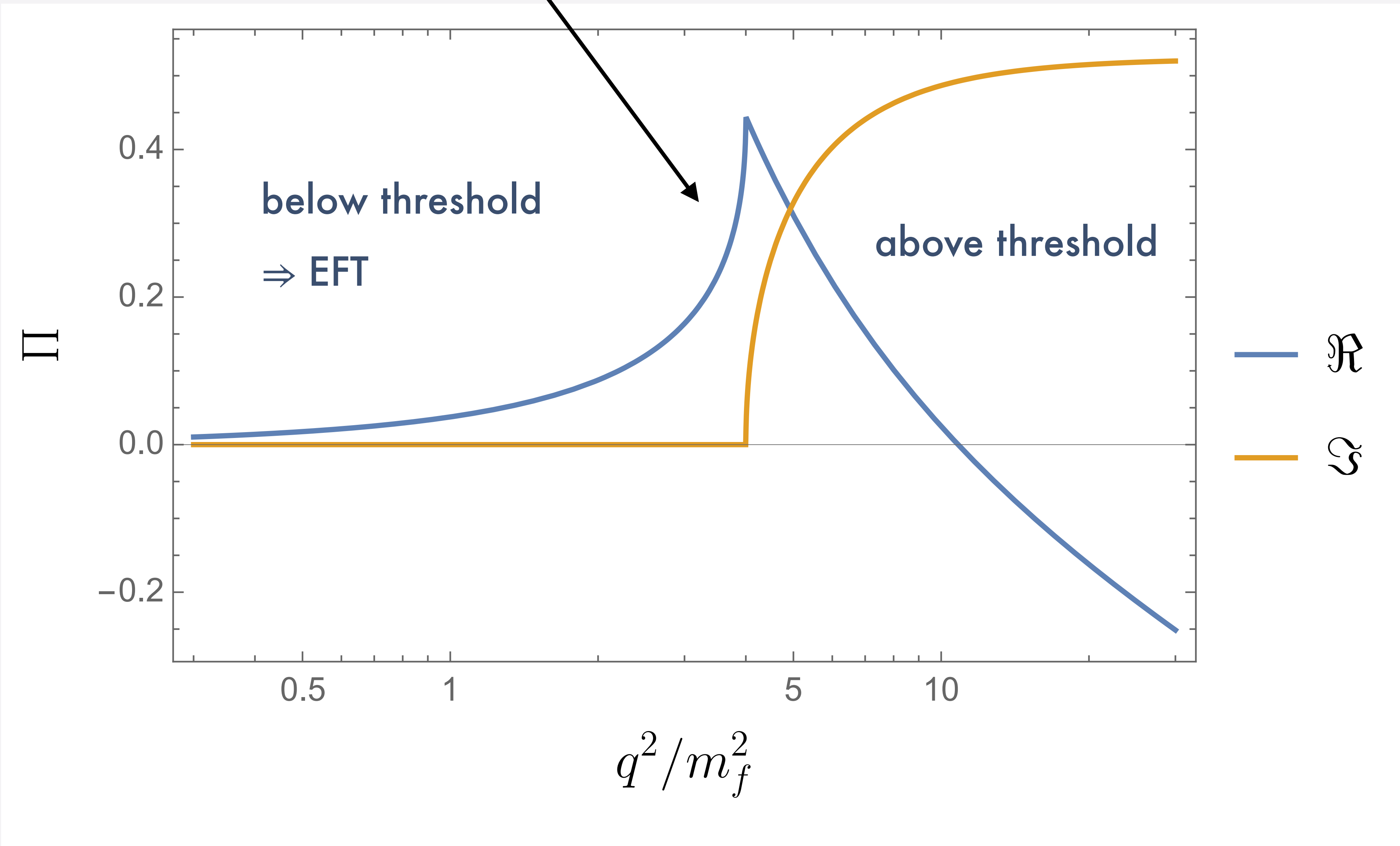
2040s

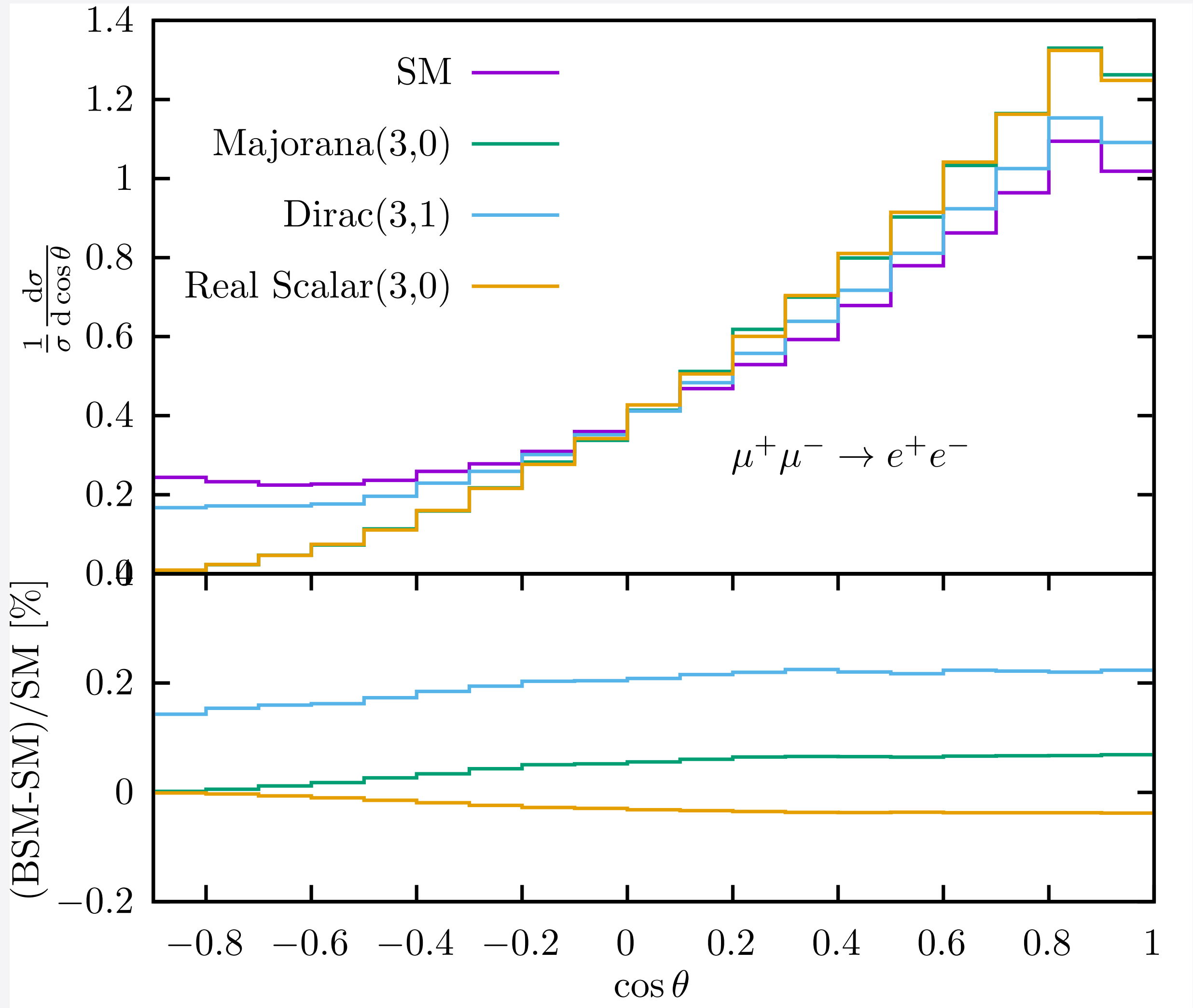
up to 10+ TeV

Virtual or propagating DM affects SM production rates



$\Pi(q^2/m_\chi^2)$





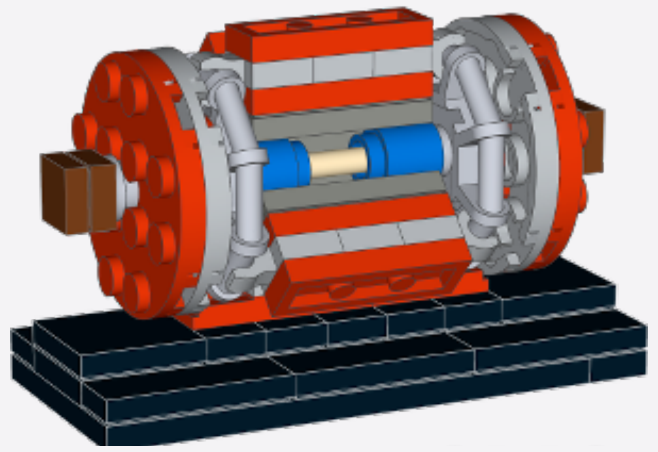
$$SM\,SM \subset f\bar{f}$$

$$\ell^+\ell^- \to e^+e^-, b\bar{b}, \mu^+\mu^-, c\bar{c}$$

- differential distributions $\dfrac{d\sigma}{d\cos\theta^*}$
- differential distributions $\dfrac{d\sigma}{d\ \ \cos\theta^*}$

VIRTUAL* PRODUCTION

s-channel and t-channel



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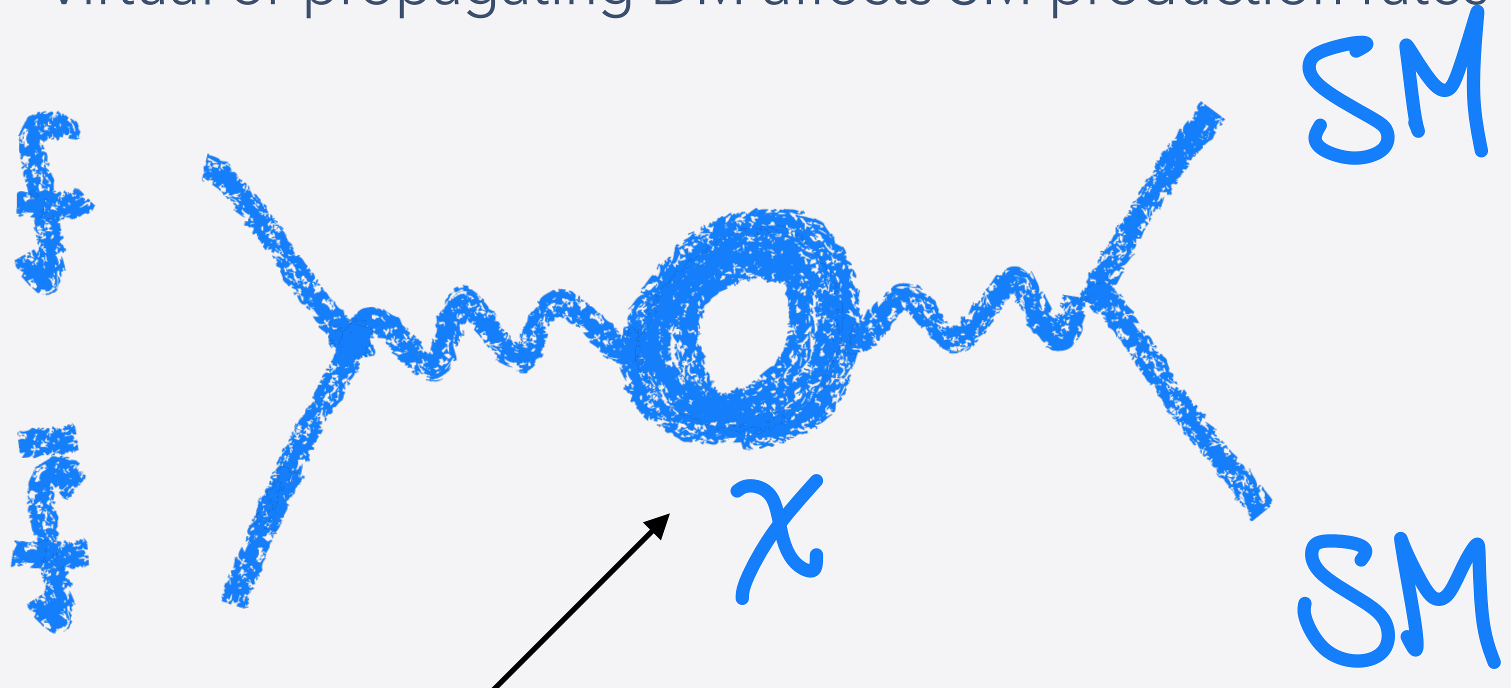

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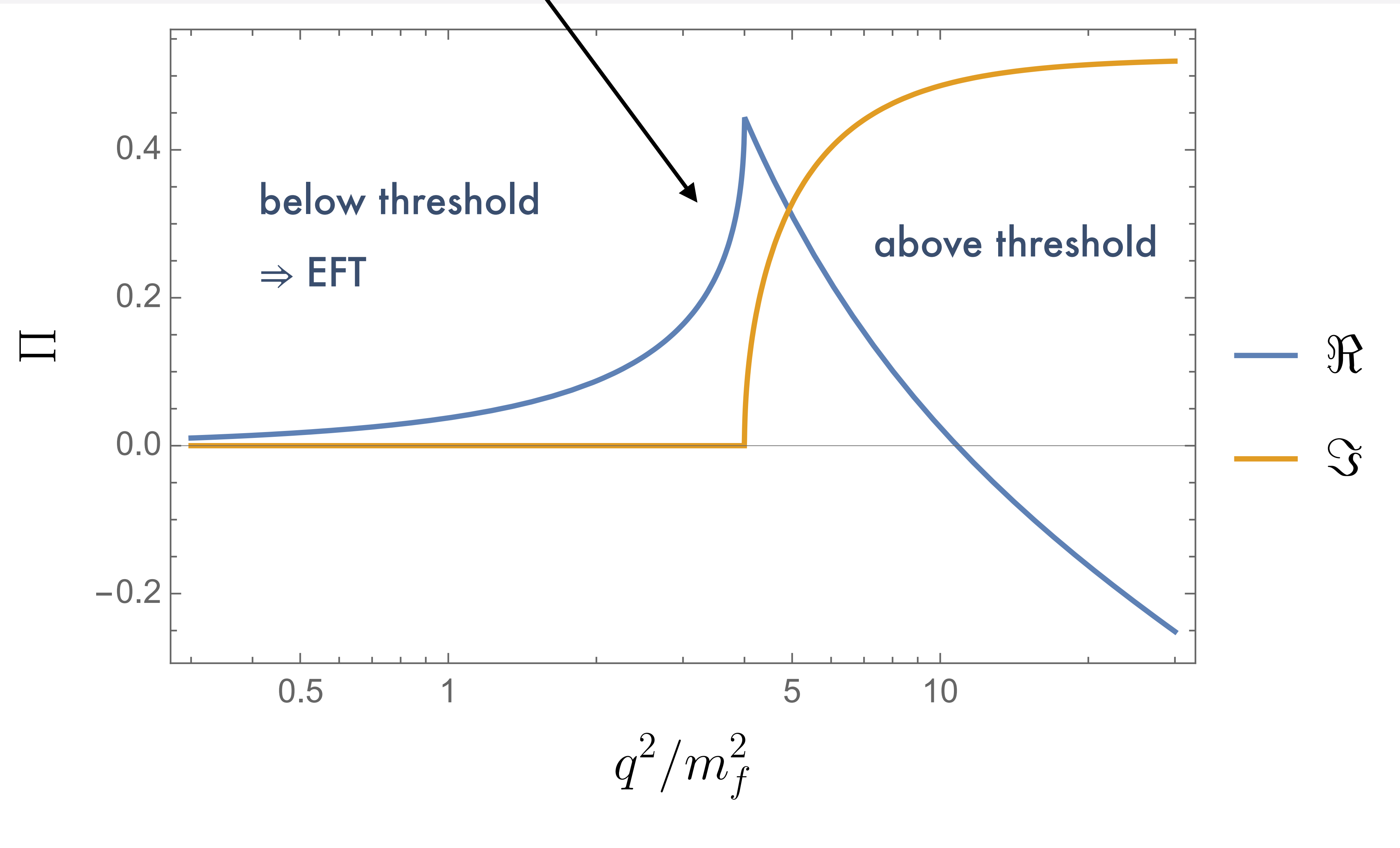

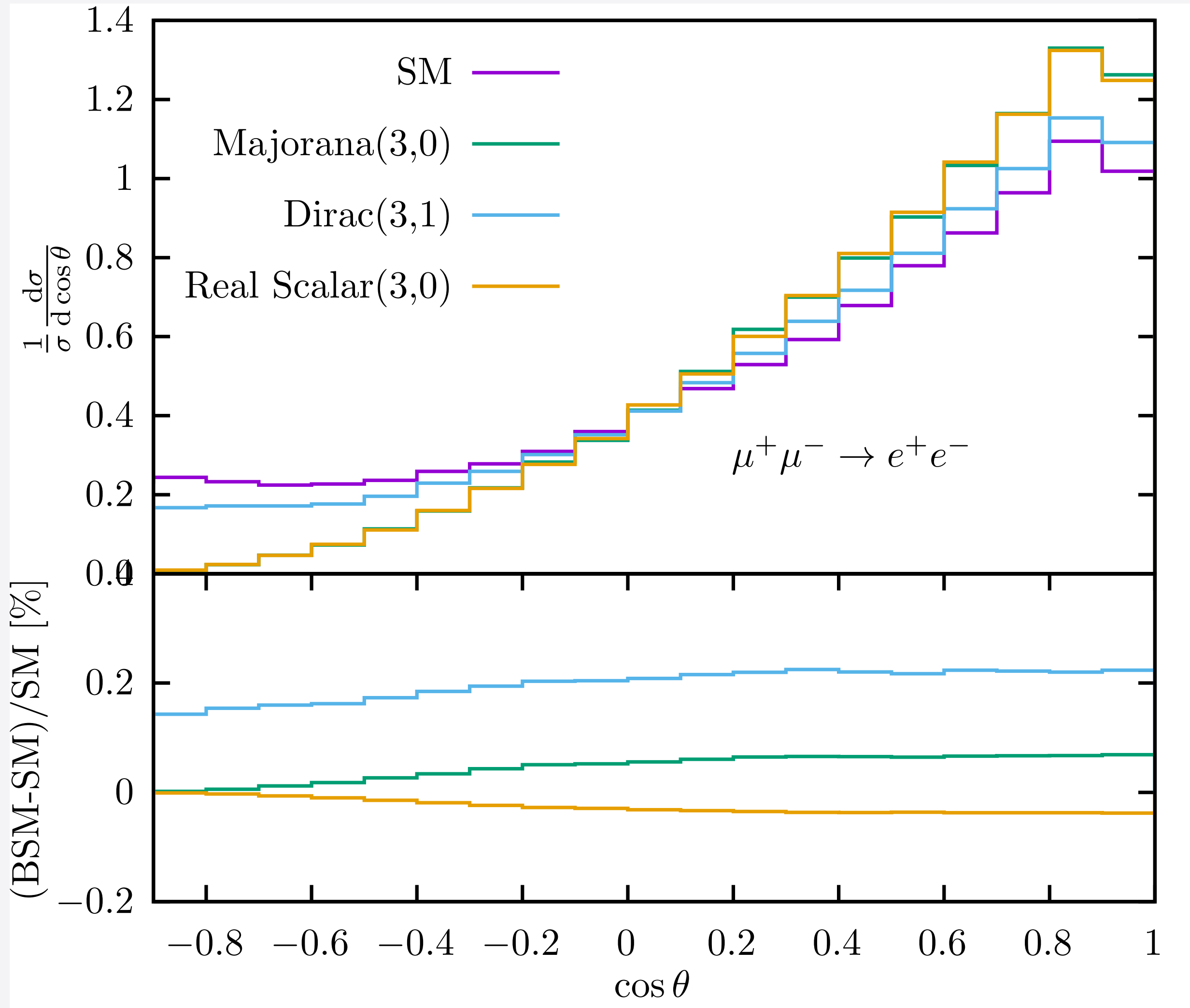

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1810.10993

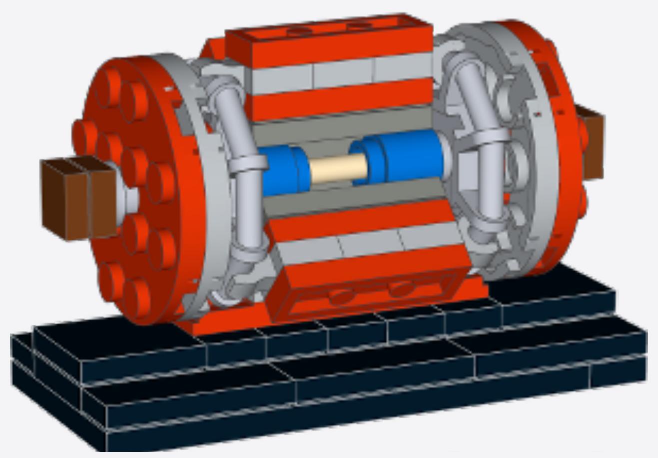
χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1,2,1/2)_{\rm DF}$	1.1	–	–	–	0.4	0.6
$(1,3,\epsilon)_{\rm CS}$	1.6	–	–	–	0.2	0.2
$(1,3,\epsilon)_{\rm DF}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1,3,0)_{\rm MF}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1,5,\epsilon)_{\rm CS}$	6.6	0.2	0.4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

clear advantage with respect to pp

RF, Xiaoran Zhao - 2212.11900

VIRTUAL* PRODUCTION

s-channel and t-channel



2040s

up to 10+ TeV

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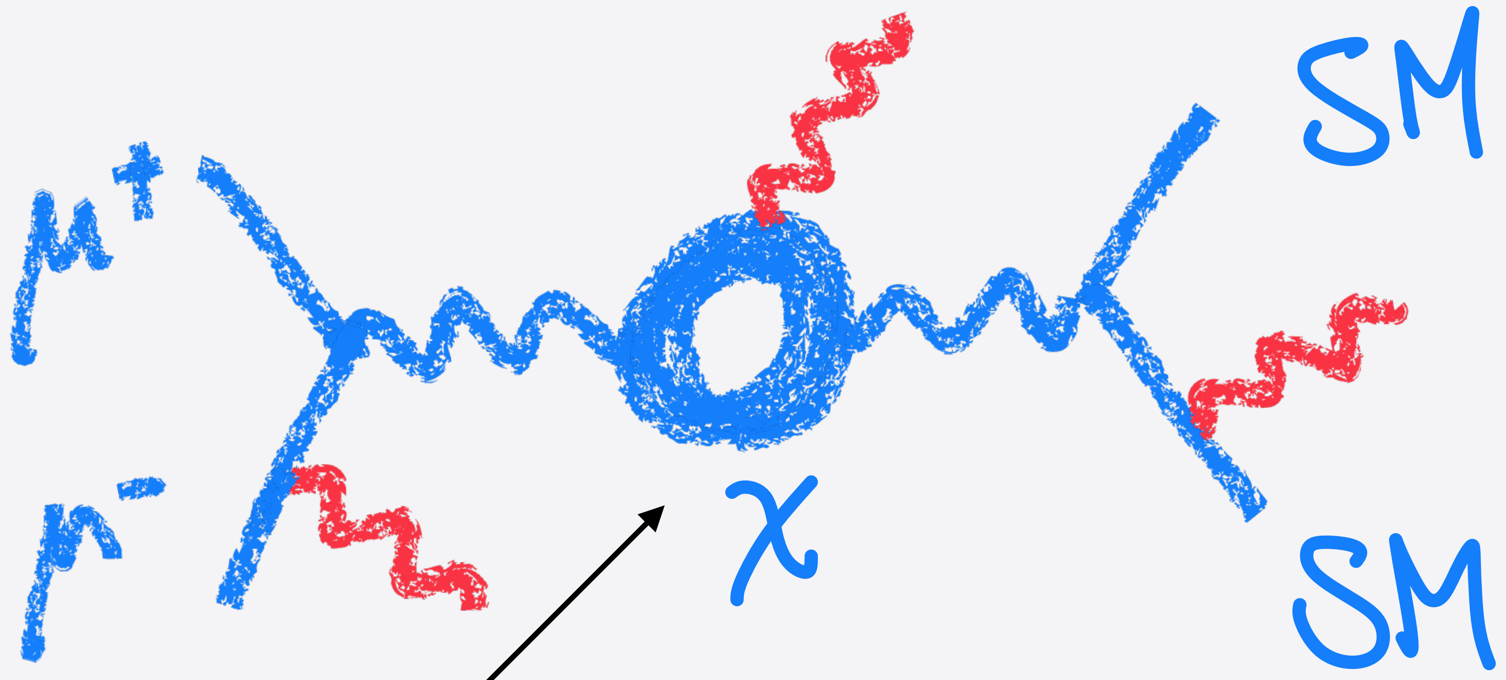
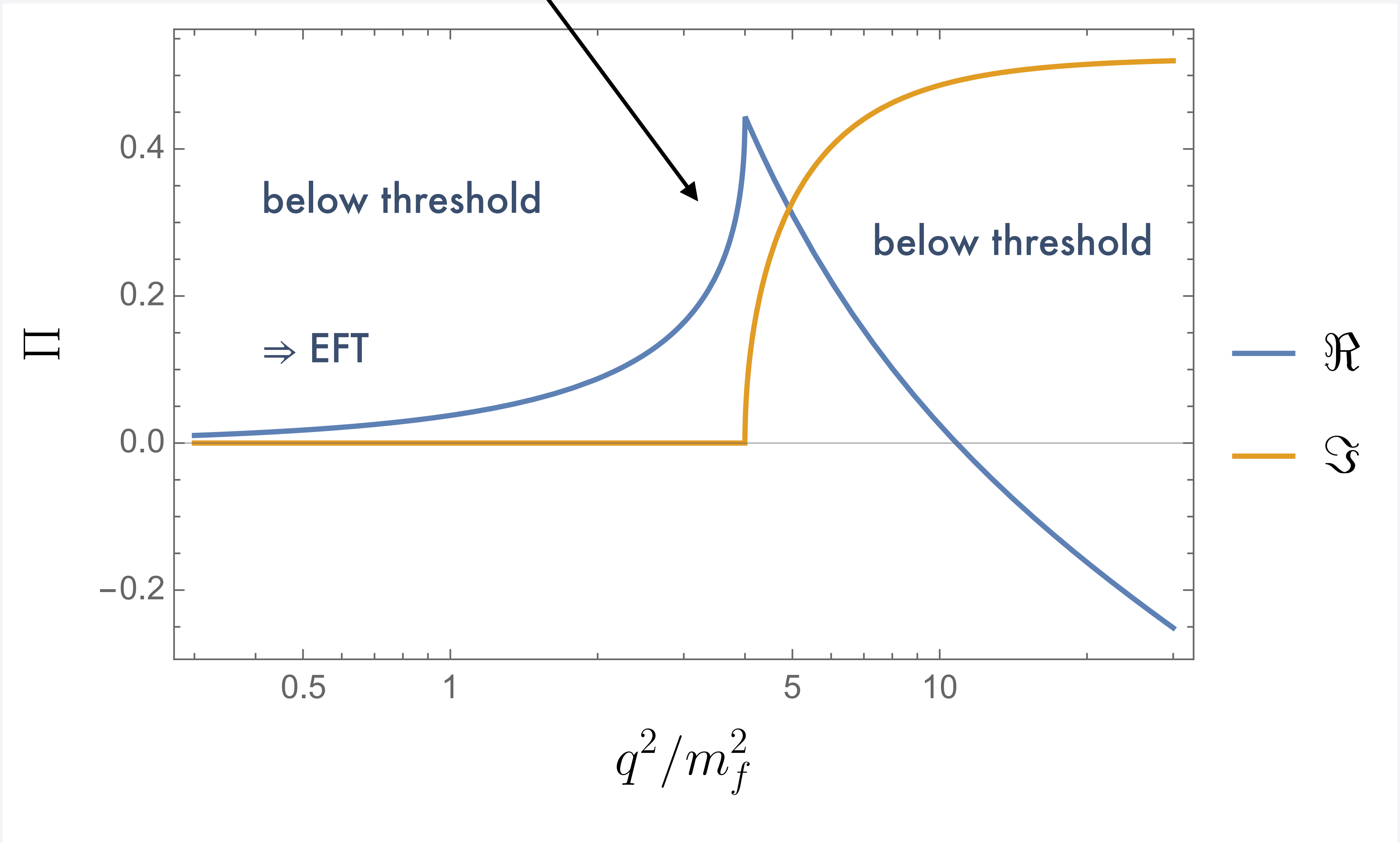


$\Pi(q^2/m_\chi^2)$



$$SM\,SM = (f\bar{f}, VV) + X$$

$\ell^+\ell^- \to e^+e^-, b\bar{b}, \mu^+\mu^-, c\bar{c}$

- differential distributions $\dfrac{d\sigma}{d\cos\theta^*}$
- differential distributions $\dfrac{d\sigma}{d\ \cos\theta^*}$

$\ell^+\ell^- \to jj, tt, Zh, W^+W^-, Wff'$

- inclusive fiducial rates

precision SM studies ⇒ systematics are the key

- luminosity measurements for inclusive fiducial measurements

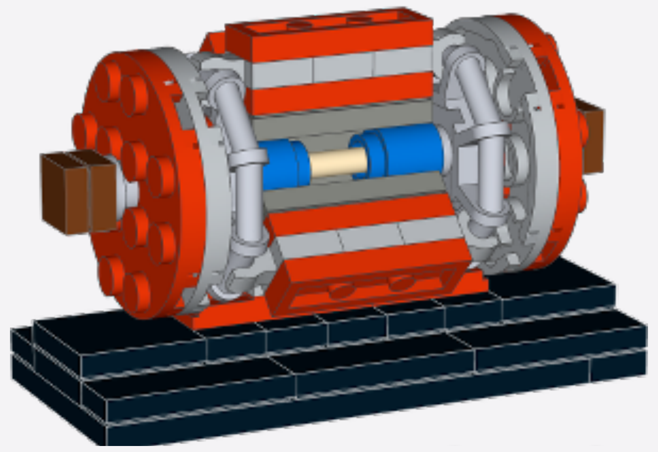
  μhaμha scattering ⇒ $\delta\mathscr{L}/\mathscr{L} = 0.2\,\%$ at 1.5 TeV (ref)

- other systematics affecting SM final states

RF, Xiaoran Zhao - 2212.11900

VIRTUAL* PRODUCTION

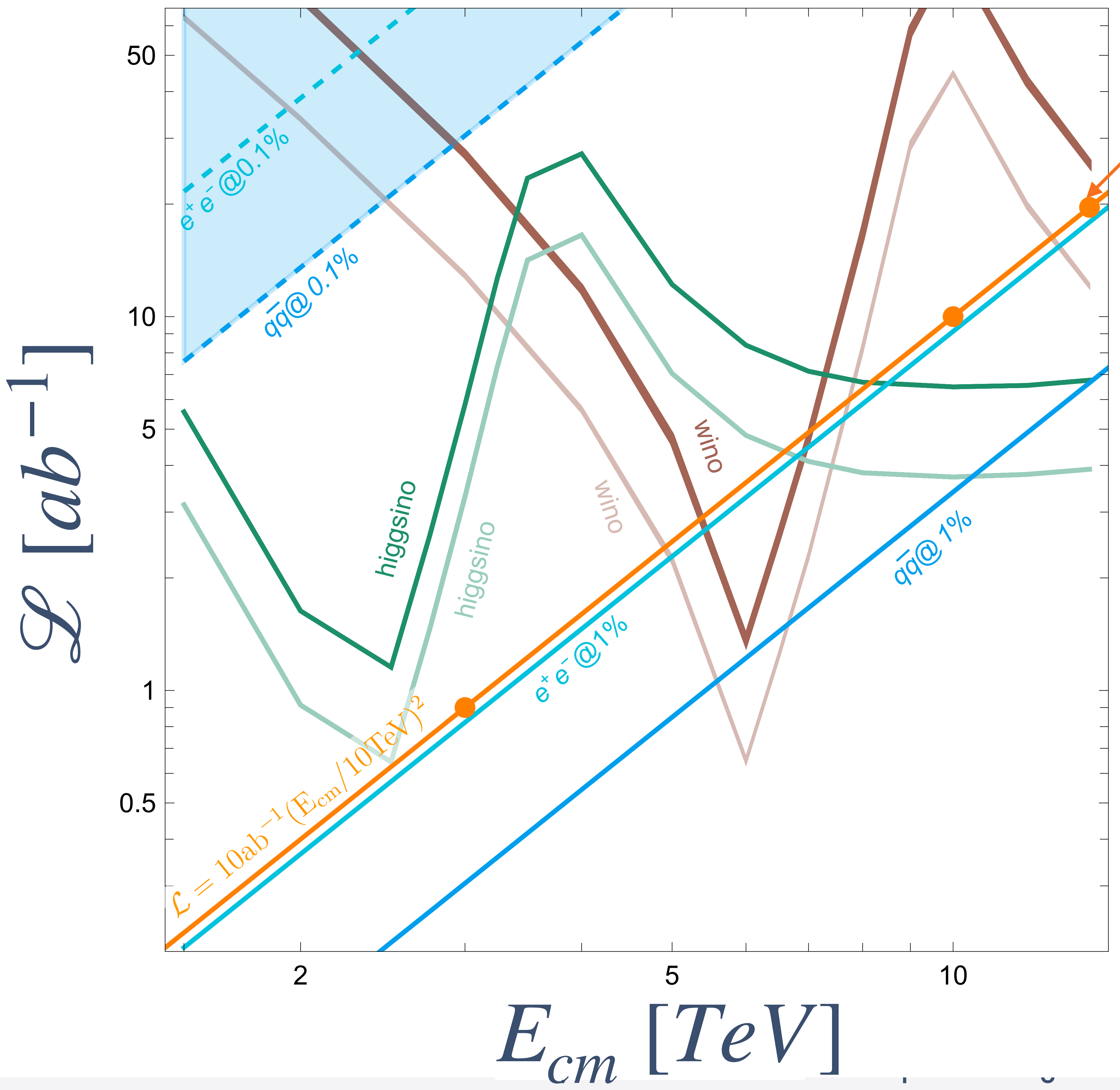
$$\mu^+\mu^- \to f\bar{f}, Zh, W^+W^-, Wff'$$

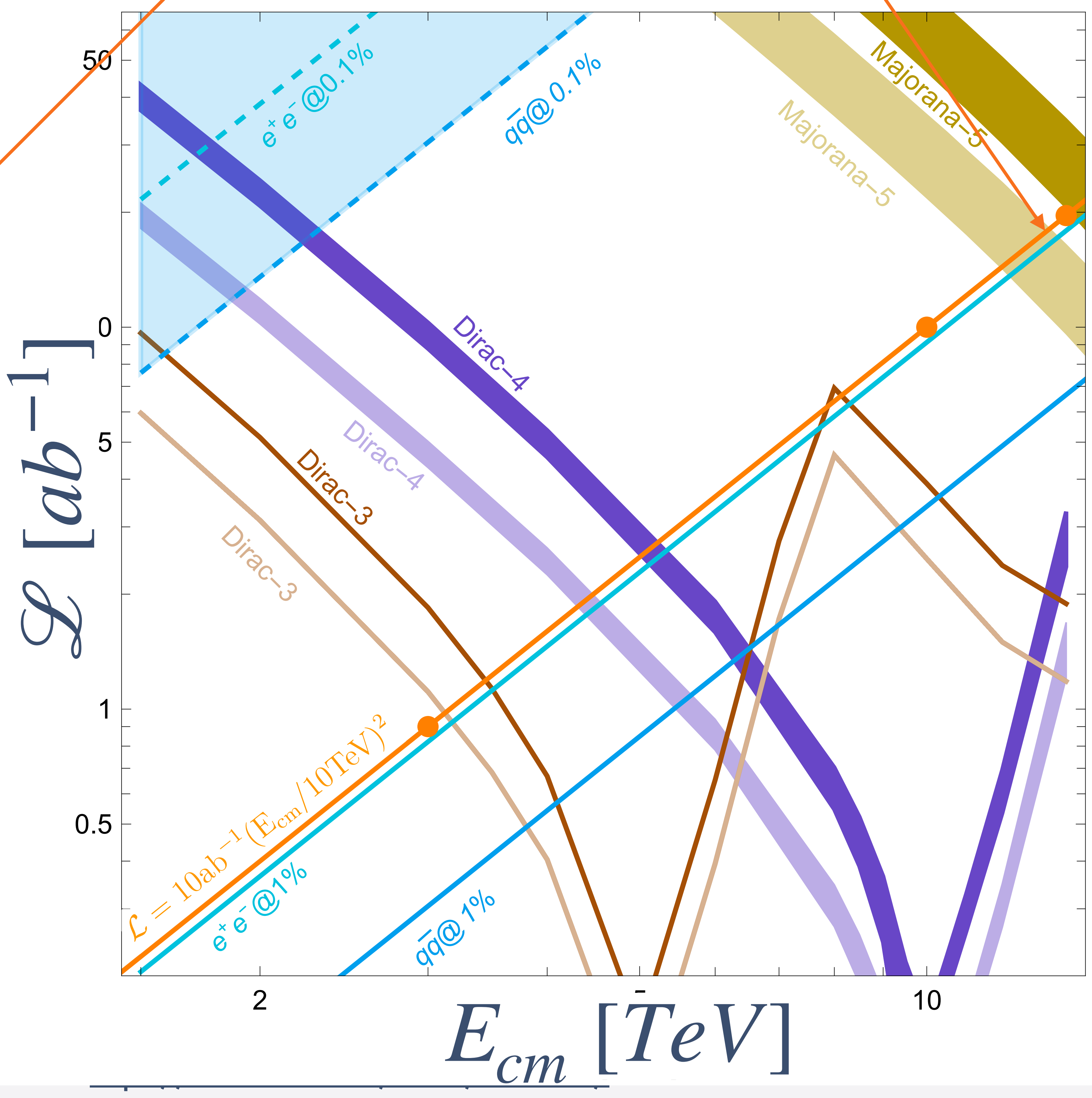


2040s

up to 10+ TeV

$$\mathcal{L} = 10\,\text{ab}^{-1} \cdot (E_{com}/10\,\text{TeV})^2$$

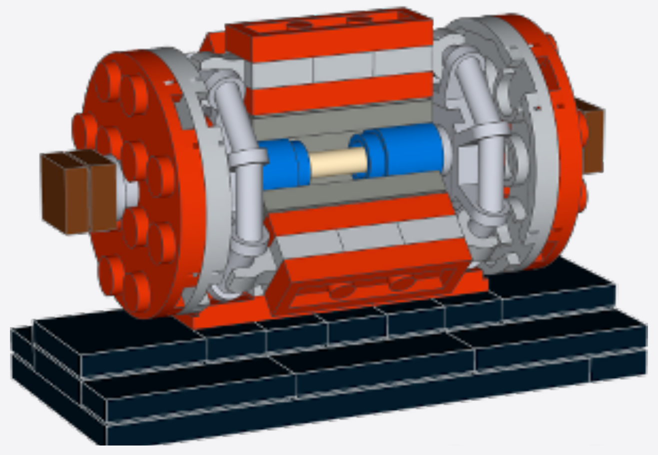




RF, Xiaoran Zhao - 2212.11900

VIRTUAL* PRODUCTION

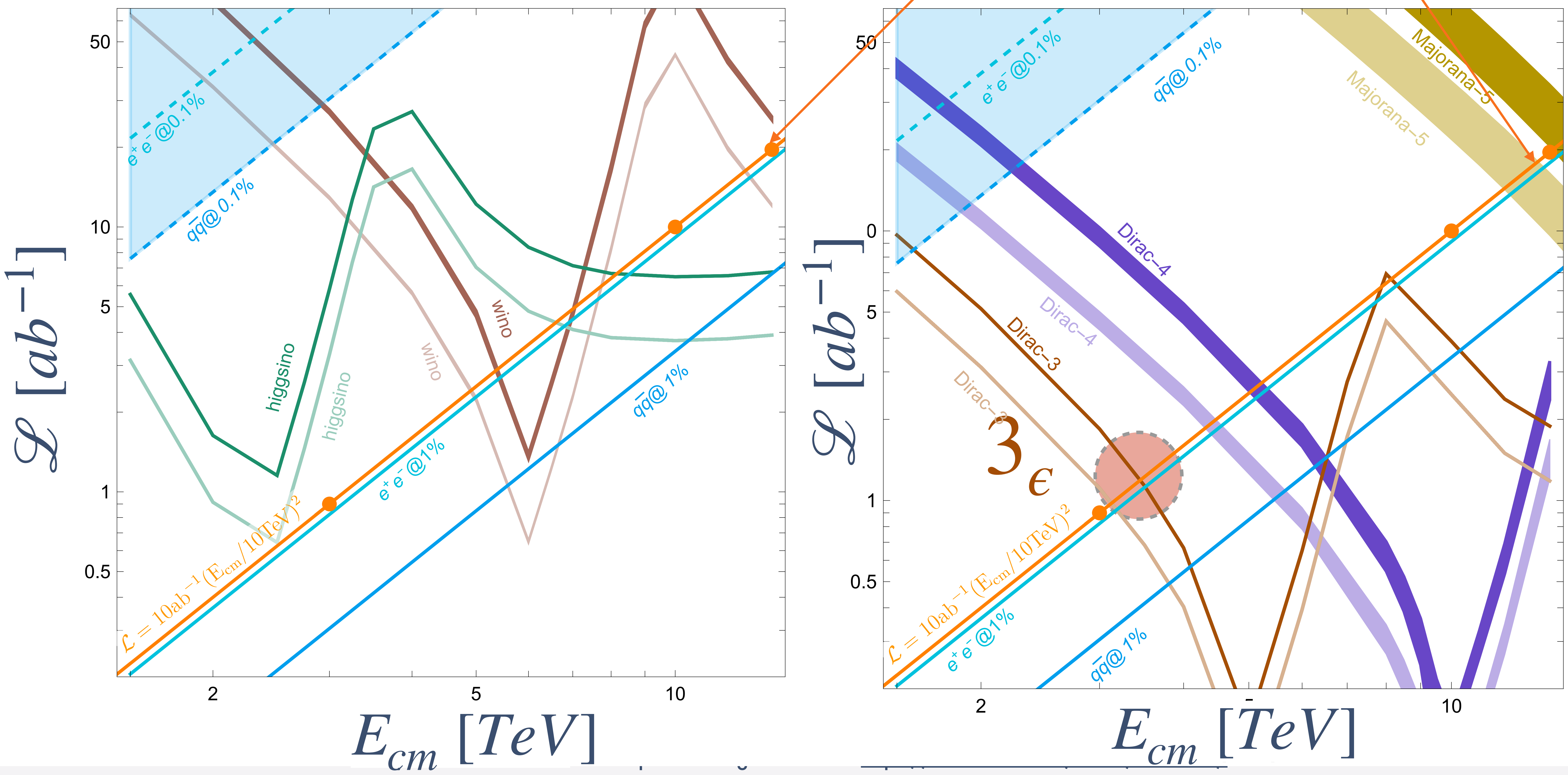
$$\mu^+\mu^- \to f\bar{f}, Zh, W^+W^-, Wff'$$



2040s

up to 10+ TeV

$\mathcal{L} = 10\,\mathrm{ab}^{-1} \cdot (E_{com}/10\,\mathrm{TeV})^2$



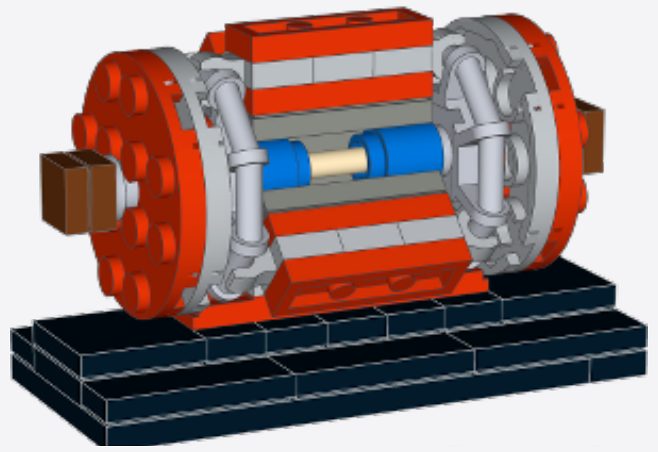
$(\mathbf{3}, \epsilon)_{Dirac}$

$\ell^+\ell^-$ 3 TeV 1 ab^{-1}

RF, Xiaoran Zhao - 2212.11900

VIRTUAL* PRODUCTION

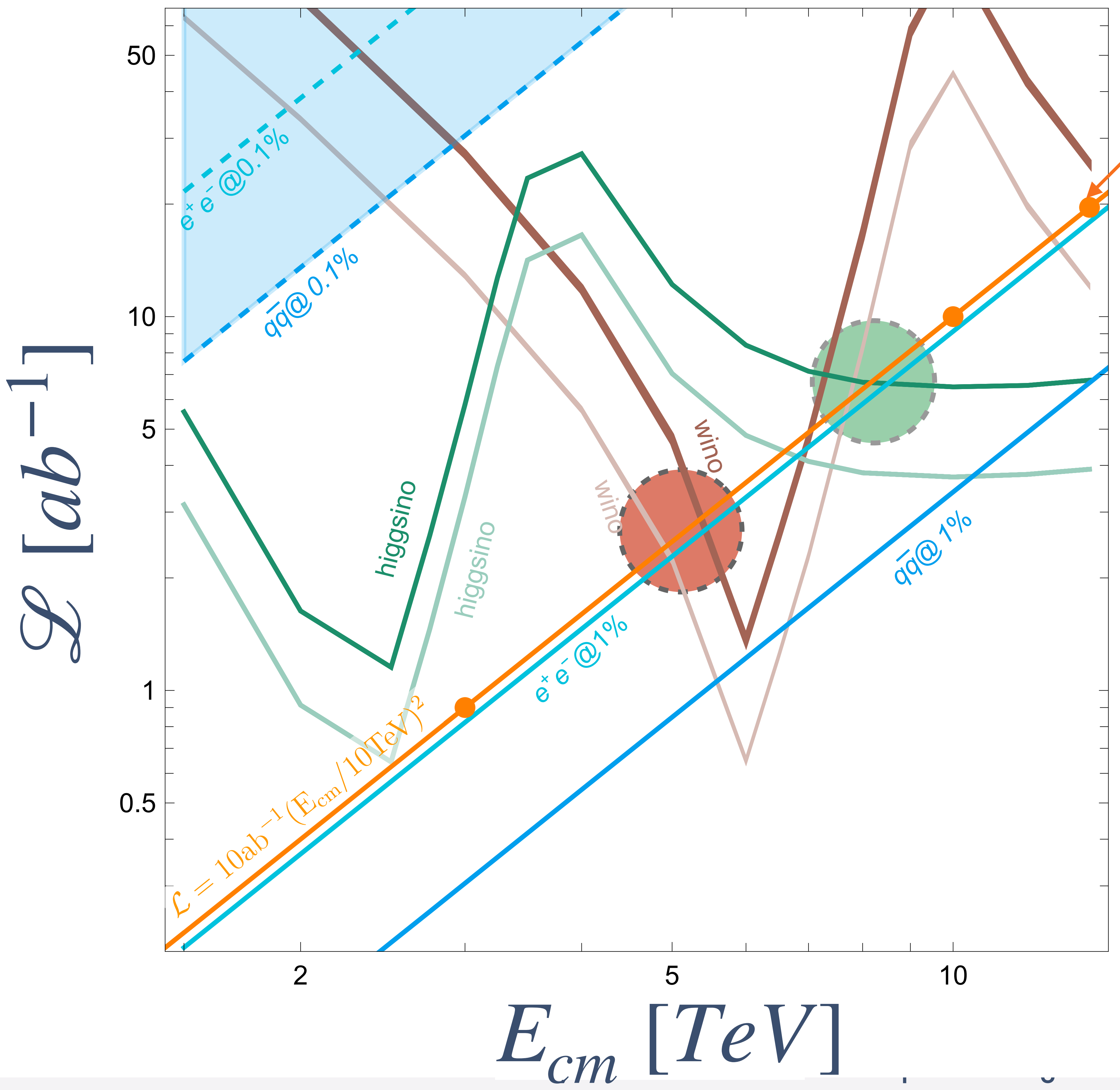
$$\mu^+\mu^- \to f\bar{f}, Zh, W^+W^-, Wff'$$

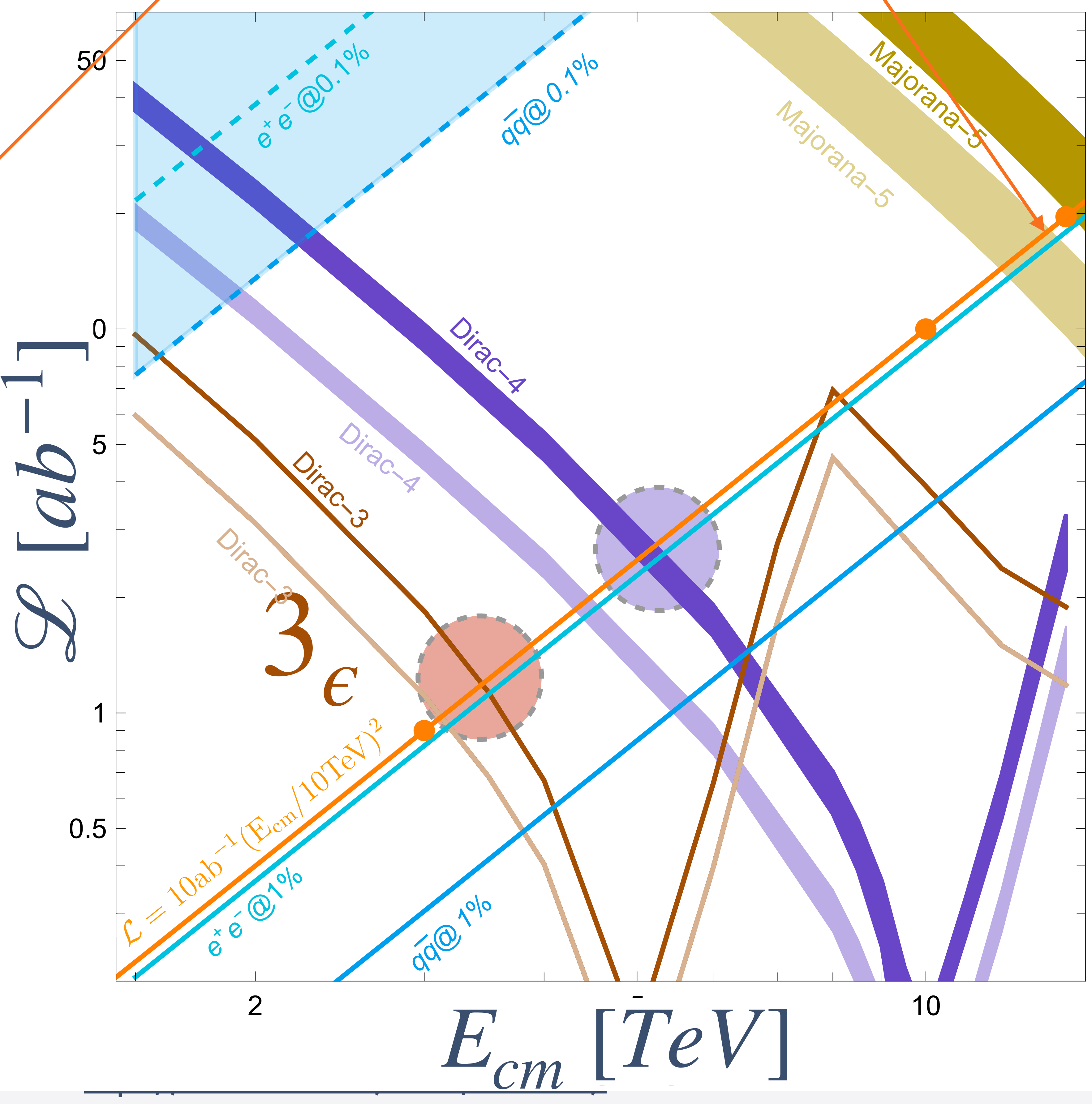


2040s

up to 10+ TeV

$$\mathscr{L} = 10\,\mathrm{ab}^{-1} \cdot (E_{com}/10\,\mathrm{TeV})^2$$





$\left(4, \frac{1}{2}\right)_{Dirac}$ — $\ell^+\ell^-$ 10 TeV 10 ab^{-1}

$(3,0)_{Majorana}$

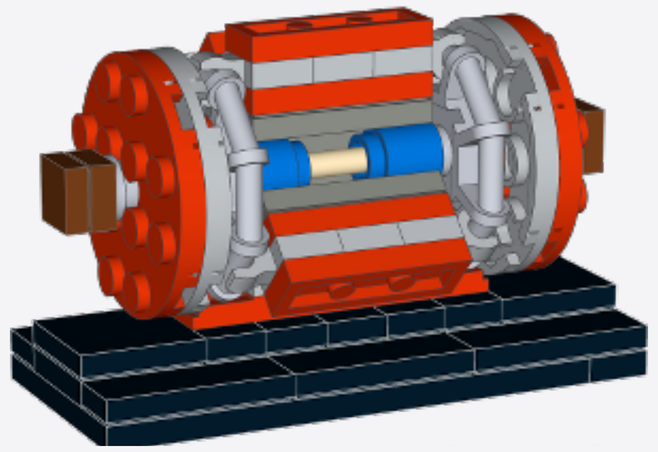
$(3, \epsilon)_{Dirac}$ — $\ell^+\ell^-$ 3 TeV 1 ab^{-1}

$\left(2, \frac{1}{2}\right)_{Dirac}$

RF, Xiaoran Zhao - 2212.11900

VIRTUAL* PRODUCTION

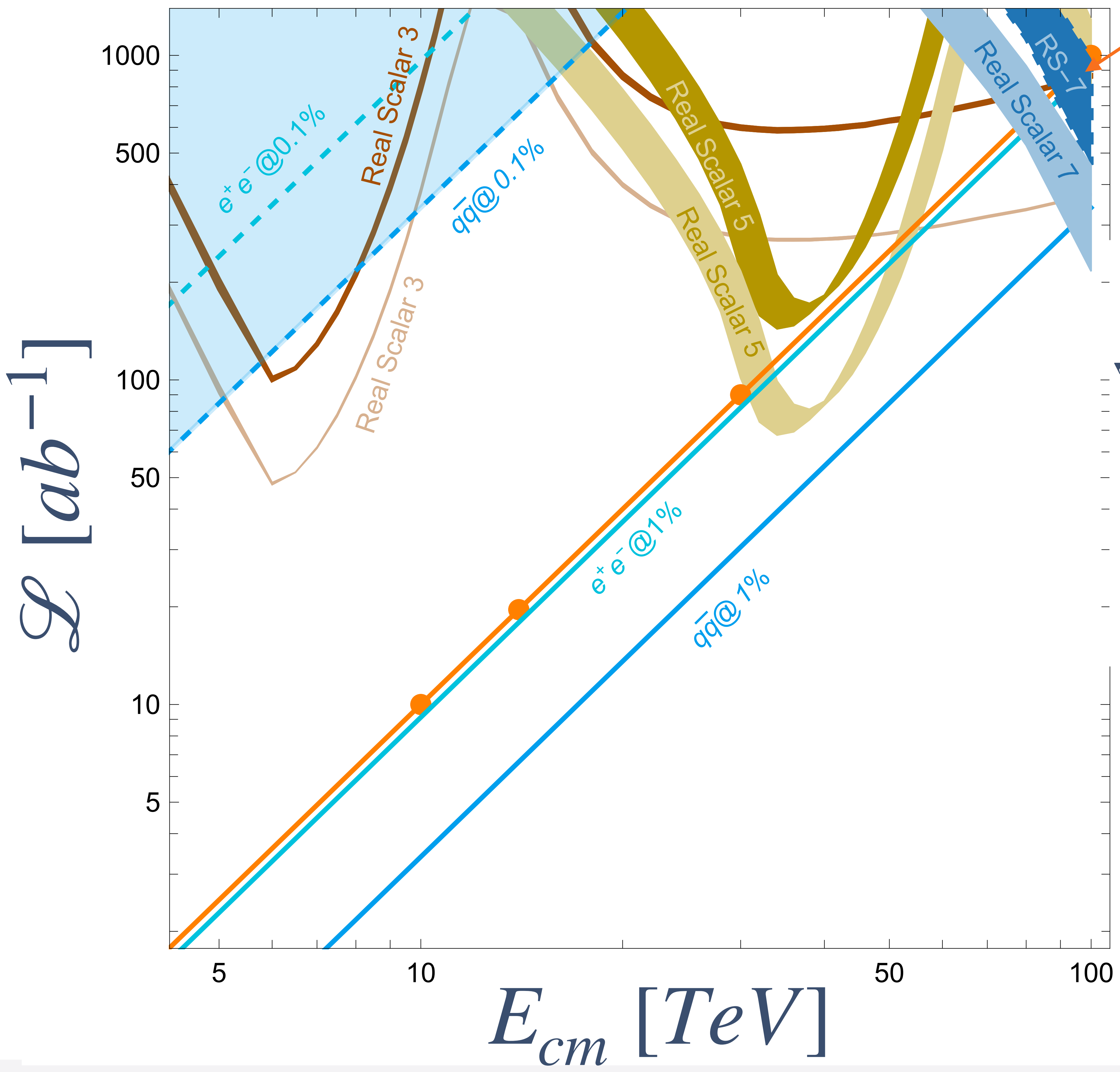
$\mu^+\mu^- \to f\bar{f}, Zh, W^+W^-, Wff'$

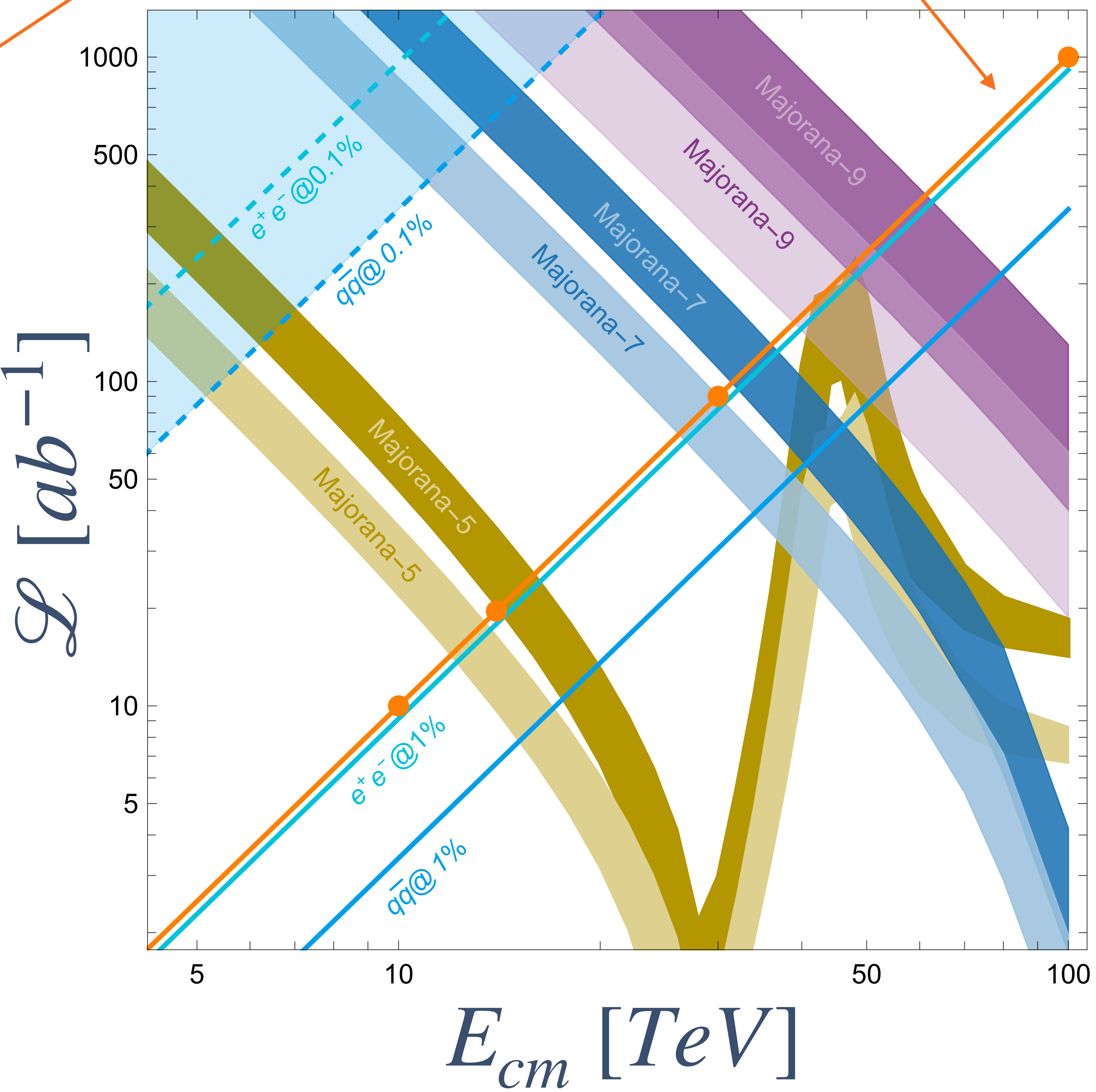


2040s

up to 10+ TeV

$\mathscr{L} = 10\,\mathrm{ab}^{-1} \cdot (E_{com}/10\,\mathrm{TeV})^2$





$\left(\mathbf{4}, \frac{1}{2}\right)_{Dirac}$ $\quad \ell^+\ell^-$ 10 TeV 10 ab^{-1}

$(\mathbf{3}, 0)_{Majorana}$

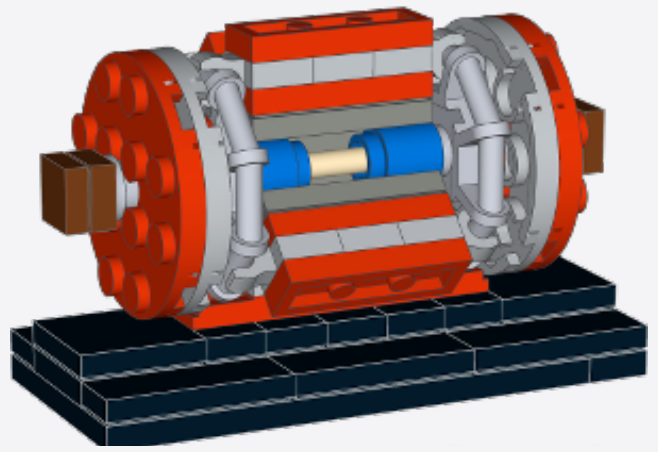
$(\mathbf{3}, \epsilon)_{Dirac}$ $\quad \ell^+\ell^-$ 3 TeV 1 ab^{-1}

$\left(\mathbf{2}, \frac{1}{2}\right)_{Dirac}$

RF, Xiaoran Zhao - 2212.11900

VIRTUAL* PRODUCTION

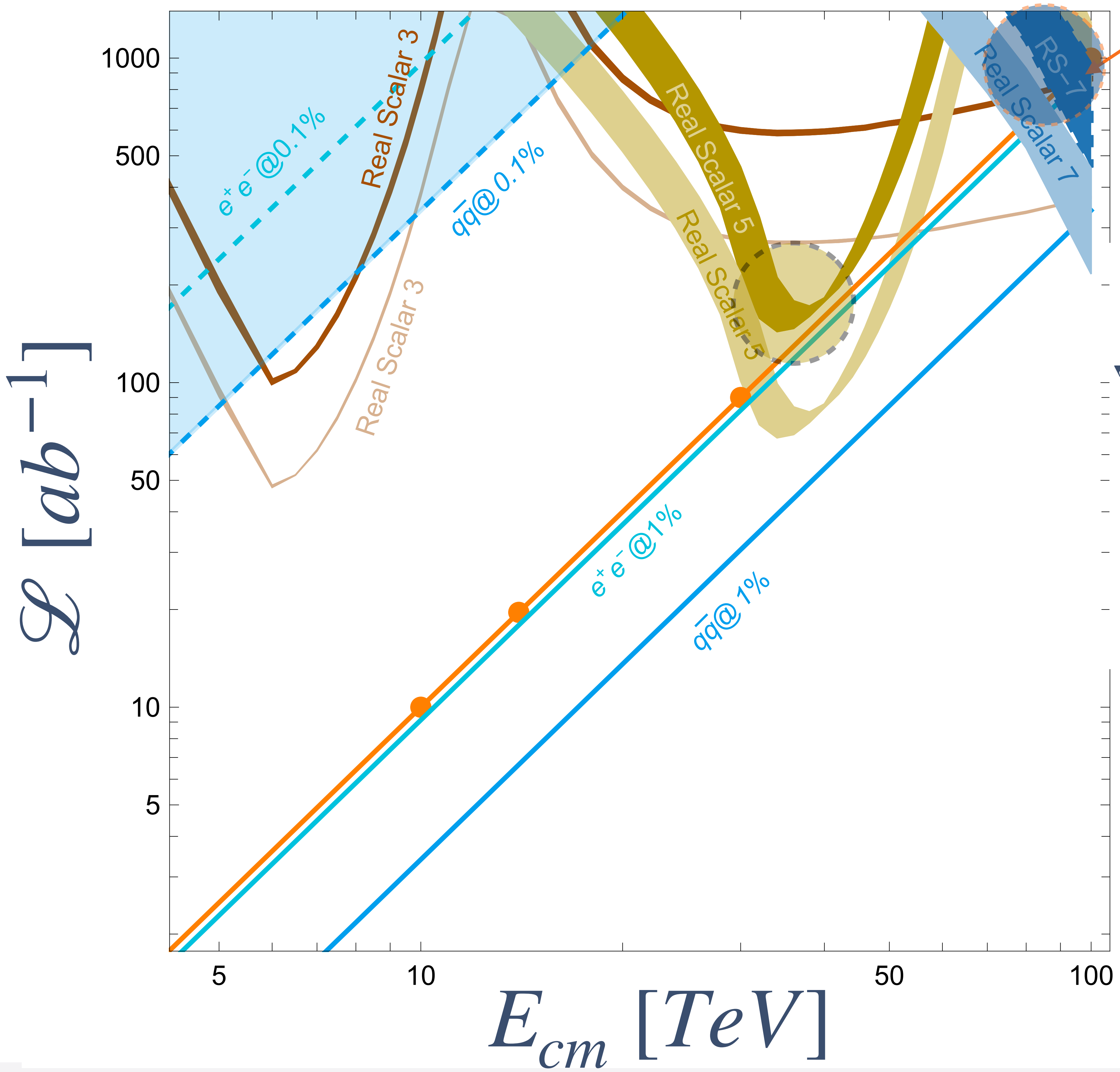
$\mu^+\mu^- \to f\bar{f}, Zh, W^+W^-, Wff'$

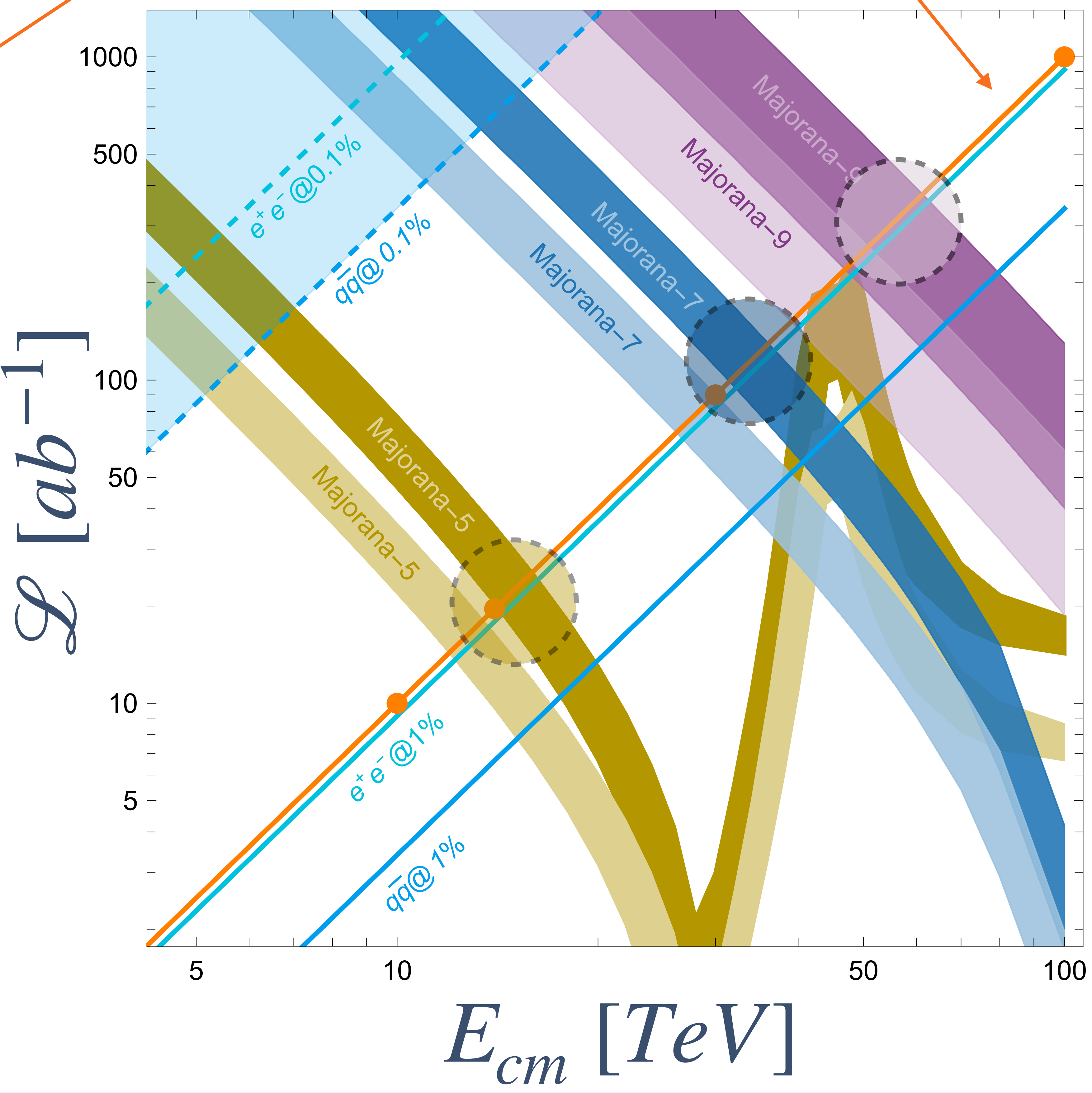


2040s

up to 10+ TeV

$\mathscr{L} = 10\,\mathrm{ab}^{-1} \cdot (E_{com}/10\,\mathrm{TeV})^2$





$(\mathbf{7},0)_{Majorana}$

$(\mathbf{7},\epsilon)_{Dirac}$

$(\mathbf{5},0)_{Majorana}$

$(\mathbf{5},\epsilon)_{Dirac}$

$\left(\mathbf{4},\frac{1}{2}\right)_{Dirac}$

$(\mathbf{3},0)_{Majorana}$

$(\mathbf{3},\epsilon)_{Dirac}$

$\left(\mathbf{2},\frac{1}{2}\right)_{Dirac}$

$\ell^+\ell^-$ 10+ TeV 10+ ab^{-1}

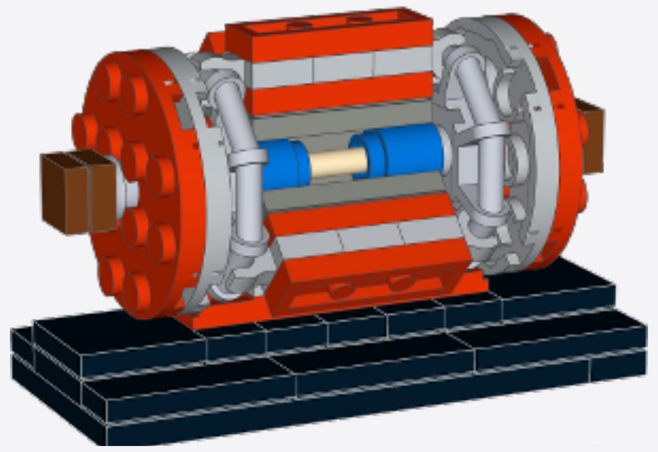
$\ell^+\ell^-$ 10 TeV 10 ab^{-1}

$\ell^+\ell^-$ 3 TeV 1 ab^{-1}

2202.10509, 2212.11900

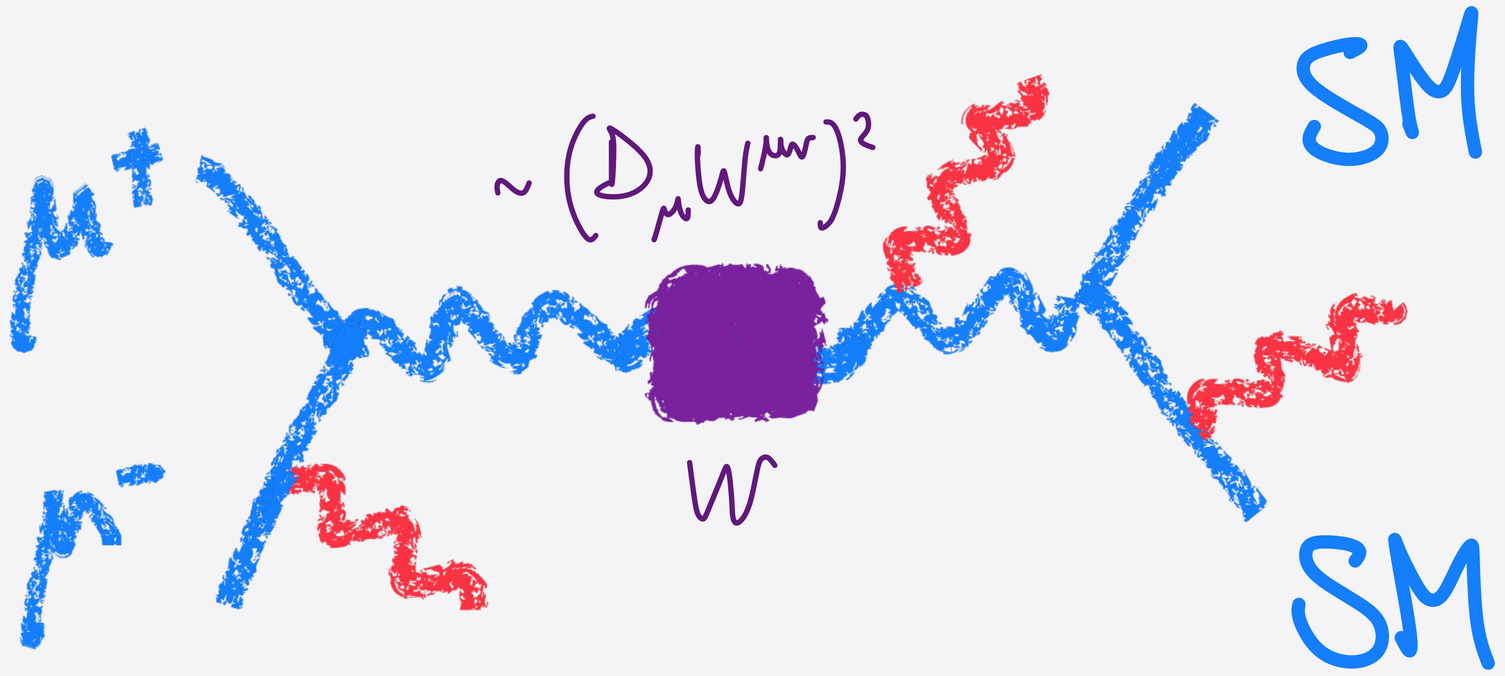
VIRTUAL* PRODUCTION

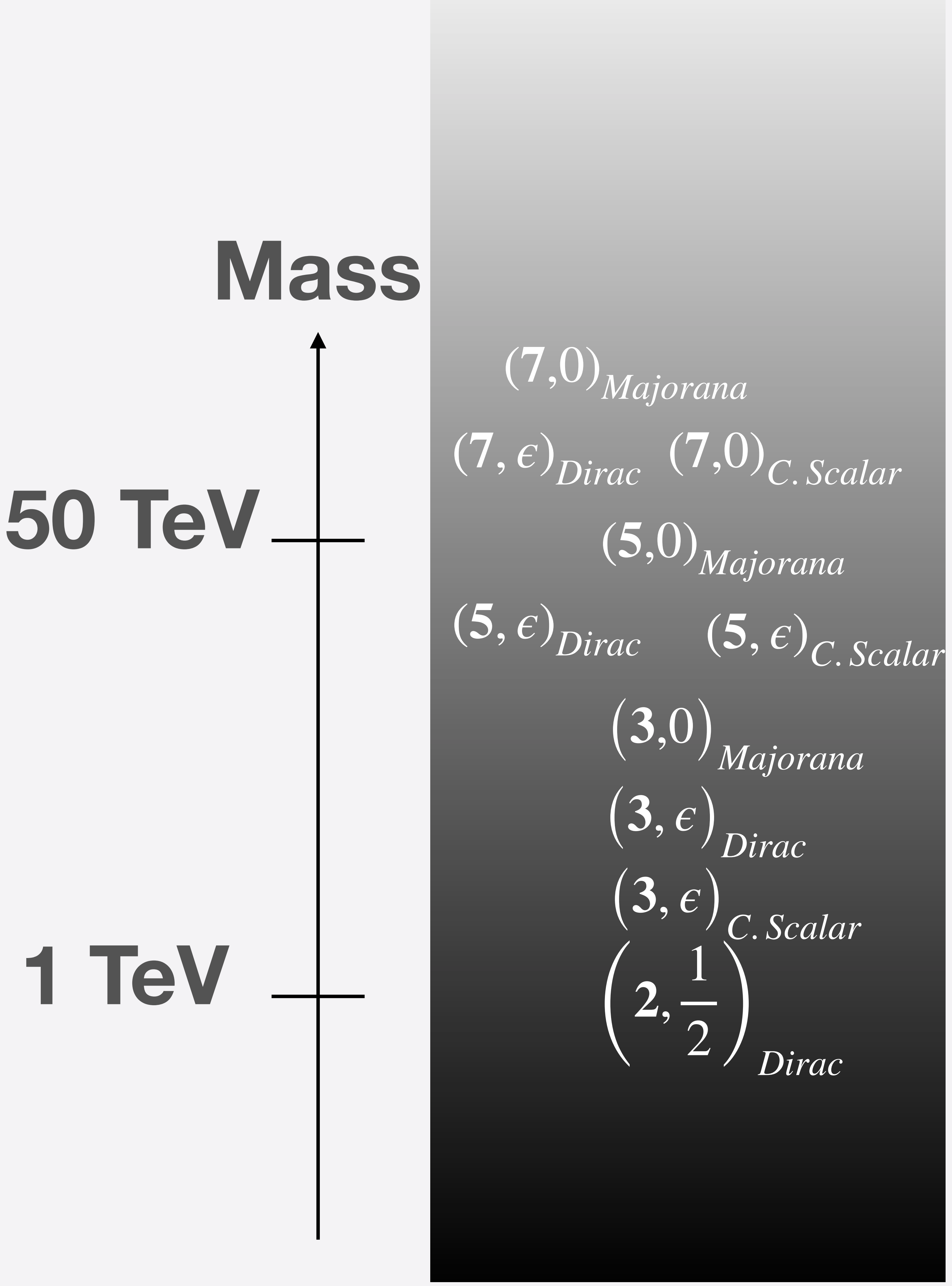
$$\mu^+\mu^- \to f\bar{f}, Zh, W^+W^-, Wff'$$



2040s

up to 10+ TeV



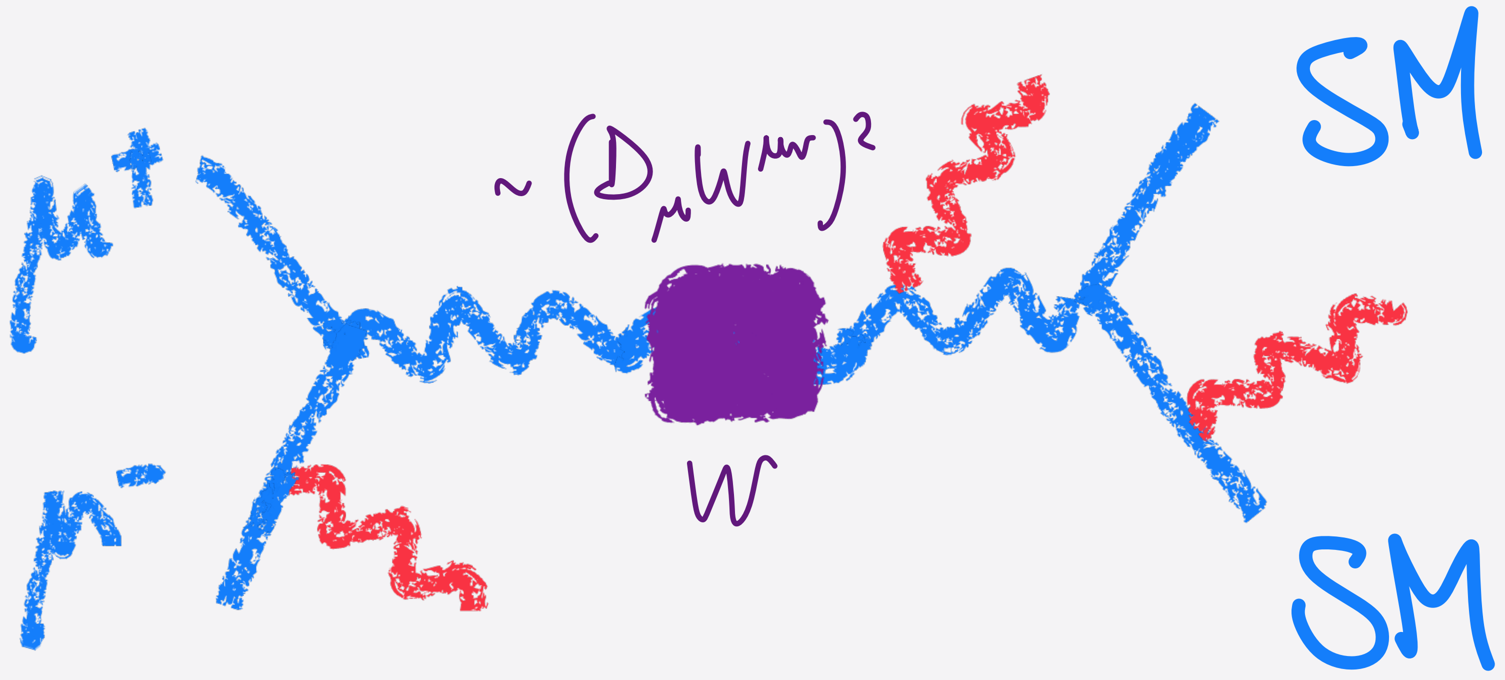


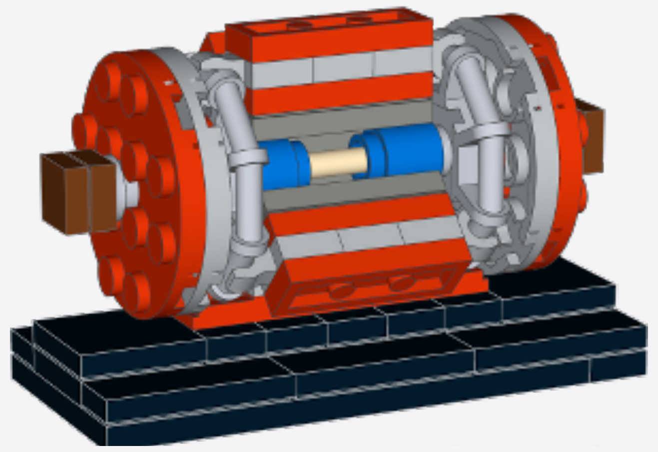
“WIMP” Dark Matter

2202.10509, 2212.11900

VIRTUAL* PRODUCTION

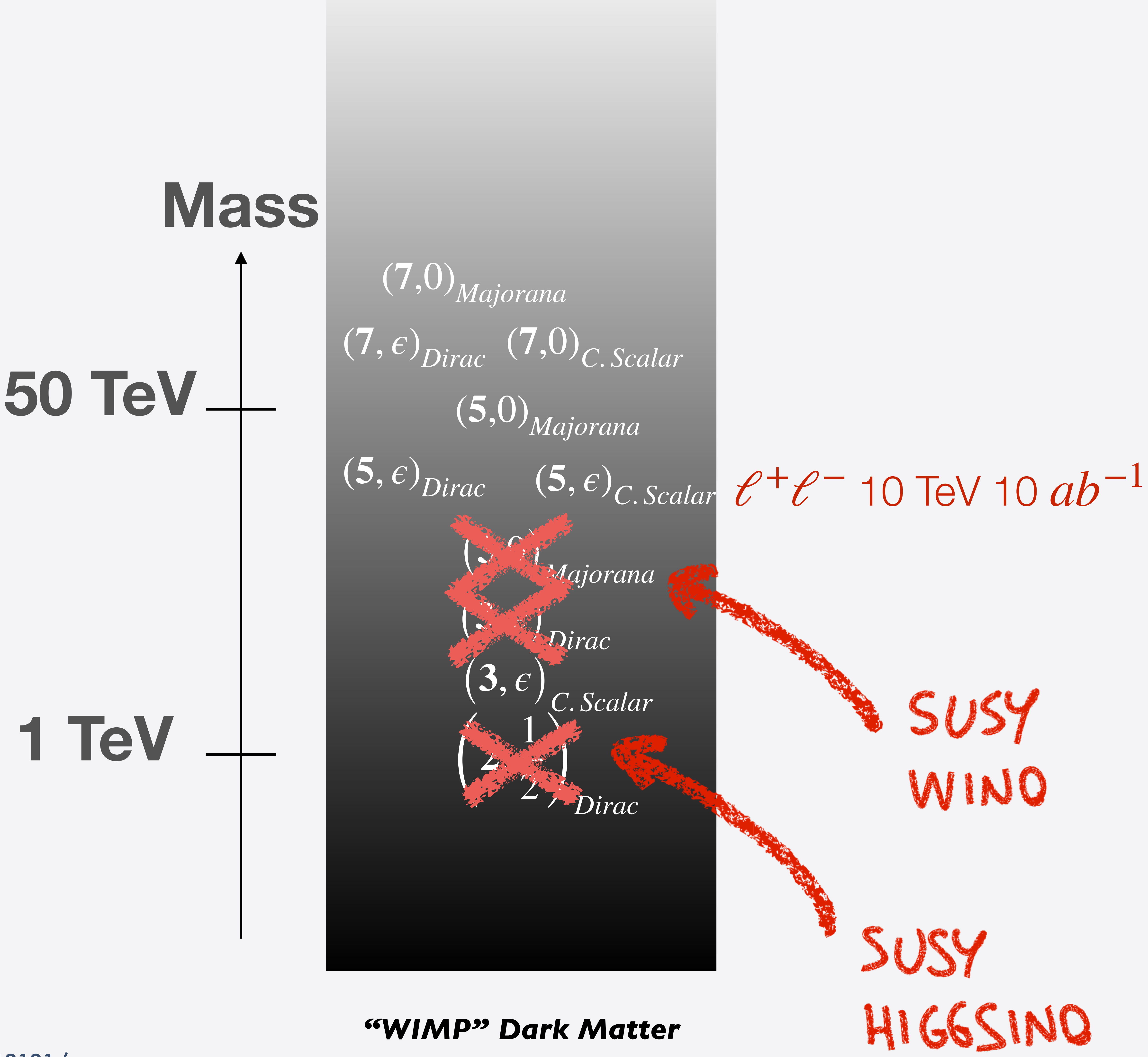
$$\mu^+\mu^- \to f\bar{f}, Zh, W^+W^-, Wff'$$





2040s

up to 10+ TeV

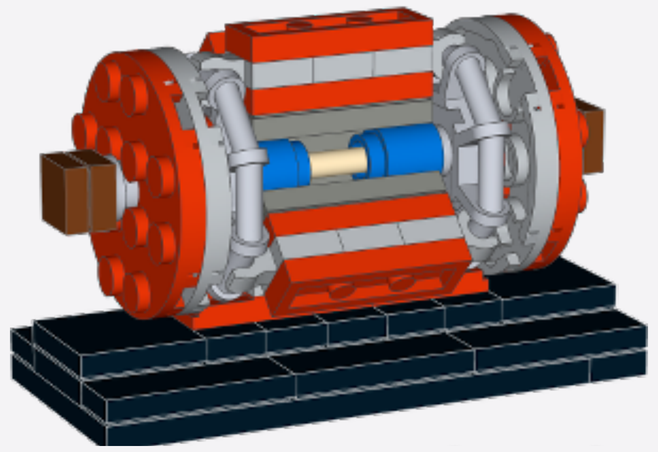


"WIMP" Dark Matter

2202.10509, 2212.11900

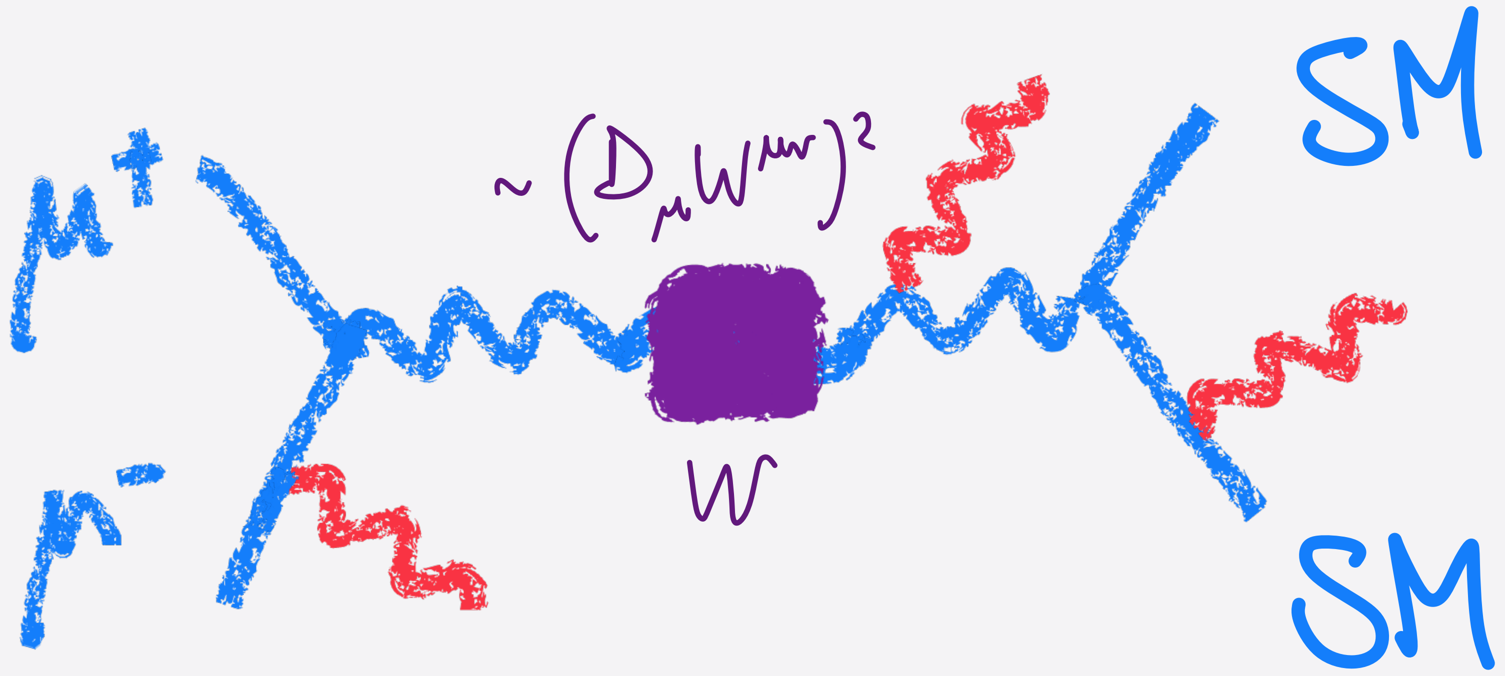
VIRTUAL* PRODUCTION

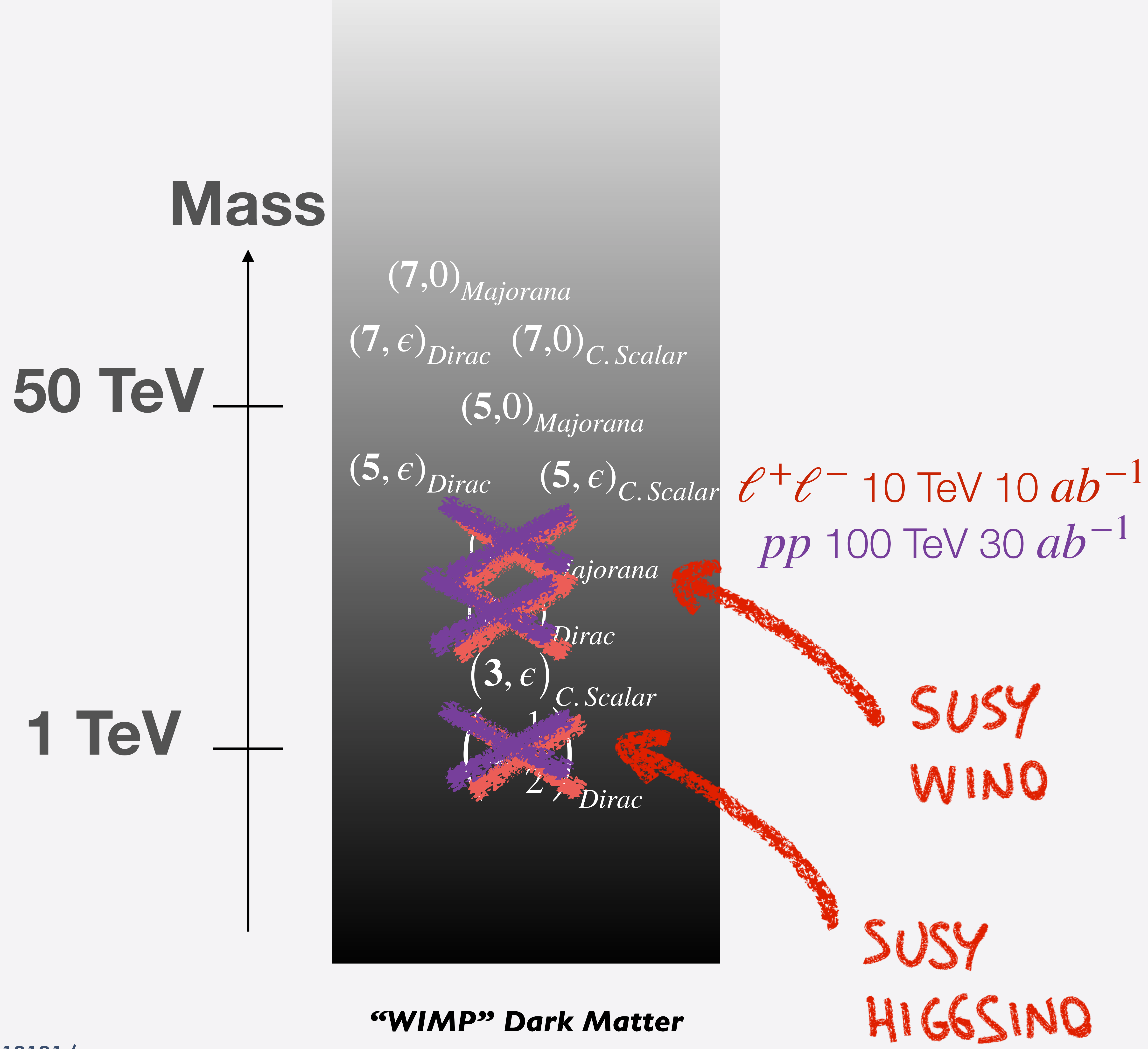
$\mu^+\mu^- \to f\bar{f}, Zh, W^+W^-, Wff'$



2040s

up to 10+ TeV

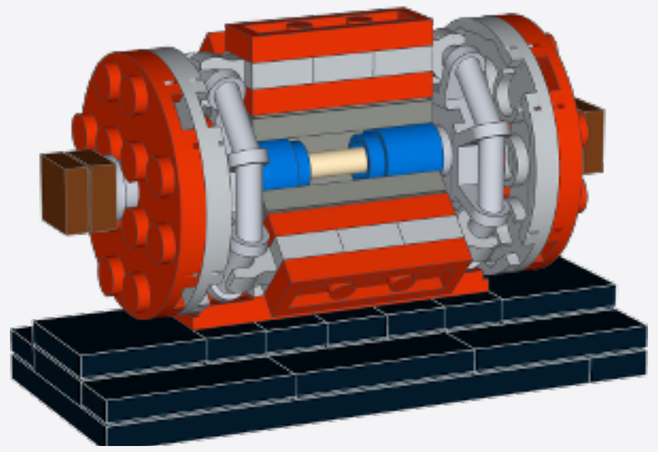




2202.10509, 2212.11900

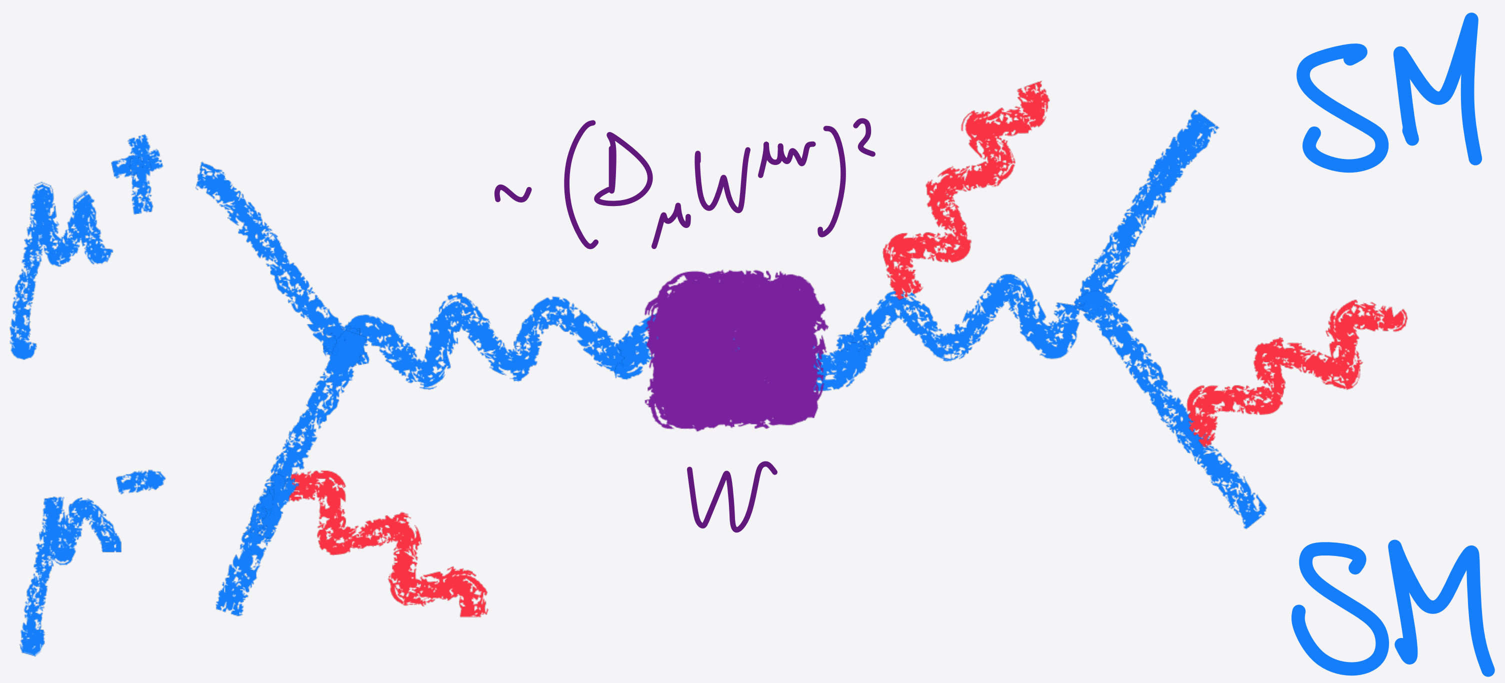
VIRTUAL* PRODUCTION

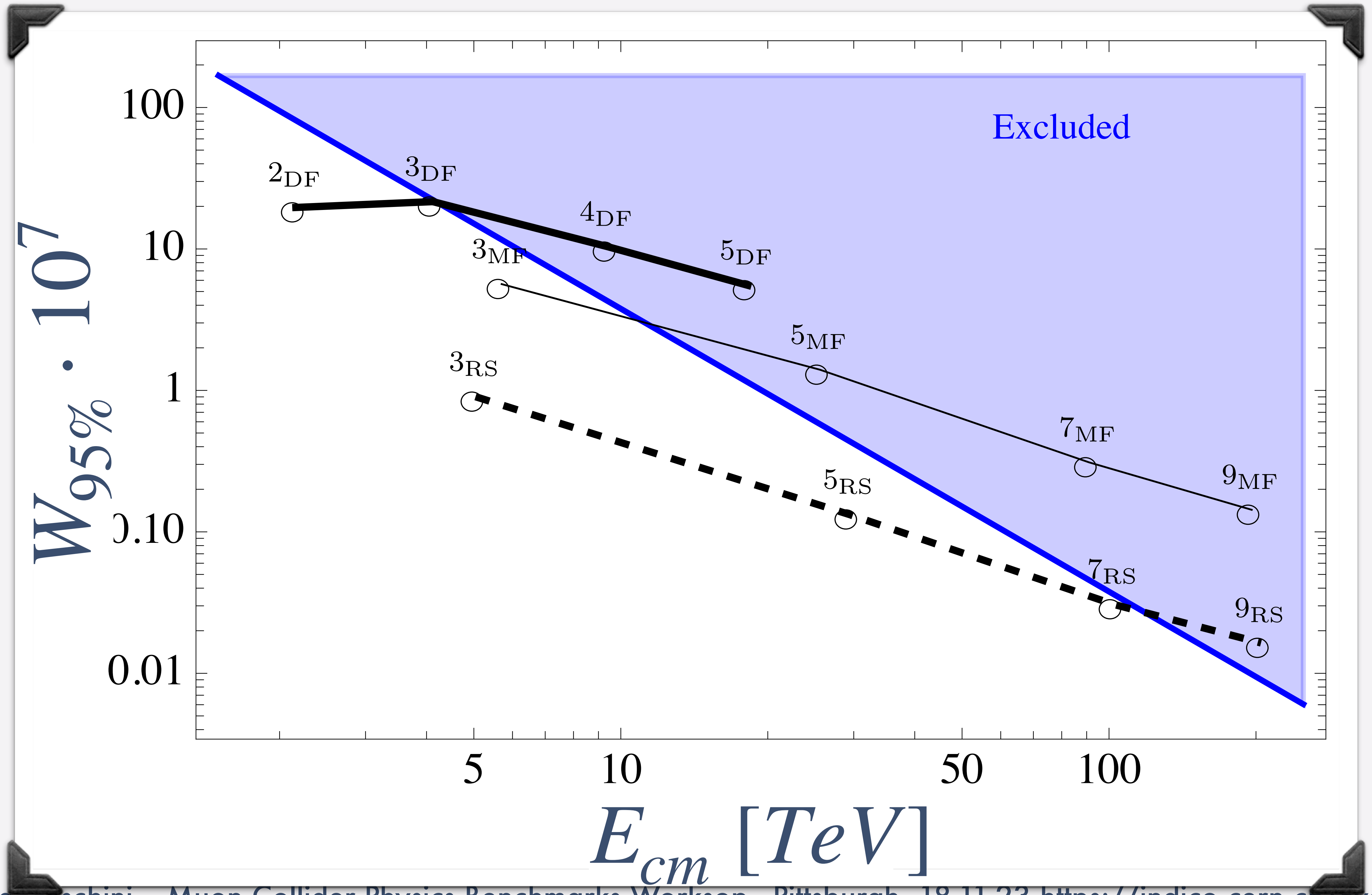
$\mu^+\mu^- \to f\bar{f}, Zh, W^+W^-, Wff'$

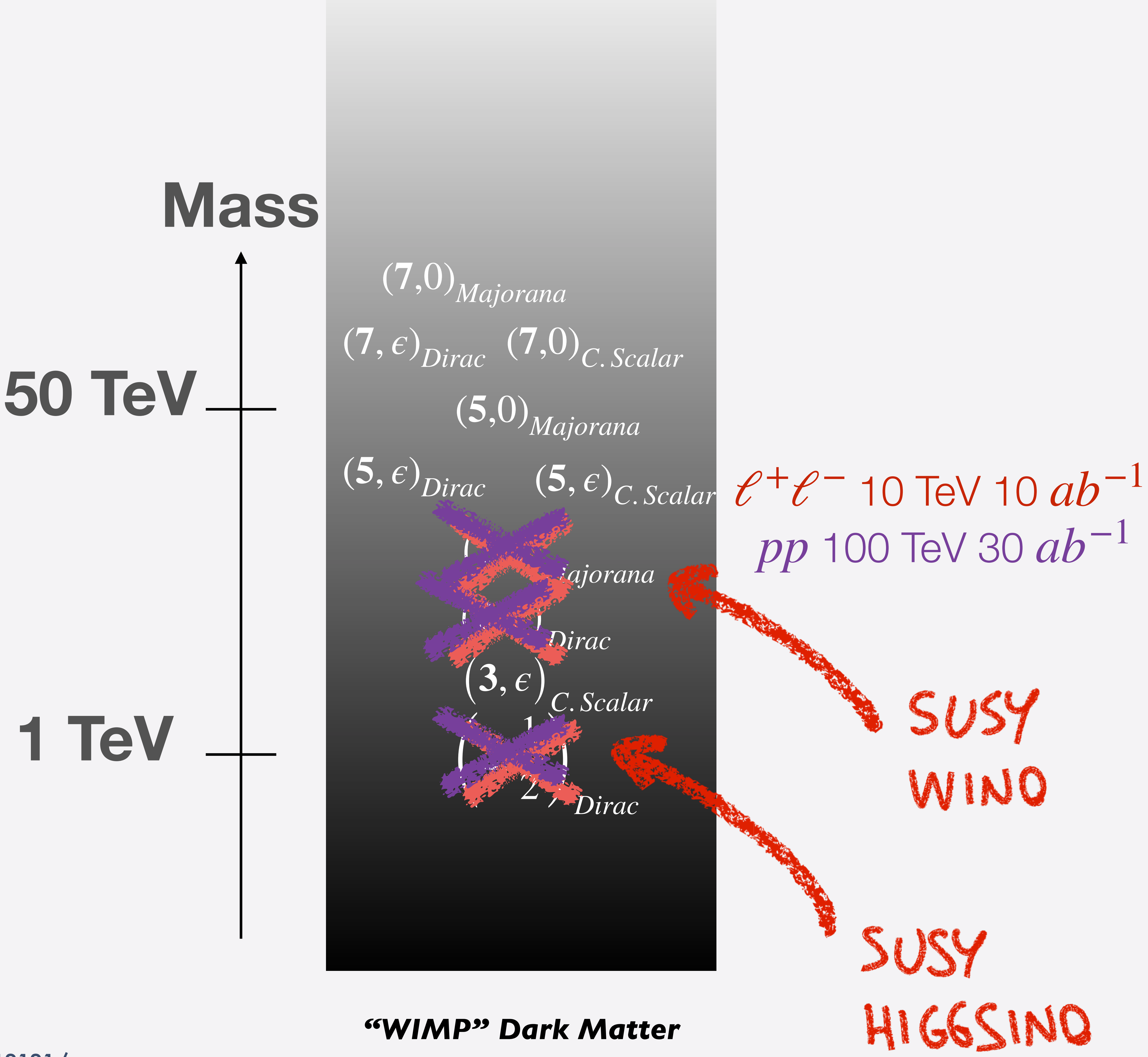


2040s

up to 10+ TeV





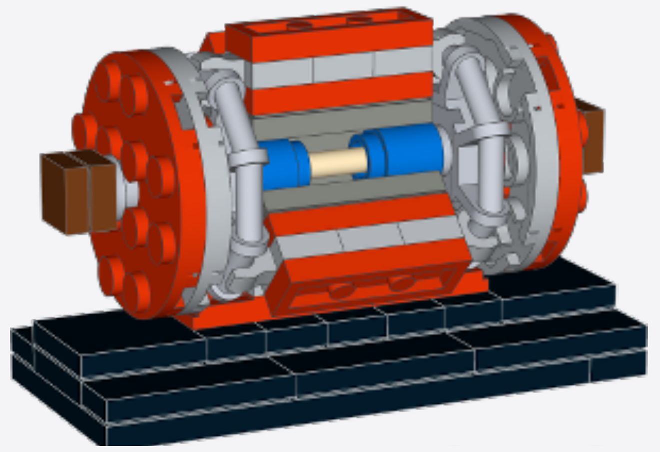


“WIMP” Dark Matter

2202.10509, 2212.11900

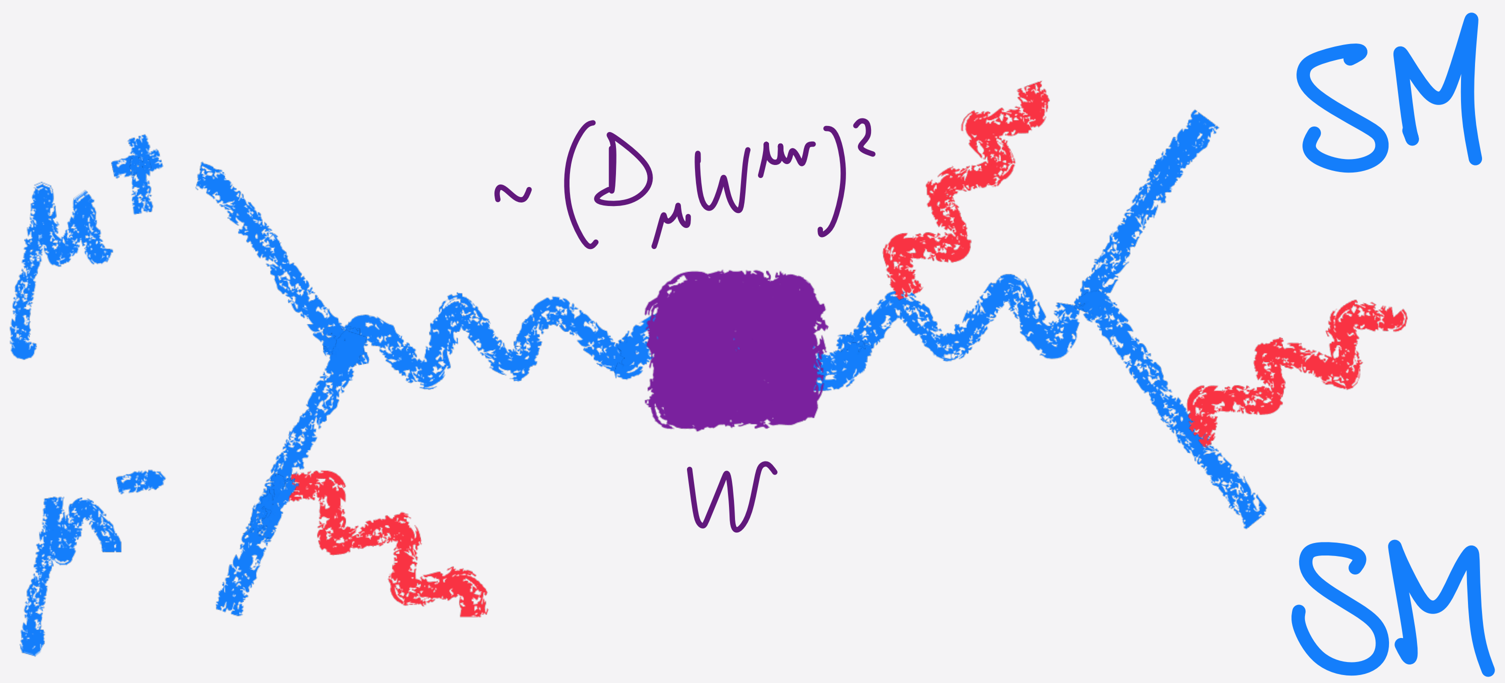
VIRTUAL* PRODUCTION

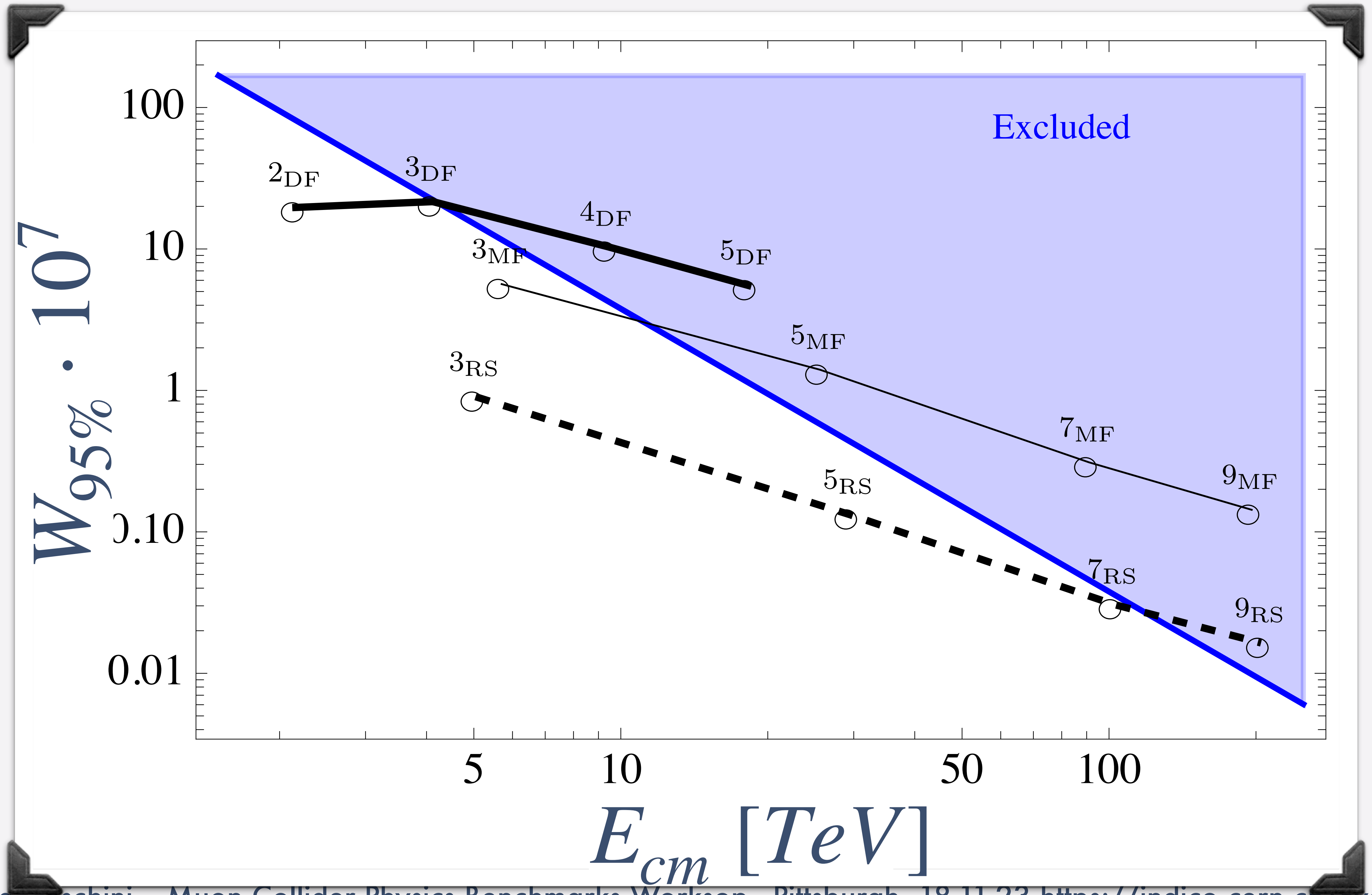
$\mu^+\mu^- \to f\bar{f}, Zh, W^+W^-, Wff'$

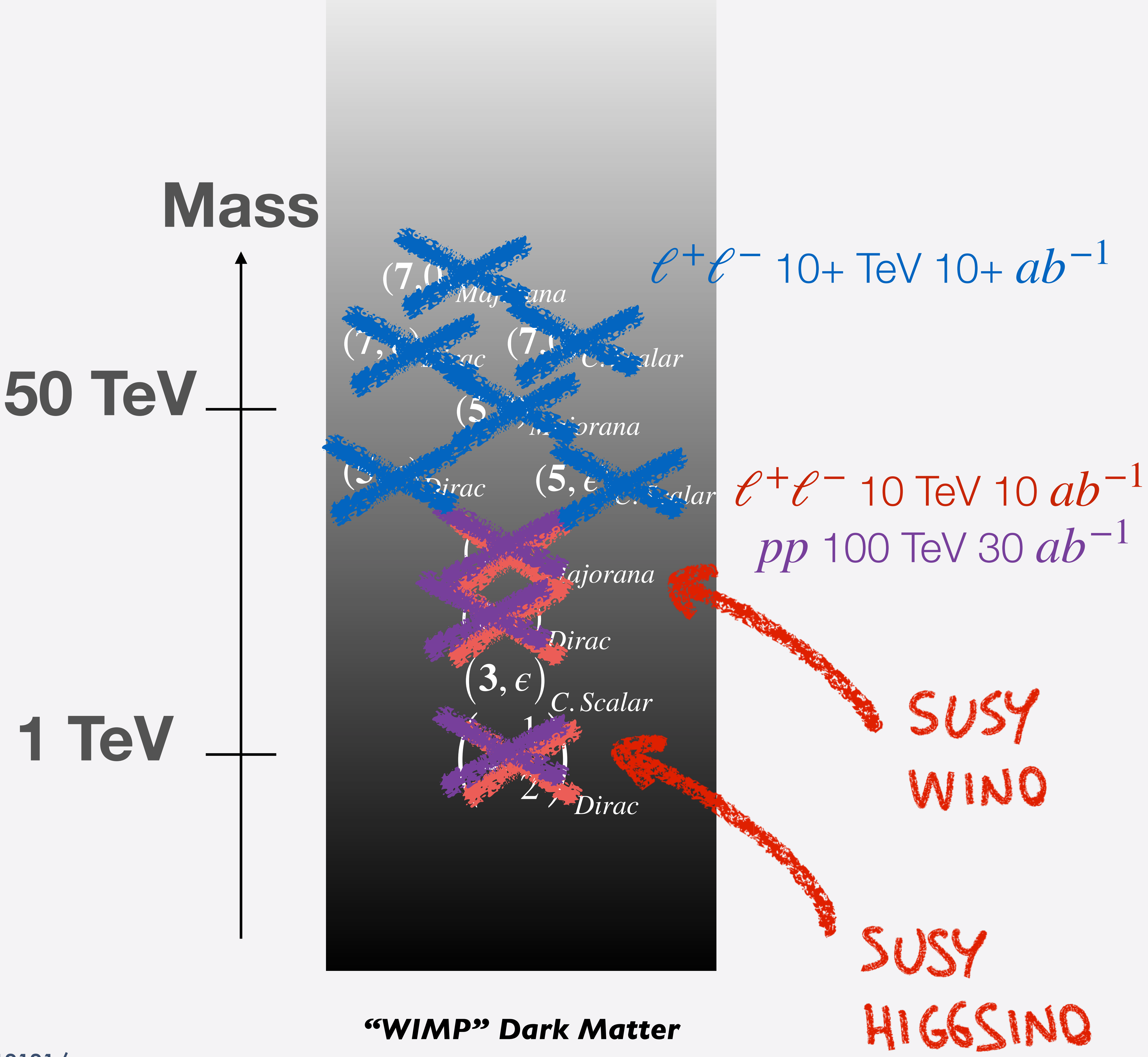


2040s

up to 10+ TeV





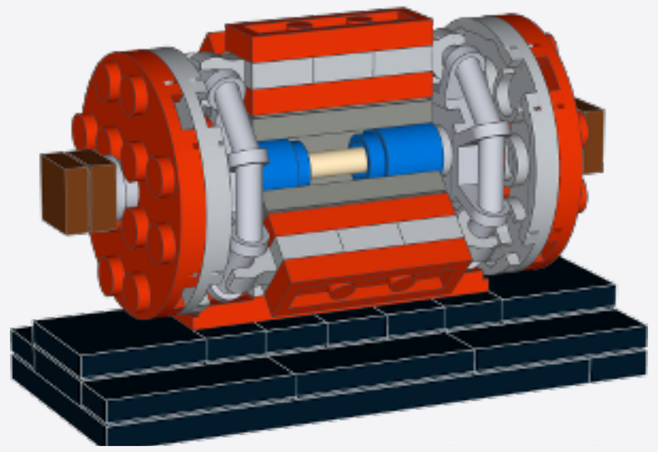


"WIMP" Dark Matter

2202.10509, 2212.11900

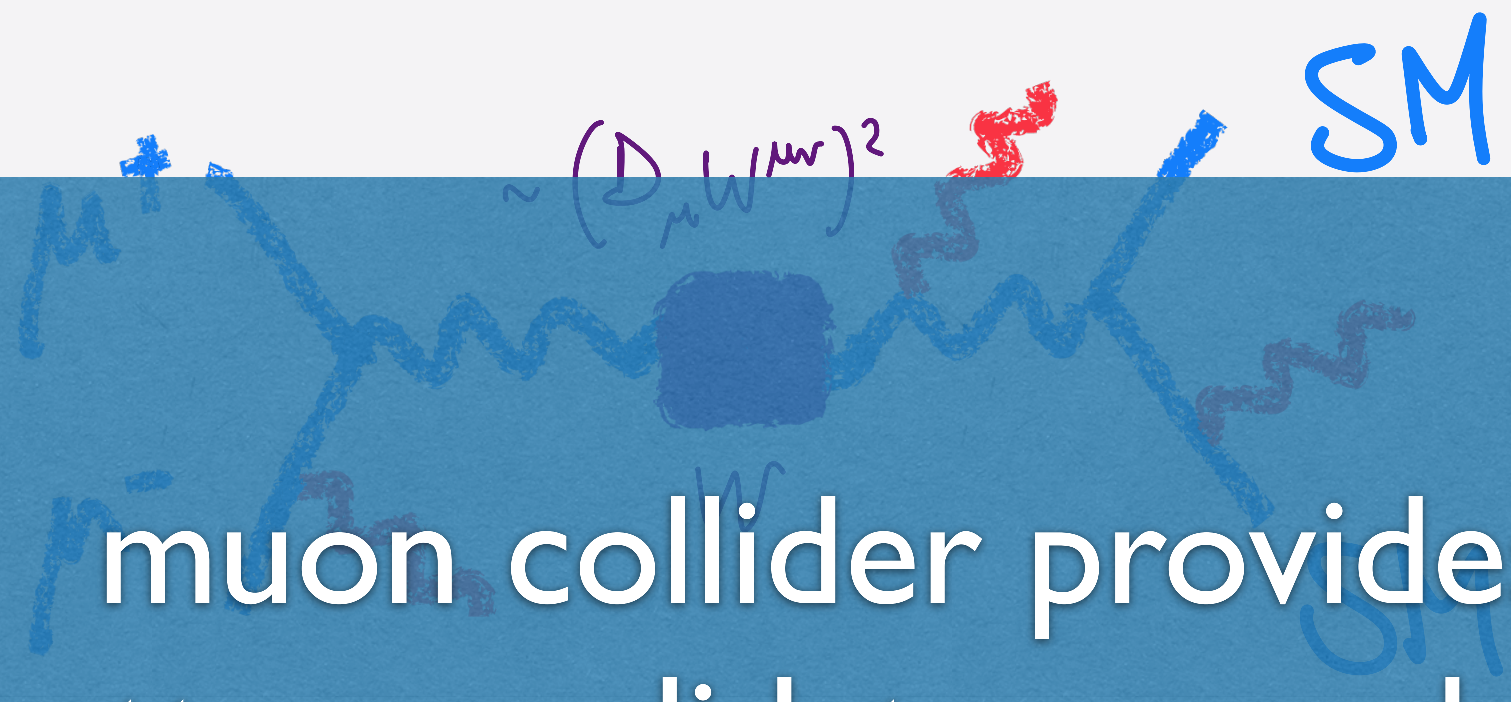
VIRTUAL* PRODUCTION

$\mu^+\mu^- \to f\bar{f}, Zh, W^+W^-, Wff'$



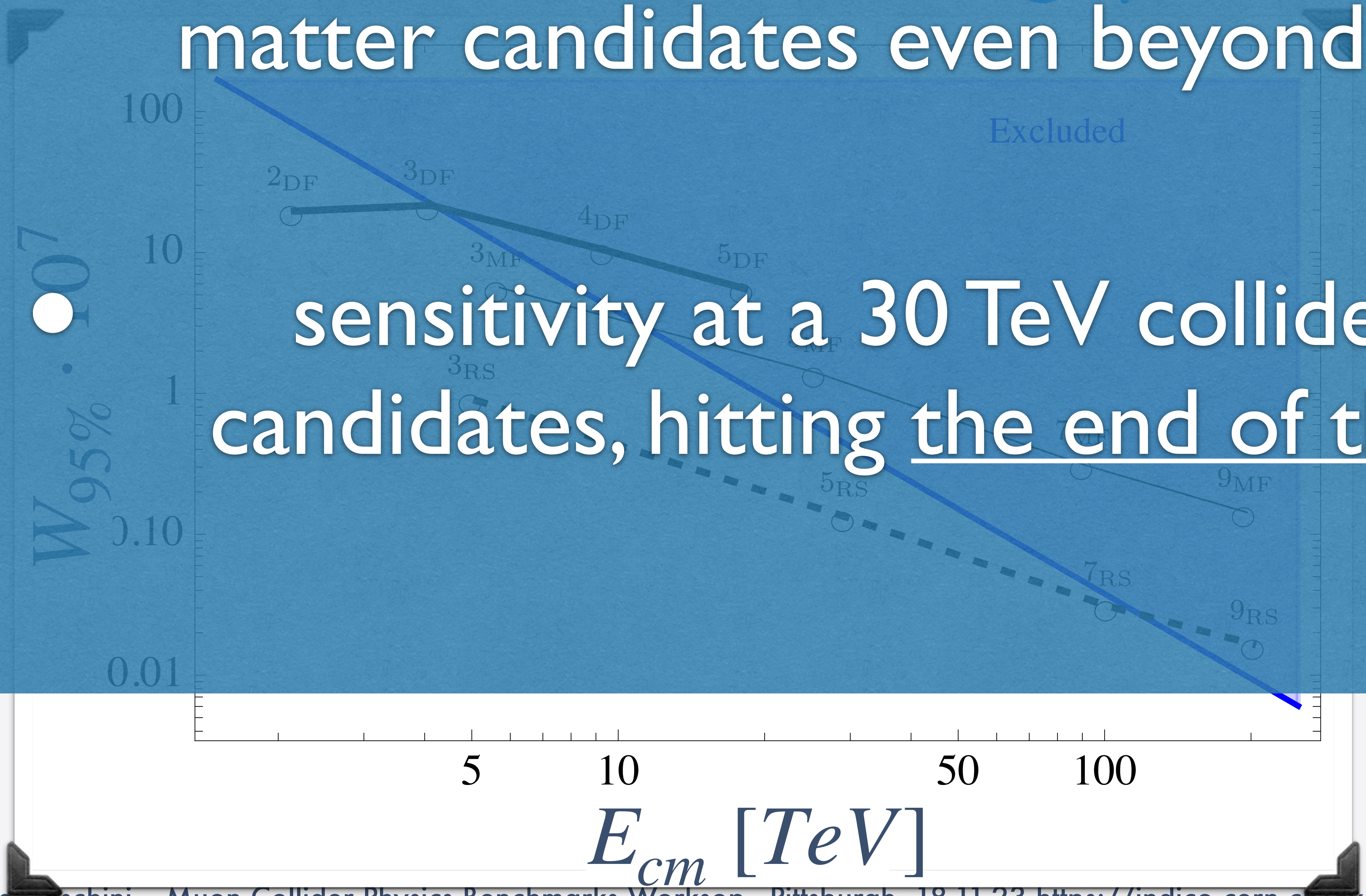
2040s

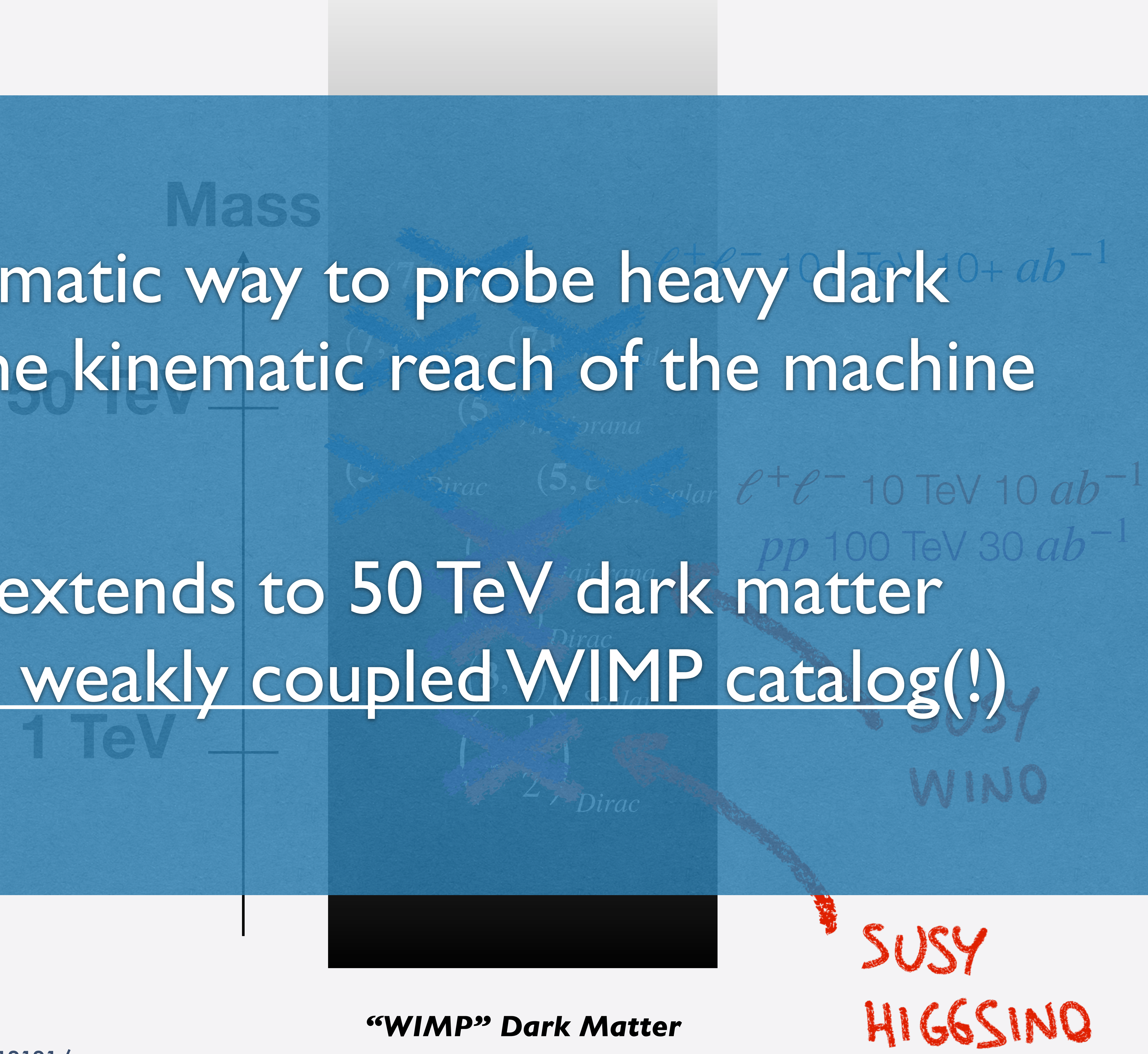
up to 10+ TeV



- muon collider provides a systematic way to probe heavy dark matter candidates even beyond the kinematic reach of the machine

- sensitivity at a 30 TeV collider extends to 50 TeV dark matter candidates, hitting the end of the weakly coupled WIMP catalog(!)

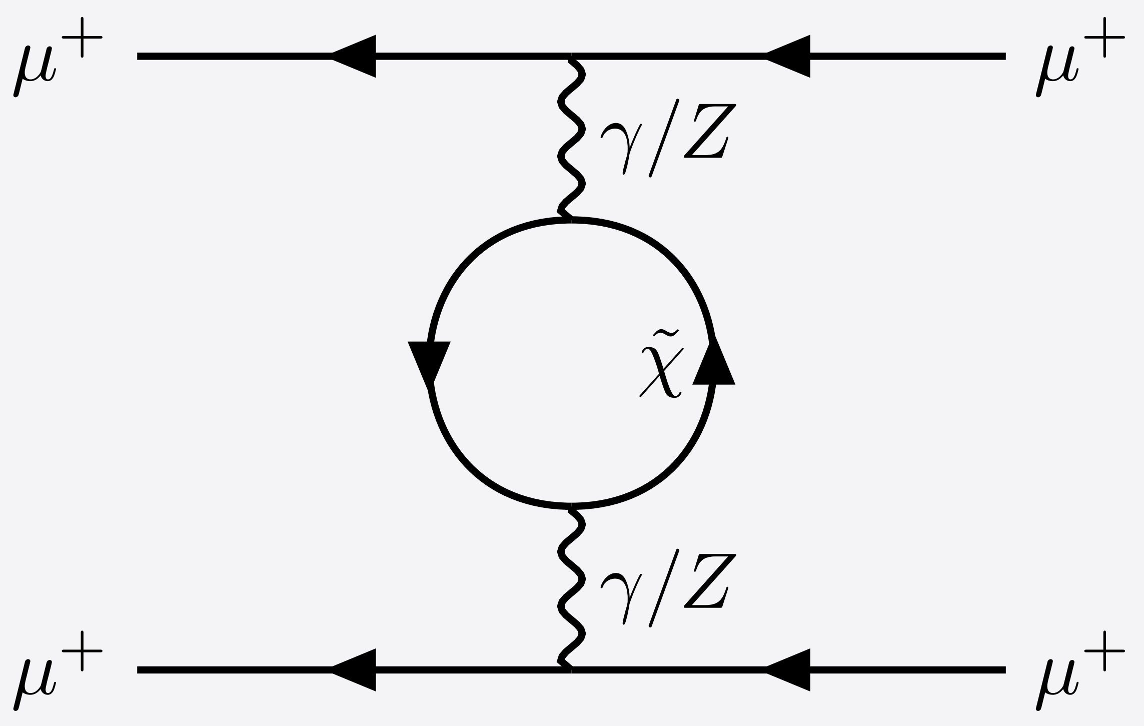


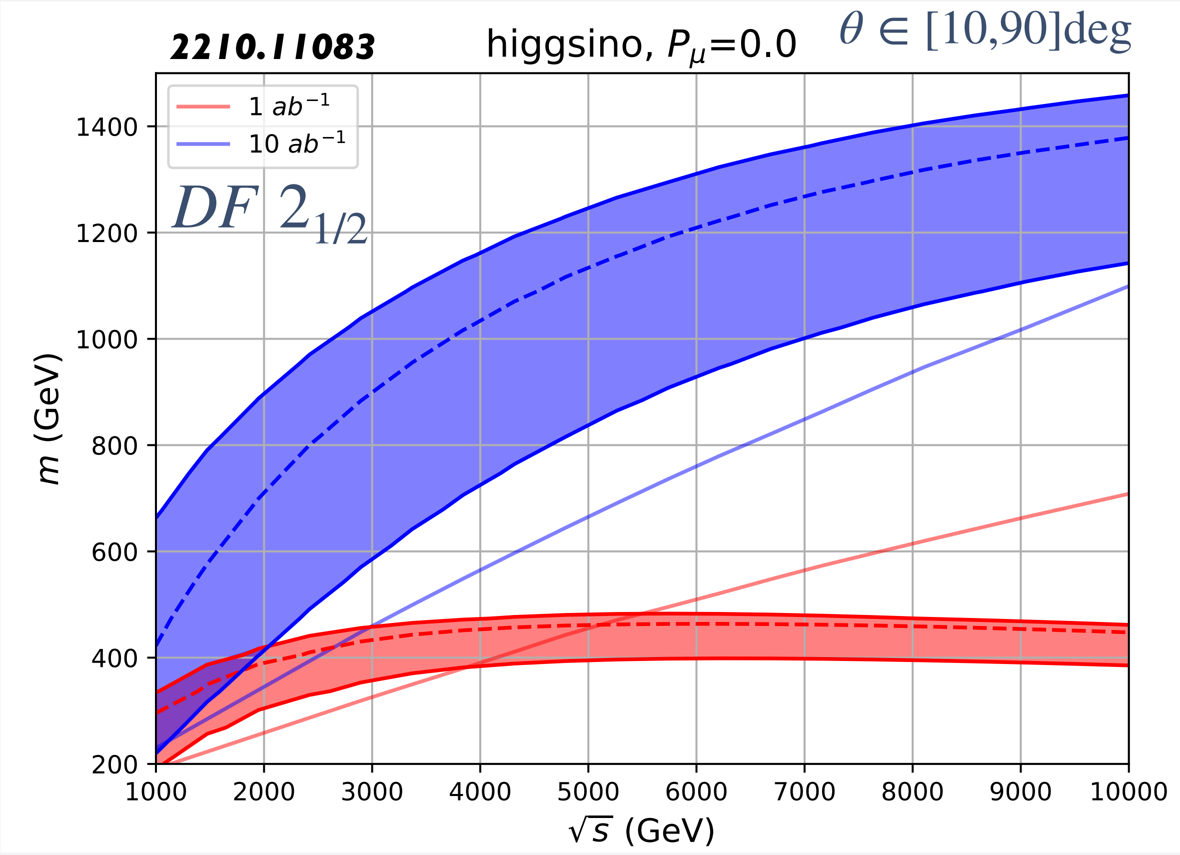


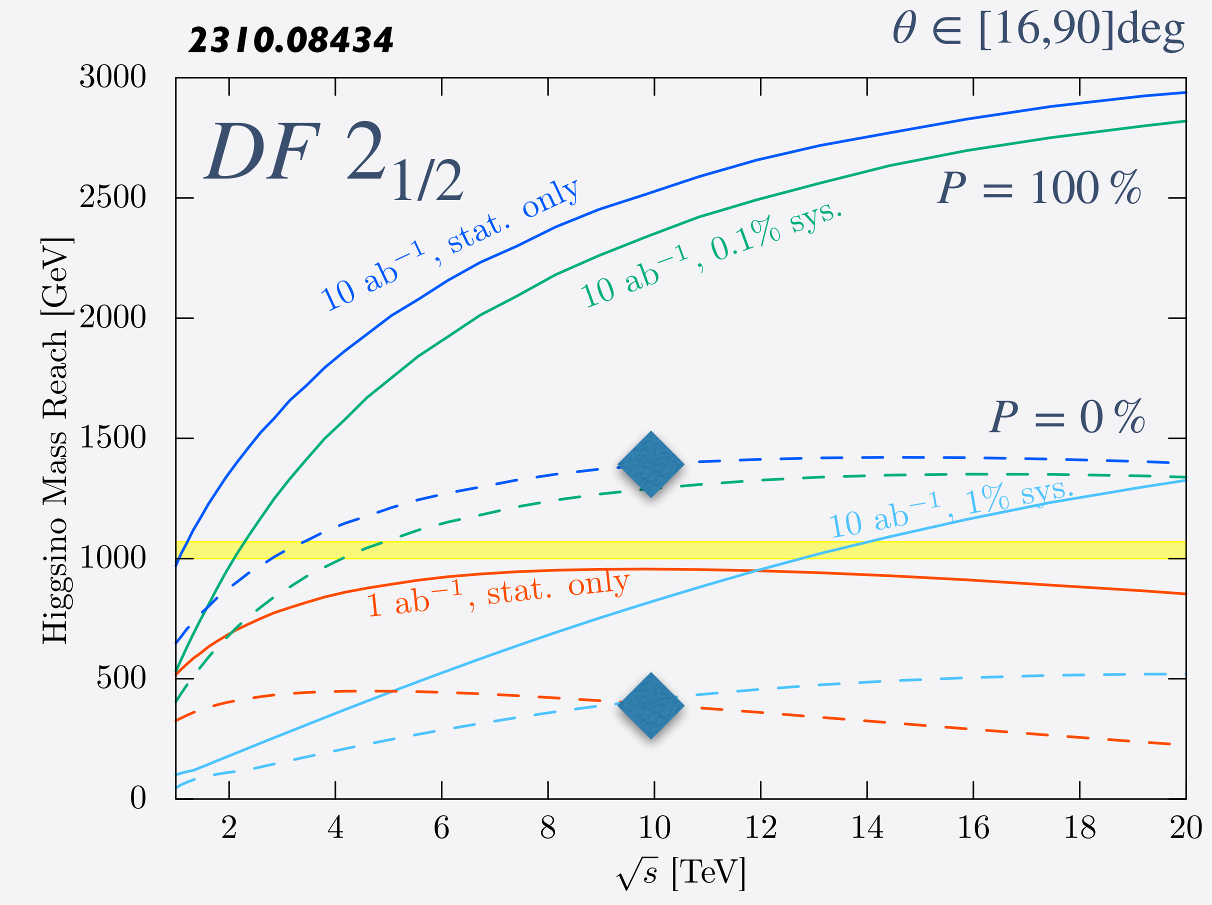
"WIMP" Dark Matter

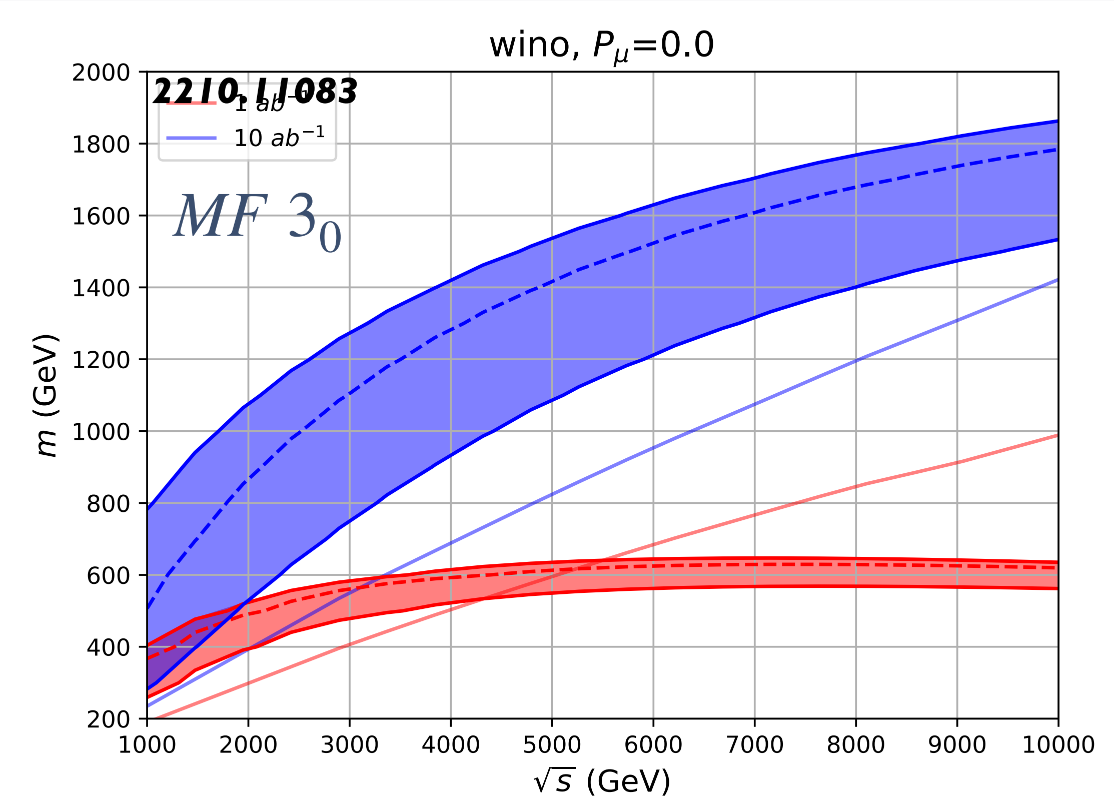
VIRTUAL* PRODUCTION

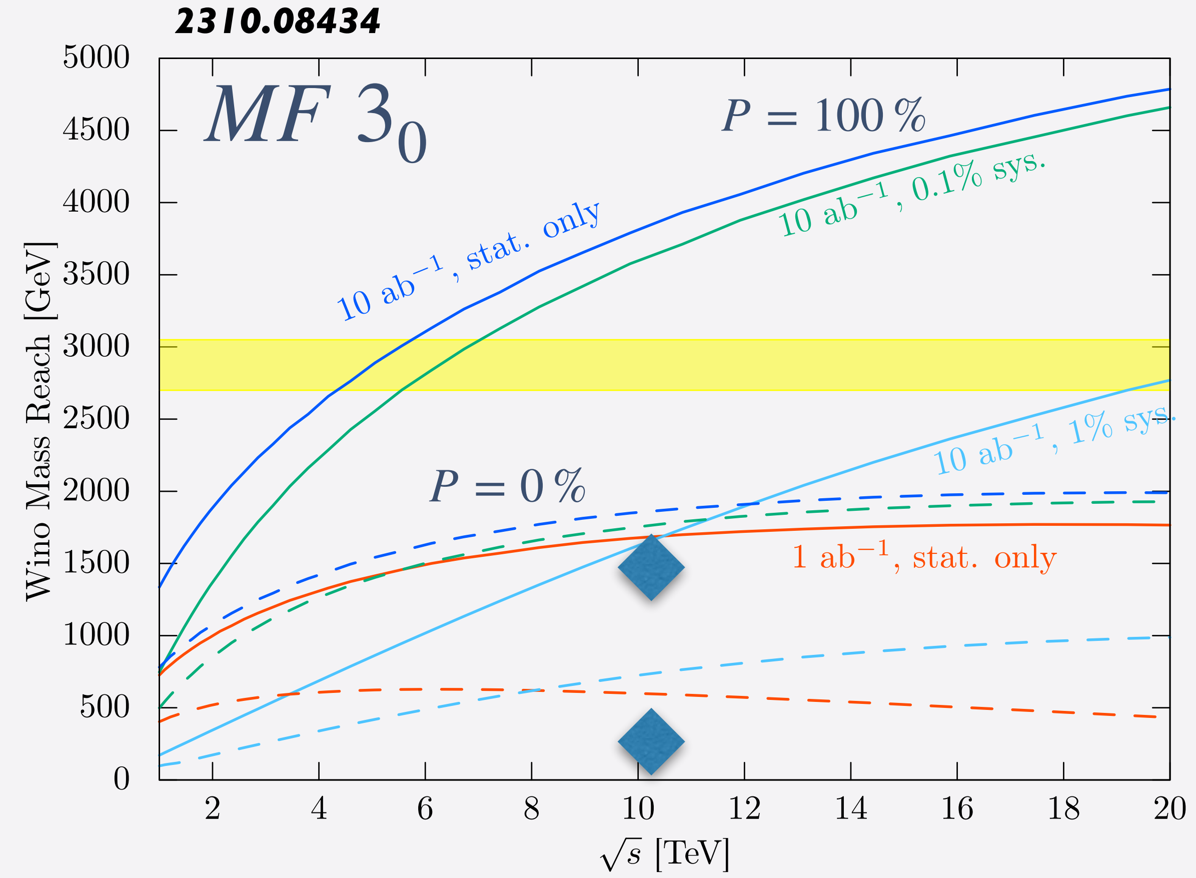
t-channel Ryuichiro's talk

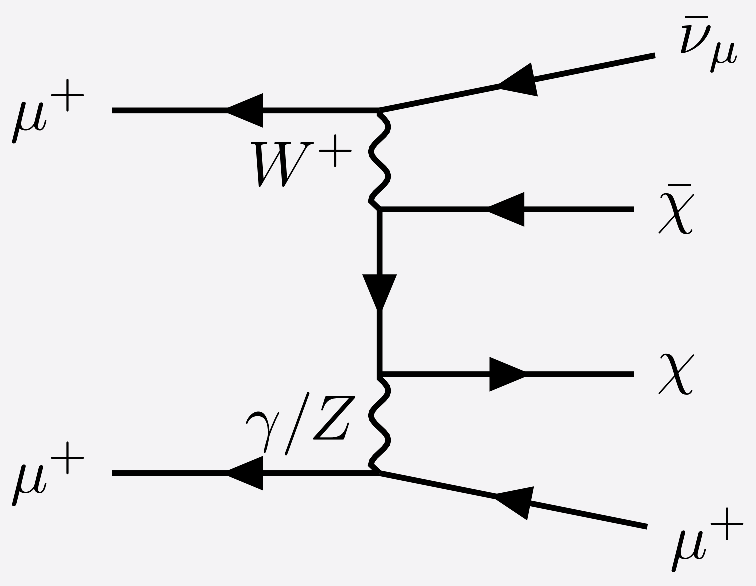


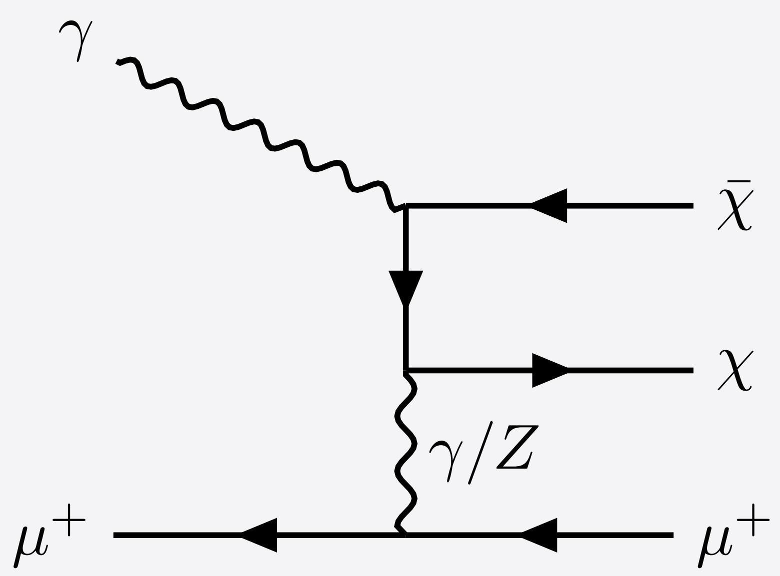


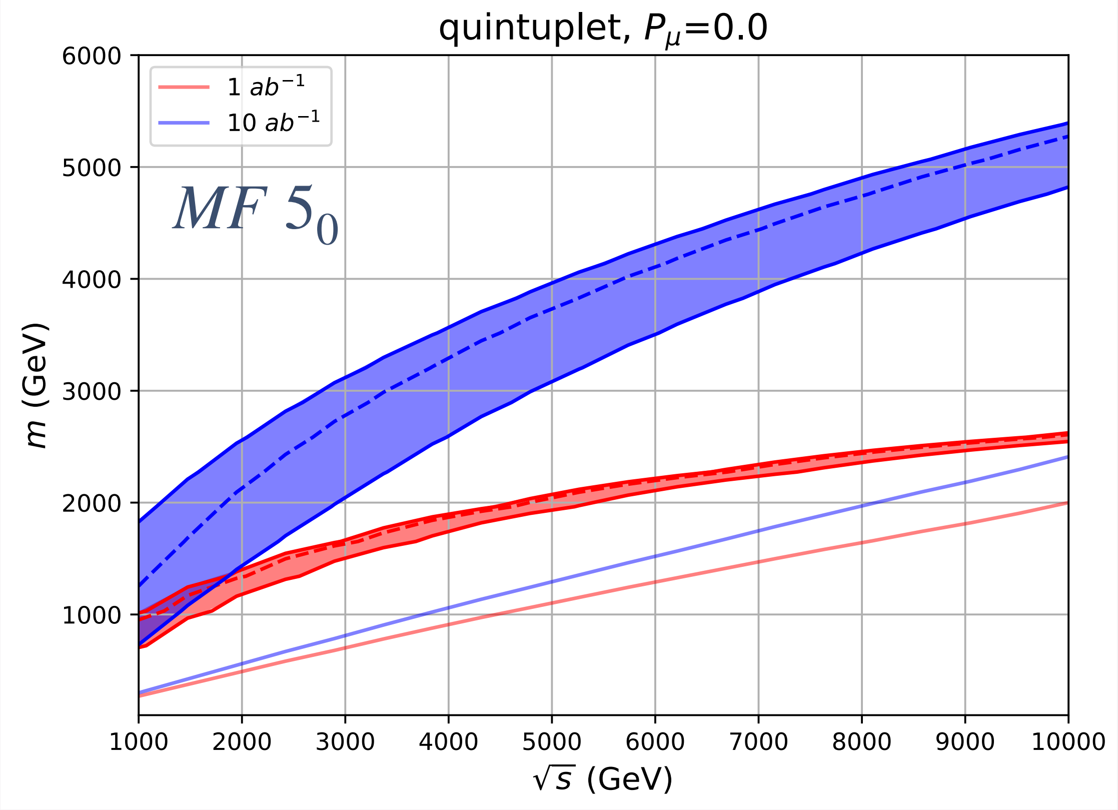


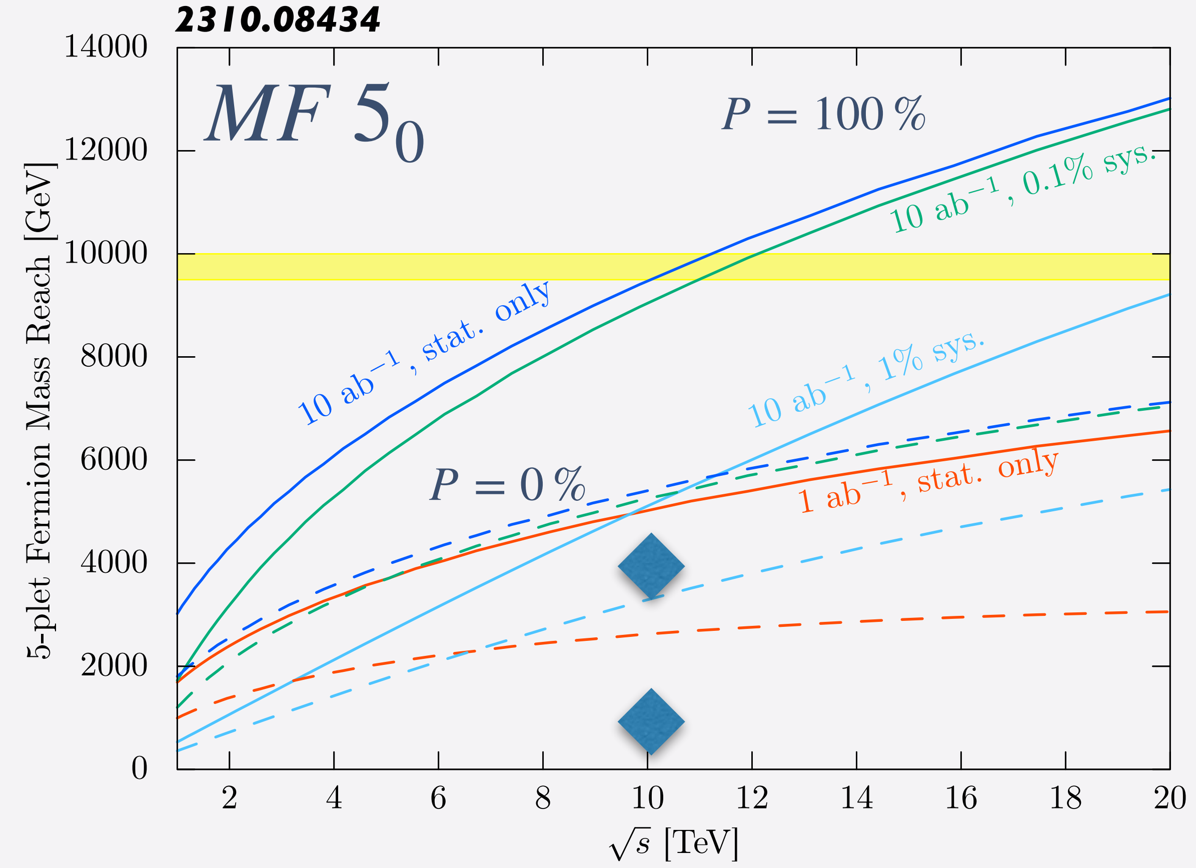












CONCLUSIONS AND OUTLOOK

WIMP dark matter can be challengingly heavy for production at colliders … still

- We can look for WIMPs in the sky
  - Establishing clear signals from the sky may prove quite hard, due to backgrounds, but are certainly intriguing
  - Signal rates are also subject to uncertainties that can make WIMPs not accessible

- We can try to detect WIMPs from the big-bang
  - Underground ultra-low background experiments can give signals soon, but cannot measure the mass of the WIMP
  - Half or so of the WIMP candidates are easily below the sensitivity of the next generations of Direct Detection experiments

Signals from the sky and from underground laboratories in the next 10-20 years can be a huge motivation for a new collider

Even in absence of signals from the sky and from underground laboratories in the next 10-20 years there is plenty of room left for WIMPs of the most simple kind

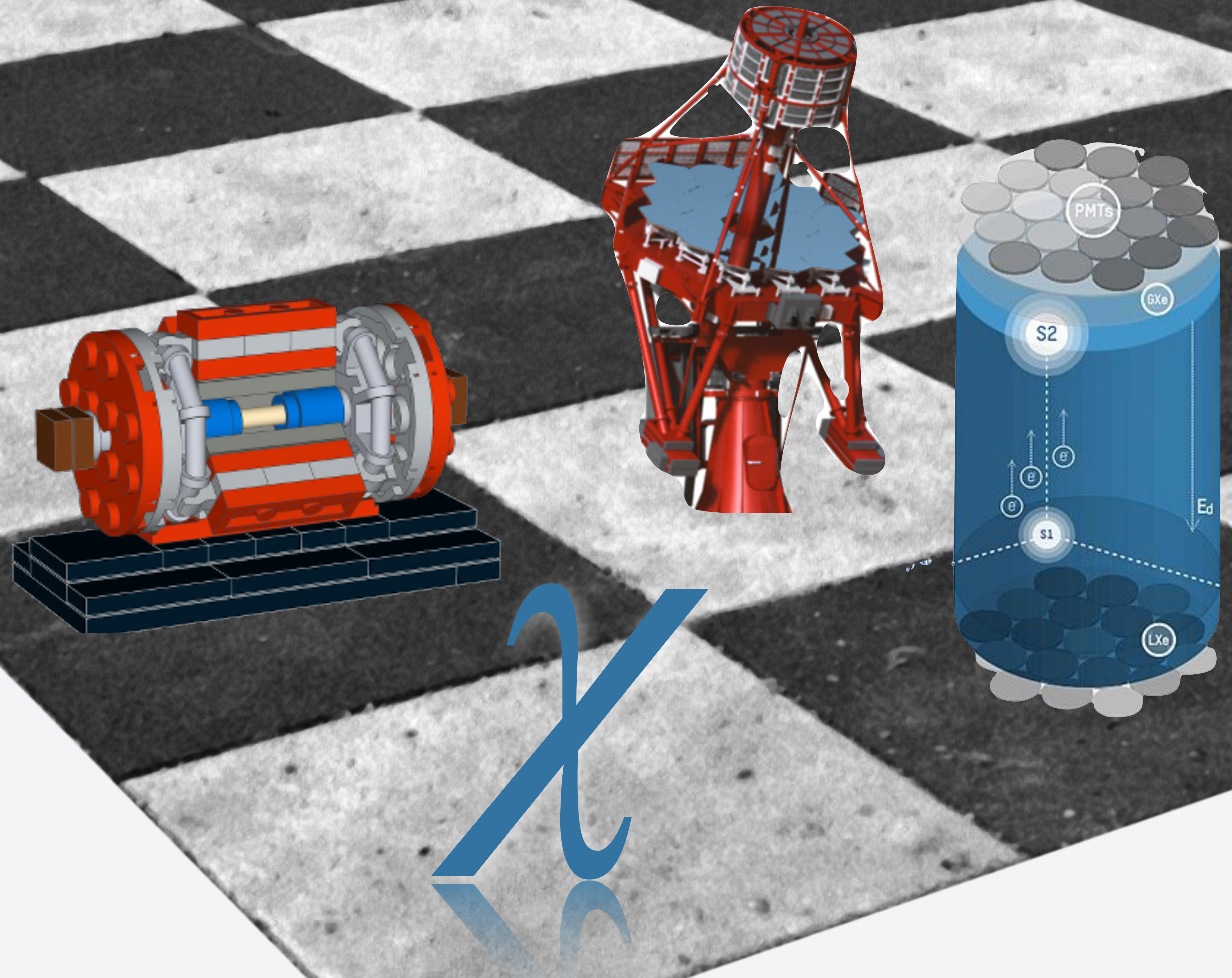
Muon collider can probe it all, up to the perturbative unitarity limit

WIMP DARK MATTER ENDGAME

The 3-10 TeV muon collider can discover Higgsino, Wino and light minimal dark matter (n=2,3,4) up to their thermal mass for 100% of Ω_{DM}

$E_{cm} > 10$ TeV is conceivable thanks to the muon beams. Heavier MDM candidates (n=5,7) up to their thermal mass for 100% of Ω_{DM} are in reach

In conjunction with direct and indirect detection experiments we have a path forward for
the complete and definitive exploration of the idea of WIMPs as Dark Matter



Thank you!

DM spin	EW n-plet	M_χ (TeV)	$\Lambda_{\rm Landau}/M_\chi$	$(\sigma v)^{J=0}_{\rm tot}/(\sigma v)^{J=0}_{\rm max}$	ΔM_0 [MeV]	$\Lambda^{\rm max}_{\rm UV}(\Delta M_0^{\rm min})/M_\chi$	ΔM_- [MeV]
Complex scalar	2	0.58 ± 0.01	$> M_{\rm Pl}$	-	0.22 - $4.6{\times}10^4$	-	4.2 - 9600
	4	4.98 ± 0.05	$> M_{\rm Pl}$	0.004	0.22 - 10^4	-	3.2 - 2000
	6	34.9 ± 0.5	$\simeq 6 \times 10^{13}$	0.016	0.54 - 2300	-	280 - 660
	8	88 ± 2	2×10^4	0.12	0.89 - 1.2 $\times 10^3$	-	324 - 507
	10	167 ± 4	20	0.45	1.27 - 800	-	340 - 450
Dirac fermion	2	1.08 ± 0.01	$> M_{\rm Pl}$	-	0.22 - 5000	2 $\times 10^5$	4.8 - 7800
	4	4.8 ± 0.1	$\simeq M_{\rm Pl}$	0.013	0.21 - 2200	$\times 10^5$	3.6 - 2600
	6	31.7 ± 0.5	2×10^4	0.057	0.51 - 510	$\times 10^4$	185 - 780
	8	82 ± 2	14	0.37	0.86 - 800	3000	290 - 550

DM spin	EW n-plet	M_χ (TeV)	$(\sigma v)^{J=0}_{\rm tot}/(\sigma v)^{J=0}_{\rm max}$	$\Lambda_{\rm Landau}/M_{\rm DM}$	$\Lambda_{\rm UV}/M_{\rm DM}$
Real scalar	3	2.53 ± 0.01	–	3×10^{37}	$4 \times 10^{24}*$
	5	15.4 ± 0.7	0.002	5×10^{36}	2×10^{24}
	7	54.2 ± 3.1	0.022	2×10^{19}	2×10^{24}
	9	117.8 ± 15.4	0.088	3×10^3	2×10^{24}
	11	199 ± 42	0.25	20	3×10^{24}
	13	338 ± 102	0.6	3.5	3×10^{24}
Majorana fermion	3	2.86 ± 0.01	–	3×10^{37}	$8 \times 10^{12}*$
	5	13.6 ± 0.8	0.003	3×10^{17}	5×10^{12}
	7	48.8 ± 3.3	0.019	1×10^4	4×10^7
	9	113 ± 15	0.07	30	3×10^7
	11	202 ± 43	0.2	6	3×10^7
	13	324.6 ± 94	0.5	2.6	3×10^7

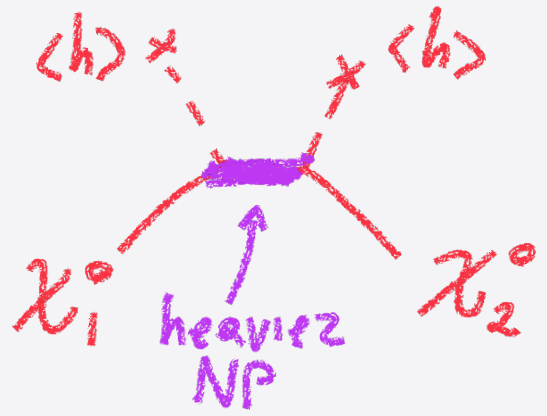
DM spin	n_Y	M_{DM} (TeV)
Dirac fermion	$2_{1/2}$	1.08 ± 0.02
	3_1	2.85 ± 0.14
	$4_{1/2}$	4.8 ± 0.3
	5_1	9.9 ± 0.7
	$6_{1/2}$	31.8 ± 5.2
	$8_{1/2}$	82 ± 8
	$10_{1/2}$	158 ± 12
	$12_{1/2}$	253 ± 20
Complex scalar	$2_{1/2}$	0.58 ± 0.01
	3_1	2.1 ± 0.1
	$4_{1/2}$	4.98 ± 0.25
	5_1	11.5 ± 0.8
	$6_{1/2}$	32.7 ± 5.3
	$8_{1/2}$	84 ± 8
	$10_{1/2}$	162 ± 13
	$12_{1/2}$	263 ± 22

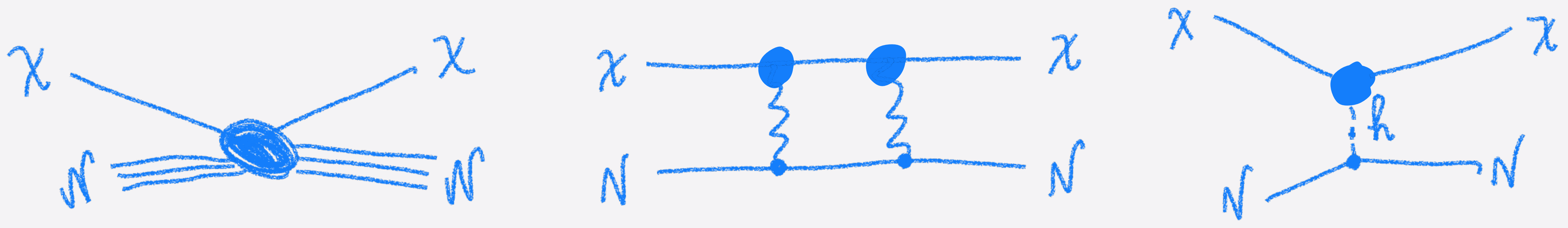
DM spin	EW n-plet	M_χ (TeV)
Real scalar	3	2.53 ± 0.01
	5	15.4 ± 0.7
	7	54.2 ± 3.1
	9	117.8 ± 15.4
	11	199 ± 42
	13	338 ± 102
Majorana fermion	3	2.86 ± 0.01
	5	13.6 ± 0.8
	7	48.8 ± 3.3
	9	113 ± 15
	11	202 ± 43
	13	324.6 ± 94

DM spin	n_ϵ	M_{DM} (TeV)
Complex scalar	3	$1.60 \pm 0.01 - 2.4^*$
	5	11.3 ± 0.6
	7	47 ± 3
	9	118 ± 9
	11	217 ± 17
	13	352 ± 30
Dirac fermion	3	$2.0 \pm 0.1 - 2.4^*$
	5	9.1 ± 0.5
	7	45 ± 3
	9	115 ± 9
	11	211 ± 16
	13	340 ± 27

DIRECT DETECTION

$Y \neq 0$, Mass-Splitting from DIM>4

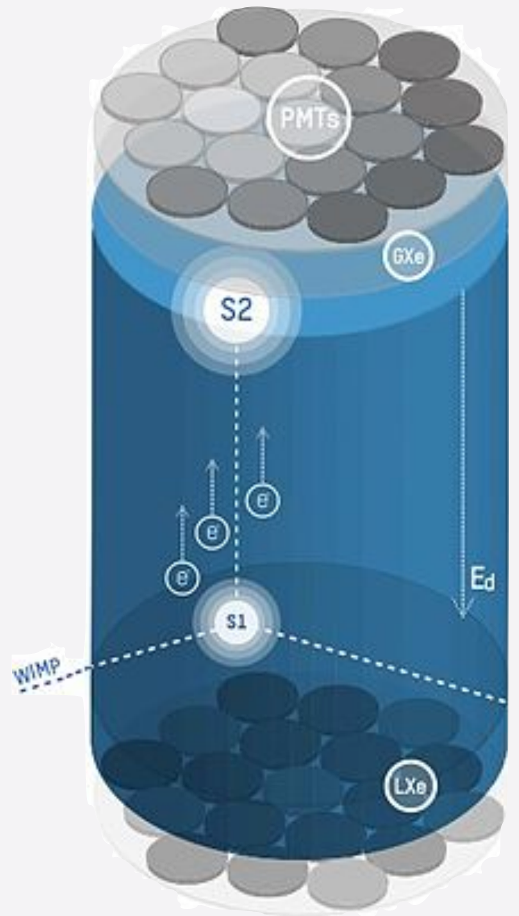




Scattering on SM materials can be detected in ultra-low background experiments

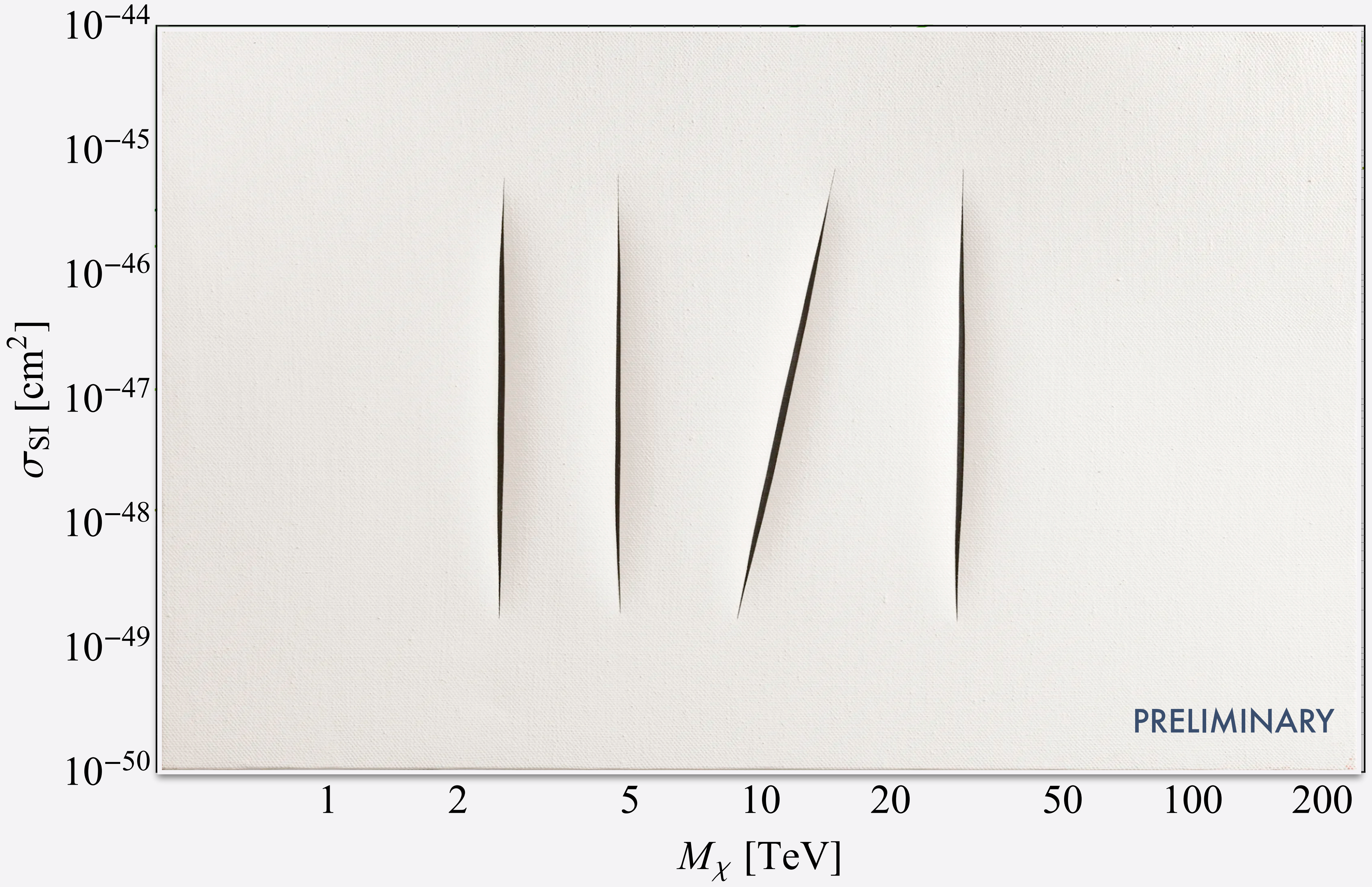
Larger rates for the larger n-plets keep them visible

For such large DM mass the signature <u>does not</u> depend on the DM mass.



2030s

up to O(PeV)

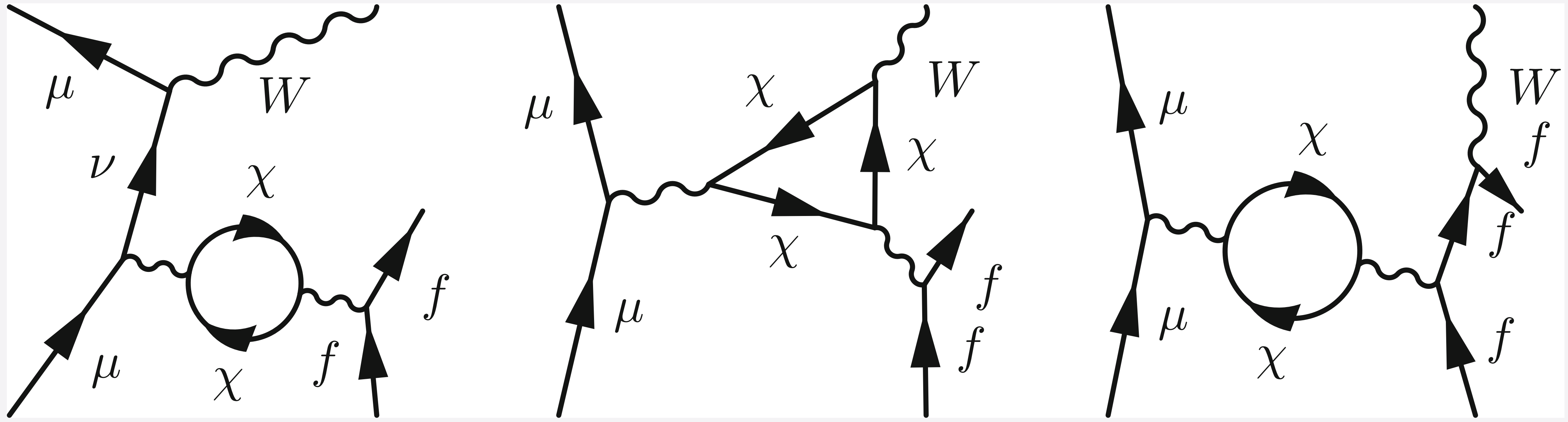


An excess would require a "seasonality" check and maybe independent confirmation (many excesses in the past in this type of experiments, though most were at the lowest accessible masses)

Wff′ PHASE SPACE

$$0.5 \cdot E_{cm} < m(f'\bar{f}) < 0.9 \cdot E_{cm}.$$

$$8^\circ < \theta(W) < 172^\circ,$$



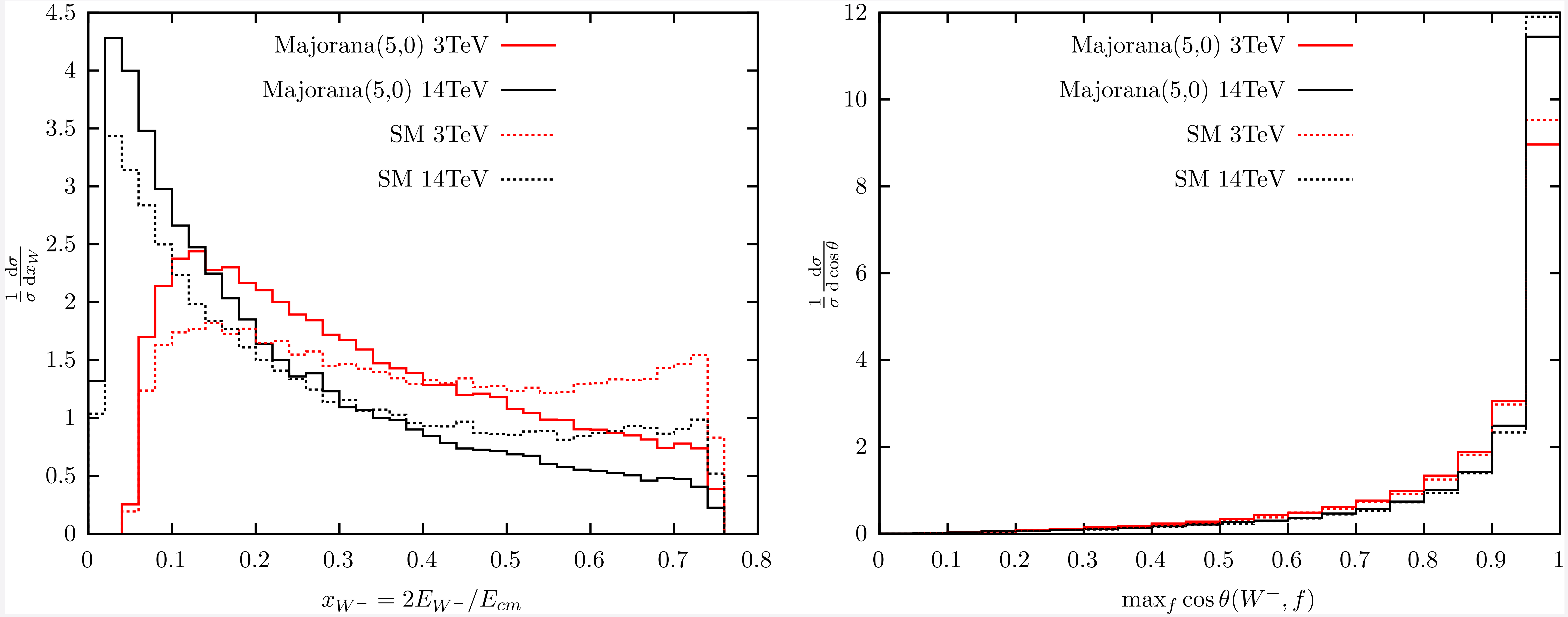
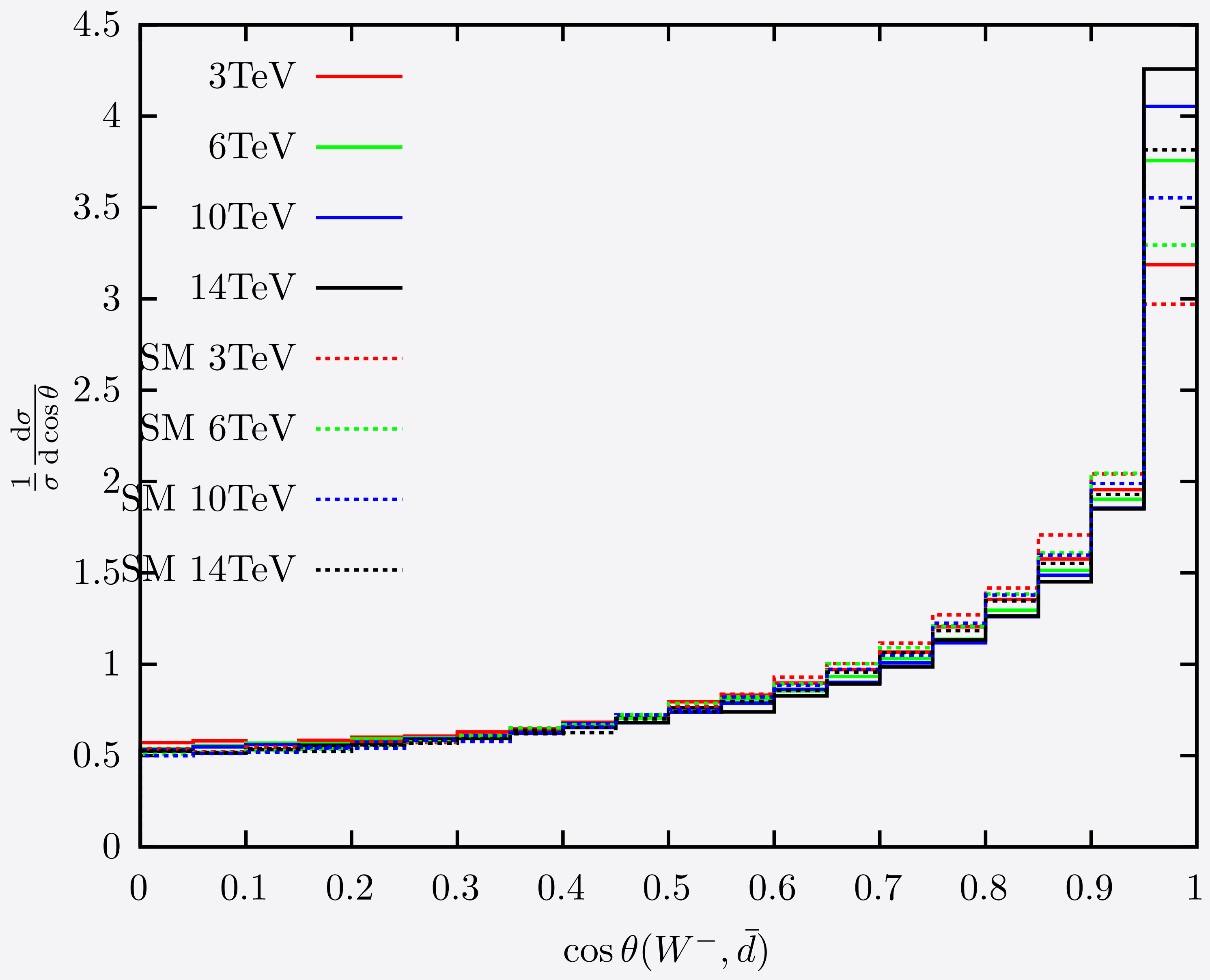
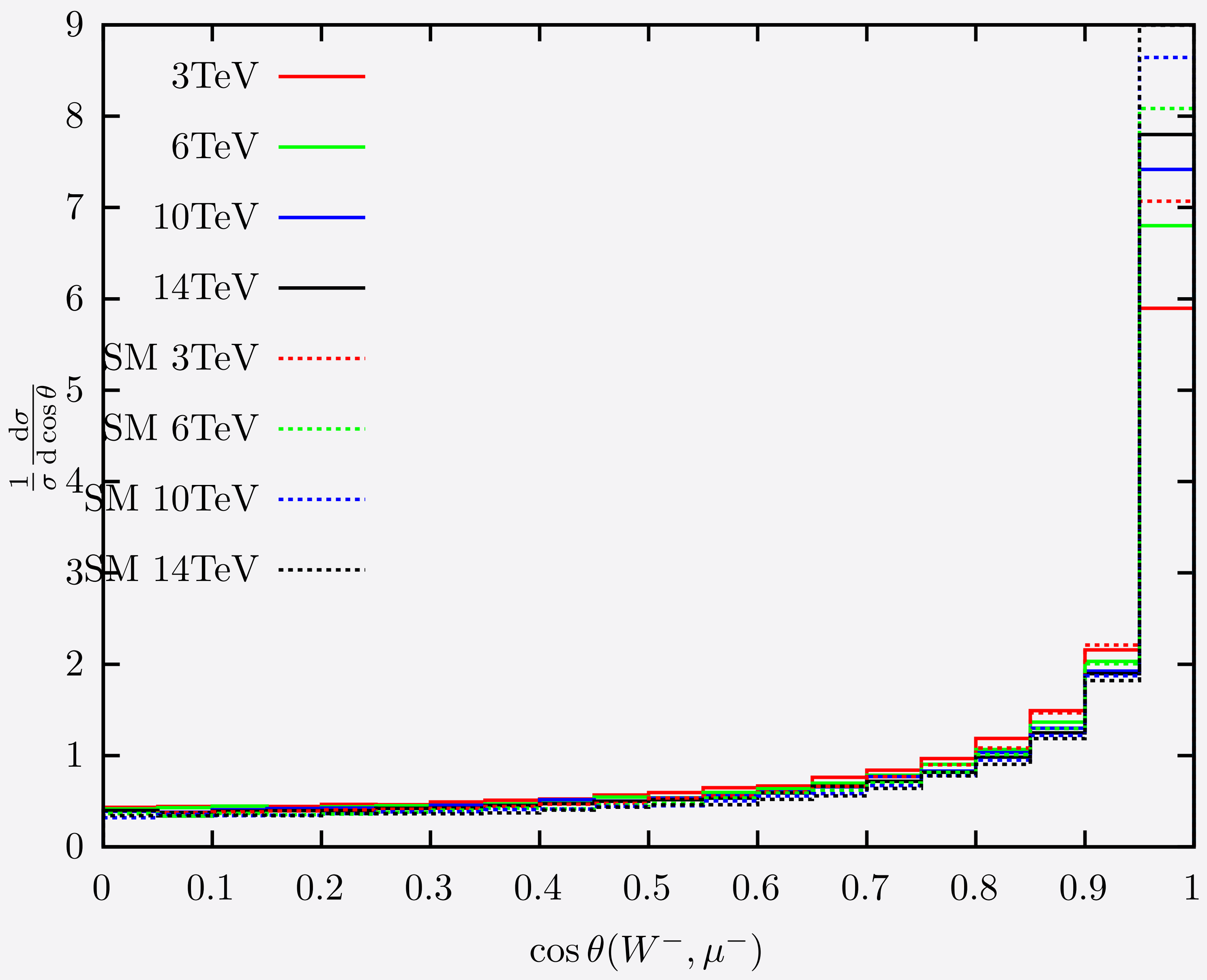
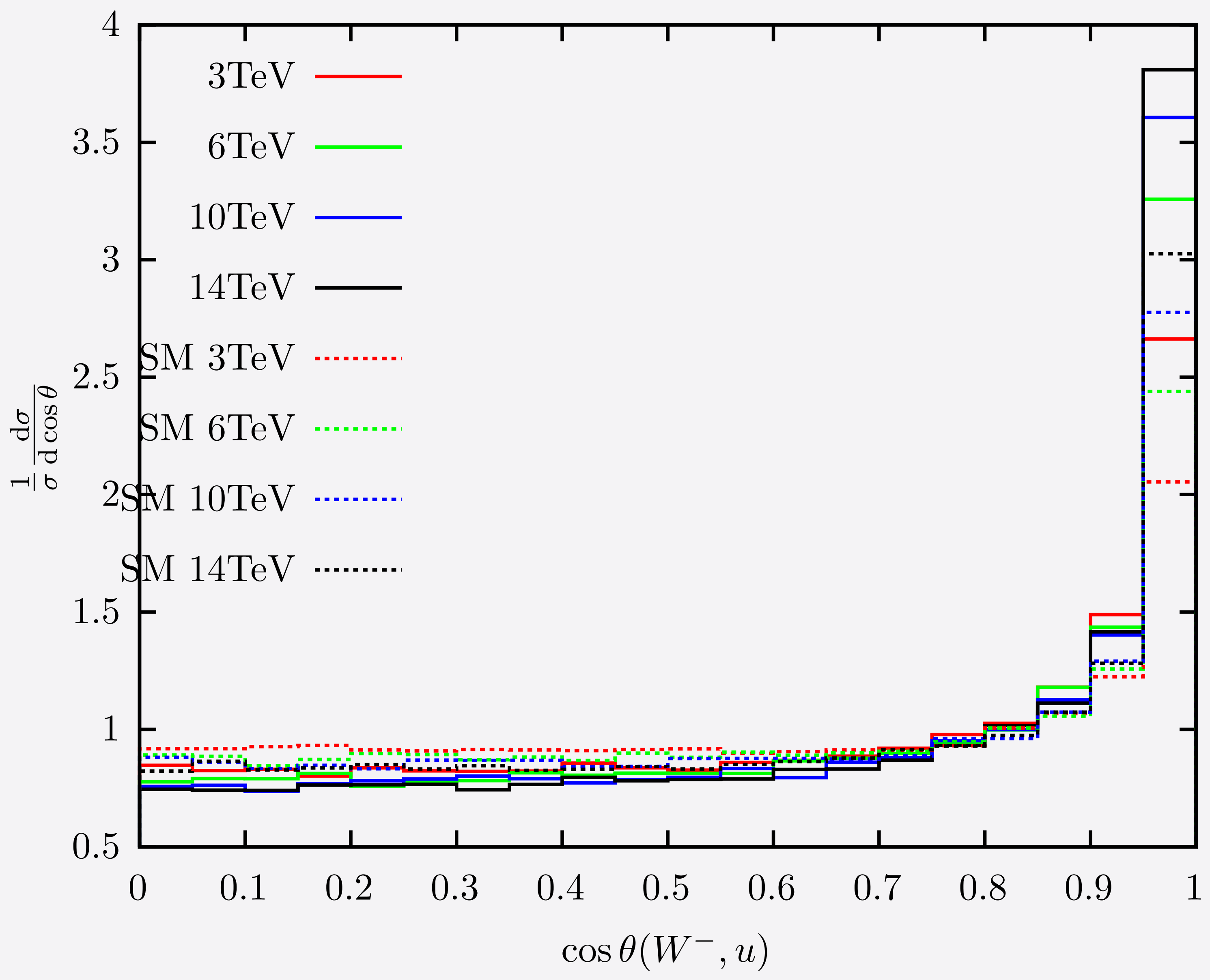


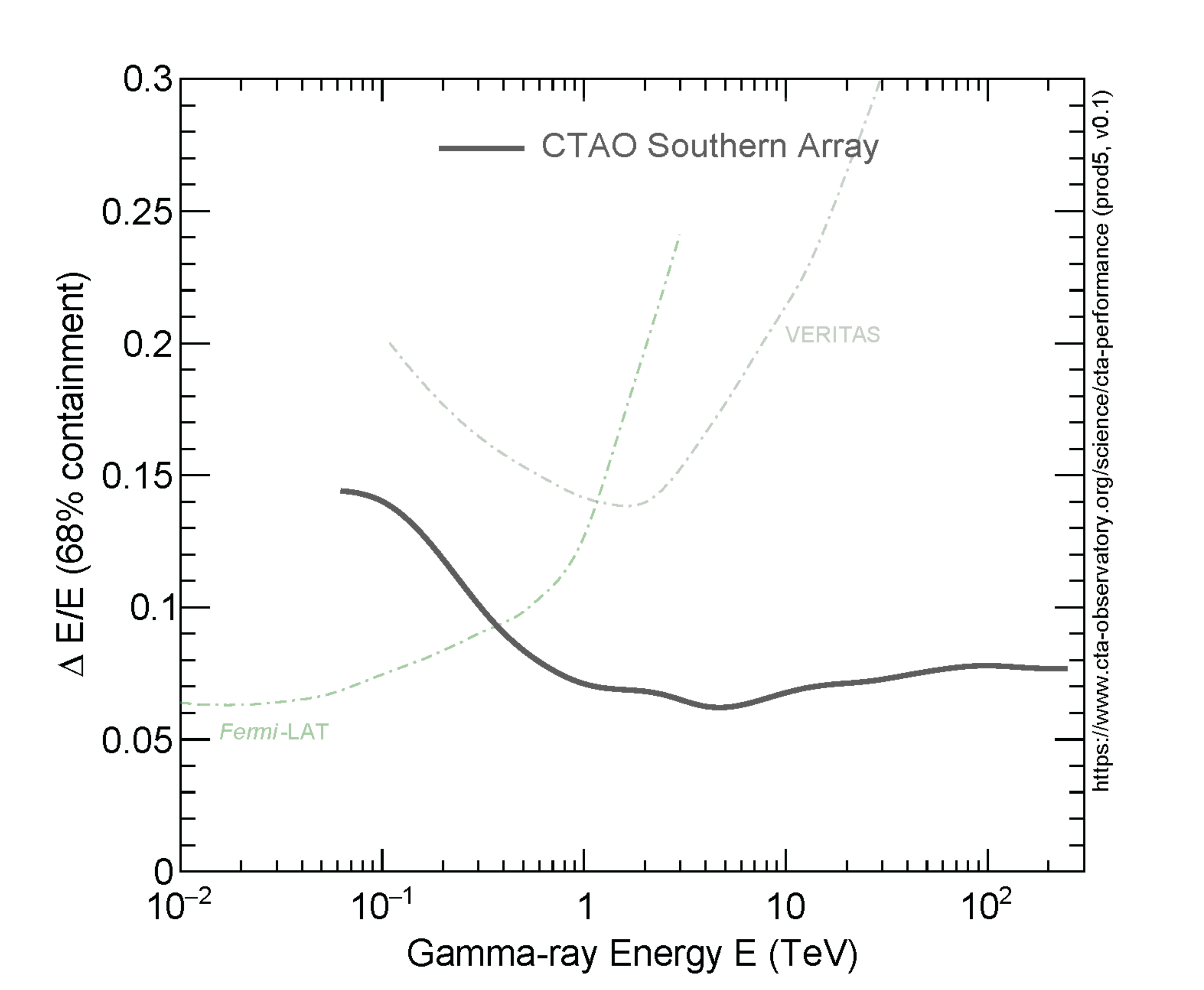
Fig. 5 Differential distribution of the normalized W boson energy ($x_W = 2E_W/E_{cm}$) and maximal $\cos\theta(W, f)(f = \mu^+, \mu^-, u, \bar{d})$ for the $\mu^+\mu^- \to W^- u\bar{d}$ in the SM and the interference with a Majorana fermion 5-plet at the 3 TeV and 14 TeV muon collider

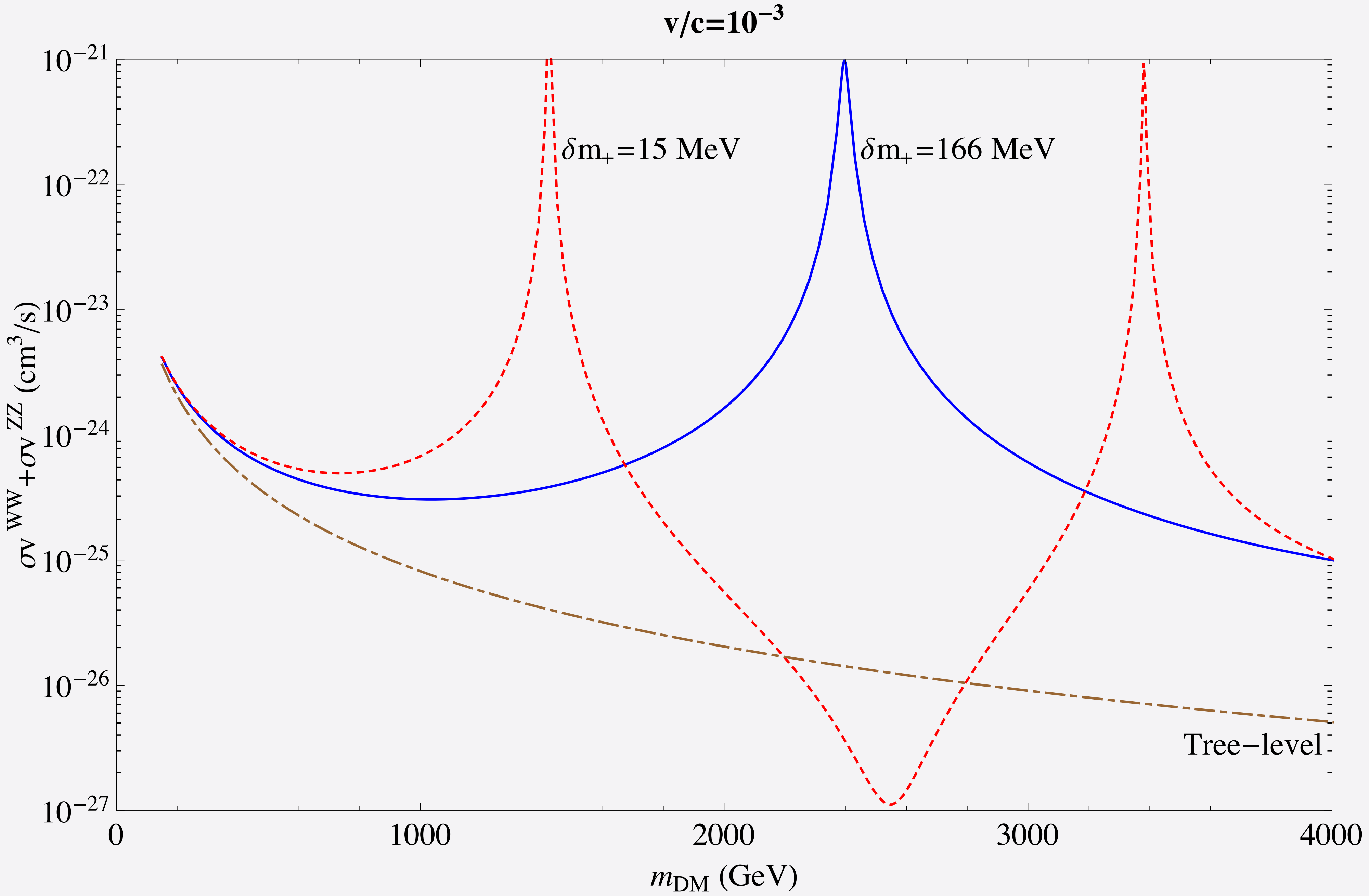
SOFT AND COLLINEAR W

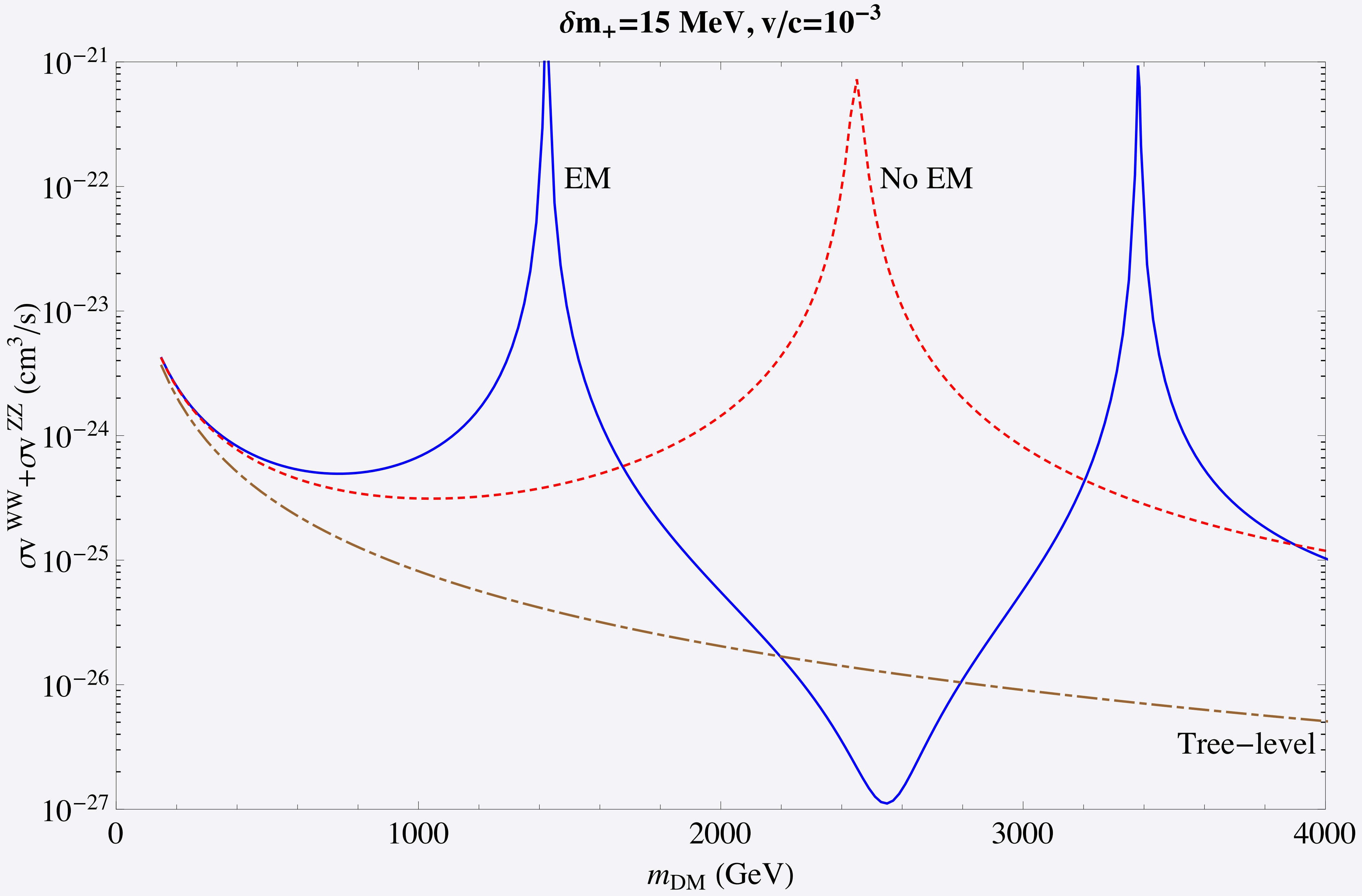







CTAO Southern Array
VERITAS
Fermi-LAT
Δ E/E (68% containment)
Gamma-ray Energy E (TeV)
https://www.cta-observatory.org/science/cta-performance (prod5, v0.1)


v/c=10^−3
δm+=15 MeV
δm+=166 MeV
Tree−level
σv^WW+σv^ZZ (cm^3/s)
m_DM (GeV)


δm+=15 MeV, v/c=10^−3
EM
No EM
Tree−level
σv^WW+σv^ZZ (cm^3/s)
m_DM (GeV)