

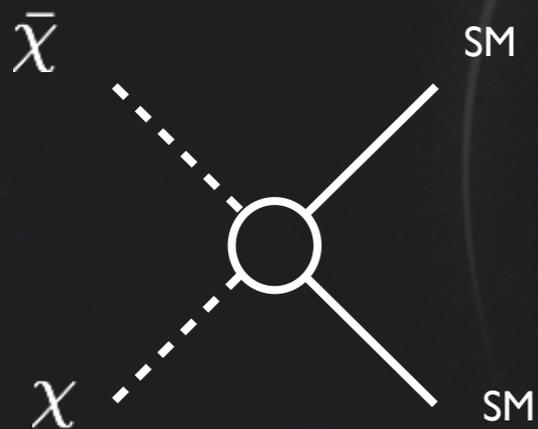
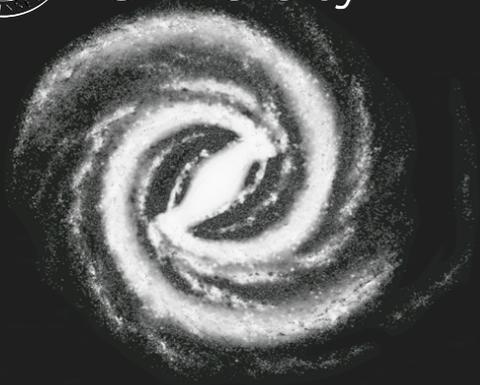


Dark Matter at Collider & Interplay

Björn Penning
Brandeis & Bristol



DM Detection

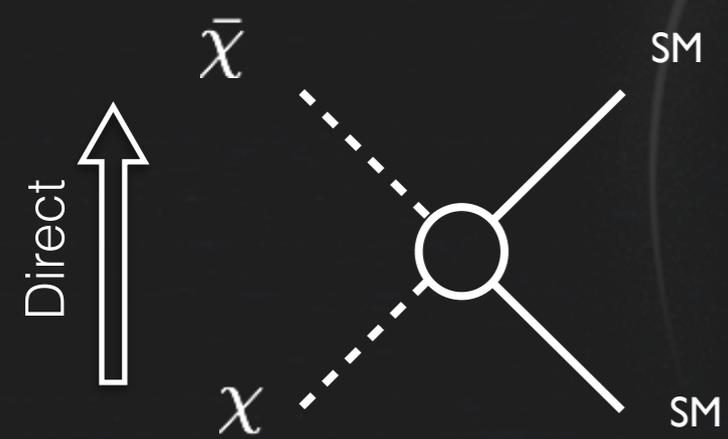




DM Detection

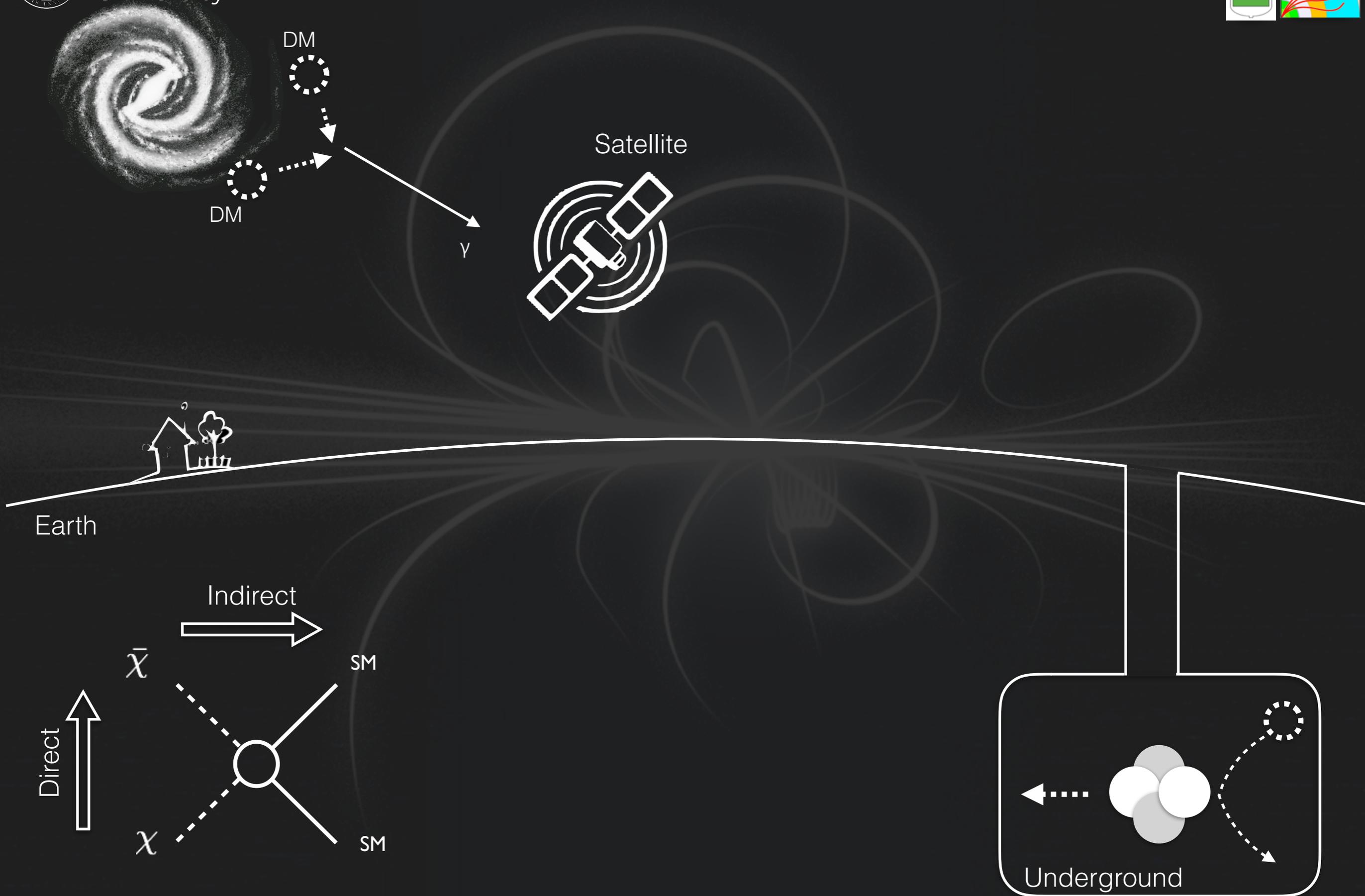


Earth



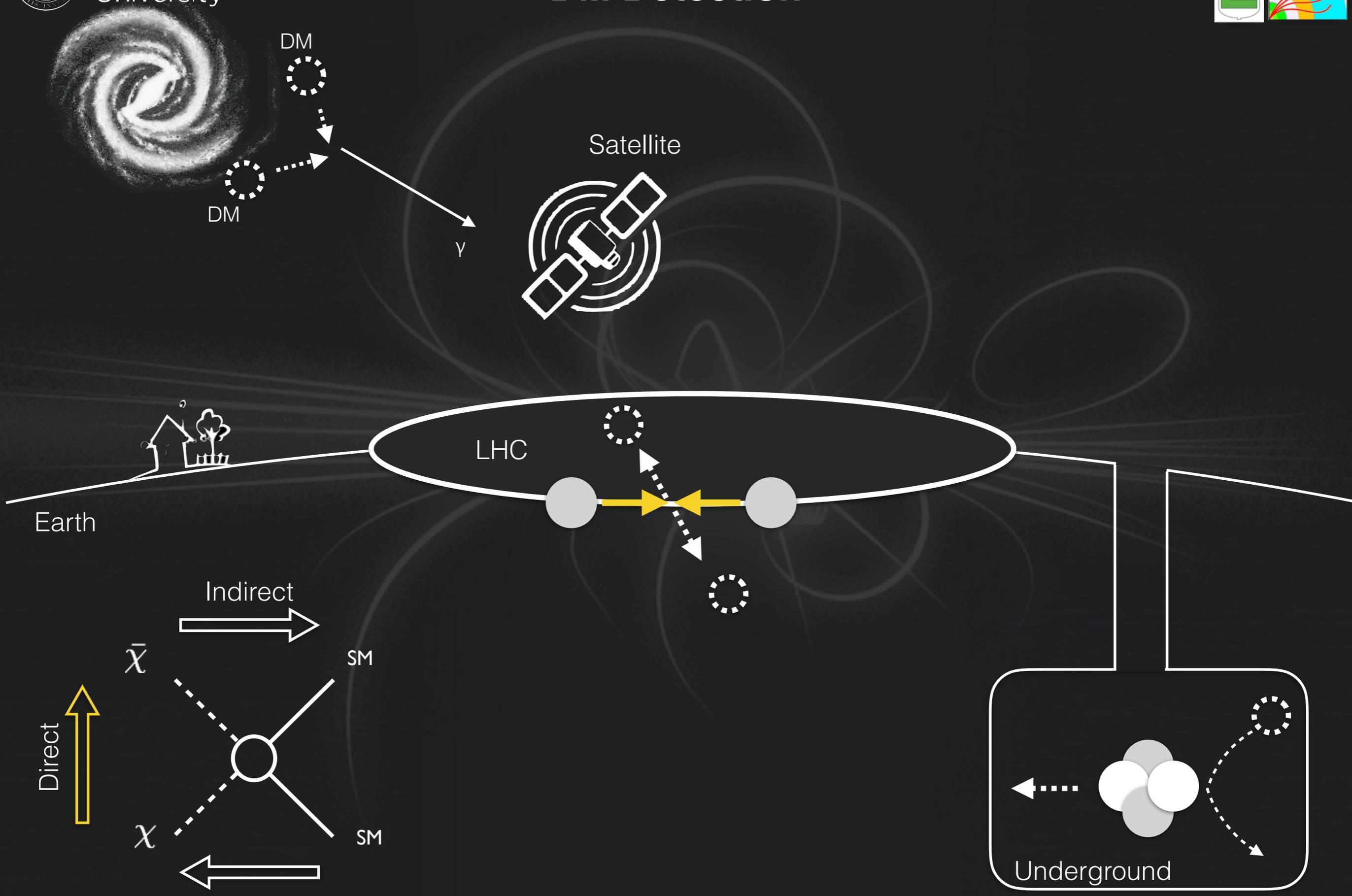


DM Detection

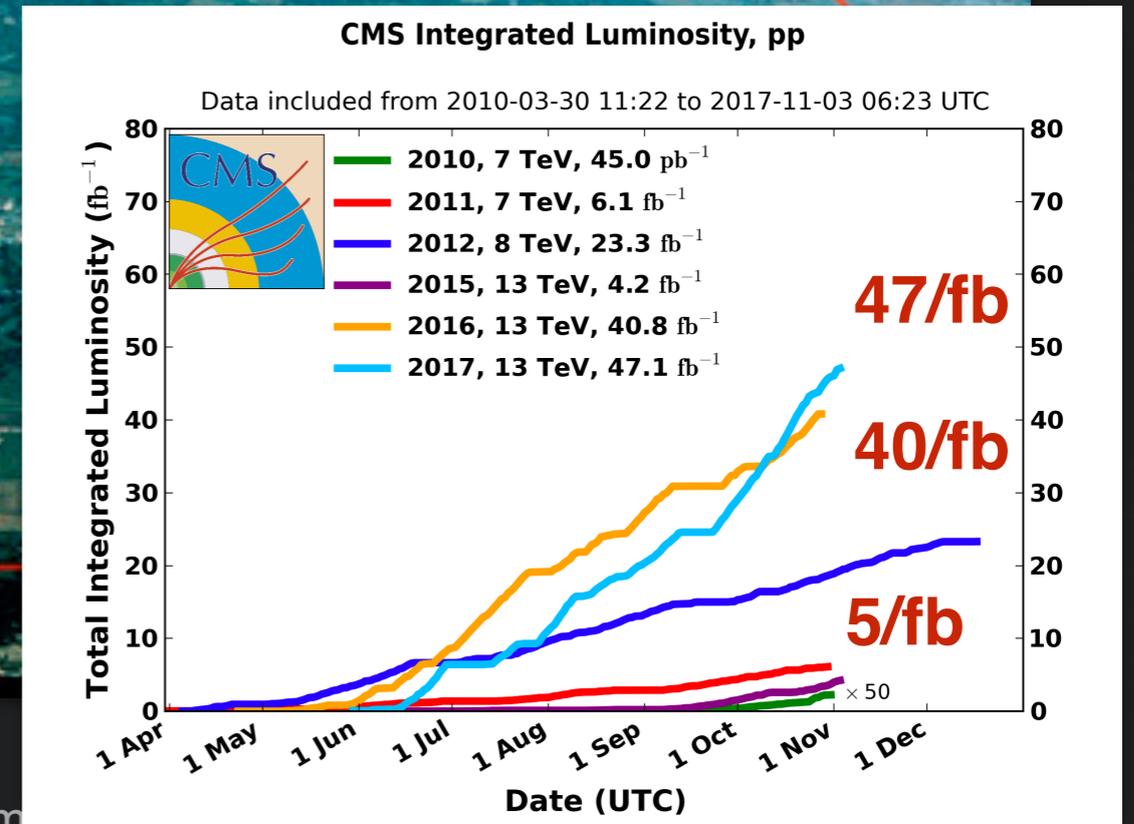
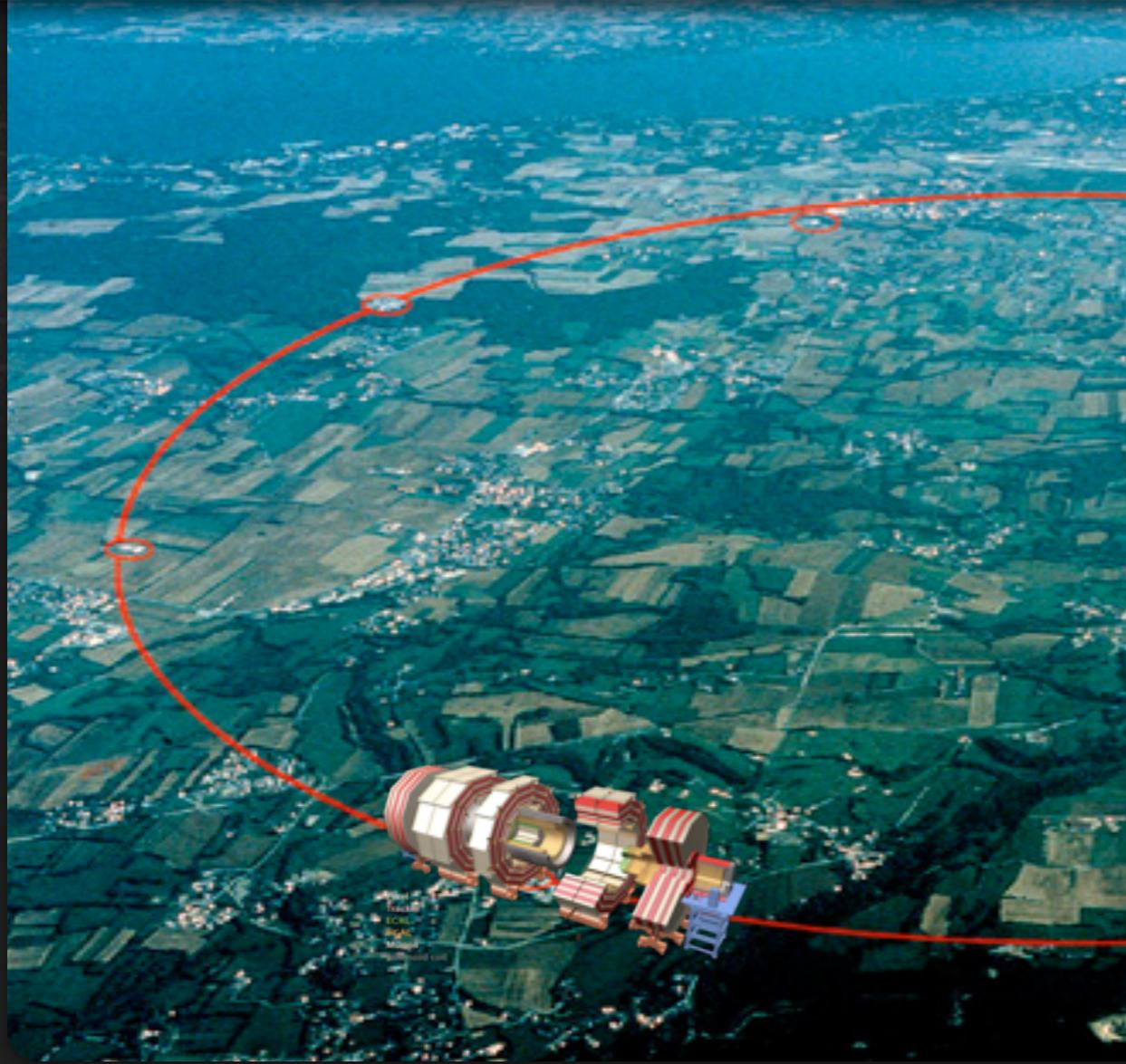


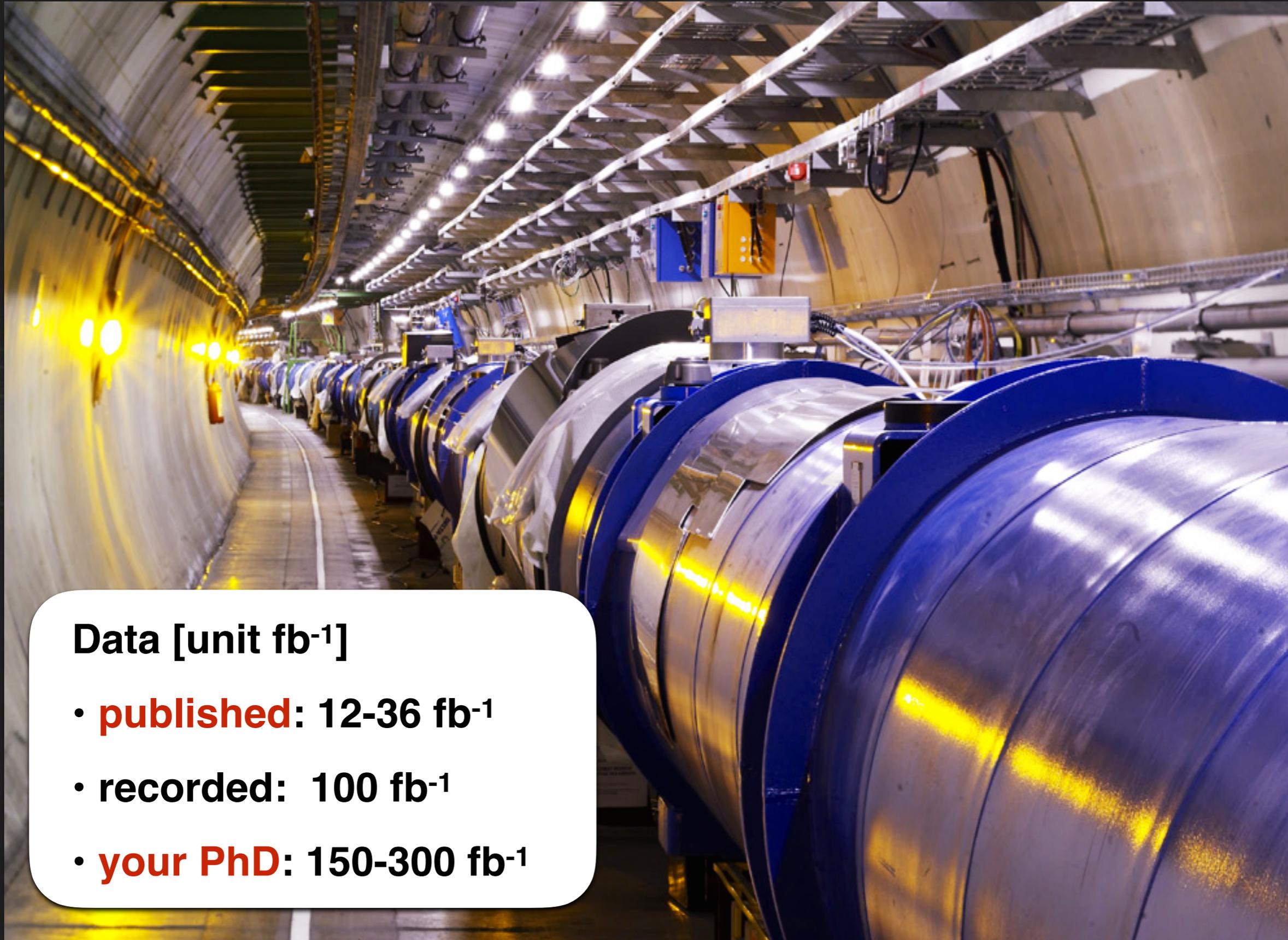


DM Detection



	2011/12	Design
Energy	7 / 8 TeV	13-14 TeV
Bunch Spacing	50ns	25(50)ns
Luminosity	$3.6/8 \times 10^{33}$	$10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Pile-Up	~20/40	~50(100)

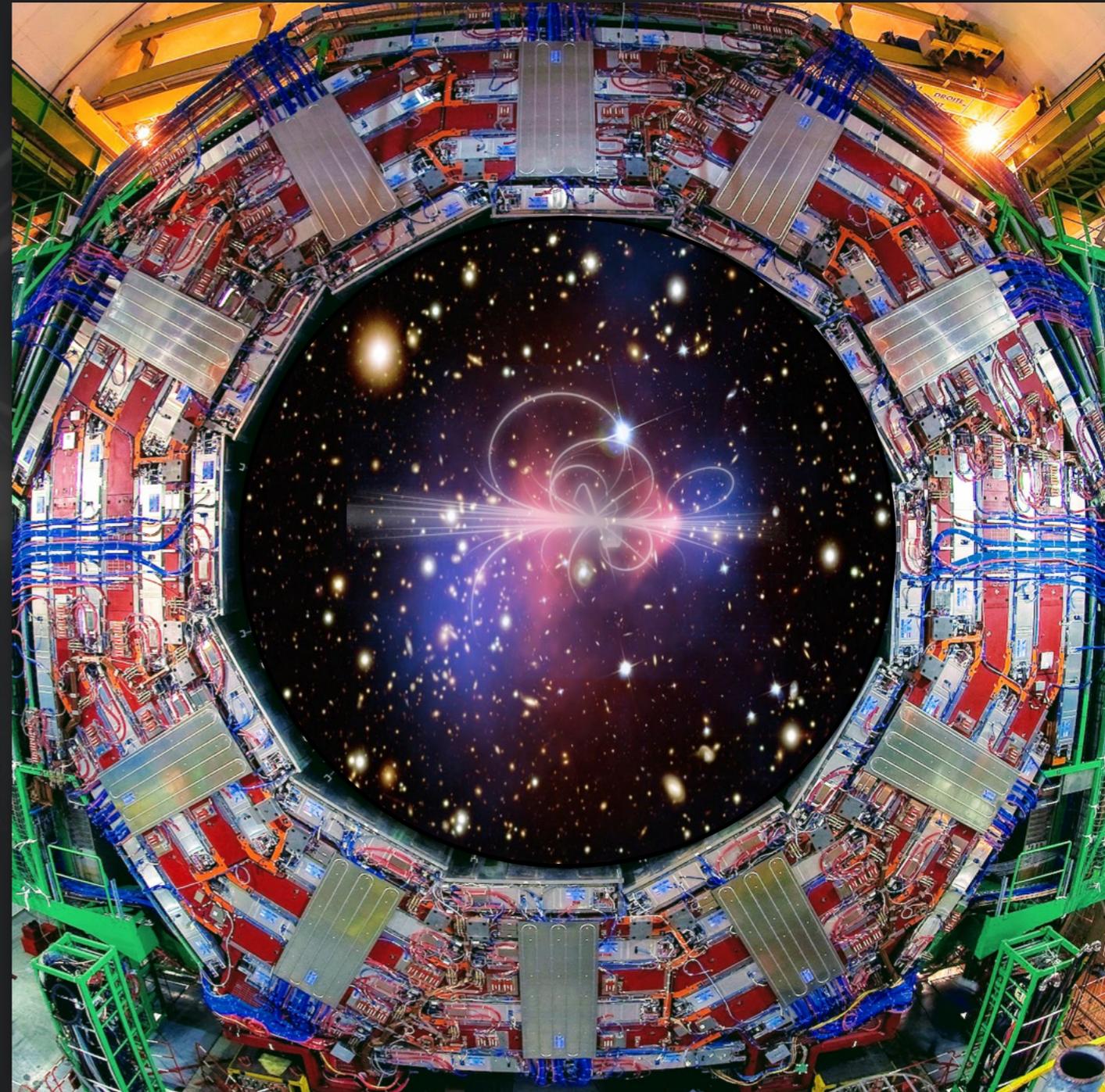




Data [unit fb⁻¹]

- **published:** 12-36 fb⁻¹
- **recorded:** 100 fb⁻¹
- **your PhD:** 150-300 fb⁻¹

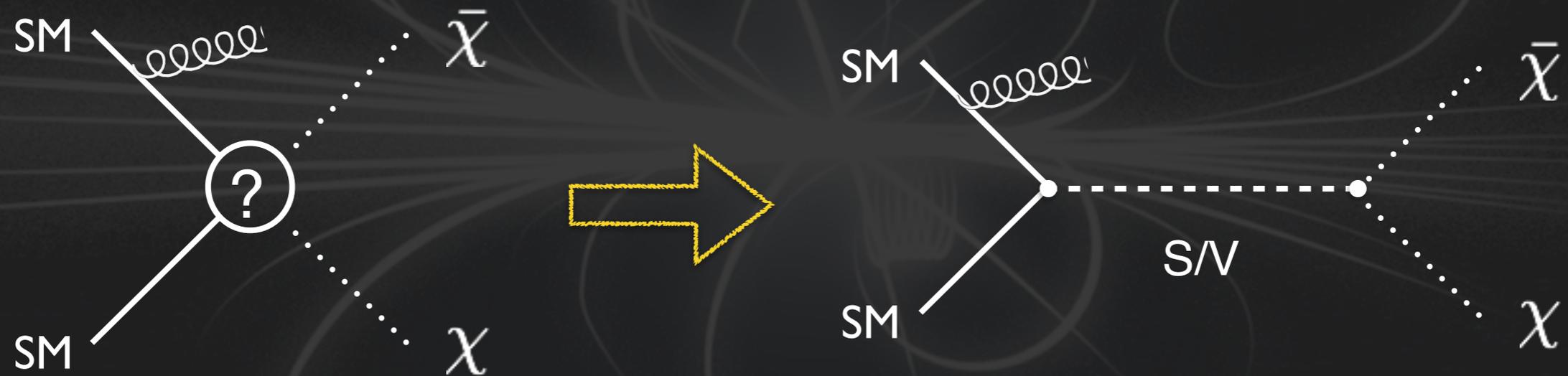
- If all evidence of DM is gravitational, **why should we look for it at collider** (particularly hadron)?
- Well motivated:
 - ‘**WIMP paradigm**’ predicts particles approximate EW scale
 - Many HEP **BSM theories predict viable DM candidates**
 - **Complementarity**, collider have different strengths and uncertainties
 - Colliders would be **uniquely able to measure** the WIMPs properties



- DM has to be **kinematically accessible**: $\sim 1-1000\text{GeV}$
- Essentially two types of collider searches:
 1. Search for DM (mono-X)
 2. Search for the Mediator



- At collider the WIMPs are invisible but are inevitably produced in association with visible particles from ISR
→ ‘**back-to-back**’ signature due to momentum conservation in the CoM
- Can be parametrize this via **EFT** or more commonly & robust as **simplified models**

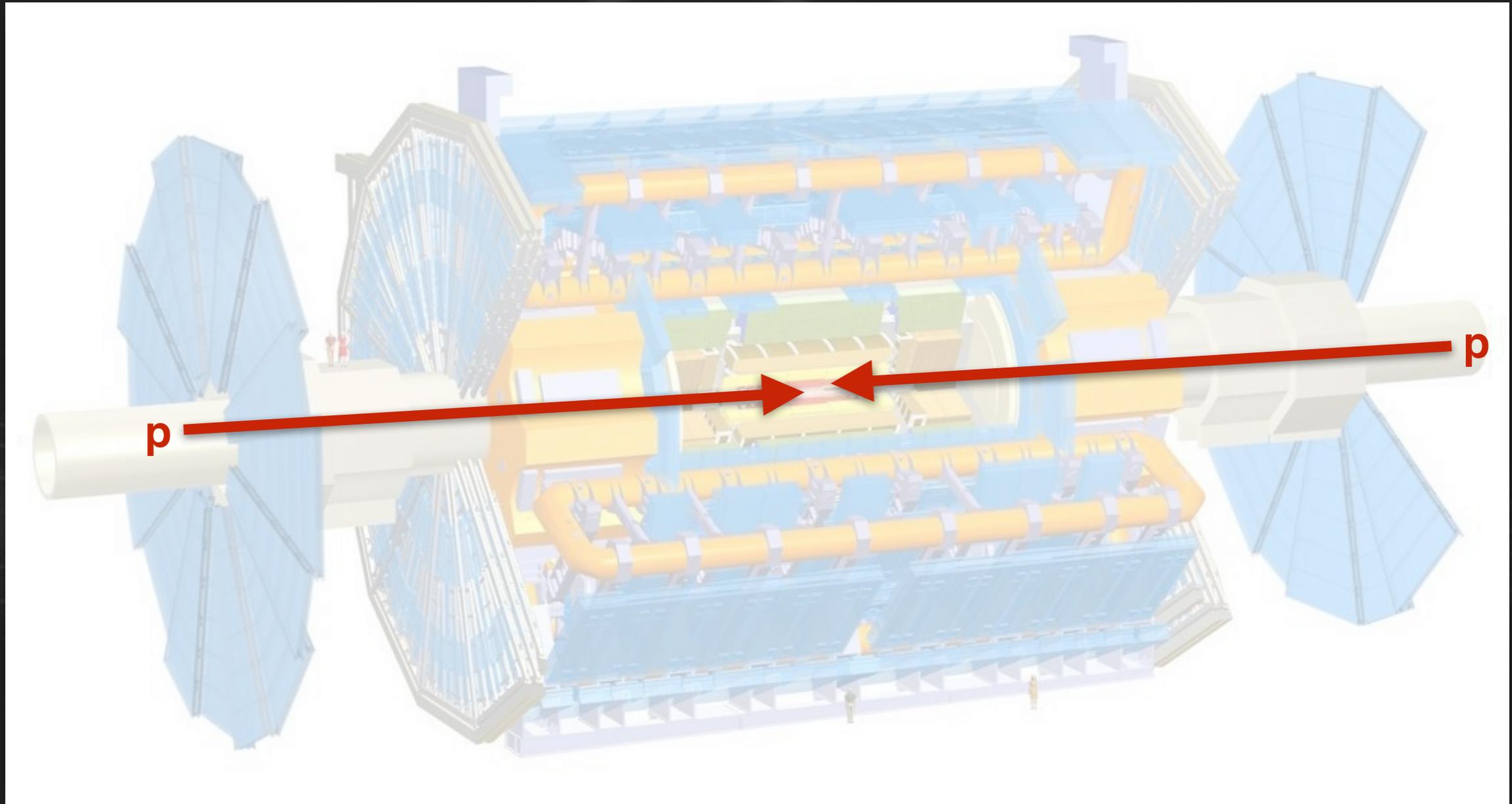


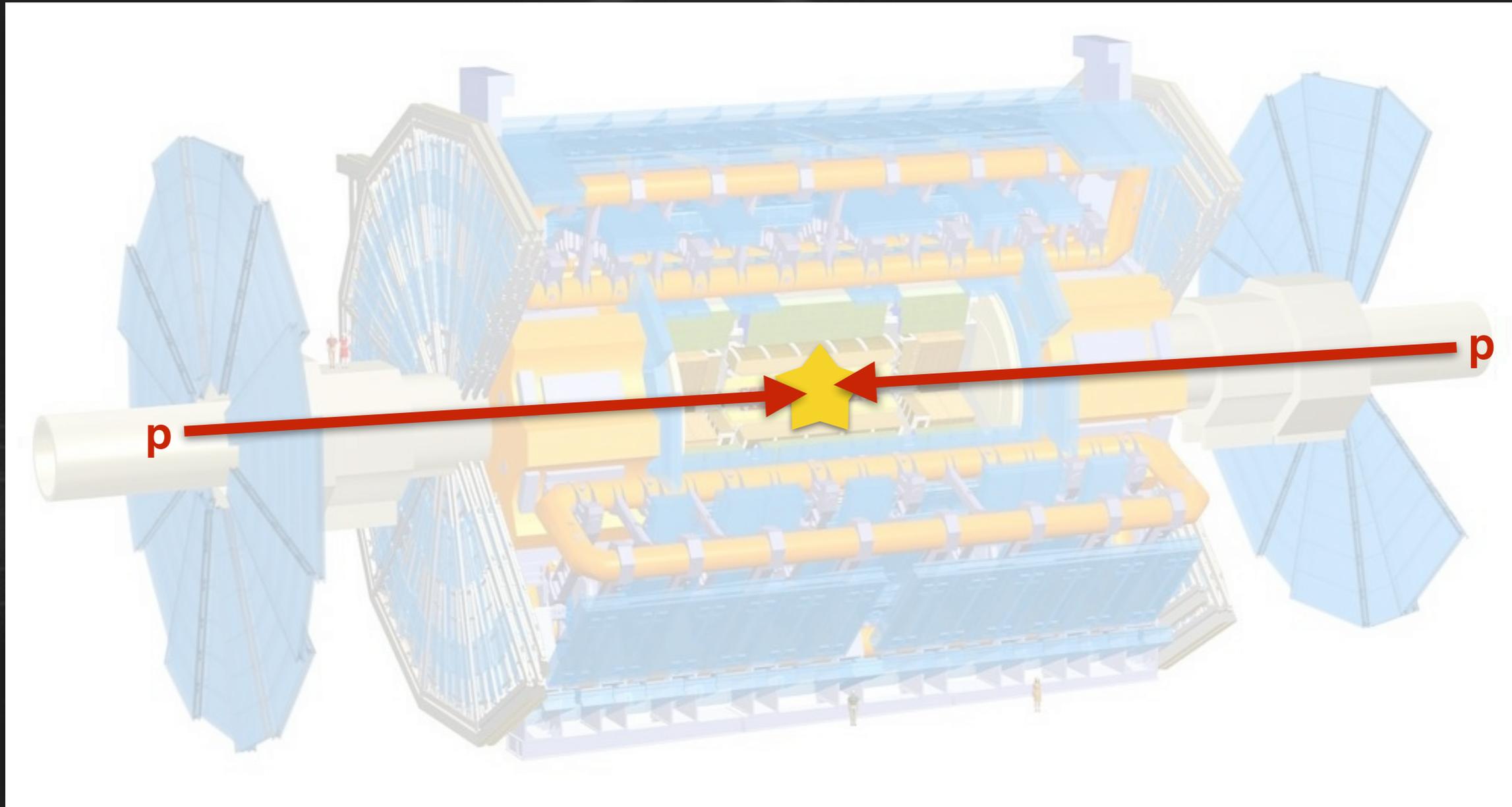
- Leads to **known interactions**

- | | |
|--|---|
| • scalar ($\psi\psi$), | • vector $\bar{\psi}\gamma^\mu\psi$, |
| • pseudo scalar ($\bar{\psi}\gamma^5\psi$) | • axial-vector ($\bar{\psi}\gamma^\mu\gamma^5\psi$) |



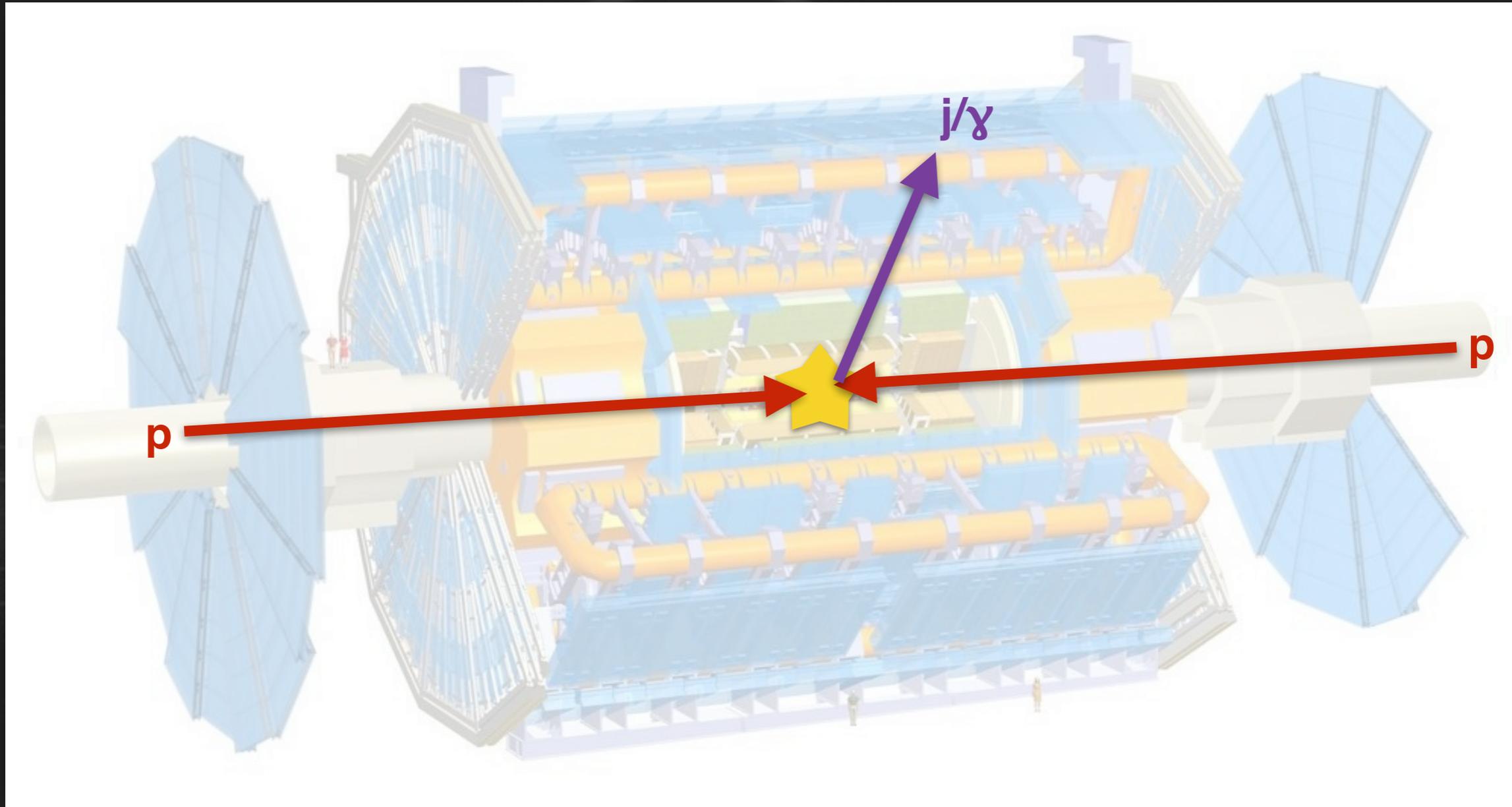
DM Detection





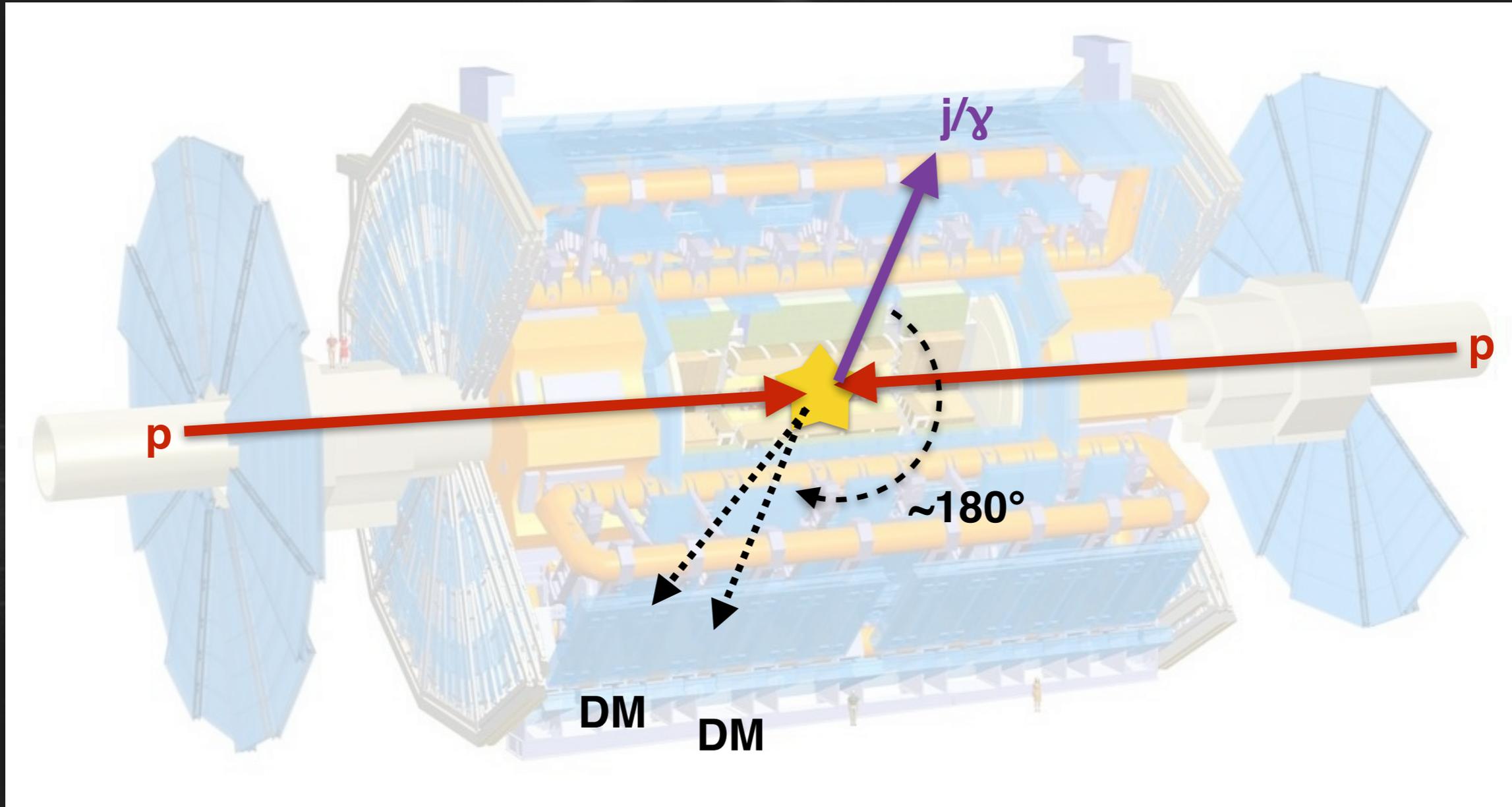
- Protons collide
- DM produced will escape the detector and recoil from the visible state
- Signature explores wide range of interactions and final states particles

DM Detection



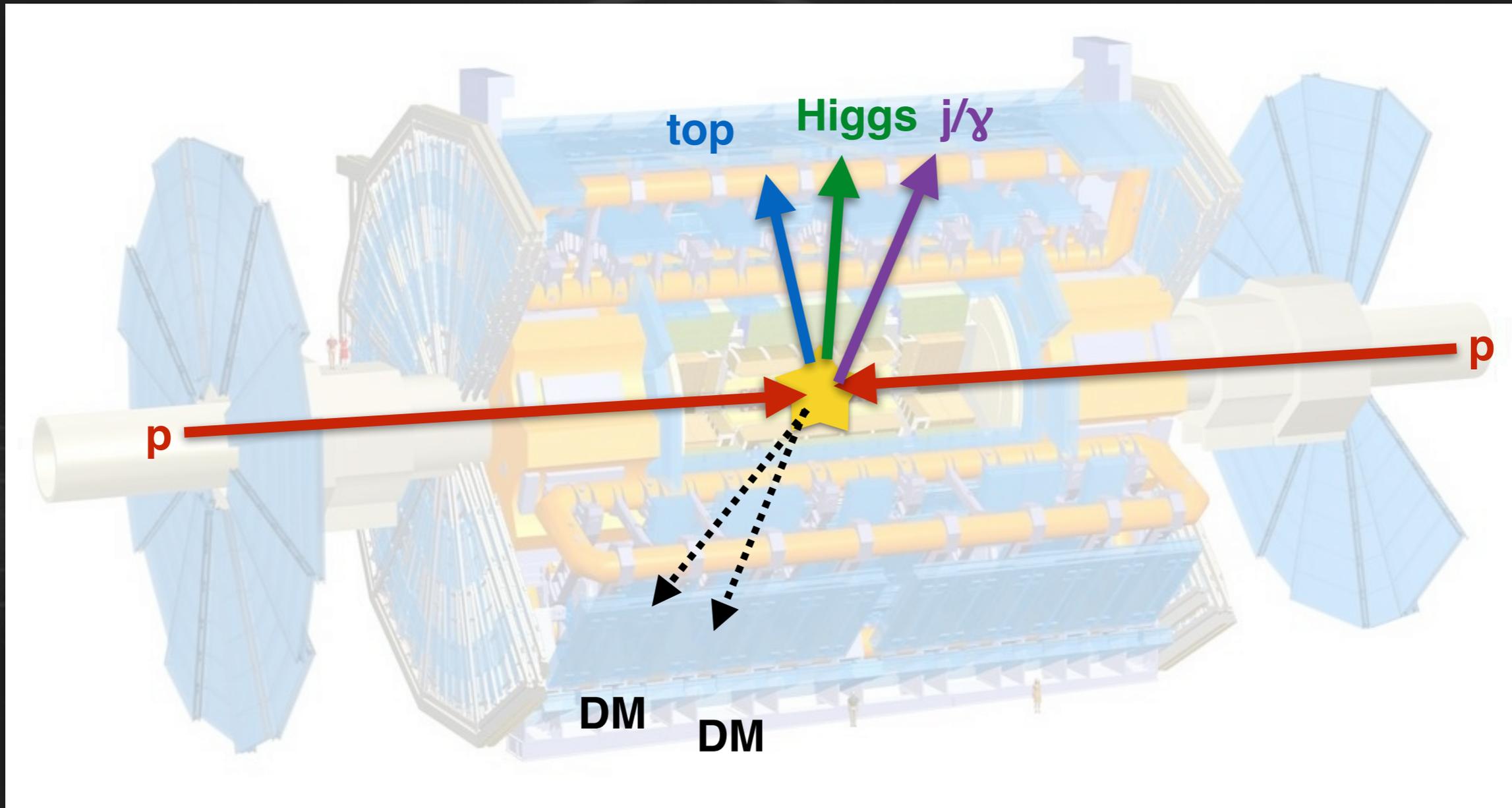
- **Protons collide** and produce almost always **visible particle**
- DM produced will escape the detector and recoil from the visible state
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DM Detection



- Protons collide and produce almost always visible particle
- DM escapes the detector and recoil from the visible state
- Signature explores wide range of interactions and final states particles

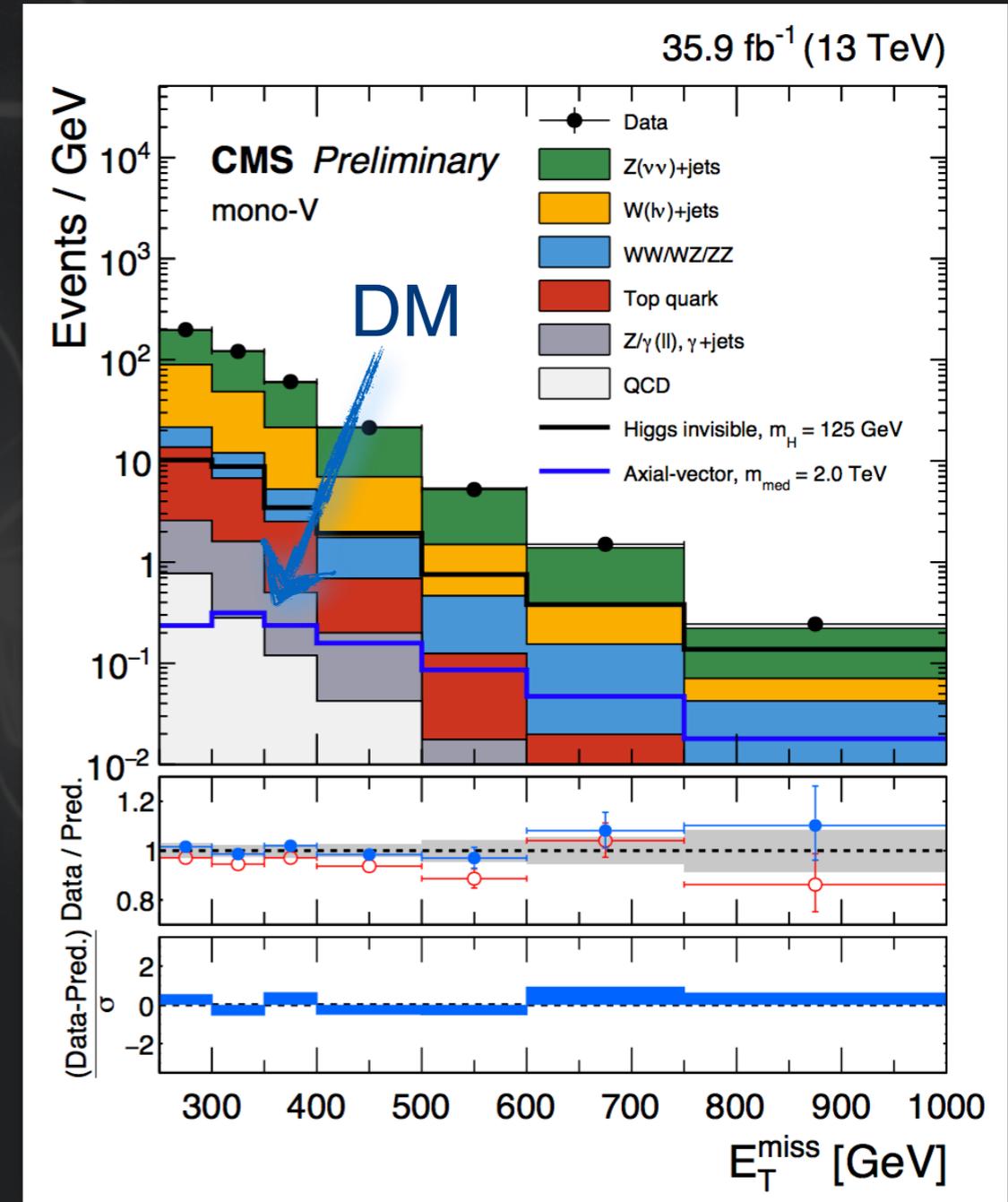
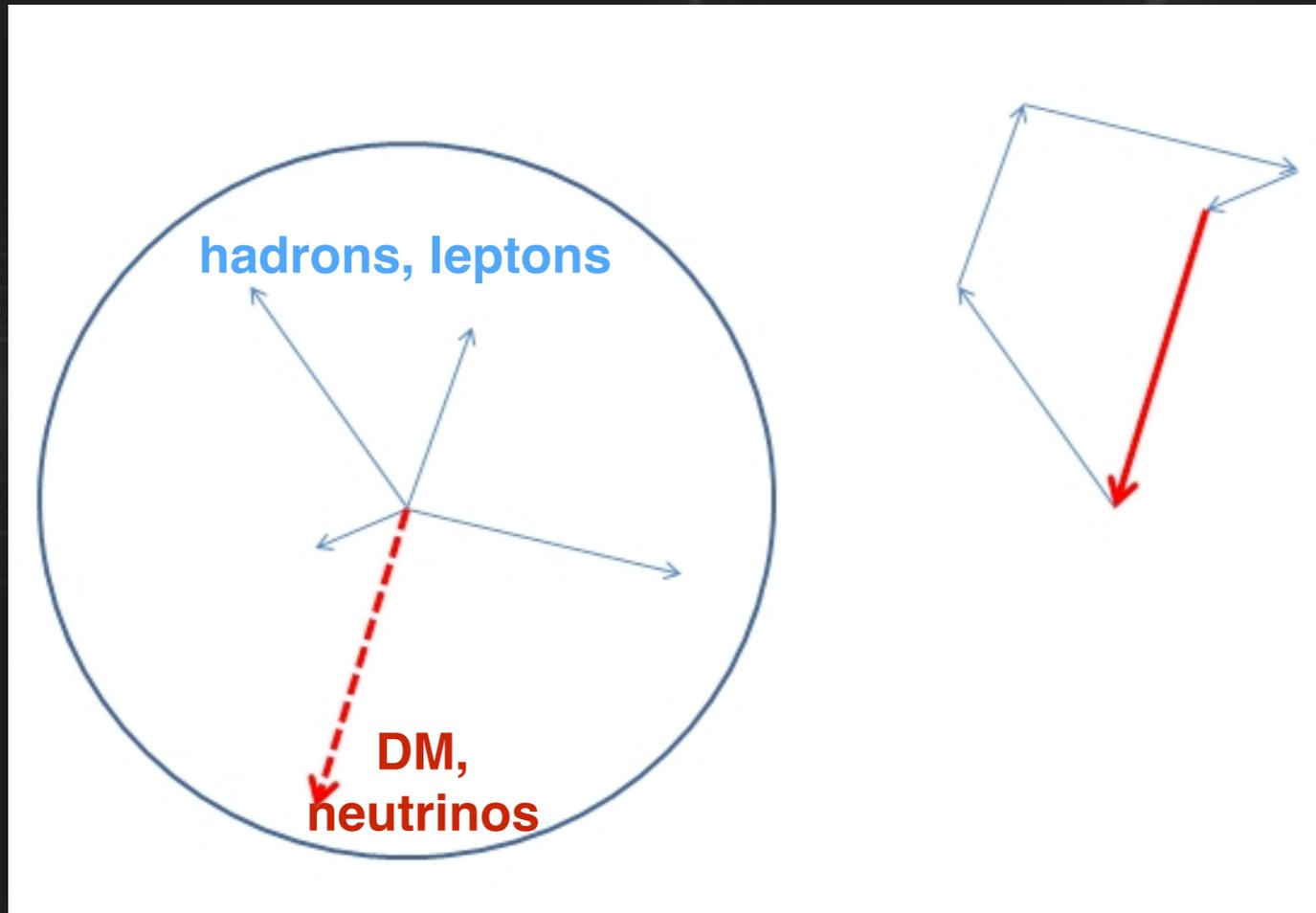
DM Detection



- Protons collide and produce almost always visible particle
- DM escapes the detector and recoil from the visible state
- Signature explores wide range of interactions and final states particles

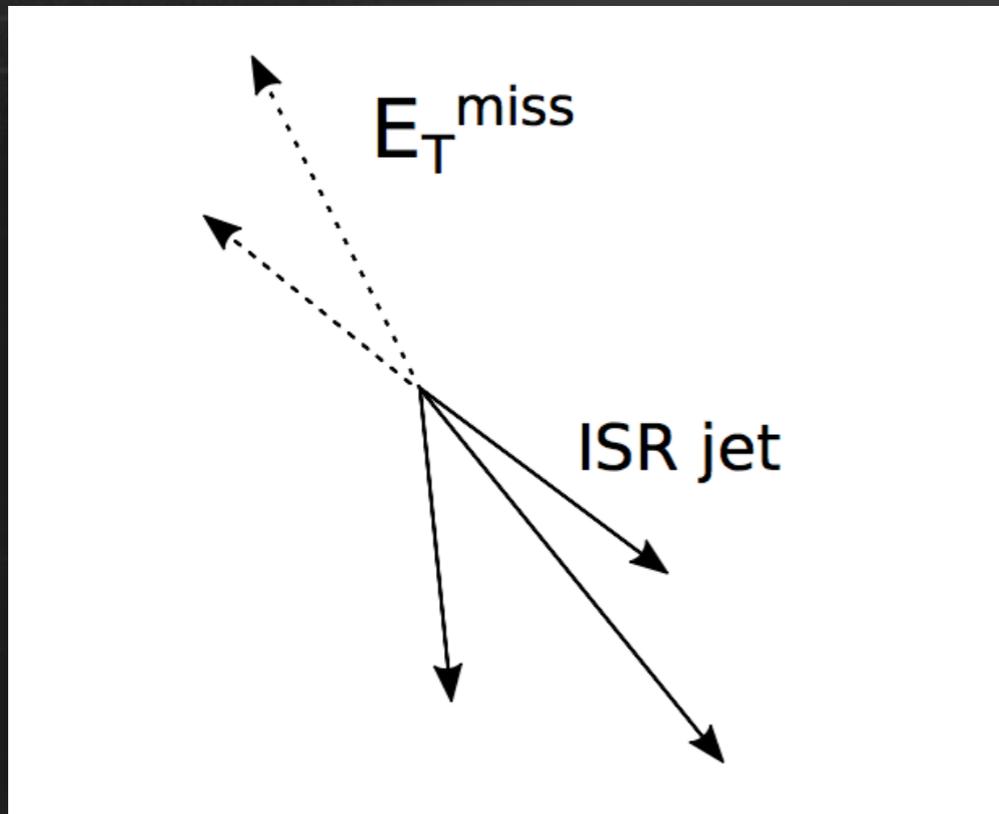
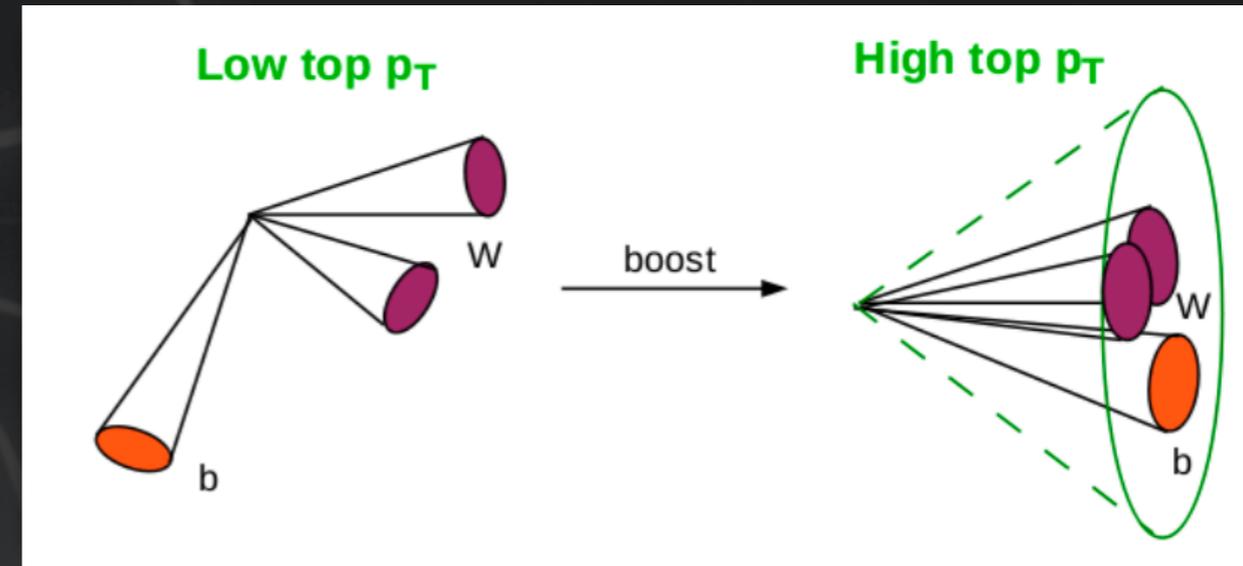
DM Detection

- Colliding **protons** have **no transverse momentum** → vectorial sum must vanish → non-vanishing (e.g. **missing**) **transverse momentum** indicates invisible particle escaping

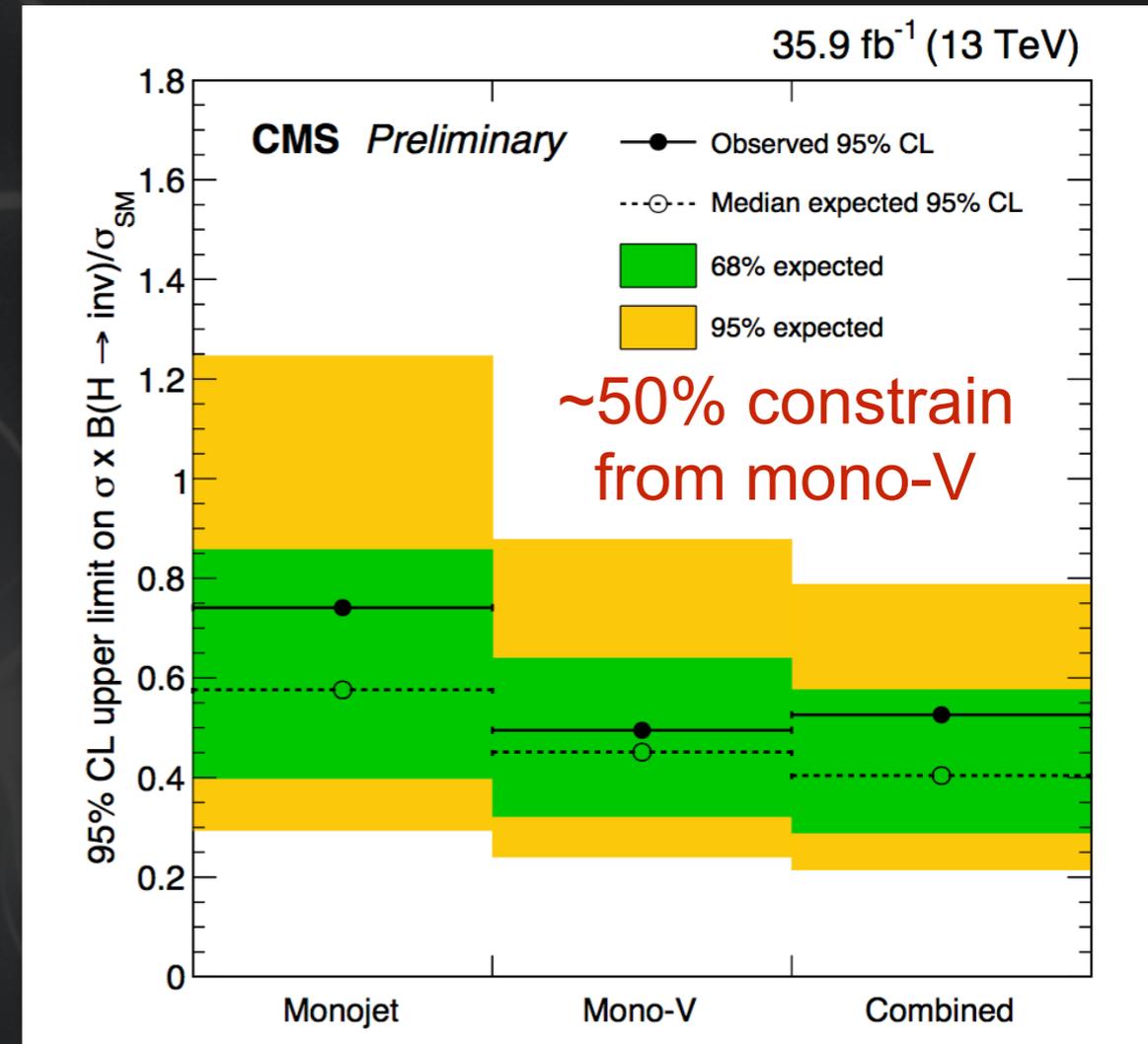
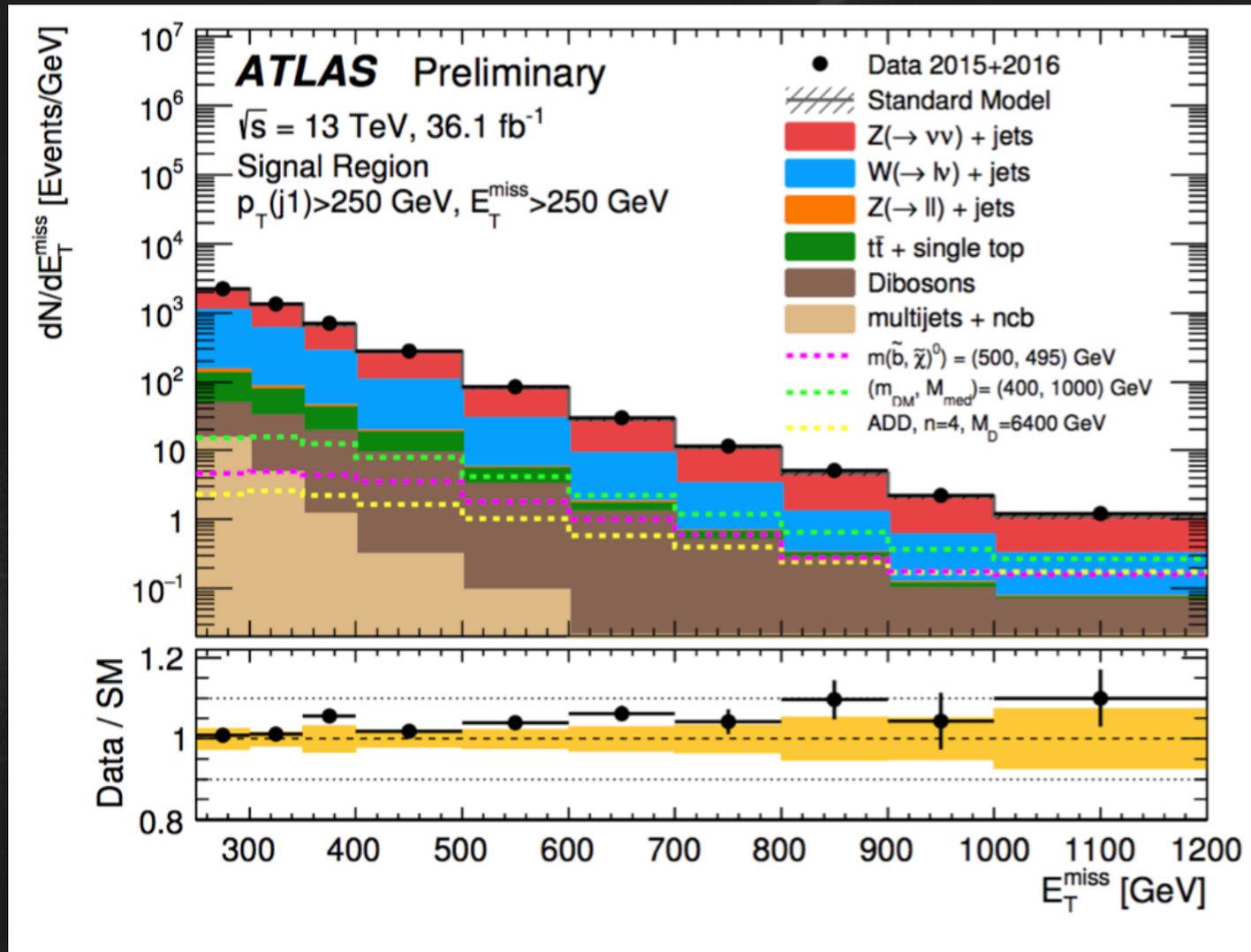


- '**Missing Energy**' most powerful variable in search for new physics
- Different **DM candidates** couple with different strengths to different **visible particles**

- Searches performed in **mono-X signature** with $X=\gamma, j, t\bar{t}, H, W, Z$ etc
- In the simplified picture mono-jet searches often most sensitive
- Energies at LHC can **boost decay particles** of final states into merged 'fat jet': mono-V

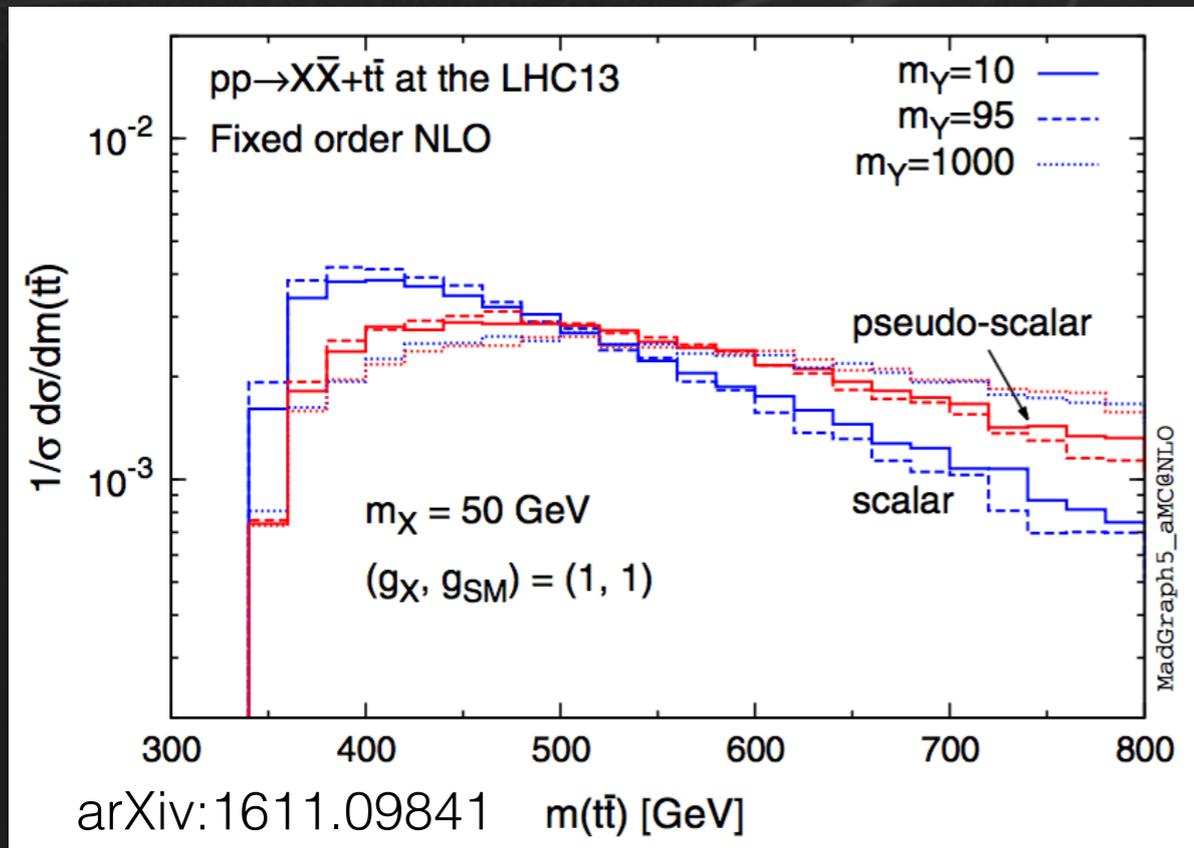
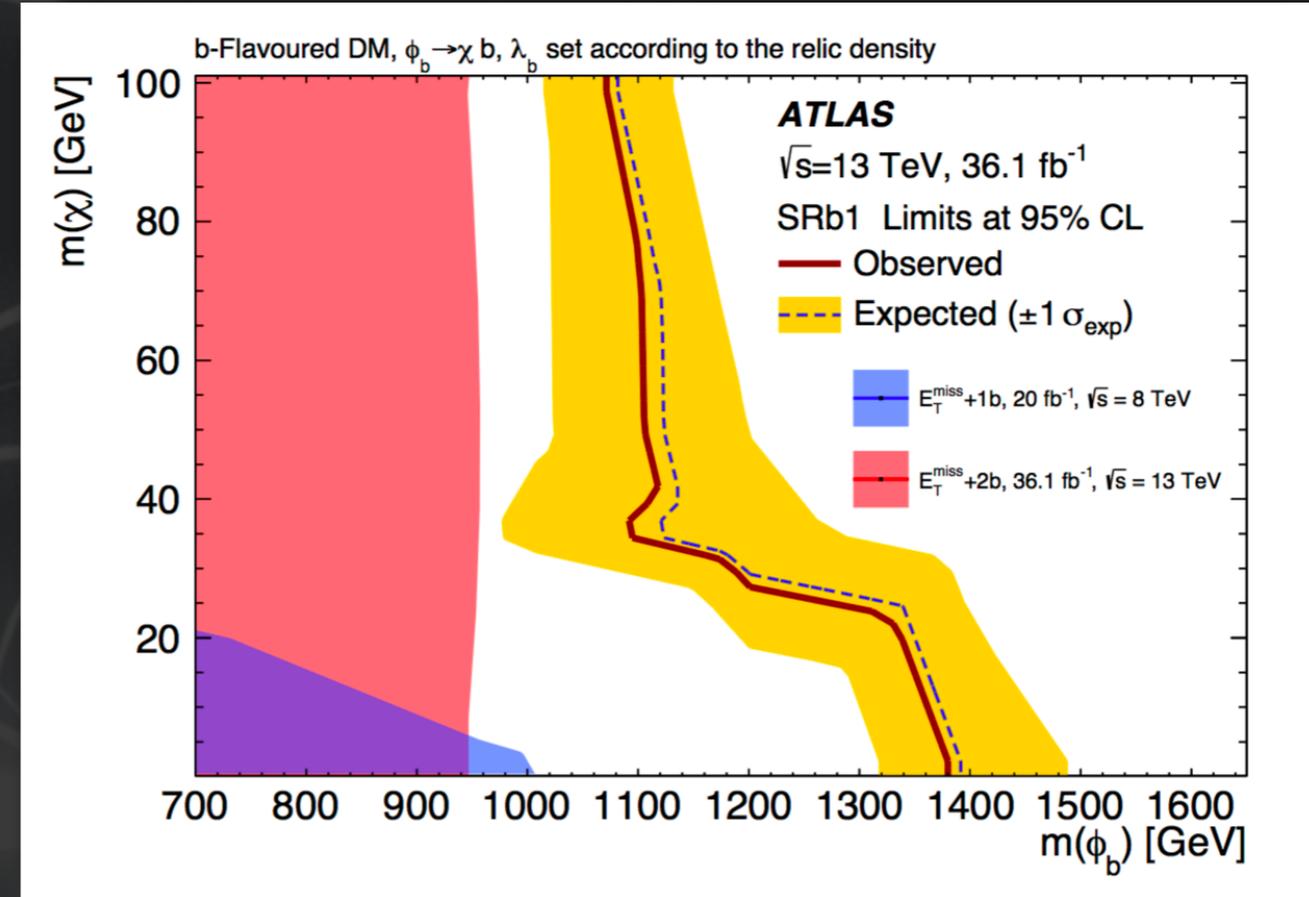
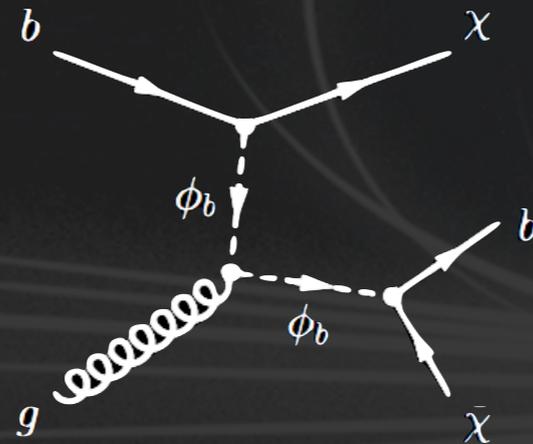


- Mono- γ , appears less sensitive bc. of α_{em} / α_s
- Such coupling difference actually lead to possibly DM natures
- **Vast majority of searches probe very trigger strategy:** MET and High p_T visible object



- Both ATLAS & CMS analysed 2016 dataset (36fb⁻¹)
- Best results for vector type couplings
- The mono-V channels also allows to constrain H→inv mostly from GF compared to dedicated searches mostly accessing VBF and VH

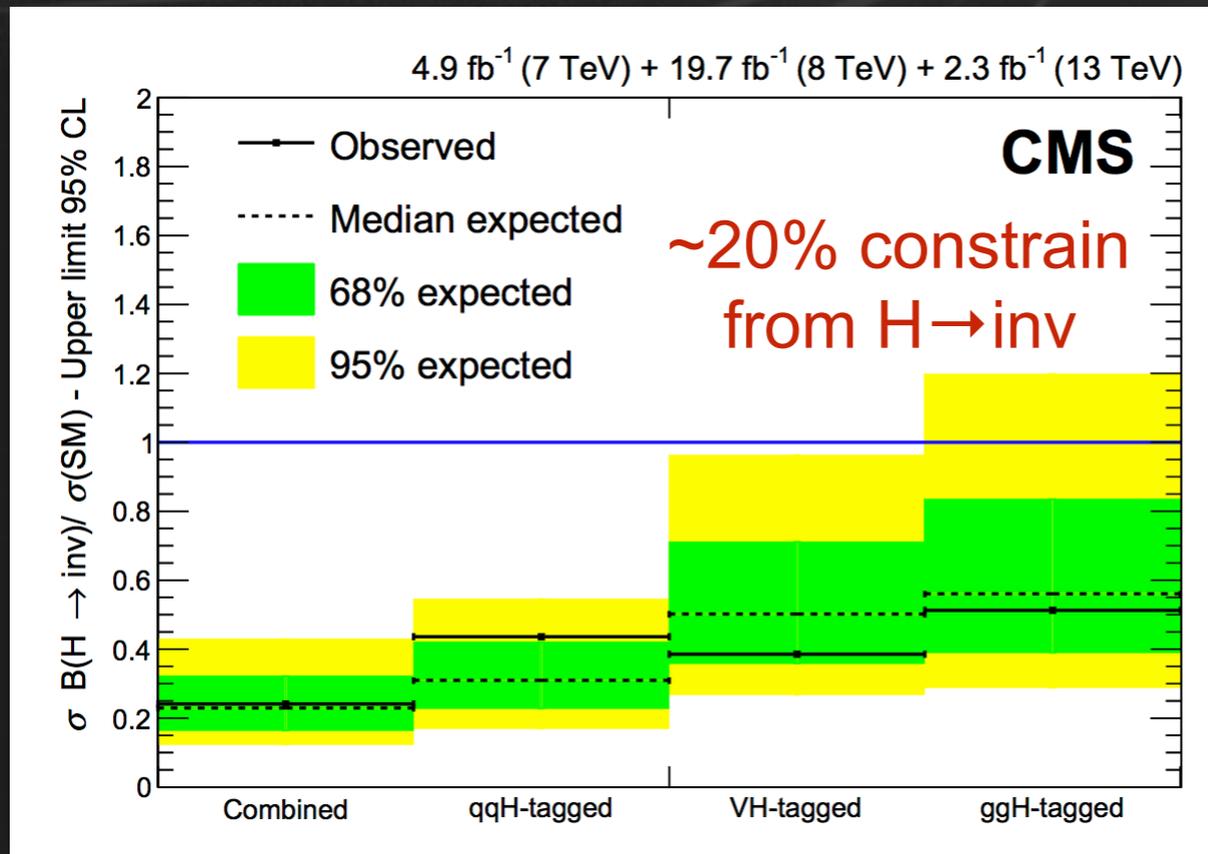
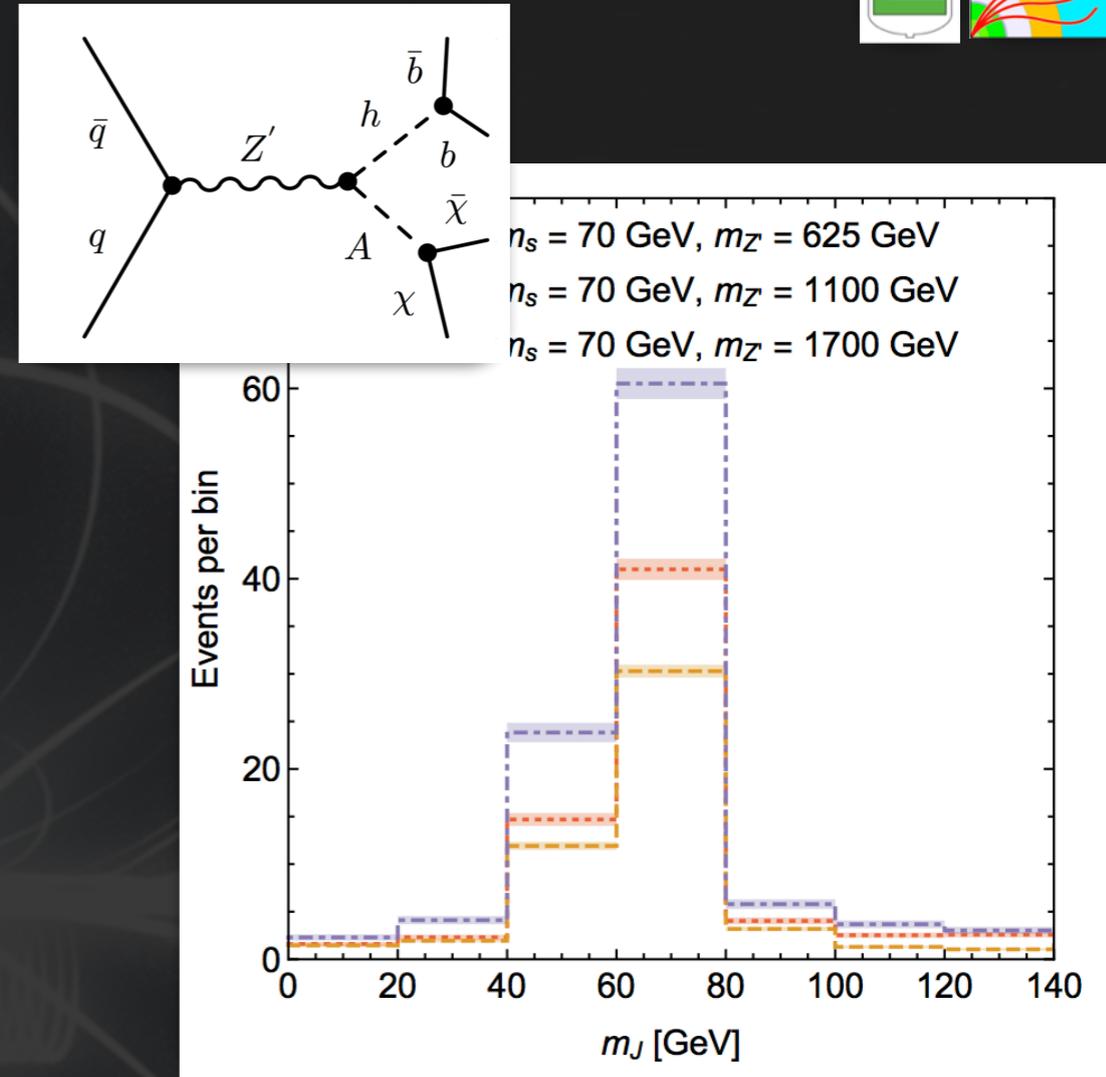
- Scalar type couplings also result in **mono- $t\bar{t}/bb$** with interesting features
- Also only current t-channel (b -FDM) model



- Scalar type couplings also result in mono- $t\bar{t}/bb$ with interesting features
- CP Structure of DM impacts **angular variables** or **$m(t\bar{t})$ spectrum**

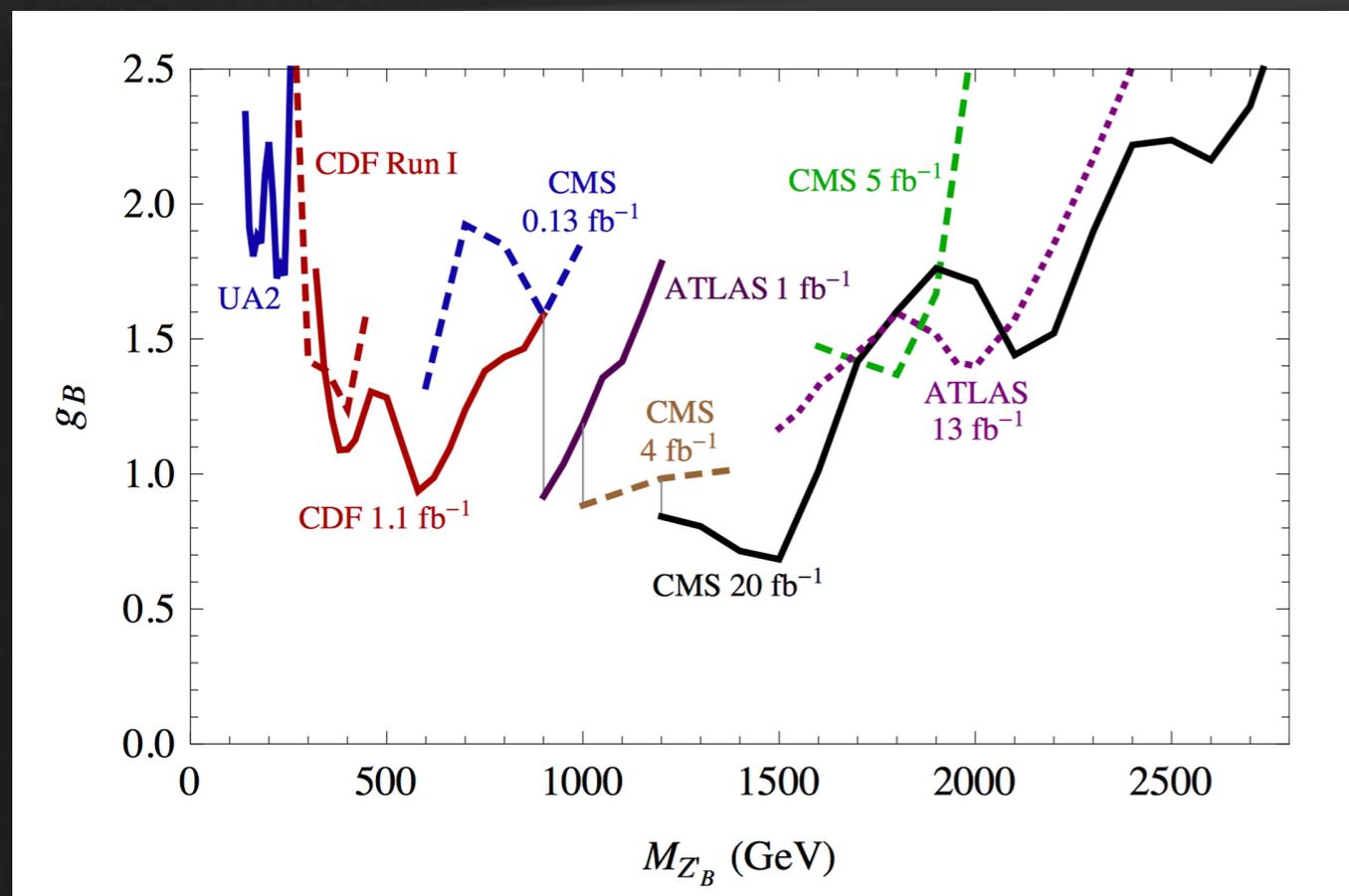
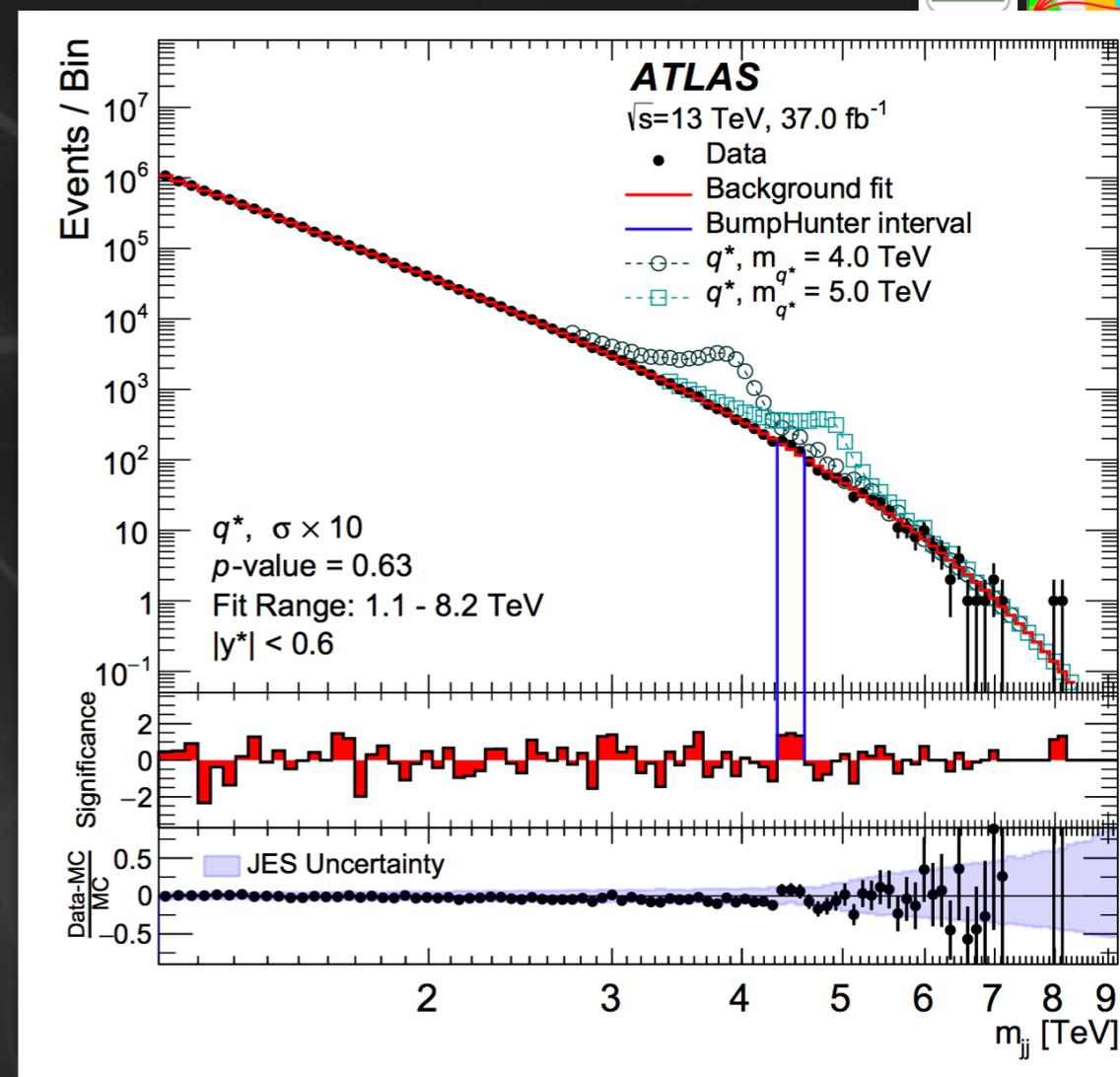
Searches with Higgs bosons

- Higgs ‘**natural**’ messenger to dark world, minimal extension to Lagrangian, ‘Higgs Portal’
- Search for $H \rightarrow XX$ or $DM+H$ production
- Mono-H searches quite similar to mono-j, **more interesting searches with more than one mediator**
- Allow for interesting signatures and to set relic density



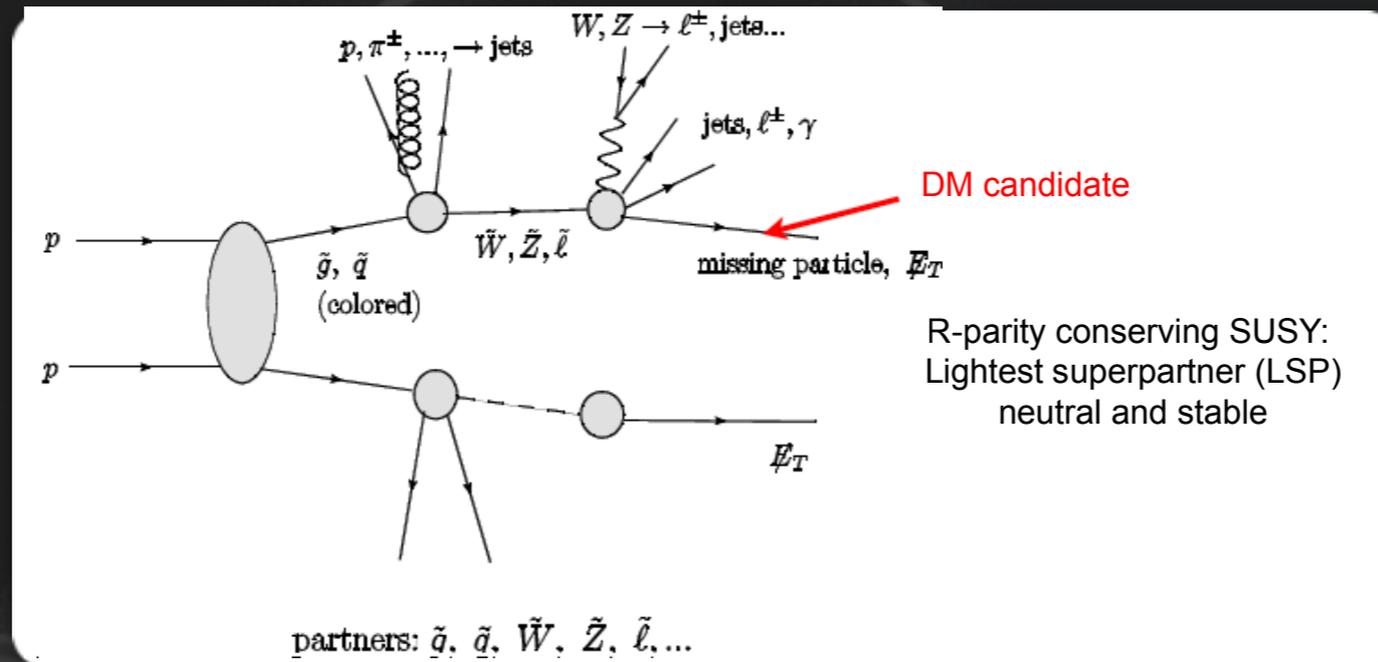
- $H \rightarrow XX$ only sensitive to masses of $m_{DM} \leq m_H$
- Leading searches utilize $H \rightarrow bb$ and $H \rightarrow \gamma\gamma$ decays

- Collider DM searches are actually searches for the mediator
- Search for the **mediator** itself in decays to **hadrons** and interpret them in **axial-vector model**
- Narrow resonance in dijet spectrum → **perhaps most straightforward searches**



- **Stringent constraints** at high masses
- Not dominated by single experiment because of challenging environment
- **At low masses** actually not well constrained

- DM part of extended sector of new physics at TeV scale



- Discovery may be rather easy, property measurement very hard

- $E_T^{\text{miss}} + \text{jets}$
- $E_T^{\text{miss}} + \text{b}$
- $E_T^{\text{miss}} + 1\ell$
- $E_T^{\text{miss}} + 2\ell$ (ss/os)
- $E_T^{\text{miss}} + \text{single jets}$
- $E_T^{\text{miss}} + \text{j} + \ell + \text{b}$
- $E_T^{\text{miss}} + \text{j} + 2\ell + \text{b}$
- $E_T^{\text{miss}} + \text{jets} + \text{Z-boson}$
- $E_T^{\text{miss}} + 3/4 \ell$
- $E_T^{\text{miss}} + \text{jets} + \gamma$
- $E_T^{\text{miss}} + \text{jets} + \gamma$
- ...

- Results interpreted in cMSSM, pMSSM and simplified models, no excess
- Often the neutralino is the DM candidate (LSP)

ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

ATLAS Preliminary
 $\sqrt{s} = 7, 8, 13$ TeV

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [fb^{-1}]$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference	
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ /1-2 τ	2-10 jets/3 b	Yes	20.3	\tilde{q}, \tilde{g}	1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{q}	1.57 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(1^{st} \text{ gen. } \tilde{q})=m(2^{nd} \text{ gen. } \tilde{q})$	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	\tilde{q}	608 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0) < 5$ GeV	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.02 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.01 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	\tilde{g}	1.825 TeV	$m(\tilde{\chi}_1^0) < 400$ GeV	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	\tilde{g}	1.8 TeV	$m(\tilde{\chi}_1^0) < 400$ GeV	ATLAS-CONF-2017-033
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	\tilde{g}	2.0 TeV	$m(\tilde{\chi}_1^0) < 400$ GeV	1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	\tilde{g}	1.65 TeV	$c\tau(\text{NLSP}) < 0.1$ mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	\tilde{g}	1.37 TeV	$m(\tilde{\chi}_1^0) < 950$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu < 0$	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	\tilde{g}	1.8 TeV	$m(\tilde{\chi}_1^0) > 680$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu > 0$	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	\tilde{g}	900 GeV	$m(\text{NLSP}) > 430$ GeV	1503.03290
Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})=1.5$ TeV	1502.01518	
3 rd gen. \tilde{g} med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	\tilde{g}	1.92 TeV	$m(\tilde{\chi}_1^0) < 600$ GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	\tilde{g}	1.97 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{\chi}_1^\pm$	0-1 e, μ	3 b	Yes	20.1	\tilde{g}	1.37 TeV	$m(\tilde{\chi}_1^0) < 300$ GeV	1407.0600
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	\tilde{b}_1	950 GeV	$m(\tilde{\chi}_1^0) < 420$ GeV	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{\chi}_1^\pm$	2 e, μ (SS)	1 b	Yes	36.1	\tilde{b}_1	275-700 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_1^0) + 100$ GeV	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$	0-2 e, μ	1-2 b	Yes	4.7/13.3	\tilde{t}_1	117-170 GeV	$m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)=55$ GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	\tilde{t}_1	90-198 GeV	$m(\tilde{\chi}_1^0)=1$ GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	\tilde{t}_1	90-323 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)=5$ GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	150-600 GeV	$m(\tilde{\chi}_1^0) > 150$ GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	\tilde{t}_2	290-790 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	\tilde{t}_2	320-880 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2017-019
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$	90-440 GeV	$m(\tilde{\chi}_1^0)=0$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu(\tilde{\ell}\bar{\nu})$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^\pm$	710 GeV	$m(\tilde{\chi}_1^\pm)=0$, $m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm/\tilde{\chi}_2^0, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu(\tilde{\tau}\bar{\nu}), \tilde{\chi}_2^0 \rightarrow \tilde{\tau}\nu(\tilde{\tau}\bar{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{\chi}_1^\pm)=0$, $m(\tilde{\tau}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L\ell(\bar{\nu}\bar{\nu}), \tilde{\ell}\tilde{\nu}\tilde{\ell}_L\ell(\bar{\nu}\bar{\nu})$	3 e, μ	0	Yes	36.1	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	1.16 TeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, $m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	580 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0h, \tilde{\chi}_1^0, h \rightarrow b\tilde{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	270 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_2^0, \tilde{\chi}_3^0$	635 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)=0$, $m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	\tilde{W}	115-370 GeV	$c\tau < 1$ mm	1507.05493
GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	2 γ	-	Yes	20.3	\tilde{W}	590 GeV	$c\tau < 1$ mm	1507.05493	
Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$	430 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^\pm) = 0.2$ ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$	495 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^\pm) < 15$ ns	1506.05332
	Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	\tilde{g}	850 GeV	$m(\tilde{\chi}_1^0)=100$ GeV, $10 \mu\text{s} < \tau(\tilde{g}) < 1000$ s	1310.6584
	Stable \tilde{g} R-hadron	trk	-	-	3.2	\tilde{g}	1.58 TeV	-	1606.05129
	Metastable \tilde{g} R-hadron	dE/dx trk	-	-	3.2	\tilde{g}	1.57 TeV	$m(\tilde{\chi}_1^0)=100$ GeV, $\tau > 10$ ns	1604.04520
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$10 < \tan\beta < 50$	1411.6795
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	$1 < \tau(\tilde{\chi}_1^0) < 3$ ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ee\nu/\mu\nu/\mu\nu\nu$	displ. $ee/\mu\nu/\mu\nu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7 < c\tau(\tilde{\chi}_1^0) < 740$ mm, $m(\tilde{g})=1.3$ TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$6 < c\tau(\tilde{\chi}_1^0) < 480$ mm, $m(\tilde{g})=1.1$ TeV	1504.05162
	RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	$\lambda_{11}^2=0.11, \lambda_{132/133/233}=0.07$
Bilinear RPV CMSSM		2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{q}, \tilde{g}	1.45 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP} < 1$ mm	1404.2500
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\nu, e\mu\nu, \mu\mu\nu$		4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^\pm$	1.14 TeV	$m(\tilde{\chi}_1^0) > 400$ GeV, $\lambda_{12k} \neq 0$ ($k=1,2$)	ATLAS-CONF-2016-075
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tau\nu_e, e\tau\nu_\tau$		3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm)$, $\lambda_{133} \neq 0$	1405.5086
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0$		0	4-5 large- R jets	-	14.8	\tilde{g}	1.08 TeV	$BR(t)=BR(b)=BR(c)=0\%$	ATLAS-CONF-2016-057
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{\chi}_1^0$		0	4-5 large- R jets	-	14.8	\tilde{g}	1.55 TeV	$m(\tilde{\chi}_1^0)=800$ GeV	ATLAS-CONF-2016-057
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{\chi}_1^0$		1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	2.1 TeV	$m(\tilde{\chi}_1^0)=1$ TeV, $\lambda_{112} \neq 0$	ATLAS-CONF-2017-013
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow bs$		1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	1.65 TeV	$m(\tilde{t}_1)=1$ TeV, $\lambda_{323} \neq 0$	ATLAS-CONF-2017-013
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$		0	2 jets + 2 b	-	15.4	\tilde{t}_1	410 GeV	-	ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$		2 e, μ	2 b	-	36.1	\tilde{t}_1	0.4-1.45 TeV	$BR(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$	ATLAS-CONF-2017-036
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{c}	510 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

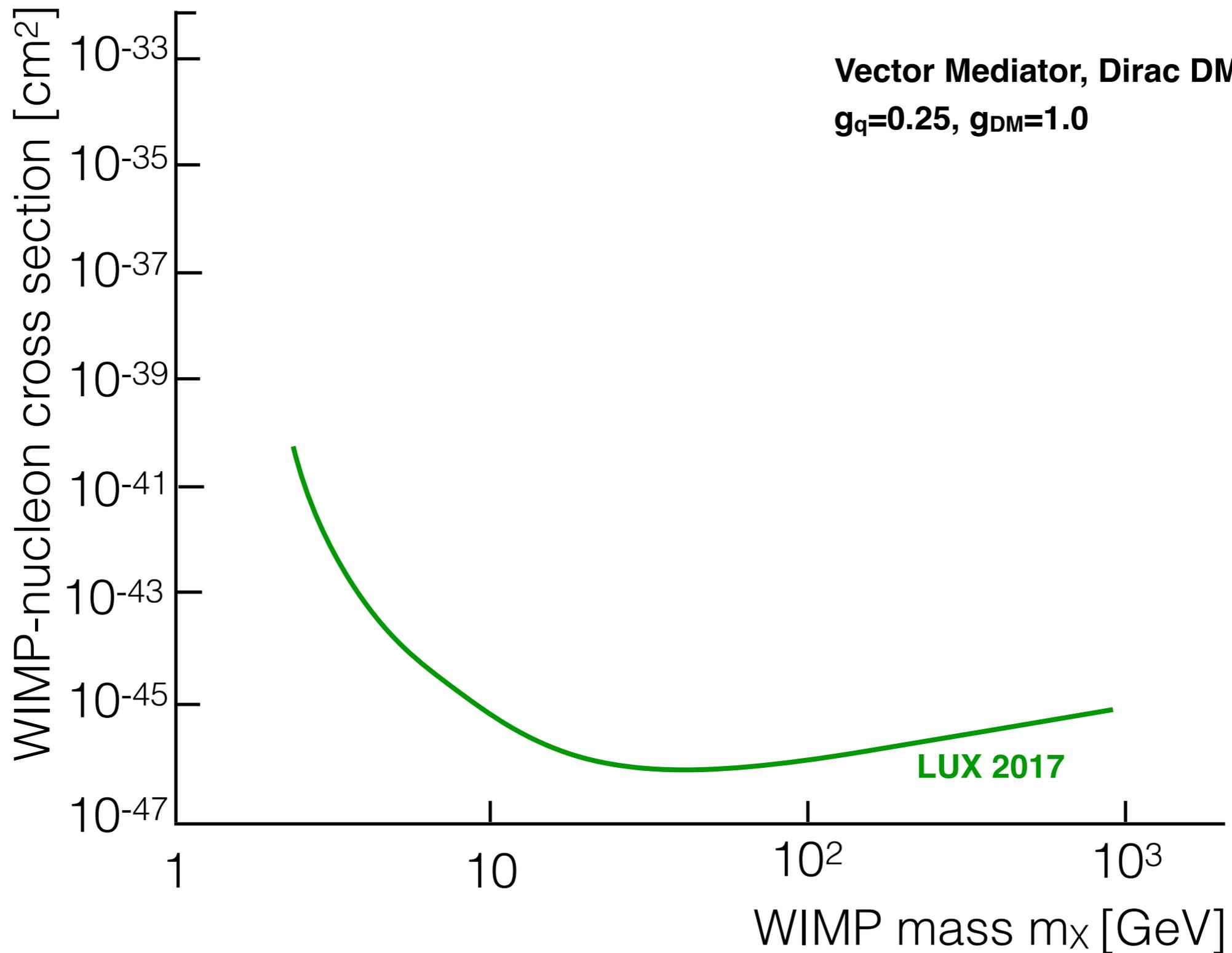
10⁻¹ 1 Mass scale [TeV]



Current Results

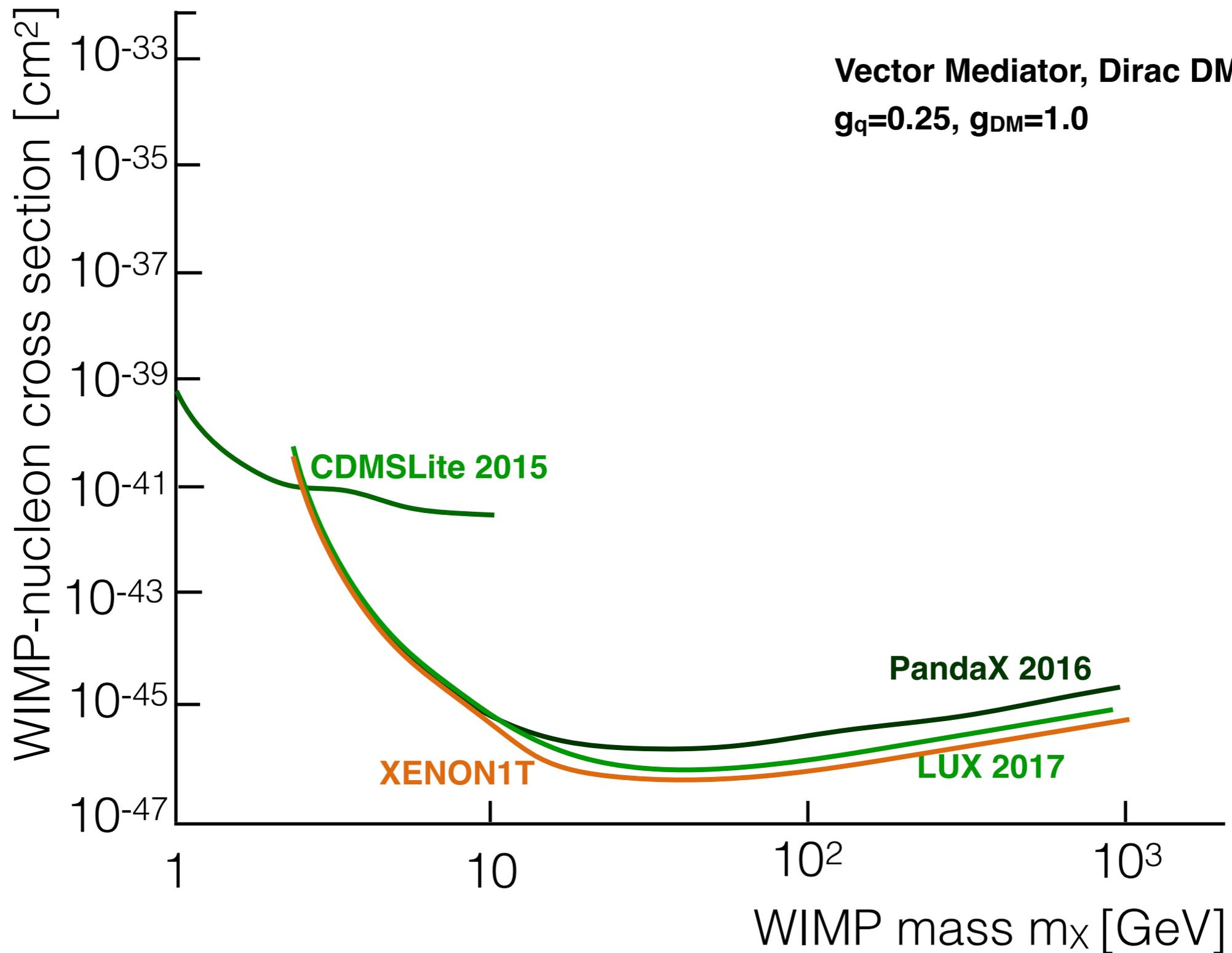


Results



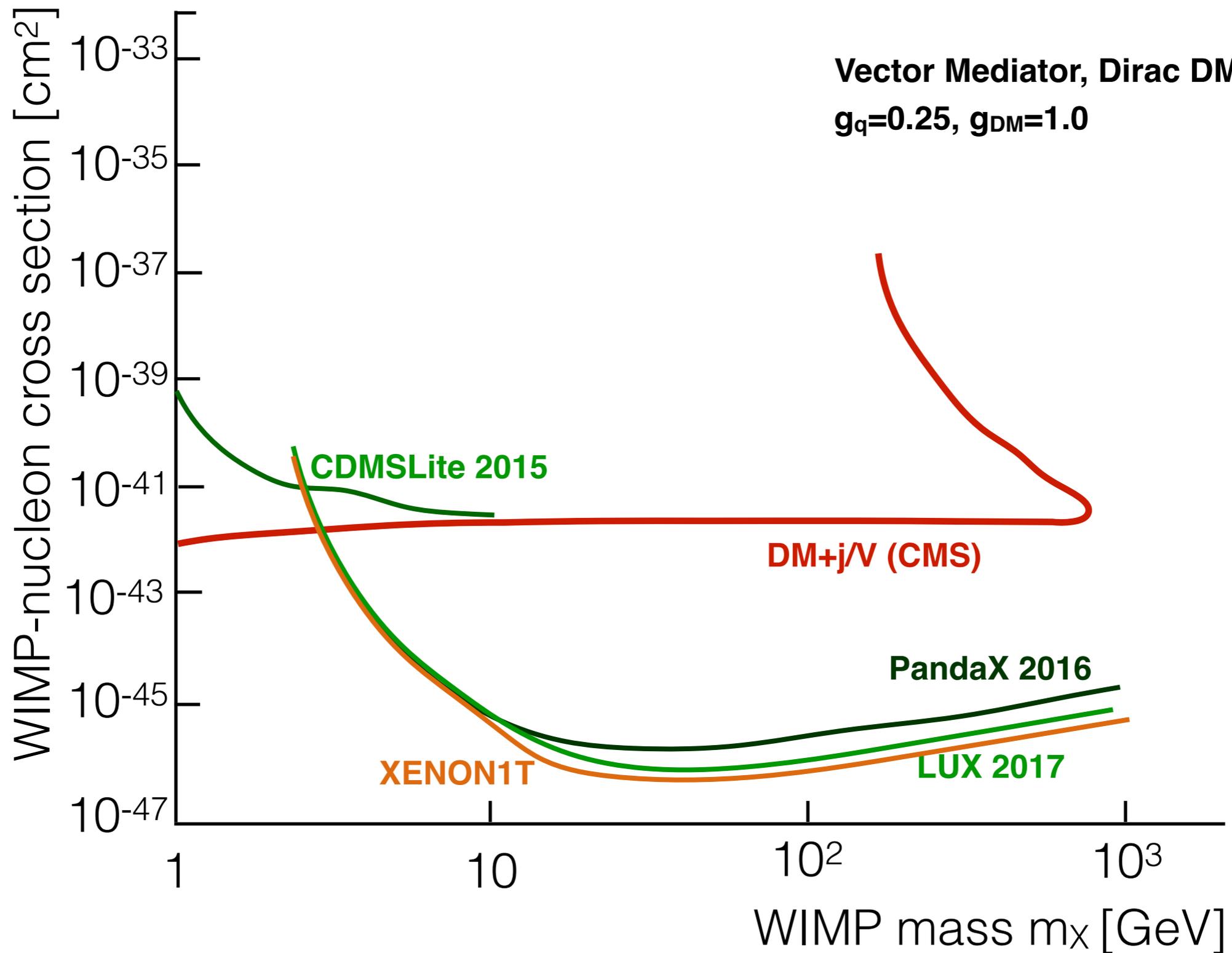


Results

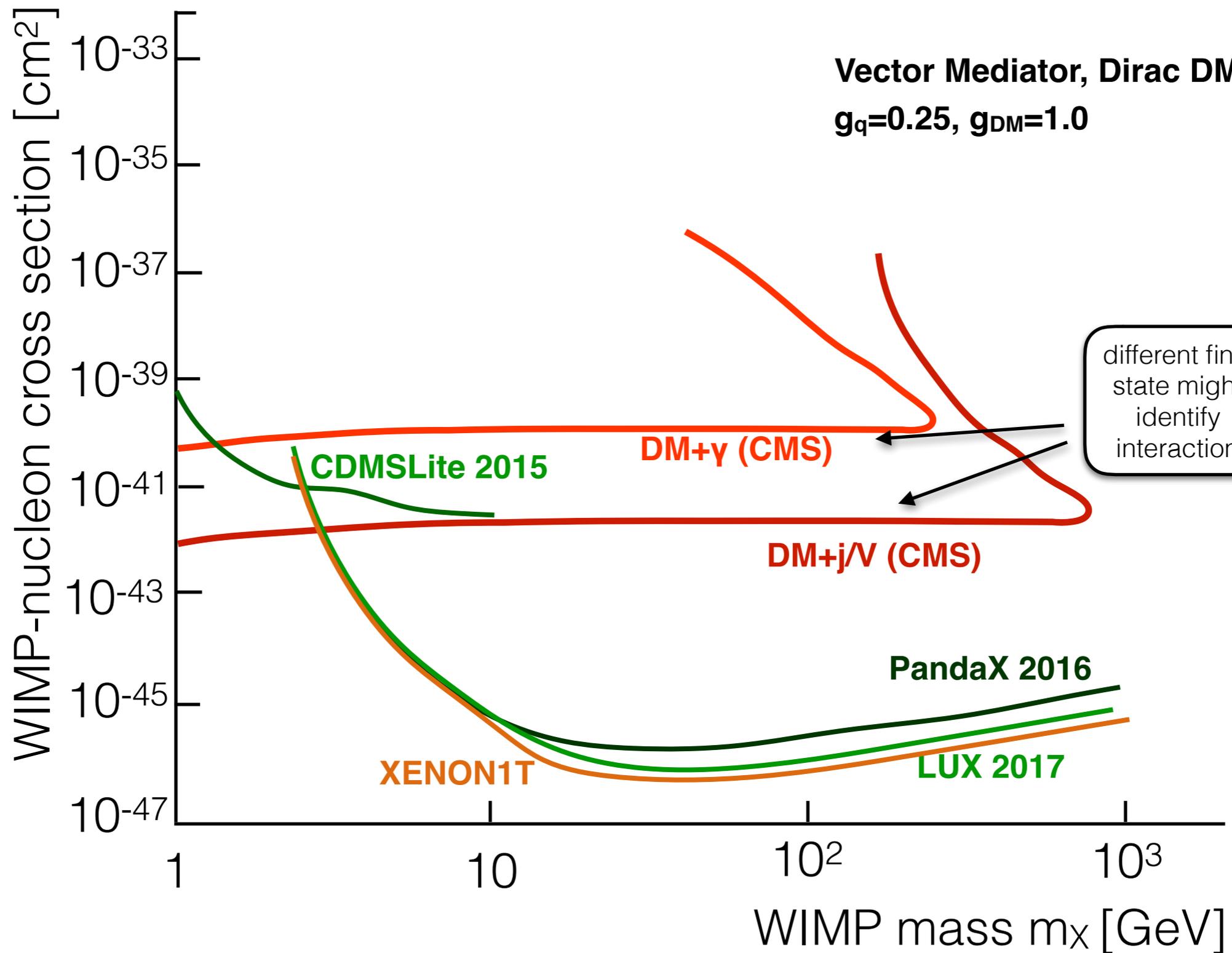




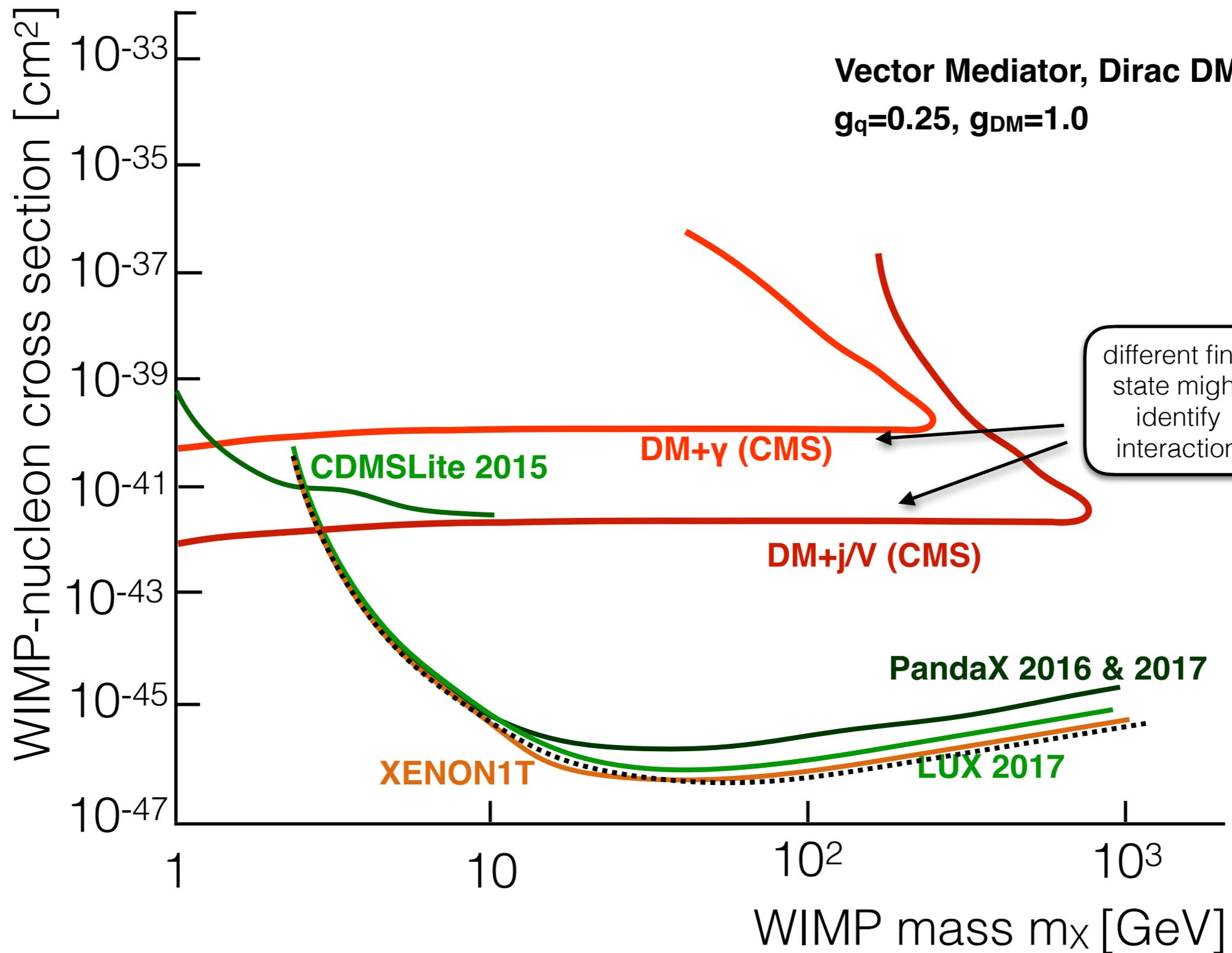
Results



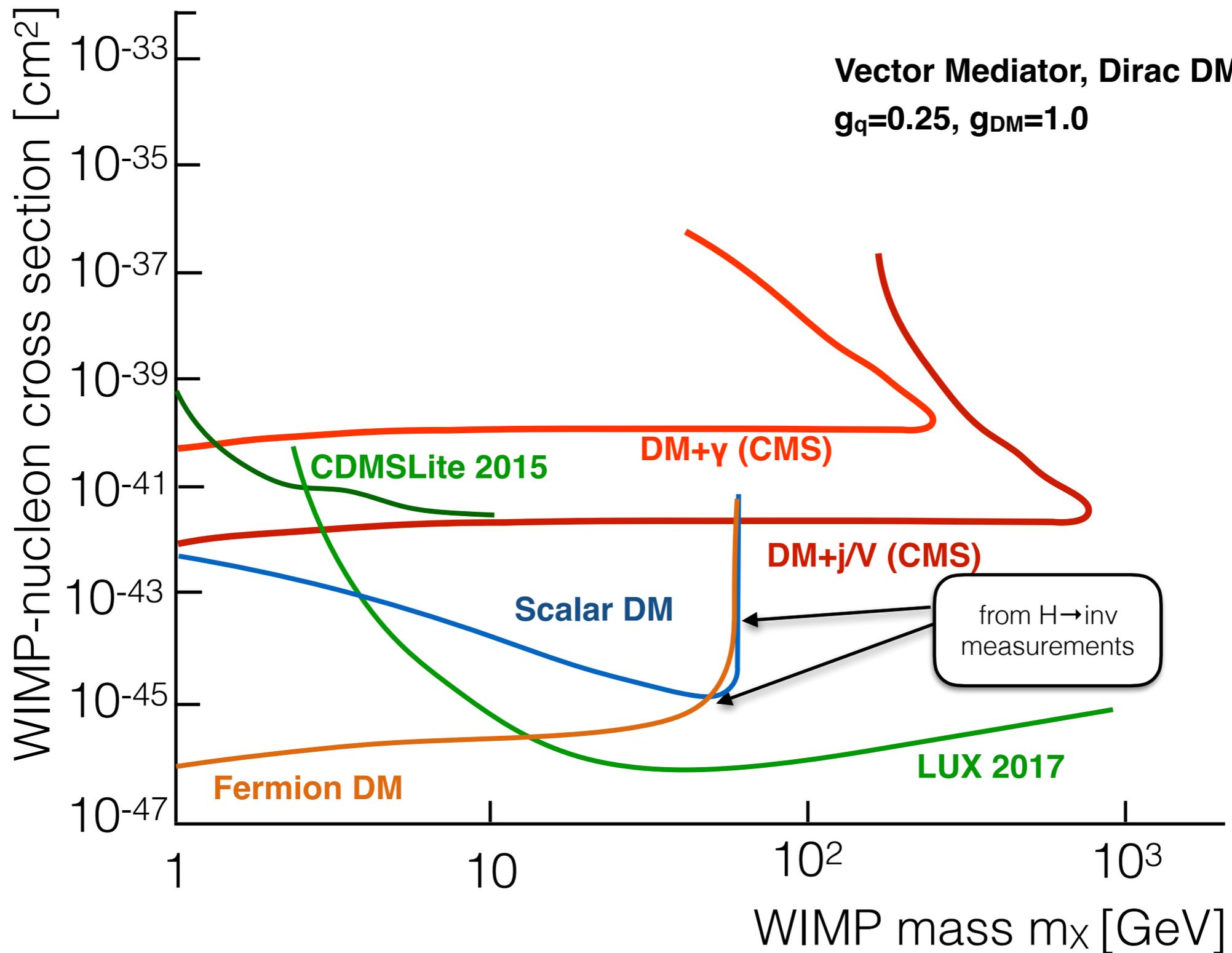
Results



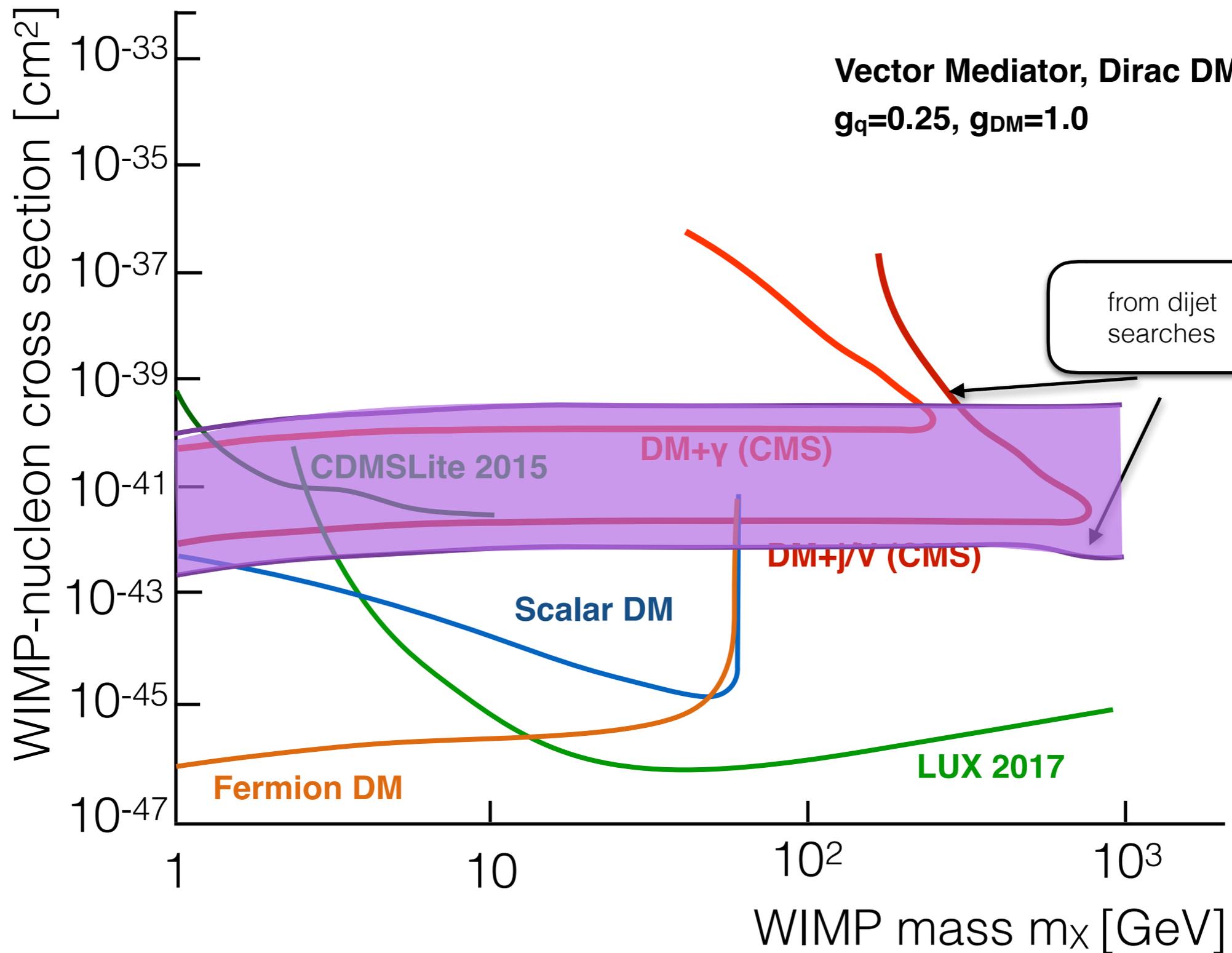
Results



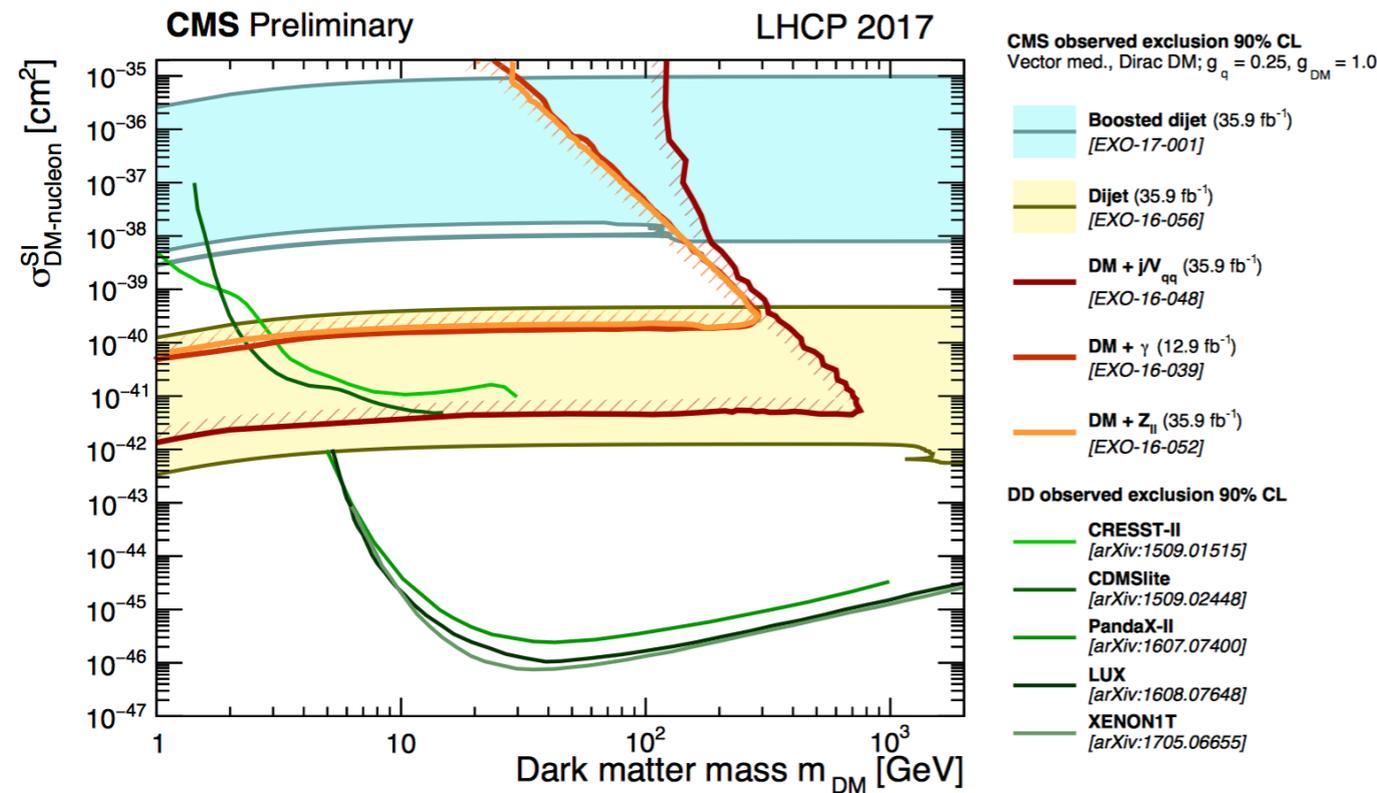
Results



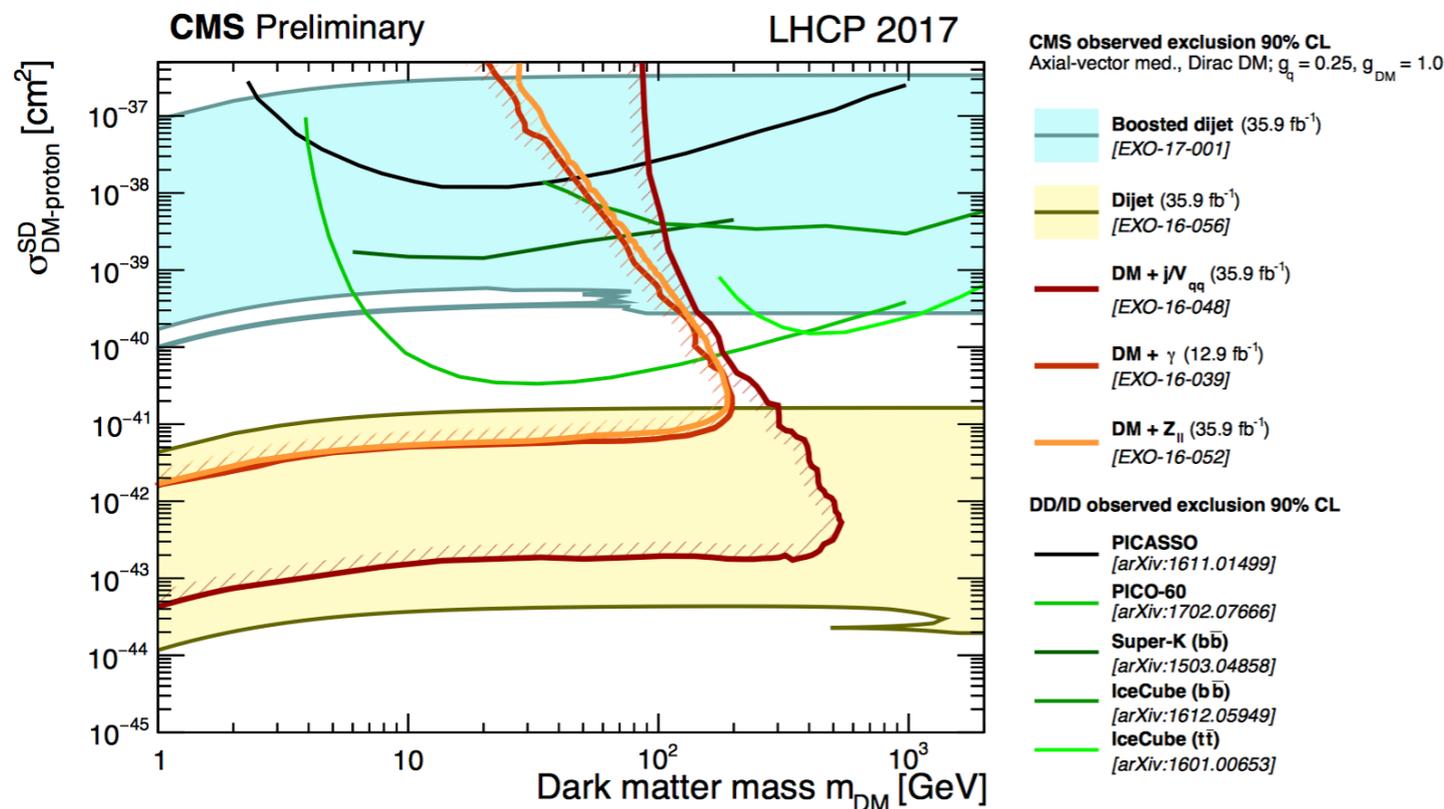
Results



spin-independent



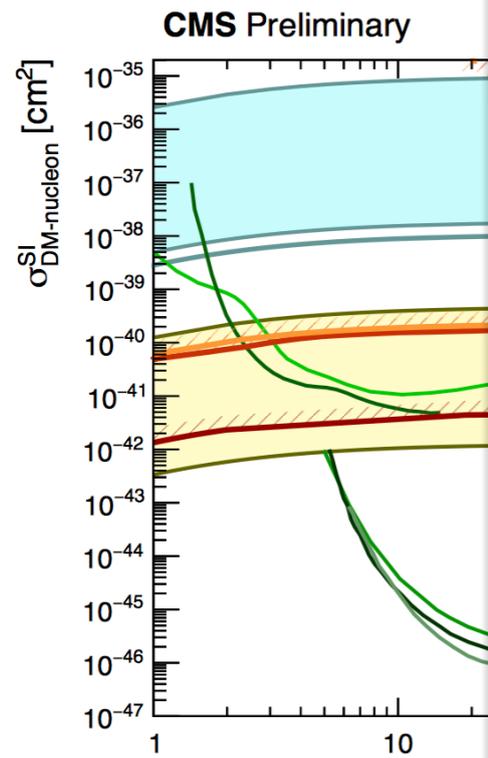
spin-dependent



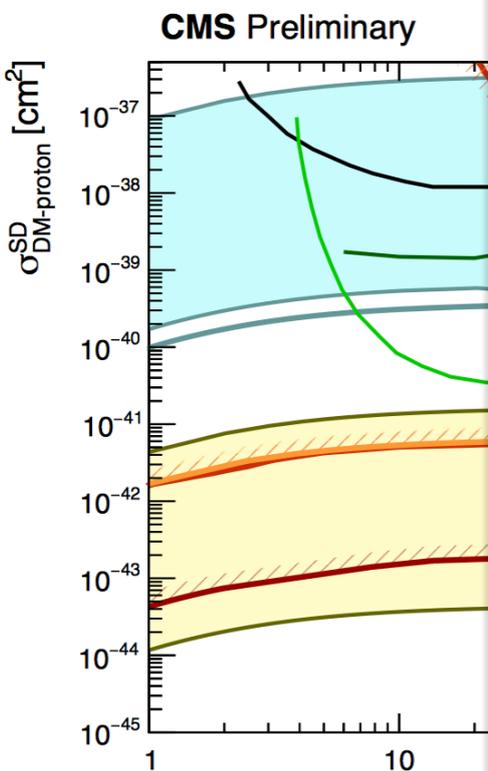
- Setting stringent constraints on spin-(in)dependent DM
- Remember, spin-independent suppressed at DD
- All searches employ similar tigger/models
- (Pseudo-)Scalar searches are just becoming sensitive
- Some model dependency
- Many more interesting searches I cannot cover here

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/>
<https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/DM-summary-plots-Jul17.pdf>

spin-independent



spin-dependent



A search for invisible phenomena with ATLAS.

Missing Transverse Momentum

The data has been corrected for detector effects.

Measured Ratios.

Measured as a function of three observables and two fiducial regions.

This data can be compared to any SM prediction or BSM prediction at particle level, where the BSM model produces MET+jets final states.

Pair Production.

WIMP Dark Matter

Standard Model

Missing transverse momentum indicates particles invisible to the detector.

$$R_{miss} = \frac{\sigma_{fid}(p_T^{miss} + jets)}{\sigma_{fid}(l^+l^- + jets)}$$

Using a ratio significantly reduces experimental and theoretical uncertainties associated with jets.

BSM Interpretations.

The presence of BSM physics in the numerator would lead to a discrepancy between the measured and predicted ratio.

To demonstrate BSM sensitivity, limits set on three BSM models:

- EFT with general interactions of EW bosons with DM.
- Higgs Boson decay to invisible particles.
- Simplified model of WIMP DM pair production.

This analysis gives the best sensitivity.

Measurement of detector-corrected observables sensitive to the anomalous production of events containing one or more hadronic jets and large missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector.

Rebecca Pickles, ATLAS Collaboration.
 [arXiv:1707.03263]
 [Eur. Phys. J. C 77 (2017) 765]

stringent constraints (in)dependent DM

ber, spin-dependent suppressed at

ches employ similar models

o-) Scalar searches becoming sensitive

model dependency

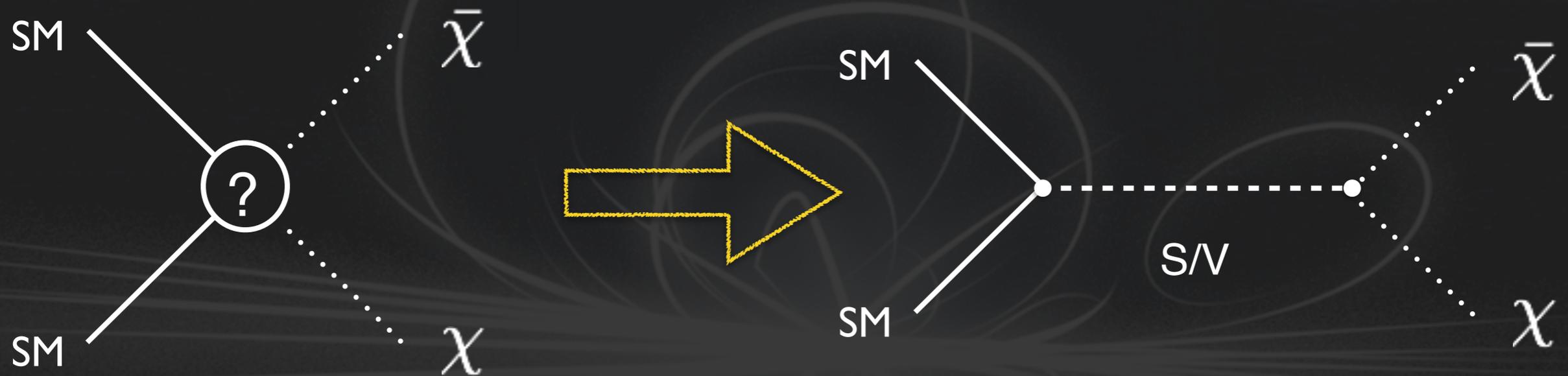
ore interesting es I cannot cover

rn.ch/Atlas/GROUPS/PHYSICS/Plots/EXOTICS/
 /twiki/pub/ CMSPublic/
 /DM-summary-plots-Jul17.pdf



How do we connect and learn from
all three fields?

- In a real life we need some mediator between the 'dark World' and the known Universe



- Leads to **known interactions**
 - scalar ($\psi\psi$),
 - pseudo scalar ($\bar{\psi}\gamma^5\psi$),
 - vector $\bar{\psi}\gamma^\mu\psi$,
 - axial-vector ($\bar{\psi}\gamma^\mu\gamma^5\psi$)
- **Interesting kinematics** and experimental **sensitivities**



EWK style
(equal to leptons)

Vector

$$g_{\text{DM}} Z'_{\mu} \bar{\chi} \gamma^{\mu} \chi$$

Besides very low DM masses
DD wins clearly over collider

Axial-Vector

$$g_{\text{DM}} Z''_{\mu} \bar{\chi} \gamma^{\mu} \gamma^5 \chi$$

DD and collider are equal in overall sensitivity but probe different regions of parameter space

mass based
(Yukawa)

Scalar

$$g_{\text{DM}} S \bar{\chi} \chi$$

DD and collider are equal in overall sensitivity but probe different regions of parameter space

Pseudo-Scalar

$$g_{\text{DM}} P \bar{\chi} \gamma^5 \chi$$

No limits from DD (only from ID). Collider provides limits similar to scalar couplings

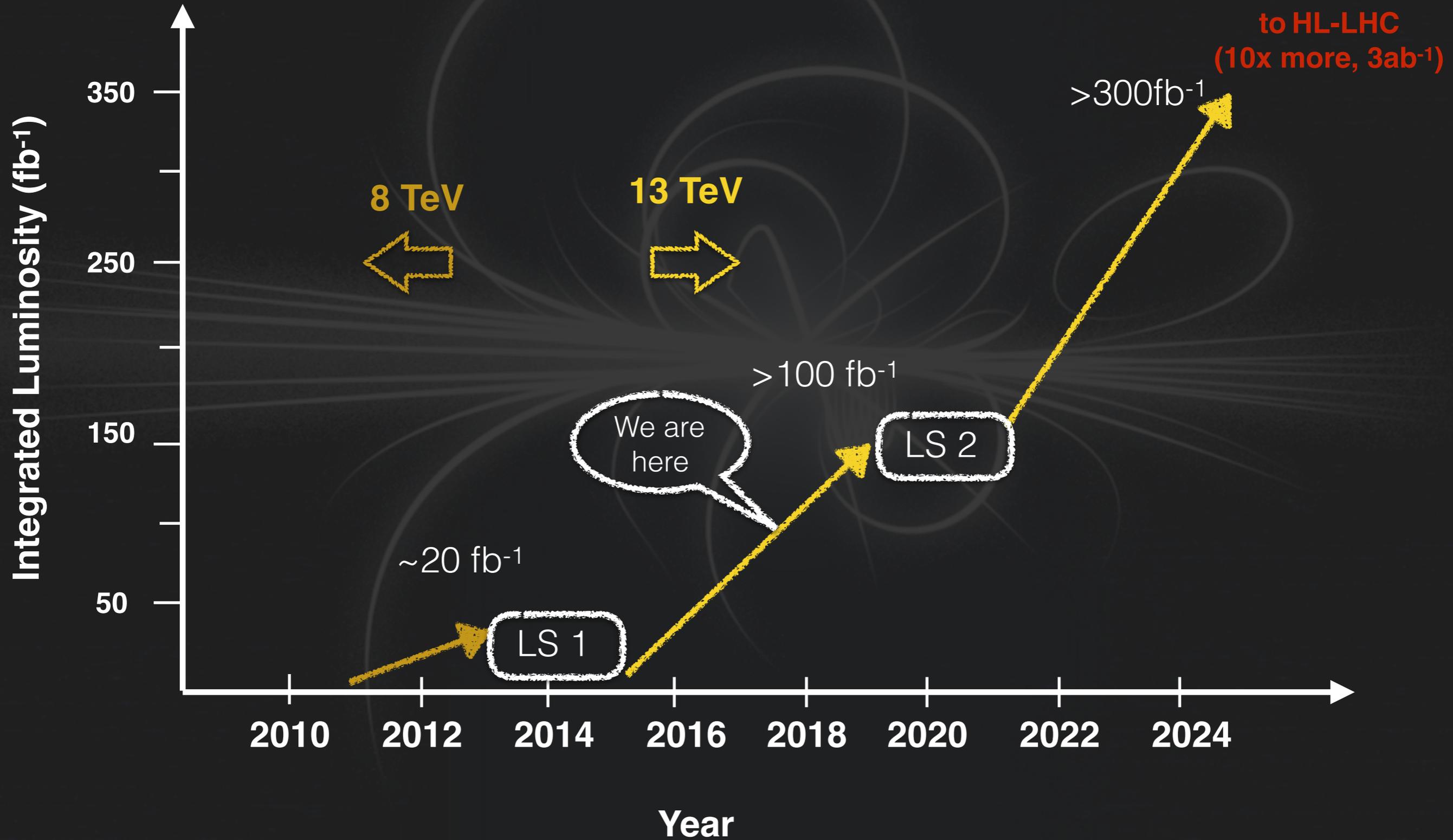
DM can only be discovered by combining these approaches



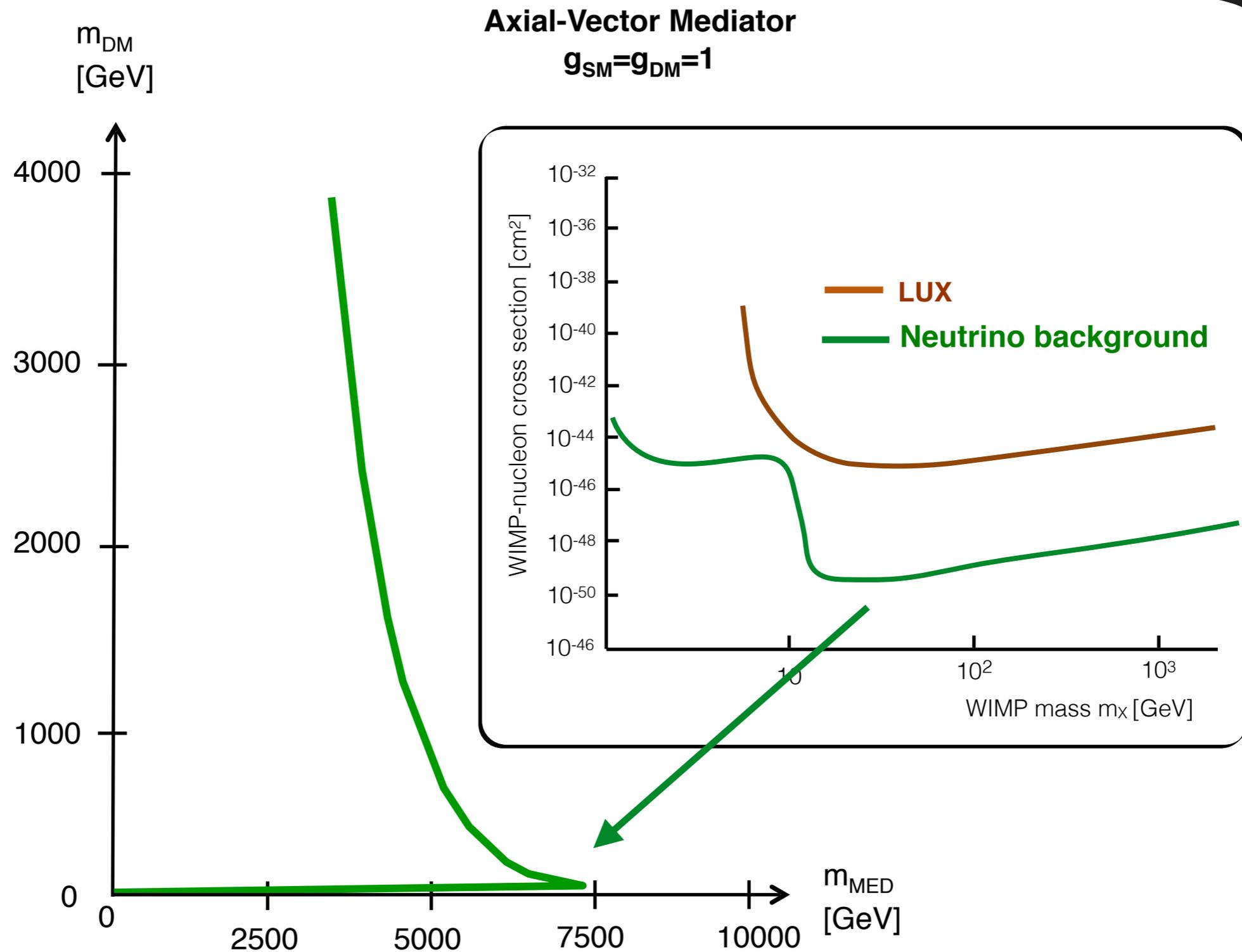
The (near) future



LHC Run Plan



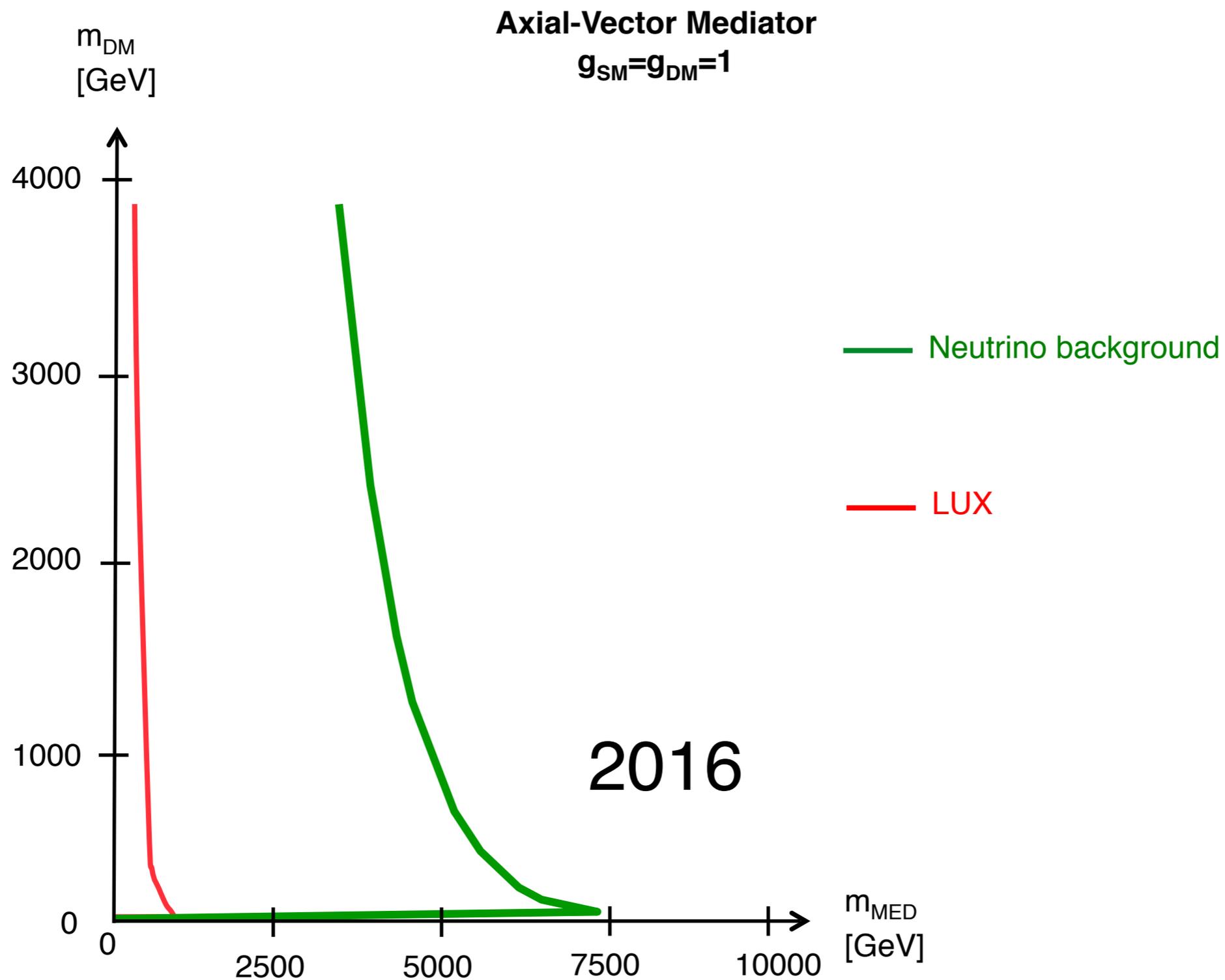
The Path to Discovery



created using code from Chris McCabe



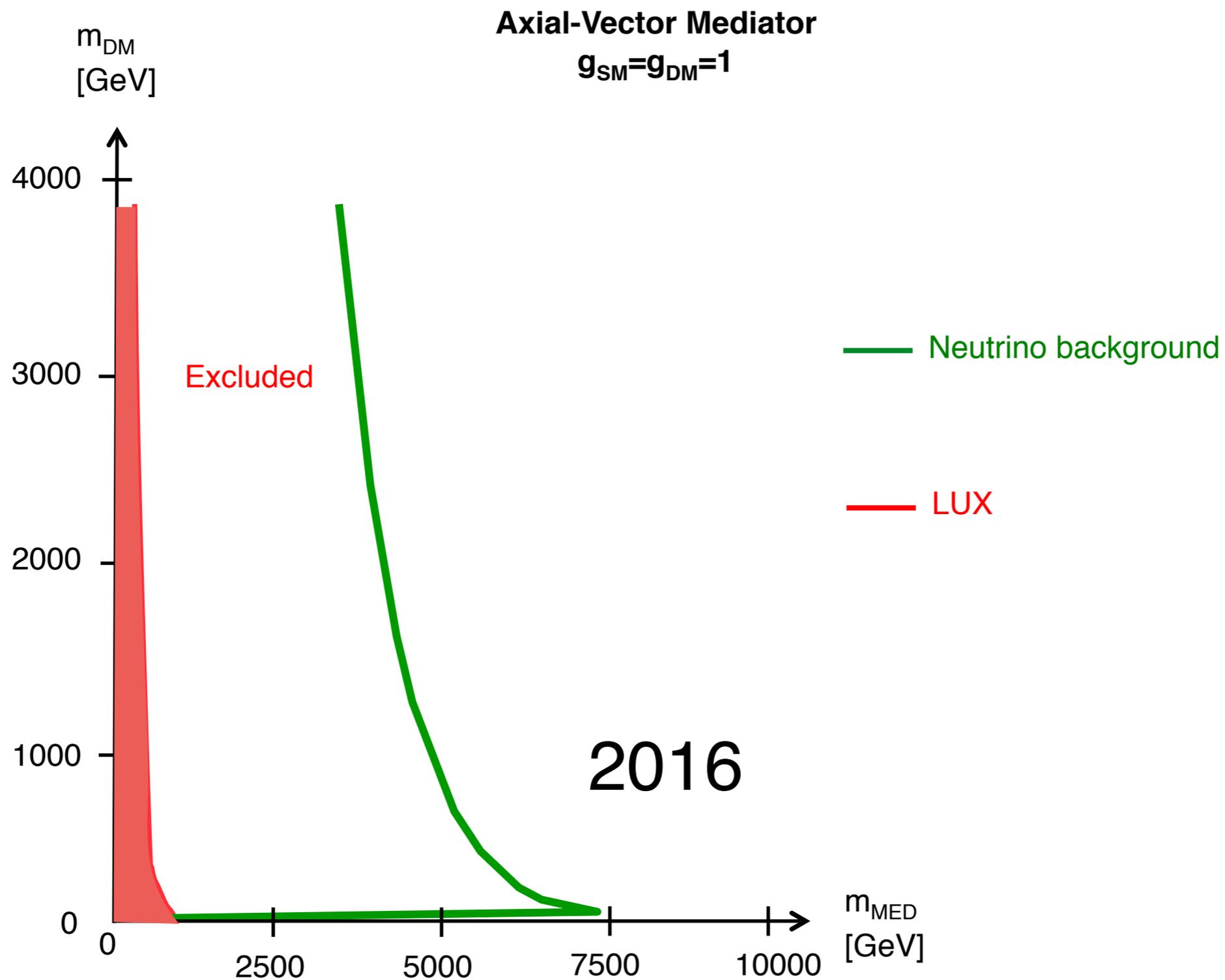
The Path to Discovery



created using code from Chris McCabe



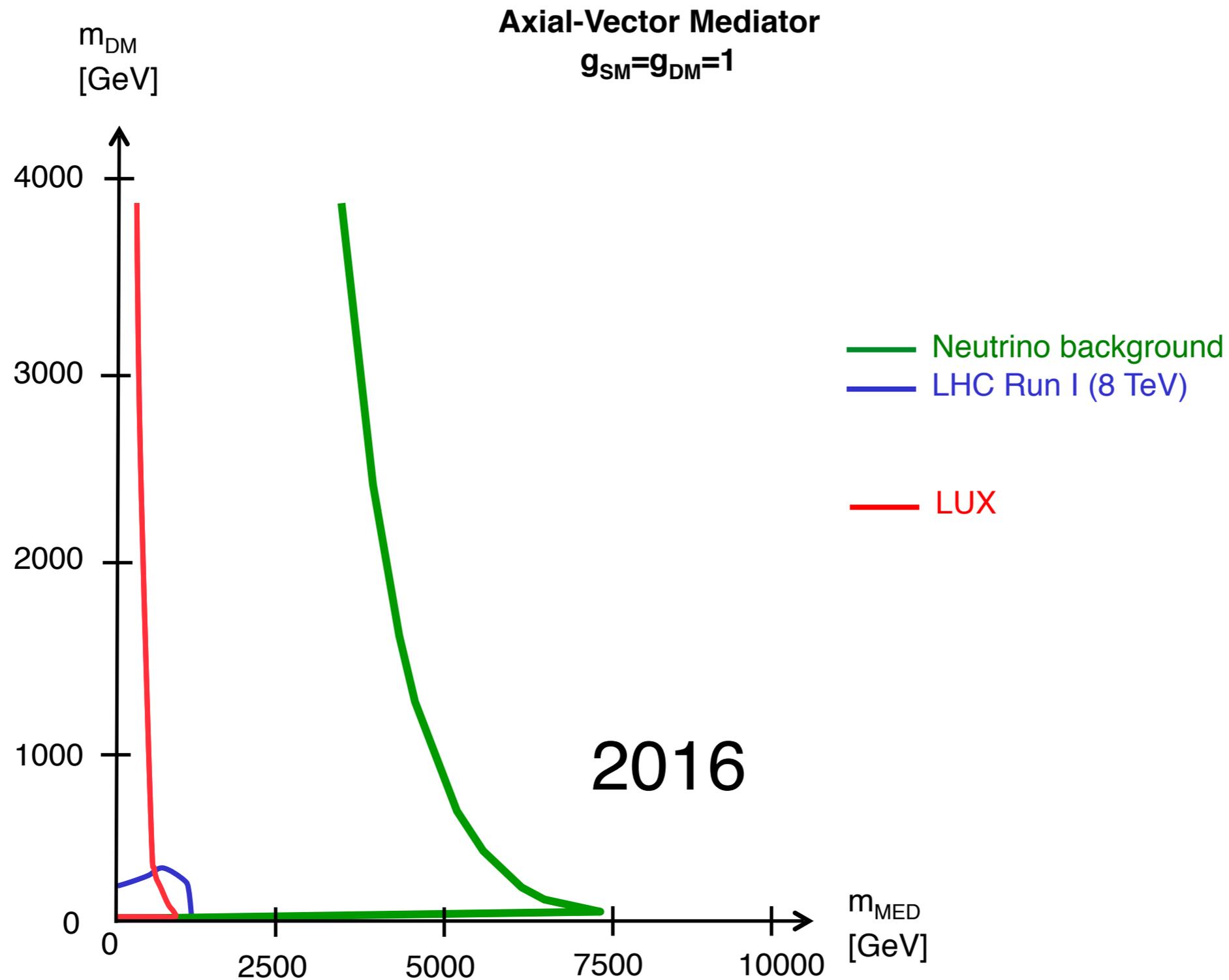
The Path to Discovery



created using code from Chris McCabe



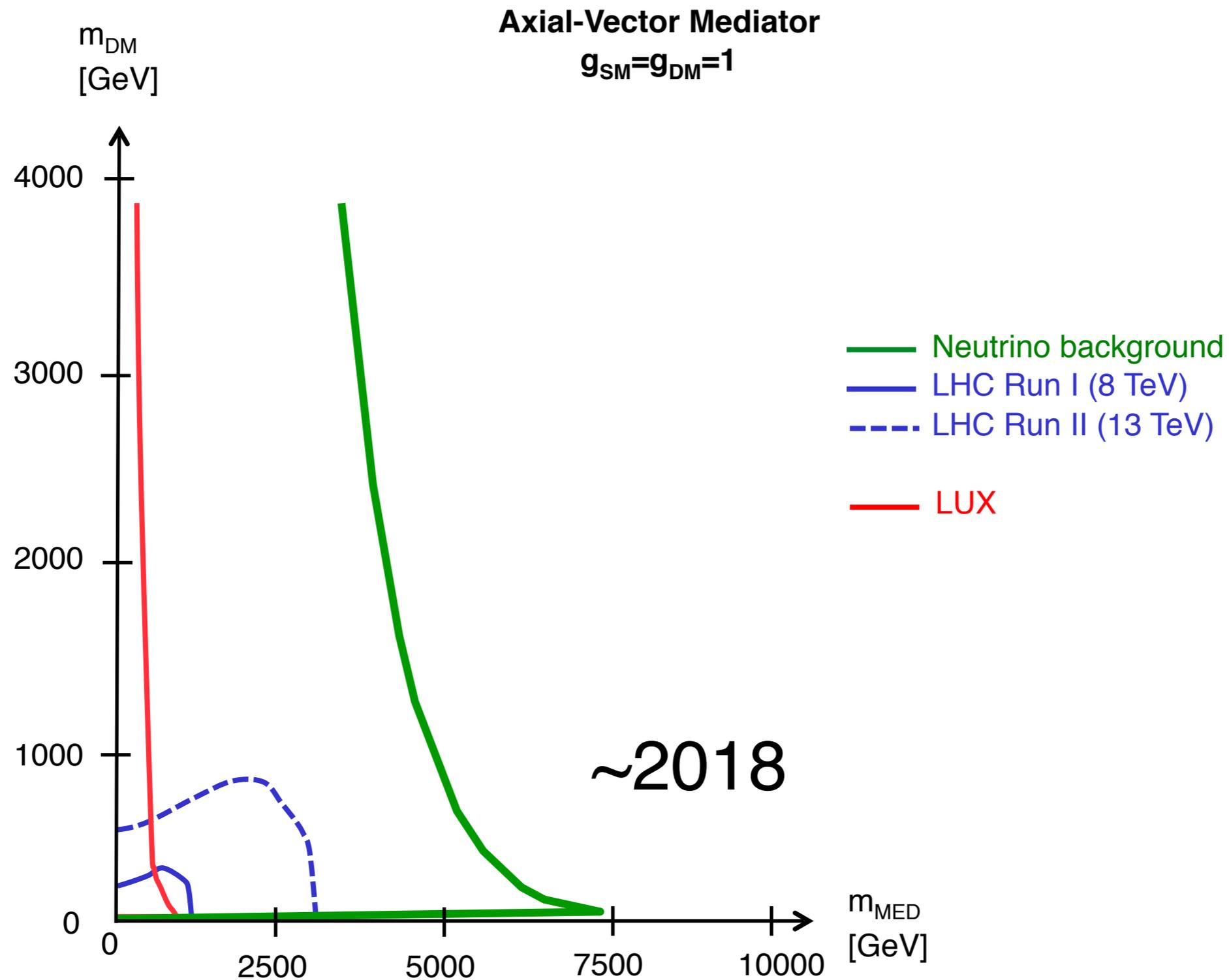
The Path to Discovery



created using code from Chris McCabe



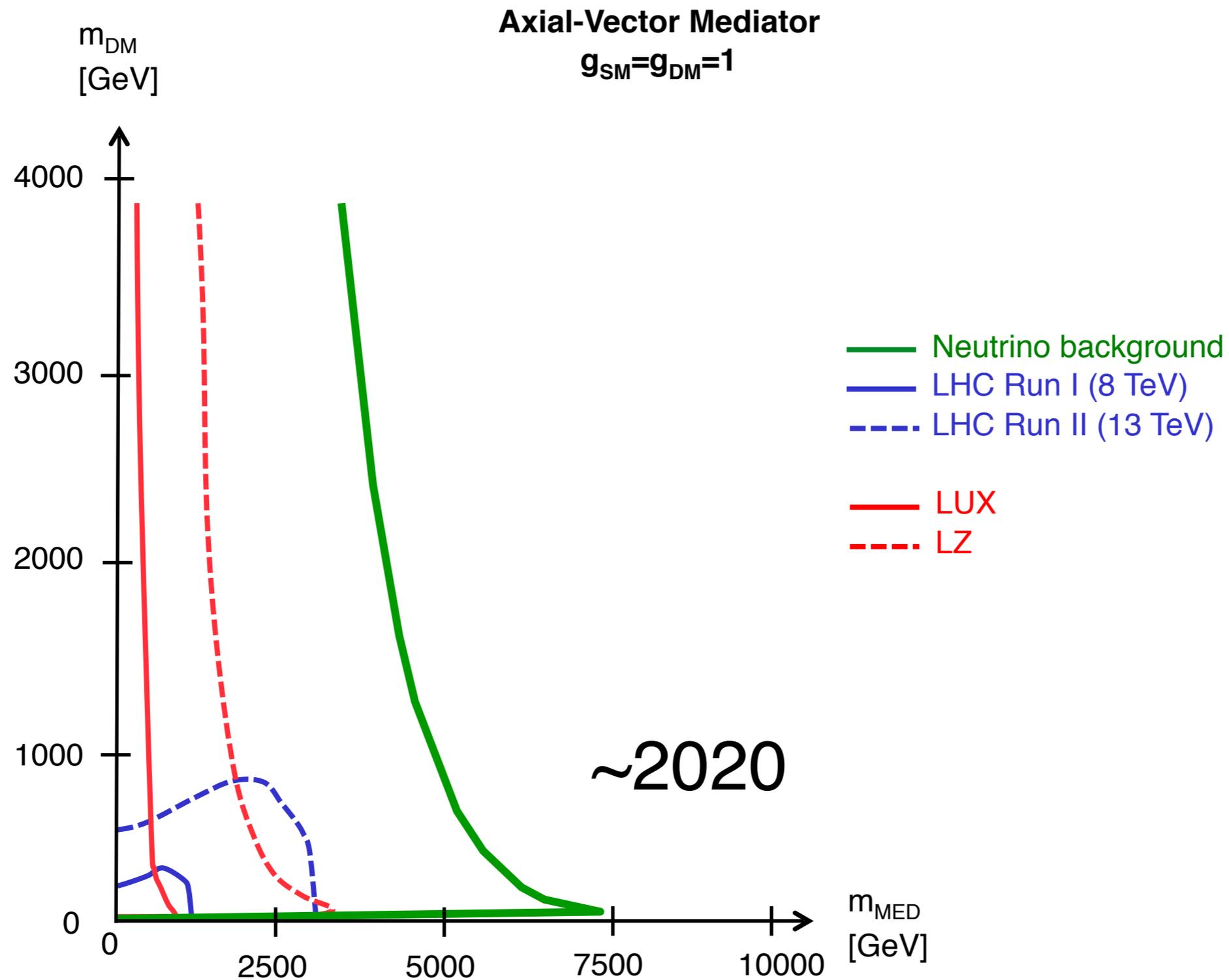
The Path to Discovery



created using code from Chris McCabe



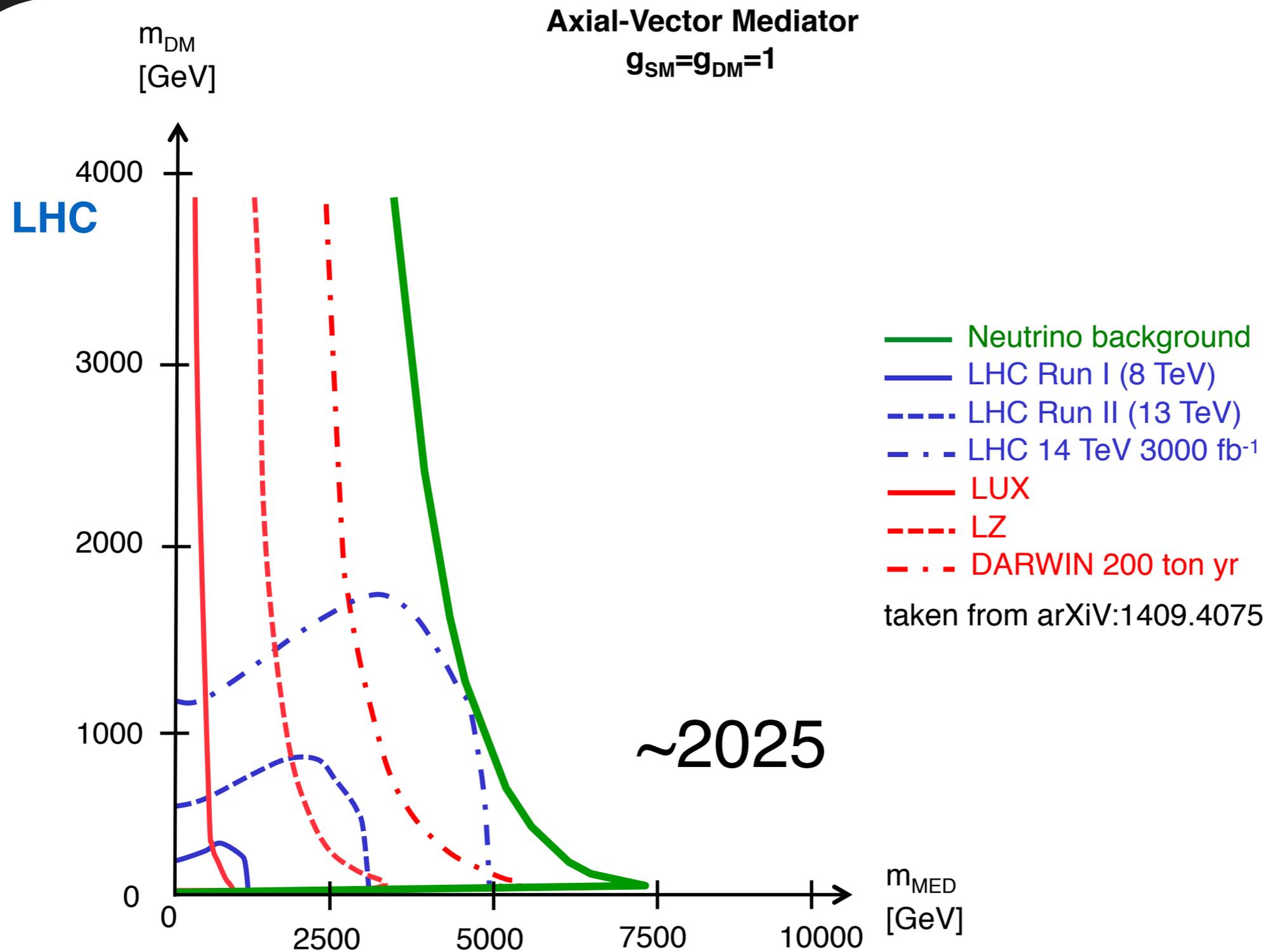
The Path to Discovery



created using code from Chris McCabe



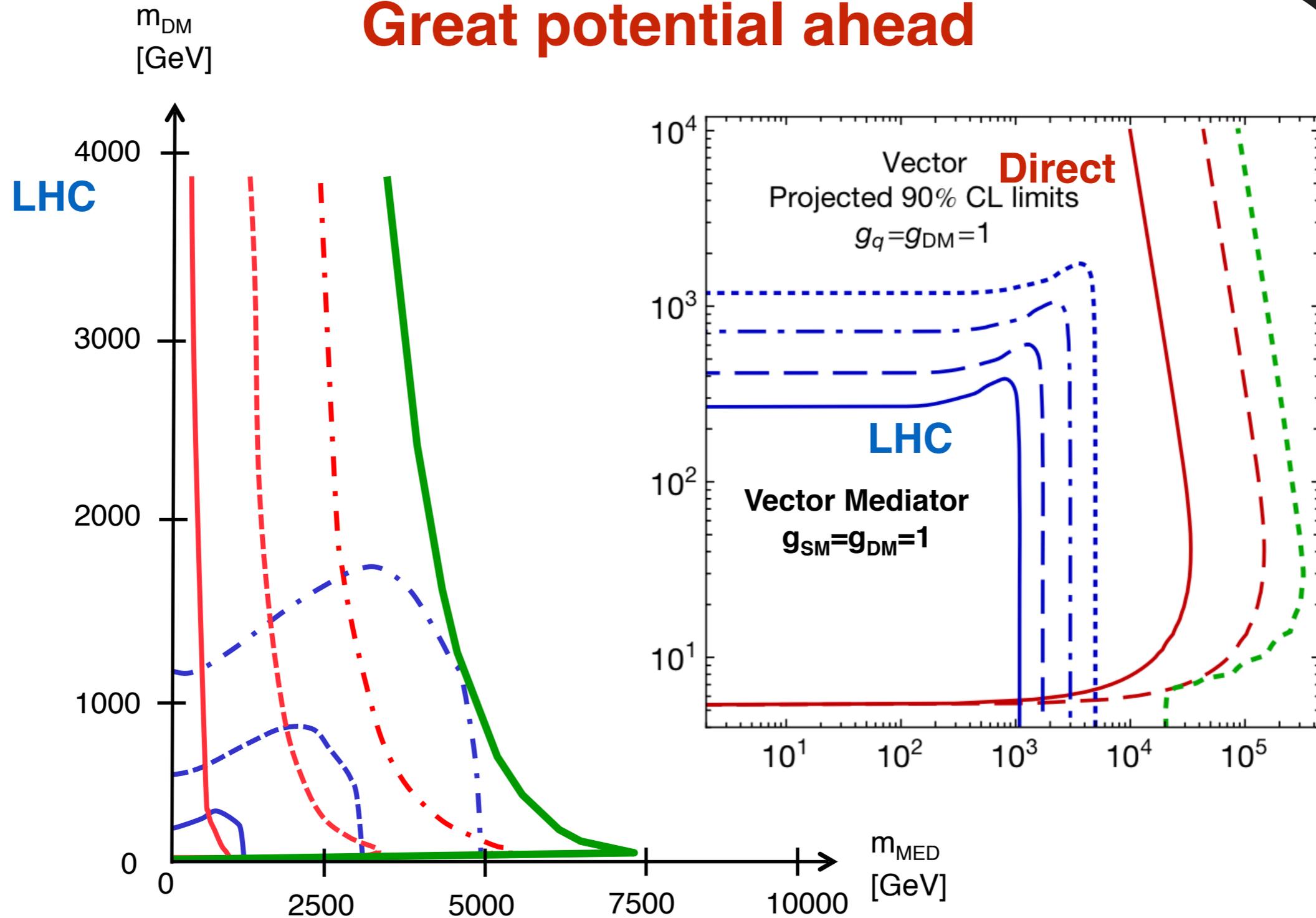
The Path to Discovery



created using code from Chris McCabe

The Path to Discovery

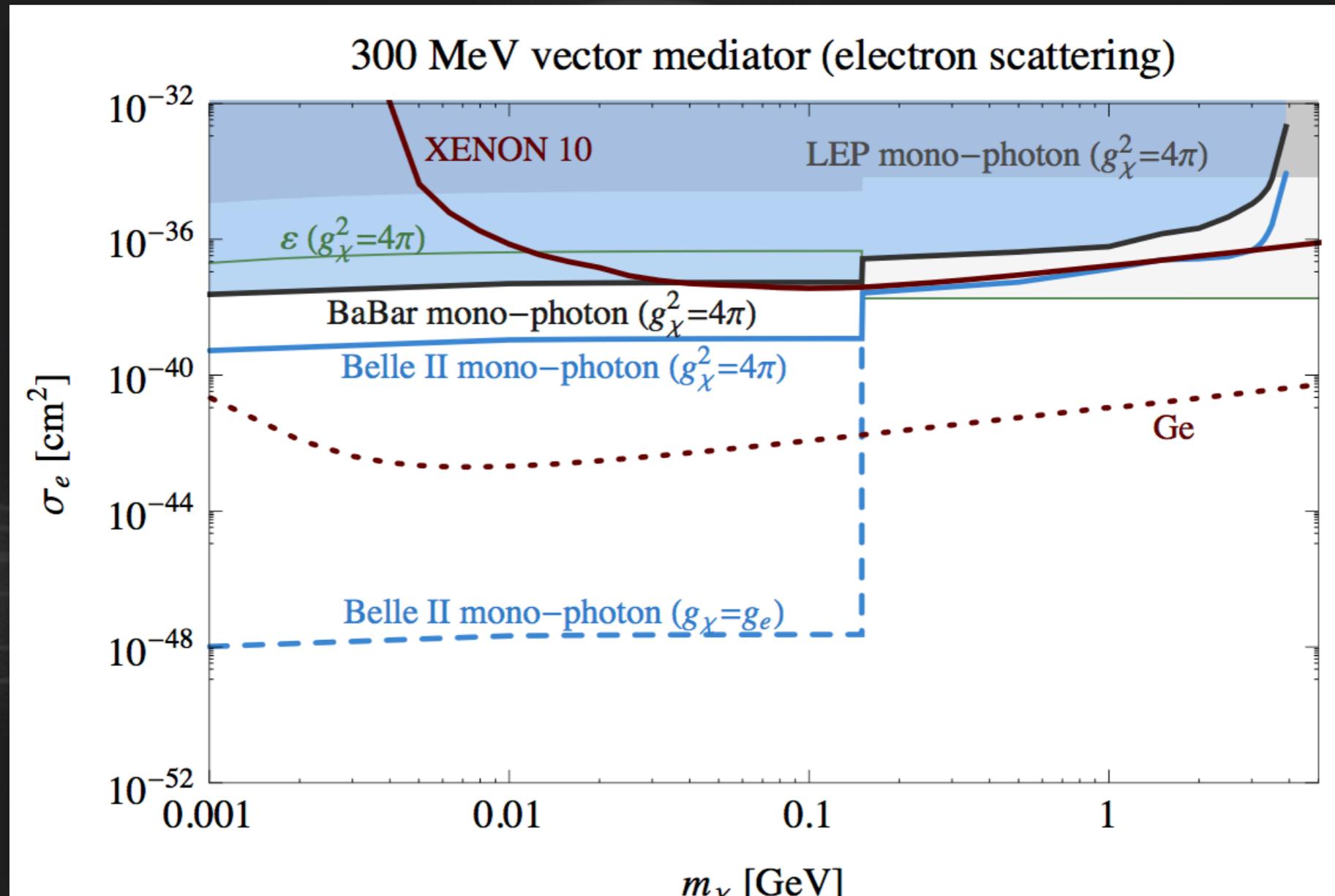
Great potential ahead



created using code from Chris McCabe

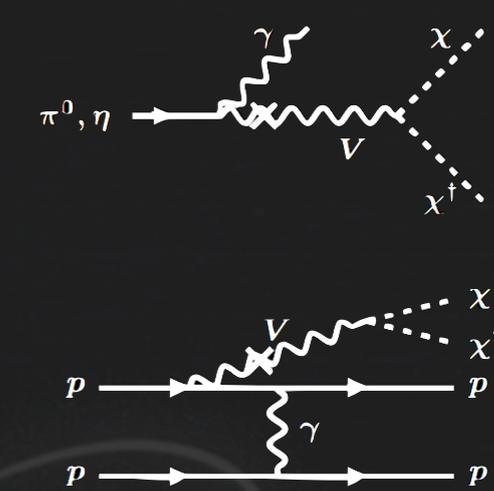
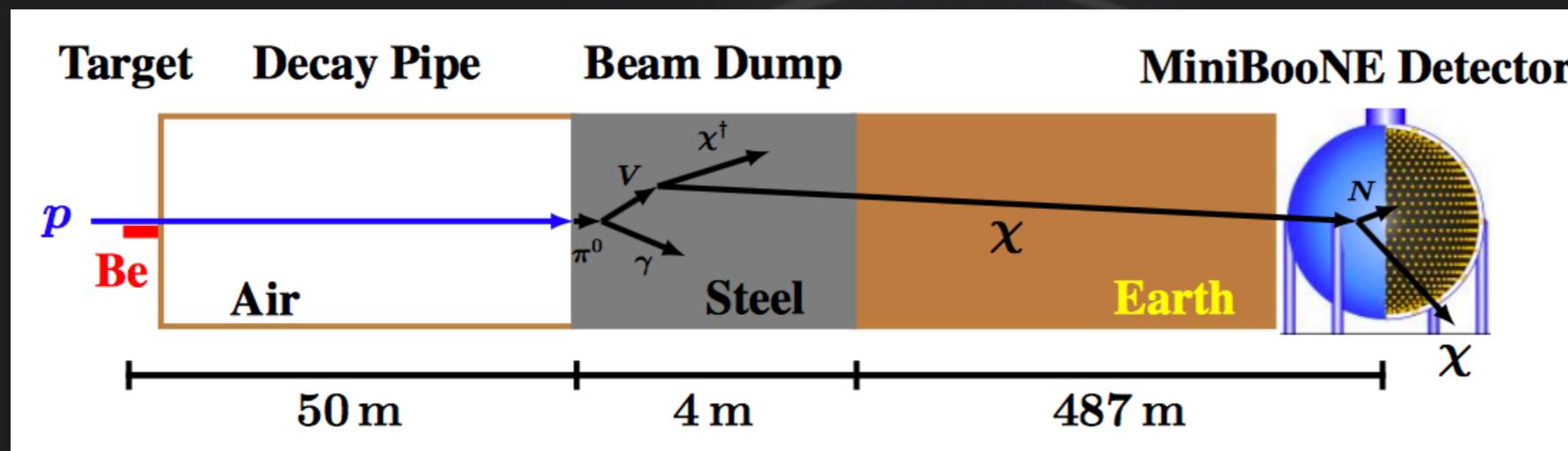


Some final remarks

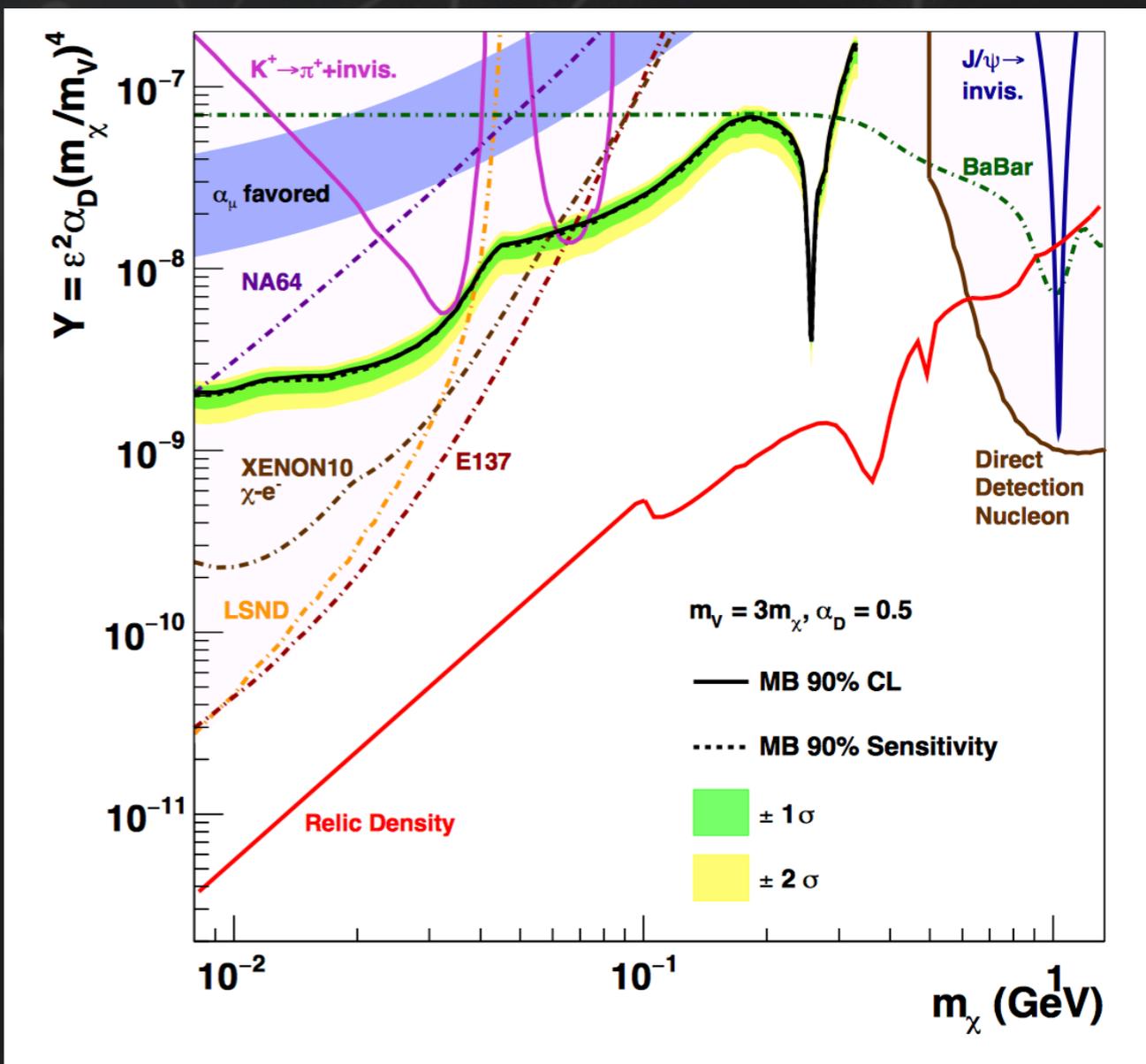


- We can also search in the clean environments of e^+e^- collider for light mediators ($\sqrt{s} \lesssim 10$ GeV)
- Barbar had (partial) mono-photon trigger, already advancing in uncharted territory
- Belle-II (2018) will provide great sensitivity
- Similar constraints from rare decays (KLEO etc) and LHCb searches are in preparation

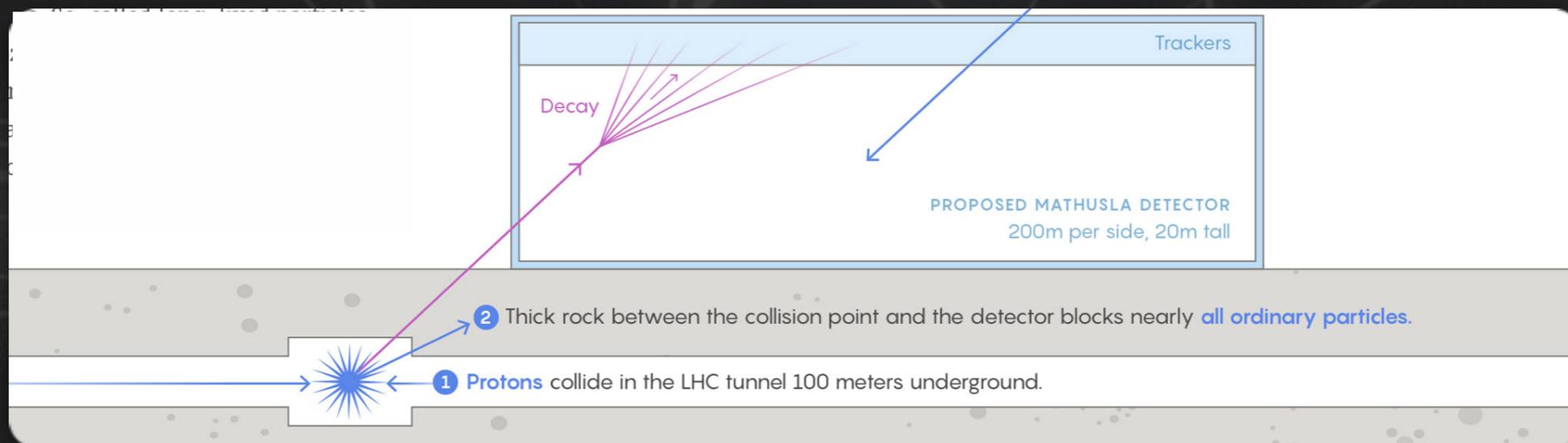
Beam Dump Experiments



- **Beam Dump experiments** performed at JLab, SLAC, Fnl, others also probe light mediators using ‘dark photon’ or ‘Vector portal’
- Limits are set using dimensionless DM annihilation xsec $Y = \epsilon^2 \alpha_D (m_X/m_V)^4$
- Potential to powerfully probe yet unexplored region, **dedicated experiments planned**

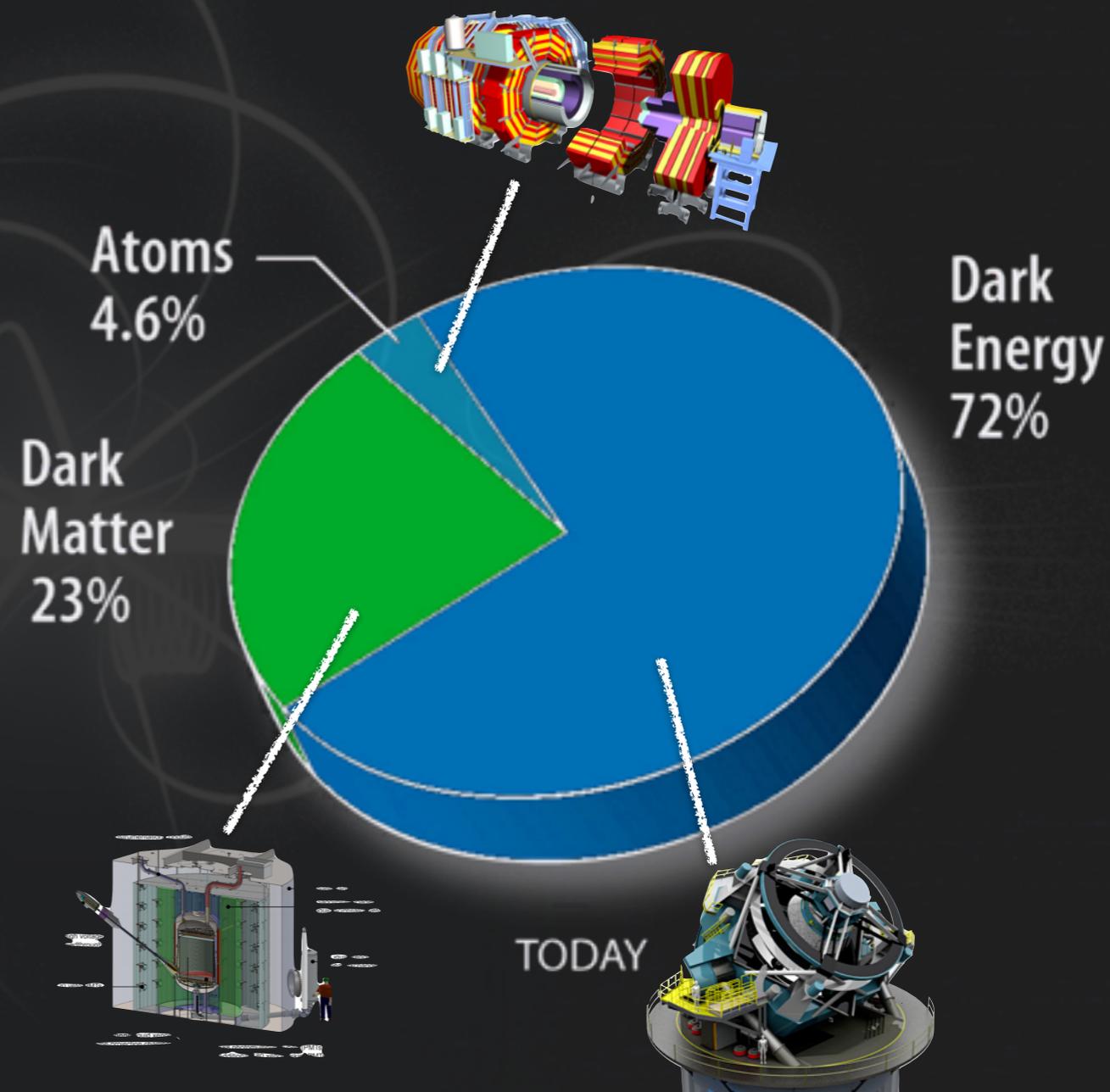


- Large experience, rapid increases in energy/lumi and great phenomenological effort led to **quite comprehensive analysis of simple s-channel** models that cause the prominent mono-X signature
- No excess, but variety of DM models have been ruled out and new inter-disciplinary developments instigated.
 - Present models and searches are among the most simple ones using similar phase space
 - ~5% of LHC data recorded, 2% analyzed using similar models and phase space



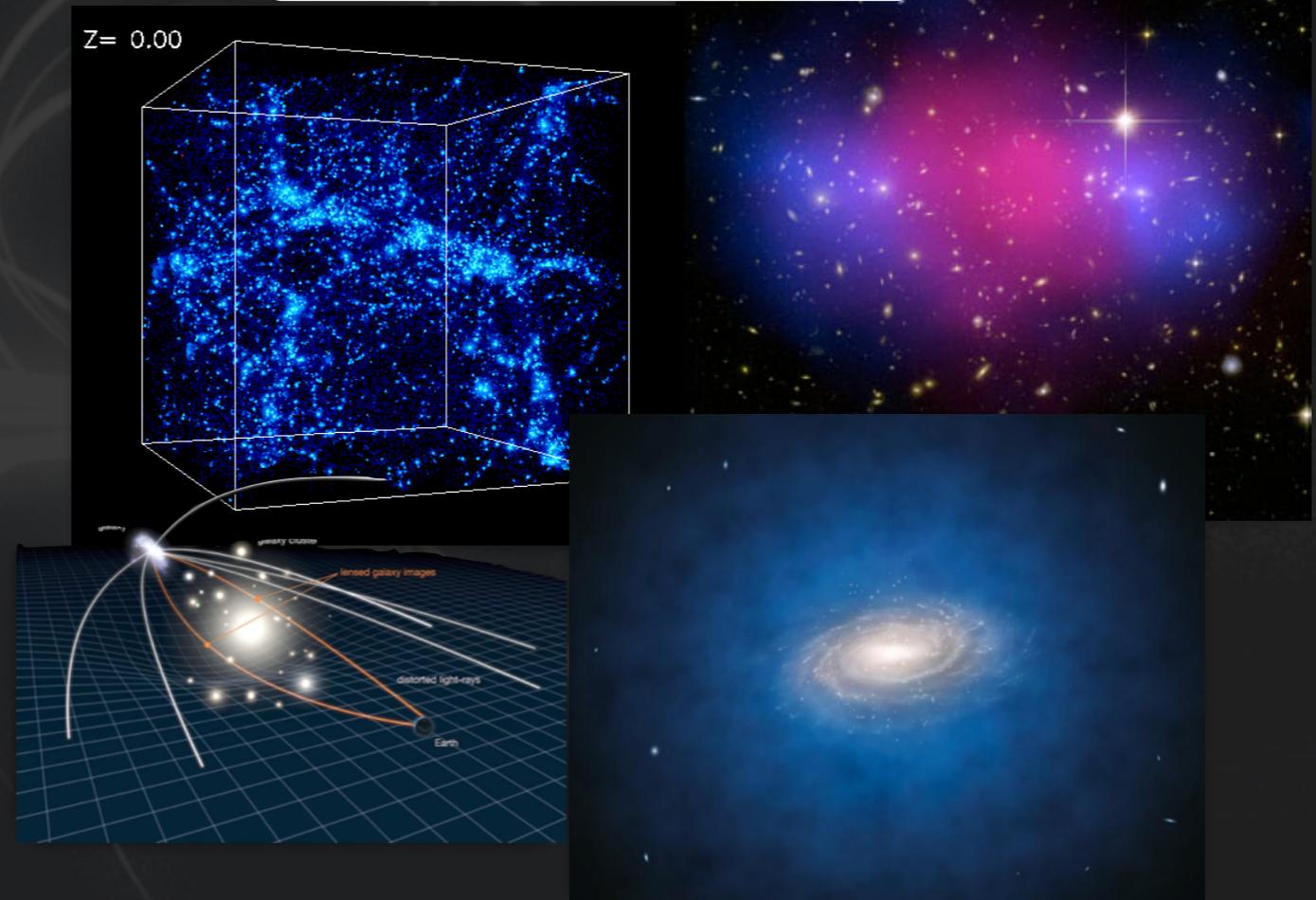
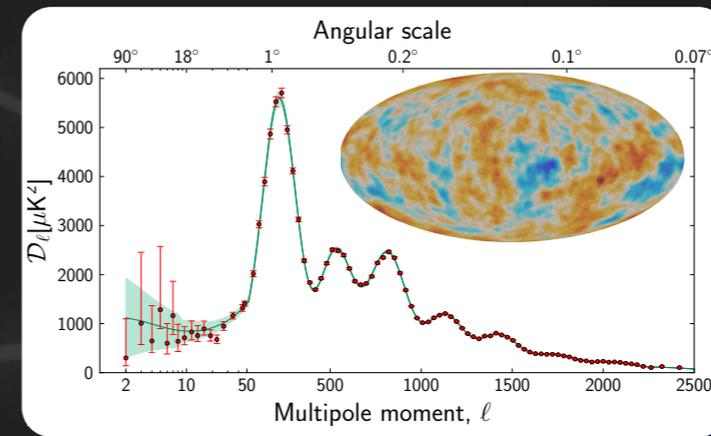
- **New approaches** will push the field far beyond today's state:
 - long-lived particle searches [1706.07407, 1704.06515]
 - new signatures [1503.00009, 1706.07407, 1308.0592]
 - new production modes [1308.0592, 1607.06680]
 - dark sectors [1707.05326]
 - dark-photon searches [1310.6752, 1311.0029]
 - Novel detectors (**milliQan, Faser, MATHUSLA**) [1705.06327, 1708.09389, 1410.6816].

- DM is out there and will **transform our understanding of the universe**
- Collider searches are **particularly powerful at low WIMP masses** and are not subject to significant astrophysical uncertainties.
- LHC is running, direct detection, and indirect detection are improving rapidly – **the field is being transformed now**
- DM searches **need to be interdisciplinary**
 - **DM has to be discovered in several fields** to be confirmed and **measured**
- The WIMP miracle does not necessarily imply vanilla dark matter: **SuperWIMPs, WIMPless DM may be warm, self-interacting...**
- **If discovery in DD or ID**, collider might be best suited to measure DM in lab → **provide physics case for future machine**



What is DM?

- Dark matter is a **hugely successful theory** to explain plenty of observations
- It is **the one theory** that can successfully simulate and reproduce the universe on **all scales**:
 - Galaxy rotation curves
 - Galaxy clustering
 - Cluster collision
 - Large-scale structures
 - CMB fluctuations
 - Gravitational lensing
- Unambiguous evidence for new physics



- Global fit of cosmological parameters, Λ CDM:
→ $\Omega_\Lambda \approx 0.68$, $\Omega_{DM} \approx 0.27$, $\Omega_b \approx 0.05$