Towards the Consistent and Systematic Dark Matter Exploration

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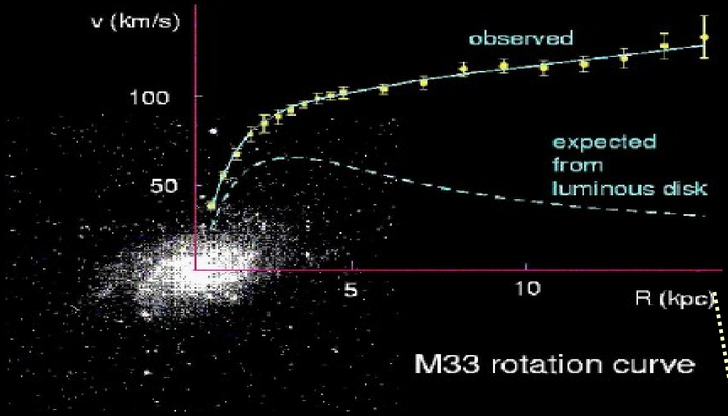
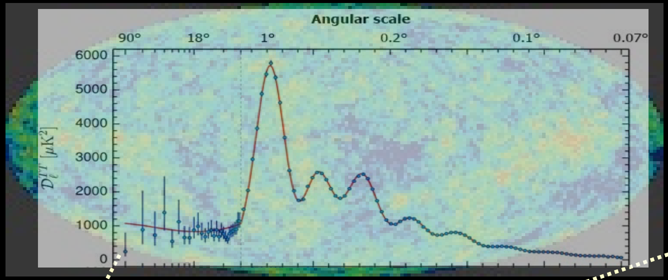
COST Advanced School
on Physics of Dark Matter and Hidden Sectors: from Theory to Experiment
18-21 October 2021

The existence of Dark Matter is confirmed by several independent observations at cosmological scale

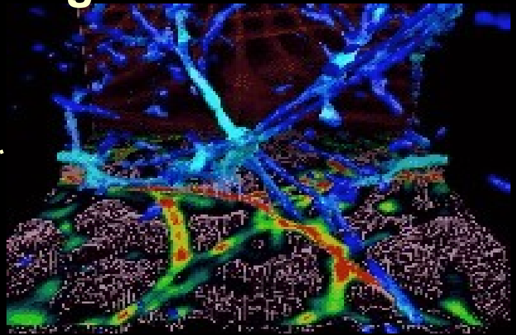
Galactic rotation curves

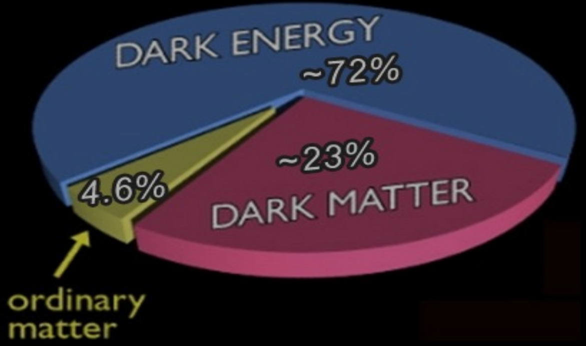


CMB: WMAP and PLANCK



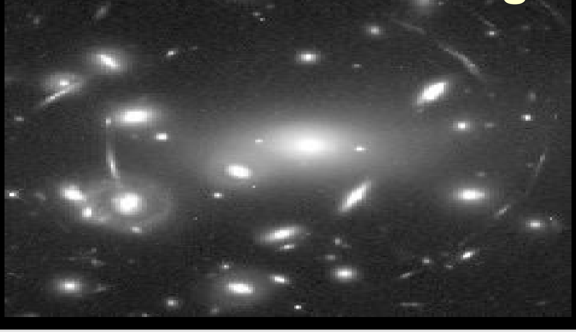
Large Scale Structures



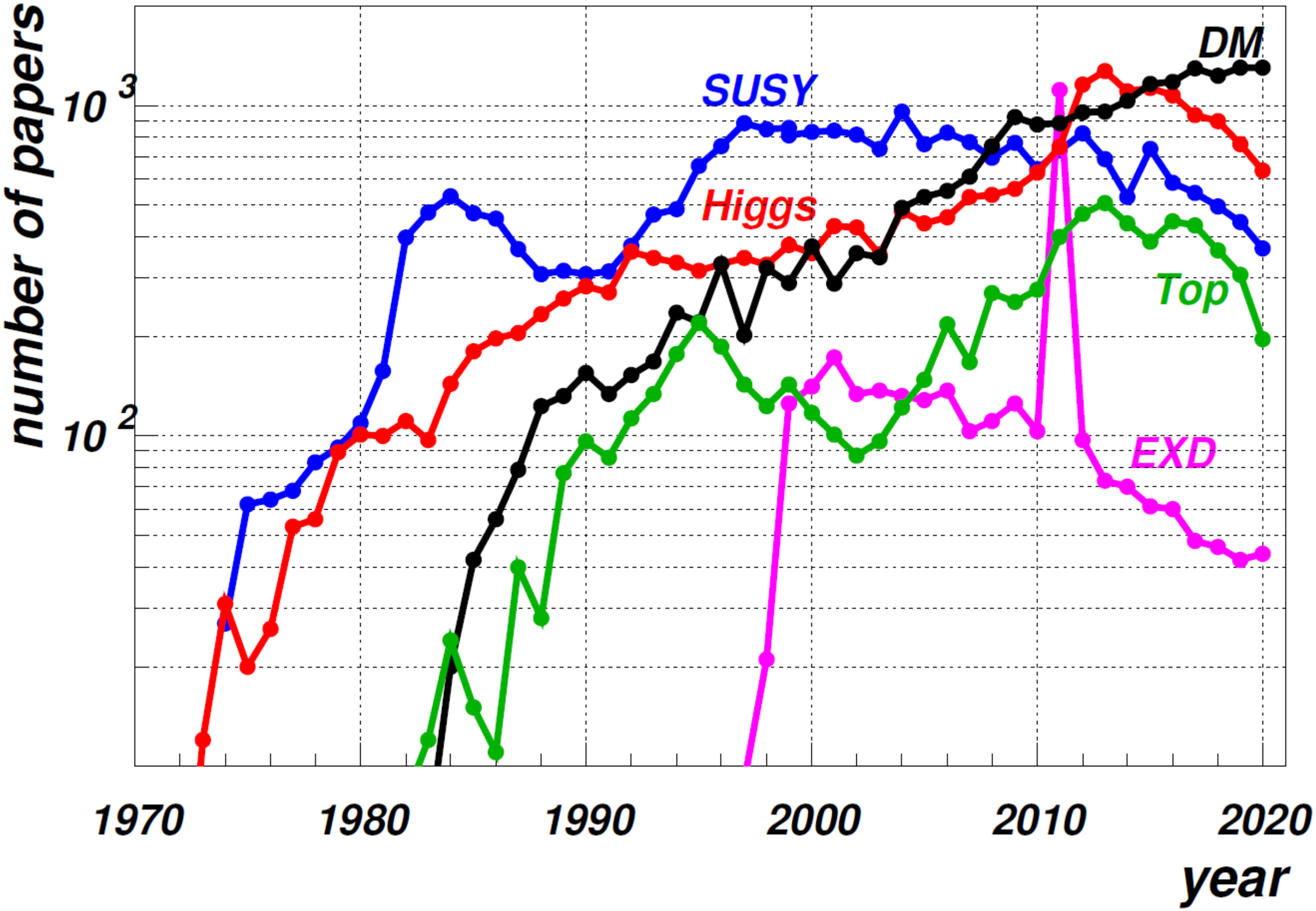


Bullet cluster

Gravitational lensing



The evidence for Dark Matter is a very appealing argument for BSM



DM is very appealing even though we know almost nothing about it!

Spin $\boxed{?}$

Mass $\boxed{?}$

Stable

Yes $\boxed{?}$ No $\boxed{?}$

symmetry behind stability $\boxed{?}$

Couplings

gravity	$\boxed{V}$
weak	$\boxed{?}$
higgs	$\boxed{?}$
quarks/gluons	$\boxed{?}$
leptons	$\boxed{?}$
New mediators	$\boxed{?}$

Thermal relic

Yes $\boxed{?}$ No $\boxed{?}$

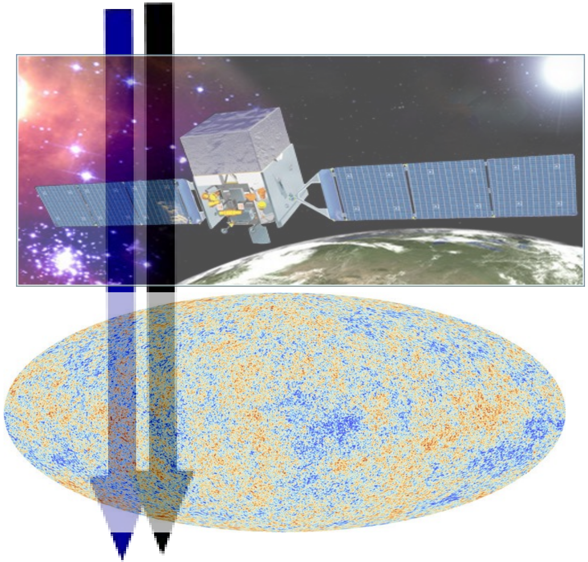
How we can decode the fundamental nature of Dark Matter?

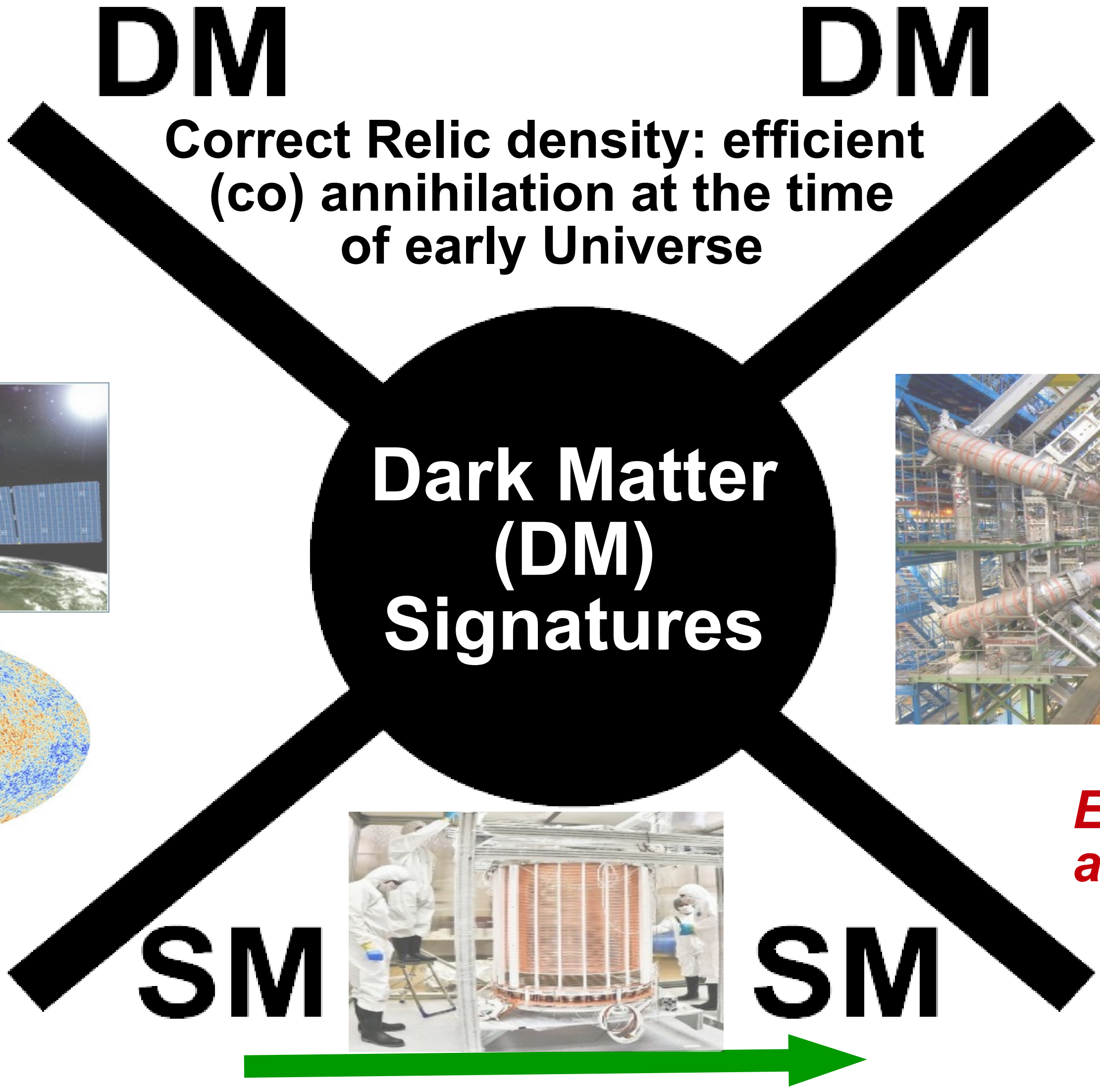
We need a DM signal first!

But at the moment we can:

- understand what kind of DM is already excluded
- explore theory space and prepare ourselves to discovery and decoding of DM

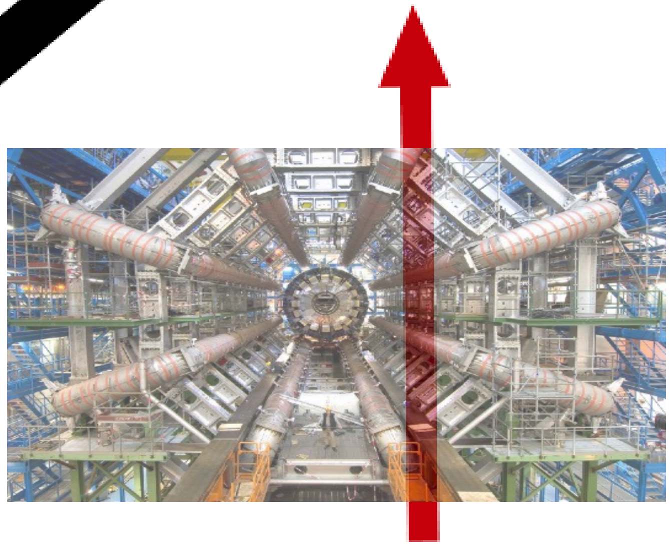
Efficient annihilation now: Indirect Detection





Correct Relic density: efficient (co) annihilation at the time of early Universe

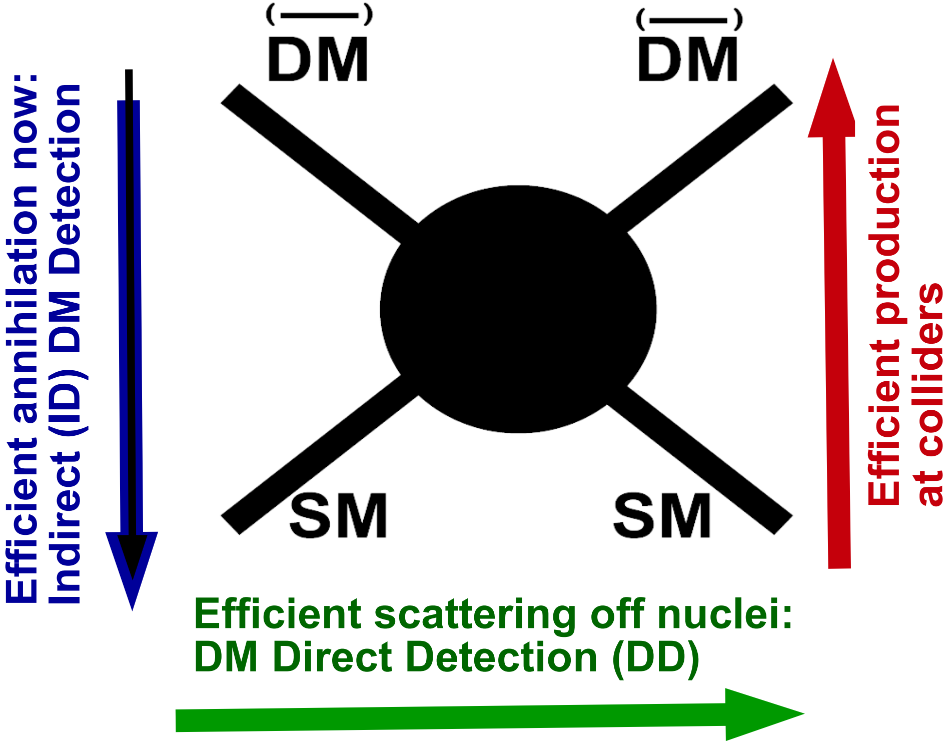
Dark Matter (DM) Signatures



Efficient production at colliders

Efficient scattering off nuclei: Direct Detection

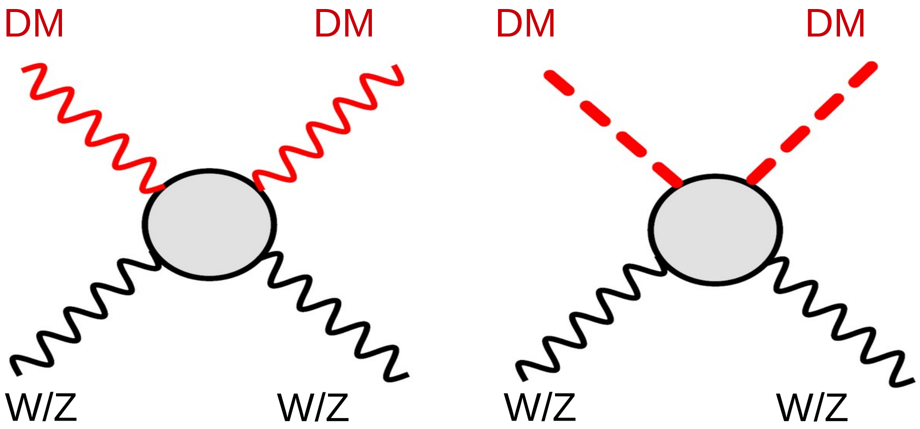
Complementarity of DM searches



Efficient annihilation now: Indirect (ID) DM Detection

Efficient production at colliders

Efficient scattering off nuclei: DM Direct Detection (DD)



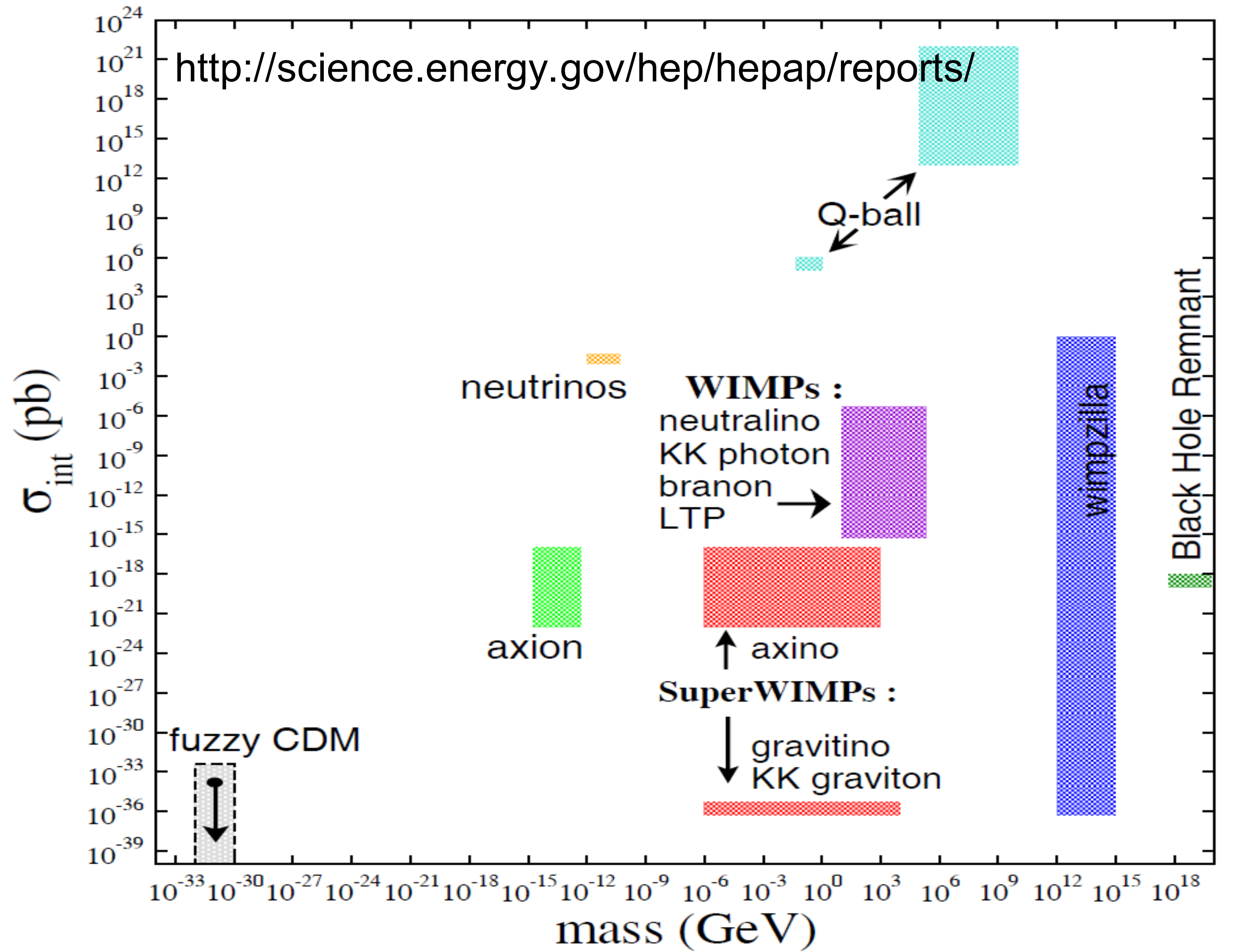
Example of DM interactions with negligible/suppressed DD rates

Important: **there is no 100%correlation between signatures above. E.g. the high rate of annihilation does not always guarantee high rate for DD!**

Complementary Exclusion power of DM observables:

Effective DM annihilation → low relic density but large signal at the LHC (and vice versa)

DM candidates: interaction vs mass



http://science.energy.gov/hep/hepap/reports/

- Planck mass BH remnants: tiny black holes protected by gravity effects [Chen '04] from decay via Hawking radiation
- Wimpzillas: very massive non-thermal WIMPs [Kolb,Chung,Riotto'98]
- Q-balls: topological solitons that occur in QFT [Coleman '86]
- EW scale WIMPs, protected by parity – LSP, LKP, LTP particles
- SuperWIMPs: electrically and color neutral DM interacting with much smaller strength (perhaps only gravitationally)
- Neutrinos: usual neutrinos are too light- HDM, subdominant component only (to be consistent with large scale structures); but heavier gauge singlet neutrinos can be CDM
- Axions: $$\frac{\theta_{QCD}}{32pi^2} F^{\mu\nu} \tilde{F}^{\mu\nu}$$

θ_{QCD} is replaced by a quantum field, the potential energy allows the field to relax to near zero strength, axion as a consequence

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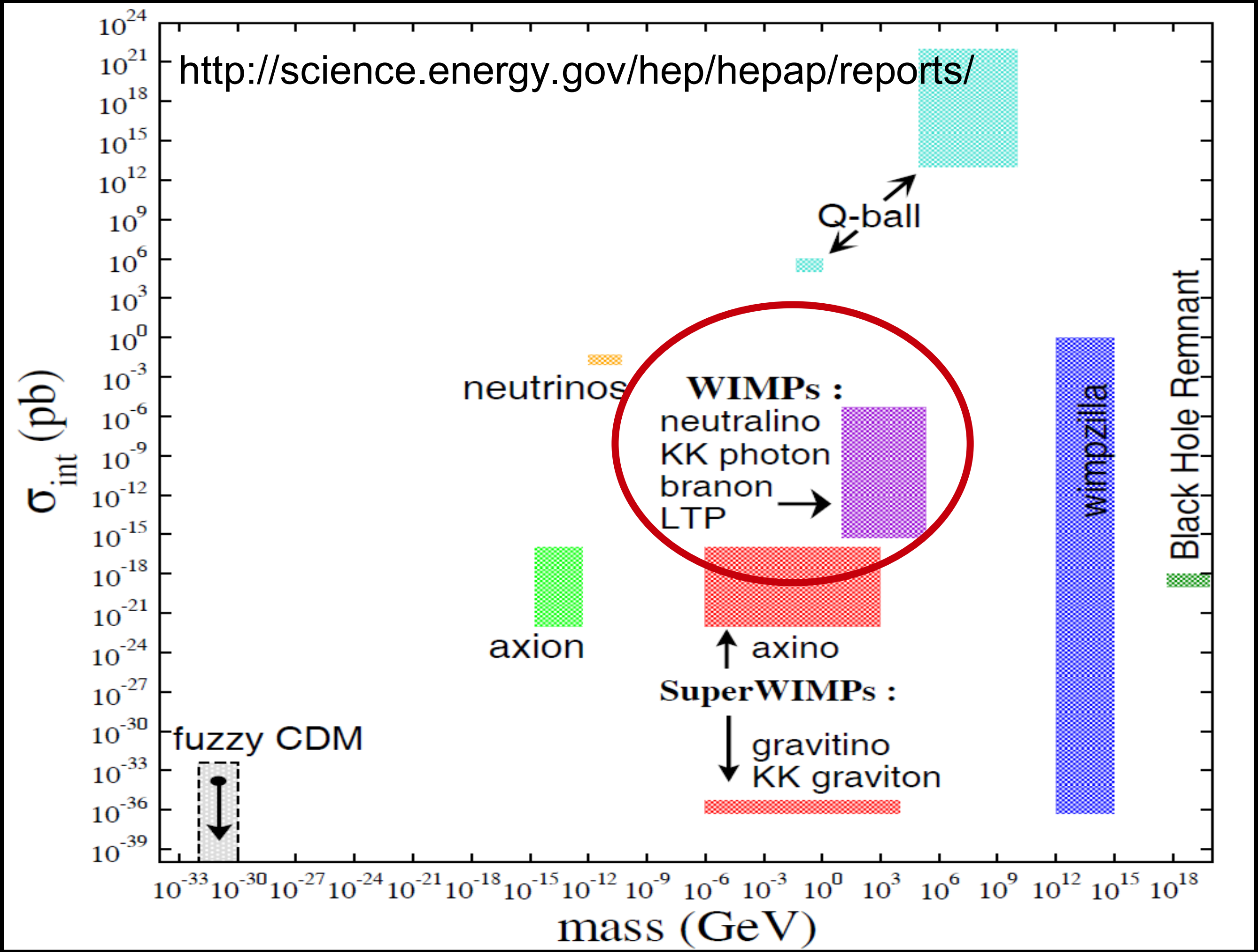
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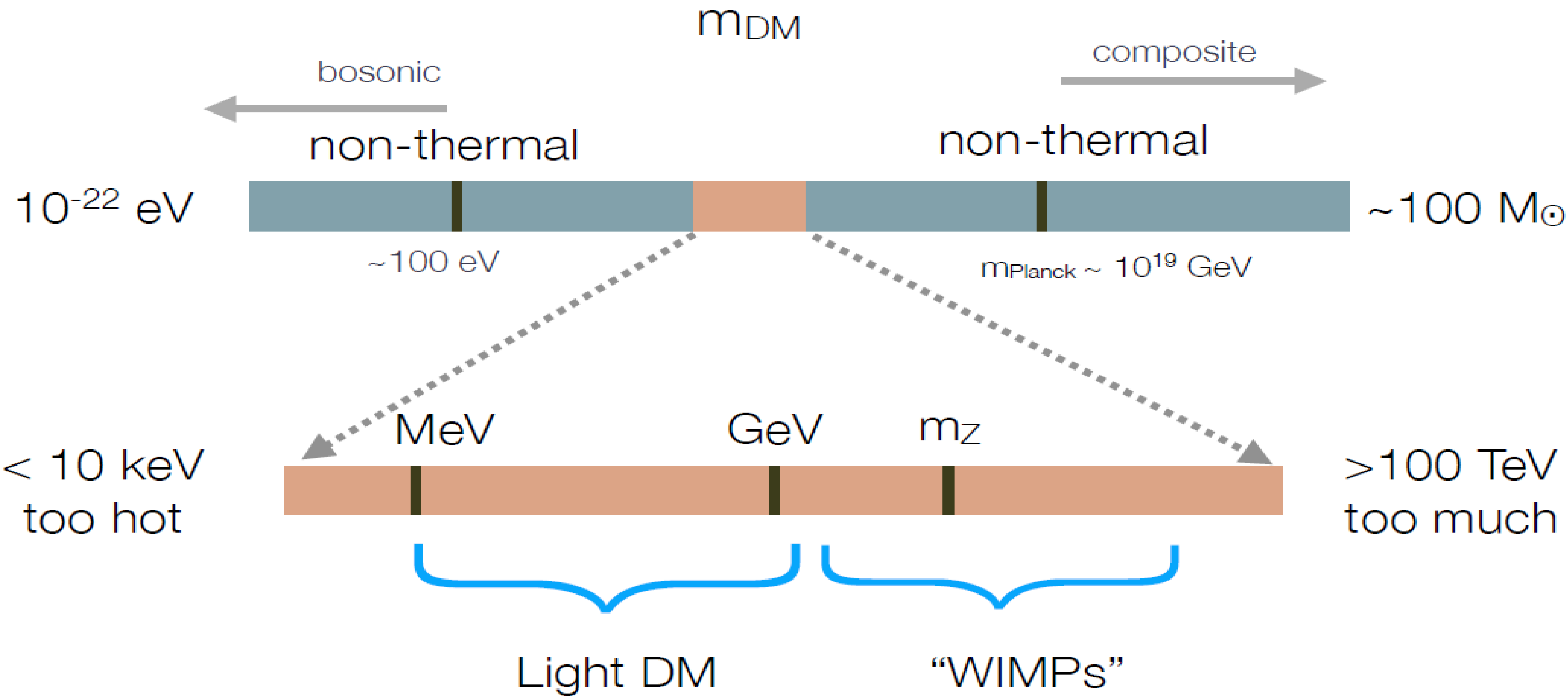
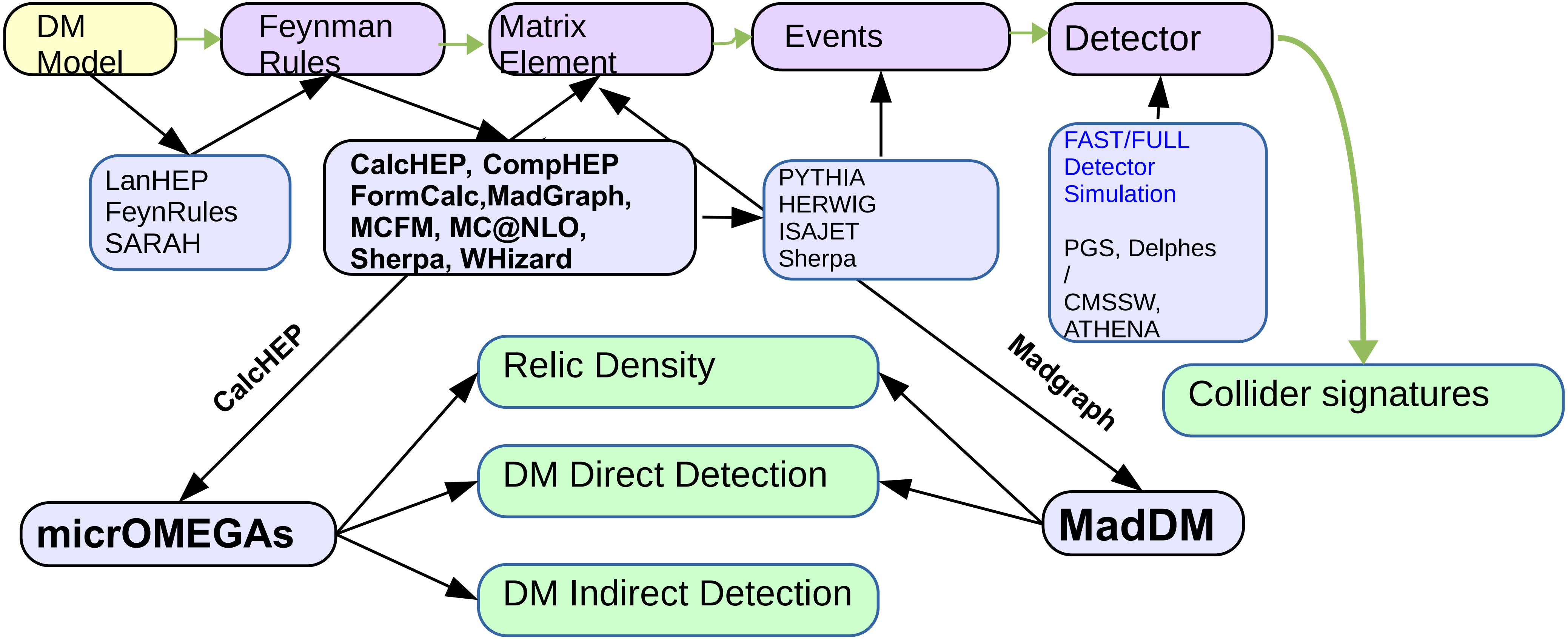
Mass range for thermal DM



Tools are important to make theory → observables link !


DM Model

Feynman Rules

Matrix Element

Events

Detector

LanHEP
FeynRules
SARAH

CalcHEP, CompHEP
FormCalc,MadGraph,
MCFM, MC@NLO,
Sherpa, WHizard

PYTHIA
HERWIG
ISAJET
Sherpa

FAST/FULL
Detector
Simulation

PGS, Delphes
/
CMSSW,
ATHENA

CalcHEP

Madgraph

Relic Density

DM Direct Detection

DM Indirect Detection

Collider signatures

micrOMEGAs

MadDM

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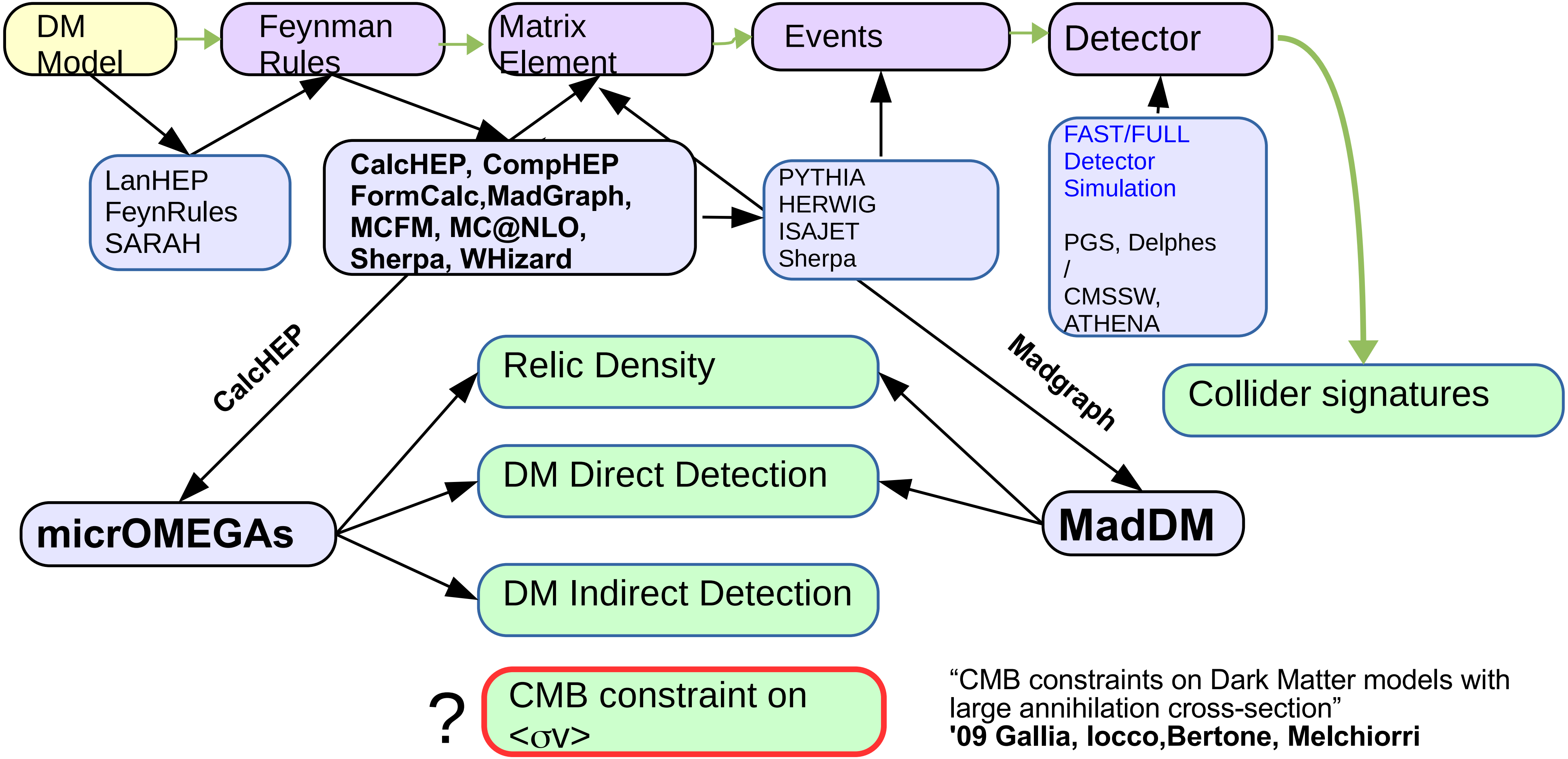

DM Model → Feynman Rules → Matrix Element → Events → Detector → Collider signatures

LanHEP
FeynRules
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CalcHEP, CompHEP
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Relic Density

DM Direct Detection

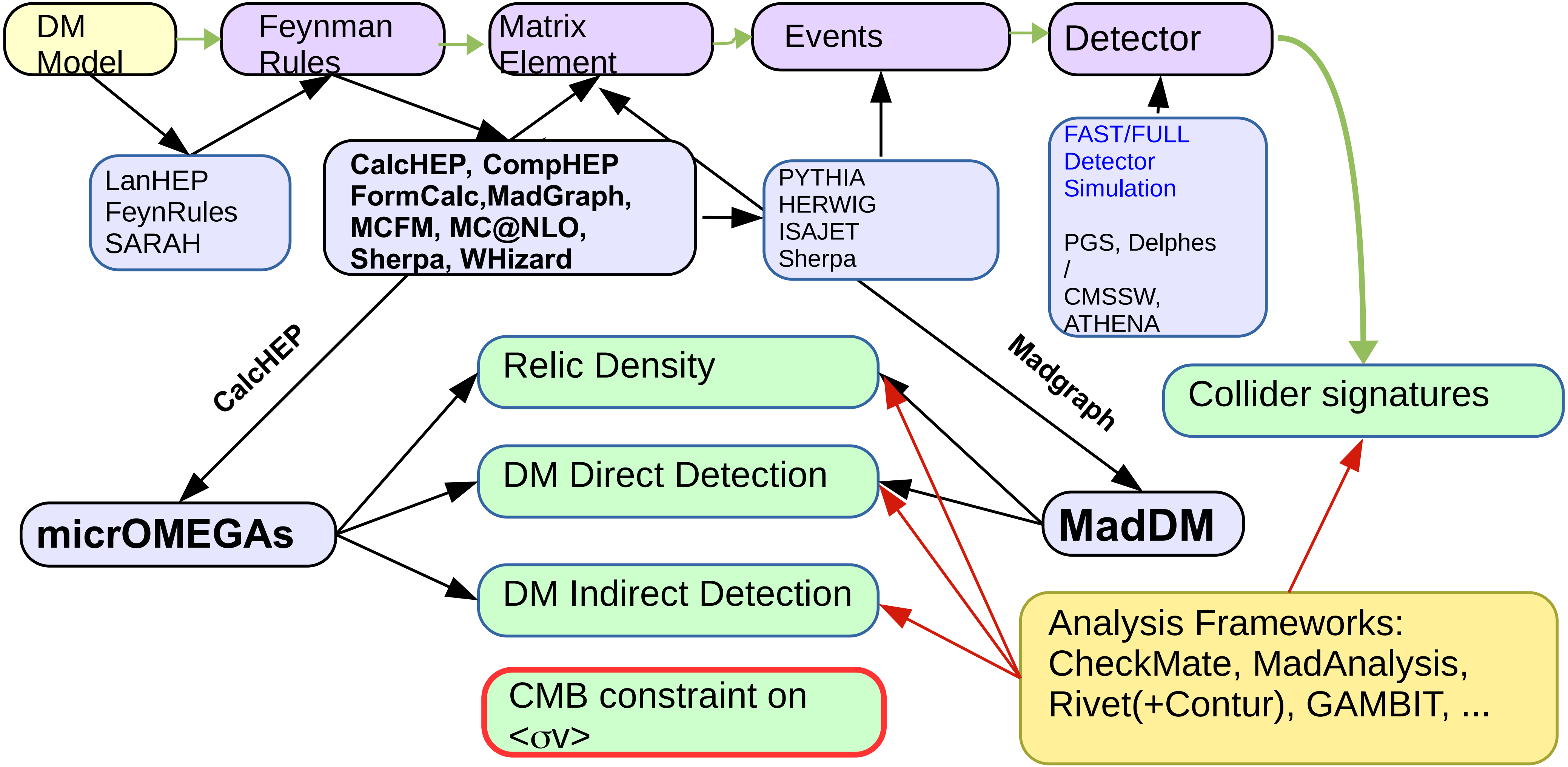
DM Indirect Detection

MadDM

? CMB constraint on $<\sigma v>$

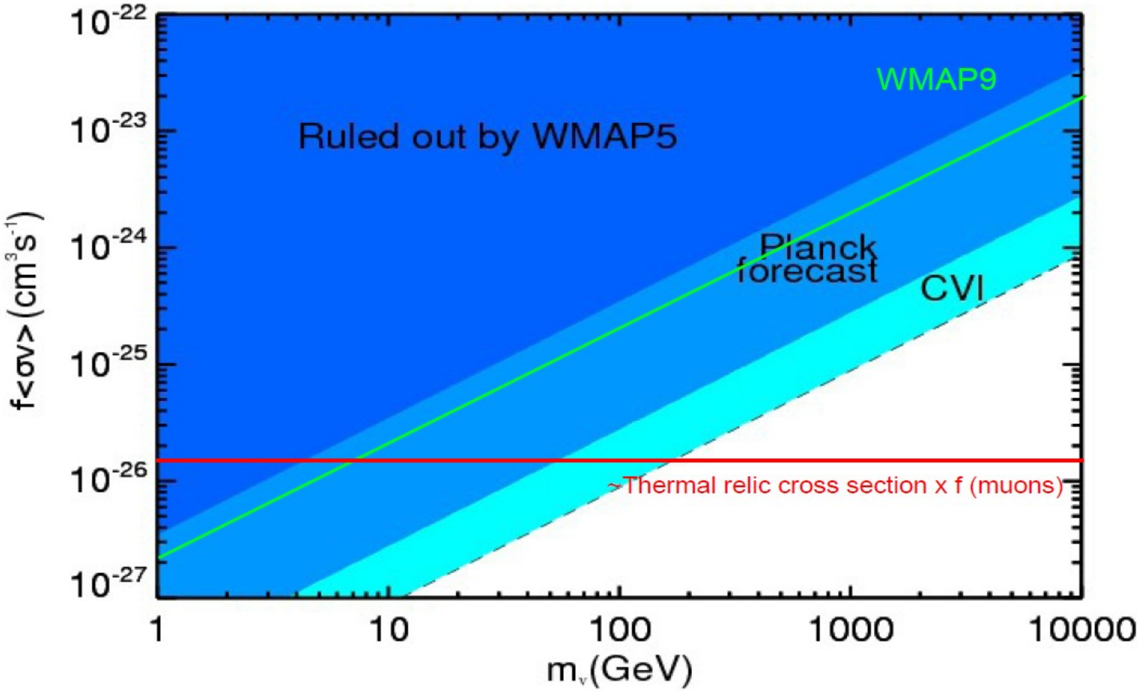
“CMB constraints on Dark Matter models with large annihilation cross-section”
'09 Gallia, Iocco,Bertone, Melchiorri

Tools are important to make theory → observables link !



CMB constraint on <σv>

'09 Gallia, Iocco,Bertone, Melchiorri



- secondary particles produced by DM annihilation with z ~1000 affect the process of recombination, leaving an imprint on CMB anisotropies and polarization

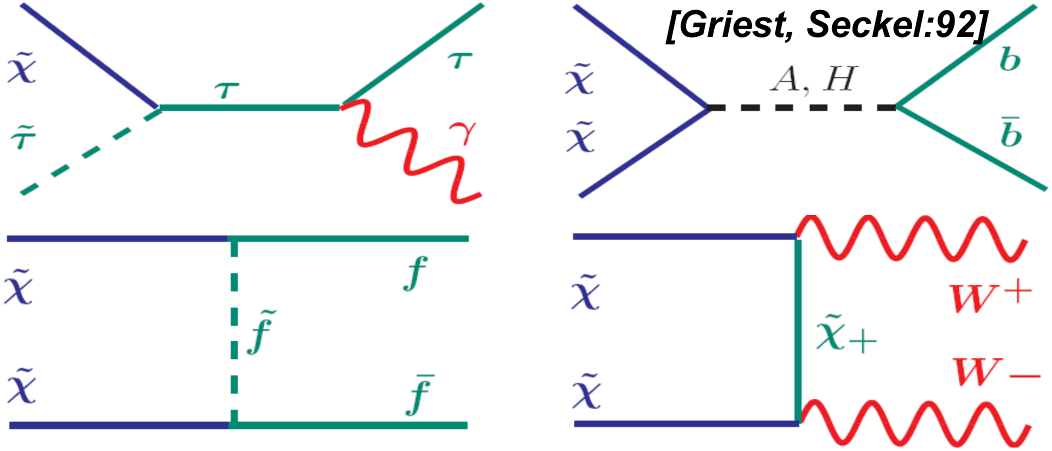
- WMAP place constraints on<σv> especially for models that exhibit a large Sommerfeld enhancement Planck improves constraints by at least one order of magnitude

- f(z) is the fraction of energy that is absorbed by the plasma at each z. Depends on DM mass and annihilation channel

It is important to incorporate this constraint to micrOMEGAs and MadDM!

Evolution of neutralino relic density

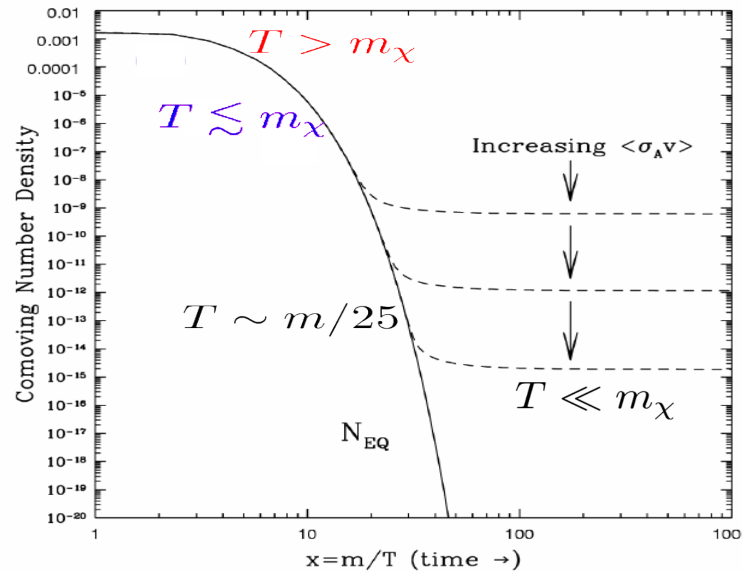
- ***The challenge is to evaluate thousands annihilation/co-annihilation diagrams***



[Griest, Seckel:92]

time evolution of number density is given by Boltzmann equation

$$dn/dt = -3Hn - \langle\sigma_A v\rangle(n^2 - n_{eq}^2)$$



- ***relic density depends crucially on thermal equilibrium stage:***

$$\langle\sigma_A v\rangle$$

$$T > m_\chi, \quad \chi\chi \leftrightarrow f\bar f$$

- ***universe cools: n = $n_{eq} \sim e^{-m/T}$***

$$T \lesssim m_\chi, \quad \chi\chi \not\leftrightarrow f\bar f$$

- ***neutralinos "freeze-out" at***

$$T_F \sim m/25$$

Packages:

MicrOMEGAs(Pukhov et al), MadDM, DarkSusy, ISARED

$$\Omega_\chi = \frac{10^{-10}\mathrm{GeV}^{-2}}{\langle\sigma_A v\rangle}$$

$$\langle\sigma_A v\rangle = 1\mathrm{pb}$$

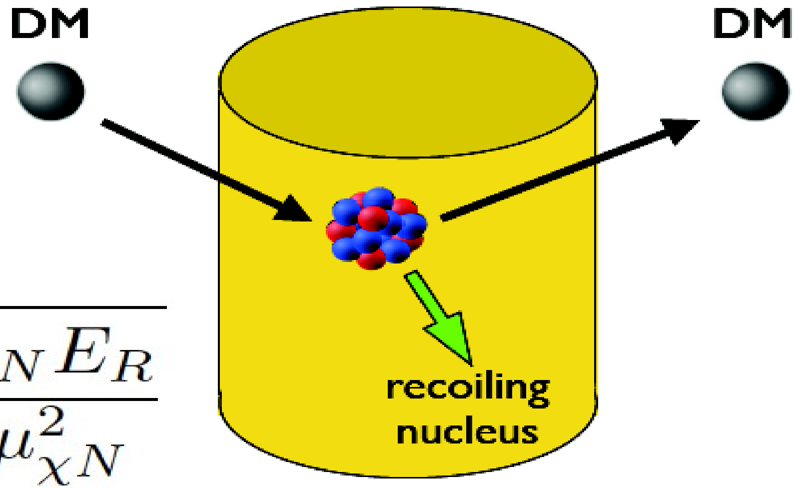
$$\langle\sigma_A v\rangle = \frac{\pi\alpha^2}{8m^2}$$

$$m = 100\mathrm{GeV}$$

mass of the mediator

Direct Dark Matter Detection

- Search for the recoil energy of a nucleus in an underground detector after collision with a WIMP



- Elastic recoil energy

$$E_R = \frac{2\mu_{\chi N}^2 v^2}{m_N} \cos^2\theta$$

- Minimum WIMP speed required to produce a recoil energy

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

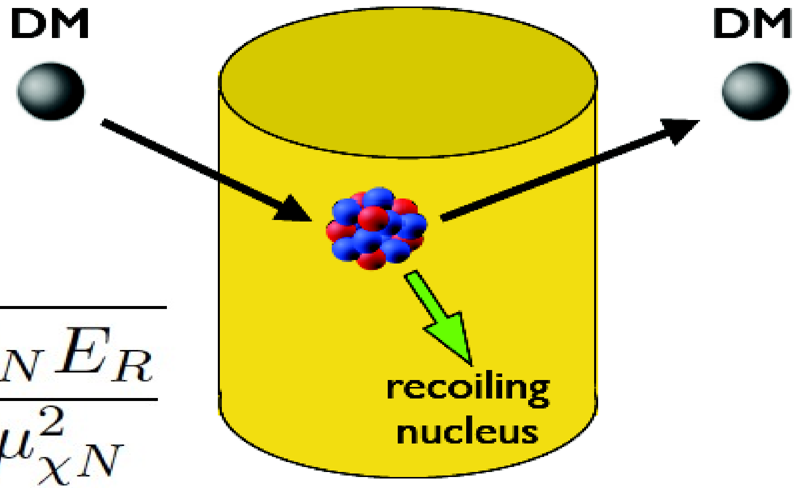
- The differential event rate (per unit detector mass):

astrophysics

$$\frac{dR}{dE_R} = \frac{\boxed{\rho_\chi}}{m_\chi m_N} \int_{v>v_{\min}} d^3v \, \frac{d\sigma_{\chi N}}{dE_R} \, v \, \boxed{f_{\det}(\mathbf{v},t)}$$

Direct Dark Matter Detection

- Search for the recoil energy of a nucleus in an underground detector after collision with a WIMP



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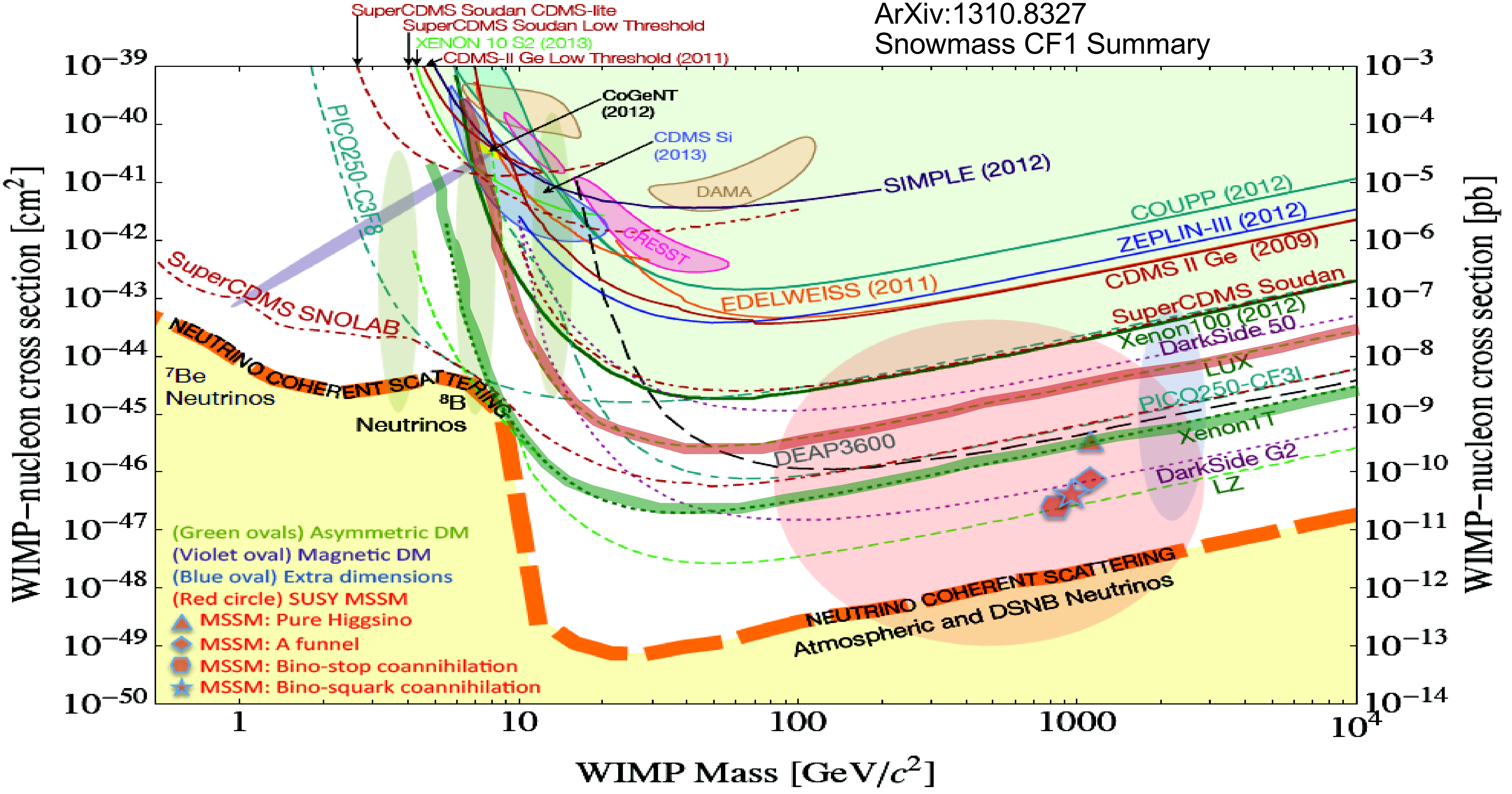
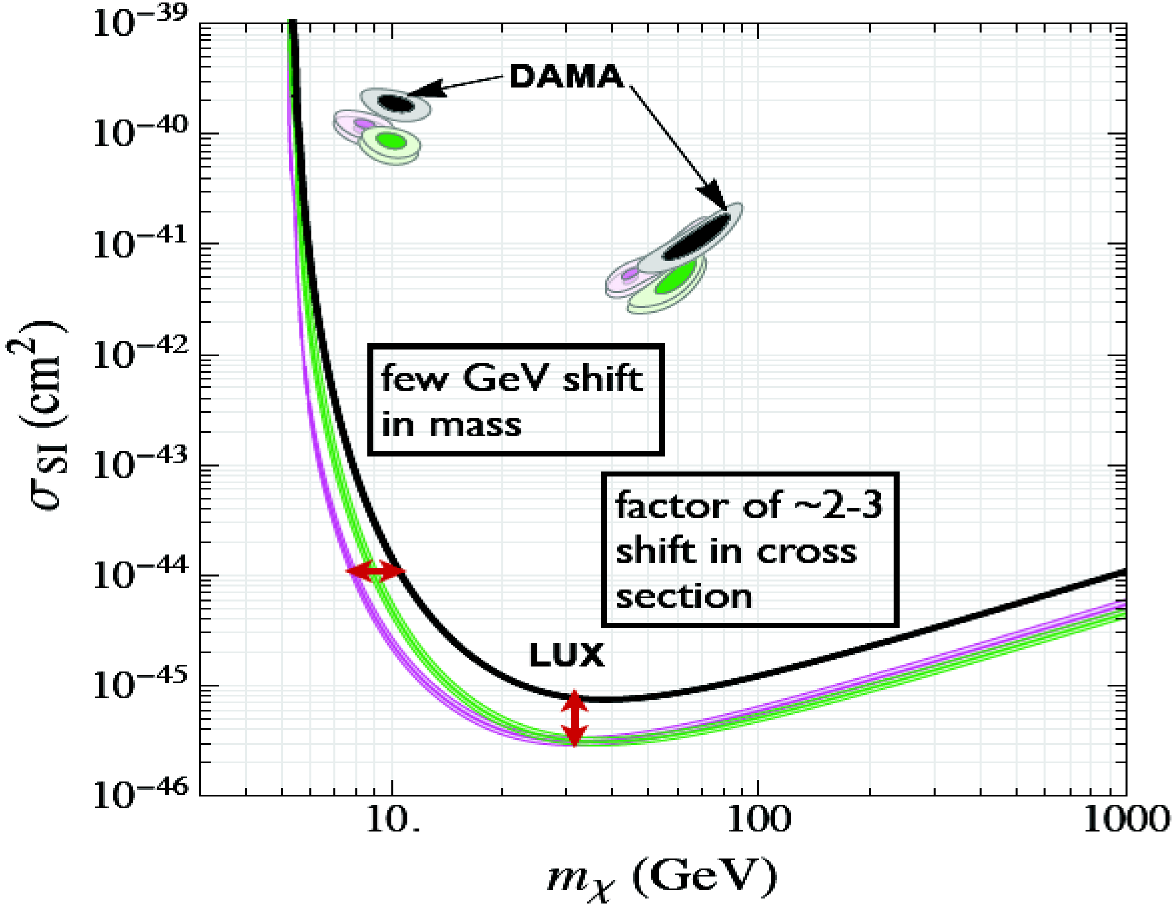
$$\frac{dR}{dE_R} = \underbrace{\frac{\sigma_0 F^2(E_R)}{2 m_\chi \mu^2_{\chi N}}}_{\text{particle physics}} \overbrace{\rho_\chi \underbrace{\eta(v_{\min}, t)}_{\text{halo integral}}}^{\text{astrophysics}}$$

Power of DM DD to rule out theory space



ArXiv:1310.8327
Snowmass CF1 Summary

DM DD: uncertainties



Ioco et al, 2011
Bozorgnia et al., 2016
Kelso et al., 2016
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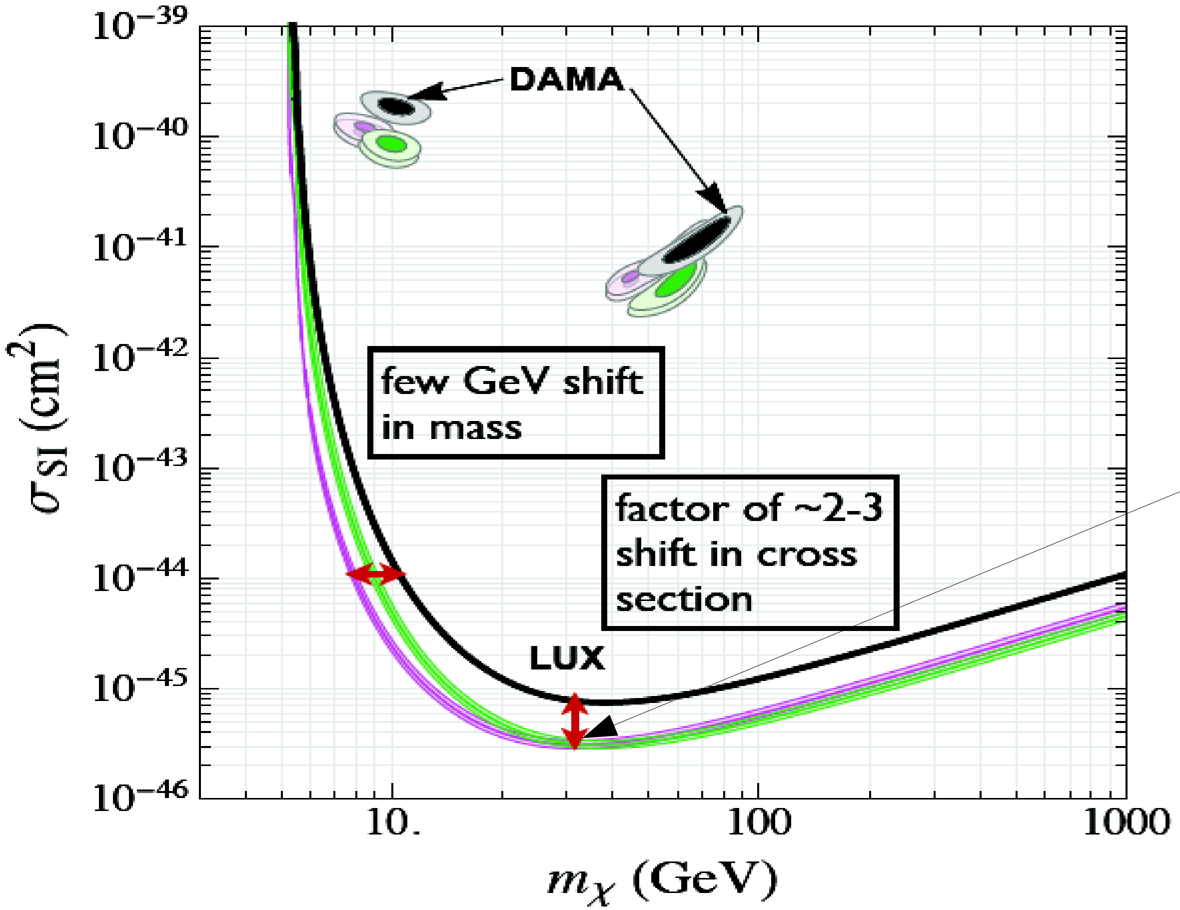
DM DD: uncertainties



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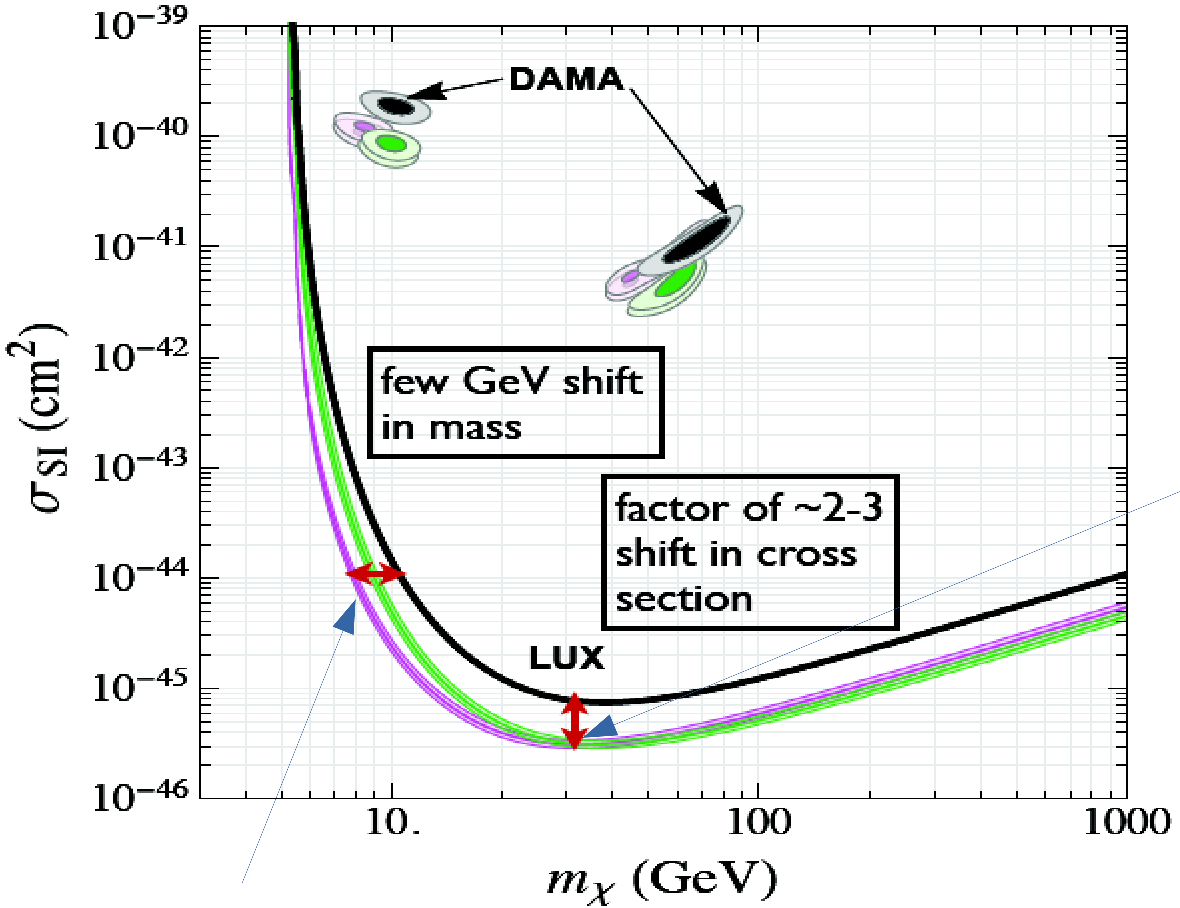
From local relic density uncertainty, based on data analysis

DM DD: uncertainties



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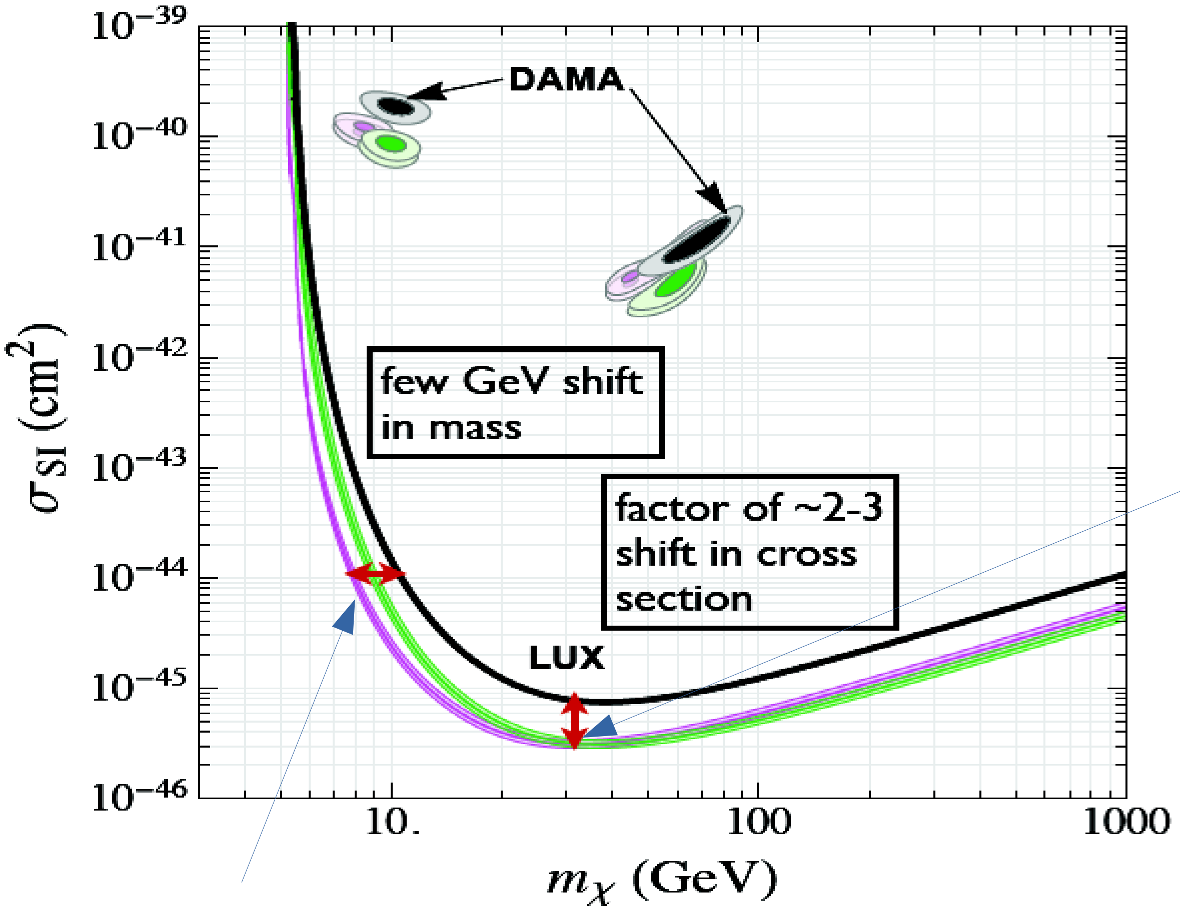
From local relic density uncertainty, based on data analysis

From DM velocity uncertainty, based on analysis of the simulations

DM DD: uncertainties



Ioco et al, 2011
Bozorgnia et al., 2016
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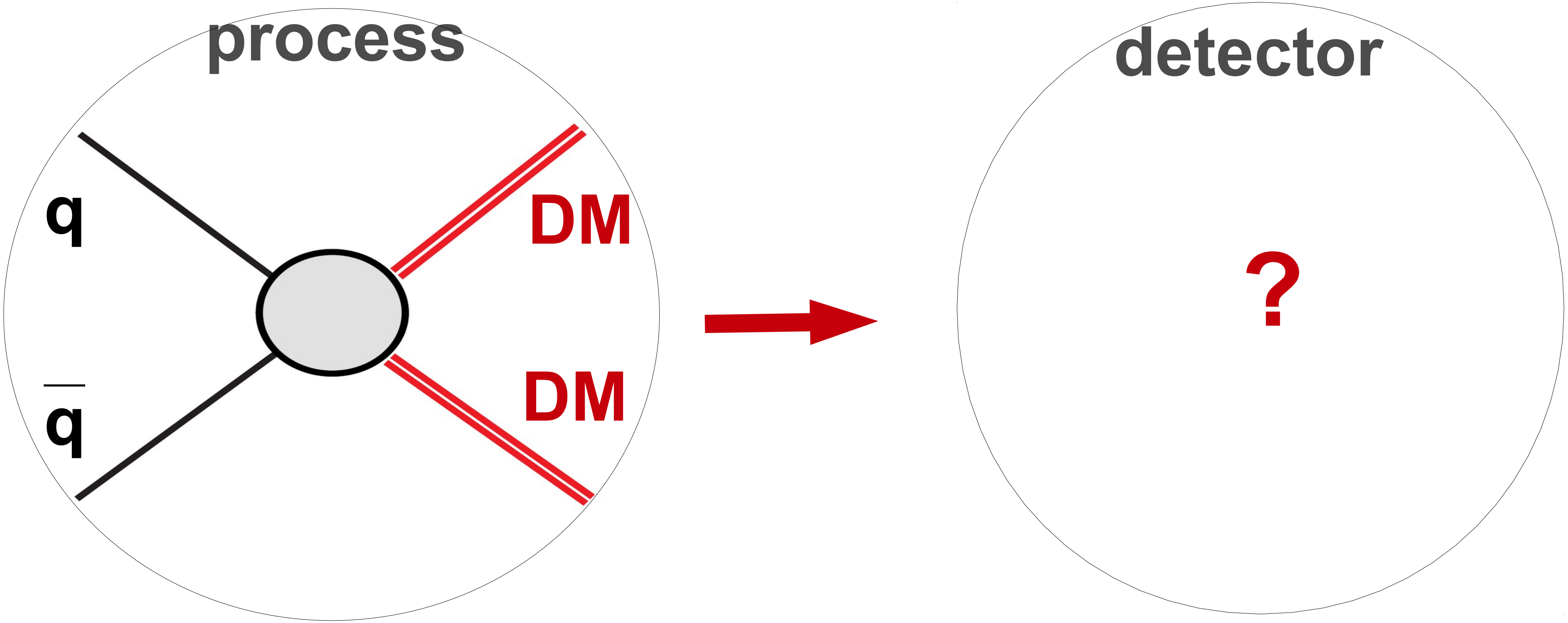
From local relic density uncertainty, based on data analysis

DAMA results, even being controversial played a very positive role:
boosted exploration
uncertainties in all details,
boosted low DM mass exploration
motivated robust cross check with SABRE in opposite hemisphere

From DM velocity uncertainty, based on analysis of the simulations

Collider Searches



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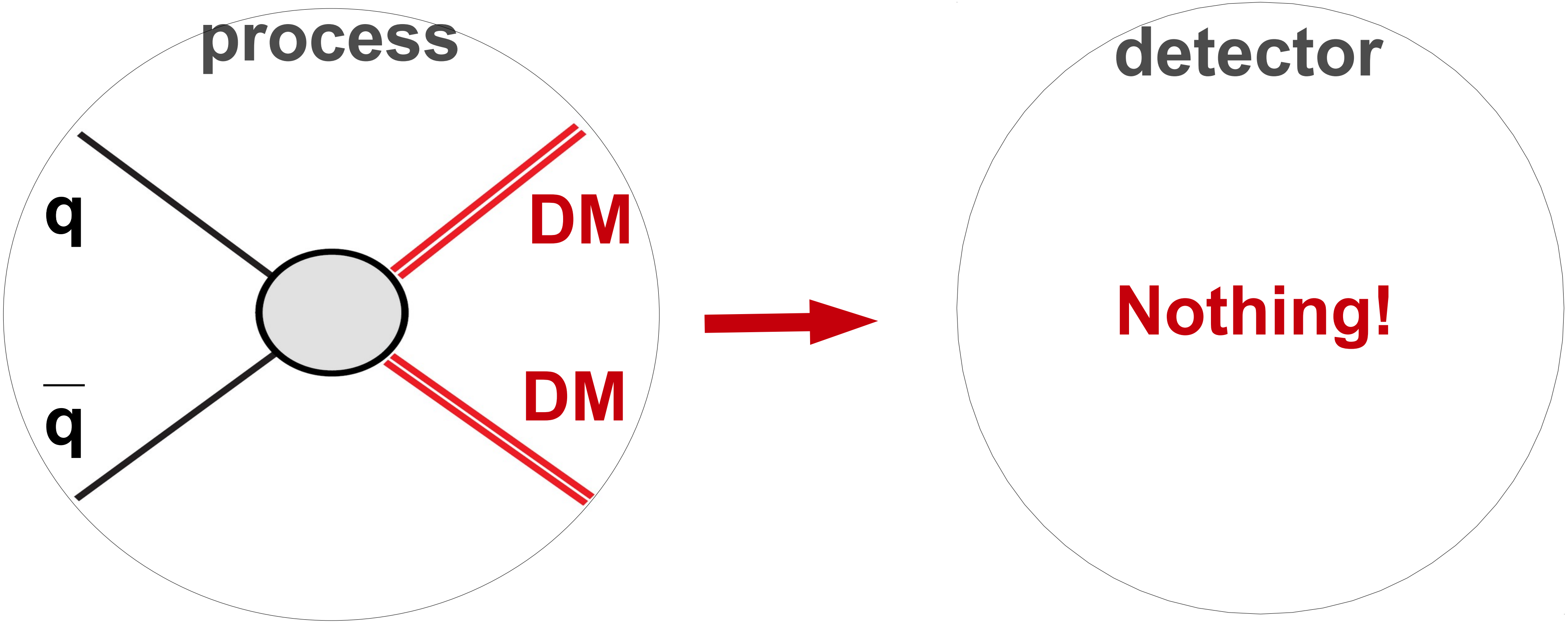
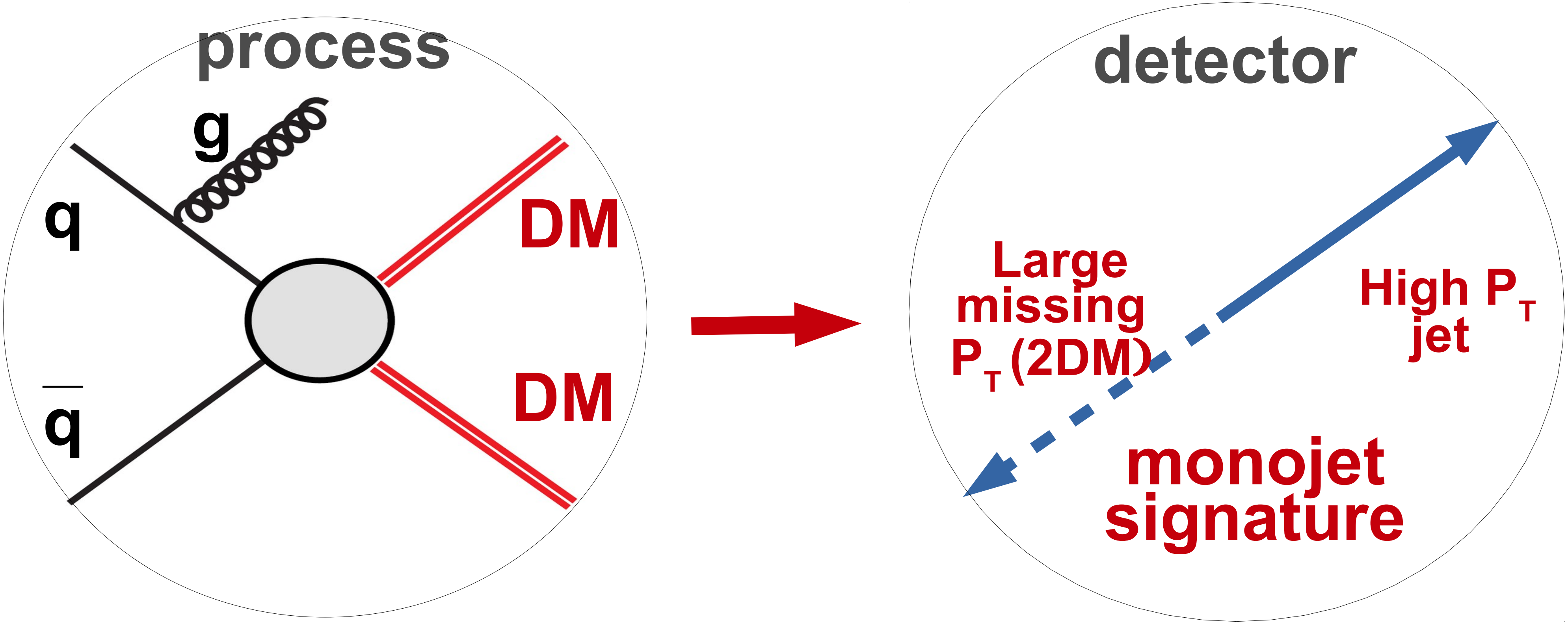


Monojet Signature

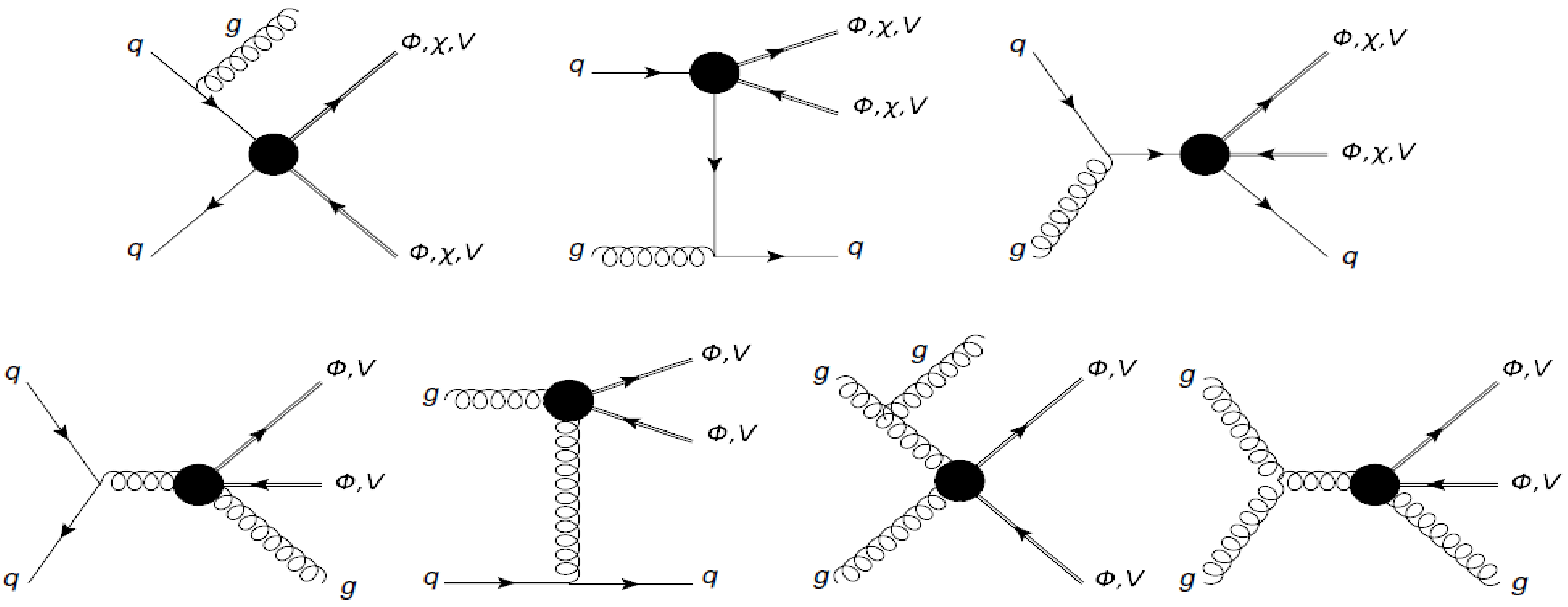


Can we test DM properties at the LHC?

Let us check the effects of DM spin on Missing transverse momentum **(MET)** distributions at the LHC:

- let us start with EFT approach first – the simplest model-independent approach:
- Complete set of DIM5/DIM6 operators involving two SM quarks (gluons) and two DM particles
- consider spin=0, 1/2, 1 DM
- mono-jet signature
- explore LHC discovery potential for scenarios with different DM spins and potential to distinguish these scenarios

Mono-jet diagrams from EFT operators



DIM5/6 operators (spin 0,1/2,1)

Complex scalar DM†	
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	[C1]*
$\frac{\tilde{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}i\gamma^5 q$	[C2]*
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu q$	[C3]
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu\gamma^5 q$	[C4]
$\frac{1}{\Lambda^2}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	[C5]*
$\frac{1}{\Lambda^2}\phi^\dagger\phi\tilde{G}^{\mu\nu}G_{\mu\nu}$	[C6]*

Dirac fermion DM†	
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$	[D1]*
$\frac{1}{\Lambda^2}\bar{\chi}i\gamma^5\chi\bar{q}q$	[D2]*
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}i\gamma^5 q$	[D3]*
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	[D4]*
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	[D5]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	[D6]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	[D7]
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	[D8]
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	[D9]*
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}i\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	[D10]*

Complex vector DM‡	
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V^\mu\bar{q}q$	[V1]*
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V^\mu\bar{q}i\gamma^5 q$	[V2]*
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar{q}\gamma^\mu q$	[V3]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial_\mu V^\nu - V^\nu\partial_\mu V_\nu^\dagger)\bar{q}i\gamma^\mu\gamma^5 q$	[V4]
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V_\nu\bar{q}i\sigma^{\mu\nu}q$	[V5]
$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V_\nu\bar{q}\sigma^{\mu\nu}\gamma^5 q$	[V6]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu + V^\nu\partial^\nu V_\mu^\dagger)\bar{q}\gamma^\mu q$	[V7P]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma^\mu q$	[V7M]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu + V^\nu\partial^\nu V_\mu^\dagger)\bar{q}\gamma^\mu\gamma^5 q$	[V8P]
$\frac{1}{2\Lambda^2}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma^\mu\gamma^5 q$	[V8M]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial_\rho V_\sigma + V_\nu\partial_\rho V_\sigma^\dagger)\bar{q}\gamma_\mu q$	[V9P]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma_\mu q$	[V9M]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial_\rho V_\sigma + V_\nu\partial_\rho V_\sigma^\dagger)\bar{q}\gamma_\mu\gamma^5 q$	[V10P]
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V_\nu^\dagger\partial^\nu V_\mu - V^\nu\partial^\nu V_\mu^\dagger)\bar{q}i\gamma_\mu\gamma^5 q$	[V10M]
$\frac{1}{\Lambda^2}V_\mu^\dagger V^\mu G^{\rho\sigma}G_{\rho\sigma}$	[V11]*
$\frac{1}{\Lambda^2}V_\mu^\dagger V^\mu\tilde{G}^{\rho\sigma}G_{\rho\sigma}$	[V12]*

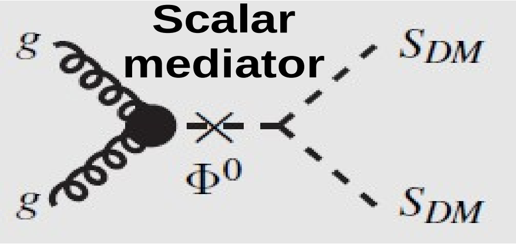
* operators applicable to real DM fields, modulo a factor $1/2$

† Listed in J. Goodman *et al.*, *Constraints on Dark Matter from Colliders*, Phys.Rev. **D82** (2010) 116010, [arXiv:1008.1783]

‡ All but V11 and V12 listed in Kumar *et al.*, *Vector dark matter at the LHC*, Phys. Rev. **D92** (2015) 095027, [arXiv:1508.04466]

Mapping EFT operators to simplified models

C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$, $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$ $\longrightarrow$



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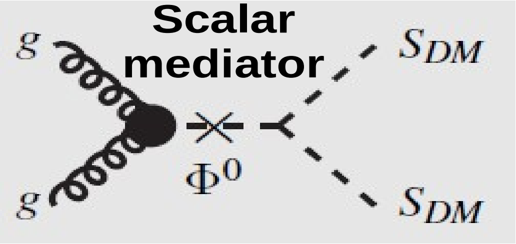
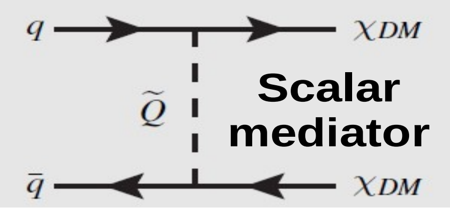
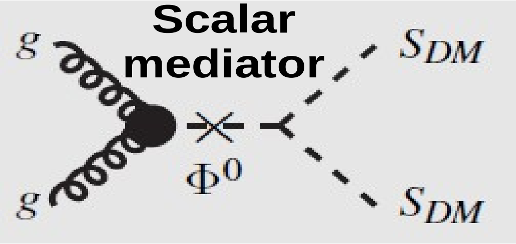


D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ $\longrightarrow$

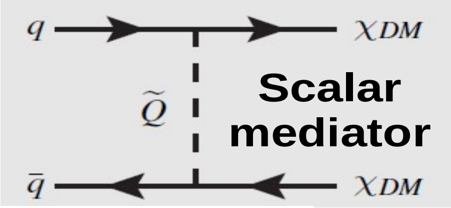


Mapping EFT operators to simplified models

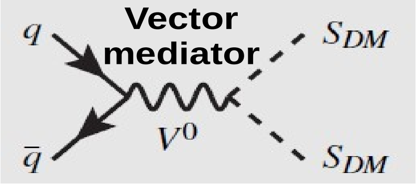
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$, $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$ $\longrightarrow$



D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ $\longrightarrow$



C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi-(\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ $\longrightarrow$



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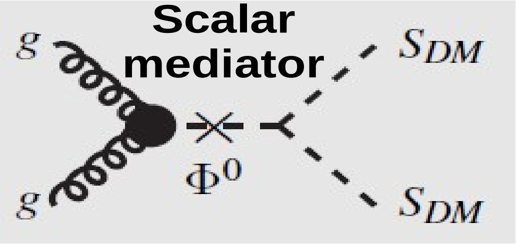

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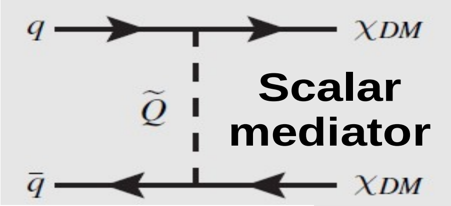

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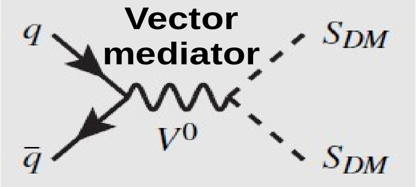
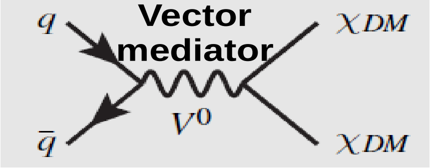
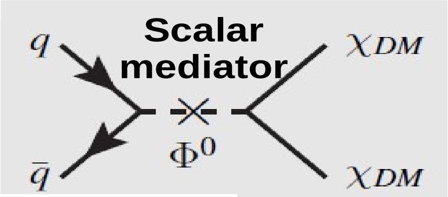


D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q \longrightarrow$





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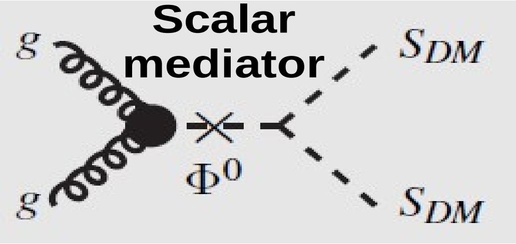

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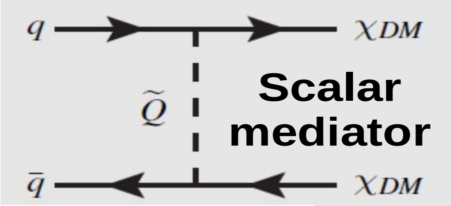

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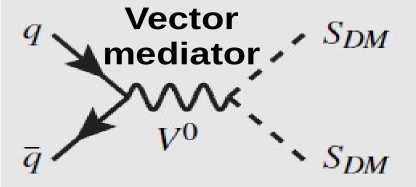

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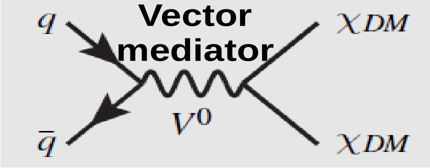
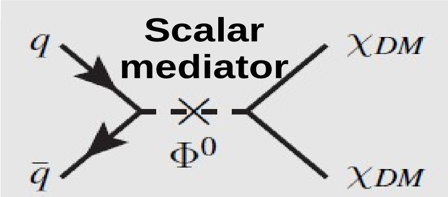
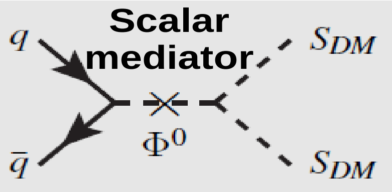




C1 $\frac{1}{\Lambda^2}\phi^*\phi\bar{q}q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar{q}q$ $\longrightarrow$



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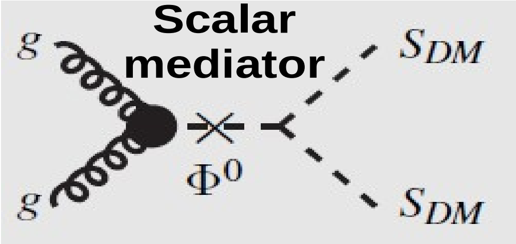

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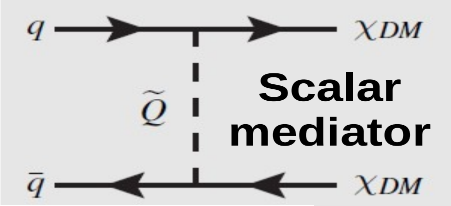

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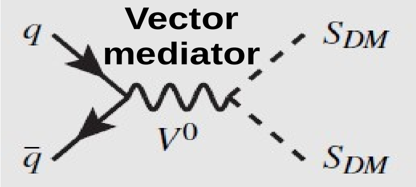

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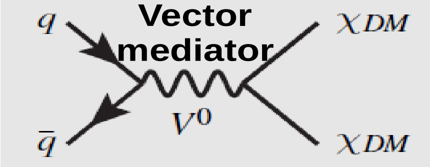

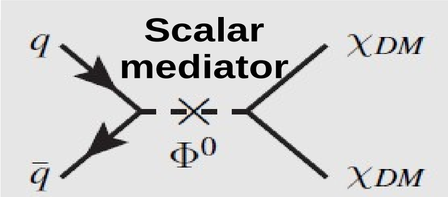

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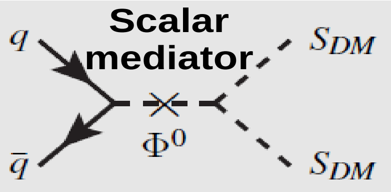
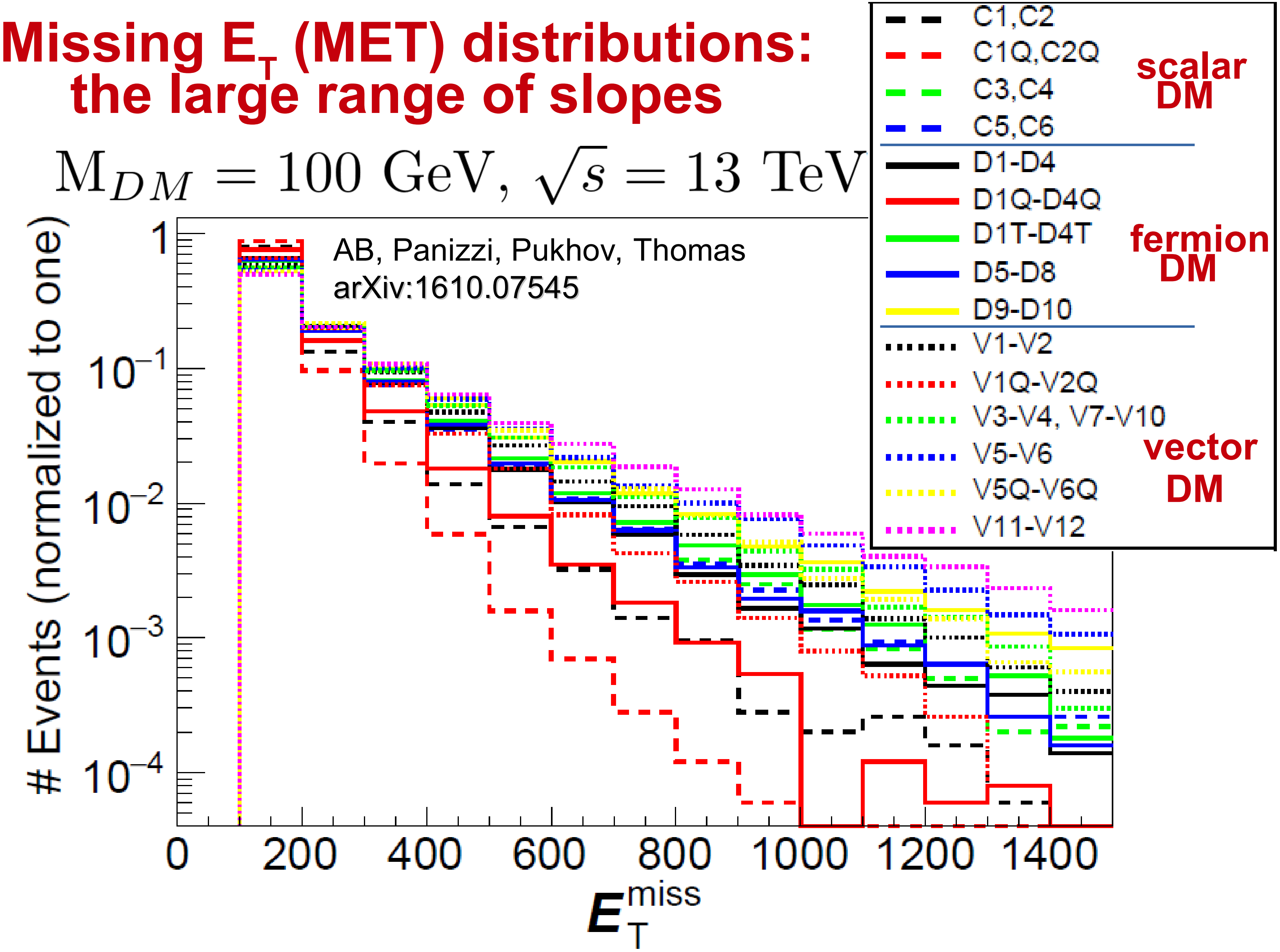


D9,D10

$$\frac{1}{\Lambda^2}\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu}q \longrightarrow \frac{8}{\Lambda^2}\Big[\,\bar\chi q\bar q\chi - \frac{1}{4}\big(\bar\chi\chi\bar q q + \bar\chi\gamma^5\chi\bar q\gamma^5 q + \bar\chi\gamma^\mu\chi\bar q\gamma_\mu q - \bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q\,\big)\Big]$$

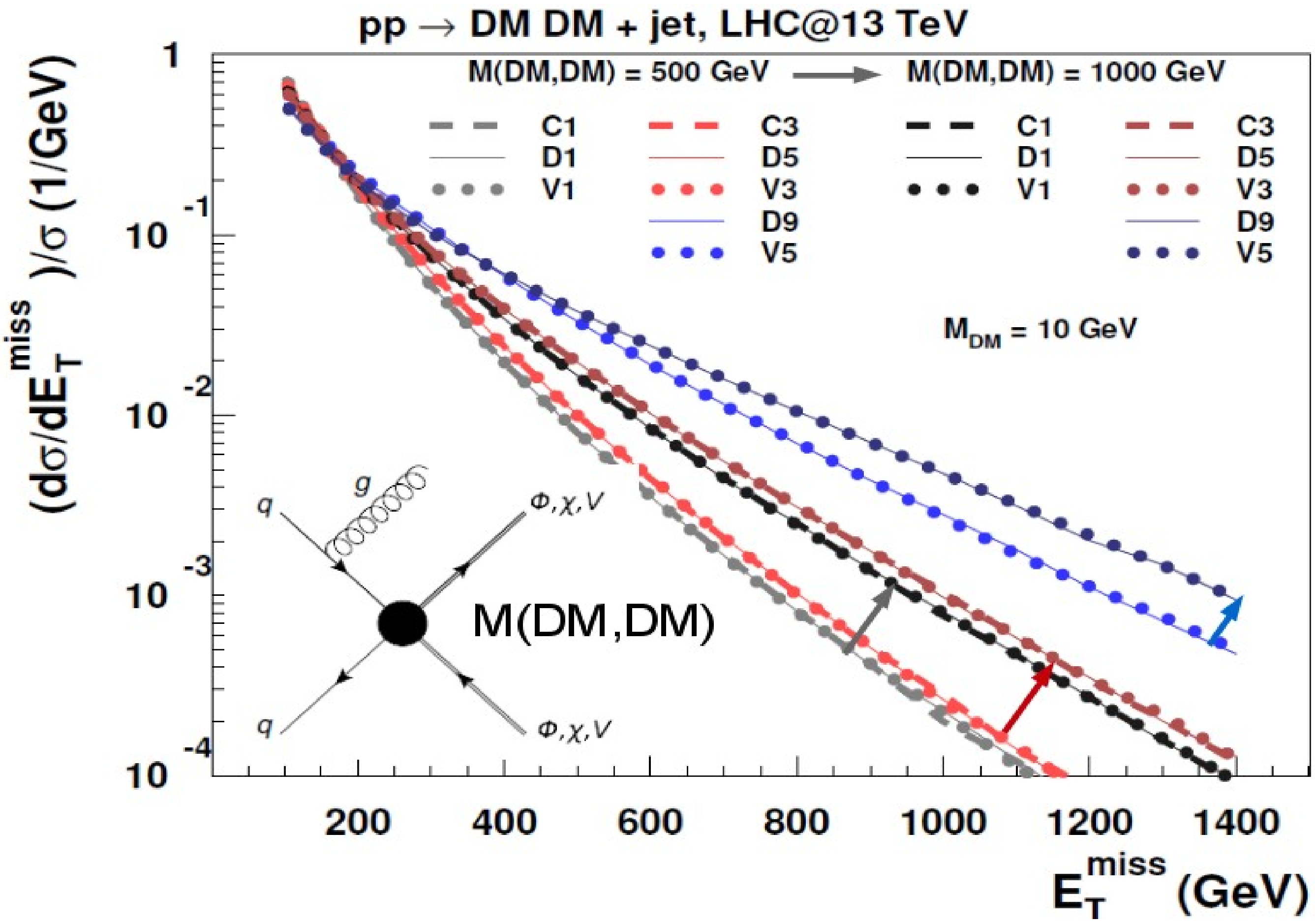
Missing E_T (MET) distributions: the large range of slopes

$$M_{DM} = 100\ \text{GeV},\ \sqrt{s} = 13\ \text{TeV}$$


AB, Panizzi, Pukhov, Thomas
arXiv:1610.07545

Properties of MET distributions:

- MET distributions are the same for the fixed mass of DM pair [M(DM,DM)] & fixed SM operator
- With the increase of M(DM,DM), MET slope decreases (PDF effect)



$$\frac{\tilde m}{\Lambda^2}\phi^*\phi\bar q q \quad [C1]$$

$$\frac{1}{\Lambda^2}\bar\chi\chi\bar q q \quad [D1]$$

$$\frac{\tilde m}{\Lambda^2}V^{\dagger\mu}V_\mu\bar q q \quad [V1]$$

$$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar q\gamma^\mu q \quad [C3]$$

$$\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q \quad [D5]$$

$$\frac{1}{\Lambda^2}\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu}q \quad [D9]$$

$$\frac{\tilde m}{\Lambda^2}V_\mu^\dagger V_\nu\bar q i\sigma^{\mu\nu}q \quad [V5]$$

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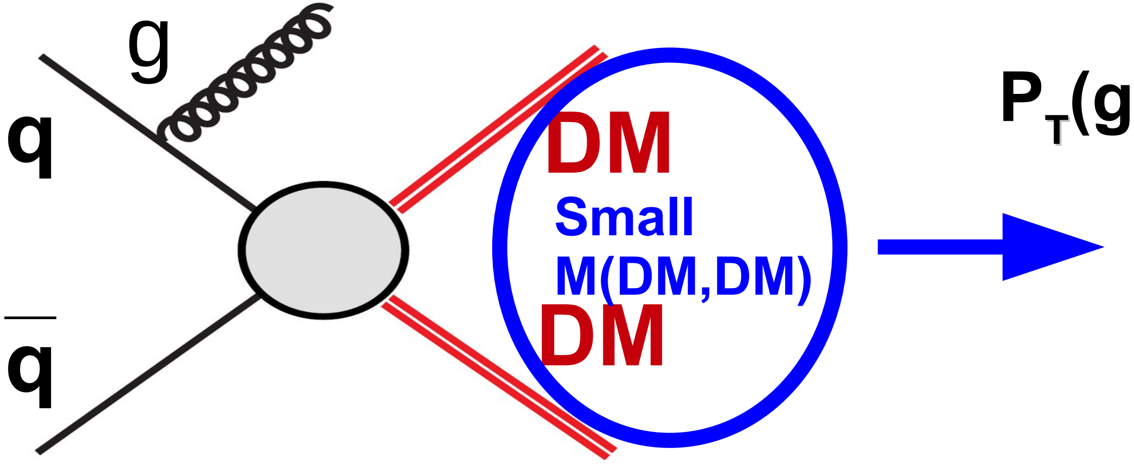

$P_T(g)$ small → $P_T(g)$large

Δ (x1 x2)/(x1 x2) is large and MET slope is steep

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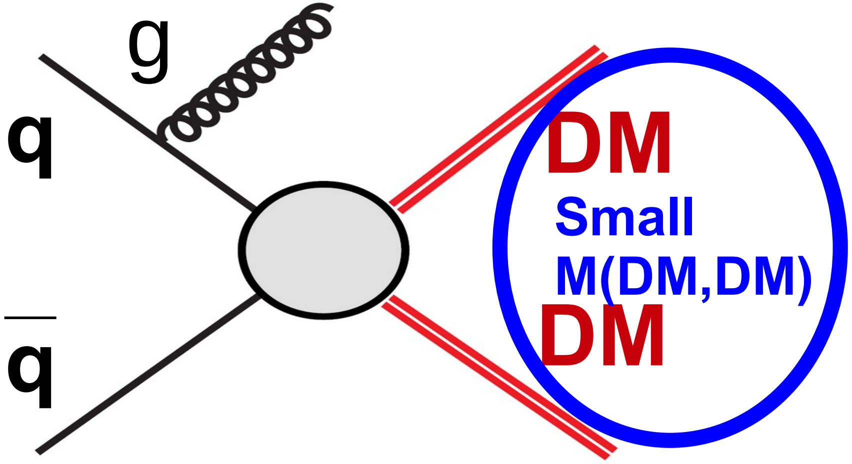

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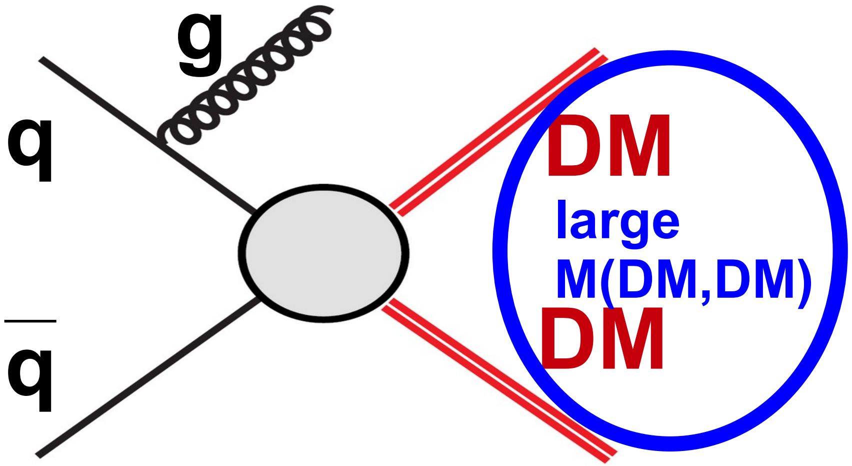


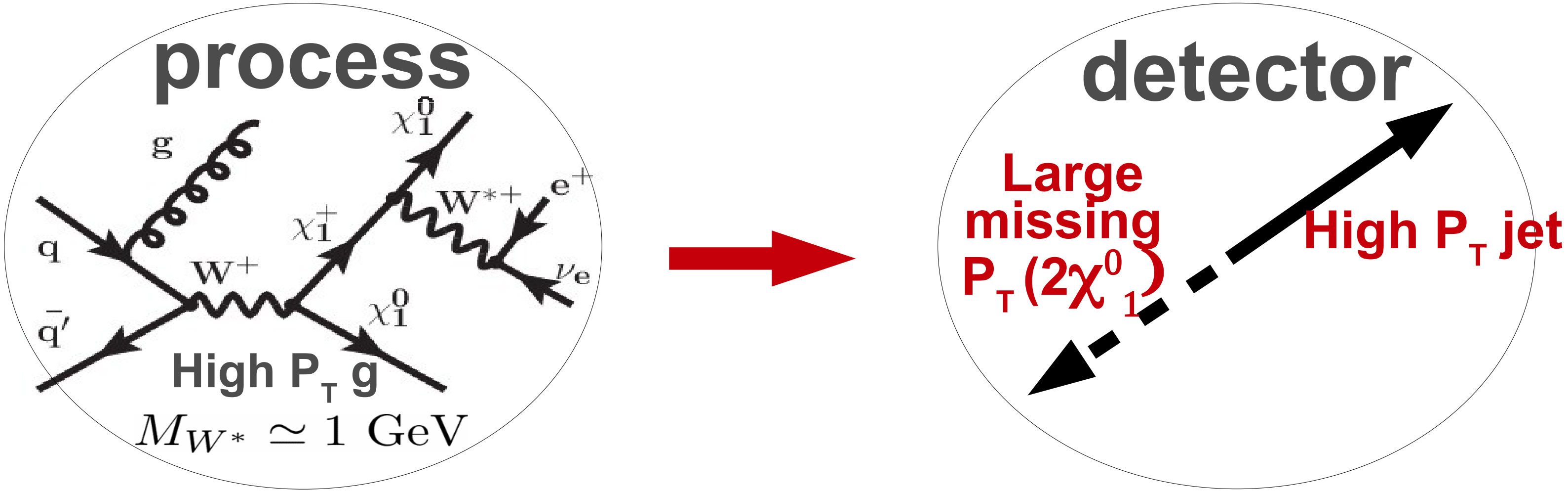
P_T(g) small → P_T(g)large

Δ (x1 x2)/(x1 x2) is small and MET slope is gradual

Application to SUSY Compressed Mass Spectrum scenario

- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for leptonic signatures

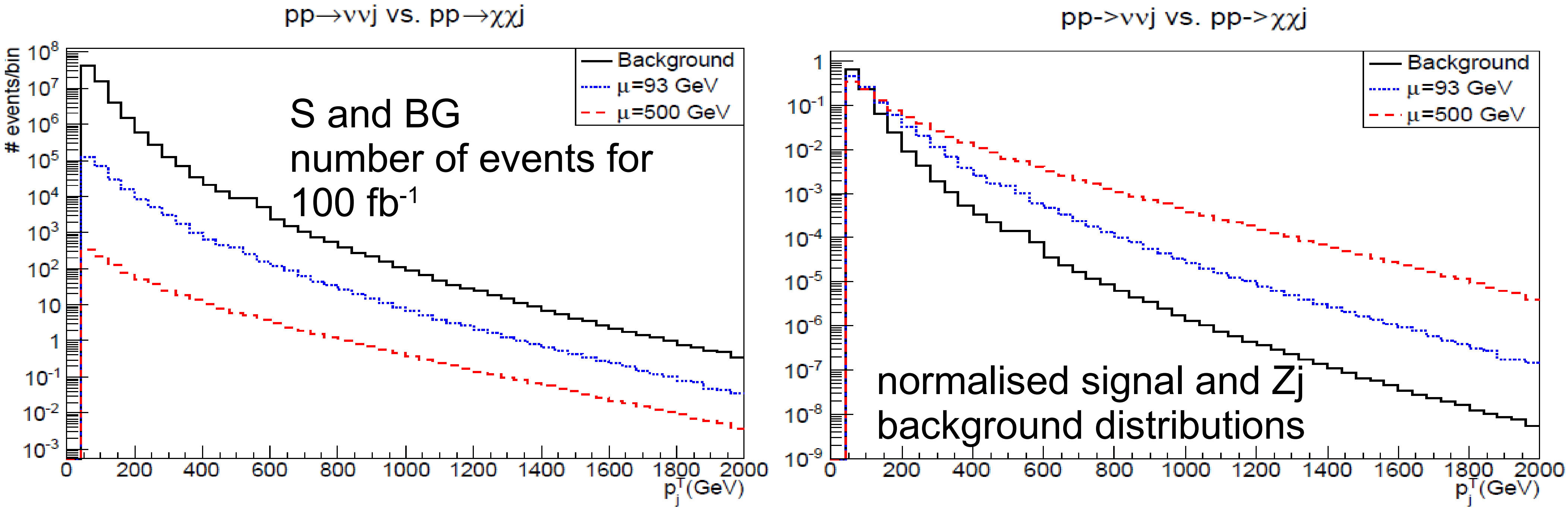
- The only way to probe CHS is a mono-jet signature
  [“Where the Sidewalk Ends? ...” Alves, Izaguirre,Wacker '11] ,
  which has been used in studies on compressed SUSY spectra, e.g. Dreiner,Kramer,Tattersall '12; Han,Kobakhidze,Liu,Saavedra,Wu'13; Han,Kribs,Martin,Menon '14



Signal vs Background

- difference in rates is pessimistic ...

- but the difference in shapes is encouraging: large DM mass → bigger M(DM,DM) → flatter MET

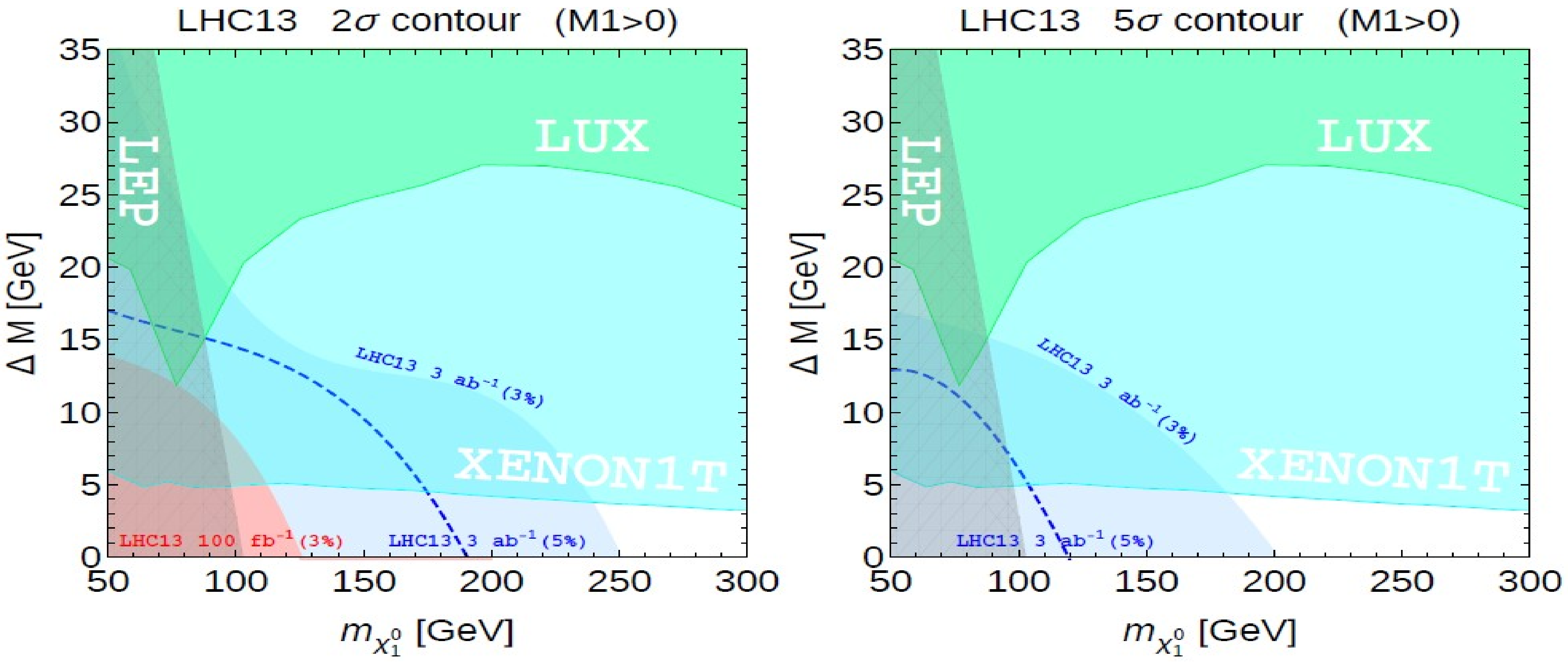


S and BG number of events for 100 fb^{-1}

normalised signal and Zj background distributions

Signal and Zj background p_T^j distributions for the 13 TeV LHC

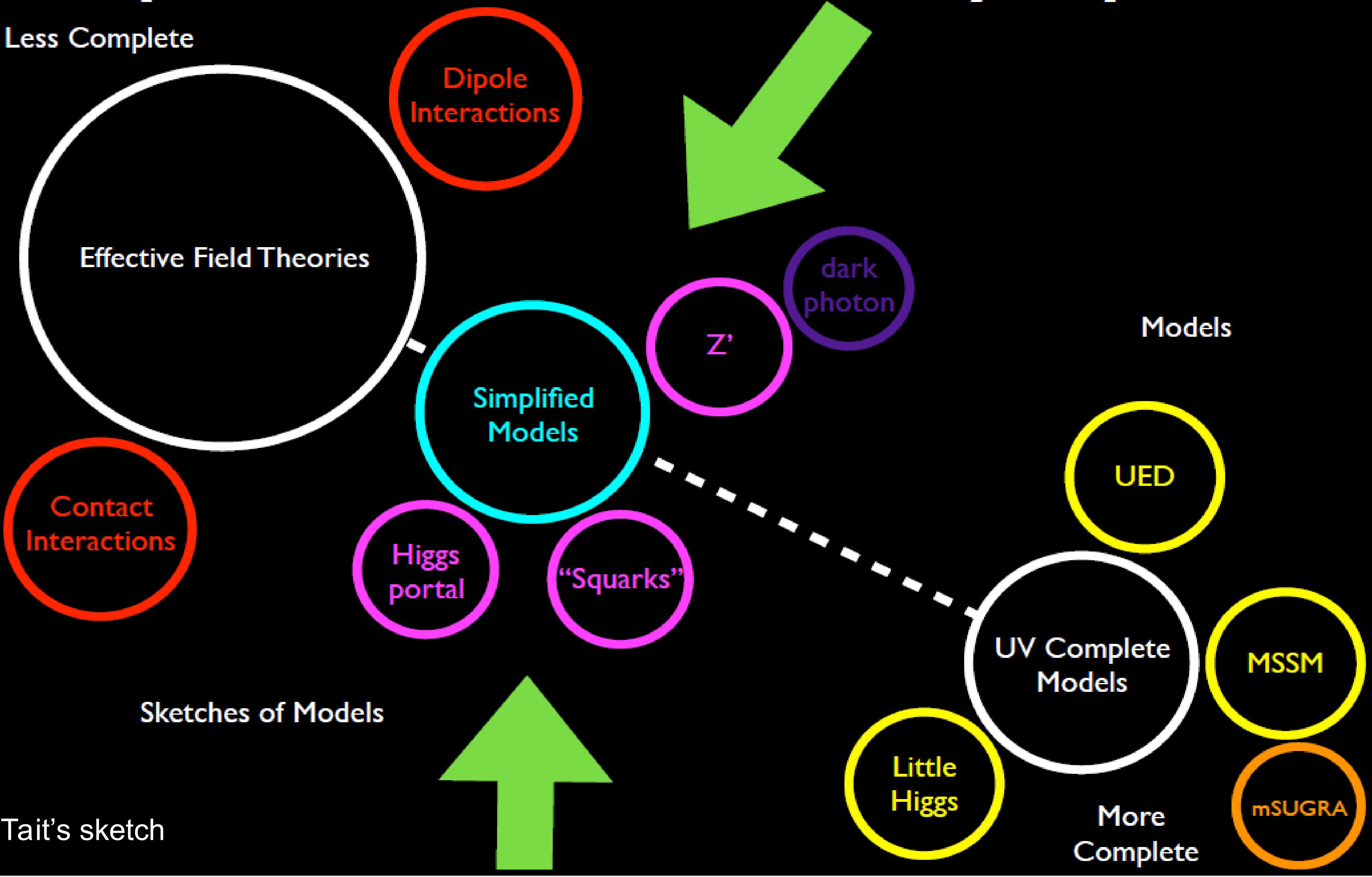
LHC/DM direct detection sensitivity



AB, Barducci,Bharucha,Porod,Sanz JHEP, 1504.02472

- SUSY DM, can be around the corner (~100 GeV), but it is hard to detect it!
- Great complementarity of DD and LHC for small DM (natural)SUSY region

Spectrum of Theory Space



Less Complete

Effective Field Theories

Dipole Interactions

Contact Interactions

Simplified Models

Z'

dark photon

Higgs portal

"Squarks"

Models

UED

UV Complete Models

MSSM

Little Higgs

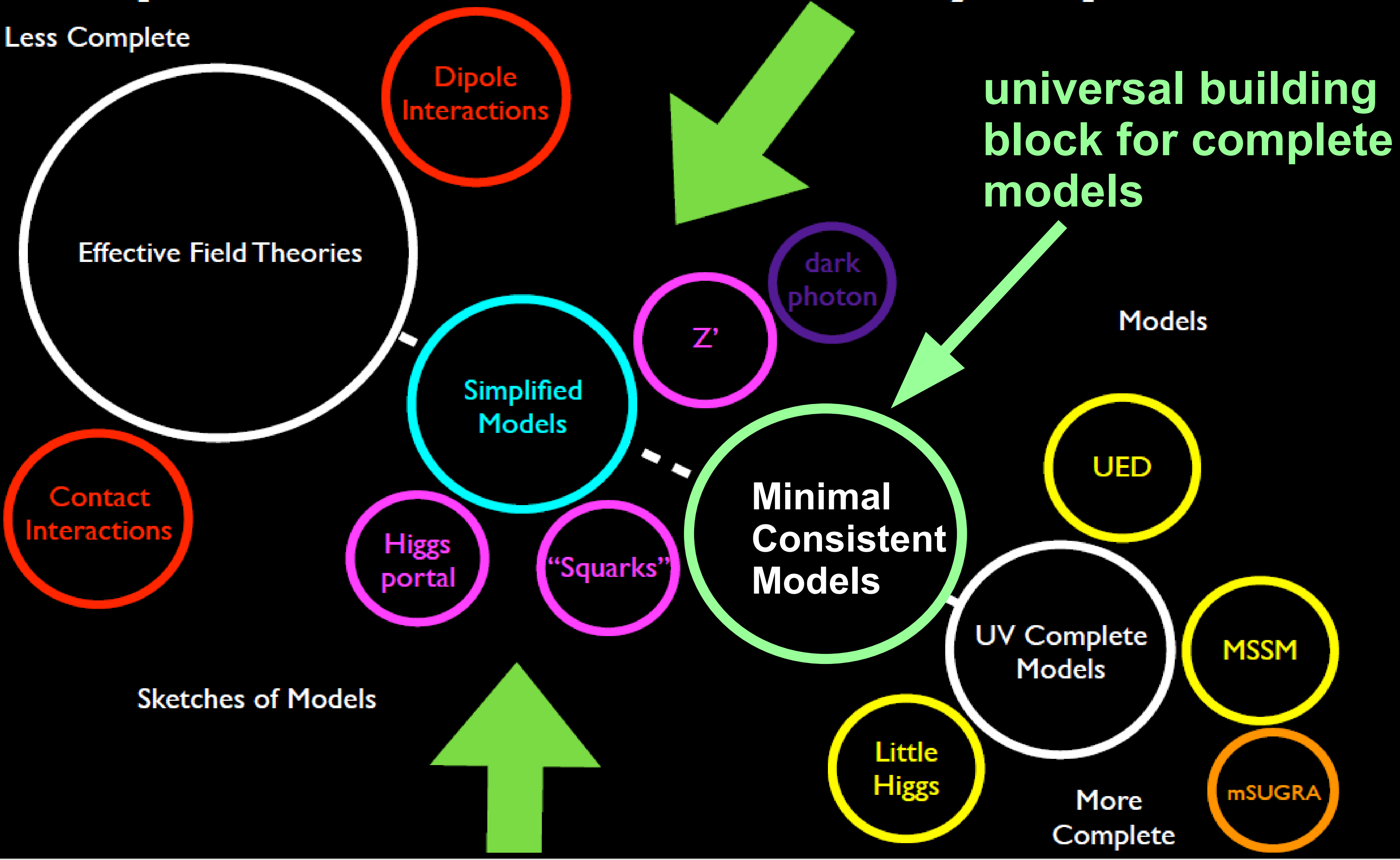
mSUGRA

More Complete

Sketches of Models

Tim Tait's sketch

Spectrum of Theory Space



Minimal Consistent DM (MCDM) Models

Properties

- gauge-invariant
- renormalisable
- anomaly-free
- can also be a building block of a bigger theory (e.g. SUSY)

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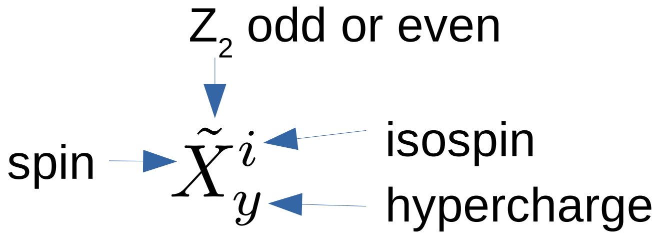
- DM is a part of EW multiplet
- at most one mediator multiplet
- very important for consistent exploration of DM theory space



Z_2 odd or even

spin

$\tilde{X}^i_y$

isospin

hypercharge

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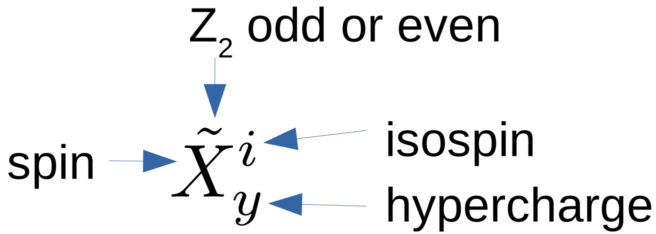

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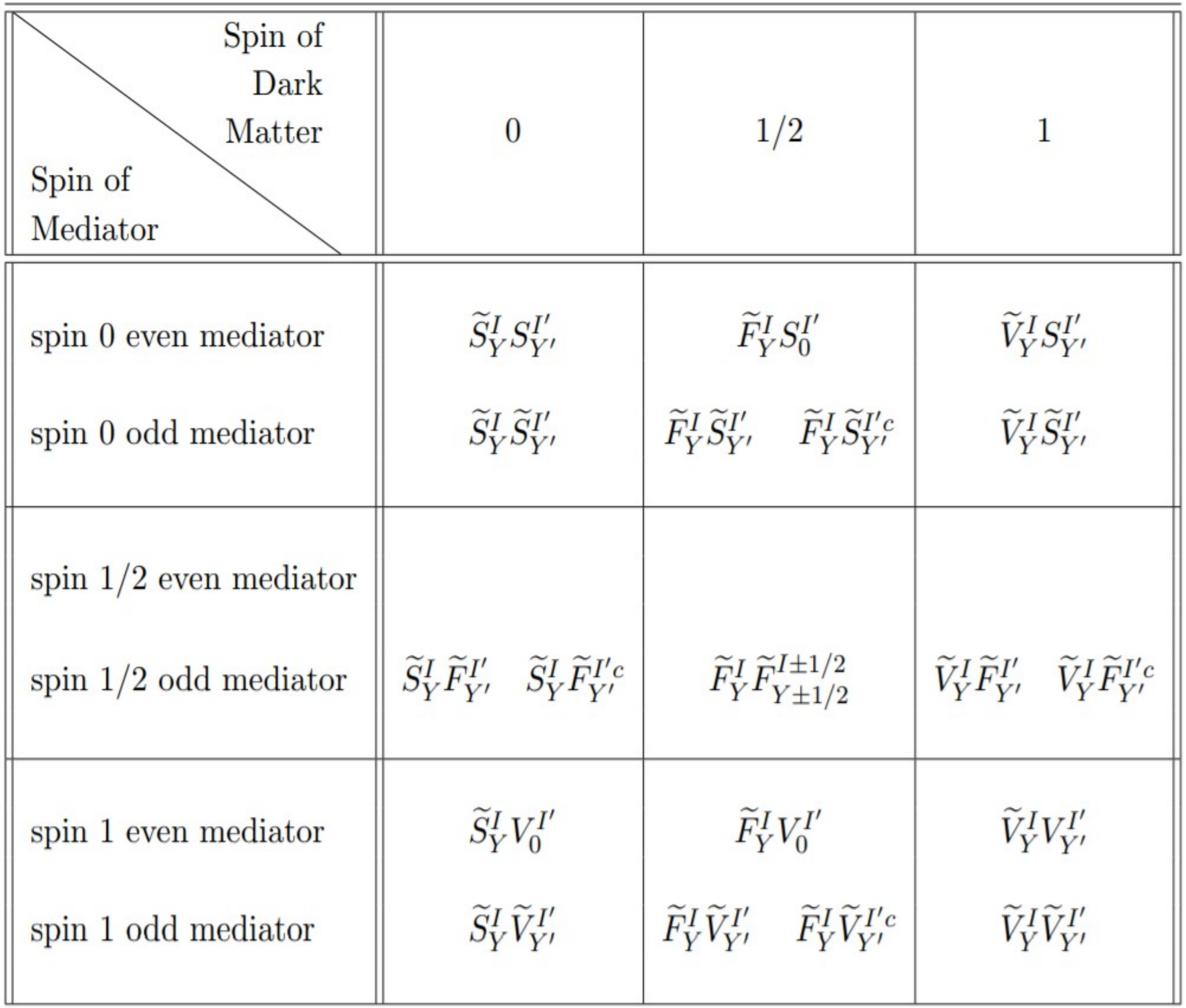


Spin of Dark Matter Spin of Mediator	0	1/2	1
spin 0 even mediator	$\tilde{S}^I_Y S^{I'}_{Y'}$	$\tilde{F}^I_Y S^{I'}_0$	$\tilde{V}^I_Y S^{I'}_{Y'}$
spin 0 odd mediator	$\tilde{S}^I_Y \tilde{S}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{S}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{S}^{I'c}_{Y'}$	$\tilde{V}^I_Y \tilde{S}^{I'}_{Y'}$
spin 1/2 even mediator			
spin 1/2 odd mediator	$\tilde{S}^I_Y \tilde{F}^{I'}_{Y'}$ $\tilde{S}^I_Y \tilde{F}^{I'c}_{Y'}$	$\tilde{F}^I_Y \tilde{F}^{I\pm1/2}_{Y\pm1/2}$	$\tilde{V}^I_Y \tilde{F}^{I'}_{Y'}$ $\tilde{V}^I_Y \tilde{F}^{I'c}_{Y'}$
spin 1 even mediator	$\tilde{S}^I_Y V^{I'}_0$	$\tilde{F}^I_Y V^{I'}_0$	$\tilde{V}^I_Y V^{I'}_{Y'}$
spin 1 odd mediator	$\tilde{S}^I_Y \tilde{V}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{V}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{V}^{I'c}_{Y'}$	$\tilde{V}^I_Y \tilde{V}^{I'}_{Y'}$

G.Cacciapaglia, D.Locke, A.Pukhov, AB to appear

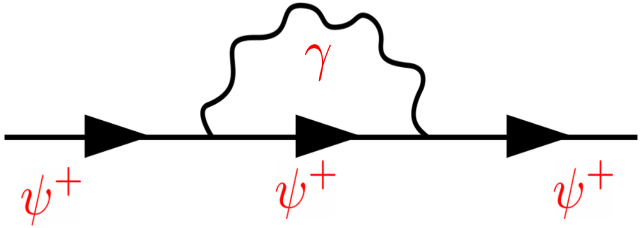
DM multiplet only

$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu \psi - m_D \bar{\psi}\psi$$

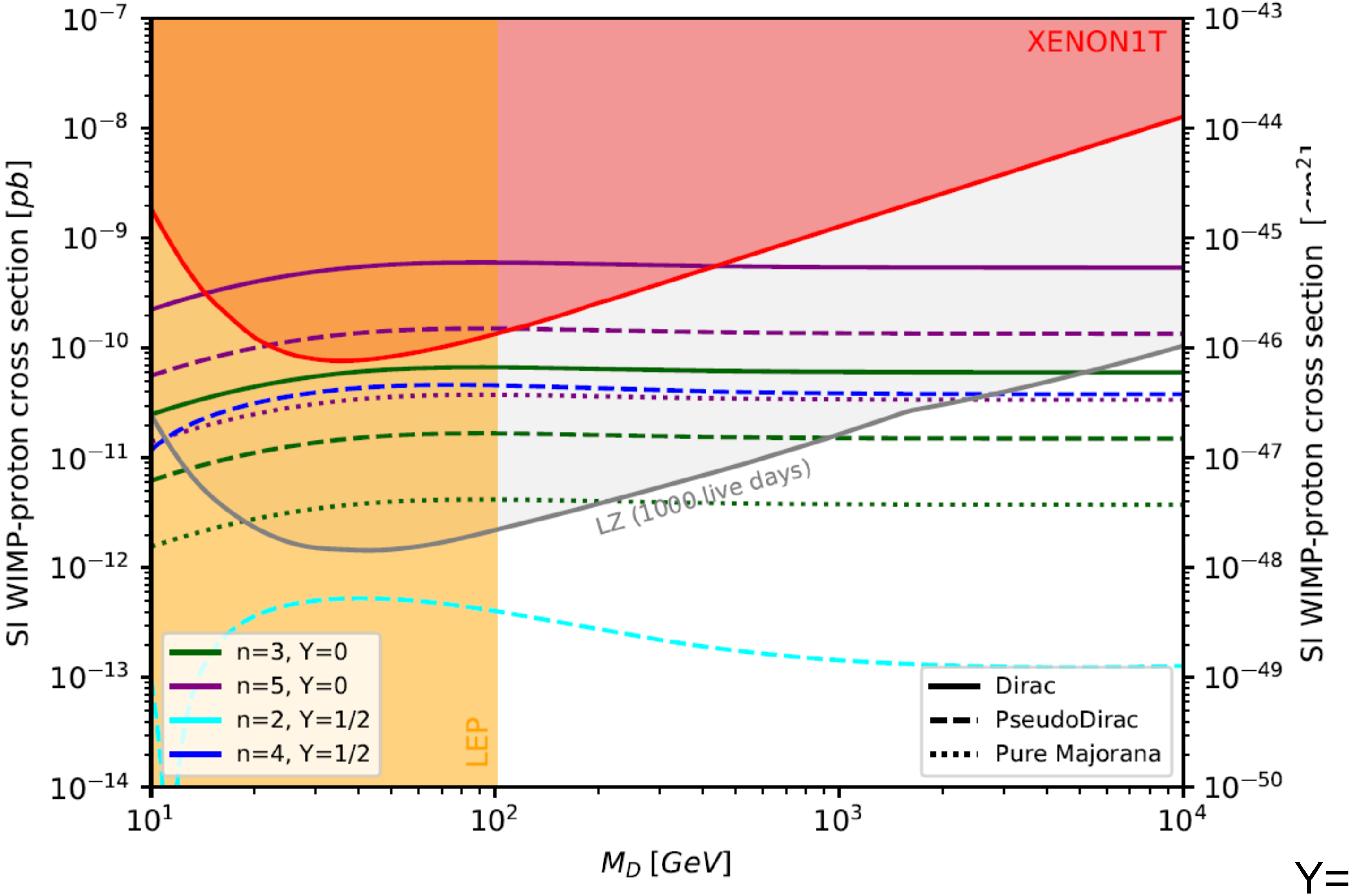
$$\psi = \begin{pmatrix} \psi^{n+} \\ \vdots \\ \psi^{+} \\ \psi_0 \\ \psi^{-} \\ \vdots \\ \psi^{m-} \end{pmatrix}$$

Cirelli,Fornengo,Strumia hep-ph/0512090 (Minimal Dark Matter)

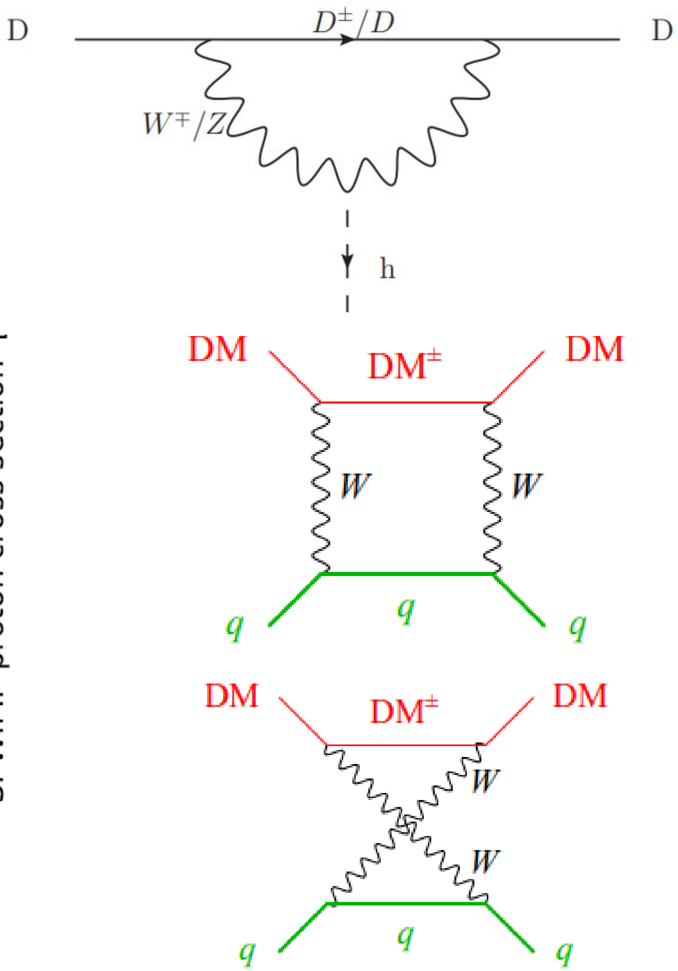
- **{I,Y}={0,0}, {½,½}, {1,0}**
- Z_2 forbids yukawa couplings
- {0,0} – no gauge-interactions – invisible to direct detection and collider but over(under) abundant if thermal (non-thermal)
- $Y \neq 0$ (Dirac DM) Is excluded by direct detection or requires additional sector – which splits the mass of ψ
- Radiative mass split – very important for the phenomenology



The role of loops in DM DD



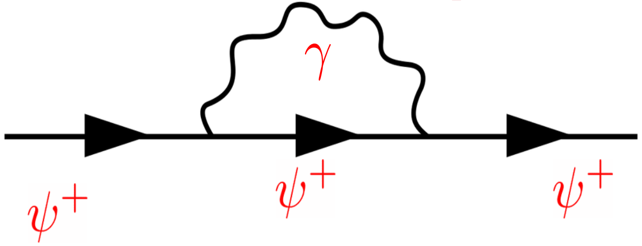
G.Cacciapaglia, D.Locke, A. Pukhov AB to appear (preliminary)



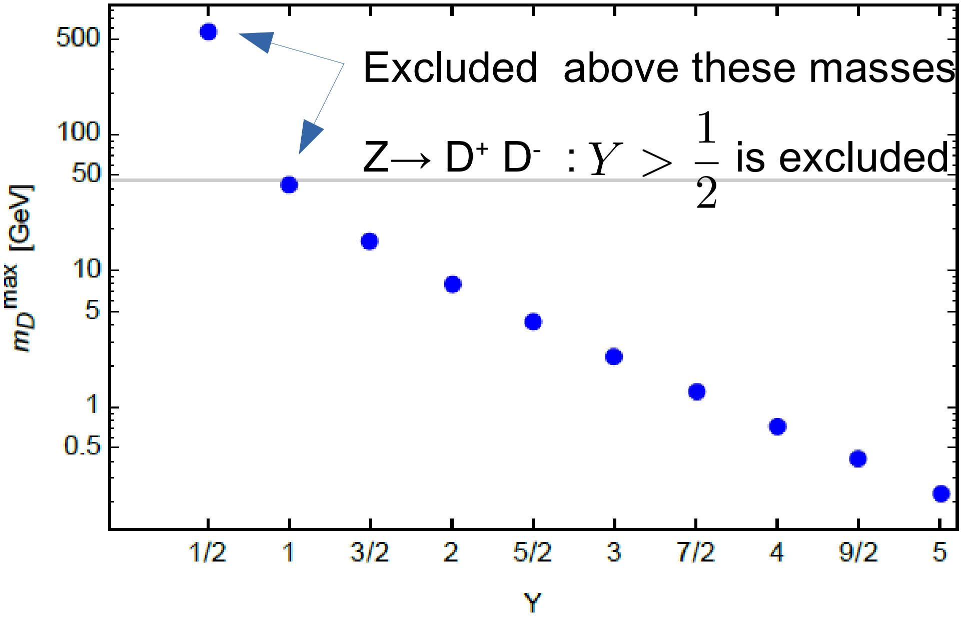
Y=0 minimal candidates may be discovered or ruled out at next generation of DD experiments

Radiative mass Split

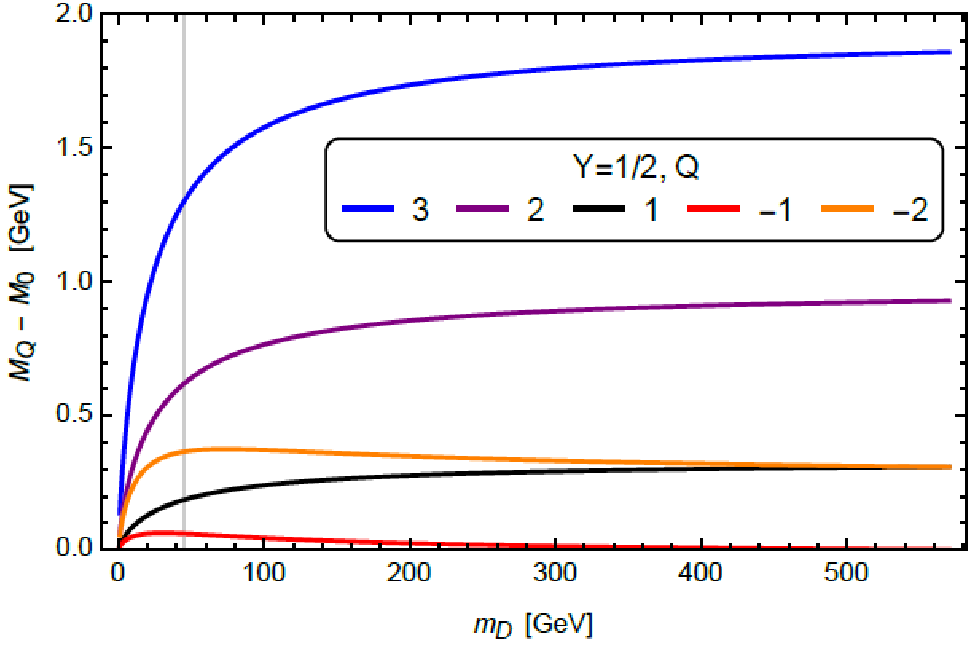
simplest models with Y>1/2 are excluded



$$M_Q - M_{Q'}\Big|_{m_D \gg m_W} \approx \frac{\alpha m_W}{2(1+c_W)}\left[(Q^2 - Q'^2) + \frac{2Y(Q-Q')}{c_W}\right]$$


Excluded above these masses

Z→ D$^+$ D$^-$: $Y > \frac{1}{2}$ is excluded



Left: maximum value of m_D above which the lightest particle has charge Q = -1 for various values of Y

Right: spectrum for a generic multiplet with Y = 1/2, with mD < 570 GeV.

The vertical line shows $m_D \sim m_Z/2$, below which the model is excluded by the Z decays

Long Lived Particles (LLPs)

- LLPs appear in the minimal DM models with DM being the part of the EW multiplet: **the radiative mass split** of charged and neutral components is of the order of pion mass
- The **hypercharge of the multiplet**
  - a) should be zero, otherwise the the model is excluded by DM DD constraints from Z-boson exchange
  - b) or neutral component (DM) of the multiplet should be split by additional (e.g.Yukawa) interactions, which eliminate DM-DM-Z
  - c) multiplet for non-zero hypercharge can not be large – negatively charged component becomes the lightest particle

$$\begin{pmatrix} D^+ \\ D^0 \\ D^- \end{pmatrix} \longrightarrow \quad \Delta M = M_{D^\pm} - M_{D^0} \sim m_\pi$$

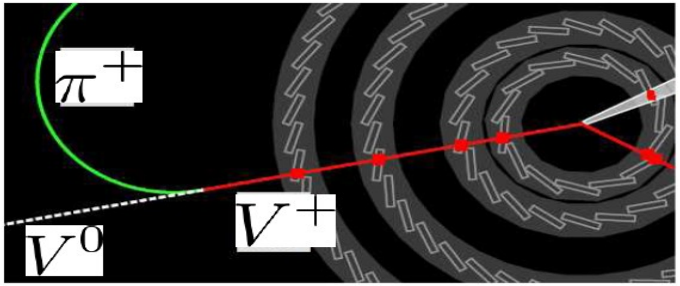
$$M_Q - M_{Q'}\big|_{m_D \gg m_W} \approx \frac{\alpha m_W}{2(1+c_W)}\left[(Q^2 - Q'^2) + \frac{2Y(Q-Q')}{c_W}\right]$$

Cirelli, Fornengo,Strumia 2005 (scalar and femion DM)

$$\Delta M = \frac{5 g_W^2 (M_W - c_W^2 M_Z)}{32\pi}$$

AB, Cacciapaglia, McKay, Marin, Zerwekh 2018 (vector DM)

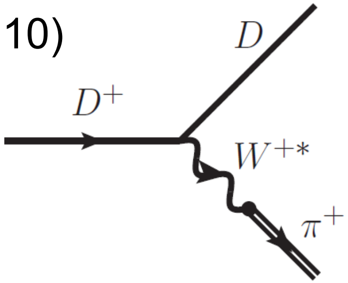
$D^+ \rightarrow D^0 \pi^+$ is the dominant decay, D^+ is LLP



This small mass gap (~ pion mass) provides disappearing track signature

D⁺ (charged partner of DM multiplet) decay

- D⁺ life-time should be properly evaluated using W-pion mixing
  (otherwise overestimated by factor of 10)



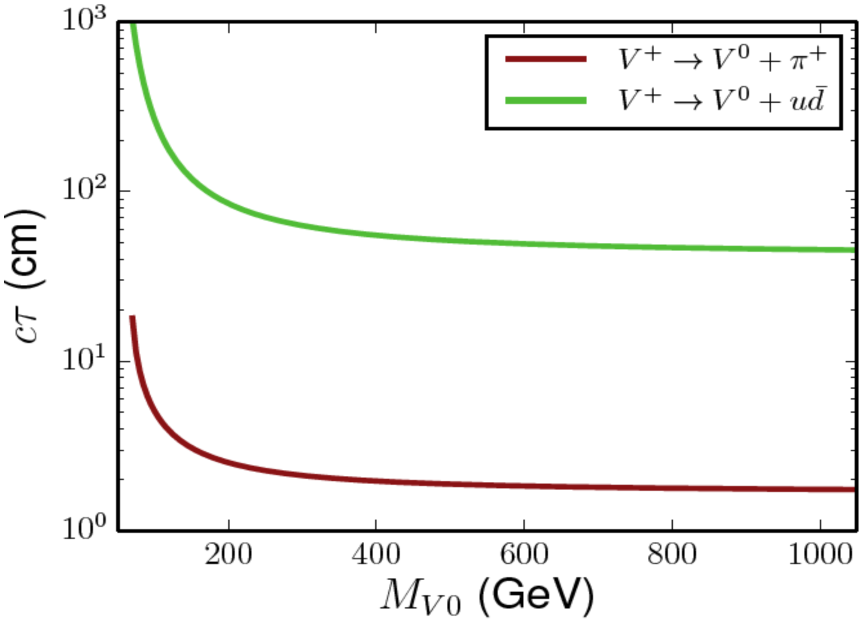
$$\mathcal{L}_{W\pi} = \frac{g f_\pi}{2\sqrt{2}} W^+_\mu \partial^\mu \pi^- + \mathrm{h.c.}$$

$$\mathcal{L}^{\mathrm{i2HDM}}_{D^+D\pi^-} = -\frac{g^2 f_\pi}{4\sqrt{2}M_W^2}\left[(p_D - p_D^+)\cdot p_{\pi^-}\right] D^+ D \pi^- + \mathrm{h.c.}$$

$$\mathcal{L}^{\mathrm{MFDM}}_{D^+D\pi^-} = -\frac{g^2 f_\pi}{4\sqrt{2}M_W^2}\cos(\theta_{DD_3}) p^\mu_{\pi^-} D^+ \gamma^\mu D \pi^- + \mathrm{h.c.}$$

$$\mathcal{L}^{\mathrm{MSSM}}_{D^+D\pi^-} = -\frac{g^2 f_\pi}{4\sqrt{2}M_W^2} p_{\pi^-\mu} D^+ \left[g_L \gamma^\mu P_L + g_R \gamma^\mu P_R\right] D \pi^- + \mathrm{h.c.}$$

$$\mathcal{L}^{\mathrm{VDM}}_{D^+D\pi^-} = -\frac{g^2 f_\pi}{2\sqrt{2}M_W^2}\left[(p_D - p_{D+})^\mu g^{\nu\rho} - p^\nu_D g^{\mu\rho} + p^\rho_{D+} g^{\mu\nu}\right] p_{\pi^-\mu} D^+_\nu D_\rho \pi^- + \mathrm{h.c.}$$



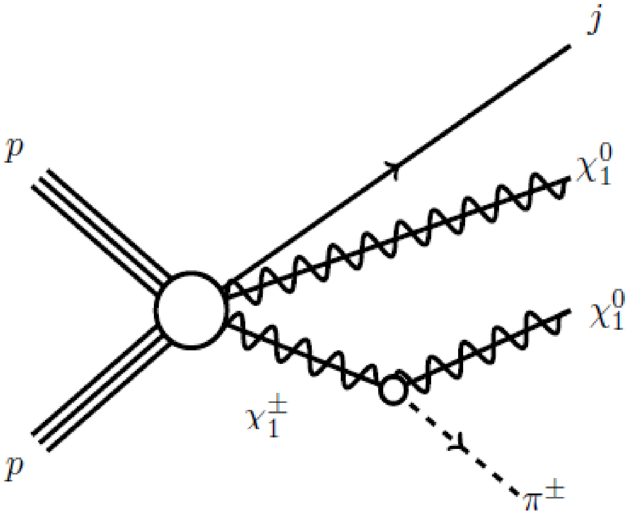
AB, Prestel, Rojas, Zurita [arXiv 2008.08581]

Using DT to probe minimal DM models

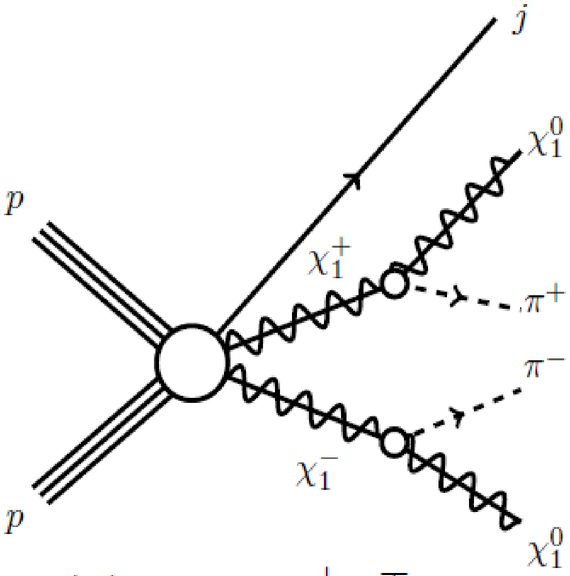
We apply our validated analysis to minimal consistent models

- Scalar: Inert two-Higgs doublet model (i2HDM)
- Minimal Fermion Dark Matter model (MFDM)
- Vector: Minimal Vector Triplet Dark Matter model (VTDM)

- Two classes of processes: D^+D^- and D^+D^0/D^-D^0 production mediated by s-channel Z/γ and W^+/W^- respectively



(a) $pp \to \chi_1^\pm \chi_1^0 j$



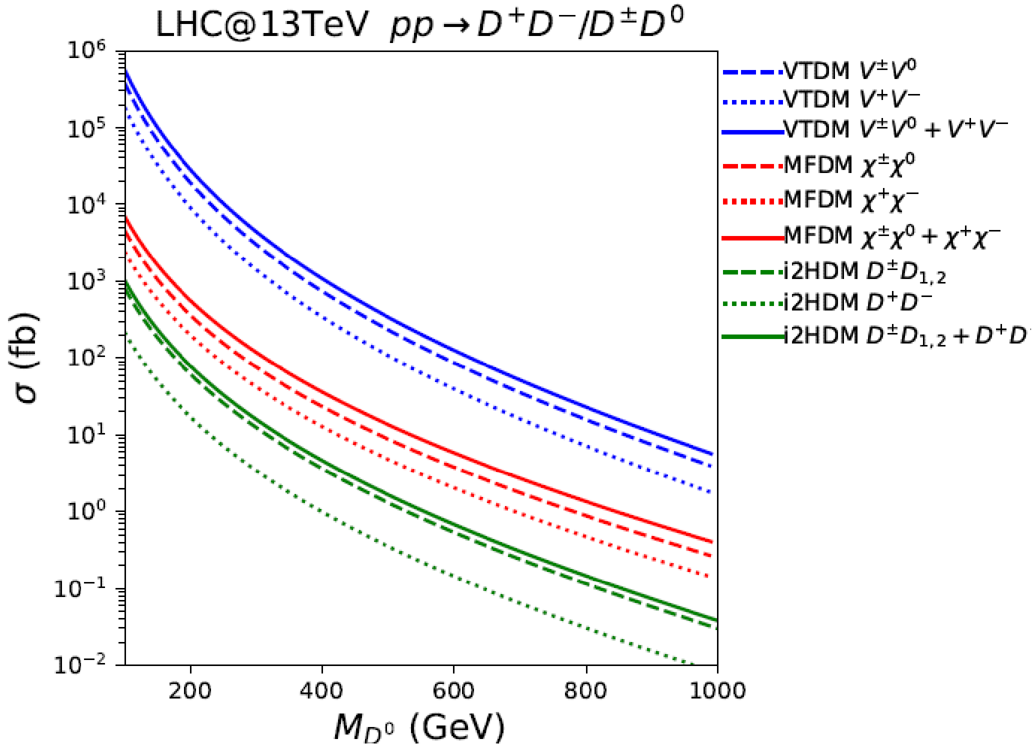
(b) $pp \to \chi_1^\pm \chi_1^\mp j$

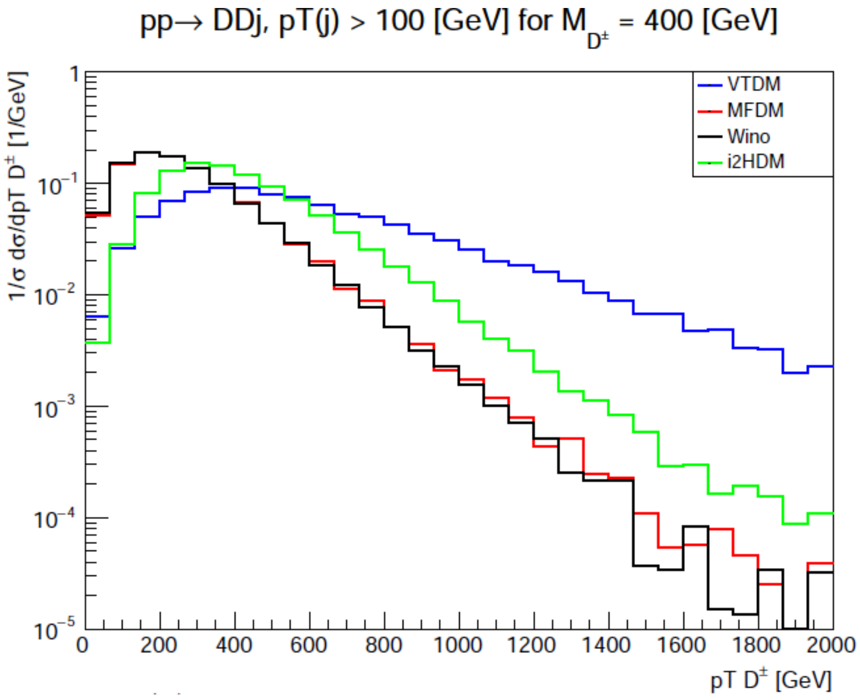
Tools to Study Disappearing Track Signature

- The strategy used [arXiv:2008.08581]
  - LanHEP→ CalcHEP (LHE) → PYTHIA 8.245 (Latest CKK merging) → Delphes 3.4.1 → analysis code
    - LanHEP/CaclHEP: i2HDM, MFDM, VTDM models with the correct W-pion mixing, models are public at HEPMDB https://hepmdb.soton.ac.uk/ (0820.0330, 0820.0329, 0820.0331)
    - PYTHIA 8.245: improved CKK merging (Stefan Prestel)
    - Delphes 3.4.1: ATLAS card, in particular, to simulate correctly MET from visible ET leptons and jets
    - analysis code (Felipe Rojas): implements ATLAS cuts and efficiency “heatmap” for tracklet ID, evaluates efficiencies and limits for general models
  - Validate our code by comparing with ATLAS limits
  - Find new limits for generic DM models with spin 0, ½ , 1
  - Provide publicly the code and efficiency/limits map in (MDM-τ) plane

Using DT to probe minimal DM models

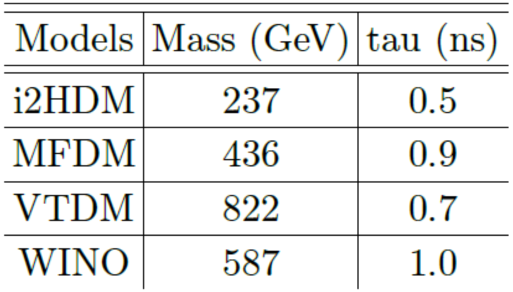
- Scalar: Inert two-Higgs doublet model (i2HDM)
- Minimal Fermion Dark Matter model (MFDM)
- Vector: Minimal Vector Triplet Dark Matter model (VTDM)
- Cross section and Transverse momentum distribution hierarchy: VTDM → MFDM → i2HDM defines the respective hierarchy of the efficiencies and the LHC sensitivity





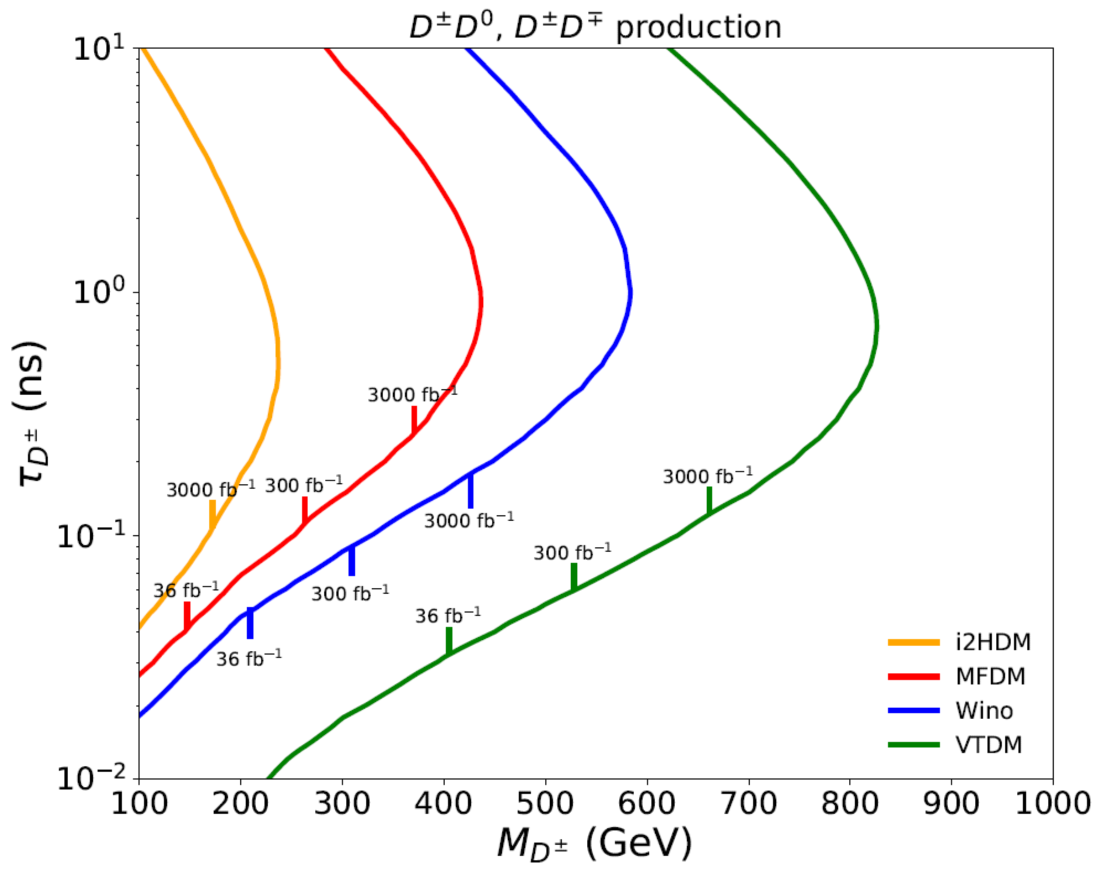
The power of DT for DM probe versus mono-jet limits

- New DT limits for DM models with different spin
- The limits are well beyond those from mono-jet signature analysis for τ ~ 1 ns



Models	Mass (GeV)	tau (ns)
i2HDM	237	0.5
MFDM	436	0.9
VTDM	822	0.7
WINO	587	1.0

- VTDM → MFDM → i2HDM hierarchy is defined by CS and PT

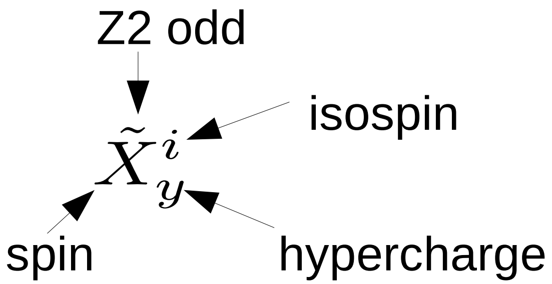


AB, Prestel, Rojas, Zurita [arXiv 2008.08581]

$\widetilde{F}^{1/2}_{1/2}\widetilde{M}^0_0$

Minimal fermion DM model

+Mediator



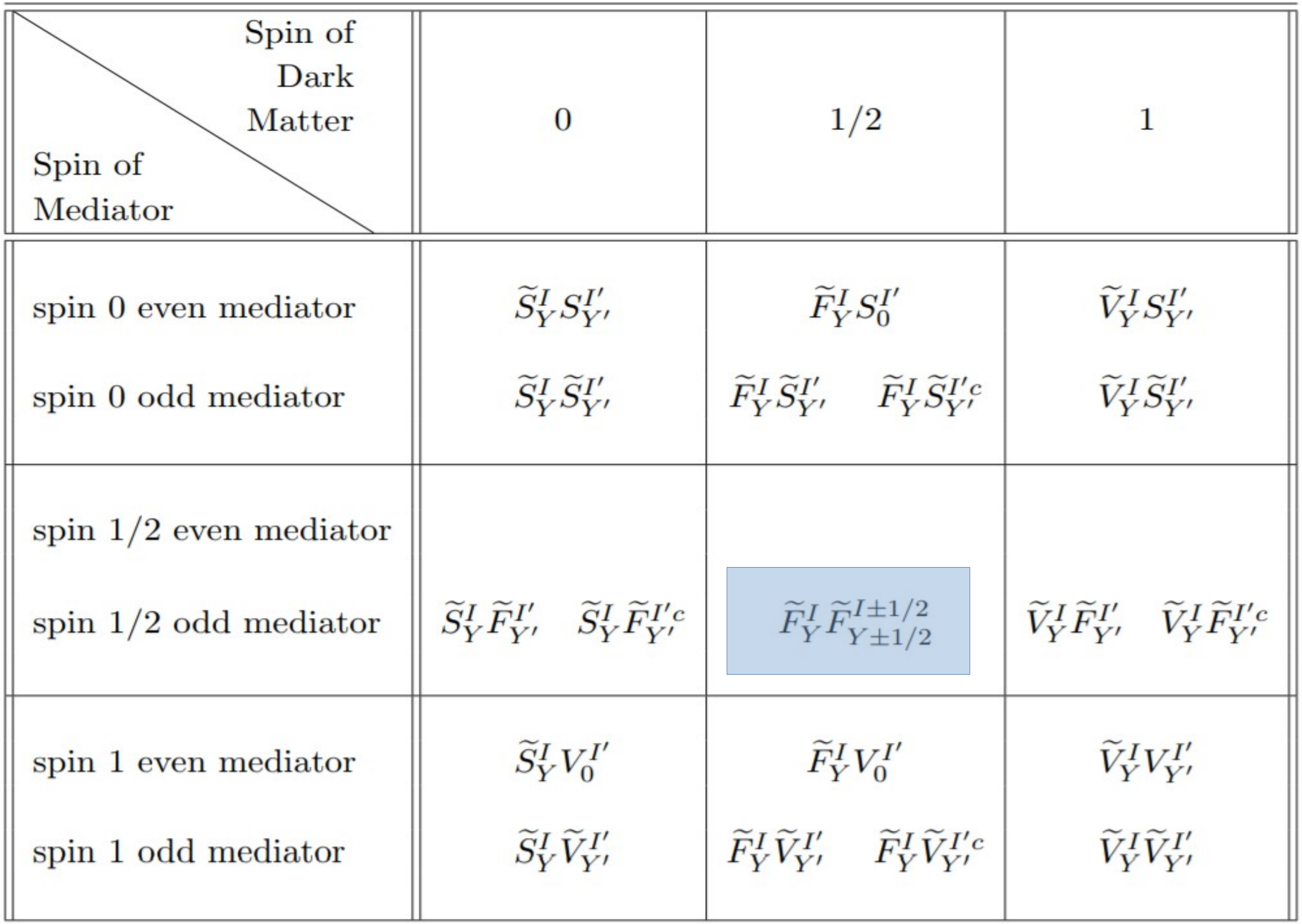
Z2 odd

isospin

$\tilde{X}^i_y$

spin

hypercharge



Spin of Dark Matter / Spin of Mediator	0	1/2	1
spin 0 even mediator	$\widetilde{S}^I_Y S^{I'}_{Y'}$	$\widetilde{F}^I_Y S^{I'}_0$	$\widetilde{V}^I_Y S^{I'}_{Y'}$
spin 0 odd mediator	$\widetilde{S}^I_Y \widetilde{S}^{I'}_{Y'}$	$\widetilde{F}^I_Y \widetilde{S}^{I'}_{Y'}$ $\widetilde{F}^I_Y \widetilde{S}^{I'c}_{Y'}$	$\widetilde{V}^I_Y \widetilde{S}^{I'}_{Y'}$
spin 1/2 even mediator			
spin 1/2 odd mediator	$\widetilde{S}^I_Y \widetilde{F}^{I'}_{Y'}$ $\widetilde{S}^I_Y \widetilde{F}^{I'c}_{Y'}$	$\widetilde{F}^I_Y \widetilde{F}^{I\pm1/2}_{Y\pm1/2}$	$\widetilde{V}^I_Y \widetilde{F}^{I'}_{Y'}$ $\widetilde{V}^I_Y \widetilde{F}^{I'c}_{Y'}$
spin 1 even mediator	$\widetilde{S}^I_Y V^{I'}_0$	$\widetilde{F}^I_Y V^{I'}_0$	$\widetilde{V}^I_Y V^{I'}_{Y'}$
spin 1 odd mediator	$\widetilde{S}^I_Y \widetilde{V}^{I'}_{Y'}$	$\widetilde{F}^I_Y \widetilde{V}^{I'}_{Y'}$ $\widetilde{F}^I_Y \widetilde{V}^{I'c}_{Y'}$	$\widetilde{V}^I_Y \widetilde{V}^{I'}_{Y'}$

- **ILC:**
  D.Locke,
  A.Freegard,
  I.Ginzburg, T.Hosken,
  A.Pukhov, AB (to appear)

- **Drell Yan, VBF**:
  U.Blumenschein,
  A.Freegard, S.Moretti, AB
  (to appear)

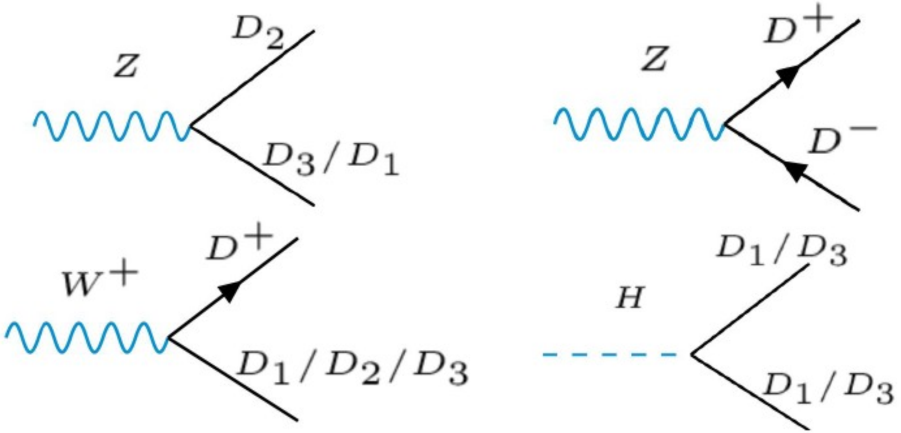
$\widetilde{F}^{1/2}_{1/2}\widetilde{M}^{0}_{0}$

Minimal fermion DM model (MFDM)

gives 2/3 -lepton signatures at the LHC

$$\mathcal{L}_{FDM} = \mathcal{L}_{SM} + \bar{\psi}(i\not{D} - m_\psi)\psi + \frac{1}{2}\bar{\chi}^0_s(i\not{\partial} - m_s)\chi^0_s - (Y(\bar{\psi}\Phi\chi^0_s) + h.c.)$$

$$\psi = \begin{pmatrix} \chi^+ \\ \frac{1}{\sqrt{2}}(\chi^0_1 + i\chi^0_2) \end{pmatrix}$$, additional Majorana singlet fermion χ^0_s



$$[M_{D1}, \Delta M_{D+}, \Delta M_{D3}]$$

only three parameters (effectively two for the LHC)

$\widetilde{F}^{1/2}_{1/2}\widetilde{M}^{0}_{0}$

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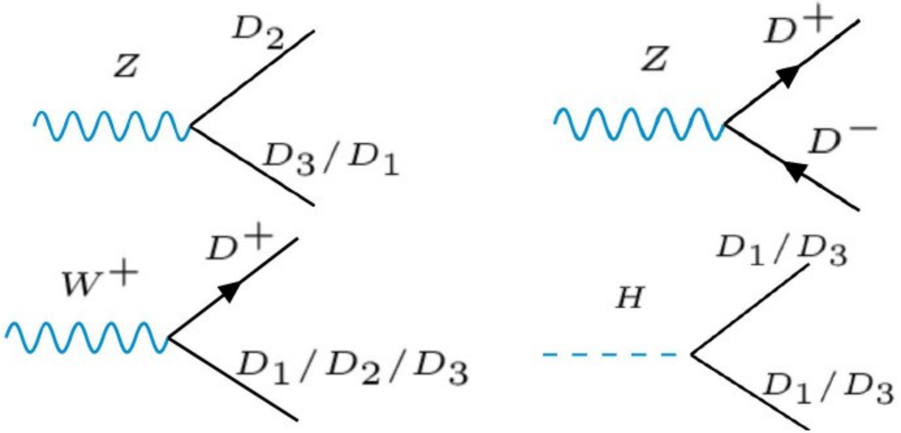

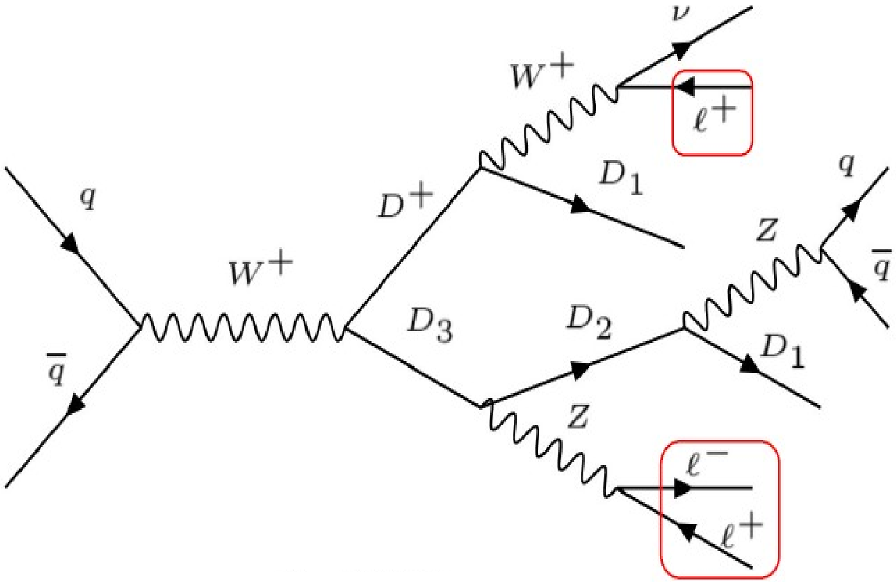

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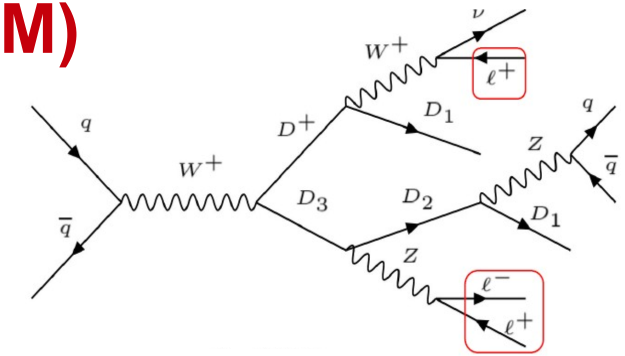

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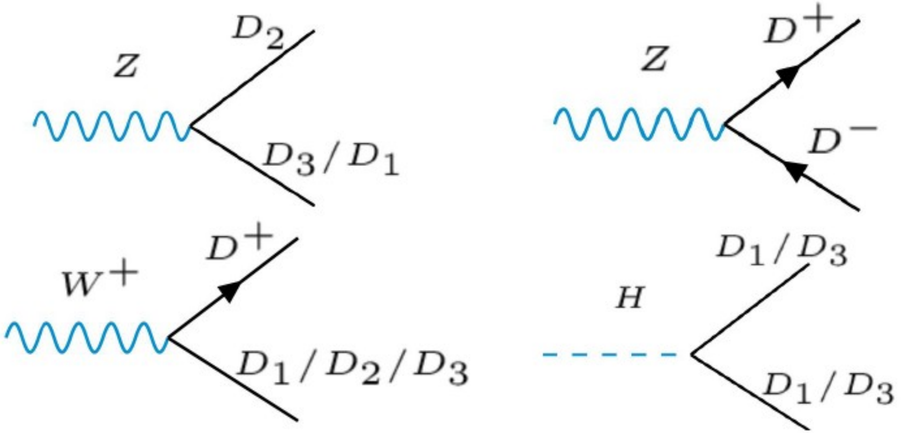

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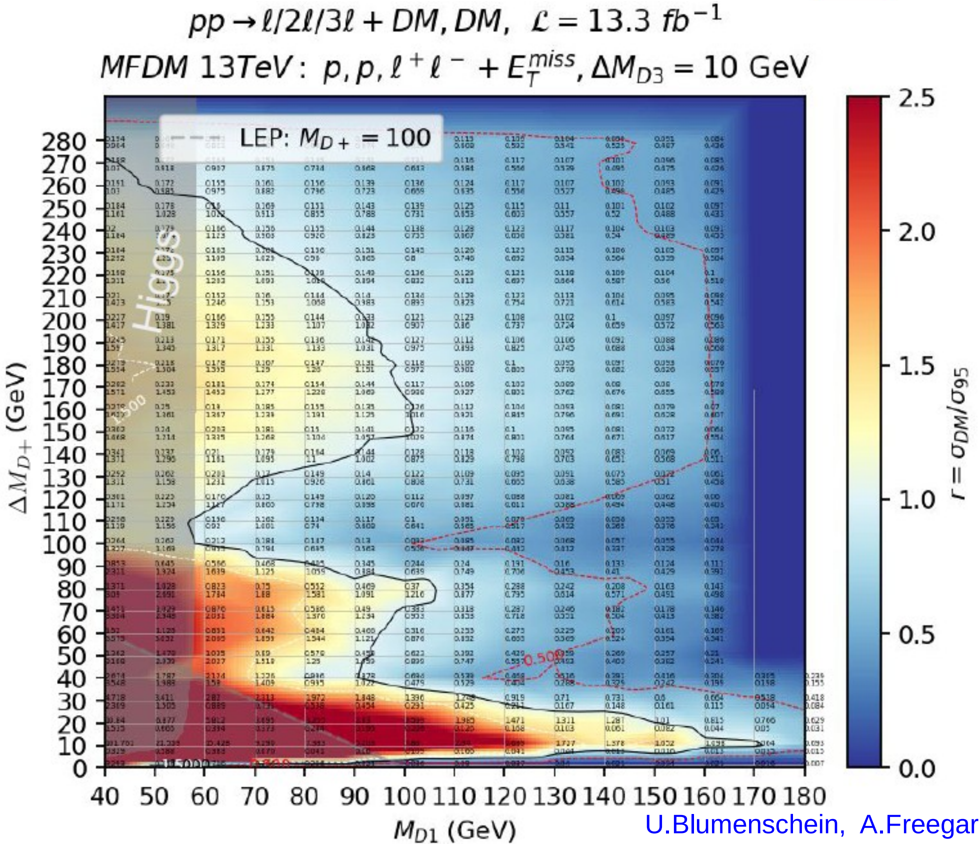
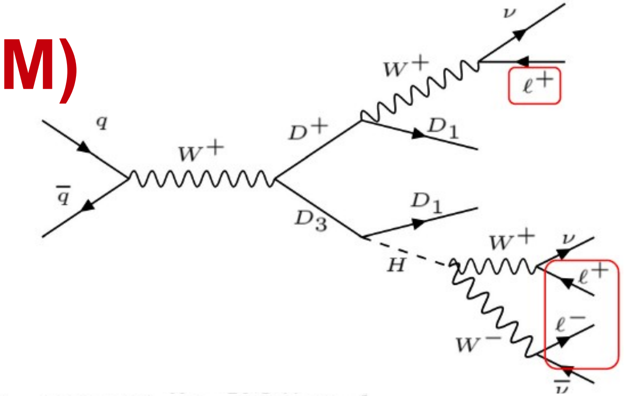


U.Blumenschein, A.Freegard, S.Moretti, AB (to appear)

$\widetilde{F}^{1/2}_{1/2}\widetilde{M}^{0}_{0}$

Minimal fermion DM model (MFDM)

gives 2/3 -lepton signatures at the LHC



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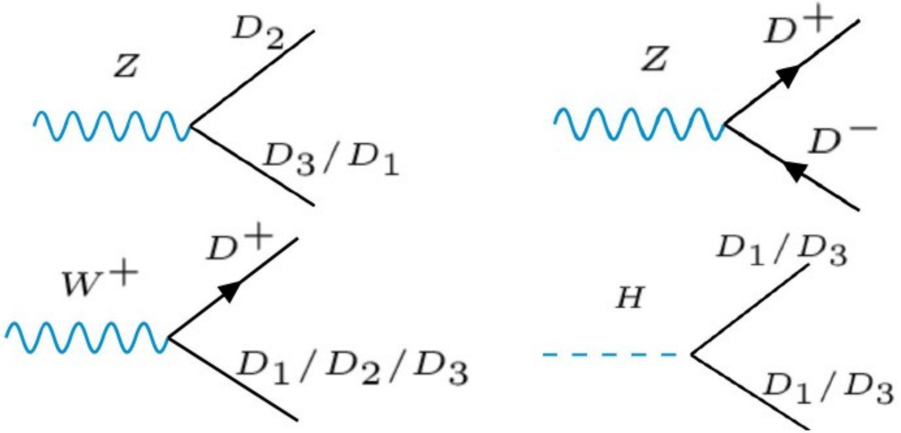
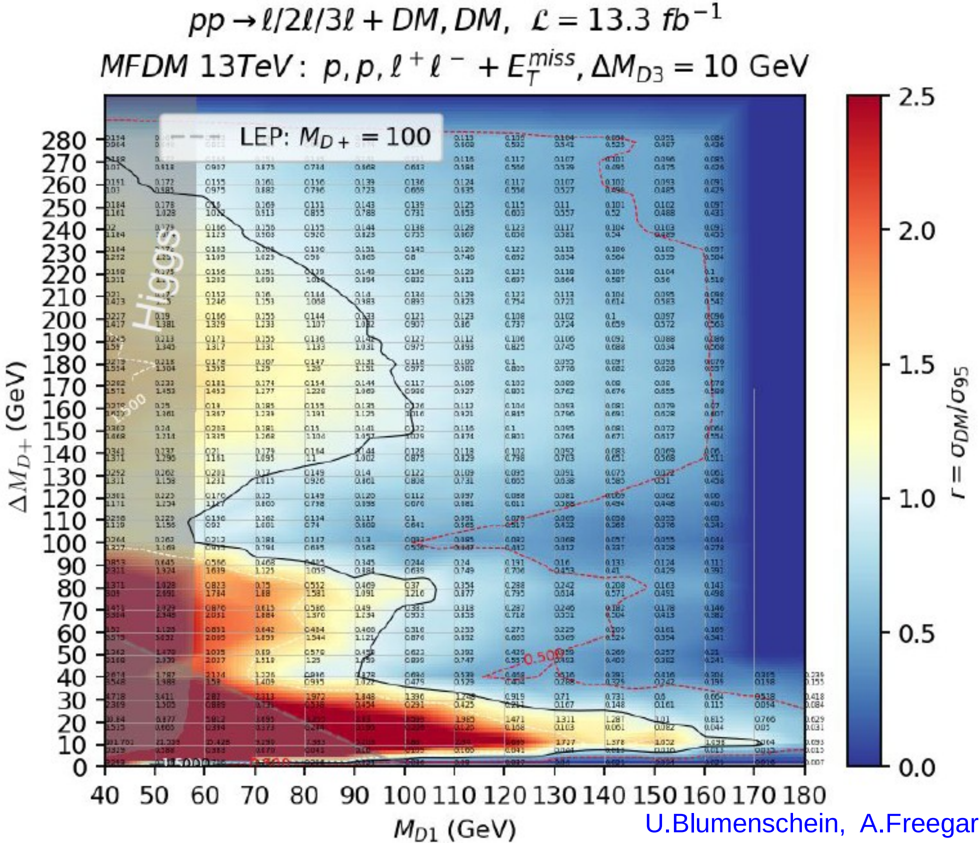


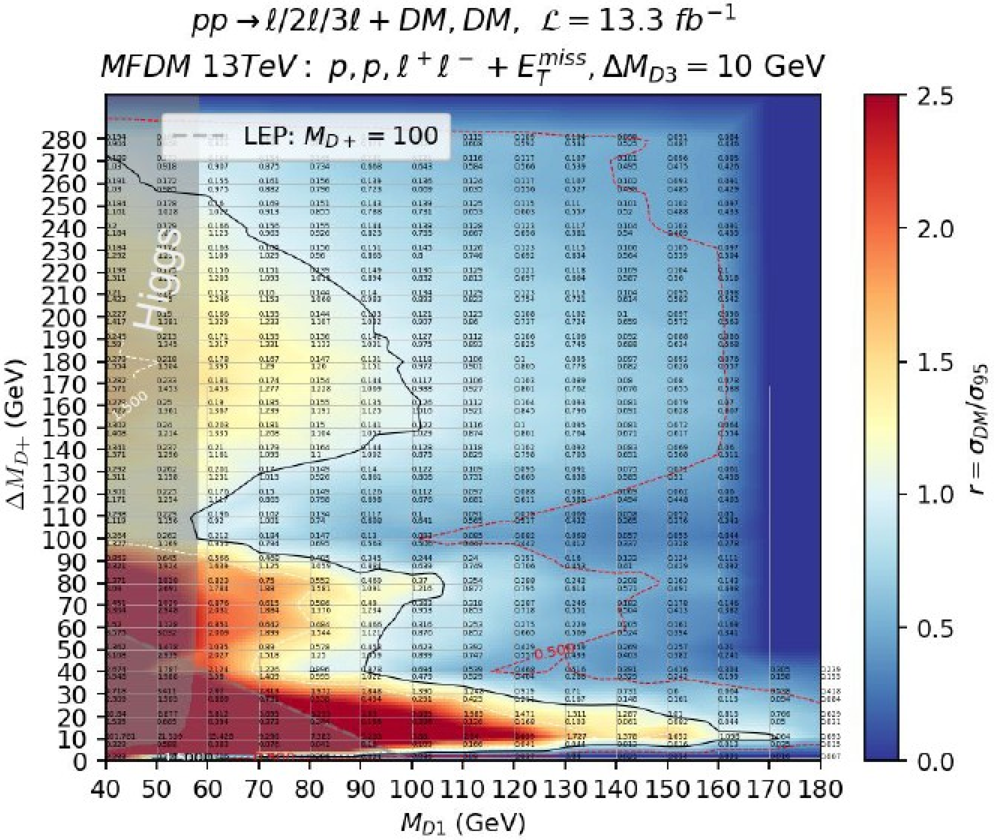
$$[M_{D1}, \Delta M_{D+}, \Delta M_{D3}]$$

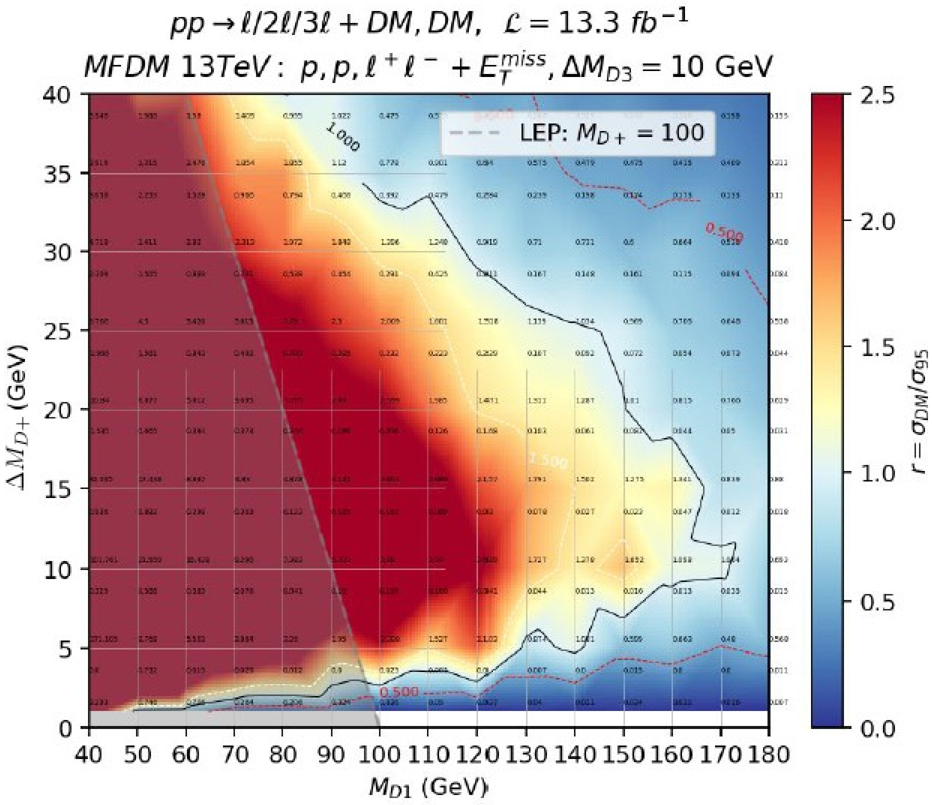


only three parameters (effectively two for the LHC)

U.Blumenschein, A.Freegard, S.Moretti, AB (to appear)

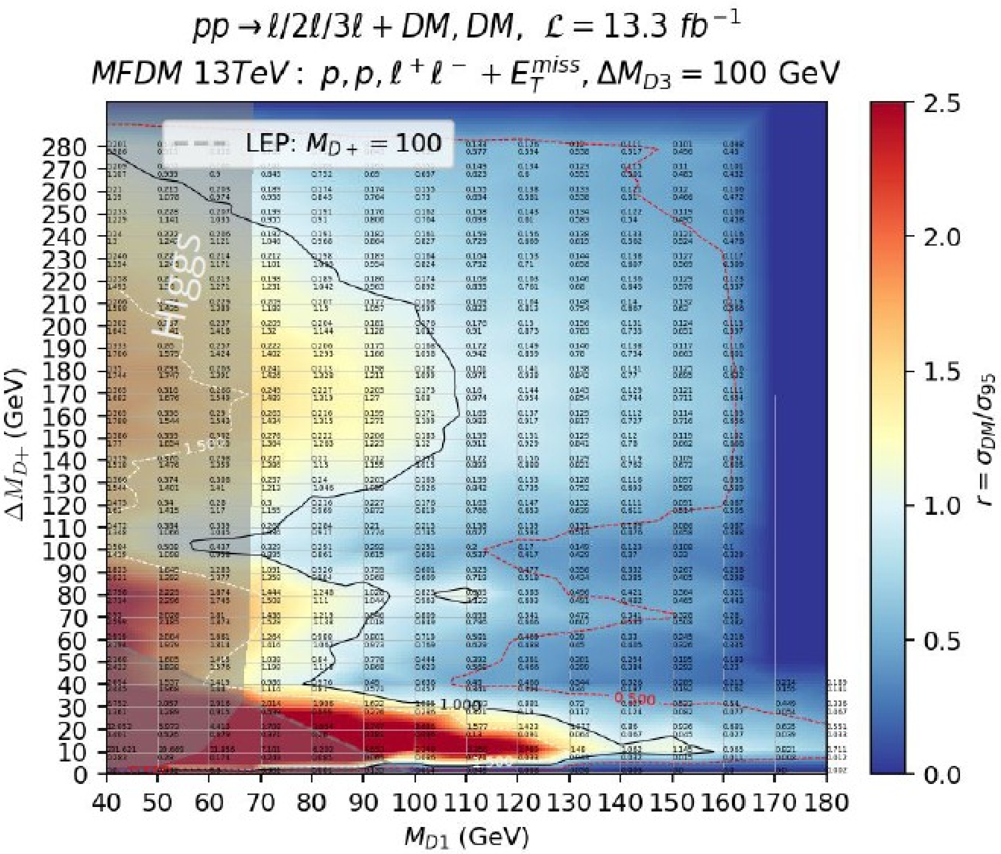
MFDM Results

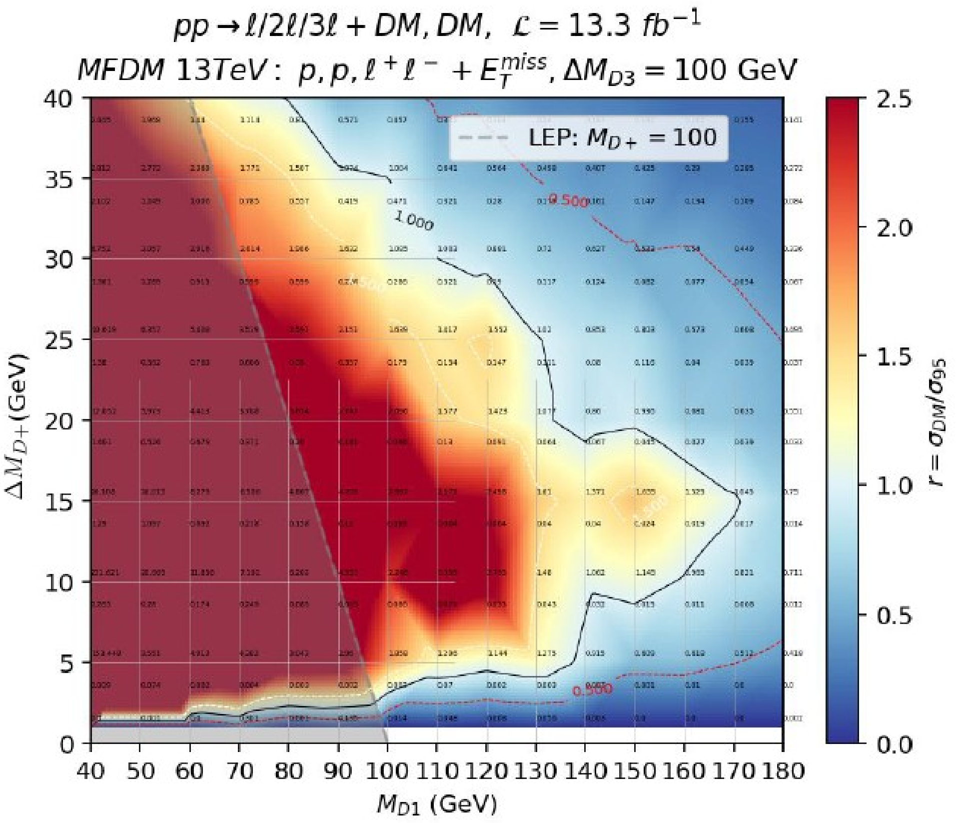




- As ΔM_{D3} increases, coupling between $D_1 - D^{\pm}$ increases, while heavy D_3 leads to suppressed production cross-section - 'no-lose' theorem

MFDM Results



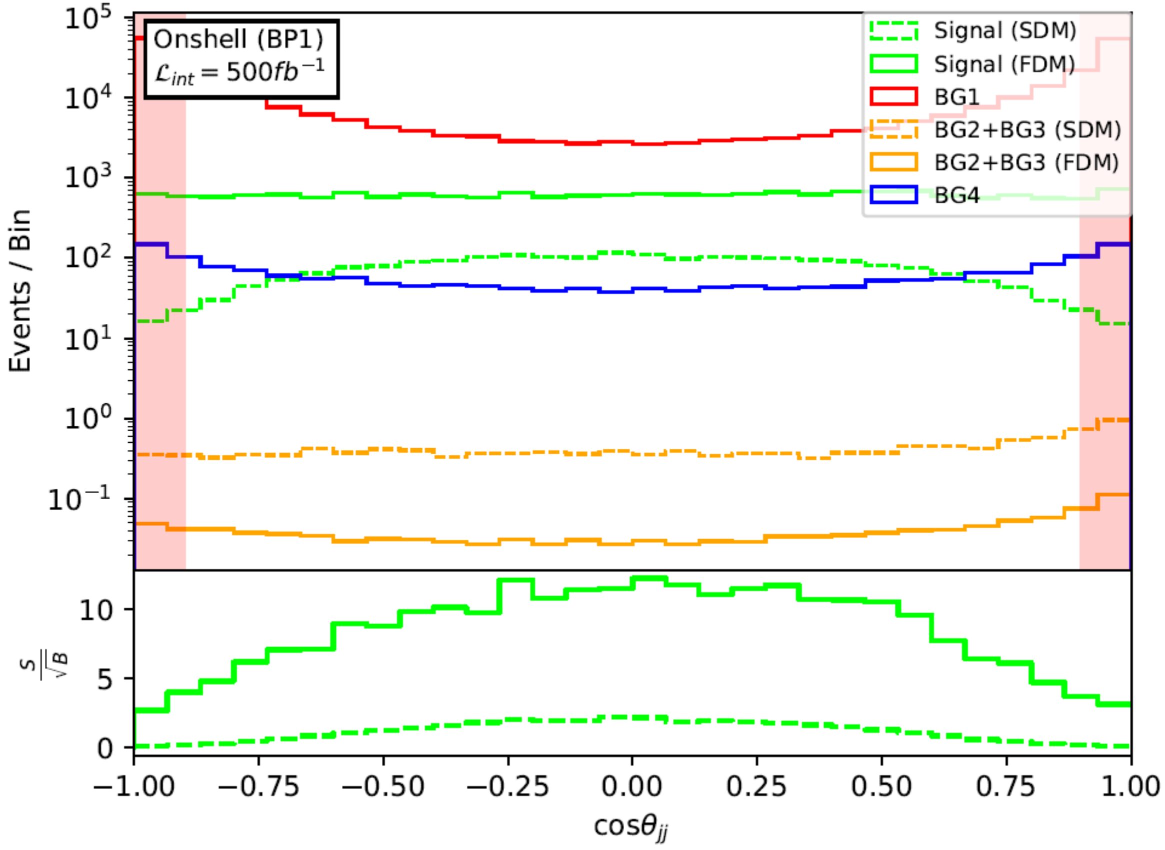


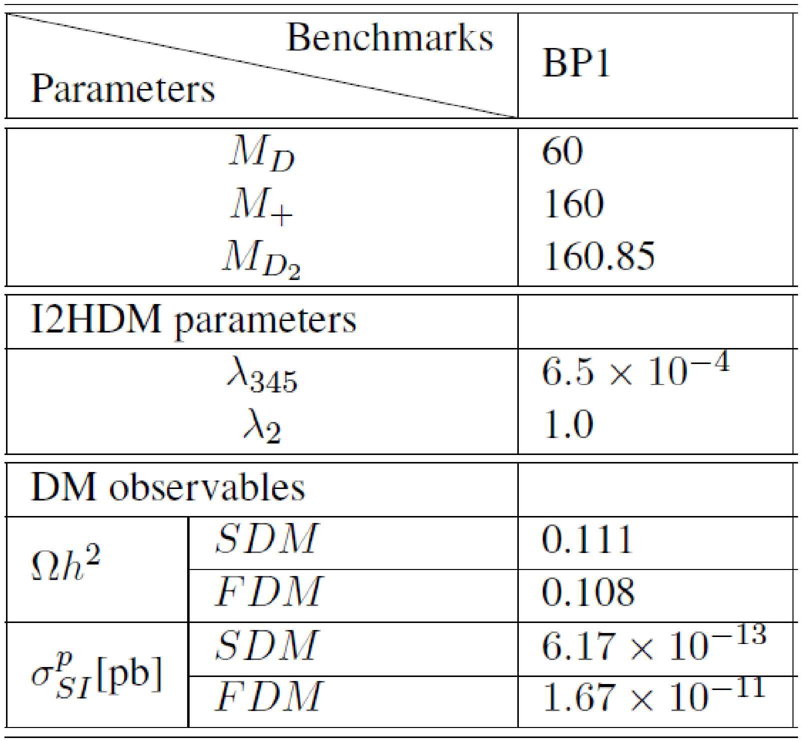
- With increasing ΔM_{D3}, Higgs to invisible limit covers larger M_{D1} upto $M_{D1} = M_H/2$

Decoding the nature of DM at the ILC

muon spectrum from the models with scalar and fermion DM

e+e- → D+ D- → DM DM W+ W- → DM DM jj μ ν



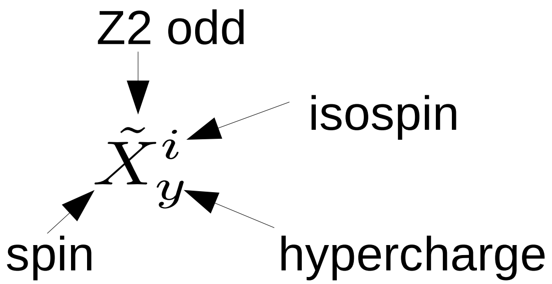


Parameters \ Benchmarks		BP1
M_D		60
M_+		160
M_{D_2}		160.85
I2HDM parameters		
λ_{345}		6.5×10^{-4}
λ_2		1.0
DM observables		
Ωh^2	SDM	0.111
	FDM	0.108
σ^p_{SI}[pb]	SDM	6.17×10^{-13}
	FDM	1.67×10^{-11}

AB, Ginzburg, Locke, Freegard, Pukhov preliminary

$\tilde{F}^0_0 S^0_0 (CP - odd)$

Minimal fermion DM model with pseudo-scalar mediator



Z2 odd

isospin

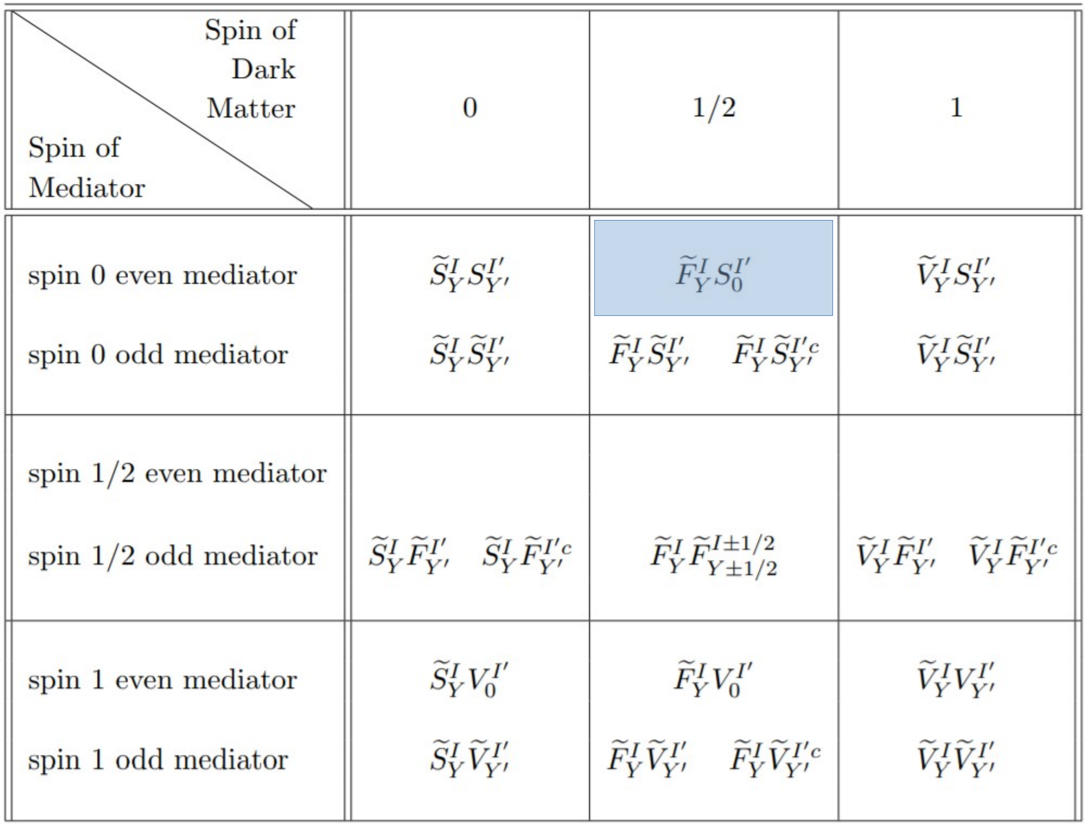
$\tilde{X}^i_y$

spin

hypercharge

new model, has not been explored previously

two-component DM model (pseudoscalar is accidentally stable)

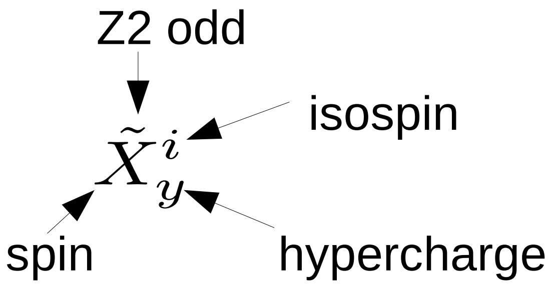


Spin of Dark Matter Spin of Mediator	0	1/2	1
spin 0 even mediator	$\tilde{S}^I_Y S^{I'}_{Y'}$	$\tilde{F}^I_Y S^{I'}_0$	$\tilde{V}^I_Y S^{I'}_{Y'}$
spin 0 odd mediator	$\tilde{S}^I_Y \tilde{S}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{S}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{S}^{I'c}_{Y'}$	$\tilde{V}^I_Y \tilde{S}^{I'}_{Y'}$
spin 1/2 even mediator			
spin 1/2 odd mediator	$\tilde{S}^I_Y \tilde{F}^{I'}_{Y'}$ $\tilde{S}^I_Y \tilde{F}^{I'c}_{Y'}$	$\tilde{F}^I_Y \tilde{F}^{I\pm1/2}_{Y\pm1/2}$	$\tilde{V}^I_Y \tilde{F}^{I'}_{Y'}$ $\tilde{V}^I_Y \tilde{F}^{I'c}_{Y'}$
spin 1 even mediator	$\tilde{S}^I_Y V^{I'}_0$	$\tilde{F}^I_Y V^{I'}_0$	$\tilde{V}^I_Y V^{I'}_{Y'}$
spin 1 odd mediator	$\tilde{S}^I_Y \tilde{V}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{V}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{V}^{I'c}_{Y'}$	$\tilde{V}^I_Y \tilde{V}^{I'}_{Y'}$

G.Cacciapaglia, D.Locke, AB arXiv:**2104.xxxxx**

$$\tilde{F}^0_0 S^0_0 (CP-odd)$$

Minimal fermion DM model with pseudo-scalar mediator



Z2 odd

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spin

hypercharge

new model, has not been explored previously

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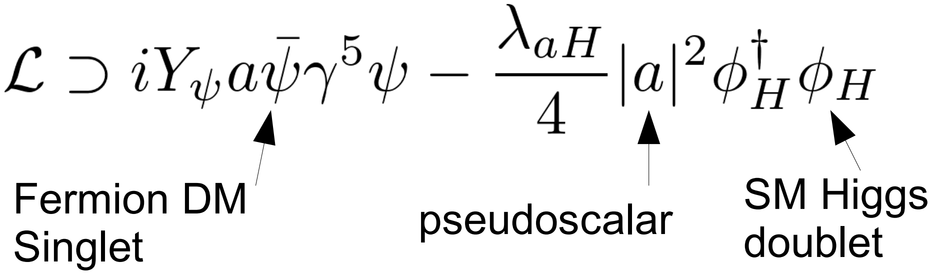


$$\mathcal{L} \supset iY_\psi a \bar{\psi}\gamma^5\psi - \frac{\lambda_{aH}}{4}|a|^2\phi^\dagger_H \phi_H$$

Fermion DM Singlet

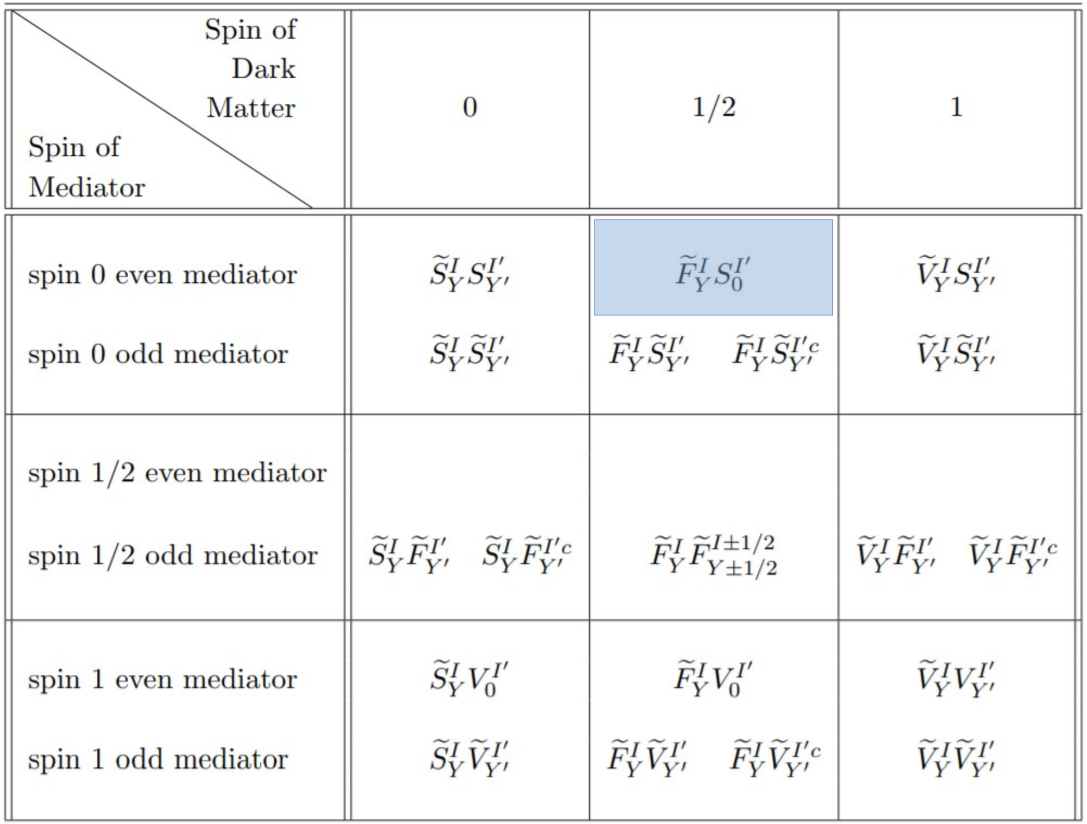
pseudoscalar

SM Higgs doublet

- a does not acquire VEV → no linear coupling to Higgs
- $m_a < 2m_\psi$ → “secluded DM”
- Model implemented in LanHEP, and numerical scan performed using micrOMEGAs.

4 relevant parameters:

$$m_\psi,\ Y_\psi,\ m_a,\ \lambda_{aH}$$



Spin of Mediator \ Spin of Dark Matter	0	1/2	1
spin 0 even mediator	$\tilde{S}^I_Y S^{I'}_{Y'}$	$\tilde{F}^I_Y S^{I'}_0$	$\tilde{V}^I_Y S^{I'}_{Y'}$
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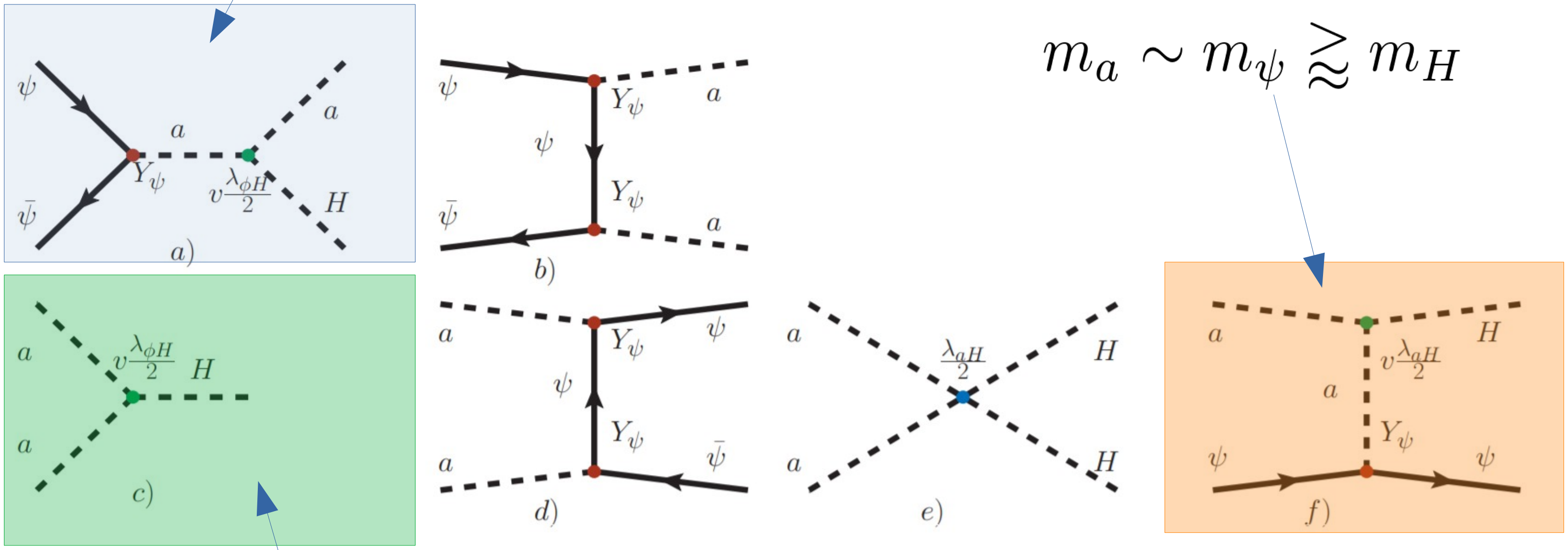
G.Cacciapaglia, D.Locke, AB arXiv:**2104.xxxxx**

Minimal fermion DM model with pseudo-scalar mediator:

rich phenomenology: relic density, DD, colliders

(co)Annihilation channels

$$m_\psi \gtrapprox \frac{m_a+m_h}{2} \gtrapprox \frac{3m_H}{4} \sim 90GeV$$



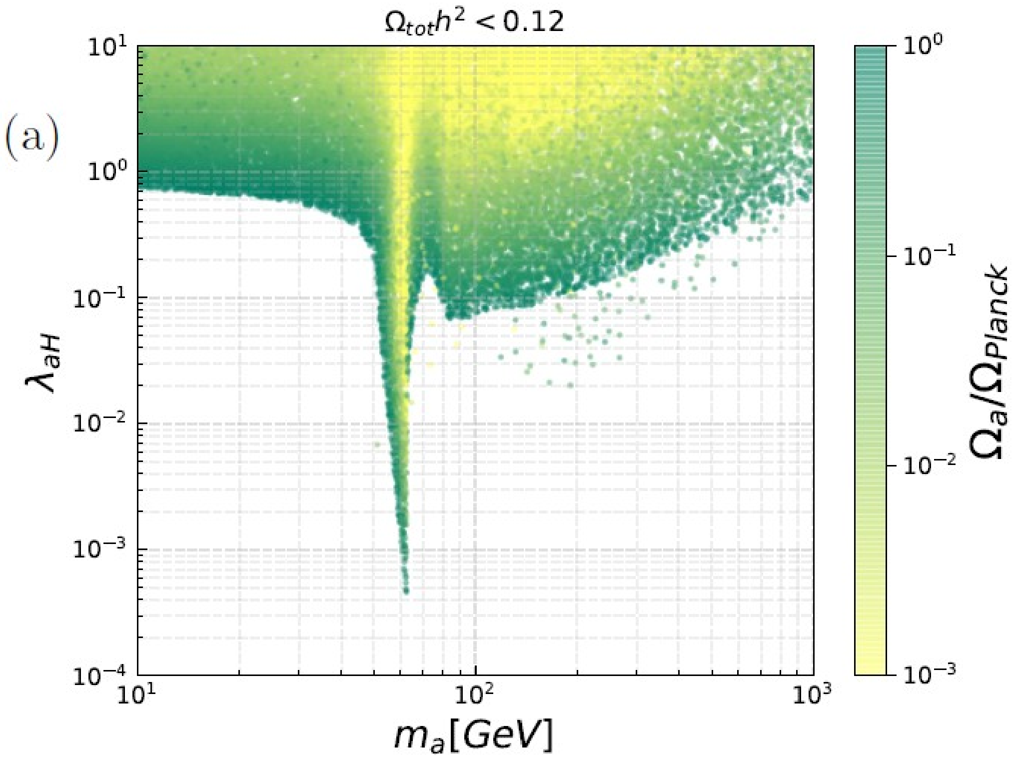
$$m_a \sim m_\psi \gtrapprox m_H$$

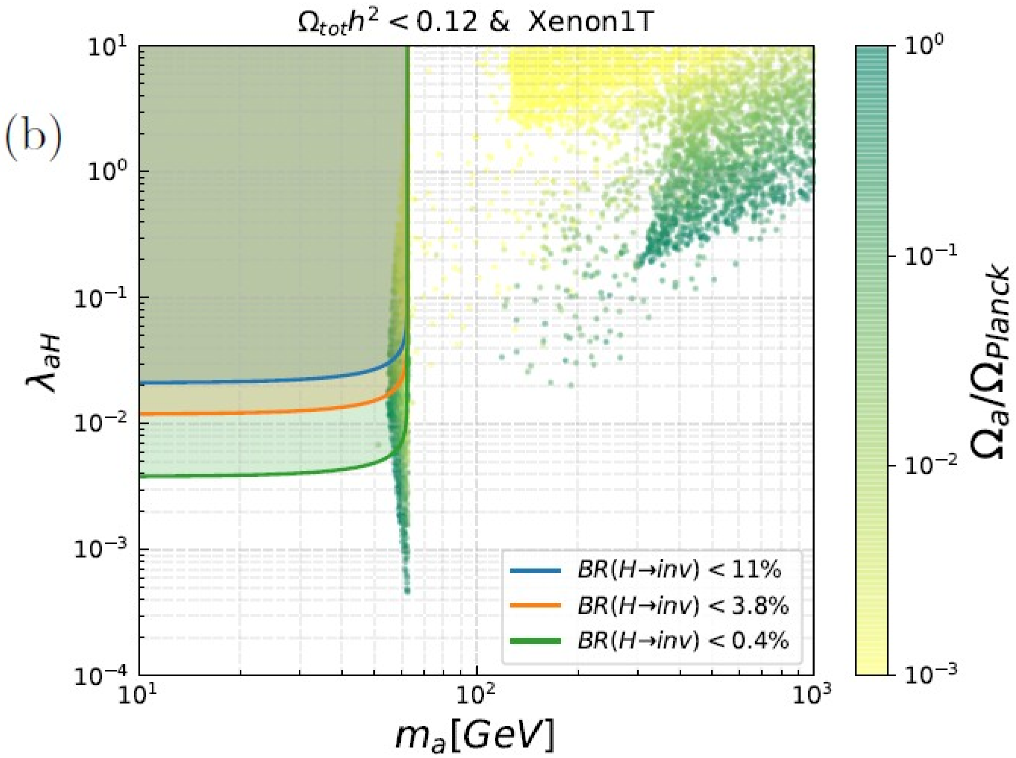
aa → WW
ma>80GeV
aa → ZZ
ma>90GeV
aa → tt
ma>173GeV

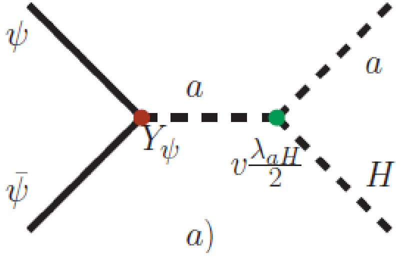
$$\sigma^{ann}_{aa\to ff}v \sim \frac{\lambda^2 m_f^2}{(4m_a^2-m_H^2)^2+m_H^2\Gamma_H^2}$$

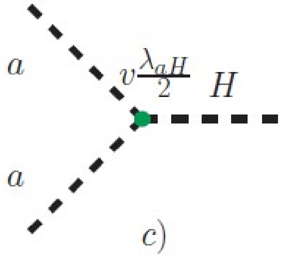
Minimal fermion DM model with pseudo-scalar mediator:

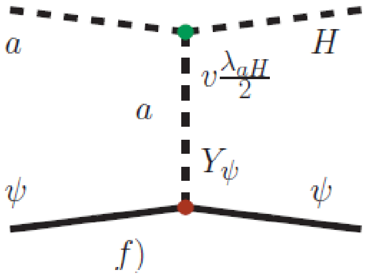
rich phenomenology: relic density, DD, colliders





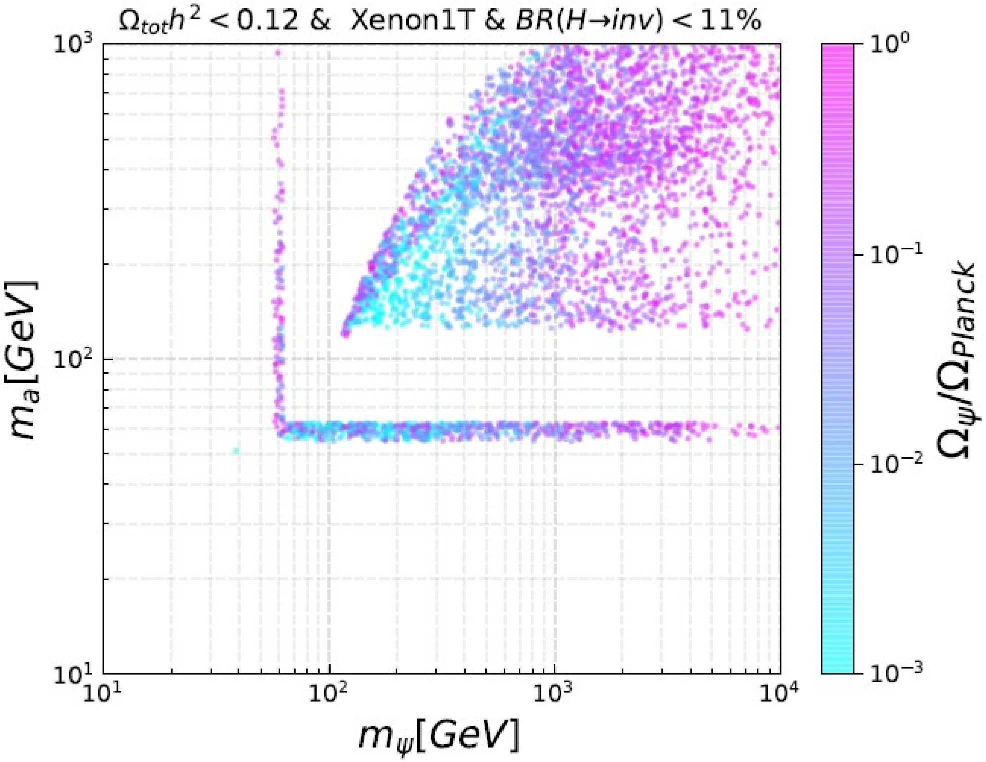


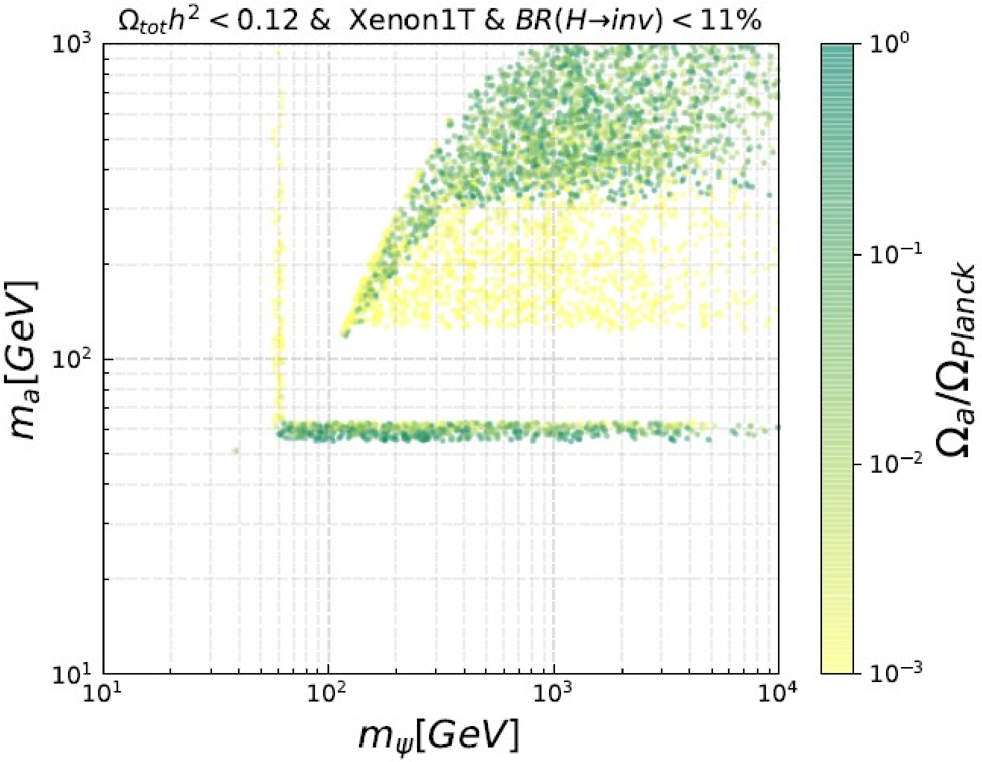




Minimal fermion DM model with pseudo-scalar mediator:

Xenon1T vs LZ exclusion


$\Omega_{tot}h^2 < 0.12$ & Xenon1T & $BR(H\to inv) < 11\%$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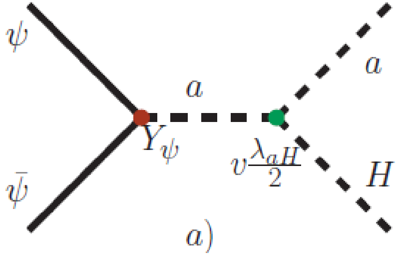

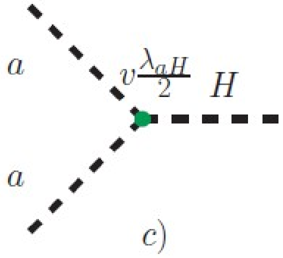

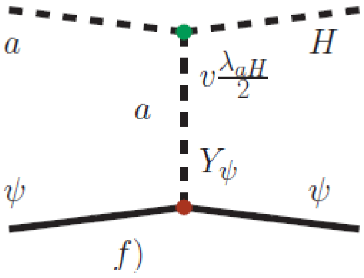

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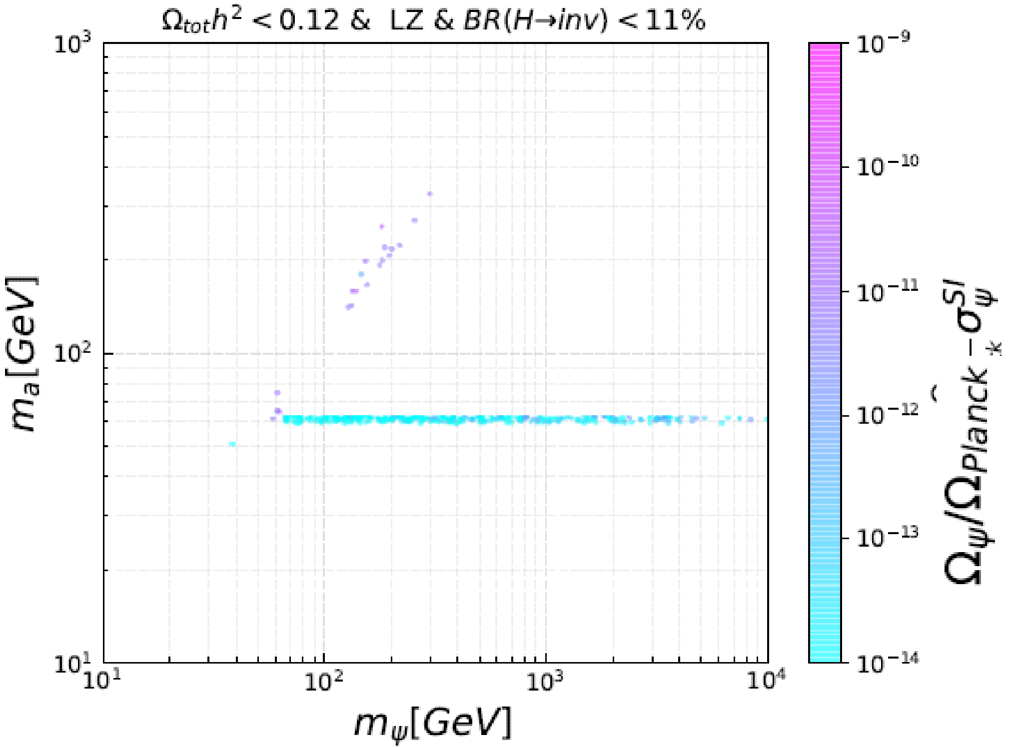
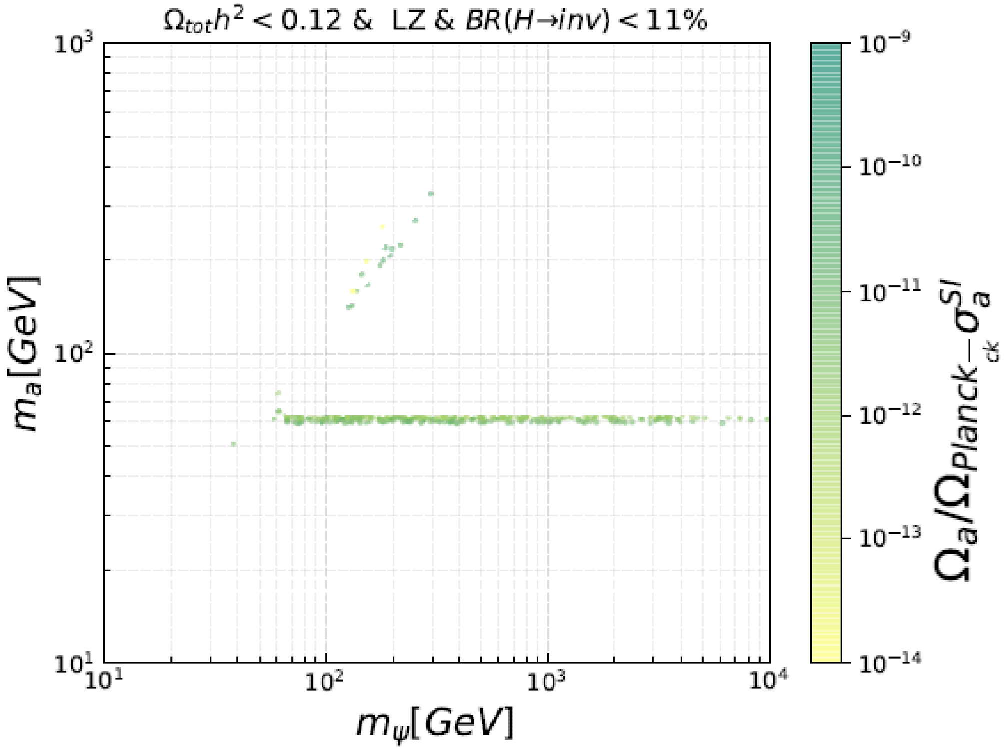
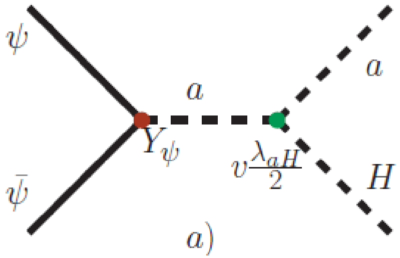
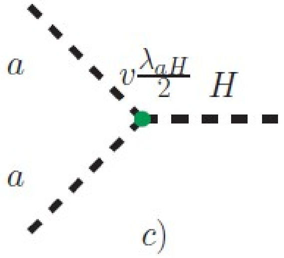
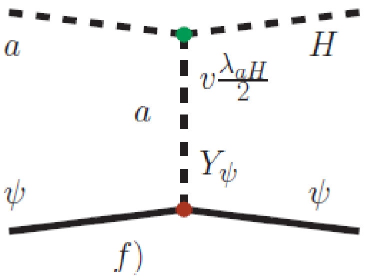




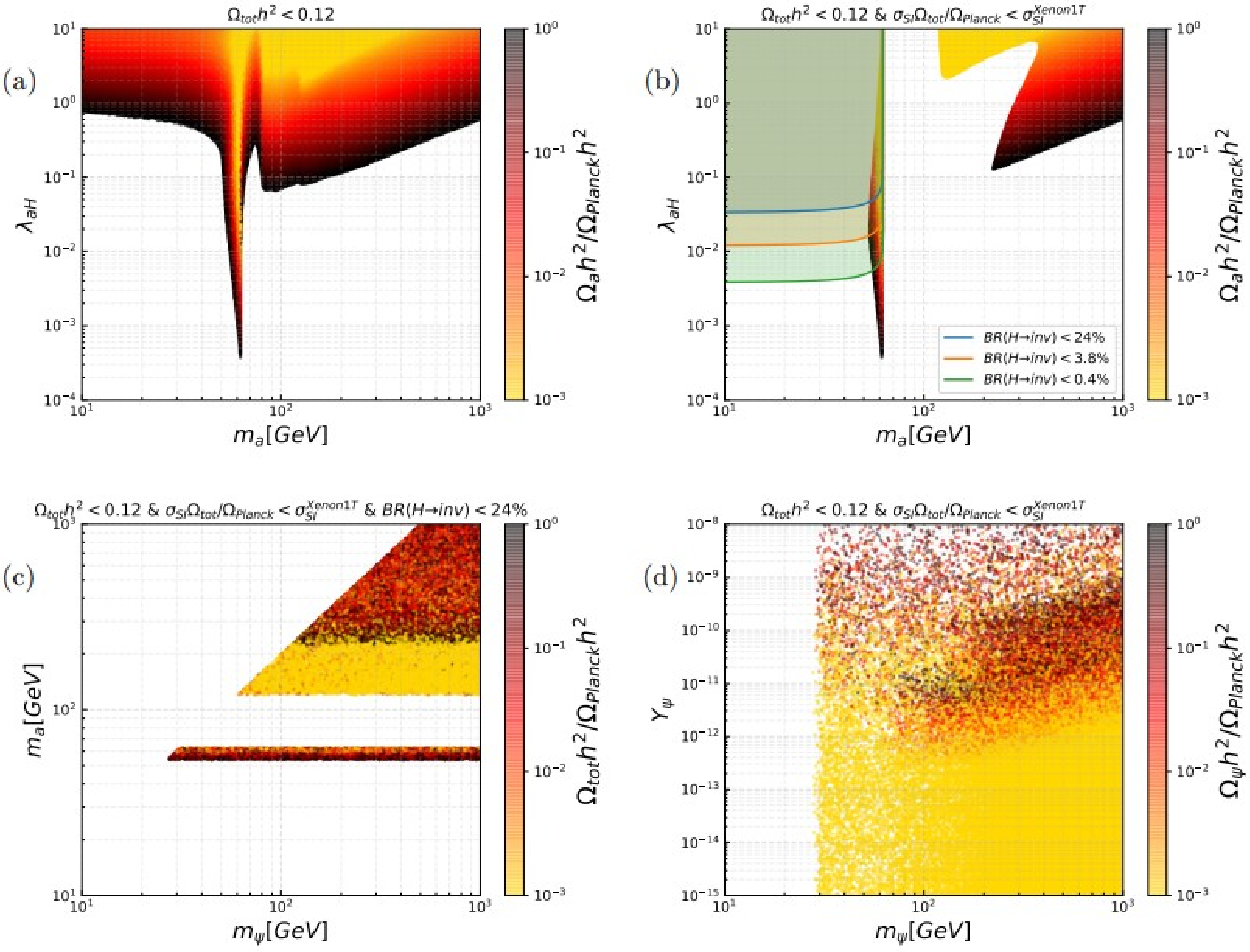


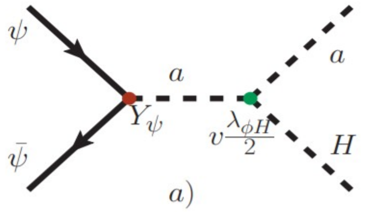


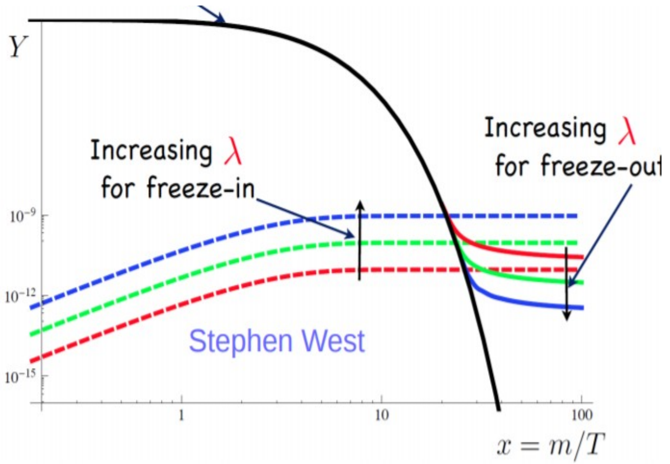


Minimal fermion DM model with pseudo-scalar mediator: non-thermal ψ

$$m_a < 2m_\psi$$







Small Y – FDM initially decoupled from SM+a bath, freezes in whilst a freezes out

Decoding Problem: Data → Theory **link**

- probably the most challenging problem to solve – **the inverse problem of decoding of the underlying theory from signal**
  - requires database of models, database of signatures
  - requires smart procedure based on machine learning of matching signal from data with the pattern of the signal from data

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- **HEPMDB (High Energy Physics Model Database)** was created in 2011 **hepmdb.soton.ac.uk**
  - convenient centralized storage environment for HEP models
  - it allows to evaluate the LHC predictions and perform event generation using CalcHEP, Madgraph for any model stored in the database
  - you can upload there your own model and perform simulation

Conclusions and Outlook

- **To decode the nature of DM** we need a signal first! But at the moment we can
  - understand what kind of DM is already excluded
  - systematically explore theory/parameter space and prepare ourselves for DM discovery and interpretation
- **MCDM models:** consistent but simple – one can explore the entire parameter space
- **Systematic classification**: new models can be found even for simplest cases
- **Probing DM space**
  - non-singlets can be probed via DT searches or multi-lepton signatures at colliders
  - DM DD is sensitive to the loop-induced diagrams but does not exclude all models
  - sensitivity is highly dependent on mass-split
  - rich phenomenology, complementarity of DM DD, collider signals and relic density
- **Data → Model link is missing, time to work on it (HEPMDB** might be useful)

Thank you!

Topics For Discussion

- What is your favourite model?
- In which experiment you would expect DM to be discovered first (and when)?
- How we can explore the full theory/parameter space of DM models?
- Which tool (or its part) for DM exploration needs to be developed further?
- What is the biggest model building problem related to DM?
- Which experiment is missing?
- Your topic for discussion goes here

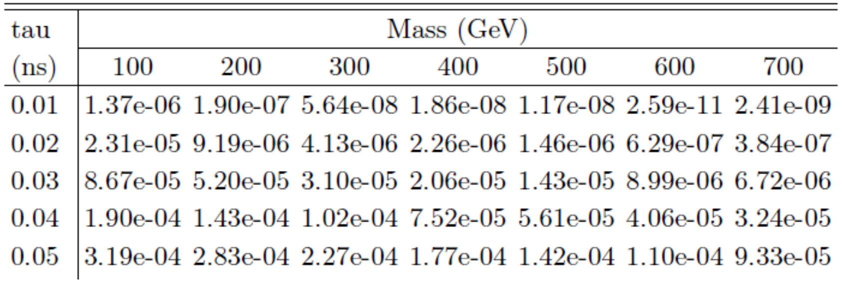
Backup slides

Details on DT studies

Public source for the interpretation

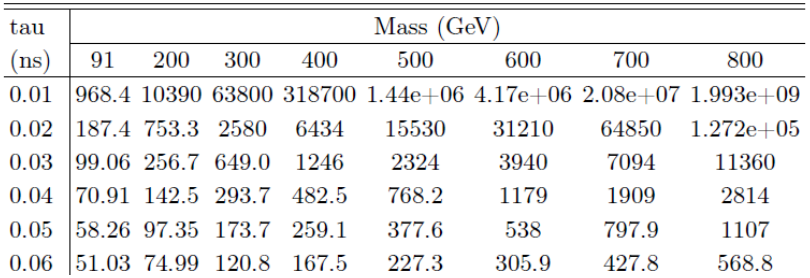
- The reinterpretation code is public at https://github.com/llprecasting/recastingCodes/ [reads root file after LHE→ PYTHIA → Delphes simulation]

- Tables of efficiencies and limits in MDM-τ plane allow to quickly find the reach for your own



tau (ns)	Mass (GeV) 100	200	300	400	500	600	700
0.01	1.37e-06	1.90e-07	5.64e-08	1.86e-08	1.17e-08	2.59e-11	2.41e-09
0.02	2.31e-05	9.19e-06	4.13e-06	2.26e-06	1.46e-06	6.29e-07	3.84e-07
0.03	8.67e-05	5.20e-05	3.10e-05	2.06e-05	1.43e-05	8.99e-06	6.72e-06
0.04	1.90e-04	1.43e-04	1.02e-04	7.52e-05	5.61e-05	4.06e-05	3.24e-05
0.05	3.19e-04	2.83e-04	2.27e-04	1.77e-04	1.42e-04	1.10e-04	9.33e-05

efficiencies



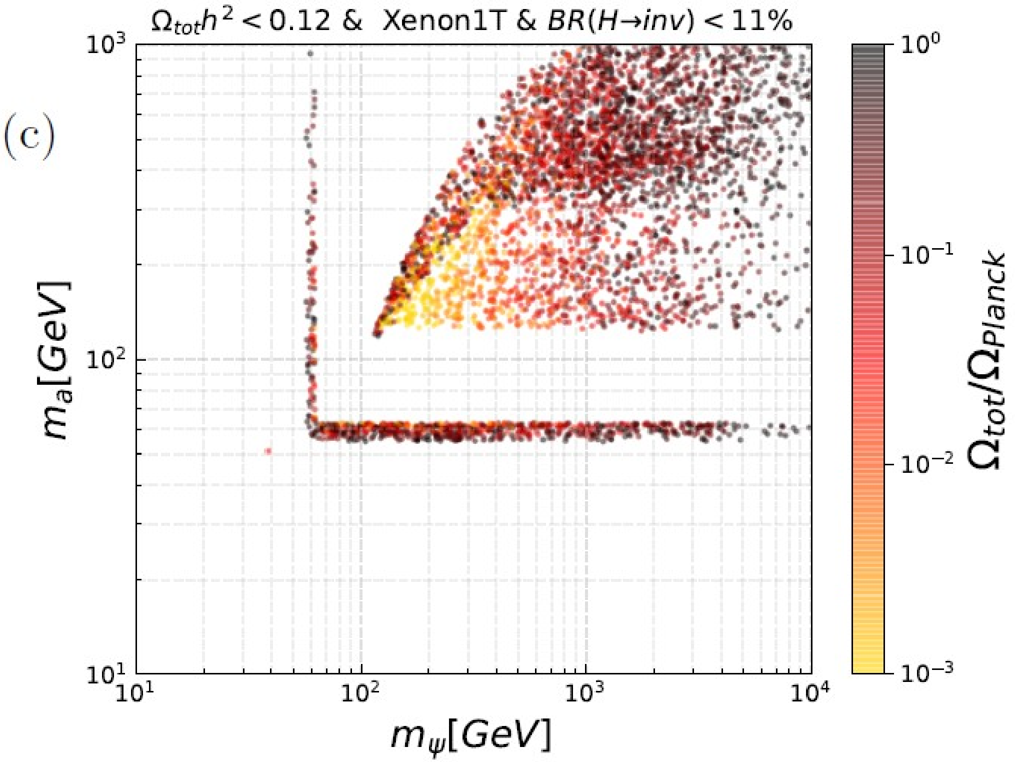
tau (ns)	Mass (GeV) 91	200	300	400	500	600	700	800
0.01	968.4	10390	63800	318700	1.44e+06	4.17e+06	2.08e+07	1.993e+09
0.02	187.4	753.3	2580	6434	15530	31210	64850	1.272e+05
0.03	99.06	256.7	649.0	1246	2324	3940	7094	11360
0.04	70.91	142.5	293.7	482.5	768.2	1179	1909	2814
0.05	58.26	97.35	173.7	259.1	377.6	538	797.9	1107
0.06	51.03	74.99	120.8	167.5	227.3	305.9	427.8	568.8

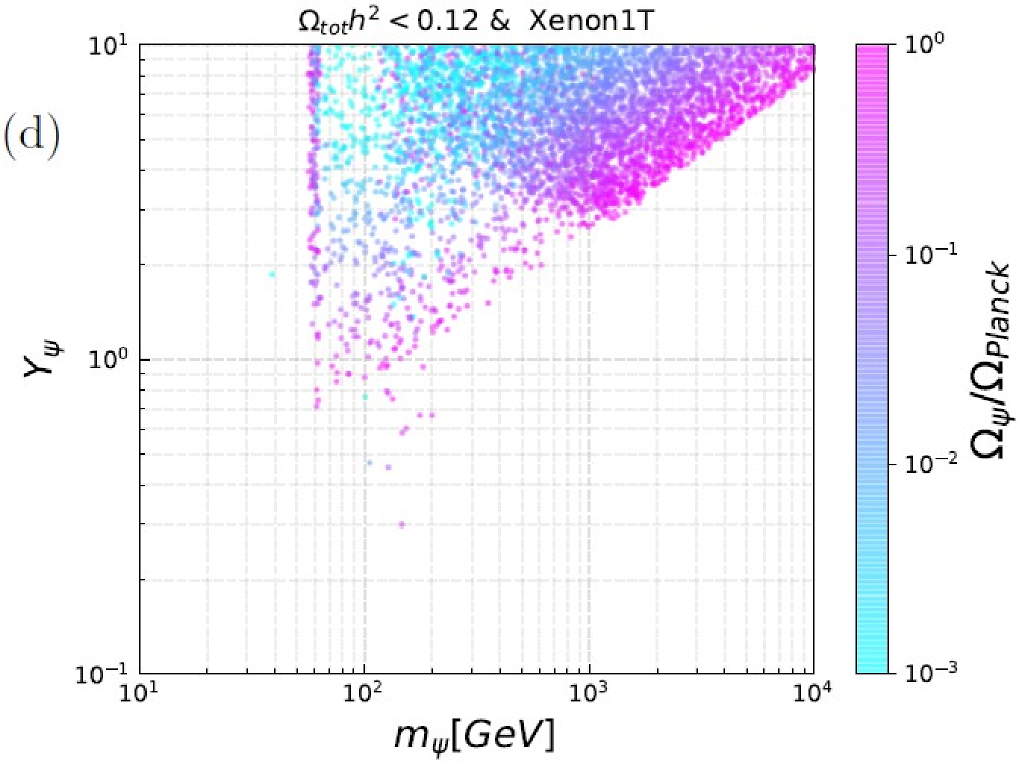
Limits in fb

- available at zenodo https://zenodo.org/record/4288736 (thanks to Sabine for idea about zenodo)
- efficiencies for separate channels of D^+D^- and D^+D^0/D^-D^0 production are important for more general interpretation – being produced now (thanks to Felipe Rojas)

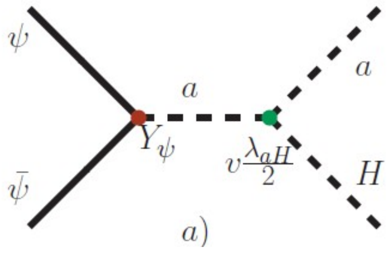
Minimal fermion DM model with pseudo-scalar mediator:

rich phenomenology: relic density, DD, colliders

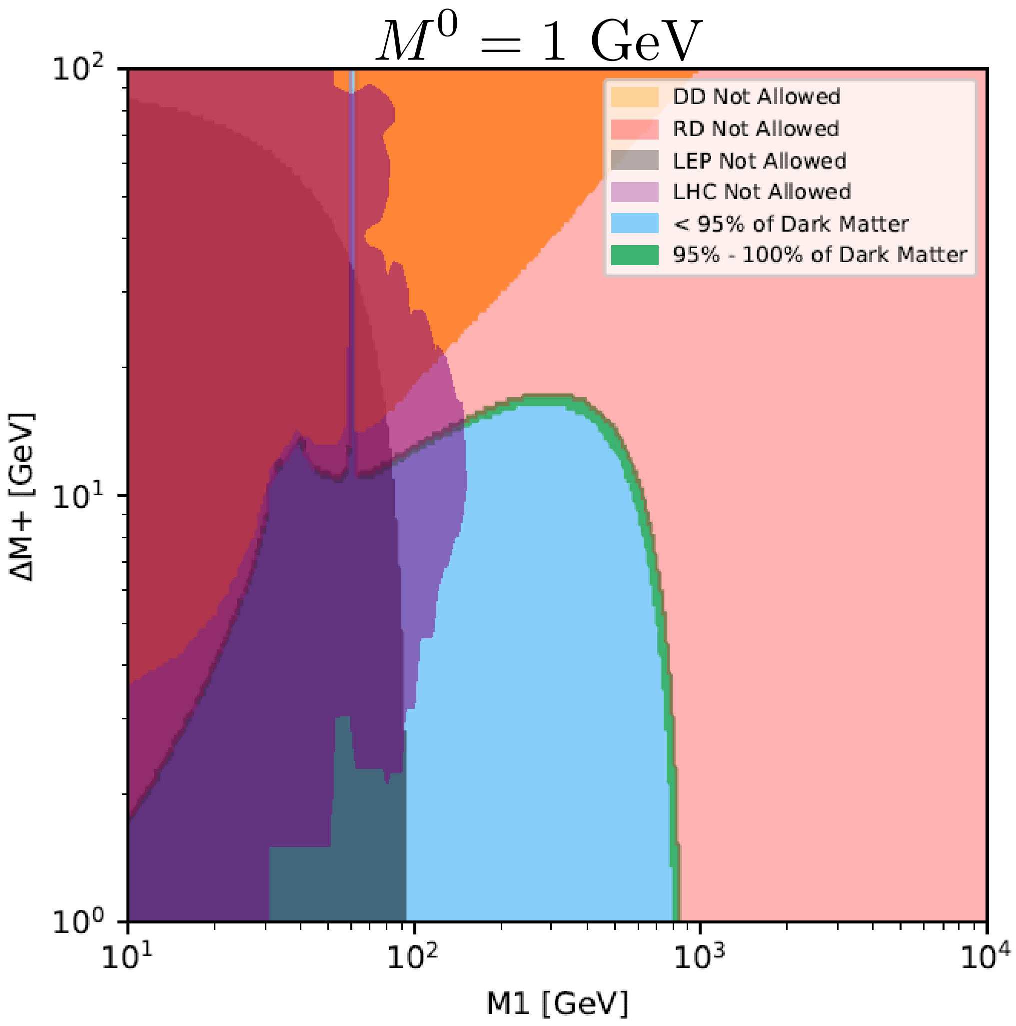


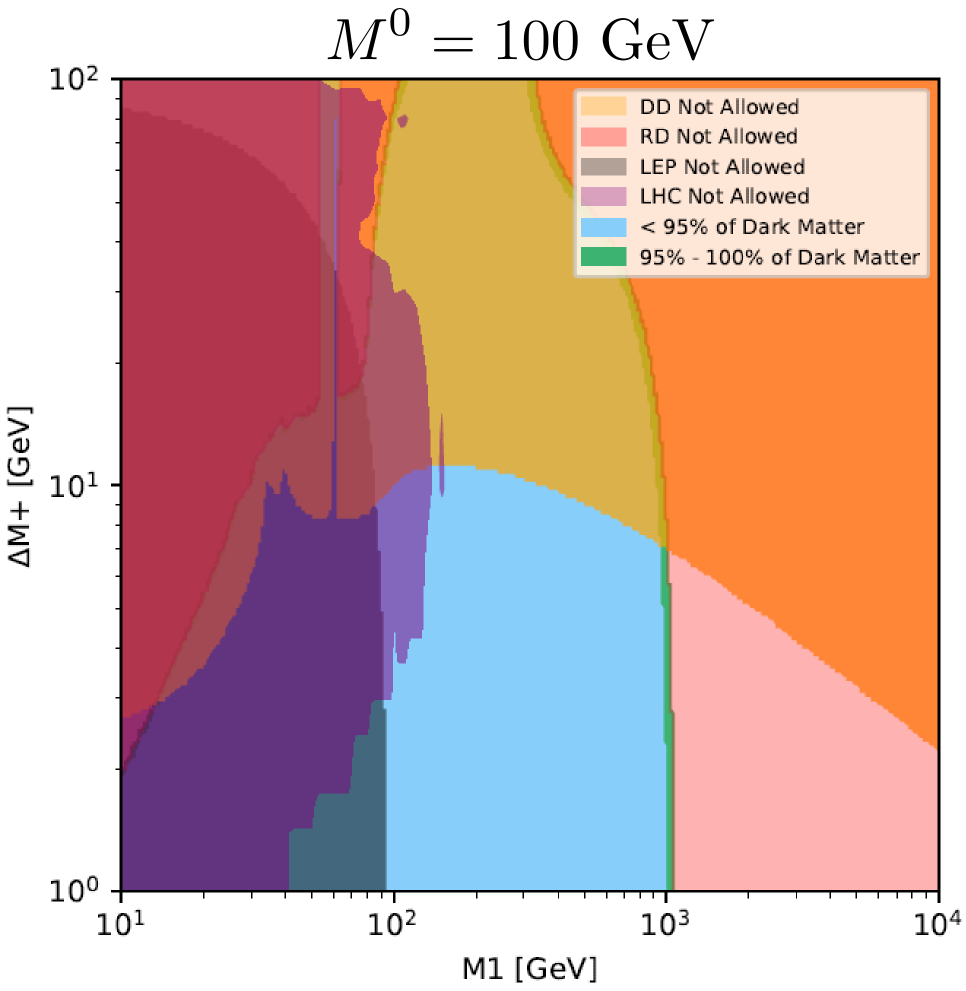


Parameter similar to that of typical portal models, however stable mediator causes “leakage” of points with FDM mass above ~90GeV caused by channel a) opening



MFDM parameter space: the current status


$M^0 = 1\ \text{GeV}$


$M^0 = 100\ \text{GeV}$