Probing the nature of DM at ILC

Dan Locke

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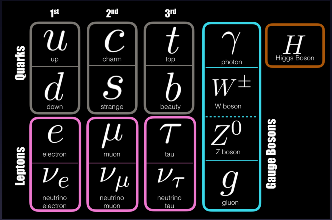

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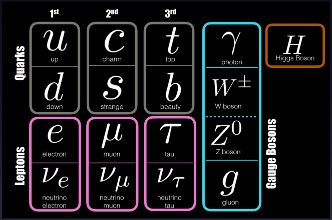

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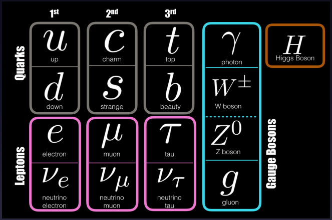

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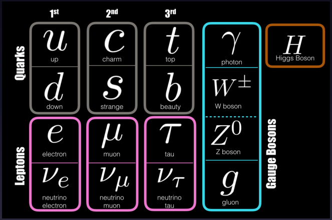

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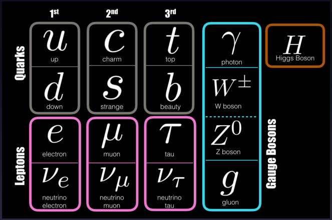

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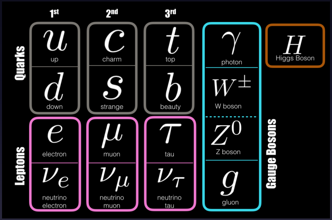

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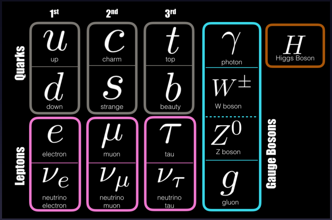

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    - Analysis

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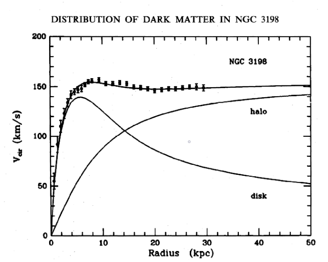

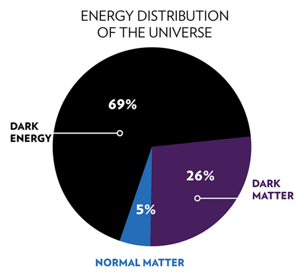

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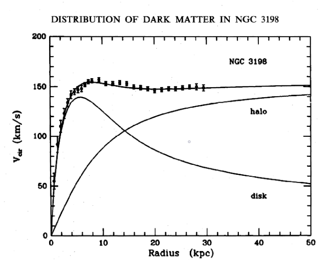
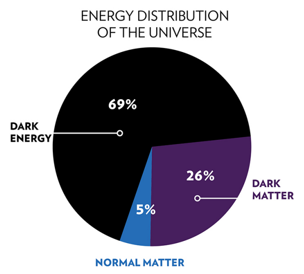

DISTRIBUTION OF DARK MATTER IN NGC 3198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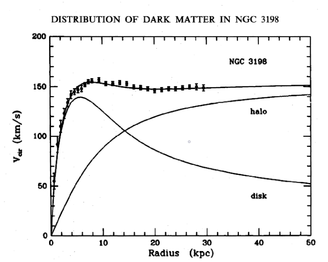

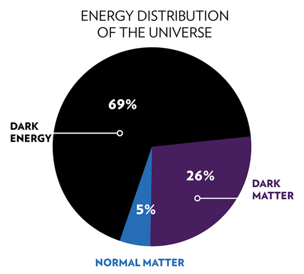

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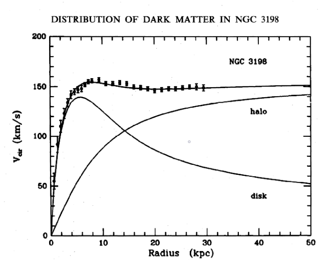
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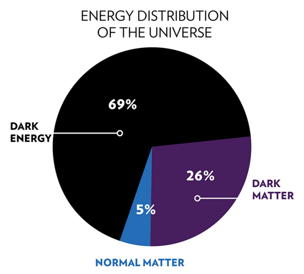
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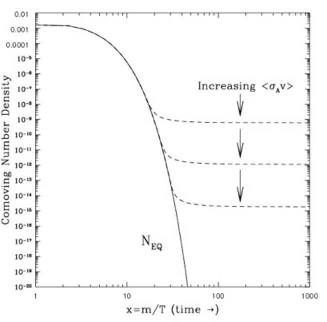

Jungman *et al* hep-ph/9506380

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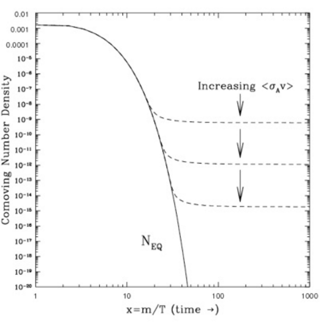

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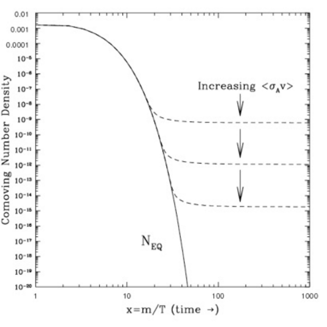

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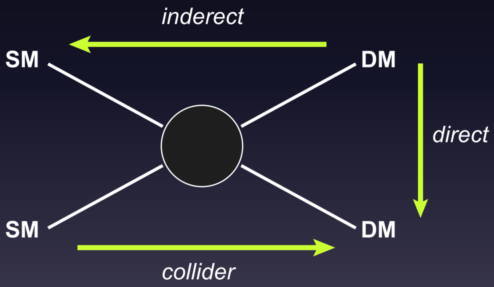
$$\Omega_\chi \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{g_\chi^4}$$

- WIMP miracle:

$$m_\chi \sim 100 GeV \quad g_\chi \sim g_w \rightarrow \Omega_\chi \sim 0.1$$

Experiments

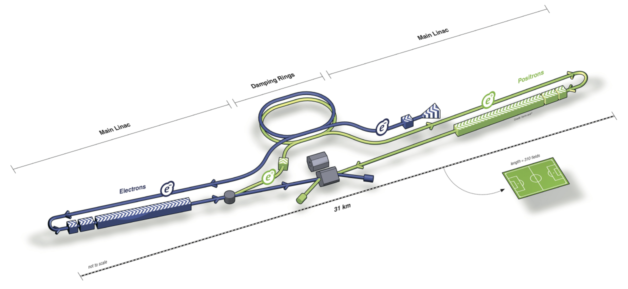
- DM annihilation in halo, core of the Earth and Sun → photons, Anti-protons, positrons, Neutrinos
- Neutrino telescopes: Amanda, Icecube, Antares



- Scattering off nuclei: DM Direct Detection (DD)
- DD experiments: LUX,XENON

- LEP sets bounds on electroweak fermions < 100GeV
- LHC signatures: mono-jet, mono-photon, mono-Z, mono Higgs, VBF+MET, soft leptons+MET, ...

International Linear Collider



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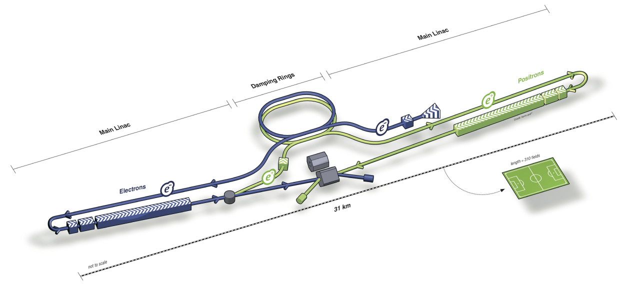

- Future e^+e^- collider starting at 500TeV, 500 fb^{-1} after run 1 (4 years)
- **LEP:** 200pb^{-1} at upto 200GeV $\rightarrow \sigma \approx 10fb$, expect 2 events
  ILC: $\rightarrow \sim 5000$ signal events

Conventions

We study the ILCs ability to measure DM and it's properties. We will consider scalar and fermionic dark matter, as defined by:

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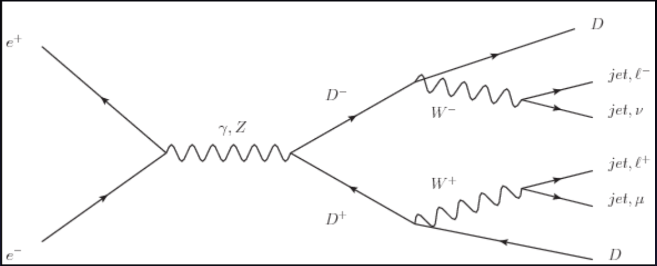
- there is new conserved quantum number, which we call D-parity. SM particles are D-even, while the D is D-odd - stablising lightest D-odd particle
- other D-odd particles exist: a charged $D^{\pm}$ and a neutral D_2, with the same spin s_D and with masses $M_+, \, M_{D_2} > M_D$



- Can produce pair of D via processes $e^+e^- \to D^+D^-$ or $e^+e^- \to D_2D_2$ with $D^\pm \to W^\pm D$, $D_2 \to ZD$.
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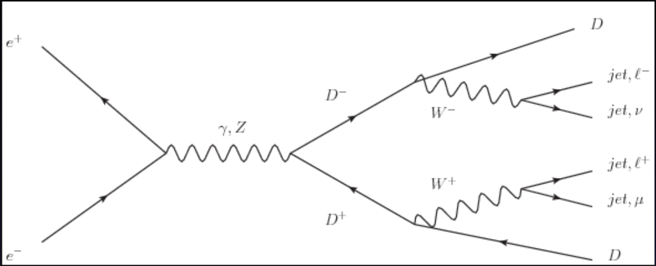

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- $W^\pm$,Z may then decay to dijet or leptonically
- Could measure M_+,M_D from edges of dijet distribution, but jet energy measurements have lots of uncertainty
- Instead use singular points of lepton energy distribution

- Total ILC annihilation at $\sqrt{s} > 200GeV$ is $\sim 10\sigma_0$ where $\sigma_0 = \sigma(e + e^- \to \gamma \to \mu^+\mu^-) = \frac{4\pi^2}{3s}$, annually: $\mathcal{L}\sigma_0 \sim 3 \cdot 10^5$

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- $e^+e^- \to D^+D^-$ can represent a significant fraction
- taking into account only photon and Z annihilation diagrams. Neglecting $\gamma - Z$ mixing:

$$\sigma_{min}(s_D) = \sigma_0 \begin{cases} \beta_+ \left[1 + \frac{2M_+^2}{s} + r_Z \beta_+^2\right] & \left(s_D = \frac{1}{2}\right), \\ \beta_+^3 \left[\frac{1}{4} + r_Z \cos^2(2\theta_W)\right] & (s_D = 0), \end{cases} \quad (1)$$

here $r_Z = \frac{\mu_M}{\left(2\sin(2\theta_W)\right)^4 (1 - M_Z^2/s)^2} = \frac{0.124\mu_M}{(1 - M_Z^2/s)^2}$, factor $\mu_M \leq 1$ is expressed via parameters of possible mixing, $\beta_+ = \sqrt{1 - 4M_+^2/s}$

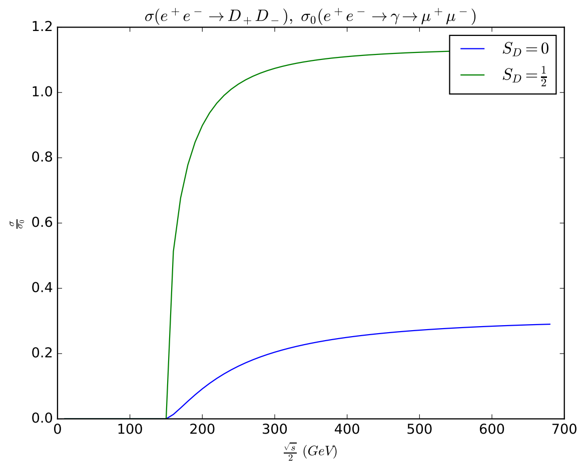
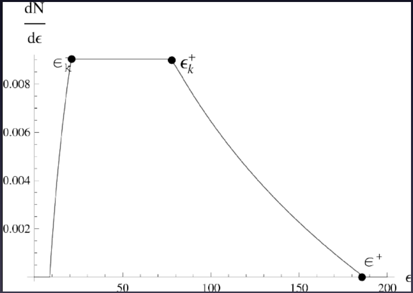


Figure: $M_+ = 150$ GeV.

Single lepton energy distribution

$$\boxed{e^+e^- \to D^+D^- \to DDW^+W^- \to DDq\bar{q}\ell\nu}$$



Onshell W energy disribution will have edges:

$$E_{on}^{\pm} = \gamma_+(E^{rest}(M_W) \pm \beta_+ p_W^{rest}(M_W)).$$

Will lead to kinks in lepton energy dist $\epsilon_k^- = \frac{E_{on}^- - \sqrt{(E_{on}^-)^2 - M_W^2}}{2}, \quad \epsilon_k^+ = \frac{M_W^2}{4\epsilon_k^-}$

Single lepton energy distribution

All muon energies lie within the interval determined by the highest value of W energy:

$$\epsilon^+ \geqslant \epsilon \geqslant \epsilon^- \equiv \frac{M_W^2}{4\epsilon^+}, \quad \epsilon^+ = \frac{E_{on}^+ + \sqrt{(E_{on}^+)^2 - M_W^2}}{2} \qquad (2)$$

From ϵ^+, ϵ_k^- and condition of positive real mass, can reconstruct M_D, M_+.

Minimal Models

To explore further, we consider gauge-invariant renormalisable models with these feature.

IHDM: new SU(2) higgs doublet which does not acquire vev, or couple to fermions. D-parity realised as Z_2 symmetry

$$\mathcal{L} = \mathcal{L}_{gf}^{SM} + \mathcal{L}_Y(\psi_f, \phi_S) + \left(\mathcal{D}_\mu \phi_S^\dagger \mathcal{D}_\mu \phi_S + \mathcal{D}_\mu \phi_D^\dagger \mathcal{D}_\mu \phi_D\right)/2 - V$$

$$V = -\frac{1}{2}\left[m_{11}^2(\phi_S^\dagger \phi_S) + m_{22}^2(\phi_D^\dagger \phi_D)\right] + \frac{\lambda_1}{2}(\phi_S^\dagger \phi_S)^2 + \frac{\lambda_2}{2}(\phi_D^\dagger \phi_D)^2 +$$
$$+ \lambda_3(\phi_S^\dagger \phi_S)(\phi_D^\dagger \phi_D) + \lambda_4(\phi_S^\dagger \phi_D)(\phi_D^\dagger \phi_S) + \frac{\lambda_5}{2}\left[(\phi_S^\dagger \phi_D)^2 + (\phi_D^\dagger \phi_S)^2\right]$$

Leads to phenomenologically interesting parameters: $\{M_D, M_{D_2}, M_+, \lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5\}$ where λ_{345} governs higgs-DM vertex

VFDM

For anomaly-free fermionic DM, introduce $SU(2)$ weak doublet of vector-like (non-chiral) Dirac fermions: $\psi = \left(\chi^{+}, \chi^{0}\right)$, along with D-odd singlet χ_s^0, which mixes with χ^0.

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$$\mathcal{L}_{VFDM} = \mathcal{L}_{SM} + i\bar{\psi}\not{D}\psi - m_\psi\bar{\psi}\psi - m_{\chi_s^0}\bar{\chi_s^0}\chi_s^0 - Y_0\bar{\psi}\Phi\chi_s^0 \quad (3)$$

We diagonalise to find expressions for lagrangian parameters in terms of physical parameters:
$\{M_D, M_{D_2}, M_+\}$, which also parametrise mixings

Effects from finite-widths, non-resonant diagrams and ISR+beamstrahlung:

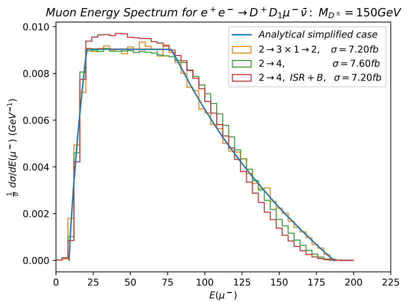


Figure: Scalar DM, muon energy dist, $M_{D\pm} = 150$ GeV, $M_D = 50$ GeV.

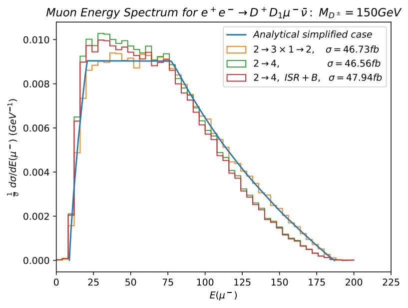
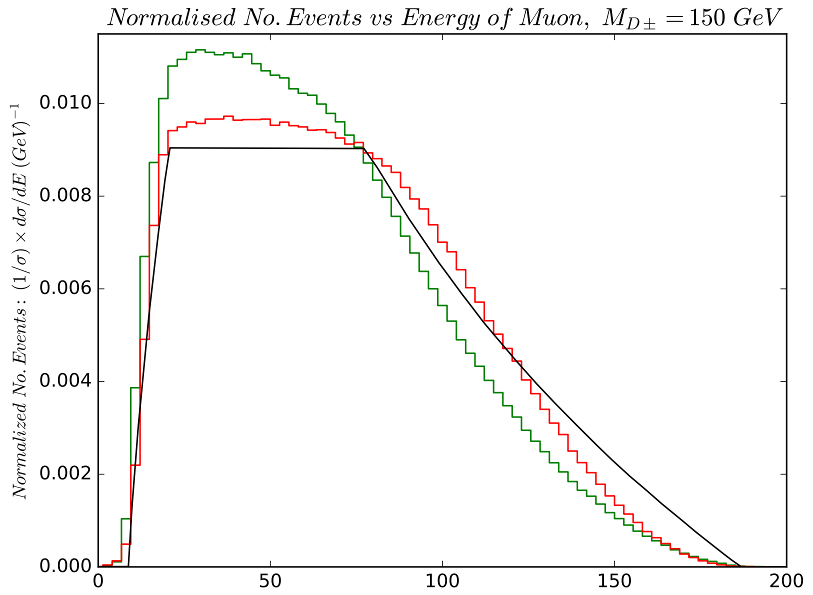


Figure: Fermion DM, muon energy dist, $M_{D\pm} = 150$ GeV, $M_D = 50$ GeV.


$Normalised\ No.\ Events\ vs\ Energy\ of\ Muon,\ M_{D\pm} = 150\ GeV$
$Normalized\ No.\ Events:\ (1/\sigma)\times d\sigma/dE\ (GeV)^{-1}$
0.000
0.002
0.004
0.006
0.008
0.010
0
50
100
150
200

Signal vs background

- Lets consider decoupled D_2 scenario, where background is mostly SM, at $\sqrt{s} = 500GeV$, $\mathcal{L} = 500fb^{-1}$.

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- $\sigma^{FDM}(e^+e^- \to W^+W^- \to j, j, \mu, \nu) = 34.98 fb$

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- $\sigma^{FDM}(e^+e^- \to W^+W^- \to j, j, \mu, \nu) = 34.98fb$

Signal vs background

$e^+e^- \to DD(W \to \ell\nu)(W \to q\bar{q})$: dijet $+$ μ + missing
with energy of each dijet or lepton $< \frac{\sqrt{s}}{2}$, with large MET and large M_{miss}.

$$M_{miss}^2 = \left((500, 0, 0, 0) - \sum_{vis} p_{vis} \right)^2 \tag{4}$$

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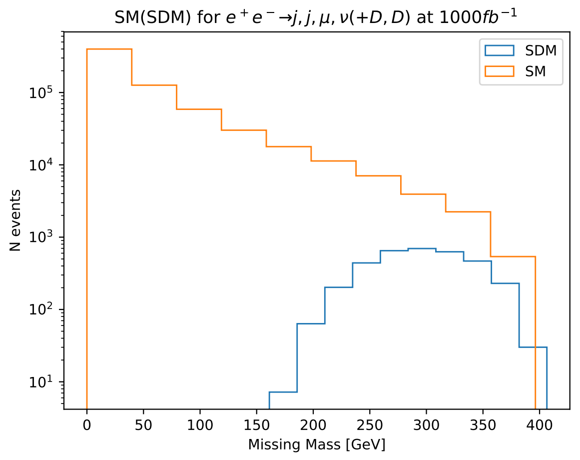
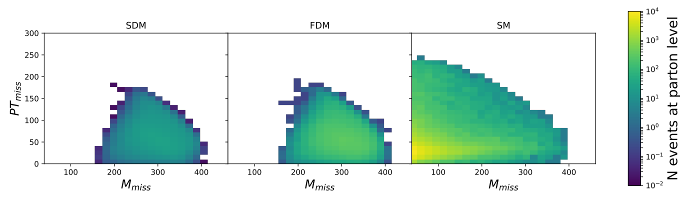
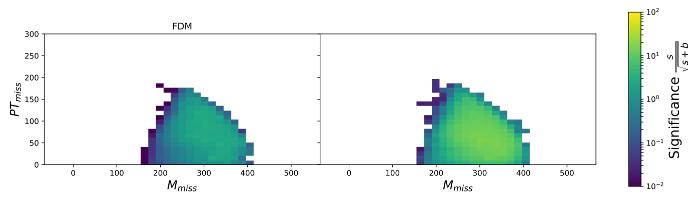
Multivariate cut in this plane is powerful, e.g:
a) $PT_{miss} < 3 * M_{miss} - 600$; b) $PT_{vis} > -M_{vis} + 300$.
signal efficiency: 0.86134
background rejection: 0.9847

Signal vs background



Signal vs background



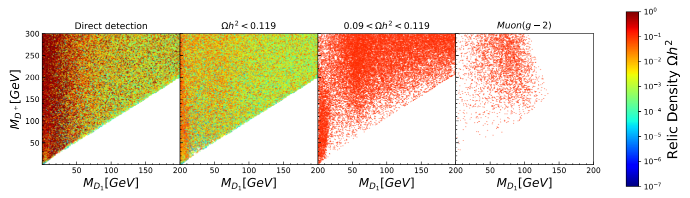


Parameter space

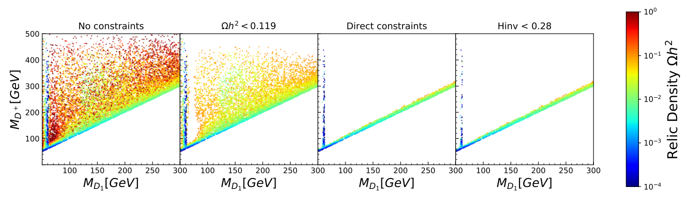
- For IHDM we can find points for our signature [arXiv:1612.00511]
- For VFDM, not so good: to suppress $g_W \chi^0 \chi^0 Z$ and avoid XENON1T bounds, require $D_2 - D^+ < 1GeV$ (mass gap controls mixing).
- This leads to small DM annihilation rates $\rightarrow$ overclose the universe.
- Can suppress Ωh^2 by introducing coannihilation partner interacting via new yukawa coupling.
- Possibilities: D-odd scalar or fermion, electroweak singlet or doublet. For minimality, choose singlet - still no viable models with this signature.
- Best solution appears to be Majorana DM, which does not contain vector couplings, so DD constraints avoided without mixings.

Parameter space

Coupling odd scalar singlet to muon doublet:



Majorana:



Conclusion and outlook

- There is a possibility to measure mass and spin of DM at ILC, provided weakly interacting DM exists
- Work in progress: detector level analysis
- We explored potential minimal consistent models for fermion dark matter, which may produce such signals
- Work in progress: Majorana dark matter
- Future work: detector level analysis for spin discrimination, benchmark planes

I made too many slides