Workshop on the Standard Model and Beyond

Corfu Summer Institute, September 8th 2018

Examples of the interplay between LHC and Dark Matter

Lorenzo Calibbi

ITP-CAS, Beijing

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Freeze-in Dark Matter and displaced vertices at the LHC

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ITP-CAS, Beijing

based on LC, L. Lopez-Honorez, S. Lowette, A. Mariotti, arXiv:1805.04423

About 26% of the energy of the universe is due to some Dark Matter

A possibility is that DM is made of WIMPs (weakly-interacting massive particles) that are thermal relics produced in the early universe through the freeze-out mechanism

Direct detection searches (the latest XENON1T) and LHC searches are giving increasingly tight constraints on WIMPs

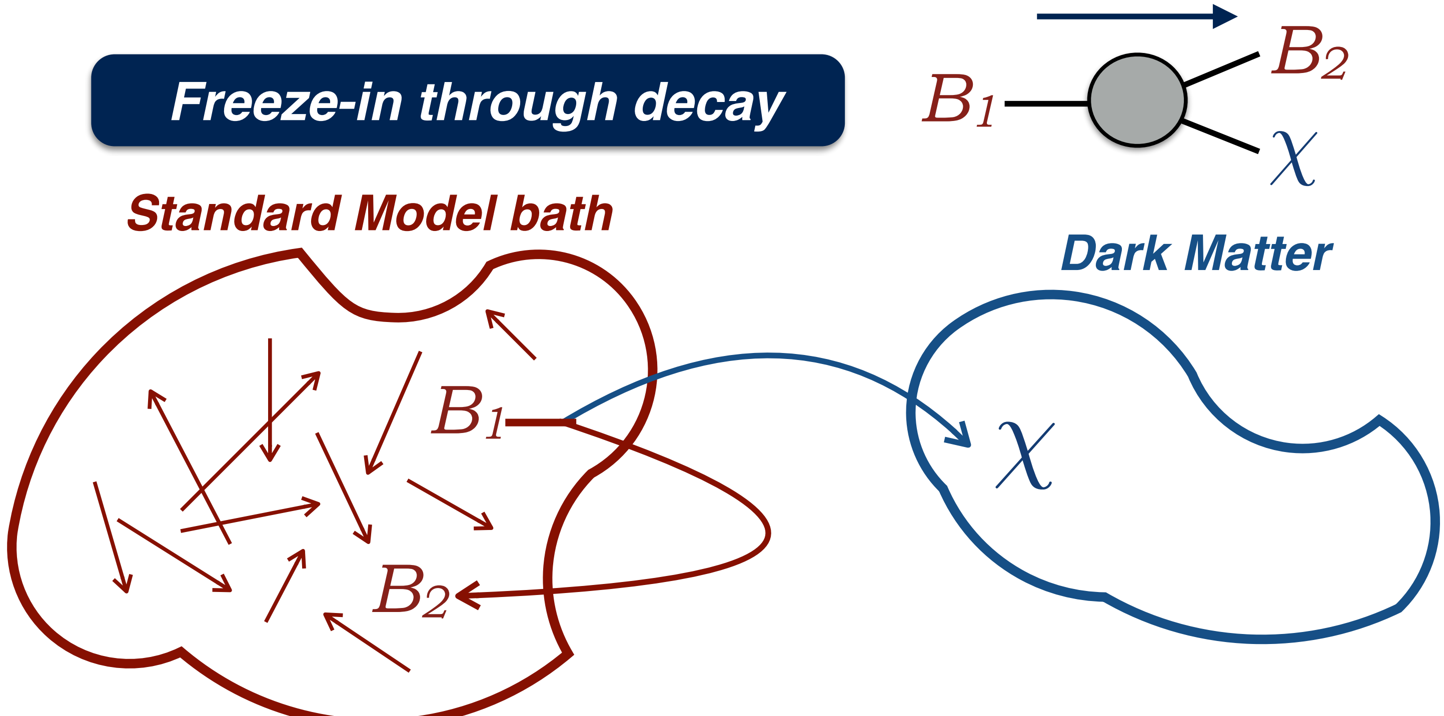
It is perhaps time to consider *also* alternative paradigms, *e.g.* axion DM or different DM production mechanisms

The freeze-in mechanism

Production mechanism for non-thermal (because *feebly-coupled*) Dark Matter

Hall et al. '09

DM never in thermal equilibrium with the SM bath, produced via scattering or decays of bath particles (the 'mediators')

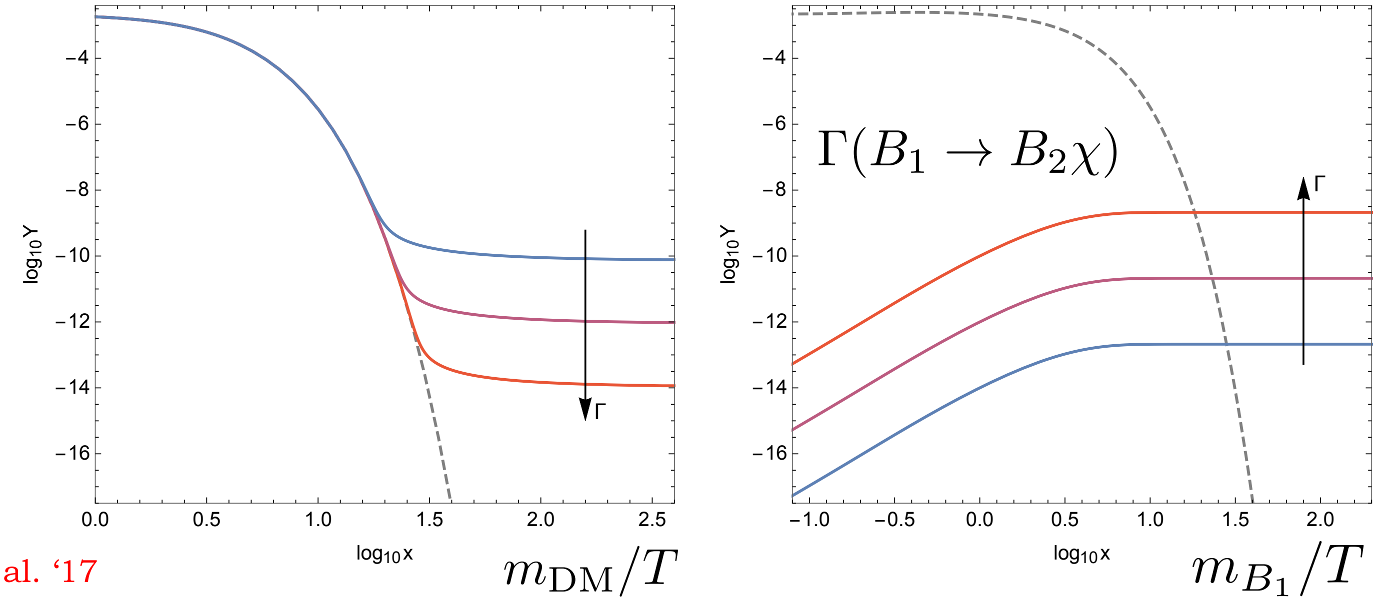


cartoon by A. Mariotti

Production mechanism for non-thermal (because *feebly-coupled*) Dark Matter

Hall et al. '09

DM abundance: Freeze-out versus Freeze-in (through decay)



Bernal et al. '17

Resulting relic density from $B_1 \to B_2\,\chi_{\rm DM}$

$$\Omega_{\rm DM} h^2 \simeq 0.1 \left(\frac{5\,{\rm cm}}{c\tau_{B_1}}\right) \left(\frac{600\,{\rm GeV}}{m_{B_1}}\right)^2 \left(\frac{m_{\rm DM}}{10\,{\rm keV}}\right)$$

The freeze-in mechanism

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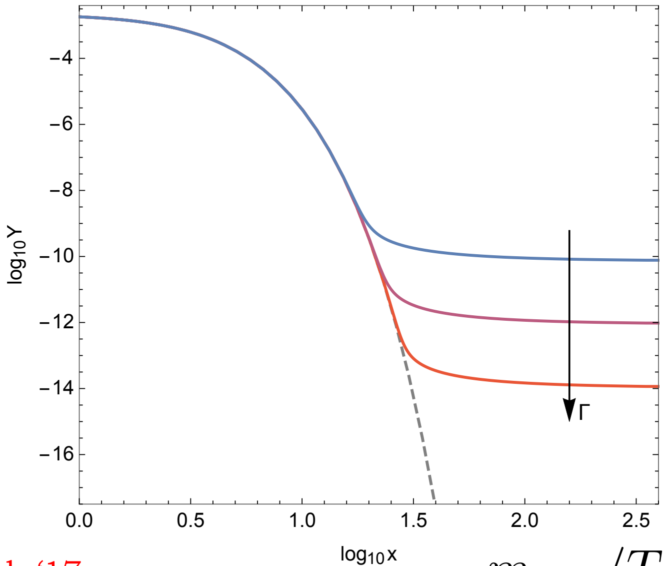
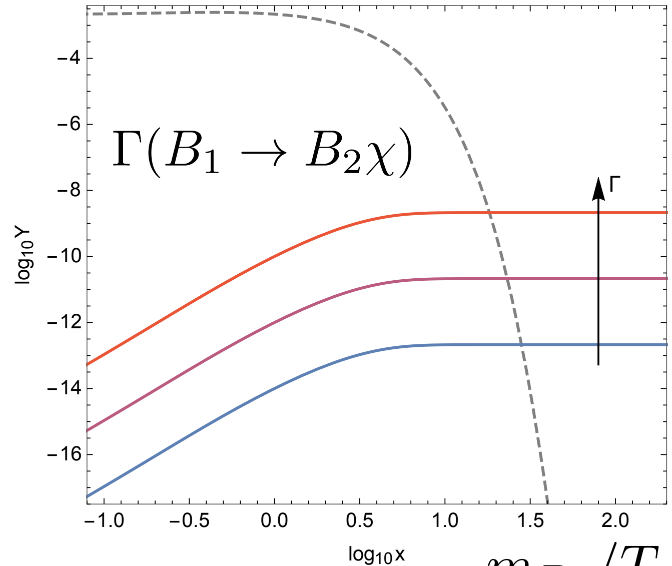


$m_{\rm DM}/T$



m_{B_1}/T

Bernal et al. '17

Light DM $\longleftrightarrow$ TeV-scale mediator $\longleftrightarrow$ Displaced decays at the LHC

Freeze-in Singlet Double Dark Matter

Singlet-Doublet model: minimal extension of the Standard Model introducing Higgs- and Z-portal DM-SM interactions

New (Z_2-odd) fields: a fermion singlet, a vectorlike pair of SU(2) doublets:

Mahbubani Senatore ‘05

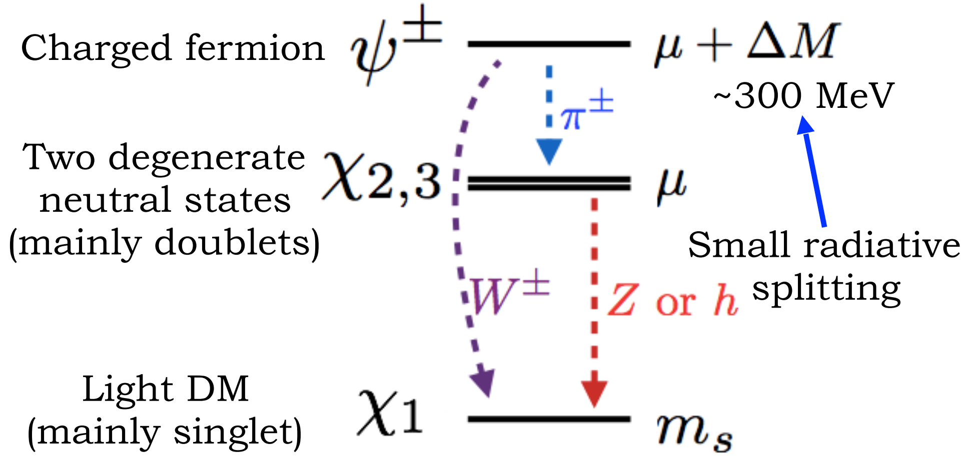
$$(\psi_u)_{2,\frac{1}{2}} = \begin{pmatrix} \psi^+ \\ \psi_u^0 \end{pmatrix}, \qquad (\psi_d)_{2,-\frac{1}{2}} = \begin{pmatrix} \psi_d^0 \\ \psi^- \end{pmatrix}, \qquad (\psi_s)_{1,0}$$

$$-\mathcal{L} \supset \mu\, \psi_d \cdot \psi_u + y_d\, \psi_d \cdot H\, \psi_s + y_u\, H^\dagger \psi_u\, \psi_s + \frac{1}{2} m_s\, \psi_s \psi_s + h.c.$$

Generalisation of the Bino-Higgsino system of the MSSM:

$$\mathcal{M} = \begin{pmatrix} m_s & \frac{y_d v}{\sqrt{2}} & \frac{y_u v}{\sqrt{2}} \\ \frac{y_d v}{\sqrt{2}} & 0 & \mu \\ \frac{y_u v}{\sqrt{2}} & \mu & 0 \end{pmatrix}$$

Freeze-in limit: $|y_{u,d}| \ll 1, \quad |m_s| \ll |\mu|$

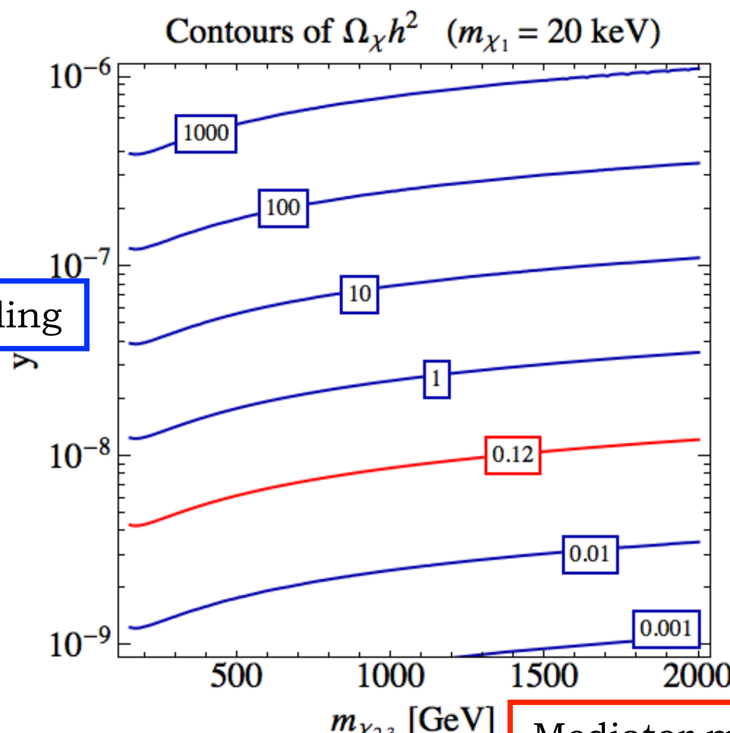


Dark Matter produced by decays of the doublet states (the freeze-in 'mediators'):

$$Y_{\chi_1} = \frac{270 M_{Pl}}{(1.66) 8\pi^3 g_*^{3/2}} \left(\sum_{B=Z,h} \frac{\Gamma[\chi_3 \to B\chi_1]}{m_{\chi_3}^2} + \sum_{B=Z,h} \frac{\Gamma[\chi_2 \to B\chi_1]}{m_{\chi_2}^2} + g_\psi \frac{\Gamma[\psi^+ \to W^+\chi_1]}{m_\psi^2} \right)$$

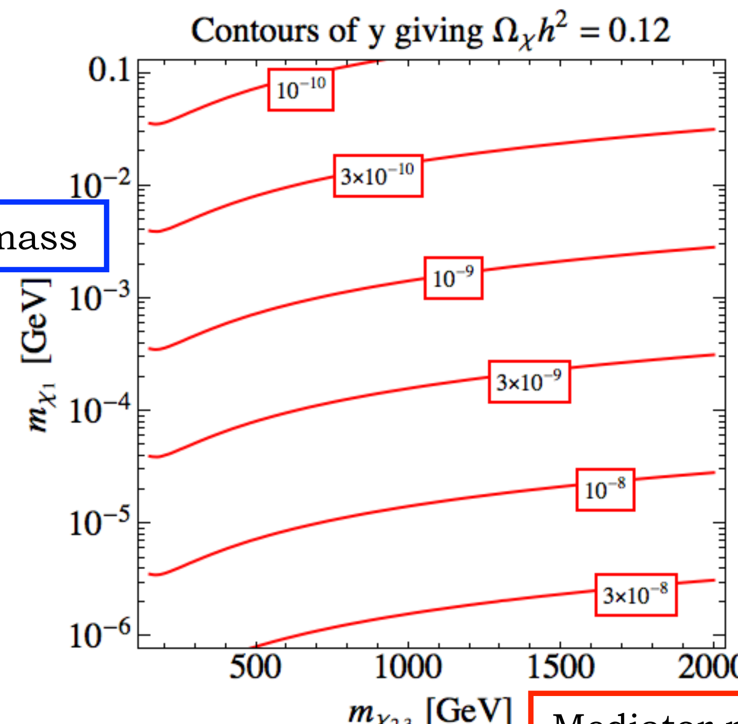
$$\Omega_{\chi_1} h^2 \simeq 0.11 \left(\frac{105}{g_*}\right)^{3/2} \left(\frac{y}{10^{-8}}\right)^2 \left(\frac{m_{\chi_1}}{10\text{ keV}}\right) \left(\frac{700\text{ GeV}}{\mu}\right)$$

Coupling



Mediator mass

DM mass



Mediator mass

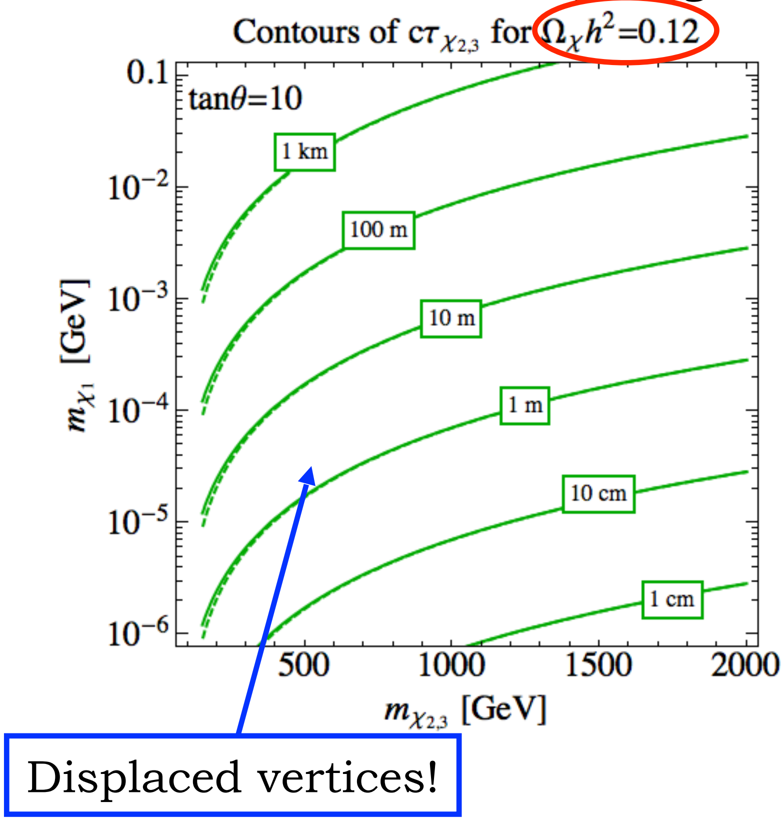
LHC phenomenology

Doublet states (with m~TeV) abundantly produced at the LHC:

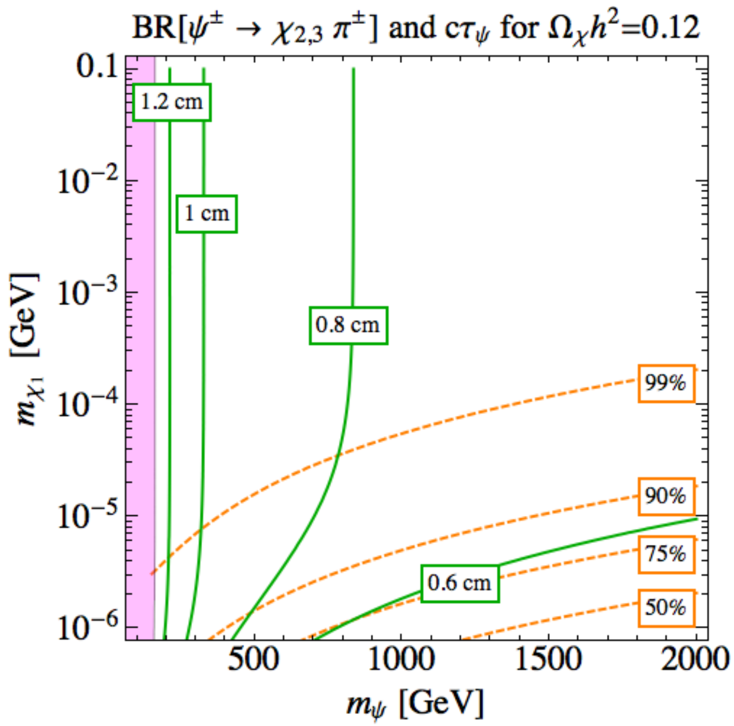
$$pp \to \chi_2\chi_3 + X, \quad pp \to \psi^+\psi^- + X, \quad pp \to \chi_{2,3}\psi^\pm + X.$$

Decays give Higgs/Z + MET: $\psi^\pm \to \pi^\pm + \chi_{2,3}, \quad \chi_{2,3} \to h/Z + \chi_1$

Neutral states decay length:



Charged states decay length:



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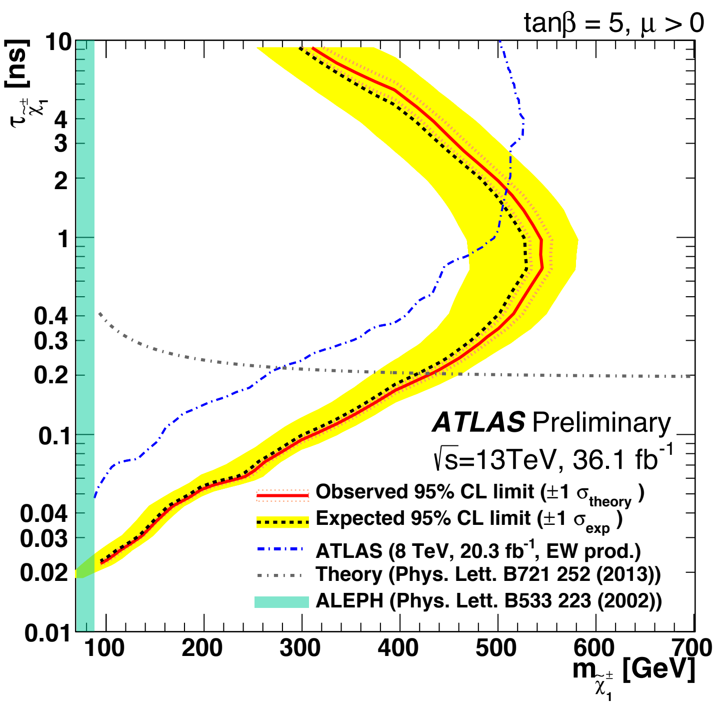
Disappearing tracks

ATLAS 1712.02118



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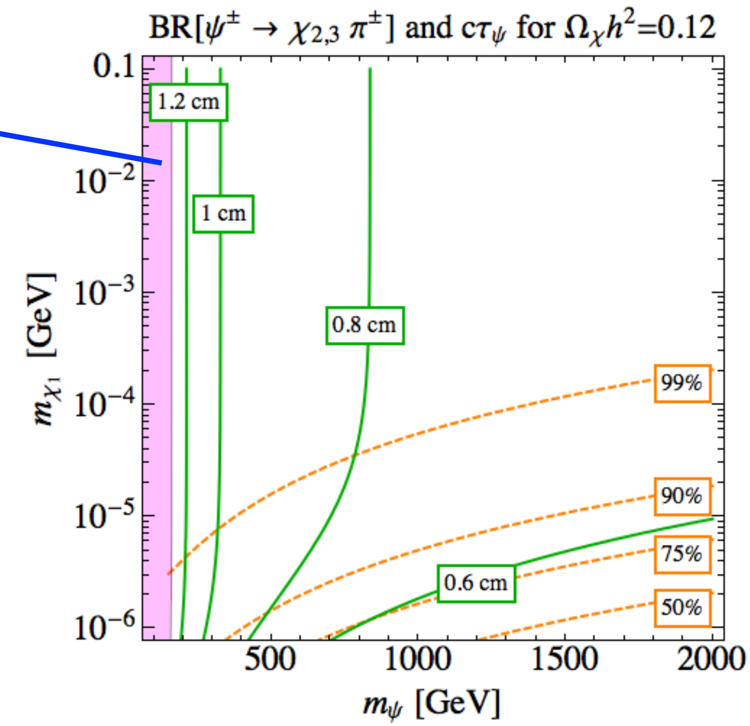

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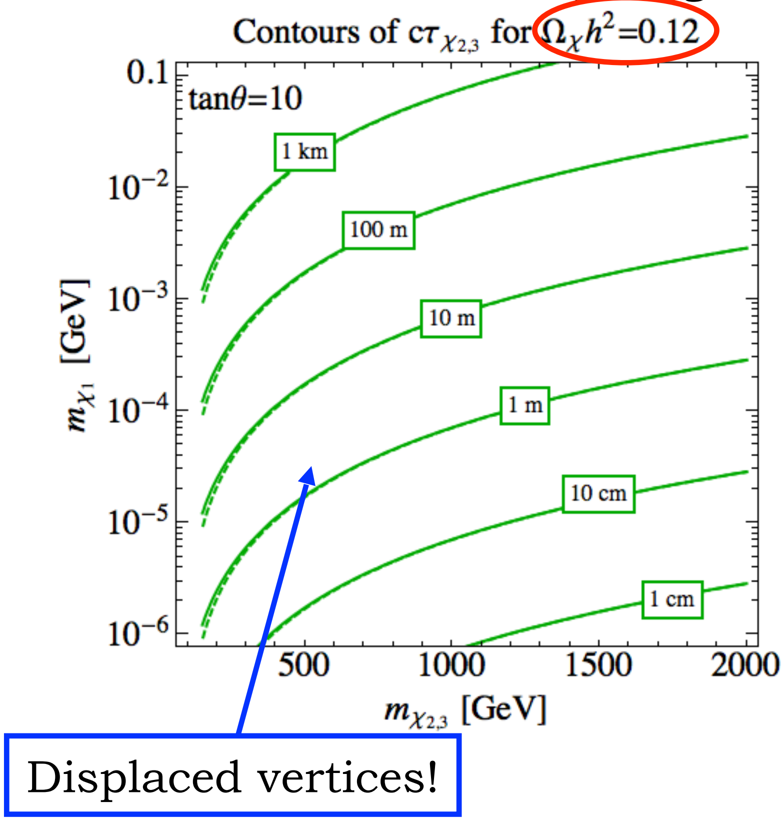
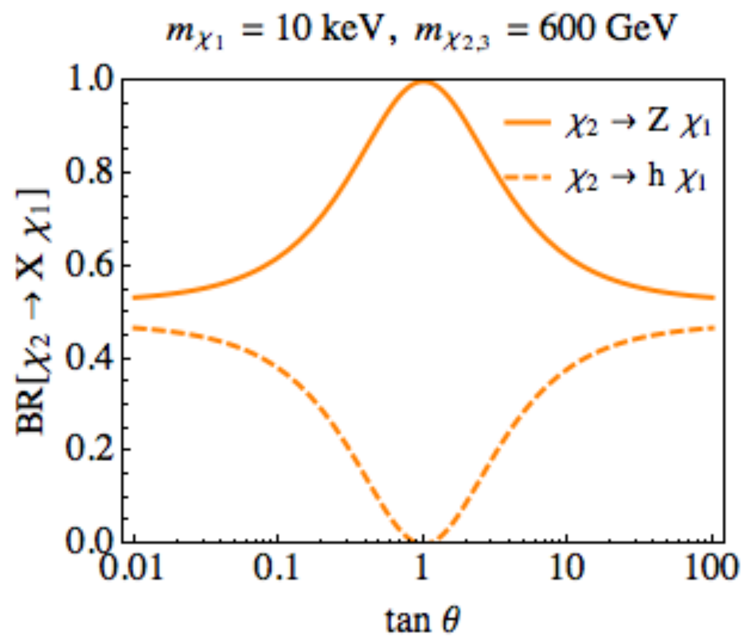


Neutral states BRs:



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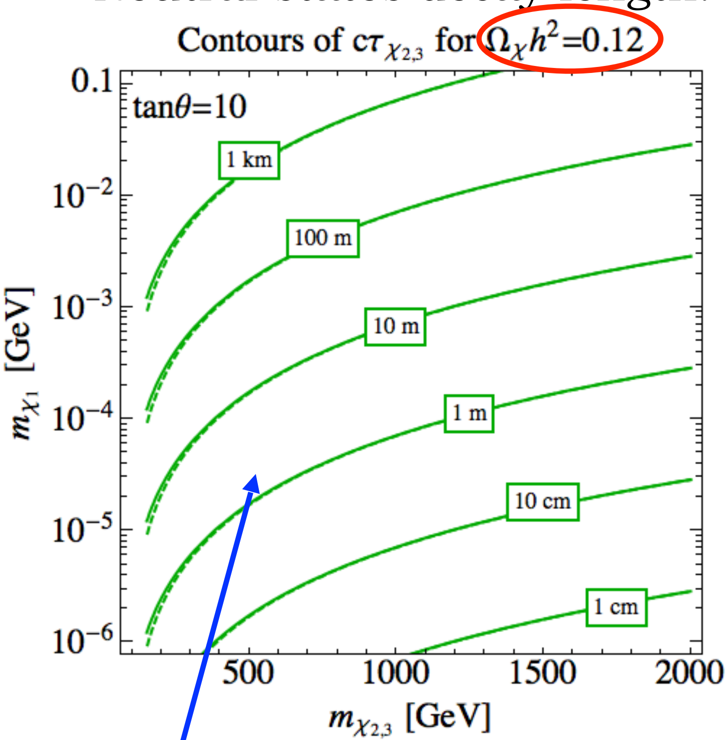

Displaced vertices!

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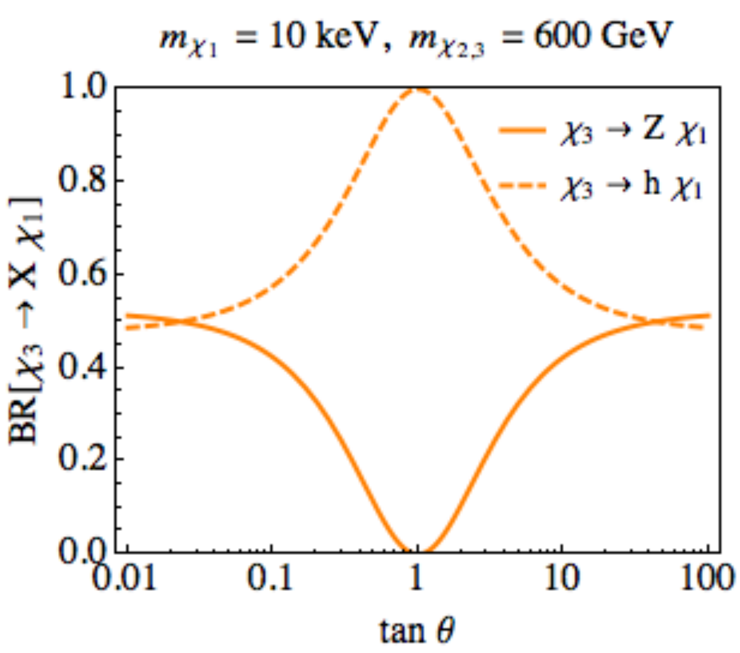

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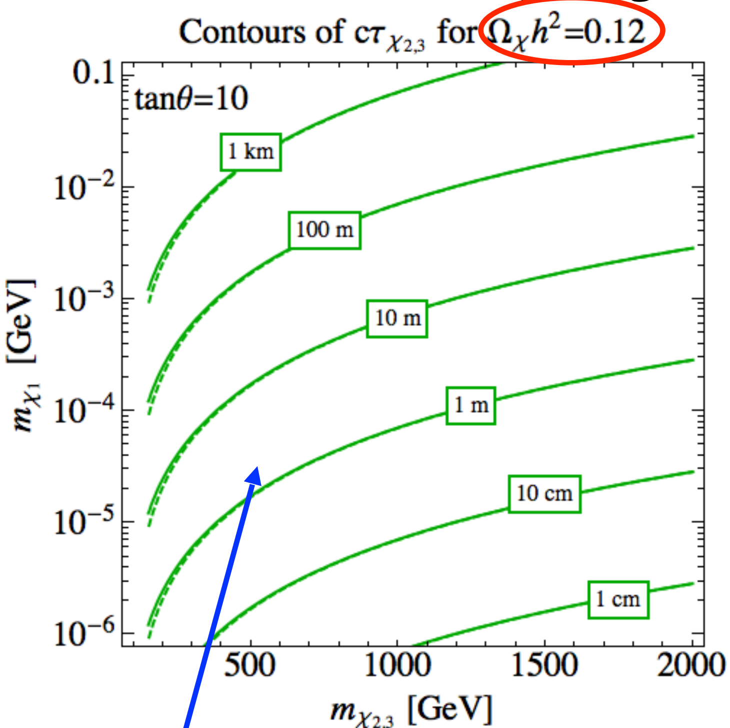

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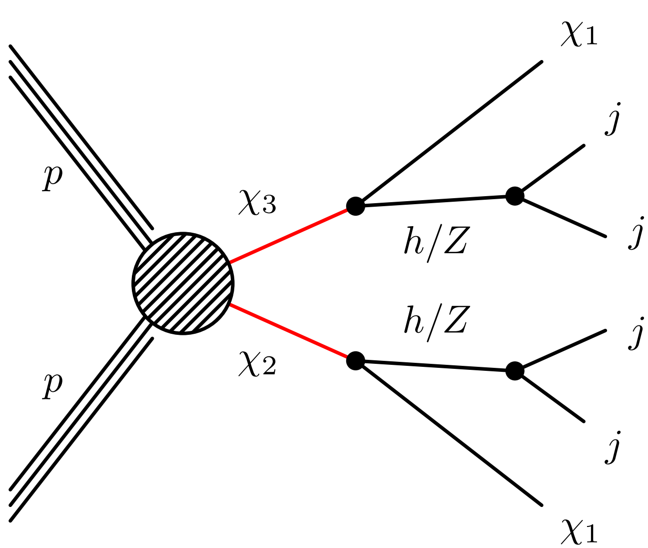


LHC signature: displaced vertices with jets and MET (~0 SM background)

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Rev. D.

CERN-EP-2017-202
October 16, 2017

Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

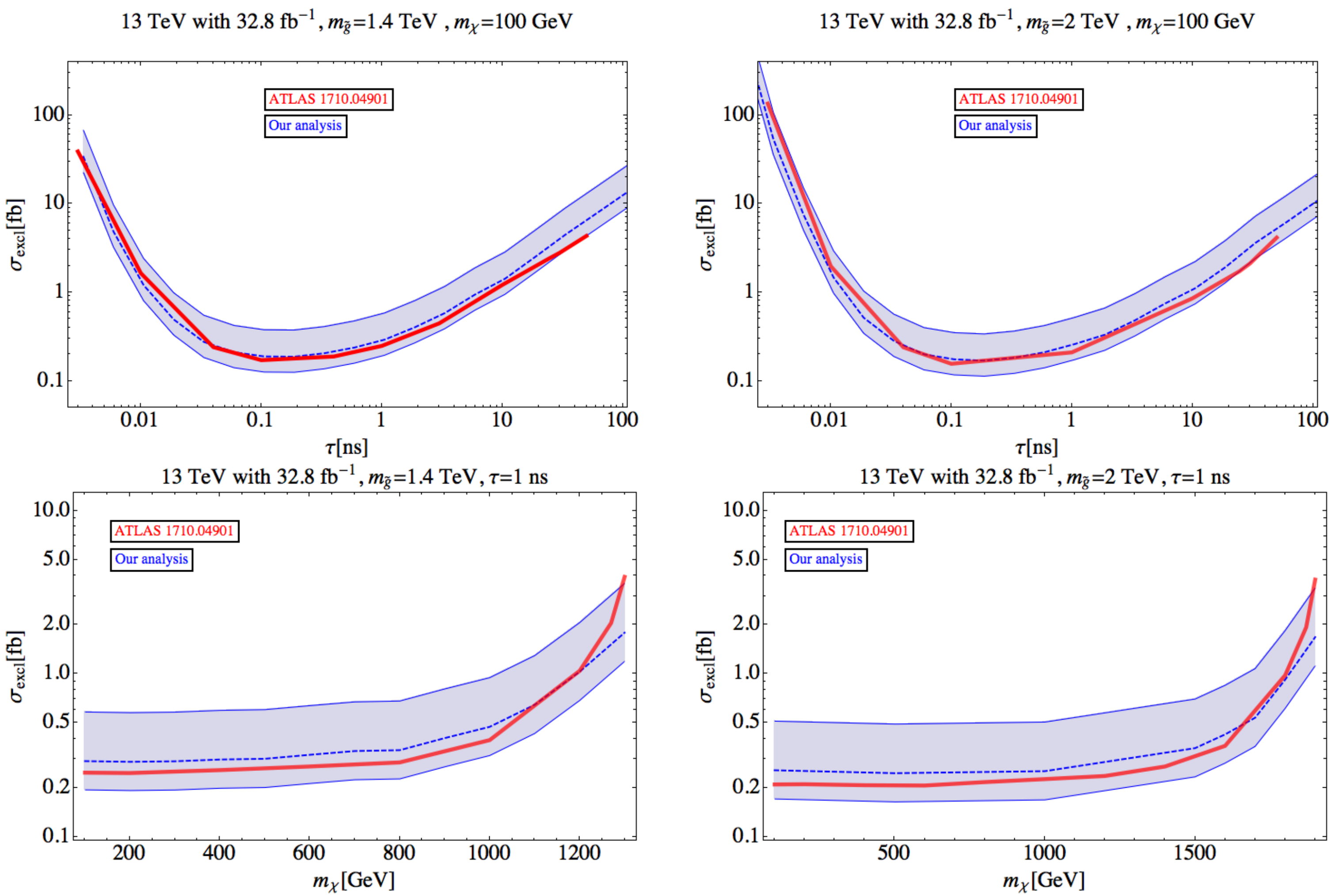
The ATLAS Collaboration

A search for long-lived, massive particles predicted by many theories beyond the Standard Model is presented. The search targets final states with large missing transverse momentum and at least one high-mass displaced vertex with five or more tracks, and uses 32.8 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collision data collected by the ATLAS detector at the LHC. The observed yield is consistent with the expected background. The results are used to extract 95% CL exclusion limits on the production of long-lived gluinos with masses up to 2.37 TeV and lifetimes of $\mathcal{O}(10^{-2})$–$\mathcal{O}(10)$ ns in a simplified model inspired by Split Supersymmetry.

arXiv:1710.04901

Recasting a DV+MET search by ATLAS

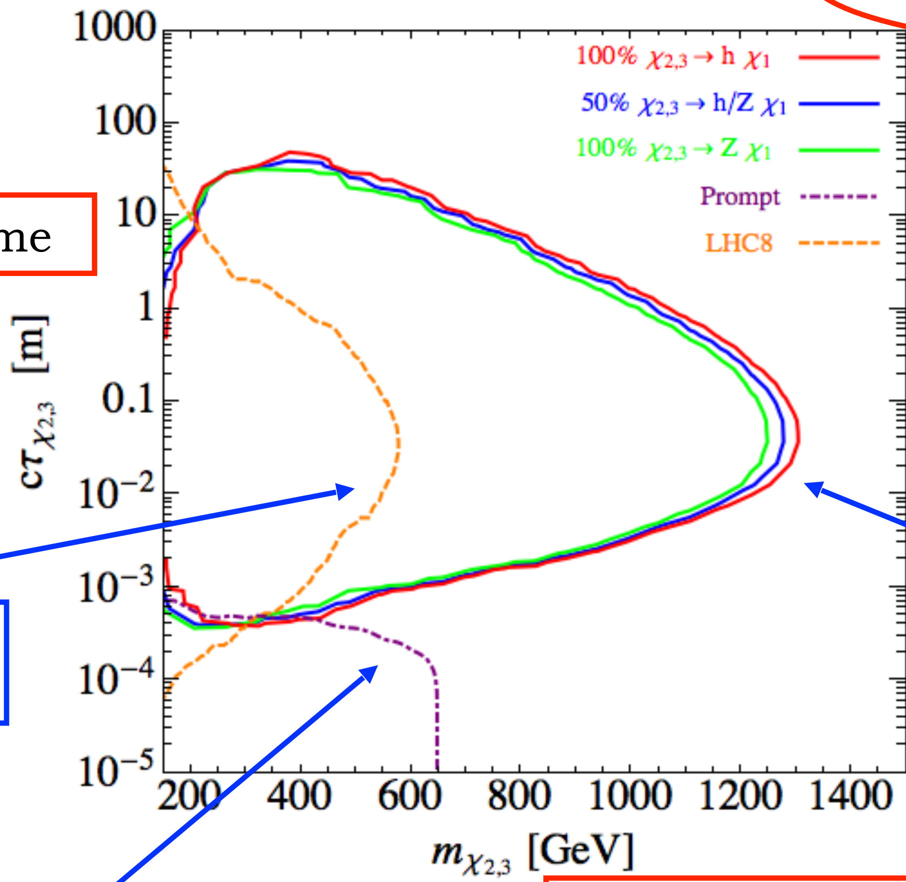
Our recasting
Madgraph/Pythia/Delphes



Recasting a DV+MET search by ATLAS

Doublet mass excluded up to 1.2 TeV!

Doublet life-time



8 TeV searches
Liu Tweedie, '15

Our recasting
Madgraph/Pythia/Delphes

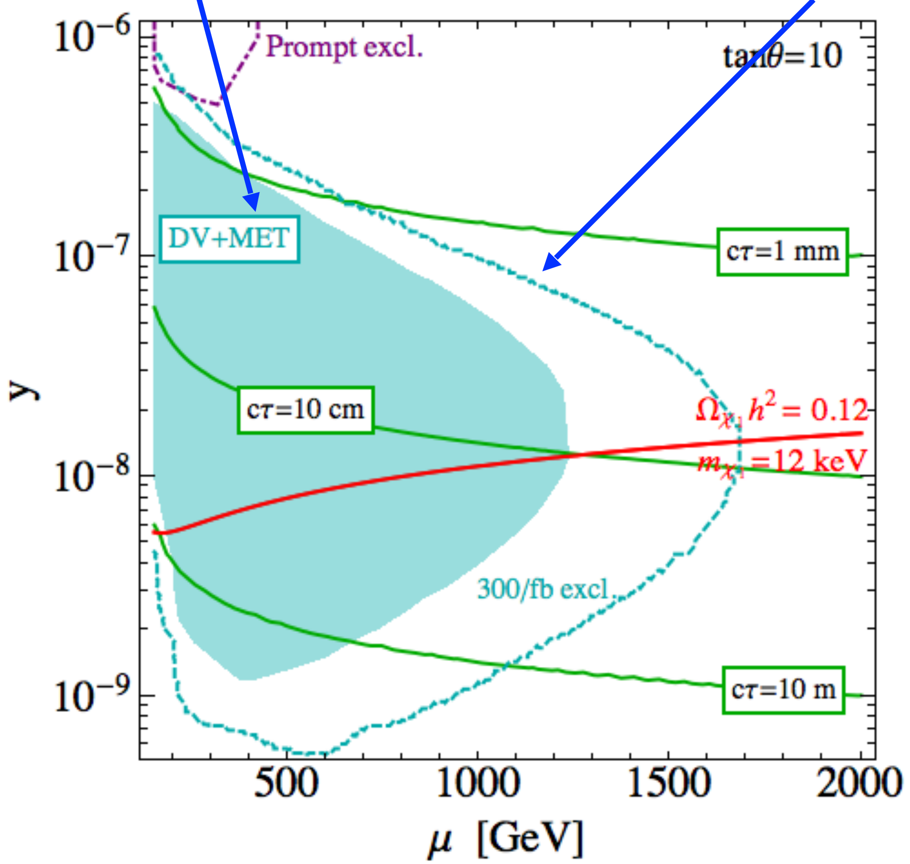
Prompt searches
CMS, 1801.03957

Doublet mass

Rather general result: it also applies e.g. to Higgsino decaying to gravitino

Impact on Singlet-Doublet Dark Matter

Our recascasting



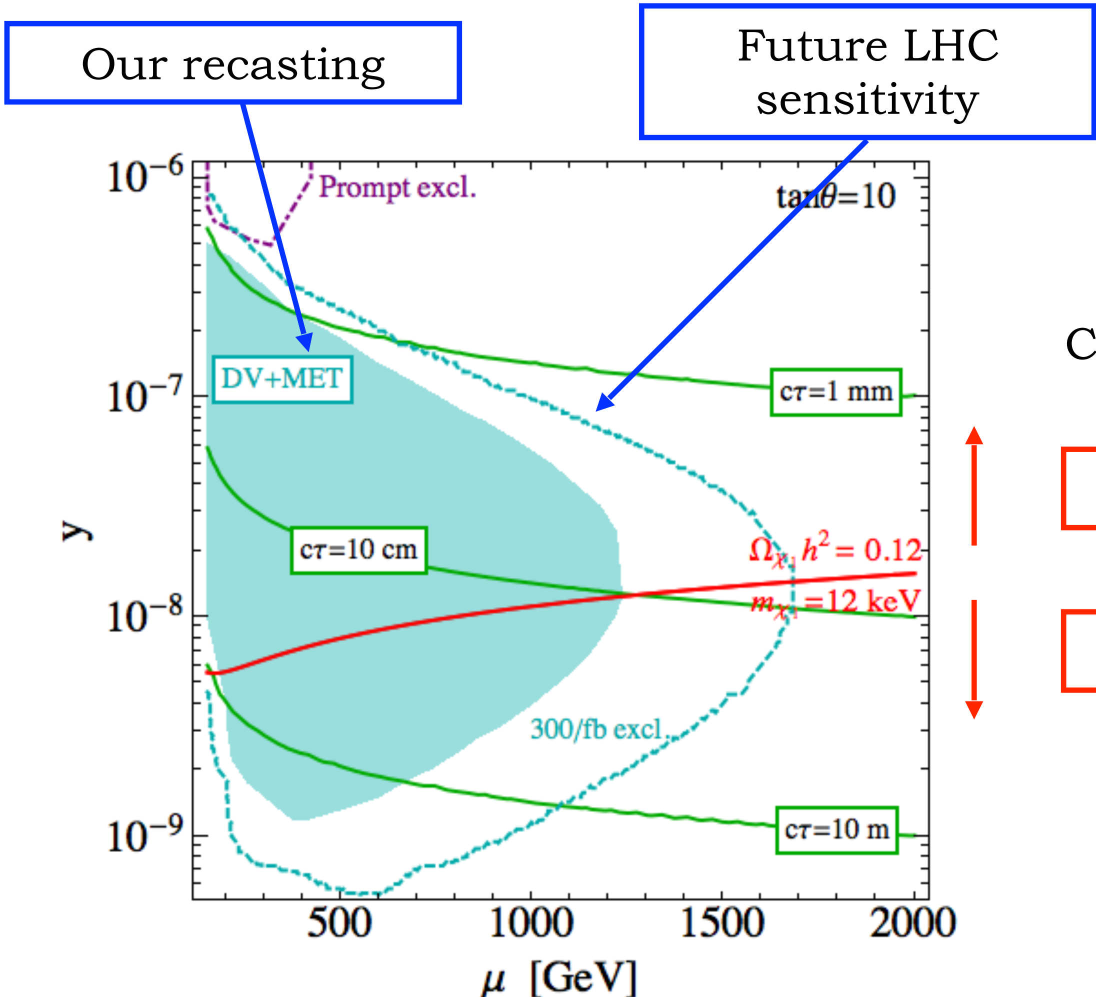
For a fixed DM mass:

DM overabundance

DM underabundance

$$\Omega_{\chi_1} h^2 \simeq 0.11 \left(\frac{105}{g_*}\right)^{3/2} \left(\frac{y}{10^{-8}}\right)^2 \left(\frac{m_{\chi_1}}{10\ \mathrm{keV}}\right) \left(\frac{700\ \mathrm{GeV}}{\mu}\right)$$

Impact on Singlet-Doublet Dark Matter



Correct relic density achieved by:

Lowering m_{DM}

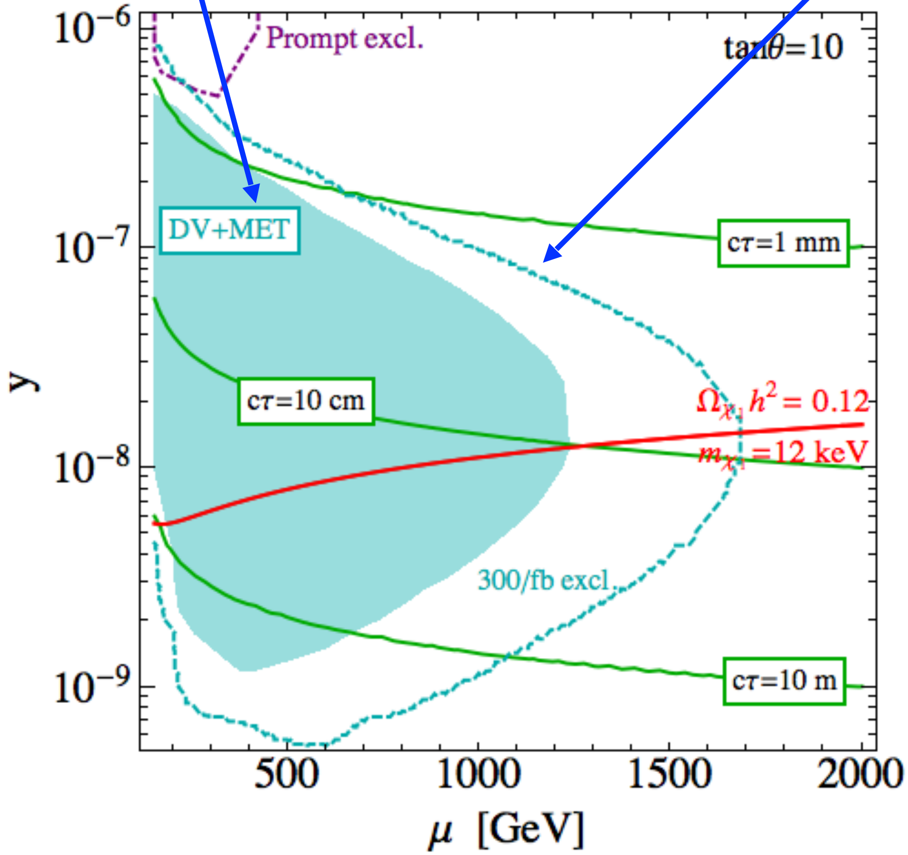
Raising m_{DM}

$$\Omega_{\chi_1} h^2 \simeq 0.11 \left(\frac{105}{g_*}\right)^{3/2} \left(\frac{y}{10^{-8}}\right)^2 \left(\frac{m_{\chi_1}}{10 \text{ keV}}\right) \left(\frac{700 \text{ GeV}}{\mu}\right)$$

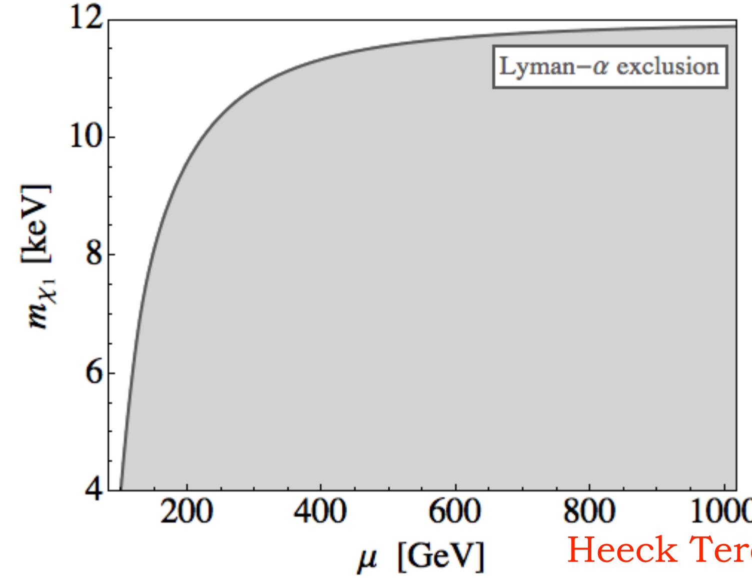
Impact on Singlet-Doublet Dark Matter

Our recasting

Future LHC sensitivity



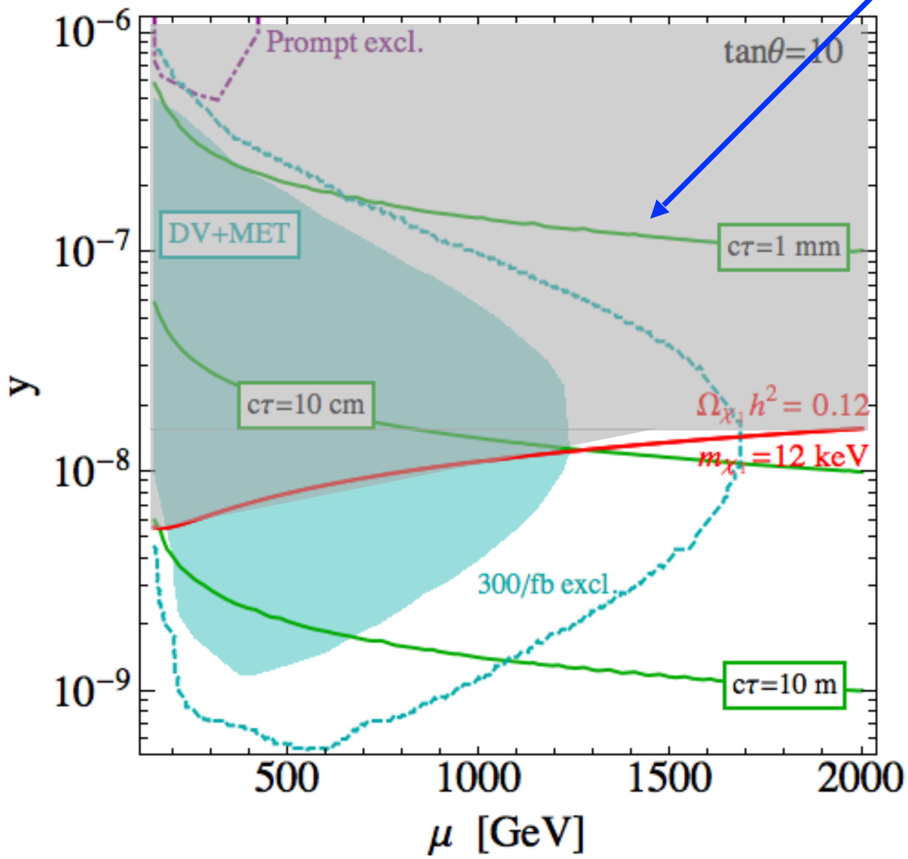
Bound from small structure formation (based on Lyman-alpha data):



Heeck Teresi '17

Impact on Singlet-Doublet Dark Matter

Combined Lyman-alpha and relic density bound (assuming standard cosmology)



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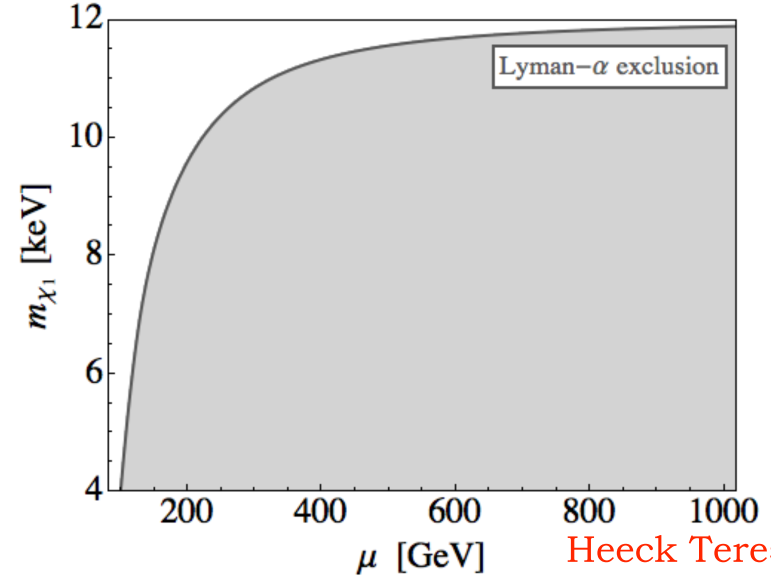

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Combined LHC and cosmology constraints

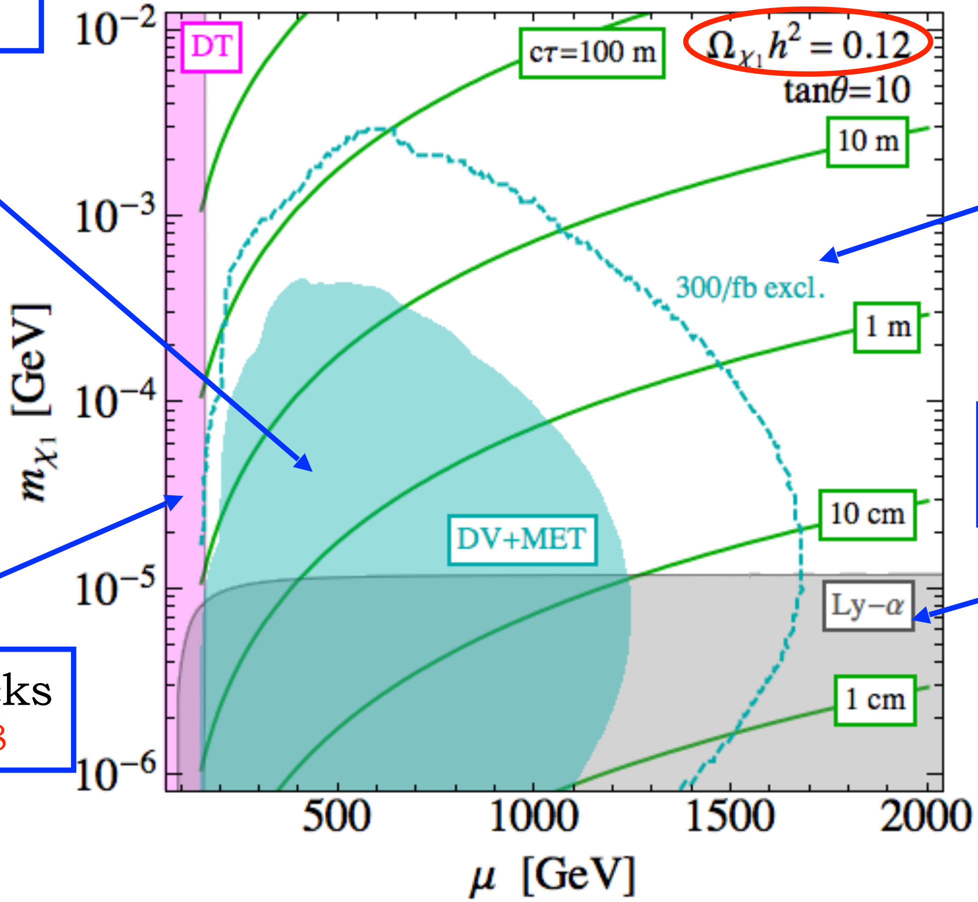
Our recasting

Future LHC sensitivity

DM mass

Lyman-alpha bound
Heeck Teresi '17

Disappearing tracks
ATLAS 1712.02118



Doublet mass

Summary

Freeze-in Dark Matter is naturally feebly coupled.
This implies long-lived mediators that LHC can test FI scenarios
via exotic (and virtually background-free) signatures

LHC searches for displaced vertices set non-trivial constrains
on the FI regime of our model. Nice interplay with cosmology/astrophysics!

Dedicated searches for heavy particles with displaced decays to Z and h
and missing energy would increase the LHC sensitivity

Long-lived particles are a general consequence of the freeze-in mechanism
Similar studies can be done to test other FI models with LHC data

Ευχαριστώ!