Fermion Portal Dark Matter

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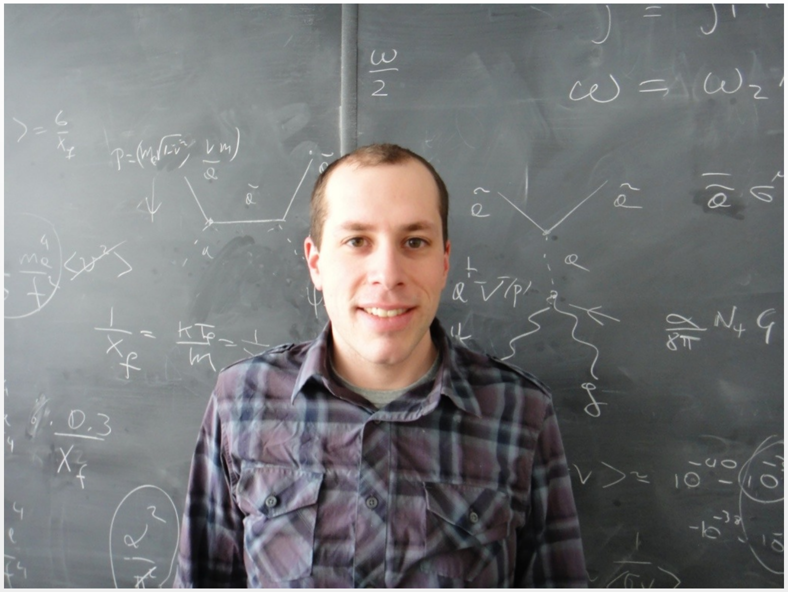
Mitchell Workshop on Collider and Dark Matter Physics

May 13, 2014



with **Joshua Berger** @ SLAC

"quark portal dark matter"

arxiv:1308.0612

"lepton portal dark matter"

arxiv:1402.6696

Chang, Edezhath, Hutchinson, Luty, 1307.8120

An, Wang, Zhang, 1308.0592

DiFranzo, Nagao, Rajaraman, Tait, 1308.2679

Batell, Lin, Wang, 1309.4462

Papucci, Vichi, Zurek, 1402.2285

Chang, Edezhath, Hutchinson, Luty, 1402.7358

Garny, Ibarra, Rydbeck, Vogl, 1403.4634

Gomez, Jackson, Shaughnessy, 1404.1918

Motivation I

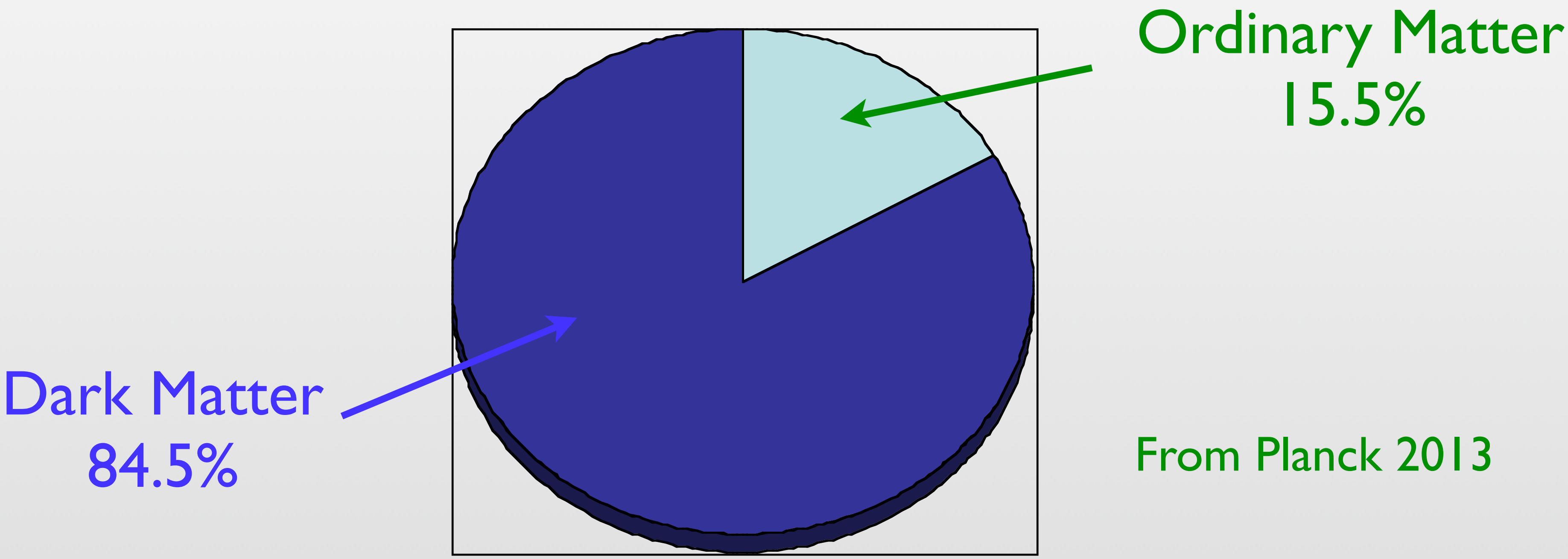
Standard Model

Dark Matter Sector

- ★ Graviton
- ★ Z boson
- ★ Higgs boson
- ★ Z', dilaton, radion ...

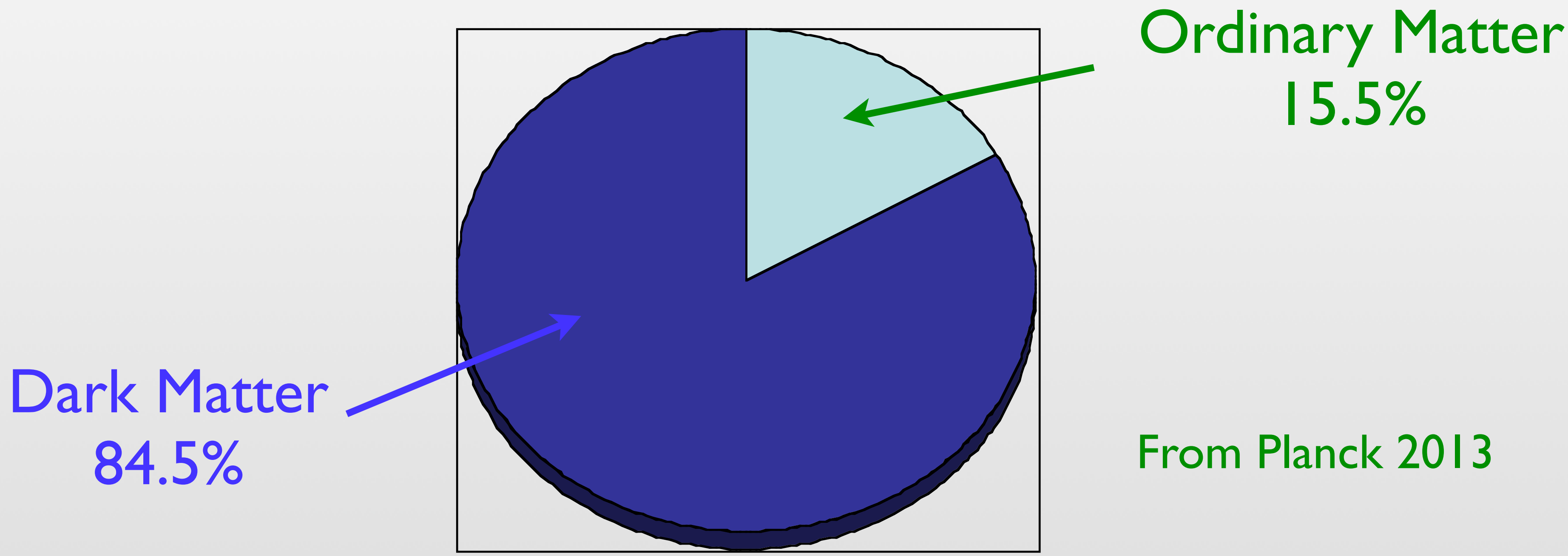
Motivation II

Dark Matter is important by itself and should deserve attention as much as SUSY.



Motivation II

Dark Matter is important by itself and should deserve attention as much as SUSY.



From Planck 2013

Dark Matter@LHC $\neq$ SUSY@LHC

Motivation III

Weakly-interaction massive particle provides an excellent motivation

But, we should not be limited by WIMP's

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Weakly-interaction massive particle provides an excellent motivation

But, we should not be limited by WIMP's

WIMPZILLAS

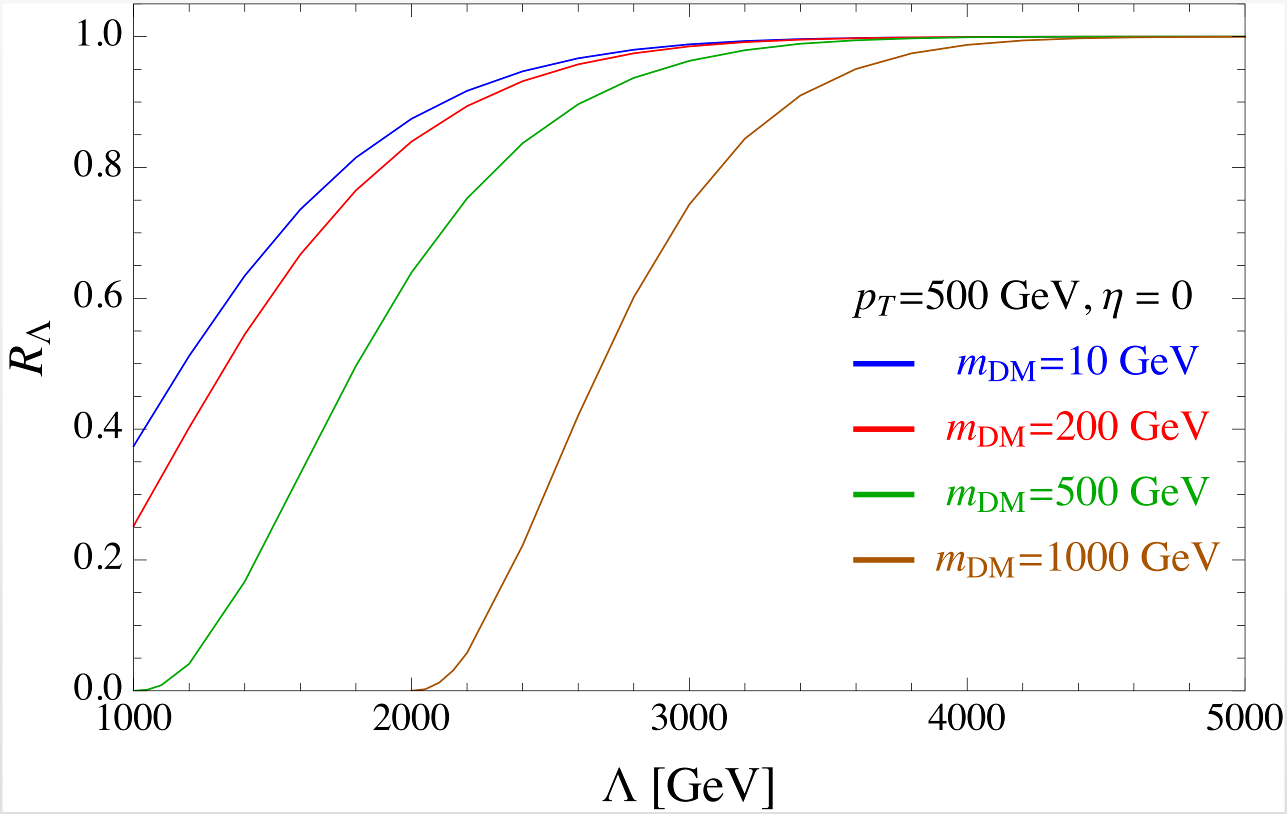
hep-ph/9810361
Kolb, Chung, Riotto

Figure 7. Dark matter may be much more massive than usually assumed, much more massive than wimpy WIMPS, perhaps in the WIMPZILLA class.

Motivation IV - Validation of EFT

$$\frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q)$$

a small R_Λ means a large uncertainty

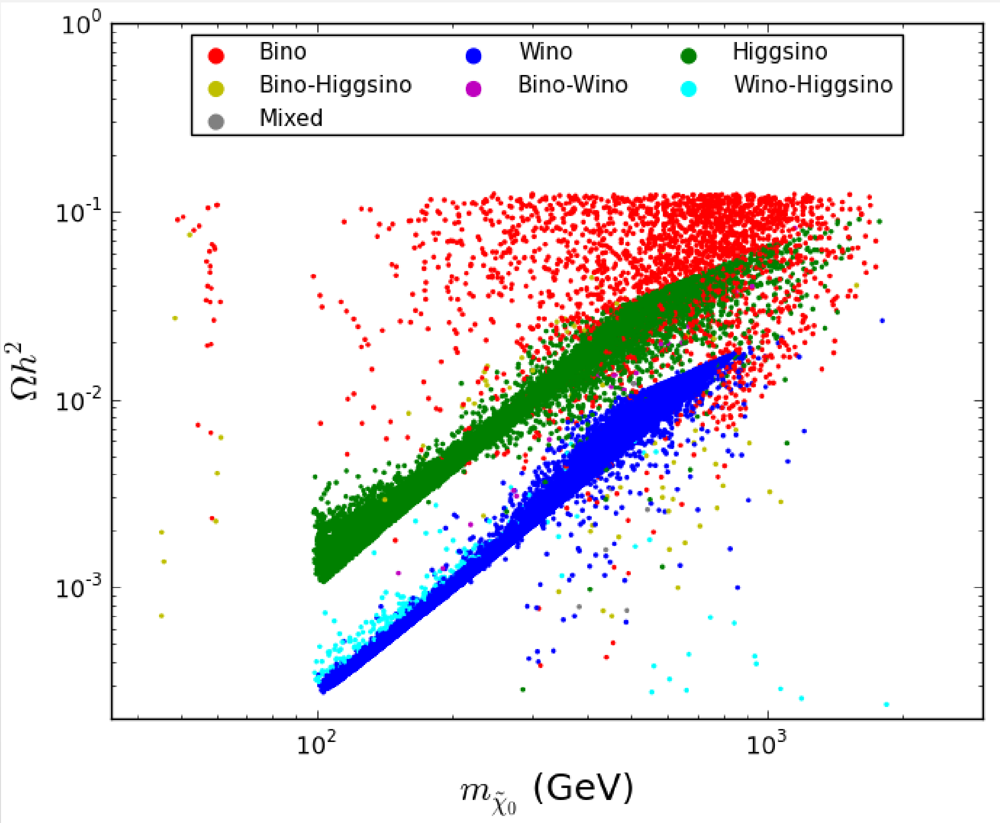


$$R_\Lambda \equiv \frac{\left.\frac{\mathrm{d}^2\sigma_{\rm eff}}{\mathrm{d}p_{\rm T}\mathrm{d}\eta}\right|_{Q_{\rm tr}<\Lambda}}{\frac{\mathrm{d}^2\sigma_{\rm eff}}{\mathrm{d}p_{\rm T}\mathrm{d}\eta}}$$

Busoni et. al. 1307.2253

Motivation V

The SUSY searches are still relevant for many DM models



1305.6921, Cahill-Rowley, Cotta, Drlica-Wagner, Funk, Hewett, Ismail, Rizzo, Wood

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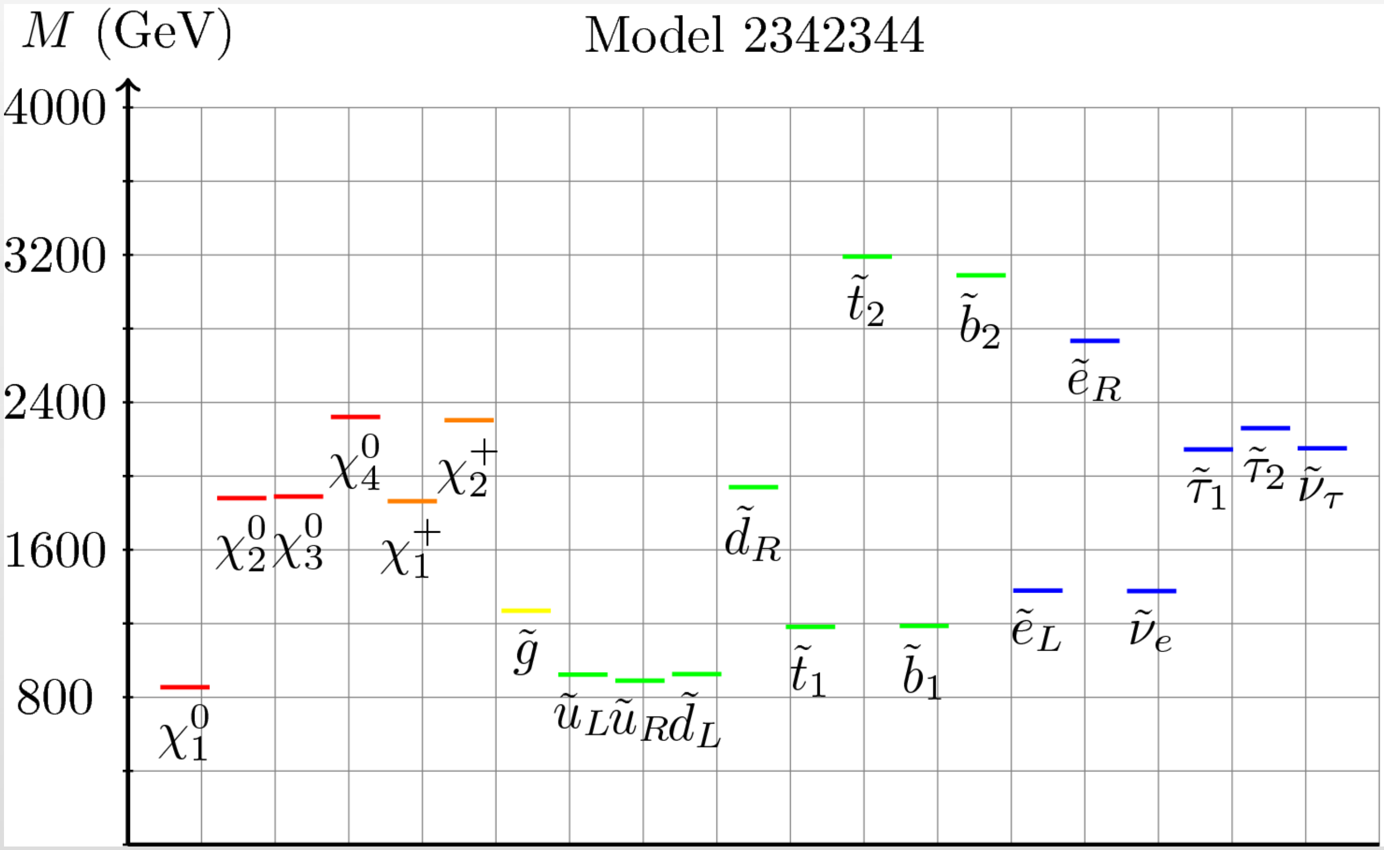
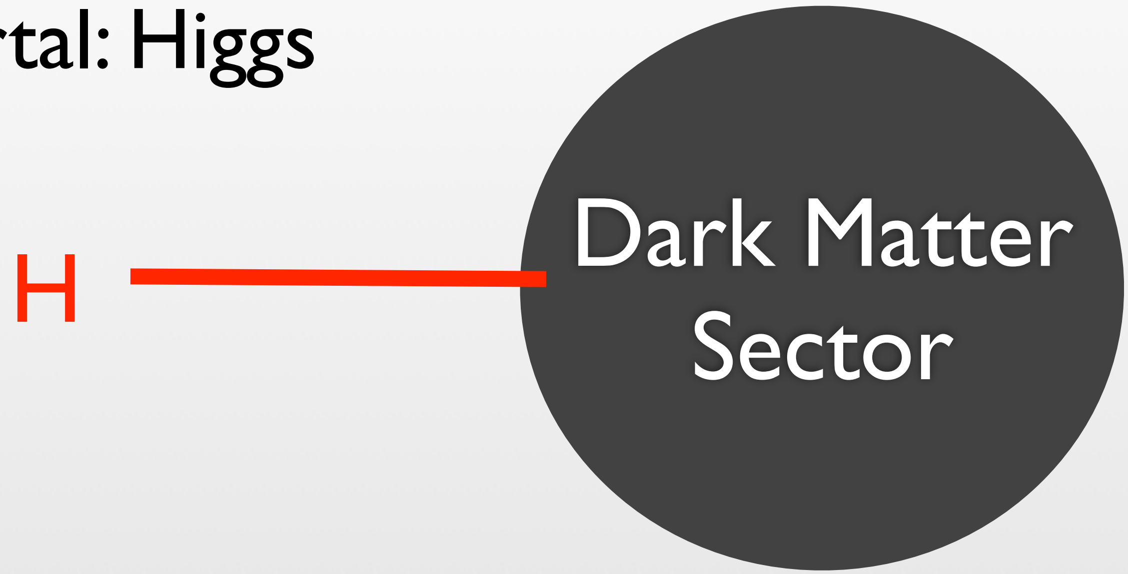


Figure 3: Bino-squark coannihilation benchmark sparticle spectrum.

Simplified Dark Matter Models

★ Boson portal: Higgs portal

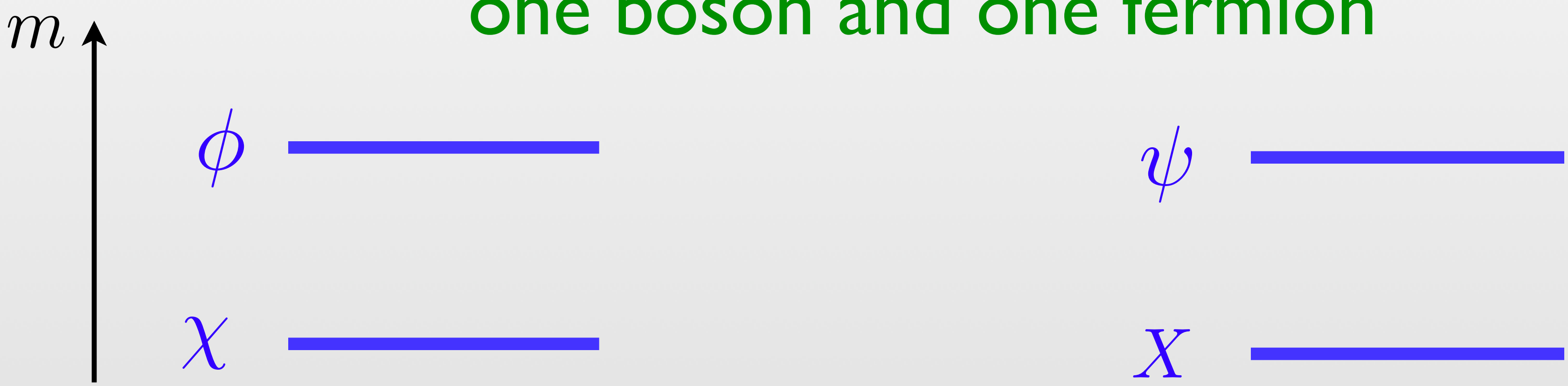


★ Fermion portal

Fermion Portal Dark Matter

Conserving the Lorentz symmetry, at least two particles in the dark matter sector are required

one boson and one fermion



a Majorana or Dirac Fermion or a scalar dark matter

Fermion Portal Dark Matter

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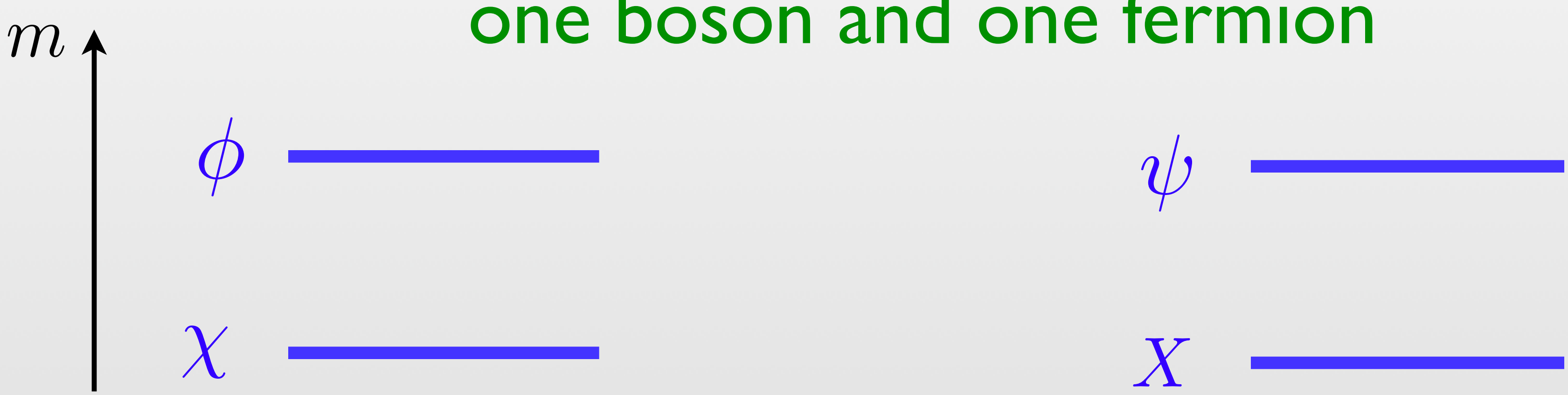
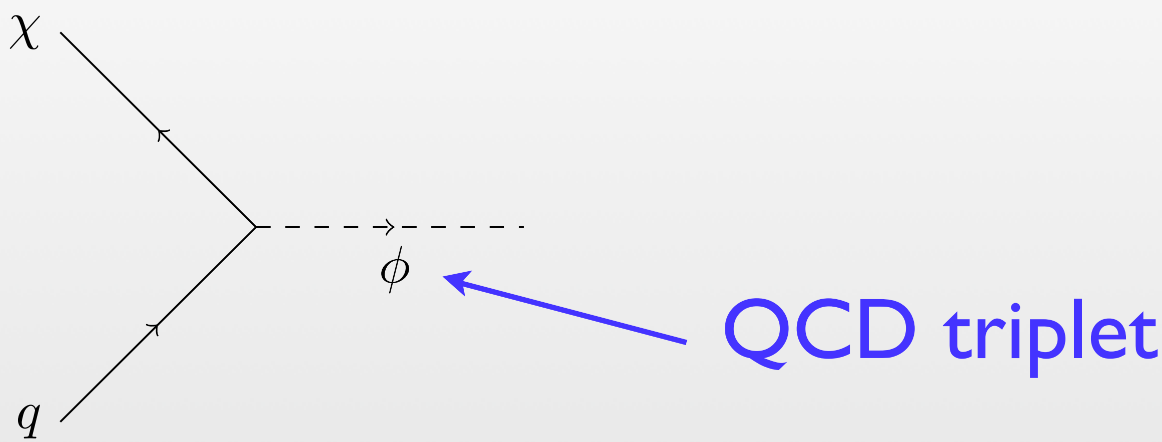


a Majorana or Dirac Fermion or a scalar dark matter

Fermion Portal DM at the LHC has "signatures" beyond the simplified SUSY DM

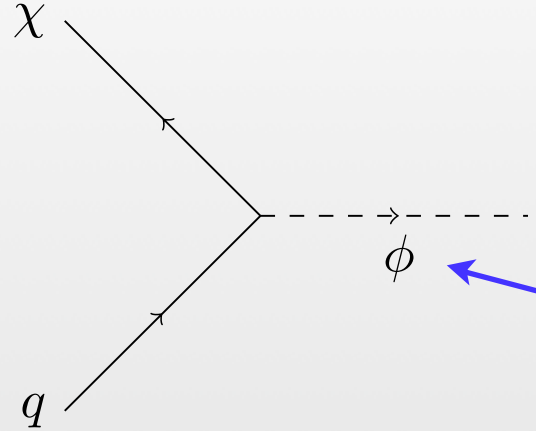
Quark Portal Dark Matter

$$\mathcal{L}_{\rm fermion} \supset \lambda_{u_i}\phi_{u_i}\overline{\chi}_L u_R^i + \lambda_{d_i}\phi_{d_i}\overline{\chi}_L d_R^i + \text{h.c.}$$



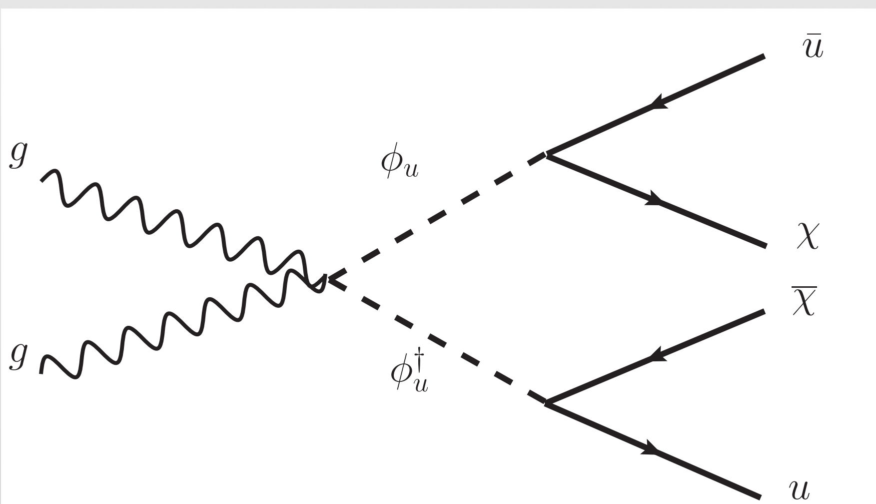
Quark Portal Dark Matter

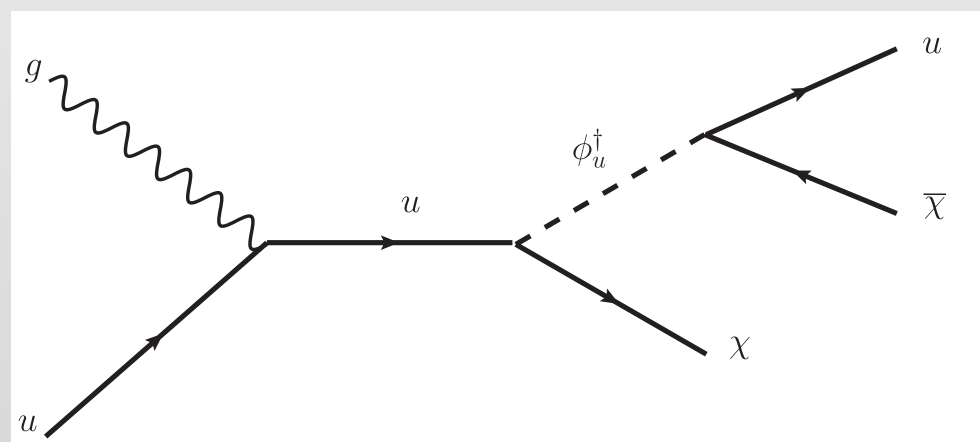
$$\mathcal{L}_{\text{fermion}} \supset \lambda_{u_i}\phi_{u_i}\overline{\chi}_L u^i_R + \lambda_{d_i}\phi_{d_i}\overline{\chi}_L d^i_R + \text{h.c.}$$



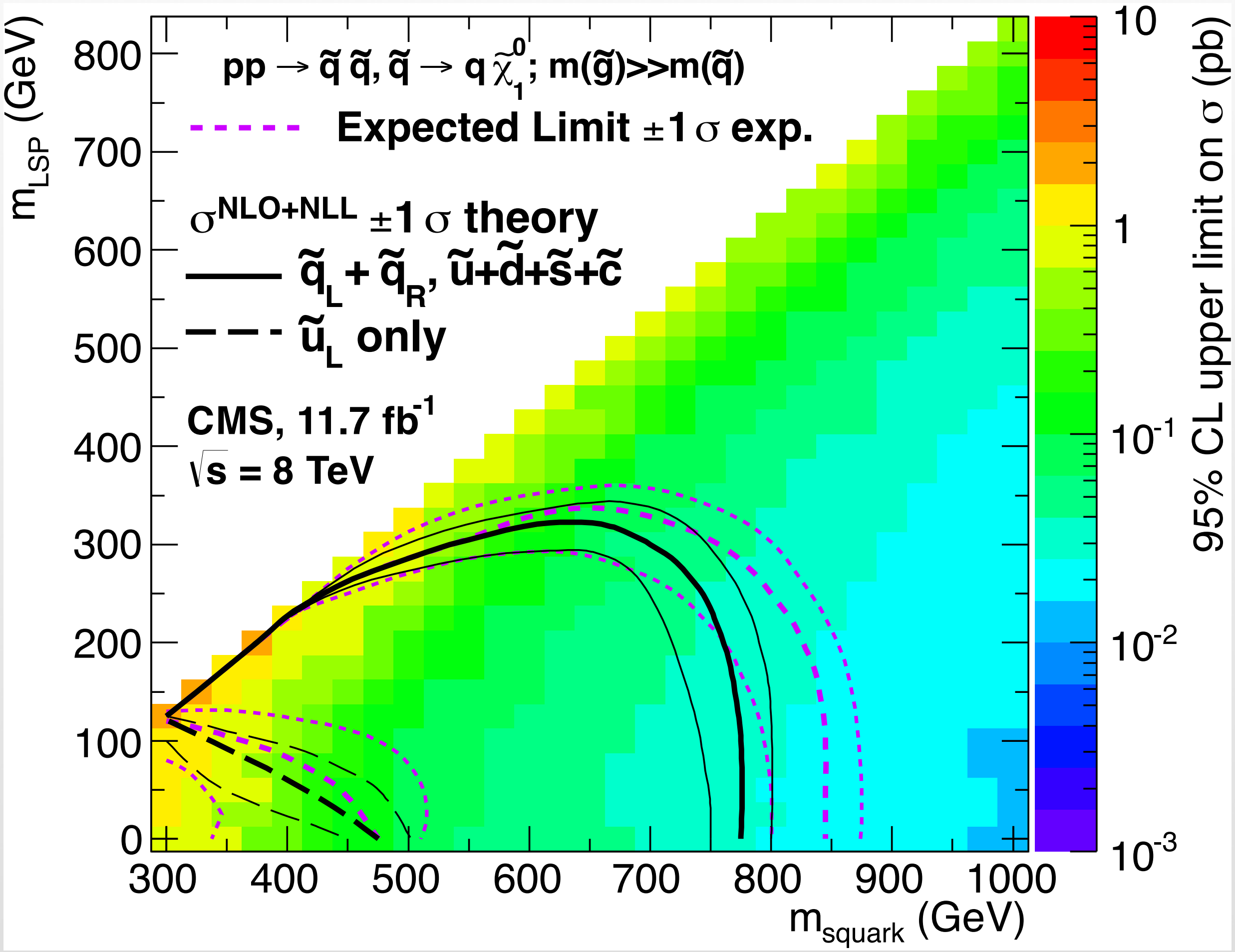
QCD triplet

at the LHC



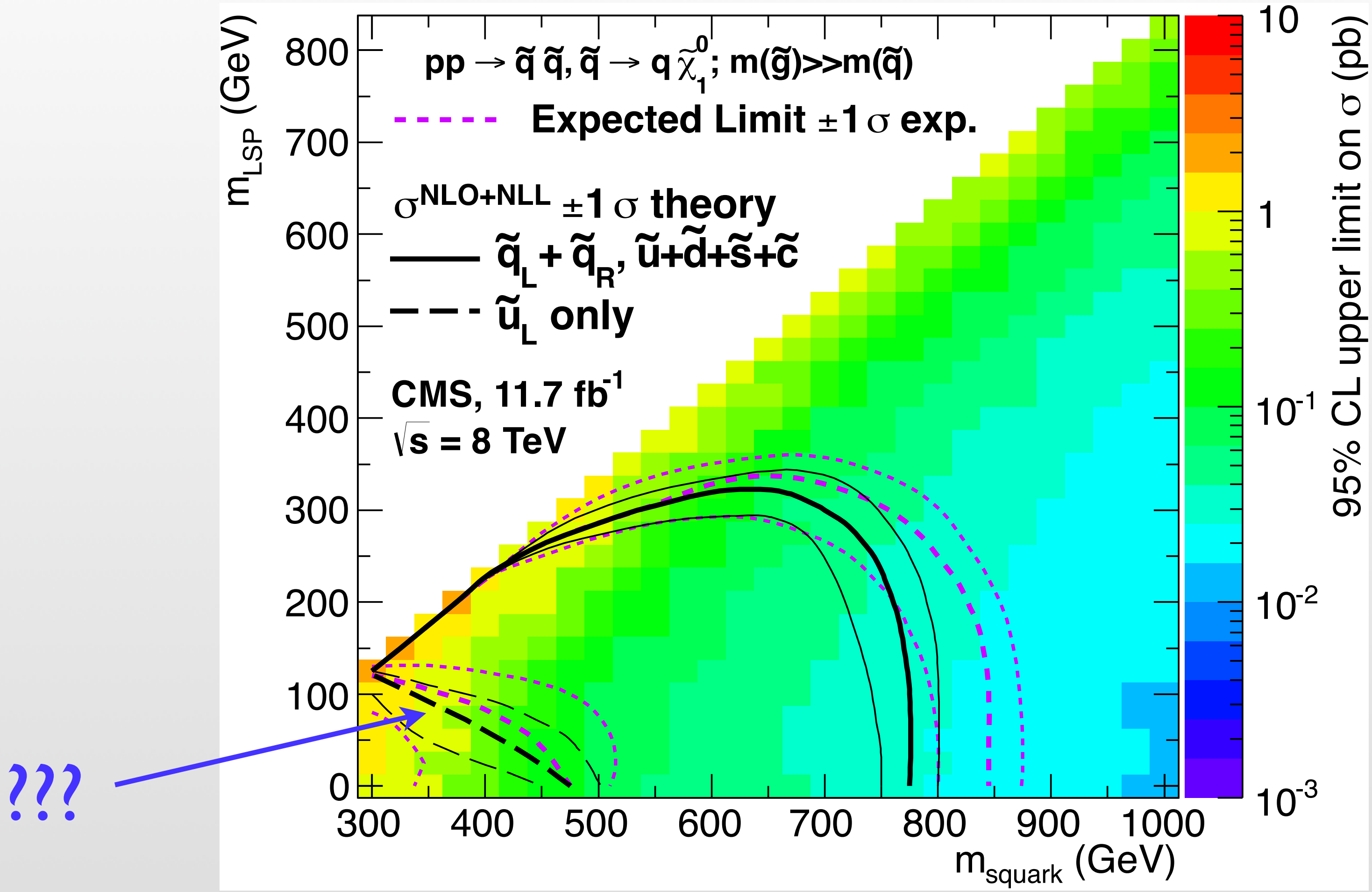


Quark Portal Dark Matter



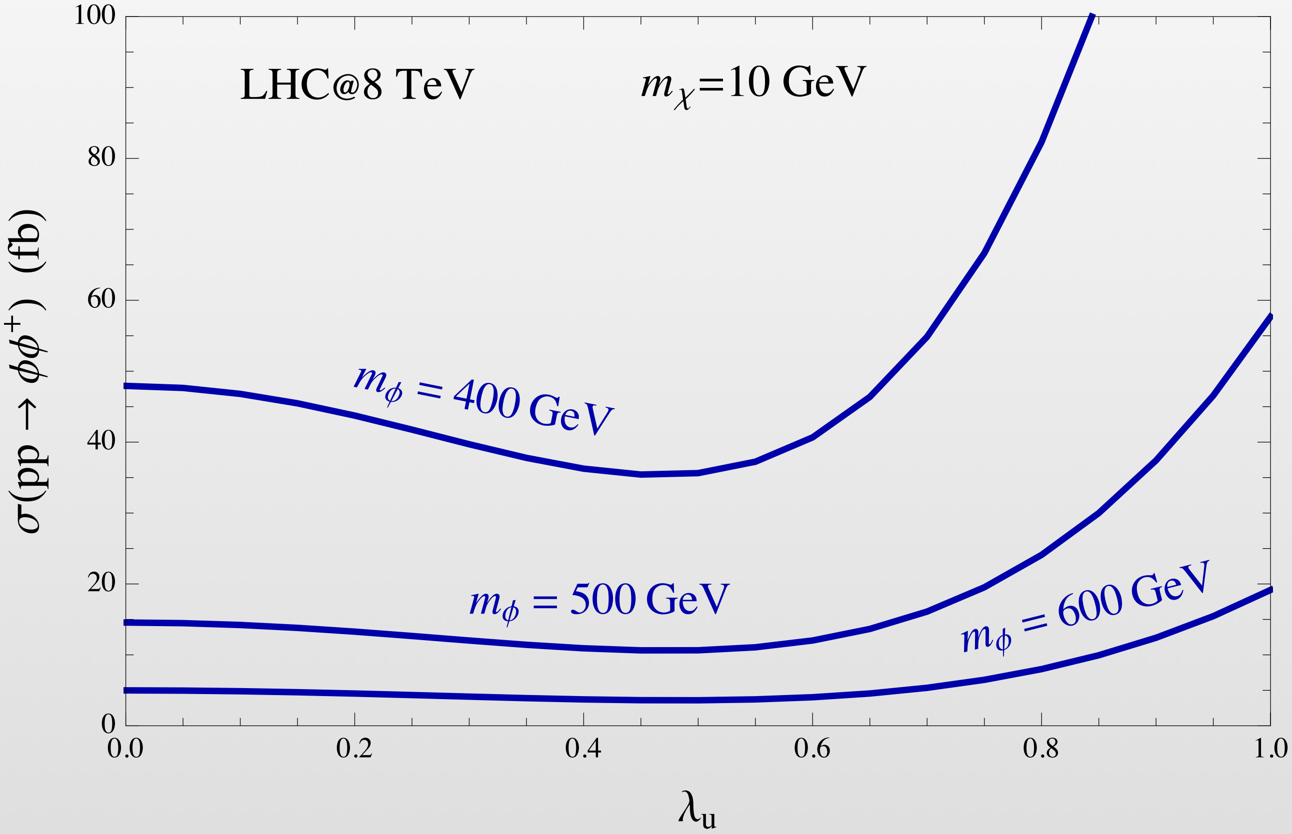
two jets + MET

Quark Portal Dark Matter



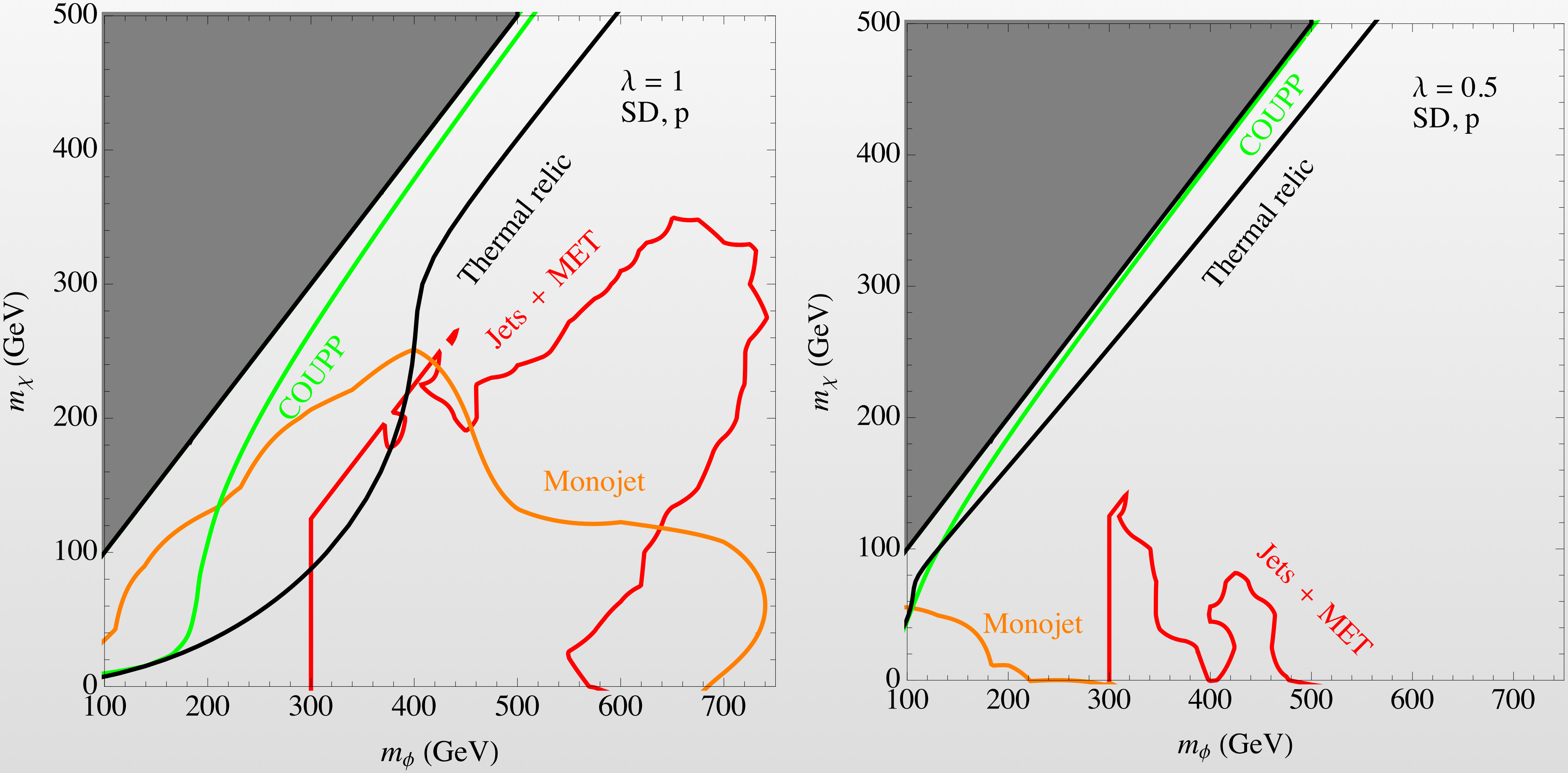
two jets + MET

QCD and Yukawa Interference



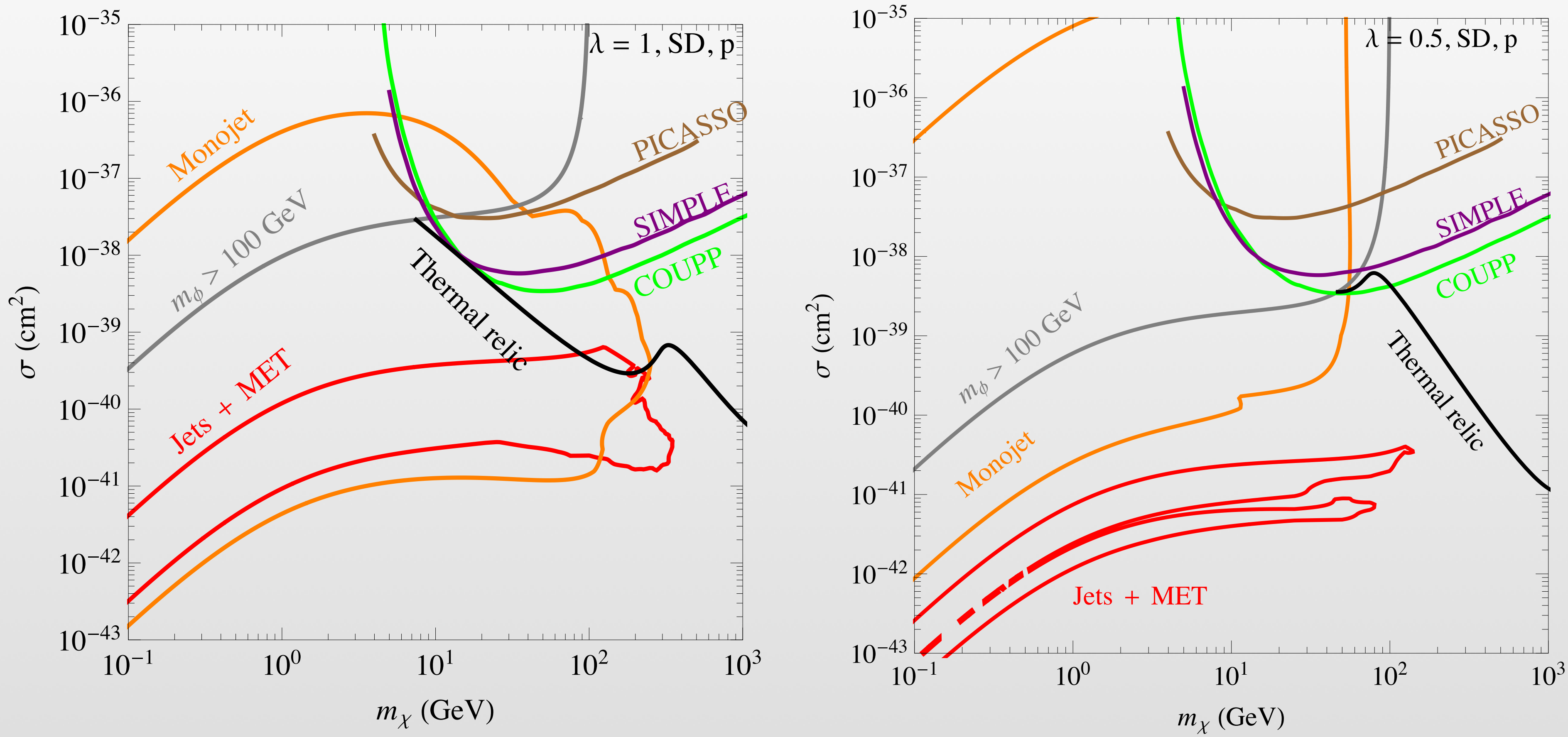
interesting deconstructive interference region

Current Allowed Parameter Space



Majorana fermion dark matter up-quark

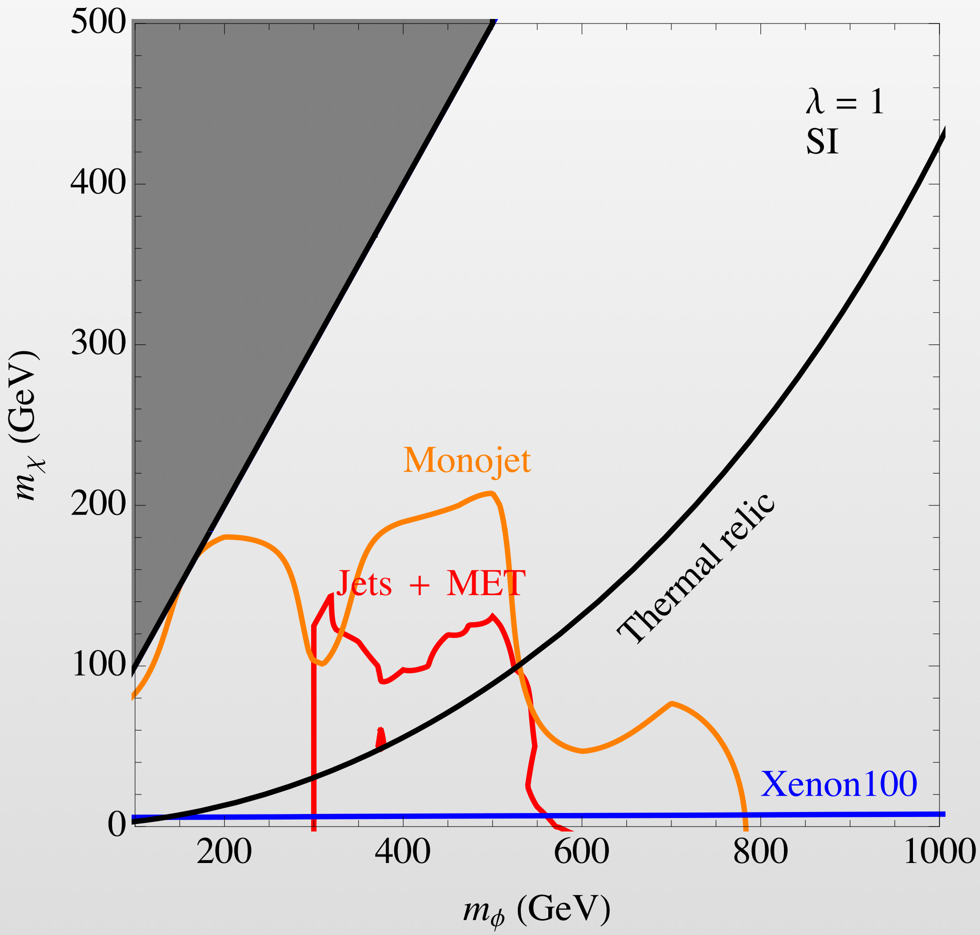
Compare to Direct Detection

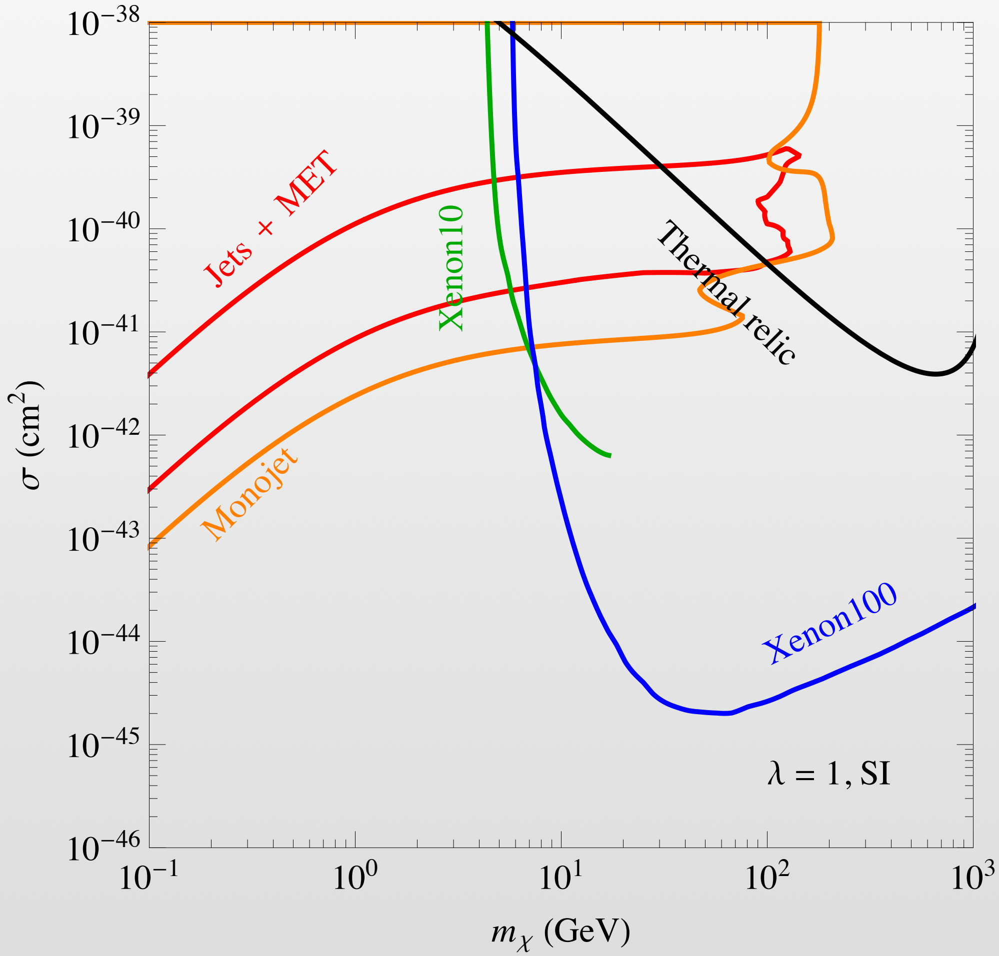


Majorana fermion dark matter

up-quark

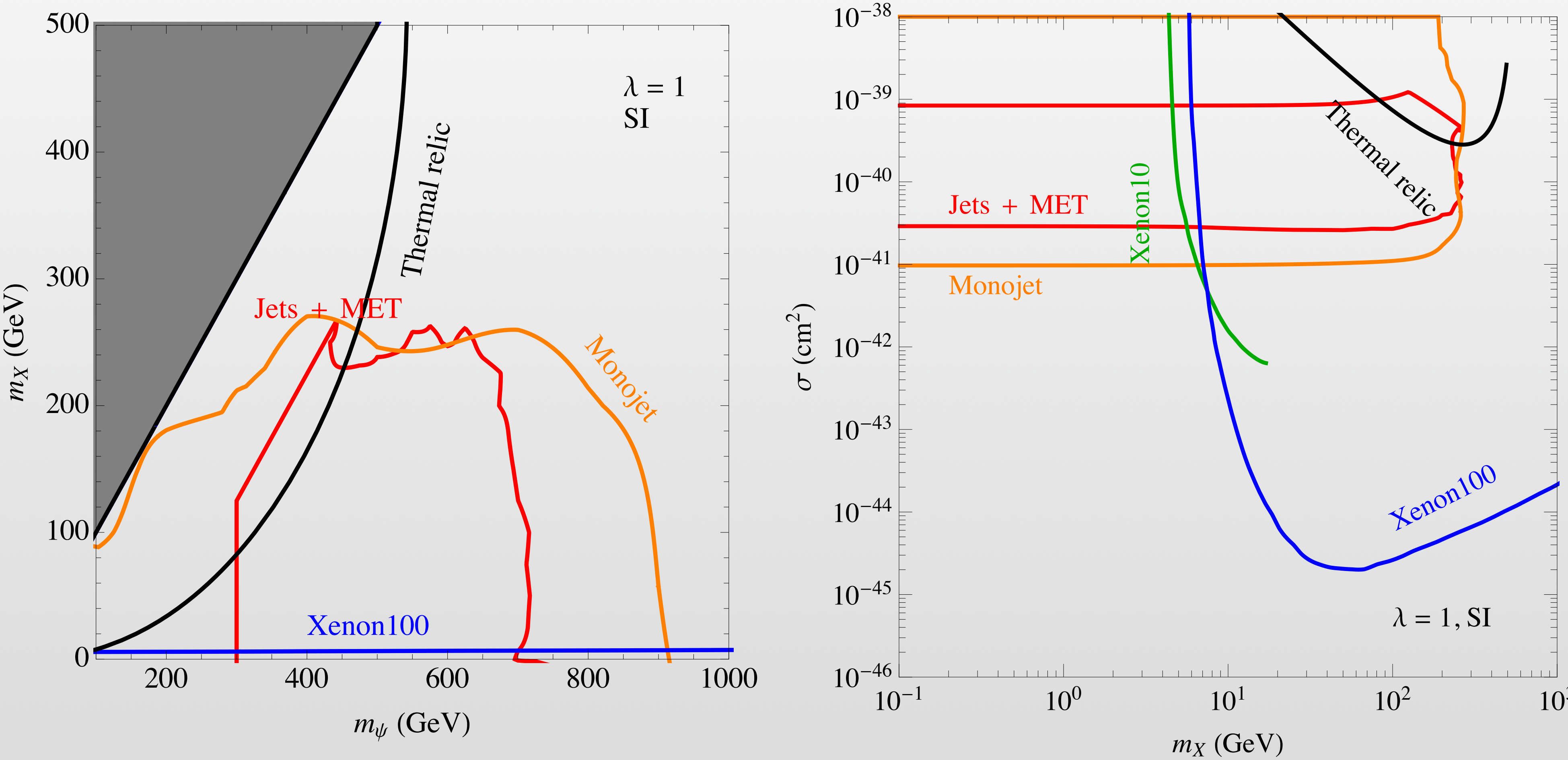
Dirac Fermion Dark Matter





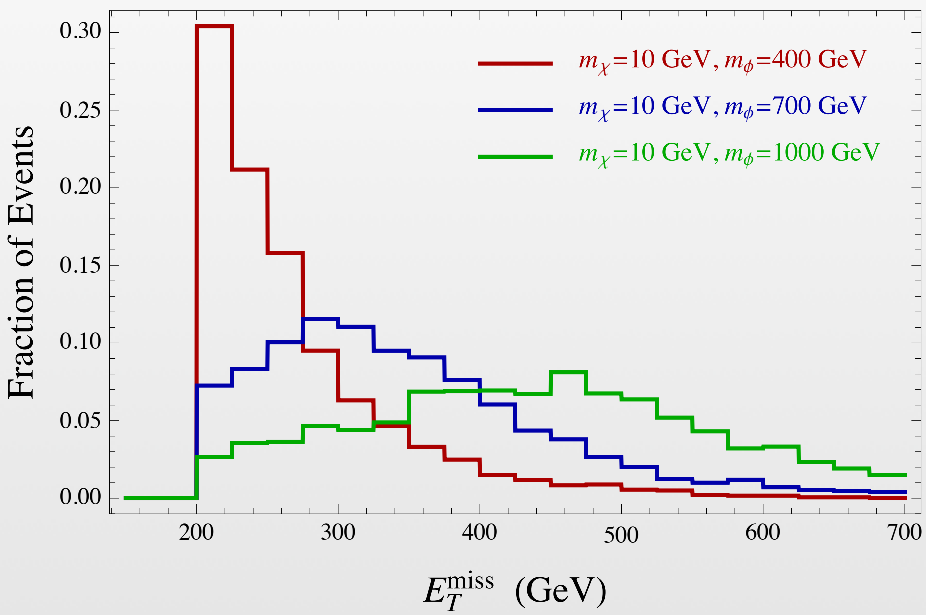
up-quark

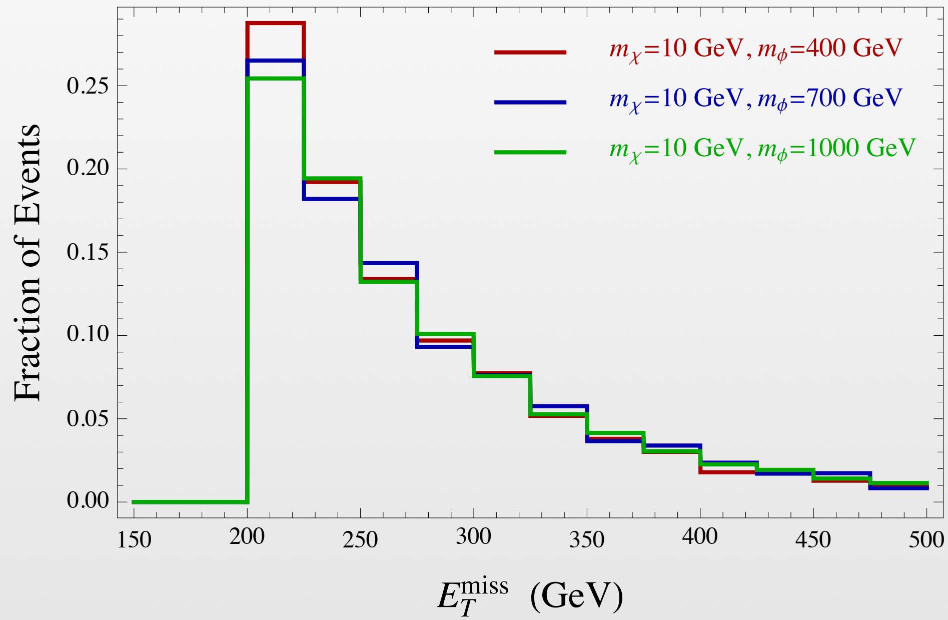
Complex Scalar Dark Matter

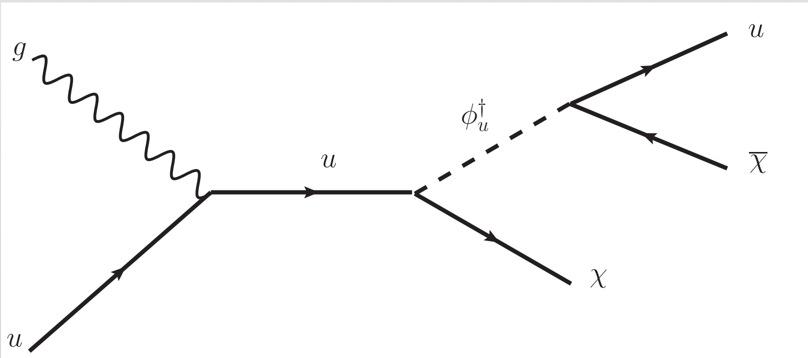


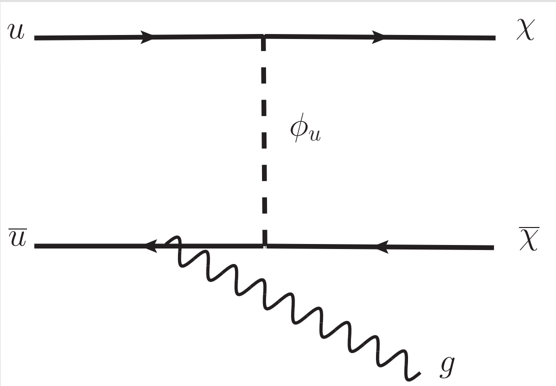
up-quark

MET Distribution in mono-jet



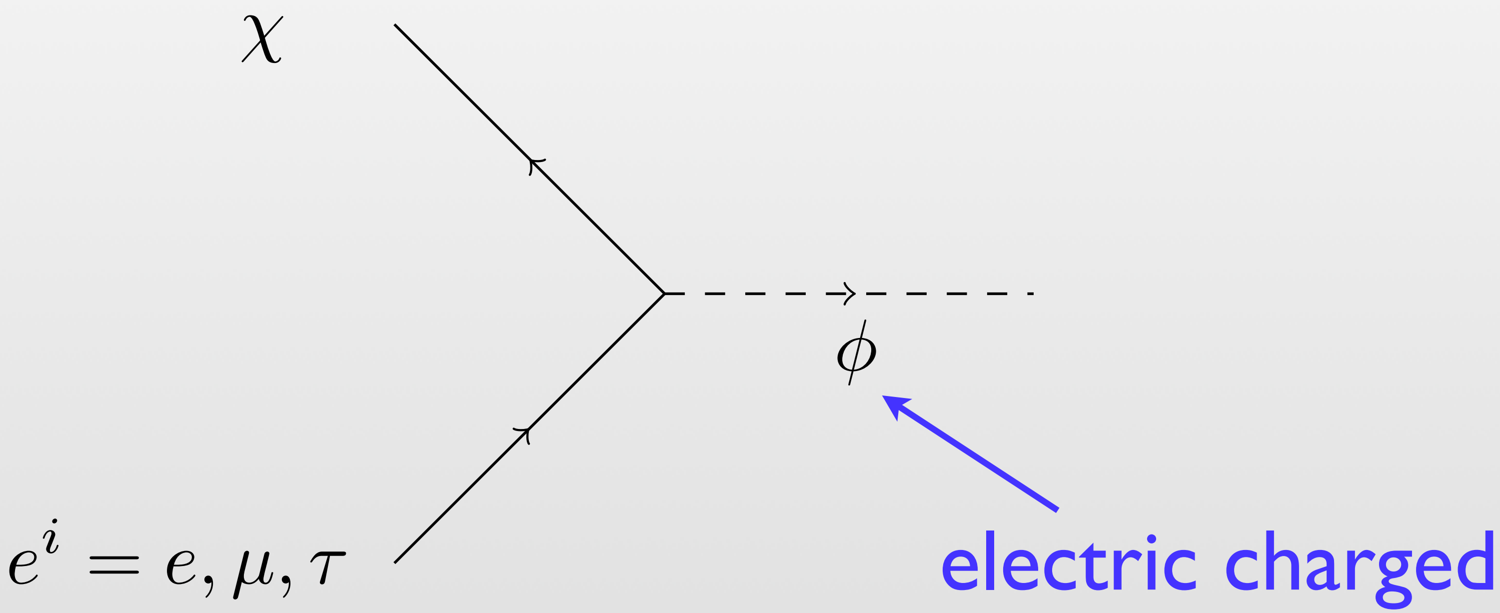






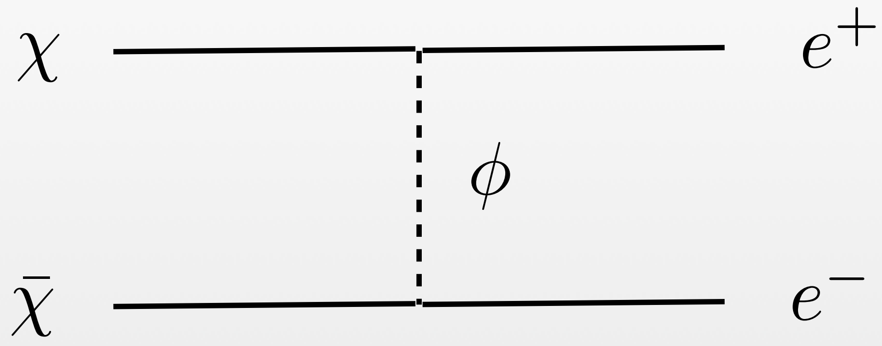
Lepton Portal Dark Matter

$$\mathcal{L}_{\rm fermion} \supset \lambda_i \phi_i \overline{\chi}_L e^i_R + {\rm h.c.}\,,$$



★ we will consider flavors one by one for Dirac fermion, Majorana fermion and complex scalar dark matter

Thermal Relic Abundance



$$\frac{1}{2}(\sigma v)^{\chi\bar{\chi}}_{\rm Dirac} = \frac{1}{2}\left[\frac{\lambda^4 m_\chi^2}{32\,\pi\,(m_\chi^2+m_\phi^2)^2} + v^2\,\frac{\lambda^4\,m_\chi^2\,(-\,5m_\chi^4\ -\ 18m_\chi^2 m_\phi^2 + 11m_\phi^4)}{768\,\pi\,(m_\chi^2+m_\phi^2)^4}\right] \equiv s + p\,v^2\,,$$

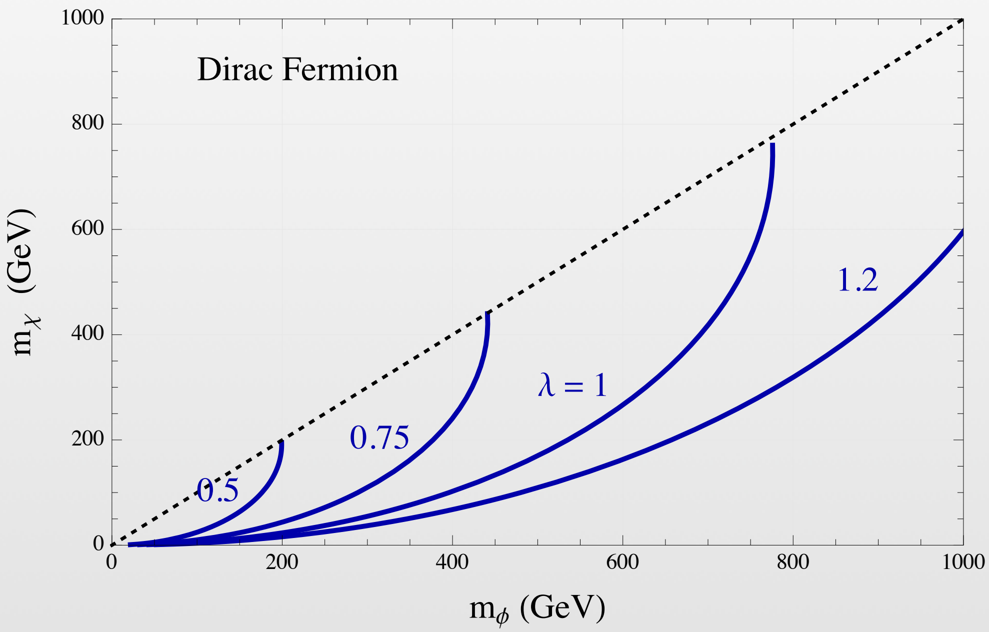
$\langle v^2\rangle \sim \mathcal{O}(0.1)$ at freeze-out $\langle v^2\rangle \sim \mathcal{O}(10^{-6})$ at current time

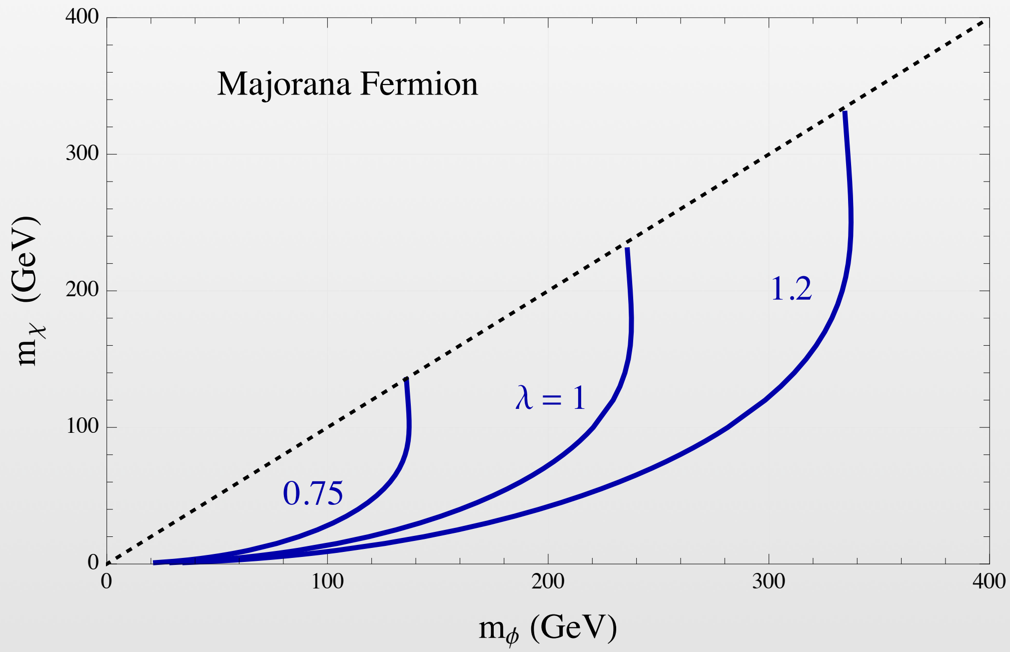
$$(\sigma v)^{\chi\chi}_{\rm Majorana} = v^2\,\frac{\lambda^4\,m_\chi^2\,(m_\chi^4+m_\phi^4)}{48\pi\,(m_\chi^2+m_\phi^2)^4} \equiv p\,v^2$$

$$\frac{1}{2}(\sigma v)^{XX^\dagger}_{\rm complex\,scalar} = \frac{1}{2}\left[v^2\,\frac{\lambda^4\,m_X^2}{48\,\pi\,(m_X^2+m_\psi^2)^2}\right] \equiv p\,v^2$$

p-wave suppressed; require lighter masses

Thermal Relic Abundance

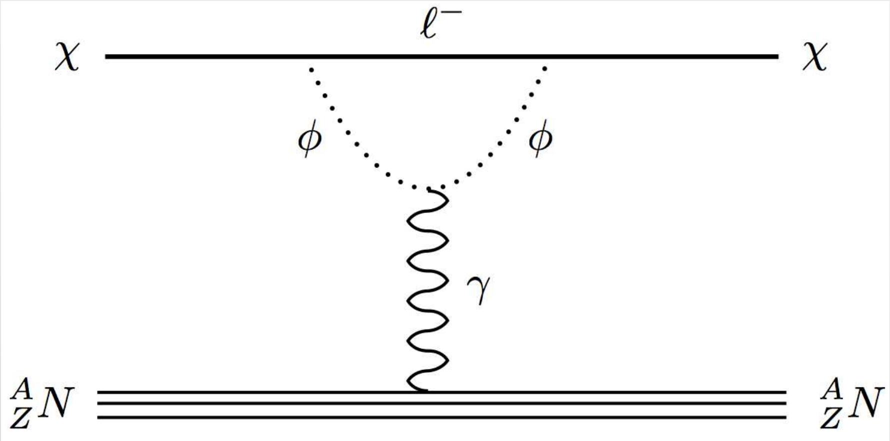




★ the degenerate region (the diagonal line) requires more a careful co-annihilation calculation, which has been ignored here

Dark Matter Direct Detection

- ★ scattering off electrons at the target is suppressed by the electron wave function
- ★ scattering off nucleons requires one-loop process



$$\mathcal{O}_1^{\rm Dirac} = \left[\overline{\chi}\gamma^\mu(1-\gamma^5)\partial^\nu\chi + {\rm h.c.}\right] F_{\mu\nu}$$

$$\mathcal{O}_2^{\rm Dirac} = \left[i\,\overline{\chi}\gamma^\mu(1-\gamma^5)\partial^\nu\chi + {\rm h.c.}\right] F^{\alpha\beta}\epsilon_{\mu\nu\alpha\beta}$$

charge+magnetic dipole

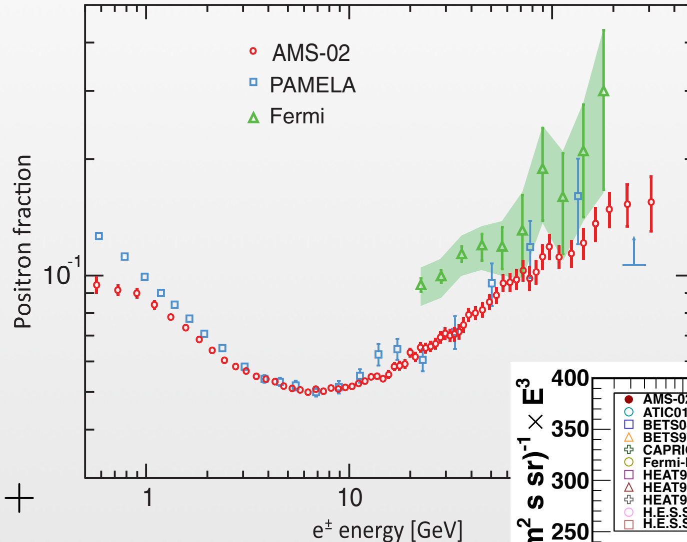
$$\mathcal{O}_1^{\rm Majorana} = \left[-\overline{\chi}\gamma^\mu\gamma^5\partial^\nu\chi + {\rm h.c.}\right] F_{\mu\nu}$$

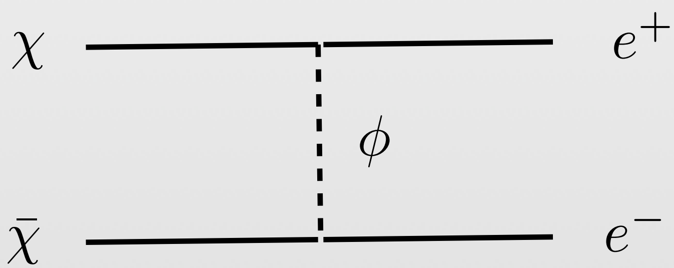
anapole moment

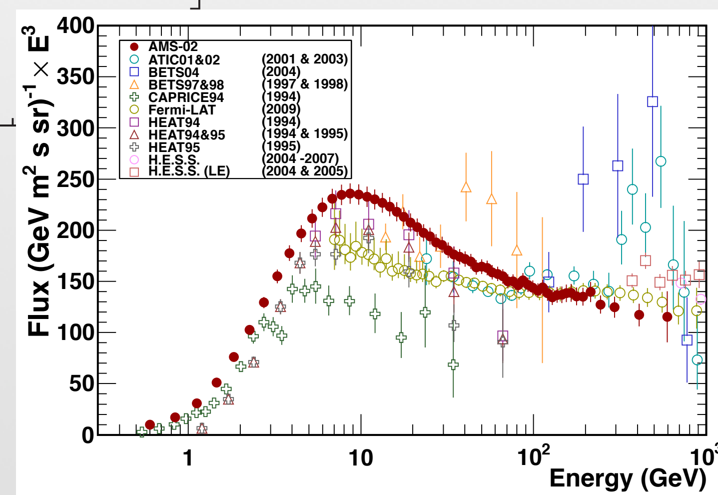
$$\mathcal{O}_1^{\rm Complex} = \partial^\mu X \partial^\nu X^\dagger F_{\mu\nu}$$

charge radius

Dark Matter Indirect Detection

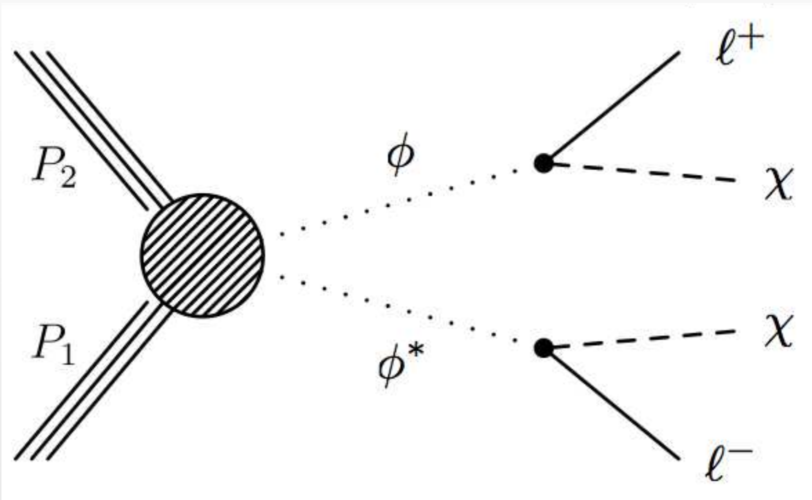


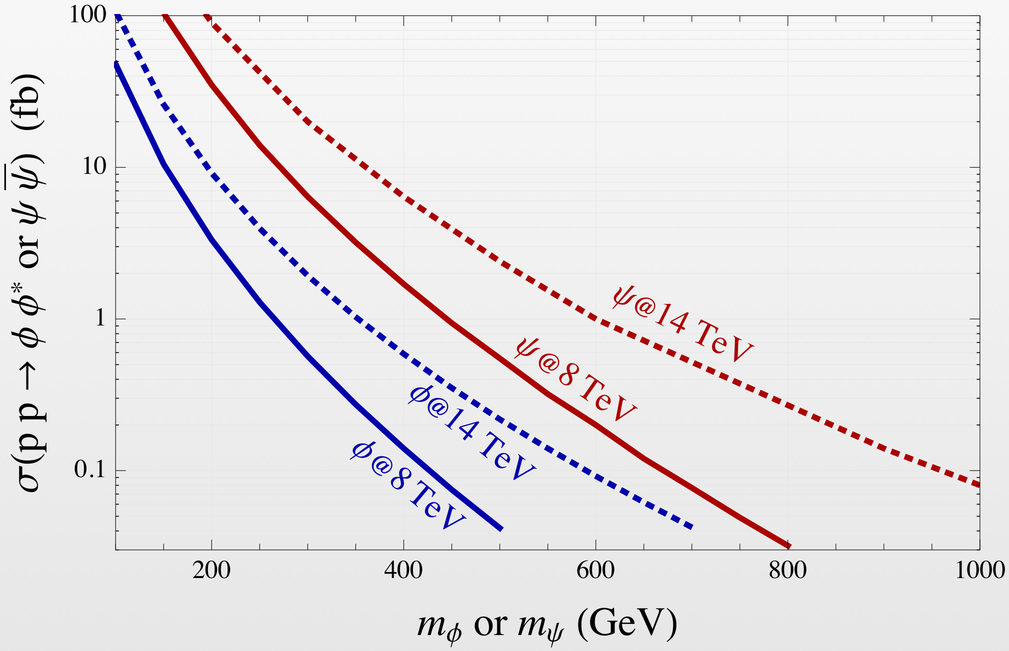




★ a model is excluded if the predicted total positron flux is 2 sigma in excess of the measured by AMS-02 in any energy bin

Production at the LHC



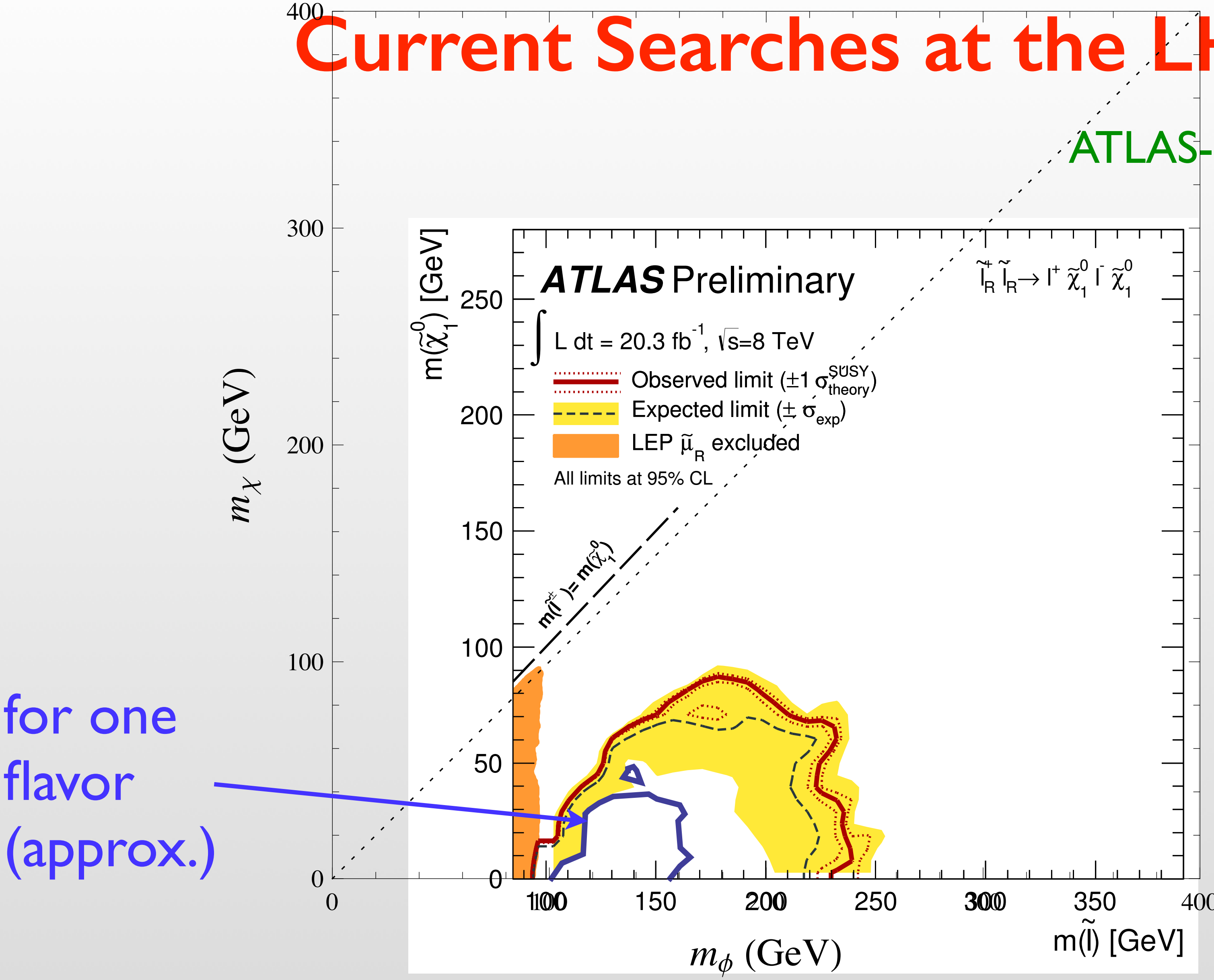


★ Fermion DM: the complex scalar mediator production (the same as the right-handed selectron one in SUSY)

★ Complex scalar DM: vector-like fermion mediators with larger cross sections

Current Searches at the LHC

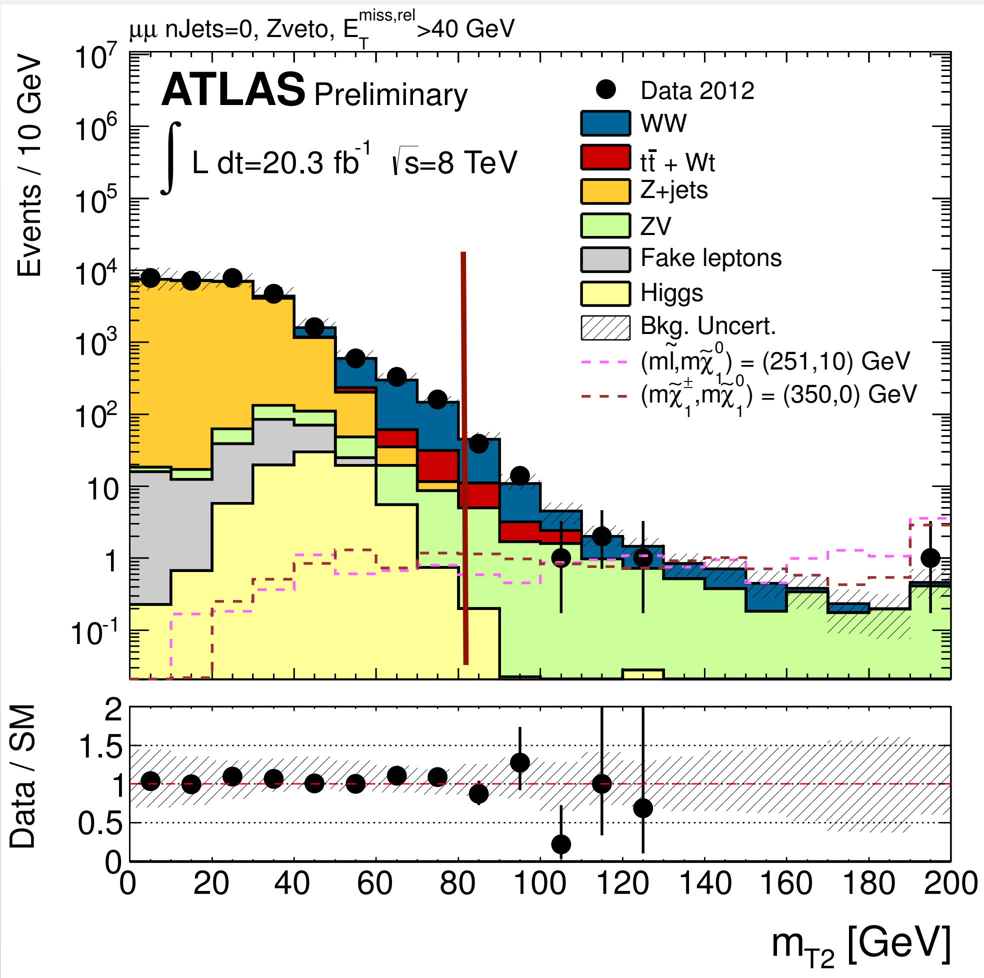
ATLAS-CONF-2013-049



ATLAS kept both selectron and smuon and used MT2

Lepton MT2

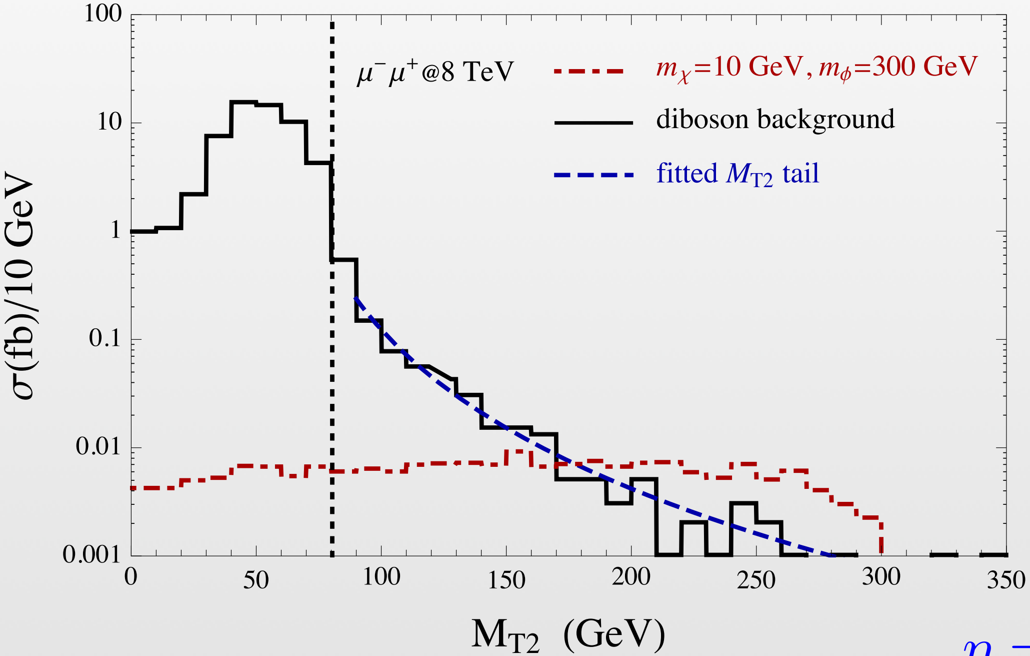
$$M_{T2} = \min \left\{ \bigcup_{\vec{p}_1^T + \vec{p}_2^T = \vec{E}_T^{\text{miss}}} \max\left[M_T(\vec{p}_{\ell_1}, \vec{p}_1^T), M_T(\vec{p}_{\ell_2}, \vec{p}_2^T) \right] \right\}$$

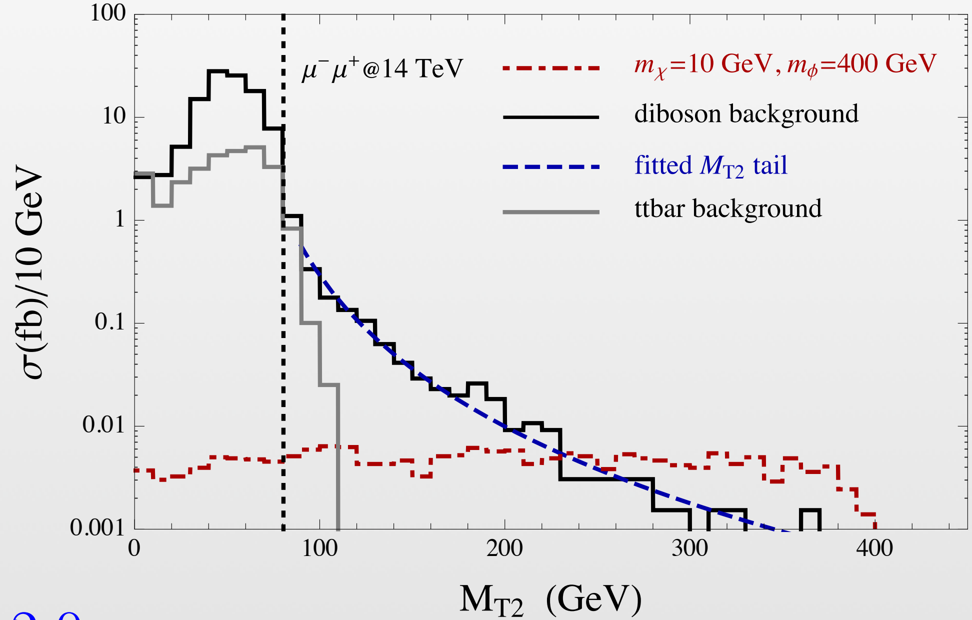


pt(j) > 20 GeV

jet veto

Tail of the Leptonic MT2



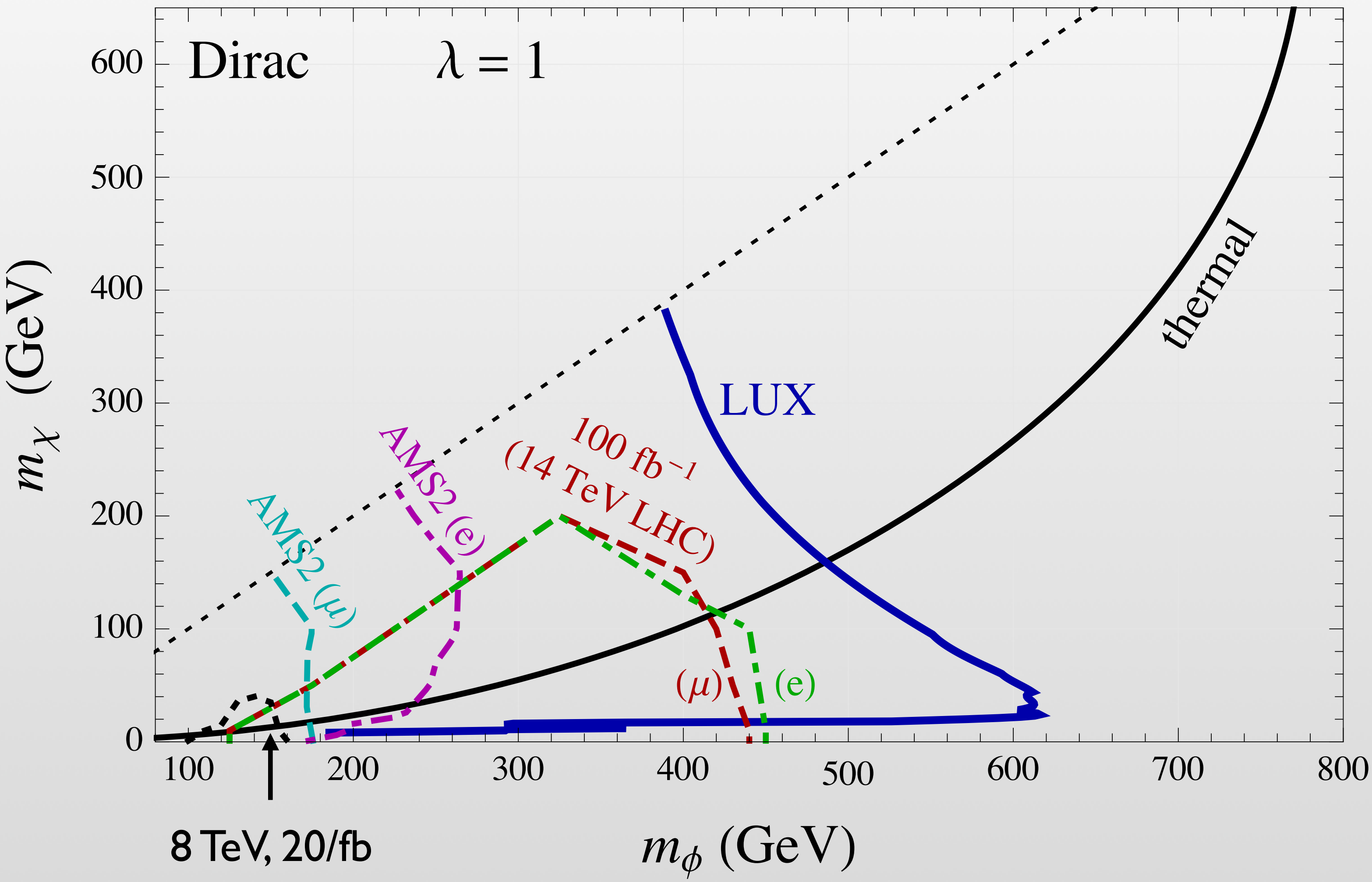


$\eta = 2.0$

$$F\left(M_{T2}\right) = \frac{N_0}{\left[\eta M_{T2}^2 - M_W^2\right]^2 + \eta^2 M_{T2}^4 \Gamma_W^2 / M_W^2}$$

★ the tail can be fitted by a Breit-Wigner formula

Status for Fermion DM



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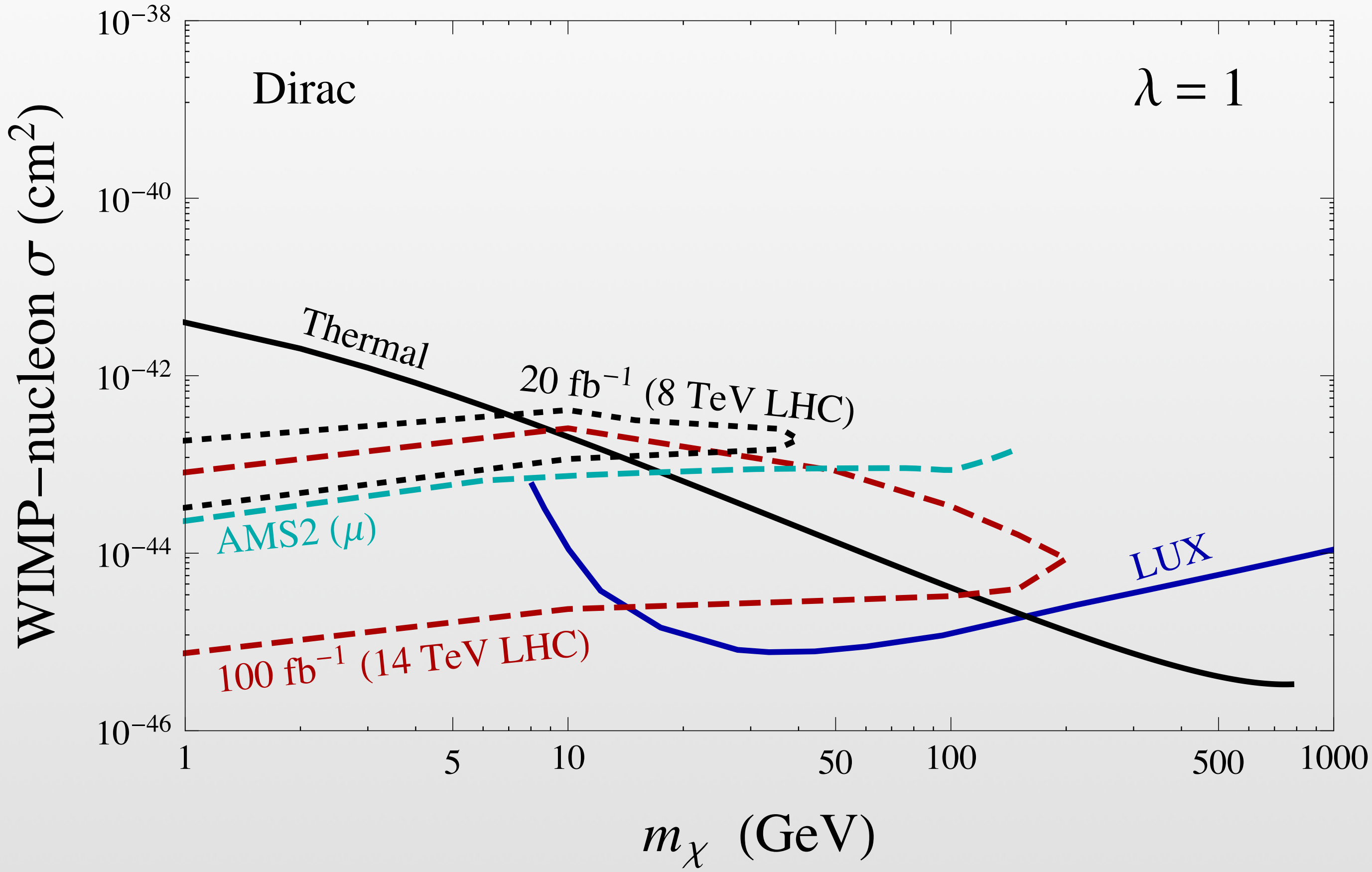
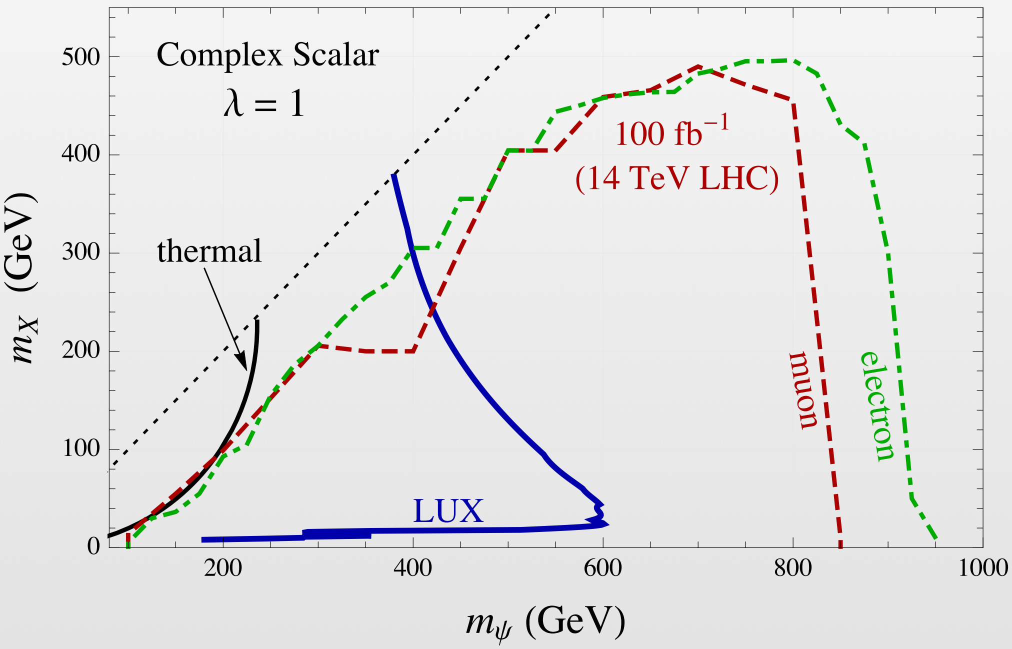
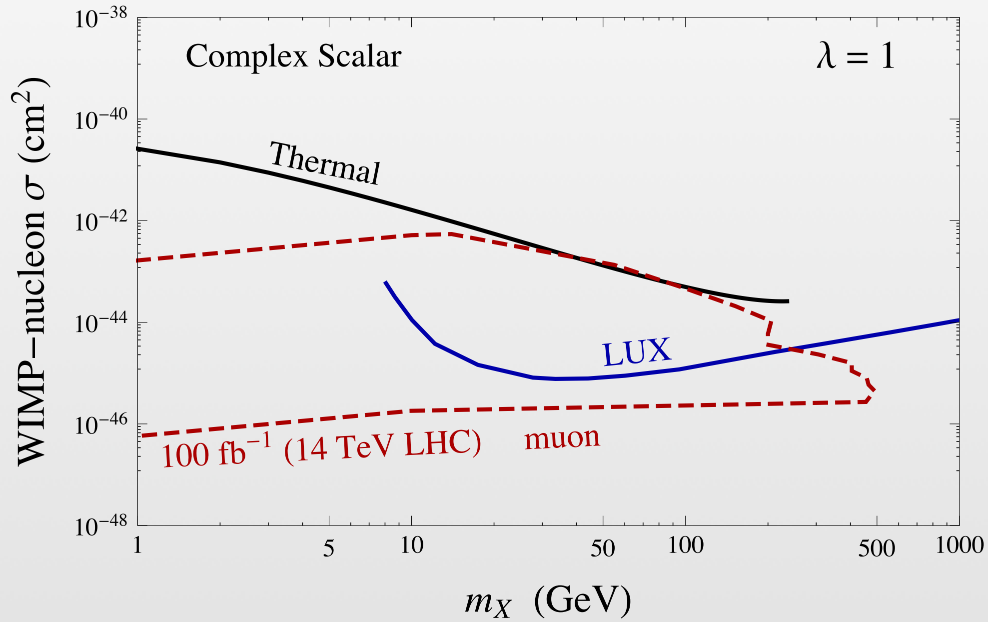


for Majorana DM: suppressed signatures for indirect detection and direct detection [$\mathcal{O}(10^{-49}\ \mathrm{cm}^2)$]; only the LHC provides useful constraints

Status for Complex Scalar DM





- ★ the indirect detection is also p-wave suppressed
- ★ much wider range of parameter space to be explored by the 14 TeV LHC

Conclusions

- ★ More searches for simplified non-SUSY dark matter models should be performed at the LHC
- ★ The lepton portal dark matter provides a useful reference model for comparing collider, direct and indirect searches of dark matter
- ★ The dilepton MT2 tail can be fitted by a simple Breit-Wigner formula
- ★ The 14 TeV LHC could have a large chance to discover the lepton portal dark matter

Thanks

Muon (g-2)

$$\mathcal{L}_{\text{fermion}} \supset \lambda_i \phi_i \overline{\chi}_L e^i_R \qquad \mathcal{L}_{\text{scalar}} \supset \lambda_i X \overline{\psi}^i_L e^i_R$$

Lepton anomalous magnetic moment:

$$a_\mu \equiv (g-2)_\mu/2$$

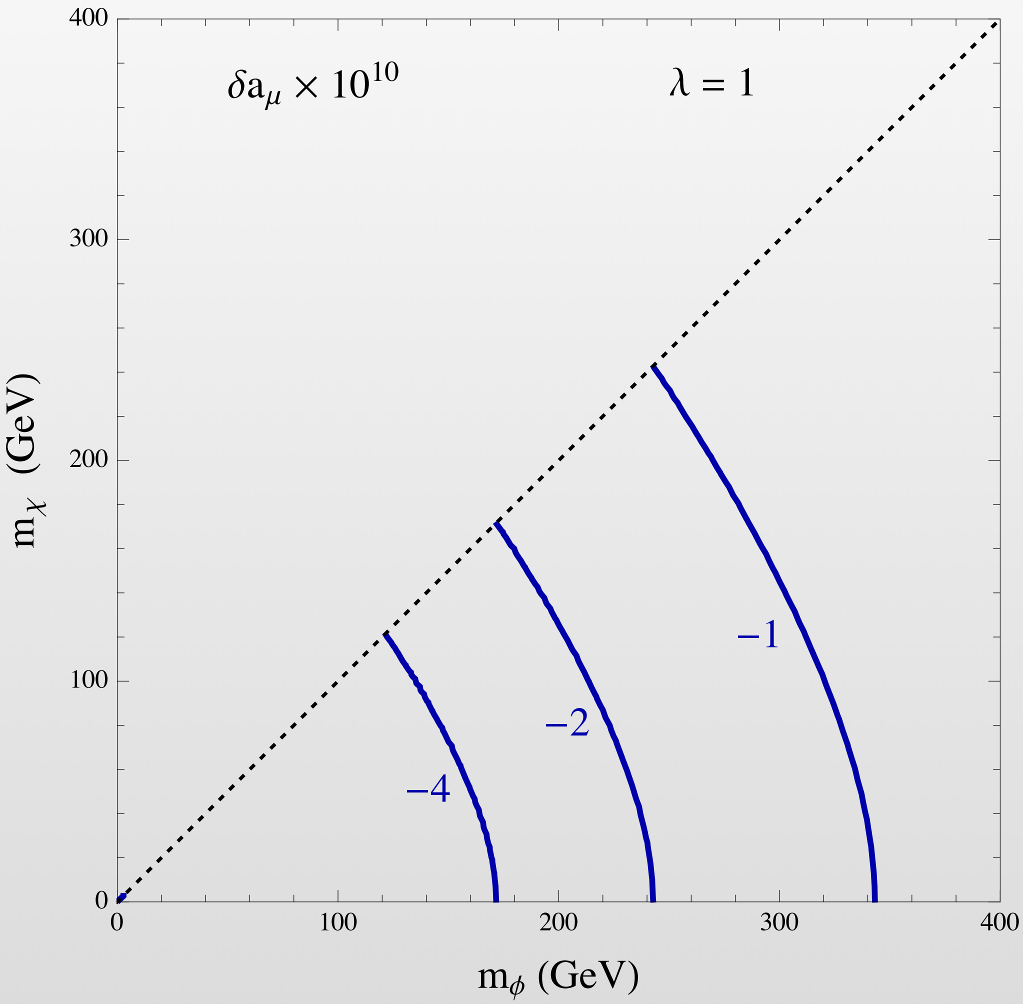
$$a_\mu^{\text{EXP}} = (11659208.9 \pm 6.3) \times 10^{-10}$$ hep-ex/0602035, Muon G-2 Collab.

$$a_\mu^{\text{SM}} = (11659182.8 \pm 4.9) \times 10^{-10}$$ 1105.3149, Hagiwara et. al.

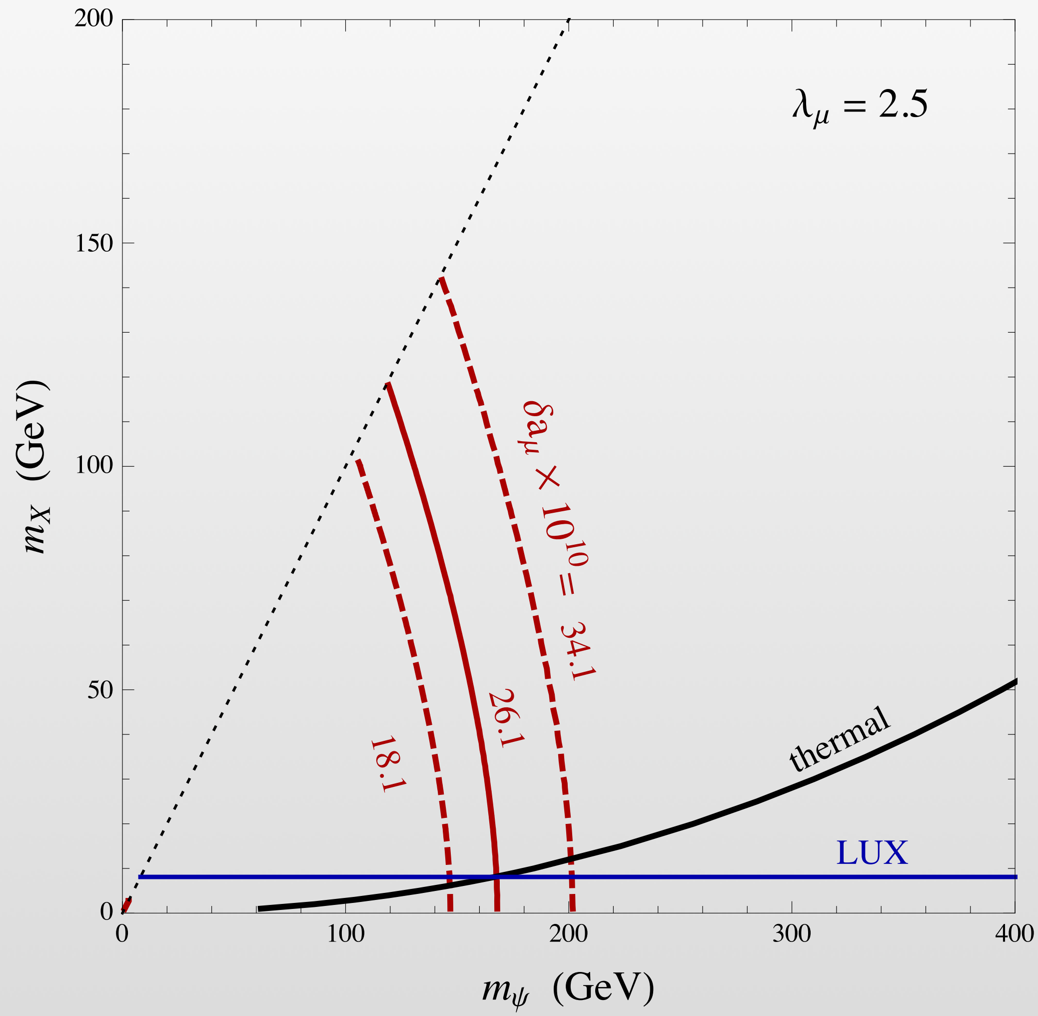
$$a_\mu^{\text{EXP}} - a_\mu^{\text{SM}} = (26.1 \pm 8.0) \times 10^{-10}$$

may need a positive contribution from new physics

Muon g-2



fermion dark matter



scalar dark matter