Fermion Portal Dark Matter

Yang Bai

University of Wisconsin-Madison

NHETC Seminar @ Rutgers

Nov. 5, 2013

with **Joshua Berger** at SLAC

"quark portal dark matter"
1308.0612

"lepton portal dark matter"
1311.xxxx

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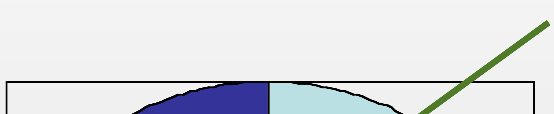
see also
Chang, Edezhath, Hutchinson, Luty, 1307:8120;
An, Wang, Zhang, 1308.0592;
DiFranzo, Nagao, Rajaraman, Tait, 1308.2679.

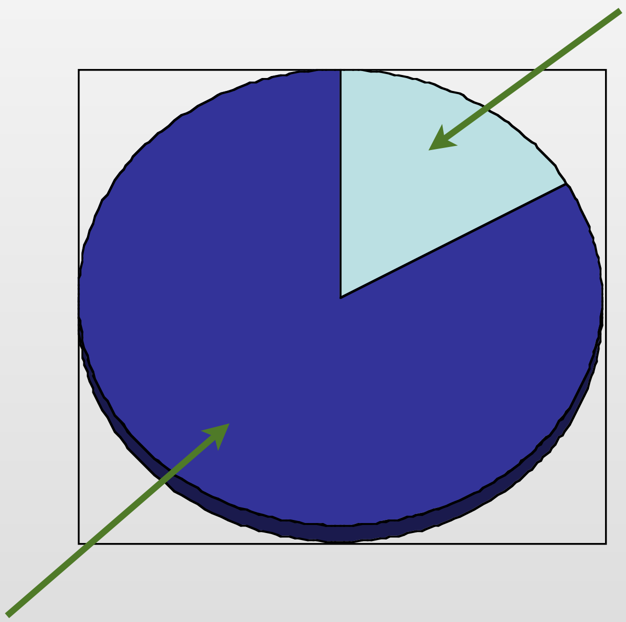
Matter Pie of Our Universe



An, Wang, Zhang, 1308.0592;
DiFranzo, Nagao, Rajaraman, Tait, 1308.2679.

Matter Pie of Our Universe

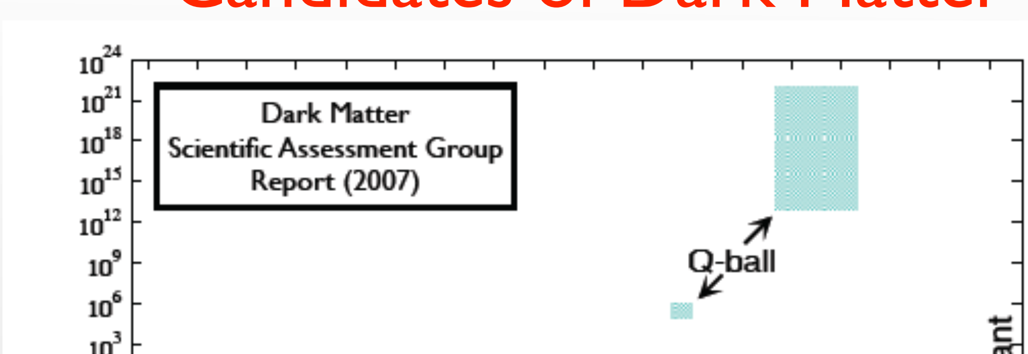
Ordinary Matter
15.5%

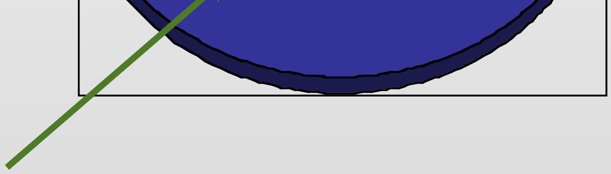


Dark Matter 84.5%

From Planck

Candidates of Dark Matter





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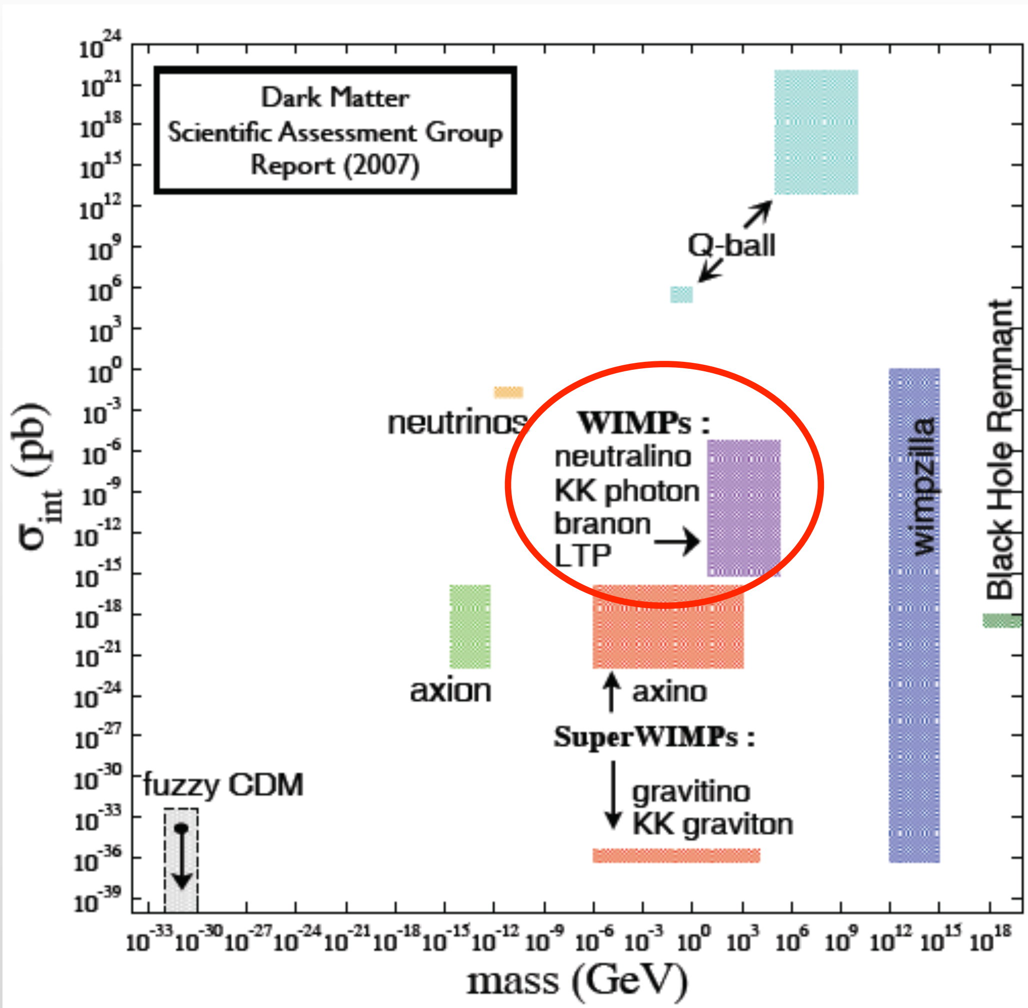
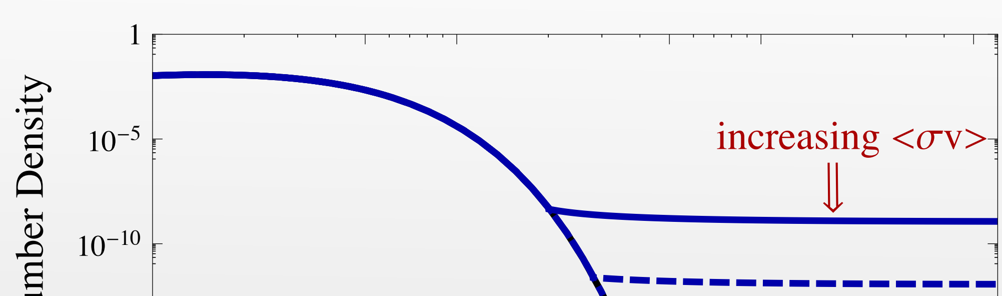
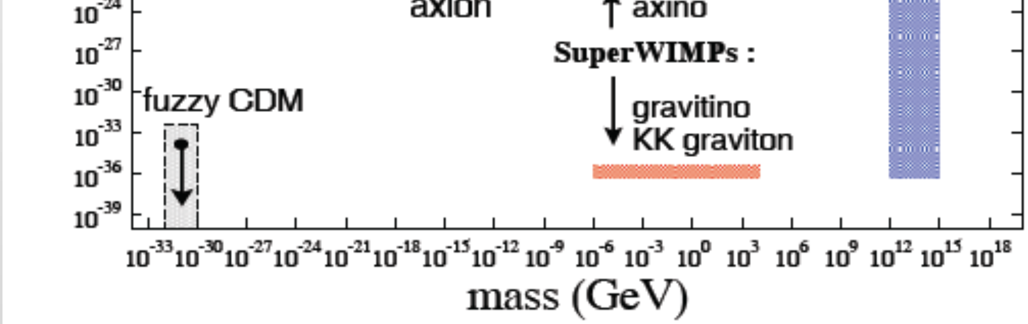


The WIMP "Miracle"





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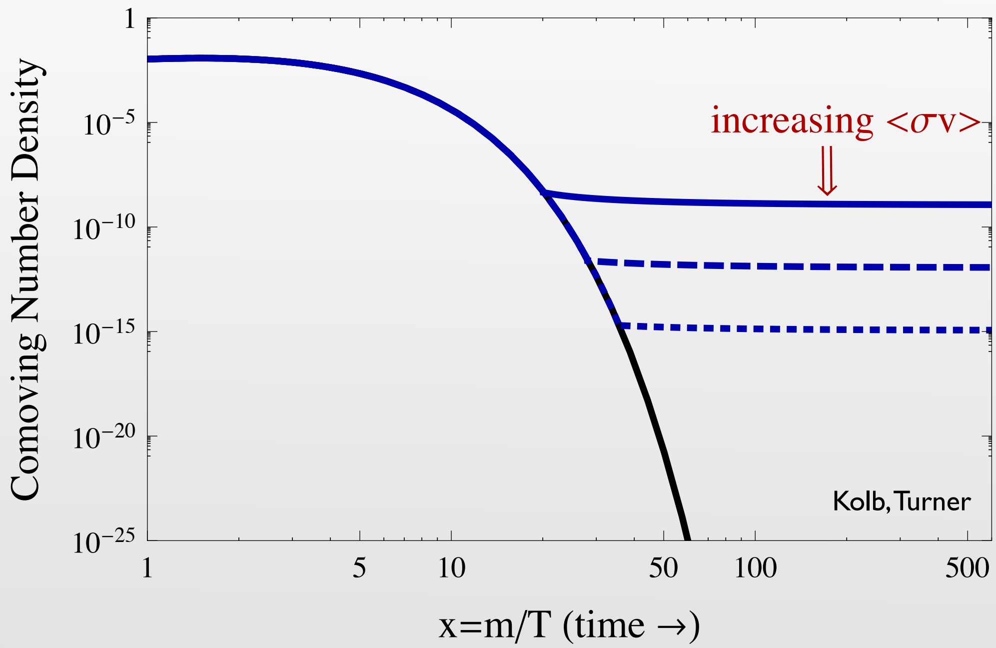
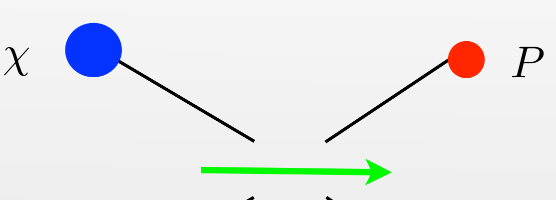


$$\Omega_{\rm DM} \sim \langle \sigma_A v \rangle^{-1} \quad + \quad \langle \sigma_A v \rangle \sim \frac{\alpha^2}{m_\chi^2} \quad \longrightarrow \quad m_\chi \sim 100 \text{ GeV} \sim \text{W mass}$$

Lots of beyond-standard models predict WIMP candidates

The Hunt of Dark Matter

Indirect Detection



Colliders

x=m/T (time →)

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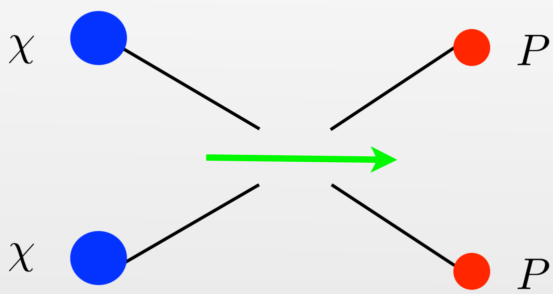
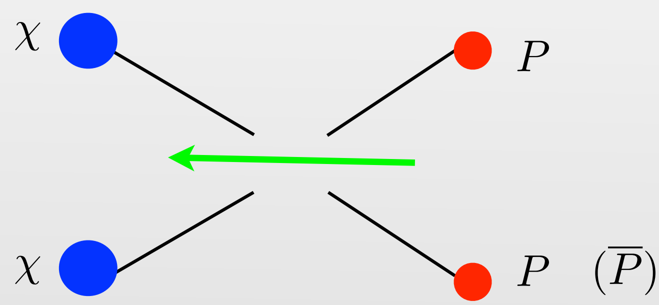
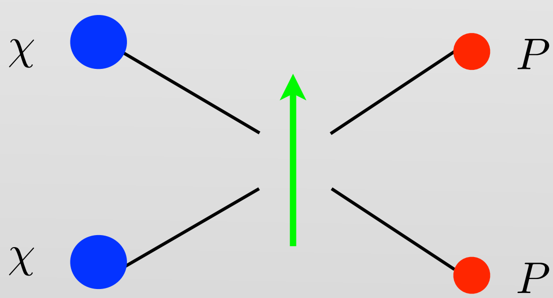
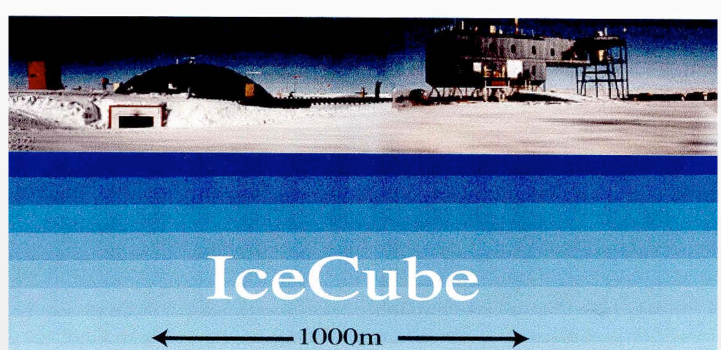


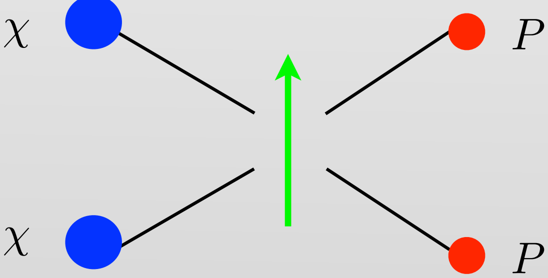
Colliders

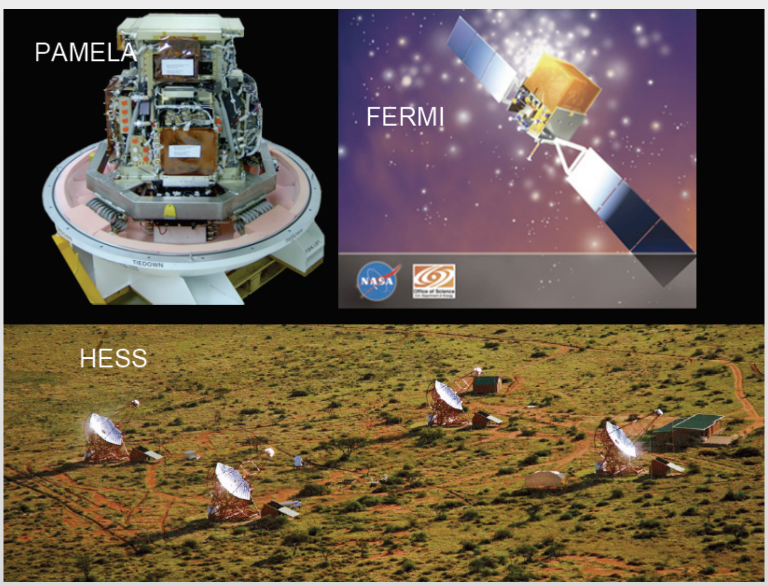


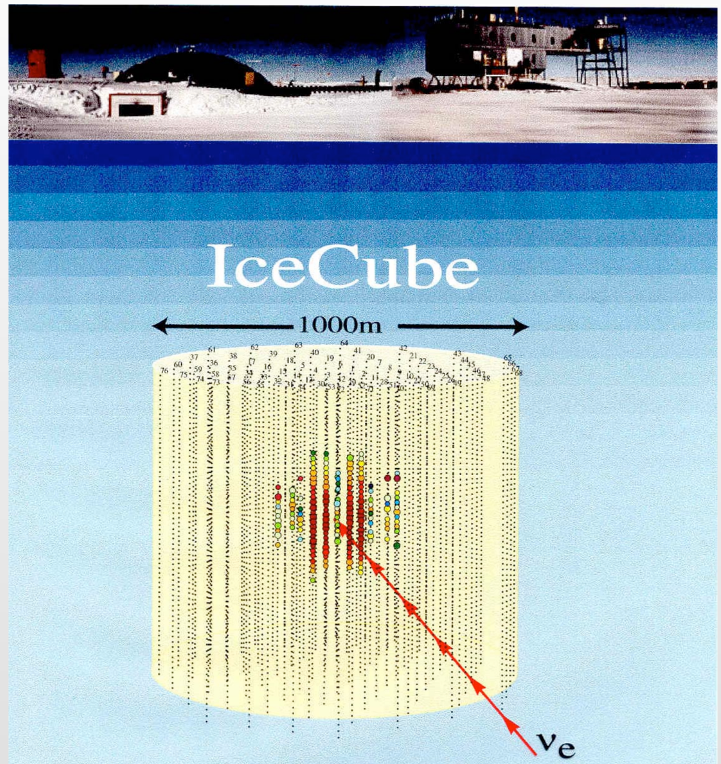
Direct Detection



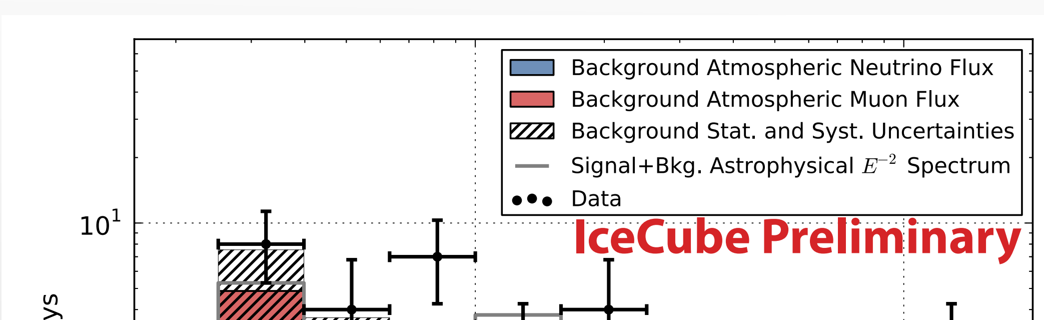


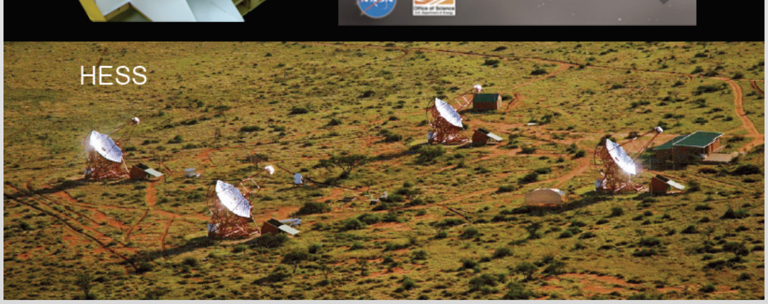


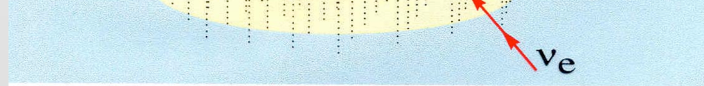




IceCube High Energy Neutrino Excess







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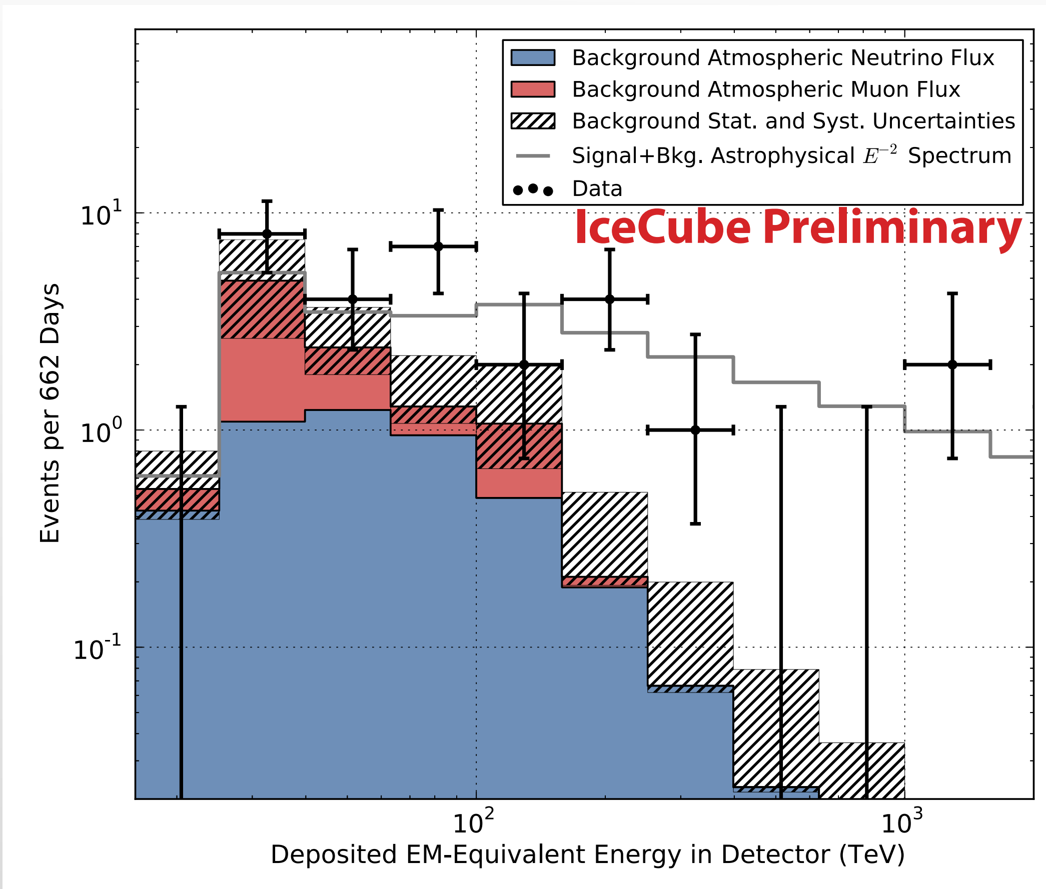
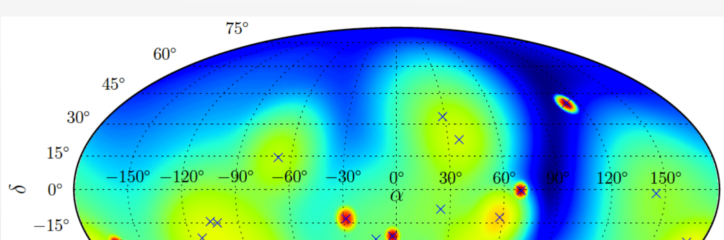
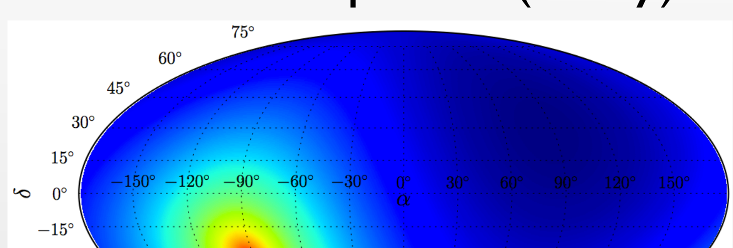


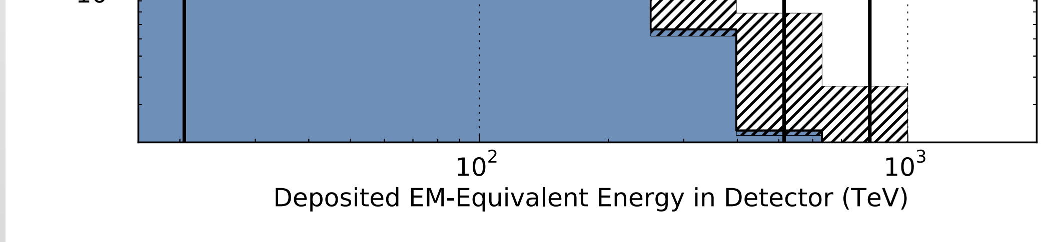
IceCube High Energy Neutrino Excess

28 events



Einasto profile (decay)





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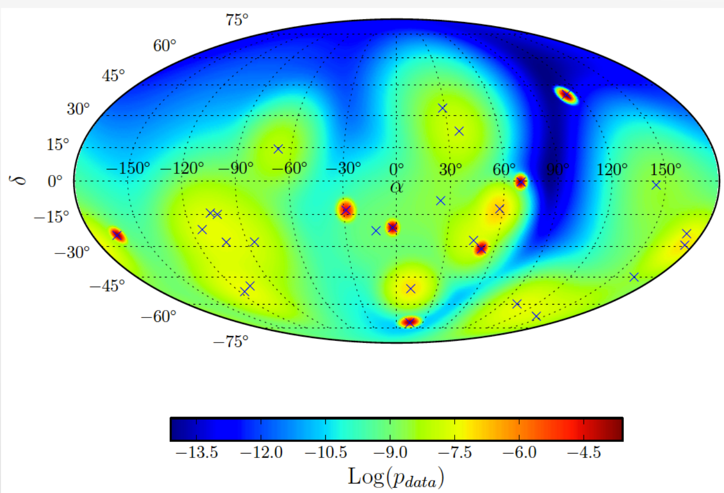

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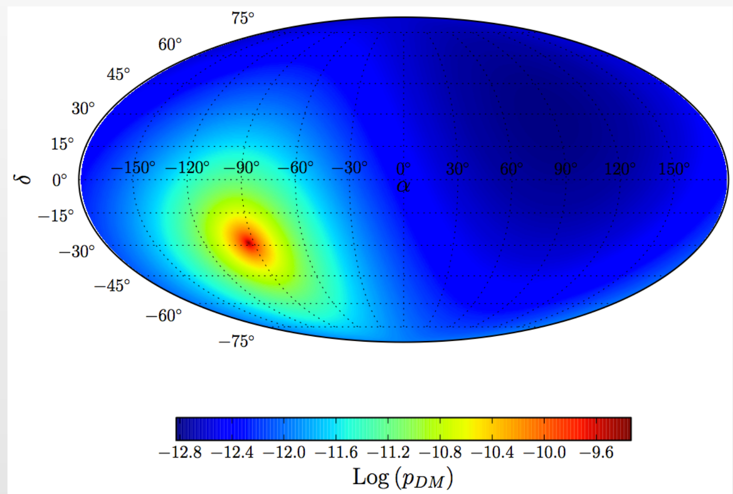


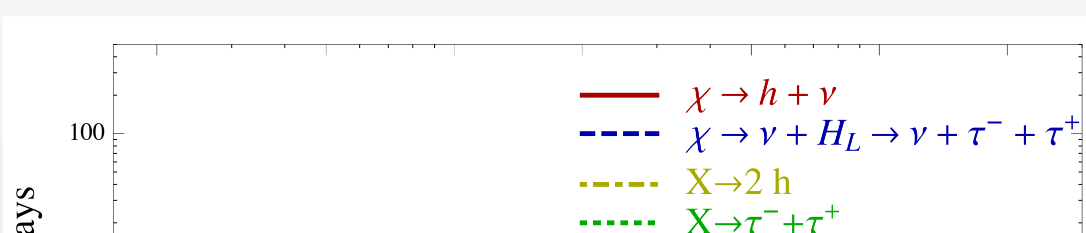
equatorial coord.

	$\bar{\alpha} = 0.25$	$\bar{\alpha} = 0.17$	Homogeneous
all 28 events	20.34%	21.98%	72.14%
18 events with $E \gtrsim 50$ TeV	18.16%	20.16%	70.14%
21 cascade events	38.84%	41.86%	95.38%

YB, Lu, Salvado, to be published

IceCube High Energy Neutrino Excess

YB, Lu, Salvado, to be published



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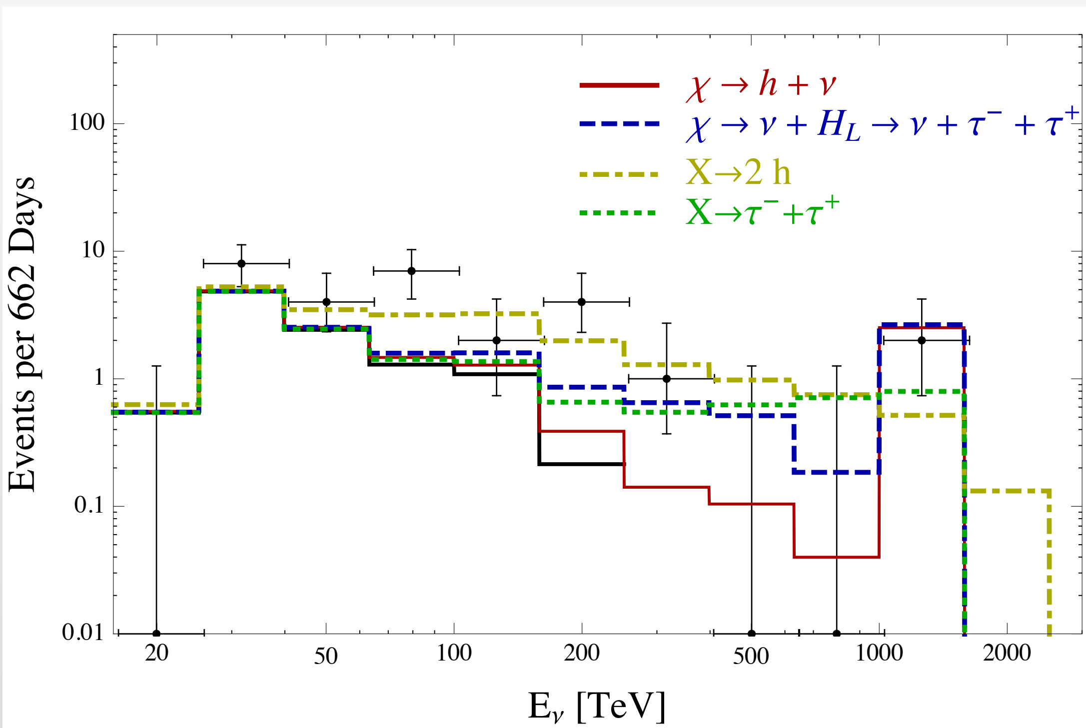
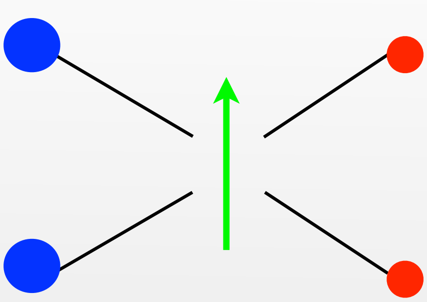
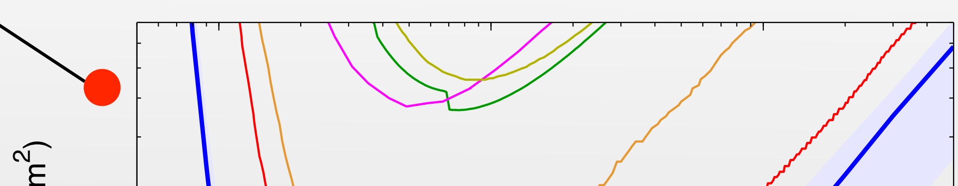


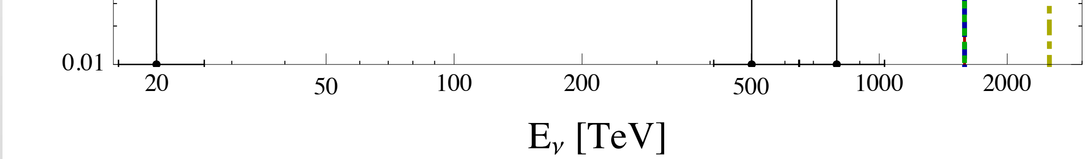
Possible explanation from dark matter decays

Direct Detection



LUX: 1310.8214





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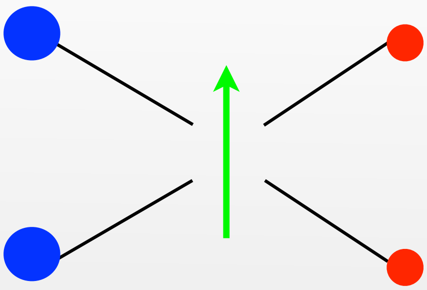

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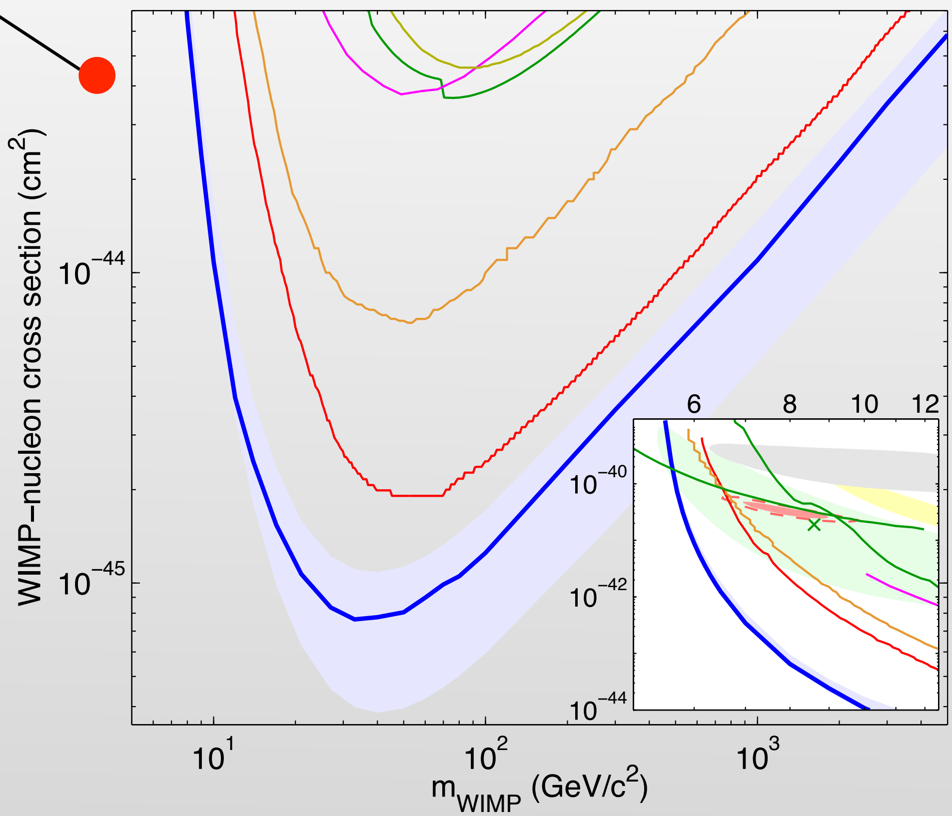

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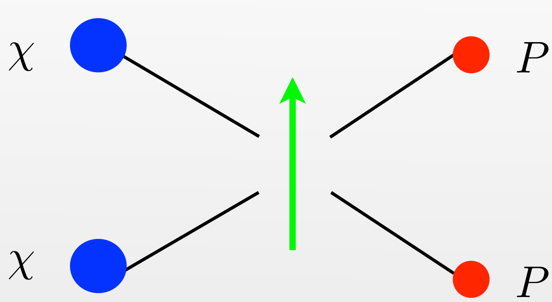

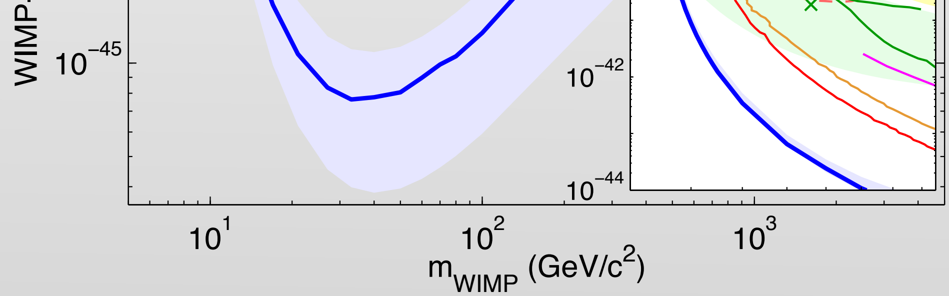

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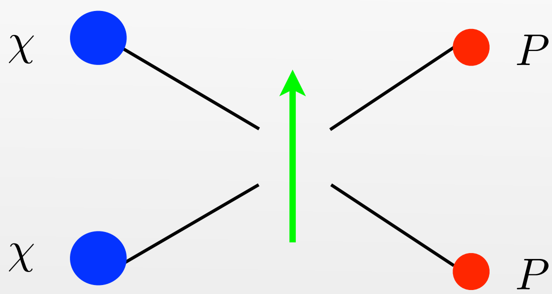
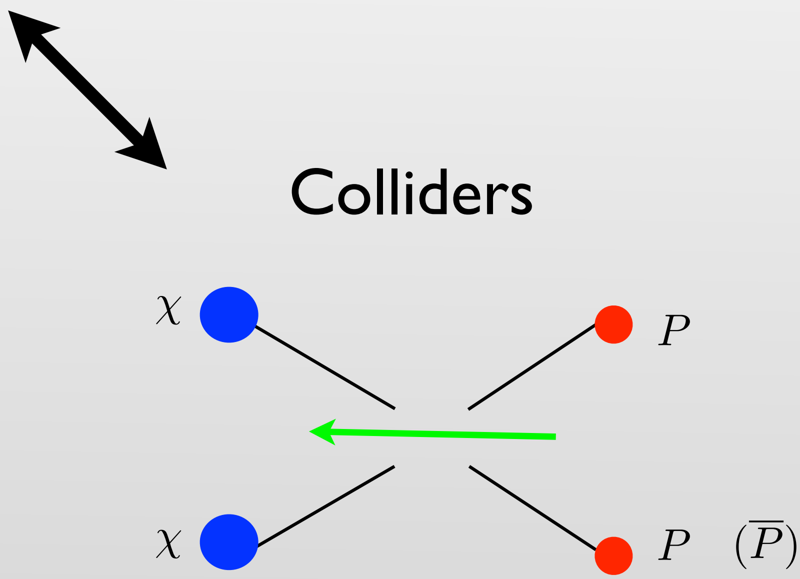
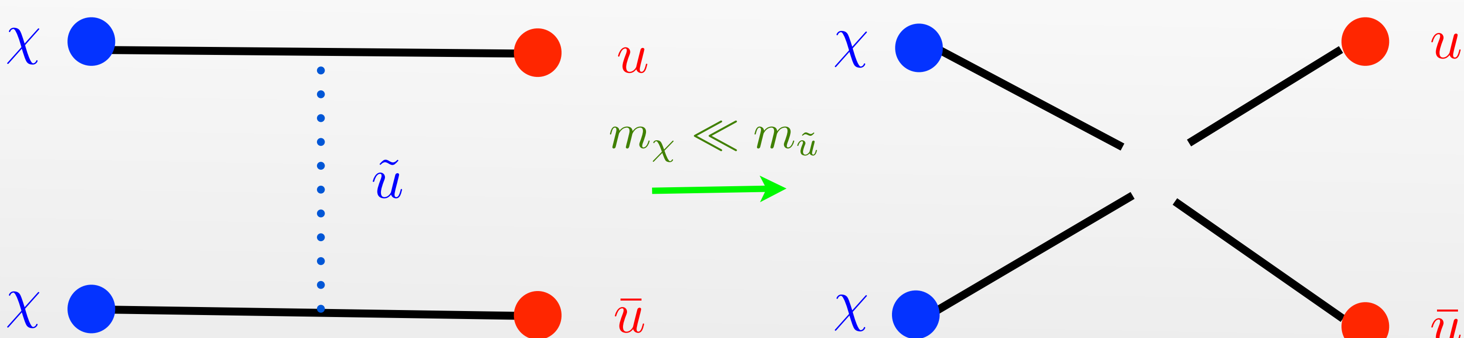
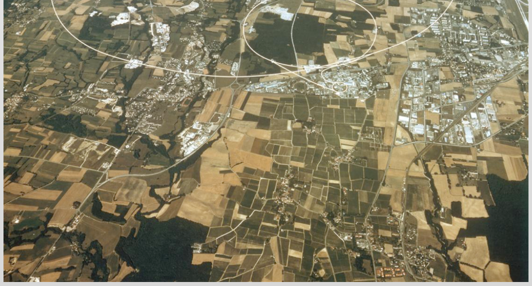


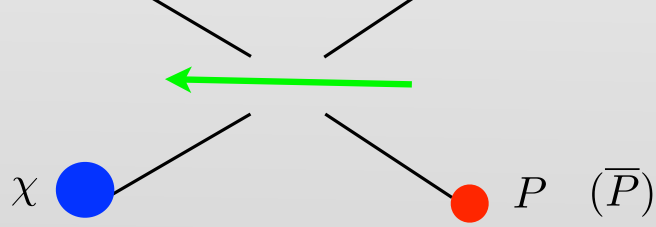
Colliders



Effective Approach to Dark Matter







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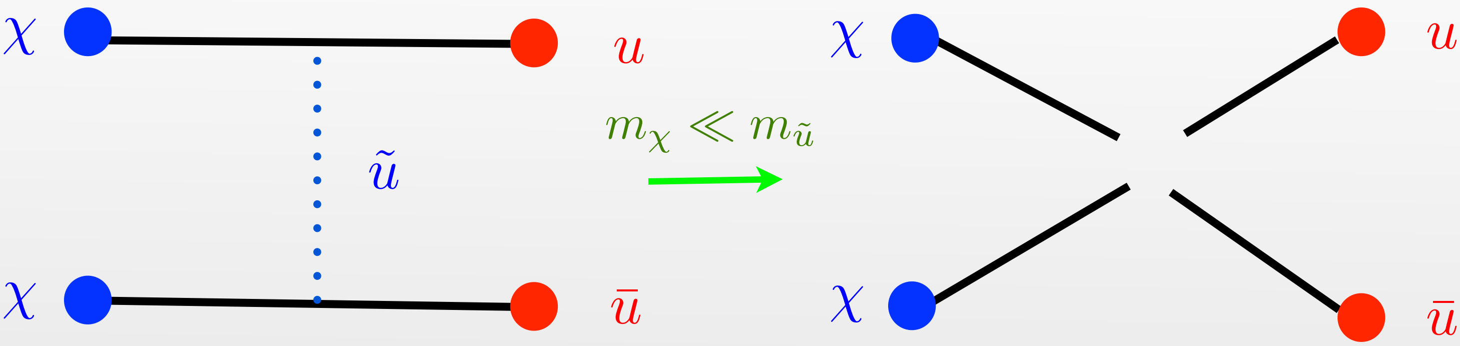
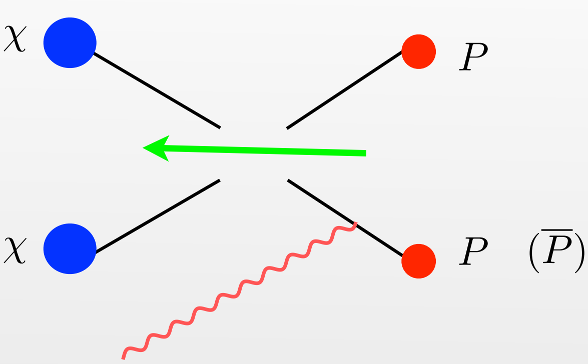


Model-independent approach to dark matter

$$\frac{1}{\Lambda^2}\bar{q}q\bar{\chi}\chi \qquad \frac{1}{\Lambda^2}\bar{q}\gamma_\mu q\,\bar{\chi}\gamma^\mu\chi \qquad \frac{1}{\Lambda^2}\bar{q}\gamma_\mu\gamma_5 q\,\bar{\chi}\gamma^\mu\gamma_5\chi$$

The same operator describes collider and direct detection searches

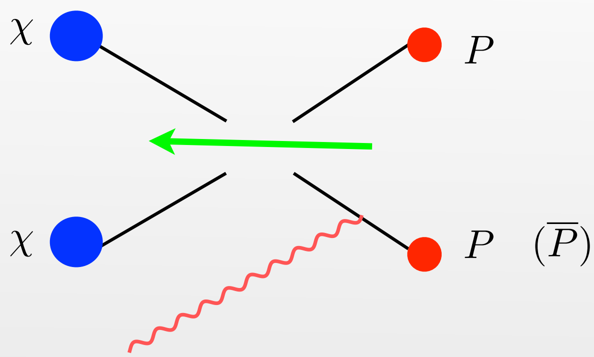
Dark Matter at Colliders



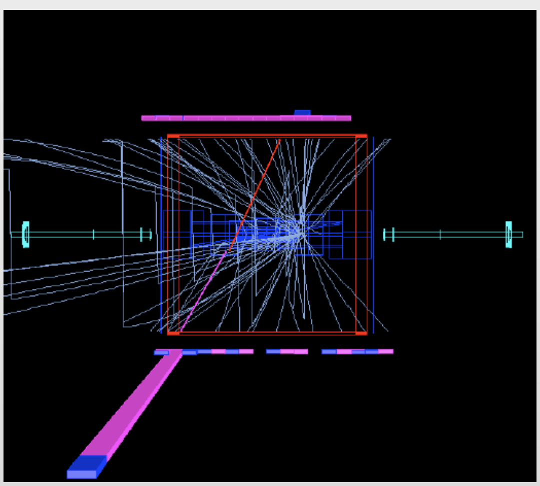
Monojet event

The same operator describes collider and direct detection searches

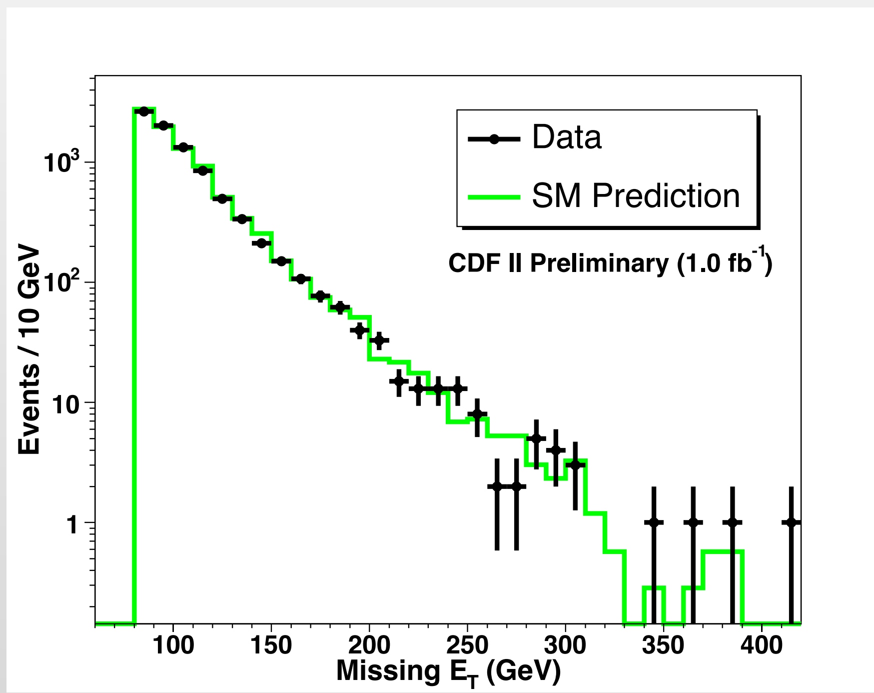
Dark Matter at Colliders



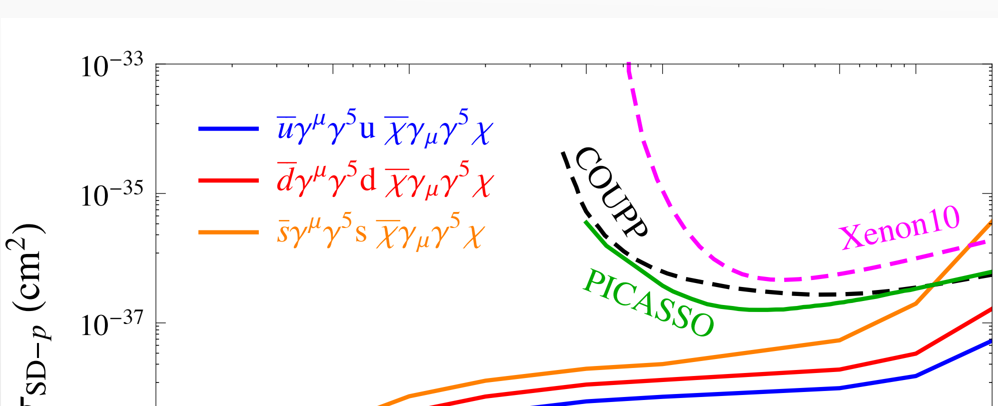
Monojet event



From CDF, Fermilab

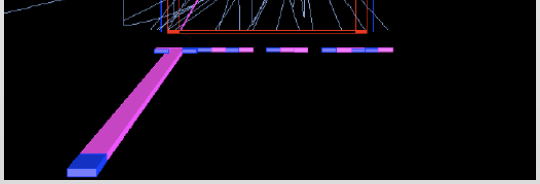


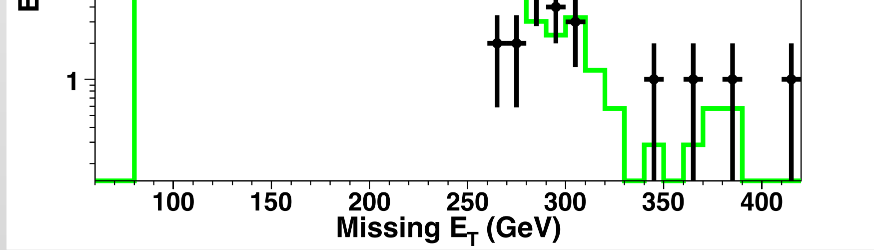
Using CDF monojet data



YB, Fox, Harnik, JHEP, 1012, 048 (2010)

see also: Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu: Phys. Lett. B695 (2011)





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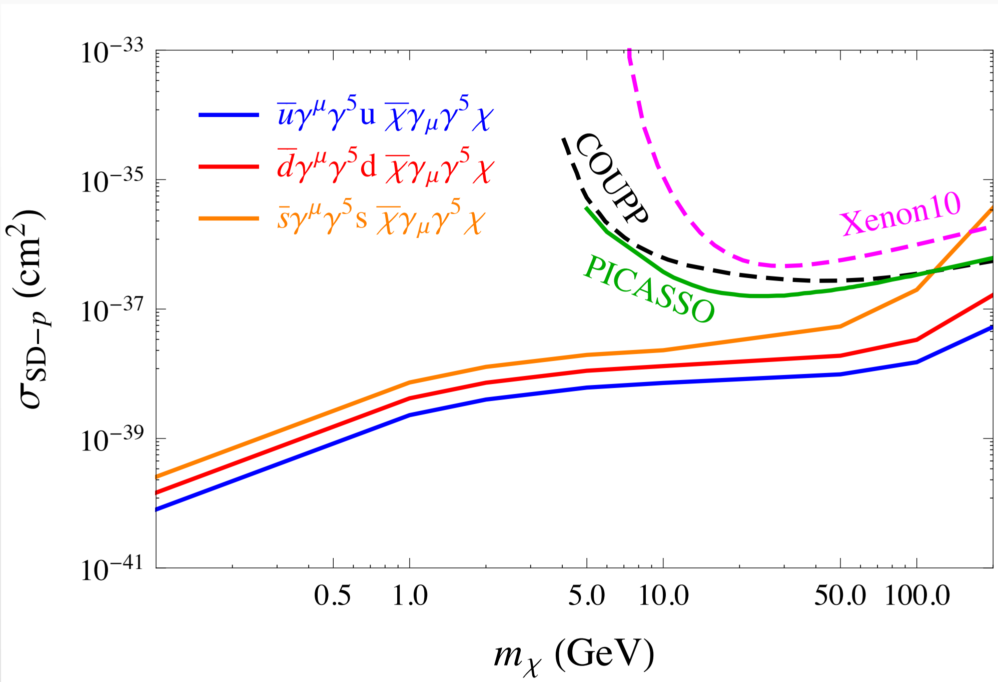

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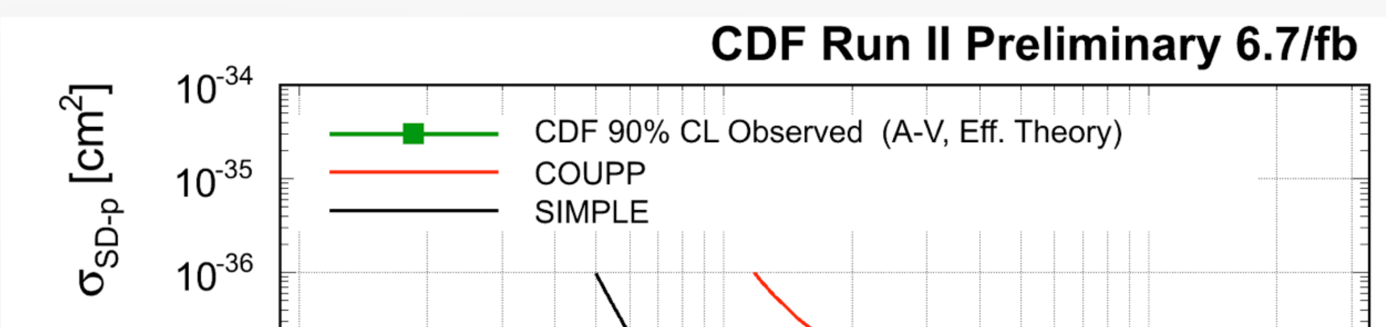
some caveats for light mediators

World's best spin-dependent limit up to 100 GeV

PRL **108,** 211804 (2012) PHYSICAL REVIEW LETTERS week ending 25 MAY 2012

Search for Dark Matter in Events with One Jet and Missing Transverse Energy in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV



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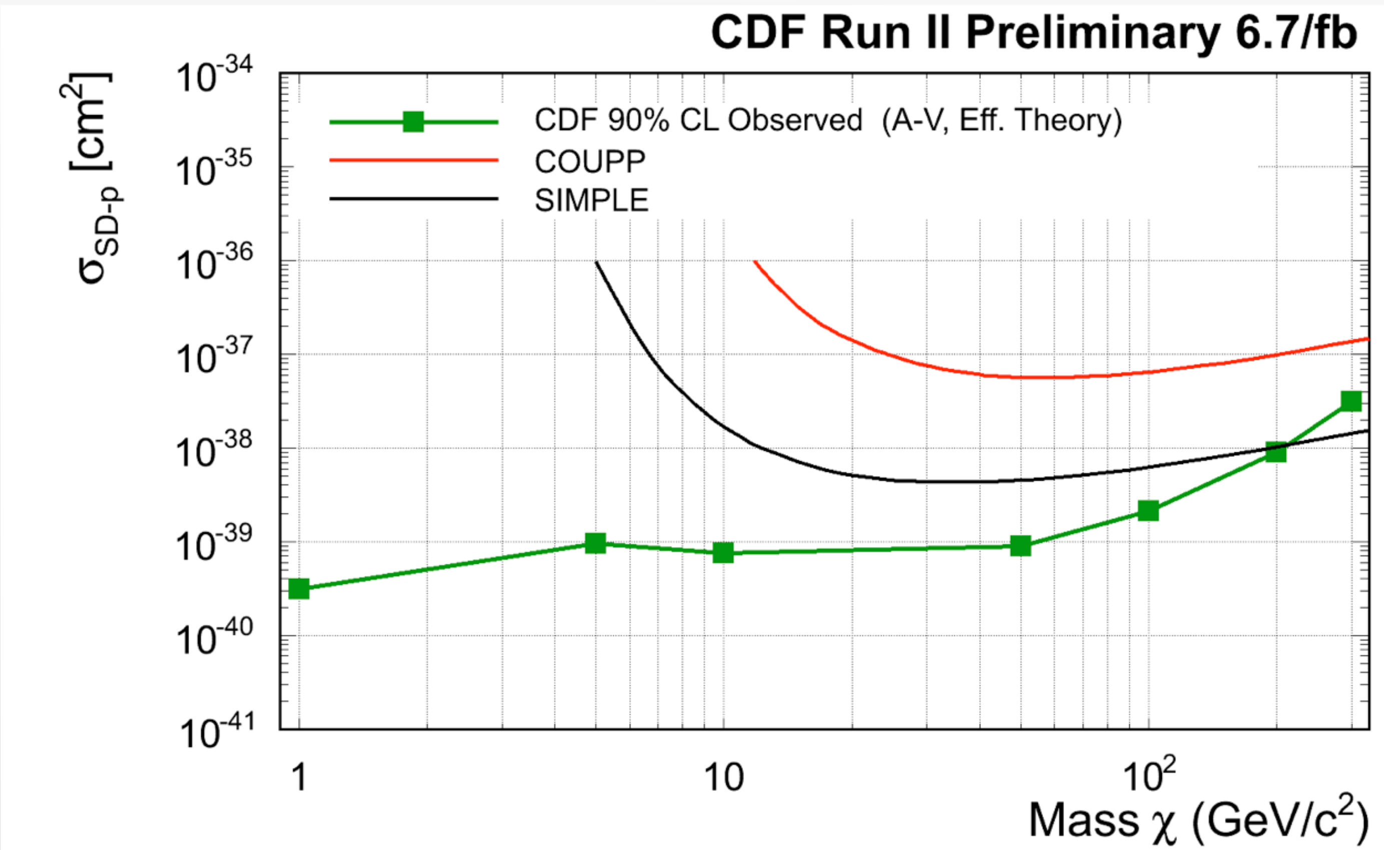
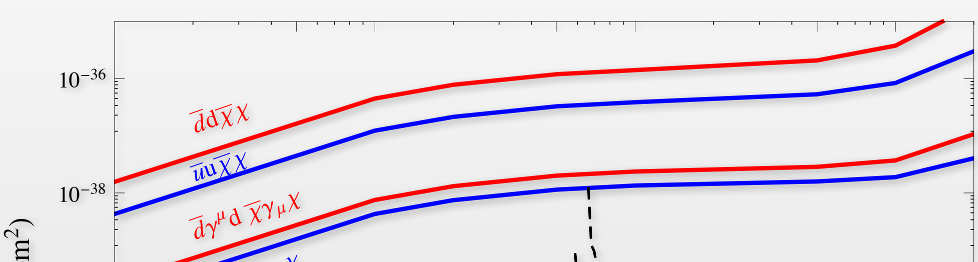
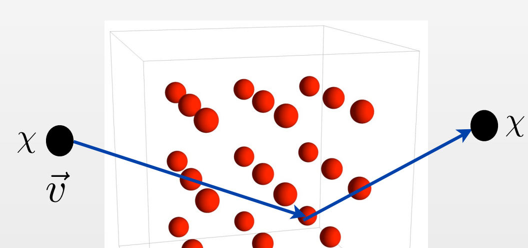


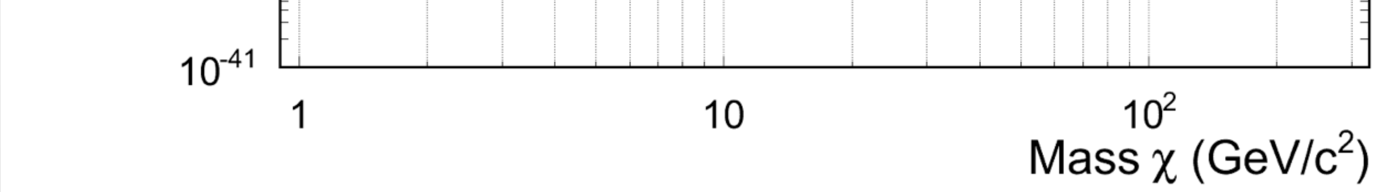
(CDF Collaboration)

Spin-independent

YB, Fox, Harnik, JHEP 1012(2010)







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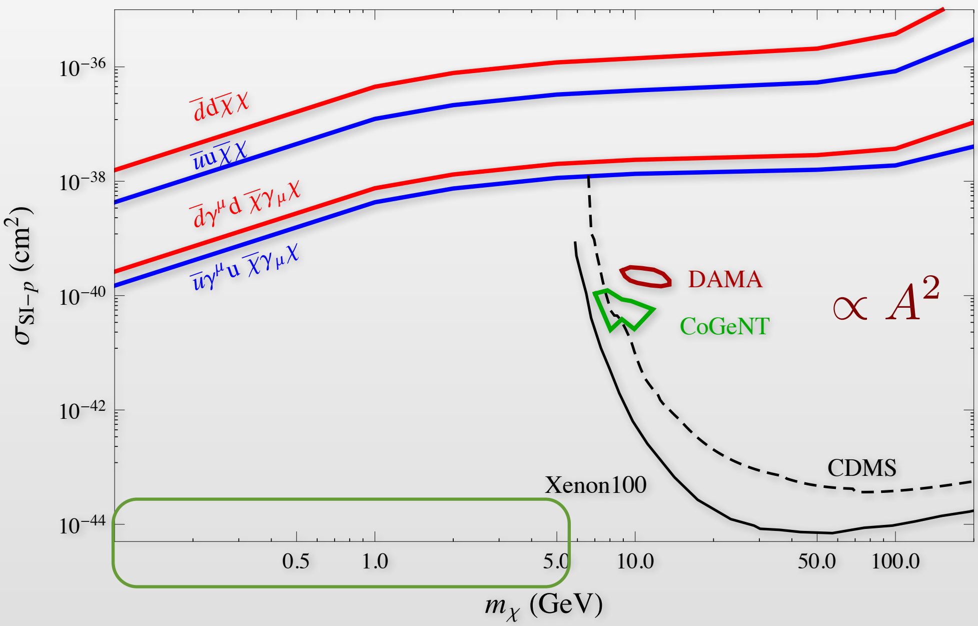
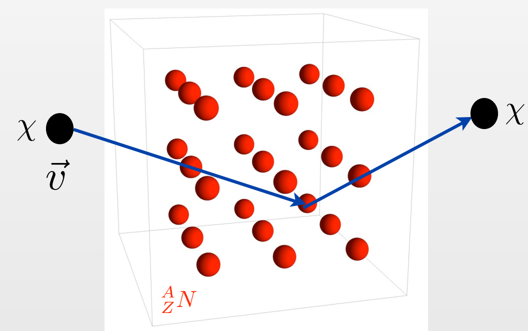


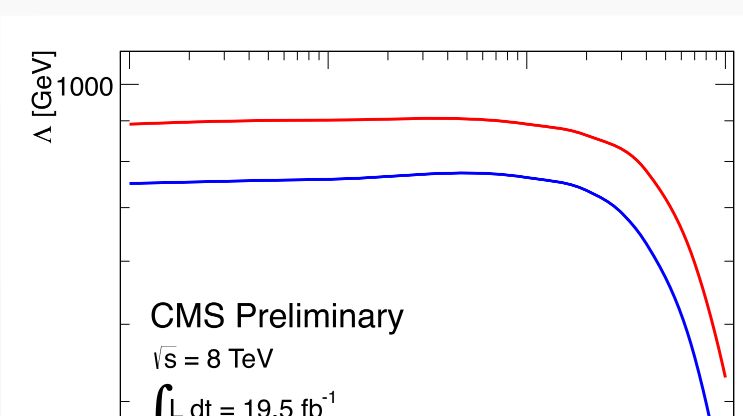


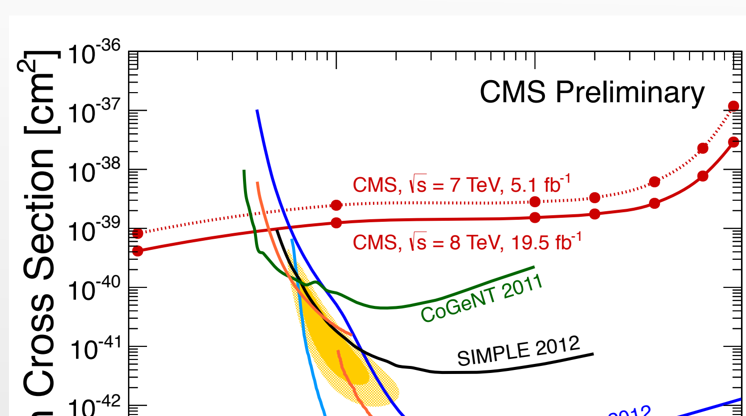
$$E_{\text{kin}} = \frac{1}{2} m_\chi v^2 \sim 1 \text{ keV}$$

$$m_\chi \sim 1 \text{ GeV}$$

World's best spin-independent limit for light dark matter

Current Limits from CMS

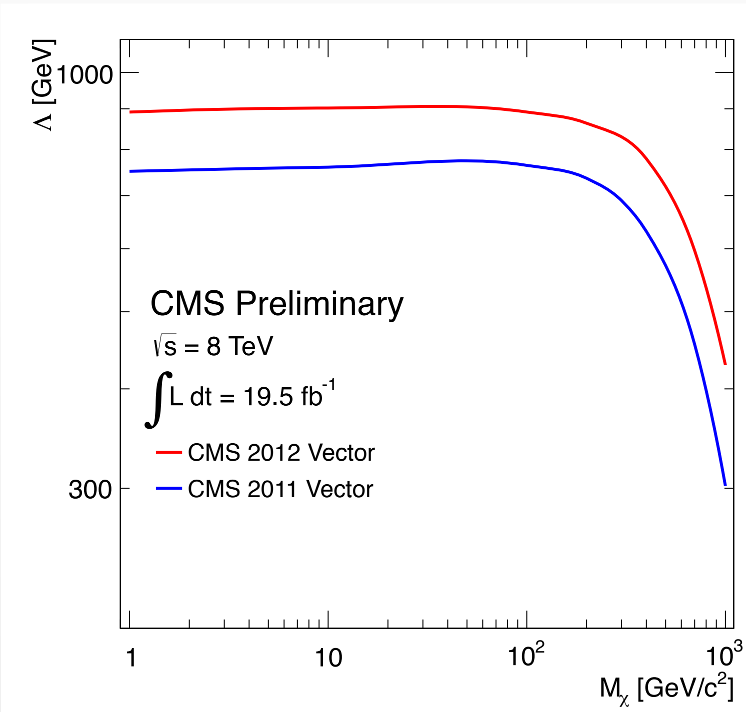


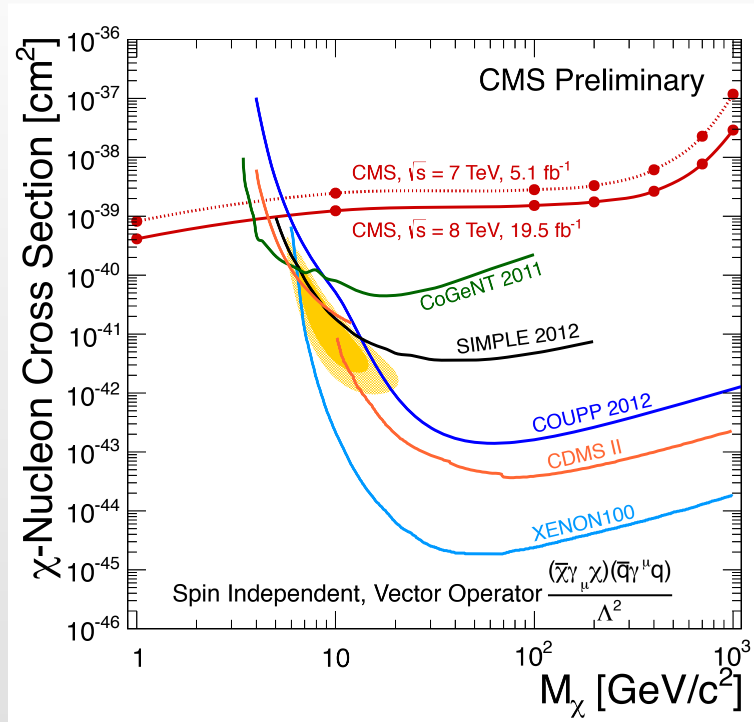


m_χ (GeV)

World’s best spin-independent limit for light dark matter

Current Limits from CMS





data driven

$$N(Z(\nu\nu)) = \frac{N^{\text{obs}} - N^{\text{bgd}}}{A \times \epsilon} \cdot R\left(\frac{Z(\nu\nu)}{Z(\mu\mu)}\right)$$

Improvement

CMS monojet search

E_T^{miss} (GeV) $\rightarrow$	> 400
$Z(\nu\nu)$+jets	2569 ± 188
W+jets	1044 ± 51
$t\bar{t}$	32 ± 16
$Z(\ell\ell)$+jets	8 ± 4.0

data driven $N(Z(\nu\nu)) = \frac{N^{\rm obs} - N^{\rm bgd}}{A \times \epsilon} \cdot R\left(\frac{Z(\nu\nu)}{Z(\mu\mu)}\right)$

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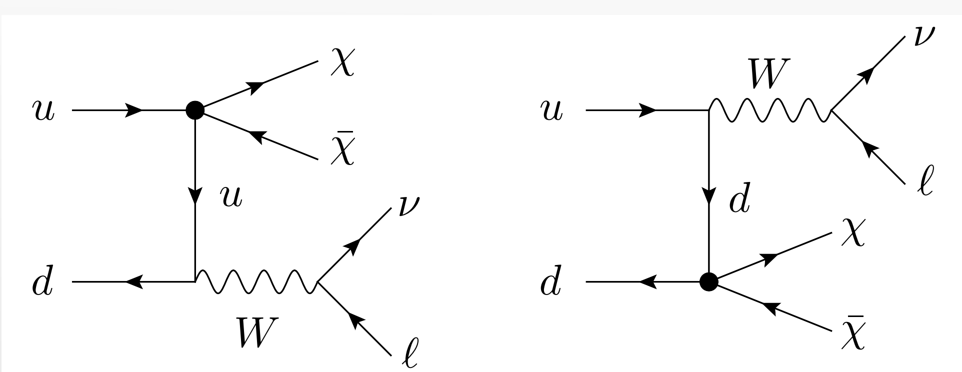
$Z(\ell\ell)$+jets	8 ± 4.0
Single t	7 ± 3.5
QCD Multijets	3 ± 1.5
Total SM	3663 ± 196
Data	3677
Exp. upper limit	424
Obs. upper limit	434

$$\frac{196}{\sqrt{3663}} \approx 3.2$$

systematic error dominants

a cleaner channel may do better

Monolepton



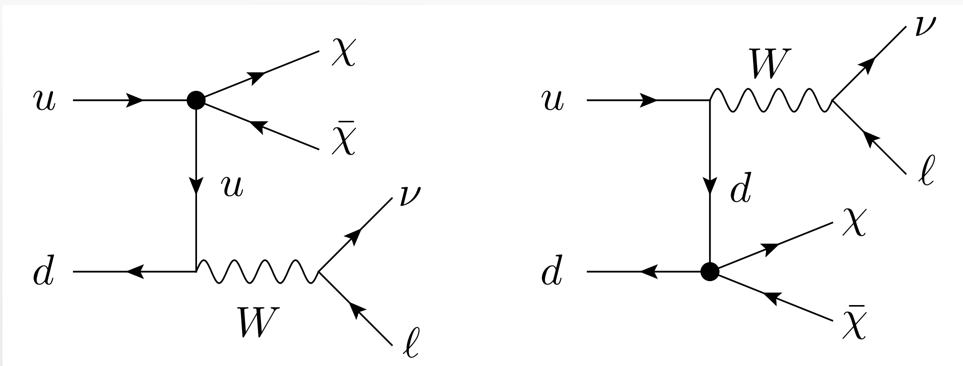
YB and Tait
1208.4361

Obs. upper limit	434

dominants

a cleaner channel may do better

Monolepton



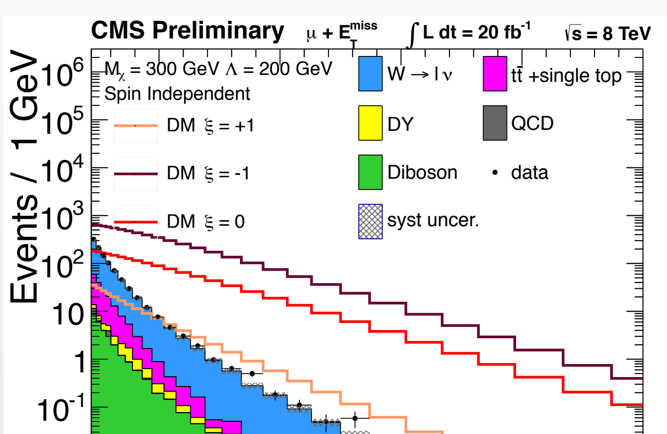
YB and Tait
1208.4361

$$\frac{1}{\Lambda^2}\ \overline{\chi}\gamma_\mu\chi\ \left(\overline{u}\gamma^\mu u + \xi\ \overline{d}\gamma^\mu d\right)$$

$$\frac{1}{\Lambda^2}\ \overline{\chi}\gamma_\mu\gamma_5\chi\ \left(\overline{u}\gamma^\mu\gamma_5 u + \xi\ \overline{d}\gamma^\mu\gamma_5 d\right)$$

interesting interference effects

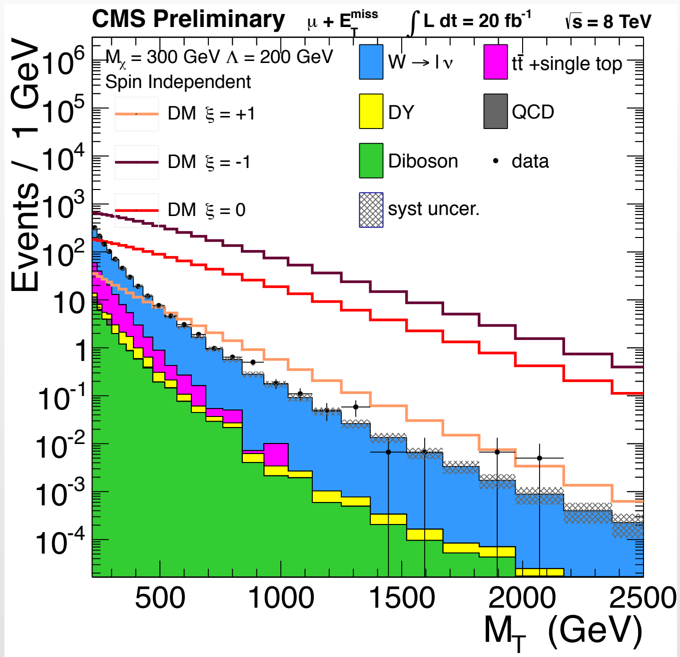
CMS Data



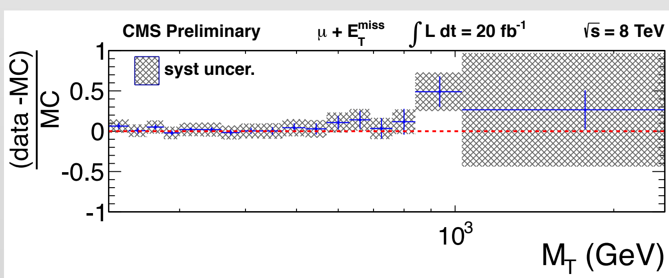
CMS: EXO-13-004-pas

interesting interference effects

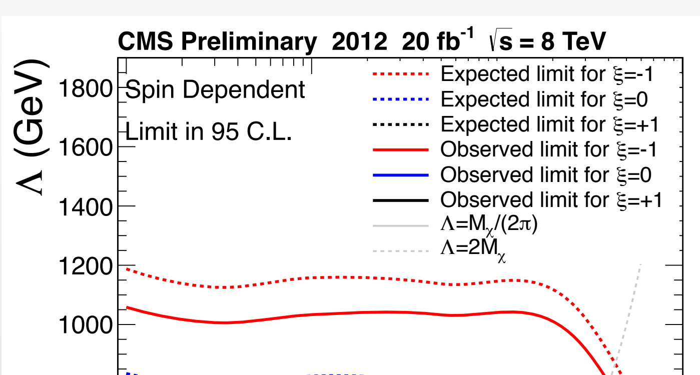
CMS Data

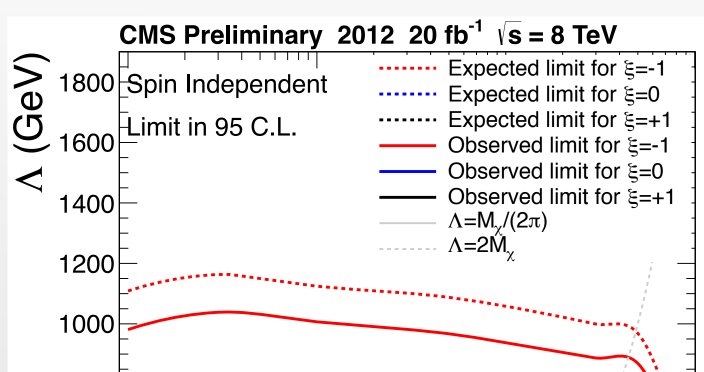


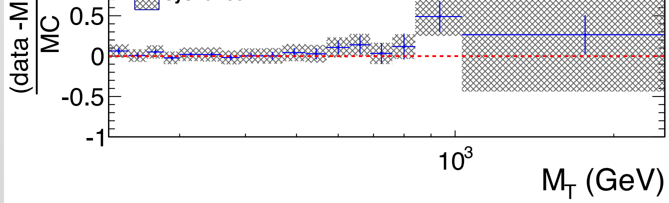
CMS: EXO-13-004-pas



Limits on cutoff







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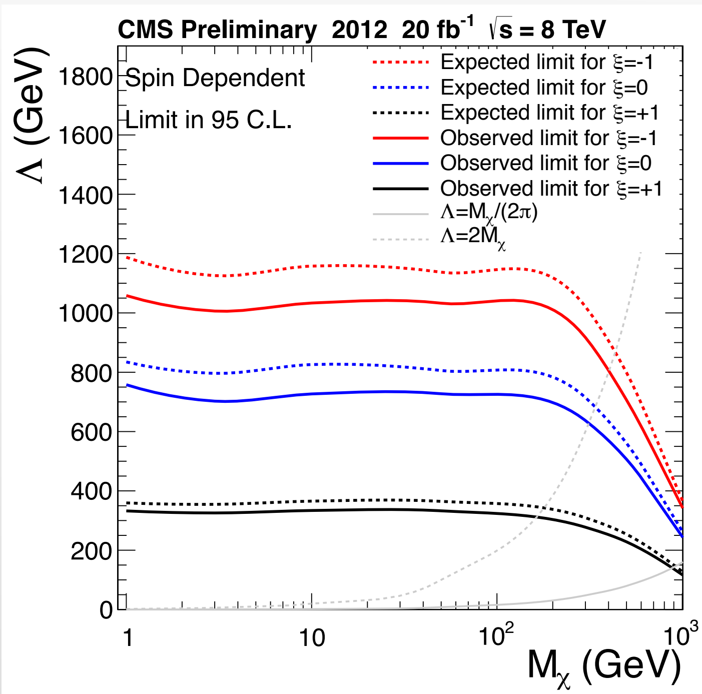

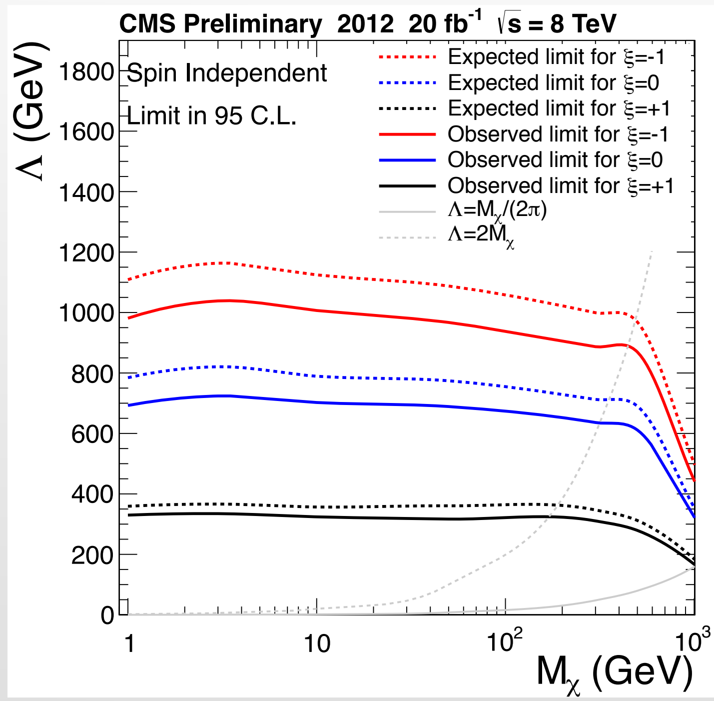

Caveat #1

★ The colliders become less effective as the mediator mass decreases

$$\sigma^{\rm DD} \sim g_\chi^2 g_q^2 \, \frac{\mu_{\chi n}^2}{[q^2 - M^2]^2} \sim g_\chi^2 g_q^2 \, \frac{\mu_{\chi n}^2}{M^4} \qquad q < \mathcal{O}(\rm GeV)$$

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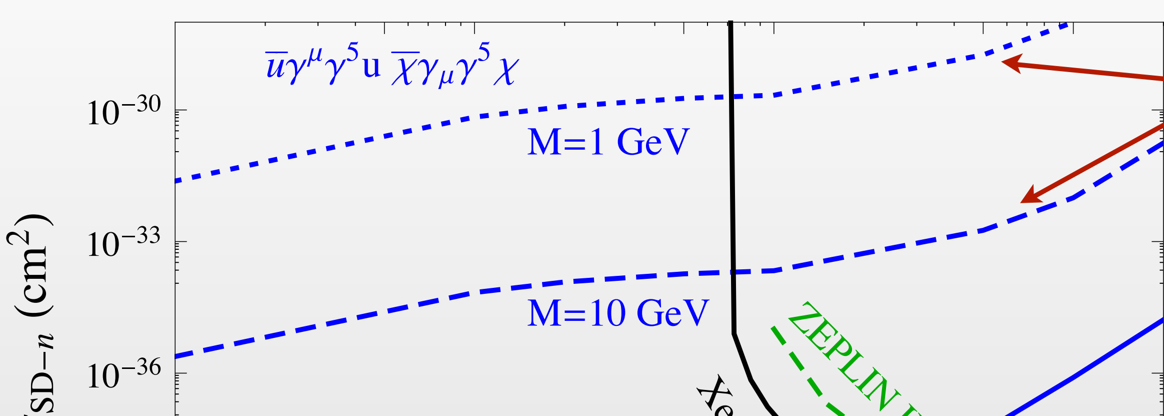
$$\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{p_T^2(1j)}{[q^2 - M^2]^2} \sim \alpha_s g_\chi^2 g_q^2 \frac{1}{p_T^2(1j)} \qquad q \sim p_T(1j)$$

σ_{1j}/σ^{DD} drops like M^4

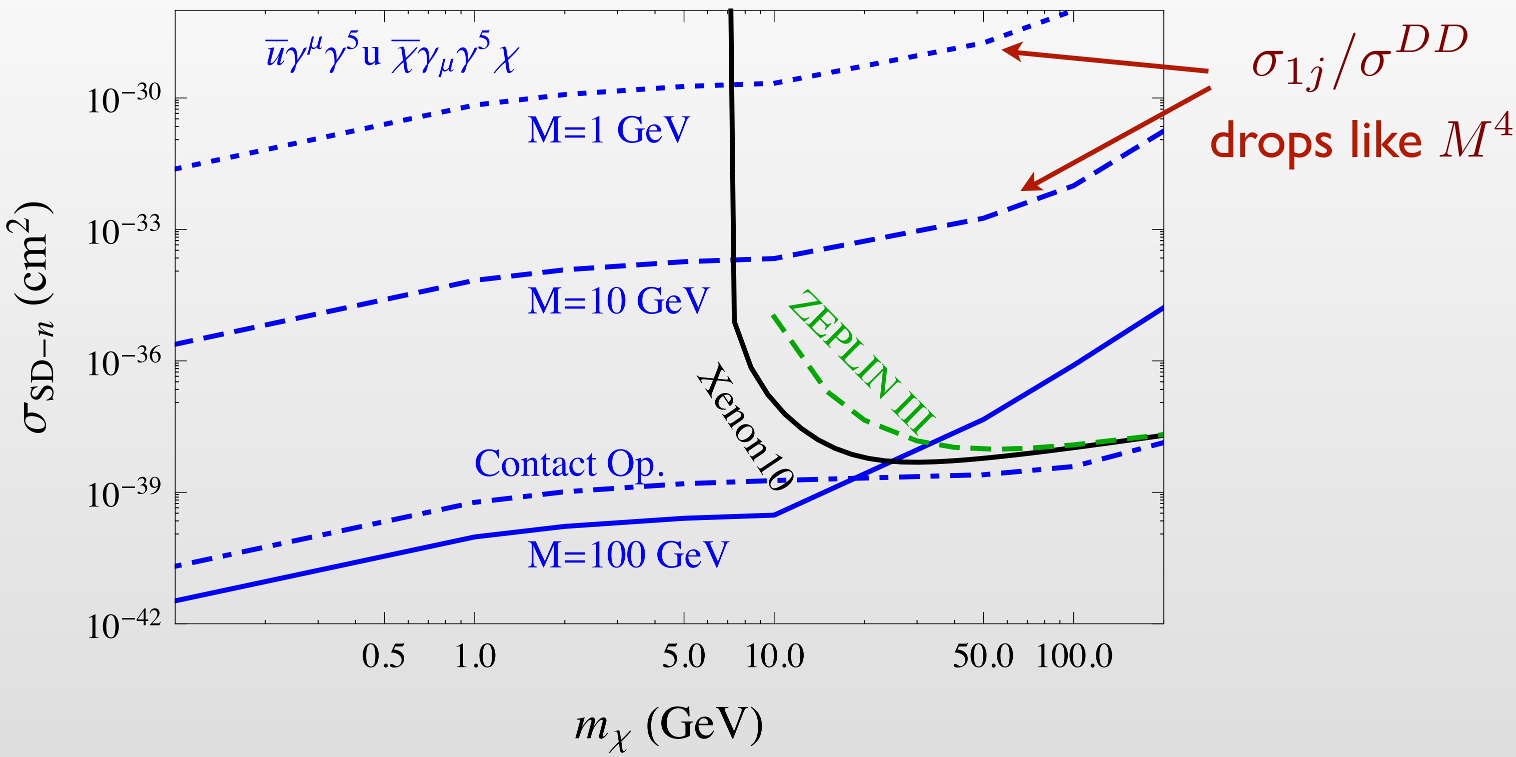
Effects of Light Mediator



σ_{1j}/σ^{DD}
drops like M^4

σ_{1j}/σ drops like M

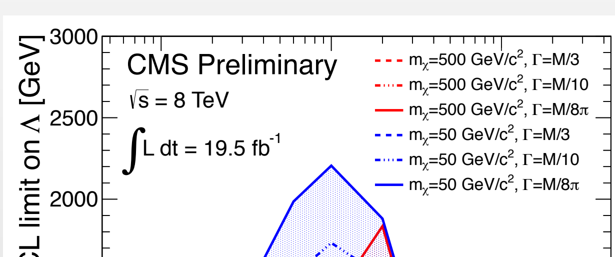
Effects of Light Mediator



If a direct dark matter signal is in conflict with collider bounds, a new light state should be introduced to reconcile

Caveat #2

★ The effective field theory could break down, especially at the 13 TeV LHC



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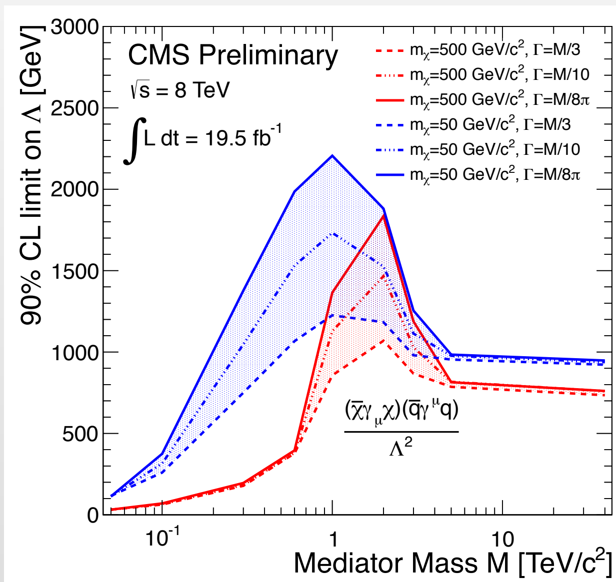
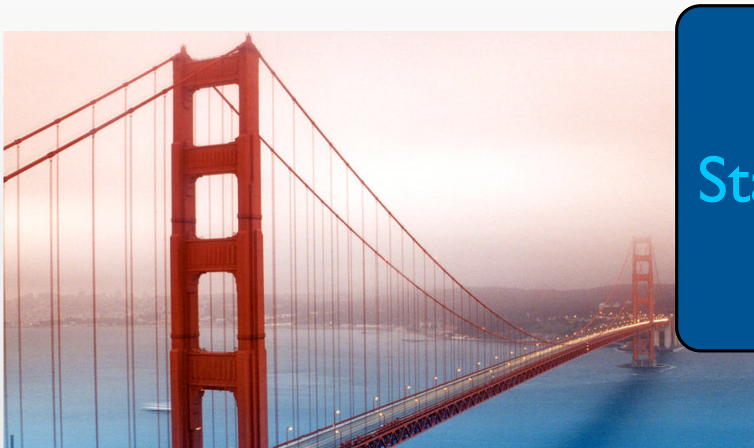


★ A UV (simple) model is required to interpret data

Possibilities



Standard Model

★ A UV (simple) model is required to interpret data

Possibilities

Standard Model

Dark Matter Sector

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

Simplified Dark Matter Models

- ★ Boson portal: Higgs portal

H —— Dark Matter Sector

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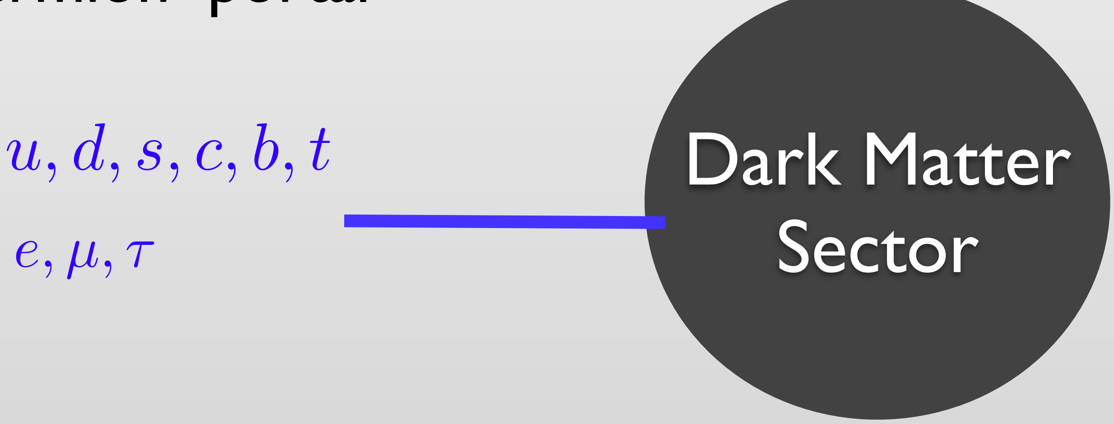
Simplified Dark Matter Models

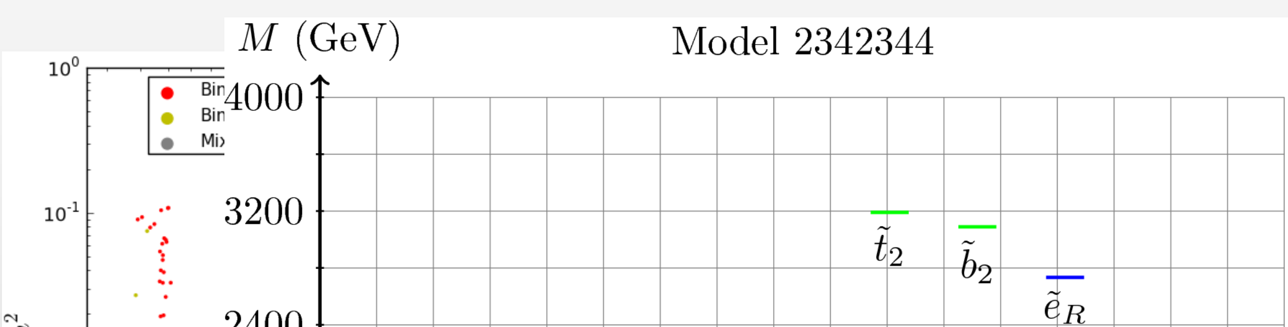
- ★ Boson portal: Higgs portal

- ★ Fermion portal



It exists in MSSM

The SUSY searches are still relevant for many DM models



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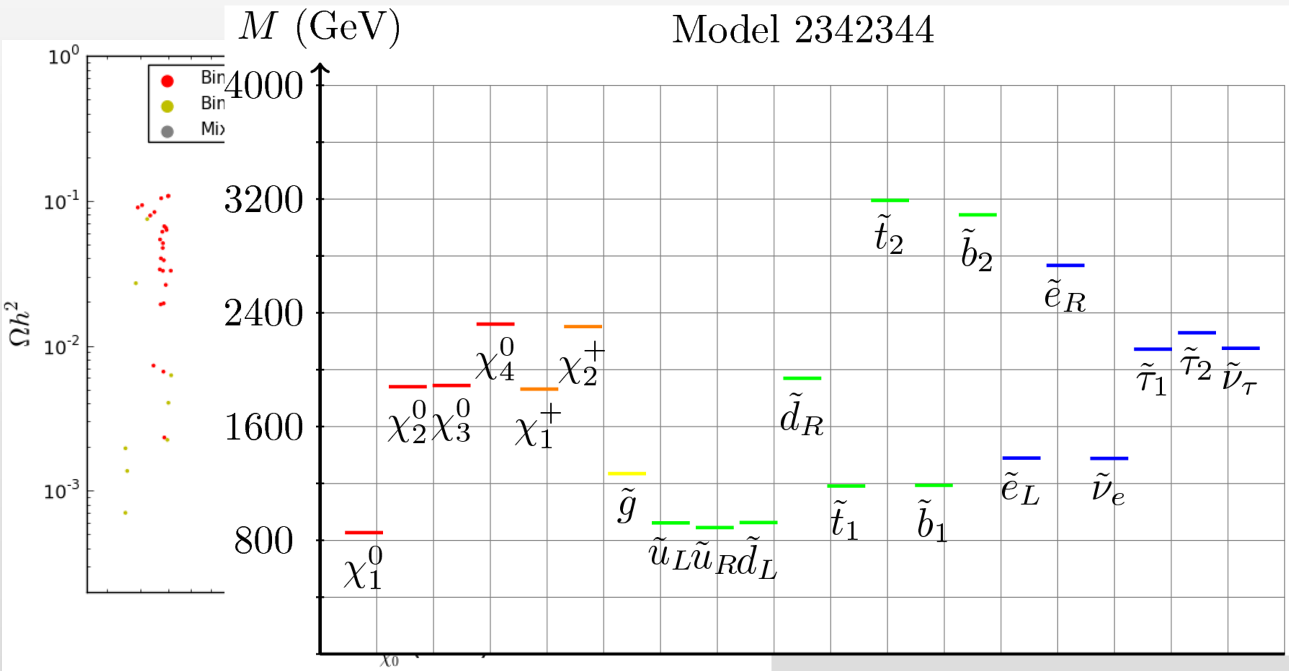

Figure 3: Bino-squark coannihilation benchmark sparticle spectrum.

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

Fermion Portal Dark Matter

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

one boson and one fermion

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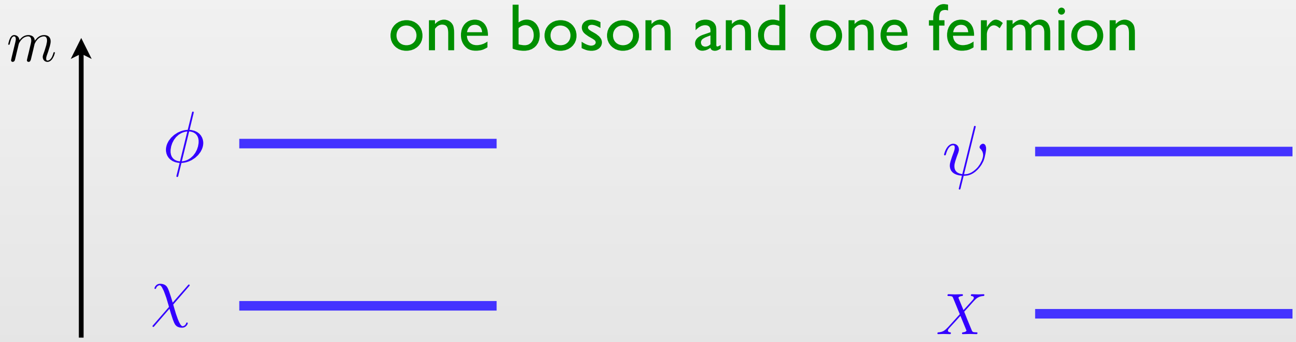
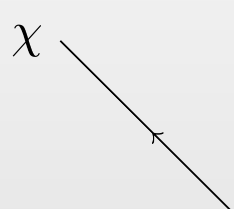


a Majorana or Dirac Fermion or a scalar dark matter

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

Quark Portal Dark Matter

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



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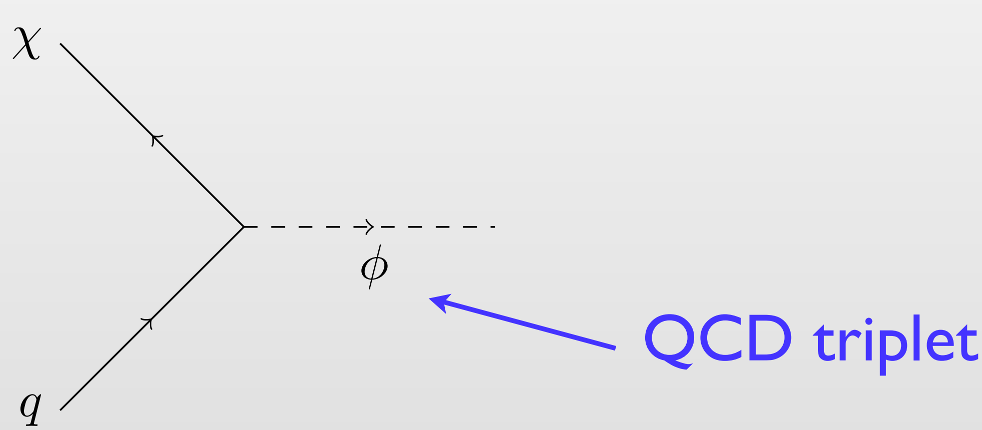
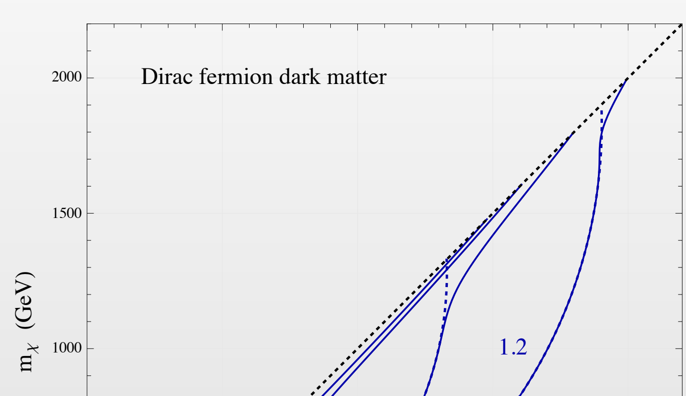
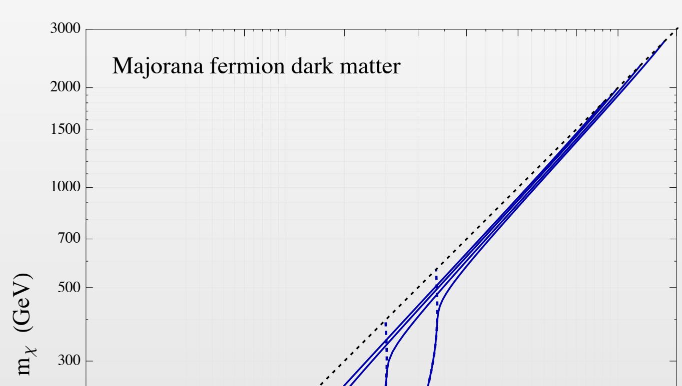


Thermal Relic Abundance





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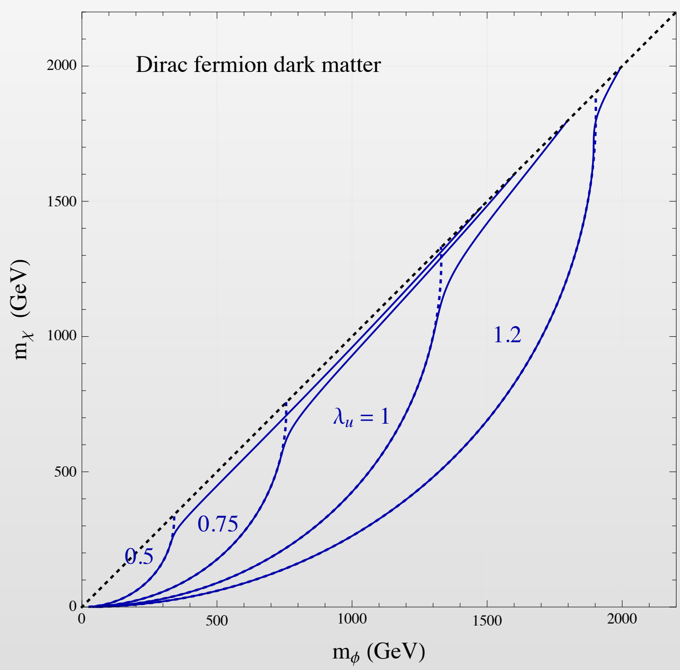
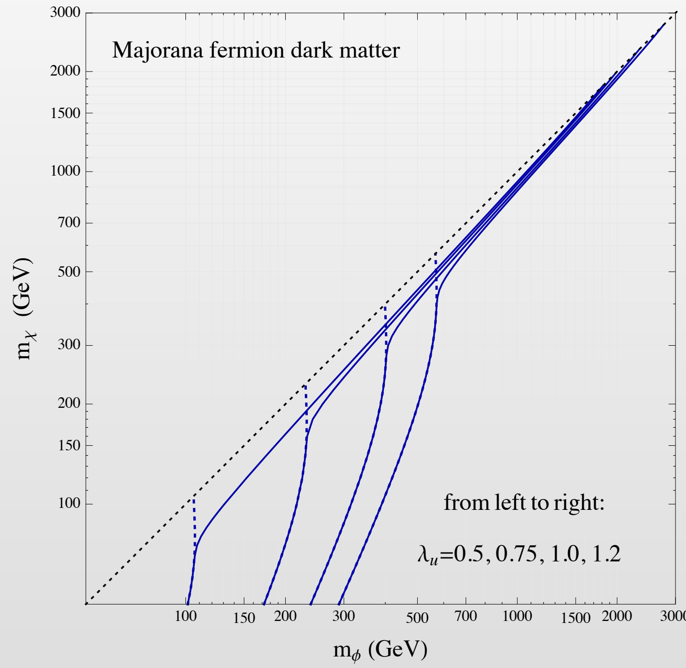
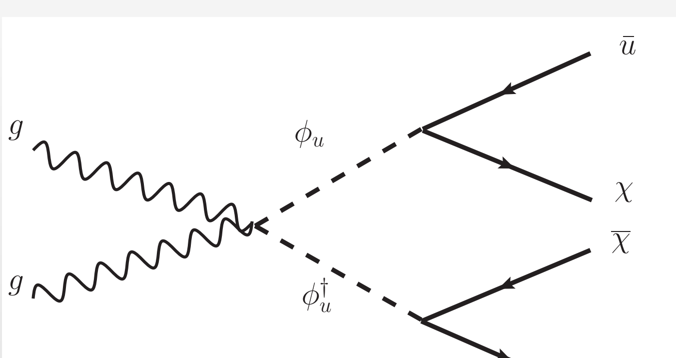


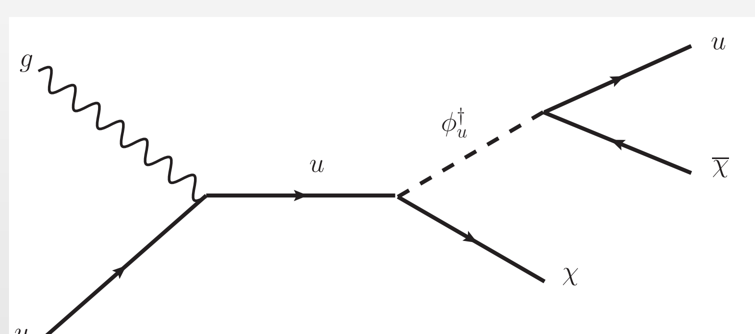


p-wave suppressed

Signatures at LHC

at the LHC





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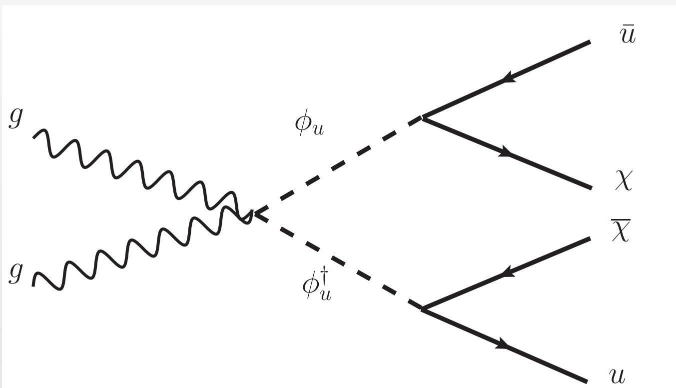
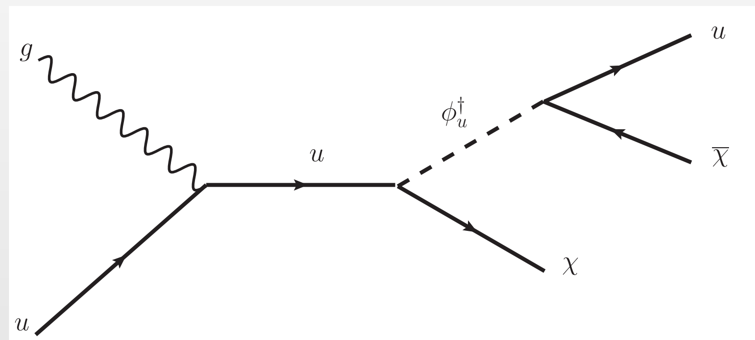
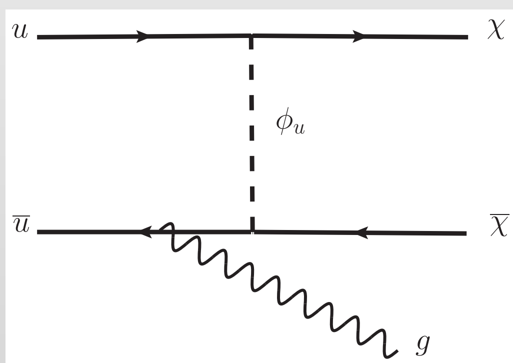
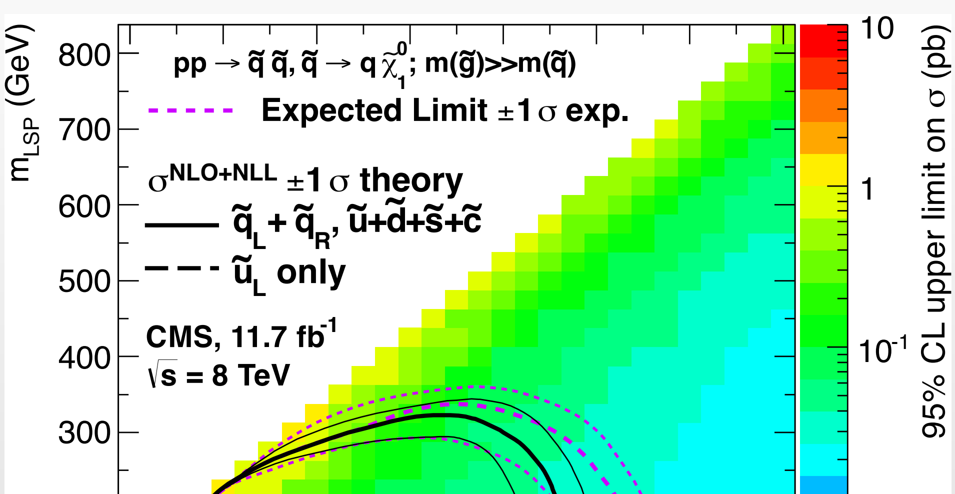
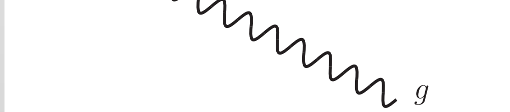






Quark Portal Dark Matter





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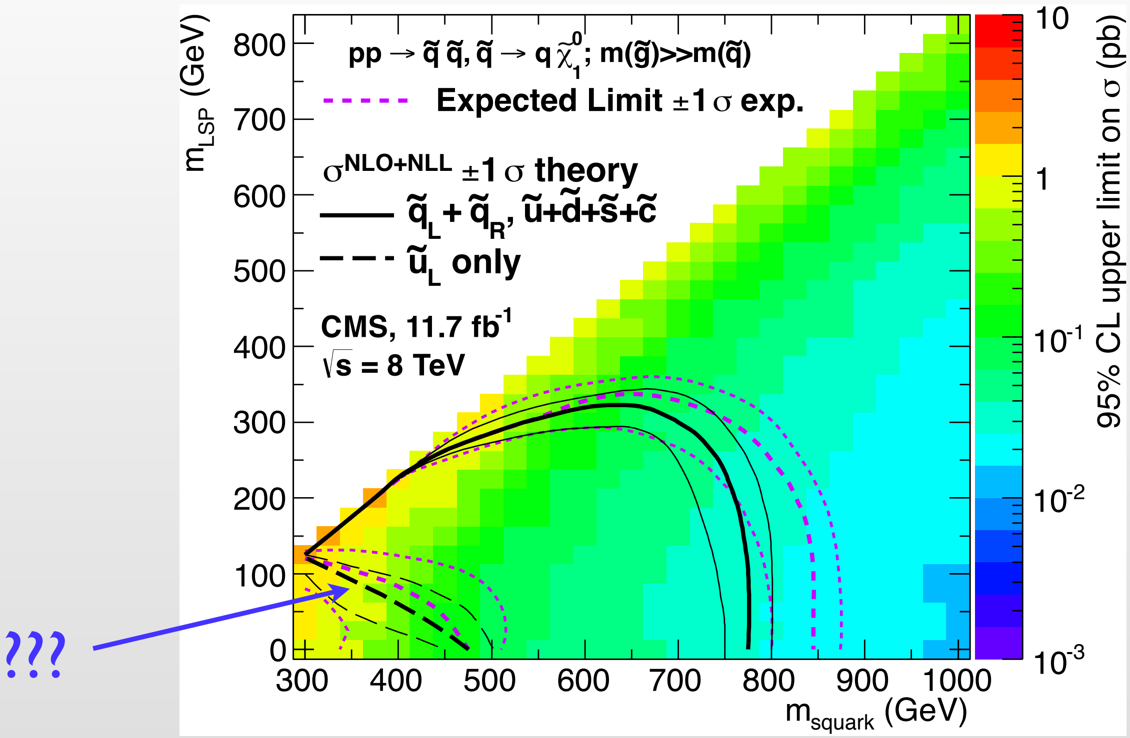
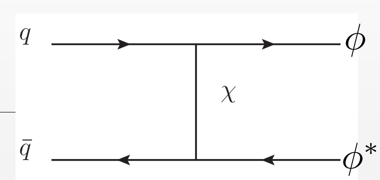
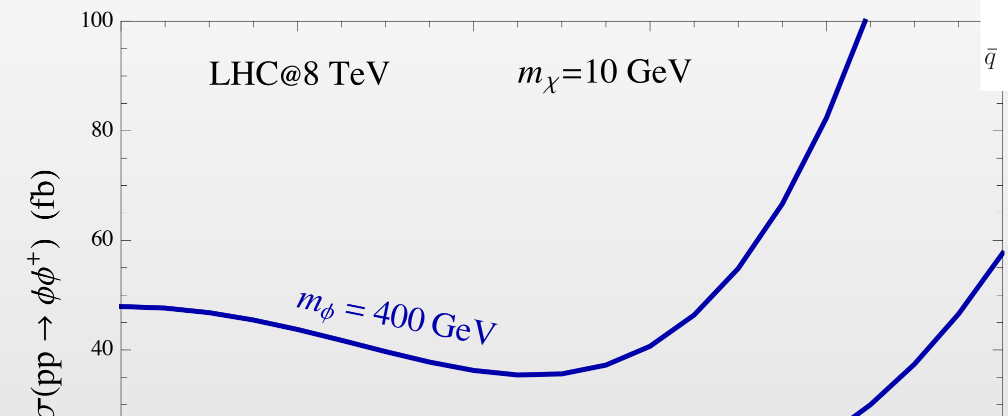


two jets + MET

QCD and Yukawa Interference





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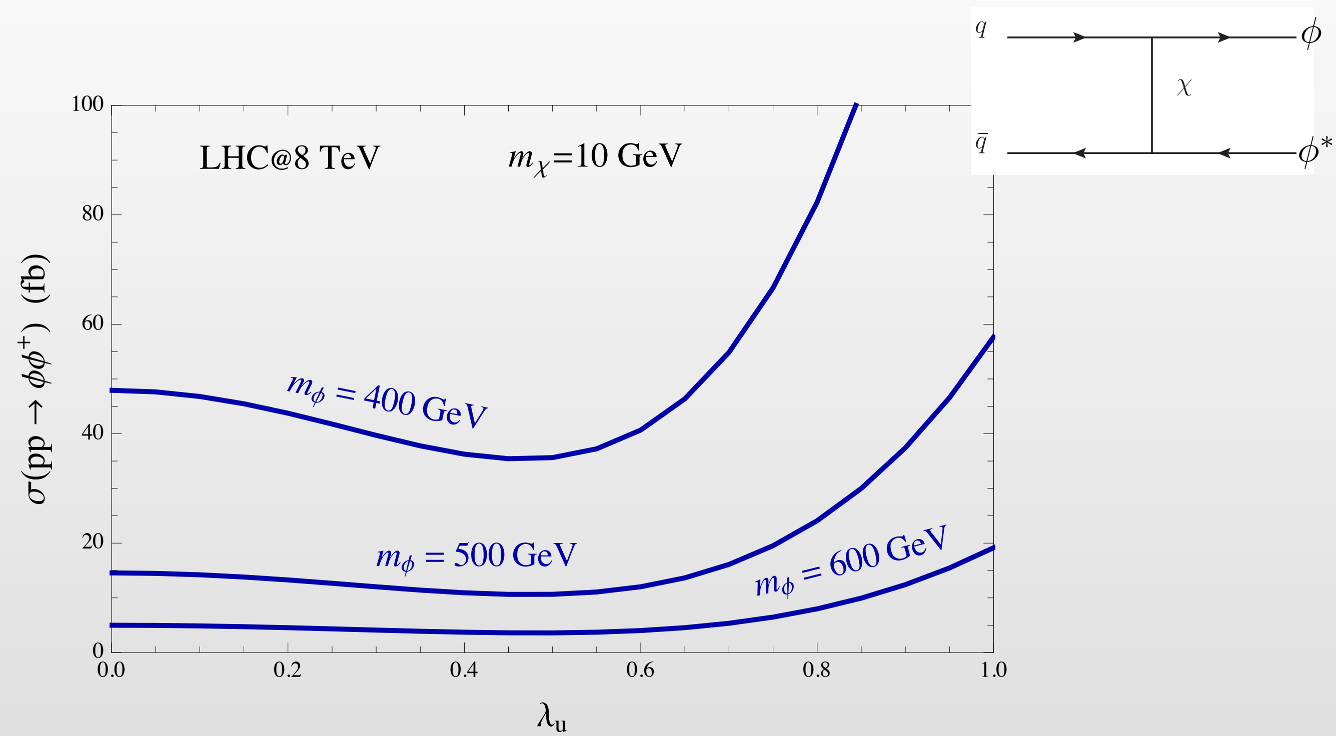
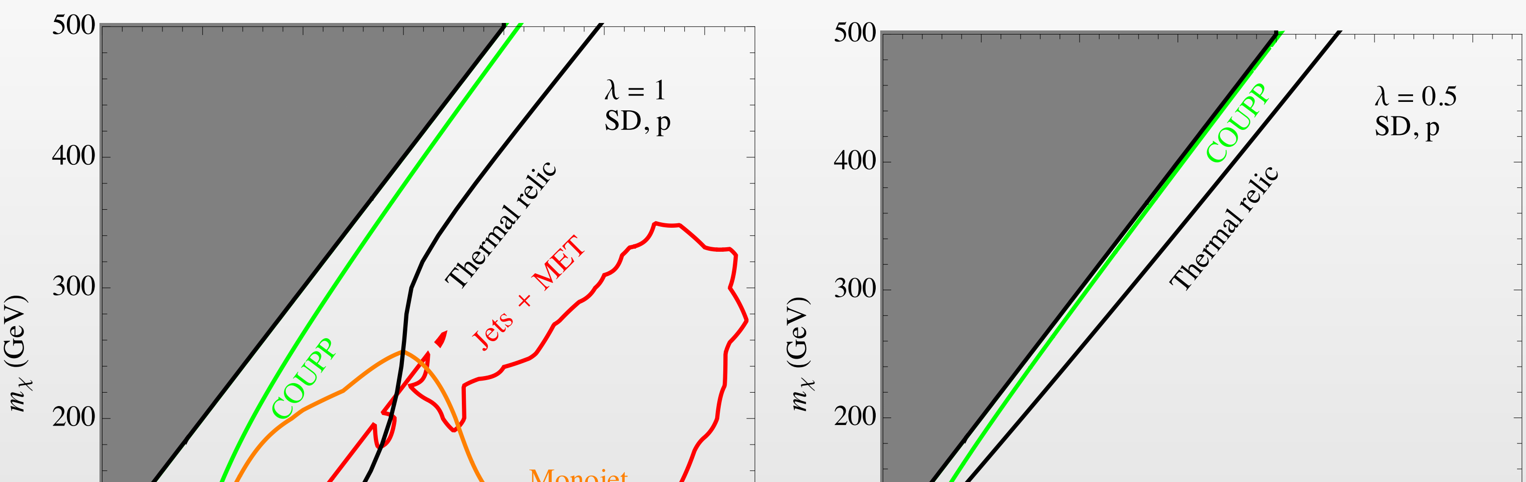


interesting deconstructive interference region

Current Allowed Parameter Space



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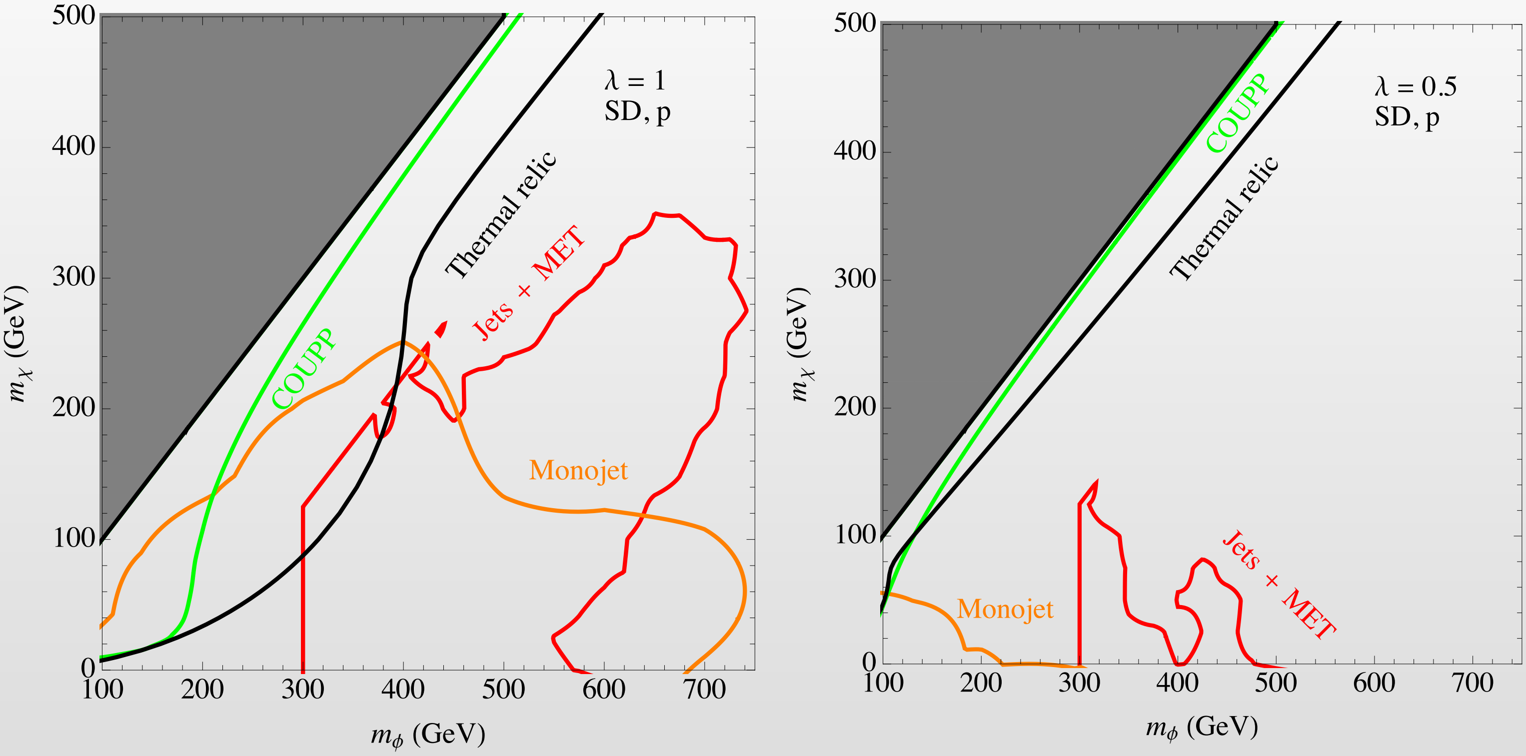
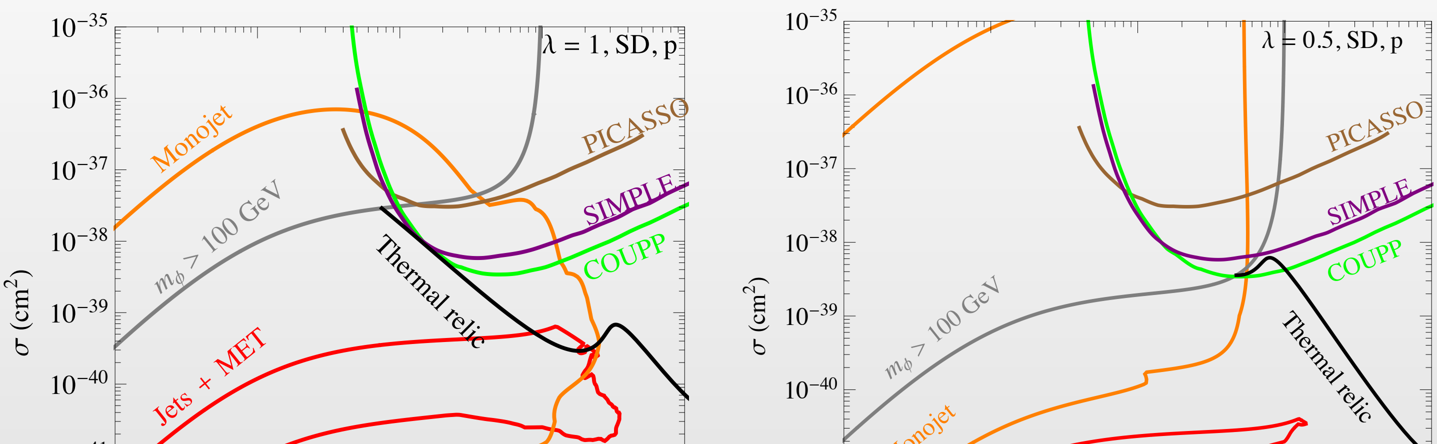


Majorana fermion dark matter up-quark

Compare to Direct Detection



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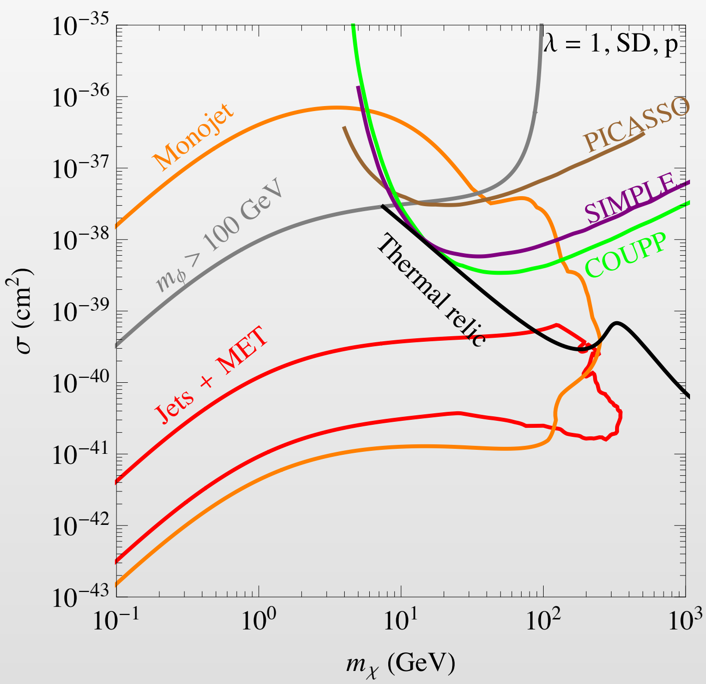

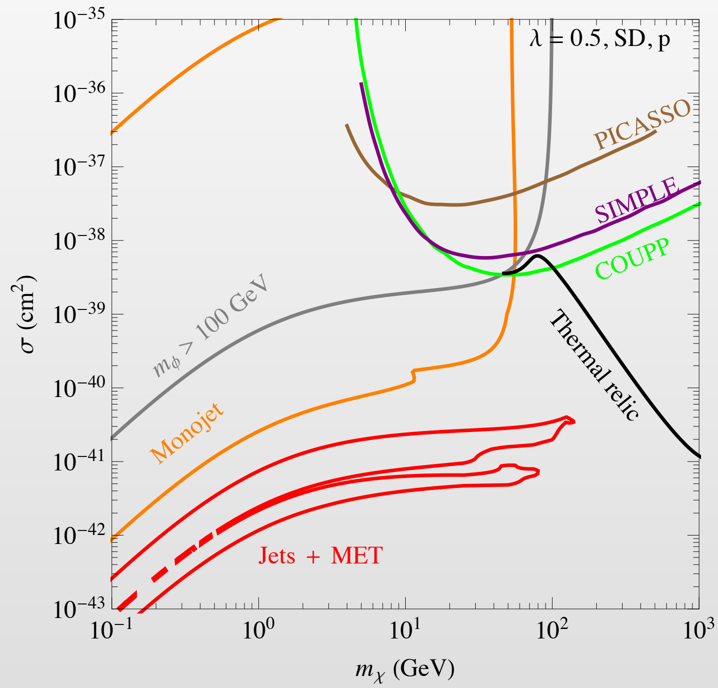

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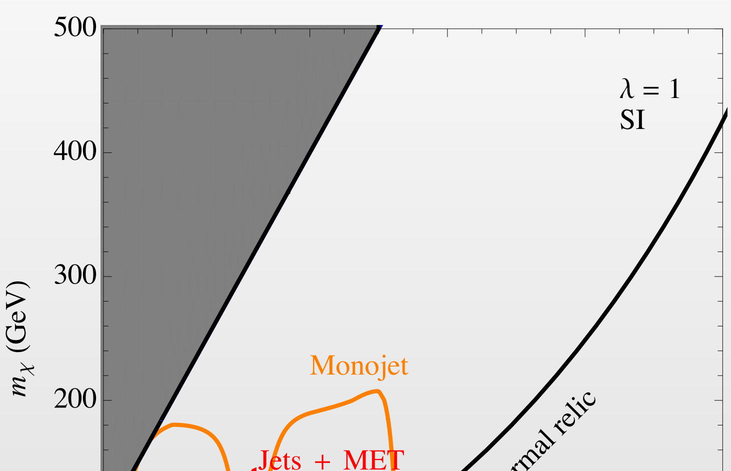
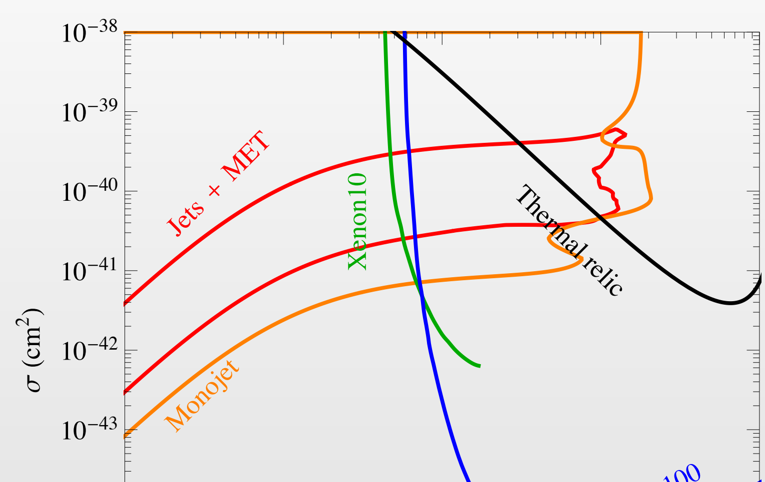
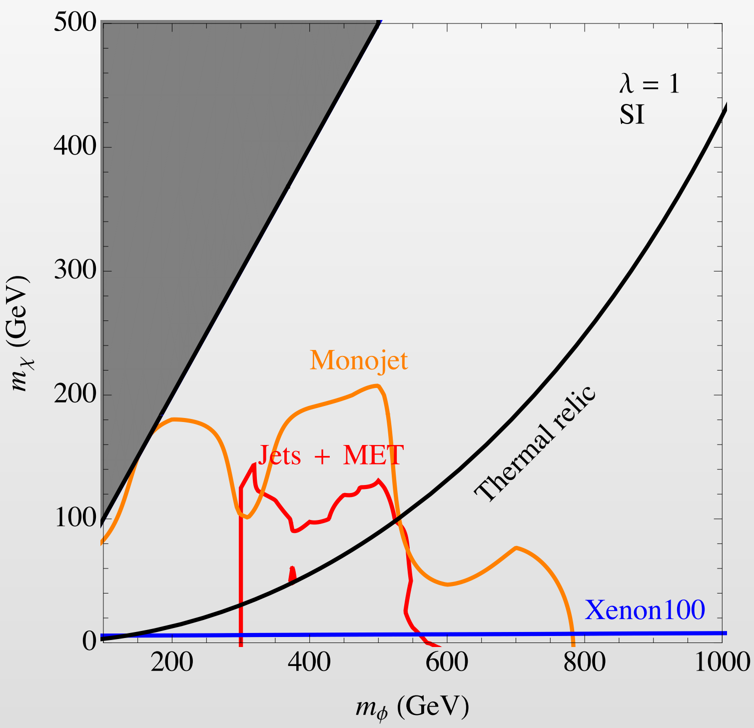
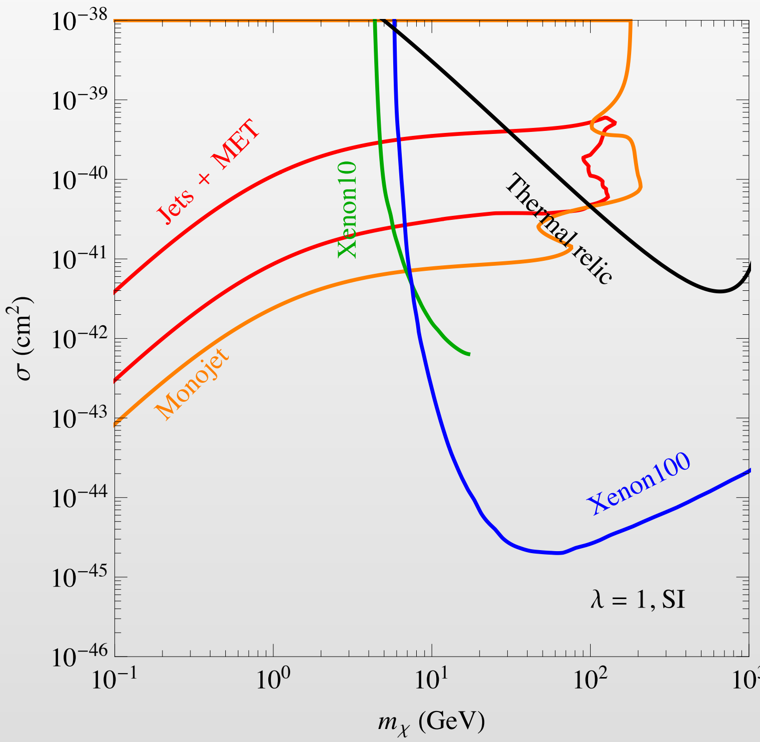
Dirac Fermion Dark Matter





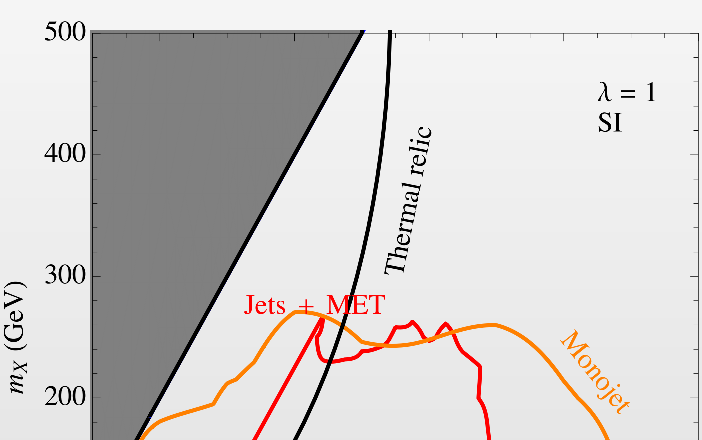
Dirac Fermion Dark Matter

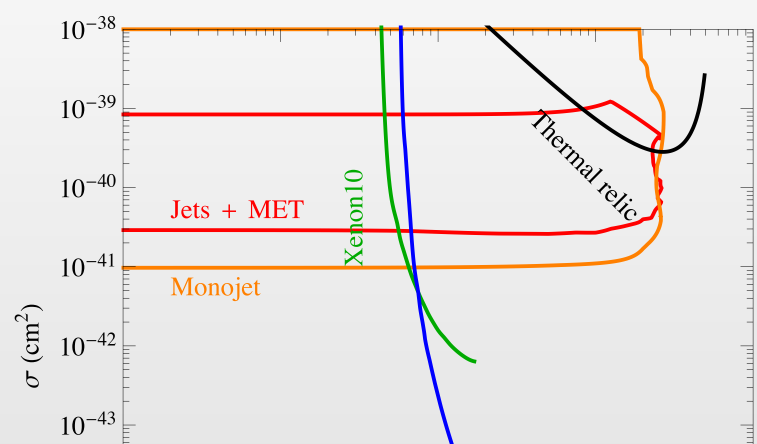




up-quark

Complex Scalar Dark Matter





up-quark

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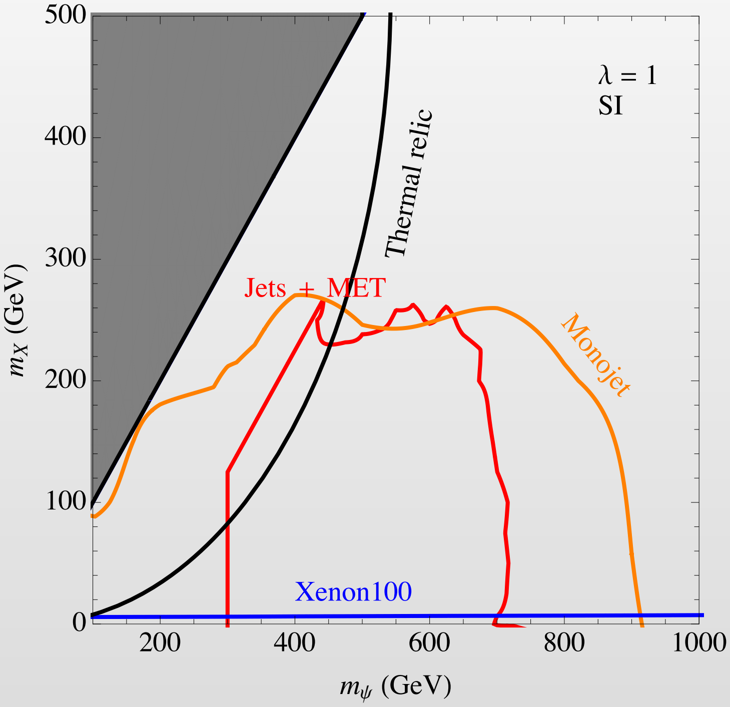
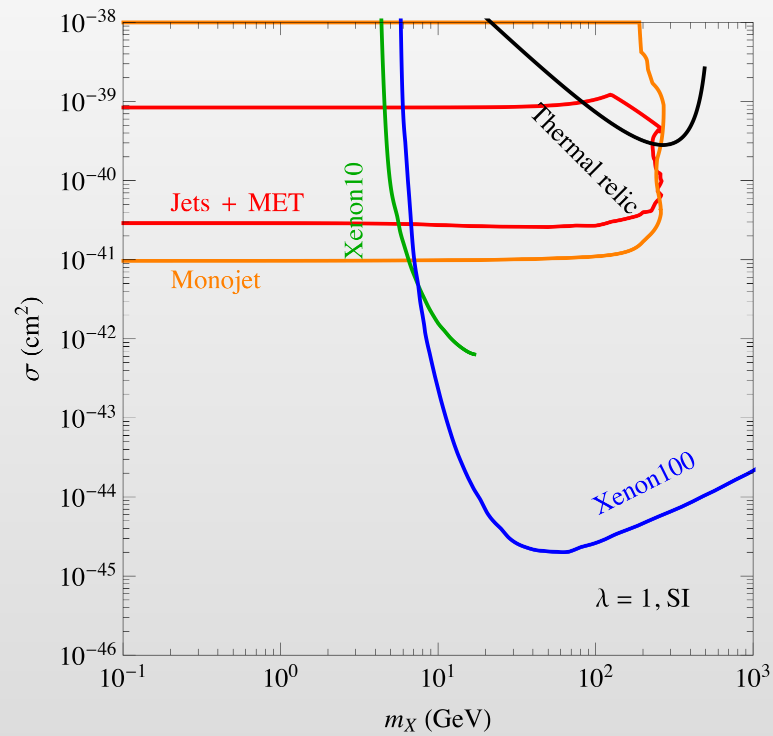
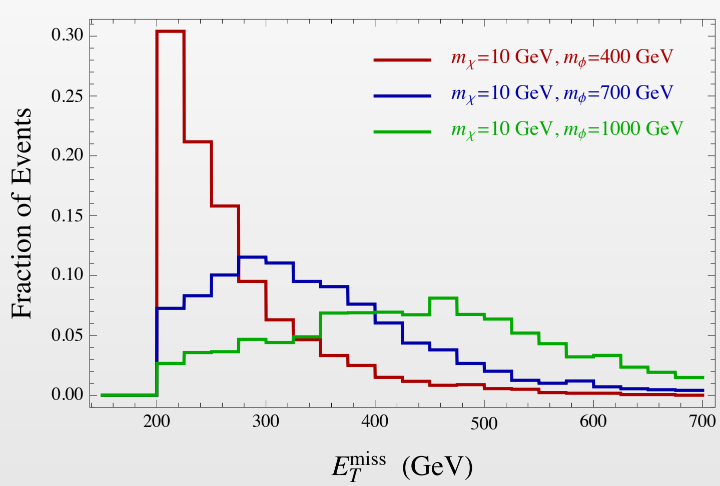
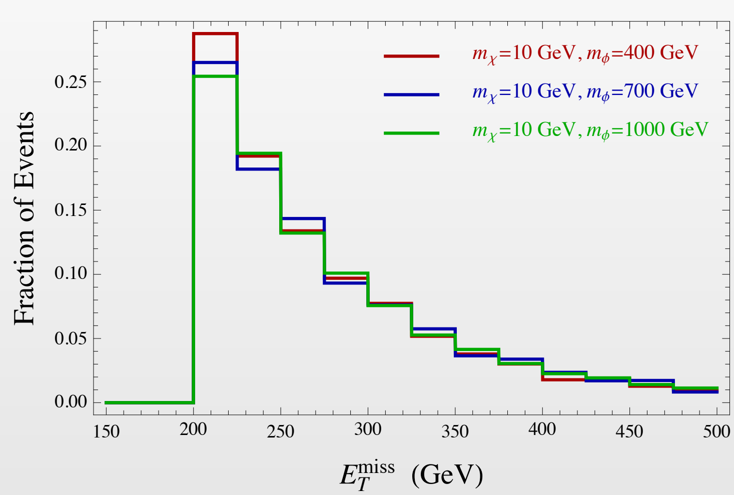




up-quark

MET Distribution in mono-jet





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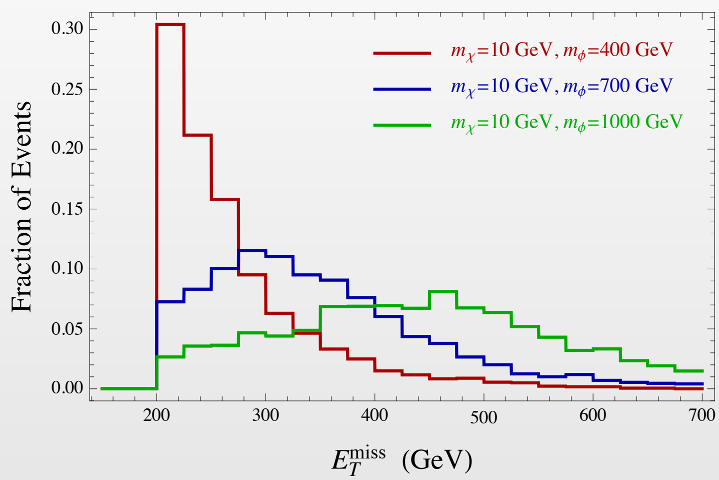
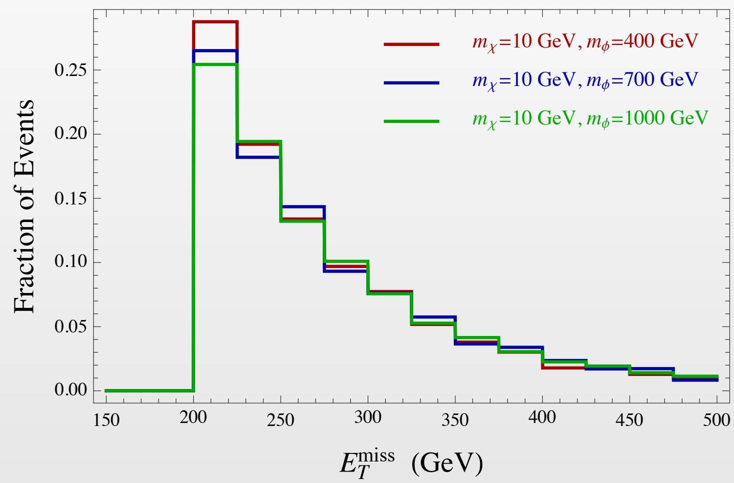
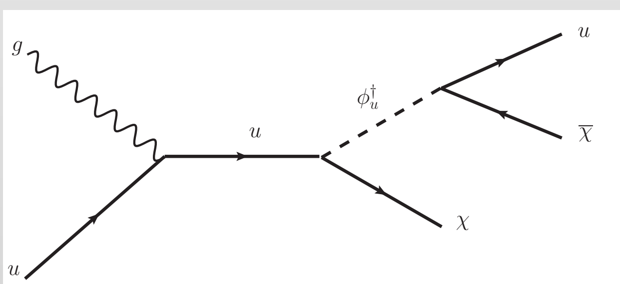
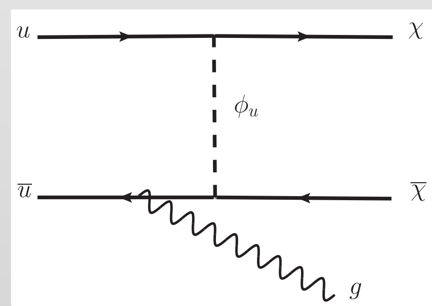
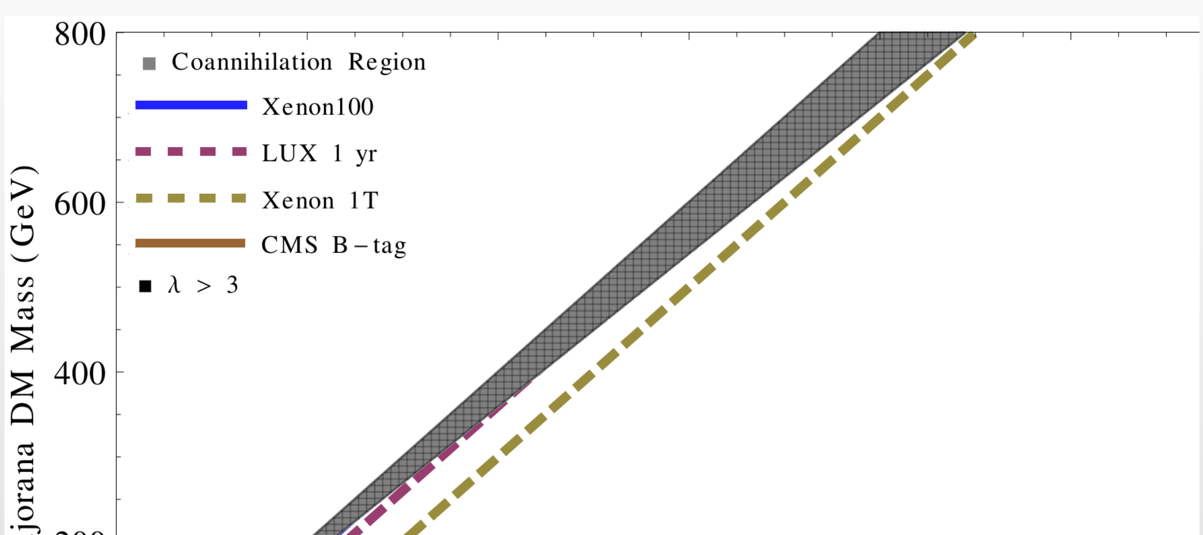








Majorana third generation



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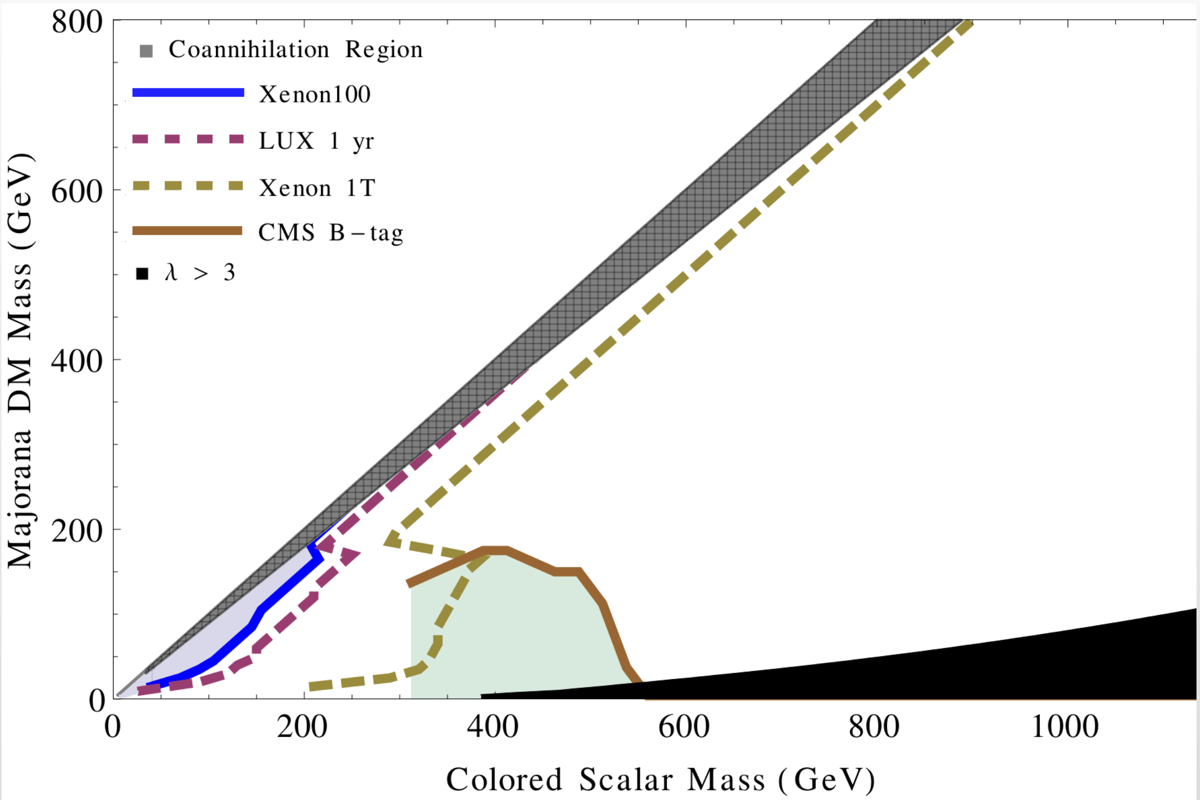

Chang, Edezhath, Hutchinson, Luty, 1307:8120

Lepton Portal Dark Matter

Chang, Edezhath, Hutchinson, Luty, 1307:8120

Lepton Portal Dark Matter

Lepton Portal Dark Matter

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

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.

Lepton Portal Dark Matter

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

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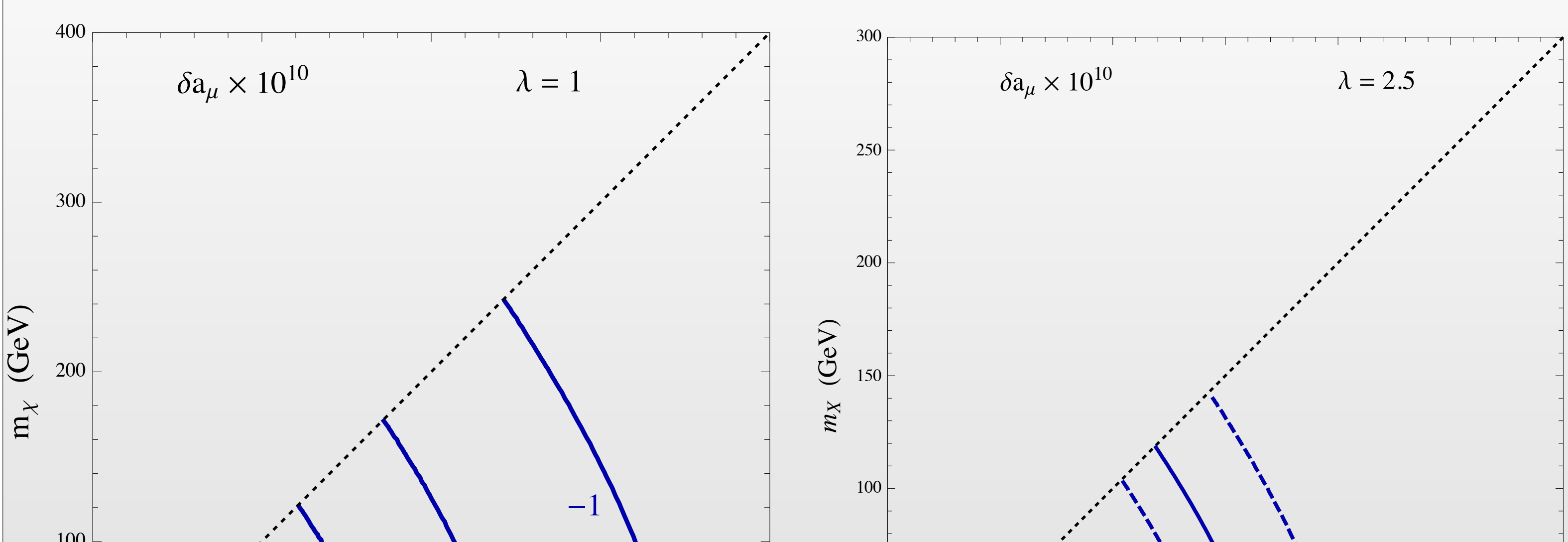
$a_\mu^{\rm SM} = (11659182.8 \pm 4.9) \times 10^{-10}$ 1105.3149, Hagiwara et. al.

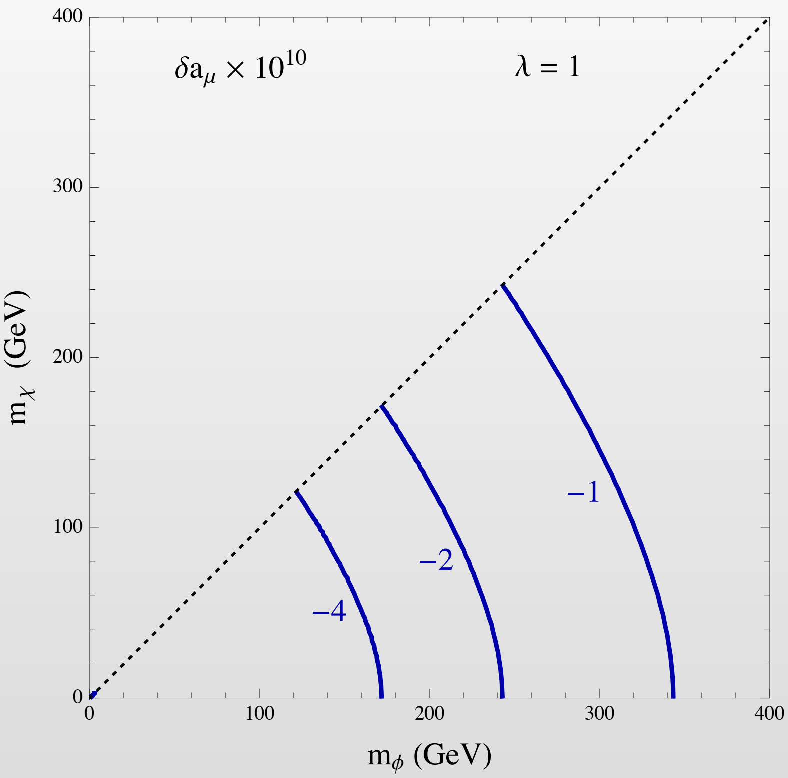
$$a_\mu^{\rm EXP} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10}$$

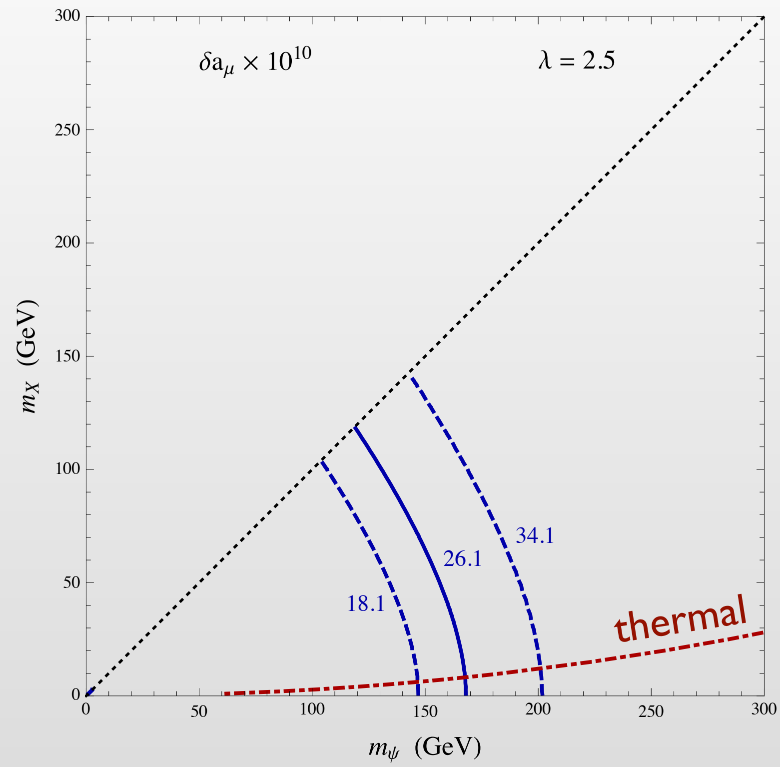
may need a positive contribution from new physics

Muon g-2



Muon g-2



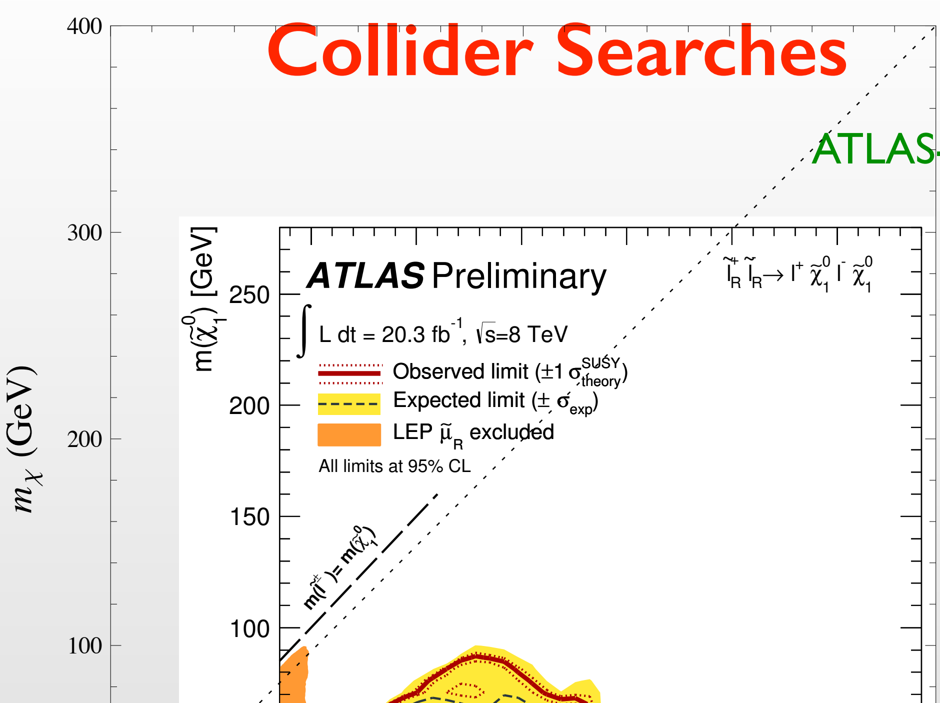


fermion dark matter

scalar dark matter

Collider Searches

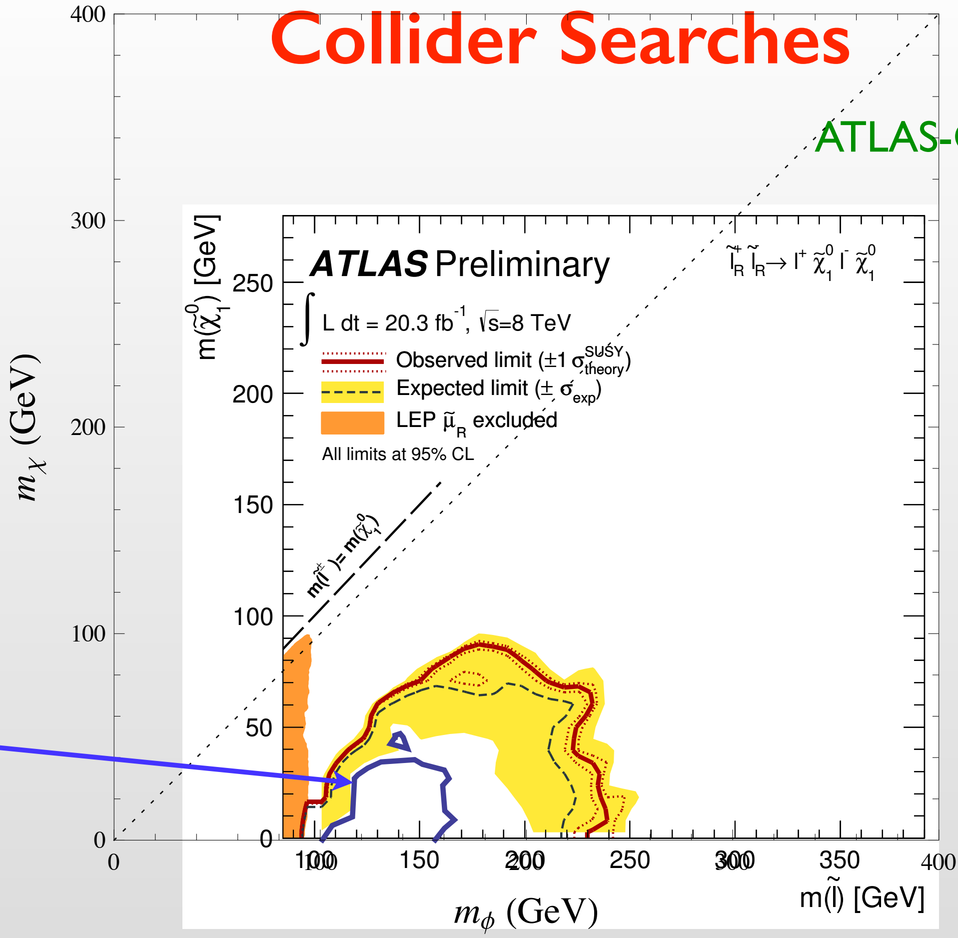
ATLAS-CONF-2013-049



for one

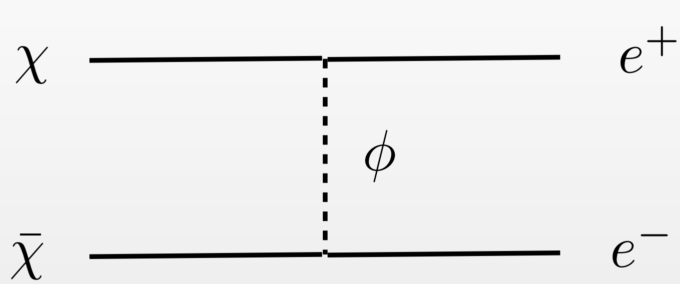
Collider Searches

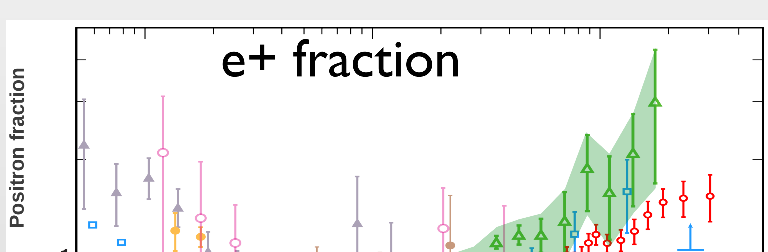
ATLAS-CONF-2013-049

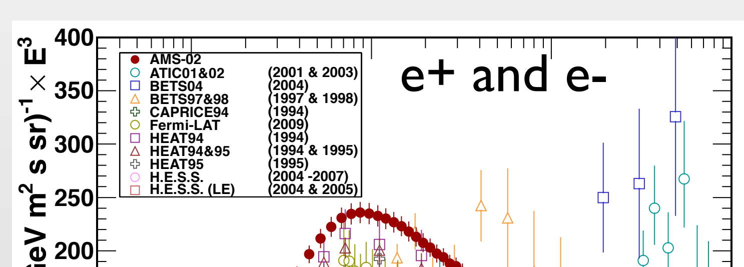


ATLAS kept both selectron and smuon and used MT2

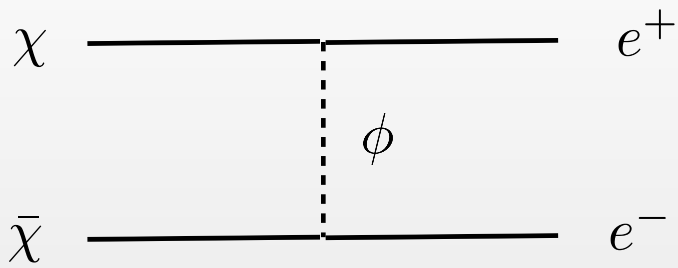
Indirect Detection

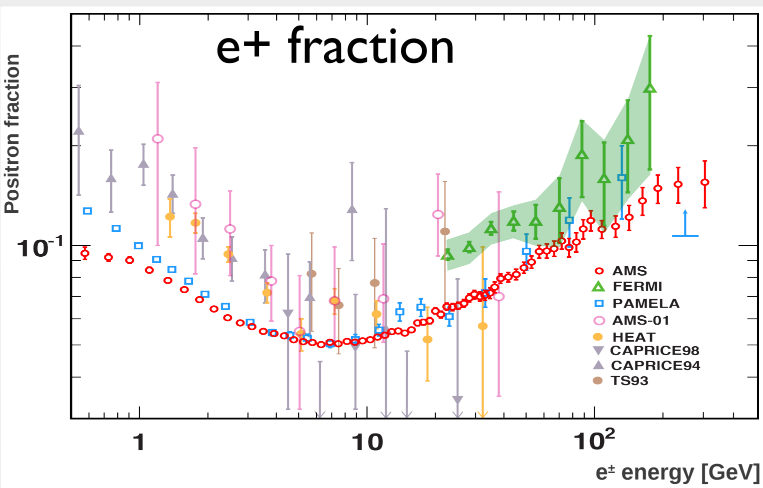


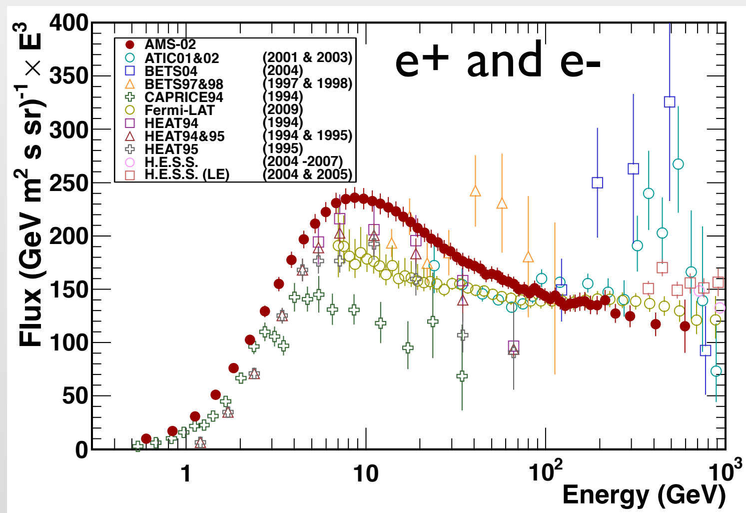




Indirect Detection

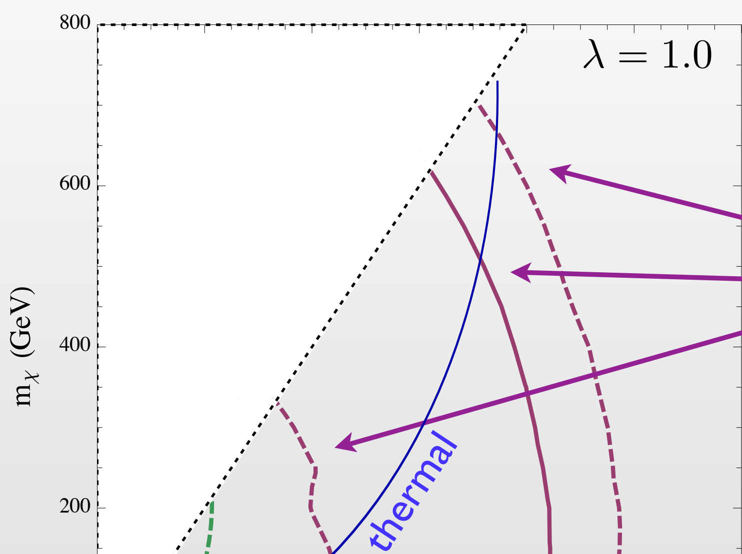






from AMS-02

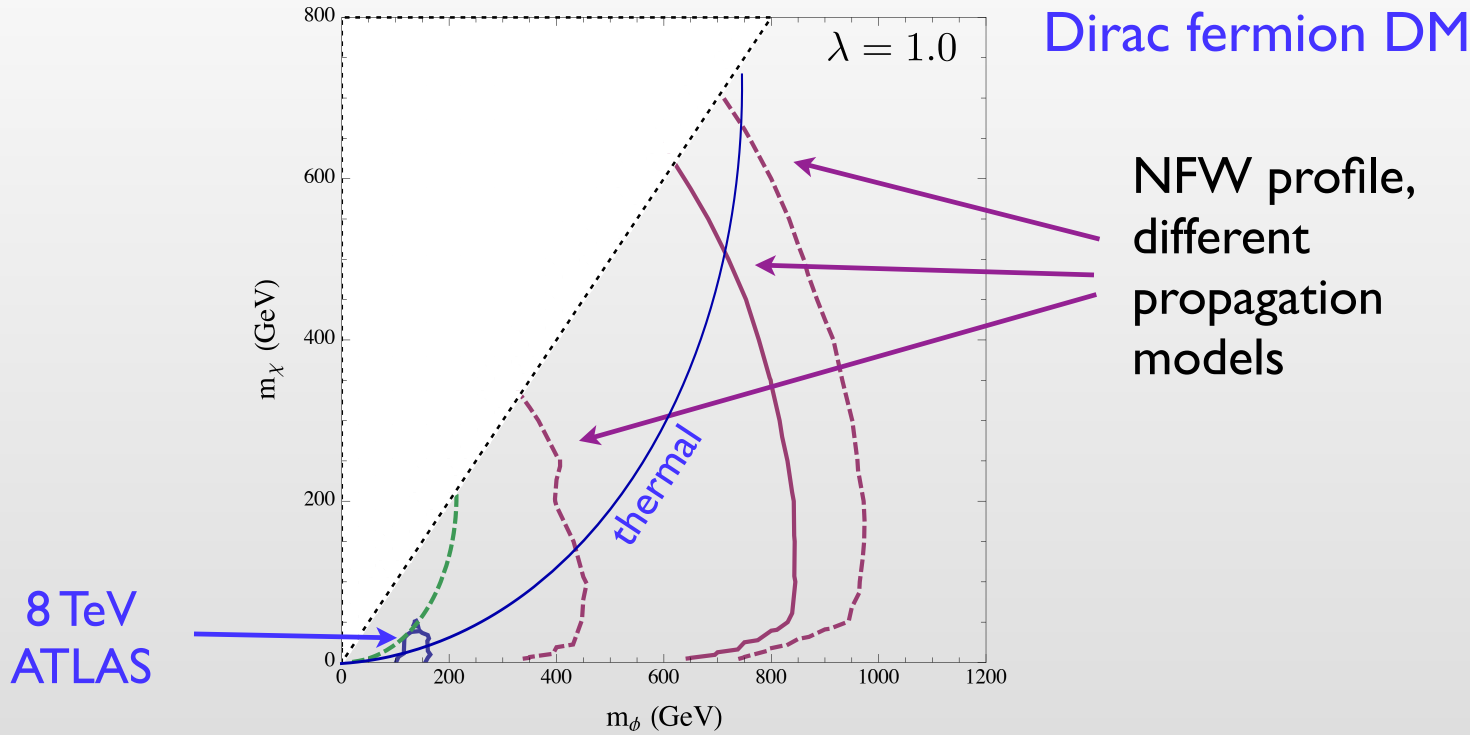
Indirect Detection Constraints



Dirac fermion DM

NFW profile, different propagation models

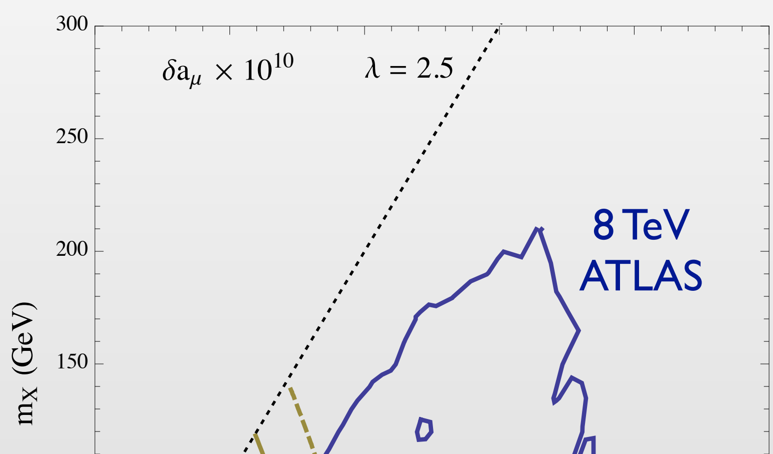
Indirect Detection Constraints



[see also model-independent constraints: 1306.3983 by Bergstrom, Bringmann, Cholis, Hooper, Weniger; 1309.2570 by Ibarra, Lamperstorfer, Silk]

Complex Scalar DM

The annihilation is p-wave suppressed; the indirect detection limits are irrelevant



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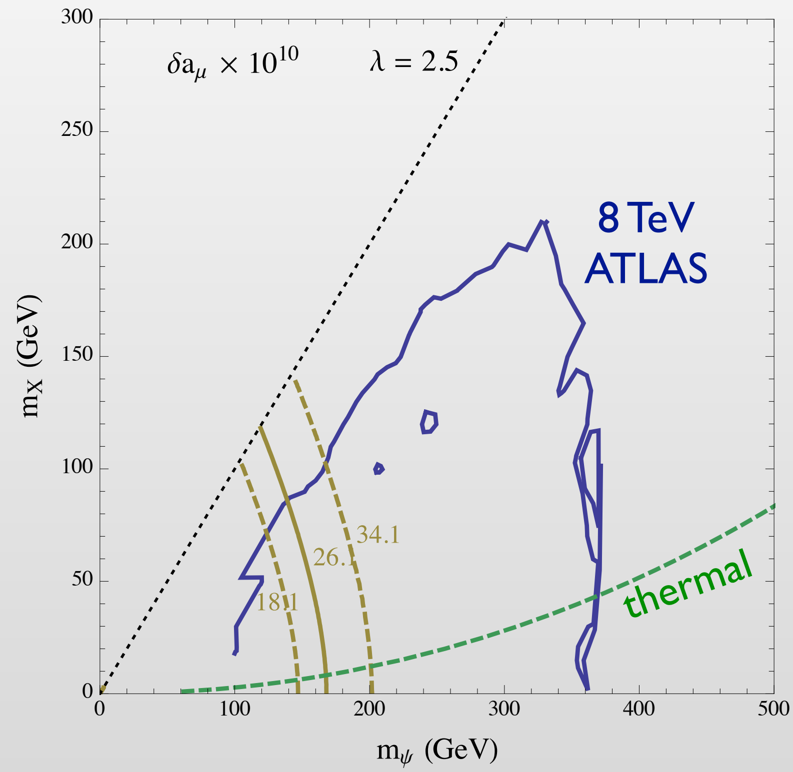
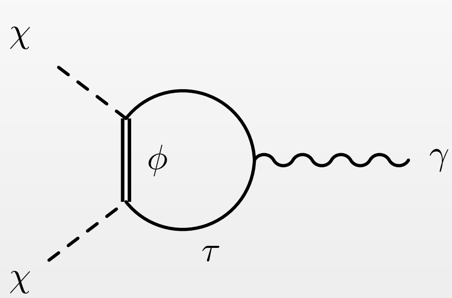
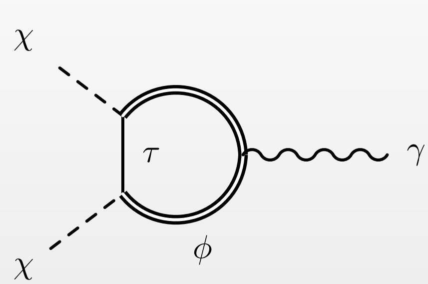


Direct detection





Agrawal, Chacko, Blanchet, Kilic, 1109.3516

for Dirac fermion DM: $\overline{\chi}\gamma^\mu(1-\gamma^5)\partial^\nu\chi\, F_{\mu\nu}$

Direct detection

Agrawal, Chacko, Blanchet, Kilic, 1109.3516

for Dirac fermion DM: $\overline{\chi}\gamma^{\mu}(1-\gamma^{5})\partial^{\nu}\chi\, F_{\mu\nu}$

charge-radius operator for complex scalar DM

$$\partial_{\mu}X\partial_{\nu}X^{\dagger}F^{\mu\nu}$$

Complex scalar DM

$$\partial_{\mu}X\partial_{\nu}X^{\dagger}F^{\mu\nu}$$

$$C(m_1,m_2) = \frac{2\,\lambda^2\,e}{16\pi^2}\left[\frac{m_1^4-6m_1^2m_2^2+m_2^4}{(m_1^2-m_2^2)^3} - \frac{4(m_1^2+m_2^2)(m_1^4-5m_1^2m_2^2+m_2^4)}{3(m_1^2-m_2^2)^4}\,\ln\left(\frac{m_1}{m_2}\right)\right]$$

two interesting limits:

$$C(m_1,m_2) \propto (m_1-m_2) \qquad\qquad m_1-m_2 \ll 0$$

$$C(m_1,m_2) = -\frac{2\,\lambda^2\,e}{16\pi^2\,m_2^2}\left[1+\frac{2}{3}\ln\left(\frac{m_1^2}{m_2^2}\right)\right] \qquad\qquad m_1 \ll m_2$$

Complex scalar DM

$$\partial_\mu X \partial_\nu X^\dagger F^{\mu\nu}$$

$$C(m_1, m_2) = \frac{2\,\lambda^2\, e}{16\pi^2}\left[\frac{m_1^4 - 6m_1^2 m_2^2 + m_2^4}{(m_1^2 - m_2^2)^3} - \frac{4(m_1^2 + m_2^2)(m_1^4 - 5m_1^2 m_2^2 + m_2^4)}{3(m_1^2 - m_2^2)^4}\ln\left(\frac{m_1}{m_2}\right)\right]$$

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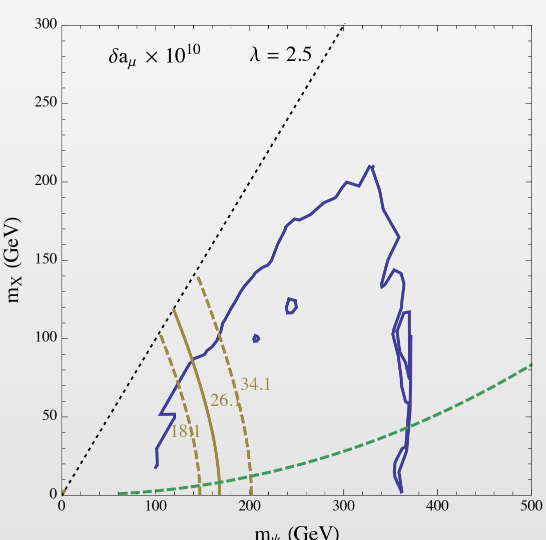
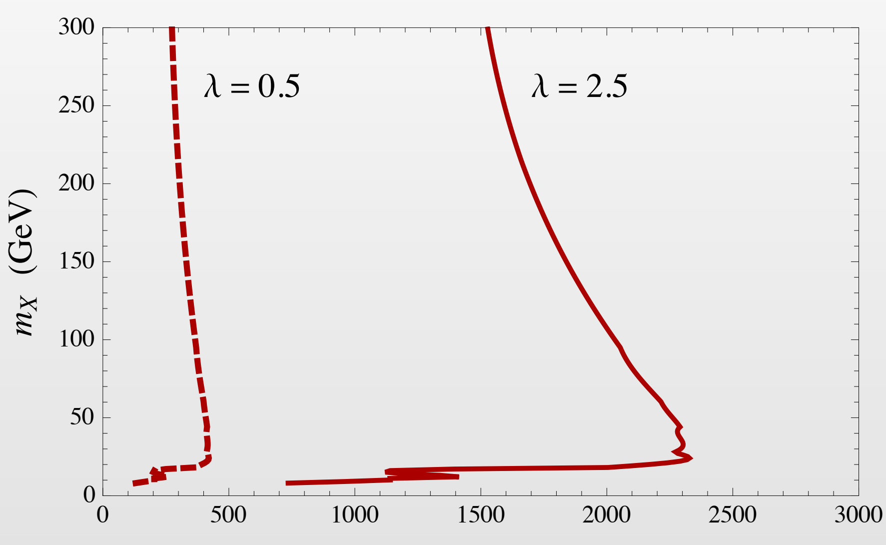
$$\sigma_{X-\text{nucleon}} = \frac{Z^2\, e^2\, C^2(m_{e^i}, m_\psi)}{8\pi\, A^2}\left[\frac{m_p^2\, m_X^2}{(m_p + m_X)^2} + \frac{m_p m_X^2 (2m_p^2 + m_X^2)}{2(m_p + m_X)^3}\, v^2\right]$$

for muon and Xenon $\quad \sigma_{X-\text{nucleon}} \approx 6 \times 10^{-45}\ \text{cm}^2 \quad \lambda = 1.0, \quad m_\psi = 500\ \text{GeV}$

Stringent constraints from LUX





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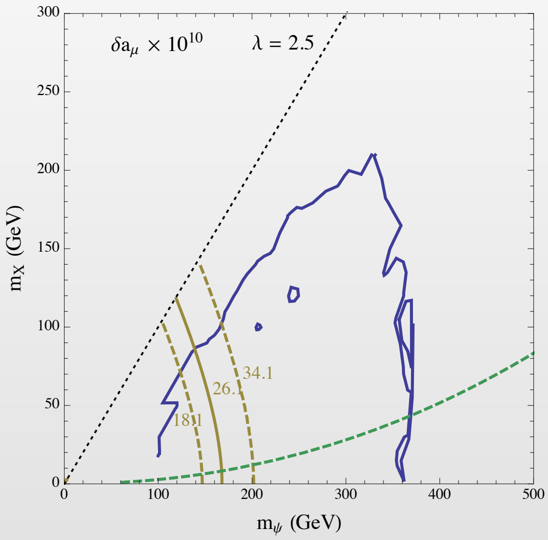
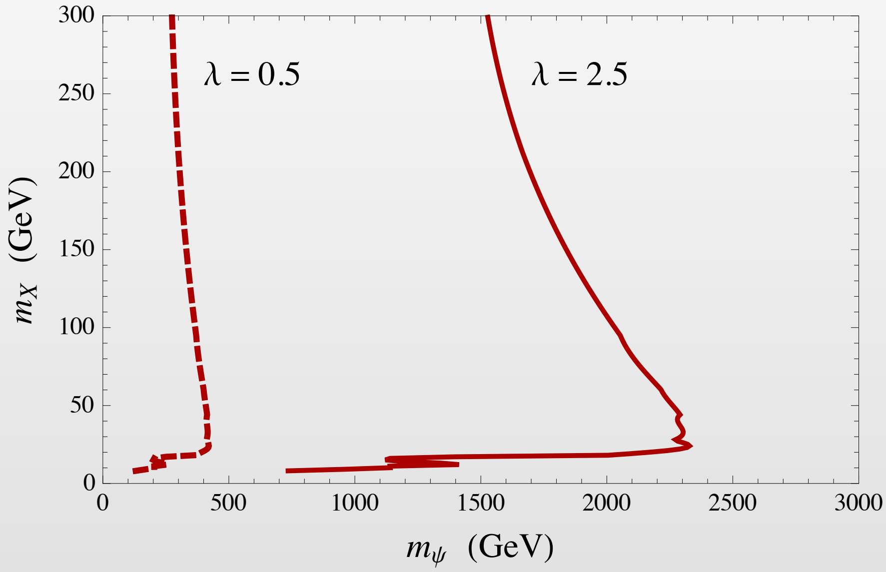
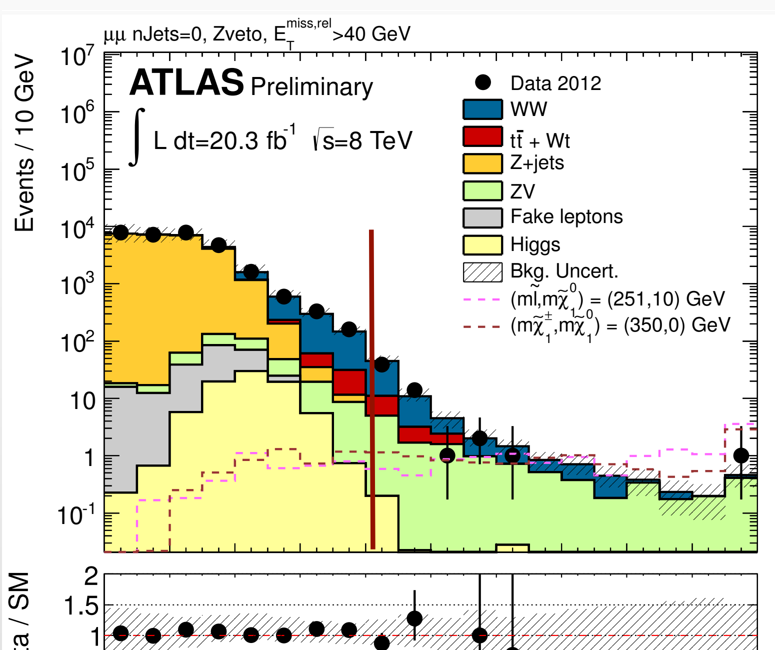




thermal complex dark matter is not in a good shape

LHC: lepton MT2



pt(j) > 20 GeV
jet veto

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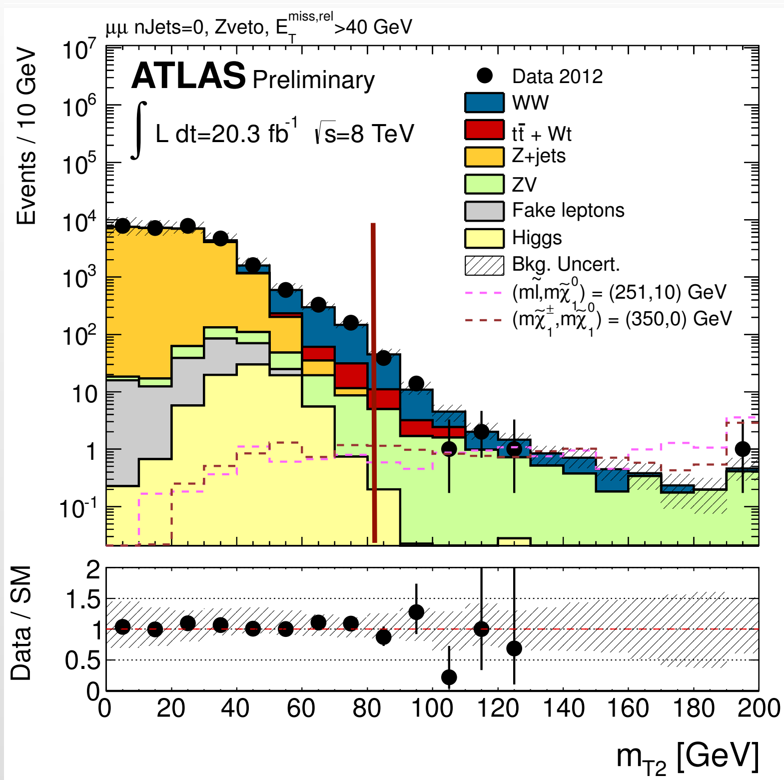

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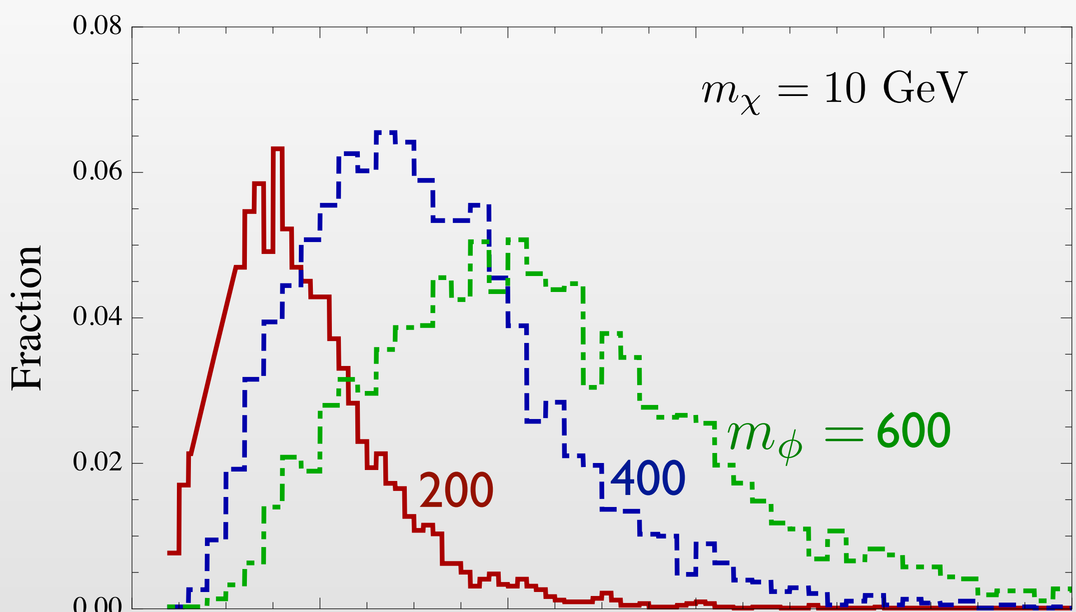
Can we define MET just based on leptons?

Another comment: lepton pt



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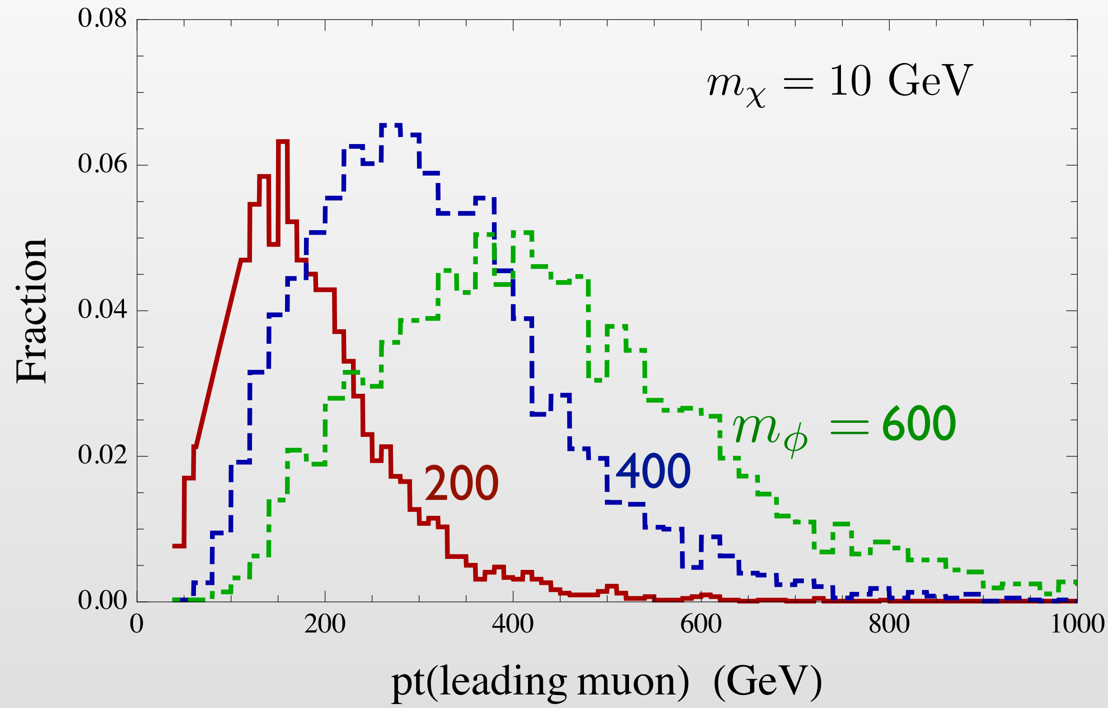


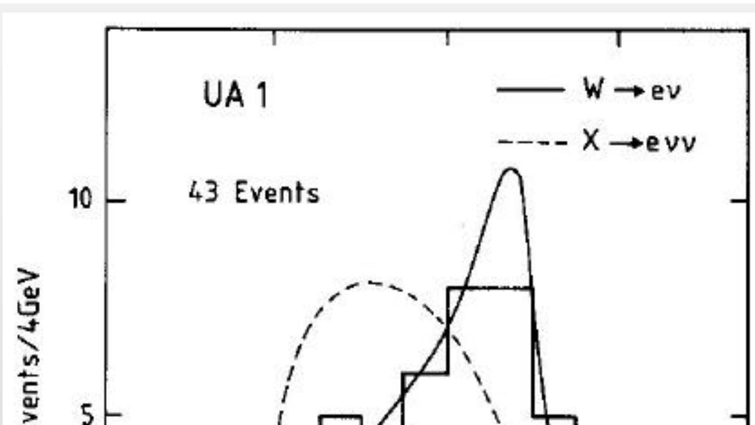
could have a large correlation with MT2

Can we repeat the W discovery?

Volume 122B, number 1 PHYSICS LETTERS 24 February 1983

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland



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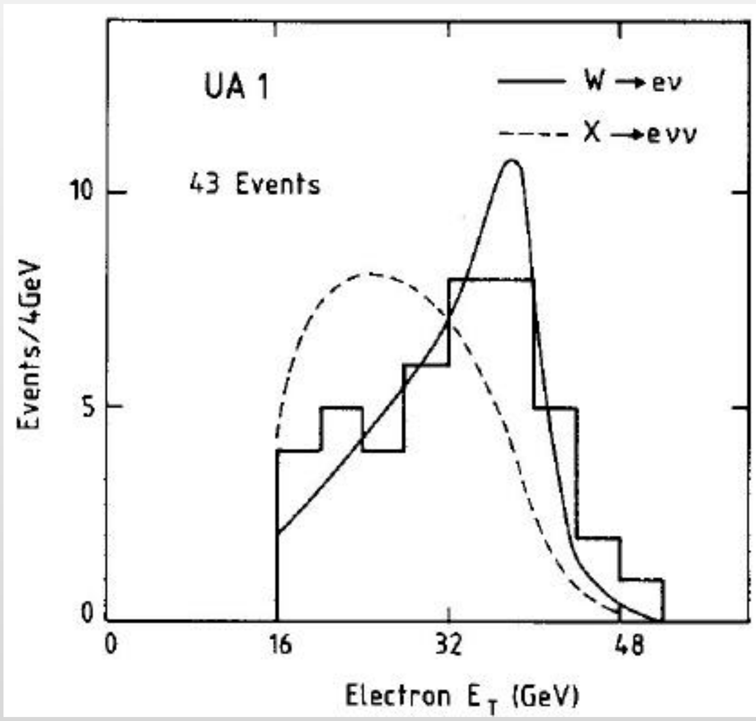

Conclusions

★ More searches for simplified SUSY or non-SUSY dark matter models should be performed at the LHC

★ Dedicated searches in the two jets + MET and two leptons + MET channels have chances to

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★ Dedicated searches in the two jets + MET and two leptons + MET channels have chances to discover the Fermion Portal Dark Matter

Thanks

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