Majorana dark matter with t-channel mediators

Mathias Garny (CERN)

MIAPP, 12.02.15

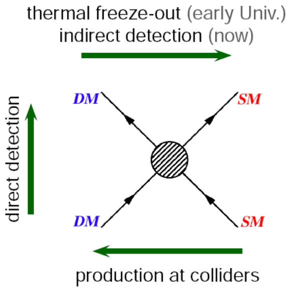
based on 1403.4634, 1306.6342

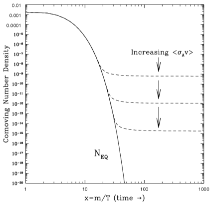
with Alejandro Ibarra, Miguel Pato, Sara Rydbeck, Stefan Vogl

‘The decade of the WIMP’

$$\Omega_\chi h^2 = 0.1198 \pm 0.0015 \simeq 0.1\,\mathrm{pb} \cdot c\,/\langle \sigma v \rangle$$

Planck 1502.01598





NB: other well-motivated possibilities: axions, ...

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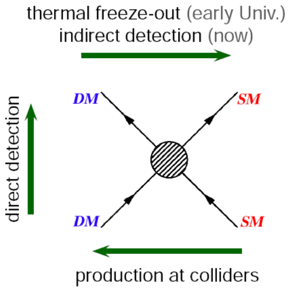
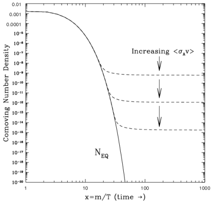
Planck 1502.01598

Fermi, H.E.S.S., AMS02, Planck. . . , CTA, GAMMA-400

e.g. 1305.5597 1310.0828, 1410.2242; 1301.1173

XENON100 *1207.5988*
LUX *1310.8214*
. . .
XENON1T
LZ





LHC7+8, LHC13

e.g. CMS 1402.4770, ATLAS 1405.7875

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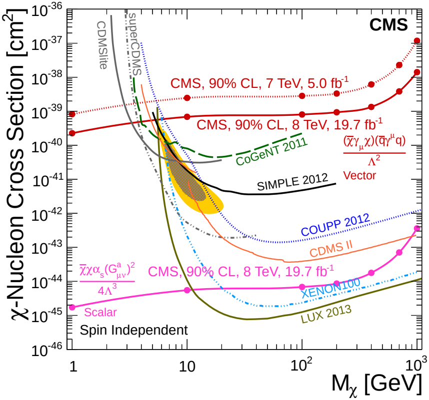
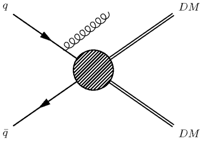
DM and the LHC



$$\mathcal{L}_V = \frac{\bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu q}{\Lambda^2}$$

$$\mathcal{L}_S = \frac{\bar{\chi}\chi\,\alpha_s G_{\mu\nu}G^{\mu\nu}}{\Lambda^3}$$

$\cdots$



CMS 1408.3583

cf. also Goodman, Ibe, Rajamaran, Sheperd, Tait, Yu 10; Bai, Fox, Harnik 10

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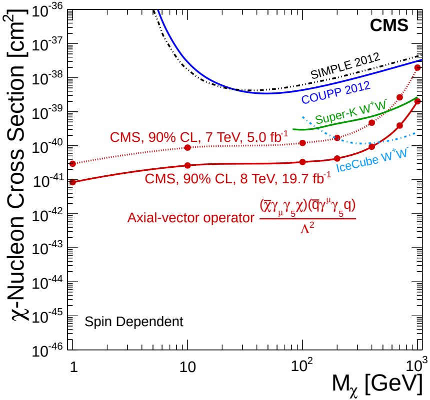

$$\mathcal{L}_V = \frac{\bar\chi\gamma_\mu\chi\,\bar q\gamma^\mu q}{\Lambda^2}$$

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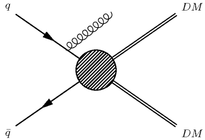
$\dots$



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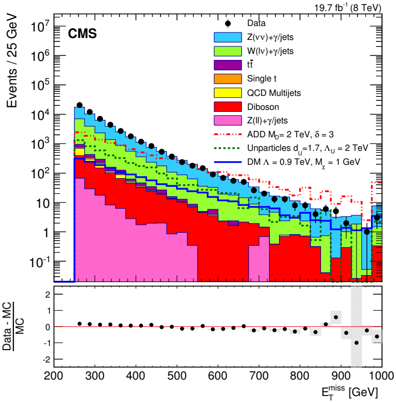

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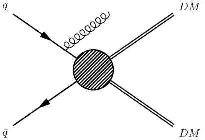


CMS 1408.3583

Validity of contact int. limit?

Momentum transfer $\sim$ TeV, limit on suppression scale $\Lambda \sim$ *TeV*

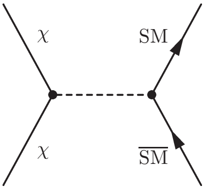
e.g. Busoni, De Simone, Morgante, Riotto 1402.1275; ...

cf. also Goodman, Ibe, Rajamaran, Sheperd, Tait, Yu 10; Bai, Fox, Harnik 10

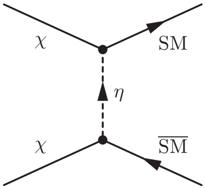
Interplay of ID, DD, LHC

- Bottom-up approach: DM + mediator

s-channel



t-channel



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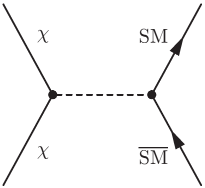
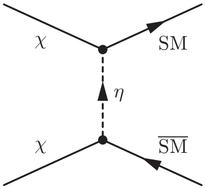


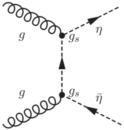
t-channel

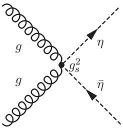


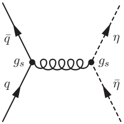
this talk

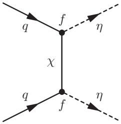
Why is the mediator important?

- Collider searches (direct production of mediator for $m_\eta \lesssim 2-3$ TeV)









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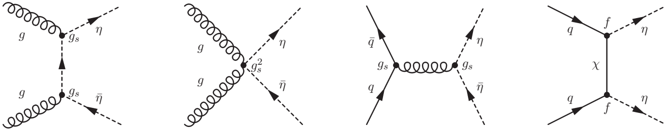
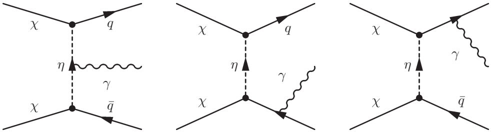


- Indirect detection (line-like bump for Majorana dm, $m_\eta \lesssim 5m_\chi$)



Bergstrom 89; Bergstrom, Bringmann, Edsjo 0710.3169

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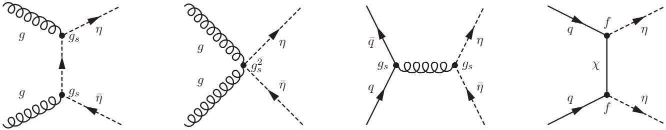

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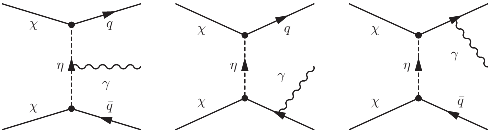
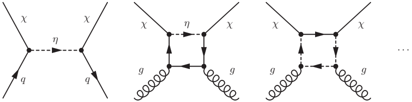


Bergstrom 89; Bergstrom, Bringmann, Edsjo 0710.3169

- Direct detection (EFT OK, except resonance for $m_\eta \simeq m_\chi$ and $q = b, t$)



Hisano, Ishiwata, Nagata 1110.3719; Gondolo, Scopel 1307.4481; Drees, Nojiri; . . .

Simplified Model

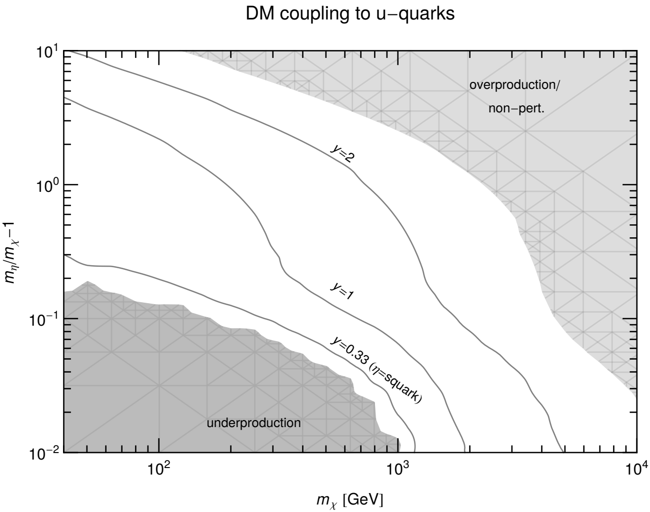
- Majorana fermion $\chi \equiv (1_c, 1_L, 0)$
- Coupling to RH quark (lepton) $\psi_R \in u_R, d_R, \ell_R$
- Scalar mediator η
  - coloured mediator $\eta \equiv (\bar{3}_c, 1_L, -Y_q)$
  - charged mediator $\eta \equiv (\bar{1}_c, 1_L, -Y_\ell)$

$$\begin{aligned} \mathcal{L}_{int}^{fermion} &= y\bar{\chi}\psi_R\eta + h.c. \\ \mathcal{L}_{int}^{scalar} &= -\lambda_3(H^\dagger H)(\eta^\dagger\eta) \end{aligned}$$

- Three parameters: m_χ, m_η, y
- Contains MSSM with bino-like neutralino, $\eta =$ squark, slepton

$$y = \sqrt{2}g' Y_\psi \approx \begin{cases} 0.33 & \psi = u_R \\ 0.5 & \psi = \ell_R \end{cases}$$

Parameter space for coloured mediator



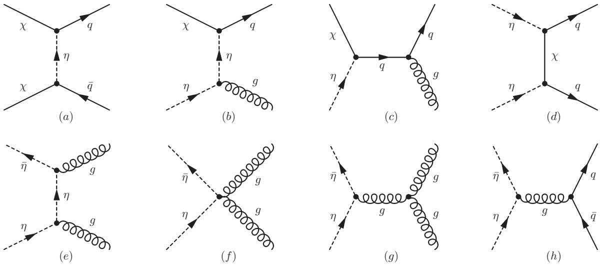
Relic density $\Omega_\chi h^2 = 0.12 \Rightarrow y$ fixed for each (m_η, m_χ)

Relic density

- Thermal relic density for $m_\eta - m_\chi \gg T_{f.o.} \sim m_\chi/25$

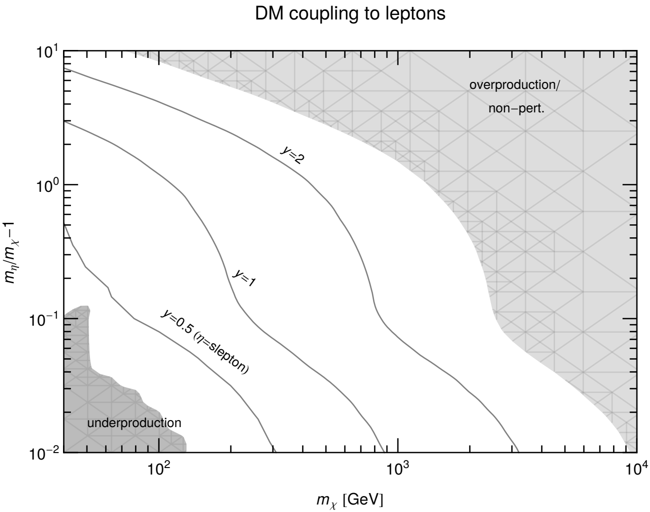
$$\Omega_\chi h^2 \simeq \frac{0.12}{N_c}\left(\frac{0.35}{y}\right)^4\left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^2\left[\sum_i \frac{1+m_{\eta_i}^4/m_\chi^4}{(1+m_{\eta_i}^2/m_\chi^2)^4}\right]^{-1}$$

- Coannihilations



$$\Omega_\chi h^2 \sim \frac{1}{\sigma v_{eff}} = \frac{m_\chi^2}{y^4\, C_{\chi\chi} + y^2\, g^2\, C_{\chi\eta} + g^4\, C_{\eta\eta}}$$

Parameter space for charged mediator



Relic density $\Omega_\chi h^2 = 0.12 \Rightarrow y$ fixed for each (m_η, m_χ)

Indirect detection

$$\chi\chi \to WW, q\bar{q}, \ell\bar{\ell}, \cdots \to \gamma, e^{\pm}, \bar{p}, \nu$$

image from wikimedia.org

Indirect Detection

- $2 \to 2$ annihilation

$$\sigma v_{\chi\chi\to q\bar{q}} \quad = \quad \left[\mathcal{O}(v^0)\mathcal{O}\left(\frac{m_q}{m_{DM}}\right)^2 + \mathcal{O}(v^2)\right]\mathcal{O}\left(\frac{m_{DM}}{m_\eta}\right)^4$$

- $2 \to 3$ annihilation via FSR from nearly on-shell q (soft/collinear)

$$\sigma v^{FSR}_{\chi\chi\to q\bar{q}\gamma} \quad \simeq \quad \frac{\alpha_{em}}{\pi}\int_0^1 dx \frac{1-x}{x}\log[4m_{DM}^2(1-x)/m_q^2] \times \sigma v_{\chi\chi\to q\bar{q}}$$

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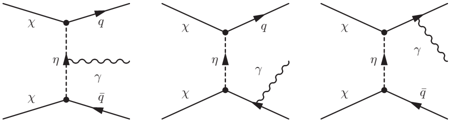
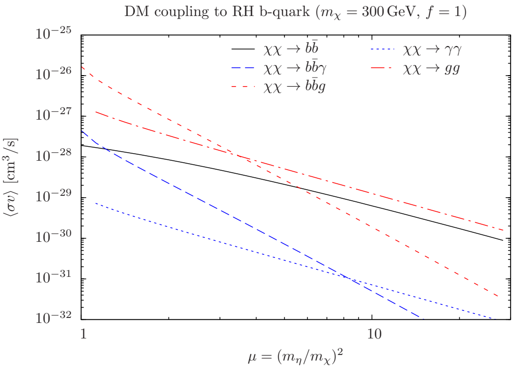
- $2 \to 3$ annihilation via VIB and FSR from off-shell q

$$\sigma v^{VIB/FSR}_{\chi\chi\to q\bar{q}\gamma} = \frac{\alpha_{em}}{\pi}\left[\mathcal{O}(v^0)\mathcal{O}\left(\frac{m_{DM}}{m_\eta}\right)^4 + \mathcal{O}(v^2)\right]\mathcal{O}\left(\frac{m_{DM}}{m_\eta}\right)^4$$



Bergstrom 89; Bergstrom, Bringmann, Edsjo 0710.3169

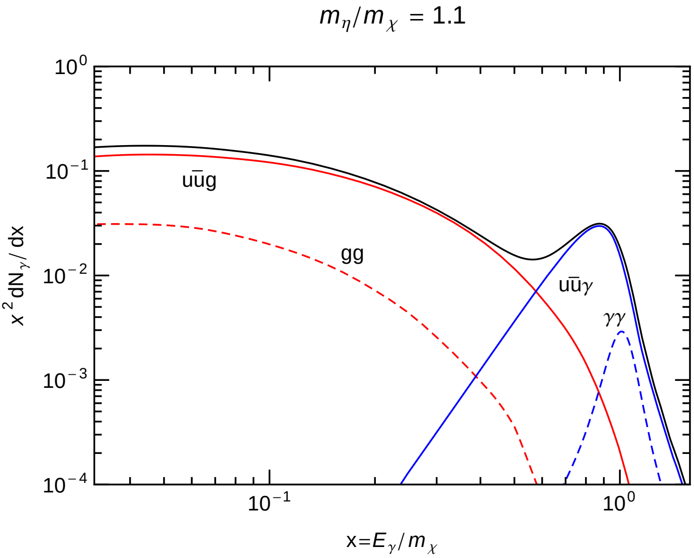
$2 \to 2$ vs $2 \to 3$ cross sections



- $\sigma v_{2\to 2} \propto 1/\mu^2$, $\sigma v_{2\to 3} \propto 1/\mu^4$ (where $\mu = (m_\eta/m_{DM})^2$)
- Dominant channel $q\bar{q}g$ for $m_\eta \lesssim 2m_\chi$, gg for $m_\eta \gtrsim 2m_\chi$

$$\frac{\sigma v(\chi\chi \to q\bar{q}\gamma)}{\sigma v(\chi\chi \to q\bar{q}g)} = \frac{Q_q^2 \alpha_{em}}{C_F \alpha_s} \simeq 3\%(0.7\%) \quad \text{for } q = u(d)$$

Spectral feature from internal bremsstrahlung



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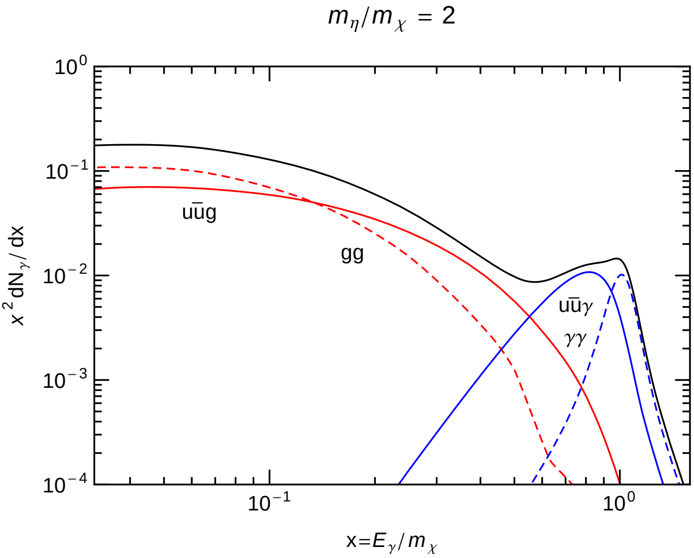
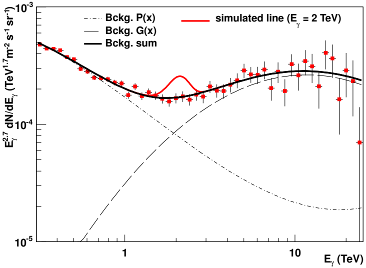


Search for 'bump' from internal bremsstrahlung

- Fermi LAT GC data $5 - 300\,\text{GeV}$

  Fermi coll. 1305.5597 (Bringmann, Huang, Ibarra, Vogl, Weniger 1203.1312; Weniger 1204.2797)

- H.E.S.S. CGH (bkg residual p) 500 GeV-25 TeV *H.E.S.S. coll. 1301.1173*



- energy resolution LAT $\sim 9 - 14\%$, H.E.S.S. $\sim 17 - 11\%$

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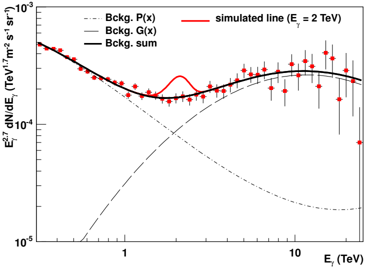
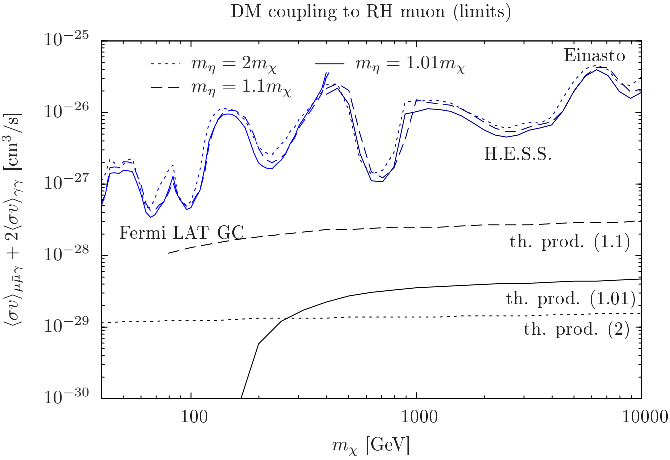


- energy resolution LAT $\sim 9 - 14\%$, H.E.S.S. $\sim 17 - 11\%$
- Spectral gamma-ray feature on top of smoothly varying background

$$\frac{d\Phi}{dE} = \beta E^{-\gamma} + \alpha \left(\frac{d\sigma v_{q\bar{q}\gamma}}{dE} + 2\sigma v_{\gamma\gamma}\delta(E - m_\chi) \right)$$

Internal bremsstrahlung + line: limits



Bringmann, Huang, Ibarra, Vogl, Weniger 1203.1312; Bergstrom, Bertone, Conrad, Farnier, Weniger 1207.6773;

Aleksic, Rico, Martinez 1209.5589; . . . *MG, Ibarra, Pato, Vogl 1306.6342*

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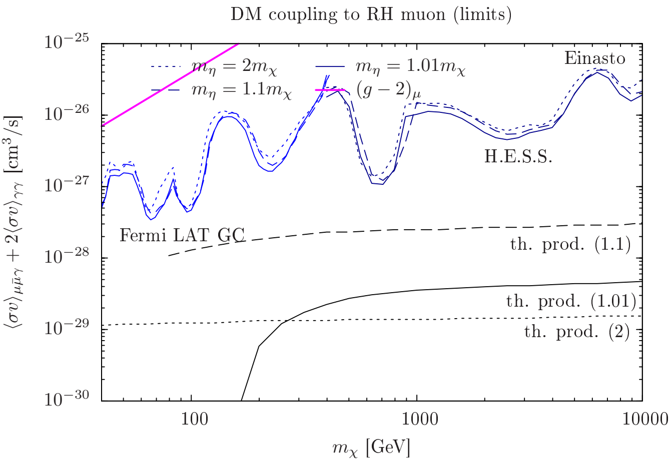

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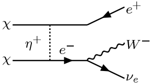
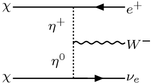
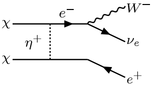
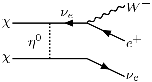
MG, Ibarra, Pato, Vogl 1306.6342

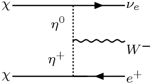
Virtual Internal Bremsstrahlung $\chi\chi \to f\bar{f}V$

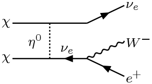












$$\frac{v d\sigma(\chi\chi \to \gamma f\bar{f})}{dE_\gamma dE_f} = \frac{C_{\gamma f\bar{f}}\alpha_{em} f^4 (1-x)[x^2 - 2x(1-y) + 2(1-y)^2]}{8\pi^2 m_{DM}^4 (1-2y-\mu_f)^2(3-2x-2y+\mu_f)^2}$$

$$\frac{v d\sigma(\chi\chi \to W f\bar{f}')}{dE_W dE_f} = \frac{C_{Wf\bar{f}'}\alpha_{em} f^4}{8\pi^2 m_{DM}^4 (1-2y-\mu_f)^2(3-2x-2y+\mu_{f'})^2} \Big\{ (1-x)[x^2 - 2x(1-y) + 2(1-y)^2$$
$$+ 2(2-x-2y)\Delta\mu] + x_0^2[x^2 + 2y^2 + 2xy - 4y + 2(2-x-2y)\Delta\mu + \Delta\mu^2]/4 - x_0^4/8$$
$$+ \Delta\mu^2[(1-2x)/2 - 4(1-y)(1-x-y)/(2x_0^2)] \Big\}$$

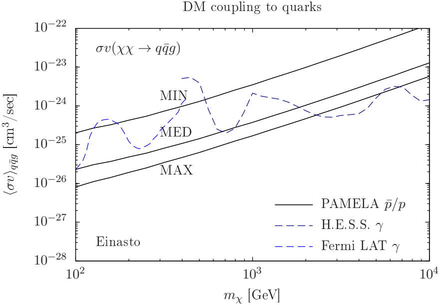
$x = E_W/m_{DM}$, $y = E_f/m_{DM}$, $x_0 = M_W/m_{DM}$, $\mu_f = m_{\eta_f}^2/m_{DM}^2$, $\mu_{f'} = m_{\eta_{f'}}^2/m_{DM}^2$, $\Delta\mu = (\mu_{f'} - \mu_f)/2$

	$C_{\gamma f\bar{f}}$	$C_{Zf\bar{f}}$	$C_{Wf\bar{f}'}$	$C_{gq\bar{q}}$
$\chi\chi \to Vf_R\bar{f}_R$	$q_f^2 N_c$	$q_f^2 N_c \tan^2(\theta_W)$	–	$N_c C_F$
$\chi\chi \to Vf_L\bar{f}_L$	$q_f^2 N_c$	$\frac{(t_{3f} - q_f \sin^2(\theta_W))^2}{\sin^2(\theta_W)\cos^2(\theta_W)} N_c$	$\frac{N_c}{2\sin^2(\theta_W)}$	$N_c C_F$

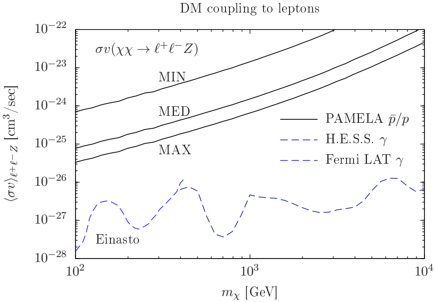
Bergstrom PLB225(89)372
Bringmann et al 0710.3169
Ciafaloni et al 1104.2996
Bell et al 1104.3823
MG, Ibarra, Vogl 1105.5367
1112.5155

Antiprotons

$\chi\chi \to q\bar{q}g$



$\chi\chi \to \ell^+\ell^- Z$



MG, Ibarra, Vogl 15

$$\frac{\sigma v(\chi\chi \to q\bar{q}\gamma)}{\sigma v(\chi\chi \to q\bar{q}g)} = \frac{Q_q^2 \alpha_{em}}{C_F \alpha_s} \simeq \begin{cases} 0.03 \\ 0.007 \end{cases}$$

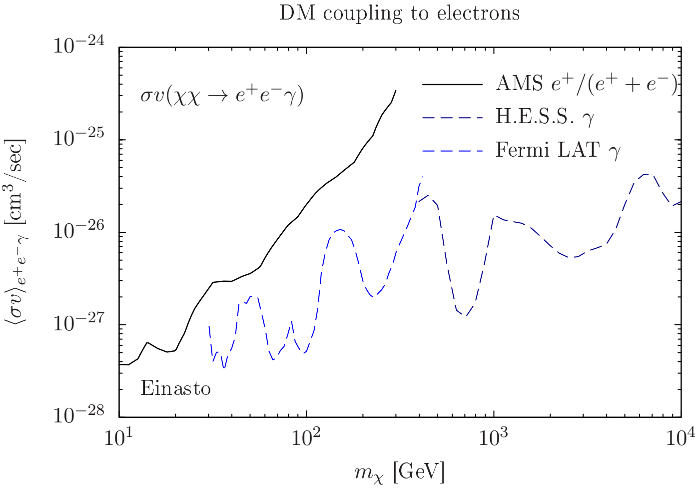
$$\frac{\sigma v(\chi\chi \to \ell^+\ell^-\gamma)}{\sigma v(\chi\chi \to \ell^+\ell^- Z)} \simeq \cot^2(\theta_W) \simeq 3.3$$

MG, Ibarra, Vogl 1105.5367,1112.5155; cf. also Ciafaloni et al 1104.2996, Bell et al 1104.3823

$\Rightarrow$ expect to see 'bump' first for DM coupled to leptons

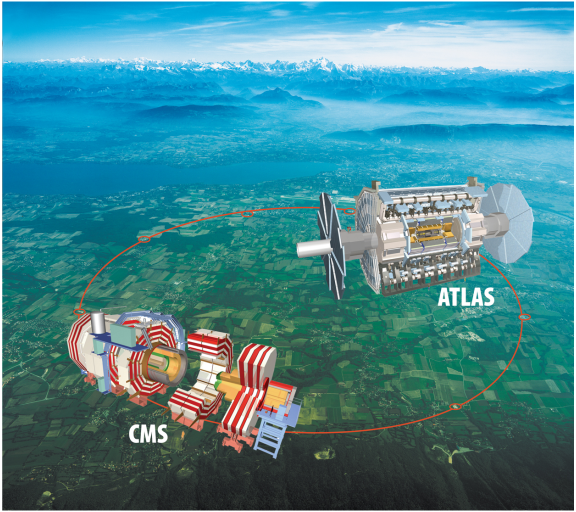
Positrons

$$\chi\chi \to e^+ e^- \gamma$$



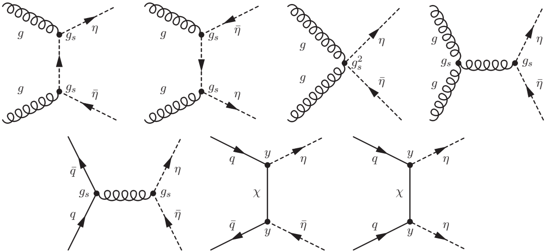
AMS limits: Bergstrom, Bringmann, Cholis, Hooper, Weniger 1306.3983

Collider

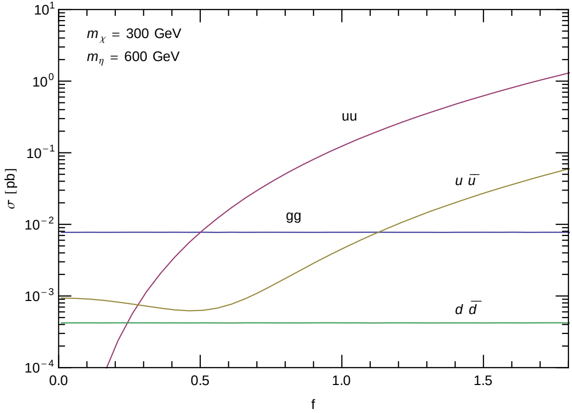


Collider constraints

- Monojet for $m_\eta \to \infty$ (... and $m_\eta \to m_\chi$)
- Direct production of the mediator for $m_\eta \lesssim 2-3$ TeV
  $\Rightarrow$ Dijet/Multijet + missing energy: $\eta \to \chi q$



Production cross section



DM-SM-η coupling strength y

$\mathcal{L}_{int} = -y\,\bar{q}_R \chi \eta$ $\qquad \sqrt{s} = 8$ TeV

ATLAS search and re-interpretation

- ATLAS search for jets + missing energy $\mathcal{L} = 20.3\ \text{fb}^{-1}$
  $p_T^{leading\ \ jet} > 130\text{GeV}$, $E_T^{miss} > 160$ GeV, $p_T^{subleading,i} > 60$ GeV

  ATLAS 1405.7875 (ATLAS-CONF-2013-047)

- ATLAS provides interpretation in terms of SUSY models

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$$S = \sigma \times \epsilon \times \mathcal{L}$$

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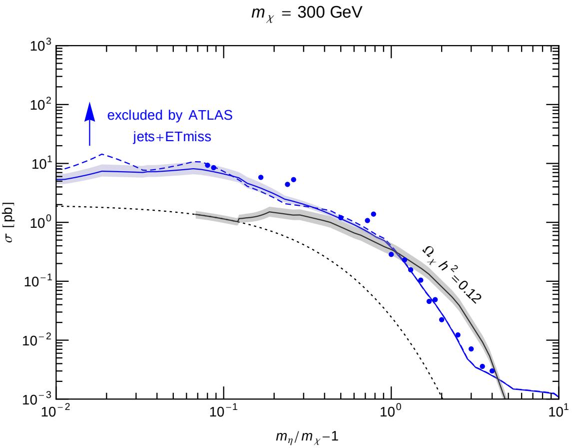
- Compute efficiencies for each (m_χ, m_η) and signal region using MadGraph/PYTHIA/Delphes
- Matrix elements with two additional hard jets (ISR, FSR, internal), jet matching to subtract double counting

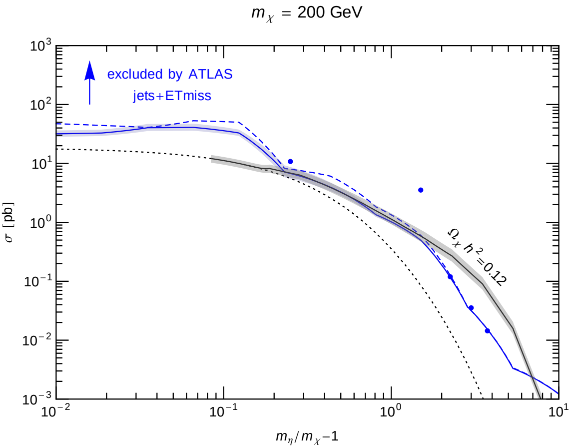
Upper limit on production cross section



$$\sigma = \sigma_{\rm QCD}^{\rm NLO+NLL} + K \times (\sigma^{\rm LO}(y) - \sigma^{\rm LO}(0))$$

MG, Ibarra, Rydbeck, Vogl 1403.4634

Upper limit on production cross section



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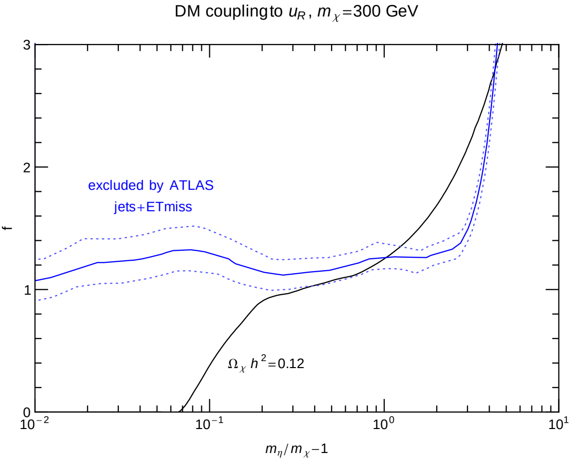
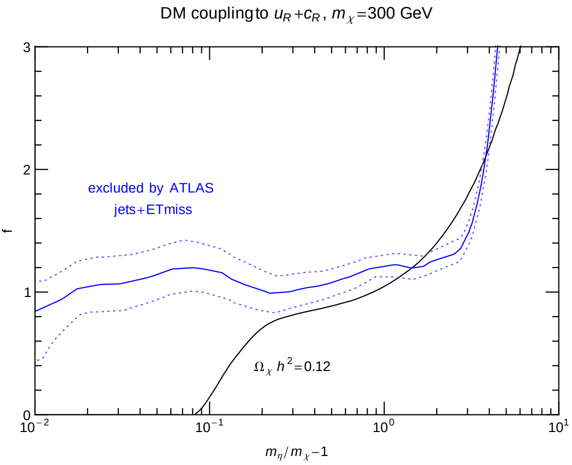
MG, Ibarra, Rydbeck, Vogl 1403.4634

Upper limit on coupling strength



MG, Ibarra, Rydbeck, Vogl 1403.4634

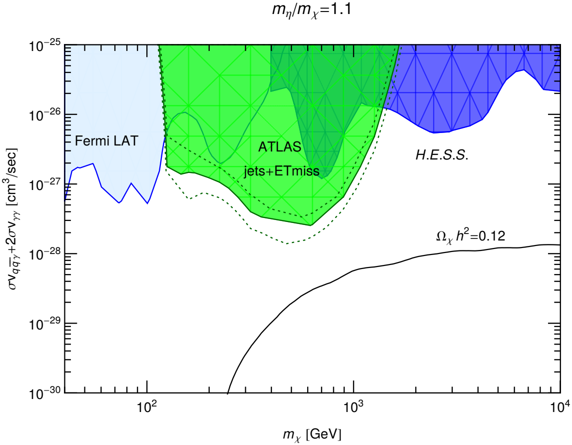
Upper limit on coupling strength



Two degenerate mediators

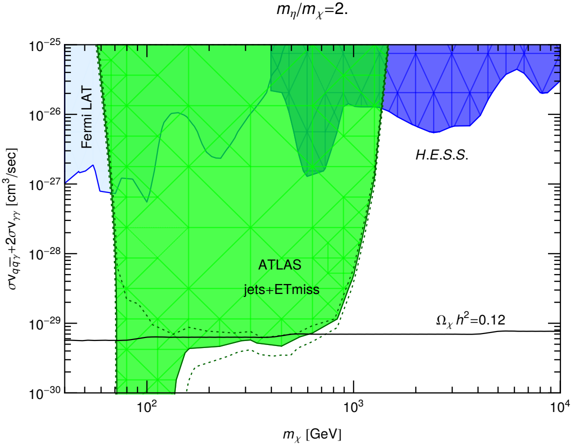
MG, Ibarra, Rydbeck, Vogl 1403.4634

ID vs LHC for DM-u coupling, $m_\eta/m_\chi = 1.1$



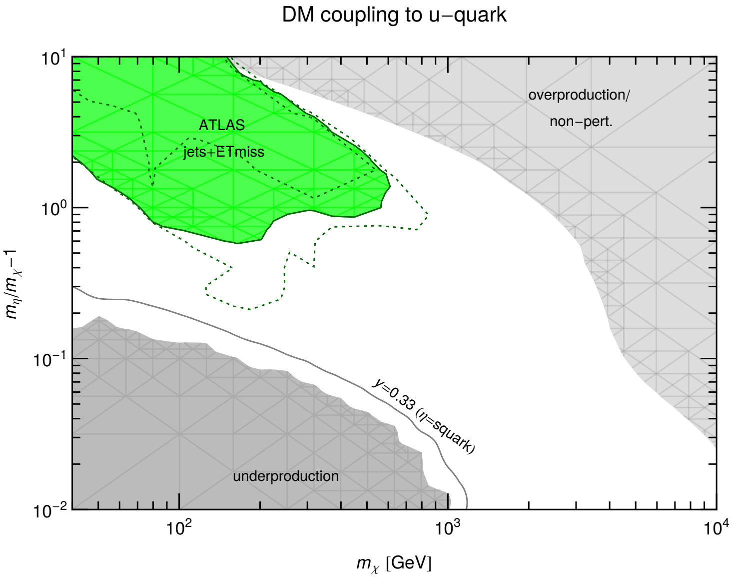
MG, Ibarra, Rydbeck, Vogl 1403.4634

ID vs LHC for DM-u coupling, $m_\eta/m_\chi = 2$



MG, Ibarra, Rydbeck, Vogl 1403.4634

Constraint for thermal production (coloured mediator)



MG, Ibarra, Rydbeck, Vogl 1403.4634

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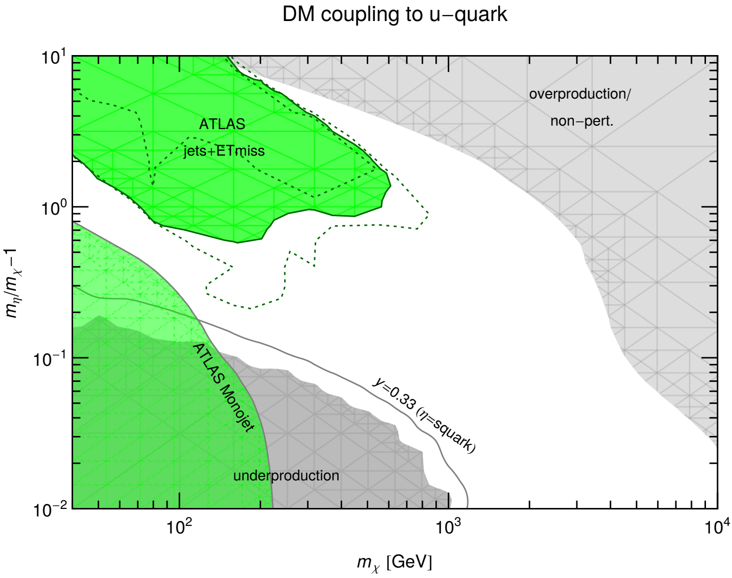

MG, Ibarra, Rydbeck, Vogl 1403.4634

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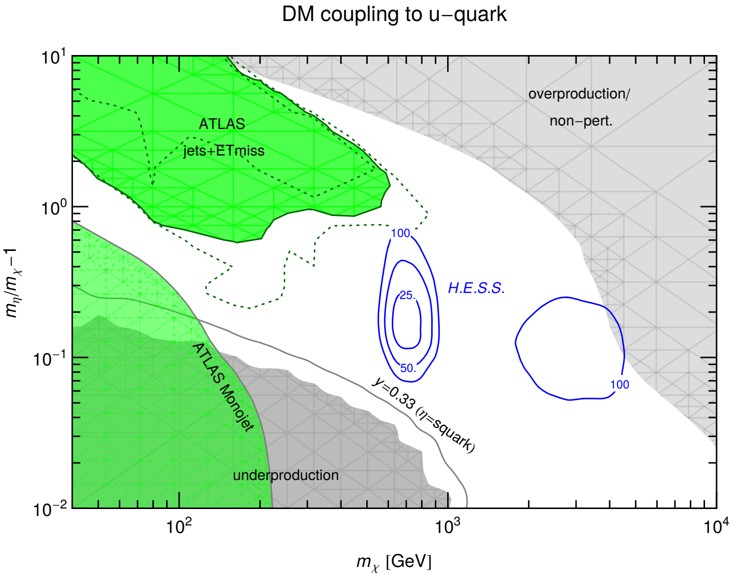

MG, Ibarra, Rydbeck, Vogl 1403.4634

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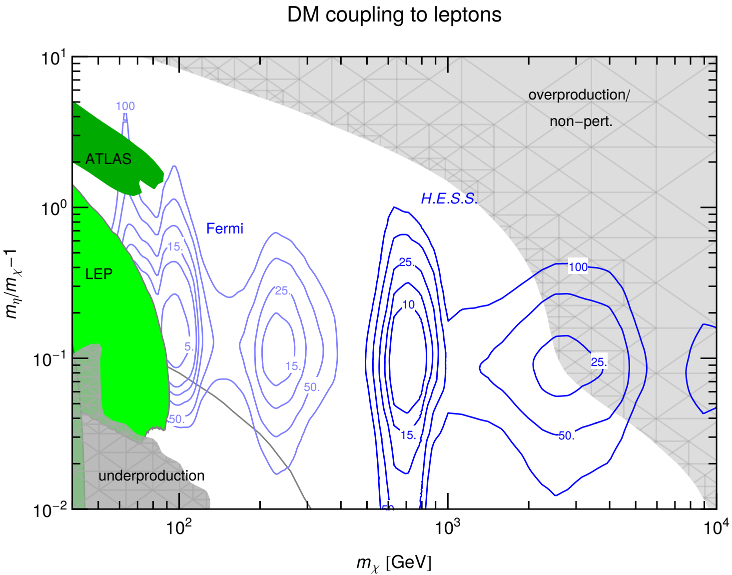
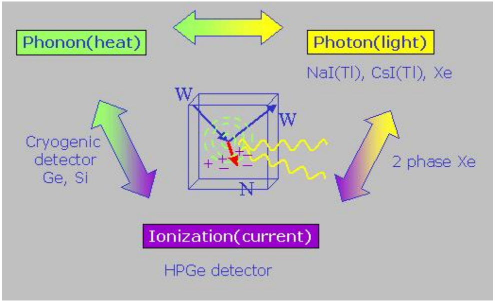


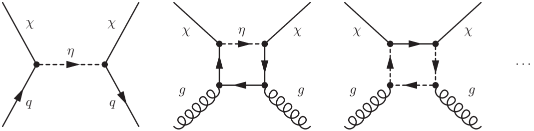
MG, Ibarra, Vogl 15xx

Direct detection



Direct detection

Hisano, Ishiwata, Nagata 1110.3719; Gondolo, Scopel 1307.4481; Drees, Nojiri; ...



- tree-level: resonance $\Delta m^2 \equiv m_\eta^2 - (m_\chi + m_q)^2$

$$\mathcal{L}_{eff} \quad = \quad y^2 \bar{\chi} q_R \frac{1}{D_\mu D^\mu + m_\eta^2} \bar{q}_R \chi + \text{h.c.}$$

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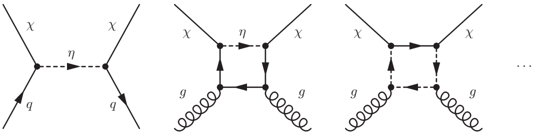

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\begin{aligned}
\mathcal{L}_{eff} &= y^2 \bar{\chi} q_R \frac{1}{D_\mu D^\mu + m_\eta^2} \bar{q}_R \chi + \text{h.c.} \\
&= y^2 \sum_{n=0}^{\infty} \bar{\chi} q_R \frac{(-D_\mu D^\mu - (m_\chi + m_q)^2)^n}{(\Delta m^2)^{n+1}} \bar{q}_R \chi + \text{h.c.}
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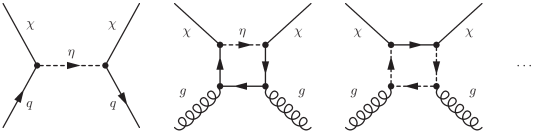

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Using the equations of motion $i\not{D} q = m_q q$ and $i\not{D}\chi = m_\chi \chi$

$$D_\mu D^\mu \bar{q}_R \chi = -(m_\chi^2 + m_q^2) q_R \chi + 2(D_\mu \bar{q}_R)(D^\mu \chi)$$

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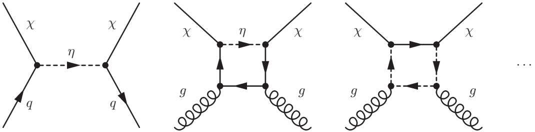

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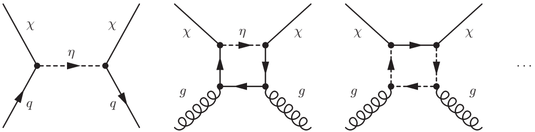

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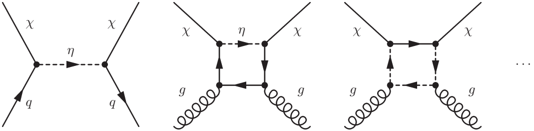
\end{aligned}
$$

$\Rightarrow$ expansion in $m_\chi E_q / \Delta m^2 \sim \frac{\Lambda_{QCD}}{m_\eta - m_\chi - m_q}$

Direct detection

Hisano, Ishiwata, Nagata 1110.3719; Gondolo, Scopel 1307.4481; Drees, Nojiri; ...



- tree-level: resonance $\Delta m^2 \equiv m_\eta^2 - (m_\chi + m_q)^2$
- SI: $\bar{\chi}\chi\bar{q}q$, $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ vanish $\Rightarrow$ dim-8 ($\sim$ twist-2)

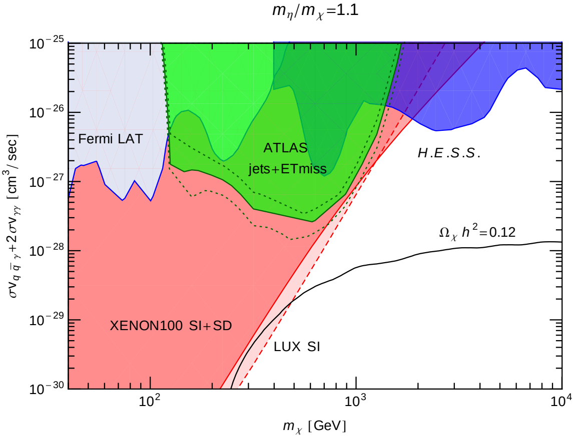
$$\mathcal{L}_{eff}^{SI} \sim -\frac{y^2}{2(\Delta m^2)^2}(\bar{\chi}\gamma^\mu D_\nu \chi)(\bar{q}_R\gamma_\mu D_\nu q_R - (D_\nu \bar{q}_R)\gamma_\mu q_R)$$

- SD:

$$\mathcal{L}_{eff}^{SD} \sim -\frac{y^2}{2\Delta m^2}\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}_R\gamma_\mu\gamma_5 q_R$$

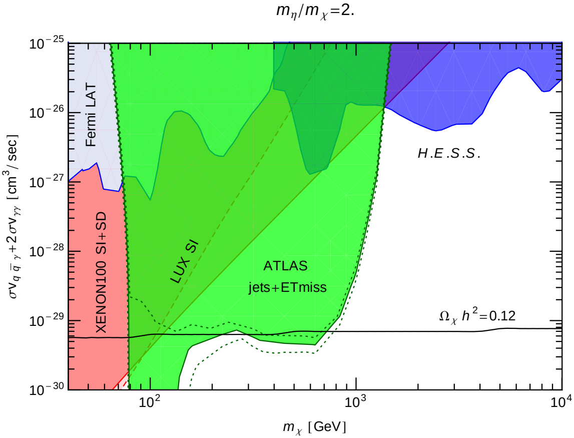
- loop: regular for $m_\eta \to m_\chi + m_q$

ID vs DD vs LHC for DM-u coupling, $m_\eta/m_\chi = 1.1$



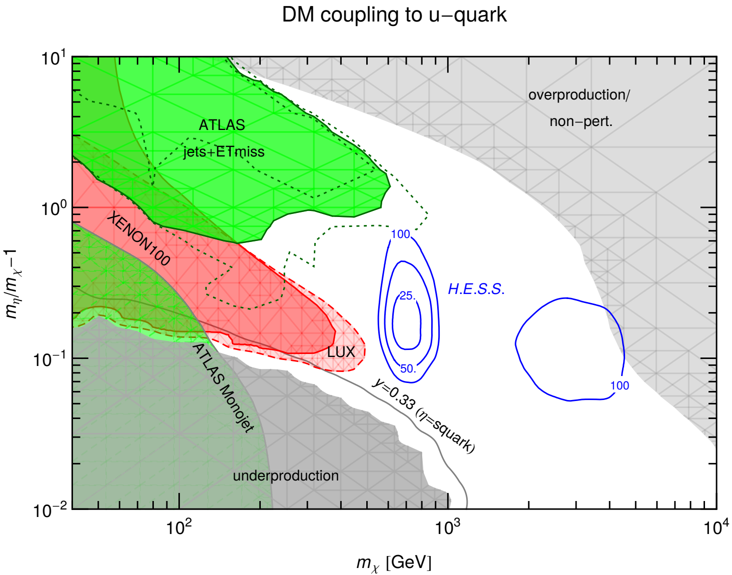
MG, Ibarra, Rydbeck, Vogl 1403.4634

ID vs DD vs LHC for DM-u coupling, $m_\eta/m_\chi = 2$



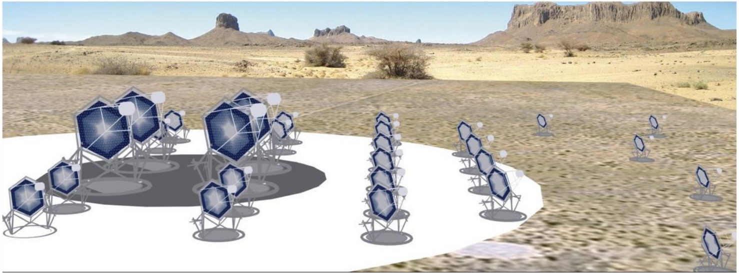
MG, Ibarra, Rydbeck, Vogl 1403.4634

Complementarity (coloured mediator)



MG, Ibarra, Rydbeck, Vogl 1403.4634

Prospects



CTA $A_{eff} \sim 0.02, 0.3, 2.3$ km^2, $\Delta E/E \sim 25\%, 10\%, 5\%$ at $E = 0.1, 1, 10$ TeV

Bernlohr et al 1210.3503

GAMMA-400 $A_{eff} \sim 1\text{m}^2$, $\Delta E/E \sim \%$

see e.g. Bergstrom, Bertone, Conrad, Farnier, Weniger 1207.6773

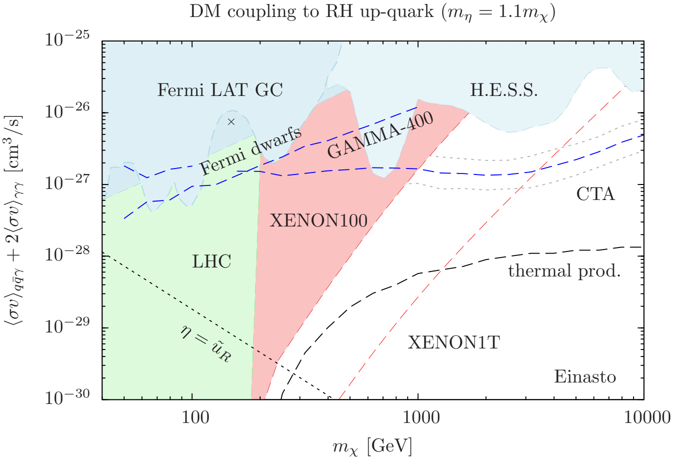
XENON1T, LZ

e.g. Baudis 1211.7222, Cushman et al 1310.8327

LHC

e.g. Bauer et al 1305.1605; Cirelli, Sala, Taoso 1407.7058; ...

Prospects (coloured mediator)



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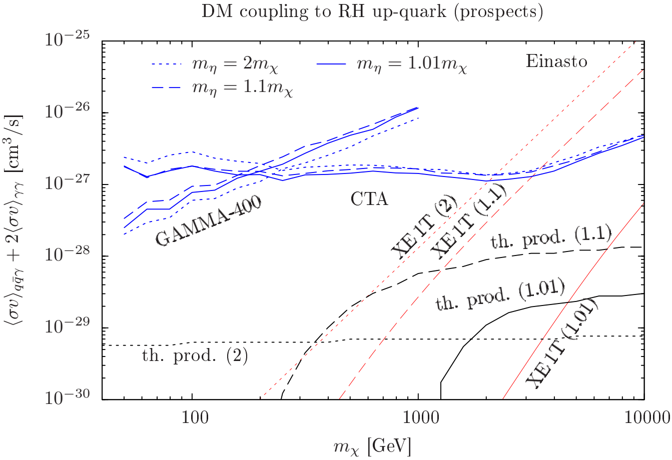

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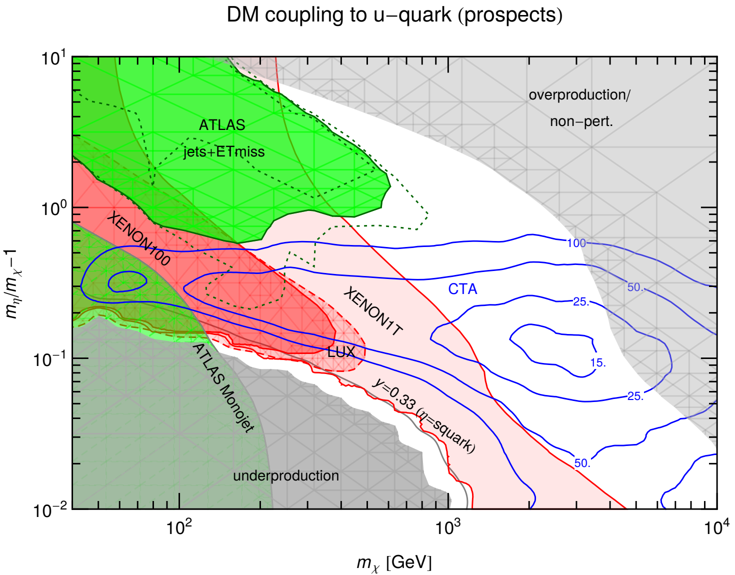
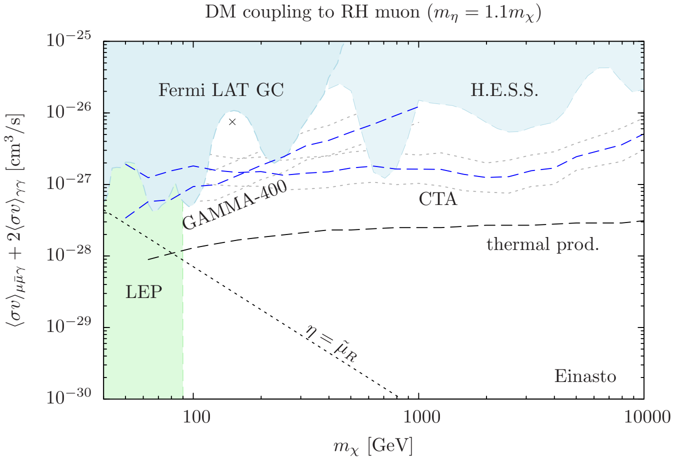


MG, Ibarra, Rydbeck, Vogl 1403.4634

Prospects (charged mediator)



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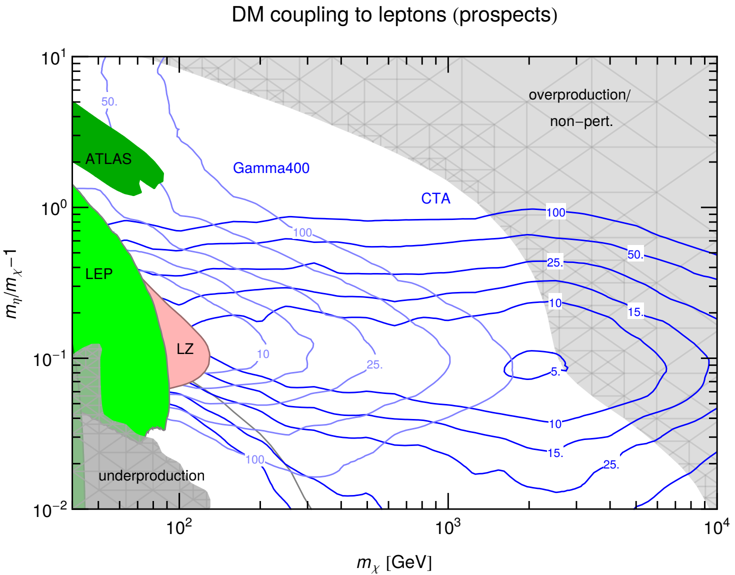
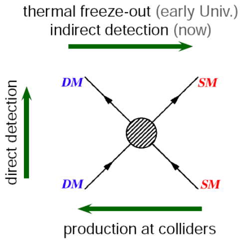


MG, Ibarra, Vogl 15

Conclusion

- Interplay of ID, DD, LHC crucial to confirm/'rule out' WIMP
- Bottom-up approach: simplified models which contain *relevant* d.o.f.



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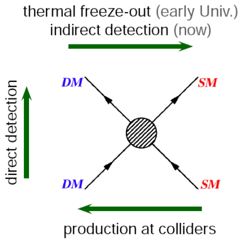

- Majorana dark matter + t-channel mediator
- Spectral feature from internal bremsstrahlung; $uu \to \eta\eta$ at LHC
- CTA/XENON1T(LZ)/LHC13 close in on coloured mediator
- GAMMA-400/CTA for leptonic mediator

Conclusion

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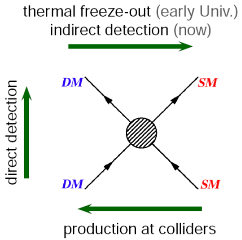

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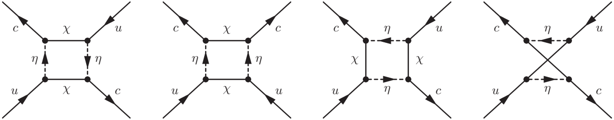
thank you!

Flavour constraints

$$\mathcal{L} = -y_i \bar{u}_{Ri} \chi \eta$$



$$\Rightarrow \quad \mathcal{L} = \frac{\tilde{z}}{m_\eta^2} \bar{u}_R^\alpha \gamma^\mu c_R^\alpha \, \bar{u}_R^\beta \gamma_\mu c_R^\beta, \quad \tilde{z} = -\frac{y_1^2 y_2^2}{96\pi^2} \left(24 \frac{m_\chi^2}{m_\eta^2} f_6(\frac{m_\chi^2}{m_\eta^2}) + 12 \tilde{f}_6(\frac{m_\chi^2}{m_\eta^2}) \right)$$

From Δm_D: $|\tilde{z}| \lesssim 5.7 \cdot 10^{-7} (m_\eta / \,\mathrm{TeV})^2$ *Gedalia et. al. 09.*

$$|y_2/y_1| \lesssim 0.026 \times (y_1)^{-2} \times \frac{m_\eta}{\mathrm{TeV}}$$

Minimal charm-coupling from RG running

$$|y_2/y_1| \simeq |V_u^R(\mu)_{uc}| \sim \frac{3}{16\pi^2} \frac{m_u}{m_c} \frac{|V_{us} V_{cs}^* m_s^2 + V_{ub} V_{cb}^* m_b^2|}{v_{EW}^2} \ln \frac{M_{GUT}}{\mu} \sim 10^{-10}$$

Other possibility: two degenerate mediators, similar to squarks

$$\frac{|m_{\eta_1} - m_{\eta_2}|}{m_{\eta_1} + m_{\eta_2}} \lesssim 0.026 \times (y_1)^{-2} \times \frac{m_\eta}{\mathrm{TeV}}$$

Constraints from PAMELA $\bar{p}/p$ measurement

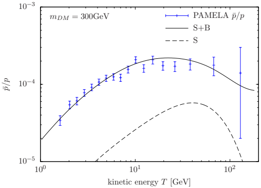
- Rate of $\bar{p}$ per unit of kinetic energy and volume

$$Q(T,\vec{r}) = \frac{1}{2}\frac{\rho^2(\vec{r})}{m_\chi^2}\sum_f \langle\sigma v\rangle_f \frac{dN^f_{\bar{p}}}{dT}$$

- Einasto profile with $\alpha_E = 0.17$, $r_s = 20\,\mathrm{kpc}$, $\rho(r_\odot) = 0.39\mathrm{GeV/cm^3}$
- Propagation: two-zone diffusion model compatible with B/C ratio, three parameter sets corresponding to MIN, MED, MAX $\bar{p}$ flux

$$0 = \frac{\partial f_{\bar{p}}}{\partial t} = \nabla\cdot(K(T,\vec{r})\nabla f_{\bar{p}}) - \nabla\cdot(\vec{V}_c(\vec{r})f_{\bar{p}}) - 2h\delta(z)\Gamma_{\mathrm{ann}} f_{\bar{p}} + Q(T,\vec{r})$$

Model	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5



- secondary $\bar{p}$ flux from *Donato, Maurin, Salati, Barrau, Boudoul, Taillet 01*
- solar modulation in force field approximation $\phi_F = 500MV$