Internal bremsstrahlung signatures of Dark Matter annihilations in light of direct detection and collider searches

Mathias Garny (CERN)

Avignon, 15.04.14

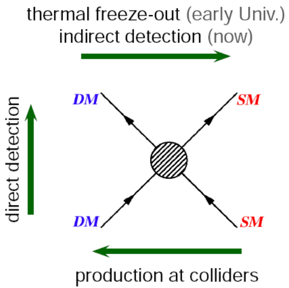
based on 1403.4634, 1306.6342

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

WIMP Dark Matter

$$\Omega_\chi h^2 = 0.1199 \pm 0.0027 \simeq 0.1\,\text{pb} \cdot c\,/\langle \sigma v \rangle$$

Planck XVI 1303.5076



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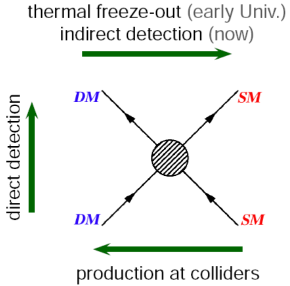
Planck XVI 1303.5076

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

e.g. 1305.5597 1310.0828; 1301.1173

XENON100 *1207.5988*
LUX *1310.8214*
XENON1T
LZ



LHC7+8, LHC13

e.g. CMS 1303.2985, ATLAS CONF-2013-047

Interplay of ID, DD, LHC

- Crucial to confirm/identify/'rule out' WIMPs
- Effective operator description essentially breaks down at LHC energies, and misses characteristic features

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

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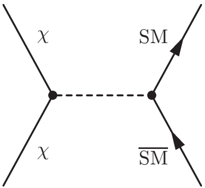
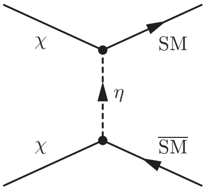
- Bottom-up approach: DM + mediator

s-channel



t-channel



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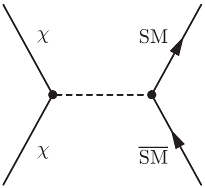

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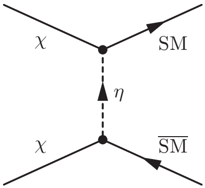
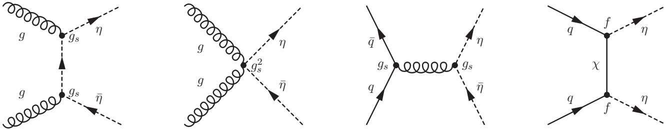


this talk

Why is the mediator important?

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



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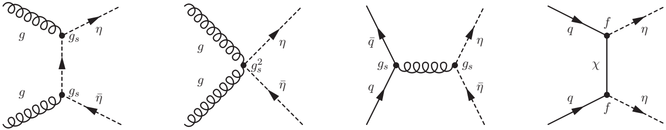
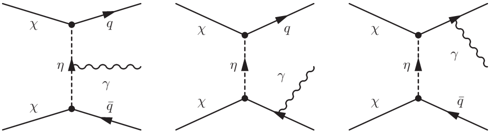


- Indirect detection (internal bremsstrahlung for $m_\eta \lesssim 5m_\chi$)



Bergstrom 89; Bergstrom, Bringmann, Edsjo 0710.3169

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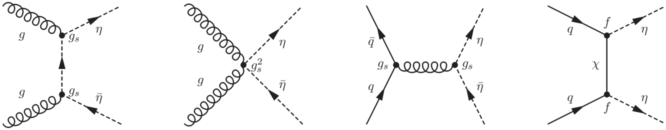

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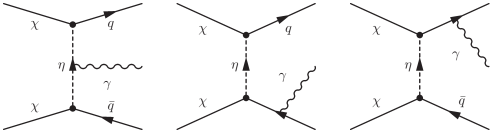

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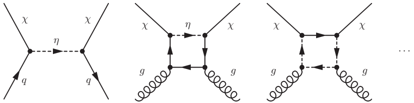
- Direct detection (EFT OK, except resonance for $m_\eta \simeq m_\chi$ and $q = b, t$)



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

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)

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

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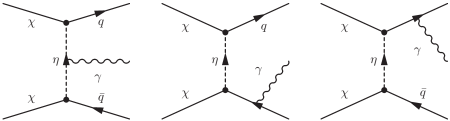
- $2 \to 3$ annihilation via VIB and FSR from off-shell q

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



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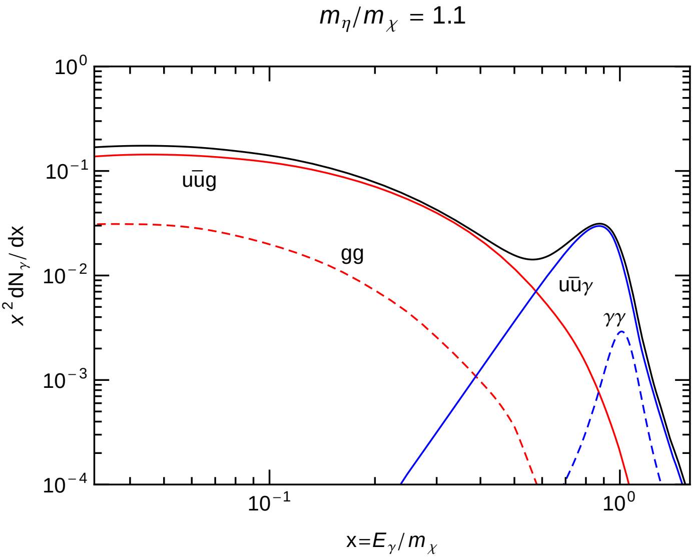
Spectral feature from internal bremsstrahlung



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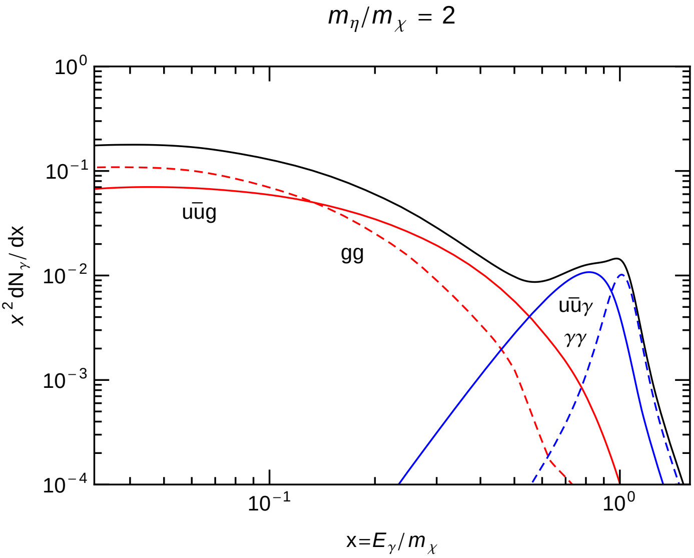
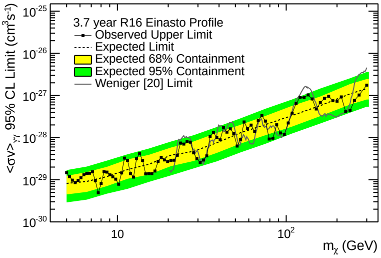


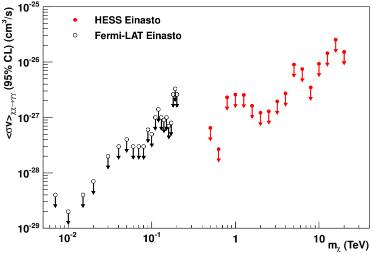
Search for ‘bump’ from internal bremsstrahlung

- Fermi LAT GC data 5 – 300 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*





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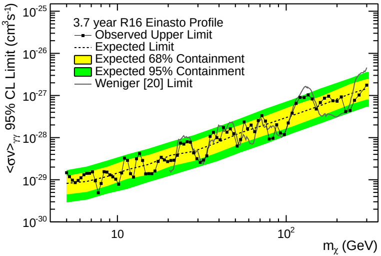
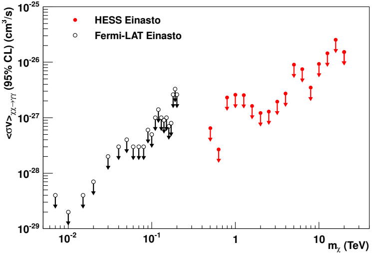
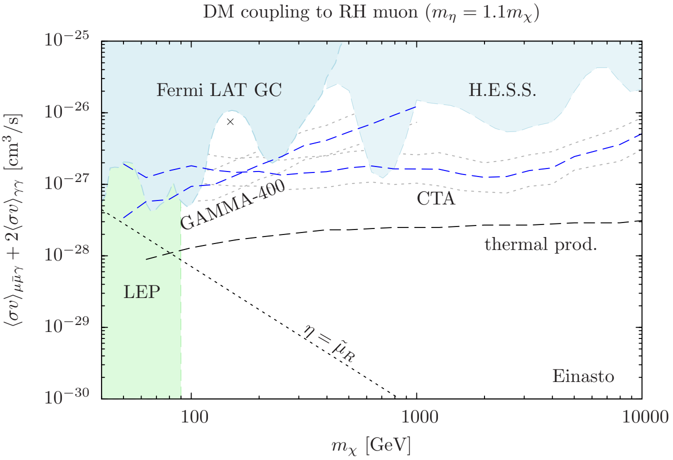




- energy resolution LAT $\sim 9-14\%$, H.E.S.S. $\sim 17-11\%$
- Spectral gamma-ray feature on top of smoothly varying background

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

Internal bremsstrahlung: limits and prospects

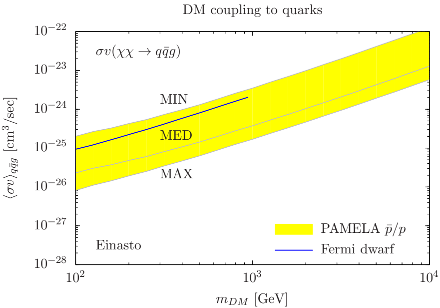


Bringmann, Huang, Ibarra, Vogl, Weniger 1203.1312; Bergstrom, Bertone, Conrad, Farnier, Weniger 1207.6773;

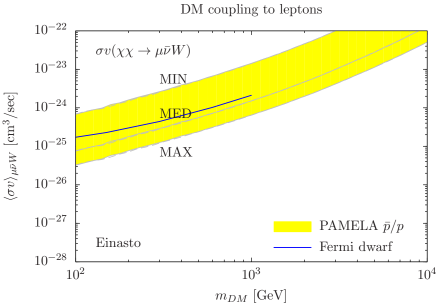
Aleksic, Rico, Martinez 1209.5589; ... *MG, Ibarra, Pato, Vogl 1306.6342*

Antiprotons and secondary gamma rays

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



$\chi\chi \to \ell\bar{\nu}W$



$$\frac{\sigma v(\chi\chi \to q\bar{q}\gamma)}{\sigma v(\chi\chi \to q\bar{q}g)} = \frac{Q_q^2 \alpha_{em}}{C_F \alpha_s} \simeq \begin{cases} 0.03 \\ 0.007 \end{cases} \qquad \frac{\sigma v(\chi\chi \to \ell\bar{\ell}\gamma)}{2\sigma v(\chi\chi \to \ell\bar{\nu}W)} \simeq \sin^2(\theta_W) \simeq 0.23$$

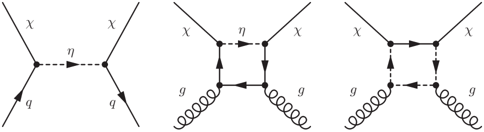
MG, Ibarra, Vogl 1105.5367,1112.5155; cf. also Ciafaloni et al 1104.2996, Bell et al 1104.3823

$\Rightarrow$ expect to see 'bump' first for DM coupled to up-type quarks, leptons

also: neutrino signal $\to$ *talk by M. Totzauer*

Direct detection

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



. . .

$$\sigma^{SI(SD)} \propto \frac{1}{[m_\eta^2 - (m_\chi + m_q)^2]^{4(2)}}$$

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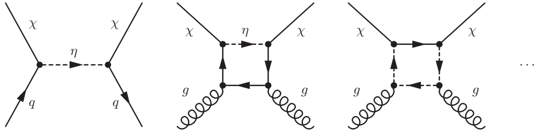

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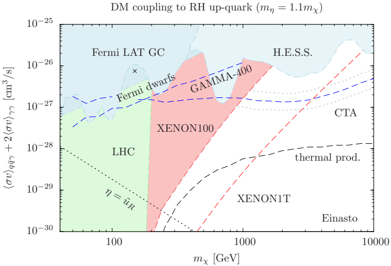
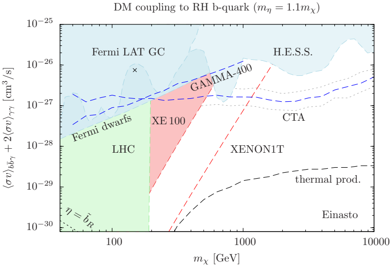
DM-u coupling



DM-b coupling

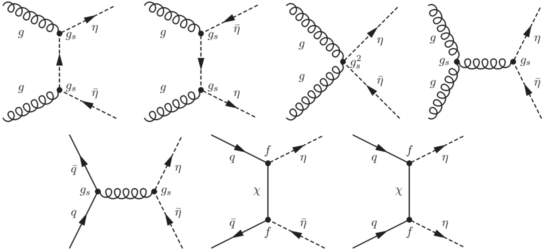


$m_\eta / m_\chi = 1.1$, much weaker for larger splitting

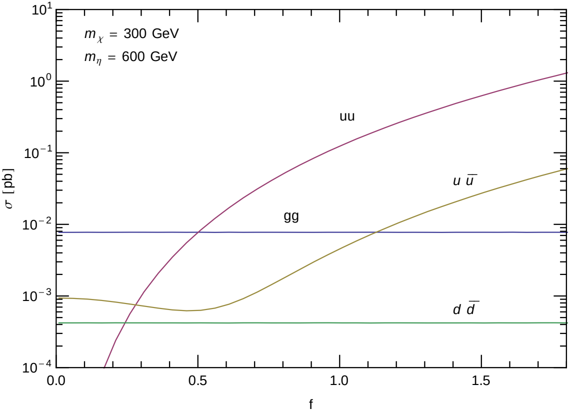
MG, Ibarra, Pato, Vogl 1306.6342

Collider constraints

- Monojet for $m_\eta \to \infty$
- 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 f

$\mathcal{L}_{int} = -f\ \bar{q}_R \chi \eta$

$\sqrt{s} = 8$ 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-CONF-2013-047

- ATLAS provides interpretation in terms of SUSY models

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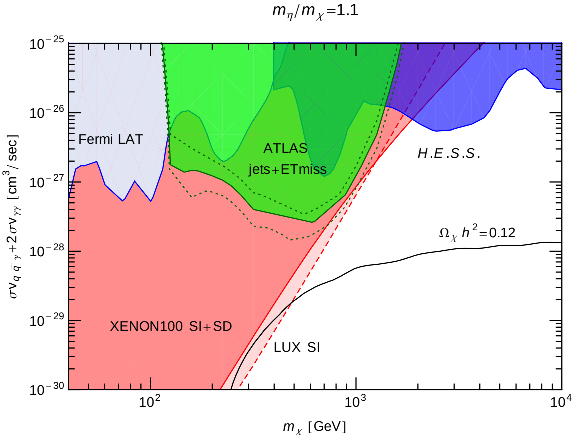
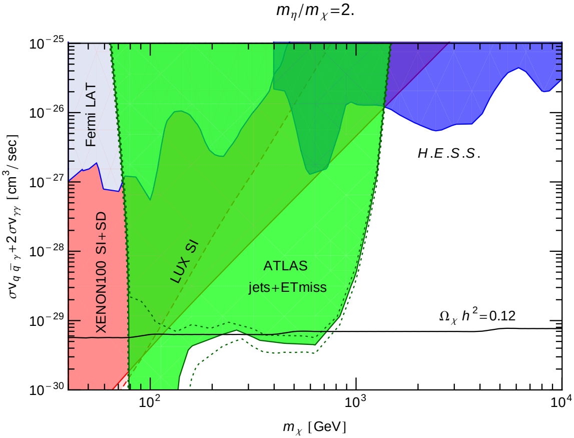
- Compute efficiencies for each (m_χ, m_η) and signal region using MadGraph/PYTHIA/Delphes
- Matrix elements with two additional hard jets (ISR, FSR, internal), jet matching to subtract double counting in hadron showering

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



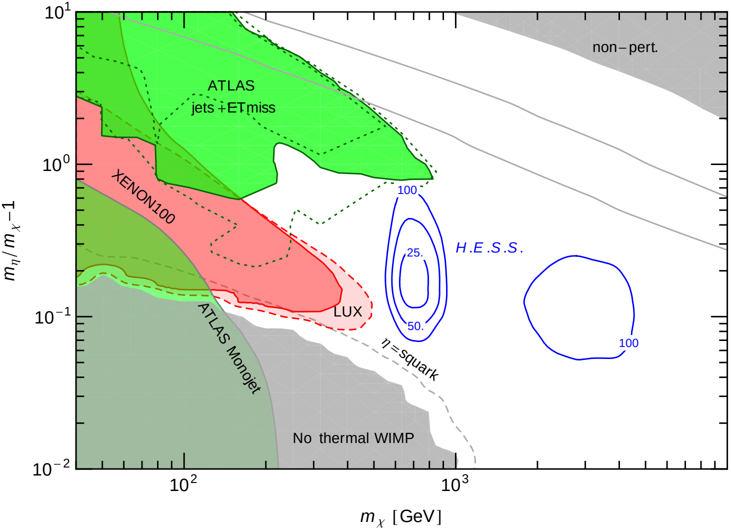
MG, Ibarra, Rydbeck, Vogl 1403.4634

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



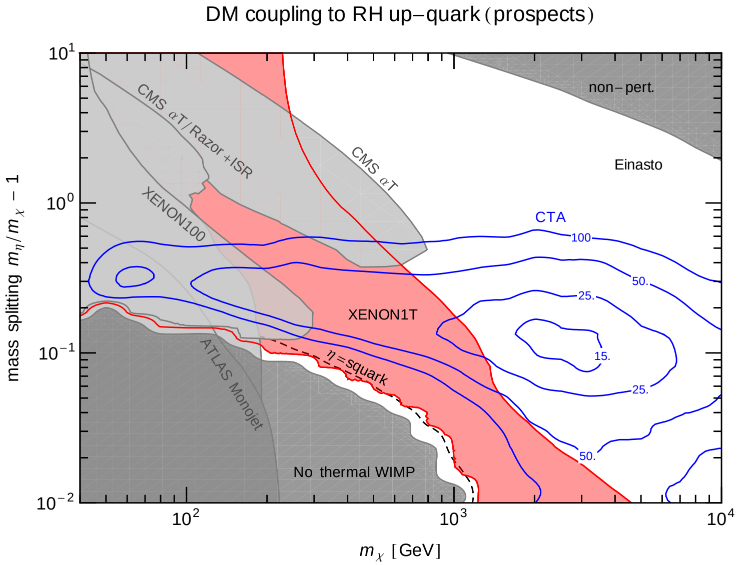
MG, Ibarra, Rydbeck, Vogl 1403.4634

Complementarity (for thermal production)

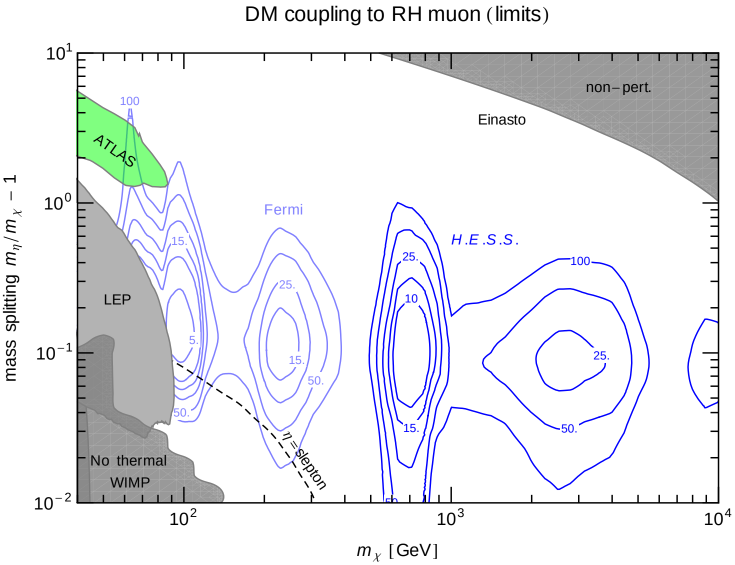


MG, Ibarra, Rydbeck, Vogl 1403.4634

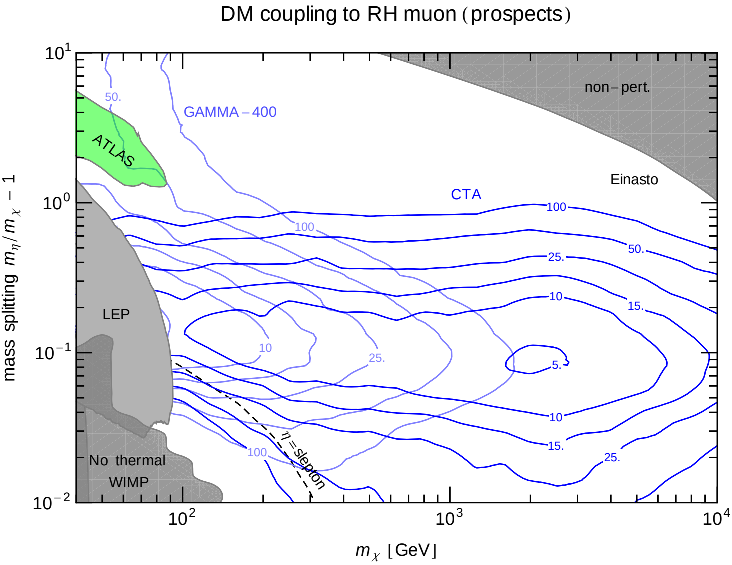
Prospects


DM coupling to RH up–quark (prospects)
non–pert.
Einasto
CMS αT/Razor+ISR
CMS αT
XENON100
CTA
100
50.
25.
15.
XENON1T
η = squark
ATLAS Monojet
No thermal WIMP
mass splitting $m_\eta/m_\chi - 1$
m_χ [GeV]
10^1
10^0
10^{-1}
10^{-2}
10^2
10^3
10^4

DM coupling to leptons



DM coupling to leptons (prospects)



Conclusion

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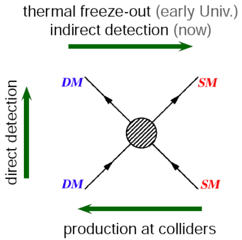
- Bottom-up approach: simplified models which contain *relevant* d.o.f.



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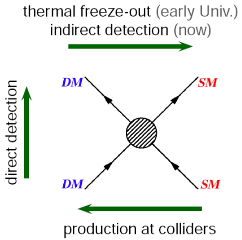

- Dark Matter + t-channel mediator
- Strong spectral feature from internal bremsstrahlung
- CTA/XENON1T(LZ)/LHC13 close in on coloured mediator
- GAMMA-400/CTA promising for leptonic mediator

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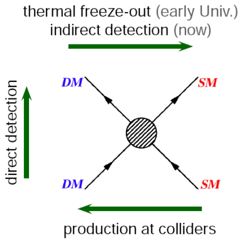

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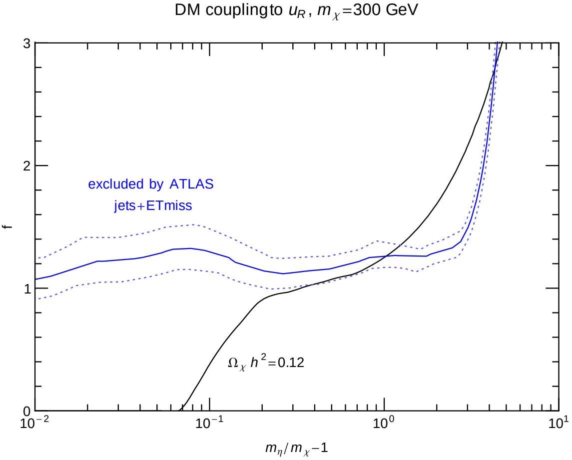
thank you!

Upper limit on coupling strength



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

MG, Ibarra, Rydbeck, Vogl 1403.4634

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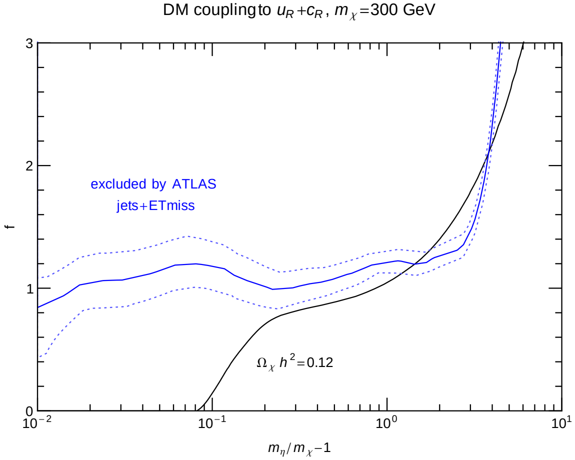

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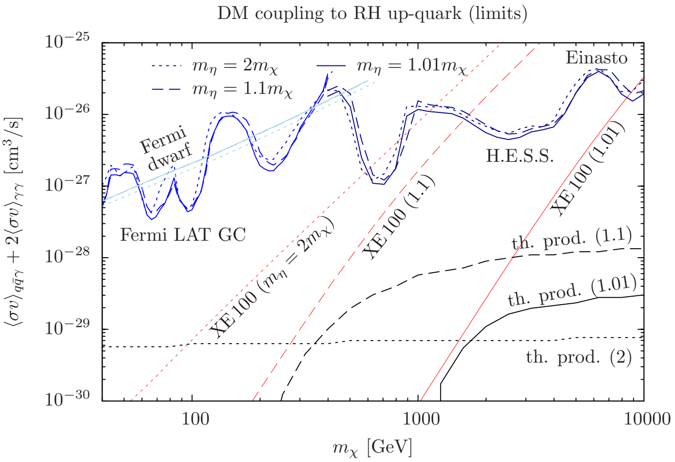
ID vs DD for DM coupling to u-quarks



MG, Ibarra, Pato, Vogl 1306.6342

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

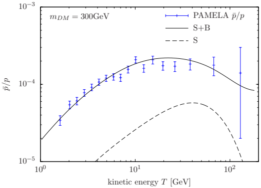
- Rate of $\bar{p}$ per unit of kinetic energy and volume

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

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

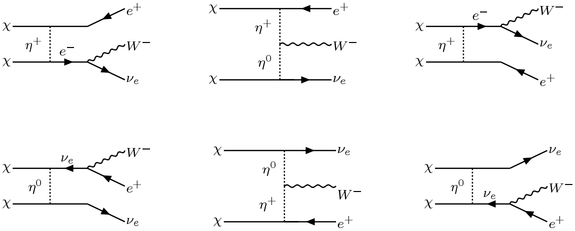
$$0 = \frac{\partial f_{\bar{p}}}{\partial t} = \nabla\cdot(K(T,\vec{r})\nabla f_{\bar{p}}) - \nabla\cdot(\vec{V}_c(\vec{r})f_{\bar{p}}) - 2h\delta(z)\Gamma_{\text{ann}} f_{\bar{p}} + Q(T,\vec{r})$$

Model	δ	K_0 $(\text{kpc}^2/\text{Myr})$	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 $\phi_F = 500MV$

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



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

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

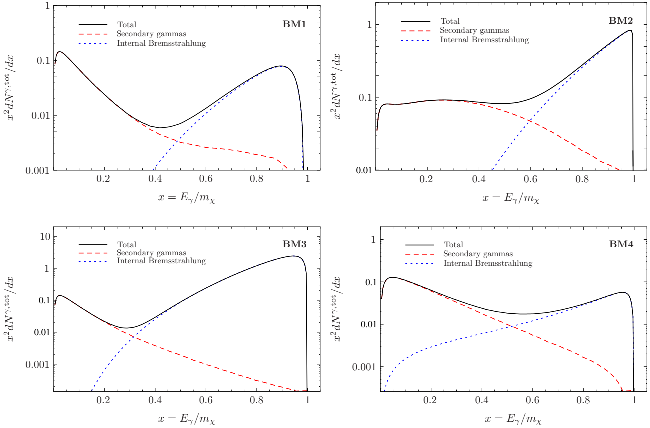
$x = E_W/m_{DM}$, $y = E_f/m_{DM}$, $x_0 = M_W/m_{DM}$, $\mu_f = m_{\eta_f}^2/m_{DM}^2$, $\mu_{f'} = m_{\eta_{f'}}^2/m_{DM}^2$, $\Delta\mu = (\mu_{f'} - \mu_f)/2$

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

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

Characteristic feature in the gamma-ray spectrum

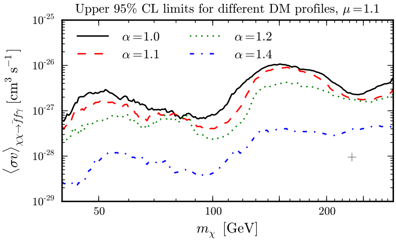
Bringmann, Bergstrom, Edsjo 0710.3169

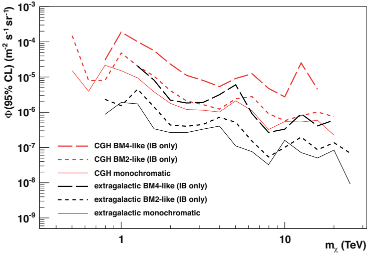


	m_0 [GeV]	$m_{1/2}$ [GeV]	$\tan\beta$	A_0 [GeV]	sgn (μ)	m_χ [GeV]	$Z_g/(1-Z_g)$	Ωh^2	t-channel	$\mathcal{S}$	IB/ sec.	IB/ lines
BM1	3700	3060	5.65	$-1.39\cdot 10^4$	-1	1396	$3.0\cdot 10^4$	0.082	$\tilde{t}(1406)$	$8\cdot 10^{-5}$	19.2	4.5
BM2	801	1046	30.2	$-3.04\cdot 10^3$	-1	446.9	1611	0.110	$\tilde{\tau}(447.5)$	0.044	10.6	8.5
BM3	107.5	576.4	3.90	28.3	$+1$	233.3	220	0.084	$\tilde{\tau}(238.9)$	1.19	$2.3\cdot 10^3$	5.0
BM4	$2.2\cdot 10^4$	7792	24.1	17.7	$+1$	1926	$1.2\cdot 10^{-4}$	0.11	$\tilde{\chi}_1^+(1996)$	0.012	10.8	2.1

Search for spectral gamma-ray feature from IB

- Spectral gamma-ray feature on top of smoothly varying background
- Fermi LAT GC data 40 – 300 GeV *Bringmann, Huang, Ibarra, Vogl, Weniger 1203.1312*
- H.E.S.S. CGH (bkg residual p) 500 GeV-25 TeV *H.E.S.S. coll. 1301.1173*





- $\sigma v \lesssim 10^{-27}..10^{-26}$cm^3/s over the range 40 GeV - 10 TeV

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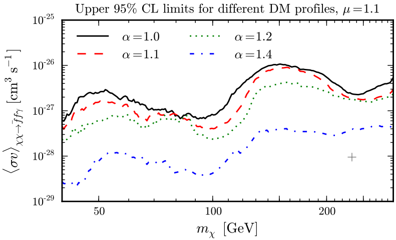

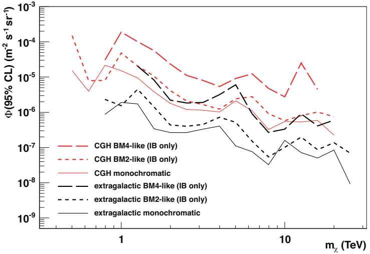

- $\sigma v \lesssim 10^{-27}..10^{-26}\text{cm}^3/\text{s}$ over the range 40 GeV - 10 TeV
- H.E.S.S. II, GAMMA-400, CTA $/= 5 - 10$

  Bringmann, Calore, Vertongen, Weniger 1106.1874; Bergstrom, Bertone, Conrad, Farnier, Weniger 1207.6773; Aleksic, Rico, Martinez 1209.5589

Toy Model for internal bremsstrahlung

- Majorana fermion χ (DM, e.g. bino) couples to a SM fermion via charged/colored scalar η (e.g. slepton/squark) with Yukawa coupling f ($f_{susy} = \sqrt{2}g'Y$)
- Coupling to RH quark (lepton) $\psi_R \in u_R, d_R, \ell_R$

$$\chi \equiv (1_c, 1_L, 0) , \qquad \eta \equiv (\bar{3}_c(1_c), 1_L, -Y_\psi)$$

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

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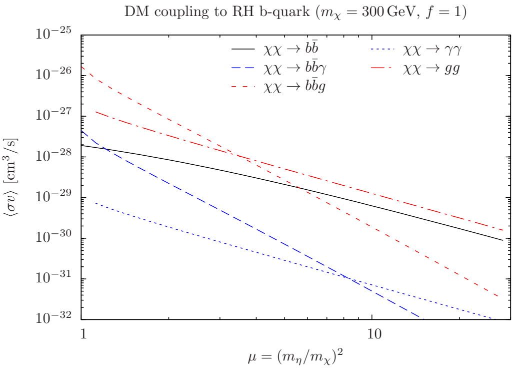
$$\begin{aligned} \mathcal{L}_{int}^{fermion} &= f \bar{\chi} \psi_R \eta + h.c. \\ \mathcal{L}_{int}^{scalar} &= -\lambda_3 (H^\dagger H)(\eta^\dagger \eta) \end{aligned}$$

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

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

- Coannihilations [micrOMEGAS2.4]
  $\rightarrow$ Yukawa coupling for thermal relic $f = f_{th}(m_\chi, m_\eta)$
  $\rightarrow$ lower bound $m_\chi \gtrsim 200\,\text{GeV}$ ($50\,\text{GeV}$) for $m_\eta/m_\chi - 1 \lesssim 1/25$

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



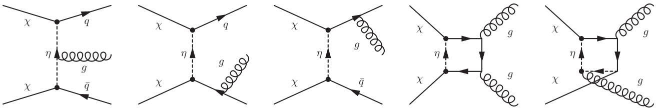
- $\sigma v_{2\to 2} \propto 1/\mu^2$, $\sigma v_{2\to 3} \propto 1/\mu^4$ (where $\mu = (m_\eta/m_{DM})^2$)
- Dominant channel $q\bar{q}g$ for $m_\eta \lesssim 2m_\chi$, gg for $m_\eta \gtrsim 2m_\chi$

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

Complementary constraints from ID and DD

- Secondary gamma rays (Fermi dwarf), antiprotons (PAMELA $\bar{p}/p$)

Geringer-Sameth, Koushiappas 1108.2914; Bringmann, Salati 0612514; ...



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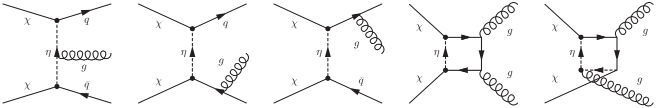
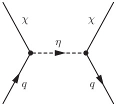


- Scattering off Xe nuclei (XENON100), resonant enhancement

Hisano, Ishiwata, Nagata 1110.3719; Drees, Nojiri 93; Jungman et al 95



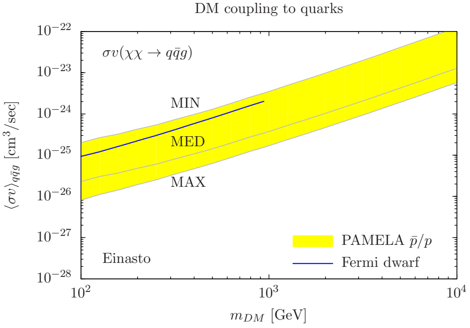
$$\sigma^{SI(SD)} \propto \frac{1}{[m_\eta^2 - (m_\chi + m_q)^2]^{4(2)}}$$

$$\frac{f_p}{m_p} = -\frac{m_\chi}{2} \sum_{q=u,d,s} f_{Tq}^{(p)} g_q - \frac{8\pi}{9} b f_{TG}^{(p)} - \frac{3}{2} m_\chi \sum_{q=u,d,s,b} g_q \left(q^{(p)}(2) + \bar{q}^{(p)}(2) \right)$$

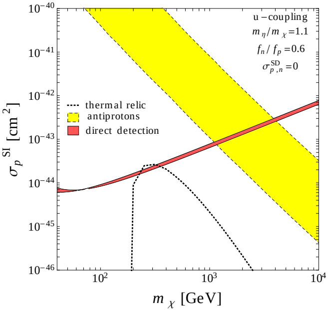
$$g_q = -\frac{1}{8} \frac{f^2}{\left(m_\eta^2 - (m_\chi + m_q)^2 \right)^2}$$

Complementary constraints from ID and DD

- Constraints on $\sigma v_{q\bar{q}g}$ and scattering rate $[\sigma^{SI(SD)}]$ at 95%C.L.



MG, Ibarra, Vogl 1105.5367,1112.5155



MG, Ibarra, Pato, Vogl 1207.1431

Complementary constraints from ID and DD

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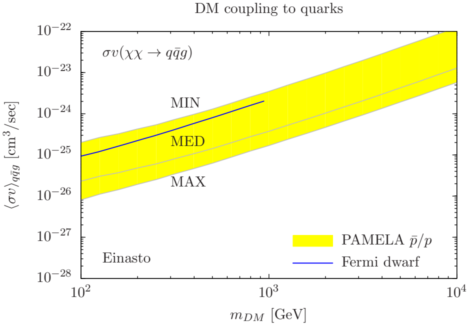

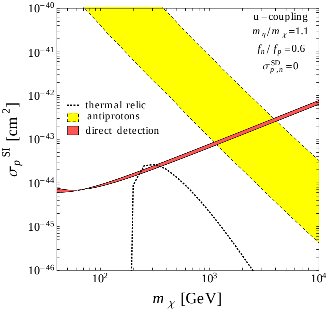

MG, Ibarra, Vogl 1105.5367,1112.5155

MG, Ibarra, Pato, Vogl 1207.1431

- Convert into constraints on Yukawa coupling f, using $\alpha_s(m_\chi)$, and conservative assumptions on nuclear uncertainties for DD, and then convert into upper limit on $\sigma v_{q\bar{q}\gamma} + 2\sigma v_{\gamma\gamma}$