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

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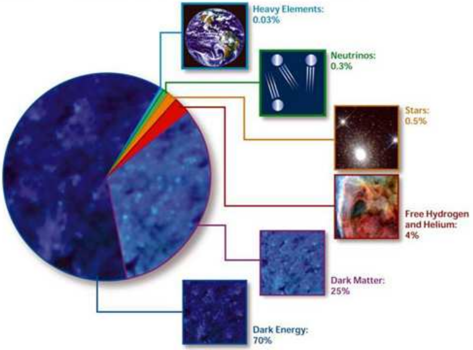
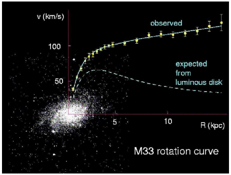
MITP, Mainz, 29.06.-02.07.13

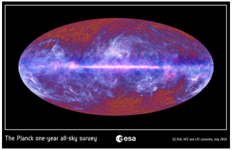
based on 1306.6342, 1207.1431, 1112.5155, 1105.5367

with Alejandro Ibarra, Miguel Pato, Stefan Vogl

Gravitational hints for a Dark Matter component







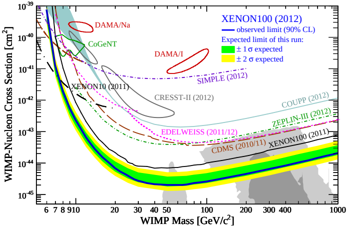
$$\Omega_{cdm} h^2 = 0.1199 \pm 0.0027 \quad \text{(Planck + WP)}$$

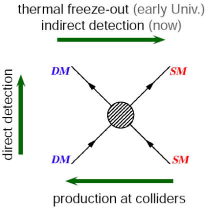
WIMP Dark Matter

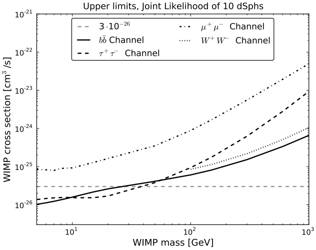
Xenon100 1207.5988

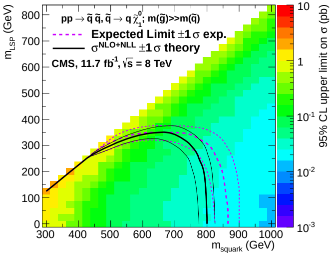
$$\Omega_\chi h^2 \simeq 0.1\,\mathrm{pb} \cdot c\,/\langle \sigma v \rangle$$

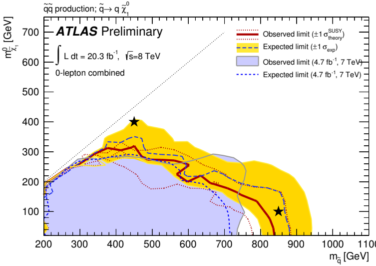
Fermi 1108.3546











CMS 1303.2985

ATLAS CONF-2013-047

WIMP Dark Matter

Interplay ID, DD, collider model dependent

- Complete models (MSSM)
- Simplified models
  - SM + DM particle: eff. operator approach

    e.g. Rajamaran, Sheperd, Tait, Wijangco 1108.1196; Fox, Harnik, Kopp, Tsai 1109.4398

  - EWino (e.g. well-tempered neutralino, $\chi^{\pm}$/Higgs/Z exchange)

    e.g. Arkani-Hamed, Delgado, Giudice 0601041; Cirelli, Fornengo, Strumia 0512090; Cheung, Hall, Pinner, Ruderman 1211.4873

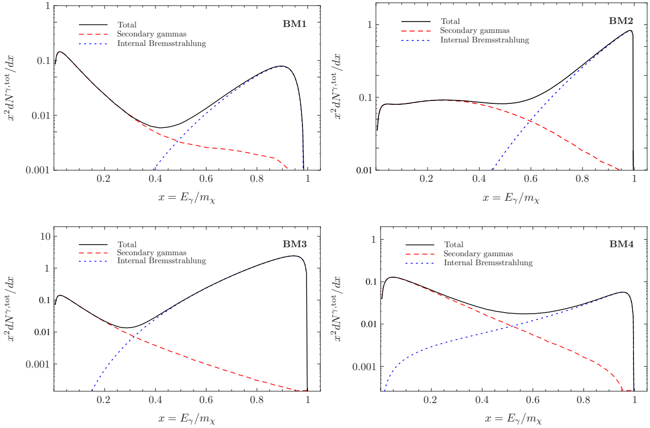
  - Compressed spectra ($\chi_1^0 + \tilde{q}$, $\chi_1^0 + \tilde{g}$, $\chi_1^0 + \tilde{\ell}$, $\chi_{1,2}^0 + \chi^{\pm} + \tilde{t}$)

    $\rightarrow$ More difficult for LHC (soft jets), but potentially interesting signatures for ID (internal bremsstrahlung) and DD

    e.g. Bergstrom PLB225(89)372; Bringmann, Bergstrom, Edsjo 0710.3169; Bringmann, Doro, Fornasa 0809.2269; Hisano, Ishiwata, Nagata, 1110.3719; ...

Characteristic feature in the gamma-ray spectrum

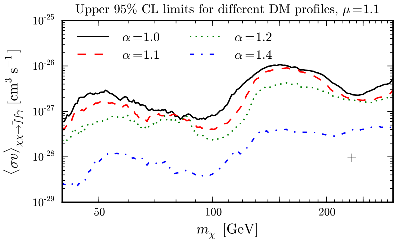
Bringmann, Bergstrom, Edsjo 0710.3169

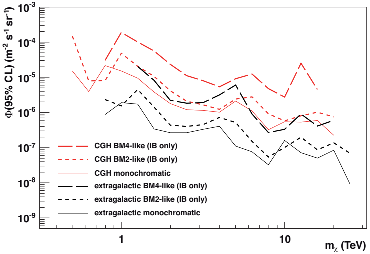


	m_0 [GeV]	$m_{1/2}$ [GeV]	$\tan\beta$	A_0 [GeV]	sgn (μ)	m_χ [GeV]	$Z_g/(1-Z_g)$	Ωh^2	t-channel	$\mathcal{S}$	IB/ sec.	IB/ lines
BM1	3700	3060	5.65	$-1.39\cdot10^4$	-1	1396	$3.0\cdot10^4$	0.082	$\tilde{t}(1406)$	$8\cdot10^{-5}$	19.2	4.5
BM2	801	1046	30.2	$-3.04\cdot10^3$	-1	446.9	1611	0.110	$\tilde{\tau}(447.5)$	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	$2.3\cdot10^3$	5.0
BM4	$2.2\cdot10^4$	7792	24.1	17.7	$+1$	1926	$1.2\cdot10^{-4}$	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 $40 - 300\,\text{GeV}$ *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*





- $\sigma v \lesssim 10^{-27}..10^{-26}\text{cm}^3/\text{s}$ 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

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

Strong IB $\Leftrightarrow$ colored/charged state close in mass
$\Rightarrow$ complementary constraints

- Toy Model for internal bremsstrahlung
- Complementary constraints from secondary gamma rays, antiprotons, and direct detection
- Prospects for CTA, GAMMA-400 and XENON1T
- Collider constraints

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) $\psi_R \in u_R, d_R, \ell_R$

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

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

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

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

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

Indirect Detection

- $2 \to 2$ annihilation

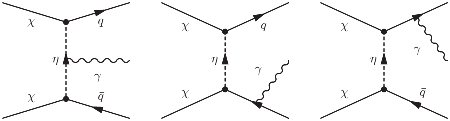
$$\sigma v_{\chi\chi\to q\bar{q}} = \left[\mathcal{O}(v^0)\mathcal{O}\left(\frac{m_q}{m_{DM}}\right)^2 + \mathcal{O}(v^2)\right]\mathcal{O}\left(\frac{m_{DM}}{m_\eta}\right)^4$$

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

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

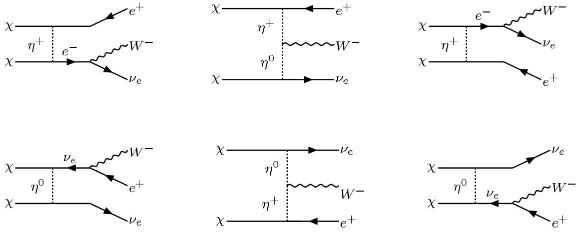
- $2 \to 3$ annihilation via VIB and FSR from off-shell q

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



Hard γ spectrum peaked at $0.8..0.95 \cdot m_{DM}$ *Bergstrom 89; Bergstrom et al 07*

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



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

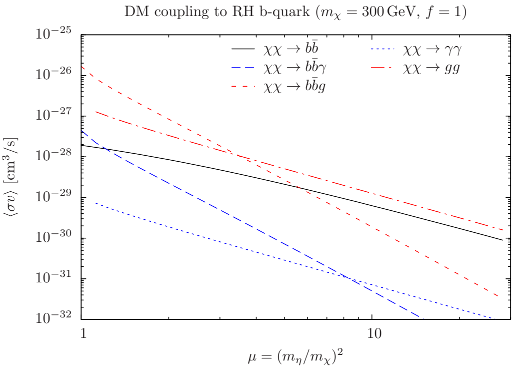
$$\frac{v d\sigma(\chi\chi \to W f\bar{f}')}{dE_W dE_f} = \frac{C_{Wf\bar{f}'}\alpha_{em} f^4}{8\pi^2 m_{DM}^4 (1-2y-\mu_f)^2 (3-2x-2y+\mu_{f'})^2}\Big\{(1-x)[x^2 - 2x(1-y) + 2(1-y)^2 + 2(2-x-2y)\Delta\mu] + x_0^2[x^2+2y^2+2xy-4y+2(2-x-2y)\Delta\mu+\Delta\mu^2]/4 - x_0^4/8 + \Delta\mu^2[(1-2x)/2 - 4(1-y)(1-x-y)/(2x_0^2)]\Big\}$$

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

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

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

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



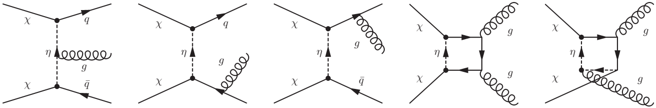
- $\sigma v_{2\to2} \propto 1/\mu^2$, $\sigma v_{2\to3} \propto 1/\mu^4$ (where $\mu = (m_\eta/m_{DM})^2$)
- Dominant channel $q\bar{q}g$ for $m_\eta \lesssim 2m_\chi$, gg for $m_\eta \gtrsim 2m_\chi$

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

Complementary constraints from ID and DD

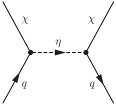
- Secondary gamma rays (Fermi dwarf), antiprotons (PAMELA $\bar{p}/p$)

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



- Scattering off Xe nuclei (XENON100), resonant enhancement

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



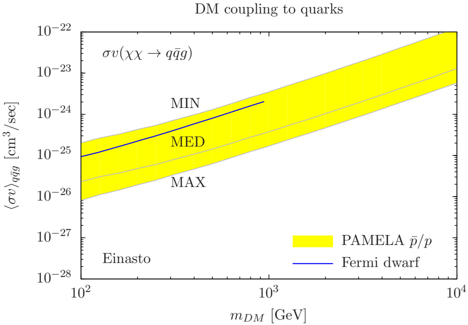
$$\sigma^{SI(SD)} \propto \frac{1}{[m_\eta^2 - (m_\chi + m_q)^2]^{4(2)}}$$

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

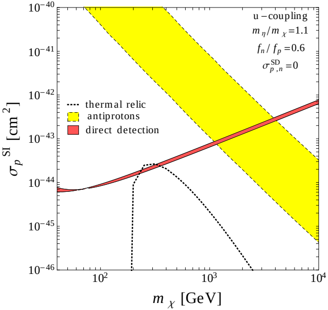
$$g_q = -\frac{1}{8} \frac{f^2}{\left(m_\eta^2 - (m_\chi + m_q)^2 \right)^2}$$

Complementary constraints from ID and DD

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



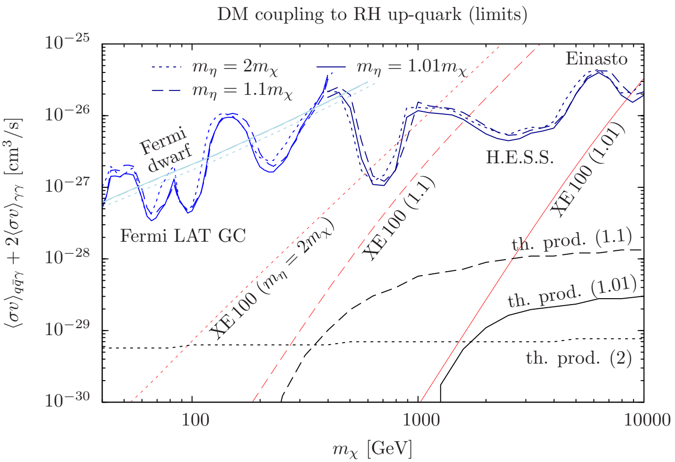
MG, Ibarra, Vogl 1105.5367,1112.5155



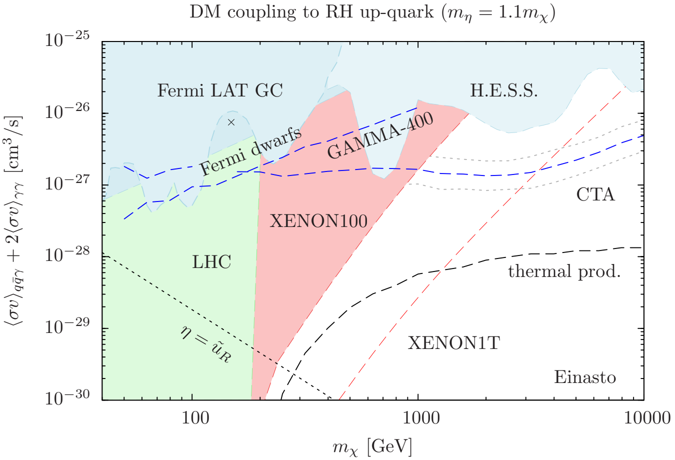
MG, Ibarra, Pato, Vogl 1207.1431

- 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 $\sigma v_{q\bar{q}\gamma} + 2\sigma v_{\gamma\gamma}$

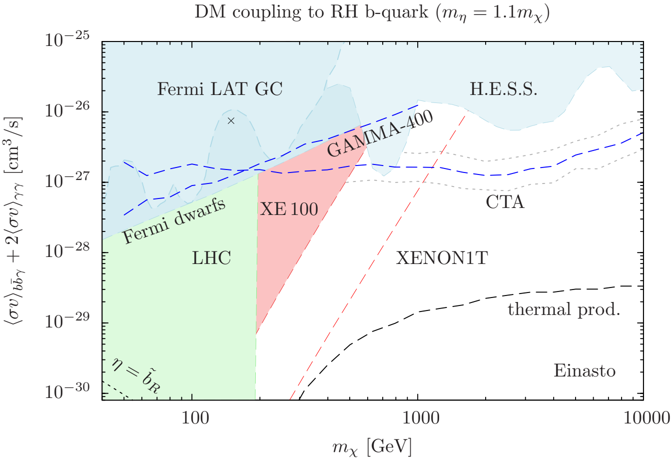
ID vs DD for DM coupling to u-quarks



ID vs DD for DM coupling to u-quarks

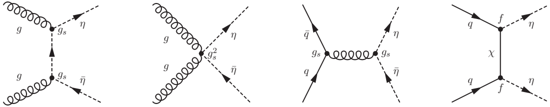


DM coupling to b-quarks



Collider constraints

- Production of η in pp collisions (LHC), $\eta \to \chi q$ (jets+E^T_{miss})



- Compressed spectrum harder to probe due to soft jets

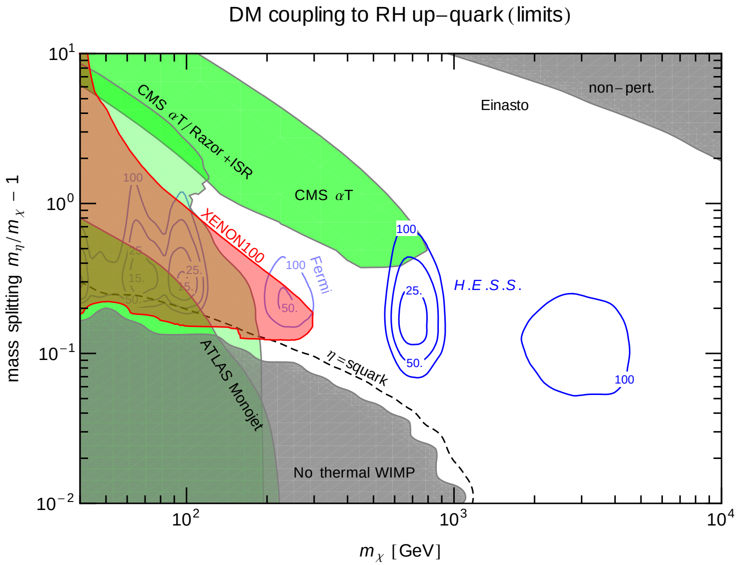
$$m_{DM} \sim 10^2 - 10^3\text{GeV}, \quad m_\eta - m_{DM} \lesssim \mathcal{O}(10-100)\text{GeV}$$

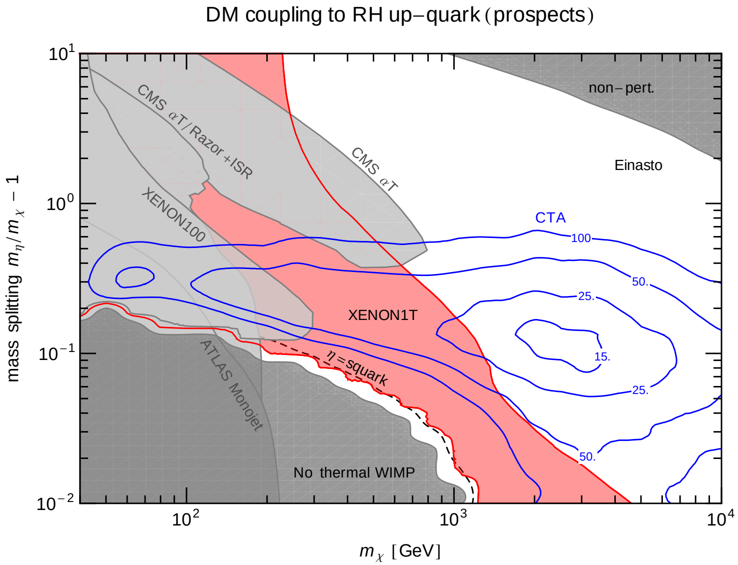
- Include recoil against ISR, for $m_\eta - m_{DM} \lesssim 20\text{GeV}$ monojet

Dreiner, Kramer, Tattersall 1207.1613

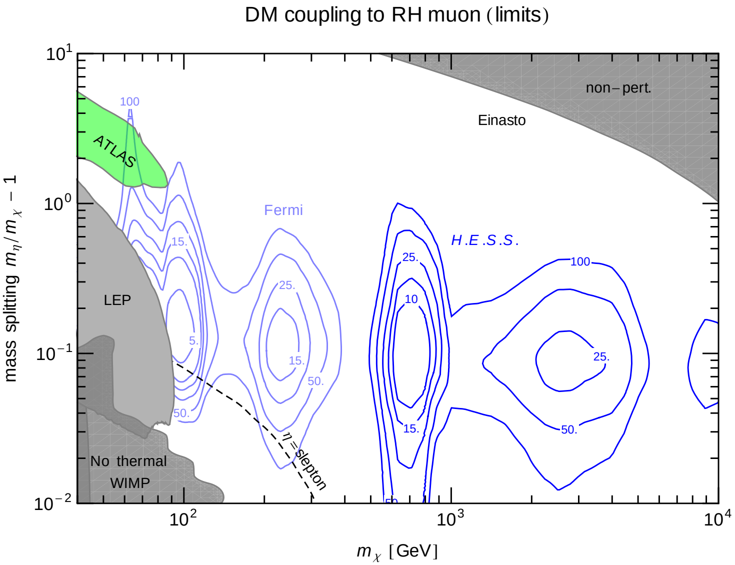
- CMS α_T analysis, SMS $\chi + \tilde{q}$, production cross section for single colored scalar (NLO+NLL) + $\sigma^{LO}_{uu\to\eta\eta}(\propto f^4)$ *CMS coll. 1303.2985*

ID vs DD vs LHC

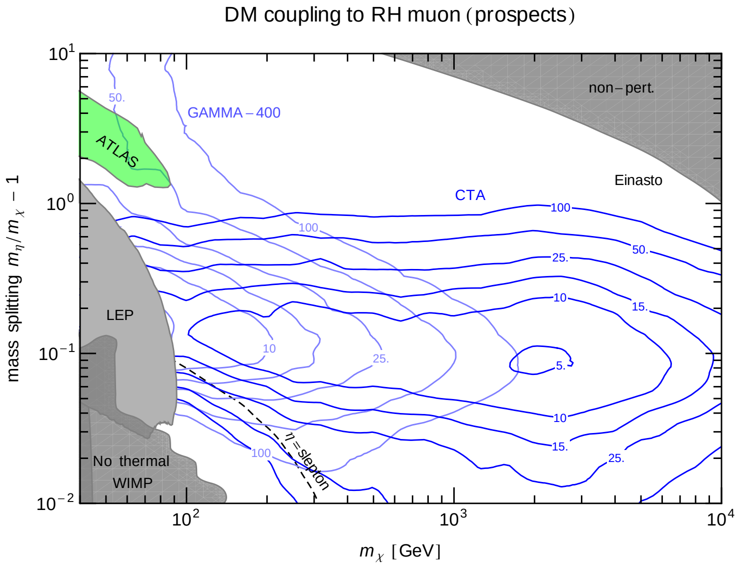



DM coupling to RH up−quark (prospects)
non−pert.
Einasto
CMS αT/Razor+ISR
CMS αT
XENON100
CTA
100
50.
25.
15.
XENON1T
η=squark
ATLAS Monojet
No thermal WIMP
mass splitting $m_\eta/m_\chi - 1$
m_χ [GeV]
10^1
10^0
10^{-1}
10^{-2}
10^2
10^3
10^4

DM coupling to leptons



DM coupling to leptons

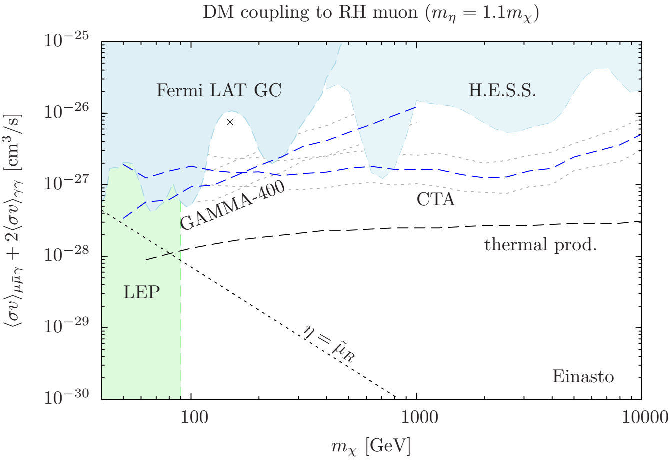


Conclusion

- Models with strong gamma-ray feature from IB typically feature charged/colored state not much heavier than DM
  $\Rightarrow$ complementary constraints
- XENON1T/CTA complementary
  - XE1T probes up to $1-2\,\text{TeV}$ for $m_\eta \lesssim 2m_{DM}$
  - CTA several TeV and $\sim 10\%$ splitting, $BF_{GC} \sim 5-10$
- IB signal at GAMMA-400 if DM couples to leptons (only)
- LHC most sensitive for large splitting

thank you!

DM coupling to leptons



Search for spectral gamma-ray feature from IB

- Spectral gamma-ray feature on top of smoothly varying background

$$\frac{d\Phi}{dE} = \beta E^{-\gamma} + \left(\frac{d\sigma v_{q\bar{q}\gamma}}{dE} + 2\sigma v_{\gamma\gamma}\delta(E - m_\chi) \right) \int_{CGH} \frac{d\Omega}{4\pi} \int_0^\infty ds\, \frac{1}{2} \left(\frac{\rho_{dm}(r)}{m_\chi} \right)^2$$

where $r = \sqrt{(r_0 - s\cos\theta)^2 + (s\sin\theta)^2}$, $r_0 = 8.5\,\text{kpc}$

- Fermi LAT data $40 - 300\,\text{GeV}$ *Bringmann, Huang, Ibarra, Vogl, Weniger 1203.1312*
  $\rightarrow$ search region with optimized expected S/B (CGH)
  $\rightarrow$ power-law bkg with free slope and normalization
  $\rightarrow$ energy resolution from LAT science tools (Pass7) $\sim 9 - 14\%$
- H.E.S.S. 500 GeV-25 TeV *H.E.S.S. coll. 1301.1173*
  $\rightarrow$ search region 1° around GC excl. plane $|b| < 0.3^\circ$
  $\rightarrow$ bkg mainly residual p showers, heuristic 7-param. model
  $\rightarrow$ energy resolution $\sim 17 - 11\%$

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

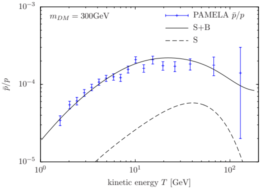
- Rate of $\bar{p}$ per unit of kinetic energy and volume

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

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

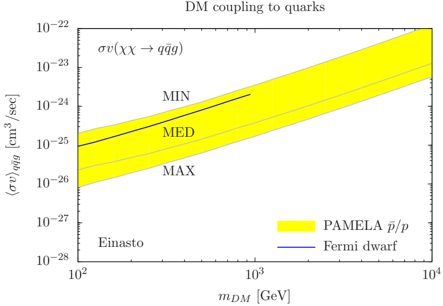
$$0 = \frac{\partial f_{\bar{p}}}{\partial t} = \nabla\cdot(K(T,\vec{r})\nabla f_{\bar{p}}) - \nabla\cdot(\vec{V}_c(\vec{r}) f_{\bar{p}}) - 2h\delta(z)\Gamma_{\rm ann} f_{\bar{p}} + Q(T,\vec{r})$$

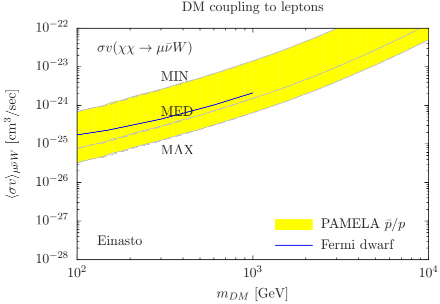
Model	δ	K_0 ($\mathrm{kpc}^2/\mathrm{Myr}$)	L (kpc)	V_c (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5



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

Antiprotons and secondary gamma rays





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