# Constraints on dark matter scenarios with nearly degenerate mass spectra from the cosmic antiproton flux

Mathias Garny (DESY)

KEK, POwLHC, 16.-18.02.12

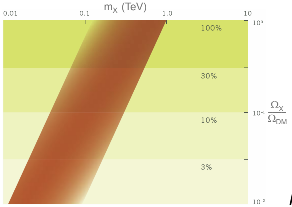
based on arXiv:1112.5155, JCAP 1107 (2011) 028 (arXiv:1105.5367)

with Alejandro Ibarra, Stefan Vogl

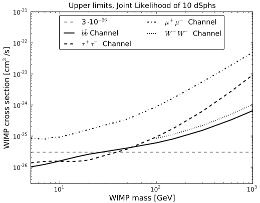
# Constraints on dark matter scenarios with nearly degenerate mass spectra from the cosmic antiproton flux

- Introduction
- Electroweak Internal Bremsstrahlung
- $SU(2)_L$ singlet (Bino-like) DM
- $SU(2)_L$ doublet (Higgsino-like) DM
- Constraints from PAMELA $\bar{p}/p$ measurement

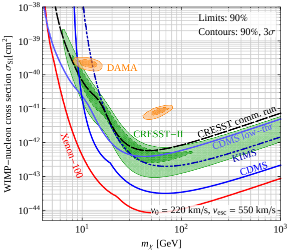
# WIMP Dark Matter

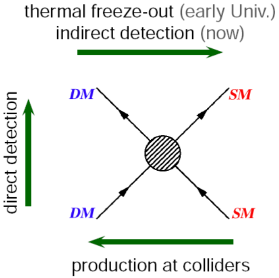


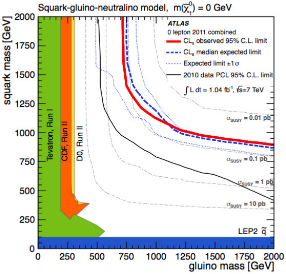

*Feng 2010*




*Fermi 1108.3546*



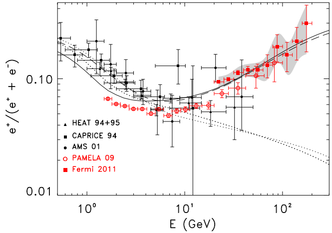



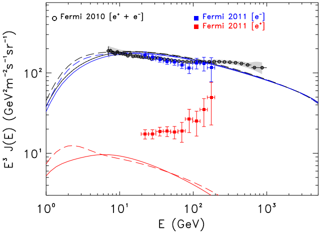




*Kopp, Schwetz, Zupan 2011*

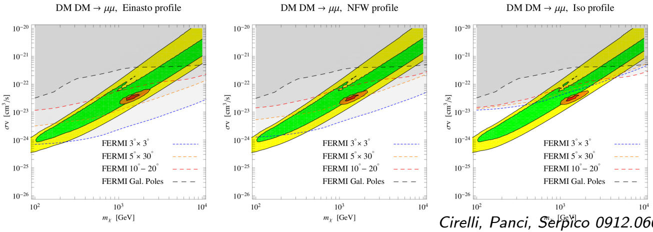
# WIMP Dark Matter

- Anomalies in $e^+/e^-$ and $e^+ + e^-$ reported by PAMELA and Fermi: Dark Matter? (not in this talk) *Fermi 1110.2591*



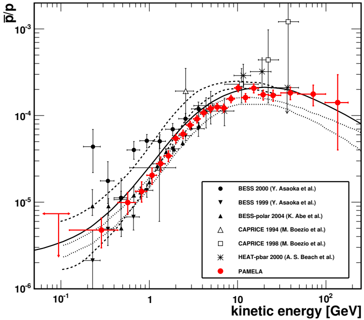

- Severe constraints from $\gamma$ (e.g. Fermi diffuse $\gamma$-ray data, IC)




*Cirelli, Panci, Serpico 0912.0663*

# WIMP Dark Matter

- PAMELA $\bar{p}/p$ ratio measurement is in good agreement with expectation from secondary production

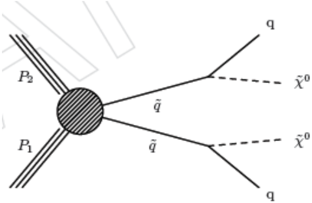



*PAMELA 1007.0821*

- This talk: Impact of $\bar{p}/p$ constraints on WIMP with nearly degenerate mass spectrum

# WIMP with nearly degenerate mass spectrum

- Scenarios where the dark matter particle $\chi$ couples to the Standard Model via a scalar particle $\eta$ (e.g. $\eta \equiv \tilde{q}$) that is nearly degenerate in mass are difficult to constrain by collider searches of exotic charged or colored particles




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

- Complementarity of collider searches and indirect detection (direct detection)

# Toy Model

- Majorana fermion $\chi$ (DM) couples to the SM via charged/colored scalar $\eta$, $m_\eta \gtrsim m_{DM}$ (e.g. slepton/squark)
- Coupling to leptons *cf. Cao, Ma, Shaughnessy 2009*

$$\chi \equiv (1,1,0)\ , \qquad \eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix} \equiv (1,2,1/2)$$

$$\mathcal{L}_{int}^{fermion} = f\bar{\chi}(L_e i\sigma_2\eta) + h.c. = f\bar{\chi}(\nu_{eL}\eta^0 - e_L\eta^+) + h.c.$$
$$\mathcal{L}_{int}^{scalar} = -\lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta) - \lambda_4(\Phi^\dagger\eta)(\eta^\dagger\Phi)$$

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$$m_{\eta^0}^2 = m_2^2 + (\lambda_3+\lambda_4)v_{EW}^2\ , m_{\eta^\pm}^2 = m_2^2 + \lambda_3 v_{EW}^2$$

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$$\Omega_{DM}h^2 \simeq 0.11\left(\frac{0.35}{f}\right)^4\left(\frac{m_{DM}}{100\,\mathrm{GeV}}\right)^2\left[\frac{1+m_{\eta^\pm}^4/m_{DM}^4}{(1+m_{\eta^\pm}^2/m_{DM}^2)^4} + \frac{1+m_{\eta^0}^4/m_{DM}^4}{(1+m_{\eta^0}^2/m_{DM}^2)^4}\right]^{-1}$$

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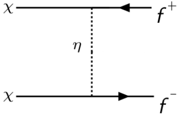
- Coupling to quarks $\eta = (3,2,1/6)$ or $\eta = (3,2,2/3)$

# Indirect detection

- For Majorana dark matter, the annihilation rate in the Milky Way halo into light fermions is strongly suppressed (e.g. MSSM Neutralino annihilating via squark/slepton)

$$\sigma v_{\chi\chi\to f\bar{f}} = a + bv^2 \qquad a \propto m_f^2/m_{DM}^2, \quad v/c \sim 10^{-3}$$



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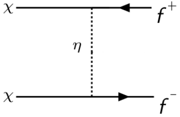


- The helicity suppression is lifted by the associated emission of a gauge boson, yielding annihilation rates which could be large enough to allow the indirect detection of the dark matter particles

$$\chi\chi \to f\bar{f}V, \qquad V = \gamma, W, Z, g$$

*Bergstrom 89; Flores, Olive, Rudaz 89; Drees, Jungman, Kamionkowski Nojiri 93*

- The $2 \to 3$ annihilation rate is particularly enhanced when the dark matter particle is degenerate with the intermediate scalar particle

# Virtual Internal Bremsstrahlung

- $2 \to 2$ annihilation

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

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

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

# Virtual Internal Bremsstrahlung

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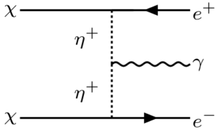
- $2 \to 3$ annihilation via VIB and FSR from off-shell $e^\pm$

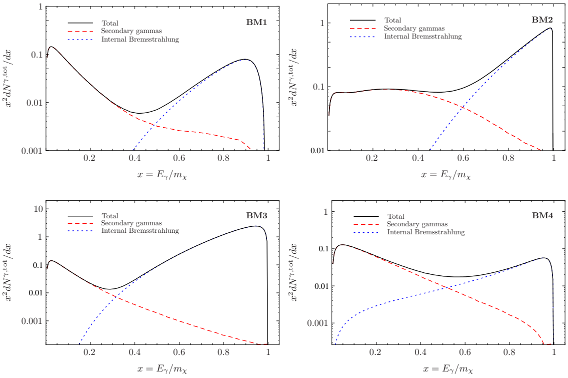
$$\sigma v^{VIB/FSR}_{\chi\chi\to f\bar{f}\gamma} = \frac{\alpha_{em}}{\pi}\left[\mathcal{O}(v^0)\mathcal{O}\left(\frac{m_{DM}}{m_\eta}\right)^8 + \mathcal{O}(v^2)\mathcal{O}\left(\frac{m_{DM}}{m_\eta}\right)^4\right]$$




*Bergstrom 89; Flores, Olive, Rudaz 89*

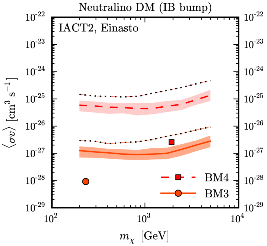
# Electromagnetic Internal Bremsstrahlung $\chi\chi \to f\bar{f}\gamma$

Characteristic feature in the gamma ray spectrum




| | $m_0$ [GeV] | $m_{1/2}$ [GeV] | $\tan\beta$ | $A_0$ [GeV] | sgn ($\mu$) | $m_\chi$ [GeV] | $Z_g/(1-Z_g)$ | $\Omega h^2$ | $t$-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 |

*Bergstrom 89; Bringmann, Bergstrom, Edsjo 07*




| | $A_{\mathrm{eff}}(1\,\mathrm{TeV})$ | $\Delta E/E(1\,\mathrm{TeV})$ | $\epsilon_p$ | $t_{\mathrm{obs}}$ |
|---|---|---|---|---|
| IACT1 | 0.18 km$^2$ | 15% | $10^{-1}$ | 50 h |
| IACT2 | 2.3 km$^2$ | 9% | $10^{-2}$ | 100 h |
| IACT3 | 23 km$^2$ | 7% | $10^{-3}$ | 5000 h |

TABLE I: IACT benchmark models that, from top to bottom, roughly correspond to the H.E.S.S. [3], the future CTA [6] and the proposed DMA [7] telescope characteristics.

solid: $2\sigma$ exclusion

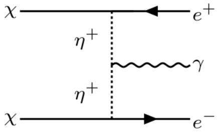
dashed: $5\sigma$ dicovery

thin: $S/B = 1\%$

*Bringmann, Calore, Vertongen, Weniger 11*

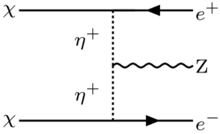
# Electroweak Internal Bremsstrahlung

- Characteristic feature in the gamma ray spectrum



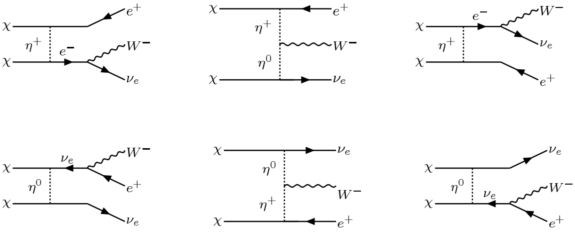

*Bergstrom 89; Bringmann, Bergstrom, Edsjo 07*

- Limits on the relevant cross sections from the non-observation of an excess in the cosmic $\bar{p}/p$ ratio measured by PAMELA




*MG, Ibarra, Vogl 11; Ciafaloni, Cirelli, Comelli, De Simone, Riotto, Urbano 11; Bell, Dent, Jacques, Weiler 11*

# Electroweak Internal Bremsstrahlung




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

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

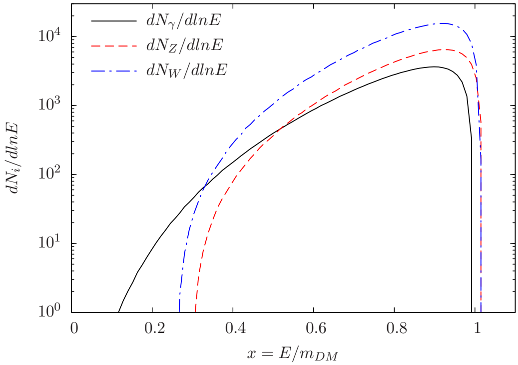
$x = E_W/m_{DM}$, $y = E_f/m_{DM}$, $x_0 = M_W/m_{DM}$, $\mu_f = m_{\eta_f}^2/m_{DM}^2$, $\mu_{f'} = m_{\eta_{f'}}^2/m_{DM}^2$, $\Delta\mu = 2(\mu_{f'} - \mu_f)$

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

*MG, Ibarra, Vogl 11*

# Electroweak Internal Bremsstrahlung

Spectrum of primary electroweak gauge bosons (for $m_{\eta^\pm} = m_{\eta^0}$)



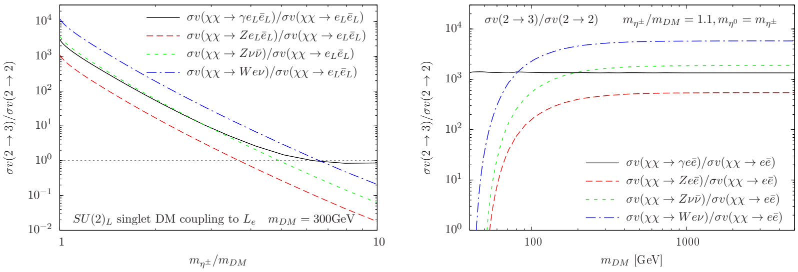

*$m_{DM} = 300$ GeV and $m_{\eta^\pm} = m_{\eta^0} = 330$ GeV*

*MG, Ibarra, Vogl 11*

$$\frac{dN_W}{d\ln E} = \frac{1}{\sigma v(\chi\chi \to e\bar{e})}\left(\frac{vd\sigma(\chi\chi \to W\bar{e}\nu)}{d\ln E} + \frac{vd\sigma(\chi\chi \to We\bar{\nu})}{d\ln E}\right)$$

# Electroweak Internal Bremsstrahlung

Ratio of $2 \to 2$ and $2 \to 3$ cross sections (for $m_{\eta^\pm} = m_{\eta^0}$)

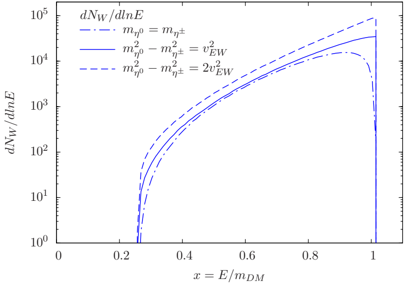


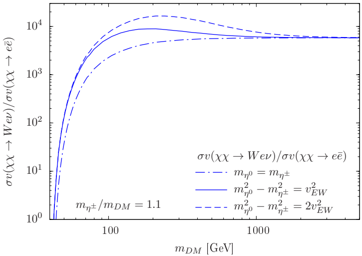

*$m_{DM} = 300$ GeV and $m_{\eta^\pm} = m_{\eta^0}$* *MG, Ibarra, Vogl 11*

- The $2 \to 3$ processes dominate for $m_\eta \lesssim 5 m_{DM}$
- Production of electroweak gauge bosons if $m_{DM} > M_W/2$, sizeable for $m_{DM} \gtrsim 100$GeV

# Electroweak Internal Bremsstrahlung

Mass splitting $m^2_{\eta^0} - m^2_{\eta^\pm} = \lambda_4 v^2_{EW}$ with $\lambda_4 \sim \mathcal{O}(1)$




Longitudinal W-bosons: no kinematic suppression at the endpoint $\Rightarrow$ harder spectrum, enhanced cross-section

$$\sigma v(\chi\chi \to We\nu) \approx \frac{1}{\sin^2(\theta_W)} \left(\frac{2m^2_{\eta^\pm}}{m^2_{\eta^0} + m^2_{\eta^\pm}}\right)^4 \left[1 + \frac{5}{8}\frac{(m^2_{\eta^0} - m^2_{\eta^\pm})^2}{M^2_W m^2_{DM}}\right] \sigma v(\chi\chi \to \gamma e\bar{e})$$

$$\approx 4.32 \left(\frac{2m^2_{\eta^\pm}}{m^2_{\eta^0} + m^2_{\eta^\pm}}\right)^4 \left[1 + \lambda_4^2 \left(\frac{300\text{ GeV}}{m_{DM}}\right)^2\right] \sigma v(\chi\chi \to \gamma e\bar{e})$$

*MG, Ibarra, Vogl 11*

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# $SU(2)_L$ singlet DM

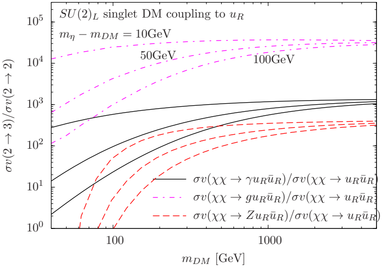
Branching ratio $\sigma v(\chi\chi \to X)/\sigma v(\chi\chi \to \gamma f\bar{f})$ for $m_{\eta^u} = m_{\eta^d}$ and $m_W/2 \ll m_{DM} = 300\text{GeV} \ll m_\eta$

| DM $\chi = (1,1,0)$ | $\eta$ | $Wf\bar{f}'$ | $Zf\bar{f}$ | $gf\bar{f}$ |
|---|---|---|---|---|
| DM coupling to $L_e$ | (1,2,1/2) | 4.32 | 1.82 | – |
| DM coupling to $e_R$ | (1,1,1) | – | 0.30 | – |
| DM coupling to $q_L$ | (3,2,1/6) | 7.79 | 3.02 | 61.4 |
| DM coupling to $u_R$ | (3,1,2/3) | – | 0.30 | 38.4 |
| DM coupling to $d_R$ | (3,1,-1/3) | – | 0.30 | 154 |

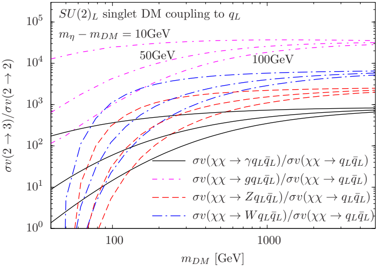
# $SU(2)_L$ singlet DM

Ratio of $2 \to 2$ and $2 \to 3$ cross sections for singlet Majorana DM annihilating into right-handed up-quarks or left-handed quarks, respectively, with mass splittings $\Delta m = 10, 50, 100$GeV

Singlet DM coupling to $u_R$




Singlet DM coupling to $Q_L$



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# $SU(2)_L$ doublet DM

- Two doublets $\chi_1 \equiv (1, 2, -\frac{1}{2})$, $\chi_2 \equiv (1, 2, \frac{1}{2})$ (anomaly free)
- Mass splitting from radiative corrections $(m_{\chi^\pm} - m_{\chi^0})_{rad} \simeq 0.34$GeV
- Mass splitting from Dim-5 operator (we assume $\Lambda \lesssim 10$TeV)

$$\delta\mathcal{L}_{\rm mass}^{\rm fermion} = \frac{1}{\Lambda}\Big[c_1(\bar\chi_1 i\sigma_2\Phi^*)(\Phi^\dagger i\sigma_2\chi_1^c) + c_2(\bar\chi_2\Phi)(\Phi^T\chi_2^c) + c_3(\bar\chi_2\Phi)(\Phi^\dagger i\sigma_2\chi_1^c)\Big] + {\rm h.c.}$$

$$\begin{aligned}\delta m_\pm &= m_{\chi^\pm} - m_\chi = \frac{v_{EW}^2}{2\Lambda}(c_3 + |c_1 - c_2|) \\ \delta m_0 &= m_{\chi'} - m_\chi = \frac{v_{EW}^2}{\Lambda}|c_1 - c_2|\end{aligned}$$

- Annihilation via gauge interaction $\chi\chi \to WW, ZZ$

$$\begin{aligned}\sigma v_{\chi\chi\to WW} &= \frac{g^4}{32\pi}\frac{m_\chi^2 - M_W^2}{(m_\chi^2 + m_{\chi^\pm}^2 - M_W^2)^2}\sqrt{1 - M_W^2/m_\chi^2} \\ \sigma v_{\chi\chi\to ZZ} &= \frac{g^4}{64\pi c_W^4}\frac{m_\chi^2 - M_Z^2}{(m_\chi^2 + m_{\chi'}^2 - M_Z^2)^2}\sqrt{1 - M_Z^2/m_\chi^2}\end{aligned}$$

# $SU(2)_L$ doublet DM

- Annihilation into fermions via charged scalar $\eta$

$$\eta \equiv (1,2,-\frac{1}{2}) : \mathcal{L}_{int} = f(\bar{\chi}_1 i\sigma_2 \eta^*) e_R - \lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta) - \lambda_4(\Phi^\dagger\eta)(\eta^\dagger\Phi)$$

$$\eta \equiv (1,1,1) : \mathcal{L}_{int} = f(\bar{\chi}_1 i\sigma_2 L_e^c)\eta - \lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta)$$

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- $\chi\chi \to \gamma e\bar{e}$ via VIB, FSR

$$\sigma v^{VIB/FSR}_{\chi\chi\to f\bar{f}\gamma} = \frac{\alpha_{em}}{\pi}\left[\mathcal{O}(v^0)\mathcal{O}\left(\frac{m_{DM}}{m_\eta}\right)^8 + \mathcal{O}(v^2)\mathcal{O}\left(\frac{m_{DM}}{m_\eta}\right)^4\right]$$

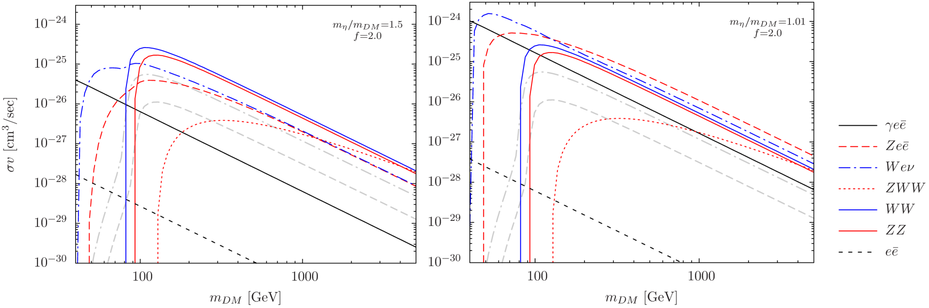
- $\chi\chi \to Ze\bar{e}$ via VIB, FSR, and ISR

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

# $SU(2)_L$ doublet DM

- Cross-sections for $2 \to 2$ and $2 \to 3$ annihilation
- Typically $\chi\chi \to WW/ZZ$ channels dominate
- The channels $\chi\chi \to f\bar{f}V$ can be important for $m_\eta \approx m_{DM}$

$m_\eta/m_{DM} = 1.5$ $\qquad$ $m_\eta/m_{DM} = 1.01$



- Introduction
- Electroweak Internal Bremsstrahlung
- $SU(2)_L$ singlet (Bino-like) DM
- $SU(2)_L$ doublet (Higgsino-like) DM
- Constraints from PAMELA $\bar{p}/p$ measurement

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

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

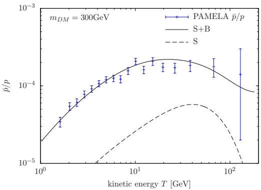
$$Q(T,\vec{r}) = \frac{1}{2}\frac{\rho^2(\vec{r})}{m_\chi^2}\sum_f \langle\sigma v\rangle_f \frac{dN_{\bar{p}}^f}{dT}$$

- Isothermal, NFW, Einasto profile with $\rho(r_\odot) = 0.39\mathrm{GeV}/\mathrm{cm}^3$
- 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 | $\delta$ | $K_0$ $(\mathrm{kpc}^2/\mathrm{Myr})$ | $L$ $(\mathrm{kpc})$ | $V_c$ $(\mathrm{km/s})$ |
|---|---|---|---|---|
| MIN | 0.85 | 0.0016 | 1 | 13.5 |
| MED | 0.70 | 0.0112 | 4 | 12 |
| MAX | 0.46 | 0.0765 | 15 | 5 |

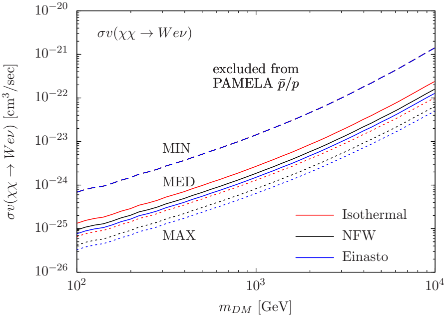
- secondary $\bar{p}$ flux from *Donato, Maurin, Salati, Barrau, Boudoul, Taillet 01*
- solar modulation in force field approximation $\phi_F = 500MV$



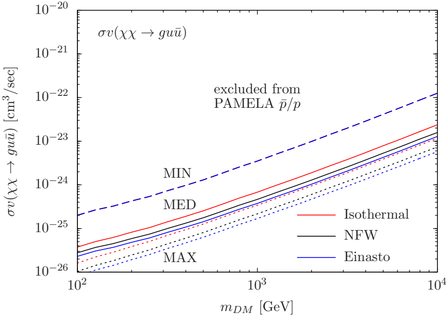
# Constraints from PAMELA $\bar{p}/p$ measurement

Maximally allowed cross section (95% C.L.) from PAMELA $\bar{p}/p$ measurement

$\chi\chi \to We\nu$




$\chi\chi \to gu\bar{u}$

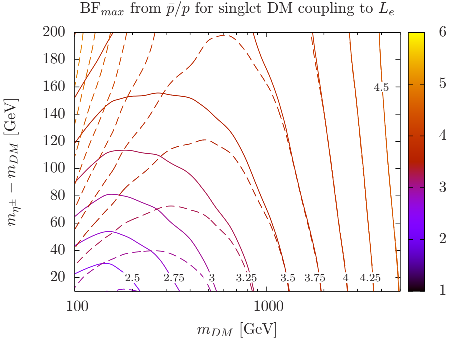



*MG, Ibarra, Vogl 11*

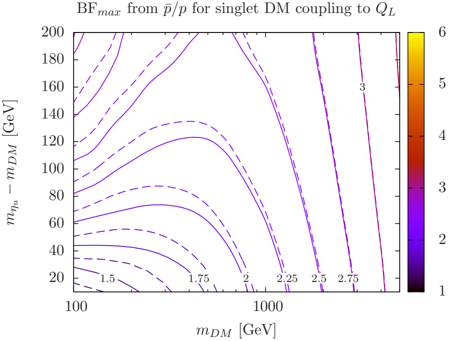
# Constraints from PAMELA $\bar{p}/p$ measurement

Constraint on the BF in the milky way by imposing thermal relic density constraint $\Omega_\chi h^2 = 0.11$ in the $m_{DM} - \Delta m$ plane for MED propagation and NFW profile

Singlet DM coupling to leptons




Singlet DM coupling to quarks




Solid: $m_{\eta^u} = m_{\eta^d}$

Dashed: $m^2_{\eta^u} - m^2_{\eta^d} = v^2_{EW}$ (log scale)

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

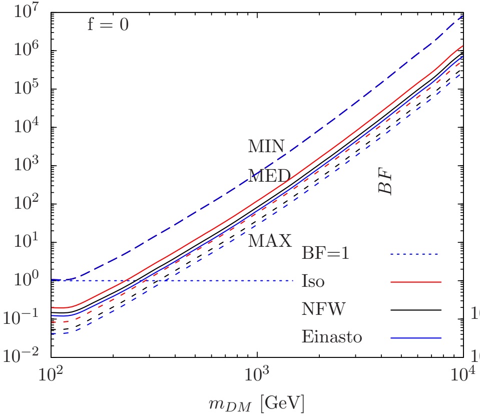
Constraint on the BF in the milky way for Doublet DM

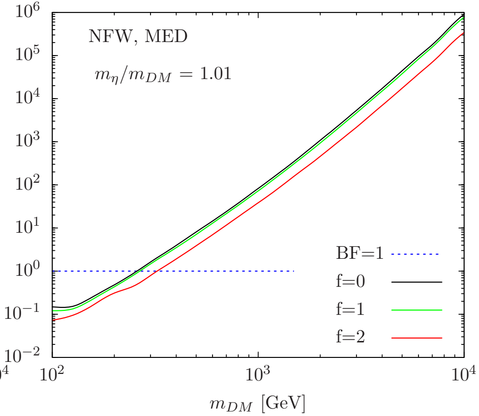
Doublet DM pure gauge

$$\chi\chi \to WW/ZZ/WWZ/WW\gamma$$

Doublet DM coupling to $L_e$

$$\chi\chi \to WW/ZZ/WWZ/WW\gamma$$
$$\chi\chi \to We\bar{\nu}/W\bar{e}\nu/Ze\bar{e}/Z\nu\bar{\nu}$$



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

Upper limits on the boost factor $BF$ in the Milky Way obtained from the PAMELA $\bar{p}/p$ data for several MSSM benchmark points at 95%C.L.

| Model | $m_{DM}$ [GeV] | $BF$ $(\bar{p}/p)$ $2 \to 2/3$ | $BF$ $(\bar{p}/p)$ $2 \to 3$ |
|---|---|---|---|
| BM2 | 453 | $< 5900$ | $< 1.3 \cdot 10^5$ |
| BM3 | 234 | $< 1500$ | $< 1.3 \cdot 10^4$ |
| BM$J'$ | 316 | $< 330$ | $< 3.5 \cdot 10^4$ |
| BM$I'$ | 141 | $< 11$ | $< 6900$ |

- in realistic models the upper bounds on the boost factor are at least one order of magnitude stronger than the conservative bounds
- BM3 has been discussed in as a possible explanation of the PAMELA positron excess, provided the boost factor in the Milky way is $\sim 3 \times 10^4$ *Bergstrom, Bringmann, Edsjo 2008*
- detection of a gamma-ray signal with a $5\sigma$ significance at MAGIC II or at the projected CTA with 30 hours of observation requires a boost factor in Draco larger than $\sim 10^4$ or $\sim 10^3$, respectively

  *Bringmann, Doro, Fornasa 2008*

# Constraints on dark matter scenarios with nearly degenerate mass spectra from the cosmic antiproton flux

## Conclusion

- For Majorana DM the annihilation channels into two fermions and one gauge boson can be important $\chi\chi \to f\bar{f}V$
- The $2 \to 3$ channel is enhanced if the charged/colored scalar mediating the annihilation is nearly degenerate in mass with the DM
  $\Rightarrow$ Complementarity of IDM/Collider searches
- Constraints from PAMELA $\bar{p}/p$ data on the order of $10^{-25}\text{cm}^3/\text{sec}$ for $\chi\chi \to We\nu$ and $10^{-26}\text{cm}^3/\text{sec}$ for $\chi\chi \to gu\bar{u}$

# Constraints on dark matter scenarios with nearly degenerate mass spectra from the cosmic antiproton flux

## Conclusion

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thank you!

*MG, Alejandro Ibarra, Stefan Vogl*

arXiv:1112.5155, JCAP 1107 (2011) 028 (arXiv:1105.5367)

# Density profile

Isothermal profile

$$\rho(r) = \frac{\rho_s}{1 + (r/r_s)^2} \ ,$$

Navarro-Frenk-White (NFW) profile

$$\rho(r) = \rho_s \frac{1}{r/r_s(1 + r/r_s)^2} \ ,$$

Einasto profile

$$\rho(r) = \rho_s \exp\left\{ -\frac{2}{\alpha} \left[ \left( \frac{r}{r_s} \right)^\alpha - 1 \right] \right\} \ .$$

Scale radius $r_s = 4.38,\ 24.42, 28.44\,\mathrm{kpc}$, respectively, $\alpha = 0.17$ for the Einasto profile. Besides, the parameter $\rho_s$ is adjusted in order to yield a local dark matter density $\rho(r_\odot) = 0.39\,\mathrm{GeV/cm^3}$ with $r_\odot = 8.5\,\mathrm{kpc}$ being the distance of the Sun to the Galactic center and is given, respectively, by $\rho_s = 1.86,\ 0.25$ and $0.044\,\mathrm{GeV/cm^3}$.

# Sommerfelfd enhancement for $SU(2)_L$ Doublet DM

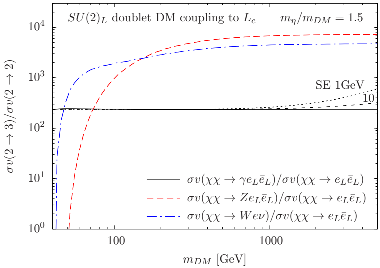
Amplitude

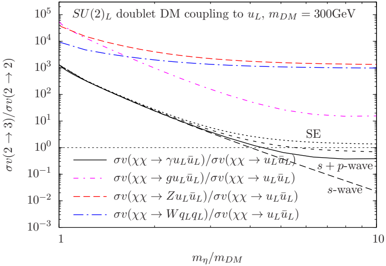
$$\mathcal{A}_{\chi\chi\to SM} = s_0 \mathcal{A}^0_{\chi\chi\to SM} + s_0' \mathcal{A}^0_{\chi'\chi'\to SM} + s_\pm \mathcal{A}^0_{\chi^+\chi^-\to SM}$$

Enhancement in the perturbative limit

$$s_0' \simeq \frac{\alpha_{em}}{\sqrt{2} s_{2W}^2} \frac{m_{DM}}{M_Z + \sqrt{2 m_{DM} \delta m_0}}, \quad s_\pm \simeq \frac{\alpha_{em}}{2\sqrt{2} s_W^2} \frac{m_{DM}}{M_W + \sqrt{2 m_{DM} \delta m_\pm}} .$$

Largest effect for $\chi\chi \to \chi^+\chi^- \to \gamma f \bar{f}$ due to 'ISR'



# Collider constraints

*(rough estimate)*

- coloured scalar
  - $m_\eta > 875\ \mathrm{GeV}$ for any $m_{\mathrm{DM}}$ (ATLAS dijet 95%$c.l$ 1.04fb$^{-}$1)
  - 97 $\mathrm{GeV} \leq m_\eta \leq 875\ \mathrm{GeV}$, if $p_T, E_T^{miss} \lesssim 130\ \mathrm{GeV}$
  - $33 - 44\ \mathrm{GeV} \leq m_\eta \leq 97\ \mathrm{GeV}$, if $m_\eta - m_{\mathrm{DM}} \lesssim 10\ \mathrm{GeV}$ (L3 )
- charged scalar
  - $60\ \mathrm{GeV} \leq m_\eta \leq 94.4 - 97.5\ \mathrm{GeV}$, if $m_\eta - m_{\mathrm{DM}} \lesssim 10 - 15\ \mathrm{GeV}$ (OPAL, L3, ALEPH)
  - $40\ \mathrm{GeV} \leq m_\eta \leq 60\ \mathrm{GeV}$, if $m_\eta - m_{\mathrm{DM}} \lesssim 5\ \mathrm{GeV}$ (DELPHI)