Determinations of Properties of Low-Mass WIMPs from Direct Dark Matter Detection Experiments with Non-Negligible Threshold Energy

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Motivation

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- Differential event rate for elastic WIMP-nucleus scattering

$$\frac{dR}{dQ} = \mathcal{A} F^2(Q) \int_{v_{\rm min}(Q)}^{v_{\rm max}} \left[\frac{f_1(v)}{v}\right] dv$$

Here

$$v_{\rm min}(Q) = \alpha \sqrt{Q}$$

is the minimal incoming velocity of incident WIMPs that can deposit the recoil energy Q in the detector,

$$\mathcal{A} \equiv \frac{\rho_0 \sigma_0}{2 m_\chi m_{\rm r,N}^2} \qquad \alpha \equiv \sqrt{\frac{m_{\rm N}}{2 m_{\rm r,N}^2}} \qquad m_{\rm r,N} = \frac{m_\chi m_{\rm N}}{m_\chi + m_{\rm N}}$$

ρ_0: WIMP density near the Earth
σ_0: total cross section ignoring the form factor suppression
$F(Q)$: elastic nuclear form factor
$f_1(v)$: one-dimensional velocity distribution of halo WIMPs

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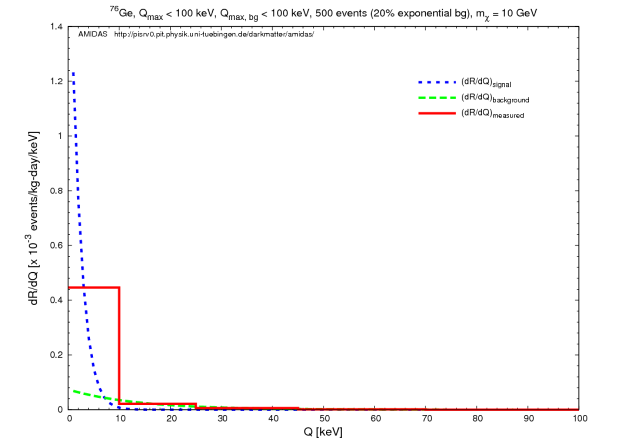
  (^{76}Ge, 0 - 100 keV, exponential bg 0 - 100 keV, 500 events, 20% bg, m_χ = 10 GeV)



[Y.-T. Chou and CLS, JCAP 1008, 014 (2010)]

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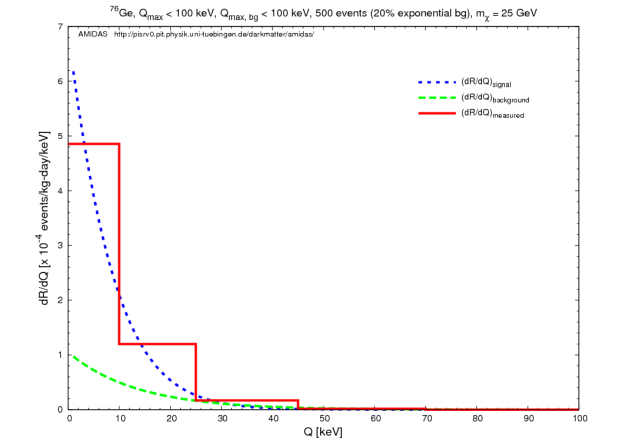

[Y.-T. Chou and CLS, JCAP 1008, 014 (2010)]

Model-independent data analyses

Reconstruction of the 1-D WIMP velocity distribution

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- Normalized one-dimensional WIMP velocity distribution function

$$f_1(v) = \mathcal{N} \left\{ -2Q \cdot \frac{d}{dQ} \left[\frac{1}{F^2(Q)} \left(\frac{dR}{dQ} \right) \right] \right\}_{Q=v^2/\alpha^2}$$

$$\mathcal{N} = \frac{2}{\alpha} \left\{ \int_0^\infty \frac{1}{\sqrt{Q}} \left[\frac{1}{F^2(Q)} \left(\frac{dR}{dQ} \right) \right] dQ \right\}^{-1}$$

- Moments of the velocity distribution function

$$\langle v^n \rangle = \mathcal{N}(Q_{\rm thre}) \left(\frac{\alpha^{n+1}}{2} \right) \left[\frac{2Q_{\rm thre}^{(n+1)/2}}{F^2(Q_{\rm thre})} \left(\frac{dR}{dQ} \right)_{Q=Q_{\rm thre}} + (n+1) I_n(Q_{\rm thre}) \right]$$

$$\mathcal{N}(Q_{\rm thre}) = \frac{2}{\alpha} \left[\frac{2Q_{\rm thre}^{1/2}}{F^2(Q_{\rm thre})} \left(\frac{dR}{dQ} \right)_{Q=Q_{\rm thre}} + I_0(Q_{\rm thre}) \right]^{-1}$$

$$I_n(Q_{\rm thre}) = \int_{Q_{\rm thre}}^\infty Q^{(n-1)/2} \left[\frac{1}{F^2(Q)} \left(\frac{dR}{dQ} \right) \right] dQ$$

[M. Drees and CLS, JCAP 0706, 011 (2007)]

Reconstruction of the 1-D WIMP velocity distribution

- Ansatz: the measured recoil spectrum in the nth Q-bin

$$\left(\frac{dR}{dQ}\right)_{\text{expt},\, Q\simeq Q_n} \equiv r_n\, e^{k_n(Q-Q_{s,n})} \qquad\qquad r_n \equiv \frac{N_n}{b_n}$$

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- Logarithmic slope and shifted point in the nth Q-bin

$$\overline{Q-Q_n}|_n \equiv \frac{1}{N_n}\sum_{i=1}^{N_n}(Q_{n,i}-Q_n) = \left(\frac{b_n}{2}\right)\coth\left(\frac{k_n b_n}{2}\right) - \frac{1}{k_n}$$

$$Q_{s,n} = Q_n + \frac{1}{k_n}\ln\left[\frac{\sinh(k_n b_n/2)}{k_n b_n/2}\right]$$

- Reconstructing the one-dimensional WIMP velocity distribution

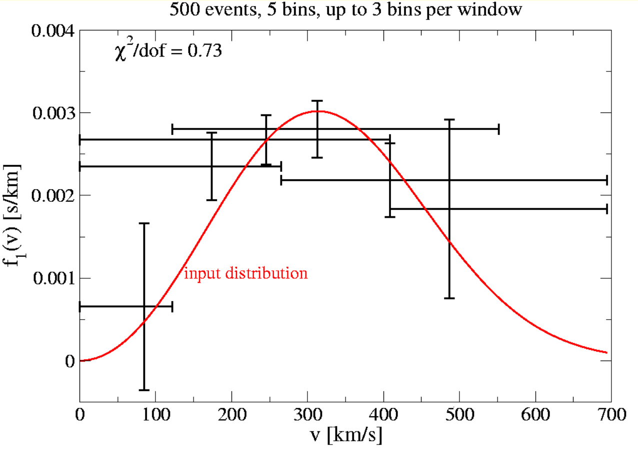
$$f_1(v_{s,n}) = \mathcal{N}\left[\frac{2Q_{s,n}r_n}{F^2(Q_{s,n})}\right]\left[\frac{d}{dQ}\ln F^2(Q)\bigg|_{Q=Q_{s,n}} - k_n\right]$$

$$\mathcal{N} = \frac{2}{\alpha}\left[\sum_a \frac{1}{\sqrt{Q_a}\,F^2(Q_a)}\right]^{-1} \qquad v_{s,n} = \alpha\sqrt{Q_{s,n}}$$

[M. Drees and CLS, JCAP 0706, 011 (2007)]

Reconstruction of the 1-D WIMP velocity distribution

- Reconstructed $f_{1,\text{rec}}(v_{s,n})$
  (^{76}Ge, 500 events, 5 bins, up to 3 bins per window)



[M. Drees and CLS, JCAP 0706, 011 (2007)]

Determination of the WIMP mass

Determination of the WIMP mass

- Estimating the moments of the WIMP velocity distribution

$$\langle v^n \rangle = \alpha^n \left[\frac{2Q_{\rm min}^{1/2} r_{\rm min}}{F^2(Q_{\rm min})} + I_0 \right]^{-1} \left[\frac{2Q_{\rm min}^{(n+1)/2} r_{\rm min}}{F^2(Q_{\rm min})} + (n+1) I_n \right]$$

$$I_n = \sum_a \frac{Q_a^{(n-1)/2}}{F^2(Q_a)} \qquad\qquad r_{\rm min} = \left(\frac{dR}{dQ} \right)_{{\rm expt},\ Q=Q_{\rm min}} = r_1\, e^{k_1 (Q_{\rm min} - Q_{s,1})}$$

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- Determining the WIMP mass

$$m_\chi \big|_{\langle v^n \rangle} = \frac{\sqrt{m_X m_Y} - m_X \mathcal{R}_n}{\mathcal{R}_n - \sqrt{m_X / m_Y}}$$

$$\mathcal{R}_n = \left[\frac{2 Q_{{\rm min},X}^{(n+1)/2} r_{{\rm min},X} / F_X^2(Q_{{\rm min},X}) + (n+1) I_{n,X}}{2 Q_{{\rm min},X}^{1/2} r_{{\rm min},X} / F_X^2(Q_{{\rm min},X}) + I_{0,X}} \right]^{1/n} (X \longrightarrow Y)^{-1} \qquad (n \neq 0)$$

[CLS and M. Drees, arXiv:0710.4296]

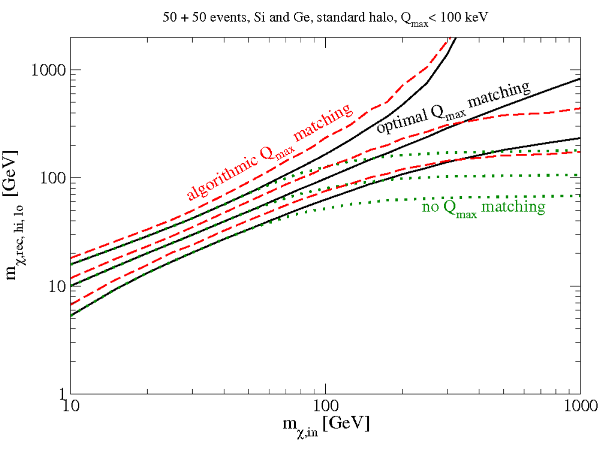
- Assuming a dominant SI scalar WIMP-nucleus interaction

$$m_\chi \big|_\sigma = \frac{(m_X / m_Y)^{5/2}\, m_Y - m_X \mathcal{R}_\sigma}{\mathcal{R}_\sigma - (m_X / m_Y)^{5/2}} \qquad\qquad \mathcal{R}_\sigma = \frac{\mathcal{E}_Y}{\mathcal{E}_X} \left[\frac{2 Q_{{\rm min},X}^{1/2} r_{{\rm min},X} / F_X^2(Q_{{\rm min},X}) + I_{0,X}}{2 Q_{{\rm min},Y}^{1/2} r_{{\rm min},X} / F_Y^2(Q_{{\rm min},Y}) + I_{0,Y}} \right]$$

[M. Drees and CLS, JCAP 0806, 012 (2008)]

Determination of the WIMP mass

- Reconstructed $m_{\chi,\mathrm{rec}}$
  (^{28}Si + ^{76}Ge, $Q_{\mathrm{max}} < 100$ keV, 2×50 events)



[M. Drees and CLS, JCAP 0806, 012 (2008)]

Estimation of the SI scalar WIMP-nucleon coupling

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- Spin-independent (SI) scalar WIMP-nucleus cross section

$$\sigma_0^{\rm SI} = \left(\frac{4}{\pi}\right) m_{\rm r,N}^2 \left[Z f_{\rm p} + (A-Z) f_{\rm n}\right]^2 \simeq \left(\frac{4}{\pi}\right) m_{\rm r,N}^2 A^2 |f_{\rm p}|^2 = A^2 \left(\frac{m_{\rm r,N}}{m_{\rm r,p}}\right)^2 \sigma_{\chi{\rm p}}^{\rm SI}$$

$$\sigma_{\chi{\rm p}}^{\rm SI} = \left(\frac{4}{\pi}\right) m_{\rm r,p}^2 |f_{\rm p}|^2$$

$f_{\rm (p,n)}$: effective SI scalar WIMP-proton/neutron couplings

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$f_{\rm (p,n)}$: effective SI scalar WIMP-proton/neutron couplings

- Rewriting the integral over $f_1(v)/v$

$$\left(\frac{dR}{dQ}\right)_{{\rm expt},\, Q = Q_{\rm min}} = \frac{\mathcal{E} \rho_0 A^2}{2 m_\chi m_{\rm r,p}^2} \left[\left(\frac{4}{\pi}\right) m_{\rm r,p}^2 |f_{\rm p}|^2\right] F^2(Q_{\rm min}) \left\{ m_{\rm r,N} \sqrt{\frac{2}{m_{\rm N}}} \left[\frac{2 Q_{\rm min}^{1/2} r_{\rm min}}{F^2(Q_{\rm min})} + I_0\right]^{-1} \left[\frac{2\, r_{\rm min}}{F^2(Q_{\rm min})}\right] \right\}$$

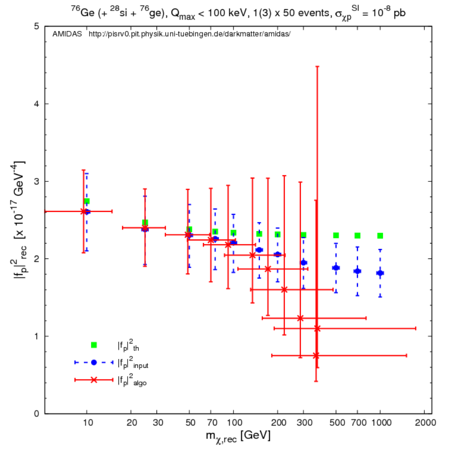
- Estimating the SI scalar WIMP-nucleon coupling

$$|f_{\rm p}|^2 = \frac{1}{\rho_0} \left[\frac{\pi}{4\sqrt{2}} \left(\frac{1}{\mathcal{E}_Z A_Z^2 \sqrt{m_Z}}\right)\right] \left[\frac{2 Q_{{\rm min},Z}^{1/2} r_{{\rm min},Z}}{F_Z^2(Q_{{\rm min},Z})} + I_{0,Z}\right] (m_\chi + m_Z)$$

[M. Drees and CLS, PoS IDM2008, 110 (2008)]

Estimation of the SI scalar WIMP-nucleon coupling

- Reconstructed $|f_{\rm p}|^2_{\rm rec}$ vs. reconstructed $m_{\chi,{\rm rec}}$
  $({}^{76}{\rm Ge}\,(+\ {}^{28}{\rm Si} + {}^{76}{\rm Ge}),\ Q_{\rm max} < 100\ {\rm keV},\ \sigma_{\chi{\rm p}}^{\rm SI} = 10^{-8}\ {\rm pb},\ 1(3) \times 50\ {\rm events})$



[CLS, arXiv:1103.0481]

Determination of the ratio of SD WIMP-nucleon couplings

- Spin-dependent (SD) axial-vector WIMP-nucleus cross section

$$\sigma_0^{\rm SD} = \left(\frac{32}{\pi}\right) G_F^2\, m_{\rm r,N}^2 \left(\frac{J+1}{J}\right) \left[\langle S_{\rm p}\rangle a_{\rm p} + \langle S_{\rm n}\rangle a_{\rm n}\right]^2$$

$$\sigma_{\chi{\rm p/n}}^{\rm SD} = \left(\frac{32}{\pi}\right) G_F^2\, m_{\rm r,p/n}^2 \cdot \left(\frac{3}{4}\right) a_{\rm p/n}^2$$

J: total nuclear spin

$\langle S_{\rm (p,n)}\rangle$: expectation values of the proton/neutron group spin

$a_{\rm (p,n)}$: effective SD axial-vector WIMP-proton/neutron couplings

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$\langle S_{\rm (p,n)}\rangle$: expectation values of the proton/neutron group spin

$a_{\rm (p,n)}$: effective SD axial-vector WIMP-proton/neutron couplings

- Determining the ratio of two SD axial-vector WIMP-nucleon couplings

$$\left(\frac{a_{\rm n}}{a_{\rm p}}\right)_{\pm,n}^{\rm SD} = -\frac{\langle S_{\rm p}\rangle_X \pm \langle S_{\rm p}\rangle_Y \mathcal{R}_{J,n}}{\langle S_{\rm n}\rangle_X \pm \langle S_{\rm n}\rangle_Y \mathcal{R}_{J,n}}$$

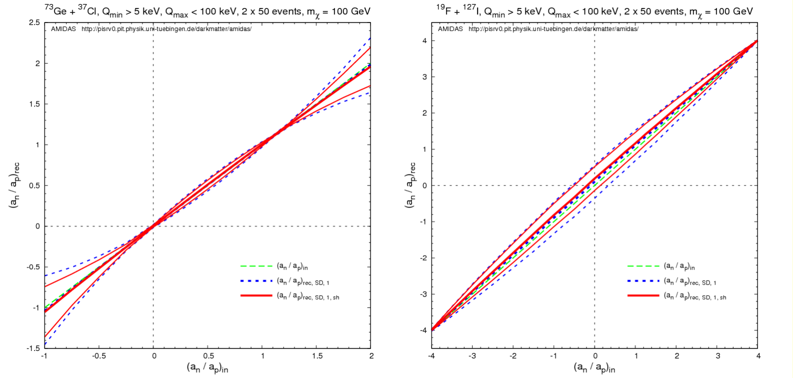
$$\mathcal{R}_{J,n} \equiv \left[\left(\frac{J_X}{J_X+1}\right)\left(\frac{J_Y+1}{J_Y}\right)\frac{\mathcal{R}_\sigma}{\mathcal{R}_n}\right]^{1/2} \qquad (n \neq 0)$$

[M. Drees and CLS, arXiv:0903.3300]

Determination of the ratio of SD WIMP-nucleon couplings

- Reconstructed $(a_n/a_p)^{SD}_{rec,1}$

  ($^{73}Ge + {}^{37}Cl$ and $^{19}F + {}^{127}I$, $Q_{min} > 5$ keV, $Q_{max} < 100$ keV, 2×50 events, $m_\chi = 100$ GeV)



[CLS, JCAP 1107, 005 (2011)]

Determinations of ratios of WIMP-nucleon cross sections

- Differential rate for combined SI and SD cross sections

$$\left(\frac{dR}{dQ}\right)_{\text{expt},\, Q=Q_{\text{min}}} = \mathcal{E}\left(\frac{\rho_0 \sigma_0^{\text{SI}}}{2 m_\chi m_{\text{r,N}}^2}\right)\left[F_{\text{SI}}^2(Q) + \left(\frac{\sigma_{\chi\text{p}}^{\text{SD}}}{\sigma_{\chi\text{p}}^{\text{SI}}}\right)\mathcal{C}_{\text{p}} F_{\text{SD}}^2(Q)\right]\int_{v_{\text{min}}}^{v_{\text{max}}}\left[\frac{f_1(v)}{v}\right]dv$$

$$\mathcal{C}_{\text{p}} \equiv \frac{4}{3}\left(\frac{J+1}{J}\right)\left[\frac{\langle S_{\text{p}}\rangle + (a_{\text{n}}/a_{\text{p}})\langle S_{\text{n}}\rangle}{A}\right]^2$$

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$$\mathcal{C}_{\rm p} \equiv \frac{4}{3}\left(\frac{J+1}{J}\right)\left[\frac{\langle S_{\rm p}\rangle+(a_{\rm n}/a_{\rm p})\langle S_{\rm n}\rangle}{A}\right]^2$$

- Determining the ratio of two WIMP-proton cross sections

$$\frac{\sigma_{\chi\rm p}^{\rm SD}}{\sigma_{\chi\rm p}^{\rm SI}} = \frac{F_{{\rm SI},Y}^2(Q_{\min,Y})\mathcal{R}_{m,XY}-F_{{\rm SI},X}^2(Q_{\min,X})}{\mathcal{C}_{{\rm p},X}F_{{\rm SD},X}^2(Q_{\min,X})-\mathcal{C}_{{\rm p},Y}F_{{\rm SD},Y}^2(Q_{\min,Y})\mathcal{R}_{m,XY}}$$

$$\mathcal{R}_{m,XY} \equiv \left(\frac{r_{\min,X}}{\mathcal{E}_X}\right)\left(\frac{\mathcal{E}_Y}{r_{\min,Y}}\right)\left(\frac{m_Y}{m_X}\right)^2$$

- Determining the ratio of two SD axial-vector WIMP-nucleon couplings

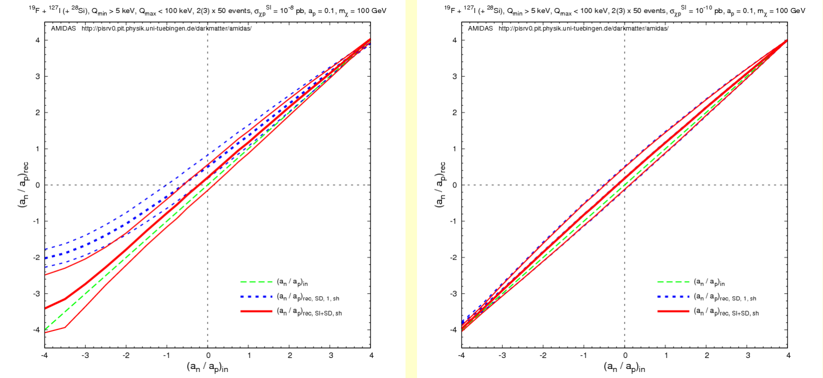
$$\left(\frac{a_{\rm n}}{a_{\rm p}}\right)_{\pm}^{\rm SI+SD} = \frac{-\left(c_{{\rm p},X}s_{{\rm n/p},X}-c_{{\rm p},Y}s_{{\rm n/p},Y}\right)\pm\sqrt{c_{{\rm p},X}c_{{\rm p},Y}}\left|s_{{\rm n/p},X}-s_{{\rm n/p},Y}\right|}{c_{{\rm p},X}s_{{\rm n/p},X}^2-c_{{\rm p},Y}s_{{\rm n/p},Y}^2}$$

$$c_{{\rm p},X} \equiv \frac{4}{3}\left(\frac{J_X+1}{J_X}\right)\left[\frac{\langle S_{\rm p}\rangle_X}{A_X}\right]^2\left[F_{{\rm SI},Z}^2(Q_{\min,Z})\mathcal{R}_{m,YZ}-F_{{\rm SI},Y}^2(Q_{\min,Y})\right]F_{{\rm SD},X}^2(Q_{\min,X})$$

[M. Drees and CLS, arXiv:0903.3300]

Determinations of ratios of WIMP-nucleon cross sections

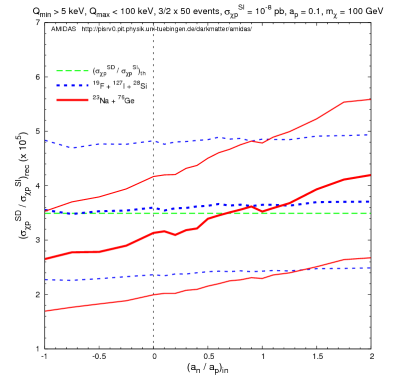
- Reconstructed $(a_n/a_p)^{SI+SD}_{rec}$ vs. $(a_n/a_p)^{SD}_{rec,1}$
  ($^{19}F + ^{127}I + ^{28}Si$, $Q_{min} > 5$ keV, $Q_{max} < 100$ keV, 3×50 events,
  $\sigma^{SI}_{\chi p} = 10^{-8}/10^{-10}$ pb, $a_p = 0.1$, $m_\chi = 100$ GeV)

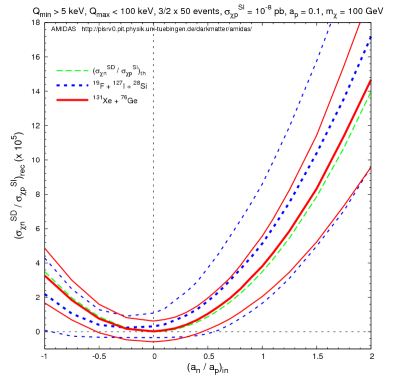


[CLS, JCAP 1107, 005 (2011)]

Determinations of ratios of WIMP-nucleon cross sections

- Reconstructed $\left(\sigma_{\chi p}^{SD}/\sigma_{\chi p}^{SI}\right)_{rec}$ and $\left(\sigma_{\chi n}^{SD}/\sigma_{\chi p}^{SI}\right)_{rec}$
  ($^{19}F + ^{127}I + ^{28}Si$ vs. $^{23}Na/^{131}Xe + ^{76}Ge$, $Q_{min} > 5$ keV, $Q_{max} < 100$ keV, $\sigma_{\chi p}^{SI} = 10^{-8}$ pb, $a_p = 0.1$, $m_\chi = 100$ GeV, $3/2 \times 50$ events)





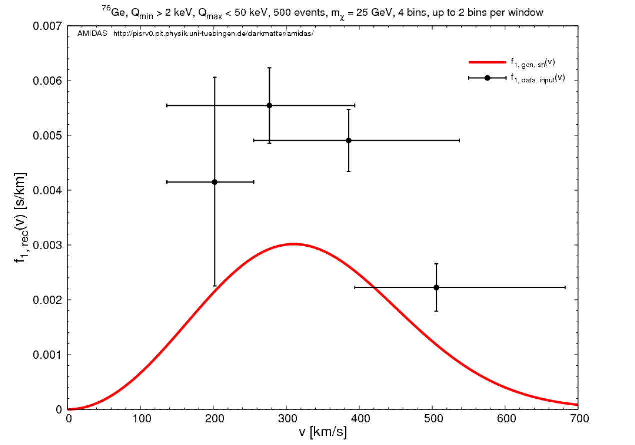
[CLS, JCAP 1107, 005 (2011)]

Effects of a non-negligible threshold energy

Reconstruction of the 1-D WIMP velocity distribution

Reconstruction of $f_1(v)$ with a non-negligible threshold energy

- Reconstructed $f_{1,\mathrm{rec}}(v_{s,n})$ (before correction!)
  (^{76}Ge, 2 - 50 keV, 500 events, $m_\chi = 25$ GeV)



[CLS, IJMPD 24, 1550090 (2015)]

Reconstruction of $f_1(v)$ with a non-negligible threshold energy

- Modification of the renormalization constant

$$\mathcal{N} = \frac{2}{\alpha}\left[\tilde{f}_{1,\rm rec}(v^*_{\rm min})\, Q_{\rm min}^{1/2} + \frac{2Q_{\rm min}^{1/2}}{F^2(Q_{\rm min})}\left(\frac{dR}{dQ}\right)_{{\rm expt},\ Q=Q_{\rm min}} + I_0(Q_{\rm min}, Q^*_{\rm max})\right]^{-1}$$

where

$$\tilde{f}_{1,\rm rec}(v^*_{\rm min}) \equiv \left[\frac{2Q_{\rm min}\, r(Q_{\rm min})}{F^2(Q_{\rm min})}\right]\left[\frac{d}{dQ}\ln F^2(Q)\bigg|_{Q=Q_{\rm min}} - k_1\right]$$

$$\left(\frac{dR}{dQ}\right)_{{\rm expt},\ Q=Q_{\rm min}} = r_1\, e^{k_1(Q_{\rm min}-Q_{s,1})} \equiv r(Q_{\rm min})$$

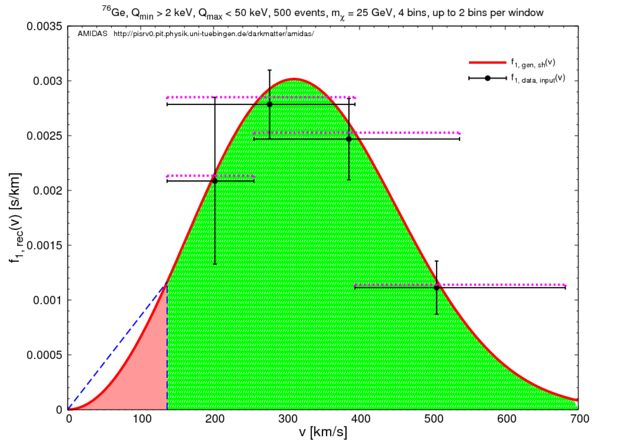
$$I_n(Q_{\rm min}, Q^*_{\rm max}) = \int_{Q_{\rm min}}^{Q^*_{\rm max}} Q^{(n-1)/2}\left[\frac{1}{F^2(Q)}\left(\frac{dR}{dQ}\right)\right] dQ \to \sum_a \frac{Q_a^{(n-1)/2}}{F^2(Q_a)}$$

$$Q^*_{\rm max} \equiv \min\left(Q_{\rm max},\ Q_{\rm max,kin} = \frac{v^2_{\rm max}}{\alpha^2}\right)$$

[CLS, IJMPD 24, 1550090 (2015)]

Reconstruction of $f_1(v)$ with a non-negligible threshold energy

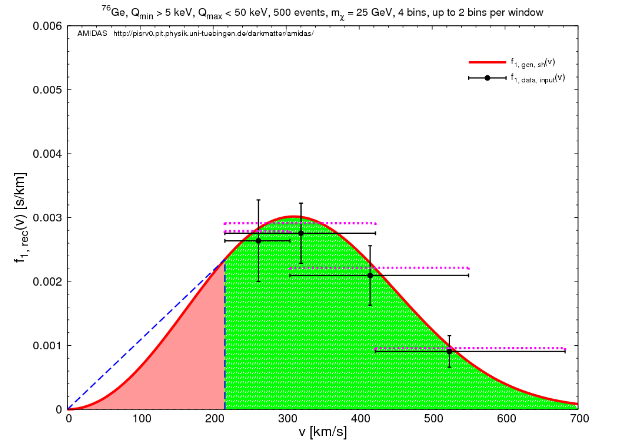
- Reconstructed $f_{1,\rm rec}(v_{s,n})$ with the input WIMP mass (after correction!)
  (^{76}Ge, 2 - 50 keV, 500 events, $m_\chi = 25$ GeV)



[CLS, IJMPD 24, 1550090 (2015)]

Reconstruction of $f_1(v)$ with a non-negligible threshold energy

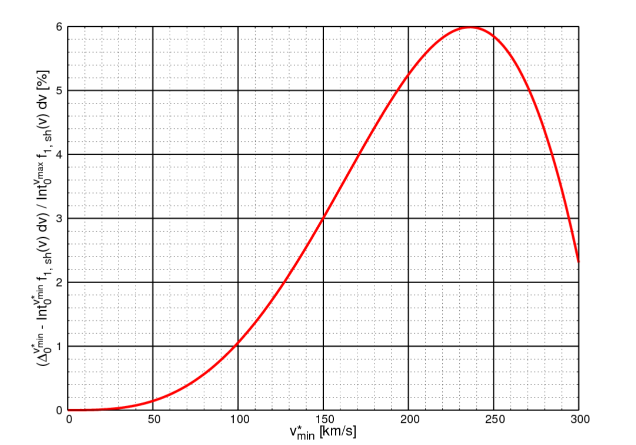
- Reconstructed $f_{1,\rm rec}(v_{s,n})$ with the input WIMP mass (after correction!)
  (^{76}Ge, 5 - 50 keV, 500 events, $m_\chi = 25$ GeV)



[CLS, IJMPD 24, 1550090 (2015)]

Reconstruction of $f_1(v)$ with a non-negligible threshold energy

- Theoretical bias estimate of $\left[\Delta_0^{v^*_{\rm min}} - \int_0^{v^*_{\rm min}} f_1(v)\, dv\right] / \int_0^{v_{\rm max}} f_1(v)\, dv$

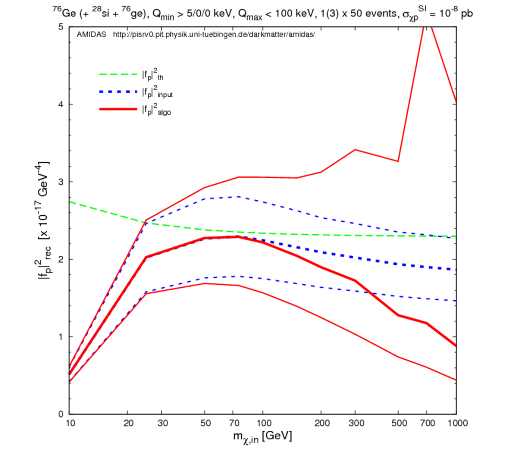


[CLS, IJMPD 24, 1550090 (2015)]

Reconstruction of WIMP particle properties (current work...)

Reconstruction of $|f_p|^2$ with a non-negligible threshold energy

- Reconstructed $|f_p|^2_{rec}$ (before correction...)
  (^{76}Ge (+ ^{28}Si + ^{76}Ge), 5 - 100 keV, 50 events)



[CLS, arXiv:1103.0481]

Reconstruction of $|f_p|^2$ with a non-negligible threshold energy

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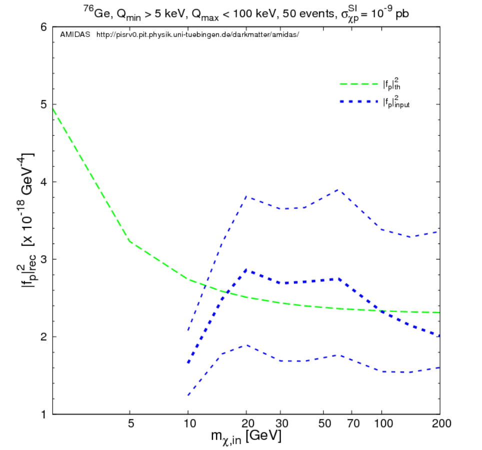
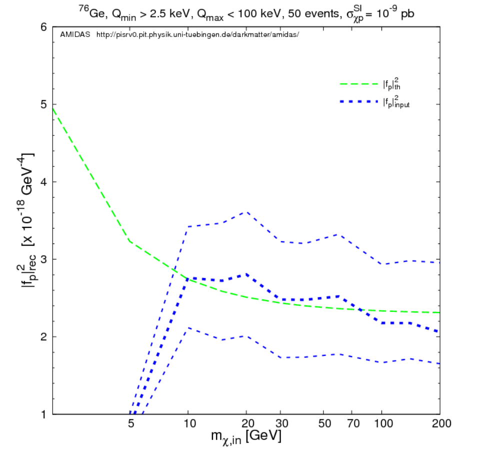
  (^{76}Ge, 5 - 100 keV, 50 events)



Reconstruction of $|f_{\rm p}|^2$ with a non-negligible threshold energy

- Reconstructed $|f_{\rm p}|^2_{\rm rec}$ (after correction)
  (^{76}Ge, 2.5 - 100 keV, 50 events)



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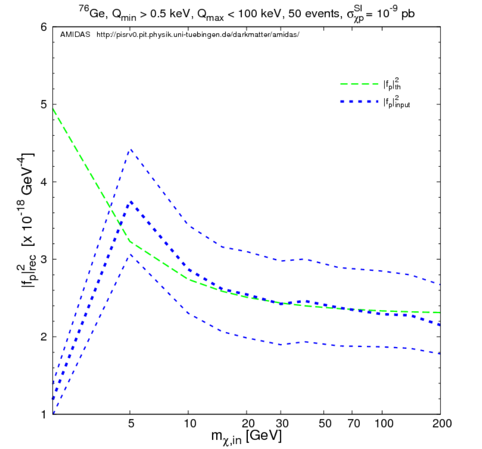
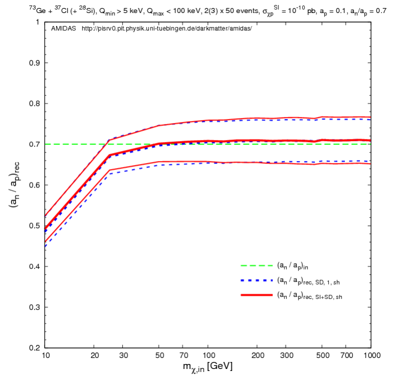
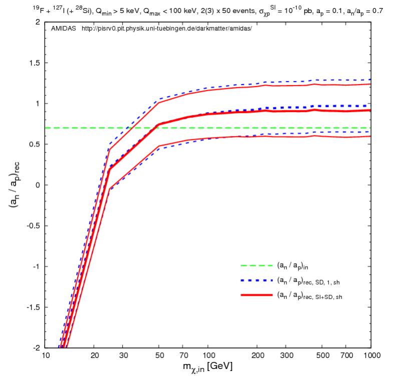


Determinations of (a_n/a_p) with a non-negligible threshold energy

- Reconstructed $(a_n/a_p)_{rec}^{SI+SD}$ vs. $(a_n/a_p)_{rec,1}^{SD}$ (before correction...)
  ($^{73}Ge + ^{37}Cl$ (+ ^{28}Si) / $^{19}F + ^{127}I$ (+ ^{28}Si), 5 - 100 keV, 2/3 × 50 events, $a_n/a_p = 0.7$)





[CLS, JCAP 1107, 005 (2011)]

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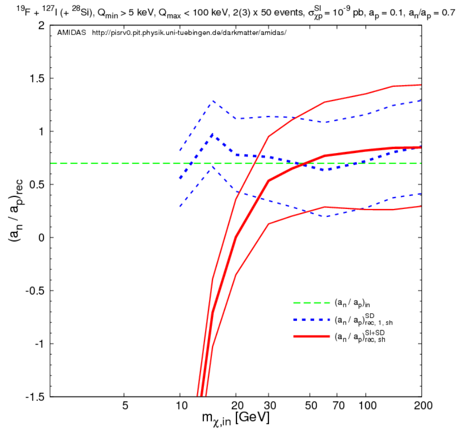

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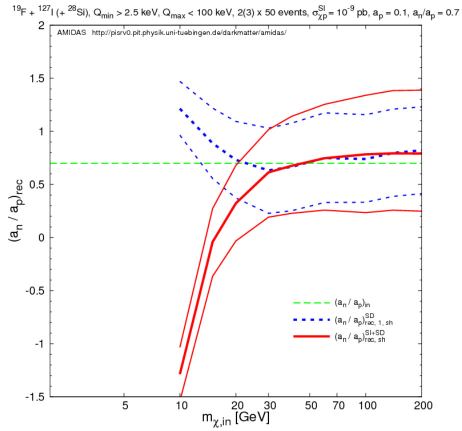

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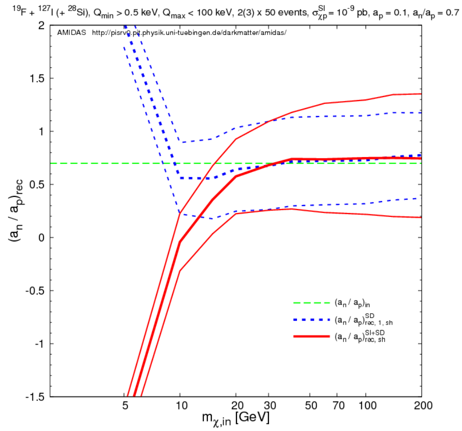

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Thank you very much for your attention!