Heavy squarks at LHC: A new paradigm for direct detection experiment comparison

Quentin Riffard

F. Mayet, M.-H. Genest, G. Bélanger, D.Santos

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LPSC, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
APC, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Paris, France
LAPTh, Université de Savoie Mont Blanc, CNRS, Annecy-le-Vieux, France

WIMP-Nucleus interaction

WIMP-Nucleus scattering event rate:

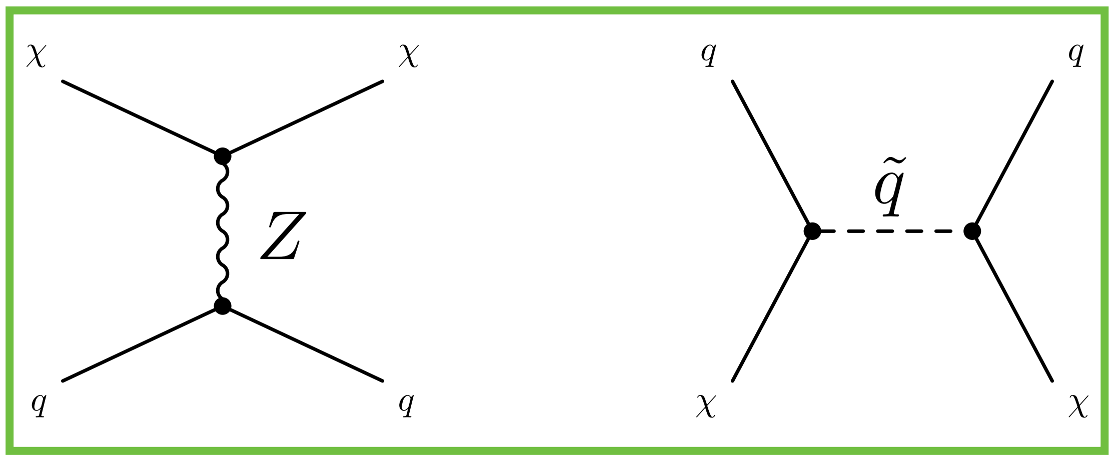
$$\frac{dR}{dE_R} \propto \left(\sigma^{SD}(X)F^{SD}(E_R) + \sigma^{SI}(X)F^{SI}(E_R)\right)$$

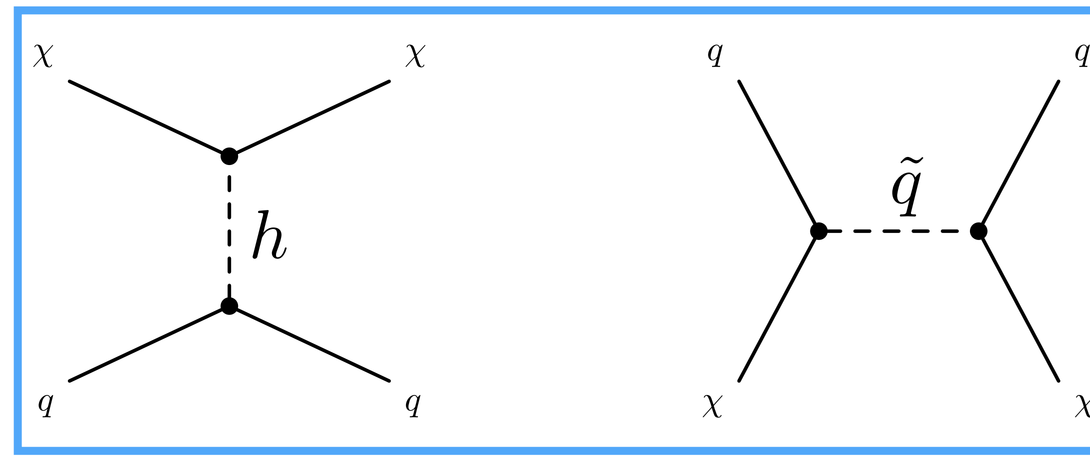
SUSY

SD contributions

SI contribution

At tree level





$$\sigma^{SD}(X) \propto \left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

$$\sigma^{SI}(X) \propto \left(Zf_p + (A-Z)f_n\right)^2$$

Elastic scattering amplitudes

Direct detection experiment: Event rate ⟷ nucleus cross-section

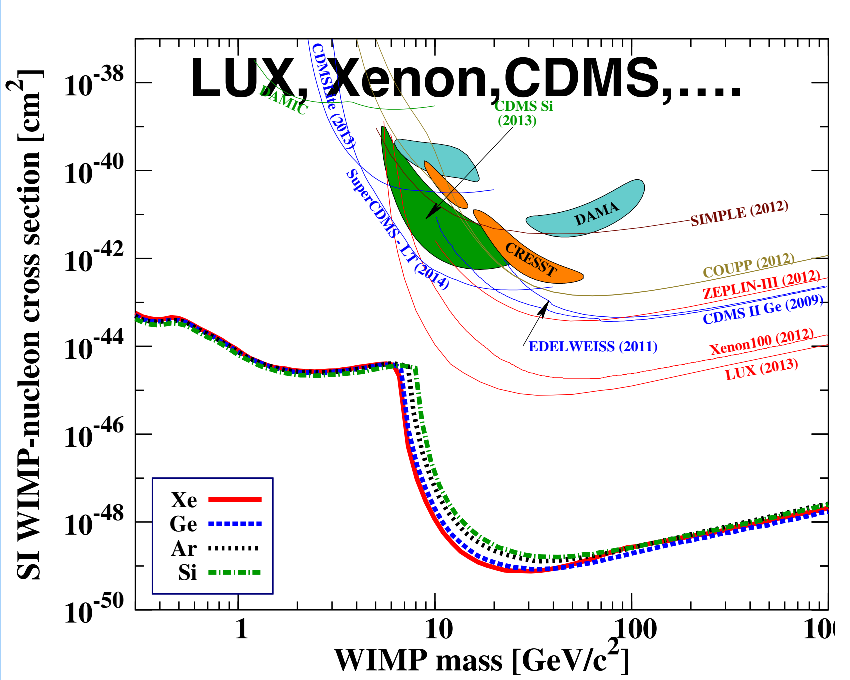
Experiment comparison: nucleon cross-sections

The standard direct detection framework

Standard direct detection framework:

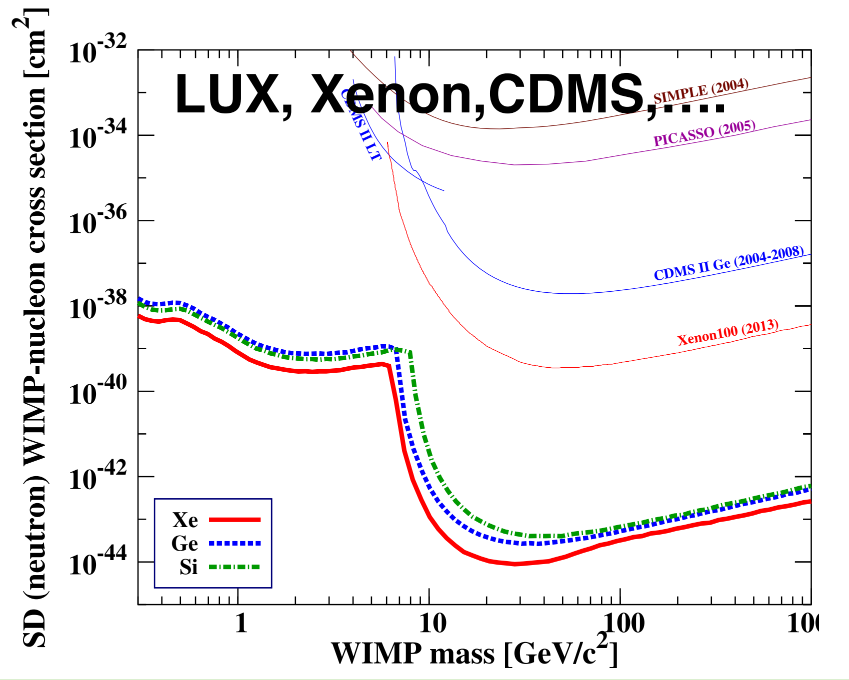
4 independent parameters $(m_\chi, \sigma^{SD}(p), \sigma^{SD}(n), \sigma^{SI}(p)) \longrightarrow$ 3 independent planes

SI-nucleon



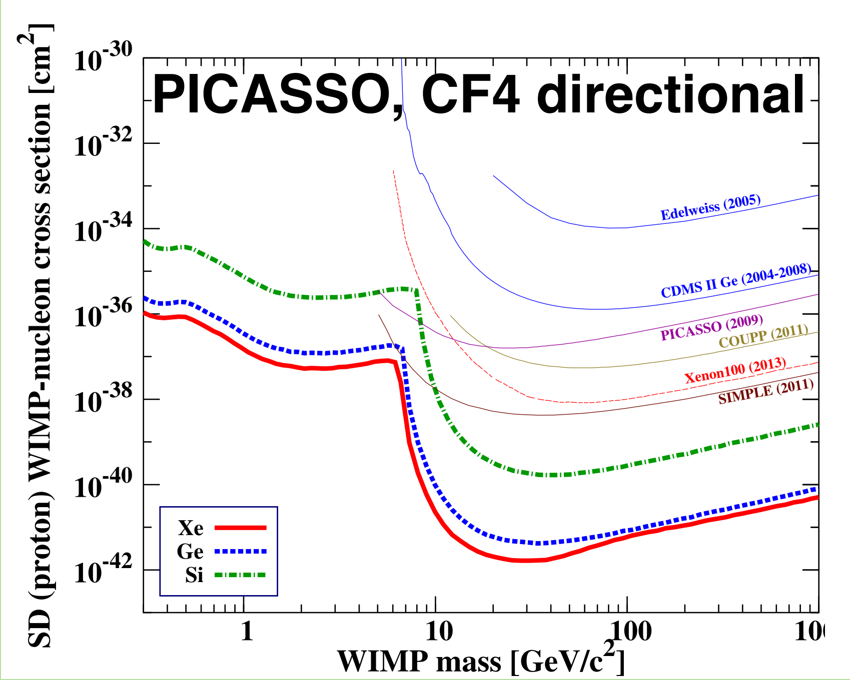
- Sea quarks approximation
  $f_p = f_n \leftrightarrow \sigma^{SI}(p) = \sigma^{SI}(n)$
- No SD interaction
  $a_p = a_n = 0$

SD-neutron



$$f_p = f_n = a_p = 0$$
&
$$a_n \neq 0$$

SD-proton



$$f_p = f_n = a_n = 0$$
&
$$a_p \neq 0$$

Experimental results depend on the arbitrary choice of parameters combination

Figures from Ruppin *et al.* Phys.Rev. D90 (2014) 083510

Outline

- **Squarks mass limits & WIMP-quark interaction**
- **New paradigm for direct detection**
- **Heavy squarks paradigm in the MSSM**
- **Application on the current experimental results**

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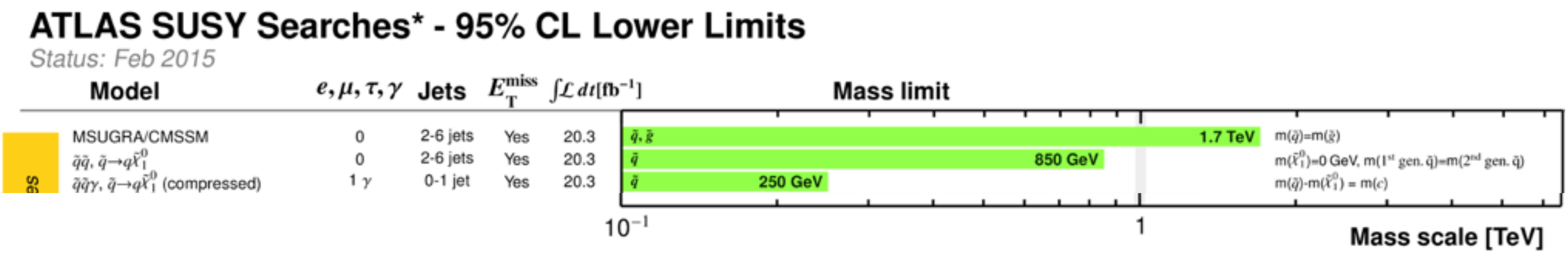
LHC: Squark Mass limits

Analysis:



LHC lower limits:

$$250 \lesssim \lim(m_{\tilde{q}}) \lesssim 1700\ \mathrm{GeV/c^2}$$

model & channel dependent limits

LHC Run2:

unless discovery $\longrightarrow$ squarks limits improvement

Squarks tend to be heavy: $m_{\tilde{q}} \sim \mathcal{O}(1\ \mathrm{TeV})$

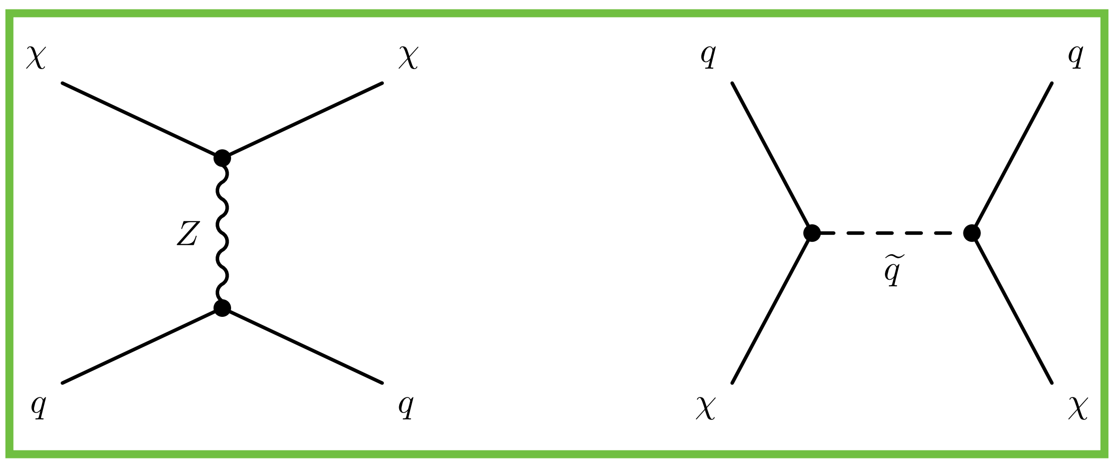
WIMP-quark interaction

LHC Run 1: heavy squarks

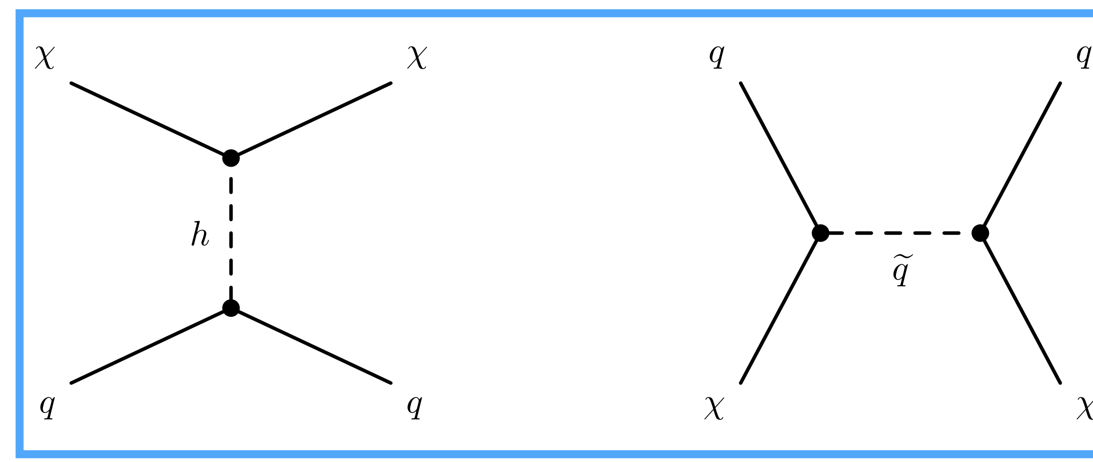
$$m_{\tilde{q}} \sim \mathcal{O}(1\,\mathrm{TeV}) >> m_{h/Z}$$

At tree level

SD contributions



SI contribution



WIMP-quark interaction

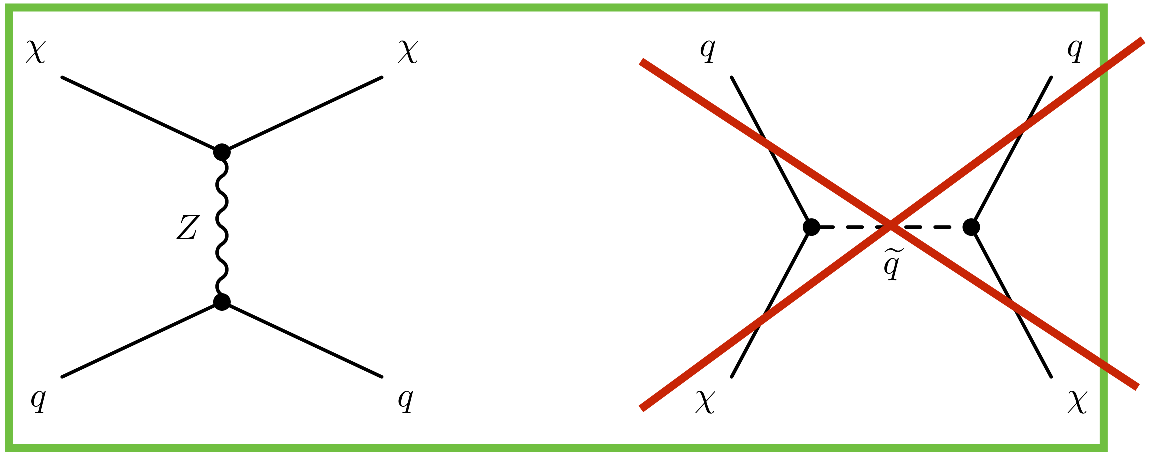
LHC Run 1: heavy squarks

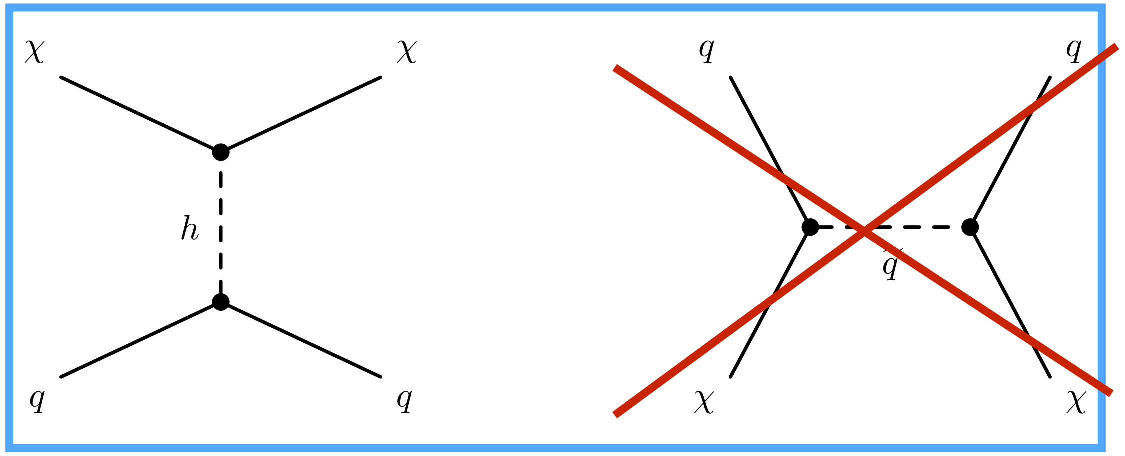
$$m_{\tilde{q}} \sim \mathcal{O}(1\,\mathrm{TeV}) >> m_{h/Z}$$

SD contributions Suppressed

SI contribution Suppressed

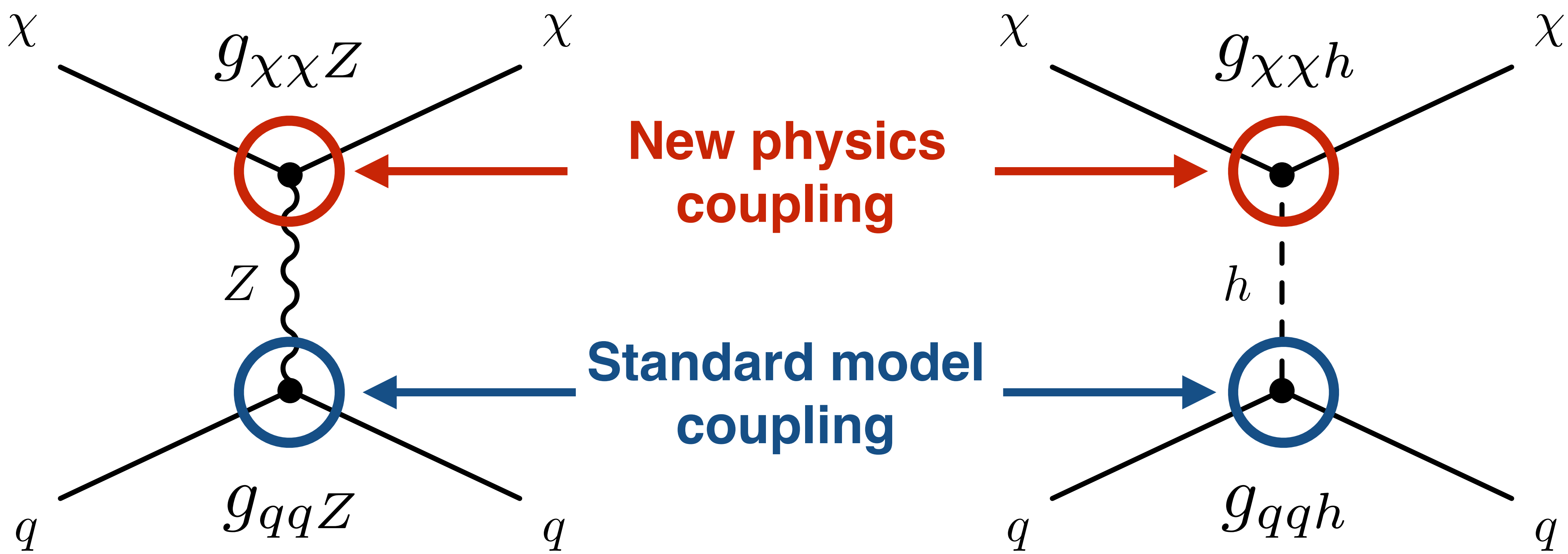
At tree level





Squarks no more contribute to the WIMP-nucleus interaction

Scattering amplitudes



$g_{\chi\chi Z}$ and $g_{\chi\chi h}$ do not depend on the quark flavor

$\longrightarrow$ f_p/f_n and a_p/a_n do not depend on new physics

$\longrightarrow$ **constant ratios**

$\longrightarrow$ **analytic** $\begin{cases} C_f = f_p/f_n = 0.98 \\ C_a = a_p/a_n = -1.14 \end{cases}$

G. Bélanger, *et al.*,
Phys. Rev. D79, 015008 (2009)

Outline

- Squarks mass limits & WIMP-quark interaction
- **New paradigm for direct detection**
- Heavy squarks paradigm in the MSSM
- Application on the current experimental results

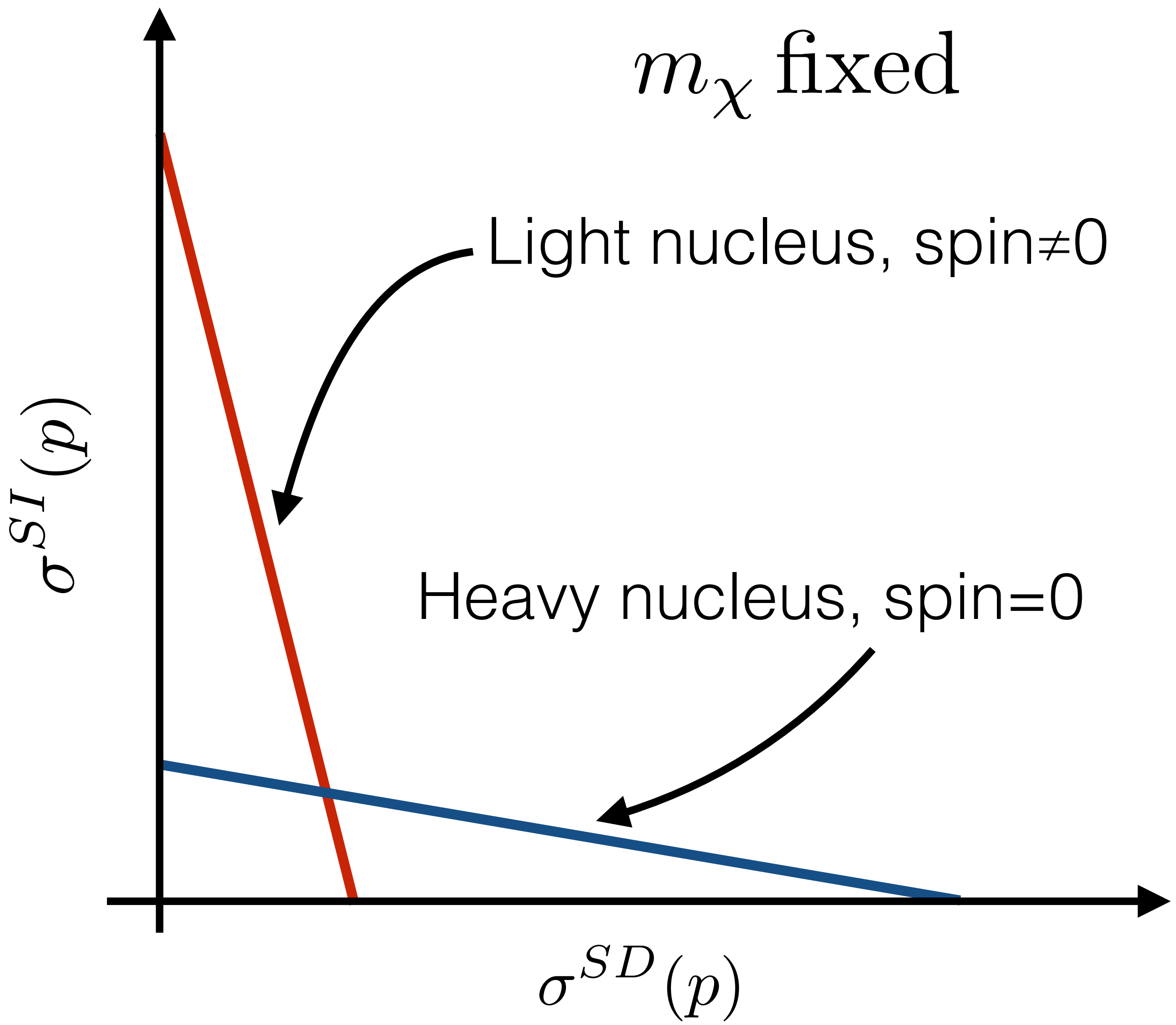
New paradigm for direct detection

New framework: $(m_\chi, \sigma^{SD}(p), \sigma^{SI}(p))$

- Proton and neutron contributions no longer independent

$$\begin{cases} \sigma^{SD}(p) = {C_a}^2 \sigma^{SD}(n) \\ \sigma^{SI}(p) = {C_f}^2 \sigma^{SI}(n) \end{cases}$$

- New representation:



SI and SD limits no longer independent

$$\sigma^{SI}(p) = \sigma^{SD}(p) \times a + b$$

Analytic calculation of a and b using experimental inputs

This new representation enables a direct comparison between SI and SD interactions

Heavy squarks paradigm

Questions:

1. Check our statement about $a_p/a_n = cste$ and $f_p/f_n = cste$

2. Validity of the heavy squark paradigm ?

$\downarrow$

Method:

Markov Chain Monte-Carlo scan of the MSSM

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Markov Chain Monte-Carlo scan of the MSSM

SUSY Model:

pMSSM with 16 free parameters

Markov Chain Monte Carlo inputs:

- pMSSM properties calculation: MicrOMEGAs (relic density, cross sections, …)
- Constraints:

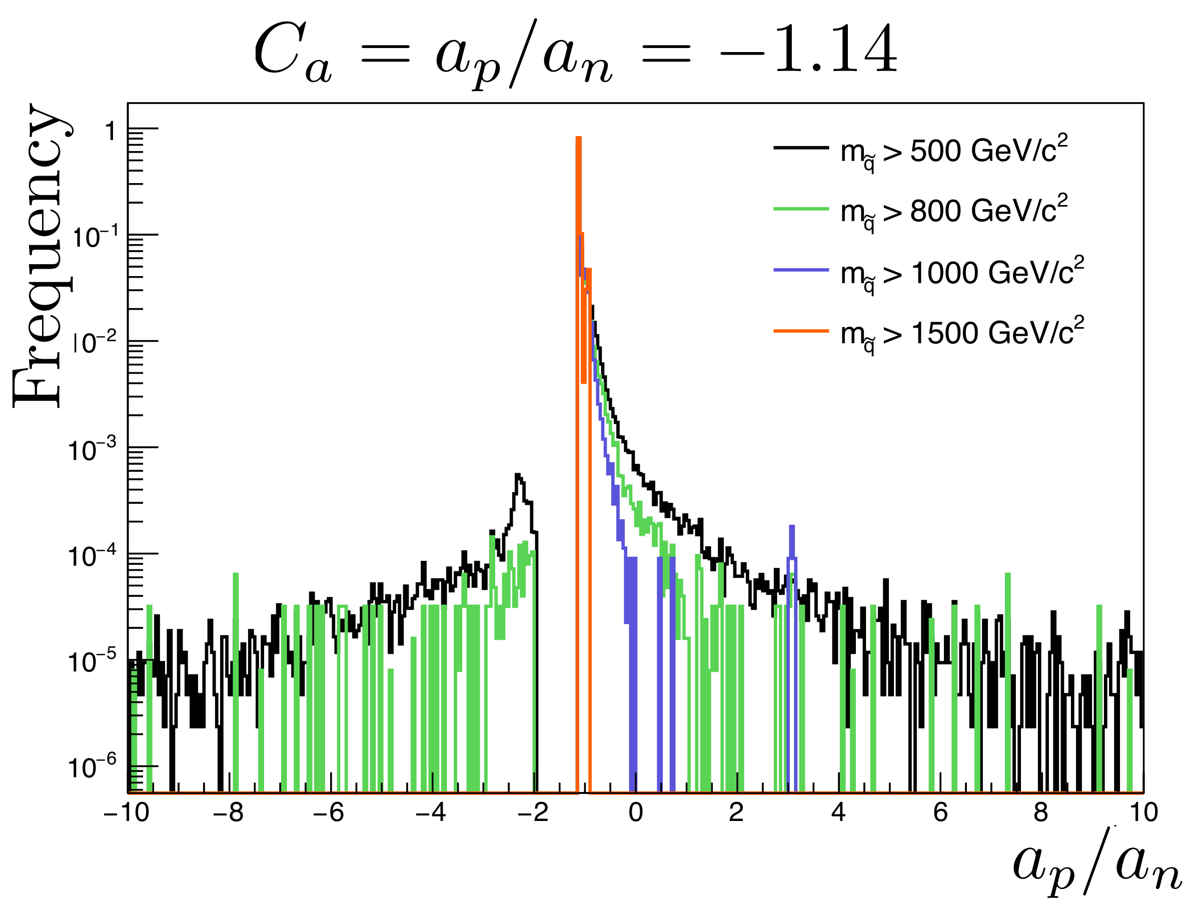
G. Bélanger *et al.*, arXiv:1407.6129 [hep-ph]

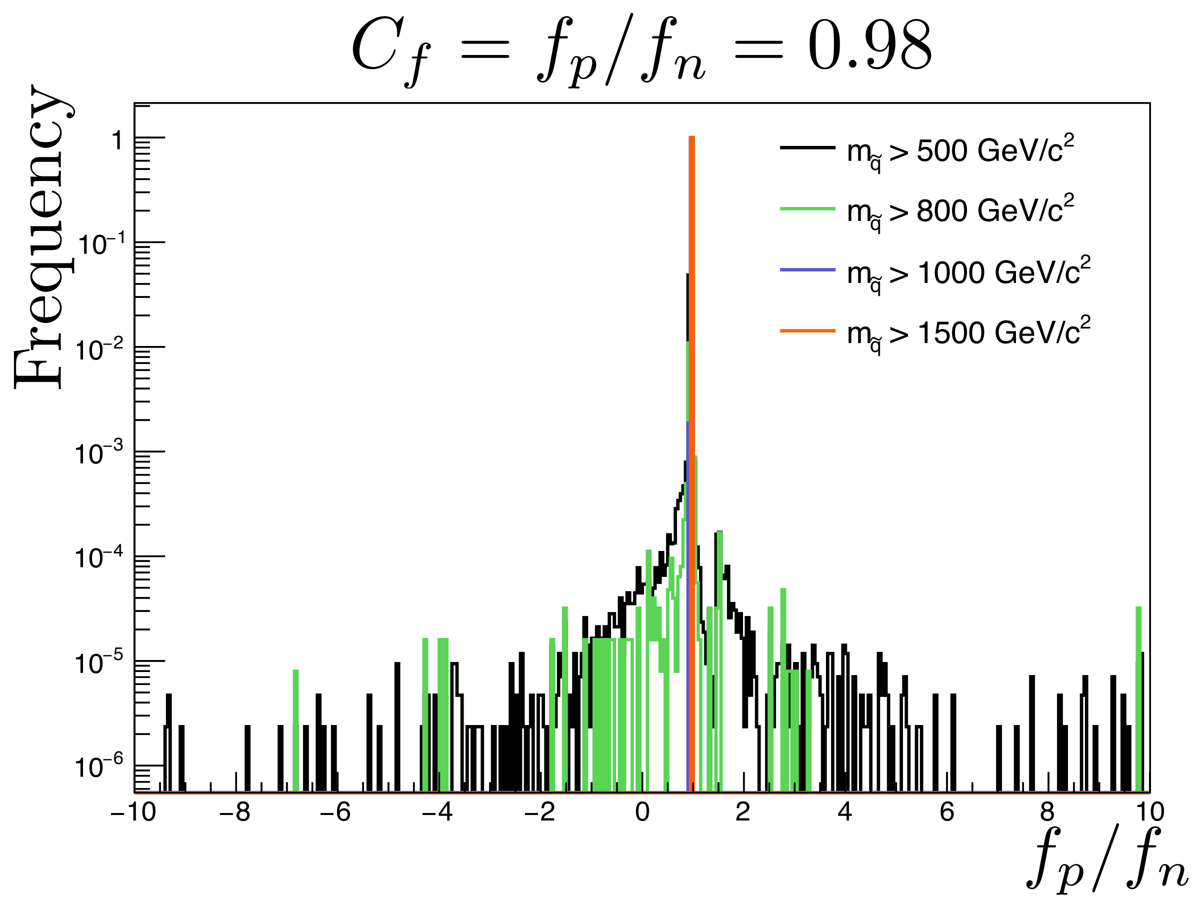
  - Cosmology: relic DM density (PLANCK)
  - Particle physics: Higgs mass and couplings, invisible Z width, $(g\text{-}2)_\mu$, $\mathcal{BR}(b \to s + \gamma)$, …

Outputs:

- Viable SUSY models in the MSSM
- Scattering amplitudes vs squarks mass

MSSM scan: scattering amplitudes





Scan results:

- Amplitude ratios tend to a constant value as the squark mass limit increase
- heavy squark paradigm valid for $\lim(m_{\tilde{q}}) \gtrsim 1\,\mathrm{TeV/c^2}$

Outline

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Standard vs heavy squarks direct detection framework

Germanium:

Isotope	J	$\langle S_p \rangle$	$\langle S_n \rangle$
^{73}Ge	$9/2$	0.030	0.378

Standard direct detection framework:

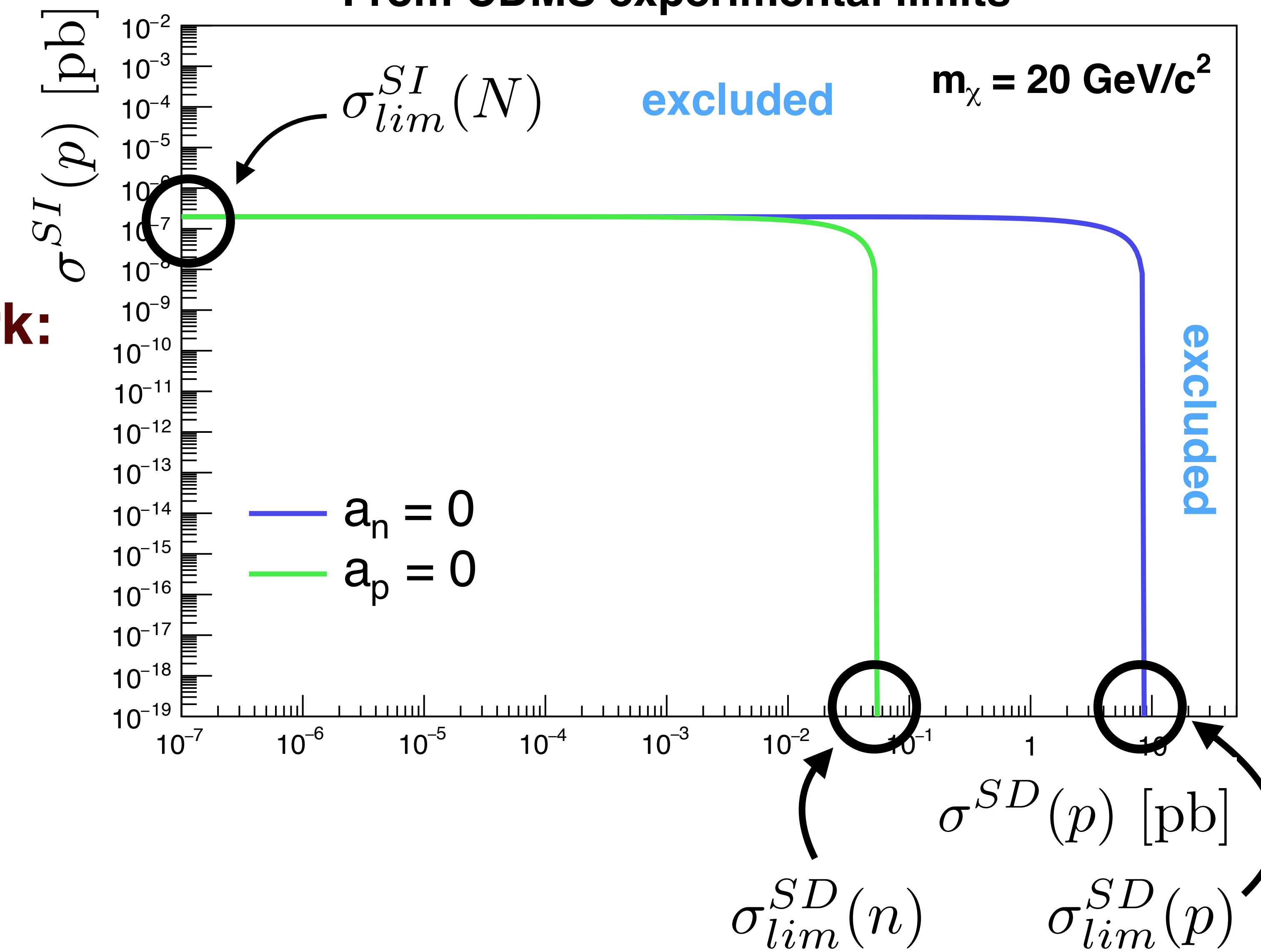
Limits on SI interaction requires:
- $f_p = f_n$
- $a_p = a_n = 0$

Limits on SD neutron interaction requires :
- $f_p = f_n = 0$
- $a_p = 0$

New direct detection framework:

$$\sigma^{SI}(p) = \sigma^{SD}(p) \times a + b$$

From CDMS experimental limits



Real limit: Combinaison of both

New direct detection framework

Interferences:

$$\sigma^{SD}(X) \propto \sigma_0^{SD}(p) \left(\langle S_p \rangle + \frac{\langle S_n \rangle}{C_a} \right)^2$$

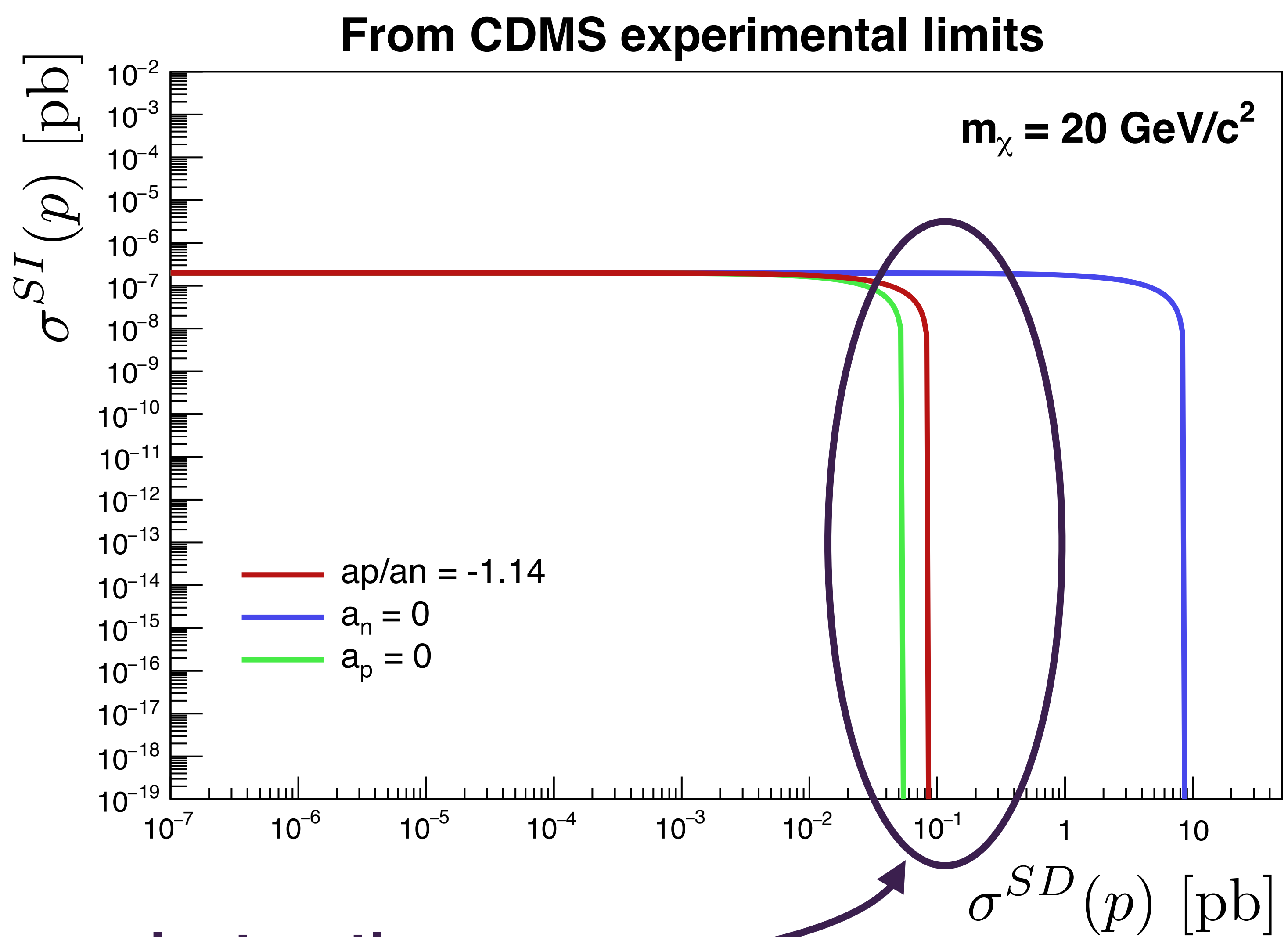
$$C_a = a_p/a_n = -1.14$$

$\langle S_p \rangle \, / \, \langle S_n \rangle > 1$

Destructive

$\langle S_p \rangle \, / \, \langle S_n \rangle < 1$

Constructive



Germanium:

Isotope	J	$\langle S_p \rangle$	$\langle S_n \rangle$
^{73}Ge	9/2	0.030	0.378

destructive

The proton and neutron contribution cannot be separated for SD cross-section calculations

Detector detection landscape

Direct experiment limits reinterpretation

Direct comparison:

$$\sigma^{SD}(p) \leftrightarrow \sigma^{SI}(p)$$

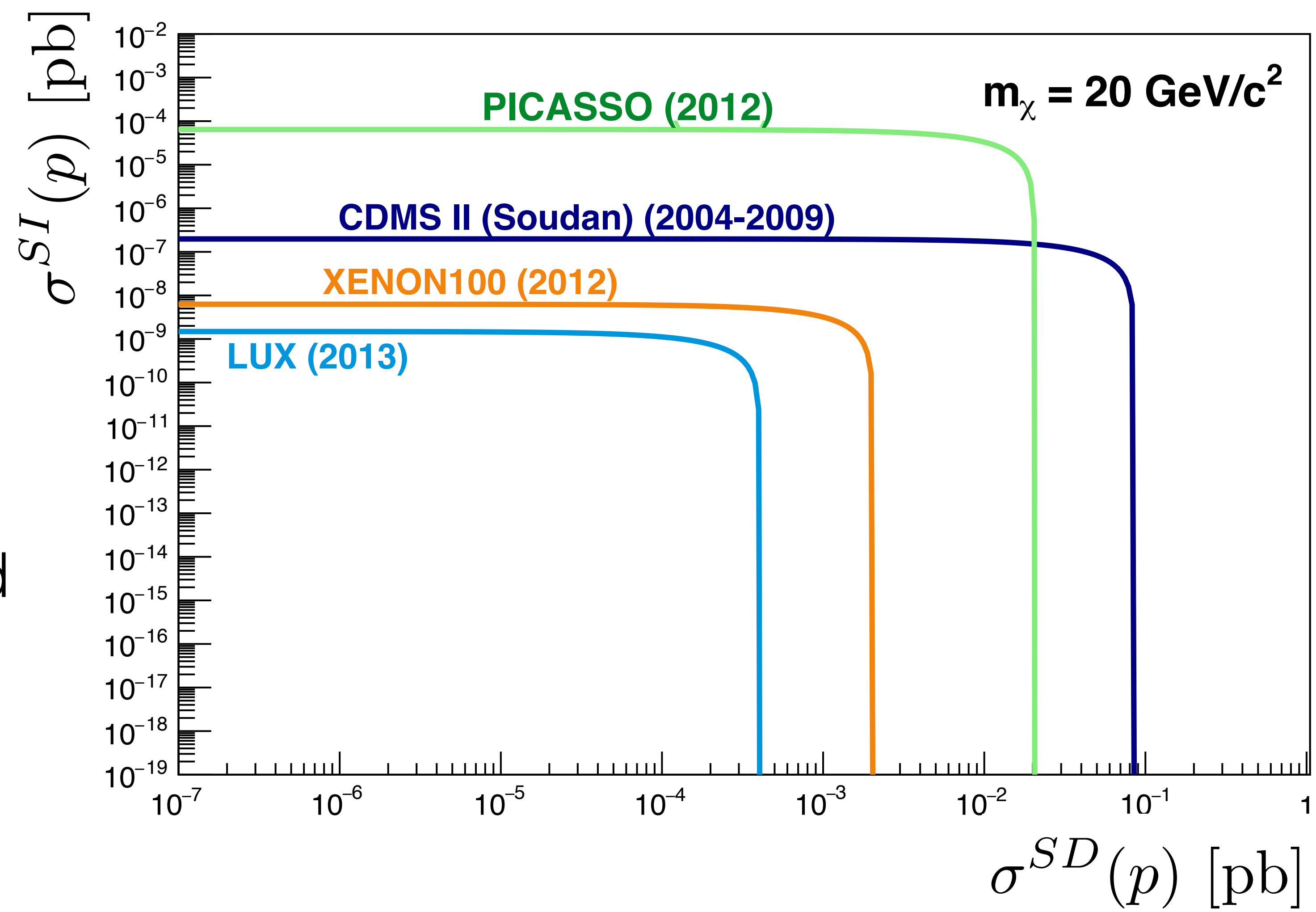
Input:

Experimental limits on the standard direct detection framework

LUX:

- Best limit in SI & SD

LUX limits apply to everyone

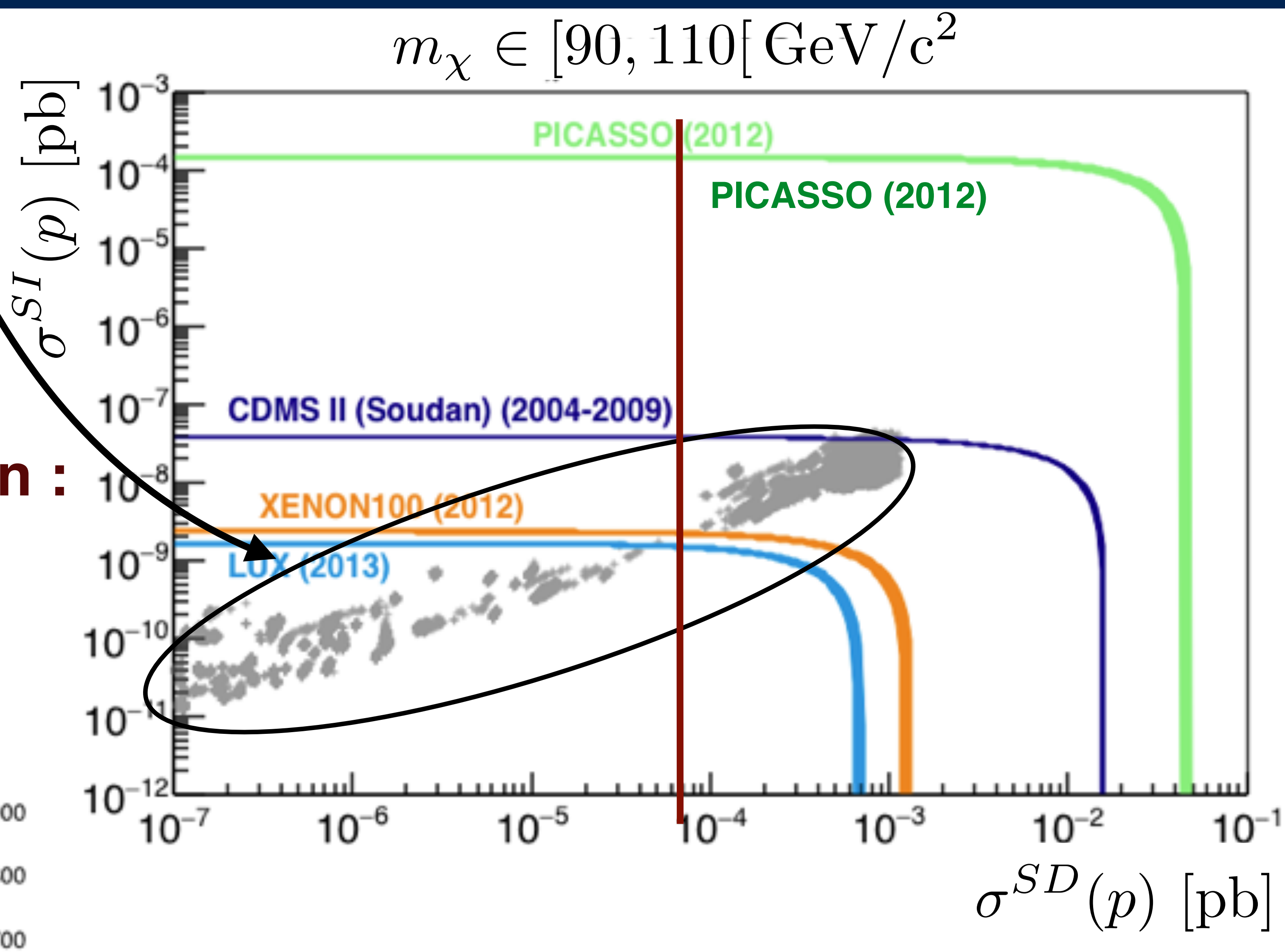


Isotope	J	$\langle S_p \rangle$	$\langle S_n \rangle$
^{129}Xe	1/2	0.010	0.329
^{131}Xe	3/2	−0.009	−0.272
^{19}F	1/2	0.441	−0.109
^{73}Ge	9/2	0.030	0.378

Impact on SUSY models

Framework : pMSSM

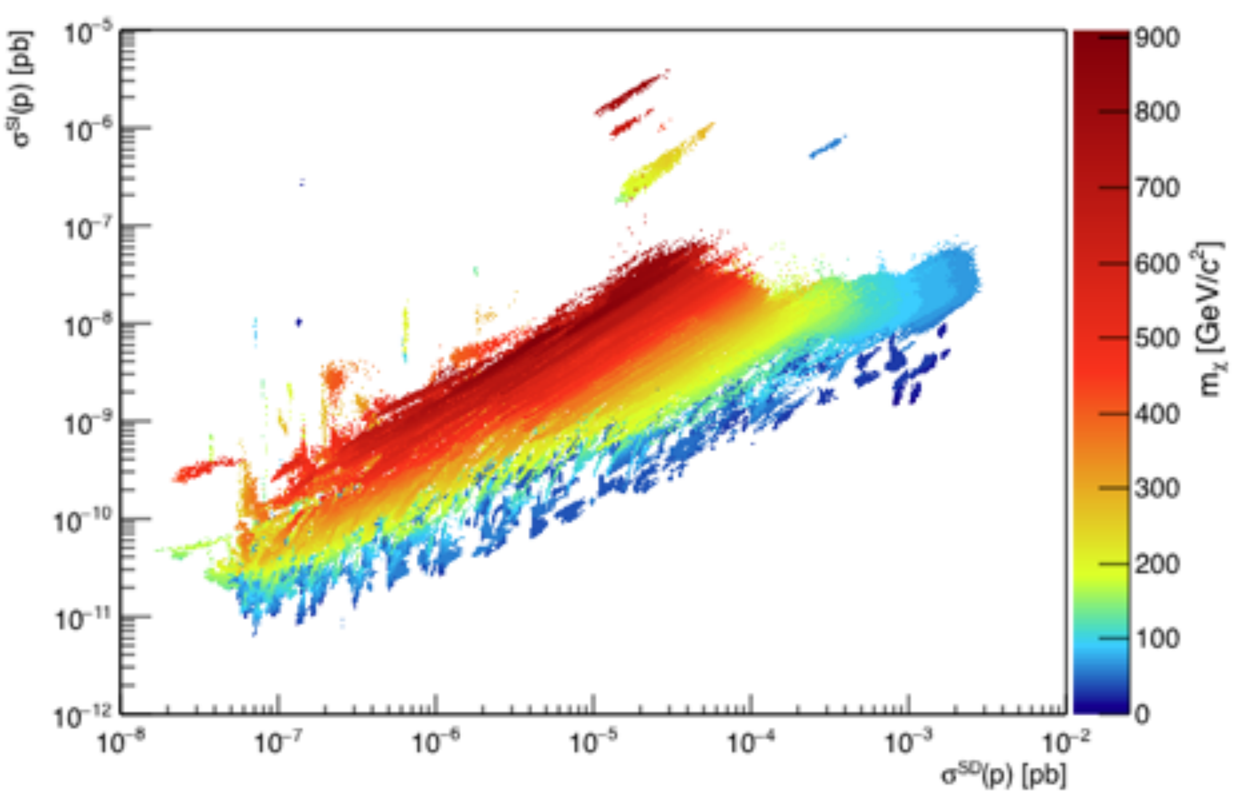
SUSY models from the MCMC scan



SI & SD cross sections correlation :

Heavy squarks & MSSM

- SI & SD no longer independent
- Do not depend on the χ mass



Experimental limits on SUSY:

$$\text{LUX}: \begin{cases} \sigma^{SI}_{\text{lim}} \sim 1 \times 10^{-9}\,\text{pb} \\ \sigma^{SD}_{\text{lim}} \sim 4 \times 10^{-5}\,\text{pb} \end{cases} \quad @100 \pm 10\ \mathrm{GeV/c^2}$$

Strong LUX limit on SUSY models

Conclusions

LHC: squark mass limits tend to be at the TeV scale

Heavy squarks:

- New framework: $(m_\chi, \sigma^{SD}(p), \sigma^{SI}(p))$

- Equivalence between proton and neutron cross sections

$$\begin{cases} \sigma^{SD}(p) = {C_a}^2 \sigma^{SD}(n) \\ \sigma^{SI}(p) = {C_f}^2 \sigma^{SI}(n) \end{cases}$$

with $C_a = a_p/a_n = -1.14$ and $C_f = f_p/f_n = 0.98$

New paradigm:

- Direct comparison $\sigma^{SD}(p) \leftrightarrow \sigma^{SI}(p)$
- MSSM SI and SD interactions are no longer independent

WIMP-Nucleus interaction

WIMP-Nucleus scattering event rate:

$$\frac{dR}{dE_R} = \frac{\rho_0}{2m_\chi {\mu_R}^2}\left(\sigma^{SD}(X)F^{SD}(E_R) + \sigma^{SI}(X)F^{SI}(E_R)\right)\int_{v_{min}} d^3v\,\frac{f(\vec{v})}{v}$$

WIMP-Nucleus scattering event rate:

Spin dependent (SD):

$$\sigma^{SD}(X) = \frac{32}{\pi}{G_F}^2{\mu_R}^2\frac{J+1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

Spin independent (SI):

$$\sigma^{SI}(X) = \frac{4{\mu_R}^2}{\pi}\left(Zf_p + (A-Z)f_n\right)^2$$

Elastic scattering amplitudes

Direct detection:

5 independent parameters

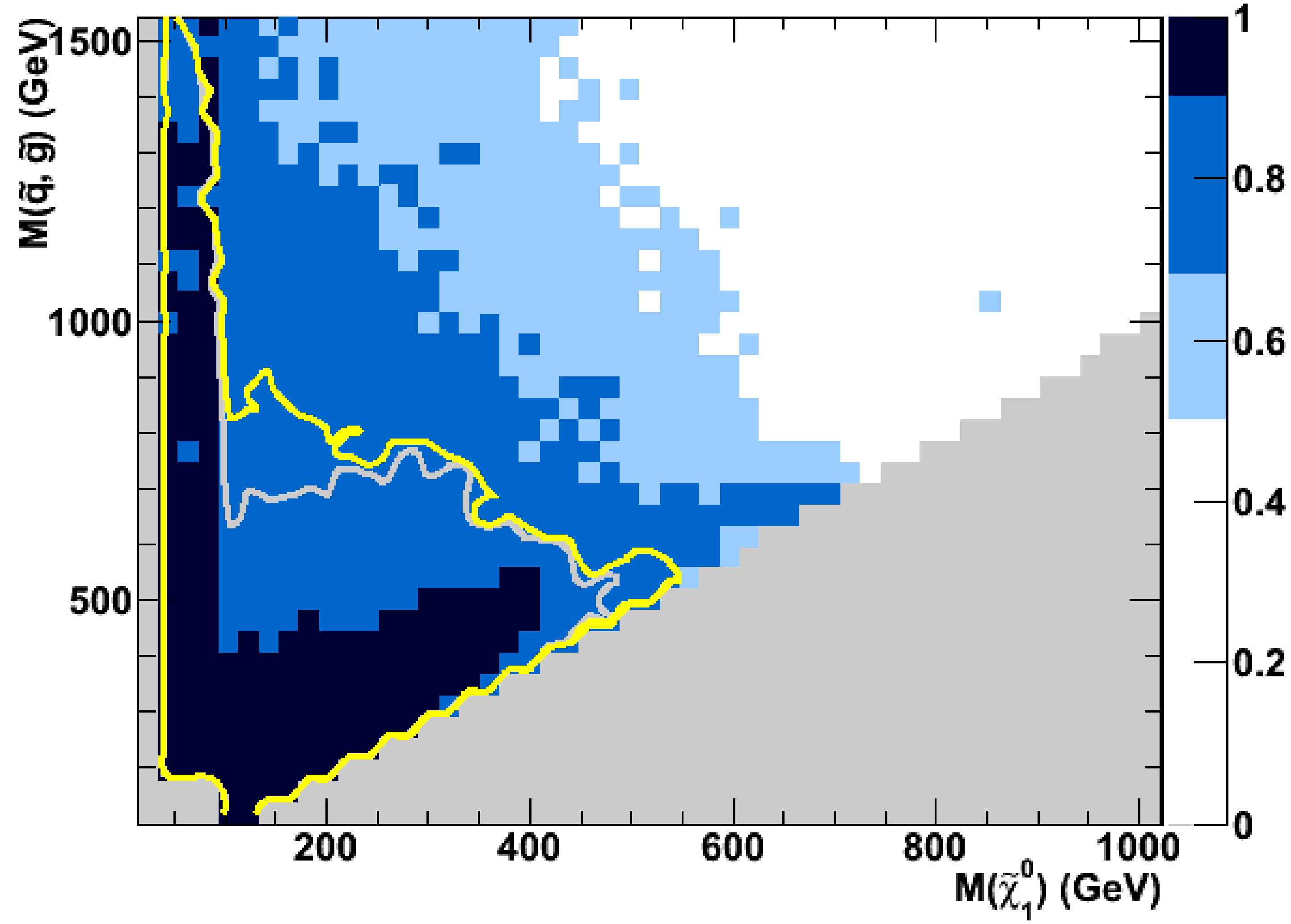
$$\left(m_\chi, \overset{\propto a_p^2}{\sigma^{SD}(p)}, \underset{\propto a_n^2}{\sigma^{SD}(n)}, \overset{\propto f_p^2}{\sigma^{SI}(p)}, \underset{\propto f_n^2}{\sigma^{SI}(n)}\right)$$

measurement : event rate $\longrightarrow$ limit on cross sections

Squarks mass in the pMSSM

Monojet search analysis

pMSSM with 19 parameters



Model-independent method for extracting SD cross section Limits

In the SD interaction phase space:

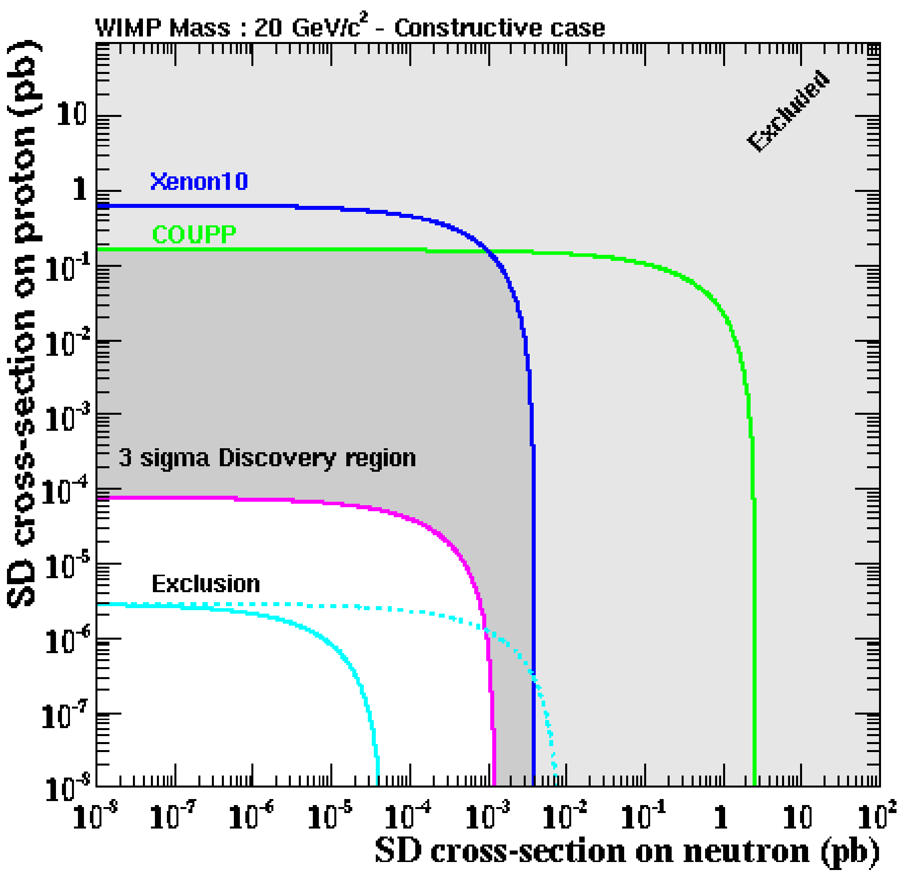
D. R. Tovey *et al.*, Phys. Lett. B, **488** (2000) 1
E. Moulin *et al.*, Phys.Lett. B614 (2005) 143-154

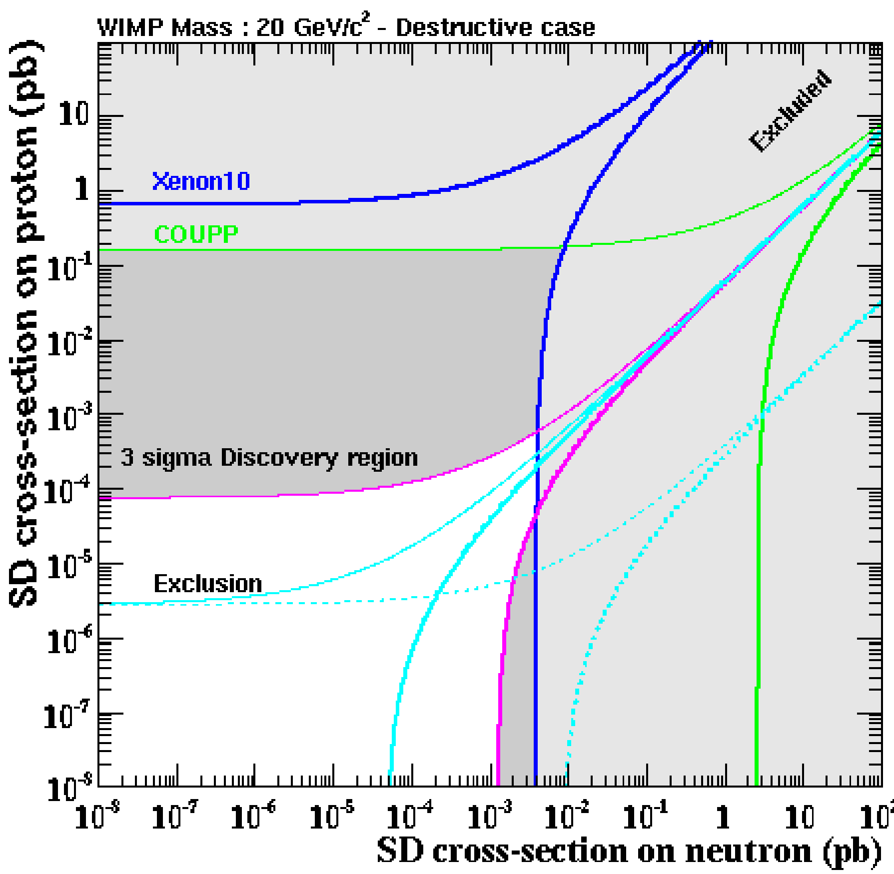
$$f_p = f_n = 0$$

$$\left(\sqrt{\frac{\sigma^{SD}(p)}{\boxed{\sigma^{SD}_{lim}(p)}}} \pm \sqrt{\frac{\sigma^{SD}(n)}{\boxed{\sigma^{SD}_{lim}(n)}}}\right)^2 > 1$$

Standard cross section limits

Interferences:





New paradigm for direct detection

$$R_{tot} = R^{SI} + R^{SD} \xrightarrow{m_\chi \text{ fixed}} \sigma^{SI}(p) = \sigma^{SD}(p) \times a + b$$

$R^{SI} \propto \sigma^{SI}(p)$, $R^{SD} \propto \sigma^{SD}(p)$

SI and SD interactions are no longer independent

Analytic calculation of a and b using experimental inputs

Experimental inputs:

a	Dark matter halo parametrization (v_0, σ_0, v_{esc}) Nuclear form factor Detector acceptance & thresholds Isotopic fractions	Nucleon spin contents $(\langle S_p \rangle, \langle S_n \rangle)$
b		Measured event rate or $\sigma^{SI}_{lim}(p)$ with $a_p = a_n = 0$

Heavy squarks: New paradigm for direct detection experiment comparison

A new paradigm

Total measurable event rate:

Isotope fraction

$$R_{mes} = \frac{\rho_0 E_c^0}{2 m_\chi v_0} \sum_i \frac{f_i}{{\mu_i}^2} \sigma_0^{SD}(X_i) \mathcal{F}^{SD}(X_i, E_R^{min}, E_R^{max}) + SD \leftrightarrow SI$$

Detector acceptance

$$\mathcal{F}^{SD/SI}(X_i, E_R^{min}, E_R^{max}) = \frac{v_0}{E_c^0} \int_{E_R^{min}}^{E_R^{max}} \mathscr{A}(E_R) F_i^{SD/SI}(E_R) \int_{v_{min}}^{v_{esc}} \frac{f(\vec{v})}{v} \mathrm{d}^3 v \mathrm{d} E_R$$

Axial cross section

$$\sigma_0^{SD}({}^A_Z X) = \sigma_0^{SD}(p) \frac{4}{3} \frac{{\mu_R}^2}{{\mu_p}^2} \frac{J+1}{J} \left(\langle S_p \rangle + \frac{\langle S_n \rangle}{C_a} \right)^2$$

Scalar cross section

$$\sigma_0^{SI}({}^A_Z X) = \sigma_0^{SI}(p) \frac{{\mu_R}^2}{{\mu_p}^2} \left(Z + \frac{A-Z}{C_f} \right)^2$$

A new paradigm (2)

Total measurable event rate:

$$\boxed{R_{mes}} = \frac{\rho_0 v_0}{4{\mu_p}^2} \left[\frac{4}{3}\boxed{\sigma_0^{SD}(p)} \sum_i f_i \frac{J_i+1}{J_i} \left(\langle S_p \rangle_i + \frac{\langle S_n \rangle_i}{C_a} \right)^2 \mathcal{F}^{SD}(X_i, E_R^{min}, E_R^{max}) + \boxed{\sigma_0^{SI}(p)} \sum_i f_i \left(Z_i + \frac{A_i - Z_i}{C_f} \right)^2 \mathcal{F}^{SI}(X_i, E_R^{min}, E_R^{max}) \right]$$

Measurement

$$\sigma_0^{SI}(p) = b - a \times \sigma_0^{SD}(p)$$

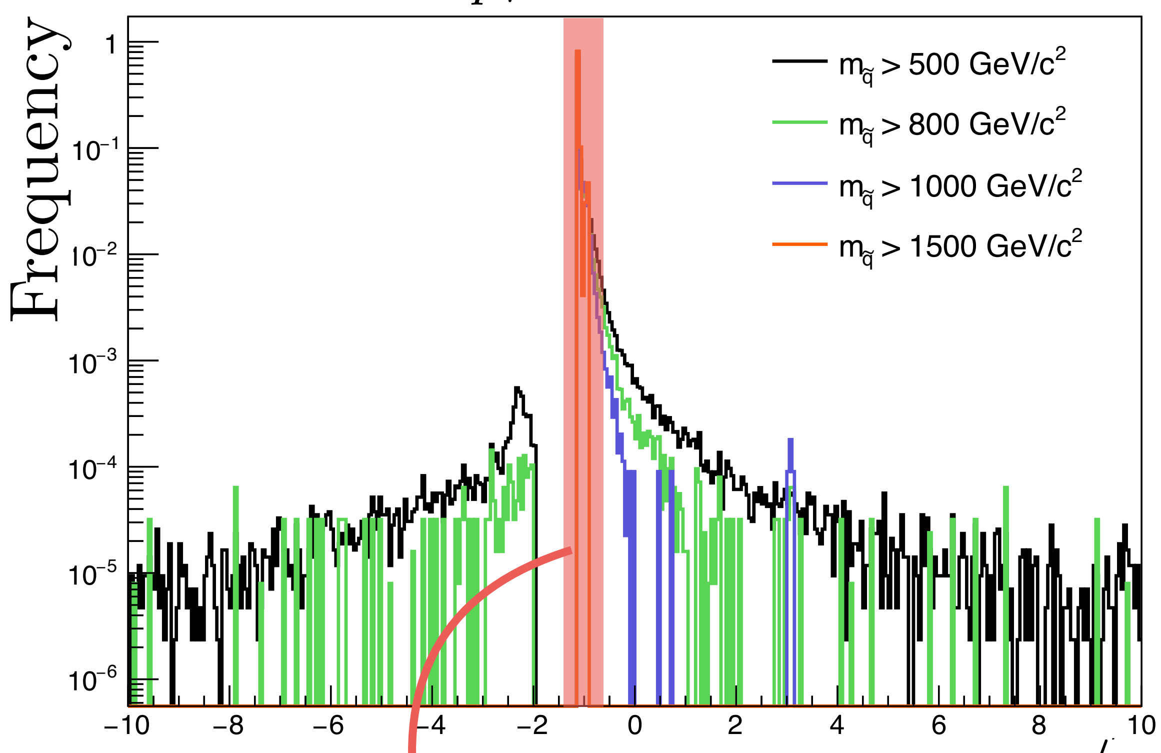
$$\begin{cases} a = \dfrac{4}{3} \times \dfrac{\sum_i f_i \frac{J_i+1}{J_i} \left(\langle S_p \rangle_i + \frac{\langle S_n \rangle_i}{C_a} \right)^2 \mathcal{F}^{SD}(X_i)}{\sum_j f_j \left(Z_j + \frac{A_j - Z_j}{C_f} \right)^2 \mathcal{F}^{SI}(X_j)} \\ b = \dfrac{\Sigma_0}{\sum_i f_i \left(Z_i + \frac{A_i - Z_i}{C_f} \right)^2 \mathcal{F}^{Si}(X_i)} \end{cases}$$

$$\Sigma_0 = \frac{4{mu_p}^2}{\rho_0 v_0} R_{mes} = \boxed{\sigma_{exp}^{SI}(p)} \sum_i f_i {A_i}^2 \mathcal{F}^{SI}(X_i)$$

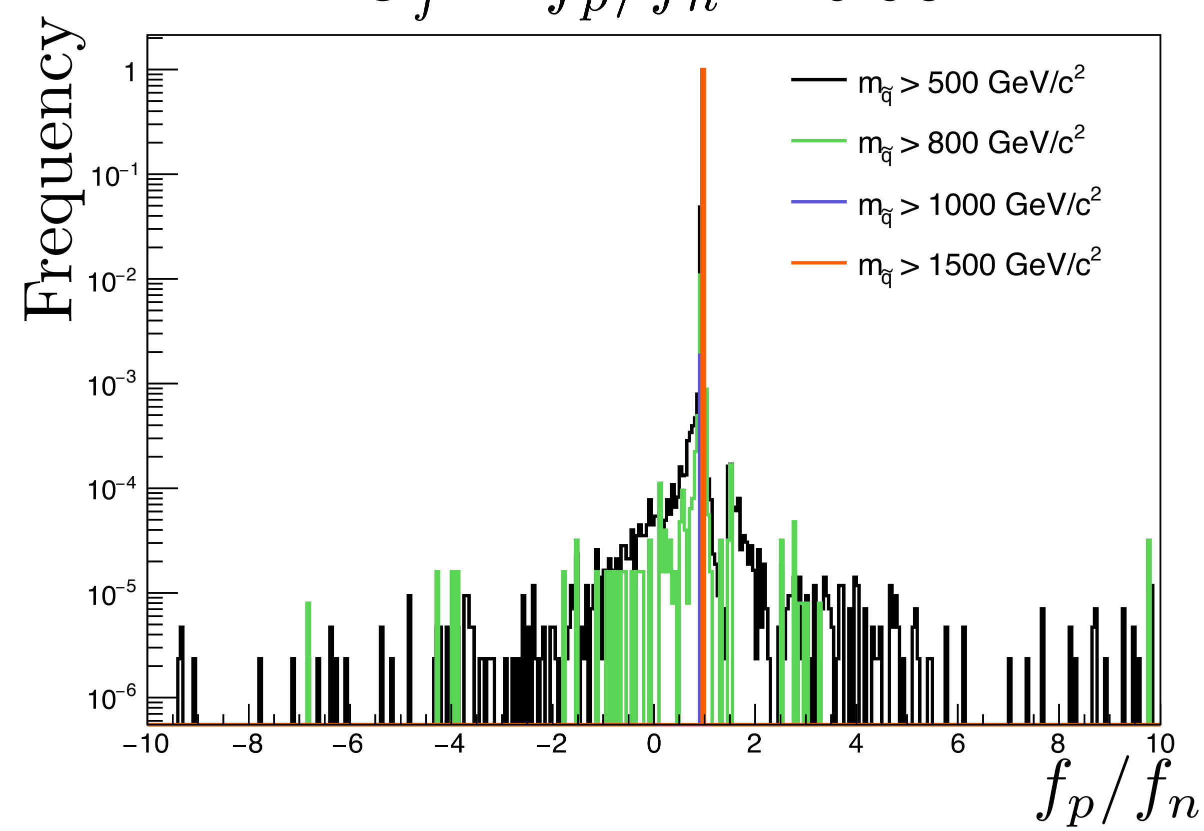
Experimental limit form direct detection

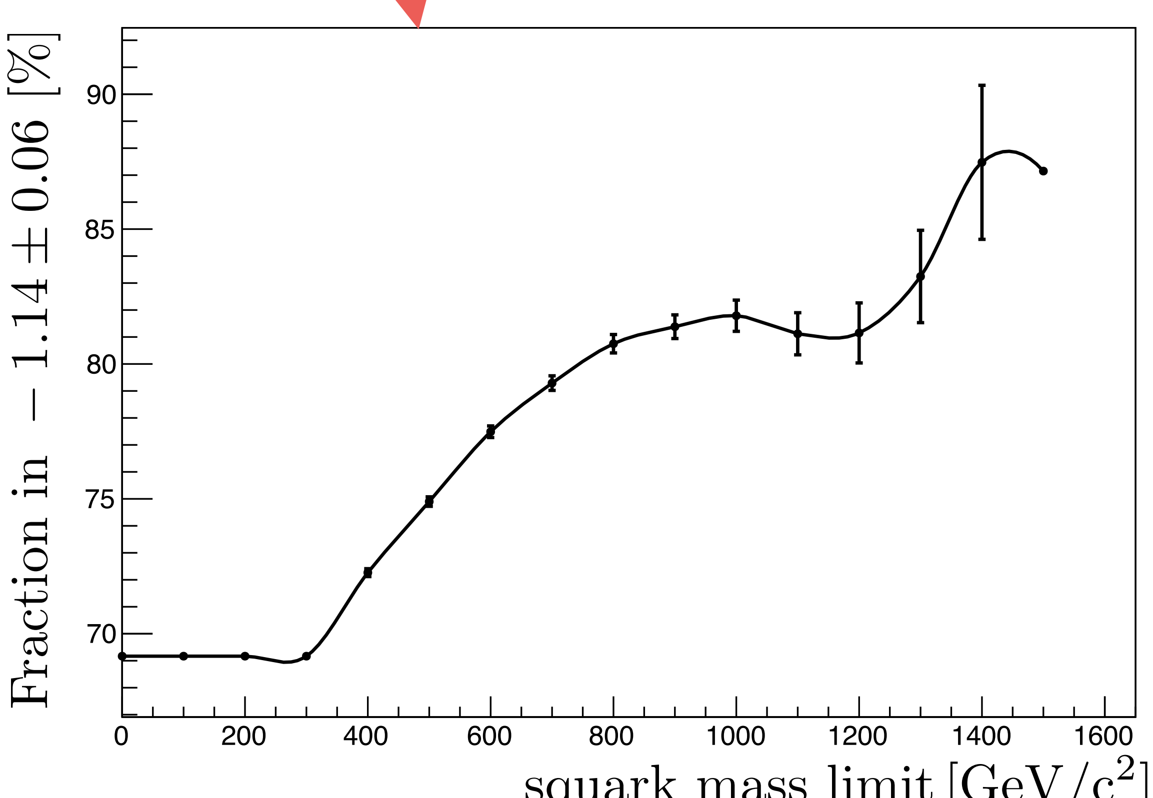
MSSM scan: scattering amplitudes

$C_a = a_p/a_n = -1.14$



$C_f = f_p/f_n = 0.98$





Scan results:

- Amplitude ratios tend to a constant value as the squark mass limit increase
- heavy squark paradigm valid for

$$\lim(m_{\tilde{q}}) > 800 \text{ GeV/c}^2$$