Summer school and workshop on high energy physics at the LHC

Phenomenology and experimental aspects of SUSY and searches for extradimensions at the LHC

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Natal, Brazil

21-31 October

Tentative outline

LECTURE 3

- dark matter

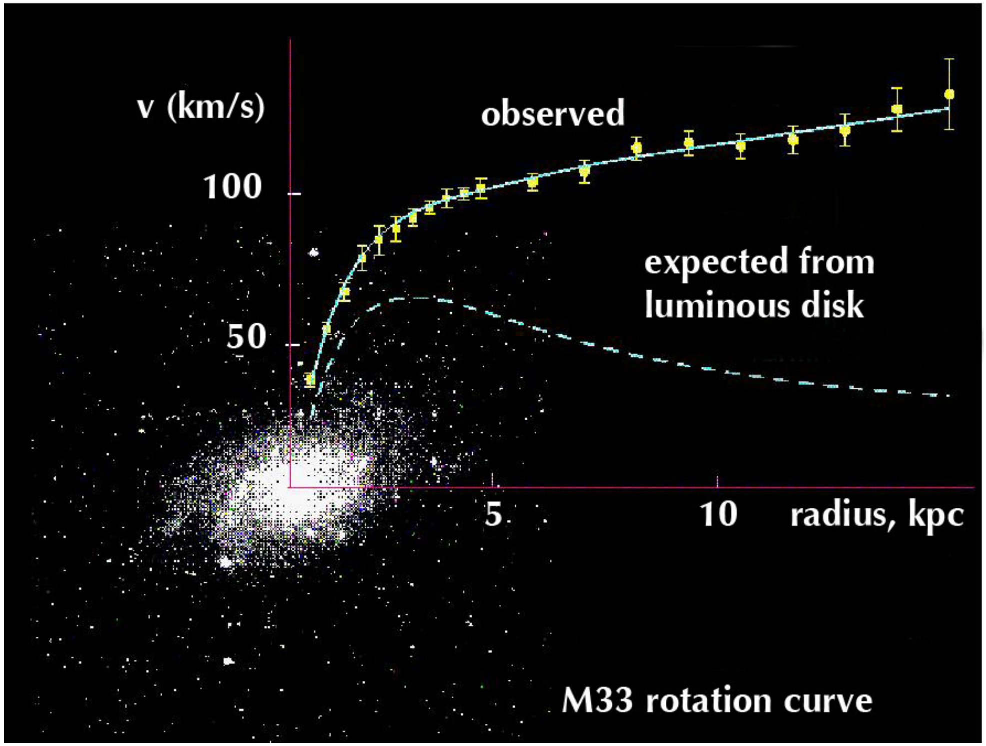
- why we need it
- WIMP "miracle" and susy
- direct, indirect searches, search for DM at LHC (effective approach)

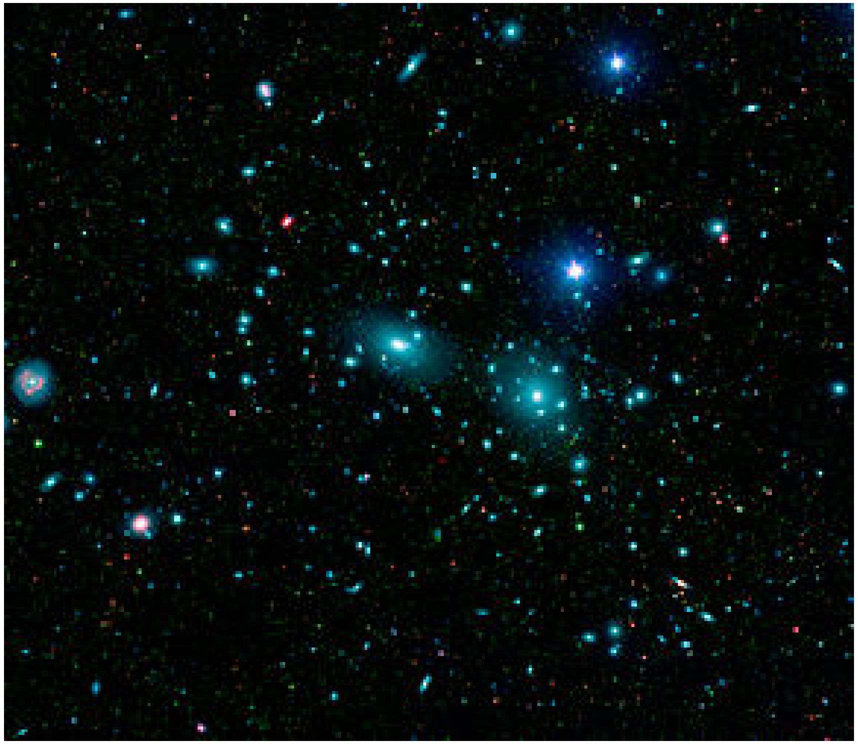
Dark Matter

motivation for dark matter arises from gravitational effect in astronomical observations at various scale

luminous (visible) matter is insufficient to account for the observed effects at galactic scale :

- rotation curves of spiral galaxies
- gas temperature in elliptic galaxies

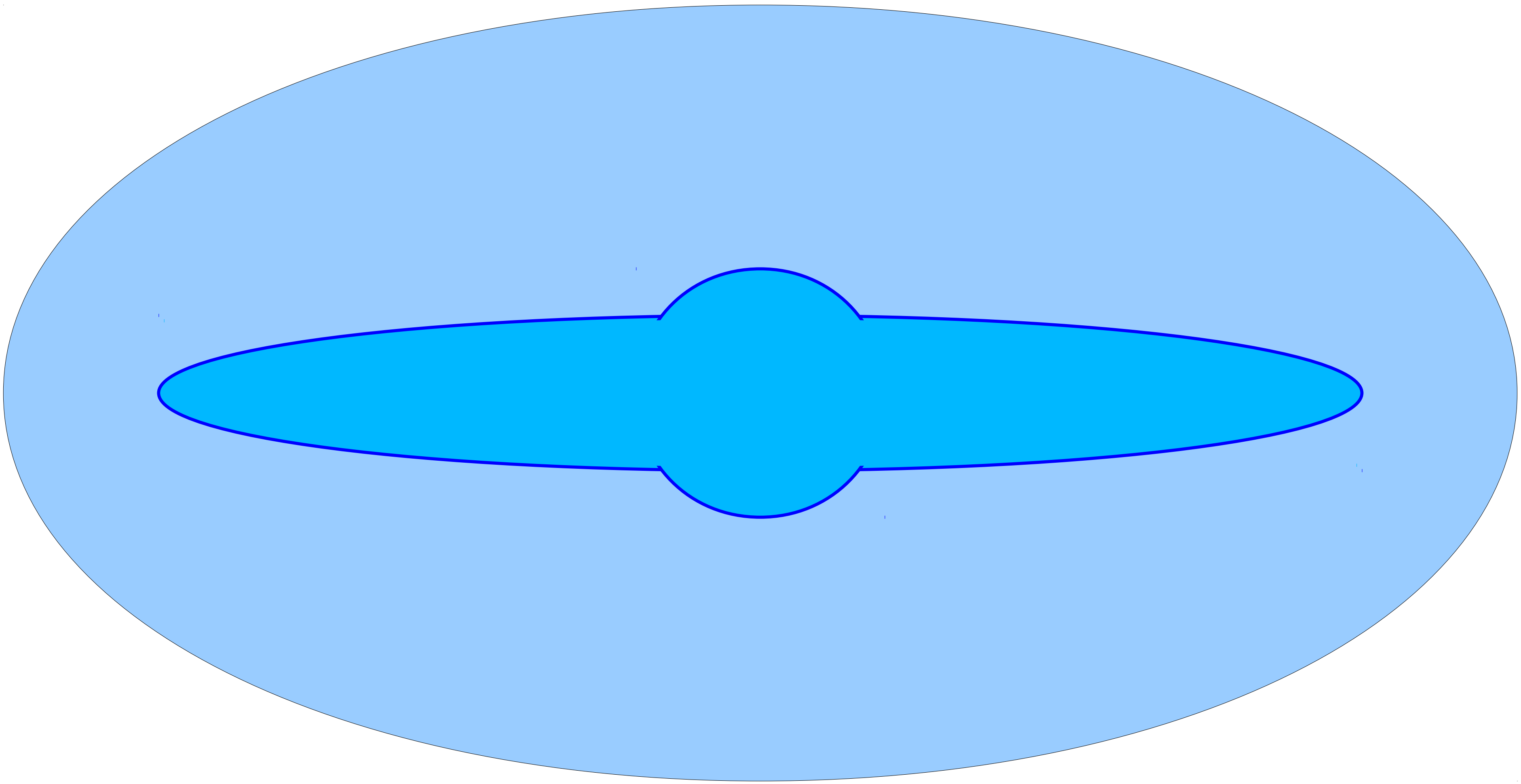




clusters of galaxies :

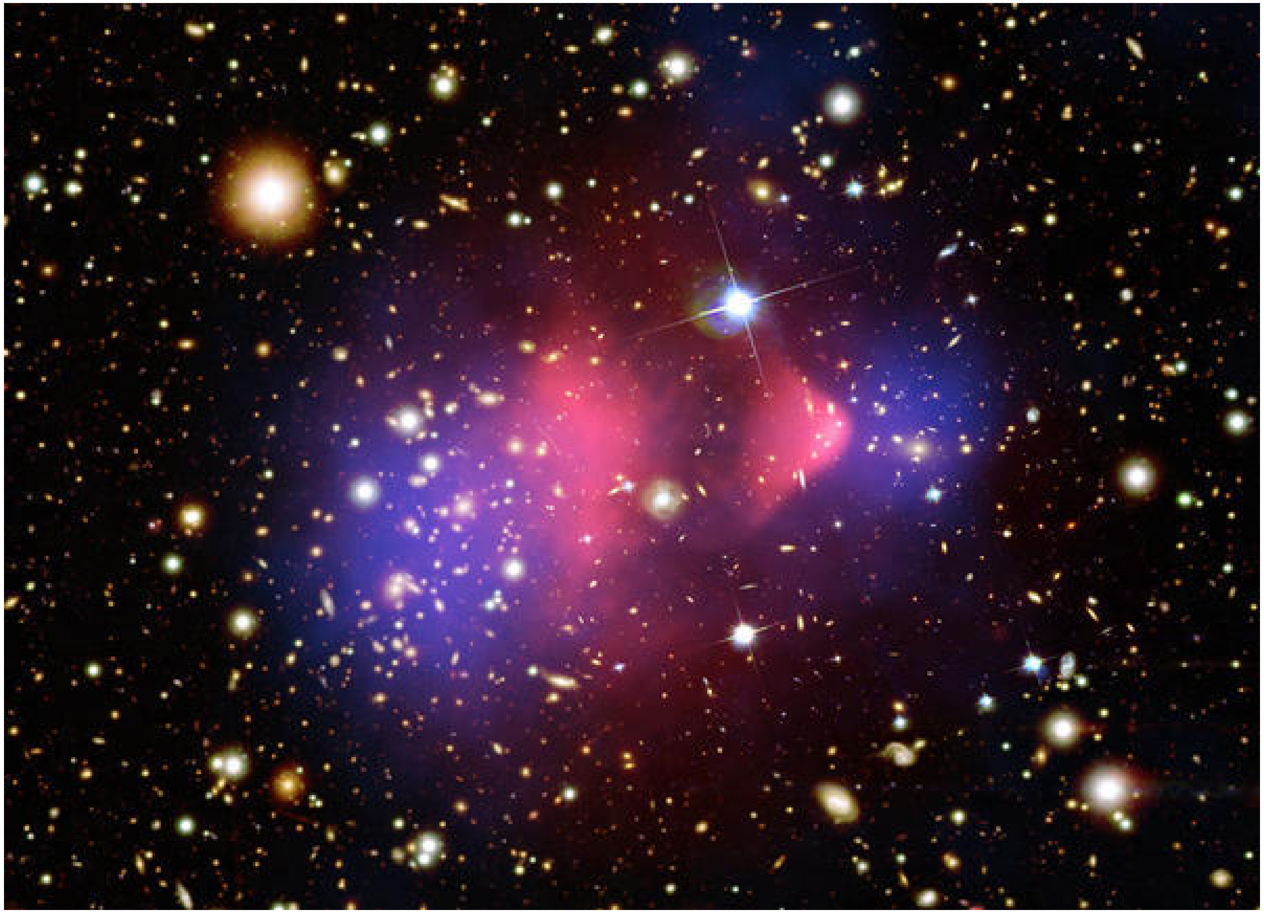
- peculiar velocities
- gas temperature (X-ray measurements)
- gravitational lensing

Dark Matter



Galaxies have a dark halo containing 70-80 % of its mass

Dark Matter



galaxy collision : bullet cluster (galaxy cluster 1E 0657-56)

two galaxies collided leaving the visible interacting matter (hot gas detected by Chandra in X ray) behind (as shown in pink color)

not where most of the mass of the cluster is as seen through gravitational lensing (shown in blue color)

Dark Matter

- needed for structure formation

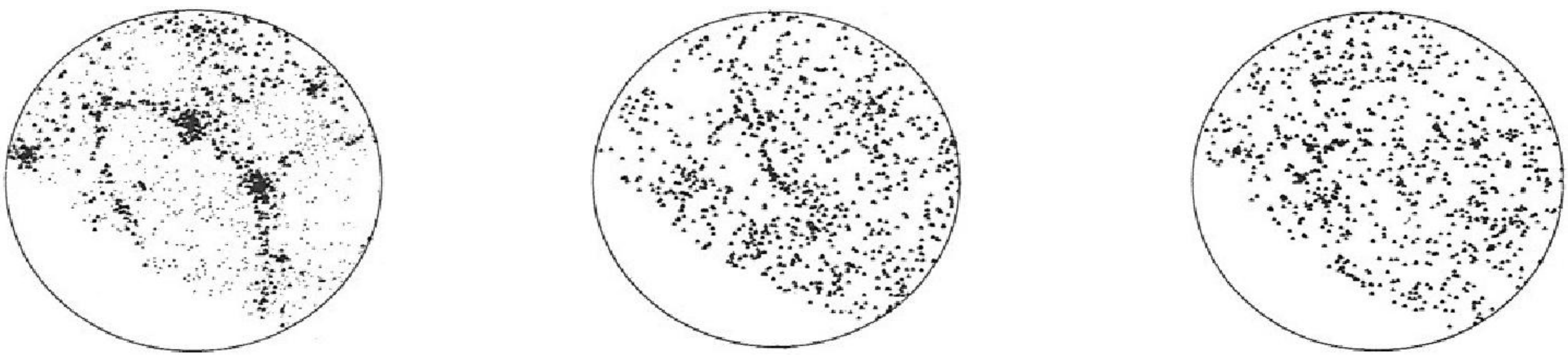
structure in baryons cannot grow until 'recombination'

baryons must then fall into potential wells of DM or not enough time for structure to form

- no Hot (i.e. relativistic) Dark Matter (HDM)

ex: relativistic light neutrinos

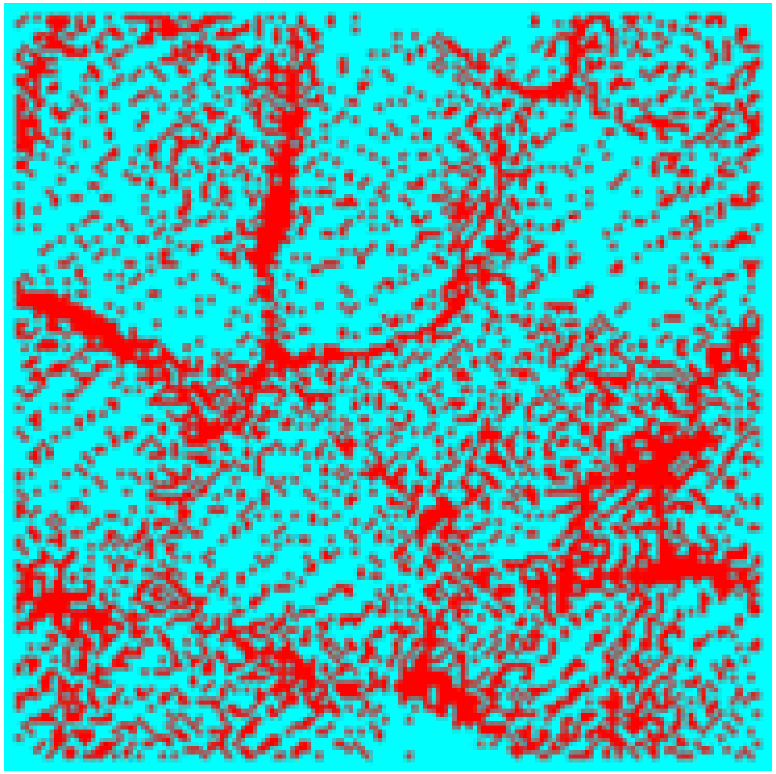
from simulations (1st from S. White 1986)



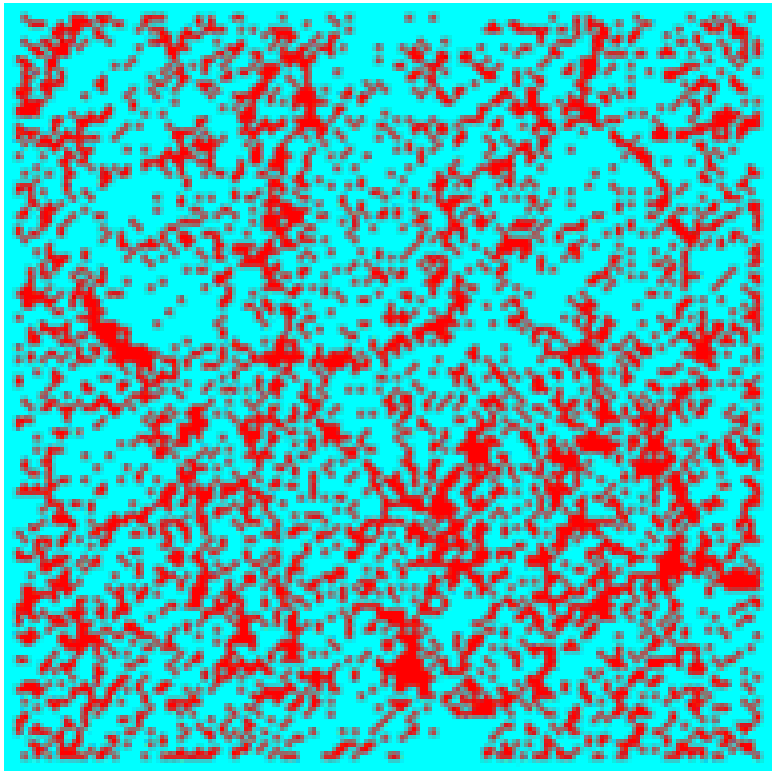
HDM **observed galaxy distribution** **CDM**

HDM does not explain the observed clustering ➔ cold dark matter (CDM) is more successful

Dark Matter



HDM



CDM

Planck results

baryons $\Omega_b h^2 = 0.02207 \pm 0.00033$

CDM $\Omega_{DM} h^2 = 0.1196 \pm 0.0031$

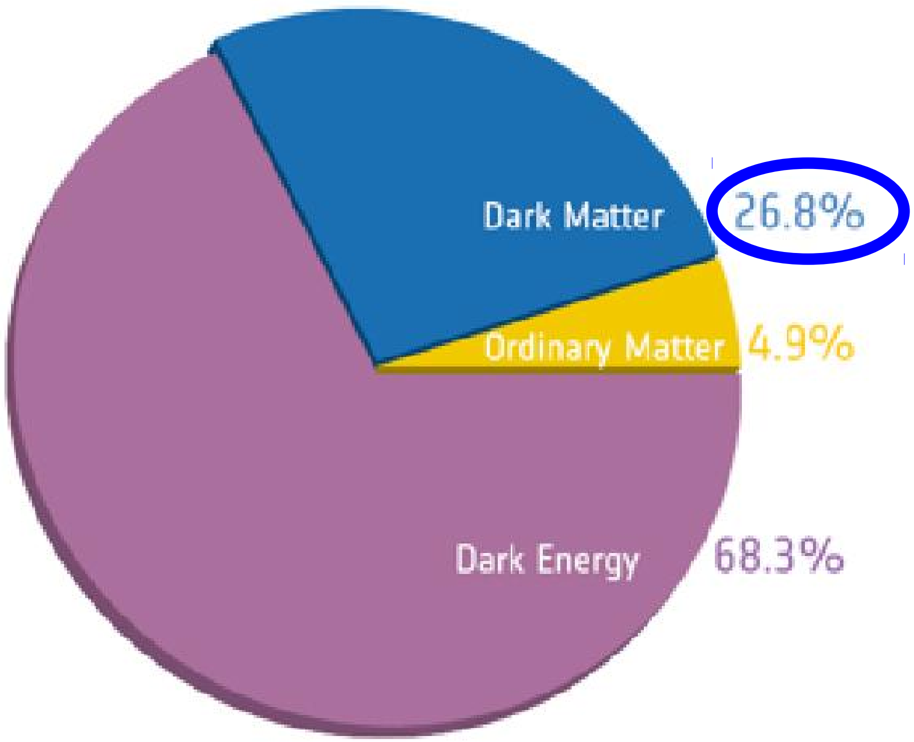
Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025

Dark energy $\Omega_\Lambda = 0.686 \pm 0.020$

with $\Omega_b = \frac{\rho_b}{\rho_c}$, $\Omega_{DM} = \frac{\rho_{DM}}{\rho_c}$, $\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c}$ ...

$\rho_c = 3\ H_0^2\ m_P^2 \approx 10^{26}\,\mathrm{kg}/m^3$ being the critical density

Planck results



baryons $\Omega_b h^2 = 0.02207 \pm 0.00033$

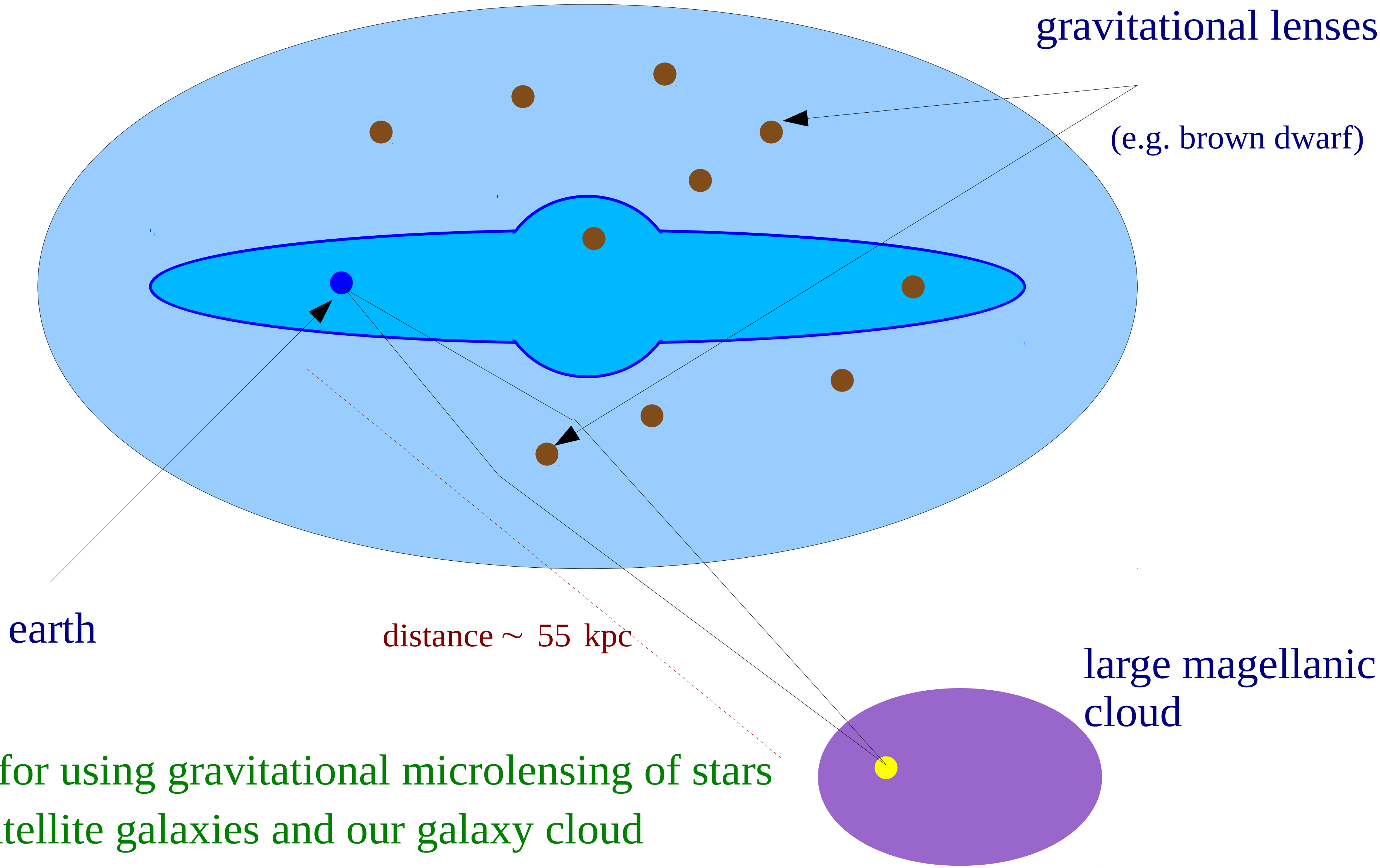
CDM $\Omega_{DM} h^2 = 0.1196 \pm 0.0031$

Dark energy $\Omega_\Lambda = 0.686 \pm 0.020$

H_o $h = 0.674 \pm 0.0014$

Dark Matter are not MACHOS

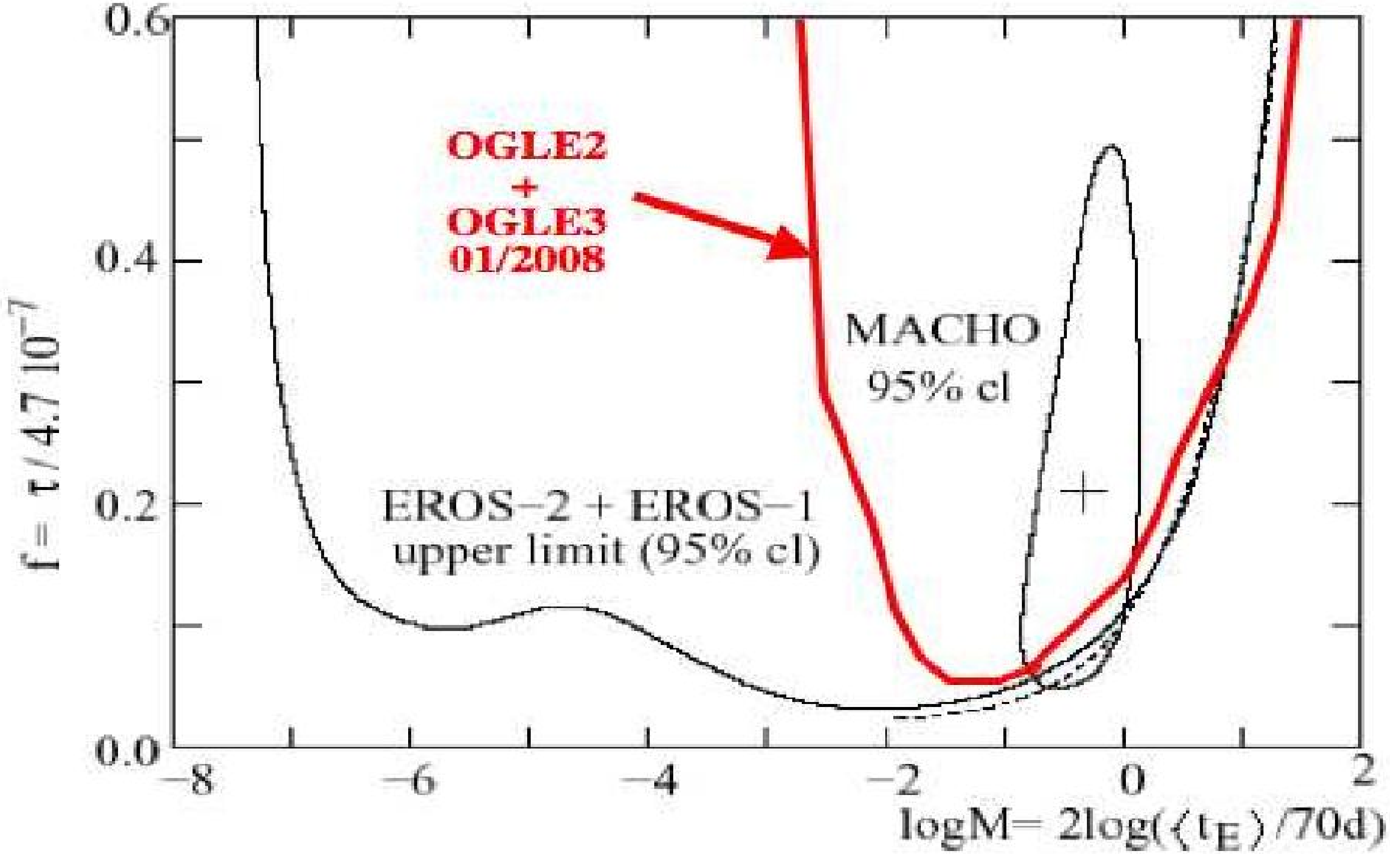
(Massive Astrophysical Compact Halo ObjectS)



searched for using gravitational microlensing of stars
in near satellite galaxies and our galaxy cloud

Dark Matter are not MACHOS

(Massive Astrophysical Compact Halo ObjectS)



not enough objects with $M > 10^{-7}\ M_{sun}$

DM are elementary particles ?

Condition on Dark Matter (DM) particle candidate

- **stable (or lifetime > > lifetime of the universe)**

- **neutral, colorless (weak interactions)**

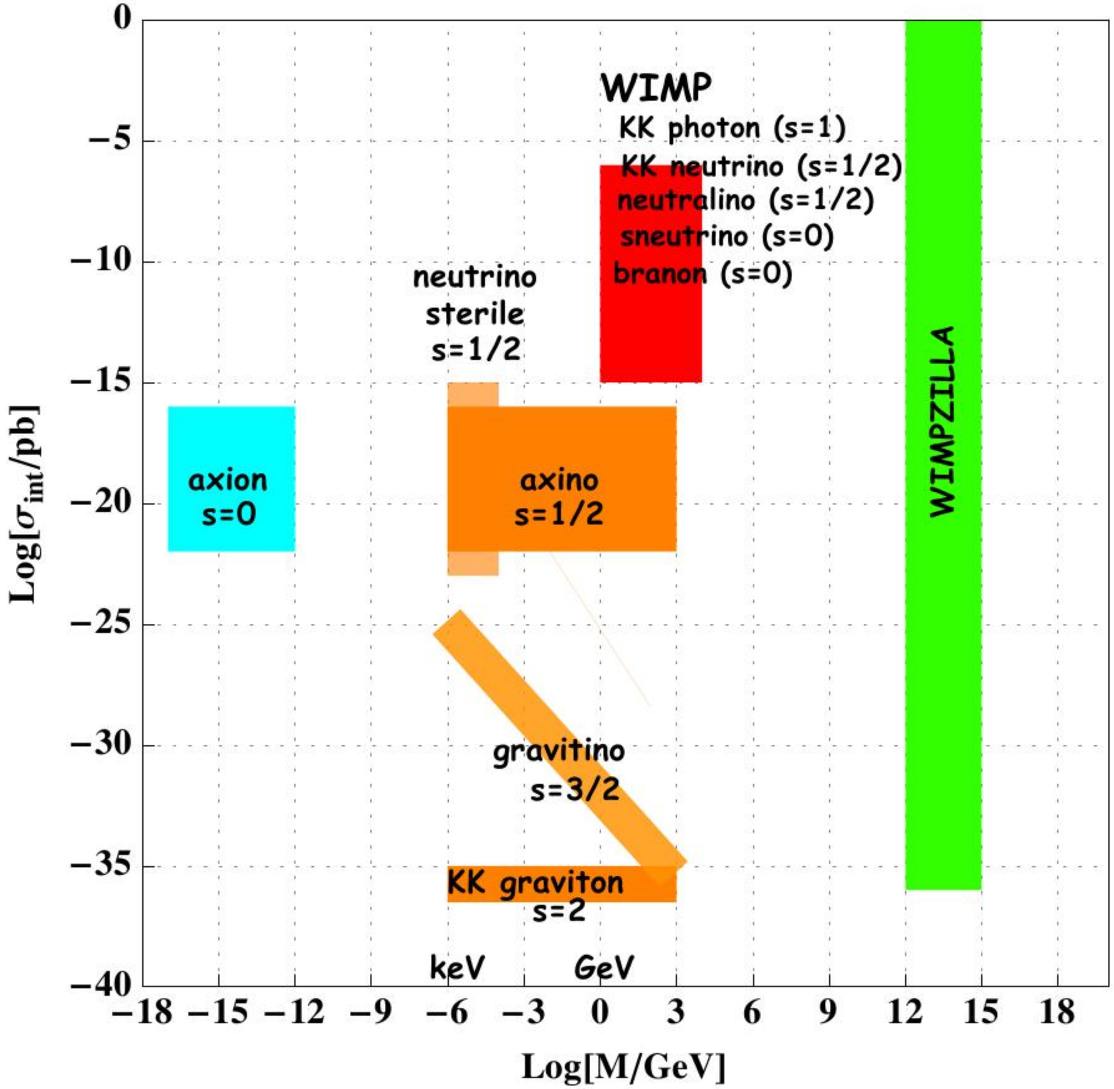
- **cold (CDM i.e. non relativistic) or warm (WDM i.e. semi relativistic)**

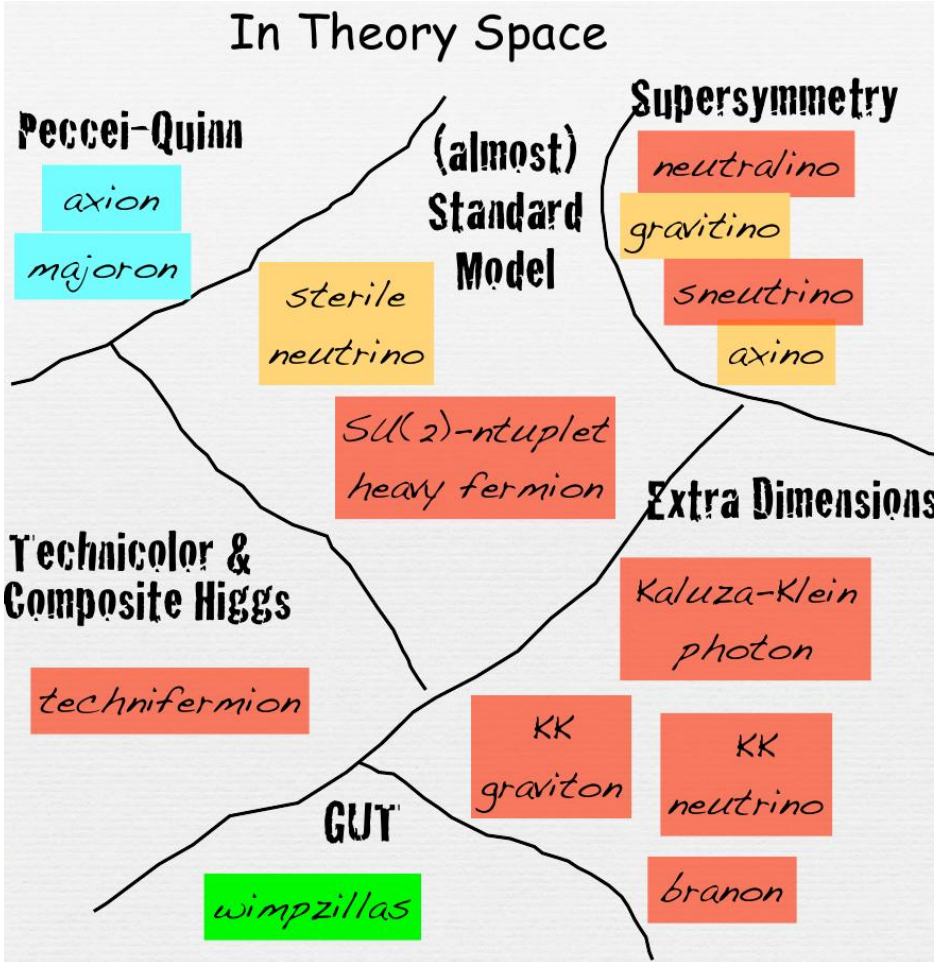
- **massive and with the right relic abundance**
  $\rightarrow$ DM constraint on particle physics models

No CDM or WDM particle candidate in the Standard Model

active neutrinos are light and in equilibrium until BBN (T ~ 1 MeV) thus they are HDM

Some Dark Matter candidates





from G. Servant Talk EPS HEP 2013

(thermal) Relic density

'initially' the early universe is dense and hot and all particles are in thermal equilibrium

the universe then cools to temperature T below the dark particle's mass m_X

$\Rightarrow$ number of dark particles becomes 'Boltzmann' suppressed

i.e. dropping exponentially as $e^{-m_X / T}$

the number of dark matter particle would drop to zero

except that in addition to cooling the universe is also expanding !

eventually the universe becomes so large and the gas so dilute
that the dark matter particles cannot find each other to annihilate

$\Rightarrow$ **the dark matter particles then 'freeze out'**

with their number asymptotically approaching a constant

i.e. their thermal relic density

note that freeze out also known as chemical decoupling is distinct from kinetic decoupling
but interactions that mediate energy exchange between dark matter and other particle may remain efficient
after thermal freeze out interactions that change the number of dark matter particle become negligible

(thermal) Relic density

expansion and annihiliation $\Rightarrow$ 2 competing effects which can modify the abundance

the faster the dilution associated with the expansion the least effective the annihilation

→ Boltzmann evolution equation

particle number density

dilution by universe expansion

relative velocity of the 2 particle annihilating

equilibrium density

$$\frac{d\,n_X}{dt} + 3\,\overbrace{H\;n_X} = -\underbrace{<\sigma_{ann}\;v>}\left(n_X^2 - n_X^{(eq)2}\right)$$

Hubble parameter

thermal average of the $X\,\bar{X}$ annihilation cross-section

when temperature drops below particle X mass m_X

→ annihilation rate becomes smaller than the expansion rate

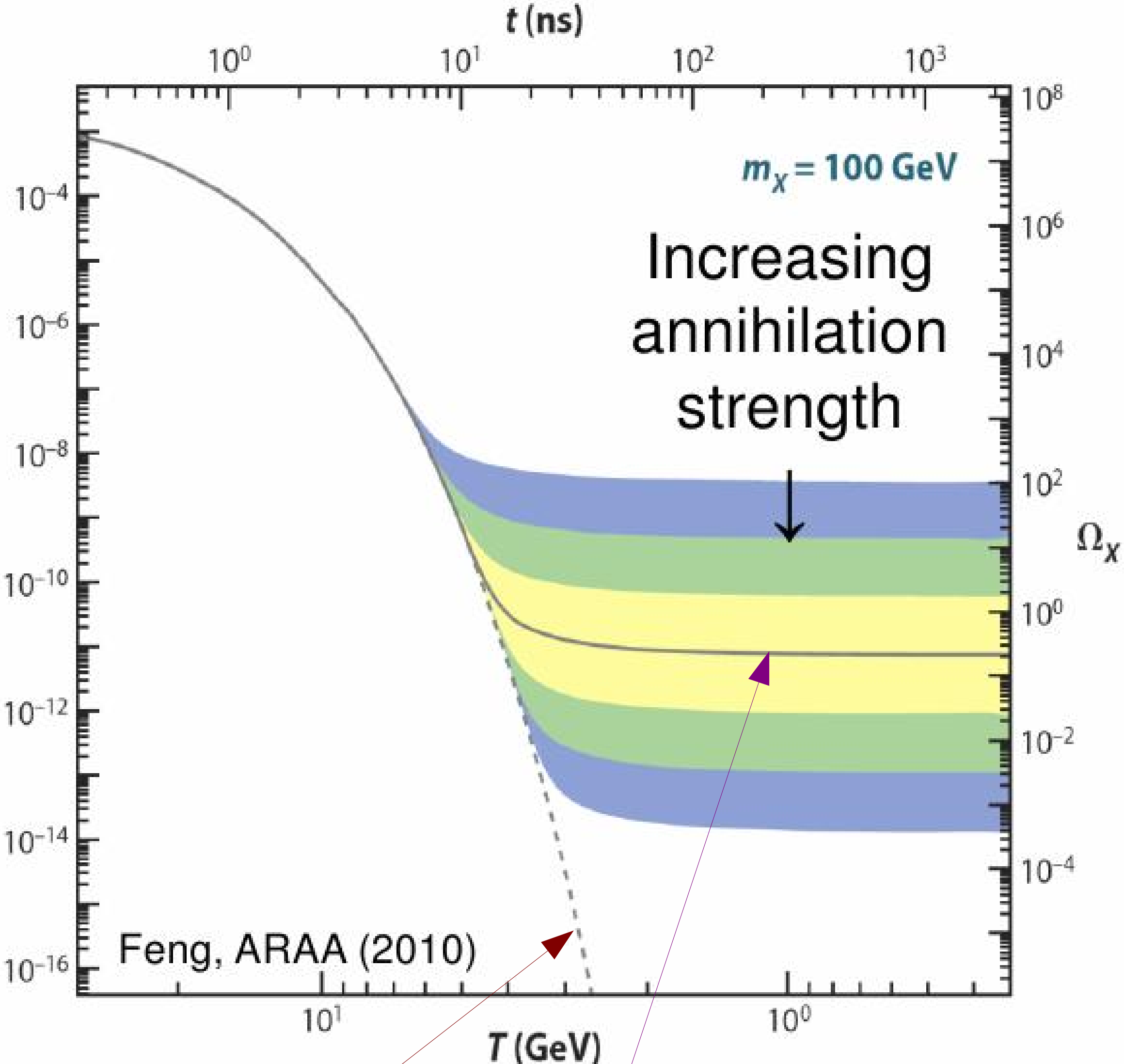
→ freezing of the number of particles in a covolume

from n_X at present temperature T_o one gets

energy density $\rho_X(T_o) = n_X(T_o)\;m_X$ and $\Omega_X = \frac{\rho_X(T_o)}{\rho_c} = \frac{8\pi\hbar}{3M_P^2}\,\frac{\rho_X(T_o)}{H_o^2}$

The WIMP "miracle"

massive particles with mass $\sim O(100)$ GeV and with annihilation interactions of the 'size' of EW interactions allowing to get the observed relic density



comoving number density Y

$$\Omega_X h^2 \propto \frac{3\times 10^{-39}\,\mathrm{cm}^2}{<\sigma_{\mathrm{annihilation}}\, v>}$$

$$\sim f(m_X, g_X)$$

with $m_X \sim 100$ GeV, $g_X \sim 0.6$

$\rightarrow \Omega_X h^2 \sim 0.1$

solid line is for annihilation cross section that yield the correct relic density

shaded regions are for cross section that differ by 10, 10^2 and 10^3 from this value

number density of particle that would remain in thermal equilibrium

in Minimal supersymmetric extension of the SM

Neutralinos (i.e. Majorana fermions in MSSM)

$$\tilde{\chi}_i^o = N_{i,1}\ \tilde{B} + N_{i,2}\ \tilde{W}_3 + N_{i,3}\ \tilde{H}_d^o + N_{i,4}\ \tilde{H}_u^o$$

Bino

Wino

Higgsinos

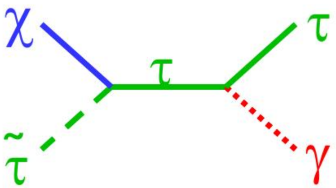
- lightest neutralino (i=1) $\%\tilde{chi}_1^0$ often considered as LSP and a candidate for DM

- assume R-parity conservation

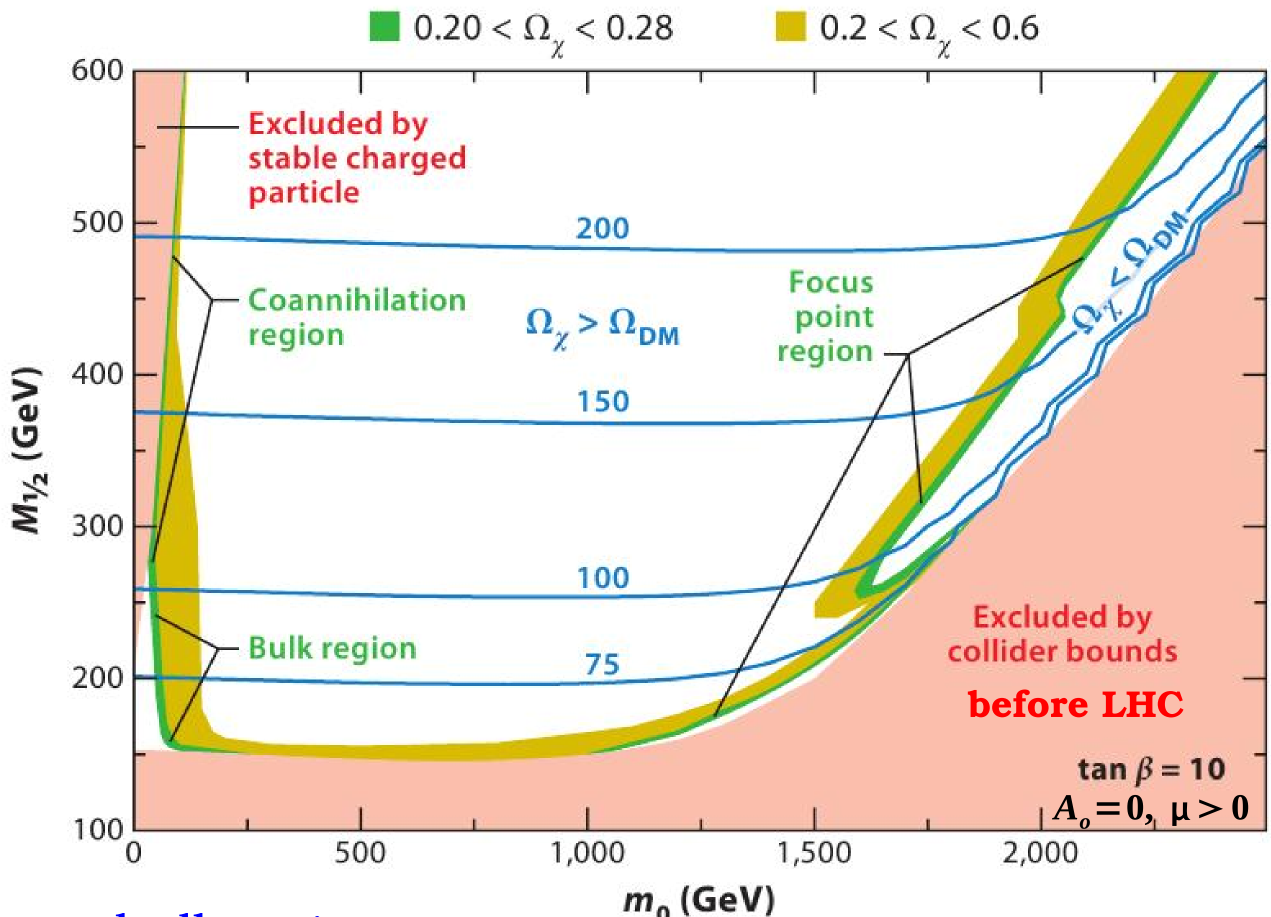
- couplings of lightest neutralino (i=1) to Z boson and Higgs boson can vanish when it is purely gaugino $N_{13} = N_{14} = 0$ or purely higgsino $N_{11} = N_{12} = 0$

Example of relic density calculation

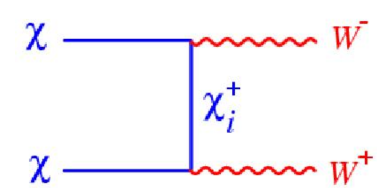
coannihilation region



degenerate neutralino and stau

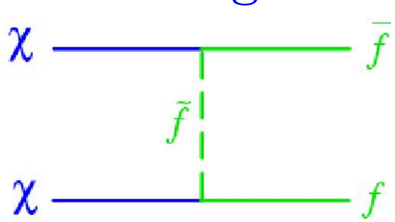


focus point region



mixed higgsino-bino neutralinos

bulk region

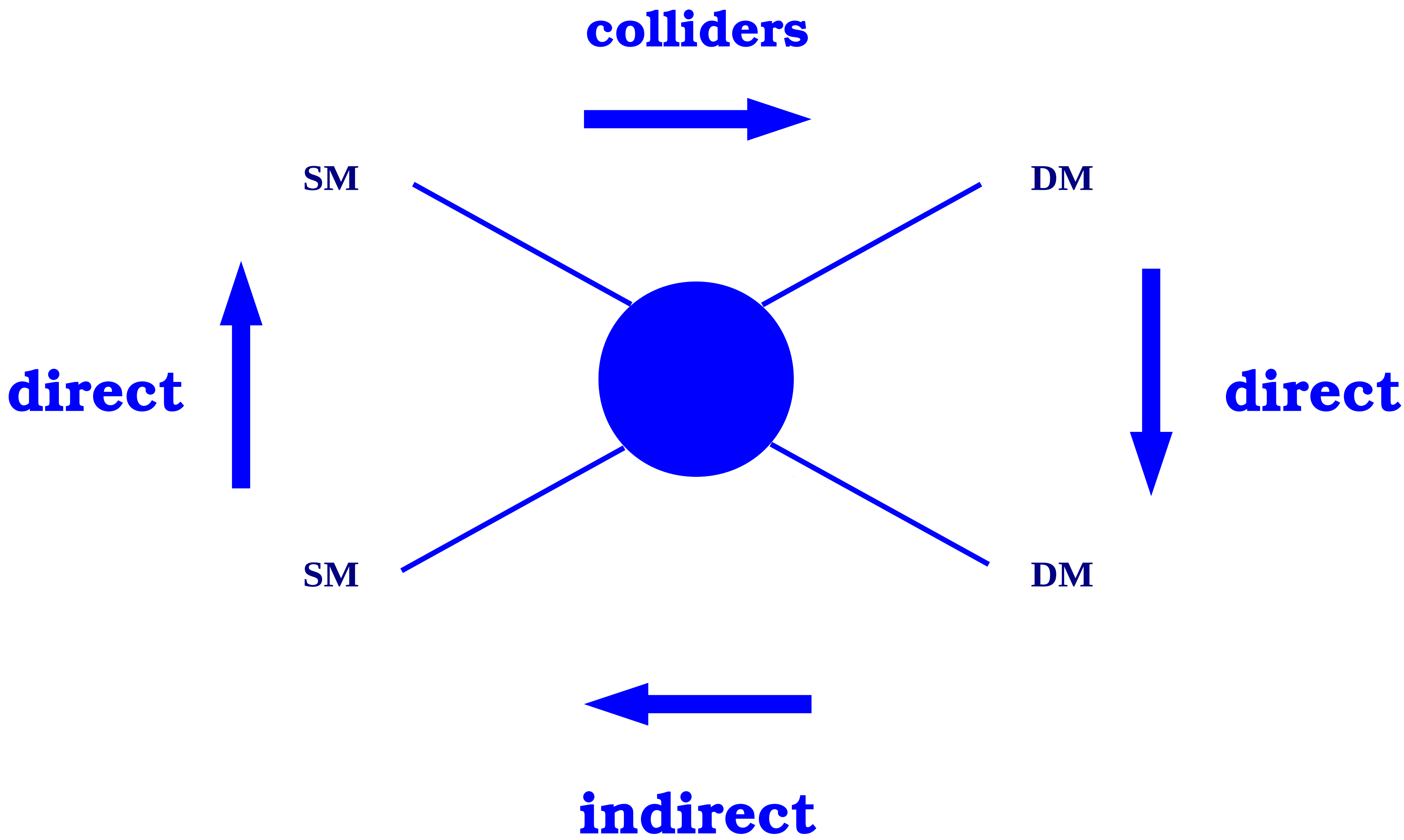


light sfermions

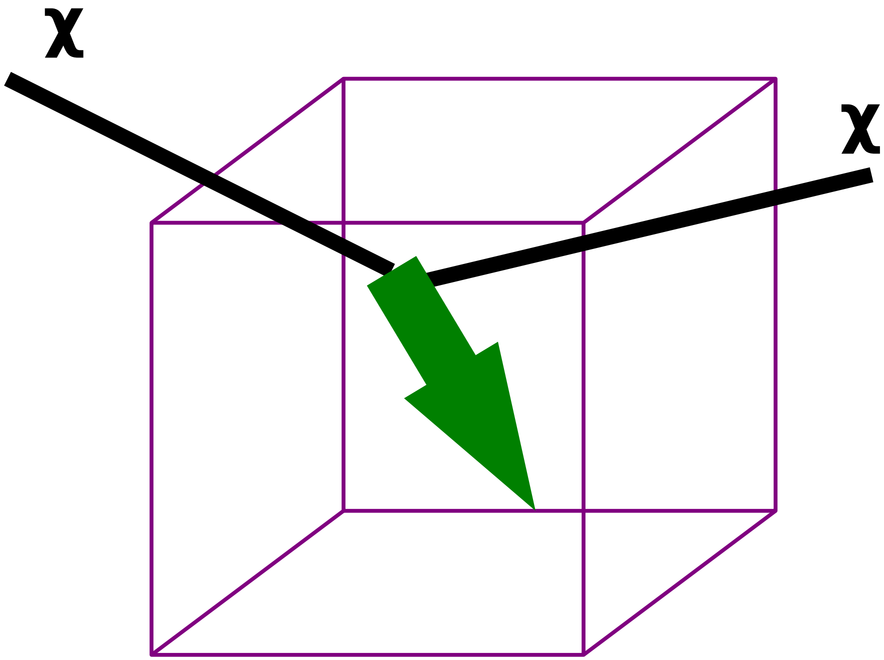
picture can change quite drastically at larger $\tan\beta$

ex: s-channel annihilation via a A boson (funnel region)

Detection of Dark Matter



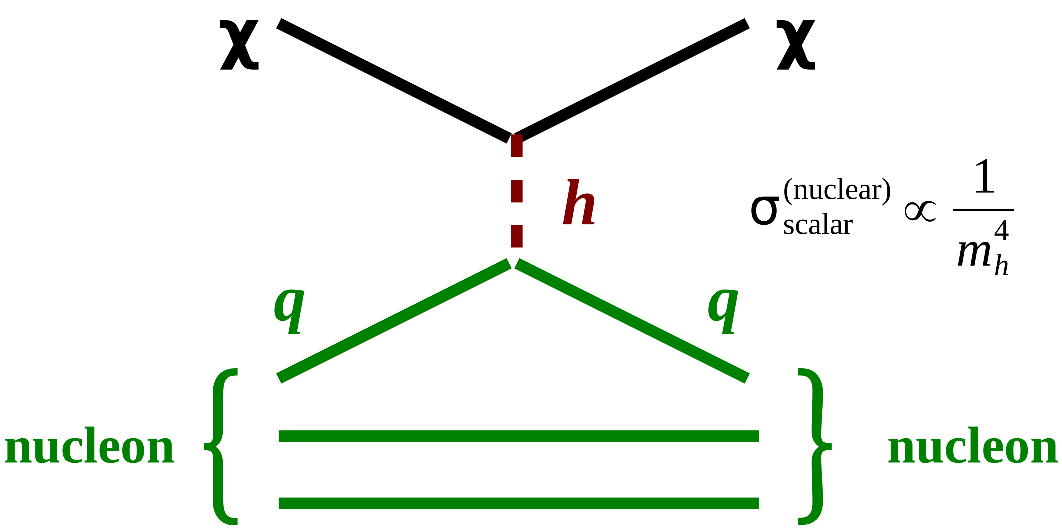
Dark Matter direct detection



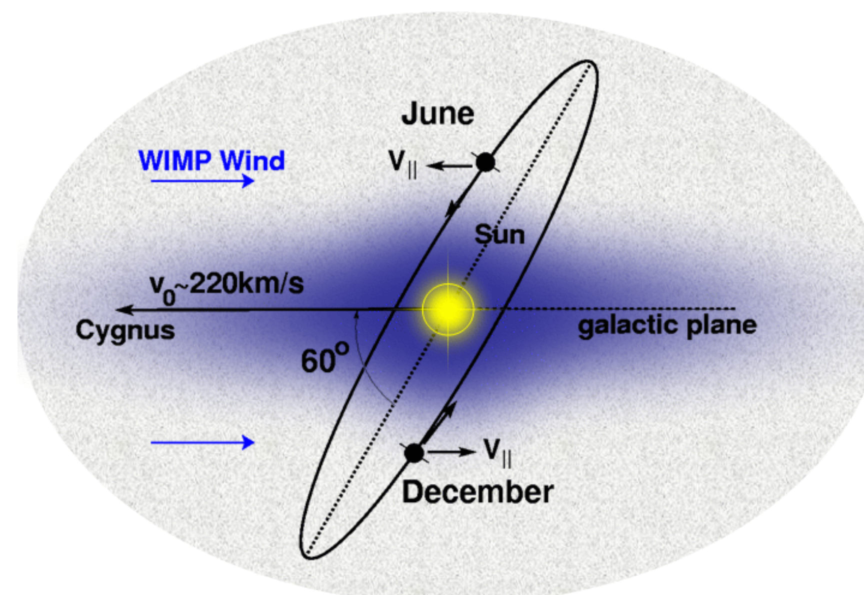
Nuclear recoil measurements

- **ionization**
  Ge, Si
- **bolometer (cryogenic detectors)**
  TeO_2, Ge, $CaWO_4$ ...
- **scintillation**
  NaI, Tl
  LXe, CaF_2(Eu), ...

e.g.



$$\sigma^{(\text{nuclear})}_{\text{scalar}} \propto \frac{1}{m_h^4}$$



annual modulation

interactions with of DM with matter
(non relativistic)

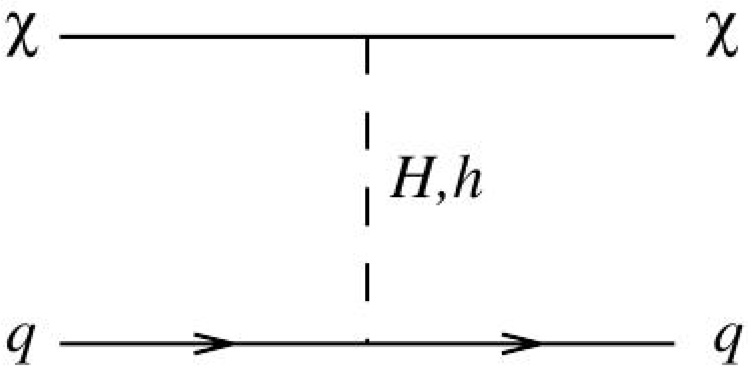
because of the Majorana nature of the $\tilde{\chi}$ (i.e. $\bar{\tilde{\chi}} \gamma^{\mu} \tilde{\chi} = 0$ and $\bar{\tilde{\chi}} \sigma^{\mu\nu} \tilde{\chi} = 0$) the most general lagrangian at the level of quarks is described by the 4-fermion lagrangian :

$$L = \sum_i \left[d_i \, \bar{\tilde{\chi}} \gamma^{\mu} \gamma^5 \tilde{\chi} \; \bar{q}_i \gamma_{\mu} \gamma^5 q_i + f_i \, \bar{\tilde{\chi}} \tilde{\chi} \; \bar{q}_i q_i \right]$$

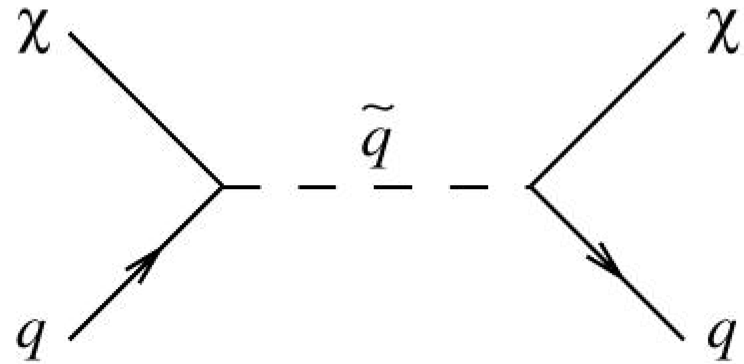
axial vector or spin dependent (SD) interactions

scalar or spin independent (SI) interactions

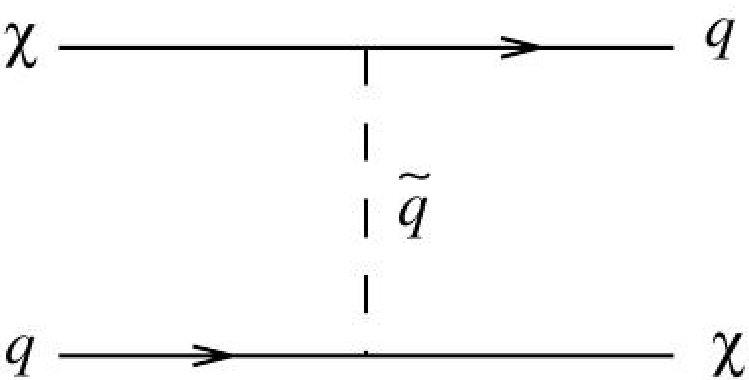
interactions with of DM with matter



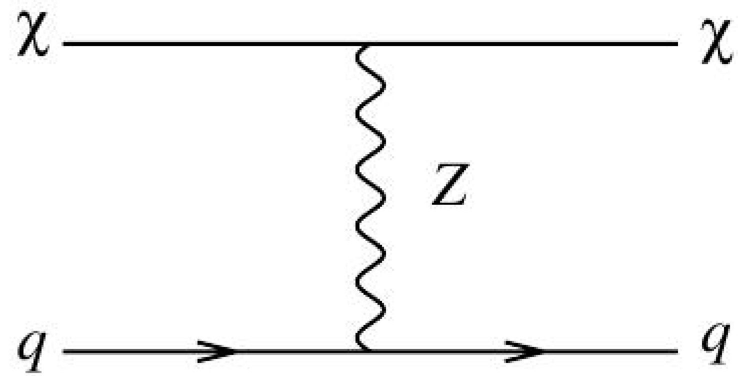
Scalar (SI)



scalar and spin dependent



scalar and spin dependent



spin dependent (SD)

scalar and spin dependent interaction of the lightest neutralino $\tilde{\chi}_1^o$ with matter

exchange of a sfermion in the s or t channel leads to both type of interactions

Dark Matter direct detection

WIMPs can scatter with nuclei through both SI and SD interactions

- experimental sensitivity to SI couplings benefit from coherent scattering

➜ cross sections and rates proportional to A^2

$$\sigma(q) = \sigma_o F^2(q)$$

$F(q)$ nuclear form factor, q momentum exchanged i.e. typically ➜ $q \simeq \text{MeV}\left(\frac{m_\chi}{\text{GeV}}\right) < MeV\left(\frac{160}{A^{1/3}}\right)$

$$\sigma_0 = \left[Z + (A - Z)\ (f_n/f_p)\right]^2 (\mu^2/\mu_p^2)\ \sigma_p = A^2\ (\mu^2/\mu_p^2)\ \sigma_p \quad \text{for} \quad f_n = f_p$$

f_n, f_p effective coupling to p and n and μ reduced mass $m\, m_\chi/(m+m_\chi)$

- cross section for SD scattering proportional to J (spin of the nucleus)

➜ cross sections and rates benefit from large target nuclei

$$\sigma(q) = 32\mu^2 G_F^2\ \frac{(J+1)}{J}\ \left[<S_p> a_p + <S_n> a_n\right]^2$$

$a_{p,n}$ axial coupling to p and n, $<S_{p,n}>$ expectation value of spin content of p,n in nucleus

SI cross sections are A^2 larger than SD

current experimental sensitivity to SD scattering below that of SI

but complementarity of different direct search to obtain s-dependence of σ

Dark Matter direct detection

one can estimate the event rate

DM density

$f(\vec{v}, t)$ **local DM density**

$$\frac{dR}{dE_{recoil}} = \frac{\sigma(q)\rho}{2 m_\chi \mu^2} \int_{v > v_\chi^{\min}} \frac{f(\vec{v}, t)}{v} d^3 v$$

for elastic scattering $v_\chi^{min} = \sqrt{m_{\text{nucl}} E_{\text{recoil}} / 2\mu^2}$

$\vec{v}$ **distribution depends on Halo model**

$\Rightarrow$ one need some assumptions on the Dark halo model

Dark Matter direct detection

taking for example a Maxwell distribution for the velocities in the galaxy halo

$$f(v) = \frac{4 v^2}{v_\chi^3 \sqrt{\pi}} e^{-v^2/v_\chi^2} \qquad \text{(isothermal model)}$$

assuming an experimental cut-off E_T for the measured recoil energy

the minimum recoil energy E_T is set by the energy threshold of the detector

$\Rightarrow$ typically in the range O(keV) - O(10 keV)

we obtain the total rate

(taking the limit $E_{max} \to \infty$)

$$\int_{E_T}^{\infty} \frac{dR}{d E_{recoil}} d(E_{recoil}) \propto \frac{\rho}{m_\chi} \exp\left(-\frac{E_T\, m_{nucleus}}{2 \mu^2 v_\chi^2} \right)$$

putting some typical numbers the event rate can be put into the form

$$R = 4.7\, \text{evts.kg}^{-1}.\text{day}^{-1} \frac{1}{A} \left(\frac{\rho}{0.3\ \text{GeV/cm}^3} \right) \left(\frac{v_\chi}{300\ \text{km/s}} \right) \left(\frac{100\ \text{GeV}}{m_\chi} \right) \left(\frac{\sigma}{1\ \text{pb}} \right)$$

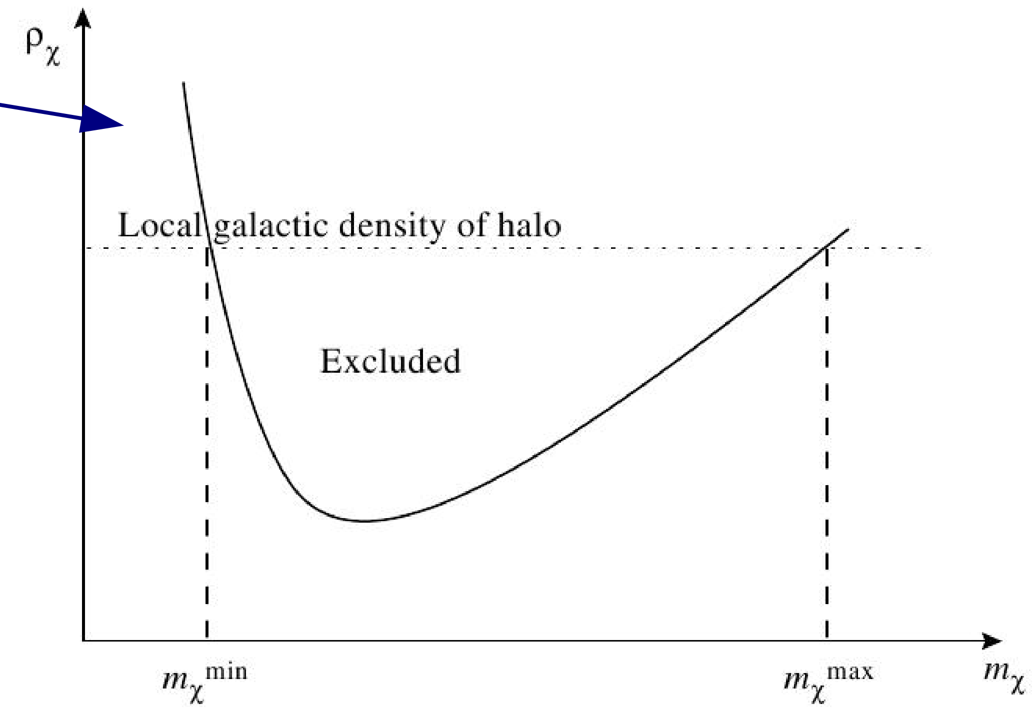
Dark Matter direct detection

if an experiment puts an upper limit on R, this translates into a upper limit on ρ of the order

$$m_\chi \ \exp\left[\frac{E_T}{2\, m_{nucleus}\, v_\chi^2} \left(1 + \frac{m_{nucleus}}{m_\chi}\right)^2 \right]$$

this behaves linearly with m_χ for large m_χ and grows exponentially for small m_χ

exclusion plots looks like this

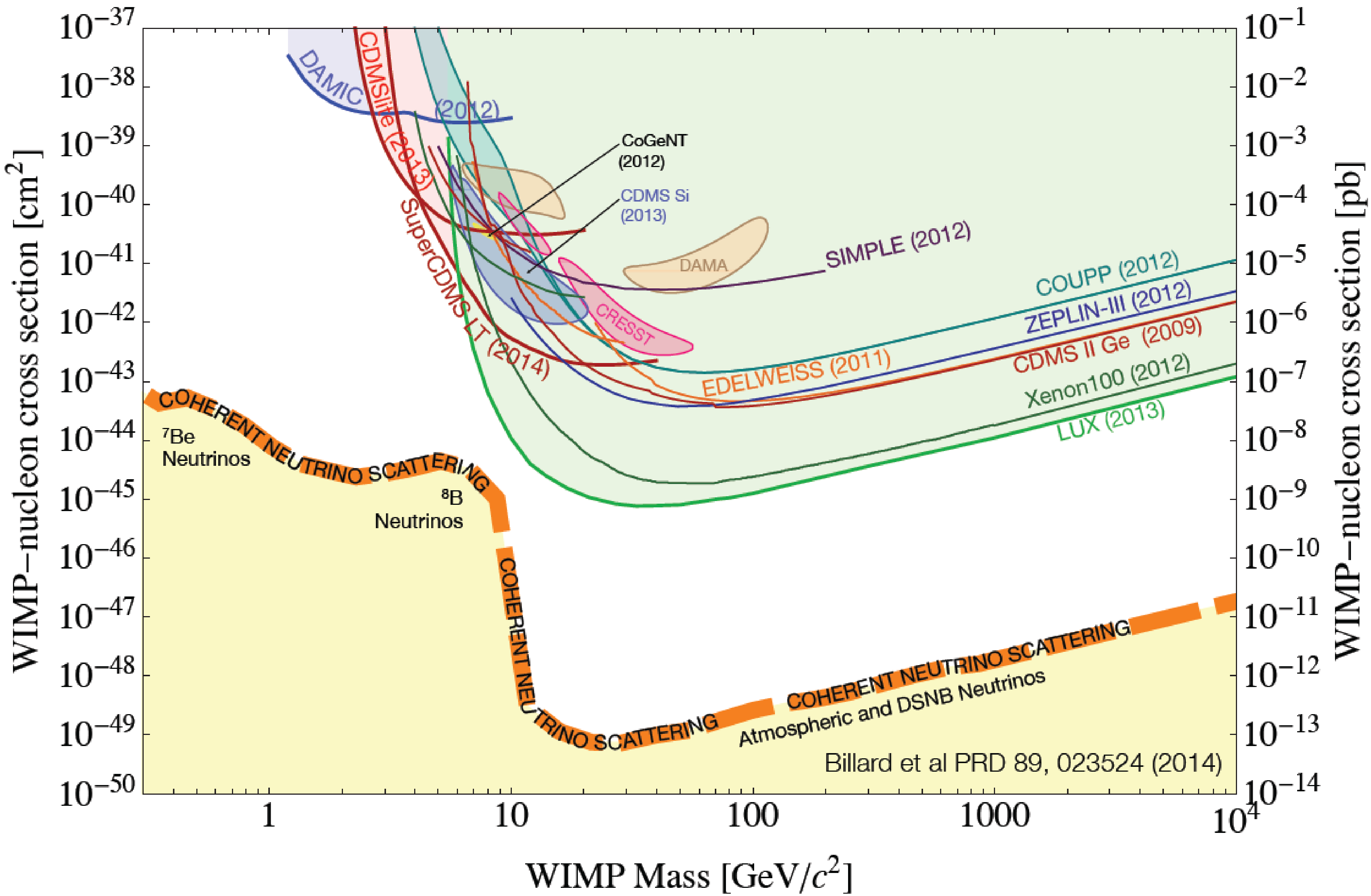


assuming a given value of ρ leads to exclusion of neutralino masses in the range $\left[m_\chi^{min}, m_\chi^{max} \right]$

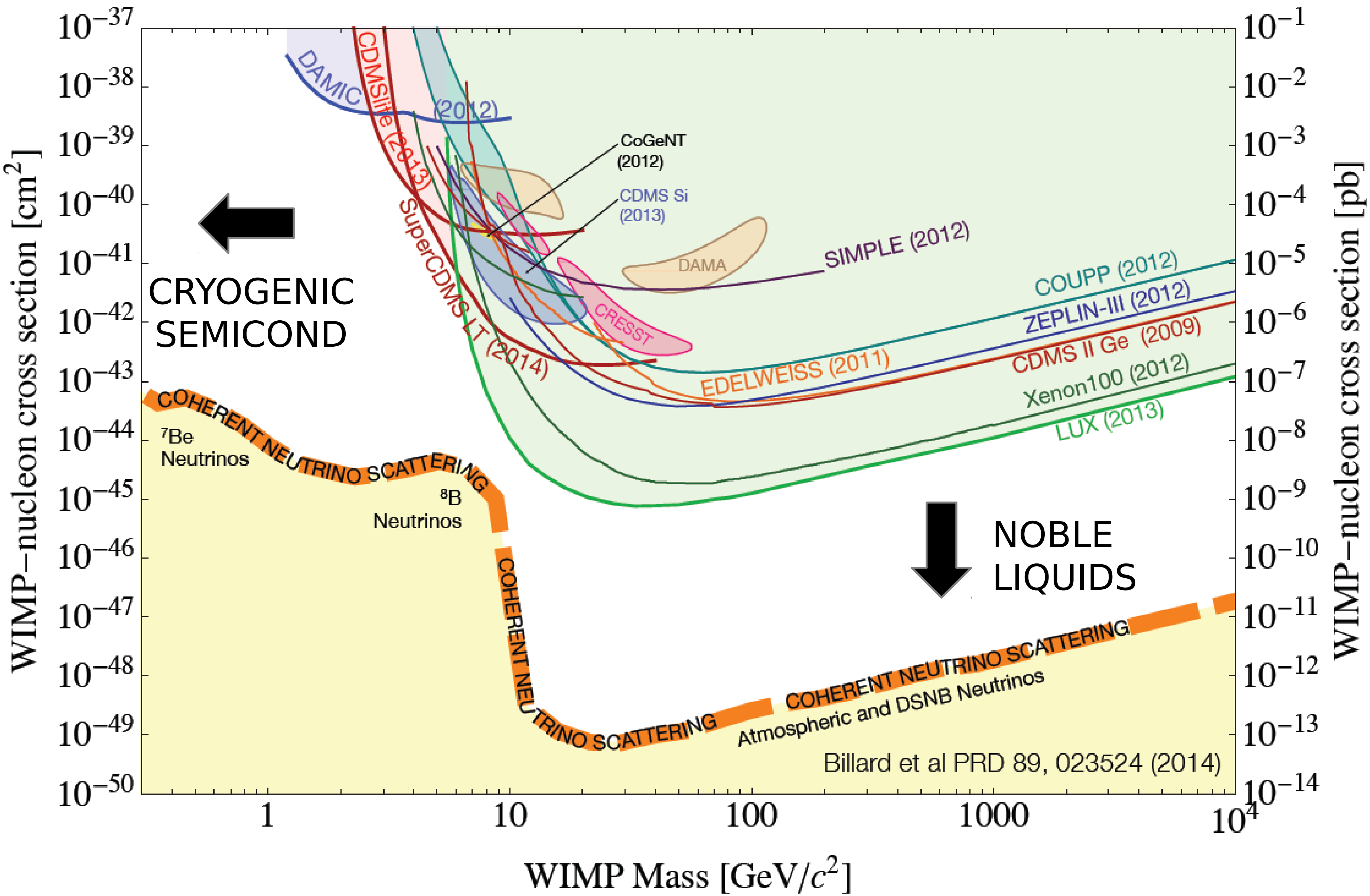
Dark Matter direct detection

many experiments

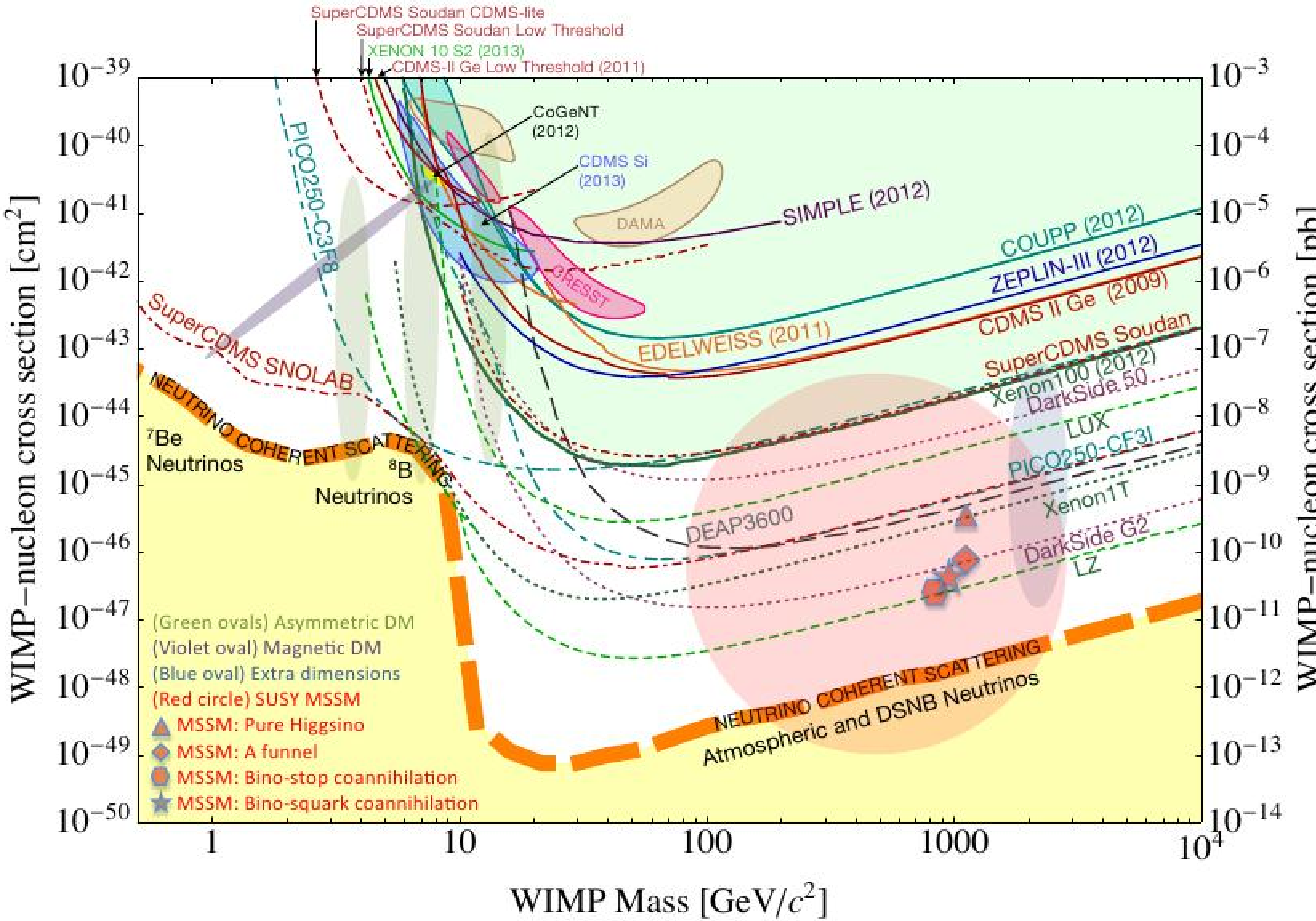
Dark Matter direct detection



Dark Matter direct detection

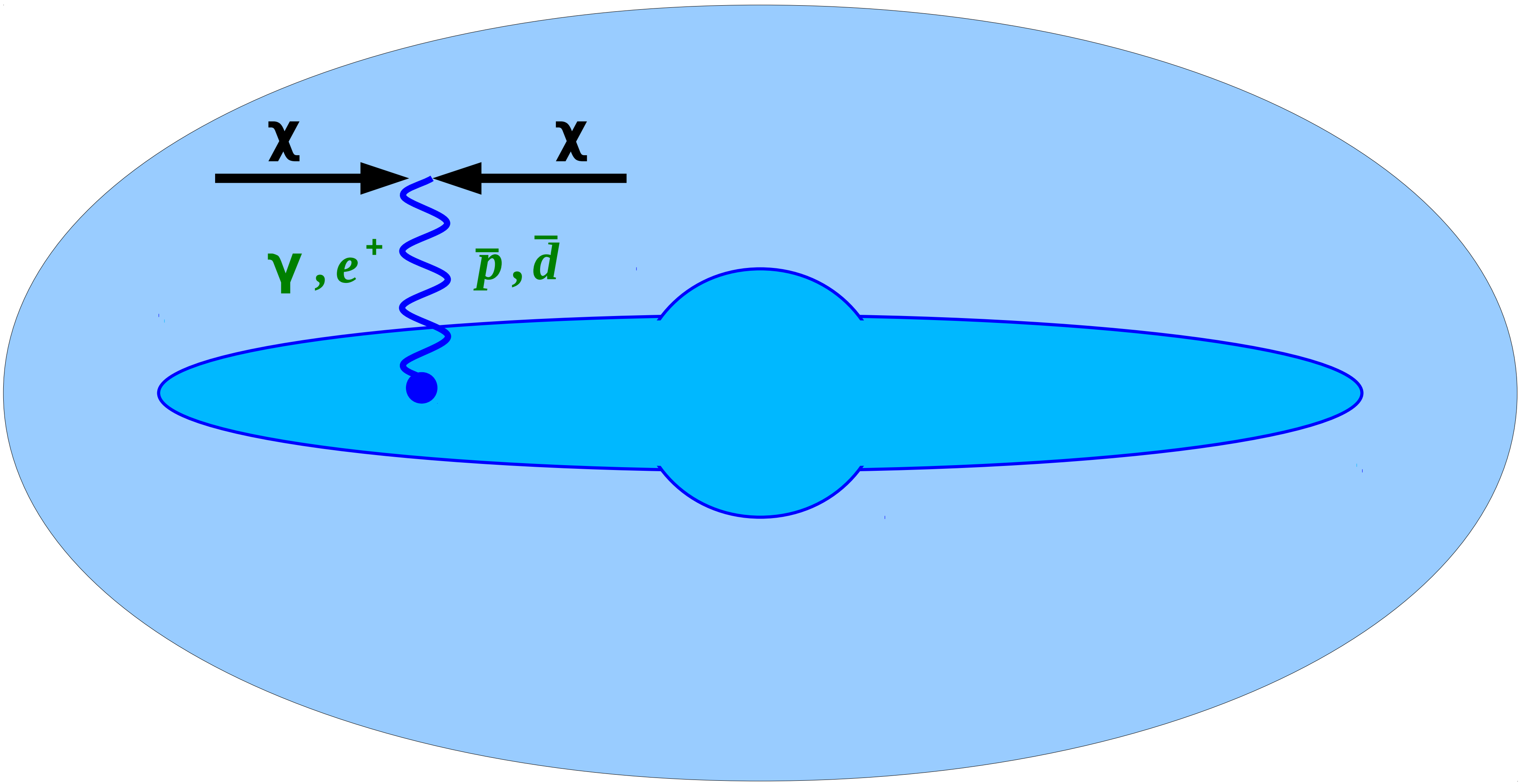


Dark Matter direct detection



Dark Matter indirect detection

from pair annihilation in the halo



$\chi\chi \rightarrow t\bar{t},\ b\bar{b},\ c\bar{c},\ \tau^+\tau^-,\ \ldots,\ W^+W^-,\ \gamma\gamma,\ \gamma Z,\ ZZ$

$\Rightarrow$ secondary particles as photons, positrons, neutrinos ...

Dark Matter indirect detection

in particular annihilation of DM in the halo can be characterized by :

- monoenergetic photons through the 1-loop processes $\chi\chi \to \gamma Z$

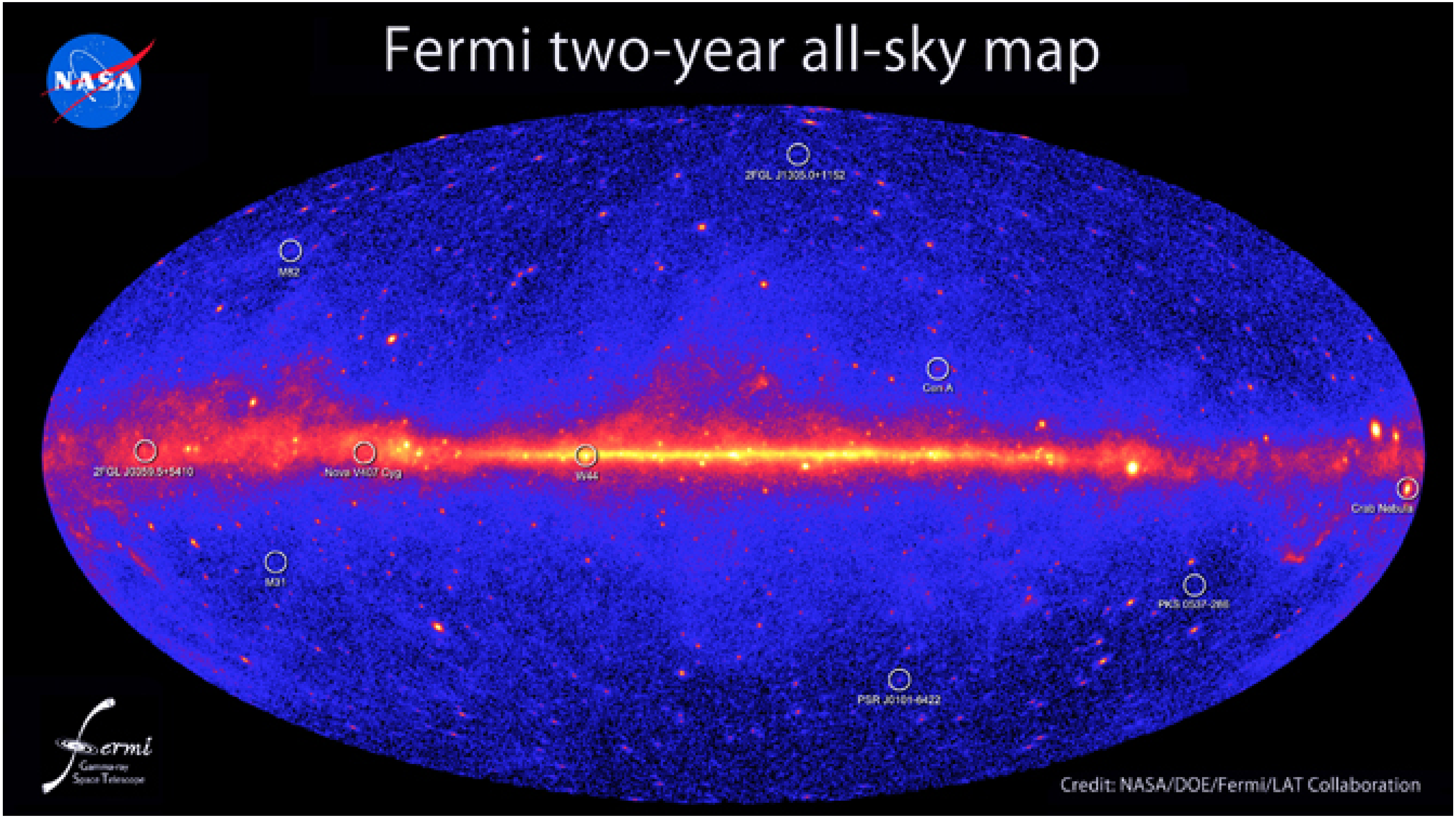
$$E_\gamma = M_{DM}\left[1-\left(\frac{M_Z}{2M_{DM}}\right)^2\right]$$

- continuous spectrum of photons through the decay of annihilation product mostly from the decay of π^o produced in hadronization

- nearly monoenergetic positrons (from direct annihilation)

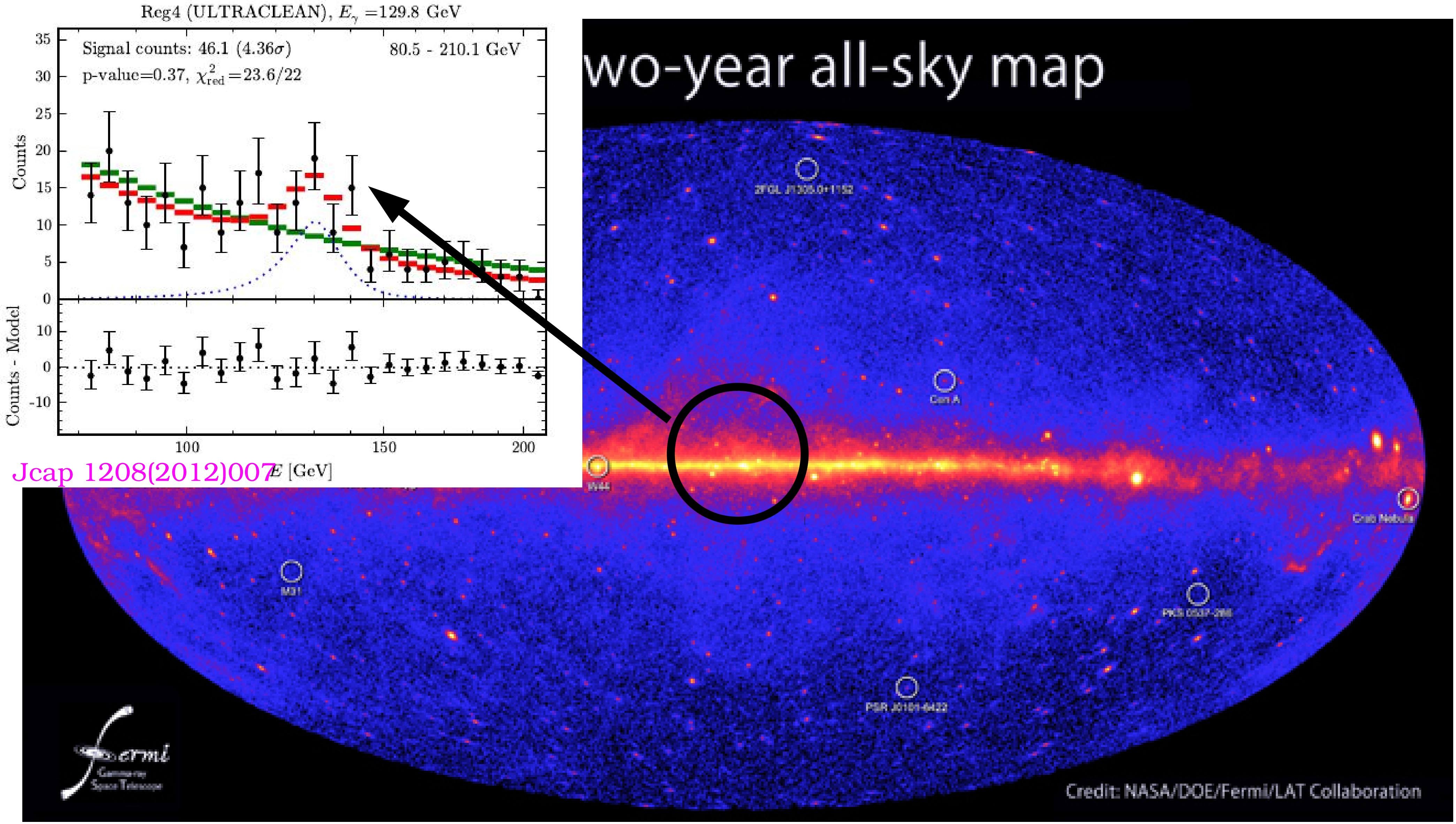
- 'soft' positrons (from π^+, τ^+, μ^+ decay)

Dark Matter indirect detection



Dark Matter indirect detection

Observation of a line in the galactic center ?



Jcap 1208(2012)007

Dark Matter indirect detection

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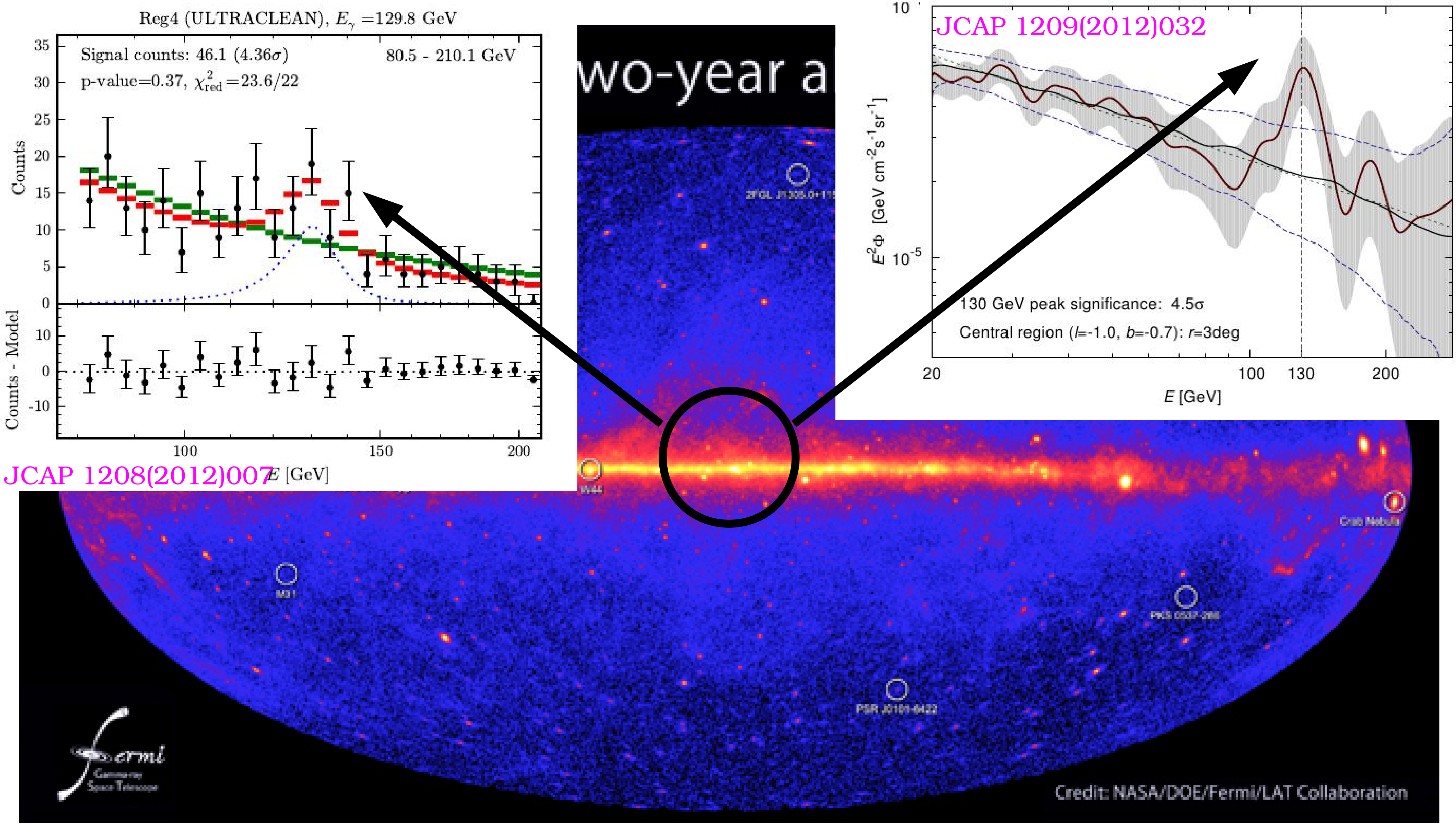

Dark Matter indirect detection

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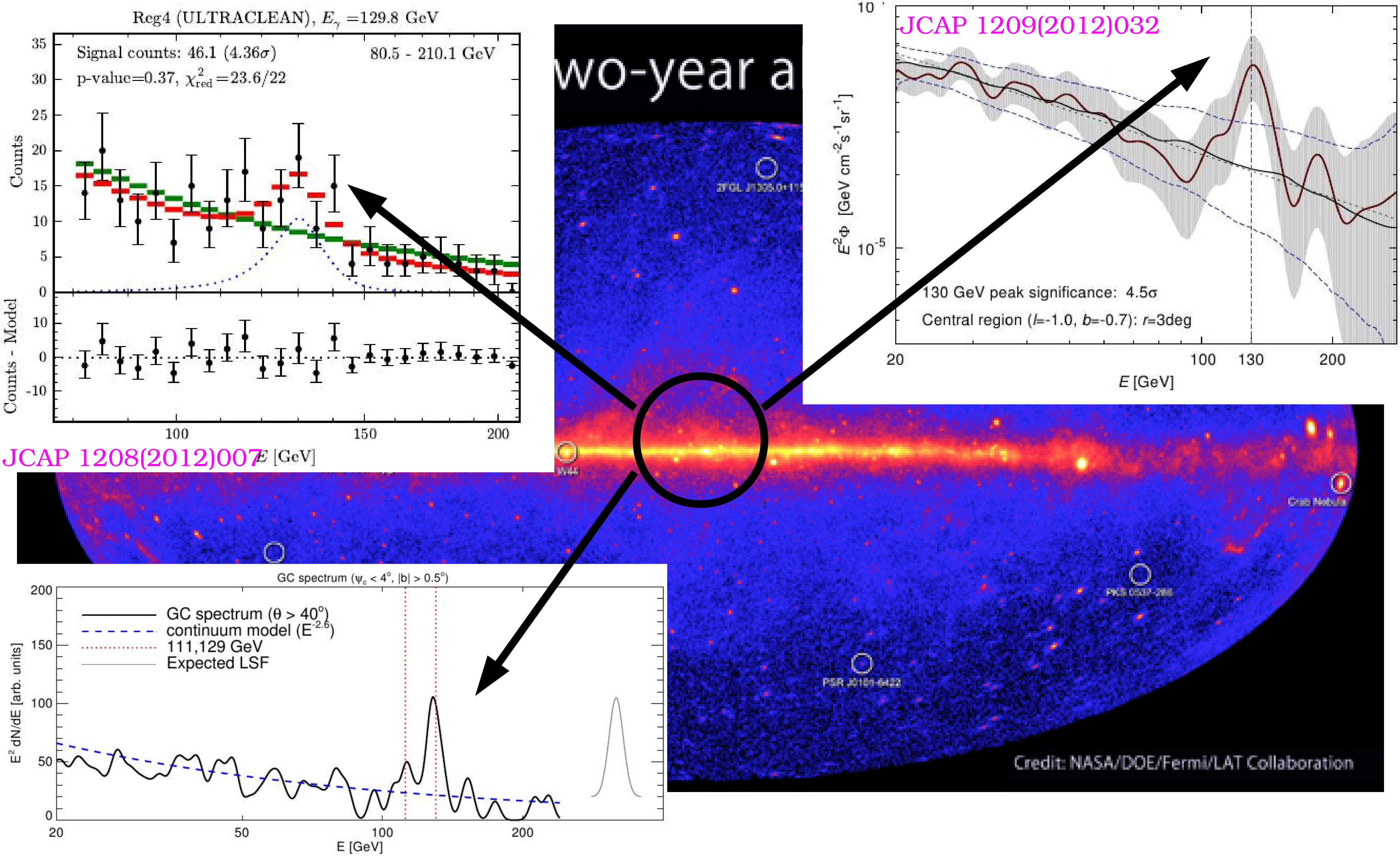
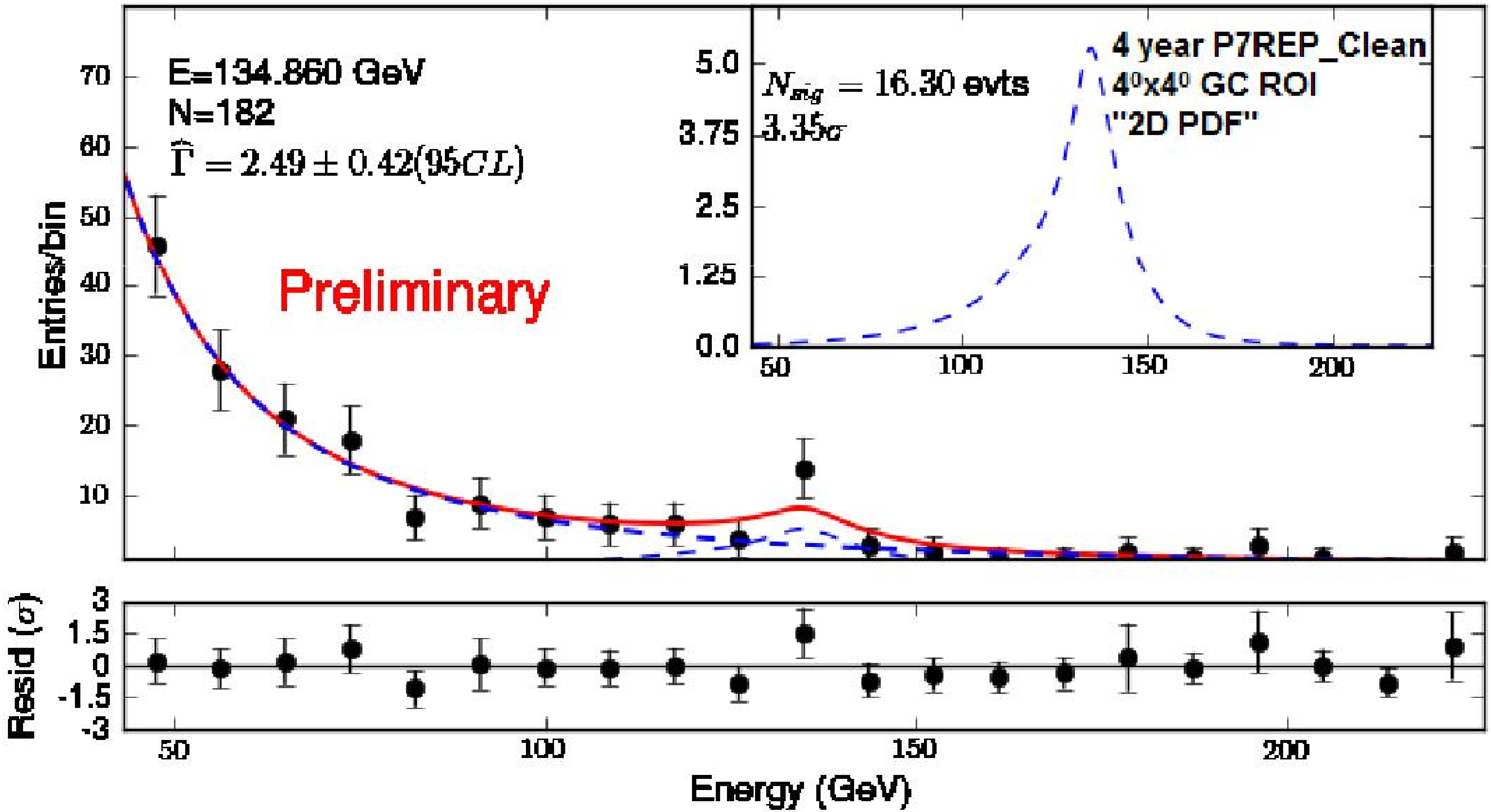


arXiv:1206.1616

Dark Matter indirect detection



FERMI-LAT team
line search with 3.7 year reprocessed data (last october)

→ **3.35 σ (local)**
<2 σ global significance

Dark Matter indirect detection

flux of secondary particle of type i

in a direction making an angle ψ with the direction of the galactic center

$$r^2 = s^2 + R_o^2 - 2\, s\, R_o \cos\psi$$

$R_o \sim 8$ kpc

solar distance to galactic center

spectrum of secondary particle of type i

$$\Phi_i(E,\psi) = \frac{<\sigma_{ann} v_\chi>}{4\pi m_\chi^2} \frac{dN_i}{dE} \int_{\text{line of sight}} \rho^2(r)\, ds$$

density profile of DM

there is thus a strong dependence on the density profile of dark matter $\rho(r)$ which is poorly known

Dark Matter indirect detection

this density profile of dark matter is usually parameterized as

$$\rho(r) = \frac{\rho_o}{\left(\frac{r}{R}\right)^{\gamma}\left[1+\left(\frac{r}{R}\right)^{\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}}$$

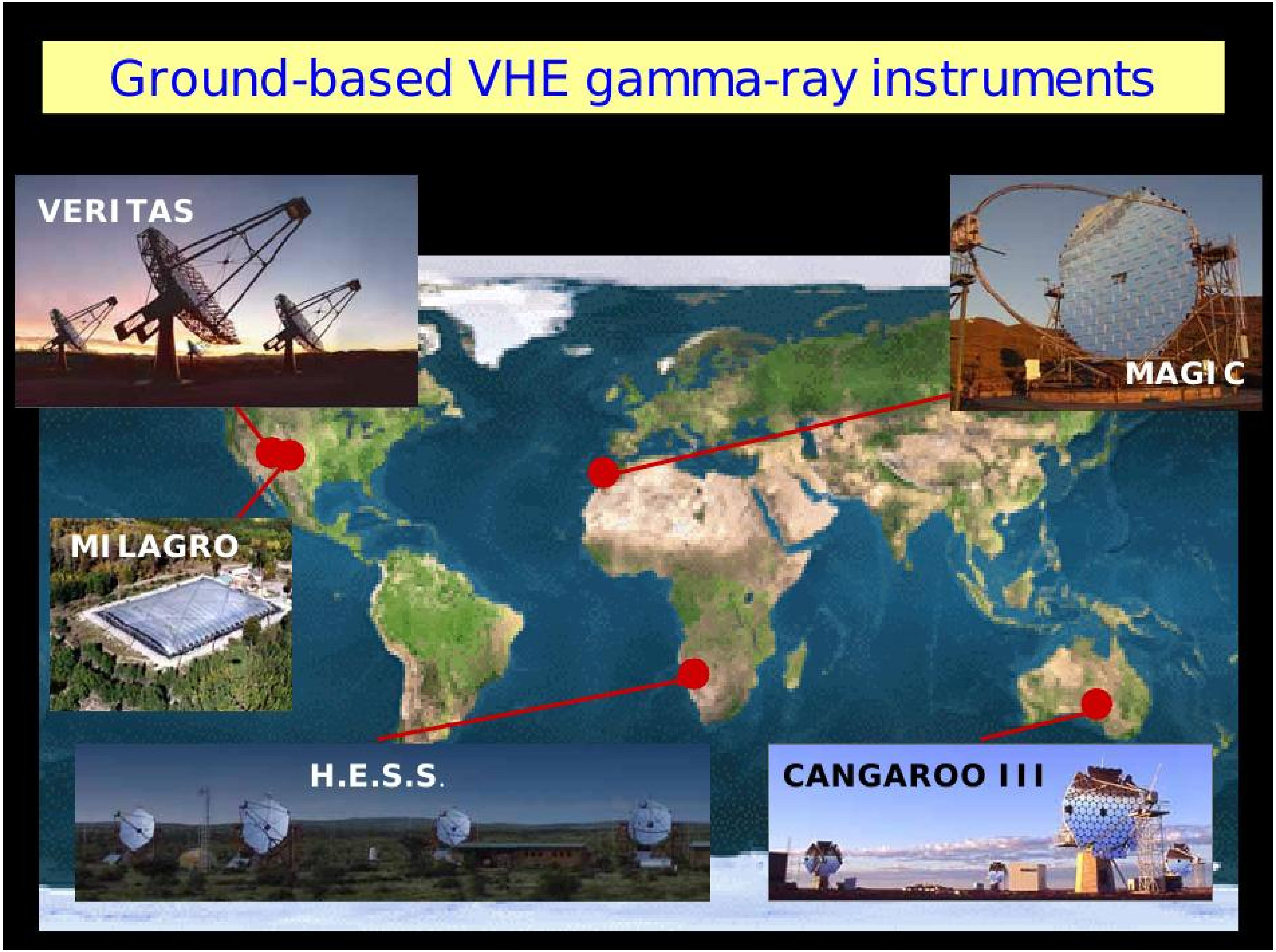
where R is a characteristic length and α, β and γ are parameters

Model	α	β	γ	R (kpc)	$\bar{J}(10^{-3})$
NFW	1.0	3.0	1.0	20	1.35×10^3
Moore	1.5	3.0	1.5	28	1.54×10^5
Isothermal	2.0	2.0	0	3.5	2.87×10^1

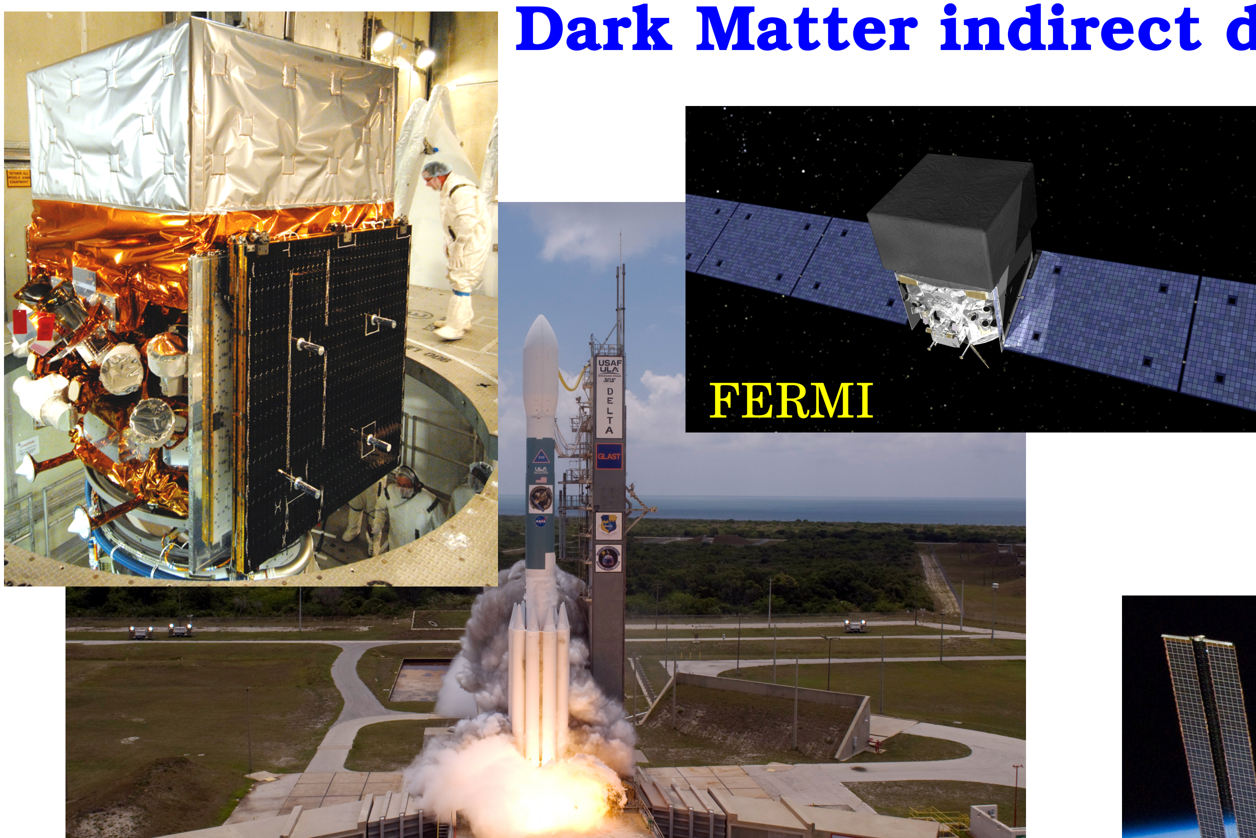
values from typical models based on N-body simualtions

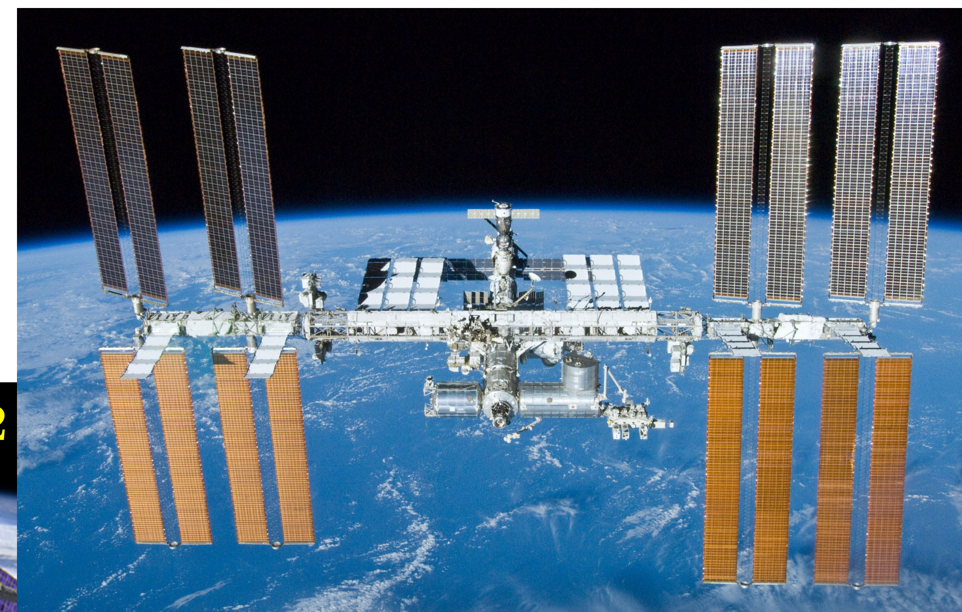
(NFW stands for Navarro Frenk White)

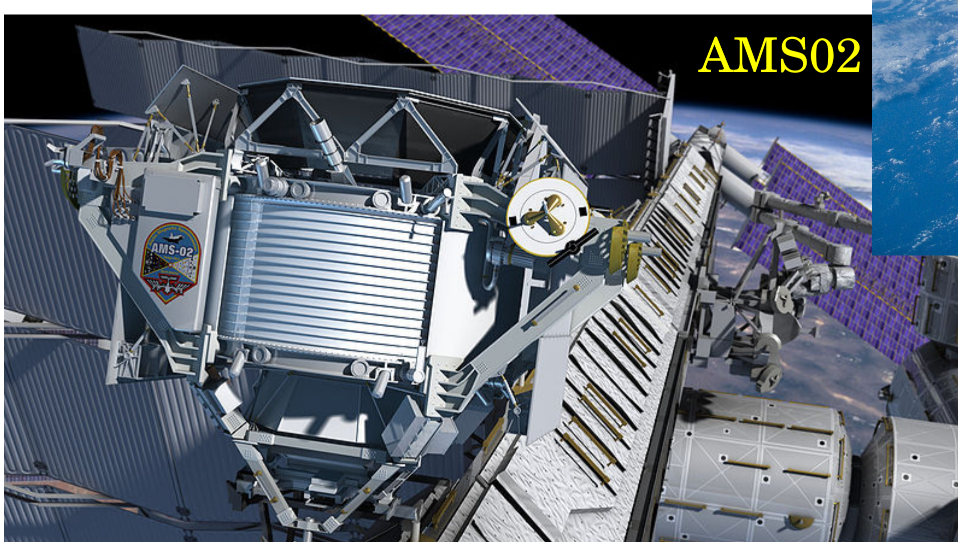
Dark Matter indirect detection



Dark Matter indirect detection

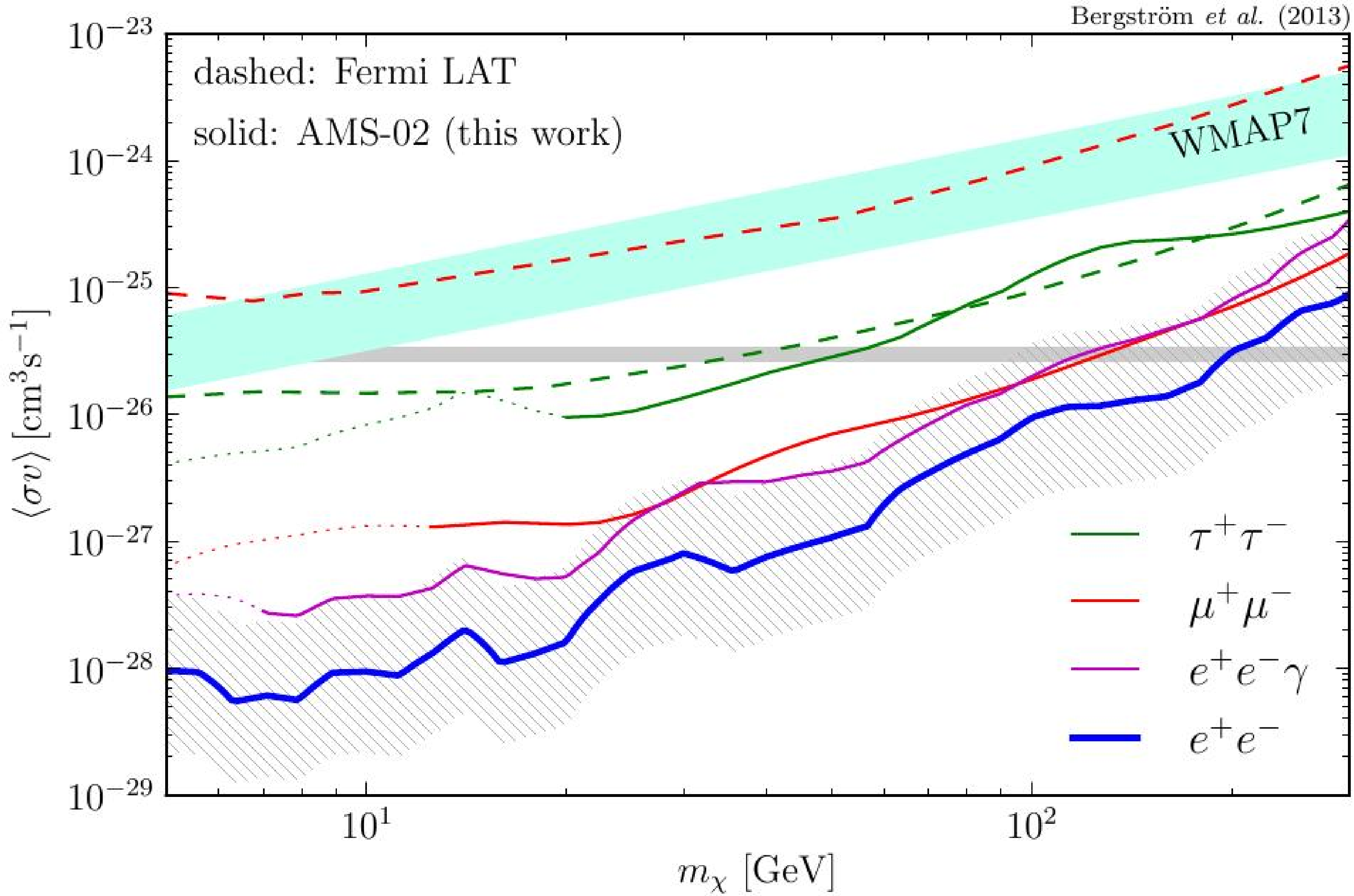






Dark Matter indirect detection

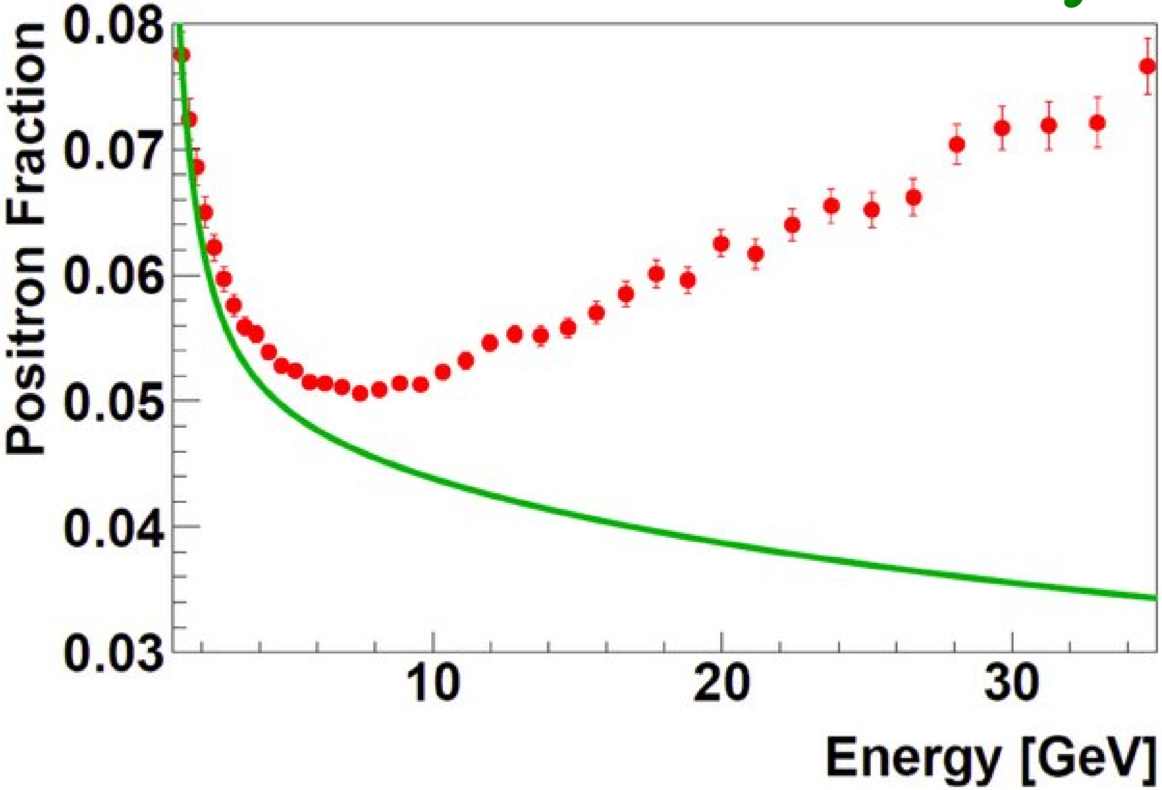
upper limit on DM annihilation Xsection into lepton from AMS2 results

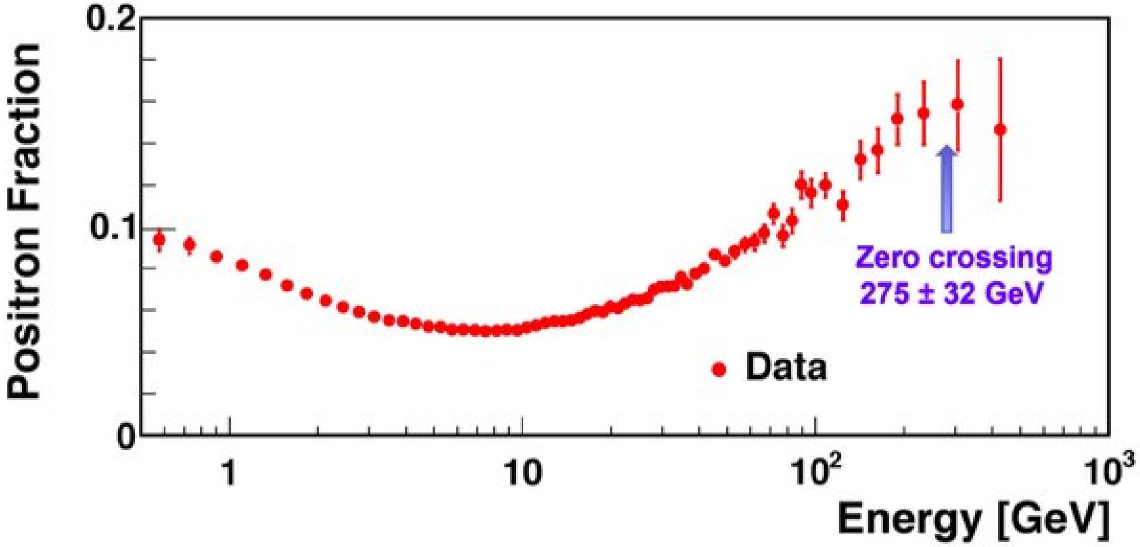


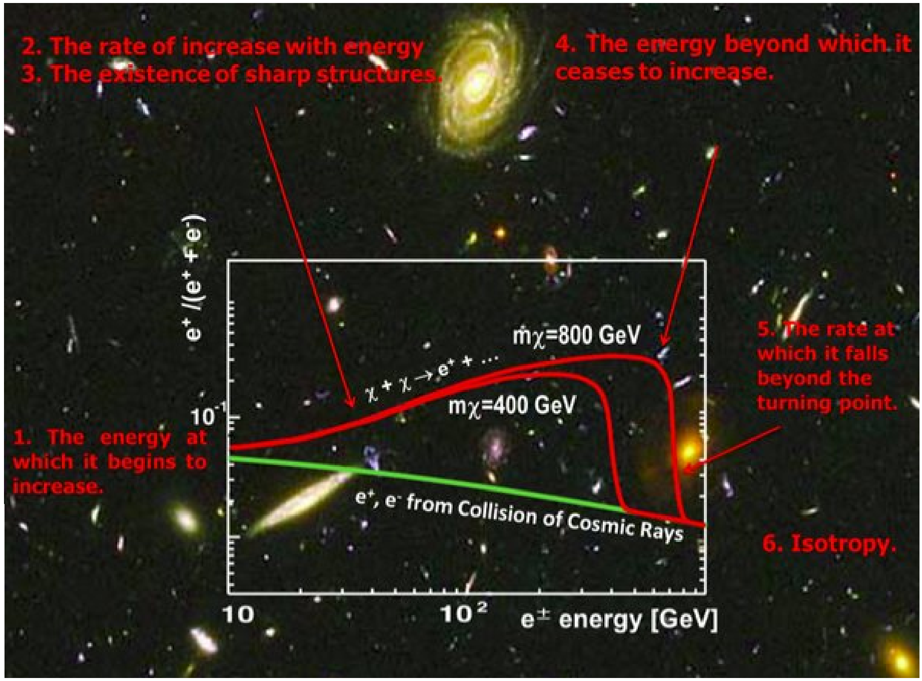
Bergstrom, Bringmann, Cholis, Hooper, Weniger, arXiv 1306.3983

Dark Matter indirect detection

more from AMS2 recently







Some global fits and constraints on Susy extension of SM

example : 'phenomenological MSSM' pMSSM

$\tan\beta$	$[5, 50]$	M_{L_3}	$[70, 500]$
M_{A^0}	$[100, 1000]$	M_{R_3}	$[70, 500]$
M_1	$[10, 70]$	A_τ	$[-1000, 1000]$
M_2	$[100, 1000]$	M_{L_1}	$[100, 500]$
μ	$[100, 1000]$	M_{R_1}	$[100, 500]$

'basics constraints'

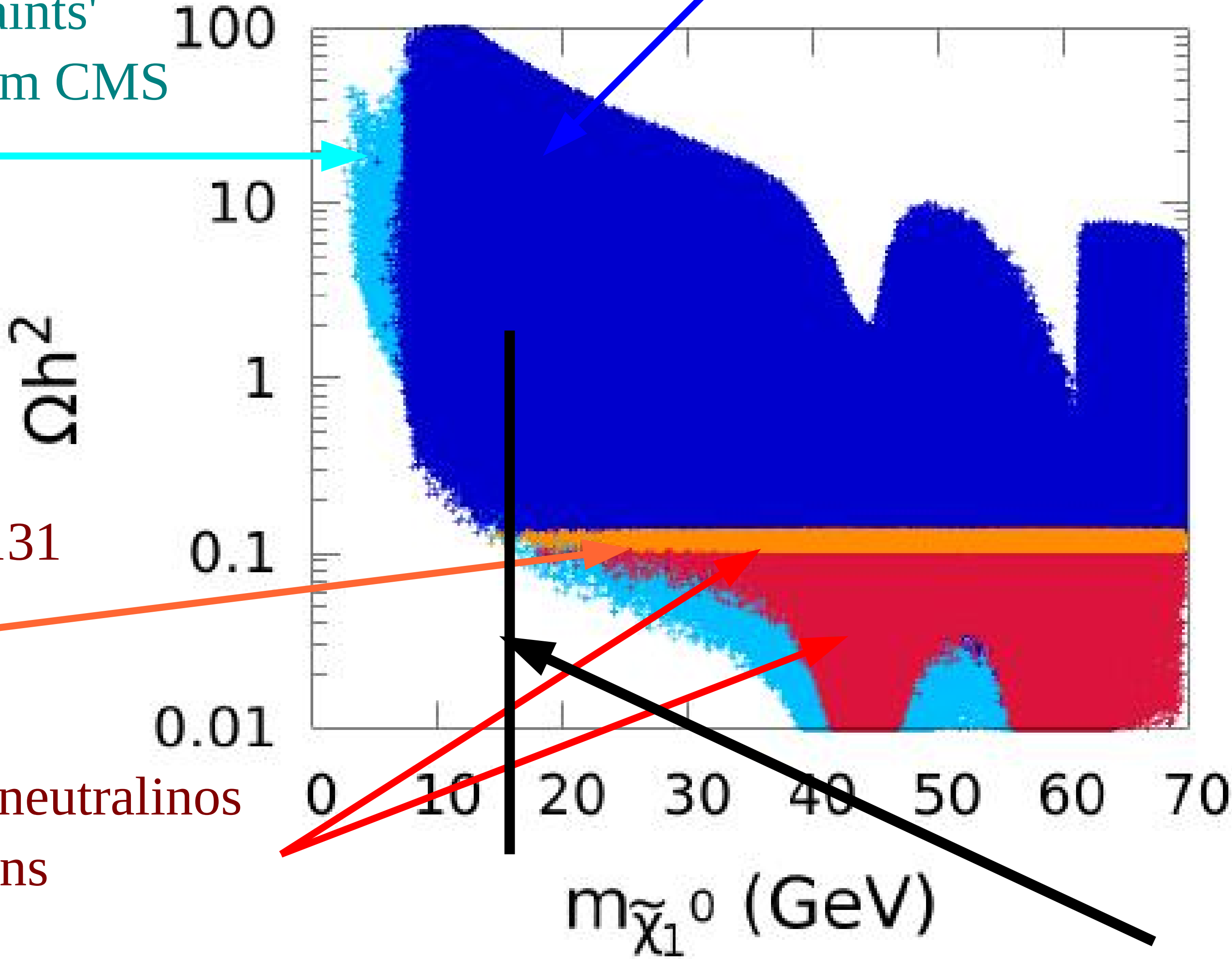
LEP limits	$m_{\tilde{\chi}_1^\pm} > 100$ GeV $m_{\tilde{\tau}_1} > 84 - 88$ GeV (depending on $m_{\tilde{\chi}_1^0}$)
invisible Z decay	$\Gamma_{Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0} < 3$ MeV
μ magnetic moment	$\Delta a_\mu < 4.5 \times 10^{-9}$
flavor constraints	$\mathrm{BR}(b \to s\gamma) \in [3.03, 4.07] \times 10^{-4}$ $\mathrm{BR}(B_s \to \mu^+\mu^-) \in [1.5, 4.3] \times 10^{-9}$
Higgs mass	$m_{h^0} \in [122.5, 128.5]$ GeV
$A^0, H^0 \to \tau^+\tau^-$	CMS results for $\mathcal{L} = 17$ fb^{-1}, $m_h^{\max}$ scenario
Higgs couplings	ATLAS, CMS and Tevatron global fit, see text
relic density	$\Omega h^2 < 0.131$ or $\Omega h^2 \in [0.107, 0.131]$
direct detection	XENON100 upper limit
indirect detection	Fermi-LAT bound on gamma rays from dSphs
$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ $pp \to \tilde{\ell}^+\tilde{\ell}^-$	Simplified Models Spectra approach, see text

Belanger, Drieu La Rochelle, Dumont, Godbole, Kraml, Kulkarni,arXiv1308.3735

Dark Matter : beyond CMSSM → pMSSM

compatible with Higgs signal strength
as derived in arXiv 1306.2941

fulfill 'basics constraints'
and $A, H \to \tau\tau$ from CMS
(cyan)



$0.107 < \Omega h^2 < 0.131$
(orange)

pass LHC limits on neutralinos
charginos and sleptons
red and orange

$m_{\chi_1^0} > 15$ **GeV**
from Ωh^2 **constraints**

grey points: pass all constraints including DM
but excluded by LHC

Belanger, Drieu La Rochelle, Dumont, Godbole, Kraml, Kulkarni,arXiv1308.3735

Some global fits and constraints on Susy extension of SM

MSSM-15 parameters and priors			
Flat priors		Log priors	
M_1 [TeV]	(-5, 5)	$\text{sgn}(M_1) \log \|M_1\|/\text{GeV}$	$(-3.7, 3.7)$
M_2 [TeV]	(0.1, 5)	$\log M_2/\text{GeV}$	$(2, 3.7)$
M_3 [TeV]	(-5, 5)	$\text{sgn}(M_3) \log \|M_3\|/\text{GeV}$	$(-3.7, 3.7)$
m_L [TeV]	(0.1,10)	$\log m_L/\text{GeV}$	$(2, 4)$
m_{L_3} [TeV]	(0.1,10)	$\log m_{L_3}/\text{GeV}$	$(2, 4)$
m_{E_3} [TeV]	(0.1,10)	$\log m_{E_3}/\text{GeV}$	$(2, 4)$
m_Q [TeV]	(0.1,10)	$\log m_Q/\text{GeV}$	$(2, 4)$
m_{Q_3} [TeV]	(0.1,10)	$\log m_{Q_3}/\text{GeV}$	$(2, 4)$
m_{U_3} [TeV]	(0.1,10)	$\log m_{U_3}/\text{GeV}$	$(2, 4)$
m_{D_3} [TeV]	(0.1,10)	$\log m_{D_3}/\text{GeV}$	$(2, 4)$
A_t [TeV]	(-10, 10)	$\text{sgn}(A_t) \log \|A_t\|/\text{GeV}$	$(-4, 4)$
A_0 [TeV]	(-10,10)	$\text{sgn}(A_0) \log \|A_0\|/\text{GeV}$	$(-4, 4)$
μ [TeV]	(-5,5)	$\text{sgn}(\mu) \log \|\mu\|/\text{GeV}$	$(-3.7, 3.7)$
m_A [TeV]	(0.01, 5)	$\log m_A/\text{GeV}$	$(1, 3.7)$
$\tan\beta$	$(2, 62)$	$\tan\beta$	$(2, 62)$
M_t [GeV]	173.2 ± 0.87 [17] (Gaussian prior)		

Strege, Bertone, Besjes, Caron, Ruiz de Austri, Strubig, Trotta, arXiv1405.0622

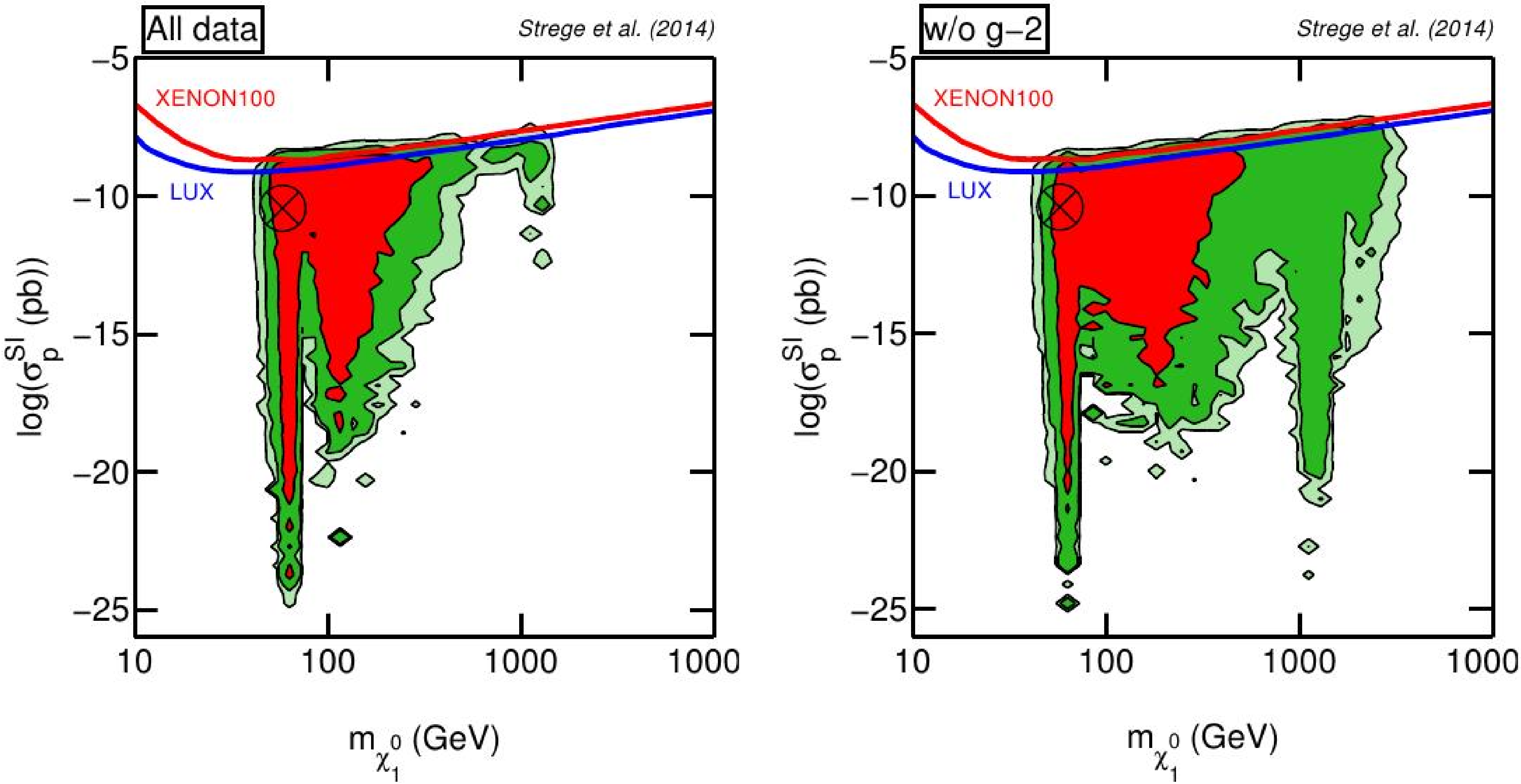
Some global fits and constraints on Susy extension of SM

Observable	Mean value	Standard deviation		Ref.
	μ	σ (exper.)	τ (theor.)	
M_W [GeV]	80.385	0.015	0.01	[48]
$\sin^2\theta_{\rm eff}$	0.23153	0.00016	0.00010	[48]
Γ_Z [GeV]	2.4952	0.0023	0.001	[48]
σ^0_{had} [nb]	41.540	0.037	-	[48]
R^0_l	20.767	0.025	-	[48]
R^0_b	0.21629	0.00066	-	[48]
R^0_c	0.1721	0.003	-	[48]
$^{\#}A^{0,l}_{FB}$	0.0171	0.001	-	[48]
$^{\#}A^{0,b}_{FB}$	0.0992	0.0016	-	[48]
$^{\#}A^{0,c}_{FB}$	0.0707	0.0035	-	[48]
$^{\#}A_l(SLD)$	0.1513	0.0021	-	[48]
$^{\#}A_b$	0.923	0.02	-	[48]
$^{\#}A_c$	0.670	0.027	-	[48]
$\delta a^{\rm SUSY}_\mu \times 10^{10}$	28.7	8.0	2.0	[63]
$BR(\bar{B} \to X_s\gamma) \times 10^4$	3.55	0.26	0.30	[49]
$R_{\Delta M_{B_s}}$	1.04	0.11	-	[50]
$\frac{BR(B_u\to\tau\nu)}{BR(B_u\to\tau\nu)_{SM}}$	1.63	0.54	-	[49]
$\Delta_{0-} \times 10^2$	3.1	2.3	1.75	[55]
$^{\#}\frac{BR(B\to D\tau\nu)}{BR(B\to De\nu)} \times 10^2$	41.6	12.8	3.5	[64]
$^{\#}R_{l23}$	0.999	0.007	-	[65]
$A_{FB}(B \to K^*\mu^+\mu^-)$	-0.18	0.063	0.05	[51]
$BR(D_s \to \tau\nu) \times 10^2$	5.44	0.22	0.1	[49]
$^{\#}BR(D_s \to \mu\nu) \times 10^3$	5.54	0.24	0.2	[49]
$^{\#}BR(D \to \mu\nu) \times 10^4$	3.82	0.33	0.2	[49]
$BR(\overline{B}_s \to \mu^+\mu^-) \times 10^9$	3.2	1.5	0.38	[52]
$\Omega_{\tilde{\chi}^0_1}h^2$	0.1186	0.0031	0.012	[56]
m_h [GeV]	125.66	0.41	2.0	[66, 67]
$^{\dagger}\mu_{\gamma\gamma}$	0.78	0.27	15%	[69]
$^{\dagger}\mu_{W^+W^-}$	0.76	0.21	15%	[70]
$^{\dagger}\mu_{ZZ}$	0.91	0.27	15%	[71]
$^{\dagger}\mu_{b\bar{b}}$	1.3	0.65	15%	[73]
$^{\dagger}\mu_{\tau^+\tau^-}$	1.1	0.4	15%	[72]

	Limit (95% C.L.)	τ (theor.)	Ref.
Sparticle masses	LEP, Tevatron. As in Table 4 of Ref. [18].		[18]
†0-lepton SUSY search	ATLAS, $\sqrt{s} = 7$ TeV, 4.7 fb^{-1}		[74]
†3-lepton SUSY search	ATLAS, $\sqrt{s} = 7$ TeV, 4.7 fb^{-1}		[75]
$m_\chi - \sigma^{\rm SI}_{\tilde{\chi}^0_1-p}$	XENON100 2012 limits (224.6 × 34 kg days)		[59]
$m_\chi - \sigma^{\rm SD}_{\tilde{\chi}^0_1-p}$	XENON100 2012 limits (224.6 × 34 kg days)		[60]

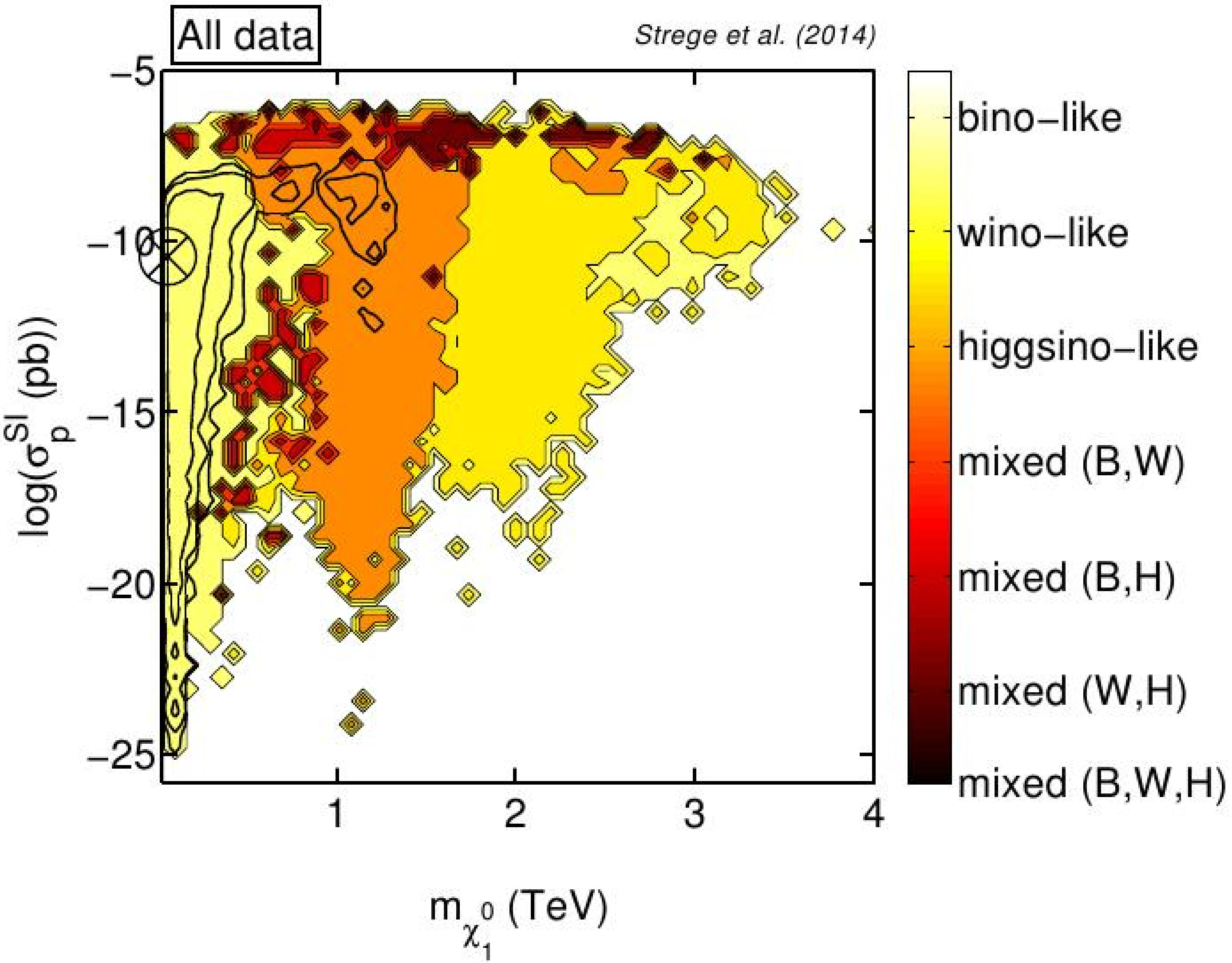
Strege, Bertone, Besjes, Caron, Ruiz de Austri, Strubig, Trotta, arXiv1405.0622

Some global fits and constraints on Susy extension of SM



no LHC SUSY searches included

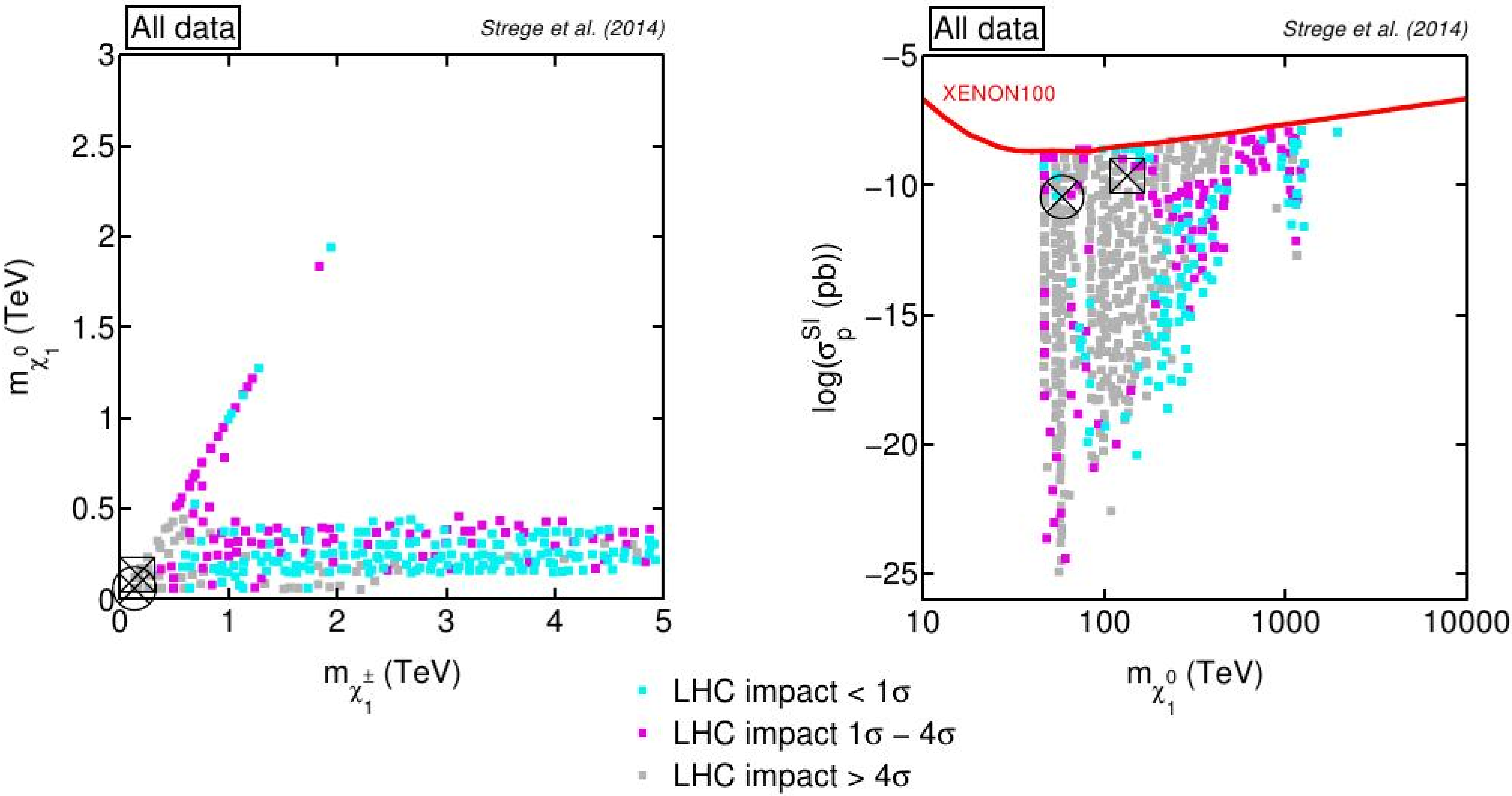
Some global fits and constraints on Susy extension of SM



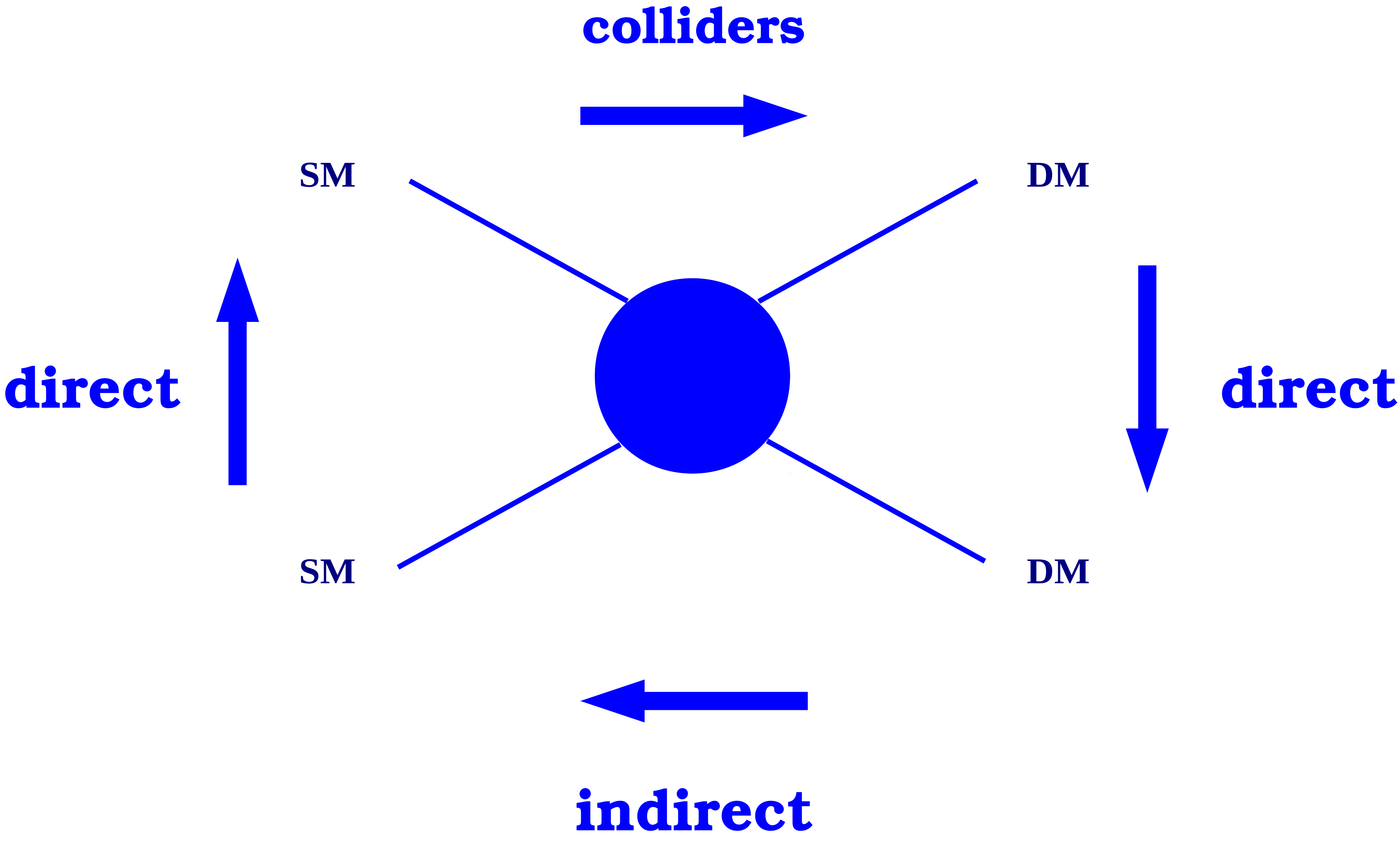
no LHC SUSY searches included

Some global fits and constraints on Susy extension of SM

LHC SUSY searches included

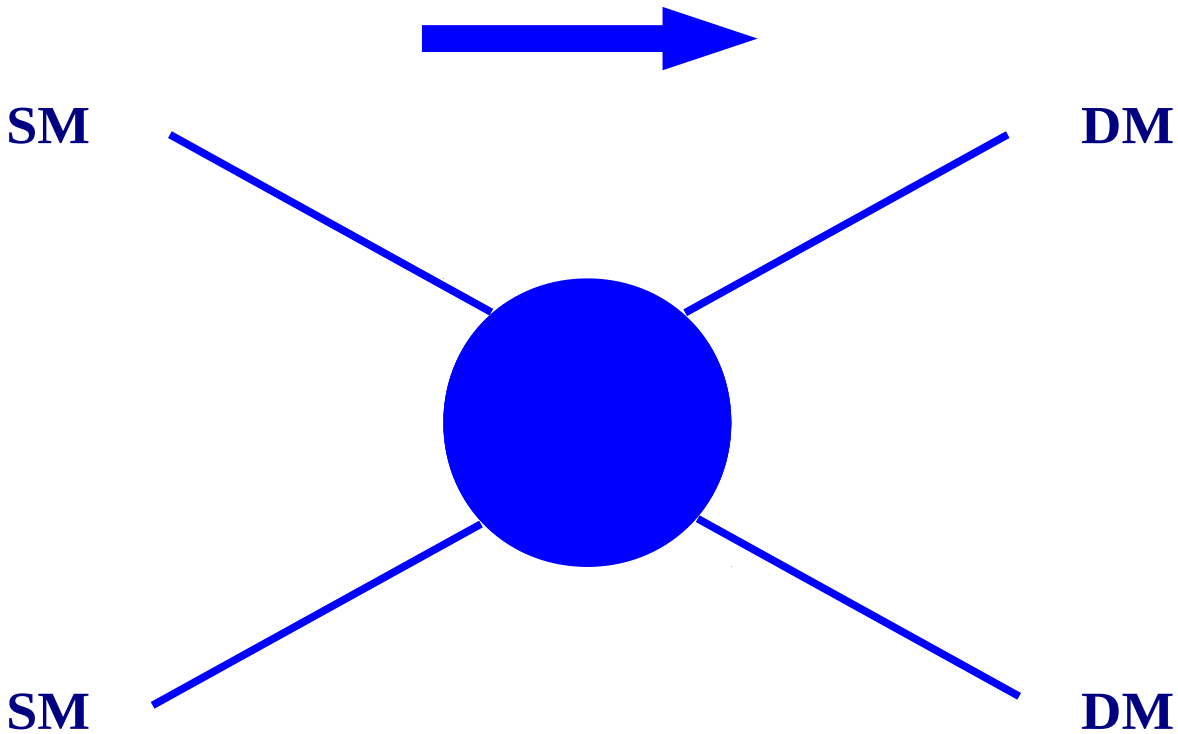


Dark Matter searches at LHC



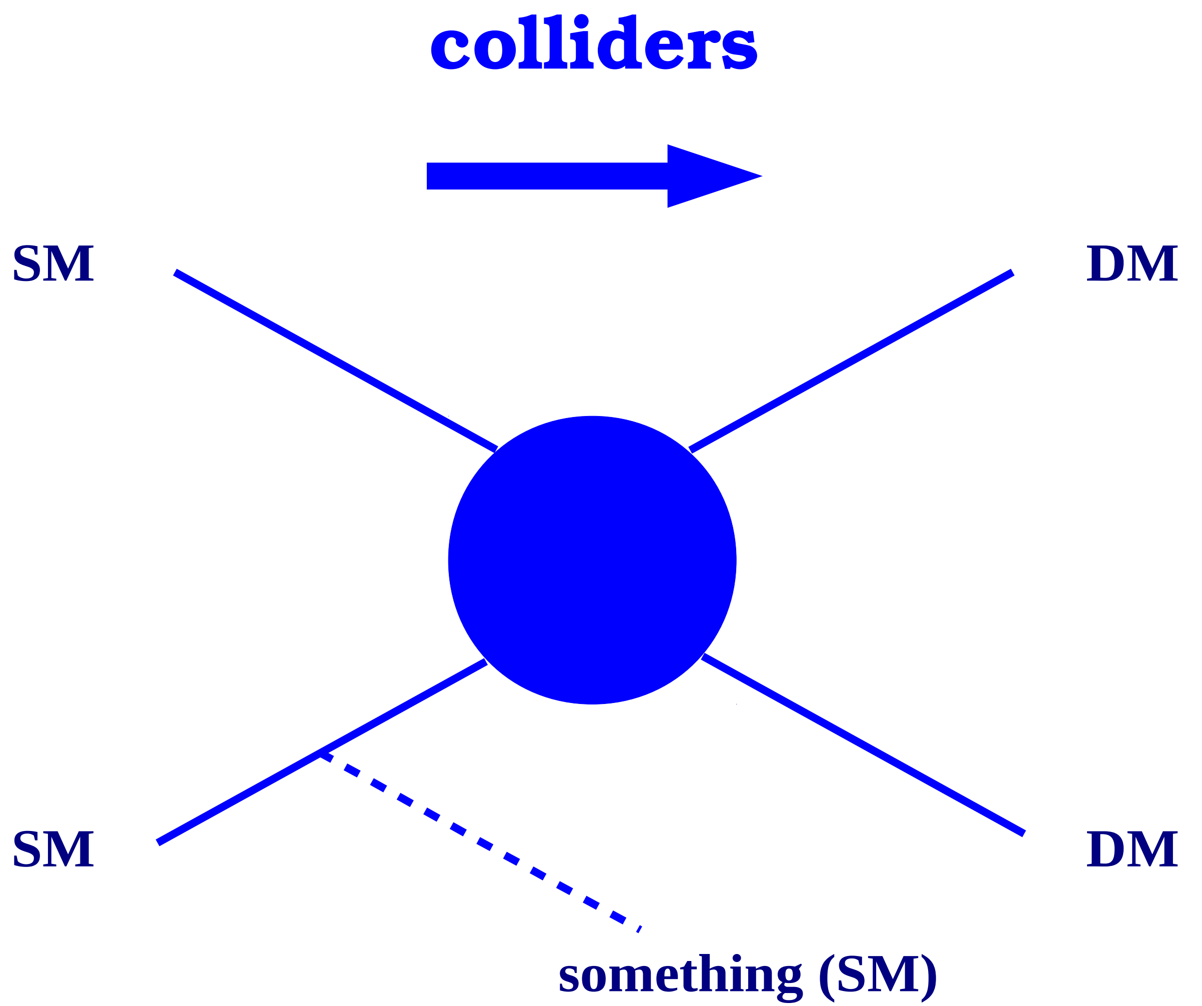
Dark Matter searches at LHC

colliders



nothing to see that way

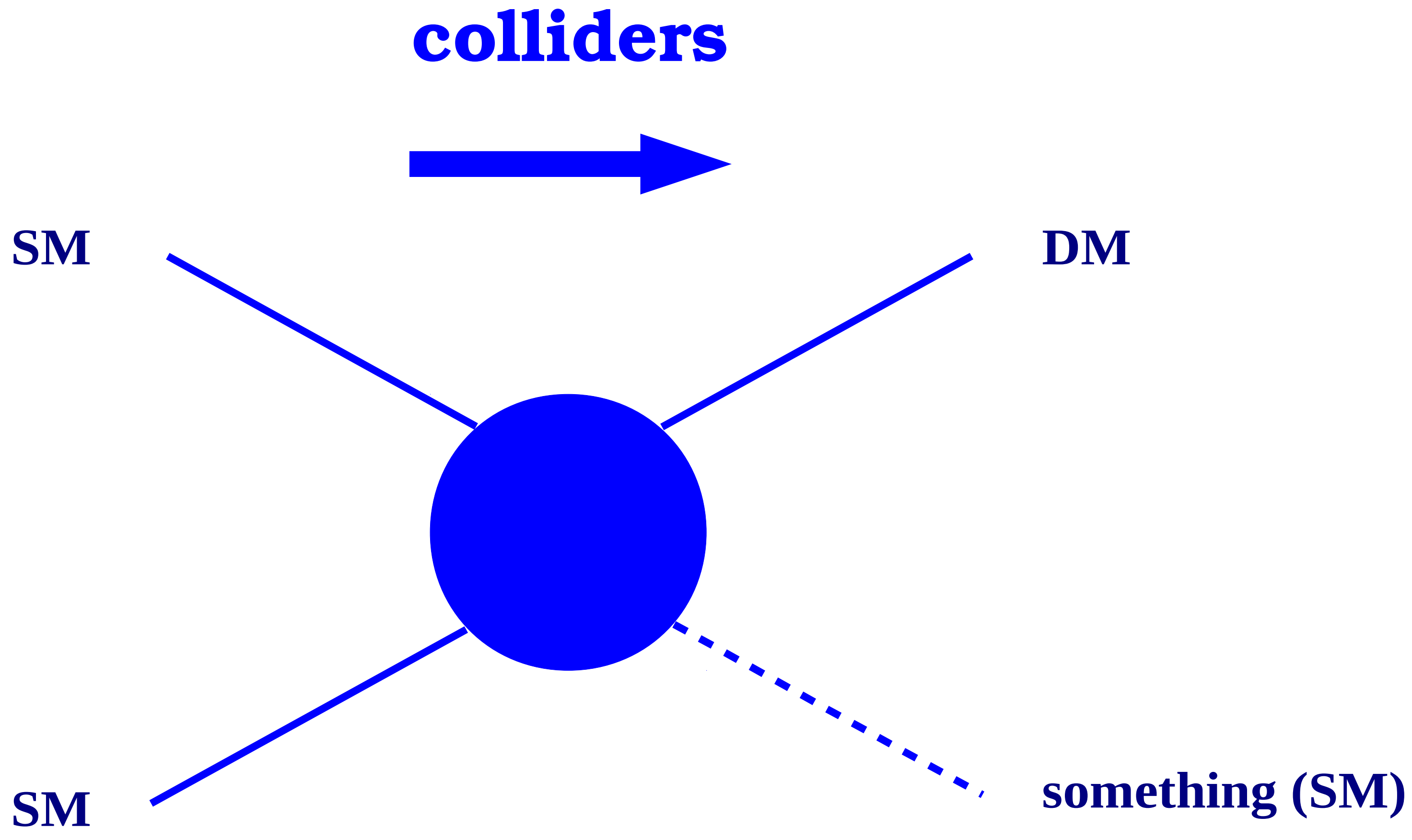
Dark Matter searches at LHC



mono something searches

something = jet , γ , Z , W

Dark Matter searches at LHC

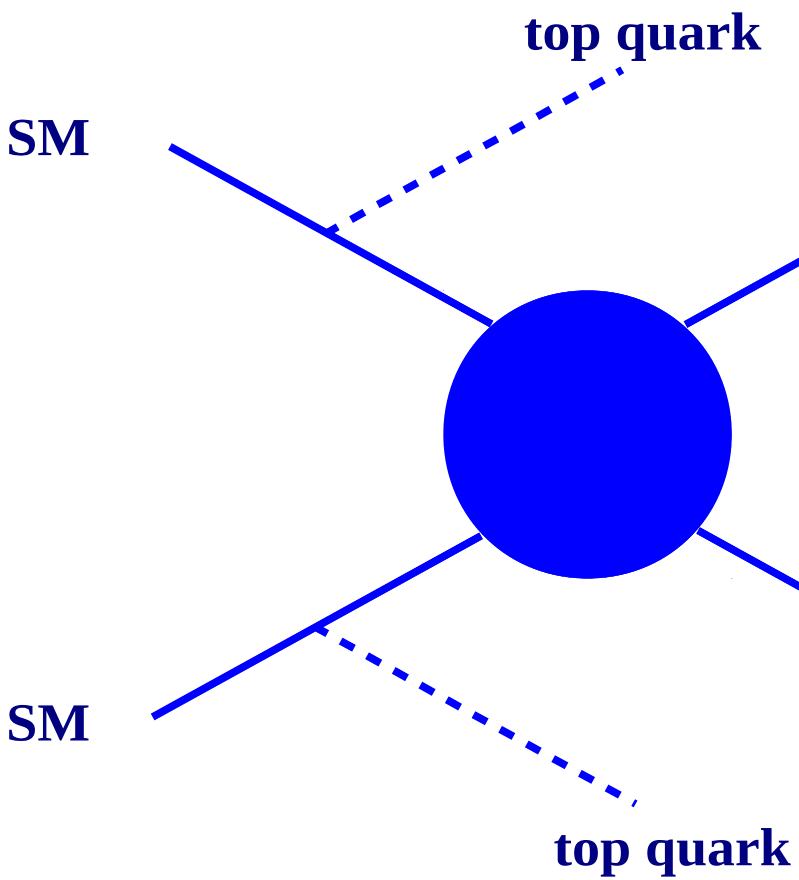


mono something searches

something = top quark (via FCNC diagrams)

Dark Matter searches at LHC

and more than mono something

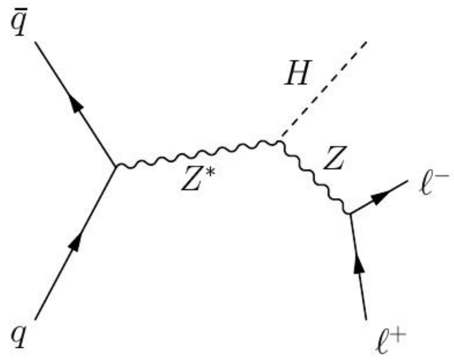


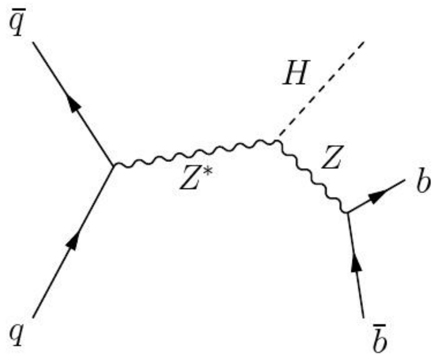
Dark Matter searches at LHC

invisible Higgs boson decay

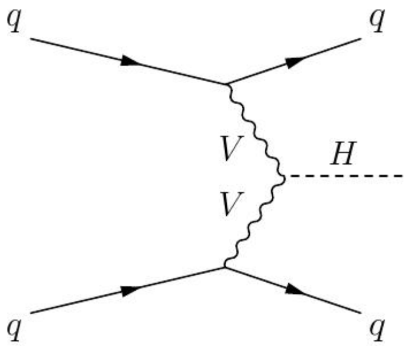
Higgs boson being produced in association and decaying invisibly

- HZ with $H \rightarrow$ invisible (DM ?) and $Z \rightarrow l\,l$ or $Z \rightarrow b\,\bar{b}$





- VBF H + 2 jets with $H \rightarrow$ invisible (DM ?)



Dark Matter searches at LHC

monophoton → ATLAS: PRL 110 (2013) 011802 (7 TeV), CMS: CMS-PAS-EXO-12-047 (8TeV)

monojet → ATLAS: JHEP 1304 (2013) 075 (7 TeV), ATLAS-Conf-2012-147 (8TeV)
CMS: CMS-PAS-EXO-12-048 (8TeV)

mono W → ATLAS: PRL 112 (2014) 041802 (8 TeV had. decay), ATLAS-Conf-2014-017 (lept.)
CMS: CMS-PAS-EXO-13-004 (8TeV)

mono Z → ATLAS: PRL 112 (2014) 041802 (8 TeV had. decay), arXiv:1404.0051 (lept.)
CMS: CMS-PAS-EXO-13-004

mono top → CMS: CMS-PAS-B2G-12-022

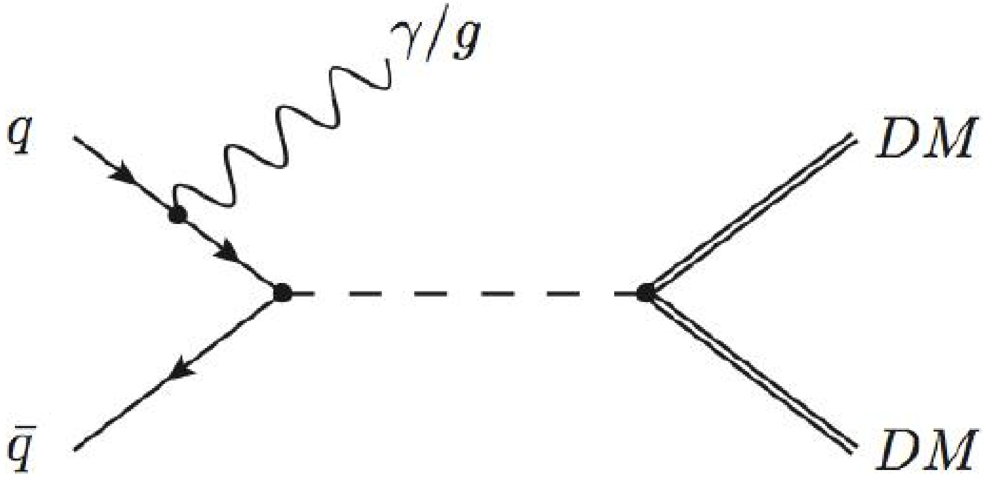
di top → CMS: CMS-PAS-B2G-13-004

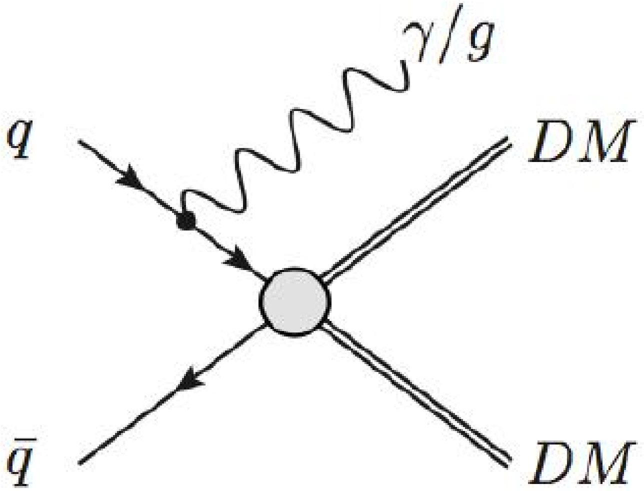
Higgs → ATLAS ATLAS-conf-2014-10, arXiv:1402.3244
CMS: CMS-PAS-HIG-13-028, CMS-PAS-HIG-13-013, CMS-PAS-HIG-13-018
arXiv:1404.1344

See A. De Roeck's lecture for a more complete survey

Dark Matter searches at LHC

effective approach very often used





at energies much smaller than the heavy mediator mass M it can be integrated out resulting non renormalizable operators for DM interactions with partons

lowest-dimensional effective operator has dimension 6
for example for scalar mediator of mass M and couplings g_χ and g_q

$$O_S = \frac{1}{\Lambda^2} (\bar{\chi}\chi)(\bar{q}q) \qquad \text{with} \quad \frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2}$$

Dark Matter searches at LHC

effective operators

assuming WIMP is SM singlet and a light Majorana particle interacting through higher dimensional operators

$$L^{\text{dim }6}_{\text{int},qq} = G_\chi \left[\bar{\chi} \Gamma^\chi \chi \right] \times \left[\bar{q} \Gamma^q q \right] \quad \text{and} \quad L^{\text{dim }7}_{\text{int},GG} = G_\chi \left[\bar{\chi} \Gamma^\chi \chi \right] \times \left(GG \text{ or } G\tilde{G} \right)$$

where G is the gluon field strength and $\tilde{G}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} G_{\rho\sigma} / 2$

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	–
M8	GG	$i\alpha_s/8M_*^3$	γ_5	–
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	–
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	–

assume only one M operator dominating at a time

Goodman, Ibe, Rajamaran, Shepherd, Tait, Yu, PLB 695 (2011) 185

Dark Matter searches at LHC
effective operators

operator names with D, C, R apply to WIMPS that are respectively

- Dirac fermions
- complex scalars
- real scalars

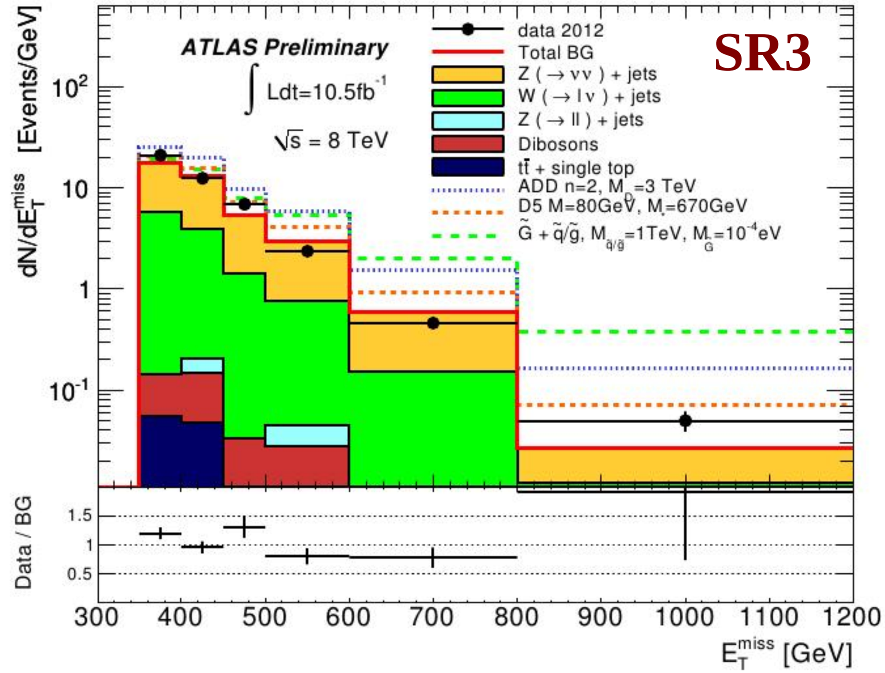
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

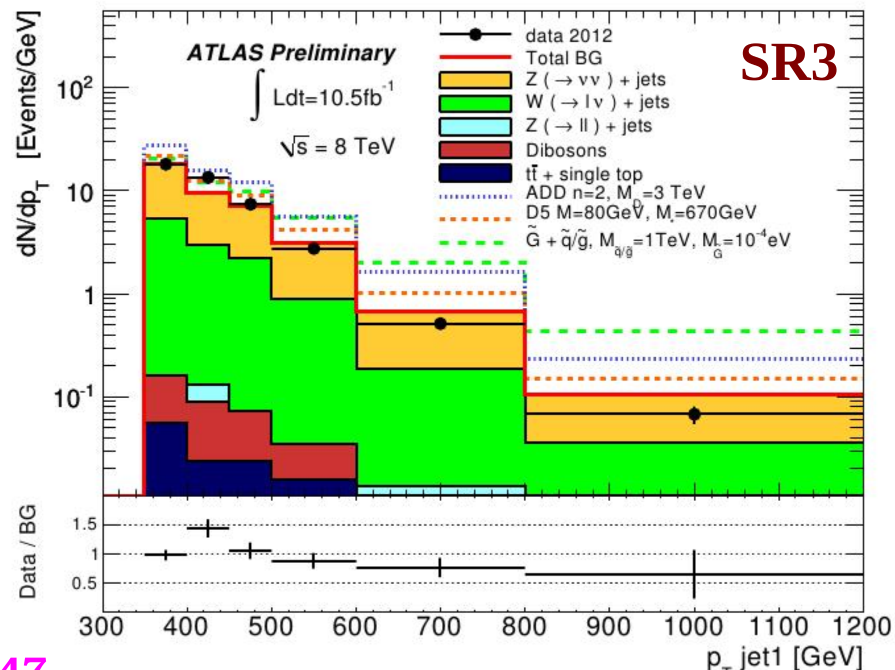
Goodman, Ibe, Rajamaran, Shepherd, Tait, Yu, PRD 82 (2010) 116010

monojet

Selection criteria				
Primary vertex				
$E_T^{miss} > 120$ GeV				
Jet cleanup requirements				
Leading jet with $p_T > 120$ GeV and $\|\eta\| < 2.0$				
At most two jets with $p_T > 30$ GeV and $\|\eta\| < 4.5$				
$\Delta\phi(\text{jet}, E_T^{miss}) > 0.5$ (second-leading jet)				
Lepton vetoes				
signal region	SR1	SR2	SR3	SR4
minimum leading jet p_T (GeV)	120	220	350	500
minimum E_T^{miss} (GeV)	120	220	350	500
Events in data (10.5 fb^{-1})	350932	25515	2353	268

4 signal regions (SR) defined



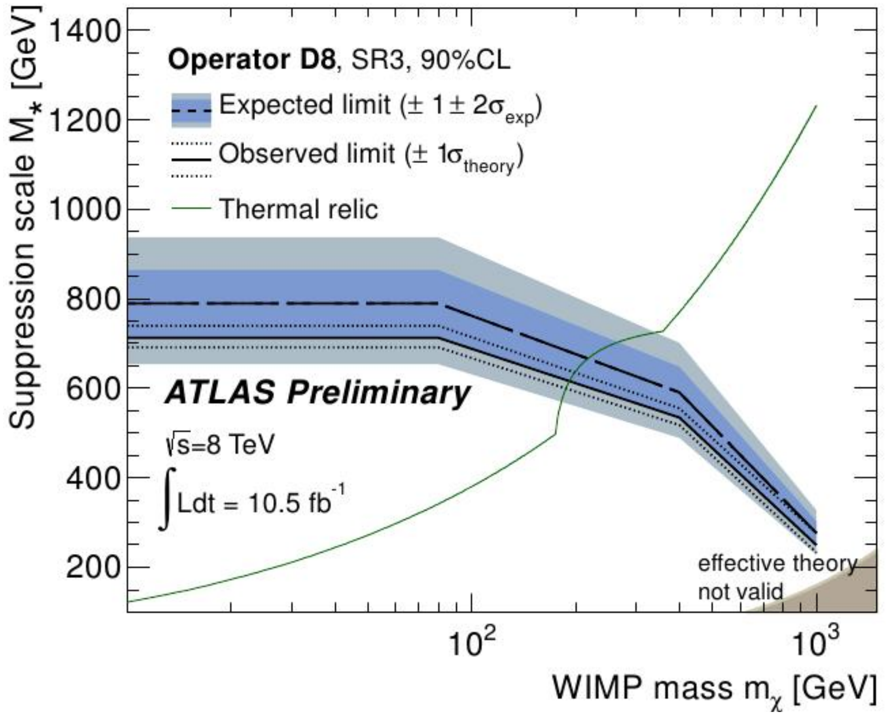


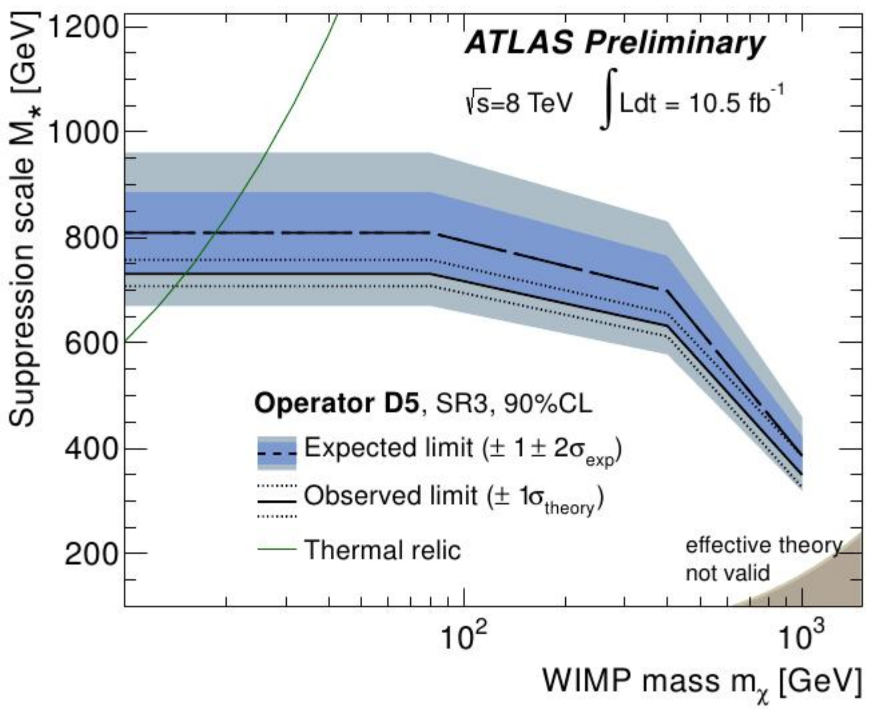
Atlas-conf-2012-147

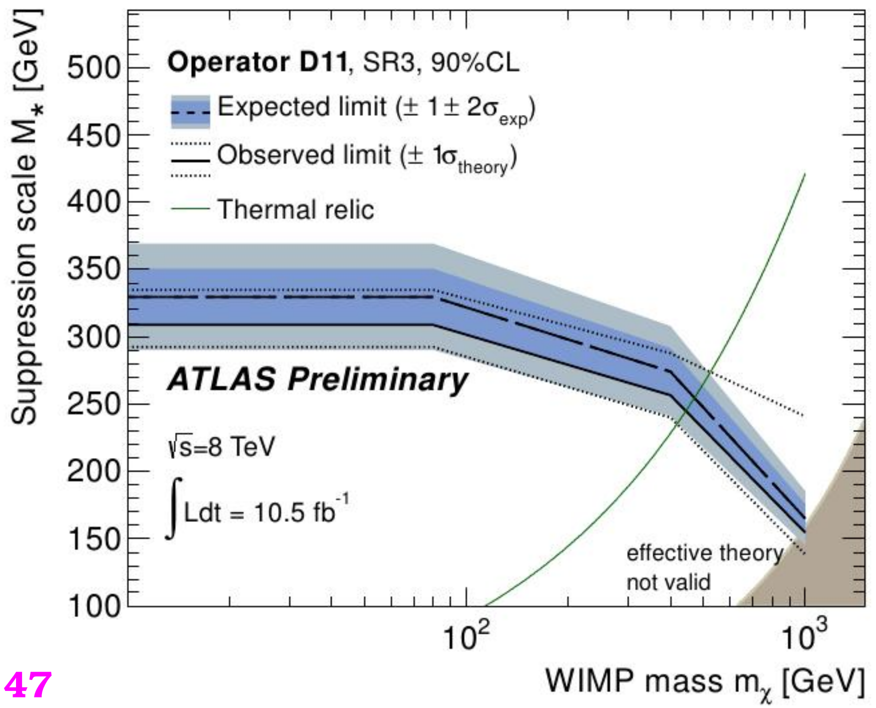
monojet

contraints from SR3

corresponding to best expected limits







Atlas-conf-2012-147

monojet

$E_T^{miss} > 120$ GeV

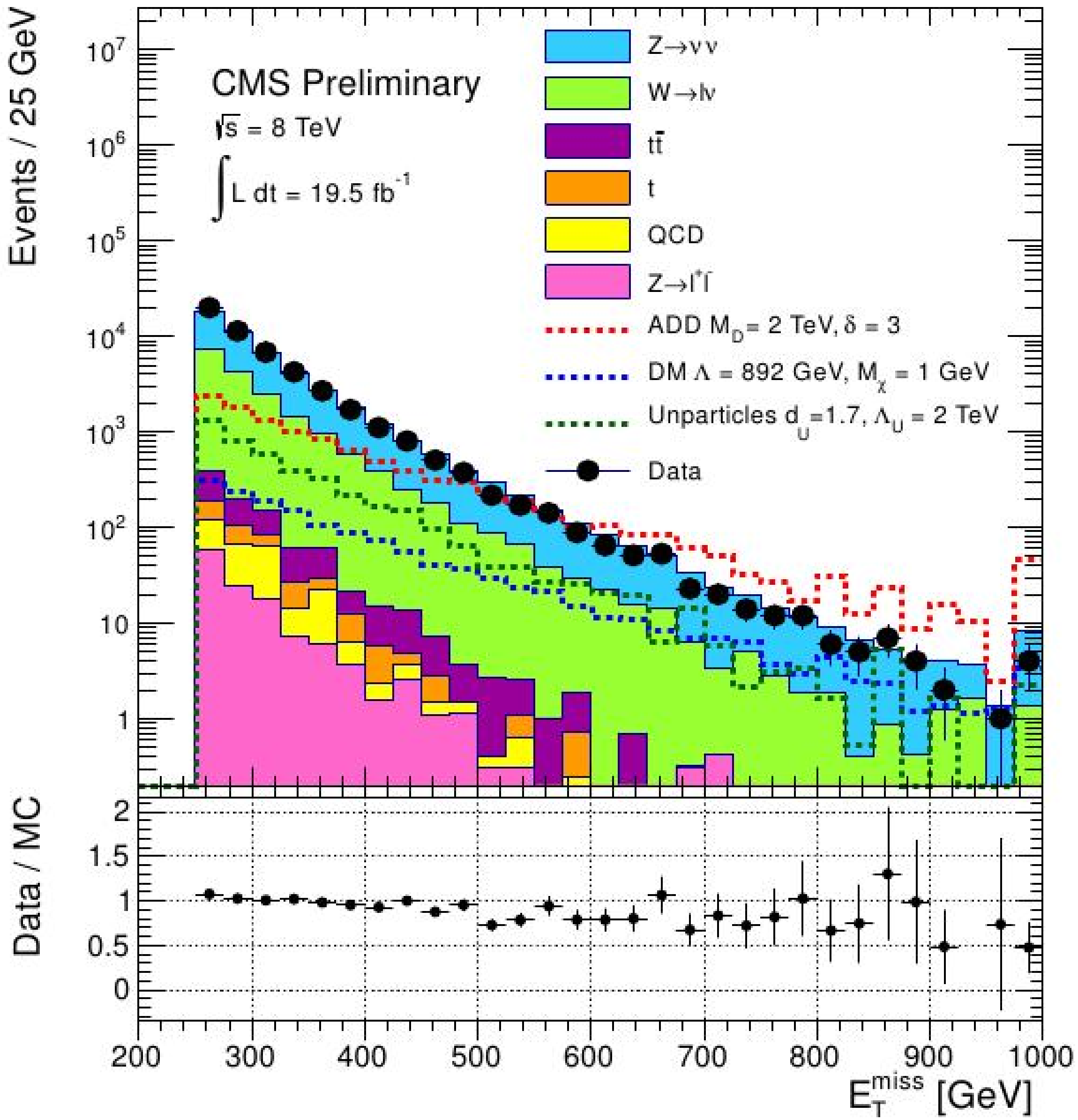
jet cleaning requirements

leading jet with $p_T > 110$ GeV and $|\eta| < 2.4$

at most 2 jets with $p_T > 30$ GeV and $|\eta| < 4.5$

lepton vetoes

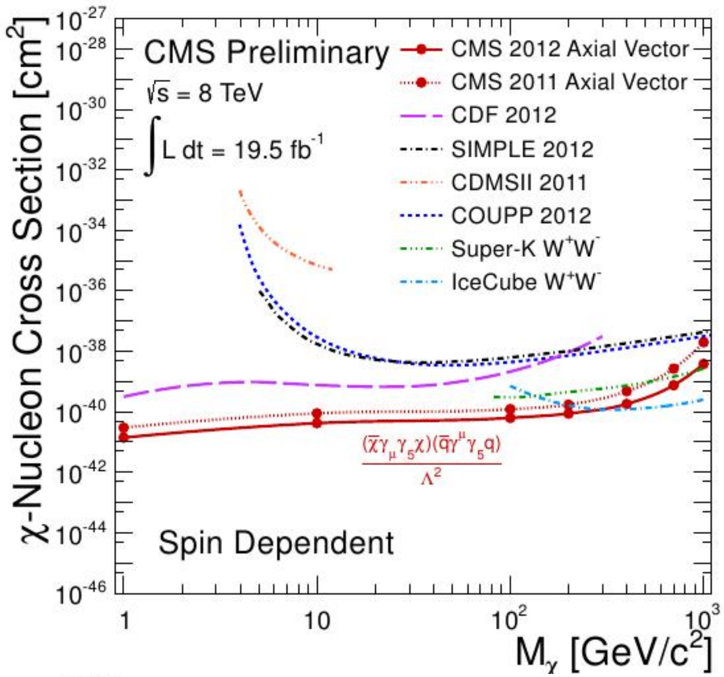
7 regions in E_T^{miss}
$E_T^{miss} > 250, 300, 350, 400, 450, 500, 550$ GeV

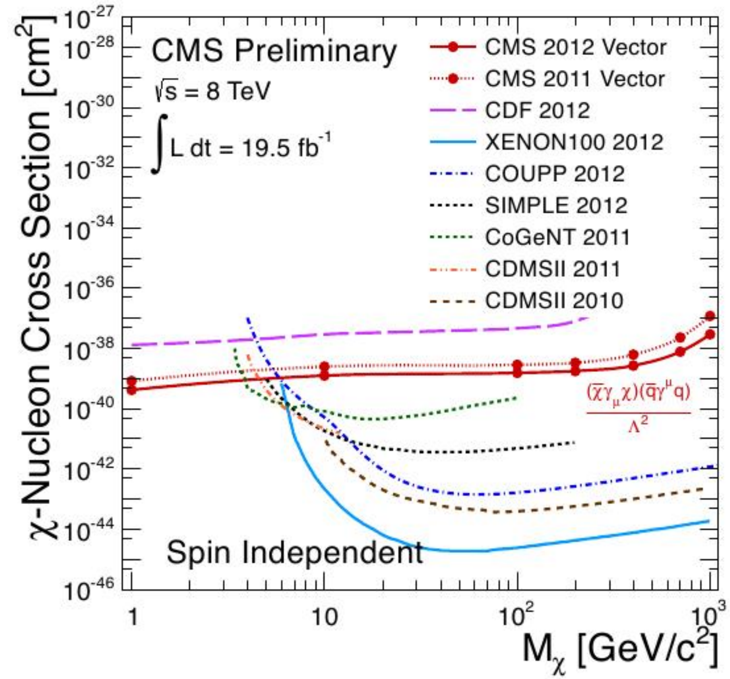


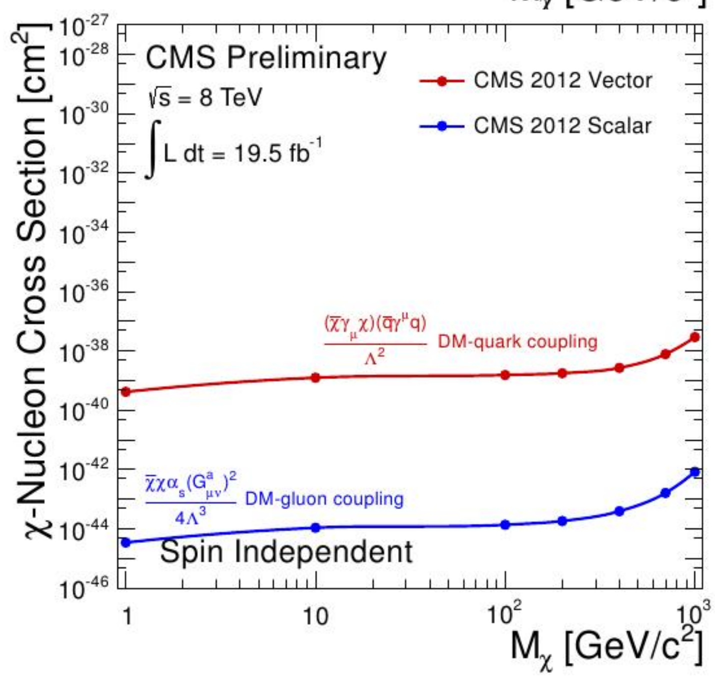
best expected limit for $E_T^{miss} > 400$ GeV

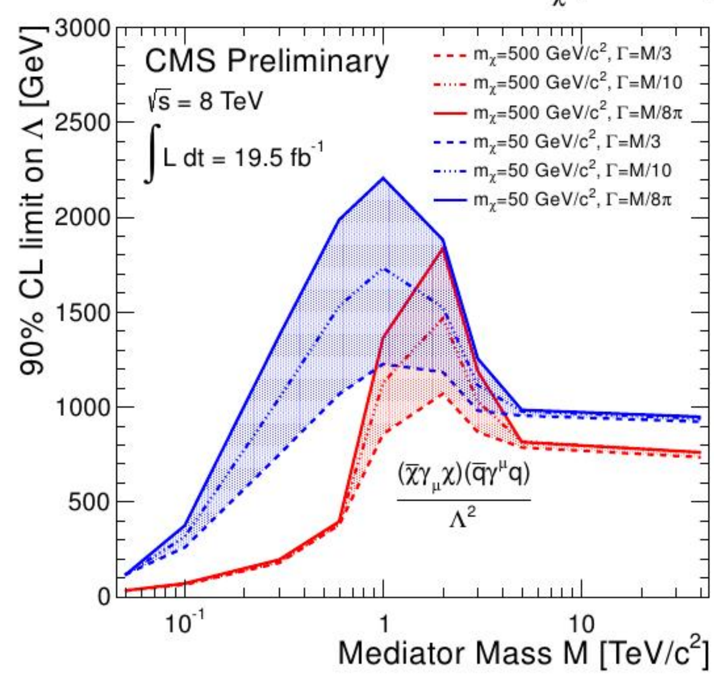
CMS-EXO-12-048

monojet



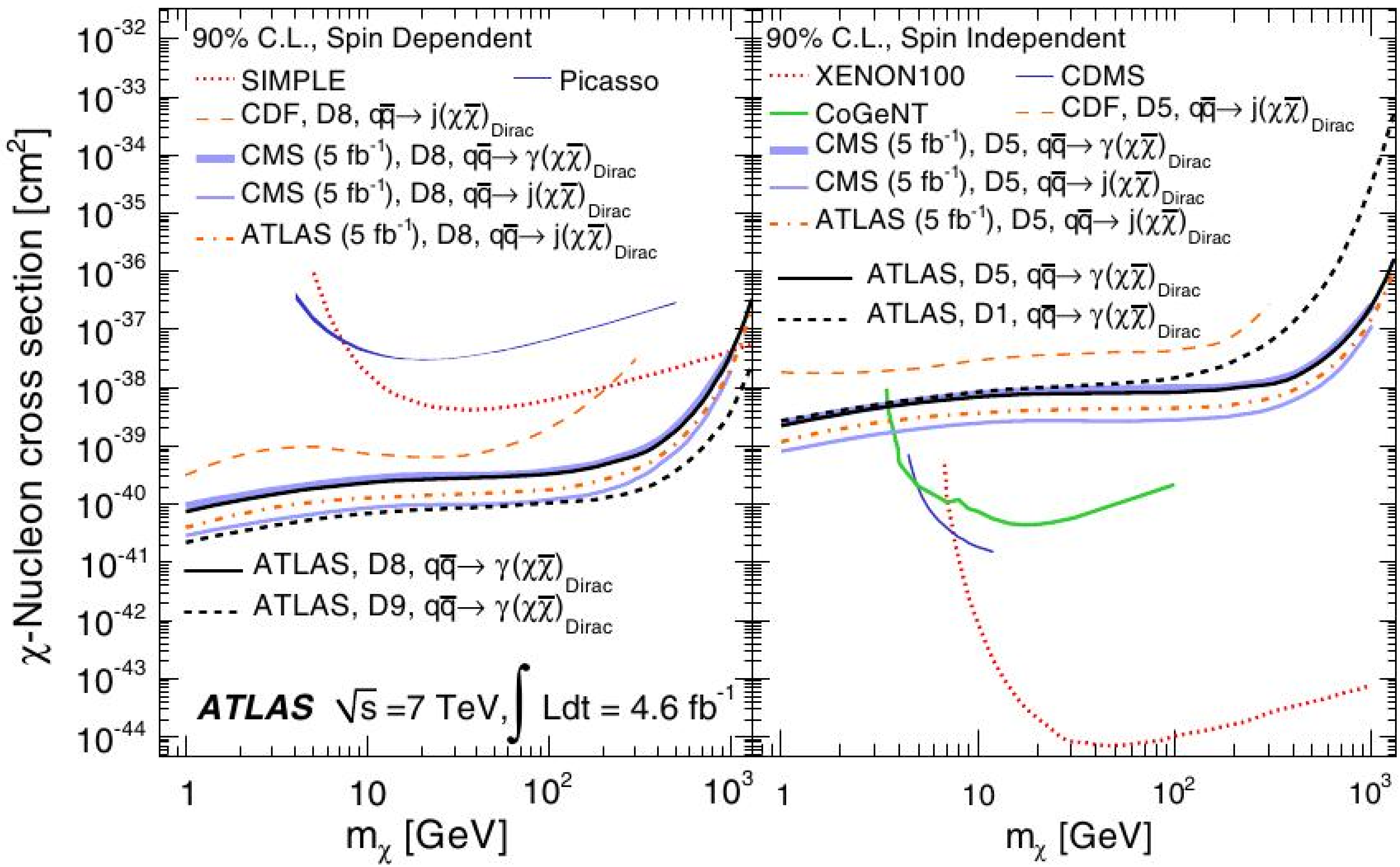






CMS-EXO-12-048

monophoton



PRL 110 (2013) 011802

monophoton

$E_T^{miss} > 140\ \text{GeV}$

medium quality isolated photon

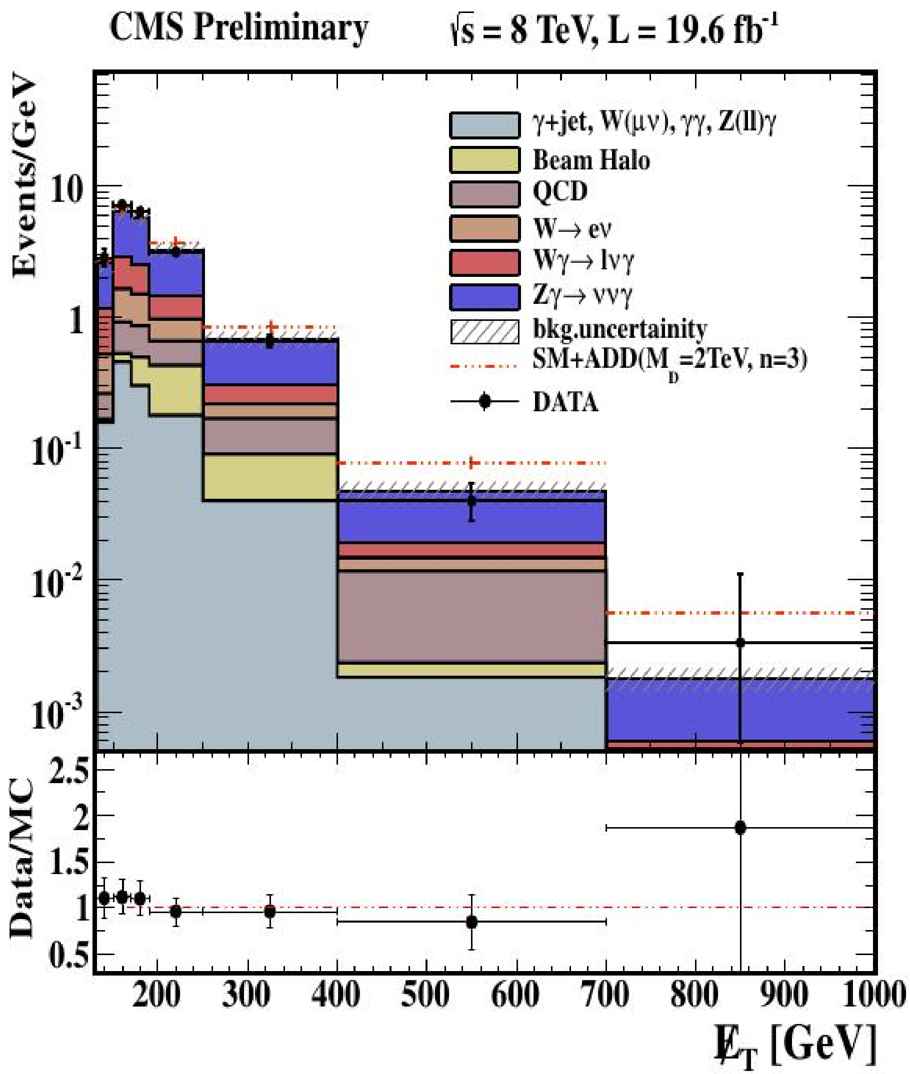
$p_T^{\gamma} > 145\ \text{GeV}$ and $|\eta^{\gamma}| < 1.44$

at most 1 jet with $p_T > 30\ \text{GeV}$ and $\Delta R(\gamma,\ \text{jet}) > 0.5$

$\Delta\phi(\gamma\ ,\ E_T^{miss}) > 2$

lepton vetoes

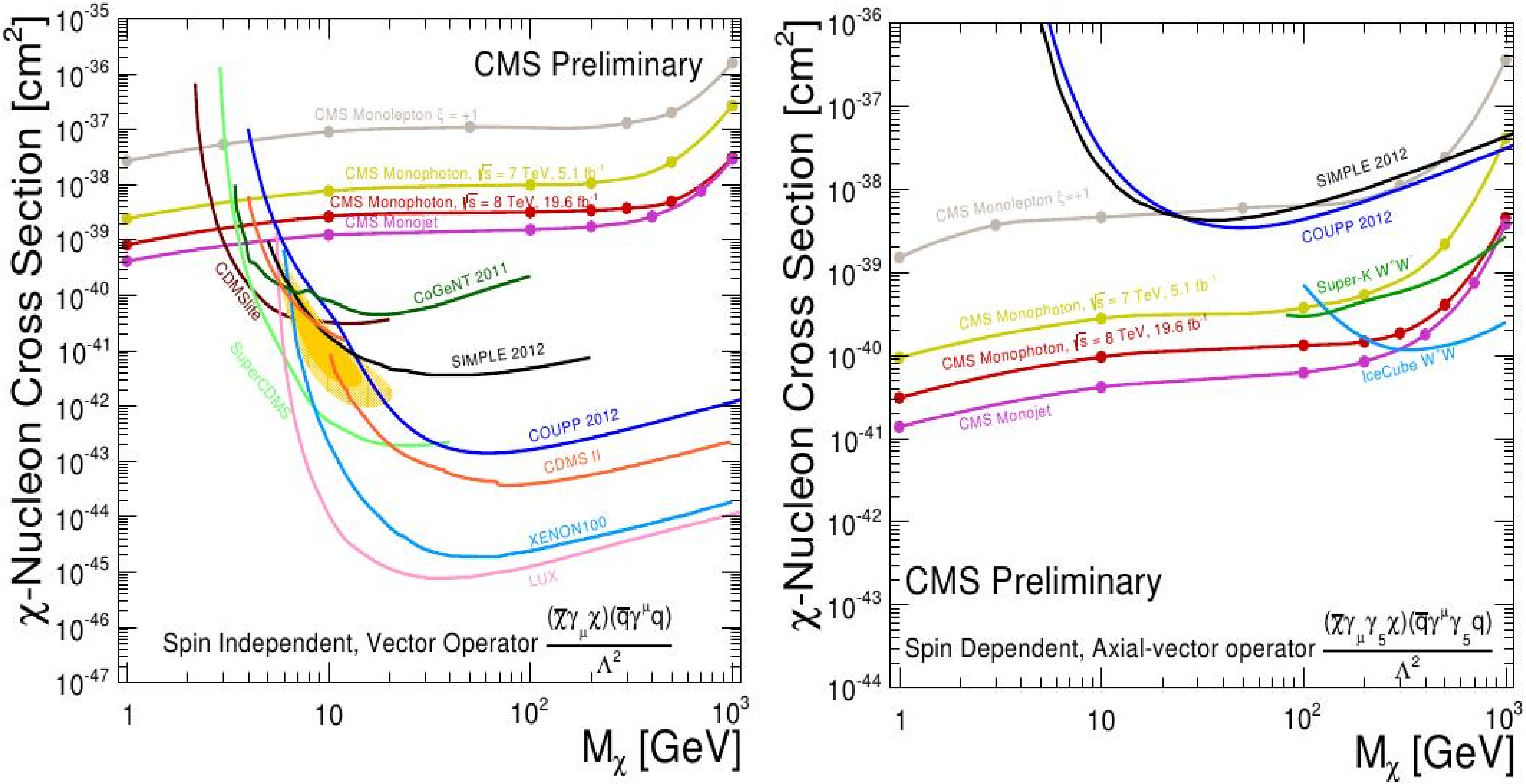
Process	Estimate
$Z(\to \nu\bar{\nu}) + \gamma$	344.8 ± 42.5
$W(\to \ell\nu) + \gamma$	102.5 ± 20.6
$W \to e\nu$	59.5 ± 5.5
jet $\to \gamma$ fakes	45.4 ± 13.9
Beam halo	24.7 ± 6.2
Others	35.7 ± 3.1
Total background	612.6 ± 63.0
Data	630.0



J. Neveu SPP Thesis

CMS-PAS-EXO-12-047

monophoton


CMS Preliminary
χ-Nucleon Cross Section [cm2]
CMS Monolepton ξ = +1
CMS Monophoton, √s = 7 TeV, 5.1 fb-1
CMS Monophoton, √s = 8 TeV, 19.6 fb-1
CMS Monojet
CoGeNT 2011
CDMSlite
SuperCDMS
SIMPLE 2012
COUPP 2012
CDMS II
XENON100
LUX
Spin Independent, Vector Operator
Mχ [GeV]
Super-K W+W-
IceCube W+W-
Spin Dependent, Axial-vector operator

mono W and Z

(hadronic decays)

mono-jet and mono-photon

→ equal effective couplings of DM to up and down type quarks

mono-W

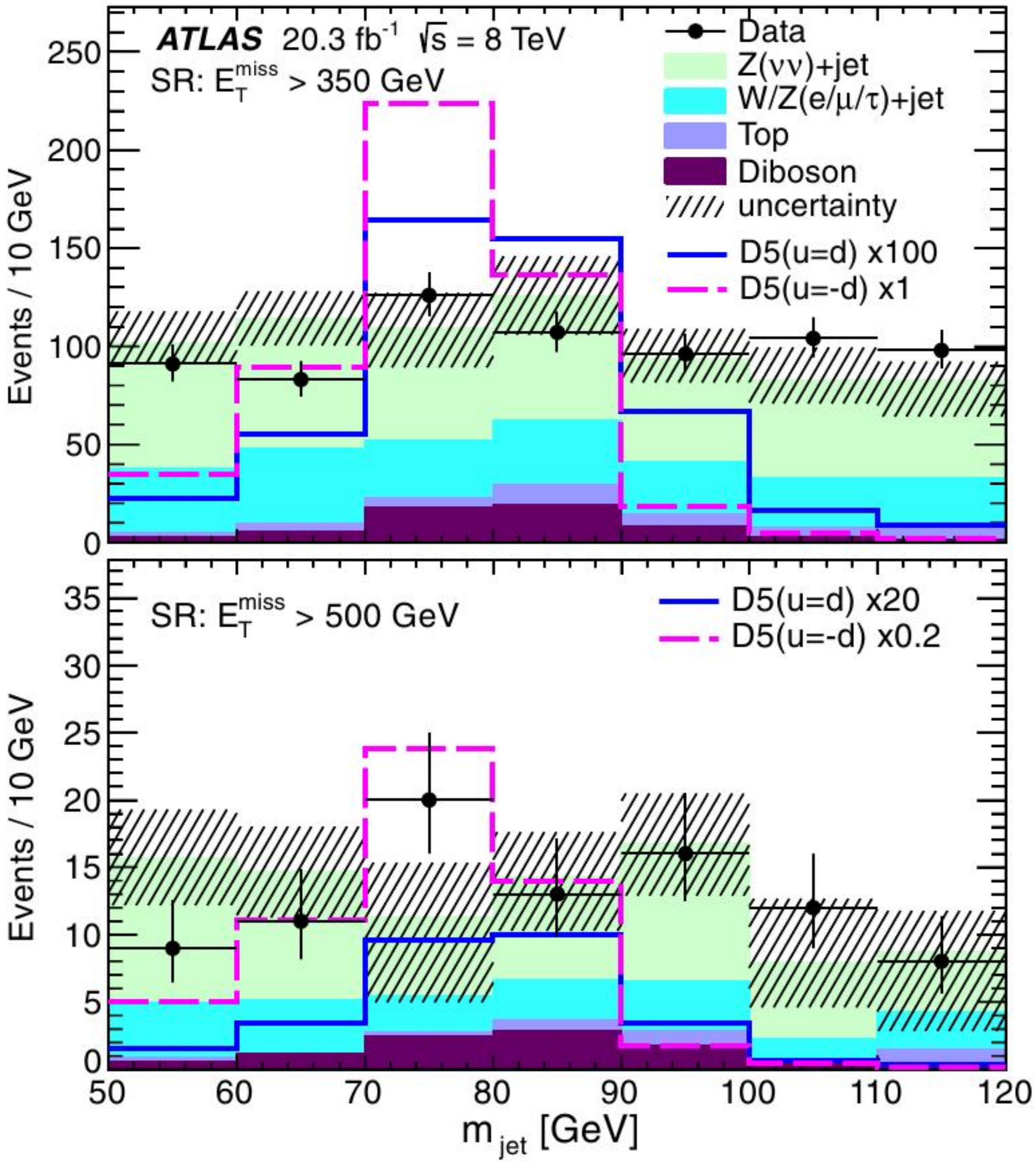
- destructive interference between radiation from u and d quark if equal couplings (u=d)
  → small W emission rate

- constructive interference if opposite sign couplings (u=-d)

large radius jet (Cam Aa R = 1.2)
capturing jets from both quarks → substructure

jet with $p_T > 250$ GeV and lepton vetoes

2 signal regions (SR) in E_T^{miss}
$E_T^{miss} > 350, 500$ GeV

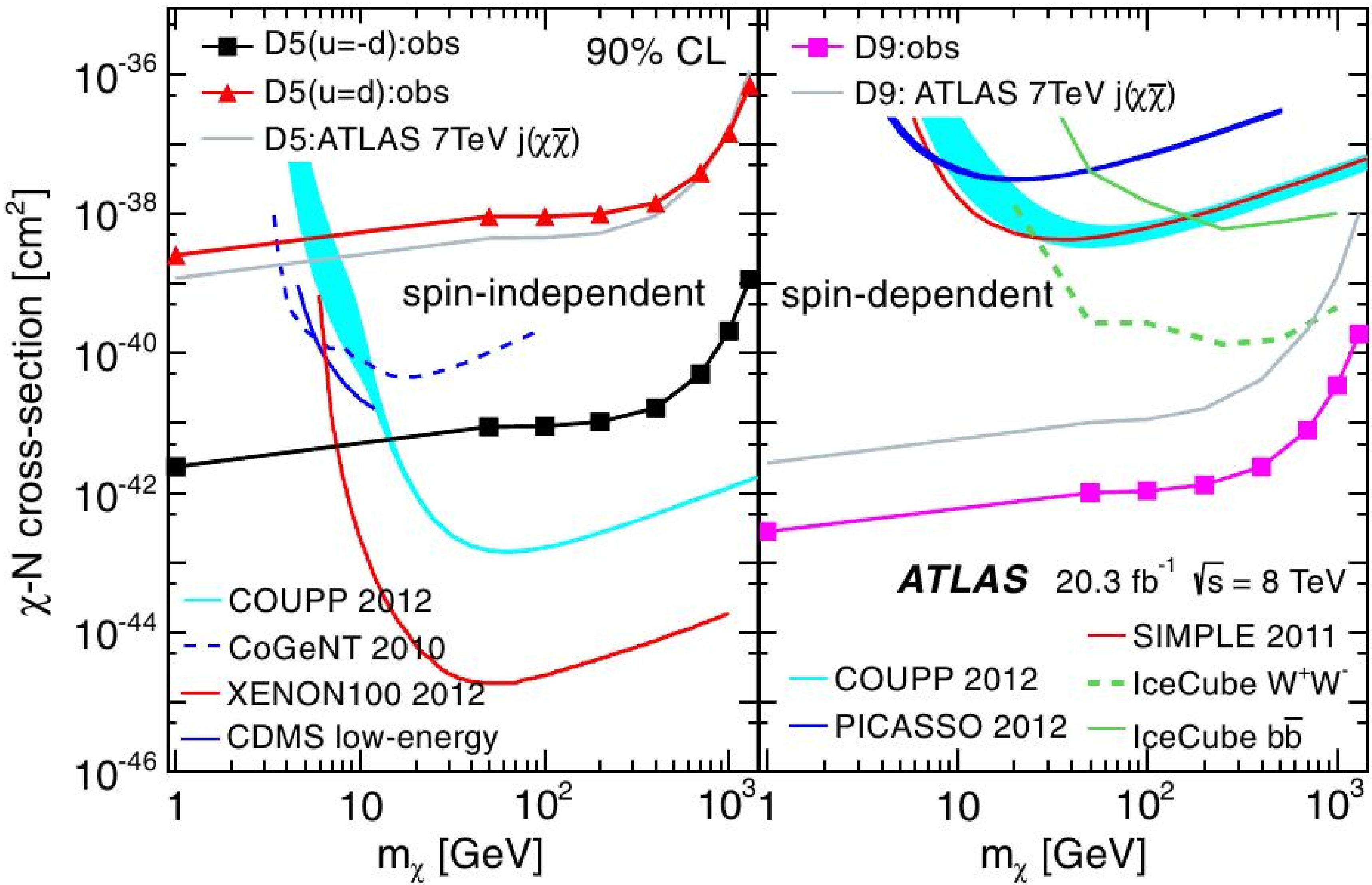


signal for $m_\chi = 1$ GeV and $M_* = 1$ TeV

PRL 112 (2014) 041802

mono W and Z

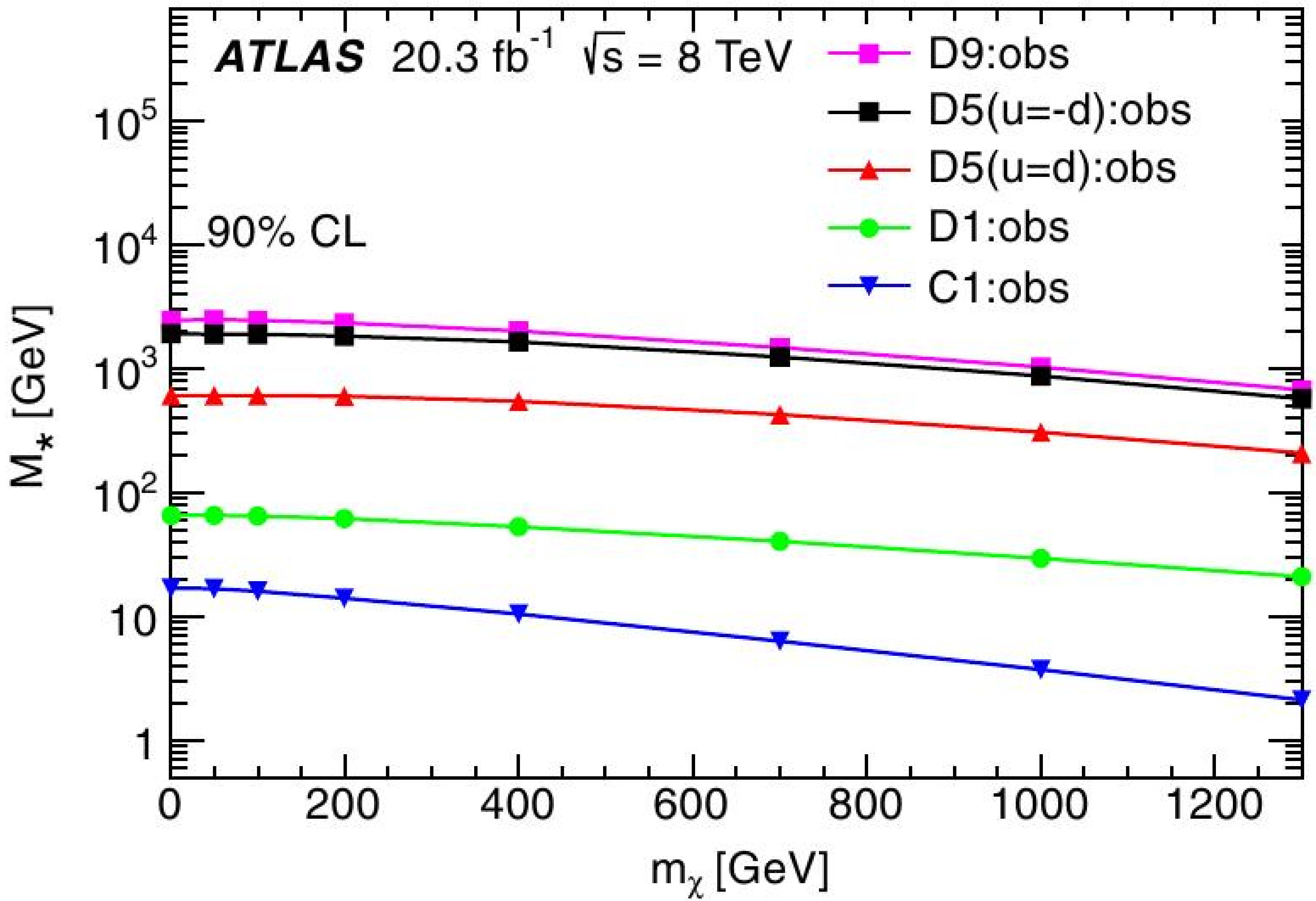
(hadronic decays)



PRL 112 (2014) 041802

mono W and Z

(hadronic decays)



PRL 112 (2014) 041802

Higgs portal

upper limit on Γ^{inv} from the combination of rate measurements from

$h \to \gamma\gamma,\quad h \to ZZ^* \to 4l,\quad h \to WW^* \to l\nu l\nu$

$h \to \tau\tau,\quad h \to b\bar{b}$

and the measured upper limit on $Zh \to ll + \mathrm{MET}$

obtain $BR_{\mathrm{inv}} < 0.37$ 95 % CL

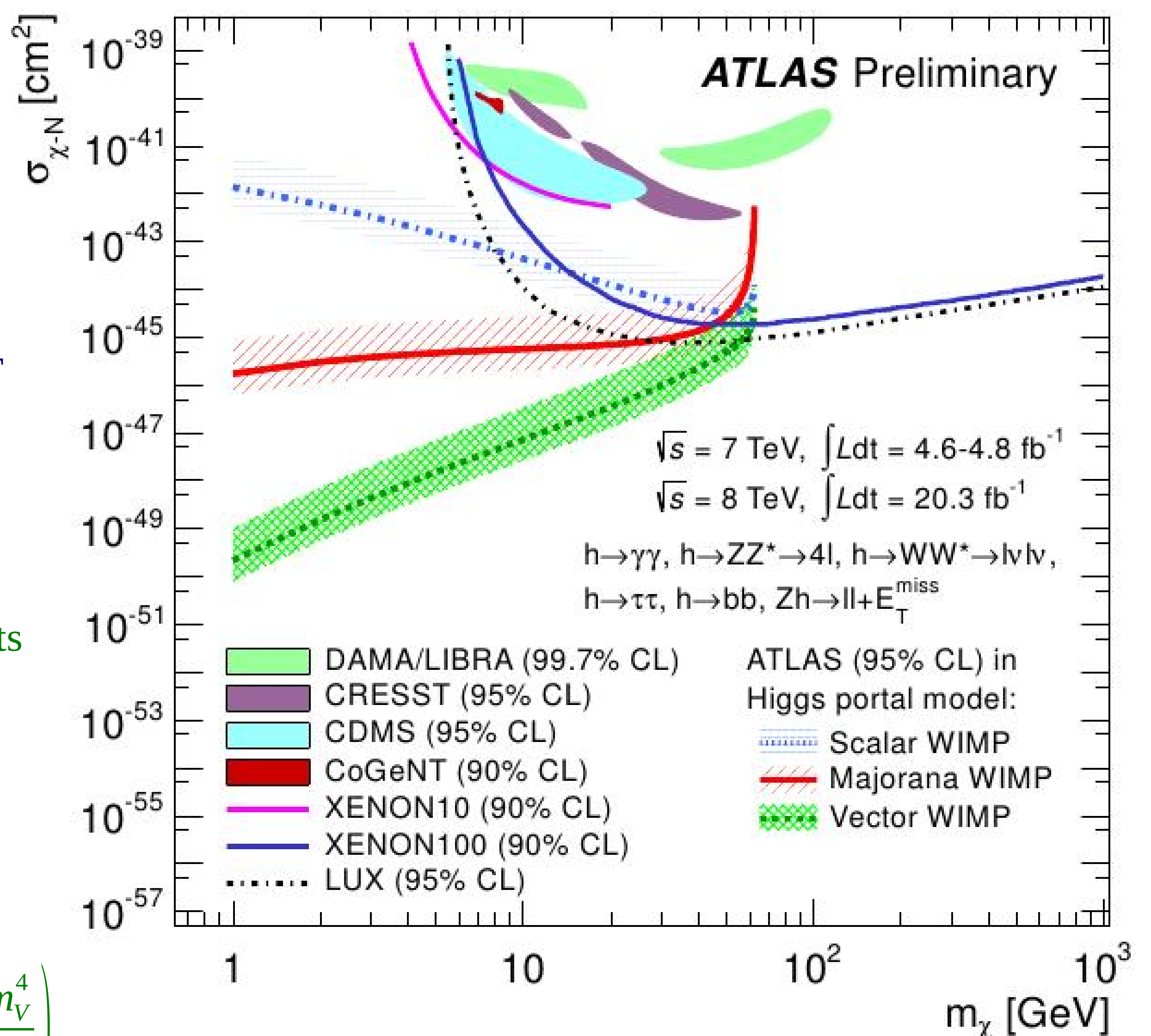
translated into WIMP-higgs coupling constraints

$$\Gamma^{\mathrm{inv}}(H \to SS) = \lambda_{hSS}^2 \frac{v^2 \beta_S}{128\pi m_h}$$

$$\Gamma^{\mathrm{inv}}(H \to ff) = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{v^2 \beta_f^3 m_h}{64\pi}$$

$$\Gamma^{\mathrm{inv}}(H \to VV) = \lambda_{hVV}^2 \frac{v^2 \beta_V m_h^3}{512\pi m_V^4}\left(1 - 4\frac{m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right)$$

$$\beta_\chi = \sqrt{1 - 4\frac{m_\chi^2}{m_h^2}}$$

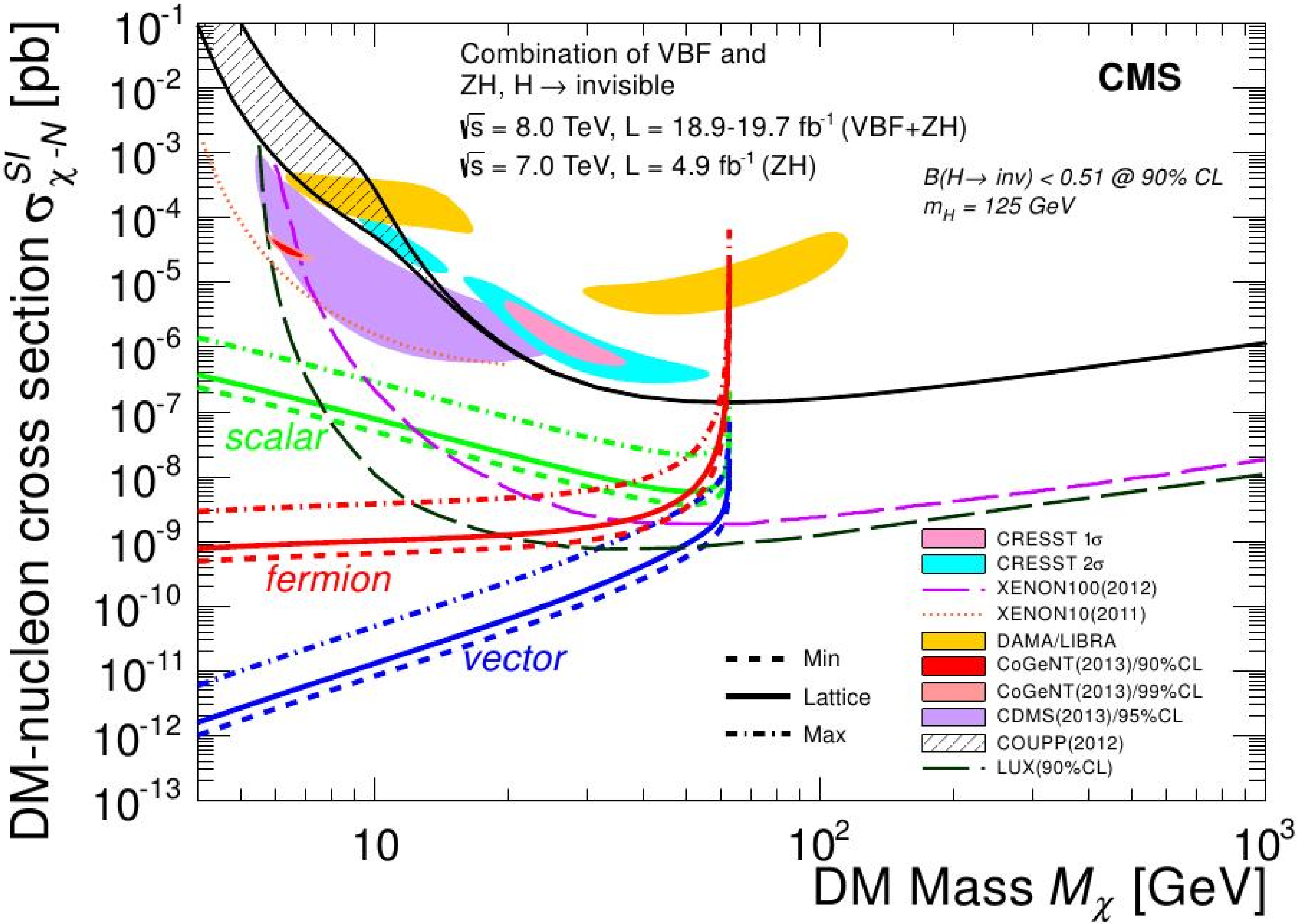


and reparameterized in terms of $\sigma_{\chi-N}$ via higgs boson exchange (see backup)

Atlas-conf-2014-010

Higgs portal

arXiv:1404.1344

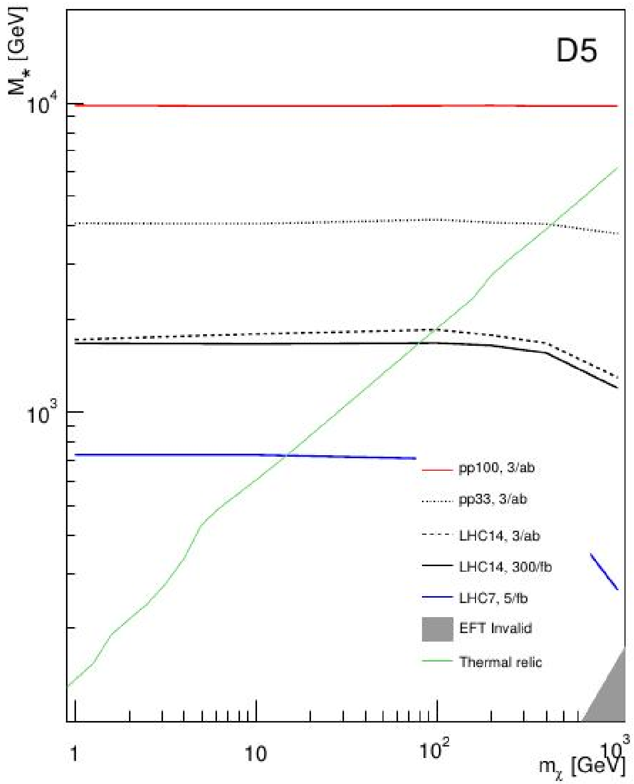


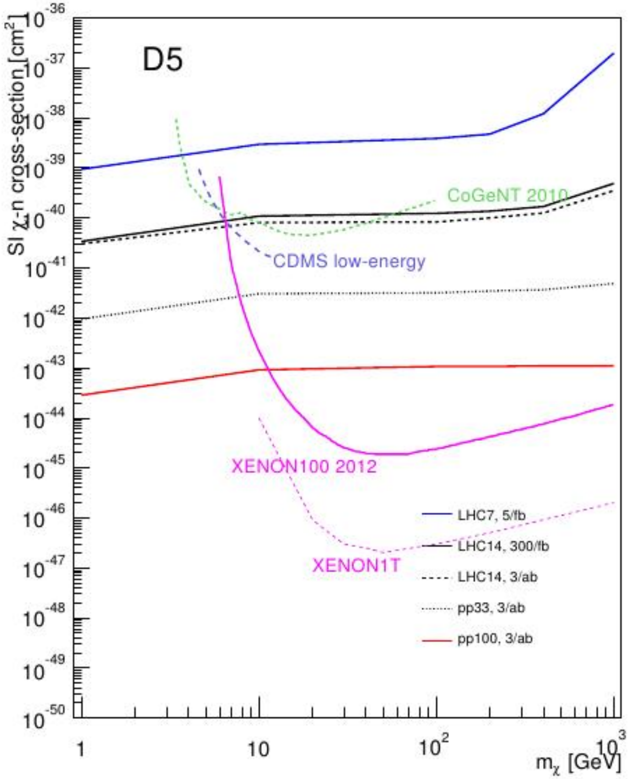
but look at Baek Ko Park PRD 90 (2014) 055014

some perspectives

- EFT

extrapolation of mono-jet searches





example for D5 from Zhou, Berge, Wang, Whiteson, Tait arXiv:1307.5327

see same reference for examples on D8 and D9

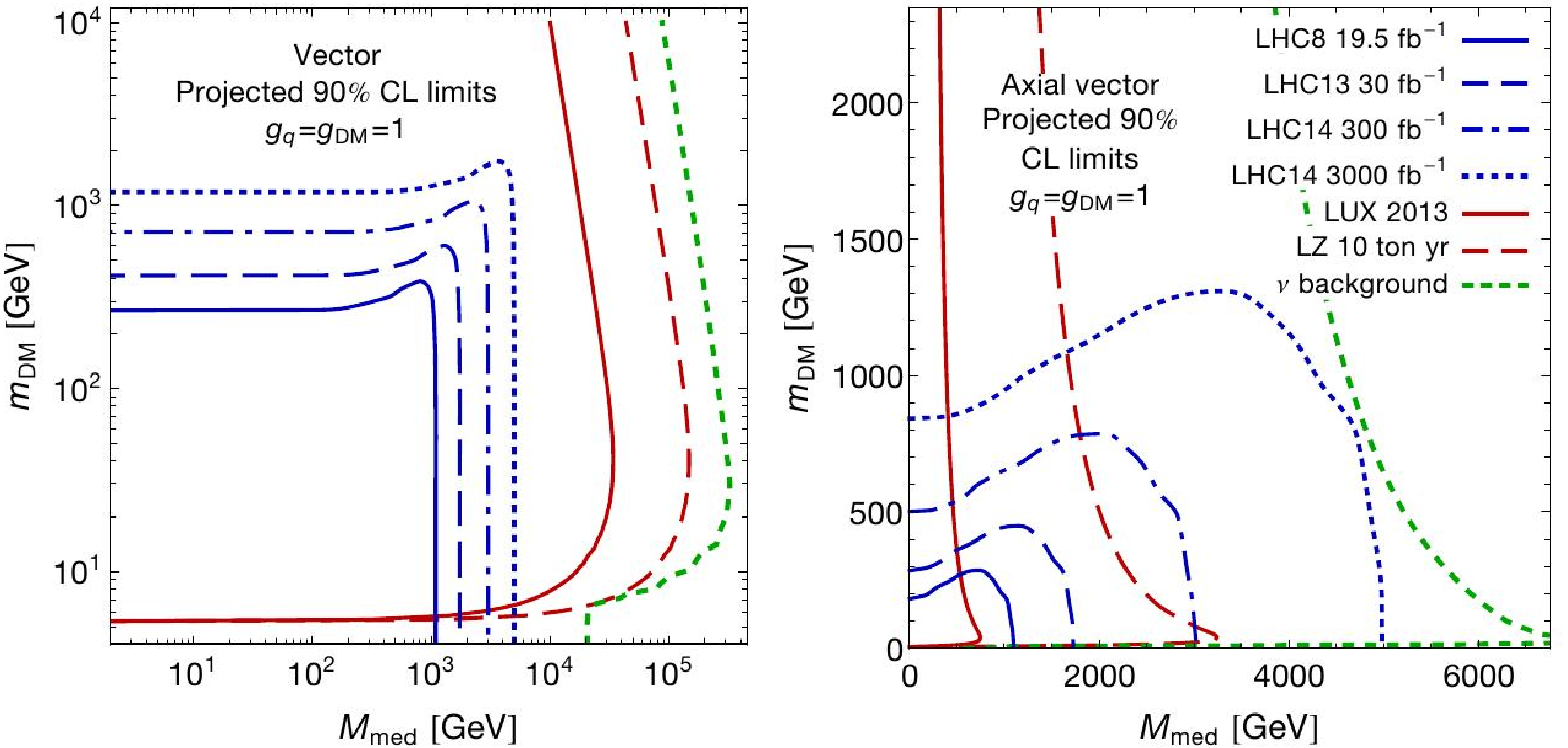
- Higgs portal

from Snowmass studies

Dawson et al. arXiv:1310.8361

$\int \mathcal{L}dt$	Higgs decay final state							
(fb^{-1})	$\gamma\gamma$	WW^*	ZZ^*	$b\bar{b}$	$\tau\tau$	$\mu\mu$	$Z\gamma$	BR_{inv}
ATLAS								
300	9 – 14%	8 – 13%	6 – 12%	N/A	16 – 22%	38 – 39%	145 – 147%	< 23 – 32%
3000	4 – 10%	5 – 9%	4 – 10%	N/A	12 – 19%	12 – 15%	54 – 57%	< 8 – 16%
CMS								
300	6 – 12%	6 – 11%	7 – 11%	11 – 14%	8 – 14%	40 – 42%	62 – 62%	< 17 – 28%
3000	4 – 8%	4 – 7%	4 – 7%	5 – 7%	5 – 8%	14 – 20%	20 – 24%	< 6 – 17%

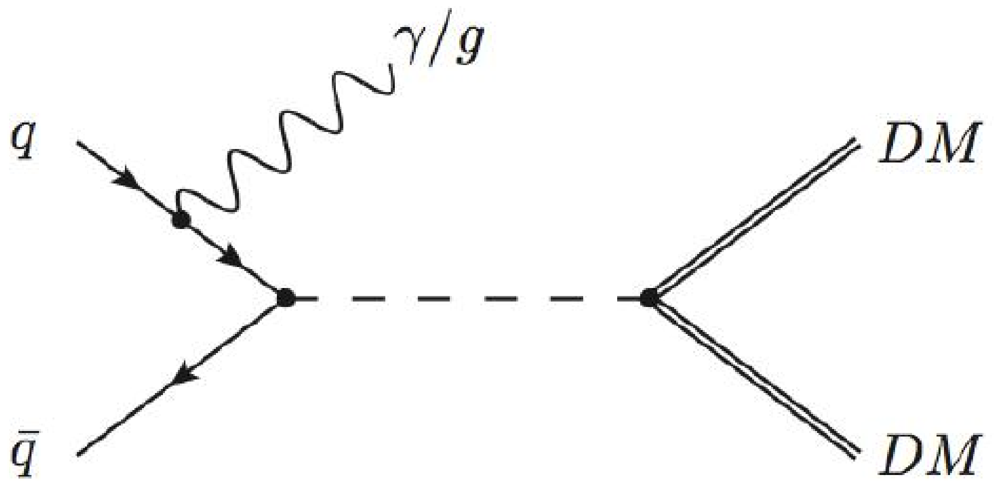
some perspectives



Buchmueller, Dolan, Malik, Mac Cabe, _arXiv:1407.8257

some perspectives

use simplified models



only SM + DM sector (including mediator)

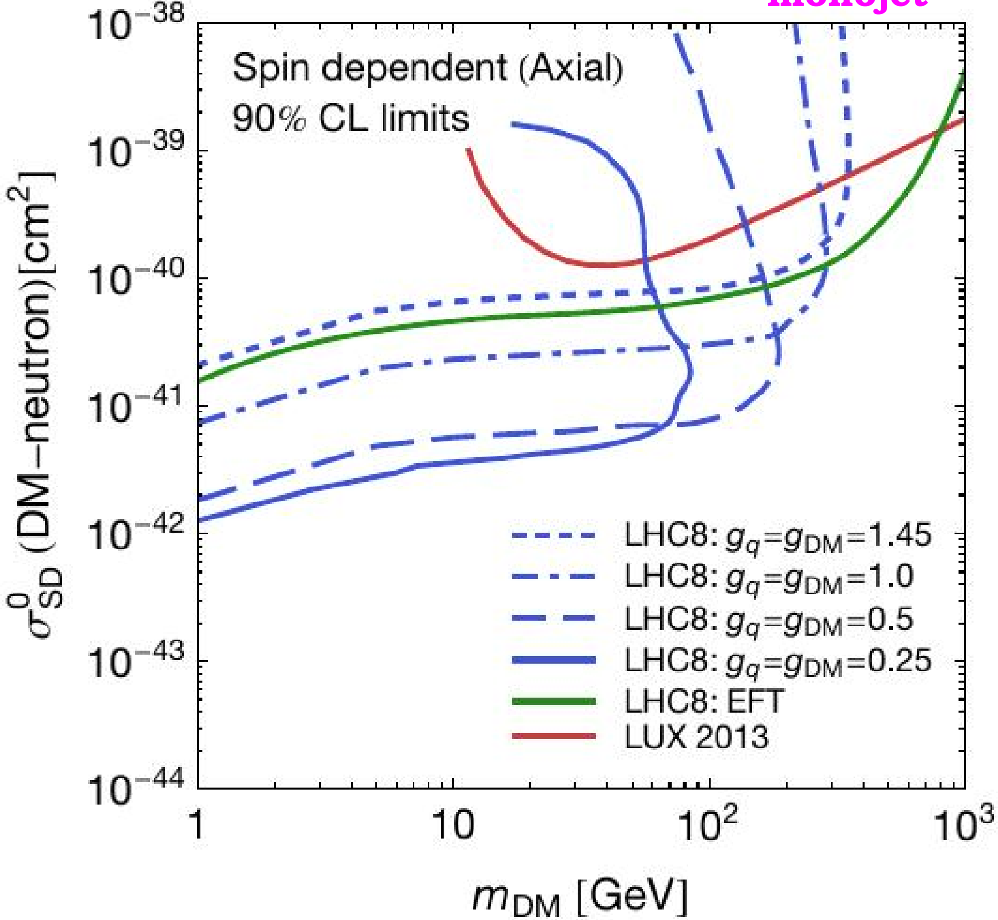
mediator and interactions specified explicitely

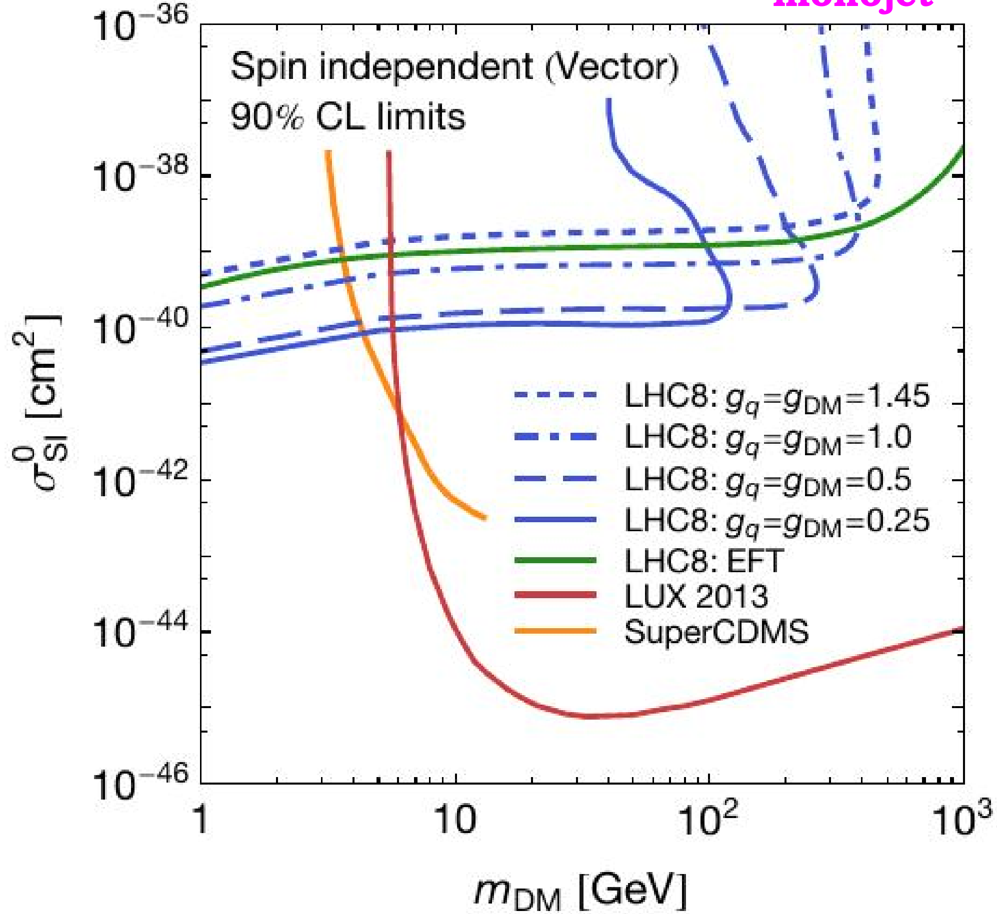
Abdallah et al. arXiv:1409.2893

Malik et al. arXiv:1409.4075

some perspectives

Malik et al. arXiv:1409.4075





$$\mathcal{L}_{\rm axial} \supset \frac{1}{2} M^2_{\rm med} Z''_\mu Z''^\mu - g_{\rm DM} Z''_\mu \bar{\chi}\gamma^\mu\gamma^5\chi - \sum_q g_q Z''_\mu \bar{q}\gamma^\mu\gamma^5 q$$

$$\mathcal{L}_{\rm vector} \supset \frac{1}{2} M^2_{\rm med} Z'_\mu Z'^\mu - g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu\chi - \sum_q g_q Z'_\mu \bar{q}\gamma^\mu q$$

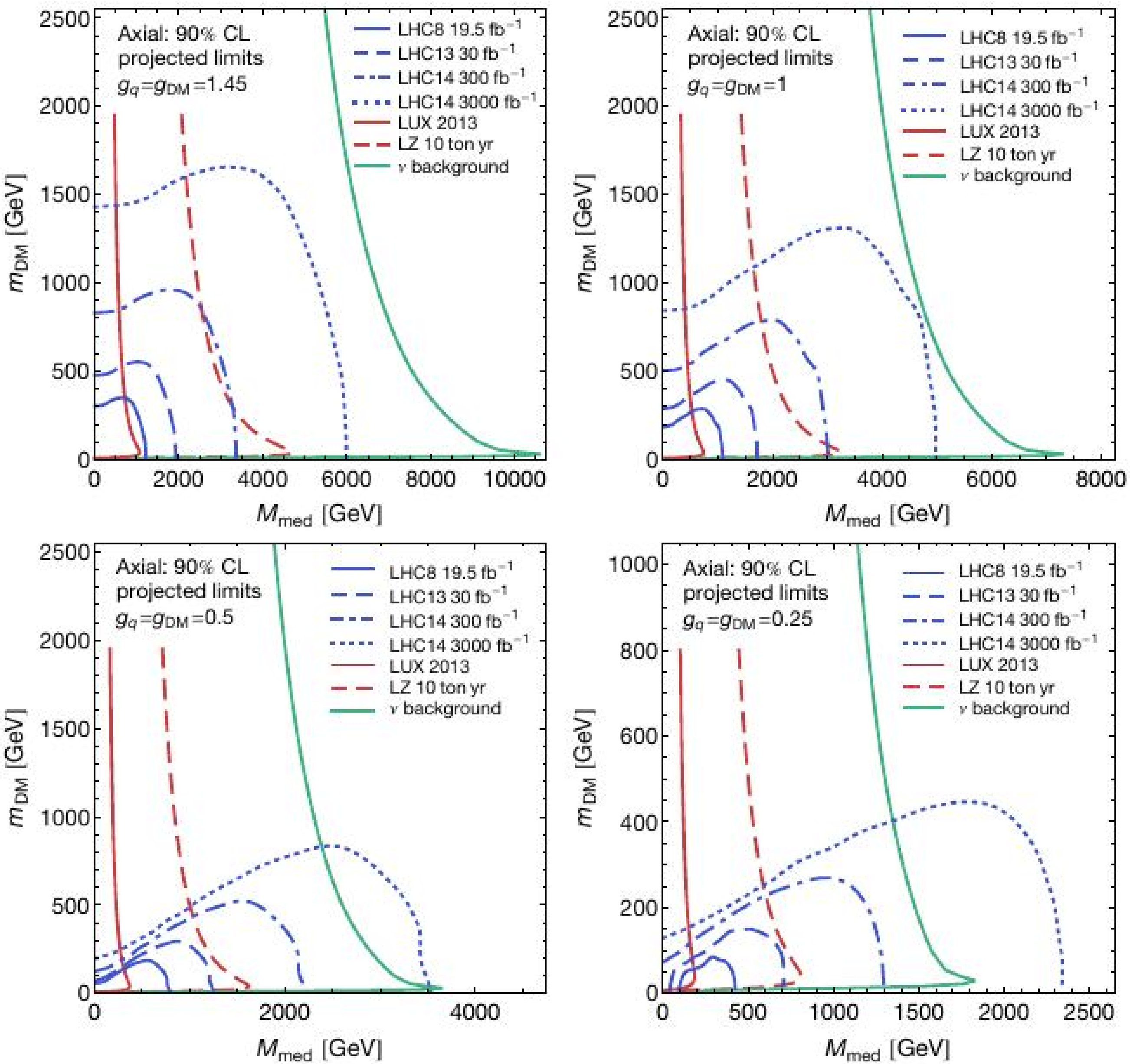
$$\sigma^0_{\rm DD} \sim \frac{g^2_{\rm DM} g^2_q \mu^2}{M^4_{\rm med}}$$

(μ reduced mass of the DM nucleon system)

some perspectives

Malik et al. arXiv:1409.4075

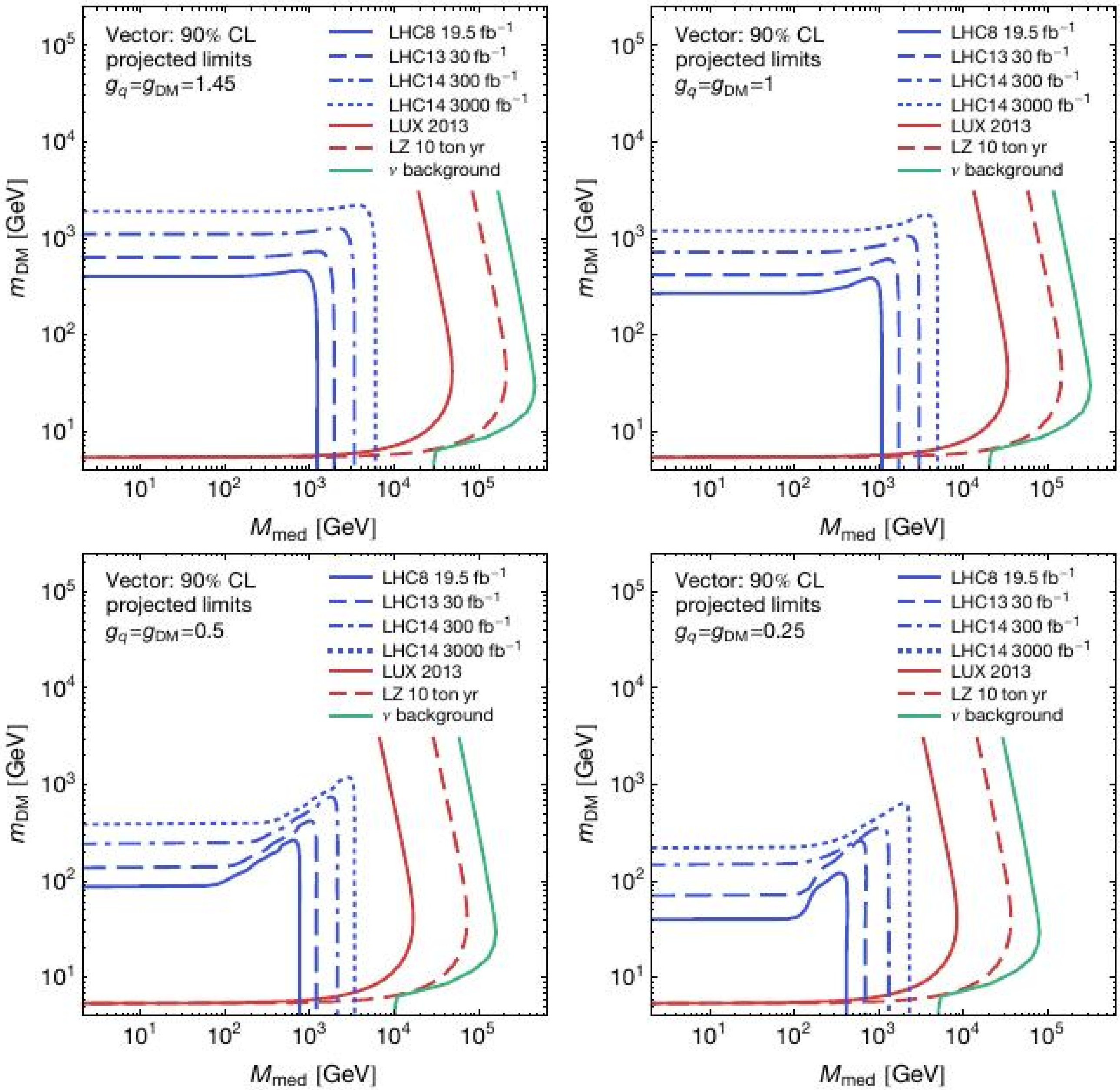
Projected limits for CMS mono jet search



some perspectives

Malik et al. arXiv:1409.4075

Projected limits for CMS mono jet search

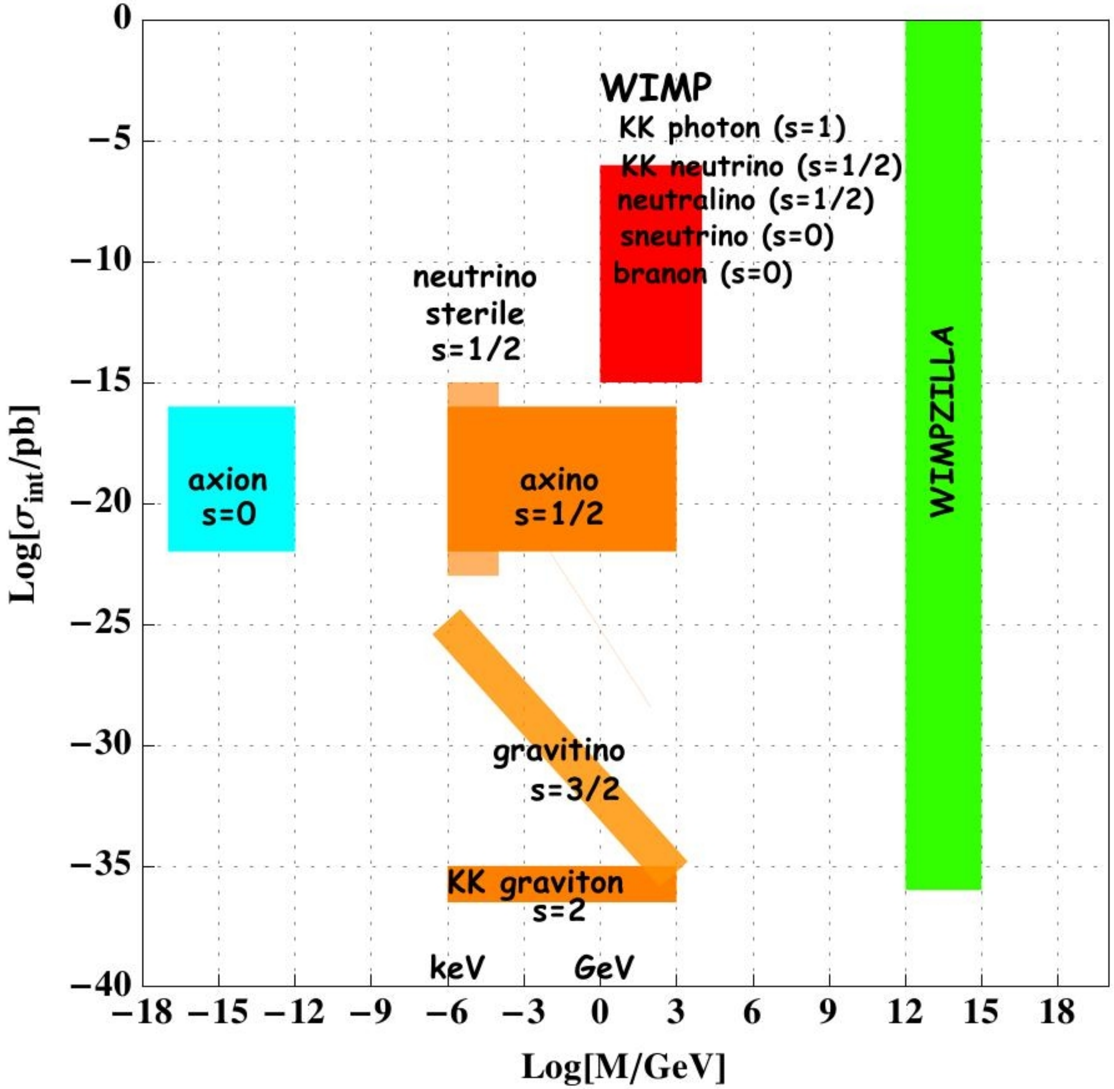


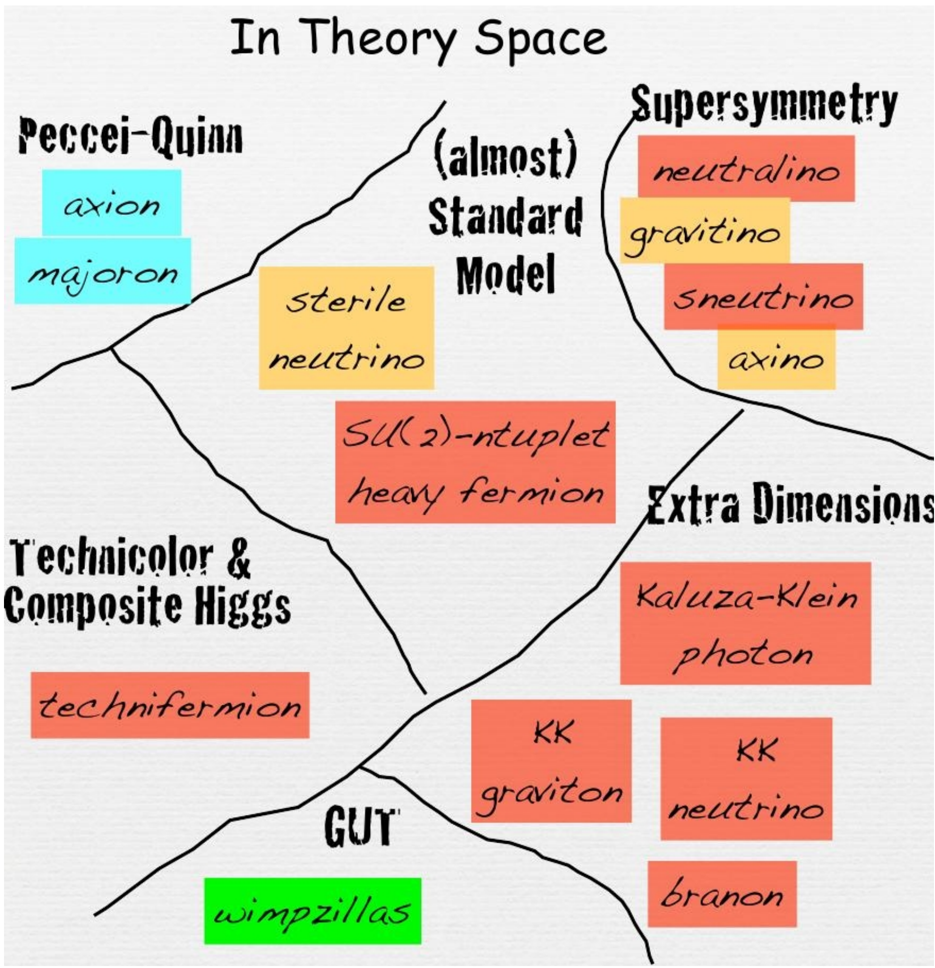
BACKUP

Parameter	Prior range	Baseline	Definition
$\omega_b \equiv \Omega_b h^2$	[0.005, 0.1]	...	Baryon density today
$\omega_c \equiv \Omega_c h^2$	[0.001, 0.99]	...	Cold dark matter density today
$100\theta_{MC}$	[0.5, 10.0]	...	$100 \times$ approximation to r_*/D_A (CosmoMC)
τ	[0.01, 0.8]	...	Thomson scattering optical depth due to reionization
Ω_K	[−0.3, 0.3]	0	Curvature parameter today with $\Omega_{tot} = 1 - \Omega_K$
$\sum m_\nu$	[0, 5]	0.06	The sum of neutrino masses in eV
$m^{eff}_{\nu,\,sterile}$	[0, 3]	0	Effective mass of sterile neutrino in eV
w_0	[−3.0, −0.3]	−1	Dark energy equation of state[a], $w(a) = w_0 + (1-a)w_a$
w_a	[−2, 2]	0	As above (perturbations modelled using PPF)
N_{eff}	[0.05, 10.0]	3.046	Effective number of neutrino-like relativistic degrees of freedom (see text)
Y_P	[0.1, 0.5]	BBN	Fraction of baryonic mass in helium
A_L	[0, 10]	1	Amplitude of the lensing power relative to the physical value
n_s	[0.9, 1.1]	...	Scalar spectrum power-law index ($k_0 = 0.05\mathrm{Mpc}^{-1}$)
n_t	$n_t = -r_{0.05}/8$	Inflation	Tensor spectrum power-law index ($k_0 = 0.05\mathrm{Mpc}^{-1}$)
$dn_s/d\ln k$	[−1, 1]	0	Running of the spectral index
$\ln(10^{10}A_s)$	[2.7, 4.0]	...	Log power of the primordial curvature perturbations ($k_0 = 0.05\,\mathrm{Mpc}^{-1}$)
$r_{0.05}$	[0, 2]	0	Ratio of tensor primordial power to curvature power at $k_0 = 0.05\,\mathrm{Mpc}^{-1}$
Ω_Λ		...	Dark energy density divided by the critical density today
t_0		...	Age of the Universe today (in Gyr)
Ω_m		...	Matter density (inc. massive neutrinos) today divided by the critical density
σ_8		...	RMS matter fluctuations today in linear theory
z_{re}		...	Redshift at which Universe is half reionized
H_0	[20,100]	...	Current expansion rate in $\mathrm{km\,s^{-1}Mpc^{-1}}$
$r_{0.002}$		0	Ratio of tensor primordial power to curvature power at $k_0 = 0.002\,\mathrm{Mpc}^{-1}$
$10^9 A_s$		...	$10^9 \times$ dimensionless curvature power spectrum at $k_0 = 0.05\,\mathrm{Mpc}^{-1}$
$\omega_m \equiv \Omega_m h^2$		...	Total matter density today (inc. massive neutrinos)
z_*		...	Redshift for which the optical depth equals unity (see text)
$r_* = r_s(z_*)$		...	Comoving size of the sound horizon at $z = z_*$
$100\theta_*$		...	$100 \times$ angular size of sound horizon at $z = z_*$ (r_*/D_A)
z_{drag}		...	Redshift at which baryon-drag optical depth equals unity (see text)
$r_{drag} = r_s(z_{drag})$		...	Comoving size of the sound horizon at $z = z_{drag}$
k_D		...	Characteristic damping comoving wavenumber (Mpc^{-1})
$100\theta_D$		...	$100 \times$ angular extent of photon diffusion at last scattering (see text)
z_{eq}		...	Redshift of matter-radiation equality (massless neutrinos)
$100\theta_{eq}$		...	$100 \times$ angular size of the comoving horizon at matter-radiation equality
$r_{drag}/D_V(0.57)$		...	BAO distance ratio at $z = 0.57$ (see Sect. 5.2)

[a] For dynamical dark energy models with constant equation of state, we denote the equation of state by w and adopt the same prior as for w_0.

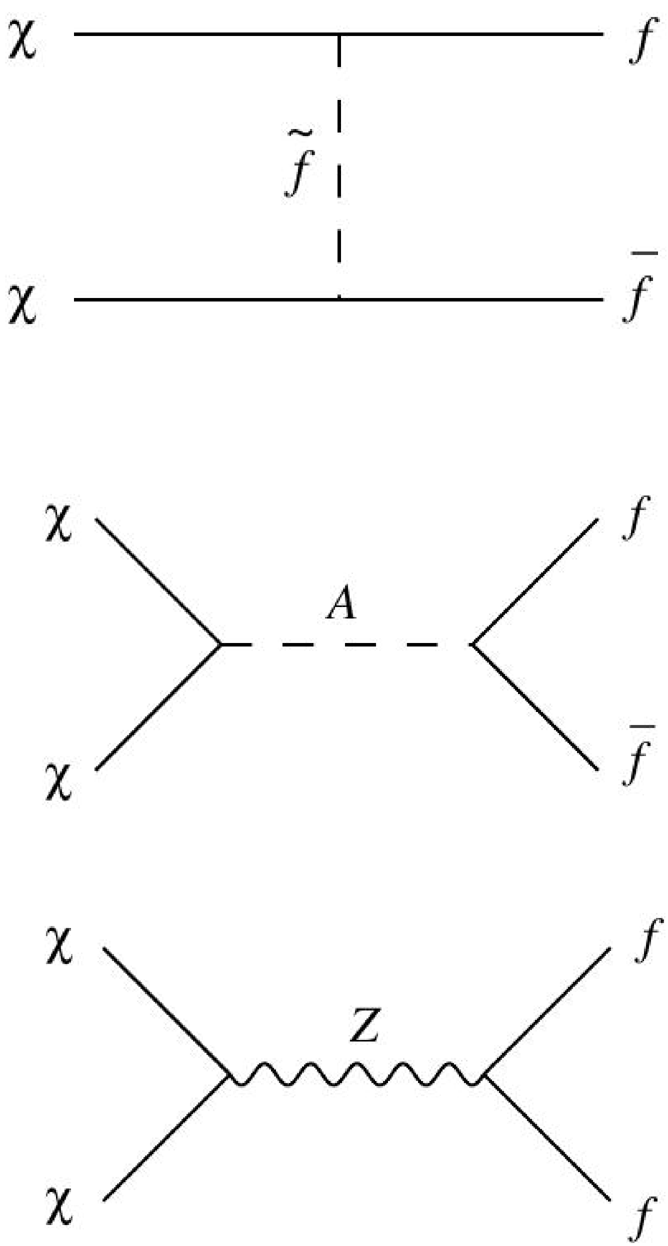
Some Dark Matter candidates

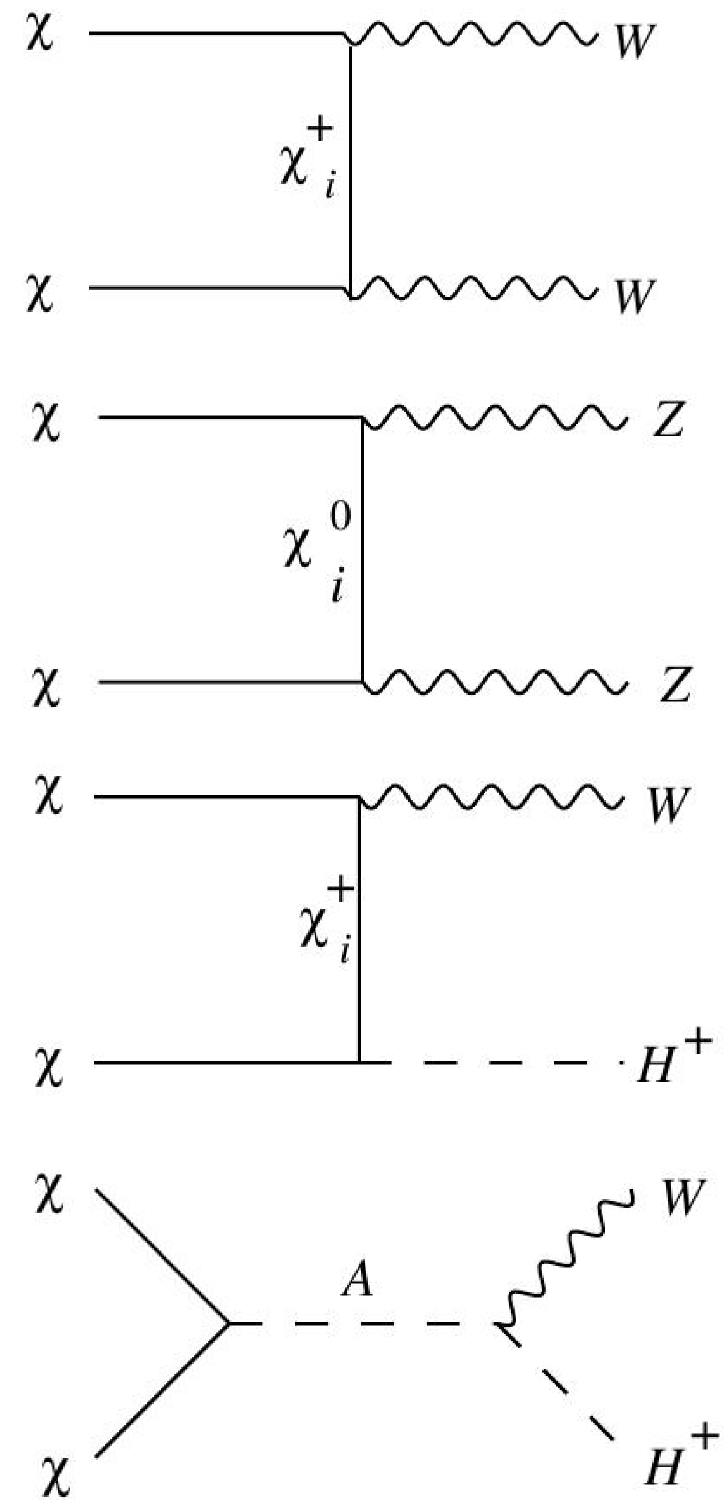




from G. Servant Talk EPS HEP 2013

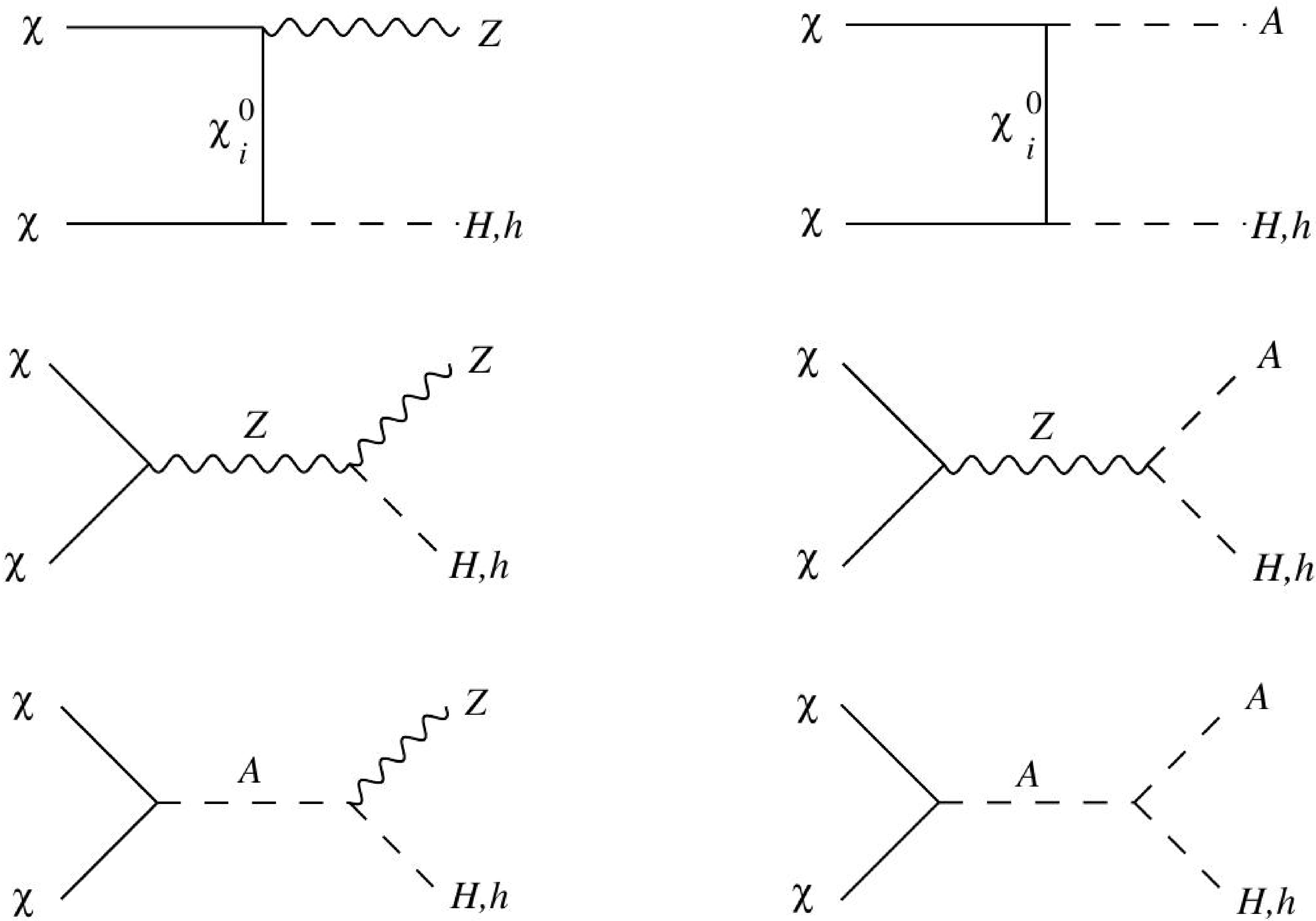
Dark Matter relic density :
main annihilation channels at rest



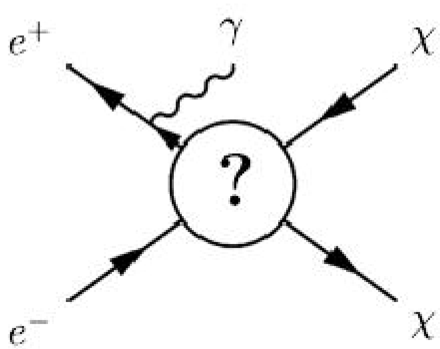


Dark Matter relic density: main annihilation channels at rest

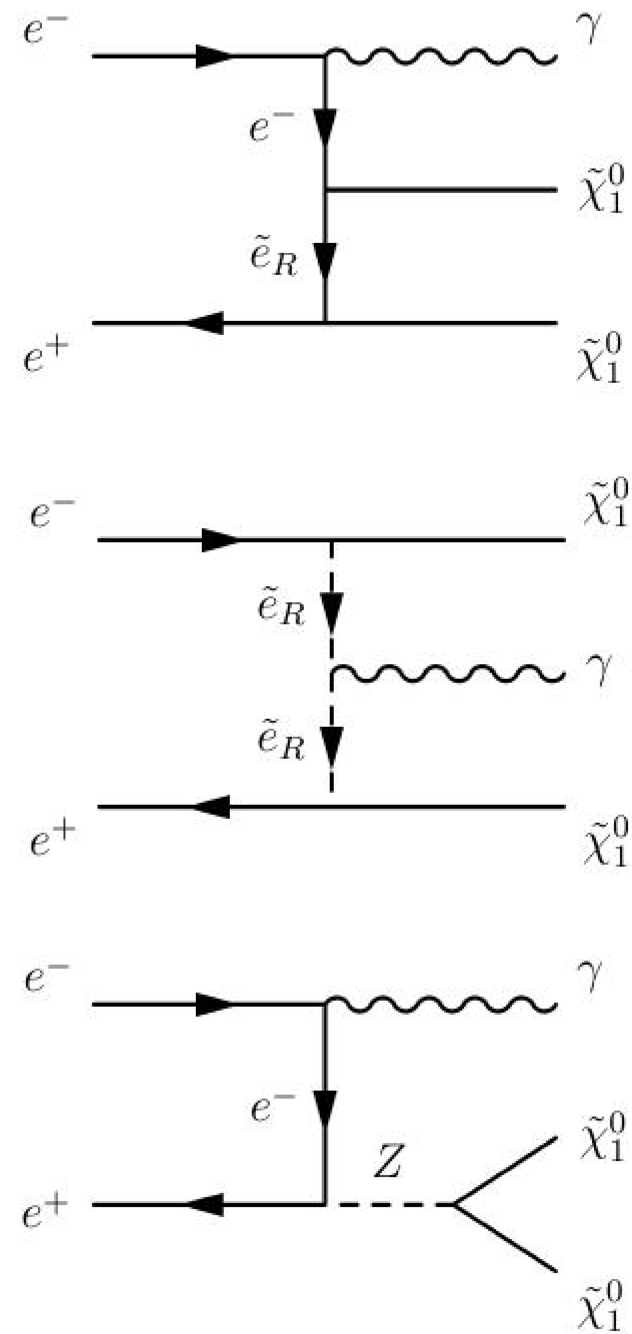
(cont')



Dark Matter at high energy lepton colliders



e.g. in MSSM



Mass constraints on lightest Neutralino

Constraints on the mass of lightest neutralino from colliders come from LEP and usually assume CMSSM and combination of various susy searches

the 'would be' invisible Z boson decay constraint at $M_Z/2$ does not hold since the lightest neutralino can decouple from the Z boson

PDG: $m_{\tilde{\chi}_1^o} > 46\,\mathrm{GeV}$ (the most stringent constraints from colliders)

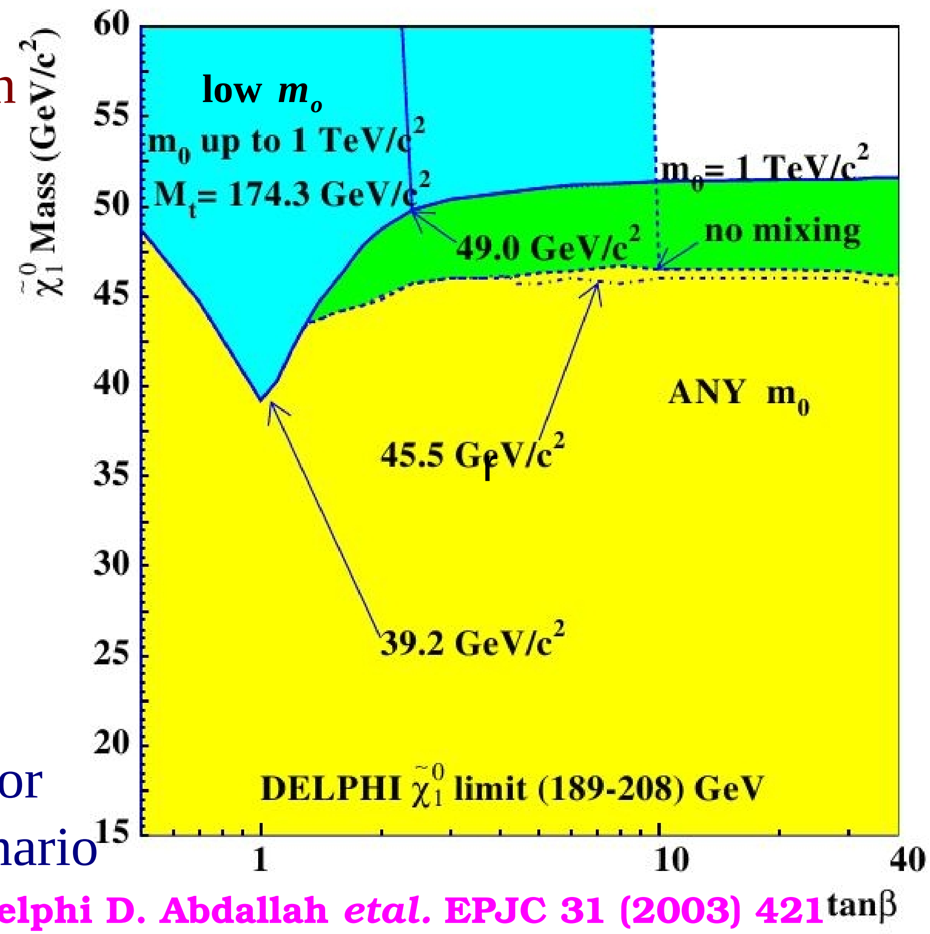
dashed curve :
assuming any m_o no mixing in the 3rd generation

dot-dashed curve :
assuming any m_o, allowing for mixing in the 3rd generation with $A_\tau = A_b = A_t = 0$

vertical solid line :
effect of h search in the max m_h scenario

vertical dashed line :
effect of h search in the no mixing scenario

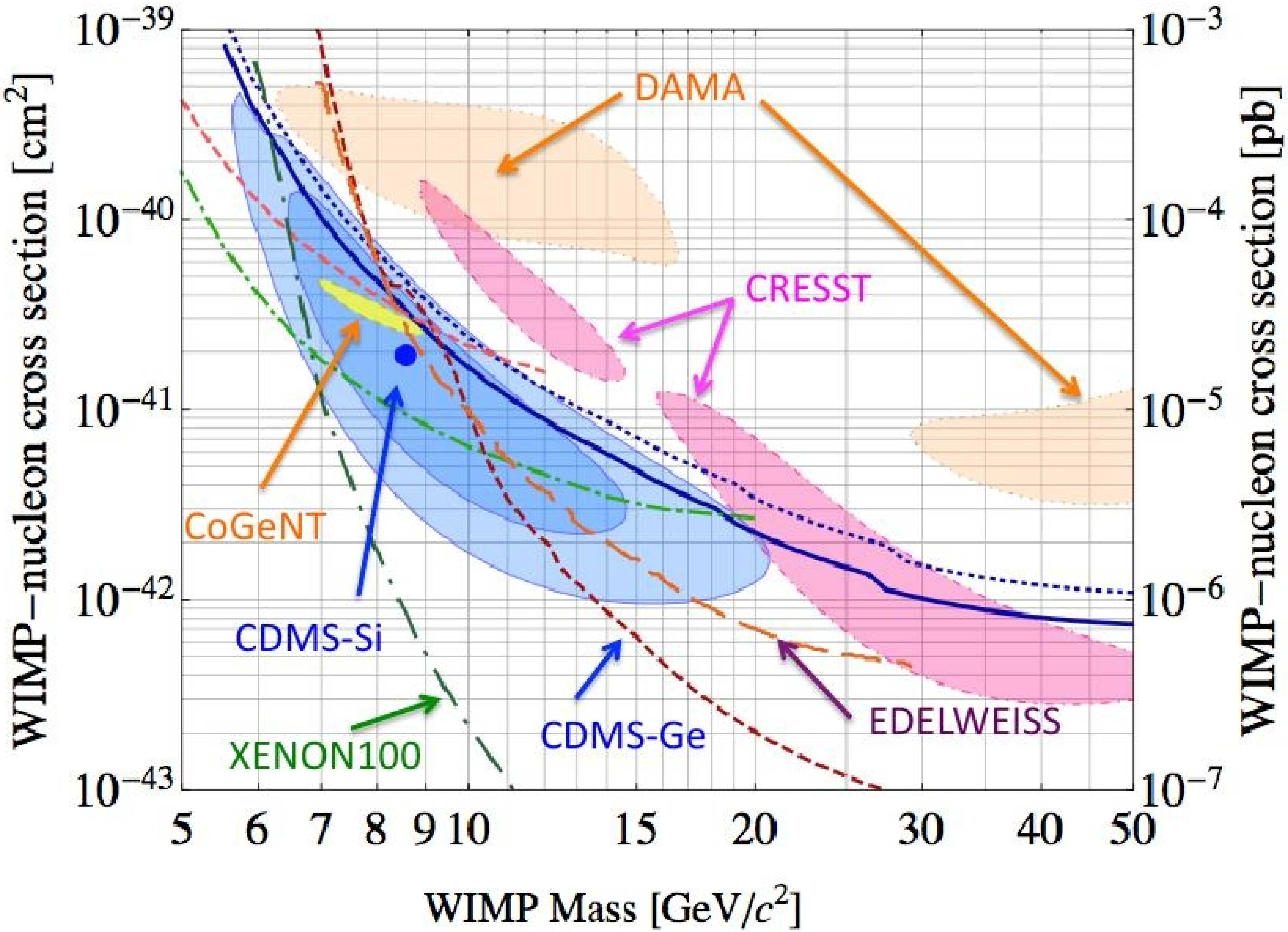
the 49 GeV limit claimed in the refered paper is for m_o up to 1 TeV, and h search in the max m_h scenario



Delphi D. Abdallah *etal.* EPJC 31 (2003) 421

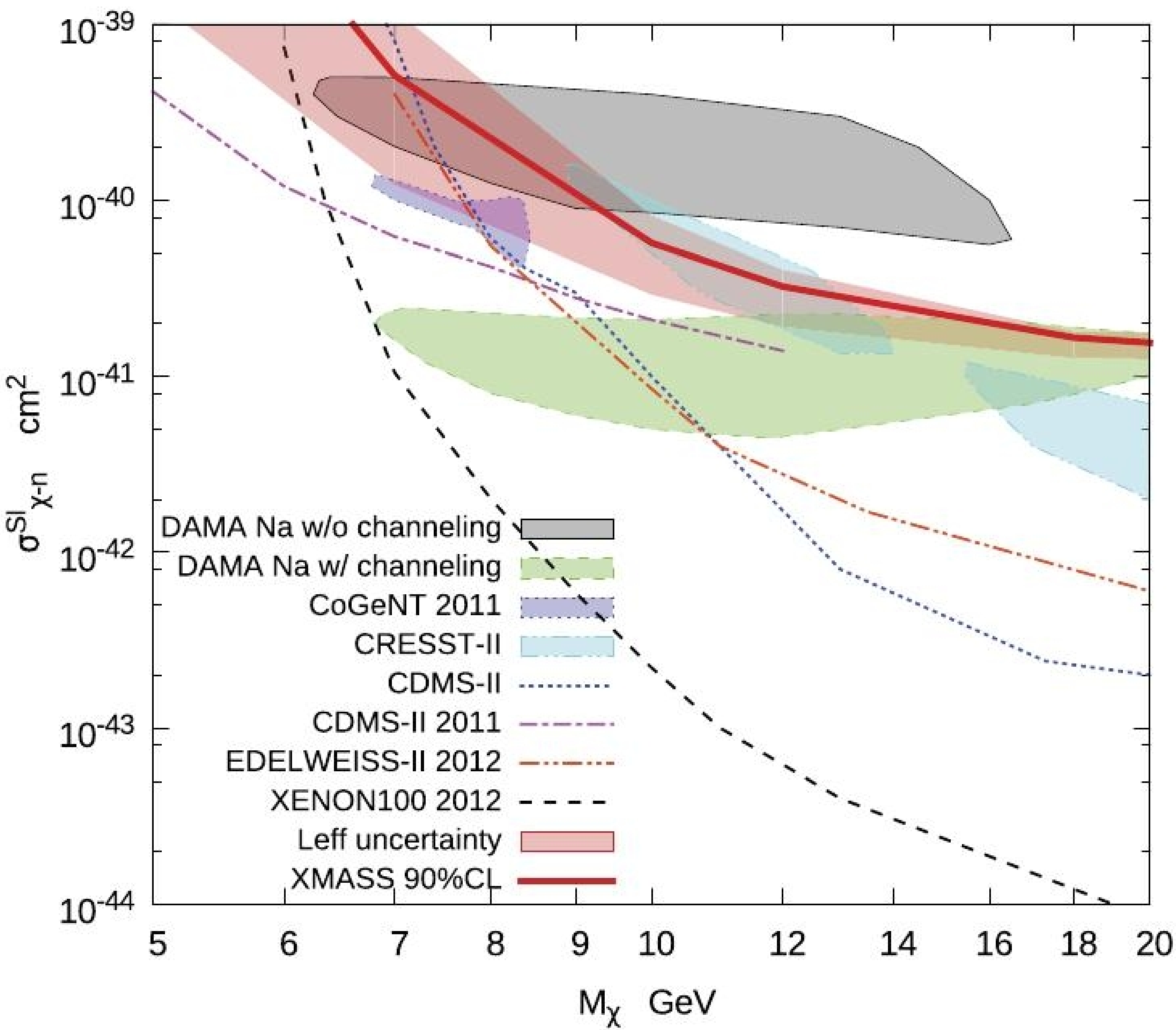
Dark Matter direct detection

DAMA, CoGent, Cresst and CDMS claim a signal in the low mass region



CDMS-Si best fit point $m_\chi = 8.6$ **GeV and** $\sigma_\chi = 1.9\times10^{-41}$ **cm^2**

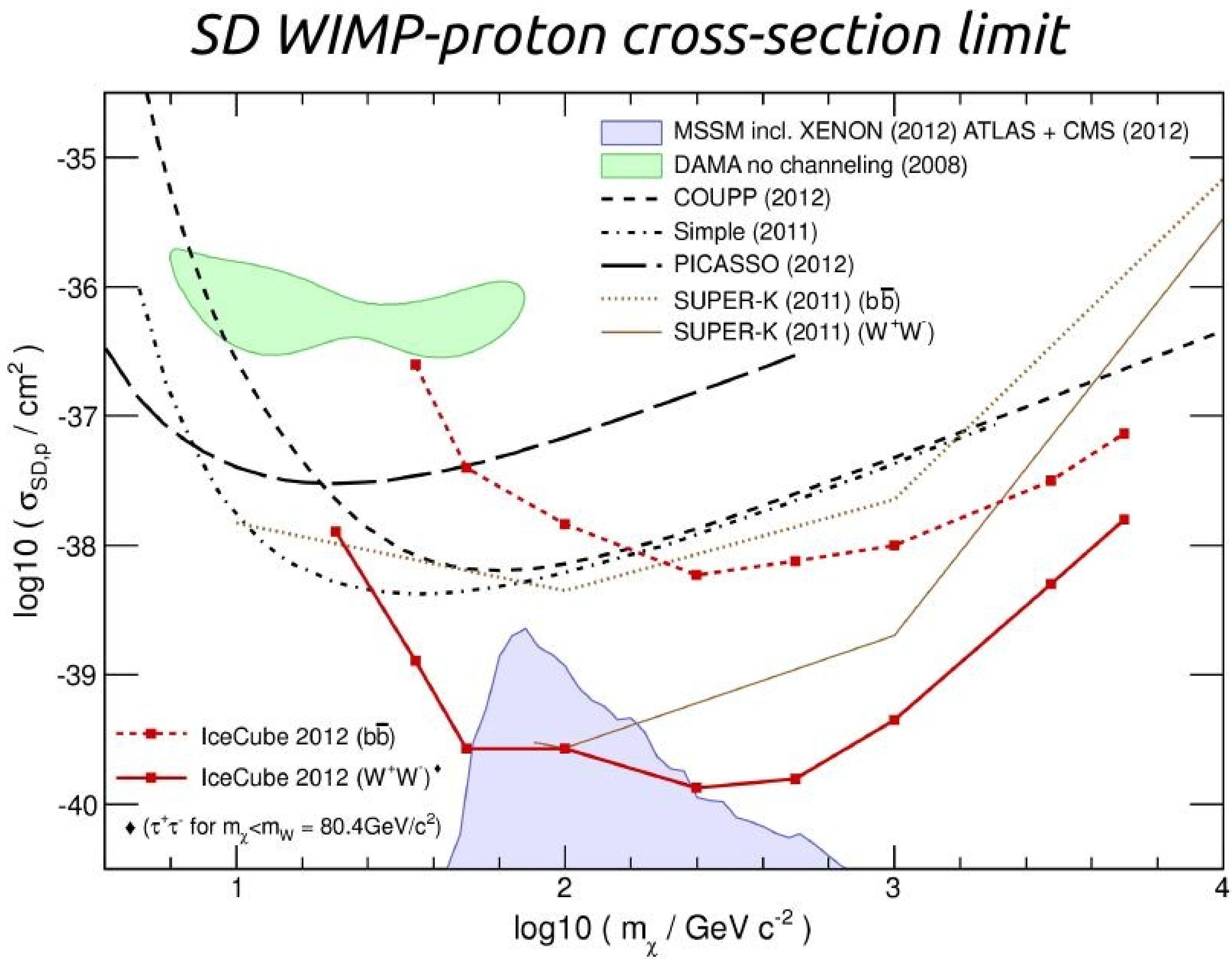
Dark Matter direct detection



from XMASS K. Abe *etal.* PLB 719 (2013) 78

Dark Matter direct detection

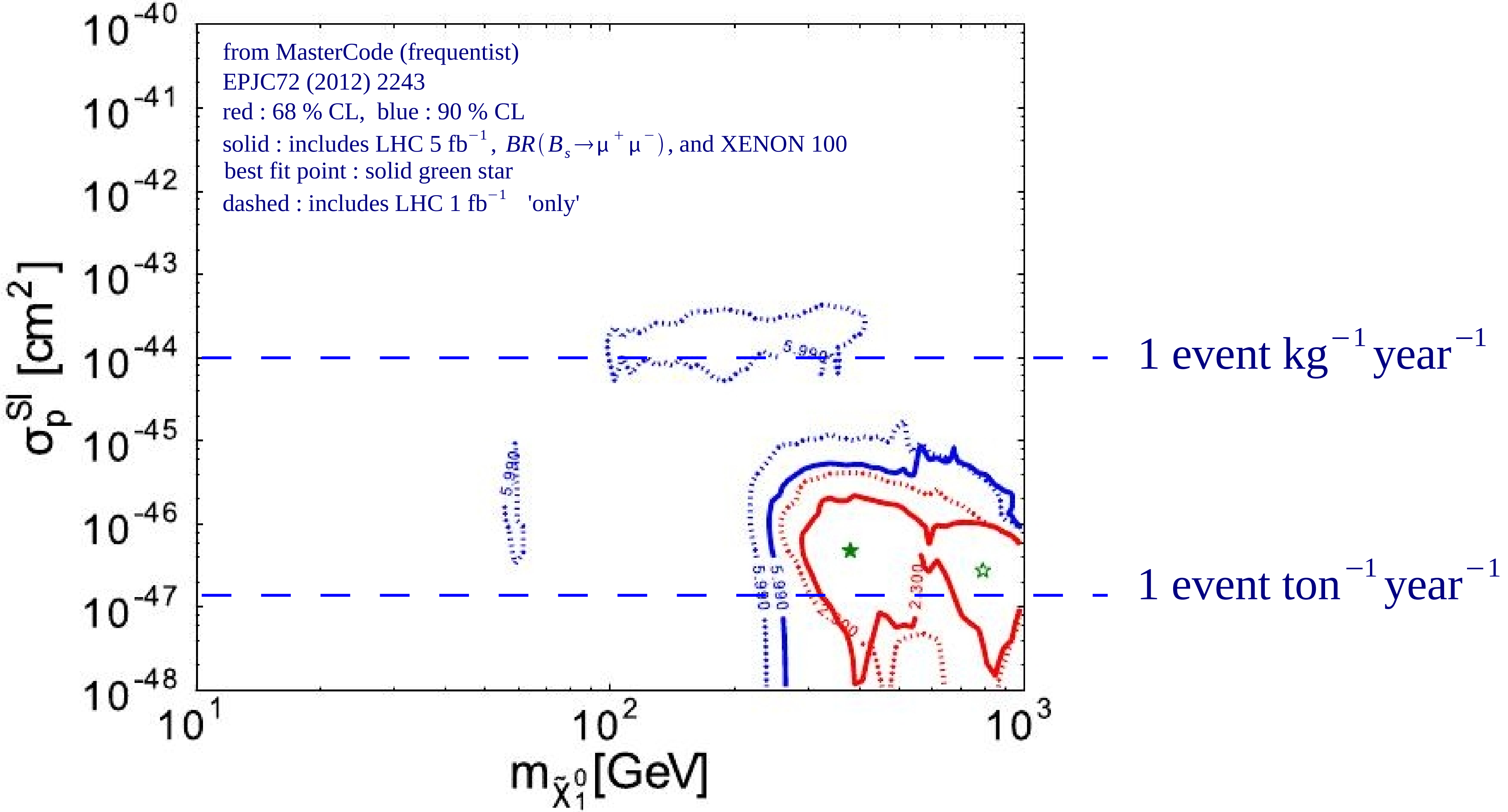
Contribution from IceCube → strongest constraints on SD Xsection



Dark Matter : global fit "MasterCode"

SUSY: scattering cross section on nucleons down to $\sim 10^{-48}$ cm^2 (10^{-13} pb)

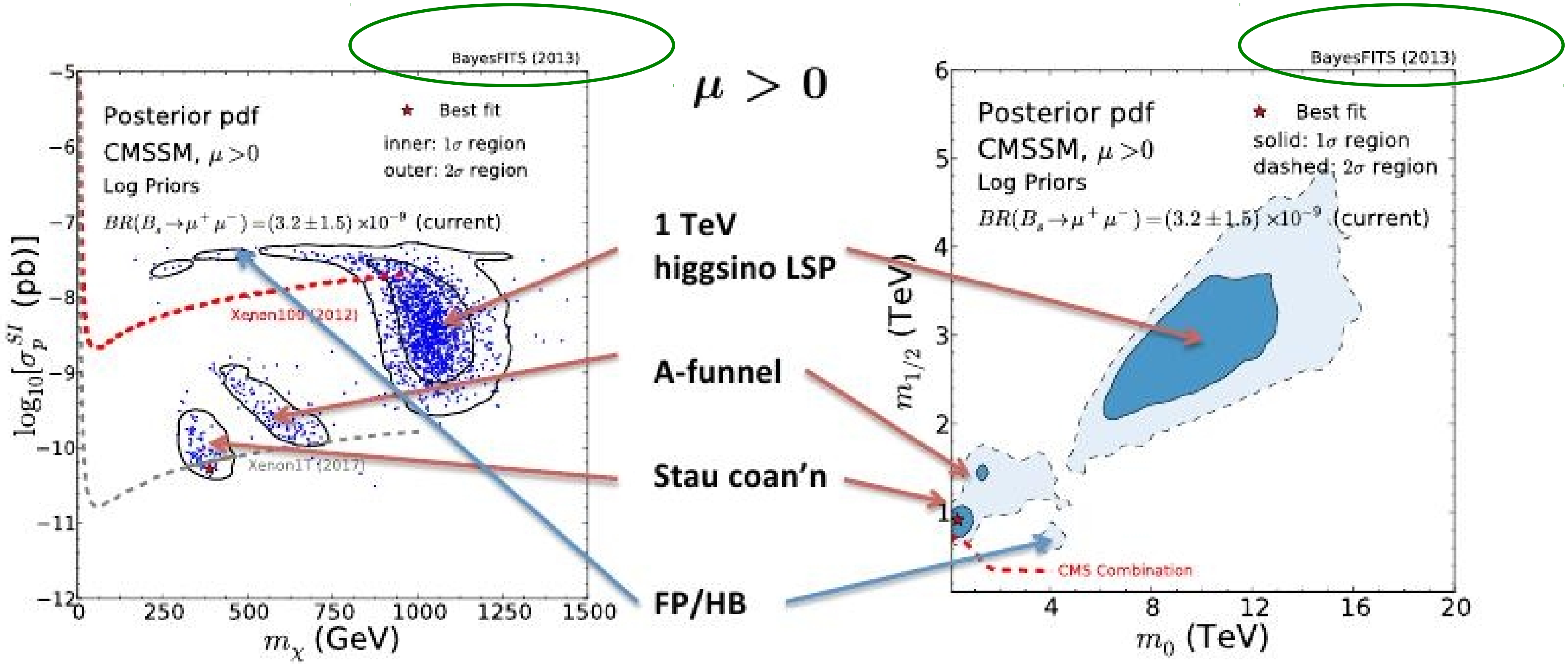
example with CMSSM after LHC 5 fb^{-1}, XENON 100 and $B_s \to \mu^+\mu^-$



from L. Baudis Talk EPS HEP 2013

Dark Matter " global fit "BayesFITS"

CMSSM and 1-tonne DM detectors



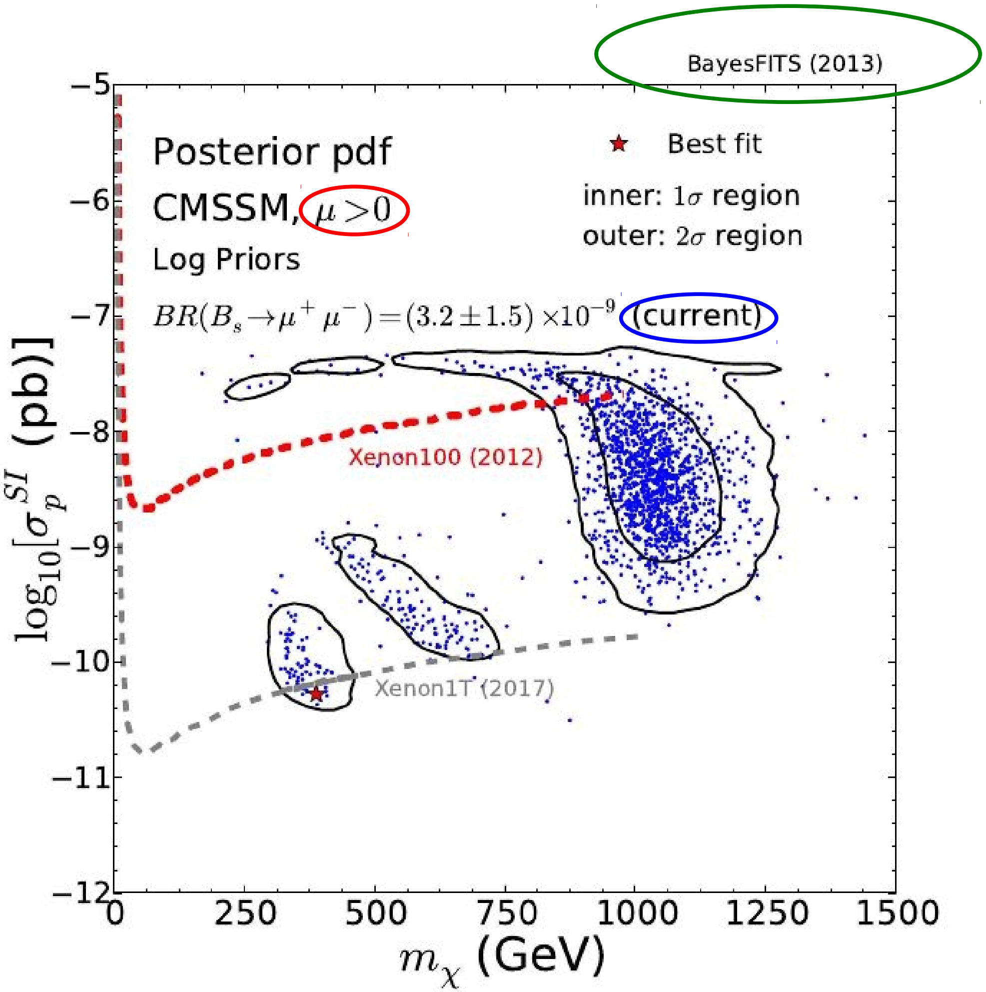
1-tonne DM detectors to cover most of CMSSM predictions

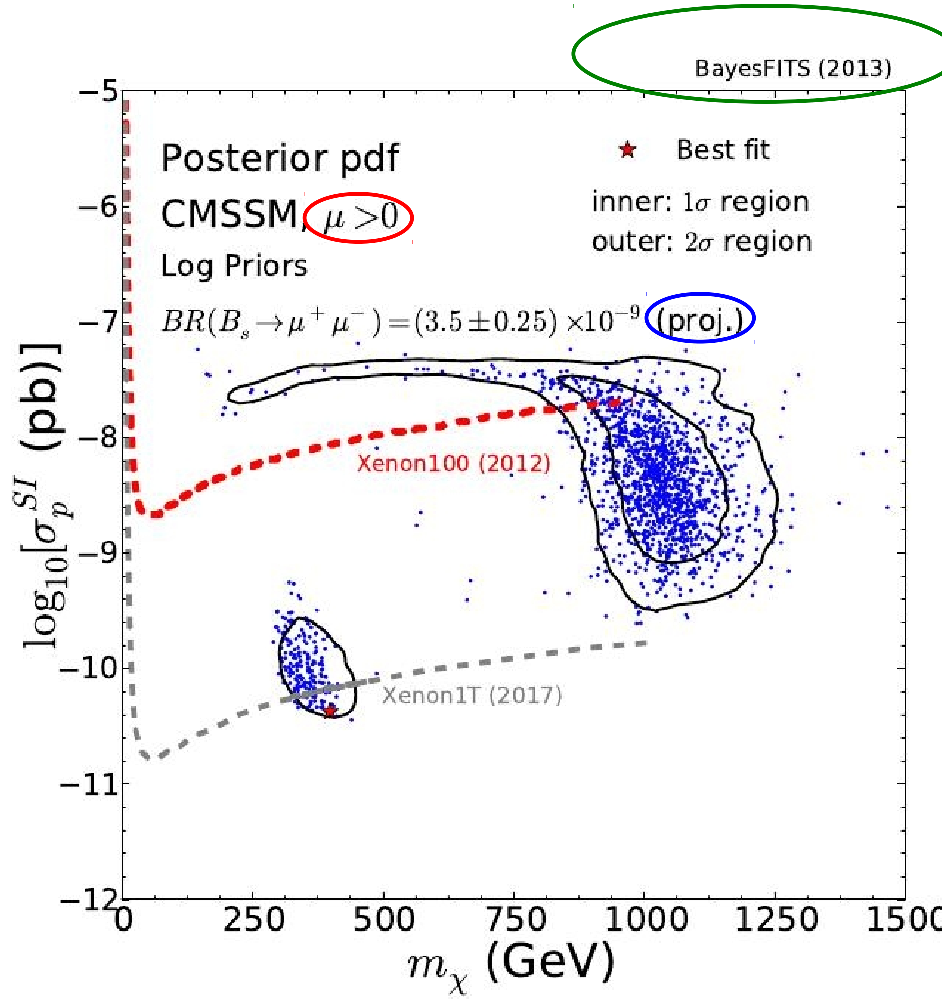
Kowalska, Roszkowski, Sessolo, JHEP 06 (2013) 078

from Roszkowski talk Moriond QCD 2013

Dark Matter " global fit "BayesFITS"

if $BR(B_s \to \mu^+ \mu^-) \simeq SM$ value with 5-10% precision $\Rightarrow$ A funnel region gone





Kowalska, Roszkowski, Sessolo, JHEP 06 (2013) 078

ways to rule out CMSSM (with $\mu > 0$) :

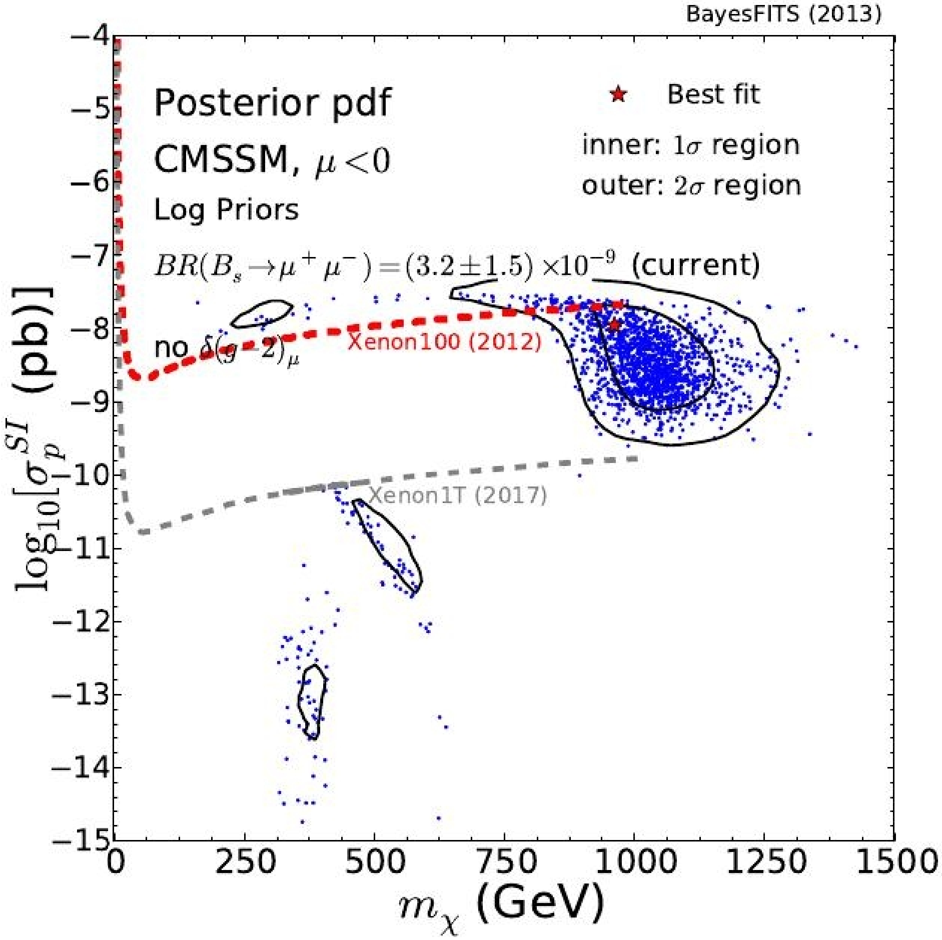
- no DM signal in 1 ton detectors

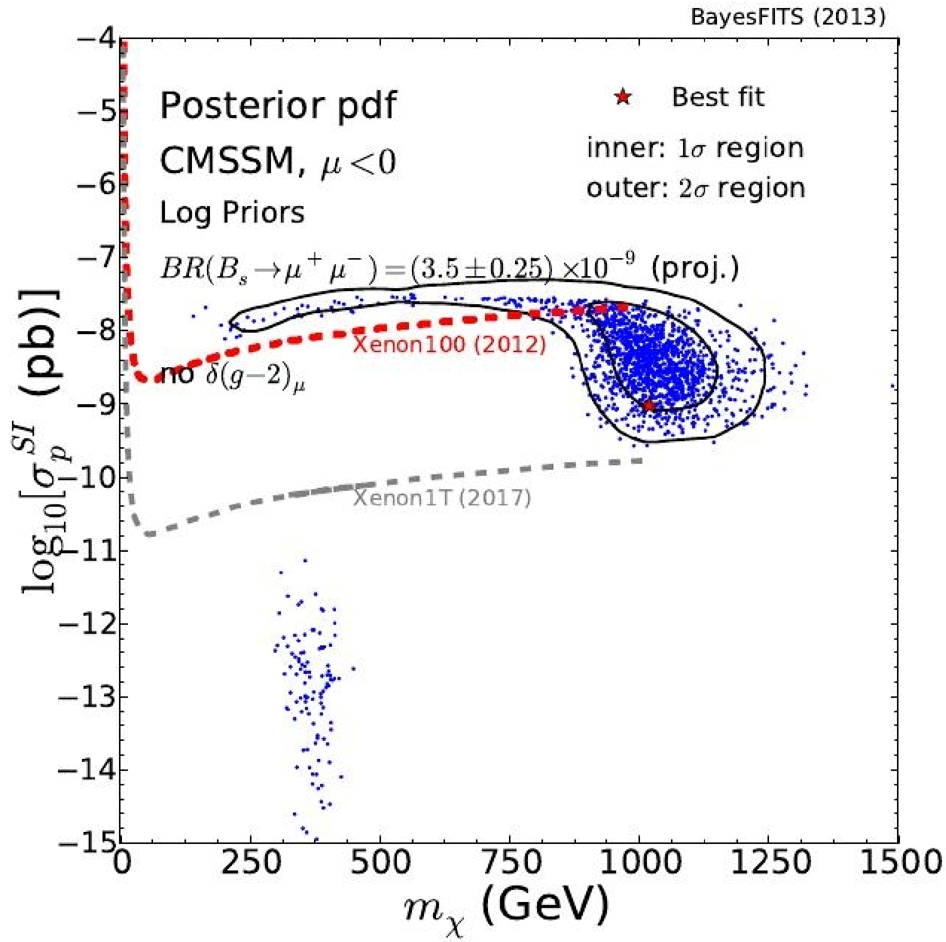
- DM signal at ~ 500-750 GeV

situation changes a bit for $\mu < 0$
(see next slide)

from Roszkowski talk Moriond QCD 2013

Dark Matter " global fit "BayesFITS"





Kowalska, Roszkowski, Sessolo, JHEP 06 (2013) 078

Dark Matter : beyond CMSSM

one can now depart from CMSSM often considered as to restrictive

⇒ 2 examples of alternatives:

example 1 : 'non universal Higgs mass models' NUHM
i.e. one or two non-universal supersymmetry-breaking
parameters contributing to the Higgs masses (NUHM1,2)

example 2 : 'phenomenological MSSM' pMSSM i.e. a MSSM version
without the 100++ parameters but a subsample of them
with no assumption at high scale but assuming :

- CP-conserving MSSM (no new CP phases)
- MFV
- first two generations of sfermions degenerate

19 parameters in pMSSM

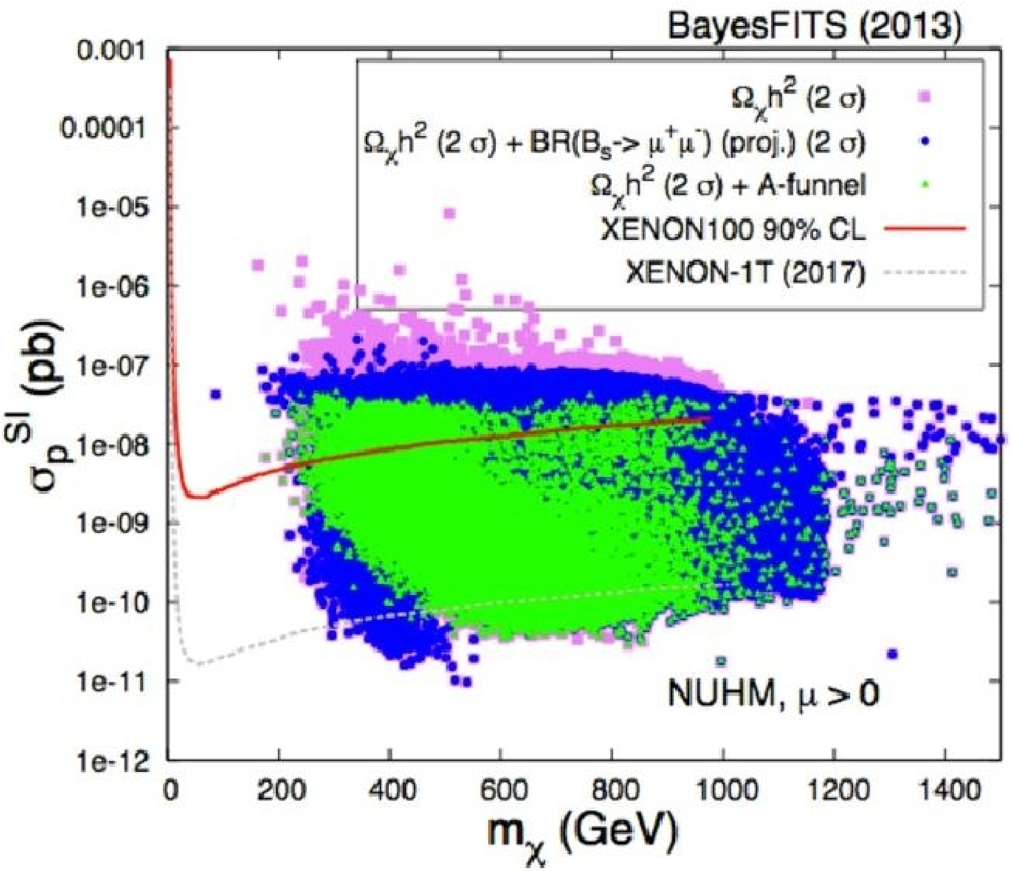
Dark Matter : beyond CMSSM → NUHM

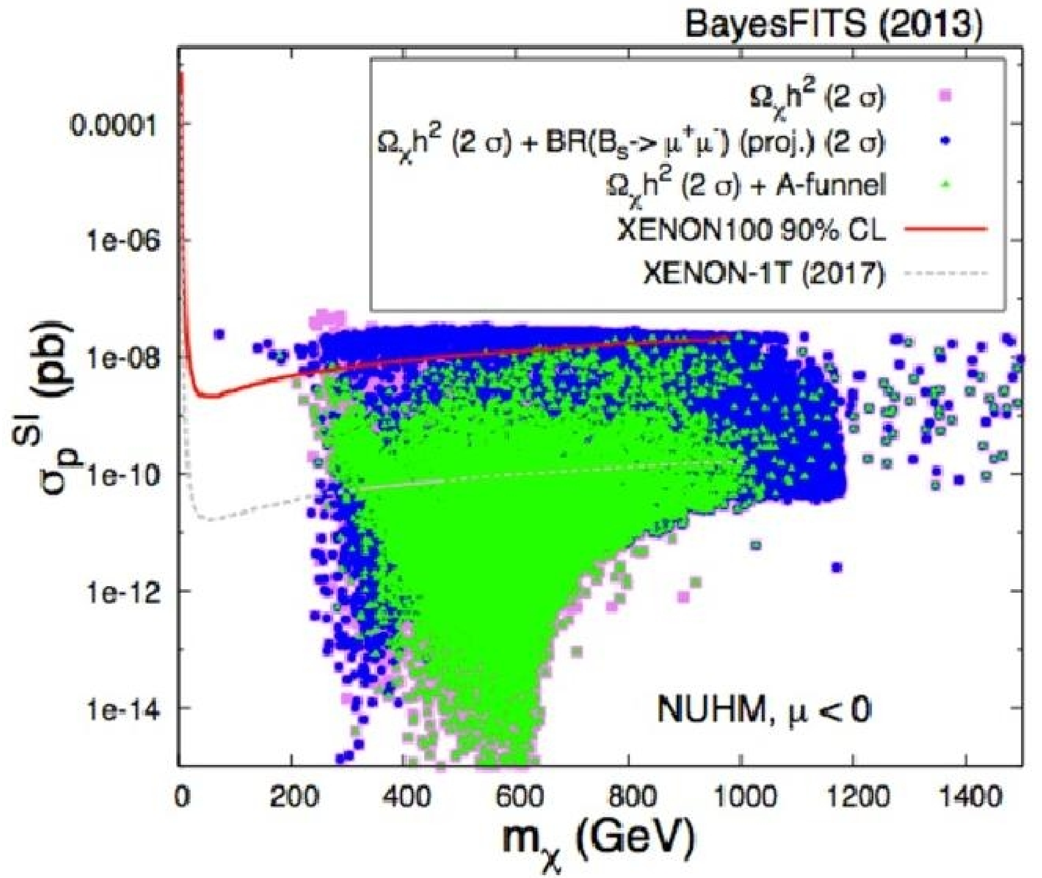
example 1 : 'non universal Higgs mass models' NUHM
i.e. one or two non-universal supersymmetry-breaking parameters contributing to the Higgs masses (NUHM1,2)

NUHM parameter	Description	Prior Range	Prior Distribution
m_0	Universal scalar mass	0.1, 4 (0.1, 20*)	Log (Linear)
$m_{1/2}$	Universal gaugino mass	0.1, 4 (0.1, 10)	Log (Linear)
A_0	Universal trilinear coupling	-7, 7 (-20, 20)	Linear
$\tan\beta$	Ratio of Higgs vevs	15, 35 (3, 62)	Linear
$\text{sgn}\,\mu$	Sign of Higgs parameter	$+1$ or -1	Fixed
m_{H_u}	GUT-scale soft mass of H_u	0.1, 4 (0.1, 20)	Linear
m_{H_d}	GUT-scale soft mass of H_d	0.1, 4 (0.1, 20)	Linear
Nuisance parameters like in the CMSSM			

Kowalska, Roszkowski, Sessolo, JHEP 06 (2013) 078

Dark Matter : beyond CMSSM → NUHM





pink square points satisfy : $\Omega_X h^2$ @ 2σ

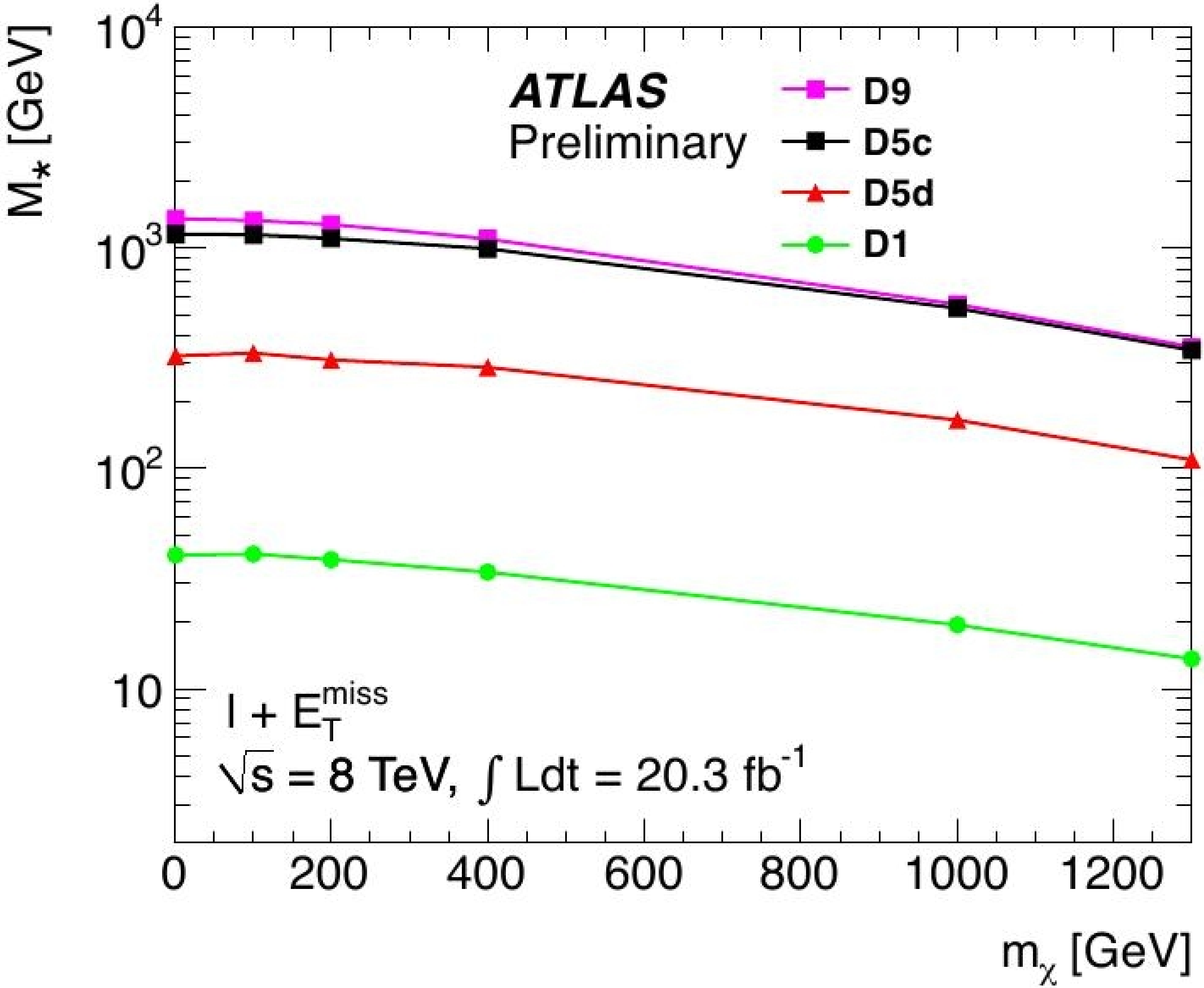
blue circle points satisfy : $\Omega_X h^2 + BR\left(B_S \rightarrow \mu^+ \mu^-\right)$ @ 2σ

green triangle points satisfy : $\Omega_X h^2$ @ 2σ + $|m_A - 2m_\chi| < 100$ GeV

the A funnel region will remain prominently allowed even if a future determination of $BR\left(B_s \rightarrow \mu^+ \mu^-\right)$ will narrow it down to basically the SM value

mono W

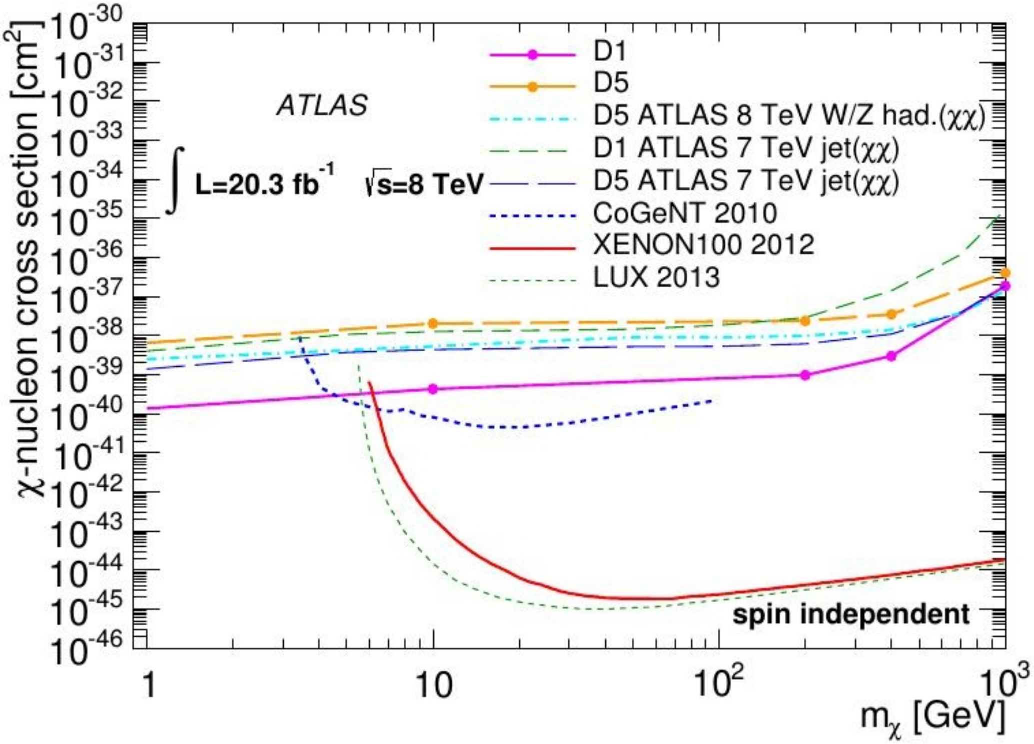
(leptonic decays)

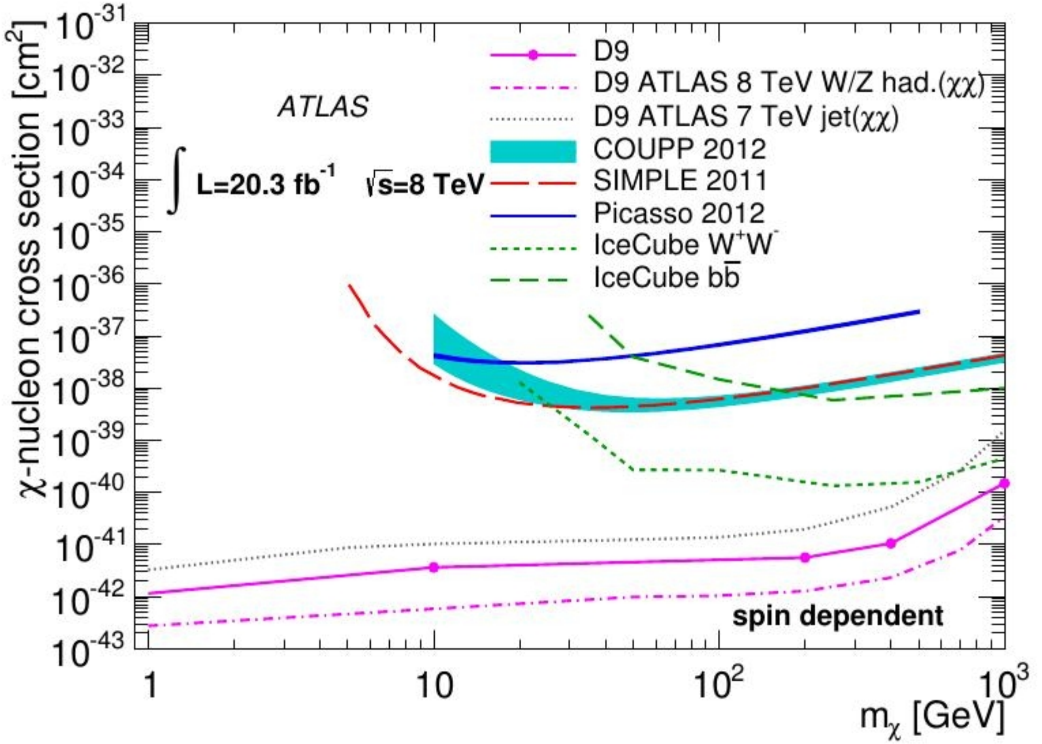


Atlas-conf-2014-017

mono Z

(leptonic decays)

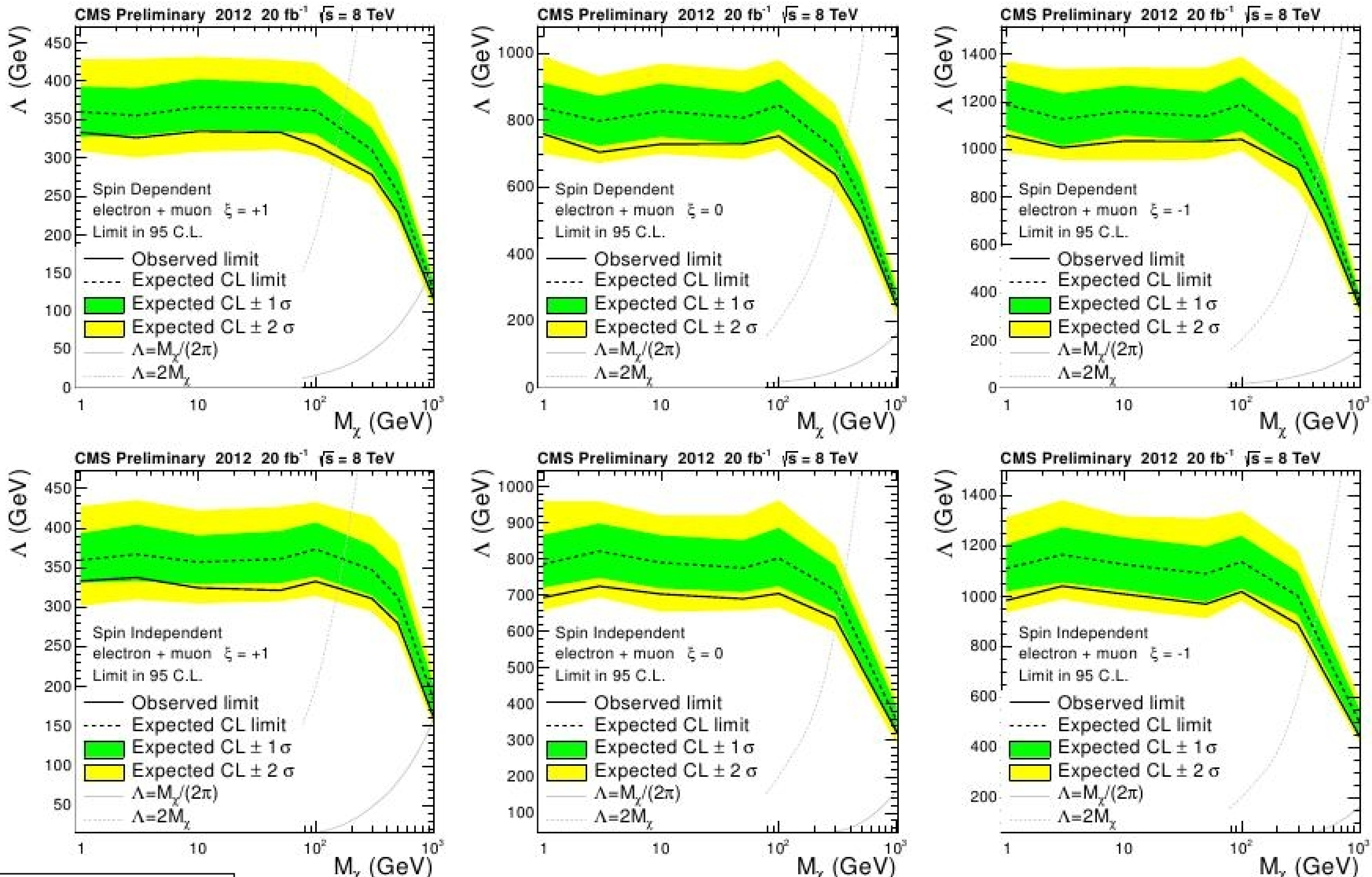


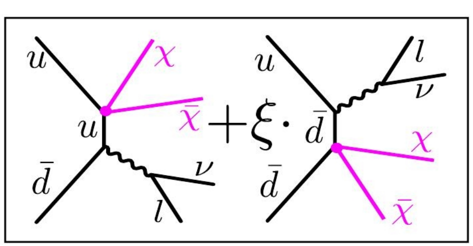


arXiv:1404.0051

mono W and Z

(leptonic decays)

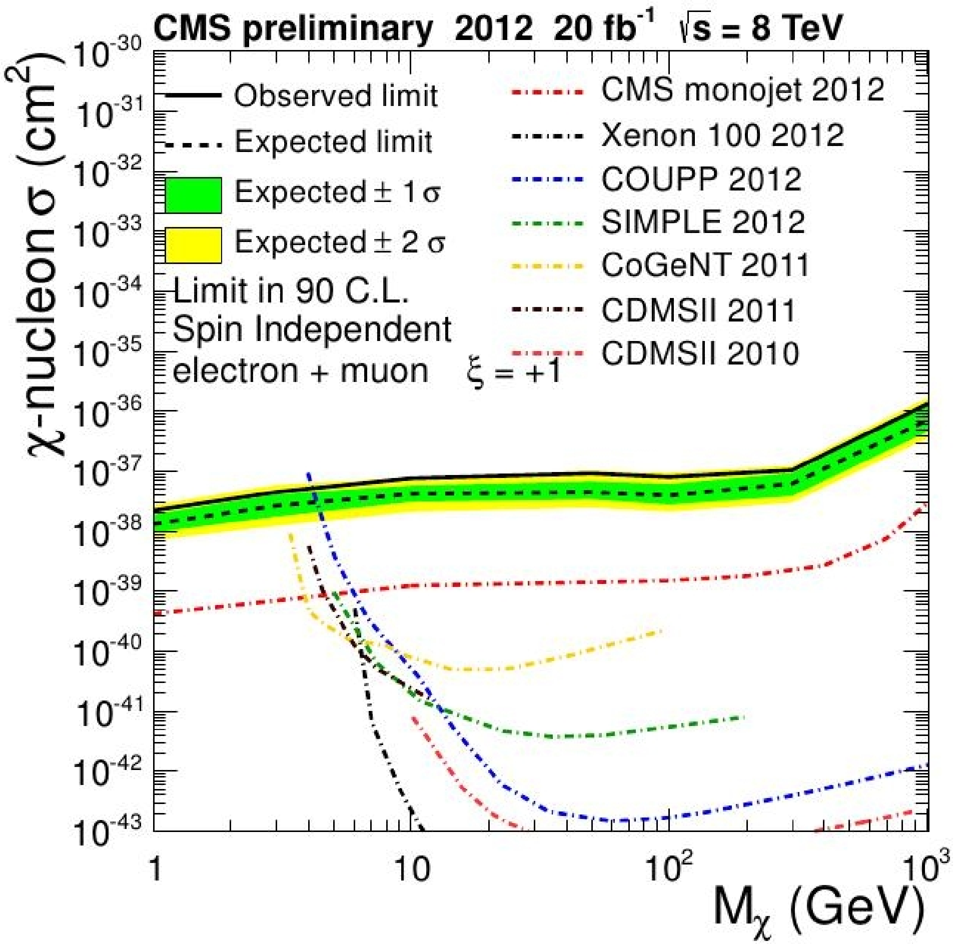


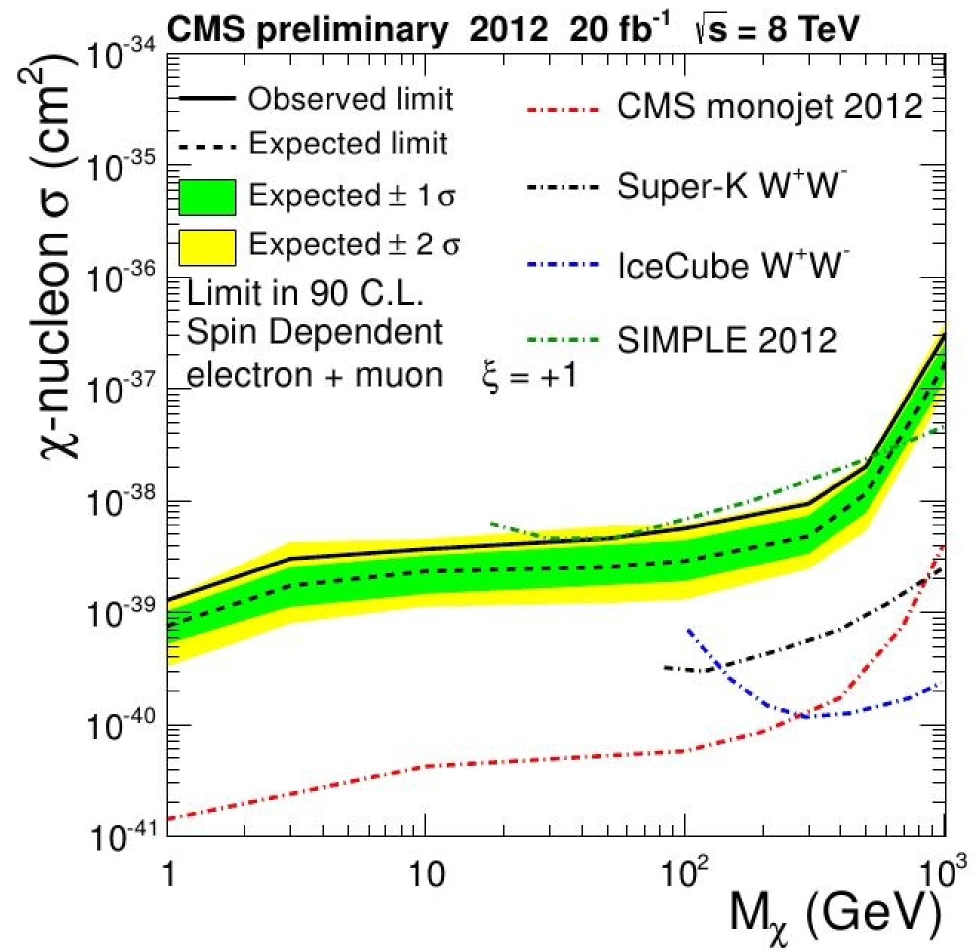


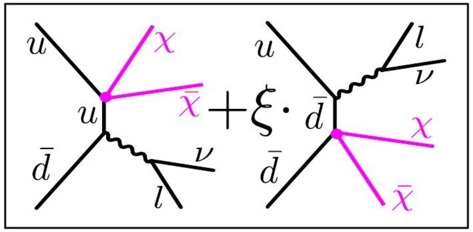
CMS-PAS-EXO-13-004

mono W and Z

(leptonic decays)



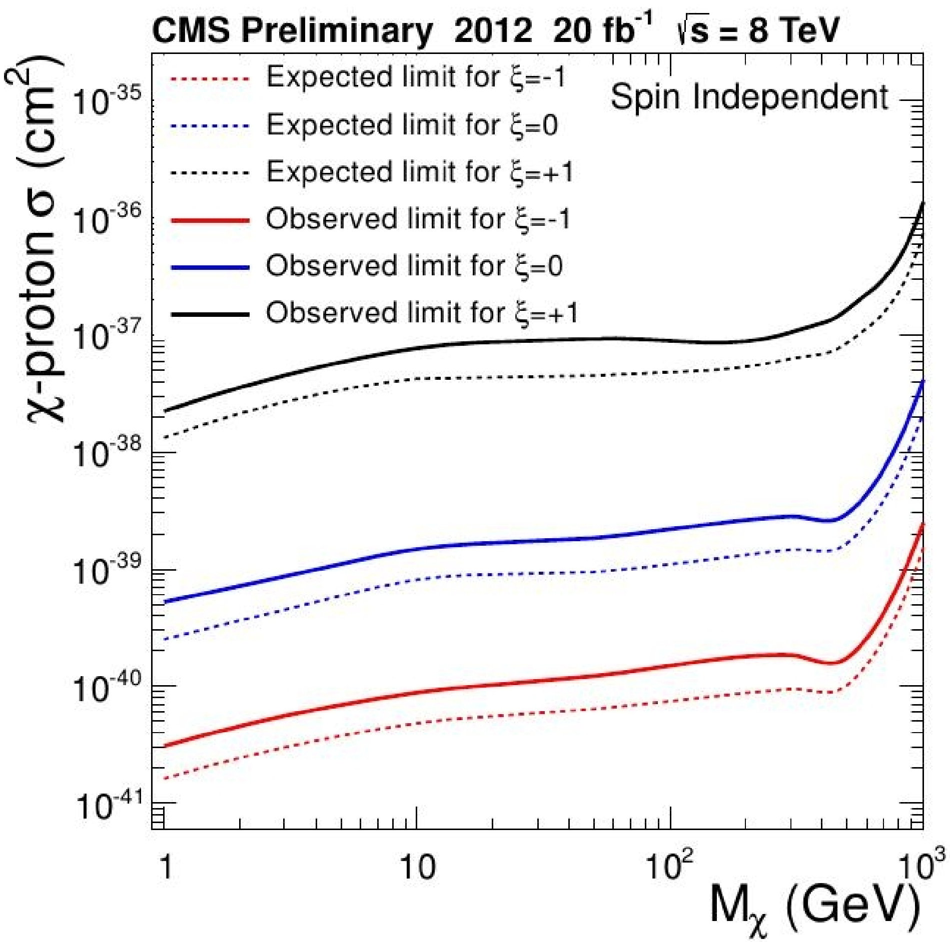


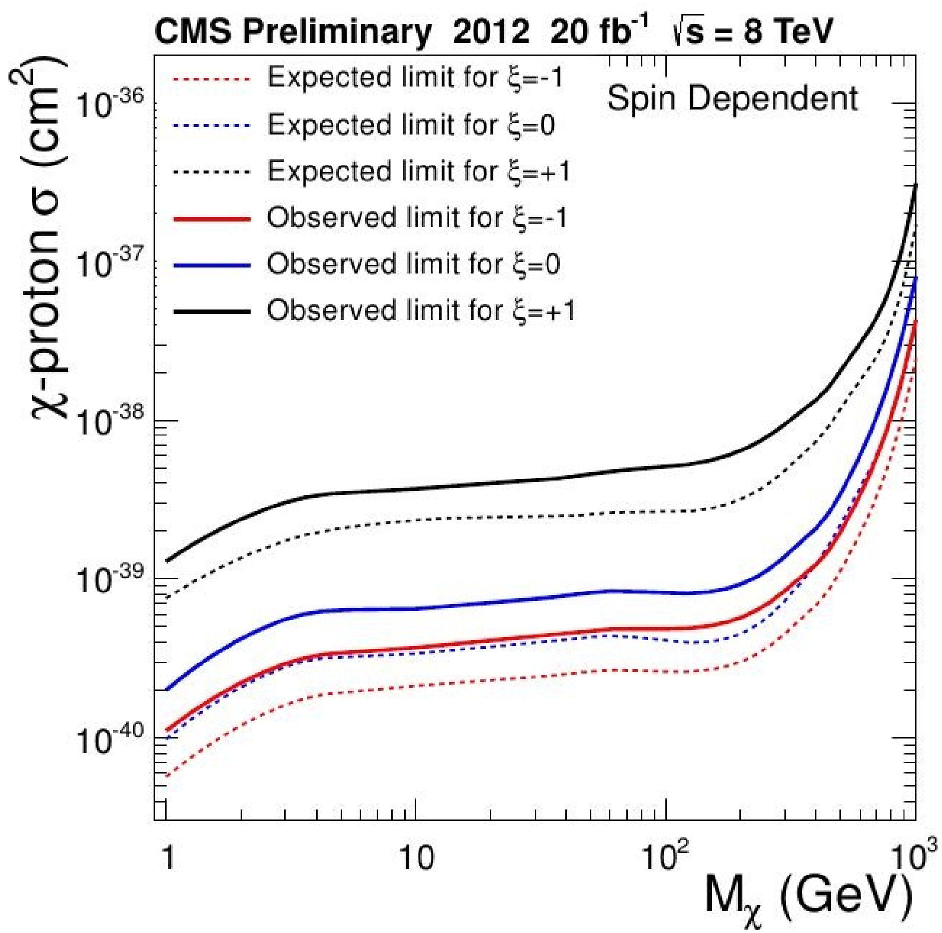


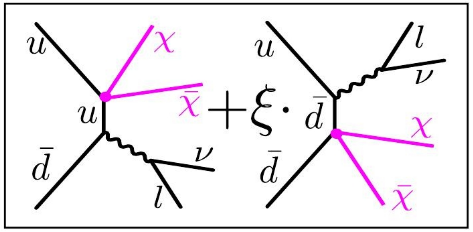
CMS-PAS-EXO-13-004

mono W and Z

(leptonic decays)



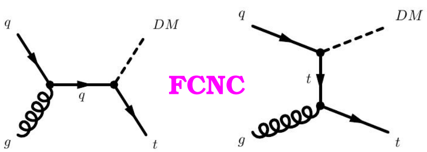




CMS-PAS-EXO-13-004

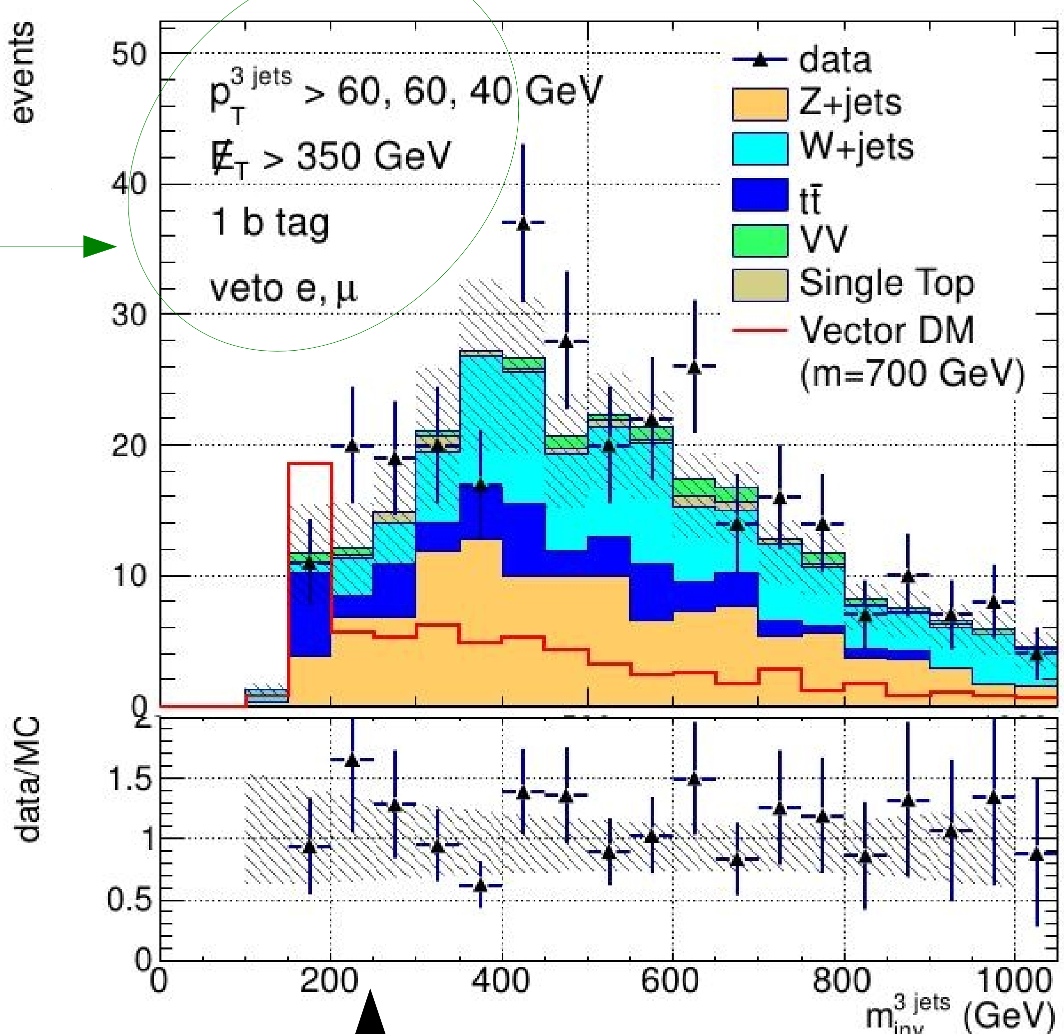
mono top

with hadronically decaying top quark



3 jets + MET final state

event selection



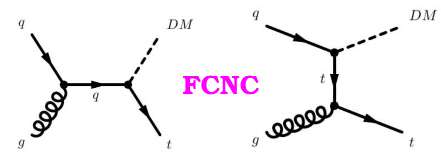
$m_{inv}^{3\ jets} < 250$ GeV

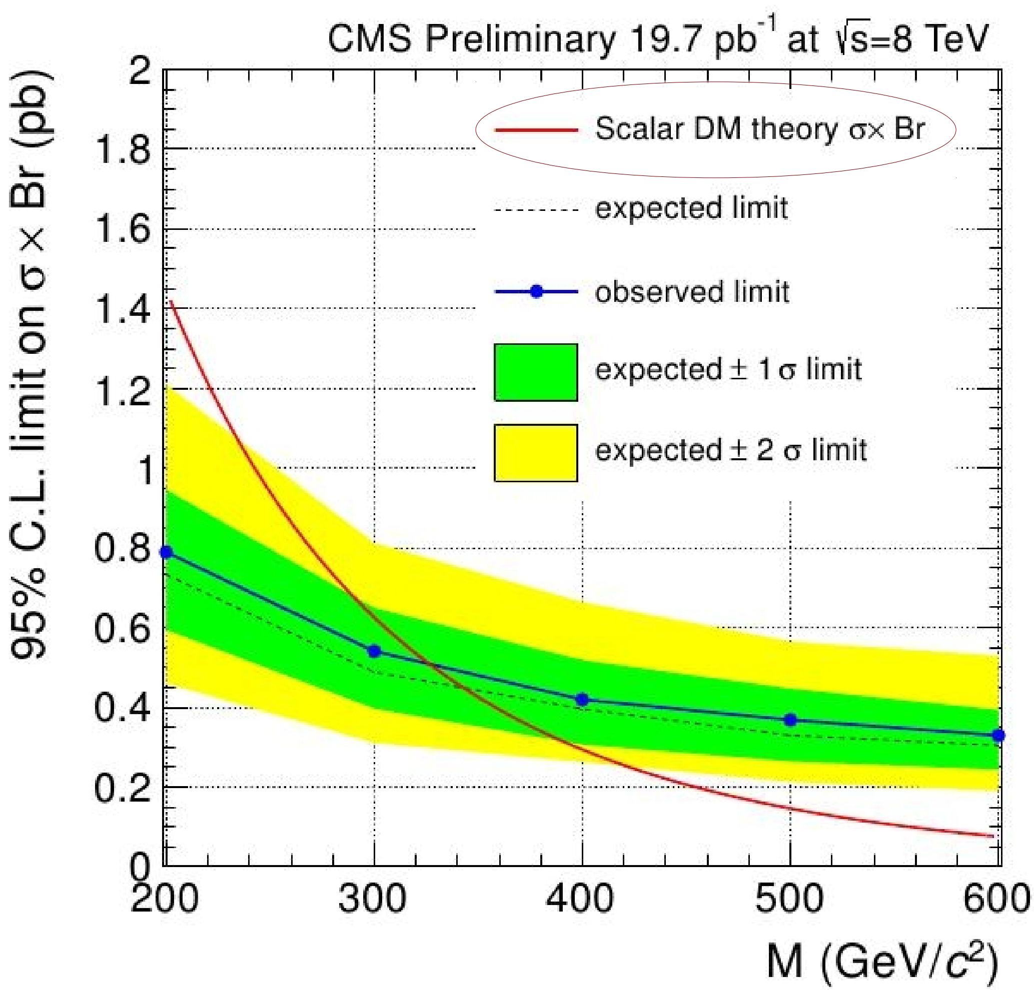
CMS-PAS-B2G-12-022

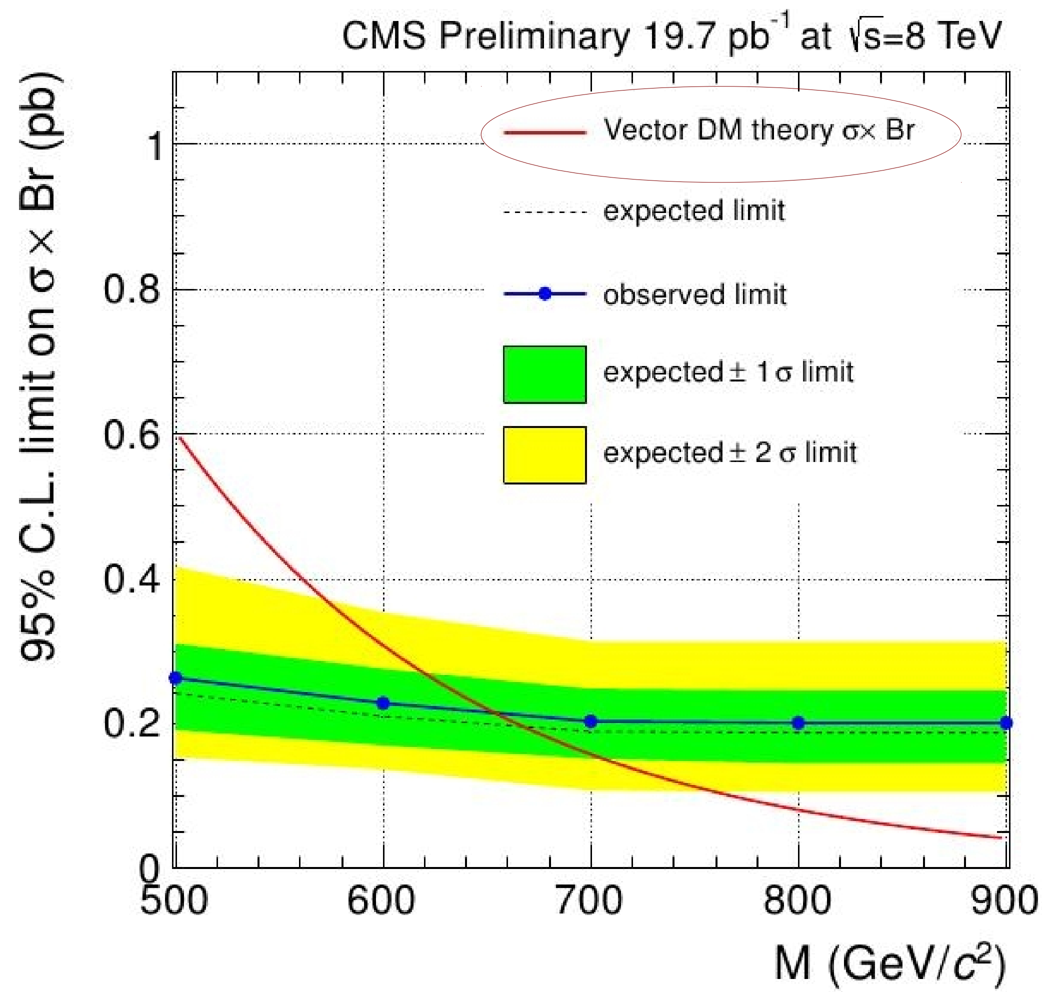
mono top

with hadronically decaying top quark

3 jets + MET final state







CMS-PAS-B2G-12-022

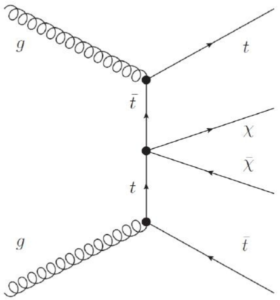
di-top

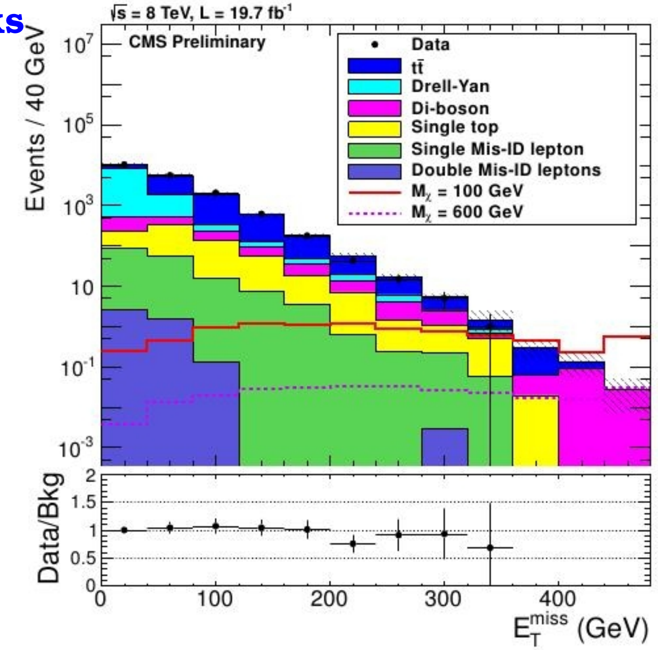
with leptonically decaying top quarks

D1 type effective term

$$L_{\text{int}} = \frac{m_q}{M_*^3} q \bar{q} \bar{\chi} \chi$$

proportional to quark mass





isolated e and μ with

$p_T^e > 20$ GeV, $|\eta^e| < 2.5$, $p_T^\mu > 20$ GeV, $|\eta^\mu| < 2.4$

require exactly 2 leptons and at least 2 jets

$p_T^{\text{jet}} > 30$ GeV , $|\eta^{\text{jet}}| < 5$

$m_{ll} > 20\,\text{GeV}$

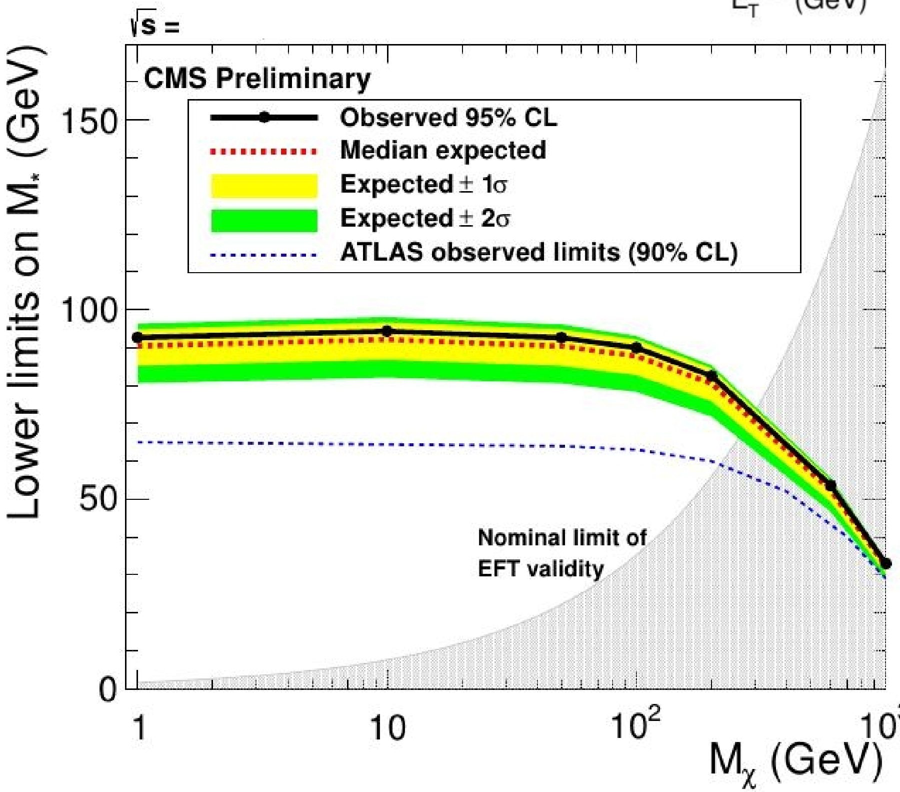
$|m_{ee} - 91\ \text{GeV}|$ and $|m_{\mu\mu} - 91\ \text{GeV}| > 15$ GeV

scalar sum of 2 jets p_T < 400 GeV

scalar sum of 2 leptons p_T < 120 GeV

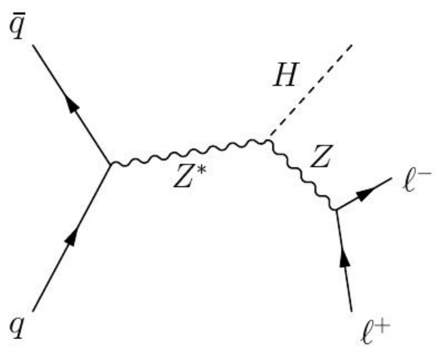
$$E_T^{\text{miss}} > 320 \text{ GeV}$$

Total Bkg	$1.89 \pm 0.53 \pm 0.39$
Data	1
Signal	$1.88 \pm 0.11 \pm 0.07$

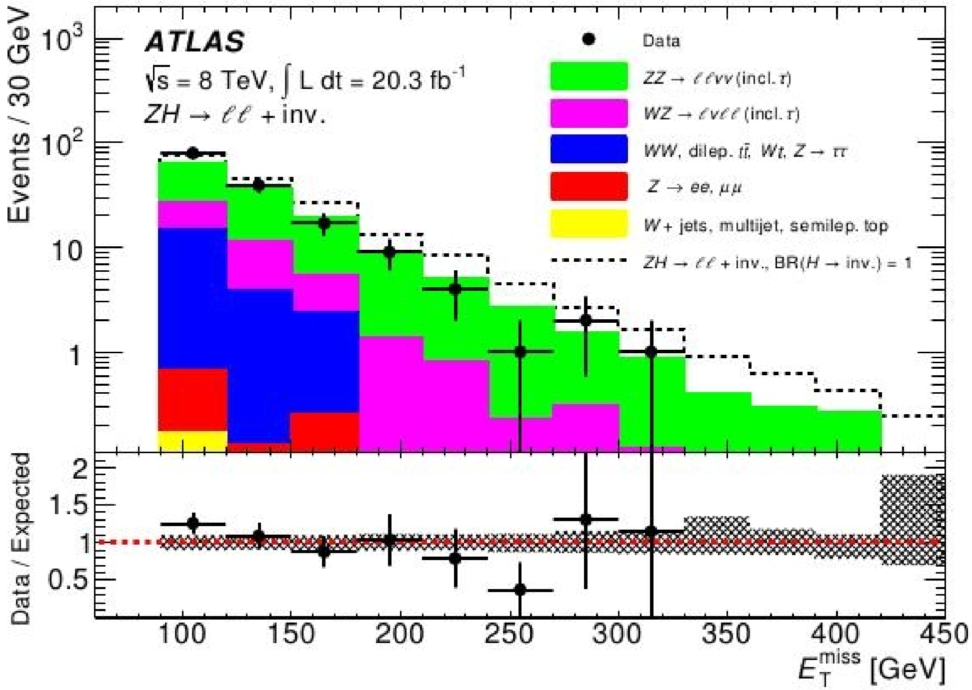


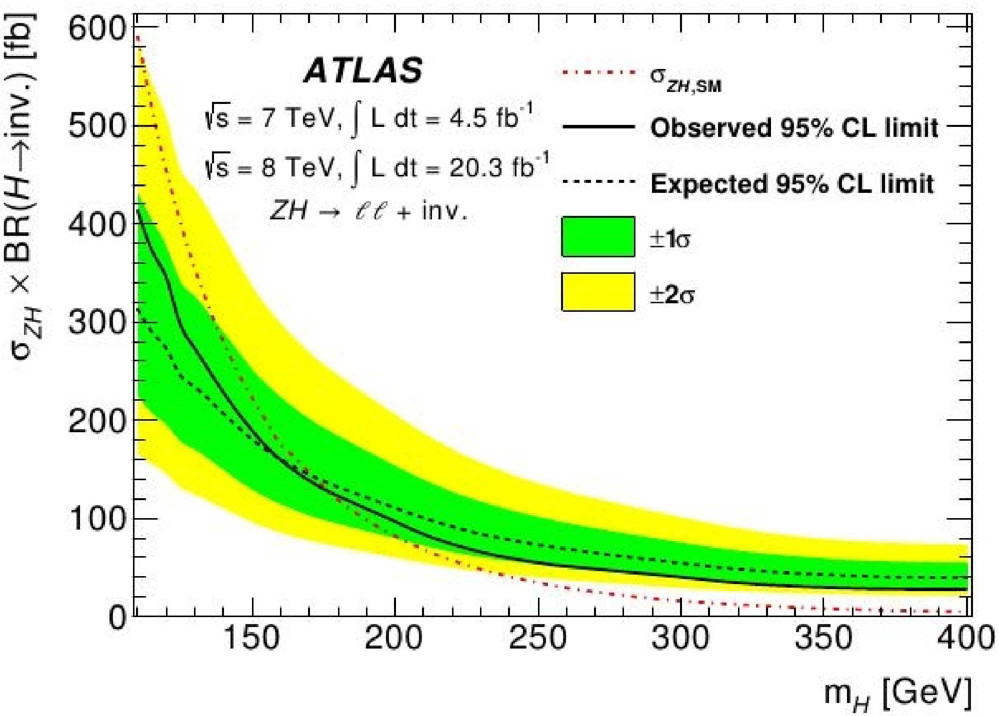
CMS-PAS-B2G-13-004

Z(ll) Higgs



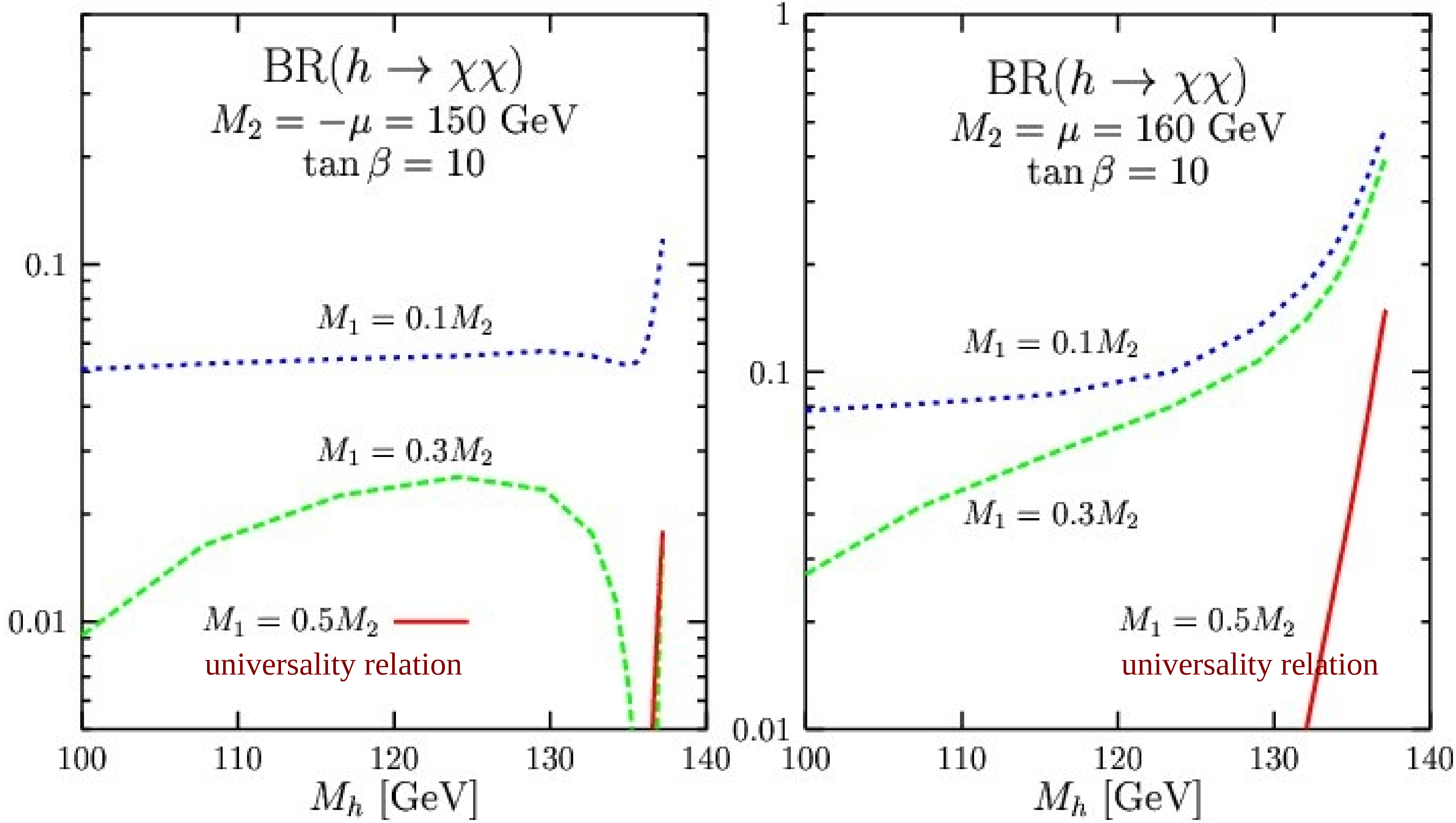
Data Period	2011 (7 TeV)	2012 (8 TeV)
$ZZ \to \ell\ell\nu\nu$	$20.0 \pm 0.7 \pm 1.6$	$91 \pm 1 \pm 7$
$WZ \to \ell\nu\ell\ell$	$4.8 \pm 0.3 \pm 0.5$	$26 \pm 1 \pm 3$
Dileptonic $t\bar{t}$, Wt, WW, $Z \to \tau\tau$	$0.5 \pm 0.4 \pm 0.1$	$20 \pm 3 \pm 5$
$Z \to ee$, $Z \to \mu\mu$	$0.13 \pm 0.12 \pm 0.07$	$0.9 \pm 0.3 \pm 0.5$
W + jets, multijet, semileptonic top	$0.020 \pm 0.005 \pm 0.008$	$0.29 \pm 0.02 \pm 0.06$
Total background	$25.4 \pm 0.8 \pm 1.7$	$138 \pm 4 \pm 9$
Signal (m_H = 125.5 GeV, $\sigma_{SM}(ZH)$, BR($H \to$ inv.) = 1)	$8.9 \pm 0.1 \pm 0.5$	$44 \pm 1 \pm 3$
Observed	28	152





arXiv:1402.3244

Invisible Higgs boson decay



Djouadi hep-ph/0503173

when kinematically allowed → sizable $BR\left(h \to \tilde{\chi}_1^o \tilde{\chi}_1^o\right)$

in particular when universality relation are relaxed

which leads to lighter LSP while the (LEP) bound $m_{\tilde{\chi}_1^\pm} < 104$ GeV is still respected

Invisible Higgs boson decay

if the DM candidate has mass below $\frac{m_h}{2}$ the invisible Higgs boson decay width Γ_{inv} can be directly translated to the spin-independent DM-nucleon elastic cross section as follows for scalar (S) vector (V) and fermionic (f) DM respectively

$$\sigma^{\text{SI}}_{\text{S-N}} = \frac{4\,\Gamma_{\text{inv}}}{m_h^3 v^2 \beta} \frac{m_N^4 f_N^2}{\left(M_\chi + m_N\right)^2}$$

$$\sigma^{\text{SI}}_{\text{V-N}} = \frac{16\,\Gamma_{\text{inv}} M_\chi^4}{m_h^3 v^2 \beta \left(m_h^4 - 4 M_\chi^2 m_h^2 + 12 M_\chi^4\right)} \frac{m_N^4 f_N^2}{\left(M_\chi + m_N\right)^2}$$

$$\sigma^{\text{SI}}_{\text{f-N}} = \frac{8\,\Gamma_{\text{inv}} M_\chi^2}{m_h^5 v^2 \beta^3} \frac{m_N^4 f_N^2}{\left(M_\chi + m_N\right)^2}$$

with $\beta_\chi = \sqrt{1 - 4\frac{m_\chi^2}{m_h^2}}$ and using $BR\left(H \rightarrow \text{inv}\right) = \frac{\Gamma_{inv}}{\left(\Gamma_{\text{SM}} + \Gamma_{\text{inv}}\right)}$

Djouadi, Lebedev, Mambrini, Quevillon, PLB709 (2012) 65

Invisible Higgs boson decay

BR are smaller for $\mu < 0$ (the inos are less mixed)

BR become smaller for increasing $\tan\beta$ except for $m_h \sim m_h^{max}$

when the universality relation $M_1 \simeq \frac{1}{2} M_2$ is assumed $\rightarrow$

the phase space allowed by the constraint $m_{\tilde{\chi}_1^{\pm}} > 104$ GeV is rather narrow

the invisible decay occurs only in a small m_h range near the maximal value

however in the $\mu > 0$ case, the BR can reach the level of 10%

when the universality assumption is relaxed : $M_1 \simeq 0.3 M_2$ and $M_1 \simeq 0.1 M_2$ $\rightarrow$

the invisible decay $h \rightarrow \tilde{\chi}_1^o \tilde{\chi}_1^o$ occurs in a much larger portion of the parameter space

despite that in this case $\tilde{\chi}_1^o$ is bino-like and its coupling to h is not very strong

(in particular for $\mu < 0$ it even vanishes for $M_1 \simeq 0.3 M_2$ in a small m_h range near the decoupling limit

Limitations of EFT approaches

to assess the extent to which the effective description is valid one has to compare the momentum transfer $Q_{\rm tr}$ of the process of interest e.g. $pp \to \chi\chi + jet/\gamma$ to the energy scale and impose that $\Lambda > Q_{tr}$

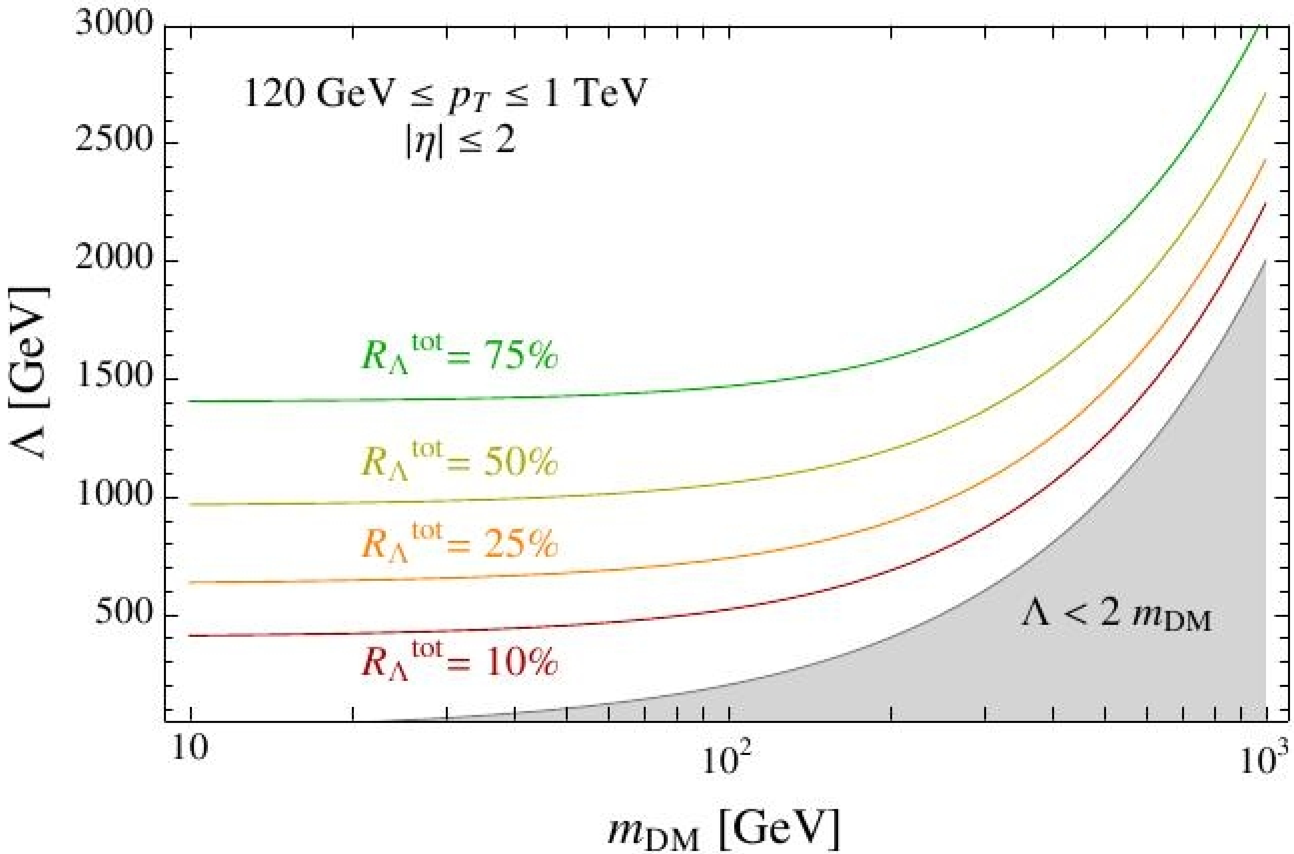
one way of doing this is to consider ratio of Xsection obtained in EFT by imposing the constraint $Q_{tr} < \Lambda$ (on the PDF intregration domain) over the Xsection obtained with the EFT without such a constraint :

$$R_{\Lambda}^{\rm tot} \equiv \frac{\sigma_{\rm eff}|_{Q_{\rm tr}<\Lambda}}{\sigma_{\rm eff}} = \frac{\int_{p_T^{\rm min}}^{1\,{\rm TeV}} dp_T \int_{-2}^{2} \frac{d^2\sigma_{\rm eff}}{dp_T\, d\eta}|_{Q_{\rm tr}<\Lambda}}{\int_{p_T^{\rm min}}^{1\,{\rm TeV}} dp_T \int_{-2}^{2} \frac{d^2\sigma_{\rm eff}}{dp_T\, d\eta}}$$

G. Busoni, A. De Simone, E. Morgante, A. Riotto, arXiv:1307.2253

Limitations of EFT approaches

contours indicate the regions in the parameter space (Λ, m_{DM}) where the description in terms of effective operator is accurate and reliable



even for very small DM masses having R_Λ^{tot} at least 75% requires a cutoff scale at least above 1 TeV

G. Busoni, A. De Simone, E. Morgante, A. Riotto, arXiv:1307.2253

Limitations of EFT approaches

one can also compare the effective operator with a UV completion (i.e. L_{UV})

for example :

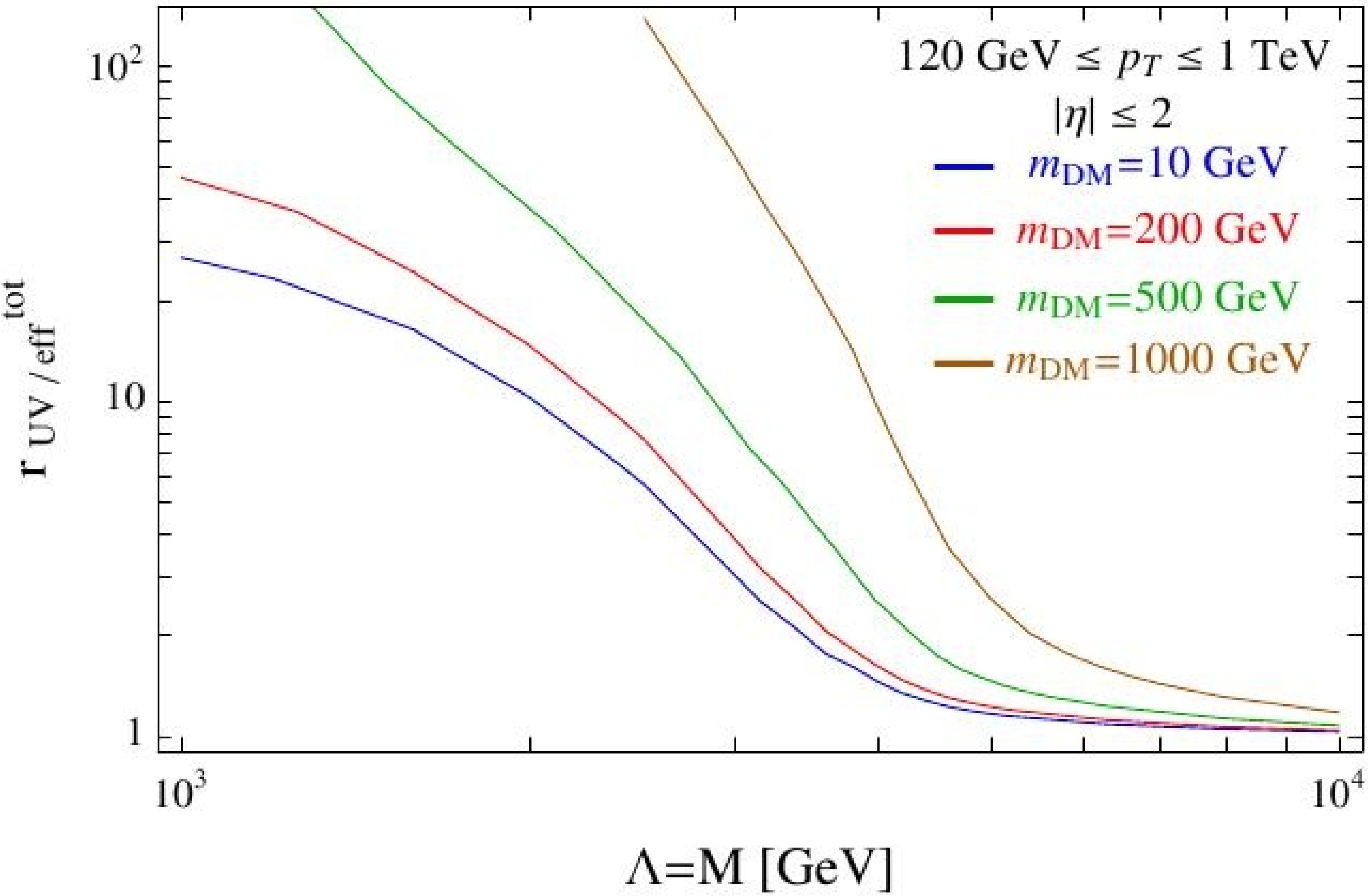
$$r_{\mathrm{UV/eff}} \equiv \frac{\left.\frac{d^2\sigma_{\mathrm{UV}}}{d\,p_T\,d\eta}\right|_{Q_{\mathrm{tr}}<M}}{\left.\frac{d^2\sigma_{\mathrm{eff}}}{d\,p_T\,d\eta}\right|_{Q_{\mathrm{tr}}<\Lambda}}$$

helps in quantifying the error using the EFT truncated at the lowest-dimensional operator w.r.t its UV completion (for given p_T, η of the radiated object)

values of $r_{\mathrm{UV/eff}}$ close to unity indicate the effective operator is accurately describing the high energy theory, whereas larger values imply a poor effective description

G. Busoni, A. De Simone, E. Morgante, A. Riotto, arXiv:1307.2253

Limitations of EFT approaches



in this example (with these numerical inputs) EFT seems to be valid when mediator has mass greater than 2-2.5 TeV

G. Busoni, A. De Simone, E. Morgante, A. Riotto, arXiv:1307.2253

Limitations of EFT approaches

further caution when comparing only the EFT limit with direct searches

from a study of monojet searches at LHC interpreted in terms of DM for vector and axial vector interactions :

- EFT valid when mediator has mass greater than 2.5 TeV
- current limits on the contact interaction scale Λ in EFT apply to theories that are perturbative for DM mass $m_{DM} < 800$ GeV
- however for all values of m_{DM} mediator width tends to be greater than the mass
  $\Rightarrow$ particle-like interpretation of mediator is doubtful

- furthermore consistency with thermal relic density occurs only for

$$170 < m_{DM} < 520 \text{ GeV}$$

- for lighter mediator masses EFT limit:

  either under-estimate true limit - because process is resonantly enhanced

  either over-estimate it - because missing energy distribution is too soft

O. Buchmueller, M. J. Dolan, C. Mc Cabe, arXiv:1308.6799