Dark matter search at B factories

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Exploring the dark sector,
KIAS, Mar. 16, 2015

Outline

- Introduction
- Dark matter search at the LHC

  (See the talk by Patrick Fox this Friday.)
- Dark matter search at B factories
- Summary

Properties of DM

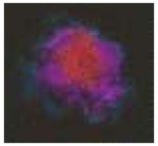
- Dark matter exists (galactic rotation curve, gravitational lensing, CMB,…)
- from PLANCK observation, DM is about 26.8% of our universe
- productions
  - thermal: WIMP,…
  - non-thermal: axion,…
- stability of dark matter
  - long-living: $\tau \geq \tau_{\text{uni}} \sim 10^{26-30}\,\text{s}$
  - absolutely stable by (dark) symmetry

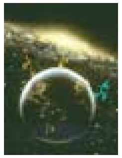
➡ escape detectors at colliders!

- all the observation is by gravitational interaction, but can have interaction other than gravity. $\Longrightarrow$ A popular scenario is WIMP.

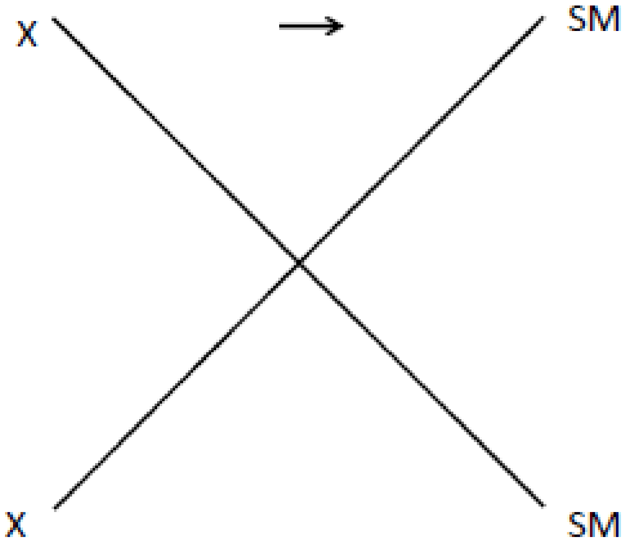
Probe of WIMP hypothesis

- indirect detection
  - dark matter annihilation in sun, Galactic Center, satellites, etc.





indirect detection →

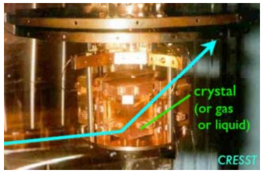


↑ direct detection

← collider

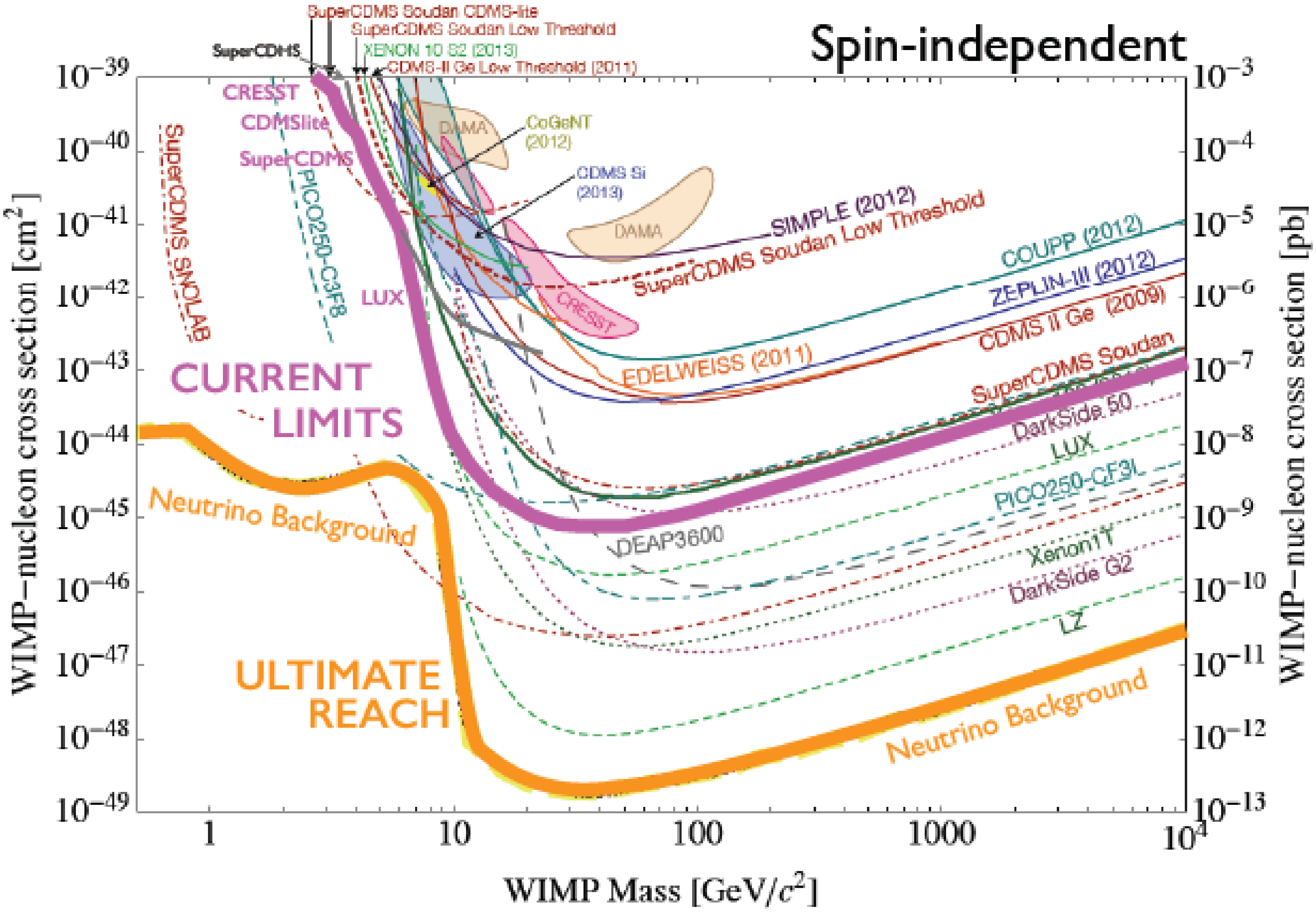
- direct detection
  - measure nuclear recoil from scattering against nuclei

Gran Sasso underground laboratories

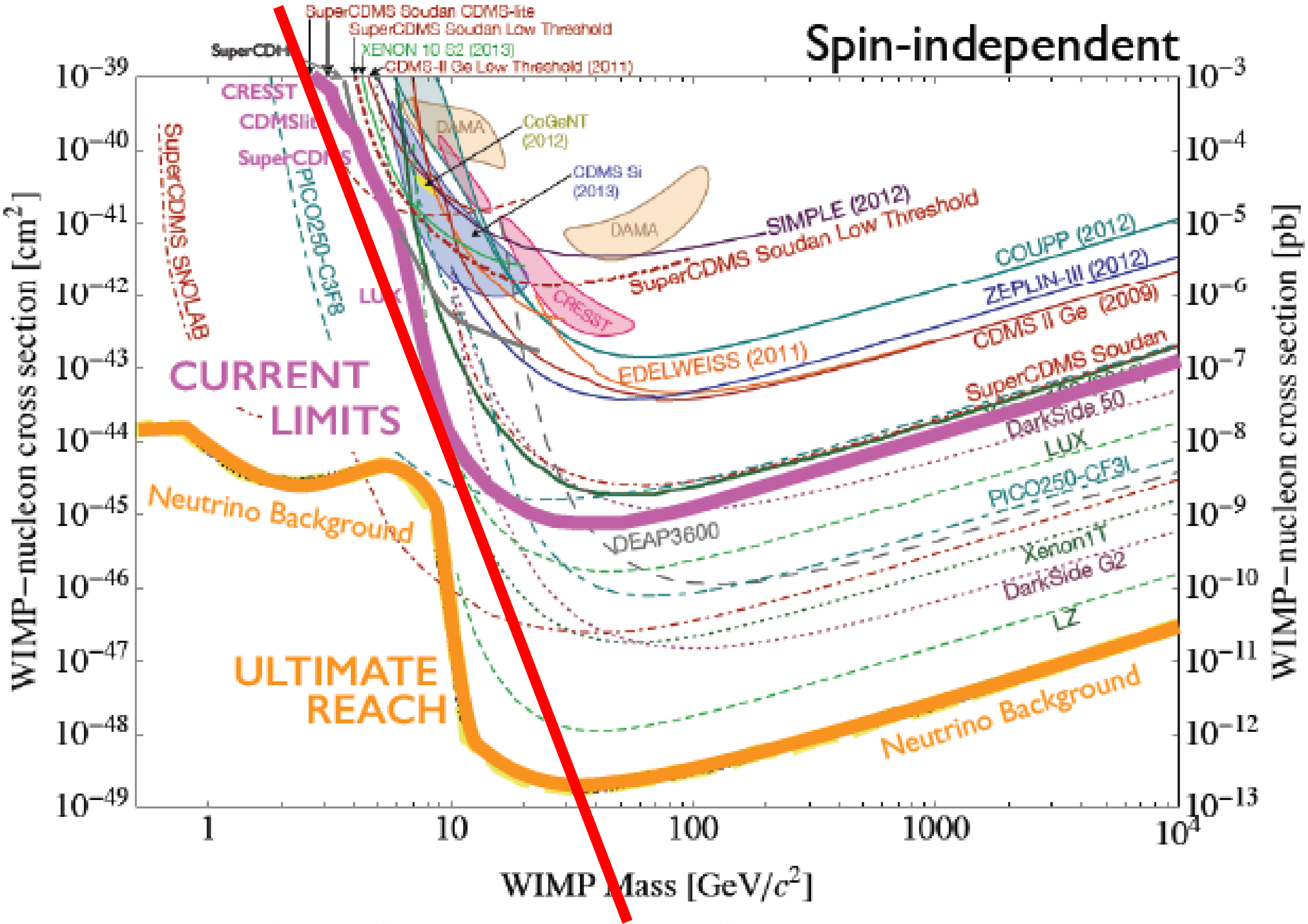


- collider search
  - dark matter production at the LHC

Direct detection of Dark Matter



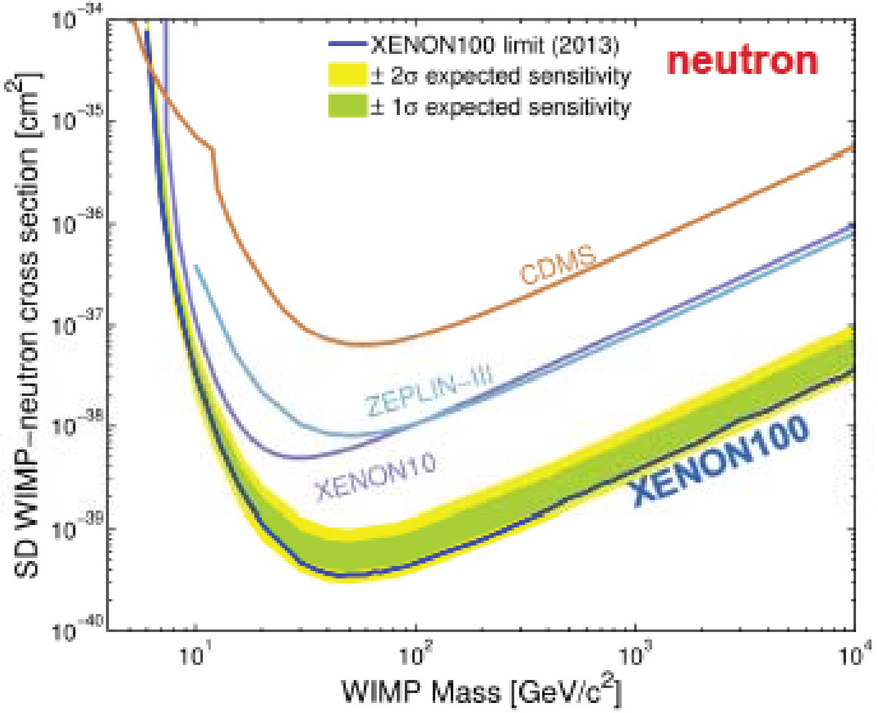
Direct detection of Dark Matter

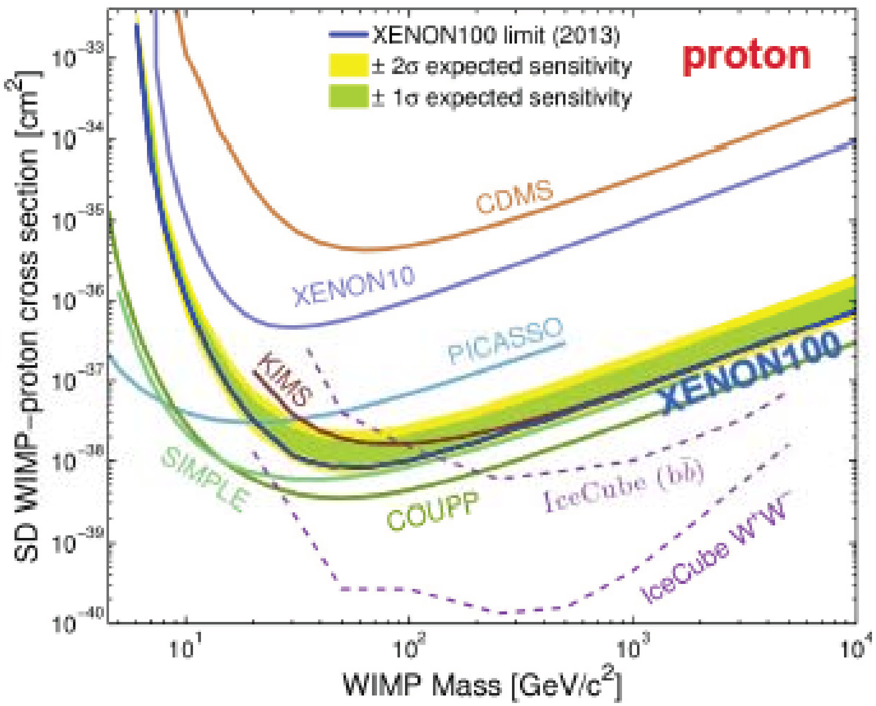


Light dark matter could not hit a nucleon.

Direct detection of Dark Matter

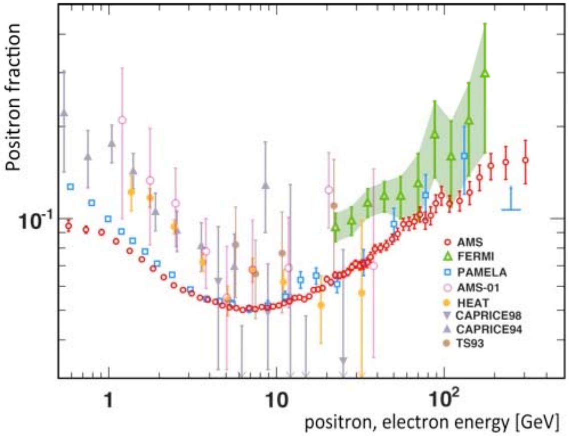
Spin-dependent



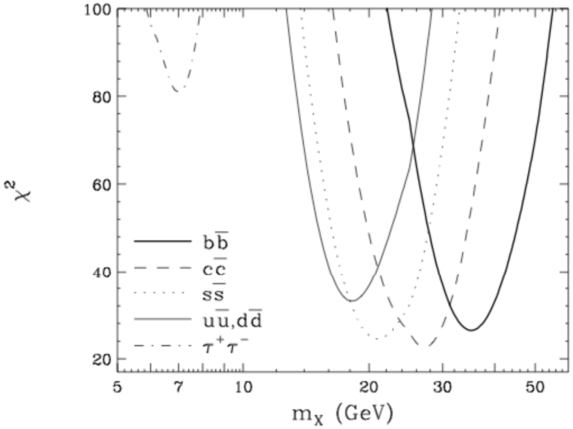


Indirect detection of Dark Matter

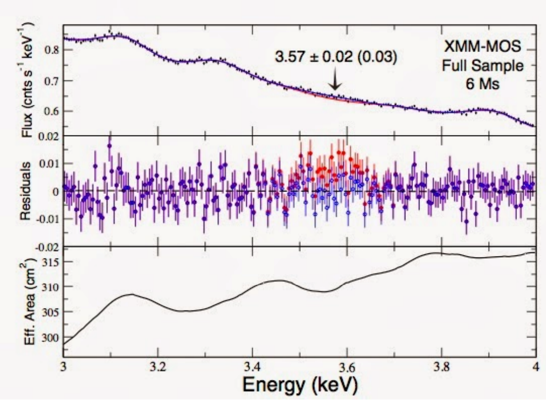
PAMELA,FERMI,AMS02



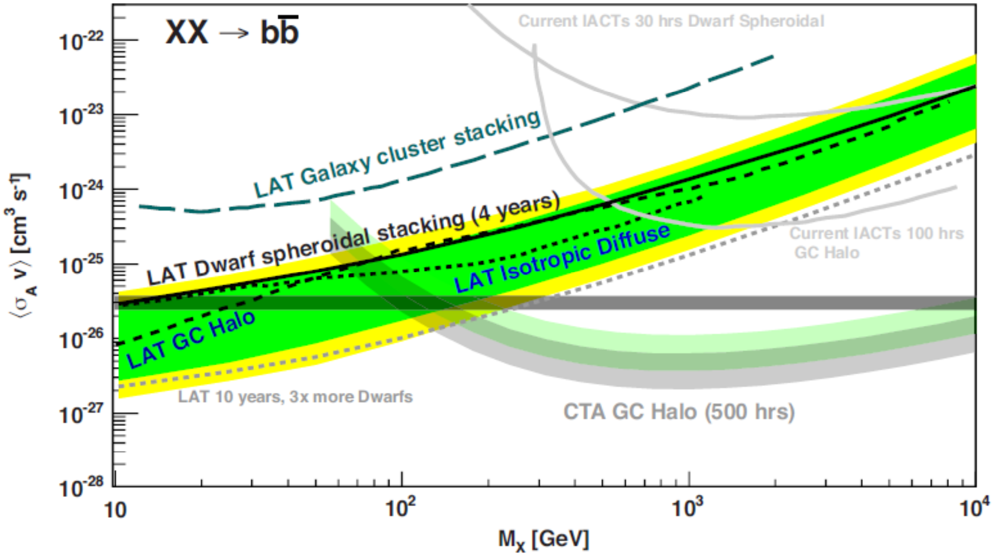
Galactic center DM signal



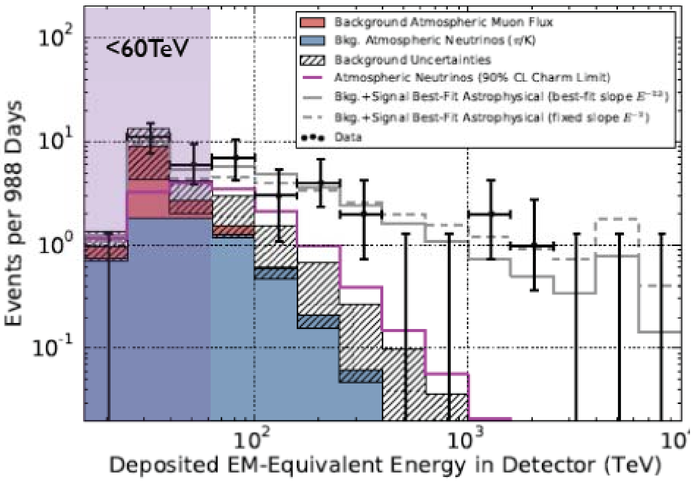
3.5keV X-ray signal



FERMI-LAT

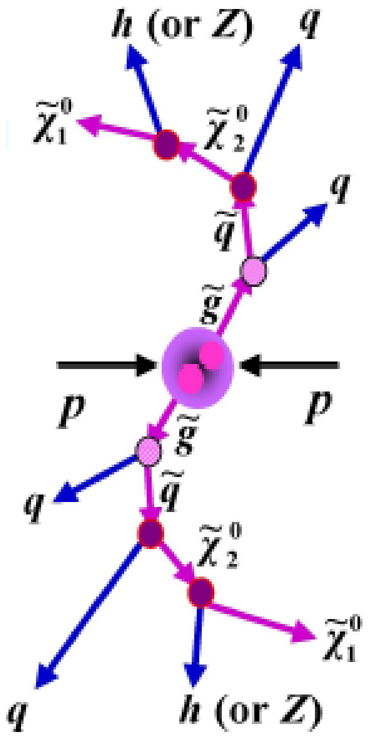


IceCube



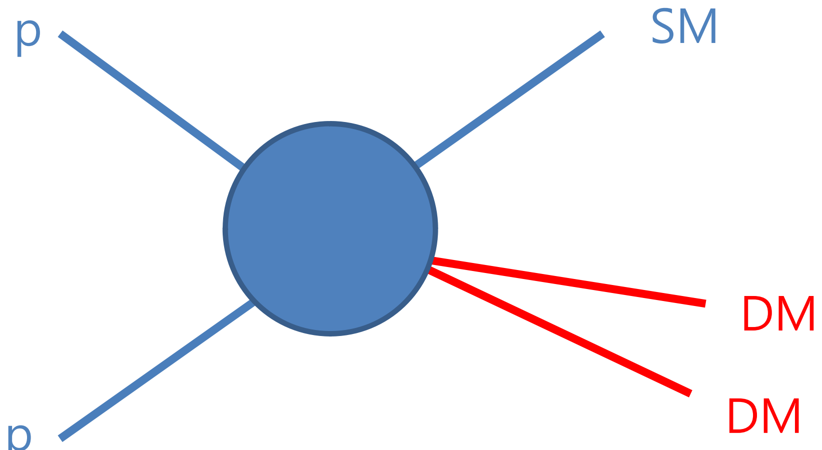
Collider signatures of dark matter

Via cascade decays



- MSSM, UED, …

Mono-X search

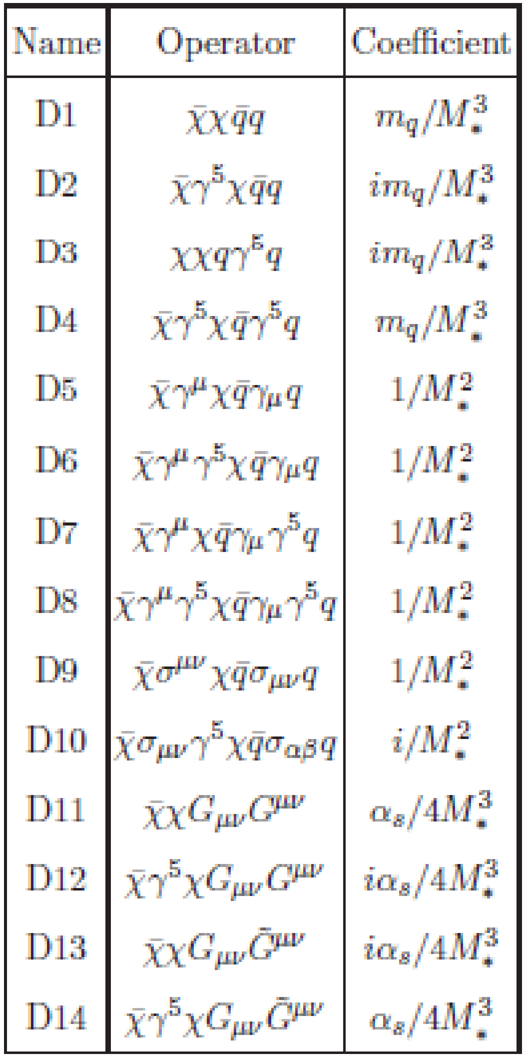


$$pp \rightarrow \mathrm{SM} + E_T$$

- any SM particle(s) possible.
  jet(s), γ, W, Z, t, tt,…

Effective operators

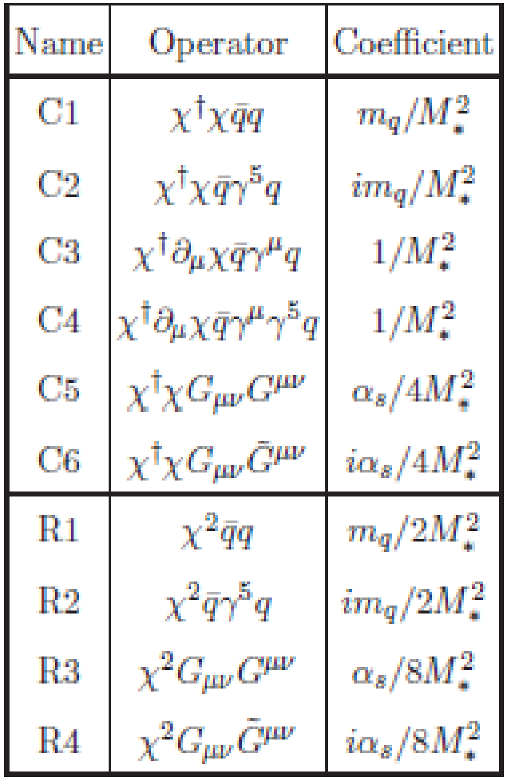
Dirac fermion



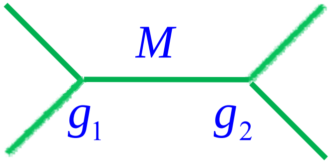
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\chi\chi q\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Goodman et al., arXiv:1008.1783

Complex, real scalars



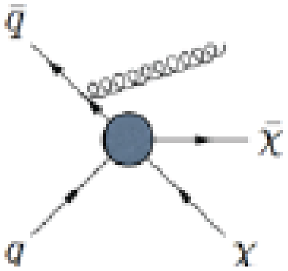
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$



$$M_* \sim \frac{M}{\sqrt{g_1 g_2}}$$

$$M_{\rm DM} \le 2\pi M_*$$

Monojet



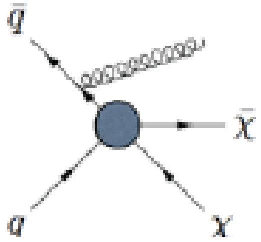
$$pp \to \text{jet} + E_T$$

- irreducible backgrounds

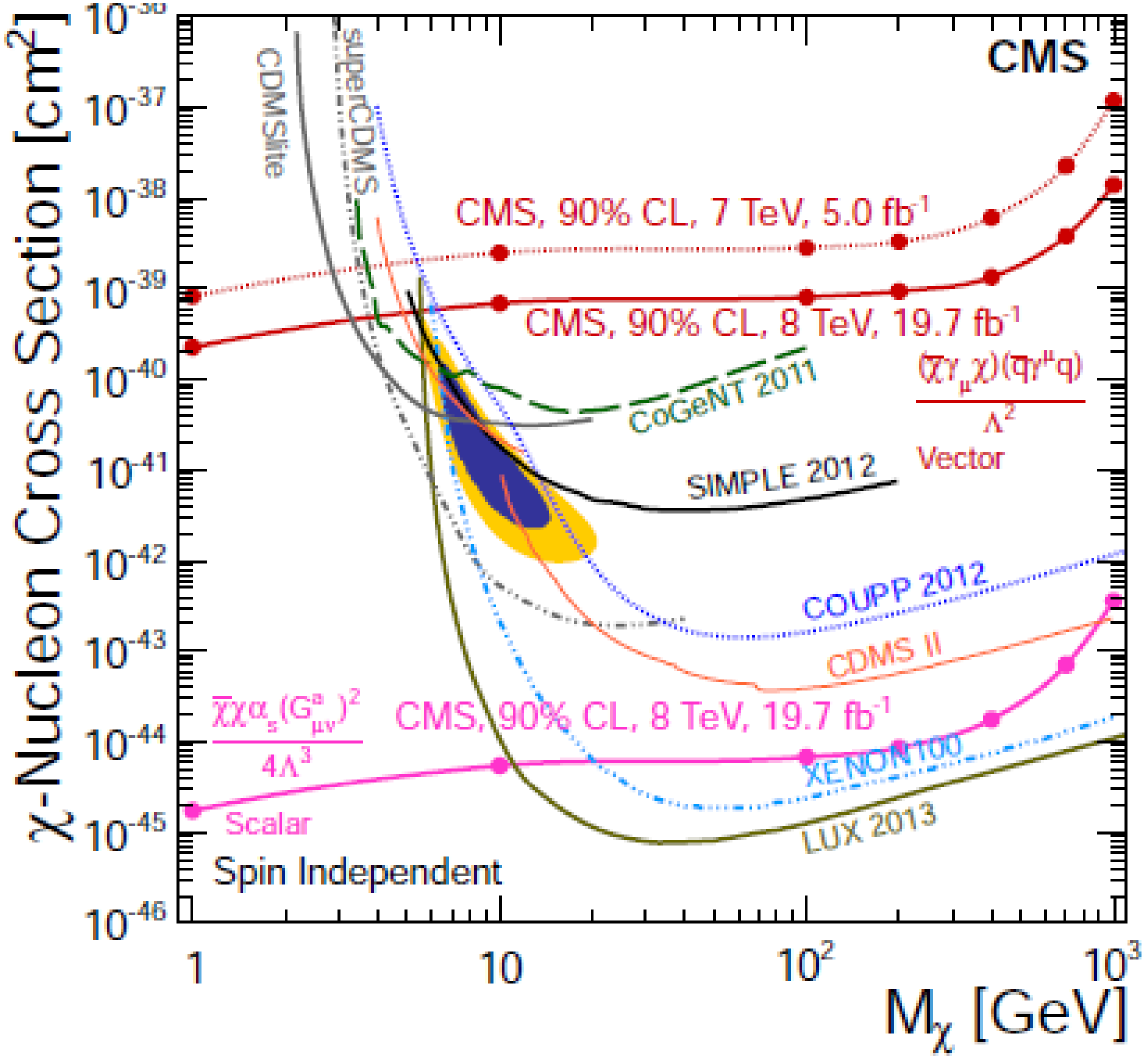
$$pp \to jet + Z(Z \to \nu\bar{\nu})$$

- backgrounds coming from events where particles are missed or misidentified.

$$pp \to jet + W(W \to l\nu)$$



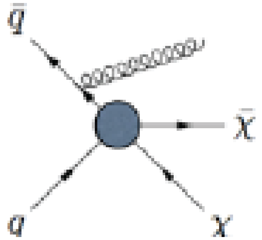
Monojet



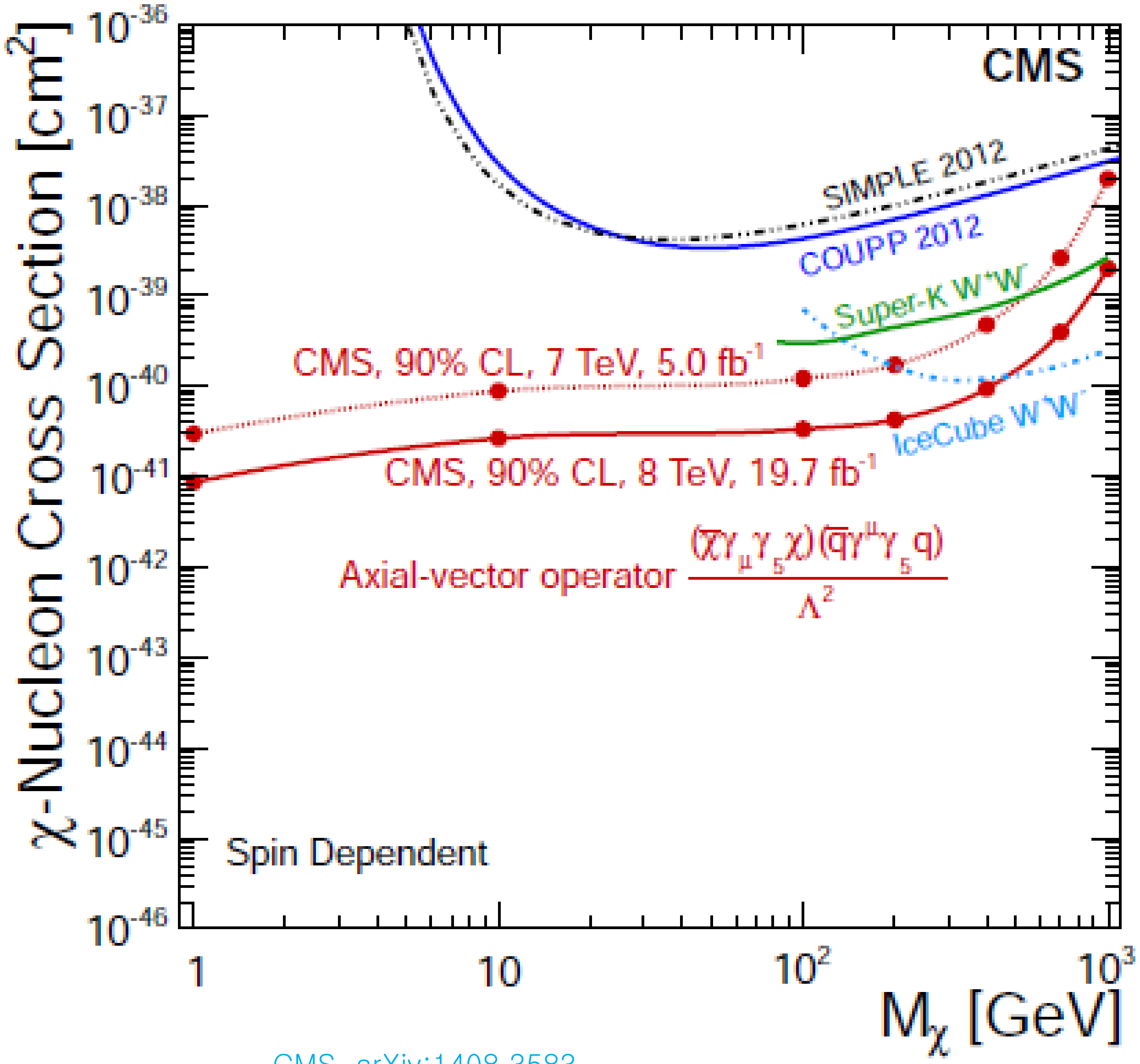
CMS, arXiv:1408.3583

- a gluonic current has the strongest bound.

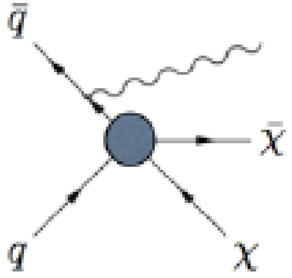
- scalar interaction has a suppression factor due to the light quark mass.



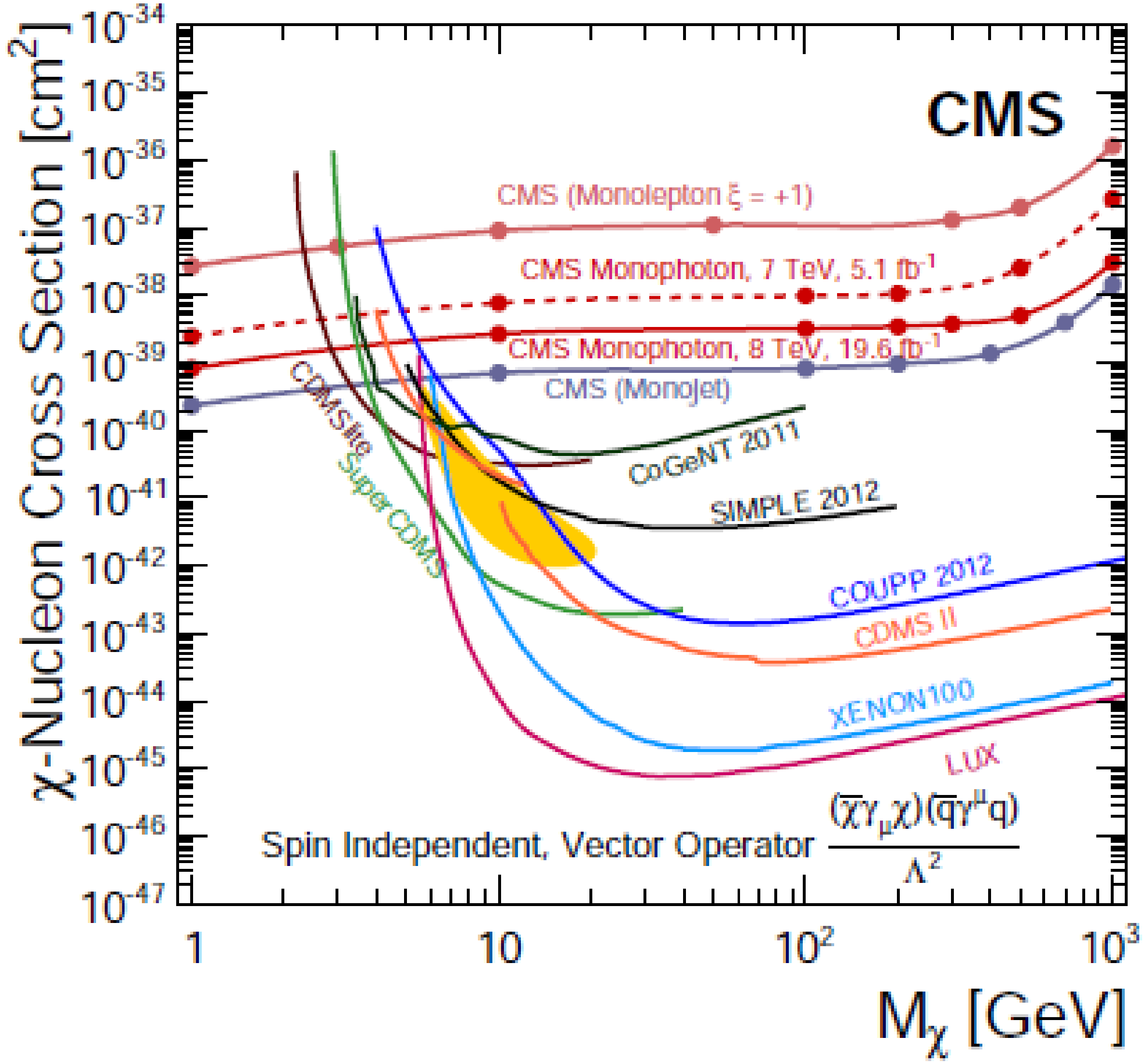
Monojet



CMS, arXiv:1408.3583

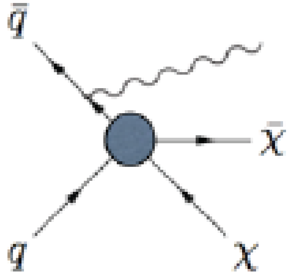


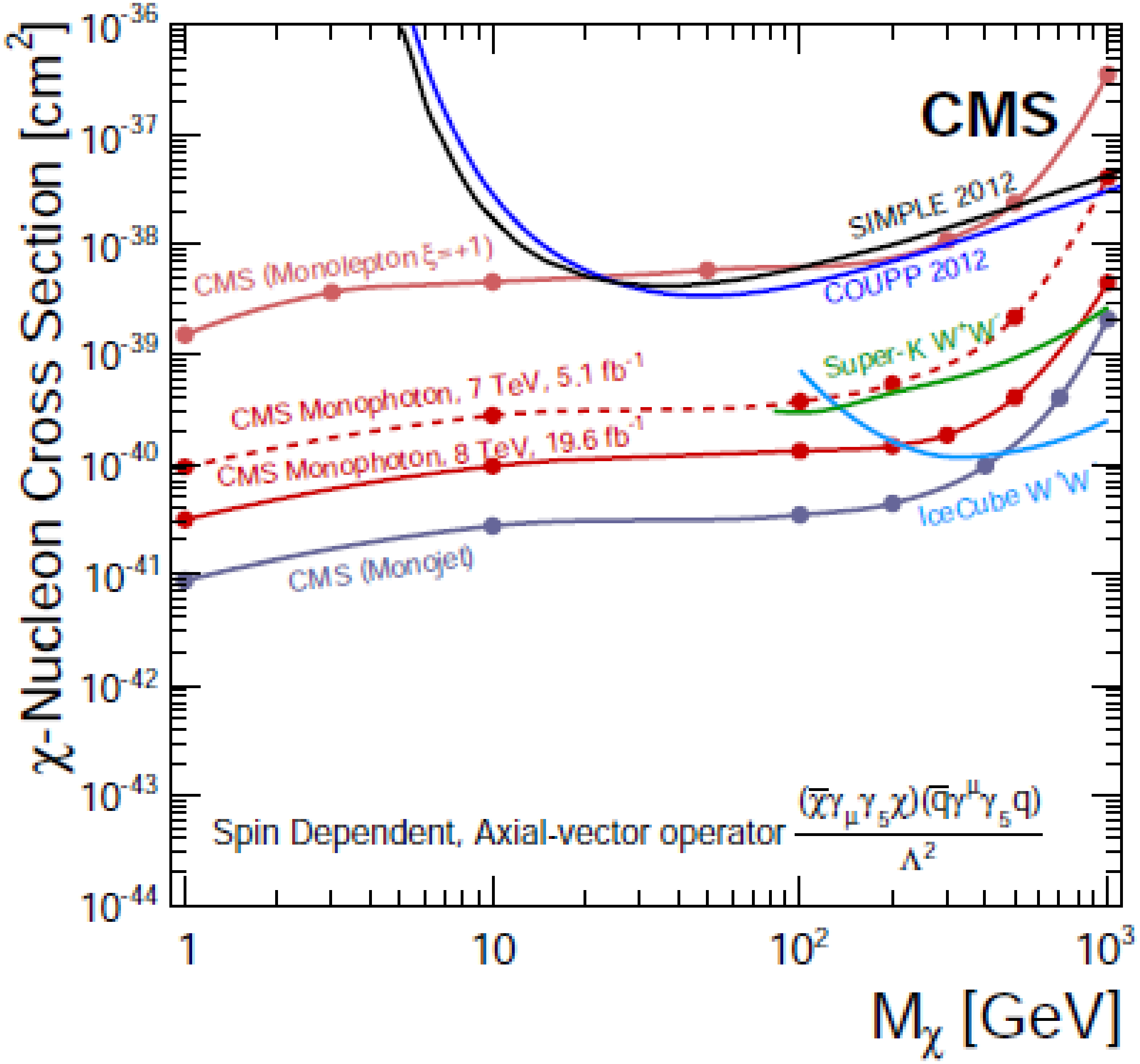
Monophoton



CMS, arXiv:1410.8812

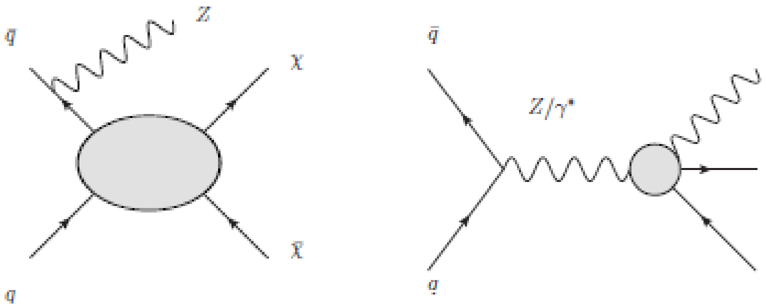
Monophoton





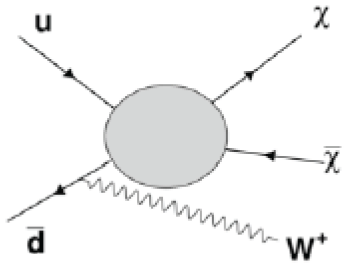
CMS, arXiv:1410.8812

Mono-W/Mono-Z



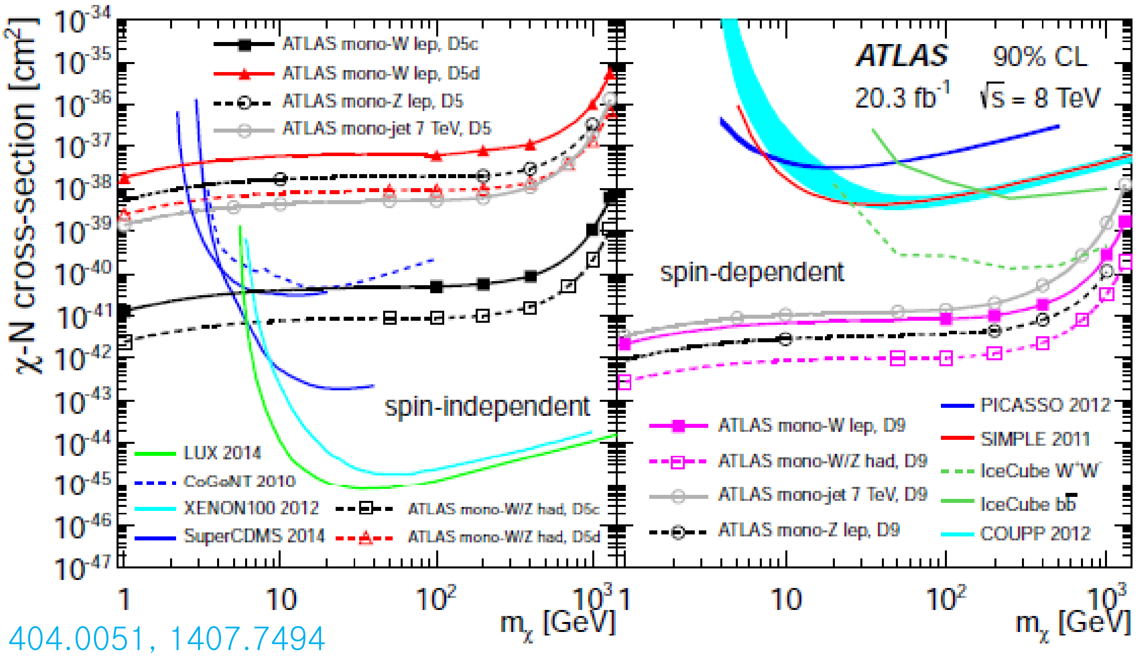
Carpenter et al, arXiv:1212.3352

$$\frac{1}{\Lambda_5^3}\,\bar{\chi}\chi\,(D_\mu H)^\dagger D^\mu H$$



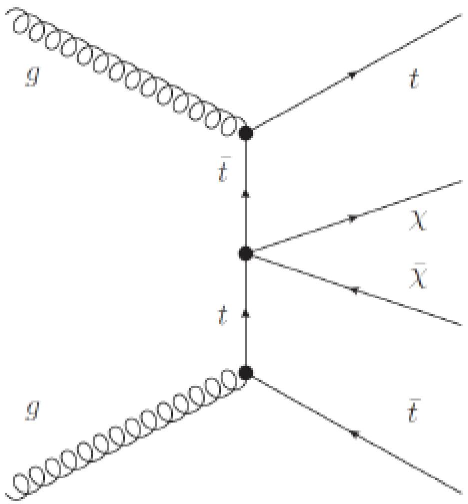
Bai,Tait, arXiv:1208.4361

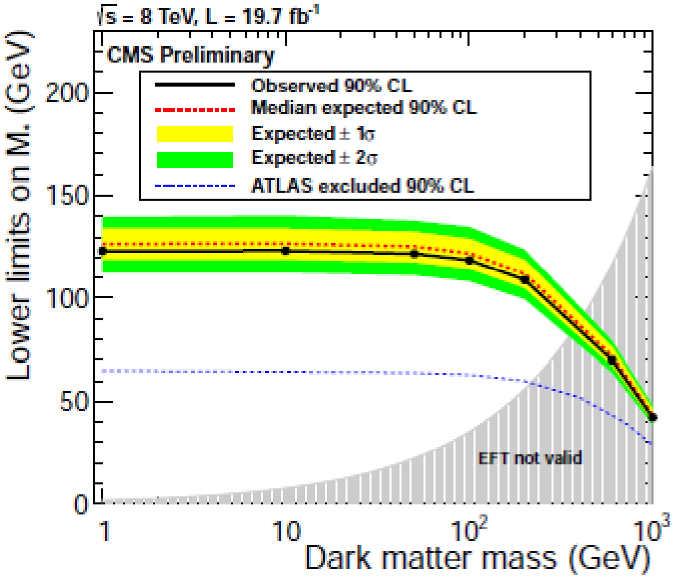
Spin-independent **Spin-dependent**

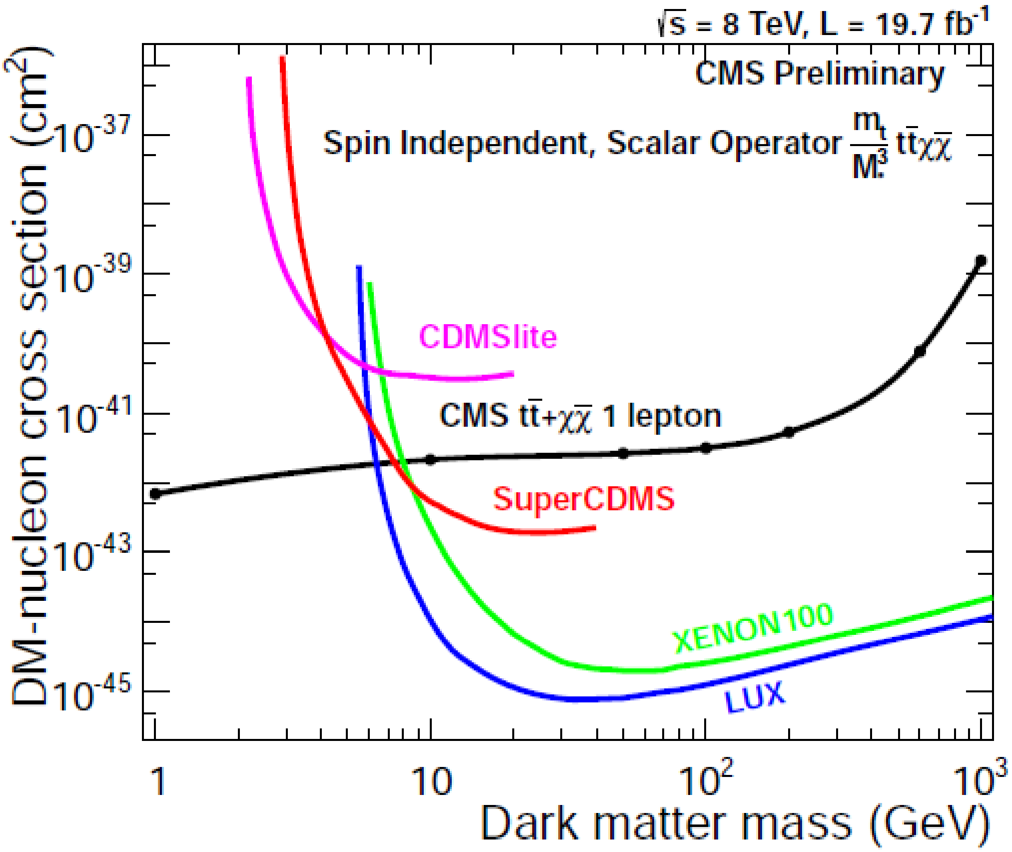


ATLAS, arXiv:1404.0051, 1407.7494

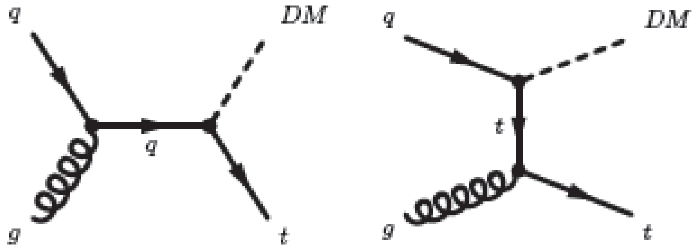
Mono-ttbar


g
t
$\bar{t}$
χ
$\bar{\chi}$
t
g
$\bar{t}$


$\sqrt{s}$ = 8 TeV, L = 19.7 fb^{-1}
CMS Preliminary
Observed 90% CL
Median expected 90% CL
Expected ± 1σ
Expected ± 2σ
ATLAS excluded 90% CL
EFT not valid
Lower limits on M. (GeV)
0
50
100
150
200
1
10
10^2
10^3
Dark matter mass (GeV)

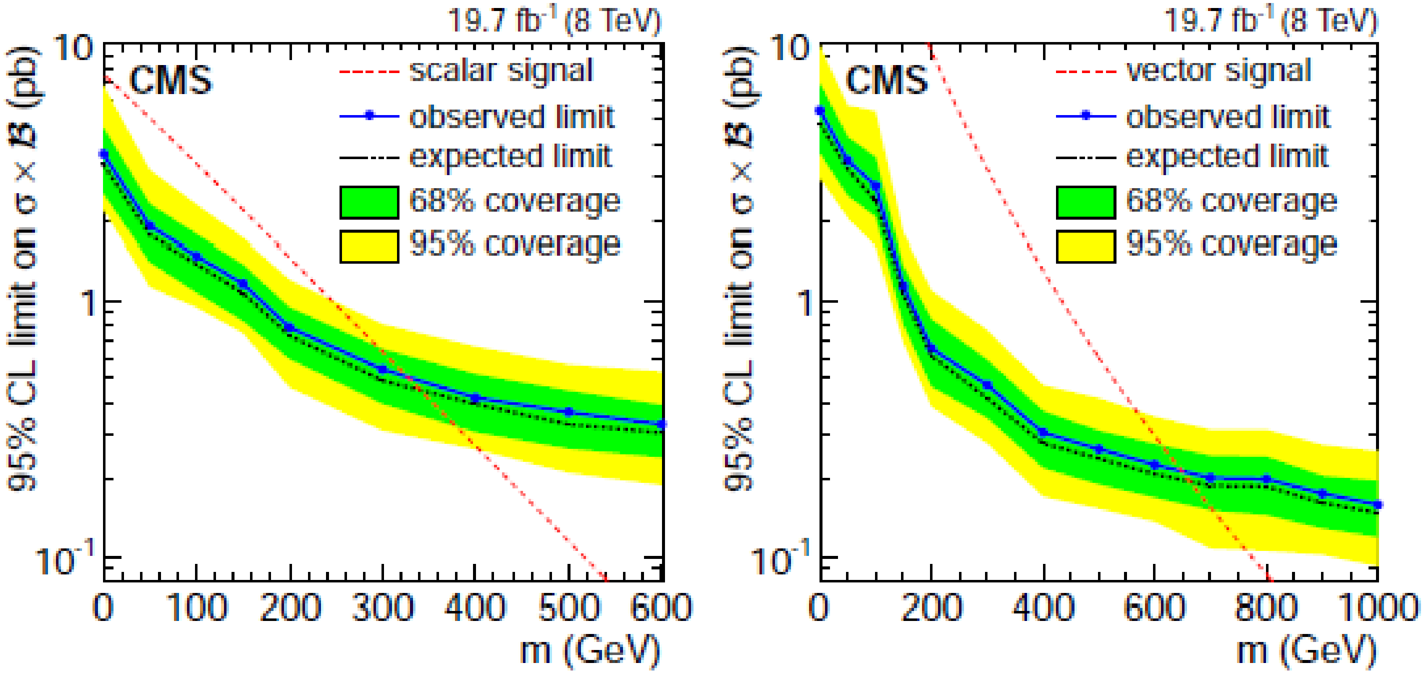

$\sqrt{s}$ = 8 TeV, L = 19.7 fb^{-1}
CMS Preliminary
Spin Independent, Scalar Operator $\frac{m_t}{M_*^3} t\bar{t}\chi\bar{\chi}$
CDMSlite
CMS $t\bar{t}+\chi\bar{\chi}$ 1 lepton
SuperCDMS
XENON100
LUX
DM-nucleon cross section (cm^2)
10^{-37}
10^{-39}
10^{-41}
10^{-43}
10^{-45}
1
10
10^2
10^3
Dark matter mass (GeV)

Mono-top



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin}$$
$$+ a^0_{\rm FC}\phi\bar{u}u + a^1_{\rm FC}v_\mu\bar{u}\gamma^\mu u + {\rm h.c.},$$

Andrea,Fuks,Maltoni, arXiv:1106.6199

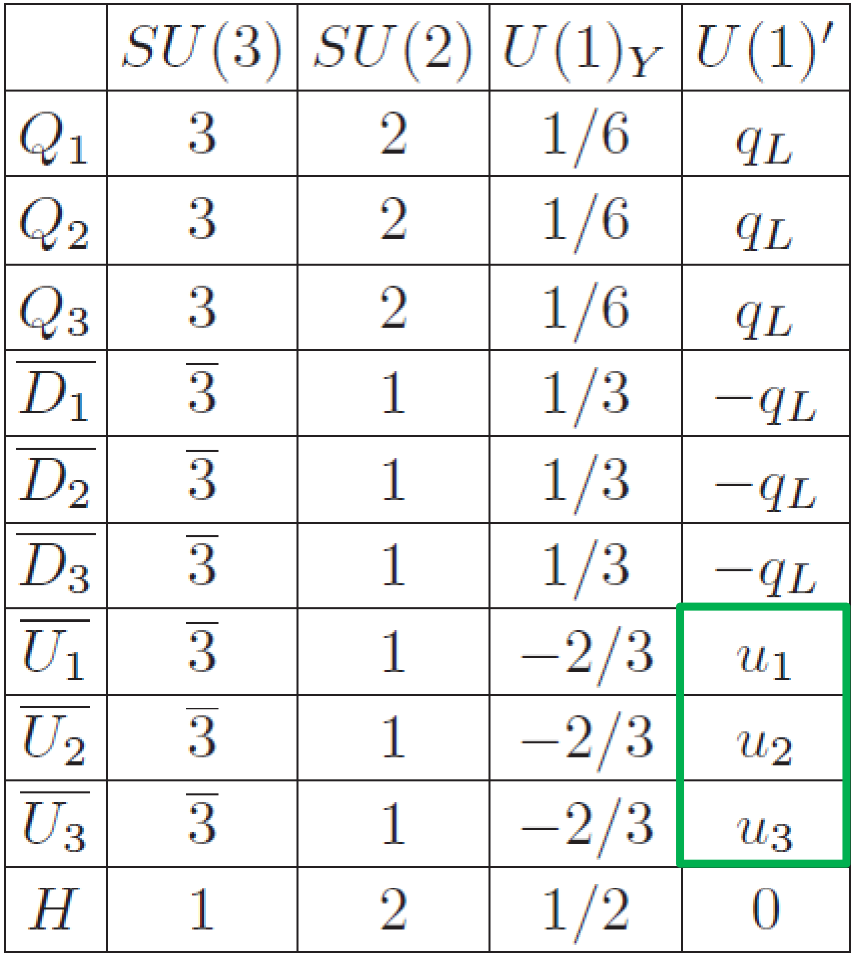


CMS, arXiv:1410.1149

Flavor-dependent U(1)′ model

- Charge assignment : SM fermions

Ko,Omura,Yu, JHEP1201,147



	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
Q_1	3	2	$1/6$	q_L
Q_2	3	2	$1/6$	q_L
Q_3	3	2	$1/6$	q_L
$\overline{D_1}$	$\overline{3}$	1	$1/3$	$-q_L$
$\overline{D_2}$	$\overline{3}$	1	$1/3$	$-q_L$
$\overline{D_3}$	$\overline{3}$	1	$1/3$	$-q_L$
$\overline{U_1}$	$\overline{3}$	1	$-2/3$	u_1
$\overline{U_2}$	$\overline{3}$	1	$-2/3$	u_2
$\overline{U_3}$	$\overline{3}$	1	$-2/3$	u_3
H	1	2	$1/2$	0

Left-handed quarks and right-handed down-type quarks have universal couplings.

Flavor-dependent

Higgs

cannot generate mass terms for right-handed up-type quarks

Flavor-dependent U(1)′ model

- Charge assignment : Higgs fields

Ko,Omura,Yu, JHEP1201,147

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H_1	1	2	1/2	$-q_L - u_1$
H_2	1	2	1/2	$-q_L - u_2$
H_3	1	2	1/2	$-q_L - u_3$
Φ	1	1	1	$-q_\Phi$

- introduce three Higgs doublets charged under U(1)′ in addition to H uncharged under U(1)′.

$$\begin{aligned} V_y &= y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\ &+ y^d_{ij} \overline{D_j} Q_i i\tau_2 H^\dagger \\ &+ y^e_{ij} \overline{E_j} L_i i\tau_2 H^\dagger + y^n_{ij} H \overline{N_j} L_i . \end{aligned}$$

- The U(1)′ is spontaneously broken by U(1)′ charged complex scalar Φ.

Anomaly Cancelation

- Anomaly cancelation requires extra fermions: SU(2) doublets

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q'	3	2	$1/6$	$-(q_1+q_2+q_3)$
D'_R	3	1	$-1/3$	$-(d_1+d_2+d_3)$
U'_R	3	1	$2/3$	$-(u_1+u_2+u_3)$
L'	1	2	$-1/2$	0
E'	1	1	-1	0
l_{L1}	1	2	$-1/2$	Q_L
l_{R1}	1	2	$-1/2$	Q_R
l_{L2}	1	2	$-1/2$	$-Q_L$
l_{R2}	1	2	$-1/2$	$-Q_R$

one extra generation

vector-like pairs

a candidate for CDM

Flavor-dependent U(1)′ model

- 2 Higgs doublet model : $(u_1, u_2, u_3) = (0, 0, 1)$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H	1	2	1/2	0
H_3	1	2	1/2	1
Φ	1	1	1	q_Φ

$$\begin{aligned} V_y &= y^u_{i1}\overline{Q_i}\widetilde{H}U_{R1} + y^u_{i2}\overline{Q_i}\widetilde{H}U_{Rj} + y^u_{i3}\overline{Q_i}\widetilde{H_3}U_{Rj} \\ &\quad + y^d_{ij}\overline{Q_i}HD_{Rj} + y^e_{ij}\overline{L_i}H\overline{E_j} + y^n_{ij}\overline{L_i}\widetilde{H}N_j. \end{aligned}$$

$$V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}\hat{h}_0 + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}\hat{h}_0,$$

$$\left.\begin{aligned} Y^u_{ij} &= \frac{m^u_i\cos\alpha}{v\cos\beta}\delta_{ij} + \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta), \\ Y^d_{ij} &= \frac{m^d_i\cos\alpha}{v\cos\beta}\delta_{ij}, \end{aligned}\right\} \propto \text{the fermion mass}$$

Flavor-dependent U(1)′ model

- Gauge coupling in the flavor eigenstates

$$\mathcal{L}_{Z'f\bar{f}} = g' Z'_\mu \left[q_i \overline{U^i_L} \gamma^\mu U^i_L + q_i \overline{D^i_L} \gamma^\mu D^i_L + u_i \overline{U^i_R} \gamma^\mu U^i_R + d_i \overline{D^i_R} \gamma^\mu D^i_R \right]$$

\- The 3 X 3 coupling matrix g^u_R is defined by

$$(g^u_R)_{ij} = (U^u_R)_{ik} u_k (U^u_R)^\dagger_{kj}$$

biunitary matrix diagonalizing the up-type quark mass matrix

- Gauge coupling in the mass eigenstates

\- Z′ interacts only with the right-handed up-type quarks

$$g' Z'_\mu \left[(g^u_L)_{ij} \overline{\hat{U}^i_L} \gamma^\mu \hat{U}^j_L + (g^d_L)_{ij} \overline{\hat{D}^i_L} \gamma^\mu \hat{D}^j_L + (g^u_R)_{ij} \overline{\hat{U}^i_R} \gamma^\mu \hat{U}^j_R + (g^d_R)_{ij} \overline{\hat{D}^i_R} \gamma^\mu \hat{D}^j_R \right]$$

~0 or δ_{ij}

flavor off-diagonal copling

~0 or δ_{ij}

$\Longrightarrow$ topphilic DM?

Dark matter search at B factories

- fixed CM energy $\sqrt{s} = 10.58 \text{ GeV}$

- relatively free from unitarity or validity of EFT.

- clean signal and low background.

- sensitive to light DM $\lesssim$ 5 GeV.

- in principle, possible to distinguish charmphilic or bottomphilic dark matter.

- already about 1ab^{-1} data were accumulated at Belle and BABAR.

- BELLE II will start to accumulate data soon.

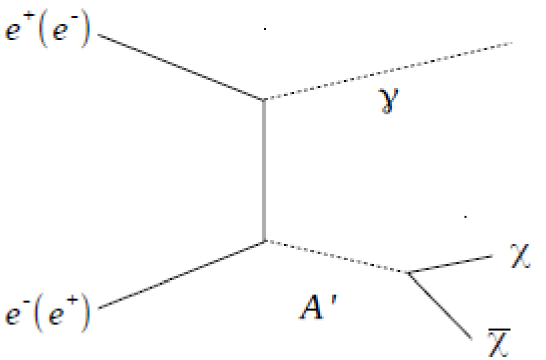
Dark photon search at B factories

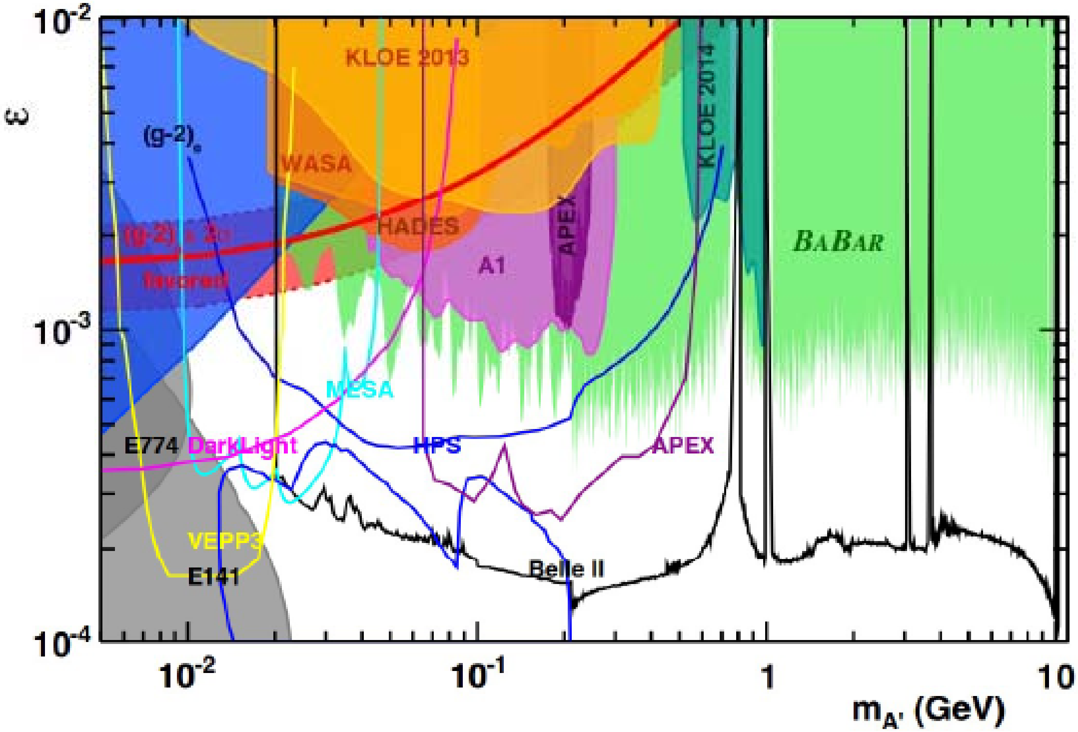
- general idea: kinetic mixing between γ and A’ ~ $\frac{1}{2}\epsilon F^{Y}_{\mu\nu}F'^{\mu\nu}$

Fayet, PLB95, 285 (1980);NPB187, 184(1981)

Holdom, 1986

$e^+e^- \to \gamma A' \to \gamma e^+e^-, \gamma\mu^+\mu^-$, *prompt*





Inguglia, QWG2014

See the talk by H.S.Lee this Friday.

Annihilation of light DM

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\,\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\Phi_{\rm PP}} \cdot \underbrace{\int_{\Delta\Omega}\left\{\int_{\rm l.o.s.}\rho^2(\boldsymbol{r}){\rm d}l\right\}{\rm d}\Omega'}_{\text{J-factor}} .$$

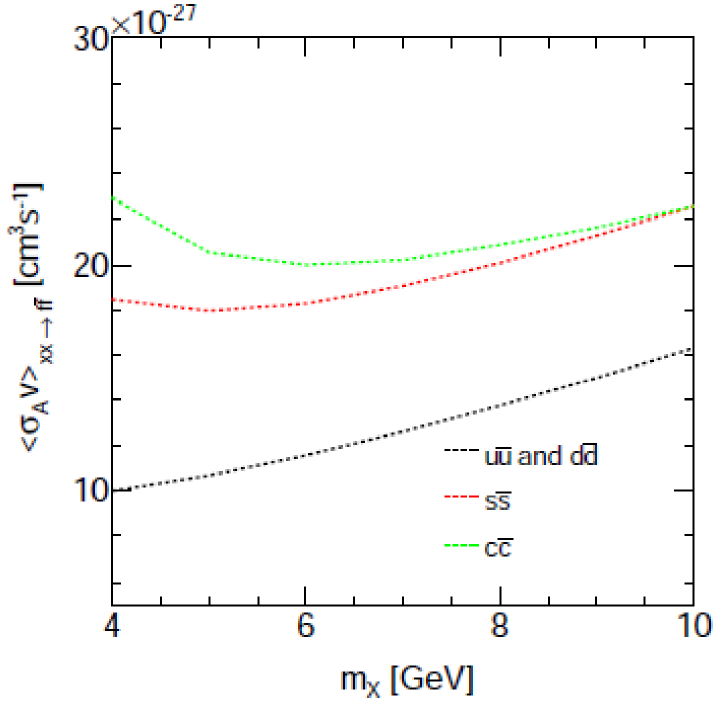
The final γ-ray spectrum.

contains information
about the distribution of DM.

- from the observation of Fermi-LAT of dwarf spheroidal galaxies

$$\Phi_{PP} < 5.0^{+4.3}_{-4.5} \times 10^{-30}\,{\rm cm}^3\,{\rm s}^{-1}\,{\rm GeV}^{-2}$$

Geringer−Sameth,Koushiappas, PRL107

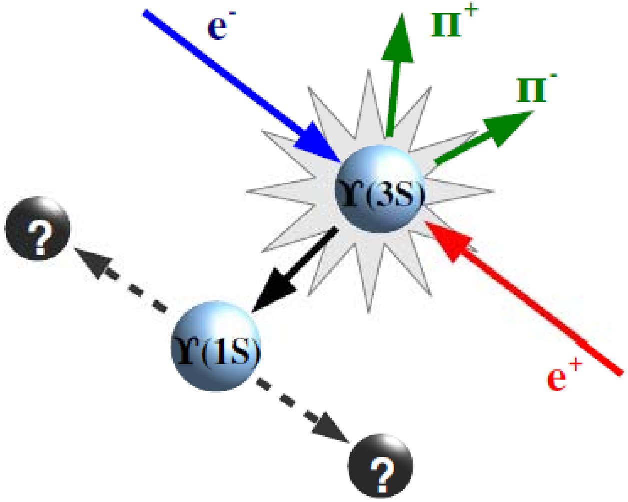


Fernandez,Kumar,Seong,Stengel, arXiv:1404.6599

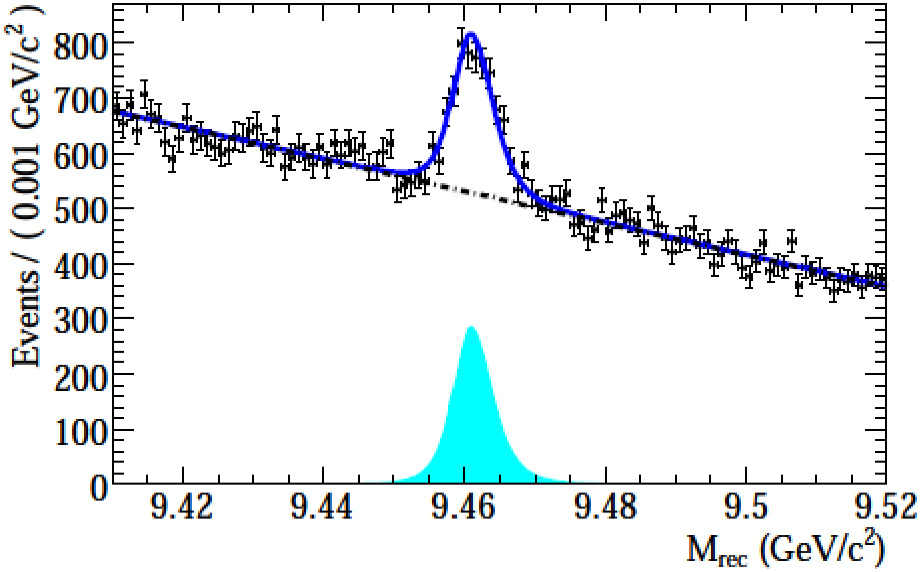
- the photon energy threshold~1 GeV
- below 5 GeV, bounds weaken due to the photon energy threshold and threshold for ccbar.
- below 4 GeV, the final state energy becomes close to the hadronization scale.
- CMB also constrains s-wave annihilation at recombination.

Υ(3S) decay

- Υ(3S)→$\pi^+\pi^-$Υ(1S) with Υ(1S)→invisible



$$M^2_{rec} = s + M^2_{\pi\pi} - 2\sqrt{s}E^*_{\pi\pi}$$

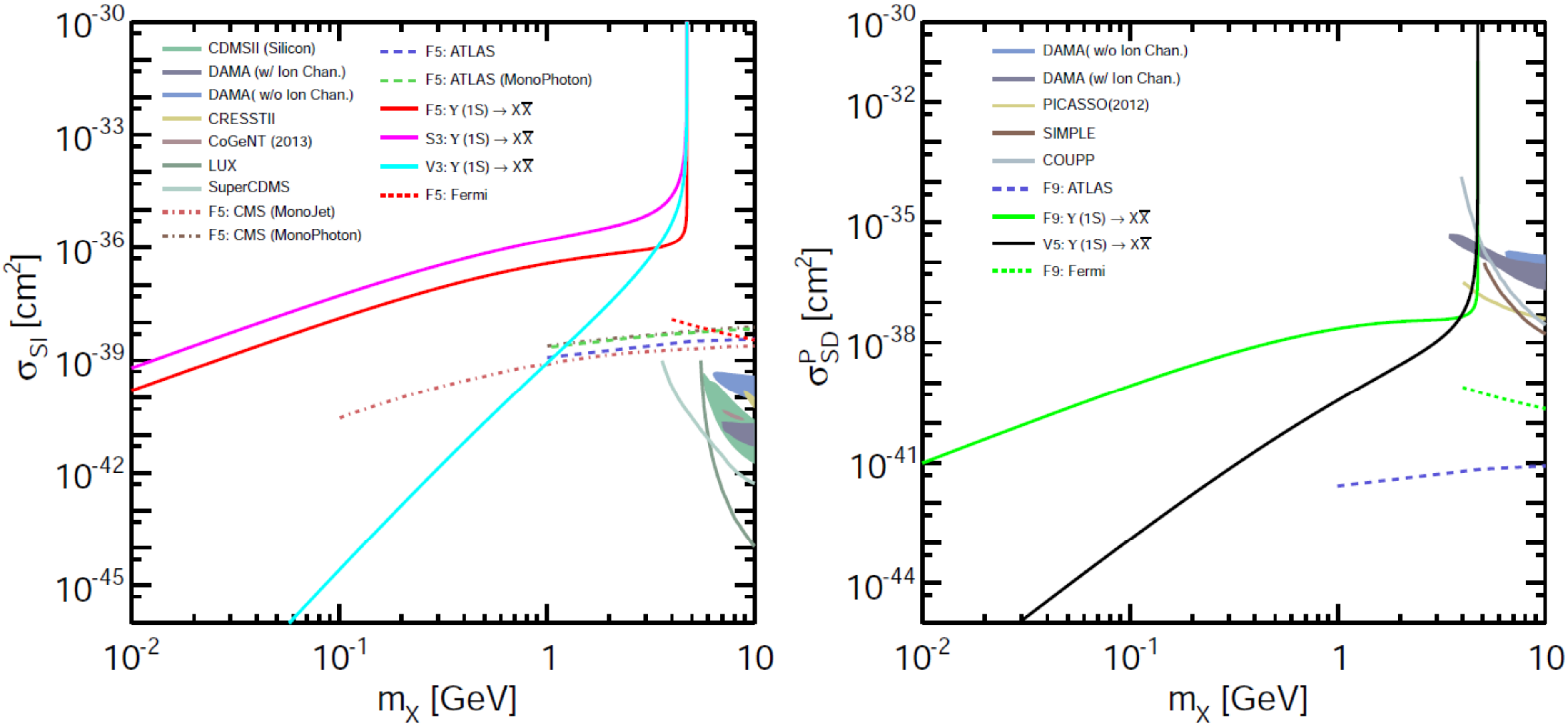


BABAR,arXiv:0908.2840

$$\mathcal{B}(\Upsilon(1S) \rightarrow invisible) < 3.0 \times 10^{-4}$$
$$\mathcal{B}(J/\Psi \rightarrow invisible) < 7.2 \times 10^{-4}$$

$$\mathcal{B}(\Upsilon(1S) \rightarrow \nu\bar{\nu}) = 9.85 \times 10^{-6}$$
$$\mathcal{B}(J/\Psi \rightarrow \nu\bar{\nu}) = 2.70 \times 10^{-8}$$

Υ(3S) decay



— $(1/\Lambda^2)\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$

— $(1/\Lambda^2)\imath Im(\phi^\dagger\partial_\mu\phi)\bar{q}\gamma^\mu q$

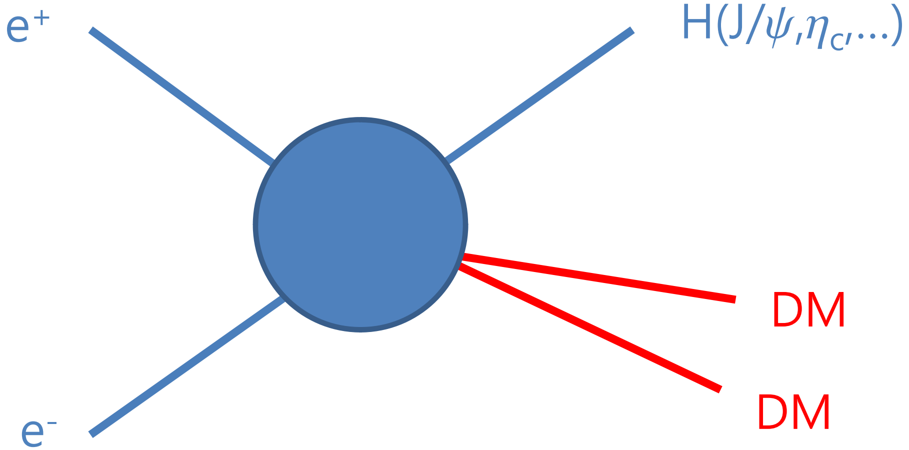
— $(1/\Lambda^2)\imath Im(B^\dagger_\nu\partial_\mu B^\nu)\bar{q}\gamma^\mu q$

— $(1/\Lambda^2)\bar{X}\sigma^{\mu\nu}X\bar{q}\sigma_{\mu\nu}q$

— $(1/\Lambda)(B^\dagger_\mu B_\nu - B^\dagger_\nu B_\mu)\bar{q}\sigma^{\mu\nu}q$

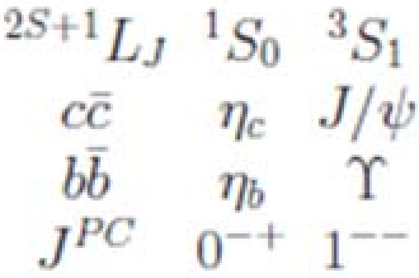
Fernandez,Kumar,Seong,Stengel, arXiv:1404.6599

Association production of DM with H



H=heavy quarkonium

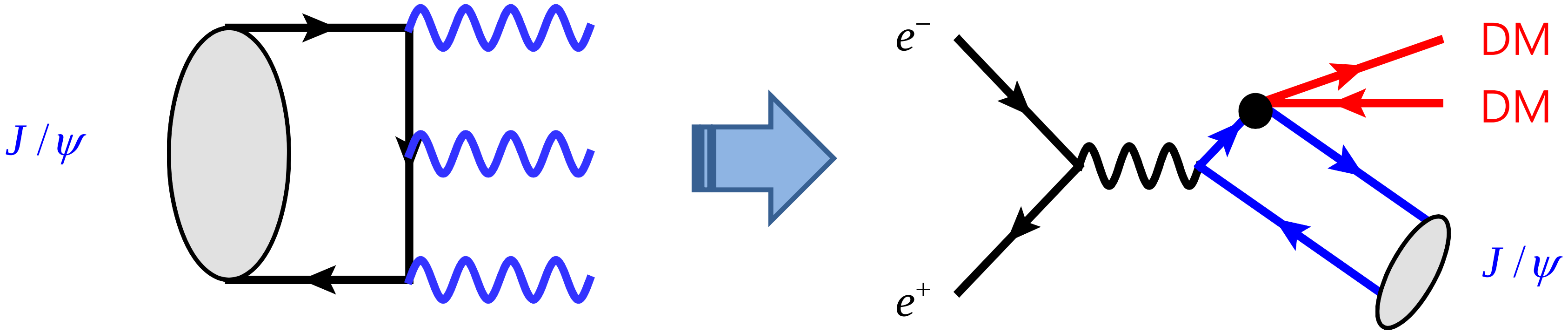
– $Q\bar{Q}$ bound state



$^{2S+1}L_J$	$^1S_0$	$^3S_1$
$c\bar{c}$	η_c	J/ψ
$b\bar{b}$	η_b	Υ
J^{PC}	0^{-+}	1^{--}

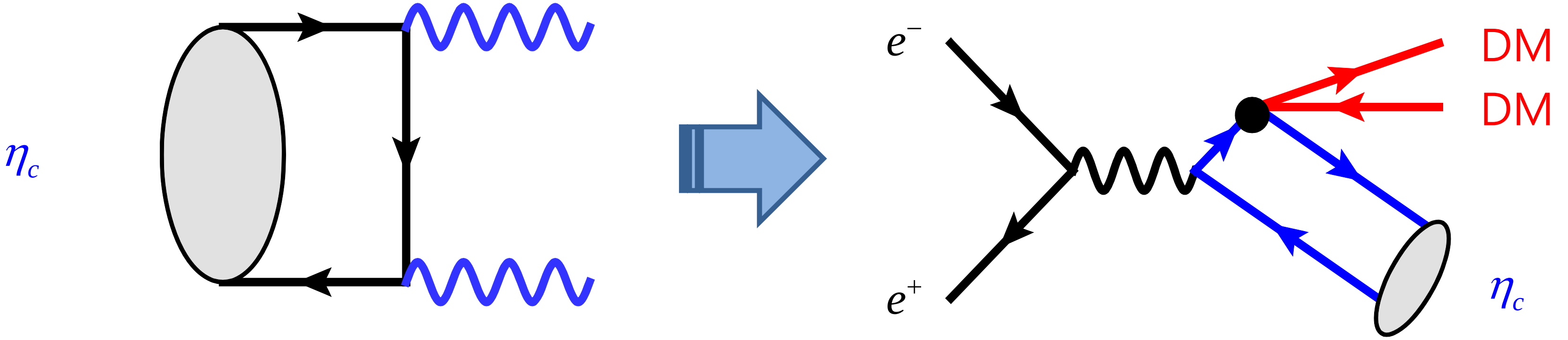
$$e^+e^- \to H(J/\psi,\eta_c,\ldots)+E_T$$

Association production of DM with H



$\Longrightarrow$ decays into an odd number of photons or gluons

● = d1, d2, d3, d4, d7, d8



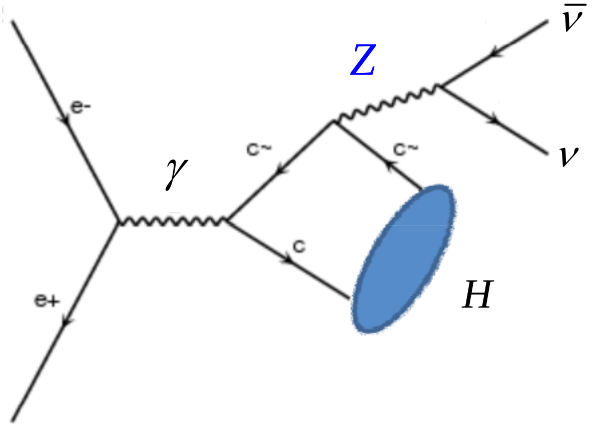
$\Longrightarrow$ decays into an even number of photons or gluons

● = d5, d6, d9, d10

SM backgrounds

1. Irreducible backgrounds

$$e^+e^- \to H + Z(Z \to \nu\overline{\nu})$$



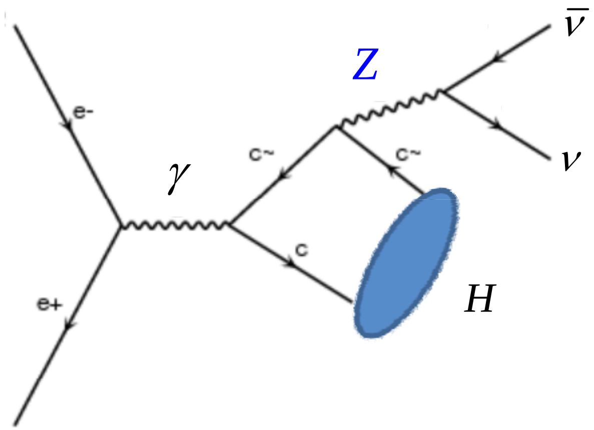
2. Background coming from events where particles are missed.

$$e^+e^- \to H + W^+W^-(W^+W^- \to l^+\nu l^-\overline{\nu})$$

$\Longrightarrow$negligible

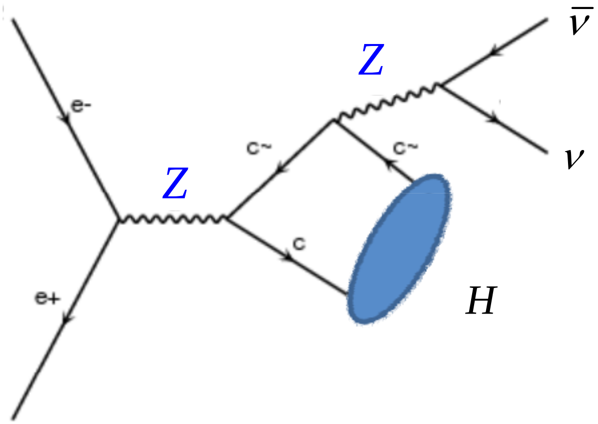
SM backgrounds: $e^+e^- \to H\nu\bar{\nu}$

1. Diagrams with one weak boson propagator



7 diagrams

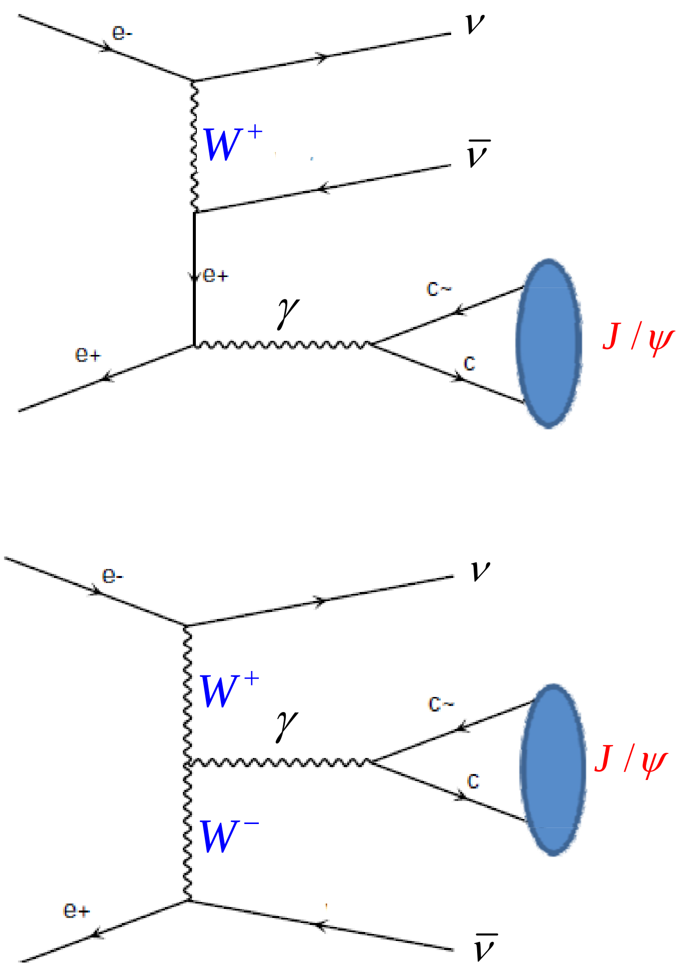
2. Diagrams with two weak boson propagators

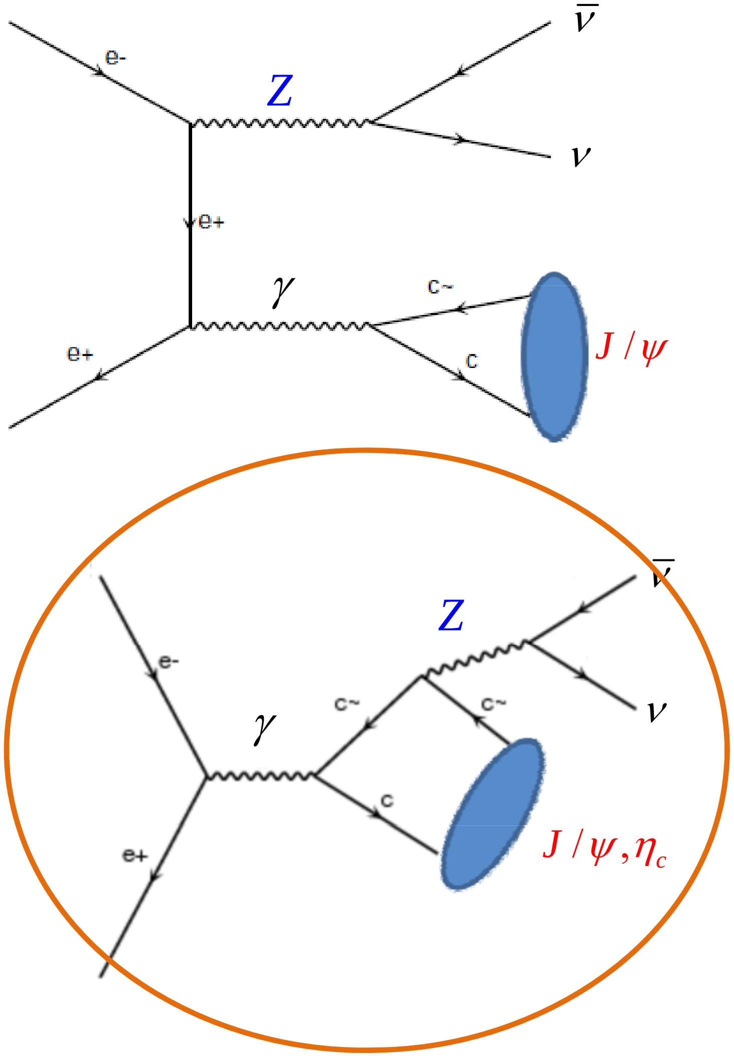


12 diagrams

Suppressed at B factories

SM backgrounds: $e^+e^- \to H\nu\bar{\nu}$





$\sqrt{s} = 10.58$ GeV

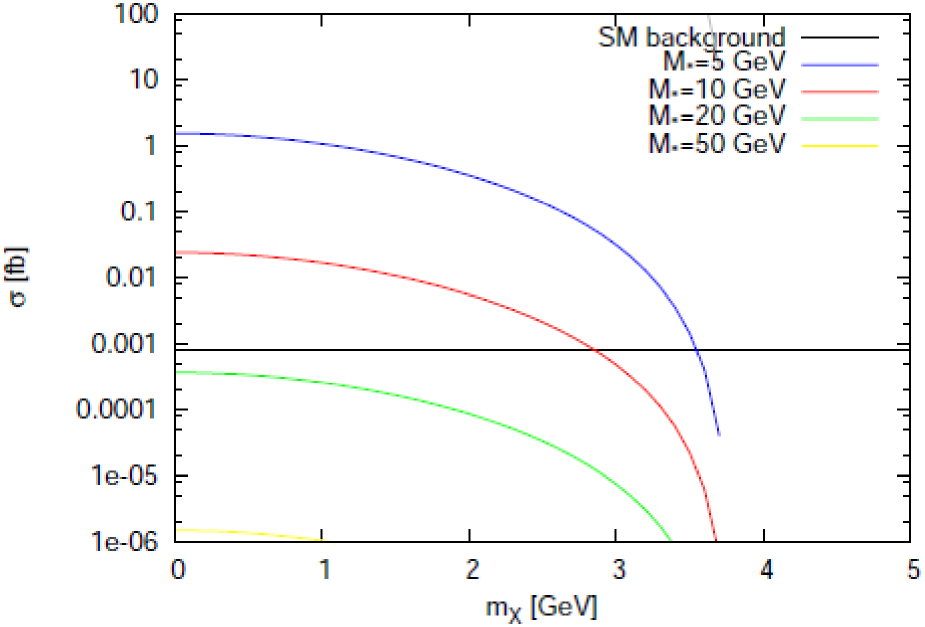
$\sigma(e^+e^- \to J/\psi\nu\bar{\nu}) = 0.00081$ fb

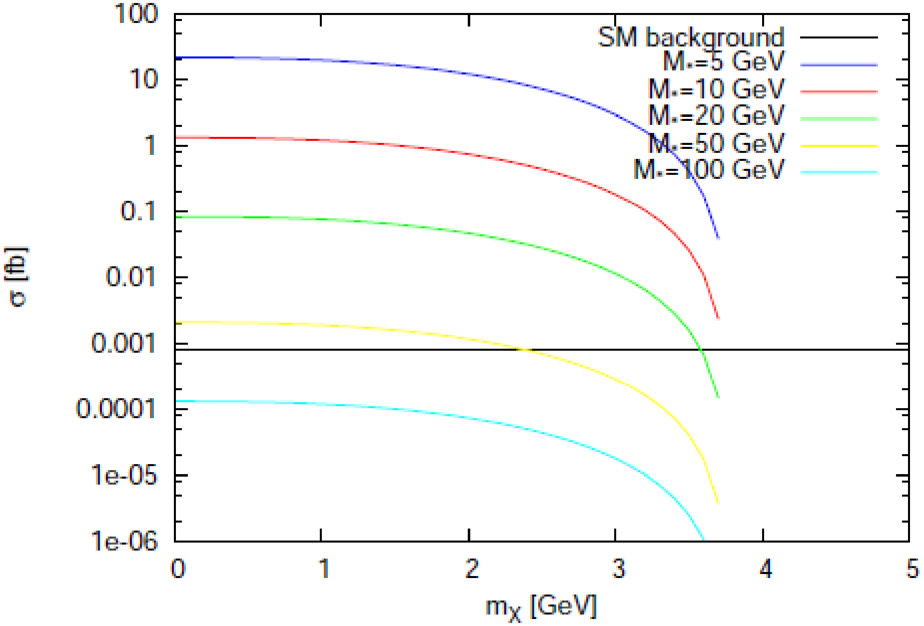
$\sigma(e^+e^- \to \eta_c\nu\bar{\nu}) = 10^{-8}$ fb

$$e^+e^- \to J/\psi + \chi\overline{\chi}$$

$$d_1 = \frac{m_c}{M_*^3}\overline{\chi}\chi\overline{q}q$$

$$d_7 = \frac{1}{M_*^2}\overline{\chi}\gamma^\mu\gamma^5\chi\overline{q}\gamma_\mu\gamma^5 q$$



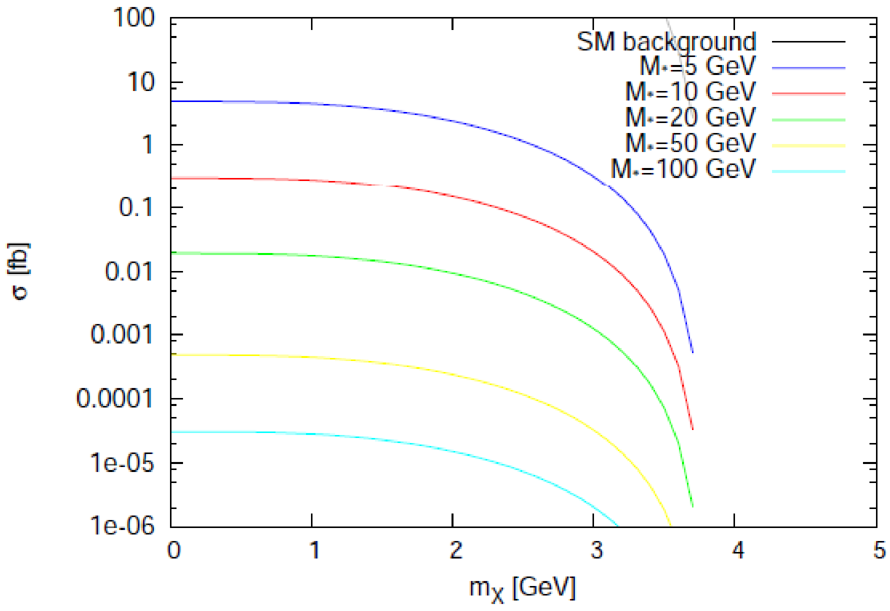


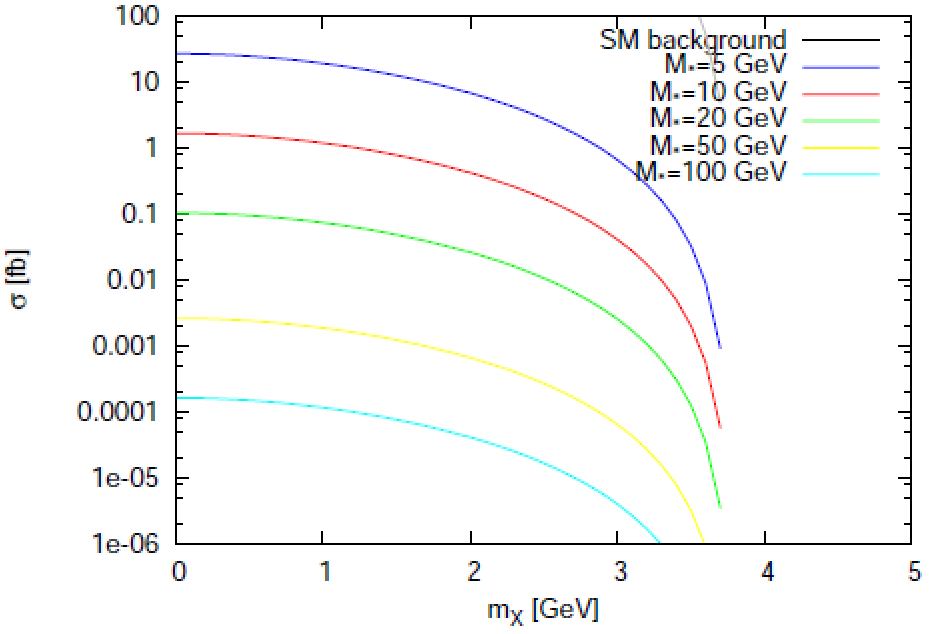
Preliminary

$$e^+e^- \to \eta_c + \chi\bar{\chi}$$

$$d_5 = \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

$$d_9 = \frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}\gamma^5 q$$

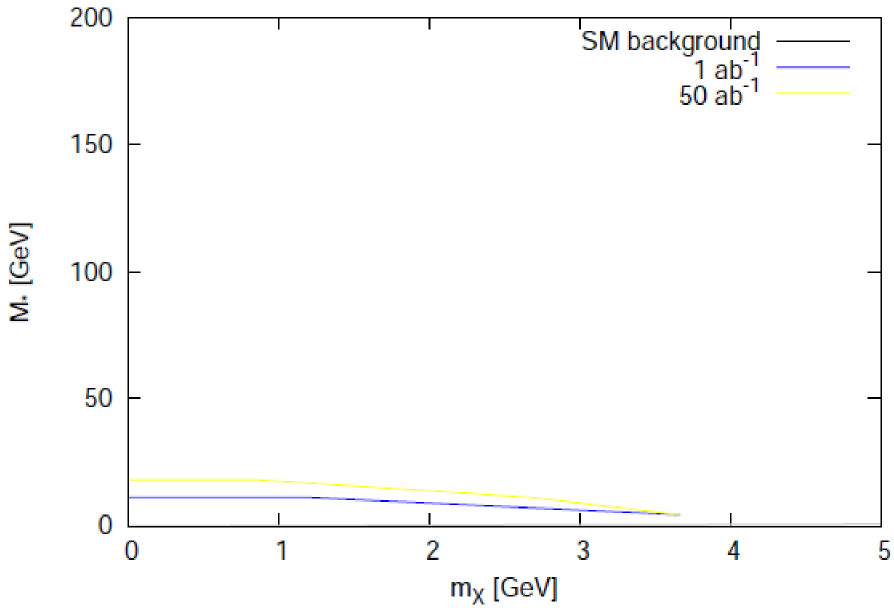




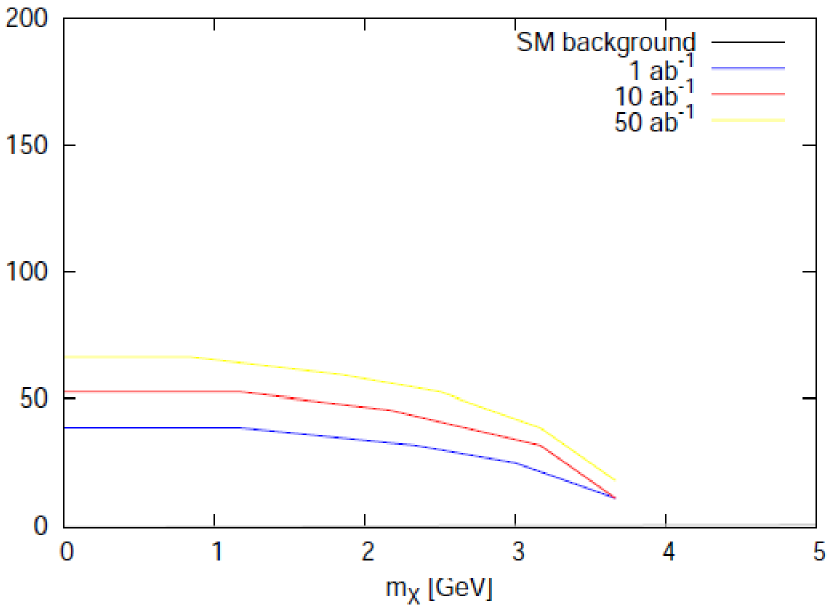
Preliminary

$$e^+e^- \rightarrow J/\psi + \chi\bar{\chi}$$

$$d_1 = \frac{m_c}{M_*^3}\bar{\chi}\chi\bar{q}q$$



$$d_7 = \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$$



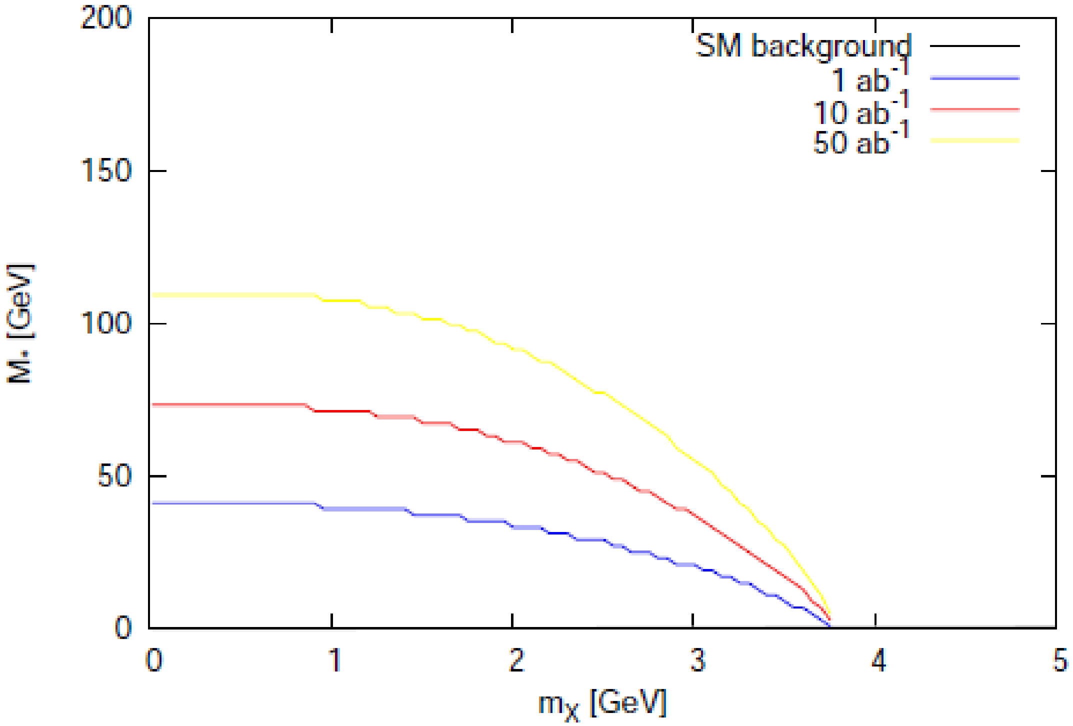
$$\frac{S}{\sqrt{B}} \geq 5$$

Preliminary

$$e^+e^- \to \eta_c + \chi\bar{\chi}$$

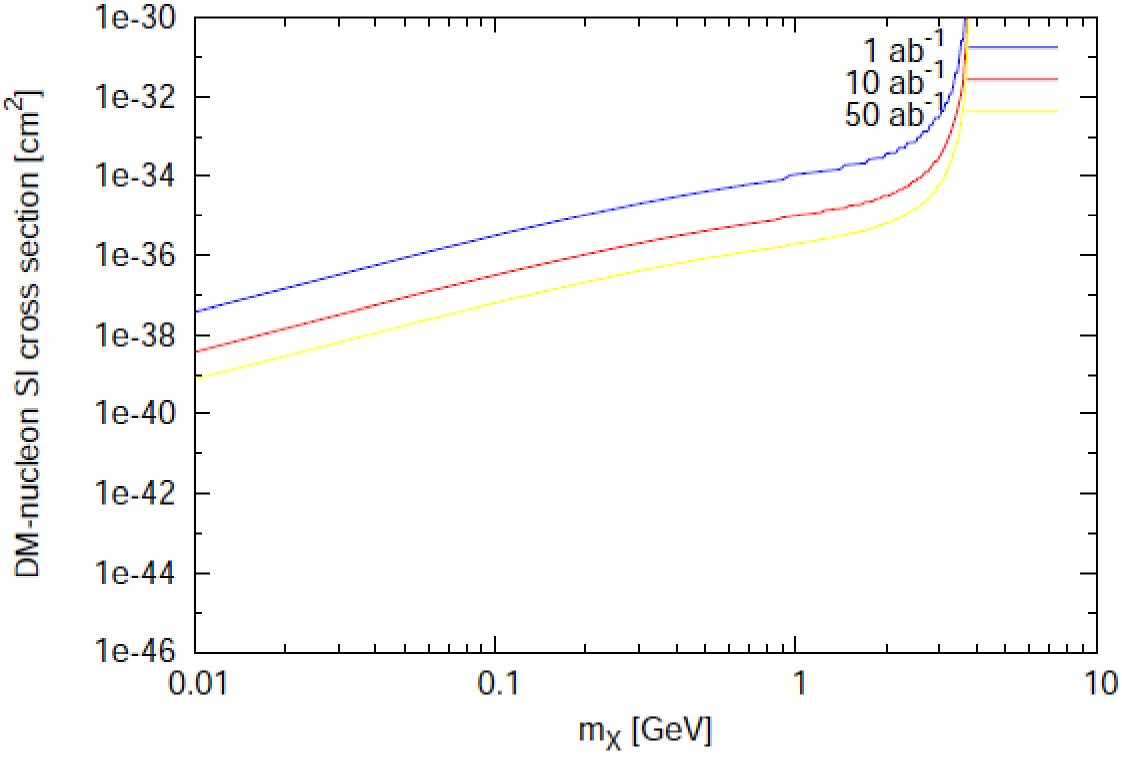
$$d_5 = \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

$$S = \mathcal{L} \times \sigma \geq 1$$



Preliminary

$$e^+e^- \rightarrow \eta_c + \chi\bar{\chi}$$



$$d_5 = \frac{1}{M_*^2}\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$$

Preliminary

Summary

- Many evidences for dark matter, but it has not discovered yet.

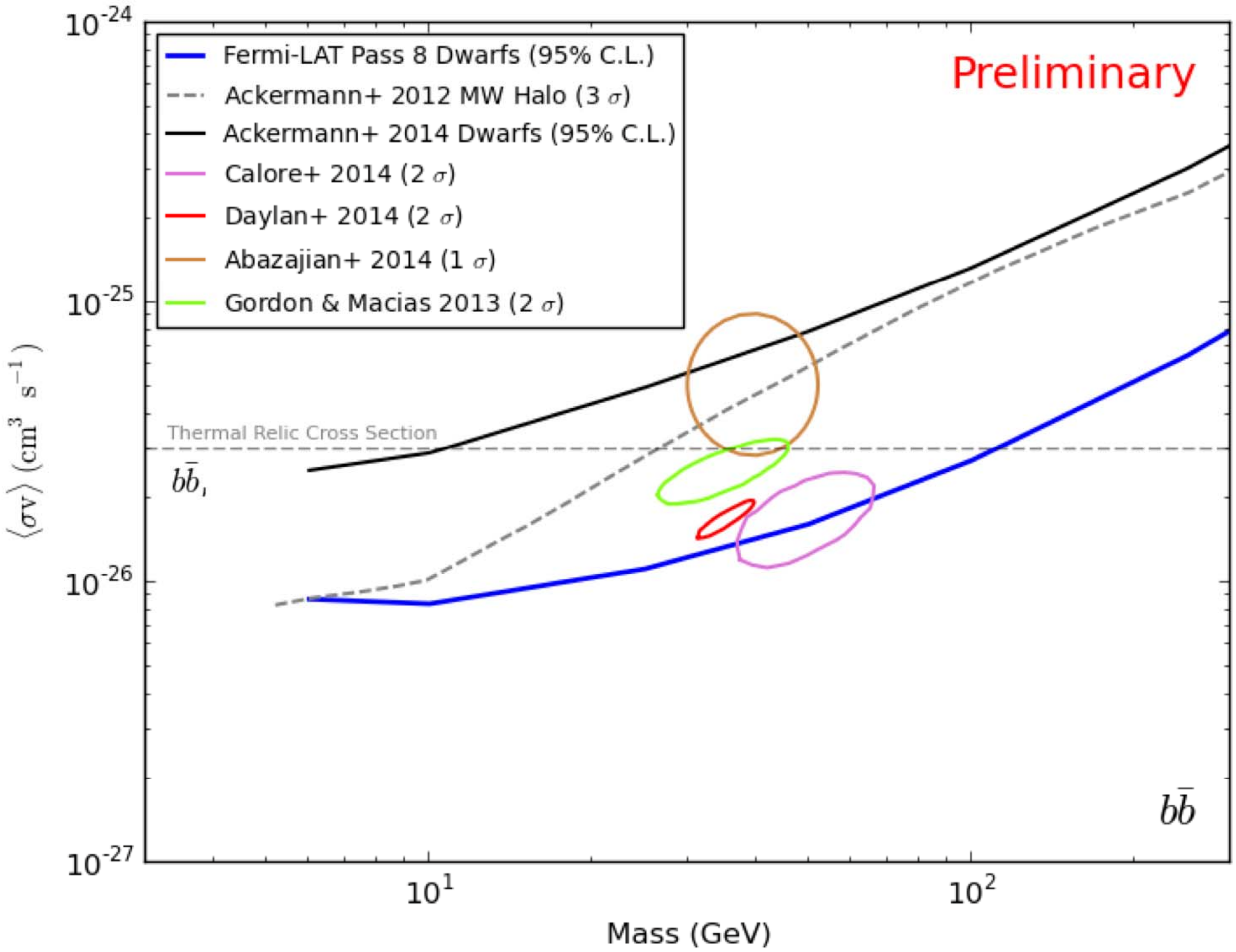
- Dark matter search at colliders would have an important role in discovering dark matter or constraining it.

- Dark matter search at B factories would provide complementary search for dark matter, in particular, in the light dark matter mass region.

- A light dark matter might be in tension with astrophysical observations like CMB.

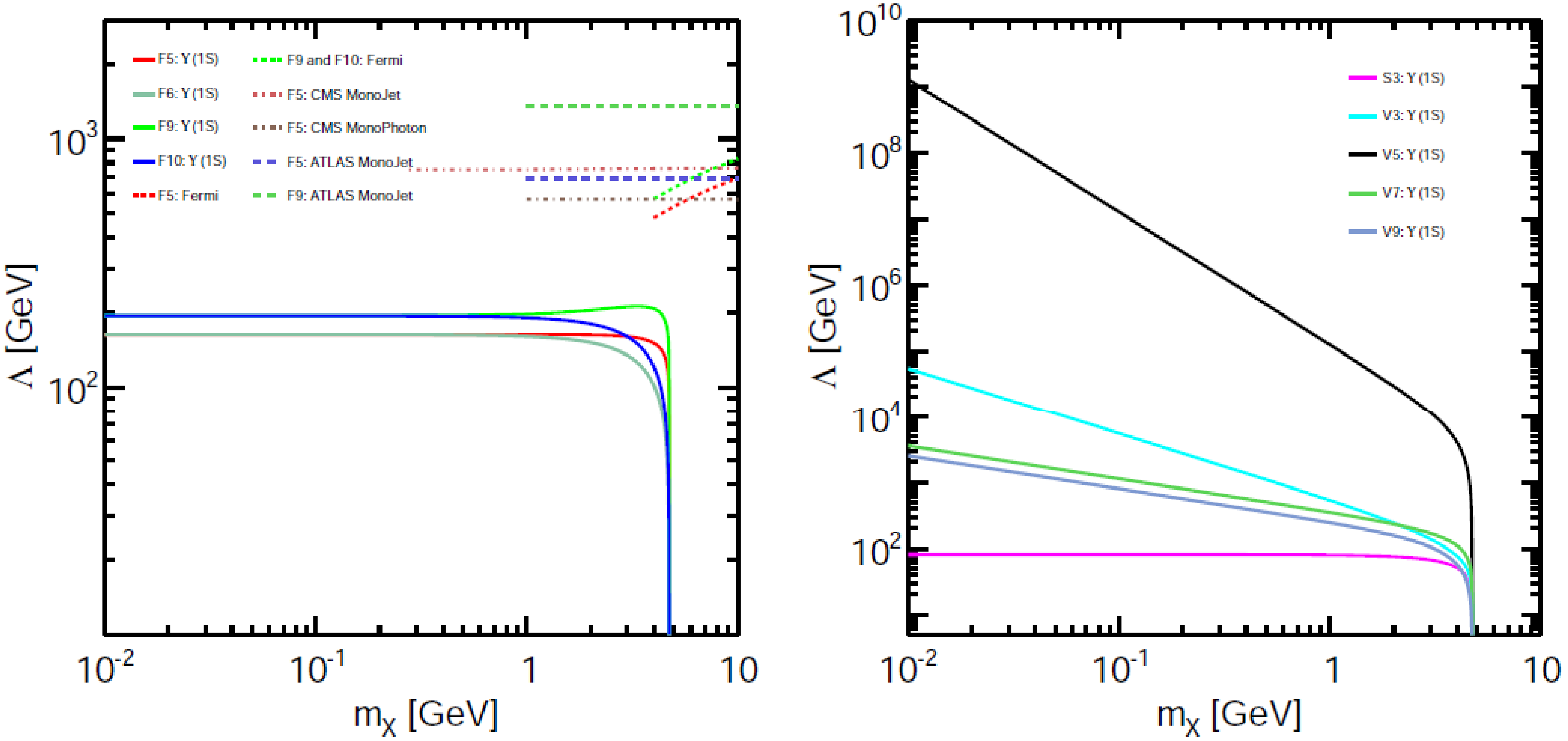
- Future study: dark matter association production with a heavy quarkonium at the LHC.

Fermi-LAT Pass 8



B.Anderson, 5th Fermi Symposium

Υ(3S) decay



🟥 $(1/\Lambda^2)\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$

🟪 $(1/\Lambda^2)\imath Im(\phi^\dagger\partial_\mu\phi)\bar{q}\gamma^\mu q$

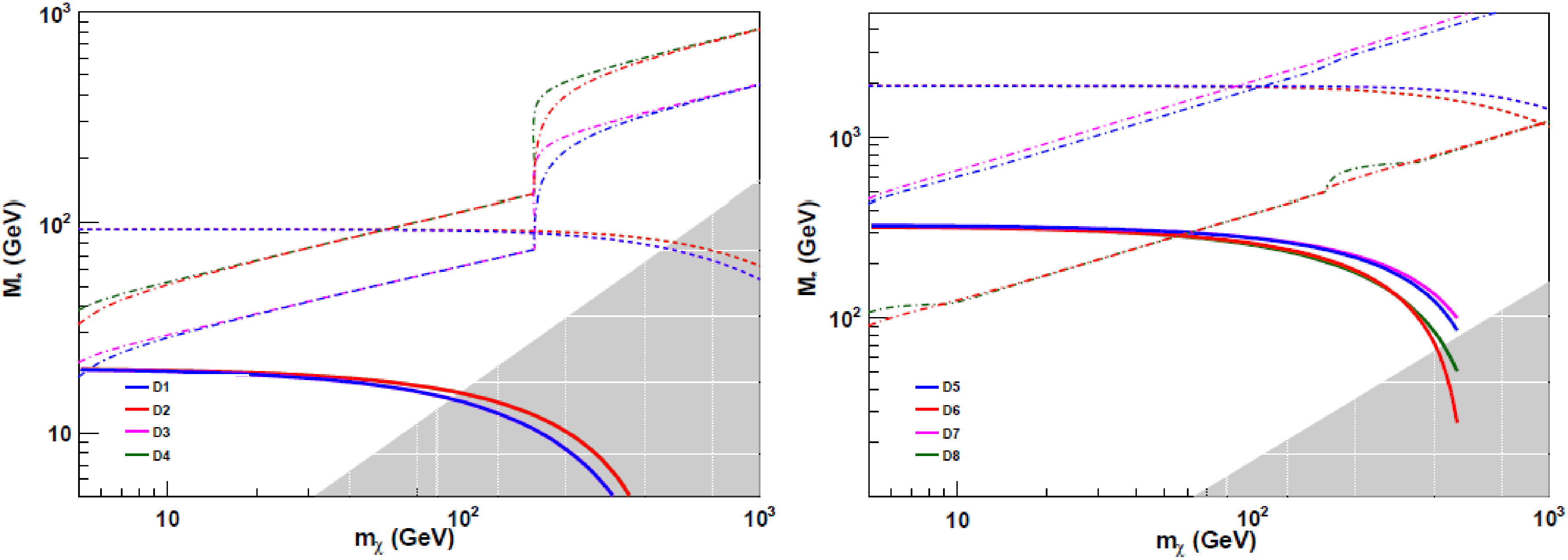
🟦 $(1/\Lambda^2)\imath Im(B_\nu^\dagger\partial_\mu B^\nu)\bar{q}\gamma^\mu q$

🟩 $(1/\Lambda^2)\bar{X}\sigma^{\mu\nu}X\bar{q}\sigma_{\mu\nu}q$

⬛ $(1/\Lambda)(B_\mu^\dagger B_\nu - B_\nu^\dagger B_\mu)\bar{q}\sigma^{\mu\nu}q$

Fernandez,Kumar,Seong,Stengel, arXiv:1404.6599

LHC reach and relic density



Goodman et al., arXiv:1008.1783

━━━ Tevatron 2σ

‑ ‑ ‑ LHC 5σ reach

‑ · ‑ Relic density