Mono-quarkonium production for dark matter search

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arXiv:1512.xxxxx with T.C.Yuan

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Dark matter

- What we know
  - gravitational interaction
  - Our universe is composed of about 26.8% DM
  - stable so far

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  - gravitational interaction
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- What we do not know
  - mass, coupling
  - decaying or annihilating DM?
  - production: thermal or non-thermal?

Dark matter

- What we know
    - gravitational interaction
    - Our universe is composed of about 26.8% DM
    - stable so far

- What we do not know
    - mass, coupling

Can we distinguish the dark matter interactions with each SM quark?

flavor-universal or flavor-dependent?

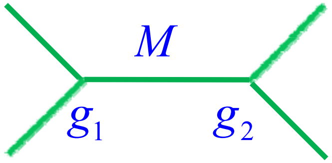
Effective operators

- Assume that the dark matter particle is the only new particle in the energy range of interest.

- After integrating out heavy degrees of freedom, the dark matter interaction with the SM particles is represented by higher-dimensional operators.

$$D1:\ O_1^D = \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$$

$$D5:\ O_5^D = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

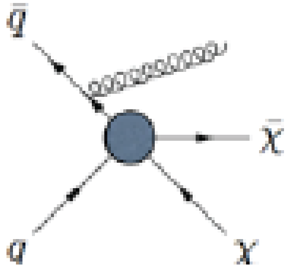


$$\Lambda \sim \frac{M}{\sqrt{g_1 g_2}}$$

$$D8:\ O_8^D = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q$$

Mono-X search

- search for missing transverse energy with X



$$pp \to X + E_T$$

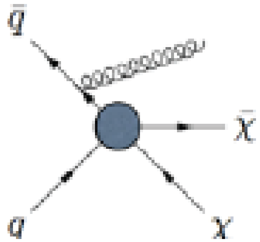
X=any SM particle(s)
jet(s), γ, W, Z, t, tt, h, …

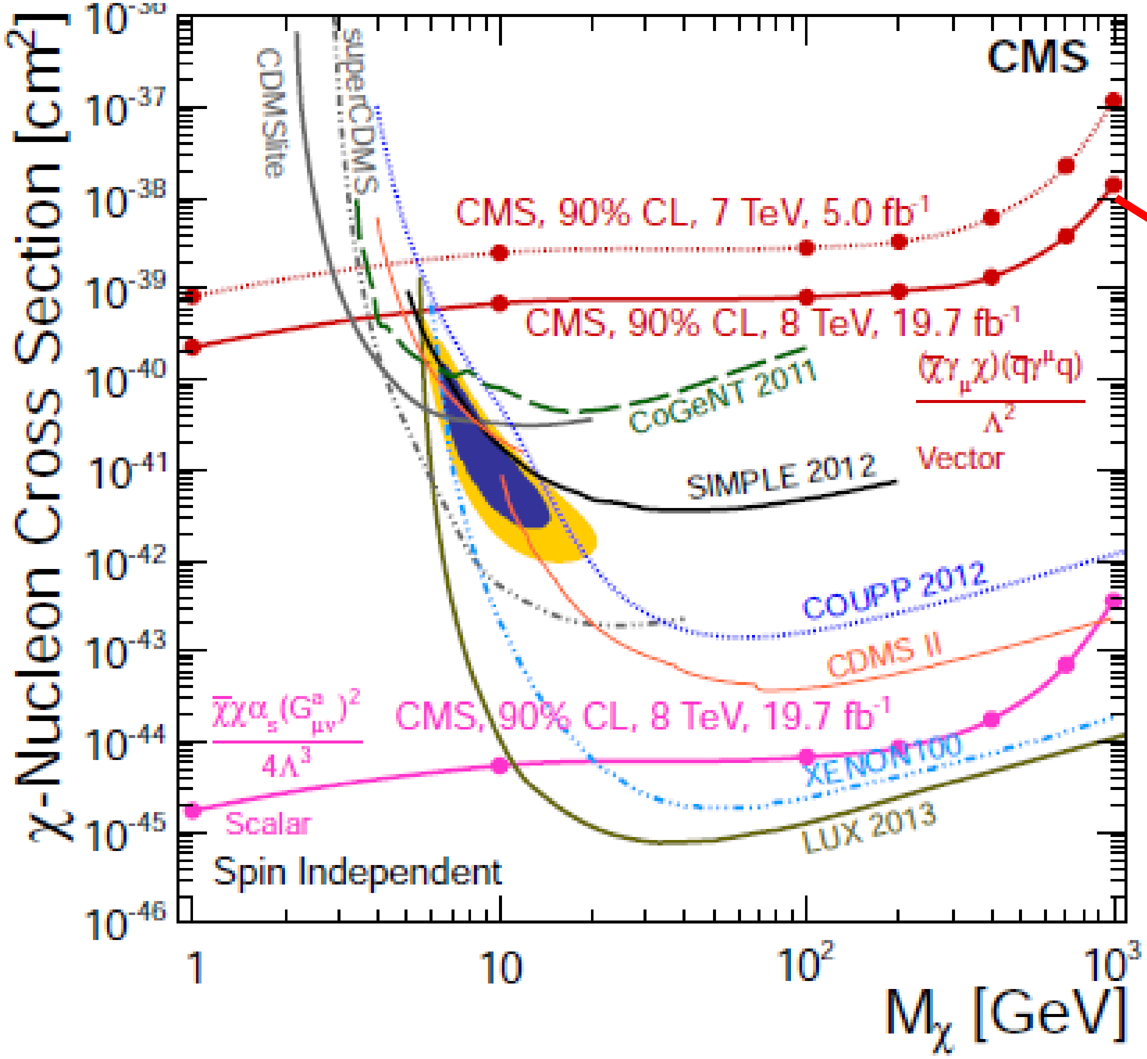
- X could be any bound state, for example, a heavy quarkonium

- possible to calculate the production cross section of a heavy quarkoniium systematically by nonrelativistic QCD

- may give a chance to the dark matter coupling to heavy quarks

Monojet

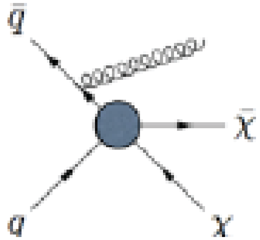


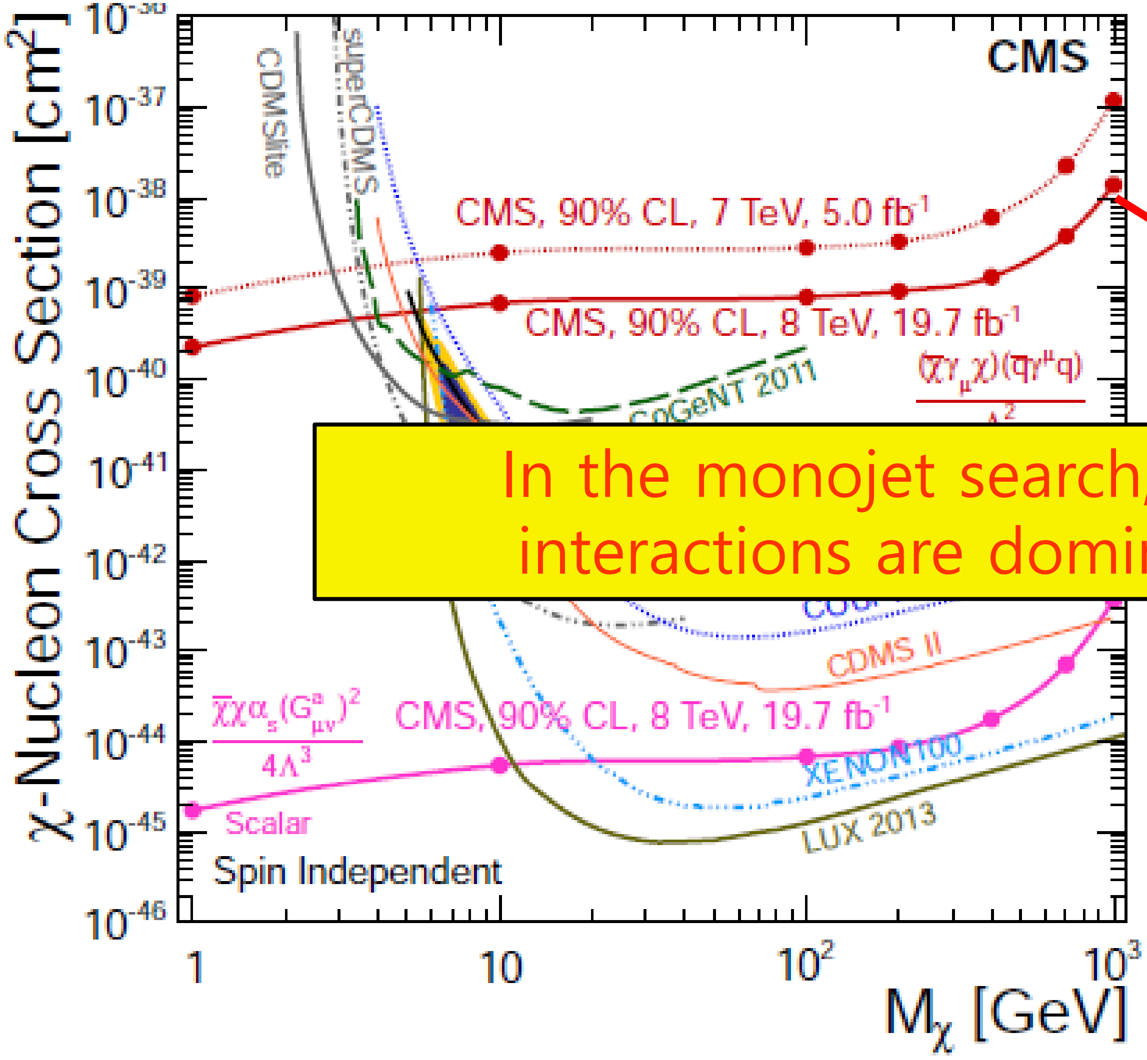


$$D5 = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

CMS, arXiv:1408.3583

Monojet



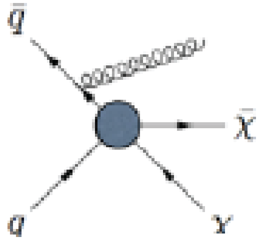


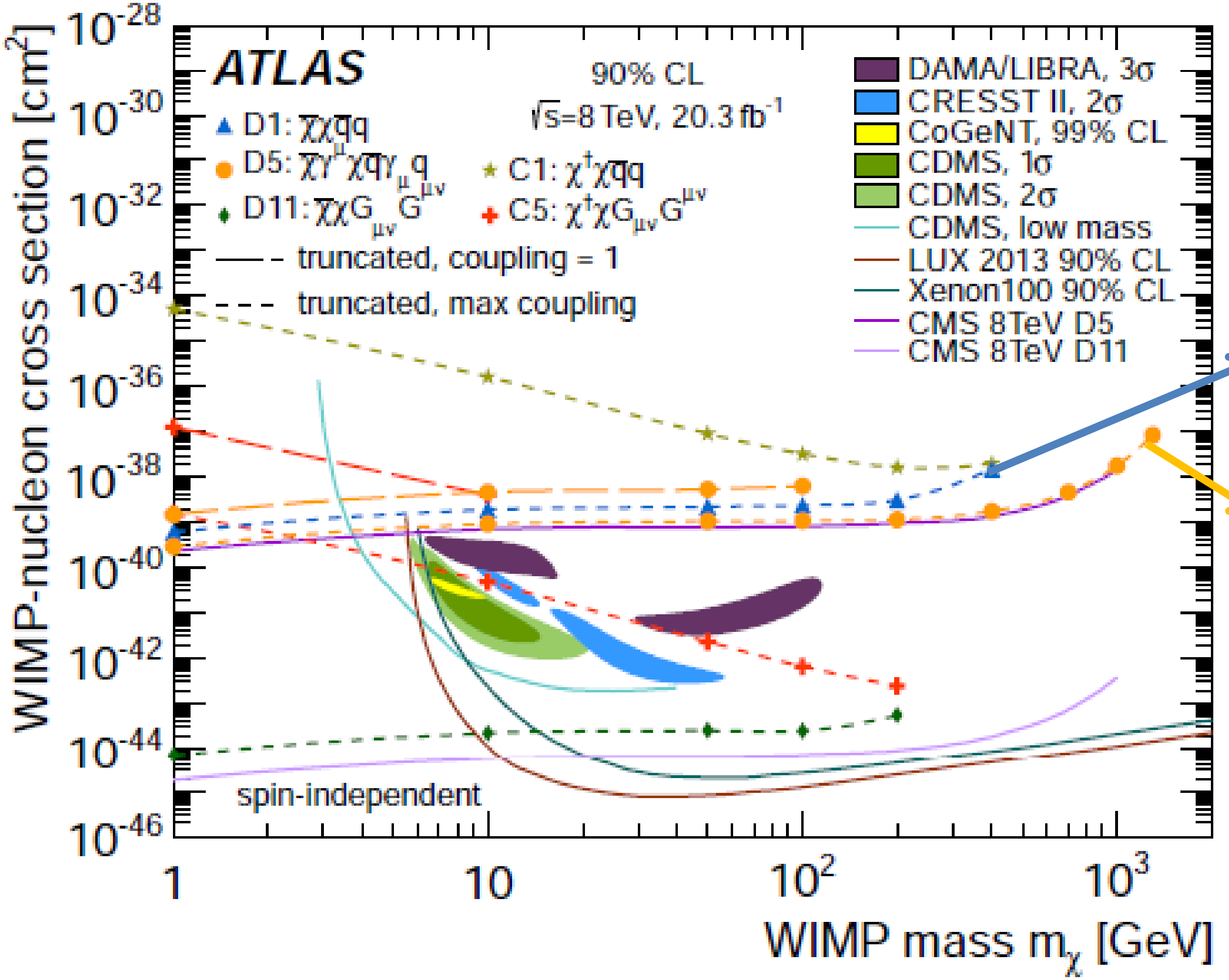
$$D5 = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

In the monojet search, qqbar (qg) interactions are dominant for D5

CMS, arXiv:1408.3583

Monojet





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

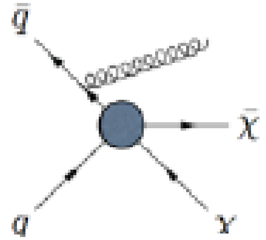
↦ charm quark is important

$$D1 = \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$$

$$D5 = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

ATLAS, arXiv:1502.01518

Monojet



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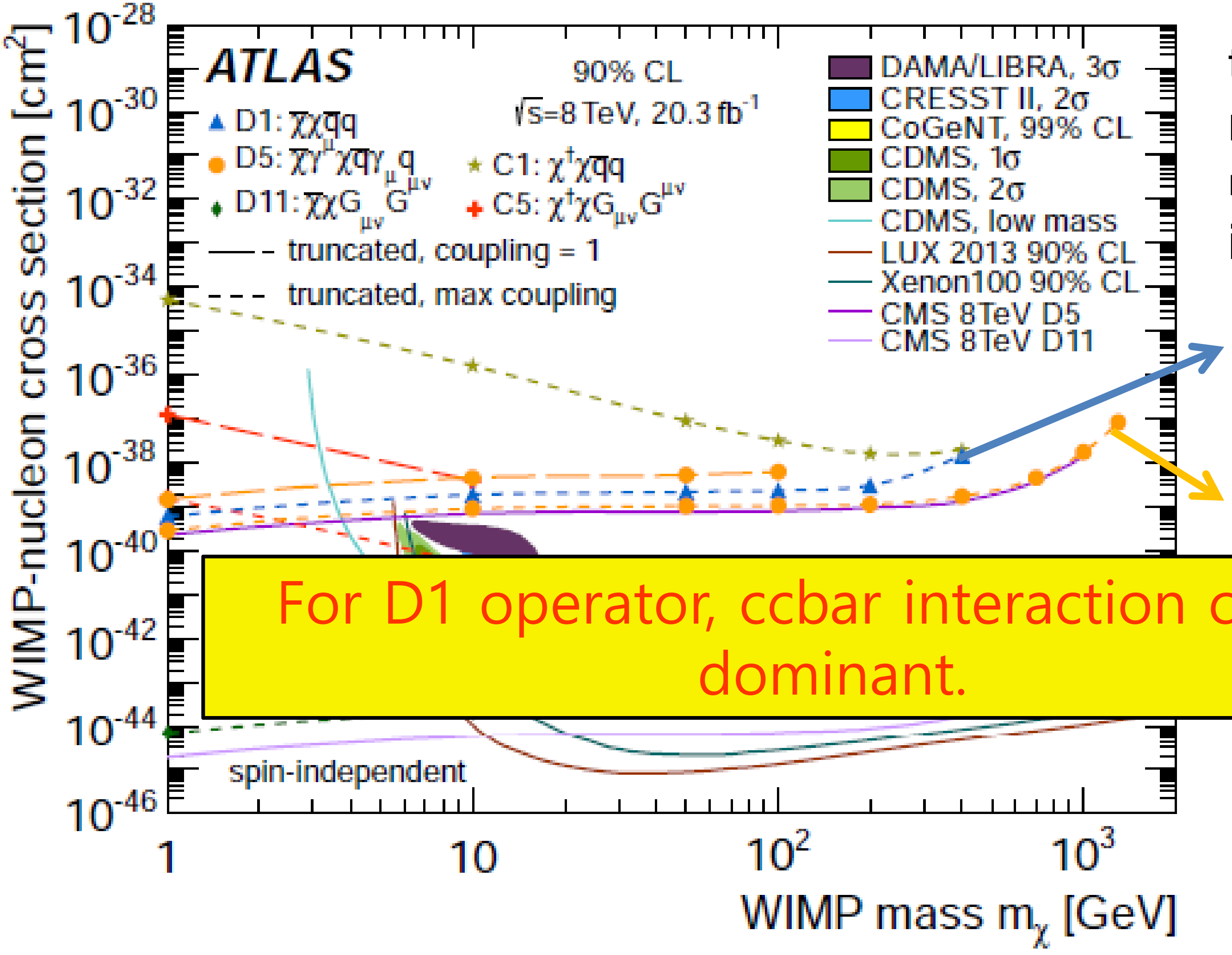


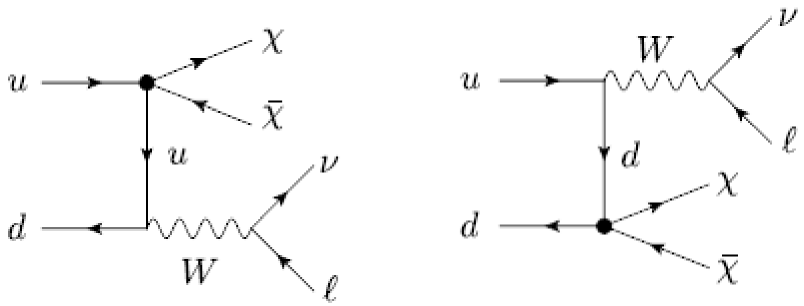
$$d_1 = \frac{m_q}{M_*^3}\bar\chi\chi\bar q q$$

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

For D1 operator, ccbar interaction can be dominant.

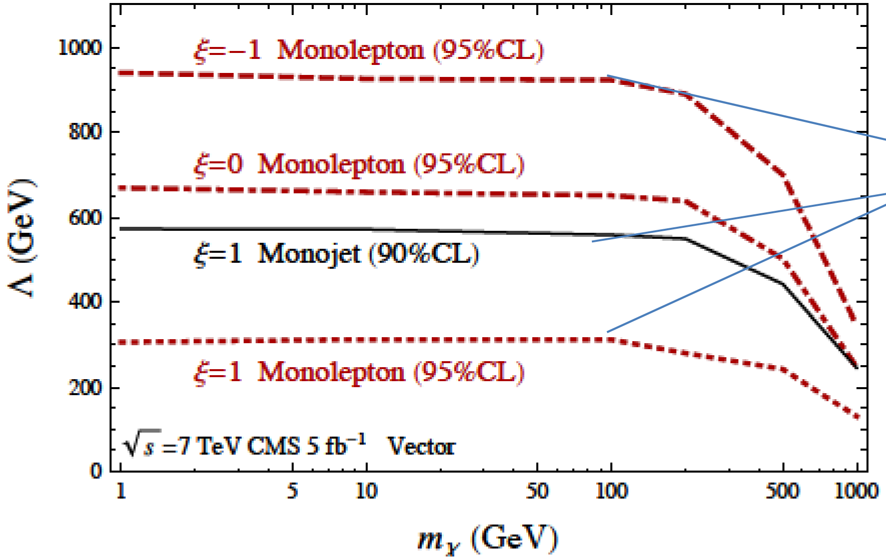
ATLAS, arXiv:1502.01518

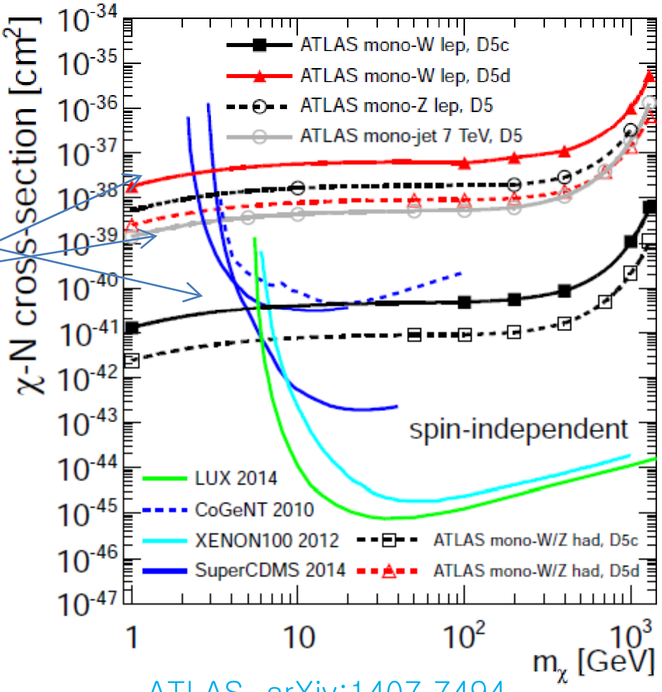
Mono-W



$$\frac{1}{\Lambda^2}\,\bar{\chi}\gamma_\mu\chi\;\left(\bar{u}\gamma^\mu u+\xi\,\bar{d}\gamma^\mu d\right)$$

Bai,Tait, arXiv:1208.4361





ATLAS, arXiv:1407.7494

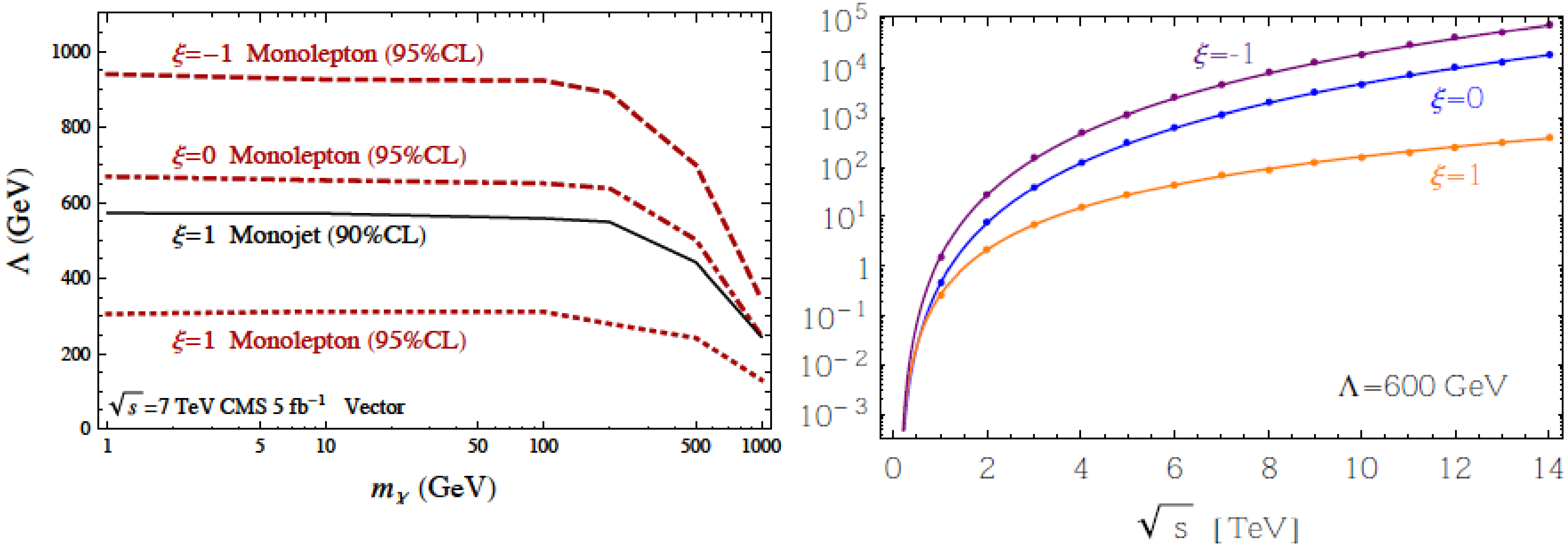
It might be possible to distinguish the dark matter interactions with u and d quark.

Gauge Invariance in Mono-W

Bell et al.,arXiv:1503.07874

$$\frac{1}{\Lambda^2}\,\overline{\chi}\gamma_\mu\chi\,\left(\overline{u}\gamma^\mu u+\xi\,\overline{d}\gamma^\mu d\right)$$

SM gauge symmetry is not respected for $\xi \neq 1$

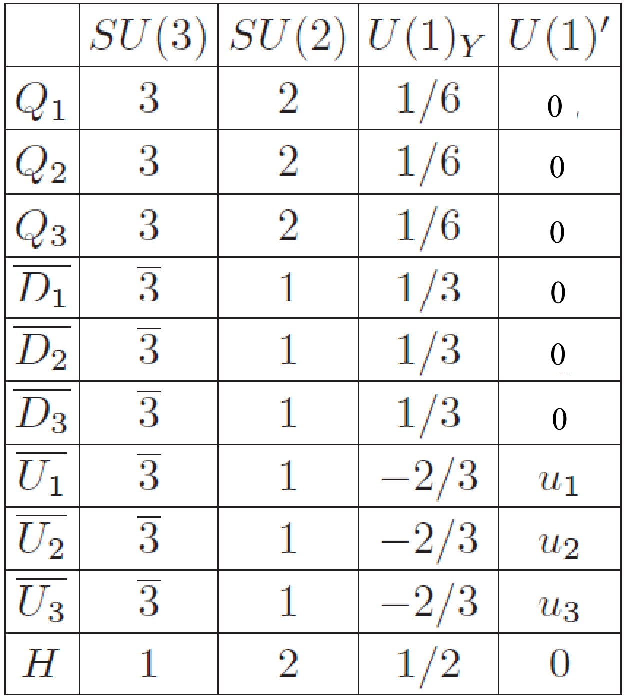


The origin of the constructive interference for $\xi \neq 1$ is SU(2) violating effect, which should be protected by the EW scale

SU(2) violating operators should be related to Higgs vev or fermion mass ~suppressed by $O(m/\Lambda)$ or $O(v/\Lambda)$

Flavor-dependent DM model

- flavored dark matter models may be possible



	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
Q_1	3	2	$1/6$	0
Q_2	3	2	$1/6$	0
Q_3	3	2	$1/6$	0
$\overline{D_1}$	$\overline{3}$	1	$1/3$	0
$\overline{D_2}$	$\overline{3}$	1	$1/3$	0
$\overline{D_3}$	$\overline{3}$	1	$1/3$	0
$\overline{U_1}$	$\overline{3}$	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

Ko,Omura,Yu,JHEP1201

- flavor-dependent chiral U(1)′ model

- DM may couple with the top quark dominantly for $(u_1,u_2,u_3)=(0,0,1)$

- Originally motivated by the top-quark AFB asymmetry and $B\to D^{(*)}\tau\nu$ anomalies

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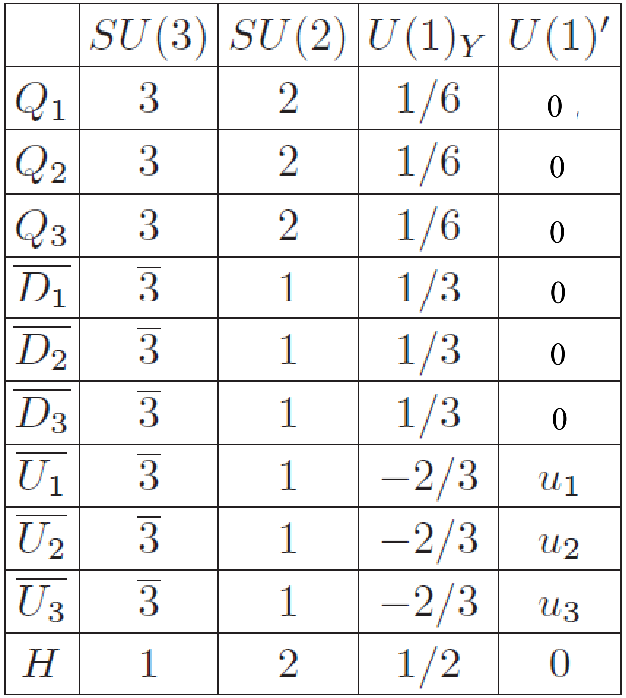

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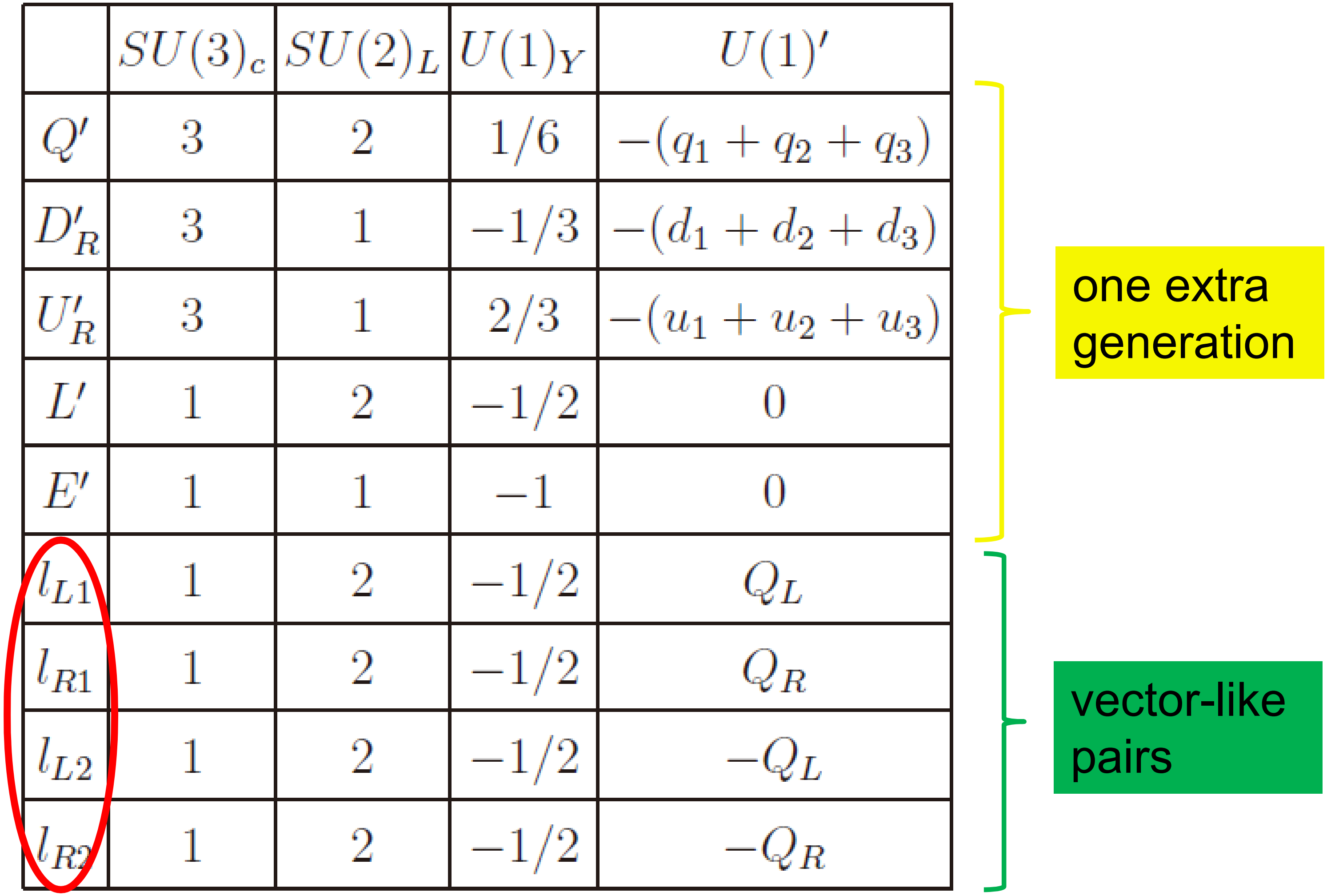
- DM may couple with the top quark dominantly for $(u_1,u_2,u_3)=(0,0,1)$

- Originally motivated by the top-quark AFB asymmetry and $B \to D^{(*)}\tau\nu$ anomalies

- Similarly it would be possible to construct the dark matter model which couple with the bottom quark or charm quark dominantly

Anomaly Cancelation

- Anomaly cancelation requires extra fermions



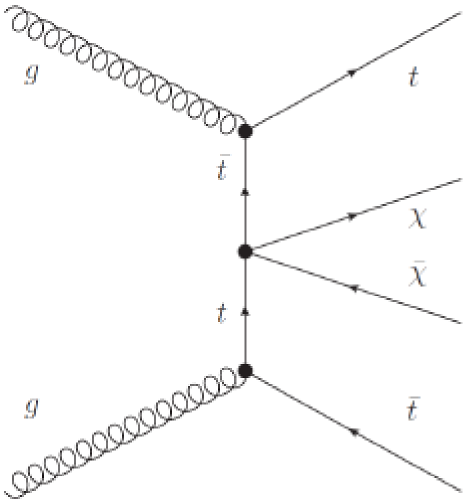
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q'	3	2	$1/6$	$-(q_1+q_2+q_3)$
D'_R	3	1	$-1/3$	$-(d_1+d_2+d_3)$
U'_R	3	1	$2/3$	$-(u_1+u_2+u_3)$
L'	1	2	$-1/2$	0
E'	1	1	-1	0
l_{L1}	1	2	$-1/2$	Q_L
l_{R1}	1	2	$-1/2$	Q_R
l_{L2}	1	2	$-1/2$	$-Q_L$
l_{R2}	1	2	$-1/2$	$-Q_R$

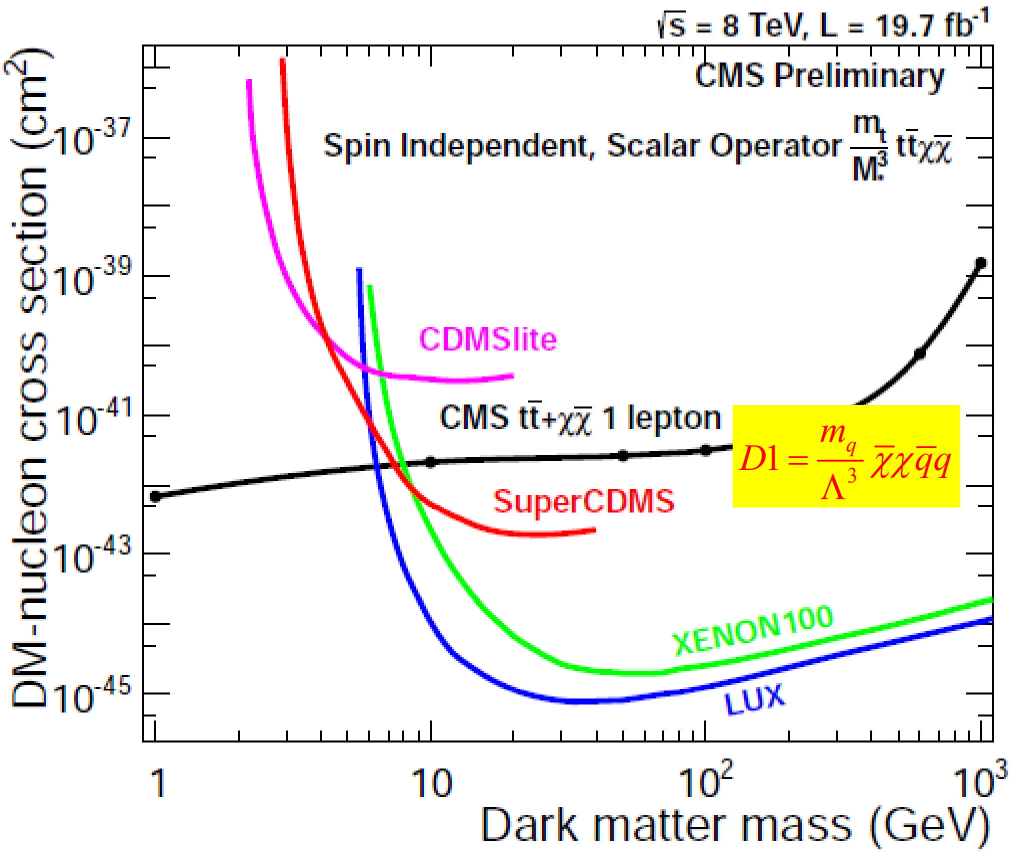
one extra generation

vector-like pairs

a candidate for CDM

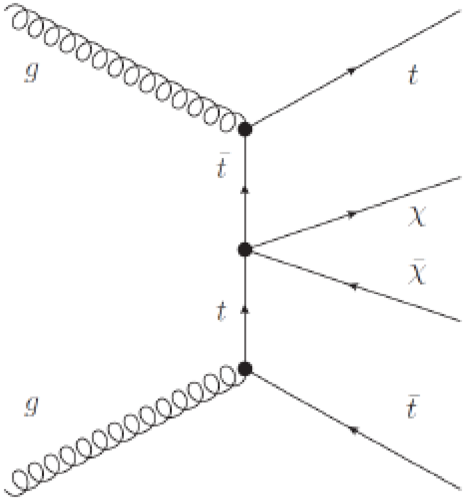
Mono-tt

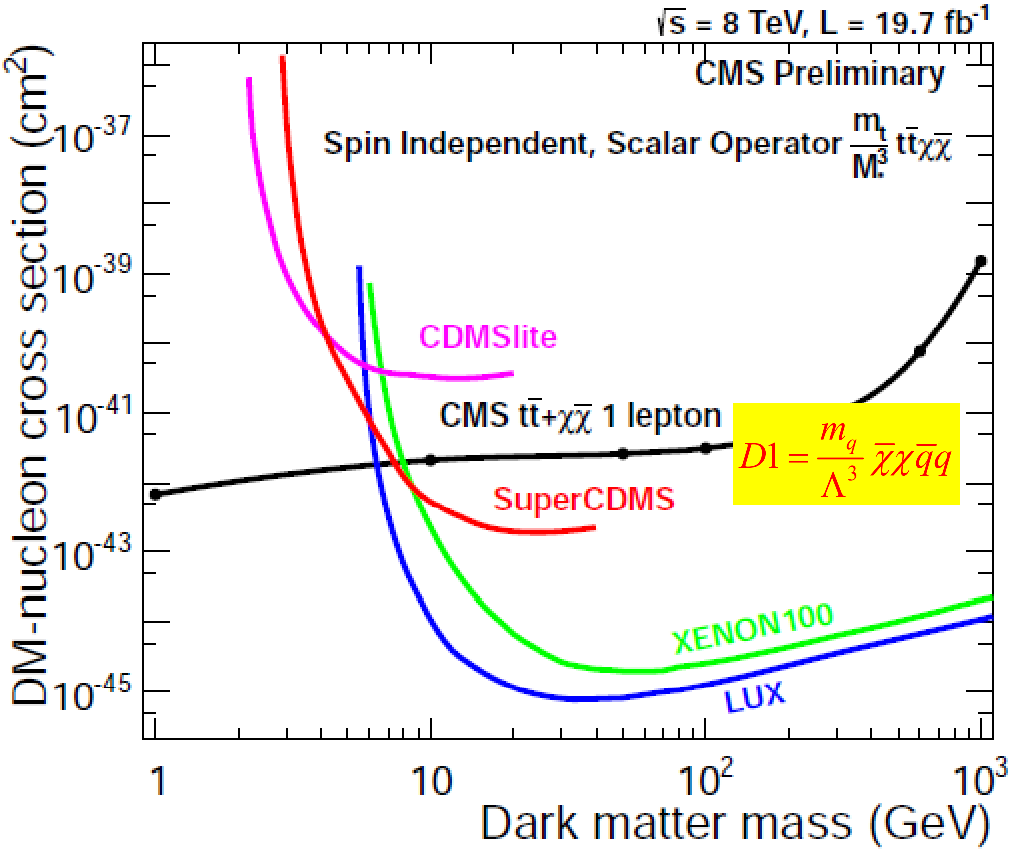




$$D1 = \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$$

Mono-tt

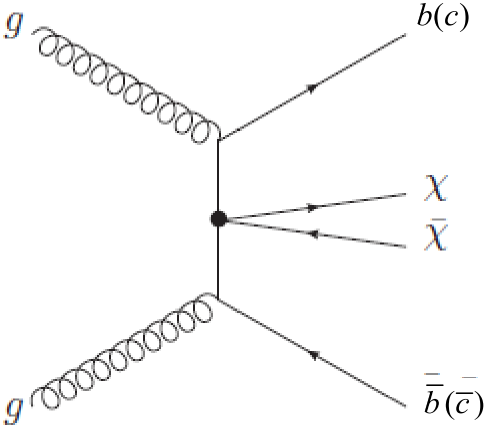


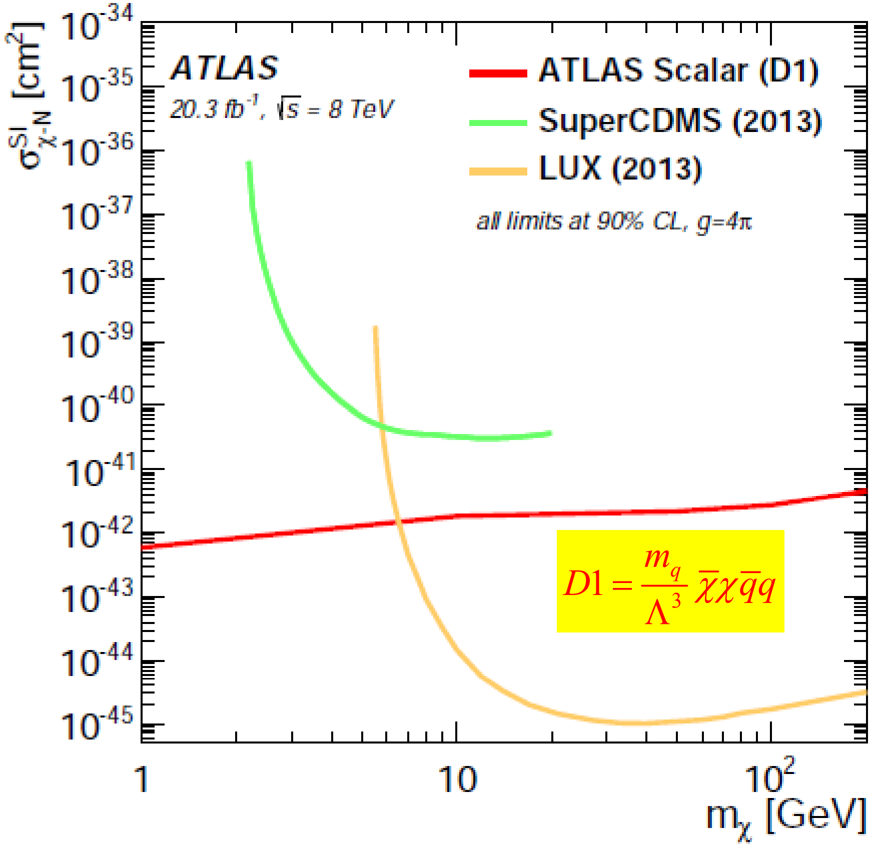


$$D1 = \frac{m_q}{\Lambda^3} \bar{\chi}\chi\bar{q}q$$

For operators other than (pseudo)scalar operators, there is contamination from qqbar →ttbar, where the DM pair is attached to the initial quarks

Mono-bb (cc)





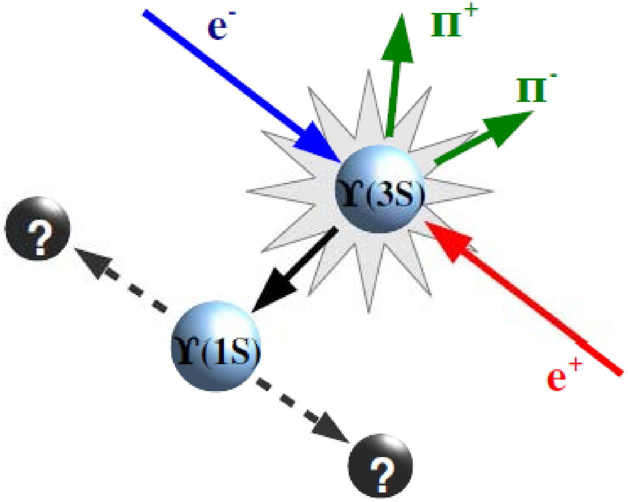
cc+DM pair would be a challenge

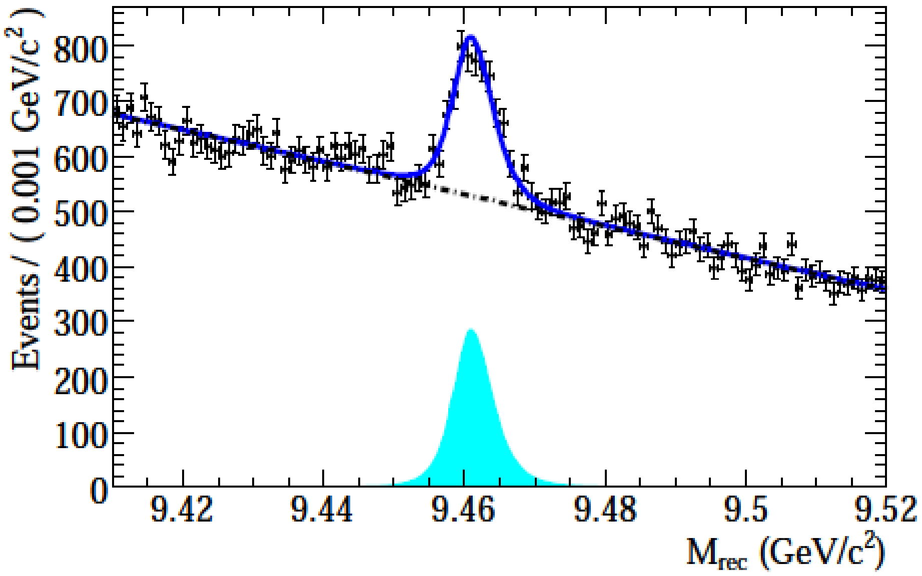
Heavy quarkonium may play a role to search for bottom(charm)philc DM or DM interactions with bottom(charm) quarks

$\Upsilon(3S)$ decay

- $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ with $\Upsilon(1S)\to$invisible

$$M_{rec}^2 = s + M_{\pi\pi}^2 - 2\sqrt{s}E_{\pi\pi}^*$$





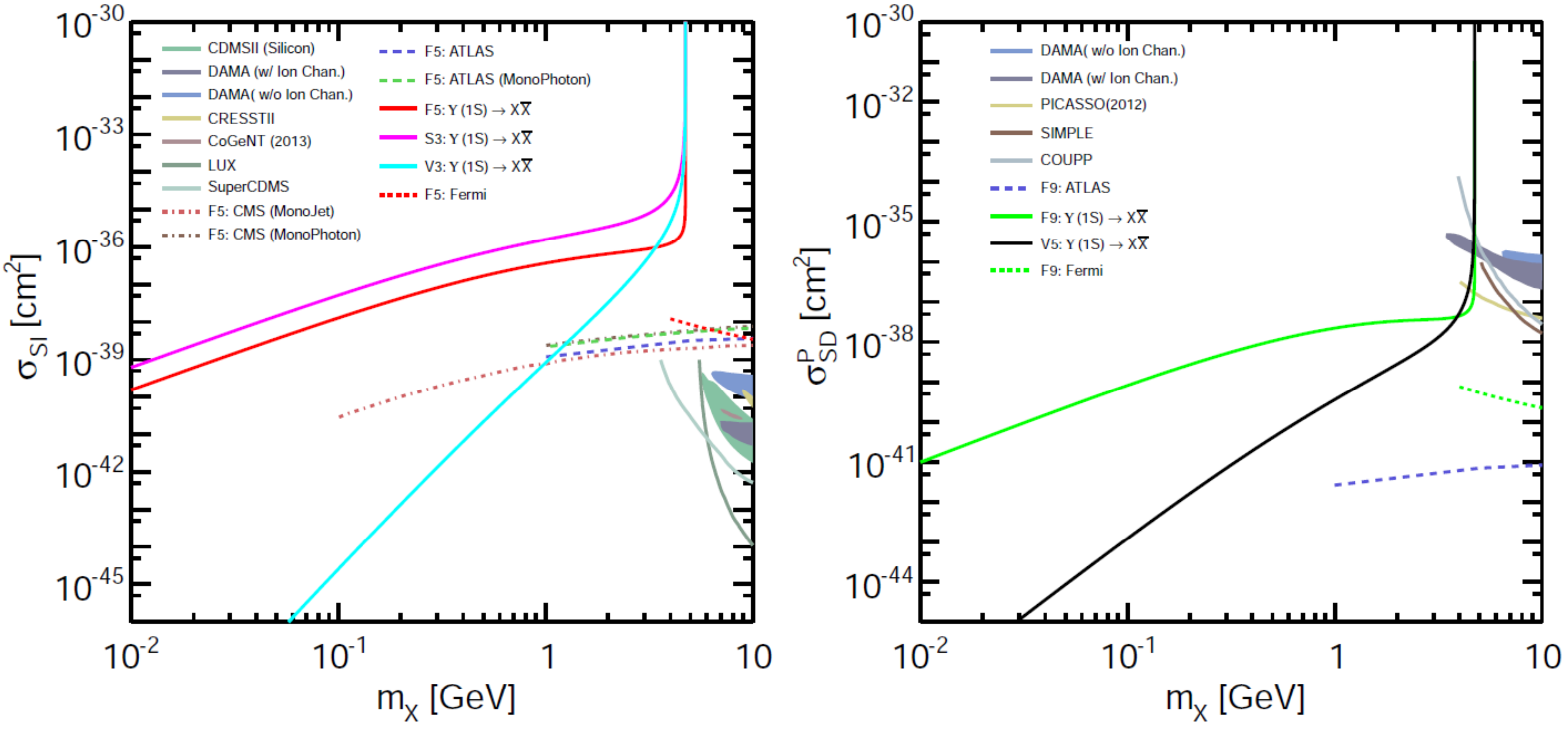
BABAR,arXiv:0908.2840

$$\mathcal{B}(\Upsilon(1S)\to invisible) < 3.0\times10^{-4}$$
$$\mathcal{B}(J/\Psi\to invisible) < 7.2\times10^{-4}$$

$$\mathcal{B}(\Upsilon(1S)\to\nu\bar{\nu}) = 9.85\times10^{-6}$$
$$\mathcal{B}(J/\Psi\to\nu\bar{\nu}) = 2.70\times10^{-8}$$

SM prediction

Υ(3S) decay



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

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

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

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

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

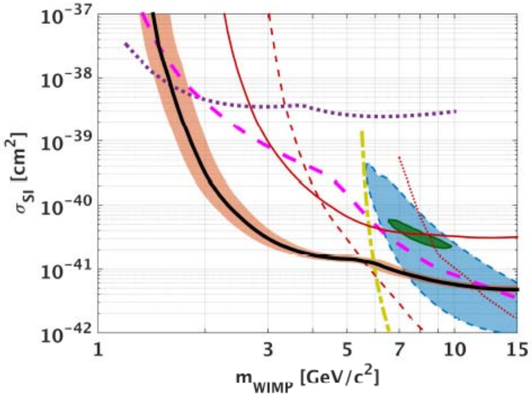
Fernandez,Kumar,Seong,Stengel, arXiv:1404.6599

Dark matter search at B factories

- fixed CM energy $\sqrt{s} = 10.58 \text{ GeV}$
- relatively free from validity of EFT
- clean signal and low background.
- sensitive to light DM $\lesssim$ 5 GeV.
- already about 1 ab^{-1} data were accumulated at Belle and BABAR.
- BELLE II will start to accumulate data soon.

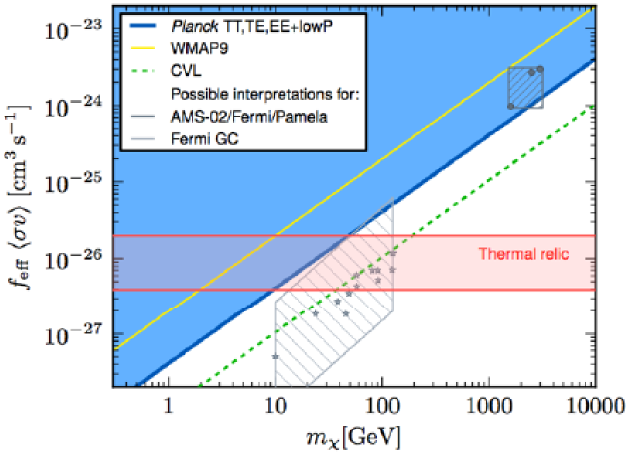
light DM constrained

- Direct detection

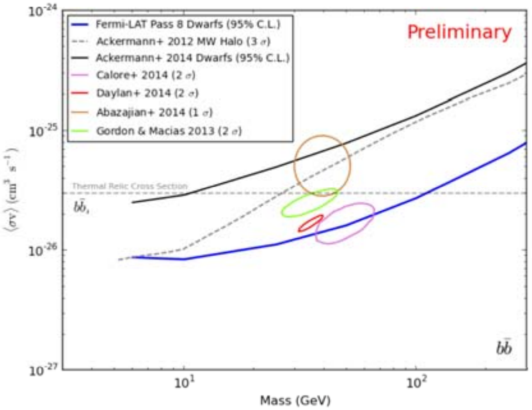


SuperCDMS,arXiv:1509.02448

- CMB



- γ-ray from dwarf galaxies



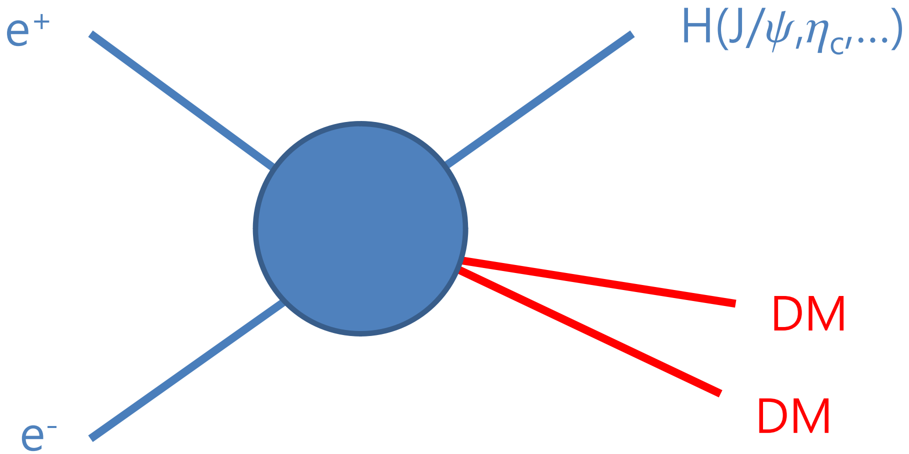
- below 5 GeV, bounds weaken due to the photon energy threshold

- below 4 GeV, the final state energy becomes close to the hadronization scale.

Fernandez et al. arXiv:1404.6599

- CMB also constrains s-wave annihilation at recombination.

Mono-quarkonium production

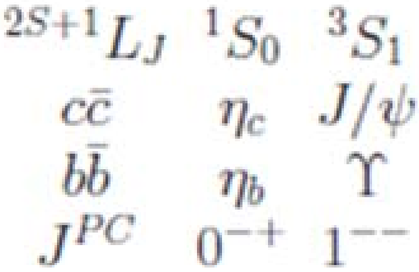


$$e^+e^- \to H(J/\psi,\eta_c,\ldots)+E_T$$

H=heavy quarkonium

– $Q\bar{Q}$ bound state

Quantum numbers of H

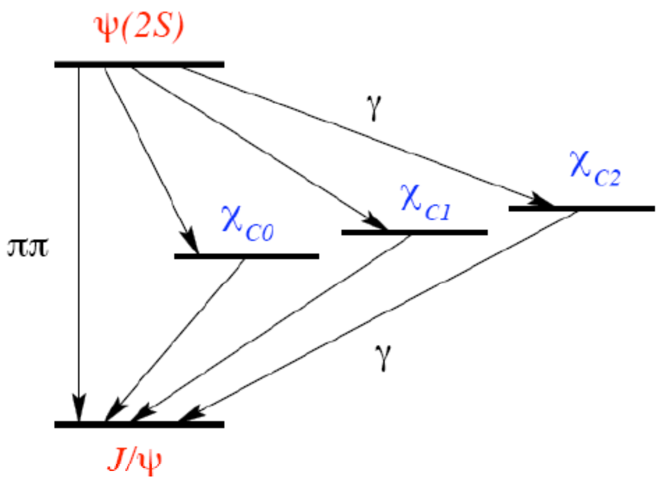


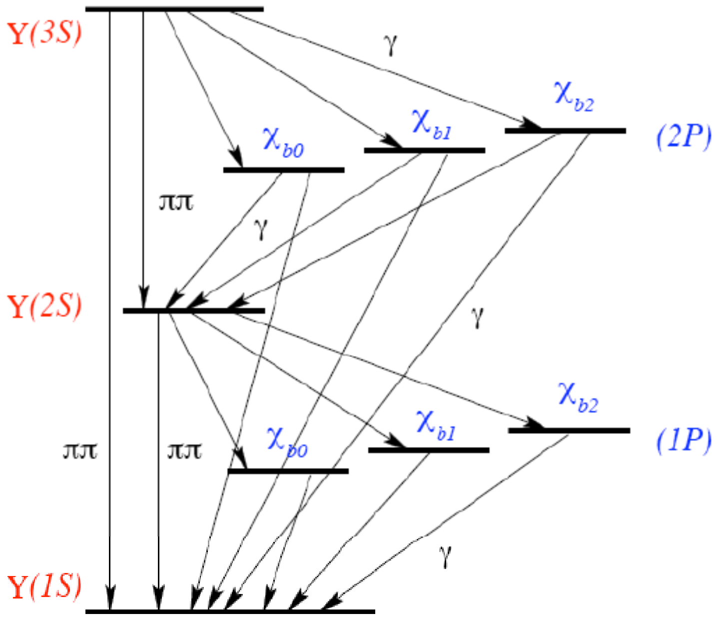
$^{2S+1}L_J$	$^1S_0$	$^3S_1$
$c\bar{c}$	η_c	J/ψ
$b\bar{b}$	η_b	Υ
J^{PC}	0^{-+}	1^{--}

Source of heavy quarkonium

- Non-prompt production of a heavy quarkonium = from B decays.

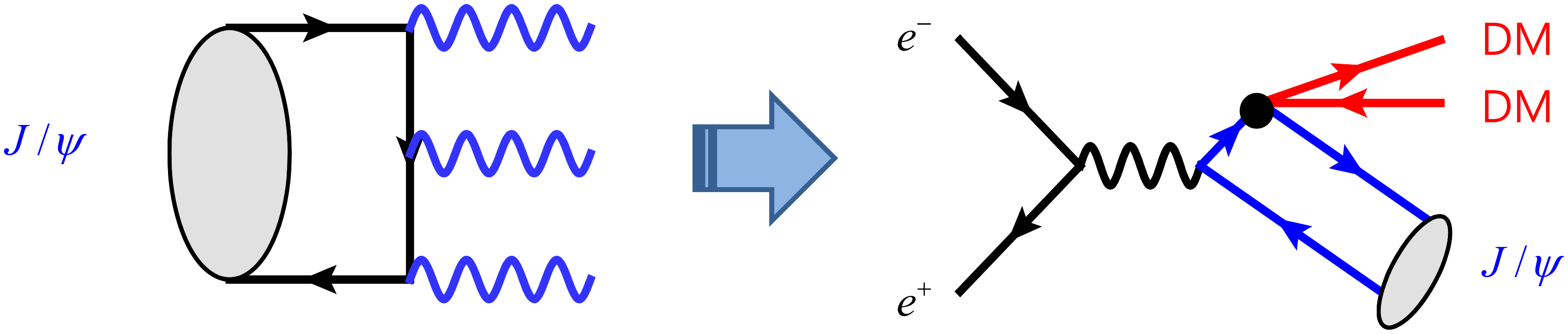
- Prompt production of a heavy quarkonium = direct production + feed-down from higher resonances.





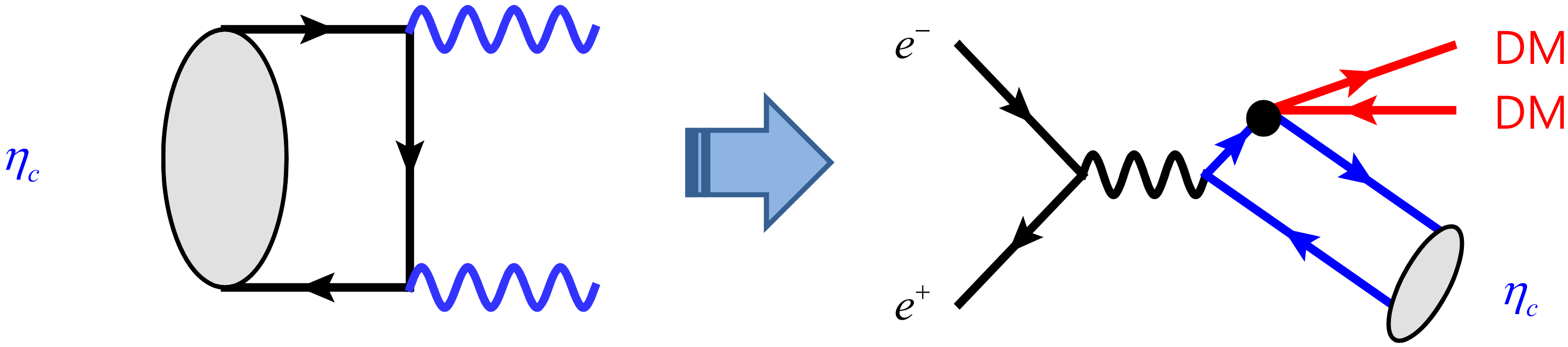
- a lot of J/ψ's from B decays, but they can be distinguished

Association production of DM with H



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

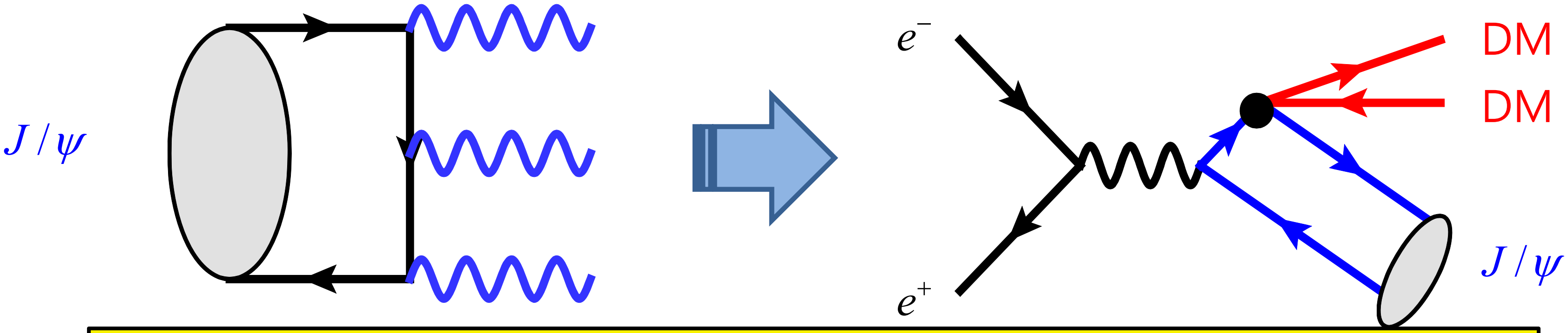
● = d1, d2, d3, d4, d7, d8



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

● = d5, d6, d9, d10

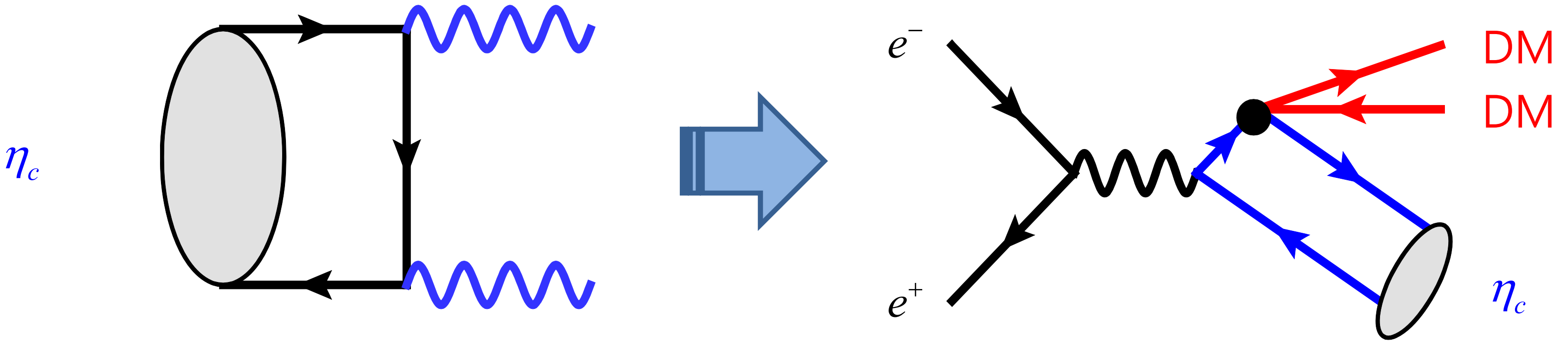
Association production of DM with H



⟹

nu

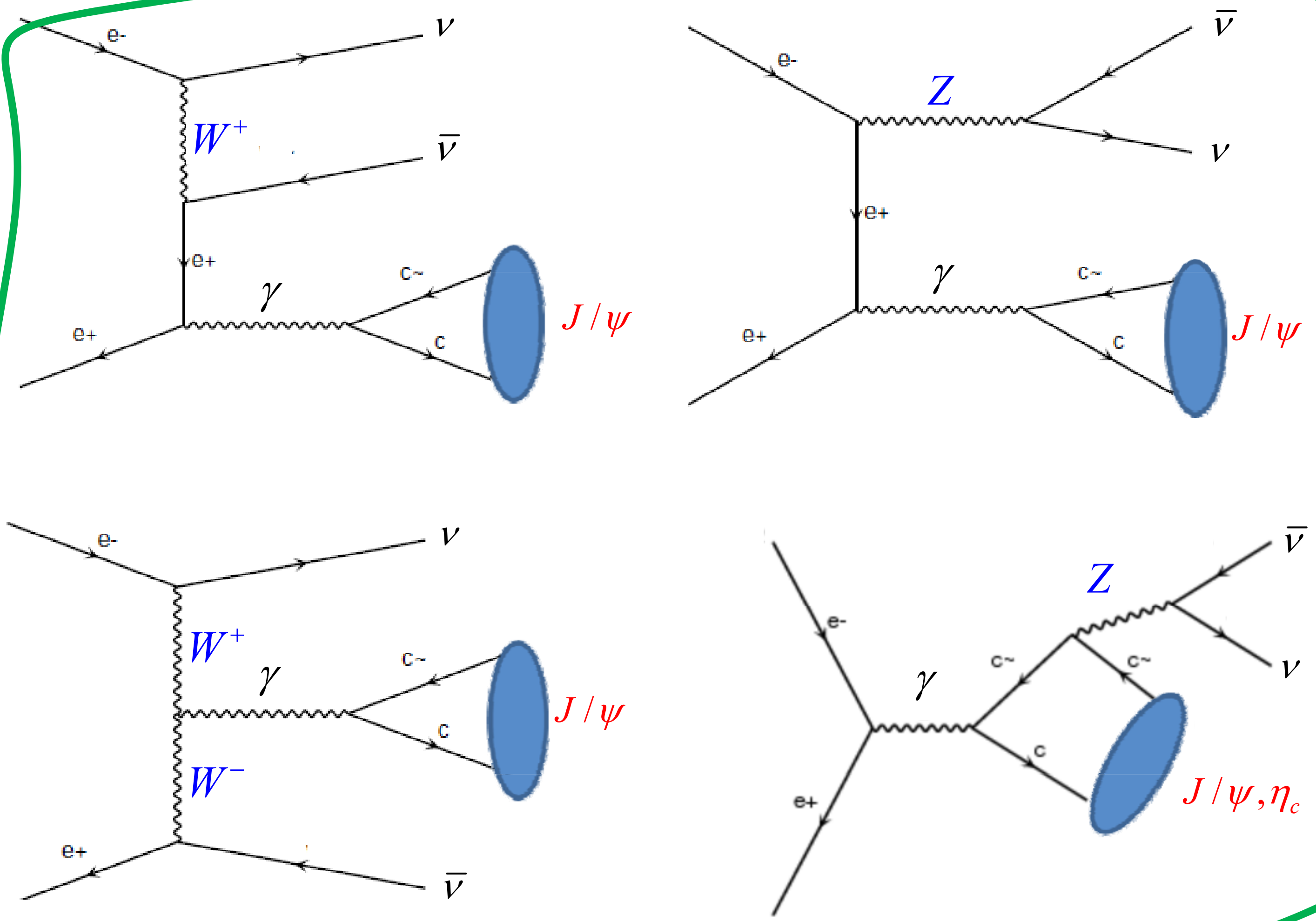
Since the number of events is very small,
the dark matter signal would be inclusive.



⟹ decays into an even number of photons or gluons

● = d5, d6, d9, d10

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

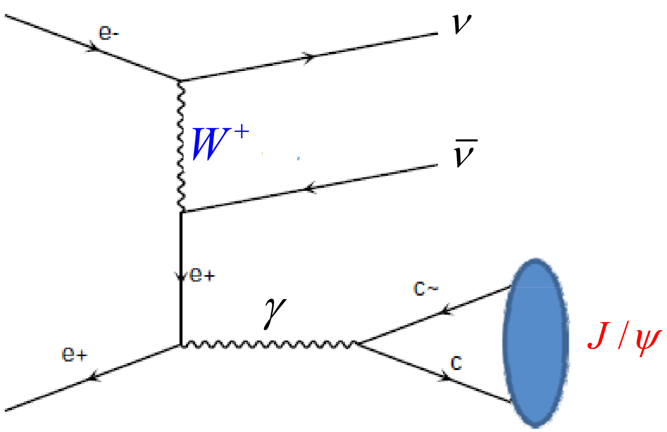


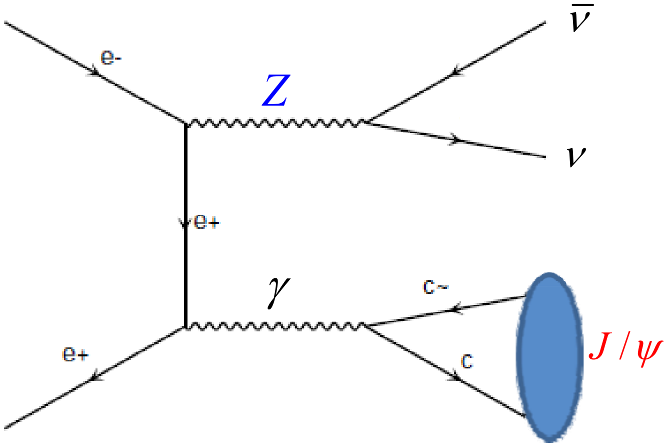
$\sqrt{s} = 10.58$ GeV

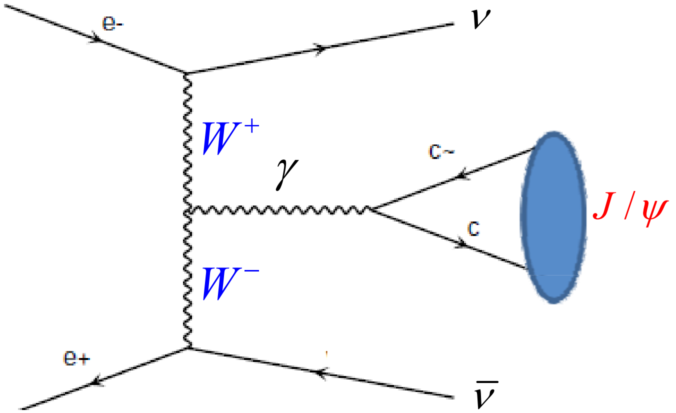
$\sigma(e^+e^- \to J/\psi\nu\bar{\nu}) = 0.00081$ fb

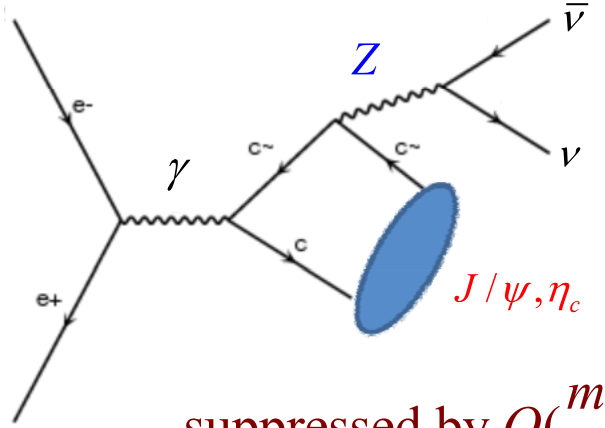
$\sigma(e^+e^- \to \eta_c\nu\bar{\nu}) = 10^{-8}$ fb

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









suppressed by $O(\frac{m_c^2}{s})$

$\sqrt{s} = 10.58$ GeV

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

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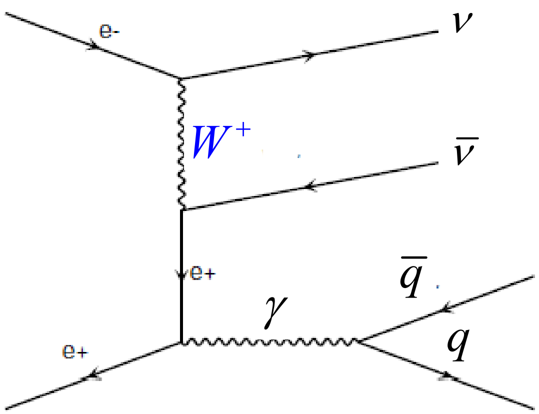
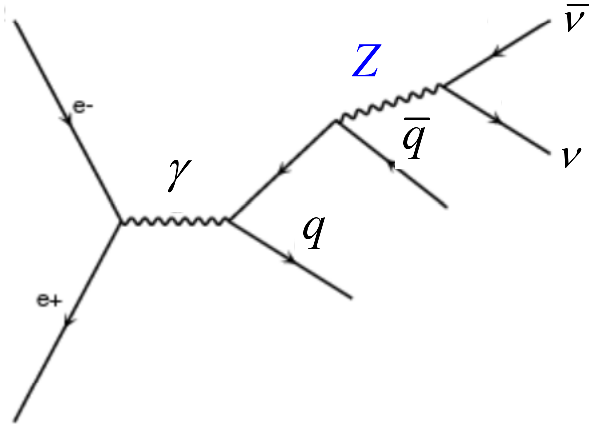




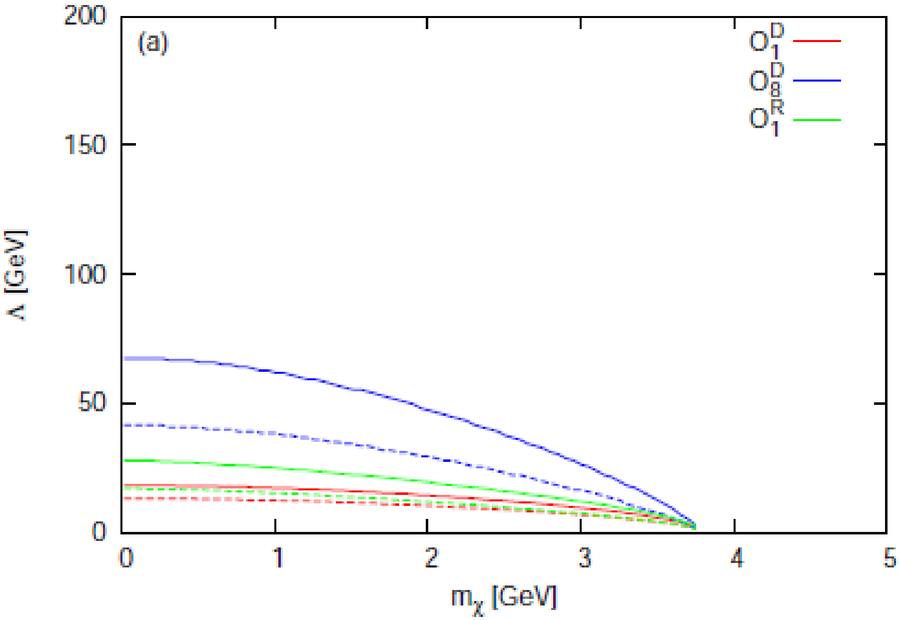
$$\sigma_{\text{cont}} < 3.5\times10^{-3}\,\text{ab}$$

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

$$O_1^D = \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$$

$$O_8^D = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma_5 q$$

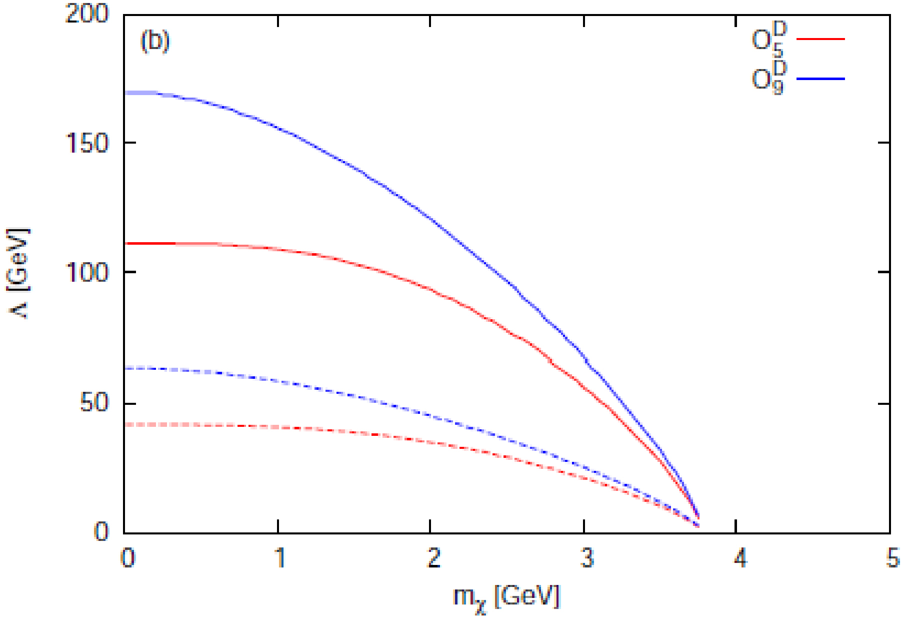
$$O_1^R = \frac{m_q}{2\Lambda^3}\chi^2\bar{q}q$$



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

$$O_5^D = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

$$O_9^D = \frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}\gamma^5 q$$



- - - - - $1\ \text{ab}^{-1}$ —— $50\ \text{ab}^{-1}$

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Dark matter-nucleon cross section

$$D5:\ O_5^D = \frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q \qquad \sigma_{D5}^{\mathrm{SI}} = \frac{\mu_\chi^2}{\pi\Lambda^4}(f_{V_q}^n)^2$$

$$f_{V_u}^p = f_{V_d}^n = 2$$

$$f_{V_d}^p = f_{V_u}^n = 1$$

$$D8:\ O_8^D = \frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}\gamma_5 q \qquad \sigma_{D8}^{\mathrm{SD}} = \frac{3\mu_\chi^2}{\pi\Lambda^4}(\Delta_q^n)^2$$

$$\Delta_u^p = 0.842$$

$$\Delta_d^p = -0.427$$

$$\Delta_s^p = -0085$$

$$D1:\ O_1^D = \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q \qquad \sigma_{D1}^{\mathrm{SI}} = \frac{\mu_\chi^2 m_n^2}{\pi\Lambda^6}f_n^2 \qquad f_n = \sum_{q=u,d,s} f_q^n + \frac{2}{27}\sum_{Q=c,b,t} f_Q^n$$

$$f_d^p = 0.033,\ f_d^p = 0.023,\ f_d^p = 0.26$$

$$f_Q^p = 1 - f_u^p - f_d^p - f_s^p$$

Heavy quark-philic DM cross section

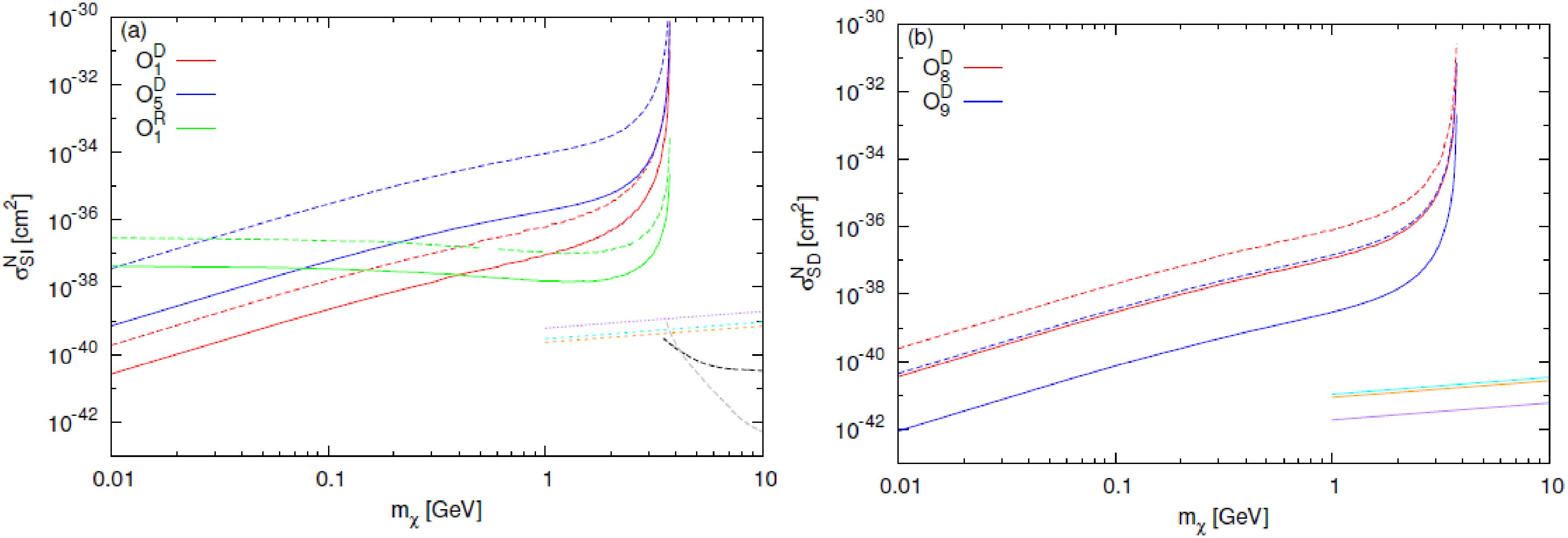
$$D5:\ O_5^D = \frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q \qquad \sigma_{D5}^{\mathrm{Q,SI}} = \frac{\mu_\chi^2}{\pi\Lambda^4}(f_{V_q}^n)^2 \sim 0$$

$$D8:\ O_8^D = \frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}\gamma_5 q \qquad \sigma_{D8}^{\mathrm{Q,SD}} = \frac{3\mu_\chi^2}{\pi\Lambda^4}(\Delta_q^n)^2 \sim 0$$

$$D1:\ O_1^D = \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q \qquad \sigma_{D1}^{\mathrm{Q,SI}} = \frac{\mu_\chi^2 m_n^2}{\pi\Lambda^6}f_n^2 \sim 0.01\times\sigma_{D1}^{\mathrm{SI}}$$

Experimental reach at Belle II

Assume that the effective operators are universal

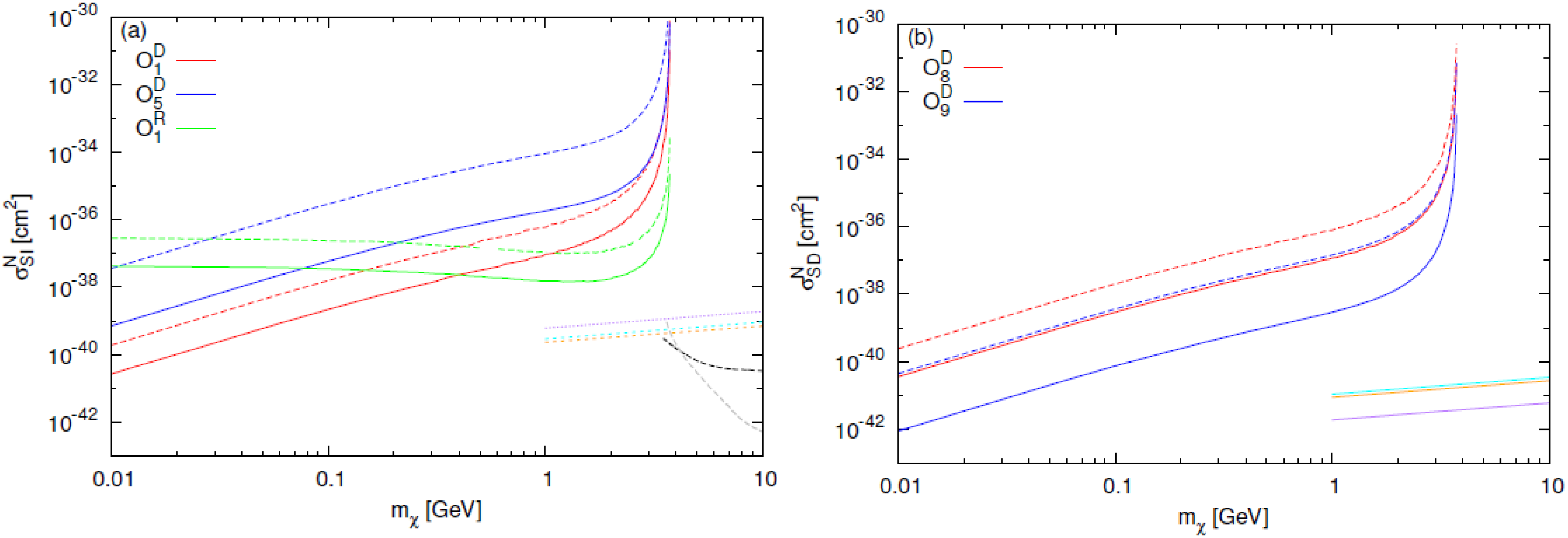


CY,Yuan

- - - - - $1\ \mathrm{ab}^{-1}$ —— $50\ \mathrm{ab}^{-1}$

Experimental reach at Belle II

Assume that the effective operators are universal



For charm(bottom)-philc DM, weaker bound from direct detection and LHC

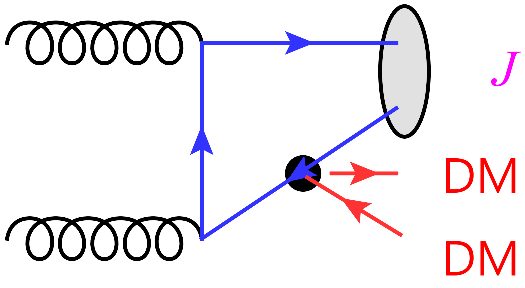
- - - - - 1 ab^{-1} ——— 50 ab^{-1}

Quarknium+DM at ILC and LHC

- easy to extend this idea to ILC and LHC

- found that the cross section at ILC is too small ~ O(0.01) fb

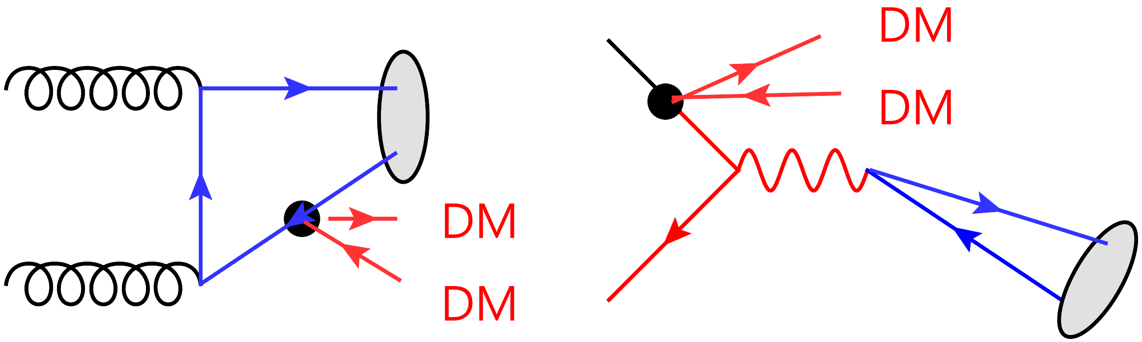
- LHC might be promising for Quarkonium+DM production



$J/\psi[{}^3S_1[1]]$ → color-singlet

- Due to large backgrounds, the exclusive decay mode, J/$\psi \to \mu\mu$(ee), must be considered

DM+J/ψ production at LHC

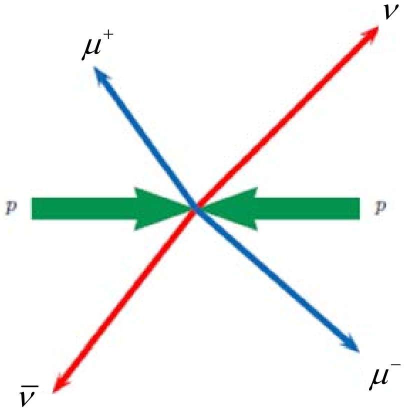


$J/\psi[{}^3S_1[1]]$ → color-singlet

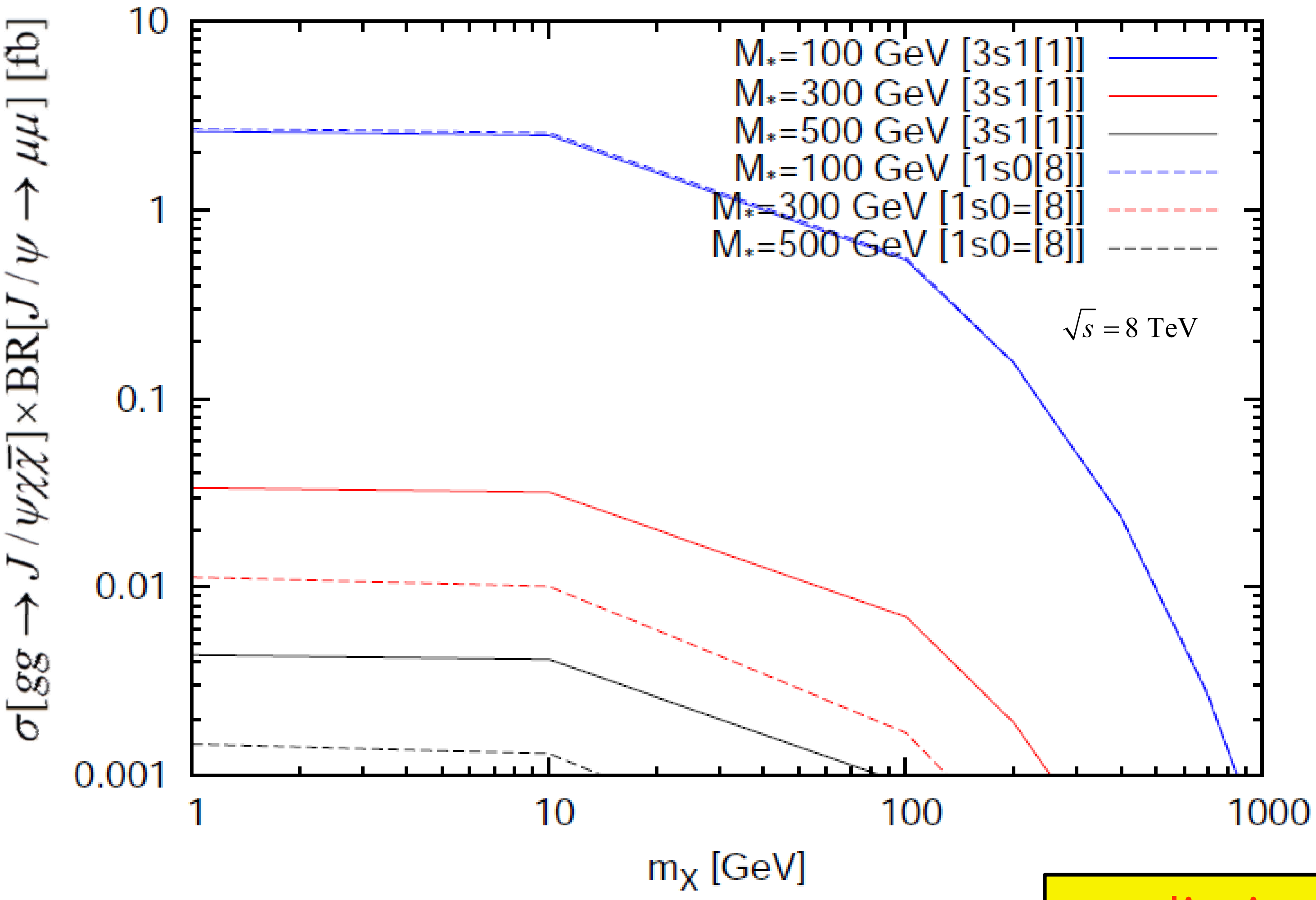
$J/\psi[{}^1S_0[8]]$ → color-octet

Contamination from color octet and initial qqbar collisions

Possible backgrounds from double parton scattering



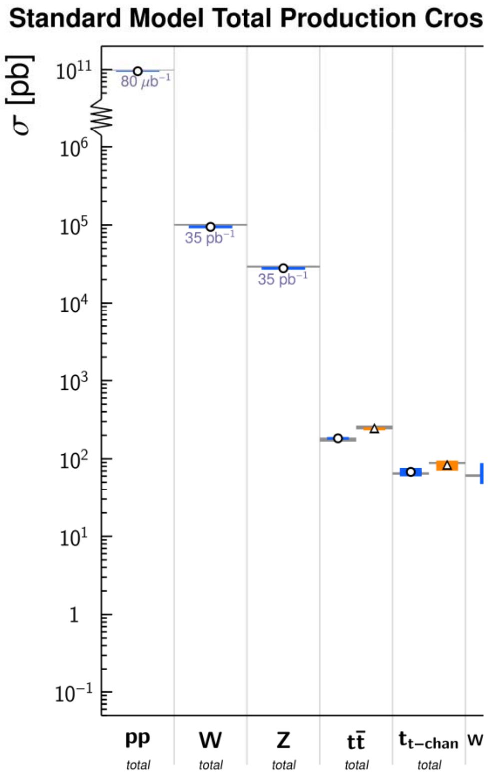
DM+ J/ψ production at LHC

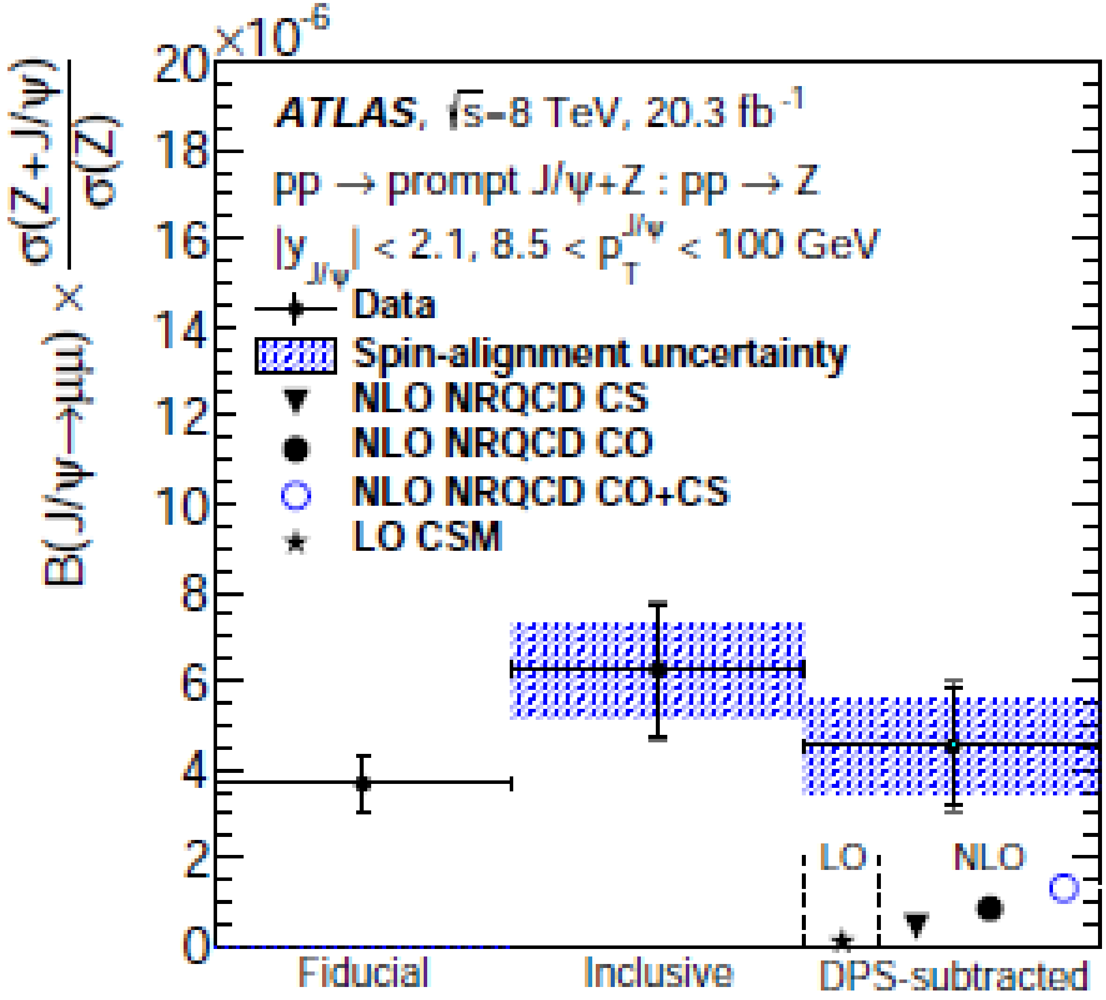


preliminary

- light DM is more sensitive

J/ψ+Z production at ATLAS





$$\sigma(J/\psi Z)\times \mathrm{BR}(J/\psi \to \mu\mu)\times \mathrm{BR}(Z\to \nu\nu)\sim 10\,\mathrm{fb}$$

Mono-quarkonium production at LHC

- backgrounds have not been completed yet

- Large NLO corrections may come from real corrections

- To reduce large NLO corrections, necessary to veto additional hard jets

- would be a challenge both theoretically and experimentally

- stay tuned for more analysis of Mono-quarkonium production at LHC

Summary

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

- Heavy quarkonium production associated with dark matter would be another channel for dark matter search and more efficient for charm(or bottom)-philc dark matter.

- LHC might have a role in searching for Heavy quark-philic dark matter through the mono-quarkonium production, but more detailed analysis is required.