Scalar Rayleigh Dark Matter

Collider and Cosmological Probes, Present and Future

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In collaboration with: *Barducci, Buttazzo, Dondarini, Franceschini, Mescia, Panci*

TPPC - Theory retreat| 2024

Motivation

- Even if DM is neutral under EM ⇒ interactions with EW gauge bosons via higher dimensional operators
- From the DM-photon EFT classification in [1] we analyze effective interactions involving a real scalar EW singlet dark matter particle with SM EW gauge bosons

$$\mathscr{L}_\phi = \tilde{\mathscr{C}}_B \phi^2 B_{\mu\nu} B^{\mu\nu} + \tilde{\mathscr{C}}_W \phi^2 W^a_{\mu\nu} W^{a,\mu\nu}$$

$$\mathscr{L}_\phi = \phi^2 \left(\tilde{\mathscr{C}}_{\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + \tilde{\mathscr{C}}_{ZZ} Z_{\mu\nu} Z^{\mu\nu} + \tilde{\mathscr{C}}_{\gamma Z} Z_{\mu\nu} A^{\mu\nu} + \tilde{\mathscr{C}}_{WW} W^+_{\mu\nu} W^{-,\mu\nu} \right)$$

First operators that appear in the EFT expansion

Real scalar case

[1] *B. J. Kavanagh, P. Panci, and R. Ziegler JHEP 04 (2019) 089, [arXiv:1810.00033]*

Motivation

Elusive DM scenario for DD
$\Rightarrow$ no couplings with lighter dof $(q, \mathcal{G})$
$\Rightarrow$ Loop suppressed cross sections

Interesting target for Indirect Detection probes
- DM annihilates with γ
- FERMI works only up to $\mathcal{O}(500\ \text{GeV})$

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How do we test this scenario at colliders?

FCCee - FCChh - μC

Could provide additional information about the model in the coming years.

Experiments

1 LHC @ $\sqrt{s} = 13$ TeV, $L = 139/fb$ → HL-LHC $\sqrt{s} = 13$ TeV, $L = 3\ ab^{-1}$

2 FCC-hh @ $\sqrt{s} = 80{,}100$ TeV, $L = 30/ab$

3 Z-factory at FCC-ee ($L = 120/ab$)

4 μC @ $\sqrt{s} = 10$ TeV

Colliders

5 LZ-2022 and XLZD

DD

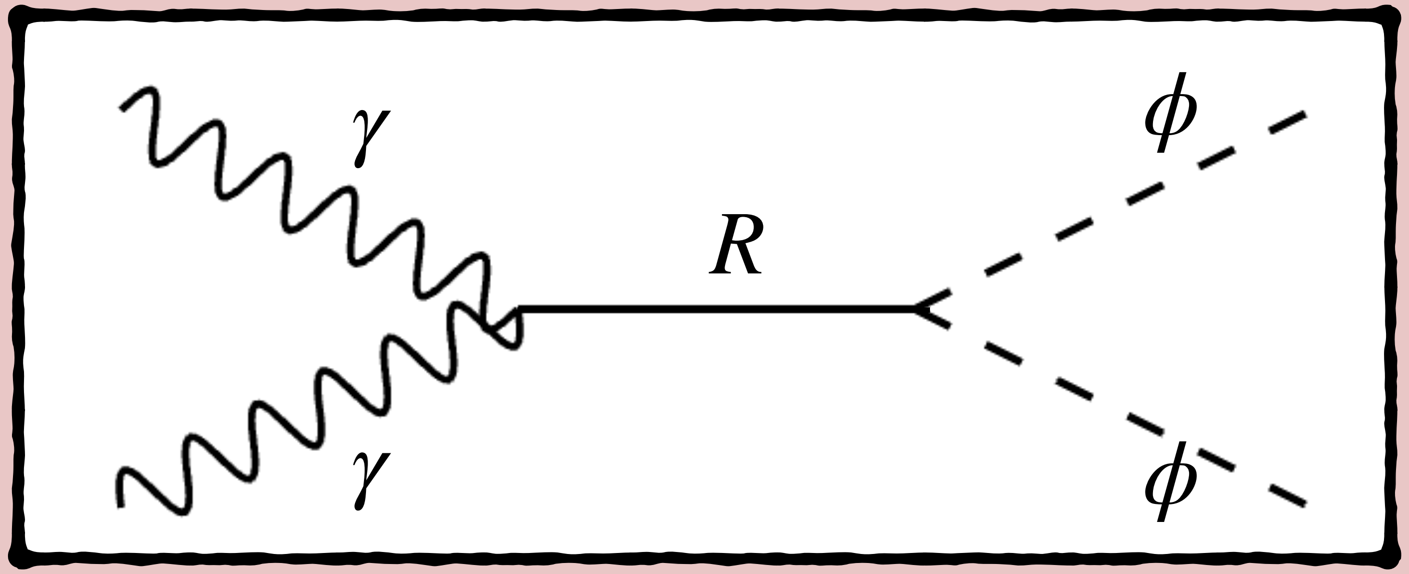
6 FERMI and CTA

ID

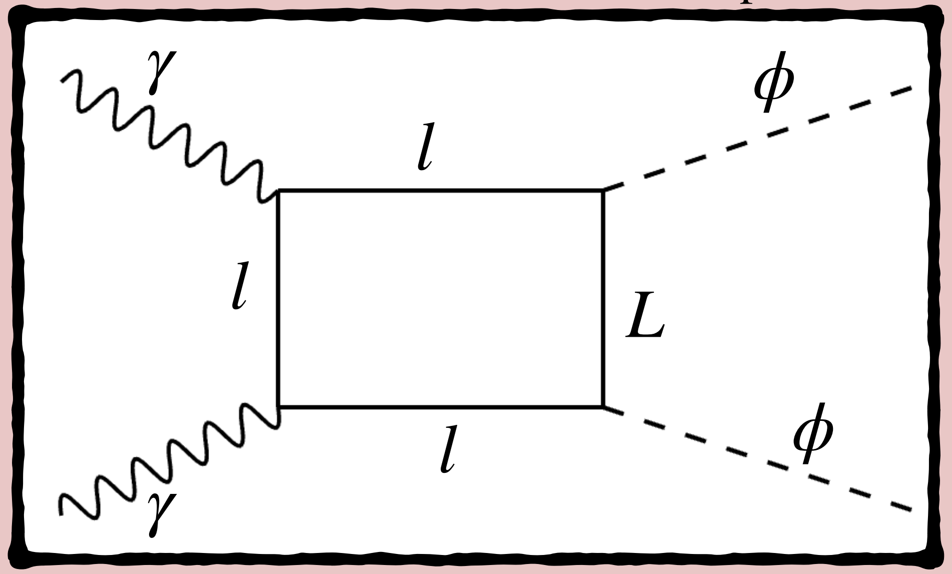
UV completion?

- Wilson coefficients are related to the scale where these operators are generated as $\tilde{\mathscr{C}}_{B,W} = \frac{g_{\mathrm{Y,W}} g_{\mathrm{tree}}}{\Lambda^2_{B,W}}$
- UV completion can be achieved through:

Tree level: $\Lambda_{B,W} = \Lambda^{tree}_{B,W}$



Loop level: $\frac{\Lambda^{\mathrm{tree}}_{B,W}}{g_{\mathrm{tree}}} = \frac{4\pi\sqrt{2}}{g_{\mathrm{loop}}} \Lambda^{loop}_{B,W}$



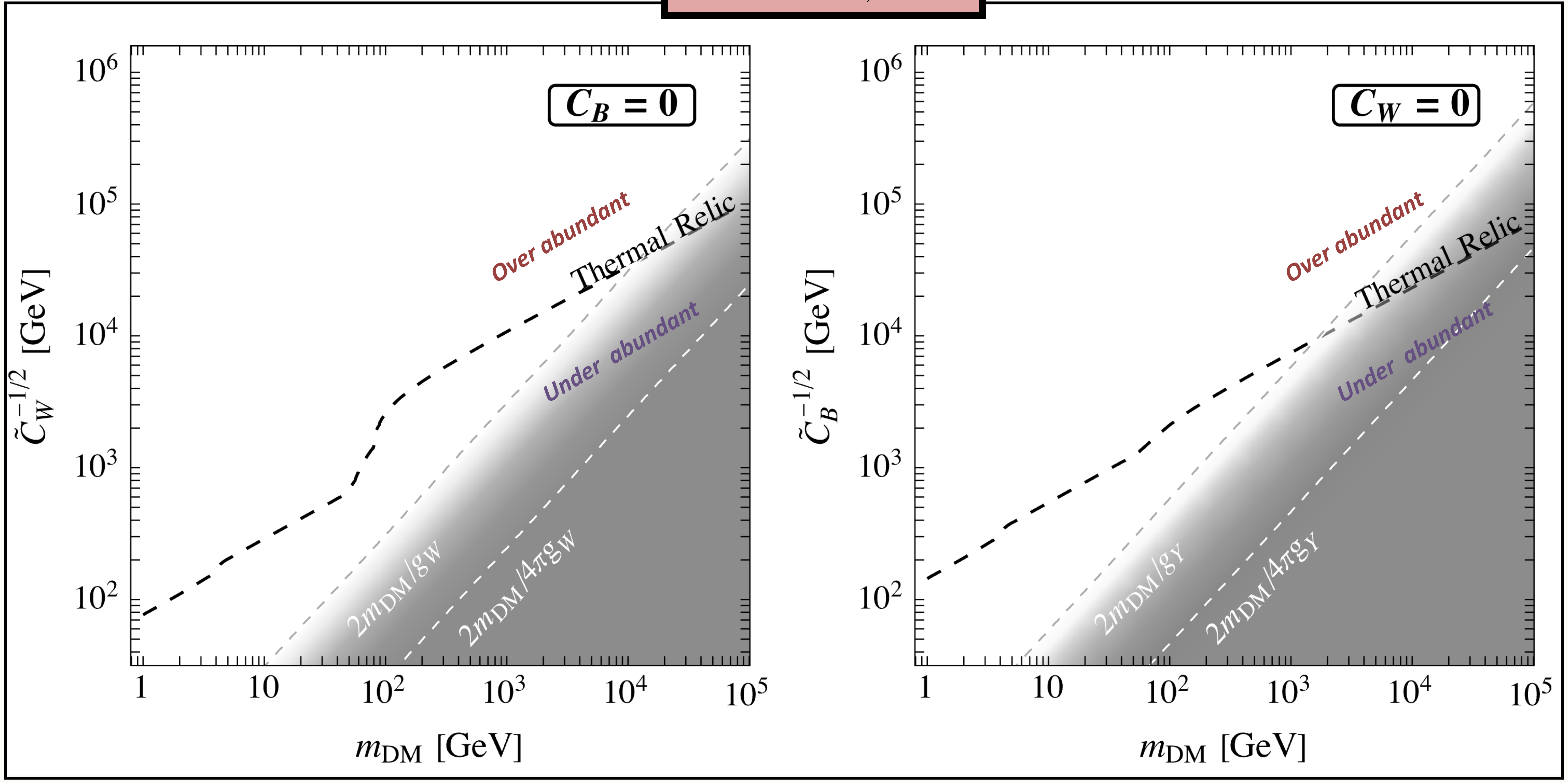
EFT VALIDITY

For all the probes we require that

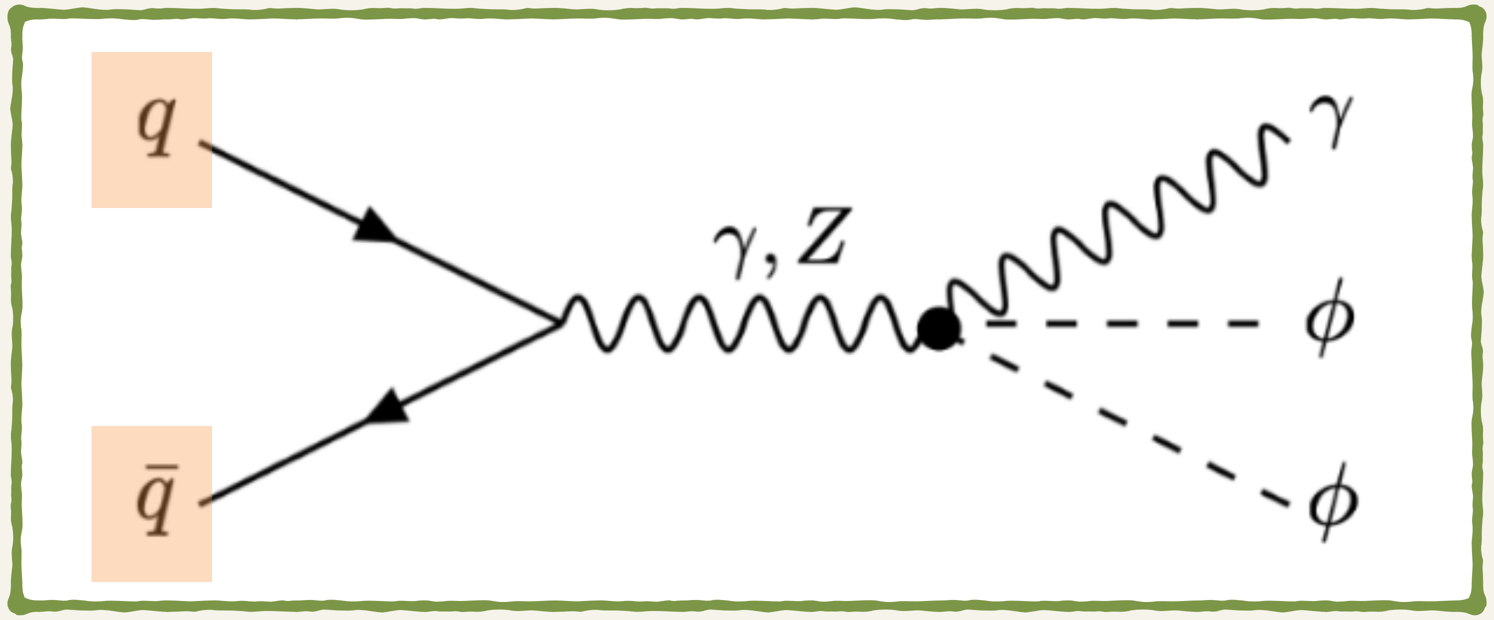
$$\Lambda > q > 2m_{\mathrm{DM}}$$

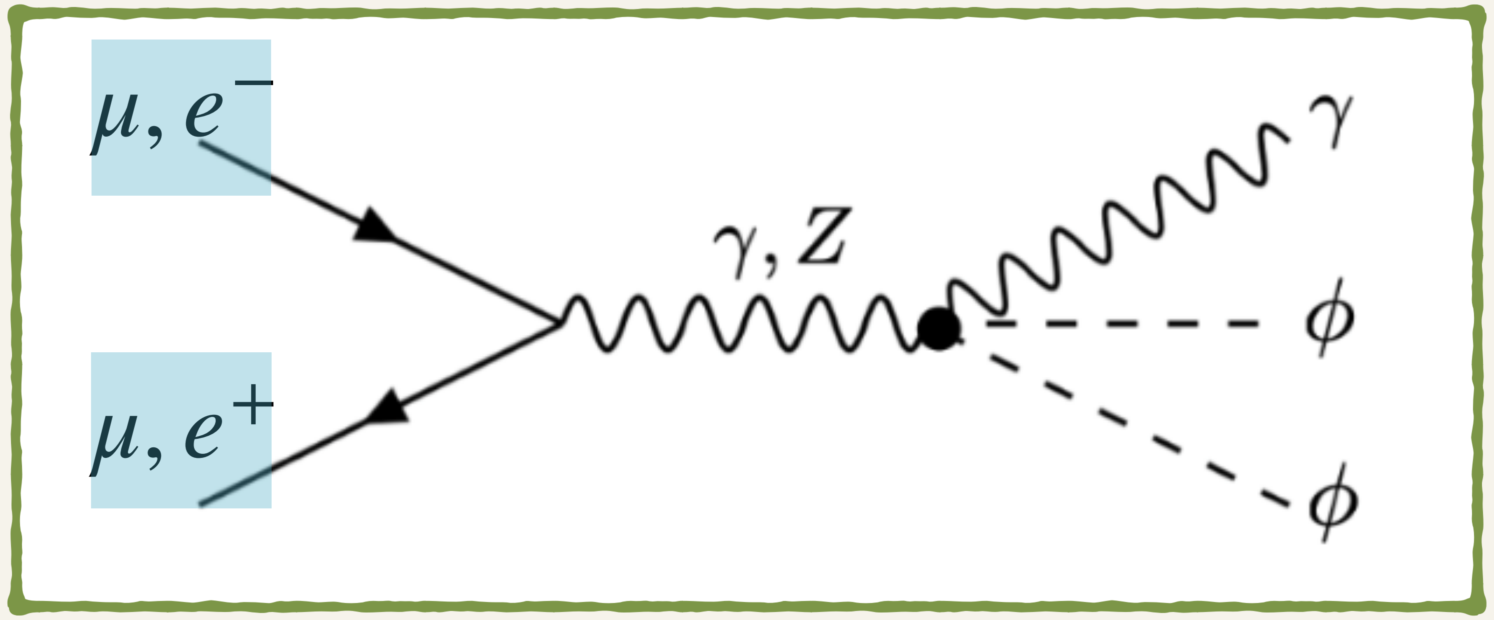
EFT ... ITY

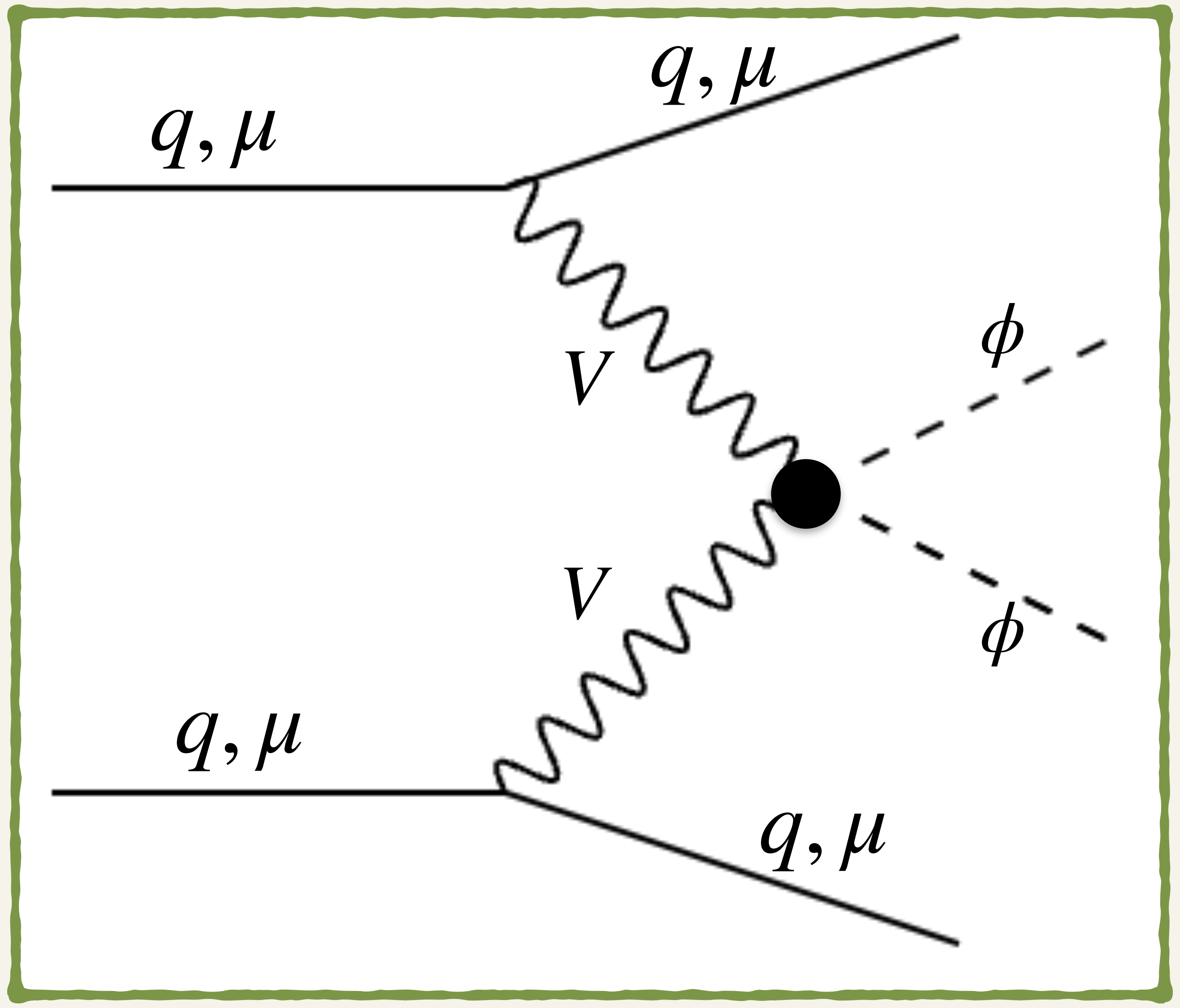
$$\tilde{\mathscr{C}}_{B,W}^{-1/2} = \frac{\Lambda_{B,W}}{g_{Y,W}\, g_{\text{tree}}}$$



Drell-Yan processes + Fusion







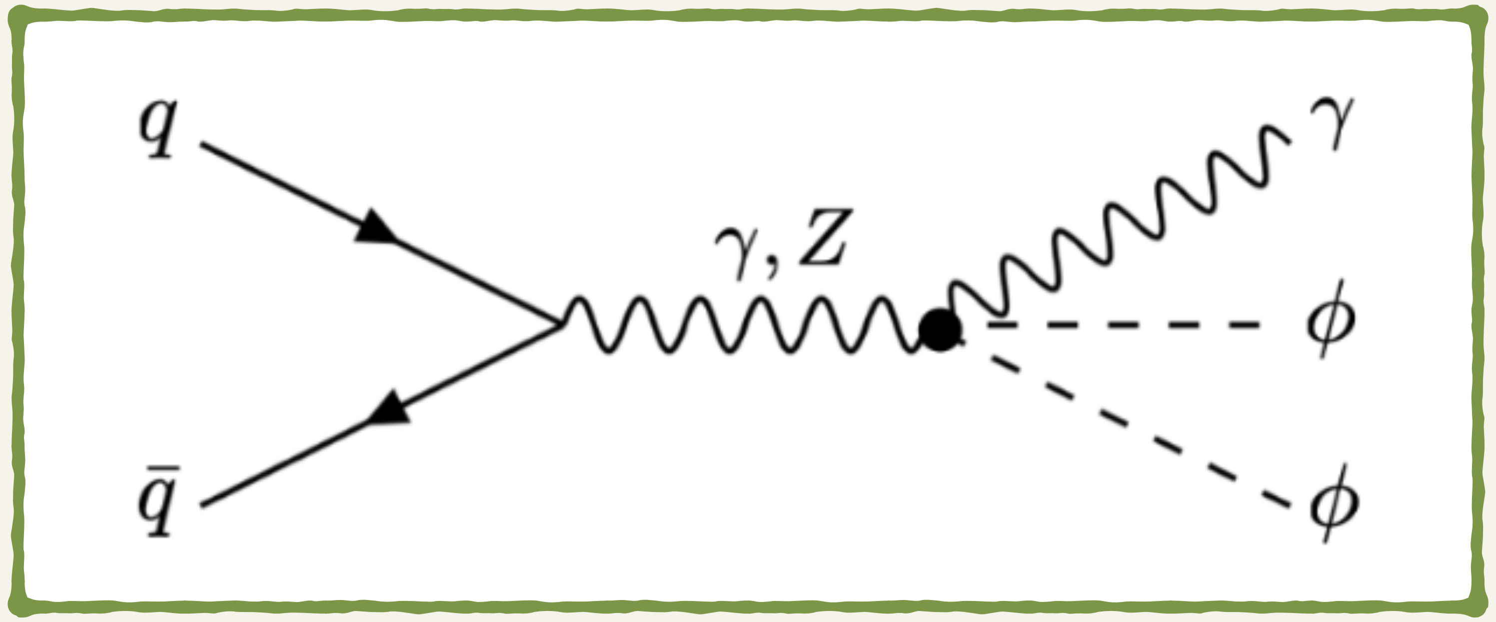
$\sqrt{s} = 13$ TeV

$L = 139\ fb^{-1} - \ 3ab^{-1}$

Colliders

1 **LHC and high-lumi LHC**: mono-γ analysis

- DM is produced in association with a high p_T^γ
- Recast the ATLAS analysis
- Work with LO Parton level for signal simulation



Analysis selections

ATLAS: 2011.05259

7 SRs defined with increasing MET

$E_T^\gamma > 150$ GeV and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$

SRI1	SRI2	SRI3	SRI4	SRE1	SRE2	SRE3
> 200	> 250	> 300	> 375	$200 - 250$	250-300	300-350

Validity of the EFT

$$\mathscr{L}_\phi^{strong} = \tilde{C}_B^\phi \phi^2 B_{\mu\nu} B^{\mu\nu} + \tilde{C}_W^\phi \phi^2 W_{\mu\nu} W^{\mu\nu}$$

we require that $p_T^\gamma < \Lambda$

Projections for high-lumi LHC

- Assume only statistical uncertainties and same selections of ATLAS analysis
- 95% CL bound with $\frac{N_S}{\sqrt{N_B}}$ rescaling the expected SM events by lumi ratio

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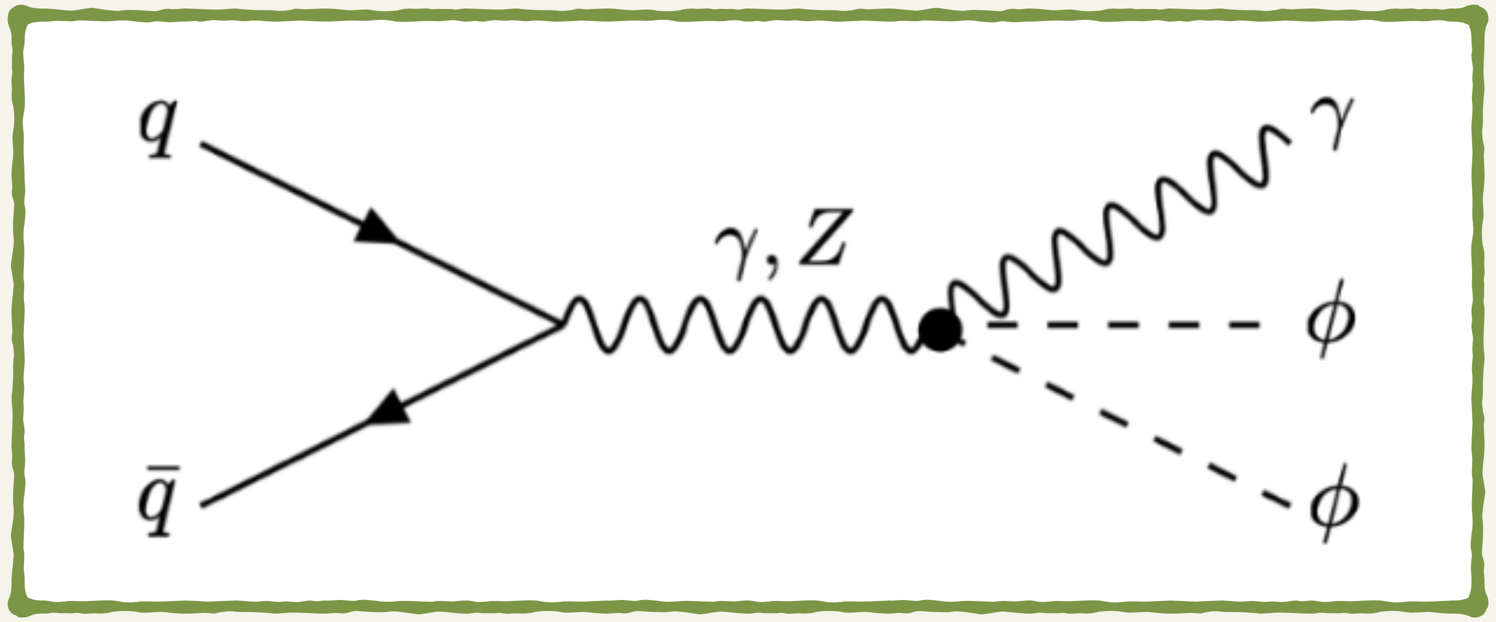

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Colliders

$\sqrt{s} = 13$ TeV

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1 **LHC and high-lumi LHC**: VBS analysis

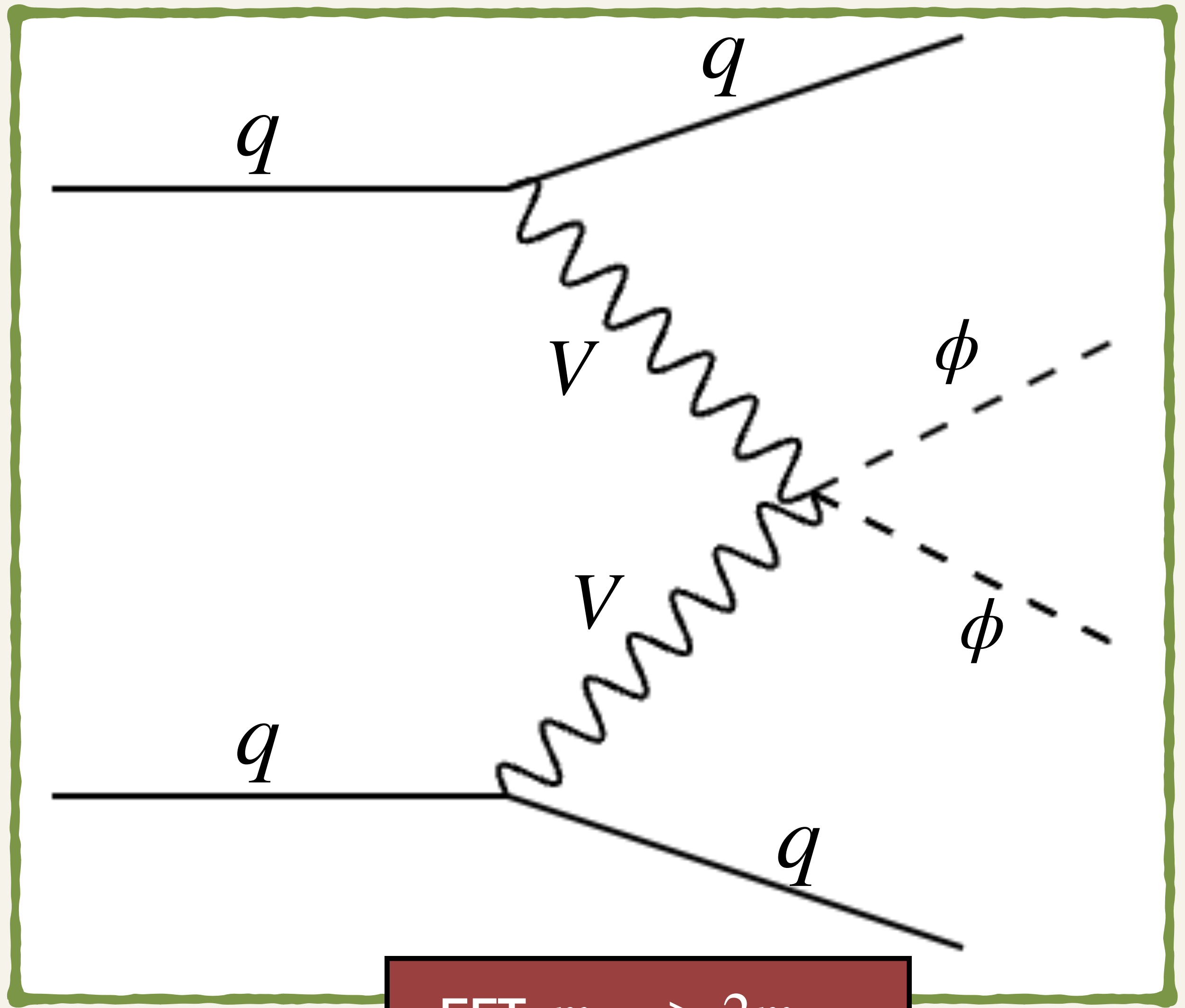
- $pp \to jj\phi\phi$
- Unlike the DY process, W boson contributes to the signal rate
- Selection of ATLAS search ATLAS: 2011.05259

$$p_T^{j_1,j_2} > 80\,\text{GeV and } |\eta_j| < 4.5,\, \eta_{j_1}\eta_{j_2} < 0,\, \Delta\eta_{j_1,j_2} > 3.8$$

To kill the QCD bkg : $\Delta\phi_{j_1 j_2} < 2,\, E_T^{\text{miss}} > 160\,\text{GeV}$

- Most stringent signal region:

$$E_T^{\text{miss}} > 200\,\text{GeV},\, \Delta\phi_{jj} < 1,\, m_{jj} \in [2{,}3.5]\,\text{TeV}$$



EFT: $m_{\phi,\phi} > 2m_{\text{DM}}$

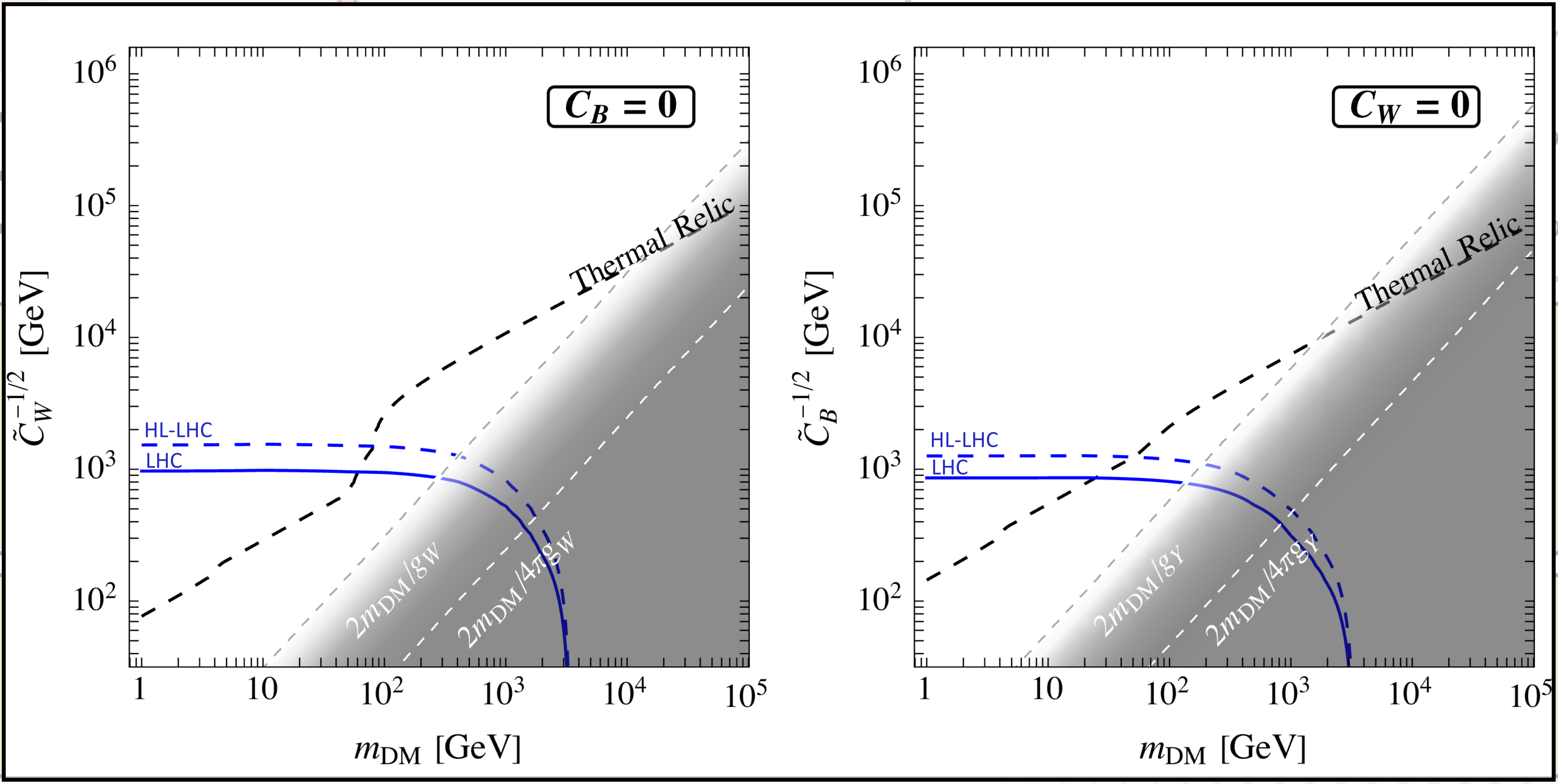
Projections for high-lumi LHC

- Assume only statistical uncertainties and same selections of ATLAS analysis
- 95% CL bound with $\frac{N_S}{\sqrt{N_B}}$ rescaling the expected SM events by lumi ratio

Colliders

$\sqrt{s} = 13$ TeV

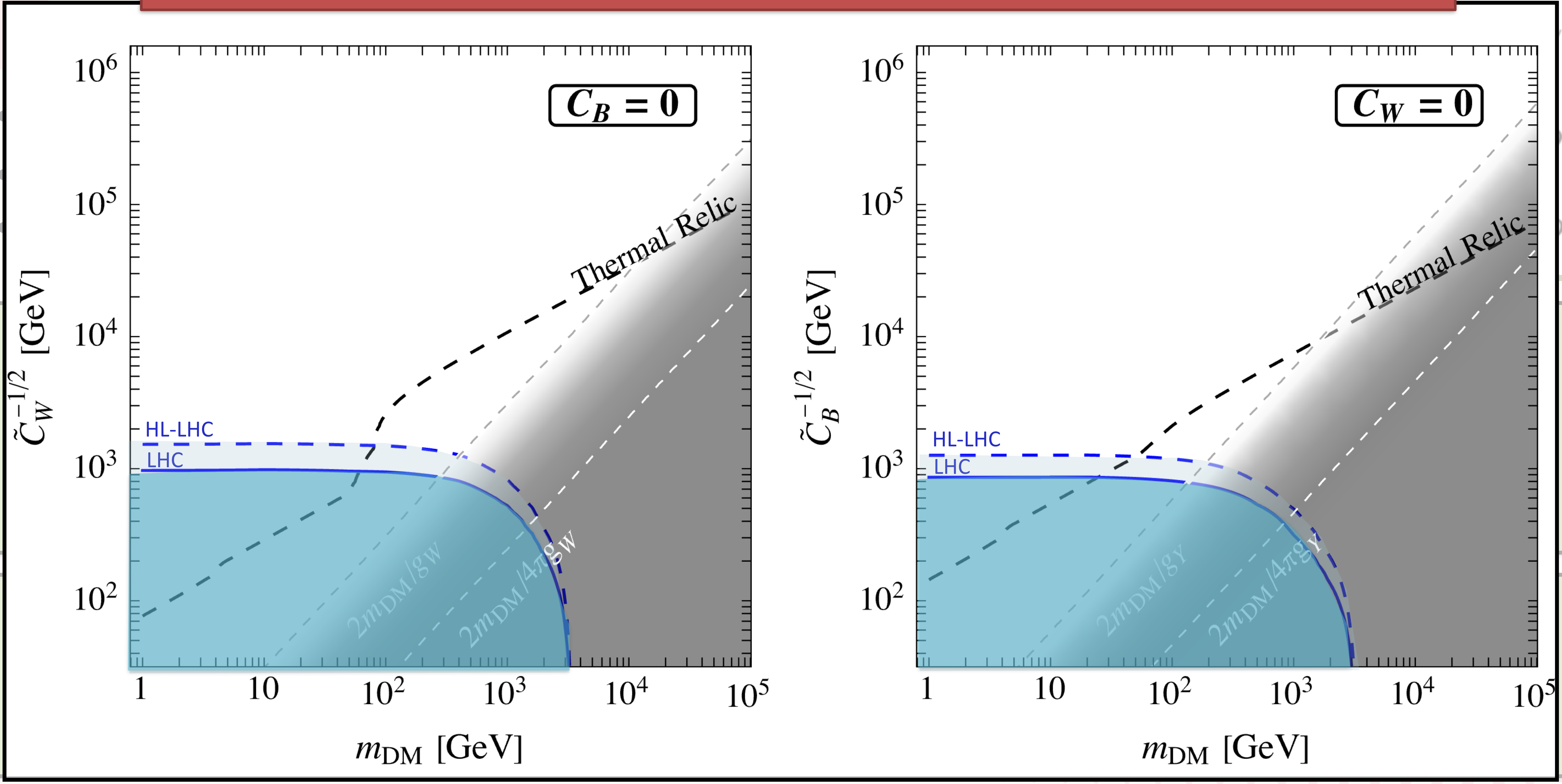
$L = 139\ fb^{-1} - \ 3ab^{-1}$



$\sqrt{s} = 13$ TeV

Colliders

HL-LHC will improve the bound by a factor ~ 2.5



Colliders

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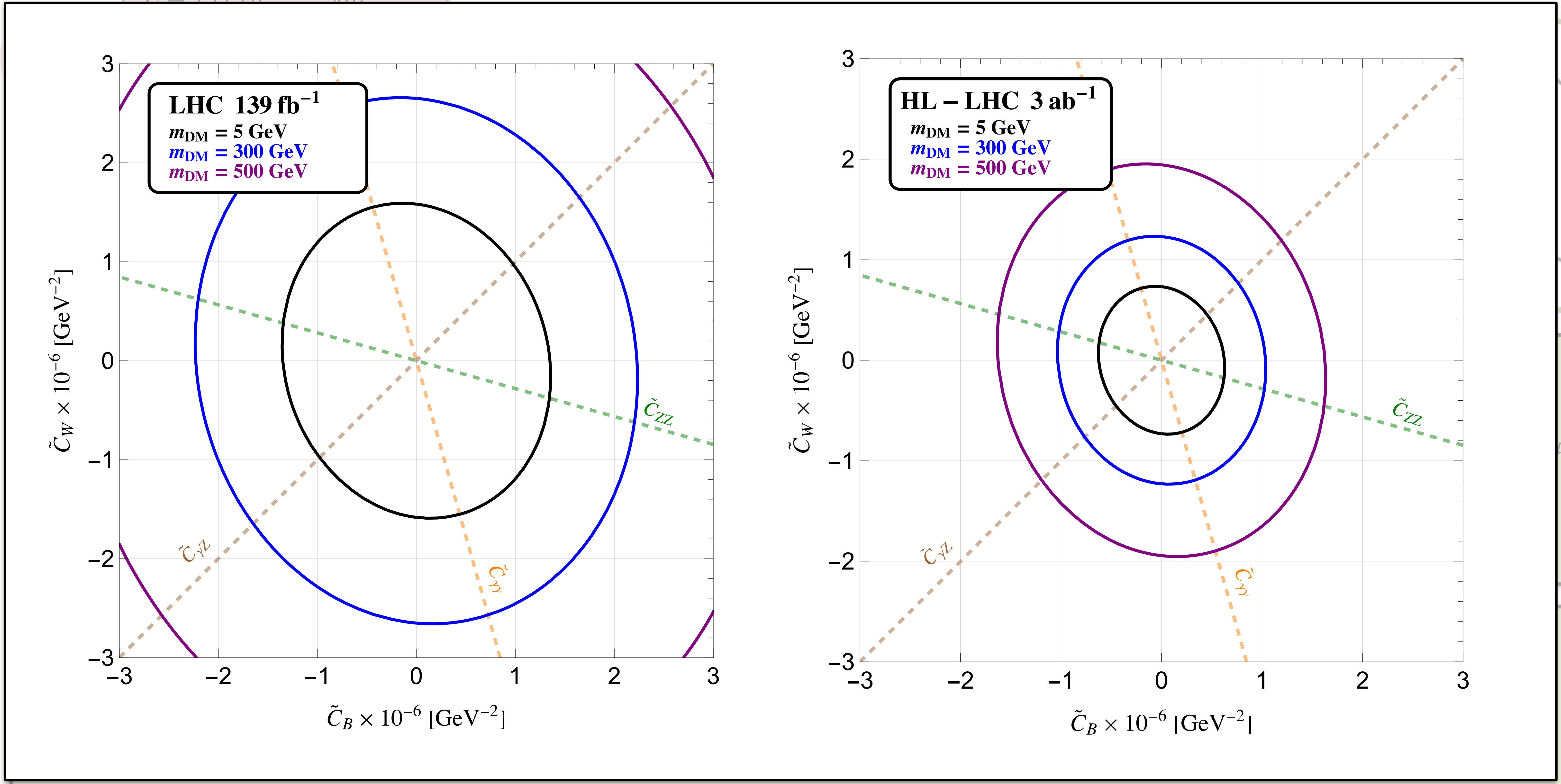

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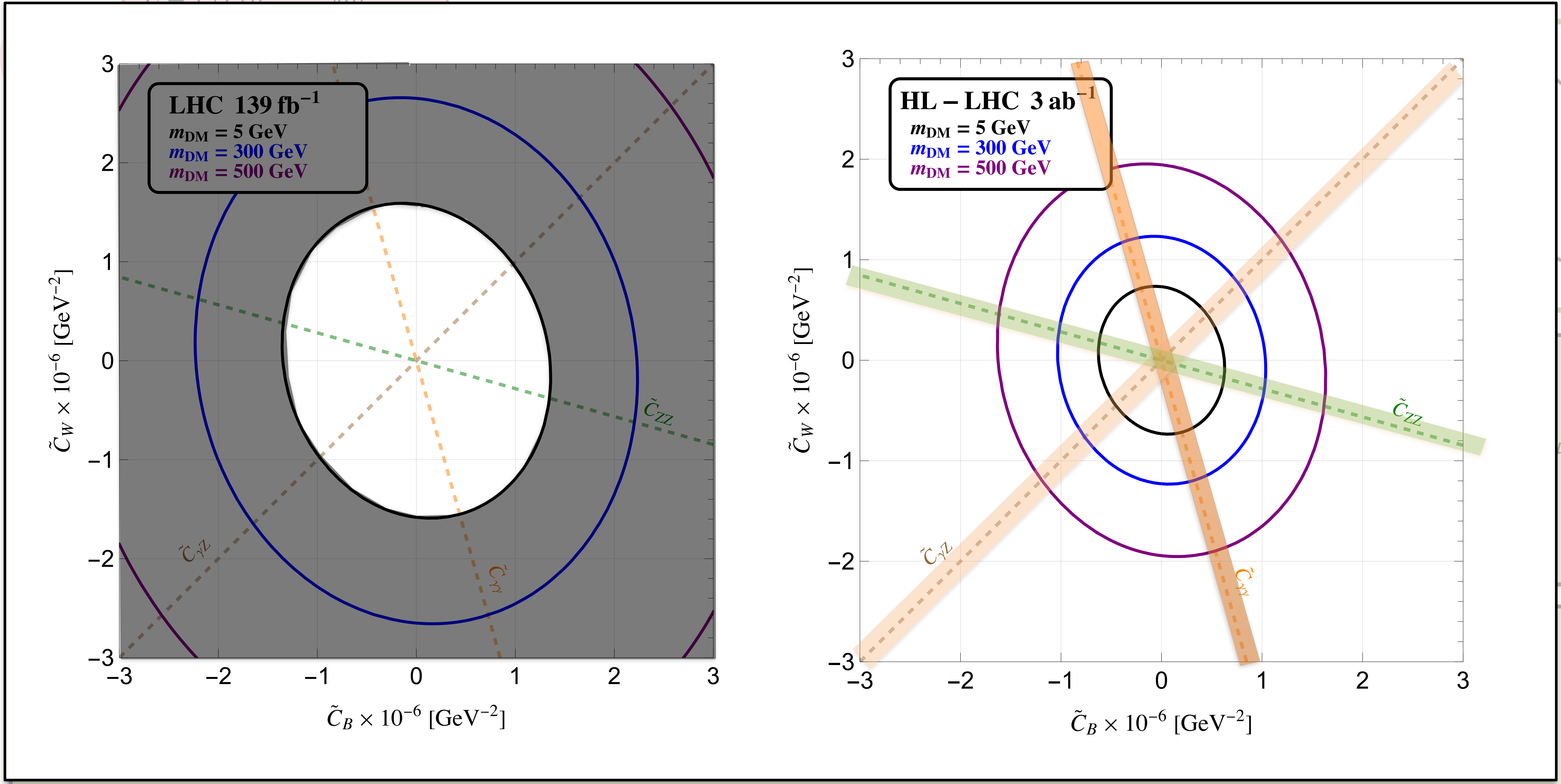
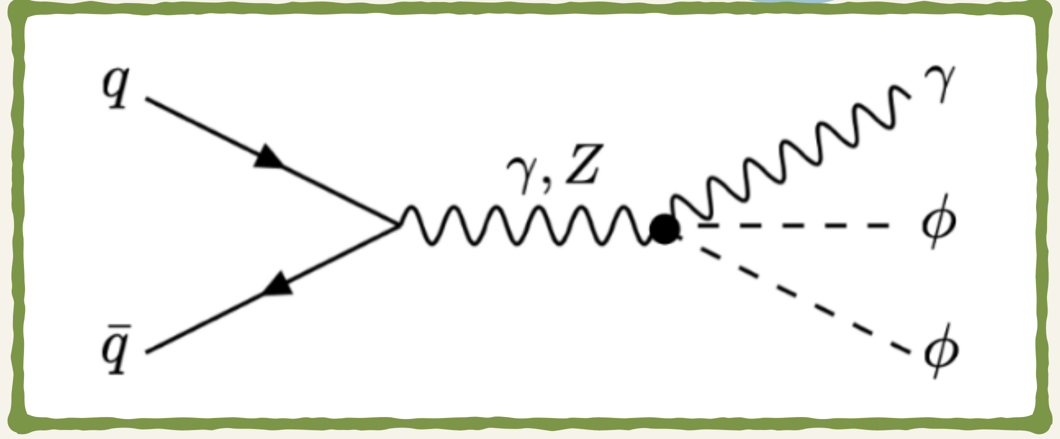


After LHC era

Colliders

2 **FCC-hh**: DY process - @ 80/100 TeV with $L = 30\ ab^{-1}$



- Process assumed to be qualitatively the same as ATLAS mono-γ
- Hard photon $\Rightarrow$ different analysis wrt the soft photon analysis already done
- The $pp \to Z\gamma, Z \to \nu\bar{\nu}$ channel is the dominant bkg

$\Rightarrow\ \sim 60\,\%$ of the total yield $(bkg)_{\nu}^{ATLAS}/(bkg)_{tot}^{ATLAS}$

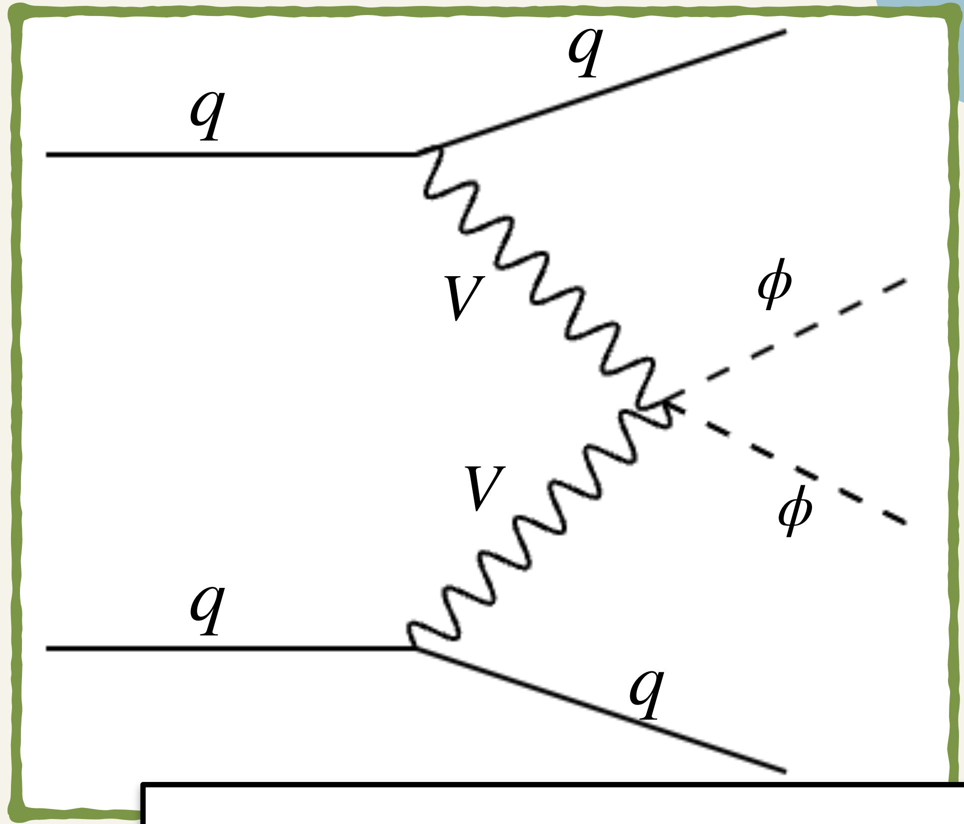
- LO simulation with MadGraph for ν channel in the fiducial regions given by ATLAS
  - We find that the LO $Z\gamma$ simulation accounts for $\sim 80\,\%$ of the experimental $Z\gamma$ ATLAS background and hence $\sim 50\,\%$ of the total experimental background

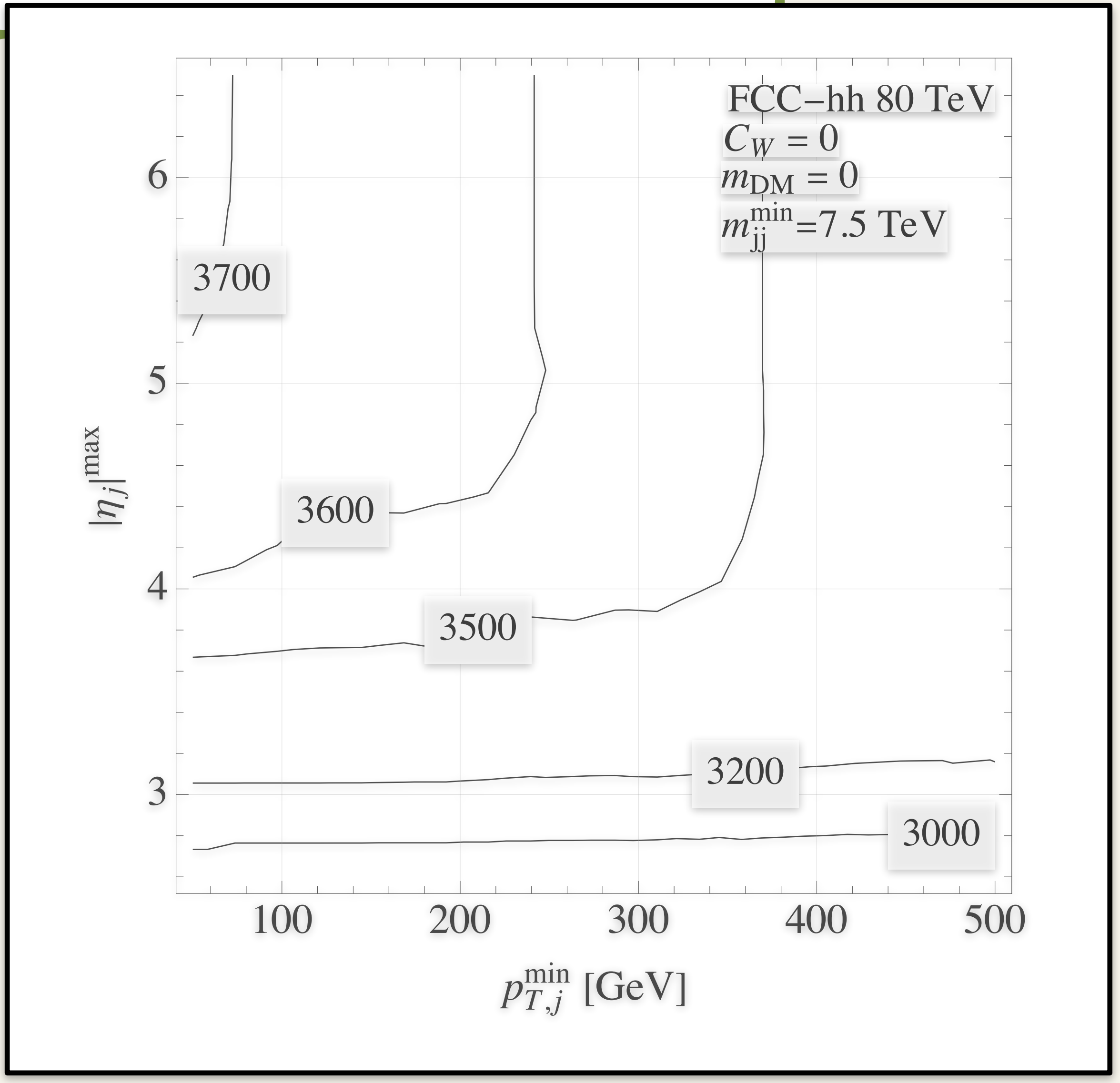
  $\Rightarrow$ this is constant in all the ATLAS signal regions;
  - We estimate the total SM bkg multiplying by a factor 2 the dominant $Z\gamma$ bkg computed using MadGraph;
- <u>Signal selection:</u> $|\eta| < 2.37$ and we optimize on the MET requirement

Colliders

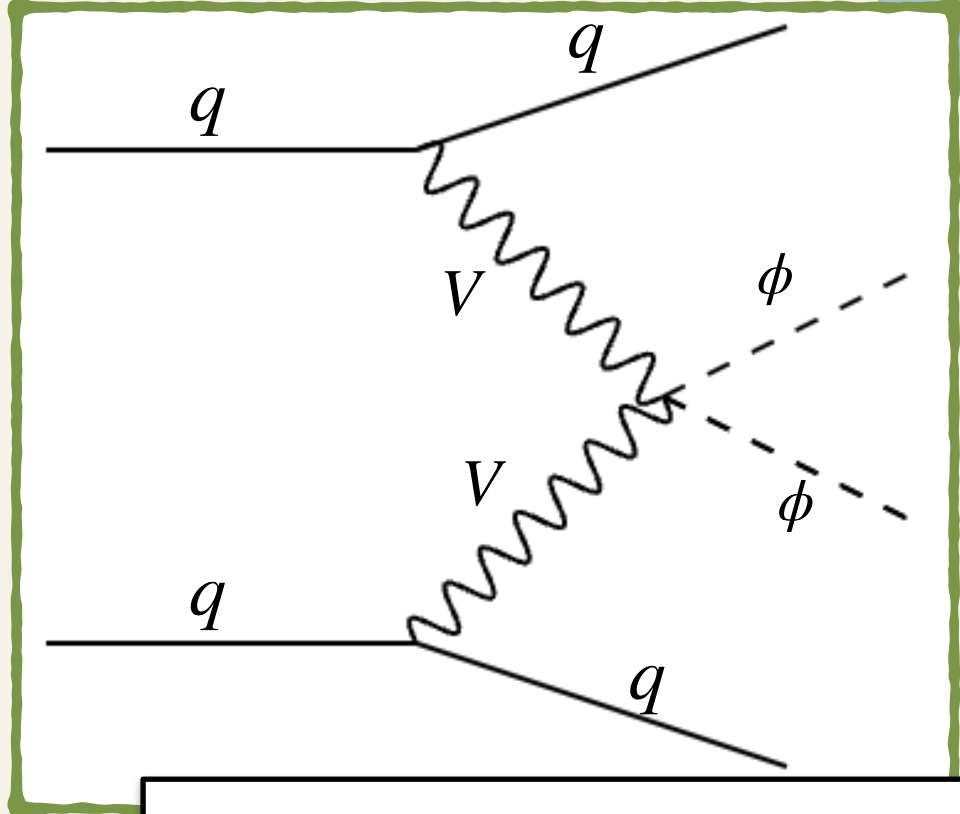
2 **FCC-hh**: VBS - @ 80/100 TeV with $L = 30\ ab^{-1}$

- We leverage the bkg estimation of the 13 TeV ATLAS search
- We consider the signal region of the ATLAS search
- Z boson bkg accounts for 1/3 of the total bkg rate.
- We compute EW Z production at LO (Madgraph)
  - overestimates the ATLAS results by approximately a factor 2.
  - Probably due to the lack of additional jet radiations in our calculation, which would be voted in the fiducial regions defined by ATLAS.
- We thus estimate the total SM bkg at FCC-hh by multiplying a factor **3/2** the rate computed at LO as to match the ATLAS results at 13 TeV.
- m_{jj} is a key variable for selection criteria and maximize the sensitivity
- As expected by the topology of the VBS process the best sensitivity is achieved:
  - i) fixing $p_{T,j}^{min}$ and increasing η^{max}
  - ii) fixing η^{max} and decreasing $p_{T,j}^{min}$





Colliders



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1. We do something similar to the estimation in the DY case

2. We estimate the total SM bkg at FCC-hh by multiplying a factor 3/2 the rate computed at LO as to match the ALTAS results at 13TeV

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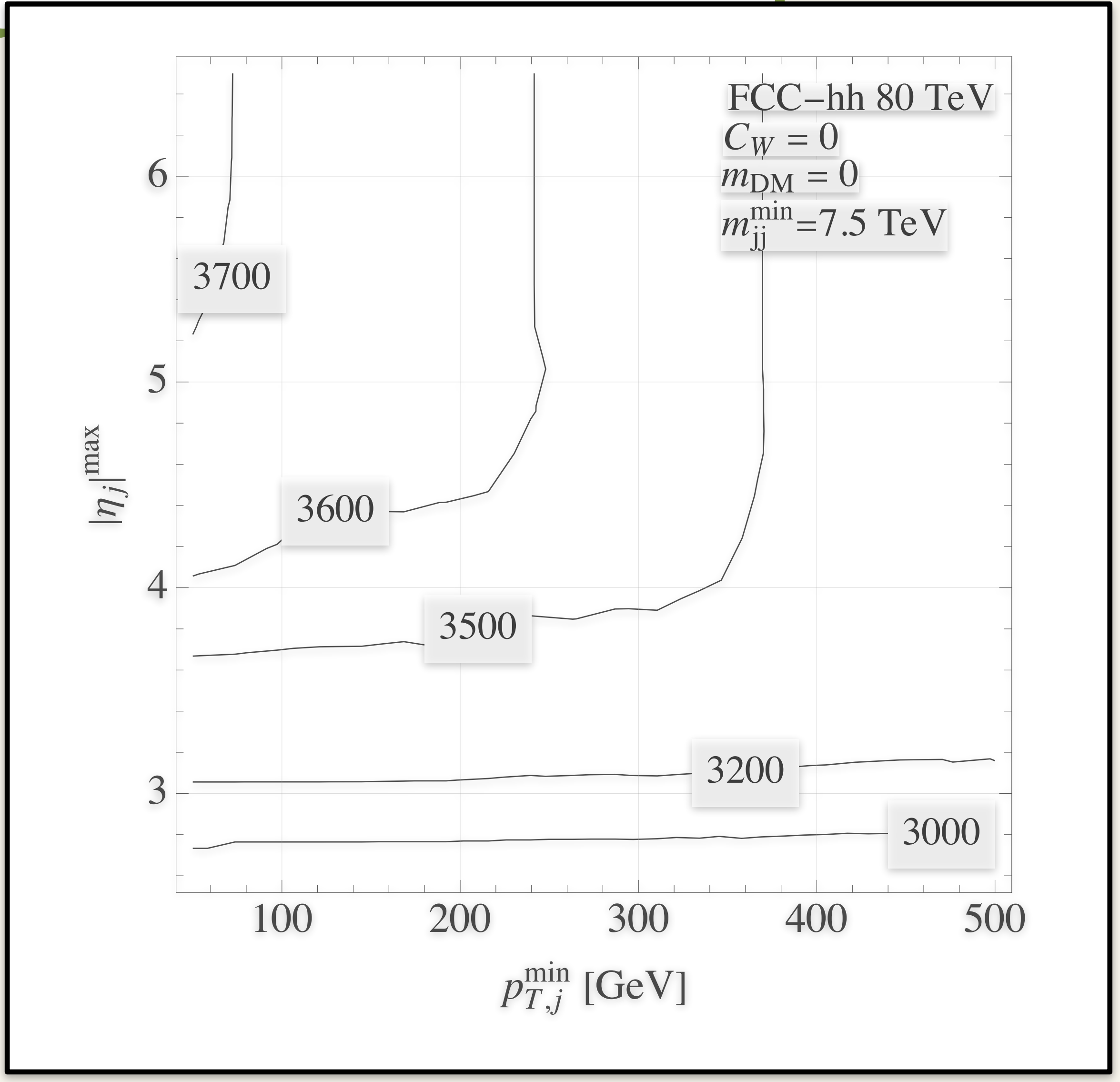
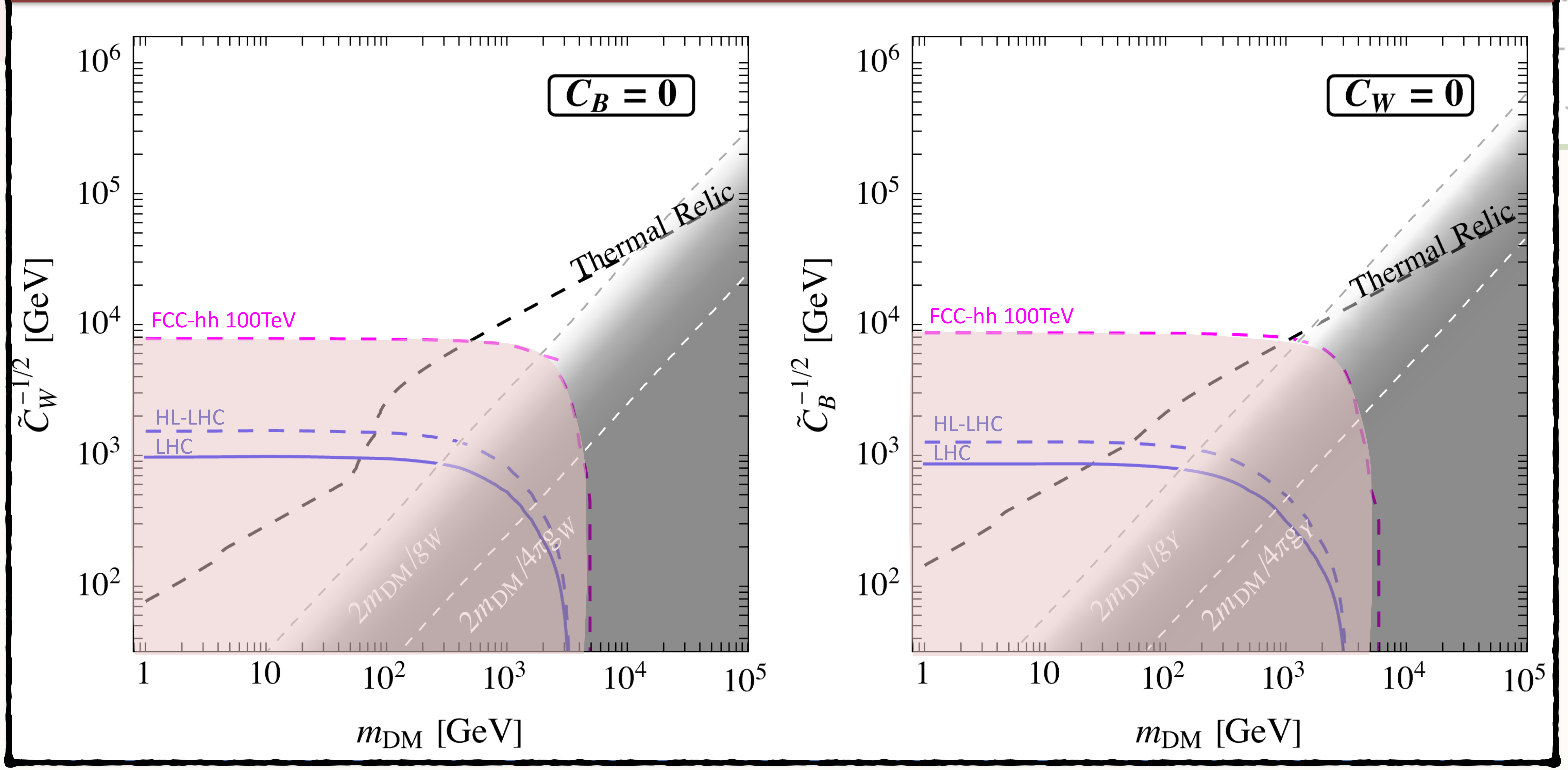
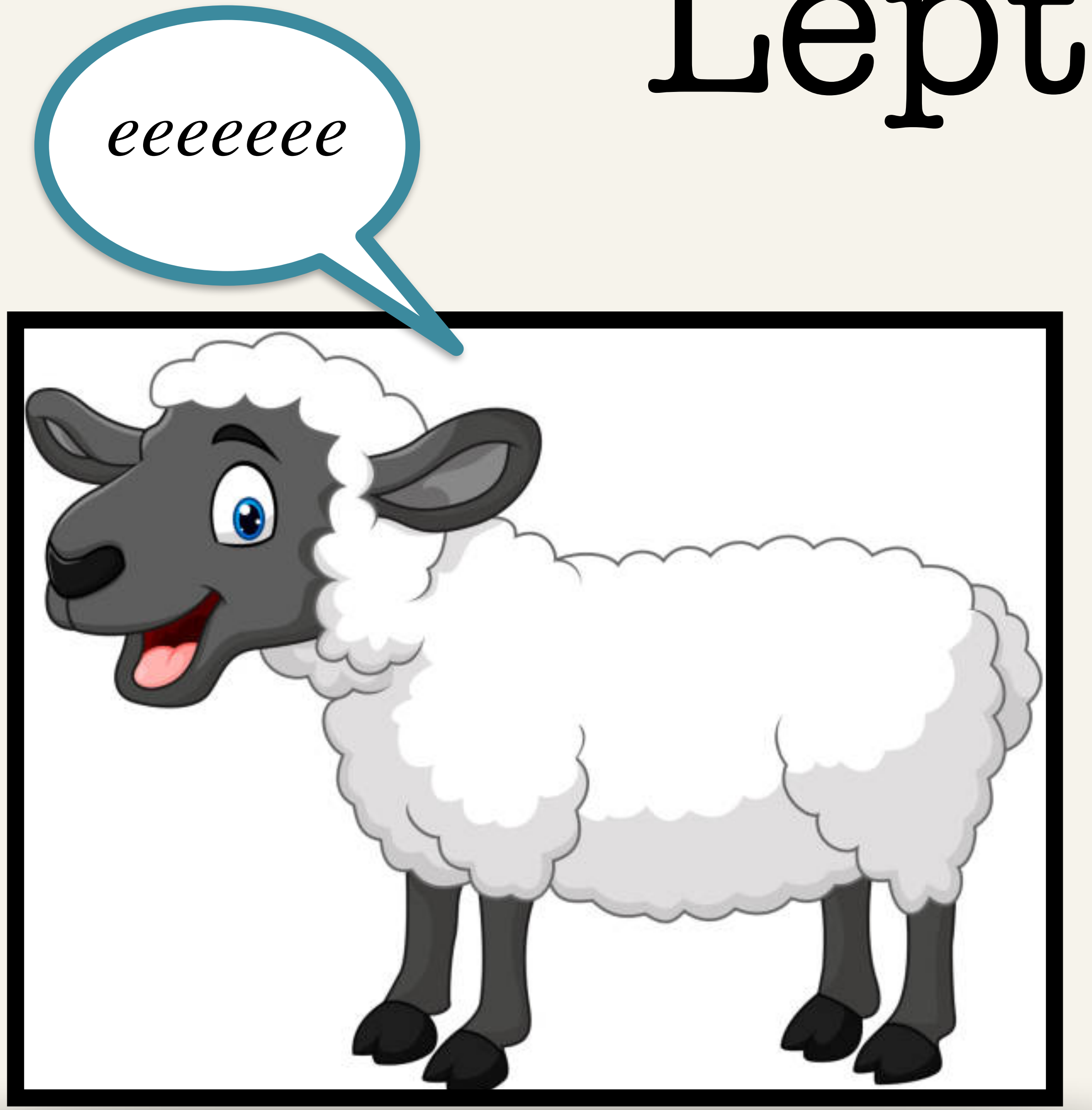


Colliders

FCC-hh will improve the bound by a factor ~ 10 wrt LHC



Lepton Colliders

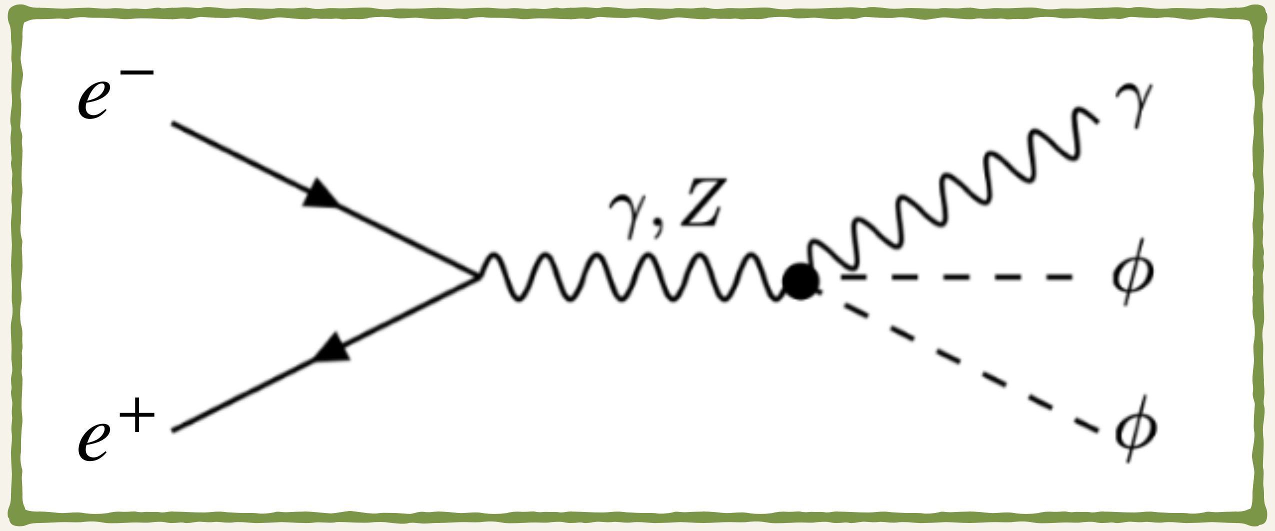


Colliders

$\sqrt{s} = 91.2$ GeV
$L = 120\, ab^{-1}$

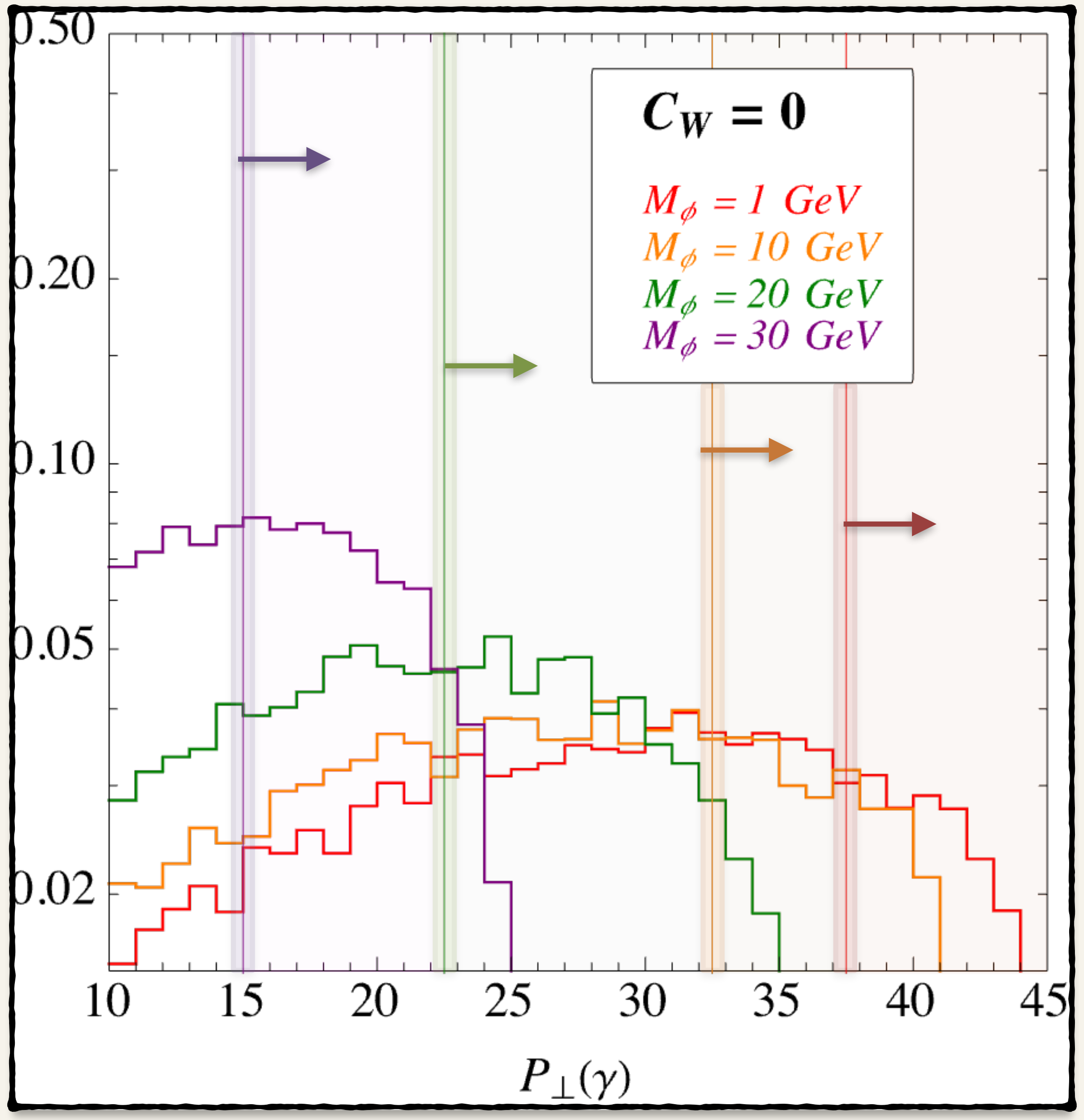
3 **FCC-ee:** DY process

- Z-pole running in Tera-Z mode to probe the scale Λ
- DM produced in association with an energetic photon
- Strongest sensitivity from on-shell Z
- The dominant bkg is $e^+e^- \to \gamma\nu\bar{\nu}$
- Baseline cuts: $|\eta| < 2.5$ and $p_T^\gamma > 5$GeV.
- We maximize the sensitivity $\frac{N_S}{\sqrt{N_B}}$ adding a cut on P_T^γ

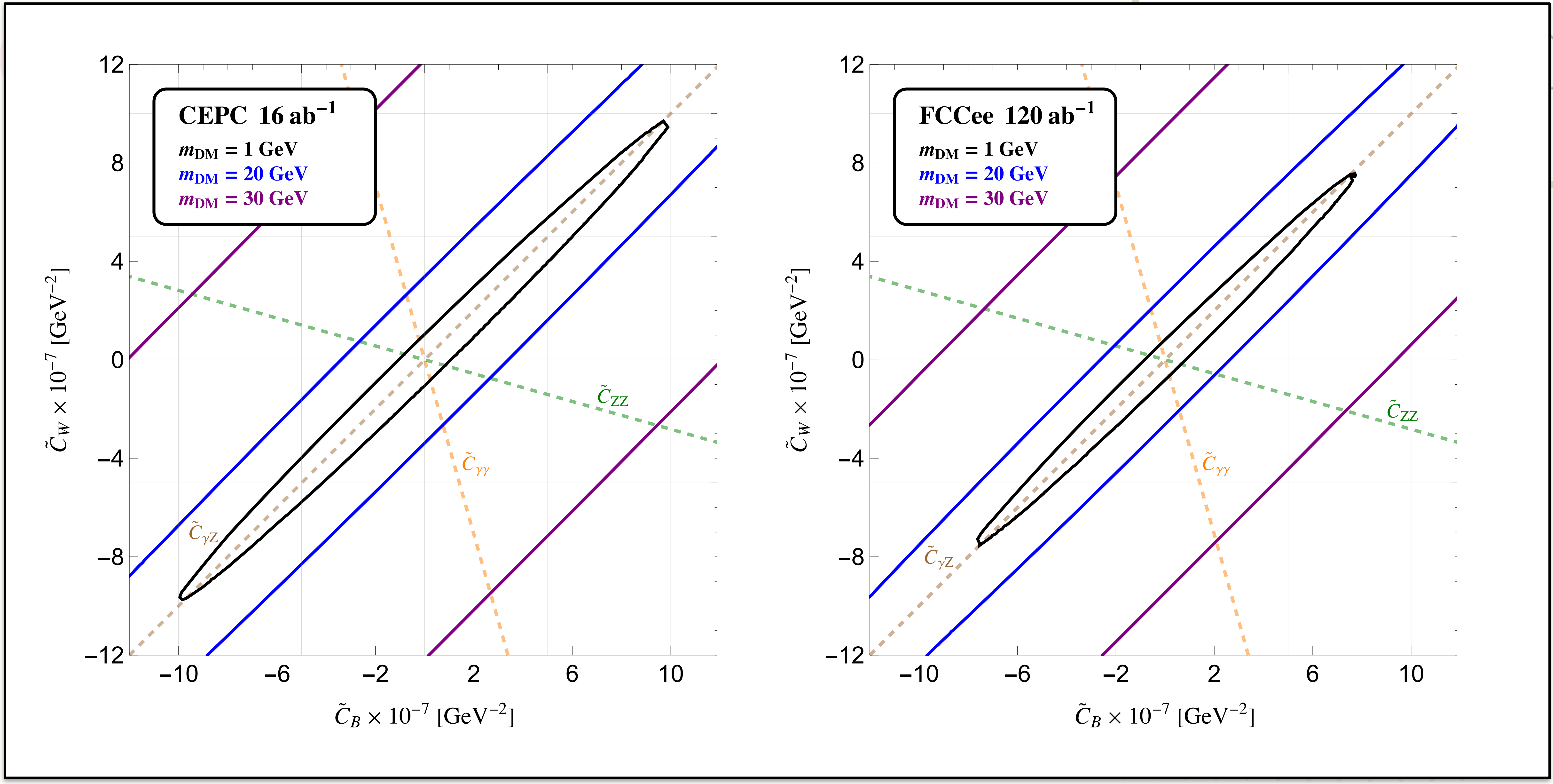


DY at e^+e^- $\sqrt{s} = m_Z$ $\tilde{C}_W = 0$

	$\mathcal{L} = 16\,\text{ab}^{-1}$		$\mathcal{L} = 120\,\text{ab}^{-1}$
m_{DM} [GeV]	$p^\gamma_{T,\text{min}}$[GeV]	$\tilde{C}_\mathcal{B}^{-1/2}$ [GeV]	$\tilde{C}_\mathcal{B}^{-1/2}$ [GeV]
1	37.5	3043	5036
10	32.5	2524	4176
20	22.5	1715	2839
30	15	910	1505
40	5	225	373

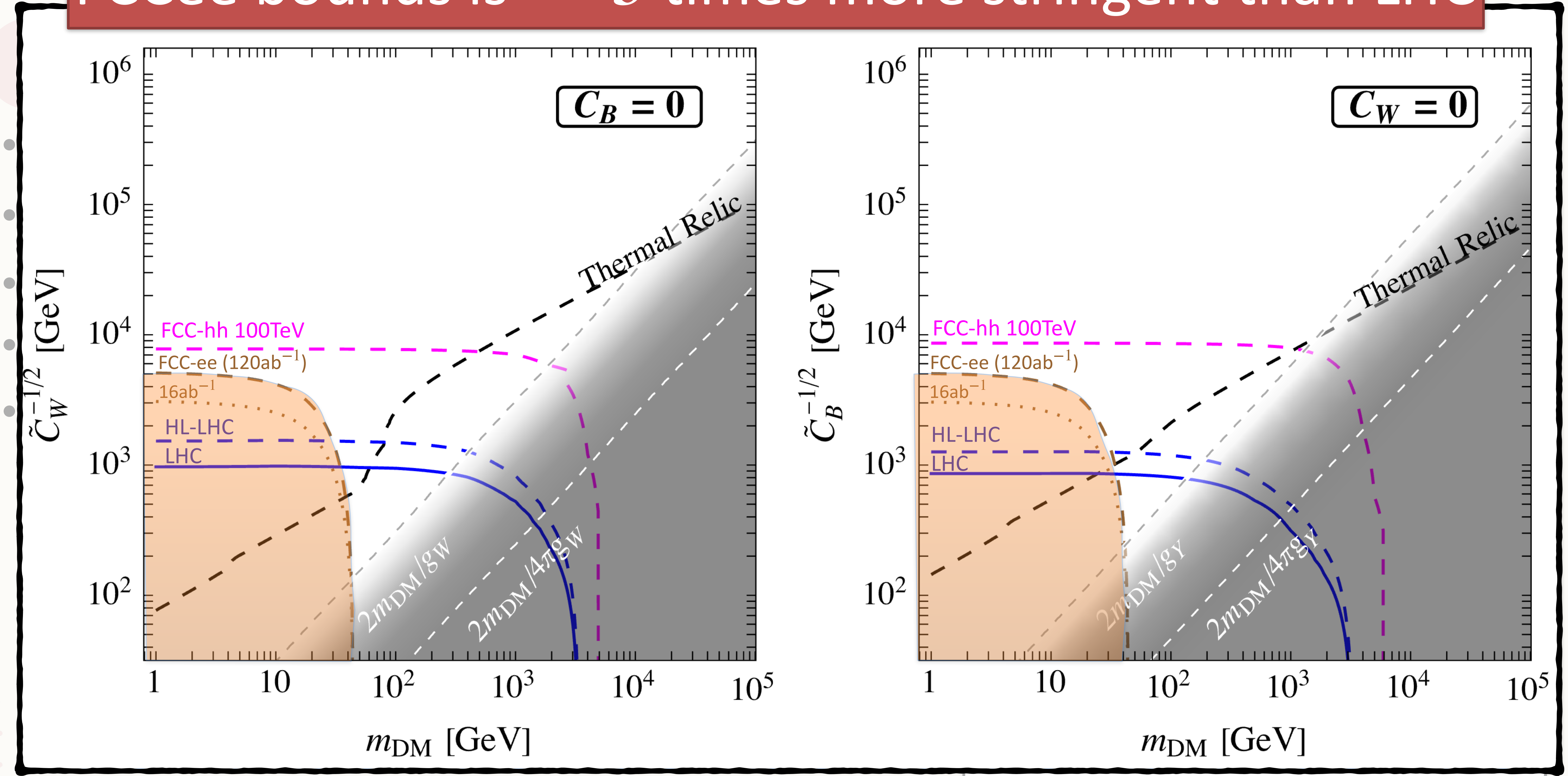


Colliders



CEPC 16 ab^{-1}
m_{DM} = 1 GeV
m_{DM} = 20 GeV
m_{DM} = 30 GeV
FCCee 120 ab^{-1}
m_{DM} = 1 GeV
m_{DM} = 20 GeV
m_{DM} = 30 GeV
$\tilde{C}_{ZZ}$
$\tilde{C}_{\gamma\gamma}$
$\tilde{C}_{\gamma Z}$
$\tilde{C}_W \times 10^{-7}$ [GeV^{-2}]
$\tilde{C}_B \times 10^{-7}$ [GeV^{-2}]

FCCee bounds is ~ 5 times more stringent than LHC



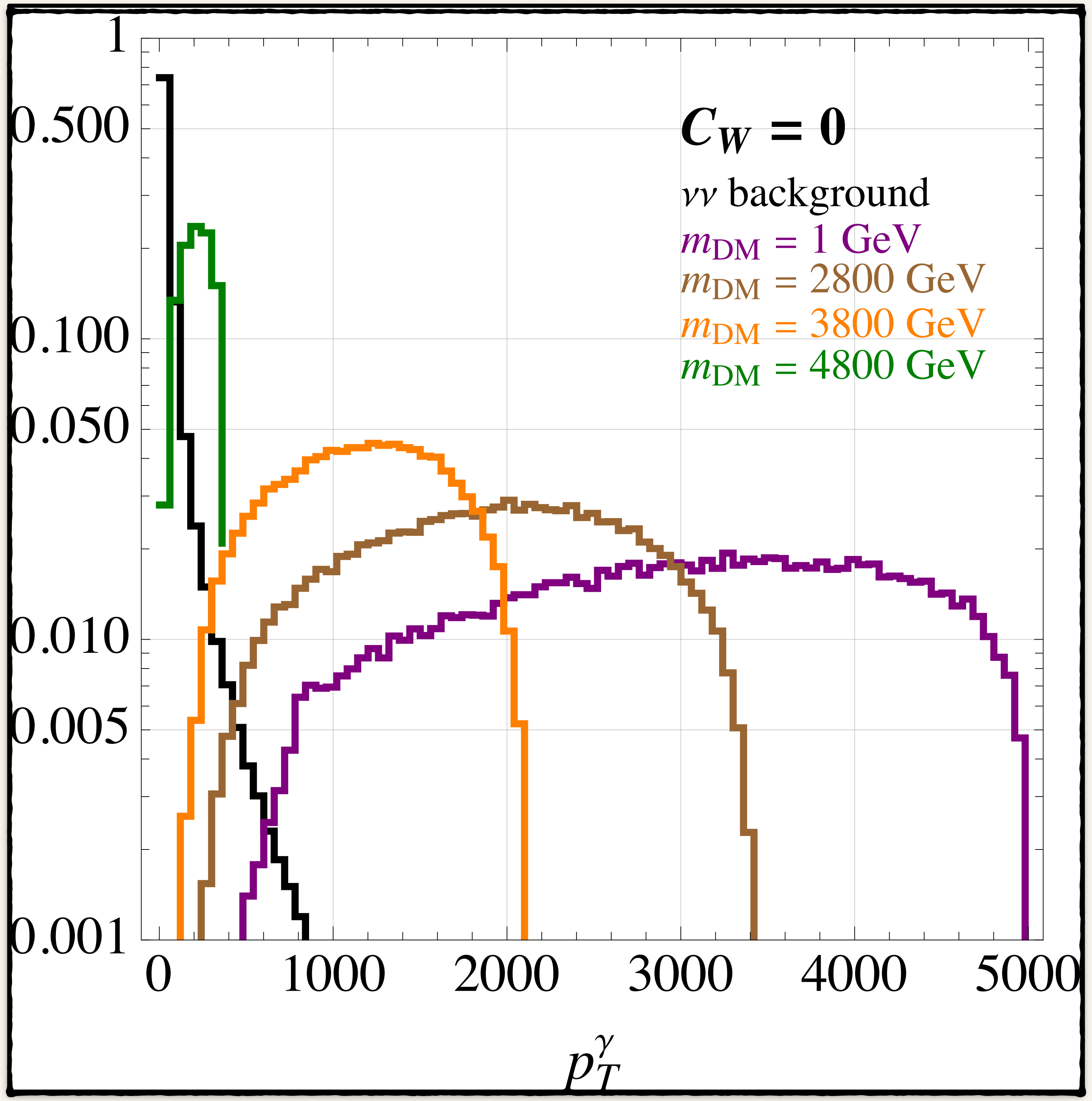
Colliders

$\sqrt{s} = 10$ TeV
$L = 10\, ab^{-1}$

4 **Muon Collider:** DY and VBS

DY: $\mu\mu \to \phi\phi\gamma$

- Mono-γ search with $|\eta^\gamma| < 2.5$
- $\nu\nu\gamma$ dominant bkg $\sigma_{\rm bkg}^{\nu\nu} \sim 4.2\,{\rm pb}$
- For $\tilde{C}_{W,B} \sim$ TeV^{-2} $\sigma_{\rm sig} \sim 0.1\,{\rm pb}$
- Cuts over p_T^γ and maximize the reach



mono-γ DY, $\sqrt{s} = 10\,$TeV $\tilde{C}_{\mathcal{W}} = 0$ μC $(\mathcal{L} = 10\,{\rm ab}^{-1})$

$m_{\rm DM}$ [GeV]	$p^\gamma_{T,\rm min}$ [GeV]	$\tilde{C}_{\mathcal{B}}^{-1/2}$ [GeV]
200	3000	10541
1000	2800	9440
2000	2300	7177
4000	900	1841

Colliders

$\sqrt{s} = 10$ TeV
$L = 10\,ab^{-1}$

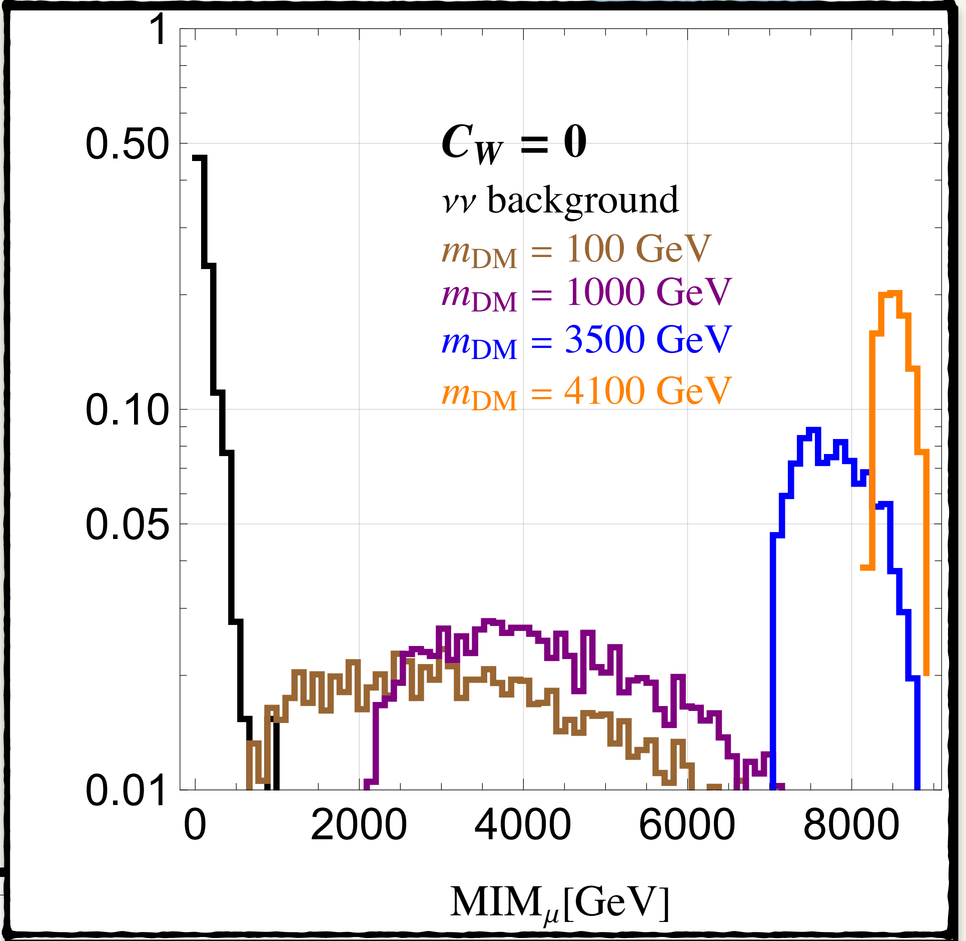
4 **Muon Collider:** DY and VBS

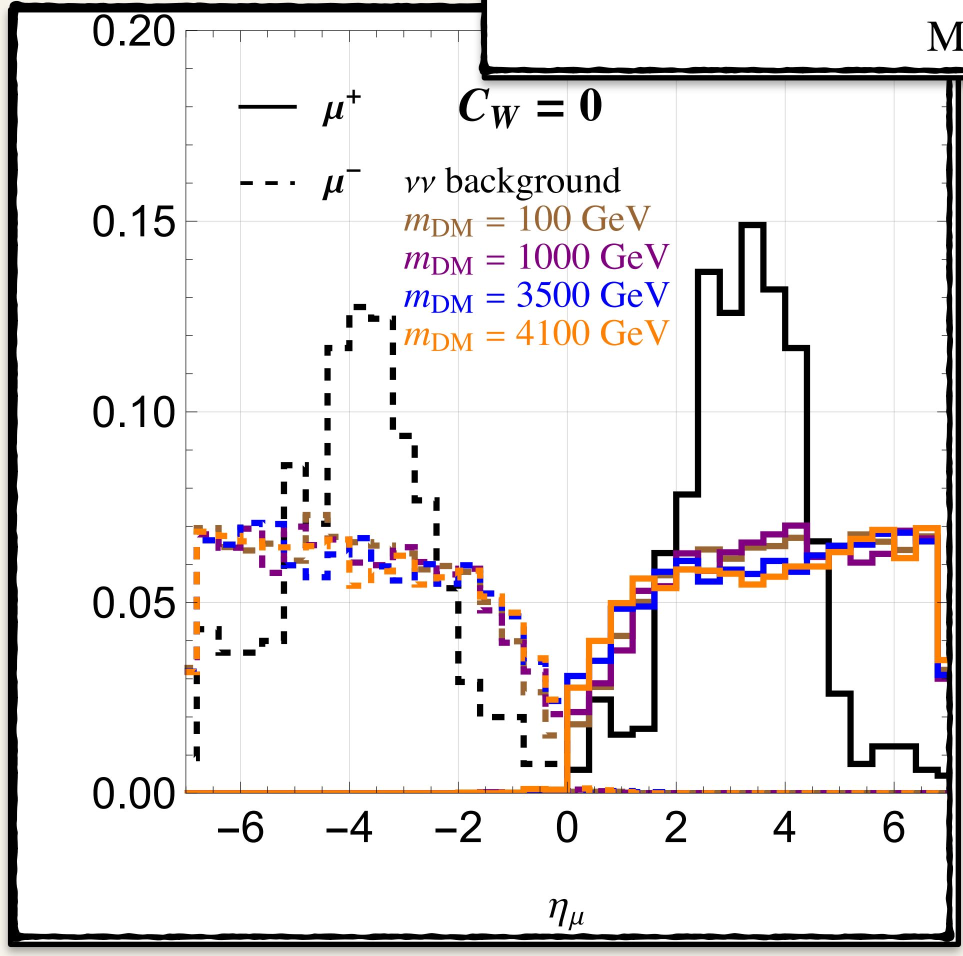
VBS: $\mu\mu \to \mu\mu\phi\phi$

- Two forward muons, with a small polar angle wrt beam direction [1,2]
- $|\eta_{\mu^\pm}| < 7, \Delta R(\mu^+\mu^-) > 0.4, p_T^{\mu\mu} > 50\,\text{GeV}, \text{sign}(\eta_{\mu^+}\eta_{\mu^-}) < 0, \text{E}_{\mu^\pm} > 500\,\text{GeV}$
- Main bkg from $\nu\nu\mu\mu$?
  - **No! Also** $\mu\mu\gamma, \mu\mu f\bar{f}, \mu\mu WW$, **but for MIM>1.5 TeV**

$$\text{MIM} = \sqrt{\Delta p_\mu \Delta p^\mu}, \Delta p^\mu = (\sqrt{s}, \vec{0}) - p_{\mu^+} - p_{\mu^-})$$

The $\nu\nu$ channel is about the 15% of the total bkg.





1. M. Ruhdorfer, E. Salvioni, and A. Wulzer Phys. Rev. D 107 (2023), no. 9 095038, [arXiv:2303.14202]
2. M. Ruhdorfer, E. Salvioni, and A. Wulzer arXiv:2411.00096.

Colliders

$\sqrt{s} = 10$ TeV
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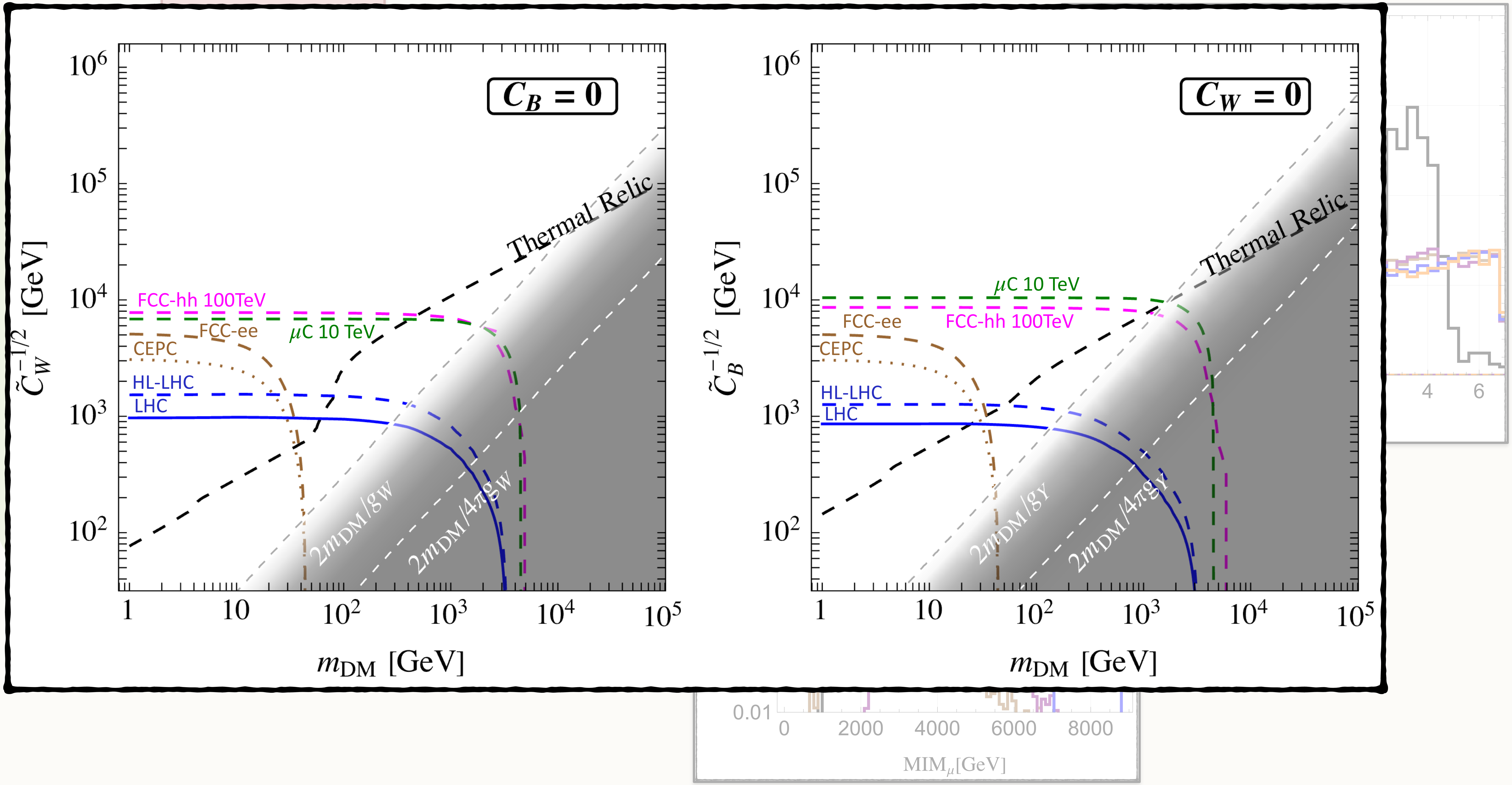


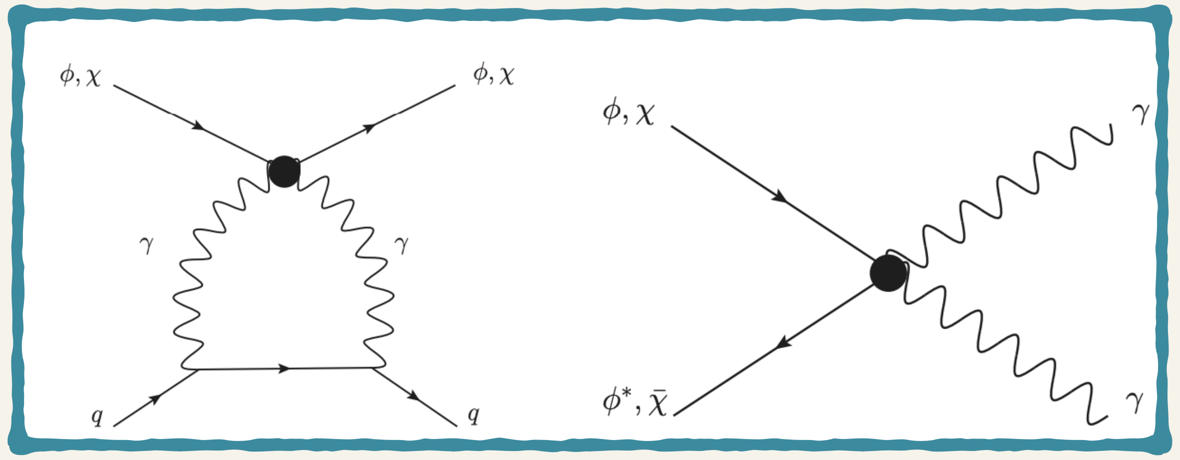
DD and ID

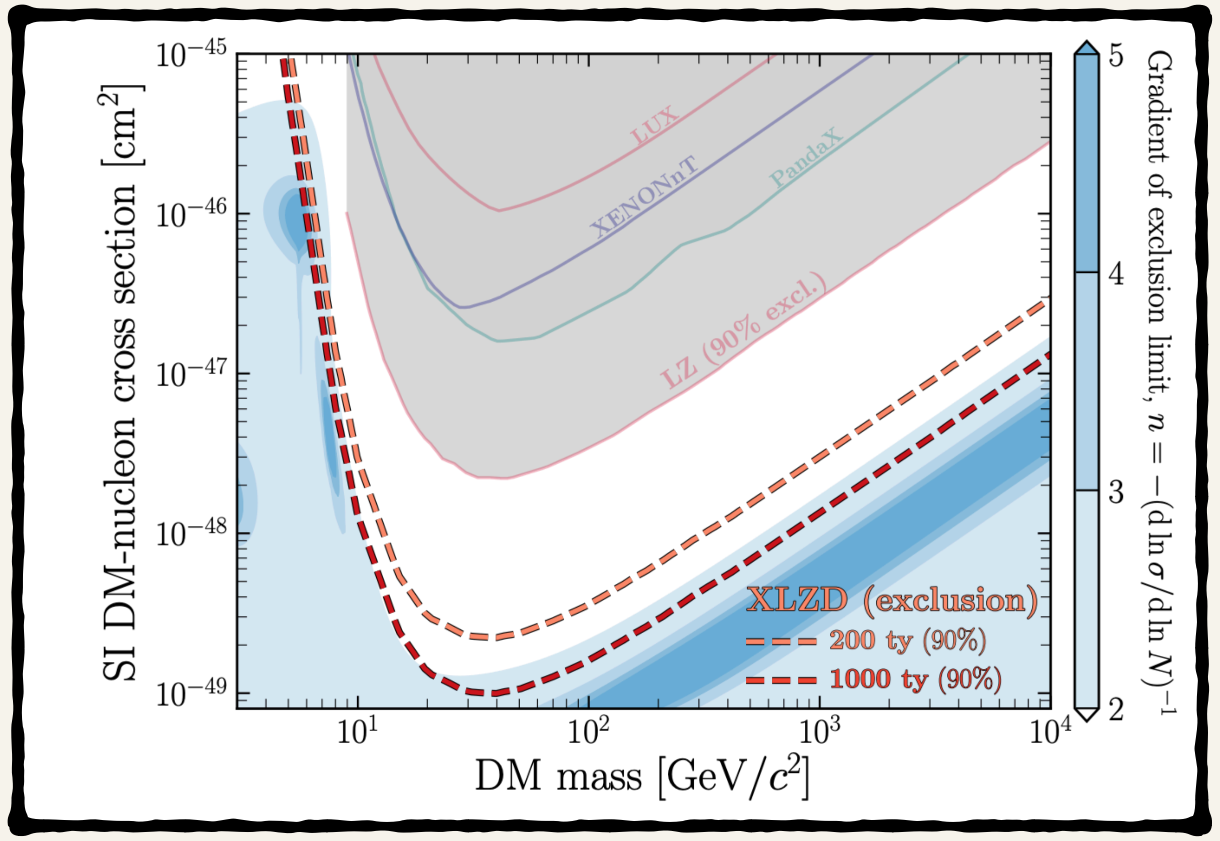
5 LZ and XLZD

$$(\tilde{C}_W, \tilde{C}_B)|_{\mu=v} \xrightarrow{\text{RGE}} (\tilde{C}_q, \tilde{C}_G, \tilde{C}_{\gamma\gamma})|_{\mu=m_N}$$

$$\frac{d\sigma^{\text{Ray}}}{dq^2} \simeq \frac{2\alpha_{\text{em}}^2}{\pi^2 b^2 m_{\text{DM}}^2 v_{\text{DM}}^2} \tilde{\mathscr{C}}_{\gamma\gamma}^2 Z_{\text{T}}^4 F_{\text{ray}}^2(y),$$

$$\frac{d\sigma^{\text{SI}}}{dq^2} = \frac{1}{4\mu_{\text{DM,n}}^2 v_{\text{DM}}^2} \sigma_n^{\text{SI}} A_{\text{T}}^2 F_{\text{H}}^2(y)$$



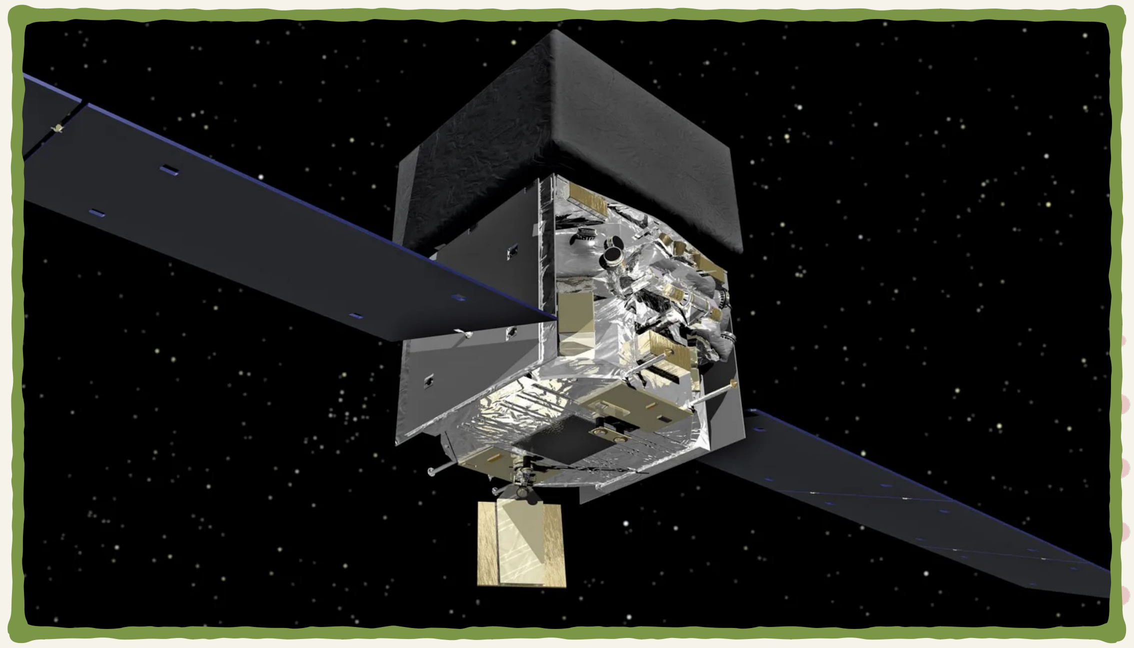


XLZD Collaboration, J. Aalbers et al. arXiv:2410.17137.

6 FERMI and CTA

- FERMI 15 yrs of data
- RoI41 region: Most profile independent
- DM annihilation into $\gamma\gamma, \gamma Z$

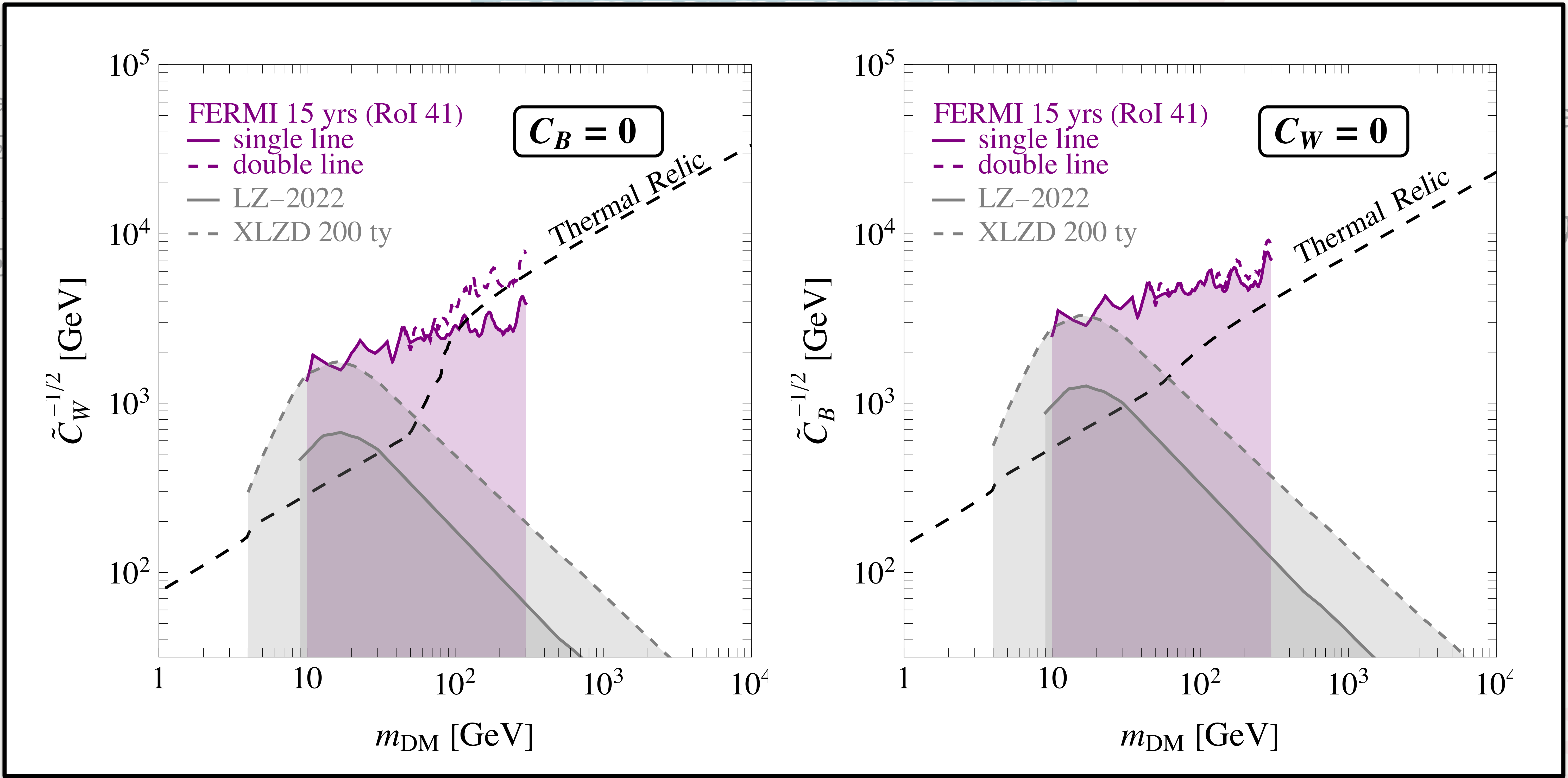
- Line search:
  - single line $\langle \sigma v \rangle_{\gamma\gamma}$ only
  - Double line $\langle \sigma v \rangle_{\gamma\gamma, \gamma Z}$
- CTA projections $\langle \sigma v \rangle_{\gamma\gamma}$



DD and ID

5 **LZ and XLZD**

6 **FERMI and CTA**



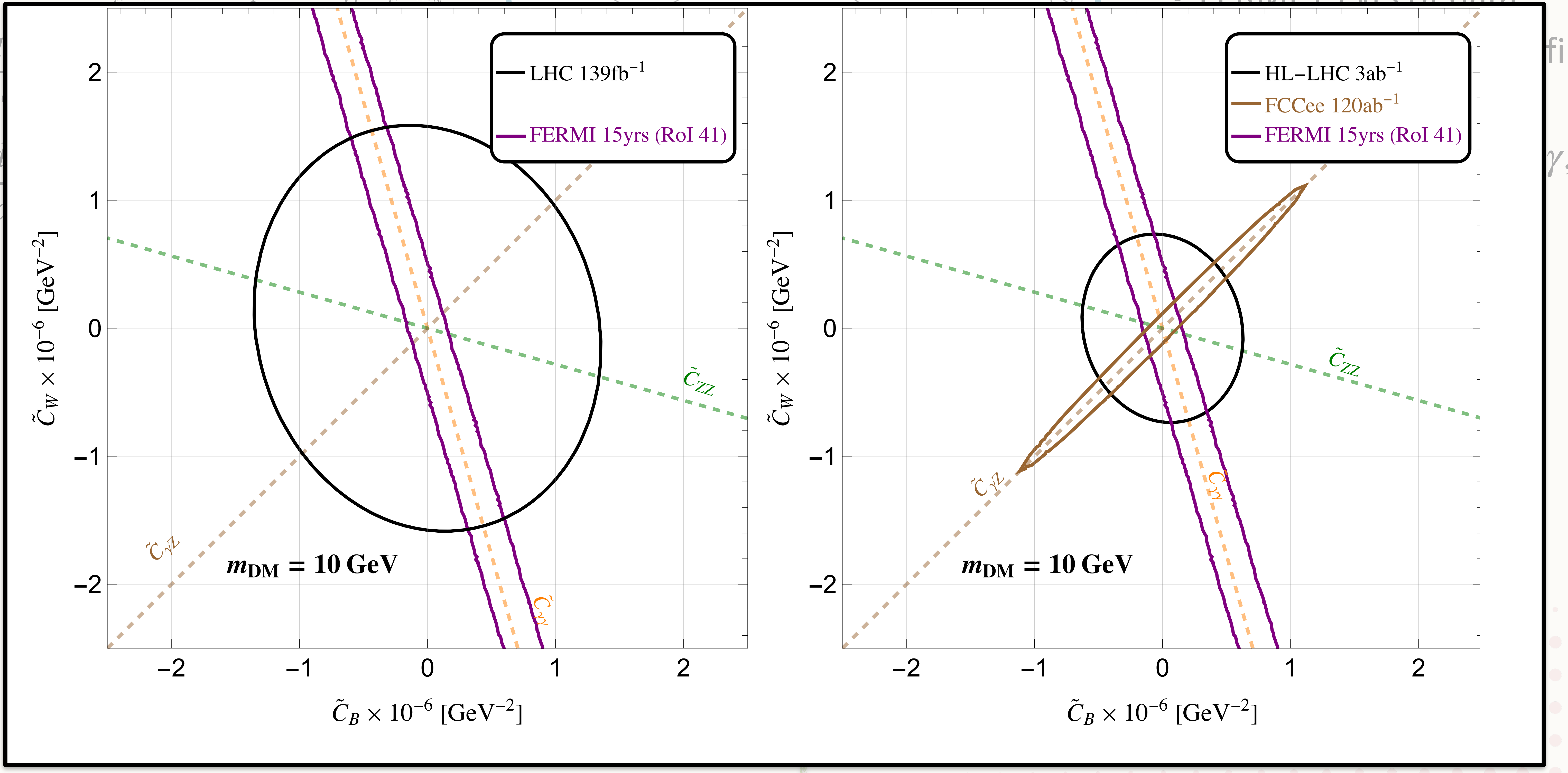
XLZD Collaboration, J. Aalbers et al. arXiv:2410.17137.

DD and ID

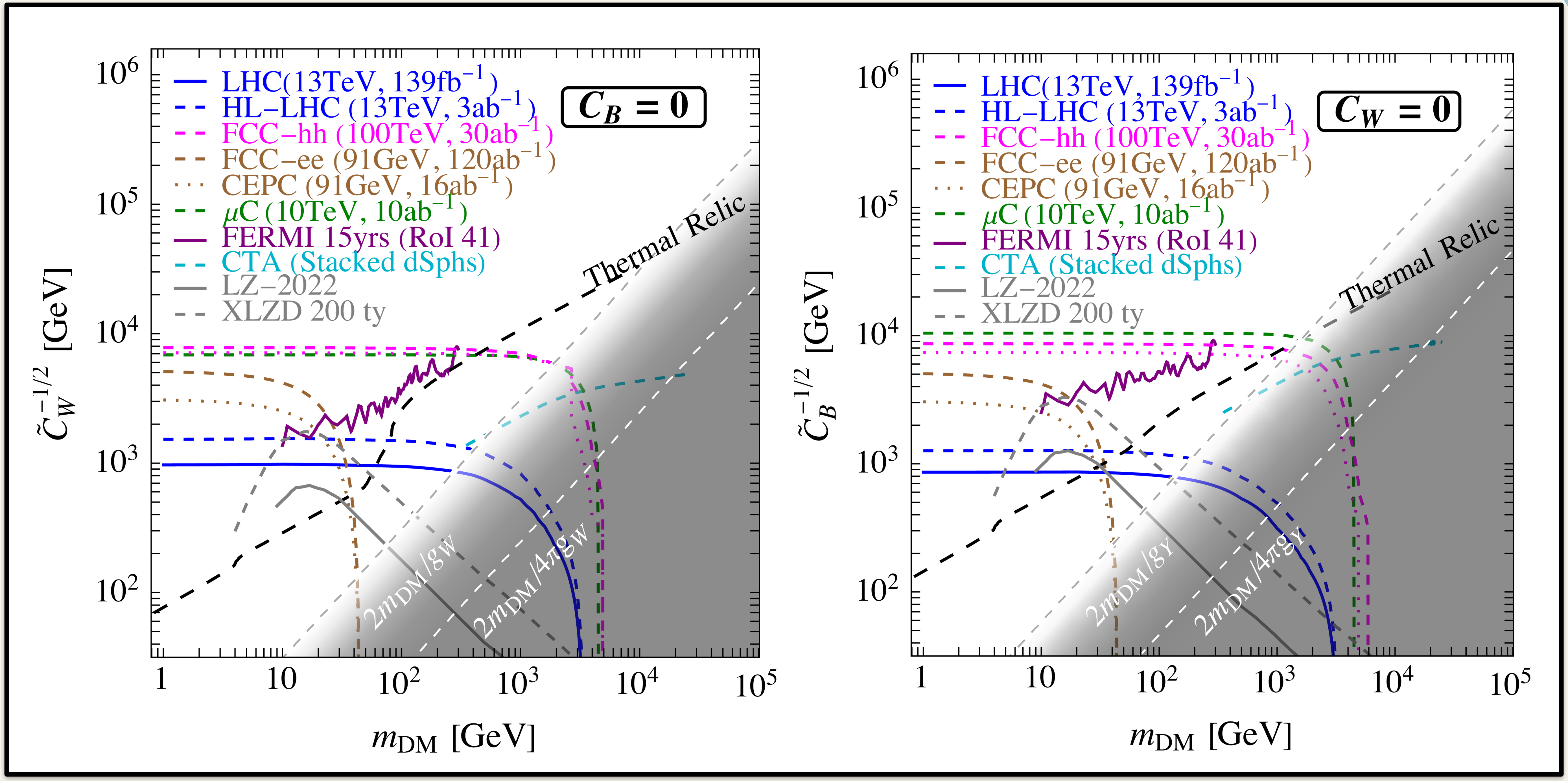
5 LZ and ...

... II and CTA

FERMI > LHC in the ⊥ direction of $\tilde{C}_{\gamma\gamma} = 0$



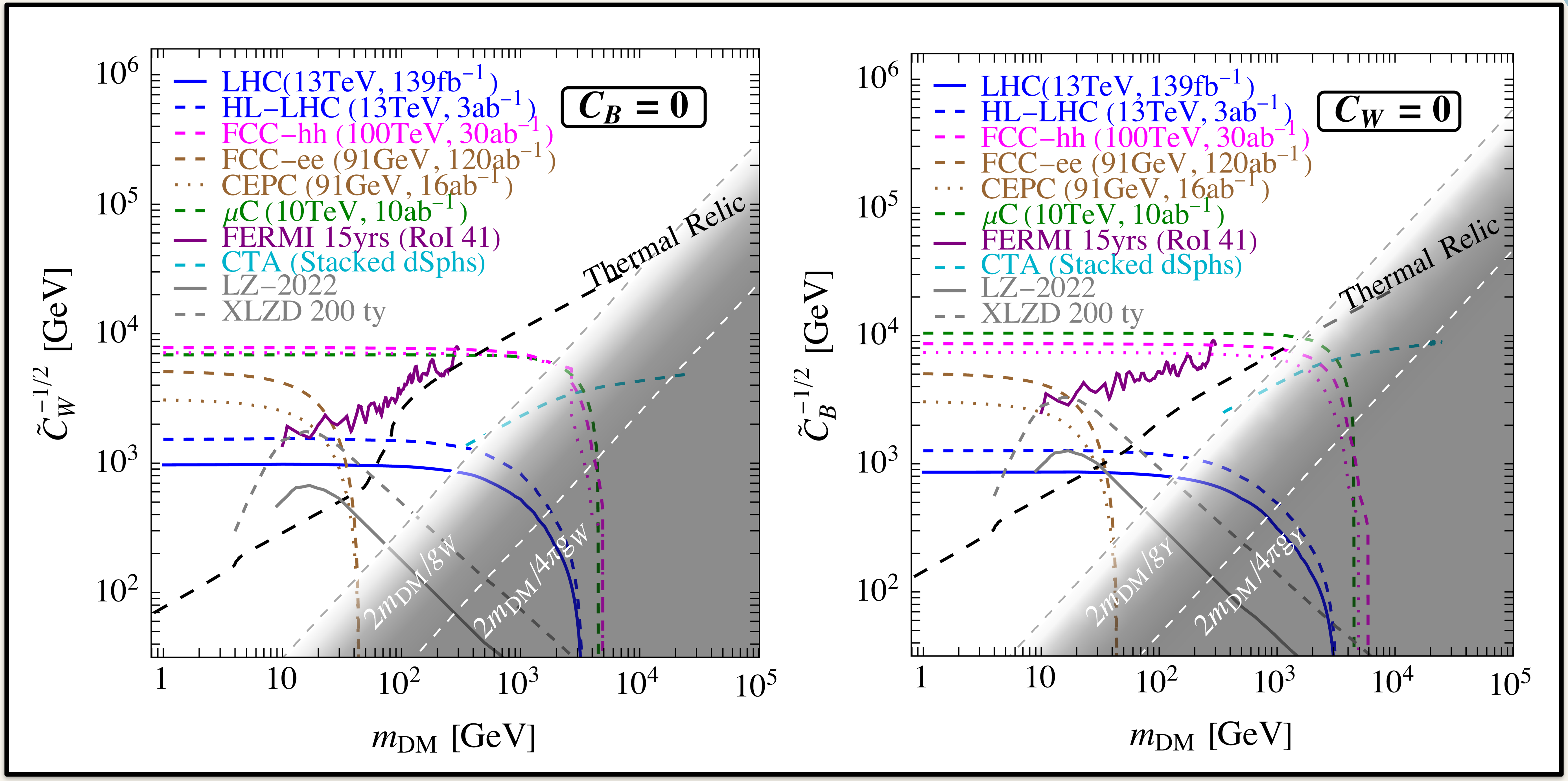
Conclusion



"Near" Future Colliders (FCCee, HL-LHC):

- Will place more stringent bounds on this dark matter scenario;
- FCCee gives one of the most stringent bound, but only for small DM mass;
- HL-LHC bounds will not be significantly greater than current LHC ones .

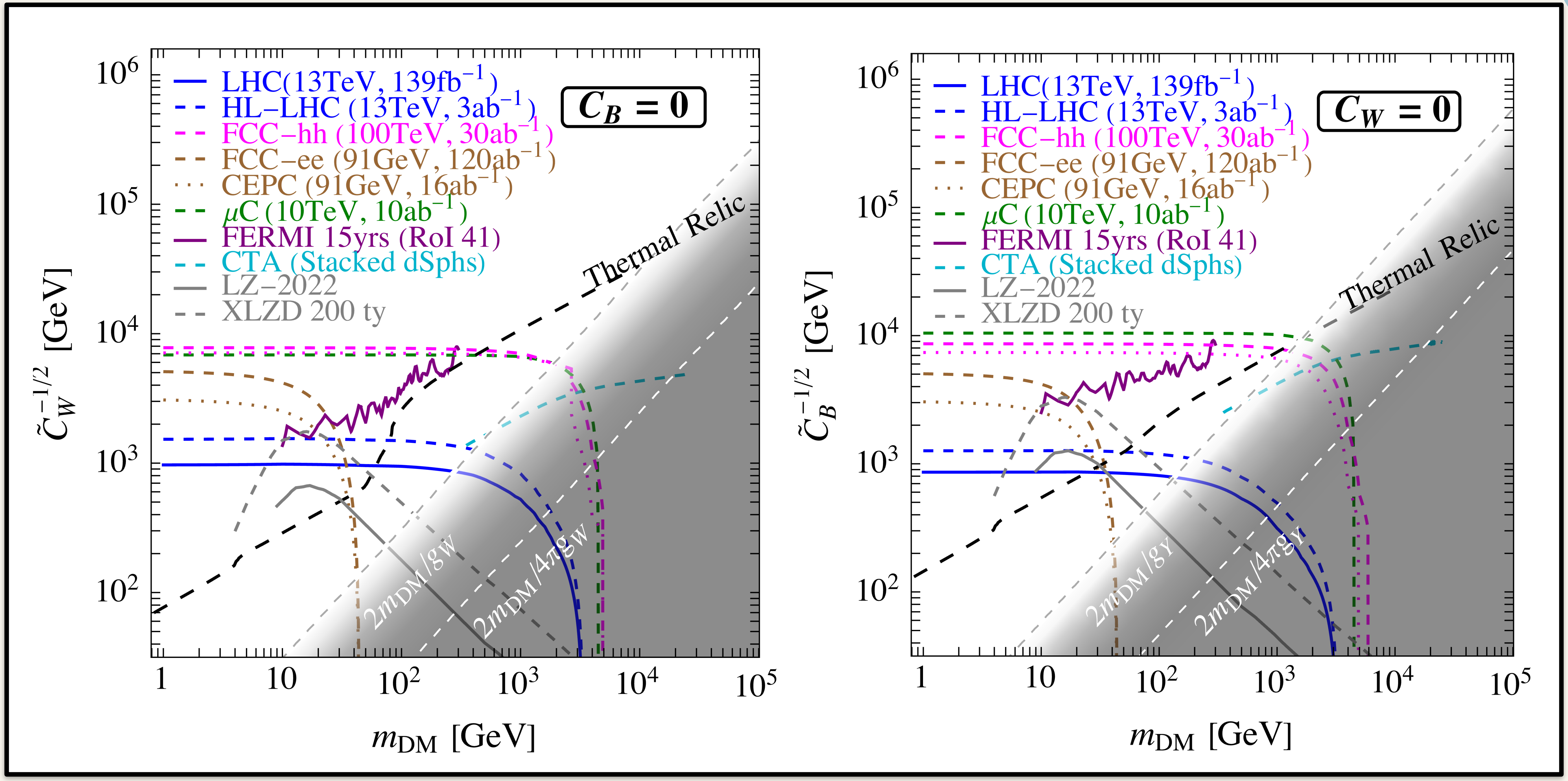
Conclusion



Indirect and Direct Detection:

- Current bounds (e.g., FERMI) and future projections (e.g., XLZD) will remain competitive, if not stronger, than FCCee or HL-LHC.

Conclusion



“Next” Future (FCChh and μC):

- Will be able to probe much higher energy scales;
- Could provide crucial insights into this dark matter benchmark.

THANK YOU

Backup Slides

Yukawa model

TYPE I

$$\mathscr{L} = \lambda \phi \bar{\psi}_L l_R + h.c.$$

ϕ is DM candidate EW singlet, l is RH SM lepton and ψ is a BSM $SU(2)_L$ singlet with $Y_\psi = -1$

Yukawa model

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TYPE II

$$\mathscr{L} = \tilde{\lambda} \phi \bar{\psi}_L F_R + h.c.$$

ϕ is DM candidate EW singlet, F and L are a BSM $SU(2)_L$ singlets with $Y_\psi = Y_F$

$$m_\phi \ll m_F \sim m_\psi$$

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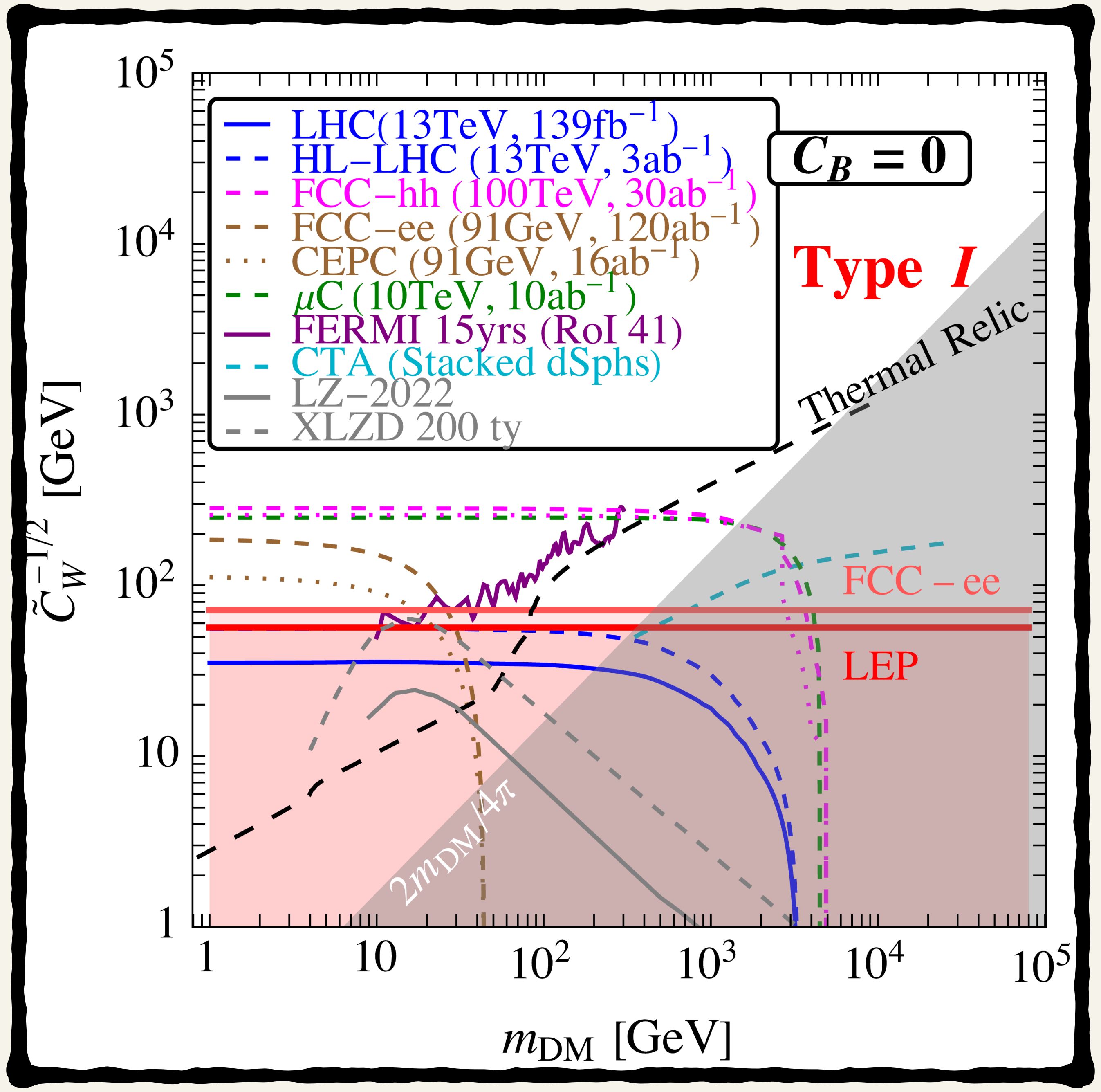
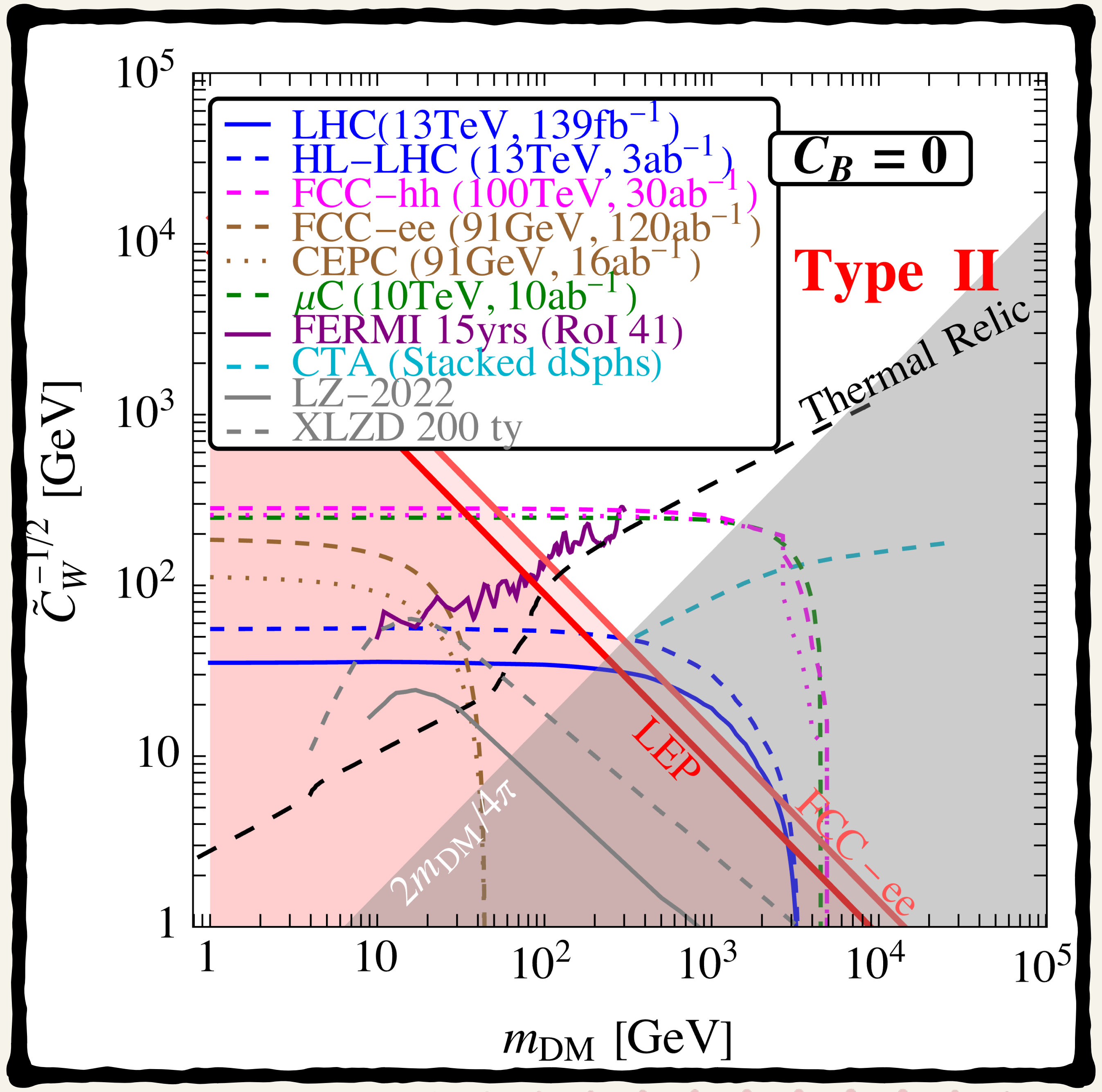
$$\begin{cases} \mathcal{C}_{\gamma\gamma}^{-1/2} = \frac{\sqrt{3}}{\lambda Y_\psi} m_\psi \Big|_{\lambda_{\max}} \gtrsim 57\,\mathrm{GeV}, & \text{(Scenario I)} \\ \mathcal{C}_{\gamma\gamma}^{-1/2} = \sqrt{\frac{90}{11}} \frac{1}{\tilde{\lambda} Y_\psi} \frac{m_\psi^2}{m_{\mathrm{DM}}} \Big|_{\tilde{\lambda}_{\max}} \gtrsim \frac{8.9\times10^3\,\mathrm{GeV}^2}{m_{\mathrm{DM}}}, & \text{(Scenario II)} \end{cases}$$

Yukawa model



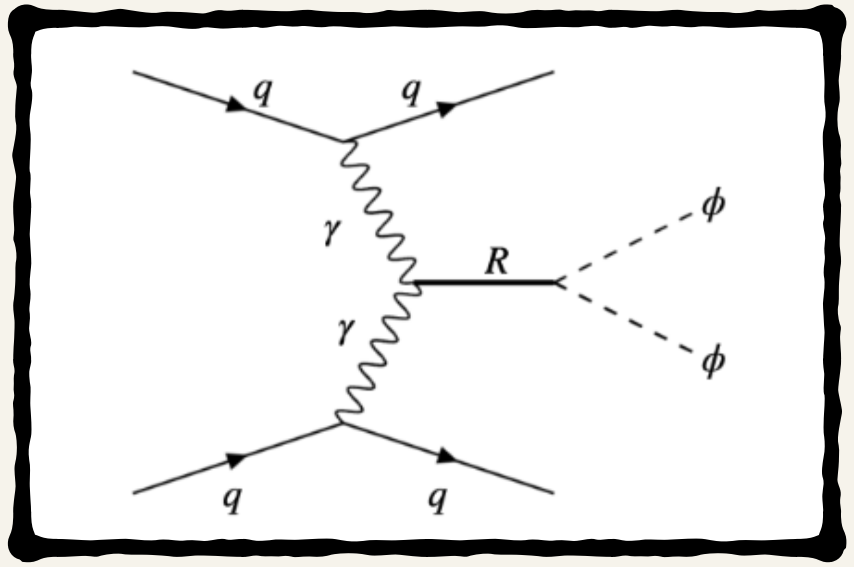


TPPC - Theory retreat| 2024

Spin-2 UV-completion

EFT MATCHING

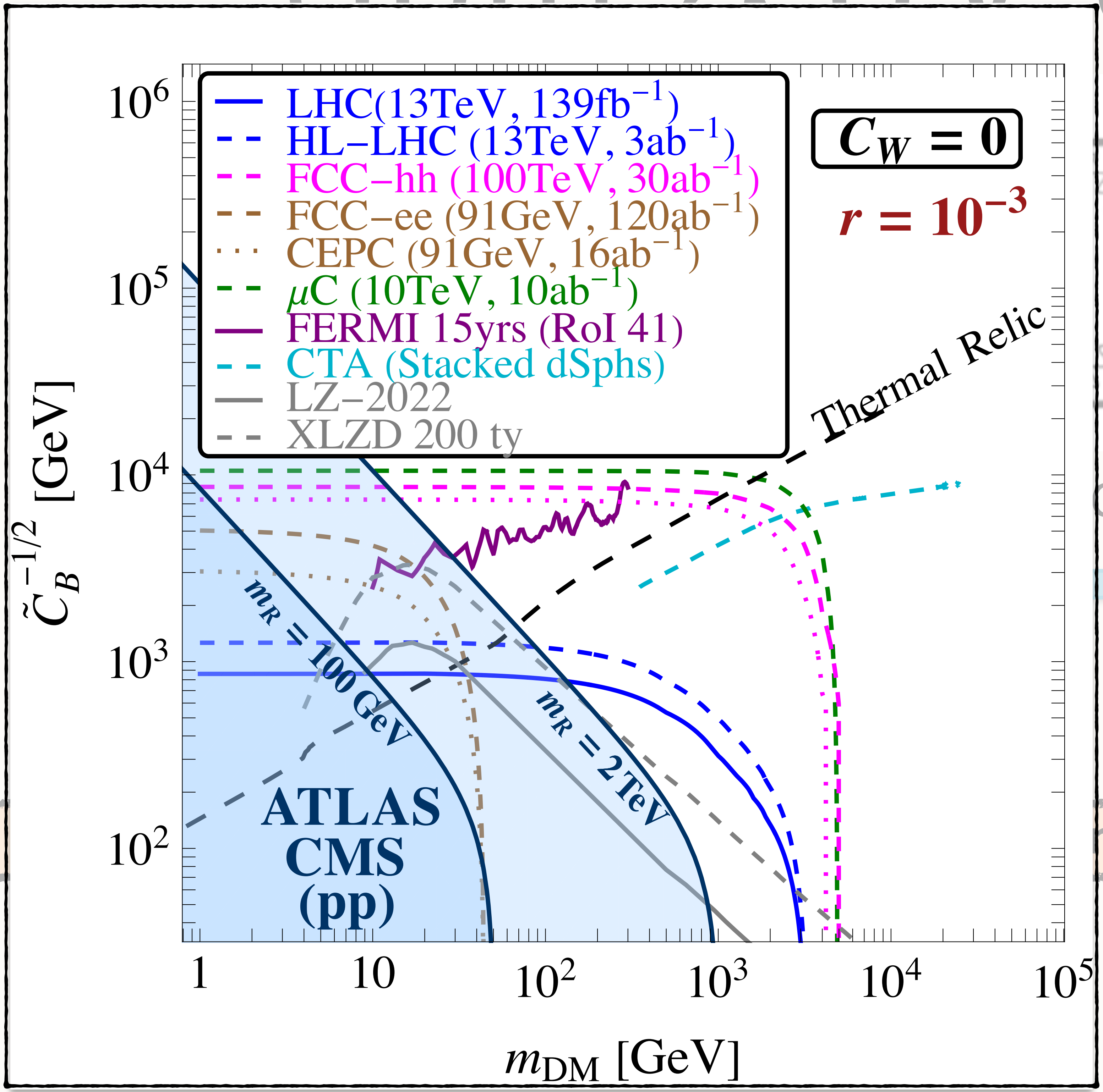
$$\mathscr{L} \supset \tilde{C}_{\gamma\gamma}\phi^2 F^2 \quad \longrightarrow \quad \mathscr{L} \supset -\frac{1}{2\Lambda_R} R_{\mu\nu}\left[c_1 T^{(F)}_{\mu\nu} + c_2 T^{(\phi)}_{\mu\nu}\right]$$

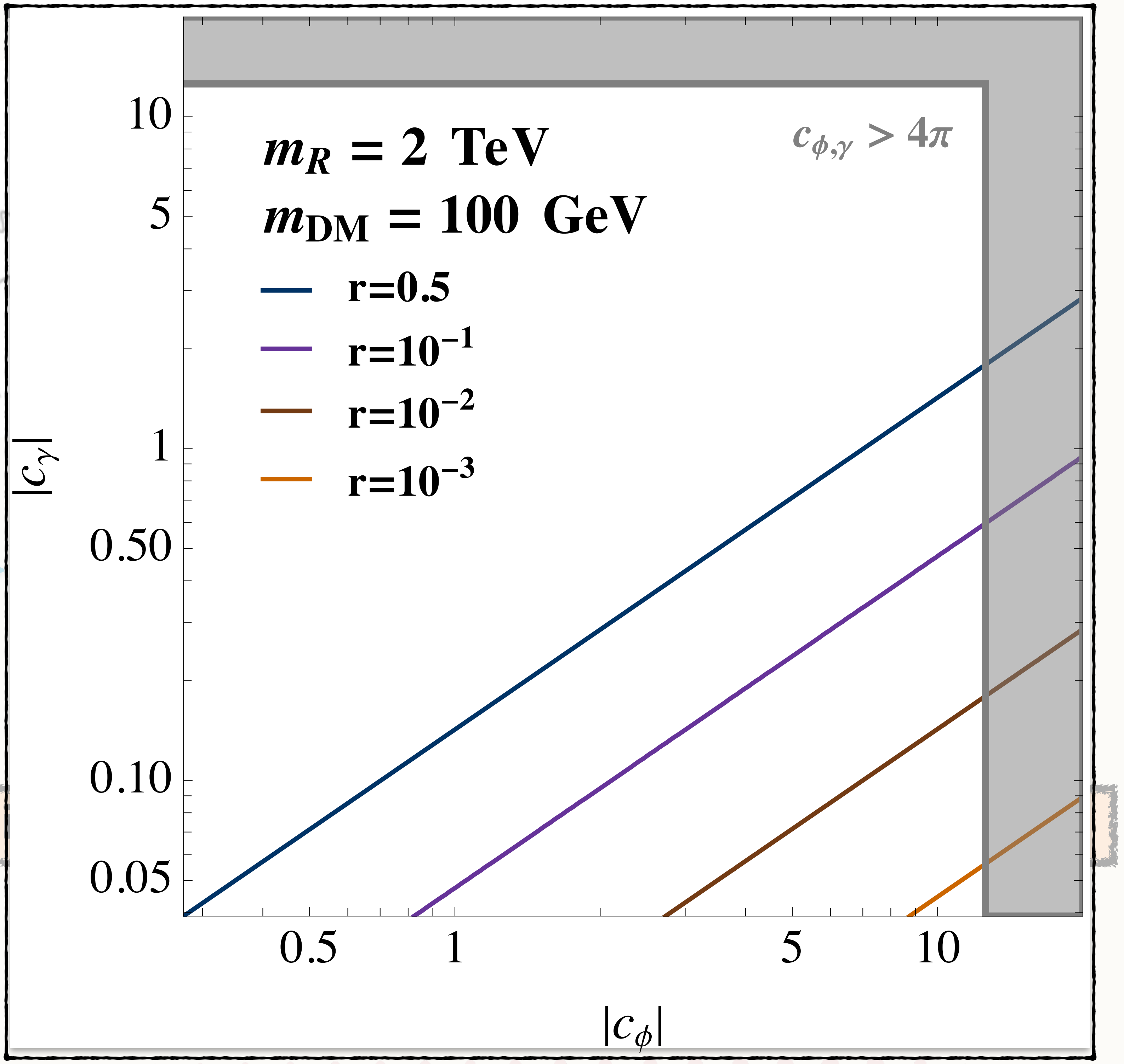


Bound for the production of the massive spin 2 particle[1] rescaling the branching ratio $R \to \gamma\gamma$

[1] *D. d'Enterria, M. A. Tamlihat, L. Schoeffel, H.-S. Shao, and Y. Tayalati Phys. Lett. B 846 (2023) 138237*

Spin-2 UV-completion





[2] D. d'Enterria, M. A. Tamlihat, L. Schoeffel, H.-S. Shao, and Y. Tayalati Phys. Lett. B 846 (2023) 138237