Scalar Rayleigh Dark Matter

Collider and Cosmological Probes, Present and Future

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

3rd ECFA workshop on e^+e^- Higgs, Electroweak and Top Factories | 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 $SU(2)_L$ singlet dark matter particle with SM EW gauge bosons

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

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

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

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How do we test this scenario at colliders?

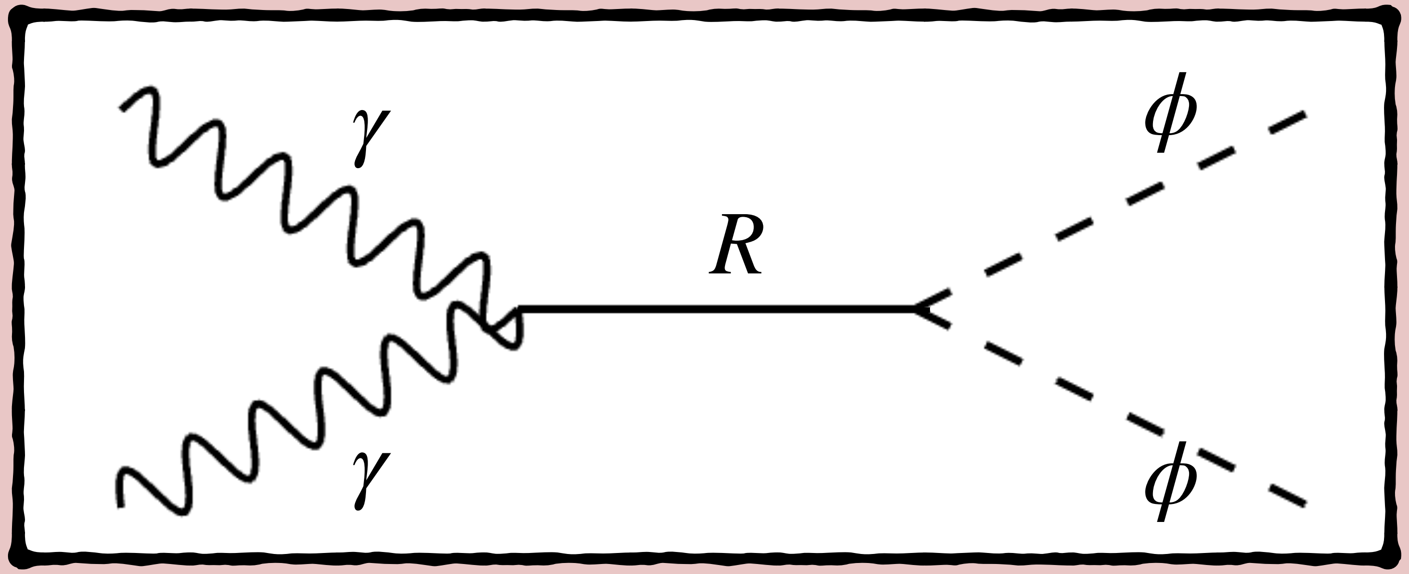
FCCee - FCChh

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

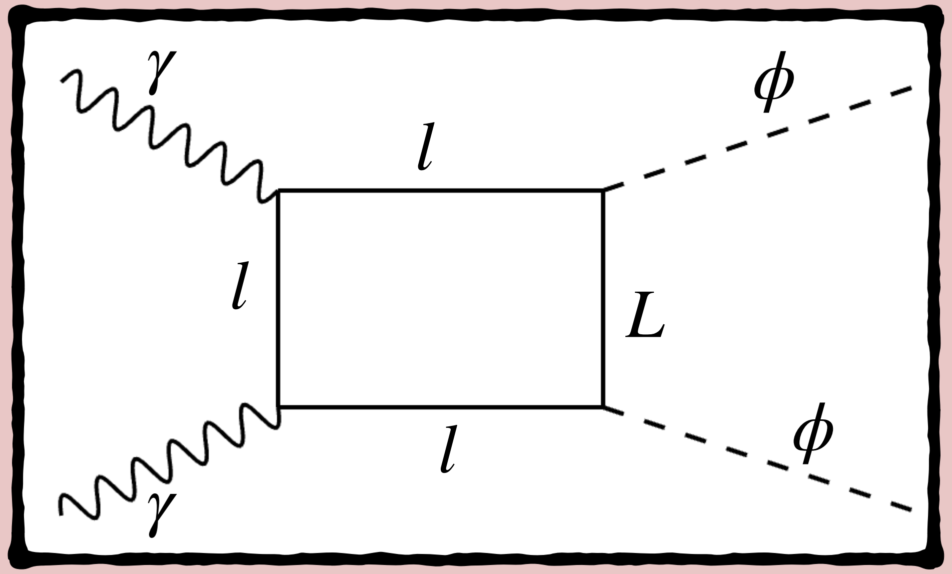
UV completion?

- Wilson coefficients are related to the scale where these operators are generated as $C^{\phi}_{\mathcal{B},\mathcal{W}} = \frac{c_{B,W}}{\Lambda^2_{B,W}}$
- UV completion can be achieved through:

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



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



Experiments

1. LHC @ $\sqrt{s} = 13$ TeV, $L = 139/fb$ → HL-LHC $\sqrt{s} = 13$ TeV, $L = 3\ ab^{-1}$
2. Z-factory at FCC-ee ($L = 120/ab$)
3. FCC-hh @ $\sqrt{s} = 80{,}100$ TeV, $L = 30/ab$
4. μC @ $\sqrt{s} = 3{,}10$ TeV
5. Xenon and Darwin
6. FERMI

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Colliders

3. FCC-hh @ $\sqrt{s} = 80{,}100$ TeV, $L = 30/ab$
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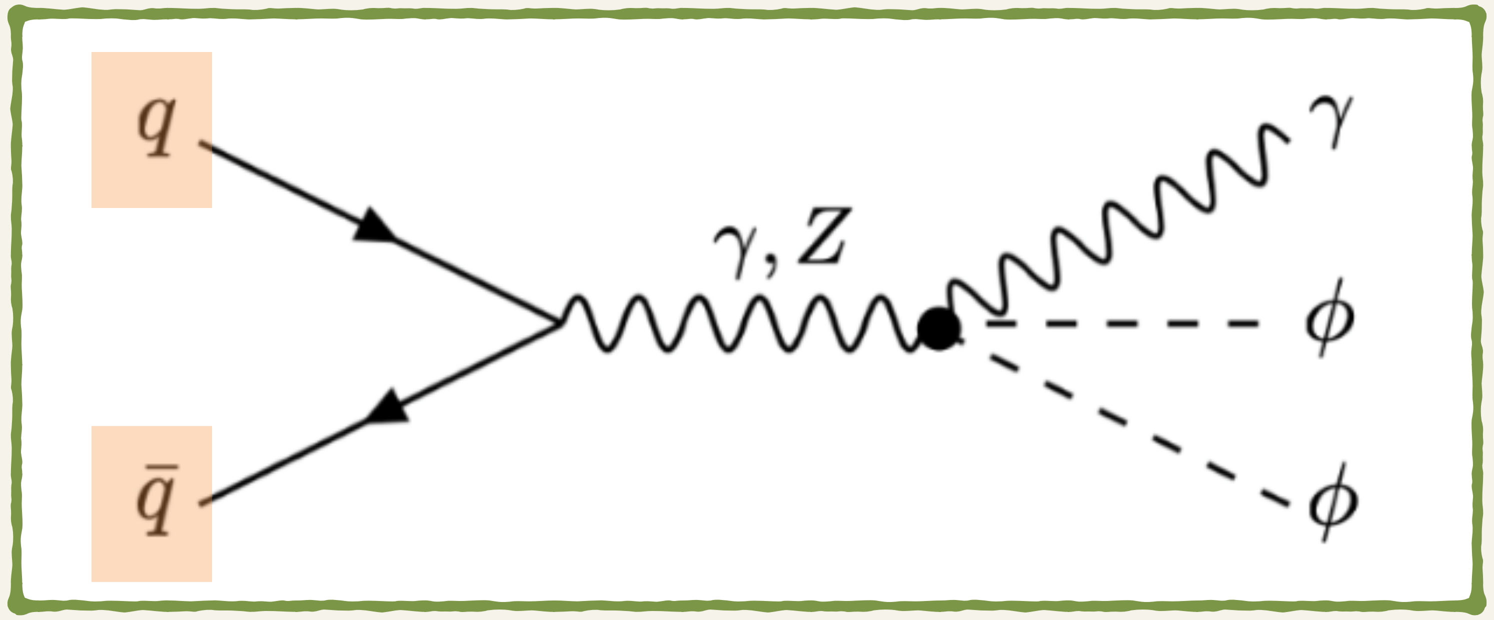
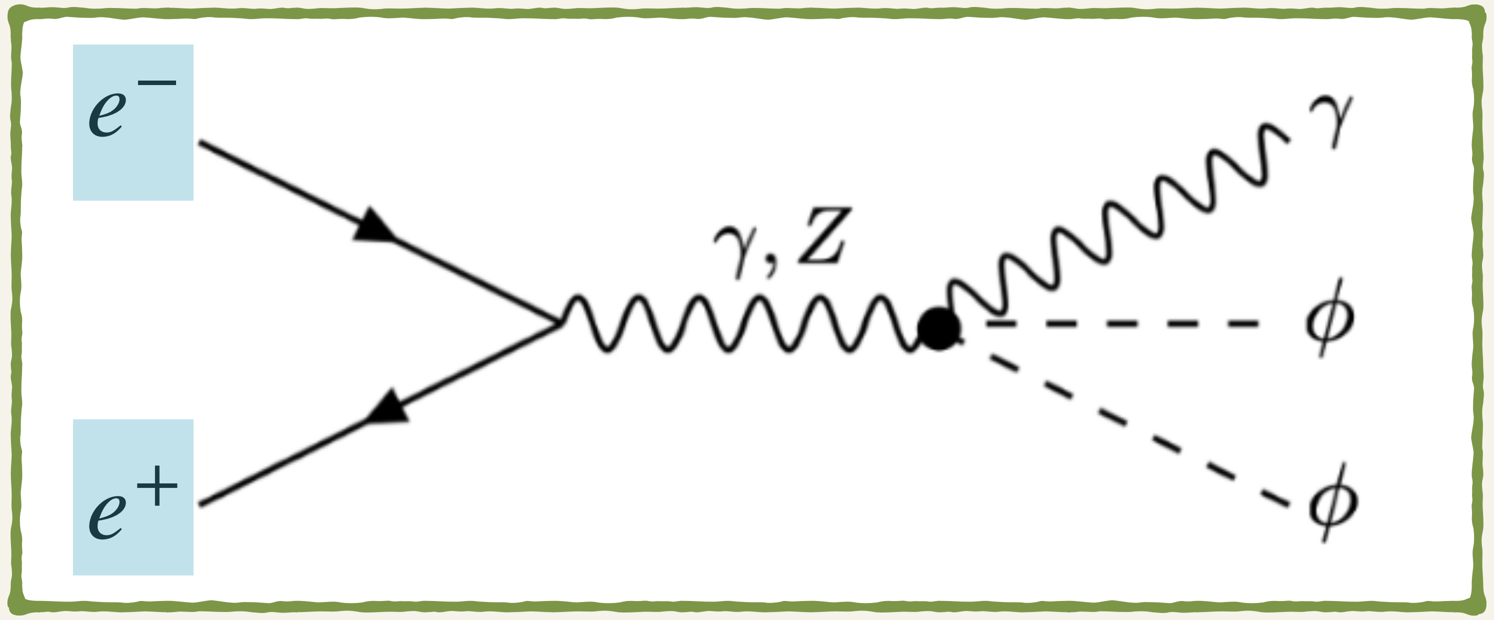
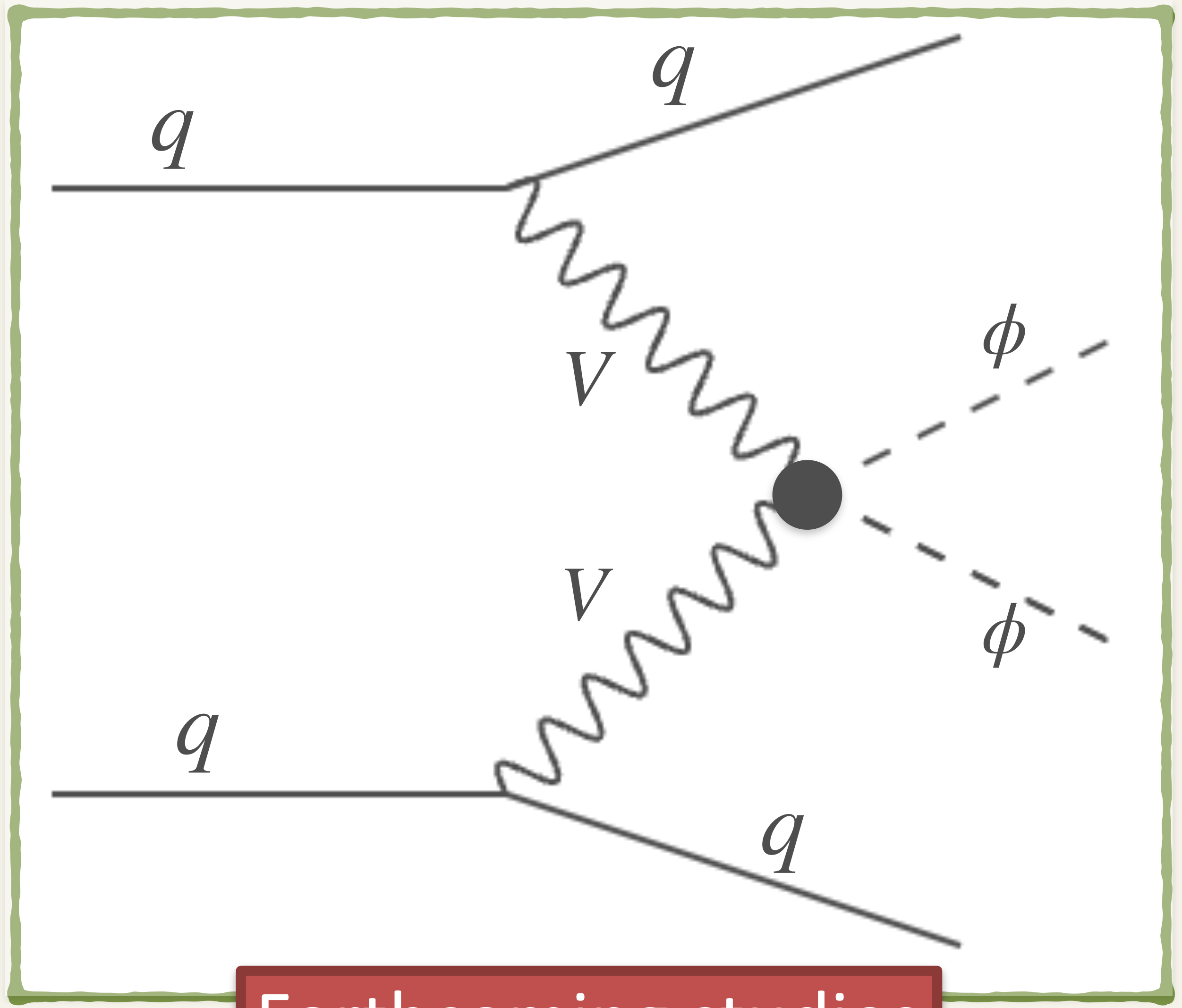
5. Xenon and Darwin — DD
6. FERMI — ID

Drell-Yan processes + Fusion TBD







Forthcoming studies

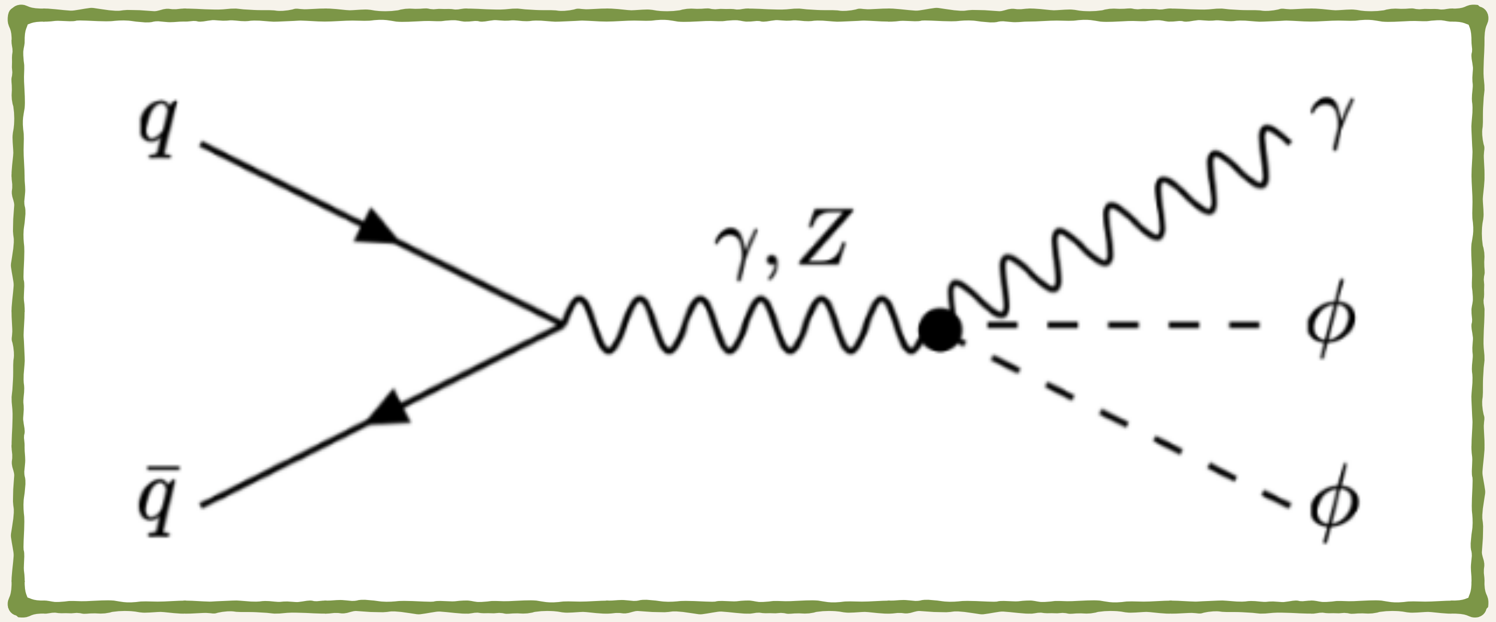
$\sqrt{s} = 13$ TeV

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

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

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

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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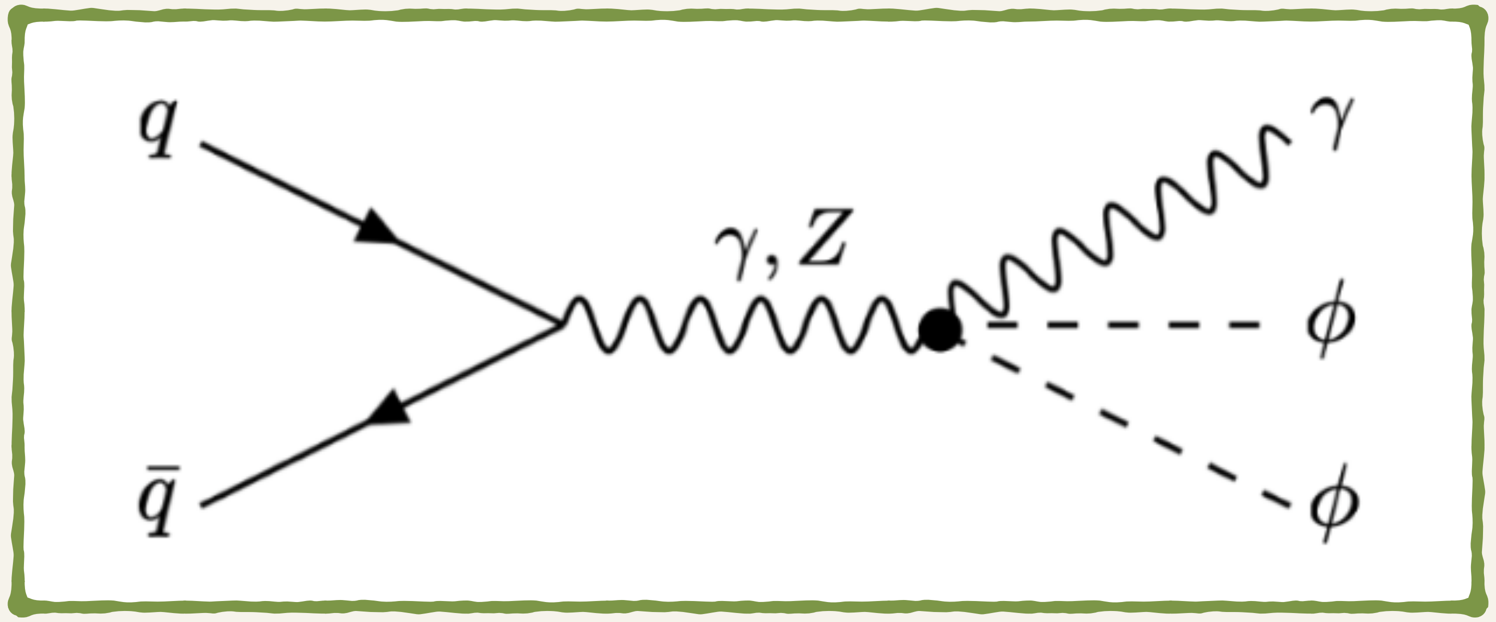

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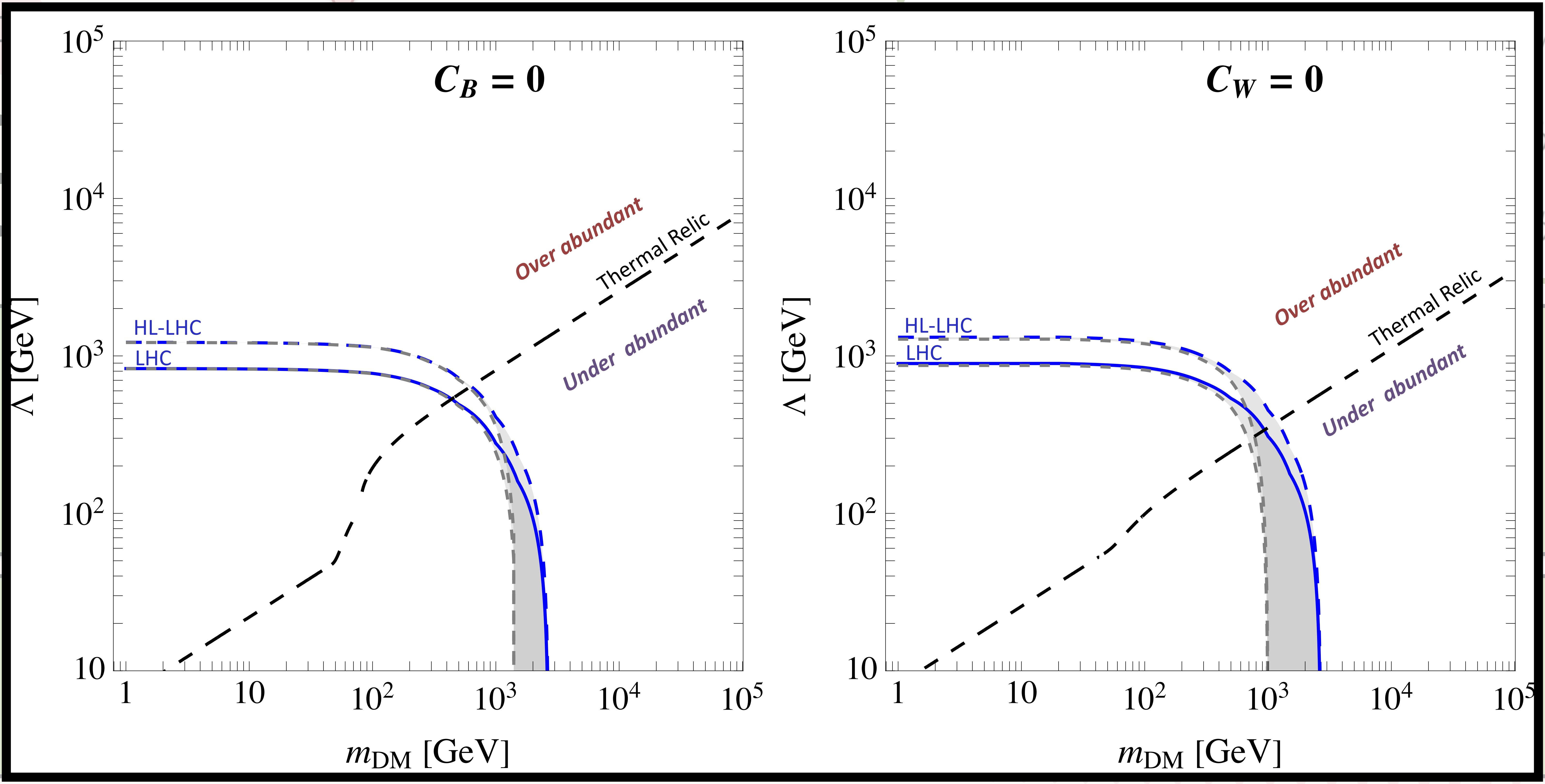
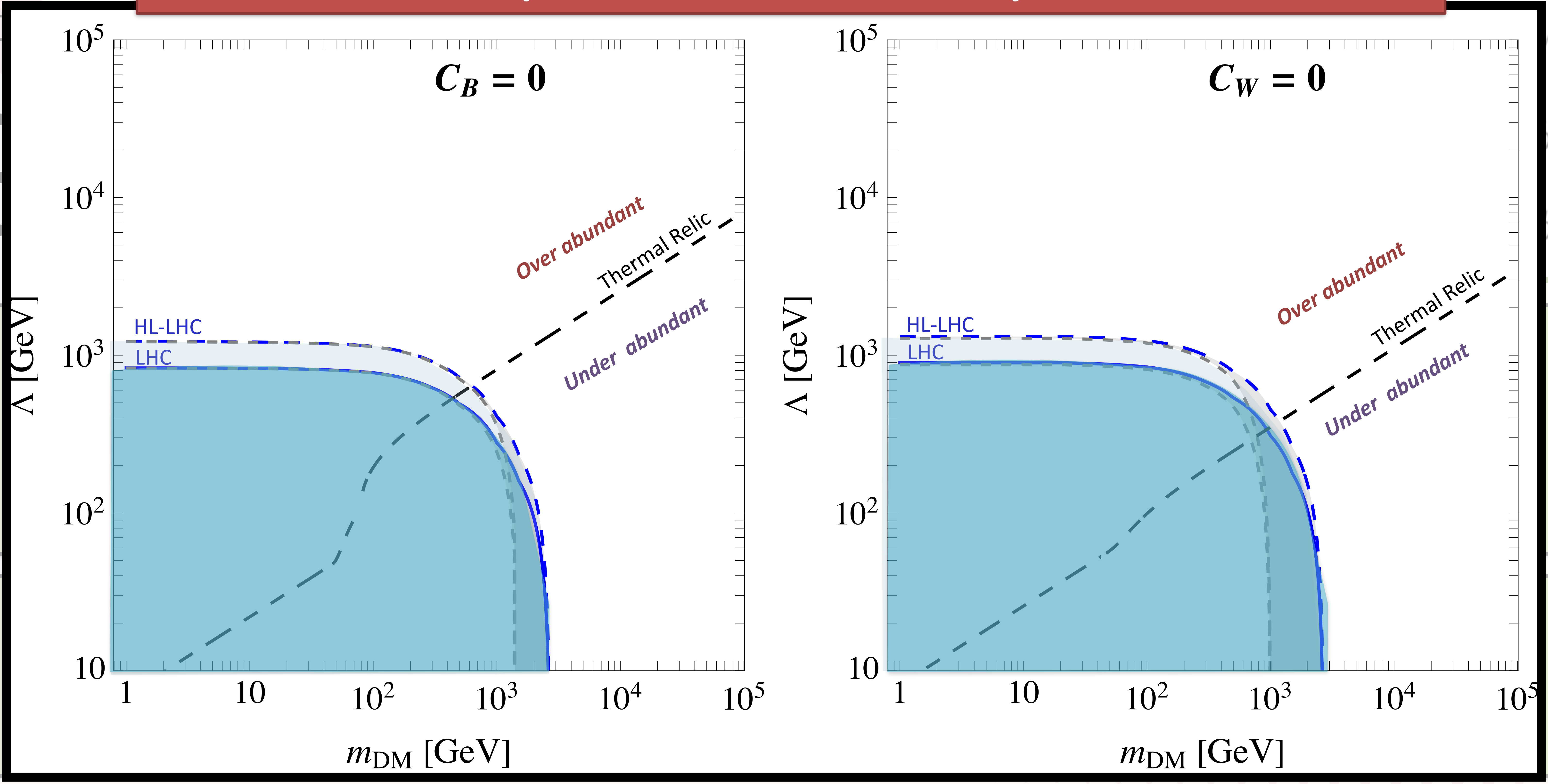


$\sqrt{s} = 13$ TeV

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



After LHC era

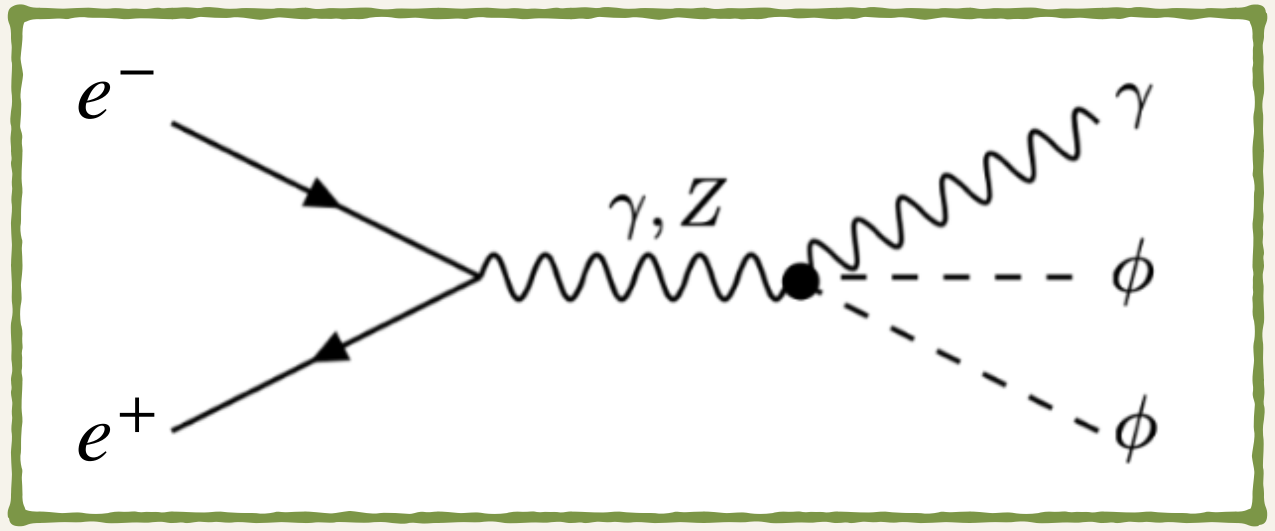
Colliders

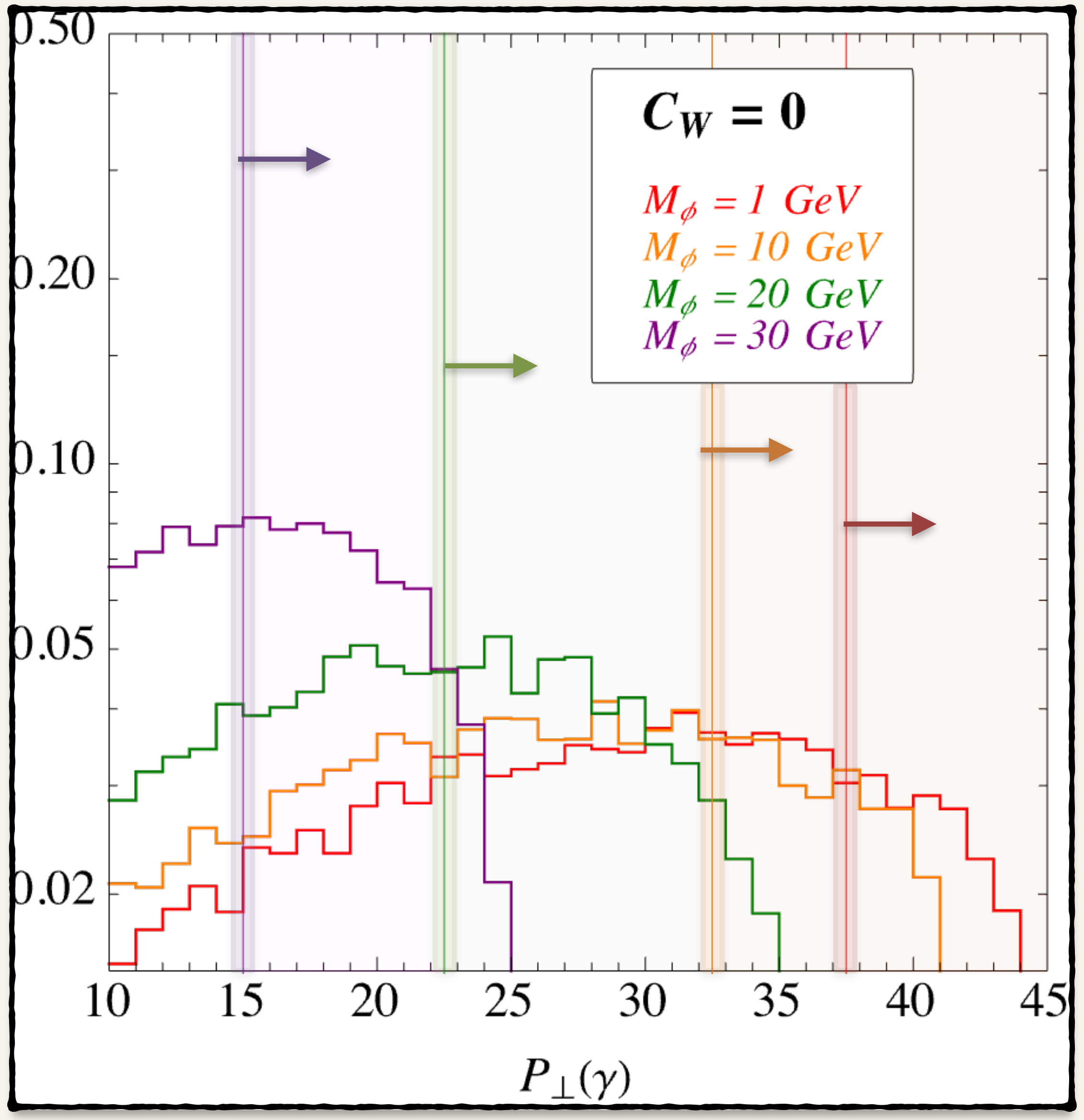
$\sqrt{s} = 91.2$ GeV
$L = 120\, ab^{-1}$

2 **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_ϕ [GeV]	$p^\gamma_{T,\text{min}}$[GeV]	Λ_{sc} [GeV]	Λ_{sc} [GeV]
1	37.5	3043	5036
10	32.5	2524	4176
20	22.5	1715	2839
30	15	910	1505





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Colliders

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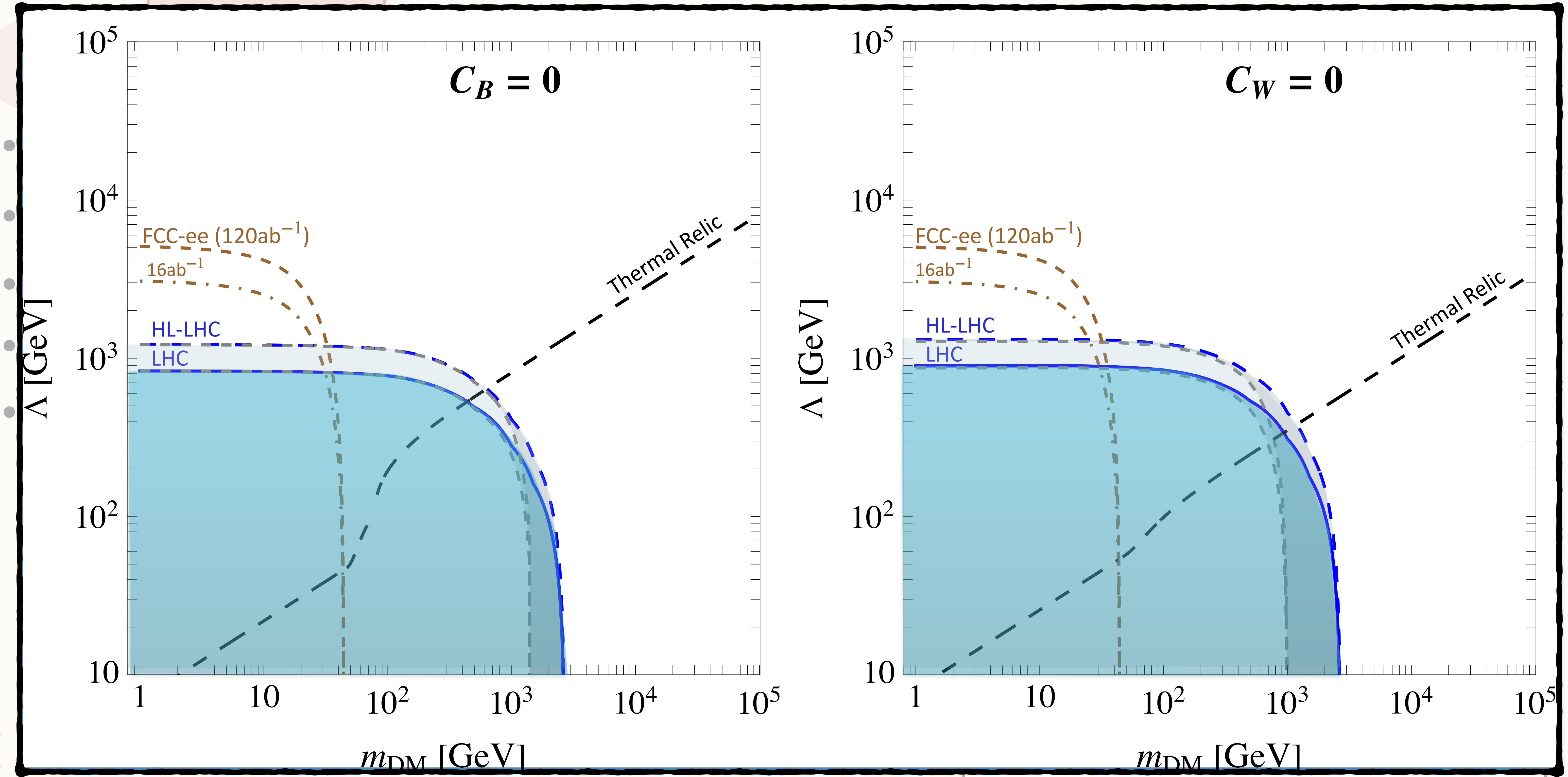
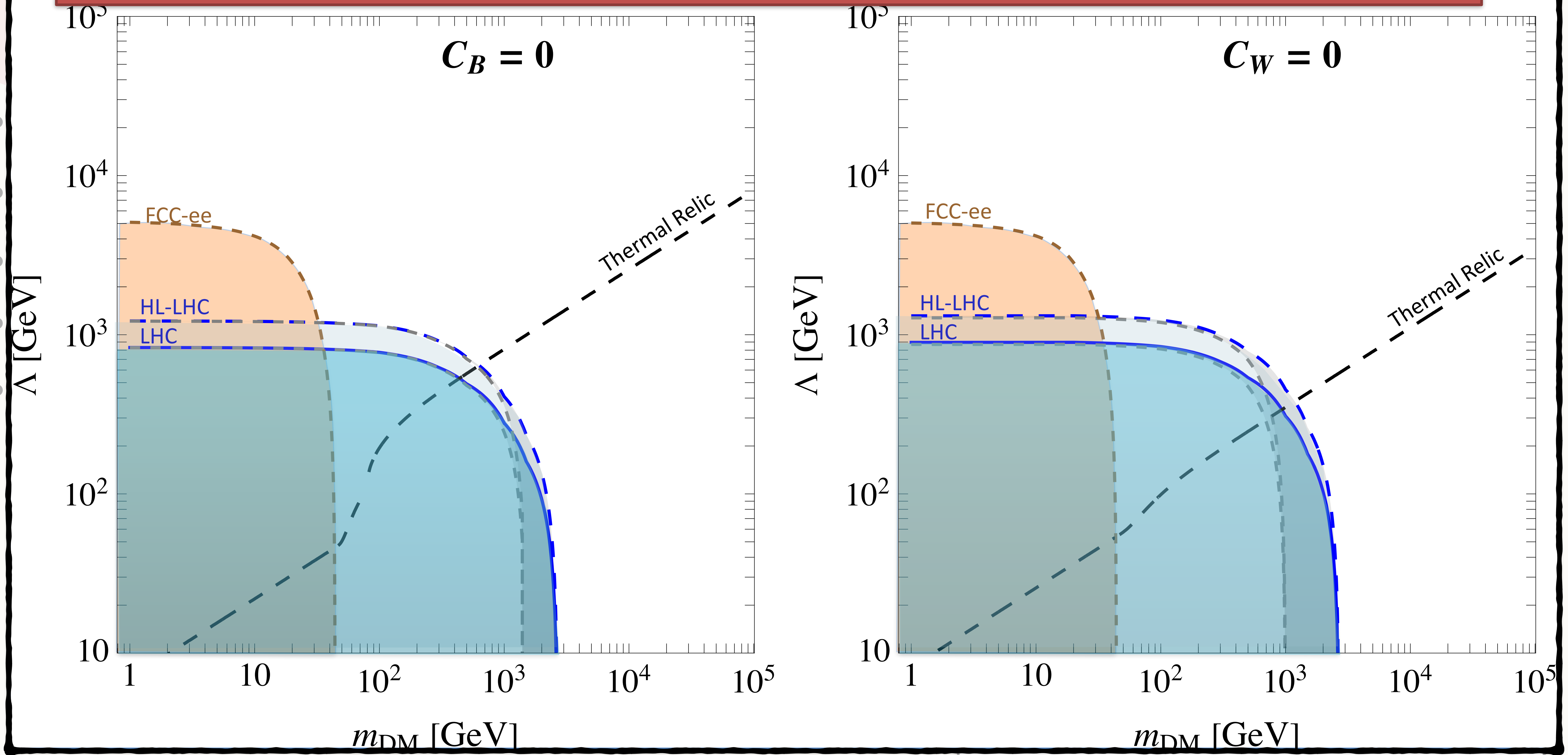


FCCee bounds is ~ 5 times more stringent than LHC

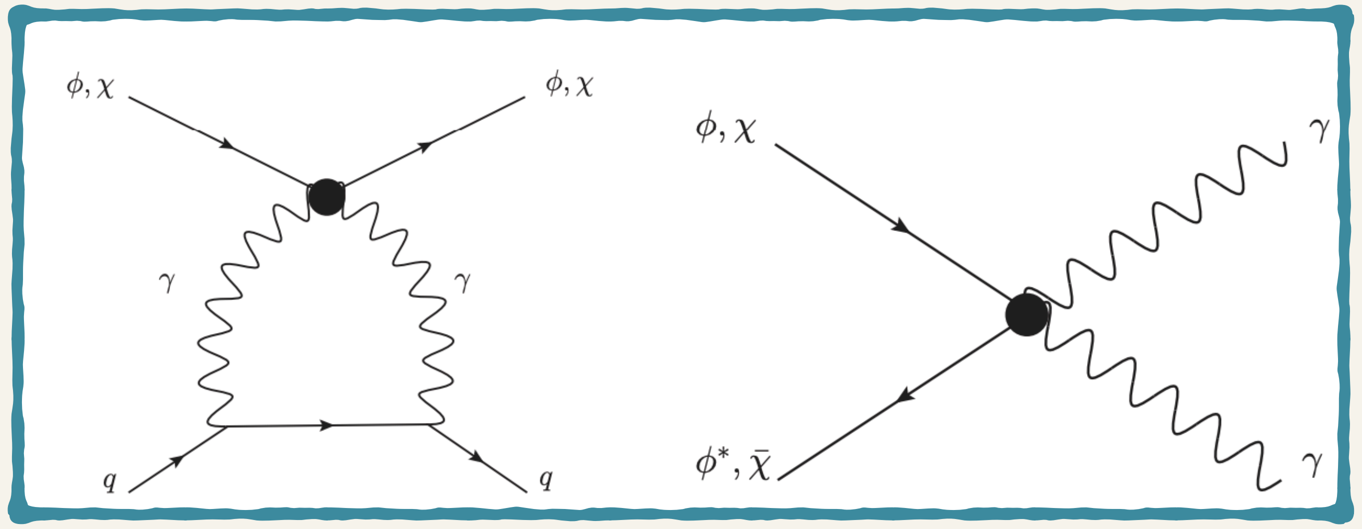


DD and ID

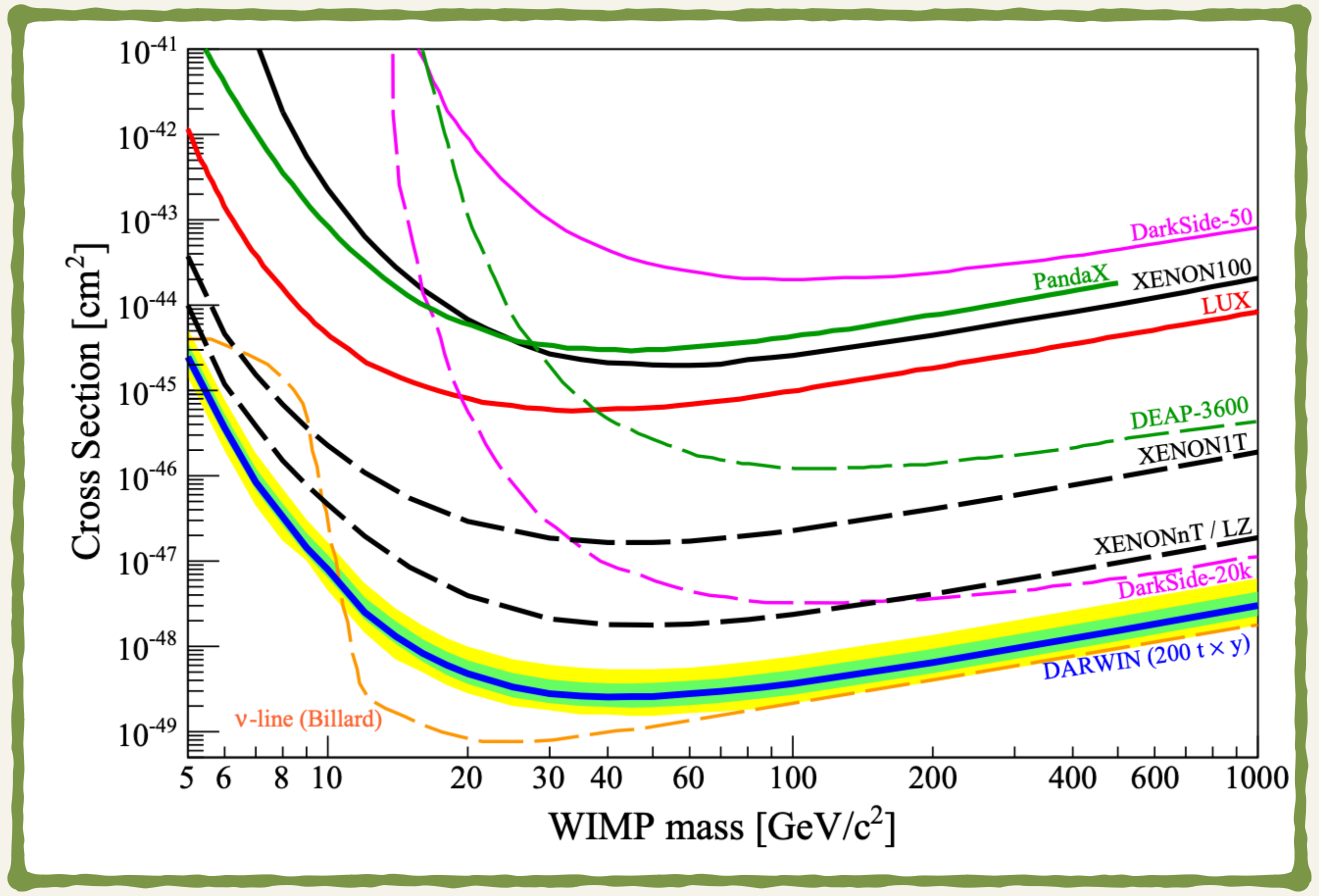
5 Xenon and Darwin

$$\frac{d\sigma^{Ray}}{dE_R} = \frac{4m_T}{m_\phi^2 v^2}\frac{c_{\gamma\gamma}}{\Lambda^4}\frac{Z^4\alpha_{em}^2}{\pi^2 b^2(A)}\mathscr{F}_{ray}^2$$

$$\frac{d\sigma^{SI}}{dE_R} = \frac{m_T}{2\mu_{\phi T}^2 v^2}\sigma_{SI}^n \mathscr{F}_h$$



PRD 131,041003 and arxiv:1606.07001



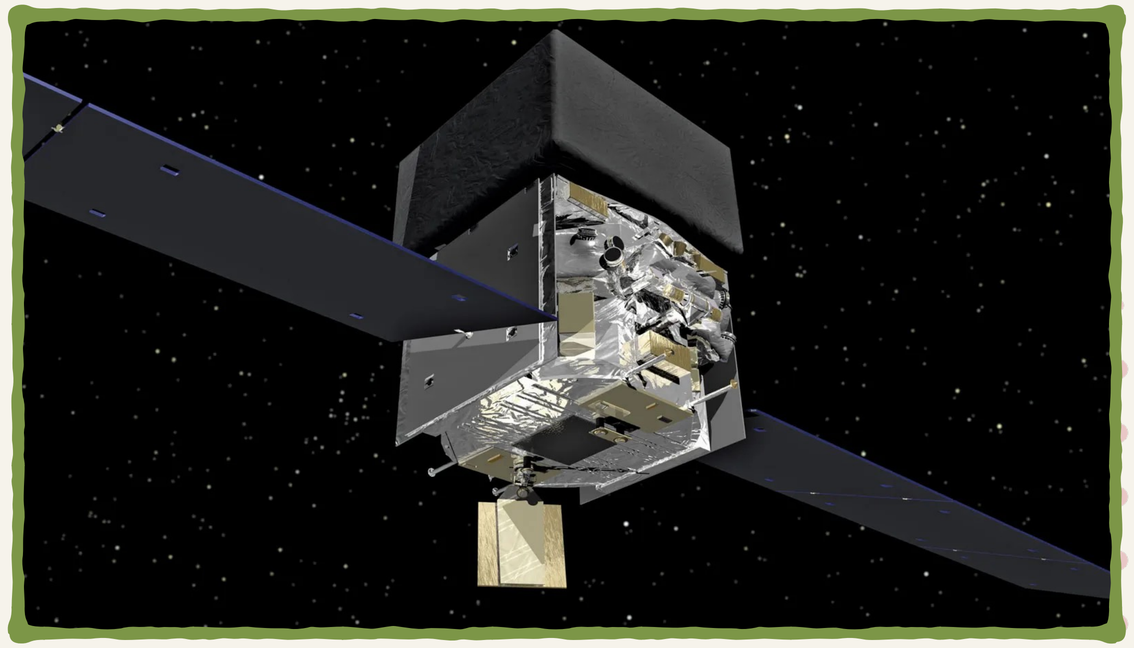
6 FERMI

- 840 weeks of data (08/2008-07/2024)

$0.7\,GeV < E_\gamma < 500\,GeV$

- ROI41: Most profile independent
- DM annihilation (*PPPC4MID Tool)*

Line($\phi\phi \to \gamma\gamma, \gamma Z$) + Continuum($ZZ, WW, \gamma Z$)



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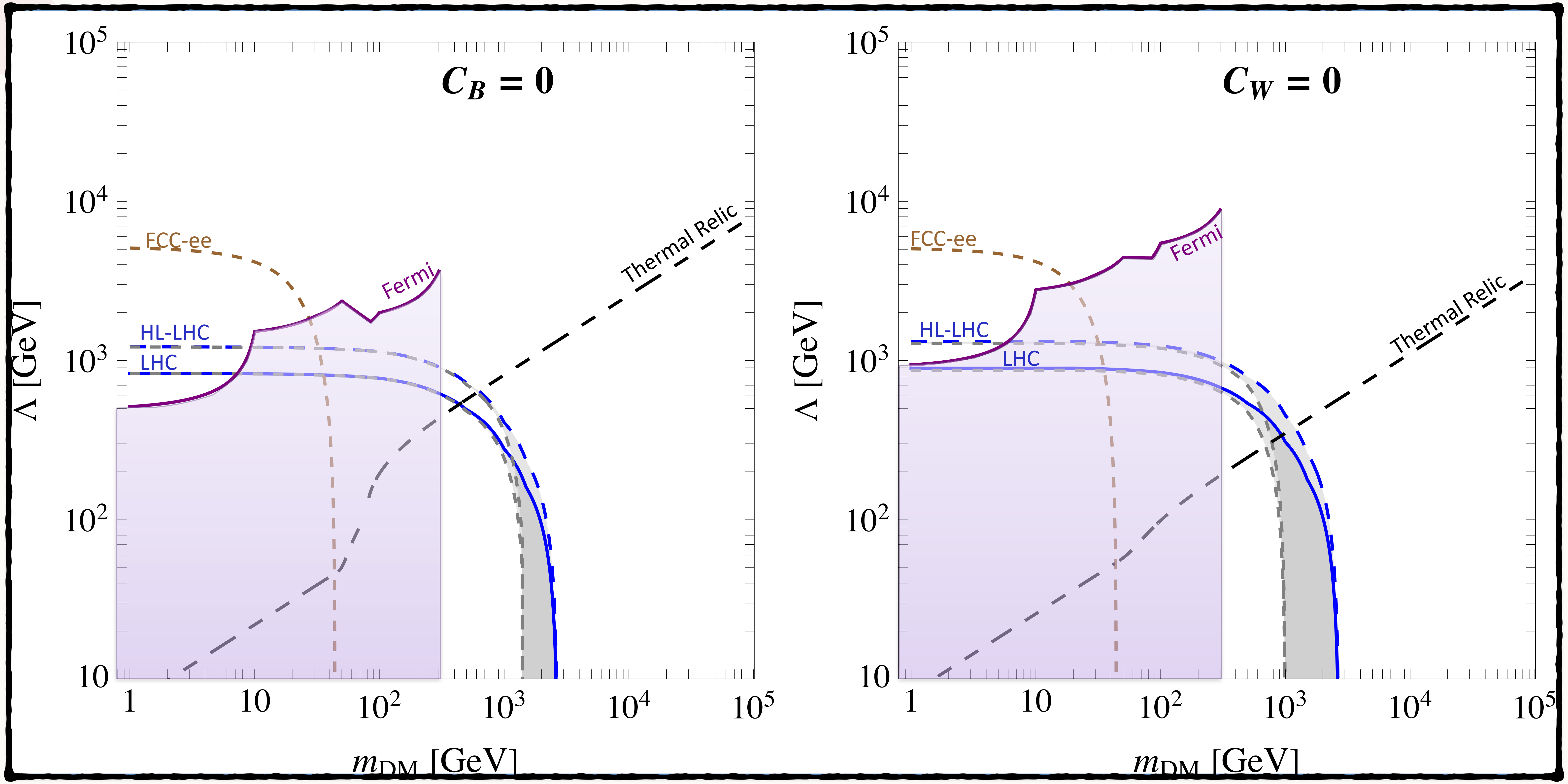

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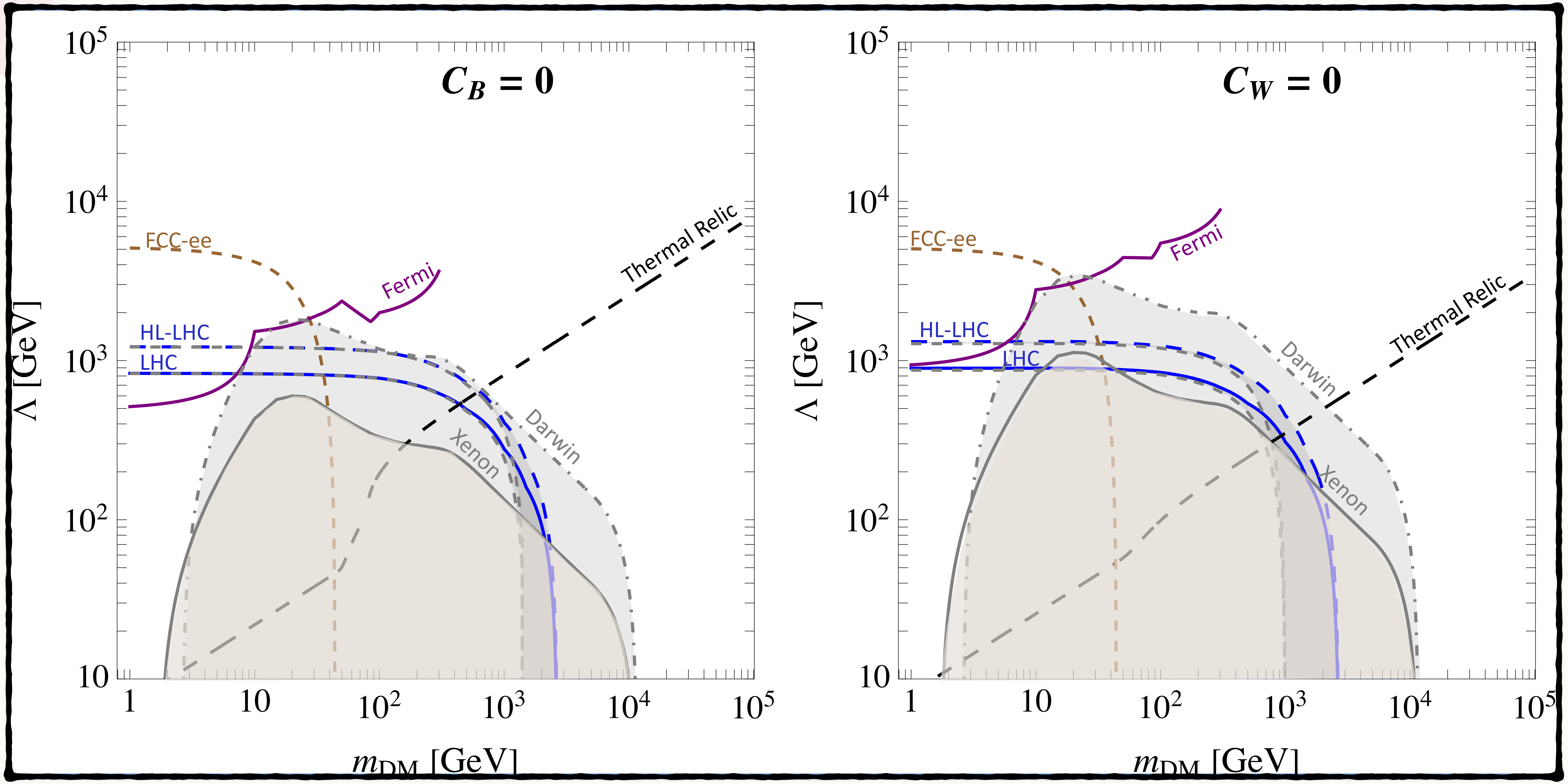
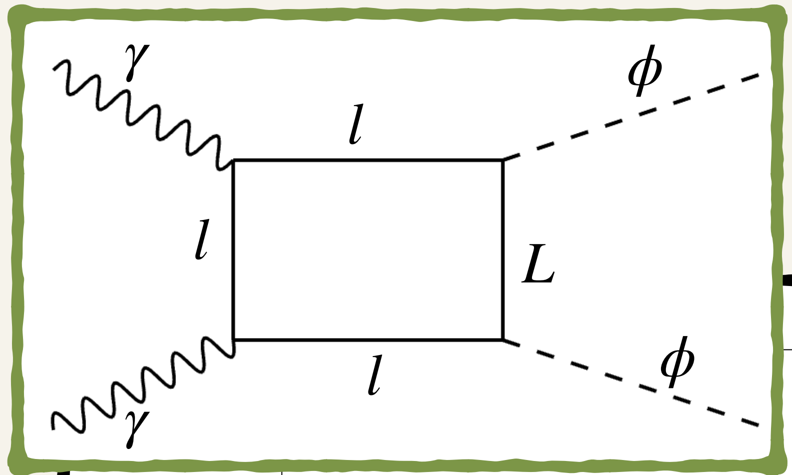
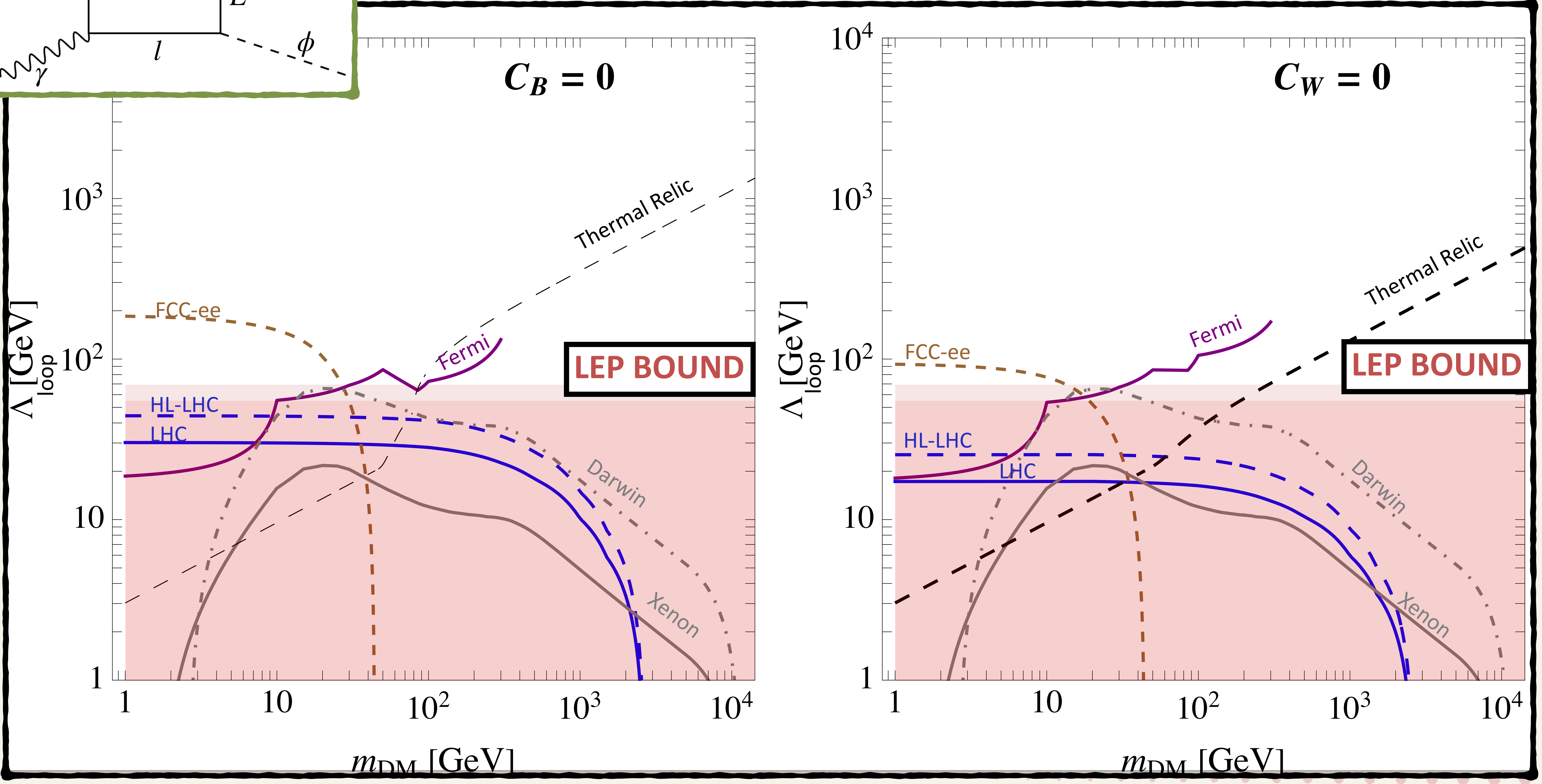

$C_B = 0$
$C_W = 0$
Λ [GeV]
m_{DM} [GeV]
FCC-ee
Fermi
HL-LHC
LHC
Thermal Relic
Darwin
Xenon
10^5
10^4
10^3
10^2
10
1
10
10^2
10^3
10^4
10^5

Loop Rescale

$$\Lambda_{B,W} = \frac{4\sqrt{2}\pi}{g_{Y,2}}\Lambda^{loop}_{B,W}$$





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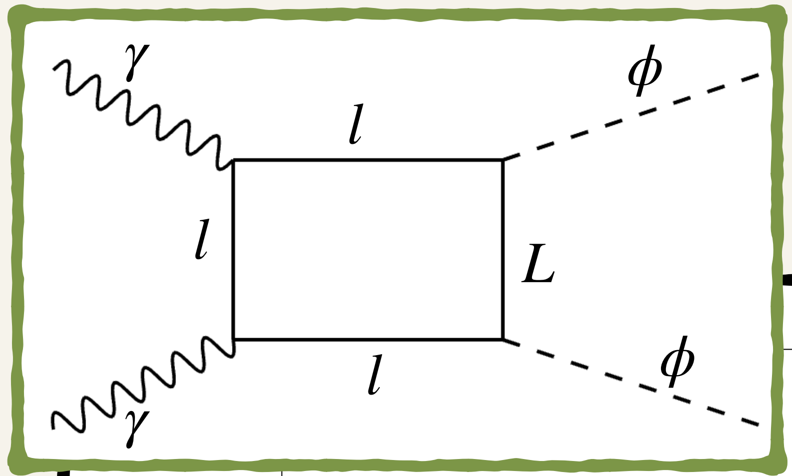
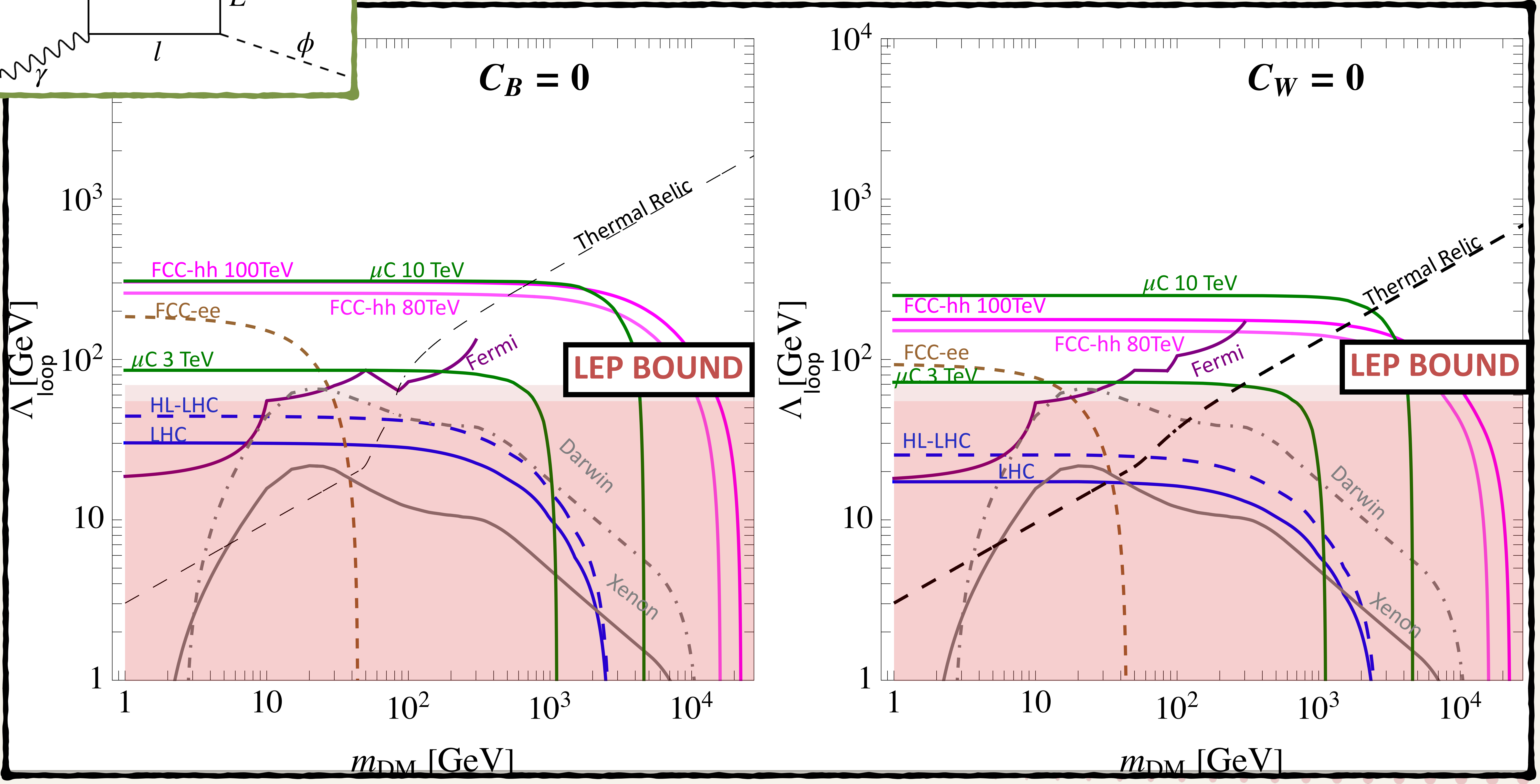




Conclusions

“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 .

Indirect and Direct Detection:

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

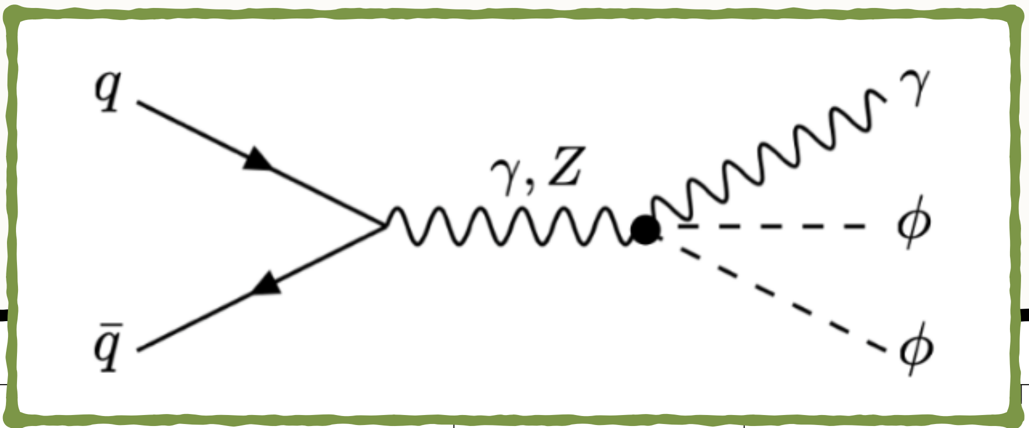
“Next” Future (FCChh):

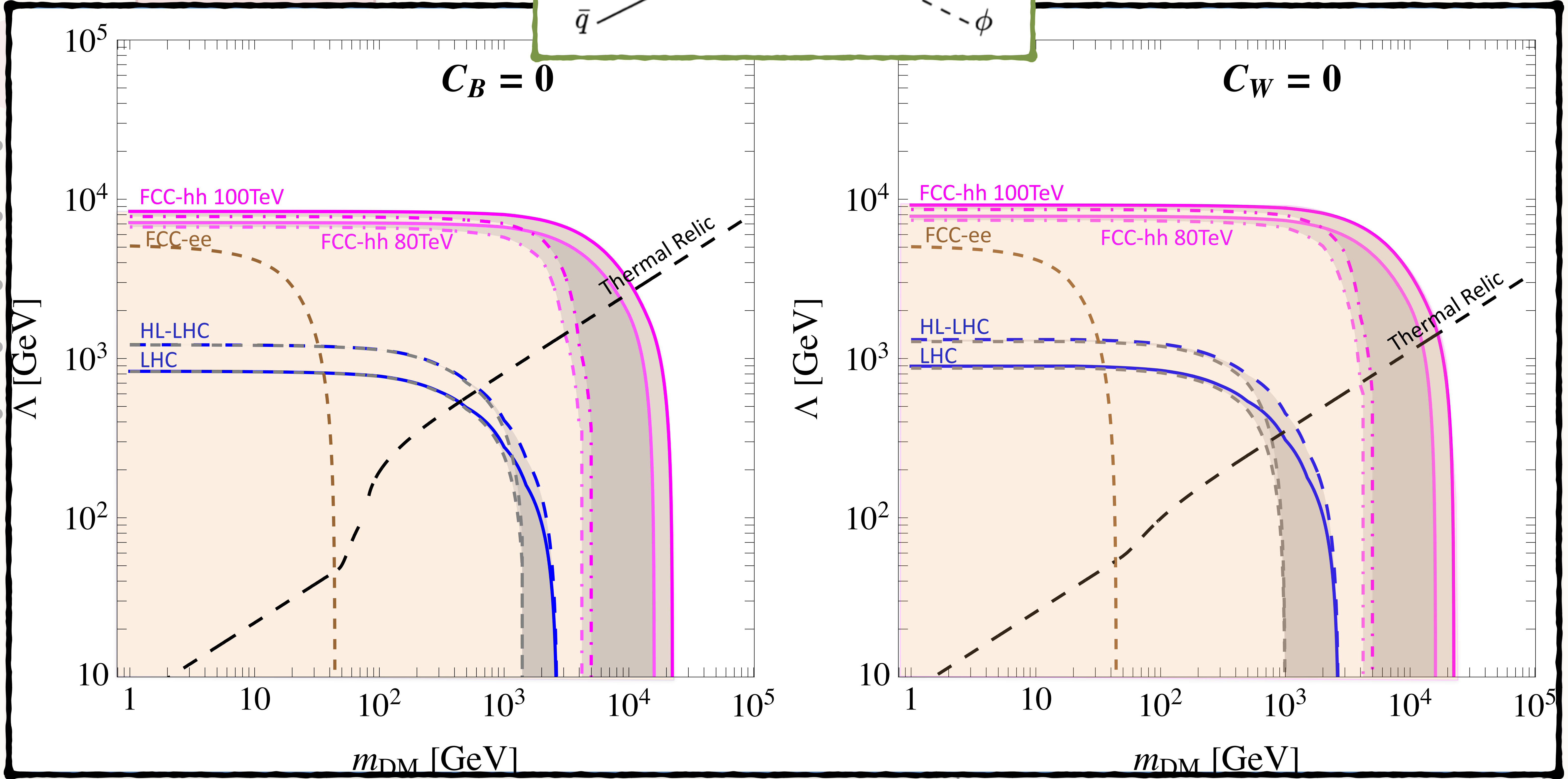
- Will be able to probe much higher energy scales;
- Could provide crucial insights into this dark matter benchmark.

THANK YOU

Backup Slides

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





10 15 20 25 30 35 40 45

$P_{\perp}(\gamma)$

$\sqrt{s} = 91.2$ GeV
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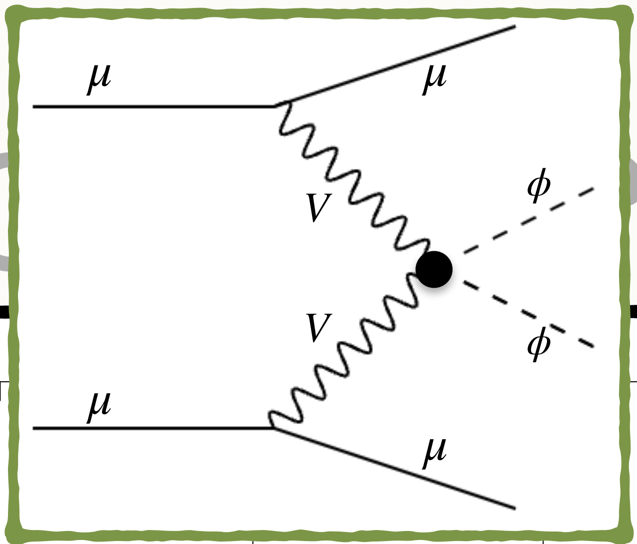
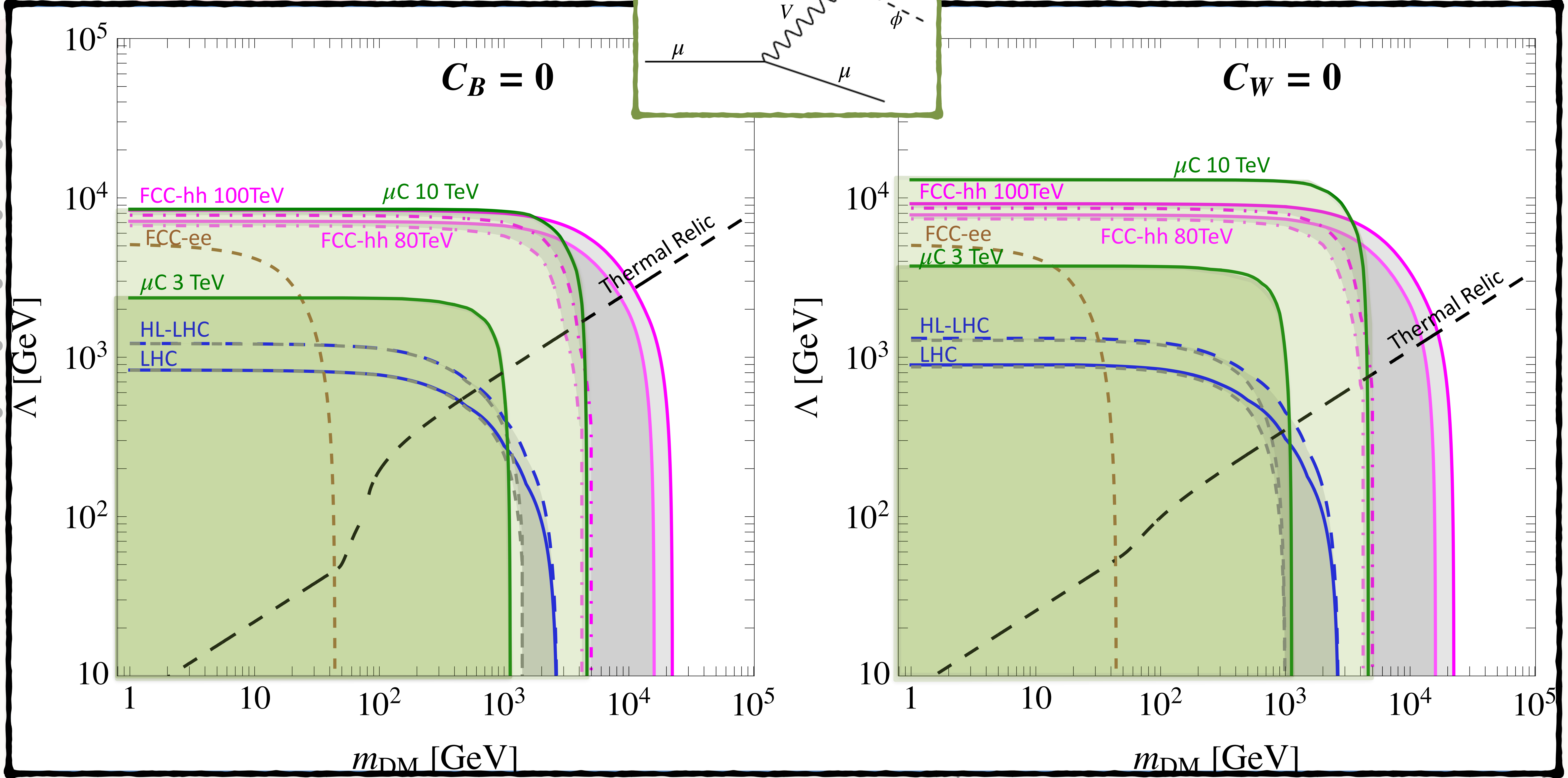
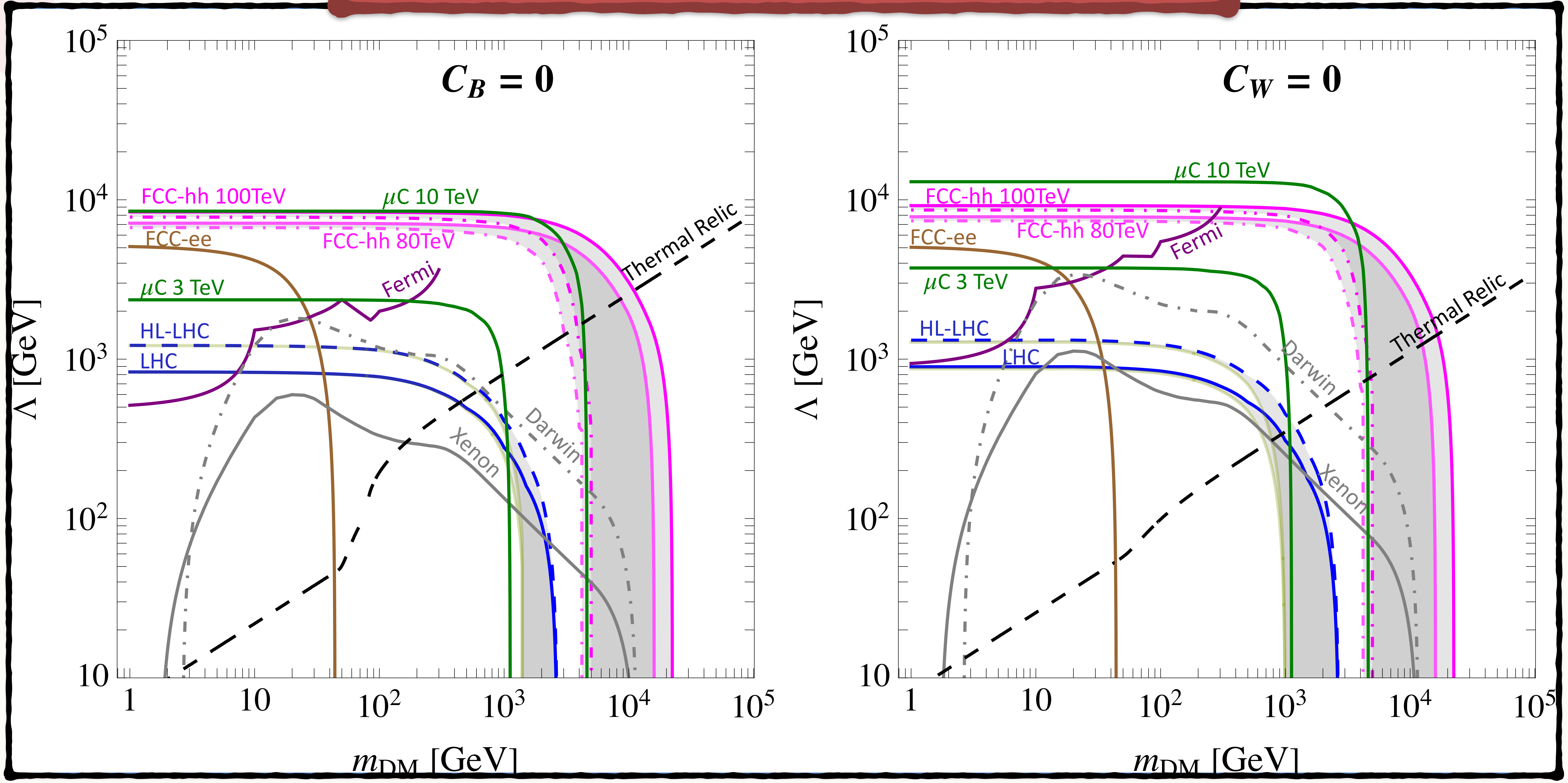




10 15 20 25 30 35 40 45
$P_\perp(\gamma)$

COMPLEX INTERPLAY BETWEEN COLLIDERS, DD AND ID



Yukawa model

$$\mathcal{L} = \lambda_l \phi \bar{L} P_R l + h.c.$$

ϕ is DM candidate EW singlet, l is RH SM lepton and L is a BSM $SU(2)_L$ singlet with $Y_L = 1$

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$$m_\phi \ll m_F \sim m_L$$

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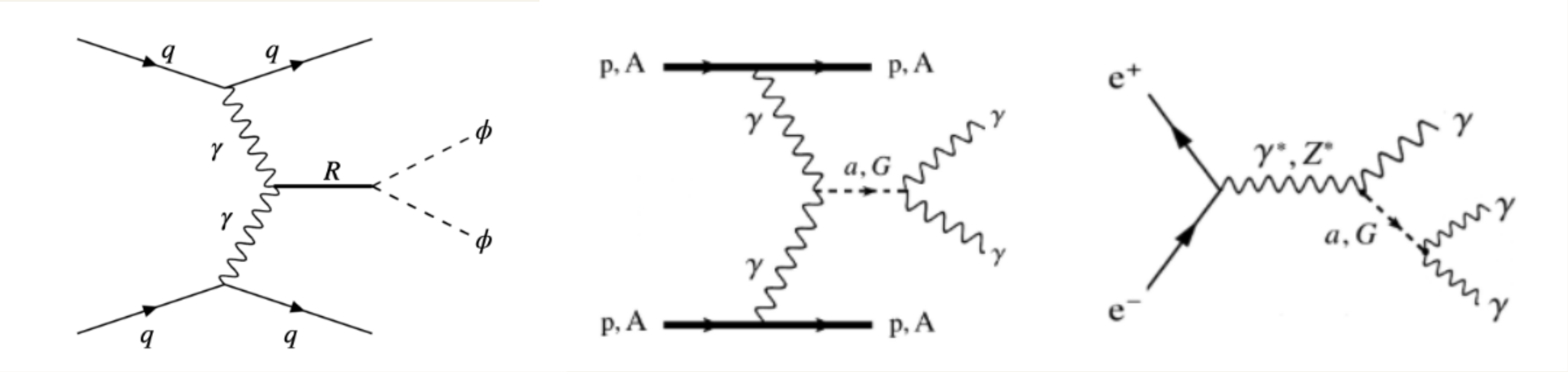
$$m_\phi \ll m_F \sim m_L$$

For this model the relevant bound is given by the *agnostic* search of an EW final state at LEP2

$$\Lambda \gtrsim 95 \text{ GeV} \frac{\sqrt{3}}{3} \simeq 54 \; GeV$$

⇒ Projections for FCCee running @ 240 GeV can push the bound up to $\Lambda \gtrsim 70$GeV

Spin-2 UV-completion



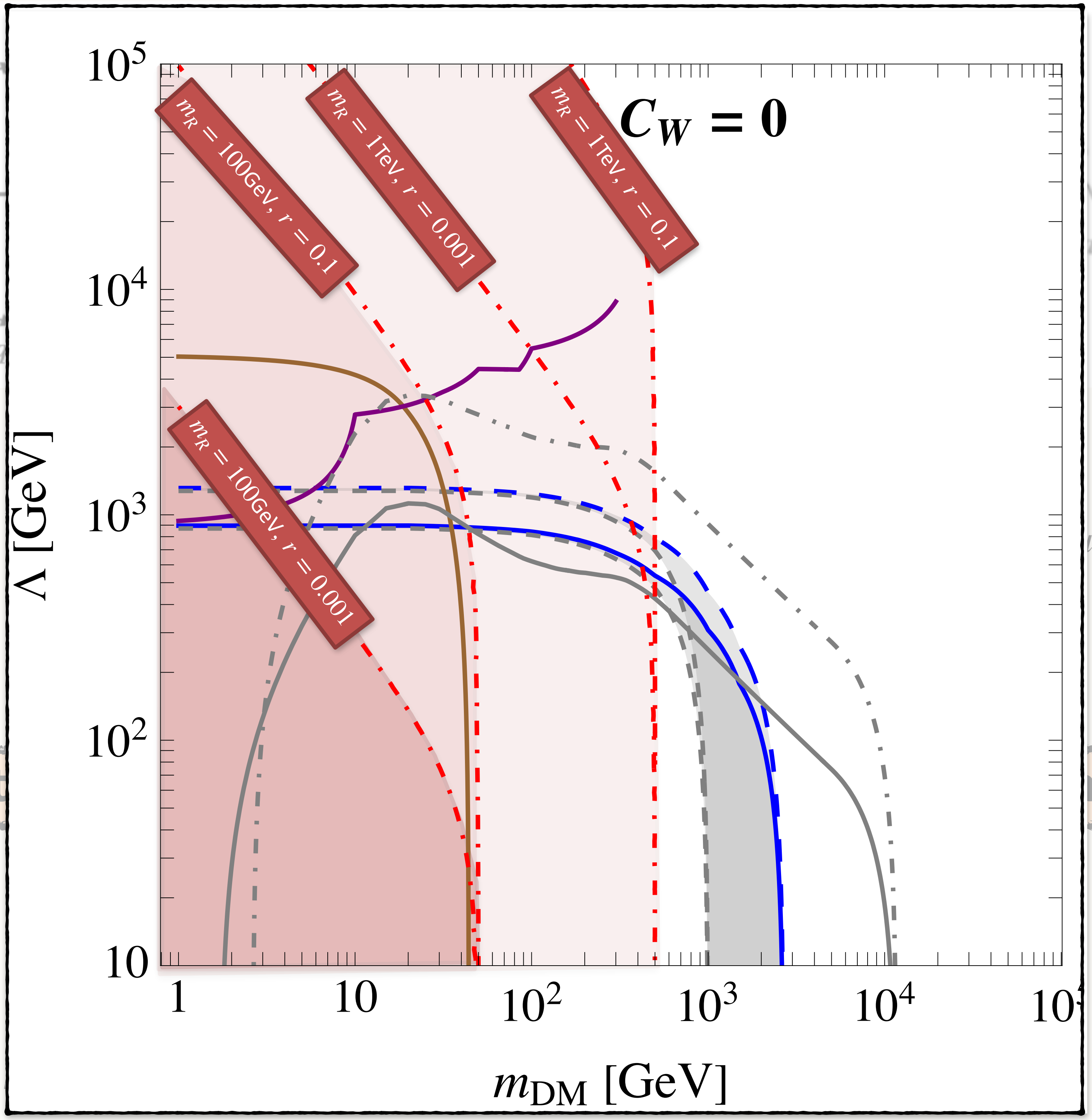
EFT MATCHING

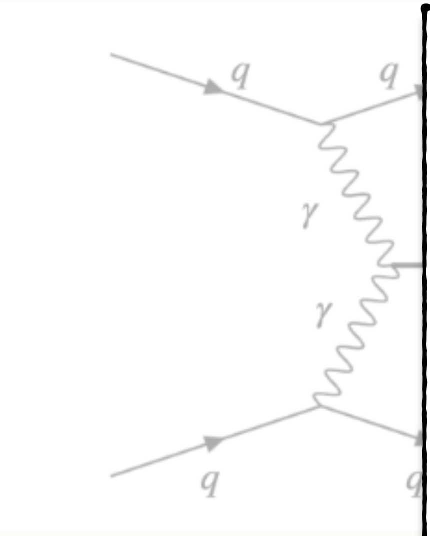
$$\mathscr{L} \supset c_{\gamma\gamma}\phi^2F^2 \quad \longrightarrow \quad \mathscr{L} \supset -\frac{1}{2\Lambda_{IR}}R_{\mu\nu}\left[c_1T^{(F)}_{\mu\nu} + c_2T^{(\phi)}_{\mu\nu}\right]$$

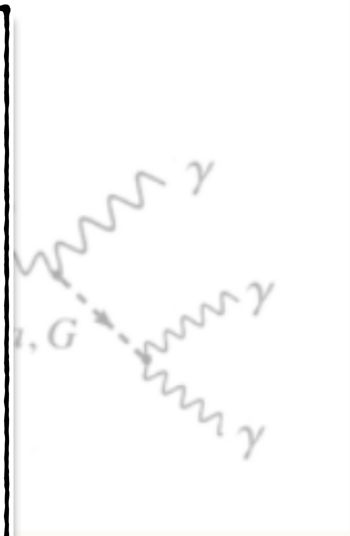
Bound for the production of the massive spin 2 particle [2] rescaling the branching ratio $R \to \gamma\gamma$

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

Spin-2 UV-completion







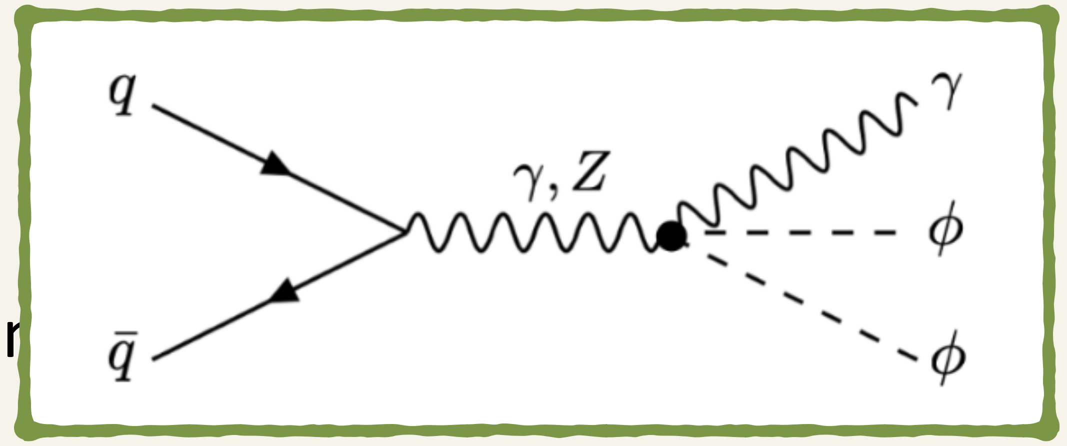
$\mathscr{L} \supset c_{\gamma\gamma}\phi$ … $_{\mu\nu}\left[c_1 T^{(F)}_{\mu\nu} + c_2 T^{(\phi)}_{\mu\nu}\right]$

Bound for the product … e branching ratio $R \to \gamma\gamma$

[2] D. d'Enterria, M. A. Tamlihat, L. Schoeffel,

Future Colliders Landscape

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 dor
- The $pp \rightarrow Z\gamma, Z \rightarrow \nu\bar{\nu}$ 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;
- Signal selection: $|\eta| < 2.37$ and we optimize on the MET requirement

Future Colliders Landscape

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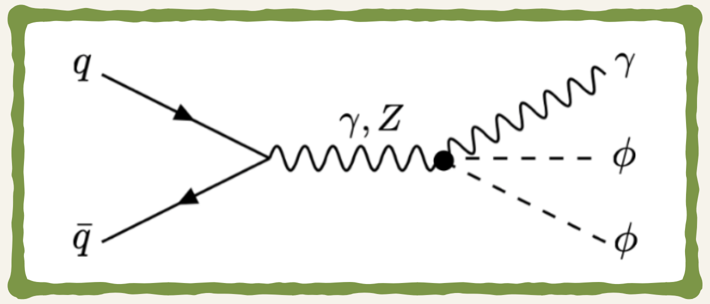
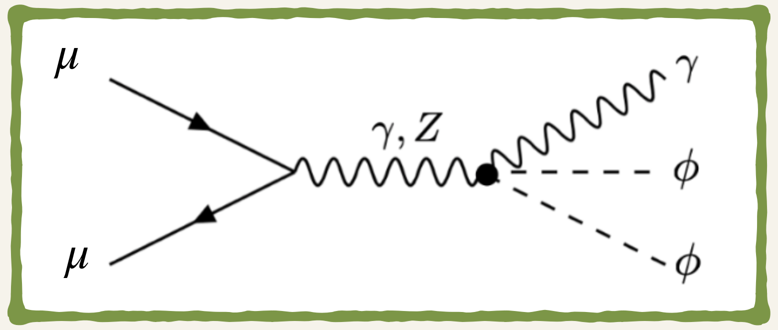
FCC-hh: DY process - @ 80/100 TeV with $L = 30\ ab^{-1}$



- Process assumed to be qualitatively the same as ATLAS mono-γ
- We recast the ATLAS analysis in order to estimate the total experimental bkg at FCChh
- Signal selection: $|\eta| < 2.37$ and we optimize on the MET requirement

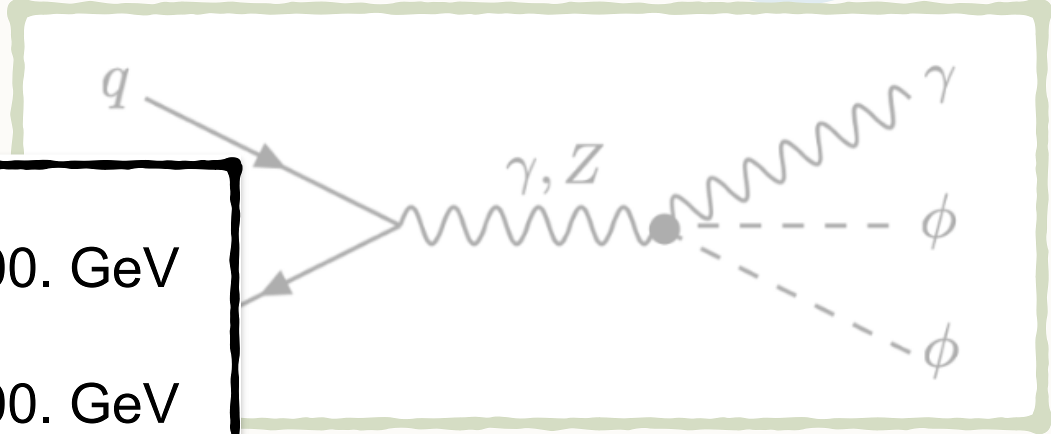
Muon Collider: DY process $\sqrt{s} = 3{,}10$ TeV with $L = 0.9{,}10\, ab^{-1}$



- Same mono-photon search of FCC-ee
- Signal selection: $|\eta^{\gamma}| < 2.5$ and $p_T^{\gamma} > 5$GeV and we optimize on the MET requirement
- Preliminary results: The EFT validity is under threat

Colliders

2 **FCC-hh**: D



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- Hard photon ⇒ dif
- The $pp \to Z\gamma, Z \to$

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- LO simulation with
  - We find that the ATLAS
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  ⇒ this is constant
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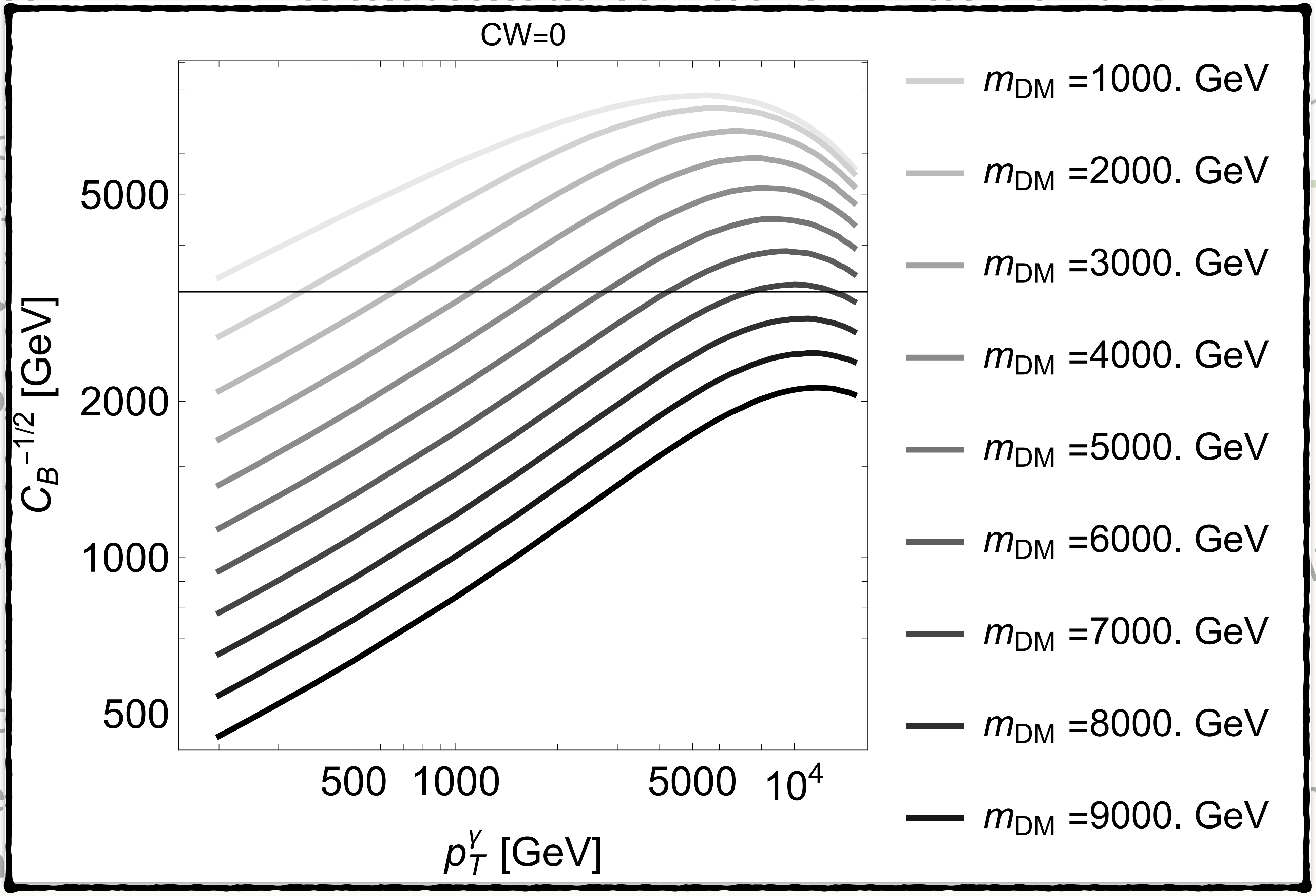

- Signal selection: $|\eta| < 2.37$ and we optimize on the MET requirement

Colliders

2 FCC-

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$\Rightarrow \sim 60\,\%$ of
- LO simulatio
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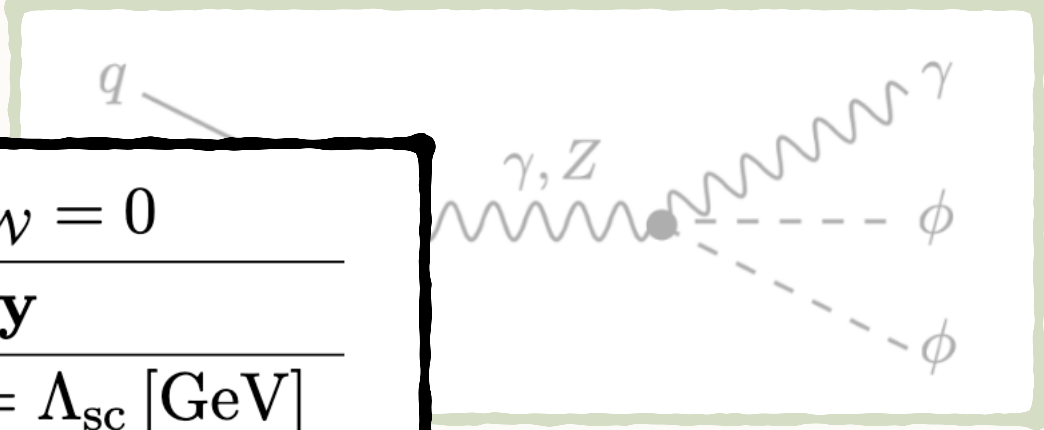


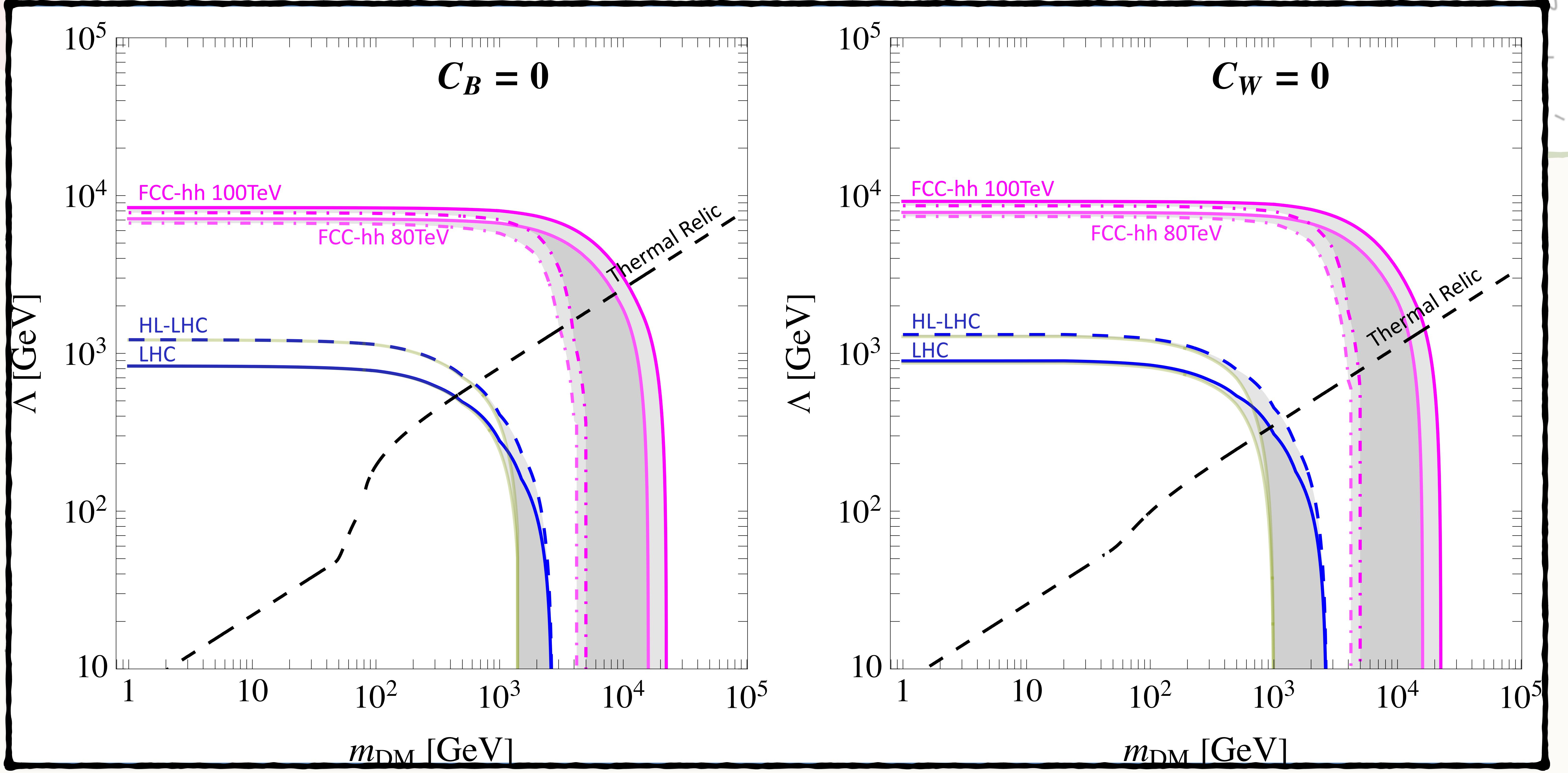
mono−γ DY at FCC-hh $\sqrt{s} = 80\,\text{TeV}$ $\mathcal{L} = 30\,\text{ab}^{-1}$ $\tilde{\mathcal{C}}_{\mathcal{W}} = 0$

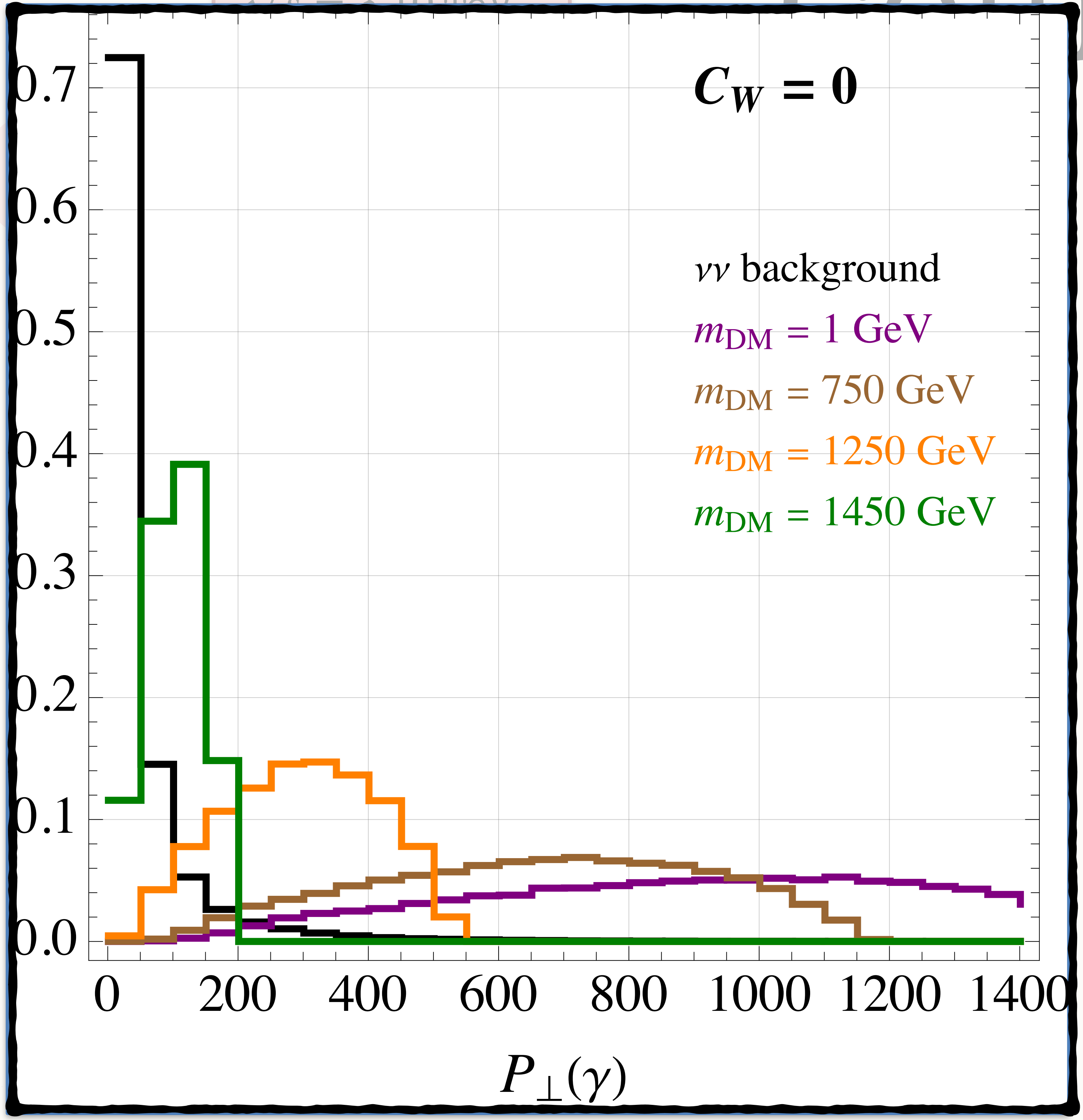
	No EFT validity		**EFT validity**	
m_ϕ [GeV]	$p_{T,\text{min}}^{\gamma}$ [GeV]	Λ_{sc} [GeV]	$p_{T,\text{min}}^{\gamma}$ [GeV]	$p_{T,\text{max}}^{\gamma} = \Lambda_{\text{sc}}$ [GeV]
100	5500	7780	4000	7300
1000	6000	7350	4000	6650
2000	6500	6640	3500	5100
5000	8500	4490	200	250

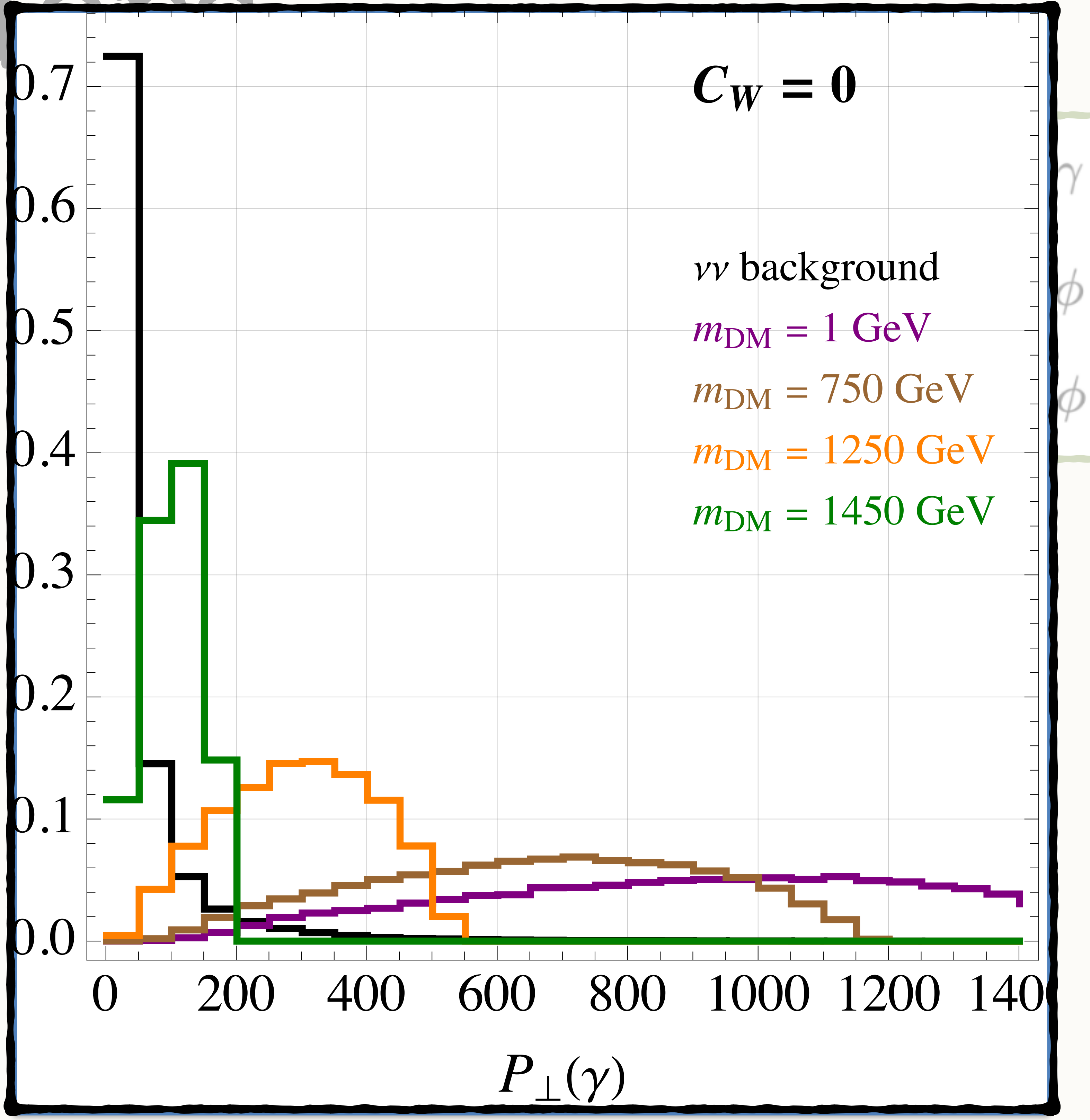
mono−γ DY at FCC-hh $\sqrt{s} = 100\,\text{TeV}$ $\mathcal{L} = 30\,\text{ab}^{-1}$ $\tilde{\mathcal{C}}_{\mathcal{W}} = 0$

	No EFT validity		**EFT validity**	
m_ϕ [GeV]	$p_{T,\text{min}}^{\gamma}$ [GeV]	Λ_{sc} [GeV]	$p_{T,\text{min}}^{\gamma}$ [GeV]	$p_{T,\text{max}}^{\gamma} = \Lambda_{\text{sc}}$ [GeV]
100	7000	9150	4500	8500
1000	7500	8800	5000	7900
2000	8000	8160	4500	6600
7000	11000	4850	300	380

Colliders


$C_B = 0$
FCC-hh 100TeV
FCC-hh 80TeV
HL-LHC
LHC
Thermal Relic
Λ [GeV]
m_{DM} [GeV]
$C_W = 0$
FCC-hh 100TeV
FCC-hh 80TeV
HL-LHC
LHC
Thermal Relic
Λ [GeV]
m_{DM} [GeV]


$C_W = 0$
$\nu\nu$ background
m_{DM} = 1 GeV
m_{DM} = 750 GeV
m_{DM} = 1250 GeV
m_{DM} = 1450 GeV
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
0 200 400 600 800 1000 1200 1400
$P_\perp(\gamma)$

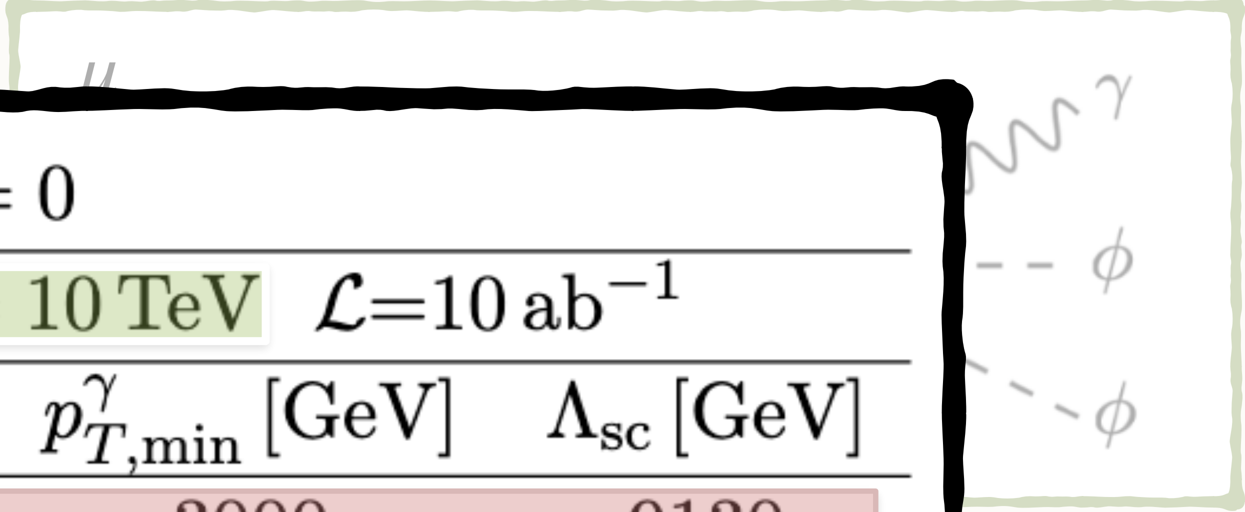

$C_W = 0$
$\nu\nu$ background
m_{DM} = 1 GeV
m_{DM} = 750 GeV
m_{DM} = 1250 GeV
m_{DM} = 1450 GeV
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
0 200 400 600 800 1000 1200 140
$P_\perp(\gamma)$

Colliders

$\sqrt{s} = 3{,}10$ TeV
$L = 0.9{,}10\, ab^{-1}$

4

- Same
- Gen.
- ν bac



mono$-\gamma$ DY at μC $\tilde{C}_{\mathcal{W}} = 0$

$\sqrt{s} = 3$ TeV $\mathcal{L}$=0.9 ab^{-1}			$\sqrt{s} = 10$ TeV $\mathcal{L}$=10 ab^{-1}		
m_ϕ [GeV]	$p^{\gamma}_{T,\min}$ [GeV]	$\Lambda_{\rm sc}$ [GeV]	m_ϕ [GeV]	$p^{\gamma}_{T,\min}$ [GeV]	$\Lambda_{\rm sc}$ [GeV]
100	900	3310	200	3000	9130
500	700	2515	1000	2700	8120
1000	400	1140	2000	2300	6225
1300	150	368	4000	900	1590

EFT APPROACH FAILS

$$\sqrt{s} > \Lambda_{sc}$$

Forthcoming studies

VBF Analysis

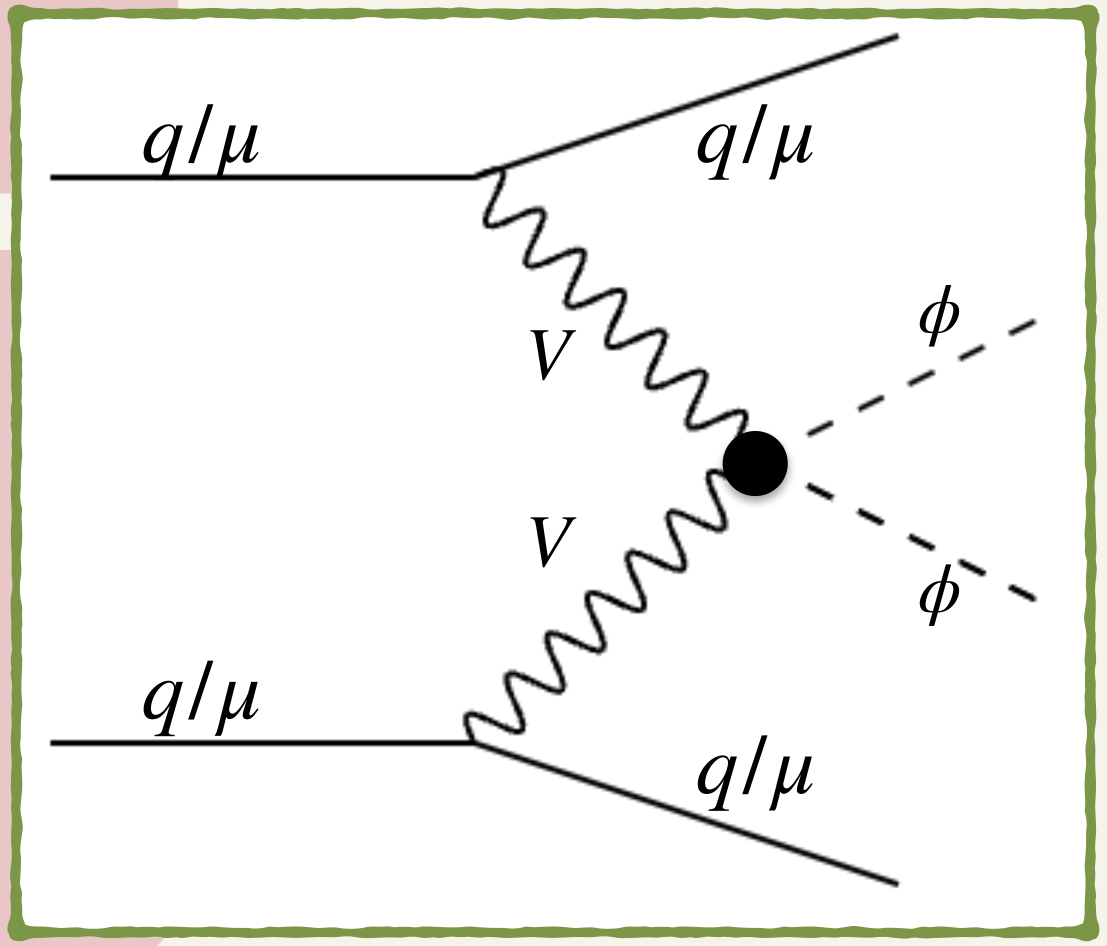
FCChh

- VBF is a relevant process ⇒ different kinematics
- We would like to perform a forward production analysis

⇒For FCC-hh No clean environment!

Muon Collider

- Forward muons: $|\eta| < 7,\ \Delta R_{\mu\pm} < 0.4,\ E_{\mu^\pm} > 500$ GeV
- We optimize over the MIM $= \sqrt{\Delta p_\mu \Delta p^\mu}$
- We have considered a $\mu\mu\nu\bar{\nu}$, but also other bkg channels are relevant, they will relax the bound by a 30% coefficient.



Colliders

$\sqrt{s} = 3{,}10\ \text{TeV}$
$L = 0.9{,}10\ ab^{-1}$

Muon Collider: VBS

- Kinematics: forward muons
- Background channels: $\mu\mu\bar{\nu}\nu,\ \mu\mu\gamma,\ \mu\mu WW, \mu\mu f\bar{f}$

- As a proxy for the momentum exchanged in the vertex we used the Missing Invariant Mass (MIM)

$$MIM = \sqrt{\Delta p_\mu \Delta p^\mu}$$

→ MIM to check the EFT validity!

Gen. level cuts:

$|\eta| < 7\ ,\ E_{\mu^\pm} > 500\text{GeV};$

$\Delta R(\mu^+\mu^-) > 0.4$, sign($\eta_{\mu^+}\eta_{\mu^-}$)<0.