Rare and exclusive few-body decays of the Higgs, Z, and W bosons, and the top quark

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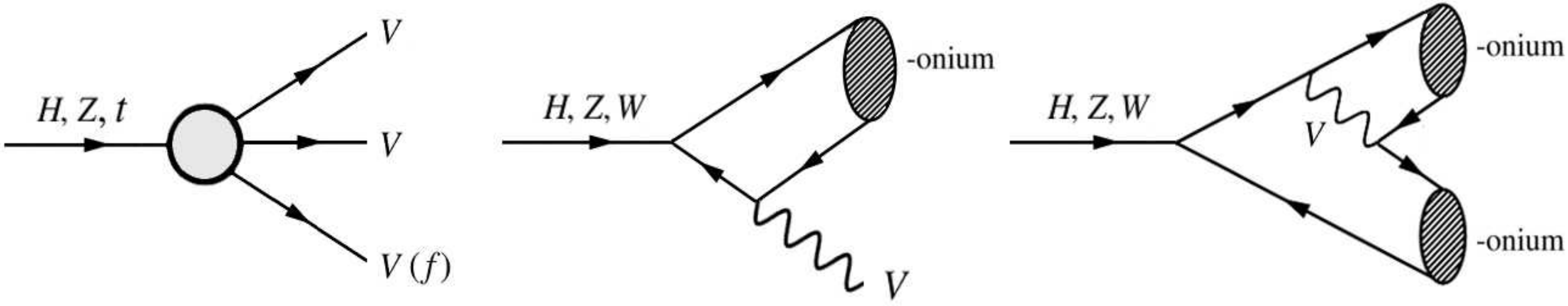
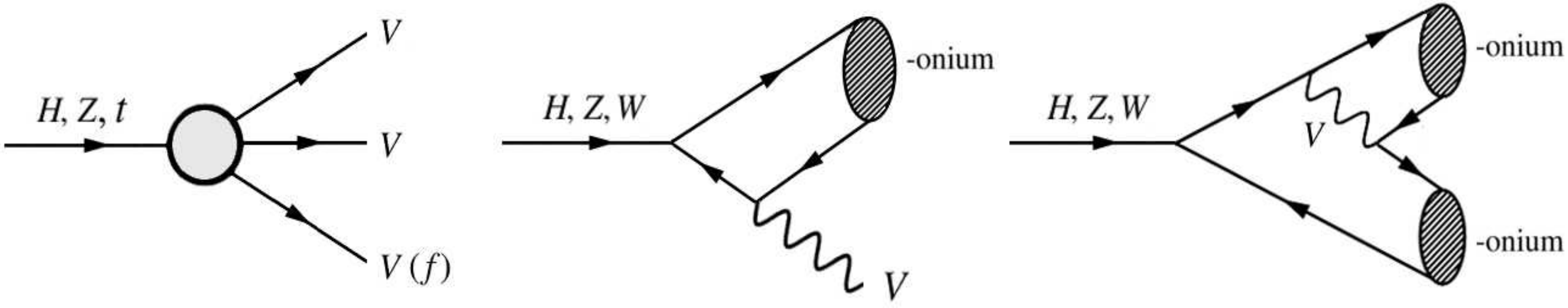


Introduction

- The work:
  - Comprehensive collection of all 2- & 3-body rare/exclusive decays branching fractions (BR<10^{-5}) of the 4 heaviest particles: ~200 unobserved channels (~ 50 experimental upper limits today).
  - Identify missing channels and estimate their rates. Explicitly compute a few new decays (Z,H → leptonium+gamma, Higgs FCNC exclusive decays,...). Update some older theoretical BR results.
  - Make projections for HL-LHC/FCC-ee searches: Help guide and prioritize future experimental searches.
- Structure of the talk - Physics motivations:
  - Explain the structure of the results.

1. Probe lighter quark Yukawa couplings: Hcc, Hqq, via exclusive final states with mesons.
2. Precision tests of very suppressed processes in the SM : FCNC in Z, H, and top decays.
3. Stringent tests of the QCD factorization formalism, constraint poorly known nonperturbative hadronic bound-state parameters
4. Effect on BSM physics searches at the FCCee.



Explanation - Theoretical predictions

- For all rare decays collected, we indicate the
  - Branching fraction
  - Theoretical framework :

Example :

$H \to \gamma$ +	X	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC
	ρ^0	$(1.68 \pm 0.18) \times 10^{-5}$	SCET+LCDA [13]	$< 8.8\times10^{-4}$ [74]	$\lesssim 6.8 \times 10^{-5}$
	ω	$(1.48 \pm 0.17) \times 10^{-6}$	SCET+LCDA [13]	$< 1.5\times10^{-4}$ [76]	$\lesssim 2.2 \times 10^{-5}$
	ϕ	$(2.31 \pm 0.26) \times 10^{-6}$	SCET+LCDA [13]	$< 4.8\times10^{-4}$ [74]	$\lesssim 3.7 \times 10^{-5}$
	J/ψ	$(2.95 \pm 0.38) \times 10^{-6}$	SCET+LCDA [13]	$< 3.5\times10^{-4}$ [77]	$\lesssim 5.5 \times 10^{-5}$ [54]
		$(3.01 \pm 0.15) \times 10^{-6}$	NRQCD (NLL)+LDME [78]		
		$\left(3.0^{+0.2}_{-0.1}\right) \times 10^{-6}$	NRQCD+LCDA [79]		

- For rare elementary decays: We indicate the perturbative level, LO/NLO
- Exclusive hadronic channels, we indicate type of QCD factorization : cross-section = perturbative ⊗ non-perturbative. Models of QCD factorization:
  - Light cone (LC): nonperturbative objects described by LCDAs. Applied for light-quark mesons (uds)
  - Soft-Collinear Effective Theory (SCET): Resums multiple scales. Nonperturbative LCDAs. Mostly used for light & energetic mesons.
  - Heavy-Quark Effective Theory (HQET): Nonperturbative LCDA describes mixed formation of light-heavy-quark mesons
  - Non-Relativistic QCD (NRQCD): Nonperturbative objects described by LDMEs. For decays to charmonium & bottomonium

- Leptonium channels: similar to hadronic ones, with much smaller BR. Never computed before. We have applied similar methods and derived the BR predictions.
- We have updated a few old results & computed a few new ones using MadGraph5_aMC@NLO (virtual QCD & EW)
- Fill in a few missing exclusive channels using the existing theoretical expressions

Explanation - Experimental limits: Present & projections

- For all rare decays collected, we:
  - Indicate all current limits (LEP, Tevatron, LHC), including most recent ones (not yet on PDG).
  - Provide extrapolation of limits for the HL-LHC either from
    - Existing dedicated CMS/ATLAS studies.
    - Our statistical projection from the current limits
      - For LHC limits: scale the 13-TeV bounds down by $\sqrt{2 \times 3\ \mathrm{ab}^{-1}/\mathcal{L}_{\mathrm{int}}(13\,\mathrm{TeV})}$ ~ Improvement by ~6.5 factor
      - For CDF limits, scale bounds down by $\sqrt{N_{\mathrm{X}}(\mathrm{HL\text{-}LHC})/N_{\mathrm{X}}(\mathrm{Tevatron})}$ ~ Improvement (W,Z) by ~70 factor

Example:

$\mathrm{H} \to \gamma\ +$	X	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
	ρ^0	$(1.68 \pm 0.18)\ \times 10^{-5}$	SCET+LCDA [13]	$< 8.8\times10^{-4}$ [74]	$\lesssim 6.8 \times 10^{-5}$	✓	✓
	ω	$(1.48 \pm 0.17)\ \times 10^{-6}$	SCET+LCDA [13]	$< 1.5\times10^{-4}$ [76]	$\lesssim 2.2 \times 10^{-5}$	✓	✓
	ϕ	$(2.31 \pm 0.26)\ \times 10^{-6}$	SCET+LCDA [13]	$< 4.8\times10^{-4}$ [74]	$\lesssim 3.7 \times 10^{-5}$	✓	✓
	J/ψ	$(2.95 \pm 0.38)\ \times 10^{-6}$	SCET+LCDA [13]	$< 3.5\times10^{-4}$ [77]	$\lesssim 5.5 \times 10^{-5}$ [54]	✓	✓
		$(3.01 \pm 0.15)\ \times 10^{-6}$	NRQCD (NLL)+LDME [78]				
		$\left(3.0^{+0.2}_{-0.1}\right)\ \times 10^{-6}$	NRQCD+LCDA [79]				

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      - For CDF limits, scale bounds down by $\sqrt{N_{\mathrm{X}}(\mathrm{HL\text{-}LHC})/N_{\mathrm{X}}(\mathrm{Tevatron})}$ ~ Improvement (W,Z) by ~70 factor

Collider	$W^\pm$ bosons		Z bosons		H bosons		top quarks	
	σ(W)	N(W)	σ(Z)	N(Z)	σ(H)	N(H)	$\sigma(t\bar{t})$	N(top)
LEP	4.0 pb	0.8×10^5	59 nb	2×10^7	~2, 1 fb	~5	–	–
FCC-ee	4.0 pb	5×10^8	59 nb	6×10^{12}	200, 30 fb	1.9×10^6	0.5 pb	3.8×10^6
Increase factor LEP ↦ FCC-ee	1	6250	1	300, 000	70, 30	400, 000	–	–
Tevatron (1.96 TeV, 10 fb^{-1})	25.3 nb	2.5×10^8	7.6 nb	7.6×10^7	1.1 pb	1.1×10^4	7.1 pb	1.4×10^5
HL-LHC (14 TeV, 2×3 ab^{-1})	200 nb	1.2×10^{12}	62.5 nb	3.8×10^{11}	58 pb	3.5×10^8	1 nb	1.2×10^{10}
FCC-hh (100 TeV, 30 ab^{-1})	1300 nb	4.1×10^{13}	415 nb	1.2×10^{13}	0.93 nb	2.8×10^{10}	35 nb	2.1×10^{12}
Increase factor Tevatron ↦ HL-LHC	8	4800	8.2	5000	52.7	31 800	141	86 000
Increase factor HL-LHC ↦ FCC-hh	6.5	34	6.7	32	16	80	35	175

Particle number ratios

Explanation - Future limits: FCC-ee and FCC-hh reaches

- For all rare decays collected, we:
  - Indicate whether the decay will be producible at FCC-ee/FCC-hh by simply checking the relation $[BR(X)\times N(X)]>1\,?$

Number of H,W,Z,top produced

Collider	W$^{\pm}$ bosons σ(W)	N(W)	Z bosons σ(Z)	N(Z)	H bosons σ(H)	N(H)	top quarks $\sigma(t\bar{t})$	N(top)
LEP	4.0 pb	0.8×10^{5}	59 nb	2×10^{7}	~2, 1 fb	~5	–	–
FCC-ee	4.0 pb	5×10^{8}	59 nb	6×10^{12}	200, 30 fb	1.9×10^{6}	0.5 pb	3.8×10^{6}
Increase factor LEP $\mapsto$ FCC-ee	1	6250	1	300,000	70, 30	400,000	–	–
Tevatron (1.96 TeV, 10 fb^{-1})	25.3 nb	2.5×10^{8}	7.6 nb	7.6×10^{7}	1.1 pb	1.1×10^{4}	7.1 pb	1.4×10^{5}
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Explanation - Future limits: FCC-ee and FCC-hh reaches

- For all rare decays collected, we:
  - Indicate whether the decay will be producible at FCC-ee/FCC-hh by simply checking the relation $[BR(X) \times N(X)] > 1$?

Example:

				Exp. limits		Producible at	
$H \to \gamma$ +	X	Branching fraction	Framework	2023	HL-LHC	FCC-ee	FCC-hh
	ρ^0	$(1.68 \pm 0.18) \times 10^{-5}$	SCET+LCDA [13]	$< 8.8\times10^{-4}$ [74]	$\lesssim 6.8 \times 10^{-5}$	✓	✓
	ω	$(1.48 \pm 0.17) \times 10^{-6}$	SCET+LCDA [13]	$< 1.5\times10^{-4}$ [76]	$\lesssim 2.2 \times 10^{-5}$	✓	✓
	ϕ	$(2.31 \pm 0.26) \times 10^{-6}$	SCET+LCDA [13]	$< 4.8\times10^{-4}$ [74]	$\lesssim 3.7 \times 10^{-5}$	✓	✓
		$(2.95 \pm 0.38) \times 10^{-6}$	SCET+LCDA [13]				
	J/ψ	$(3.01 \pm 0.15) \times 10^{-6}$	NRQCD (NLL)+LDME [78]	$< 3.5\times10^{-4}$ [77]	$\lesssim 5.5 \times 10^{-5}$ [54]	✓	✓
		$\left(3.0^{+0.2}_{-0.1}\right) \times 10^{-6}$	NRQCD+LCDA [79]				
	$\psi(2S)$	$(1.3 \pm 0.1) \times 10^{-6}$	SCET+LCDA [13]	$< 2.0\times10^{-3}$ [80]	$\lesssim 1.6 \times 10^{-4}$	✓	✓
		$\left(4.6^{+3.9}_{-2.8}\right) \times 10^{-9}$	SCET+LCDA [13]				
$H \to \gamma$ +	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Explanation - Future limits: FCC-ee and FCC-hh reaches

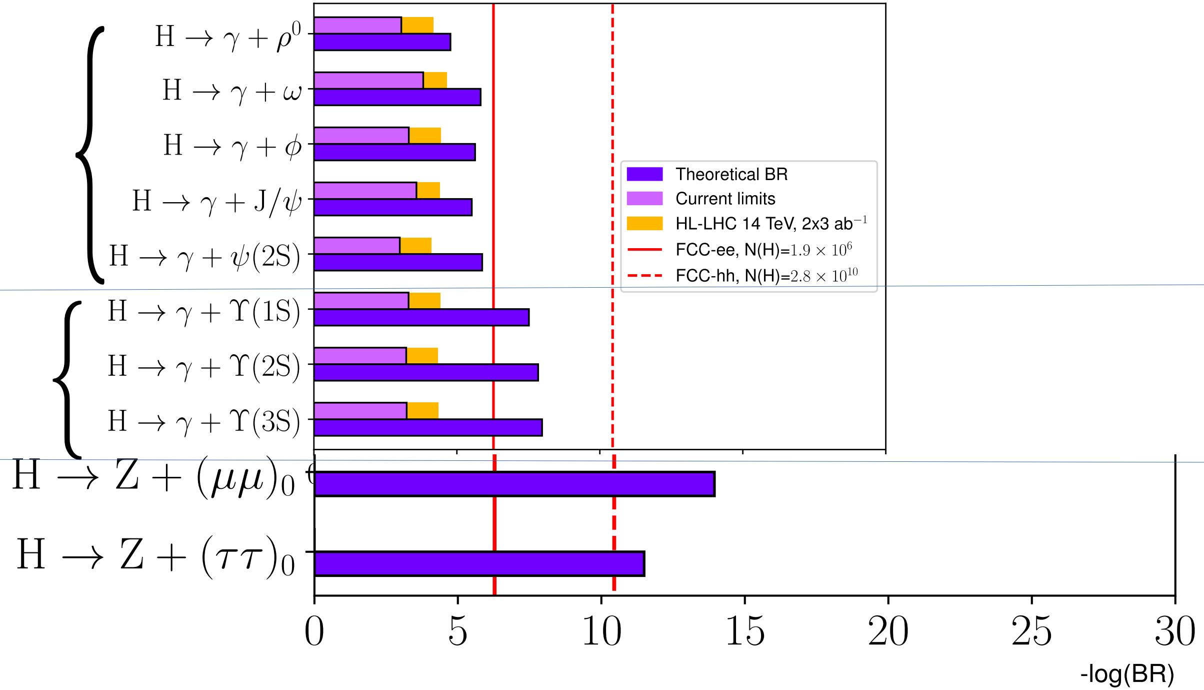
- For all rare decays collected, we:
  - Indicate whether the decay will be producible at FCC-ee/FCC-hh by simply checking the relation $[BR(X) \times N(X)] > 1\,?$
  - Graphically present in negative log plot – The shorter the purple line, the larger the BR

Example:

Producible at FCC-ee

Producible at FCC-h

Not Producible at FCC-h

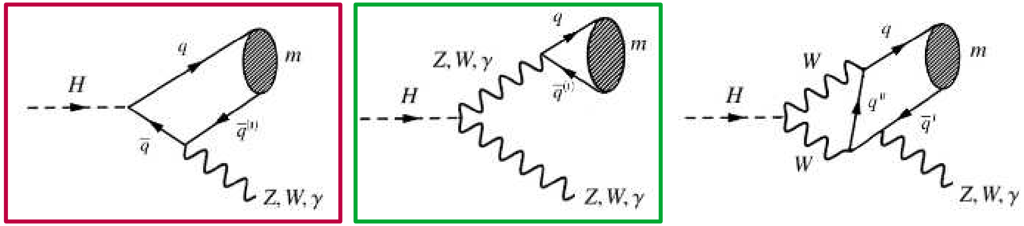


1. Higgs yukawa couplings
Exclusive Higgs decays: radiative + meson

- Due to the smallness of the H → cc,qq partial widths, it has been proposed to constrain quark Yukawa couplings via exclusive decays of Higgs into:
  - EW boson + 1 meson:
    - Contributions from 2 main mechanisms (direct, indirect) which interfere destructively.
    - Can be used to probe hZγ effective couplings

direct

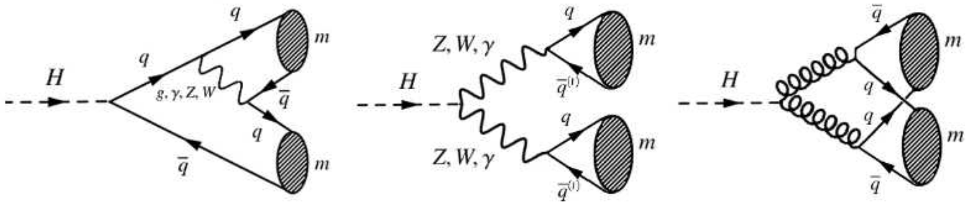
indirect



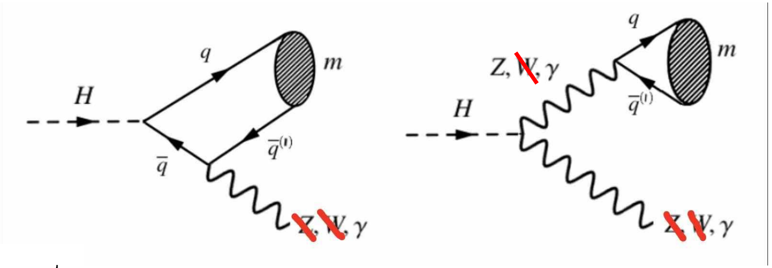
Sub-dominant,
small uncertainty

Dominant,
Large uncertainty

  - double meson:
    - Doubly suppressed → very small BR
      → Can't be produced until FCC-hh rates
    - Theoretical predictions have included more of these diagrams with time...



H → γ + meson



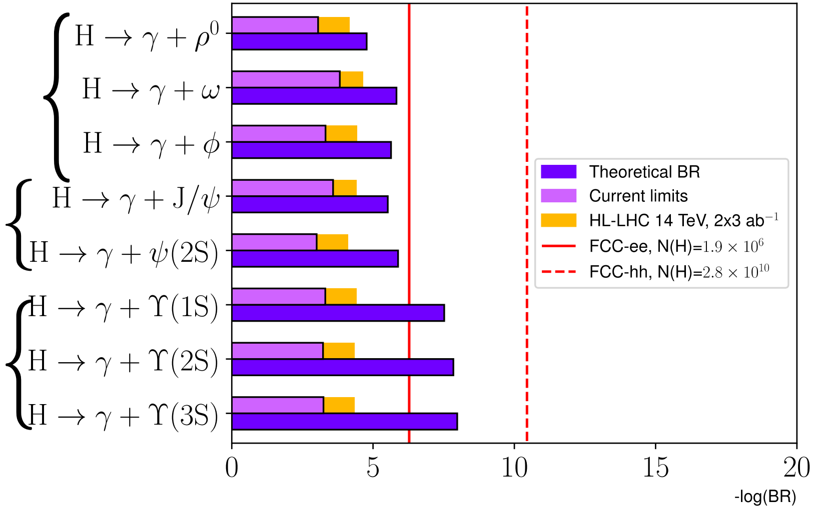
H → γ +	M	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
H → γ +	ρ^0	$(1.68 \pm 0.08) \times 10^{-5}$	SCET+LCDA [14]	$< 8.8\times 10^{-4}$ [73]	$\lesssim 6.8\times 10^{-5}$	✓	✓
	ω	$(1.48 \pm 0.08) \times 10^{-6}$	SCET+LCDA [14]	$< 1.5\times 10^{-4}$ [76]	$\lesssim 2.2\times 10^{-5}$	✓	✓
	ϕ	$(2.31 \pm 0.11) \times 10^{-6}$	SCET+LCDA [14]	$< 4.8\times 10^{-4}$ [73]	$\lesssim 3.7\times 10^{-5}$	✓	✓
	J/ψ	$(2.95 \pm 0.17) \times 10^{-6}$	SCET+LCDA [14]	$< 2.6\times 10^{-4}$ [75, 77]	$\lesssim 3.9\times 10^{-5}$ [55]	✓	✓
		$(3.01 \pm 0.15) \times 10^{-6}$	NRQCD (NLL)+LDME [144]				
		$(2.99^{+0.16}_{-0.15}) \times 10^{-6}$	NRQCD+LCDA [145]				
	$\psi(2S)$	$(1.3 \pm 0.0) \times 10^{-6}$	SCET+LCDA [14]	$< 9.9\times 10^{-4}$ [74, 77]	$\lesssim 7.7\times 10^{-5}$	✓	✓
	$\Upsilon(1S)$	$(4.61^{+1.76}_{-1.23}) \times 10^{-9}$	SCET+LCDA [14]	$< 4.9\times 10^{-4}$ [74]	$\lesssim 3.8\times 10^{-5}$	✘	✓
		$(9.97^{+4.04}_{-3.03}) \times 10^{-9}$	NRQCD (NLL)+LDME [144]				
		3.0×10^{-8}	NRQCD (NLO)+LDME [146]				
		$(5.22^{+2.02}_{-1.70}) \times 10^{-9}$	NRQCD+LCDA [145]				
	$\Upsilon(2S)$	$(2.34^{+0.76}_{-1.00}) \times 10^{-9}$	SCET+LCDA [14]	$< 5.9\times 10^{-4}$ [74]	$\lesssim 4.6\times 10^{-5}$	✘	✓
		$(2.62^{+1.39}_{-0.91}) \times 10^{-9}$	NRQCD (NLL)+LDME [144]				
		1.4×10^{-8}	NRQCD (NLO)+LDME [146]				
		$(1.42^{+0.72}_{-0.57}) \times 10^{-9}$	NRQCD+LCDA [145]				
	$\Upsilon(3S)$	$(2.13^{+0.76}_{-1.12}) \times 10^{-9}$	SCET+LCDA [14]	$< 5.7\times 10^{-4}$ [74]	$\lesssim 4.4\times 10^{-5}$	✘	✓
		$(1.87^{+1.05}_{-0.69}) \times 10^{-9}$	NRQCD (NLL)+LDME [144]				
		1.1×10^{-8}	NRQCD (NLO)+LDME [146]				
		$(9.1^{+4.8}_{-3.8}) \times 10^{-10}$	NRQCD+LCDA [145]				

$$\frac{A_{\text{direct}}}{A_{\text{indirect}}}$$

-0.002

-0.06

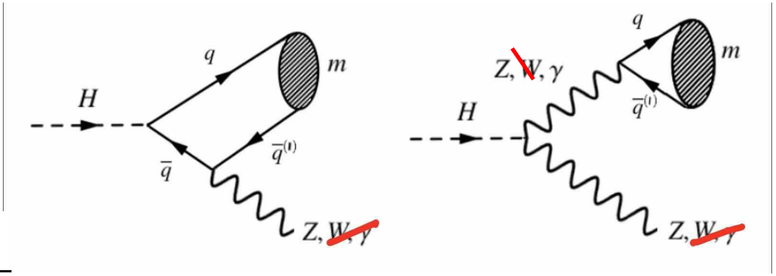
-0.8



- Theory BRs: O(10^{-5} – 10^{-10}). Exp. limits: O(10^{-3} – 10^{-4})
- 9 channels studied . 5 (8) producible channels at FCC-ee (FCC-hh).
- H→γ+ρ maybe observed at HL-LHC (set upper bound for light quark Yukawa of higgs)

H → Z + meson

H → Z +	M	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
H → Z +	π^0	$(2.3 \pm 0.1) \times 10^{-6}$	EFT+NRQM [10]	–	–	✓	✓
		$(2.3 \pm 0.1) \times 10^{-6}$	EFT+LCDA [83]				
	η	$(8.3 \pm 0.9) \times 10^{-7}$	EFT+LCDA [83]	–	–	✓	✓
	ρ^0	$(1.4 \pm 0.1) \times 10^{-5}$	EFT+NRQM [10]	$< 1.2\times 10^{-2}$ [147]	$\lesssim 1.8\times 10^{-3}$	✓	✓
		$(7.19 \pm 0.29) \times 10^{-6}$	EFT+LCDA [83]				
	ω	$(1.6 \pm 0.1) \times 10^{-6}$	EFT+NRQM [10]	–	–	✓	✓
		$(5.6 \pm 0.2) \times 10^{-7}$	EFT+LCDA [83]				
	η'	$(1.24 \pm 0.13) \times 10^{-6}$	EFT+LCDA [83]	–	–	✓	✓
	ϕ	$(4.2 \pm 0.3) \times 10^{-6}$	EFT+NRQM [10]	$< 3.6\times 10^{-3}$ [147]	$\lesssim 5.4\times 10^{-4}$	✓	✓
		$(2.42 \pm 0.10) \times 10^{-6}$	EFT+LCDA [83]				
	η_c	$(1.0 \pm 0.1) \times 10^{-5}$	EFT+NRQM [10]	–	–	✓	✓
		$(1.0 \pm 0.0) \times 10^{-5}$	EFT+LCDA [148]				
	J/ψ	3.4×10^{-6}	NRQCD (NLO)+LMDE [149]	$< 1.9\times 10^{-3}$ [99]	$\lesssim 2.1\times 10^{-4}$ [57]	✓	✓
		3.2×10^{-6}	EFT+NRQM [88]				
		$(2.3 \pm 0.1) \times 10^{-6}$	EFT+LCDA [83]				
	$\psi(2S)$	1.5×10^{-6}	EFT+NRQM [88]	$< 6.6\times 10^{-3}$ [99]	$\lesssim 1.0\times 10^{-3}$	✓	✓
	η_b	$(2.69 \pm 0.05) \times 10^{-5}$	EFT+LCDA [148]	–	–	✓	✓
		$(4.739^{+0.276}_{-0.244}) \times 10^{-5}$	EFT (NLO)+LCDA [150]				
	$\Upsilon(1S)$	1.7×10^{-5}	NRQCD (NLO)+LMDE [149]	–	–	✓	✓
		1.7×10^{-5}	EFT+NRQM [88]				
		$(1.54 \pm 0.06) \times 10^{-5}$	EFT+LCDA [83]				
	$\Upsilon(2S)$	8.9×10^{-6}	EFT+NRQM [88]	–	–	✓	✓
		$(7.5 \pm 0.3) \times 10^{-6}$	EFT+LCDA [83]				
	$\Upsilon(3S)$	6.7×10^{-6}	EFT+NRQM [88]	–	–	✓	✓
		$(5.63 \pm 0.24) \times 10^{-6}$	EFT+LCDA [83]				

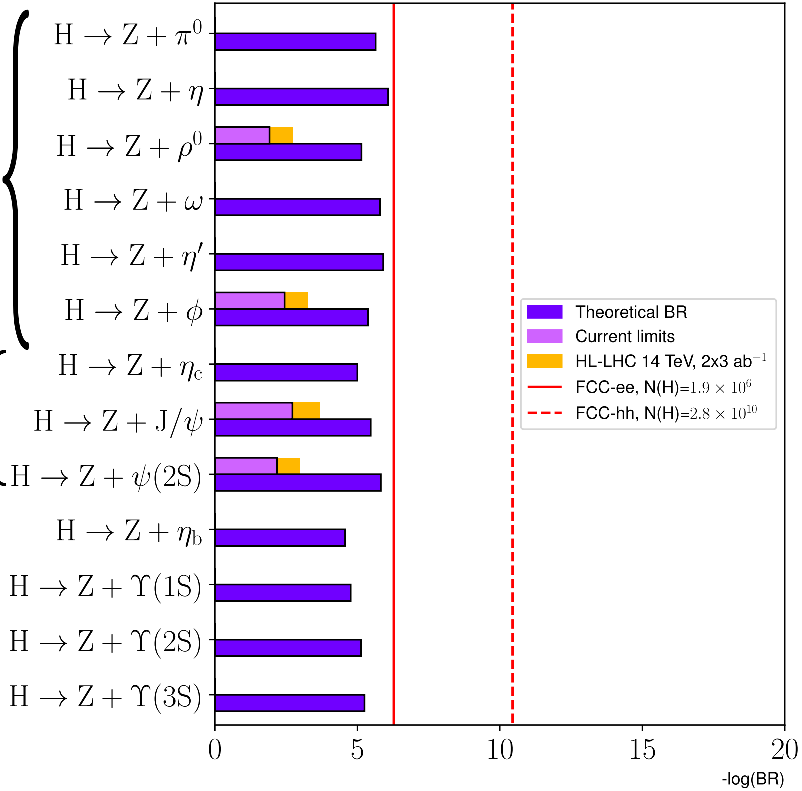


$$\frac{A_{\text{direct}}}{A_{\text{indirect}}}$$

<0.0001

-0.014

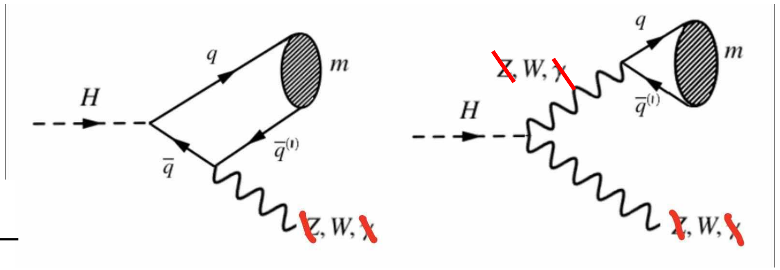
+0.05



- Theory BRs: O(10^{-5} – 10^{-7}). Exp. limits: O(10^{-2} – 10^{-3})
- 4 channels searched for . All channels are producible at FCC-ee
- Botomonia have largest BRs, but no bound set so far.
- No observable channel at HL-LHC

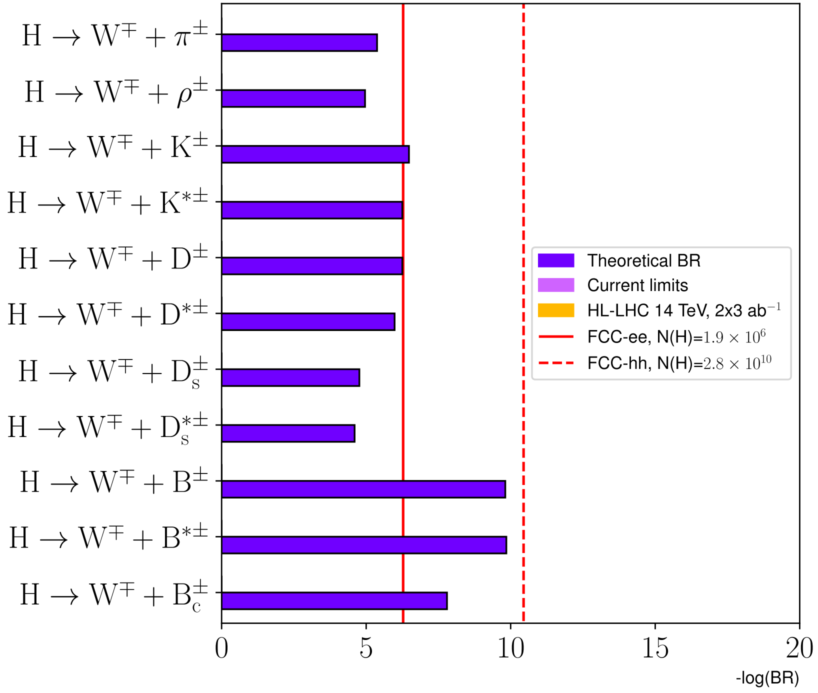
H → W + meson

H → W	+	M	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
$H \to W^{\mp}$	+	$\pi^{\pm}$	$(4.2 \pm 0.2) \times 10^{-6}$	EFT+NRQM [10]	–	–	✓	✓
			$(4.3 \pm 0.2) \times 10^{-6}$	EFT+LCDA [83]				
		$\rho^{\pm}$	$(1.5 \pm 0.1) \times 10^{-5}$	EFT+NRQM [10]	–	–	✓	✓
			$(1.09 \pm 0.05) \times 10^{-5}$	EFT+LCDA [83]				
		$K^{\pm}$	$(3.3 \pm 0.1) \times 10^{-7}$	EFT+NRQM [10]	–	–	✘	✓
			$(3.3 \pm 0.1) \times 10^{-7}$	EFT+LCDA [83]				
		$K^{*\pm}$	$(4.3 \pm 0.2) \times 10^{-7}$	EFT+NRQM [10]	–	–	✘	✓
			$(5.6 \pm 0.4) \times 10^{-7}$	EFT+LCDA [83]				
		$D^{\pm}$	$(5.8 \pm 0.6) \times 10^{-7}$	EFT+NRQM [10]	–	–	✓	✓
			$(5.6 \pm 0.5) \times 10^{-7}$	EFT+LCDA [83]				
		$D^{*\pm}$	$(1.3 \pm 0.1) \times 10^{-6}$	EFT+NRQM [10]	–	–	✓	✓
			$(1.04 \pm 0.14) \times 10^{-6}$	EFT+LCDA [83]				
		$D_s^{\pm}$	$(1.6 \pm 0.1) \times 10^{-5}$	EFT+NRQM [10]	–	–	✓	✓
			$(1.71 \pm 0.11) \times 10^{-5}$	EFT+LCDA [83]				
		$D_s^{*\pm}$	$(3.5 \pm 0.2) \times 10^{-5}$	EFT+NRQM [10]	–	–	✓	✓
			$(2.51 \pm 0.19) \times 10^{-5}$	EFT+LCDA [83]				
		$B^{\pm}$	$(1.6 \pm 0.4) \times 10^{-10}$	EFT+NRQM [10]	–	–	✘	✓
			$(1.54 \pm 0.40) \times 10^{-10}$	EFT+LCDA [83]				
		$B^{*\pm}$	$(1.3 \pm 0.2) \times 10^{-5}$	EFT+NRQM [10]	–	–	✓	✓
			$(1.41 \pm 0.36) \times 10^{-10}$	EFT+LCDA [83]				
		$B_c^{\pm}$	$(1.6 \pm 0.2) \times 10^{-8}$	EFT+NRQM [10]	–	–	✘	✓
			$(8.21 \pm 0.83) \times 10^{-8}$	EFT+LCDA [83]				



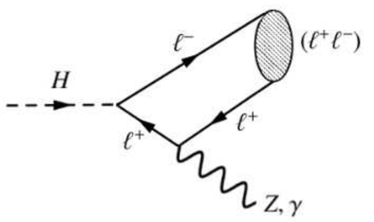
$$\frac{A_{\text{direct}}}{A_{\text{indirect}}}$$

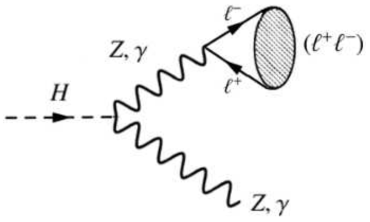
0
(ignored)



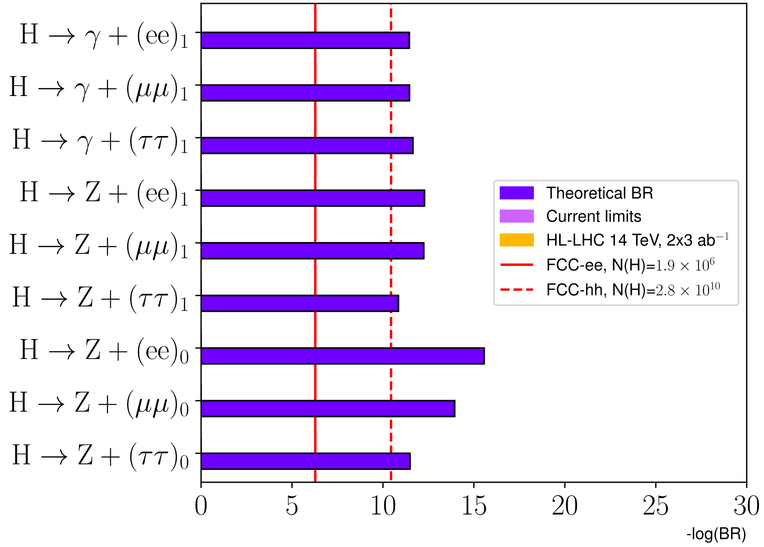
- Theory BRs: O(10^{-5} – 10^{-10}). No Exp. Limits.
- No search-performed so far. 7 (11) producible channels at FCC-ee (FCC-hh)
- No bound set so far

H → γ + leptonium





H → V +	$(\ell\ell)$	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
H → γ +	$(ee)_1$	3.5×10^{-12}	(this work)	–	–	✘	✘
	$(\mu\mu)_1$	3.5×10^{-12}	(this work)	–	–	✘	✘
	$(\tau\tau)_1$	2.2×10^{-12}	(this work)	–	–	✘	✘
H → Z +	$(ee)_1$	5.2×10^{-13}	(this work)	–	–	✘	✘
	$(\mu\mu)_1$	5.7×10^{-13}	(this work)	–	–	✘	✘
	$(\tau\tau)_1$	1.4×10^{-11}	(this work)	–	–	✘	✘
	$(ee)_0$	2.7×10^{-16}	(this work)	–	–	✘	✘
	$(\mu\mu)_0$	1.1×10^{-14}	(this work)	–	–	✘	✘
	$(\tau\tau)_0$	3.2×10^{-12}	(this work)	–	–	✘	✘

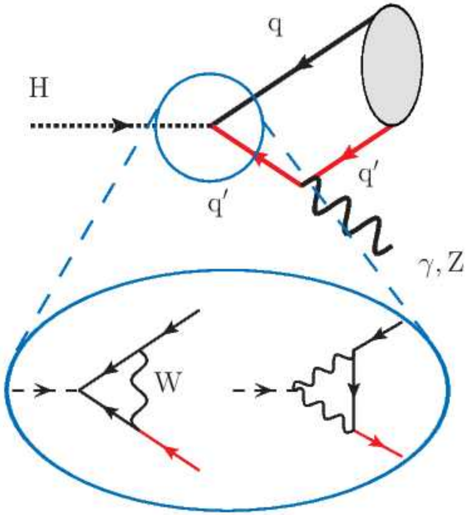


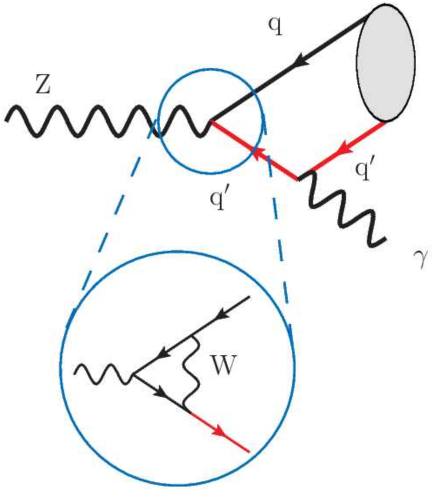
- Tiny BRs O(10^{-12} – 10^{-16}). First time computed here.
- No channel searched for. No (0) producible channels at FCC-ee (FCC-hh)
- Note: Leptonia are long-lived = LLP signature (displaced γ, e, μ vertices)

2. <u>Flavour changing neutral current (FCNC)</u> of H, Z, and top

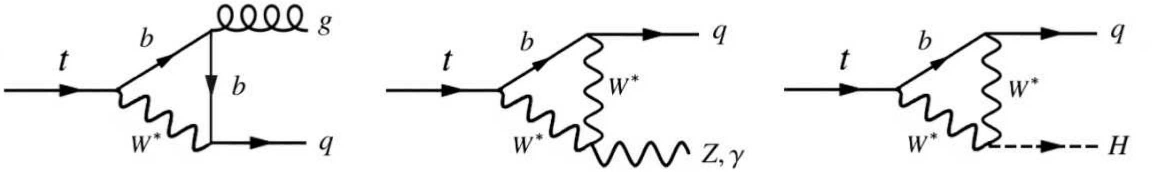
- Precision tests of suppressed (or forbidden) processes in the SM —FCNC— are powerful probes of BSM physics that have been mostly studied so far in b-quark decays

- Exclusive FCNC H,Z decay:
  - Goes through flavour changing vertex
  - Low theoretical uncertainty
  - Very supressed rate (BR < 10^{-15})
  - Interesting channels to search for BSM FCNC with a negligible SM background

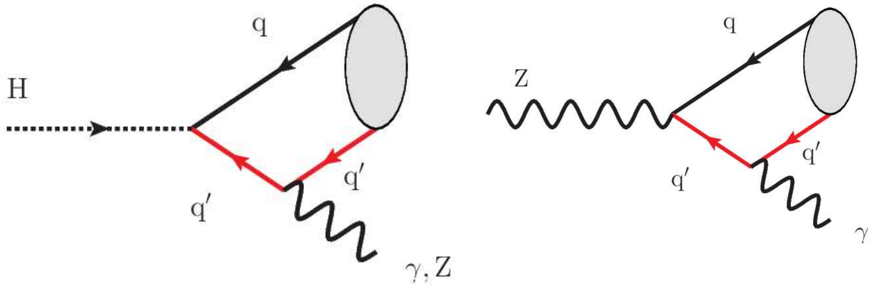




- Rare top FCNC decay:
  - many BSM extensions can enhance ratios by orders of magnitude, yielding compelling phenomenology.

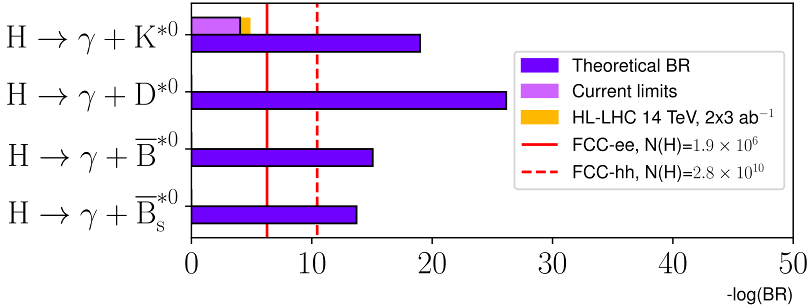


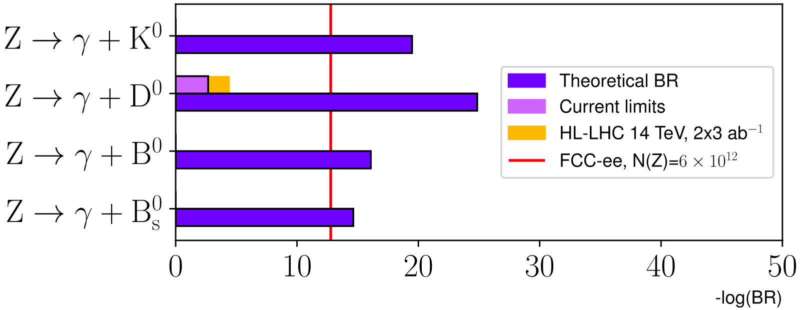
H,Z→ flavoured meson + γ



H → γ +	M	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
H → γ +	K^{*0}	1.0×10^{-19}	EFT+LCDA (this work)	$< 8.9\times 10^{-5}$ [76]	$\lesssim 1.3\times 10^{-5}$	✘	✘
	D^{*0}	7.0×10^{-27}	EFT+LCDA (this work)	–	–	✘	✘
	$\overline{B}^{*0}$	8.6×10^{-16}	EFT+LCDA (this work)	–	–	✘	✘
	$\overline{B}_s^{*0}$	1.9×10^{-14}	EFT+LCDA (this work)	–	–	✘	✘

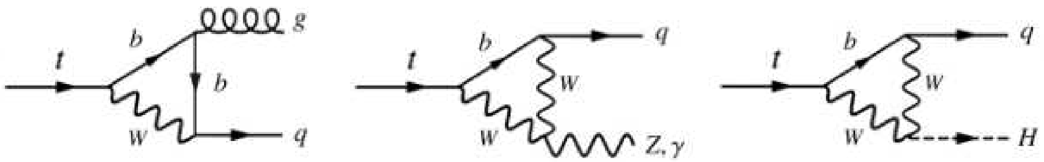
Z → γ +	M	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee
Z → γ +	K^0	3.3×10^{-20}	(this work)	–	–	✘
	D^0	$< 1.0 \times 10^{-15}$	SCET+LCDA [113, 116]	$< 2.1\times 10^{-3}$ [113]	$\lesssim 3.8\times 10^{-5}$	✘
		1.4×10^{-25}	(this work)			
	B^0	8.3×10^{-17}	(this work)	–	–	✘
	B_s^0	2.3×10^{-15}	(this work)	–	–	✘



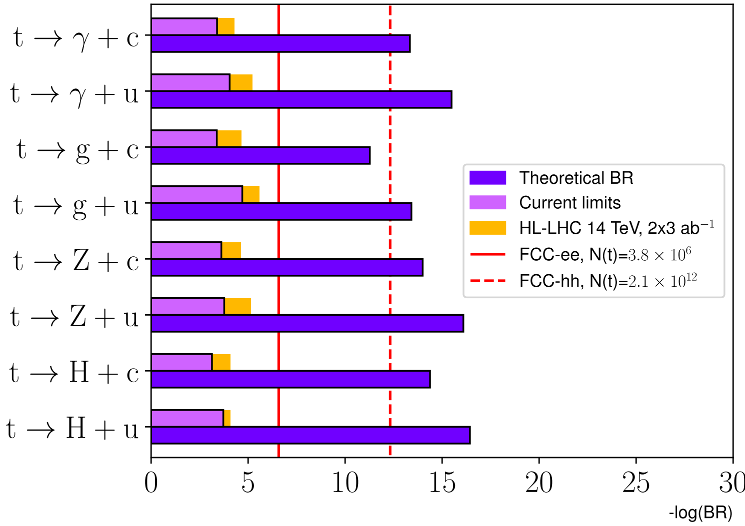


- Theory BRs: O(10^{-14}–10^{-27}). Exp. limits: O(10^{-3} – 10^{-5})
- 2 channels searched-for. No channels producible at FCC-ee (FCC-hh), (in the absence of BSM)

top-quark FCNC decays



t →	V +	q	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
t →	γ +	c	$(4.55 \pm 0.23) \times 10^{-14}$	NLO SM [168]	$< 4.0\times 10^{-4}$ [169]	$\lesssim 5.2 \times 10^{-5}$ [57]	✘	✘
			$\left(4.6^{+2.0}_{-1.0}\right) \times 10^{-14}$	NLO SM [28]				
		u	$(3.26 \pm 0.34) \times 10^{-16}$	NLO SM [168]	$< 8.9\times 10^{-5}$ [169]	$\lesssim 6.1 \times 10^{-6}$ [57]	✘	✘
			3.7×10^{-16}	NLO SM [28]				
	g +	c	$(5.31 \pm 0.27) \times 10^{-12}$	NLO SM [168]	$< 4.1\times 10^{-4}$ [170]	$\lesssim 2.3 \times 10^{-5}$ [57]	✘	✓
			$\left(4.6^{+3.0}_{-1.0}\right) \times 10^{-12}$	NLO SM [28]				
			5.7×10^{-12}	NLO SM [131]				
		u	$(3.81 \pm 0.34) \times 10^{-14}$	NLO SM [168]	$< 2.0\times 10^{-5}$ [170]	$\lesssim 2.7 \times 10^{-6}$ [57]	✘	✘
			3.7×10^{-14}	NLO SM [28]				
	Z +	c	1.0×10^{-14}	NLO SM [28]	$< 2.4\times 10^{-4}$ [109]	$\lesssim 2.3 \times 10^{-5}$ [58]	✘	✘
		u	8.0×10^{-17}	NLO SM [28]	$< 1.7\times 10^{-4}$ [109]	$\lesssim 7.3 \times 10^{-6}$ [58]	✘	✘
	H +	c	$\left(4.19^{+1.09}_{-0.86}\right) \times 10^{-15}$	NLO SM [171]	$< 7.3\times 10^{-4}$ [172]	$\lesssim 8.5 \times 10^{-5}$ [59]	✘	✘
			3.0×10^{-15}	NLO SM [28]				
		u	$\left(3.66^{+1.15}_{-0.97}\right) \times 10^{-17}$	NLO SM [171]	$< 1.9\times 10^{-4}$ [172]	$\lesssim 8.5 \times 10^{-5}$ [59]	✘	✘
			2.0×10^{-17}	NLO SM [28]				



- Theory BRs: O(10^{-3}–10^{-17}). Exp. limits: O(10^{-4} – 10^{-5})
- All 8 channels searched-for. No (1) channels producible at FCC-ee (FCC-hh), in the absence of BSM

3. Study of QCD factorization using exclusive Z decays

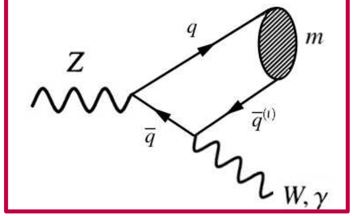
Exclusive Z decays:

- Similar mechanism to the exclusive Higgs radiative decays.
- Large Z boson yields at colliders.

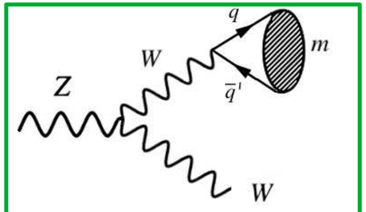
They provides valuable information both theoretical (SCET & NRQCD validation, and LCDAs/LDMEs) and experimental (optimization of search techniques to study exclusive Higgs boson decays).

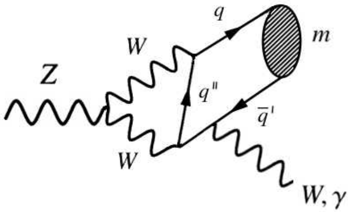
- 2 major mechanism:
  - γ,W + 1 meson:

direct



indirect

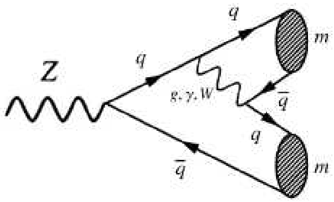


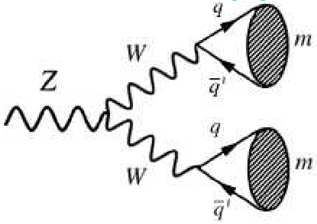


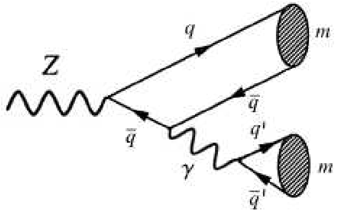
sub-dominant

dominant

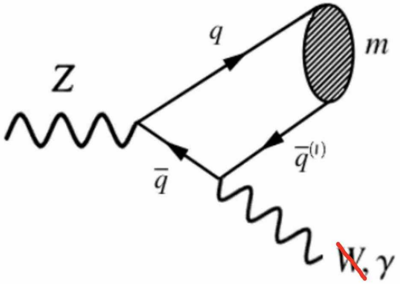
  - Double mesons:





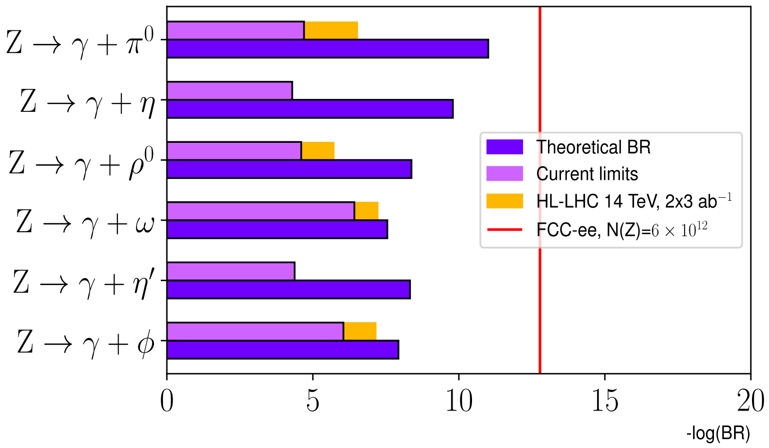


Z→ γ + light meson



←light quarks (u, d ,s)

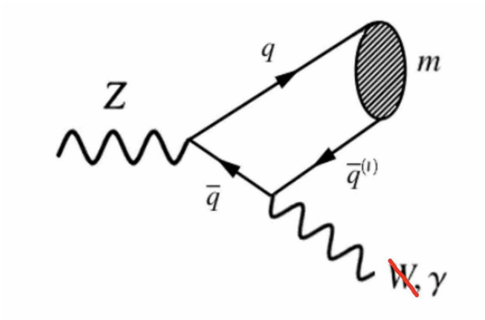
Z → γ +	M	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee
Z → γ +	π^0	$(9.8 \pm 1.0) \times 10^{-12}$	SCET+LCDA [116]	$< 2.0\times 10^{-5}$ [107]	$\lesssim 2.8\times 10^{-7}$	✓
	η	$(1.0 - 17.0) \times 10^{-10}$	SCET+LCDA [152]	$< 5.1\times 10^{-5}$ [114]	–	✓
	ρ^0	$(4.19 \pm 0.47) \times 10^{-9}$	SCET+LCDA [116]	$< 2.5\times 10^{-5}$ [73]	$\lesssim 1.8\times 10^{-6}$	✓
	ω	$(2.82 \pm 0.41) \times 10^{-8}$	SCET+LCDA [116]	$< 3.8\times 10^{-7}$ [76]	$\lesssim 5.7\times 10^{-8}$	✓
	η'	$(3.1 - 4.8) \times 10^{-9}$	SCET+LCDA [152]	$< 4.2\times 10^{-5}$ [114]	–	✓
	ϕ	$(1.17 \pm 0.08) \times 10^{-8}$ $(1.04 \pm 0.12) \times 10^{-8}$	LC+LCDA [153] SCET+LCDA [116]	$< 9.0\times 10^{-7}$ [73]	$\lesssim 6.6\times 10^{-8}$	✓



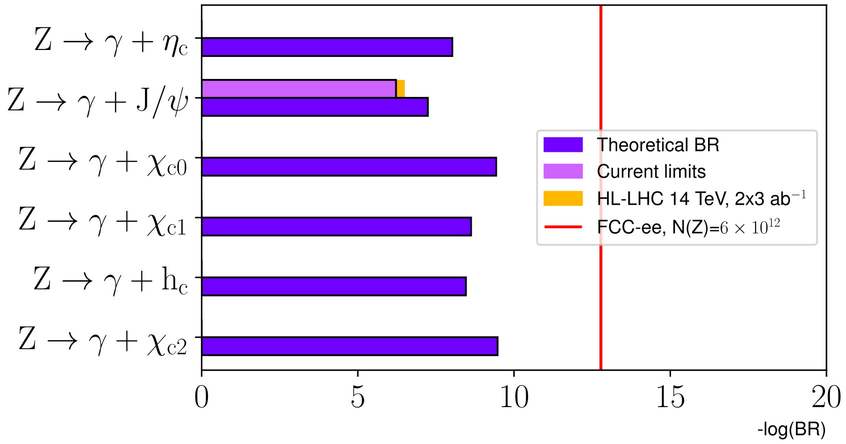
- Theory BRs: O(10^{-8} – 10^{-11}). Exp. Limits: O(10^{-5} – 10^{-7})
- 6 channels searched for. 6 producible channels at FCC-ee.
- Z→γ+ω is very close to be detected at HL-LHC (BR = ½ of projected limit)
- All channels will be visible at FCC-ee

$Z\rightarrow\ \gamma$ + charmonium

$Z\rightarrow\gamma\ +$	X	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee
$Z\rightarrow\gamma\ +$	η_c	$(9.5\pm0.2)\ \times10^{-9}$	NRQCD (NNLO+NLL) [120]	–	–	✓
		$(7.42\pm0.61)\ \times10^{-9}$	NRQCD (NLO+NLL) [121]			
		$6.6\ \times10^{-9}$	NRQCD+LDME [122]			
		$(9.4\pm1.0)\ \times10^{-9}$	LC+LCDA [122]			
	J/ψ	$\left(5.75^{+0.08}_{-0.09}\right)\ \times10^{-8}$	NRQCD (NNLO+NLL) [120]	$<1.4\times10^{-6}$ [114]	$\lesssim4.4\times10^{-7}$ [54]	✓
		$\left(9.0^{+1.5}_{-1.4}\right)\ \times10^{-8}$	LC+LCDA [123]			
		$4.5\ \times10^{-8}$	NRQCD+LDME [122]			
		$(8.8\pm0.9)\ \times10^{-8}$	LC+LCDA [122]			
		$(9.96\pm1.86)\ \times10^{-8}$	NRQCD+LDME [119]			
		$(8.02\pm0.45)\ \times10^{-8}$	SCET+LCDA [58]			
	χ_{c0}	$(3.74\pm0.05)\ \times10^{-10}$	NRQCD+LDME [124]	–	–	✓
		$1.4\ \times10^{-10}$	NRQCD+LDME [122]			
		$(5.0\pm2.0)\ \times10^{-10}$	LC+LCDA [122]			
	χ_{c1}	$\left(2.38^{+0.01}_{-0.02}\right)\ \times10^{-9}$	NRQCD+LDME [124]	–	–	✓
		$8.7\ \times10^{-10}$	NRQCD+LDME [122]			
		$(5.6\pm2.0)\ \times10^{-9}$	LC+LCDA [122]			
	h_c	$\left(3.49^{+0.21}_{-0.23}\right)\ \times10^{-9}$	NRQCD+LDME [124]	–	–	✓
		$3.0\ \times10^{-9}$	NRQCD+LDME [122]			
		$(1.0\pm0.4)\ \times10^{-8}$	LC+LCDA [122]			
	χ_{c2}	$\left(3.38^{+0.19}_{-0.22}\right)\ \times10^{-10}$	NRQCD+LDME [124]	–	–	✓
		$2.9\ \times10^{-10}$	NRQCD+LDME [122]			
		$(1.0\pm0.4)\ \times10^{-9}$	LC+LCDA [122]			

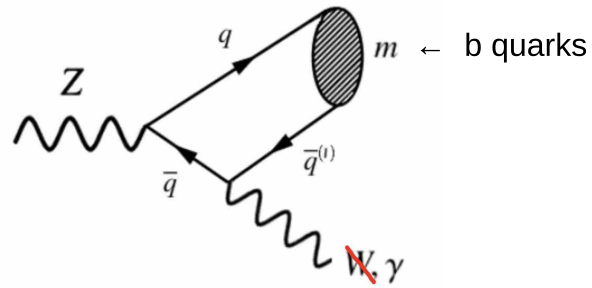


← c quarks

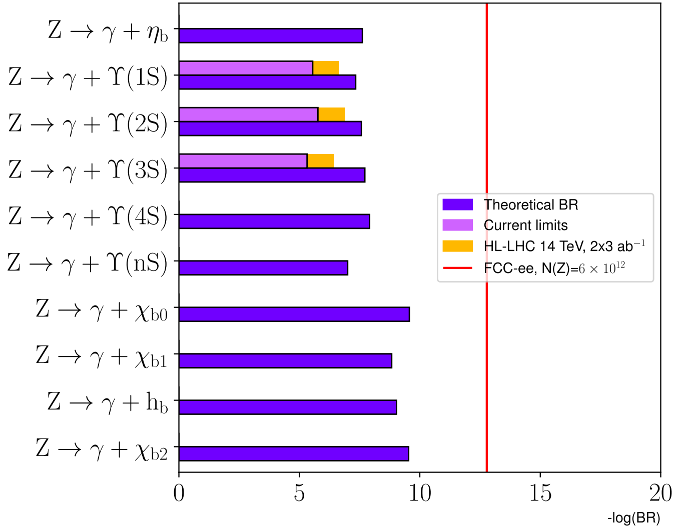


- Theory BRs: O(10^{-8} – 10^{-10}). Multiple calculations (LC, SCET, NRQCD). Exp. limits: O(10^{-6}).
- 1 channel searched for. 6 producible channel at FCC-ee
- $Z\rightarrow\gamma$+ J/ψ maybe visible at HL-LHC

Z→ γ + bottomonium

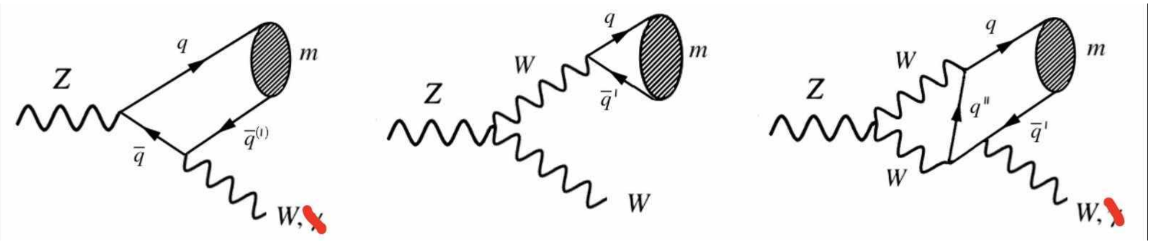


$Z \to \gamma$ +	X	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee
$Z \to \gamma$ +	η_b	$(2.43 \pm 0.01) \times 10^{-8}$	NRQCD (NNLO+NLL) [120]	–	–	✓
		$(2.8 \pm 0.5) \times 10^{-8}$	NRQCD (NLO+NLL) [121]			
	$\Upsilon(1S)$	$(4.63 \pm 0.02) \times 10^{-8}$	NRQCD (NNLO+NLL) [120]	$< 2.8\times10^{-6}$ [80]	$\lesssim 2.2 \times 10^{-7}$	✓
		$(5.61 \pm 0.29) \times 10^{-8}$	NRQCD+LDME [125]			
		$\left(4.8^{+0.3}_{-0.2}\right) \times 10^{-8}$	LC+LCDA [123]			
		$(4.93 \pm 0.51) \times 10^{-8}$	NRQCD+LDME [119]			
		$(5.39 \pm 0.16) \times 10^{-8}$	SCET+LCDA [58]			
	$\Upsilon(2S)$	$(2.66 \pm 0.31) \times 10^{-8}$	NRQCD+LDME [125]	$< 1.7\times10^{-6}$ [80]	$\lesssim 1.3 \times 10^{-7}$	✓
		$\left(2.44^{+0.14}_{-0.13}\right) \times 10^{-8}$	LC+LCDA [123]			
	$\Upsilon(3S)$	$(1.93 \pm 0.25) \times 10^{-8}$	NRQCD+LDME [125]	$< 4.8\times10^{-6}$ [80]	$\lesssim 3.7 \times 10^{-7}$	✓
		$\left(1.88^{+0.11}_{-0.10}\right) \times 10^{-8}$	LC+LCDA [123]			
	$\Upsilon(4S)$	$(1.22 \pm 0.13) \times 10^{-8}$	SCET+LCDA [58]	–	–	✓
	$\Upsilon(nS)$	$\left(9.96^{+0.28}_{-0.26}\right) \times 10^{-8}$	SCET+LCDA [58]	–	–	✓
	χ_{b0}	$\left(2.7^{+0.1}_{-0.0}\right) \times 10^{-10}$	NRQCD+LDME [124]	–	–	✓
	χ_{b1}	$\left(1.473^{+0.010}_{-0.011}\right) \times 10^{-9}$	NRQCD+LDME [124]	–	–	✓
	h_b	$\left(9.27^{+0.36}_{-0.41}\right) \times 10^{-10}$	NRQCD+LDME [124]	–	–	✓
	χ_{b2}	$\left(2.92^{+0.12}_{-0.14}\right) \times 10^{-10}$	NRQCD+LDME [124]	–	–	✓

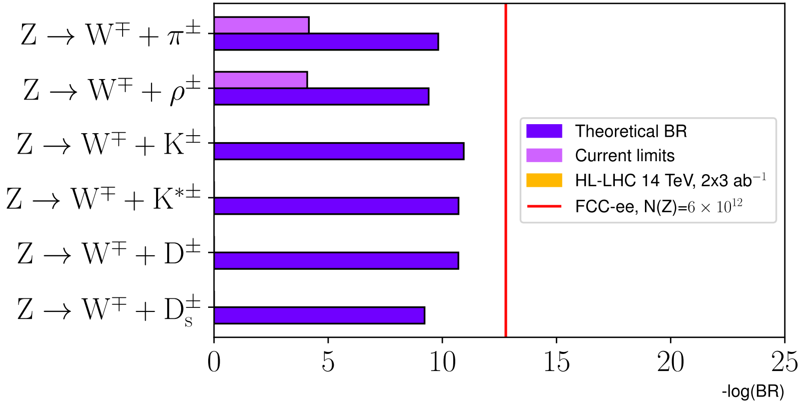


- Theory BRs: $O(10^{-8} – 10^{-10})$. Multiple calculations (LC, SCET, NRQCD). Exp. limits: $O(10^{-6})$.
- 3 channels searched-for (ATLAS). 10 producible channel at FCC-ee
- Z→ γ+Y(1S), might be visible at HL-LHC, (BR = 1/4 projected limit)

$Z \rightarrow W$ + meson

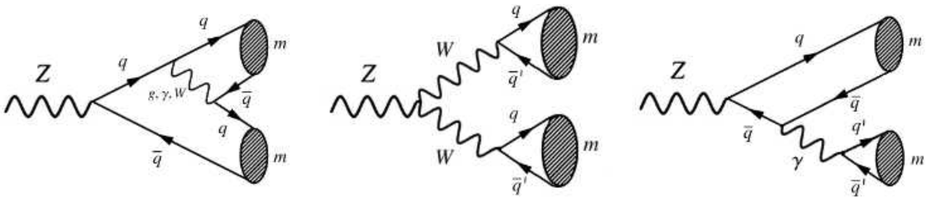


$Z \rightarrow W$	+	M	Branching fraction	Framework	Exp. limits 2023	HL-LHC	Producible at FCC-ee
$Z \rightarrow W^{\mp}$	+	$\pi^{\pm}$	$(1.51 \pm 0.01) \times 10^{-10}$	SCET+LCDA [116]	$< 7.0\times 10^{-5}$ [114]	–	✓
		$\rho^{\pm}$	$(4.0 \pm 0.1) \times 10^{-10}$	SCET+LCDA [116]	$< 8.3\times 10^{-5}$ [114]	–	✓
		$K^{\pm}$	$(1.16 \pm 0.01) \times 10^{-11}$	SCET+LCDA [116]	–	–	✓
		$K^{*\pm}$	$(1.96 \pm 0.12) \times 10^{-11}$	SCET+LCDA [116]	–	–	✓
		$D^{\pm}$	$(1.99 \pm 0.17) \times 10^{-11}$	SCET+LCDA [116]	–	–	✓
		$D_s^{\pm}$	$(6.04 \pm 0.30) \times 10^{-10}$	SCET+LCDA [116]	–	–	✓



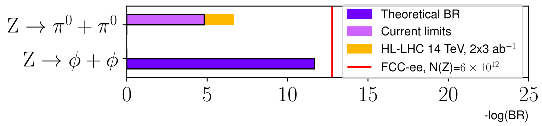
- Theory BRs: $O(10^{-10} – 10^{-11})$. Exp. limits: $O(10^{-5})$
- 2 channels searched for. 6 producible channels at FCC-ee
- Have not been studied since LEP time.
  → Improvement of limits at LHC ?

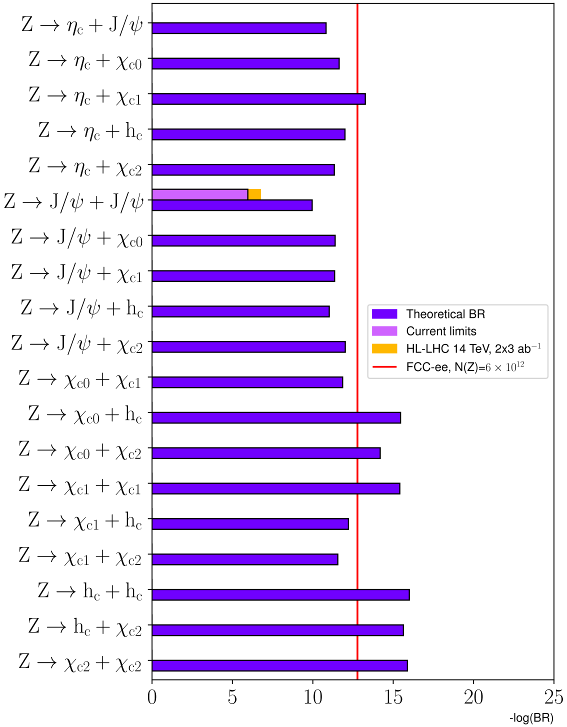
Z→ c-meson + c-meson



Z →	M	+	M	Branching fraction	Framework	Exp. limits 2023	HL-LHC	Producible at at FCC-ee
				$(1.5 \pm 0.4) \times 10^{-11}$	NRQCD/NRCSM [120]			
			J/ψ	$(1.8-2.7) \times 10^{-11}$	NRQCD+LDME (NLO) [122]	–	–	✓
				2.7×10^{-14}	NRQCD+LDME [121]			
			χ_{c0}	2.3×10^{-12}	NRQCD+LDME [121]	–	–	✓
	η_c	+		$(2.3 \pm 1.0) \times 10^{-12}$				
			χ_{c1}	5.4×10^{-14}				
			h_c	2.1×10^{-13}				
				$(1.0 \pm 0.5) \times 10^{-12}$				
			χ_{c2}	9.7×10^{-13}				
				$(4.6 \pm 2.0) \times 10^{-12}$				
				$(1.1 \pm 0.3) \times 10^{-10}$				
				$\left(1.11^{+0.34}_{-0.24}\right) \times 10^{-10}$				
			J/ψ	$(1.1-1.3) \times 10^{-10}$				
				2.3×10^{-14}				
				2.7×10^{-11}				
				$(1.1-4.1) \times 10^{-12}$				
			χ_{c0}	8.3×10^{-14}				
	J/ψ	+		$(4.7 \pm 2.0) \times 10^{-13}$				
Z →			χ_{c1}	$(3.5-4.4) \times 10^{-12}$				
				3.5×10^{-15}				
				1.5×10^{-12}				

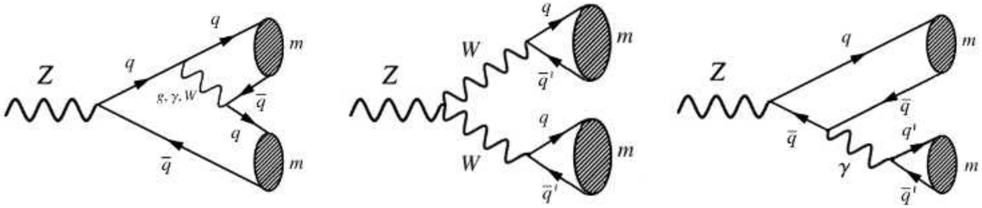
M	+	M	Branching fraction	Framework	Exp. limits 2023	HL-LHC	Producible at FCC-ee
		h_c	1.5×10^{-12}	NRQCD+LDME [121]	–	–	✓
			$(9.5 \pm 5.0) \times 10^{-12}$	LC+LCDA [121]			
			$(9.6-24.8) \times 10^{-13}$	NRQCD+LDME (NLO) [122]			
		χ_{c2}	1.4×10^{-13}	NRQCD+LDME [121]	–	–	✓
			$(9.3 \pm 4.0) \times 10^{-13}$	LC+LCDA [121]			
		χ_{c1}	7.6×10^{-14}	NRQCD+LDME [121]	–	–	✘
χ_{c0}	+		$(1.4 \pm 1.0) \times 10^{-12}$	LC+LCDA [121]			
		h_c	3.5×10^{-16}	NRQCD+LDME [121]	–	–	✘
		χ_{c2}	6.4×10^{-15}	NRQCD+LDME [121]	–	–	✘
		χ_{c1}	3.9×10^{-16}	NRQCD+LDME [121]	–	–	✘
		h_c	2.9×10^{-14}	NRQCD+LDME [121]	–	–	✘
χ_{c1}	+		$(6.1 \pm 5.0) \times 10^{-13}$	LC+LCDA [121]			
		χ_{c2}	1.3×10^{-13}	NRQCD+LDME [121]	–	–	✘
			$(2.8 \pm 2.0) \times 10^{-12}$	LC+LCDA [121]			
h_c	+	h_c	9.9×10^{-17}	NRQCD+LDME [121]	–	–	✘
		χ_{c2}	2.3×10^{-16}	NRQCD+LDME [121]	–	–	✘
χ_{c2}	+	χ_{c2}	1.3×10^{-16}	NRQCD+LDME [121]	–	–	✘



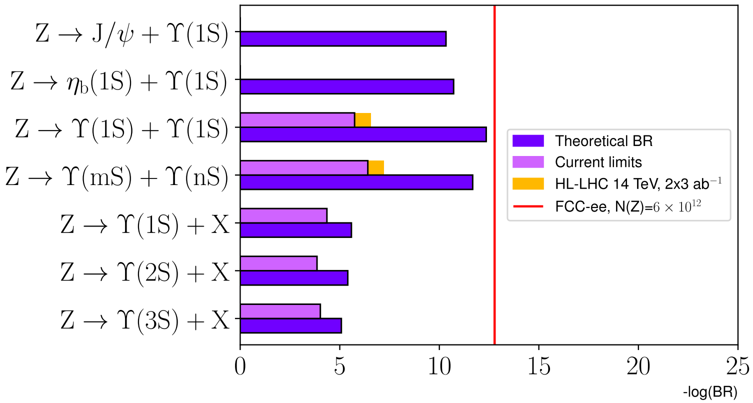


- Theory BRs: O(10^{-10} – 10^{-17}). Exp. limits: O(10^{-6})
- 1 channel searched for. 10 producible channels at FCC-ee
- Calculations are carried out in multiple frameworks (LC, RQM, NRQCD/NRCSM, NRQCD). More contributions are considered overtime.
- Most promising place to study double meson decay.

Z→ b-meson + b-meson



Z →	M	+	M	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at at FCC-ee
Z →	J/ψ	+	$\Upsilon(1S)$	4.6×10^{-11}	NRQCD [119]	–	–	✓
	$\eta_b(1S)$	+	$\Upsilon(1S)$	$(1.9 \pm 0.2) \times 10^{-11}$	NRQCD/NRCSM [120]	–	–	✓
	$\Upsilon(1S)$	+	$\Upsilon(1S)$	$\left(4.4^{+0.6}_{-0.3}\right) \times 10^{-13}$	NRQCD/NRCSM [120]	$< 1.8 \times 10^{-6}$ [99]	$\lesssim 2.7 \times 10^{-7}$	✓
	$\Upsilon(mS)$	+	$\Upsilon(nS)$	2.1×10^{-12}	NRQCD [119]	$< 3.9 \times 10^{-7}$ [99]	$\lesssim 5.9 \times 10^{-8}$	✓
Z →	$\Upsilon(1S)$	+	X	$(2.6 - 2.9) \times 10^{-6}$	NRQCD+LDME (NLO) [161]	$< 4.4 \times 10^{-5}$ [162]	–	✓
	$\Upsilon(2S)$	+	X	$(3.7 - 4.3) \times 10^{-6}$	NRQCD+LDME (NLO) [161]	$< 1.4 \times 10^{-4}$ [163]	–	✓
	$\Upsilon(3S)$	+	X	$(7.6 - 8.3) \times 10^{-6}$	NRQCD+LDME (NLO) [161]	$< 9.4 \times 10^{-5}$ [163]	–	✓
	$\Upsilon(nS)$	+	X	$(1.4 - 1.5) \times 10^{-5}$	NRQCD+LDME (NLO) [161]	$(1.0 \pm 0.5) \times 10^{-4}$ [164]	–	✓



- Theory BRs: O(10^{-10} – 10^{-17}). Exp. limits: O(10^{-4} – 10^{-7})
- 5 channels searched for. 7 producible channels at FCC-ee
- Most promising place to study double-bottomonia decays.

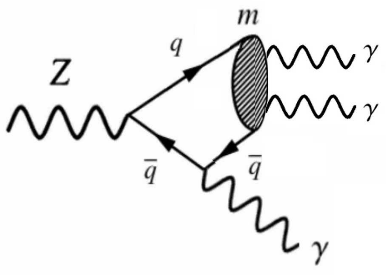
4. Background to BSM searches

- Backgrounds due to rare/exclusive H,Z,W,t decays are usually neglected in BSM searches.
- Exclusive decay channels may share the same final states as in BSM searches: e.g. Meson> $\gamma\gamma$ and ALP> $\gamma\gamma$
- With large number of Z bosons at FCC-ee, rare/exclusive decays become potentially large backgrounds for BSM searches.

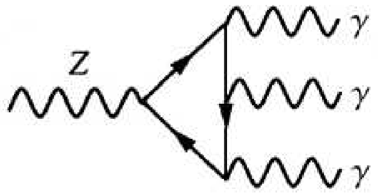
$\rightarrow$ We suggest these decays should be considered as background for BSM searches at FCC-ee

BSM example in Z → 3 photon

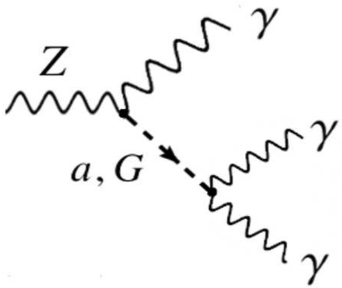
$Z \to \gamma$	+	$X(\gamma\gamma)$	Branching fraction
		$\pi^0(\gamma\gamma)$	9.7×10^{-12}
		$\eta(\gamma\gamma)$	6.3×10^{-11}
		$\eta'(\gamma\gamma)$	1.1×10^{-10}
		$\eta_c(\gamma\gamma)$	2.1×10^{-12}
$Z \to \gamma$	+	$\chi_{c0}(\gamma\gamma)$	7.6×10^{-14}
		$\chi_{c1}(\gamma\gamma)$	1.5×10^{-14}
		$\chi_{c2}(\gamma\gamma)$	9.6×10^{-14}
		$\chi_{b0}(\gamma\gamma)$	1.6×10^{-14}
		$\chi_{b2}(\gamma\gamma)$	1.6×10^{-14}
Sum			1.8×10^{-10}
Z	$\longrightarrow$	$\gamma\gamma\gamma$	6.4×10^{-10}



Exclusive SM final state



direct SM decay



BSM process

- Z → 3γ decay is very suppressed in the SM (6.5 10^{-10}). ~1000 events at the FCCee
- Z → γ + meson(γγ) provides about 30% extra contributions to the SM BR[Z→3γ] .~300 events
- Z → γ + a(γγ) is a typical ALP/graviton search channel. 10 mesonic channels share similar final state.

→ Rare & Exclusive decays need to be considered in BSM searches at FCCee

Summary

- Comprehensive survey of the theoretical & experimental status of more than 200 rare and exclusive few-body decays of the 4 heaviest SM particles (H,Z,W,t). They can be used for:
  - Determining Higgs Yukawa coupling - upper bound for lighter quarks couplings
  - Searches for BSM FCNC decays of H, Z and top quark
  - Studies of QCD factorization/meson formation
  - Backgrounds to many BSM decays (H,Z $\rightarrow$ ALPs, gravitons, dark γ, …) at FCC-ee

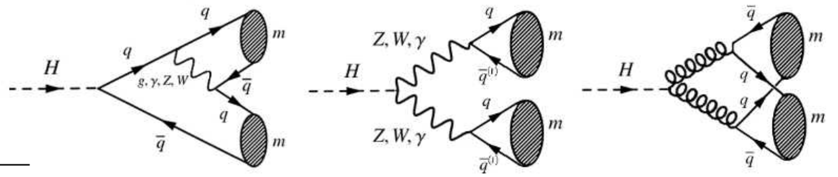
- Estimation of reachabilities of HL-LHC, FCC-ee/FCC-hh observations (if not BSM-enhanced):
  - HL-LHC can potentially observe a few of them: $H \rightarrow \gamma+\rho$, $Z \rightarrow \gamma+\omega$, $Z \rightarrow \gamma+J/\psi$
  - FCC-ee can discover about 50% of such experimentally unobserved decays
  - FCC-hh can produce most of those decays channels

Backup

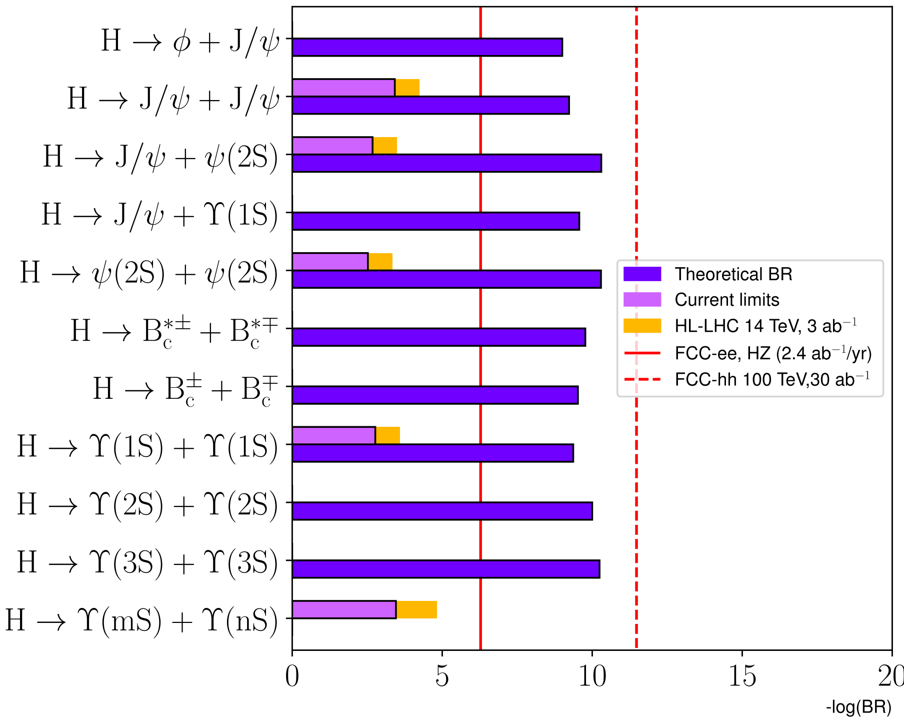
Summary

- Comprehensive survey of the theoretical & experimental status of more than 150 rare and exclusive few-body decays of the 4 heaviest SM particles (H,Z,W,t)
  - Sensitive to BSM physics scenarios (FCNC), backgrounds to many BSM decays (H,Z → ALPs, gravitons, dark γ, ...), and study of pQCD factorization/meson formation.
- Up-to-date collection of TH BRs and EXP limits from the literature.
  - Current LHC limits for 44 decays.
- Calculation of new rare decay channels: radiative leptonium, exclusive Higgs FCNC decays, Z boson 3-body decays, semiexclusive t → b-quark +m, ...
  - H, Z → leptonium + γ decays: Tiny. Very hard to measure.
- Estimation of reachabilities of HL-LHC, FCC-ee/FCC-hh observations (if not BSM-enhanced):
  - HL-LHC can potentially observe a few of them: H→γ+ρ, Z→γ+ω, Z→γ+J/ψ
  - FCC-ee can discover about 50% of such experimentally unobserved decays
  - FCC-hh can produce most all those decays channels

Exclusive Higgs decays
H → meson + meson

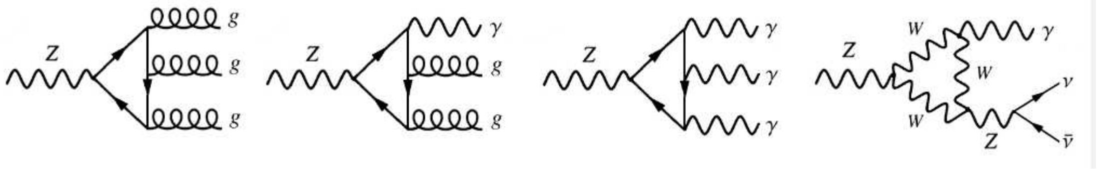


H →	X	+	X	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
H→	ϕ	+	J/ψ	1.0 $\times10^{-9}$	LC+LCDA [96]	–	–	✘	✓
	J/ψ	+	J/ψ	(5.8 – 6.0) $\times10^{-9}$	NRQCD+LDME [101]	$< 3.8\times10^{-4}$ [90]	$\lesssim 5.8\times10^{-5}$	✘	✓
				1.7 $\times10^{-10}$	RQM [98]				
				2.1 $\times10^{-10}$	RQM [100]				
				(5.9 ± 2.3) $\times10^{-10}$	NRQCD/NRCSM [99]				
				1.5 $\times10^{-10}$	LC+LCDA [96]				
	$\psi(2S)$	+	J/ψ	5.0 $\times10^{-11}$	–	$< 2.1\times10^{-3}$ [90]	$\lesssim 3.2\times10^{-4}$	✘	✓
			$\psi(2S)$	(5.1 ± 2.0) $\times10^{-11}$	NRQCD/NRCSM [99]	$< 3.0\times10^{-3}$ [90]	$\lesssim 4.5\times10^{-4}$	✘	✓
	$B_c^{*\mp}$	+	$B_c^{*\pm}$	(1.4 – 1.7) $\times10^{-10}$	RQM [97]	–	–	✘	✓
	$B_c^{\mp}$	+	$B_c^{\pm}$	(2.0 – 3.0) $\times10^{-10}$	RQM [97]	–	–	✘	✓
	$\Upsilon(1S)$	+	J/ψ	(2.7 – 3.6) $\times10^{-10}$	NRQCD+LDME [101]	–	–	✘	✓
				1.6 $\times10^{-11}$	LC+LCDA [96]				
			$\Upsilon(1S)$	(8.5 – 9.2) $\times10^{-10}$	NRQCD+LDME [101]	$< 1.7\times10^{-3}$ [90]	$\lesssim 2.6\times10^{-4}$	✘	✓
				1.8 $\times10^{-10}$	RQM [98]				
				2.3 $\times10^{-9}$	RQM [100]				
				(4.3 ± 0.9) $\times10^{-10}$	NRQCD/NRCSM [99]				
				2.3 $\times10^{-9}$	LC+LCDA [96]				
	$\Upsilon(2S)$	+	$\Upsilon(2S)$	(1.0 ± 0.2) $\times10^{-10}$	NRQCD/NRCSM [99]	–	–	✘	✓
	$\Upsilon(3S)$	+	$\Upsilon(3S)$	(5.7 ± 1.2) $\times10^{-11}$	NRQCD/NRCSM [99]	–	–	✘	✓
	$\Upsilon(mS)$	+	$\Upsilon(nS)$		–	$< 3.5\times10^{-4}$ [90]	$\lesssim 1.5\times10^{-5}$ [56]	✘	✘

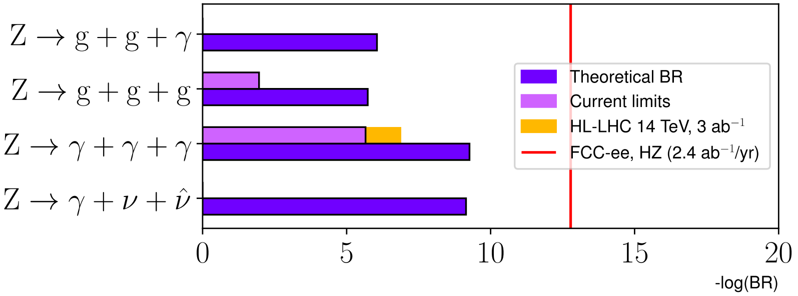


- Theory BRs: O(10^{-9}–10^{-11}). Exp. limits: O(10^{-3} – 10^{-4}).
- 5 channels searched-for. No (all) producible channels at FCC-ee (FCC-hh)
- Many predictions for double-QQbar from adding more contributing diagrams.

Rare Z decays

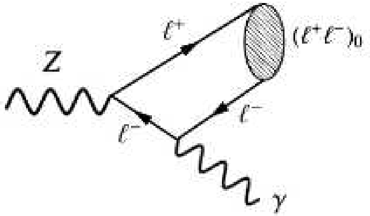


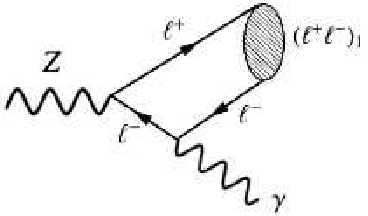
Z→ X+Y+Z	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee
$Z \to g+g+g$	1.9×10^{-6} $(1.752^{+0.003}_{-0.003}) \times 10^{-6}$	NLO QCD [107] NLO QCD This work	$< 1.1\times 10^{-2}$ [109]	?	✓
$Z \to \gamma+g+g$	8.8×10^{-7} $(6.62 \pm 0.01) \times 10^{-7}$	NLO QCD [105] NLO QCD+EW This work	–	–	✓
$Z \to \gamma+\gamma+\gamma$	5.4×10^{-10} $(6.58 \pm 0.01) \times 10^{-10}$	NLO QCD+EW [106] NLO EW This work	$< 2.2\times 10^{-6}$ [110]	$\lesssim 1.3 \times 10^{-7}$	✓
$Z \to \gamma+\nu+\hat{\nu}$	7.2×10^{-10} $(1.195^{+0.003}_{-0.003}) \times 10^{-10}$	NLO EW [108] NLO QCD+EW This work	–	–	✓



- Theory BRs: O(10^{-5} – 10^{-10}). Exp. limits: O(10^{-2} – 10^{-6}).
- 2 channels searched for. 4 producible channels at FCC-ee.
- Recomputed/Updated with MG5@NLO here.
- All SM channels are unobservable at HL-LHC, but will be cleanly visible at FCC-ee

Exclusive Z decays
Z→ γ + leptonium

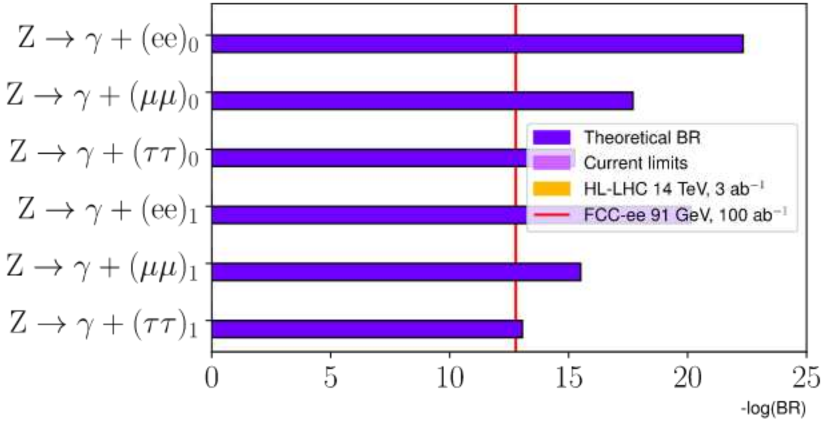




$$\mathcal{B}(Z \to (\ell^+\ell^-)_0 + \gamma) = \frac{\alpha(0)^4 \alpha(m_Z)^2}{9 \cdot 256\, n^3} \frac{m^2_{\ell^+\ell^-}}{m_Z^2} \frac{\left(1-4s_w^2\right)^2 \left(8s_w^4 - 4s_w^2 + 1\right)\left(m_Z^2 - m^2_{\ell^+\ell^-}\right)}{\Gamma_{ee}\Gamma_Z s_w^4 c_w^4}$$

$$\mathcal{B}(Z \to (\ell^+\ell^-)_1 + \gamma) = \frac{\alpha(0)^4 \alpha(m_Z)^2}{9 \cdot 256\, n^3} \frac{m^2_{\ell^+\ell^-}}{m_Z^4} \frac{\left(8s_w^4 - 4s_w^2 + 1\right)\left(m_Z^4 - m^4_{\ell^+\ell^-}\right)}{\Gamma_{ee}\Gamma_Z s_w^4 c_w^4}$$

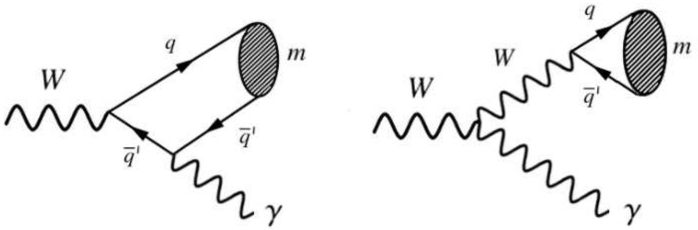
				Exp. limits		Producible at
$Z \to \gamma$ +	X	Branching fraction	Framework	2023	HL-LHC	FCC-ee
$Z \to \gamma$ +	$(ee)_0$	4.7×10^{-23}	This work	–	–	✘
	$(\mu\mu)_0$	2.0×10^{-18}	This work	–	–	✘
	$(\tau\tau)_0$	5.7×10^{-16}	This work	–	–	✘
	$(ee)_1$	7.3×10^{-21}	This work	–	–	✘
	$(\mu\mu)_1$	3.1×10^{-16}	This work	–	–	✘
	$(\tau\tau)_1$	8.9×10^{-14}	This work	–	–	✘



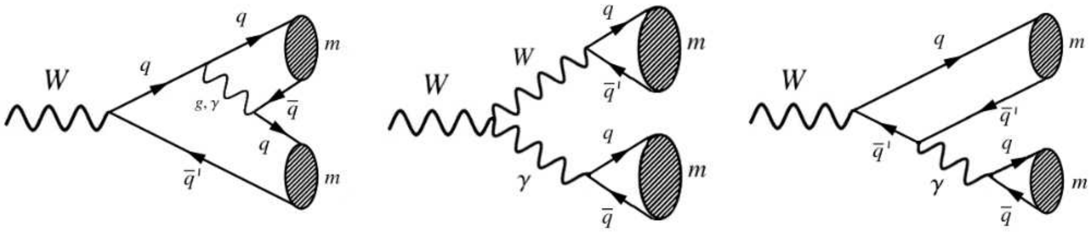
- Tiny BRs: O(10^{-14} – 10^{-23}). First time computed here.
- No channel searched-for. No producible channel at FCC-ee.
- Note: Leptonia are long-lived = LLP signature (displaced γ, e, μ vertices)

Exclusive W decays

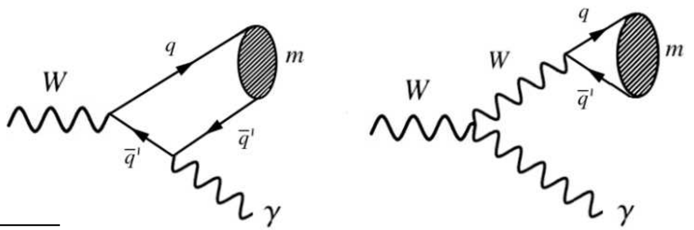
- <u>Exclusive W decays</u>:
  - Similar mechanism to exclusive Z and H decays.
  - Provides cross-check of pQCD factorization models and info on open-flavour meson form factors.
  - Exclusive Z decays into:
    - γ + 1 charged meson



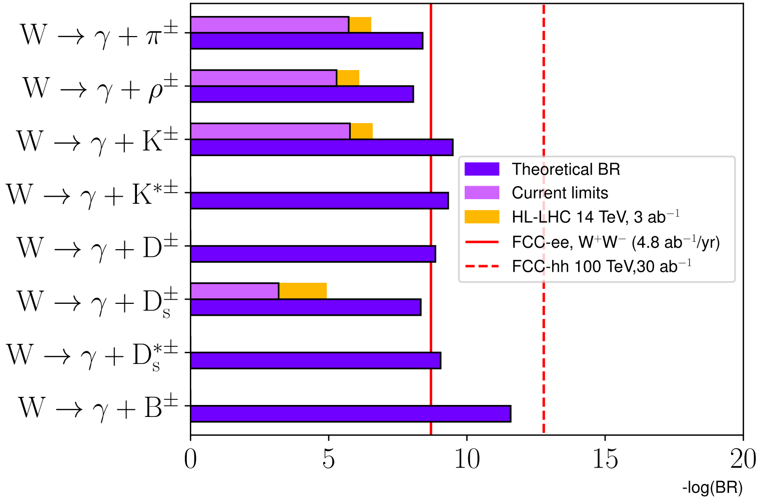
    - Meson + charged meson



Exclusive W decays
W→ γ + meson



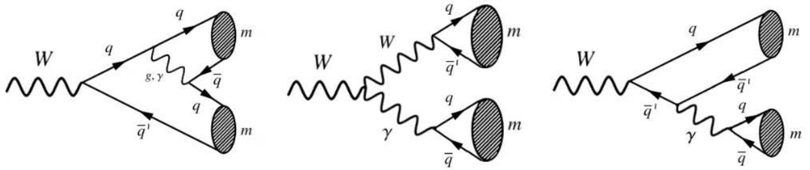
$W^{\mp} \to \gamma$ +	X	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
	$\pi^{\pm}$	$(4.0 \pm 0.8)\ \times 10^{-9}$	SCET+LCDA [58]	$< 1.9\times10^{-6}$ [136, 137]	$\lesssim 2.9\times10^{-7}$	✓	✓
	$\rho^{\pm}$	$(8.74 \pm 1.91)\ \times 10^{-9}$	SCET+LCDA [58]	$< 5.2\times10^{-6}$ [136]	$\lesssim 7.9\times10^{-7}$	✓	✓
	$K^{\pm}$	$(3.25 \pm 0.69)\ \times 10^{-10}$	SCET+LCDA [58]	$< 1.7\times10^{-6}$ [136]	$\lesssim 2.6\times10^{-7}$	✘	✓
	$K^{*\pm}$	$(4.78 \pm 1.15)\ \times 10^{-10}$	SCET+LCDA [58]	–	–	✘	✓
	$D^{\pm}$	$\left(1.4^{+0.5}_{-0.3}\right)\ \times 10^{-9}$	SCET+LCDA [58]	–	–	✘	✓
$W^{\mp} \to \gamma$ +	$D_s^{\pm}$	$\left(3.7^{+1.5}_{-0.8}\right)\ \times 10^{-8}$	SCET+LCDA [58]	$< 6.5\times10^{-4}$ [115]	$\lesssim 1.2\times10^{-5}$	✓	✓
		$4.7\ \times 10^{-9}$	NRQCD+LDME [138]				
		$3.4\ \times 10^{-9}$	LC+LCDA [138]				
	$D_s^{*\pm}$	$8.9\ \times 10^{-10}$	NRQCD+LDME [138]	–	–	✘	✓
		$3.4\ \times 10^{-9}$	LC+LCDA [138]				
	$B^{\pm}$	$\left(1.6^{+0.8}_{-0.6}\right)\ \times 10^{-12}$	SCET+LCDA [58]	–	–	✘	✓
		$\left(2.6^{+3.1}_{-1.3}\right)\ \times 10^{-12}$	HQET+LCDA [139]				
		$\left(2.0^{+2.5}_{-0.8}\right)\ \times 10^{-12}$	SCET+LCDA[a] [139]				

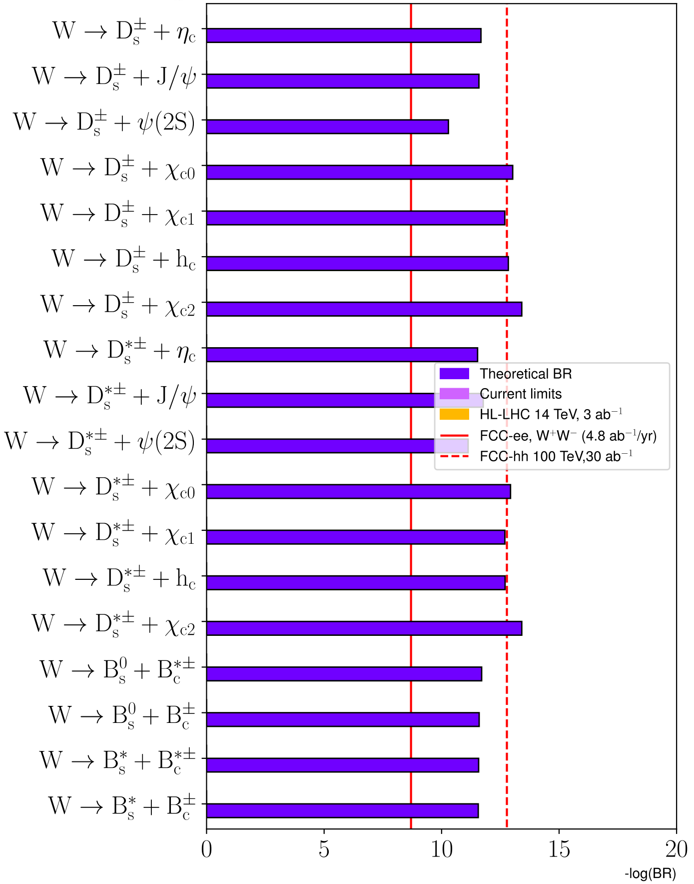


- Theory BRs: O(10^{-8} – 10^{-12}). Exp. limits: O(10^{-4} – 10^{-6})
- 4 channels searched-for.
- 3 (5) channels producible at FCC-ee (FCC-hh)

Exclusive W decays
W→ meson + meson

$W^\pm \to$	X	+	X	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
$W^\pm \to$	η_c	+	$D_s^\pm$	2.1×10^{-12}	NRCSM+LCDA [140]	–	–	✘	✓
				$(1.3^{+0.3}_{-0.2}) \times 10^{-11}$	LC+LCDA [140]				
			$D_s^{*\pm}$	3.0×10^{-12}	NRCSM+LCDA [140]	–	–	✘	✓
				$(1.5^{+0.4}_{-0.2}) \times 10^{-11}$	LC+LCDA [140]				
	J/ψ	+	$D_s^\pm$	2.6×10^{-12}	NRQCD+LDME [138]	–	–	✘	✓
				2.1×10^{-12}	NRCSM+LCDA [140]				
				$(1.8^{+0.4}_{-0.2}) \times 10^{-11}$	LC+LCDA [140]				
			$D_s^{*\pm}$	1.7×10^{-12}	NRQCD+LDME [138]	–	–	✘	✓
				3.0×10^{-12}	NRCSM+LCDA [140]				
				$(2.0^{+0.5}_{-0.2}) \times 10^{-11}$	LC+LCDA [140]				
	$\psi(2S)$	+	$D_s^\pm$	5.1×10^{-11}	NRQCD+LDME [138]	–	–	✘	✓
			$D_s^{*\pm}$	7.4×10^{-12}	NRQCD+LDME [138]	–	–	✘	✓
	χ_{c0}	+	$D_s^\pm$	9.4×10^{-14}	NRQCD+LDME [138]				
				4.7×10^{-14}	NRCS				
				$(7.1^{+3.5}_{-3.1}) \times 10^{-13}$	LC+L				
			$D_s^{*\pm}$	1.2×10^{-13}	NRQ				
				8.1×10^{-14}	NRCS				
				$(8.0^{+3.7}_{-3.1}) \times 10^{-13}$	LC+L				
	χ_{c1}	+	$D_s^\pm$	2.0×10^{-13}	NRQ				
				2.9×10^{-13}	NRCS				
				$(7.8^{+3.4}_{-3.0}) \times 10^{-12}$	LC+L				
			$D_s^{*\pm}$	2.0×10^{-13}	NRQ				
				4.0×10^{-13}	NRCS				
				$(8.8^{+3.5}_{-3.1}) \times 10^{-12}$	LC+L				
			$D^\pm$	1.4×10^{-13}	NRCS				
	h_c	+	$D_s^\pm$	1.4×10^{-13}	NRCSM+LCDA [140]	–	–	✘	✘
				$(2.1^{+1.0}_{-0.8}) \times 10^{-12}$	LC+LCDA [140]				
			$D_s^{*\pm}$	2.0×10^{-13}	NRCSM+LCDA [140]	–	–	✘	✓
				$(2.4^{+1.1}_{-0.9}) \times 10^{-12}$	LC+LCDA [140]				
	χ_{c2}	+	$D_s^\pm$	3.9×10^{-14}	NRQCD+LDME [138]	–	–	✘	✘
				9.6×10^{-14}	NRCSM+LCDA [140]				
				$(1.4^{+0.6}_{-0.5}) \times 10^{-12}$	LC+LCDA [140]				
			$D_s^{*\pm}$	3.9×10^{-14}	NRQCD+LDME [138]	–	–	✘	✘
				1.4×10^{-13}	NRCSM+LCDA [140]				
				$(1.6^{+0.7}_{-0.6}) \times 10^{-12}$	LC+LCDA [140]				
	B_s^0	+	$B_c^{*\pm}$	2.0×10^{-12}	NRQCD+LDME [138]	–	–	✘	✓
			$B_c^\pm$	2.5×10^{-12}	NRQCD+LDME [138]	–	–	✘	✓
	B_s^*	+	$B_c^{*\pm}$	2.7×10^{-12}	NRQCD+LDME [138]	–	–	✘	✓
			$B_c^\pm$	2.7×10^{-12}	NRQCD+LDME [138]	–	–	✘	✓





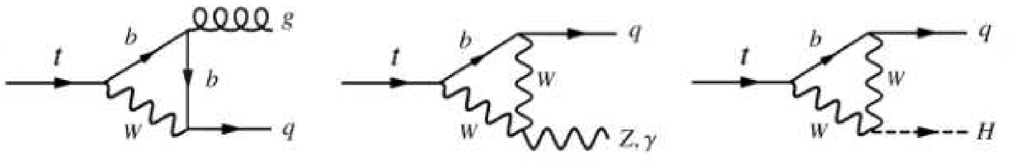
- Theory BRs: $O(10^{-11} - 10^{-14})$. No existing exp. limit
- No channels searched-for anywhere.
- No (13) channels producible at FCC-ee (FCC-hh)

Rare top decays

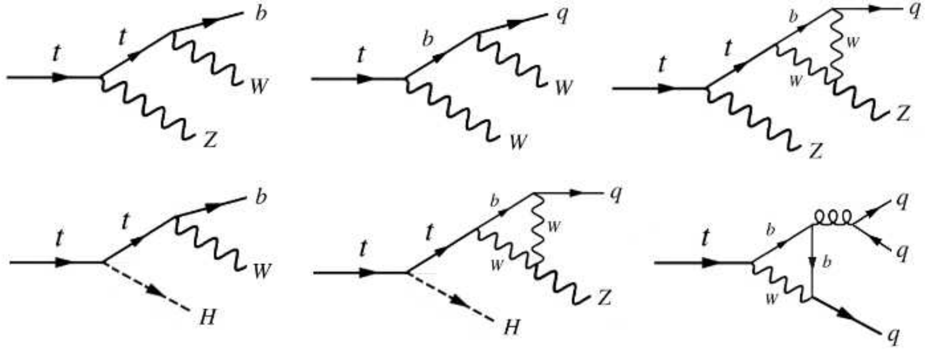
- The FCNC top-quark decays:

  t → Zq, t → cγ, and t → cg;

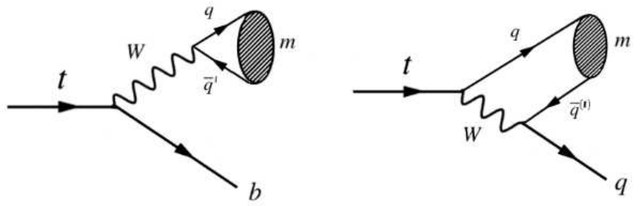
  Highly suppressed in the SM (loops, GIM), but significantly enhanced in BSM models



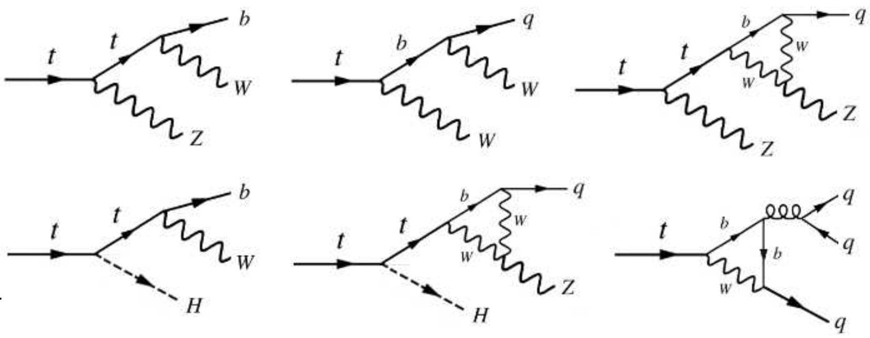
- Three-body top decays:
  possible thanks to the
  large top mass
  → multiple onshell heavy boson
  decays kinematically accessible



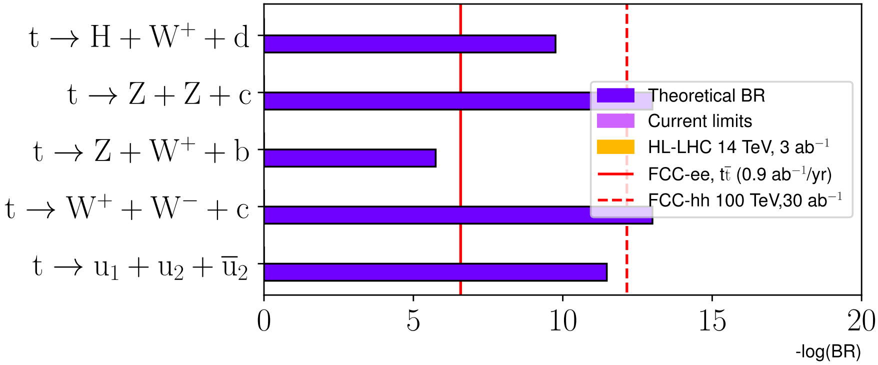
- Semi-exclusive top quark decays:
  t → q+meson: alternative m_{top} determination?



Rare 3-body top-quark decays

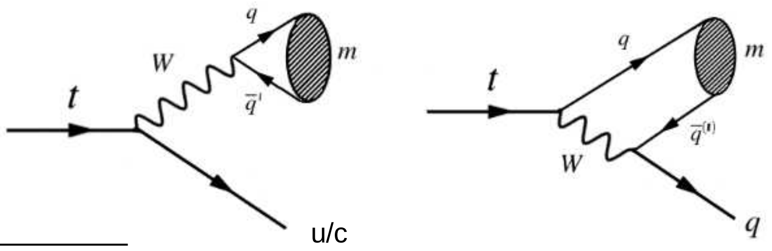


t →	X	+	Y	+	Z	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
t	H	+	W^+	+	d	1.8×10^{-10}	NLO QCD+EW This work	–	–	✘	✓
			Z	+	c	$< 1.0 \times 10^{-13}$	LO SM [151]	–	–	✘	✘
	Z	+	W^+	+	b	1.8×10^{-6}	LO SM [152]	–	–	✓	✓
						$\left(5.4^{+4.7}_{-2.0}\right) \times 10^{-7}$	LO SM [148]				
						2.0×10^{-6}	LO SM [149]				
	W^+	+	W^-	+	c	1.0×10^{-13}	LO [26]	–	–	✘	✘
						2.0×10^{-13}	LO SM [151]				
	u_2	+	u_1	+	$\bar{u}_2$	3.4×10^{-12}	1-loop SM [150]	–	–	✘	✓

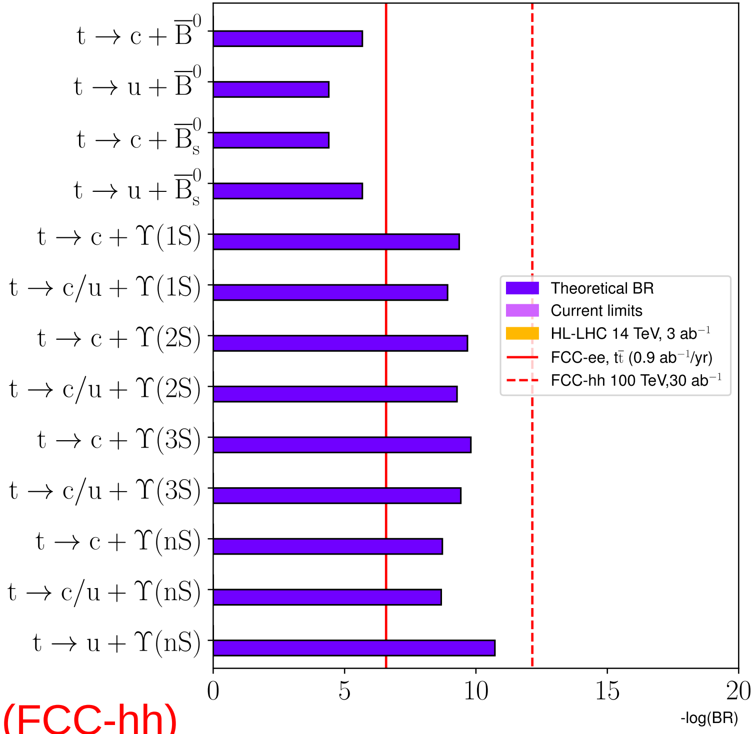


- Theory BRs: $O(10^{-6} - 10^{-13})$. No existing exp. limits
- 4 channels searched-for. 1 (3) channels producible at FCC-ee (FCC-hh)
- Note: t→ Z+W+b (91.2+80.4+4. GeV ≈ m_{top}) has "large" BR: $2 \cdot 10^{-6}$

Semi-exclusive decays
t → meson + c/u quark

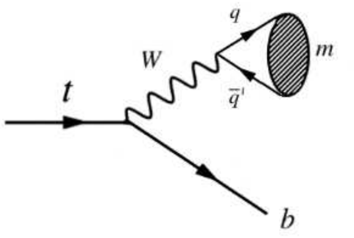


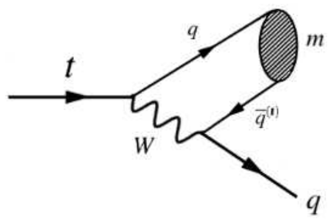
t →	X	+	Y	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
t →	$\overline{B}^0$	+	c	$(2.1^{+2.1}_{-1.1})\ \times10^{-6}$	NRQCD+LDME [25]	–	–	✓	✓
			u	$(4.0^{+4.0}_{-2.0})\ \times10^{-5}$	NRQCD+LDME [25]	–	–	✓	✓
	$\overline{B}^0_s$	+	c	$(4.0^{+4.0}_{-2.0})\ \times10^{-5}$	NRQCD+LDME [25]	–	–	✓	✓
			u	$(2.1^{+2.1}_{-1.1})\ \times10^{-6}$	NRQCD+LDME [25]	–	–	✓	✓
	$\Upsilon(1S)$	+	c	$4.3\ \times10^{-10}$	NRQCD+CSM [155]	–	–	✘	✓
				$(6.4 \pm 1.3)\ \times10^{-10}$	NRQCD+COM [154]				
			c/u	$(1.0 – 1.5)\ \times10^{-9}$	NRQCD+LDME [25]	–	–	✘	✓
	$\Upsilon(2S)$	+	c	$2.1\ \times10^{-10}$	NRQCD+CSM [155]	–	–	✘	✓
			c/u	$(1.7 – 5.3)\ \times10^{-10}$	NRQCD+LDME [25]	–	–	✘	✓
	$\Upsilon(3S)$	+	c	$1.6\ \times10^{-10}$	NRQCD+CSM [155]	–	–	✘	✓
			c/u	$(2.7 – 3.8)\ \times10^{-10}$	NRQCD+LDME [25]	–	–	✘	✓
	$\Upsilon(nS)$	+	c	$(1.9^{+0.2}_{-0.1})\ \times10^{-9}$	NRQCD+LDME [25]	–	–	✘	✓
			c/u	$(1.5 – 2.1)\ \times10^{-9}$	NRQCD+LDME [25]	–	–	✘	✓
			u	$(1.9^{+0.2}_{-0.1})\ \times10^{-11}$	NRQCD+LDME [25]	–	–	✘	✓



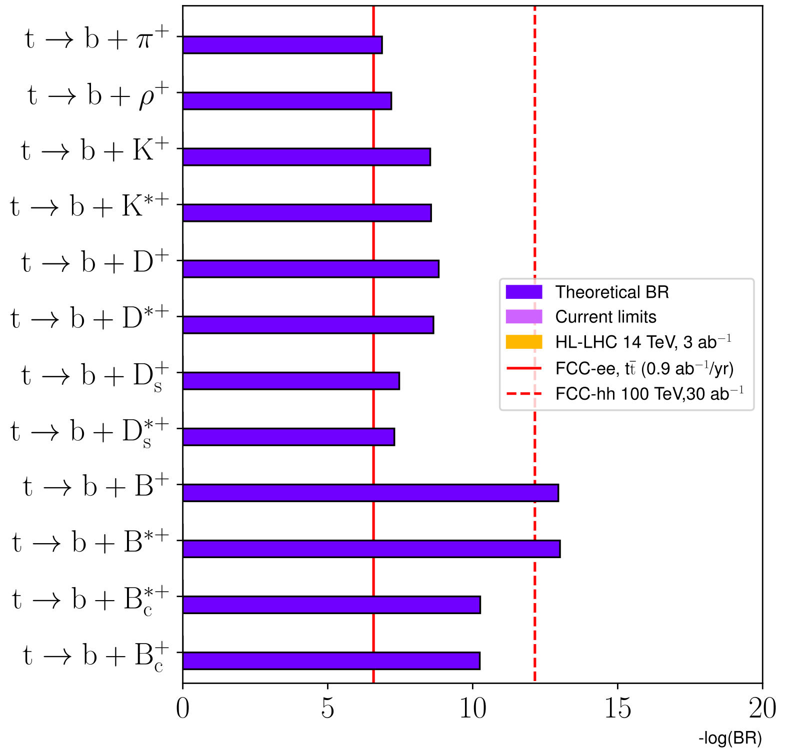
- Theory BRs: O(10^{-5} – 10^{-11}). No existing exp. limits
- No channel searched for. 4 (9) visible channels at FCC-ee (FCC-hh)
- Note: t→ B+c/u-quark have "large" BR: $4\cdot10^{-5}$

Semi-exclusive decays
t → meson + b quark





t →	X	+	Y	Branching fraction	Framework	Exp. limits 2023	Exp. limits HL-LHC	Producible at FCC-ee	Producible at FCC-hh
	π^+	+	b	$1.3\ \times10^{-7}$	EFT+LCDA This work	–	–	✘	✓
	ρ^+	+	b	$6.4\ \times10^{-8}$	EFT+LCDA This work	–	–	✘	✓
	K^+	+	b	$2.9\ \times10^{-9}$	EFT+LCDA This work	–	–	✘	✓
	K^{*+}	+	b	$2.7\ \times10^{-9}$	EFT+LCDA This work	–	–	✘	✓
	D^+	+	b	$1.5\ \times10^{-9}$	EFT+LCDA This work	–	–	✘	✓
t →	D^{*+}	+	b	$2.3\ \times10^{-9}$	EFT+LCDA This work	–	–	✘	✓
	D_s^+	+	b	$3.4\ \times10^{-8}$	EFT+LCDA This work	–	–	✘	✓
	D_s^{*+}	+	b	$5.1\ \times10^{-8}$	EFT+LCDA This work	–	–	✘	✓
	B^+	+	b	$1.1\ \times10^{-13}$	EFT+LCDA This work	–	–	✘	✘
	B^{*+}	+	b	$9.8\ \times10^{-14}$	EFT+LCDA This work	–	–	✘	✘
	B_c^{*+}	+	b	$5.5\ \times10^{-11}$	EFT+LCDA This work	–	–	✘	✓
	B_c^+	+	b	$5.7\ \times10^{-11}$	EFT+LCDA This work	–	–	✘	✓



- Theory BRs: O(10^{-7} – 10^{-14}). No existing exp. limits
- No channel searched for. No (10) visible channels at FCC-ee(FCC-hh)
- First time those decays have been estimated.

Outlook

- Paper (~50 pages) in preparation…

We hope it motivates people (LHC, FCC-ee) to perform new BSM searches...
(and find new physics ;-))

Rare and exclusive few-body decays of the Higgs, Z, W bosons, and the top quark

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(Dated: October 17, 2023)

We perform an extensive survey of rare and exclusive few-body decays —defined as those with two or three final-state particles, and branching fractions $\mathcal{B} \lesssim 10^{-5}$— of the Higgs, Z, and W bosons, and the top quark. Such rare decays can probe physics beyond the Standard Model (BSM), may constitute a background for possible decays into new BSM particles, and/or provide precise information on quantum chromodynamics factorization with small nonperturbative corrections. First, we collect and tabulate the $\mathcal{B}$ values calculated for more than 150 decay channels of the four heaviest elementary particles, indicating the current experimental limits in their observation. Second, we compute for the first time H and Z boson decays into leptonium-plus-photon, very rare H boson decays to photons and/or neutrinos, and radiative H and Z quark-flavour-changing exclusive decays, while revisiting and updating predictions for a few other rare Z boson and top quark partial widths. Third, the feasibility of measuring each of these unobserved decays is estimated for proton-proton collisions at the high-luminosity Large Hadron Collider (HL-LHC), and for e^+e^- and p-p collisions at the future circular collider (FCC).

I. INTRODUCTION

With the discovery of the Higgs boson at the CERN Large Hadron Collider (LHC) ten years ago [1, 2], the full particle content of the Standard Model (SM) of particle physics has become fully fixed. Among the 17 existing elementary particles (6 quarks, 6 leptons, 4 gauge bosons, and the scalar boson), the top quark, the Higgs and the electroweak (W, Z) bosons are the most massive ones. Studying in detail the properties of the four heaviest elementary particles, with masses around the electroweak scale $\Lambda_{EW} \approx \mathcal{O}(100\text{ GeV})$, is an important priority in precision SM studies and in searches for new physics beyond it (BSM). At the LHC, the large center-of-mass (c.m.) energies and integrated luminosities (up to $\mathcal{L}_{int} = 3\text{ ab}^{-1}$ expected at the end of the high-luminosity, HL-LHC, phase) [3] available in