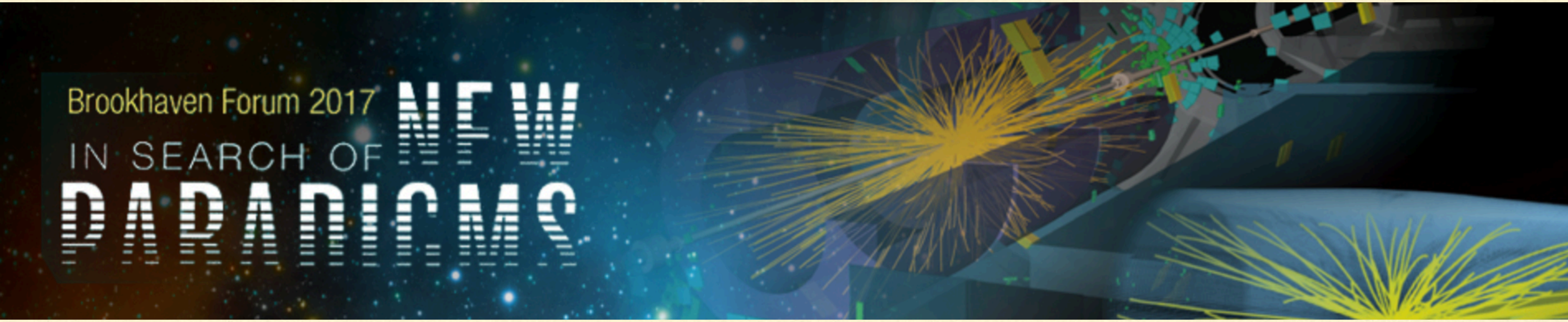


Radiative Higgs Decay to a Fermion Pair

Xing Wang

University of Pittsburgh

BF 2017 @ BNL

Oct 12, 2017

Tao Han & XW, arXiv:1704.00790

Introduction

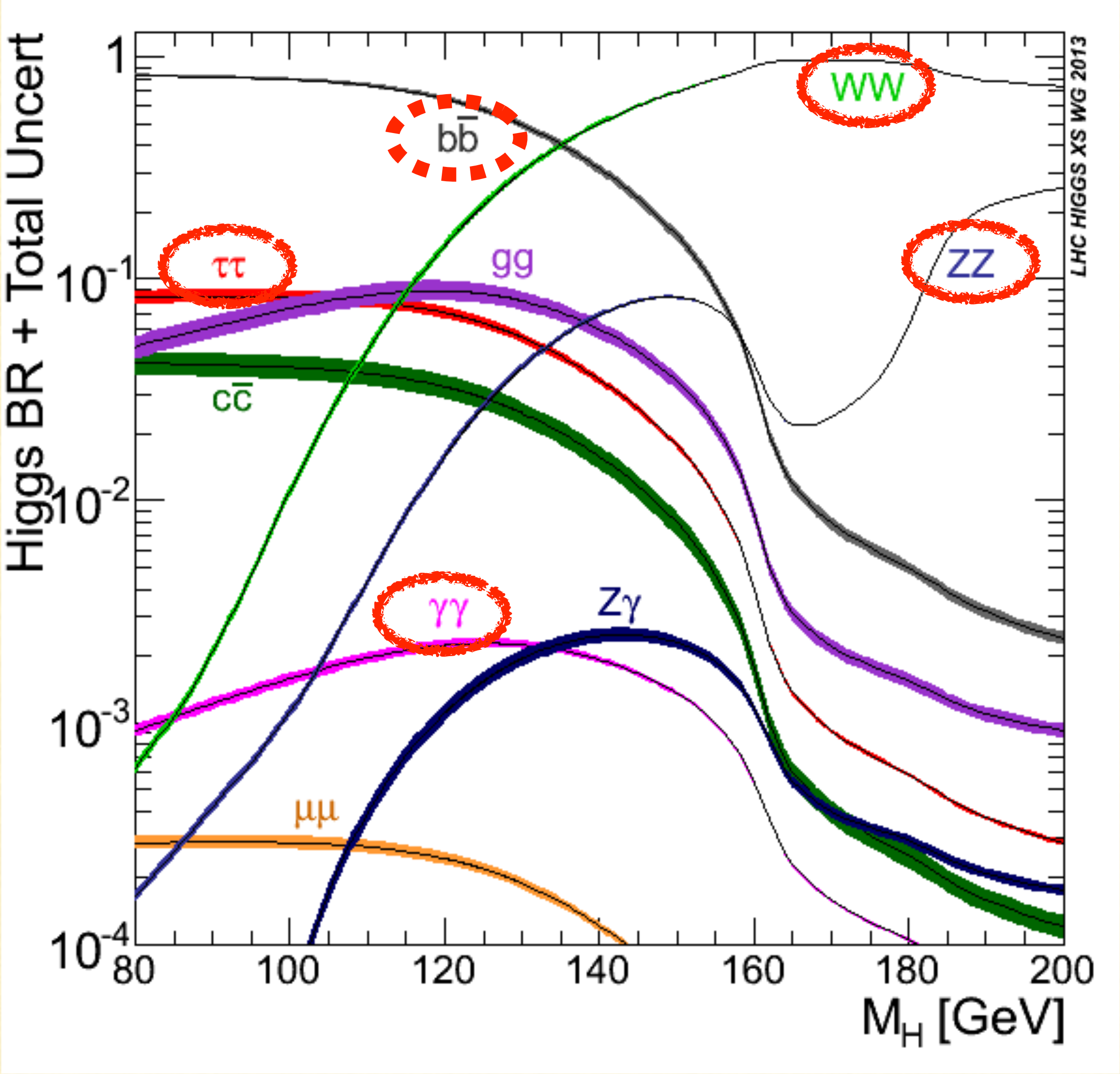
- Higgs for the next 20 years!
- Since the Higgs discovery, only handful decay channels observed:

$$h \to \gamma\gamma, ZZ^*, WW^*, \tau\tau, (b\bar{b})$$

- A huge amount of data at future HL-LHC:

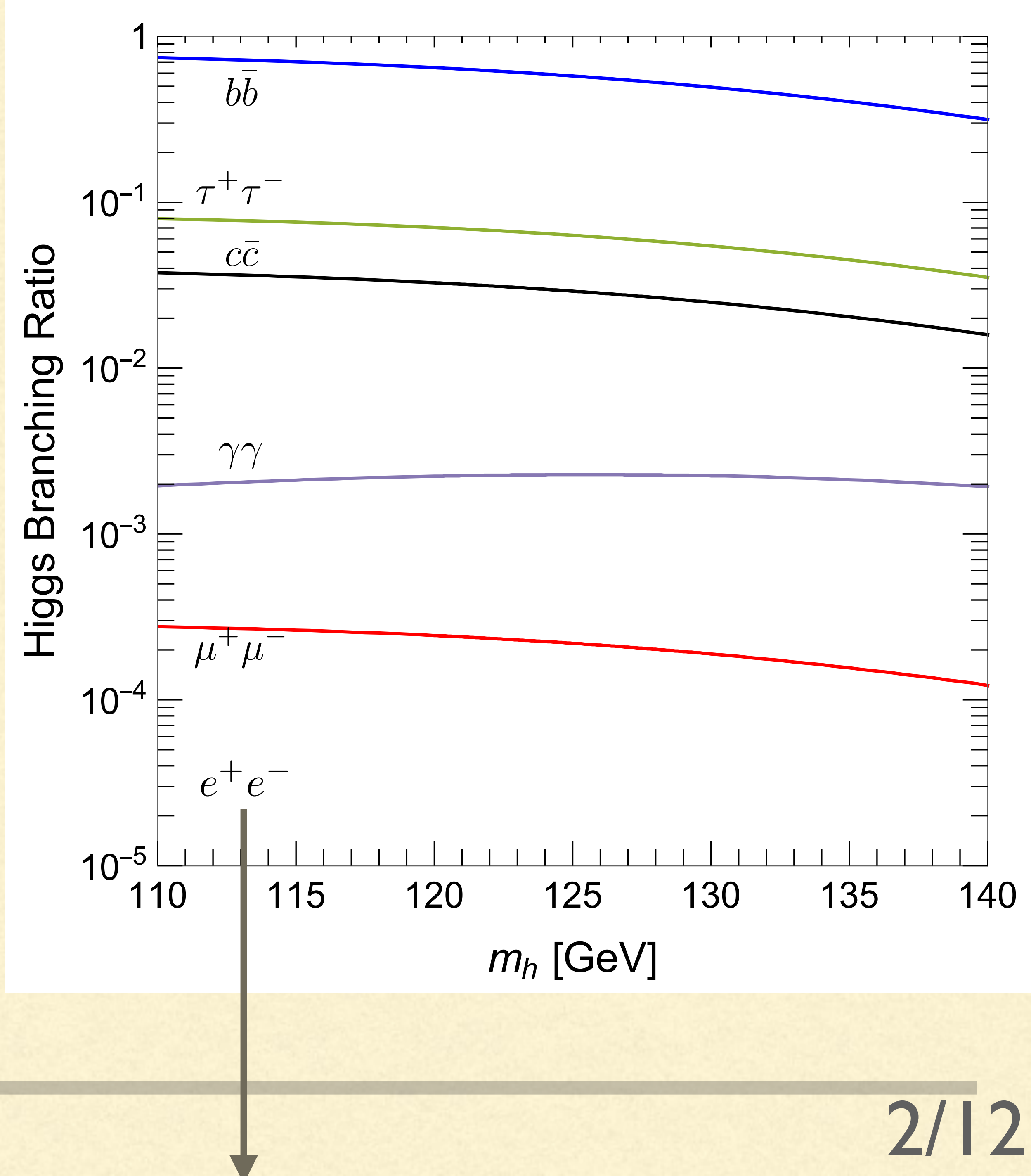
$$3\ \mathrm{ab}^{-1} \to 10^8\ \mathrm{Higg's}$$

- Search for rare decays.



Fermionic Decays

- In SM, Fermionic decays establish interesting hierarchy, due to Yukawa couplings.



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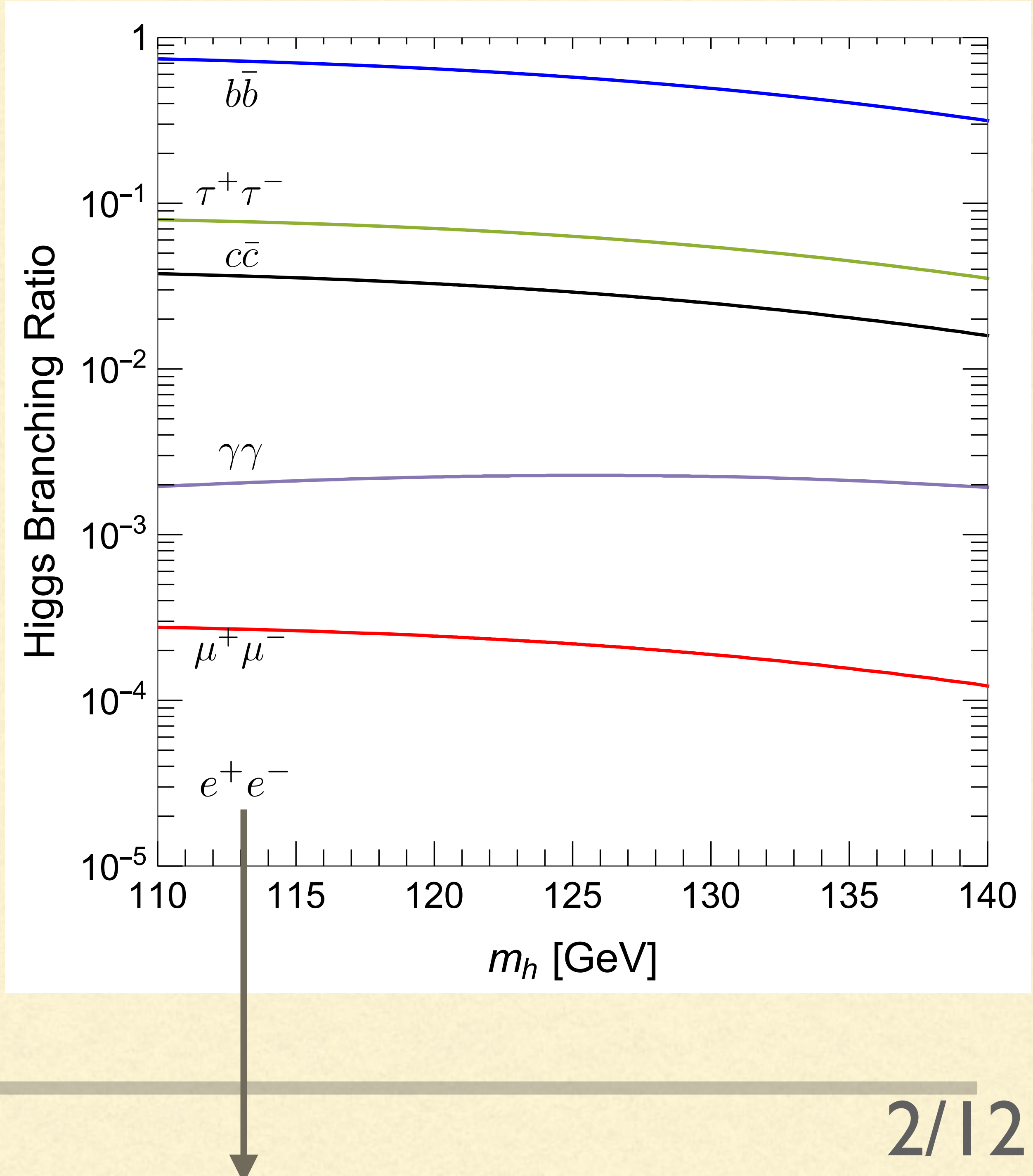

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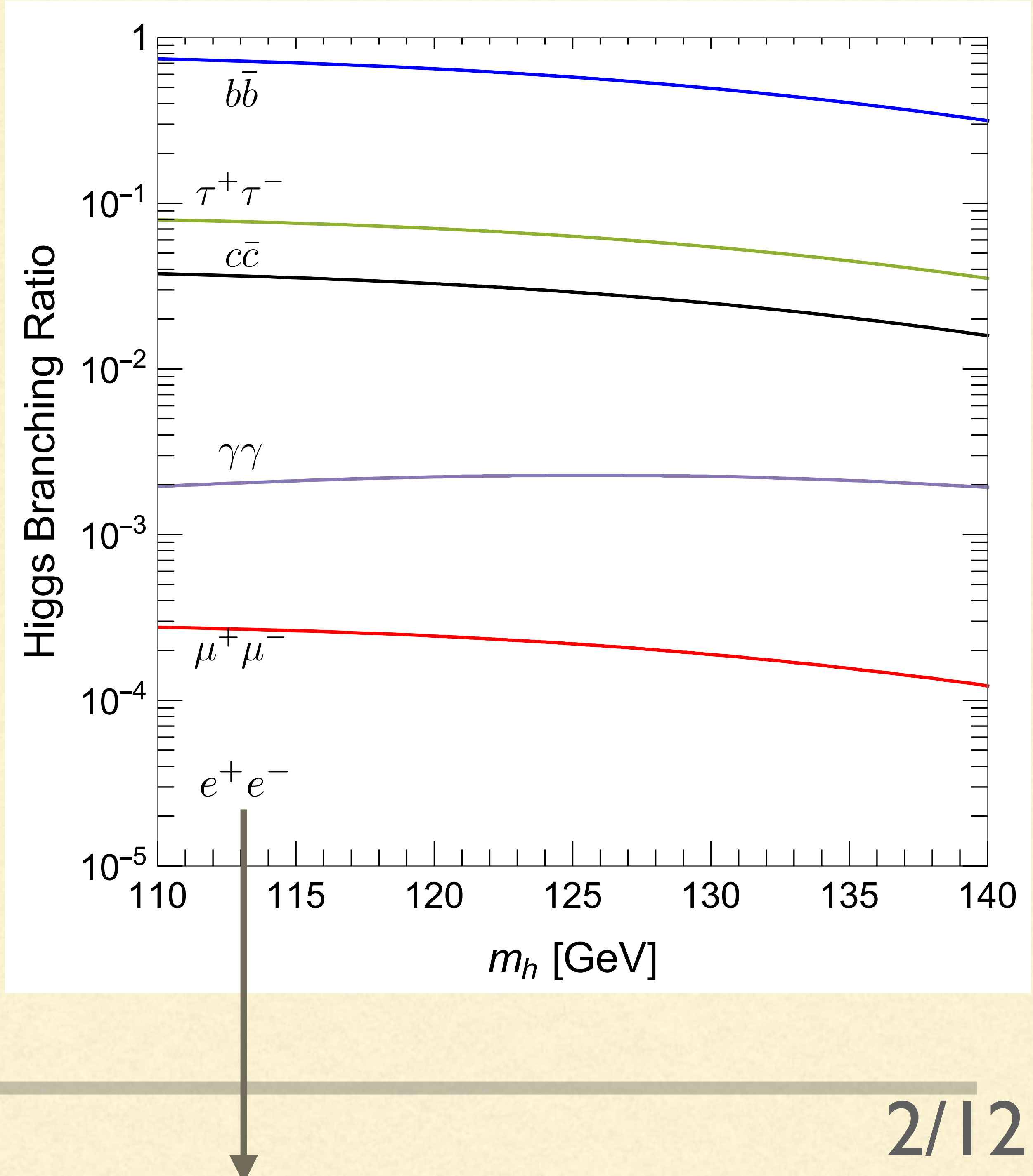

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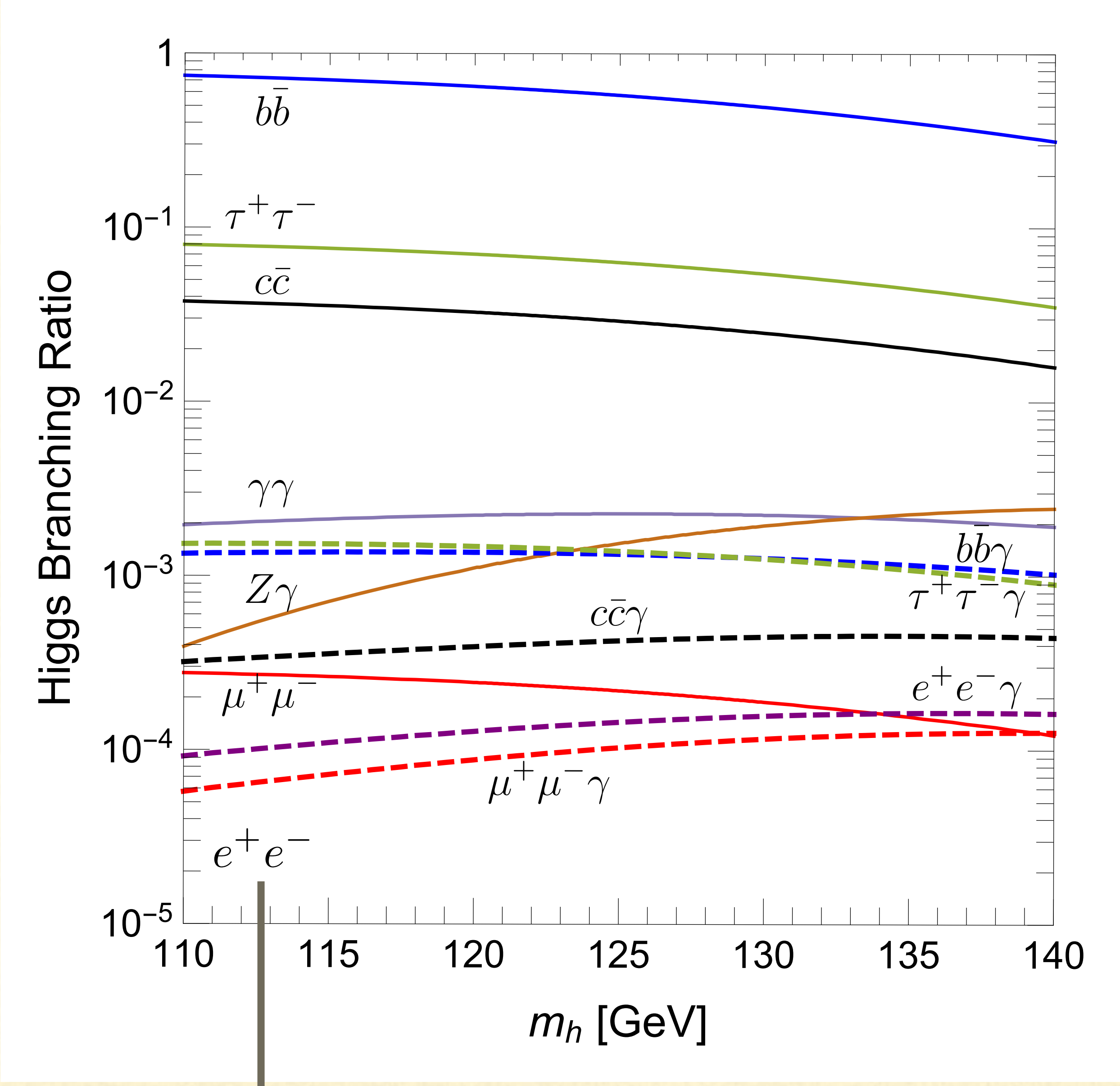

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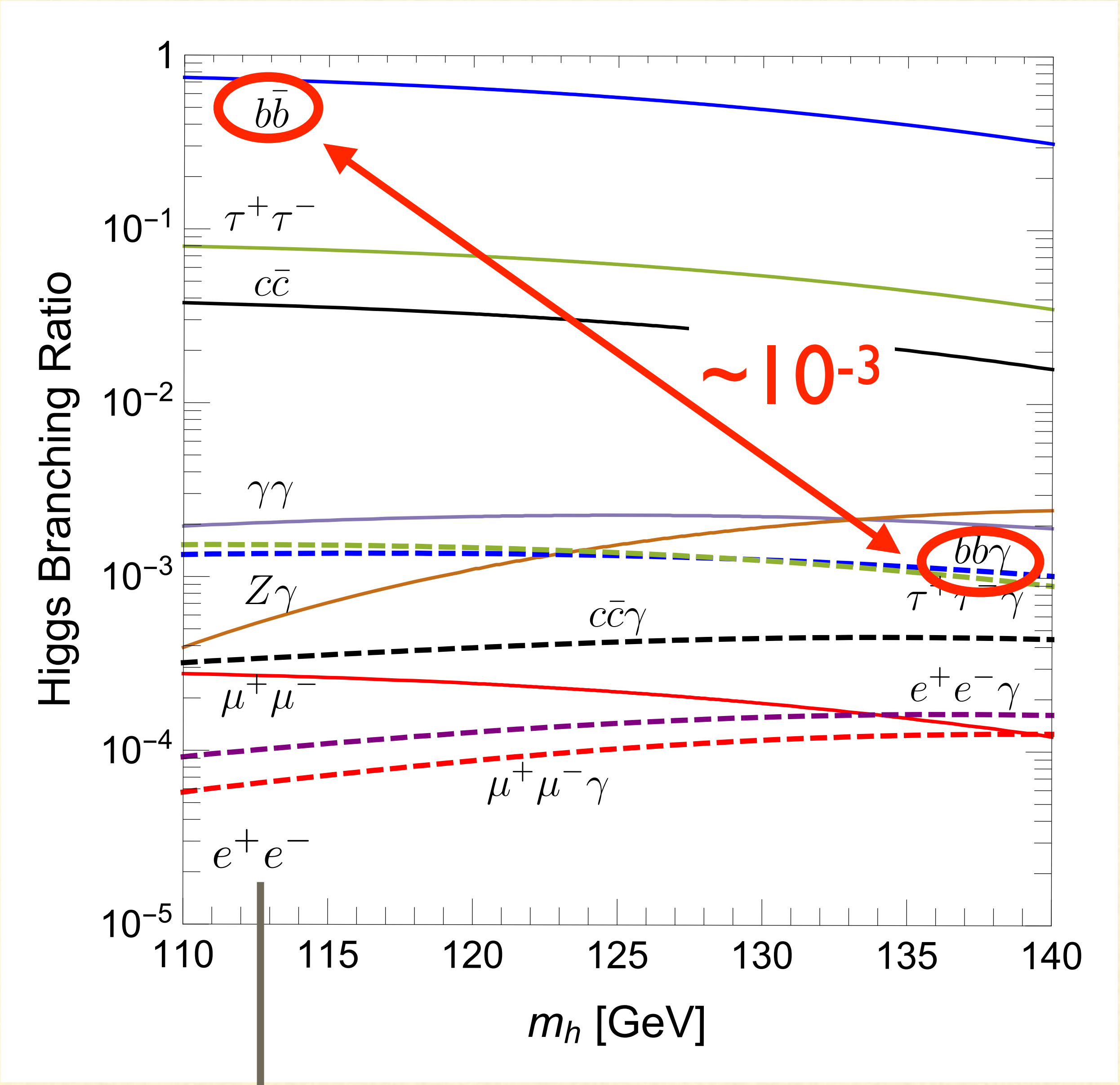

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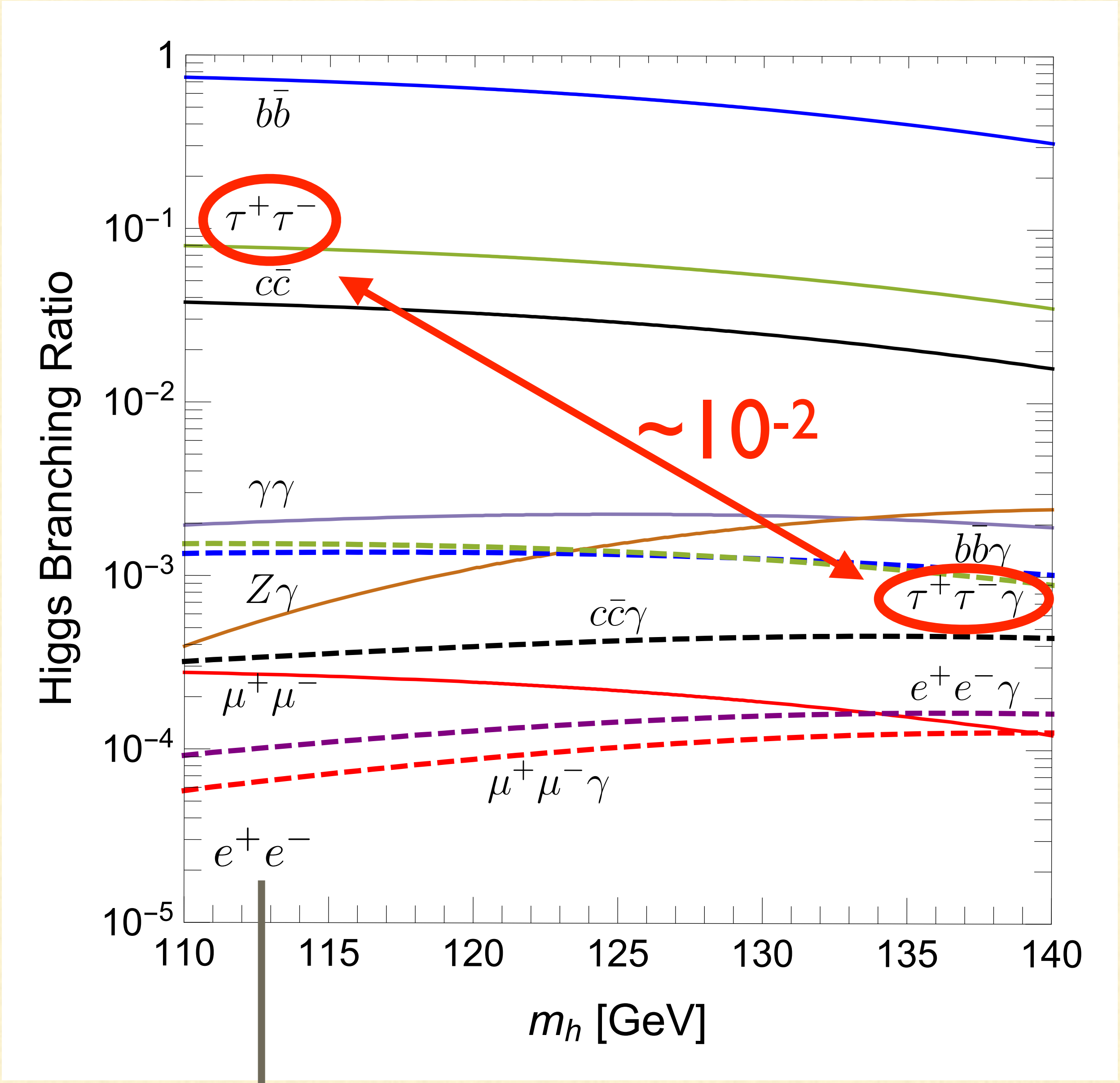

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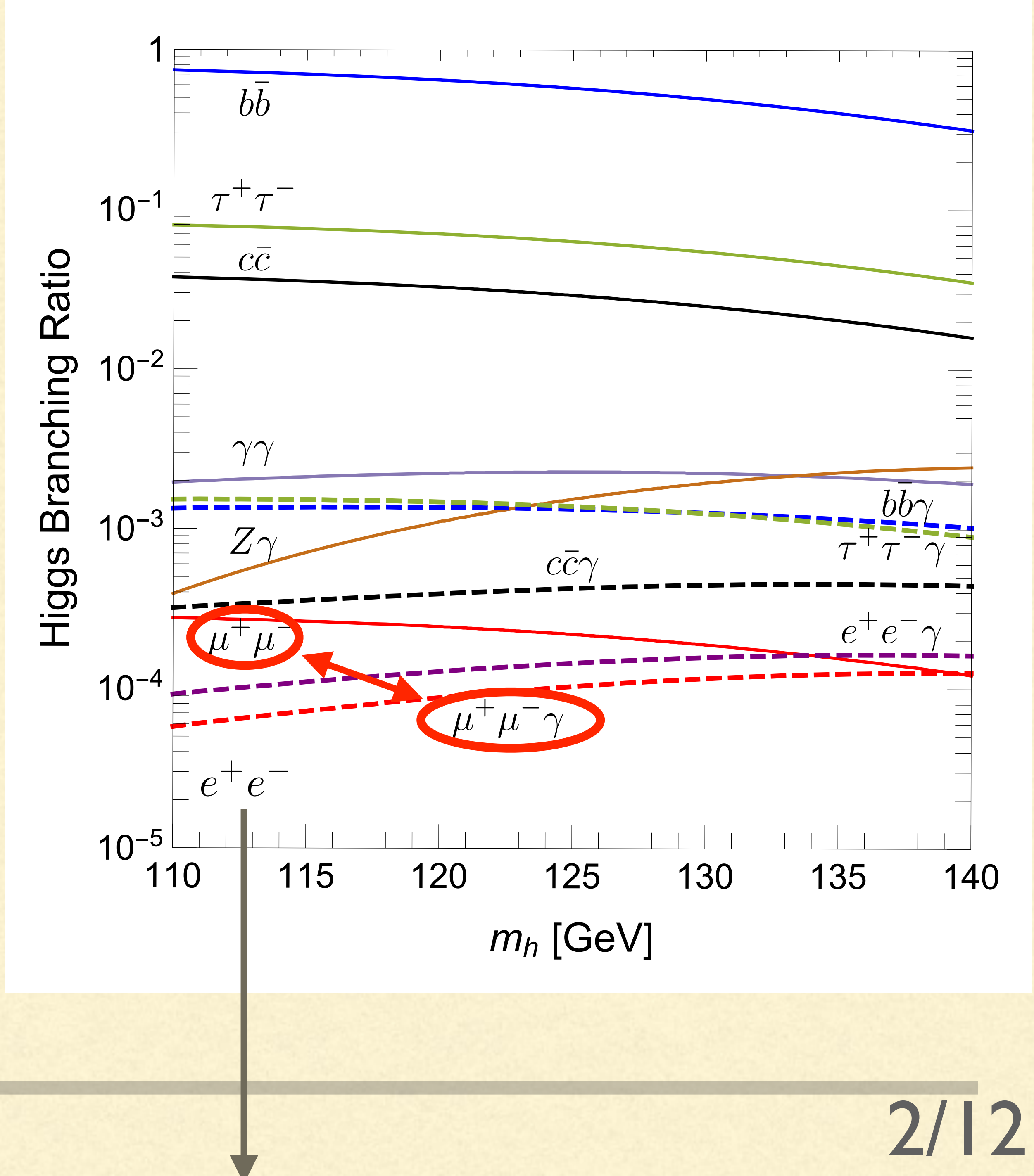

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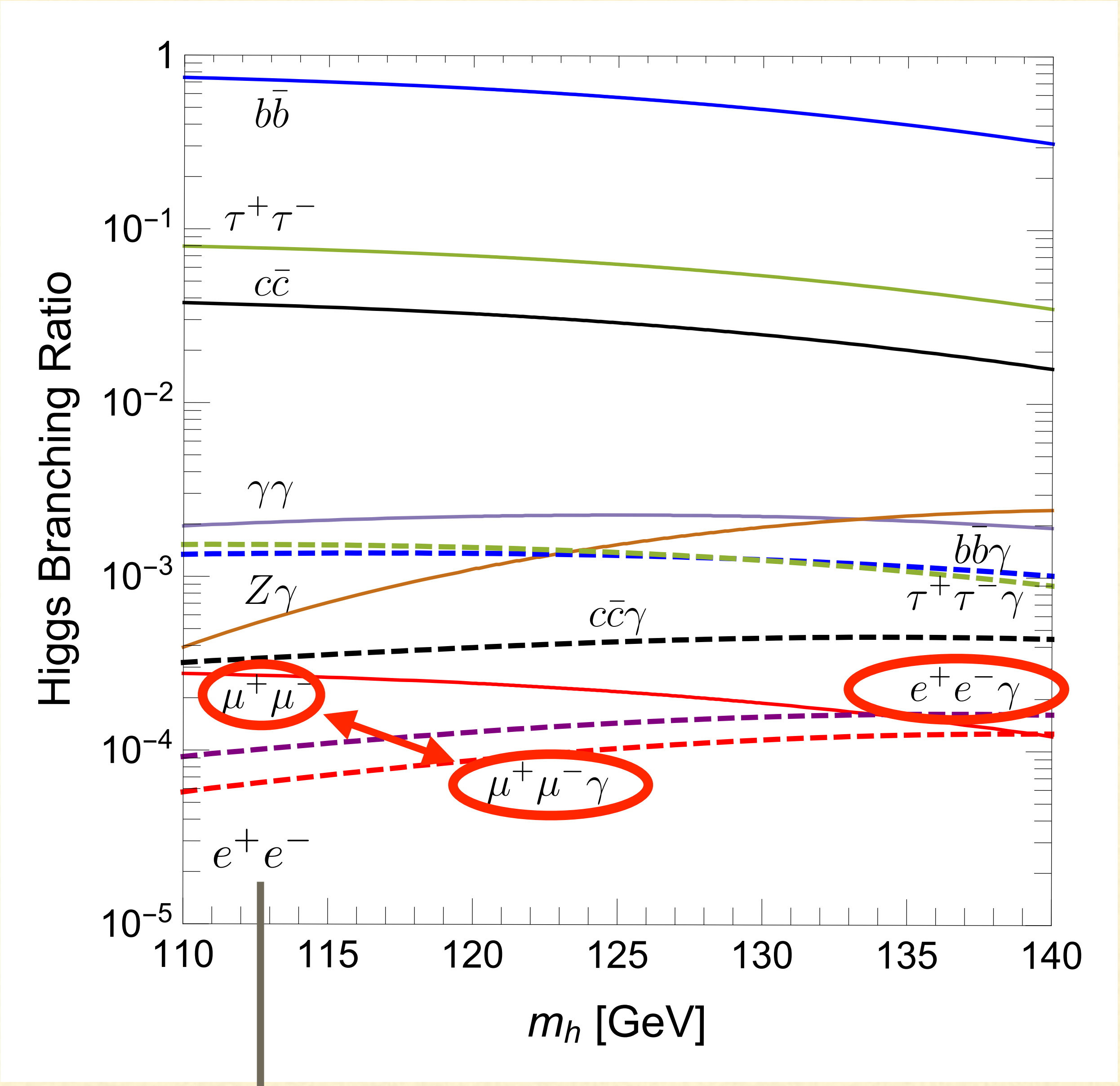
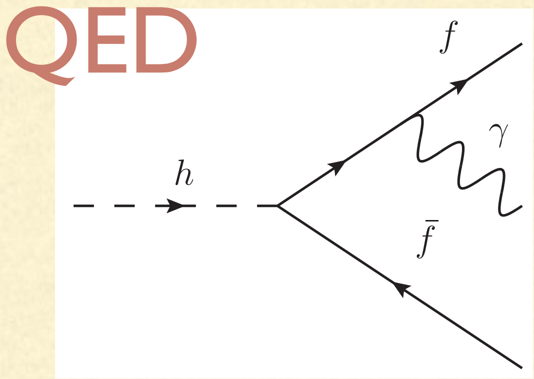
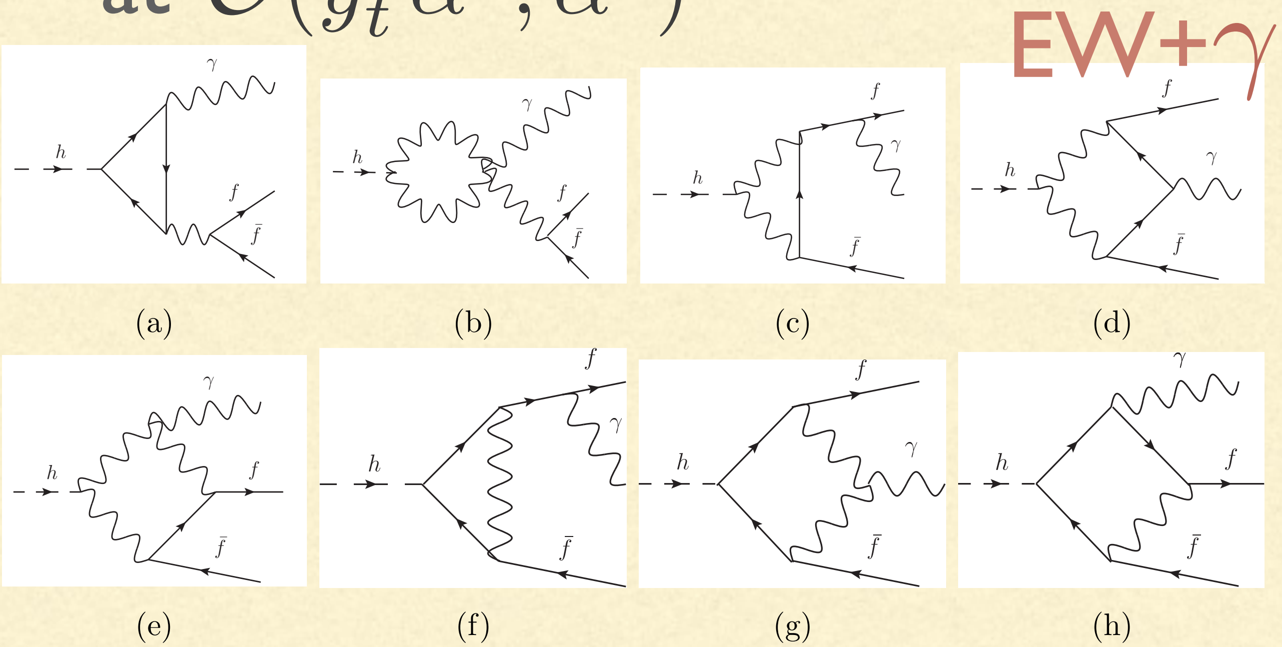


$h \to f\bar{f}\gamma$

- QED radiation at $\mathcal{O}(y_f^2\alpha)$



- EW-loop-induced diagrams at $\mathcal{O}(y_t^2\alpha^3, \alpha^4)$



Abbasabadi et al. hep-ph/9611209

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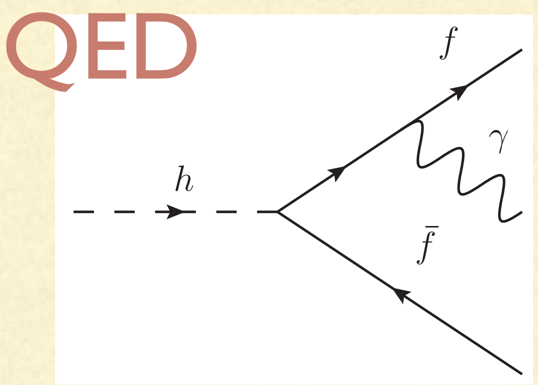

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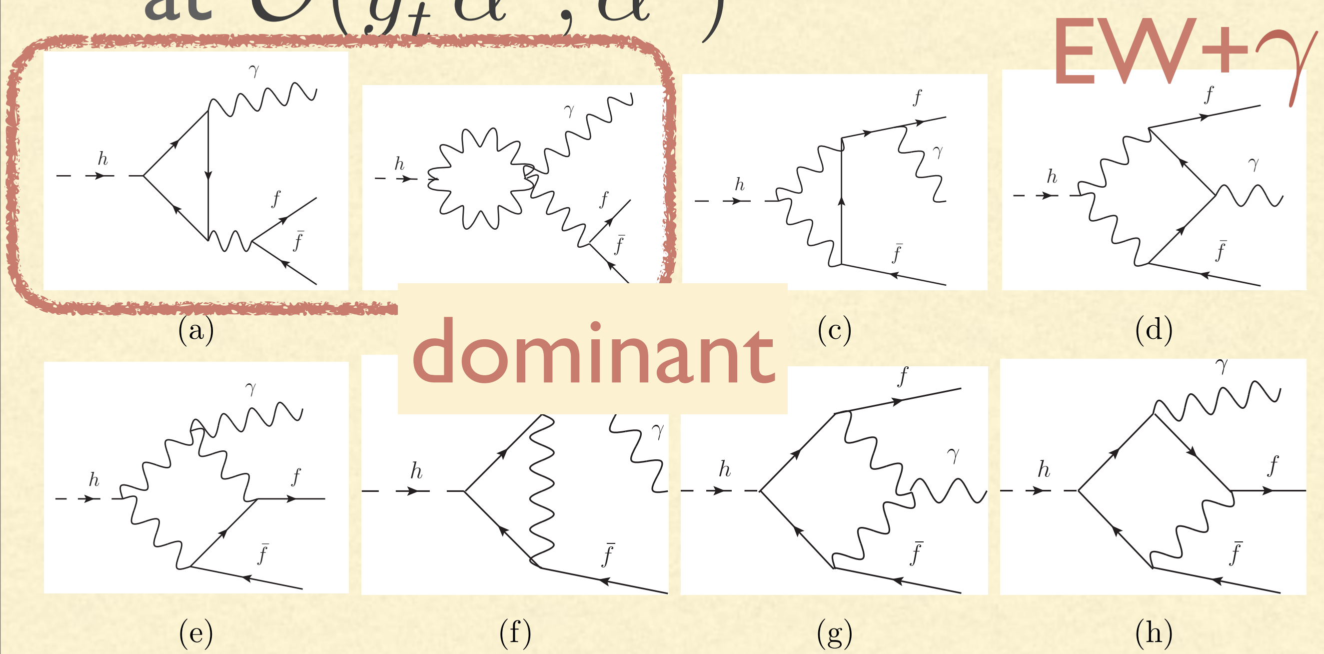

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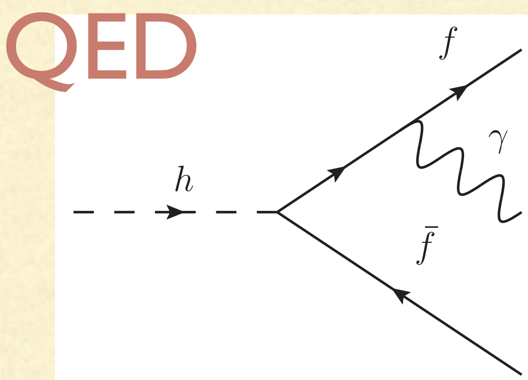
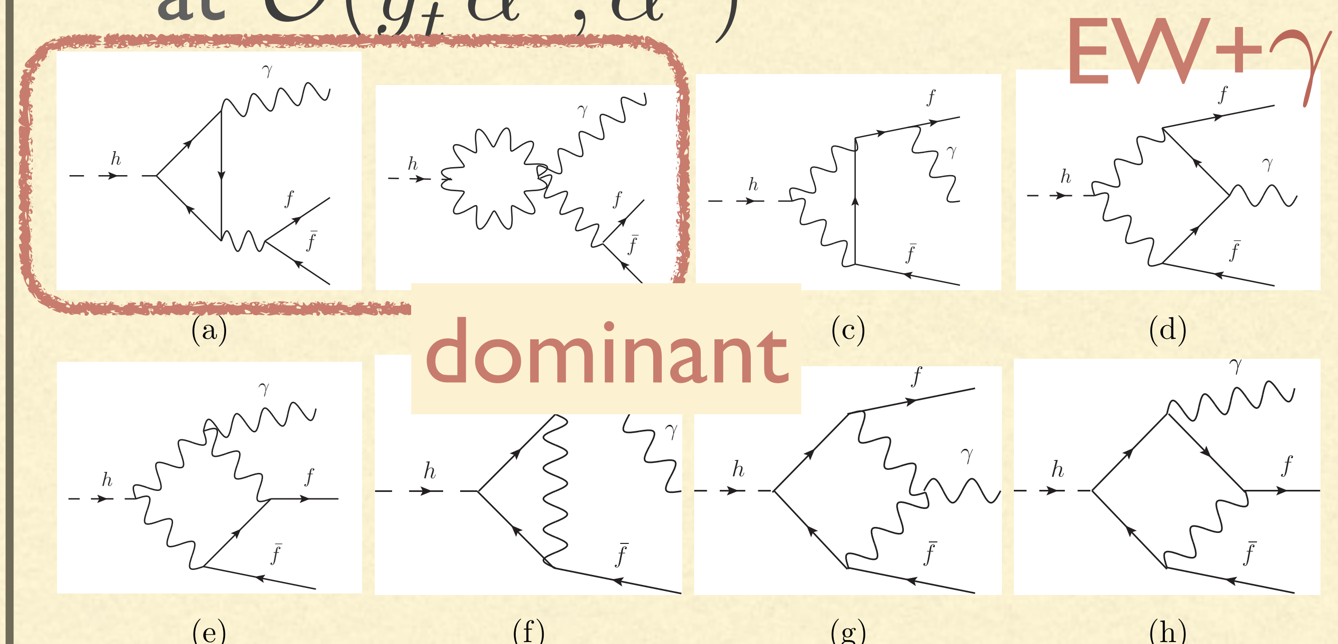


- Suppressed by Yukawa coupling y_f
- Chirality flipping.

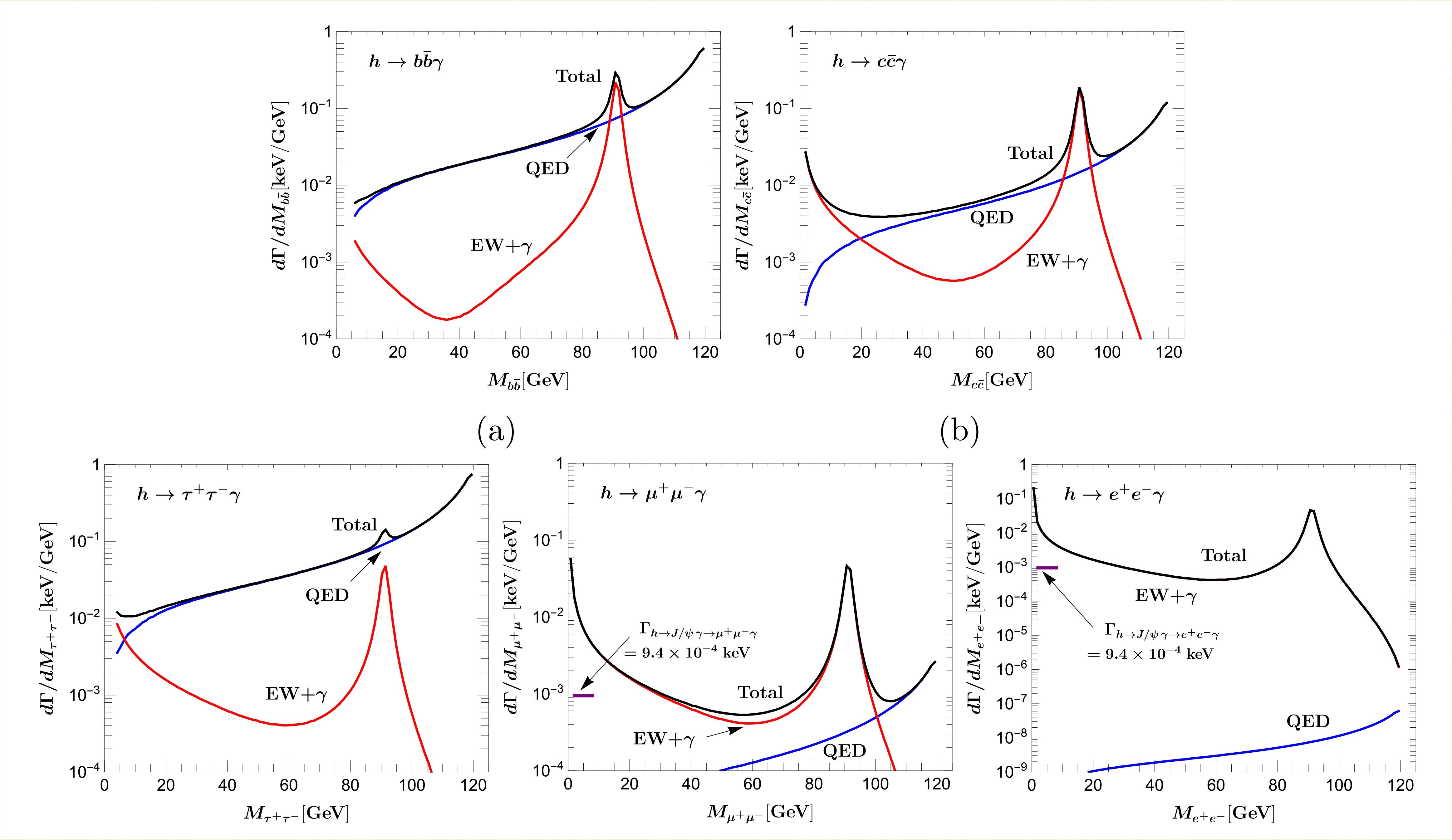
- EW-loop-induced diagrams at $\mathcal{O}(y_t^2\alpha^3, \alpha^4)$



Abbasabadi et al. hep-ph/9611209

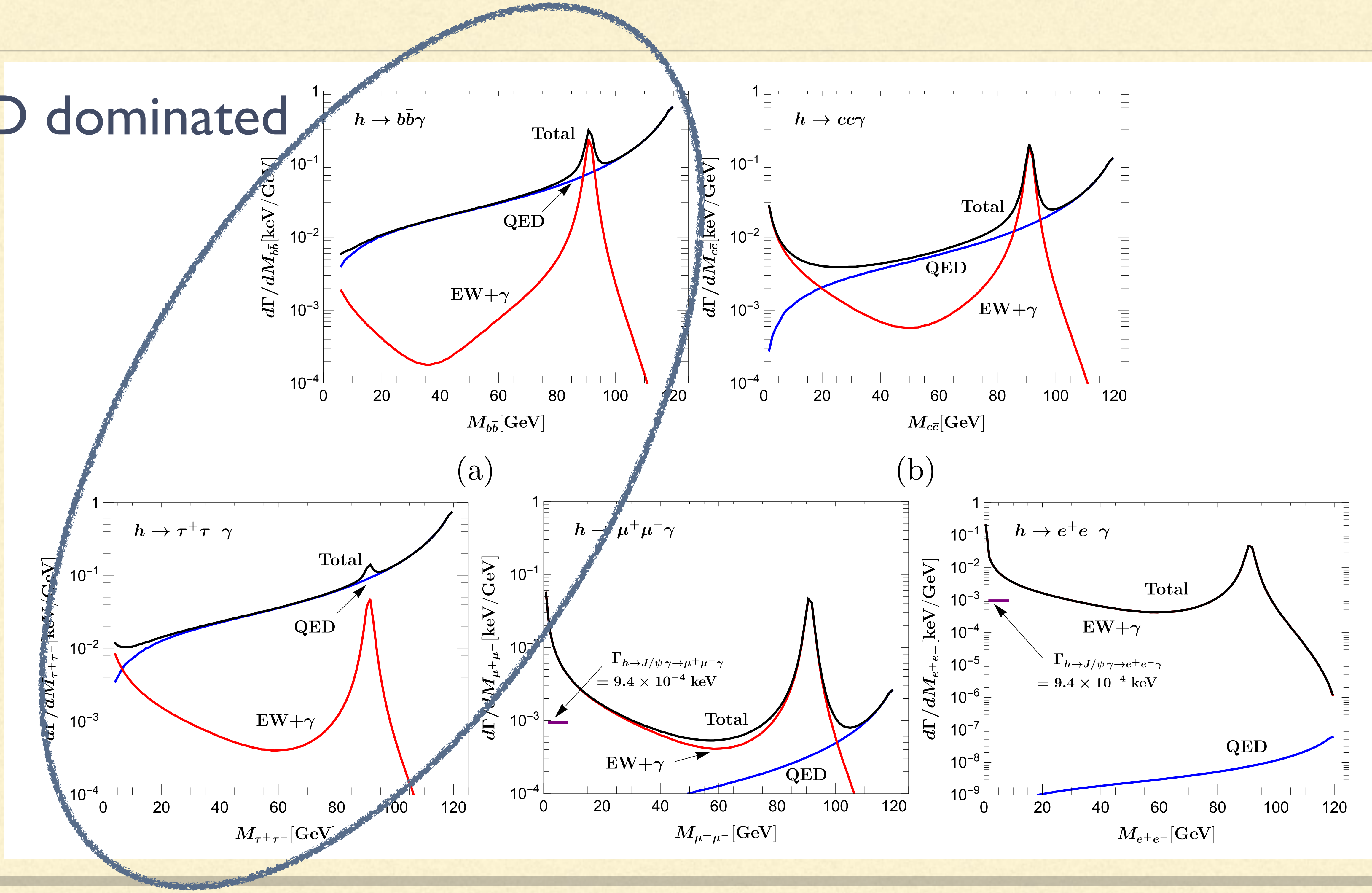
- Not suppressed by Yukawa couplings.
- Chirality-conserving.

$M_{f\bar{f}}$ Distributions



$M_{f\bar{f}}$ Distributions

QED dominated



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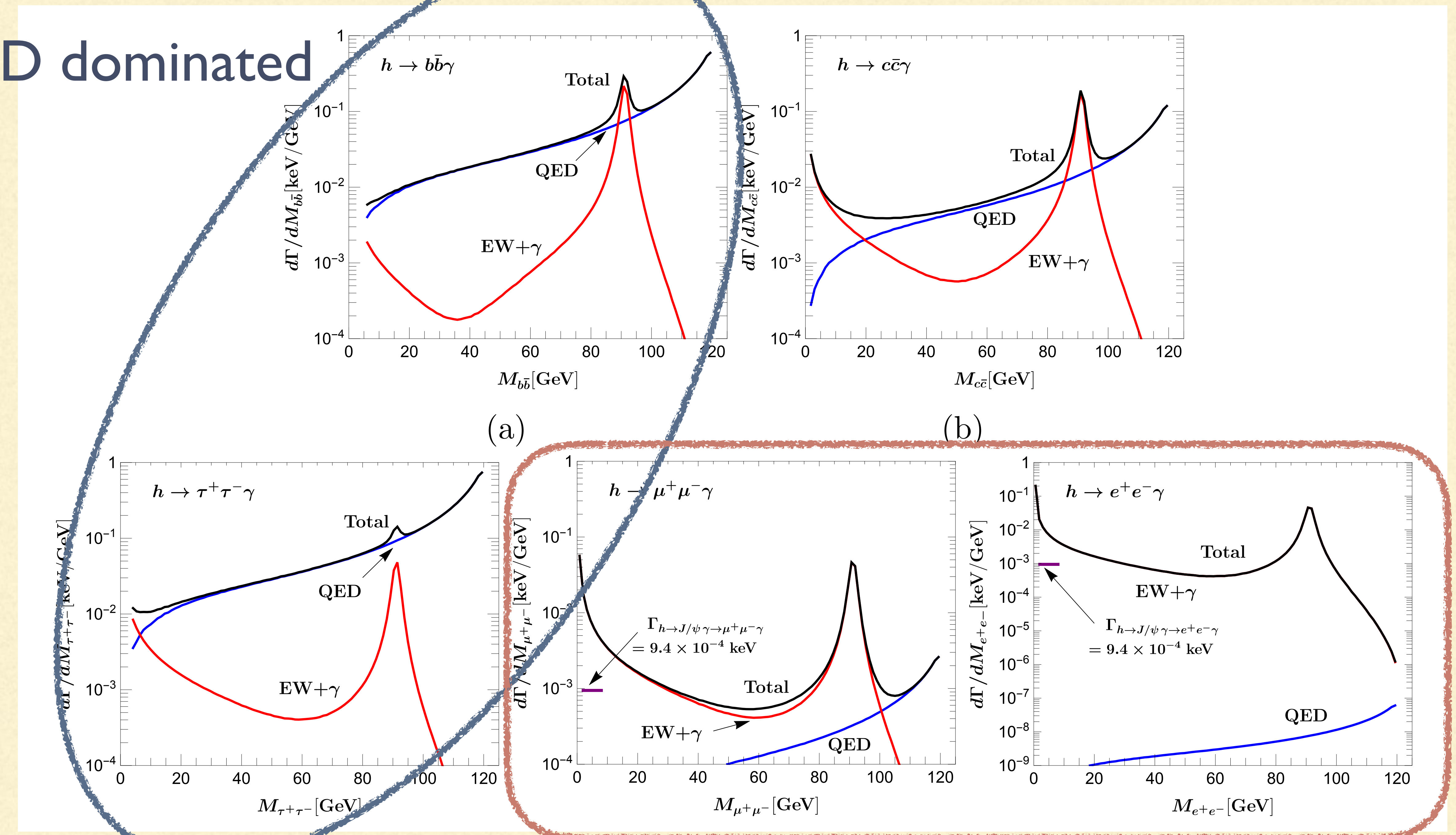
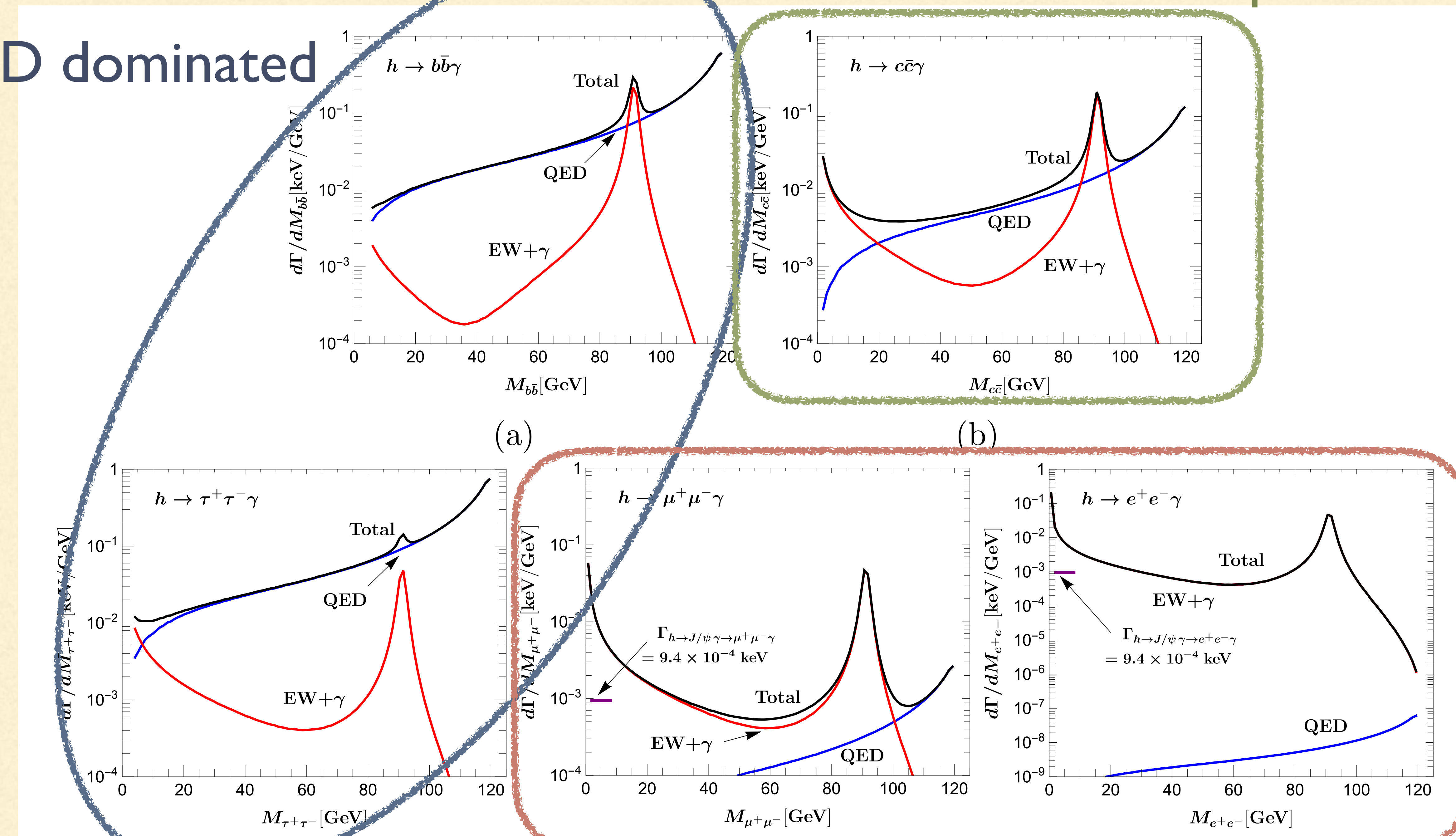


EW+γ dominated

$M_{f\bar{f}}$ Distributions

QED dominated

comparable



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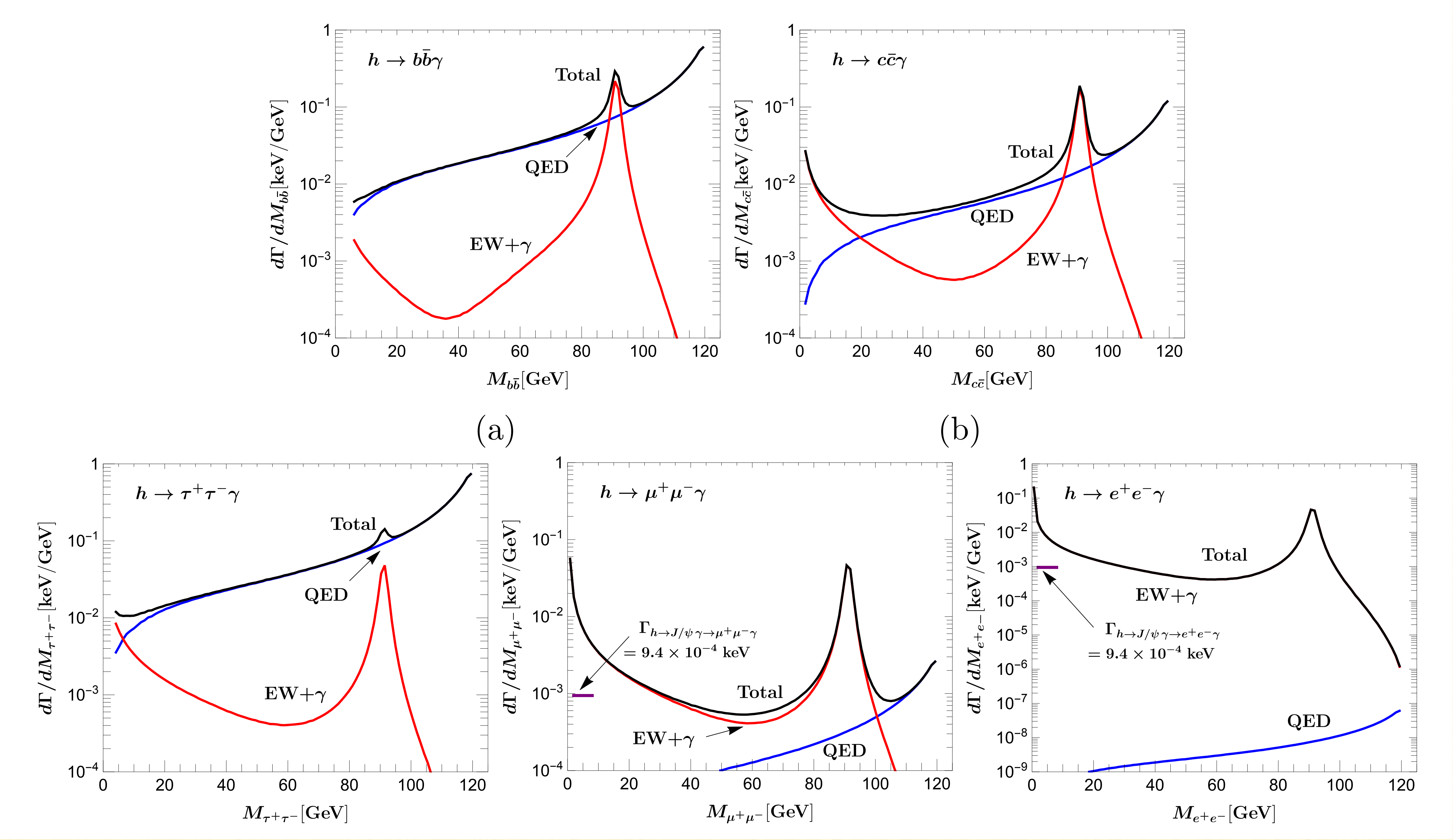

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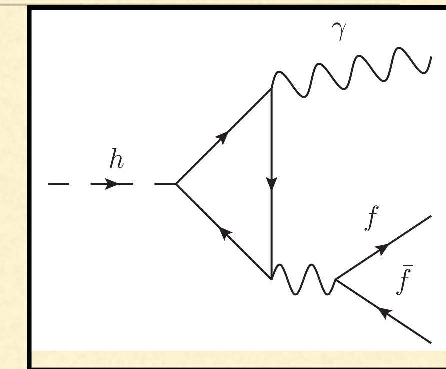

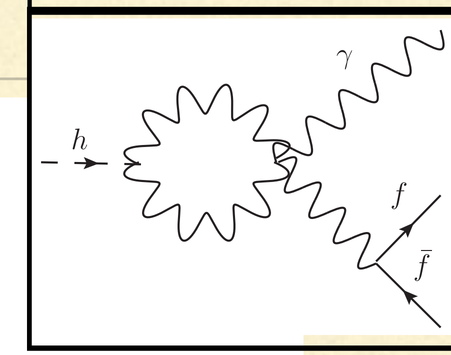

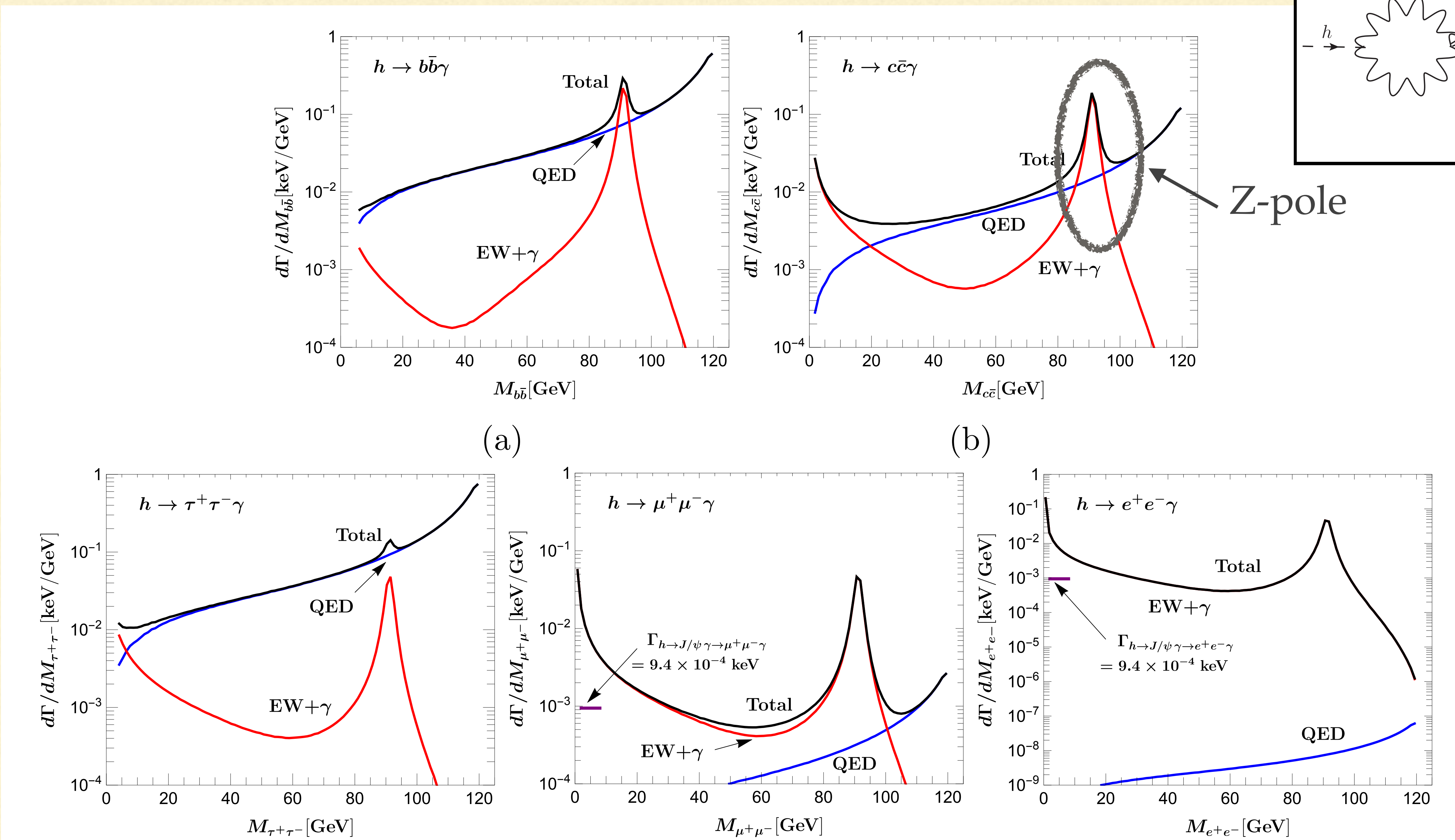

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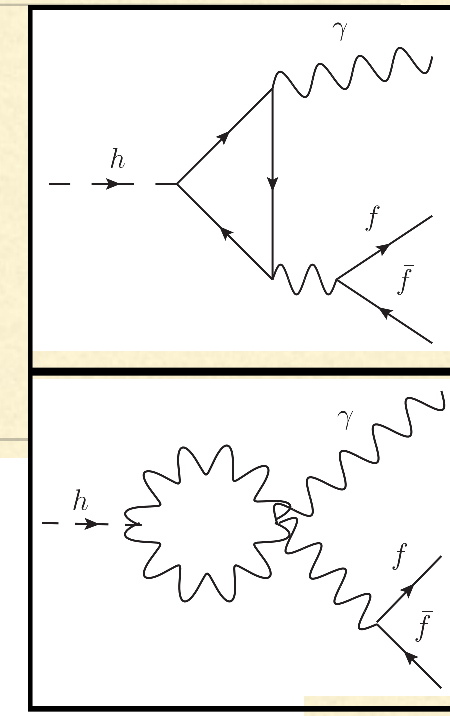
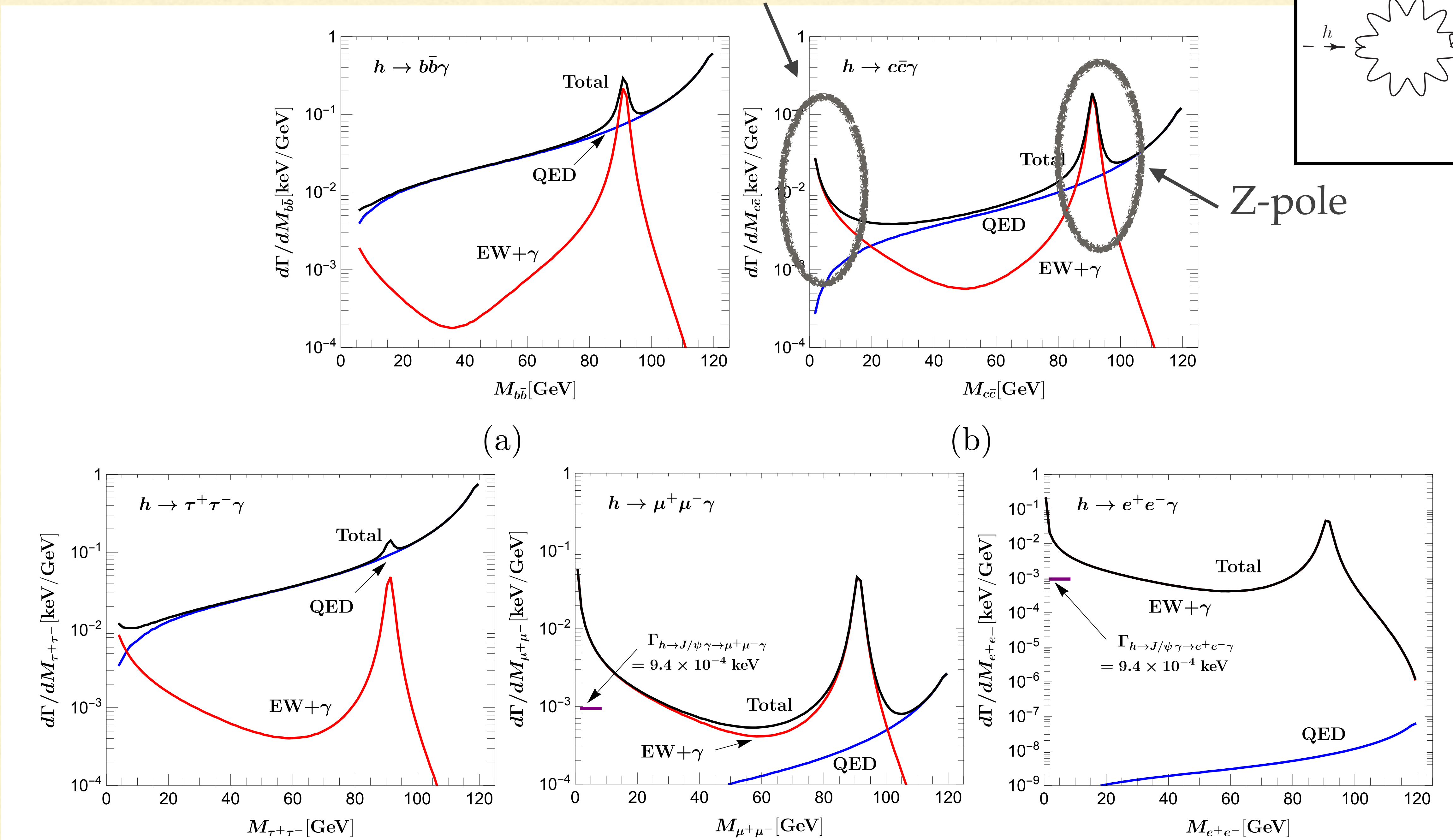


γ-pole, regulated by $m_{f\bar{f}} > 4m_f^2$

Z-pole



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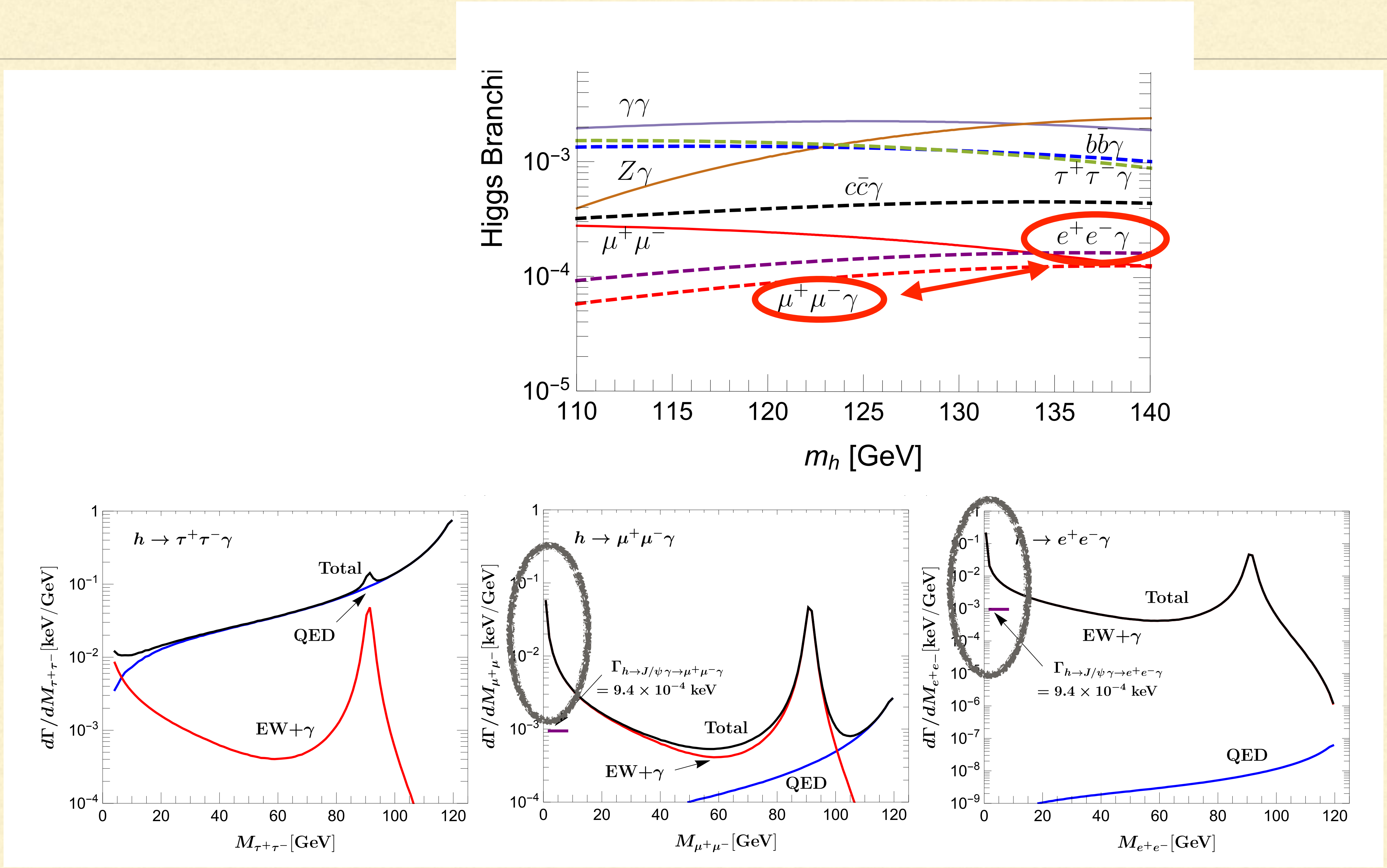
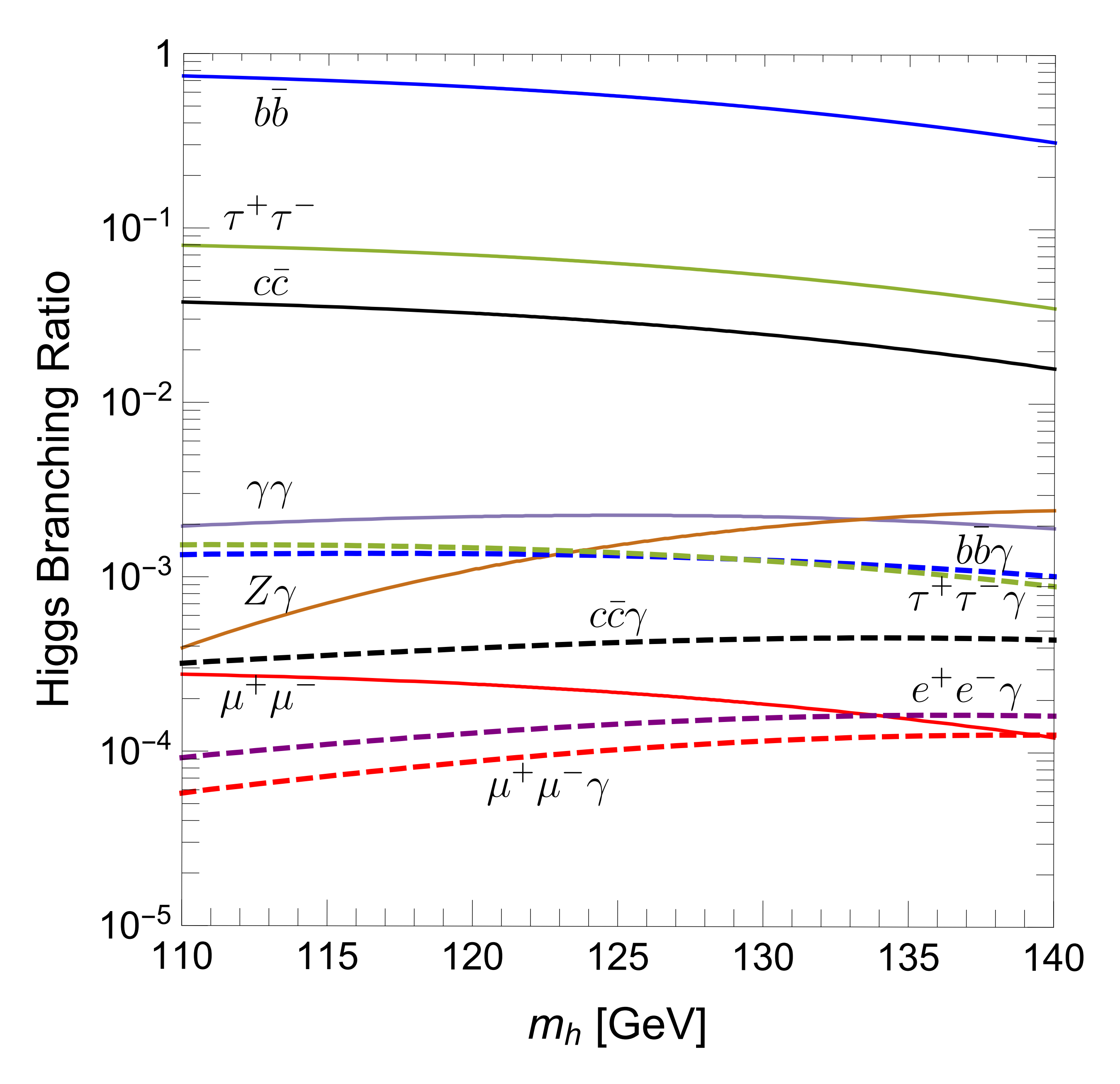


LHC Search for $\ell^+\ell^-\gamma$

- BRs of $\ell^+\ell^-\gamma$ are comparable to $\mu^+\mu^-$.
- Very promising considering the ATLAS/CMS projections of 7σ for $h \to \mu^+\mu^-$ at HL-LHC.



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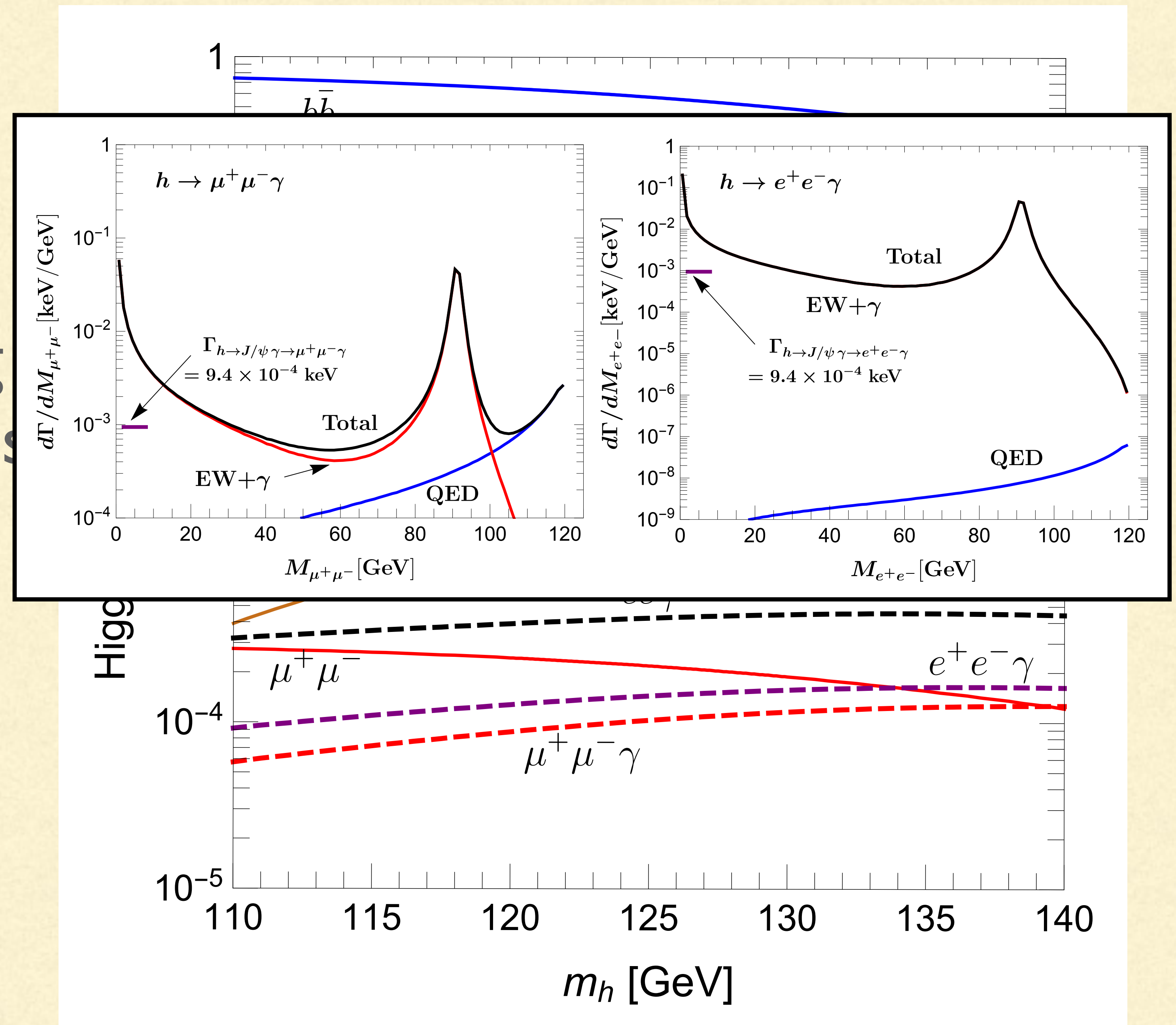
- Very promising considering the ATLAS/CMS projections of 7σ for $h \to \mu^+\mu^-$ at HL-LHC.
- Dominated by EW+γ .
- Two well-separated peaks: (Z-/γ-pole)



Observability at LHC

Channel	Signal [fb]	Background [fb]	Statistical Significance with 0.3 (3) ab^{-1} luminosity
$pp \to \gamma^*\gamma \to \mu^+\mu^-\gamma$	0.69	23.5	2.47 (7.79)
$60 < E_\gamma < 63$ GeV	0.69	14.6	3.13 (9.89)
$p_{T\gamma} > 55$ GeV	0.46	11.8	2.32 (7.33)
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highly collimated
mimic photon

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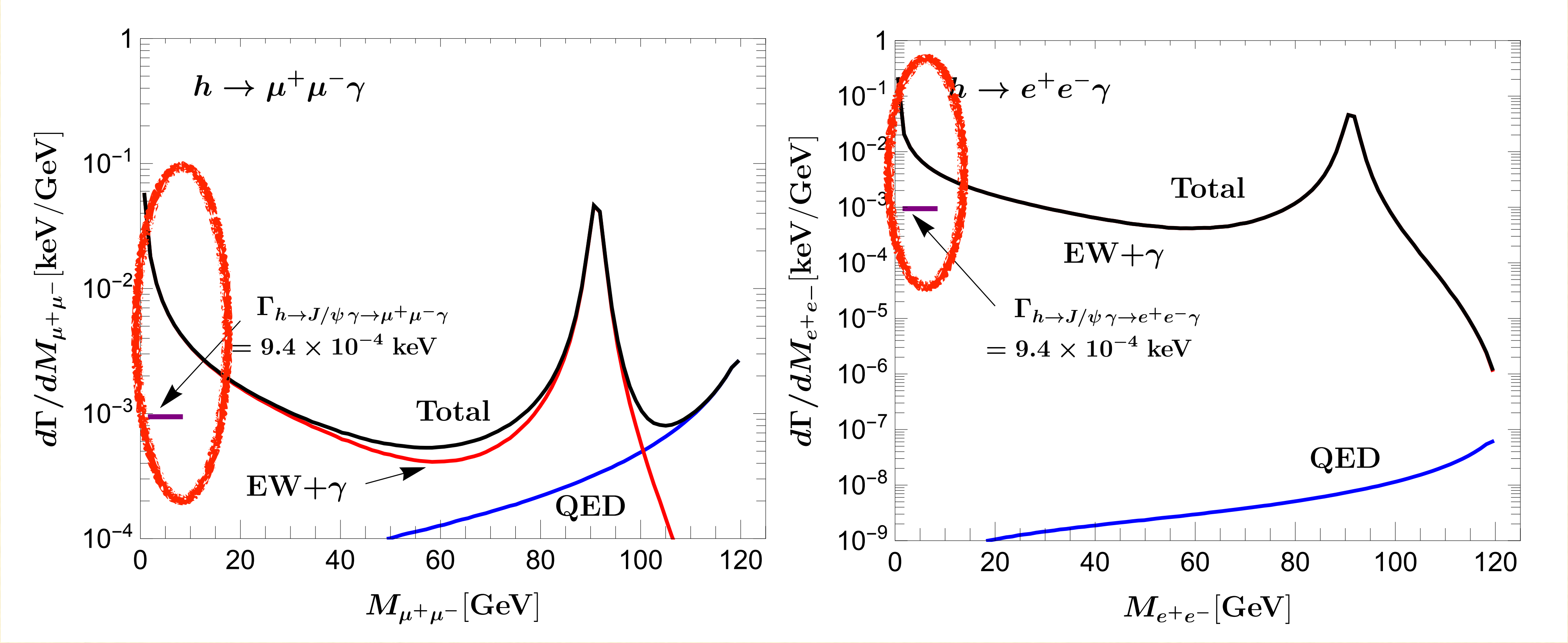
A Note on $h \to J/\psi\ \gamma$

- $h \to J/\psi\ \gamma$ has been proposed to constrain the charm-Yukawa coupling.
  Bodwin, Petriello et al. (2013, 2014, 2017)
  Konig, Neubert (2015)
- Same final state: $h \to J/\psi\ \gamma \to \ell\ell\gamma$, but much smaller rate.



- Must observe the continuum $h \to \ell\ell\gamma$ first.

$\tau^+\tau^-\gamma$

- The dominant production mechanisms for the current LHC observation of $h \to \tau^+\tau^-$ are VBF & boosted Higgs.

- With an additional photon to trigger on, we can consider the leading production mechanism gluon fusion.

$$\sigma(WW, ZZ \to h \to \tau^+\tau^-) = (4.2 \text{ pb}) \times (6.3\%) \approx 260 \text{ fb};$$

$$\sigma(gg \to h \to \tau^+\tau^-\gamma) = (49 \text{ pb}) \times (0.1\%) \approx 50 \text{ fb}.$$

- Completely different decay mechanism, QED dominated.

- Sensitive to the tau magnetic dipole moment [arXiv:1610.01601].

Charm-Yukawa Via Radiative Decay

- Current searches for $h \to b\bar{b}$ via VH / VBF / highly boosted.
- With an additional γ to trigger on, we could use LO ggF

$$gg \to h \to c\bar{c}\gamma$$

- Compare $c\bar{c}\gamma$ vs. $J/\psi\ \gamma$

much larger BR: 10^{-4} vs. 10^{-7}

poor resolution: $jj\gamma$ vs. $\mu\mu\gamma$

Require charm-tagging!

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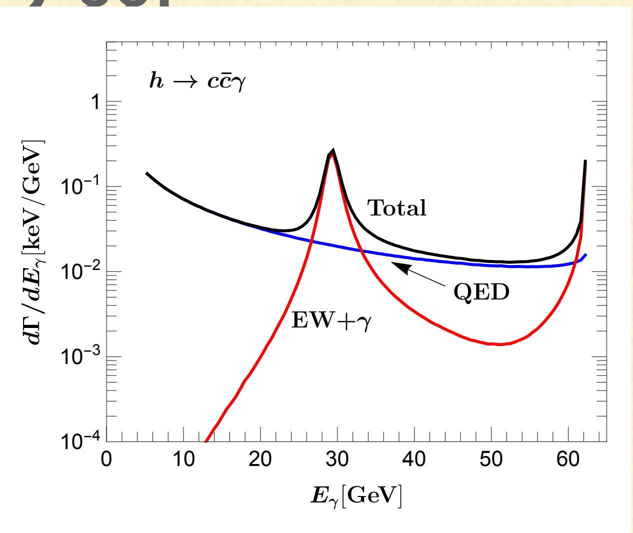

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$J/\psi\ \gamma$ is dominated by $\gamma^* \to J/\psi$, not very sensitive to the Yukawa coupling.

Results for $gg \to h \to c\bar{c}\gamma$

- Numbers of events:

	ϵ_c	ϵ_b	ϵ_l
I	20%	10%	1%
II	30%	20%	3%
III	45%	50%	10%

Luminosity	Operating Point	Signal (Total)	Signal (QED)	Signal (EW+γ)	Background
3000 fb^{-1}	I	683	252	431	3.84×10^7
	II	1537	567	970	1.25×10^8
	III	3459	1275	2184	6.51×10^8

1. 2 jets plus a photon, with 2 jets (mis-)tagged as c-jets.
2. 3 jets, with 2 jets (mis-)tagged as c-jets and the 3rd jet mis-identified as a photon.

- B/S ~ 10^5.

- Very difficult to reach the SM expectations.

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Systematics!

- B/S ~ 10^5.
- Very difficult to reach the SM expectations.

Comparison

Method	κ_c upper limit projection at HL-LHC (3 ab^{-1})
$h \to c\bar{c}\gamma$ (this work)	6.3
$h \to c\bar{c}$+fit	2.5
$h + c$ production	2.6
Higgs kinematics	4.2
$h \to J/\psi\gamma$	50

Perez et al. 1505.06689
Brivio et al. 1507.02916
Bishara et al. 1606.09253
Bodwin et al. 1306.5770

Projected sensitivities for probing the $hc\bar{c}$ Yukawa coupling $\kappa_c = y_c^{\rm BSM}/y_c^{\rm SM}$ at the HL-LHC with various methods.

Summary

- Higgs radiative decay to a fermion pair is not necessarily suppressed by the Yukawa coupling.

- The observability of $h \to \mu^+\mu^-\gamma,\ e^+e^-\gamma$ at LHC is comparable to $h \to \mu^+\mu^-$.

- With charm-tagging, $h \to c\bar{c}\gamma$ can be used to constrain the charm-quark Yukawa coupling.

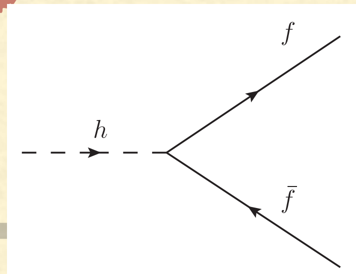
Back-up

Running Masses

- Most significant corrections are from mass running (m_f to m_h)

Fermion	$\bar{m}_f(m_f)$ [GeV]	$\delta\bar{m}_f^{\mathrm{QCD}}$ [GeV]	$\delta\bar{m}_f^{\mathrm{QED}}$ [MeV]	$\bar{m}_f(m_h)$ [GeV]	$\Gamma^0_{h\to f\bar{f}}$ [keV]
b	4.18	-1.39	-5.72	2.78	1900
c	1.27	-0.657	-9.33	0.604	89.7
τ	1.78	-	-27.2	1.75	251
μ	0.106	-	-4.05	0.102	0.852
e	0.511×10^{-3}	-	-2.20×10^{-2}	0.489×10^{-3}	1.96×10^{-5}

$\sim Q_f^2 \times \mathcal{O}(1\%)$



$$\Gamma^0 = \frac{N_c}{8\pi}\, m_h\, \frac{\bar{m}_f^2}{v^2}\, \beta_f^3$$

Decay Widths

	Inclusive corrections		Exclusive decay	
Decay Channels	$\delta\Gamma\ (y_f^2\alpha)$ [keV]	$\delta\Gamma\ (y_t^2\alpha^3, \alpha^4)$ [keV]	$\Gamma(f\bar{f}\gamma)$ [keV] $E_\gamma^{\text{cut}} = 5/15$ GeV	$\text{BR}(f\bar{f}\gamma)$ $[10^{-4}]$ $E_\gamma^{\text{cut}} = 5/15$ GeV
$h \to b\bar{b}$	-25.3	0.99	$9.45/5.44$	$23/13$
$h \to c\bar{c}$	-1.17	0.91	$2.48/1.73$	$6.1/4.2$
$h \to \tau^+\tau^-$	-1.37	0.31	$10.4/5.63$	$25/14$
$h \to \mu^+\mu^-$	-4.72×10^{-2}	0.41	$0.436/0.420$	$1.1/1.0$
$h \to e^+e^-$	-1.29×10^{-6}	0.60	$0.589/0.588$	$1.4/1.4$

$E_\gamma > 5$ or 15 GeV and $\Delta R_{\gamma f},\ \Delta R_{\gamma\bar{f}} > 0.4$

$$\delta\Gamma_{\text{EW}} = \Gamma^0 \left(\frac{2\delta m_f^{\text{QED}}}{\bar{m}_f} + Q_f^2 \frac{\bar{\alpha}}{\pi}\,\frac{17}{4} + \Delta_{\text{weak}} + \mathcal{O}(\alpha^2) \right)$$

EW+γ

Observability at LHC

- Selection cuts:

$$M_{\mu\mu} < 20 \text{ GeV}, \quad M_{ee} < 1.5 \text{ GeV}$$
$$120 \text{ GeV} < M_{\ell\ell\gamma} < 130 \text{ GeV}$$
$$p_T^\mu > 23\ (4) \text{ GeV}, \quad |\eta_\mu| < 2.4$$
$$|p_{Te^+}| + |p_{Te^-}| > 44 \text{ GeV}, \quad |\eta_e| < 1.44$$
$$p_T^\gamma > 0.3 M_{\ell\ell}, \quad |\eta_\gamma| < 1.44, \quad \Delta R_{\gamma\ell} > 1$$

γ-pole

Collimated electron pair

Reduce continuous background: Drell-Yan + ISR/FSR.

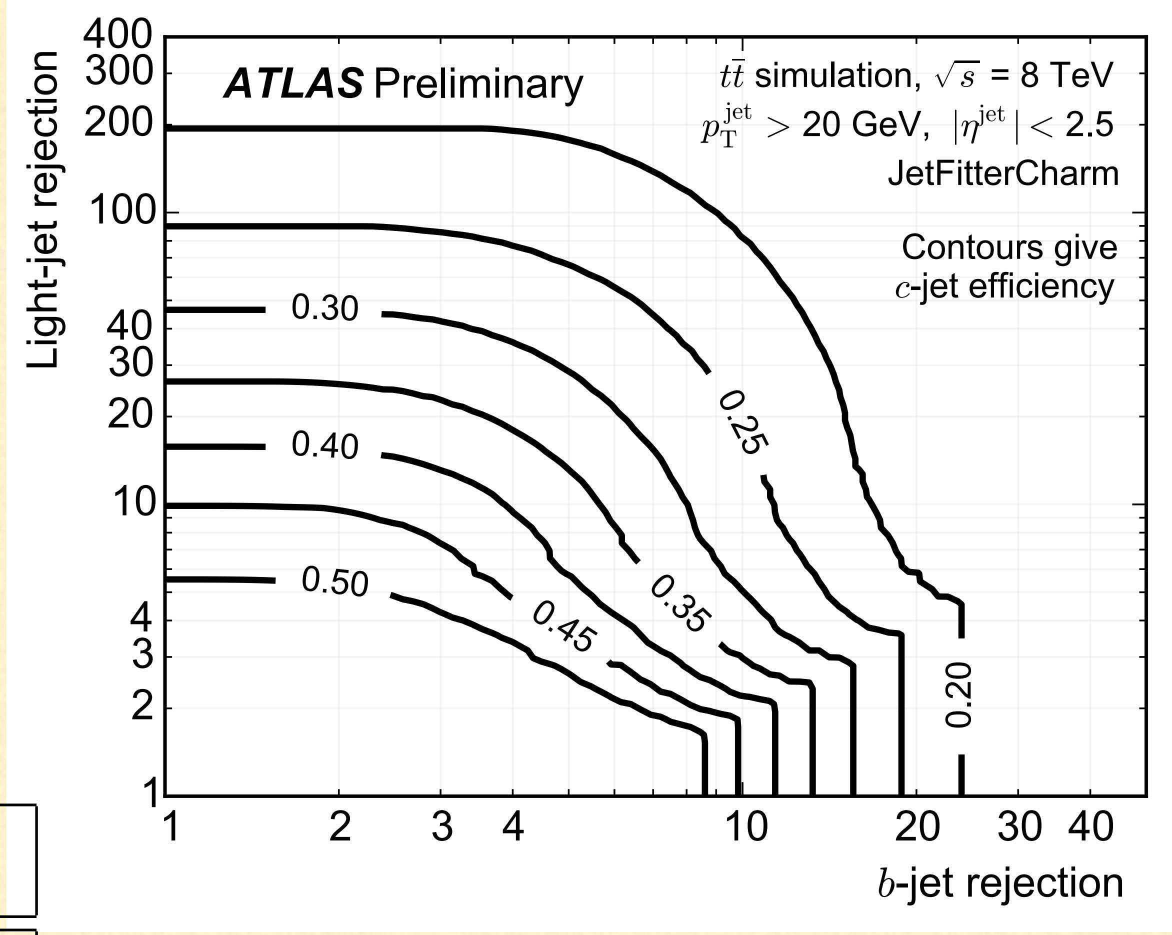
$$M_{\ell\ell} > 50 \text{ GeV}$$
$$120 \text{ GeV} < M_{\ell\ell\gamma} < 130 \text{ GeV}$$
$$p_T^\ell > 20\ (10) \text{ GeV}, \quad |\eta_\mu| < 2.5, \quad |\eta_e| < 2.4$$
$$p_T^\gamma > 15 \text{ GeV}, \quad |\eta_\gamma| < 2.5, \quad \Delta R_{\gamma\ell} > 0.4$$

Z-pole

Charm Tagging

- c-jets are very similar to b-jets.
- c-tag efficiency is correlated with b-/light-jet rejection.
- We choose 3 working points:

Operating Point	ϵ_c	ϵ_b	ϵ_l
I	20%	10%	1%
II	30%	20%	3%
III	45%	50%	10%



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Events Selection

- Selection cuts:

$$p_{Tc} > 40(20)\ \text{GeV} \qquad |\eta| < 2.5 \qquad 100 < m_{cc\gamma} < 150\ \text{GeV}$$

$$p_{T\gamma} > 20\ \text{GeV} \qquad \Delta R > 0.4$$

- Numbers of events:

Luminosity	Operating Point	Signal (Total)	Signal (QED)	Signal (EW+γ)	Background
$3000\ \text{fb}^{-1}$	I	683	252	431	3.84×10^7
	II	1537	567	970	1.25×10^8
	III	3459	1275	2184	6.51×10^8

Upper Bound

- If BSM significantly modifies the charm-Yukawa coupling by

$$y_c^{\mathrm{BSM}} = \kappa_c y_c^{\mathrm{SM}}$$

The statistical significance

$$\sigma_{\mathrm{SD}} = \frac{N_{\mathrm{S}}^{\mathrm{BSM}}}{\sqrt{N_{\mathrm{B}}}} \simeq \frac{\kappa_c^2 \ N_{\mathrm{S}}^{\mathrm{QED}} + N_{\mathrm{S}}^{\mathrm{EW}+\gamma}}{\sqrt{N_{\mathrm{B}}}} \simeq \frac{\kappa_c^2 \ N_{\mathrm{S}}^{\mathrm{QED}}}{\sqrt{N_{\mathrm{B}}}}$$

- 2σ-bound on the charm-Yukawa coupling:

$$\kappa_c < 12.5 \ (7.0), \quad 11.1 \ (6.3), \quad 11.2 \ (6.3)$$

for operating points I, II, III with a luminosity of 300 (3000) fb^{-1}.