The Higgs Boson Radiative Decays*

Tao Han
PITT PACC, Univ. of Pittsburgh

New Physics Interpretations at the LHC 2 Workshop
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* TH & Xing Wang, arXiv:1704.00790

Pheno 2017, May 8-10

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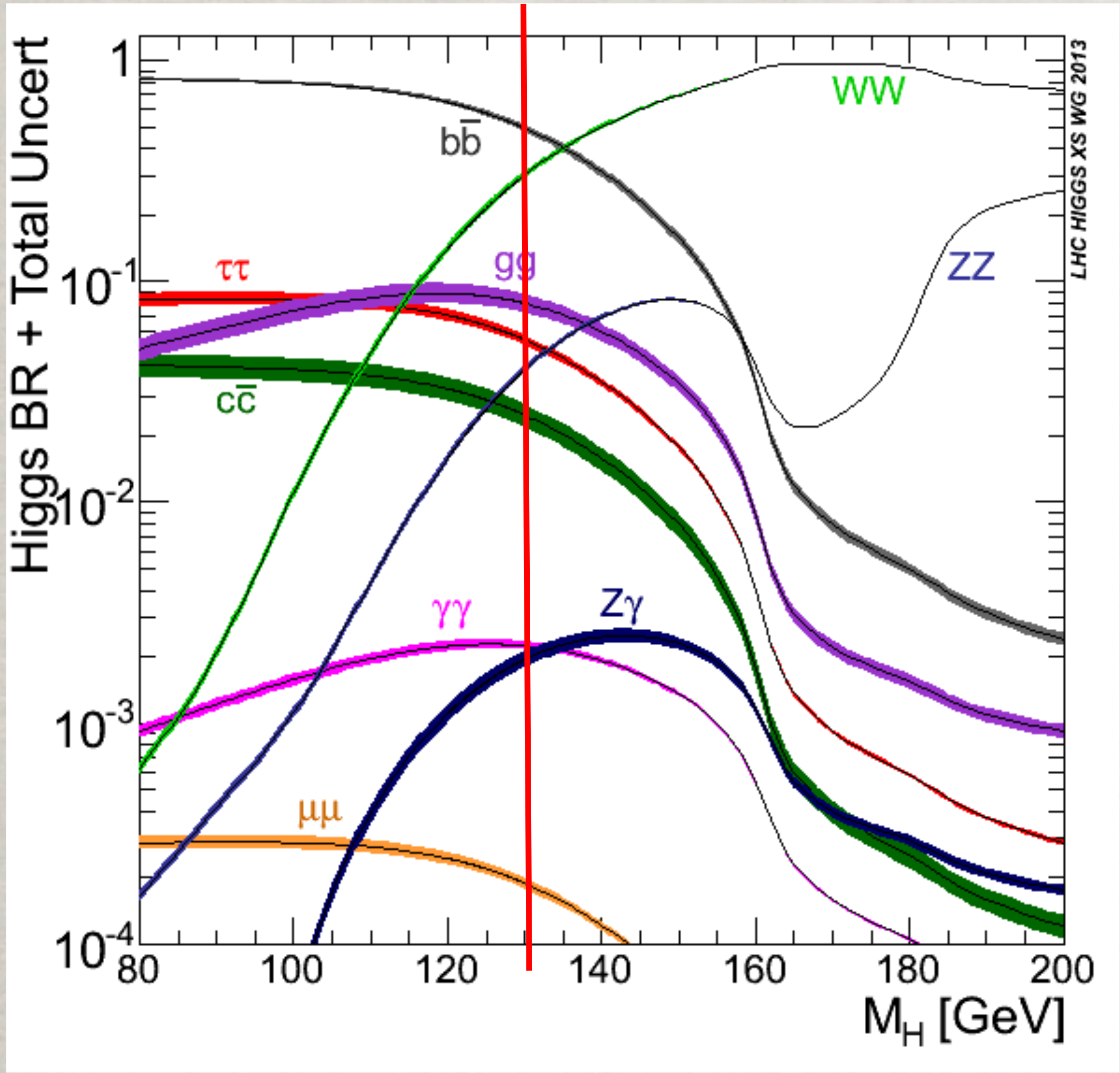
Higgs "Rare Decays"

Anything not well-done is "Rare", but "exotic" !

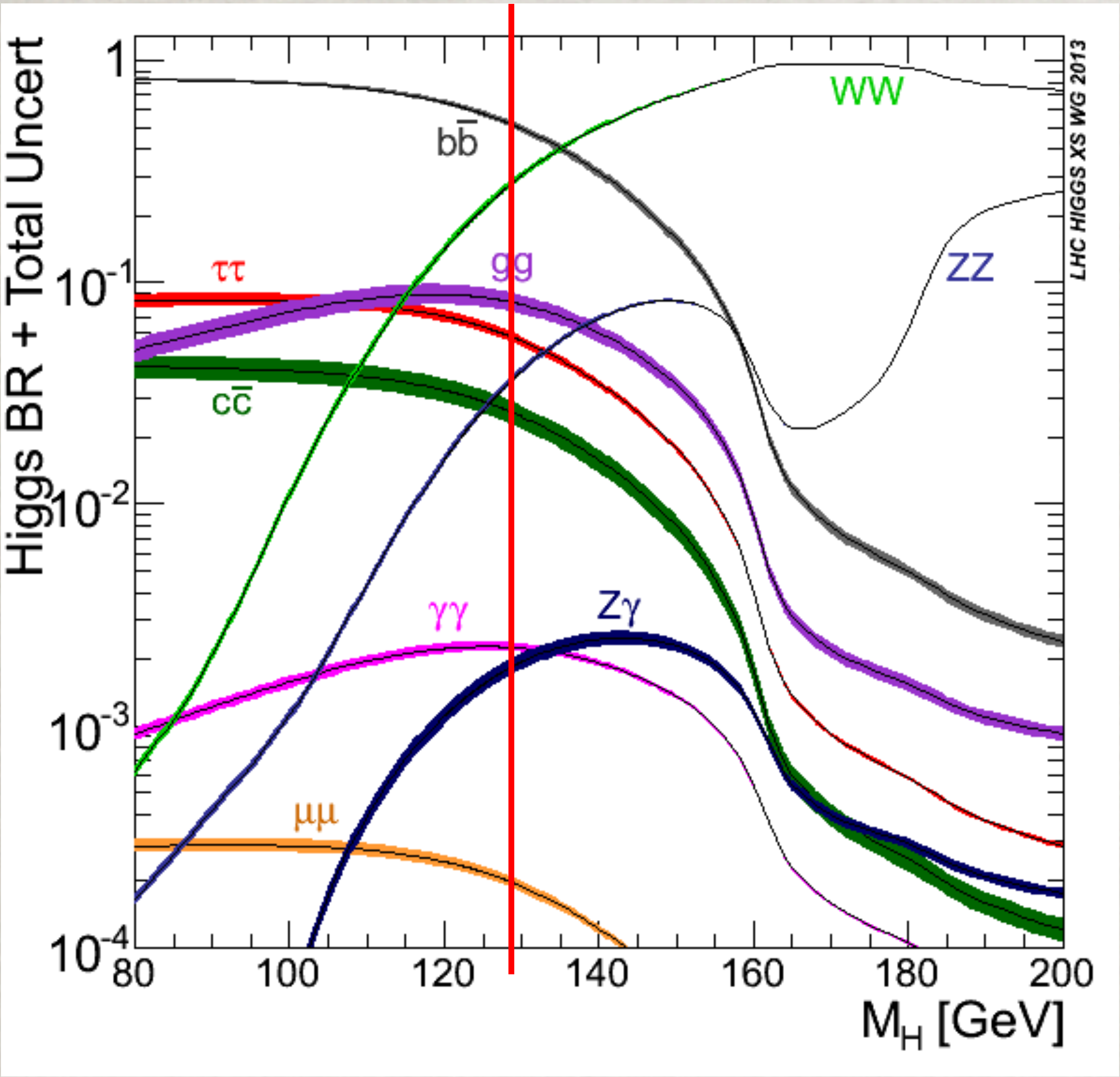


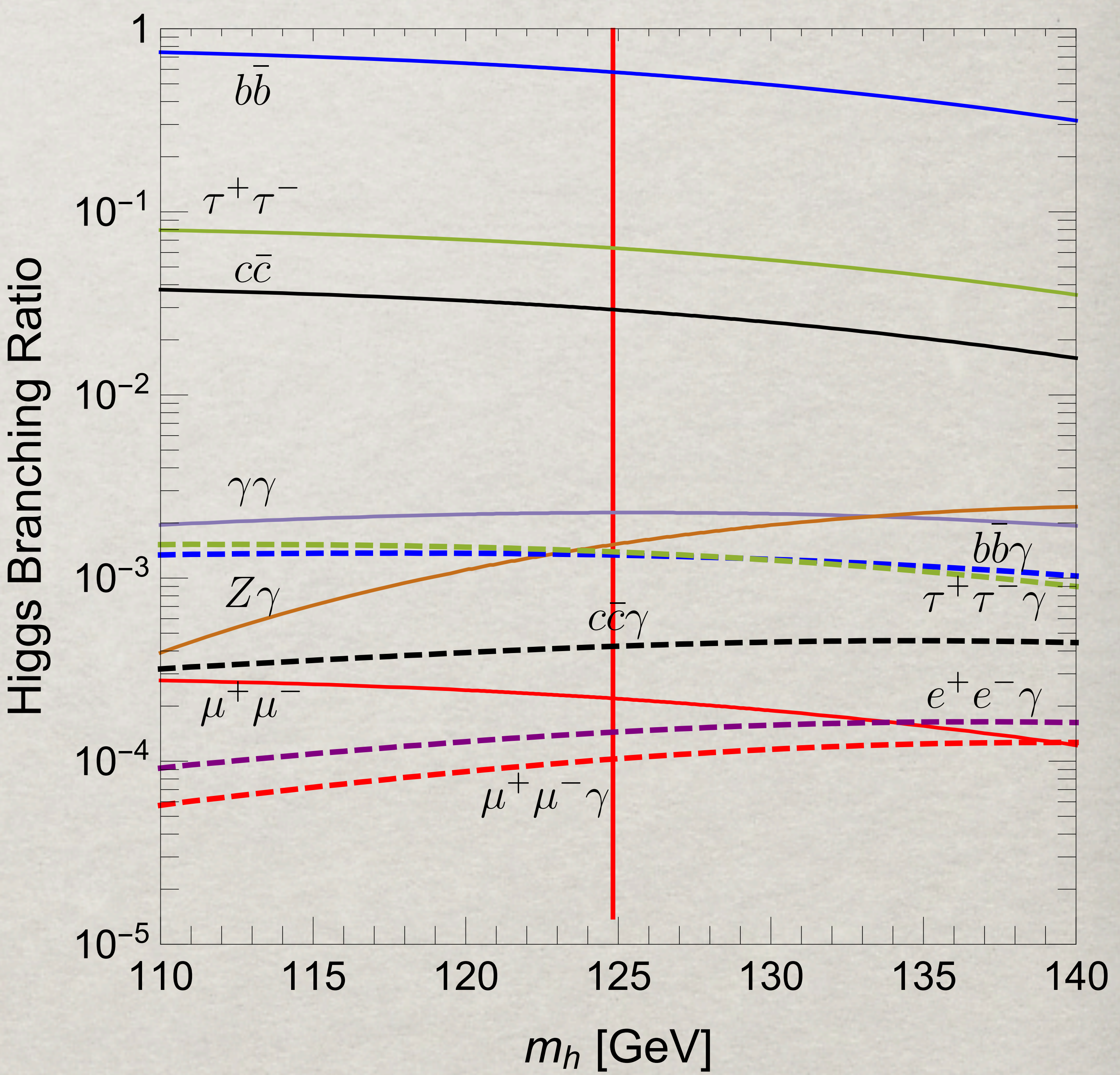
With HL-LHC:

(0.3 - 3) ab^{-1} → 15 - 150M h's !

Higgs Radiative Decays

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

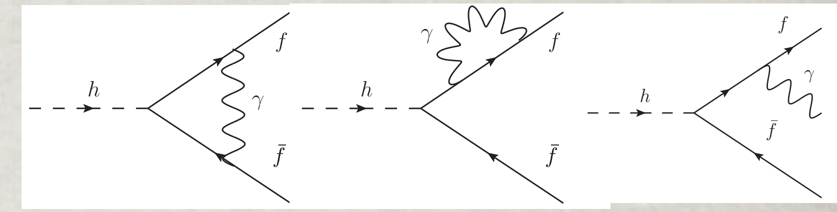




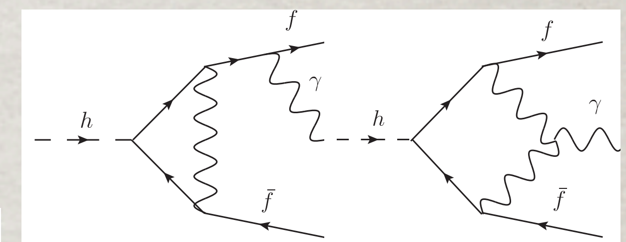
Will focus on radiative decays.

Summary

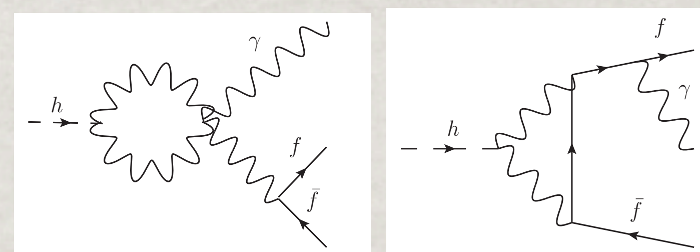
Revisit theoretical calculations:



- QED correction to Yukawa: $O(y_f^2\alpha)$
- EW correction to top-Yukawa: $O(y_t^2\alpha^3)$



- EW correction: $O(\alpha^4)$



Summary

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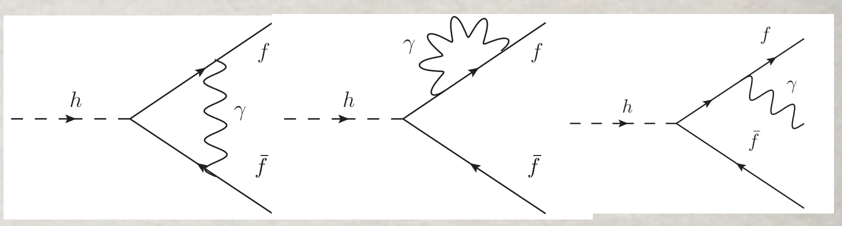

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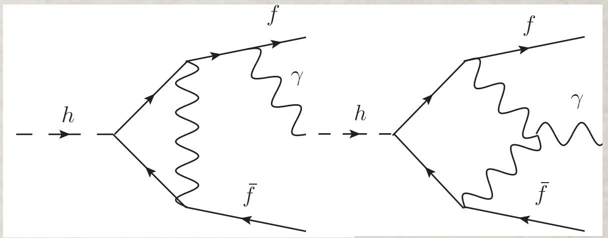

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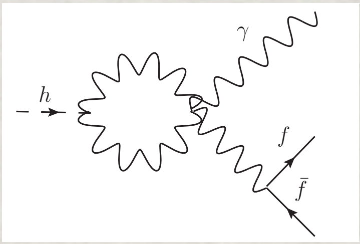
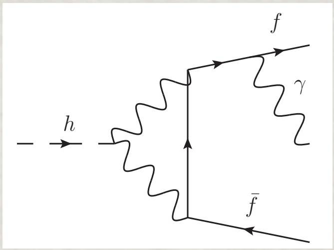




Re-evaluate the LHC search:

$$h \to \mu^+\mu^-\gamma, \quad e^+e^-\gamma.$$

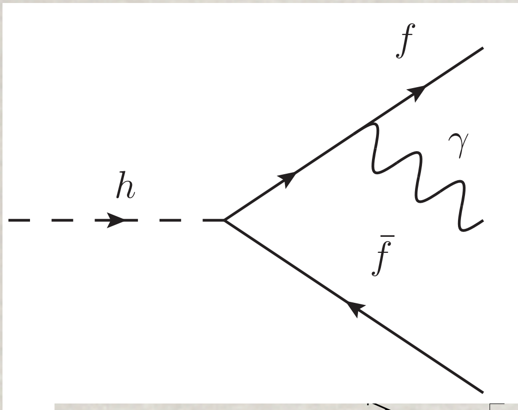
Propose the LHC search for $h \to \tau^+\tau^-\gamma.$

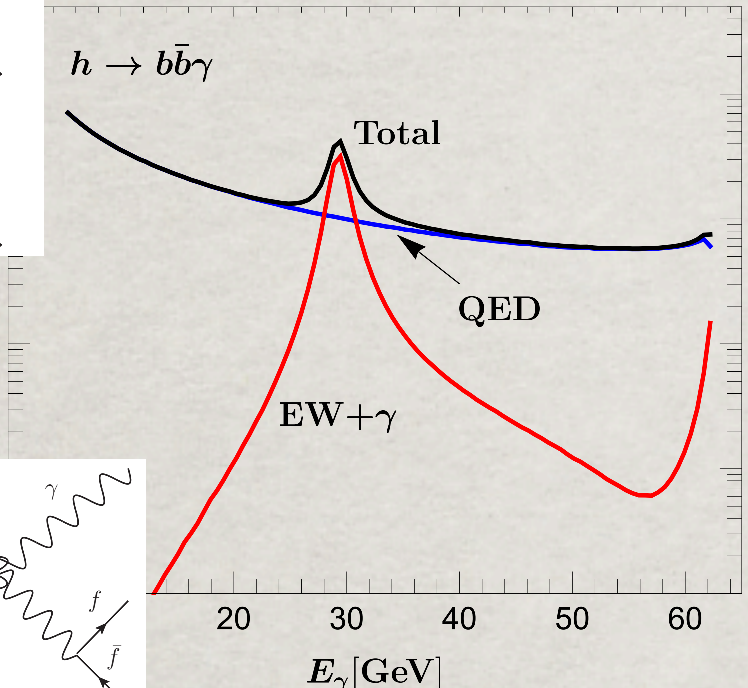
New LHC study for $h \to c\,\bar{c}\,\gamma.$

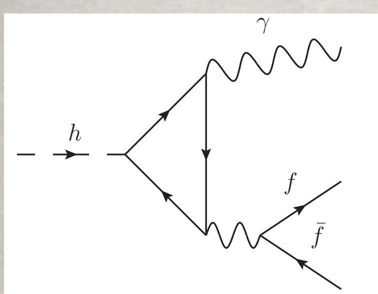
Exclusive $h \to f\bar{f}\gamma$

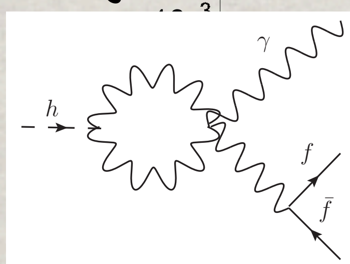
$$E_\gamma = \frac{m_h}{2}\left(1 - \frac{m_Z^2}{m_h^2}\right) \approx 30 \text{ GeV}, \text{ for } \gamma Z \text{ production},$$

$$E_\gamma = \frac{m_h}{2}\left(1 - \frac{m_{\gamma^*}^2}{m_h^2}\right) \approx 63 \text{ GeV}, \text{ for } \gamma\gamma^* \text{ production}.$$

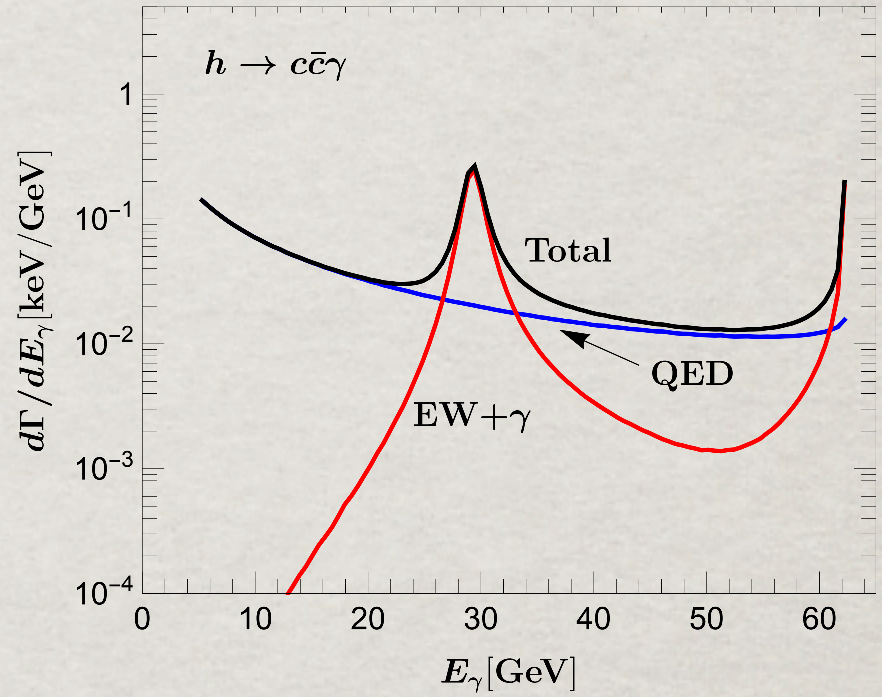








(a)



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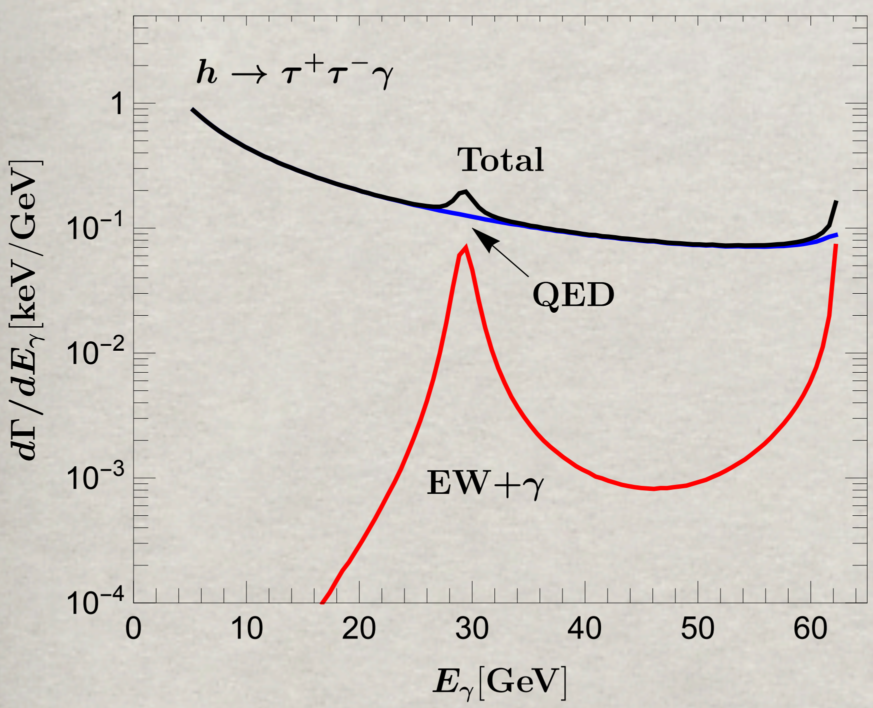
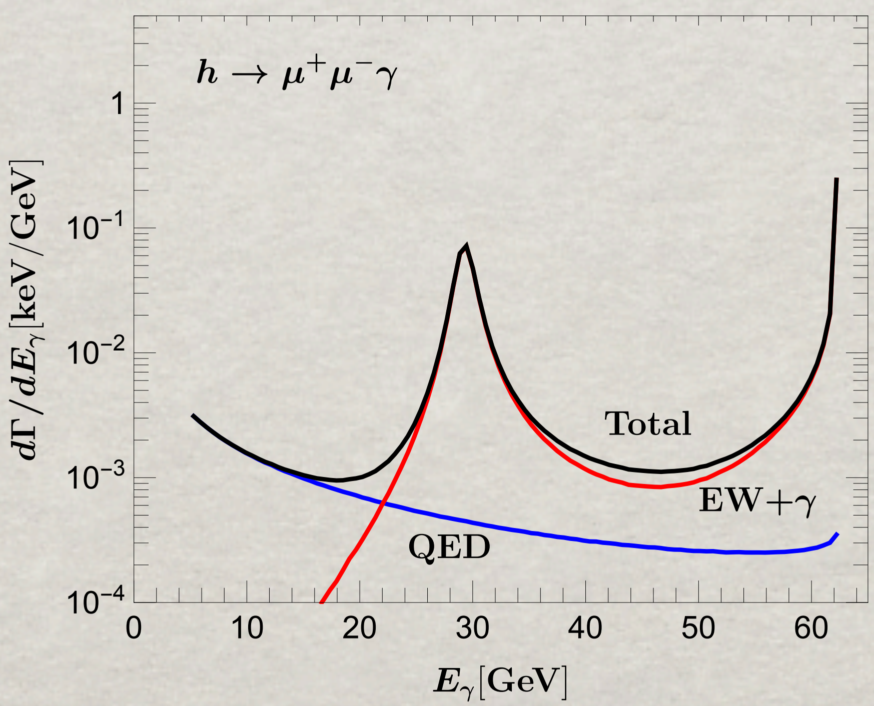
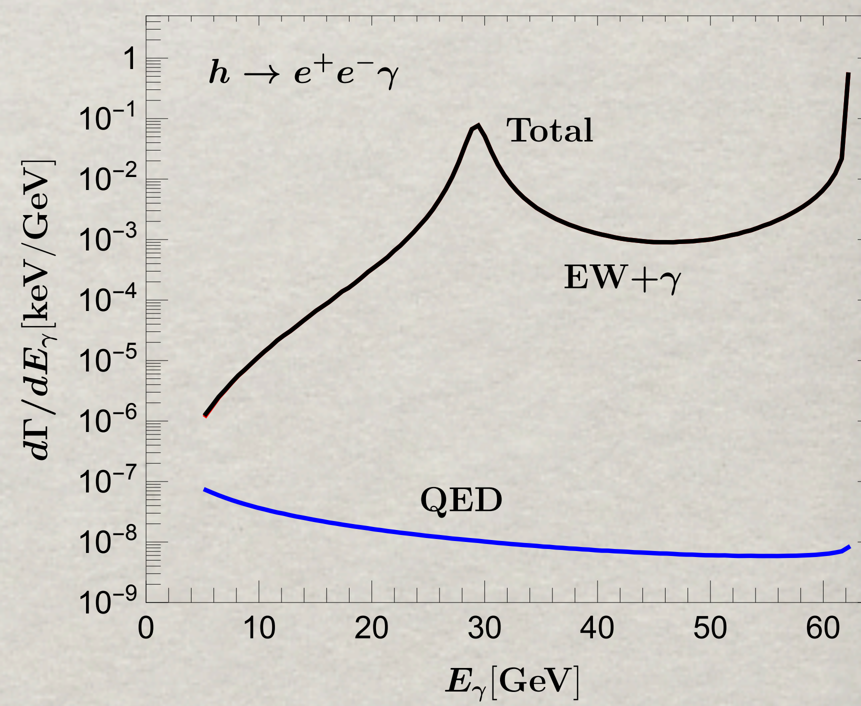


(c)

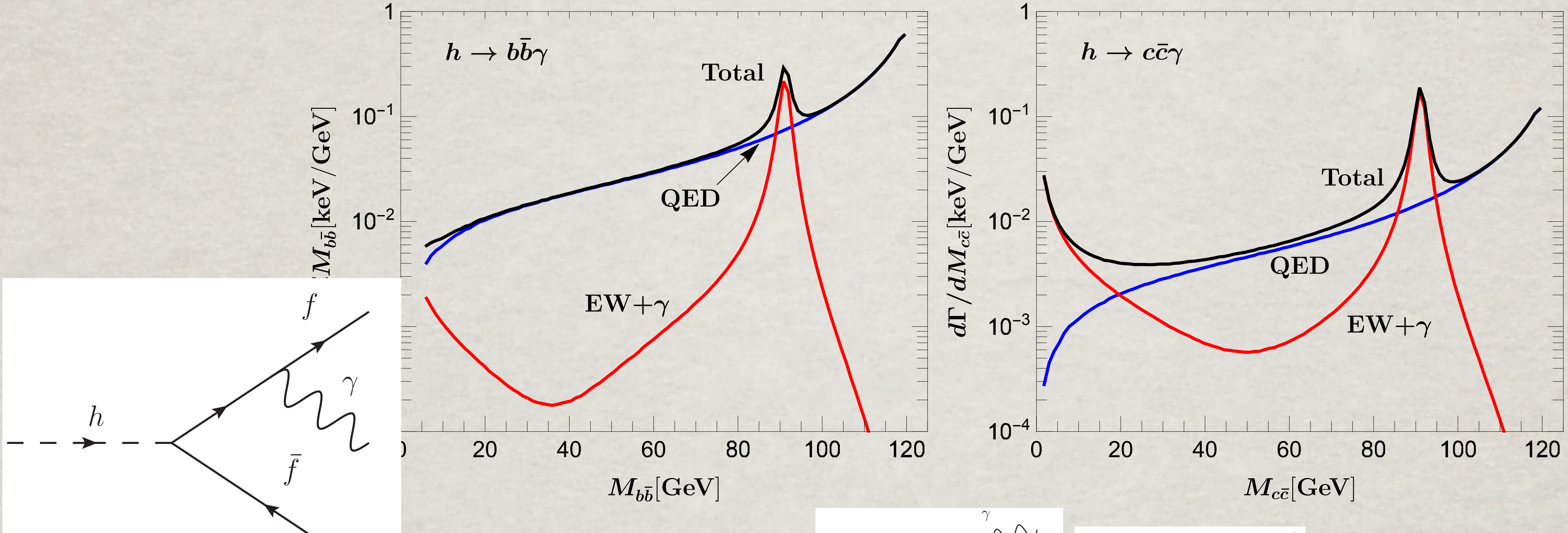


(d)



(e)

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



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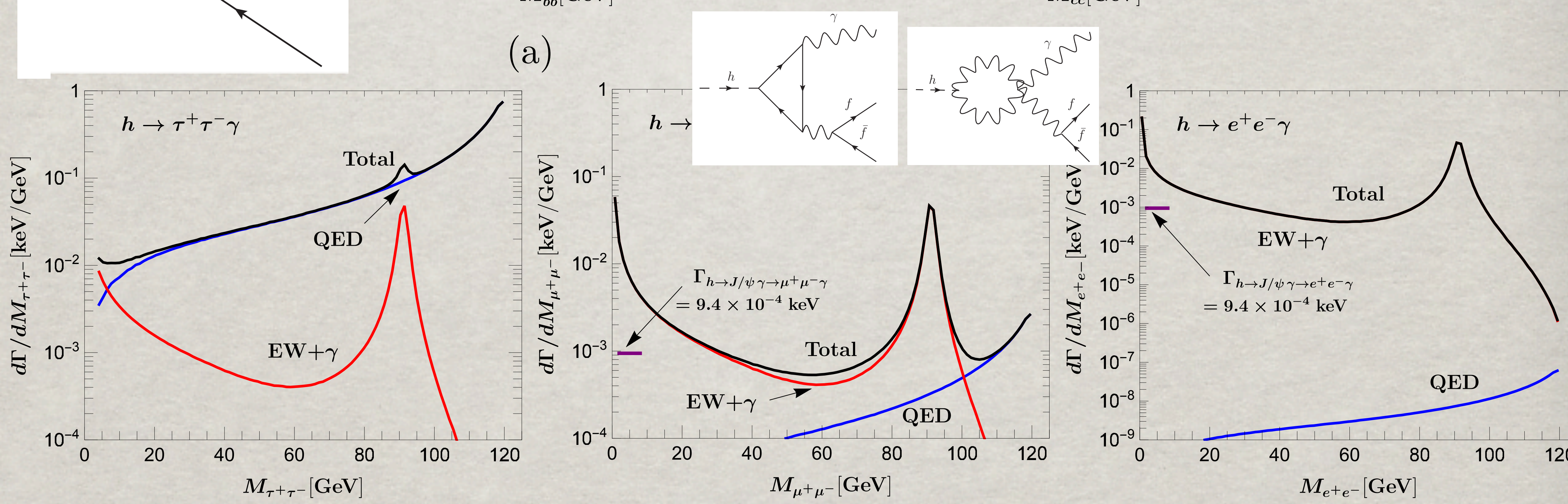

(c) (d) (e)

Results for $gg \to h \to \mu^+\mu^-\gamma, \quad h \to e^+e^-\gamma:$

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)
$pp \to \gamma^*\gamma \to e^+e^-\gamma$	1.06	27.0	3.53 (11.2)
$60 < E_\gamma < 63$ GeV	1.06	17.0	4.45 (14.1)
$p_{T\gamma} > 55$ GeV	0.79	17.6	3.26 (10.3)
$pp \to Z\gamma \to \mu^+\mu^-\gamma$	1.40	214	1.66 (5.24)
$27 < E_\gamma < 33$ GeV	1.10	121	1.73 (5.48)
$p_{T\gamma} > 25$ GeV	0.91	95.9	1.61 (5.09)
$pp \to Z\gamma \to e^+e^-\gamma$	1.38	224	1.60 (5.05)
$27 < E_\gamma < 33$ GeV	1.13	126	1.74 (5.51)
$p_{T\gamma} > 25$ GeV	0.91	100	1.58 (4.98)

Table 3: The cross sections of signals and backgrounds, and the statistical significances of $pp \to V\gamma \to \ell^+\ell^-\gamma$, $V = Z, \gamma^*$.

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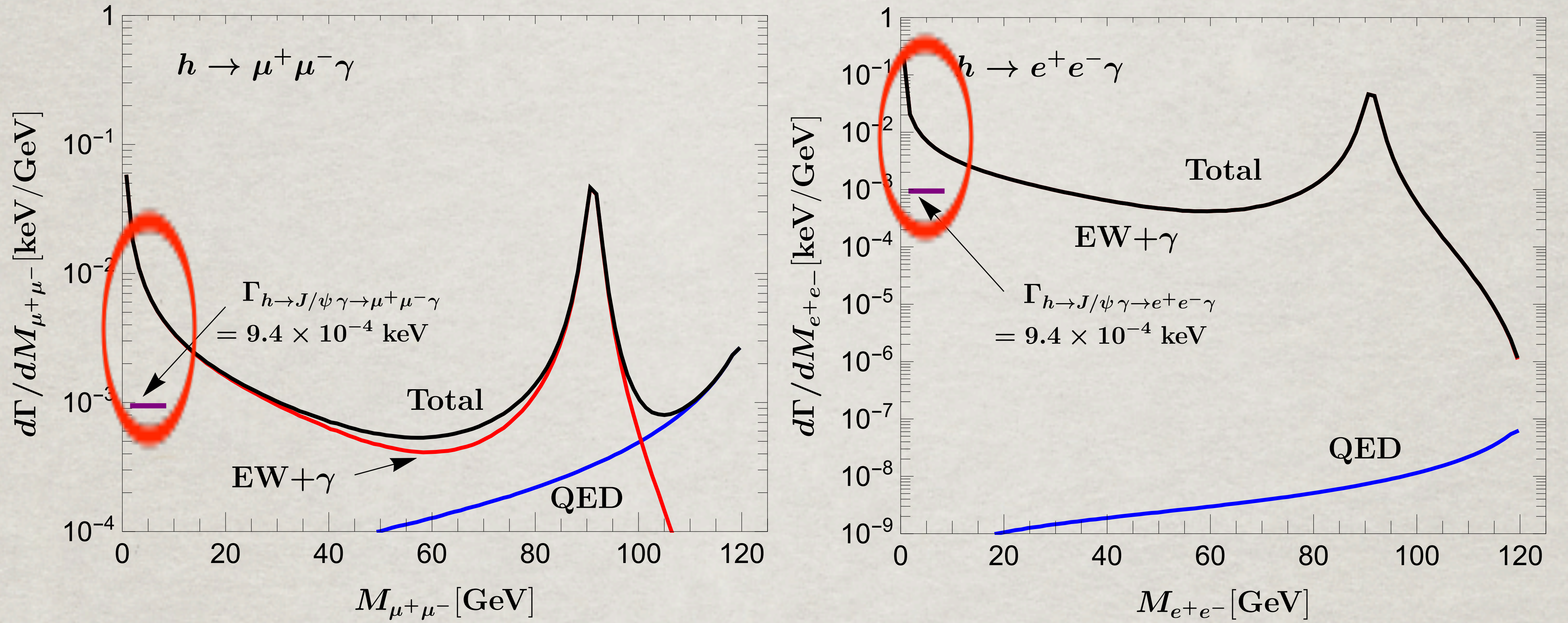
ATLAS/CMS expectation for direct decay: $h \to \mu^+\mu^-$

$2.3\sigma/7.0\sigma$

for 0.3 ab^{-1}/3 ab^{-1}

Table 3: The cross sections of signals and backgrounds, and the statistical significances of $pp \to V\gamma \to \ell^+\ell^-\gamma$, $V = Z, \gamma^*$.

A remark on $gg \to h \to J/\psi\,\gamma \to \ell^+\ell^-\gamma$:



J/ψ γ is more than an order of magnitude smaller;
Further, the dominant contribution is from **γ*→ J/ψ**,
not from the direct hcc Yukawa.
Must observe the continuum $\ell^+\ell^-\gamma$ first …

Bodwin, Petriello et al. (2013, 2014, 2017);
Konig, Neubert (2015)

$gg \to h \to \tau^+\tau^-\gamma$:

Ccurrent LHC observation is largely from VBF due to the $m_{\tau\tau}$ reconstruction & DY backgrounds. Now there is an additional γ, we could consider to use the leading production mechanism:

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

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

Need dedicated analyses to draw a conclusion.

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

The currently related search h → bb:

$$q\bar{q} \to Z/W + h \to \ell's + b\bar{b}$$

$$\text{VBF} \to h \to b\bar{b}\; jj.$$

Now there is an additional γ to trigger on, we could consider to use the leading production mechanism:

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

→ Crucially depends on charm-tagging!

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

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

Luminosity	Operating Point	Signal (Total)	Signal (QED)	Signal (EW+γ)	Background
3000 fb^{-1}	I	778	252	492	3.84×10^7
	II	1750	567	1107	1.25×10^8
	III	3937	1275	2491	6.51×10^8

Very difficult to reach the SM expectations.

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Very difficult to reach the SM expectations.

Compare with the literature:

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 [61]	2.5
$h + c$ production [62]	2.6
Higgs kinematics [63]	4.2
$h \to J/\psi\gamma$ [47]	50

Table 6: 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.

Conclusions

Theoretical calculations revisited:

- QED & running masses O(Q_f^2 x 1%) → comparable to the Higgs factory need ~0.3% !
- EW corrections → interesting features/channels.

Re-evaluated the LHC search:

$$h \to \mu^+\mu^-\gamma, \quad e^+e^-\gamma.$$

comparable to $h \to \mu^+\mu^-$!

Propose the LHC search for $h \to \tau^+\tau^-\gamma$.

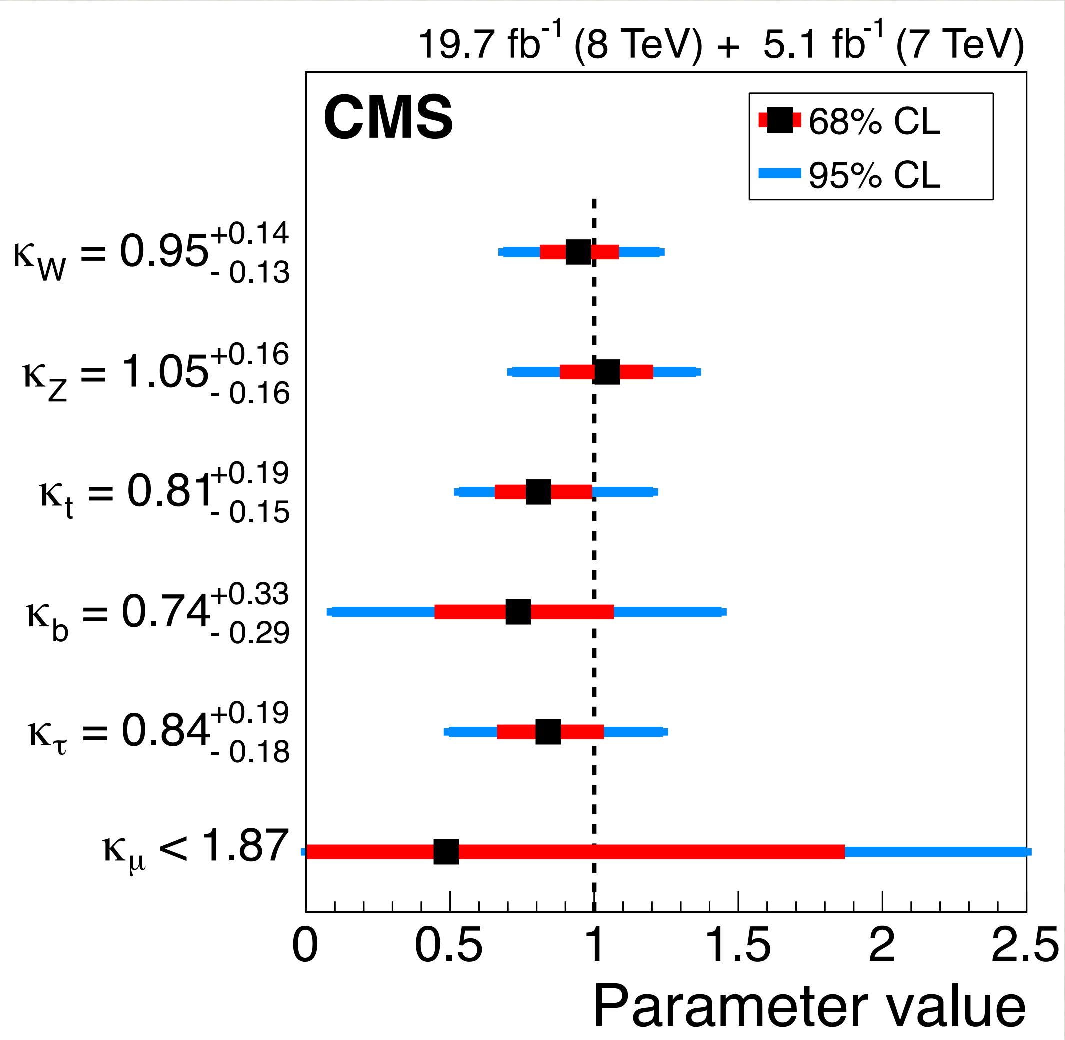
New LHC study: $h \to c\,\bar{c}\,\gamma$.

complementary to other channels.

"Rare Decays" the next target!

Introduction:

Excellent results from the LHC:



Current accuracies:

ZZ,WW: 15%

Tau tau, tt (ind): 20%

bb: 30%

Fermion	$\bar{m}_f(m_f)$ [GeV]	$\delta\bar{m}_f^{\rm QCD}$ [GeV]	$\delta\bar{m}_f^{\rm QED}$ [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}

Table 1: The $\overline{\rm MS}$ running masses with N^{4}LO QCD and NLO QED corrections. The last column is the LO width with the running Yukawa coupling effect.

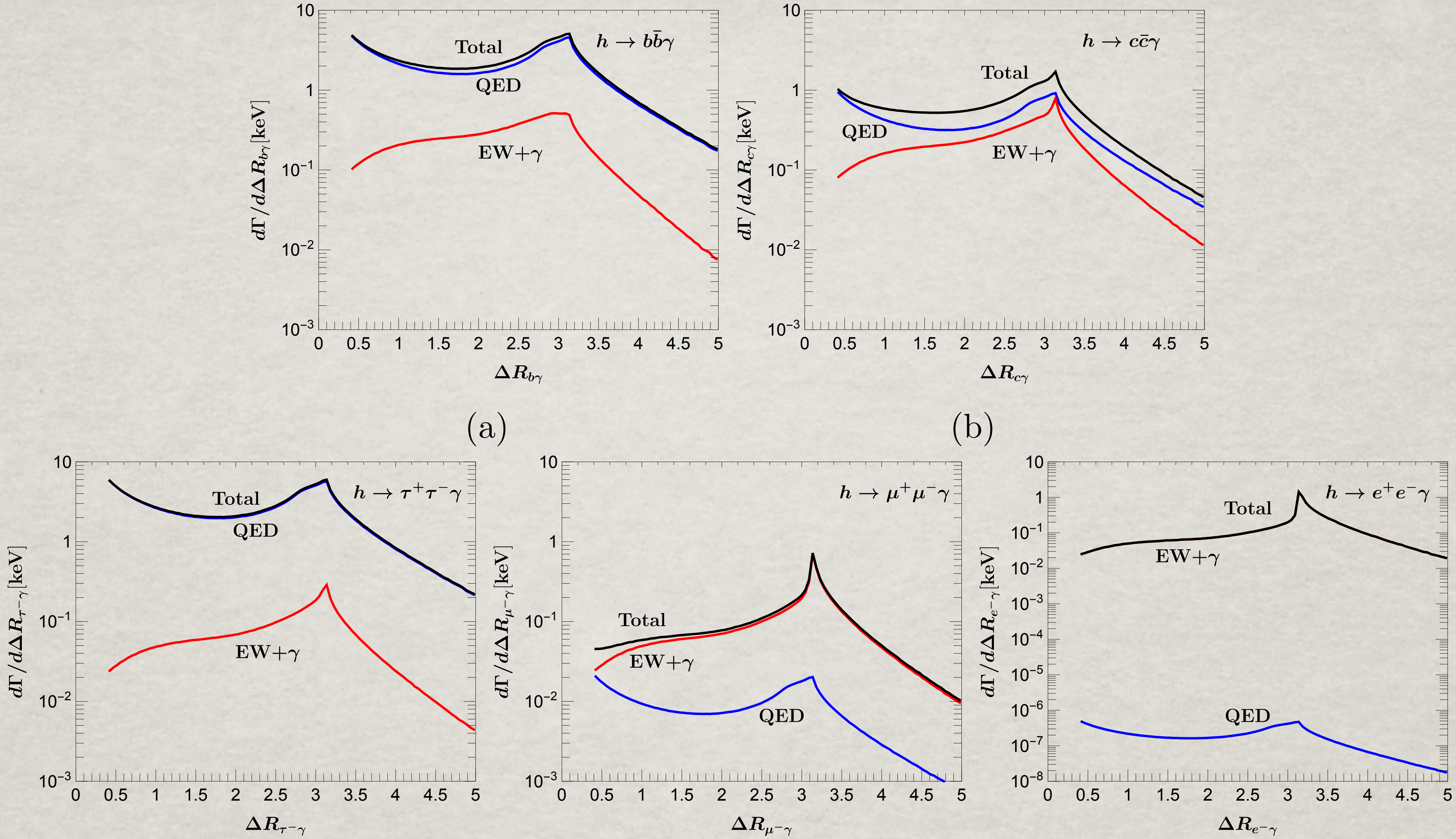
$$\Gamma_{\rm NLO\ QCD} = \Gamma^0 \left(1 + C_F \frac{\bar{\alpha}_s}{\pi}\ \frac{17}{4} + \mathcal{O}(\alpha_s^2)\right), \quad \Gamma^0 = \frac{N_c}{8\pi}\ m_h\ \frac{\bar{m}_f^2}{v^2}\ \beta_f^3$$

$$\Gamma_{\rm NLO\ QED} = \Gamma^0 \left(1 + Q_f^2 \frac{\bar{\alpha}}{\pi}\ \frac{17}{4} + \mathcal{O}(\alpha^2)\right)$$

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

	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

Table 2: One-loop Yukawa and EW+γ corrections to Higgs fermionic decays. The first two columns are the inclusive corrections at the order $\mathcal{O}(y_f^2\alpha)$ and at $\mathcal{O}(y_t^2\alpha^3, \alpha^4)$, respectively. The widths and branching fractions for the exclusive decay are shown in the last two columns ($E_\gamma > 5/15$ GeV, and $\Delta R_{f\gamma} > 0.4$).



$h \to b\bar{b}\gamma$
Total
QED
EW+γ
$d\Gamma/d\Delta R_{b\gamma}$[keV]
$\Delta R_{b\gamma}$
$h \to c\bar{c}\gamma$
Total
QED
EW+γ
$d\Gamma/d\Delta R_{c\gamma}$[keV]
$\Delta R_{c\gamma}$
$h \to \tau^+\tau^-\gamma$
Total
QED
EW+γ
$d\Gamma/d\Delta R_{\tau^-\gamma}$[keV]
$\Delta R_{\tau^-\gamma}$
$h \to \mu^+\mu^-\gamma$
Total
EW+γ
QED
$d\Gamma/d\Delta R_{\mu^-\gamma}$[keV]
$\Delta R_{\mu^-\gamma}$
$h \to e^+e^-\gamma$
Total
EW+γ
QED
$d\Gamma/d\Delta R_{e^-\gamma}$[keV]
$\Delta R_{e^-\gamma}$

(a) (b)

(c) (d) (e)

Higgs decay and effectively suppress the backgrounds, we require the invariant masses to be

$$M_{\mu\mu} < 20\ \text{GeV}, \quad M_{ee} < 1.5\ \text{GeV}, \quad 120\ \text{GeV} < M_{\ell\ell\gamma} < 130\ \text{GeV}. \tag{3.1}$$

The leading (sub-leading) muon must satisfy the acceptance of the transverse momentum and pseudo-rapidity

$$p_T^{\mu} > 23\ (4)\ \text{GeV}, \quad |\eta_\mu| < 2.4. \tag{3.2}$$

The electrons must satisfy

$$|p_{Te^+}| + |p_{Te^-}| > 44\ \text{GeV}, \quad |\eta_e| < 1.44. \tag{3.3}$$

so that a multivariate discriminator can be used to separate $\gamma^* \to e^+e^-$ from jets or single electrons [34].[2] The photon must satisfy the following acceptance and be well-separated from leptons

$$p_T^{\gamma} > 0.3 M_{\ell\ell}, \quad |\eta_\gamma| < 1.44, \quad \Delta R_{\gamma\ell} > 1. \tag{3.4}$$

our simulations, we require that both the c-jets and the photon be hard and well-isolated in the central region

$$p_T \ > \ 20 \text{ GeV}, \ \ |\eta| < 2.5, \ \ \text{and} \ \ \Delta R > 0.4. \tag{4.2}$$

The ultimate sensitivity for the signal $h \to c\bar{c}\gamma$ depends on the invariant mass reconstruction $M_{jj\gamma} = m_h$, and thus the energy resolution of the charm-jets. In this study, we assume that the Higgs resonance peak can be reconstructed within 20% and thus we require

$$100 \text{ GeV} < M_{jj\gamma} < 150 \text{ GeV}. \tag{4.3}$$