The Higgs Boson Radiative Decays*

Tao Han

Univ. of Pittsburgh / Tsinghua U., Beijing

NCTS 20th Anniversary Symposium

Frontiers in Physics, August 3rd, 2017

* TH & Xing Wang, arXiv:1704.00790

The completion of the SM:

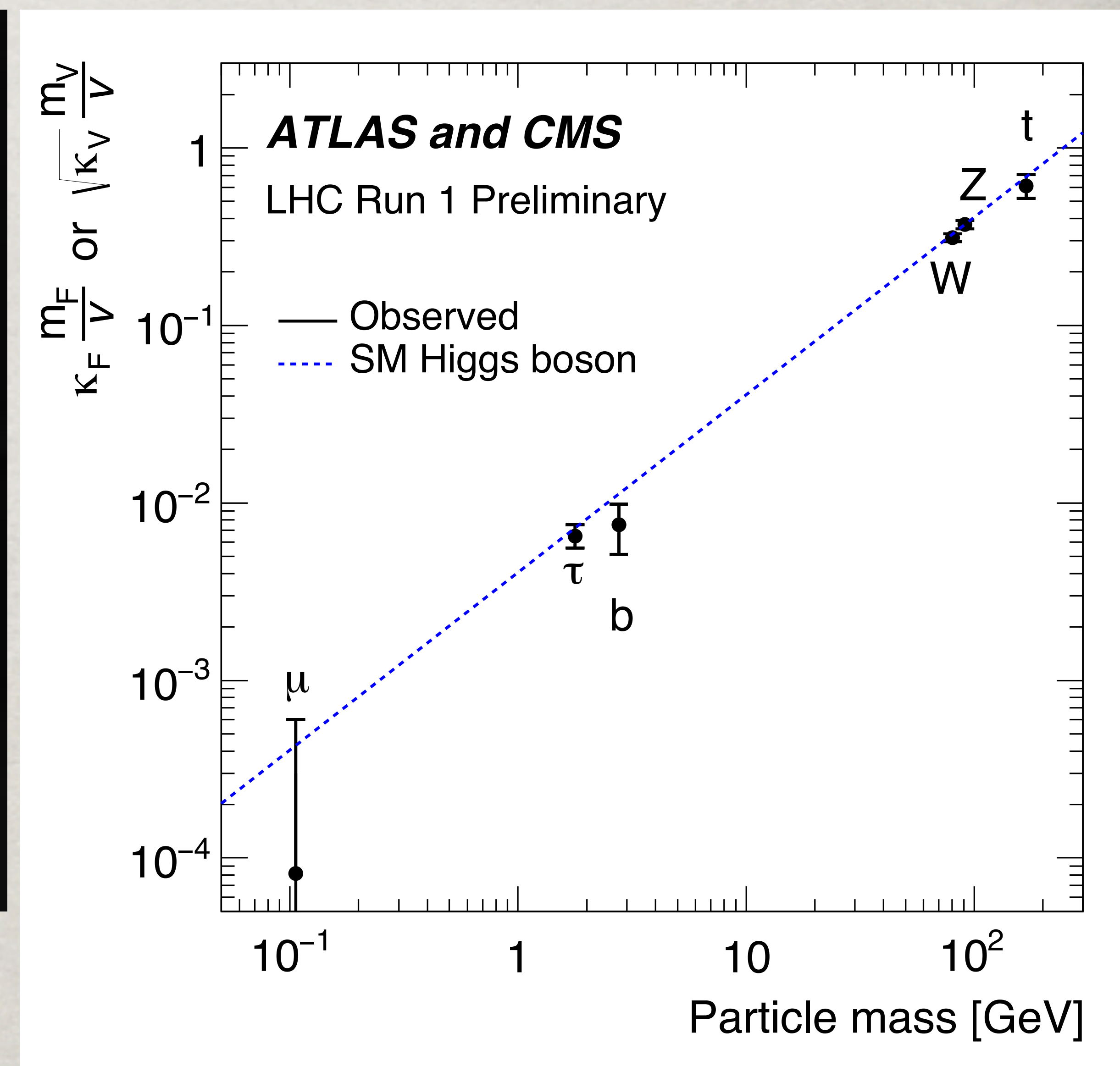
First time ever, we have a consistent relativistic, quantum mechanical theory: weakly coupled, unitary, renormalizable, vacuum-(quasi?)stable, valid up to an exponentially high scale, perhaps to the Planck scale M_{Pl}!

Further fundamental questions:

- Nature of EWSB: Higgs potential, EW phase trans.
- Vacuum stability: top quark mass/Yukawa coupling
- "Naturalness": TeV scale new physics
- Puzzles: DM, flavor physics, neutrino mass
- … … …

New Era:
Under the Higgs lamp post

Energy threshold for new particles
+ precision Higgs physics



Precision Higgs Physics

In a pessimistic scenario, the LHC does not see a new particle associated with the Higgs sector, then the effects of a heavy state on Higgs coupling g_i at the scale M:

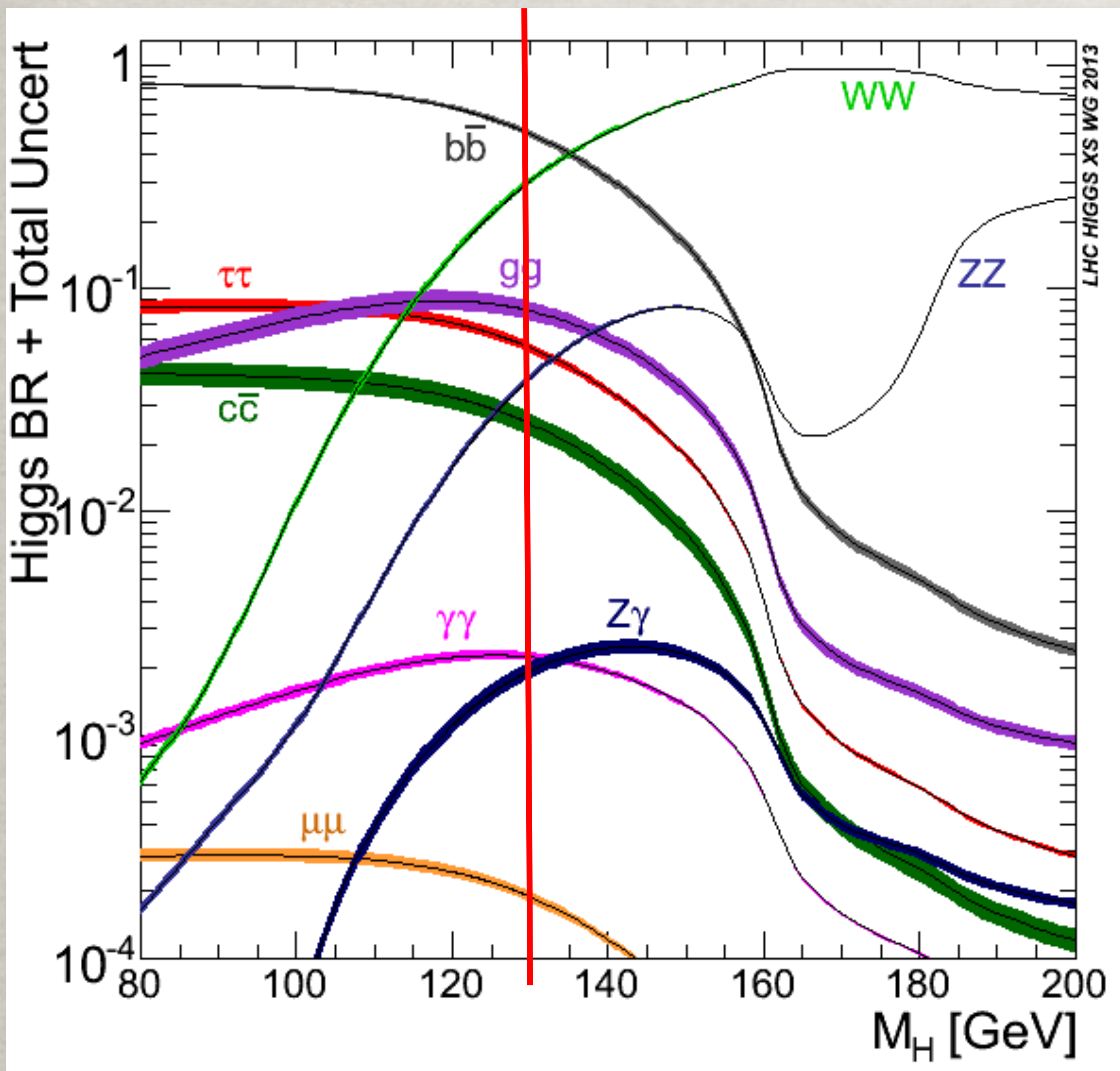
$$\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2)$$ ≈ a few % for M ≈ 1 TeV

Higgs coupling deviations:

Δ:	VVH	bbH,ττH	ggH,γγH	HHH
Composite	(3-9)%	$(1\ \mathrm{TeV}/f)^2$		100%
			(loop)	
SUSY/H^0, A^0	X	6% $(500\ \mathrm{GeV}/M_A)^2$		
		(tree-level)		
T'			-10% $(1\ \mathrm{TeV}/M_T)^2$	
LHC 14 TeV, $3ab^{-1}$:	8%	15%	few%	50%

Higgs "Rare Decays"

Anything not "well-done" is "Rare"
(but NOT "exotic" !)



$$\bar{m}(\mu) = \bar{m}(\mu_0)\left(\frac{\bar{\alpha}_s(\mu)}{\bar{\alpha}_s(\mu_0)}\right)^{\frac{\gamma_0}{b_0}} = \bar{m}(\mu_0)\left(1 + \frac{b_0}{4\pi}\bar{\alpha}_s(\mu_0)\ln\frac{\mu^2}{\mu_0^2}\right)^{-\frac{\gamma_0}{b_0}}$$

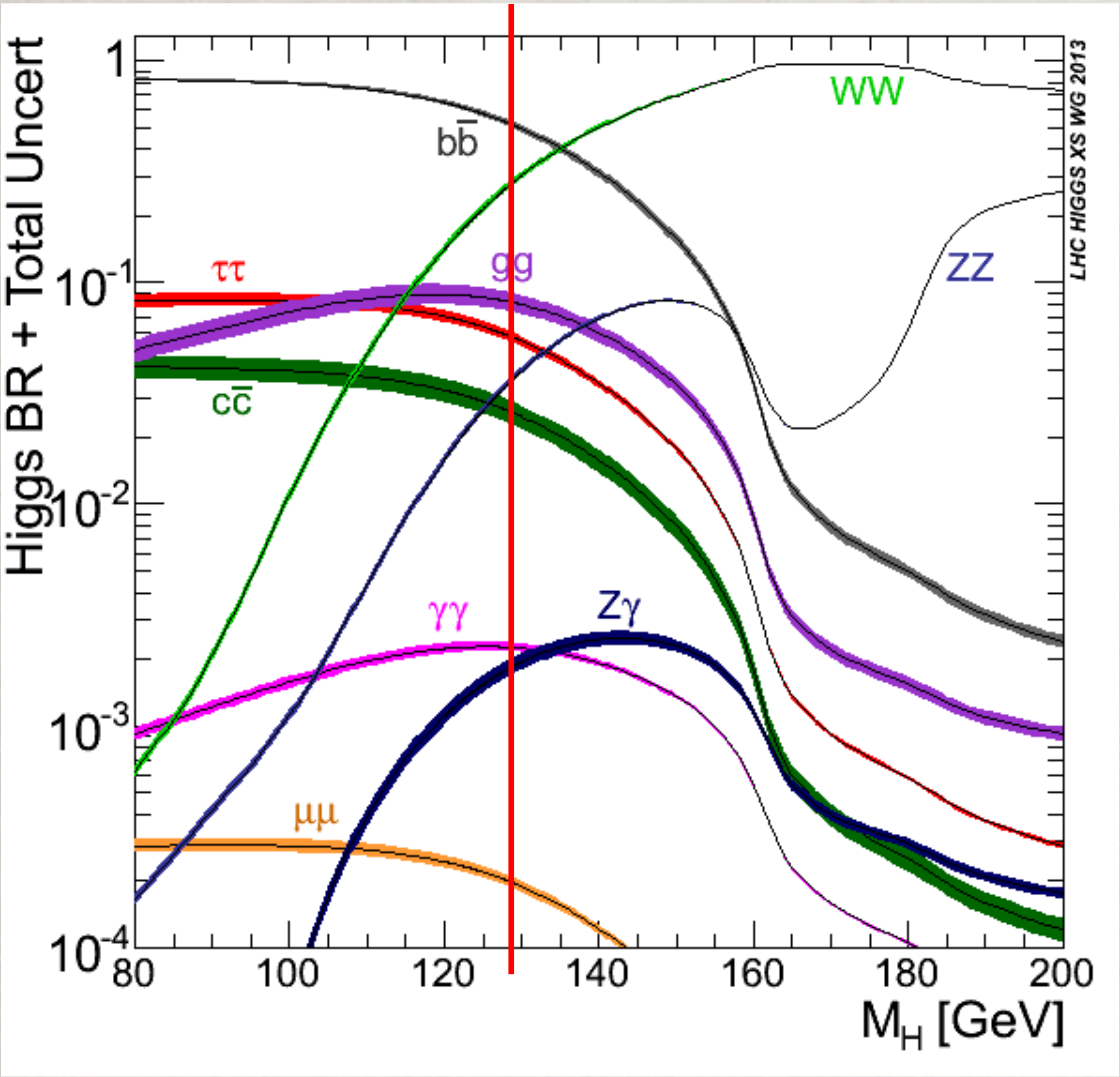
With HL-LHC:

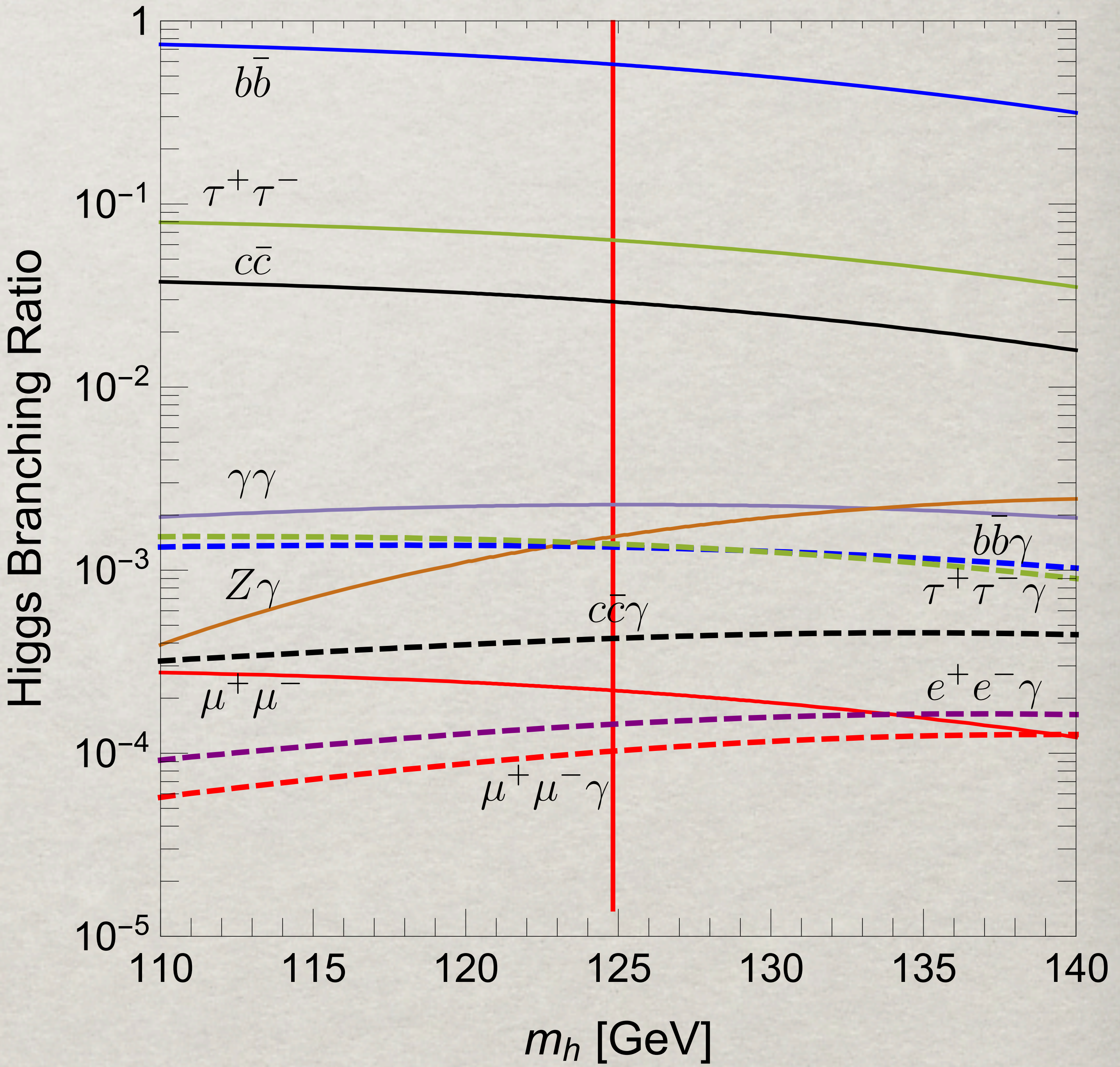
(0.3 - 3) ab^{-1} → 15 - 150M h's !

(now already about 1M!)

Higgs Radiative Decays

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

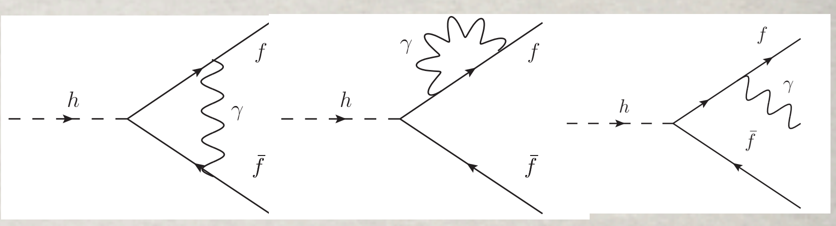




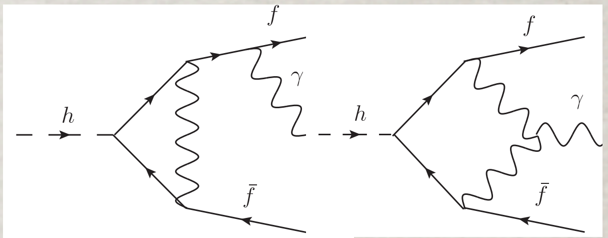
Will focus on radiative decays (dashed curves).

Summary on What We Did

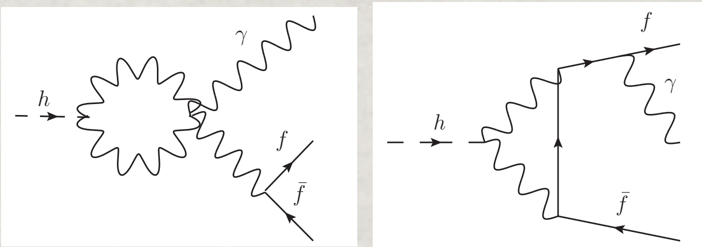
Revisit theoretical calculations:



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



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



Re-evaluate the LHC search:

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

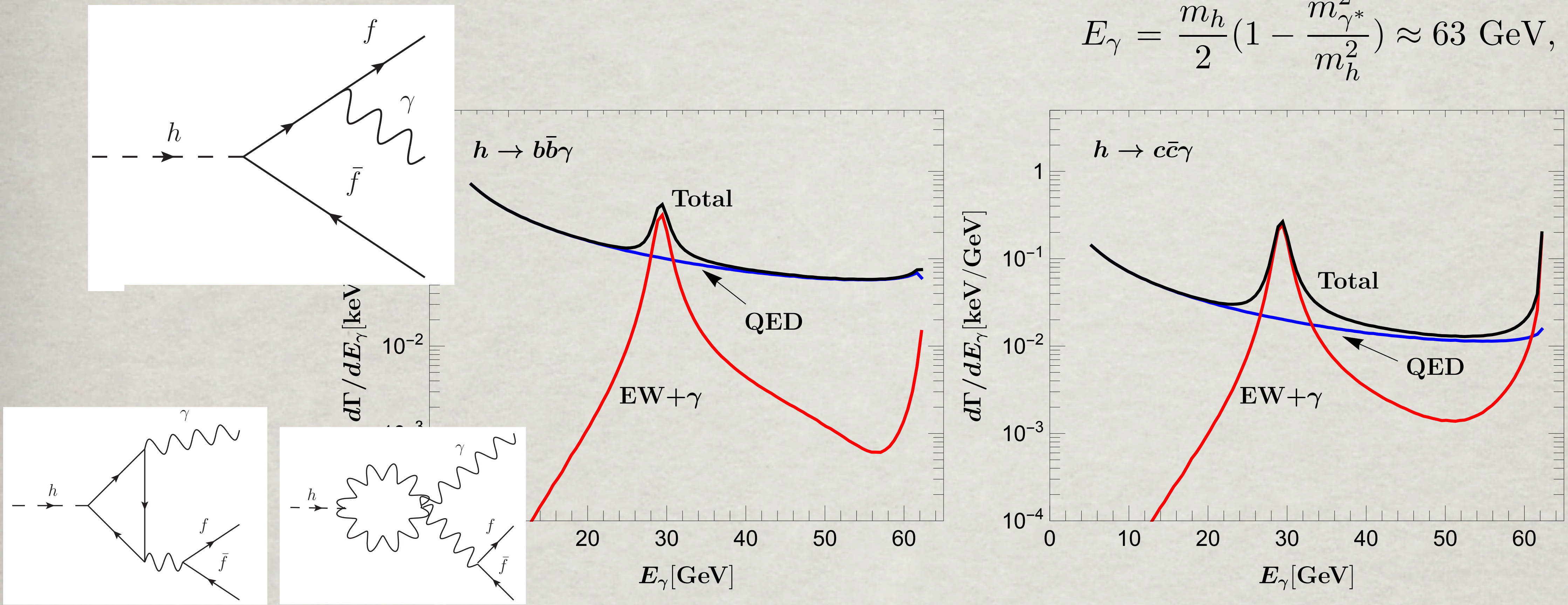
Propose the LHC search for $h \to \tau^+\tau^-\gamma.$

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

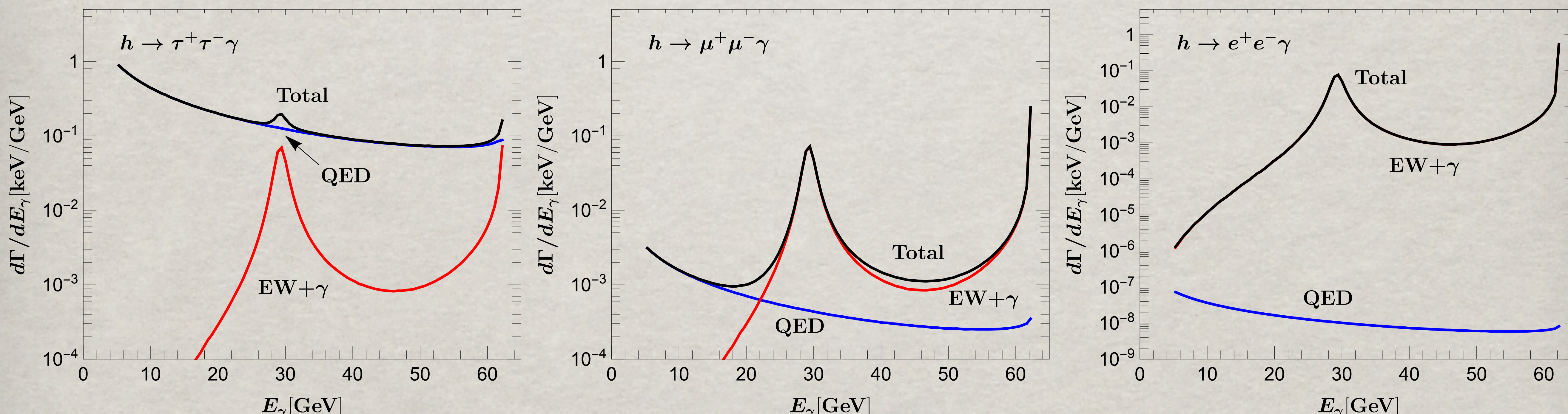
Exclusive $h \to f\bar{f}\gamma$

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

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

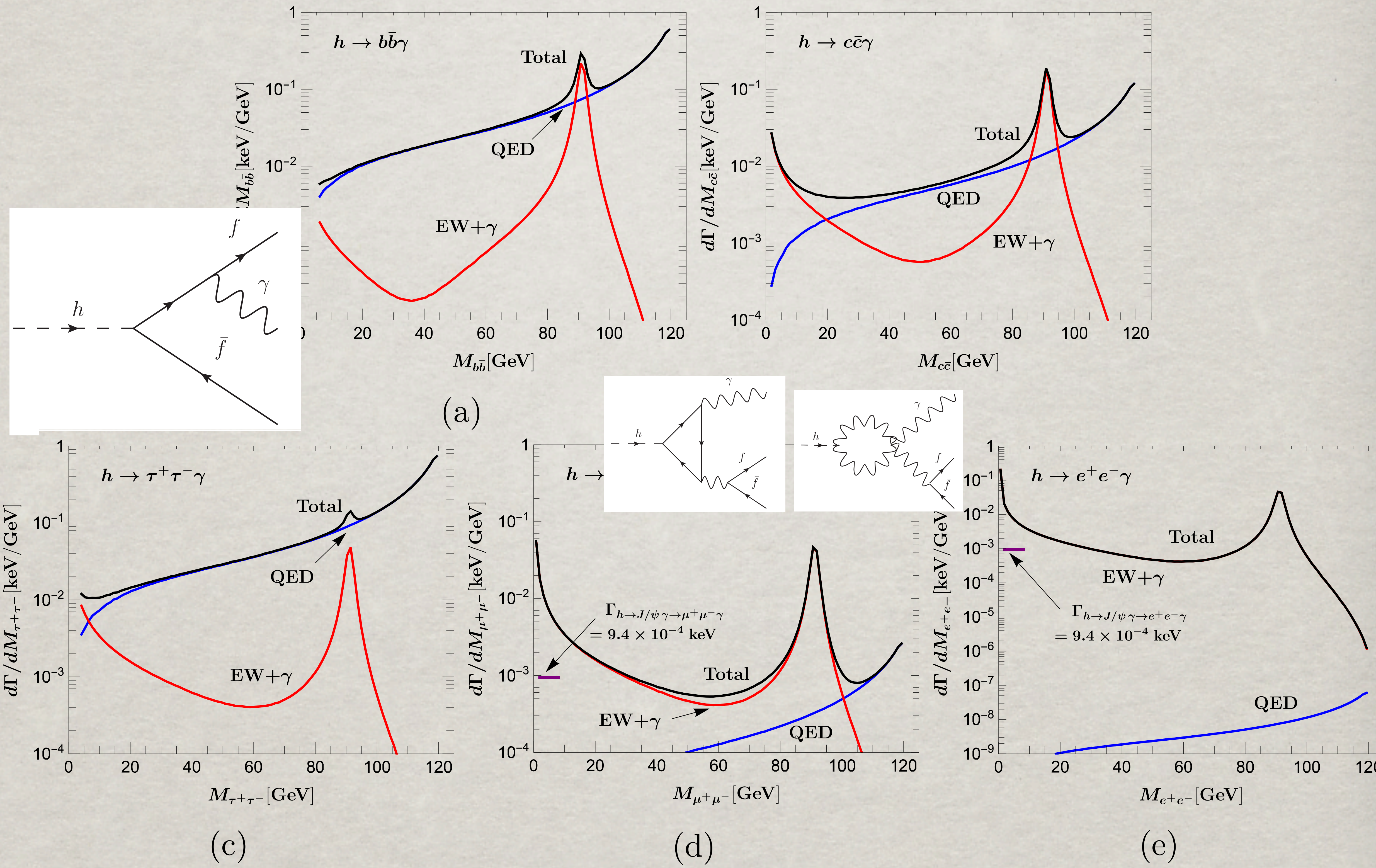


(a) (b)



(c) (d) (e)

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



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)

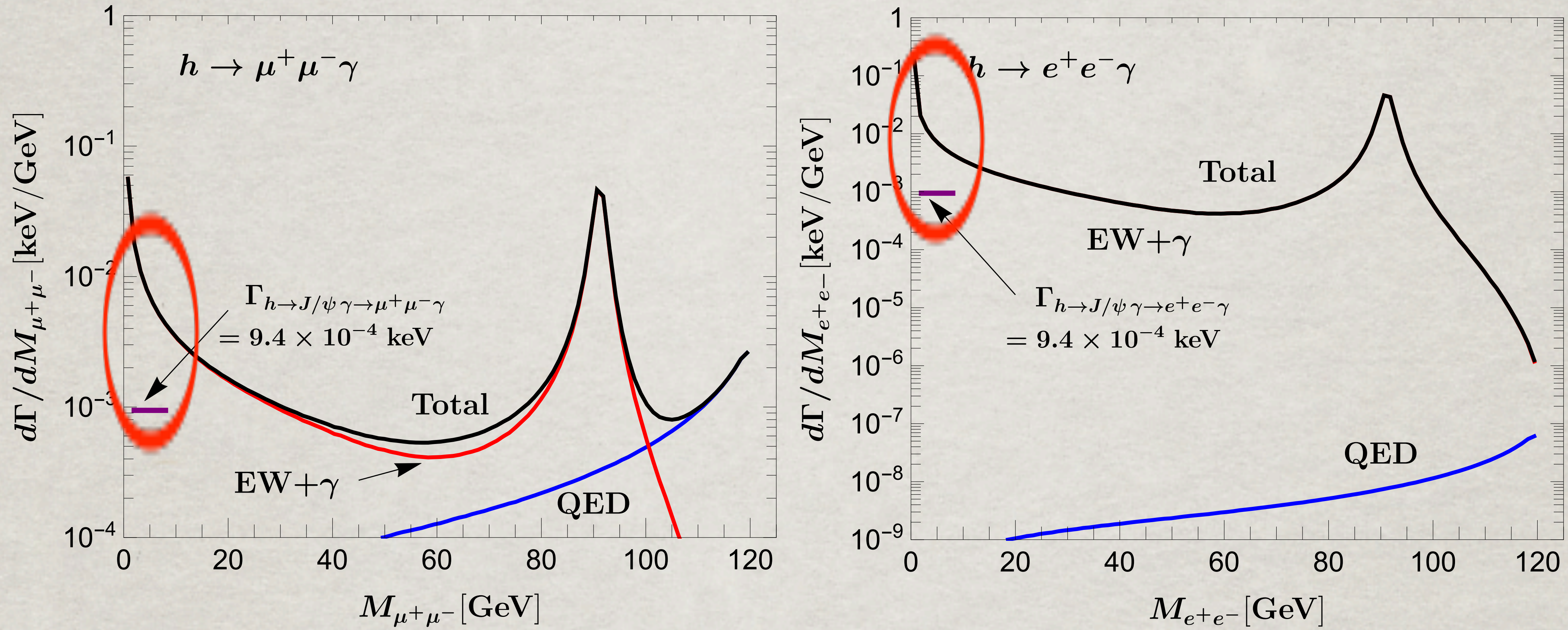
ATLAS/CMS expectation for direct decay: $h \to \mu^+\mu^-$

$2.3\sigma/7.0\sigma$

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)

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

Current 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:

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

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

Need dedicated analyses to draw a conclusion.

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

The currently related search h → bb:

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

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

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
$3000\ \mathrm{fb}^{-1}$	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.

Compare with the literature:

Method	κ_c upper limit projection at HL-LHC ($3\ \mathrm{ab}^{-1}$)
$h \to c\bar{c}\gamma$ (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 $\kappa_c = y_c^{\mathrm{BSM}}/y_c^{\mathrm{SM}}$ 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.

Radiative Higgs Decay is the next target!

Happy 20th Anniversary NCTS!