Radiative Higgs Decay to a fermion pair

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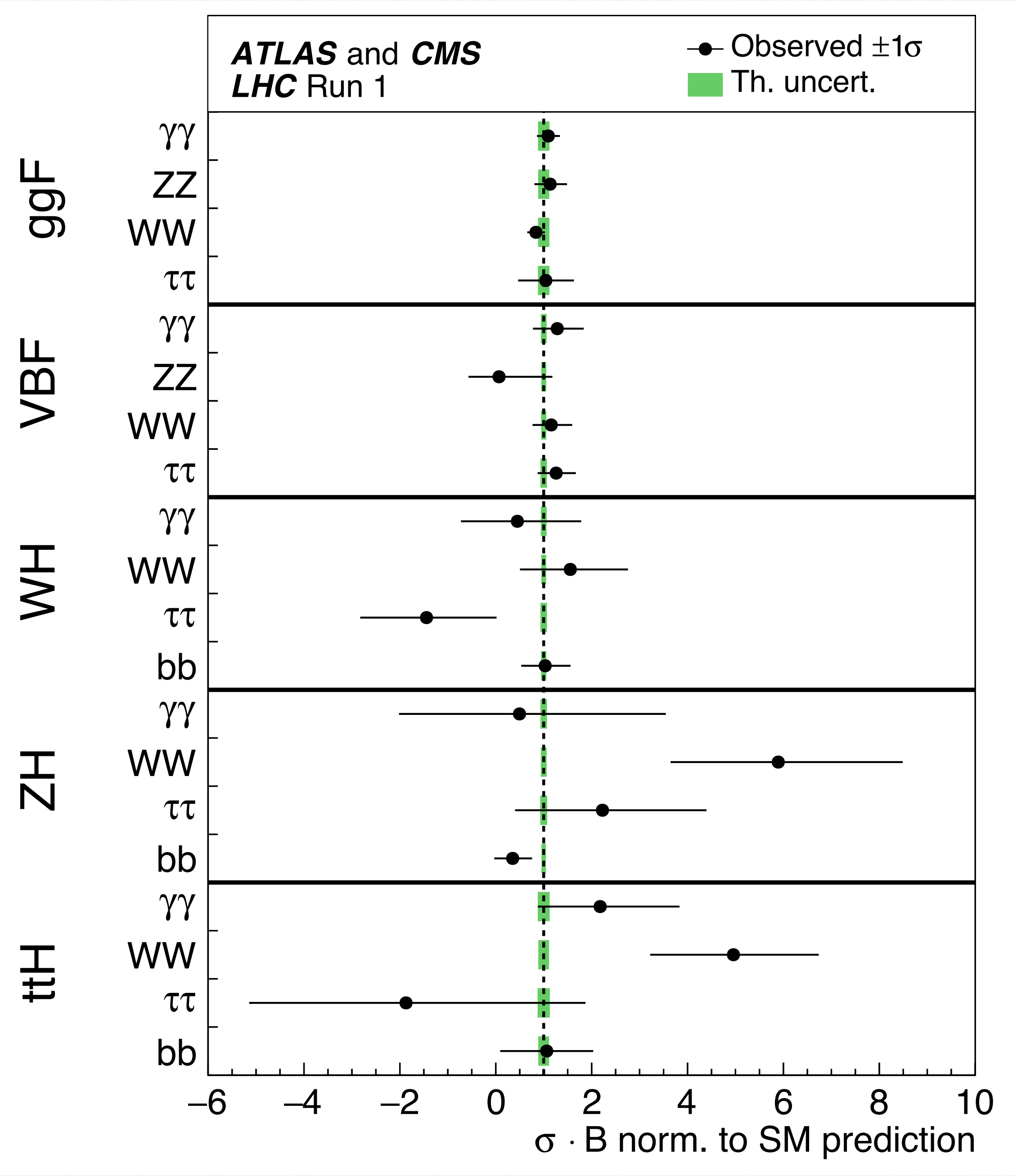
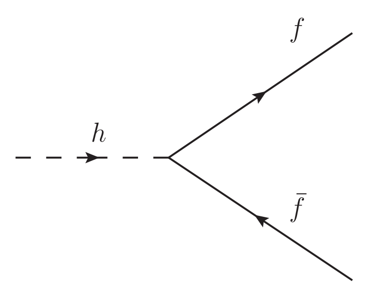
Introduction

- Many decay channels have been established and measured so far.
- Bosonic decay: $h \to \gamma\gamma, \;\; ZZ^*, \;\; WW^*$
- Fermionic decay: $h \to b\bar{b}, \;\; \tau^+\tau^-$
- Rare decays:

$$h \to Z\gamma, \;\; \mu\mu, \;\; ee,$$



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

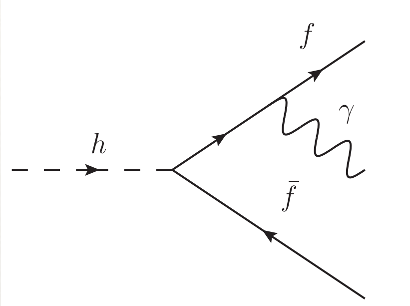


- The higgs decay to a fermion pair is a very interesting channel.

  It varies from $\mathcal{O}(10^{-5})$ keV to $\mathcal{O}(1)$ MeV, depending on the mass.

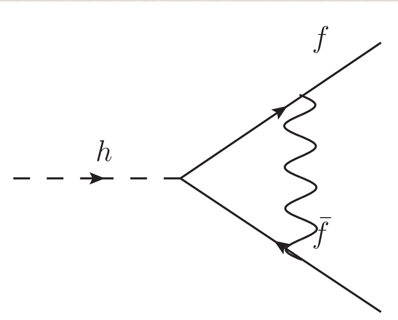
- How about its radiative corrections (QED)?

- Real emissions:



$$\Gamma^{\mathrm{R}}_{h\to f\bar{f}\gamma} = \Gamma^0 \times \frac{\alpha}{2\pi} Q_f^2 \left(\frac{4\pi\mu^2}{m_h^2}\right)^{\epsilon} \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{21}{2} - \frac{2\pi^2}{3}\right)$$

- Virtual corrections:



$$\Gamma^{\mathrm{V}}_{h\to f\bar{f}} = \Gamma^0 \times \frac{\alpha}{2\pi} Q_f^2 \left(\frac{4\pi\mu^2}{m_h^2}\right)^{\epsilon} \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 2 + \frac{2\pi^2}{3} + 3\ln\frac{\mu^2}{m_h^2}\right)$$

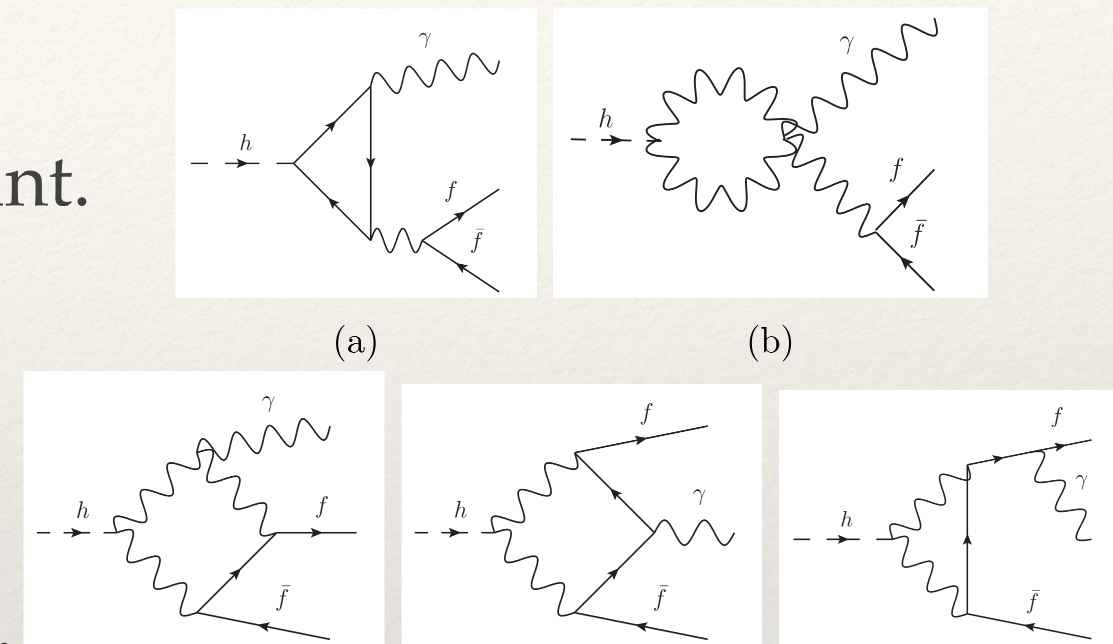
- Inclusive:

$$\Gamma_{\mathrm{tot}} = \Gamma^0 \left[1 + \frac{17\alpha}{4\pi} Q_f^2 + \mathcal{O}(\alpha^2)\right]$$

- That’s it?

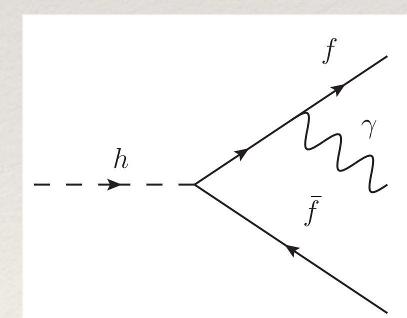
Dalitz Decays

- $\mathcal{O}(y_t \alpha^3, \alpha^4)$ corrections may also be important.
- Not suppressed by the Yukawa y_f .



(a) (b) (c) (d) (e)

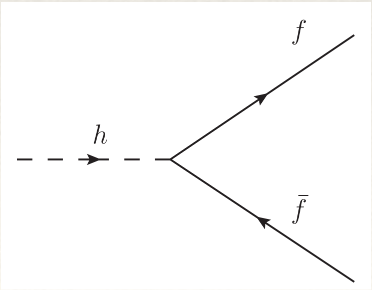
- They have difference chirality configurations.
- The interference between them $\sim m_f^2 \to 0$.



- To observe, it requires a hard isolated photon.

Decay Widths

	$\Gamma(f\bar{f})$ [keV]	$\mathcal{O}(y_f^2\alpha)$ [keV]	$\mathcal{O}(y_t^2\alpha^3,\alpha^4)$ [keV]	$\Gamma(f\bar{f}\gamma)$ [keV]	$\text{Br}(f\bar{f}\gamma)$ $[10^{-4}]$
b	1896	2.20	0.95	8.82	21.0
c	94.05	0.437	0.88	2.53	6.01
τ	261	2.72	0.30	10.3	24.5
μ	0.923	9.65×10^{-3}	0.40	0.43	1.02
e	2.16×10^{-5}	2.25×10^{-7}	0.58	0.58	1.38



Inclusive QED

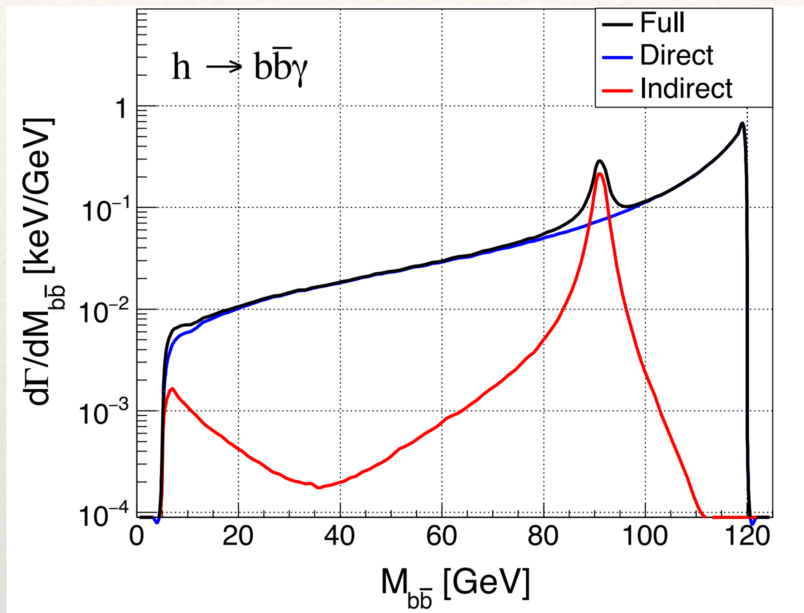
EW loops
"Indirect"

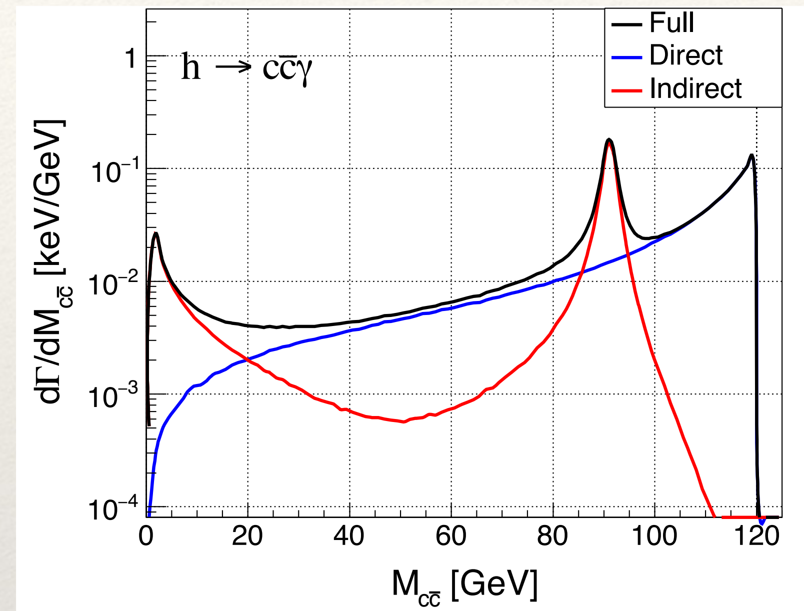
"direct" + "indirect"
with a hard isolated
photon with

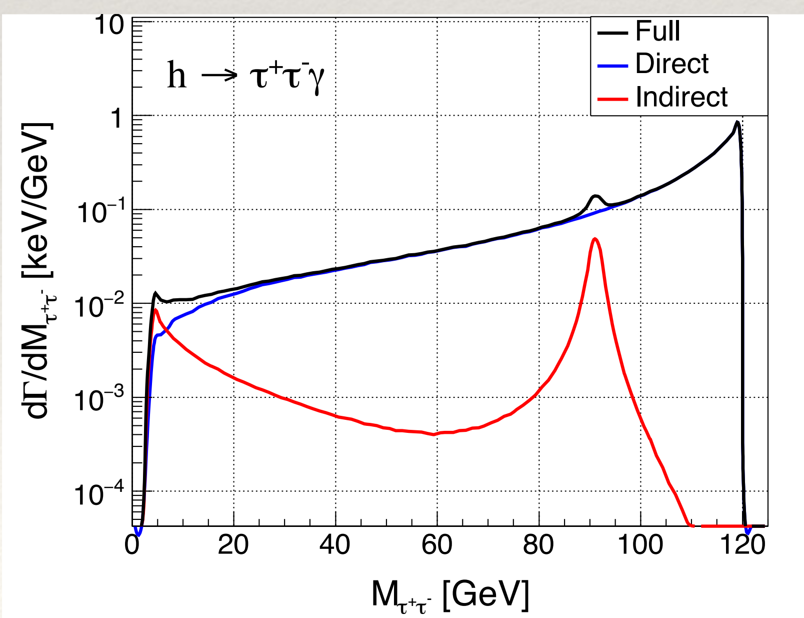
$E_\gamma > 5$ GeV

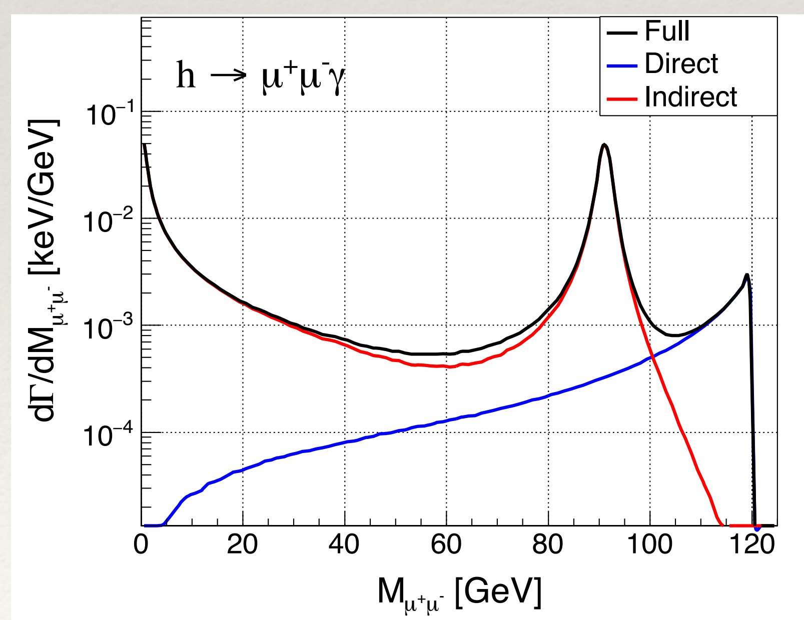
$\Delta R_{f\gamma} > 0.4$

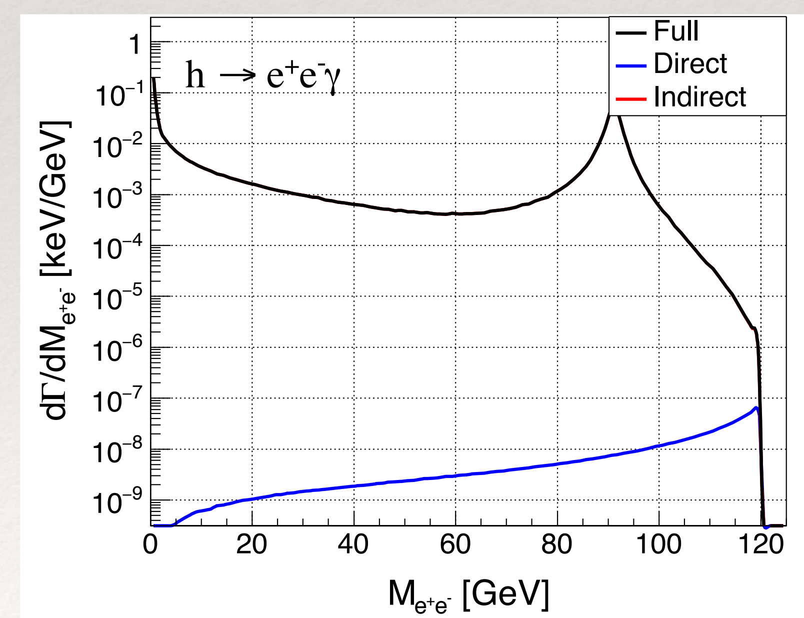
$M_{f\bar{f}}$ Distribution





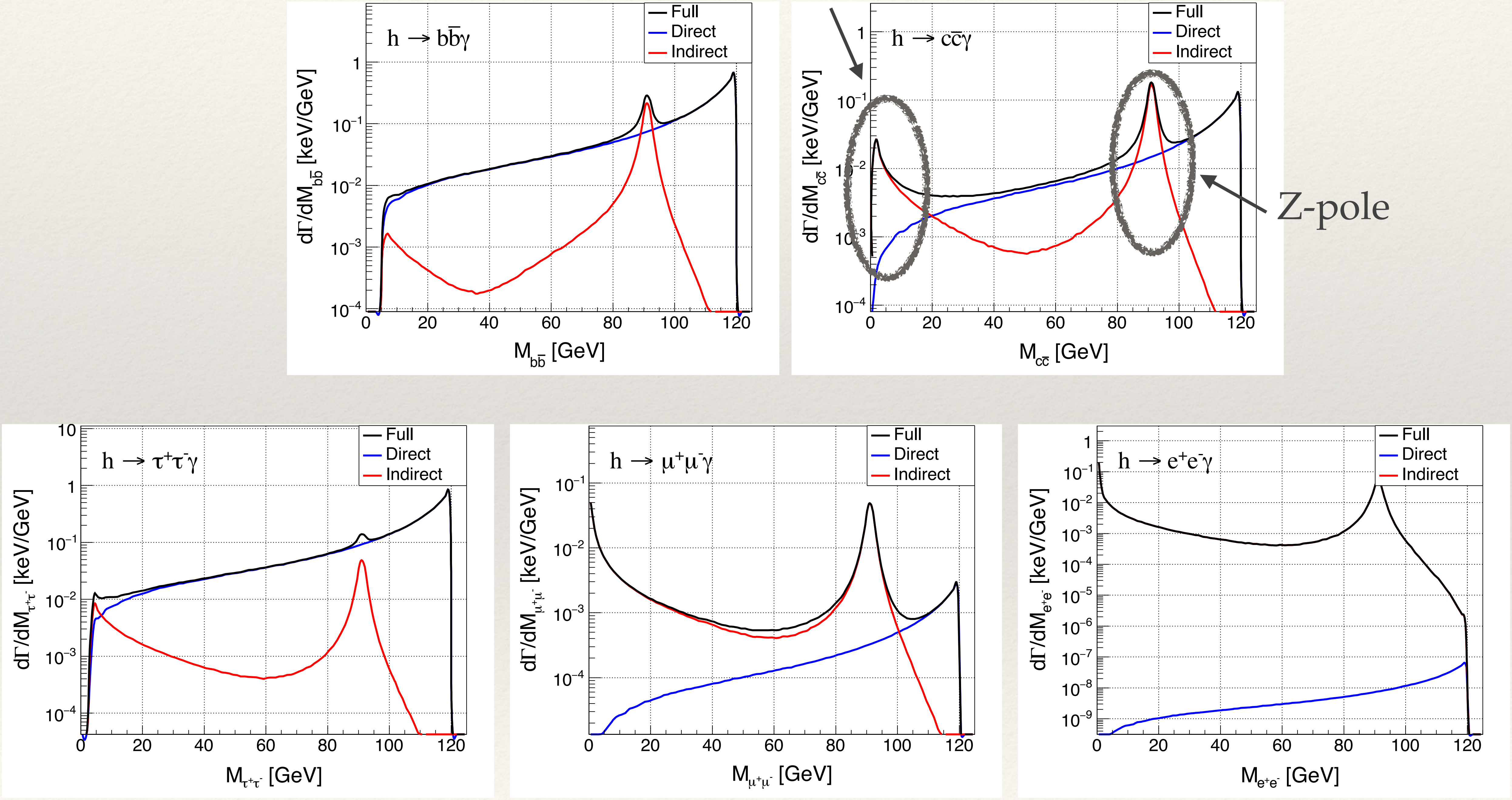




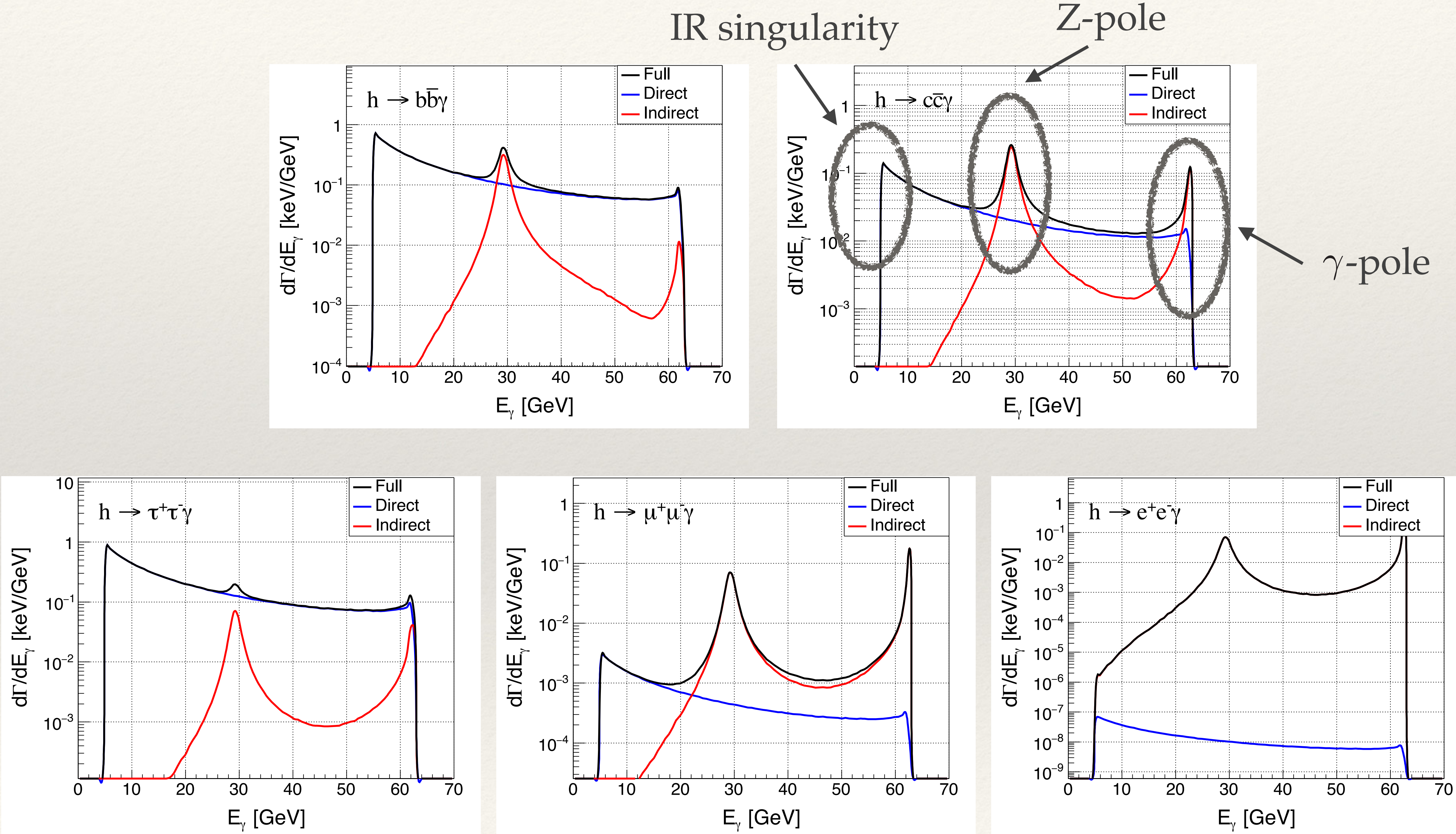


$M_{f\bar{f}}$ Distribution

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



E_γ Distribution



Probe the charm-Yukawa at LHC

Yukawa Couplings

- The Yukawa couplings to the 3rd generation has been measured through $t\bar{t}h\ (4.4\sigma)$ $h \to bb\ (2.6\sigma)$ $h \to \tau\tau\ (> 5\sigma)$
- Di-muon channel $h \to \mu\mu < 3.5 \times \mathrm{SM}$
- Charm (or other light quarks)— many methods proposed.

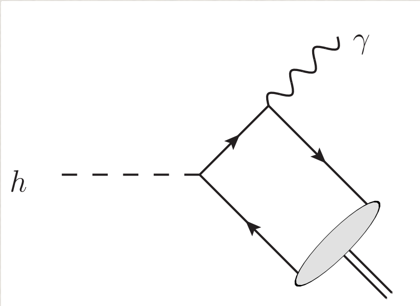
$h \to b\bar{b},\ c\bar{c}$	$\Rightarrow$ Stamou's talk	Higgs kinematics $\Rightarrow$ Soreq's talk	
$h \to J/\psi\gamma$	$\Rightarrow$ Alte's talk	$W^{\pm}h$ asymmetry $\Rightarrow$ Yu's talk	
Global fit	Perez, et. al. arXiv: 1503.00290		etc.

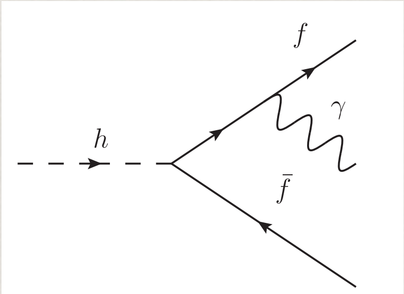
- Di-electron channel $h \to ee < 4 \times 10^5 \times \mathrm{SM}$

Charm-Yukawa via Radiative Decay

- Bound state to open-flavor.
- Larger branch ratio.

$$3 \times 10^{-6} \qquad \Rightarrow \qquad 6 \times 10^{-4}$$





- Require charm-tagging.

Charm Tagging

- Currently NO c-tagging.
- Difficult. c-jets sit between b-jets and light-jets.
- Trade off between b- and light-jets rejection.
- ATLAS proposed an algorithm — JetFitterCharm.

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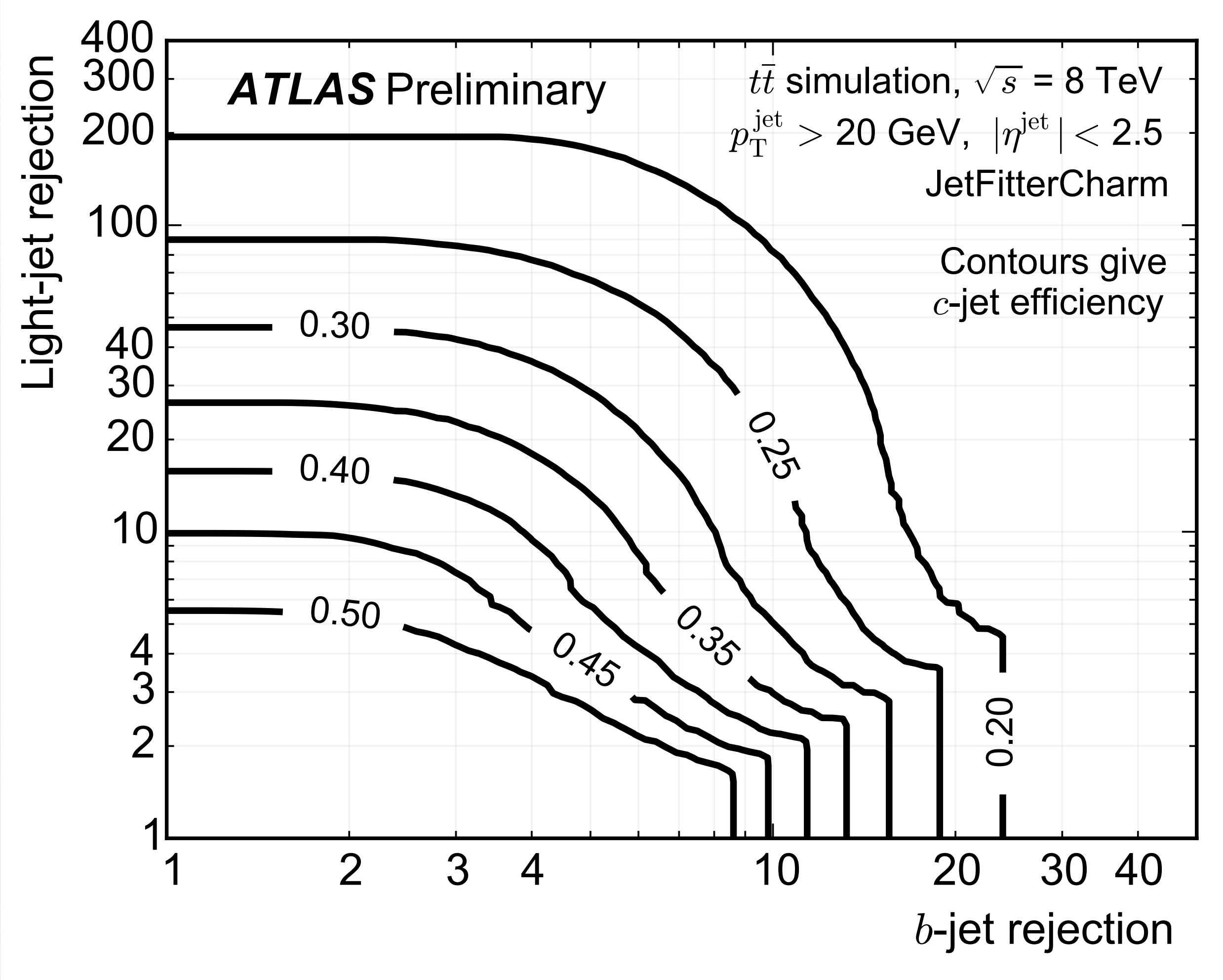


Selection Cuts

- Higgs production via ggF at LO multiplied by K=2.7
- Background $pp \to c\bar{c}\gamma$ at LO by Madgraph

$$p_{Tc} > 40(20)\ \text{GeV}$$

$$p_{T\gamma} > 20\ \text{GeV}$$

$$|\eta_\gamma| < 2.5$$

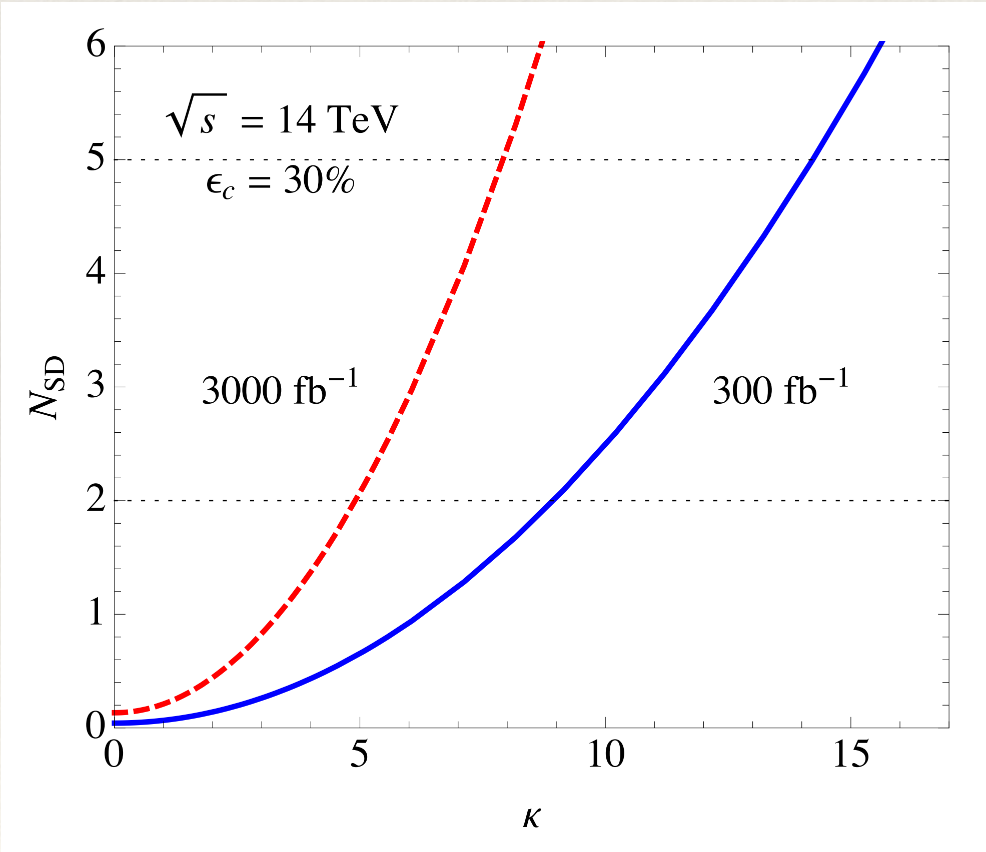
$$\Delta R > 0.4$$

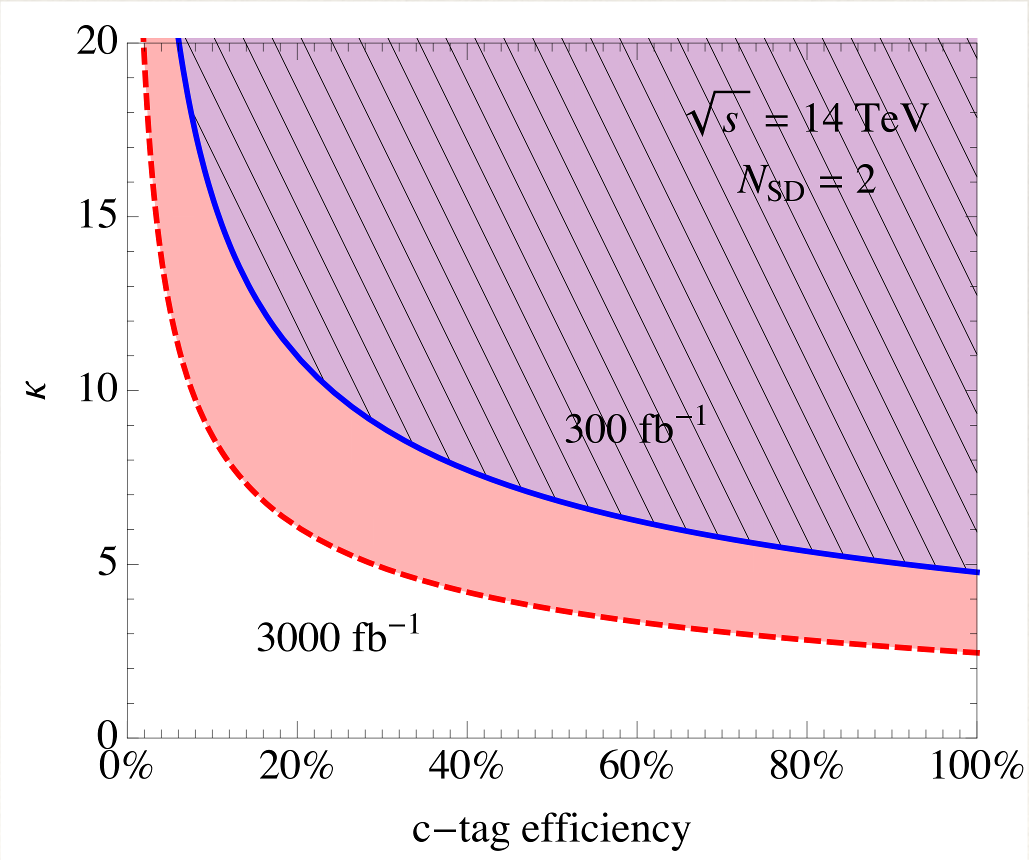
$$100 < m_{cc\gamma} < 150\ \text{GeV}$$

Charm-Yukawa

If NP only modifies the charm-Yukawa, the statistical significance is

$$N_{\rm SD} = \frac{S}{\sqrt{S+B}} \simeq \epsilon_c \times \frac{\kappa^2 \sigma_{\rm direct} + \sigma_{\rm indirect}}{\sqrt{\sigma_{\rm bkg}}} \sqrt{\mathcal{L}}$$





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

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

- In the SM, $h \to \ell^+\ell^-\gamma$ is not suppressed by their small Yukawa couplings.
- $pp \to \gamma^*\gamma \to \ell^+\ell^-\gamma$ and $pp \to Z\gamma \to \ell^+\ell^-\gamma$ are well separated in $m_{\ell\ell}$, and thus are essentially different observables.
- Different triggers and selection cuts.

$pp \to Z\gamma \to \ell\ell\gamma$
$m_{\ell\ell} > 50$ GeV
$p_{T\ell} > 20(10)$ GeV
$\|\eta_{\mu,e}\| < 2.5, 2.4$
$\Delta R_{\ell\gamma} > 0.4$
$p_{T\gamma} > 15$ GeV
$\|\eta_\gamma\| < 2.5$ exclude $(1.44, 1.57)$
$120 < m_{\ell\ell\gamma} < 130$
$p_{T\gamma} > 15/110 * m_{\ell\ell\gamma}$
$m_{\ell\ell\gamma} + m_{\ell\ell} > 185$ GeV

$pp \to \gamma^*\gamma \to \mu\mu\gamma$
$m_{\mu\mu} < 20$ GeV
$p_{T\mu} > 23(4)$ GeV
$\|\eta_\mu\| < 2.4$
$\Delta R_{\mu\gamma} > 1$
$p_{T\gamma} > 0.3 m_{\mu\mu\gamma}$
$\|\eta_\gamma\| < 1.44$
$120 < m_{\mu\mu\gamma} < 130$ GeV

$pp \to \gamma^*\gamma \to ee\gamma$
$m_{ee} < 1.5$ GeV
$\|p_{Te^+}\| + \|p_{Te^-}\| > 44$ GeV
$\|\eta_e\| < 1.44$
$\Delta R_{e\gamma} > 1$
$p_{T\gamma} > 0.3 m_{ee\gamma}$
$\|\eta_\gamma\| < 1.44$
$120 < m_{ee\gamma} < 130$ GeV

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

Channel	Signal [fb]	Background [fb]	Statistical Significance with 0.3 (3) ab^{-1} luminosity
$pp \to Z\gamma \to \mu^+\mu^-\gamma$	1.40	214	1.66 (5.24)
$pp \to \gamma^*\gamma \to \mu^+\mu^-\gamma$	0.69	23.5	2.47 (7.79)
$pp \to Z\gamma \to e^+e^-\gamma$	1.38	224	1.60 (5.05)
$pp \to \gamma^*\gamma \to e^+e^-\gamma$	1.06	27.0	3.53 (11.2)

LO ggF $\times$ K-factor

LO $\times$ K-factor for $pp \to Z(\gamma)\gamma$

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LO ggF × K-factor

LO × K-factor for $pp \to Z(\gamma^*)\gamma$

Conclusion

- Higgs radiative decay to a fermion pair is not necessarily suppressed by the yukawa coupling.
- Interesting channel to observe at LHC.
- With charm-tagging, it can be used to constrain the charm-yukawa.
- Observability at LHC for leptons.

Thanks!