Workshop on Physics at the CEPC @ IHEP

Probing $H\gamma\gamma$ and $HZ\gamma$ anomalous couplings at e^+e^- colliders

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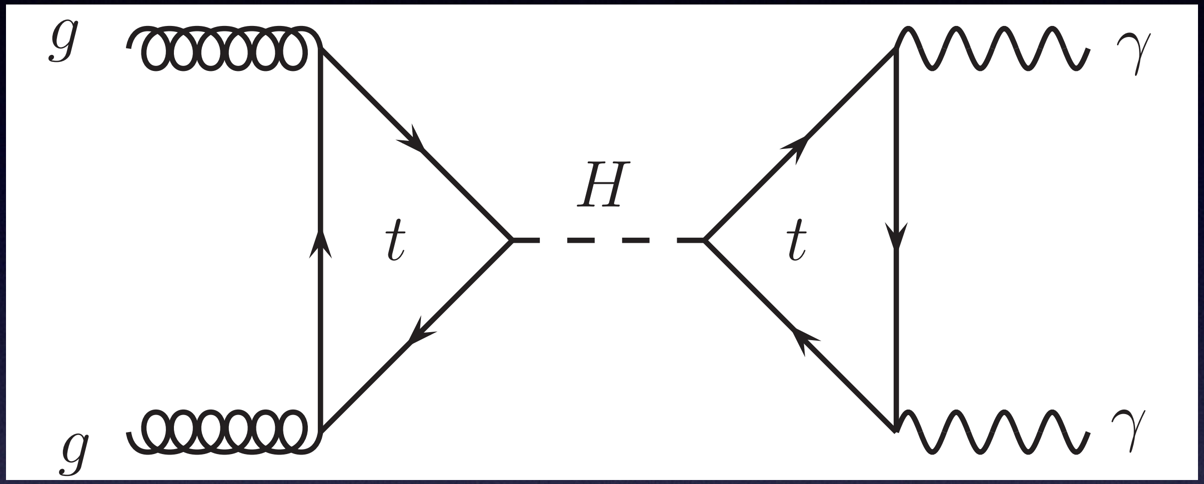
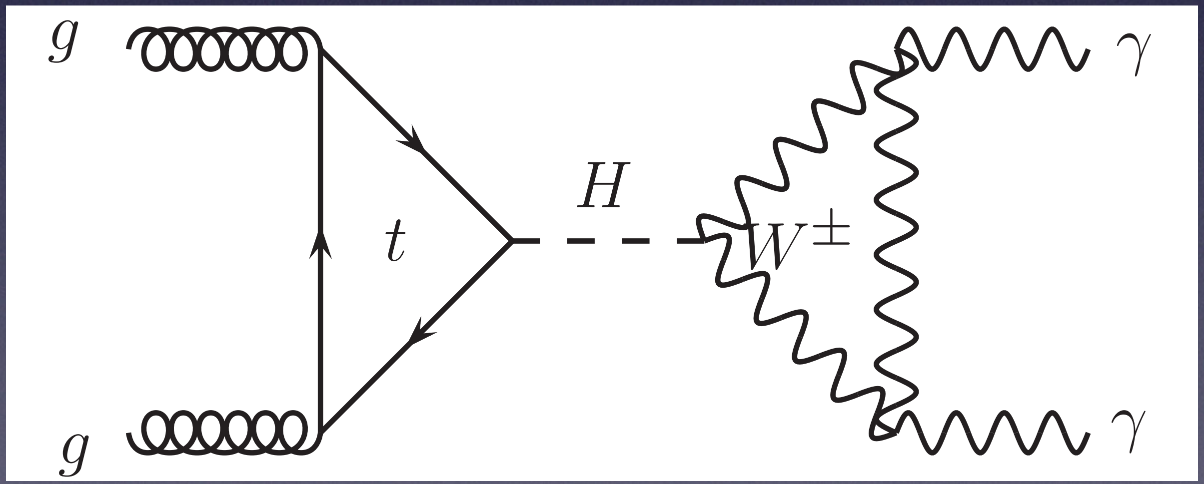
In collaboration with Hao-Ran Wang and Ya Zhang
arXiv:1503.05060

Higgs Discovery:
A Great Success of Anomalous Couplings

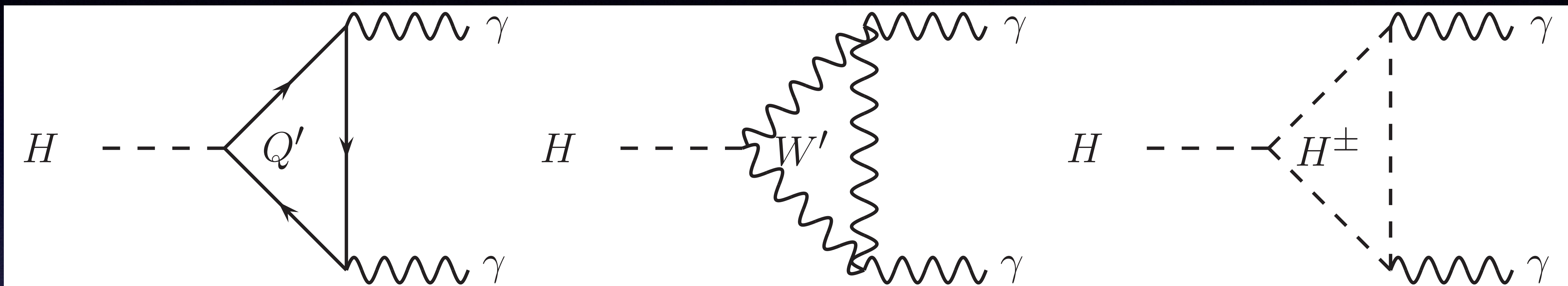




Rare can tell more!

HZA/HAA and New Physics

Higgs rare decay is sensitive to NP



HZA and HAA are correlated in MSSM-like models,

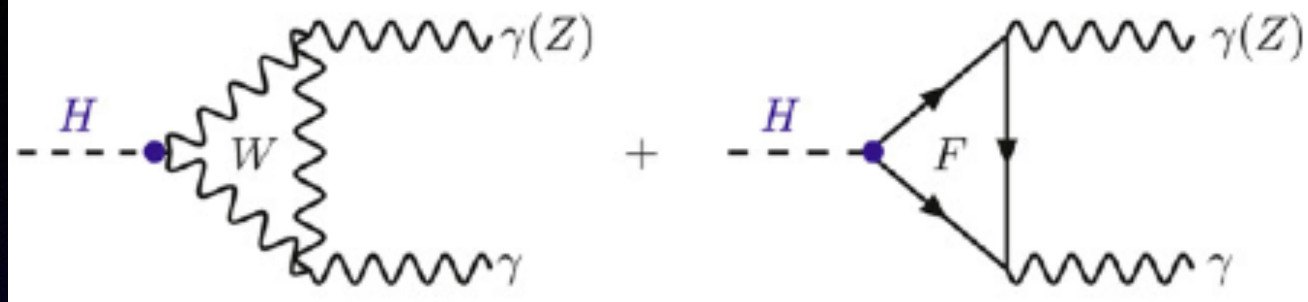
Carena, Low and Wagner, 1206.1082, Cao, Wu, Yang, 1301.4641;
Belanger, Bizouard, Chalons, 1402.3422, ……

but they could be independent to each other.

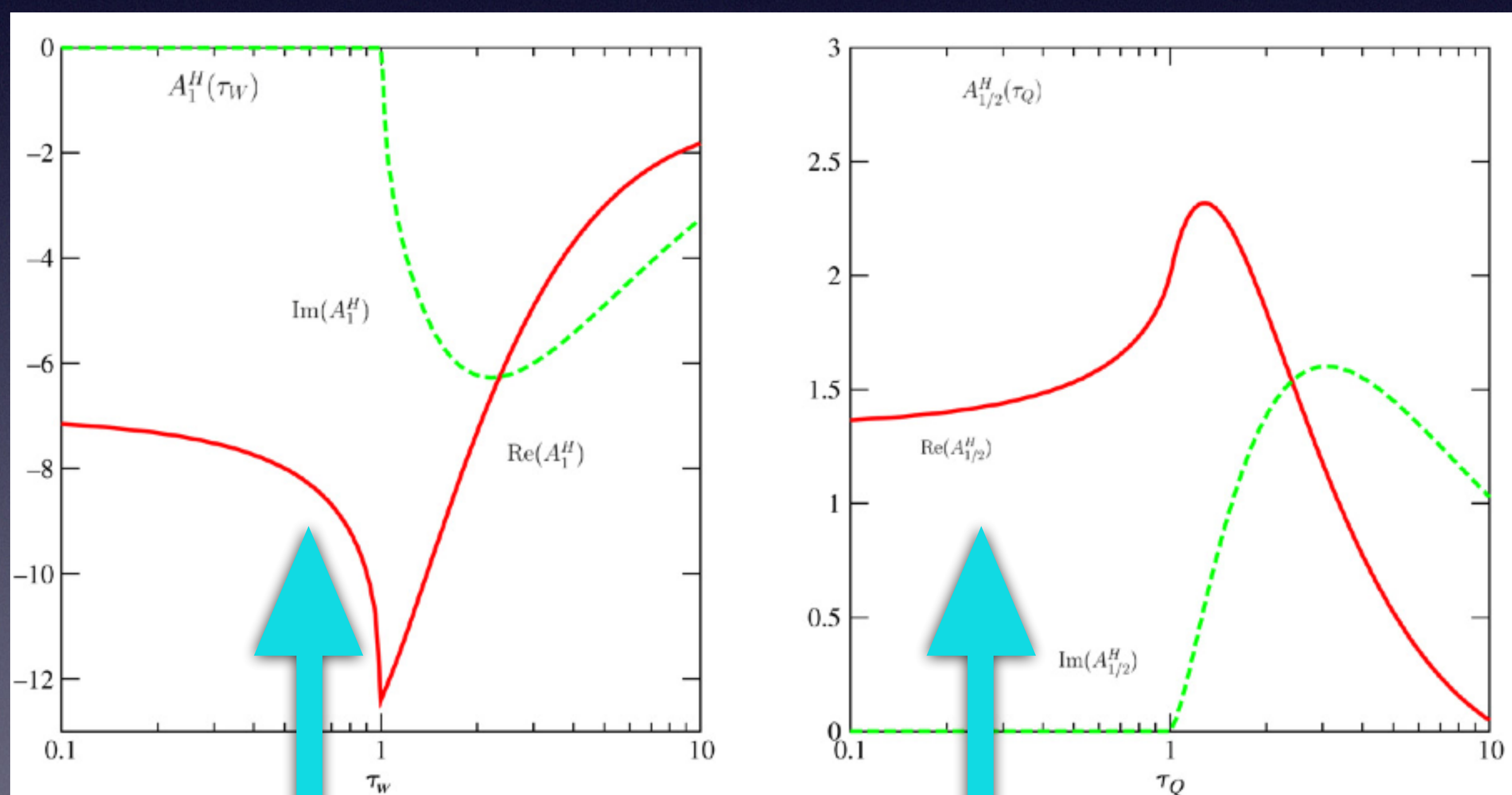
Azatov, Contino, Di Iura and Galloway, 1308.2676

It is important to measure both the HZA and HAA anomalous couplings separately.

$H\gamma\gamma$ and $HZ\gamma$ couplings in the SM



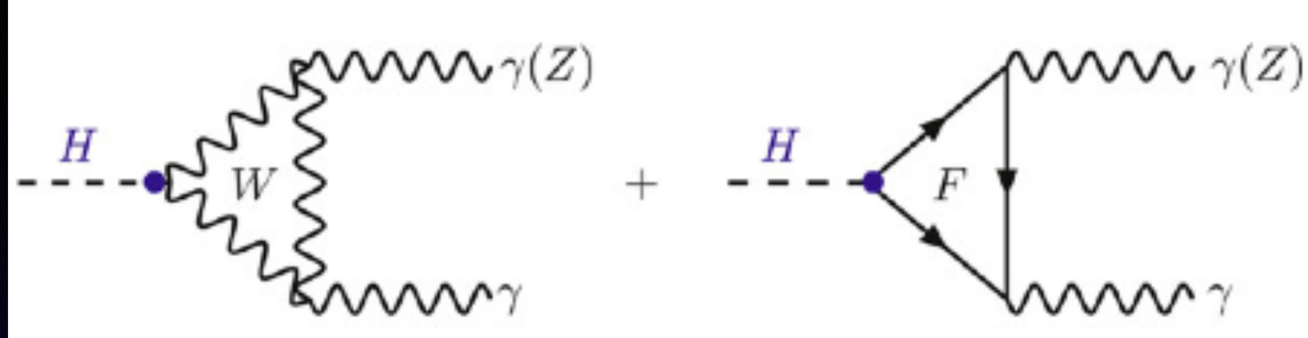
$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$



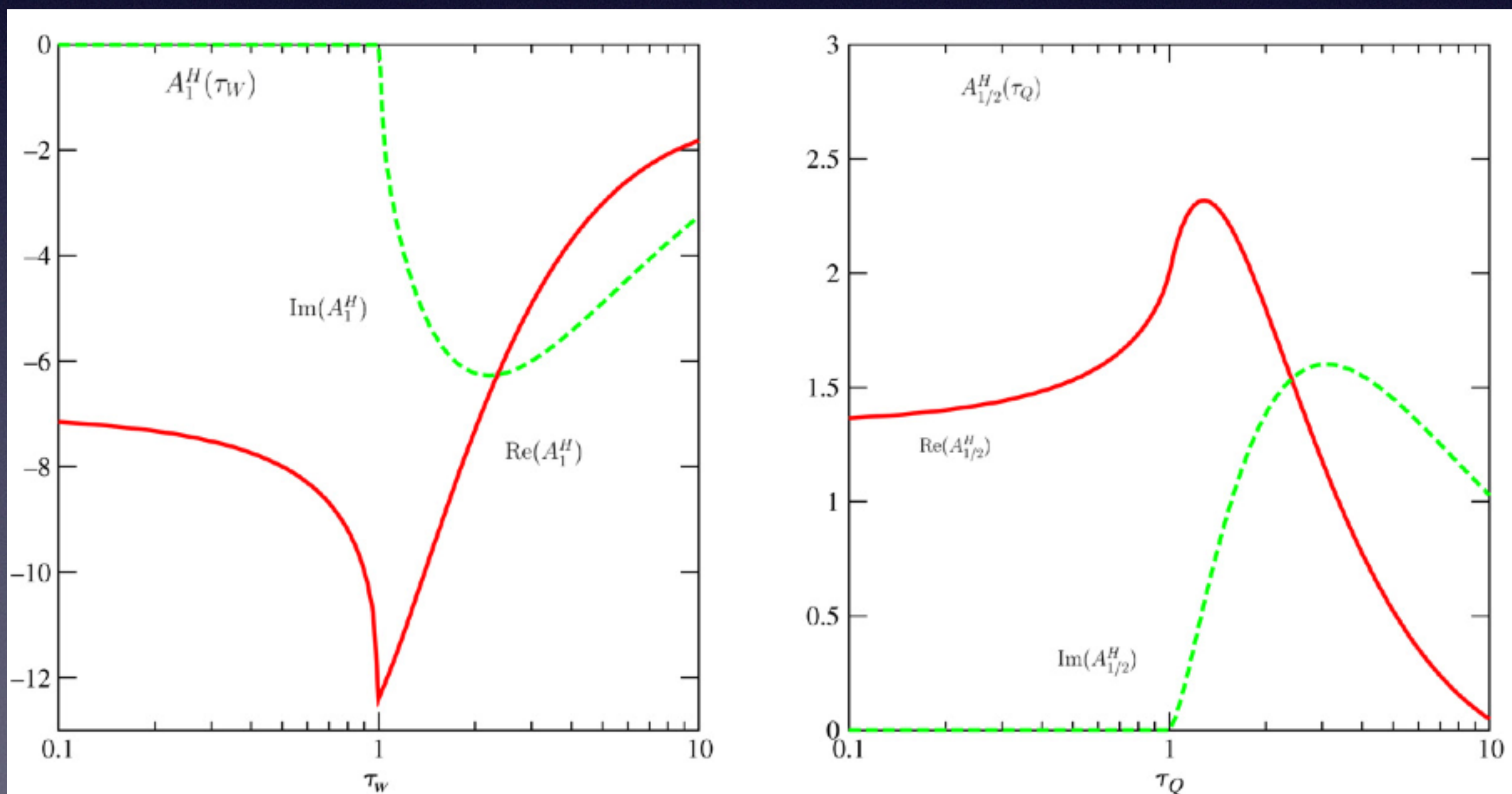
SM Higgs boson

$$\tau_i = \frac{m_H^2}{4m_i^2}$$

HZA/HAA couplings in the SM



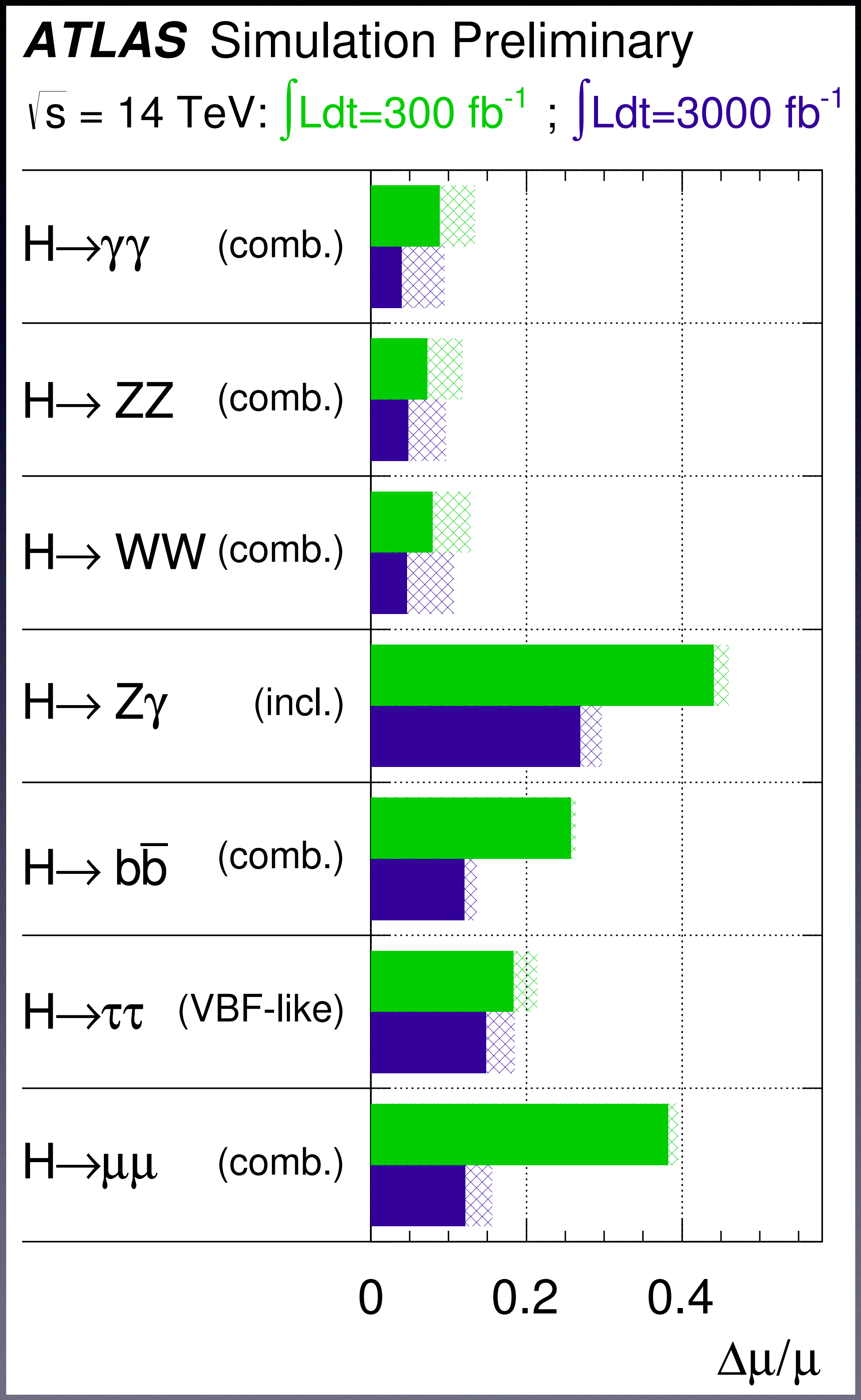
$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$



Loose $R_{Z\gamma} \equiv \dfrac{\Gamma(H \to Z\gamma)}{\Gamma_{\mathrm{SM}}(H \to Z\gamma)} \leq 9.5$

Tight $0.91 \leq R_{\gamma\gamma} \equiv \dfrac{\Gamma(H \to \gamma\gamma)}{\Gamma_{\mathrm{SM}}(H \to \gamma\gamma)} \leq 1.4$

Higgs Precision at a High Luminosity LHC



$\mathscr{L}$ Scenario	300 fb^{-1} 2	300 fb^{-1} 1	3000 fb^{-1} 2	3000 fb^{-1} 1
$\gamma\gamma$	6%	12%	4%	8%
WW	6%	11%	4%	7%
ZZ	7%	11%	4%	7%
bb	11%	14%	5%	7%
$\tau\tau$	8%	14%	5%	8%
$Z\gamma$	62%	62%	20%	24%
$\mu\mu$	40%	42%	14%	20%

HAA is expected to reach 5% accuracy while HZA to 20%.

Effective Field Theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i (c_i \mathcal{O}_i + h.c.) + O\left(\frac{1}{\Lambda^3}\right)$$

linearly realized symmetry breaking

$$\mathcal{O}_{WW} = \left(\phi^\dagger \phi\right) W^I_{\mu\nu} W^{I\mu\nu}$$

$$\mathcal{O}_{BB} = \left(\phi^\dagger \phi\right) B_{\mu\nu} B^{\mu\nu}$$

$$\left.\begin{aligned} \mathcal{O}_{BW} &= \left(\phi^\dagger \tau^I \phi\right) B_{\mu\nu} W^{I\mu\nu} \\ \mathcal{O}_{\phi\phi} &= \left(D_\mu \phi\right)^\dagger \phi\phi^\dagger \left(D^\mu \phi\right) \end{aligned}\right\} \text{Tightly bounded by EWPT}$$

$$\mathcal{L} = \frac{v}{\Lambda^2}\left(\mathcal{F}_{Z\gamma} H Z_{\mu\nu} A^{\mu\nu} + \mathcal{F}_{\gamma\gamma} H A_{\mu\nu} A^{\mu\nu}\right)$$

Degenerate scenario

What if we only observe a lone Higgs at the LHC eventually

$$\Gamma(H \to Z\gamma) = \frac{m_H^3}{8\pi v^2}\left(1-\frac{m_Z^2}{m_H^2}\right)^3 \left|\mathcal{F}_{Z\gamma}^{\rm SM} + \frac{v^2}{\Lambda^2}\mathcal{F}_{Z\gamma}\right|^2$$

$$\Gamma(H \to \gamma\gamma) = \frac{m_H^3}{16\pi v^2}\left|\mathcal{F}_{\gamma\gamma}^{\rm SM} + \frac{v^2}{\Lambda^2}\mathcal{F}_{\gamma\gamma}\right|^2,$$

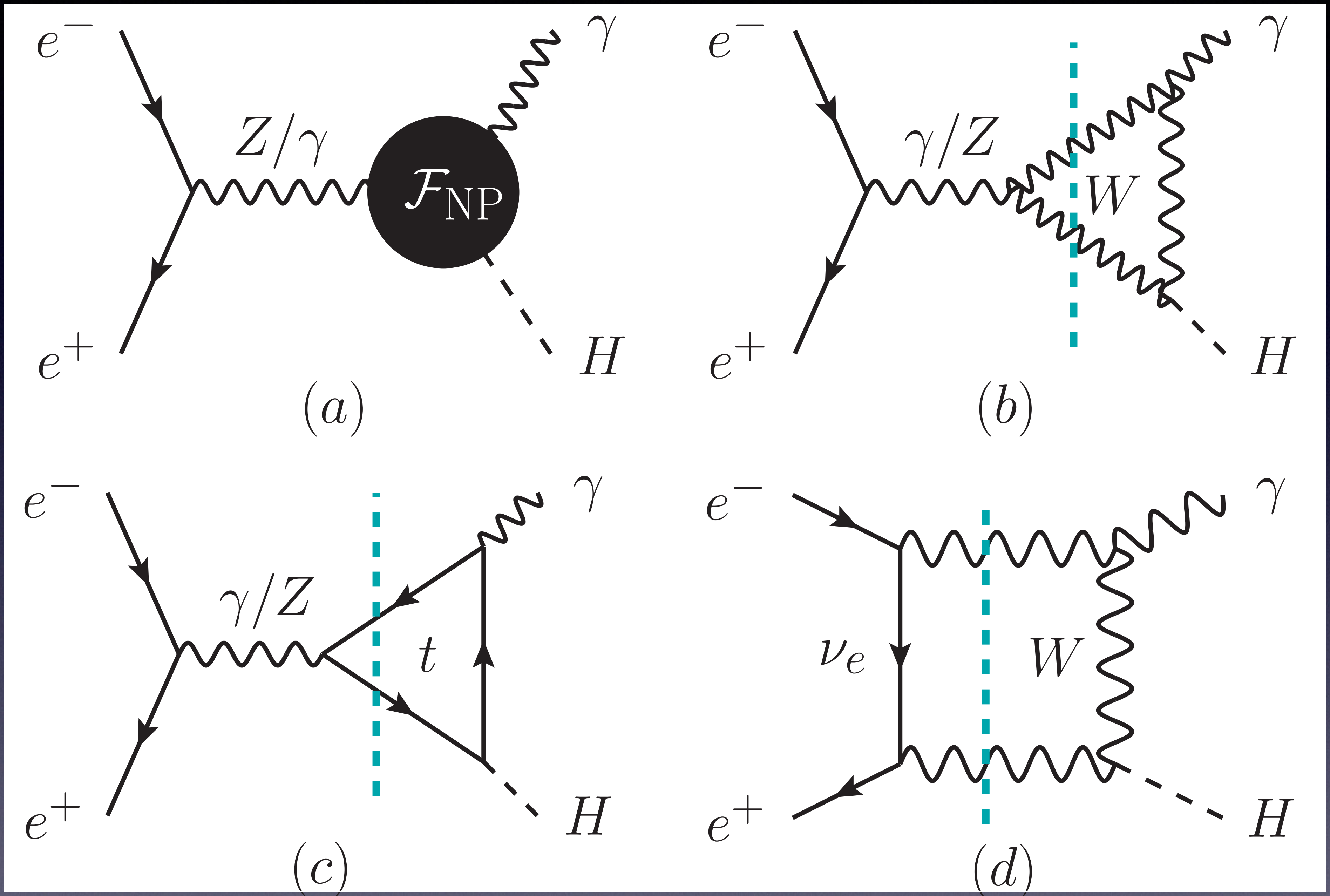
$$\mathcal{F}_{Z\gamma}^{\rm SM} \sim 0.007, \quad \mathcal{F}_{\gamma\gamma}^{\rm SM} \simeq -0.004$$

with $\Gamma(H \to Z\gamma) \simeq \Gamma_{\rm SM}(H \to Z\gamma)$

$$\Rightarrow \begin{cases} \dfrac{v^2}{\Lambda^2}\mathcal{F}_{Z\gamma} \sim -2\mathcal{F}_{Z\gamma}^{\rm SM} \\[2ex] \dfrac{v^2}{\Lambda^2}\mathcal{F}_{Z\gamma} \sim 0 \end{cases}$$

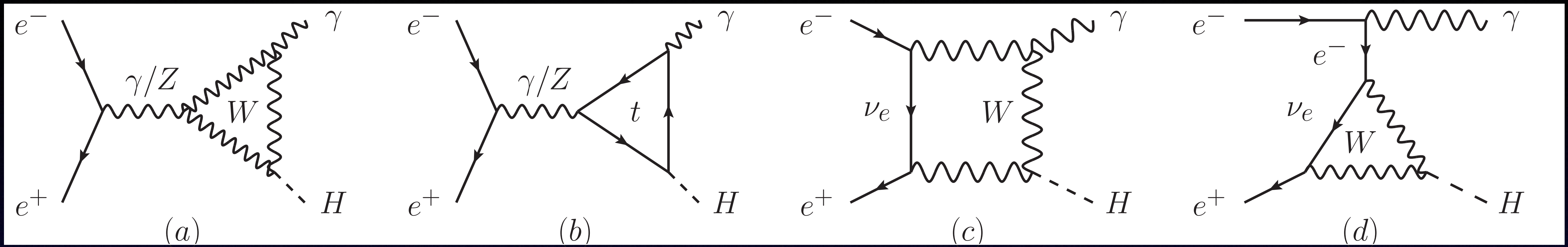
Degeneracy in *H* decay
(It cannot be resolved at HL-LHC)

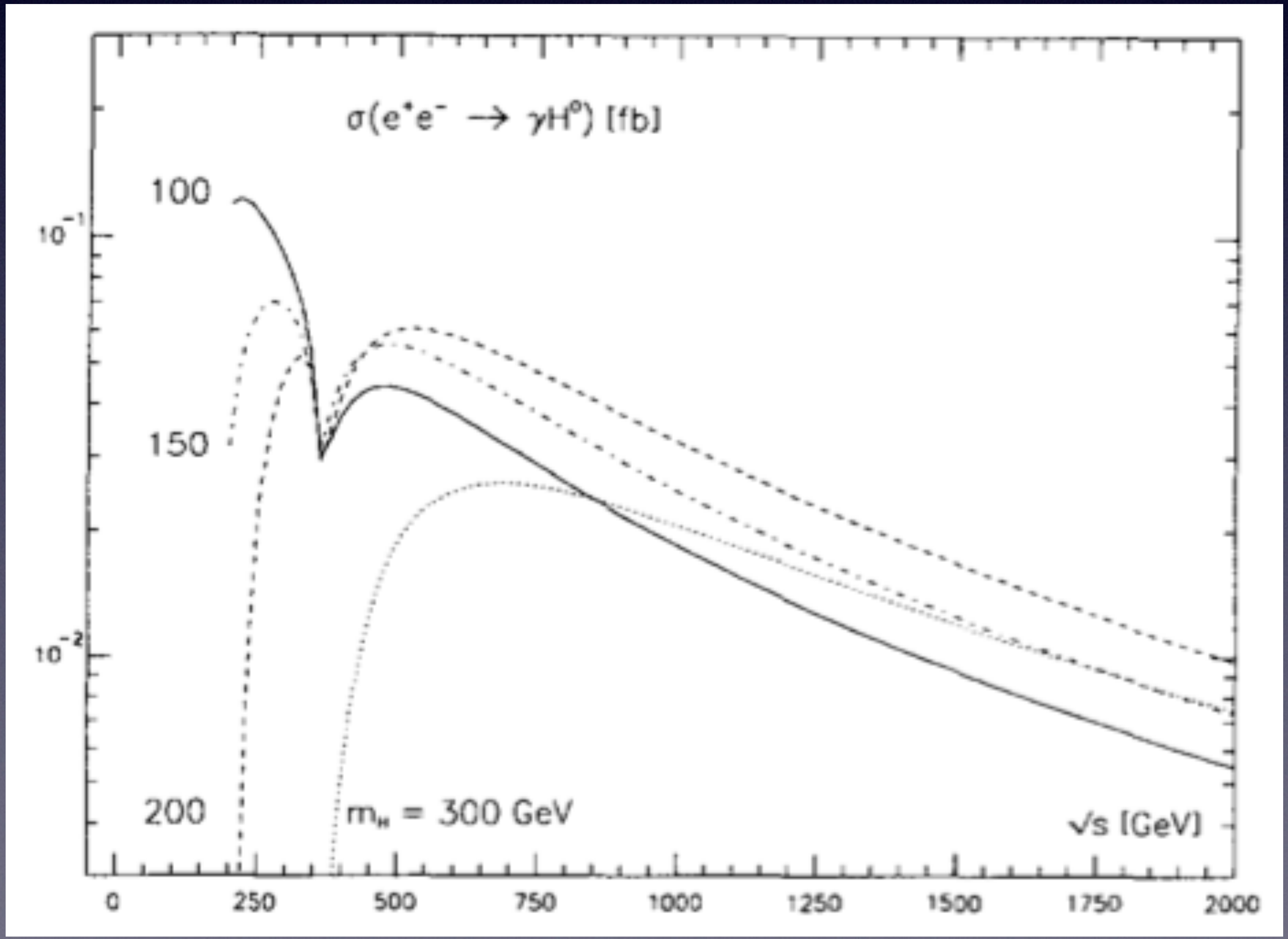
$H\gamma$ Production at e+e- colliders



The Interference between the anomalous couplings and the SM amplitudes can help resolving the degeneracy.

The SM cross-section is tiny

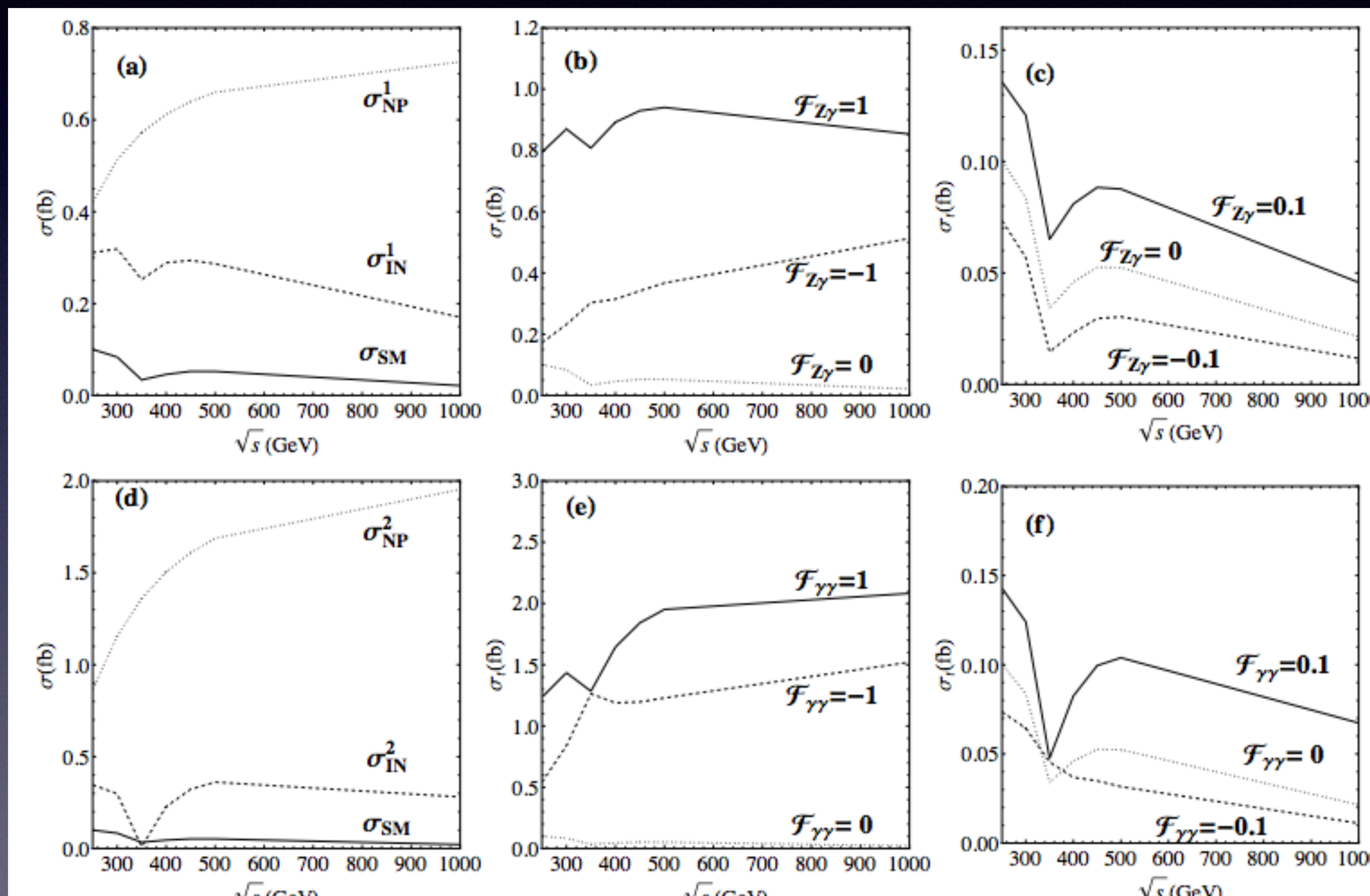




Ajouadi, *et al*
NPB 491, 68
(1997)

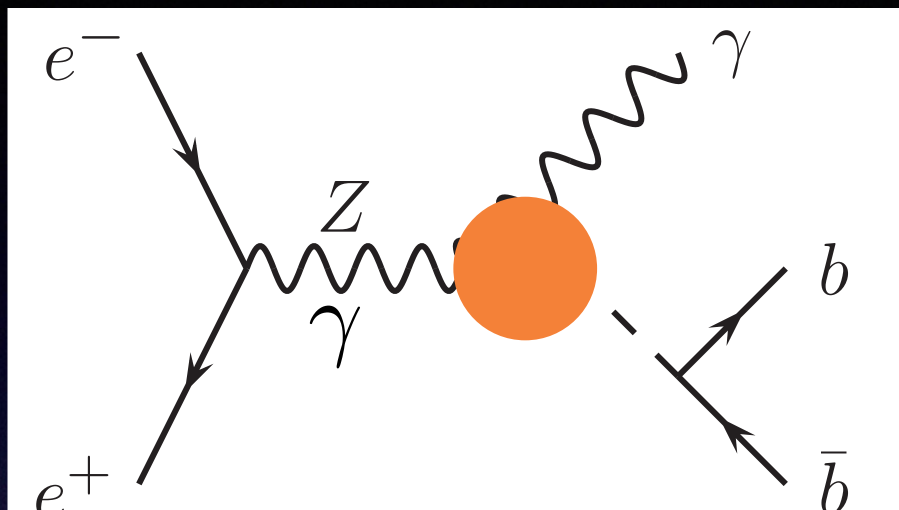
The cross section of NP operators

$$\sigma_{\rm t} = \sigma_{\rm SM} + \left[\sigma_{\rm IN}^{(1)}\mathcal{F}_{Z\gamma} + \sigma_{\rm IN}^{(2)}\mathcal{F}_{\gamma\gamma}\right]\left(\frac{2{\rm TeV}}{\Lambda}\right)^2 + \left[\sigma_{\rm NP}^{(1)}\mathcal{F}_{Z\gamma}^2 + \sigma_{\rm NP}^{(2)}\mathcal{F}_{\gamma\gamma}^2 + \sigma_{\rm NP}^{(3)}\mathcal{F}_{Z\gamma}\mathcal{F}_{\gamma\gamma}\right]\left(\frac{2{\rm TeV}}{\Lambda}\right)^4$$



We first consider one parameter at a time and both later.

Collider simulations

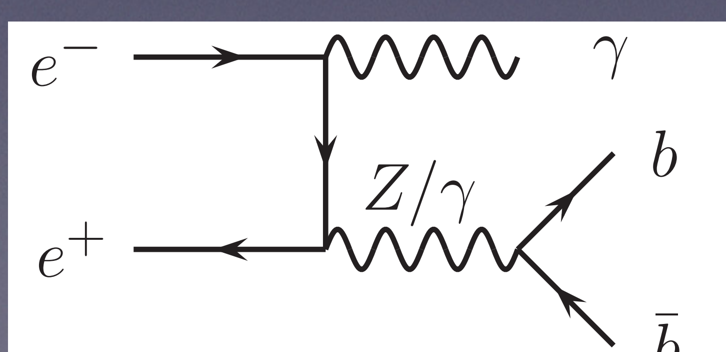


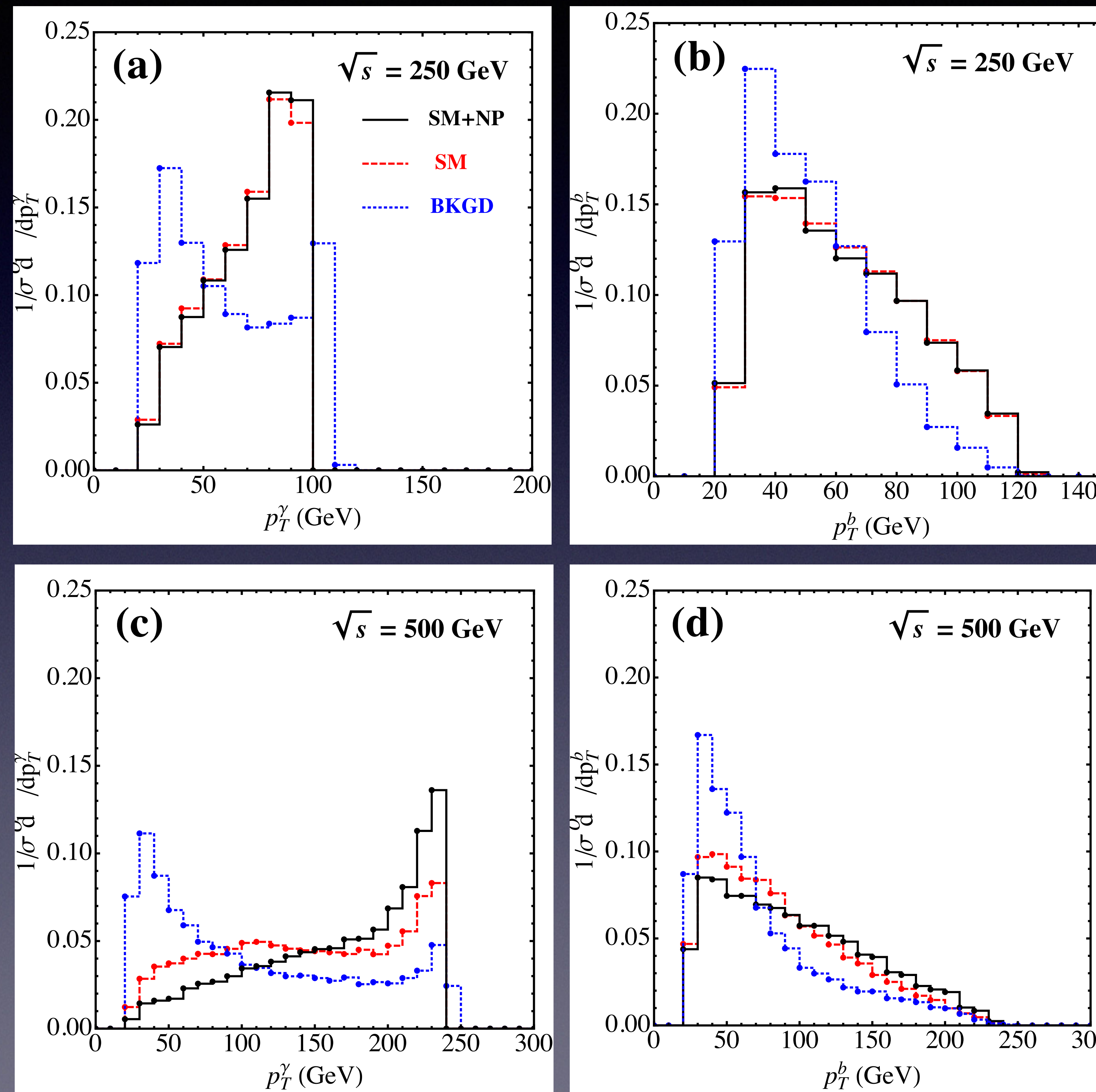
$$p_T^{\gamma,b,\bar{b}} \geq 25 \text{ GeV}$$

$$\left|\eta^{\gamma,b,\bar{b}}\right| \leq 3.5$$

$$\Delta R_{b\bar{b},b\gamma,\bar{b}\gamma} \geq 0.7$$

SM backgrounds





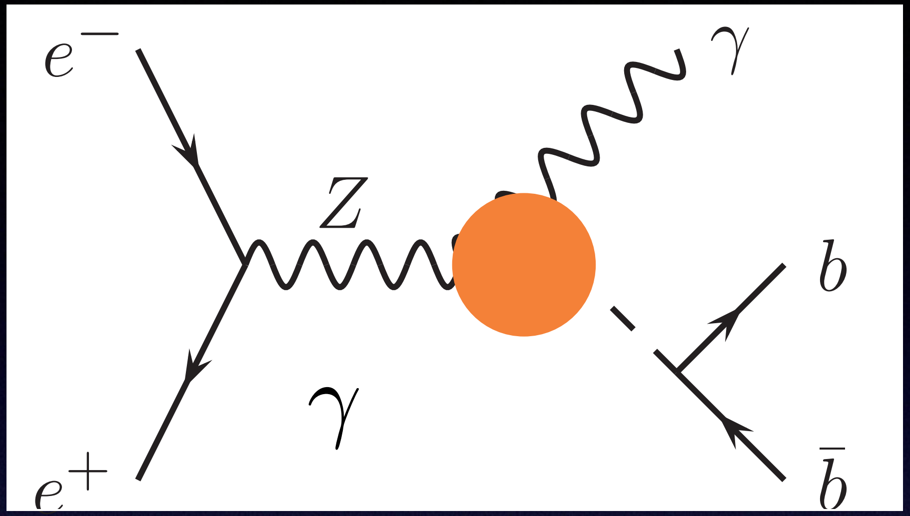
Collider simulations

$\mathcal{L} = 1000\ \mathrm{fb}^{-1}$

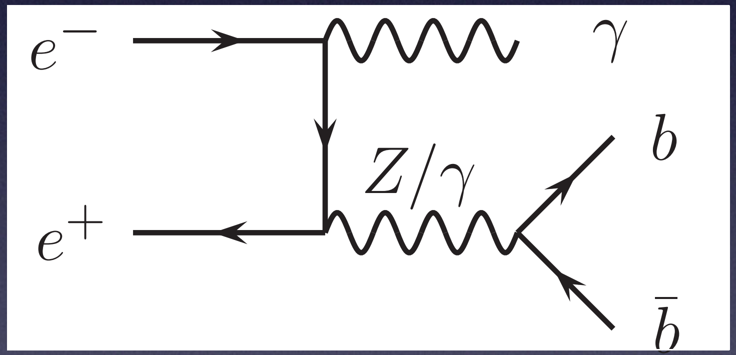
$\sqrt{s}$ (GeV)		250	350	500	1000
$\mathcal{B}$	*selection cuts* ($\times 10^5$)	7.169	4.229	2.450	0.708
$\mathcal{S}_{\rm SM}$ $ee \to h\gamma, h \to b\bar{b}$	*selection cuts*	58	21	33	12
$\mathcal{S}$					
$\mathcal{S}_{Z\gamma}$ $(ee \to h\gamma)$		794	808	940	853
$\mathcal{S}_{Z\gamma}$ $ee \to h\gamma, h \to b\bar{b}$	*selection cuts*	451	482	569	341
$\mathcal{S}$					
$\mathcal{S}_{\gamma\gamma}$ $(ee \to h\gamma)$		1234	1284	1951	2082
$\mathcal{S}_{\gamma\gamma}$ $ee \to h\gamma, h \to b\bar{b}$	*selection cuts*	701	754	1180	834
$\mathcal{S}$					

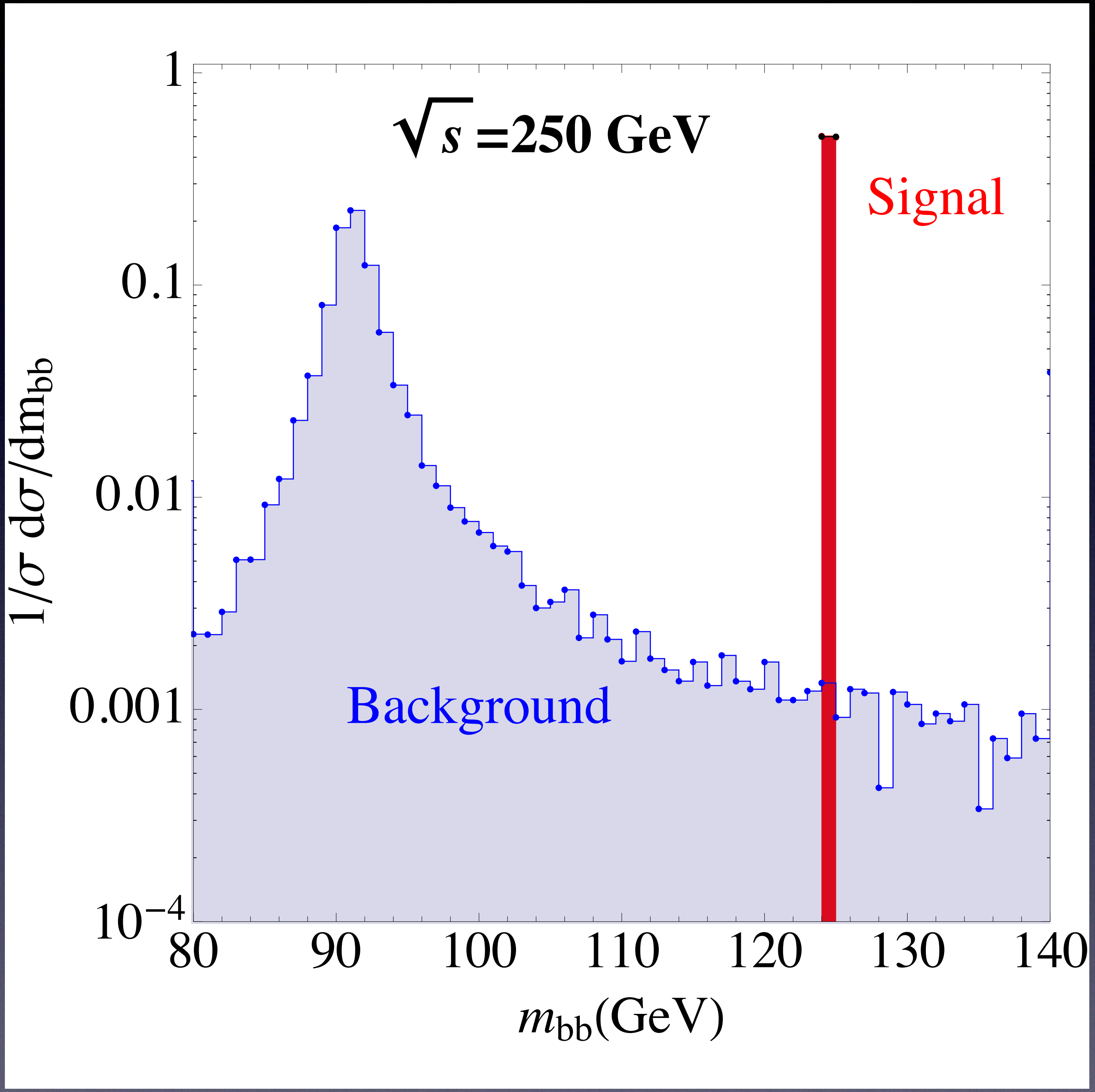
Optimal cuts are needed to suppress the huge SM backgrounds.

Collider simulations



SM backgrounds





$$E_\gamma = \frac{s - m_H^2}{2\sqrt{s}}$$

Cut on the recoil mass

$$\Delta M = |M_R - m_H| \leq 5 \text{ GeV}$$

Discovery Potential

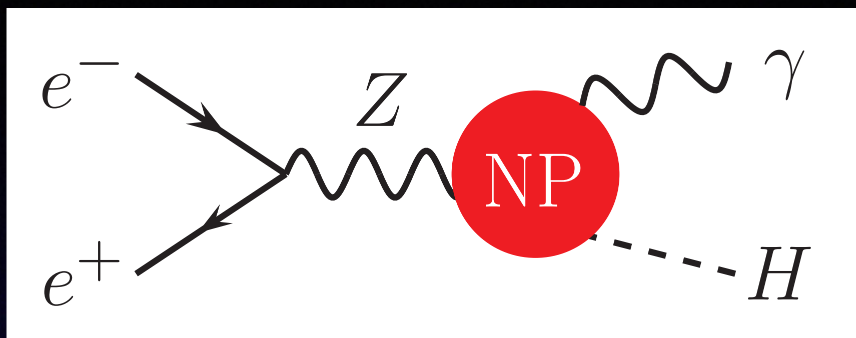
$\mathcal{L} = 1000\ \mathrm{fb}^{-1}$

$\sqrt{s}$ (GeV)		250	350	500	1000
$\mathcal{B}$	*selection cuts* ($\times 10^5$)	7.169	4.229	2.450	0.708
	ΔM *cut*	7640	3993	2104	475
$\mathcal{S}_{\mathrm{SM}}$ $ee \to h\gamma, h \to b\bar{b}$	*selection cuts*	58	21	33	12
	ΔM *cut*	58	21	33	12
$\mathcal{S}_{\mathrm{SM}}/\sqrt{\mathcal{B}}$		0.664	0.33	0.72	0.55
$\mathcal{S}_{Z\gamma}$ $(ee \to h\gamma)$		794	808	940	853
$\mathcal{S}_{Z\gamma}$ $ee \to h\gamma, h \to b\bar{b}$	*selection cuts*	451	482	569	341
	ΔM *cut*	451	482	569	341
$\mathcal{S}_{Z\gamma}/\sqrt{\mathcal{B}}$		5.2	7.6	12.4	15.6
$\mathcal{S}_{\gamma\gamma}$ $(ee \to h\gamma)$		1234	1284	1951	2082
$\mathcal{S}_{\gamma\gamma}$ $ee \to h\gamma, h \to b\bar{b}$	*selection cuts*	701	754	1180	834
	ΔM *cut*	701	754	1180	834
$\mathcal{S}_{\gamma\gamma}/\sqrt{\mathcal{B}}$		8.0	11.9	26.3	38.2

It is hard to measure the SM channel.

$\sigma(e^+e^- \to H\gamma)$ and $\Gamma(H \to Z\gamma)$

$\mathcal{L} = 1000\ \text{fb}^{-1}$



$$R_{Z\gamma} \equiv \frac{\Gamma(H \to Z\gamma)}{\Gamma_{\text{SM}}(H \to Z\gamma)}$$

$$R_\sigma \equiv \frac{\sigma(e^+e^- \to H\gamma)}{\sigma_{\text{SM}}(e^+e^- \to H\gamma)}$$

$\mathcal{F}_{Z\gamma}$ only $\quad \mathcal{F}_{\gamma\gamma} = 0$

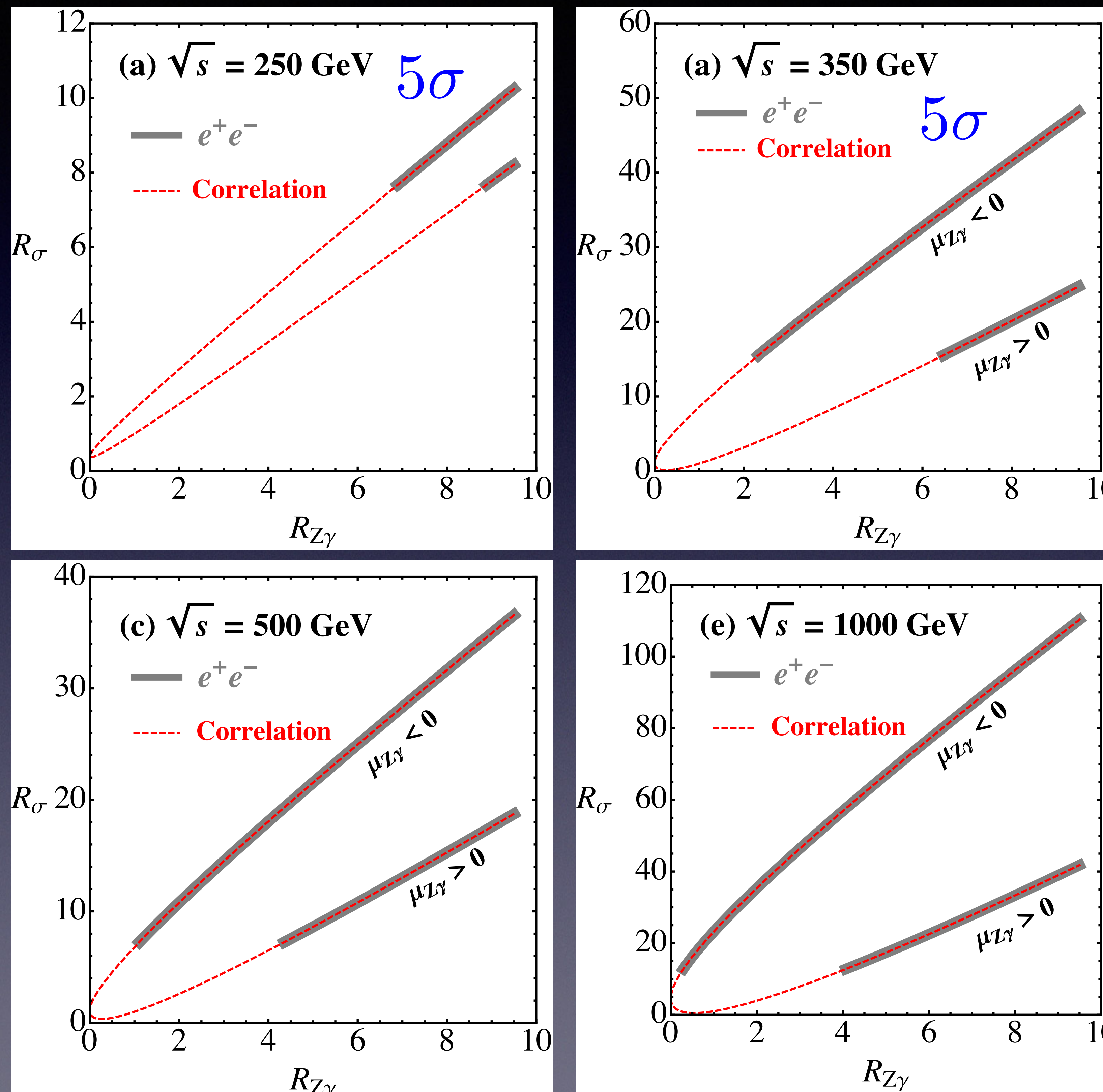
At CEPC (**250GeV & 200fb-1**)

For $\Lambda = 2\text{TeV}$

$$-0.027 < f_{Z\gamma}\frac{v^2}{\Lambda^2} < 0.015$$

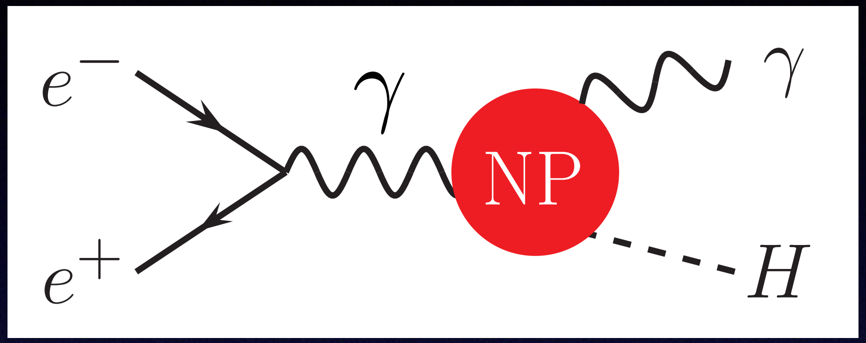
95% bound

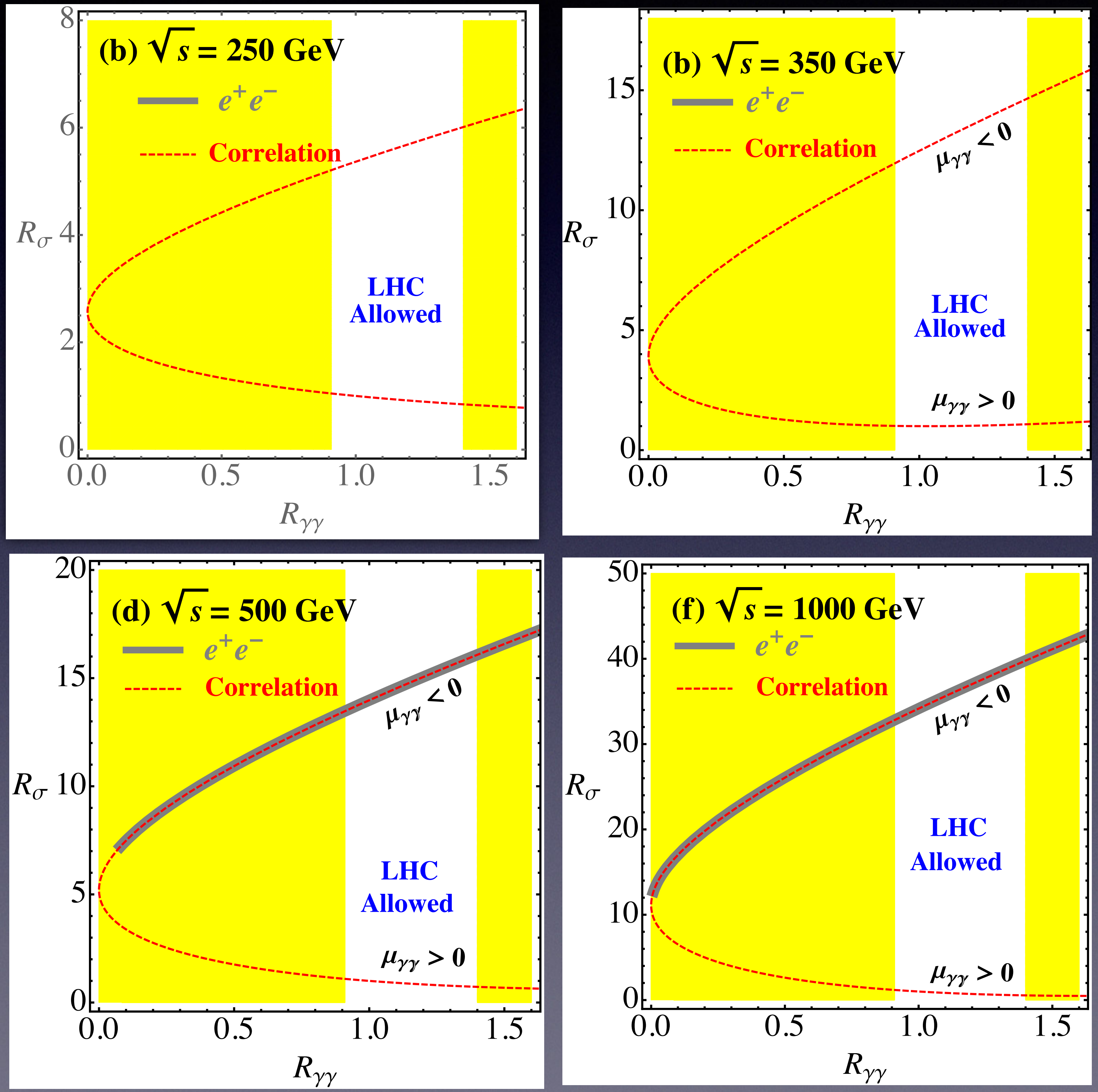
$\mathcal{F}^{\text{SM}}_{Z\gamma} \sim 0.007$



$\sigma(e^+e^- \to H\gamma)$ and $\Gamma(H \to \gamma\gamma)$

$\mathcal{L} = 1000\ \mathrm{fb}^{-1}$



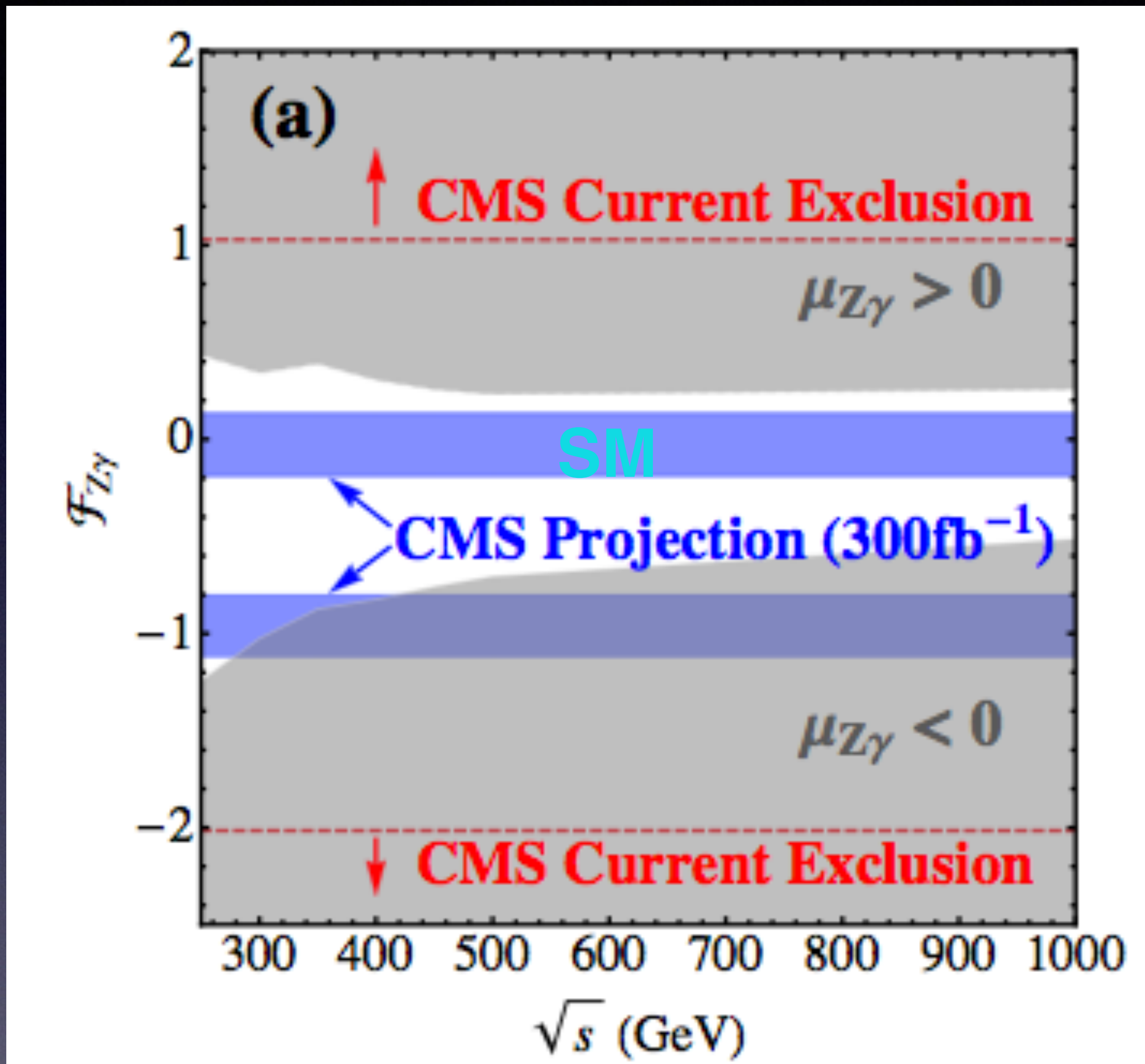


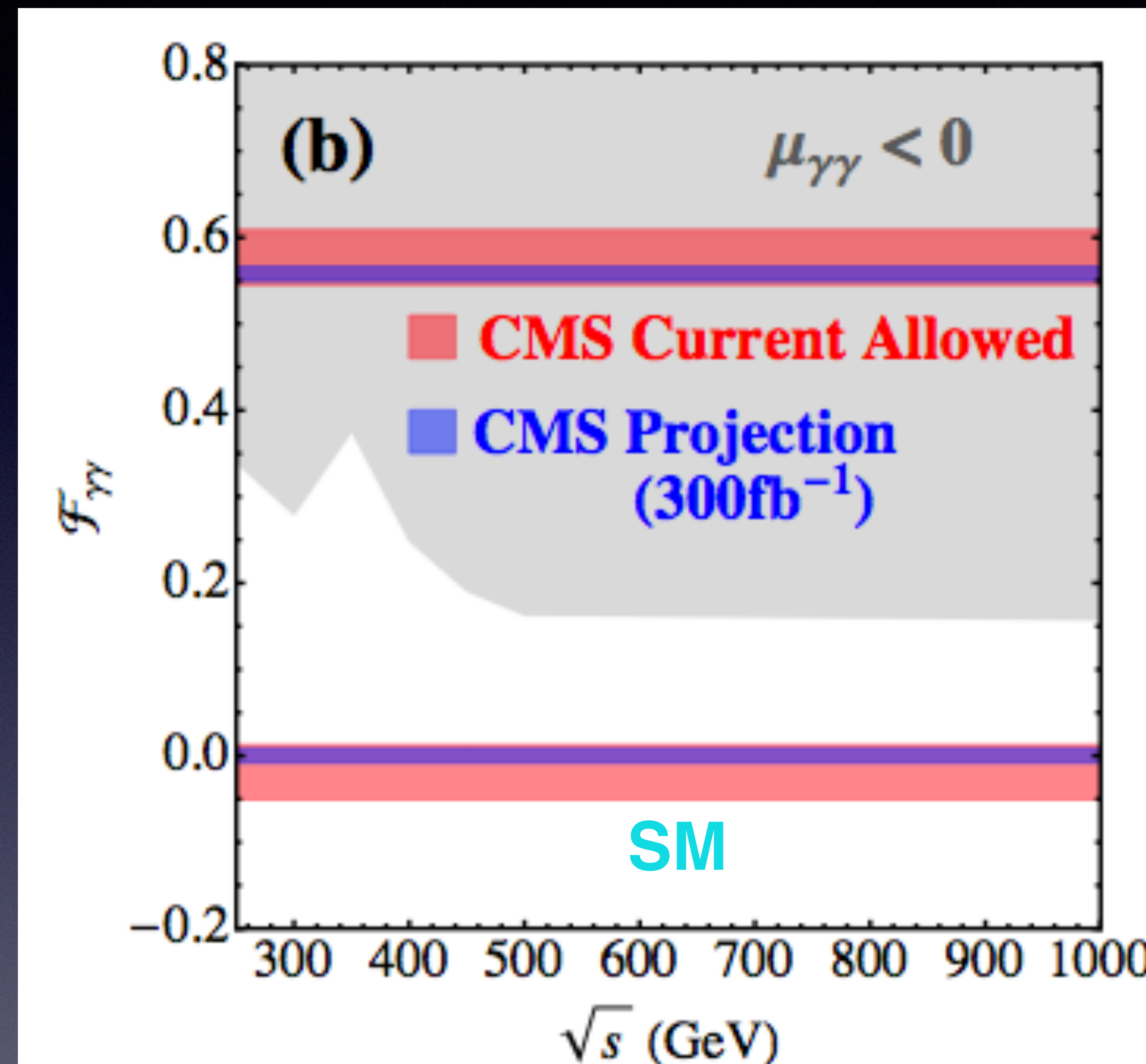
$$R_{\gamma\gamma} \equiv \frac{\Gamma(H \to \gamma\gamma)}{\Gamma_{\mathrm{SM}}(H \to \gamma\gamma)}$$

$\mathcal{F}_{\gamma\gamma}$ only

$\mathcal{F}_{Z\gamma} = 0$

No Loose — Exclusion on HZA/HAA

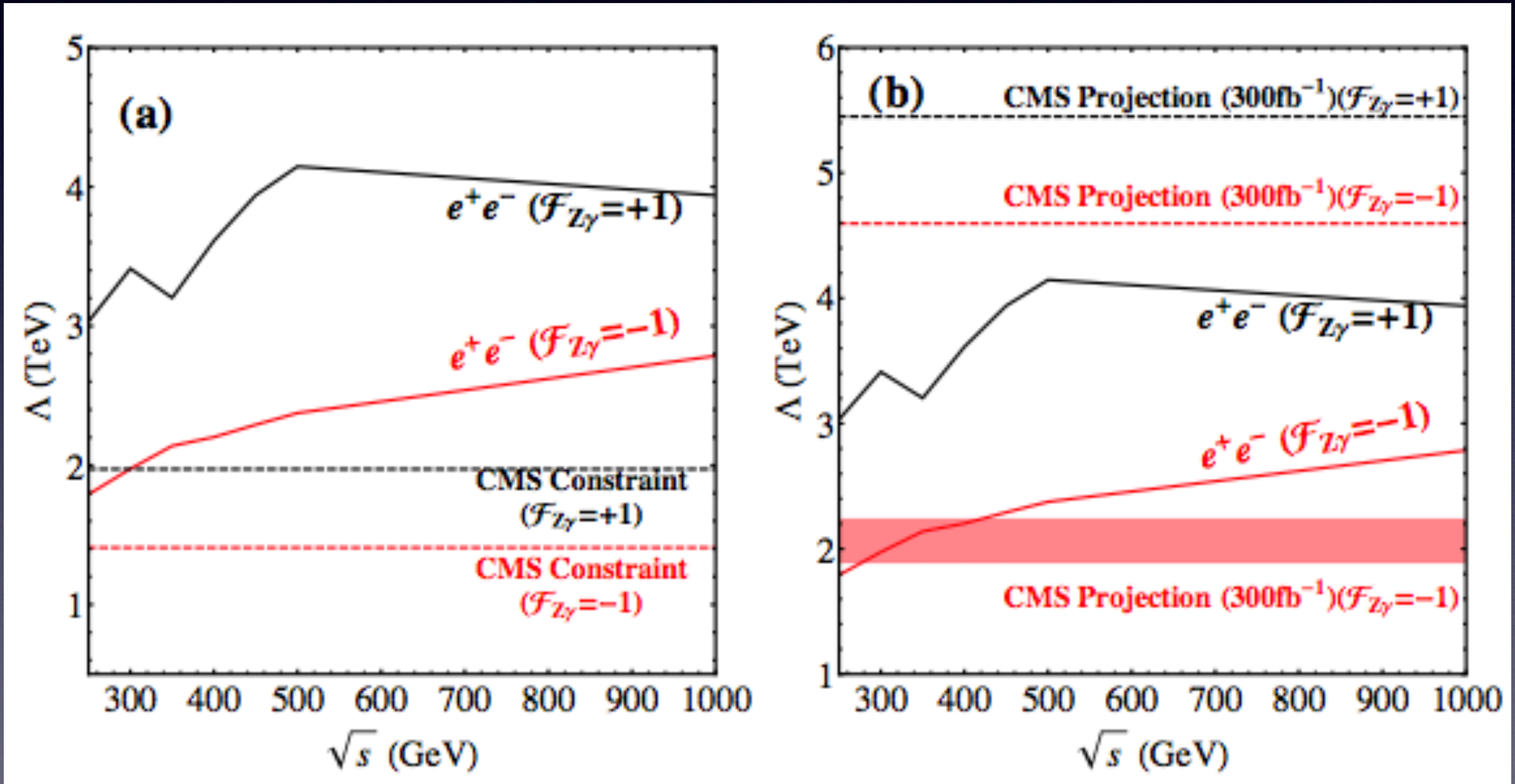




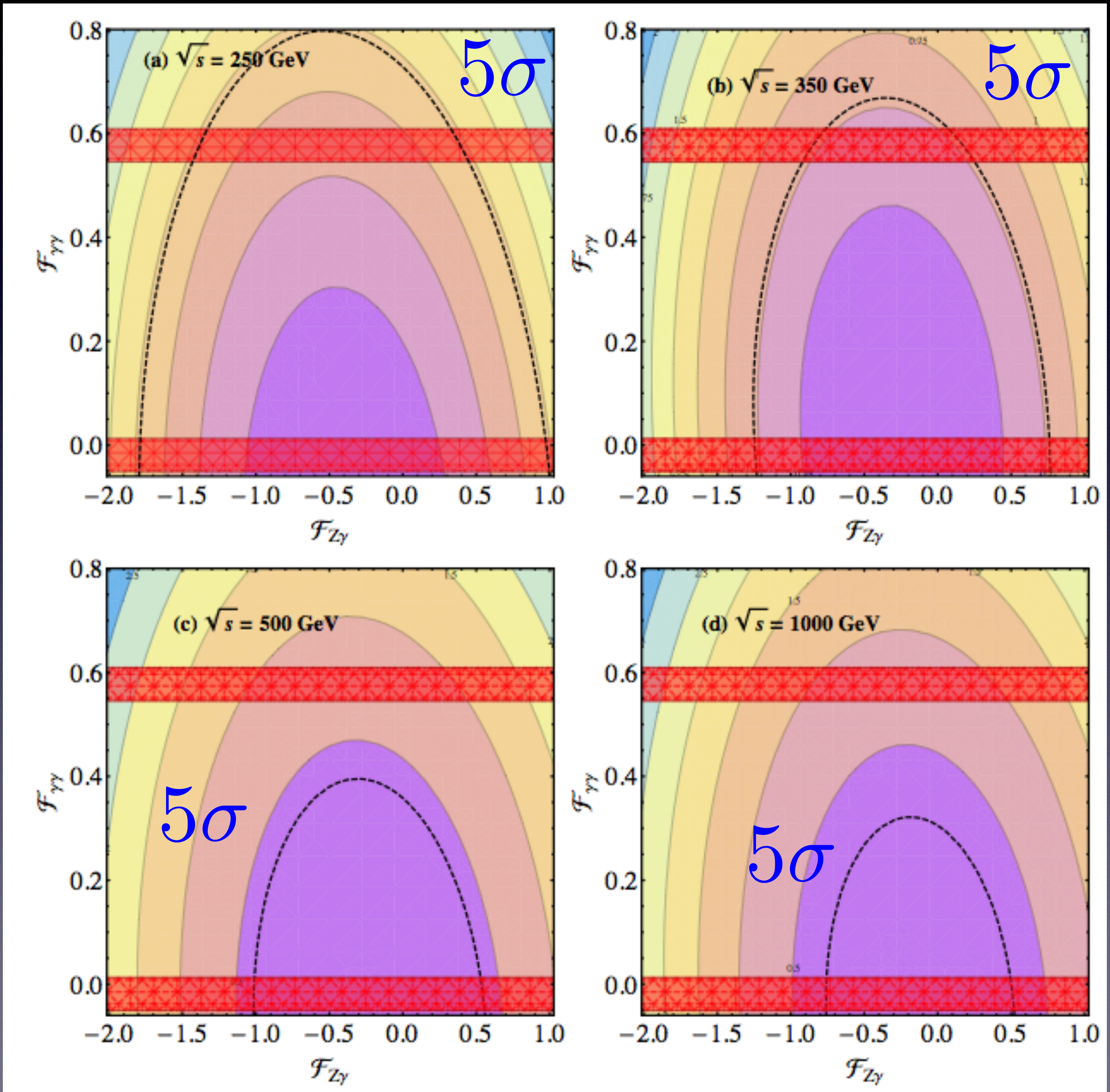
The degeneracy in $\Gamma(H \to \gamma\gamma)$ can be easily resolved at CEPC (250GeV), but ~400GeV is needed for $\Gamma(H \to Z\gamma)$

Exclusion on the NP scale

$$c_i/\Lambda^2 \xrightarrow{c_i \sim 1} \text{Bound on } \Lambda \text{ (95\% CL)}$$



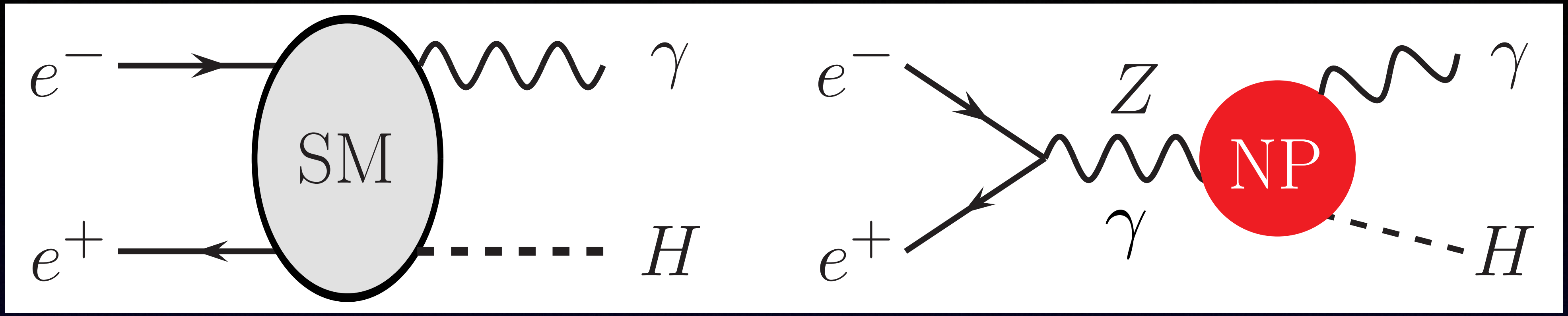
Both $H\gamma\gamma$ and $HZ\gamma$ present simultaneously



Red-shaded: LHC allowed $H\gamma\gamma$

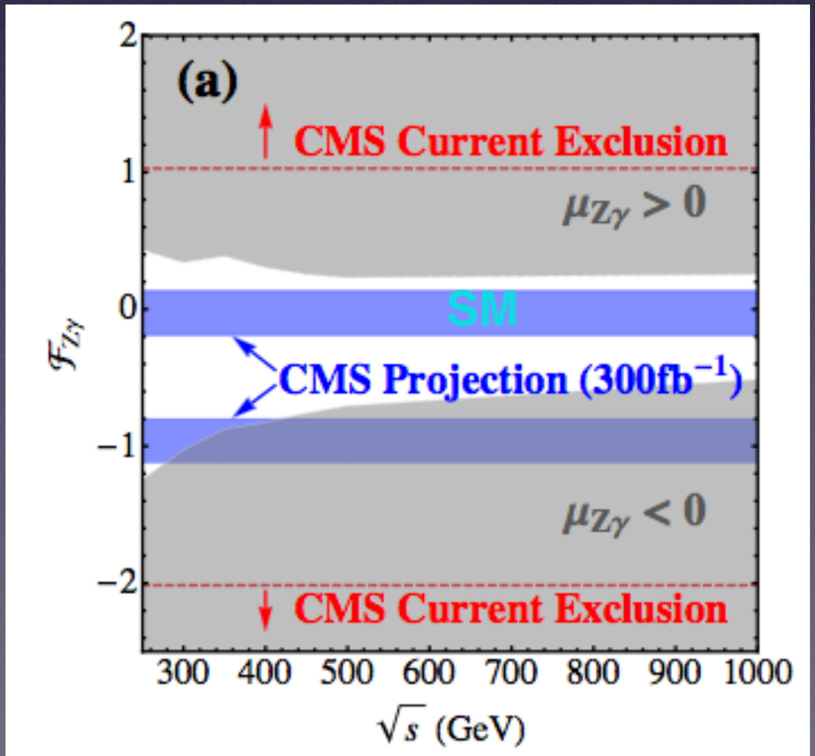
Black-Dashed: 5σ Discovery contour of $e^+e^- \to H\gamma$

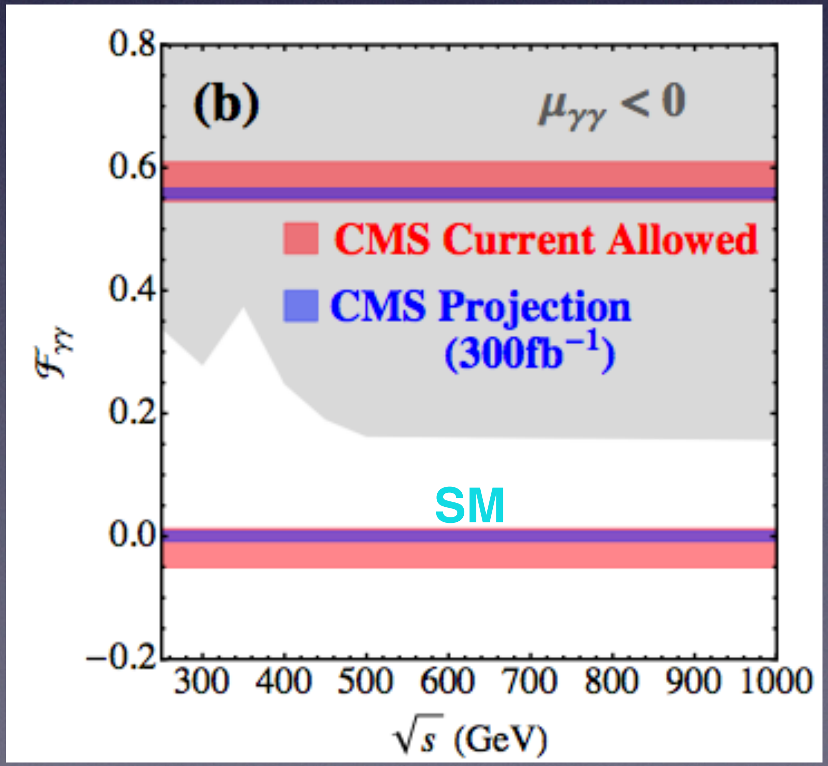
Summary



The $H\gamma$ production can be used to probe the NP hidden in the Higgs boson rare decay.

The degeneracy in Higgs rare decays, which cannot be tested at the HL-LHC, could be fully excluded at a high energy e^+e^- collider.





Thank You!