BSM Higgs physics at the photon collider

Photon colliders: simulation and di-Higgs production as physics case

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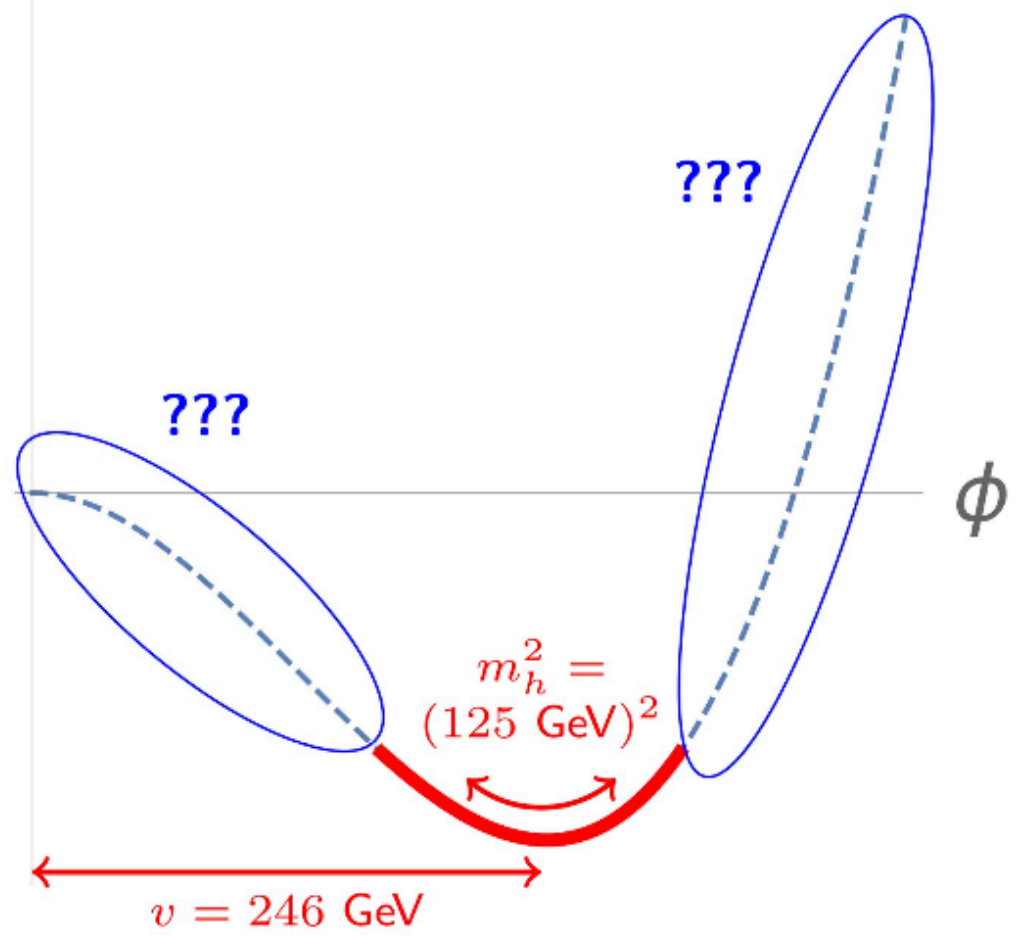
Motivation



- Shape of the Higgs potential is unknown

$$V = \frac{1}{2}m_h^2 h^2 + v\lambda_{hhh}h^3 + \lambda_{hhhh}h^4 + \ldots$$

- This is one of the major challenges and goals of future colliders

- Not a lot of studies for $\gamma\gamma \to hh$, and so far no high-energy photon collider

- A photon collider would give unprecedented access to this channel and many more

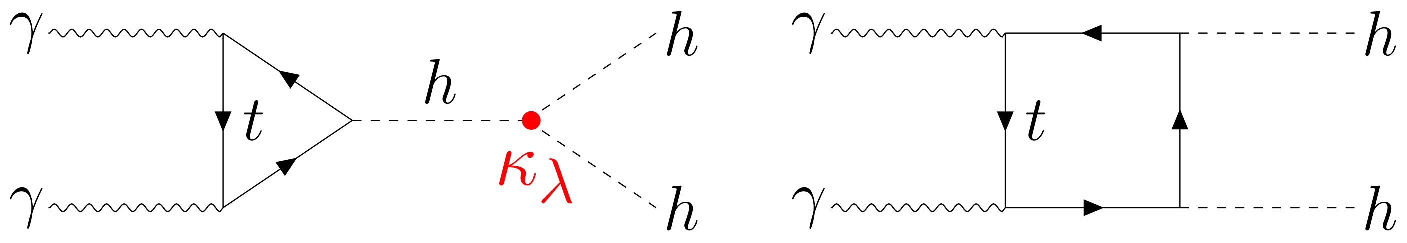
- Combining the luminosity spectrum of the collider with the $\gamma\gamma \to hh$ process

$$\sigma = \int_{4m_h^2/\hat{s}}^{y_m^2} d\tau \frac{1}{2}\left[\frac{1}{L_{\gamma\gamma}^{++}}\frac{dL_{\gamma\gamma}^{++}}{d\tau}\hat{\sigma}_{++}(\hat{s}) + \frac{1}{L_{\gamma\gamma}^{+-}}\frac{dL_{\gamma\gamma}^{+-}}{d\tau}\hat{\sigma}_{+-}(\hat{s})\right]$$

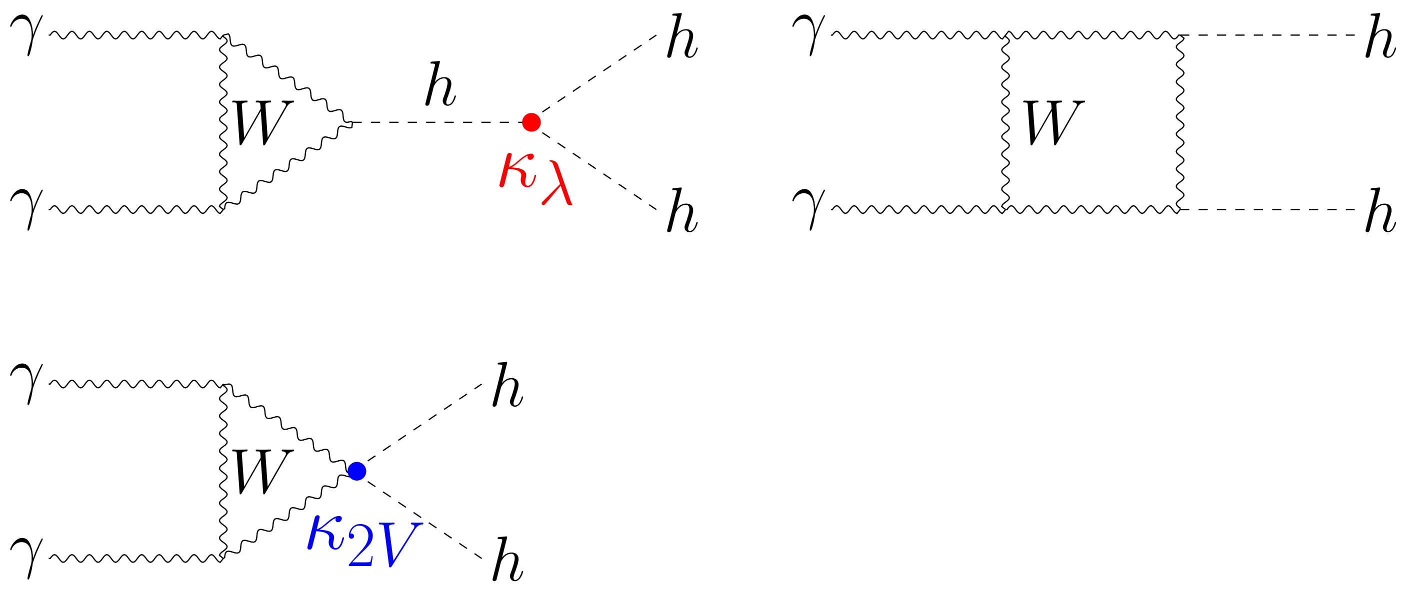
Di-Higgs production at photon colliders

$$\kappa_\lambda \equiv \frac{\lambda_{hhh}}{(\lambda^{(0)}_{hhh})^{\mathrm{SM}}}$$

- Similar structure to $gg \to hh$



- With additional gauge sector contributions



- To simplify the process, use the representation in helicity amplitudes

$$\frac{d\hat{\sigma}(\lambda_1, \lambda_2)}{dt} = \frac{\alpha^2 \alpha_W^2}{32\pi \hat{s}^2} \left| M(\lambda_1, \lambda_2) \right|^2$$

Di-Higgs production at photon colliders

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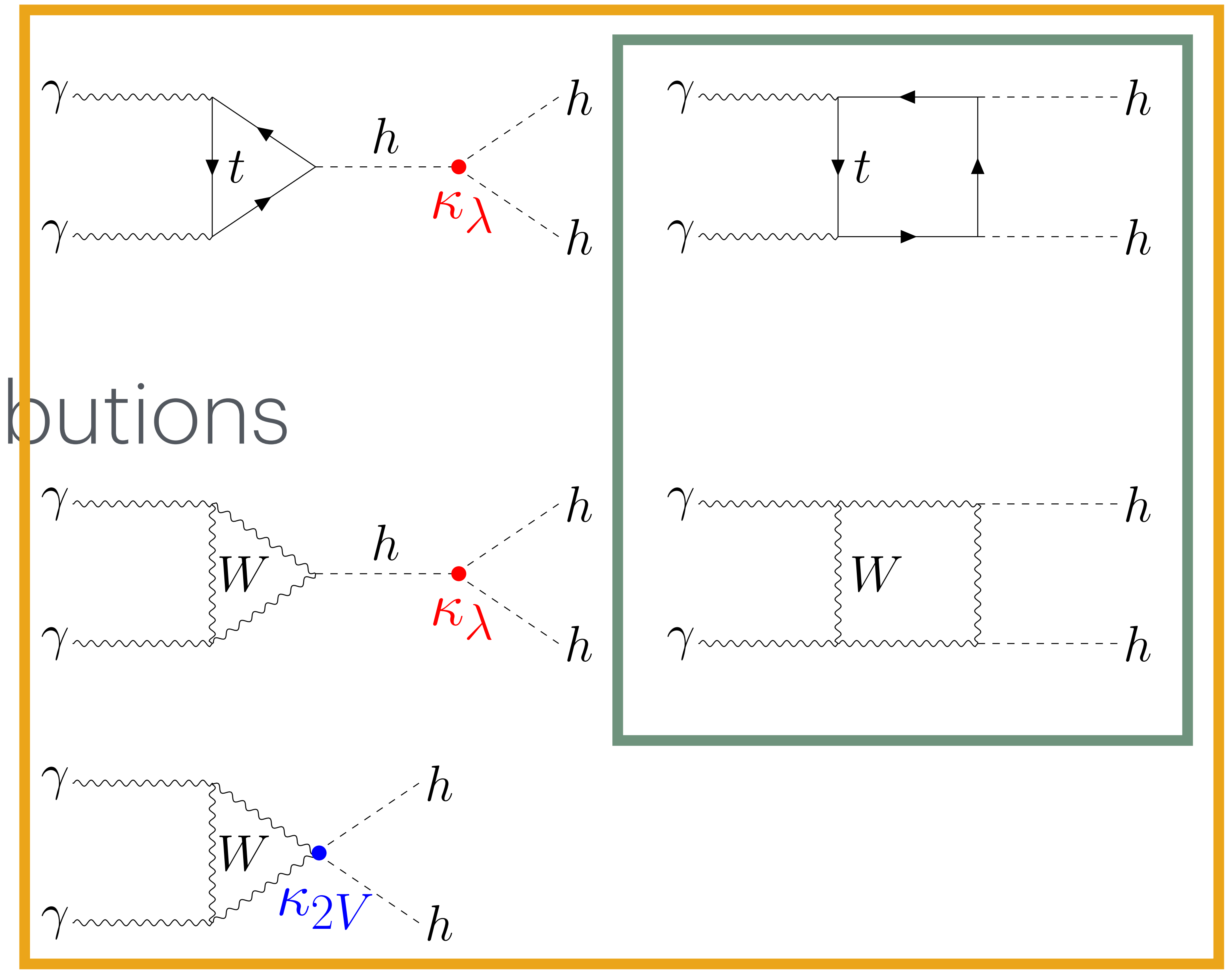
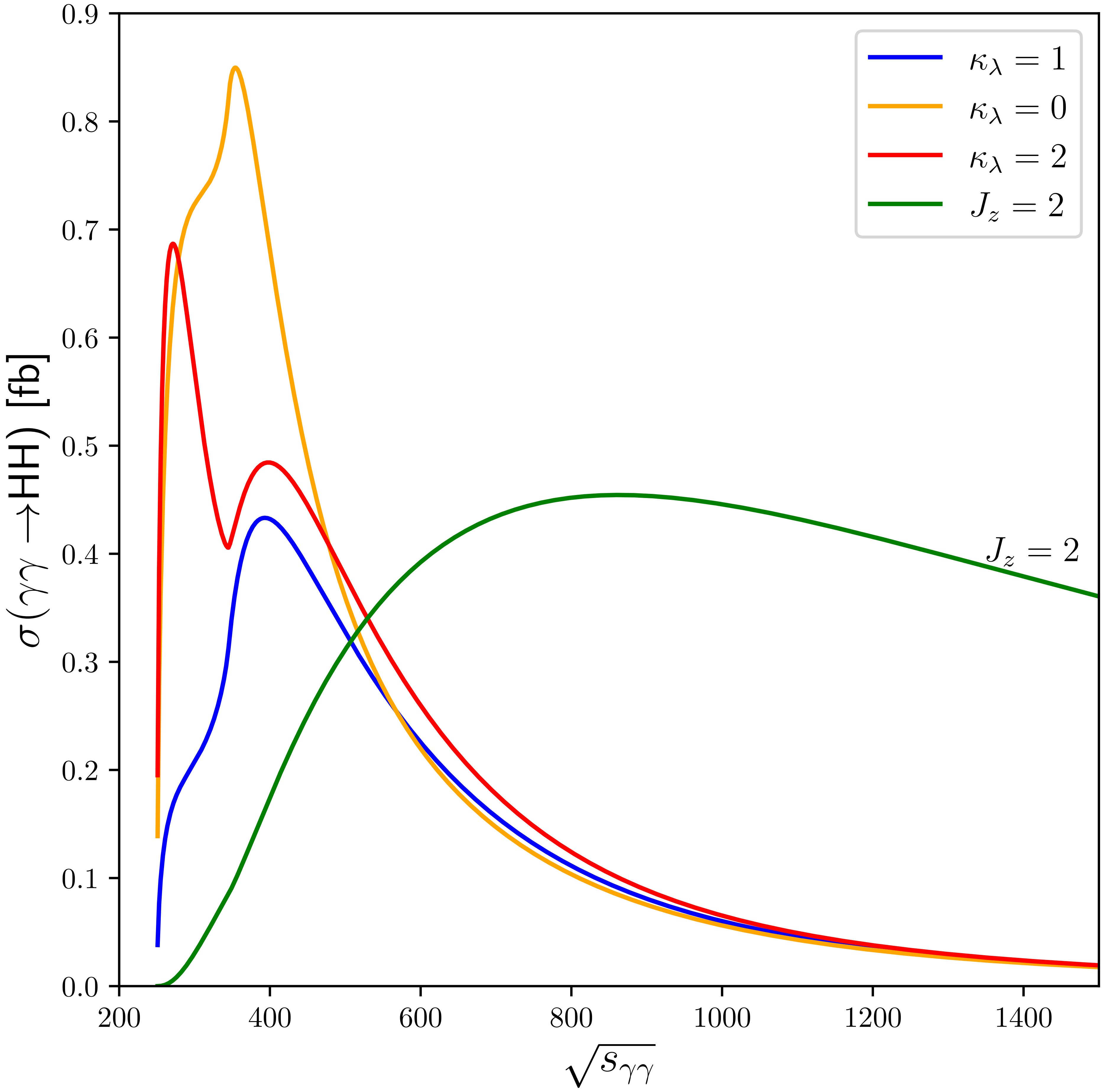
- Similar structure to $gg \to hh$

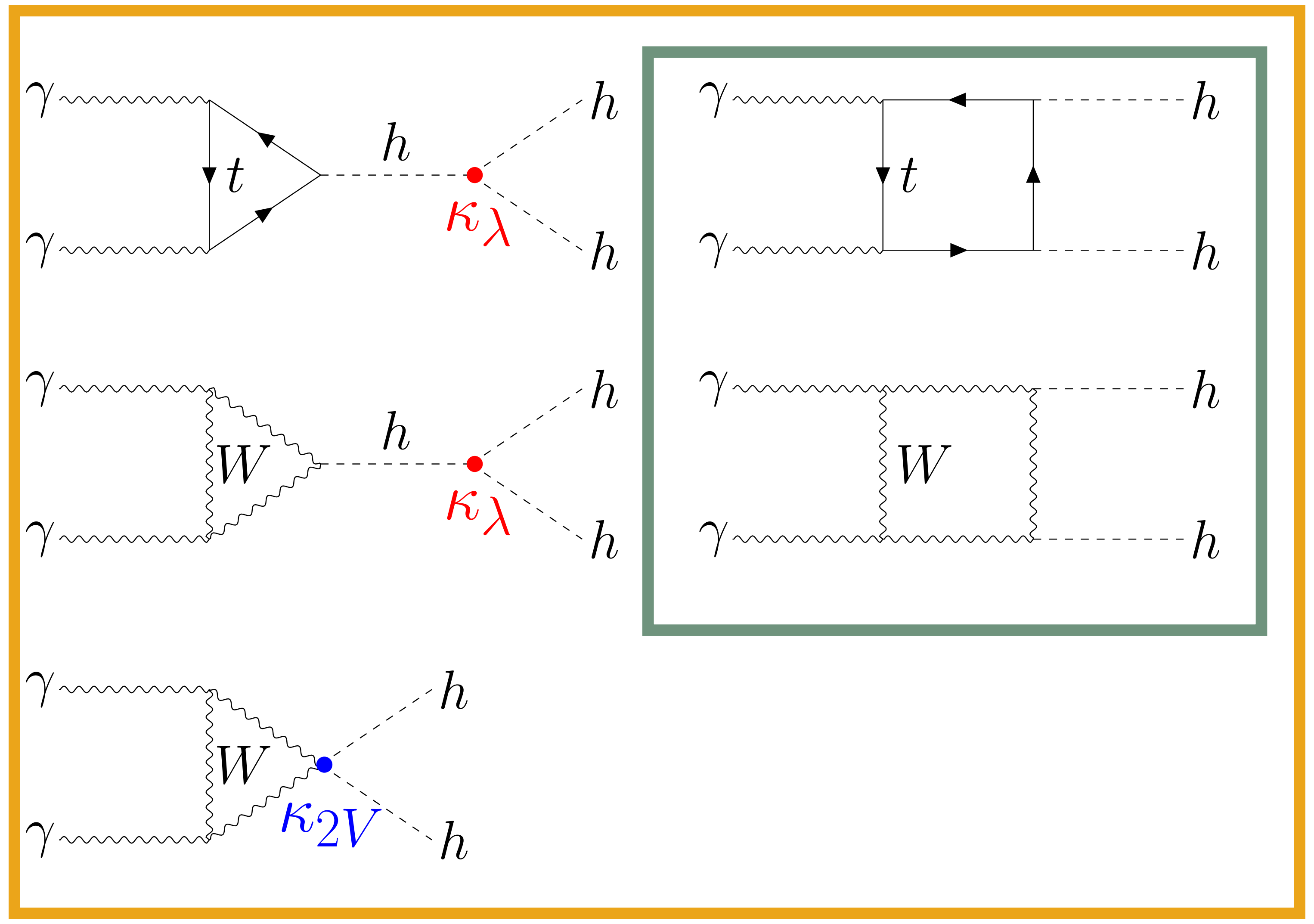


- With additional bosonic contributions
- To simplify the process, use the representation in helicity amplitudes
- Giving two distinct states $J_z = 0$ and $J_z = 2$, for equal and opposite polarization of the initial photons

Di-Higgs production at photon colliders



$$\kappa_\lambda \equiv \frac{\lambda_{hhh}}{(\lambda_{hhh}^{(0)})^{\mathrm{SM}}}$$



$$\frac{d\hat{\sigma}(\lambda_1, \lambda_2)}{dt} = \frac{\alpha^2 \alpha_W^2}{32\pi \hat{s}^2} |M(\lambda_1, \lambda_2)|^2$$

- At lower energies, the $J_z = 0$ state dominates and is very sensitive to κ_λ

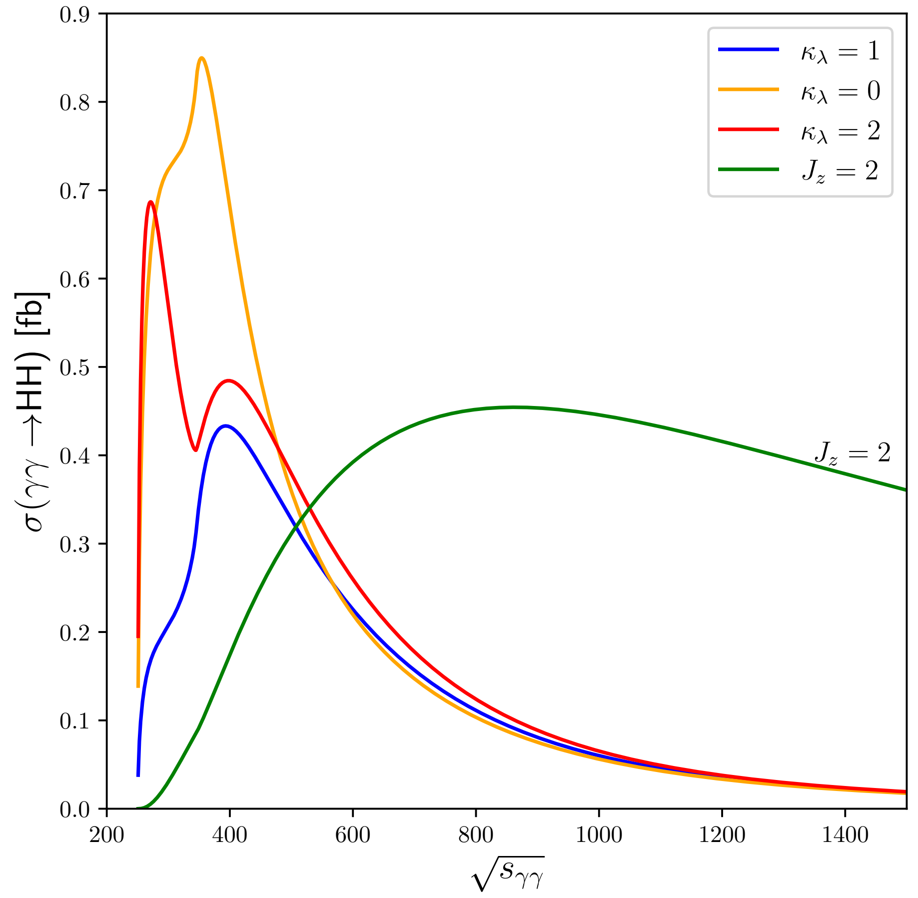
κ_λ in photon photon collision

- The minimum of the $\gamma\gamma \to hh$ cross-section shifts between 1 and 1.5, depending on the energy

- **380 GeV** maximises the cross-section for $\kappa_\lambda = 1$, from the $J_z = 0$ contribution

- **280 GeV** has the strongest dependency on κ_λ, even though the cross-section is lower between 0 and 2

Fixed $\kappa_{2V} = 1$



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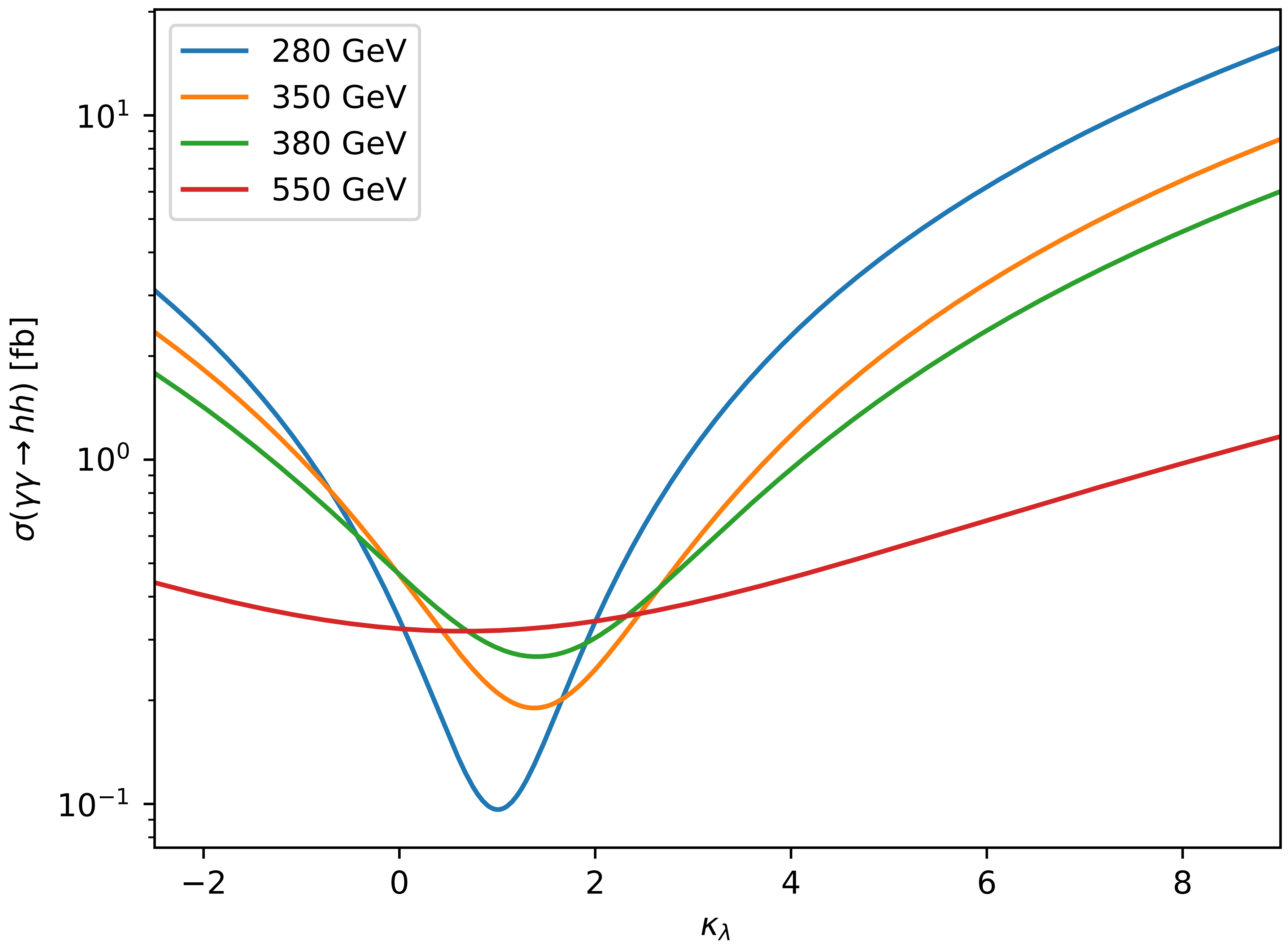
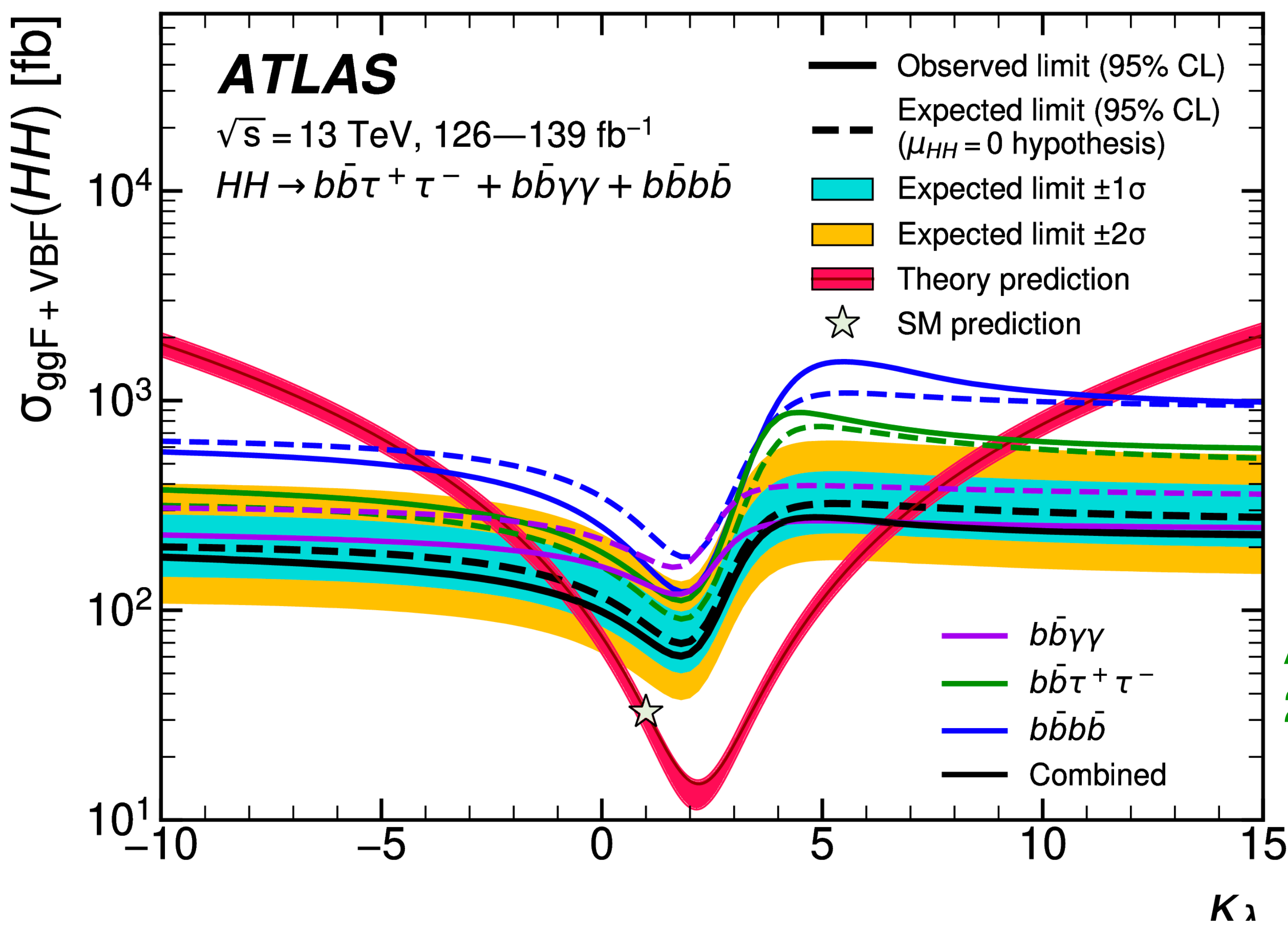


κ_λ at other colliders



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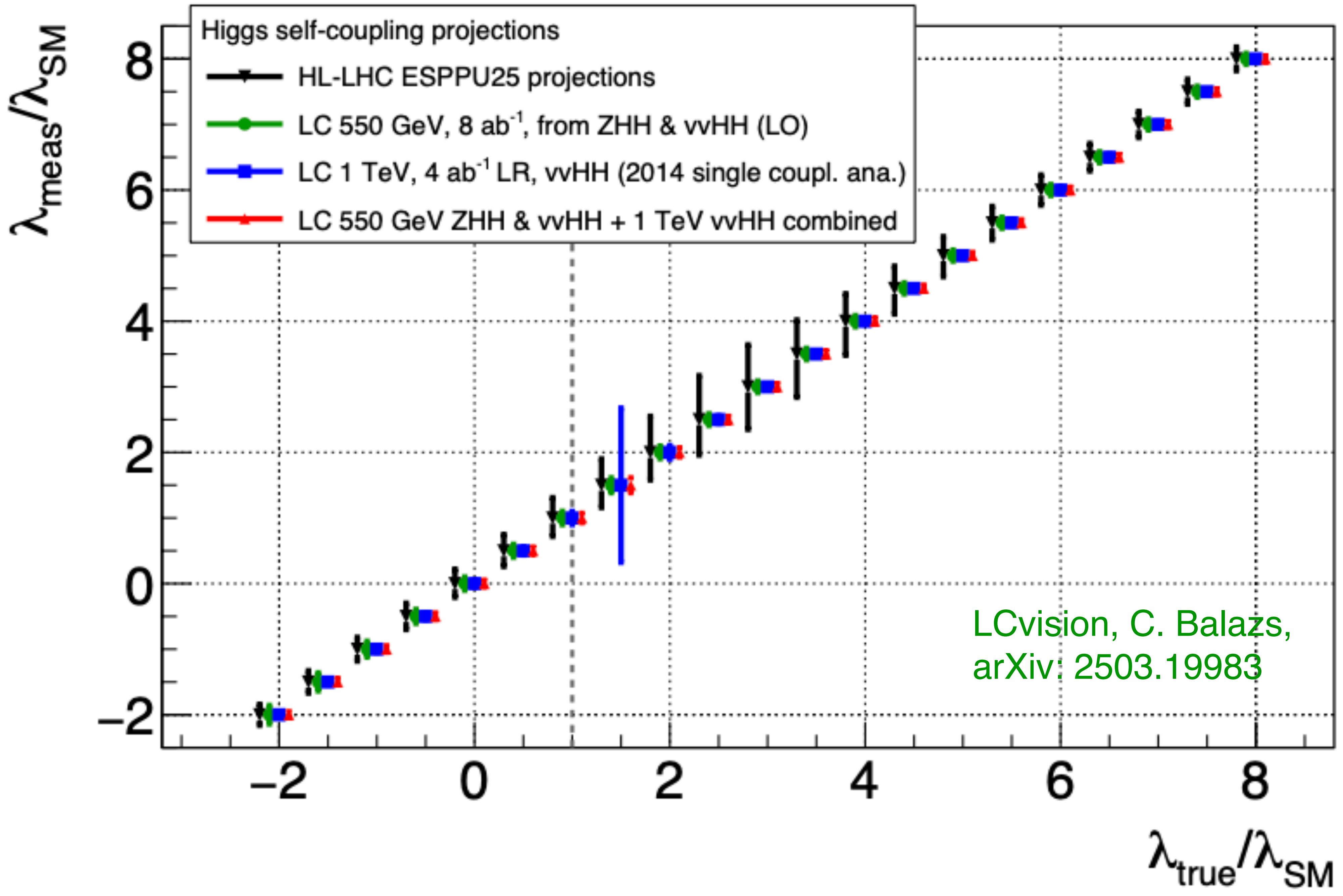

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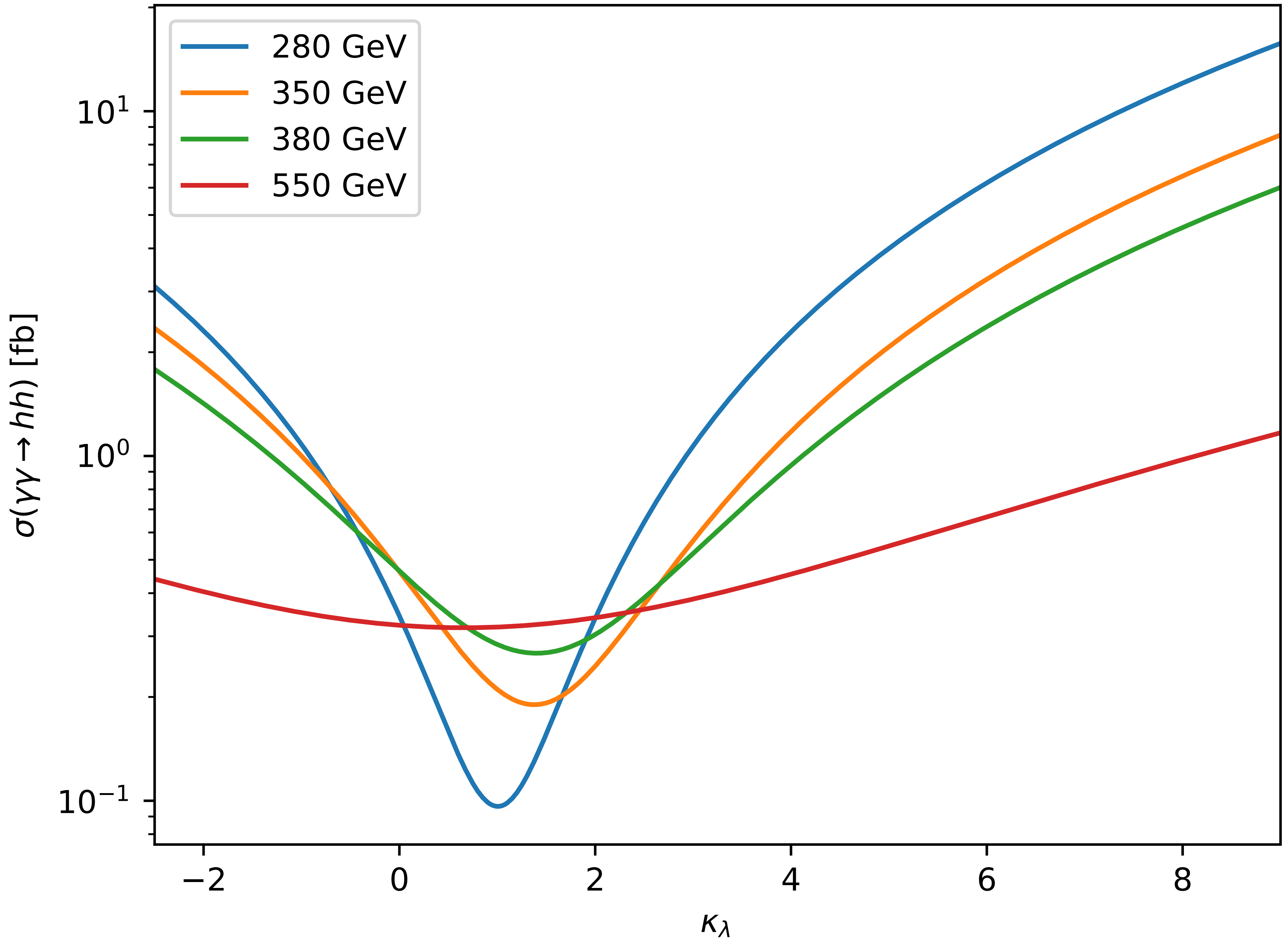
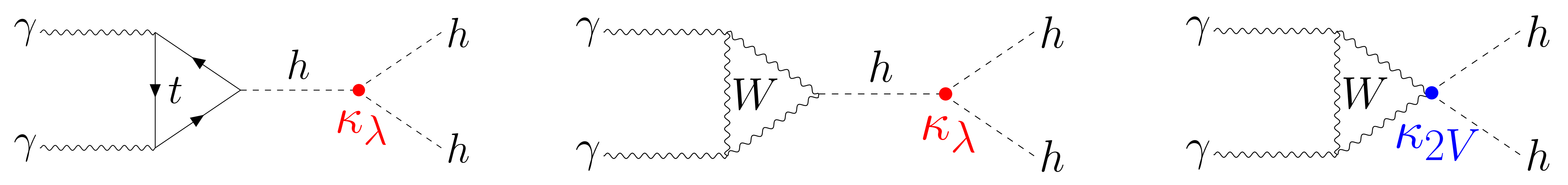


The minima are at different values of κ_λ, allowing for complementary searches

κ_λ and κ_{2V}



- Greatest sensitivity to κ_λ
- κ_{2V} less impactful
- For $\kappa_{2V} < 1$ the minimum shifts to higher values of κ_λ
- For $\kappa_{2V} > 1$ the minimum shifts to lower values of κ_λ

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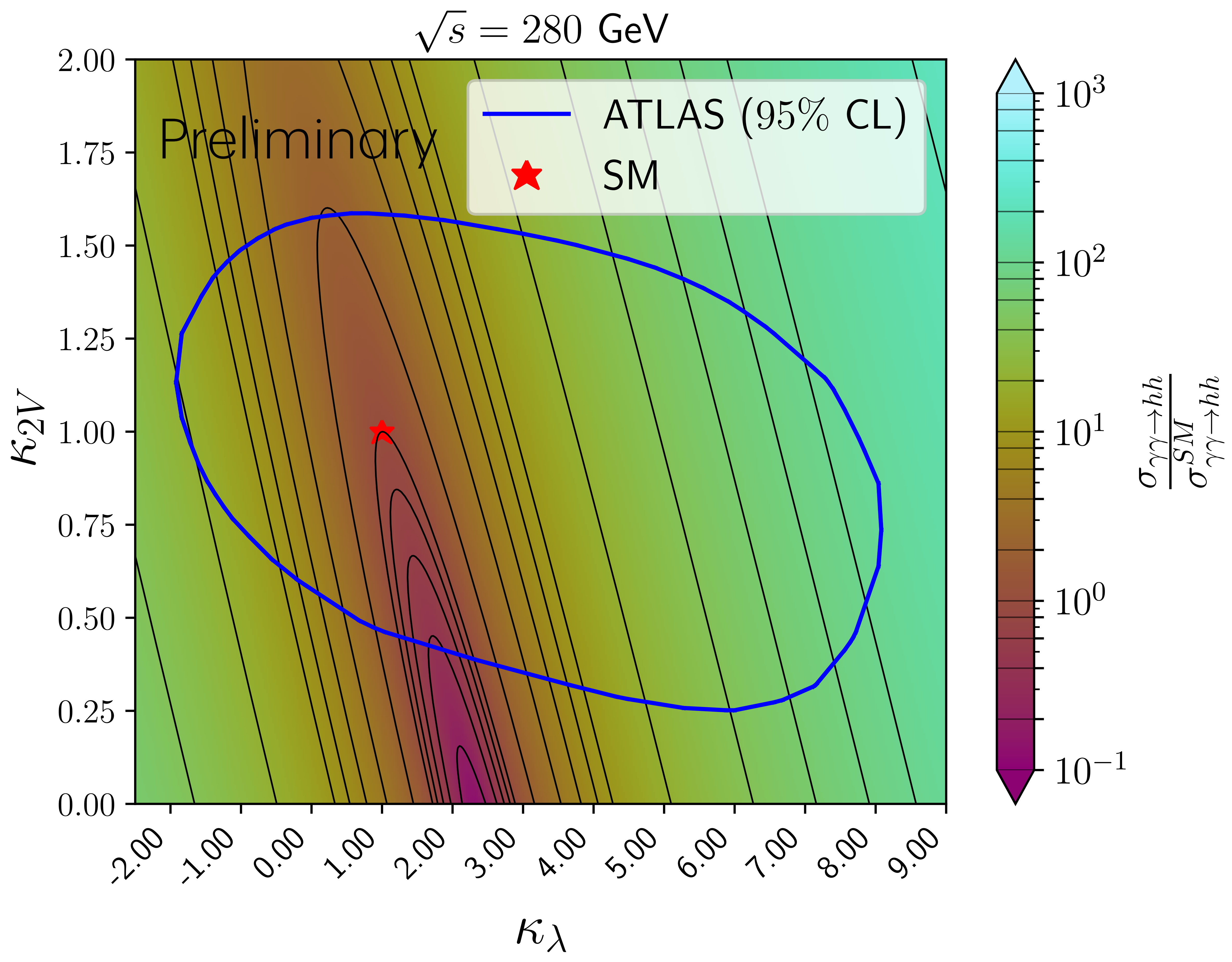
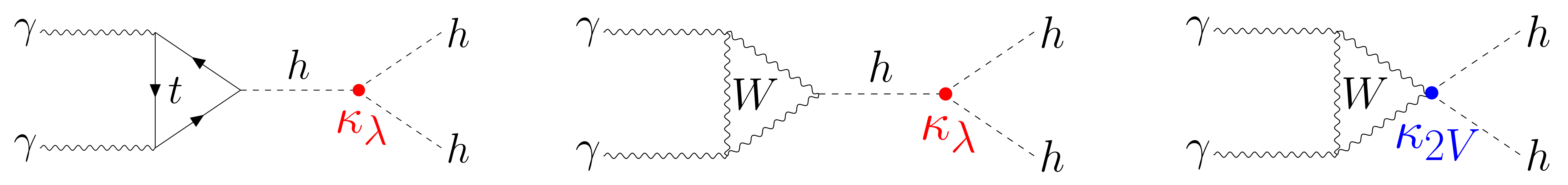


κ_λ and κ_{2V}



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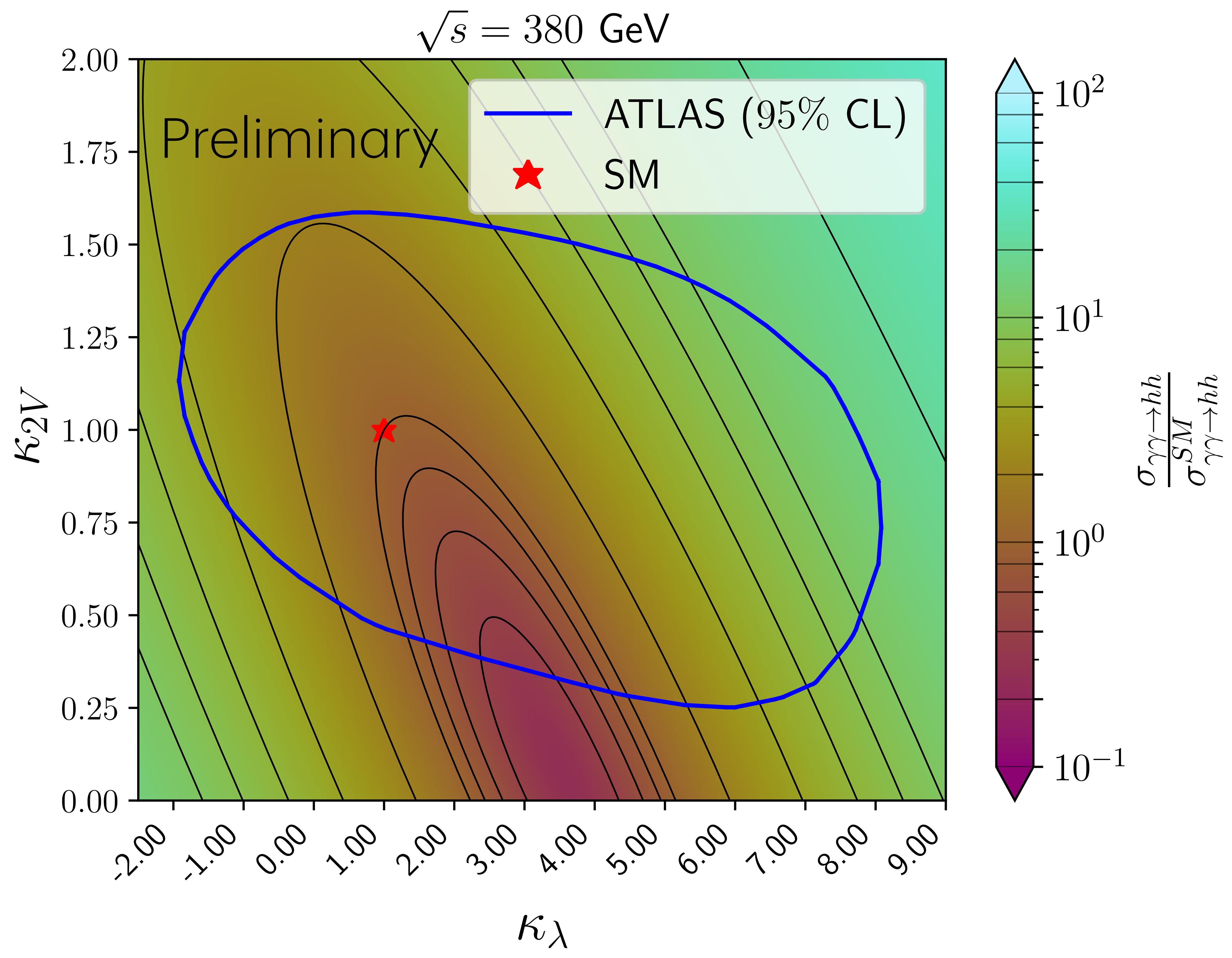
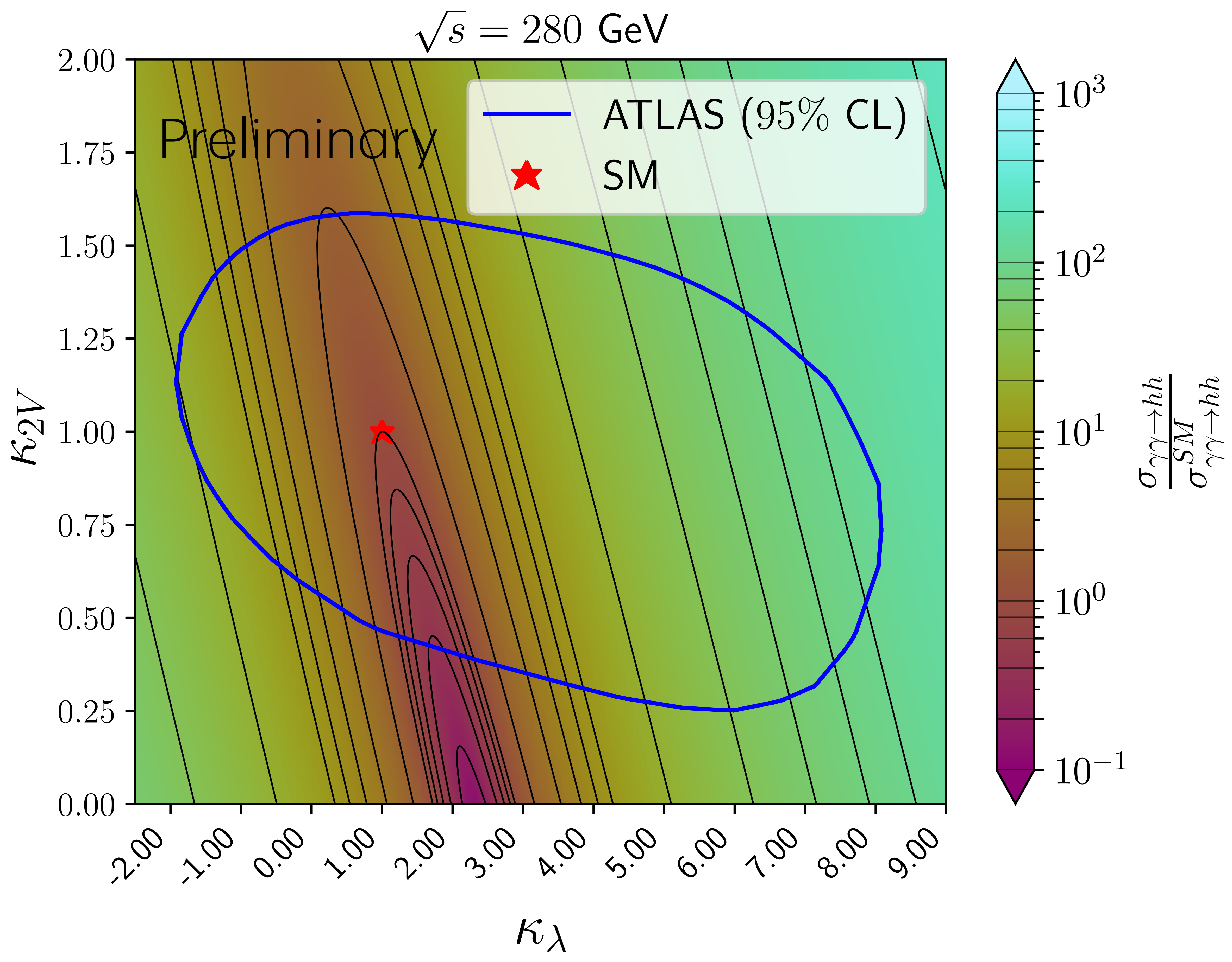
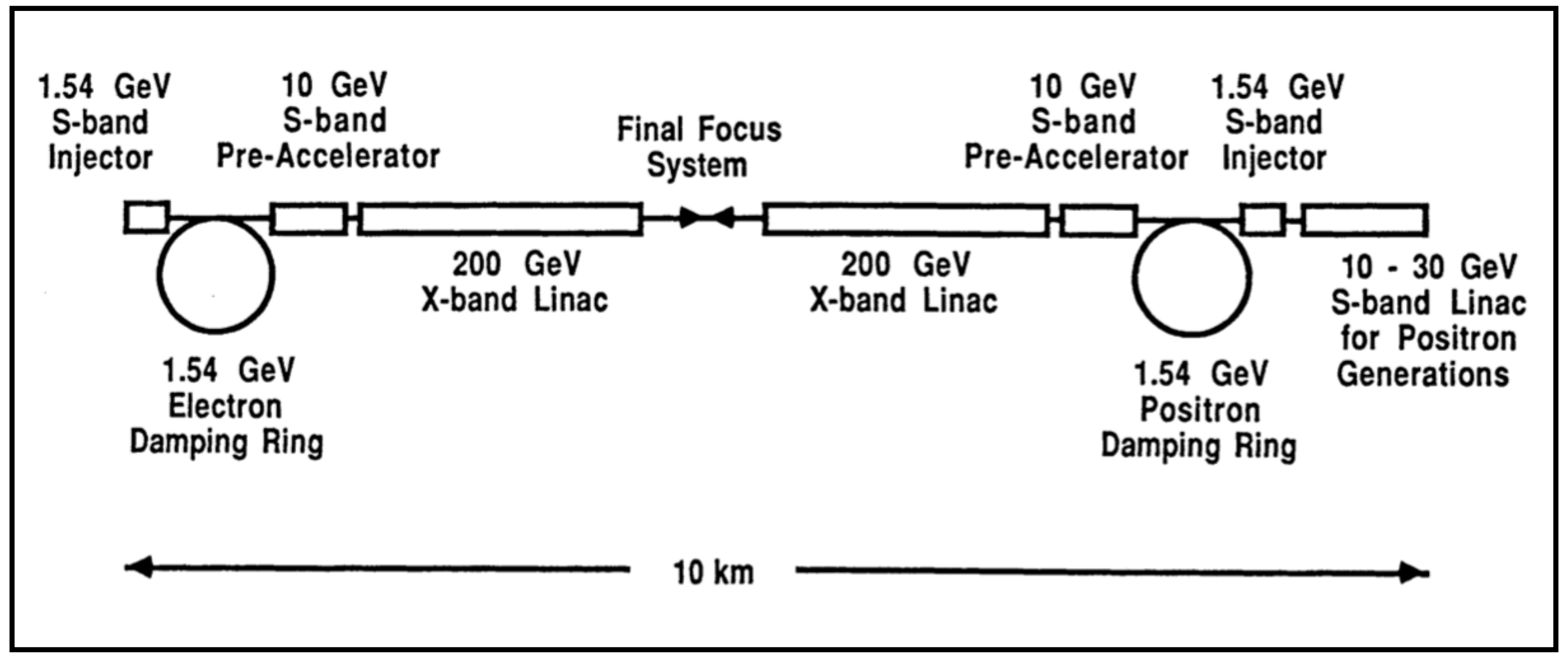


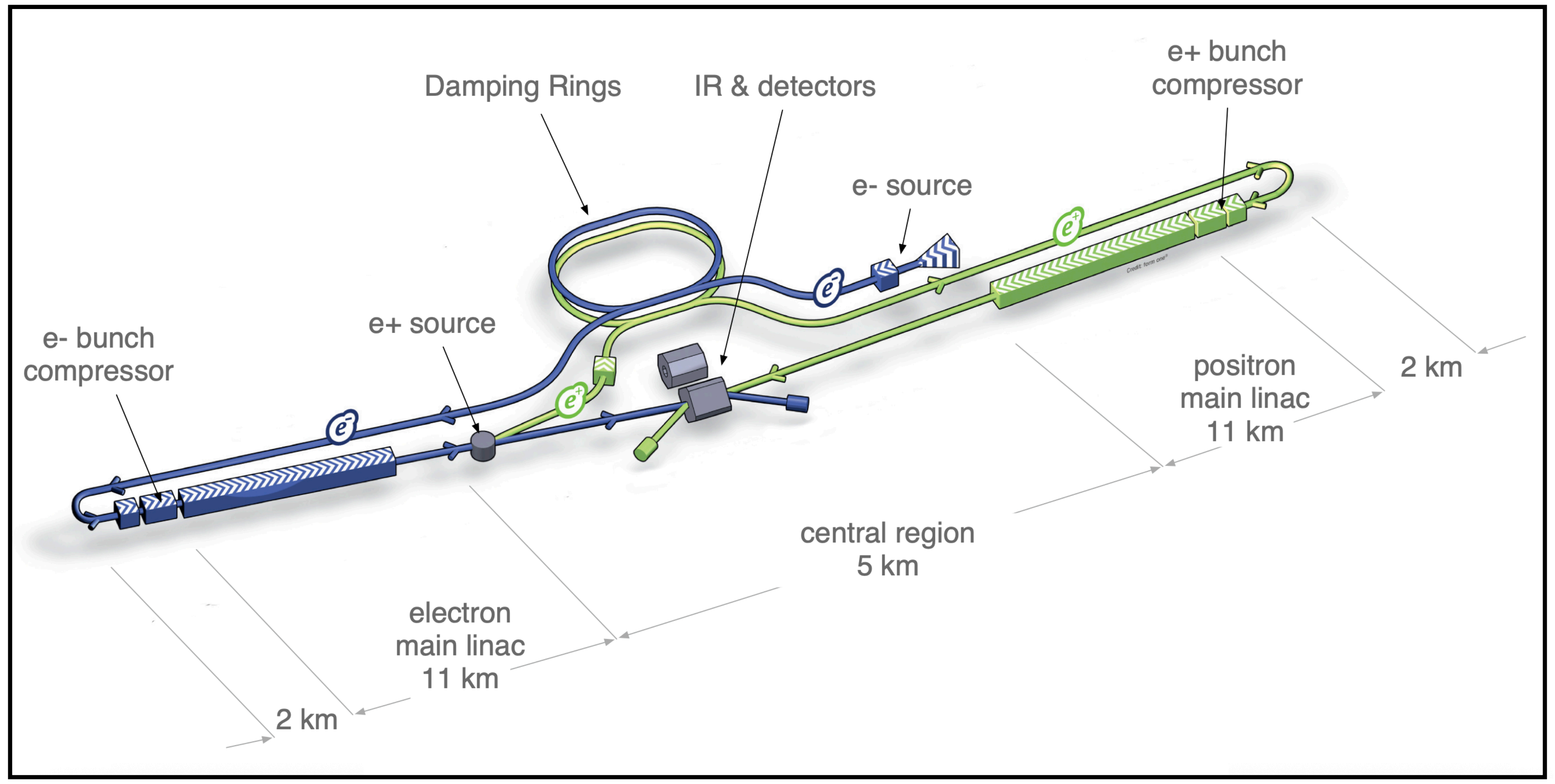


Collider setups

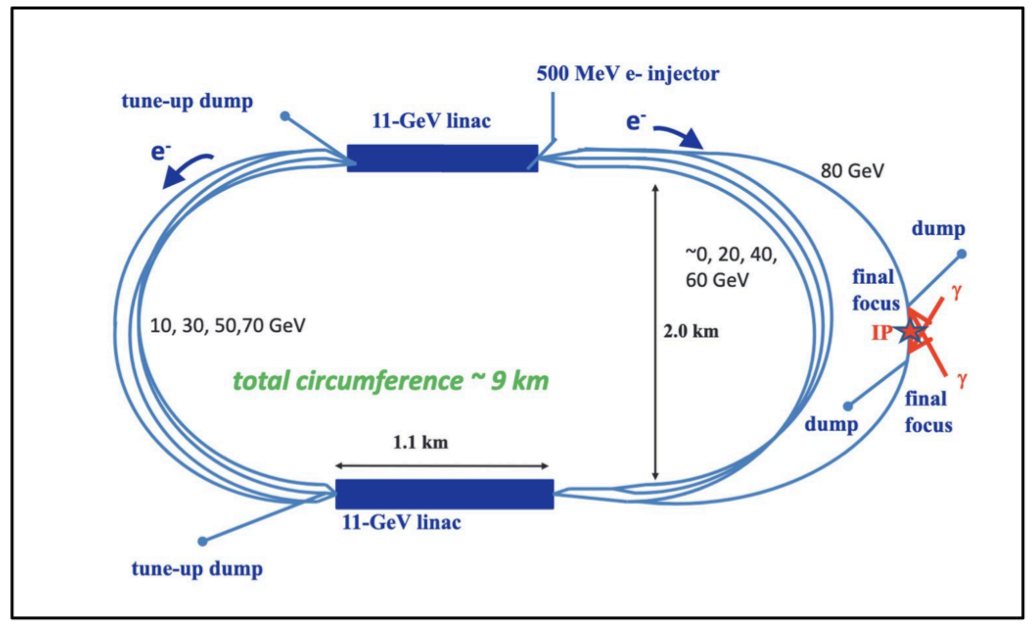
JLC



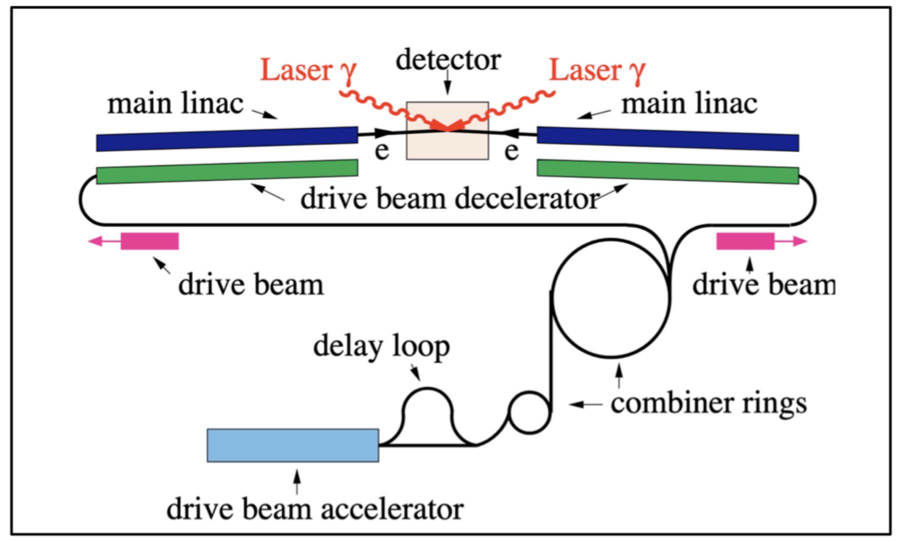
ILC



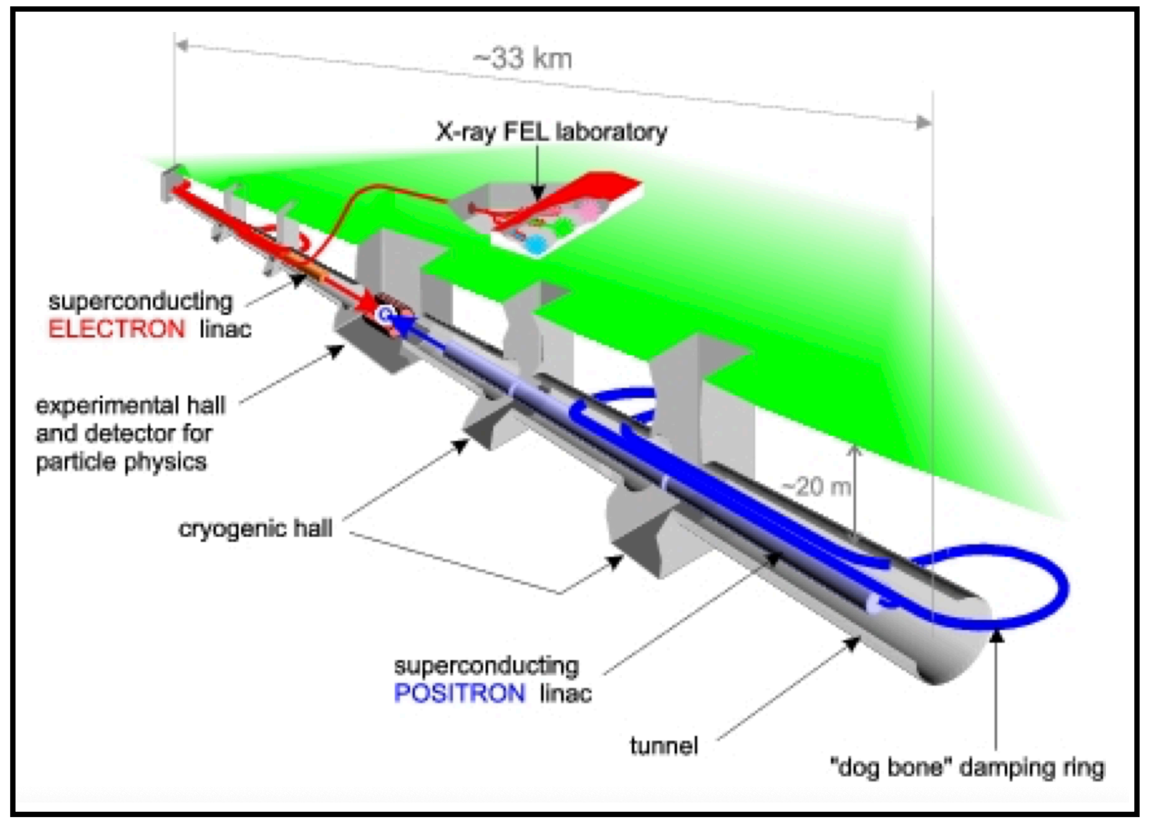
SAPPHIRE



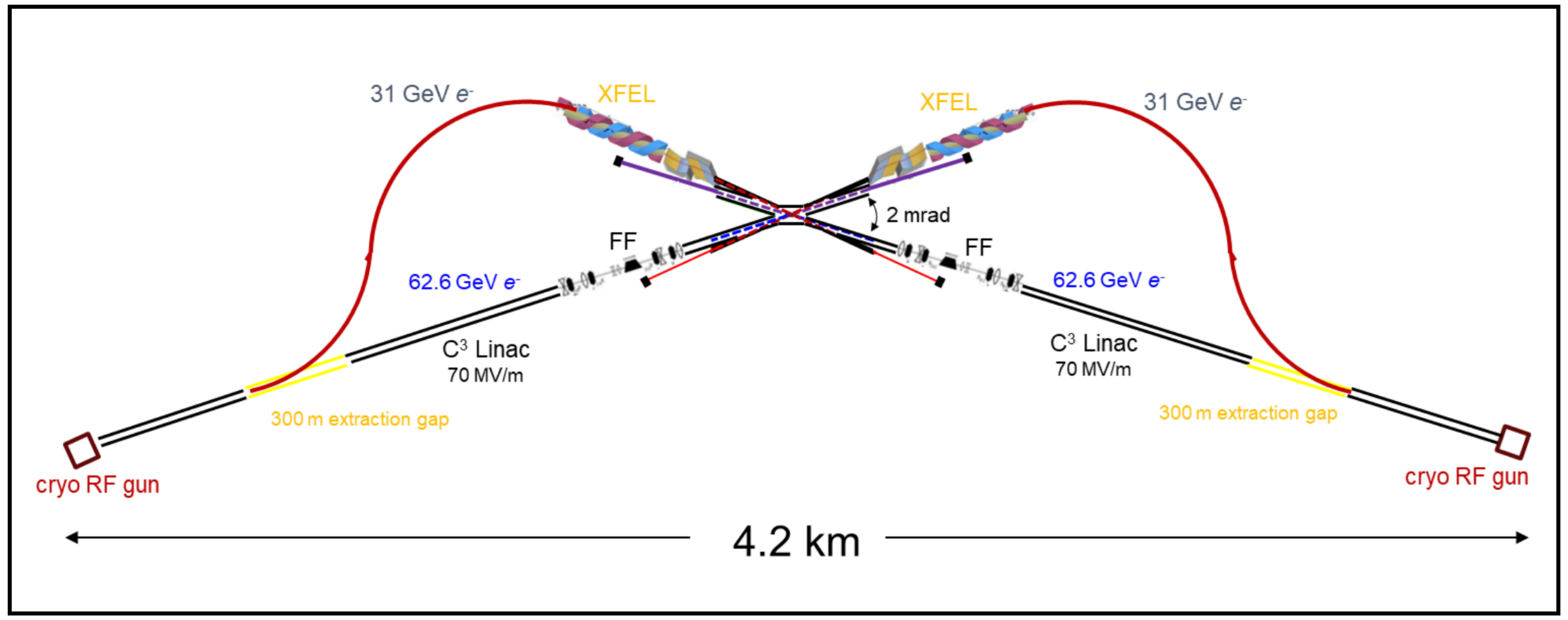
CLICHE



TESLA



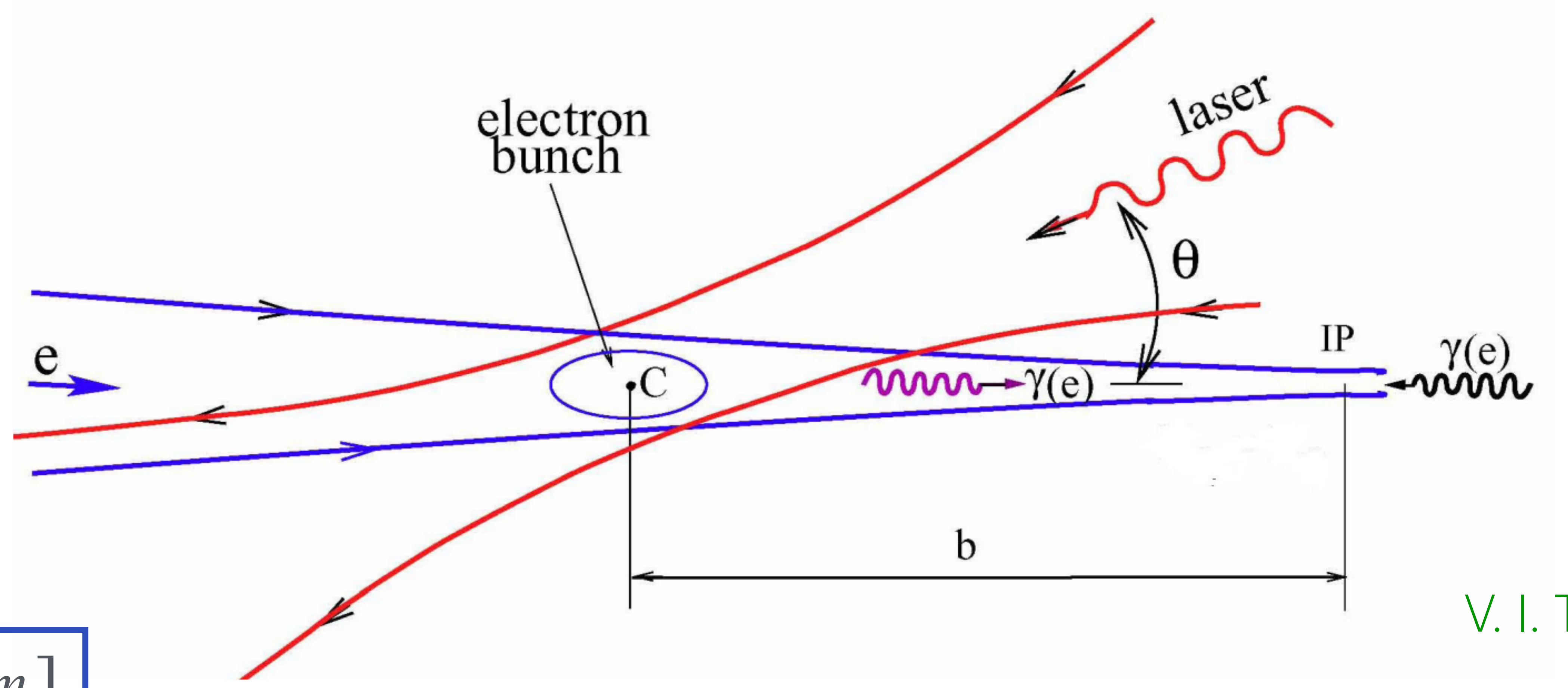
XCC



I. F. Ginzburg, G. L. Kotkin, V. G. Serbo, V. I. Telnov '82

Principles of a photon collider

- Addition to $e^- e^-$-collider
- Compton backscattering process
- Getting access to $\gamma\gamma$ and γe processes



V. I. Telnov '20

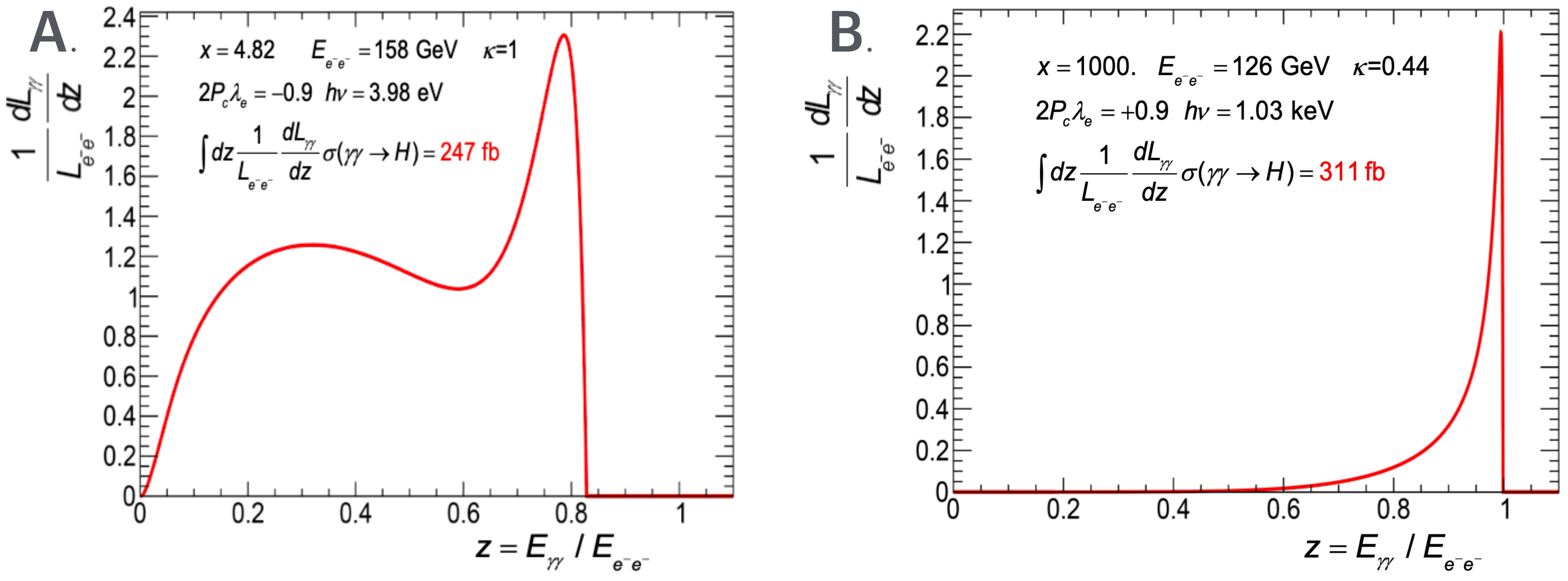
$$\omega_m \approx \frac{x}{1+x} E_0, \quad x = \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3 \left[\frac{E_0}{\text{TeV}}\right] \left[\frac{\omega_0}{\text{eV}}\right] = 19 \left[\frac{E_0}{\text{TeV}}\right] \left[\frac{\mu m}{\lambda}\right]$$

T.Barklow '24

Type of laser is decisive

A. Optical

B. XFEL-like (XCC)



Collider setups

- The polarization of the incoming laser and electron beam defines the spectrum

$$\langle\lambda_\gamma\rangle = \frac{\lambda_e x r[1+(1-y)(2r-1)^2] - P_c(2r-1)[(1-y)^{-1}+1-y]}{(1-y)^{-1}+1-y-4r(1-r)-\lambda_e P_c x r(2-y)(2r-1)}$$

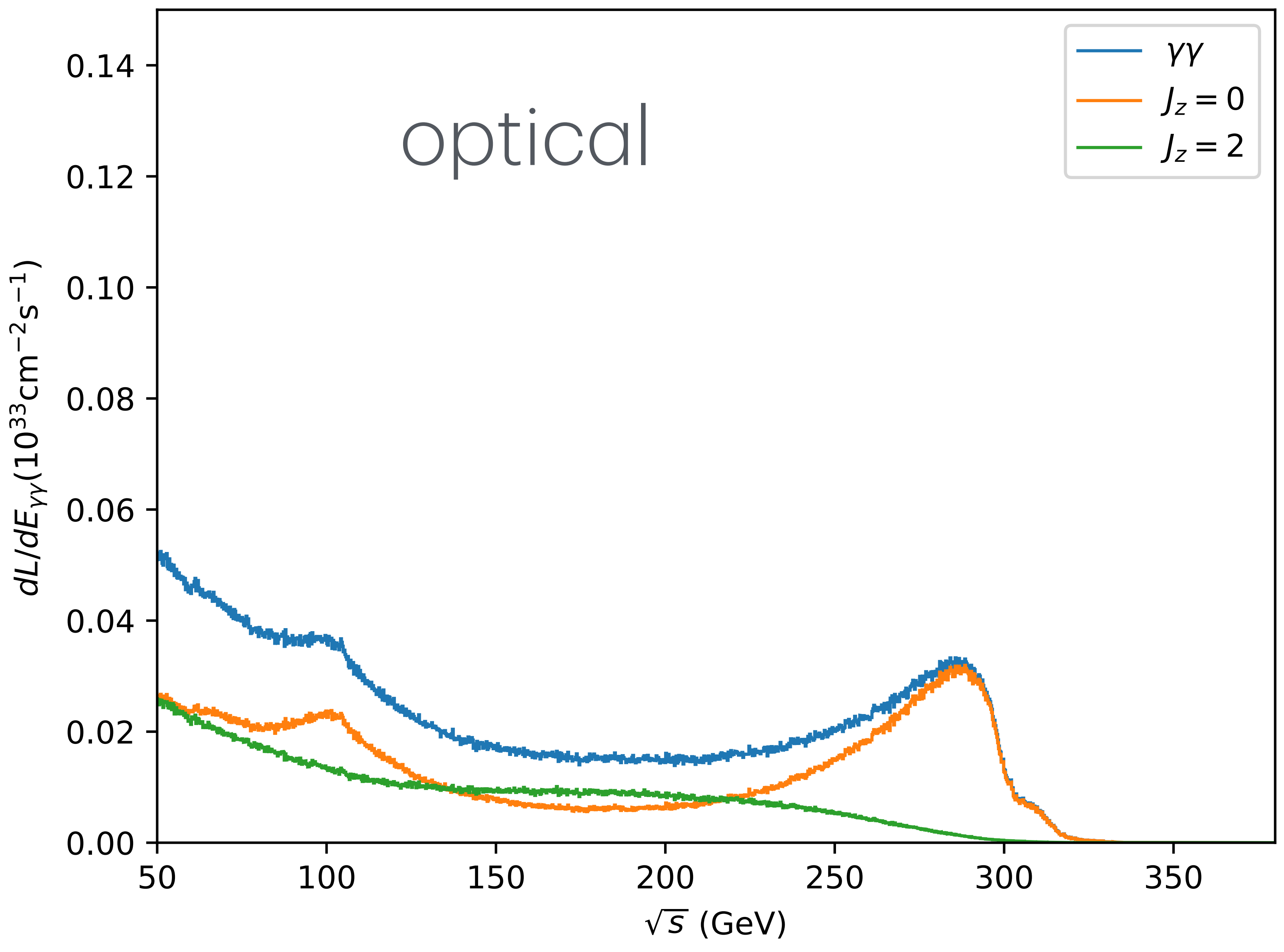
- Maximise the spectrum around 280 GeV for $J_z = 0$
  - Optical: Needs a 380 GeV ee-collider with $\lambda_e P_c < 0$
  - XCC: Needs a 280 GeV ee-collider with $\lambda_e P_c > 0$ to suppress pair-production

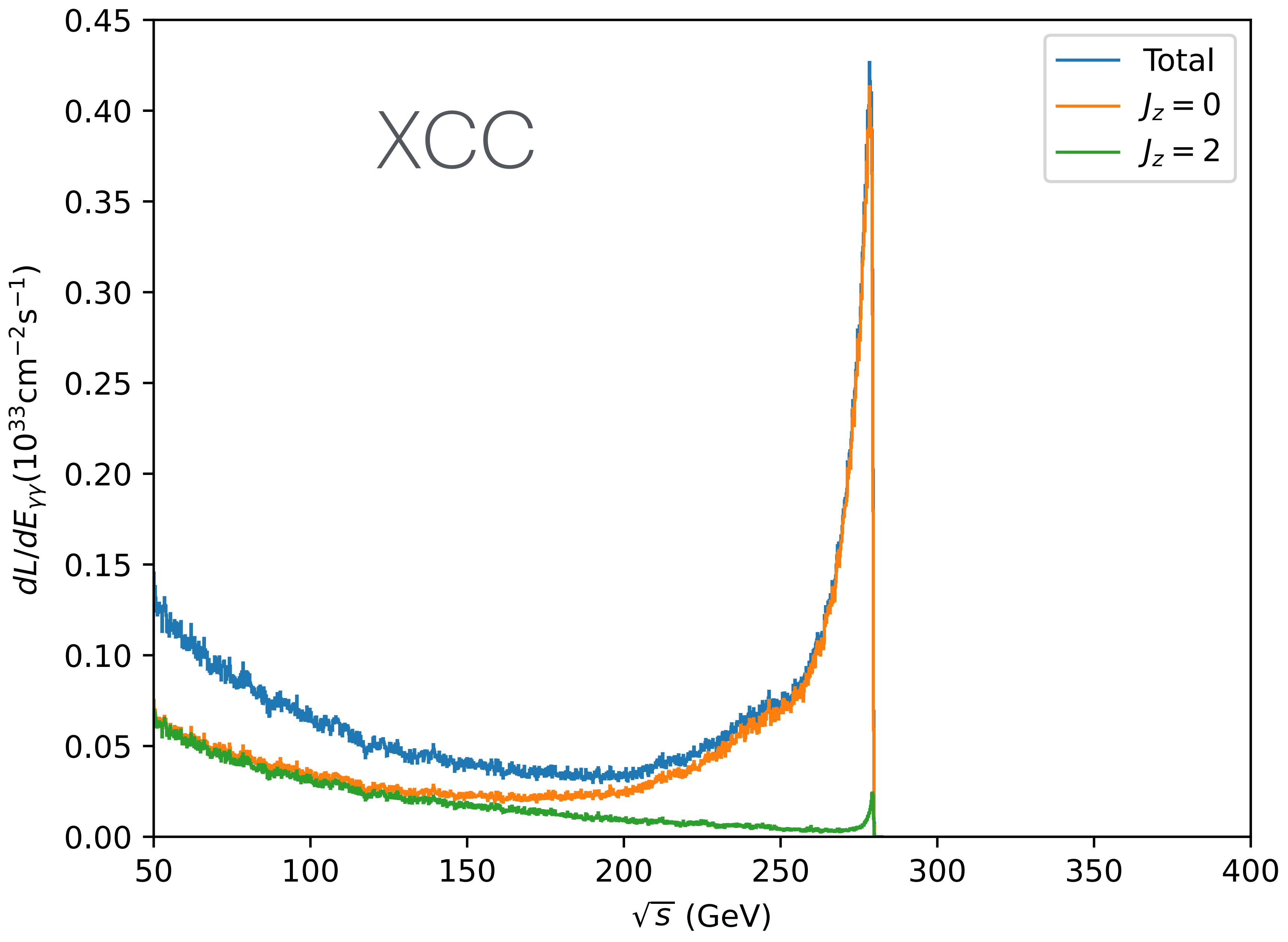
Collider setups

- The polarization of the incoming laser and electron beam defines the spectrum

$$\langle\lambda_\gamma\rangle = \frac{\lambda_e x r[1+(1-y)(2r-1)^2] - P_c(2r-1)[(1-y)^{-1}+1-y]}{(1-y)^{-1}+1-y-4r(1-r)-\lambda_e P_c x r(2-y)(2r-1)}$$

- Maximise the spectrum around 280 GeV for $J_z = 0$

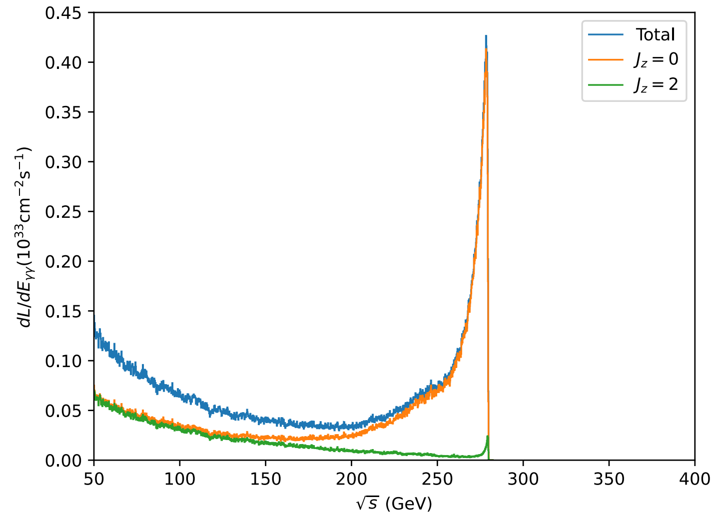




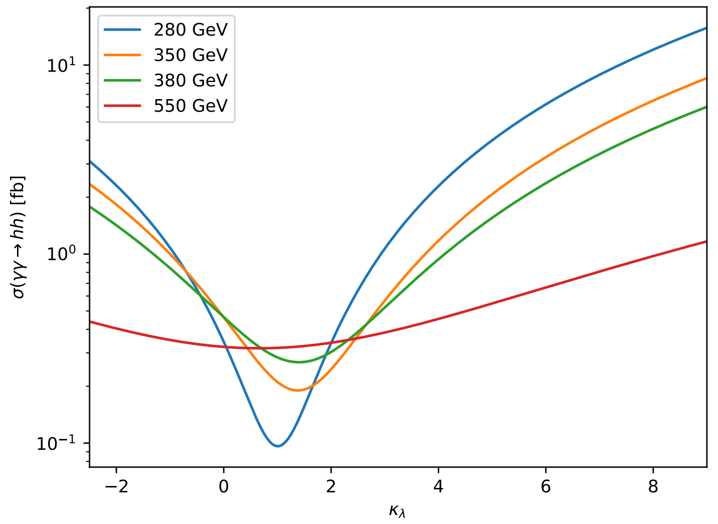
Putting it all together

$$\sigma = \int_{4m_h^2/\hat{s}}^{y_m^2} d\tau \frac{1}{2} \left[\frac{1}{L_{\gamma\gamma}^{++}} \frac{dL_{\gamma\gamma}^{++}}{d\tau} \hat{\sigma}_{++}(\hat{s}) + \frac{1}{L_{\gamma\gamma}^{+-}} \frac{dL_{\gamma\gamma}^{+-}}{d\tau} \hat{\sigma}_{+-}(\hat{s}) \right]$$

- We now have the collider spectra for $\frac{1}{L_{\gamma\gamma}^{++}} \frac{dL_{\gamma\gamma}^{++}}{d\tau}$ and $\frac{1}{L_{\gamma\gamma}^{+-}} \frac{dL_{\gamma\gamma}^{+-}}{d\tau}$



- And the cross-sections $\hat{\sigma}_{++}(\hat{s})$ and $\hat{\sigma}_{+-}(\hat{s})$



- NB: Considering $\boldsymbol{\sigma}$ for the photon colliders not optimal due to the broad spectrum, but events per year gives good comparison

Putting it all together

- Similar structure to the subprocess $\gamma\gamma \rightarrow hh$
- Strongest dependency on κ_λ for the XCC 280 GeV and the Optical 380 GeV
- Optical can run in parallel to ee-collider

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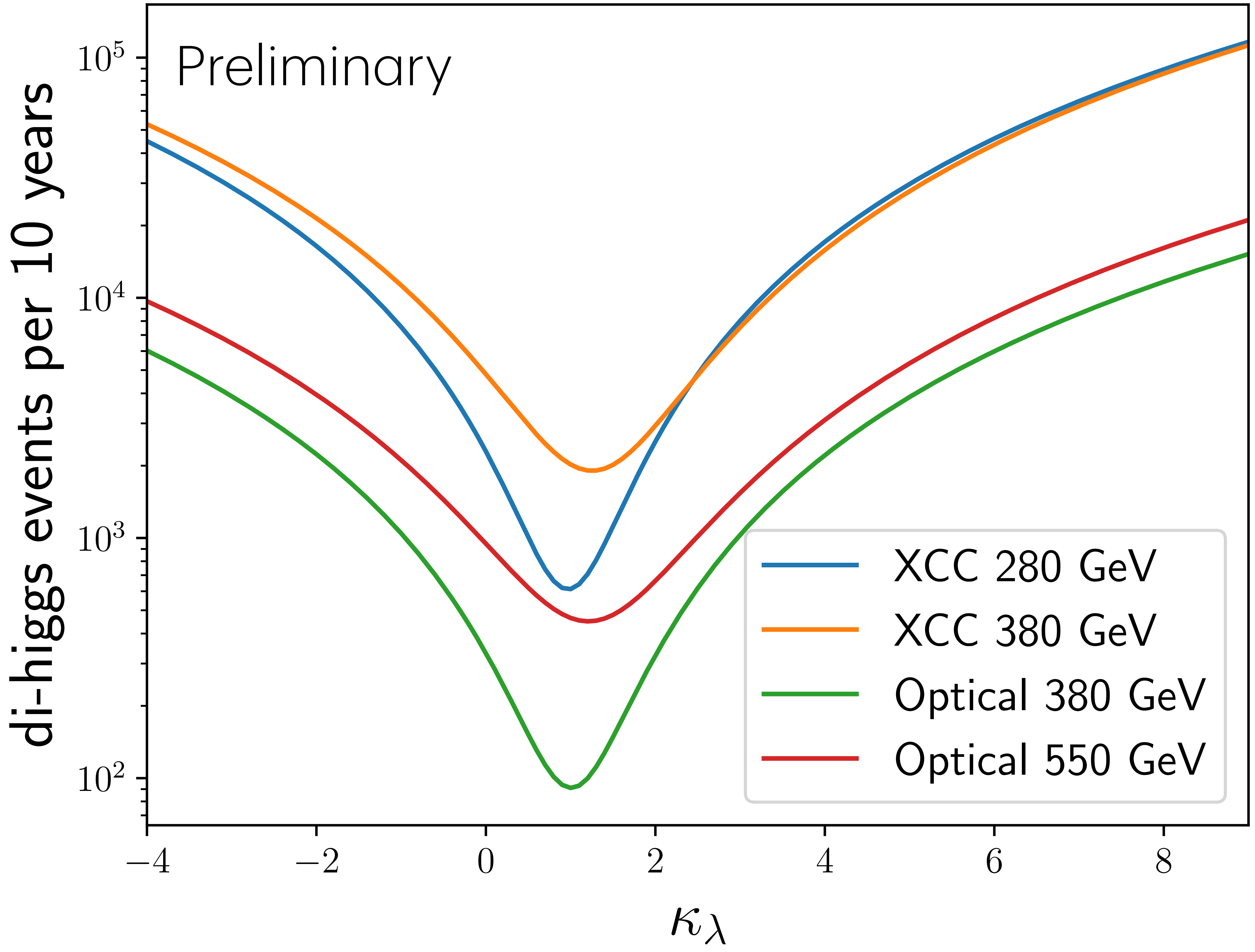
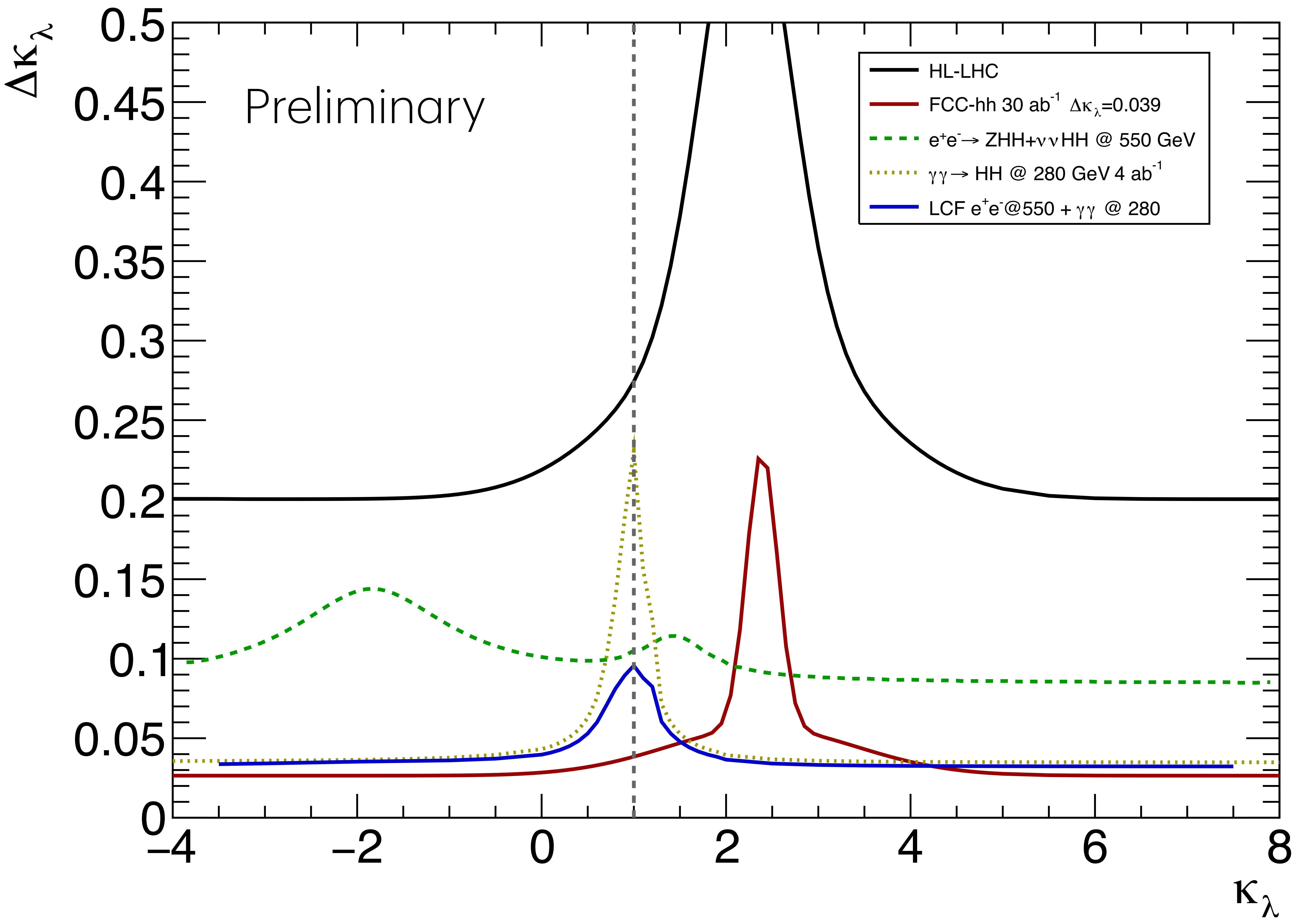


Fixed $\kappa_{2V} = 1$

Sensitivity for κ_λ

T.Barklow, A. Schwartzman WIP

- The XCC 280 GeV reaches 4% at lower energies than comparable colliders
- Lowest sensitivity around $\kappa_\lambda = 1$ for the XCC, perfect to combine with current and future results from other colliders



Summary

- Photon colliders are great additions to any e^+e^--collider, or even stand alone
- Offer rich opportunities to explore the trilinear Higgs coupling at lower energies
- Complementary with pp- and e^+e^--analyses
- Still room to improve and optimize the technology
- Need active groups working on the XCC and optical laser technologies

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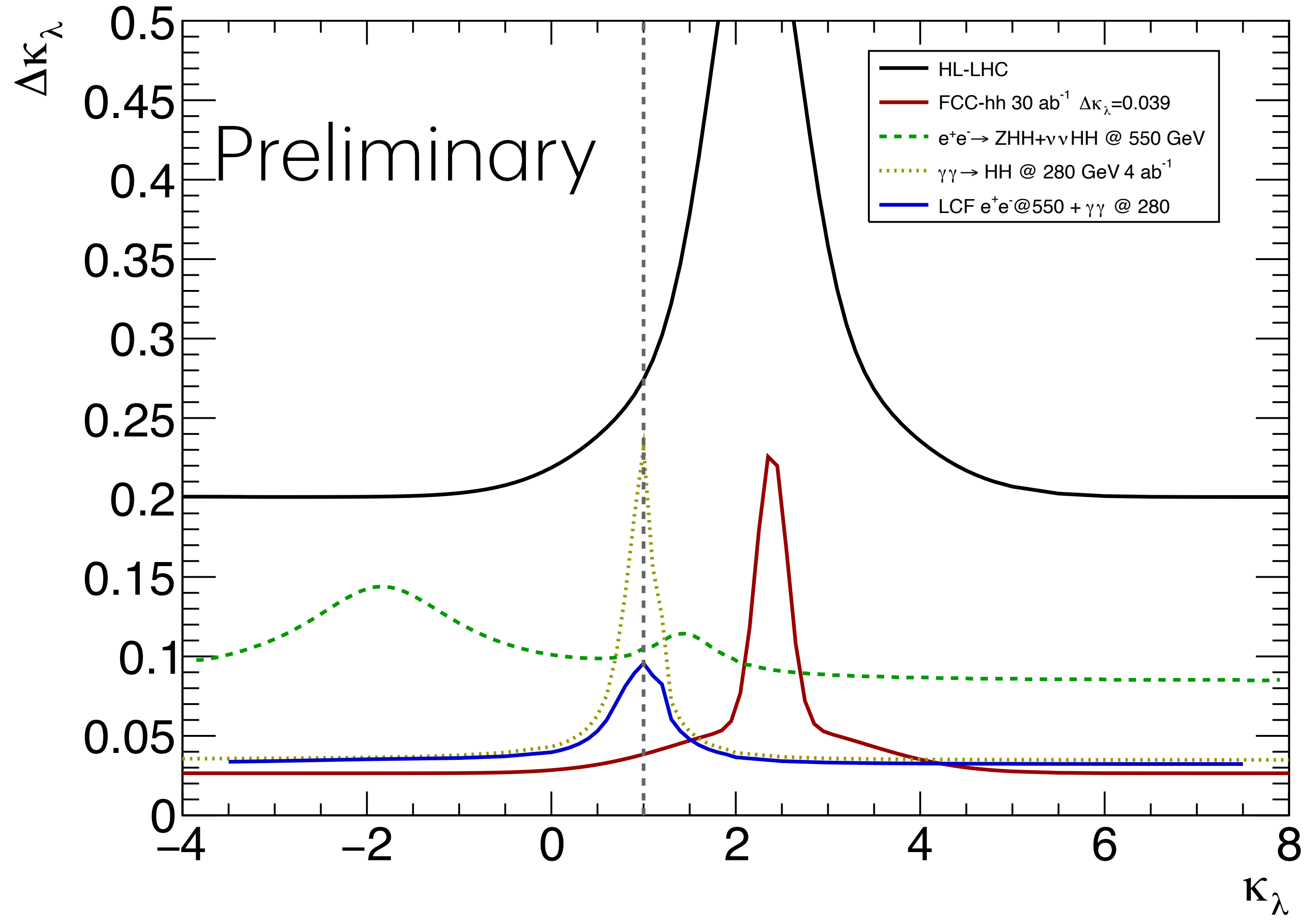

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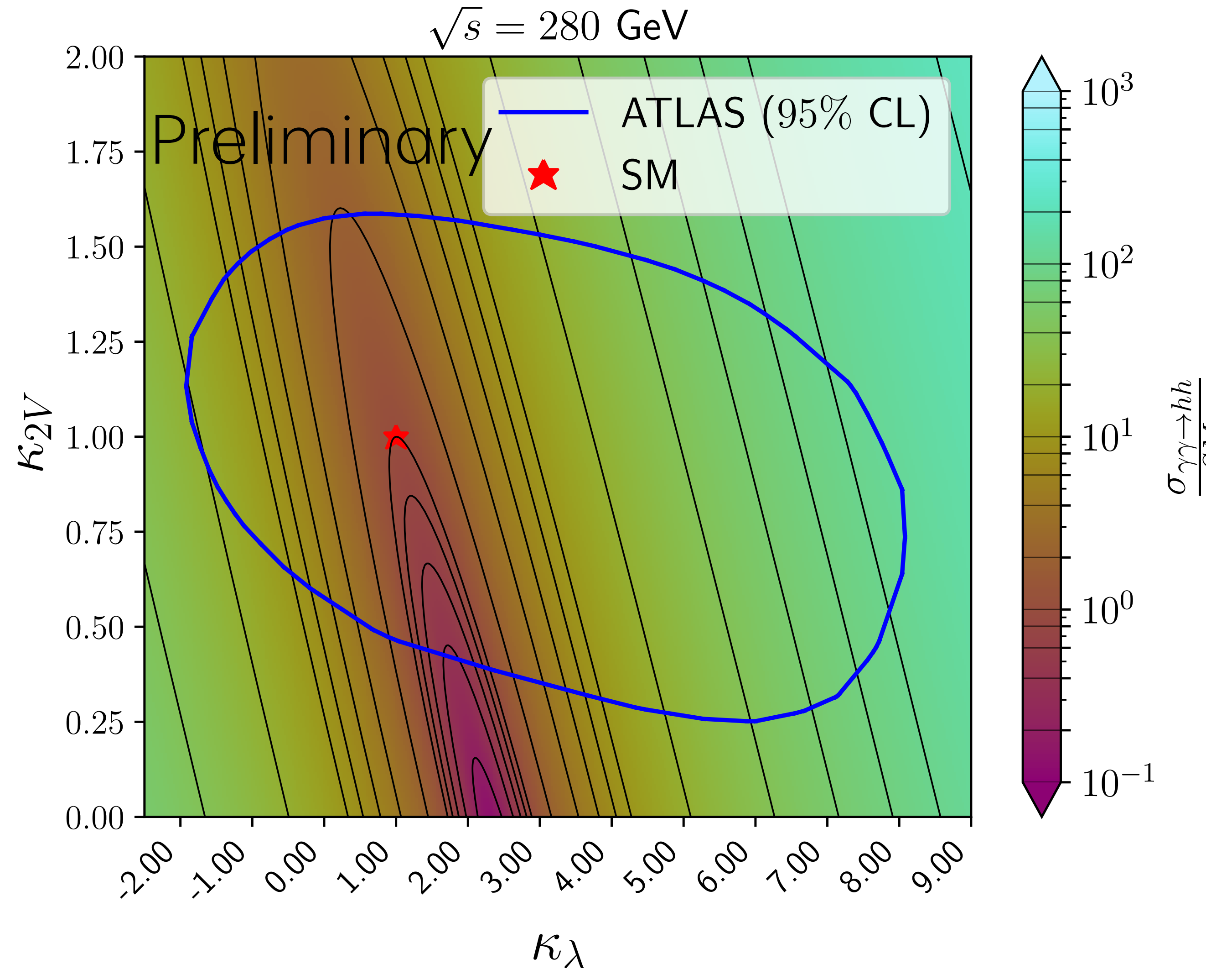
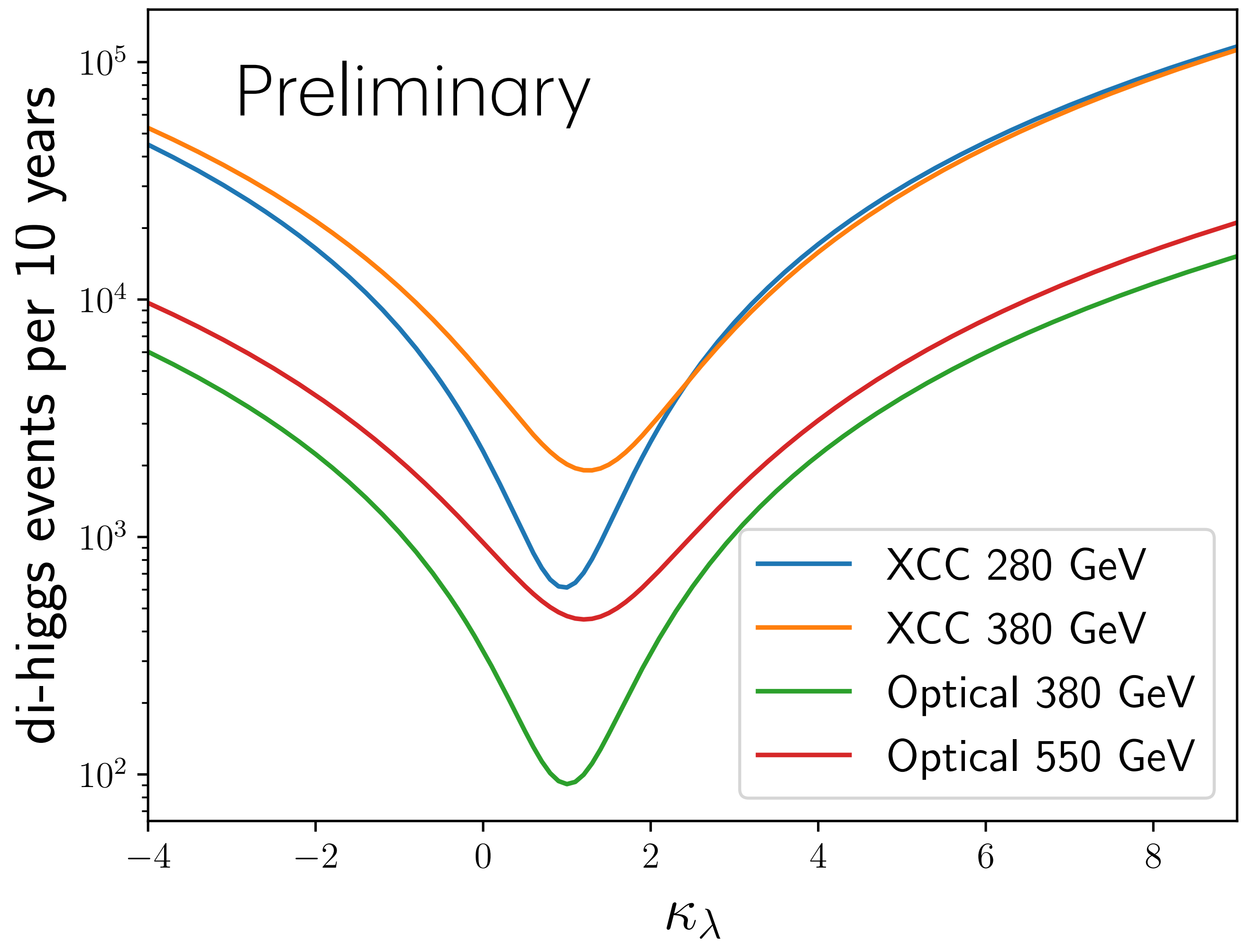
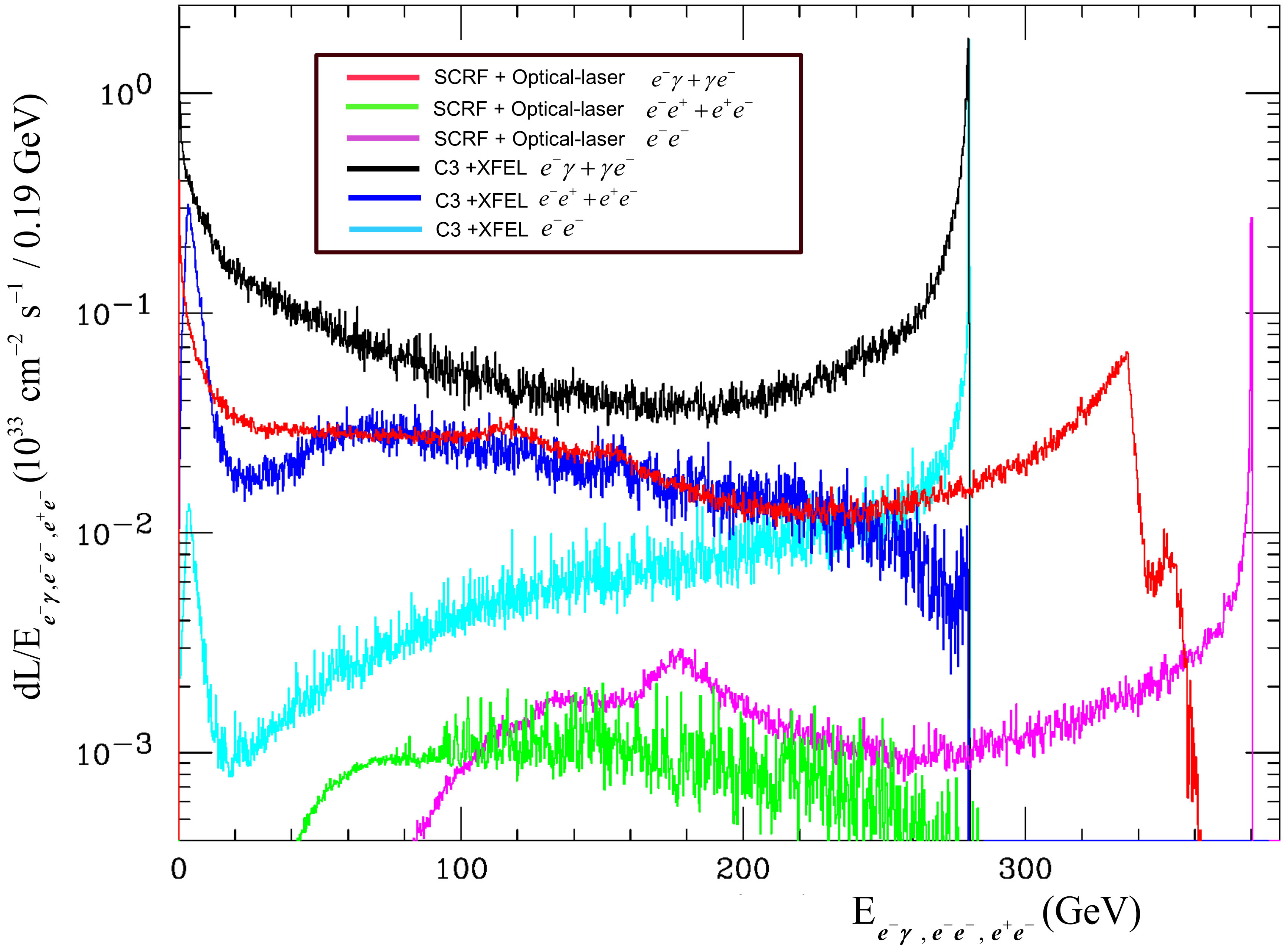




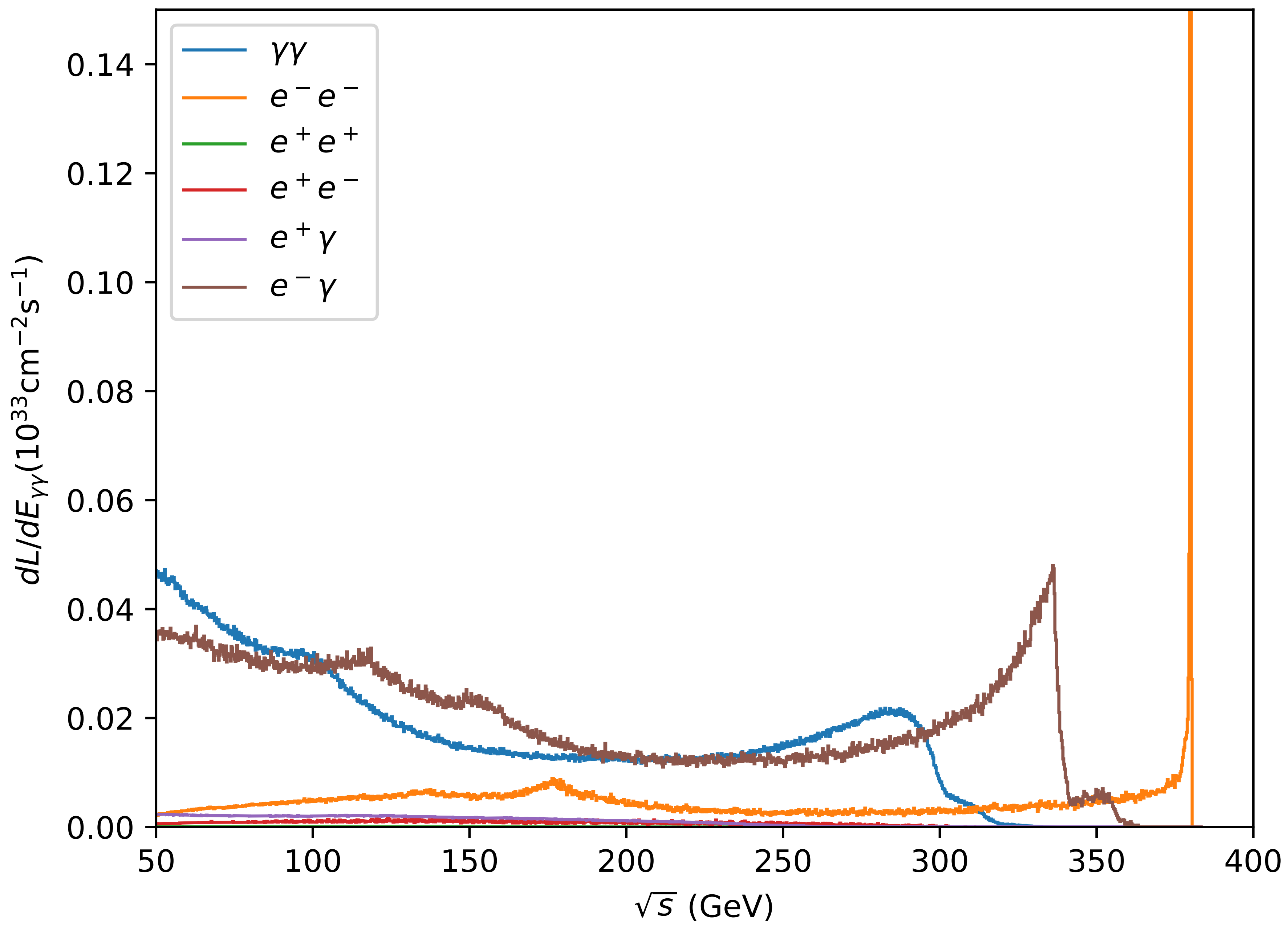
Thank you for listening

Background for the colliders

- Not all e are converted to photons
- Even in e^-e^--mode the XCC still offers large number of e^+e^- collisions
- As well as γe and e^-e^- collisions for both setups

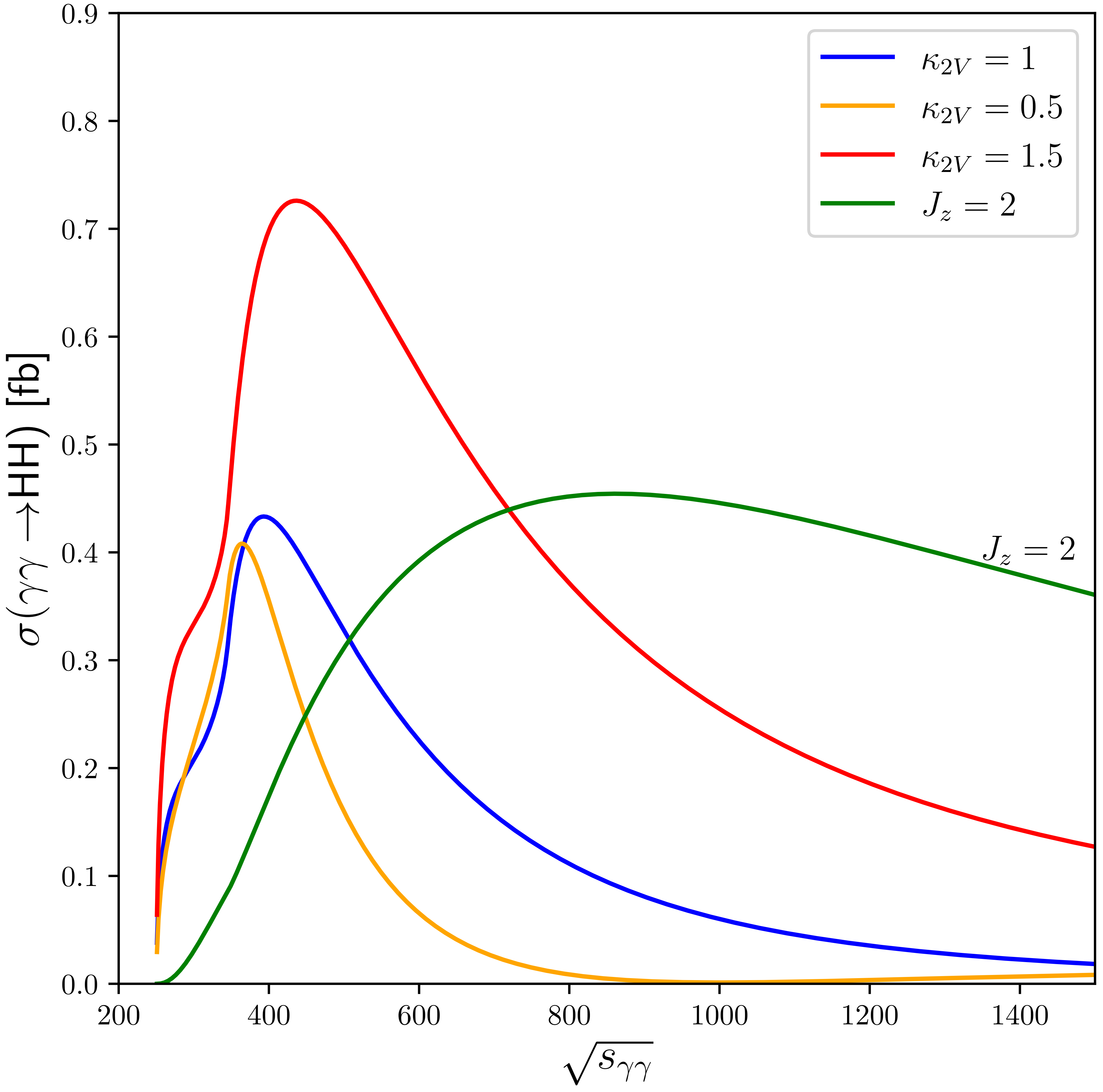


LCvision, C. Balazs, arXiv: 2503.19983



κ_{2V} dependence

- Fixing $\kappa_\lambda = 1$ shows similar behaviour for variations in κ_{2V}
- Effect is still strong at high energies, but overshadowed by the $J_z = 2$ contribution



e^+e^- setup

- Classically, choice of e^-e^--colliders, due to low polarization of e^+
- Possible polarization of 60% for e^+ would allow running in the e^+e^- mode
- So far only looked at for optical, due to strong beam effects for the XCC
- Access to both channels at the same time