Phenomenology of photon colliders: Higgs pair production and coupling measurements

Marten Berger (University of Hamburg)

based on 2603.00264 (M. B., G. Moortgat-Pick) and contributions to 2503.24049 (H. Abramowicz, M.B. et al.)
and work in progress (M. B., J. Braathen, G. Moortgat-Pick, W. Naskar, G. Weiglein)

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9 September 2026

Universität Hamburg
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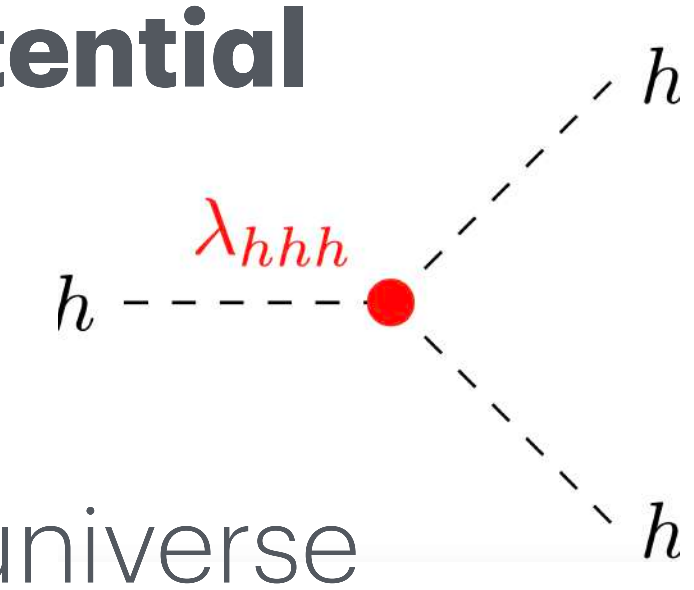
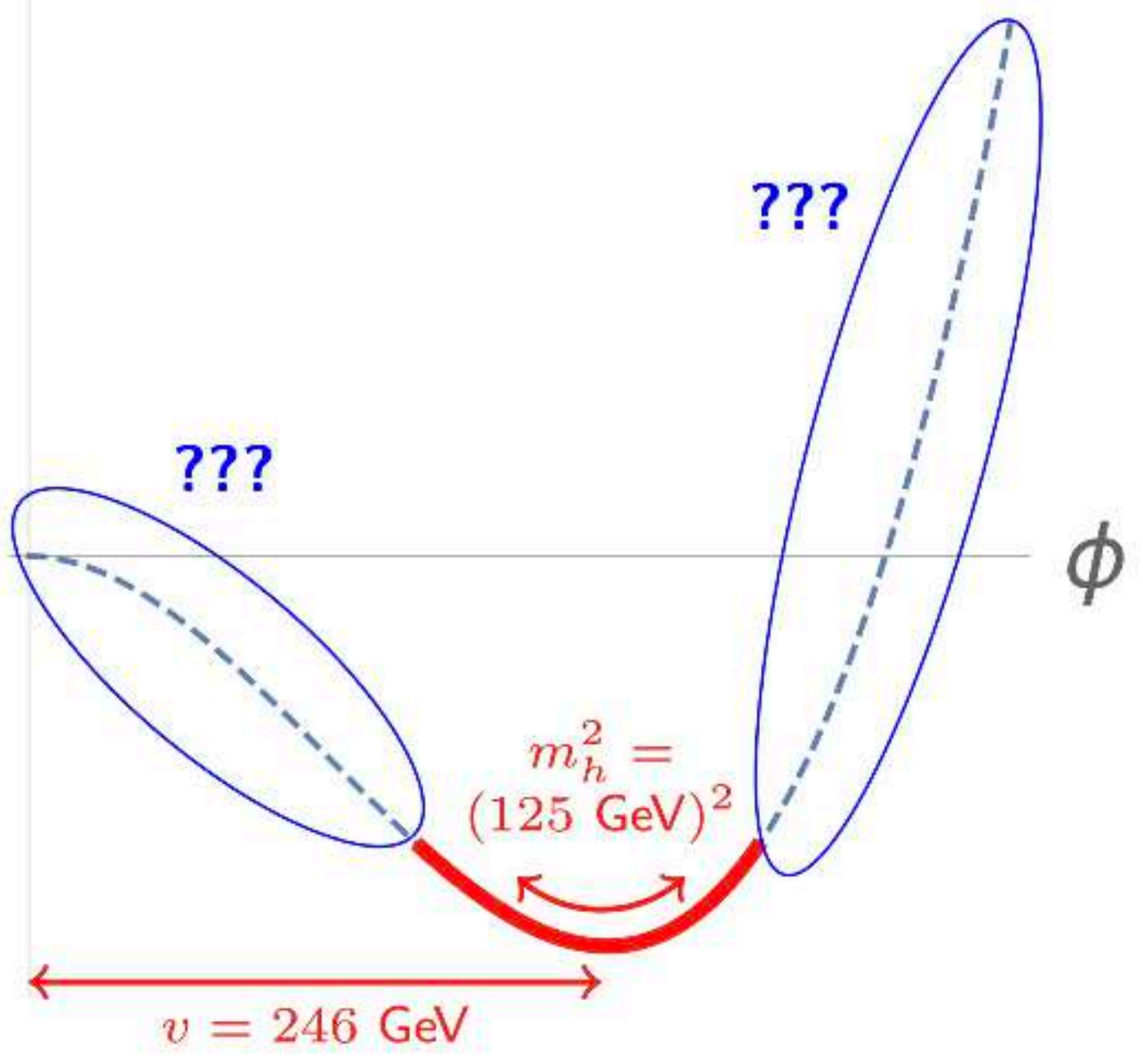
DESY.

Motivation - Higgs pair production

- **4 July 2012** Higgs discovery was announced
  - Is it the SM Higgs boson?
- Very little is known about the **Higgs potential**
- $V = \frac{1}{2}m_h^2 h^2 + v\lambda_{hhh}h^3 + \lambda_{hhhh}h^4 + \ldots$



- Holds strong implications for the early universe
  - Strong first-order electroweak phase transition
  - 3rd Sakharov condition [Sakharov '67]



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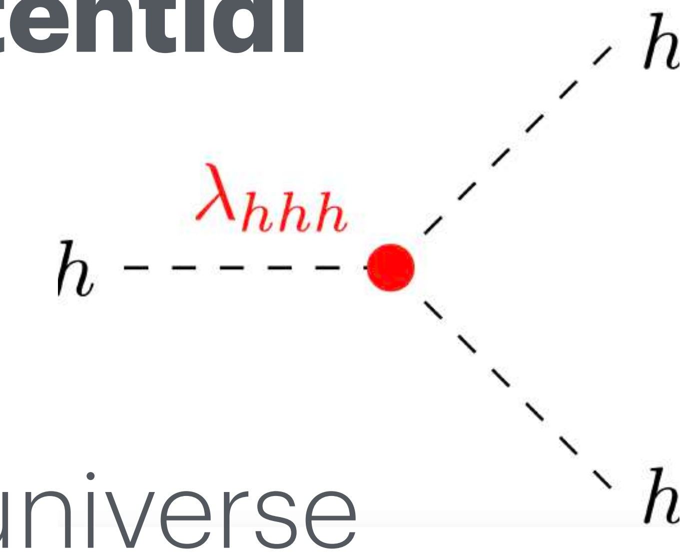
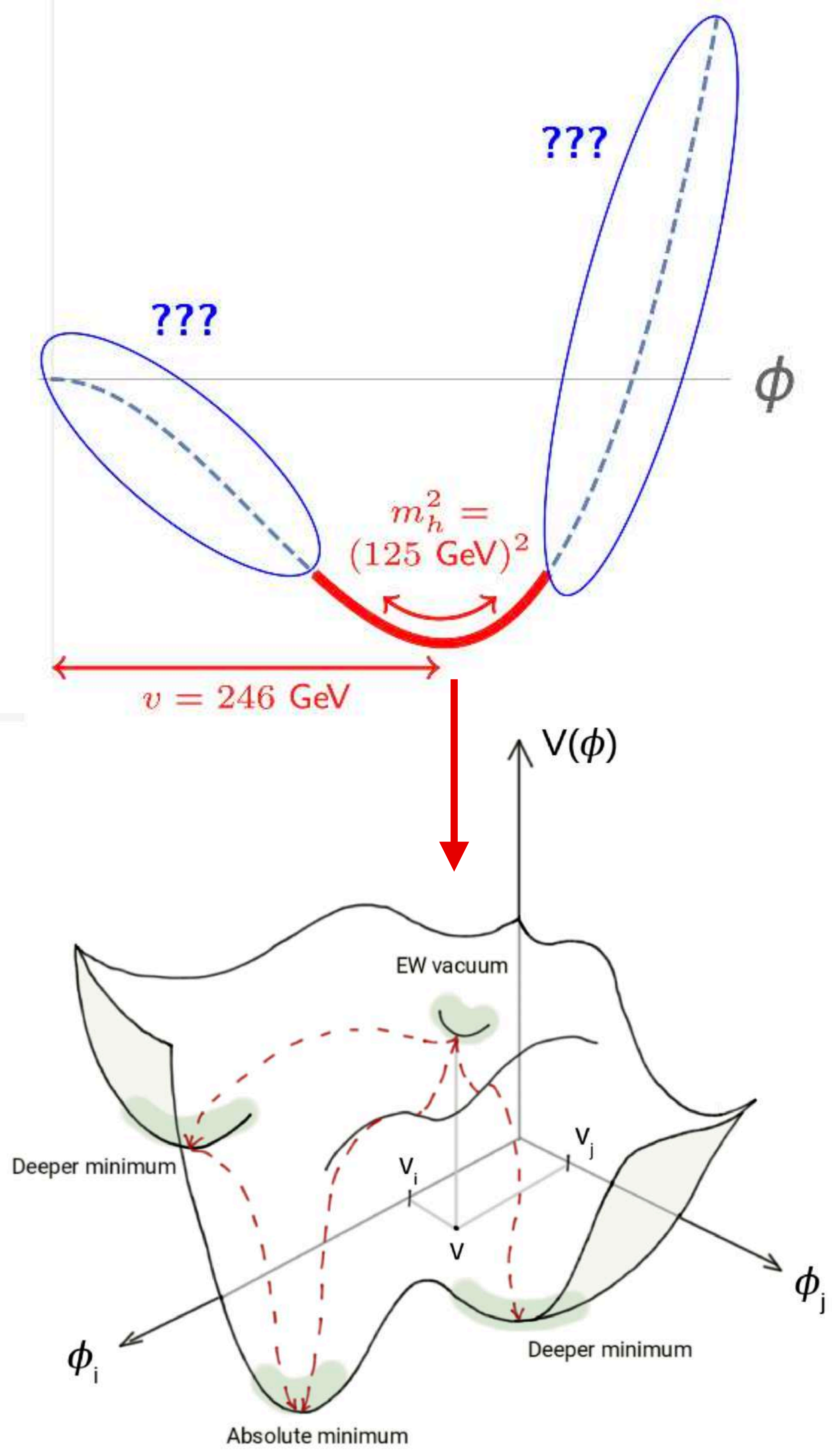


- Holds strong implications for the early universe
  - Strong first-order electroweak phase transition
  - 3rd Sakharov condition [Sakharov '67]
- Beyond-the-Standard-Model theories can offer multiple field directions and minima



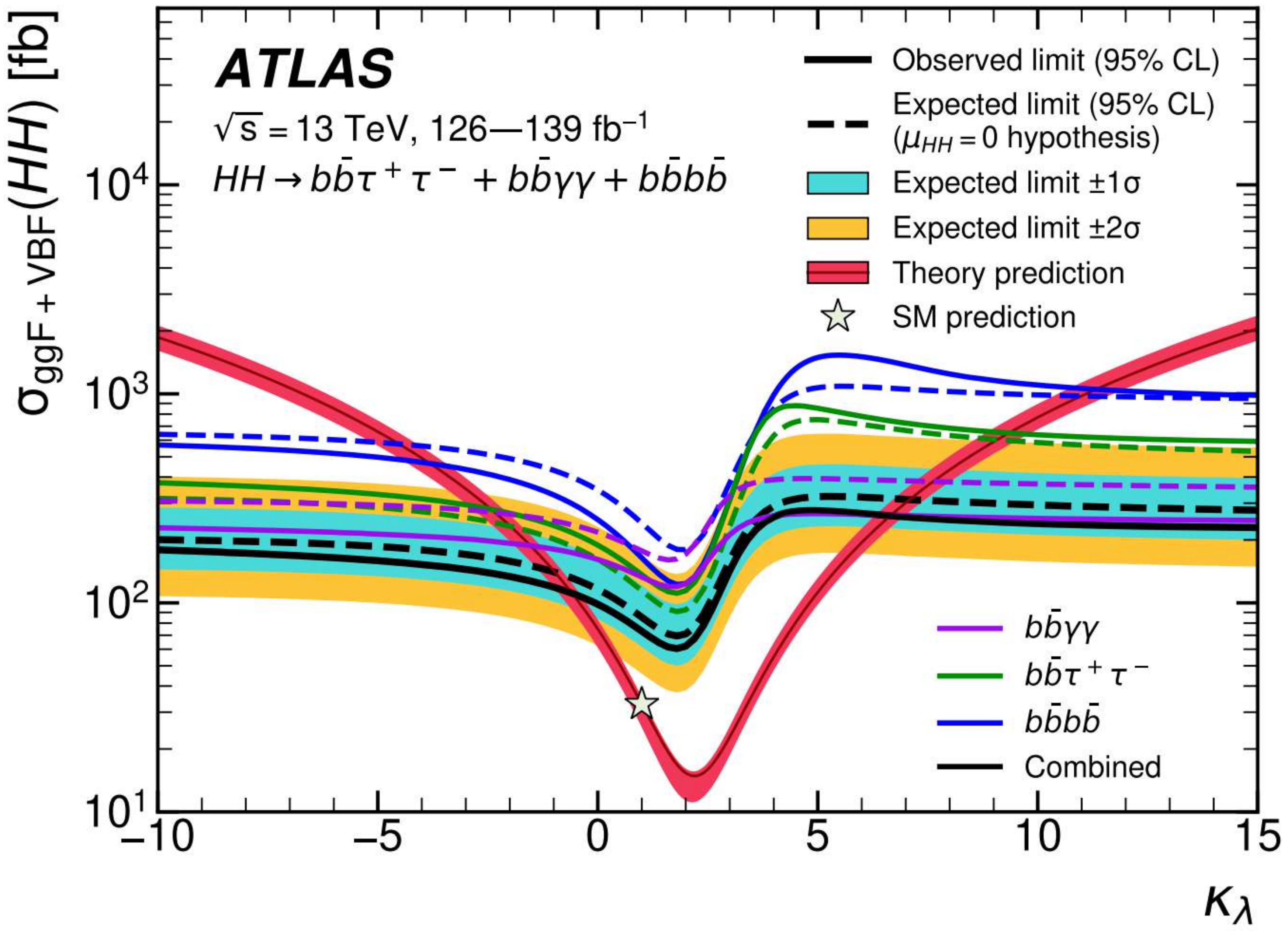
[K. Radchenko Serdula '24]

Motivation - Higgs pair production

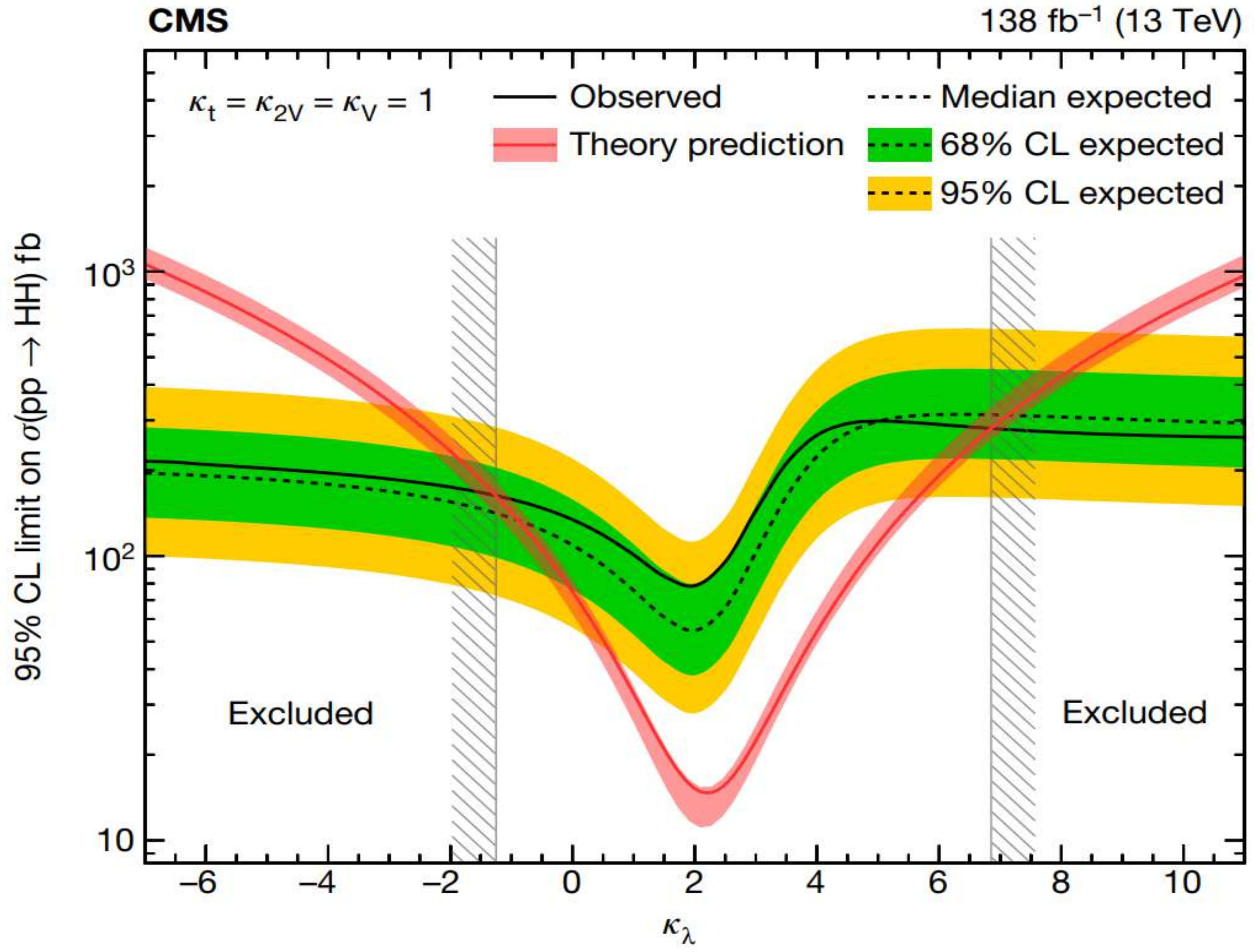
- Higgs pair production at the LHC (gluon fusion, $gg \to hh$)
  - ATLAS $[-1.2 < \kappa_\lambda < 7.2]$ [ATLAS '24] and CMS $[-1.2 < \kappa_\lambda < 7.5]$ [CMS '24]
  - Combined results $[-0.71 < \kappa_\lambda < 6.1]$ [ATLAS and CMS '26]

Notation:
$$\kappa_\lambda = \frac{\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM}(0)}}$$

[ATLAS '22]



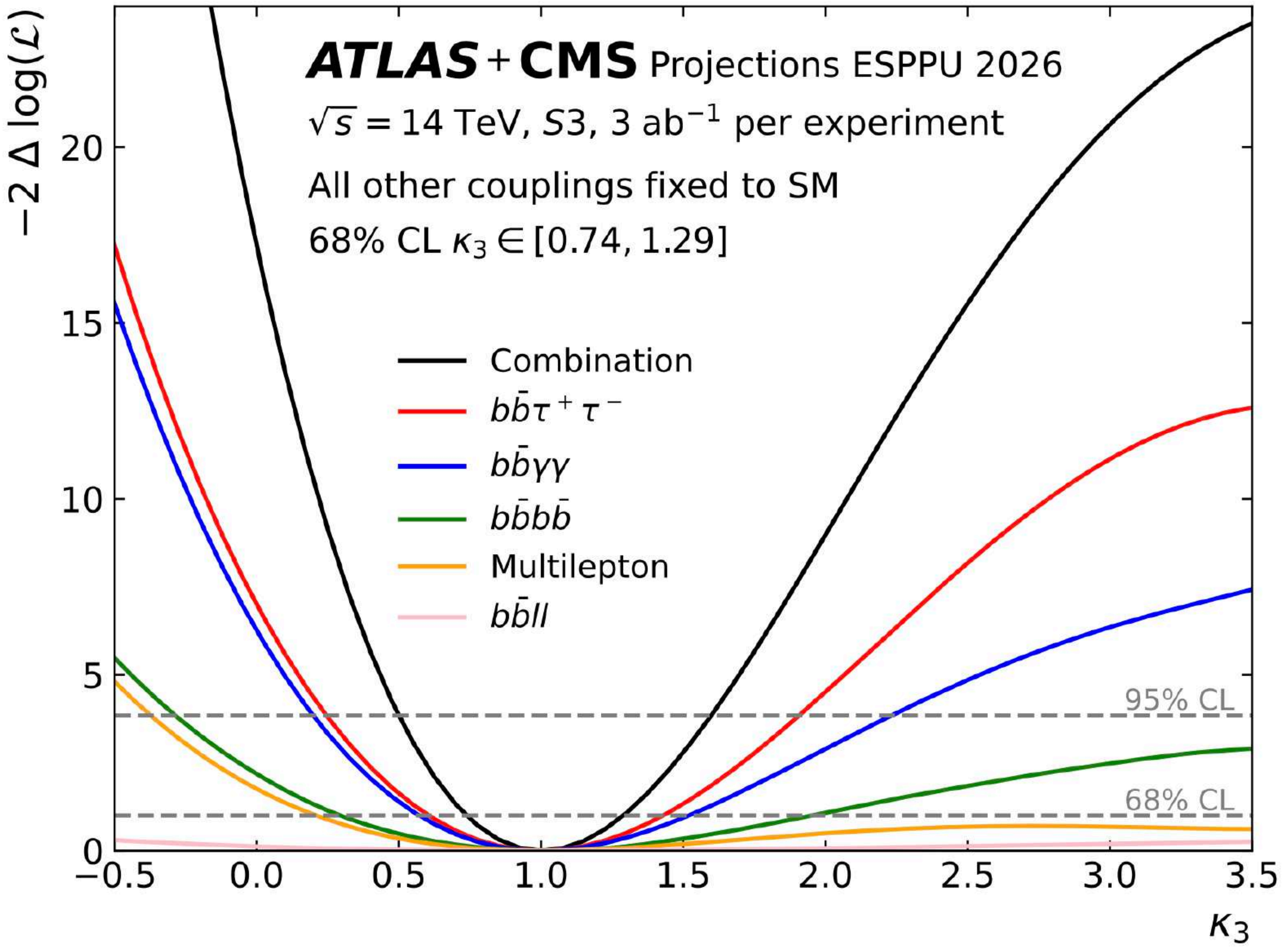
[CMS '22]



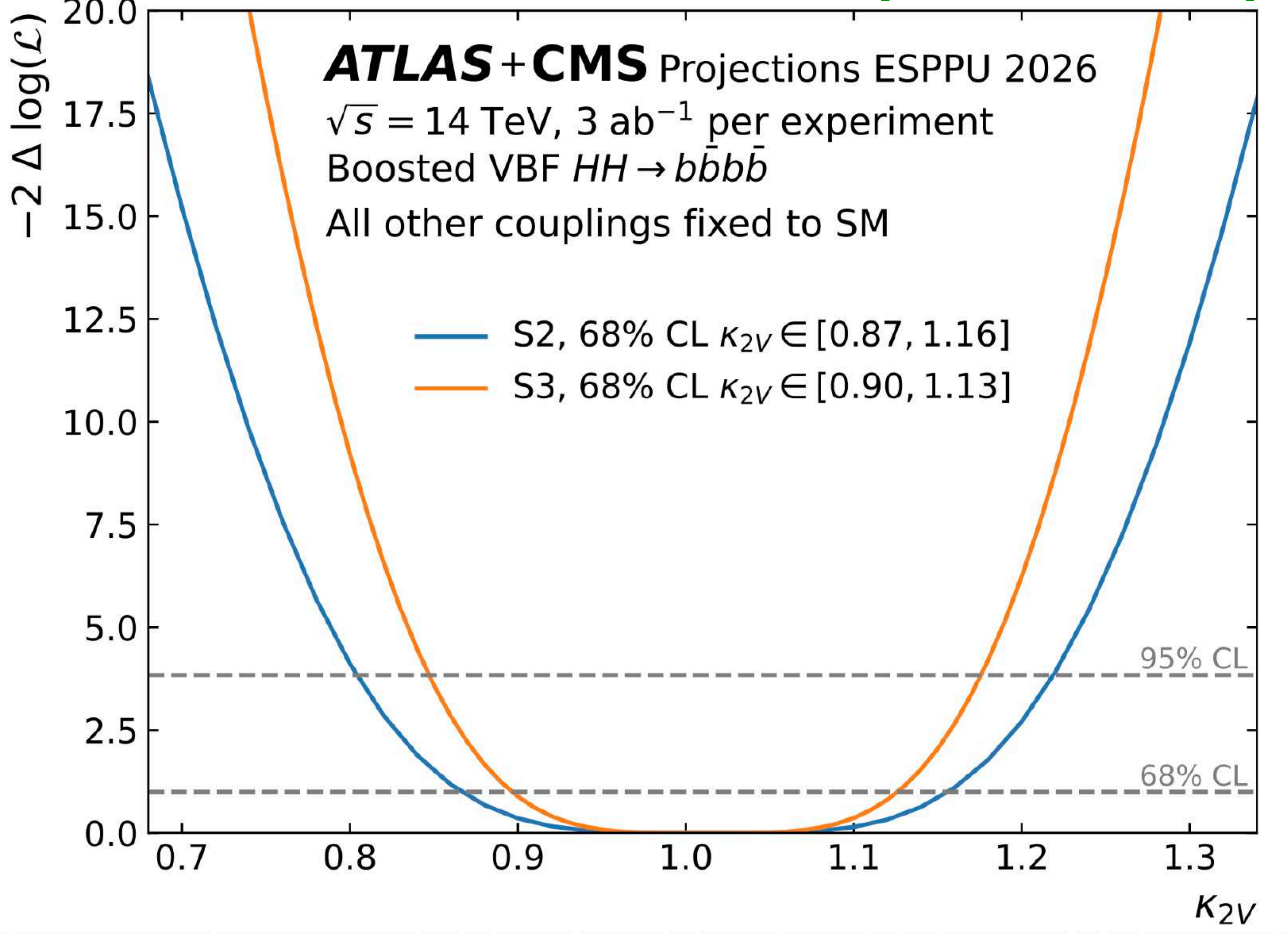
HL-LHC projected limits

- Projected sensitivity on κ_λ (here κ_3) and κ_{2V} assuming the Standard Model
- $\kappa_\lambda \in [0.53, 1.62]$ and $\kappa_{2V} \in [0.85, 1.17]$ at 95% CL

[ATLAS and CMS '25]



[ATLAS and CMS '25]



Motivation - Photon collider

→ HiLumi LARGE HADRON COLLIDER → ?

Motivation - Photon collider

HiLumi
LARGE HADRON COLLIDER

FUTURE CIRCULAR COLLIDER

ilc
Linear Collider Vision

International MUON Collider Collaboration

MuCol

Motivation - Photon collider

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Motivation - Photon collider

Photon collider

- Measuring the trilinear Higgs coupling is one of the goals of all future colliders

$$gg \to hh, \quad e^+e^- \to Zhh, \quad e^+e^- \to \nu_e\bar{\nu}_e hh, \quad \gamma\gamma \to hh$$

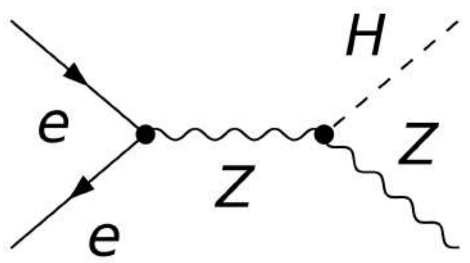
Why photon colliders?

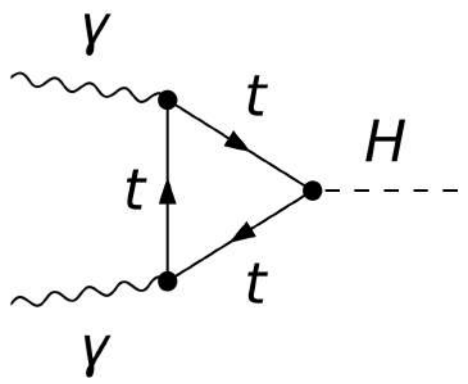
- Photon physics is complementary to other collider searches
  - Different channels for searches
  - High cross-sections at lower centre-of-mass energy
- Especially for Higgs physics
  - $\gamma\gamma \to h$

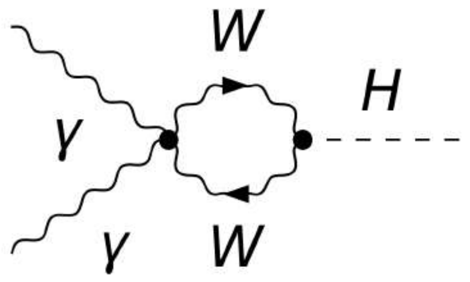
[U.S. Qureshi, T. Barklow, A. Schwartzman '26]

- And SUSY, production of charged particles
  - $e\gamma \to \tilde{e}\tilde{\chi}_1^0$

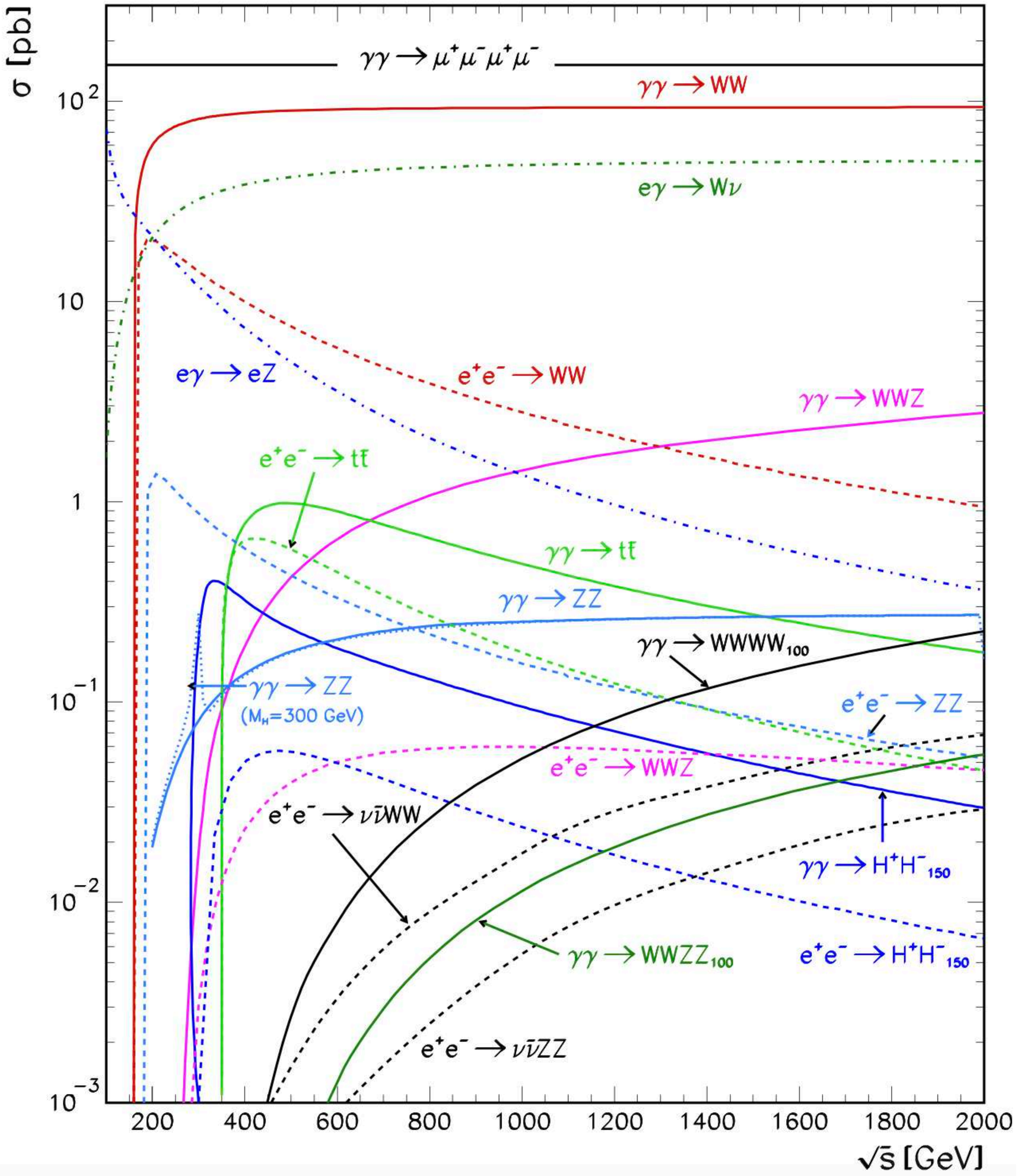
[A. Goto and T. Kon '92][F. Cuypersa, G. J. van Oldenborgha, R. Rückl '92]
[S. Kanemura '01][M. Mühlleitner et al. '06]







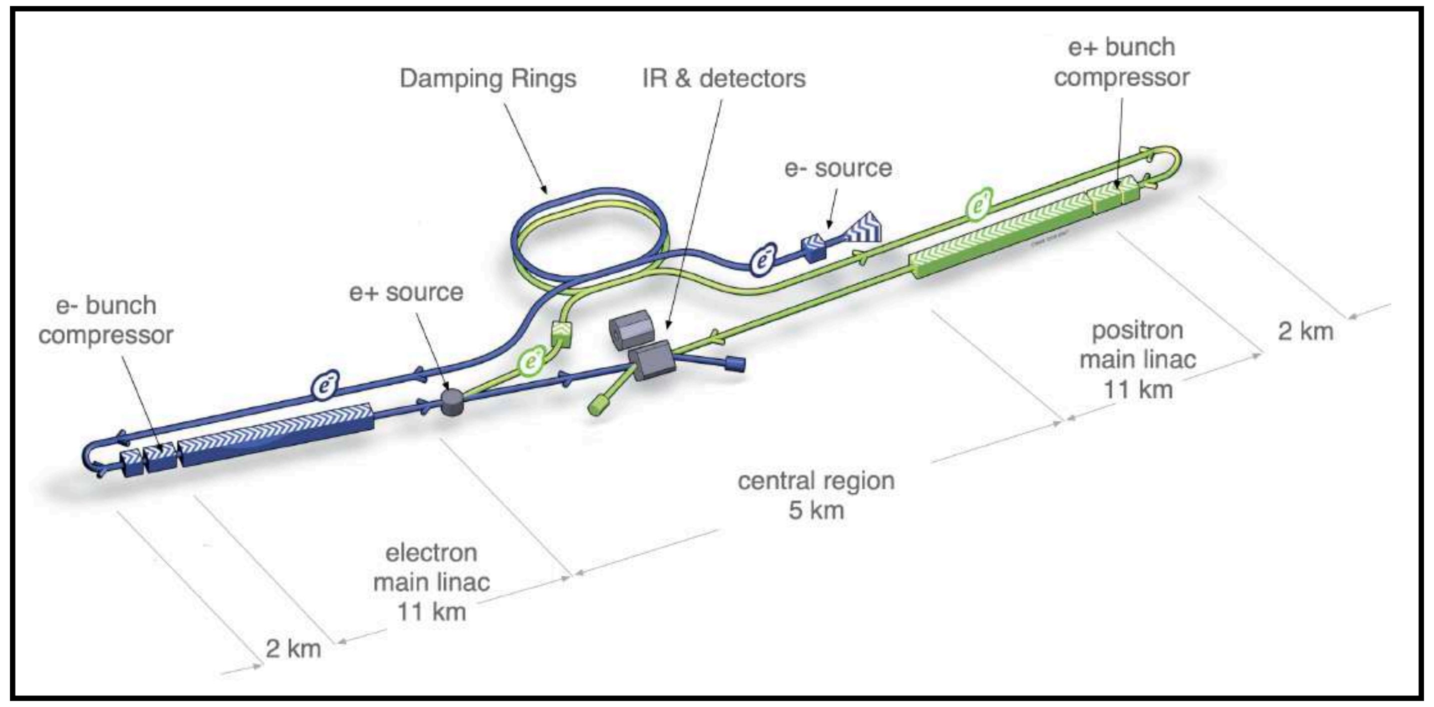
[H. Abramowicz, **MB** et al. '25]
[B. Badelek et al. '04]



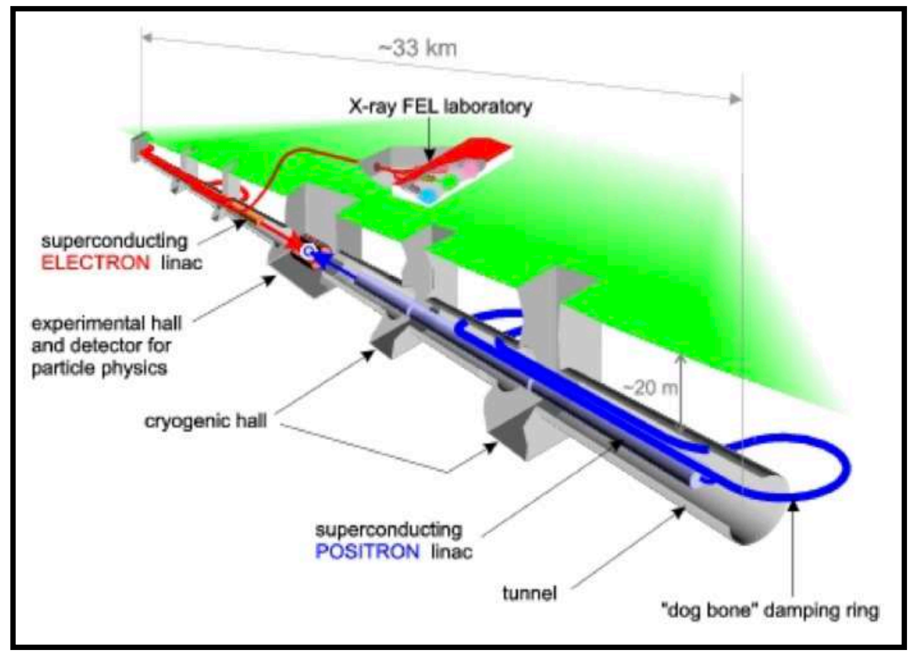
Photon collider designs

- Many future linear collider designs have been considered for photon collider upgrades
- Expanding the physics reach at low center-of-mass energies

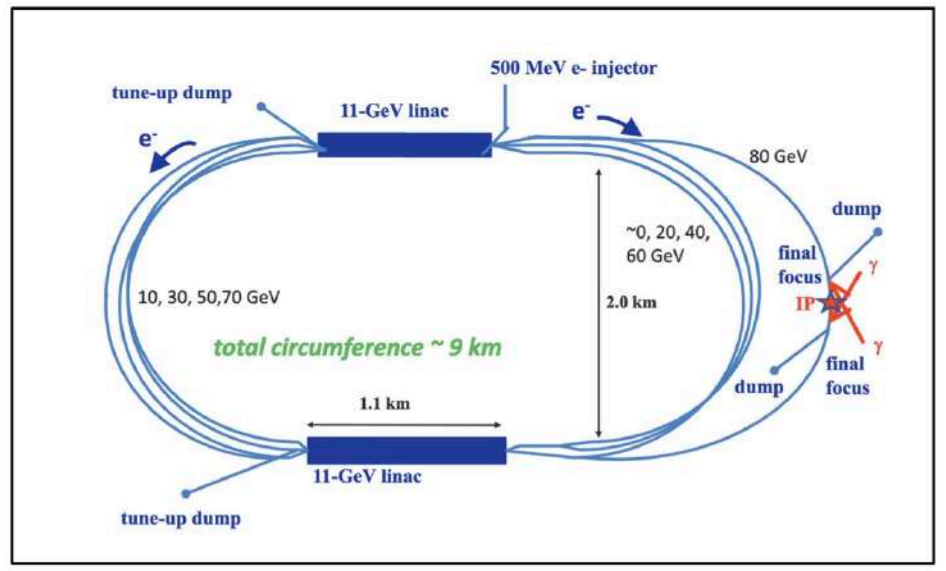
ILC



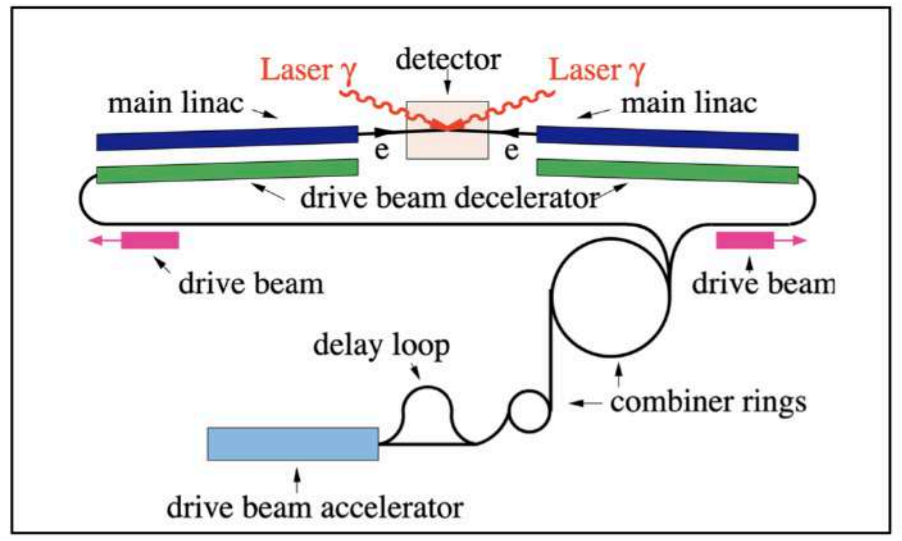
TESLA



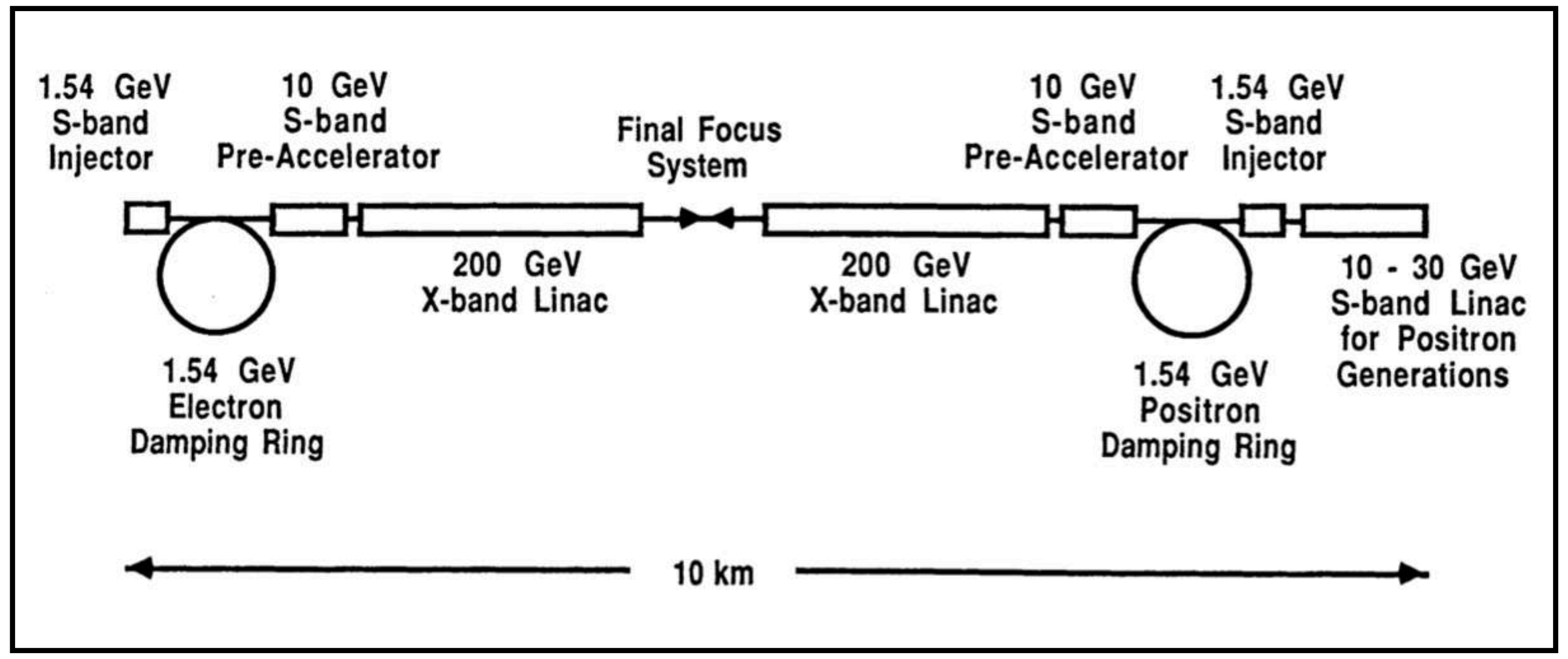
SAPPHiRE



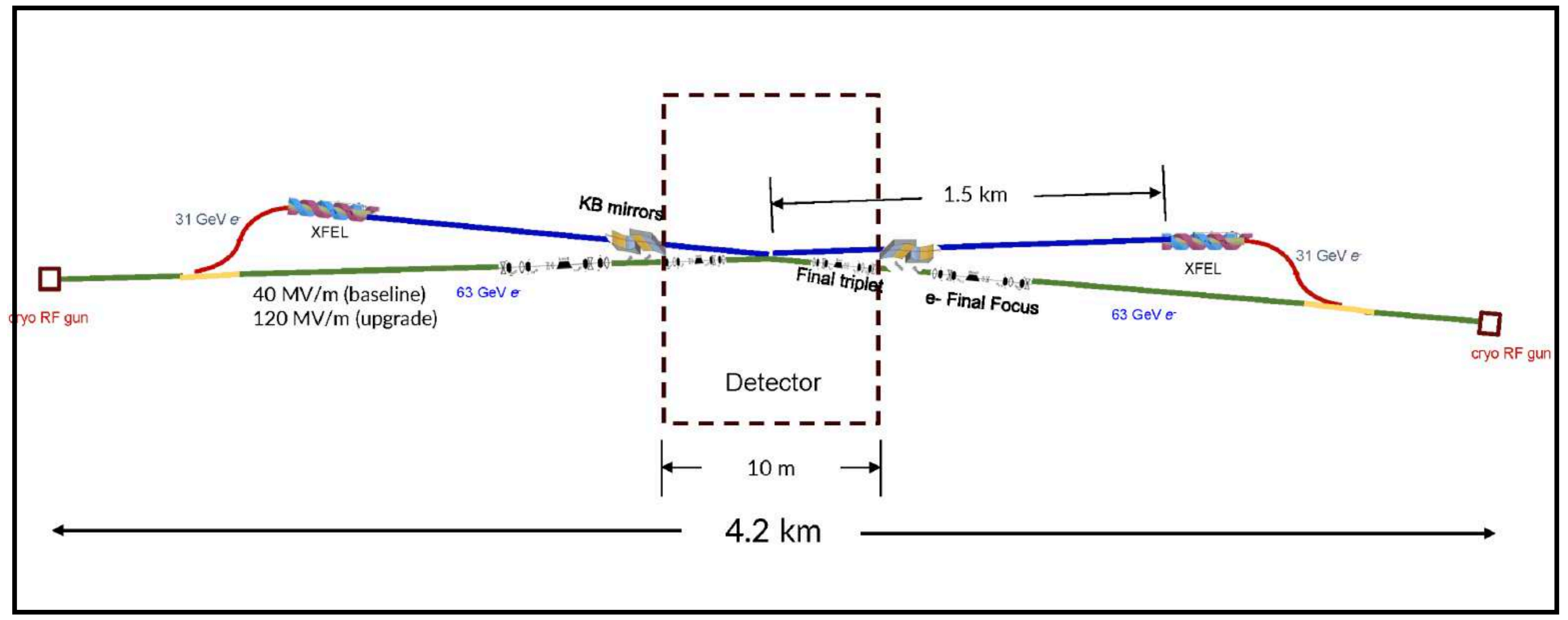
CLICHE



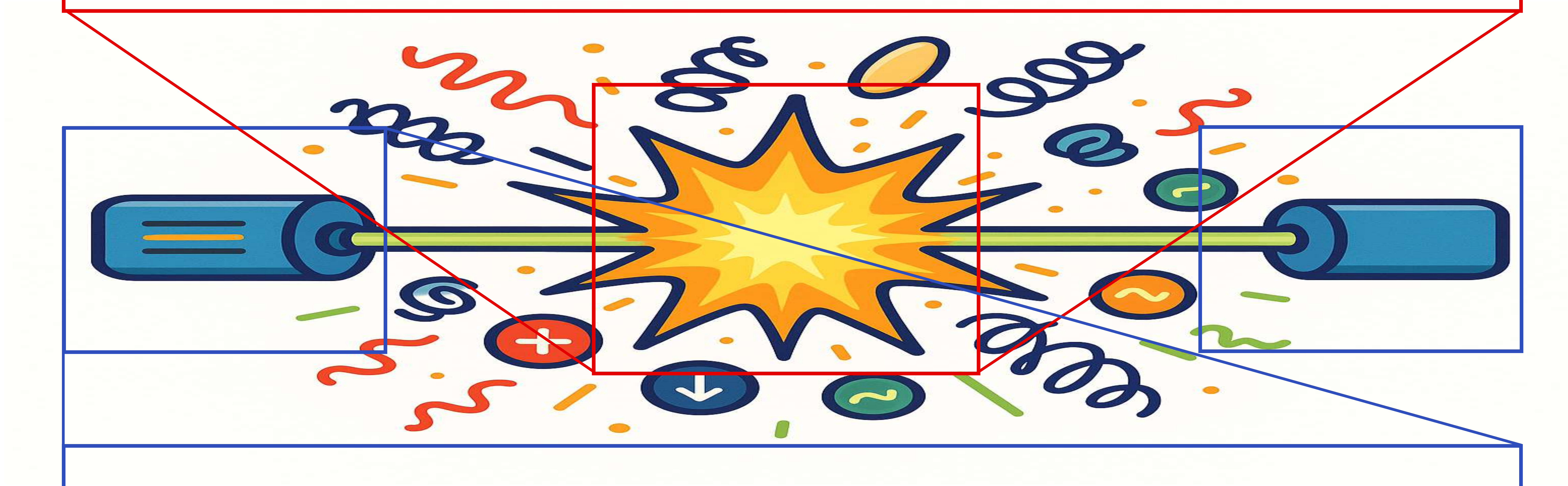
JLC



XCC



Study of $\gamma\gamma$-processes



How do we produce high-energy photons?

Study of $\gamma\gamma$-processes

How do we produce high-energy photons?

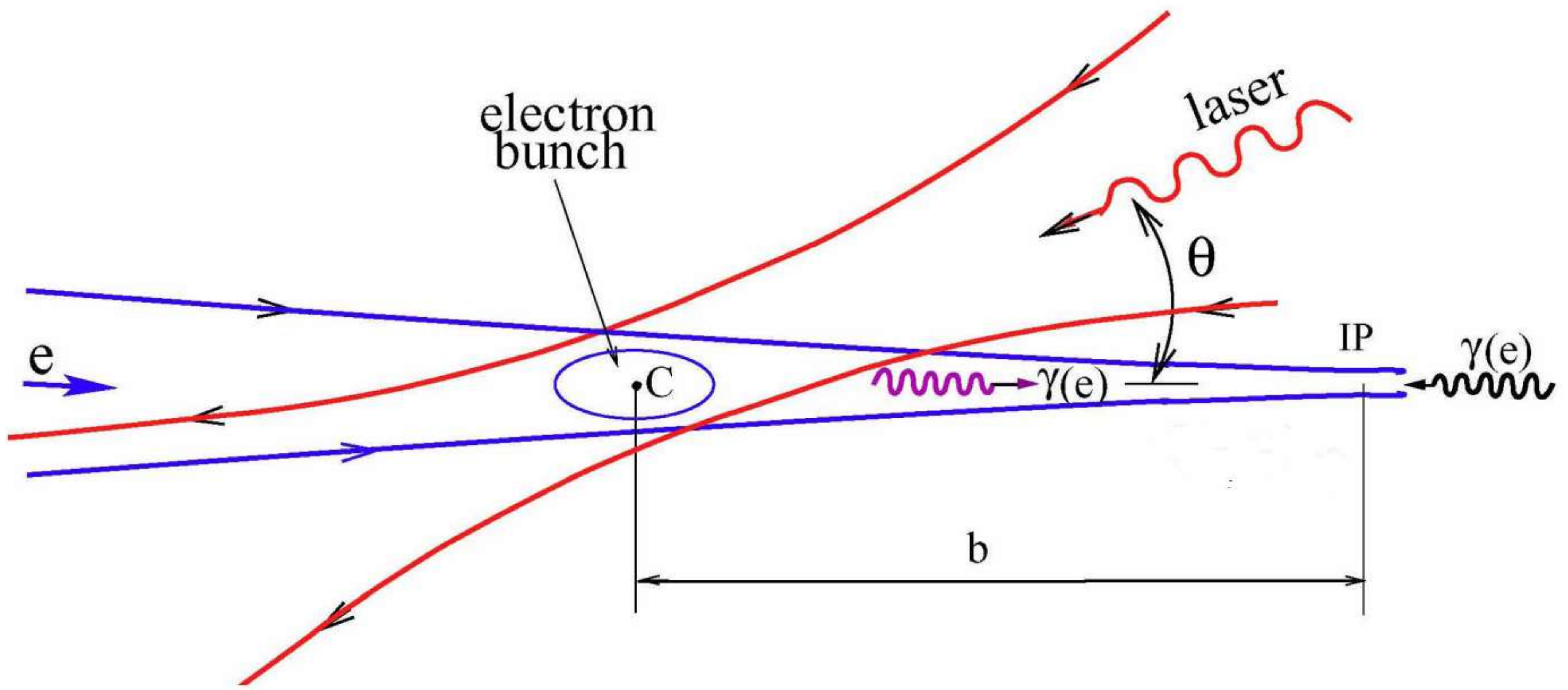
[I. F. Ginzburg, G. L. Kotkin, V. G. Serbo, V. I. Telnov '82]

Principles of a photon collider

- Simple laser collider is too weak (eV to ~MeV)
- Compton scattering at ee-collider
- Getting access to $\gamma\gamma$ and γe processes

$$E_\gamma^{\max} \approx \frac{x}{1+x} E_e, \quad x = \frac{4E_e\omega_0}{m_e^2} \simeq 15.3 \left[\frac{E_e}{\mathrm{TeV}}\right]\left[\frac{\omega_0}{\mathrm{eV}}\right] = 19 \left[\frac{E_e}{\mathrm{TeV}}\right]\left[\frac{\mu\mathrm{m}}{\lambda}\right]$$

[V. I. Telnov '20]

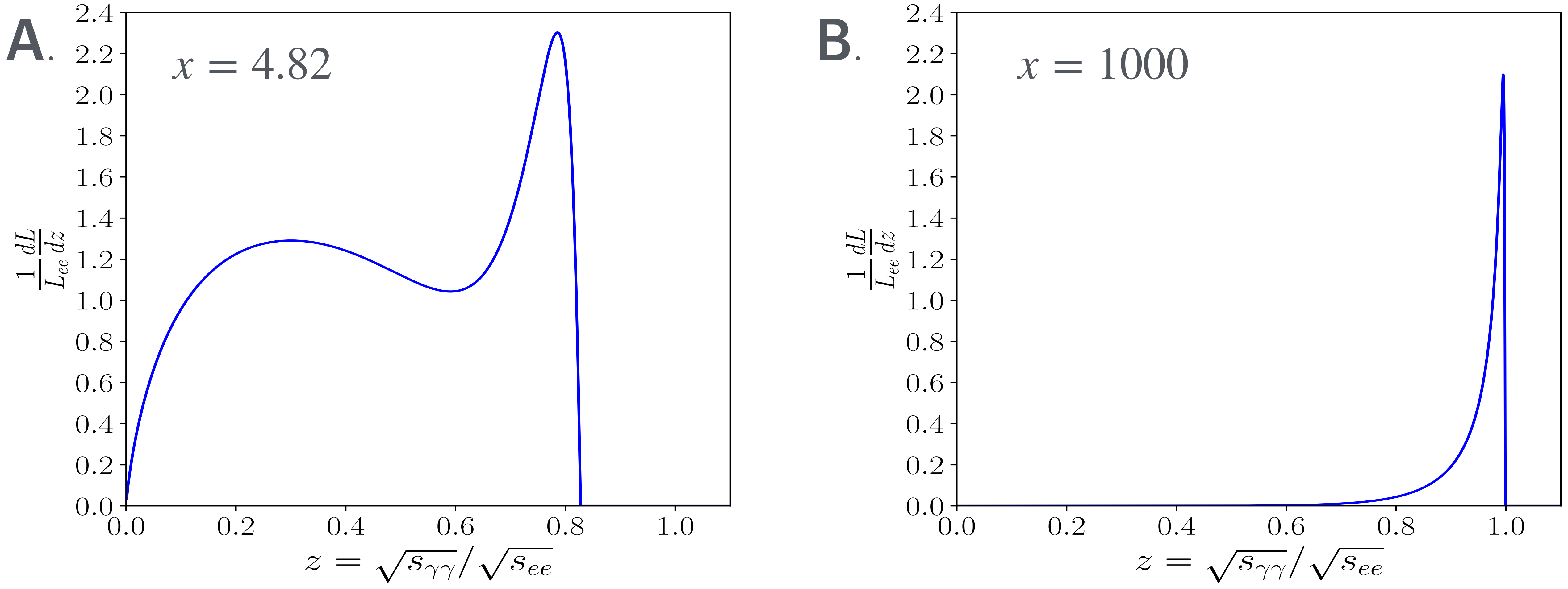


Type of laser is decisive

A. Optical $x \lesssim 4.82$

[T. Barklow et al. '21]

B. XFEL-like (XCC) $x \geq 1000$



[I. F. Ginzburg, G. L. Kotkin, V. G. Serbo, V. I. Telnov '84]

Polarisation effects

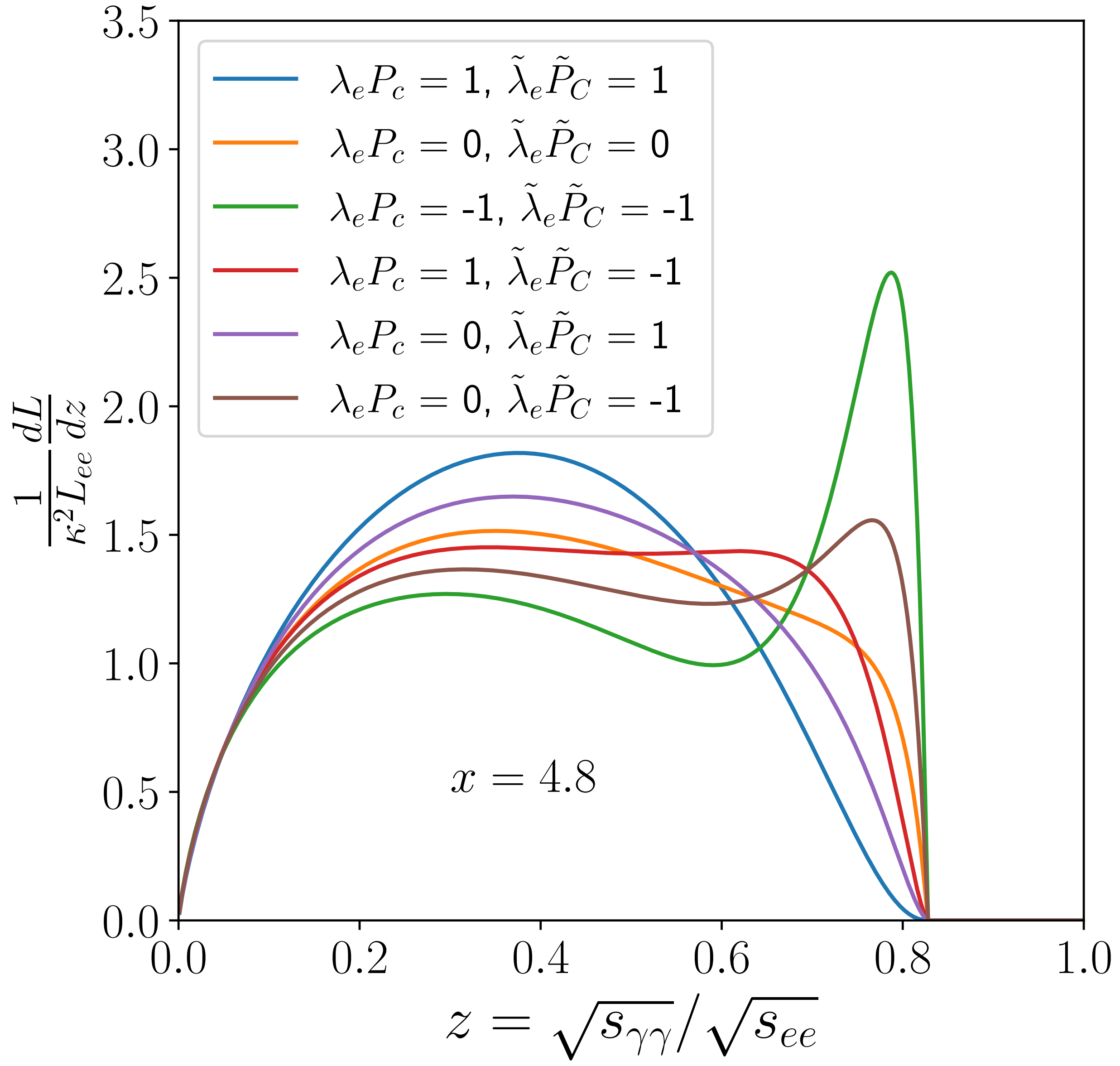
- The total luminosity depends on the product of the electron polarisation λ_e and laser photon polarisation P_c: $\frac{1}{k^2 L_{ee}} \frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}z} = F(x, y, \lambda_e P_c, \rho)$

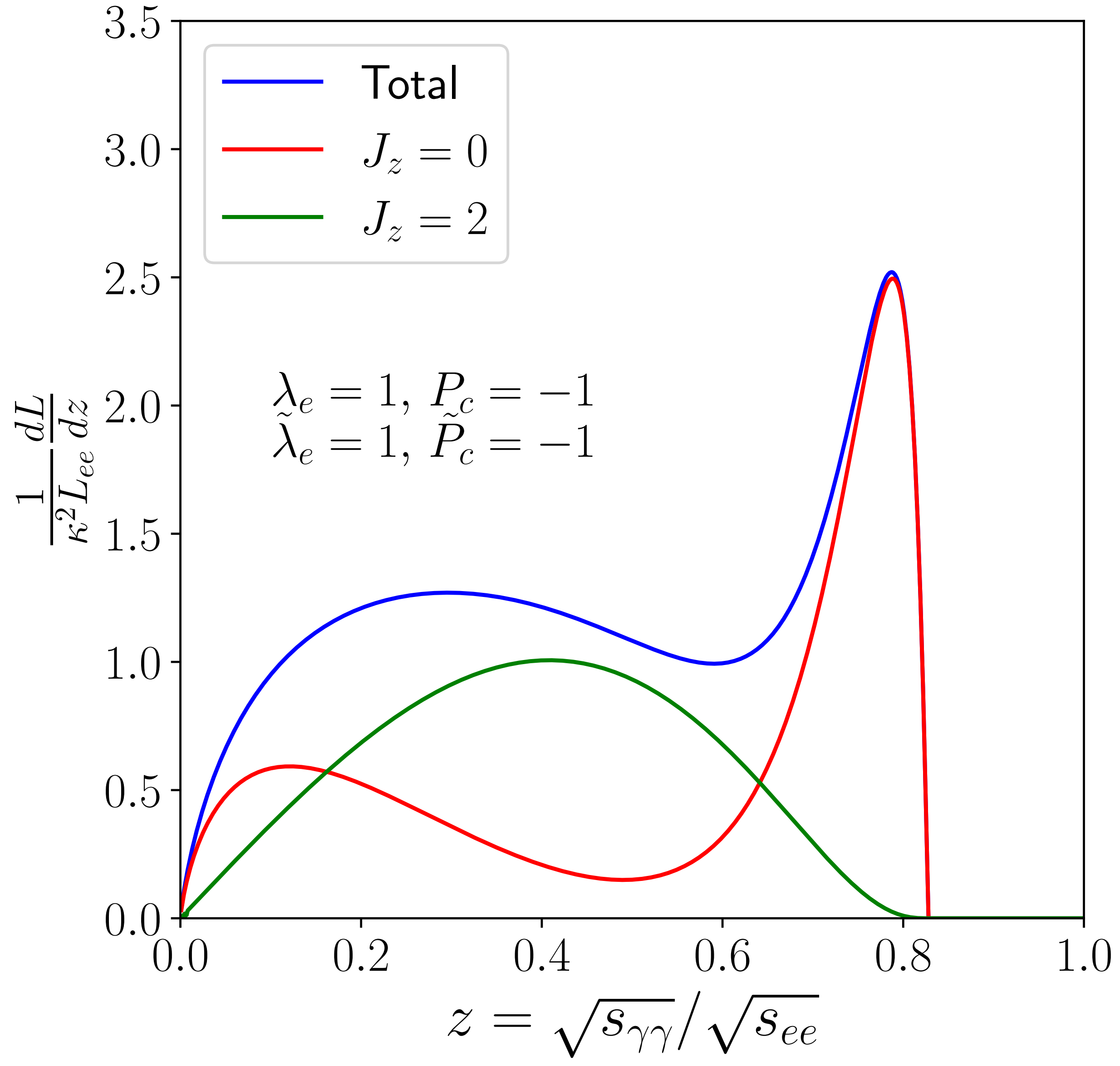
- But the scattered photon polarisation also depends on the incoming beam polarisation individually

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

- Two distinct total angular momentum states can be defined

	$J_z = 0$	$J_z = 2$
Photons with:	equal polarisation	opposite polarisation





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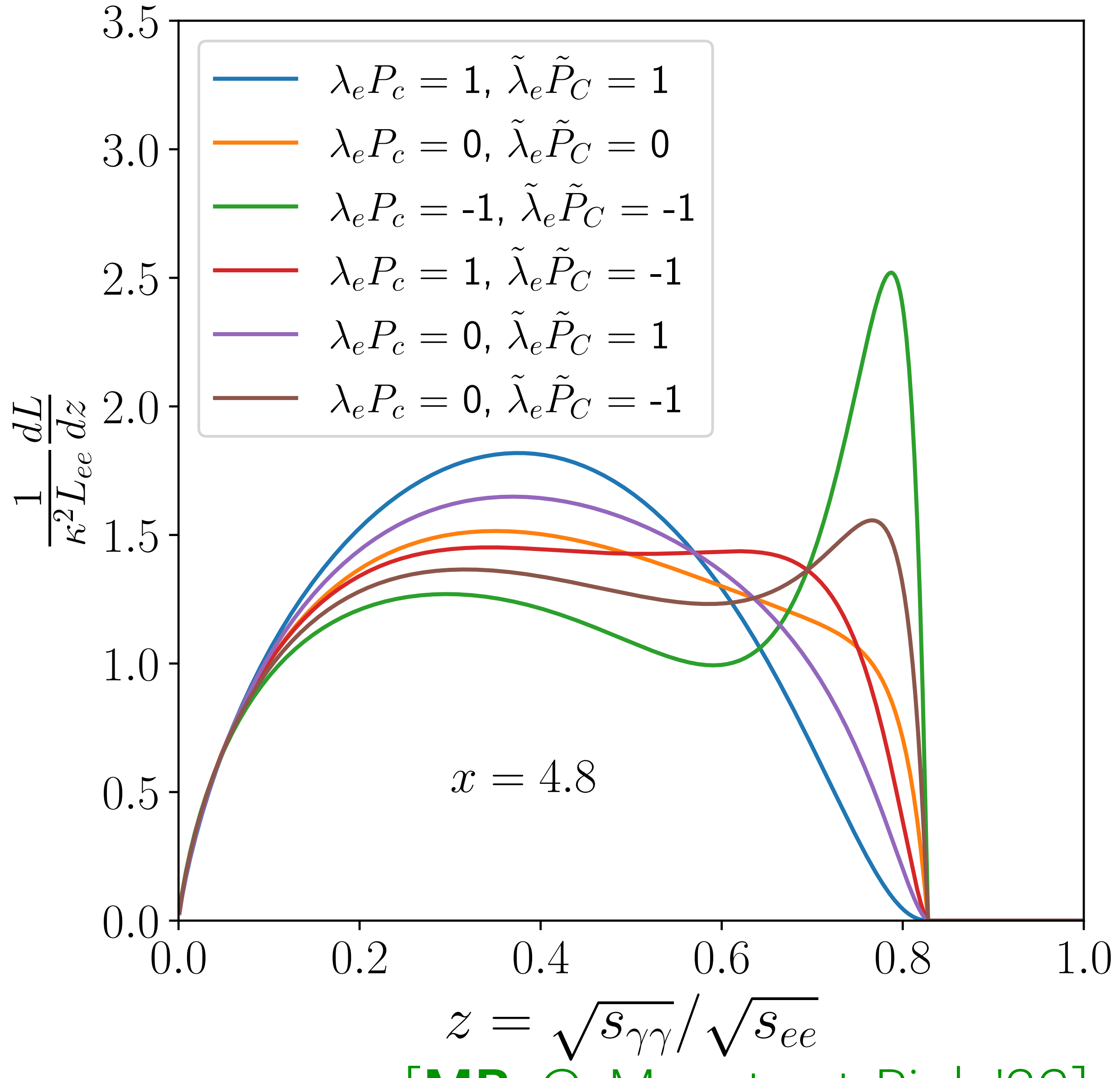
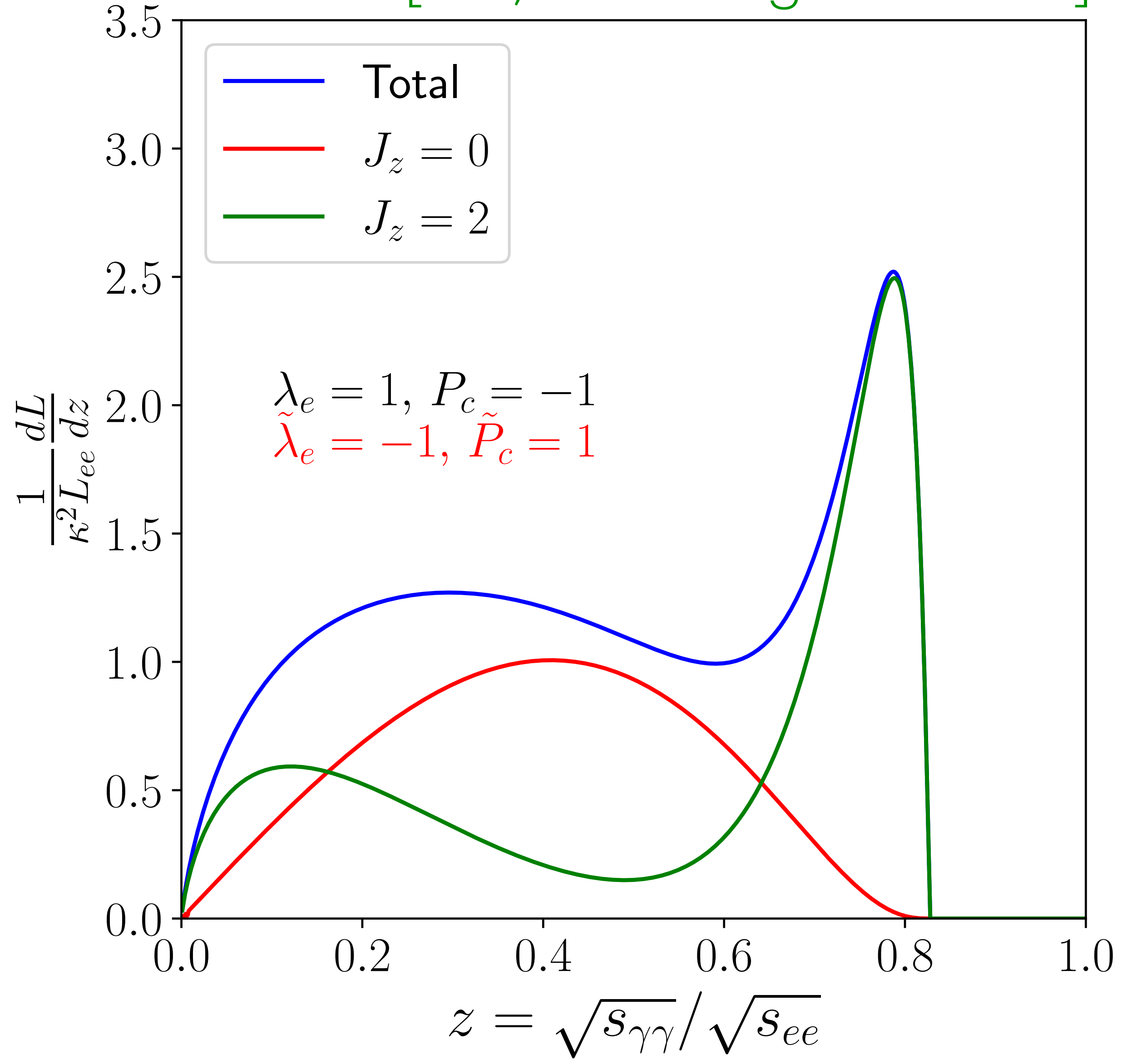
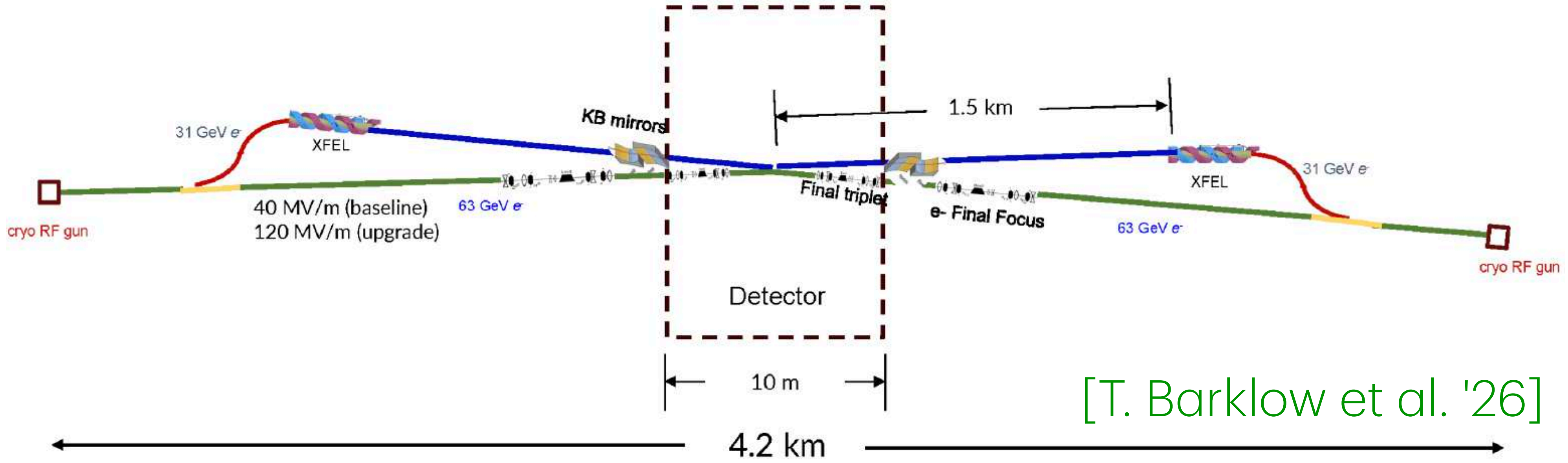


[**MB**, G. Moortgat-Pick '26]



Photon collider designs



[T. Barklow et al. '26]

Optical collider design

- Mercury laser system or Nd:YAG laser
- $\lambda = 1047$ nm or $\lambda = 1064$ nm
- $x \lesssim 4.82$
- $\lambda_e P_c = -0.9$
- $\sqrt{s_{\gamma\gamma}^{\max}} \approx 0.8\,\sqrt{s_{ee}}$
- Two photon collider energies: $\sqrt{s_{\gamma\gamma}} \approx 270$ GeV and $\sqrt{s_{\gamma\gamma}} \approx 380$ GeV
- Electron collider energies:
  - $\sqrt{s_{ee}} = 380$ GeV
  - $\sqrt{s_{ee}} = 550$ GeV

XFEL-Compton-Collider [H. Abramowicz, **MB** et al. '25]

- XFEL photon source
- $\lambda \approx 2$ nm
- $x \geq 1000$
- $\lambda_e P_c = 0.9$
- $\sqrt{s_{\gamma\gamma}^{\max}} = \sqrt{s_{ee}}$
- Two photon collider energies: $\sqrt{s_{\gamma\gamma}} = 270$ GeV and $\sqrt{s_{\gamma\gamma}} = 380$ GeV
- Electron collider energies:
  - $\sqrt{s_{ee}} = 270$ GeV
  - $\sqrt{s_{ee}} = 380$ GeV

Photon collider designs

- We used the Monte-Carlo code CAIN [P. Chen et al. '95] to simulate realistic photon collider spectra
- The optical collider designs are based on ILC photon collider design [F. Bechtle et al. '06] and LCF at CERN [H. Abramowicz, **MB** et al. '25]
- The XCC designs are based on C^3 [K.L. Bane et al. '18][T. Barklow et al. '22] but have also been checked using a SCRF accelerator [H. Abramowicz, **MB** et al. '25]

Optical collider

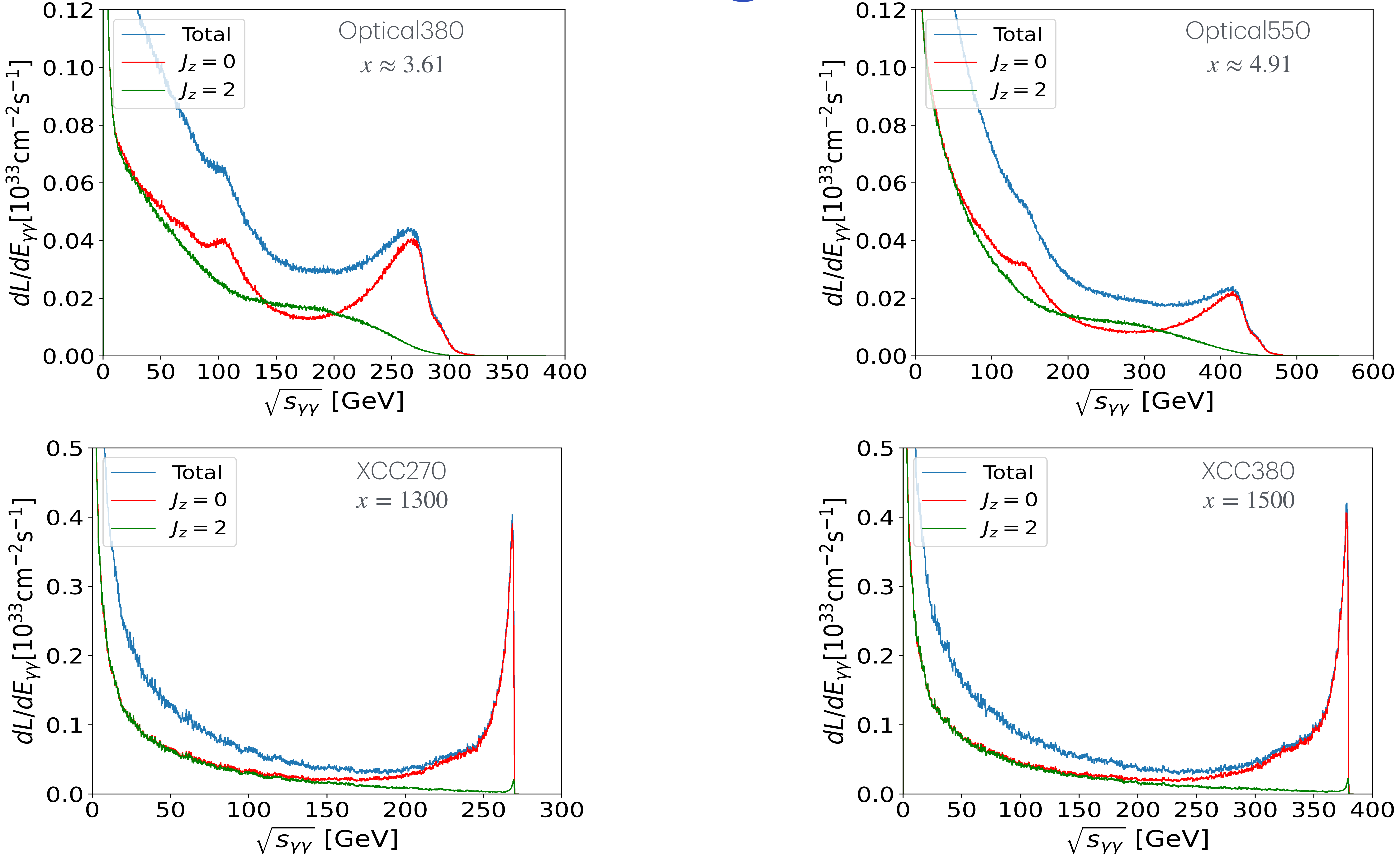
Parameters	$\sqrt{s_{\gamma\gamma}} = 270$ GeV	$\sqrt{s_{\gamma\gamma}} = 420$ GeV
Electron energy E_0 [GeV]	190	275
β_x/β_y [μm]	1500/300	11000/482
$\gamma\varepsilon_x/\gamma\varepsilon_y$ [nm· mrad]	2500/30	10000/35
σ_x/σ_y [nm]	88/4.3	452/5.6
σ_z [μm]	300	300
Bunch charge [10^{10} e^-]	2	2
Collision rate [kHz]	14.2	26.25
Crossing angle [mrad]	20	20
b (C-IP distance) [mm]	2.6	2.6
Laser λ (energy) [μm (eV)]	1 (1.17)	1 (1.17)
Laser flash energy [J]	9	9
Laser pulse duration [ps]	1.5	1.5
f# $\equiv F/D$ of laser system	17	17
Parameter x and ξ^2	3.61, 0.34	4.91, 0.39
Power density laser [10^{21}W/m^2]	9.3	9.3
$\alpha_{e\lambda}$ [mrad]	47	47

XCC

Parameters	$\sqrt{s_{\gamma\gamma}} = 270$ GeV	$\sqrt{s_{\gamma\gamma}} = 380$ GeV
Electron energy E_0 [GeV]	135	190
β_x/β_y [μm]	10/10	10/10
$\gamma\varepsilon_x/\gamma\varepsilon_y$ [nm· mrad]	60/60	60/60
σ_x/σ_y [nm]	1.5/1.5	1.5/1.5
σ_z [μm]	10	10
Bunch charge [10^{10} e^-]	0.62	0.62
Collision rate [kHz]	14.52	11.16
Crossing angle [mrad]	2	2
b (C-IP distance) [mm]	0.04	0.04
Laser λ (energy) [nm (keV)]	2.0 (0.61)	2.4 (0.52)
Laser flash energy [J]	1	1
Laser pulse length [fs]	33	67
Parameter x and ξ^2	1300, 0.76	1500, 1.13
Power density laser [10^{27}W/m^2]	5.3	5.3
$\alpha_{e\lambda}$ [mrad]	1	1

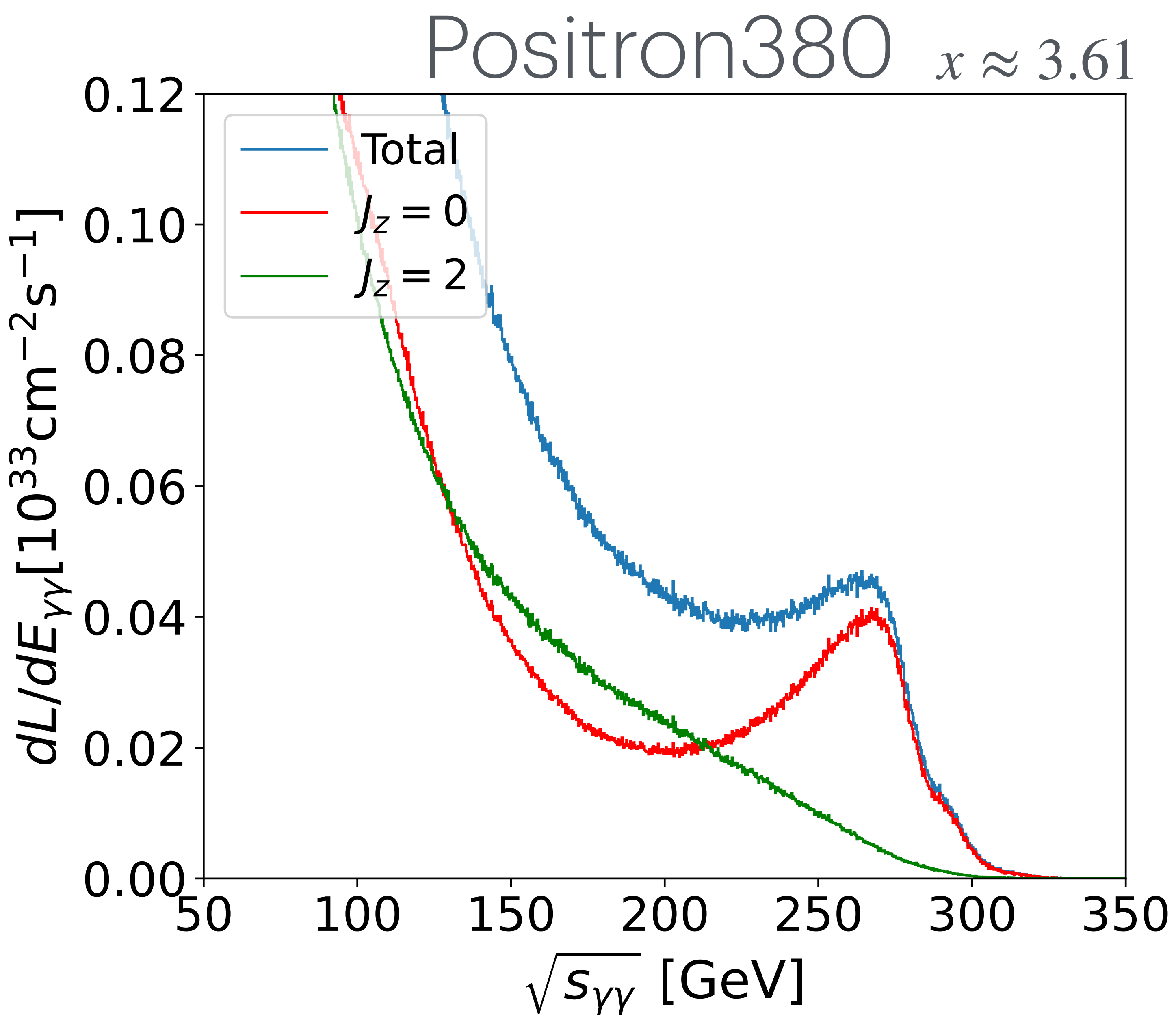
[H. Abramowicz, **MB** et al. '25]

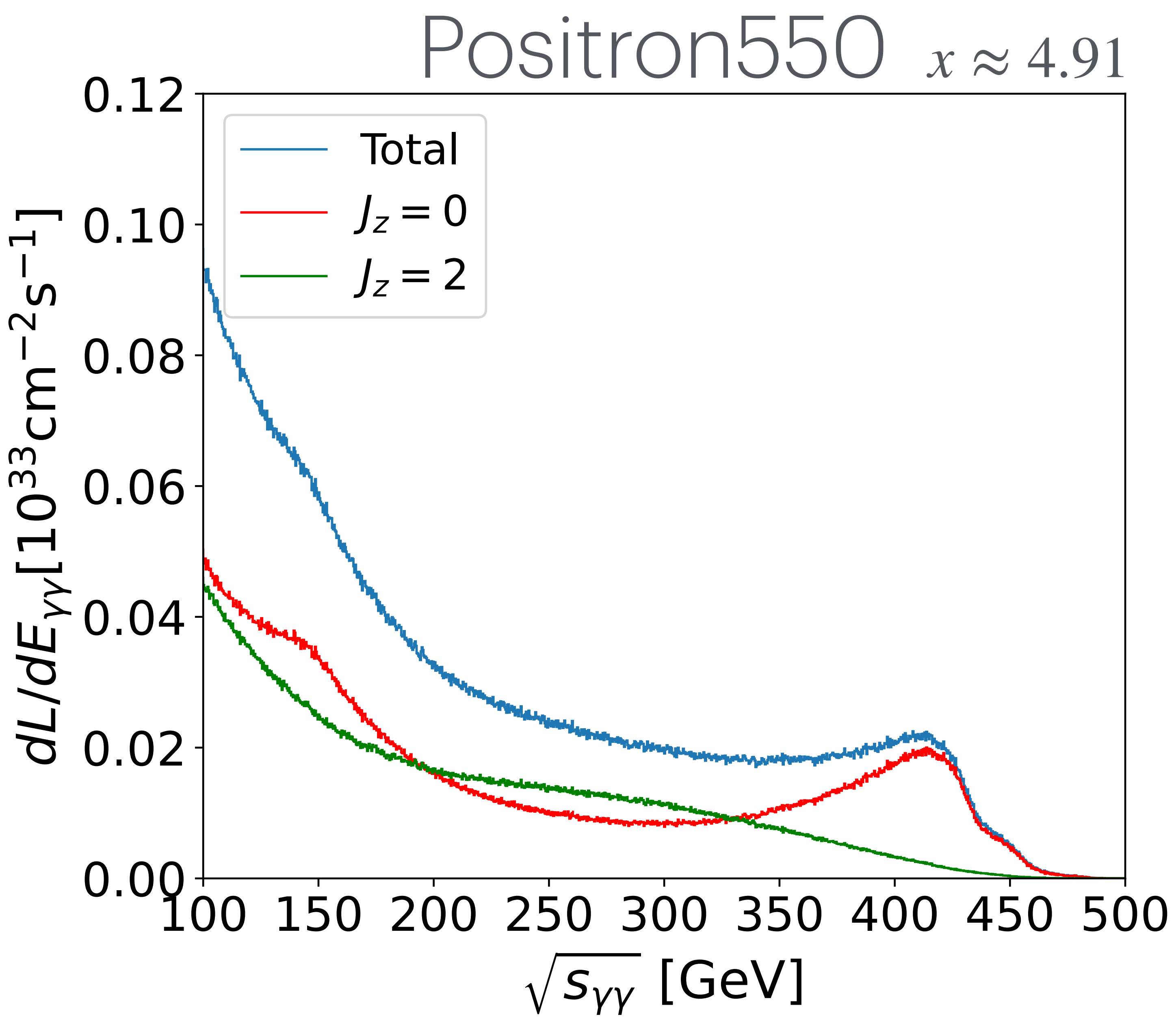
Photon collider designs



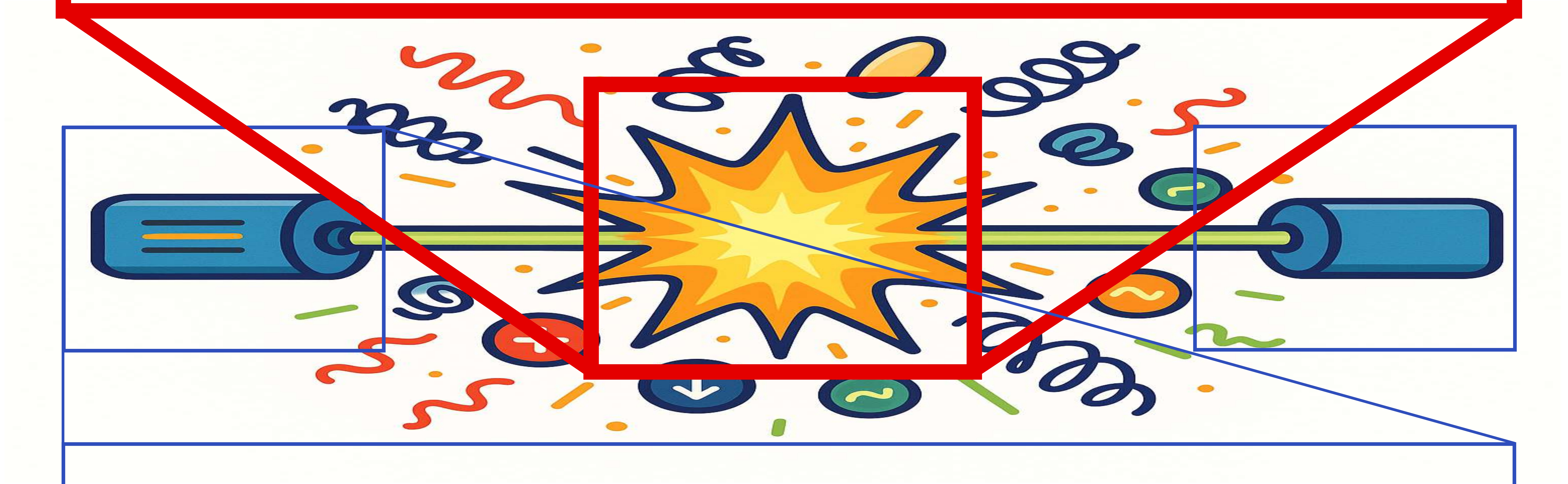
Photon collider designs - e^+e^- base

- Positron beams have not been considered in photon collider designs
  - Polarisation is very important, now can reach 60% polarised e^+ beams [S. Riemann, F. Staufenbiel, G. Moortgat-Pick, A. Ushakov '14] [J.A. Clarke et al. '08] [K. Alharbi et al. '21]
- Same Compton scattering, but additional photon collisions at lower energies
- Designs work for optical collider setups, not tested for XCC





Study of $\gamma\gamma$-processes

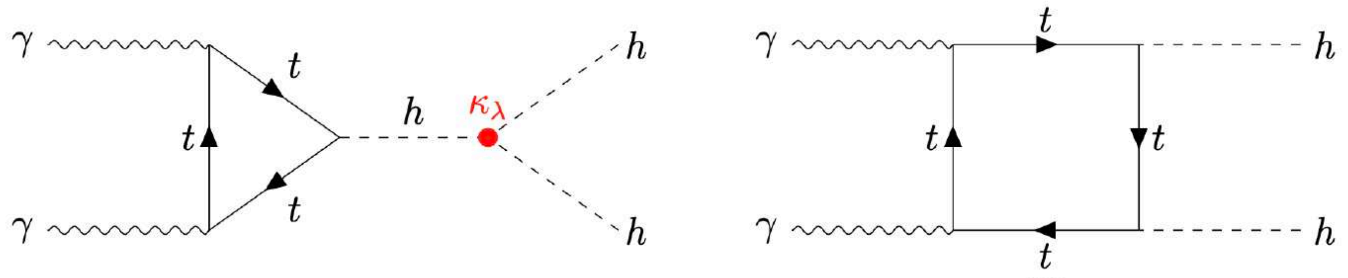


How do we produce high-energy photons?

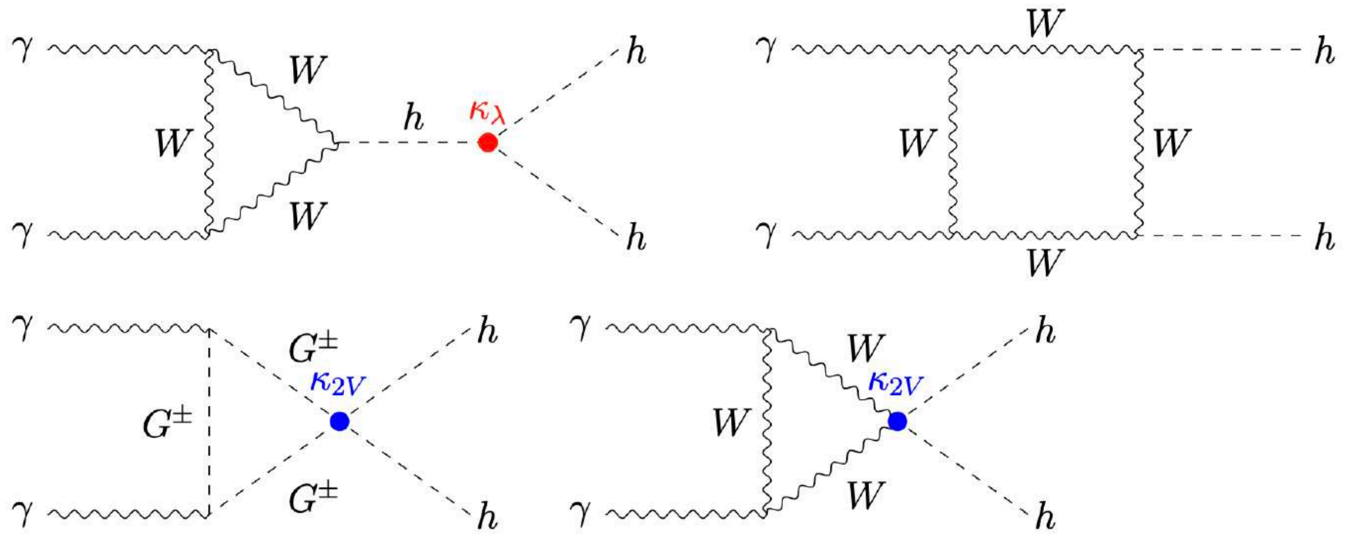
Higgs pair production

$$\kappa_i \equiv \frac{g_i}{g_i^{\mathrm{SM},(0)}}$$

- Similar structure to $gg \to hh$



- With additional gauge sector contributions



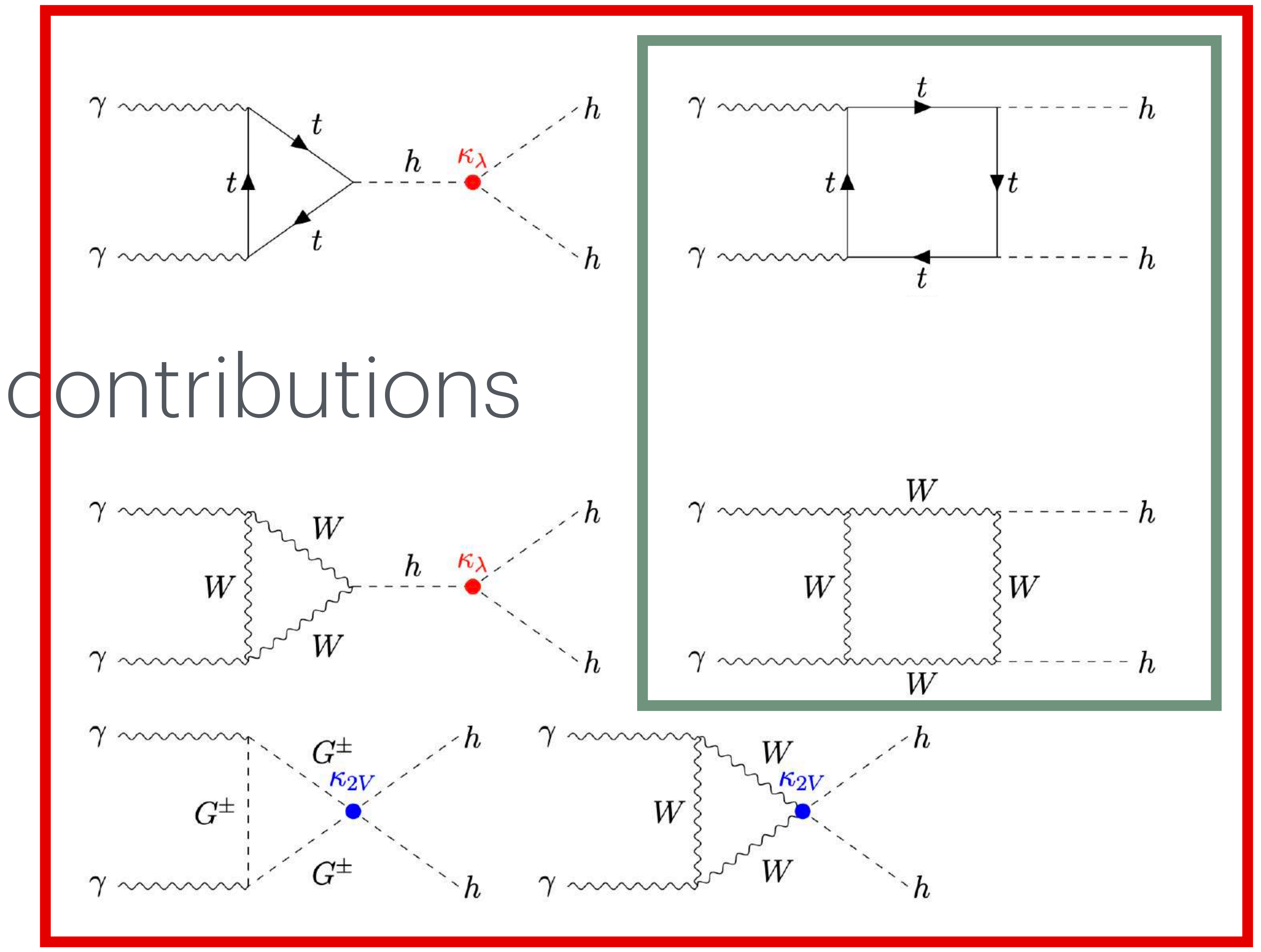
- Compute the helicity amplitudes for the process $\gamma\gamma \to hh$

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

Higgs pair production

$$\kappa_i \equiv \frac{g_i}{g_i^{\mathrm{SM},(0)}}$$

- Similar structure to $gg \to hh$
- With additional gauge sector contributions



- Compute the helicity amplitudes for the process $\gamma\gamma \to hh$
- Some diagrams only contribute to $J_z = 2$ and κ_λ only contained in the $J_z = 0$ contribution

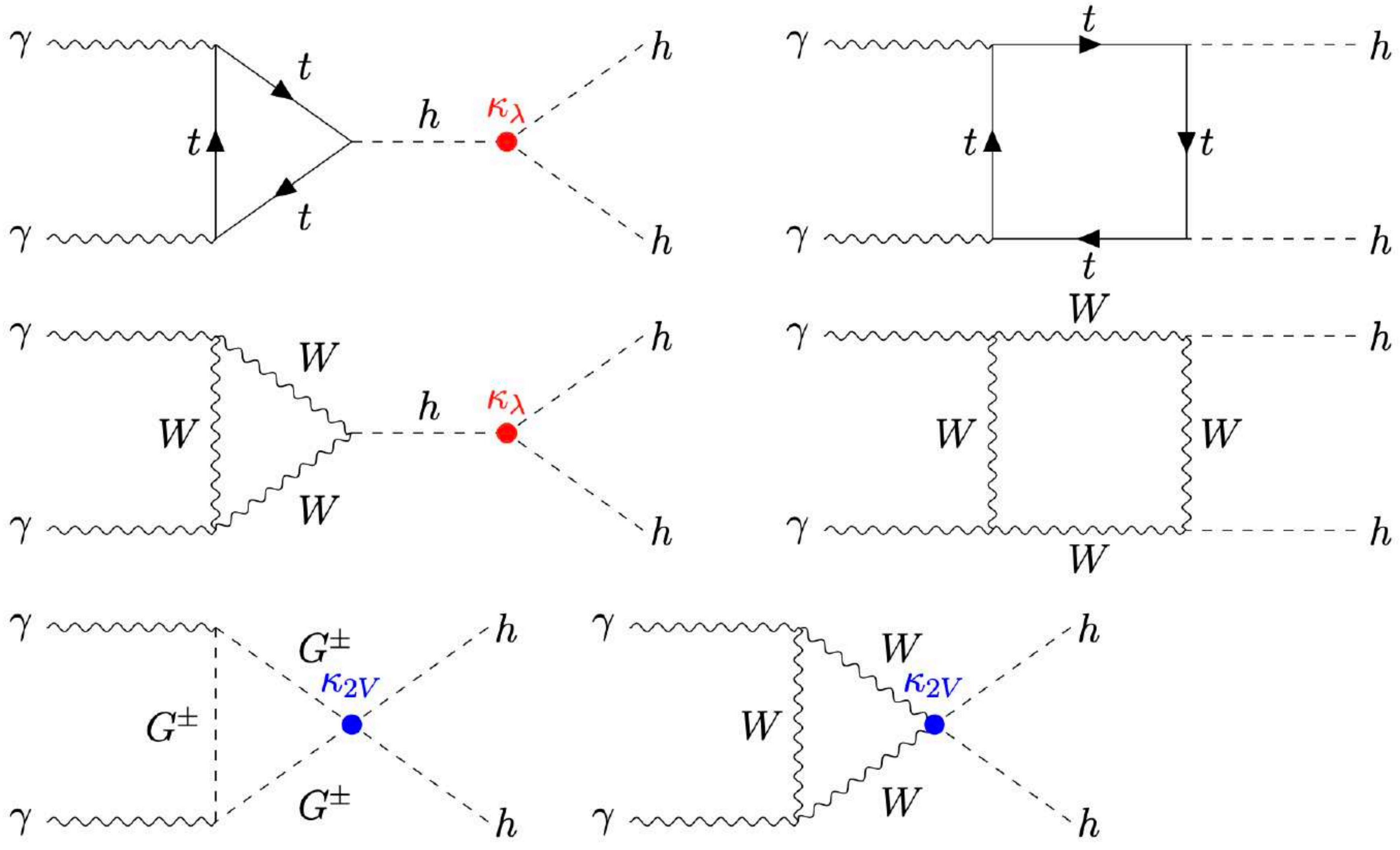
Higgs pair production - Frameworks

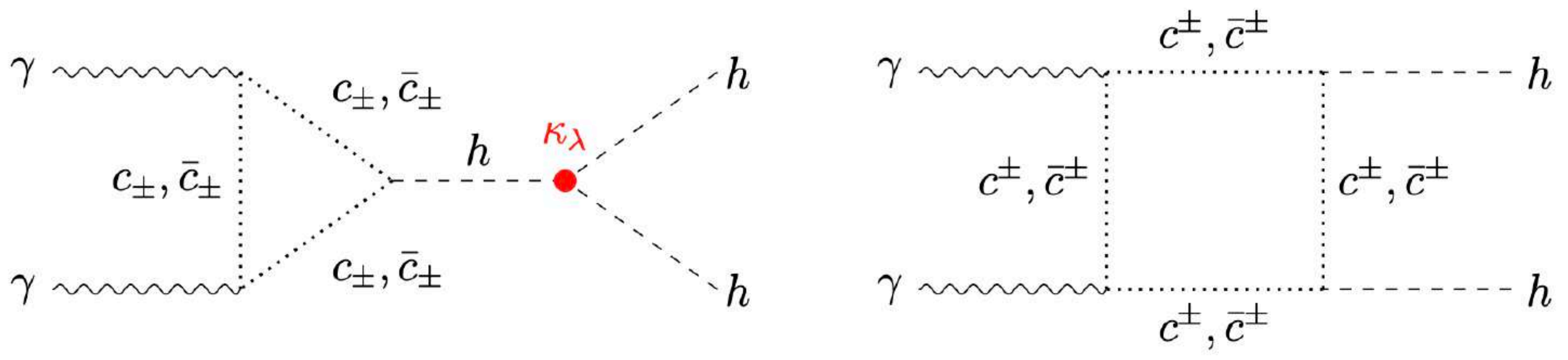
κ-framework

- Rescaling of couplings by hand
- Gauge invariance not guaranteed
- No consistent handling of higher-order / loop corrections

Couplings in this analysis:

- κ_λ
- κ_{2V}



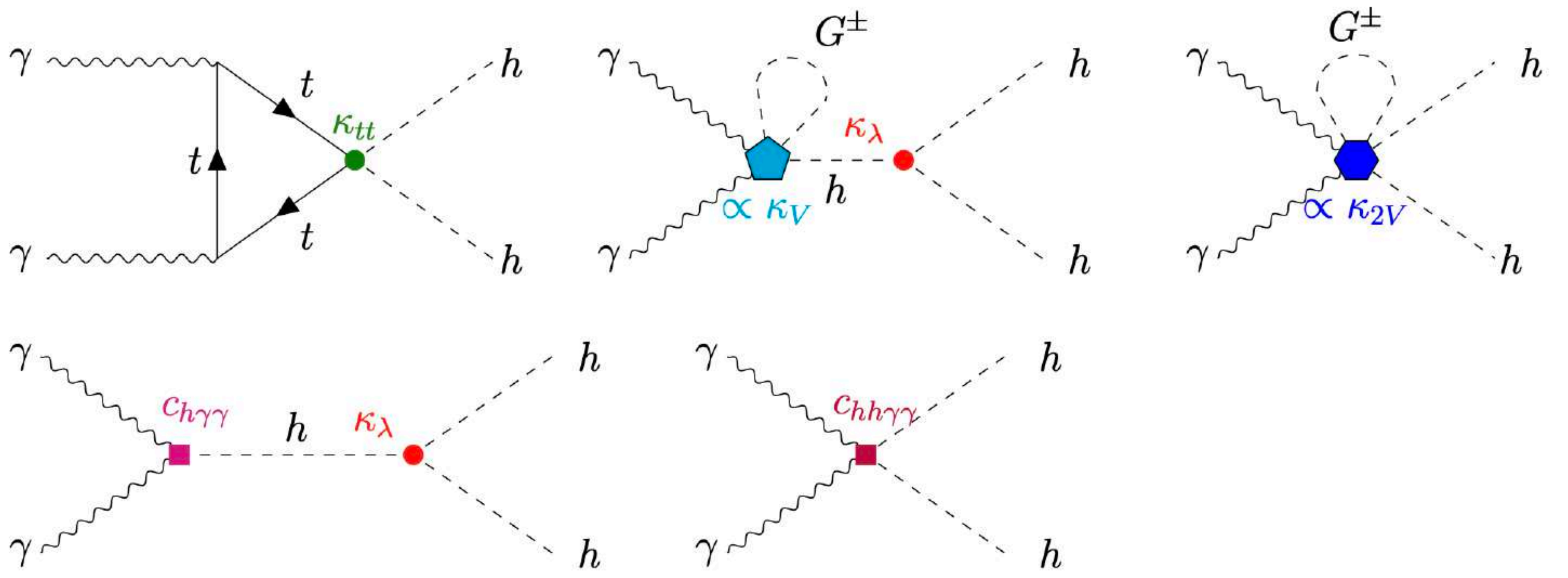


Higgs Effective Field Theory

- Independent study of single and double Higgs couplings
- Consistent EFT framework

Couplings in this analysis:

- κ_λ
- κ_{2V}
- κ_{tt}



Higgs Effective Field Theory

- The physical Higgs Boson is treated as a singlet, independent of the elctroweak Goldstones

$$h, \qquad U(x) = \exp\left(i\frac{\sigma^a \pi^a(x)}{v}\right)$$

  - Electroweak symmetry breaking is realised nonlinear
  - With the leading order Lagrangian

$$\mathscr{L}^{\text{LO}}_{\text{HEFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{fermions}} + \mathscr{L}_{\text{Yukawa}} + \frac{v^2}{4}\mathscr{F}_C(h/v)\text{Tr}\left[\mathbf{D}_\mu \mathbf{U}^\dagger \mathbf{D}^\mu \mathbf{U}\right] + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$

  - Higgs interactions with Goldstone bosons and gauge bosons are described by the flare function $\mathscr{F}_C(h/v)$

$$\mathscr{F}_C(h) = 1 + 2a_C\frac{h}{v} + b_C\frac{h^2}{v^2} + c_C\frac{h^3}{v^3} + \dots$$

Higgs Effective Field Theory

- The effective Lagrangian

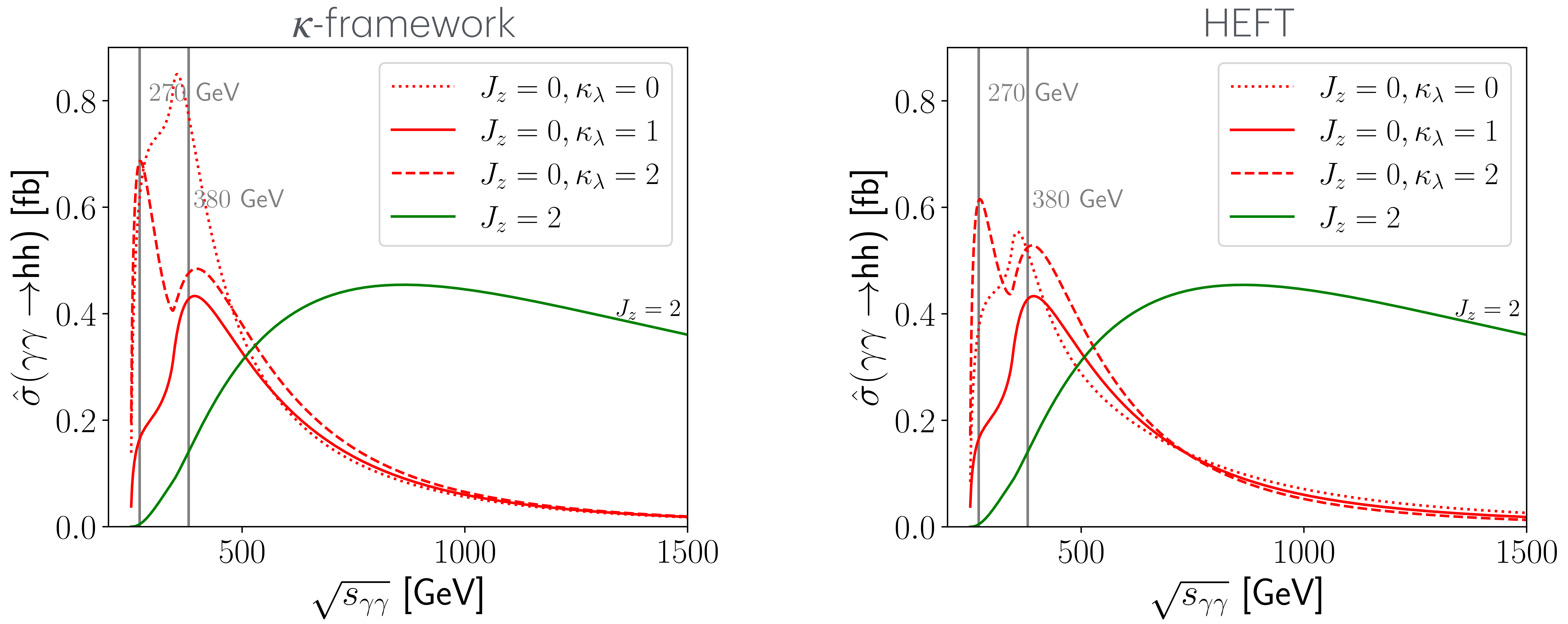
$$\mathscr{L}_{\text{eff}} \supset -\frac{1}{2}\kappa_\lambda \frac{m_h^2}{v} h^3 - \frac{y_t v}{\sqrt{2}} \bar{t}\left(\kappa_t \frac{h}{v} + \kappa_{tt}\frac{h^2}{v^2}\right) t$$
$$+\frac{v^2}{4}\left(2\kappa_V \frac{h}{v} + \kappa_{2V}\frac{h^2}{v^2}\right) \mathrm{Tr}\left[\mathbf{D}_\mu \mathbf{U}^\dagger \mathbf{D}^\mu \mathbf{U}\right]$$
$$-\frac{\alpha}{16\pi} F_{\mu\nu}F^{\mu\nu}\left(c_{h\gamma\gamma}\frac{h}{v} + c_{hh\gamma\gamma}\frac{h^2}{v^2}\right)$$

- In the SM: $\kappa_\lambda = 1, \kappa_V = 1, \kappa_{2V} = 1, \kappa_t = 1, \kappa_{tt} = 0, c_{h\gamma\gamma} = 0, c_{hh\gamma\gamma} = 0$

- We keep the other couplings at their SM value

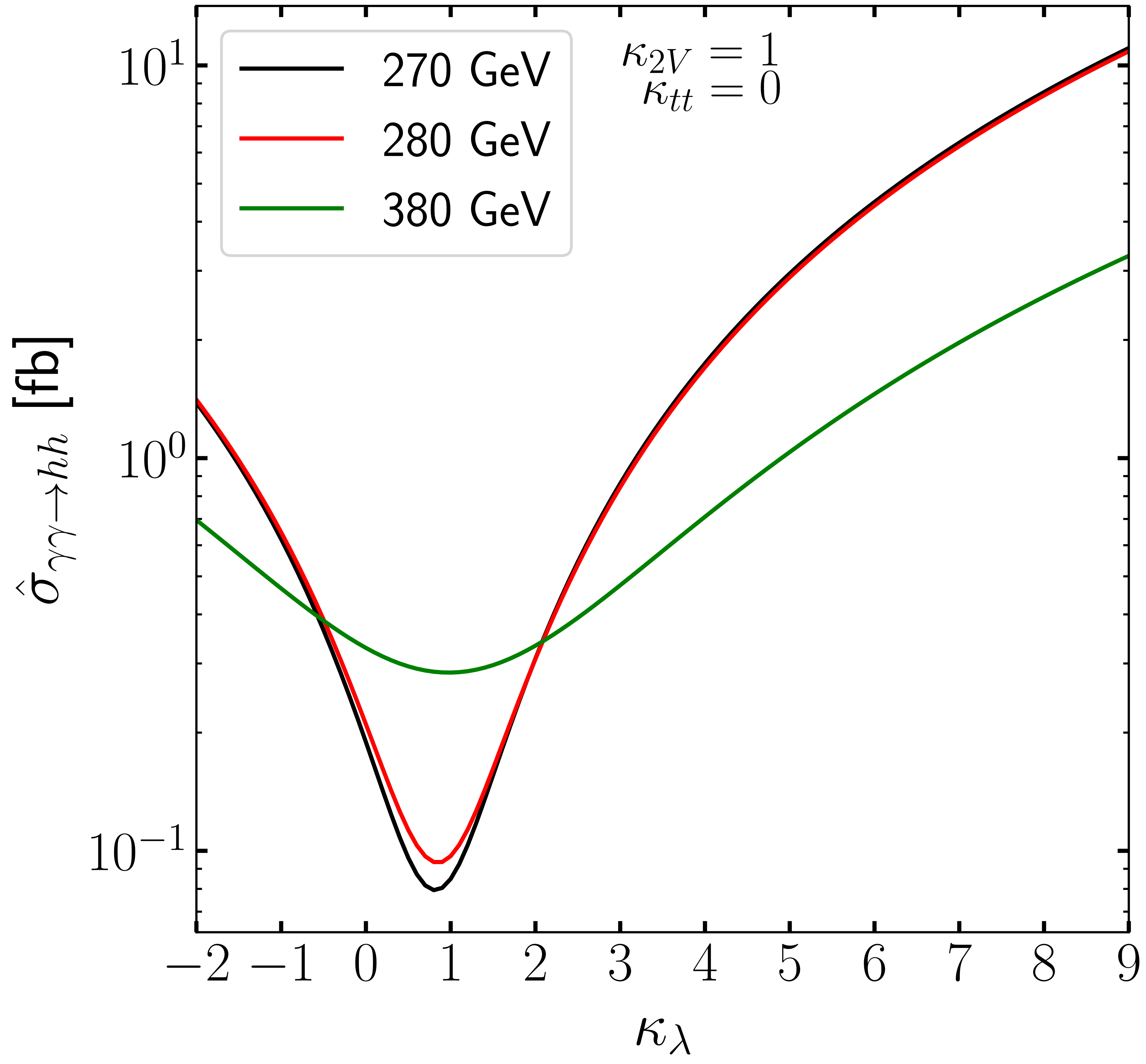
Higgs pair production - Partonic level

- Both frameworks agree for the SM cross-section
- Disagree for $\kappa_\lambda \neq 1$, need a consistent framework ⟶ HEFT



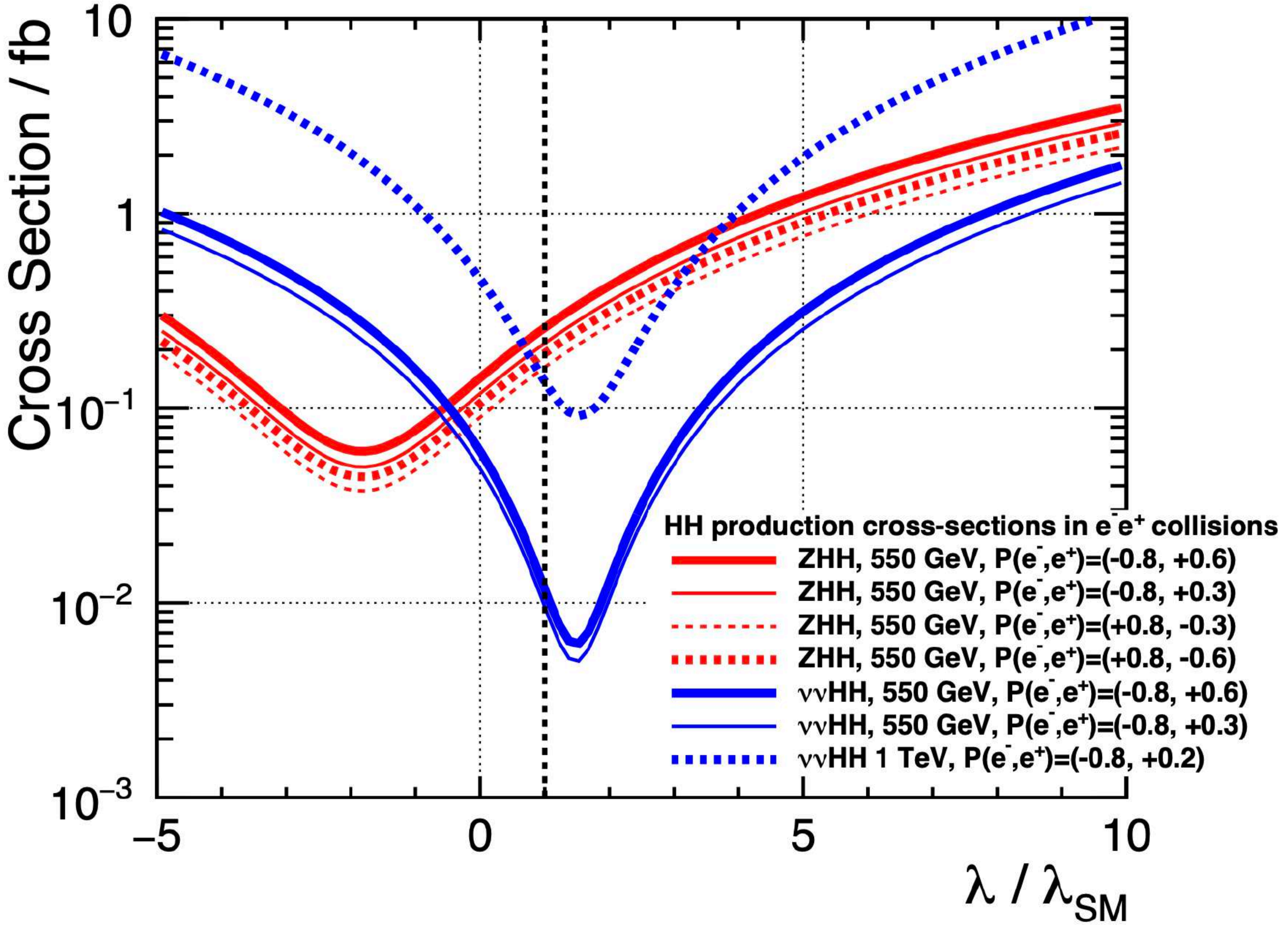
Higgs pair production - Partonic level

- The minimum is at different values of κ_λ, offers complementarity between different collider searches
- Lower energies are better for sensitivity studies due to the strong dependency on κ_λ



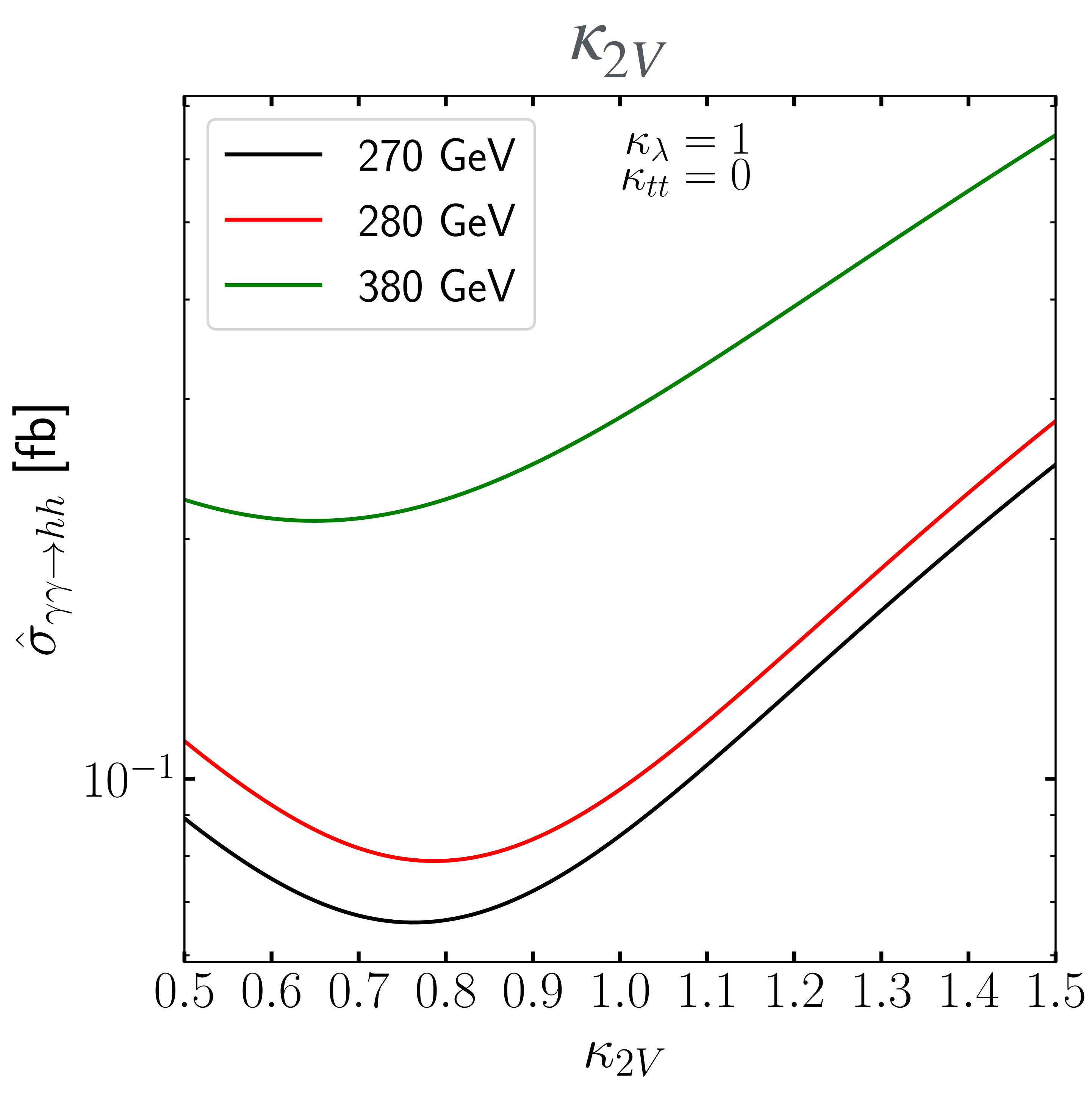
[H. Abramowicz, **MB** et al. '25]

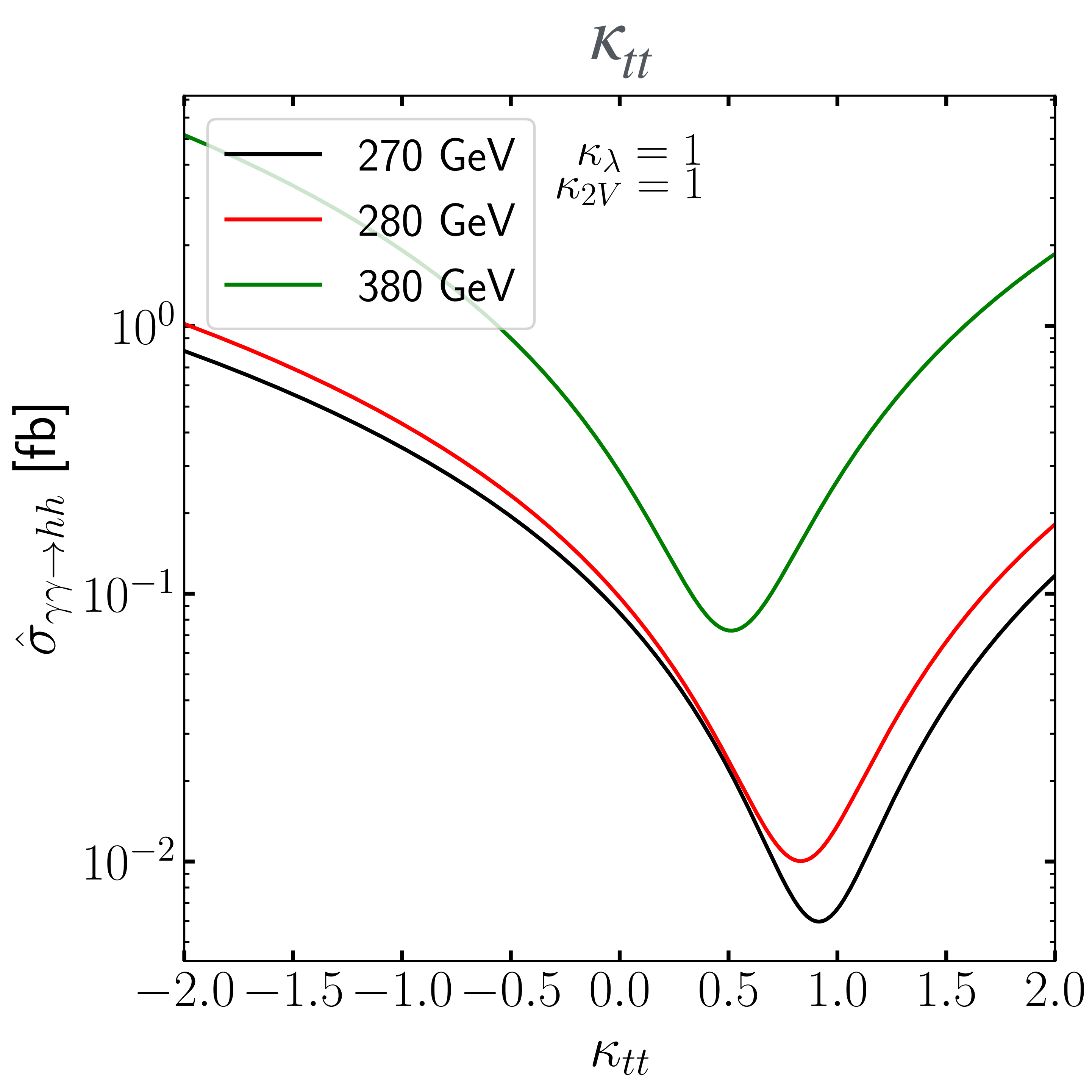
e^+e^- collider



Higgs pair production - Partonic level

- The dependency on κ_{2V} and κ_{tt} does not show different behaviour at the different energies
- No s-channel suppression compared to the κ_λ dependency



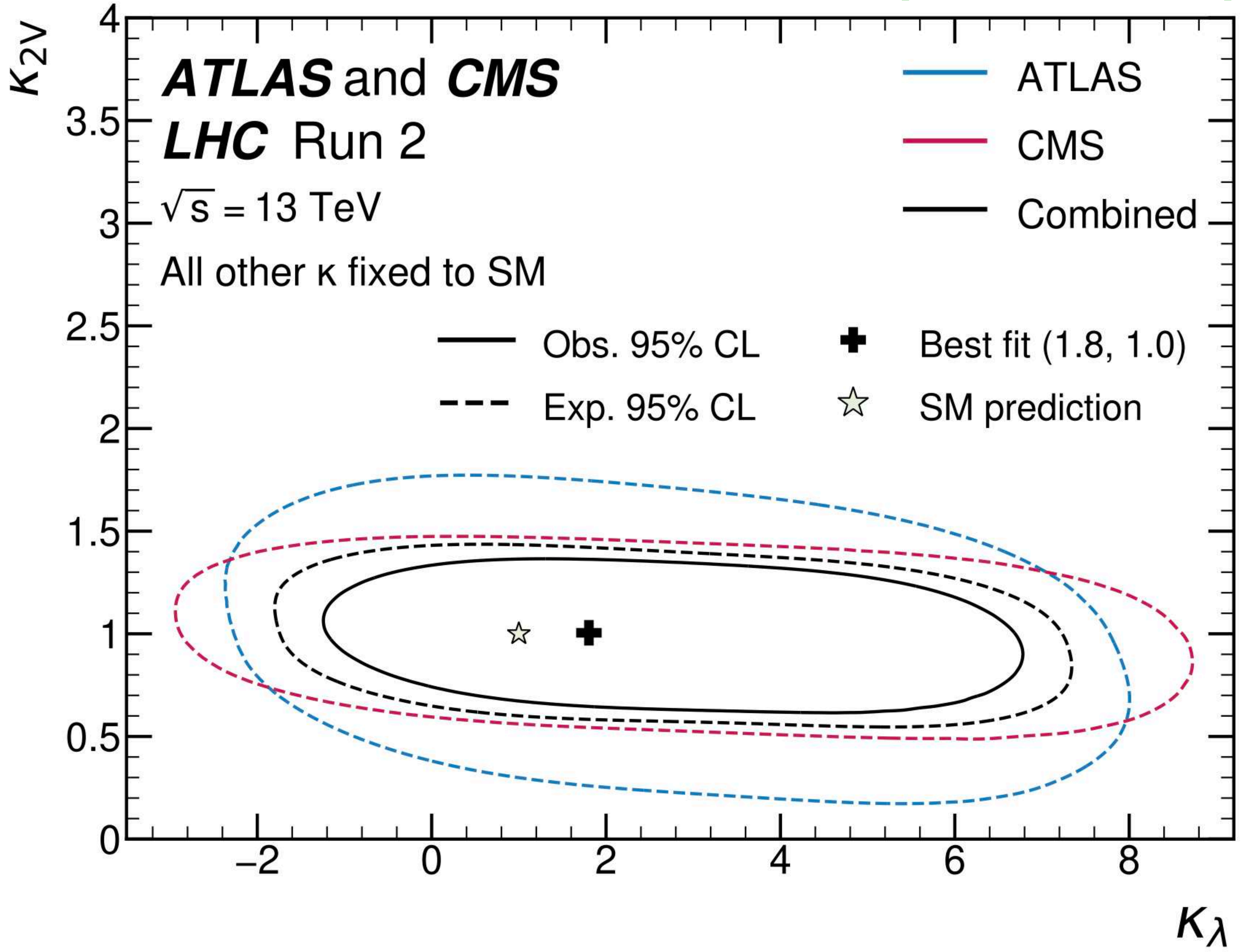


Higgs pair production - Limits

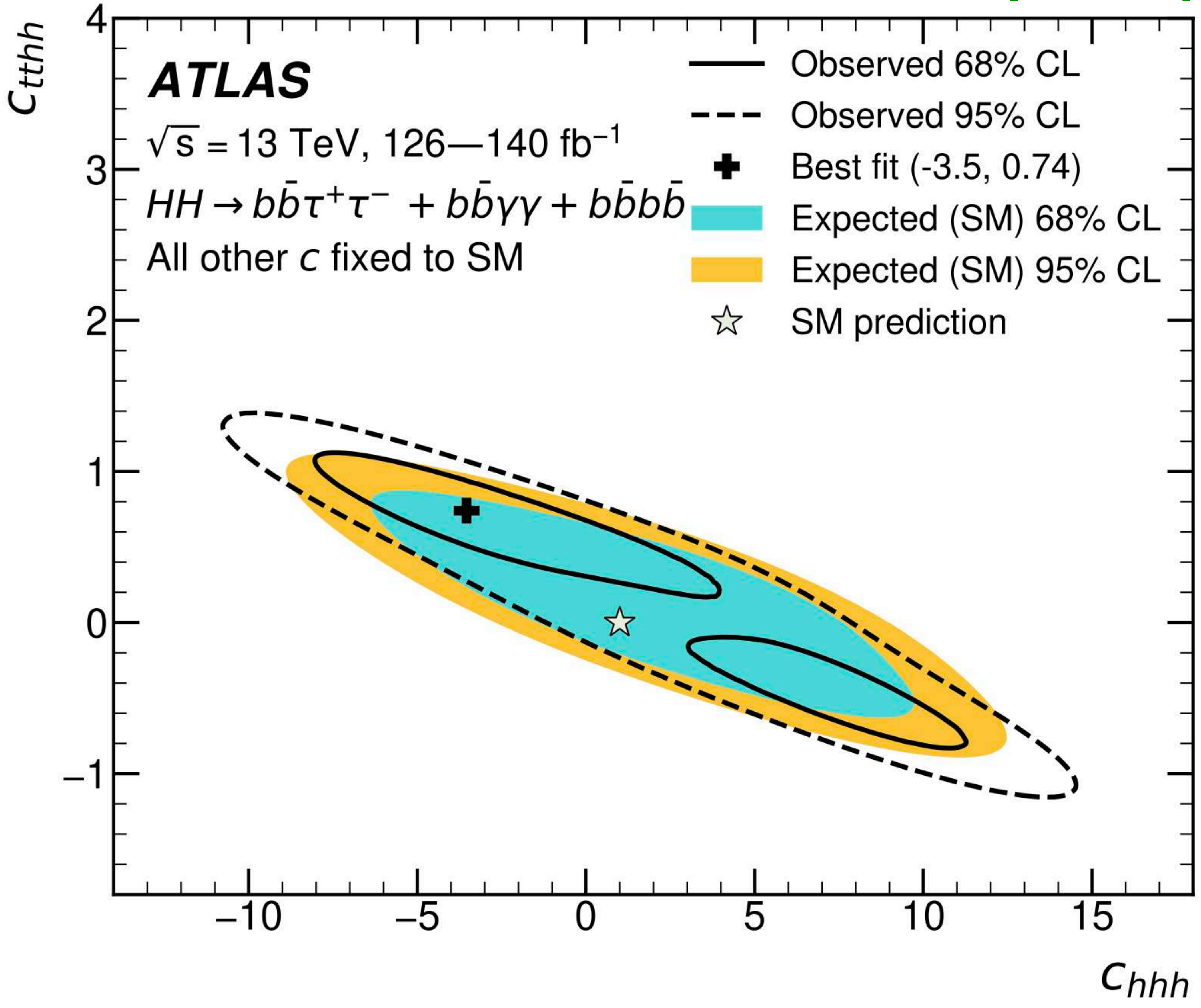
$[-0.71 < \kappa_\lambda < 6.1]$ [ATLAS and CMS '26]
while all other couplings fixed to SM

- By including additional couplings the sensitivity on κ_λ decreases

[ATLAS and CMS '26]

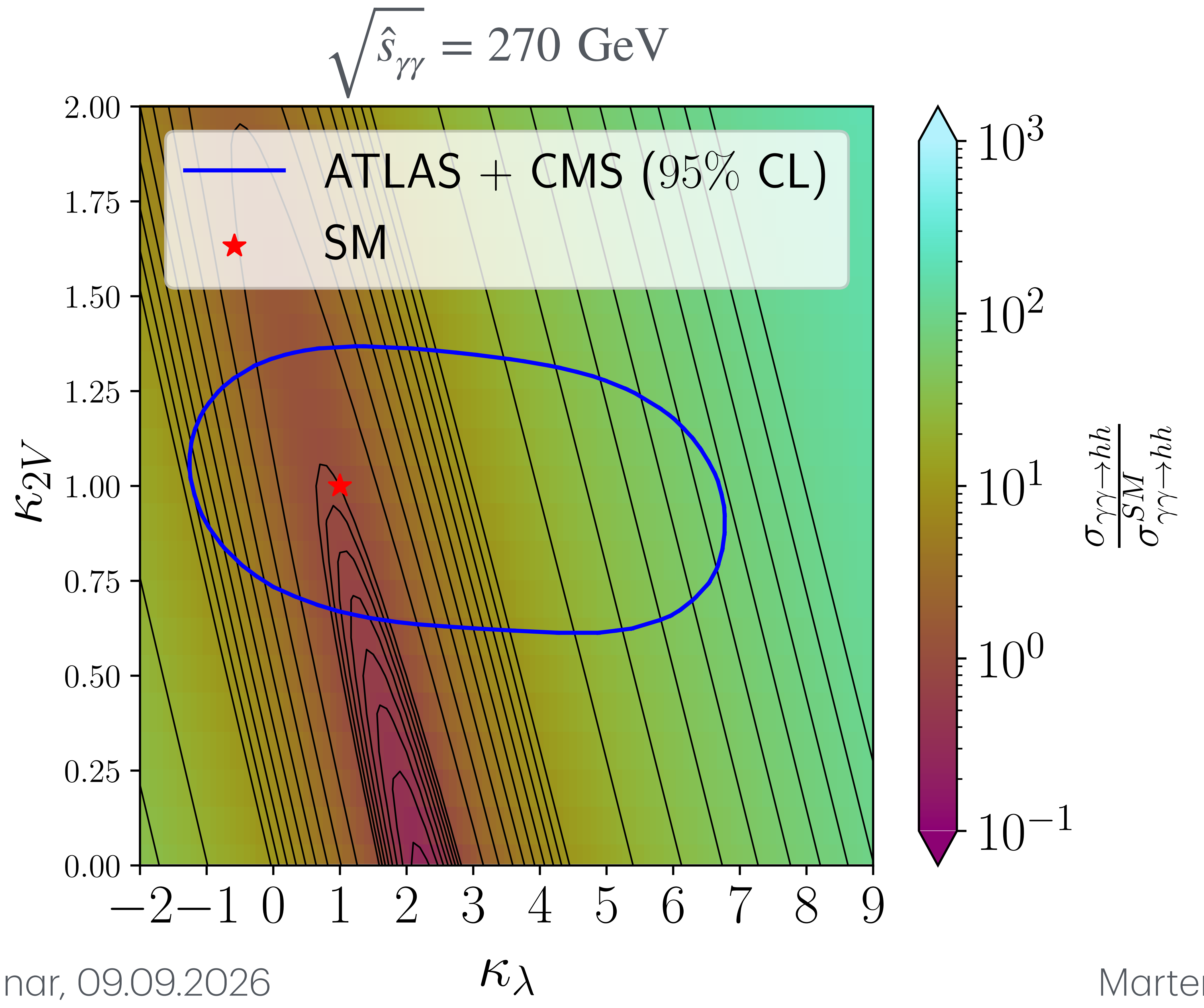


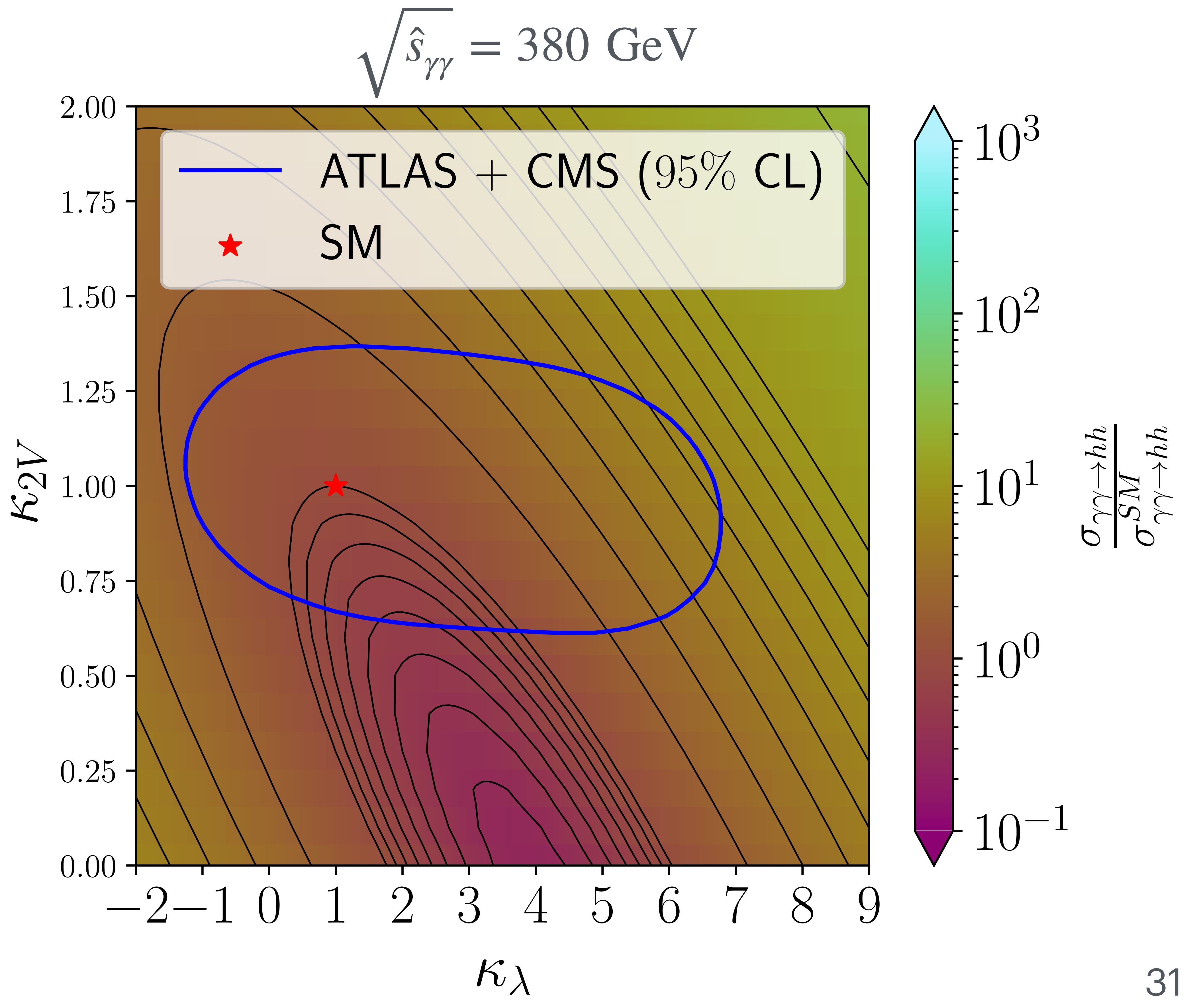
[ATLAS '24]



Higgs pair production - Partonic level

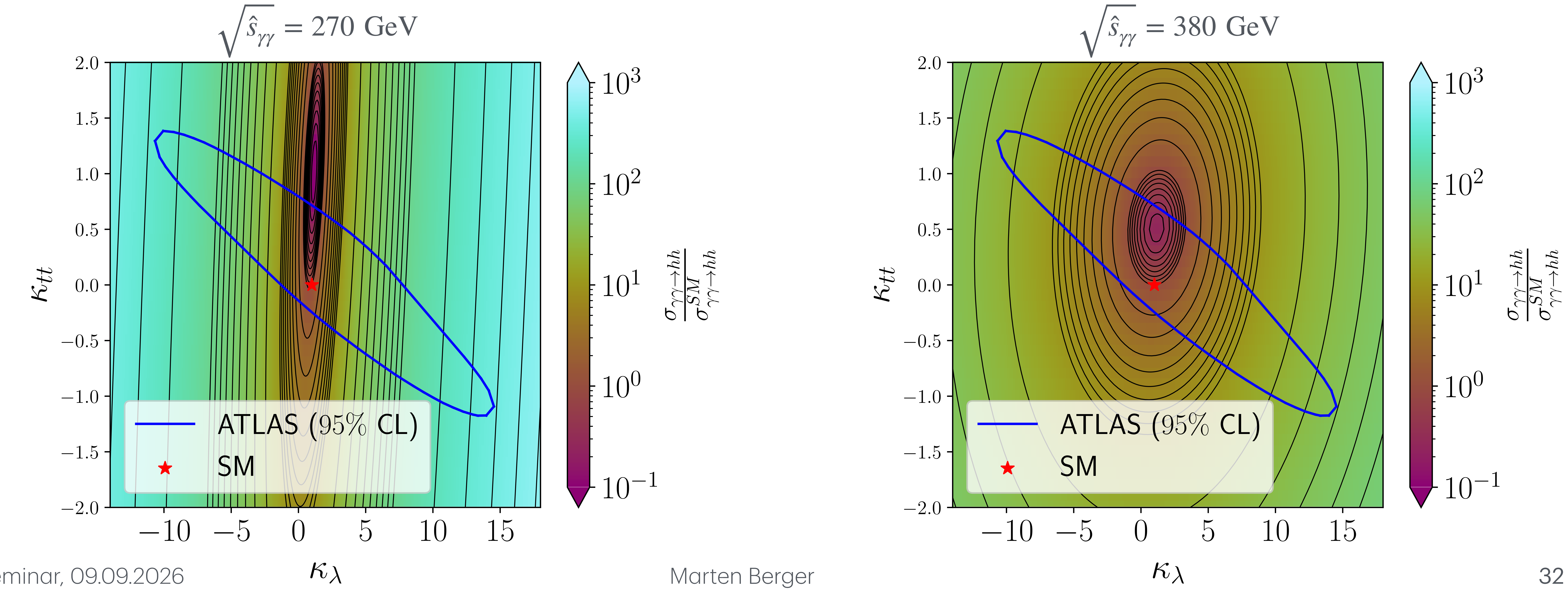
- The contour in the $\kappa_\lambda/\kappa_{2V}$ plane at 270 GeV is close to vertical behaviour, while at 380 GeV at larger angle
- Cross-section dependency shown within the combined 95% CL from ATLAS and CMS [ATLAS and CMS '26]



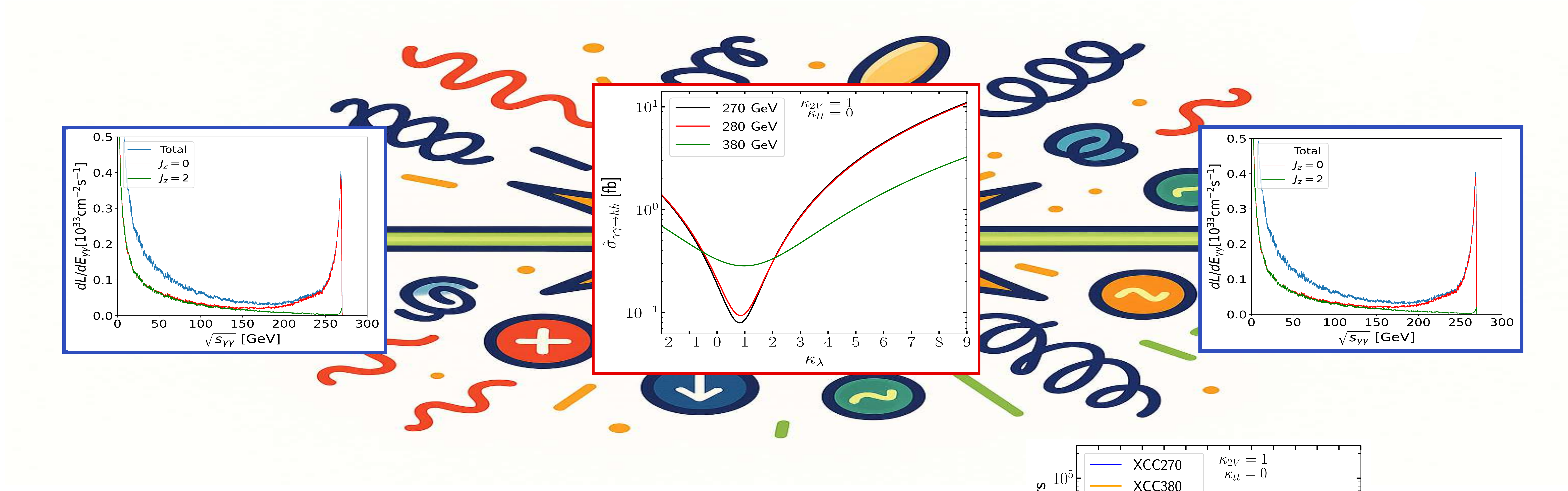


Higgs pair production - Partonic level

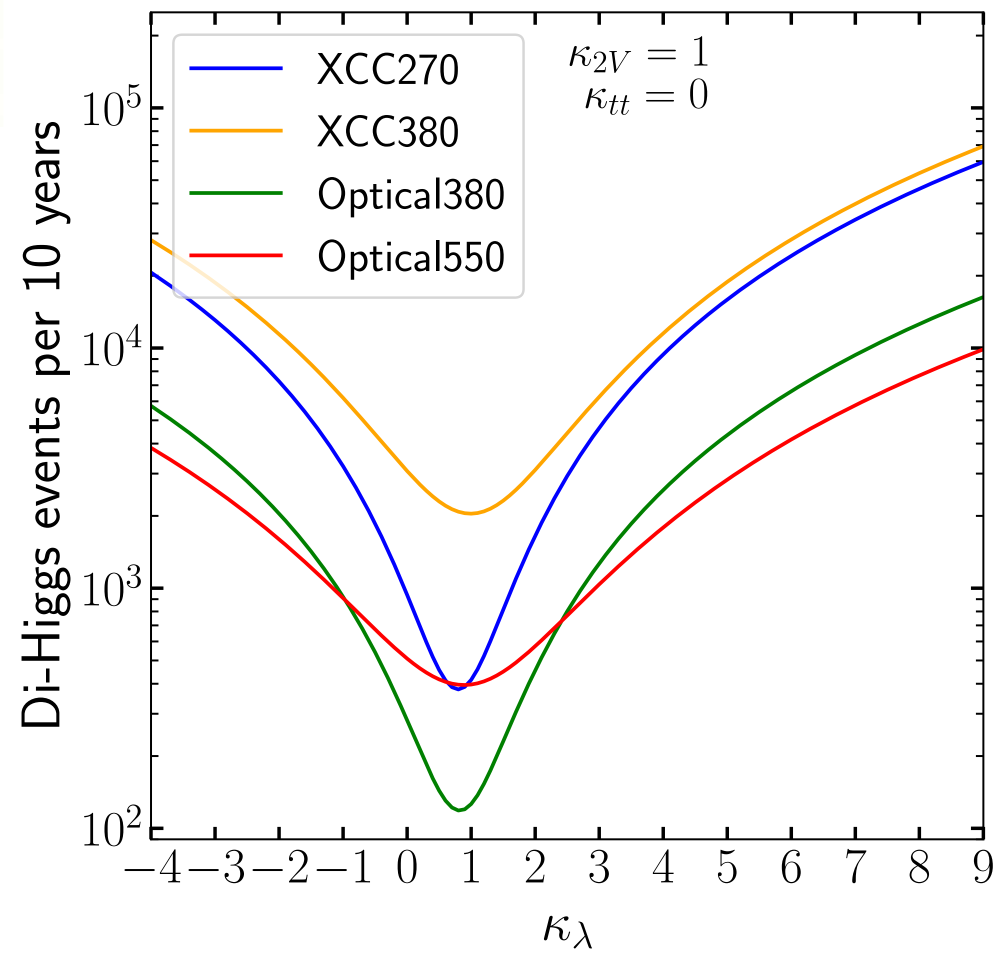
- The contours in the $\kappa_\lambda/\kappa_{tt}$ plane at both energies arrange in nearly vertical ellipses, with very tight spacing at 270 GeV
- Cross-section dependency shown within the 95% CL from ATLAS [ATLAS '24]



Photon collider - Higgs pair production



- Take both results and smash them together

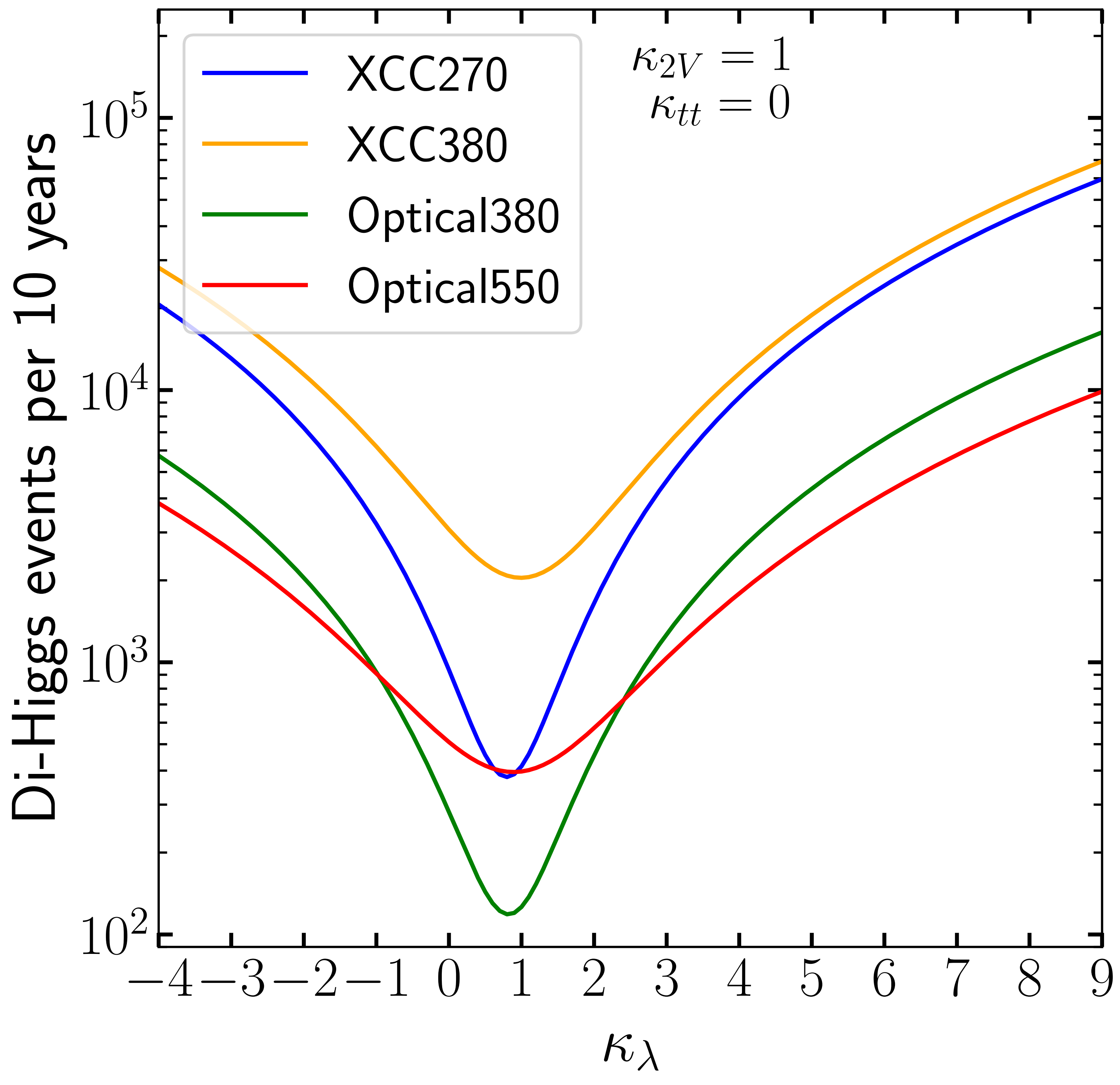


Photon collider - Higgs pair production

- Combine the partonic cross section and the luminosity spectra

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

- 10 years of runtime ($1.6 * 10^7$ seconds per year)
- SM Higgs pair production
  - Optical380: 126 events
  - Optical550: 397 events
  - XCC270: 415 events
  - XCC380: 2043 events



Photon collider - Higgs pair production

- Combine the partonic cross section and the luminosity spectra

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

- 10 years of runtime ($1.6 * 10^7$ seconds per year)

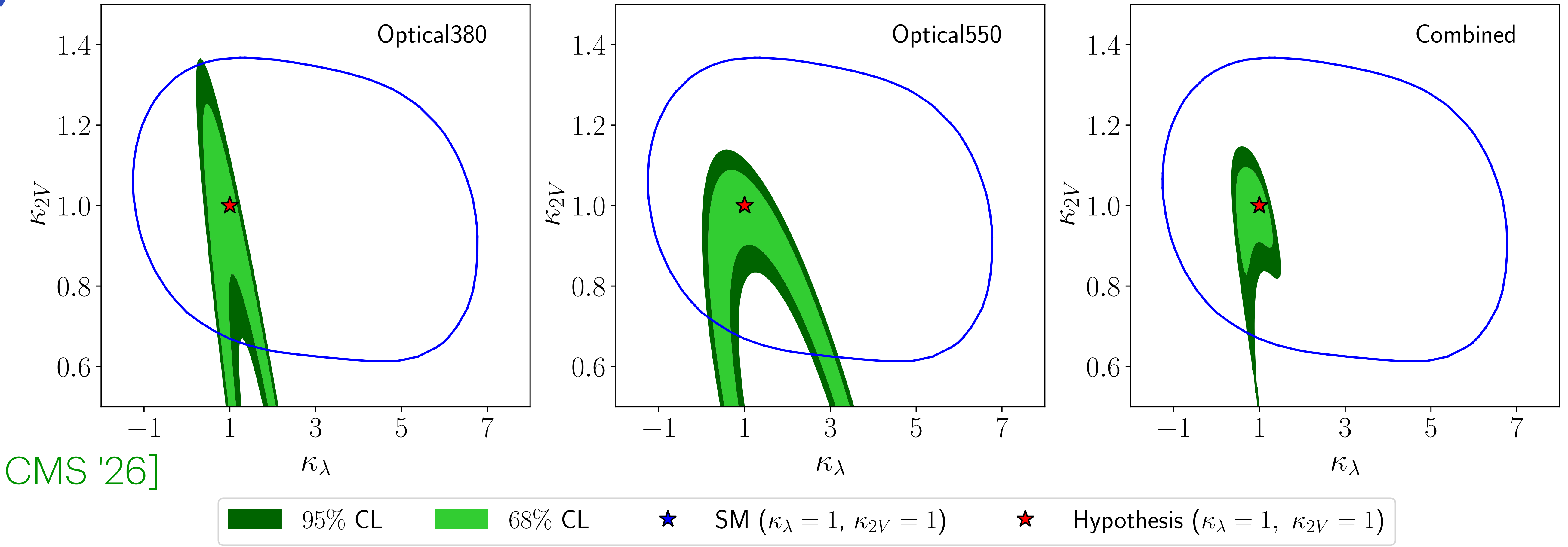
- Run 5 years at each of the energies and combine the sensitivity

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i + (\epsilon E_i)^2}$$

- For each choice of true κ_λ, κ_{2V} and κ_{tt} confidence level regions have to be calculated

Optical collider - $\kappa_\lambda/\kappa_{2V}$ analysis

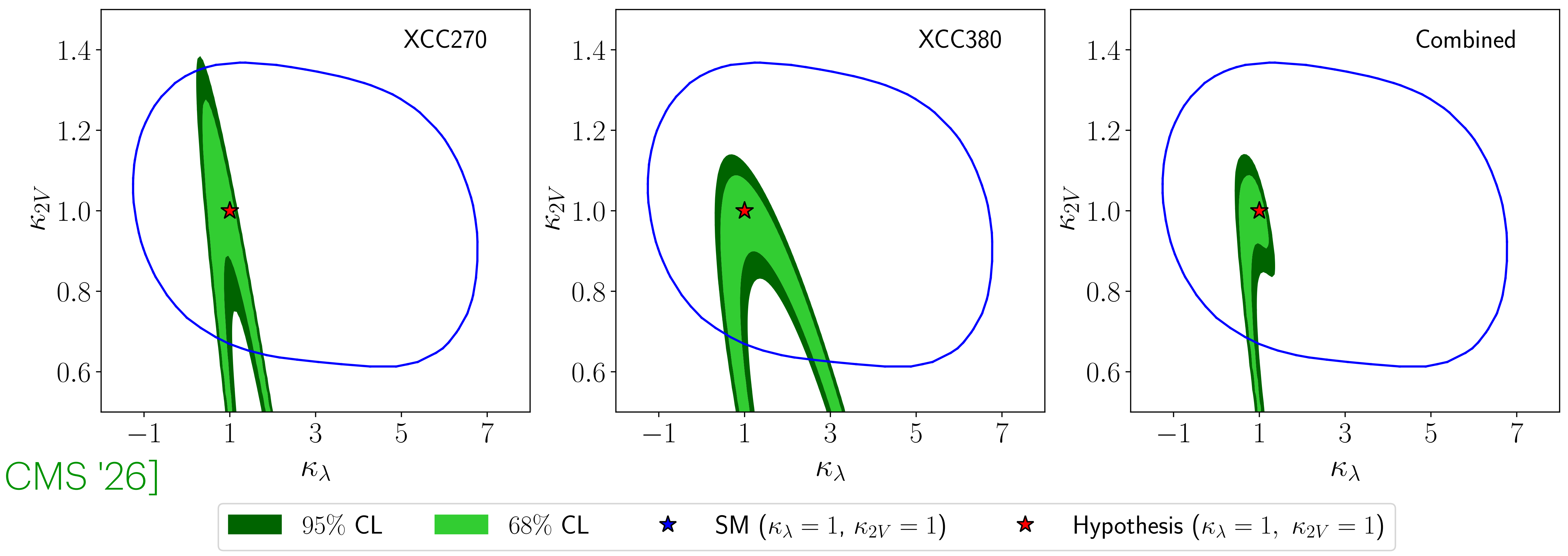
- Possible to achieve more precise limits
- In the full plane between κ_λ and κ_{2V}
- Current limits by ATLAS and CMS:
  - $\kappa_\lambda \in [-0.71,\ 6.1]$ and $\kappa_{2V} \in [0.73,\ 1.3]$ [ATLAS, CMS '26]



$\kappa_\lambda^{true} = 1,\ \kappa_{2V}^{true} = 1$ 95 % CL	**Both parameters free**	**Both parameters free**	$\kappa_{2V} = 1$	$\kappa_\lambda = 1$
Optical380	$\kappa_\lambda \in [0.25,\ 1.81]$	$\kappa_{2V} \in [0.66,\ 1.35]$	$\kappa_\lambda \in [0.44,\ 1.23]$	$\kappa_{2V} \in [0.68,\ 1.13]$
Optical550	$\kappa_\lambda \in [0.05,\ 3.06]$	$\kappa_{2V} \in [0.66,\ 1.14]$	$\kappa_\lambda \in [0.12,\ 1.62]$	$\kappa_{2V} \in [0.84,\ 1.10]$
Optical combined	$\kappa_\lambda \in [0.38,\ 1.49]$	$\kappa_{2V} \in [0.68,\ 1.15]$	$\kappa_\lambda \in [0.44,\ 1.23]$	$\kappa_{2V} \in [0.87,\ 1.08]$

XCC - $\kappa_\lambda/\kappa_{2V}$ analysis

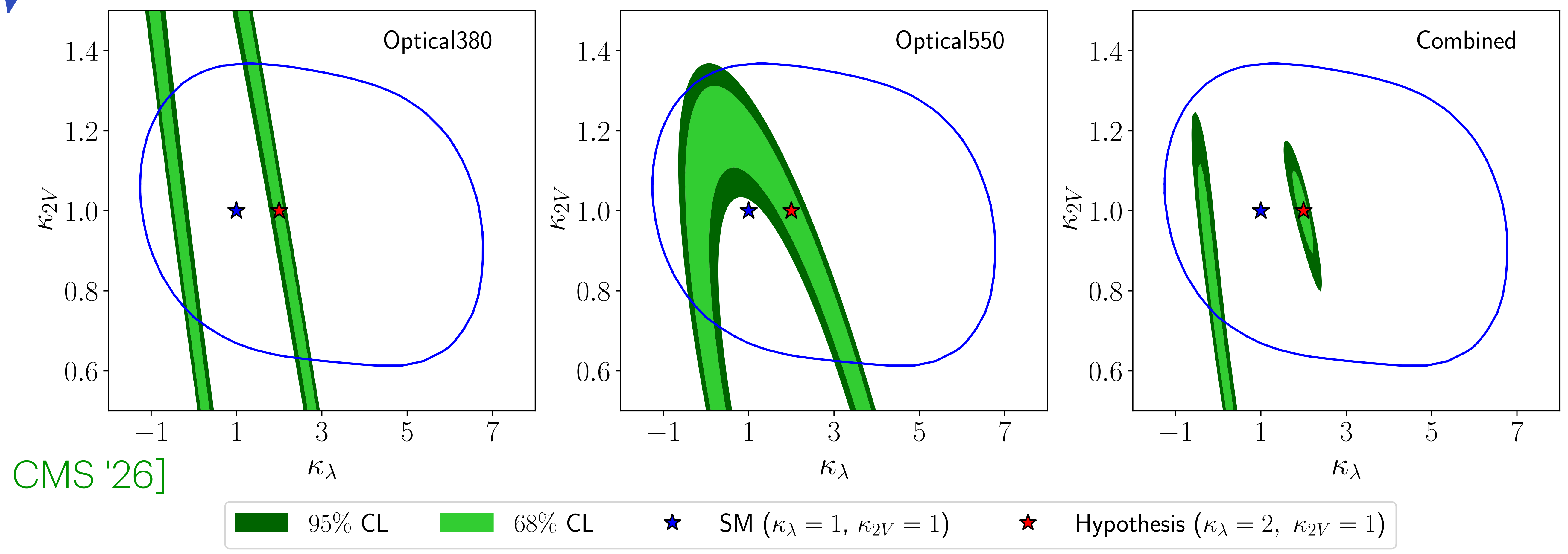
- Possible to achieve more precise limits
- In the full plane between κ_λ and κ_{2V}
- Current limits by ATLAS and CMS:
  - $\kappa_\lambda \in [-0.71,\ 6.1]$ and $\kappa_{2V} \in [0.73,\ 1.3]$ [ATLAS, CMS '26]



$\kappa_\lambda^{\text{true}} = 1,\ \kappa_{2V}^{\text{true}} = 1$ 95 % CL	**Both parameters free**	**Both parameters free**	$\kappa_{2V} = 1$	$\kappa_\lambda = 1$
XCC270	$\kappa_\lambda \in [0.25,\ 1.75]$	$\kappa_{2V} \in [0.66,\ 1.35]$	$\kappa_\lambda \in [0.44,\ 1.16]$	$\kappa_{2V} \in [0.68,\ 1.10]$
XCC380	$\kappa_\lambda \in [0.31,\ 2.86]$	$\kappa_{2V} \in [0.66,\ 1.14]$	$\kappa_\lambda \in [0.38,\ 1.62]$	$\kappa_{2V} \in [0.68,\ 1.10]$
XCC combined	$\kappa_\lambda \in [0.44,\ 1.36]$	$\kappa_{2V} \in [0.68,\ 1.14]$	$\kappa_\lambda \in [0.51,\ 1.16]$	$\kappa_{2V} \in [0.89,\ 1.07]$

Optical collider - $\kappa_\lambda/\kappa_{2V}$ analysis

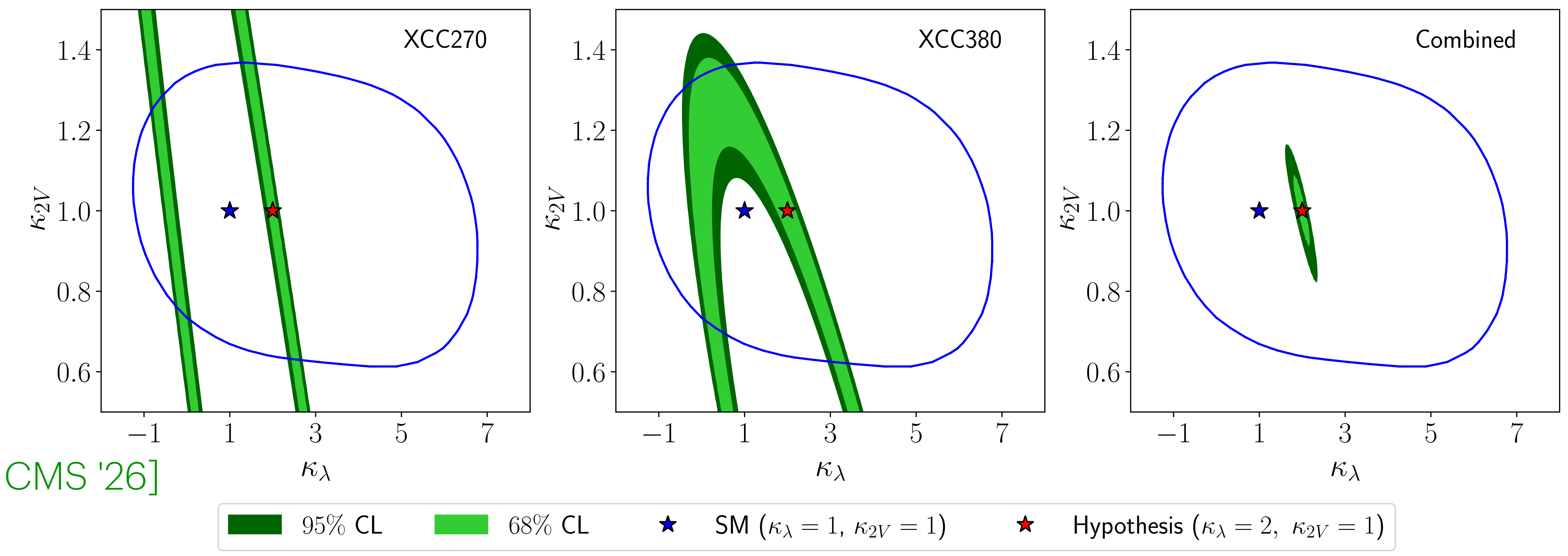
- Possible to achieve more precise limits
- In the full plane between κ_λ and κ_{2V}
- Current limits by ATLAS and CMS:
  - $\kappa_\lambda \in [-0.71,\ 6.1]$ and $\kappa_{2V} \in [0.73,\ 1.3]$ [ATLAS, CMS '26]



$\kappa_\lambda^{\mathrm{true}} = 2,\ \kappa_{2V}^{\mathrm{true}} = 1$ 95 % CL	**Both parameters free**	**Both parameters free**	$\kappa_{2V} = 1$	$\kappa_\lambda = 2$
Optical380	$\kappa_\lambda \in [-0.80,\ 0.18] \cup [1.16,\ 2.66]$	$\kappa_{2V} \in [0.66,\ 1.36]$	$\kappa_\lambda \in [-0.47, -0.21] \cup [1.81,\ 2.14]$	$\kappa_{2V} \in [0.87,\ 1.08]$
Optical550	$\kappa_\lambda \in [-0.60,\ 3.51]$	$\kappa_{2V} \in [0.66,\ 1.35]$	$\kappa_\lambda \in [-0.54,\ 0.25] \cup [1.42,\ 2.34]$	$\kappa_{2V} \in [0.90,\ 1.07]$
Optical combined	$\kappa_\lambda \in [-0.60,\ 0.12] \cup [1.55,\ 2.40]$	$\kappa_{2V} \in [0.73,\ 1.25]$	$\kappa_\lambda \in [-0.47, -0.21] \cup [1.81,\ 2.14]$	$\kappa_{2V} \in [0.93,\ 1.05]$

XCC - $\kappa_\lambda/\kappa_{2V}$ analysis

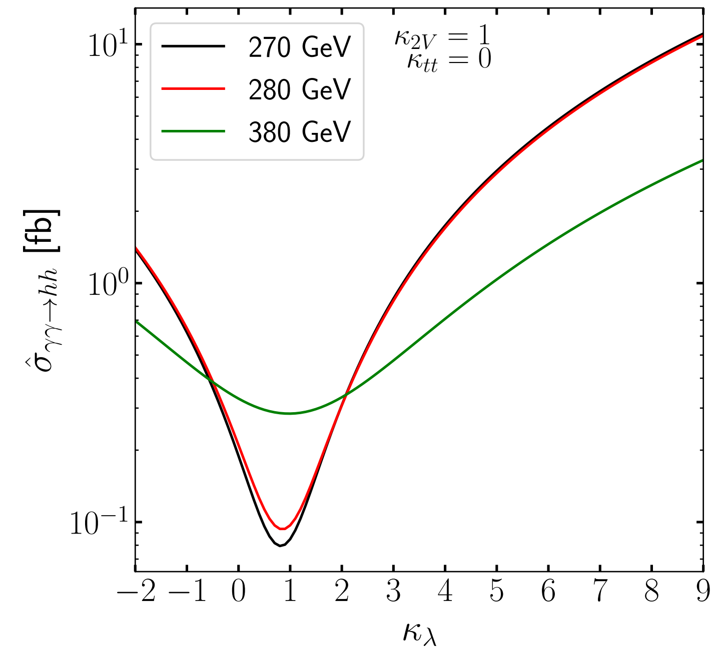
- Possible to achieve more precise limits
- In the full plane between κ_λ and κ_{2V}
- Current limits by ATLAS and CMS:
  - $\kappa_\lambda \in [-0.71,\ 6.1]$ and $\kappa_{2V} \in [0.73,\ 1.3]$ [ATLAS, CMS '26]



$\kappa_\lambda^{\text{true}} = 2,\ \kappa_{2V}^{\text{true}} = 1$ 95 % CL	**Both parameters free**	**Both parameters free**	$\kappa_{2V} = 1$	$\kappa_\lambda = 2$
XCC270	$\kappa_\lambda \in [-0.80,\ 0.05] \cup [1.29,\ 2.60]$	$\kappa_{2V} \in [0.66,\ 1.36]$	$\kappa_\lambda \in [-0.54, -0.28] \cup [1.88,\ 2.14]$	$\kappa_{2V} \in [0.89,\ 1.08]$
XCC380	$\kappa_\lambda \in [-0.41,\ 3.32]$	$\kappa_{2V} \in [0.66,\ 1.36]$	$\kappa_\lambda \in [-0.28,\ 0.31] \cup [1.68,\ 2.21]$	$\kappa_{2V} \in [0.92,\ 1.07]$
XCC combined	$\kappa_\lambda \in [1.62,\ 2.34]$	$\kappa_{2V} \in [0.82,\ 1.16]$	$\kappa_\lambda \in [1.88,\ 2.08]$	$\kappa_{2V} \in [0.95,\ 1.04]$

HL-LHC + Photon collider

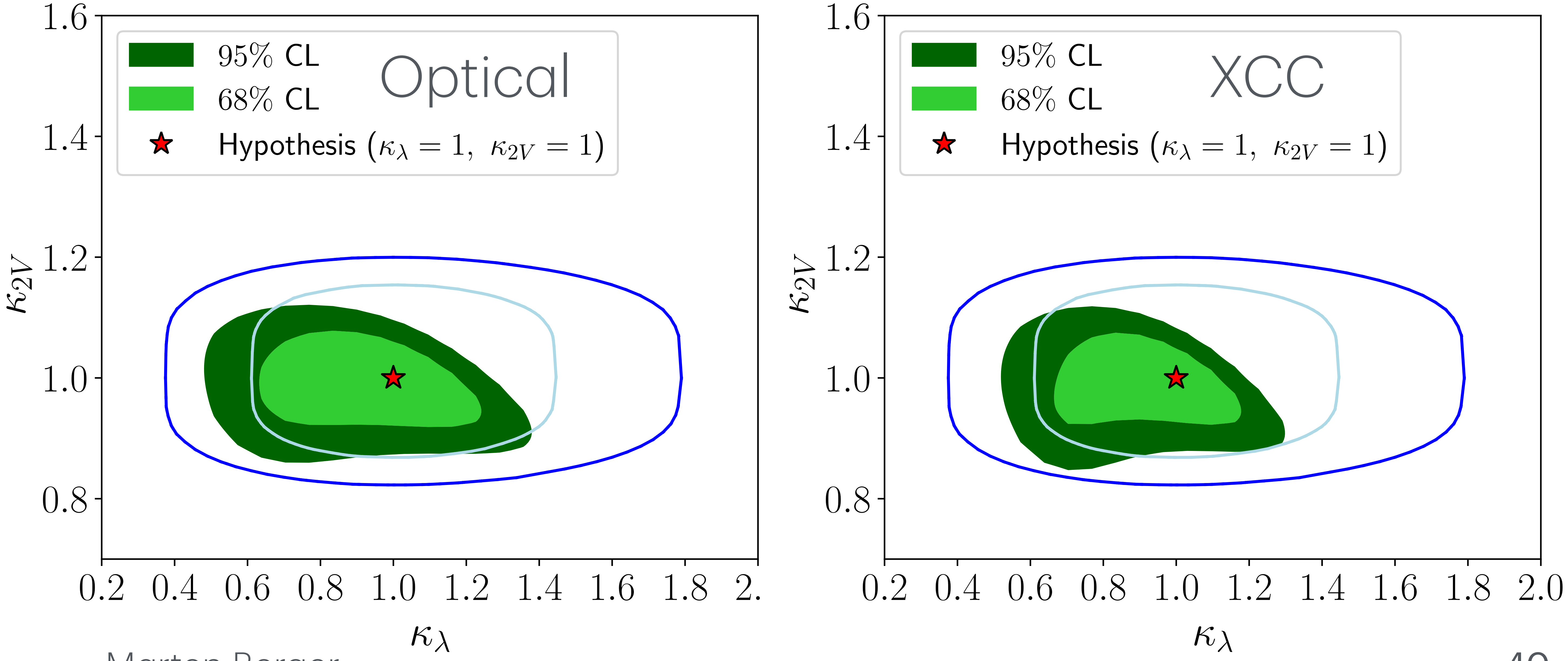
Reminder: minimum just below $\kappa_\lambda = 1$



- Combining the projected limits for HL-LHC with the photon collider

	κ_λ **68% CL**	κ_λ **95% CL**	κ_{2V} **68% CL**	κ_{2V} **95% CL**	$\kappa_{2V} = 1$ **68% CL**	$\kappa_{2V} = 1$ **95% CL**
Optical combined	$\kappa_\lambda \in [0.64,\ 1.23]$	$\kappa_\lambda \in [0.51,\ 1.36]$	$\kappa_{2V} \in [0.92,\ 1.07]$	$\kappa_{2V} \in [0.86,\ 1.12]$	$\kappa_\lambda \in [0.77,\ 1.10]$	$\kappa_\lambda \in [0.57,\ 1.23]$
XCC combined	$\kappa_\lambda \in [0.70,\ 1.16]$	$\kappa_\lambda \in [0.57,\ 1.29]$	$\kappa_{2V} \in [0.93,\ 1.07]$	$\kappa_{2V} \in [0.85,\ 1.12]$	$\kappa_\lambda \in [0.83,\ 1.03]$	$\kappa_\lambda \in [0.64,\ 1.16]$

- XCC at 68% CL manages -17%, +3% for $\kappa_{2V} = 1$
- Asymmetry due to the location of the cross-section minimum

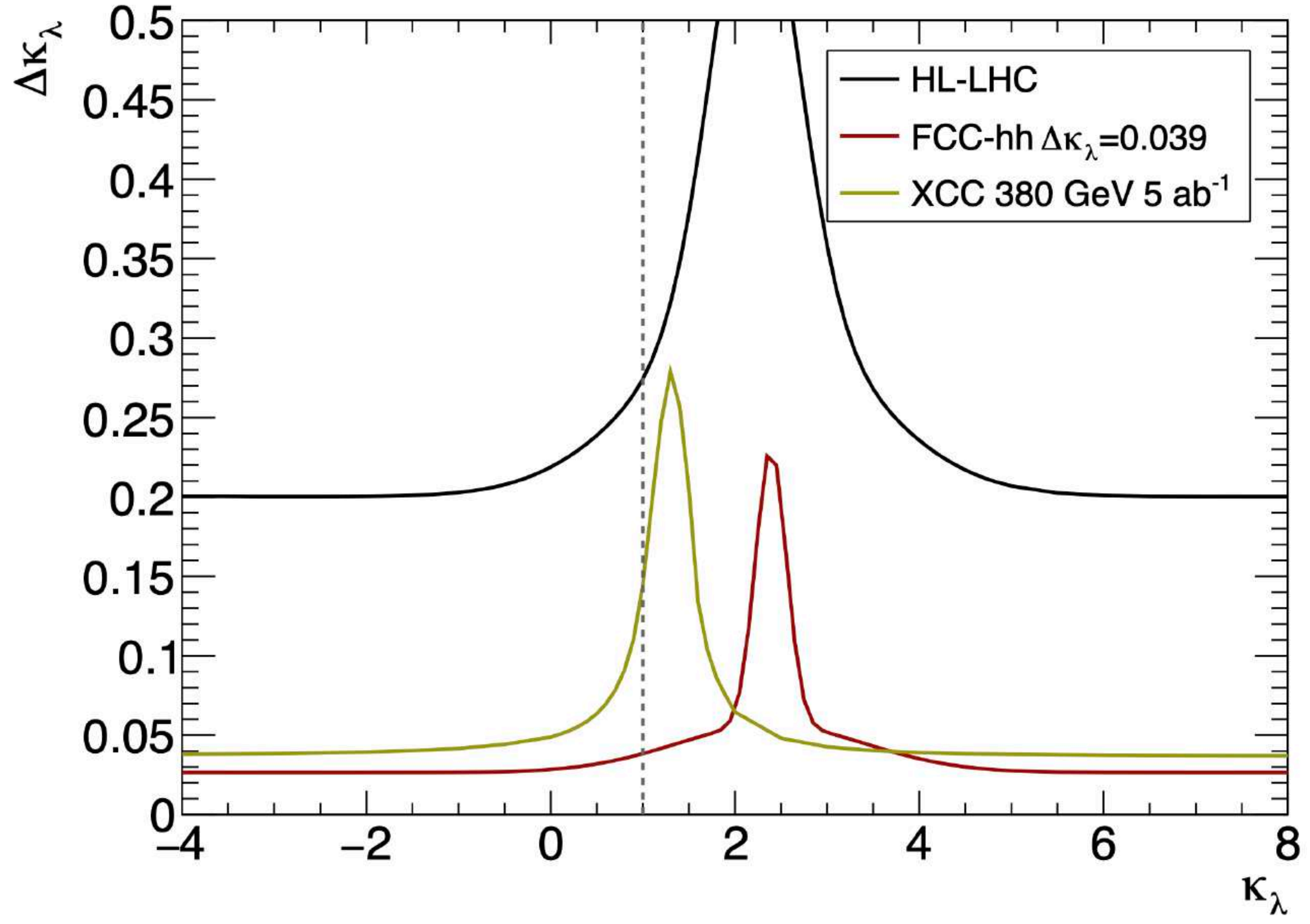


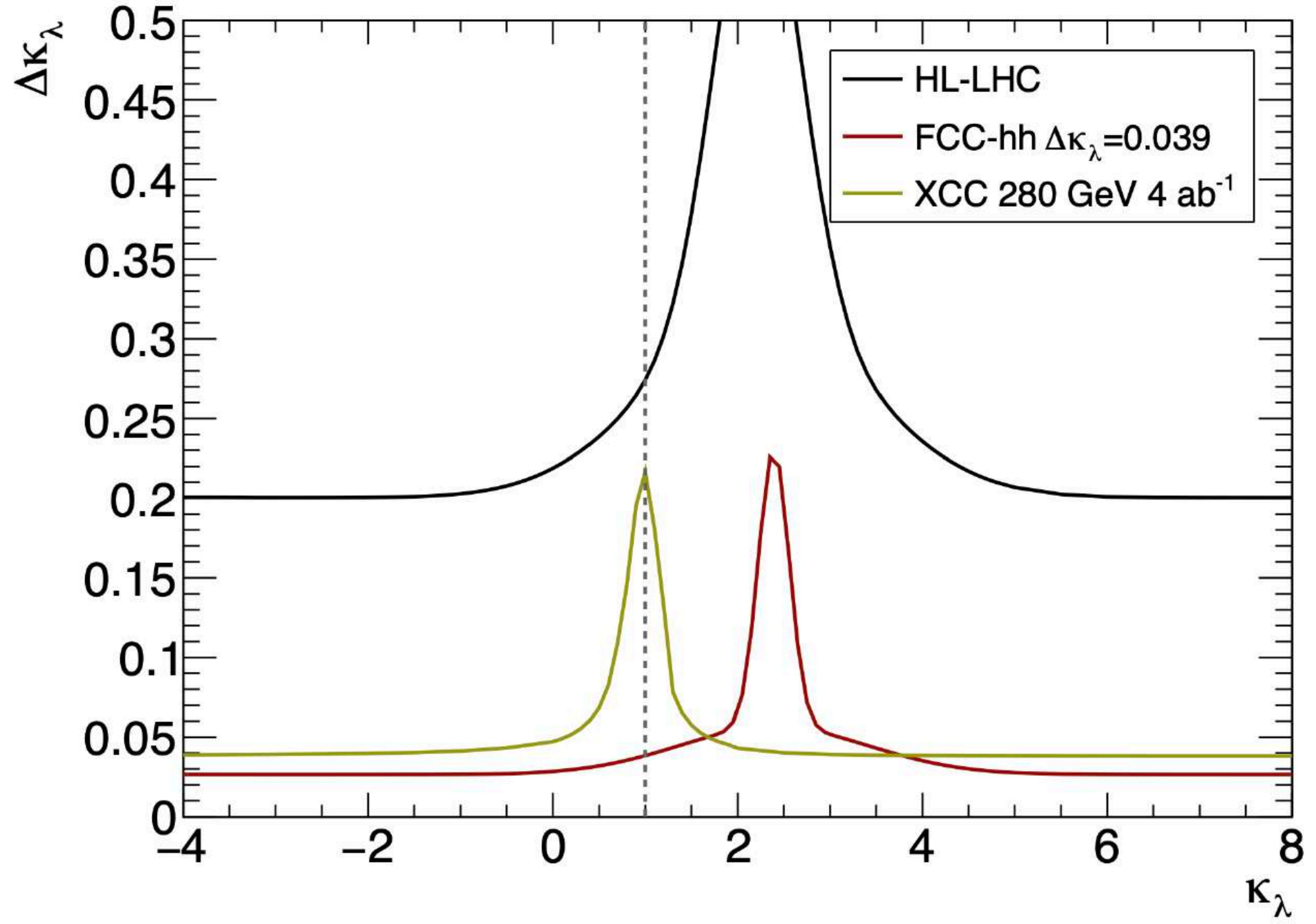
Photon collider - Detector analysis

[S. A. Castelazo, U. S. Qureshi, T. Barklow and A. Schwartzman '26]

Process	Initial Events	After Preselection	After GA
$\gamma\gamma \to HH \to b\bar{b}b\bar{b}$	**1,812**	**703**	**151**
$\gamma\gamma \to W^+W^- \to q\bar{q}q\bar{q}$	3,813,000	4,717	2
$\gamma\gamma \to t\bar{t}$	2,866,000	34,695	29
$\gamma\gamma \to ZZ \to q\bar{q}q\bar{q}$	1,378,000	98,527	8
$\gamma\gamma \to q\bar{q}$	307,700	11,112	6
$\gamma\gamma \to ZH \to q\bar{q}H$	8,202	1,004	9
$e\gamma \to eq\bar{q}$ or $\nu q\bar{q}$	41,195	1,206	1
$e\gamma \to eq\bar{q}q\bar{q}$ or $\nu q\bar{q}q\bar{q}$	7,681	137	0
$e\gamma \to eq\bar{q}H$	3,282	217	0
$e^+e^- \to q\bar{q}$	753,615	54,067	12
$e^+e^- \to W^+W^-$ or $ZZ \to q\bar{q}q\bar{q}$	152,212	14,121	2
$e^+e^- \to ZH \to q\bar{q}H$	123,698	13,771	62
$e^+e^- \to t\bar{t}$	57,001	648	1

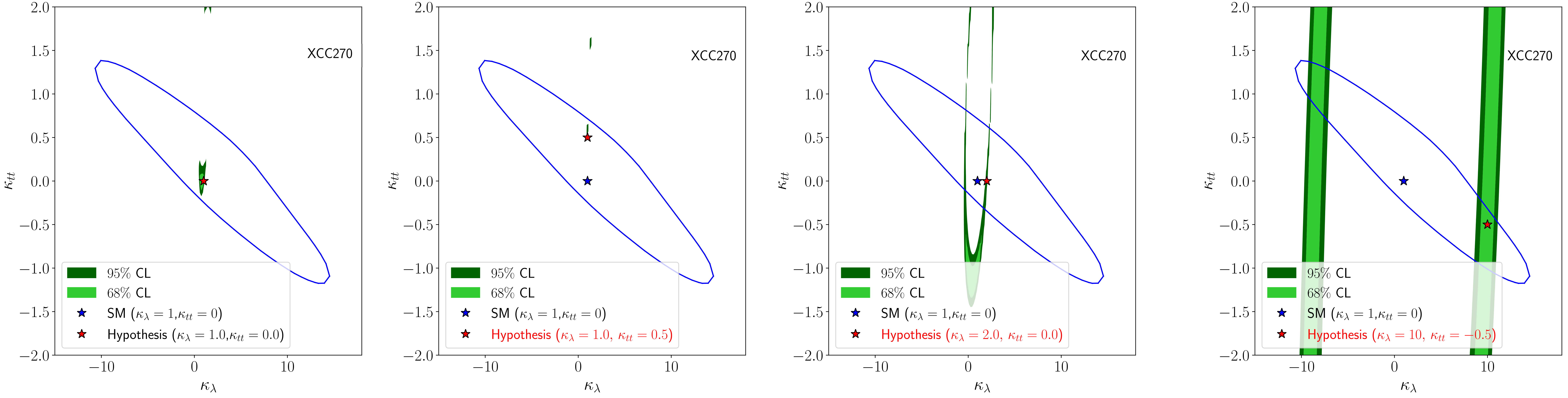
Table 3. Number of events after GA cuts on the BDT output distributions for the signal and backgrounds.





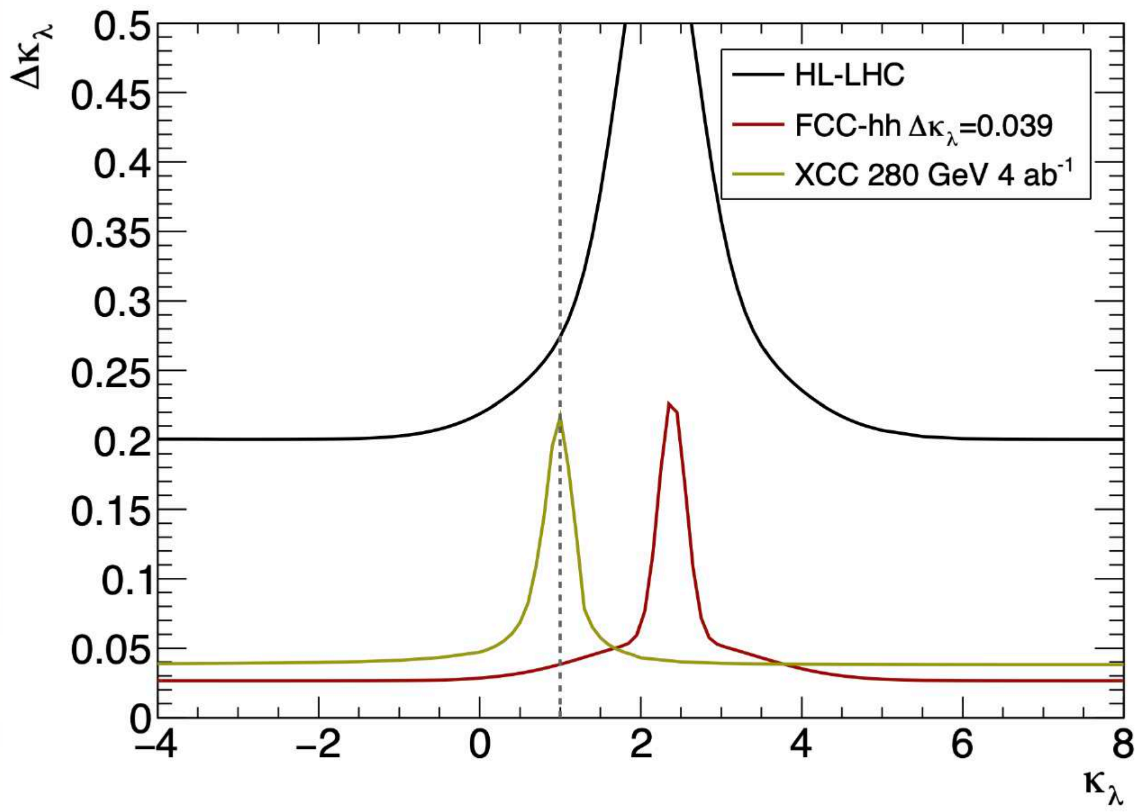
Photon collider - κ_{tt} dependency

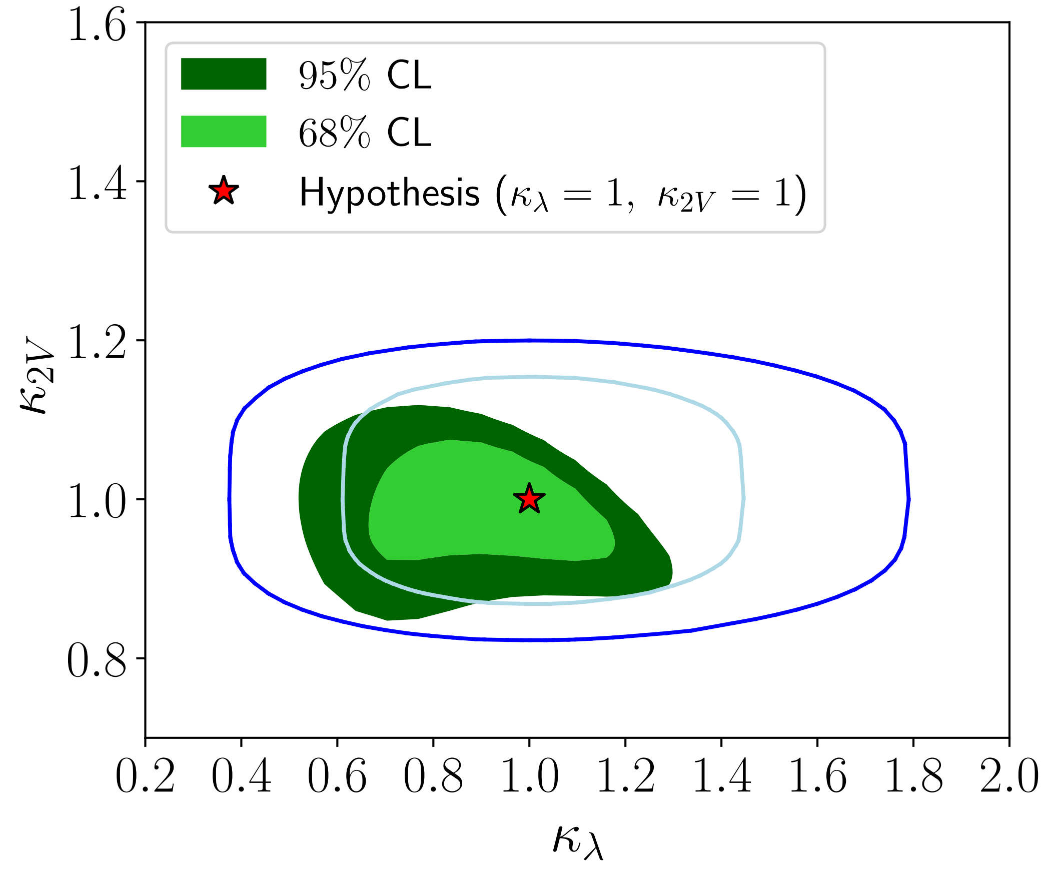
- The full XCC270 results in the $\kappa_\lambda/\kappa_{tt}$ plane
- The tight contours lead to very small exclusion ranges
- Slim connected areas between the limits not shown due to plotting limitation



Summary

- Photon colliders offer a vast physics program at the lowest centre-of-mass energies
- Two types of photon colliders: optical collider and the XCC, both offer similar physics reach but vastly different underlying technology
- Combining two energy searches for Higgs pair production offeres the best sensitivity and combining with HL-LHC projected limits gives $\Delta\kappa_\lambda = -27\,\%, +10\,\%$ for the optical collider and $\Delta\kappa_\lambda = -17\,\%, +3\,\%$ for the XCC at $\kappa_{2V} = 1,\ \kappa_{tt} = 0$
- Currently still a small community always looking for interested people





Heraeus Photon Collider Workshop

Hosted by the University of Hamburg and DESY, 17-19 March 2027

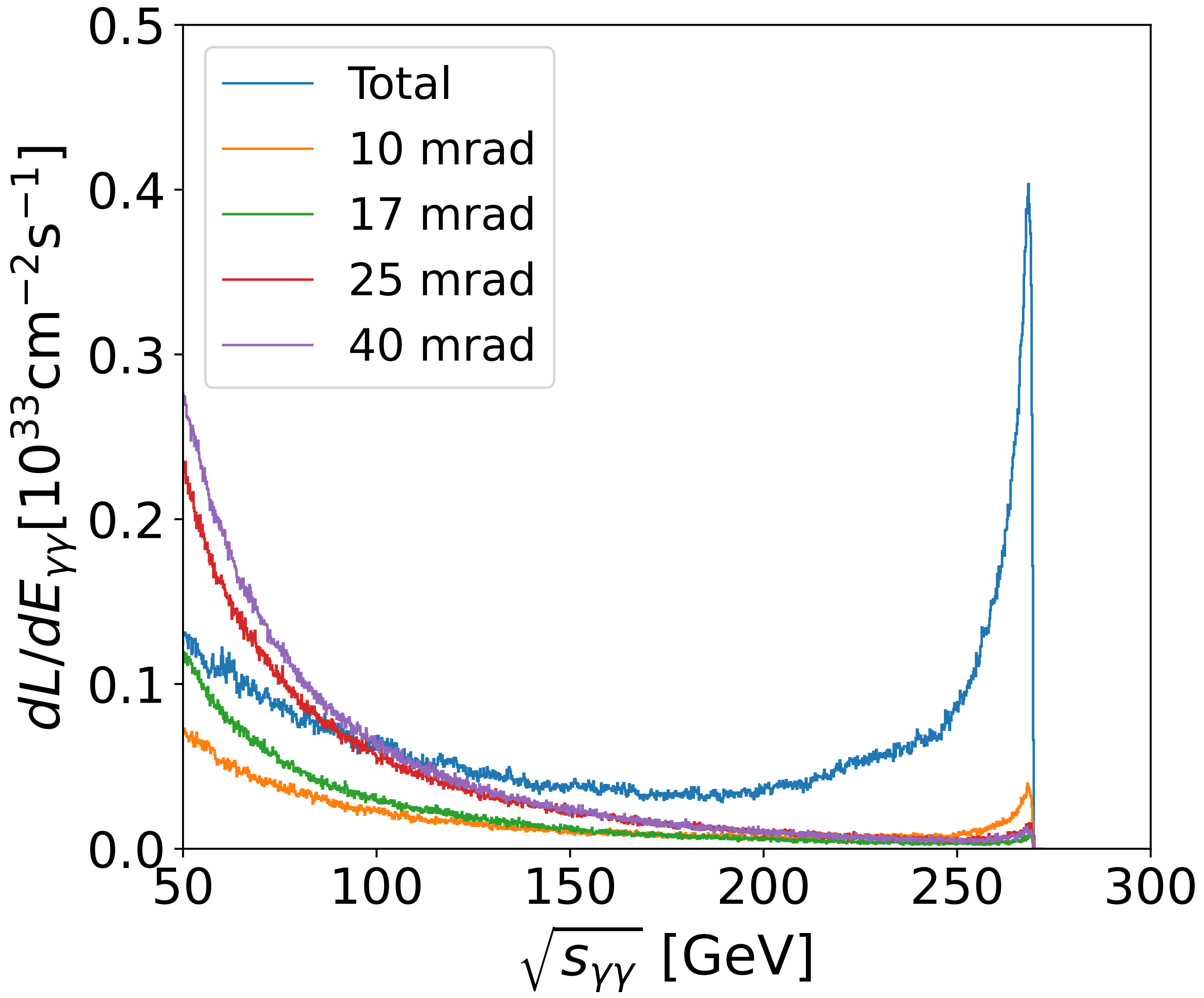
- Higgs and BSM precision physics at photon colliders
- Physics potential, new BSM searches, event generators, progress in lasers, accelerators and detectors
- **LOC**:
  G. Moortgat-Pick (UHH)
  J. Braathen (DESY)
- Registration will open in late October/early November
  Details and Indico page will follow
- **Please mark your calendars!**

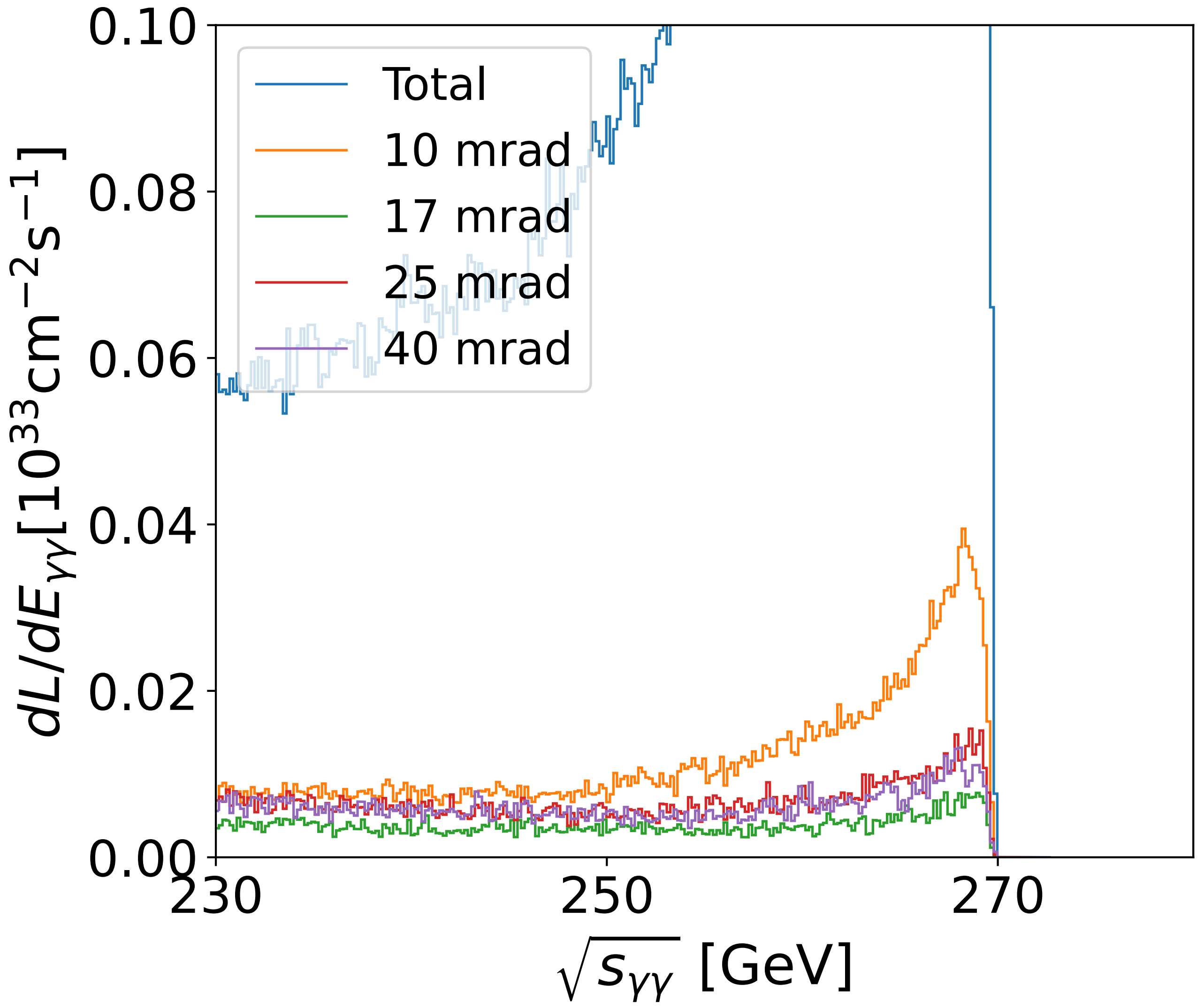
皆様のご参加をお待ちしています!

Thank you for listening

Photon collider - XCC open questions

- The XCC design currently opperates with a small crab crossing angle (2 mrad)
- Most future colliders plan for a crab crossing angle of 14-20 mrad
- Can use larger crab crossing for the XCC design, but requires 4 times the laser intesity
- Additionally the angle between the laser and electron beam at conversion point requires a full study within a test facility, due to changes in the angle leading to large drops in luminosity





Why photon colliders?

- Photon collider would be ~60% of the cost of a comparable e^+e^--collider [T. Barklow et al. '23]
- Requires detailed study for modern optical collider
- No need for a positron source allows for large savings

Compared to the capital cost of $3.7B for one specific C^3-250 scenario
[M. Bai et al. '21]

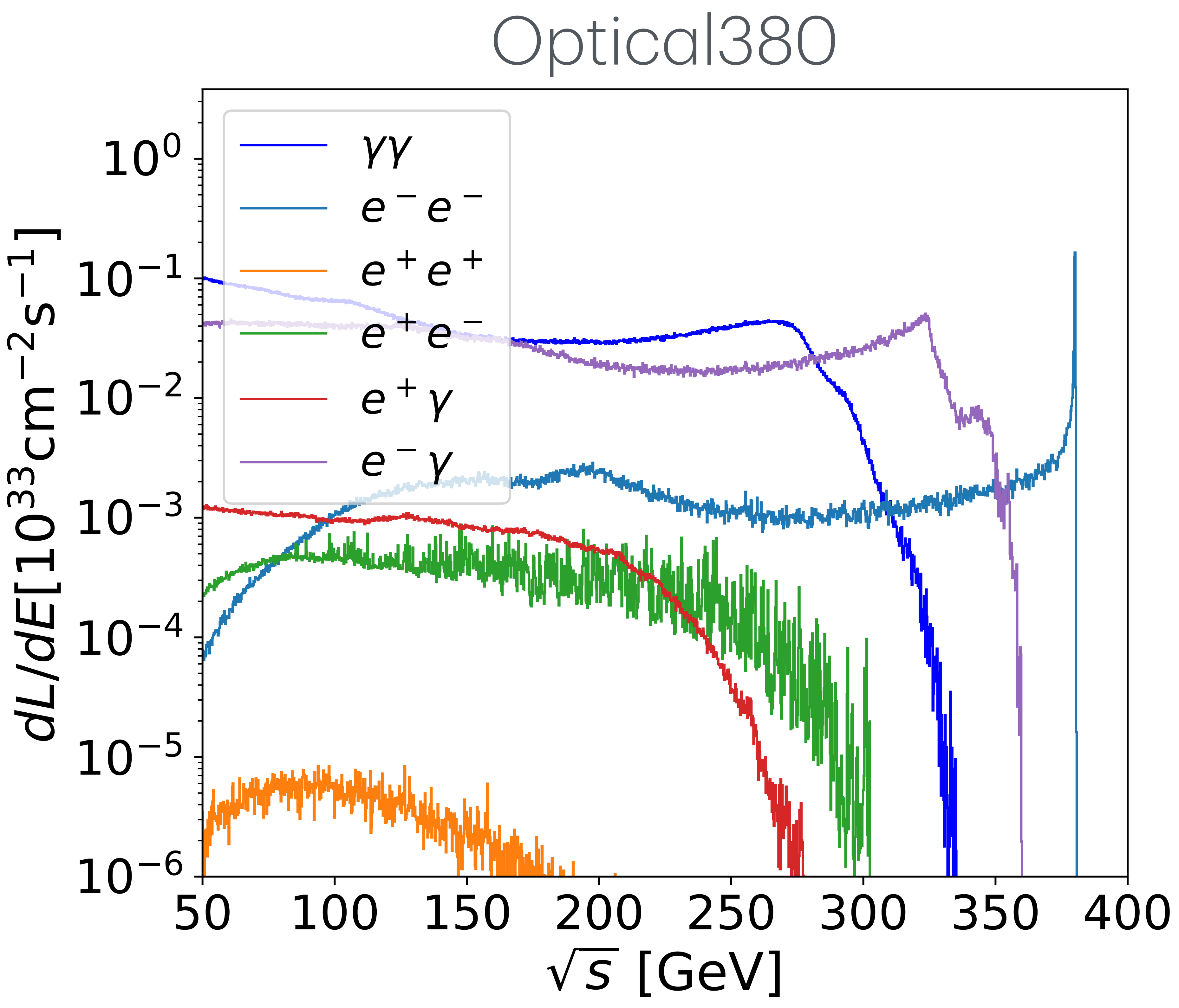
[T. Barklow et al. '23]

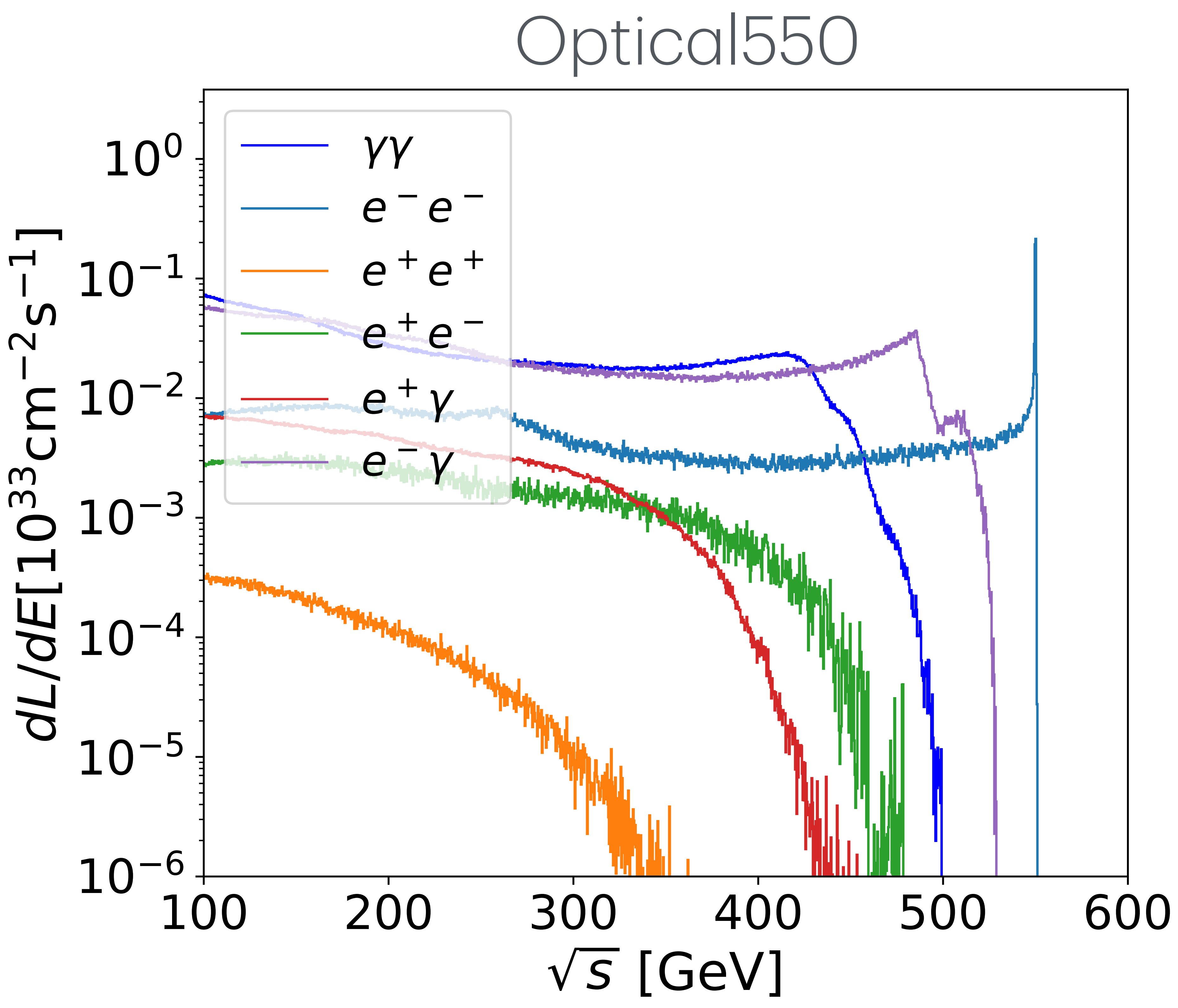
	Sub-Domain	%	%
Sources	Injectors	9	26
	FEL	9	
	Beam Transport	9	
Main Linac	Cryomodule	9	30
	C-band Klystron	22	
BDS	Beam Delivery and Final Focus	7	15
	IR	8	
Support Infrastructure	Civil Engineering	5	28
	Common Facilities	18	
	Cryo-plant	6	
Total	2.3B$	100	100

Table 5. Initial estimate of XCC cost breakout using the C^3-250 cost model.

Photon collider - Optical background

- Not all electrons are converted, leading to different processes in the same interaction point

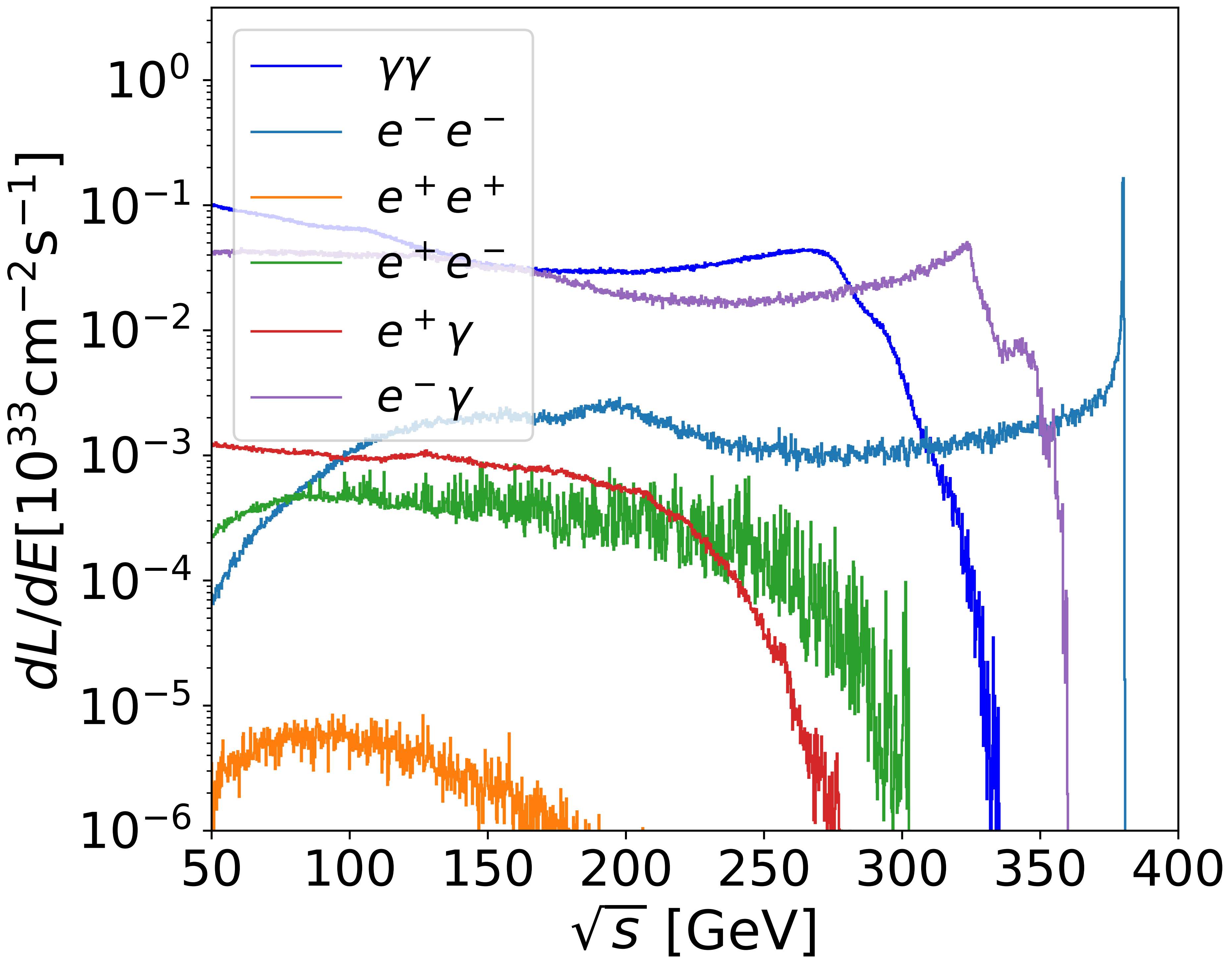




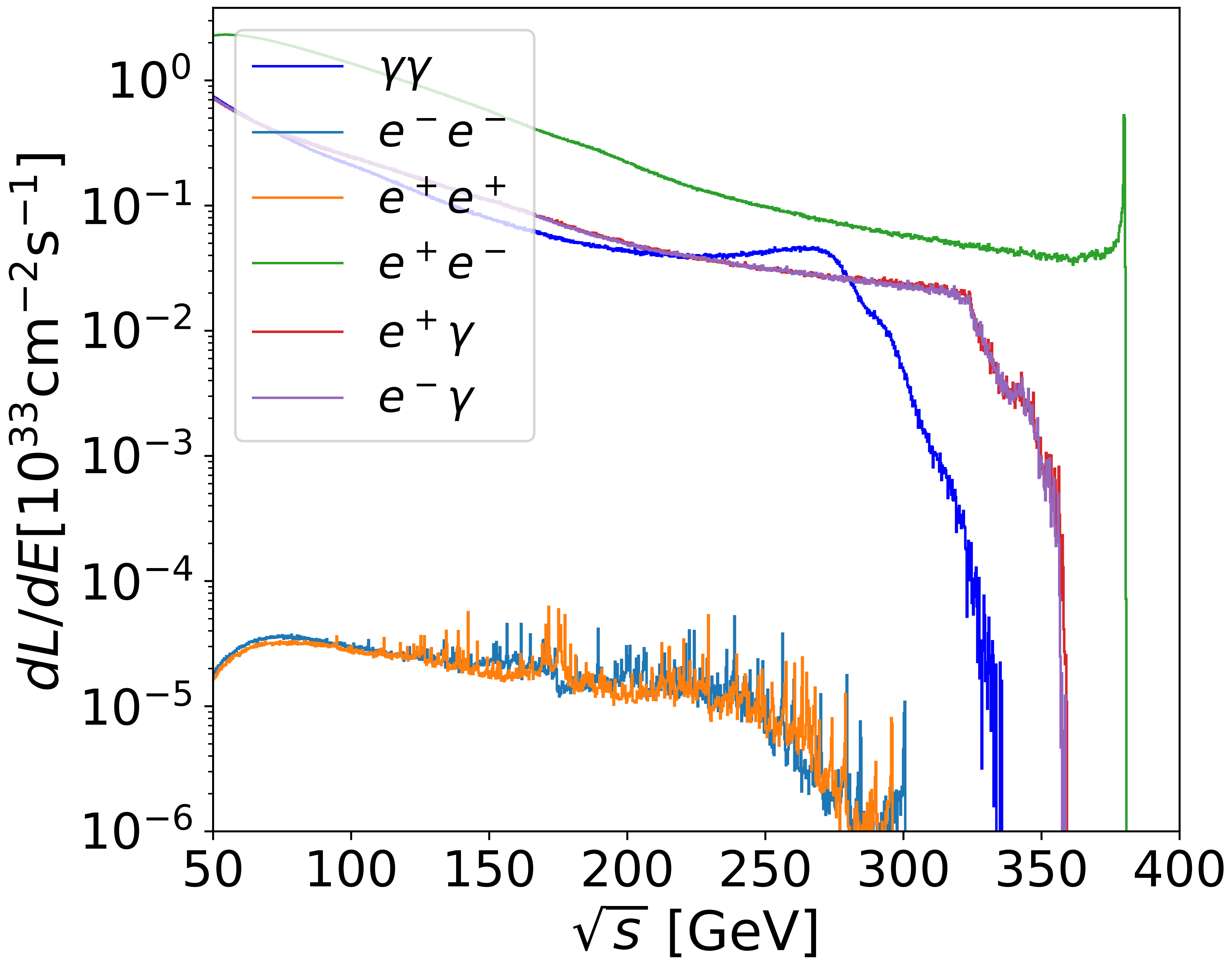
Photon collider - Positron background

- Not all electrons are converted, leading to different processes in the same interaction point

Optical380

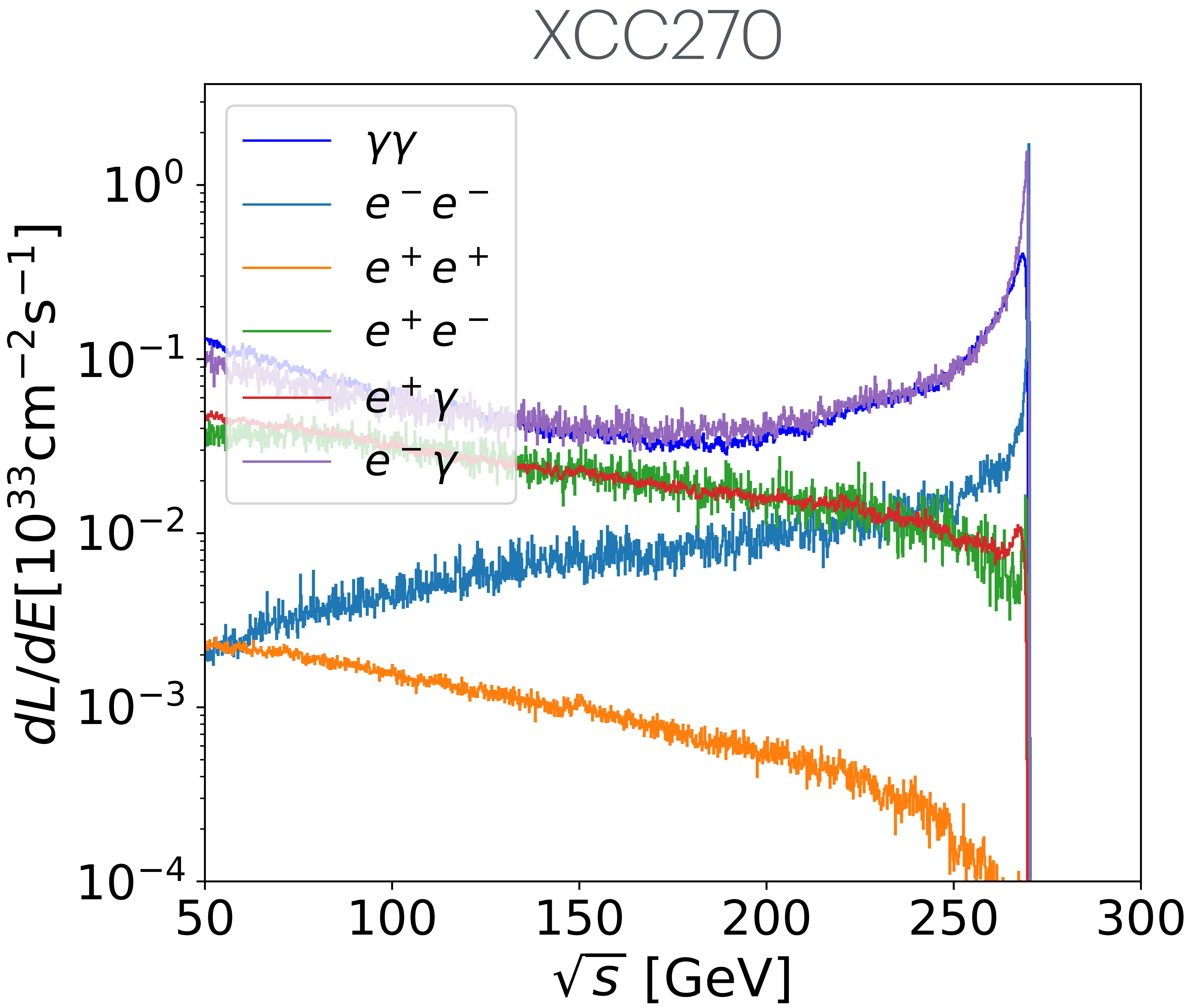


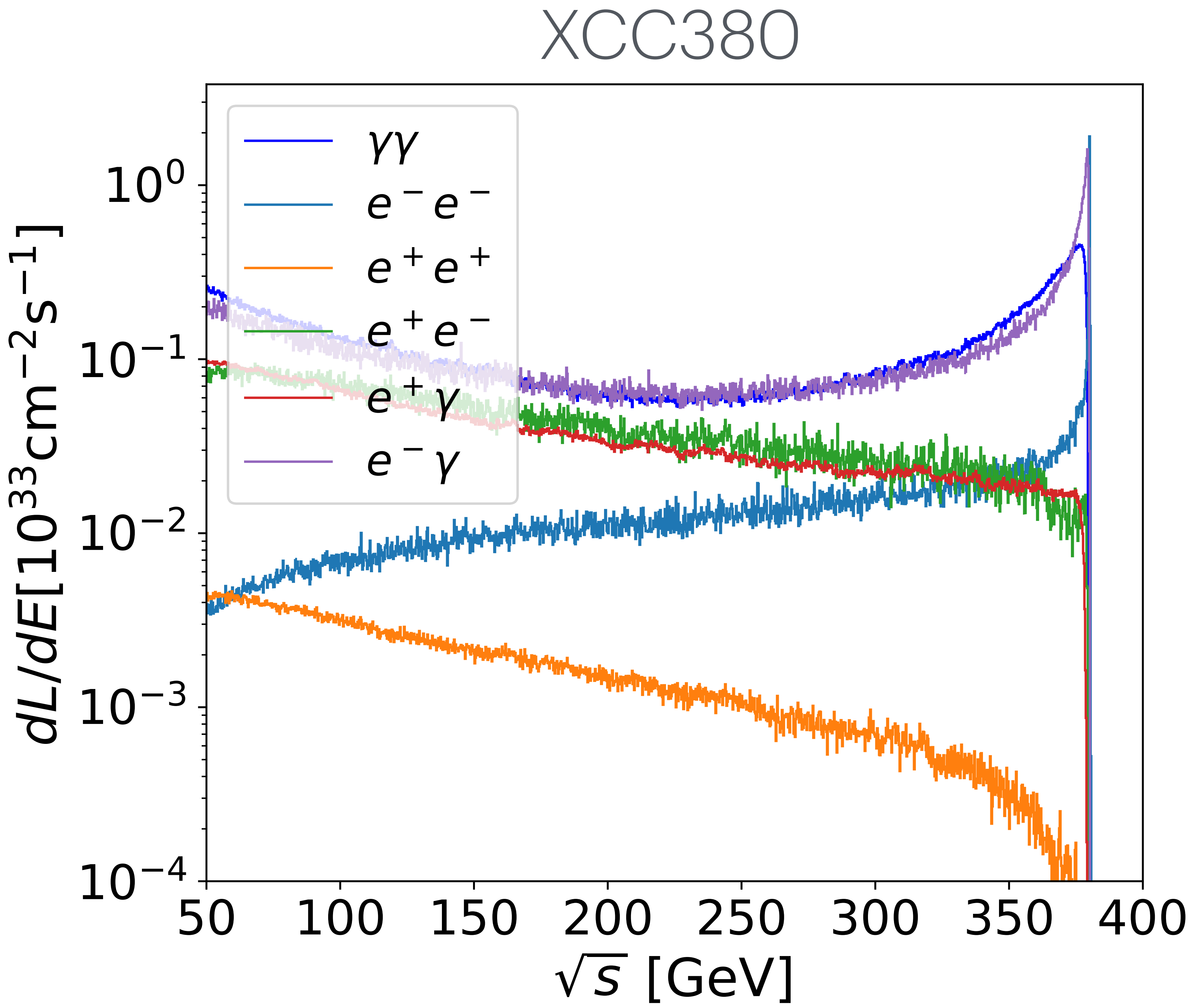
Positron380



Photon collider - XCC background

- Not all electrons are converted, leading to different processes in the same interaction point





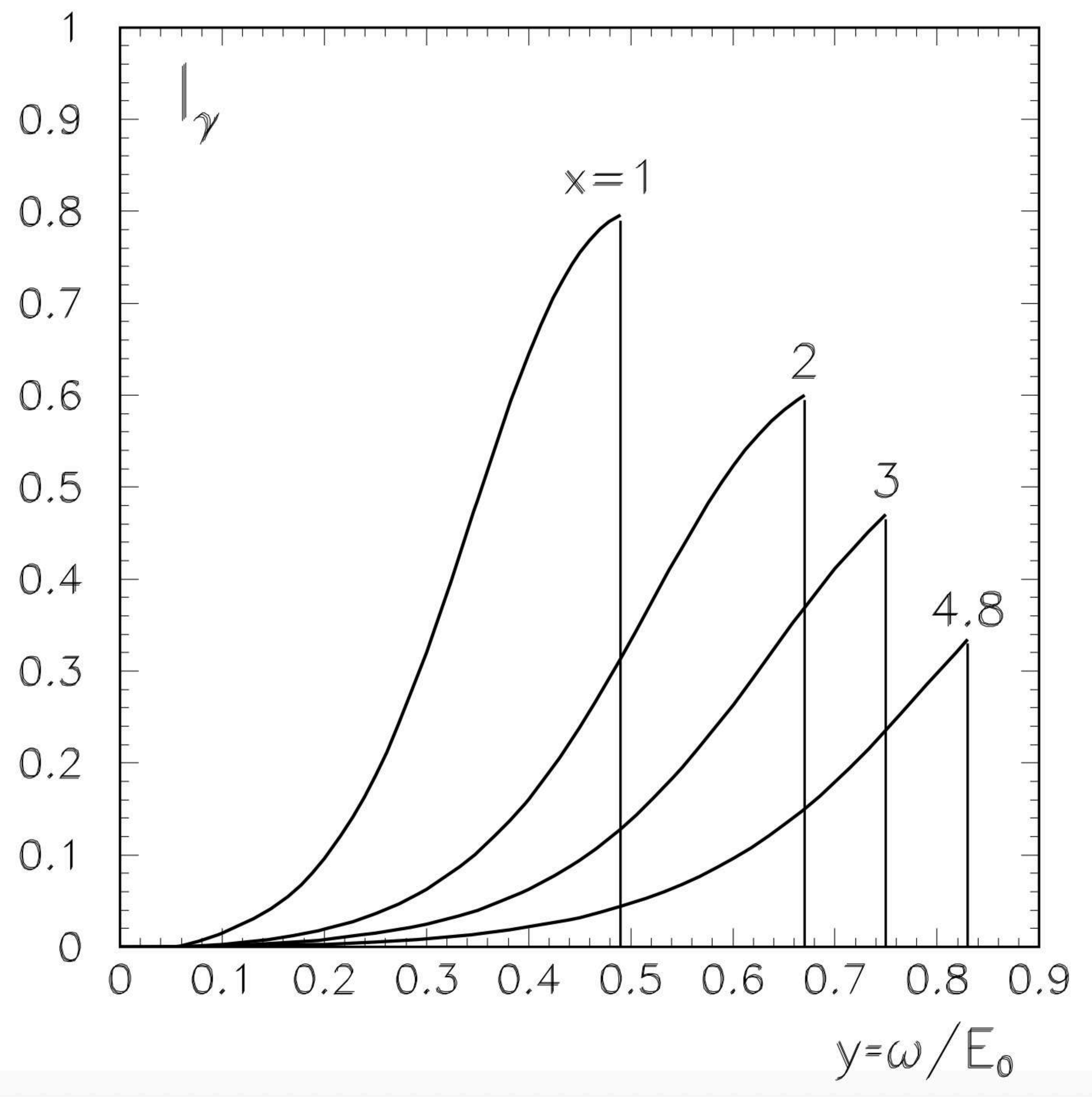
[I. F. Ginzburg, G. L. Kotkin, V. G. Serbo, V. I. Telnov '84]

Photon collider - Linear polarisation

- Scattered photons can also carry linear polarisation

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

- Very useful for CP studies of the Higgs
- Could increase the reach of ALPs searches



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

Photon collider - How to get the Beams

- Compton backscattering $\sigma_c = \sigma_c^{np} + \lambda_e P_c \sigma_c^p$, where

$$\sigma_c^{np} = \frac{2\pi\alpha^2}{x m_e^2}\left[\left(1 - \frac{4}{x} - \frac{8}{x^2}\right)\ln(x+1) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(x+1)^2}\right],$$

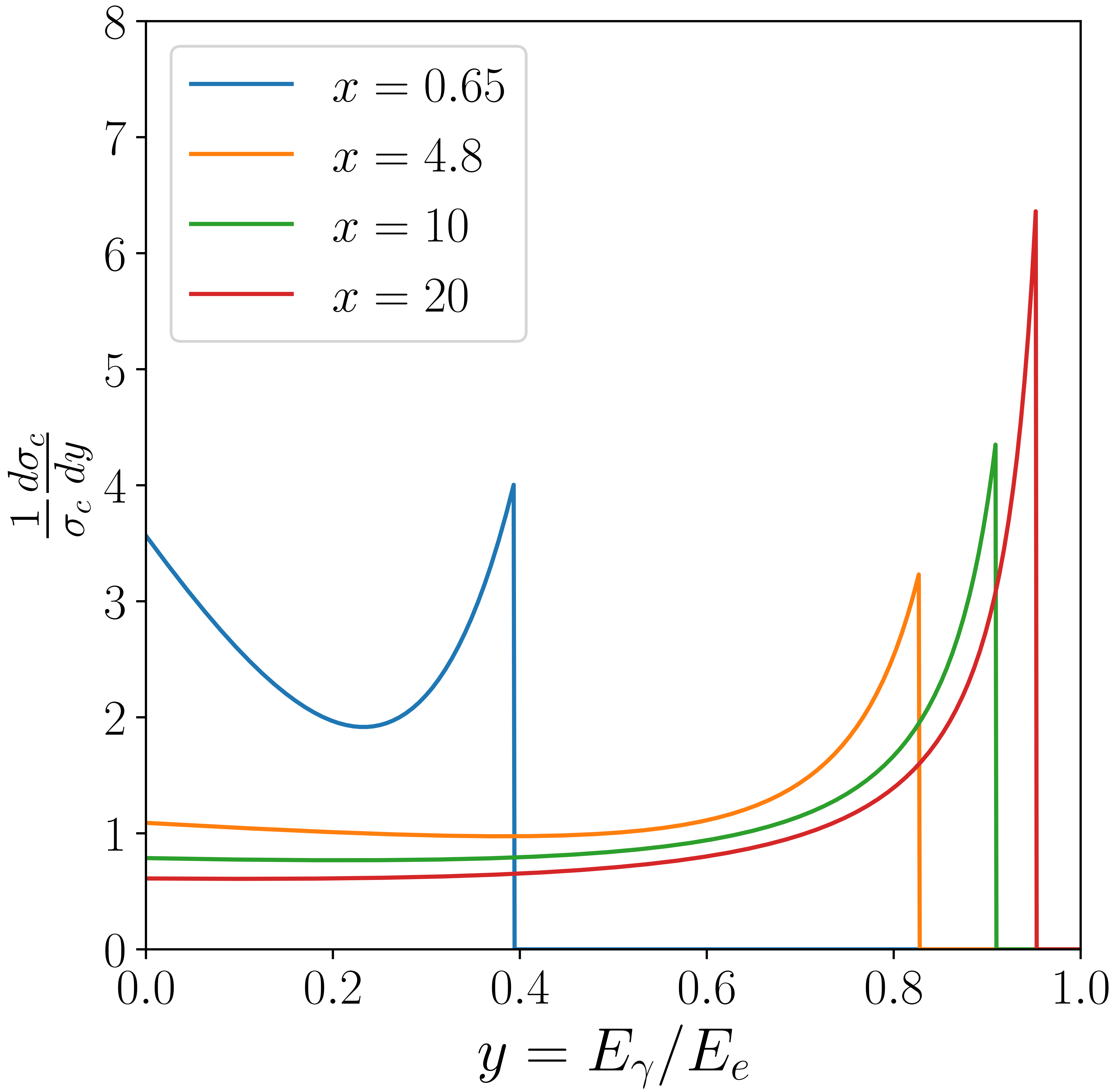
$$\sigma_c^{p} = \frac{2\pi\alpha^2}{x m_e^2}\left[\left(1 + \frac{2}{x}\right)\ln x + 1 - \frac{5}{2} + \frac{1}{x+1} - \frac{1}{2(x+1)^2}\right]$$

- The energy spectrum of the scattered photon beam

$$\frac{1}{\sigma_c}\frac{d\sigma_c}{dy} \equiv f(x,y)$$

$$= \frac{2\pi\alpha^2}{\sigma_c x m_e^2}\left[\frac{1}{1-y} + 1 - y - 4r(1-r) - \lambda_e P_c r x(2r-1)(2-y)\right]$$

$$r = \frac{y}{x(1-y)}$$



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

Photon collider - Additional parameters

- Non-linear QED effects, leads to additional harmonics

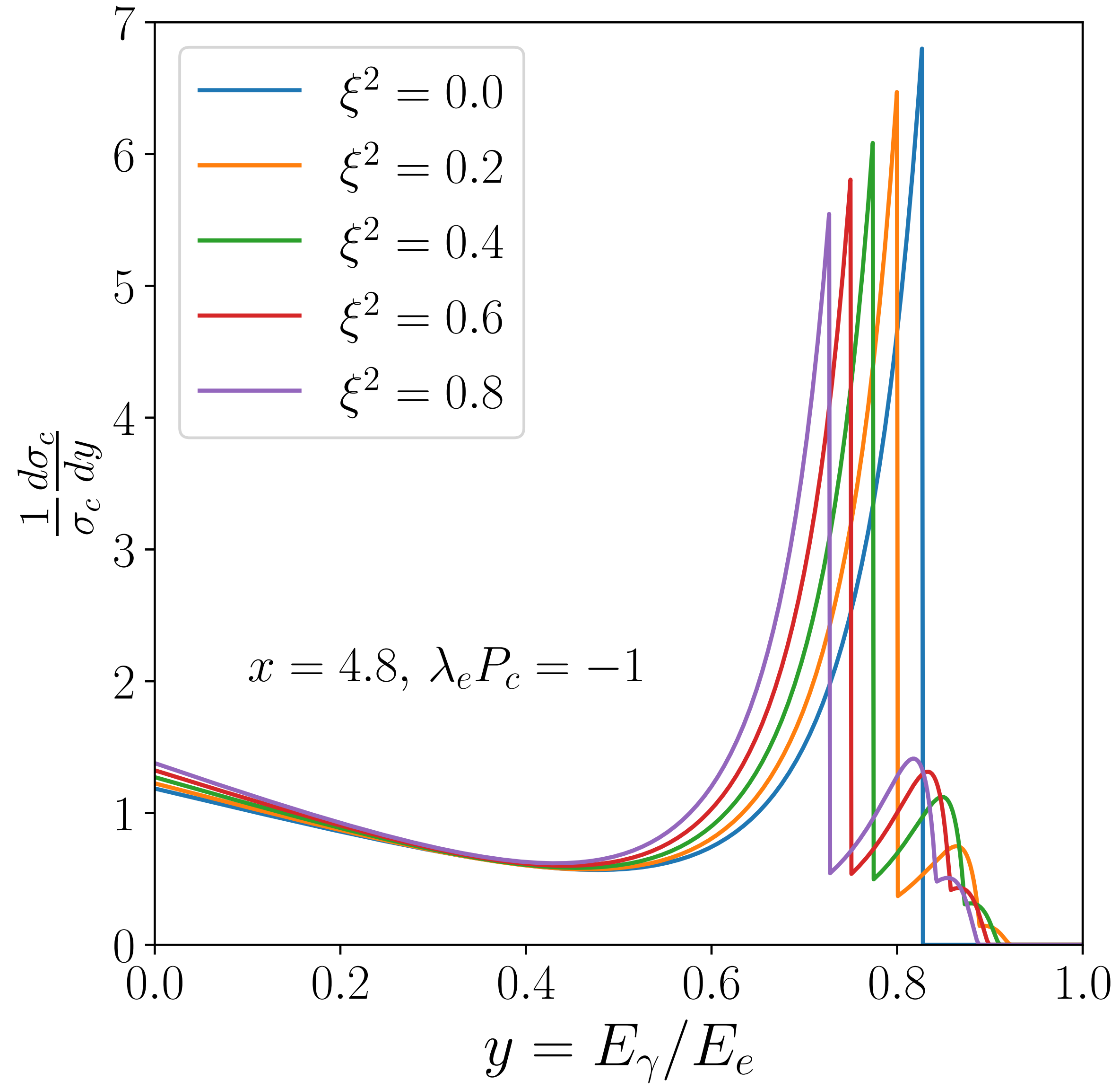
$$\xi^2 = \frac{e^2\bar{F}^2\hbar^2}{m_e^2c^2\omega_0^2} = \frac{2n_\gamma r_e^2\lambda}{\alpha} = \left(\frac{\lambda}{2\pi m_e}\right)^2 \mu_0 c P$$

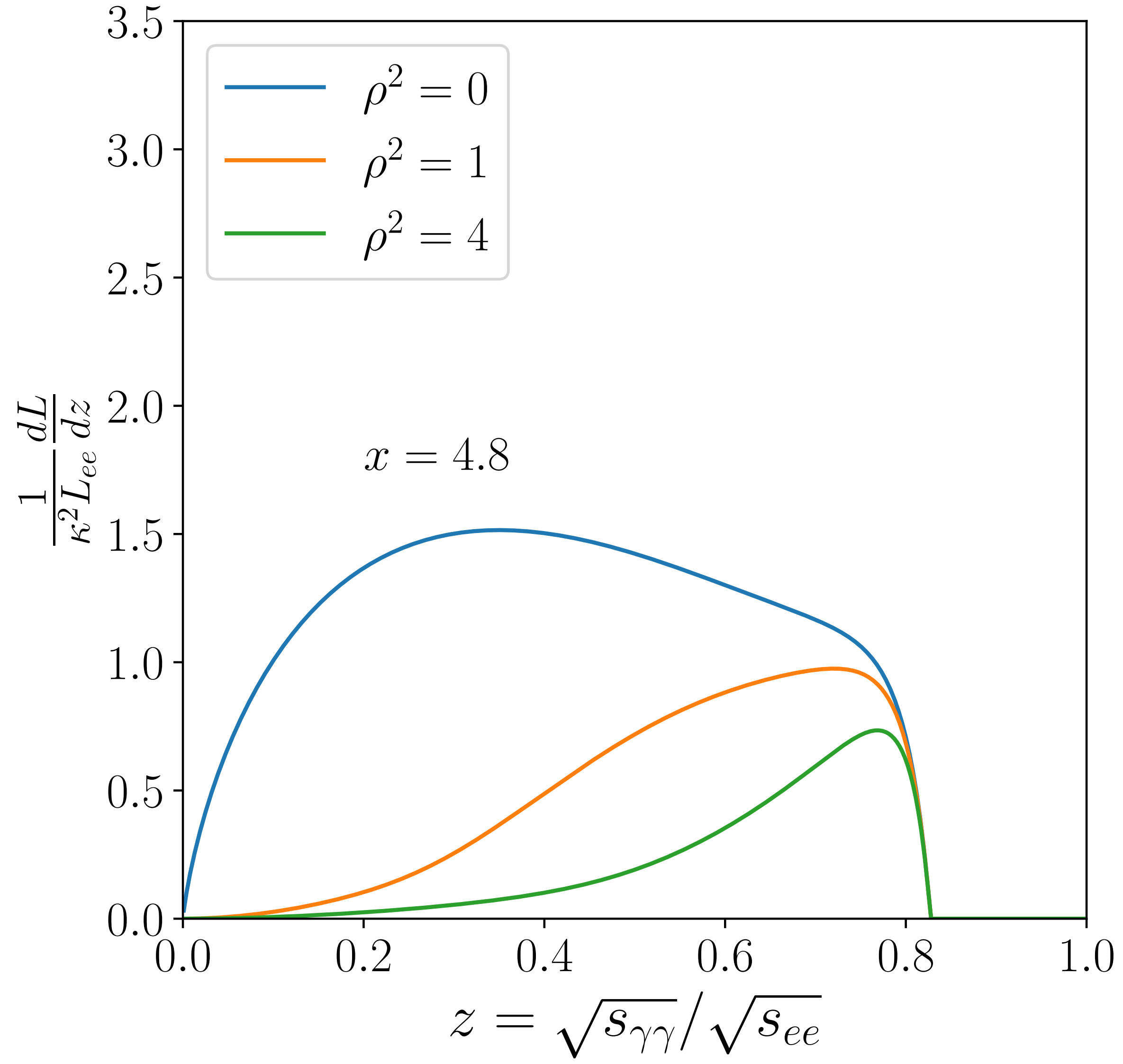
- The distance b between the conversion and interaction point

$\rho^2 = \left(\frac{b}{\gamma\sigma_x}\right)^2 + \left(\frac{b}{\gamma\sigma_y}\right)^2$, with $\sigma_{x/y}$ the transverse electron beam size

$$\frac{1}{L_{\gamma\gamma}}\frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}z} = \frac{1}{k^2L_{ee}}\frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}z} = 2z\int_{z^2/y_{max}}^{y_{max}}\frac{\mathrm{d}y}{y}f(x,y)f\left(x,\frac{z^2}{y}\right) * F(\rho),$$

$$F(\rho) = I_0\left(\rho^2\sqrt{\left(\frac{y_{max}}{y}-1\right)\left(\frac{y_{max}y}{z^2}-1\right)}\right)\exp\left[-\frac{\rho^2}{2}\left(\frac{y_{max}}{y}+\frac{y_{max}y}{z^2}-2\right)\right]$$





Photon collider - Flat-top laser

- New photon collider designs use flat-top laser beams, providing a higher effective conversion efficiency compared to Gaussian beam

	Flat-top	Gaussian
$I(r, z=0)$	$I_0 \left[\frac{2J_1(r/s)}{r/s}\right]^2$	$I_0 \exp\left(-2\frac{r^2}{\omega^2(z)}\right)$
	$s = \frac{f_\# \lambda}{\pi}$	$\omega(z) = \omega_0 \left[1 + \left(\frac{z}{z_R}\right)^2\right]^{1/2}$
$I(r=0, z)$	$I_0 \left[\frac{\sin(z/z_0)}{z/z_0}\right]^2$	$I_0 \left[1 + \left(\frac{z}{z_R}\right)^2\right]^{-1}$
	$z_0 = \frac{8}{\pi} f_\#^2 \lambda$	$z_R = \frac{4}{\pi} f_\#^2 \lambda$
Effective area	$\frac{f_\#^2 \lambda^2}{\pi}$	$\frac{\pi \omega_0^2}{2} = \frac{2 f_\#^2 \lambda^2}{\pi}$