BSM Higgs physics at the gamma-gamma collider

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In cooperation with
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Georg Weiglein, Monika Wüst

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- Introduction Gamma-gamma collider
- Laser Set-ups
- Di-Higgs
- Conclusion

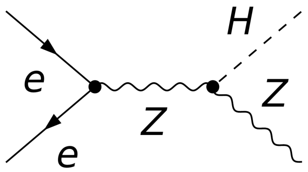
UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY.

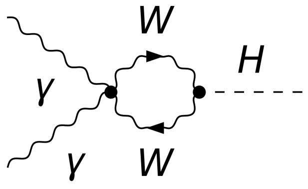
Introduction

- High energy photons collisions (ɣɣ and e-ɣ) offer a complementary physics program to e+e-:

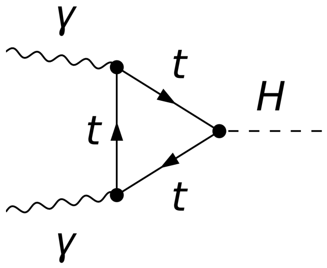
TESLA TDR 2001, JLC TDR 1998



- **The Higgs boson is produced in the s channel**
  - The electron beam energy is lower than what is required in e+e- collisions (65-80 GeV vs 125 GeV)
  - At higher center of mass energies, all phase space is available for producing the Higgs boson → higher mass reach for heavy Higgs bosons than e^+e^- at the same center of mass energy
  - ɣɣ can directly couple to spin-0 resonances whereas e+e- require the production of another spin-1 particle
    - complementary probe of the scalar sector



Ginzburg et al. 1983



- **Polarization of both electrons and photons**
  - Allows for a rich study of CP violation in the scalar sector

Complementarity ee vs γγ

- γγ collisions can produce **heavy Higgs bosons** with masses >1.5 times higher than e^+e^-:
  - $e^+e^- \to HA$ vs. $\gamma\gamma \to H$, $\gamma\gamma \to A$

Mühlleitner, Zerwas 2006

- $e^-\gamma$ collisions can produce **charged particles** with masses higher than pair-production in e^+e^-:
  - $e^-\gamma \to \tilde{e}\,\chi^0$

Kanemura 2001, Nauenberg 2001, Mühlleitner 2006

- Since $\gamma\gamma \to H$ is a loop-induced process, it can probe new physics contributions to the Higgs photon coupling: **sensitive to BSM particles in loops**

Grzadkowski,Gunion 1992, Krämer et al. 1994

Godbole, Kraml et al. 2006

- Ability to control the photon polarizations provides a powerful tool for the **exploration of CP properties** of any single neutral Higgs boson
  - The $J_z=0$ γγ initial state can form a CP-even or a CP-odd state using linear polarizations of the laser beams
  - CP-even Higgs bosons (h^0, H^0) couple to linearly polarized photons with maximum strength for parallel polarisation vectors
  - CP-odd Higgs boson (A^0) couple to linearly polarized photons with perpendicular polarization vectors

Telnov 2020, 2023

Physics Opportunities

Jikia 1994, Bharucha et al. 2001
Berger, Braathen, Weiglein, GMP

- Di-Higgs production and measurement of trilinear couplings

- Enhanced production cross sections of any charged particles by factor of ~10 compared to e^+e^- (e.g. SUSY, etc.)

Mühlleitner et al. 2006, Kanemura 2001

- $e^-\gamma$-options extends kinematic reach for charged particles (BSM, SUSY, heavy Higgs, etc.)

- Access to hadronic and electromagnetic structure of photons via photon-photon and photon-electron scattering

- Access to precise measurement of the two-photon decay width of the Higgs boson due to the higher rates which is particularly sensitive to new heavy charged particles beyond the kinematic range *Gunion et al. 1997*

- Spectroscopy of C-even resonances (e.g. in multi-quark states, glueballs) *Telnov et al. 2023*

Physi

- Di-Higgs
- Enhance
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- e-ɣ-optio … gs,
etc.)
- Access t … d
photon-e
- Access t … due
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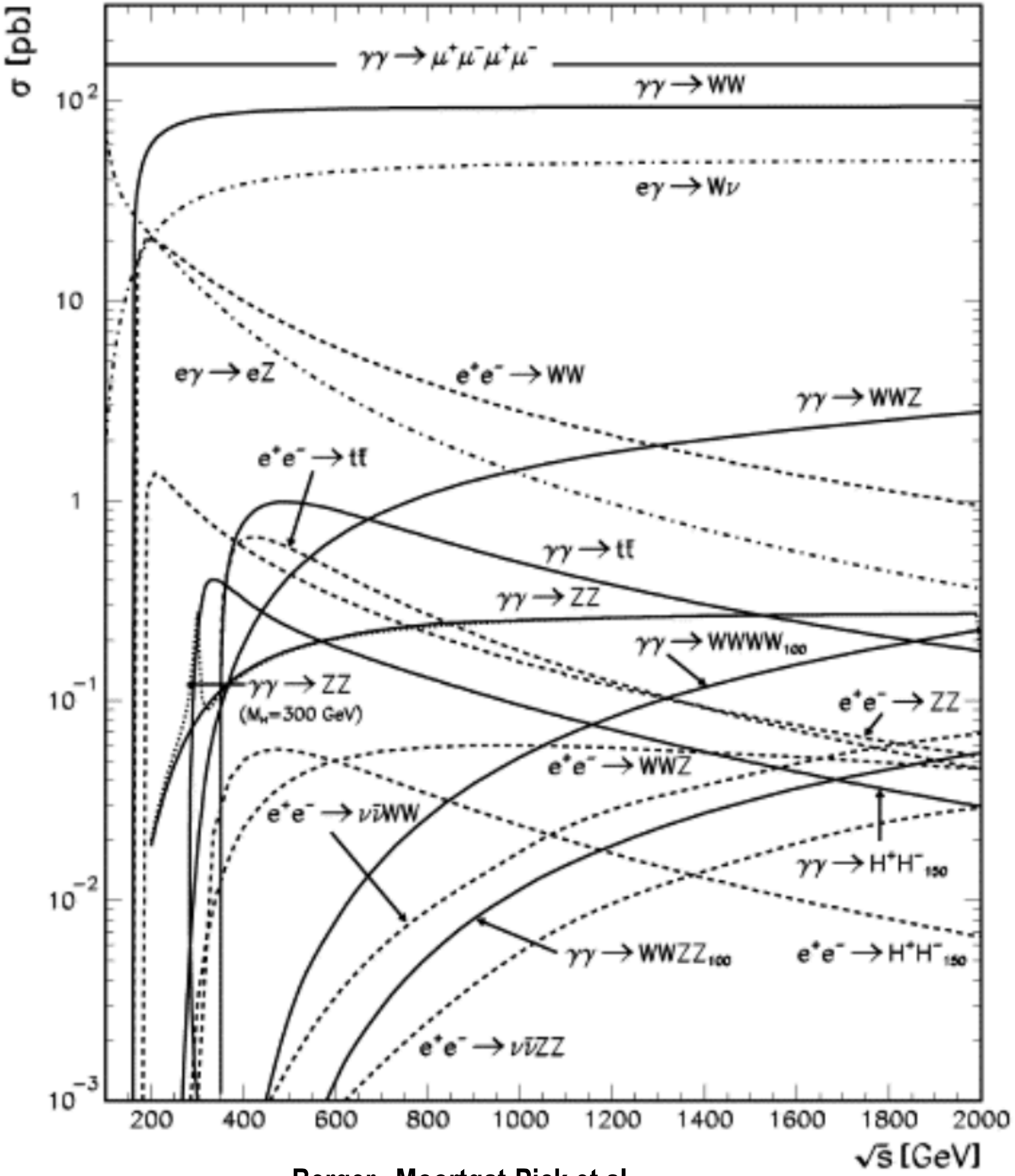
- Spectros



Berger, Moortgat-Pick et al.

see also Balazs et al., arXiv 2503.19983

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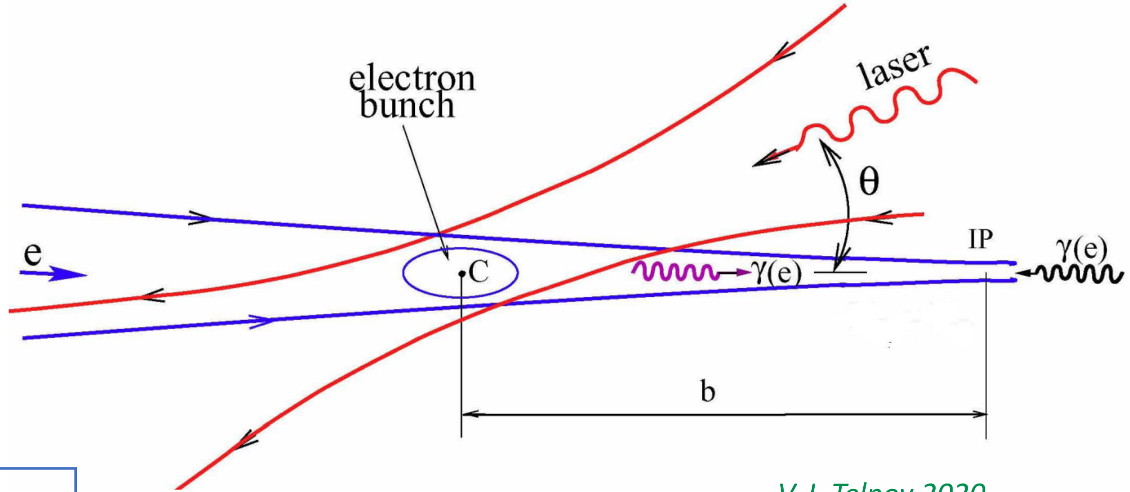
Gamma-gamma collider

- Addition to e^+e^- colliders
- Compton backscattering
- Getting access to $\gamma\gamma$ and γe processes



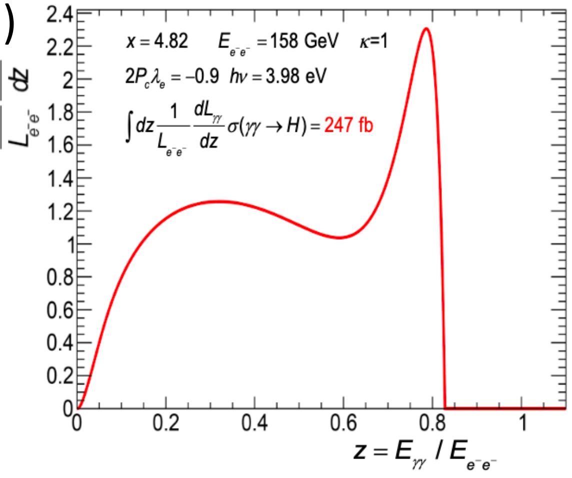
V. I. Telnov 2020

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

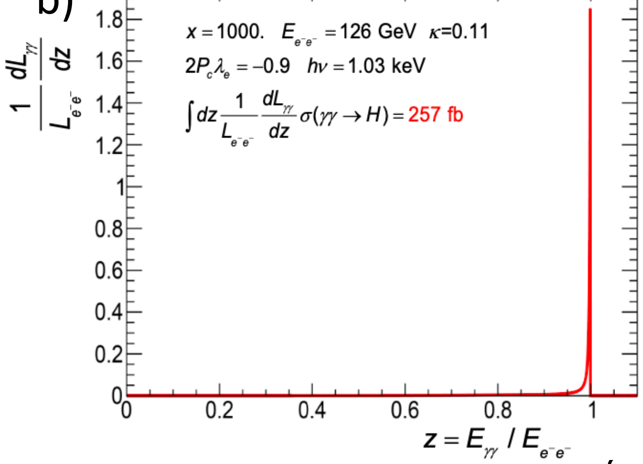
Laser is decisive:

a) optical
b) XFEL-like

a)



b)



How to get the beams?

Ilya Ginzburg '83

- Compton backscattering $\sigma_c = \sigma_c^{np} + \lambda_e P_c \sigma_c^1$

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

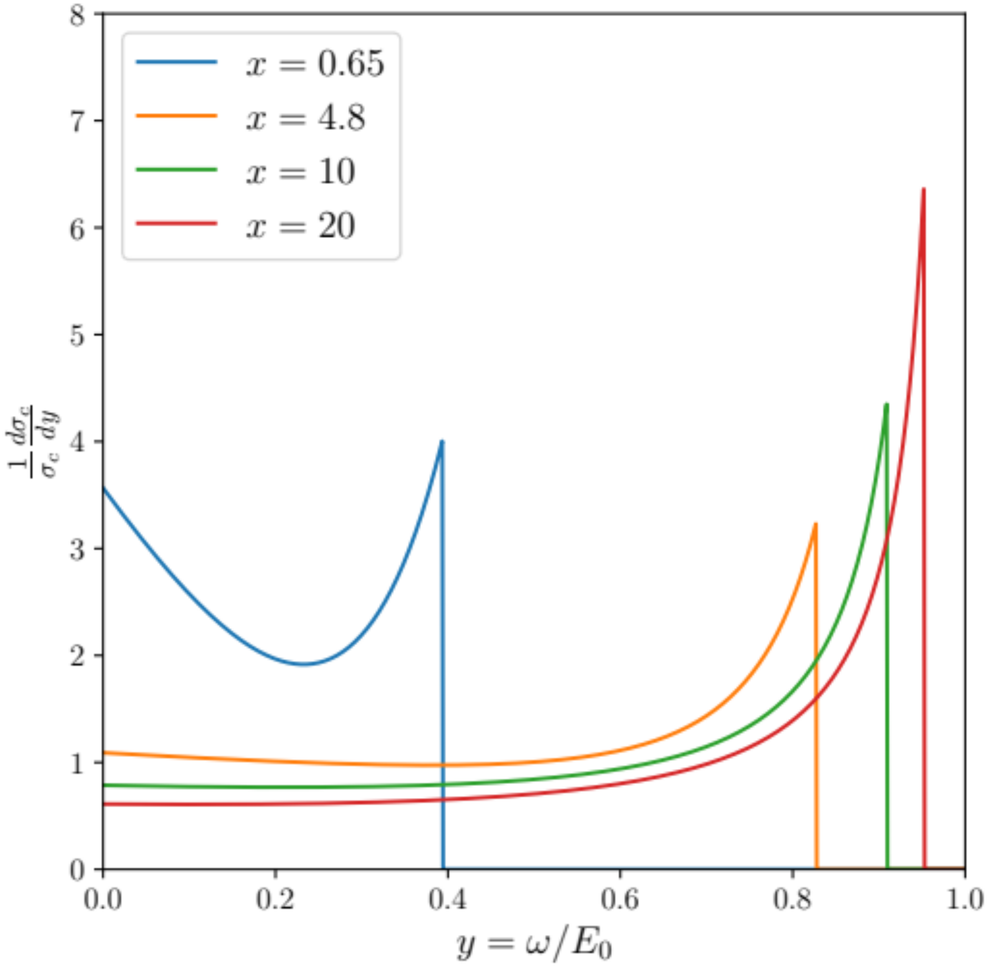
$$\sigma_c^1 = \frac{2\pi\alpha^2}{x m_e^2}\left[\left(1 + \frac{2}{x}\right)\ln x + 1 - \frac{5}{2} + \frac{1}{x+1} - \frac{1}{2(x+1)^2}\right]$$

- Energy Spectrum

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

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

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



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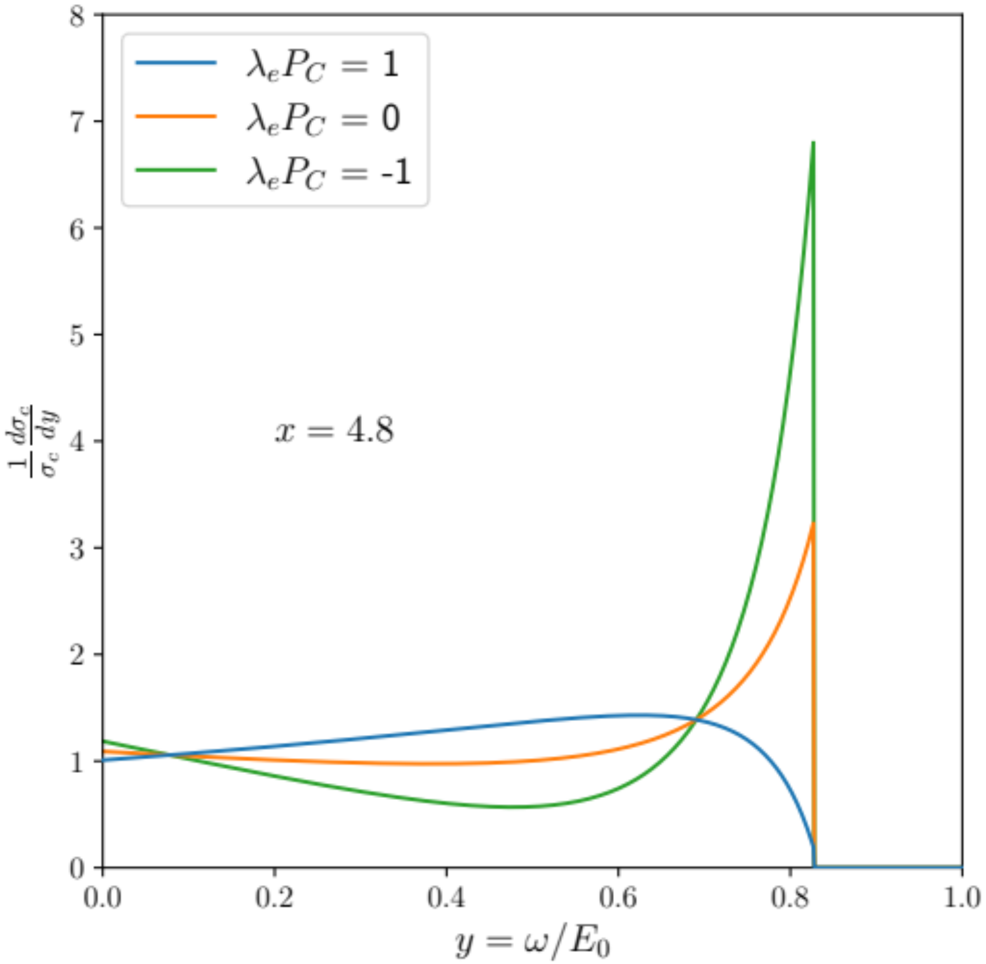
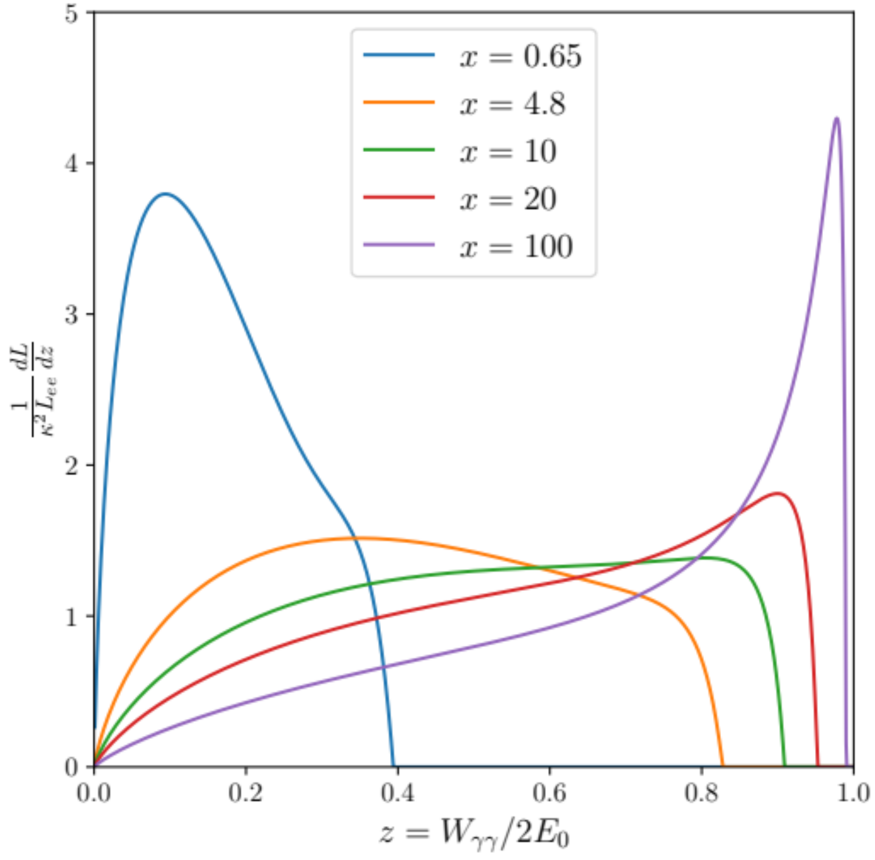


Spectral Luminosity

$$\frac{1}{k^2 L_{ee}} \frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}z} = 2z \int_{z^2/y_{max}}^{y_{max}} \frac{\mathrm{d}y}{y} f(x,y) f\left(x, \frac{z^2}{y}\right)$$
$$I_0\left(\rho^2 \sqrt{\left(\frac{y_{max}}{y} - 1\right)\left(\frac{y_{max}y}{z^2} - 1\right)}\right)$$
$$\exp\left[-\frac{\rho^2}{2}\left(\frac{y_{max}}{y} + \frac{y_{max}y}{z^2} - 2\right)\right],$$

$$\rho^2 = \left(\frac{b}{\gamma\sigma_x}\right)^2 + \left(\frac{b}{\gamma\sigma_y}\right)^2$$



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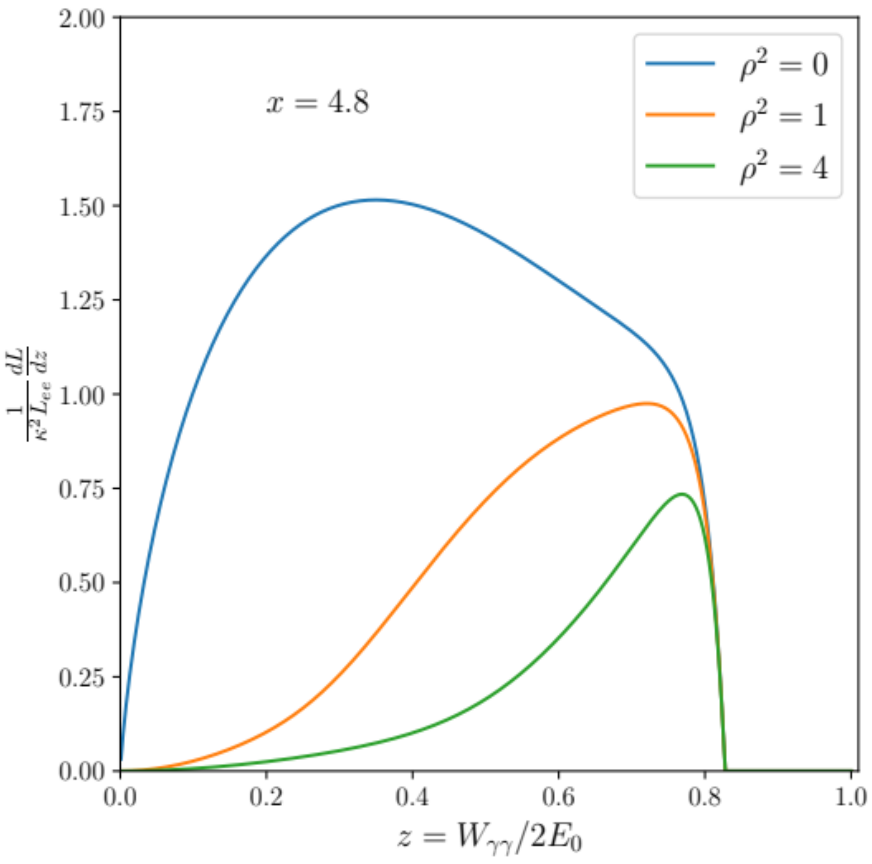


Polarization at Gamma-gamma collider

- Polarization effects
  - Mean helicity of the beams

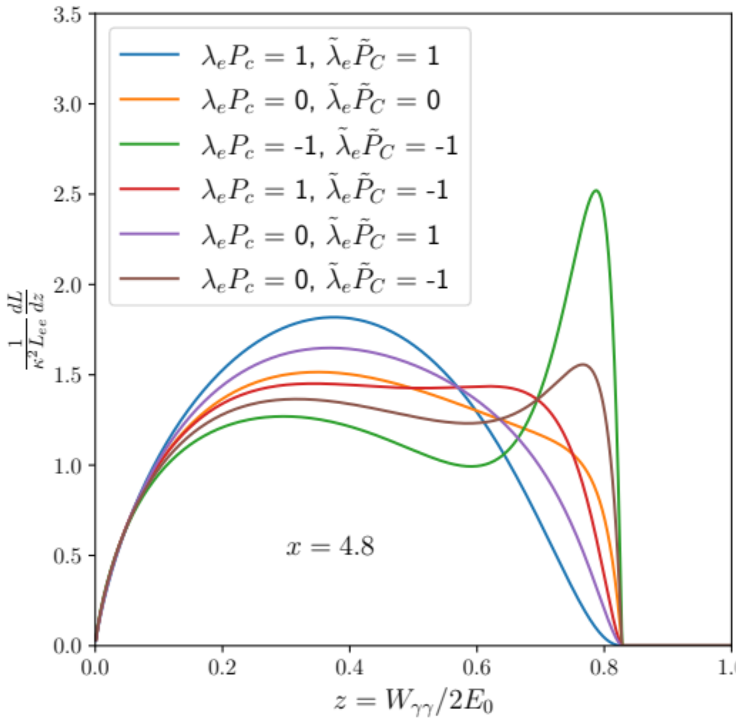
$$\langle\lambda_\gamma\rangle = \frac{\lambda_e x r[1+(1-y)(2r-1)^2] - P_c(2r-1)[(1-y)^{-1}+1-y]}{(1-y)^{-1}+1-y-4r(1-r)-\lambda_e P_c x r(2-y)(2r-1)}$$

  - Effect on the luminosity

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

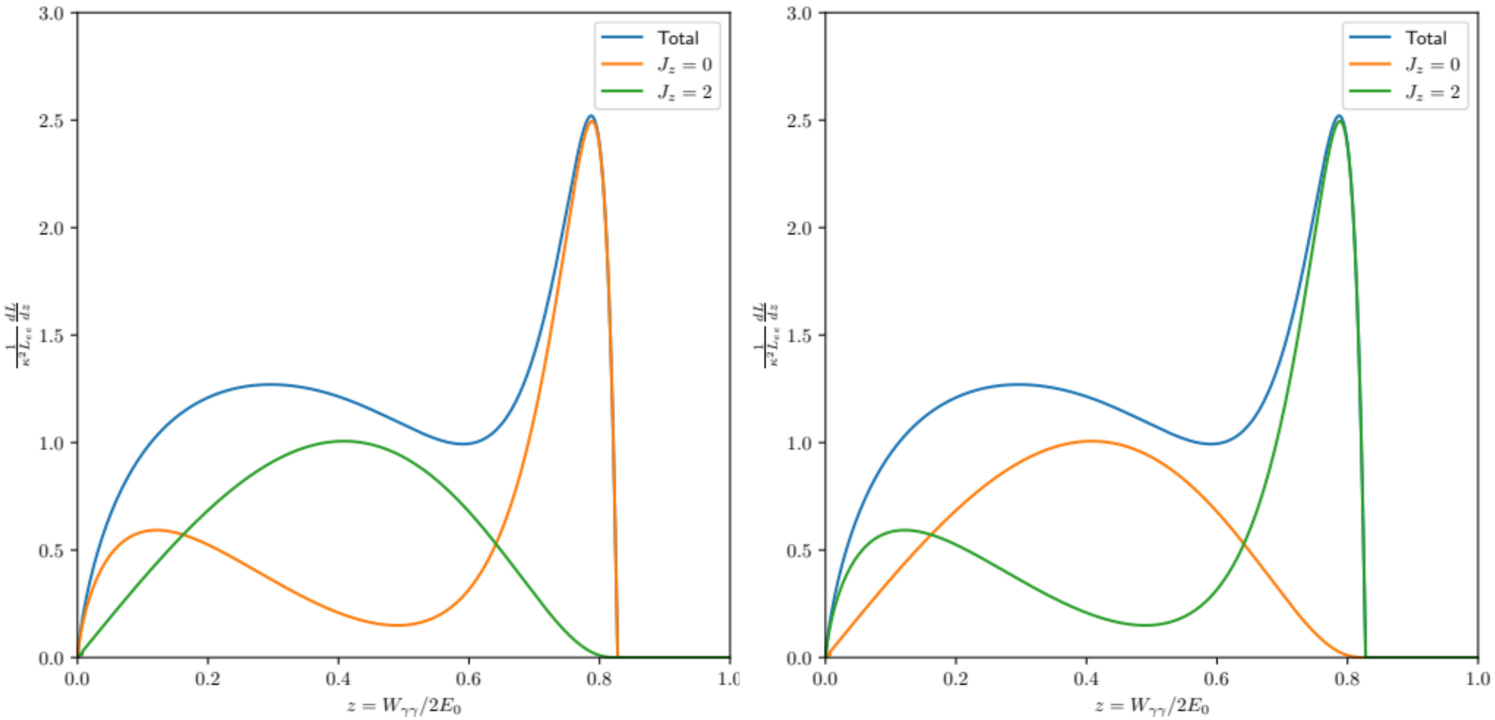
$$L_{\gamma\gamma} = L^{++}_{\gamma\gamma} + L^{+-}_{\gamma\gamma}$$

Polarization at Gamma-gamma collider



Include polarization in energy spectrum

Flipping of the J_z = 0, 2 contribution, with same total spectrum



Beam polarization included with

$$\lambda_e = 1, \quad P_c = -1, \quad \tilde{\lambda}_e = 1, \quad \tilde{P}_c = -1$$

Beam polarization included with

$$\lambda_e = 1, \quad P_c = -1, \quad \tilde{\lambda}_e = -1, \quad \tilde{P}_c = 1$$

Realistic spectrum

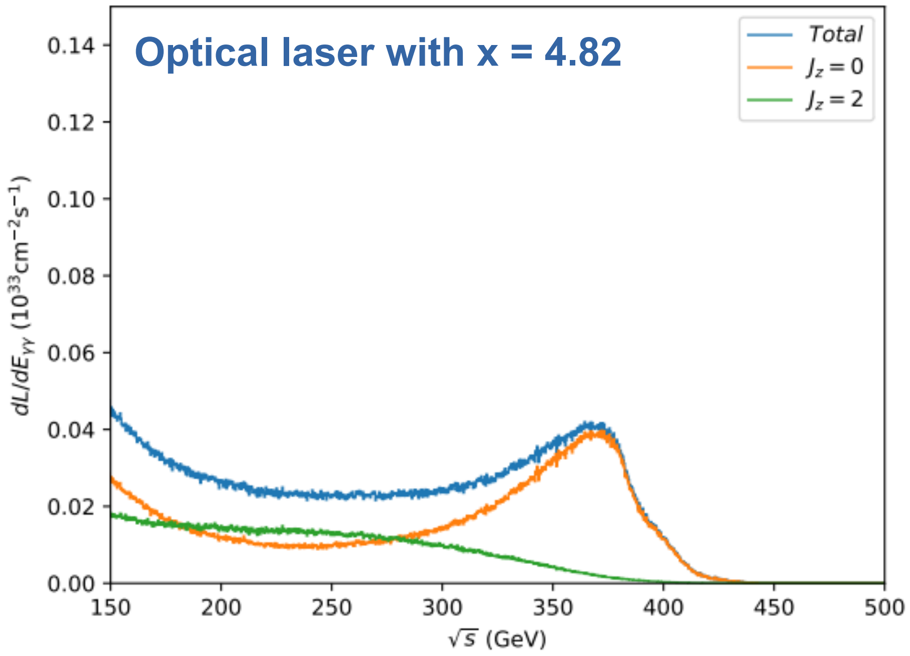
- CAIN includes important effects *Yokoya et al.*
  - Breit-Wheeler and Bethe-Heitler
  - Needs fine-tuning of laser and electron beam parameters to optimize spectrum

- Possible to use 2D-Spectrum *Kilian, Ohl, Reuter, et al.*
  - Used with other codes like WHIZARD
  - Also gain information on boost

Laser Set-ups Design

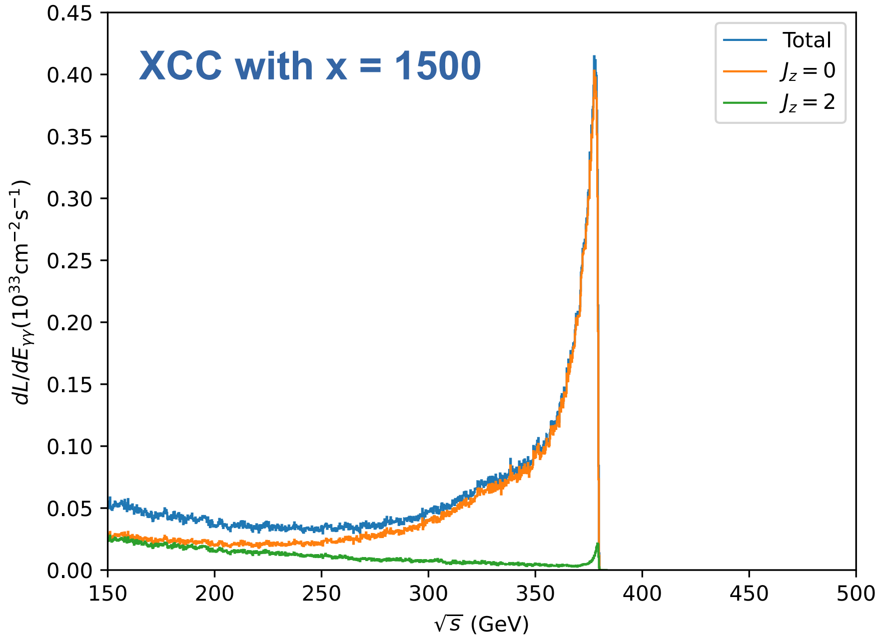
Optical

- Laser for $x = 4.82$
- Energy of colliding photon up to ~80% E_e
- Broad spectrum
- most electrons converted
- h-production at $E_e = 108$ GeV
- di-Higgs at $E_e = 250$ GeV
- $\lambda_e P_c = -0.9$



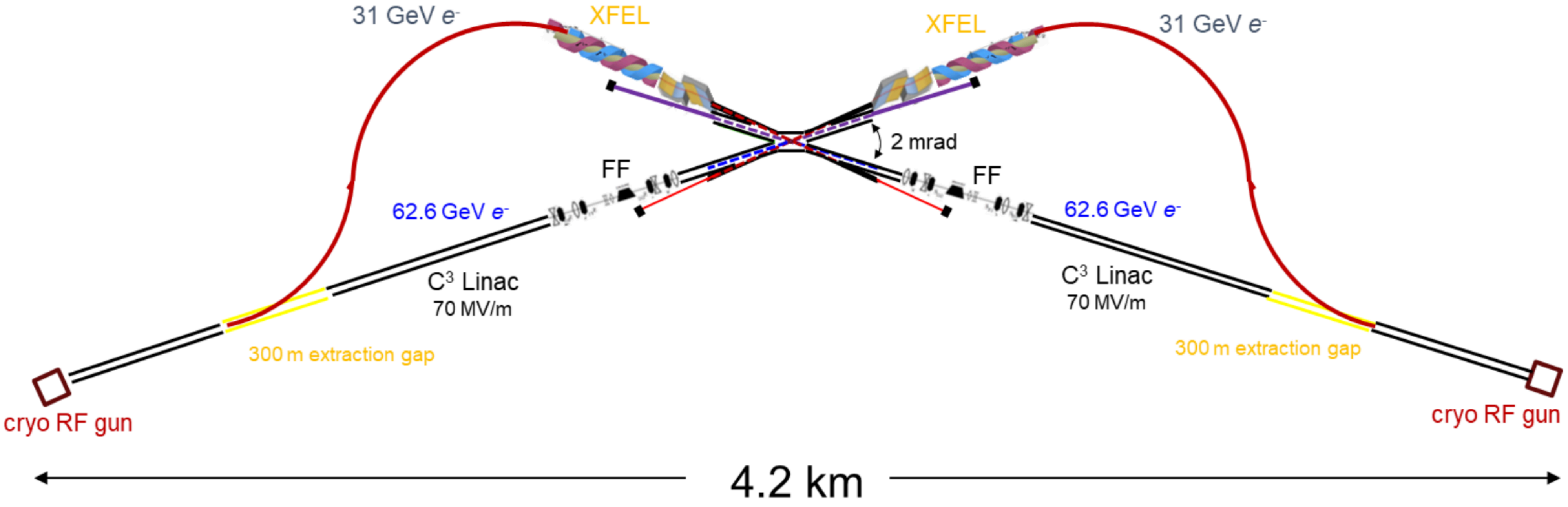
XCC

- XFEL for $x > 1000$
- Energy of colliding photon close to 100% E_e
- Peaked spectrum
- ~20% of electrons converted
- h-production at $E_e = 62.8$ GeV
- di-Higgs at $E_e = 190$ (140) GeV
- $\lambda_e P_c = 0.9$



Design for XCC $\sqrt{s}$ = 125 GeV

Barklow et al. 2023

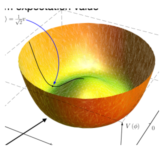


- Might fit into 2nd interaction area of LCF!

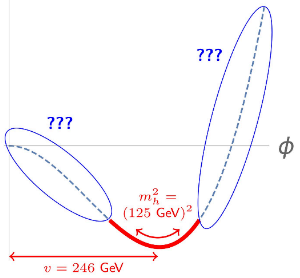
Parameters for cms = 380 GeV

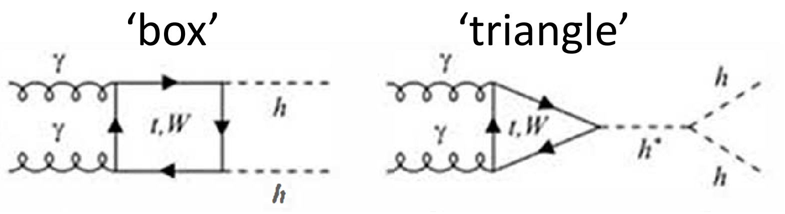
LCVision, Balazs et al., arXiv 2503.19983

Final Focus parameters	SCRF + Optical Laser	C3 + XFEL
Electron energy [GeV]	250	190
Electron beam power [MW]	10.5	2.1
β_x/β_y [mm]	1.5/0.3	0.01/0.01
$\gamma\varepsilon_x/\gamma\varepsilon_y$ [nm]	2500/30	60/60
σ_x/σ_y at e^-e^- IP [nm]	88/4.3	1.3/1.3
σ_z [μm]	300	10
Bunch charge [$10^{10} e^-$]	2	0.62
Bunches/train at IP	2625	93
Train Rep. Rate at IP [Hz]	5	120
Bunch spacing at IP [ns]	366	5.2
σ_x/σ_y at IPC [nm]	176/37.5	5,2/5.2
$\mathscr{L}_{\rm geometric}$ [10^{34}cm^2 s^{-1}]	12	180
δ_E/E [%]		0.1
L^* (QD0 exit to e^-e^- IP) [m]	3.8	1.5 or 3.0
d_{cp} (IPC to IP) [μm]	2600	40
crossing angle [mrad]	20	2 or 20

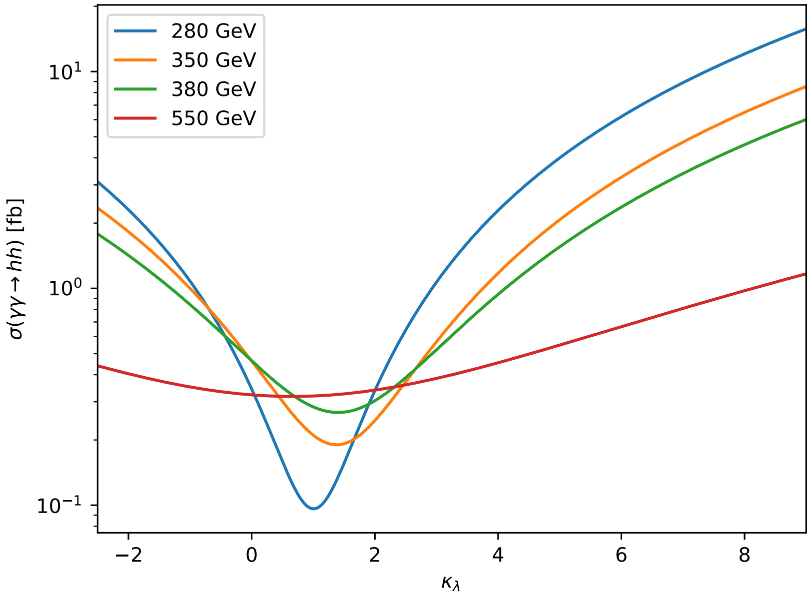


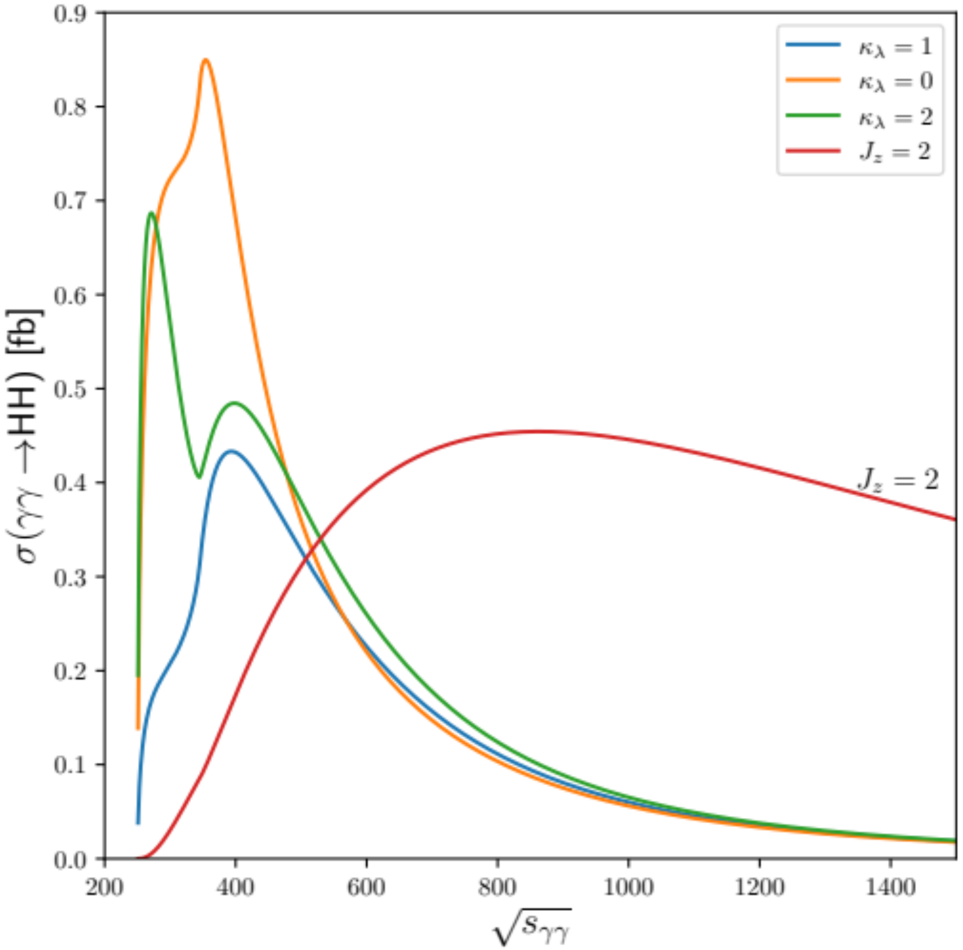
Di-Higgs production

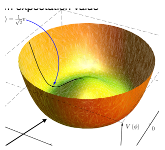




- Triangle contribution only for J_z=0
- Highly depending on trilinear Higgs-coupling

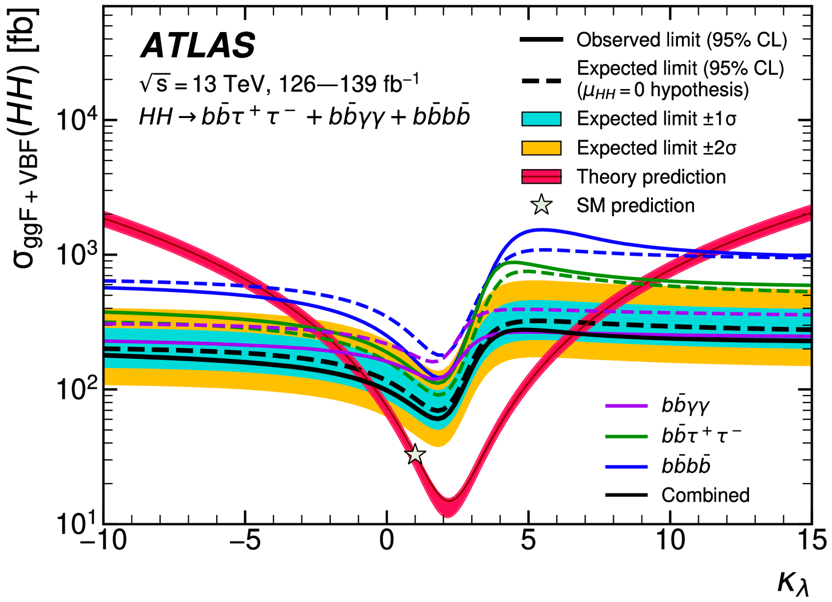


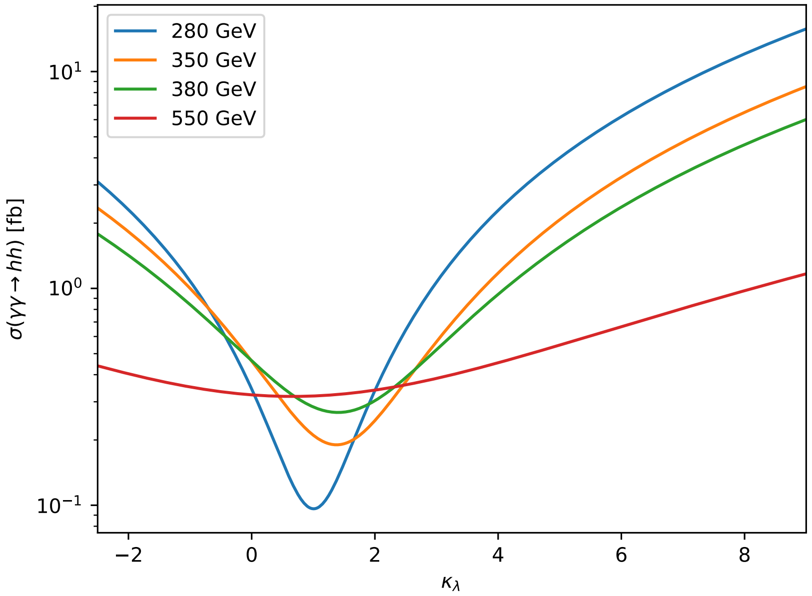


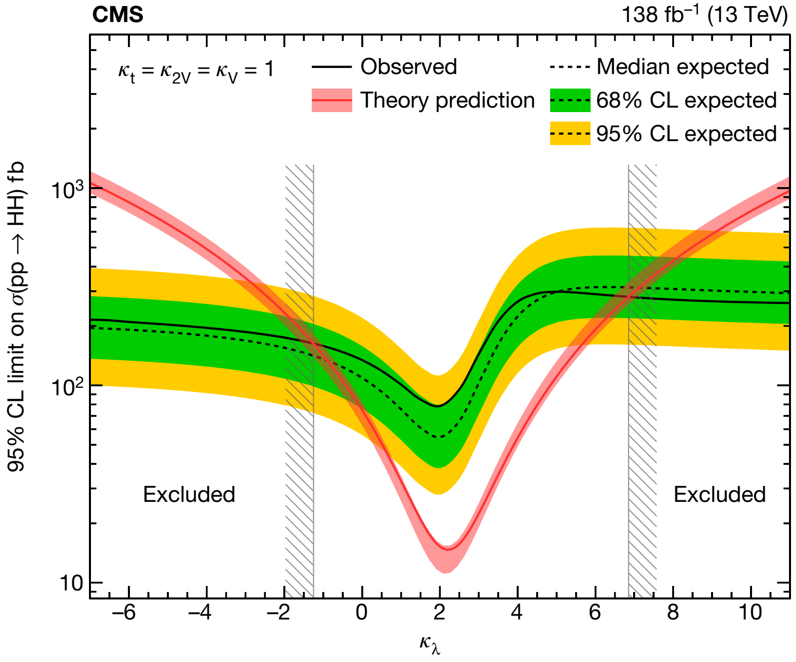


Comparison Di-Higgs production γγ-collider and LHC

- Minimum around $\kappa_\lambda = 1$
- Compared to LHC minimum around $\kappa_\lambda = 2$

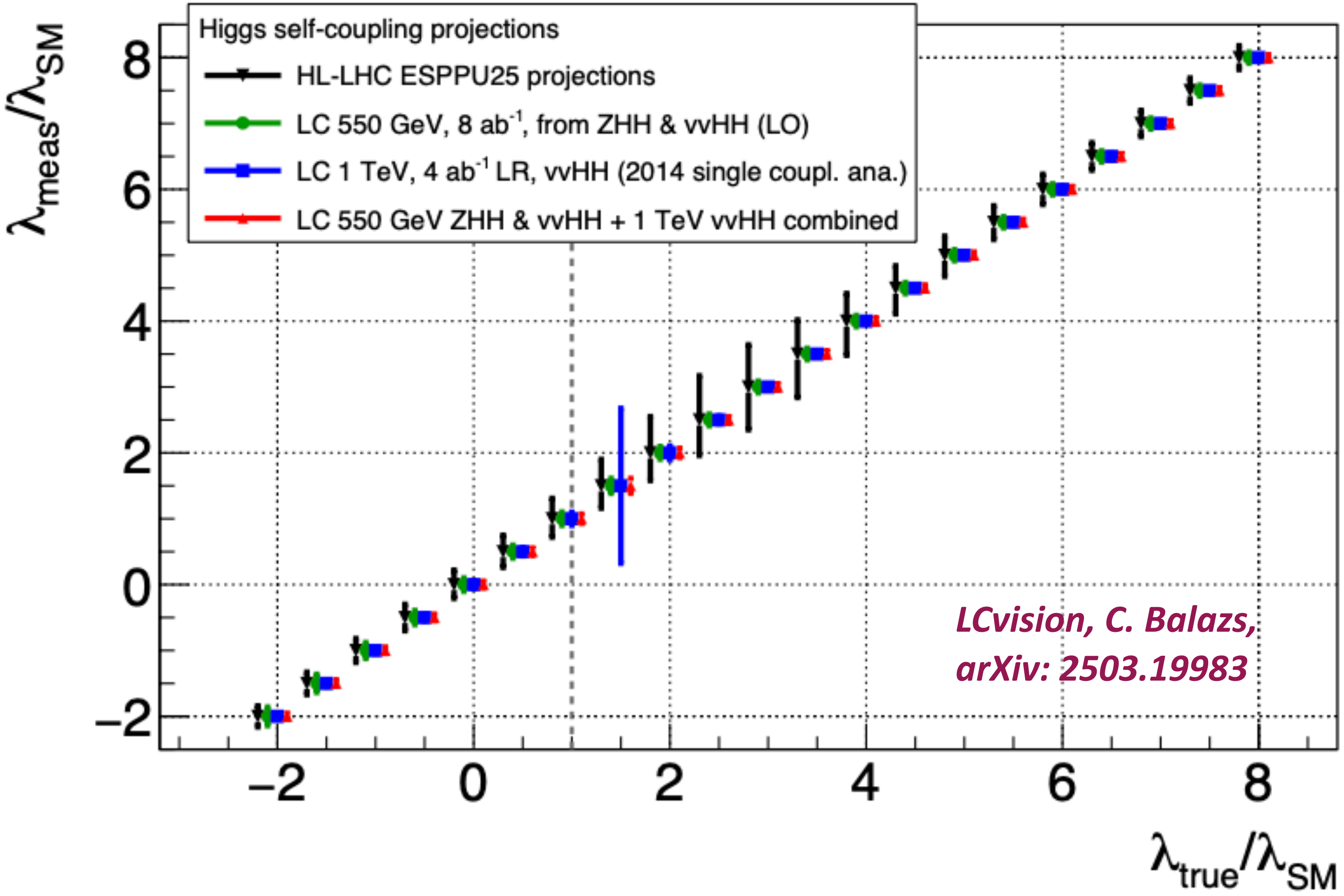


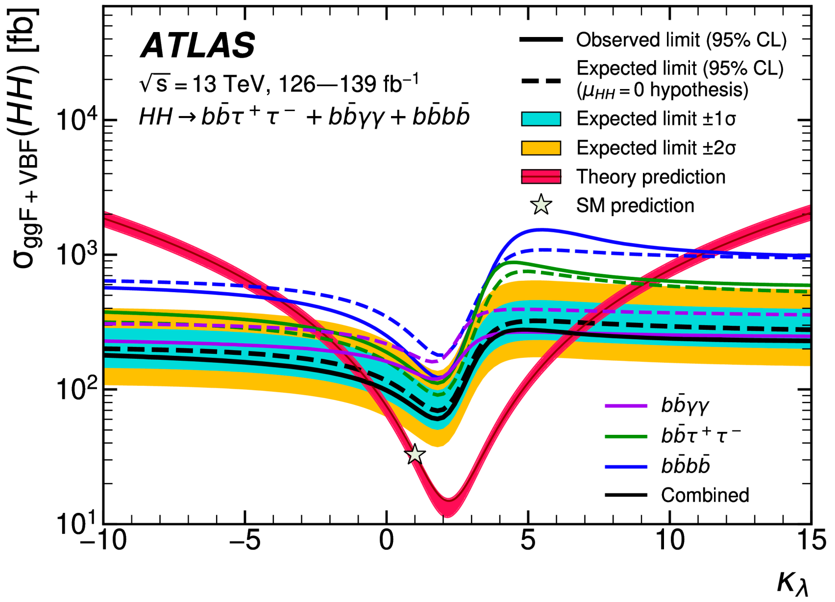


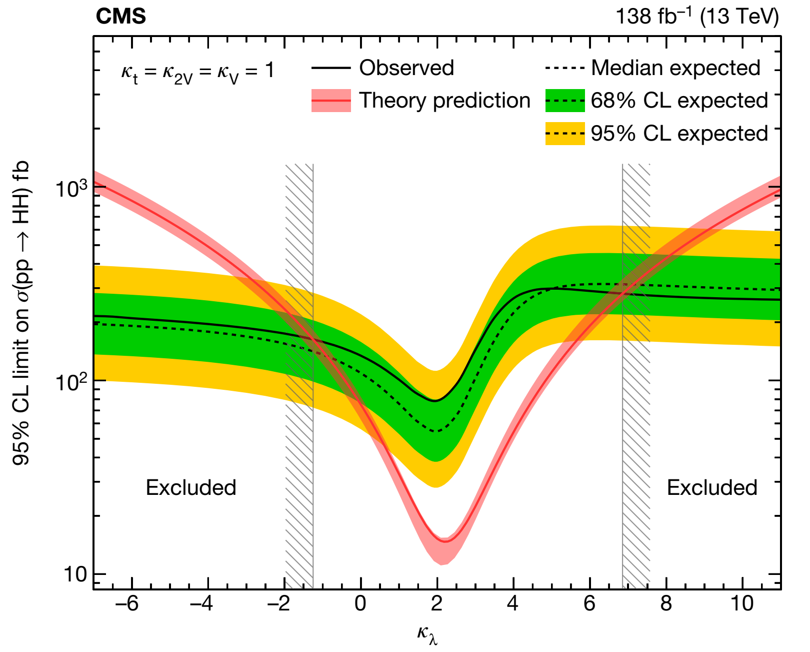


Trilinear Higgs self-coupling: $\varkappa_\lambda$

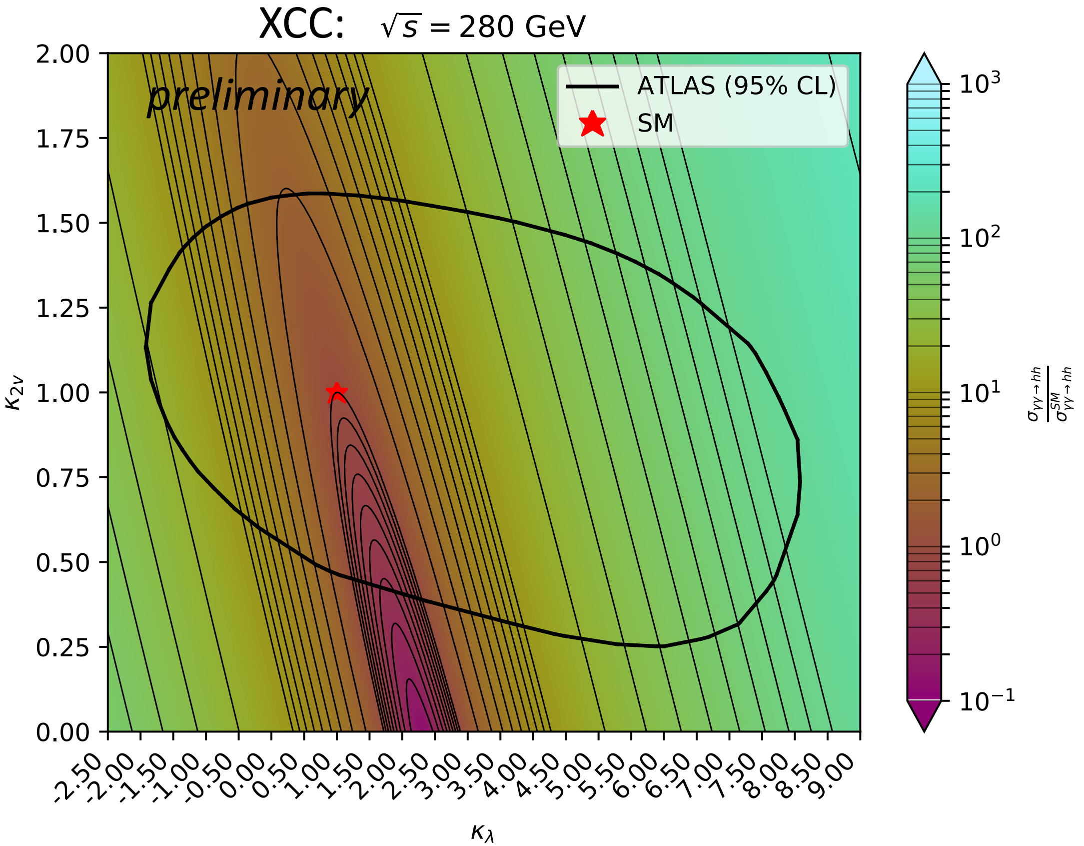
Projections for HL-LHC / future LC (below) and current LHC (right panels)

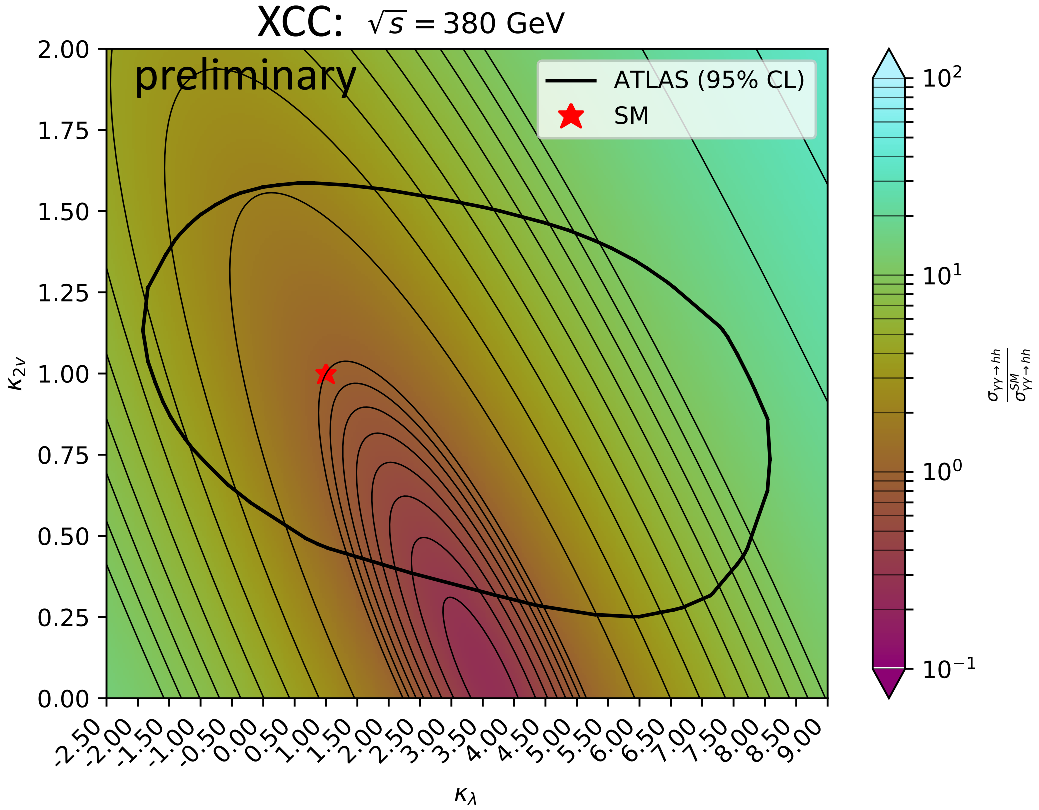






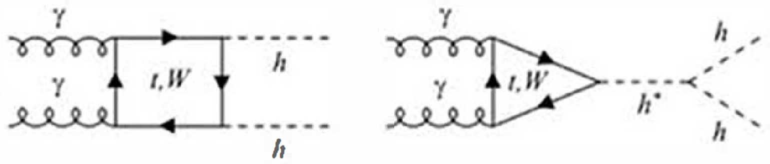
Comparison κ_λ and κ_{2V} contributions





- Impact of variation of κ_λ significantly larger than that of κ_{2V}

Di-Higgs production



- CAIN spectrum for colliding photons
- Assuming SM-like couplings
- Optical

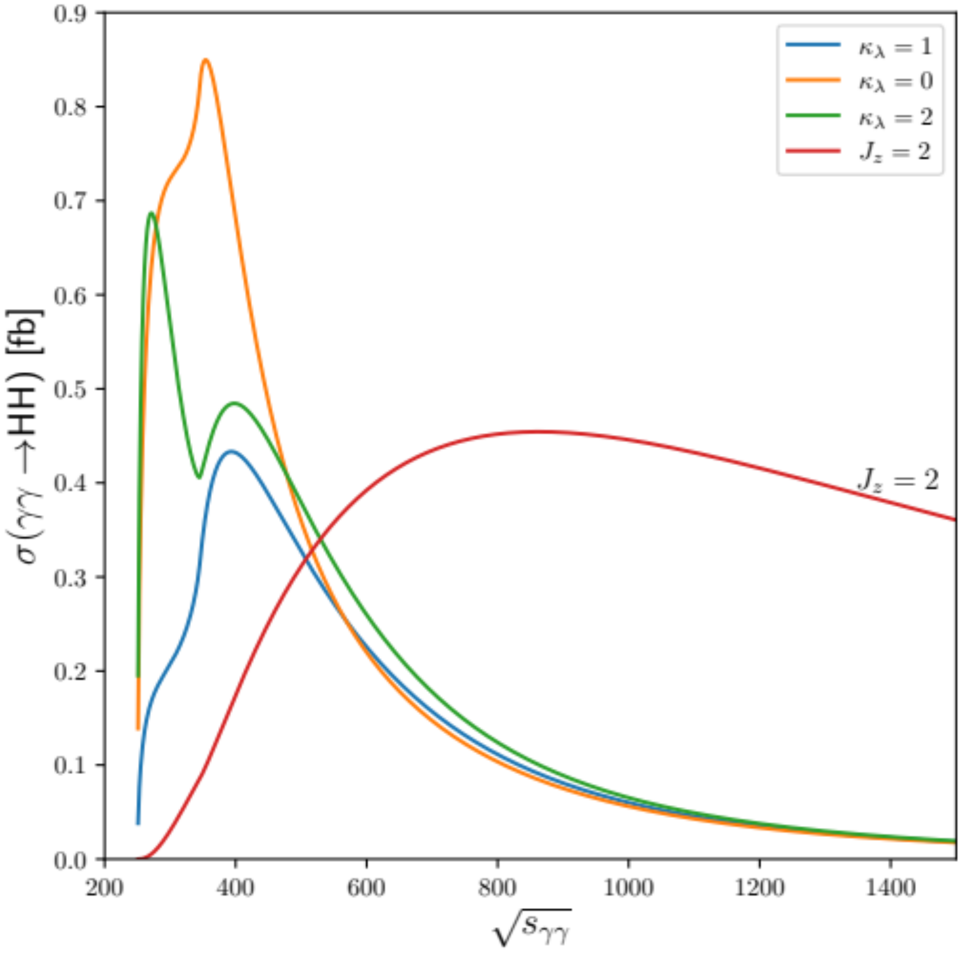
$$\mathscr{L}_{\gamma\gamma} = 9.84592 * 10^{34}\text{cm}^{-2}\text{s}^{-1}$$

  – 65 events per year

- XCC

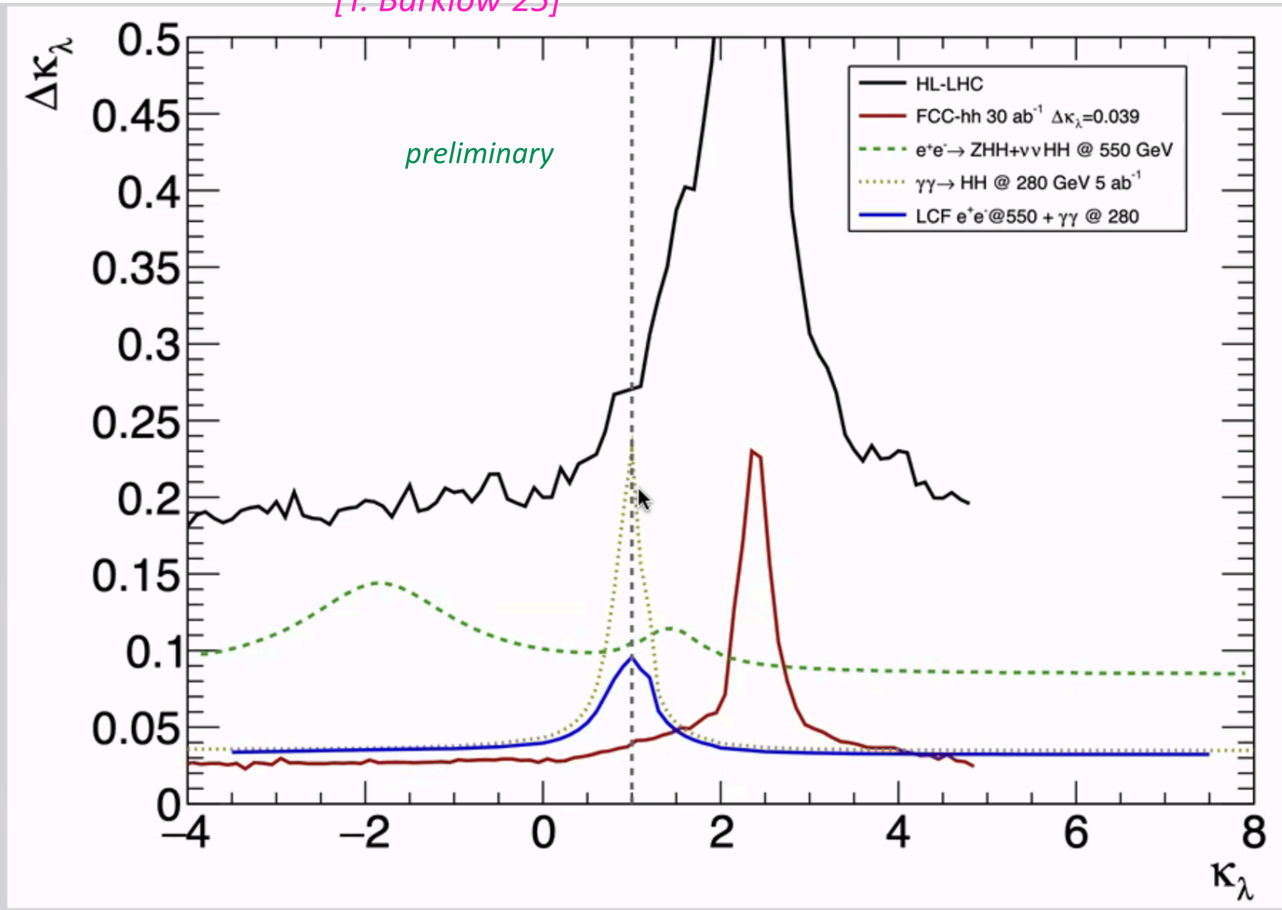
$$\mathscr{L}_{\gamma\gamma} = 1.83008 * 10^{35}\text{cm}^{-2}\text{s}^{-1}$$

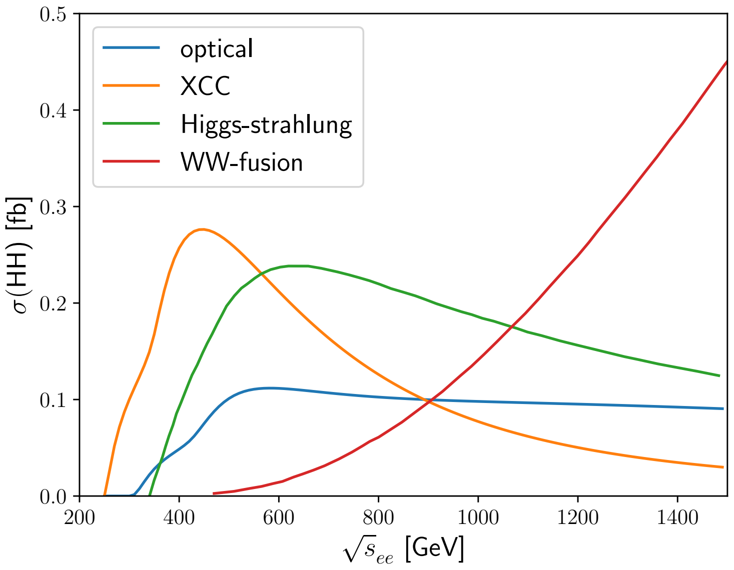
  – 202 events per year



Expectations: λ_{hhh} precision at HL-LHC, FCC-hh, e+e-(@550) and γγ

[T. Barklow'25]





➡ Minimum cross section at different κ_λ than at e^+e^- LC

➡ ***Complementary between both runnings: e^+e^- and γγ collisions runnings !!!***

➡ ***compatible with FCC-hh precision expectations…..excellent news for HEP!***

Indirect measurement of trilinear couplings?

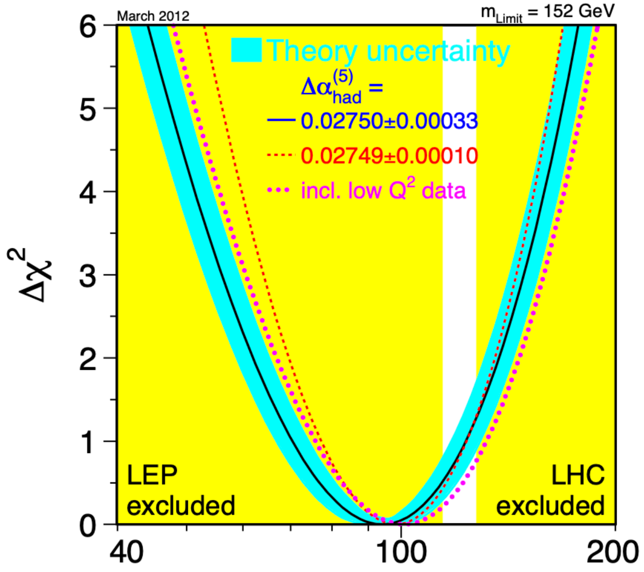
Indirect access to λ_{hhh} via

➡ cf talk M. Vellasco, Higgs Session

- single Higgs processes: λ_{hhh} enters at 1-loop order
- electroweak precision observables: λ_{hhh} enters at 2-loop order

Loop contribution of λ_{hhh} competes with much larger lowest-order contributions, other loop contributions (e.g. top loop) that are numerically dominant and potentially with BSM loop contributions → Indirect sensitivity via loop effects is limited !!!

A lesson from the past: the ``blue band plot", global fit for the Higgs-boson mass in the S



[LEPEWWG '12]

We did not claim a measurement of the Higgs-boson mass at 95 GeV from this analysis!

⇒ This is not a ``measurement" of m_h, but an indirect constraint from loop contributions within a specific model (in this case the SM)

Conclusions

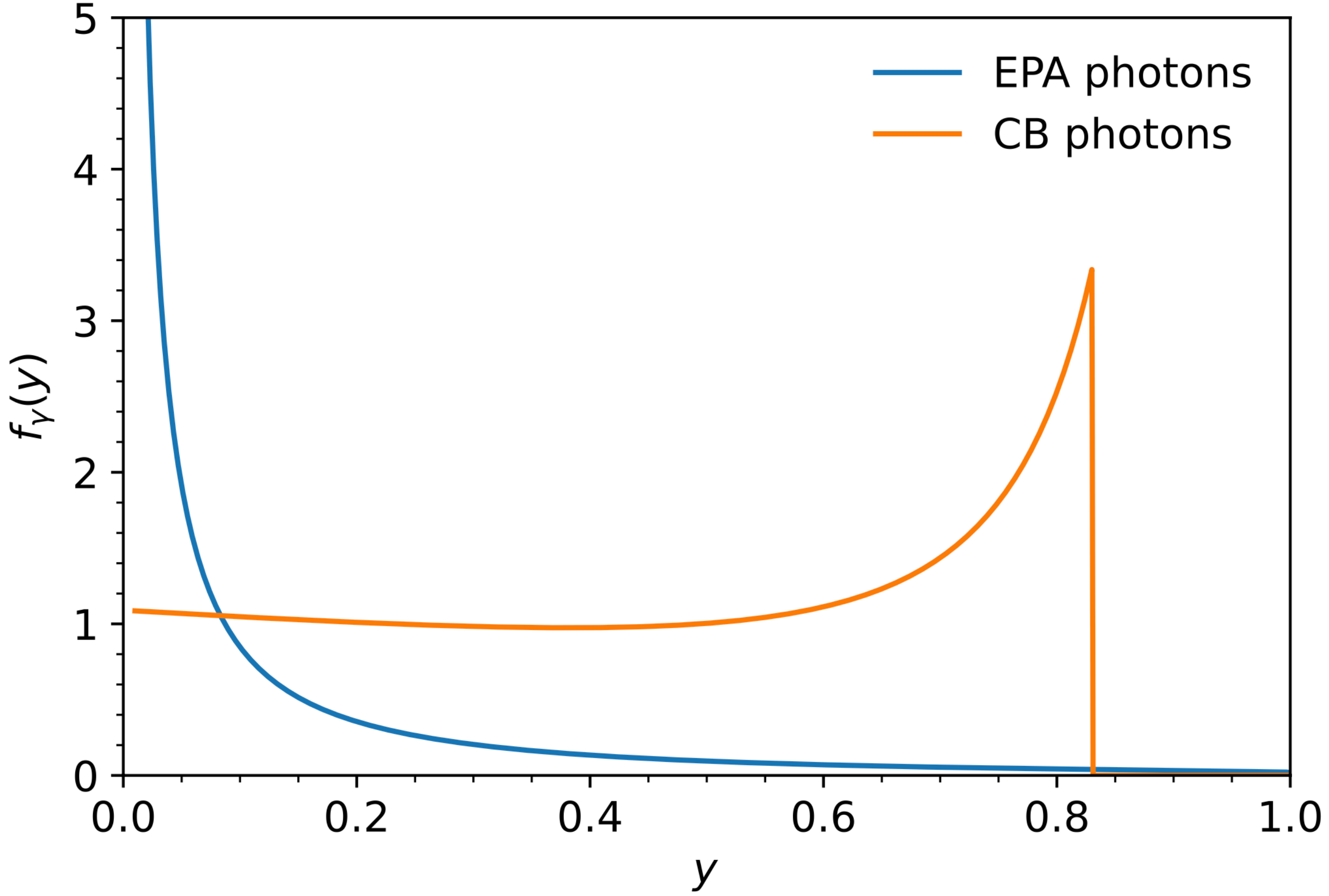
- Gamma-gamma colliders are great additions to e^+e^- colliders
- Great opportunity to measure tri-linear Higgs coupling at lower energies !
- Complimentary with pp and e+e- analyses

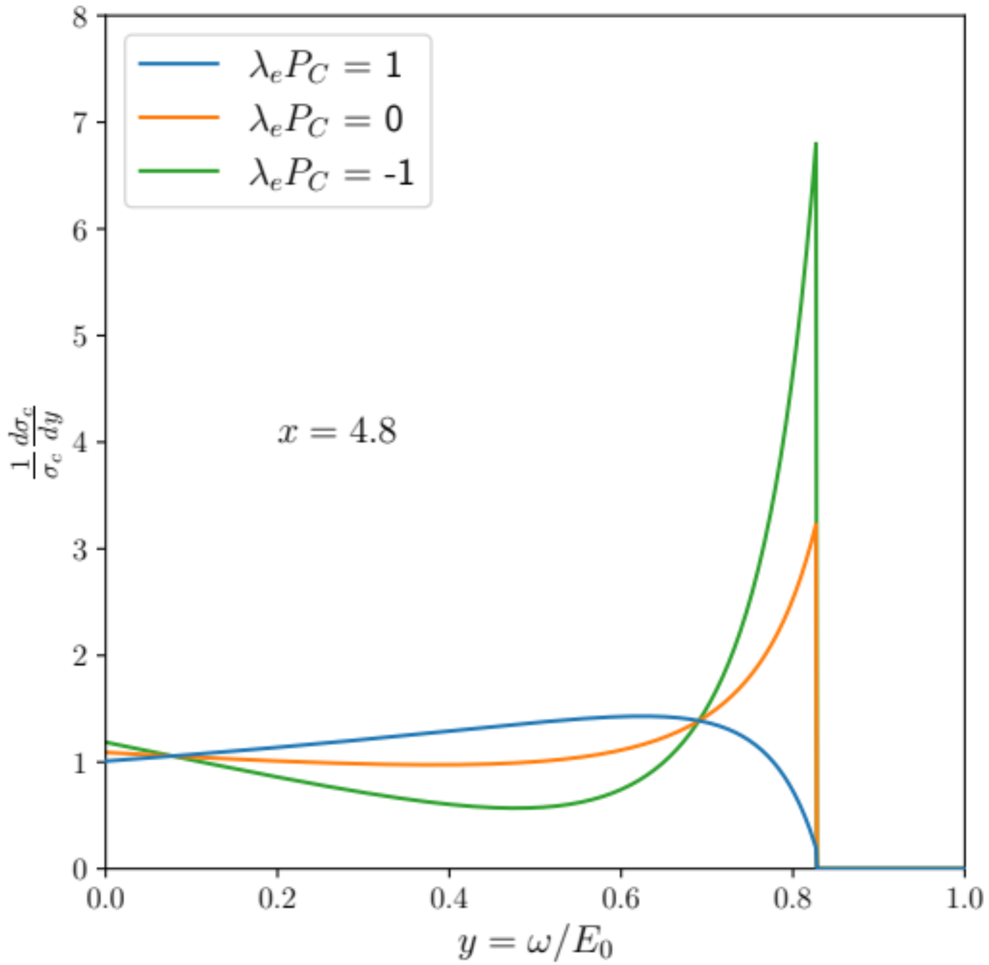
Ongoing Work

- Determination of tri-linear Higgs couplings for (B)SM Higgs with different set-ups
- Further optimizing current collider choices

Compared to EPA photons

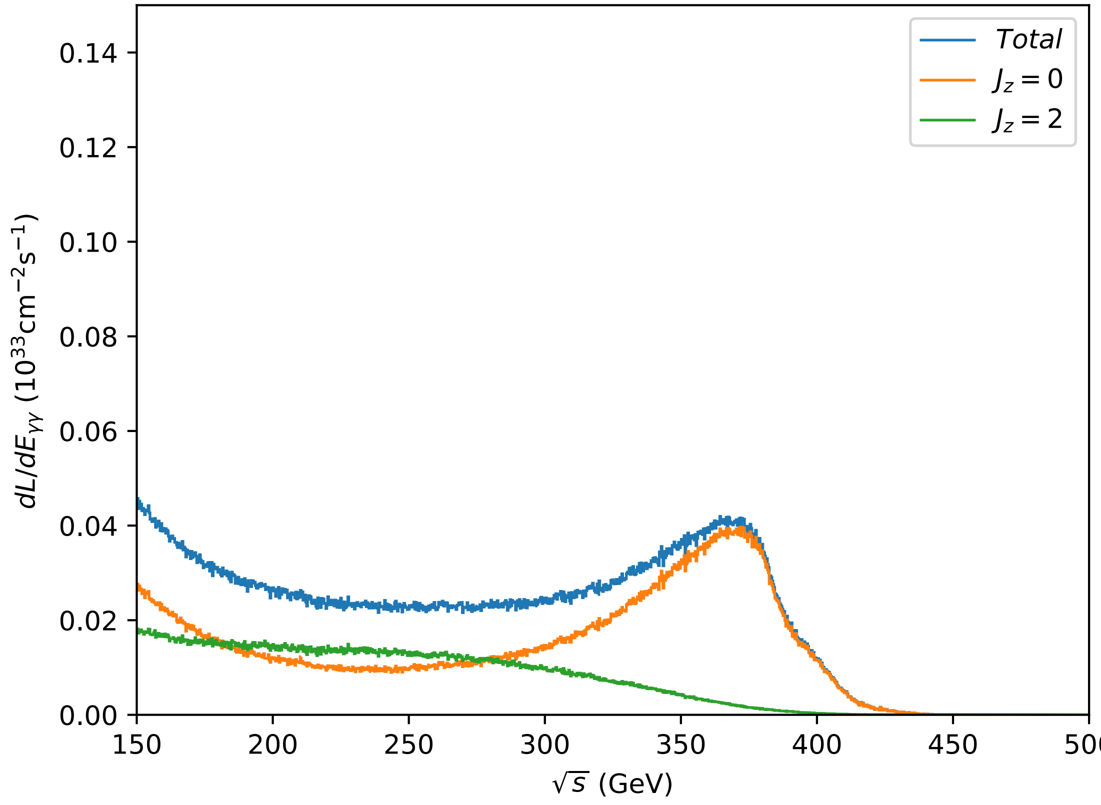
Wüst



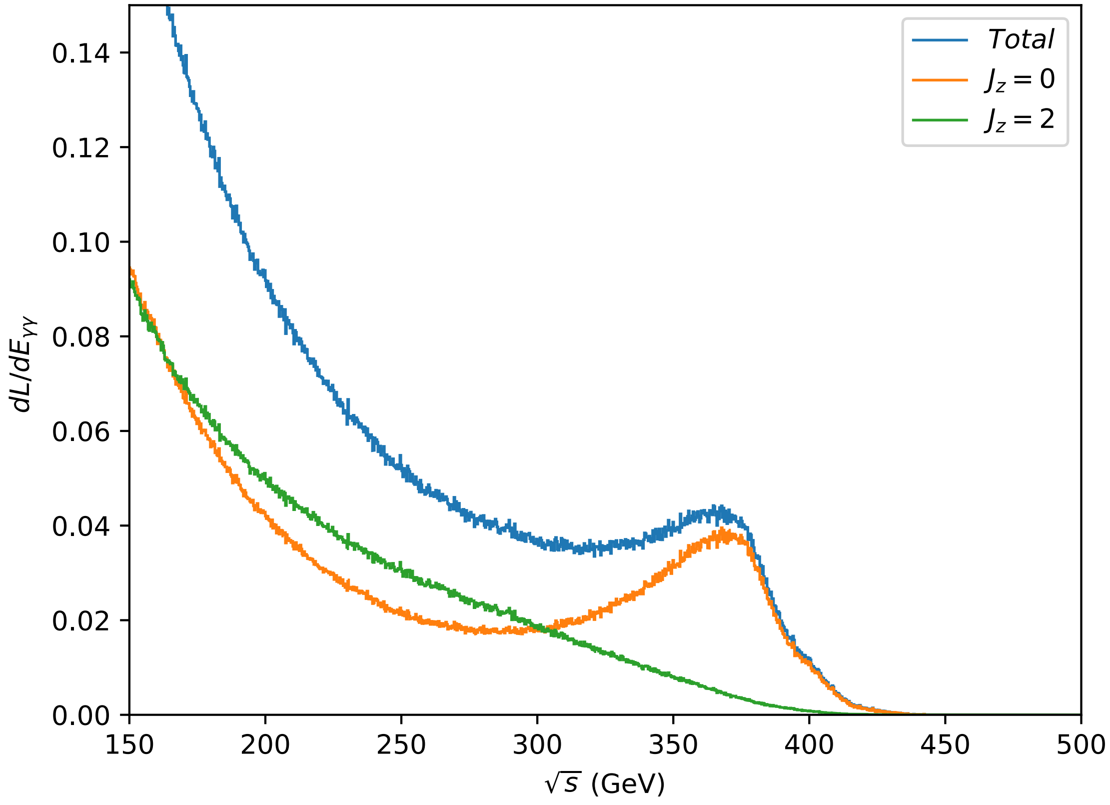


Comparison between e^-e^- and e^+e^-

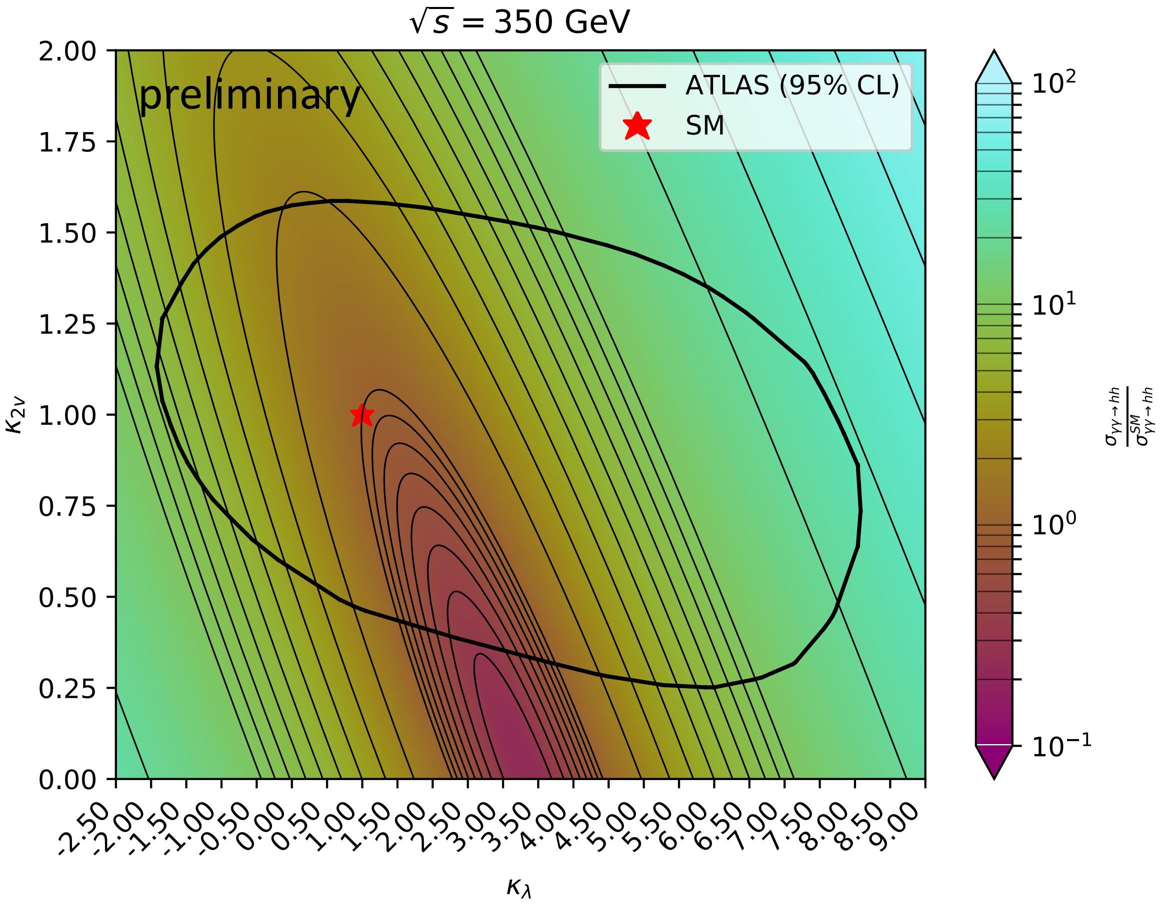
e^-e^--mode

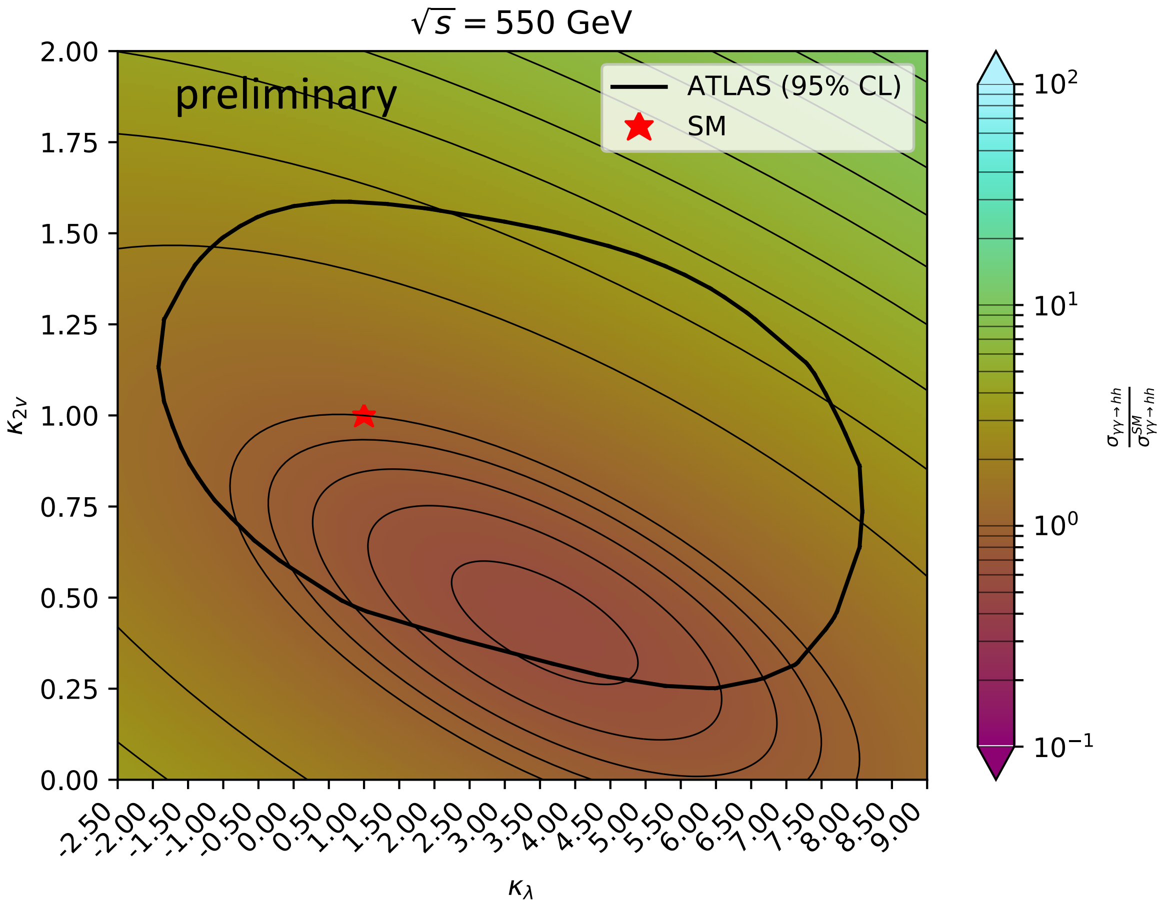


e^+e^--mode



Comparison κ_λ and κ_{2V} contributions for √s=350 and 550 GeV

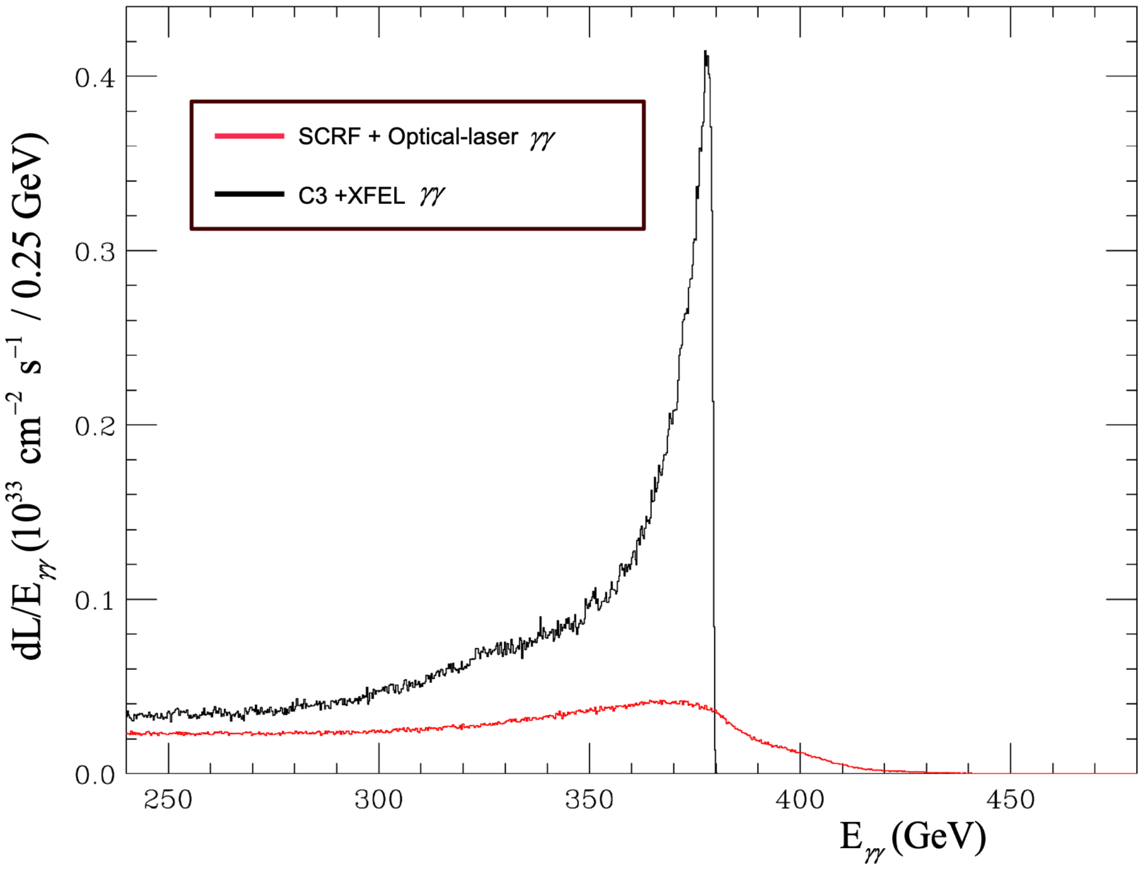


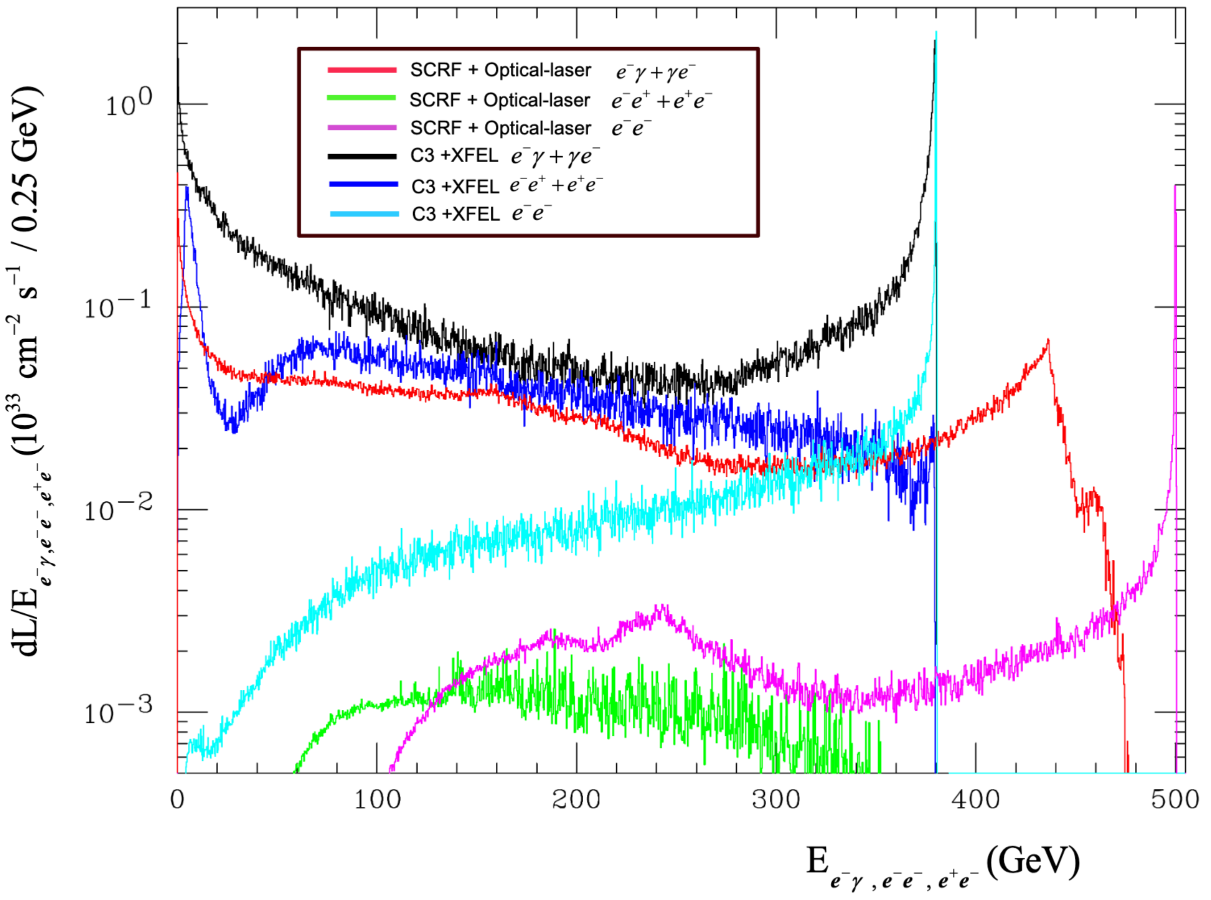


- Impact κ_{2V} variation neglible compared to κ_λ

Additional processes in $\gamma\gamma$ mode

LCVision, Balazs et al., arXiv 2503.19983





Prototyping: Gamma-gamma collider at XFEL

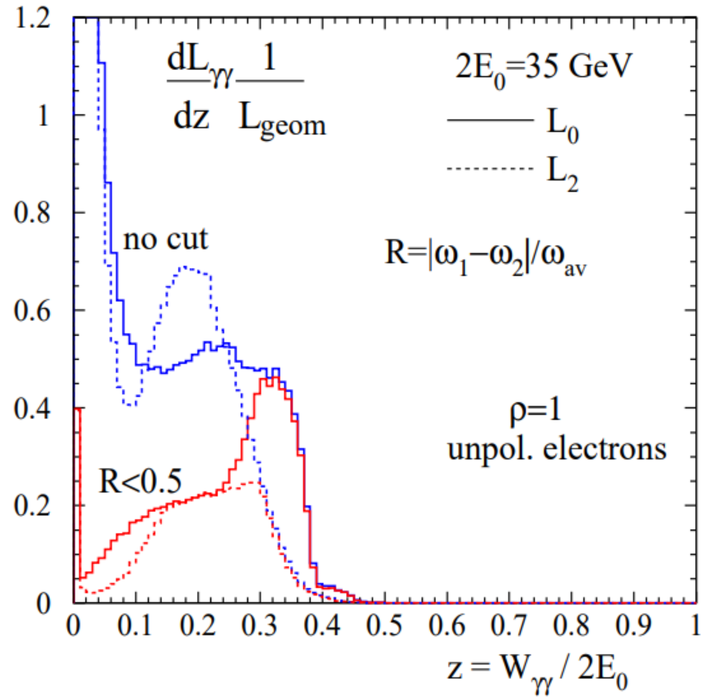
$$\omega_m \approx \frac{x}{x+1} E_0$$

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

[V. Telnov]

- Use European XFEL (E_0 = 17.5 GeV)
- At the beam dump

- 12 GeV peak
- Excellent for $b\bar{b}$ and $c\bar{c}$ range



[V. I. Telnov 2020]

Parameters of a Gamma-gamma collider@XFEL

$2E_0$	GeV	35
N per bunch	10^{10}	0.62
Collision rate	kHz	13.5
σ_z	μm	70
$\varepsilon_{x,n}/\varepsilon_{y,n}$	mm · mrad	1.4/1.4
β_x/β_y at IP	μm	70/70
σ_x/σ_y at IP	nm	53/53
Laser wavelength λ	μm	0.5
Parameters x and ξ^2		0.65, 0.05
Laser flash energy	J	3
Laser pulse duration	ps	2
f# $\equiv F/D$ of laser system		27
Crossing angle	mrad	~ 30
b (CP–IP distance)	mm	1.8
$\mathcal{L}_{ee,\mathrm{geom}}$	10^{33} cm^{-2}s^{-1}	1.45
$\mathcal{L}_{\gamma\gamma}$ $(z > 0.5z_m)$	10^{33} cm^{-2}s^{-1}	0.19
$W_{\gamma\gamma}$ (peak)	GeV	12

[V. I. Telnov 2020]

Indirect constraints on λ_{hhh} are much more difficult to obtain than the indirect constraints on M_h in the SM

- M_h is a free parameter of the SM, but λ_{hhh} is not!

⇒ Cannot vary λ_{hhh} "within" the SM, need consistent theoretical framework for possible deviations in λ_{hhh} from SM value, e.g. EFT

- EFT: need complete basis of operators, involves model-dependence: consistent sub-set of operators? dim-6 vs. dim-8 operators? possible effects of light new particles? range of validity of the EFT description? …

⇒ Need much more than avoiding just some "blind directions" among certain operators
Recent SMEFT analysis emphasising importance of complete operator basis and EW SMEFT corrections
[K. Asteriadis, S. Dawson, P. P. Giardino, R. Szafron '24 — see Pier Paolo's talk]

Example of EW precision observables: possible deviations of M_W, $g_\mu-2$, $\sin^2\theta_{eff}$, … have given rise to many possible model interpretations

How much can we learn about λ_{hhh} from its impact on loop corrections?

We want to determine λ_{hhh}, accounting for the fact that it may differ substantially from the SM value

If the observables used for a global fit based on data from the LHC and CEPC or FCC-ee, i.e. no input from the e^+e^- machines on the Higgs pair production process, show a deviation from the SM prediction that is compatible with a non-SM value for λ_{hhh} (within the LHC uncertainties) it will be very difficult to show that this deviation is indeed associated with λ_{hhh} rather than with other higher-order contributions

This issue has not at all been demonstrated for the FCC-ee fits so far; the future experimental results have always been assumed to perfectly agree with the SM; up to now not even statistical fluctuations of the assumed central values around the SM predictions have been taken into account