$e^+e^- \rightarrow \gamma\gamma$: SM rate measurement and deviations from New Physics

(note in progress)

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Outline

- Introduction: allowed new physics deviations in the $e^+e^- \to \gamma\gamma$ process
- QED deviations reach at future colliders and sensitivity of FCC-ee measurements to them
- Some guesses/thoughts about how to control systematic uncertainties for this process at the FCC-ee

Interest of the $e^+e^-\to\gamma\gamma$ at FCC-ee

- Process minimally affected by theoretical uncertainties:
  - Hadronic corrections only appear at the 10^{-5} level (arXiv:1906.08056)
- Measurable at "relatively" high polar angles with respect to the beam:
  - **$1/\sqrt{N}$=1.3e-5 for $|\cos\theta|<0.95$,**
  - **$1/\sqrt{N}$=2.0e-5 for $|\cos\theta|<0.7$**

  ($\sqrt{s}$=91.2 GeV, assuming LO cross section and 100% acceptance)

arXiv:1906.08056

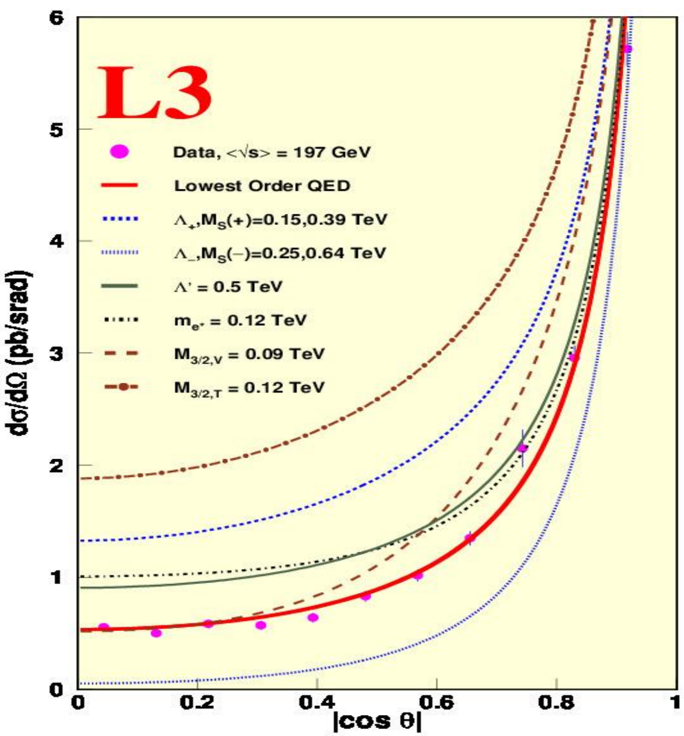
$\sqrt{s}$ (GeV)	$\sigma^{\rm NNLO}_{\Delta\alpha\ {\rm lep+top}}/\sigma_{LO}$	$\sigma^{\rm NNLO}_{\Delta\alpha\ {\rm had}}/\sigma_{LO}$	$\delta\sigma_{\rm had}/\sigma_{LO}$
91	0.096%	0.085%	$3.7\cdot10^{-6}$
160	0.108%	0.098%	$3.8\cdot10^{-6}$
240	0.115%	0.108%	$3.9\cdot10^{-6}$
365	0.119%	0.120%	$4.0\cdot10^{-6}$

Table 3: Relative contribution of the NNLO leptonic(+top) and hadronic vacuum polarization correction to the cross section in setup [b] and for four FCC-ee c.m. energies. In the last column, the uncertainty due to the hadronic contribution is shown.

- Hopefully not much sensitive to new physics.
  - **Can we quantify a bit more the potential of this channel ?**

New physics deviations in $e^+e^-\rightarrow\gamma\gamma$

- Old approach (up to LEP2 included): consider any possible Lagrangian fro QED deviations



Model and Fit parameter	Fit result	95% CL limit (GeV)
Cut-off parameters $\Lambda_\pm^{-4}$	$(-37^{+24}_{-23})\cdot 10^{-12}\ \mathrm{GeV}^{-4}$	$\Lambda_+ > 431$ $\Lambda_- > 339$
effective Lagrangian dimension 7 Λ_7^{-6}	$(-2.8^{+1.8}_{-1.7})\cdot 10^{-18}\ \mathrm{GeV}^{-6}$	$\Lambda_7 > 880$
effective Lagrangian dimension 6 and 8	derived from Λ_+ derived from Λ_7	$\Lambda_6 > 1752$ $\Lambda_8 > 24.3$
quantum gravity λ/M_s^4	$(-0.85^{+0.54}_{-0.55})\cdot 10^{-12}\ \mathrm{GeV}^{-4}$	$\lambda=+1$: $M_s > 868$ $\lambda=-1$: $M_s > 1108$
excited electrons $M_{e^*}(f_\gamma=1)$ $f_\gamma^2(M_{e^*}=200\ \mathrm{GeV})$	see Figure 2.6 $-0.17^{+0.12}_{-0.12}$	$M_{e^*} > 366$ $f_\gamma/\Lambda < 7.0\ \mathrm{TeV}^{-1}$

Table 2.5: Results of the fits to the differential cross-section for $e^+e^-\rightarrow\gamma\gamma(\gamma)$ and the 95% confidence level limits on the model parameters.

- More appropriate approach: consider only deviations that respect the $SU(2)_L \times U(1)_Y$ symmetry of the SM

New physics deviations in $e^+e^-\to\gamma\gamma$

- If we respect the $SU(2)_L \times U(1)_Y$ symmetry and take $m_e=0$, one finds no $ee\gamma\gamma$ effective Lagrangians at dimension 6 ⇒ all possible constructions are redundant with dimension-8 effects (not difficult to prove: see for instance https://arxiv.org/abs/1008.4884 (Warsaw basis paper))

- **⇒ Leading QED deviations in $ee\to\gamma\gamma$ go at least as $(\text{energy})^4/\Lambda^4$**

- Moreover, the relevant dimension-8 deviations (CP converving, opposite electron-positron helicities) can only be of the following type:

$$\mathcal{O}_{e_R e_R \mathrm{BB}} = (i\ \bar{e_R}\gamma_\mu D_\nu e_R)\mathrm{B}^{\mu\rho}\ \mathrm{B}_\rho^{\ \nu} + \ h.\ c.$$
$$\mathcal{O}_{e_L e_L \mathrm{BB}} = (i\ \bar{e_L}\gamma_\mu D_\nu e_L)\mathrm{B}^{\mu\rho}\ \mathrm{B}_\rho^{\ \nu} + \ h.\ c.$$
$$\mathcal{O}_{e_R e_R \mathrm{WW}} = (i\ \bar{e_R}\gamma_\mu D_\nu e_R)\mathrm{W}^{I\ \mu\rho}\ \mathrm{W}^{I\ \nu}_{\ \rho} + \ h.\ c.$$
$$\mathcal{O}_{e_L e_L \mathrm{WW}} = (i\ \bar{e_L}\gamma_\mu D_\nu e_L)\mathrm{W}^{I\ \mu\rho}\ \mathrm{W}^{I\ \nu}_{\ \rho} + \ h.\ c.$$
$$\mathcal{O}_{e_L e_L \mathrm{WB}} = (i\ \bar{e_L}\tau^I\gamma_\mu D_\nu e_L)\mathrm{W}^{I\ \mu\rho}\ \mathrm{B}_\rho^{\ \nu} + \ h.\ c.$$
$$\mathcal{O}_{e_L e_L \mathrm{BW}} = (i\ \bar{e_L}\tau^I\gamma_\mu D_\nu e_L)\mathrm{B}^{\mu\rho}\ \mathrm{W}^{I\ \nu}_{\ \rho} + \ h.\ c.$$

$$\mathcal{O}_{ee\gamma\gamma} \to \left[i\ \bar{e}\gamma_\mu \frac{1\pm\gamma_5}{2}\partial_\nu e\right] \mathrm{A}^{\mu\rho}\ \mathrm{A}_\rho^{\ \nu} + \ h.\ c.$$

New physics deviations in $e^+e^- \rightarrow \gamma\gamma$

- If we stop at the s^2/Λ^4 order (justified with large statistics and well below the true scale of physics, which is guaranteed in e^+e^- collisions):

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{SM+new} = \left(\frac{d\sigma}{d\cos\theta}\right)_{SM} \left[1 + \frac{c_8\ s^2}{8\pi\alpha\Lambda^4}\ \sin^2\theta\right]$$

- **This is the only possible "leading" behavior of new physics deviations in $e^+e^- \rightarrow \gamma\gamma$. It largely simplifies the task of measuring/excluding new physics effects if we want to use this process as luminosity reference**

- Physical examples (actually all, according to the previous statement, but just in case…):
  - Excited electrons (exchanged in t-channel), large extra-dimension effects (graviton exchange in s-channel)

Measurements: what to expect

- First we will estimate purely statistical uncertainties. Some comments:
  - LEP2 studies have shown that efficiencies and acceptances in the γγ state are high and can be easily controlled, at least at the percent level of precision.
  - Also, at LEP2, radiative corrections could be reduced at the few percent level using relatively simple cuts on acollinearity and vetoing the presence of additional energetic photons in the process
  - Future analyses will require more precise theoretical predictions, at the 10^{-5} level, and likely the inclusion of higher order QED corrections to new-physics effective terms, but for our tests we can assume the following (LO) dependence:

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{SM+new} = \left(\frac{d\sigma}{d\cos\theta}\right)_{SM} \left[1 + \frac{c_8\ s^2}{8\pi\alpha\Lambda^4}\ \sin^2\theta\right]$$

does not depend on Λ

explicit Λ dependence is here

Likelihood fit to "λ" with $|\cos\theta|$ cut c_0

$$\frac{d\sigma}{d\cos\theta} = \frac{2\pi\alpha^2}{s}\,\frac{1+\cos^2\theta}{\sin^2\theta}\,\left[1+\lambda\,\frac{s^2}{2}\sin^2\theta\right]$$

, WITH:

$$\lambda \equiv \pm 1/\Lambda_\pm^4 \equiv \pm f/(e^2\Lambda^4)$$

- **$\Lambda_\pm$ are the scales known as "QED cutoff parameters", introduced by Feynman long time ago**
- **Λ is the EFT scale introduced in the slides before**

$$\Delta\lambda = \frac{2}{s^2\sqrt{<\sin^4\theta>}}\,\frac{1}{\sqrt{N_{ev}}}$$

, WITH:

$$N_{ev} \approx L\,\frac{2\pi\alpha^2}{s}\,\left(\log(\frac{1+c_0}{1-c_0}) - c_0\right)\;,\quad <\sin^4\theta> \approx \frac{\left(c_0 - \frac{c_0^5}{5}\right)}{\left(\log(\frac{1+c_0}{1-c_0}) - c_0\right)}$$

Likelihood fit to "λ" with $|\cos\theta|<0.95$

Collider option	$\sqrt{s}$ [TeV]	L [ab^{-1}]	$\Delta\lambda$ [TeV^{-4}]	$\Delta\sigma_{NP}/\sigma_{SM}$	$\Lambda_{\pm}$ limit [TeV]	Λ limit [TeV]
LEP	< 0.21	0.003	$^{+24}_{-23}$	-	0.431/0.339	0.783/0.616
FCC-ee	0.09	150.0	6.7×10^{-1}	1.1×10^{-5}	0.9	1.7
FCC-ee	0.16	10.0	4.8×10^{-1}	7.2×10^{-5}	1.1	1.8
FCC-ee	0.24	5.0	2.0×10^{-1}	1.5×10^{-4}	1.3	2.3
FCC-ee	0.35	1.5	1.2×10^{-1}	4.0×10^{-4}	1.4	2.6
ILC	0.25	2.0	2.8×10^{-1}	2.5×10^{-4}	1.2	2.1
ILC	0.50	4.0	2.5×10^{-2}	3.5×10^{-4}	2.1	3.8
CLIC	0.38	1.0	1.1×10^{-1}	5.4×10^{-4}	1.4	2.6
CLIC	1.50	1.5	1.5×10^{-3}	1.7×10^{-3}	4.3	7.8
CLIC	3.00	5.0	1.0×10^{-4}	1.9×10^{-3}	8.3	15.2

- Only statistical uncertainties here, as commented before
- CLIC 3 TeV is best (with no surprise, given the dim-8 $\propto$ s^2 effect)
- Reaching the ultimate FCC-ee limit at the Z demands $<10^{-4}$ precision (and luminosity uncertainty counts here: more about this later)

Follow-up of fit results

- Maybe Λ scales of ≈ 1.7 TeV already excluded by other experiments?
  - Not by LEP2, obviously
  - ee→$\gamma\gamma$ or $\gamma\gamma$→ee at LHC ? **no**
    - Lepton PDFs not enough to say much for high (≈ TeV) ee invariant masses
    - Elastic scattering pp→ee still in "propaganda" phase (and requires an interpretation, because also "proton dissociation" events contribute)
  - qq→$\gamma\gamma$ excluded for Λ < 5.5 TeV scales (reinterpretation of the CMS limit M_S > 7.8 TeV on GRW large extra-dimensions)
    - but this can only be translated to the ee case for "fermion universal" new physics effects (we can have high mass excited quarks but excited electrons with lower mass, for instance)

- Running first at the WW or HZ thresholds only requires ≈ 10^{-4} precision and would exclude new physics effects at the required level for the Z run

- **Can we perform a pure shape fit at FCC-ee (i.e. non-extended likelihood fit, no luminosity dependence) ?**

Shape likelihood fit to "λ"

$$\Delta\lambda = \frac{2}{s^2\sqrt{<\sin^4\theta> - <\sin^2\theta>^2}}\,\frac{1}{\sqrt{N_{ev}}}$$

, WITH:

$$<\sin^2\theta> \approx \frac{\left(c_0 + \frac{c_0^3}{3}\right)}{\left(\log(\frac{1+c_0}{1-c_0}) - c_0\right)}$$

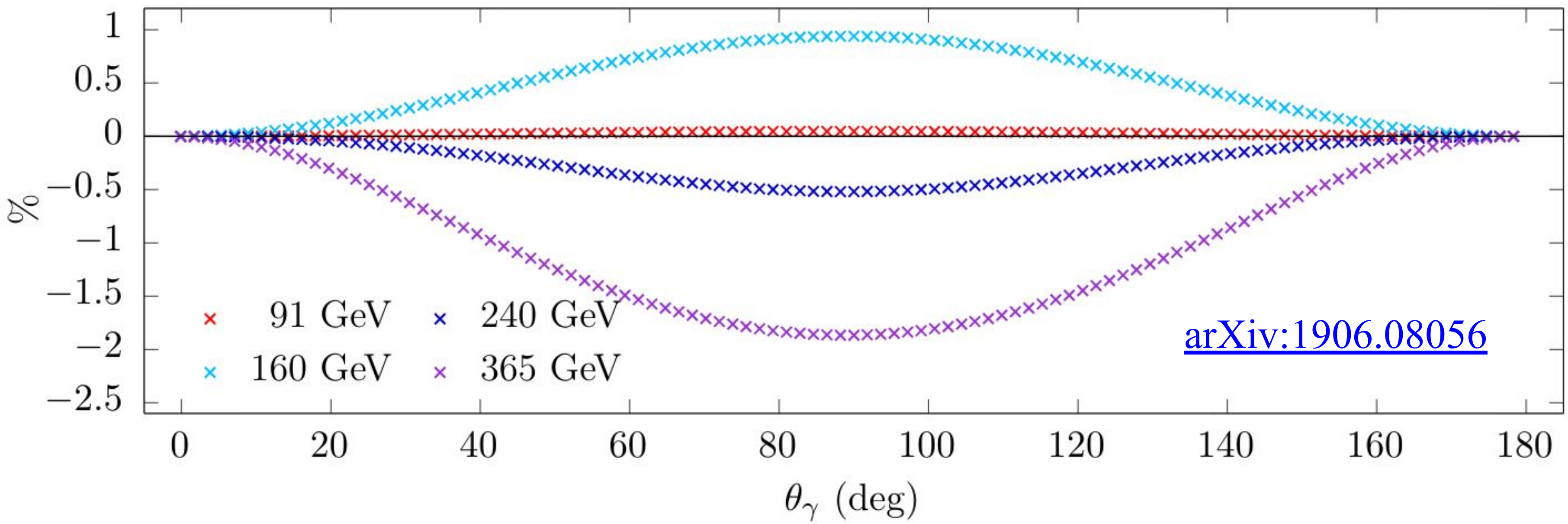
Likelihood shape fit with $|\cos\theta|<0.95$

Collider option	$\sqrt{s}$ [TeV]	L [ab^{-1}]	$\Delta\lambda$ [TeV^{-4}]	$\Delta\sigma_{NP}/\sigma_{SM}$	$\Lambda_{\pm}$ limit [TeV]	Λ limit [TeV]
FCC-ee	0.09	150.0	1.2	1.9×10^{-5}	0.8	1.4
FCC-ee	0.16	10.0	8.9×10^{-1}	1.3×10^{-4}	0.9	1.6
FCC-ee	0.24	5.0	3.7×10^{-1}	2.8×10^{-4}	1.1	2.0
FCC-ee	0.35	1.5	2.2×10^{-1}	7.5×10^{-4}	1.2	2.2
ILC	0.25	2.0	5.2×10^{-1}	4.6×10^{-4}	1.0	1.8
ILC	0.50	4.0	4.6×10^{-2}	6.5×10^{-4}	1.8	3.3
CLIC	0.38	1.0	2.1×10^{-1}	9.9×10^{-4}	1.2	2.3
CLIC	1.50	1.5	2.8×10^{-3}	3.3×10^{-3}	3.7	6.7
CLIC	3.00	5.0	1.9×10^{-4}	3.5×10^{-3}	7.2	13.0

- Sensitivity reduced, but not dramatically (⇔ factor of 3 loss in statistics)
- Reaching the ultimate FCC-ee limit at the Z still requires $\lesssim 10^{-4}$ precision, but one can decouple SM rate and new physics effects
  - for instance, one could envisage a simultaneous fit to SM rate and λ

Curiosities/questions (to theorists)

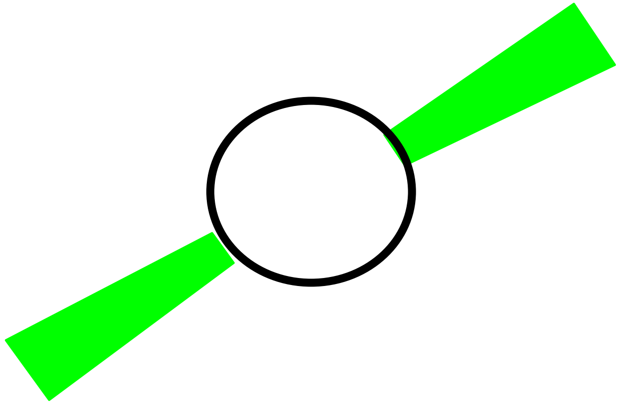
- **Do QED radiative corrections include anyway terms equivalent to SM deviations of this $\sin^2\theta$ type ?**



Relative contribution of the weak NLO corrections to the ee→$\gamma\gamma$ cross section (which approximately follows a $\sin^2\theta_\gamma$ dependence)

Some thoughts on systematics control

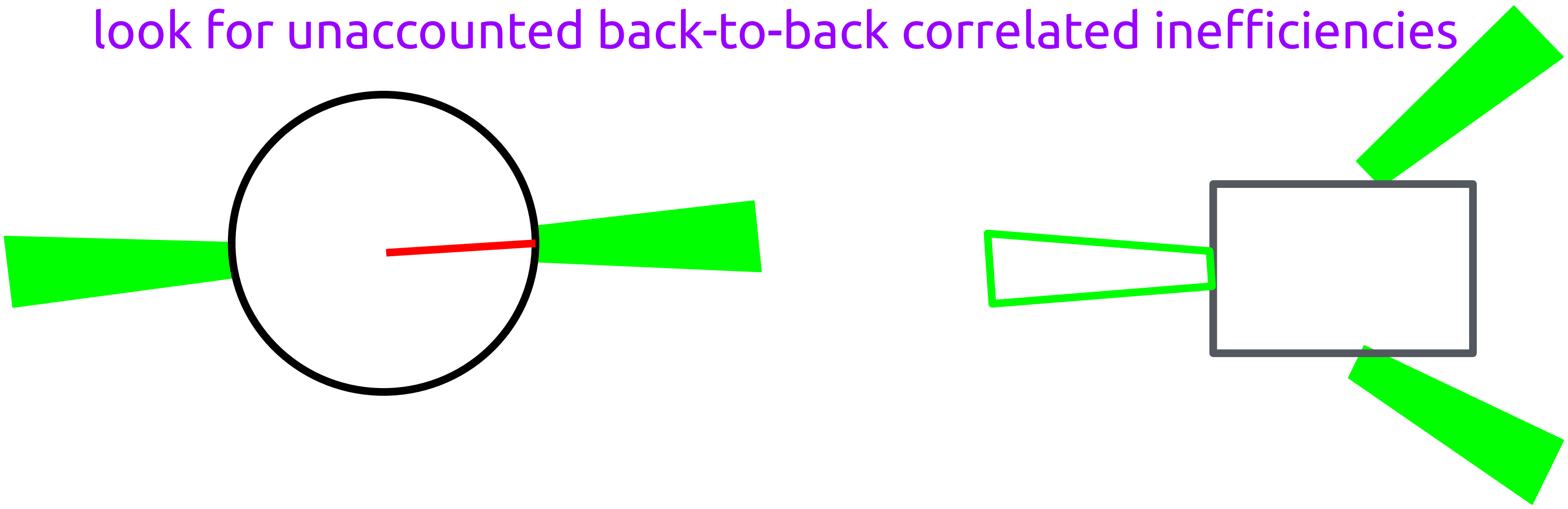
- Mostly based on past LEP2 experience:
  - Use relatively soft em-shape criteria: at the end of the day almost any high-energy electromagnetic-only deposit with no track activity in an event without jets does the job
  - Use (loose) acollinearity cuts to reduce the size of radiative corrections (LEP2 studies). This also rejects additional high-energy (ISR) photons in the beam pipe



  - Compact detector is a must. Minimize barrel-endcap gaps or just eliminate that region in analysis in a limit case
  - Edge effects and precise measurement of the fiducial region also important (like in the $\mu\mu$ case, I guess)

Some thoughts on systematics control

- Accounting for percent effects:
  - Control sample: events with 1 good photon with zero track activity and another "loosely tagged" photon: stronger acollinearity cuts and electromagnetic energy
    - Measure/correct photon conversion probability and fermion-pair FSR on loosely tagged photons
    - Measure/correct electron identification acceptance on loosely tagged photons with zero track activity
    - Maybe a good idea to measure everything in a kind of global fit
  - Use acollinear $\gamma\gamma$ (or ee) events (hard photon in the beam pipe) to look for unaccounted back-to-back correlated inefficiencies



Some thoughts on systematics control

- These ideas could be tested on realistic simulations, of course, but several of them could be just tested at the generator level (to be done)
  - Generator level:
    - gamma*->fermion-pair contributions
    - Rates of collinear vs acollinear photons
  - Simulation level:
    - Rate of conversion effects (much smaller for pixel+TPC ?)
    - Homogeneity of calorimeter, back-to-back effects, holes, ...

- We will be hardly able to conclude on an optimal polar angle cut before time is due. Typically, problems related with acceptance, electromagnetic identification or the presence of additional tracks / photons are more disturbing at the large $|\cos\theta|$ edges, while the sensitivity loss by going more central is not so big.

- Not clear whether detailed simulations will offer much more than approximate simulations to conclude whether 10^{-5} precisions (or $\approx 10^{-4}$ precision in a local $\cos(\theta)$ region) are reachable/realistic...

Summary/outlook

- **Possible physics deviations in $e^+e^- \rightarrow \gamma\gamma$ at FCC-ee at the Z pole have a simple and well defined functional form and are relatively easy to control. They can even be "measured" in situ or excluded with previous e^+e^- runs at larger center-of-mass energies**

- **Measuring the cross section of this process with precisions < 10^{-4} seems feasible a priori. We have several level arms to control the different sources of uncertainty, although more studies are needed**

Backup

Past QED deviations explored at LEP

- Lagrangians considered at LEP times (see Phys. Lett. B271, 274):

$$ig_6(\bar{e}\gamma_\mu D_\nu e)F^{\mu\nu} + h.c.$$

Dimension 6 term, but redundant (due to the equations of motion) ⇒ deviations are of dimension 8 type/size ($\propto s^2/\Lambda^4$), as expected.

$$\frac{1}{4}\bar{e}(g_7^S F^{\mu\nu} + ig_7^P\gamma_5\tilde{F}^{\mu\nu})eF_{\mu\nu}$$

Dimension 7 term. To get $SU(2)_L$ invariance, one has to add a ϕ Higgs term to it, thus converting it into a dimension 8 term. In addition, it connects e- and e+ with same helicity, so it does not interfere with the standard SM process ⇒ effect goes as v^2s^3/Λ^8 ⇒ dimension 12 effect, not a large effect

$$\frac{1}{8}\bar{e}\gamma^\mu(g_8^V - g_8^A\gamma_5 e)(\partial_\mu\tilde{F}^{\alpha\beta})F_{\alpha\beta}$$

Dimension 8 term. Connected with a Lagrangian proportional to m_e via equations of motion ⇒ goes as $m_e^2s^3/\Lambda^8$ and is negligible for $m_e=0$