Precision studies of quantum electrodynamics at future e^+e^- colliders

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Outline

- Introduction
- Allowed new physics deviations in the $e^+e^-\rightarrow\gamma\gamma$ process
- Sensitivity of future lepton colliders to QED deviations
- Excluding potential new physics deviations in luminosity measurements

Based on J.A., arXiv:2206.07564 (CIEMAT Technical Report 1499) and using additional info from C.M. Carloni Calame et al, arXiv:1906.08056 (Phys. Lett. B798 (2019) 134976)

$e^+e^- \to \gamma\gamma$ as luminometer ?

- Process minimally affected by theoretical uncertainties in the SM:
  - Hadronic corrections only appear at the 10^{-5} level (arXiv:1906.08056)

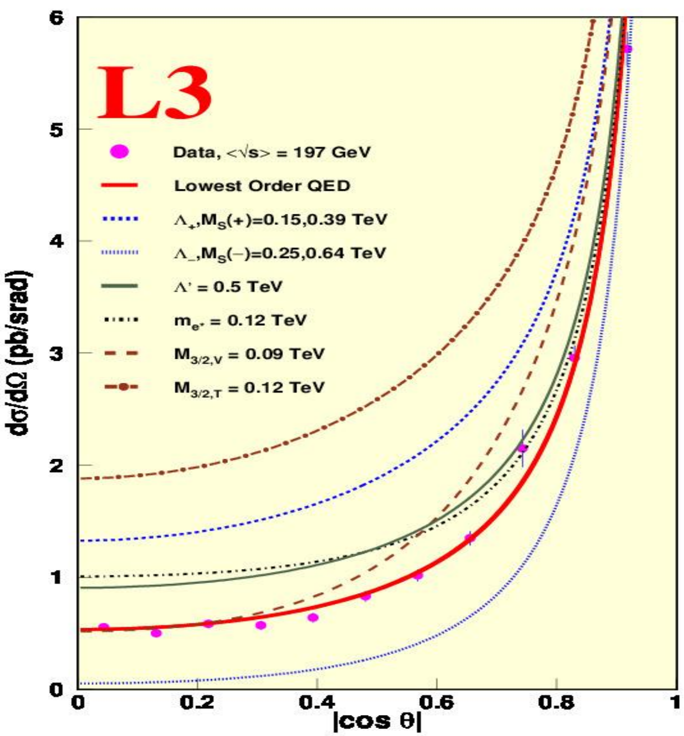
$\sqrt{s}$ (GeV)	$\sigma^{NNLO}_{\Delta\alpha\,\mathrm{lep+top}}/\sigma_{LO}$	$\sigma^{NNLO}_{\Delta\alpha\,\mathrm{had}}/\sigma_{LO}$	$\delta\sigma_{\mathrm{had}}/\sigma_{LO}$
91	0.096%	0.085%	$3.7 \cdot 10^{-6}$
160	0.108%	0.098%	$3.8 \cdot 10^{-6}$
240	0.115%	0.108%	$3.9 \cdot 10^{-6}$
365	0.119%	0.120%	$4.0 \cdot 10^{-6}$

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.

- Measurable at "relatively" high polar angles with respect to the beam. At FCC-ee, $\sqrt{s}$ = 91.2 GeV, assuming LO cross section and 100% acceptance:
  - $1/\sqrt{N} \approx 1.3\text{e-}5$ for $|\cos\theta|<0.95$,
  - $1/\sqrt{N} \approx 2.0\text{e-}5$ for $|\cos\theta|<0.7$
- But the process could be sensitive to new physics (it is not low Q^2):
  - **can we quantify a bit more ?**

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

- Past approach (up to LEP2 included): considering any possible Lagrangian contribution providing QED deviations



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

Table 2.5: Results of the fits to the differential cross-section for $e^+e^- \to \gamma\gamma(\gamma)$ 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 $e^+e^- \to \gamma\gamma$

- Respecting the $SU(2)_L \times U(1)_Y$ symmetry, and in the $m_e \to 0$ limit, no $ee\gamma\gamma$ effective terms at dimension 6 are found ⇒ 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 (energy)^4/ Λ^4**

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

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

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

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 $m_e=0$

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

- At the s^2/Λ^4 order (dominant term for large statistics samples when the true scale of physics $\Lambda >> \sqrt{s}$):

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

- **This is the only possible leading behavior of new physics deviations in $e^+e^-\to\gamma\gamma$. It largely simplifies the task of measuring/excluding new physics effects when using 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 demand more precise theoretical predictions, at the 10^{-5} level or so, with the inclusion of high order EW corrections, but for our estimates we can assume the 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 |cosθ| 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:

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

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 FCC-ee limit at the Z demands < 10^{-4} precision in luminosity
- FCC-ee: running first at the WW or HZ thresholds only requires ≈ 10^{-4} precision and would exclude new physics effects for the Z run

New physics already excluded?

- **For FCC: Λ scales of ≈ 1.7 TeV already excluded by other experiments?**
  - Not by LEP2 (Λ > 0.7 TeV ⇒ $\Delta\sigma_{NP} / \sigma_{SM} < 4 \times 10^{-4}$)
    - But no problem if we wnt a luminosity precision $\gtrsim 4 \times 10^{-4}$ ...
  - qq→$\gamma\gamma$ excluded for $\Lambda \lesssim 7$ TeV scales (reinterpreting a limit of $M_S \gtrsim 10$ TeV on GRW large extra-dimensions)
    - but this can only be strictly translated to the ee case assuming universal new physics effects (for instance, we could still have excited electrons at lower scales)
  - ee→$\gamma\gamma$ or $\gamma\gamma$→ee with high Q^2 at LHC ?
    - Not enough precision from ee initiated states, PDF uncertainties dominate ee high mass final states, elastic scattering in pp→ee affected by "proton dissociation" events, …
- **Anyway, running first at the HZ threshold, for instance, would be an easy way to constrain any new QED physics at the Z pole**

Luminosity measurement (FCC-ee, Z pole)

Collider option	$\sqrt{s}$ [TeV]	L [ab^{-1}]	$\cos\theta$ cut	$\Delta\sigma/\sigma$
FCC-ee	0.09	150.0	0.95	1.1×10^{-5}
FCC-ee	0.09	150.0	0.90	1.3×10^{-5}
FCC-ee	0.09	150.0	0.85	1.5×10^{-5}
FCC-ee	0.09	150.0	0.80	1.7×10^{-5}
FCC-ee	0.09	150.0	0.75	1.8×10^{-5}
FCC-ee	0.09	150.0	0.70	2.0×10^{-5}

- Only statistical uncertainties, assuming no new physics effects
- A luminosity measurement with ≈ 10^{-4} statistical precision PER YEAR seems feasible, even with a fiducial cut as stringent as $|\cos\theta| < 0.7$
- Keeping systematics (exp ⊕ theo) at the same level is the challenge
  - See G. Wilson talk for more details on the experimental challenges

Shape likelihood fit to "λ"

- **But can we perform a pure shape fit to search for QED deviations (i.e. a fit insensitive to luminosity uncertainties) ?**
- **Not=extended likelihood fit:**

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

, WITH:

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

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 statistical power)
- One can decouple really SM rate and new physics effects:
  - I.e, one could envisage a simultaneous fit of the SM rate (⇒ luminosity measurement at the 10^{-4}-10^{-5} level) and the λ parameter

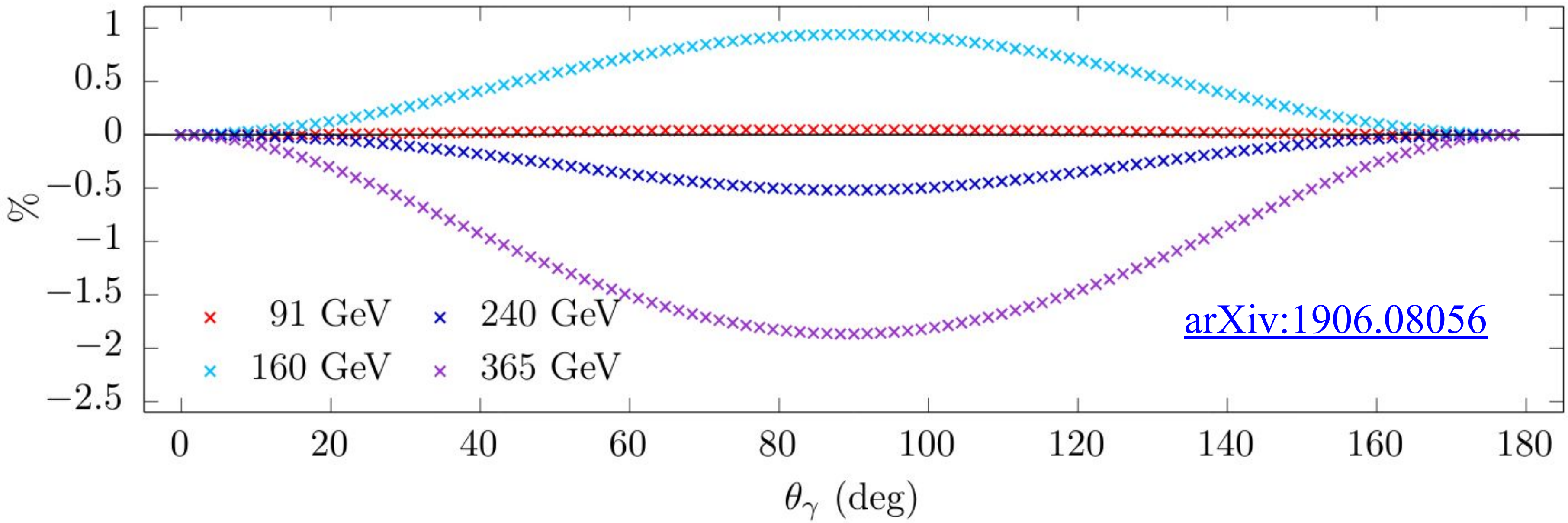
Luminosity measurement (FCC-ee, Z pole)

Collider option	$\sqrt{s}$ [TeV]	L [ab^{-1}]	$\cos\theta$ cut	$\Delta\sigma/\sigma$
FCC-ee	0.09	150.0	0.95	1.9×10^{-5}
FCC-ee	0.09	150.0	0.90	3.1×10^{-5}
FCC-ee	0.09	150.0	0.85	4.3×10^{-5}
FCC-ee	0.09	150.0	0.80	5.8×10^{-5}
FCC-ee	0.09	150.0	0.75	7.8×10^{-5}
FCC-ee	0.09	150.0	0.70	1.0×10^{-4}

- Only statistical uncertainties, shape fit, insensitive to new physics
- A luminosity measurement with ≈ 10^{-4} statistical precision PER YEAR in this context still seems feasible for $|\cos\theta_{cut}| \gtrsim 0.9$)

Interesting features

- **Higher order SM corrections:**
  - Virtual+real photonic corrections (MC implementation)
  - NLO weak corrections

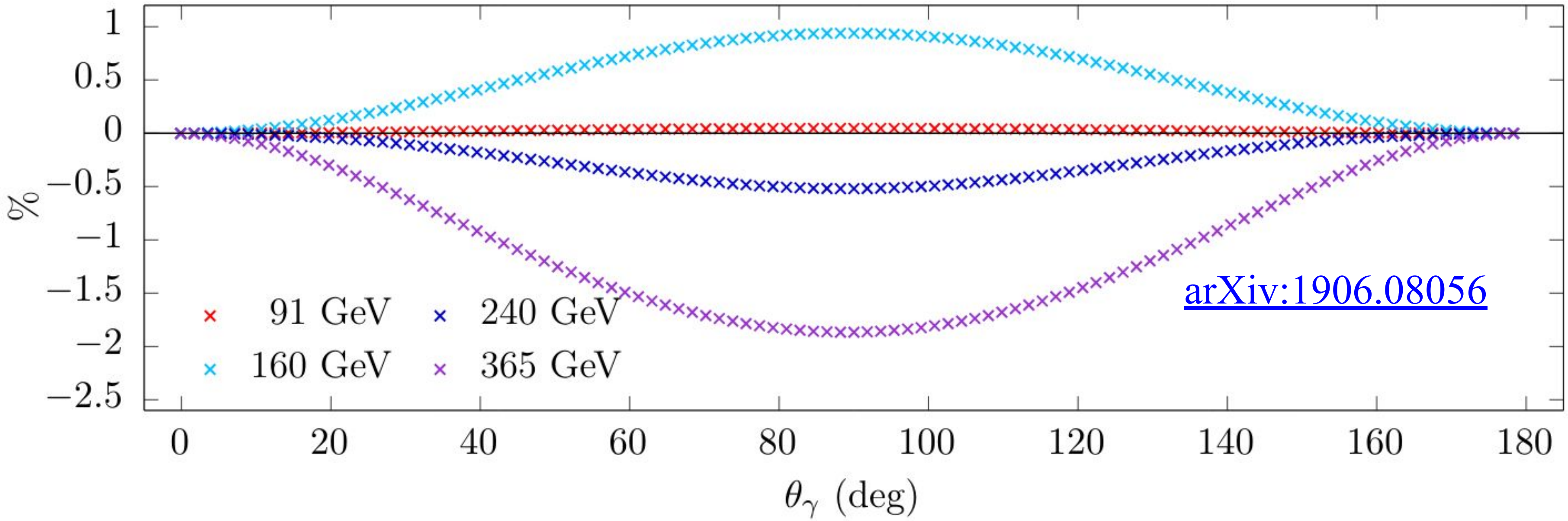


- Relative contribution of the weak NLO corrections to the ee→$\gamma\gamma$ cross section indeed follows a $\sin^2\theta_\gamma$ dependence (not surprisingly)

- A luminosity measurement that decouples from NP effects via a shape fit will implicitly absorb these corrections

Interesting features: positivity

- $\sigma_{SM+NP}(e^+e^- \to \gamma\gamma) > \sigma_{SM}(e^+e^- \to \gamma\gamma) \Rightarrow \lambda > 0$
  - i.e. always a positive excess from new physics at a scale Λ
  - discussed for instance in arXiv:2011.03055)



But one has to be careful, because SM corrections (which happen below Λ) may have negative contributions too (see plot)

On the ultimate precision in luminosity

- Typically, problems related with acceptance, electromagnetic identification, or the presence of additional tracks / photons are more disturbing at large $|\cos\theta|$, while the sensitivity loss by going more central is not so big.

- Detailed detector simulations will require very precise tunings using control sample studies as input. No way to conclude today whether 10^{-5} precisions (or $\approx 10^{-4}$ precision in a local $\cos(\theta)$ region) will be reachable without a final detector in hand…

- The accurate knowledge of the detector edges of the measurement is important, but note that we are not just “counting”, we should profit from the expected “shapes” to reduce this uncertainty (to be studied)

- Still, we need further developments on the theory/MC side too to reach a $\approx 10^{-5}$ precision goal

Summary/outlook

- Leading new physics deviation in the $e^+e^- \to \gamma\gamma$ process only appear at dimension 8 and have a very specific behaviour as a function of the polar angle. Higgs factories should improve current limits on QED deviations, in particular when √s increases (deviations increase as s^2/Λ^4)

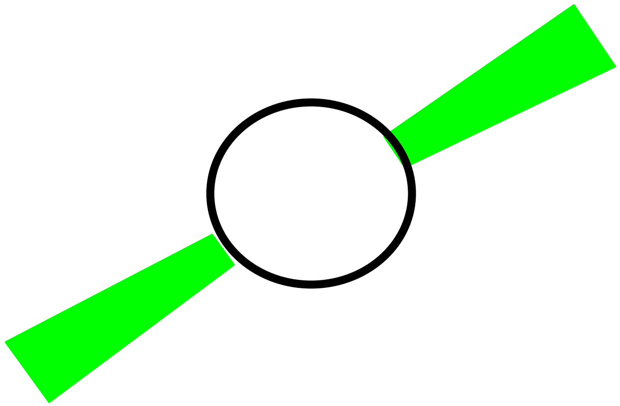
- Possible physics deviations in $e^+e^- \to \gamma\gamma$ at the Z pole have a simple and well defined functional form and are relatively easy to control. They can even be "measured" in situ or excluded with previous e^+e^- runs at larger center-of-mass energies

- Measuring the luminosity via this process with precisions $\lesssim 10^{-4}$ per year at the FCC-ee seems feasible a priori. We have several level arms to control the different sources of uncertainty, although more studies are still needed

Backup

On the experimental side

- Mostly based on past LEP2 experience (see also G. Wilson's talk):
  - Relatively soft em-shape criteria are enough
  - LEP2 used acollinearity cuts to reduce the size of radiative corrections and reject additional high-energy (ISR) photons in the beam pipe. With more precise MCs we should revisit the optimal strategy to follow



  - A compact and homogeneous detector is a must: eliminate the barrel-endcap transition region in the analysis if more convenient
  - A precise definition of the edges of the fiducial region is important

On backgrounds

- See again previous talk from G. Wilson about a more detailed study of several background components. Nevertheless:
  - Background from electrons in final state not an issue in normal conditions: two energetic back-to-back neutral e.m. bumps in tracker acceptance with **zero hit** activity in tracker becomes a pure sample, really
  - The challenge is thus transferred to a precise estimate of losses due to conversions ⇒ dedicated control samples
  - Need a precise monitoring of the acceptance as a function of cosθ