Investigating New Physics contamination in luminosity measurements at FCC-ee

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Luminosity Measurements

Cross section measurements

$$\sigma^{\text{exp}}_{e^+e^-\to X} = \frac{1}{\epsilon}\frac{N^{\text{exp}}_{e^+e^-\to X}}{L}$$

$N^{\text{exp}}_{e^+e^-\to X}$	# of observed Events
L	Machine Luminosity
ϵ	Experimental Acceptance

$$\frac{\delta\sigma^{\text{exp}}_{e^+e^-\to X}}{\sigma^{\text{exp}}_{e^+e^-\to X}} = \frac{\delta N^{\text{exp}}_{e^+e^-\to X}}{N^{\text{exp}}_{e^+e^-\to X}} \oplus \frac{\delta L}{L}$$

Has to be kept small

Precision on the cross section

Statistical error

Reduced by increasing the integrated luminosity (collecting more data)

Luminosity error

Luminosity Measurements

$$L = \int \mathscr{L} \mathrm{dt} = \frac{1}{\epsilon} \frac{\mathrm{N}_0}{\sigma_0^{\mathrm{th}}}$$

At Lepton colliders the Luminosity is measured via a **benchmark process**

Small Angle Bhabha Scattering (SABH)

$$\sigma(e^+e^- \to e^+e^-) \sim \left(\frac{1}{\theta^2_{\mathrm{min}}} - \frac{1}{\theta^2_{\mathrm{max}}} \right) \sim \frac{1}{\theta^2_{\mathrm{min}}}$$

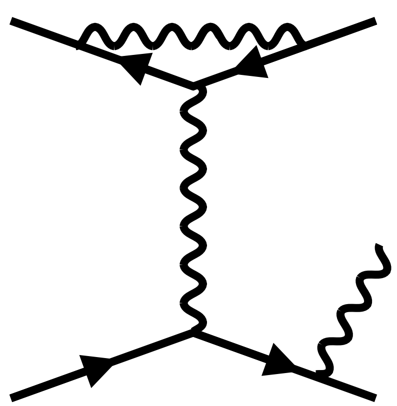
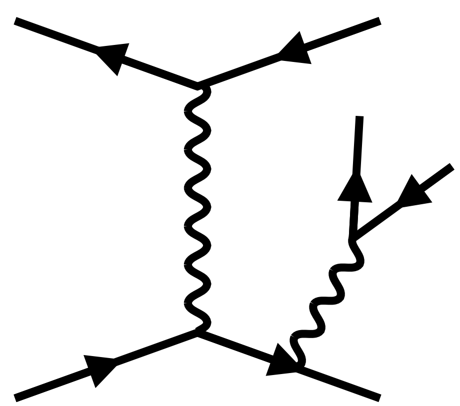
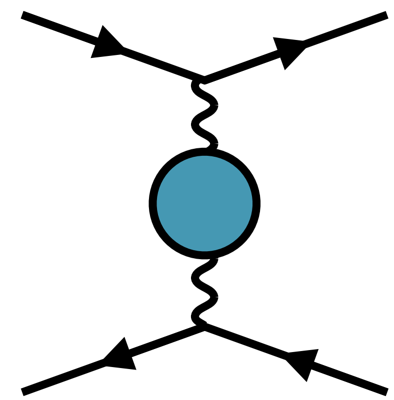
- High cross section so $\delta N_0 / N_0$ very small
- Cross section very well known theoretically
- Experimentally well distinguishable

$$\frac{\delta L}{L} = 2 \frac{\delta \theta_{\mathrm{min}}}{\theta_{\mathrm{min}}} \oplus \frac{\delta N_0}{N_0} \oplus \frac{\delta \sigma_0^{\mathrm{th}}}{\sigma_0^{\mathrm{th}}}$$

Dominant source of uncertainty

Radiative Corrections @ LEP

A. Arbuzov et al. *Phys.Lett.B* 383 (1996) 238-242
S. Jadach et al. Physics Letters B 790 (2019) 314–321

	Photonic	**Light pairs**	**Vacuum Pol.**	**Total**
				
LEP 1999 18-52 mrad	0.030% $\mathcal{O}\left(\alpha^2 L \oplus \alpha^3 L^3\right)$	0.030%	0.040%	0.061%

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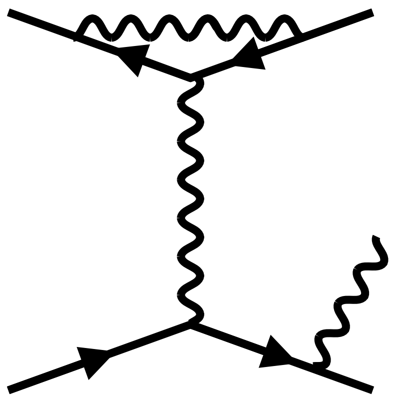
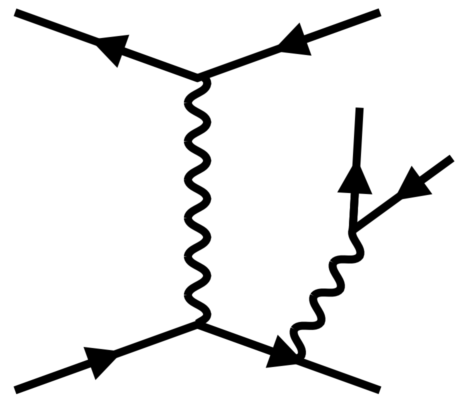
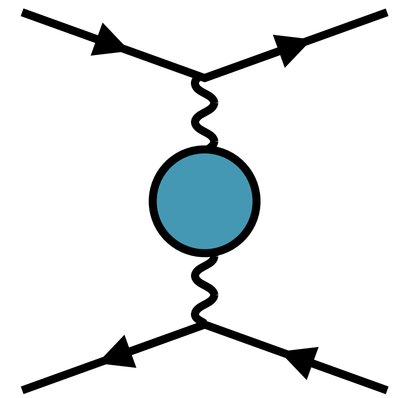
Photonic



Light pairs



Vacuum Pol.



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LEP 1999 18-52 mrad	0.030% $\mathcal{O}\left(\alpha^2 L \oplus \alpha^3 L^3\right)$	0.030%	0.040%	0.061%
2018 18-52 mrad		0.010%	0.013%	0.038%
		G. Montagna et al. Nucl. Phys. B 547 (1999) Phys. Lett. B 459 (1999)	F. Jegerlehner, indico.cern.ch/event/469561	

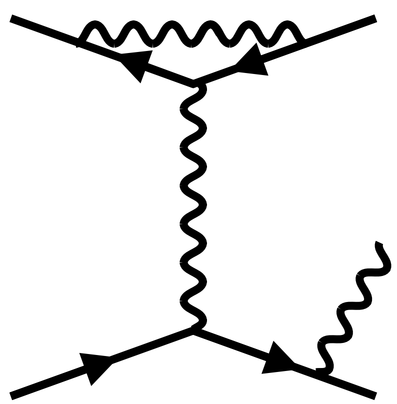
Janot and Jadach Phys.Lett.B 803 (2020) — 0.037%

N_ν

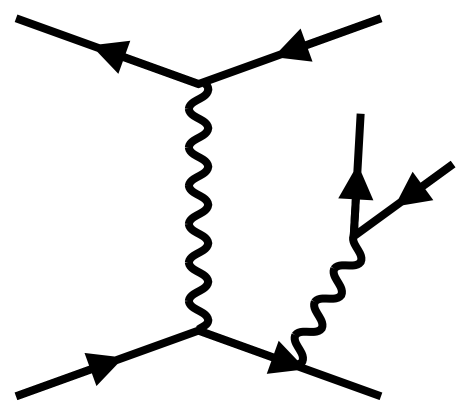
Radiative Corrections @ FCC-ee

S. Jadach et al. Physics Letters B 790 (2019) 314–321

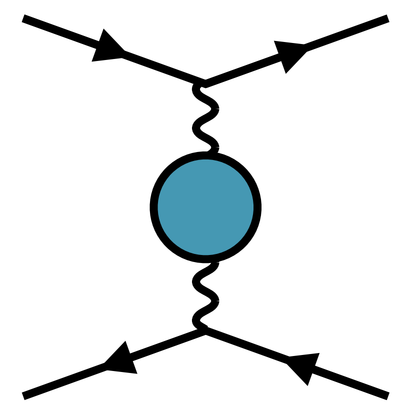
Photonic



Light pairs



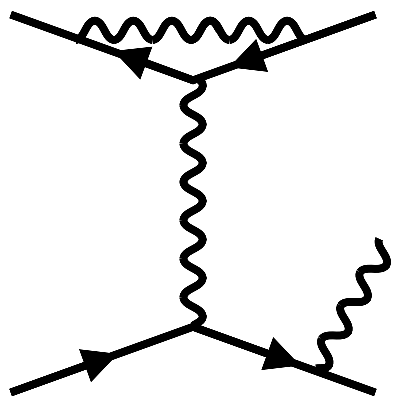
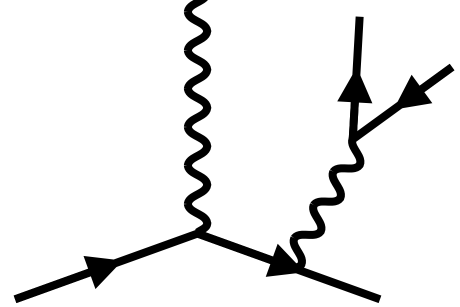
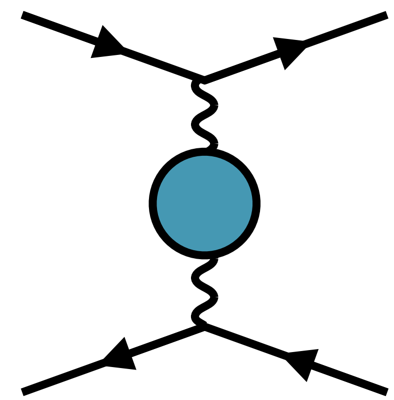
Vacuum Pol.



	Photonic	Light pairs	Vacuum Pol.	Total
2018 64-86 mrad	0.030% $\mathcal{O}\left(\alpha^2 L \oplus \alpha^3 L^3\right)$	0.010%	0.014%	0.097%
FCC-ee Forecast				

Radiative Corrections @ FCC-ee

S. Jadach et al. Physics Letters B 790 (2019) 314–321

	Photonic	Light pairs	Vacuum Pol.	
				Total
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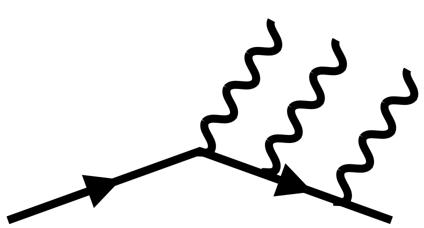
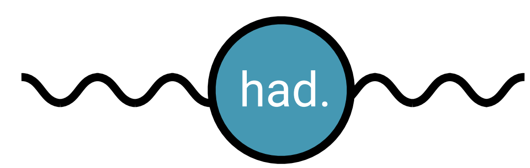
FCC-ee Forecast	0.011% $\mathcal{O}\left(\alpha^3 L^2 \oplus \alpha^4 L^4\right)$	0.005%	0.006%	**0.01%** Goal



QED H.O. resummation is needed



$$\frac{\delta_{VP}\sigma}{\sigma} \simeq 2.4 \times 10^{-4}$$

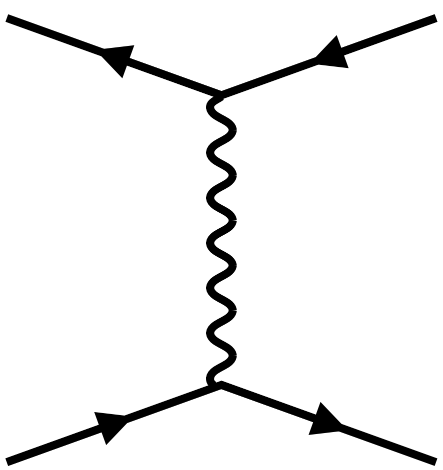
Janot, P. Direct measurement of αQED(m^2_Z) at the FCC-ee. *J. High Energ. Phys.* **2016**, 53 (2016)

New Physics Contribution

FCC-ee goal

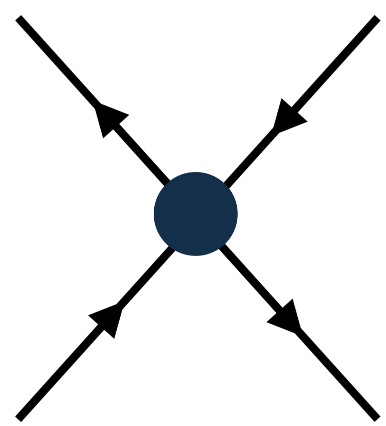
$$\left.\frac{\delta L}{L}\right|_{\text{th}} \leq 10^{-4}$$

Is the theoretical prediction of the Bhabha safe from **New Physics** contributions at **future colliders**?

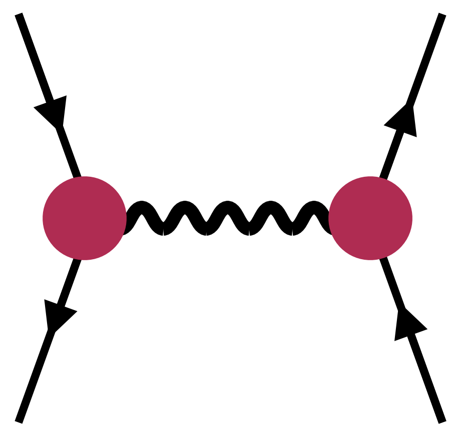


$\times$

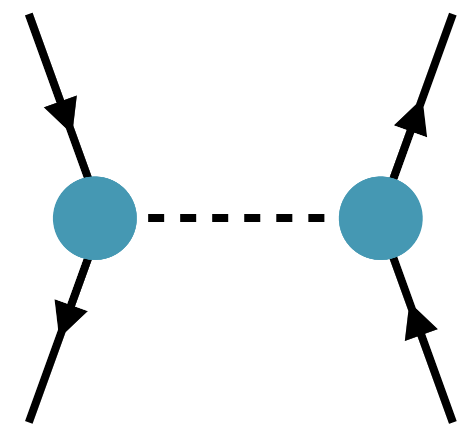
Contact interactions



Massive d.o.f



Light/Weakly coupled d.o.f.



New Physics could interfere with the SM
At which level?

$$\frac{\delta\sigma_{\text{NP}}}{\sigma_{\text{SM}}} \simeq ?$$

New Physics Contribution

1. NP scale is **below** or **above** the electroweak scale?

Below

$\mathscr{L}_{\rm model}$

2. Specify the spin and the parity of the BSM d.o.f.

$$\leq \frac{g_i^2}{4\pi M_i^2} \leq$$

3. Find the **bounds** on masses and couplings

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Above

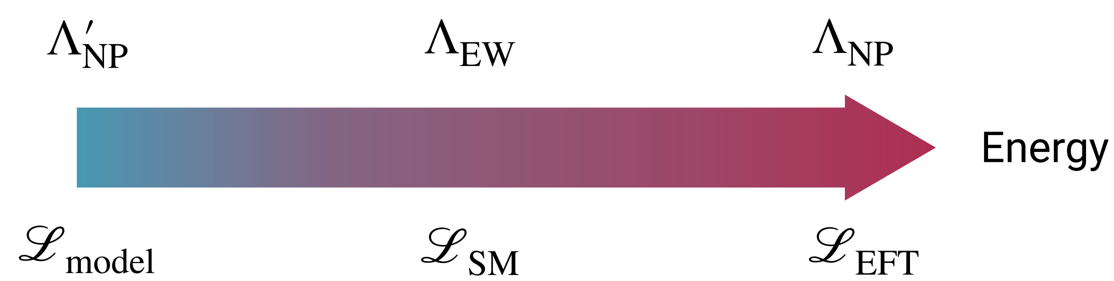
$\mathscr{L}_{\text{EFT}}$

2. Parameterize the NP in a model independent way **SMEFT**

$$\leq \frac{C_i}{\Lambda_{\text{NP}}^2} \leq$$

3. Rely on a **global fit** of the Wilson Coefficients of NP interactions

New Physics Contribution



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$\mathscr{L}_{\mathrm{EFT}}$

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$$\leq \frac{C_i}{\Lambda^2_{\mathrm{NP}}} \leq$$

3. Rely on a **global fit** of the Wilson Coefficients of NP interactions

$$\frac{\delta\sigma_{\mathrm{NP}}}{\sigma_{\mathrm{SM}}} \simeq ?$$

4. Quantify the deviation of the Bhabha prediction from the SM

Contact Interactions

"Electroweak Measurements in Electron–Positron Collisions at W-Boson-Pair Energies at LEP."
Physics Reports, vol. 532, no. 4, Nov. 2013, pp. 119–244. arXiv:1302.3415

In LEP analysis contact interactions were parameterized as

$$\mathscr{L}_{\text{eff}} = \frac{g^2}{2\Lambda^2} \sum_{i,j=L,R} \eta_{ij} \left(\bar{e}_i \gamma_\mu e_i\right) \left(\bar{e}_j \gamma^\mu e_j\right)$$

$$\frac{g^2}{4\pi} = 1$$

Model	Λ^-_{ee} (TeV)	Λ^+_{ee}
LL	8.0	8.7
RR	7.9	8.6
VV	15.3	20.6
AA	14.0	10.1
LR	8.5	11.9
RL	8.5	11.9
V0	11.2	12.4
A0	11.8	17.0
A1	4.0	3.9

For the Bhabha scattering one has

$$\mathscr{L}^{\pm}_{\text{eff}} = \pm \frac{2\pi}{\Lambda^2_{\pm}} \sum_{ij \in \text{Models}} \eta^{\pm}_{ij} \hat{O}_{ij}$$

Bounds are obtained for the NP scale

Λ_+
Positive interference

Λ_-
Negative interference

Contact Interactions

"Electroweak Measurements in Electron−Positron Collisions at W-Boson-Pair Energies at LEP."
Physics Reports, vol. 532, no. 4, Nov. 2013, pp. 119−244. arXiv:1302.3415

First study for FCC-ee in $e^+e^- \to \gamma\gamma$:
J. A. Maestre arXiv:2206.07564

We consider only the linear interference with the SM as

$$|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}| \pm \frac{2\pi}{\Lambda_\pm^2} \sum_{ij \in \rm Models} \eta_{ij}^{\pm} 2{\rm Re}\{\mathcal{M}_{\rm SM}^{\dagger}\mathcal{M}_{ij}^{\pm}\}$$

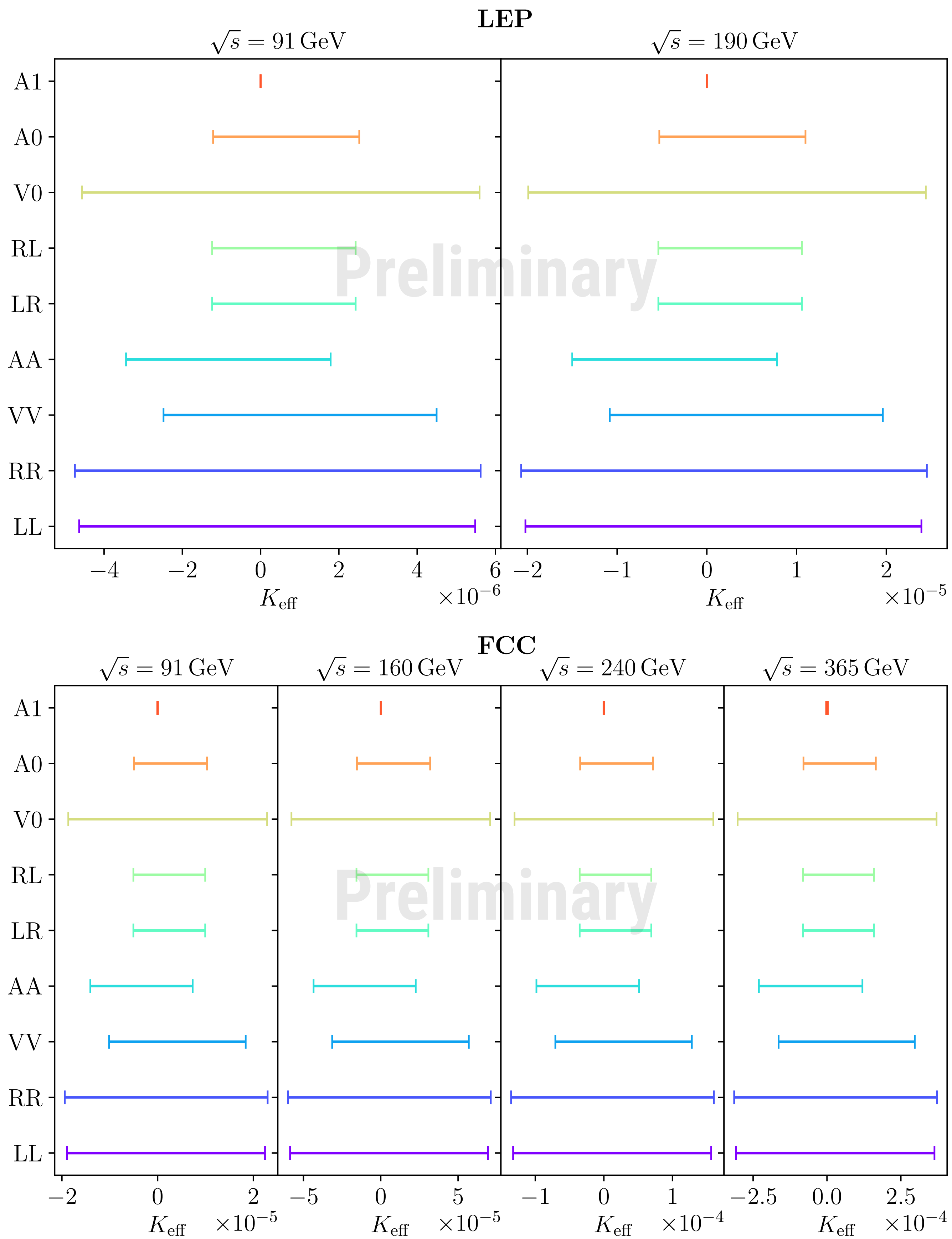
Model	η_{LL}	η_{RR}	η_{LR}	η_{RL}
$LL^{\pm}$	±1	0	0	0
$RR^{\pm}$	0	±1	0	0
$VV^{\pm}$	±1	±1	±1	±1
$AA^{\pm}$	±1	±1	∓1	∓1
$LR^{\pm}$	0	0	±1	0
$RL^{\pm}$	0	0	0	±1
$V0^{\pm}$	±1	±1	0	0
$A0^{\pm}$	0	0	±1	±1
$A1^{\pm}$	±1	∓1	0	0

The QED t channel is the dominant contribution for SABH

$$\mathcal{M}(t)_{\gamma}^{\dagger}\mathcal{M}_{\rm LL/RR} = -32\pi\alpha\frac{(1+\cos\theta)^2}{(1-\cos\theta)}s$$

$$\mathcal{M}(t)_{\gamma}^{\dagger}\mathcal{M}_{\rm RL/LR} = -64\pi\alpha\frac{s}{(1-\cos\theta)}$$

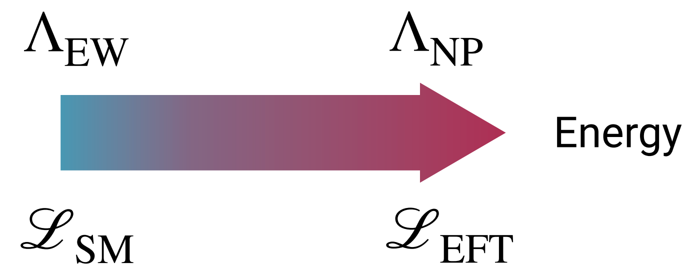
Contact Interactions: results



SMEFT

The most comprehensive way to parameterise NP
is to treat the SM as low-energy limit of an EFT

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda_{\mathrm{NP}}^2} Q_i^{(6)} + \mathcal{O}(\Lambda_{\mathrm{NP}}^{-4})$$



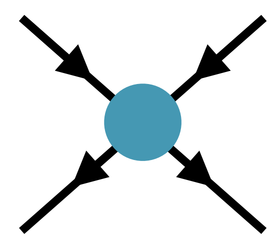
Shift of input parameters

$$g = g_{\mathrm{SM}} + \Delta g$$

$$G_\mu = \frac{1}{\sqrt{2} v_T^2}\left(1 + \frac{1}{\sqrt{2} G_\mu}\left(C_{Hl}^{(3)11} + C_{Hl}^{(3)22} - C_{ll}^{1221}\right)\right.$$

$$\alpha_{\mathrm{em}} = \frac{1}{4\pi}\frac{g_W^2 g_1^2}{g_W^2 + g_1^2}(1 + \Delta\alpha_{\mathrm{em}})$$

New vertices



$$\mathscr{L}_{\mathrm{eff}} \in \mathscr{L}_{\mathrm{SMEFT}}^{4f} = \frac{C_{ij}}{\Lambda_{\mathrm{NP}}^2} Q_{ij}^{(6)}$$

The Lagrangian used in LEP studies is a linear combination of SMEFT operators

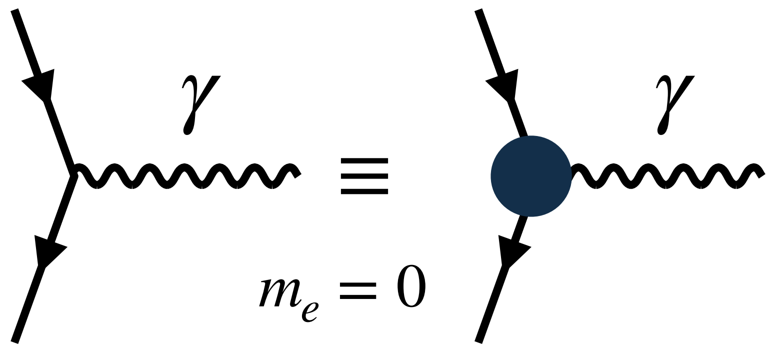
I. Brivio, "SMEFTsim3.0 - a practical guide"
arXiv:2012.11343

SMEFT: EW sector

A. Falkowski et al., "Compilation of low-energy constraints on 4-fermion operators in the SMEFT" arXiv:1706.03783

We use the $\{\alpha, M_Z, G_\mu\}$ scheme to compute the SMEFT prediction

QED



$\Delta\alpha_{\text{em}} = 0$

Weak NC

$$\mathscr{L}^{\text{NC}}_{\text{SMEFT}} = \frac{\sqrt{4\pi\alpha}}{s_w c_W}\left\{ \bar{e}_L\left(g_L^Z + \frac{\delta g_L^{Z,e}}{\Lambda^2}\right)\gamma^\mu e_L + \bar{e}_R\left(g_R^Z + \frac{\delta g_R^{Z,e}}{\Lambda^2}\right)\gamma^\mu e_R \right\} Z_\mu$$

Shifts in L/R handed couplings of Z boson with electrons

$$\delta g_L^{Z,e} = -\frac{1}{2}C_{\phi l}^{(3)} - \frac{1}{2}C_{\phi l} + f\left(-\frac{1}{2}, -1\right)$$

$$\delta g_R^{Z,e} = -\frac{1}{2}C_{\phi e} + f(0, -1)$$

$$f(T^3, Q) = -Q\frac{s_w c_w}{c_w^2 - s_w^2}C_{\phi WB} + \left(\frac{1}{4}C_{ll,1221} - \frac{1}{2}C_{\phi l,11}^{(3)} - \frac{1}{2}C_{\phi l,22}^{(3)}\right)\left(T^3 + Q\frac{s_w^2}{c_w^2 - s_w^2}\right)$$

Linear combinations of Warsaw basis WCs

For SILH Basis arXiv:1610.07922

SMEFT: results

Coefficients fitted in

A. Falkowski et al., "Compilation of low-energy constraints on 4-fermion operators in the SMEFT" arXiv:1706.03783

$$K = \frac{\sigma_{\text{SMEFT}}}{\sigma_{\text{SM}}} - 1$$

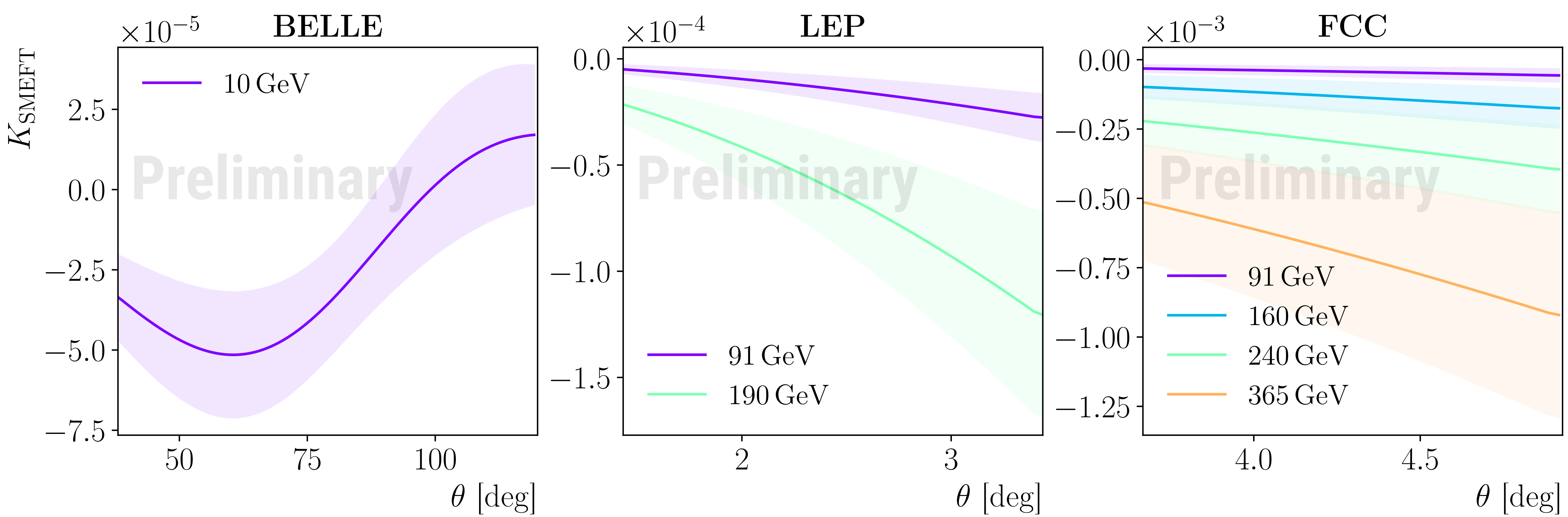
Relative deviation from SM

$$\Delta K = \sum_{i,j} \mathscr{K}_i \text{Cov}_{\text{i,j}} \mathscr{K}_{\text{j}}$$

1 σ error taking correlations among WCs into account

Experiment	$\sqrt{s}$ [GeV]	$K \pm \Delta K$
BELLE	10	$(-3.9 \pm 1.5) \times 10^{-5}$
LEP	91	$(-1.0 \pm 0.4) \times 10^{-5}$
	190	$(-4.4 \pm 1.8) \times 10^{-5}$
FCC	91	$(-4.2 \pm 1.7) \times 10^{-5}$
	160	$(-1.3 \pm 0.5) \times 10^{-4}$
	240	$(-2.9 \pm 1.2) \times 10^{-4}$
	365	$(-6.7 \pm 2.7) \times 10^{-4}$

Preliminary



Light New Physics @ FCC

$M_{\rm NP}^2 \ll v^2$ If NP is light we cannot apply the EFT formalism

ALPs

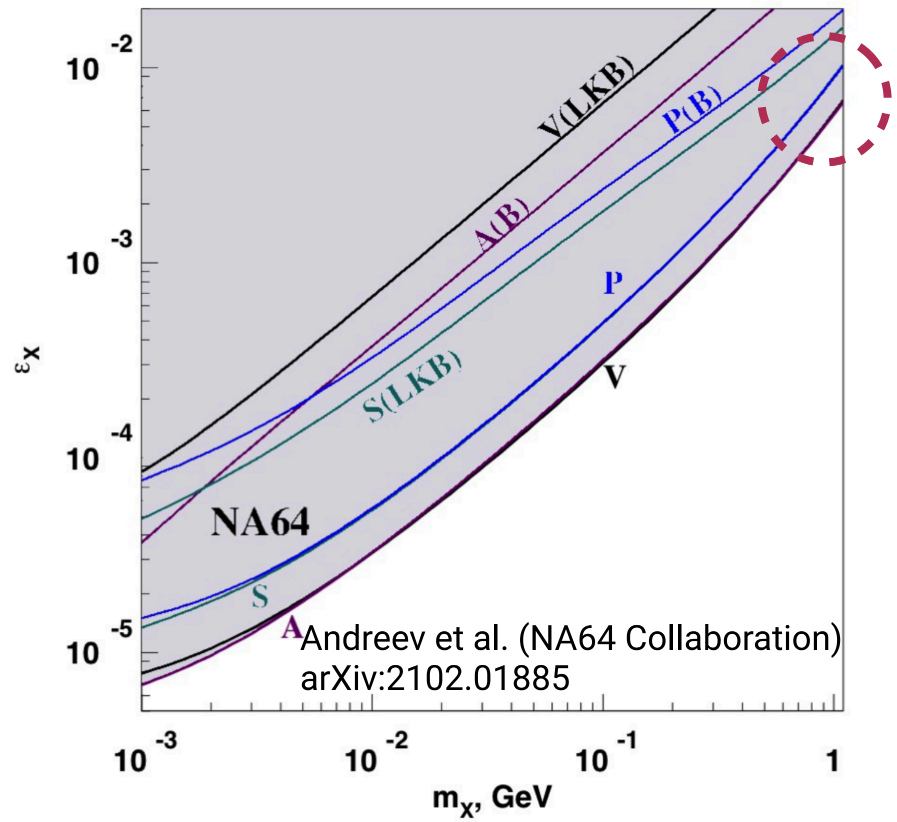
Pseudoscalar

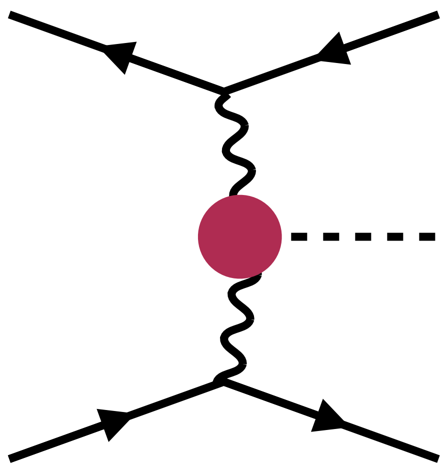
$$\mathscr{L}^a_{\rm ALPs} = \frac{1}{4} g_{a\gamma\gamma} (F_{\mu\nu}\tilde{F}^{\mu\nu}) a + g_A (\bar{e}\, i\gamma_5 e) a$$

Scalar

$$\mathscr{L}^s_{\rm ALPs} = \frac{1}{4} g_{s\gamma\gamma} (F_{\mu\nu}F^{\mu\nu}) s + g_S (\bar{e}\, e) s$$

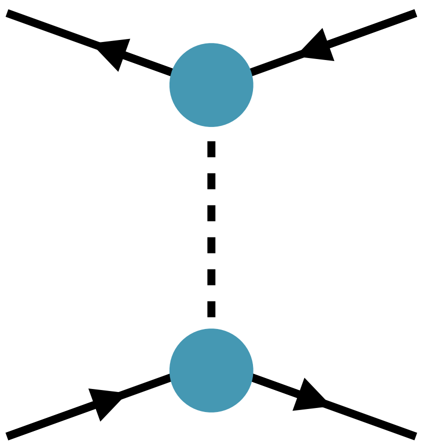
$g_X = \epsilon_X \sqrt{4\pi\alpha}$ We look for the maximal effect





$g_{a\gamma\gamma} \leq 10^{-5}\,\text{GeV}$

Highly suppressed,
$\sigma(e^+e^- \to e^+e^-a) \sim g^2_{a\gamma\gamma}$



$$\frac{\sigma_{\rm ALPs}}{\sigma_{\rm SM}} \leq 10^{-5}$$

Light New Physics @ FCC

$M_{\rm NP}^2 \ll v^2$

If NP is light we cannot apply the EFT formalism

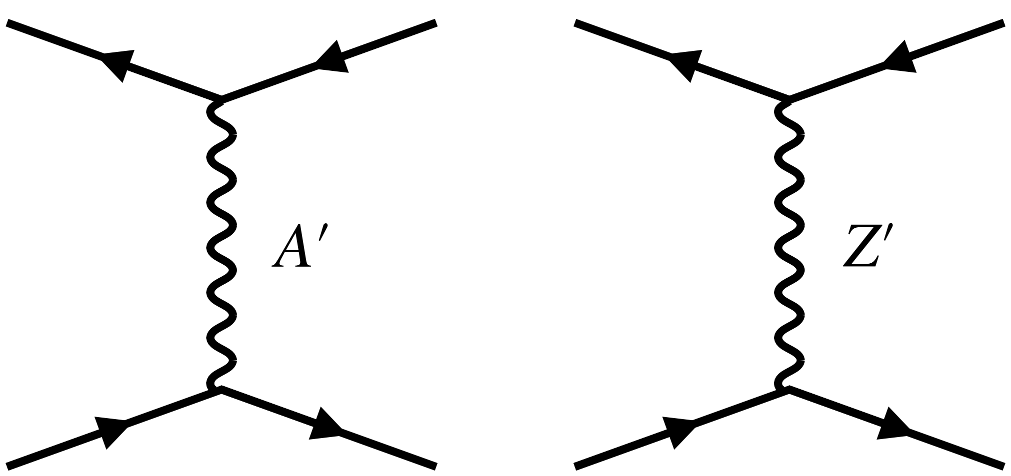
Dark Vectors

Additional $U(1)'$ gauge symmetry

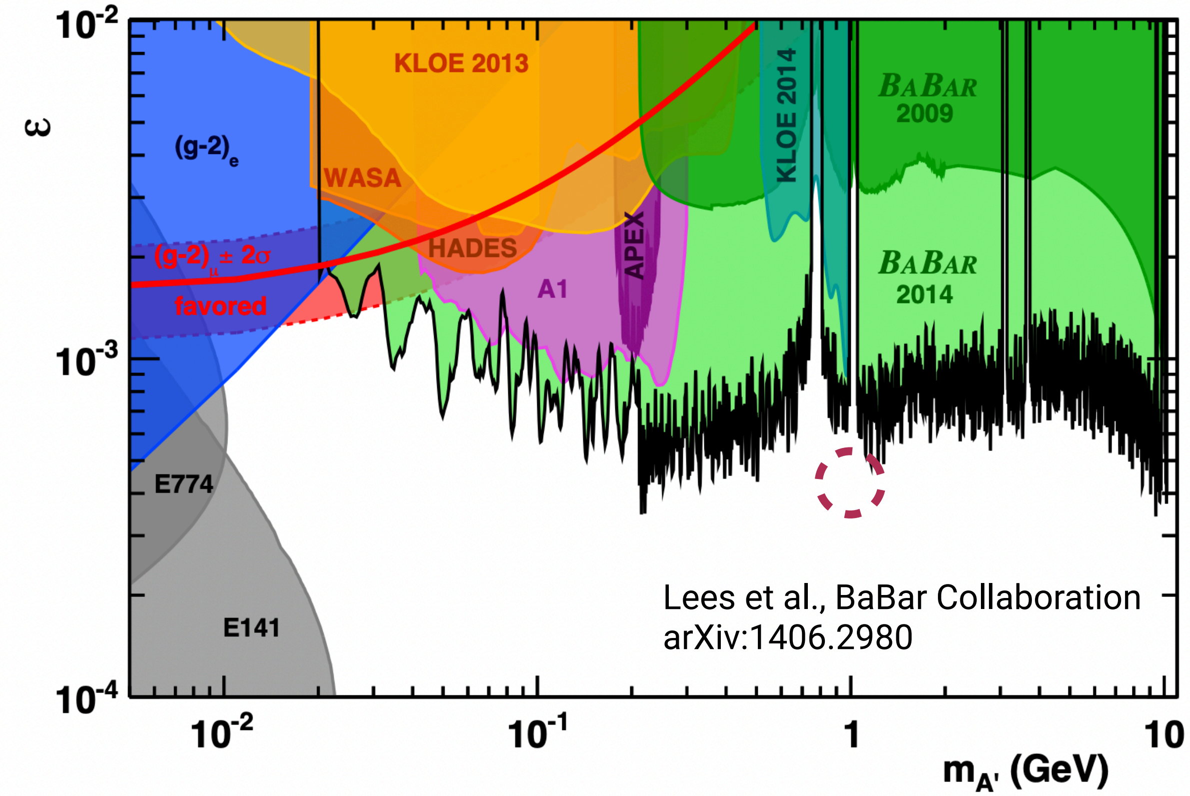
Vector + Axial Vector

$$\mathscr{L}^a_{\rm Axions} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}V_\mu V^\mu$$

$$+g'_V\left(\bar{e}\,\gamma^\mu\, e\right)\, V_\mu + g'_A \bar{e}\,\left(\gamma^\mu \gamma_5\right)\, e\, V_\mu$$



$g = \epsilon\sqrt{4\pi\alpha}$



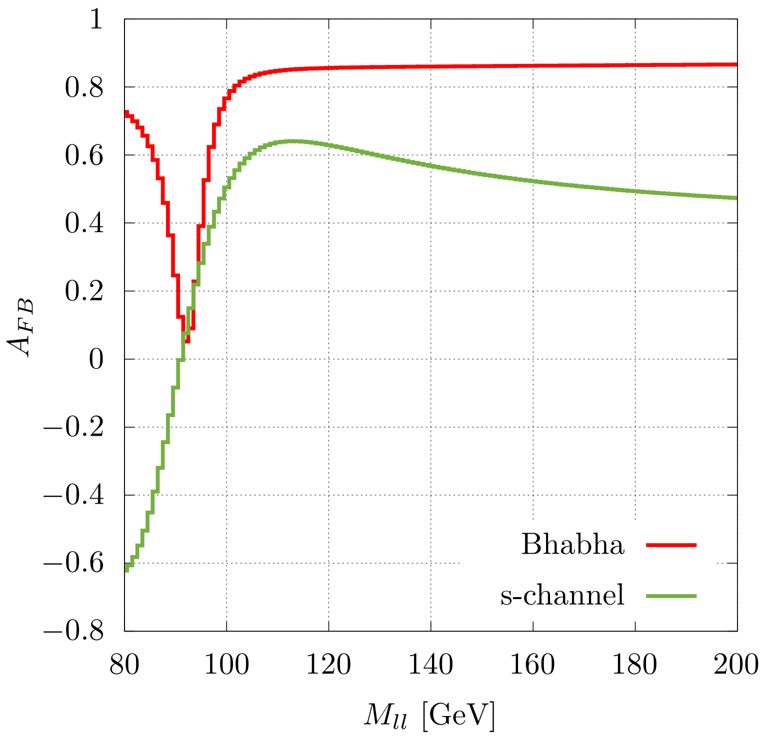
$$\frac{\sigma_{\rm Dark}}{\sigma_{\rm SM}} \leq 10^{-6}$$

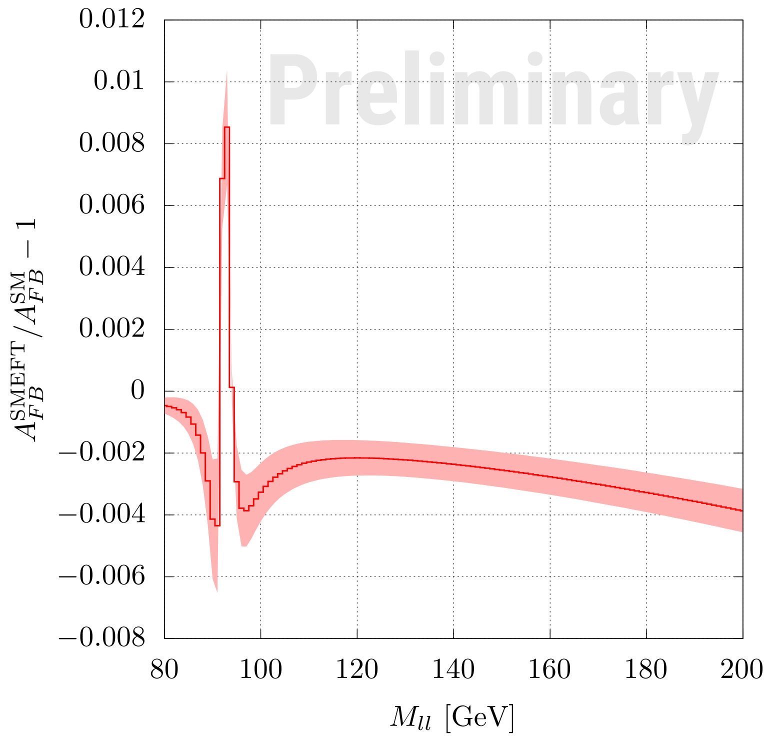
A way out: asymmetries?

Work in Progress

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B} = A_{FB}^{\rm SM}\left(1 - \frac{2(\delta\sigma_B\,\sigma_F - \sigma_B\,\delta\sigma_F)}{(\sigma_B + \sigma_F)^2}\right)$$

e.g. one can subtract the SM asymmetry and fit the coefficients to the shift





$$C_{ll}^{1111} + C_{ee}^{1111} \pm 2C_{le}^{1111}$$

Example of 4-lepton operator combination constrained by A_{FB}

No flavour ass.

Specific coefficients for Bhabha

$$C_{ll}^{1111}$$

Only Bhabha asymmetry can be used

$$A_{FB}(e^+e^- \to e^+e^-)$$

Flavour universality

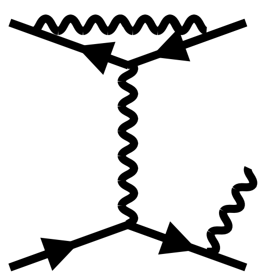
Degeneration between coefficients

$$C_{ij}^{IIJJ} = C_{ij}^{IIII}$$

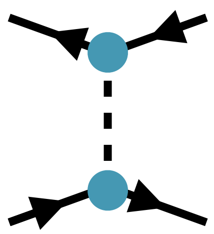
One can use all final states

$$A_{FB}(e^+e^- \to l^+l^-, q\bar{q})$$

Summary



- Radiative corrections in the SM are essential to reach FCC precision target
- Belle II is free from NP contamination: its data can be used to fit WCs
- Light NP does not contaminate FCC-ee luminosity



$< 10^{-5}$

- FCC-ee luminosity could receive a Heavy NP contamination at 10^{-4} level
- Asymmetries can be used to constrain 4-fermion operators