New Physics contamination in precise luminosity measurements at future colliders

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arXiv:2501.05256 [hep-ph]

with M. Chiesa, G. Montagna, O. Nicrosini, F. Piccinini and F. P. Ucci

HET Lunch discussion - January 17, 2025

Brookhaven
National Laboratory

Outline

- Luminosity calibration at e^+e^- machines: why and how
- New Physics contribution to luminosity measurements
- Constraining new physics effects to reduce the impact on luminosity

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Why luminosity?

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

$N^{\text{exp}}_{e^+e^- \to X}$ # of observed events - statistical error

ϵ experimental acceptance

$L = \int dt \, \mathscr{L}$ machine integrated luminosity

Why luminosity?

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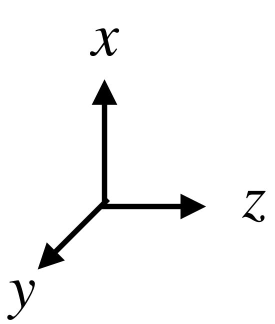
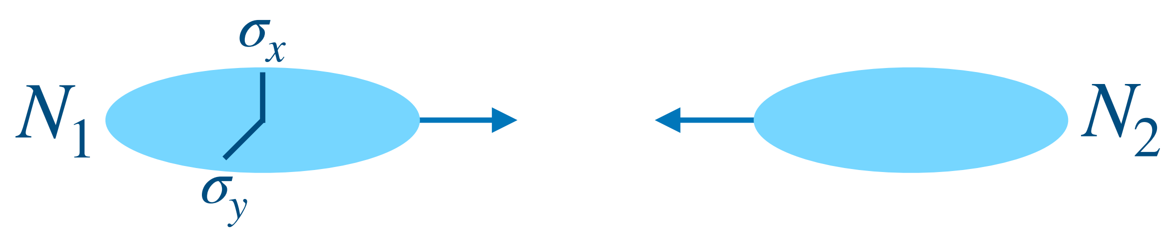
- Luminosity is a machine parameter - for two equal gaussian beams colliding head-on:





$$\mathscr{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$

$N_{1,2}$ # of particles per bunch

f revolution frequency

N_b # of bunches

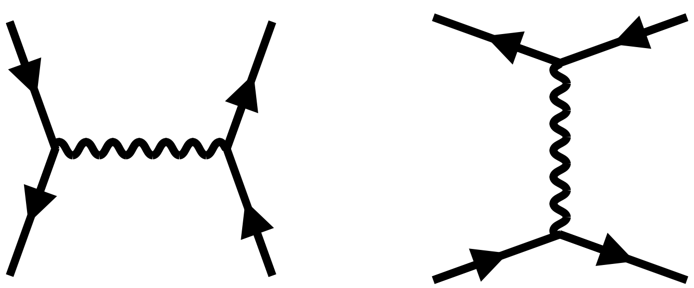
$\sigma_{x,y}$ spread of the beams in x and y directions

Why luminosity?

- Use a benchmark process
  - high cross section so $\delta N_0/N_0$ very small
  - σ_0^{th} very well known theoretically
  - experimentally well distinguishable

$$L = \int \mathscr{L} \mathrm{d}t = \frac{1}{\epsilon} \frac{N_0}{\sigma_0^{\text{th}}}$$

At lepton colliders **Small Angle Bhabha Scattering** (SABS) for $\theta \sim \mathcal{O}(30 - 100\,\text{mrad})$



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

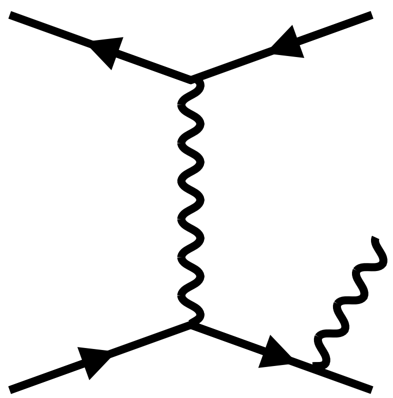
$$\frac{\Delta L}{L} = \frac{\Delta N_0}{N_0} \oplus \frac{\Delta \sigma_0^{\text{th}}}{\sigma_0^{\text{th}}}$$

How good do we know SABS?

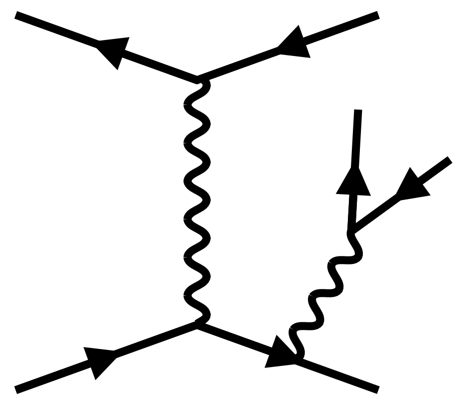
In the Standard Model

S. Jadach, arXiv:1812.01004 [hep-ph]
P. Janot, S. Jadach, Phys. Lett. B 790 (2019) 314–321

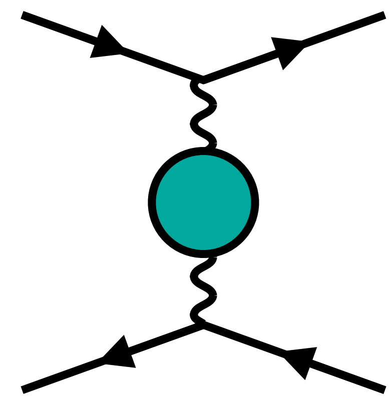
Photonic



Light pairs



Vacuum Pol.



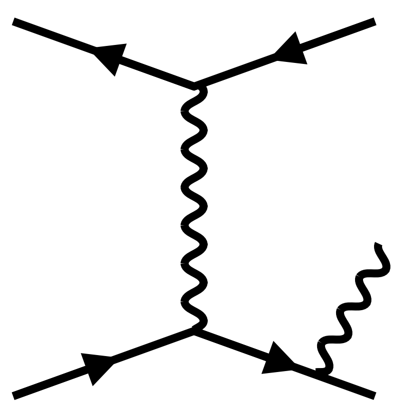
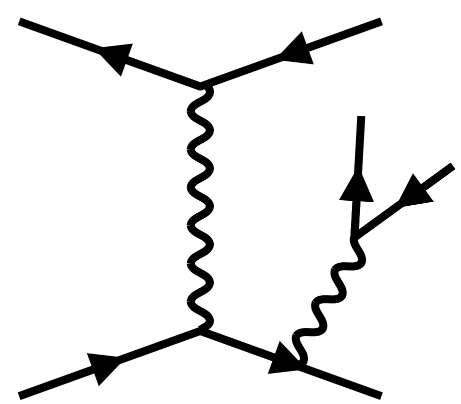
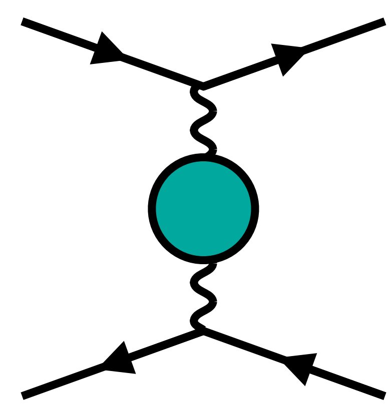
	Photonic	Light pairs	Vacuum Pol.	Total
LEP 1999 18-52 mrad	0.030% $\mathcal{O}\left(\alpha^2 L \oplus \alpha^3 L^3\right)$	0.030%	0.040%	0.061%
2018 18-52 mrad		0.010%	0.013%	0.037%

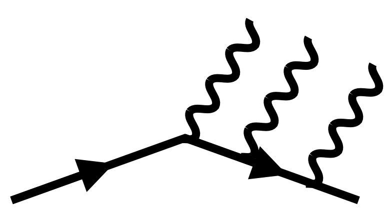
“The 20-years-old 2σ tension [on the number of neutrino species] with the Standard Model is gone.”

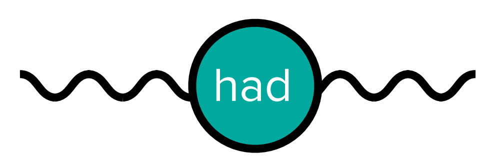
How good do we know SABS?

FCC projections

S. Jadach, arXiv:1812.01004 [hep-ph]
P. Janot, S. Jadach, Phys. Lett. B 790 (2019) 314–321

	Photonic	Light pairs	Vacuum Pol.	Total
				
2018 64-86 mrad	0.030%	0.010%	0.014%	0.097%
	$\mathcal{O}\left(\alpha^2 L \oplus \alpha^3 L^3\right)$			
FCC-ee	0.012%	0.005%	0.006%	0.01%
	$\mathcal{O}\left(\alpha^3 L^2 \oplus \alpha^4 L^4\right)$			





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

P. Janot, JHEP 1602 (2016) 053
G. Abbiendi et al., Eur. Phys. J. C77 (2017) 3 139

Outline

- Luminosity calibration at e^+e^- machines: why and how

- New Physics contribution to luminosity measurements

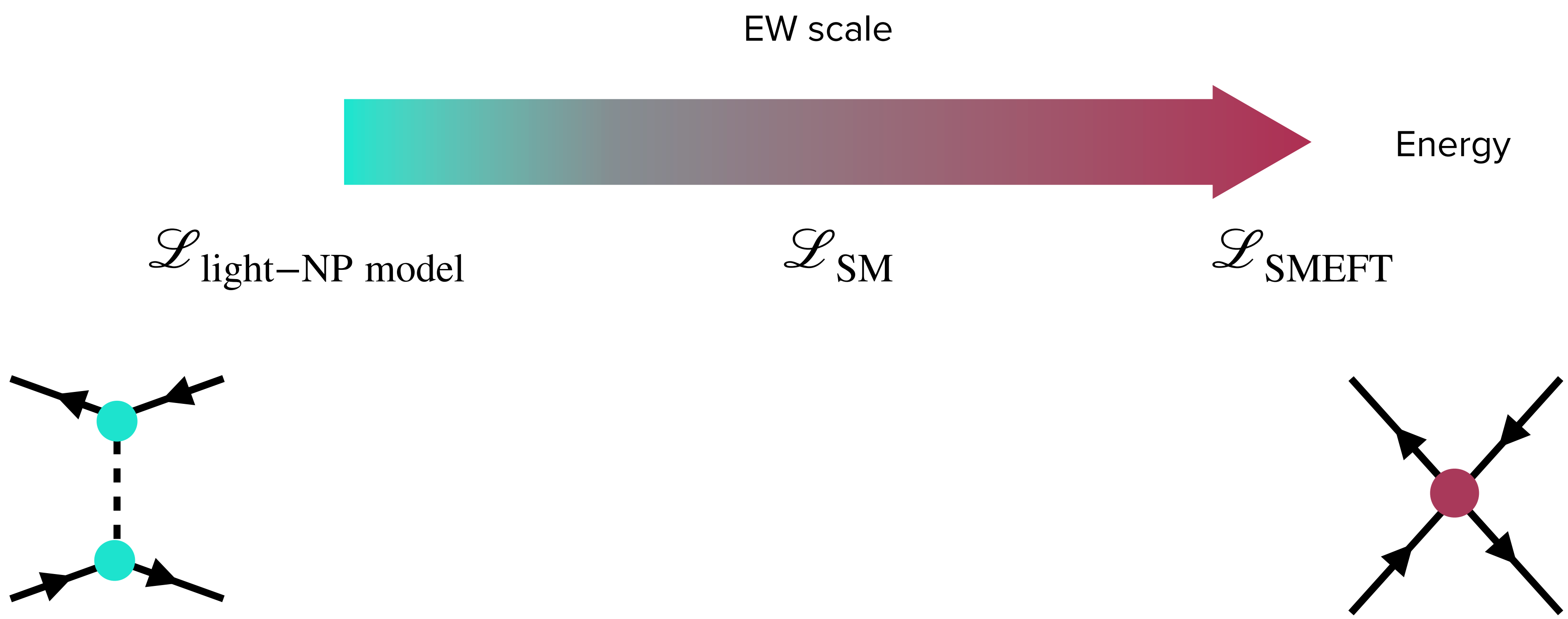
- Constraining new physics effects to reduce the impact on luminosity

New Physics contamination

FCC-ee goal

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

Do possible New Physics effects impact on the luminosity calibration at future colliders?



The analysis

Disclaimer

We aim at a preliminary “negative” result able to exclude NP contamination: leading order analysis

Different experimental scenarios: FCC/CEPC, ILC, CLIC

A. Abada et al.
Eur. Phys, J. C 79, 474 (2019)
Eur. Phys. J. ST 228, 261 (2019)

CEPC Conceptual Design Report Vol. I and II (2018)

The International Linear Collider Technical Design Report Vol. 1, 2, 3.I and 3.II (2013)

CLIC Conceptual Design Report (2012)
CLIC Collab, Updated baseline for a staged Compact Linear Collider (2016)
CLIC 2018 Summary Study Report (2018)

Exp.	$[\theta_{\min}, \theta_{\max}]$	$\sqrt{s}$ [GeV]
FCC	$[3.7°, 4.9°]$	91 160 240 365
ILC	$[1.7°, 4.4°]$	250 500
CLIC	$[2.2°, 7.7°]$	1500 3000

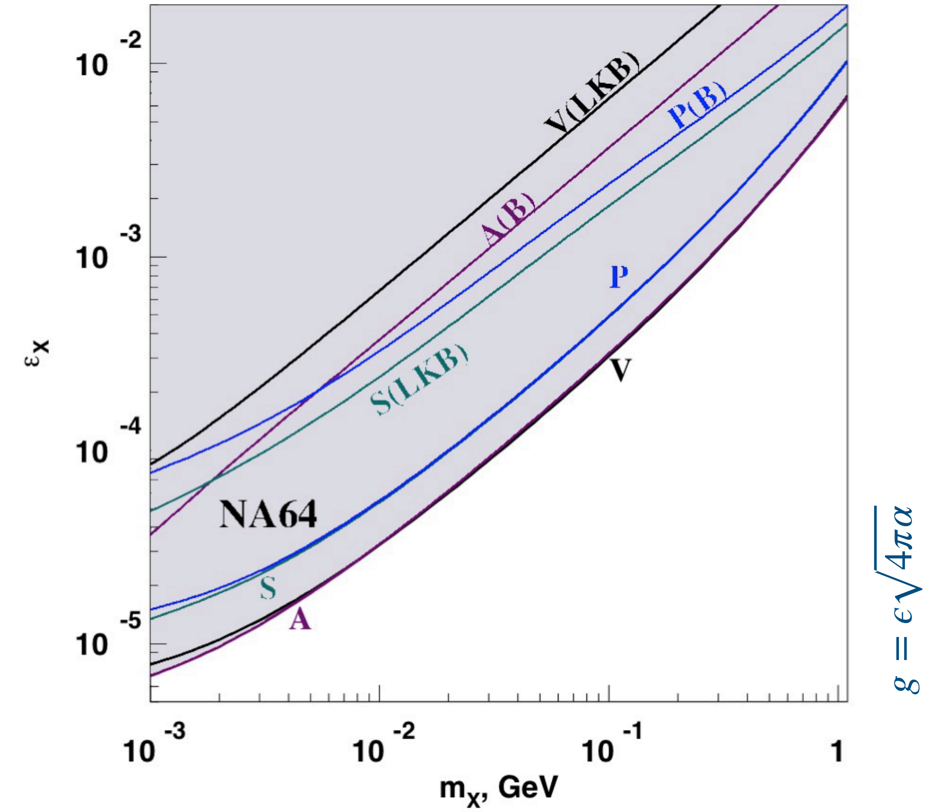
BabaYaga@NLO Monte Carlo event generator updated to include light and heavy NP contributions, featuring also interface to MadGraph for cross-checks

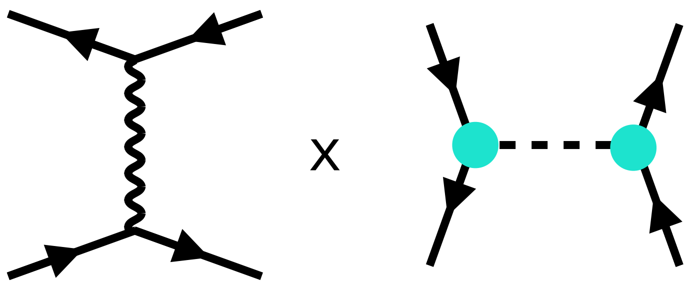
Light New Physics

ALPs

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

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



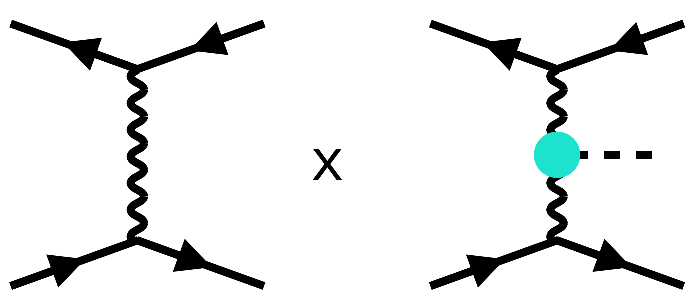


$$\delta^{aee}_{ALP} \simeq \frac{g^2_{aee}}{4\pi\alpha} \frac{s^2 t}{\left(s - m_a^2\right)\left(s^2 + u^2\right)} \simeq -\frac{g^2_{aee}}{8\pi\alpha}(1 - \cos\theta)$$

$\delta^{aee}_{ALP} < 10^{-7}$

$\left(g_{aee}, m_a\right) \simeq (3 \times 10^{-3}, 1\ \mathrm{GeV})$

NA64 Collab. Phys. Rev. Lett. 126, 211802 (2021)



$\delta^{a\gamma\gamma}_{ALP} < 10^{-5}$

$g_{a\gamma\gamma} \simeq 2 \cdot 10^{-4}\ \mathrm{GeV}^{-1}$

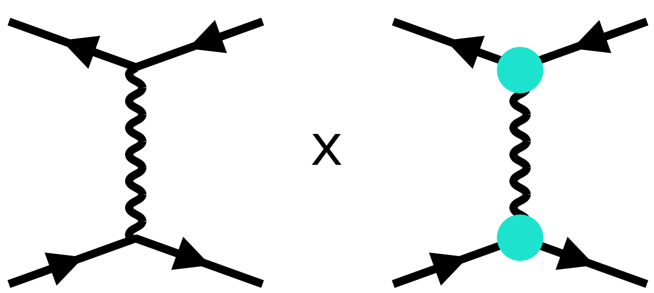
BABAR Collab. Phys. Rev. Lett. 119, 131804 (2017)

M. Dolan et al., JHEP 12 (2017) 094

Light New Physics

Dark Vectors

$$\mathscr{L}_{\text{Dark}} = -\frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{1}{2}M_V^2 V_\mu V^\mu + g'_V\left(\bar{e}\,\gamma^\mu\,e\right)V_\mu + g'_A\left(\bar{e}\,\gamma^\mu\gamma_5\,e\right)V_\mu$$

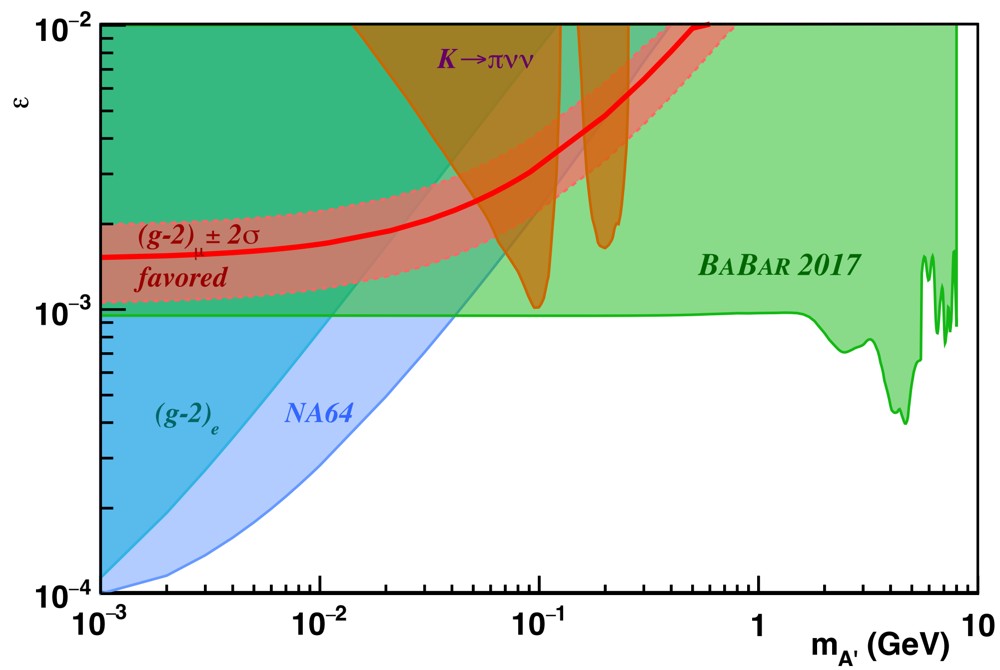


$$\delta_{\text{Dark}} \simeq \frac{t\left[{g'_V}^2\left(s^2+u^2\right) - {g'_A}^2\left(s^2-u^2\right)\right]}{2\pi\alpha\left(t-M_V^2\right)\left(s^2+u^2\right)}$$

$\delta_{\text{Dark}} \sim 10^{-6}$ $\quad \left(g'_V, M_V\right) \simeq (3\times 10^{-4}, 1\ \text{GeV})$

NA64 Collab. Phys. Rev. Lett. 126, 211802 (2021)

BABAR Collab. Phys. Rev. Lett. 119, 131804 (2017)



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

Heavy New Physics

- dim-6 and LO SMEFT contributions
- general flavour assumption
- (α, G_μ, M_Z) scheme

A. Falkowski et al., JHEP 08 123

$$\mathcal{L}_{\rm SMEFT}^{\rm EW} = -\sqrt{4\pi\alpha}\,(\,\bar{e}\gamma^\mu e)A_\mu + \frac{\sqrt{4\pi\alpha}}{s_W c_W}\left[\bar{e}_L\gamma^\mu\left(\hat{g}_L + \frac{\Delta g_L^{Ze}}{\Lambda_{\rm NP}^2}\right)e_L + \bar{e}_R\gamma^\mu\left(\hat{g}_R + \frac{\Delta g_R^{Ze}}{\Lambda_{\rm NP}^2}\right)e_R\right]Z_\mu$$

$$\hat{g}_L = s_w^2 - 1/2\,, \quad \hat{g}_R = s_w^2$$

$$s_w^2 = \frac{1}{2}\left(1 - \sqrt{1 - 2\sqrt{2}\pi\alpha/G_\mu M_Z^2}\right)$$

$$\mathcal{L}_{\rm SMEFT}^{4f} = \frac{1}{2}\frac{C_{ll}}{\Lambda_{\rm NP}^2}(\bar{e}_L\gamma^\mu e_L)(\bar{e}_L\gamma_\mu e_L) + \frac{C_{le}}{\Lambda_{\rm NP}^2}(\bar{e}_L\gamma^\mu e_L)(\bar{e}_R\gamma_\mu e_R) + \frac{1}{2}\frac{C_{ee}}{\Lambda_{\rm NP}^2}(\bar{e}_R\gamma^\mu e_R)(\bar{e}_R\gamma_\mu e_R)$$

C_i	$C_i \pm \Delta(C_i)$
Δg_L^{Ze}	-0.0038 ± 0.0046
Δg_R^{Ze}	-0.0054 ± 0.0045
C_{ll}	0.17 ± 0.06
C_{le}	-0.037 ± 0.036
C_{ee}	0.034 ± 0.062

$\Lambda_{\rm NP} = 1$ TeV

Heavy New Physics

Numerical results

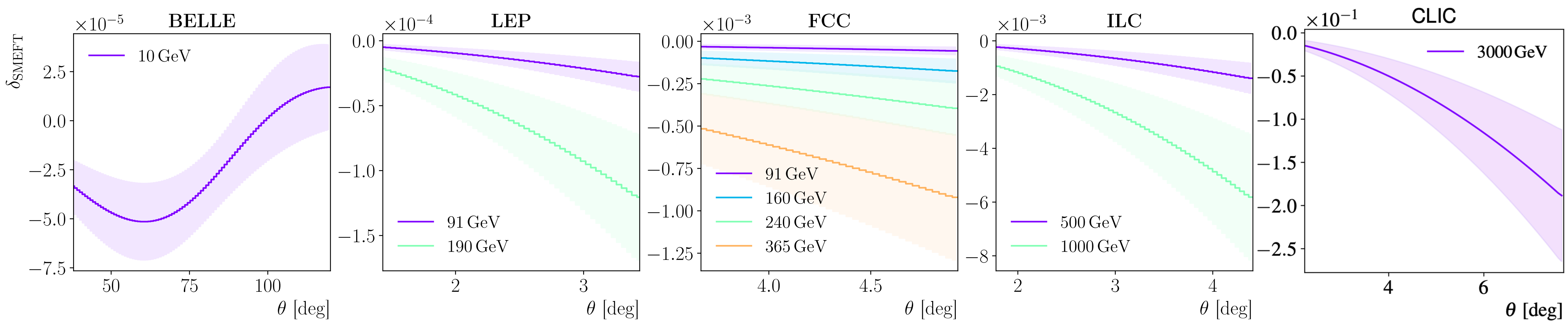
Exp.	$[\theta_{\min}, \theta_{\max}]$	$\sqrt{s}$ [GeV]	$(\delta \pm \Delta\delta)_{\text{SMEFT}}$	$\Delta L/L$
FCC	$[3.7°, 4.9°]$	91	$(-4.2 \pm 1.7) \times 10^{-5}$	$< 10^{-4}$
		160	$(-1.3 \pm 0.5) \times 10^{-4}$	
		240	$(-2.9 \pm 1.2) \times 10^{-4}$	10^{-4}
		365	$(-6.7 \pm 2.7) \times 10^{-4}$	
ILC	$[1.7°, 4.4°]$	250	$(-2.5 \pm 0.9) \times 10^{-4}$	$< 10^{-3}$
		500	$(-4.9 \pm 1.9) \times 10^{-4}$	
CLIC	$[2.2°, 7.7°]$	1500	$(-9.7 \pm 3.9) \times 10^{-3}$	$< 10^{-2}$
		3000	$(-4.2 \pm 1.7) \times 10^{-2}$	

New Physics effects are driven mainly by 4-electron contributions and affect every future collider scenario

results with polarised beams at ILC and CLIC are a factor of 2 worse

Heavy New Physics

Numerical results



New Physics effects are driven mainly by 4-electron contributions and affect every future collider scenario

luminosity determination at BELLE and LEP is safe

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- Luminosity calibration at e^+e^- machines: why and how
- New physics contribution to luminosity measurements
- Constraining new physics effects to reduce the impact on luminosity

Constraining $4e$ interactions

HL-LHC will not constrain $4e$ coefficients

E. Celada et al., JHEP 09 (2024) 091

Idea

Use **Large Angle Bhabha Scattering** (LABS) and measure observables not sensitive to the luminosity at future colliders

$\theta \in [40^\circ, 140^\circ]$

Asymmetries

- Forward-backward
- Left-right and polarisation asymmetries

$$A_{ab} = \frac{N_a - N_b}{N_a + N_b} \qquad \Delta A_{ab} = 2\sqrt{\frac{N_a N_b}{(N_a + N_b)^3}}$$

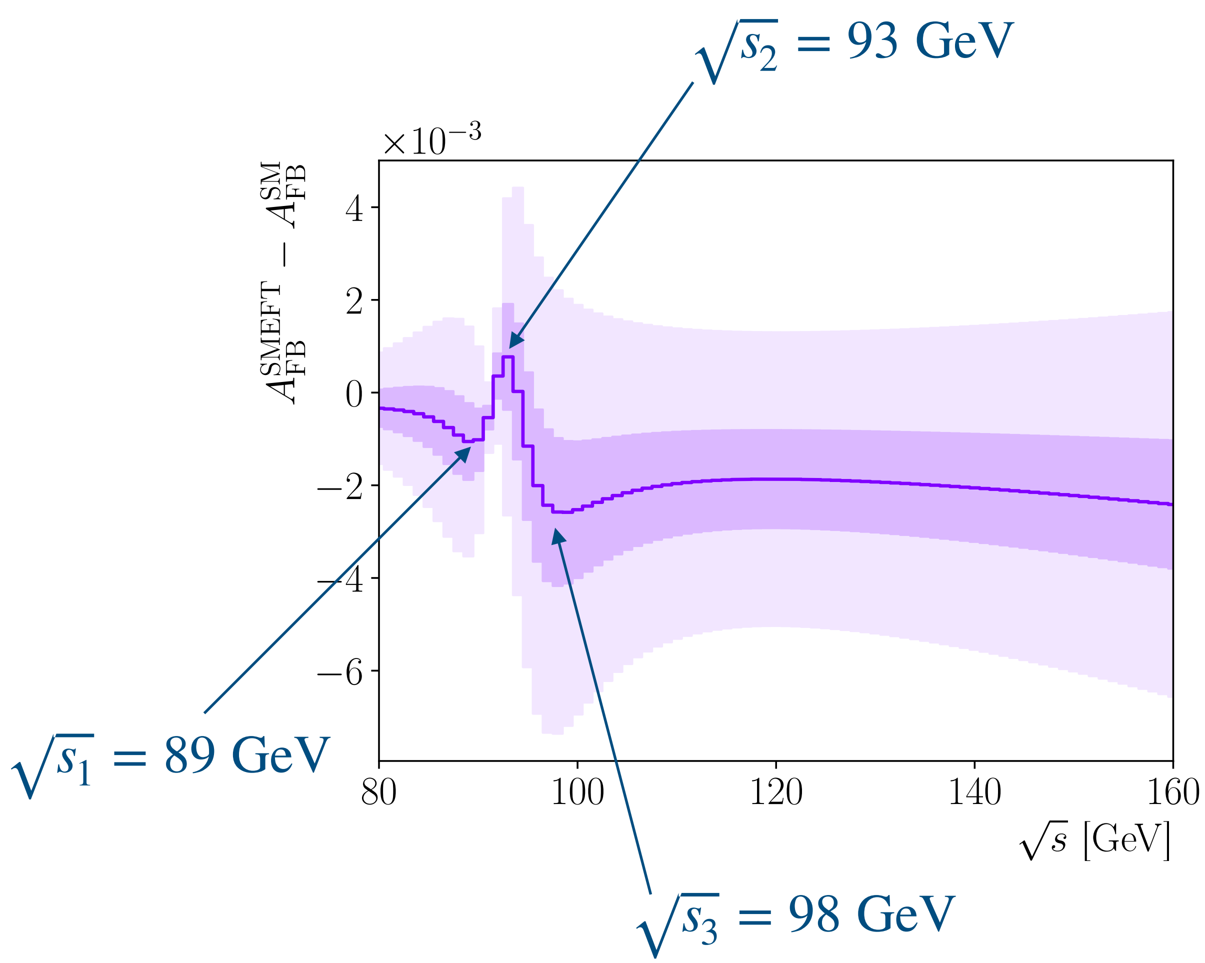
Constraints on $4e$ interactions

Forward-backward asymmetry

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{N_F - N_B}{N_F + N_B}$$

$$\sigma_F = \int_0^{c_{max}} d\cos\theta \frac{d\sigma}{d\cos\theta} \qquad c_{max} = 0.77$$

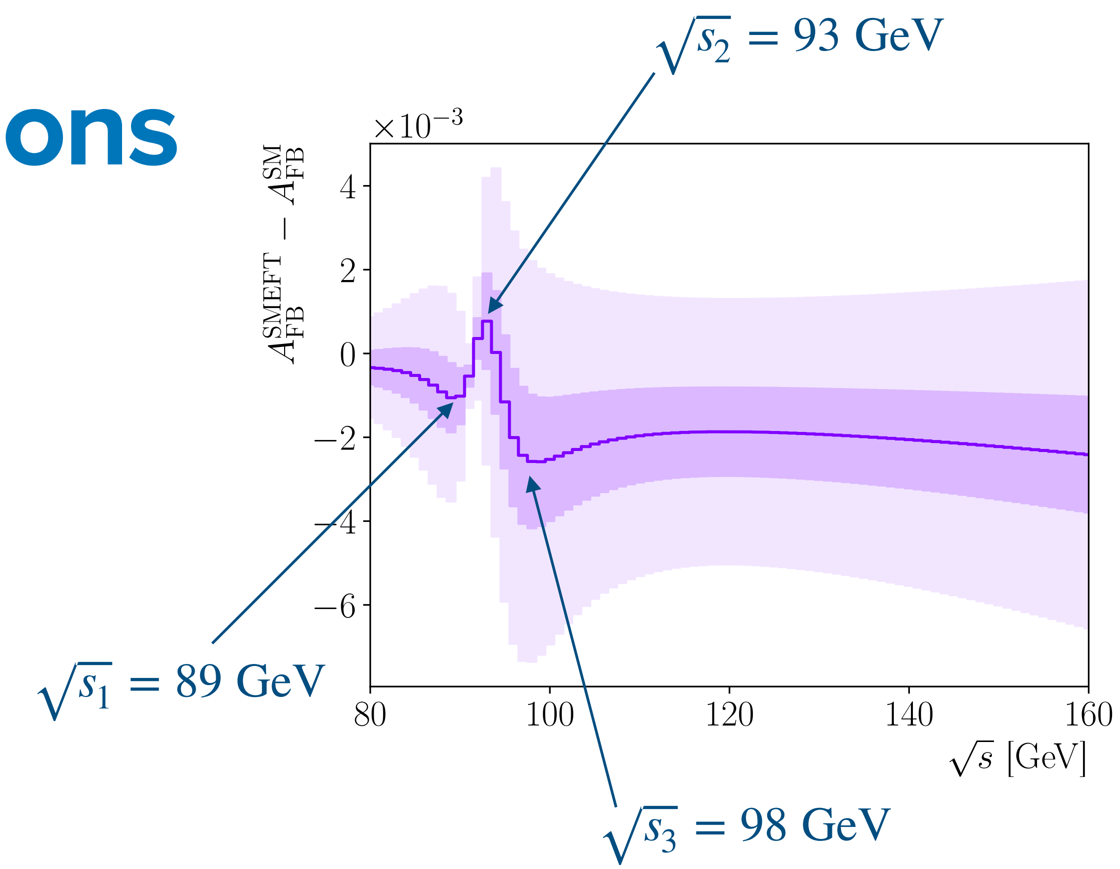
$$\sigma_B = \int_{-c_{max}}^{0} d\cos\theta \frac{d\sigma}{d\cos\theta}$$



Warning: picture changes at NLO

Constraints on $4e$ interactions

Forward-backward asymmetry



$$\sum_{i\in 4f} \frac{C_i}{\Lambda_{\rm NP}^2}\left[\frac{(\sigma_F-\sigma_B)_i^{(6)}}{(\sigma_F-\sigma_B)_{\rm SM}} - \frac{(\sigma_F+\sigma_B)_i^{(6)}}{(\sigma_F+\sigma_B)_{\rm SM}}\right]_\alpha = \frac{\Delta A^0_{FB,\alpha}}{A^0_{FB,\alpha}}$$

$\alpha = 1,2,3$

$A^0_{FB,\alpha} \sim \text{Gauss}\left(A^{\rm SM}_{FB}, \Delta A^0_{FB}\right)_\alpha$

1-year run for each $\sqrt{s_\alpha}$ with $\mathscr{L}_{\rm FCC} = 1.4\cdot 10^{36}\ {\rm cm^{-2}s^{-1}}$
$\to \Delta A^0_{\rm FB,\alpha} \lesssim 2\cdot 10^{-5}$

$\Delta C_{ll/ee} \lesssim 10^{-2}$, $\Delta C_{le} \lesssim 10^{-3} \to \delta_{\rm SMEFT} \sim 5\times 10^{-6}$

Constraining $4e$ interactions

Polarisation asymmetries

$$\frac{d\sigma(P_{e^\pm})}{d\cos\theta} = \frac{1}{4}\sum_{I,J=L,R}\left(1+P_{e_I^+}\right)\left(1+P_{e_J^-}\right)\frac{d\sigma_{e_I^+e_J^-}}{d\cos\theta}$$

$$A_{\rm LR} = \frac{\sigma_{\rm L}-\sigma_{\rm R}}{\sigma_{\rm L}+\sigma_{\rm R}}$$

$L \leftrightarrow \left(P_{e^-} = -0.8,\, P_{e^+} = 0.3\right)$

$R \leftrightarrow \left(P_{e^-} = 0.8,\, P_{e^+} = -0.3\right)$

small sensitivity to C_{le}

$$A^-_{\uparrow\downarrow}(P_{e^\pm}, \cos\theta) = \frac{d\sigma(P_{e^+}, P_{e^-}) - d\sigma(P_{e^+}, -P_{e^-})}{d\sigma(P_{e^+}, P_{e^-}) + d\sigma(P_{e^+}, -P_{e^-})}$$

Constraining $4e$ interactions

Polarisation asymmetries

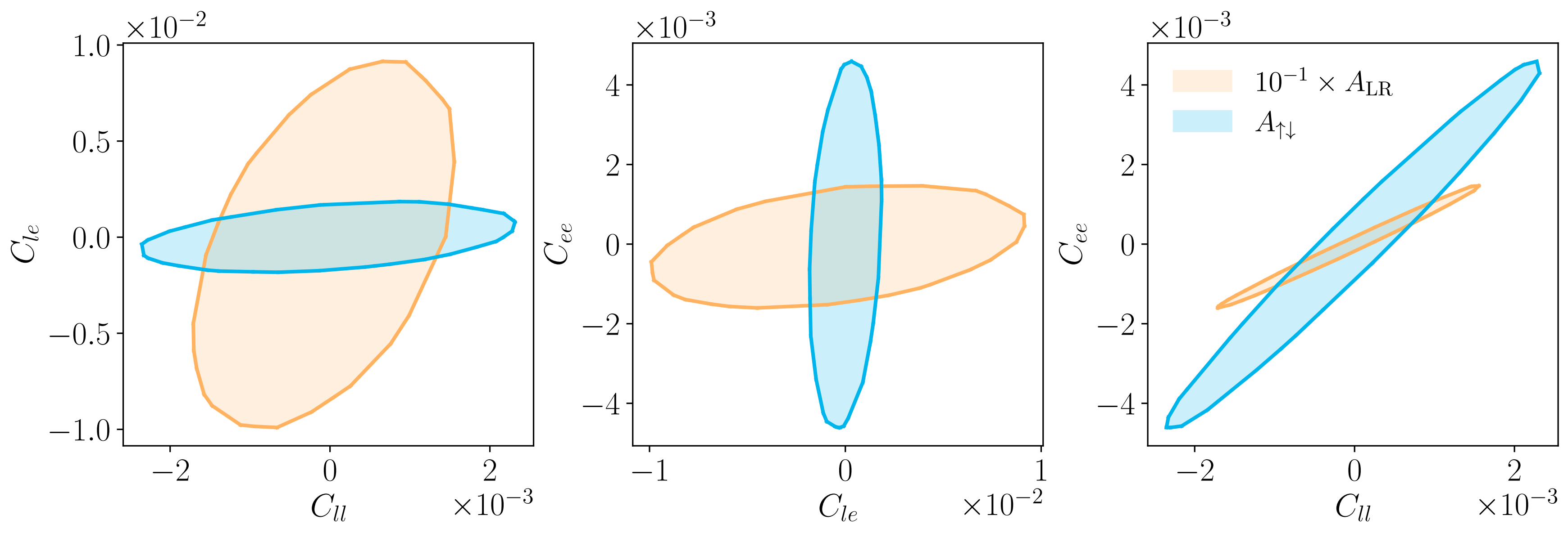
$$\chi^2 = \sum_{\alpha=1}^{n} \frac{\left(A^0_{\text{pol}} - A^{\text{th}}_{\text{pol}}(\overrightarrow{C}_{4f})\right)^2_\alpha}{(\Delta A^0_{\text{pol}})^2_\alpha}$$

$n = 78$

$\#_{\text{d.o.f.}} = \#_{C_i}$

6-month run for each configuration with
$\mathscr{L}_{\text{ILC}} = 1.35 \cdot 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 250\,\text{GeV}$

$\rightarrow \delta_{\text{SMEFT}} \lesssim 10^{-7}$



Outlook

The calibration of the machine luminosity is crucial for the high-precision physics programme at future colliders

New Physics effects can contaminate this determination, making it necessary to discuss possible strategies to remove the related uncertainties

- Investigate other processes considered for luminosity calibration e.g. $e^+e^- \to \gamma\gamma$

  J. De Blas, Focus topics for the ECFA study on Higgs / Top / EW factories, 2024

  J. Alcaraz Maestre, CIEMAT Technical Report 1499, 2022

  C. M. Carloni Calame et al., Phys.Lett.B 798 (2019) 134976

- Complete NLO analysis for more reliable results

- Look for other experimental quantities to constrain the $4e$ coefficients e.g. $N_{\mu^+\mu^-}/N_{e^+e^-}$ ratios

- Muon collider

Thank you!

Backup

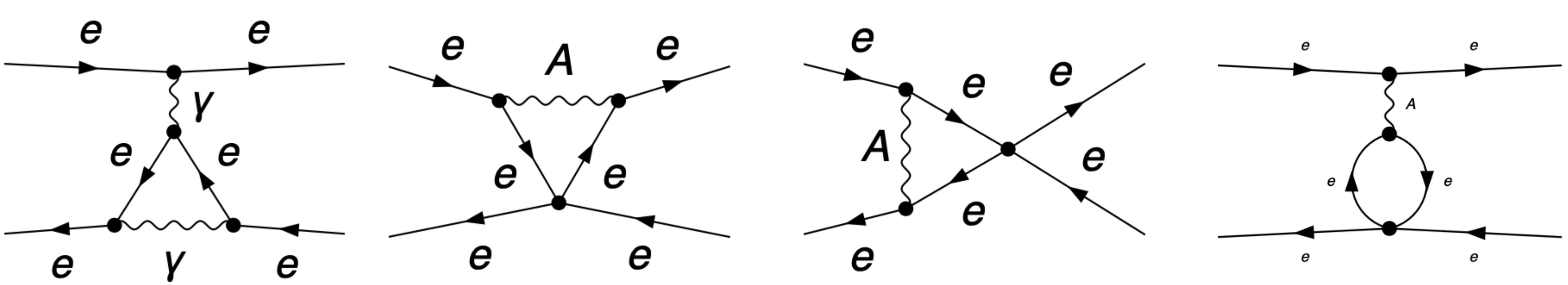
NLO contribution

$$\delta_{\rm NLO} \sim \mathcal{O}\left(\frac{\alpha}{\pi}\ln\frac{\Lambda_{\rm NP}^2}{|t|}\right) \sim 10\,\%$$

w.r.t. LO

$$t \sim 50\ {\rm GeV} \quad \Lambda_{\rm NP} = 1\ {\rm TeV}$$

$$\delta_{{\rm NLO},C_j} \sim \frac{|t|}{\Lambda_{\rm NP}^2}\frac{C_j}{16\pi^2}\log\frac{\Lambda_{\rm NP}^2}{|t|} \sim 10^{-3}\,C_j$$



Asymmetries and fit details

$$A_{ab}^{\rm th} = A_{ab}^{\rm SM} \left\{ 1 + \frac{(\sigma_a - \sigma_b)^{(6)}}{(\sigma_a - \sigma_{\rm b})_{\rm SM}} - \frac{(\sigma_a + \sigma_b)^{(6)}}{(\sigma_a + \sigma_b)_{\rm SM}} \right\}$$

$$L(\overrightarrow{C}) = \mathcal{N} \exp \left\{ -\frac{1}{2} \mathbf{A}^T(\overrightarrow{C})\, W^{-1}\, \mathbf{A}(\overrightarrow{C}) \right\}$$

$$V_{ij}^{-1} = \sum_{\alpha,\beta} \kappa_{i,\alpha}^{(6)}\, W_{\alpha\beta}^{-1}\, \kappa_{j,\beta}^{(6)}$$

$$\chi^2(\overrightarrow{C}) = \frac{1}{\Lambda_{\rm NP}^4} \sum_{i,j} \sum_{\alpha,\beta} C_i\, \kappa_{i,\alpha}^{(6)}\, W_{\alpha\beta}^{-1}\, \kappa_{j,\beta}^{(6)}\, C_j$$

$$\kappa_{i,\alpha}^{(6)} = \partial A_{{\rm pol},\alpha}^{\rm th} / \partial C_i$$