UNIVERSITÀ DI PAVIA

INFN

Supervisors
Prof. Guido **Montagna**
Prof. Fulvio **Piccinini**

Precision SM tests at present and future e+e- colliders

more at:

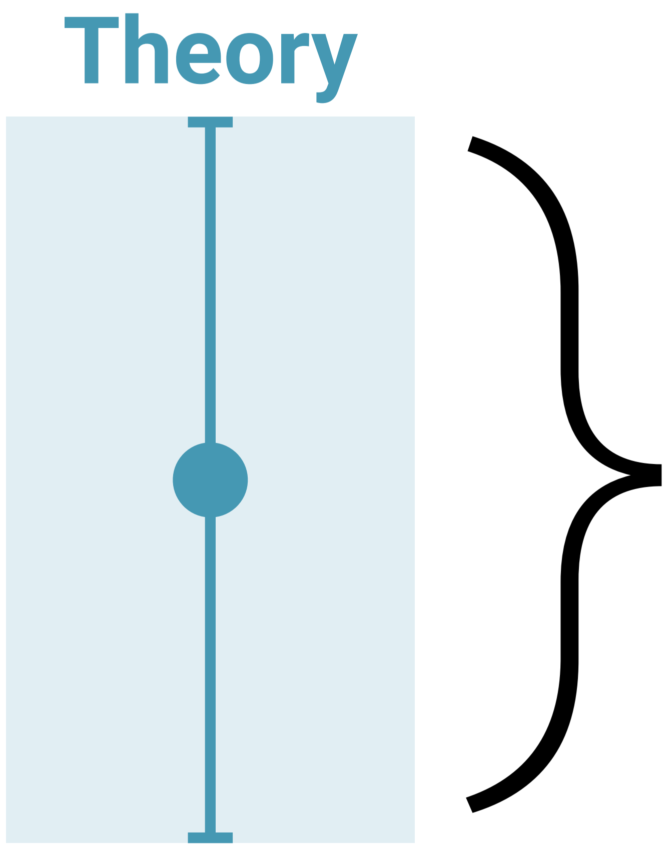
Francesco Pio Ucci
XXXIX Cycle

End-of-Year Seminars
18th September 2025

Introduction

"The closer you look the more there is to see"
— Fred Jegerlehner

Precision
SM tests at present and future e+e- colliders



Errors well below the % level

Precision

SM tests

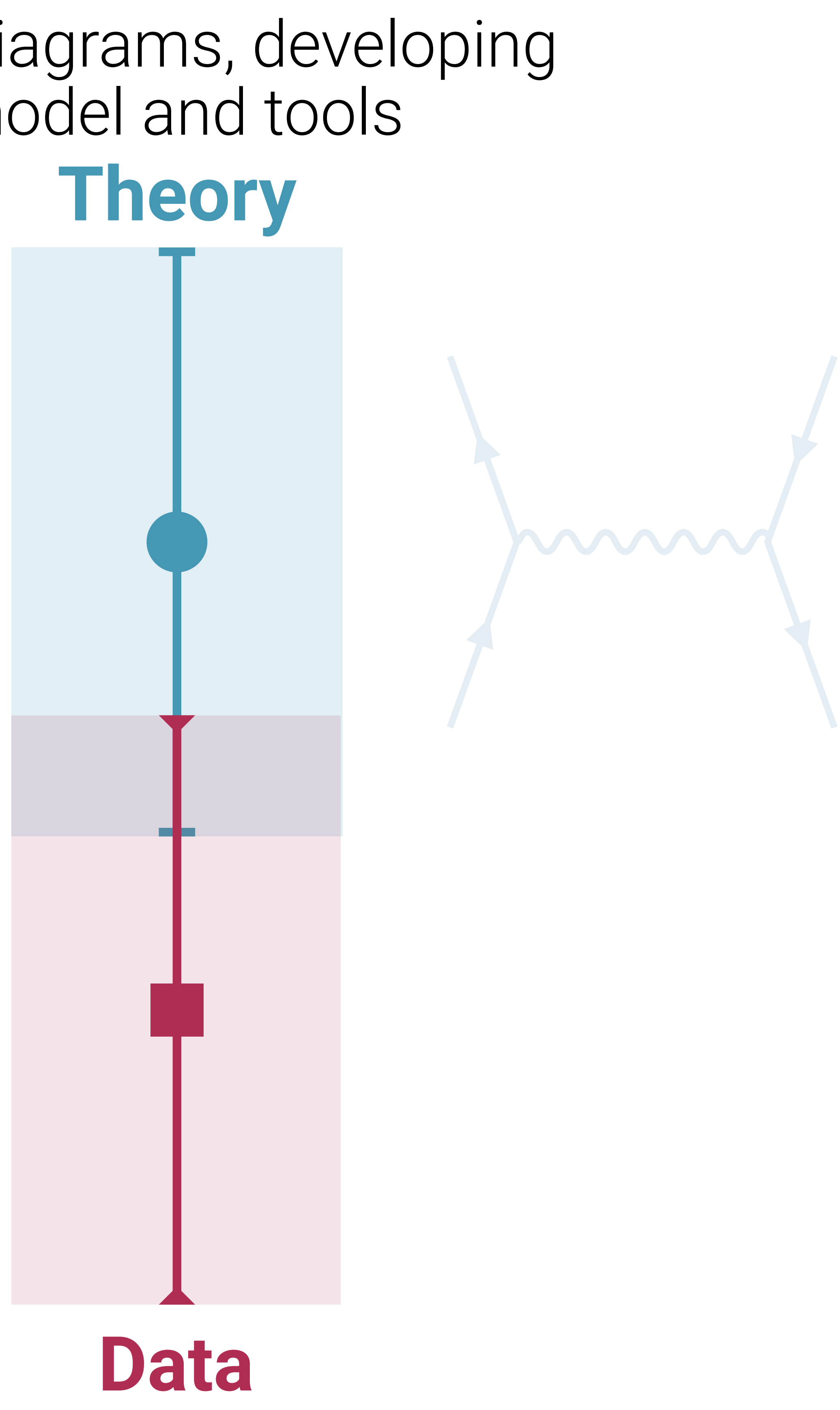
at present and future e+e- colliders

The SM works **very well**
with most of existing data

Testing its weaknesses
at higher precisions =
finding something new?

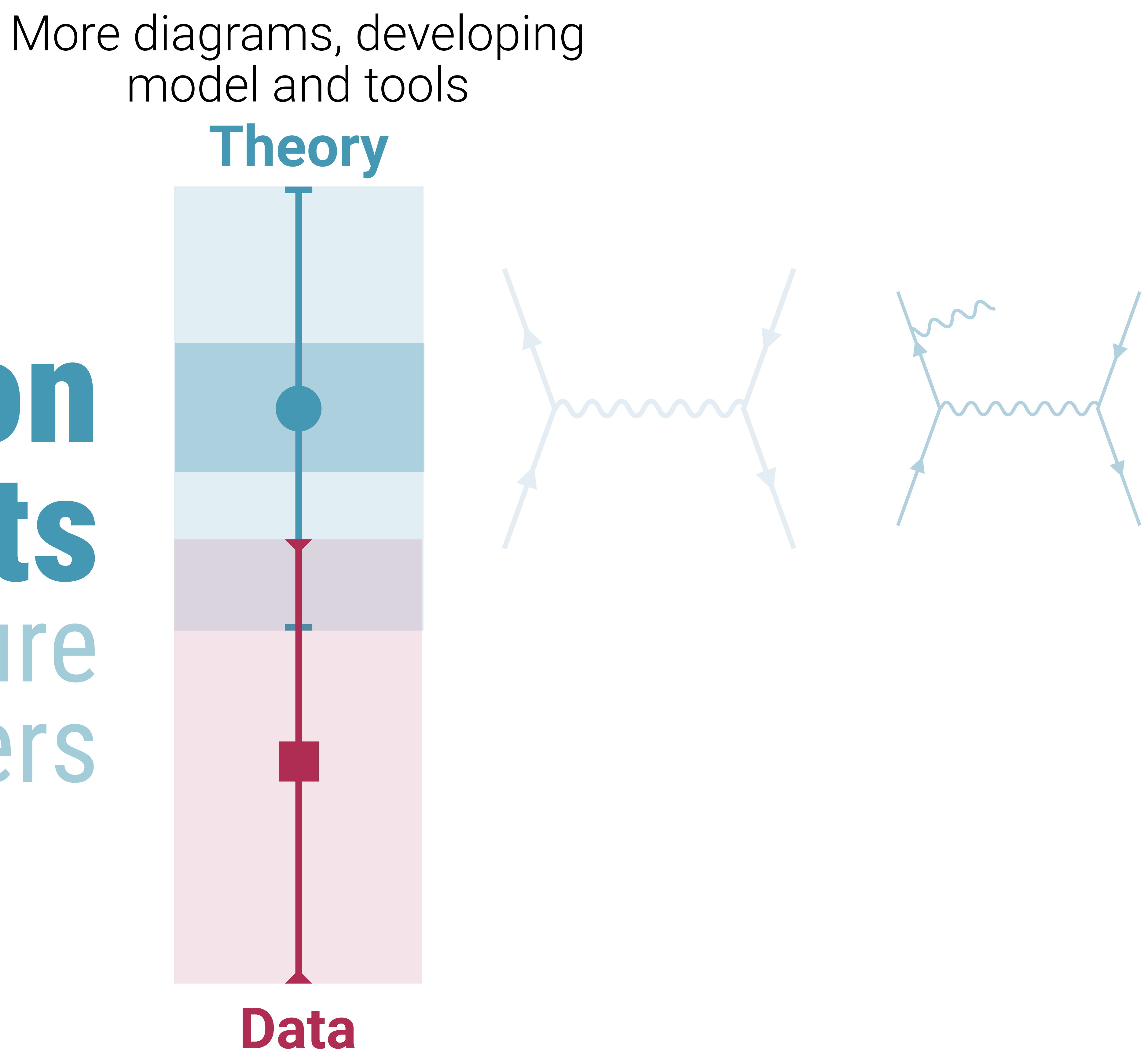
Precision SM tests

at present and future e+e- colliders



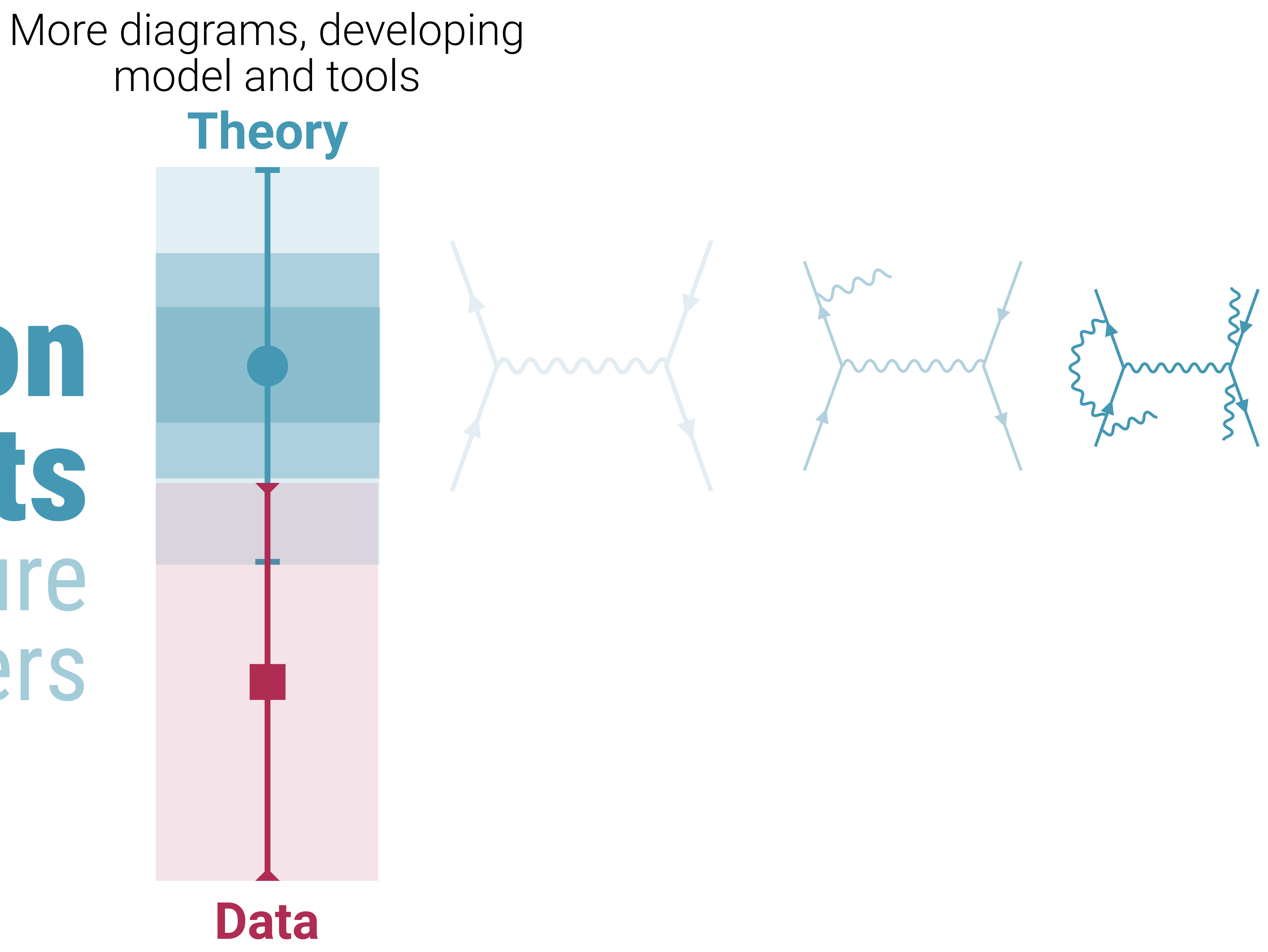
Precision SM tests

at present and future e+e- colliders



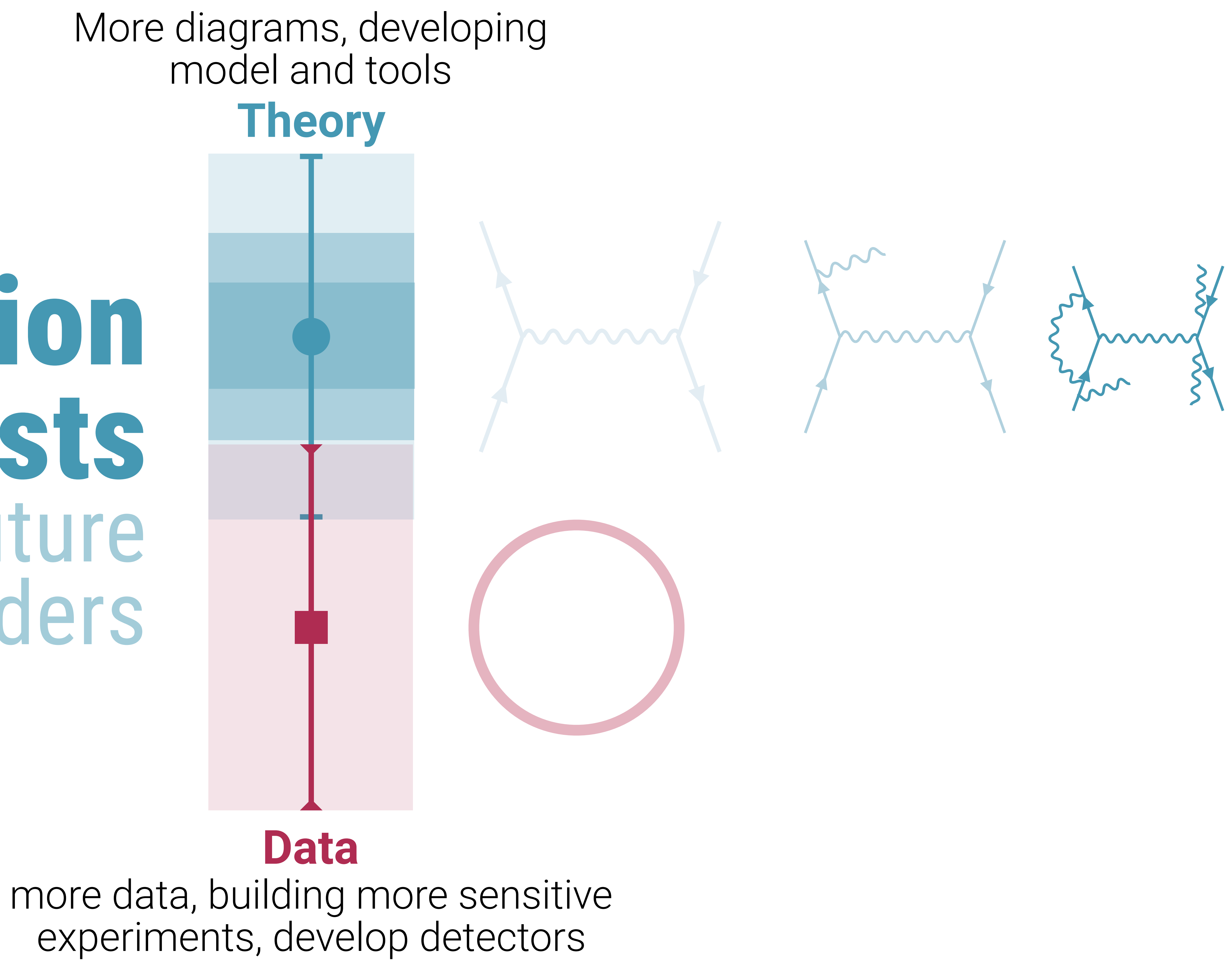
Precision SM tests

at present and future e+e- colliders



Precision SM tests

at present and future e+e- colliders

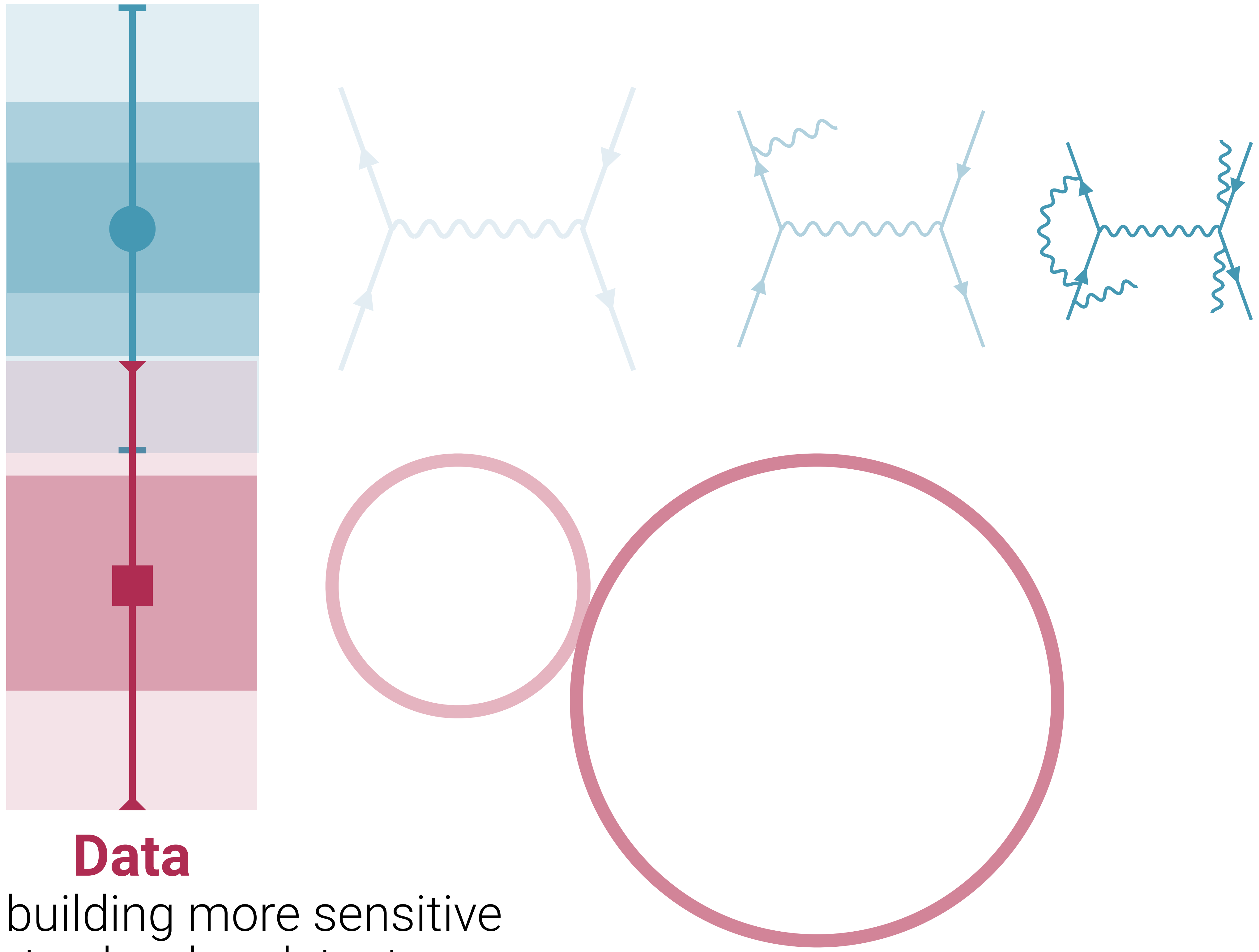


Precision SM tests

at present and future e+e- colliders

More diagrams, developing model and tools

Theory

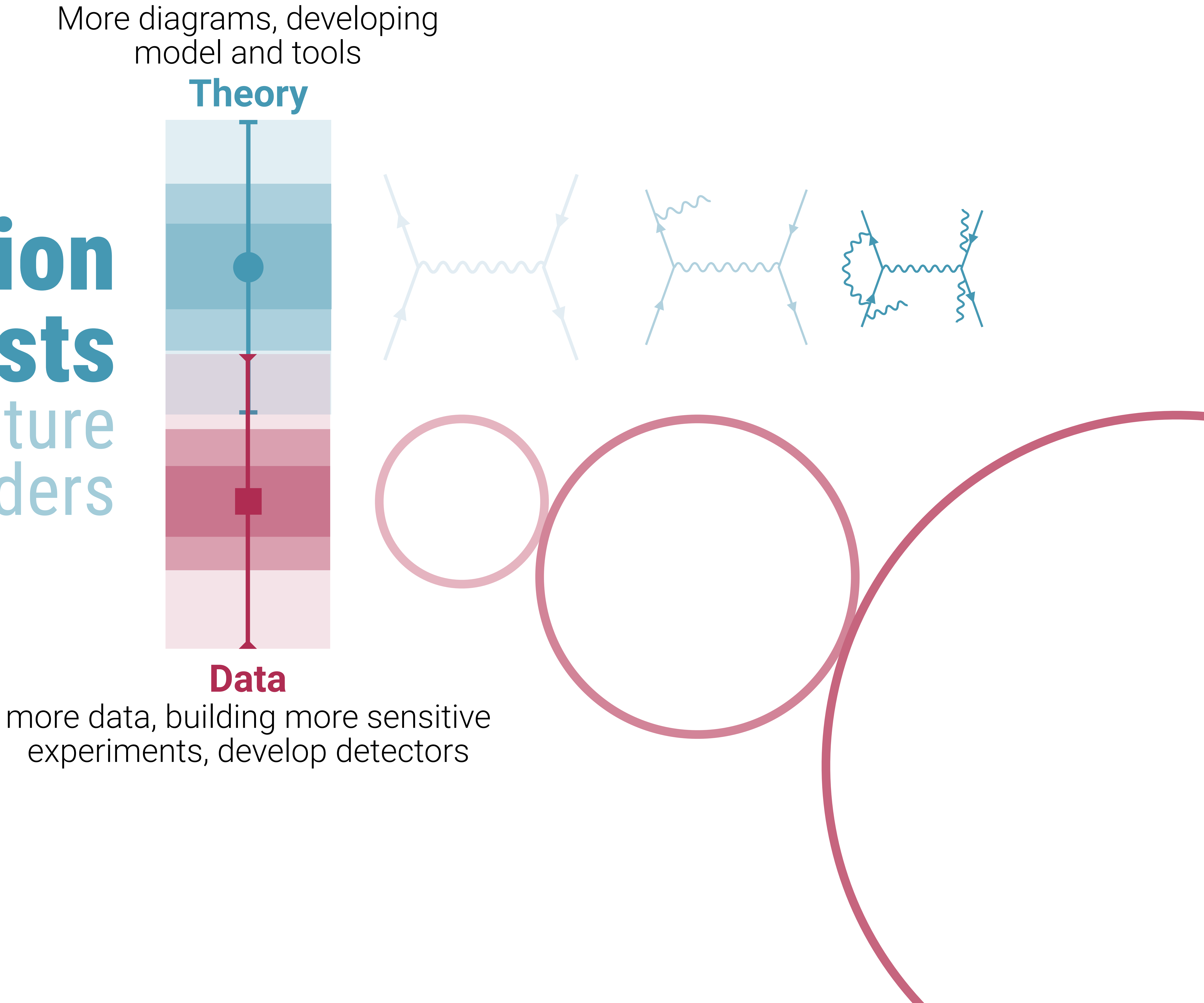


Data

more data, building more sensitive experiments, develop detectors

Precision SM tests

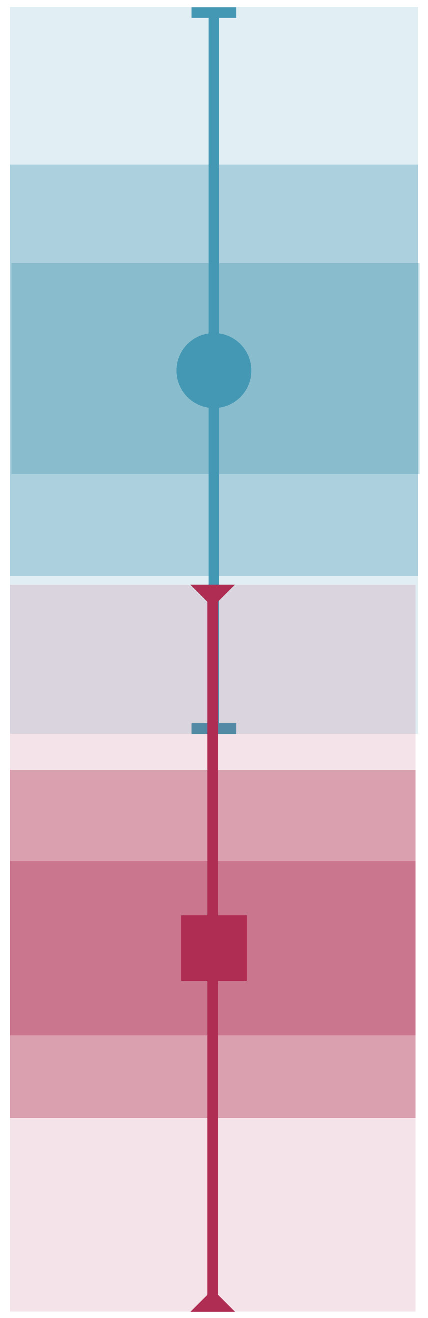
at present and future e+e- colliders

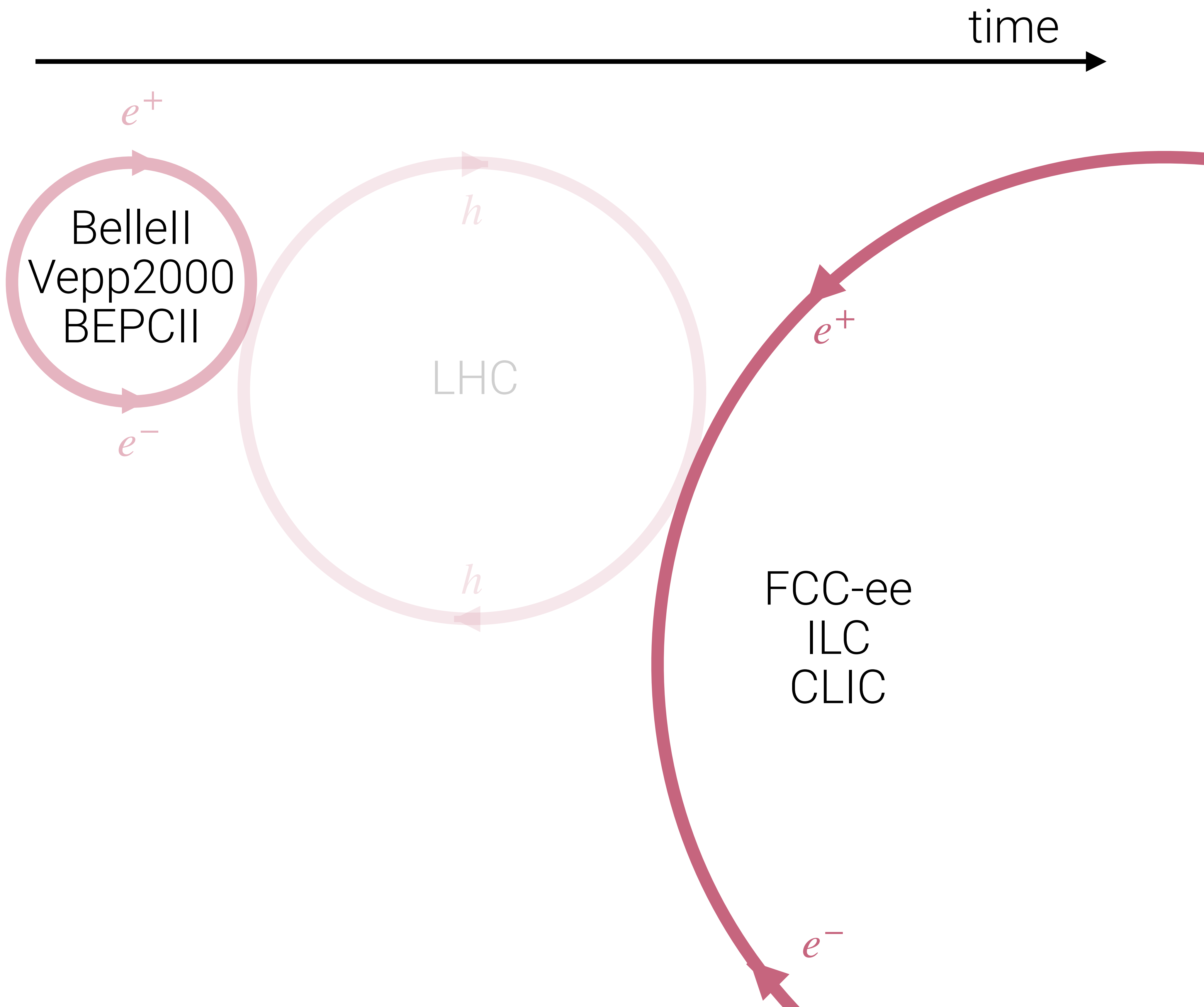


Precision SM tests

at present and future e+e- colliders

e^+e^- colliders are operating now and different projects are expected in the future






Colliders
Past
Present
Future
DAΦNE
Energy
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
Observables

Colliders
Past
Present
Future
DAΦNE
VEPP2000
Belle II
BEPC II
Energy
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
Observables


Colliders
Past
Present
Future
DAΦNE
VEPP2000
BEPC II
Belle II
ILC/CLIC
Energy
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
Observables
lepton g-2


Colliders
Past
Present
Future
DAΦNE
VEPP2000
BEPC II
Belle II
Energy
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
Observables
lepton g-2
e+e- → hadrons


Colliders
Past
Present
Future
DAΦNE
VEPP2000
BEPC II
Belle II
LEP I-II
(HL) LHC
FCC-ee/CEPC
Muon Collider
ILC/CLIC
Energy
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
Observables
lepton g-2
e+e- → hadrons

Colliders
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1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
Observables
lepton g-2
Z
W
EWPO
e+e- → hadrons

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Energy
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Observables
lepton g-2
Z
W
EWPO
Top
H
Higgs
e+e- → hadrons


Colliders
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Energy
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10 GeV
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1 TeV
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100 TeV
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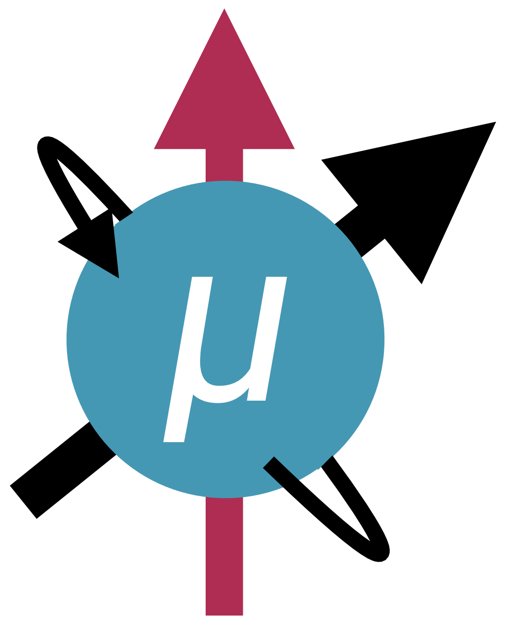
lepton g-2
e+e- → hadrons
Z
W
EWPO
Top
H
Higgs
Λ_NP > TeV
χ̃
New Physics?

Present colliders

Colliders
Past
Present
Future
DAΦNE
VEPP2000
BEPC II
Belle II
Energy
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
Observables
lepton g-2
e+e- → hadrons

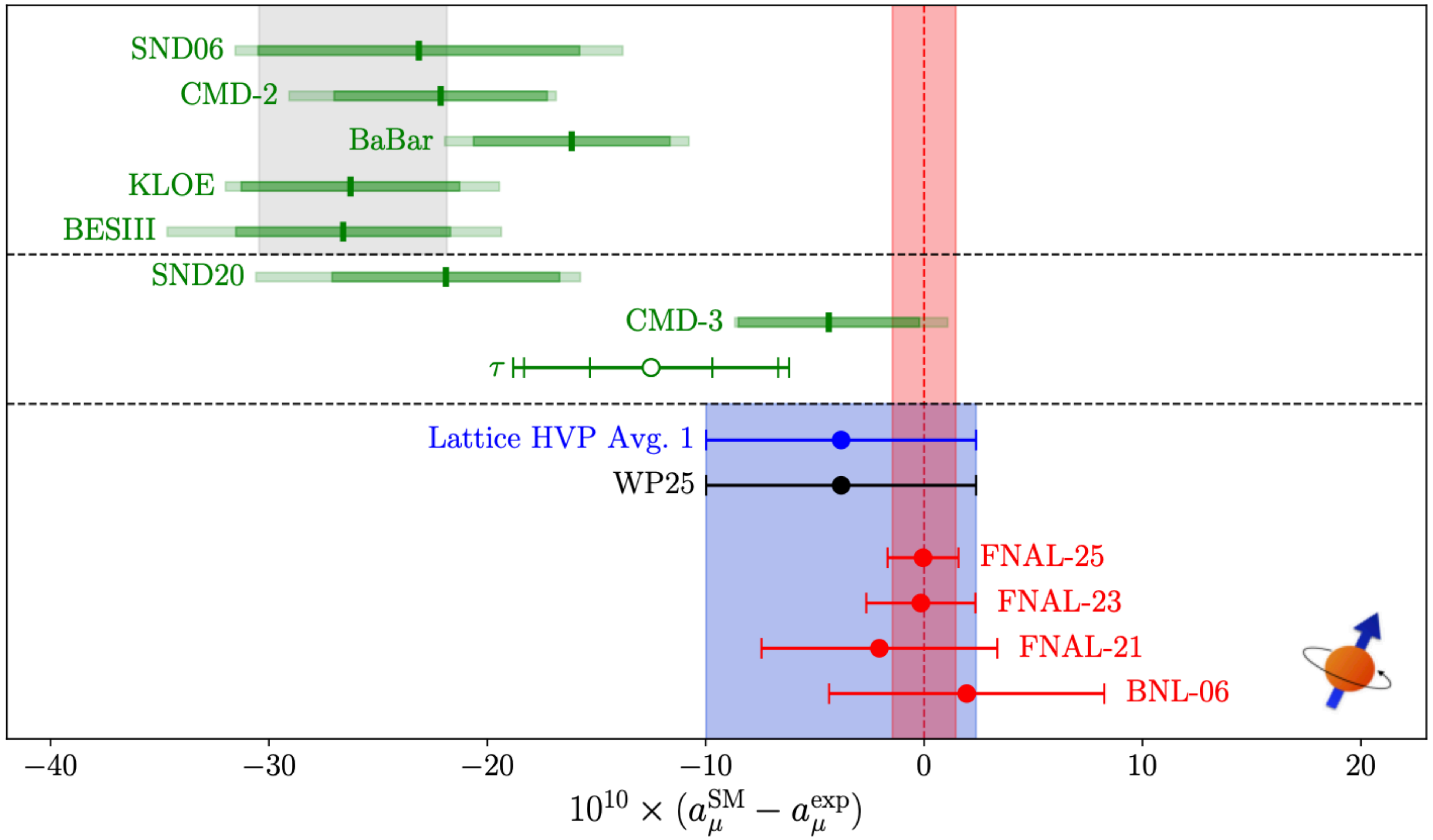
The muon g-2

The anomalous magnetic moment of the muon in the Standard Model
R. Aliberti et al.
Phys.Rept. 1143 (2025) 1-158



Muon g-2
Magnetic Momentum
associated with the spin

One of the most precise measurements in physics!



The muon g-2 and Monte Carlo Generators

Radiative Corrections and Monte Carlo tools for low-energy hadronic cross sections in e+e- collisions
R. Aliberti et al.
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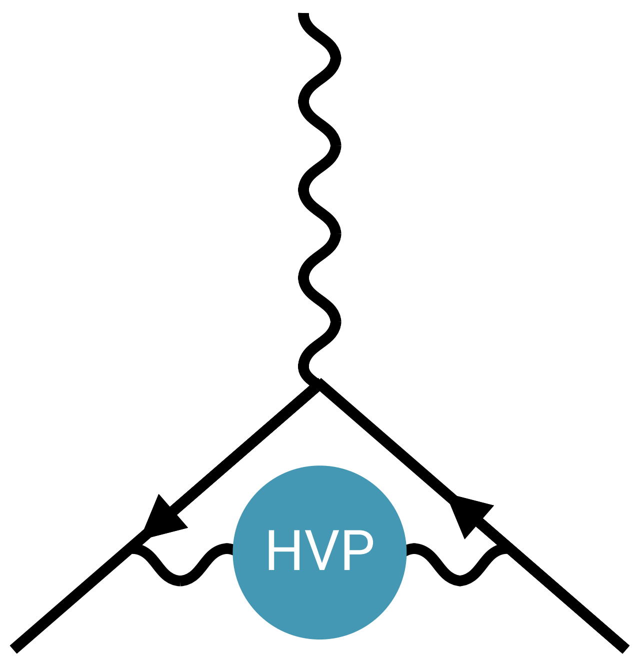
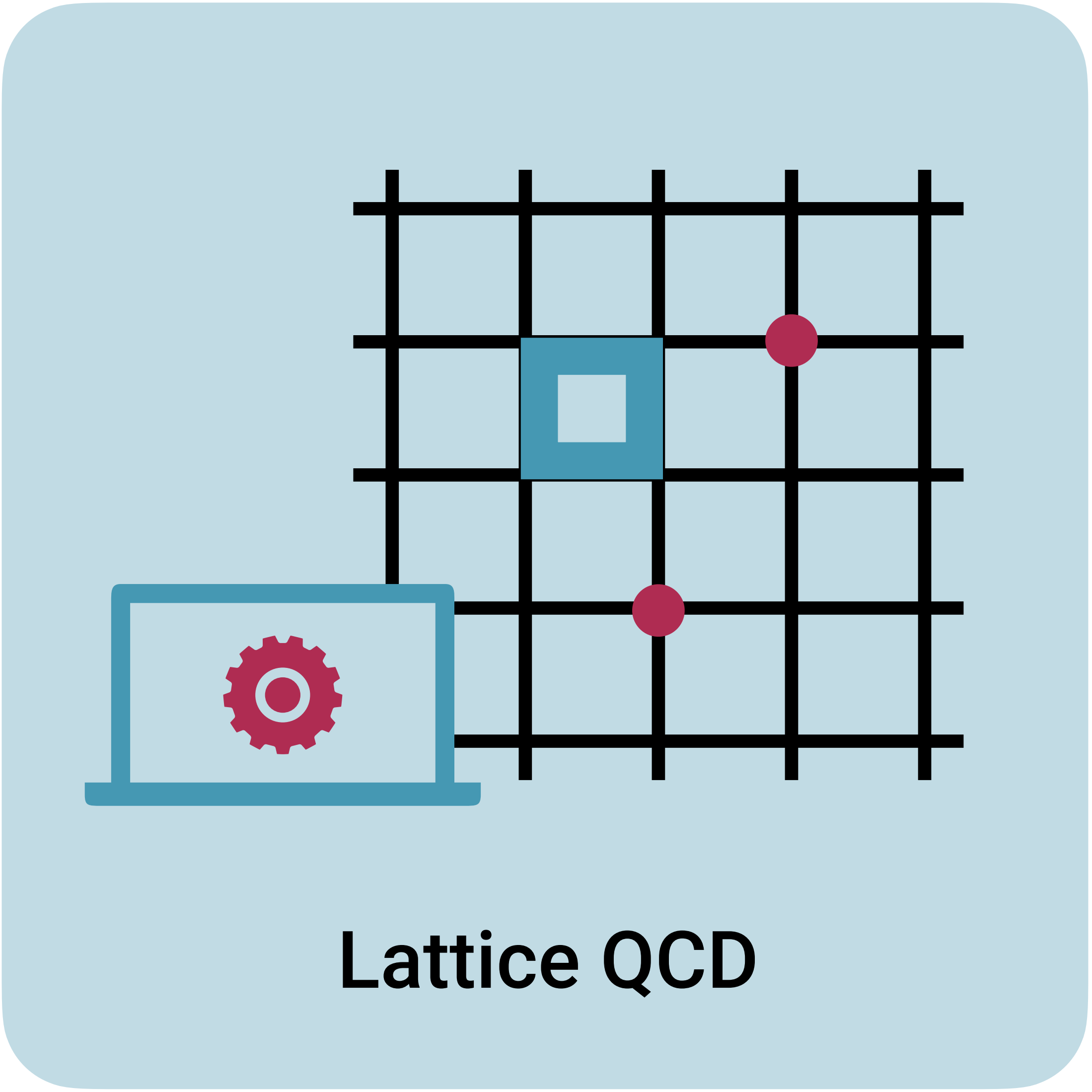


Hadronic Vacuum Polarisation

Non perturbative QCD correction give most of the uncertainty



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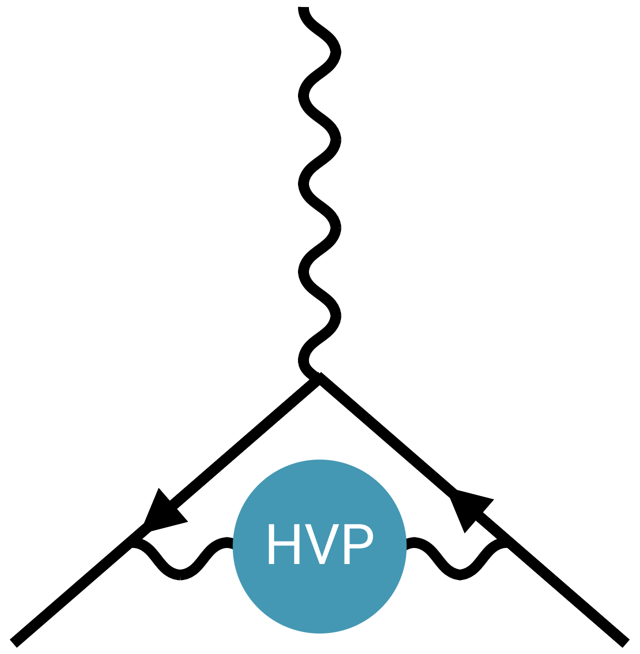

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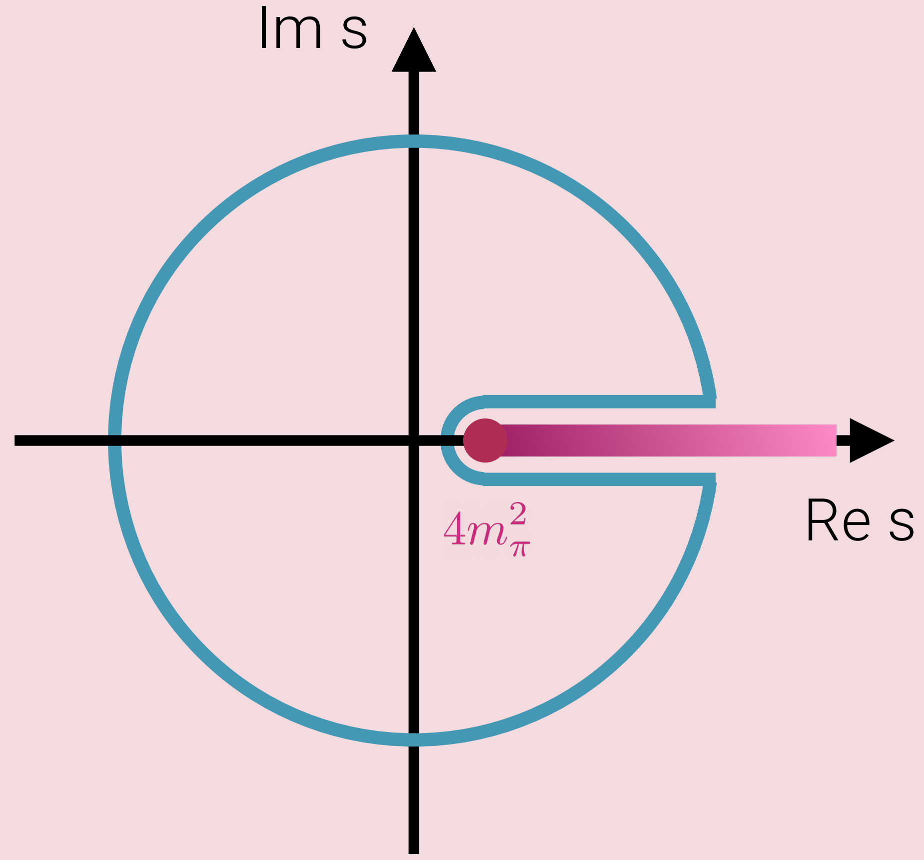
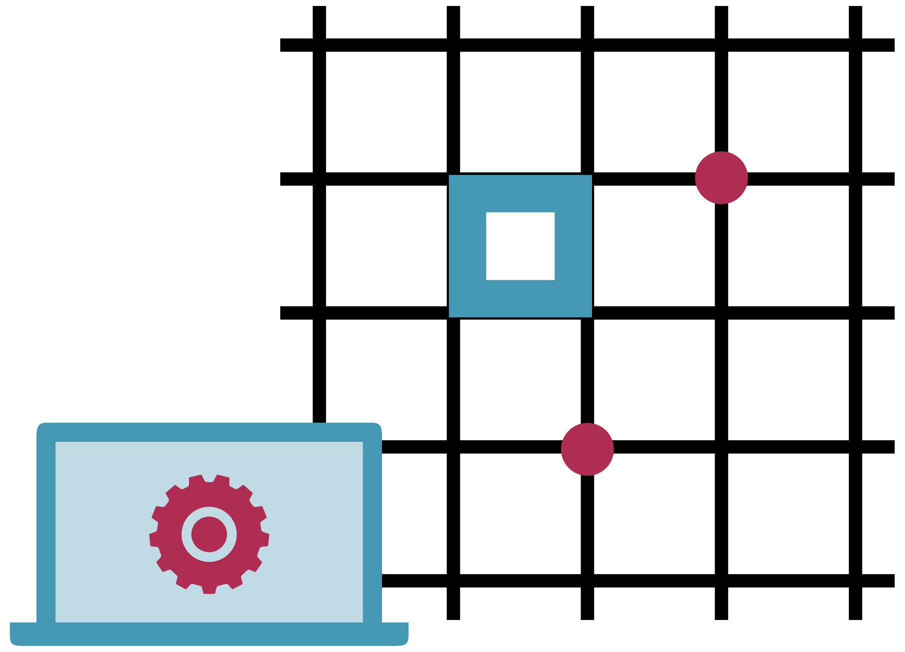


Dispersive approach



Lattice QCD

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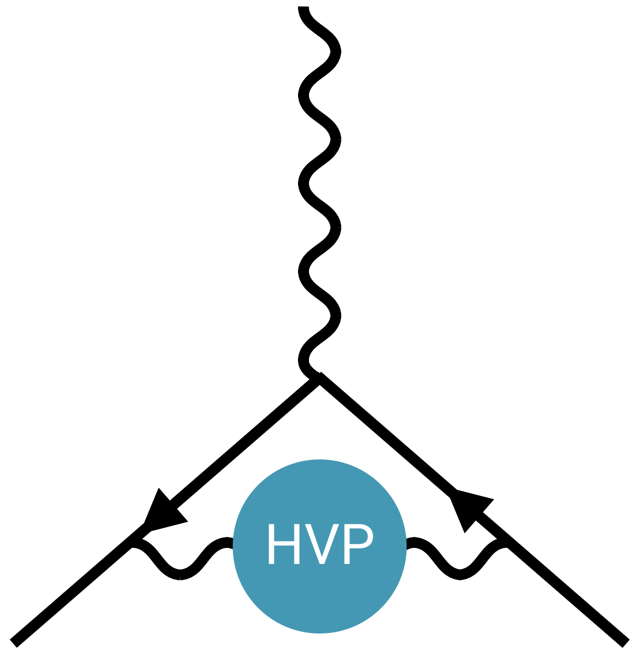

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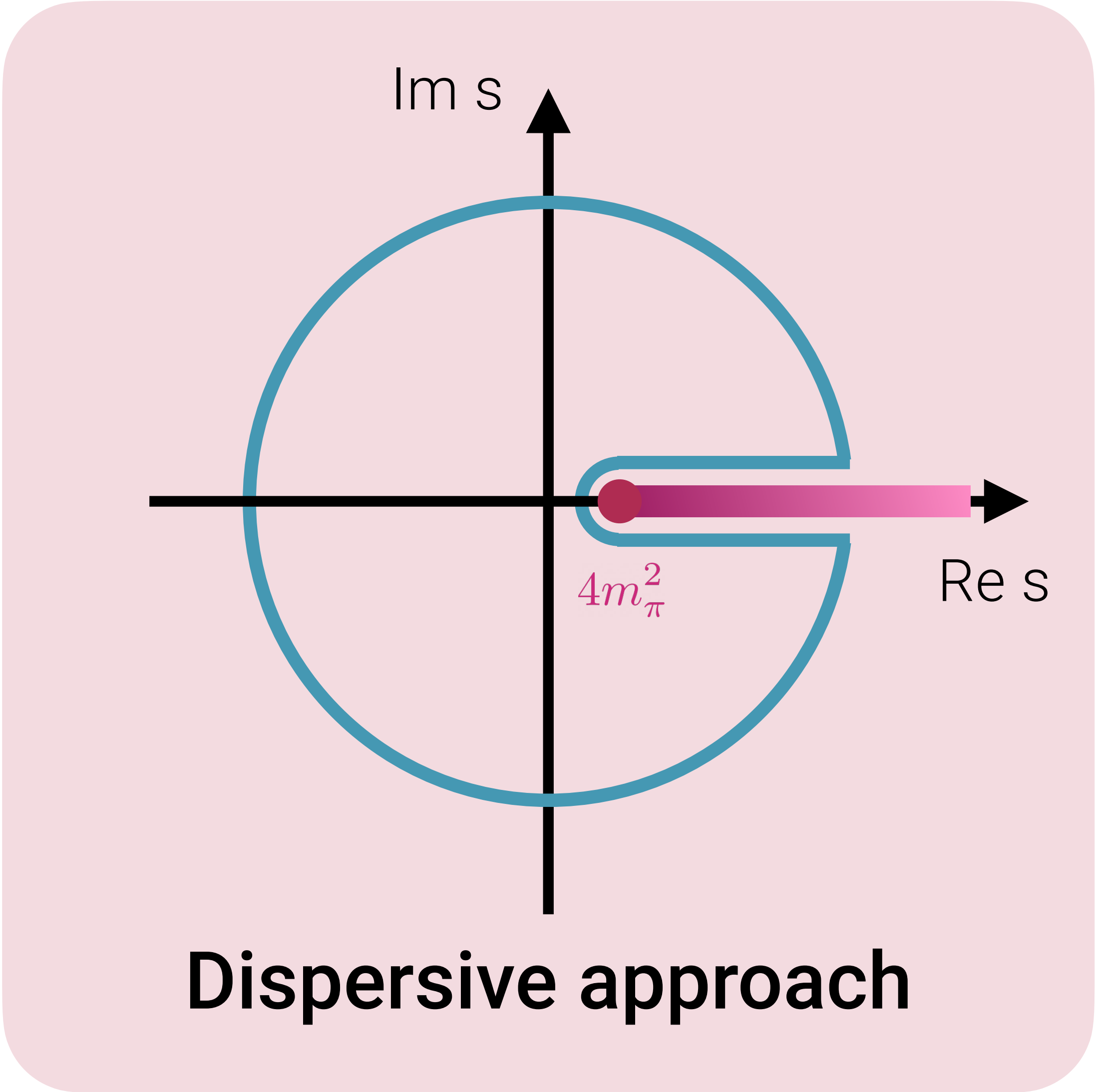

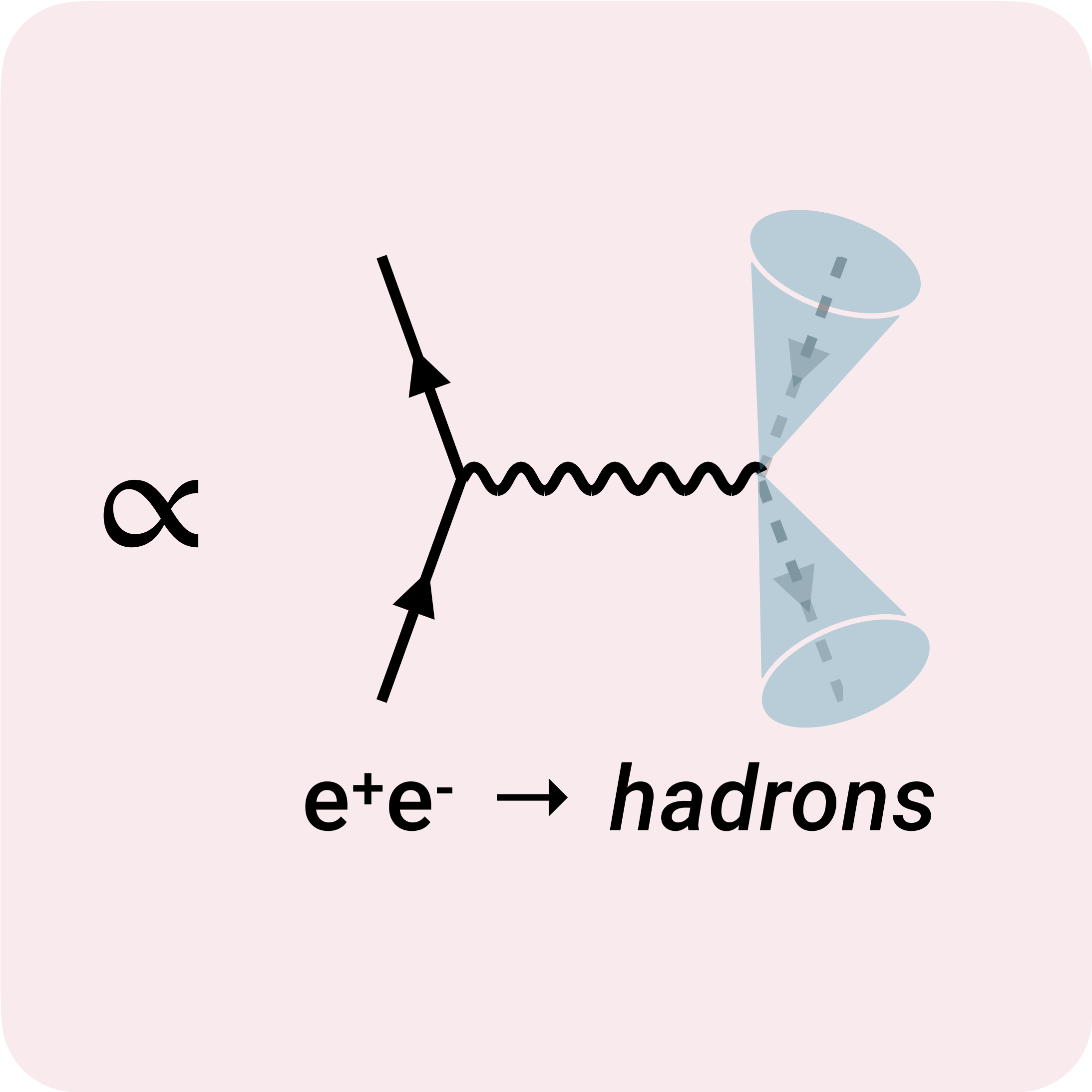

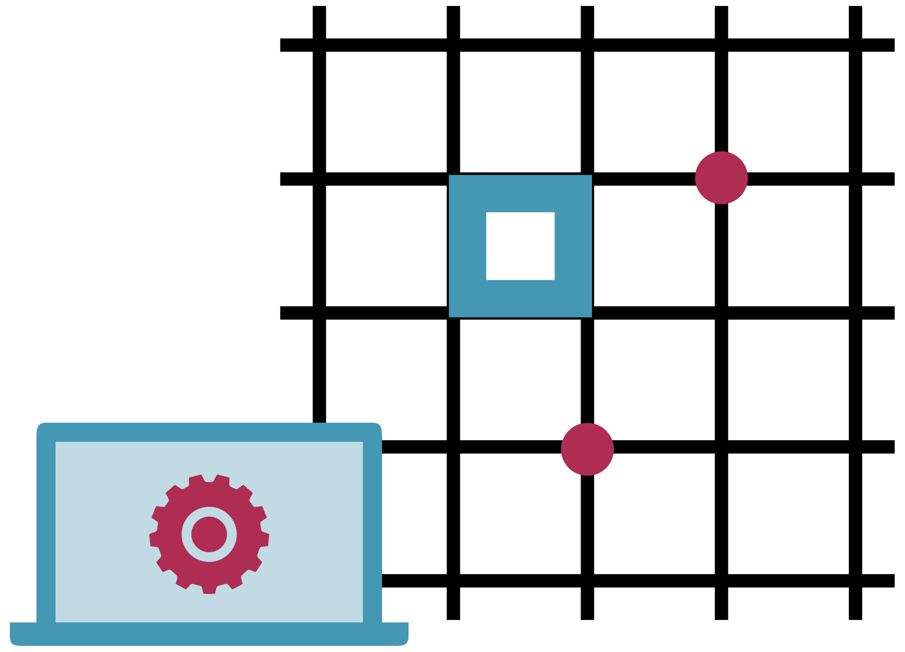

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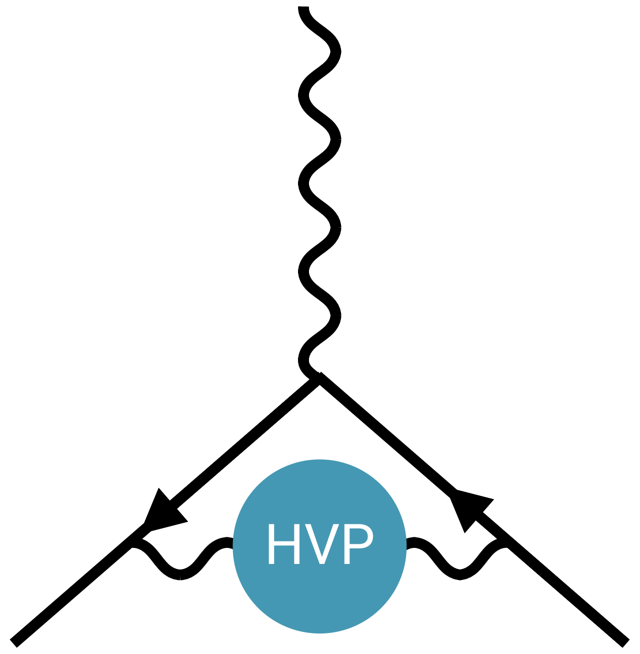

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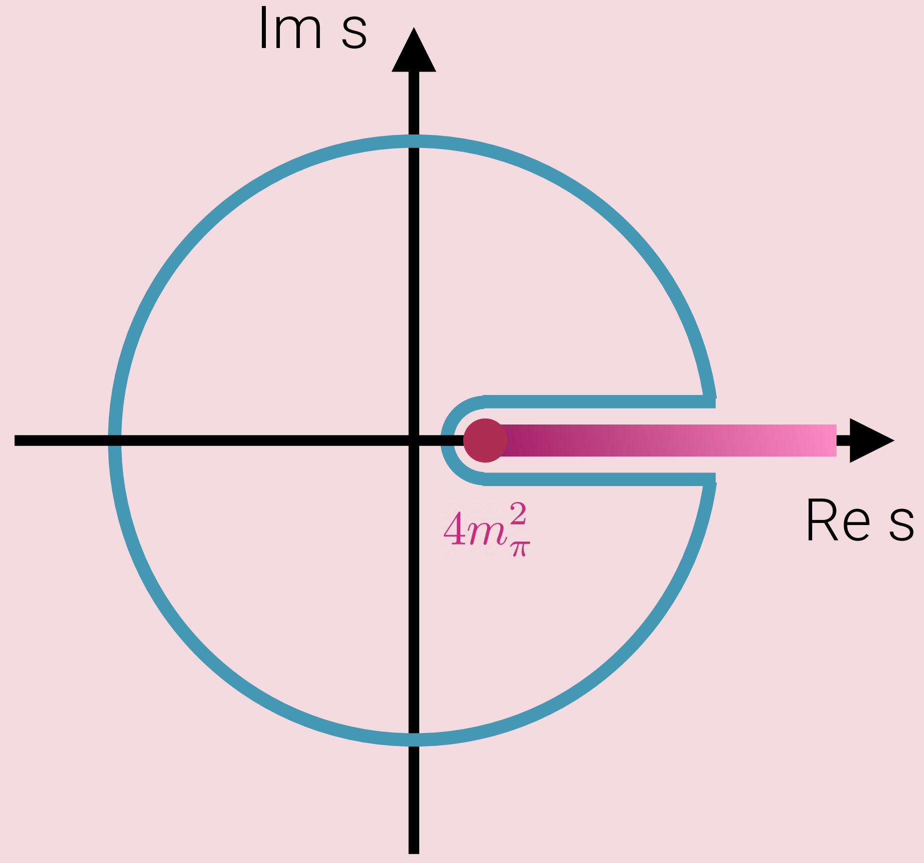

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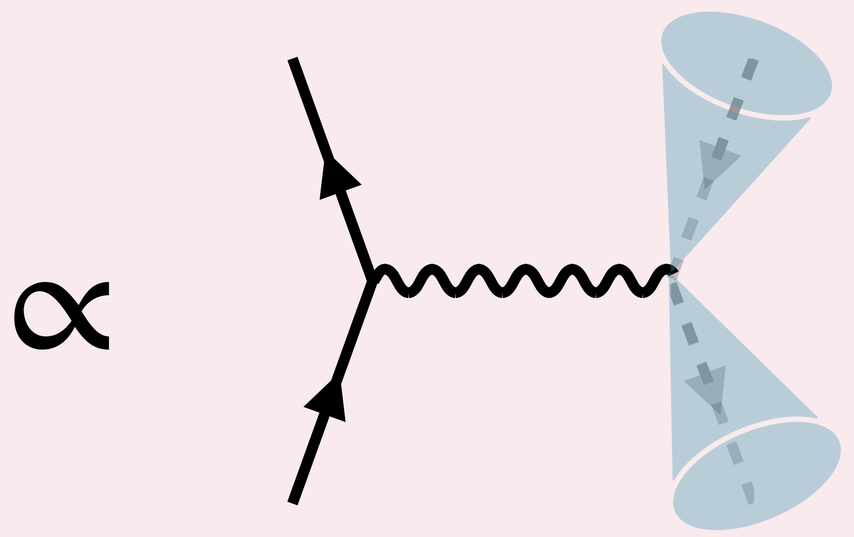
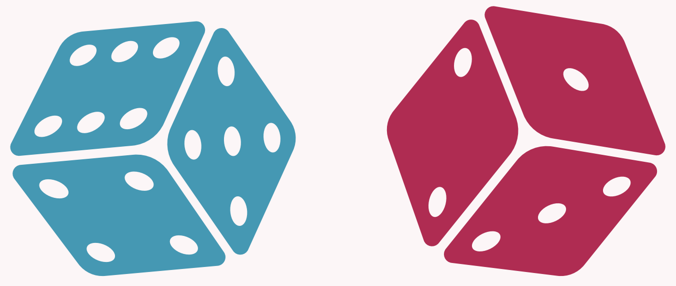
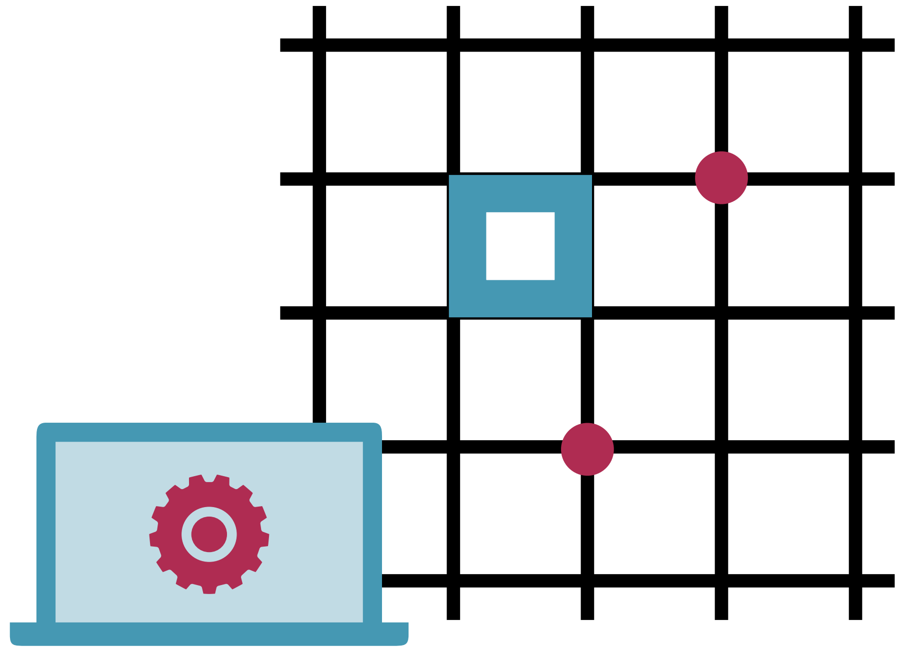


$e^+e^- \to$ ***hadrons***



Monte Carlo Generators
Analyse data with high precision

Learn more in Marco's talk!



Lattice QCD

The pion form factor

Pion Pair production in e+e- annihilation at next-to-leading order matched to Parton shower
E. Budassi, C. M. Carloni Calame, M. Ghilardi, A. Gurgone, G. Montagna,
M. Moretti, O. Nicrosini, F. Piccinini, F.P.U., *JHEP 05 (2025)*

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi^2}\int_{4m_\pi^2}^{\infty}\frac{\mathrm{d}s}{s}K(s)\left(\frac{\alpha(s)}{3}\frac{\sigma(e^+e^-\to \mathrm{hadrons})}{\sigma(e^+e^-\to \mu^+\mu^-)}\right) \simeq \frac{\alpha}{\pi^2}\int\frac{\mathrm{d}s}{s}K(s)\beta_\pi^2\,|F_\pi(s)|^2\,f(s)$$

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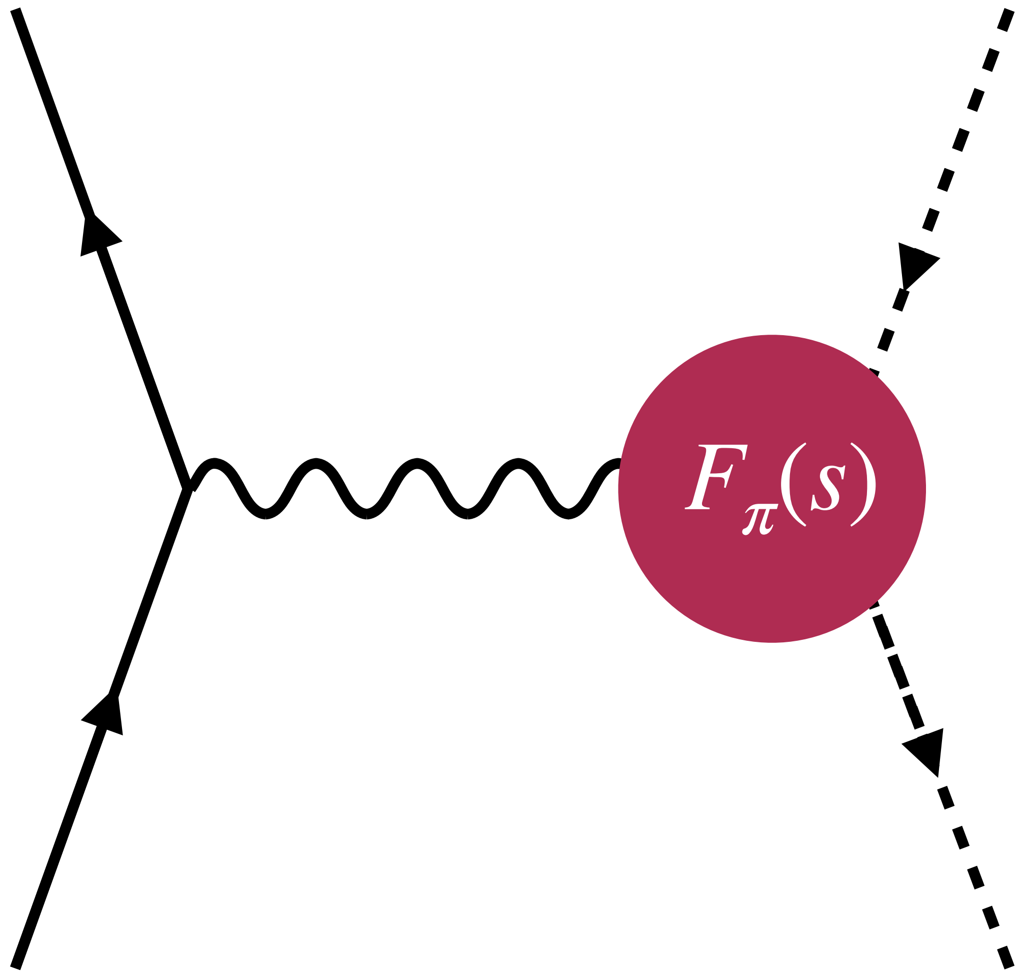

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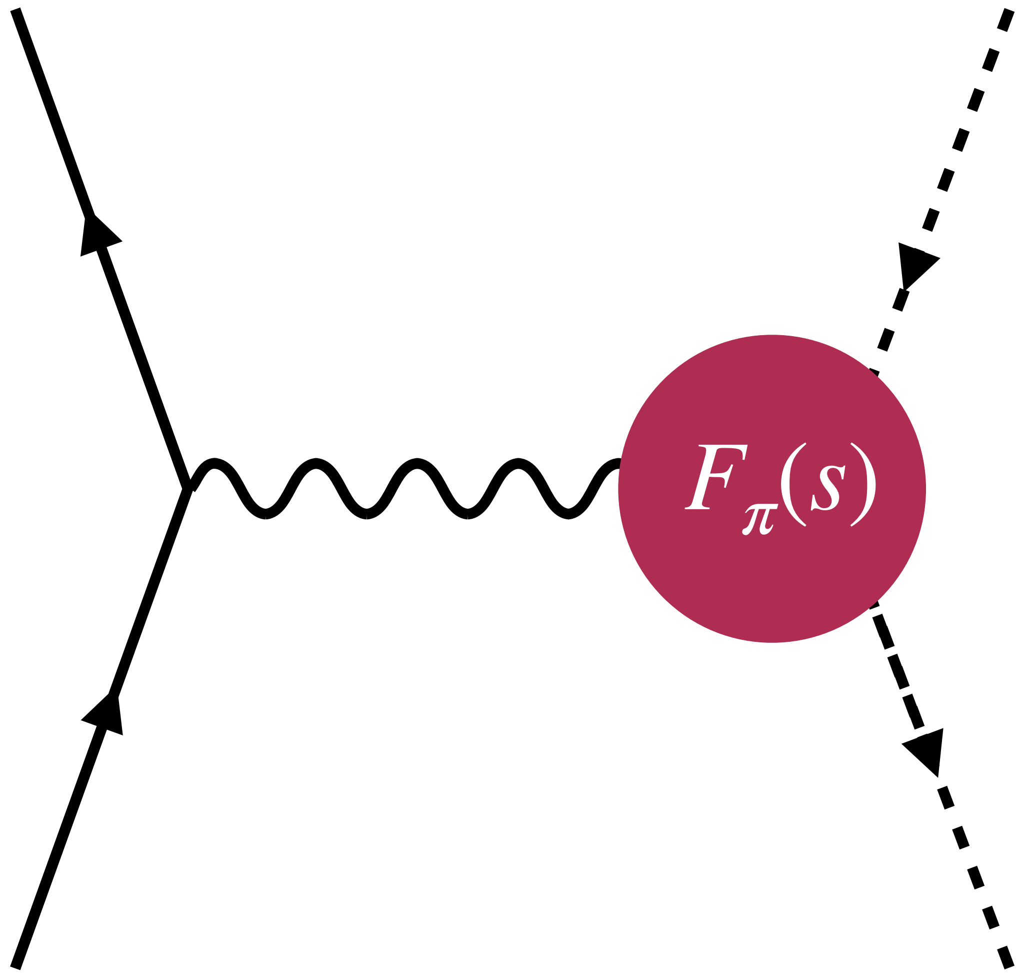

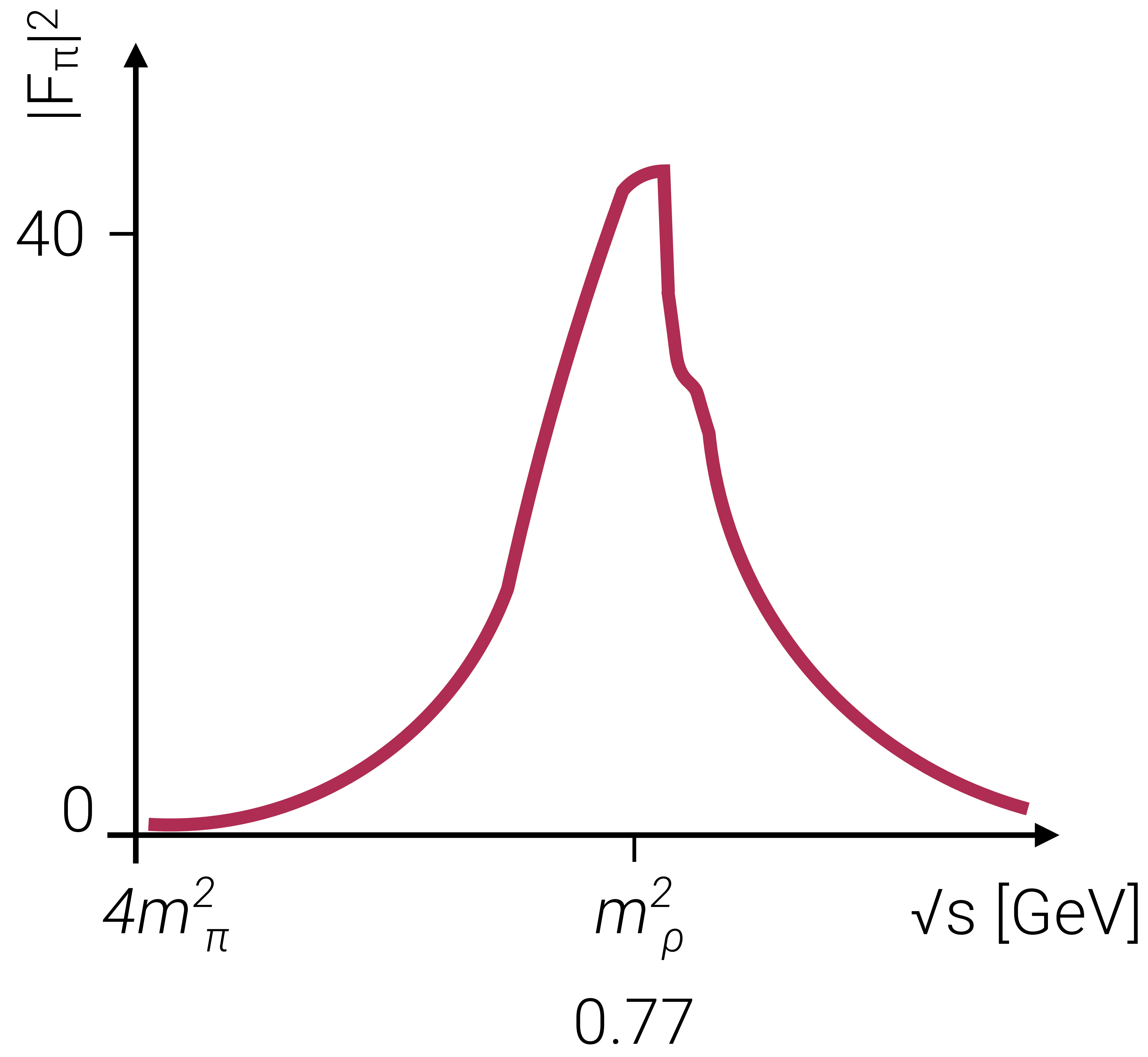

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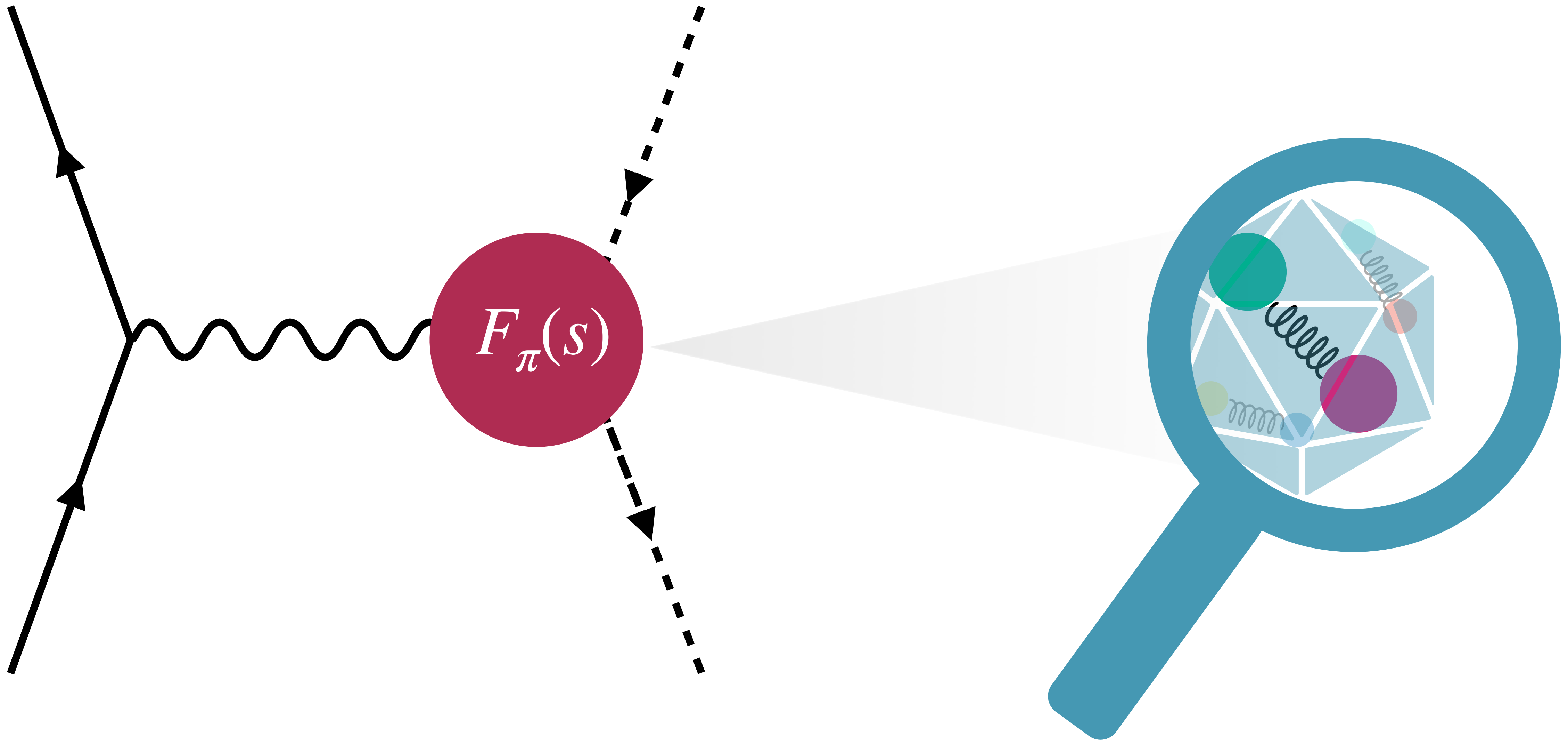
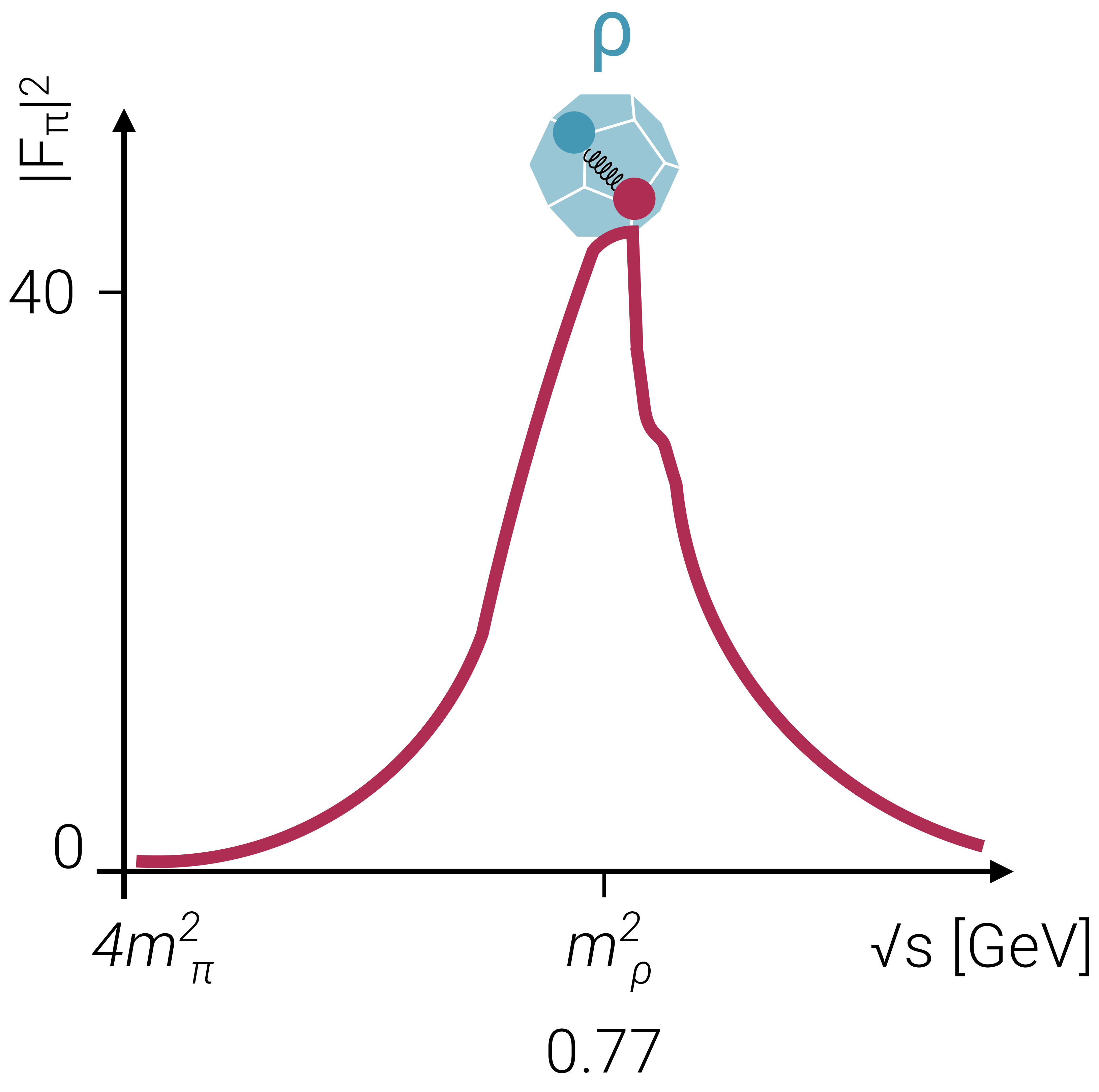


Testing the **internal structure** of the pion



The pion form factor at NLO

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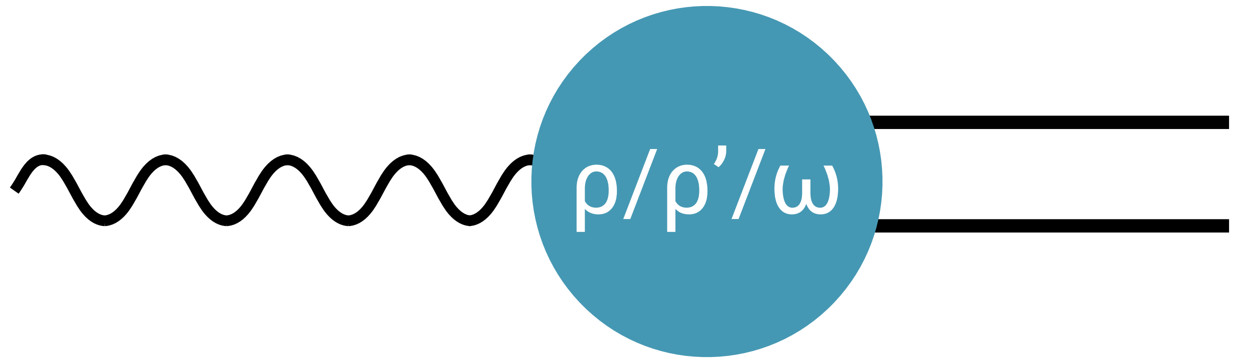
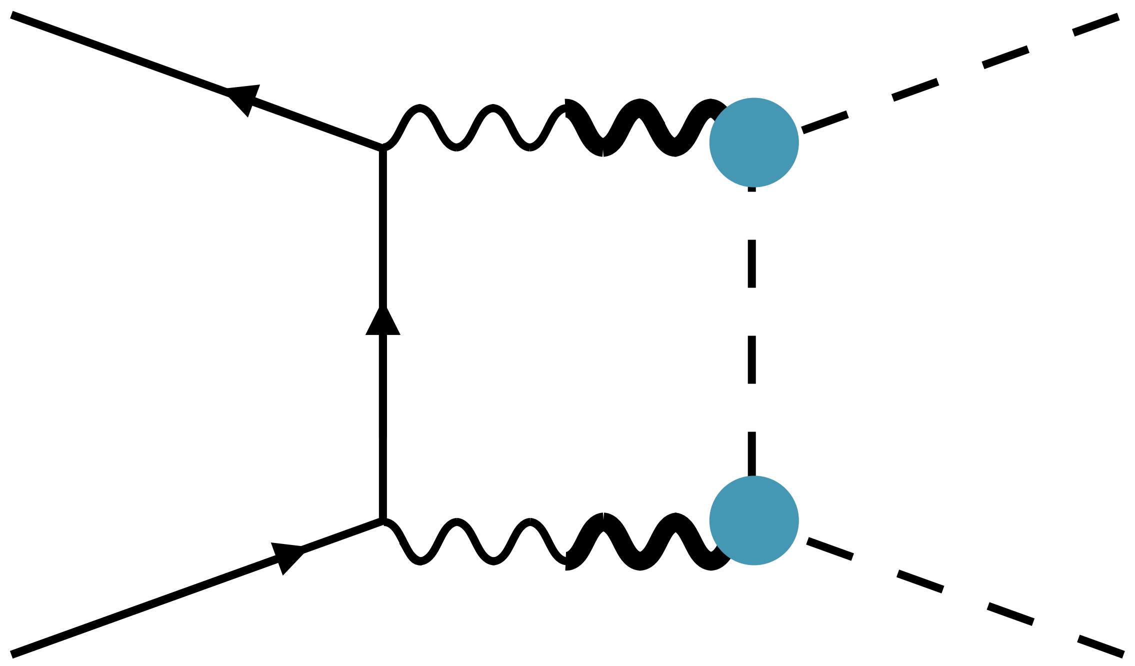
GVMD Model



$$F_\pi^{\mathrm{BW}}(q^2) = \sum_{v=1}^{n_r} F_{\pi,v}^{\mathrm{BW}}(q^2) = \frac{1}{c_t}\sum_{v=1}^{n_r} c_v \frac{\Lambda_v^2}{\Lambda_v^2 - q^2}$$



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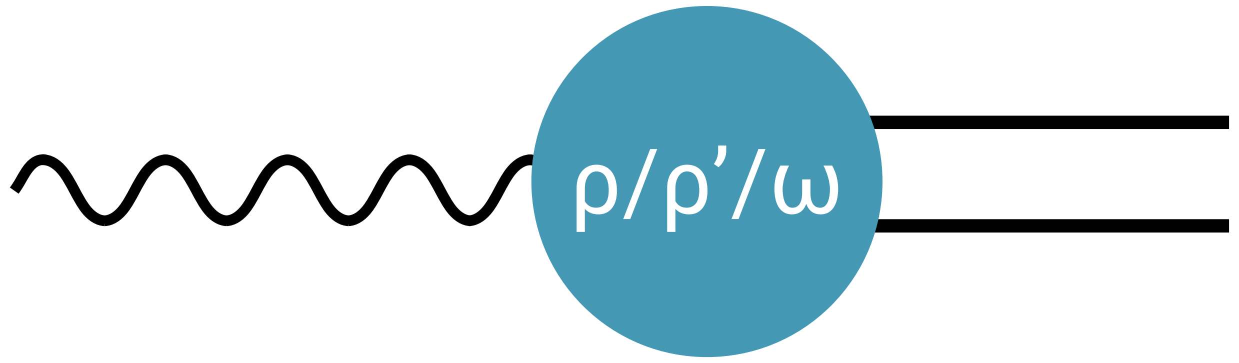

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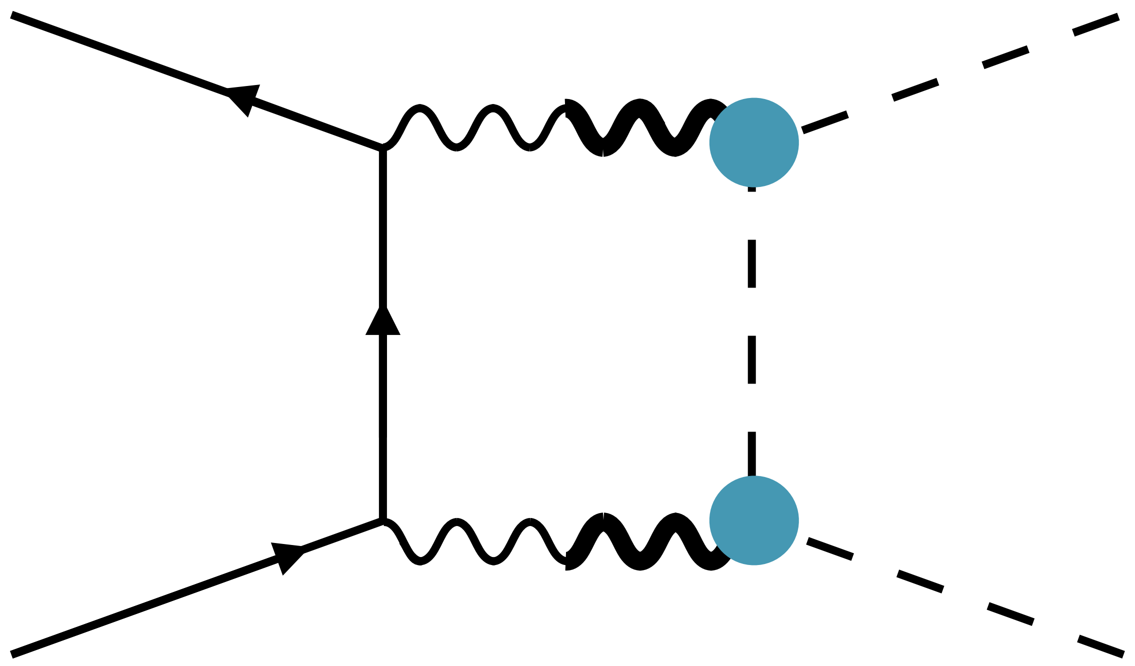
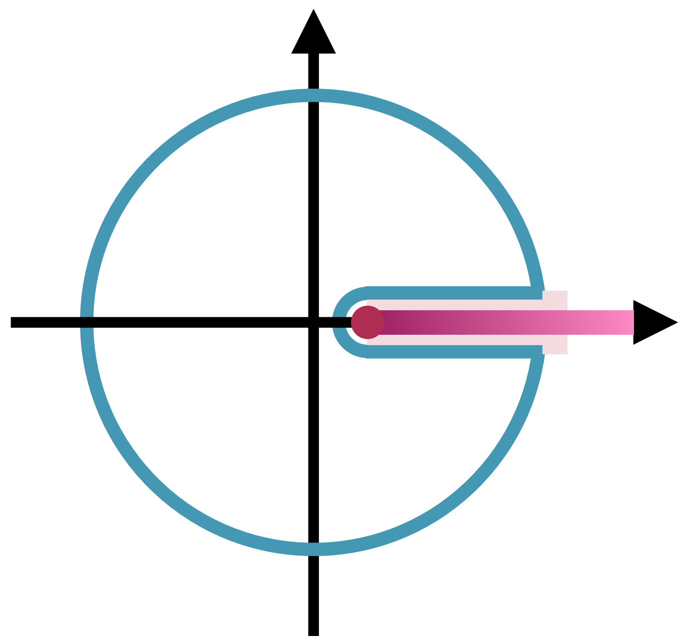
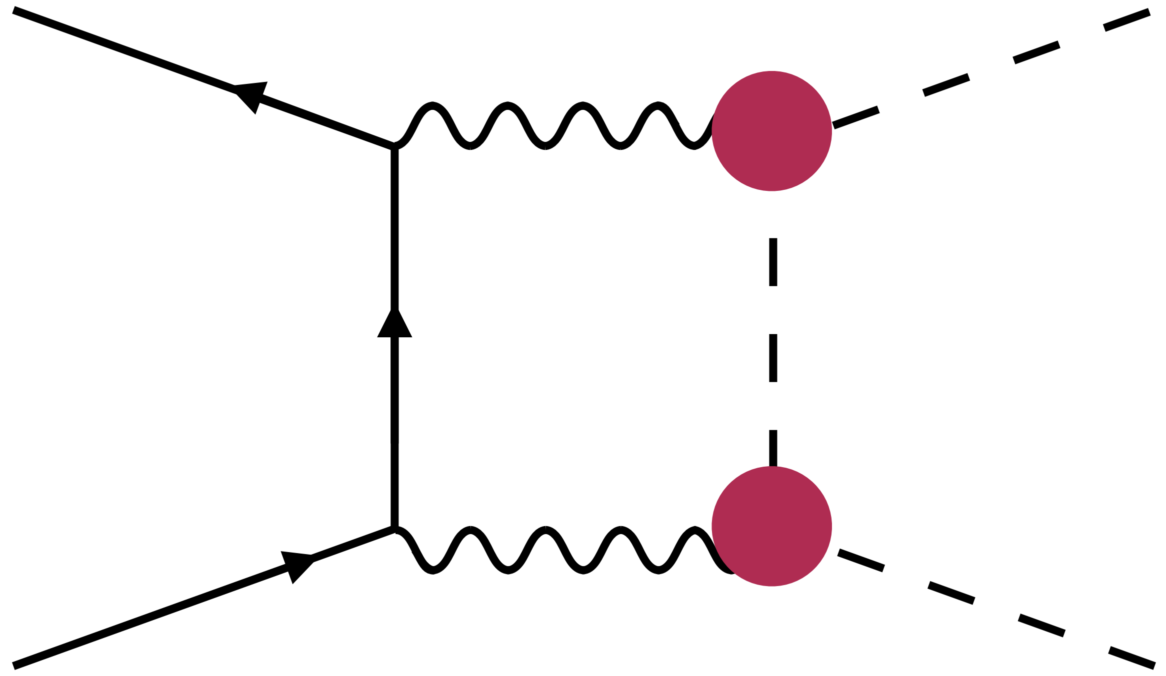




$$F_\pi(q^2) = 1 + \frac{q^2}{\pi}\int_{4m_\pi^2}^{\infty} \frac{\mathrm{d}s'}{s'} \frac{\mathrm{Im}F_\pi(s')}{s' - q^2 - i\varepsilon'}$$

FsQED



Numerical results

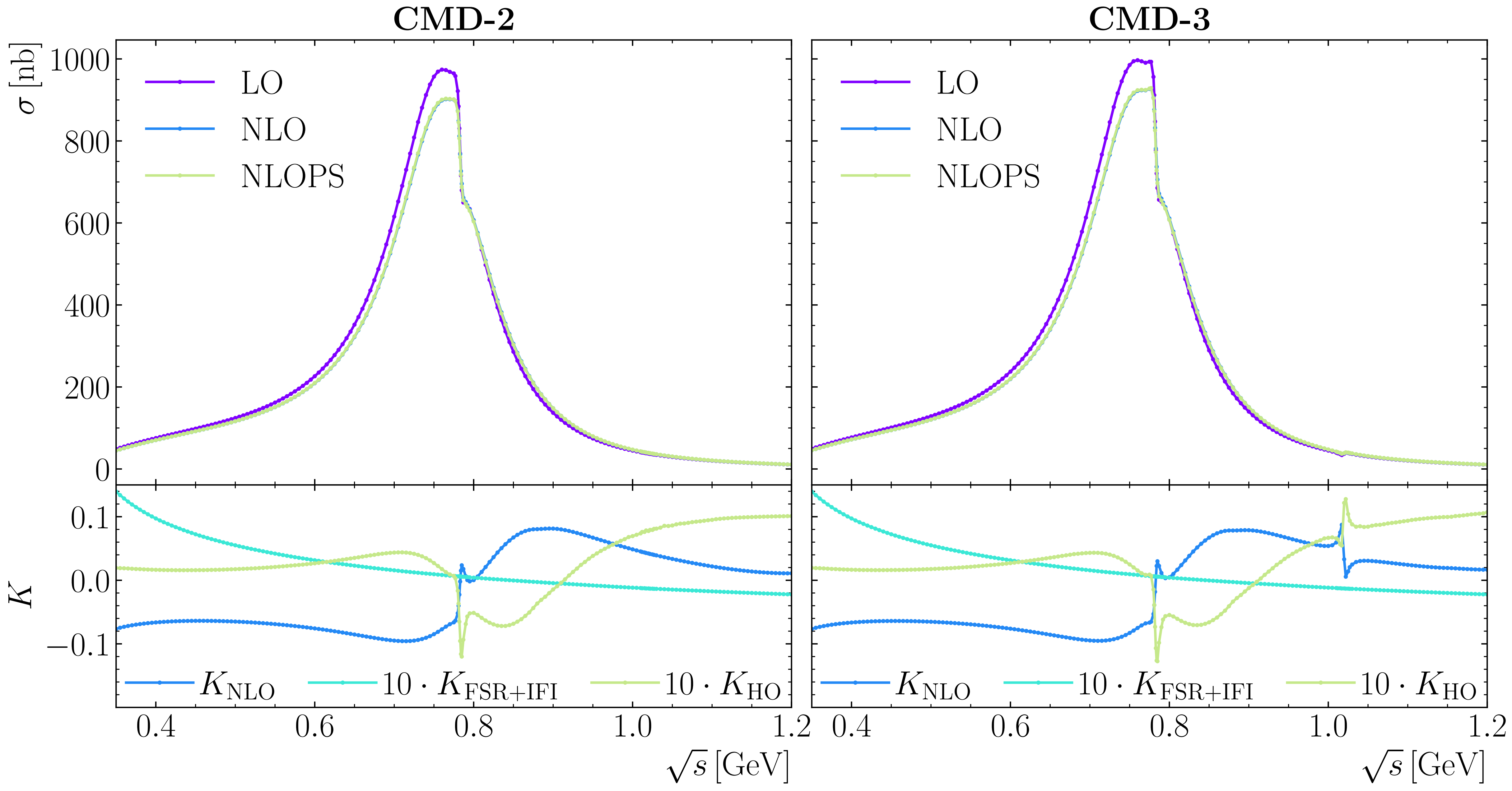
We studied the impact of Radiative corrections and of the form factor approach in a typical scenario

$$p^{\pm} \equiv |\boldsymbol{p}^{\pm}| > 0.45E\,,$$

$$\vartheta_{\text{avg}} \equiv \frac{1}{2}(\pi - \vartheta^{+} + \vartheta^{-}) \in [1, \pi - 1]\,,$$

$$\delta\vartheta \equiv |\vartheta^{+} + \vartheta^{-} - \pi| < 0.25\,,$$

$$\delta\phi \equiv \big||\phi^{+} - \phi^{-}| - \pi\big| < 0.15\,,$$



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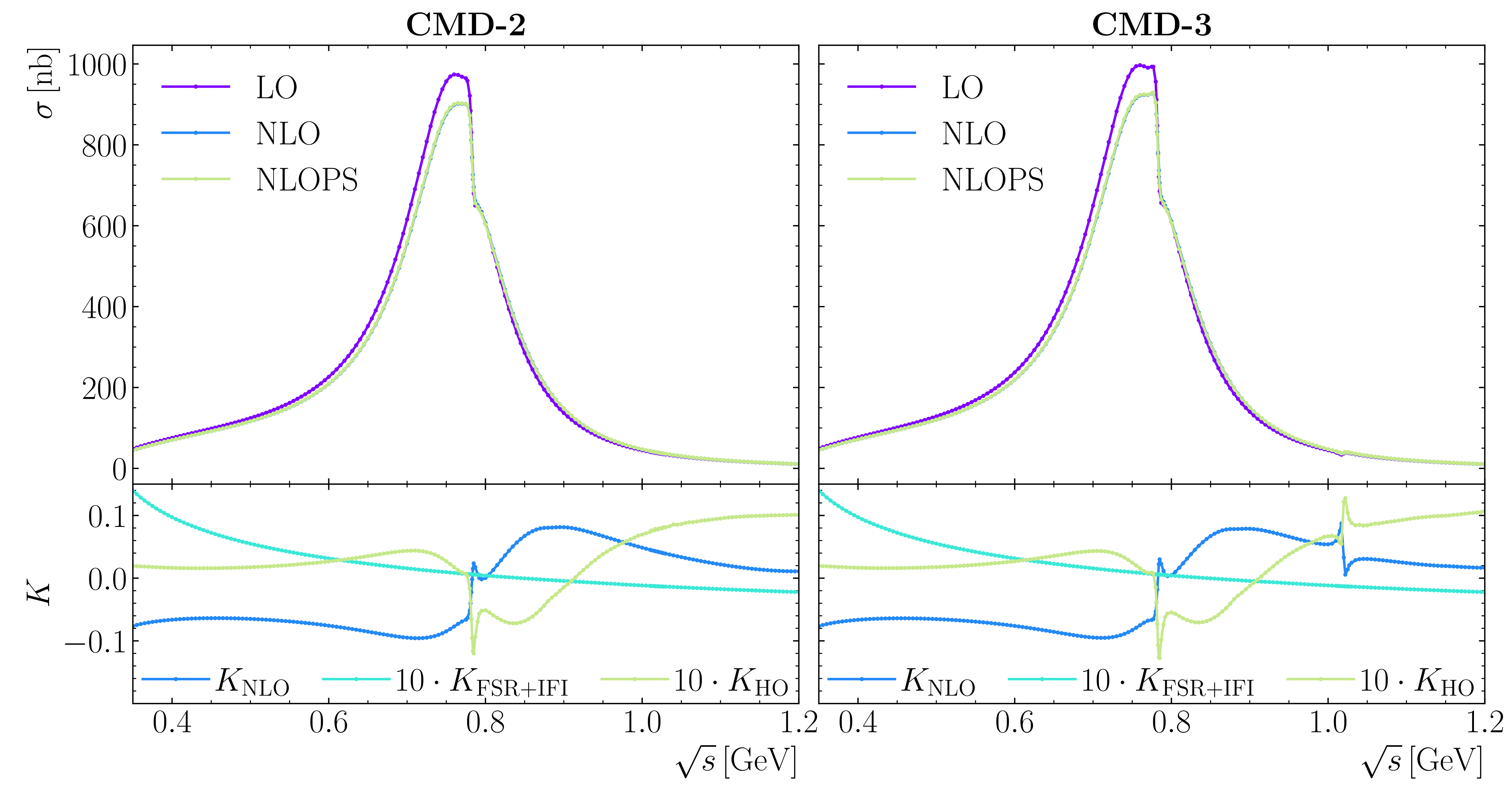


Radiative corrections

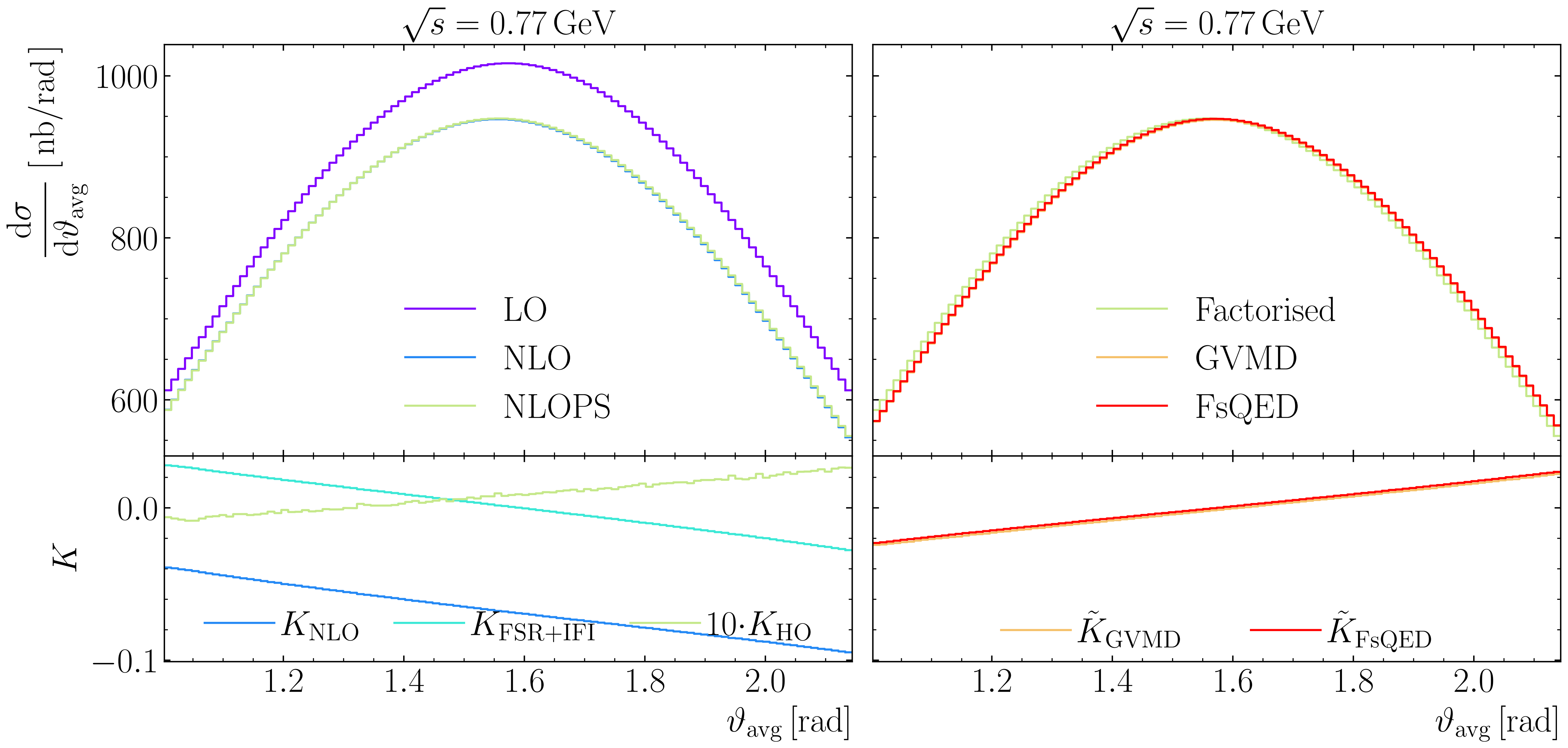
$$K_{\text{NLO}} = \frac{\sigma_{\text{NLO}} - \sigma_{\text{LO}}}{\sigma_{\text{LO}}}\,,$$

$$K_{\text{FSR+IFI}} = \frac{\sigma_{\text{NLO}} - \sigma_{\text{ISR}}}{\sigma_{\text{LO}}}\,,$$

$$K_{\text{HO}} = \frac{\sigma_{\text{NLOPS}} - \sigma_{\text{NLO}}}{\sigma_{\text{LO}}}\,,$$

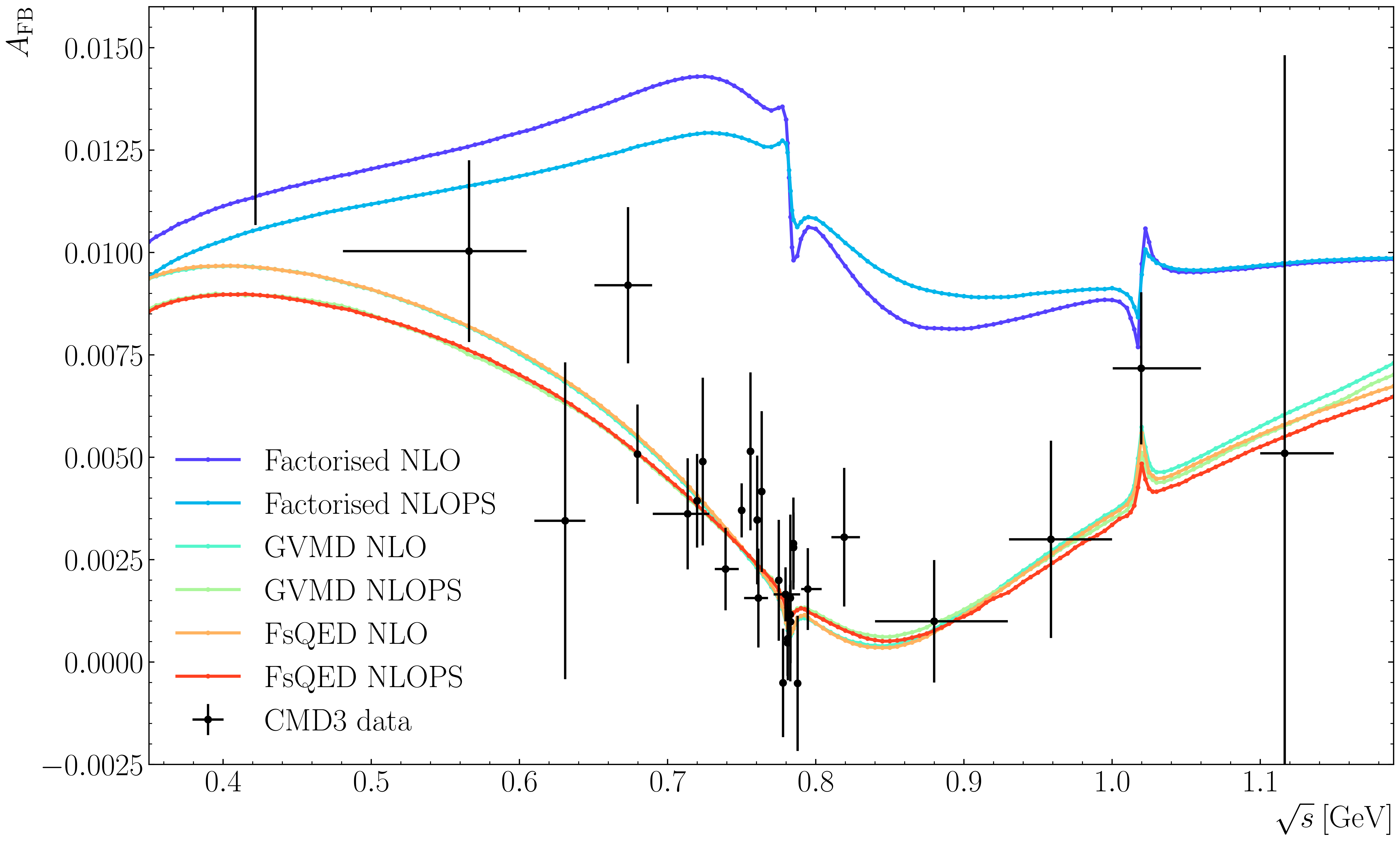
FF approach

$$\tilde{K}_{\text{FF}} = \left(\frac{\mathrm{d}\sigma_{\text{FF}}}{\mathrm{d}\vartheta_{\text{avg}}}\right)\left(\frac{\mathrm{d}\sigma_{\text{Factorised}}}{\mathrm{d}\vartheta_{\text{avg}}}\right)^{-1}$$



Charge asymmetry

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



Future colliders

Why a new collider?

ECFA Higgs, Electroweak and Top factory study
J. Altmann et al, *CERN Yellow Rep. Monogr. 5*

2025 — 2027
LHC Run3

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- **2025 — 2027**
  LHC Run3
- **2029 — 2041**
  HLLHC

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2025 — 2027
LHC Run3

2029 — 2041
HLLHC

204X — 20XX
FCC-ee
ILC
CLIC
CEPC

Precision era

Why a new collider?

ECFA Higgs, Electroweak and Top factory study
J. Altmann et al, *CERN Yellow Rep. Monogr. 5*

2025 — 2027
LHC Run3

2029 — 2041
HLLHC

204X — 20XX
FCC-ee
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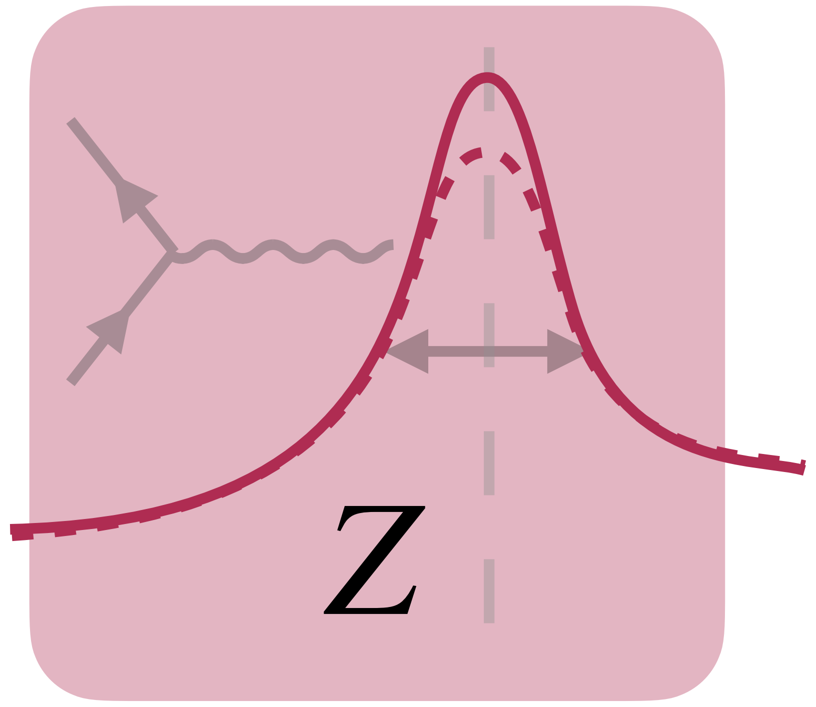

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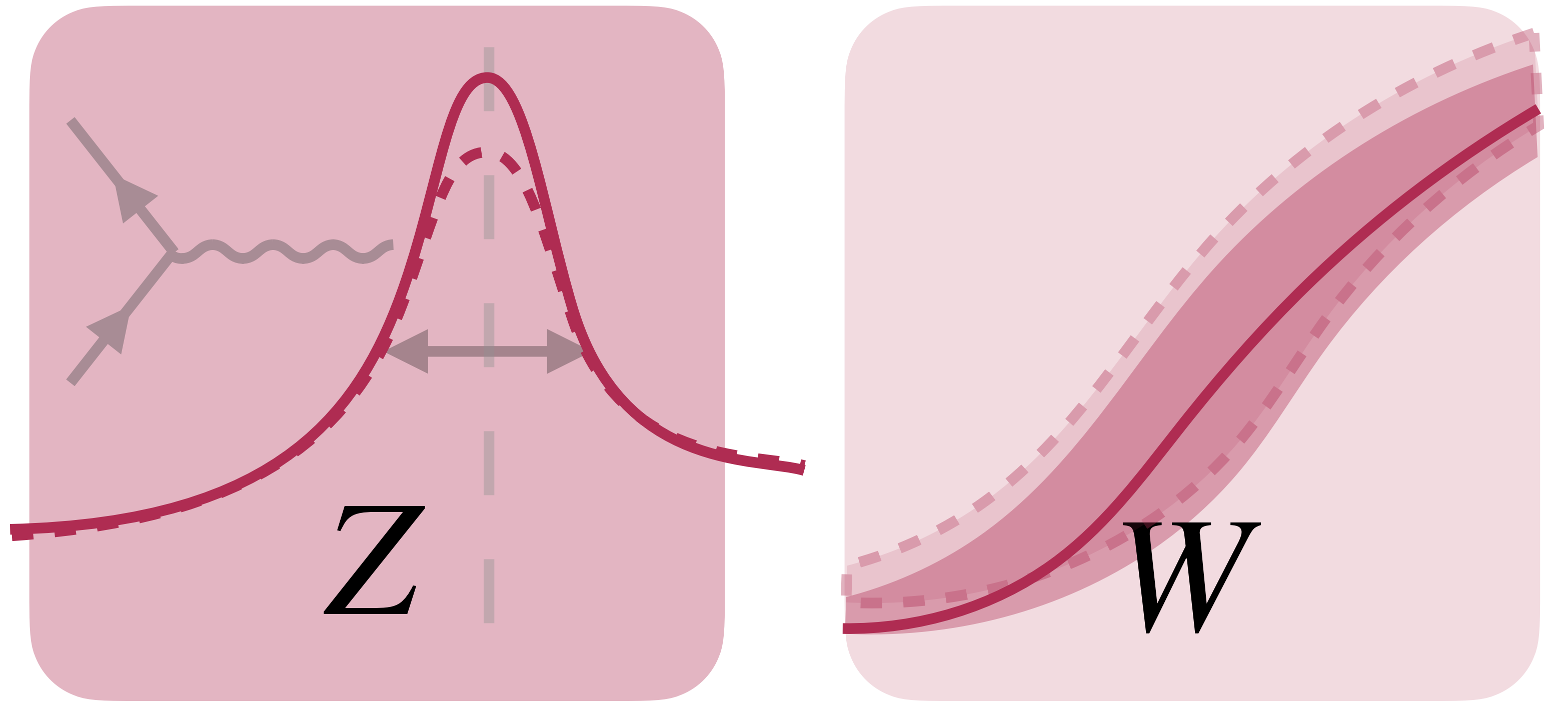

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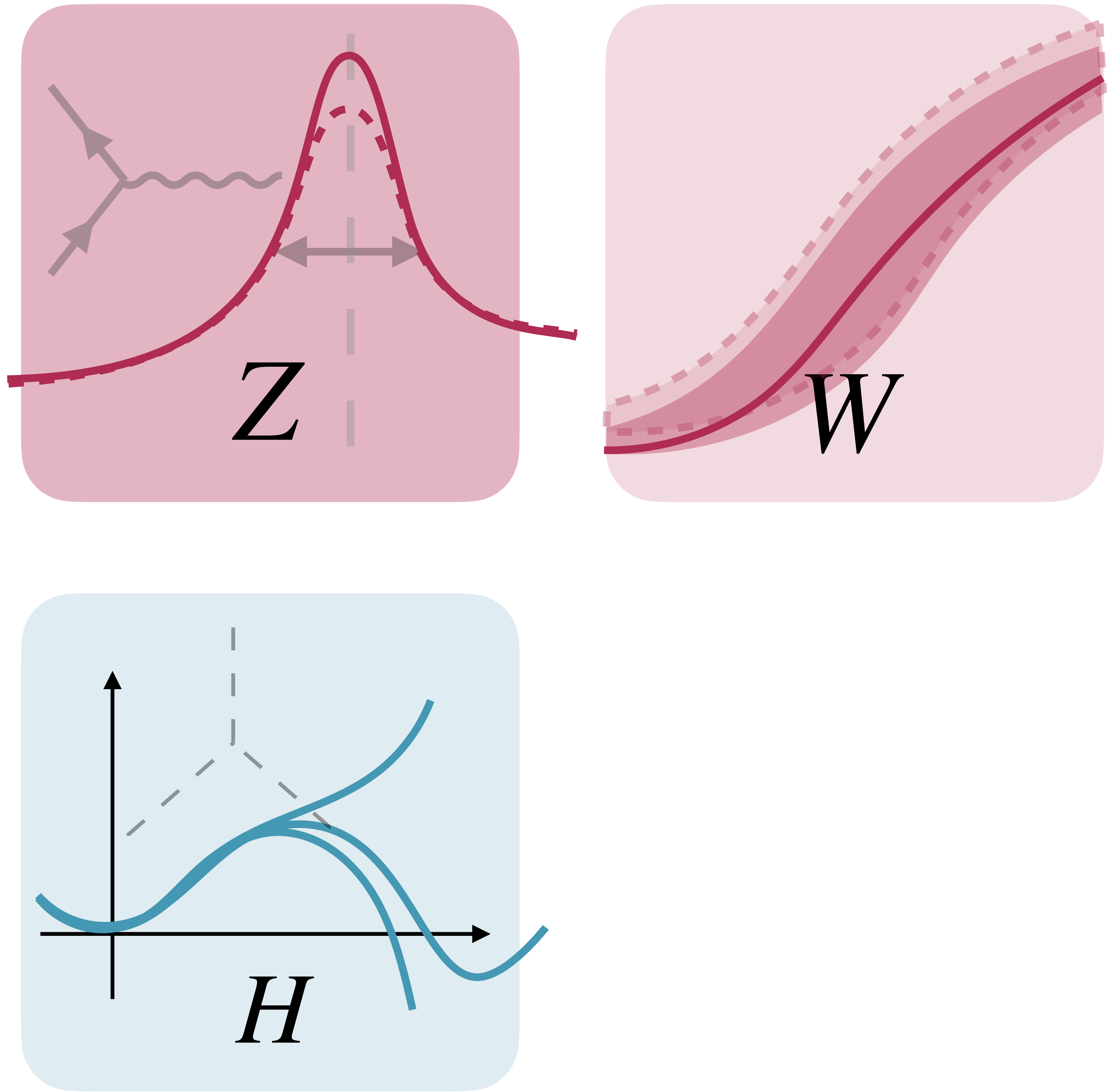

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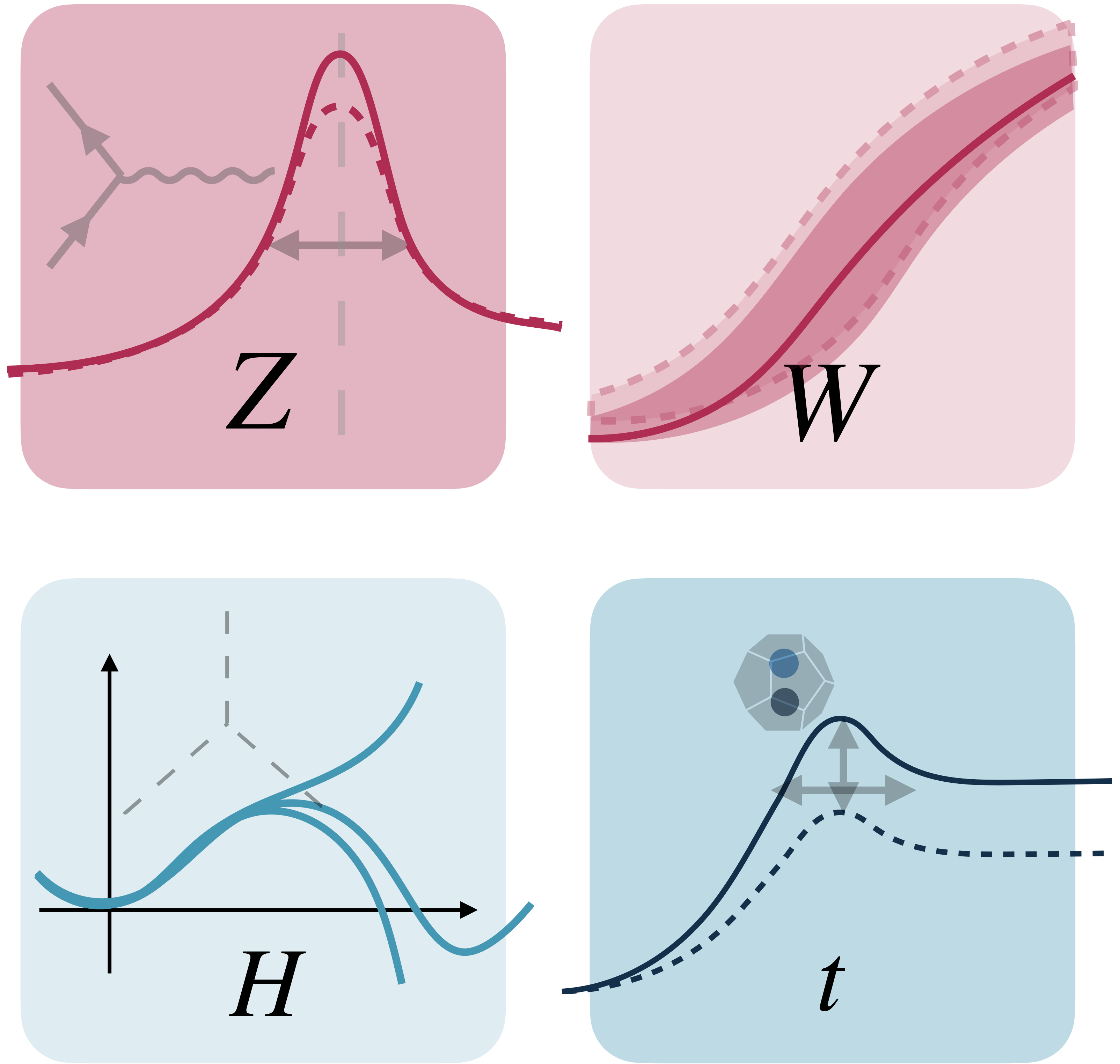

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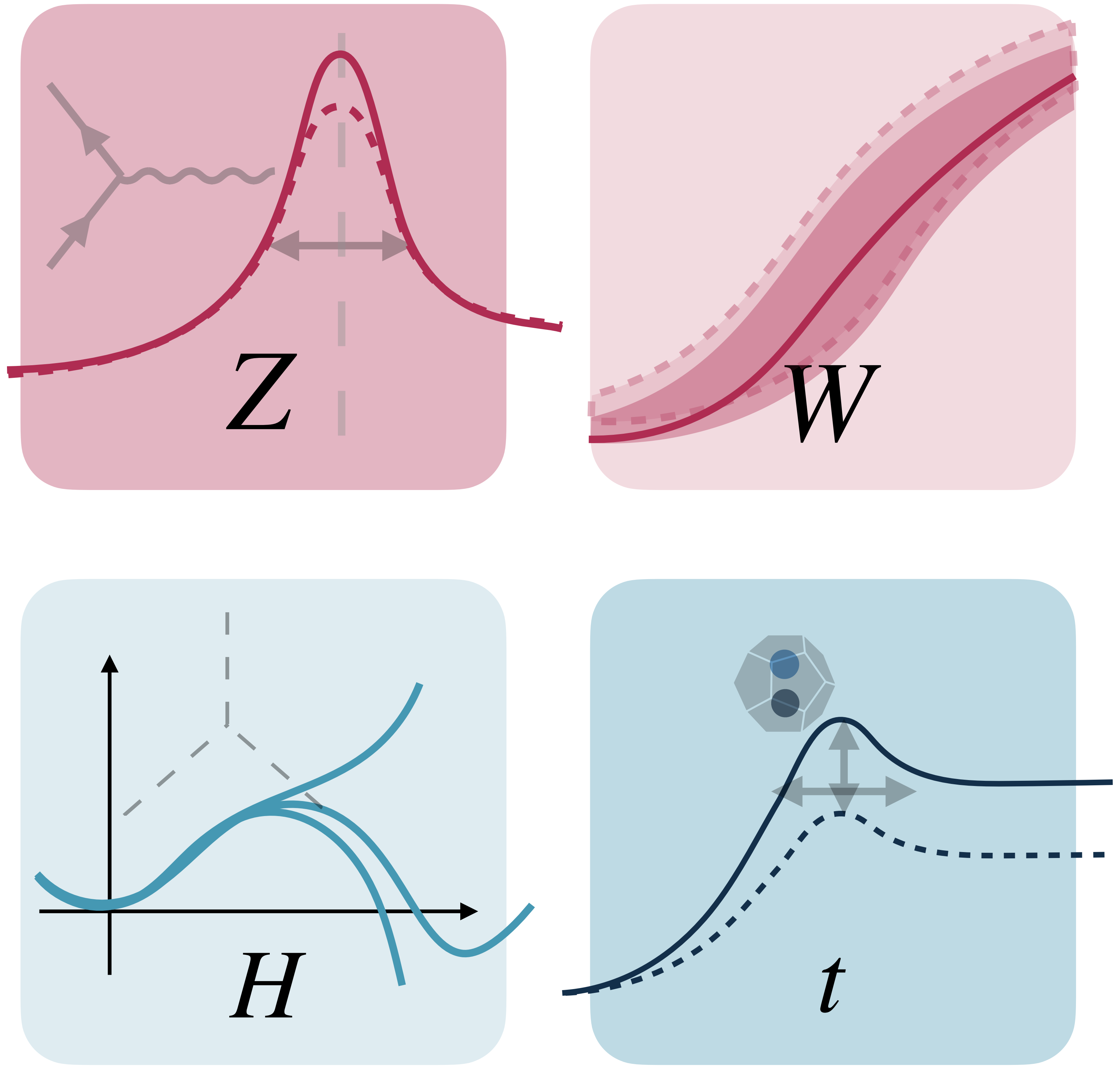

+ hints for **New Physics**

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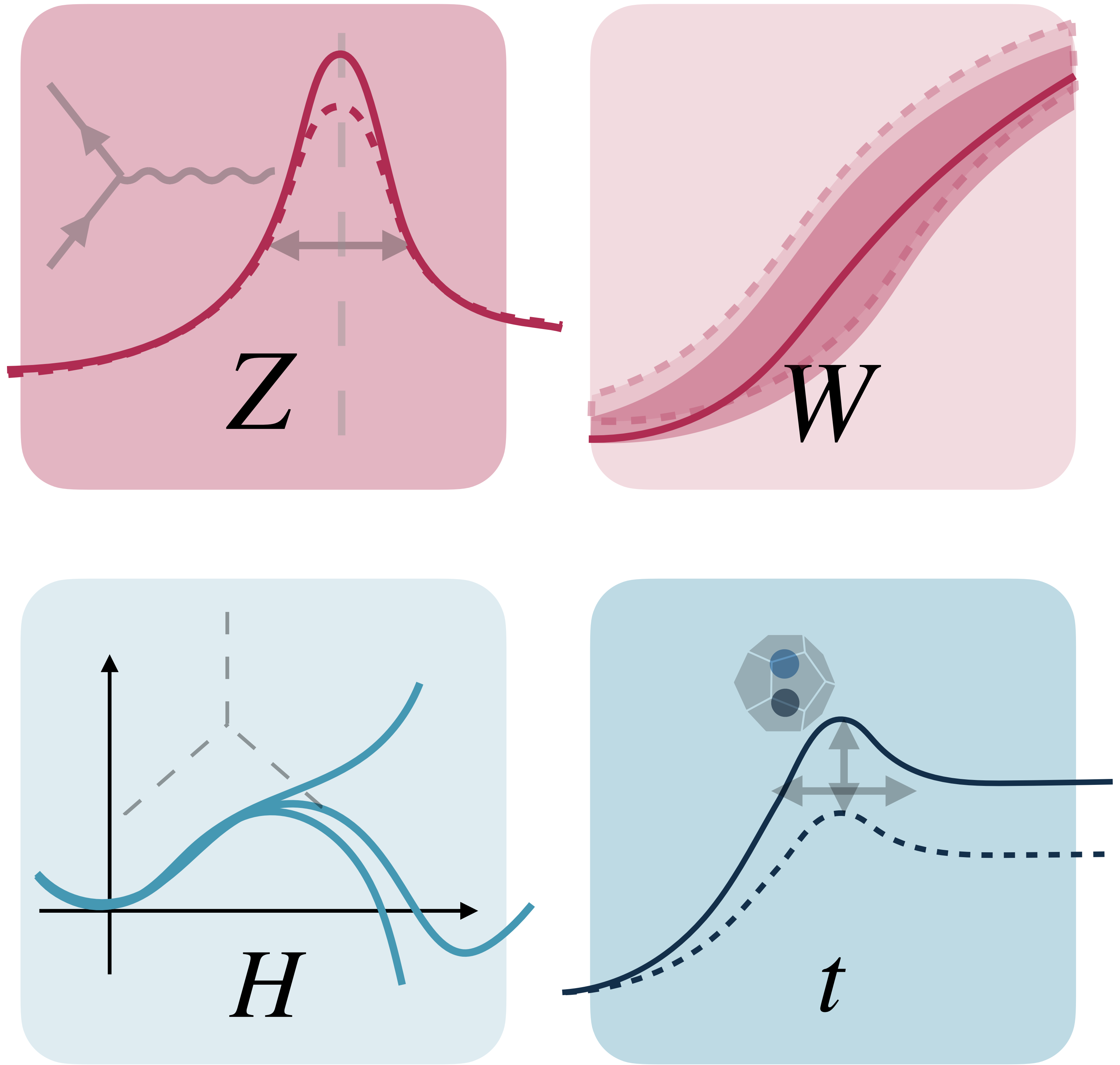

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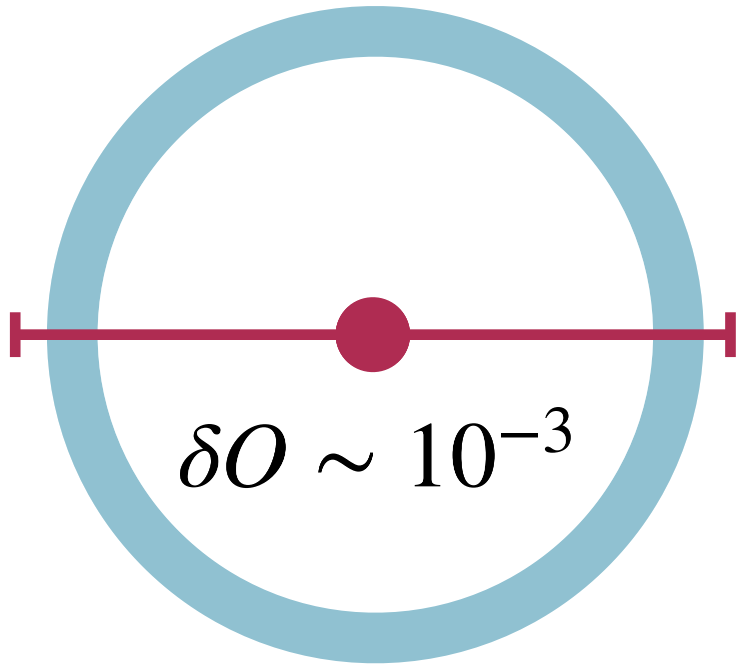
LEP I-II
LHC



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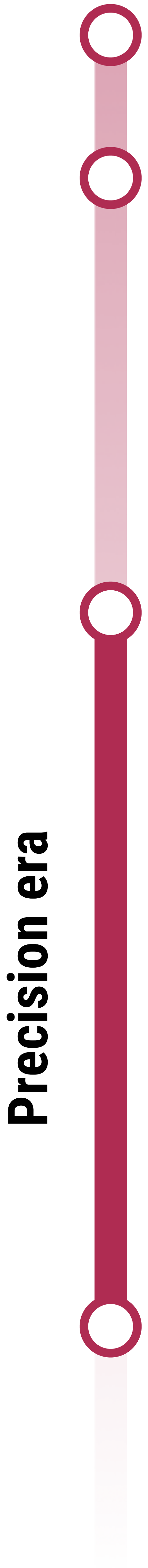

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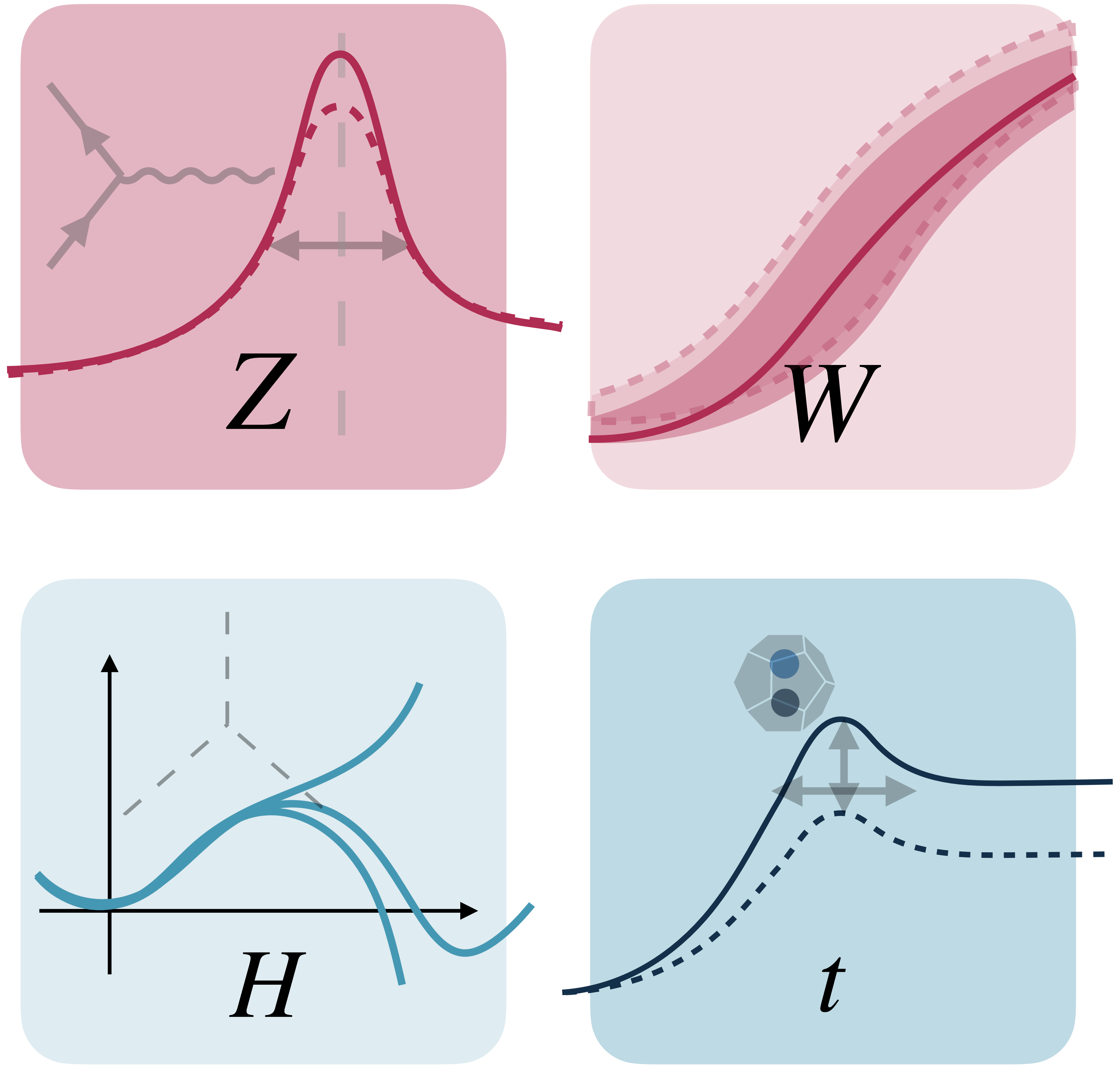

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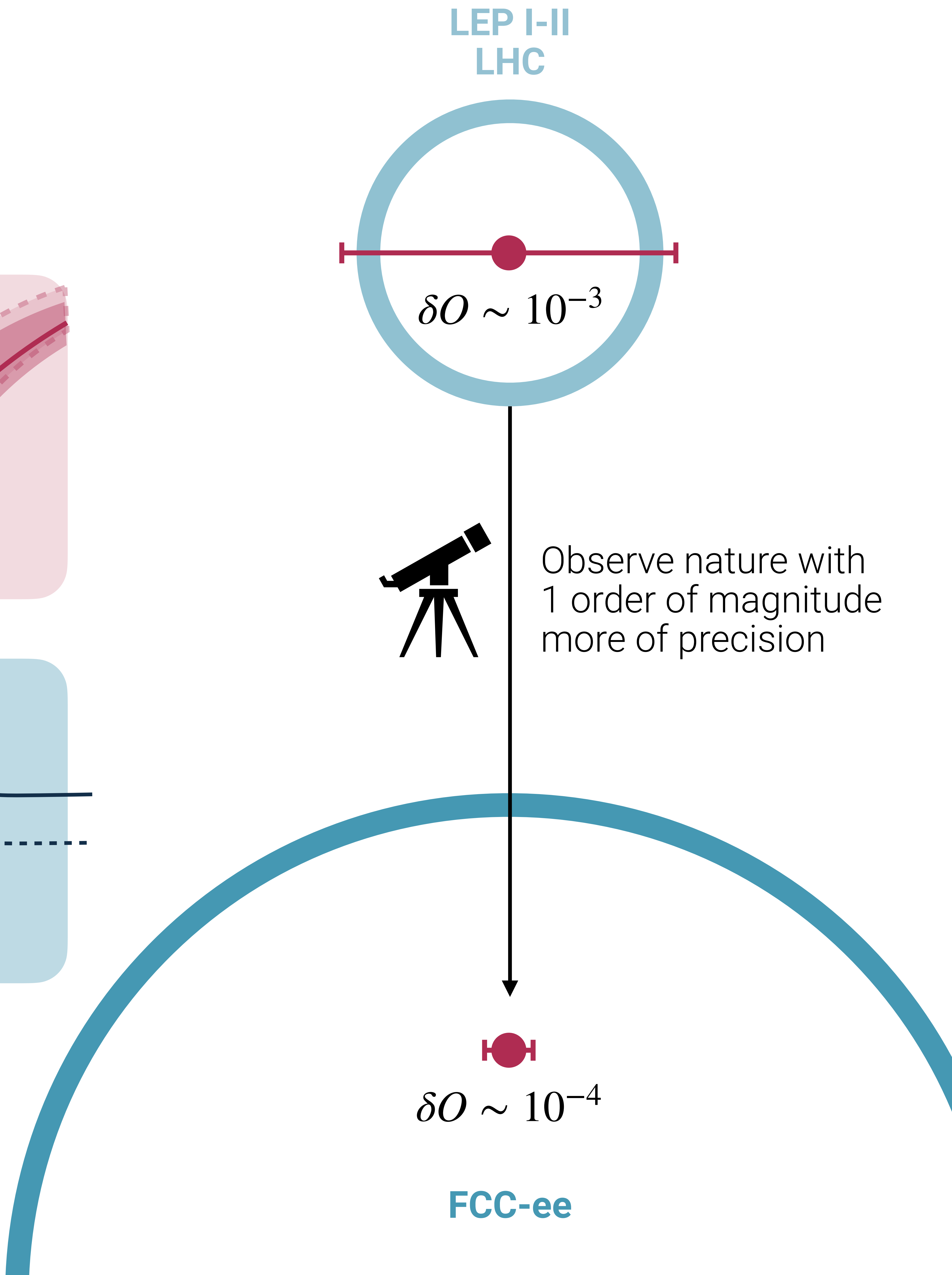

Cross section measurements

Luminosity converts
events into cross sections

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

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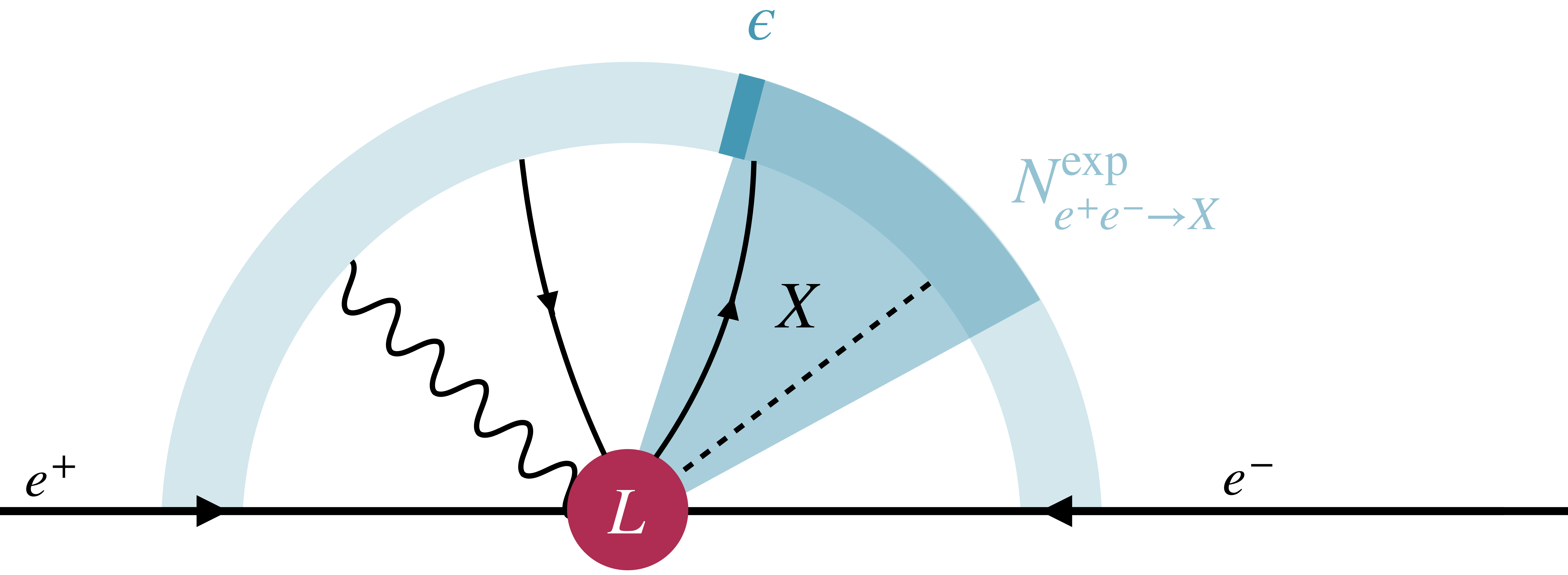

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Source of uncertainty to

σ_0^{had} N_ν M_W Γ_W

0.3 MeV 1.2 MeV

Luminosity measurements

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

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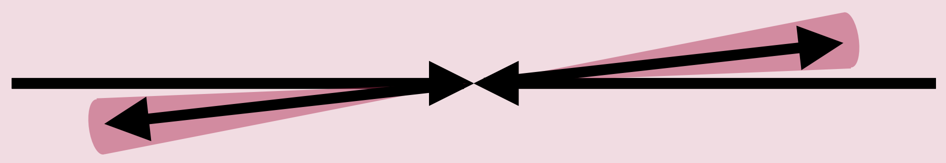
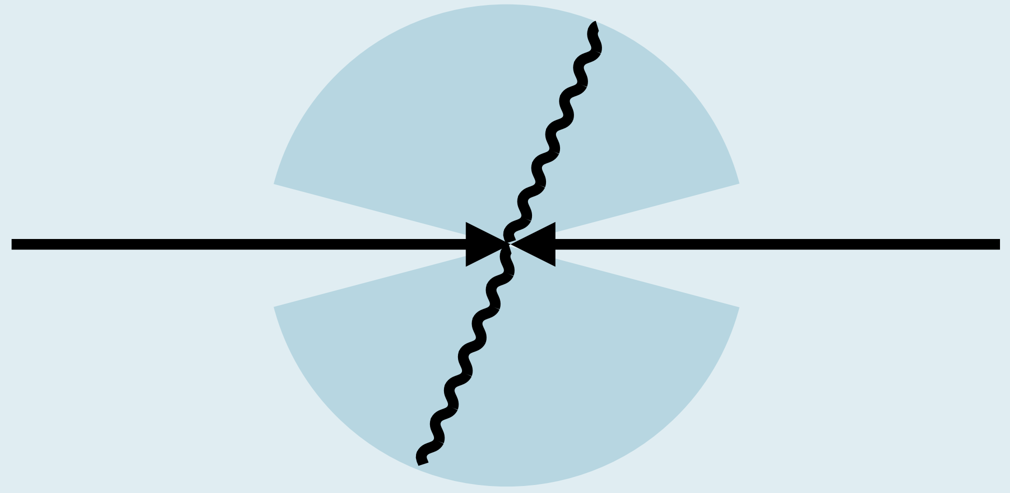
Luminosity is measured via two **benchmark processes**

$e^+e^- \to e^+e^-$



Bhabha (SABS)

$e^+e^- \to \gamma\gamma$



Di-photon

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$\frac{\delta L}{L}$	$< 10^{-4} \div 10^{-5}$
$=$	
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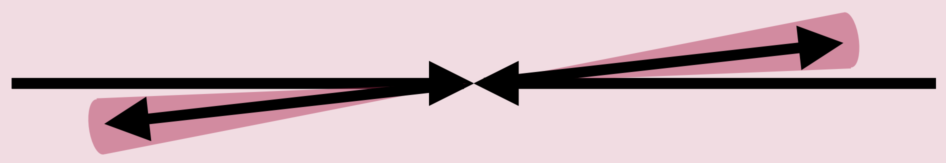

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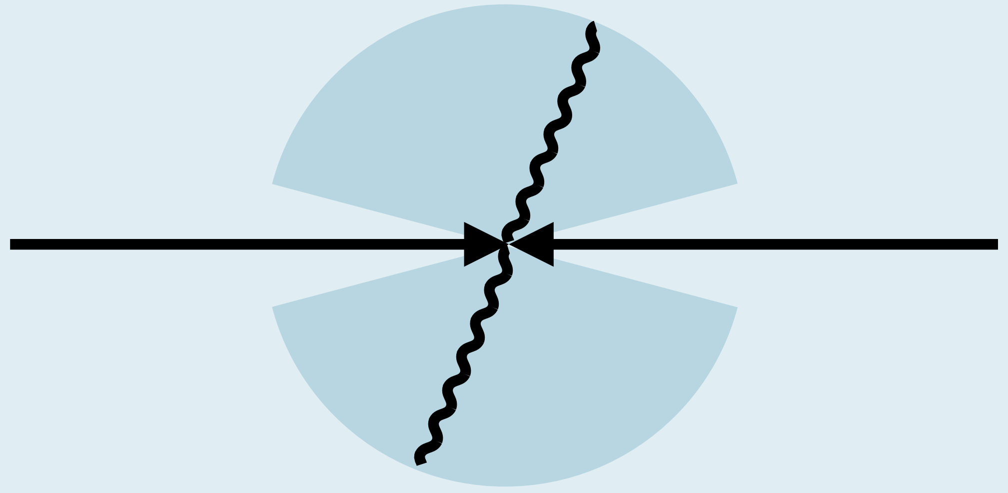
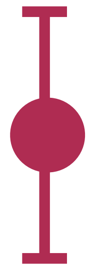


Di-photon

$\simeq 10^{-4}$



Current knowledge

Error	FCC precision
$\frac{\delta L}{L}$	$< 10^{-4} \div 10^{-5}$
=	
$\frac{\delta \epsilon_{\mathrm{exp}}}{\epsilon_{\mathrm{exp}}}$	$\simeq 10^{-5}$
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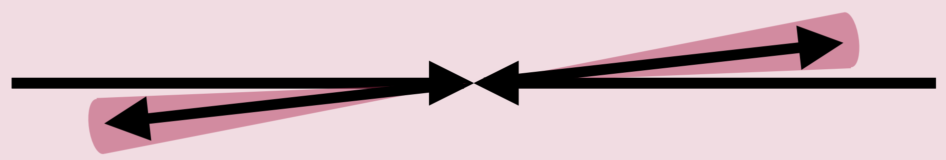

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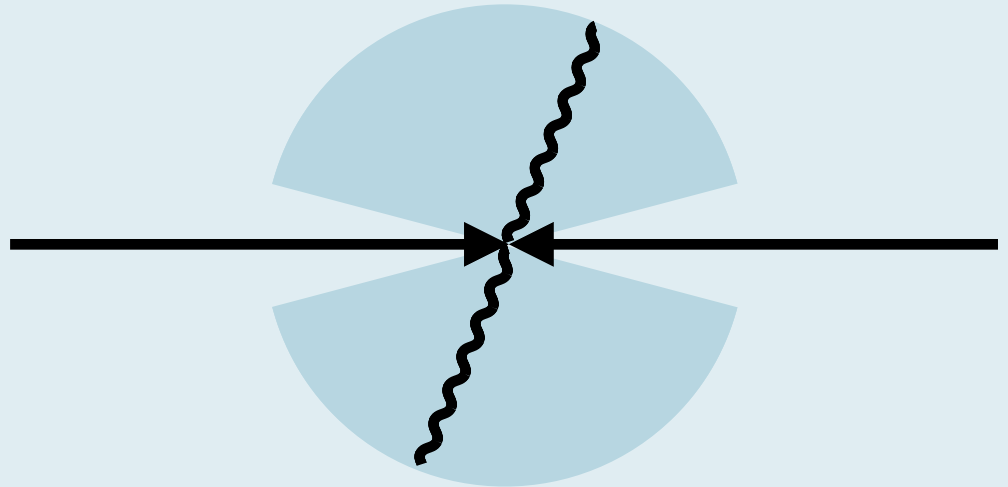
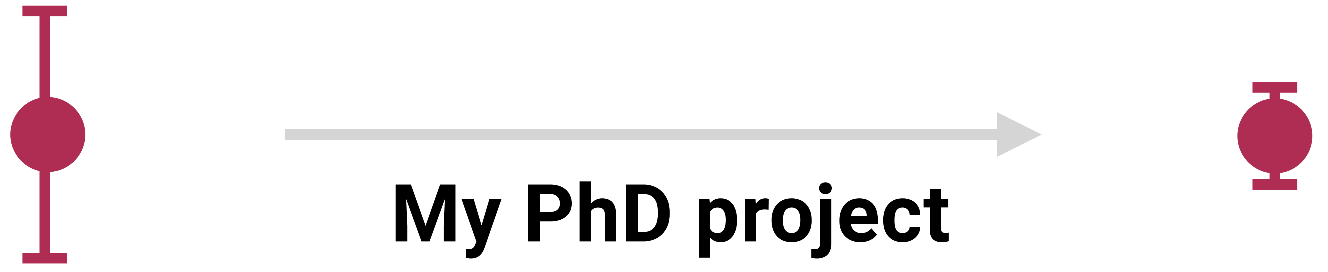


Di-photon

$\simeq 10^{-4}$ $\simeq 10^{-5}$



My PhD project

Current knowledge

Precision target

Error	**FCC precision**
$\frac{\delta L}{L}$	$< 10^{-4} \div 10^{-5}$
$\|\|$	
$\frac{\delta \epsilon_{\mathrm{exp}}}{\epsilon_{\mathrm{exp}}}$	$\simeq 10^{-5}$
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Improving theory in SABS

Standard Model

Monte Carlo generators for radiative corrections

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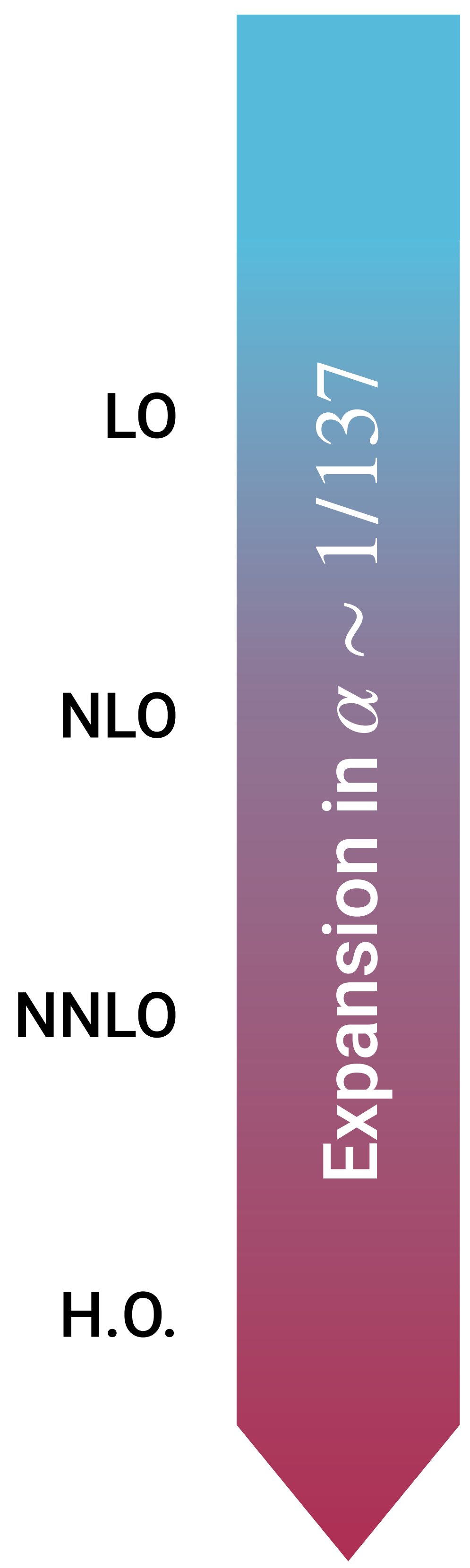

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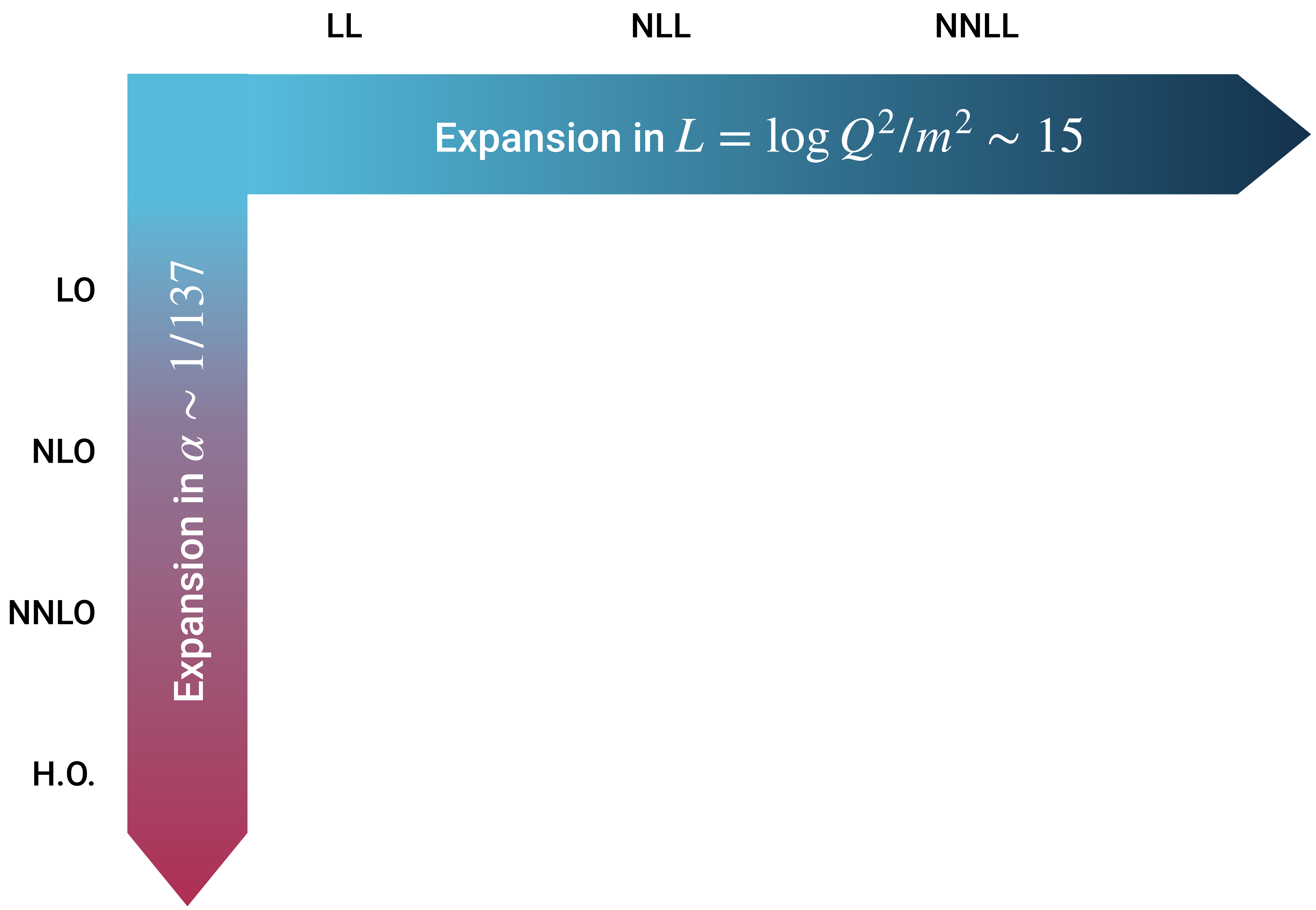

Improving theory in SABS

Standard Model

Monte Carlo generators for radiative corrections

Expansion in $L = \log Q^2/m^2 \sim 15$

Expansion in $\alpha \sim 1/137$

	LL	NLL	NNLL	
LO	α^0			
NLO	$\alpha\, L$	α		
NNLO	$\frac{1}{2}\alpha^2 L^2$	$\frac{1}{2}\alpha^2 L$	$\frac{1}{2}\alpha^2$	
H.O.	$\sum_{n=3}^{\infty} \frac{1}{n!}\alpha^n L^n$	$\sum_{n=3}^{\infty} \frac{1}{n!}\alpha^n L^{n-1}$	$\ldots$	$\ldots$

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BabaYaga@NLO

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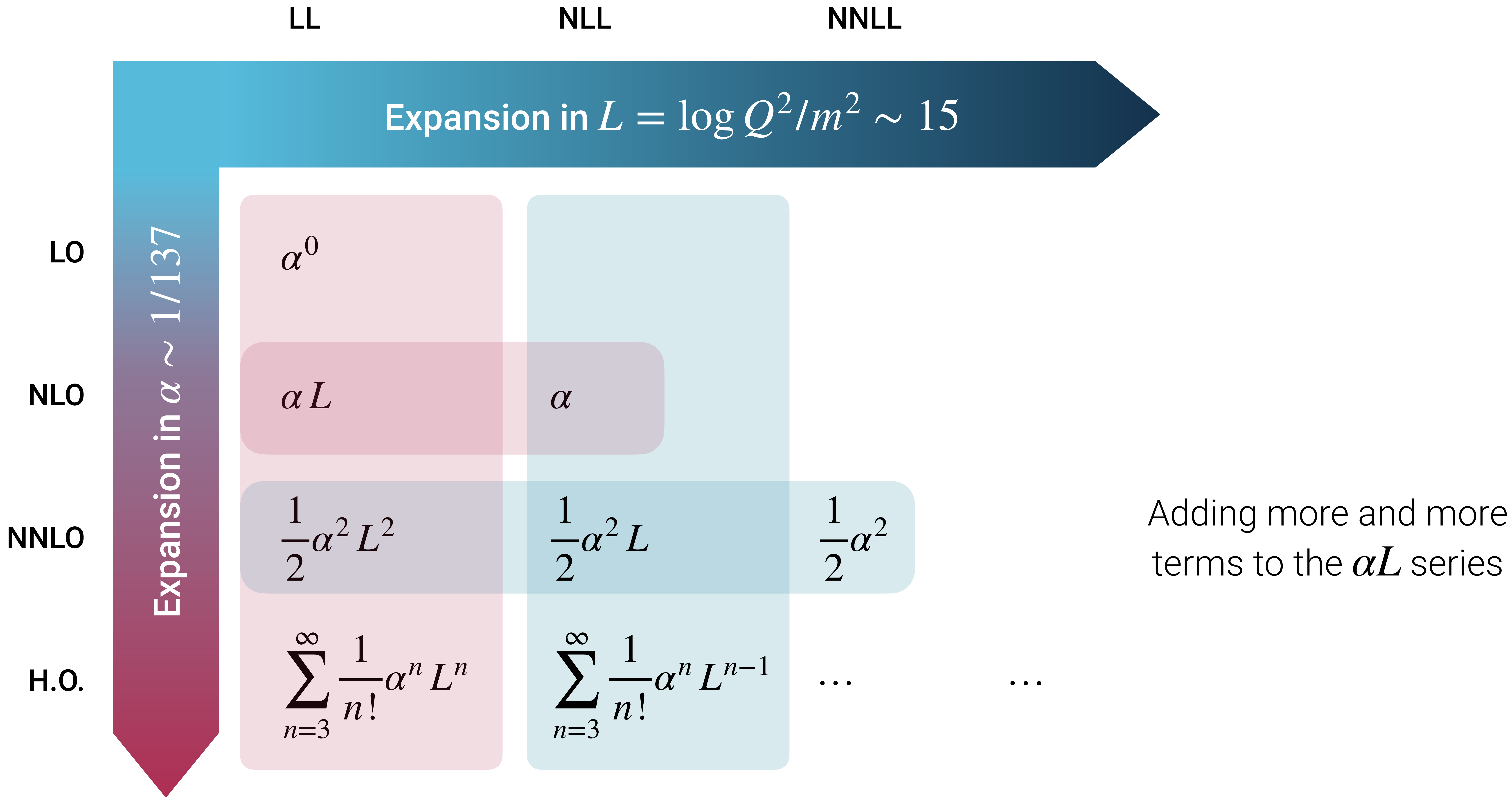

BabaYaga@NLO

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New Physics contamination to precision luminosity measurements at future e+e- colliders

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Phys. Rev. D. 112 (2025) 1

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Can unknown mediators contaminate the luminosity?

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

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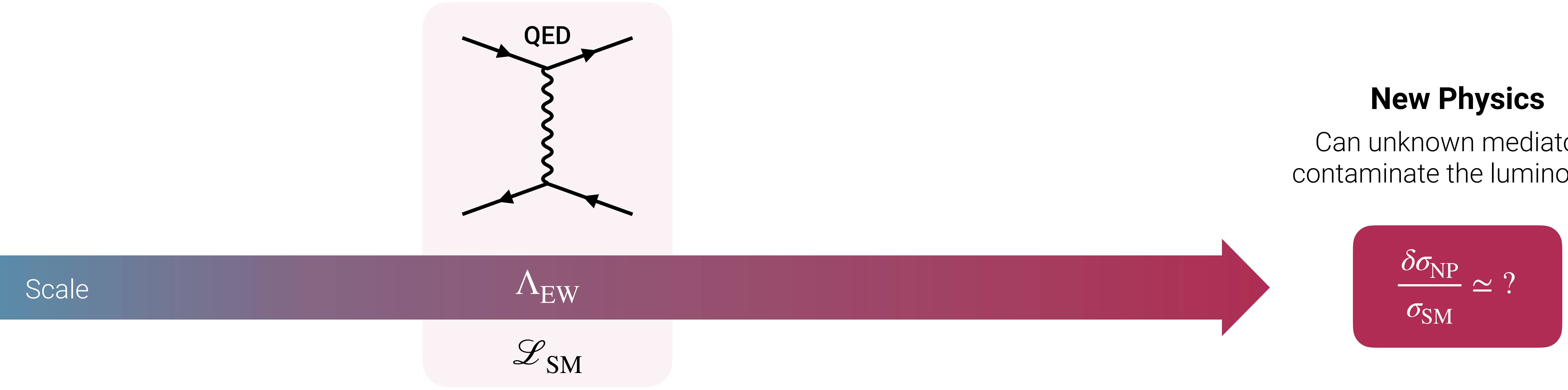

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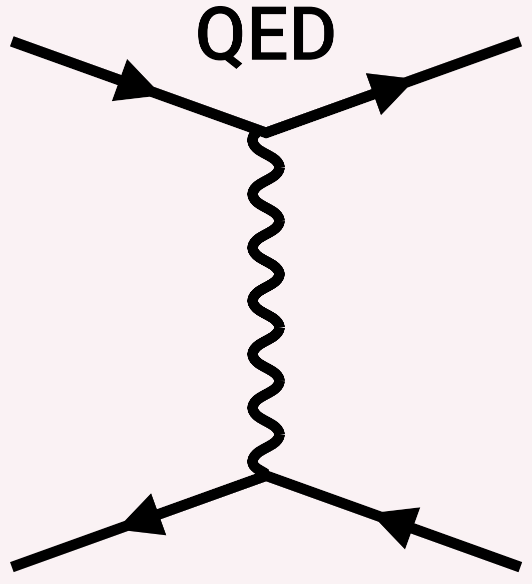
QED



Scale

Λ_{EW}

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

α, α_s, G_F

Valid up to
1TeV

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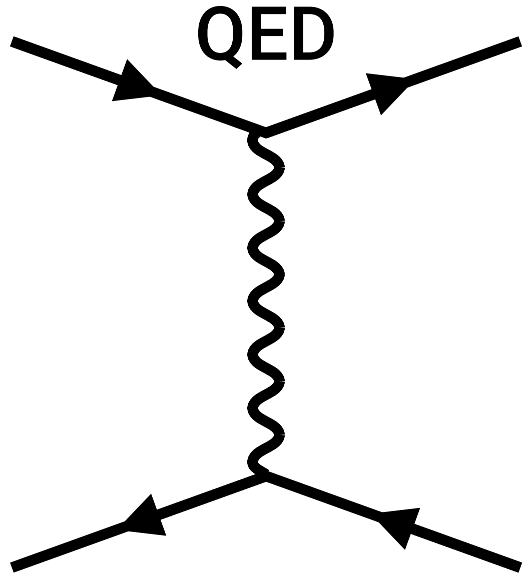

Scale Λ_{LNP} Λ_{EW}

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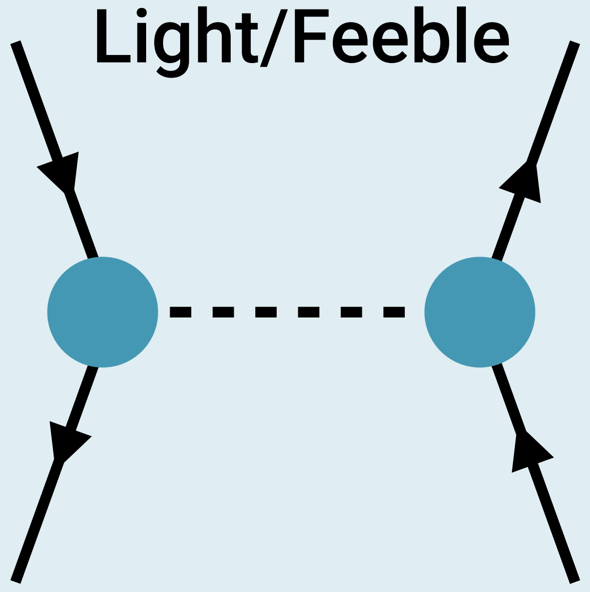
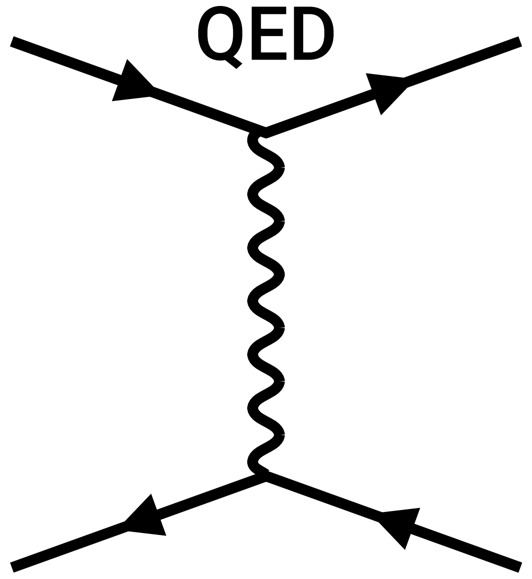
Light/Feeble



QED



Scale Λ_{LNP} Λ_{EW}

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

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

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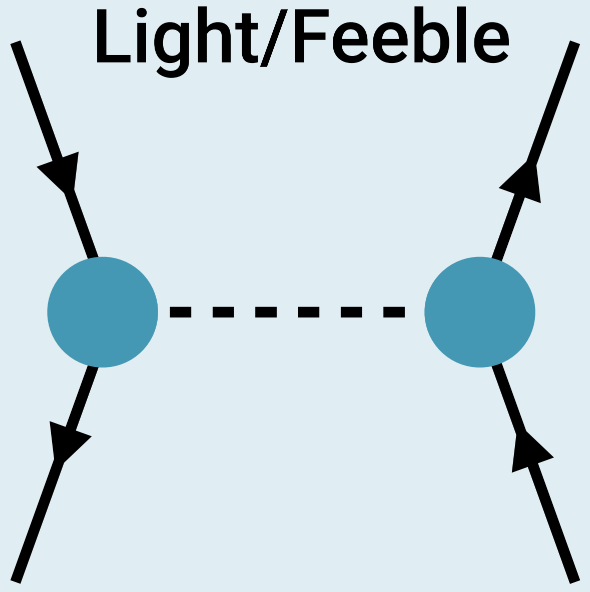

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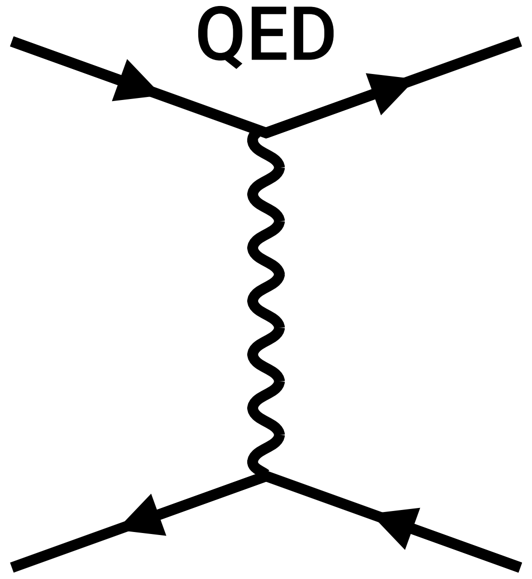

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Scale

Λ_{LNP} Λ_{EW}

$\mathscr{L}_{\mathrm{model}}$ $\mathscr{L}_{\mathrm{SM}}$

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

$$\alpha, \alpha_s, G_F$$

Valid up to $1\mathrm{TeV}$

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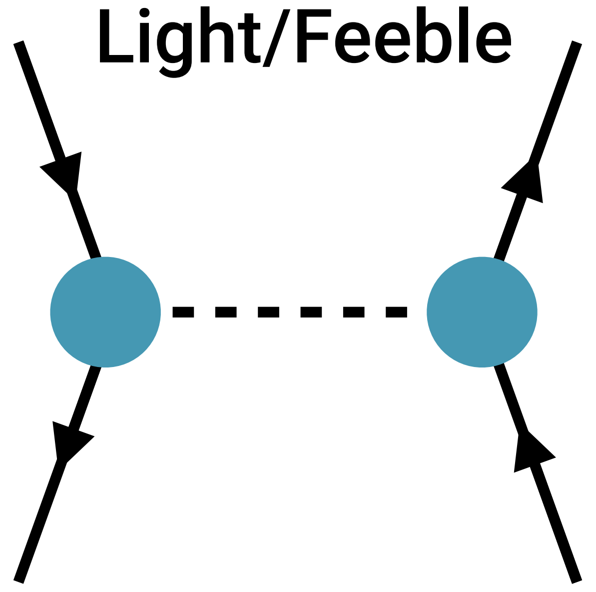

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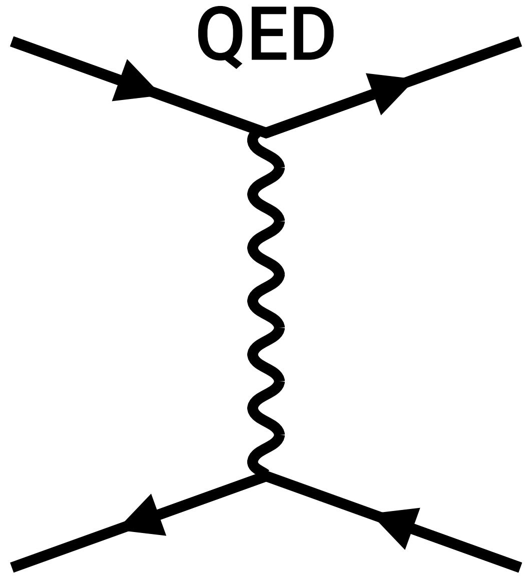

Scale Λ_{LNP} Λ_{EW} Λ_{HNP}

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

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

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1TeV

New Physics

Can unknown mediators contaminate the luminosity?

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

Improving theory in SABS

New Physics contamination to precision luminosity measurements at future e+e- colliders

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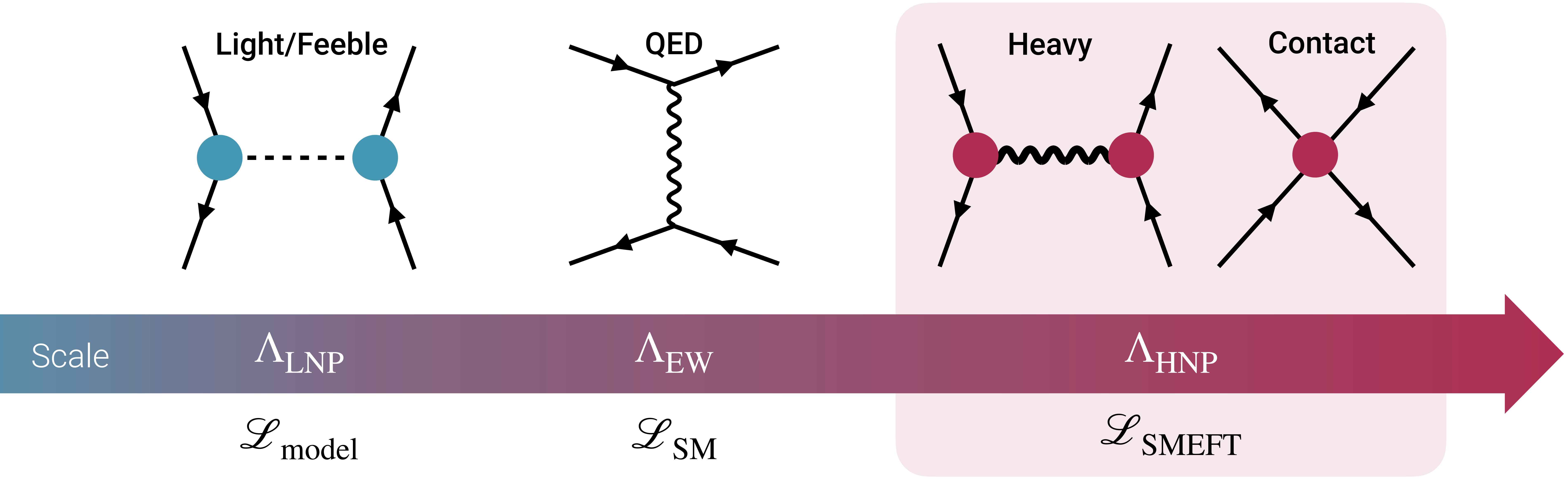
Phys. Rev. D. 112 (2025) 1



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

$$\alpha, \alpha_s, G_F$$

Valid up to
$1\,\mathrm{TeV}$

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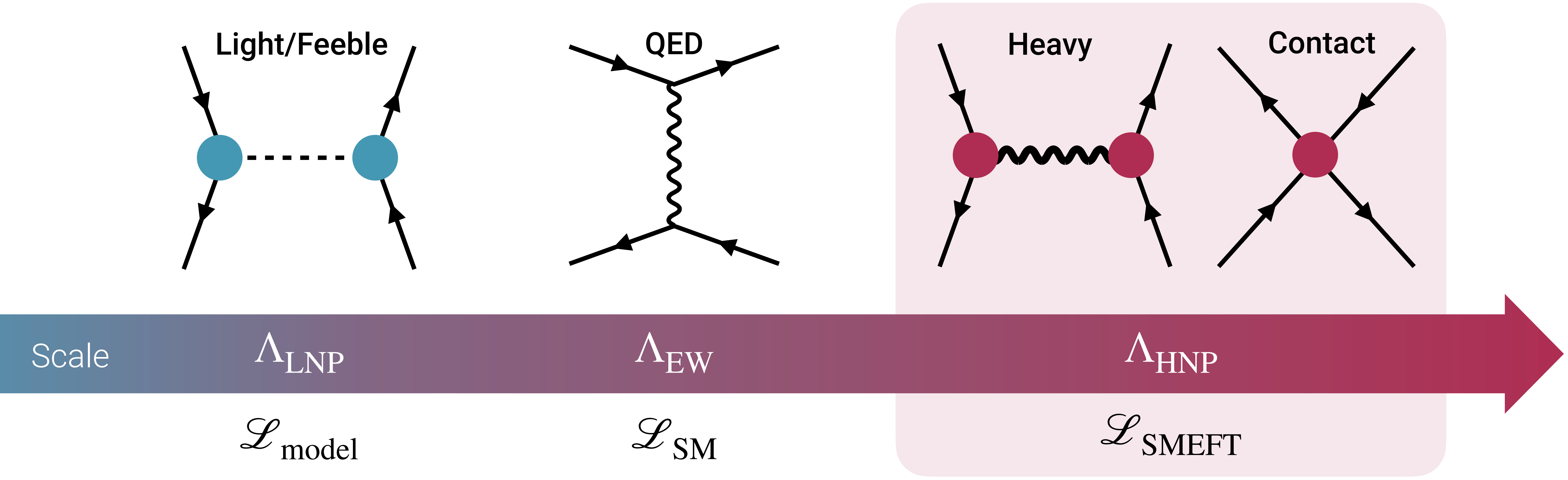

$$\leq \frac{g_i^2}{4\pi M_i^2} \leq$$

$$\alpha, \alpha_s, G_F$$

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

Valid up to
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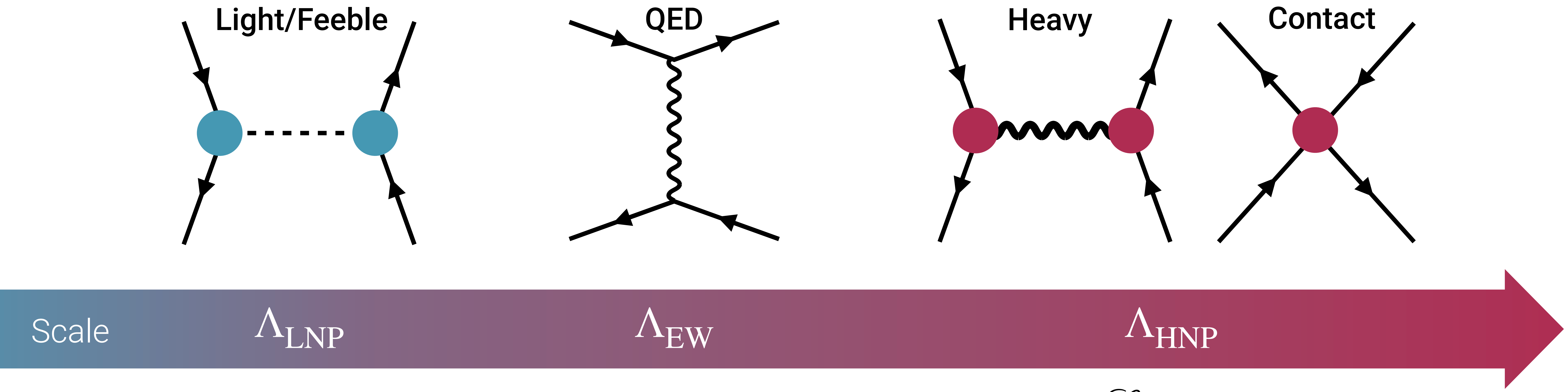

$\mathscr{L}_{\text{model}}$ $\mathscr{L}_{\text{SM}}$ $\mathscr{L}_{\text{SMEFT}}$

$$\leq \frac{g_i^2}{4\pi M_i^2} \leq \qquad \alpha, \alpha_s, G_F \qquad \leq \frac{C_i}{\Lambda_{\text{NP}}^2} \leq$$

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Specific model with assigned **spin** and **parity**

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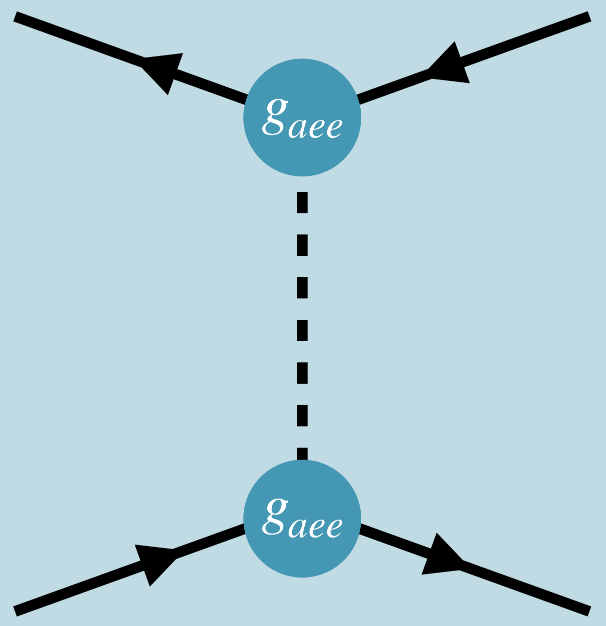
(Pseudo)scalar ALPs

$g_{aee}\,(\bar{e}\, i\gamma_5 e)a$



(g_{aee}, m_a)

$\simeq (3 \times 10^{-3}, 1\ \mathrm{GeV})$

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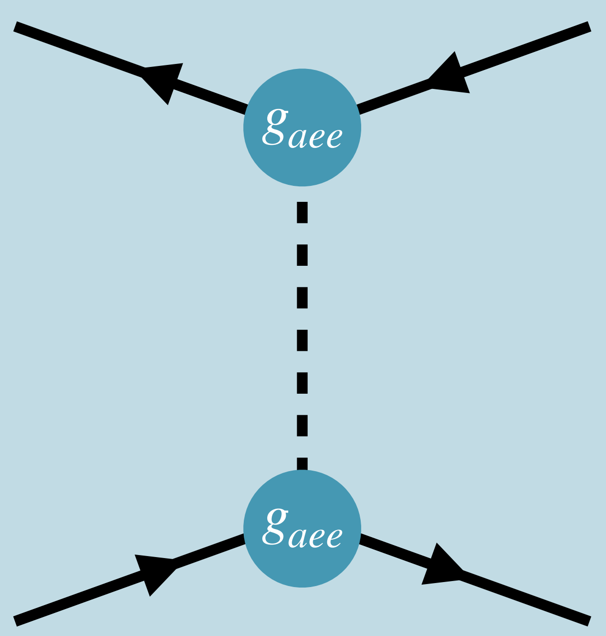
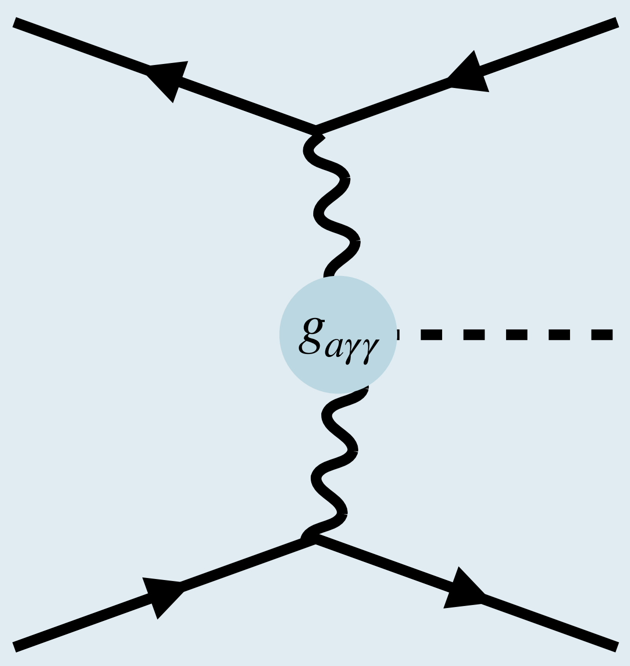


$$(g_{aee}, m_a)$$

$$\simeq (3\times 10^{-3}, 1\,\mathrm{GeV})$$

ALP mixing with photons

$$\frac{1}{4} g_{a\gamma\gamma}(F_{\mu\nu}\tilde{F}^{\mu\nu})a$$



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

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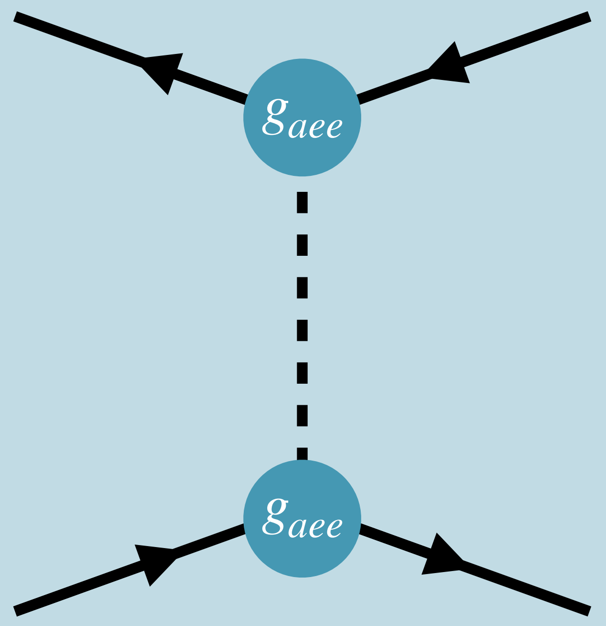

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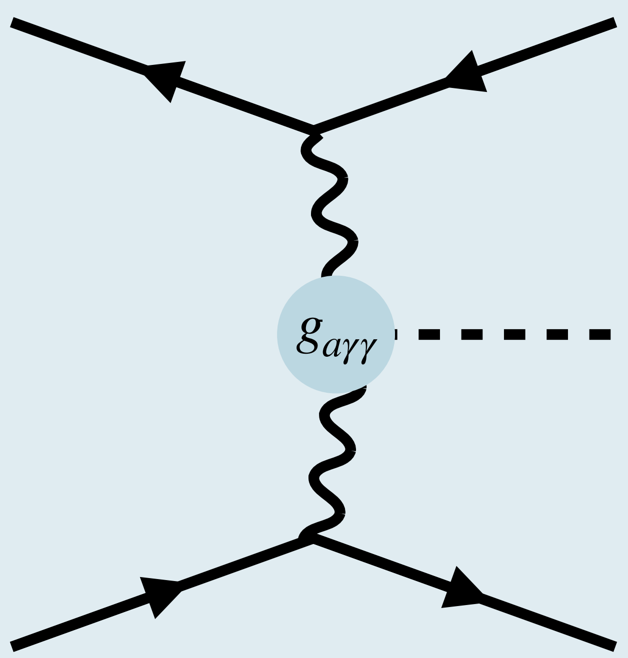
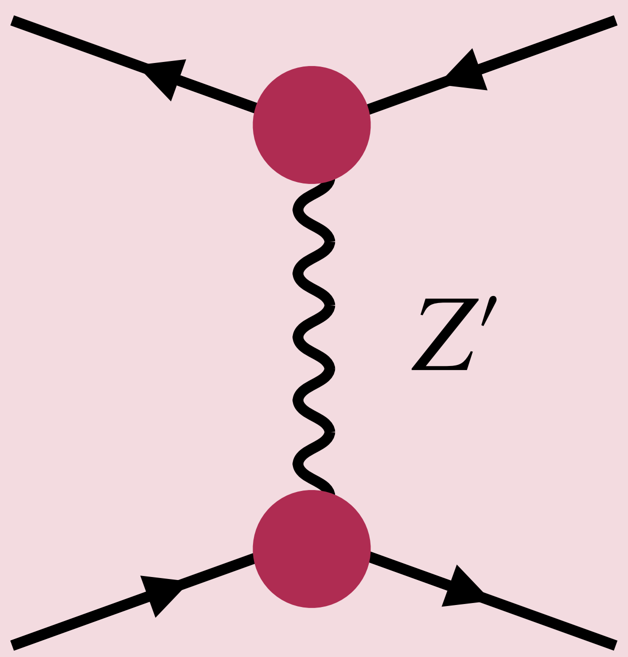


$$g_{a\gamma\gamma} \simeq 2 \times 10^{-4}\,\mathrm{GeV}^{-1}$$

Dark Vectors

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



$$(g'_V, M_V)$$
$$\simeq (3 \times 10^{-4}, 1\,\mathrm{GeV})$$

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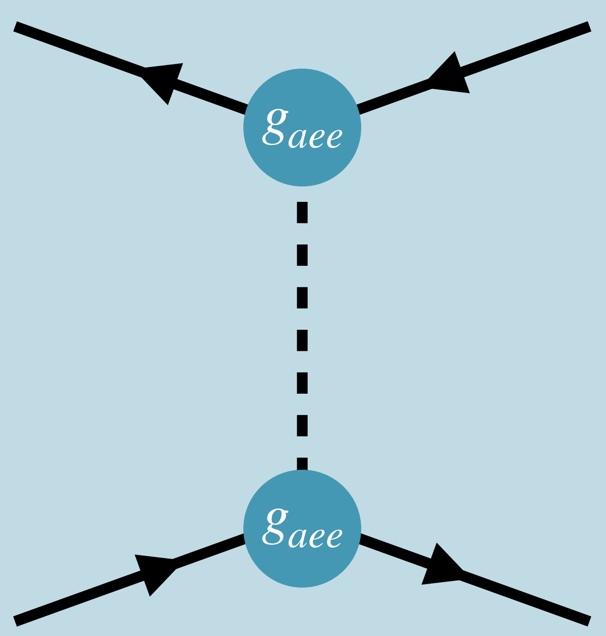

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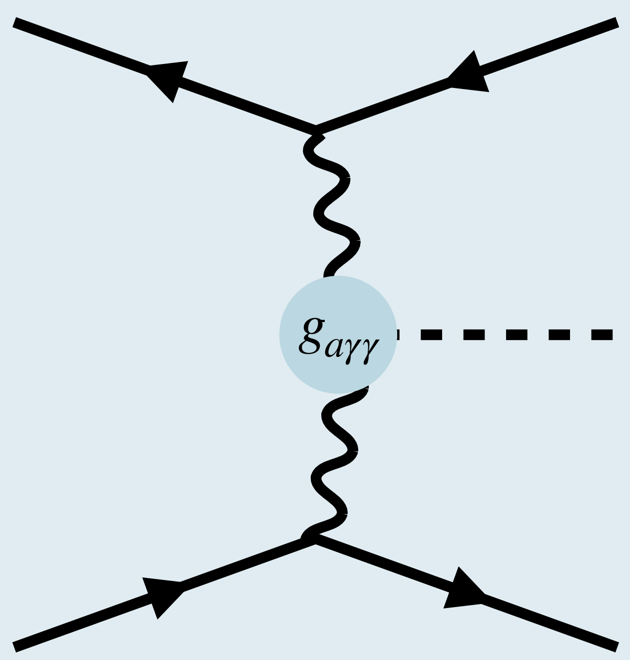

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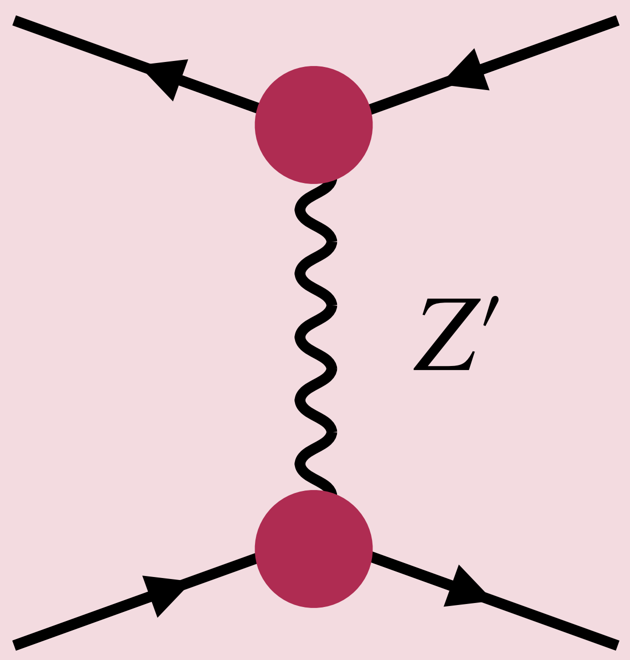
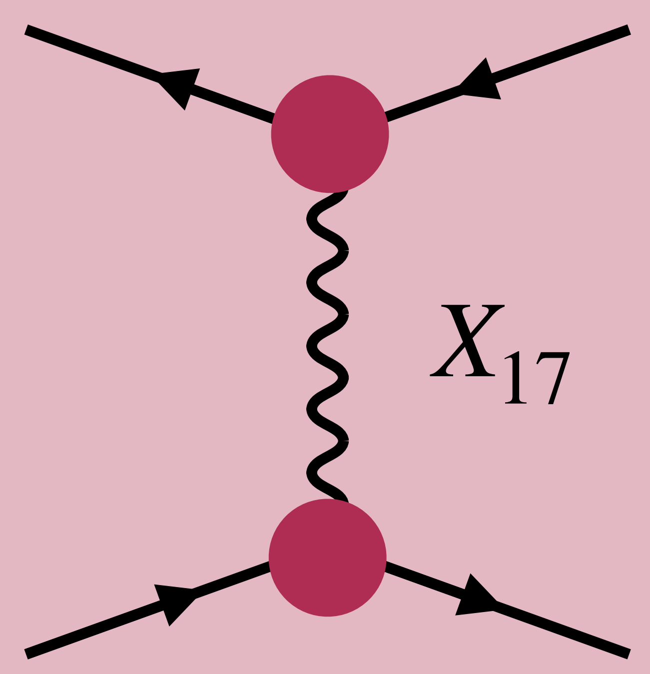


$$(g'_V, M_V)$$
$$\simeq (3\times 10^{-4}, 1\,\mathrm{GeV})$$

X17

$$g'_V\,(\bar{e}\,\gamma^\mu\, e)\, V_\mu$$



$$(g'_V, M_{X_{17}})$$
$$(6\times 10^{-4}, 17\,\mathrm{MeV})$$

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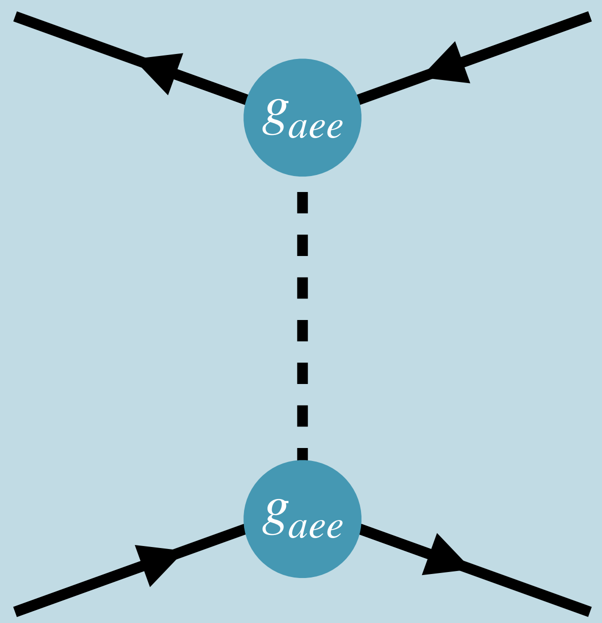

$$(g_{aee}, m_a)$$

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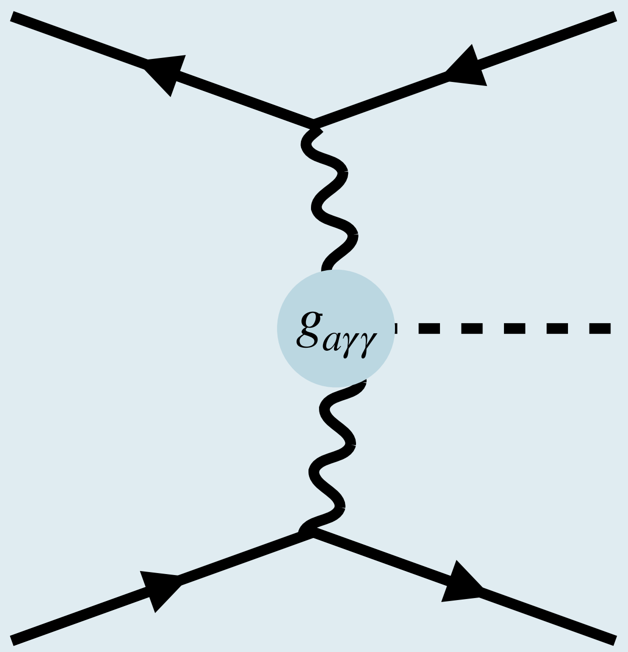

$$g_{a\gamma\gamma} \simeq 2 \times 10^{-4}\,\mathrm{GeV}^{-1}$$

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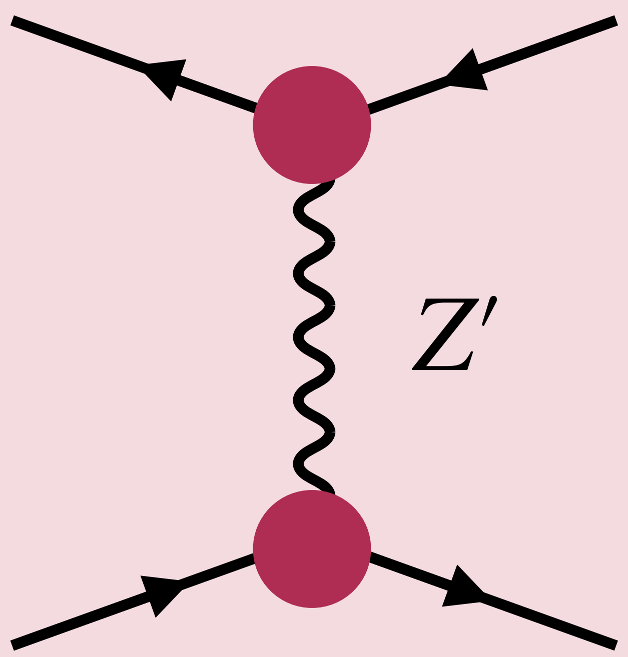

$$(g'_V, M_V)$$

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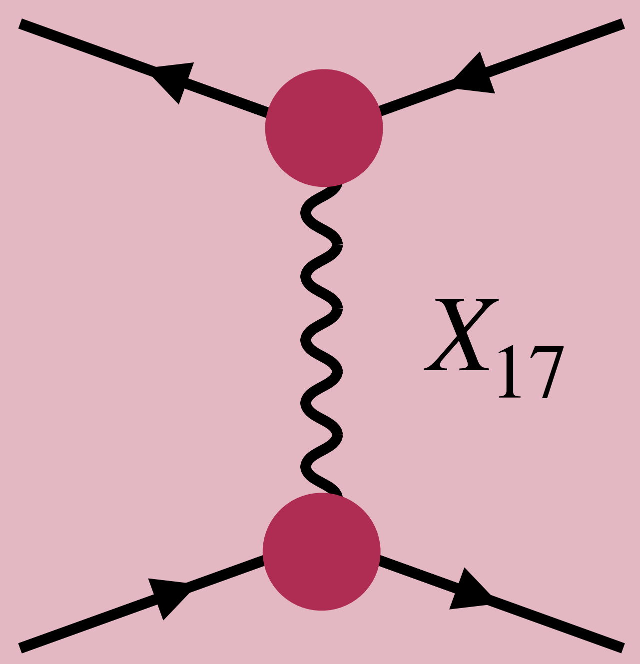

$$(g'_V, M_{X_{17}})$$

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The LNP contribution is **negligible** at 10^{-5} level

Heavy New Physics

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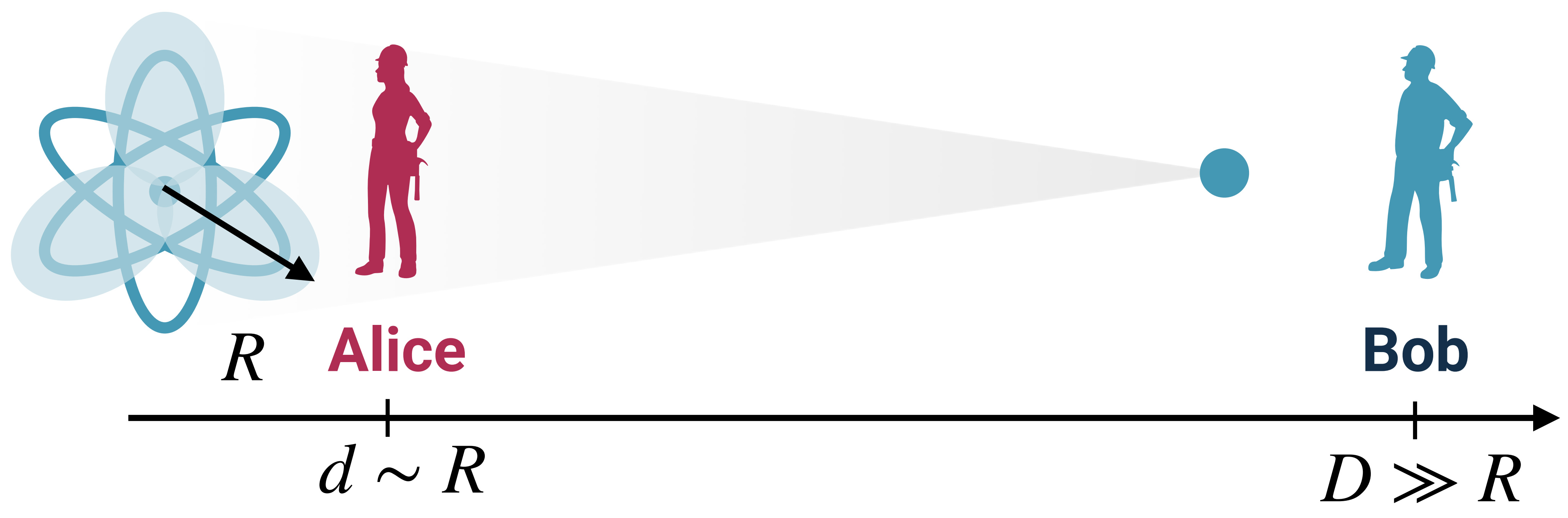

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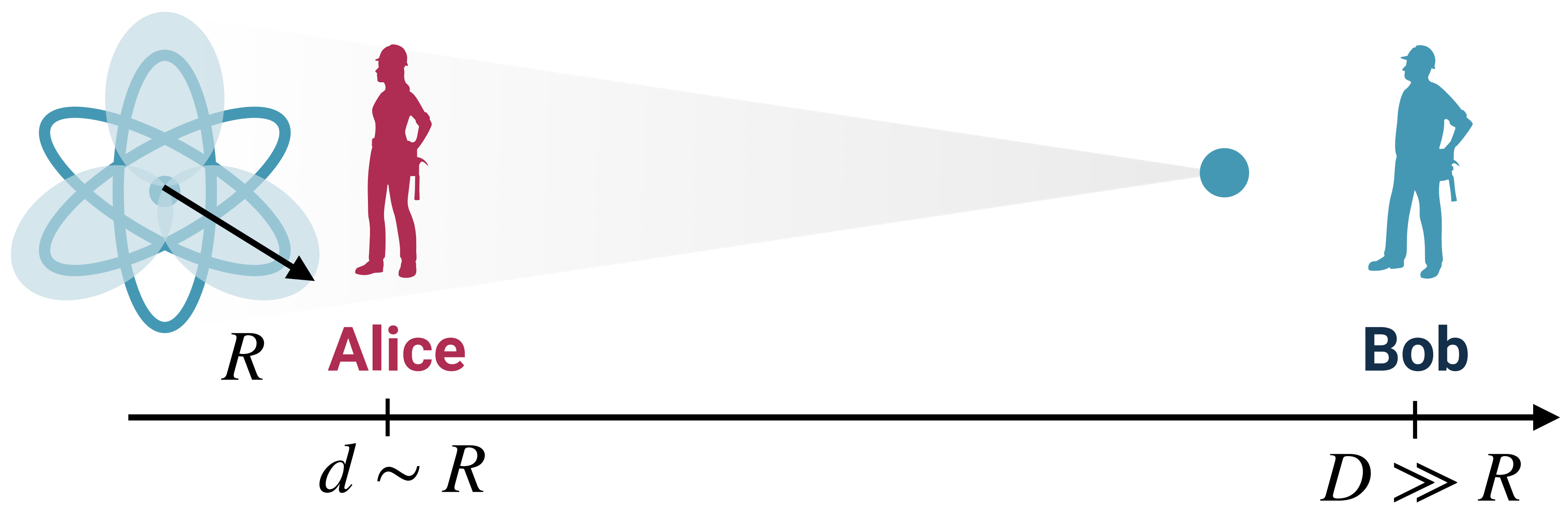

Physics at **short-distance/high-energy** is encoded in the coefficients of the expansion

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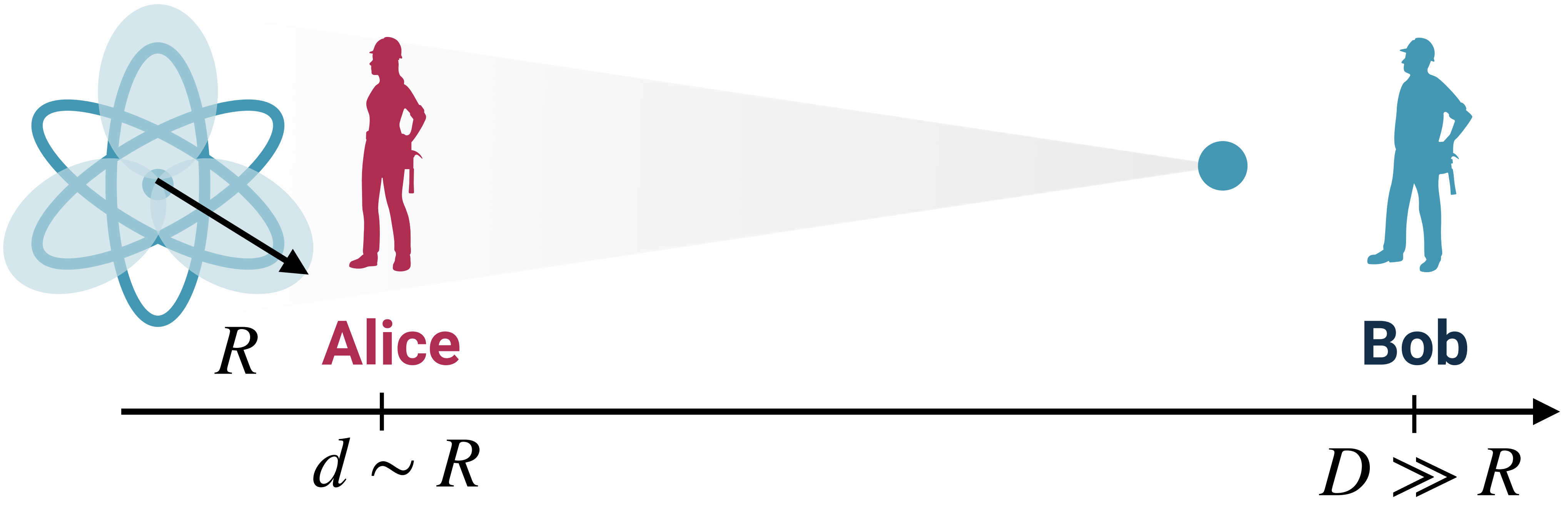

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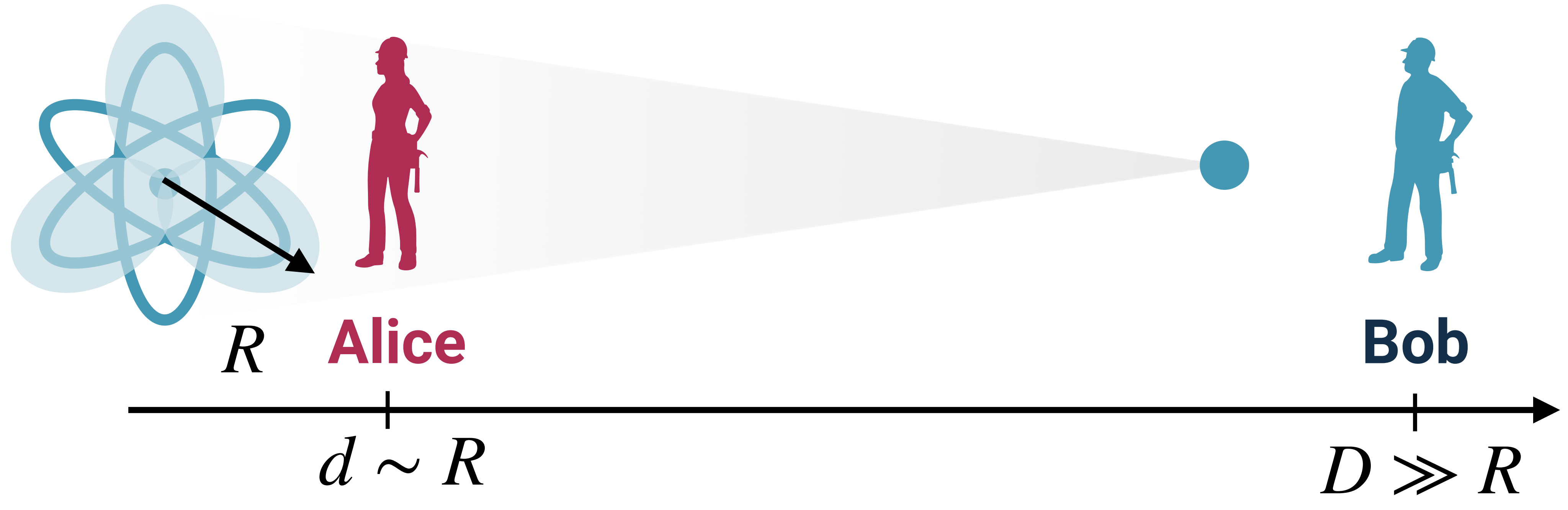

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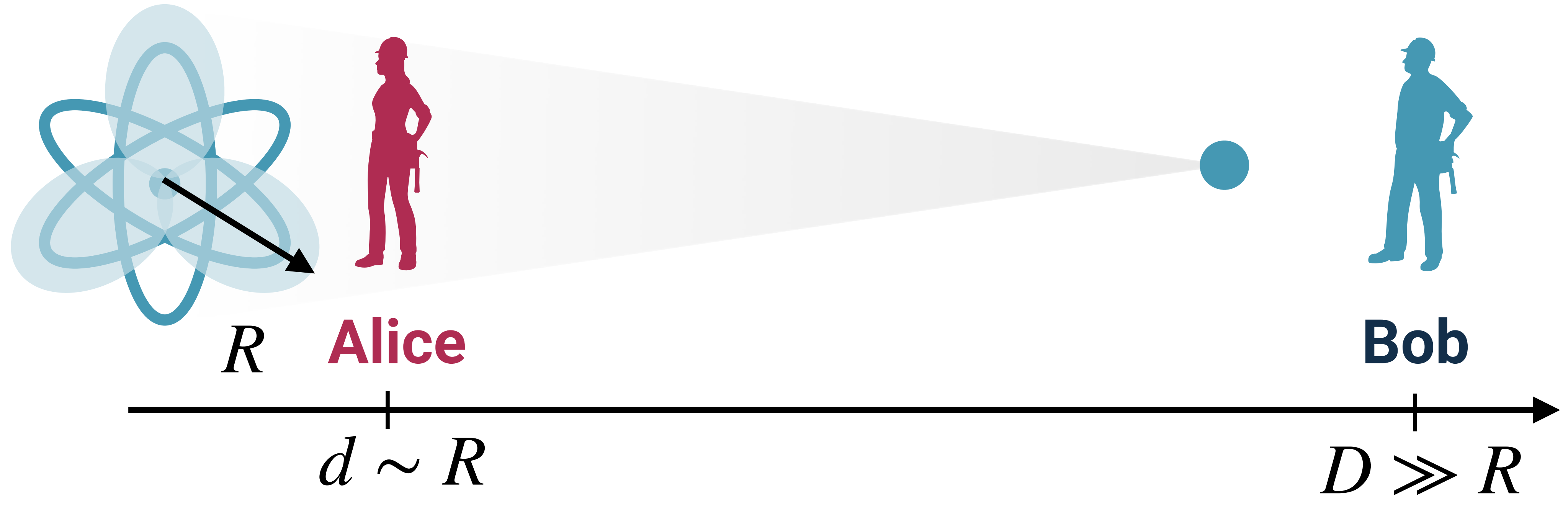

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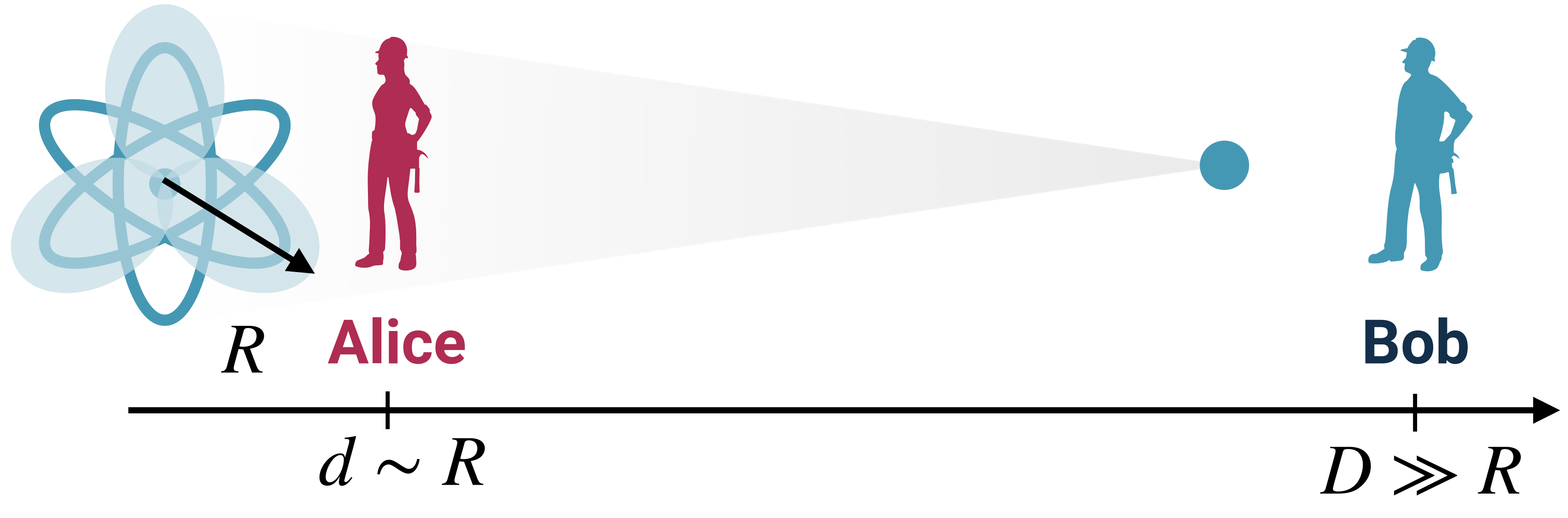

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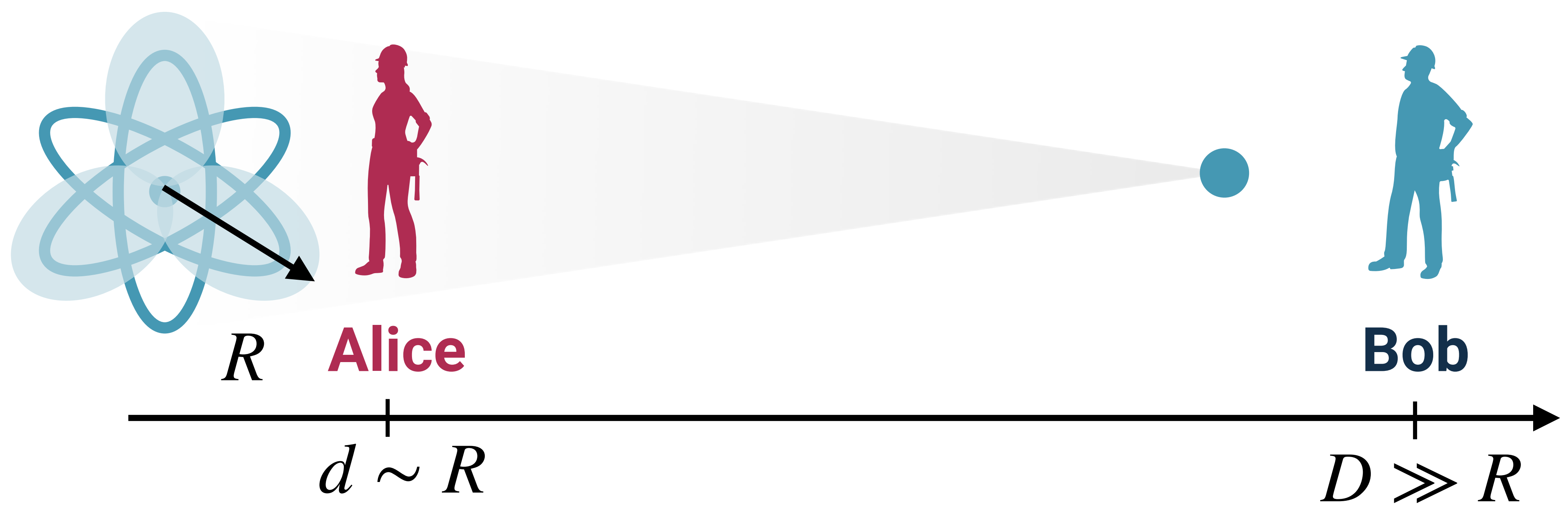

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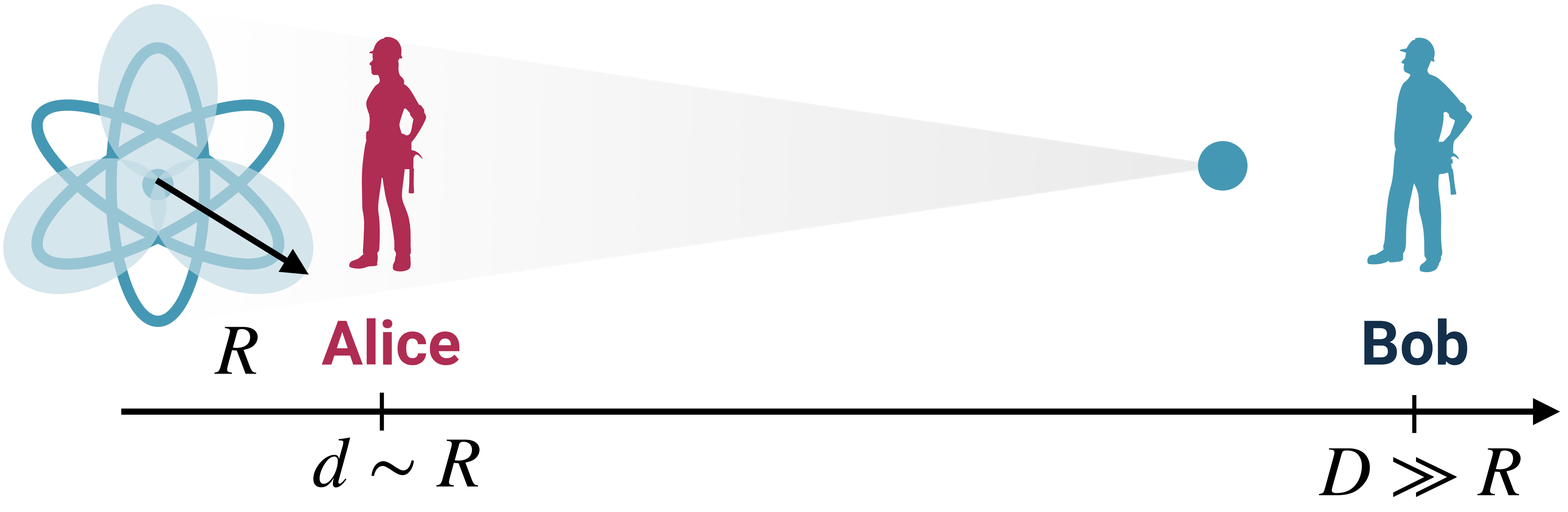

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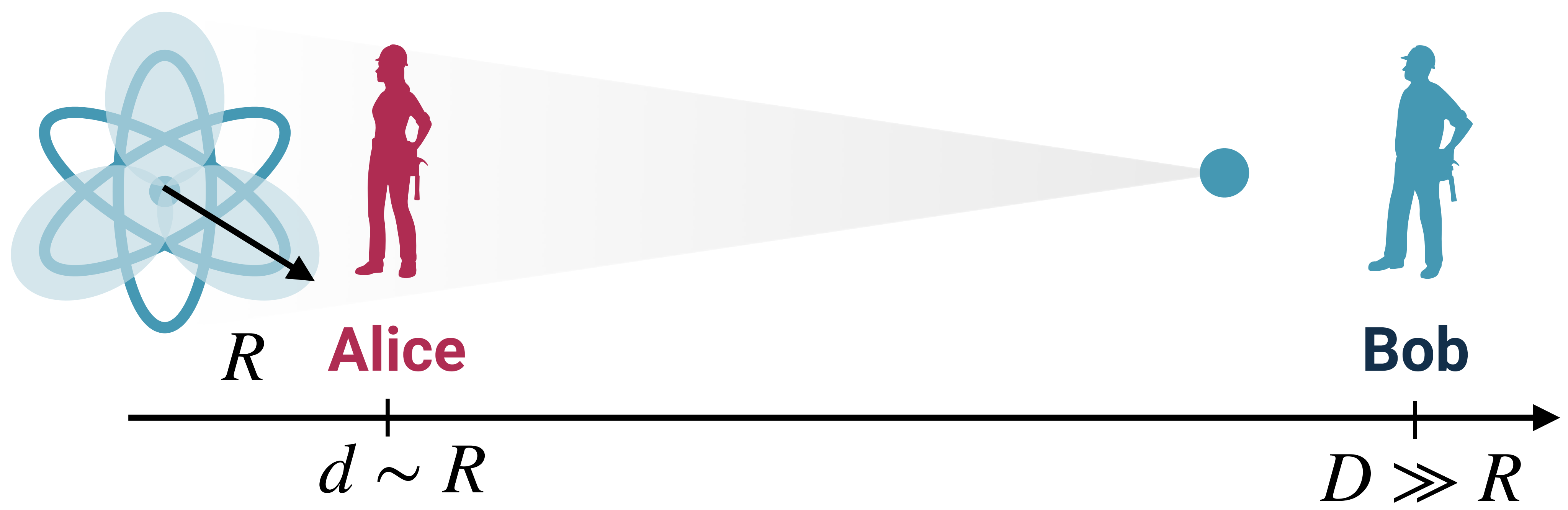

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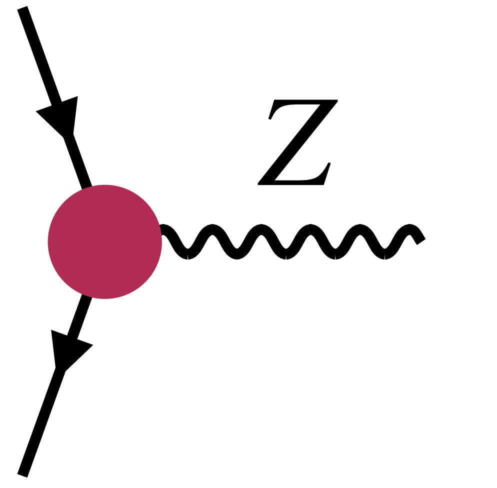

$\delta g_L^{Ze}, \delta g_R^{Ze}$

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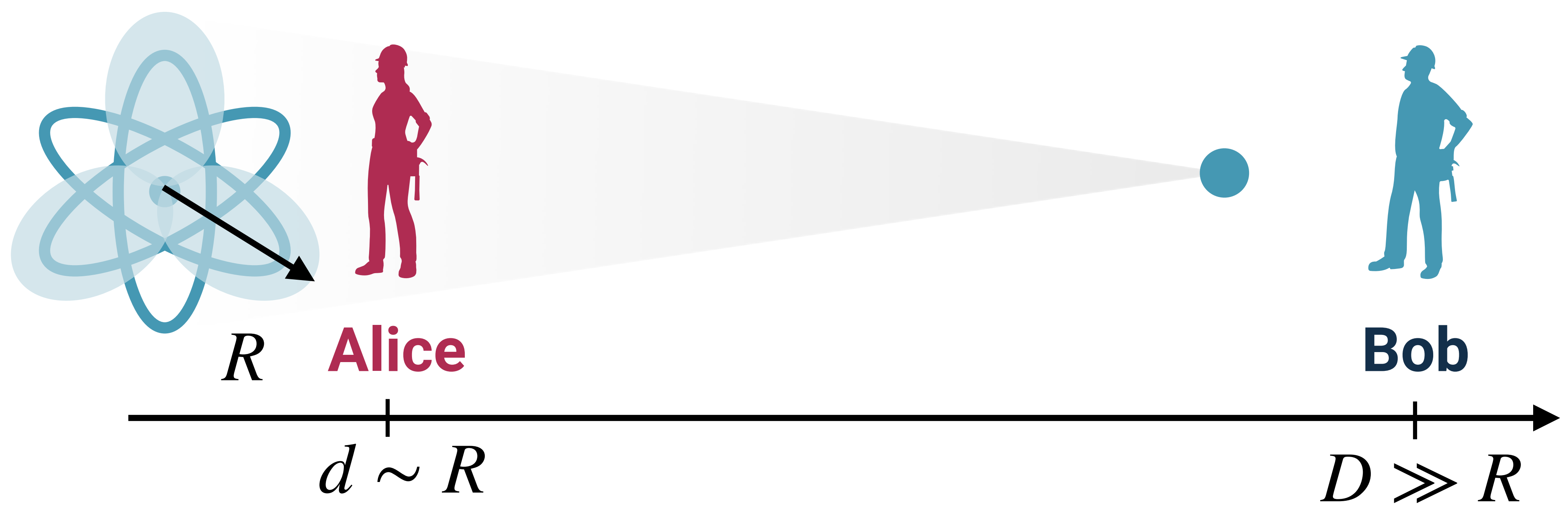

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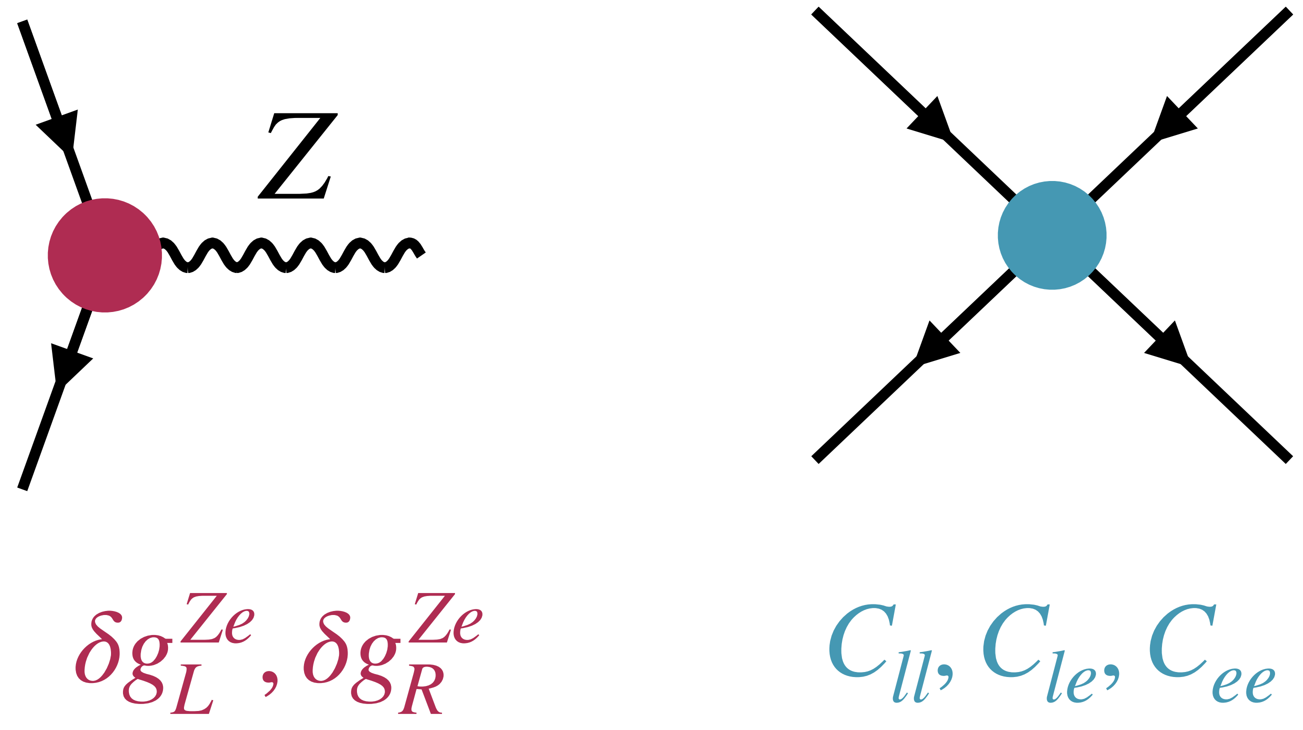

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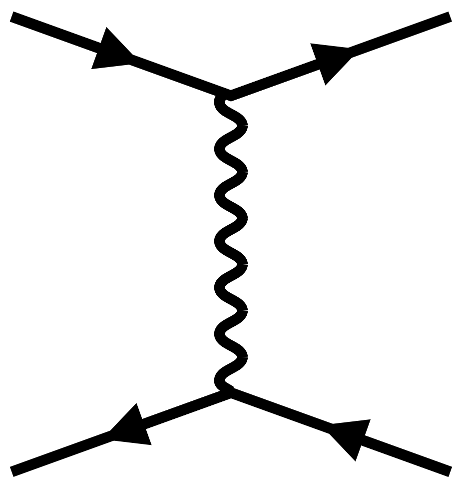

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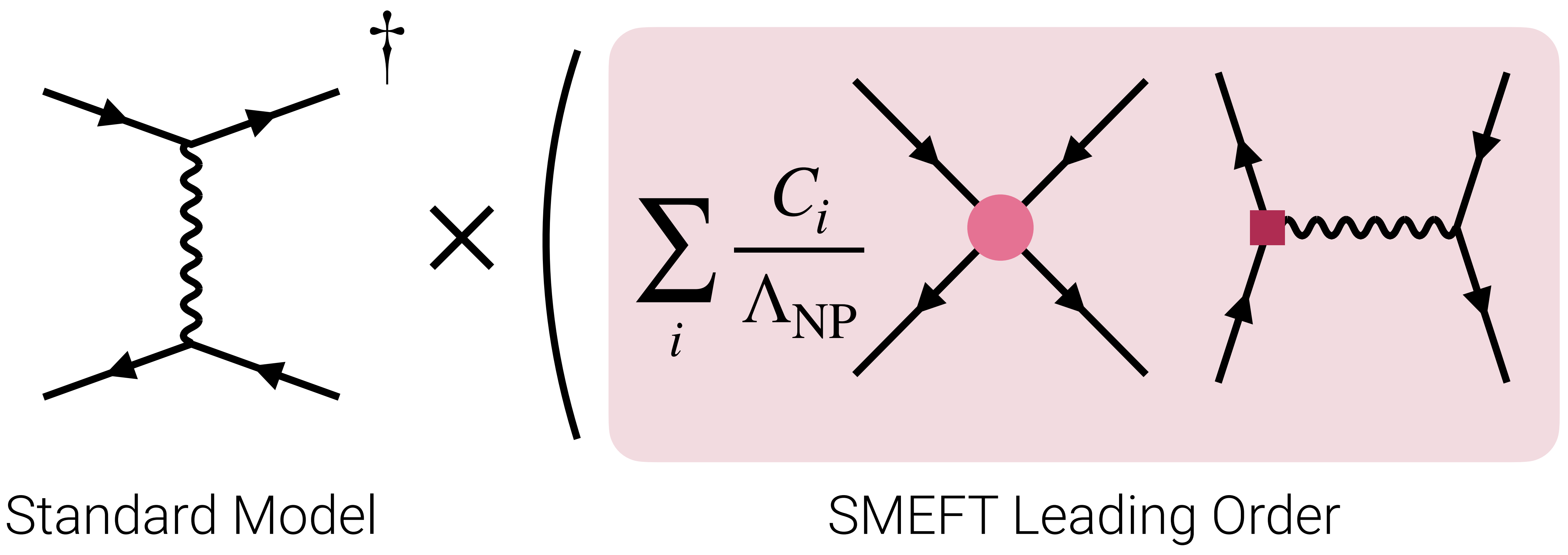

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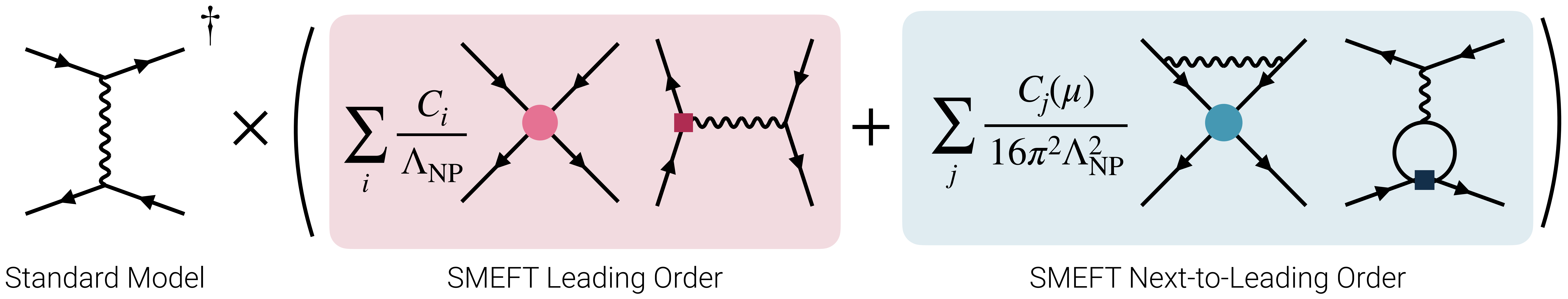

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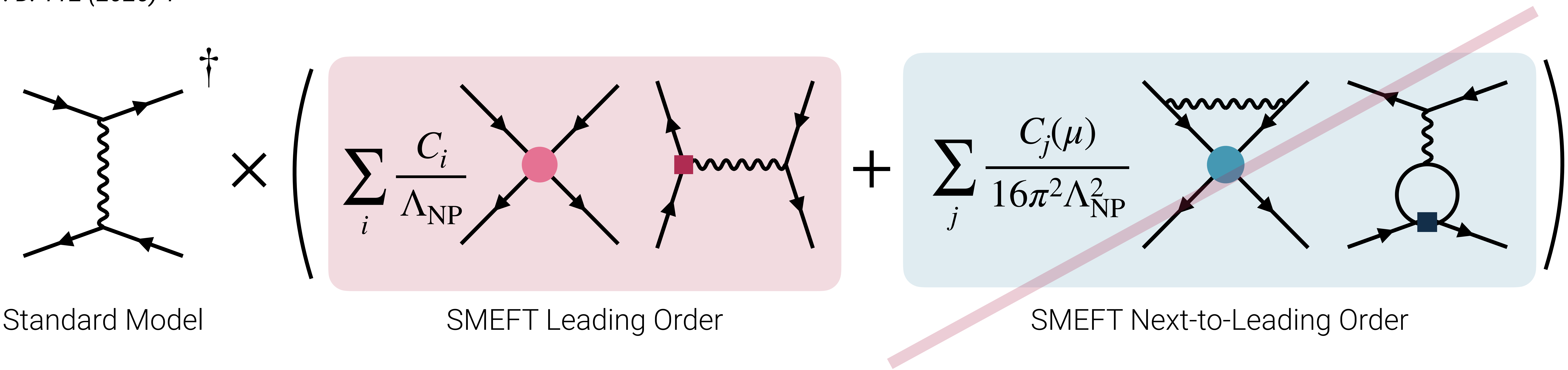

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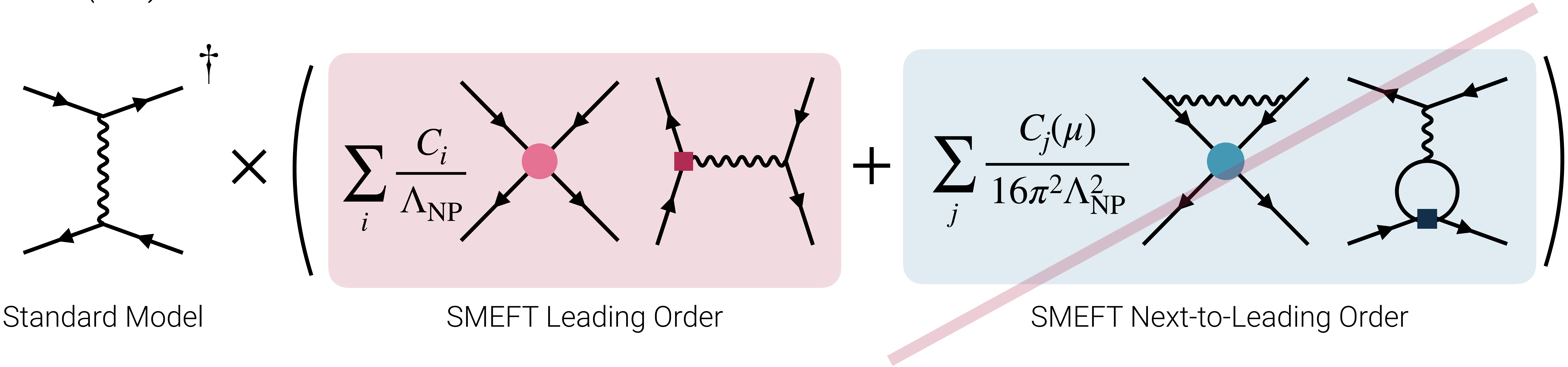

WCs are obtained by **global fits**
from LEP data

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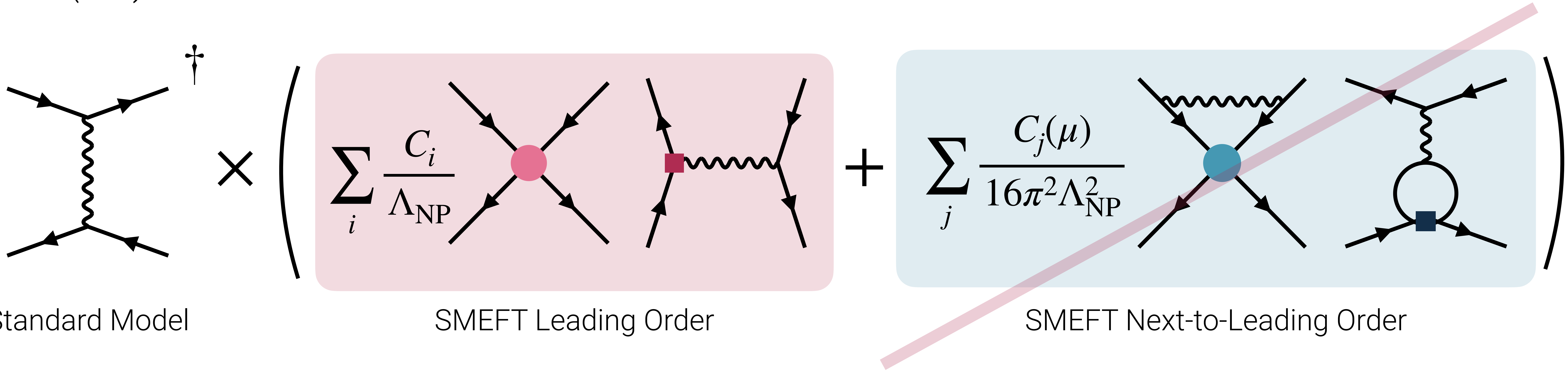

Exp	$[\theta_{min}, \theta_{max}]$	$\sqrt{s}$[GeV]	$(\delta \pm \Delta\delta)_{SMEFT}$	$\Delta L/L$
FCC	[3.7°, 4.9°]	91	$(-4.2 \pm 1.7) \times 10^{-5}$	$<10^{-4}$
		160	$(-1.3 \pm 0.5) \times 10^{-4}$	10^{-4}
		240	$(-2.9 \pm 1.2) \times 10^{-4}$	
		365	$(-6.7 \pm 2.7) \times 10^{-4}$	
ILC	[1.7°, 4.4]°	250	$(-1.2 \pm 0.5) \times 10^{-4}$	$<10^{-3}$
		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	$(-4.2 \pm 1.7) \times 10^{-2}$	

WCs are obtained by **global fits** from LEP data

Heavy New Physics

New Physics contamination to precision luminosity measurements at future e+e- colliders
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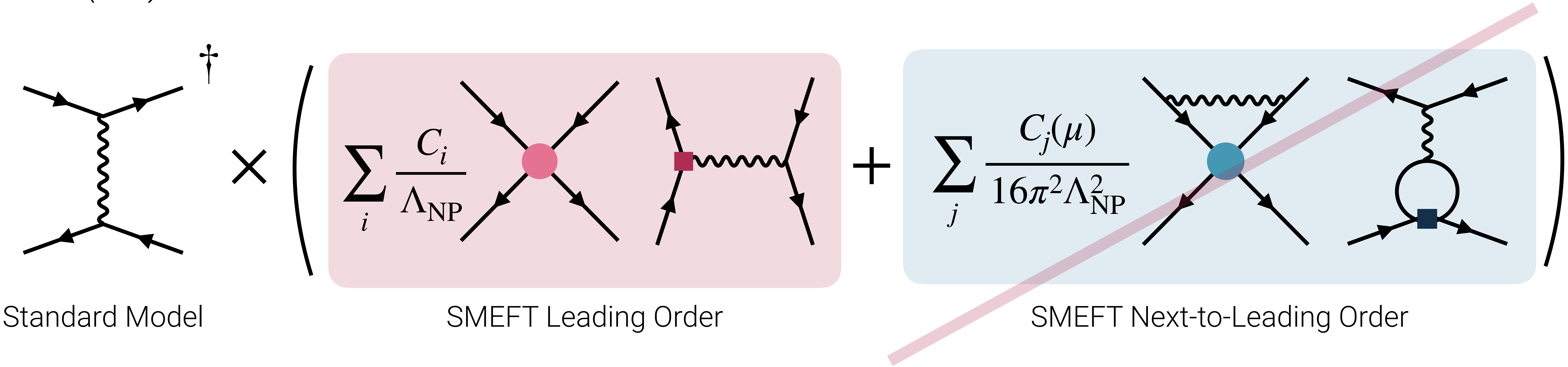
Phys. Rev. D. 112 (2025) 1



Exp	$[\theta_{min}, \theta_{max}]$	$\sqrt{s}$[GeV]	$(\delta \pm \Delta\delta)_{SMEFT}$	$\Delta L/L$
FCC	$[3.7°, 4.9°]$	91	$(-4.2 \pm 1.7) \times 10^{-5}$	$<10^{-4}$
		160	$(-1.3 \pm 0.5) \times 10^{-4}$	10^{-4}
		240	$(-2.9 \pm 1.2) \times 10^{-4}$	
		365	$(-6.7 \pm 2.7) \times 10^{-4}$	
ILC	$[1.7°, 4.4]°$	250	$(-1.2 \pm 0.5) \times 10^{-4}$	$<10^{-3}$
		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	$(-4.2 \pm 1.7) \times 10^{-2}$	

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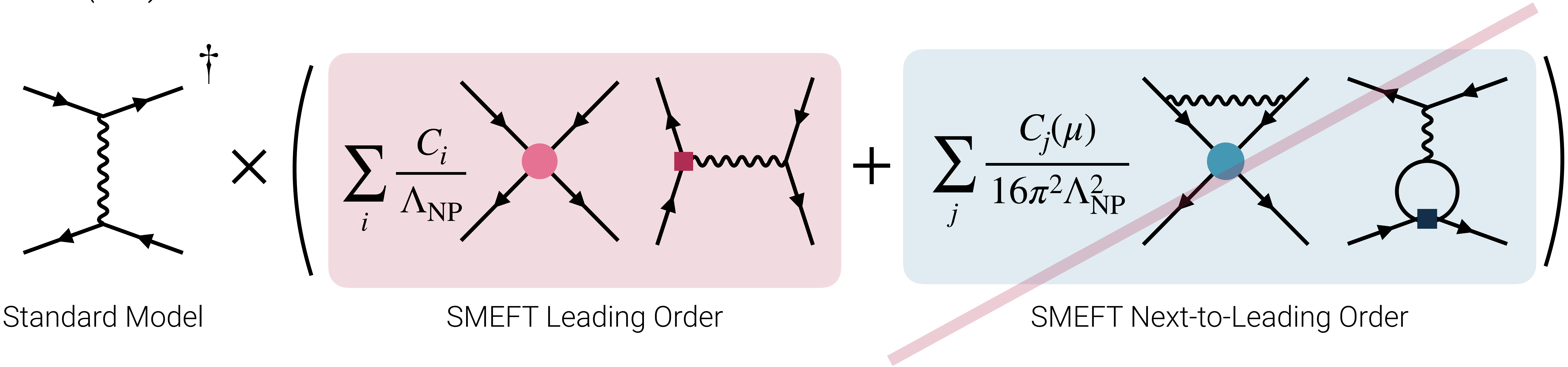

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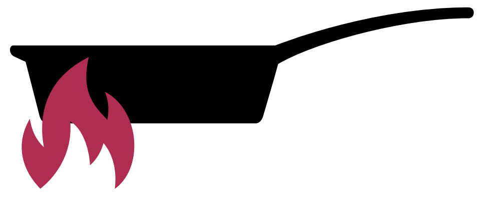
Not negligible!



FCs are cooked?

WCs are obtained by **global fits** from LEP data

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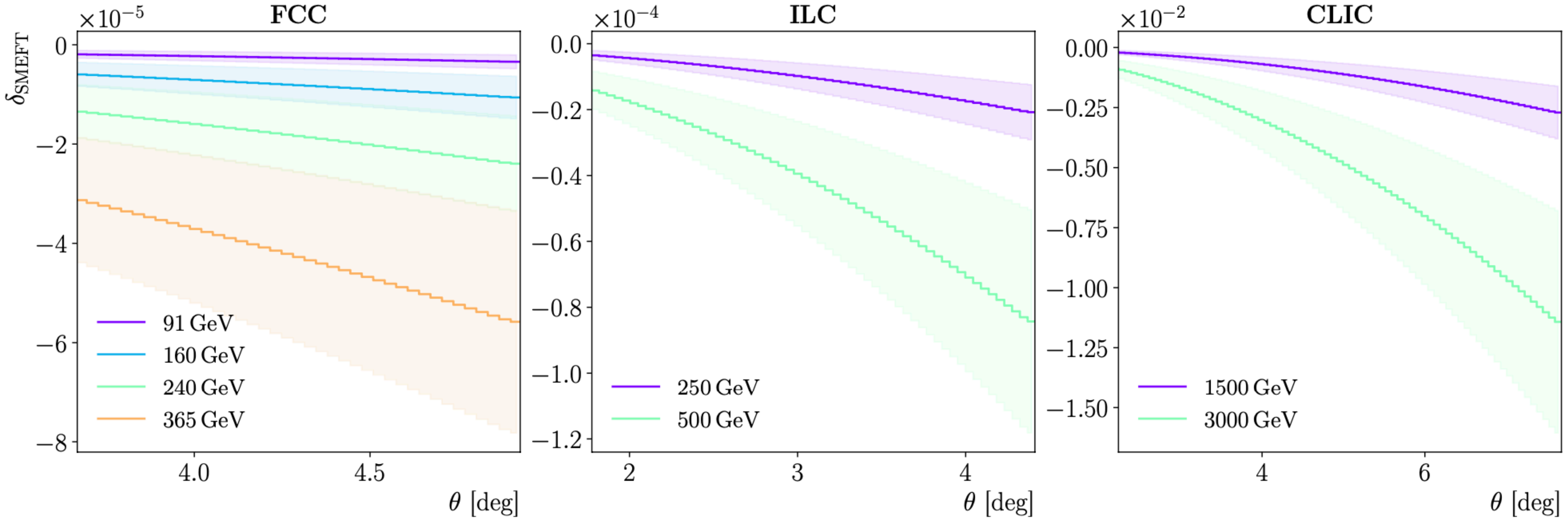

Large Angle Bhabha: Asymmetries

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$$A_{ab} = \frac{N_a - N_b}{N_a + N_b} \quad \not\propto L$$

$$\{a, b\} = \{\mathrm{F}, \mathrm{B}\}, \{\mathrm{L}, \mathrm{R}\}, \{\uparrow, \downarrow\}$$

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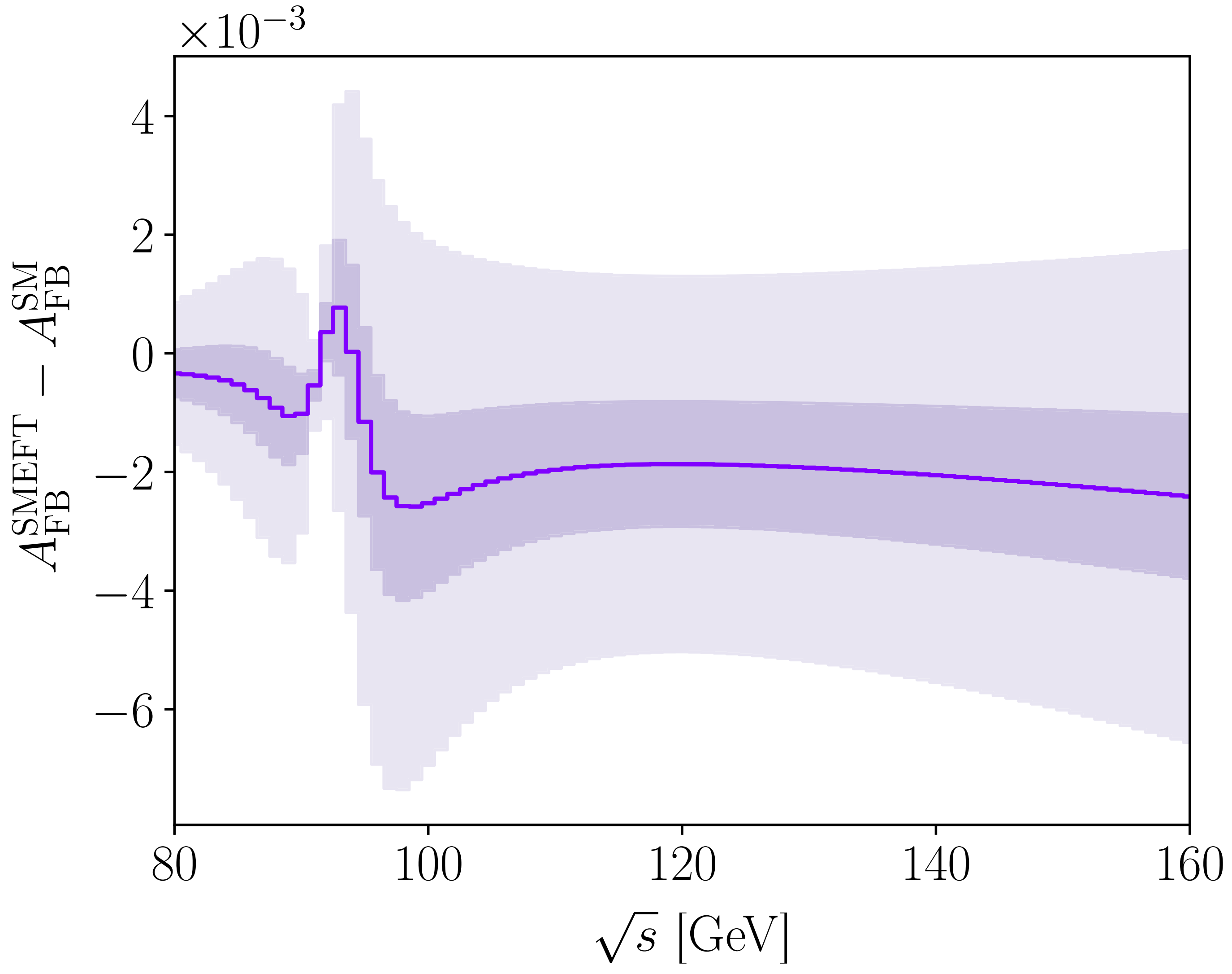
Z peak runs



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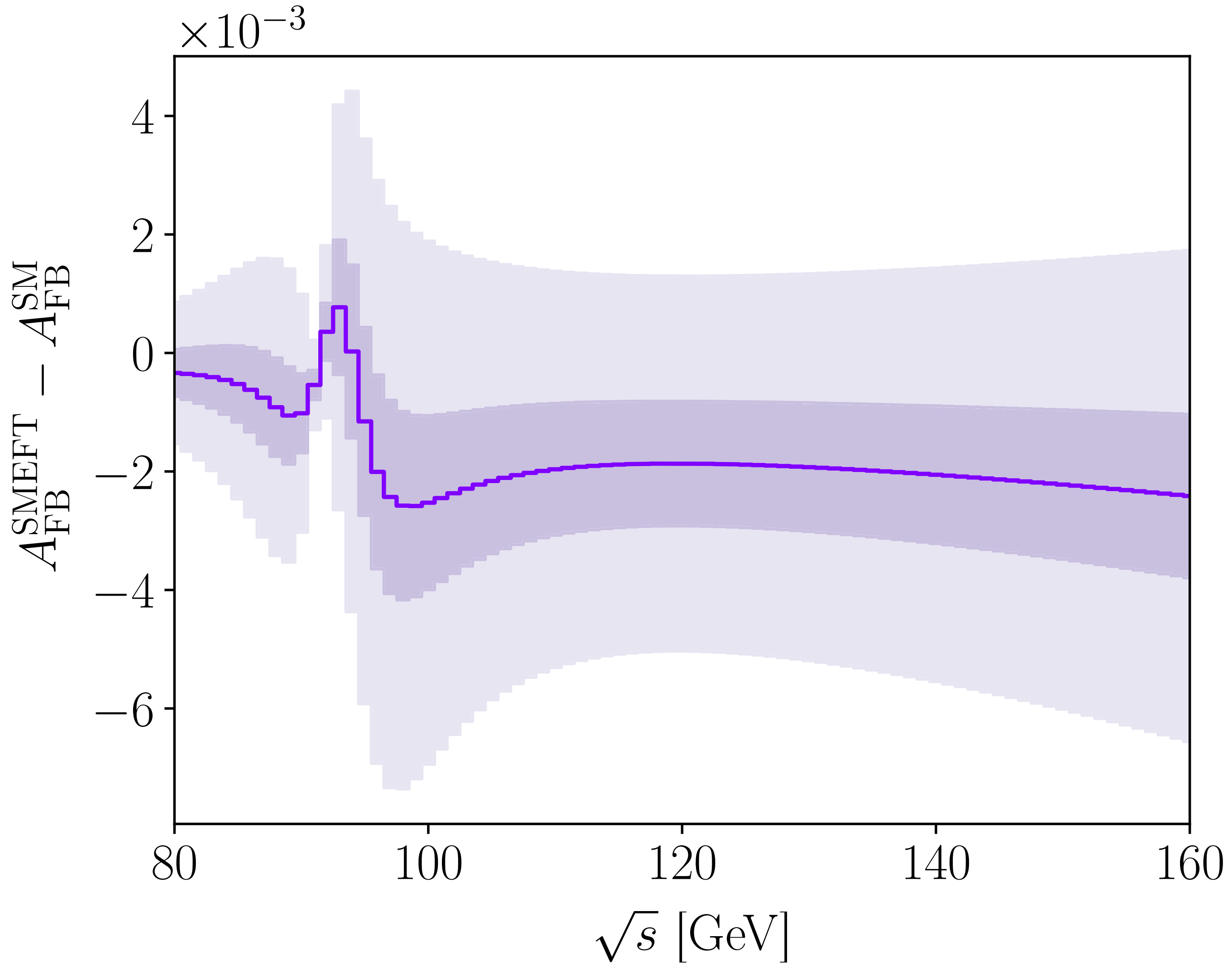

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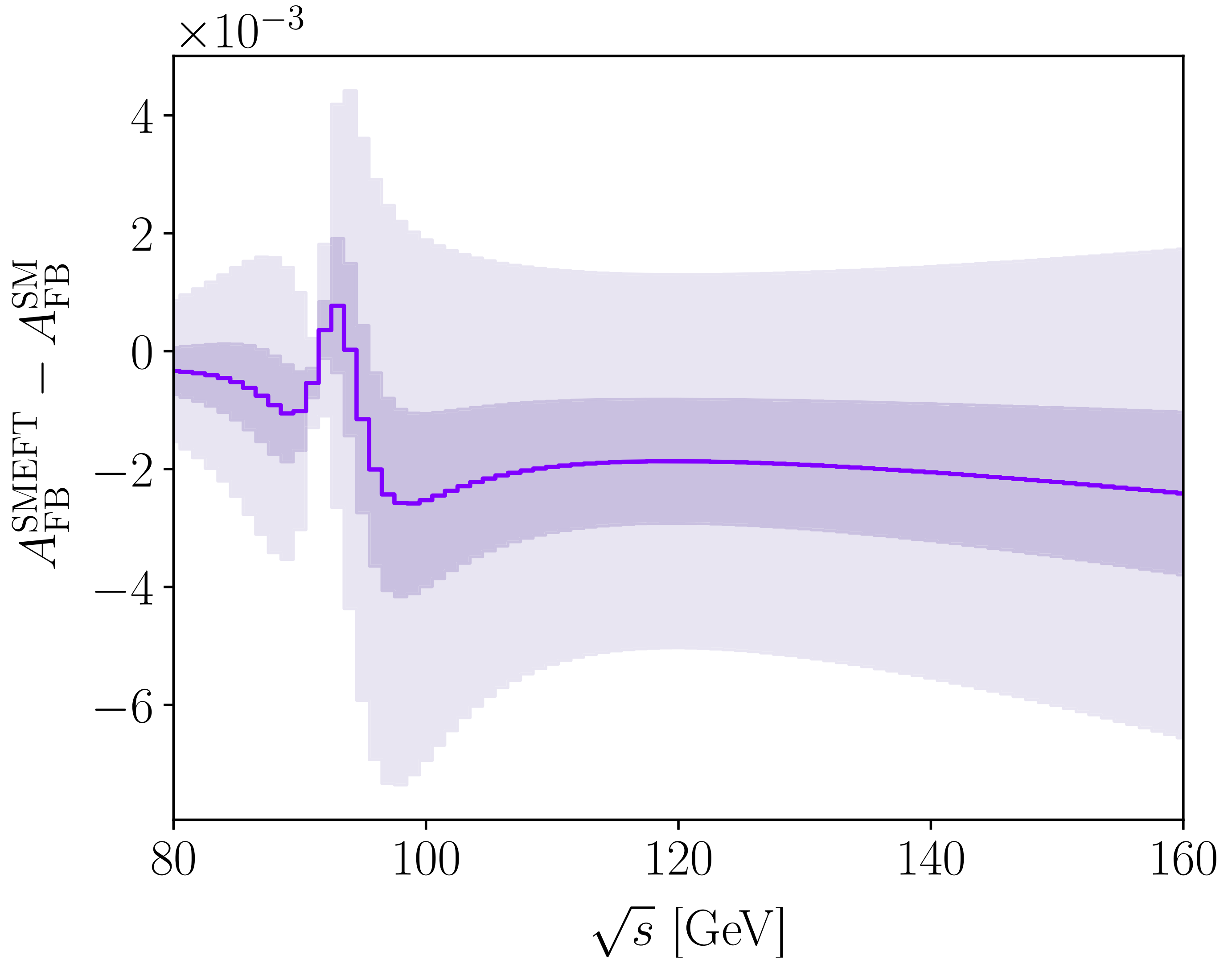

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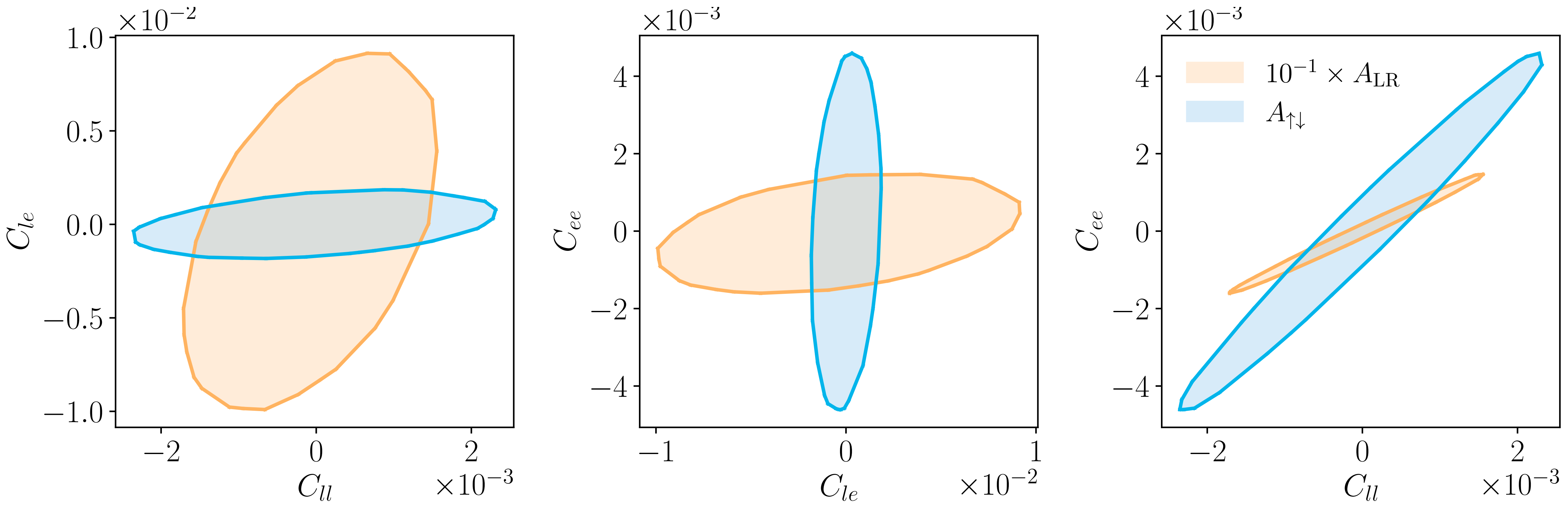
250 GeV run



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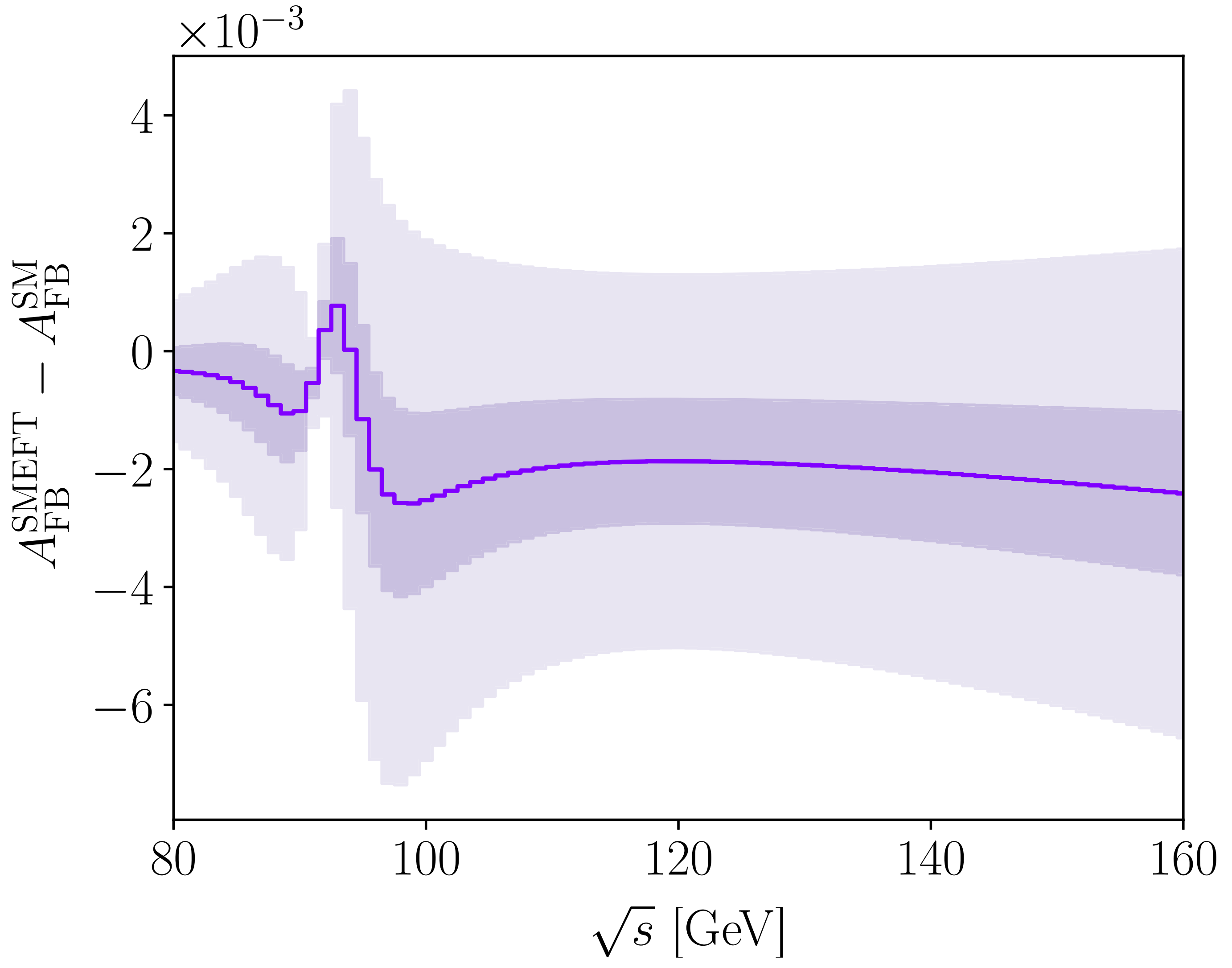

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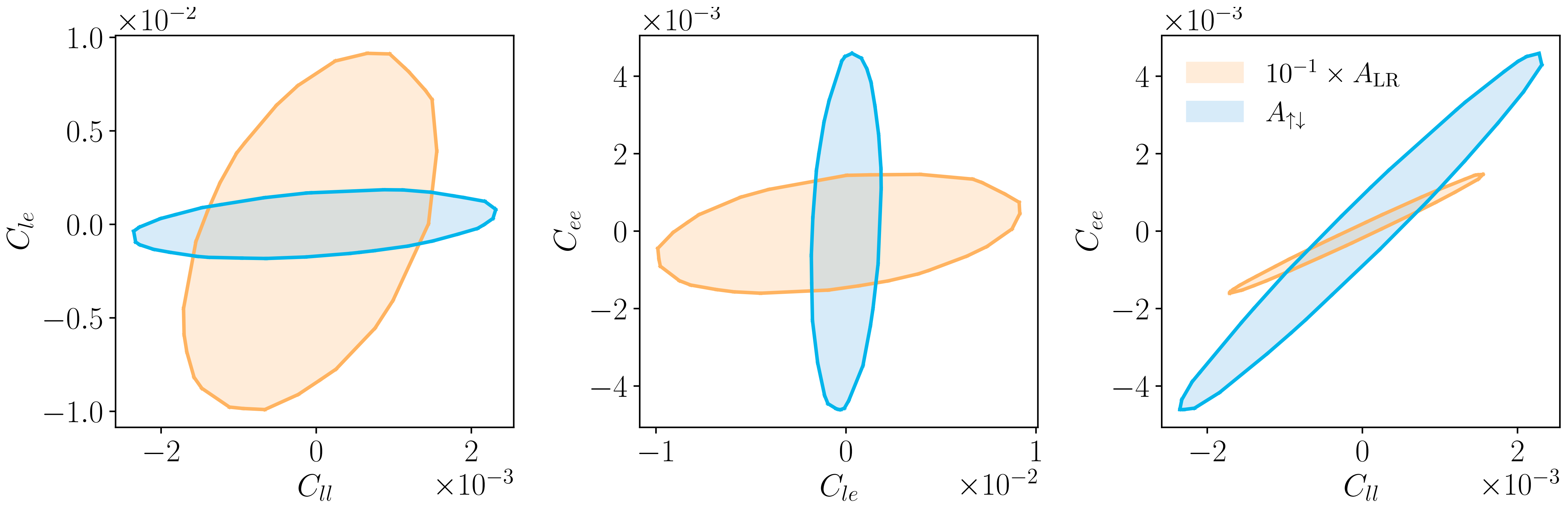
250 GeV run

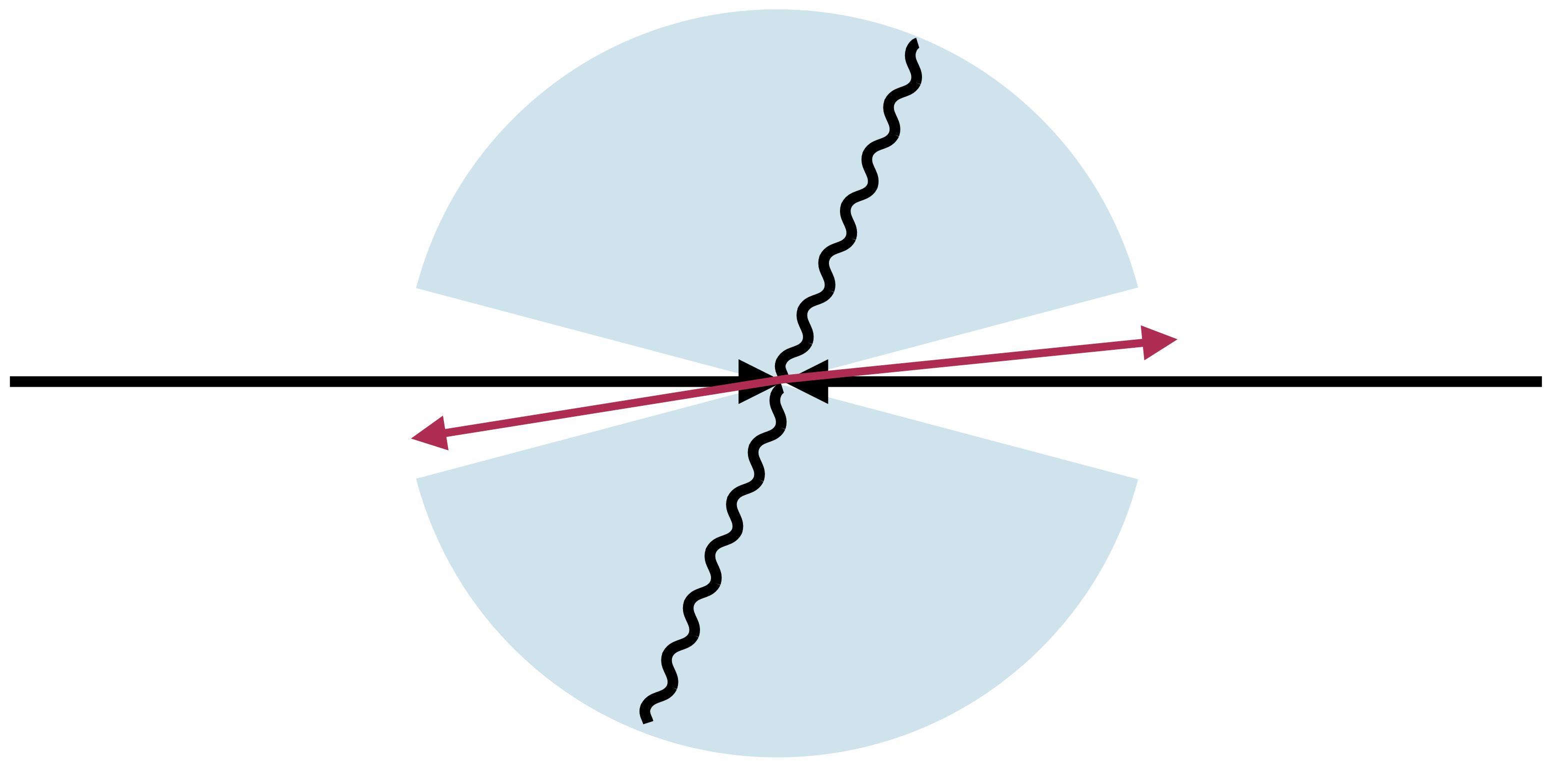


$$\chi^2 = \sum_{\alpha=1}^{n} \frac{\left(A_{\mathrm{pol}}^{0} - A_{\mathrm{pol}}^{\mathrm{th}}(\vec{C}_{4f})\right)_\alpha^2}{(\Delta A_{\mathrm{pol}}^{0})_\alpha^2} \rightarrow \delta_{\mathrm{SMEFT}} < 10^{-7}$$

Improving theory in Diphoton

Standard Model

NNLO pair corrections



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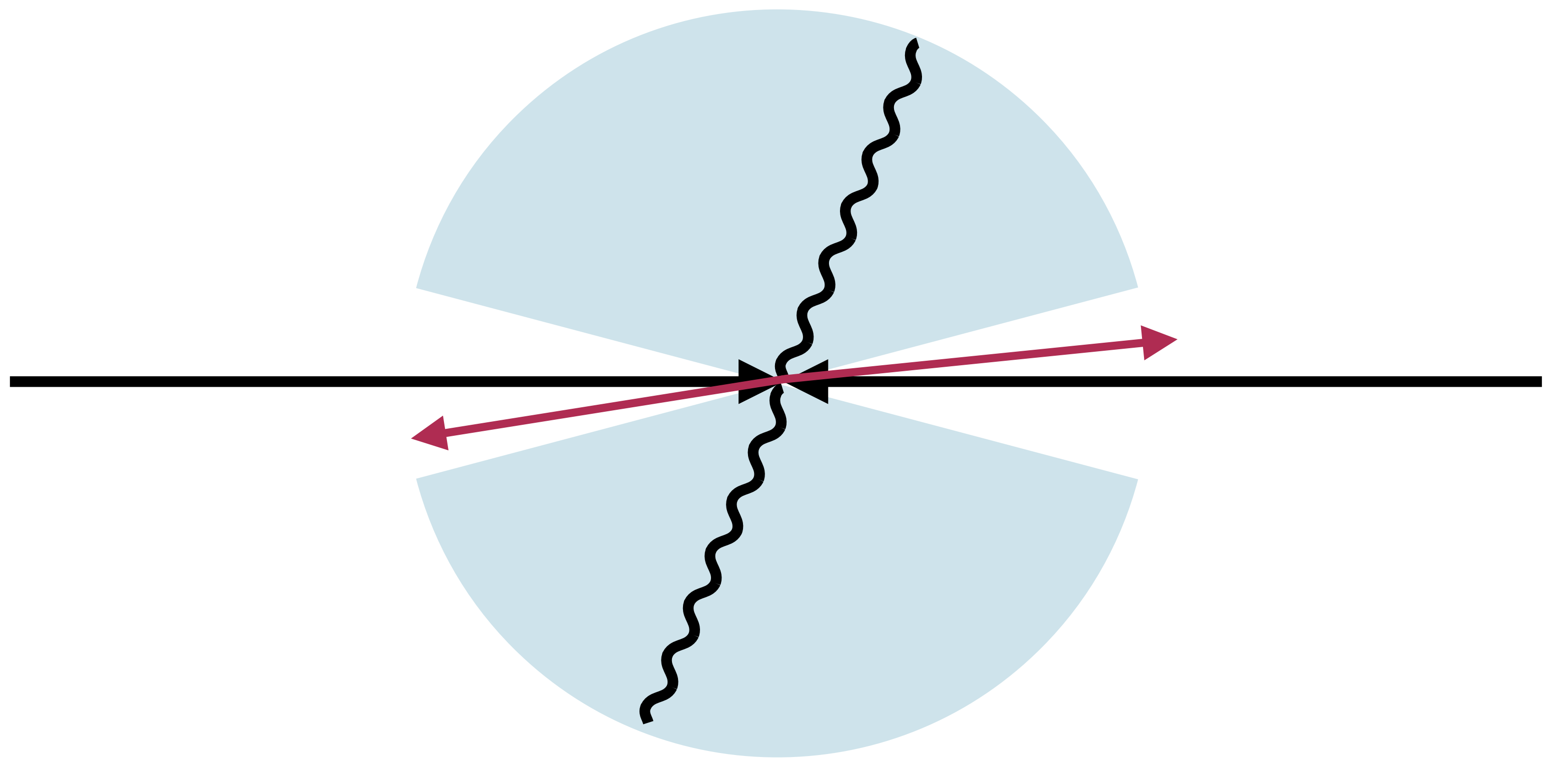
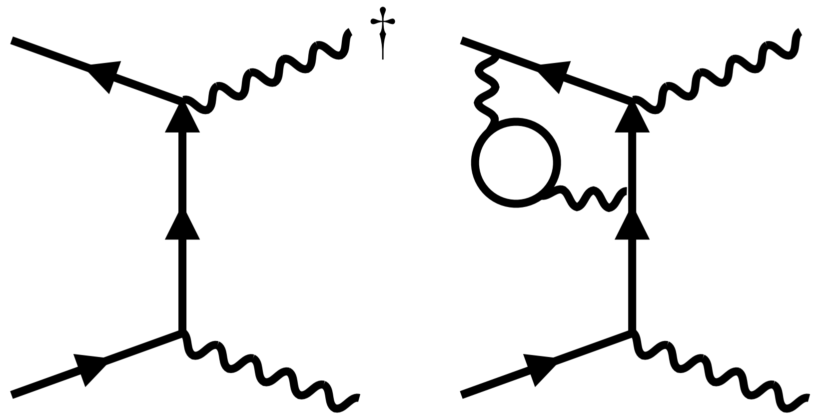


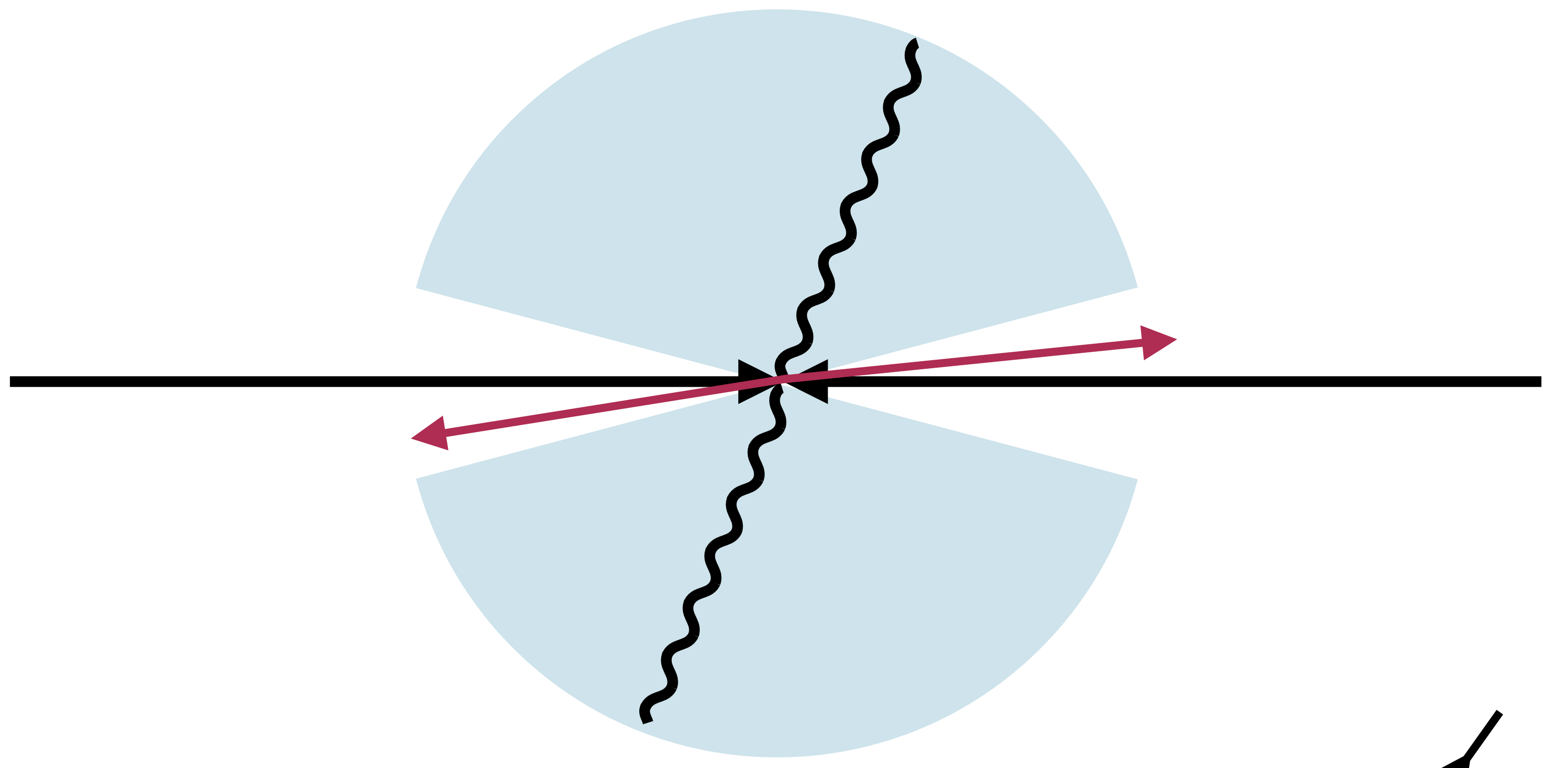


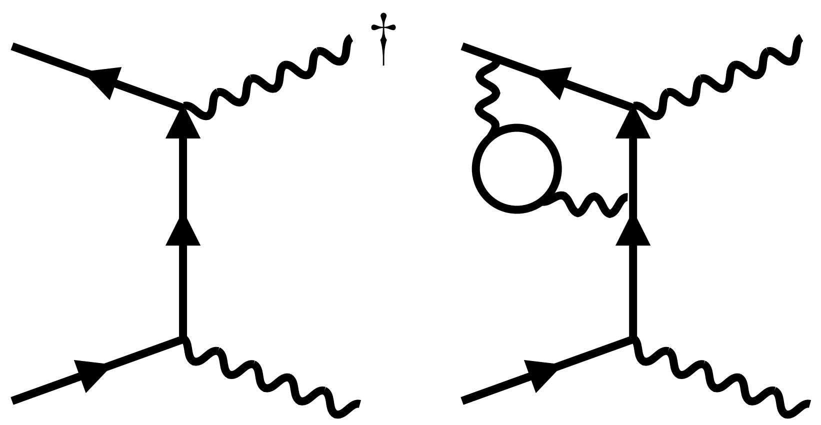
Virtual pairs

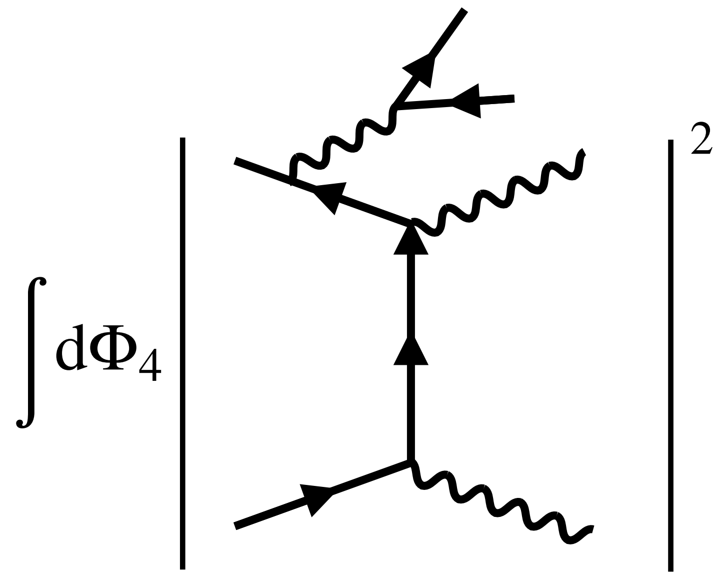
Done via dispersive techniques

Improving theory in Diphoton

Standard Model
NNLO pair corrections







Virtual pairs

✓

Done via dispersive techniques

Real pairs

~

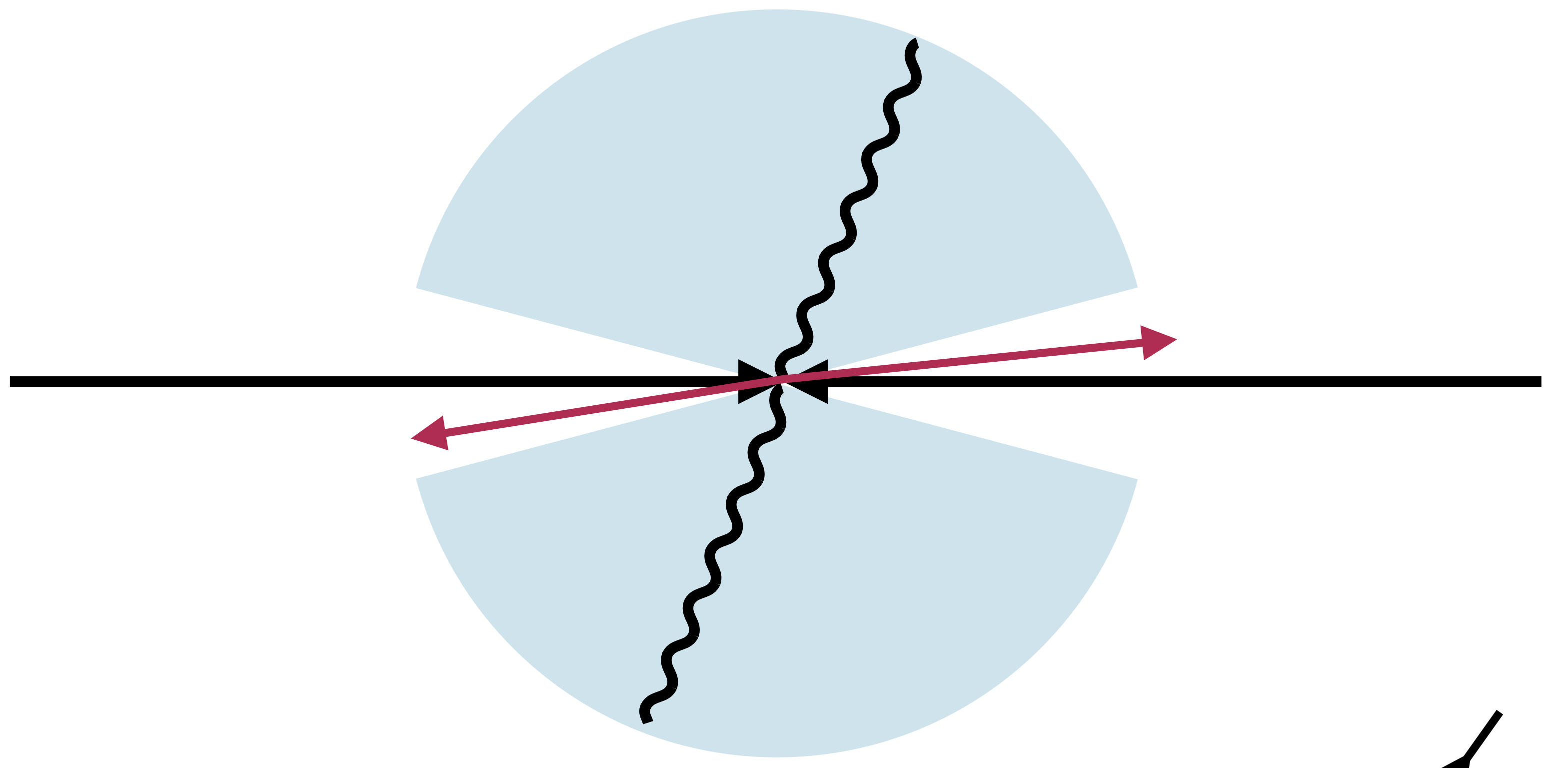
Convergence of MC integration

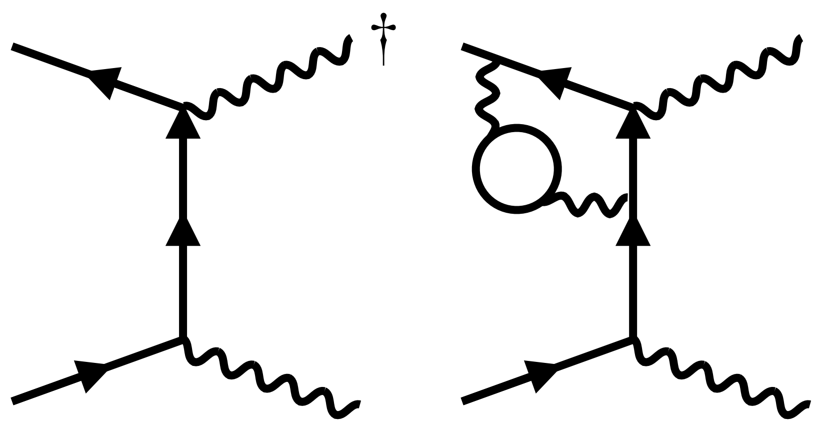
⚠ **Work in progress!**

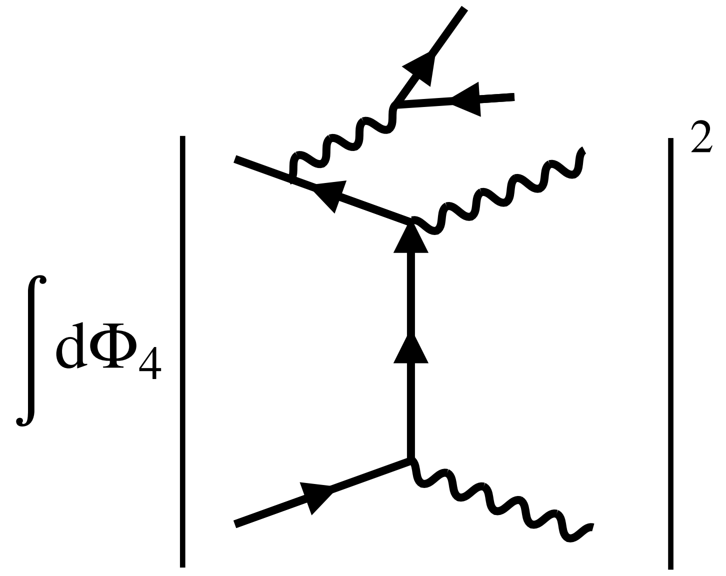
Improving theory in Diphoton

Standard Model

NNLO pair corrections







Virtual pairs

Done via dispersive techniques

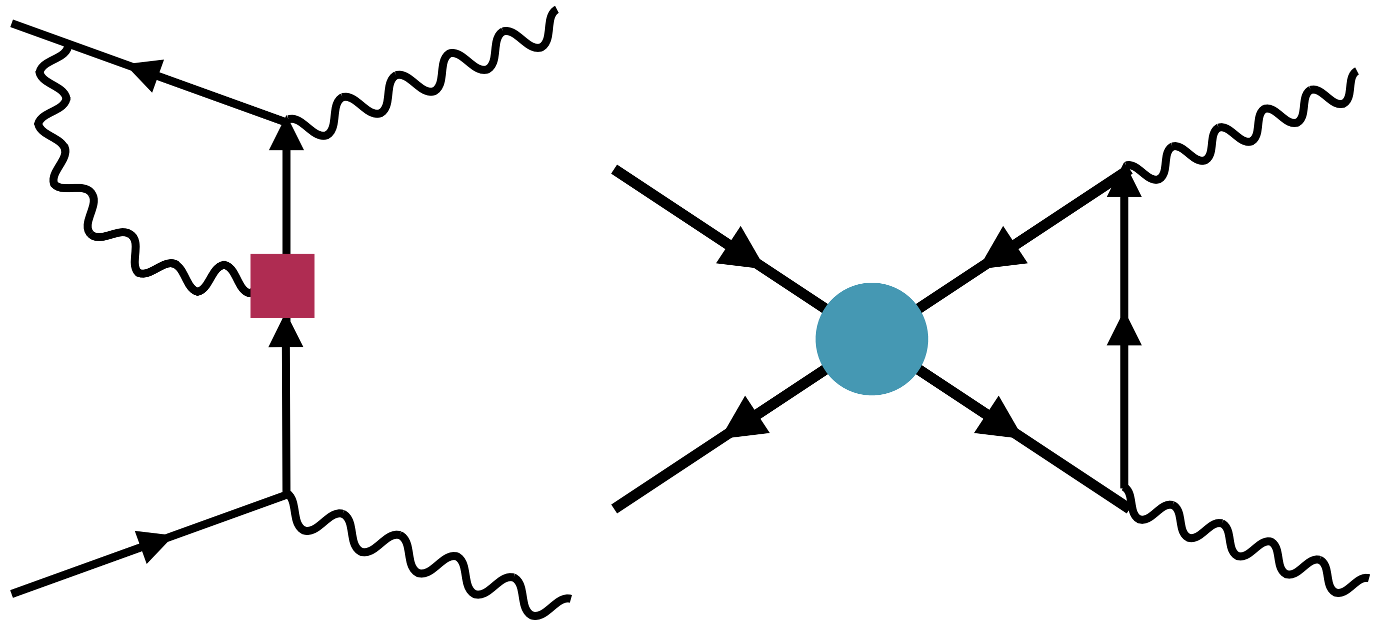
Real pairs

Convergence of MC integration

Work in progress!

SMEFT

LO dim8 + NLO dim6 corrections



Next semester at UAM in Madrid

Backup

The pion form factor

The Pion FF is a key quantity to determine the $(g-2)_\mu$

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi^2}\int_{4m_\pi^2}^{\infty}\frac{\mathrm{d}s}{s}K(s)\left(\frac{\alpha(s)}{3}\frac{\sigma(e^+e^-\to \mathrm{hadrons})}{\sigma(e^+e^-\to\mu^+\mu^-)}\right)$$

$$\simeq \frac{\alpha}{\pi^2}\int\frac{\mathrm{d}s}{s}K(s)\beta_\pi^2\,|F_\pi(s)|^2 f(s)$$

In scan experiments, the PionFF is given by the ratio

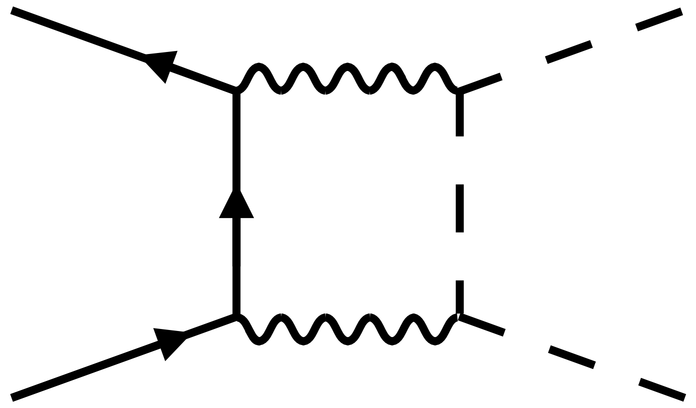
$$|F_\pi|^2 = \left(\frac{N_{\pi^+\pi^-}}{N_{e^+e^-}} - \Delta^{\mathrm{bg}}\right)\cdot\frac{\sigma^0_{e^+e^-}\cdot(1+\delta_{e^+e^-})\cdot\varepsilon_{e^+e^-}}{\sigma^0_{\pi^+\pi^-}\cdot(1+\delta_{\pi^+\pi^-})\cdot\varepsilon_{\pi^+\pi^-}}$$

$\delta_{\pi^+\pi^-}$ Radiative corrections are estimated via MC

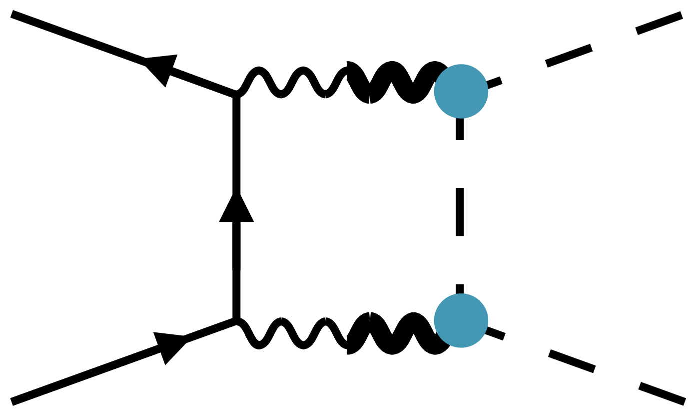
$\epsilon_{\pi^+\pi^-}$ Also the acceptance has a MC dependence via the **charge asymmetry**

$$A_{FB}^{\mathrm{NLO}} = A_{FB}^{\mathrm{LO}} + \frac{\alpha}{\pi}A_{FB}^{\alpha} = 0 + \frac{\alpha}{\pi}\left(\frac{\sigma_B^{\mathrm{odd}} - \sigma_F^{\mathrm{odd}}}{\sigma^{\mathrm{NLO}}}\right)$$

The FF has to be modelled due its non-perturbative nature

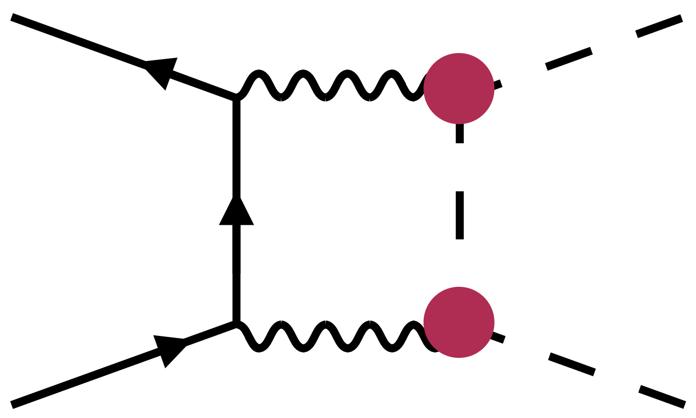


Factorised sQED — The FF is attached to virtual amplitude as to cancel infrared divergences



GVMD — A model based on the mixing of the photon with light resonances

$$F_\pi^{\mathrm{BW}}(q^2) = \sum_{v=1}^{n_r} F_{\pi,v}^{\mathrm{BW}}(q^2) = \frac{1}{c_t}\sum_{v=1}^{n_r} c_v\frac{\Lambda_v^2}{\Lambda_v^2 - q^2}$$



FsQED — Relies on the analytic properties of the FF, written via a dispersion relation

$$F_\pi(q^2) = 1 + \frac{q^2}{\pi}\int_{4m_\pi^2}^{\infty}\frac{\mathrm{d}s'}{s'}\frac{\mathrm{Im}F_\pi(s')}{s' - q^2 - i\epsilon'}$$

QED Structure functions

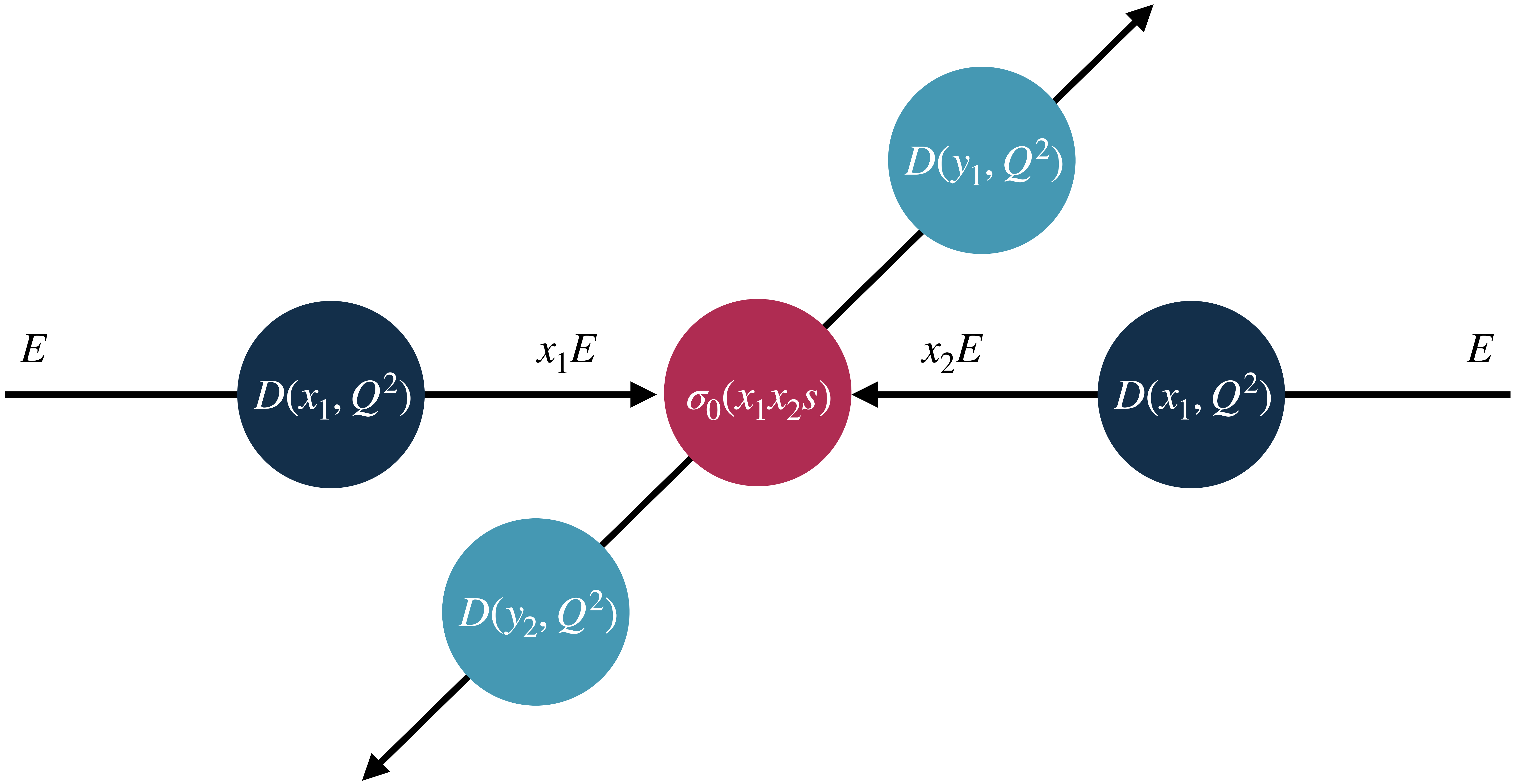
Master Formula

QED corrected cross section

$$\sigma(s) = \int dx_1 dx_2 dy_1 dy_2 \int d\Omega D(x_1, Q^2) D(x_2, Q^2) D(y_1, Q^2) D(y_2, Q^2) \frac{d\sigma_0(x_1 x_2 s)}{d\Omega} \Theta(\text{cuts})$$

Convolution of SFs

Hard-process cross section



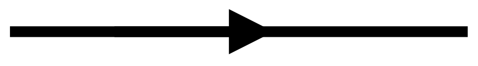
QED Structure functions

DGLAP Equation

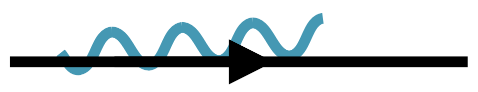
$$Q^2 \frac{\partial}{\partial Q^2} D(x, Q^2) = \frac{\alpha}{2\pi} \int_0^1 \frac{ds'}{s'} P_+(s') D\left(\frac{x}{s'}, Q^2\right)$$

Structure Functions (FS) are solutions of the DGLAP equation

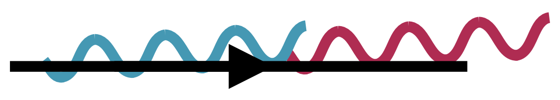
$$D(x, Q^2) =$$



$$\Pi(Q^2, m^2)\delta(1-x)$$



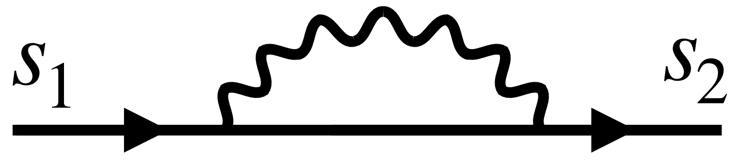
$$+\frac{\alpha}{2\pi} \int_{m^2}^{s} \Pi(Q^2, s') \frac{ds'}{s'} \Pi(s', m^2) \int_0^{x_+} dy\, P(y) \delta(x-y)$$



$$+2 \text{ photons} \ldots$$

SF generate all the emissions in collinear approximation

Sudakov form factor

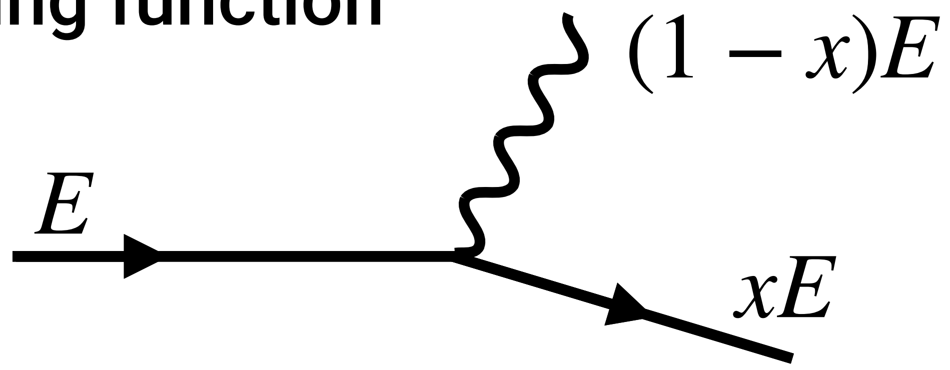


$$\Pi(s_1, s_2) = \exp\left[-\frac{\alpha}{2\pi} \int_{s_1}^{s_2} \frac{ds'}{s'} \int_0^{x_+} dz P(z)\right]$$

Probability that the particle evolves from virtuality s_1 to s_2 without emitting a photon with energy fraction bigger than $\epsilon = 1 - x_+$

Altarelli-Parisi splitting function

$$P(z) = \frac{1+z^2}{1-z}$$



Splitting of a particle of energy E in a daughter of energy xE

QED PS algorithm

The **Parton Shower (PS)** algorithm is a Monte Carlo exact solution of the DGLAP equation

$$d\sigma_{PS}^{LL} = \Pi(\epsilon, Q^2) \sum_{n=0}^{\infty} \frac{1}{n!} \left| \mathcal{M}_n^{LL} \right|^2 d\Phi_n$$

$$\left| \mathcal{M}_1^{LL} \right|^2 = \frac{\alpha}{2\pi} P(z) \; I(k) |\mathcal{M}_0|^2 J$$

Energy spectrum

Energy generated as the A-P splitting

$$P(z) = \frac{1+z^2}{1-z}$$

Angular spectrum

In the PS approach, you can generate the photon kinematics with $p_\perp \neq 0$

$$I(k) = \sum_{ij} \eta_i \eta_j \frac{p_i \cdot p_j}{(p_i \cdot k)(p_j \cdot k)} k_0^2$$

$$\Pi(\epsilon, Q^2) = \exp\left\{ -\frac{\alpha}{2\pi} \int_0^{1-\epsilon} dz P(z) \int d\Omega_k I(k) \right\}$$

Sudakov FF

The eikonal function $I(k)$ is exponentiated, as it gives the same integral as of the PS kinematics

$$= \exp\left\{ -\frac{\alpha}{2\pi} \quad I_+ \quad \log \frac{Q^2}{m^2} \right\}$$

BabaYaga@NLO master formula

BabaYaga@NLO

$$d\sigma_{\rm NLOPS} = F_{\rm SV}\,\Pi(\epsilon, Q^2)\sum_{n=0}^{\infty}\frac{1}{n!}\left(\prod_{i=0}^{n} F_{H,i}\right)\left|\mathcal{M}_n^{\rm LL}\right|^2 d\Phi_n$$

	Exact NLO	LL PS	Matched PS	
	virtual and real corrections are exact	virtual and real emissions are approximated	In BabaYaga@NLO, the PS is matched with the NLO calculation via the correction factors	
$\mathcal{O}(\alpha)$	$d\sigma_\alpha$	$d\sigma_\alpha^{\rm LL}$	$d\sigma^\alpha_{\rm NLOPS}$	
Soft+virtual	$(1 + C_\alpha)\,\lvert\mathcal{M}_0\rvert^2 d\Phi_0$	$(1 + C_\alpha^{\rm LL})\,\lvert\mathcal{M}_0\rvert^2 d\Phi_0$	$F_{\rm SV} = 1 + \left(C_\alpha - C_\alpha^{\rm LL}\right)$	affects the normalisation
Real	$\lvert\mathcal{M}_1\rvert^2 d\Phi_1$	$\lvert\mathcal{M}_1^{\rm LL}\rvert^2 d\Phi_1$	$F_{\rm H} = 1 + \dfrac{\lvert\mathcal{M}_1\rvert^2 - \lvert\mathcal{M}_1^{\rm LL}\rvert^2}{\lvert\mathcal{M}_1^{\rm LL}\rvert^2}$	1γ exact Matrix Element $n\gamma$ permutations of 1γ ME

$d\Phi_n$ The phase space is exact at all orders

Radiative return

Flavour factories can measure the Pion FF also by radiative return, *i.e.* when the CMS energy is reduced by the emission of an ISR photon

There are just two MC: `Phokhara` and `AfkQED`.

Signal $e^+e^- \to \pi^+\pi^-\gamma$

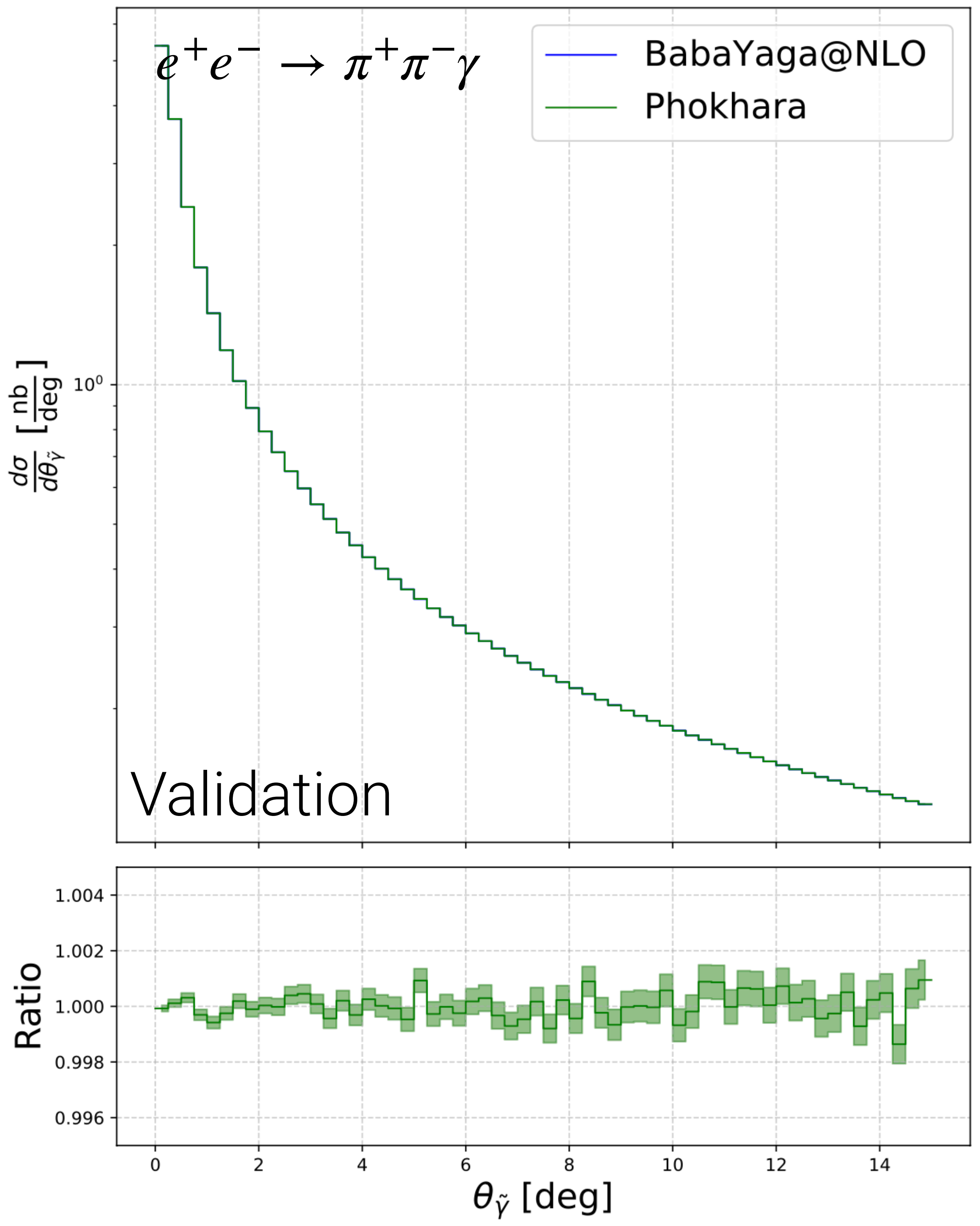
Normalisation $e^+e^- \to l^+l^-\gamma$

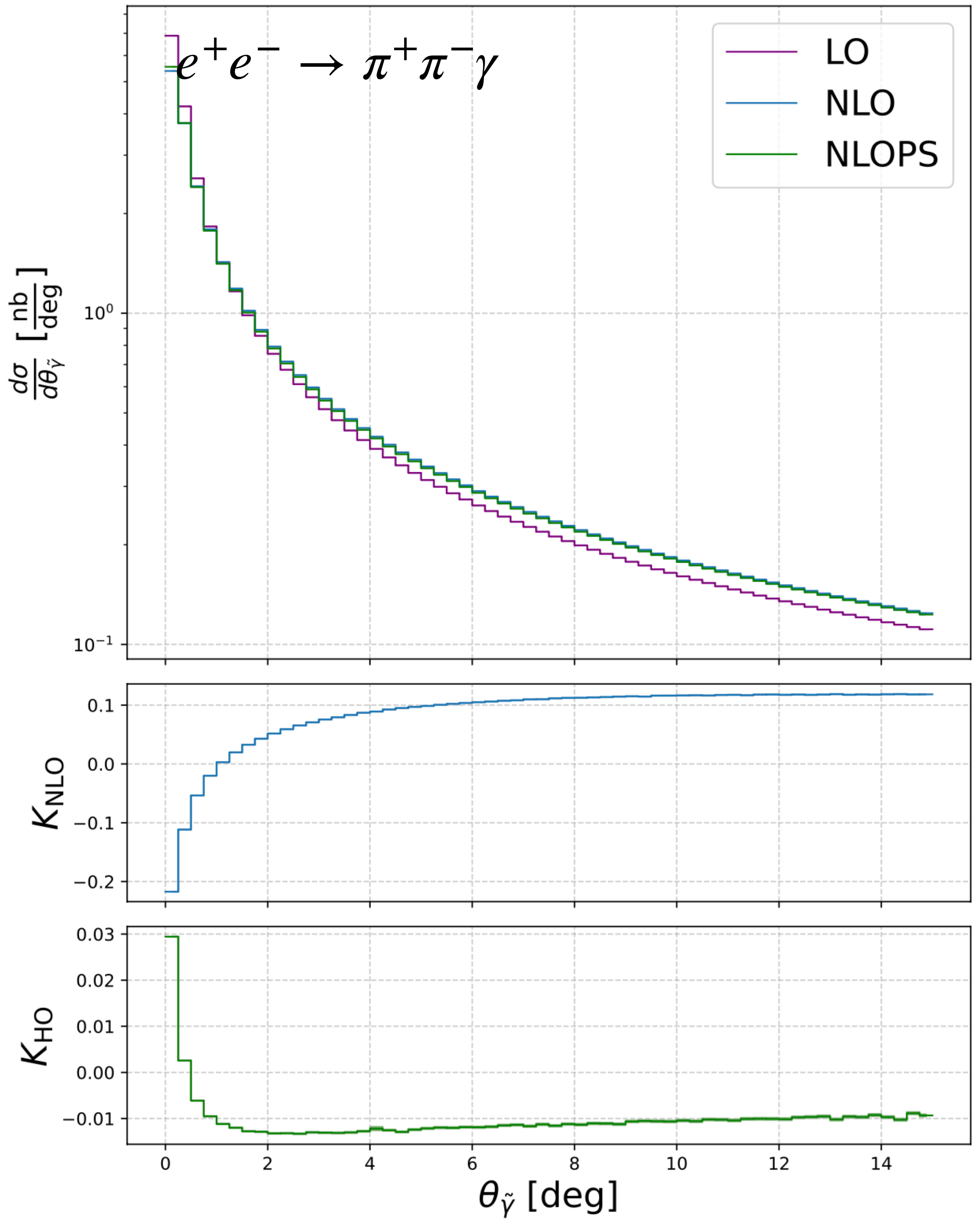
KLOE-like Small Angle

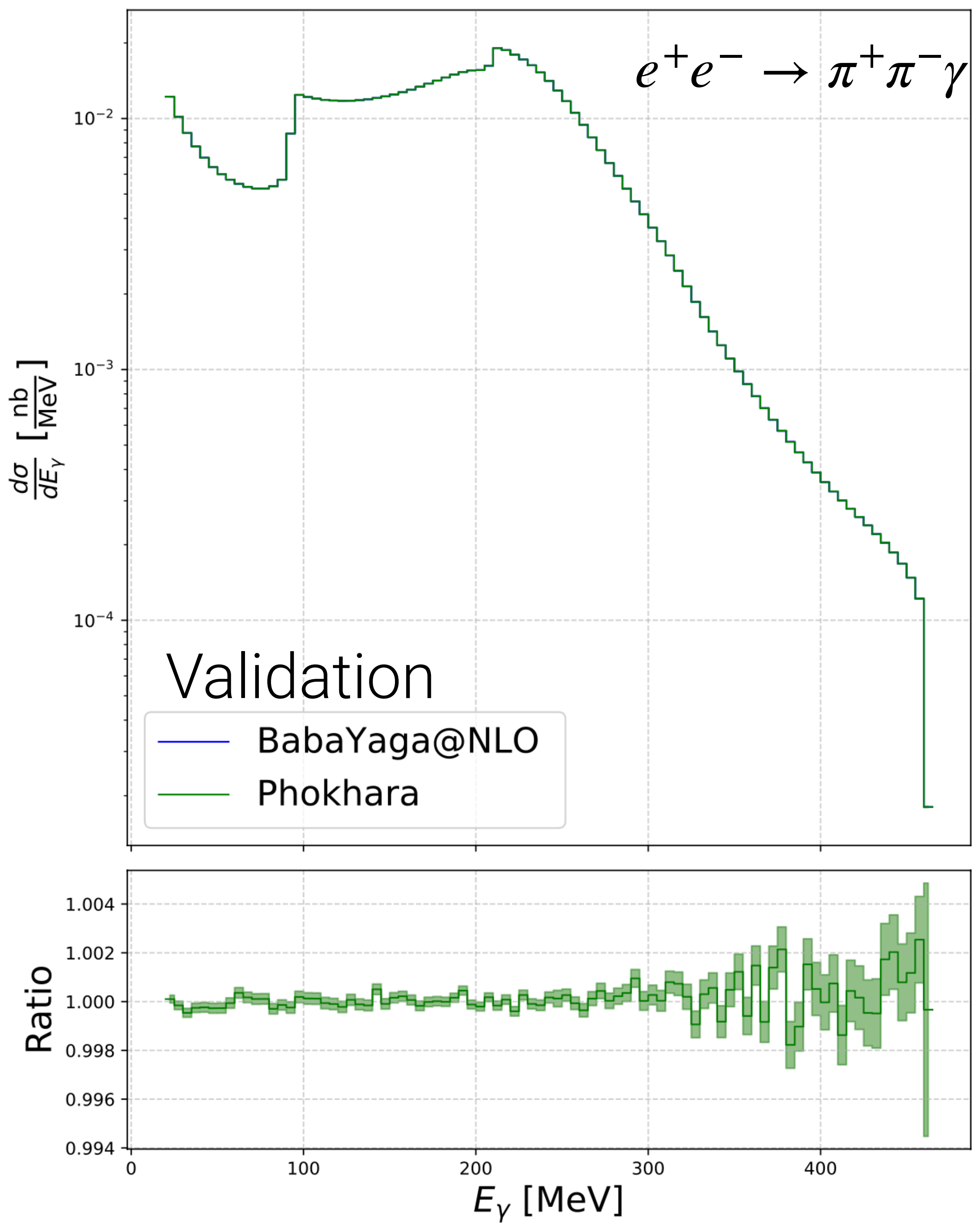
$$\theta_{\tilde\gamma} \le 15^\circ \quad \text{or} \quad \theta_{\tilde\gamma} > 165^\circ\,, \qquad 50^\circ \le \theta^\pm \le 130^\circ\,,$$
$$0.35\,\text{GeV}^2 \le M^2_{XX} \le 0.95\,\text{GeV}^2\,, \qquad |\mathrm{p}^z_\pm| > 90\,\text{MeV} \quad \text{or} \quad \mathrm{p}^\perp_\pm > 160\,\text{MeV}\,,$$

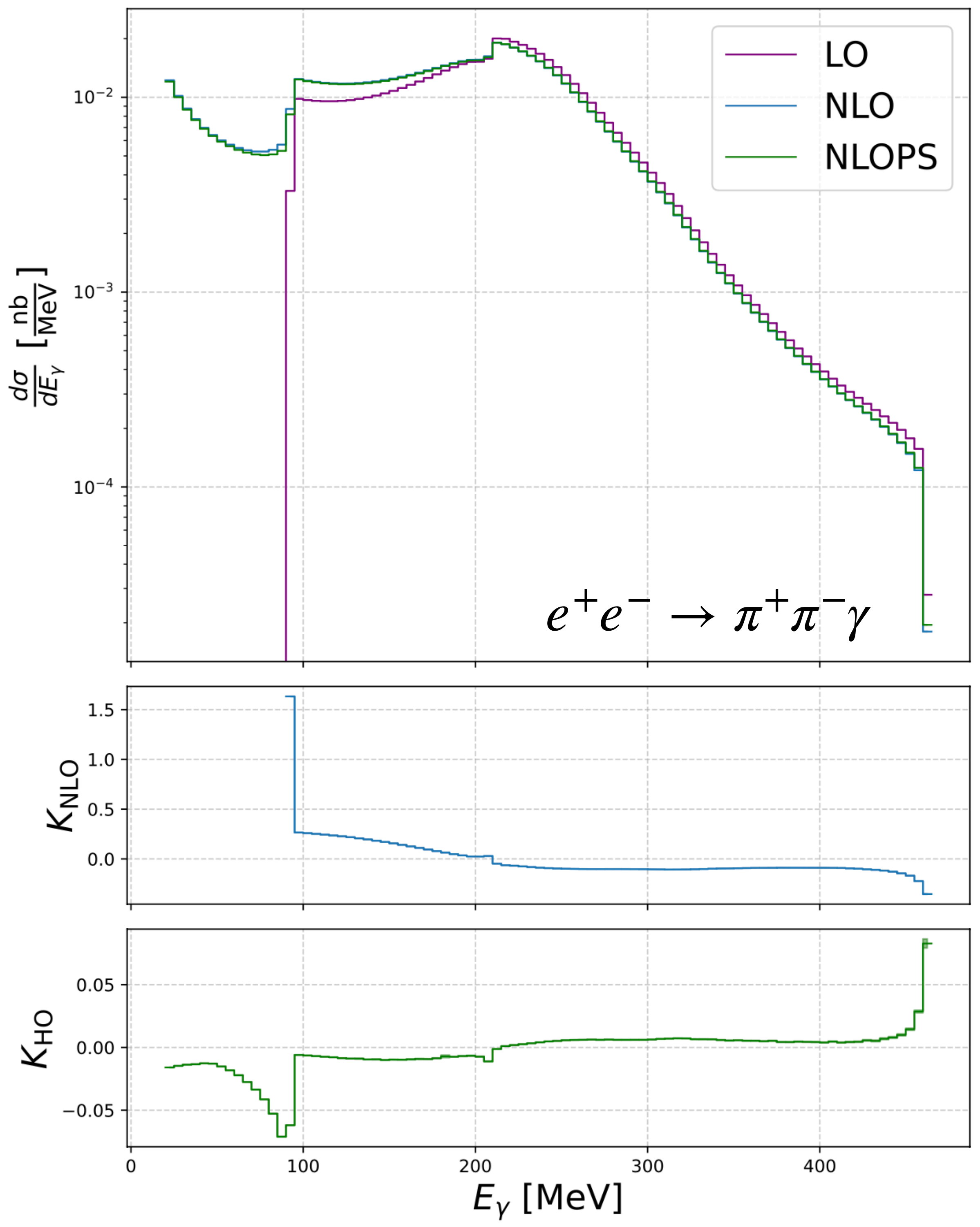
KLOE-like Large Angle

$$E_\gamma > 20\,\text{MeV} \quad \text{and} \quad 50^\circ \le \theta_\gamma \le 130^\circ\,,$$
$$|\mathrm{p}^z_\pm| > 90\,\text{MeV or } \mathrm{p}^\perp_\pm > 160\,\text{MeV} \quad \text{and} \quad 50^\circ \le \theta^\pm \le 130^\circ\,,$$
$$0.1\,\text{GeV}^2 \le M^2_{XX} \le 0.85\,\text{GeV}^2\,,$$









Heavy New Physics

$\Lambda_{NP} \gg \Lambda_{EW}$

Leading Order

$$\sigma_{SMEFT} = \sigma_{SM} + \sigma^{(6)} = \sigma_{SM} + \sum_{i=1}^{n} \frac{C_i}{\Lambda_{NP}^2} \sigma_i^{(6)}$$

$\sigma_i^{(6)}$ Interference between SM and dim-6

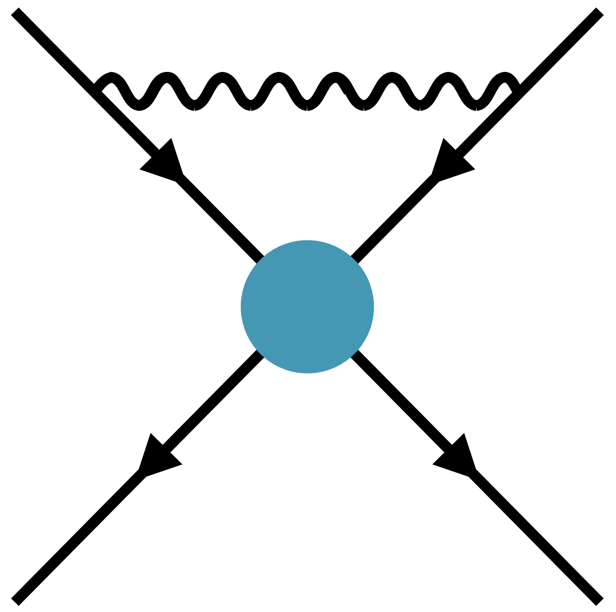
Work Hypothesis

$\sigma^{\gamma} + \sigma^{Z} + \sigma^{\gamma Z}$	Complete SM
$\mathcal{O}(\Lambda_{NP}^{-2})$	Up to dim-6
$\left(\mathcal{M}_{SM}^{\dagger}\mathcal{M}^{(6)}\right)_{LO}$	LO approximation
$\{\alpha, M_Z, G_\mu\}$	EW scheme

Next-to-Leading Order

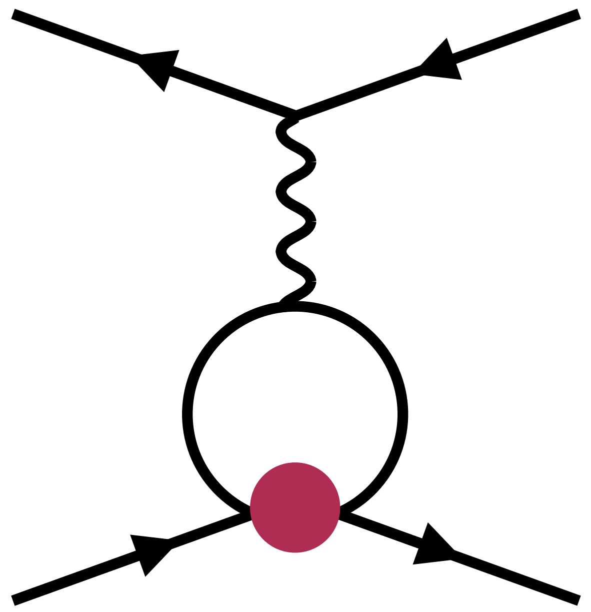
$$\sigma_{NLO}^{(6)} = \sum_j \frac{C_j(\mu)}{16\pi^2\Lambda_{NP}^2} 2\mathrm{Re}\left(\mathcal{M}_{SM}^{\dagger}\mathcal{M}_{NLO,j}^{(6)}(\mu)\right)$$

Two sets of contributions



SM NLO corrections to dim-6 operators appearing at LO

$$\frac{\sigma_{NLO,i}^{(6)}}{\sigma_{LO,i}^{(6)}} \simeq \frac{g_{SM}^2}{16\pi^2} \log \frac{M_Z^2}{|t|} \simeq \mathcal{O}(1\%)$$



Dim-6 operators loop insertions

$$\frac{\sigma_{NLO,j}^{(6)}}{\sigma_{SM}} \simeq \frac{|t|}{\Lambda_{NP}^2} \frac{C_j}{16\pi^2} \log \frac{\Lambda_{NP}^2}{|t|} \simeq 2 \times 10^{-4} C_j$$

Heavy New Physics: Results

The deviation is computed taking into account **correlations** between WCs

$$(\delta \pm \Delta\delta)_{\text{SMEFT}} = \frac{1}{\sigma_{\text{SM}}}\left(\sigma^{(6)} \pm \sqrt{\sum_{ij} \sigma_i^{(6)} V_{ij} \sigma_j^{(6)}}\right)$$

Future Colliders scenarios taken from EPPSU inputs

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	$(-1.3 \pm 0.5) \times 10^{-4}$	10^{-4}
		240	$(-2.9 \pm 1.2) \times 10^{-4}$	
		365	$(-6.7 \pm 2.7) \times 10^{-4}$	
ILC	$[1.7°, 4.4°]$	250	$(-1.2 \pm 0.5) \times 10^{-4}$	$< 10^{-3}$
		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	$(-4.2 \pm 1.7) \times 10^{-2}$	

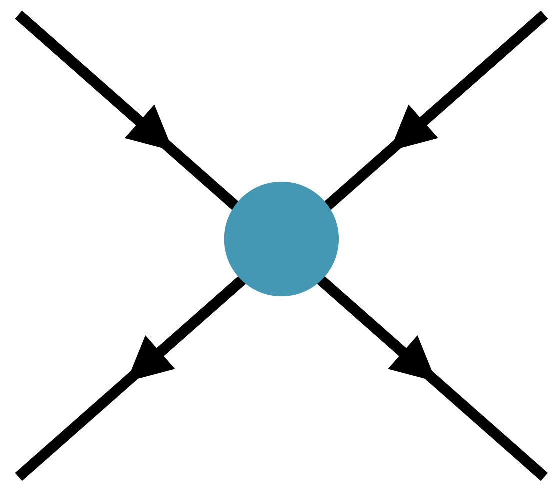
$\delta_{\text{SMEFT}} \simeq \delta L$

A. Falkowski et al. arXiv:1706.03783

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

Global fit of **LEP+flavour** data

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



$C_{ll,le,ee}$

The contribution grows with **angle** and **energy**

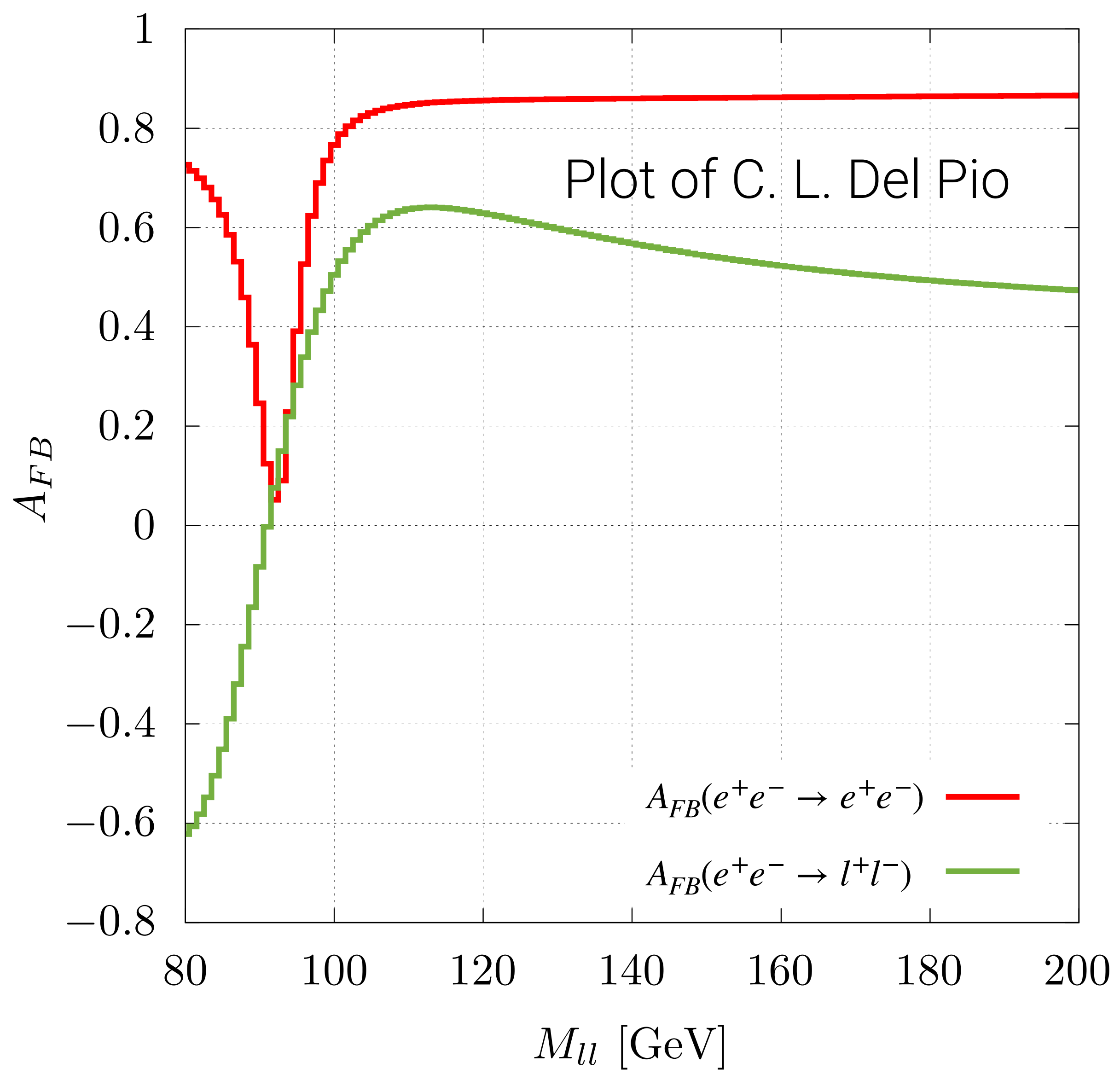
Large Angle asymmetries

$\Delta C_{\mathrm{HLLHC}}$

HL-LHC will not improve significantly 4fermions WCs bounds

$C = 0$

Hypothesis: no NP observed

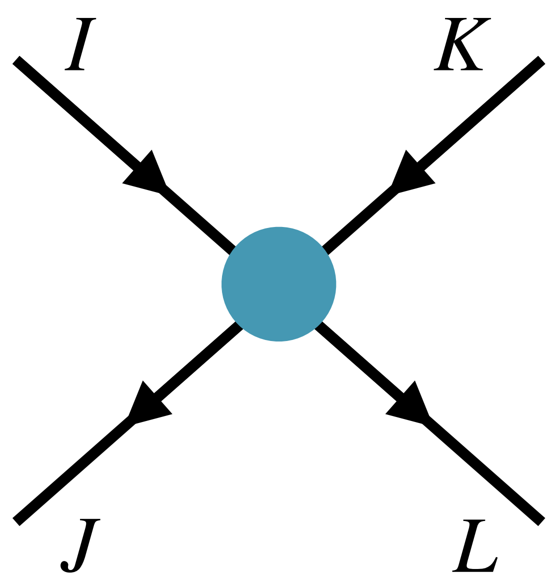


Asymmetries $\theta \in [40,140]$ deg Large Angle Bhabha Scattering (LABS)

$$A_{ab} = \frac{N_a - N_b}{N_a + N_b} \qquad \{a, b\} = \{\mathrm{F}, \mathrm{B}\}, \{\mathrm{L}, \mathrm{R}\}, \{\uparrow, \downarrow\}$$

The theoretical prediction depends on WCs

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



Flavour	Coefficients	Data
Generic	$C_{ll}^{1111} \neq C_{ll}^{1234}$	$A_{ab}(e^+e^- \to e^+e^-)$
Universal	$C_{ij}^{IIJJ} = C_{ij}^{IIII}$	$A_{ab}(e^+e^- \to l^+l^-, q\bar{q})$

We do not make any flavour symmetry assumptions

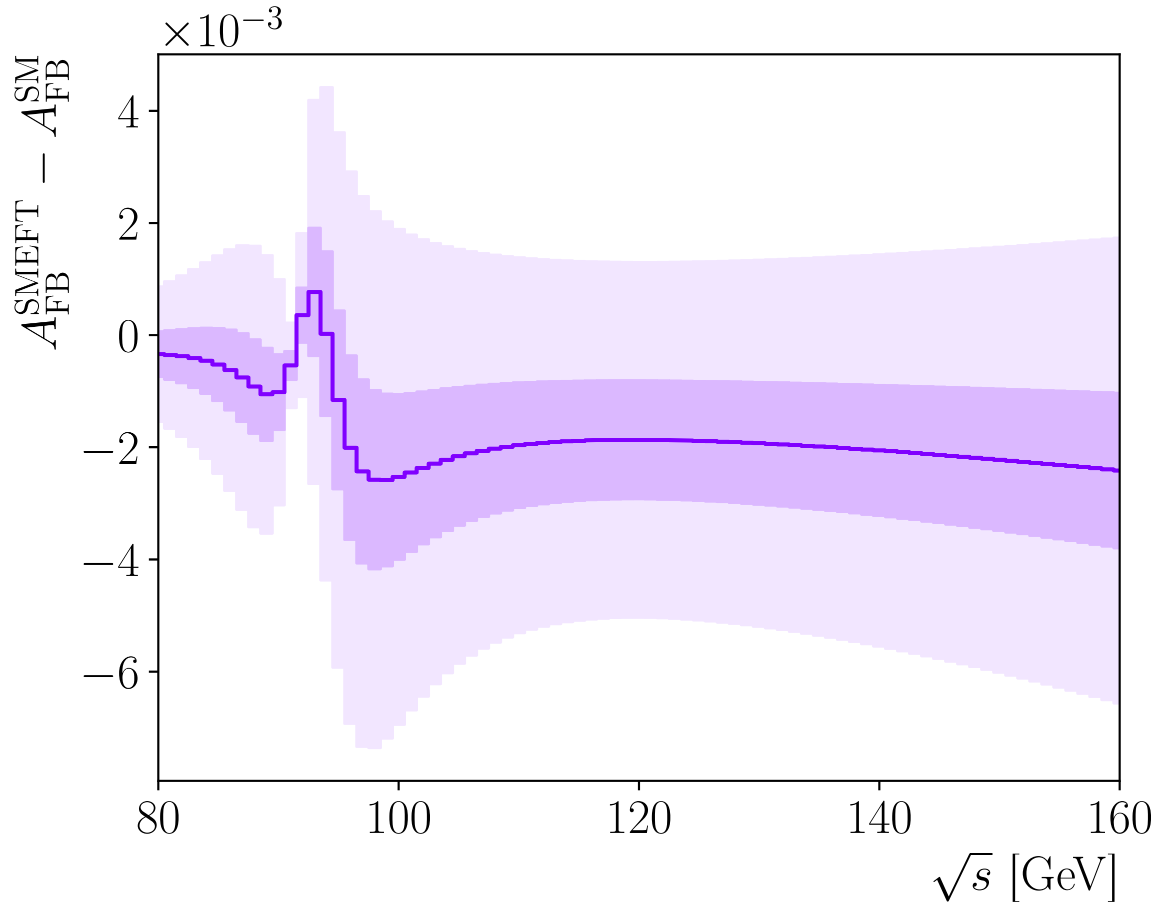
Alternatie Scenarios

Z peak runs — FCC-ee

We use the FB asymmetry as a function of $\sqrt{s_\alpha}$

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

To fit the three WCs we can use three points



$$\sqrt{s_1}=89\ {\rm GeV}$$
$$\sqrt{s_2}=93\ {\rm GeV}$$
$$\sqrt{s_3}=98\ {\rm GeV}$$

In 6 months of run on every point

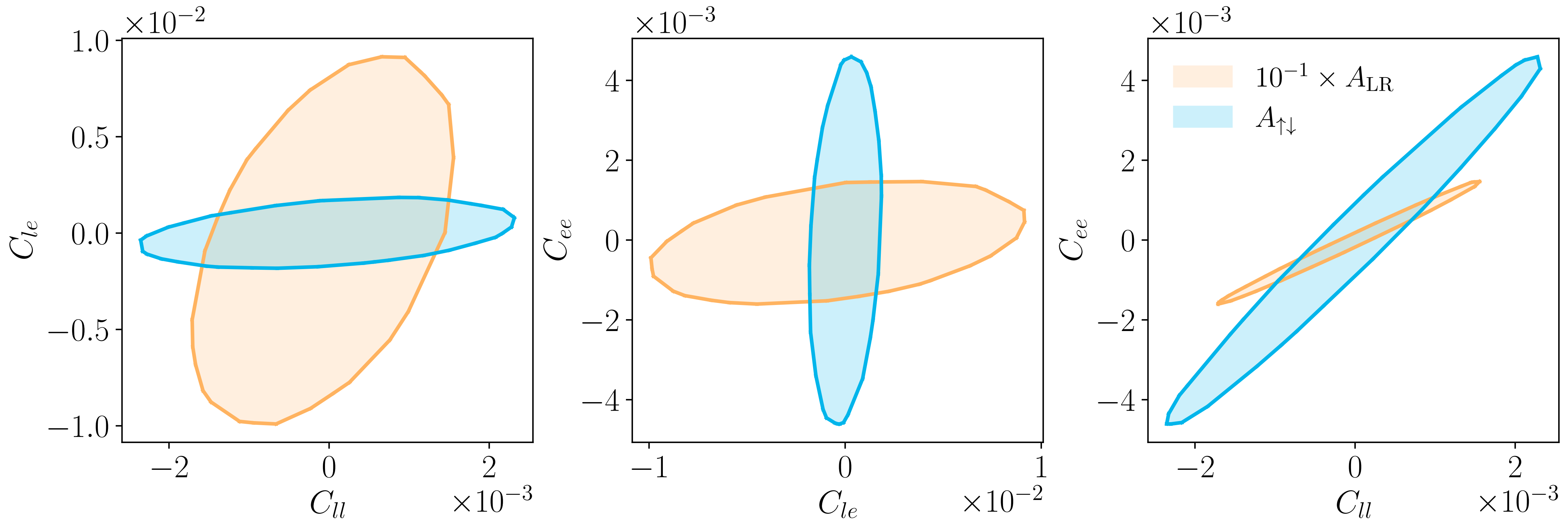
$\Delta C_{4f}<10^{-2}$ → $\delta_{\rm SMEFT}<10^{-5}$

250 GeV run — ILC

For polarised beams A_{LR} is not sensitive to all WCs.
We propose another polarisation asymmetry

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

Up-down asymmetry



We calculate the 68% CLs using

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

→ $\delta_{\rm SMEFT}<10^{-7}$