NLO QCD effects on angular observables in single Higgs production at electron-proton collider

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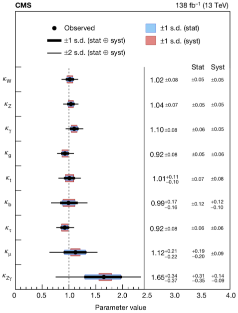
1. Role of angular observables in probing anomalous *HZZ* couplings at an electron-proton (*ep*) collider

2. NLO QCD corrections to single Higgs production at *ep* collider

1. Role of angular observables in probing anomalous HZZ couplings at an electron-proton (ep) collider

Central point $\rightarrow$ New physics

Uncertainty $<$ 10% in Higgs to gauge boson couplings



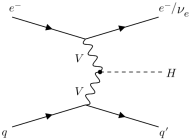
Ref[1]: Eur. Phys. J. C 79, 421 (2019)

$$\Gamma^{\mu\nu}_{HVV}(q_1, q_2) = g_V m_V \kappa_V g^{\mu\nu}$$

$$+\frac{g}{m_W}[\lambda_{1V}(q_1^\nu q_2^\mu - g^{\mu\nu} q_1.q_2)$$

$$+\lambda_{2V}(q_1^\mu q_1^\nu + q_2^\mu q_2^\nu - g^{\mu\nu} q_1.q_1 - g^{\mu\nu} q_2.q_2)$$

$$+\widetilde{\lambda}_V\ \epsilon^{\mu\nu\alpha\beta} q_{1\alpha} q_{2\beta}].$$



q_1 & q_2 $\rightarrow$ momenta of off-shell gauge bosons

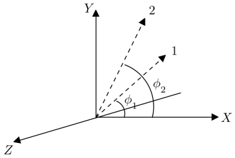
$V = W^\pm$ (CC) and Z (NC)

collider	COM energy (TeV)	process	cross-section (pb)
LHC	14	$pp \to hjj$	3.7
ILC	1	$e^+e^- \to e^+e^-h$ $e^+e^- \to \nu_e\bar{\nu}_e h$	0.007 0.21
CLIC	3	$e^+e^- \to e^+e^-h$ $e^+e^- \to \nu_e\bar{\nu}_e h$	6×10^{-4} 0.50
LHeC	1.3	$e^-p \to e^-hj$ $e^-p \to \nu_e hj$	0.016 0.088

LHeC: e^- energy 60 to 120 GeV with 7 TeV available proton energy

- Sufficiently large cross-section as compared to e^+e^- collider for Higgs production
- Clean environment with the suppressed background as compared to *pp* collider

Observables



- $\Delta\phi_{12} \rightarrow$ difference of azimuthal angle of two particles 1 and 2
  - $\alpha_{12} \rightarrow$ angle between particle 1 and 2
    $$\alpha_{12} = cos^{-1}(\hat{p}_1.\hat{p}_2)$$
  - $\beta_{123} \rightarrow$ angle between particle 3, and normal of the plane in 1 and 2
    $$\beta_{123} = cos^{-1}(\hat{p}_3.\hat{p}_{12}), \text{ where } \vec{p}_{12} = \vec{p}_1 \times \vec{p}_2$$
  - $\theta_1 \rightarrow$ angle of particle 1 with longitudinal direction

Observables

$$e^-(p_1) + q(p_2) \to e^-(p_3) + H(p_4) + q(p_5)$$

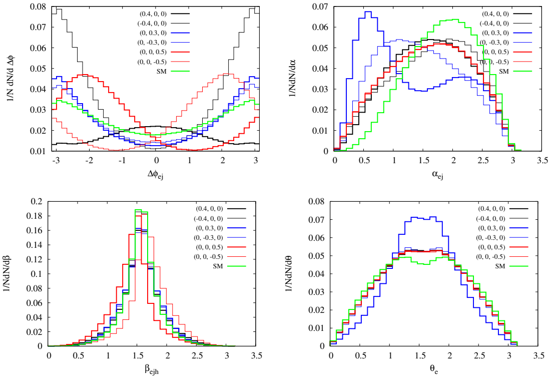
$$\mathcal{L}_{odd} = \frac{\tilde{\lambda}_Z}{4} Z^{\mu\nu} \widetilde{Z}_{\mu\nu} H$$

$$\begin{aligned}\mathcal{M} &= \widetilde{\lambda}_Z \mathcal{J}_\mu \epsilon^{\mu\nu\alpha\beta} q_{1\alpha} q_{2\beta} \mathcal{J}_\nu \\ &\propto \widetilde{\lambda}_Z \epsilon^{\mu\nu\alpha\beta} p_{1\mu} p_{2\nu} p_{3\alpha} p_{5\beta} \\ &= -\widetilde{\lambda}_Z (E_1 p_{2z} + E_2 p_{1z})(\vec{p}_3 \times \vec{p}_5).\hat{z}\end{aligned}$$

And

$$\Delta\phi = tan^{-1}\left[\frac{(\vec{p}_3 \times \vec{p}_5).\hat{z}}{\vec{p}_{T3}.\vec{p}_{T5}}\right]$$

$$(\vec{p}_3 \times \vec{p}_5).\vec{p}_4 = (p_{2z} - p_{1z})(\vec{p}_3 \times \vec{p}_5).\hat{z}$$



Numerical values in the brackets refer to the values of BSM parameters $(\lambda_{1Z}, \lambda_{2Z}, \tilde{\lambda}_Z)$.

Bounds on *HZZ* parameters

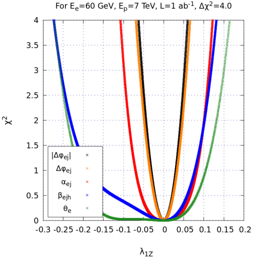
With respect to $|\Delta\phi|$ [3], constraints reduced by

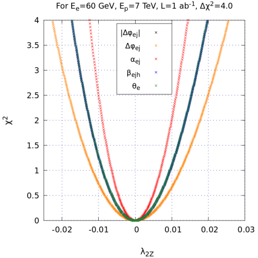
$$\lambda_{2Z}, \tilde{\lambda}_Z \to 43\%, 46\%$$

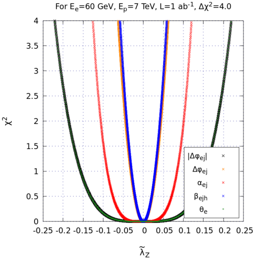
Most stringent bound on individual couplings is given by

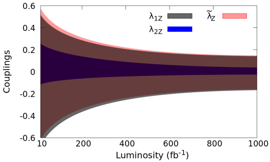
$$\lambda_{1Z} \to |\Delta\phi|$$
$$\lambda_{1Z} \to \alpha_{ej}$$
$$\tilde{\lambda}_Z \to \beta_{ejh}$$

Ref.[3]: arXiv:2207.03862



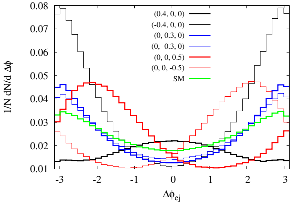


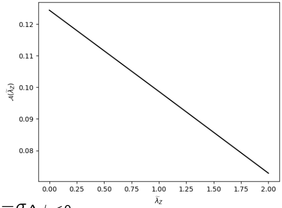




Asymmtery in $\Delta\phi$

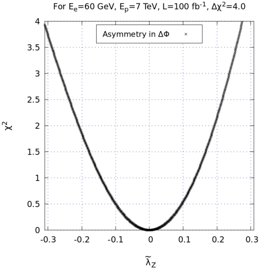
$\Delta\phi \rightarrow [-\pi, \pi] \implies$ more differential information than $|\Delta\phi|$



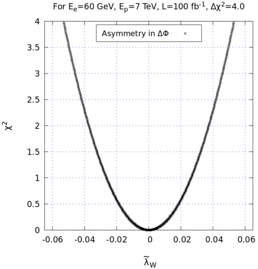


$$\text{Asymmetry in } \Delta\phi = \frac{\sigma_{\Delta\phi>0} - \sigma_{\Delta\phi<0}}{\sigma}$$

NC process



CC process



2. Higher order corrections to single Higgs production at *ep* collider

Motivation: Precision

No automation for higher order correction for *ep* collision!

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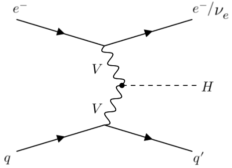
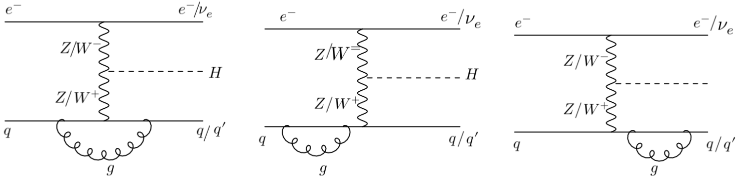
QCD correctons

Tree level

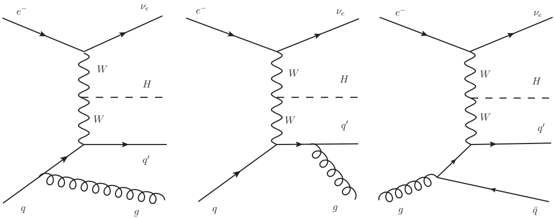


Virtual corrections

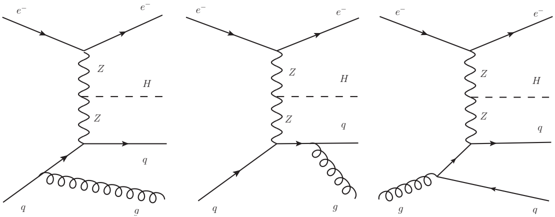


Real Corrections

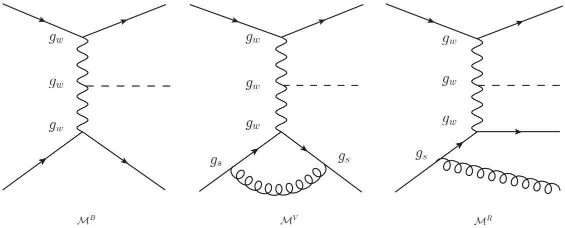
CC process:



NC process:



Coupling Order :



$$\mathcal{M}^B \sim \mathcal{O}(g_w^3)\,, \quad \mathcal{M}^V \sim \mathcal{O}(g_s^2 g_w^3)\,, \quad \mathcal{M}^R \sim \mathcal{O}(g_s g_w^3)\,.$$

$$\Longrightarrow |\ \mathcal{M}\ |_m^2 \sim |\ \mathcal{M}^B\ |^2 + 2.Re[\mathcal{M}^B.\,\mathcal{M}^{V^*}]\,, \quad |\ \mathcal{M}\ |_{m+1}^2 \sim |\ \mathcal{M}^R\ |^2$$

$$\therefore \sigma^T = \sigma^B(\alpha_w^3) + \sigma^V(\alpha_w^3\alpha_s) + \sigma^R(\alpha_w^3\alpha_s)$$

Amplitude computation :

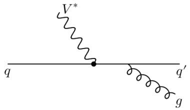
- Spinor helicity formalism is used to compute the matrix element.
- Virtual amplitude is calculated in t'Hooft-Veltman (HV) regularization scheme where only the loop part has been computed in d-dimension, and the rest part has been computed in 4-dimension.

  Virtual Amplitude :

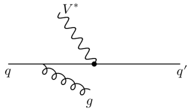
$$\mathcal{M}^V = \frac{\alpha_s}{2\pi} . \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} . C_F . \left(\frac{\mu^2}{t}\right)^\epsilon . \left\{ -\frac{1}{\epsilon^2} - \frac{3}{2\epsilon} - 4 + \mathcal{O}(\epsilon) \right\} \times \mathcal{M}^B$$

- The phase-space integral is being done with the Monte-Carlo package called AMCI. The package AMCI is based on the VEGAS algorithm.

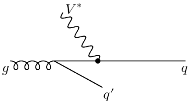
Real corrections



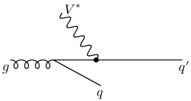
(1)



(2)



(3)



(4)

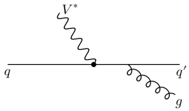
$$
\begin{aligned}
(1,2): &\quad q(p_a)V^* \to q'(p_1) + g(p_2) \\
(3,4): &\quad g(p_a)V^* \to q'(p_1) + q(p_2)
\end{aligned}
$$

$$\frac{1}{p_1.p_2} = \frac{1}{E_1 E_2(1 - cos\theta_{12})}$$

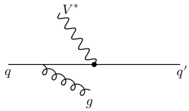
Soft divergence: $E_2 \to 0$, Collinear divergence: $\theta_{12} \to 0$
By KLN theorem

$$d\sigma^{NLO} = \int_{m+1} d\sigma^R + \int_m d\sigma^V$$

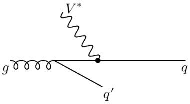
Real corrections



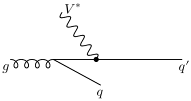
(5)



(6)



(7)



(8)

$$(1,2): \quad q(p_a)V^* \rightarrow q'(p_1) + g(p_2)$$
$$(3,4): \quad g(p_a)V^* \rightarrow q'(p_1) + q(p_2)$$

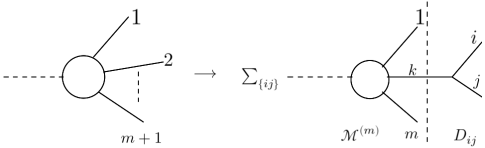
$$\frac{1}{p_1.p_2} = \frac{1}{E_1 E_2(1 - cos\theta_{12})}$$

Soft divergence: $E_2 \rightarrow 0$, Collinear divergence: $\theta_{12} \rightarrow 0$

$$d\sigma^{NLO} = \int_{m+1} d\sigma^R + \int_m d\sigma^V + \int_m d\sigma^C$$

Dipole substraction scheme

$$d\sigma^{NLO} = \int_{m+1} \left[d\sigma^R - d\sigma^A\right] + \int_m d\sigma^V + \int_{m+1} d\sigma^A + \int_m d\sigma^C$$
$$= \int_{m+1} \left[(d\sigma^R)_{\varepsilon=0} - (d\sigma^A)_{\varepsilon=0}\right] + \int_m \left[d\sigma^V + \int_1 d\sigma^A + d\sigma^C\right]_{\varepsilon=0}$$



$$|\mathcal{M}^{(m+1)}|^2 \longrightarrow \mathcal{D}_{ij}\ |\mathcal{M}^{(m)}|^2, \qquad \text{here } \mathcal{D}_{ij} \sim \frac{1}{p_i . p_j}$$

$$d\sigma^A = \sum_{i=1}^{4} d\sigma_i^A$$

Ref: Catani & Seymour, arXiv:hep-ph/9605323

Dipole Subtraction scheme

$$\int_{m+1} d\sigma^A + \int_m d\sigma^C = \int d\sigma^B . I(\epsilon) + \text{finite remnant}$$

The insertion operator:

$$I(\epsilon) = \frac{\alpha_s}{2\pi} . \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} . 2C_F . \left(\frac{\mu^2}{t}\right)^\epsilon . \left\{ \frac{1}{\epsilon^2} + \frac{3}{2\epsilon} + 5 - \frac{\pi^2}{2} + \mathcal{O}(\epsilon) \right\}$$

- This **I**-term cancels all IR poles $(\frac{1}{\epsilon^2}, \frac{1}{\epsilon})$ from $d\sigma^V$.
- These dipole terms exhibit the same singular behavior as $d\sigma^R$ in collinear and soft regions.
- There is also collinear-subtraction counterterm $(d\sigma^C)$ which gives the finite remnant after leftover collinear singularities absorbed in PDF.

Input parameters and Scale choice

- Input parameter:

$$\mathrm{M}_W = 80.379\,\mathrm{GeV}, \quad \Gamma_W = 2.085\mathrm{GeV}$$
$$\mathrm{M}_Z = 91.1876\,\mathrm{GeV}, \quad \Gamma_Z = 2.4952\,\mathrm{GeV}$$
$$G_\mu = 1.16638 \times 10^{-5}\mathrm{GeV}^2, \quad \alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \Big(1 - \frac{M_W^2}{M_Z^2}\Big)$$

- We consider the following dynamical scale for PDF evolution and running of strong coupling.

$$\mu_R = \mu_F = \mu_0 = \frac{1}{3}\Big(p_{T,\ell} + \sqrt{p_{T,H}^2 + M_H^2} + p_{T,j}\Big)$$

- We compute the scale uncertainty by varying $\mu_{R/F}$ in between $0.5\mu_0 \leq \mu_{R/F} \leq 2\mu_0$.

Results : NC and CC

Collider Energy : $E_e = 140$ GeV, $E_p = 7$ TeV (CME$=1.98$ TeV)

Process $e^- p \to$	σ_0 (fb)	σ_{qcd}^{NLO} (fb)	RE (%)
$e^- Hj$	$44.70^{+1.97\%}_{-1.86\%}$	$49.08^{+0.41\%}_{-0.53\%}$	9.80
$\nu_e Hj$	$214.31^{+2.30\%}_{-2.13\%}$	$237.59^{+0.89\%}_{-0.72\%}$	10.86

Here $\sigma_{qcd}^{NLO} = \sigma^0 + \sigma^V + \sigma^I + \sigma^{PK} + \sigma^{DSR}$. Where DSR stands for dipole subtracted real emission.

The relative enhancement is defined as $RE = \left(\frac{\sigma_{qcd}^{NLO} - \sigma_0}{\sigma_0}\right) \times 100$.

p_T distributions

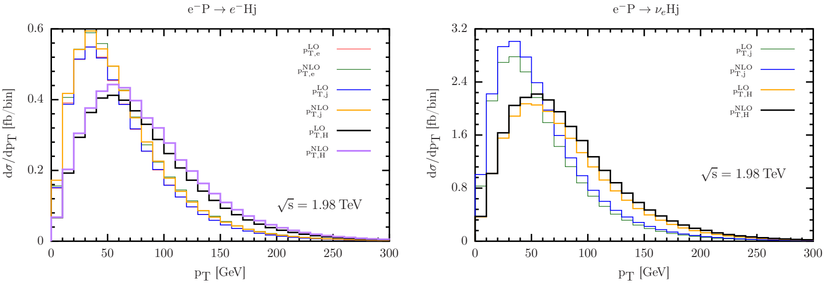


Figure: $e^- p \to e^- Hj$ (left), $e^- p \to \nu_e Hj$(right)

Invariant-mass distributions

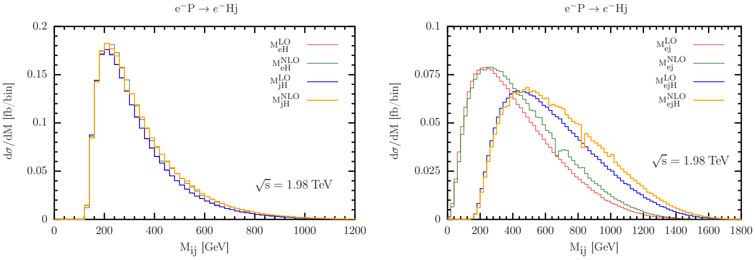


Figure: $e^- p \to e^- Hj$.

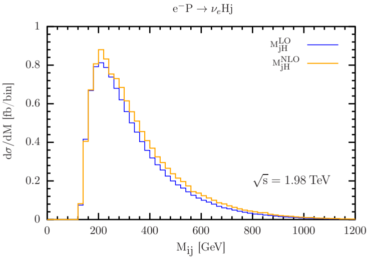


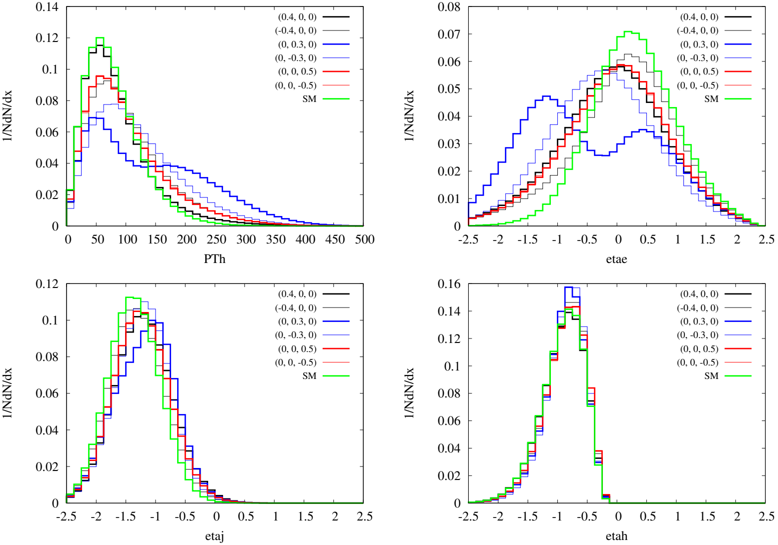
Figure: $e^- p \to \nu_e Hj$..

Summary and Outlook

- We have computed the QCD NLO correction to H production with one jet at ep collider.
- We found the NLO QCD correction around 10% at 1.98 TeV CME.
- We found that the invariant mass and the p_T distributions are harder with NLO-corrected results.
- We will implement our calculation to see the effects of NLO QCD corrections on angular observables sensitive to anomalous HVV coupling.

Back Up

p_T and η



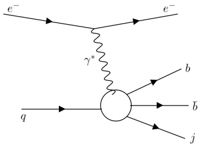
1/NdN/dx
PTh
etae
etaj
etah
0 50 100 150 200 250 300 350 400 450 500
-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08
0 0.02 0.04 0.06 0.08 0.1 0.12
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16
(0.4, 0, 0)
(-0.4, 0, 0)
(0, 0.3, 0)
(0, -0.3, 0)
(0, 0, 0.5)
(0, 0, -0.5)
SM

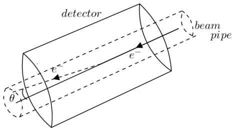
Signal vs Background

Signal for CC (NC) $e^- p \to \nu_e(e^-)hj, h \to b\bar{b}$ where $j = u, c, d, s, g$

Backgrounds for CC (NC)

- Irreducible background: $e^- p \to \nu_e(e^-)b\bar{b}j$
- Reducible background:
  1. $e^- p \to \nu_e(e^-)jjj$
     Negligible for miss-tagging rates, c jet $\to$ 0.1 light jet $\to$ 0.01
  2. $e^- p \to \nu_e(e^-)b\bar{b}jj$
  3. Photo production from $e^- p \to e^- b\bar{b}j$: $\gamma^* p \to b\bar{b}j$





e^- missing in detector can account as missing transverse energy ($\not{E}_T$) of neutrino for CC process $e^- p \to \nu_e hj, h \to b\bar{b}$
and e^- should be very close to beam pipe $\implies$ $p_T(e^-)$ very small

$\implies$ by minimum $\not{E}_T$ cut, photo production background is suppressed

Signal vs Background

Energy smearing of partons by $\frac{\Delta E}{E} = a/\sqrt{E} \oplus b$, where $x \oplus y = \sqrt{x^2 + y^2}$
a=0.6, b=0.04 for parton jets, a=0.12, b=0.02 for electron [2]

Cuts for NC

$p_T(e) > 20\ GeV, p_T(j) > 30\ GeV, p_T(b) > 30\ GeV$
$|M_{b\bar{b}} - m_H| < 15\ GeV$
$|\eta_e| < 2.5, 2 < \eta_j < 5.0, 0.5 < \eta_b < 4.0, M_{Hj} < 300\ GeV$

Process	Events at generation level	events after cuts
signal	534	76
$e^- b\bar{b}j$	2.75×10^6	161
$e^- b\bar{b}jj$	6.3×10^5	24
S/B	0.02×10^{-2}	0.41

Cuts for CC

$p_T(j) > 30\ GeV, p_T(b) > 30\ GeV, \not{E}_T > 25\ GeV$
$|M_{b\bar{b}} - m_H| < 15\ GeV$
$1 < \eta_j < 5.0, -1 < \eta_b < 4.0, M_{Hj} < 250\ GeV$

Process	Events at generation level	events after cuts
signal	3011	819
$\nu_e b\bar{b}j$	18883	30
$\nu_e b\bar{b}jj$	10985	38
S/B	0.1	12.0

Ref [2]: LHeC, FCC-he Study Group collaboration, J. Phys. G 48 (2021)

χ^2 function for asymmetry in $\Delta\phi$ is given by,

$$\chi^2(\lambda_i) = \sum_j \left(\frac{\mathcal{O}_j^{BSM}(\lambda_i) - \mathcal{O}_j^{SM}}{\Delta \mathcal{O}} \right)^2$$

$\Delta\mathcal{A}$ is the quadrsum of statistical and systematic uncertainties. Statistical uncertainity for asymmetry is given as,

$$\Delta\mathcal{A}_{stat} = \sqrt{\frac{1 - \mathcal{A}_{SM}^2}{\sigma_{SM}.L}}. \tag{1}$$

UV renormalisation

Lagrangian for 3-point interaction

$$\mathcal{L} = \bar{\psi} A_\mu \gamma^\mu (C_V + C_A \gamma^5)\psi$$

$\psi = \sqrt{Z_\psi}\psi_R$ where $Z_\psi = 1 + \delta_\psi$

Counter term Lagrangian

$$\mathcal{L} = \delta_\psi \bar{\psi}_R A_\mu \gamma^\mu (C_V + C_A \gamma^5)\psi_R$$

$$\text{counter term } \delta_\psi = \frac{\alpha}{4\pi}.C_F \left(\frac{1}{\epsilon_{UV}} - \frac{1}{\epsilon_{IR}}\right)$$

$$\Gamma^\mu \equiv \left\{\frac{2}{\epsilon_{IR}^2} + \frac{4}{\epsilon_{IR}} - \frac{1}{\epsilon_{UV}} + 10 - \pi^2 + \mathcal{O}(\epsilon)\right\}$$

$$\Gamma_R^\mu = \Gamma^\mu + \Gamma_{CT}^\mu$$