Anomalous triple gauge couplings in electroweak dilepton tails at the LHC and interference resurrection

UI MIN

Tsung-Dao Lee Institute

Dec. 1st, 2023

Higgs 2023 in Beijing

Haeyun Hwang, Ui Min, Junghyeon Park, Minho Son, and Jae Hyeok Yoo, *JHEP* 08 (2023) 069, arXiv: 2301.13663 [hep-ph]

Outline

I. Introduction

- Noninterference in the diboson process
- Interference resurrection in the diboson process

II. EW dilepton production with two associated jets

III. Toy process for analytic study: Single lepton with an associated jet

- Cross section for on-shell W boson
- Cross section for off-shell W boson
- Numerical calculation of toy process and interference resurrection

IV. Numerical analysis of EW dilepton with two associated jets

V. Conclusion

Introduction

- No evidence for the new physics, or beyond the Standard Model (BSM) at the LHC after the discovery of the Higgs boson

- If new particles exist, they are very weakly coupled to the SM or hidden in the energy scale beyond the LHC reach.

- With the mass gap between the electroweak and new physics scales, the effective field theory approach makes sense to parametrize the possible new physics effects encoded in the higher-dimensional operators.

- Standard Model Effective Field Theory (SMEFT) below the cutoff Λ with the assumption of the lepton number conservation :

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathscr{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathscr{O}_i^{(8)} + \cdots \quad ,$$

Introduction

- We focus on the precision measurements of the cubic interaction of the gauge bosons at the LHC.

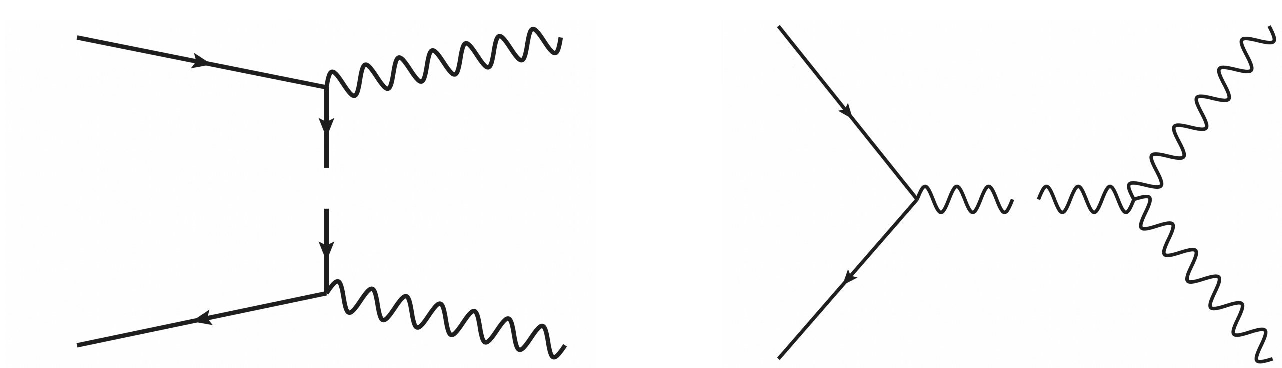
- In the SMEFT up to dimension-6 operators, the deviation of the triple gauge couplings from the SM can be parametrized in terms of three **anomalous Triple Gauge Couplings** (aTGC) : $\lambda_z, \delta g_{1,z}, \delta\kappa_z$

$$
\begin{aligned}
\mathscr{L}_{\rm tgc} = & \; ie\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + ie\frac{c_\theta}{s_\theta}\left(1+\delta g_{1,z}\right)\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu \\
& + ie(1+\delta\kappa_\gamma)A_{\mu\nu}\,W^+_\mu W^-_\nu + ie\frac{c_\theta}{s_\theta}\left(1+\delta\kappa_z\right)Z_{\mu\nu}\,W^+_\mu W^-_\nu \\
& + i\frac{\lambda_z e}{m_W^2}\left[W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + \frac{c_\theta}{s_\theta}W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}\right], \qquad \text{where } \delta\kappa_z = \delta g_{1,z} - \frac{s_\theta^2}{c_\theta^2}\delta\kappa_\gamma
\end{aligned}
$$

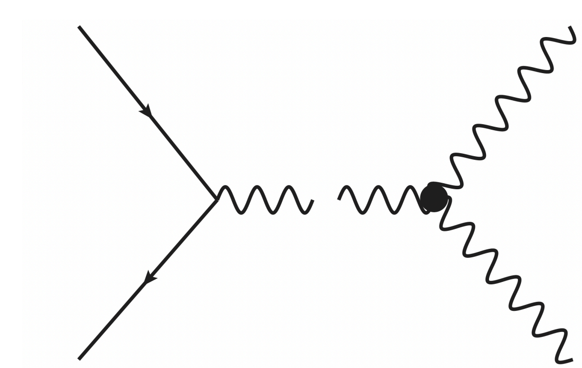
- Typically, measurements of aTGC at the LHC have been performed by using diboson processes such as WW, WZ and $W\gamma$ in the lepton final state channels

ATL-PHYS-PUB-2021-022 (2021), JHEP **07** (2022) 032, Phys. Rev. D **105** (2022) 5

- the sensitivity on aTGC from the LHC relies on the accessibility to the higher energy as long as it does not violate the validity of the EFT, $E/\Lambda \lesssim 1$



SM diagrams for diboson production

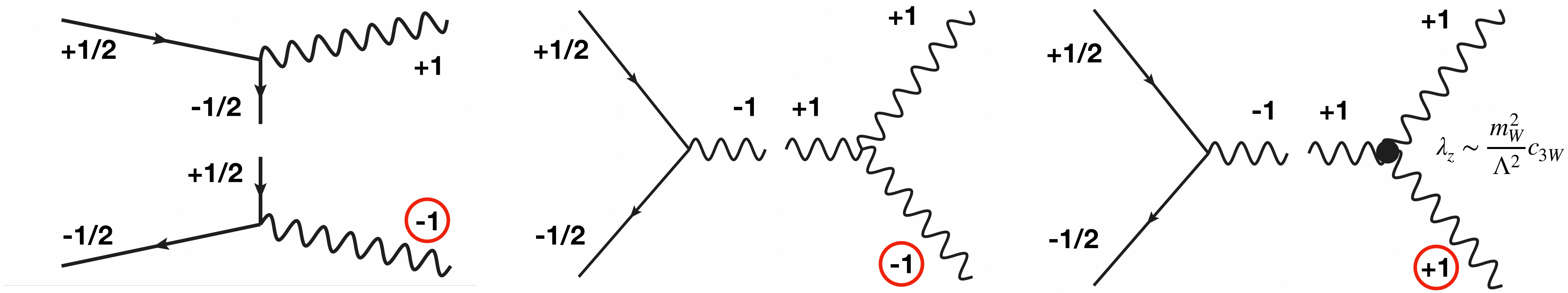


BSM diagram with aTGC vertex

Noninterference in the Diboson Process

In the high energy limit, for the transverse modes of the gauge bosons the **noninterference between the SM and BSM** amplitudes was found due to the **helicity structure** of the amplitudes including the dim-6 $\mathcal{O}_{3W} \sim \mathrm{Tr}[W_{\mu\nu}W_{\nu\lambda}W_{\lambda\mu}]$.

Phys. Rev. Lett. 115 (2015) no. 7 071601 , Phys. Rev. D 95 (2017) no. 6 065014



SM Feynman diagrams **BSM diagram with $\mathcal{O}_{3W}$**

1. The leading BSM contribution to the total cross section scales $\mathcal{O}(\Lambda^{-4})$, and it may **invalidate the EFT expansion** in terms of Λ.

$$\frac{\sigma_{\text{tot}}}{\sigma_{\text{SM}}} = 1 + \cancel{c_i^{(6)} \frac{E^2}{\Lambda^2}} + c_i^{(6)} c_j^{(6)} \frac{E^4}{\Lambda^4}$$

2. It also makes the SMEFT data sensitive to the dimension-8 operators : the interference between the SM amplitude and one with dimension-8 operators.

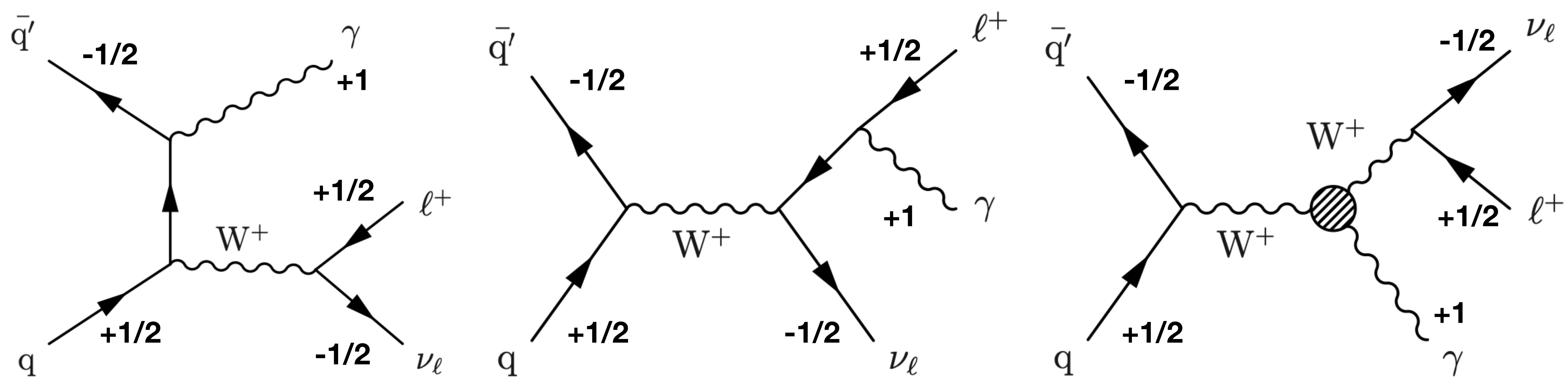
$$\frac{\sigma_{tot}}{\sigma_{SM}} = 1 + c_i^{(8)} \frac{E^4}{\Lambda^4} + \ldots$$

Interference Resurrection in the Diboson Process

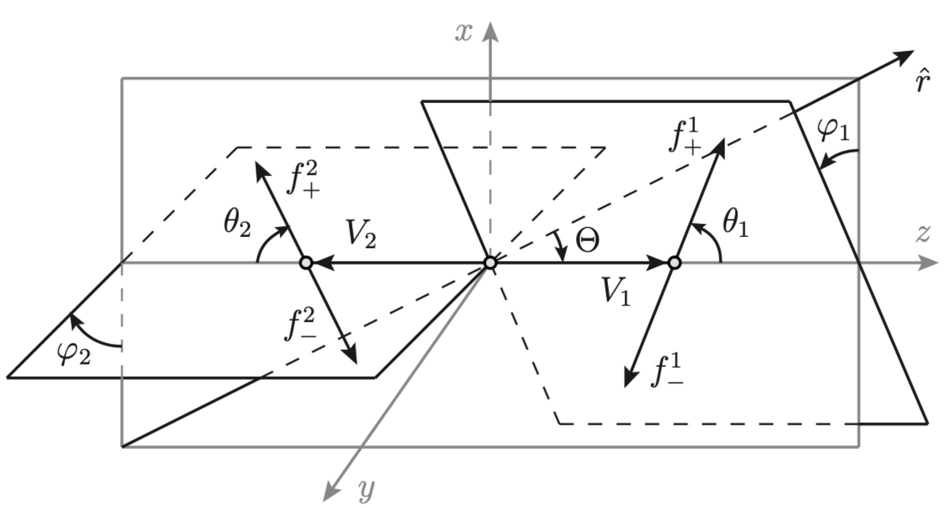
Many attempts to resurrect the interference in the diboson process:

JHEP 10 (2017) 027 , Phys. Lett. B 776 (2018) 473–480 , JHEP 04 (2019) 075 , JHEP 02 (2018) 111 , JHEP 08 (2019) 009

The $2 \to 2$ diboson amplitude can be extended to $2 \to 3\,(4)$ by gluing with the three point amplitudes for a gauge boson decay into two fermions, the total helicity of both amplitudes of the dimension-6 and the SM can match.



Non-vanishing differential angular distributions in the leptonic decay channels.



Phys. Lett. B 776 (2018) 473–480

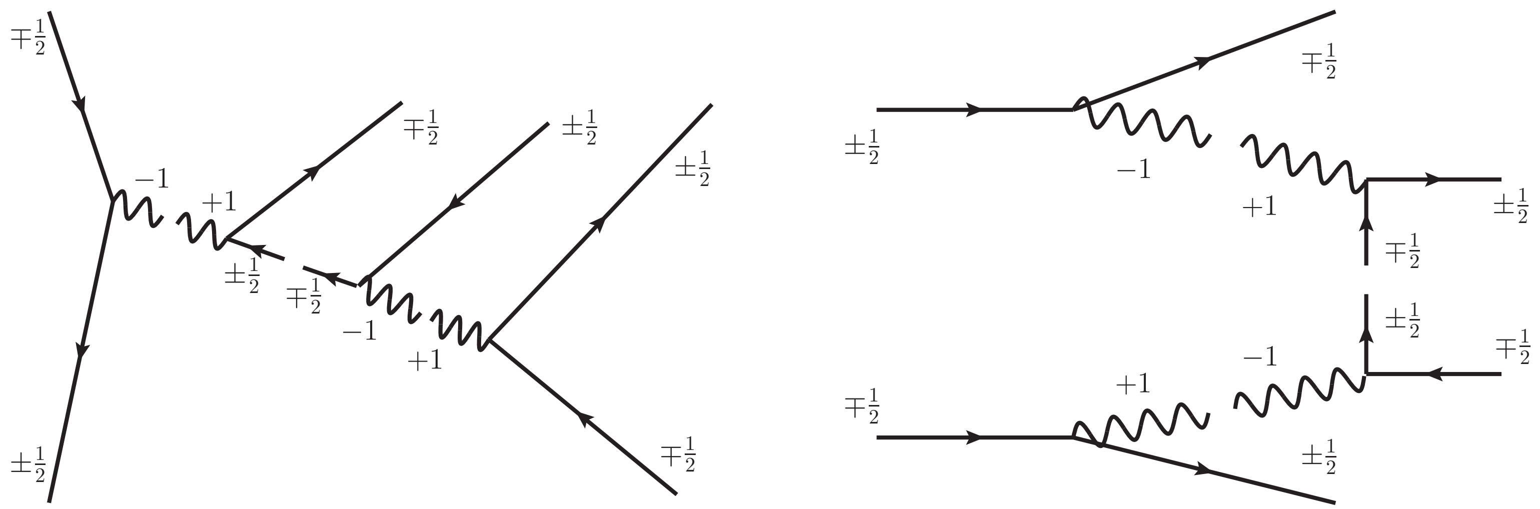
$$\frac{1}{\sigma_{\rm SM}} \cdot \frac{d\sigma_{\rm SM\times BSM^{(6)}}}{d\phi} \propto c^{(6)} \frac{E^2}{\Lambda^2} f(\phi_1, \phi_2)$$

For on-shell $V_{1,2}$,

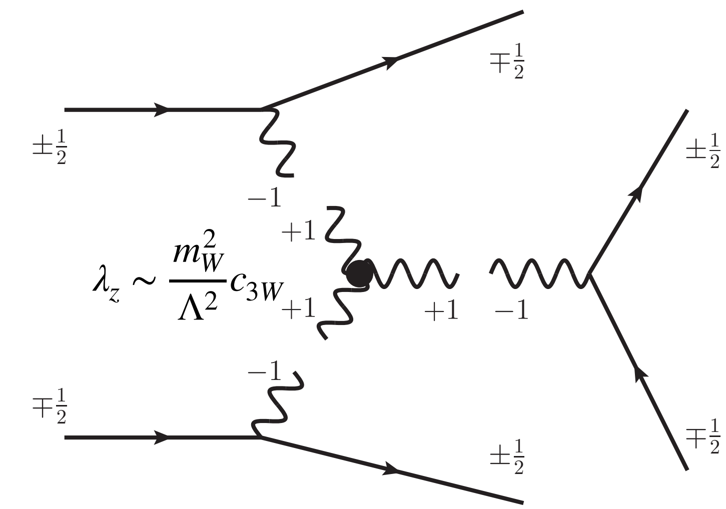
$$\sigma_{\rm SM\times BSM^{(6)}} = \int d\phi \, \frac{d\sigma_{\rm SM\times BSM^{(6)}}}{d\phi} = 0$$

EW Dilepton Production with Two Associated Jets

In our work, we consider the **dilepton production process with two associated forward jets** in the vector boson fusion (VBF) for the interference resurrection at $\sqrt{s} = 13\,\mathrm{TeV}$ and the integrated luminosity of $35.9\,\mathrm{fb}^{-1}$



SM diagrams for $\ell\ell + qq'$



BSM diagram with $\mathcal{O}_{3W}$

Strong point compared to the diboson process:
the interference between the amplitudes with dimension-6 operators and those from the SM is resurrected in the inclusive cross section of the $2 \to 4$ process

In the vector boson fusion (VBF) processes, $\dfrac{\sigma_{\mathrm{SM}\times\mathrm{BSM}^{(6)}}}{\sigma_{\mathrm{SM}}} \propto c^{(6)} \dfrac{E^2}{\Lambda^2}$

Effective W-boson Approximation

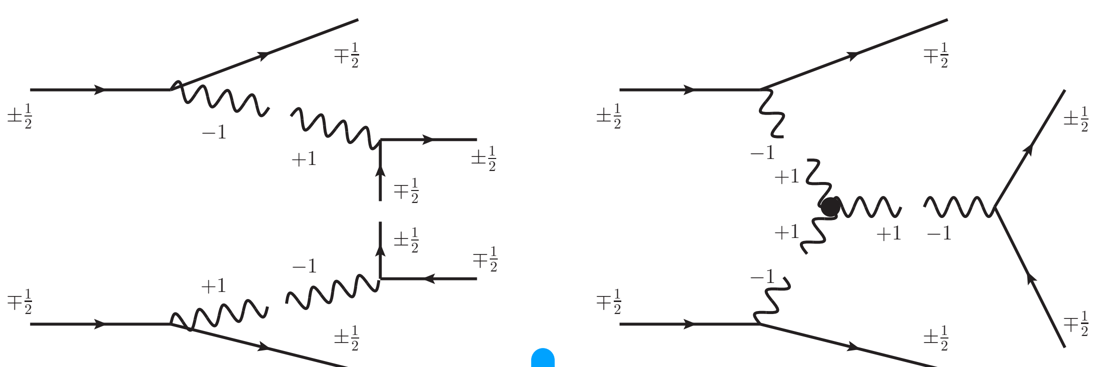
Effective W-boson Approximation (EWA) :
Approximation to factorize W bosons from the quark lines and to make the W boson initiated subprocesses

- One can effectively treat the virtual W as on-shell gauge boson at $\Delta t \gg t$.

  $\Delta t \sim E/V^2$, $t \sim 1/E$, E: energy scale of hard subprocess, V: virtuality of the gauge boson

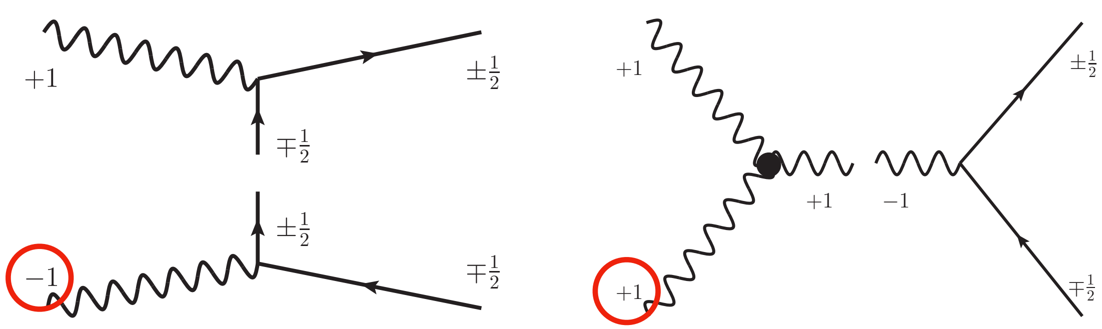
- Total cross-section is approximated by the convolution of the probability density function of the gauge boson and the the partonic cross-section of the hard subprocess.

$$\frac{d\sigma_{\mathrm{EWA}}}{dx}\left(qX \to q'Y\right) \simeq \sum_i f_{W_i}(x) \times d\sigma\left(W_i(x)\, X \to Y\right)$$



In $2 \to 4$ process (before EWA):
interference allowed by the same helicity structures between SM and BSM

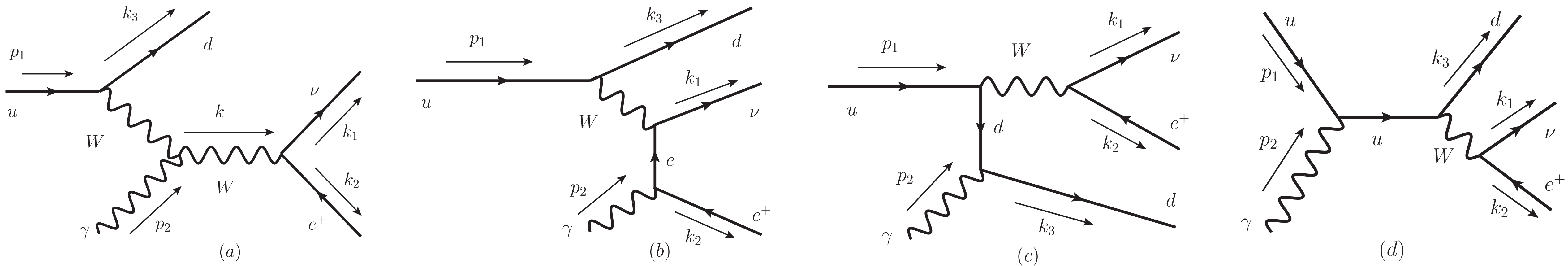
EWA phase space integration over the regime where EWA works



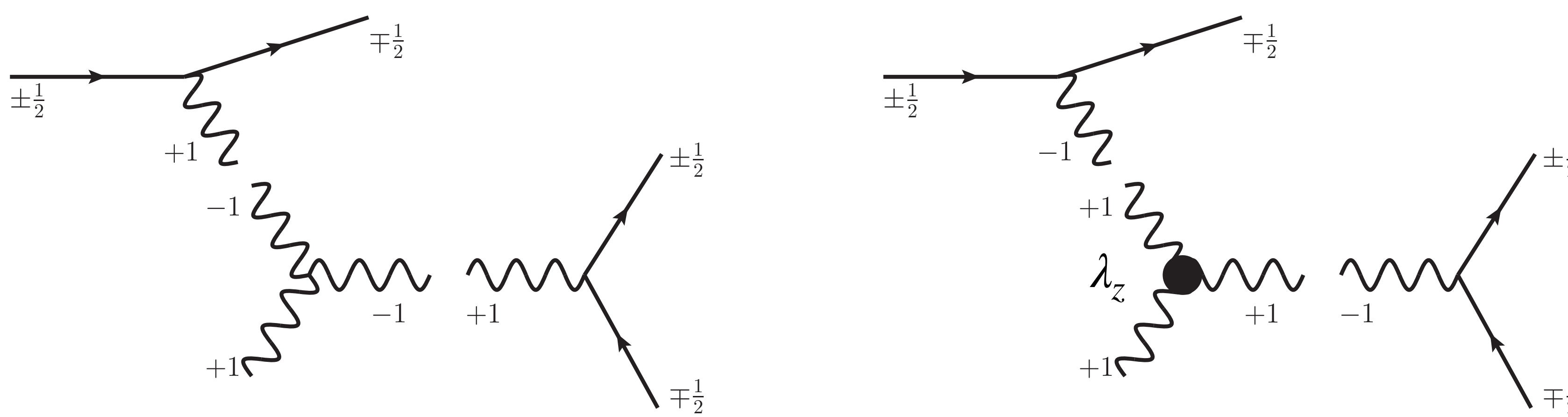
In $2 \to 2$ process (after EWA):
vanishing interference due to distinct helicity structures between SM and BSM

Toy Process: Single Lepton with an Associated Jet

For an analytic study of the process, a simpler $2 \to 3$ process $u\gamma \to d\nu e^+$ involving only one forward quark current and intermediate gauge boson(s) is considered.



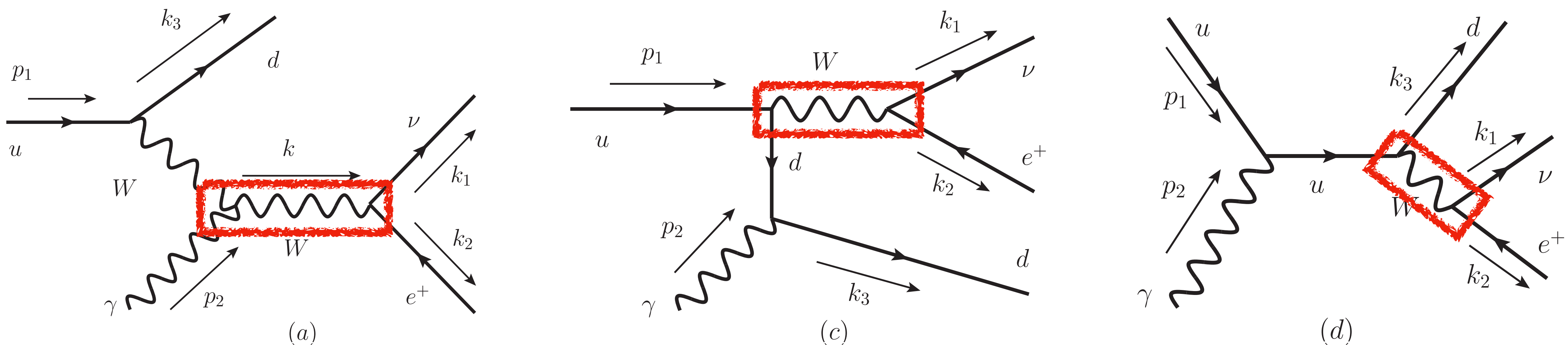
- Helicity assignment of diagrams for the interference between the SM and BSM with aTGC λ_z



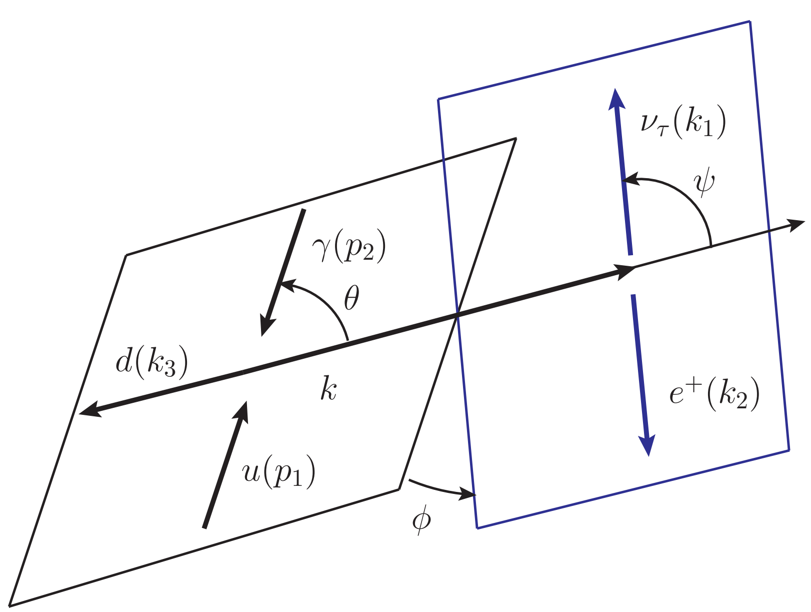
- In the end, we find that the interference cross-section of $u\gamma \to d\nu e^+$ with respect to the SM does resurrect the energy growing behavior in the inclusive cross section, that has been lost in the EWA limit.

Cross-section for On-shell W-boson

The $2 \to 3$ toy process $u\gamma \to d\nu e^+$ can be factorized into the $2 \to 2$ process of $u\gamma \to dW$ and the decay of W to $\nu_e e^+$ using the **narrow width approximation** for the **on-shell W boson** of the width Γ_W.



partonic differential cross-section for the interference in the high energy limit $\hat{s} \gg m_W^2$:



kinematics of $2 \to 3$ process

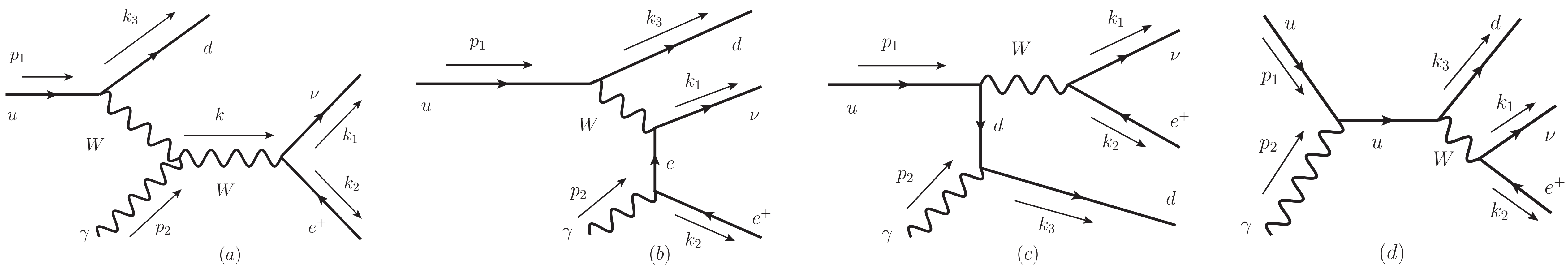
$$\frac{d\sigma_{\mathrm{SM}\times\mathrm{BSM}^{(6)}}}{d\phi} = \frac{1}{2\cdot 2}\frac{\lambda_z}{512\pi^4}\frac{\pi e^2 g^4}{3}\frac{2}{m_W\Gamma_W}\cos(2\phi)\left[2 - \log\frac{\hat{s}}{m_W^2} + \mathcal{O}(\hat{s}^{-1/2})\right]$$

- Upon the integration over the angle ϕ, the interference term vanishes.

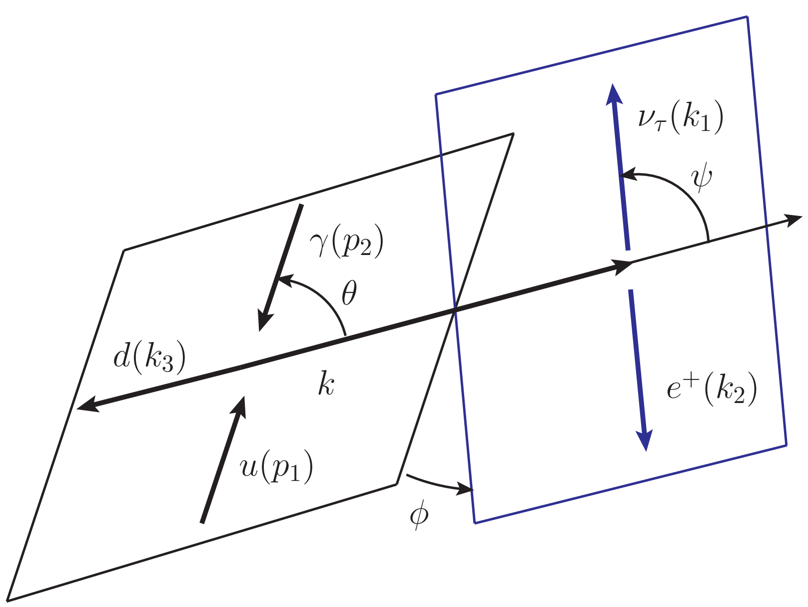
- Noninterference at the inclusive level because it is basically $2 \to 2$ process $u\gamma \to dW$ where the W decay process can be factorized.

Cross-section for Off-shell W-boson

The intermediate W bosons are **off-shell** in this situation.
All the possible diagrams for $2 \to 3$ process of $u\gamma \to d\nu e^+$ should be considered.



Leading contribution to the total cross-section for the interference in the limit of $\hat{s} \gg m_W^2$ far away from the W mass window:



kinematics of $2 \to 3$ process

$$\sigma_{\mathrm{SM}\times\mathrm{BSM}^{(6)}} = \frac{1}{2\cdot 2}\,\frac{\lambda_z}{512\pi^4}\,\frac{e^2 g^4}{m_W^2} \times \frac{\pi}{3}\left(13 - 6\ln\frac{\hat{s}}{m_W^2}\right) + \cdots$$

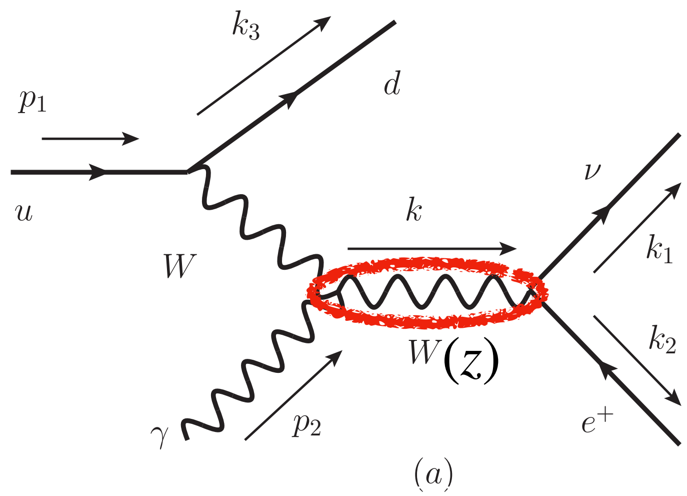
Interference resurrection in the inclusive cross-section (even after integration over the angle ϕ)

$$\frac{\sigma_{\mathrm{SM}\times\mathrm{BSM}^{(6)}}}{\sigma_{\mathrm{SM}}} \propto \frac{\lambda_z}{m_W^2} \times \hat{s} + \cdots$$

Energy growing behavior in the region where the virtuality of the W boson is large (narrow width approximation cannot be applied.)

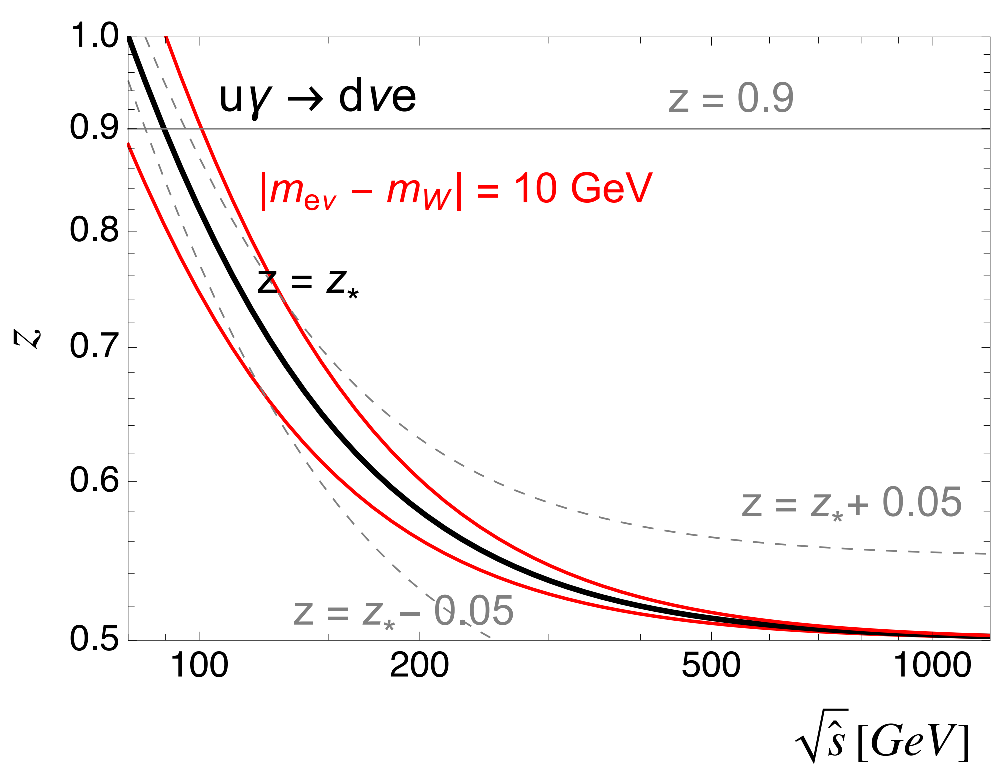
Numerical Calculation of Toy Process

Numerical investigation on the toy process $u\gamma \to d\nu e^+$



$z = E_{e\nu}/\sqrt{\hat{s}}$: energy fraction carried by $e\nu$ system

$z_\star = 1/2 + m_W^2/(2\hat{s})$: energy fraction carried by on-shell W



To access the off-shell region of W, we impose

1. bound on z corresponding to W mass window of 10 GeV

2. cut on $\Delta z = \left| z - z_\star \right|$ for large virtuality at large $\sqrt{\hat{s}}$

Solid back line denotes z for the on-shell W of $e\nu$ system

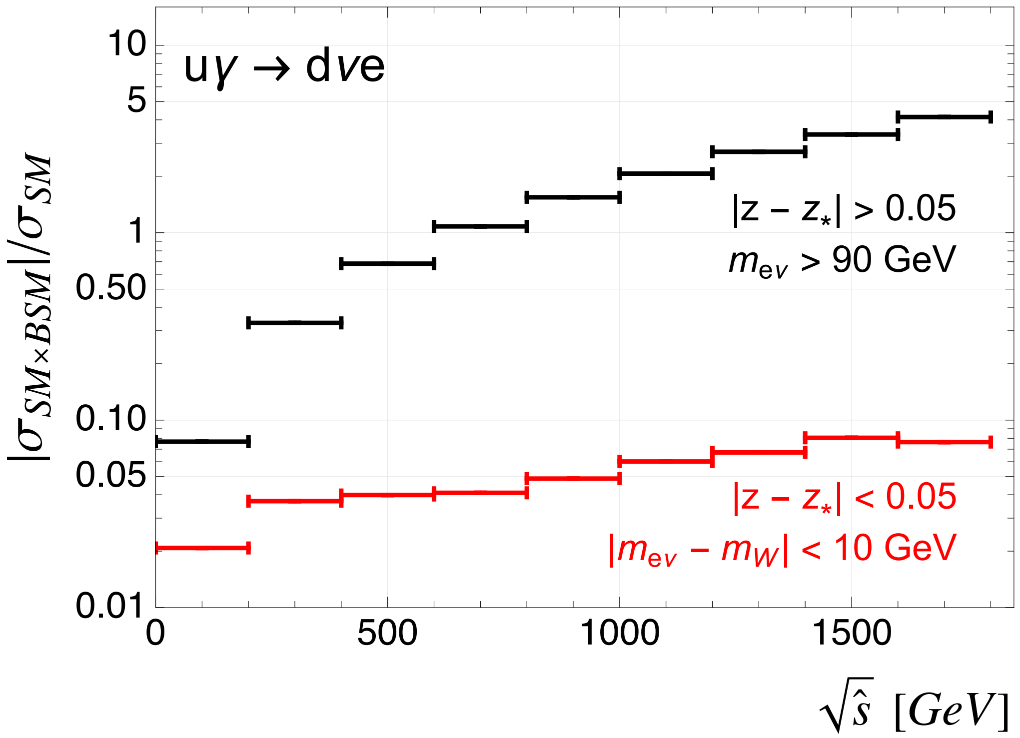
Numerical Calculation of Toy Process

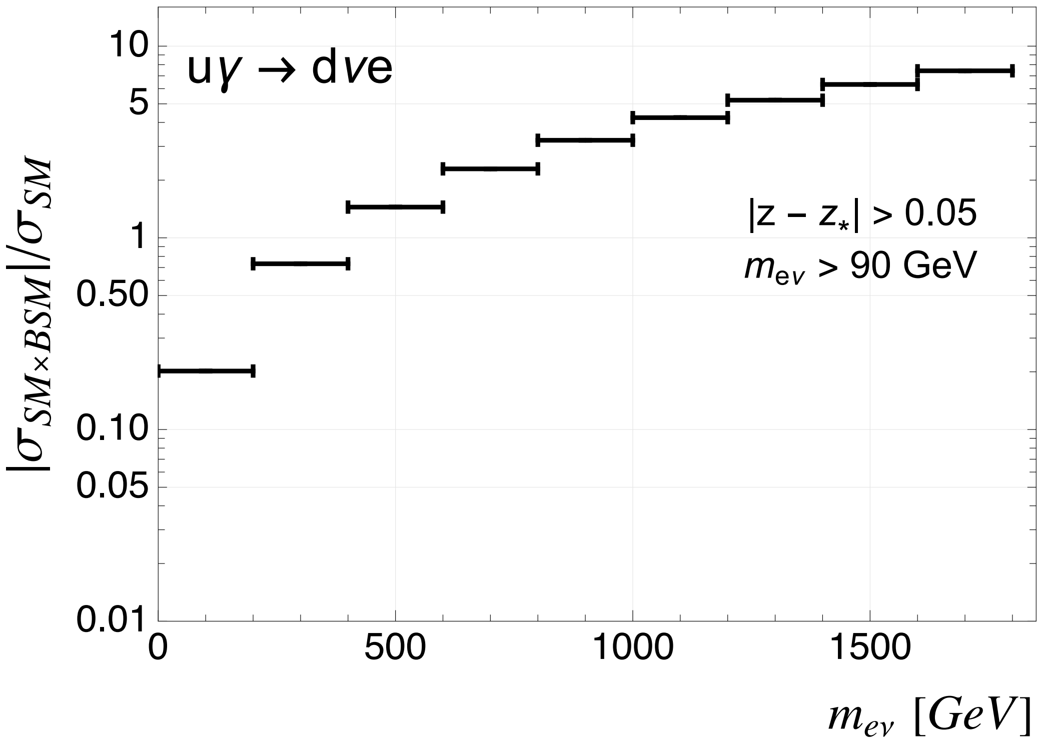
$z = E_{e\nu}/\sqrt{\hat{s}}$: energy fraction carried by $e\nu$ system

$z_\star = 1/2 + m_W^2/(2\hat{s})$: energy fraction carried by on-shell W

Event generation at the partonic level for the EW $u\gamma \to d\nu e^+$ process using MadGraph5_aMC@NLO :

- events for the interference only with λ_z coupling
- p_T cuts : $p_T(d) > 10\,\mathrm{GeV},\ p_T(e) > 10\,\mathrm{GeV},\ p_T(\nu) > 10\,\mathrm{GeV}$





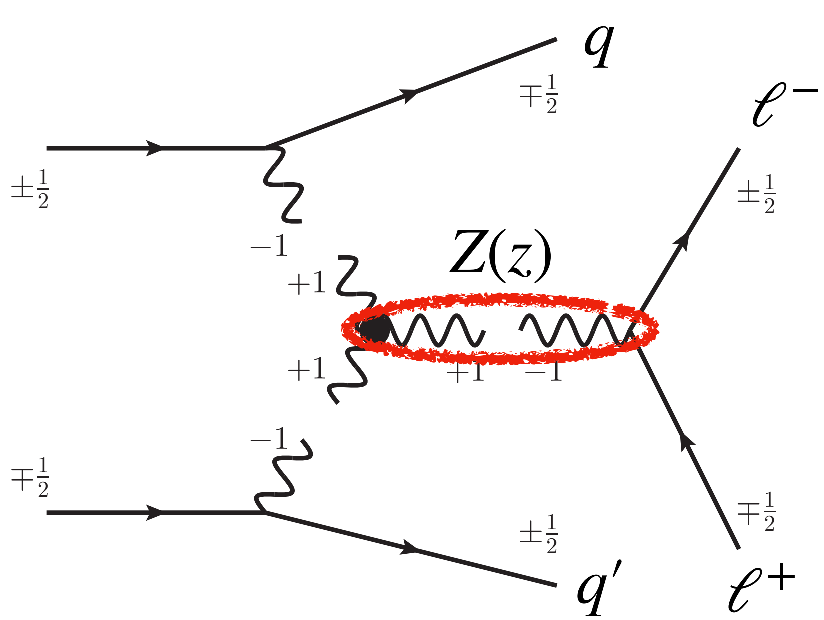
1. distribution of $\sigma_{\mathrm{SM}\times\mathrm{BSM}^{(6)}}$ in the off-shell region

2. distribution of $\sigma_{\mathrm{SM}\times\mathrm{BSM}^{(6)}}$ in the on-shell W mass window

resurrected energy growing interference in the inclusive cross section for the off-shell W , which will get lost if one assumes the EWA and works on the $2 \to 2$ subprocess with the on-shell W.

Numerical Analysis of EW Dilepton with Two Associated Jets

Numerical investigation on the EW $\ell\ell + qq'$ process at the LHC.



$z = E_{\ell\ell}/\sqrt{\hat{s}} = 1/2 + (m_{\ell\ell}^2 - m_{qq'}^2)/(2\hat{s})$: energy fraction carried by $\ell\ell$ system

$z_\star = 1/2 + (m_Z^2 - m_{qq'}^2)/(2\hat{s})$: energy fraction carried by on-shell Z

The variable z can be translated into the nontrivial combination of various kinematic variables via the relation :

$$\mathrm{VBFhardness} \equiv \frac{m_{\ell\ell}^2 - m_{qq'}^2}{p_T^2(qq')\cosh^2\eta_{qq'} + m_{qq'}^2} = \frac{2z-1}{(1-z)^2} \geq \frac{2z_{\mathrm{cut}}-1}{(1-z_{\mathrm{cut}})^2} \quad \text{for} \quad z \geq z_{\mathrm{cut}} \ ,$$

cut on the energy fraction of dilepton system, z

→ cut on "VBFhardness" for an off-shell limit of the intermediate Z boson

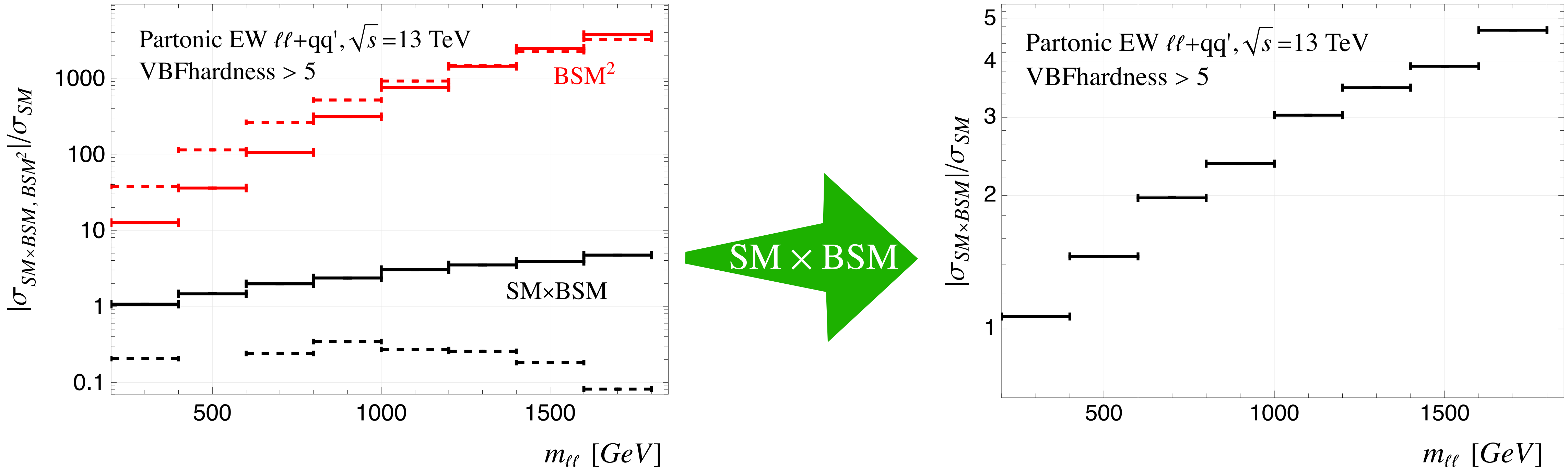
Numerical Analysis of EW Dilepton with Two Associated Jets

$z = E_{\ell\ell}/\sqrt{\hat{s}} = 1/2 + (m_{\ell\ell}^2 - m_{qq'}^2)/(2\hat{s})$: energy fraction carried by $\ell\ell$ system

$z_\star = 1/2 + (m_Z^2 - m_{qq'}^2)/(2\hat{s})$: energy fraction carried by on-shell Z

Event generation at the partonic level for the EW $\ell\ell + qq'$ process for the λ_z coupling using MadGraph5_aMC@NLO :

- cuts : $p_T(q) > 25\,\mathrm{GeV},\ p_T(\ell) > 10\,\mathrm{GeV},\ m_{qq'} > 120\,\mathrm{GeV}$



solid lines : $\mathrm{VBFhardness} > 5 \ \leftrightarrow\ z > 0.71$ for far off-shell region of Z boson
dashed lines : no VBFhardness cut, dominant contribution from the regime where EWA works

black solid line : energy growing interference at the inclusive level for the λ_z coupling

Conclusion

- We have explored the EW dilepton production with two associated jets for the precision measurement of aTGC couplings.

- The interference between the SM and BSM amplitudes is subject to the helicity selection rule.

- The sizable interference in the total cross section can arise from beyond the relevant regime for the EWA.

- We have introduced a new variable, VBFhardness, that can control the amount of energy flowing into the dilepton system. Using this variable, we have demonstrated that the interference clearly appears when an appropriate cut is applied.

THANK YOU