Multi Boson Interactions, Aug 28 – Sep 1, 2023, UC San Diego

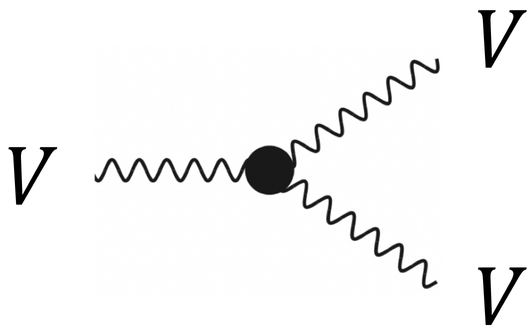
Interference resurrection in VBF dilepton production

Minho SON
KAIST
(**K**orea **A**dvanced **I**nstitute of **S**cience and **T**echnology)

Hwang, Yoo (Korea Univ.) + Min, Park, **SON** (KAIST)
JHEP 08 (2023) 069 [arXiv:2301.13663]

Also see Talk by Michael Schmitt

anomalous Triple Gauge Coupling (aTGC)



$$\mathcal{L}_{TGC} = ie\left[\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + \left(1+\delta\kappa_\gamma\right)A_{\mu\nu}W^+_\mu W^-_\nu\right]$$

$$+ ig_L cos\theta\left[\left(1+\delta g_{1,z}\right)\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu + (1+\delta\kappa_z)Z_{\mu\nu}W^+_\mu W^-_\nu\right]$$

$$+ ie\frac{\lambda_\gamma}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + ig_L cos\theta\frac{\lambda_z}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}$$

$$\delta\kappa_z = \delta g_{1,z} - \frac{g_Y^2}{g_L^2}\delta\kappa_\gamma \qquad \lambda_z = \lambda_\gamma$$

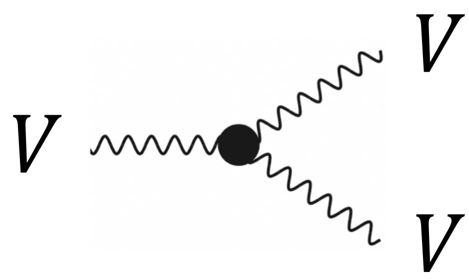
At the level of dim6 operators in SMEFT

→ Three variables for VV

$$\{\lambda_z, \delta g_{1,z}, \delta\kappa_\gamma\} \sim c^{(6)}\frac{m_W^2}{\Lambda^2}$$

We will mainly focus on this term in this talk

In terms of dim-6 operators



$$\lambda_z = \lambda_\gamma = c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2}$$

: sensitive only to transverse polarizations

$\longleftrightarrow$ $\mathrm{tr}(W_{\mu\nu}^3)$

$$\delta\kappa_\gamma = (c_W + c_B)\frac{m_W^2}{2\Lambda^2}$$

$$\delta g_{1,z} = c_W\frac{m_Z^2}{2\Lambda^2}$$

Hagiwara et. al. (HISZ basis)

$$\frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}(\widehat{W}_{\mu\nu}\widehat{W}_{\nu\rho}\widehat{W}_{\rho\mu})$$

$$\frac{c_W}{\Lambda^2}(D_\mu H)^+ W^{a\,\mu\nu}\frac{\sigma^a}{2}g(D_\nu H)$$

$$\frac{c_B}{\Lambda^2}(D_\mu H)^+ B^{\mu\nu}\frac{1}{2}g'(D_\nu H)$$

adopted in

CMS $Z(\ell\ell) + 2j$

Warsaw basis

(NLO MC available)

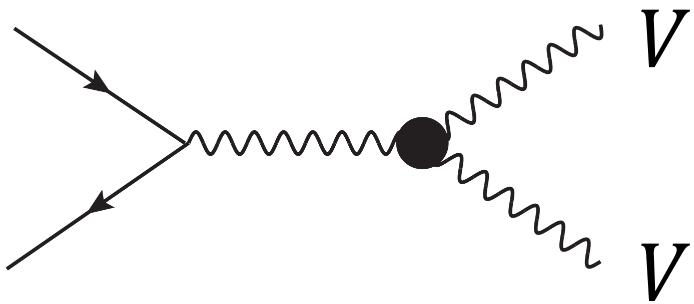
$$C_{3W}\epsilon_{abc}W_{\mu\nu}^a W_{\nu\rho}^b W_{\rho\mu}^c$$

……

adopted in

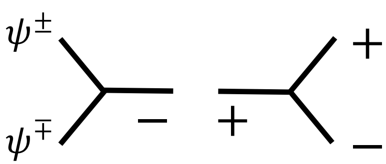
CMS $W\gamma$

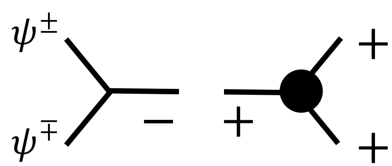
aTGC in VV process and noninterference



Helicity selection rule: total helicity should match

$\left|h(A_3^{SM})\right| = 1 - [g] = 1$ $\quad\quad$ $\left|h(A_3^{BSM})\right| = 1 - [c_{3W}] = 3$





SM amplitude

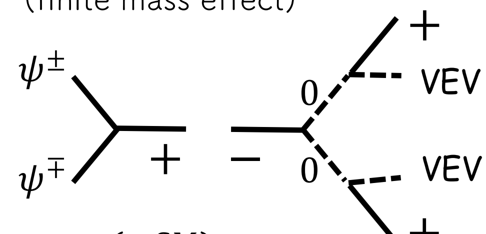
Similarly for t-channel diagram

$h\left(A_4^{SM}\right) = 0$

BSM amplitude
with insertion of $\mathcal{O}_{3W} \sim \mathrm{tr}(W^3)$

$h\left(A_4^{BSM}\right) = 2$

Flip the helicity via VEV insertion
(finite mass effect)



$h\left(A_6^{SM}\right) = 2$

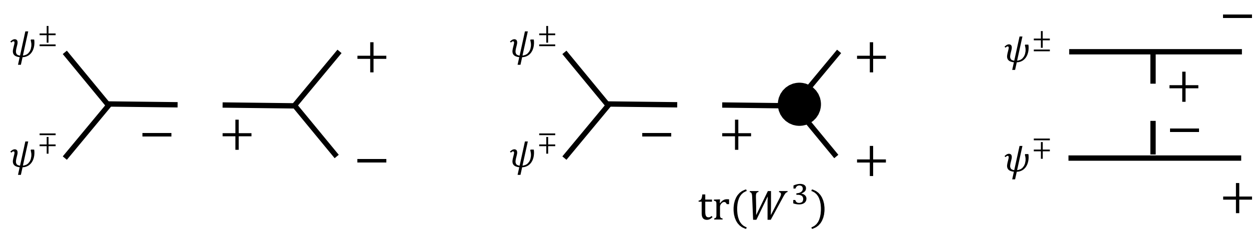
$\propto \left(\frac{m_W}{E}\right)^2 = \varepsilon_V^2$

→ can not interfere in massless limit

Azatov, Contino, Machado, Riva 16'

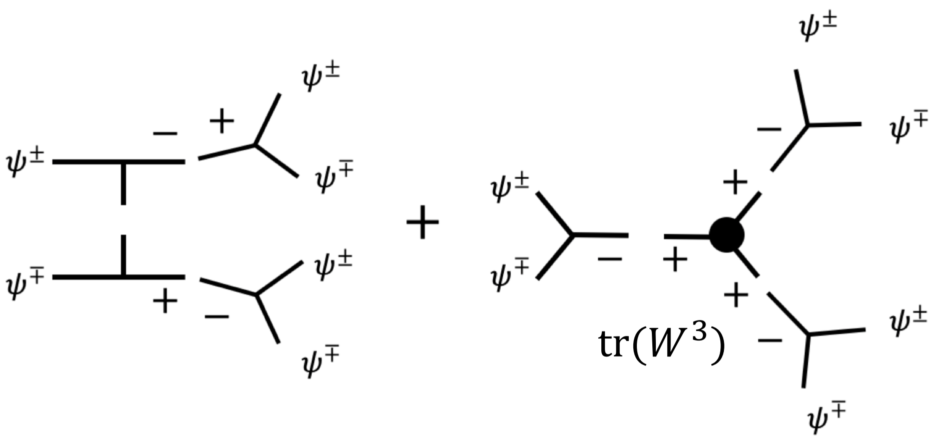
Noninterference in VV process

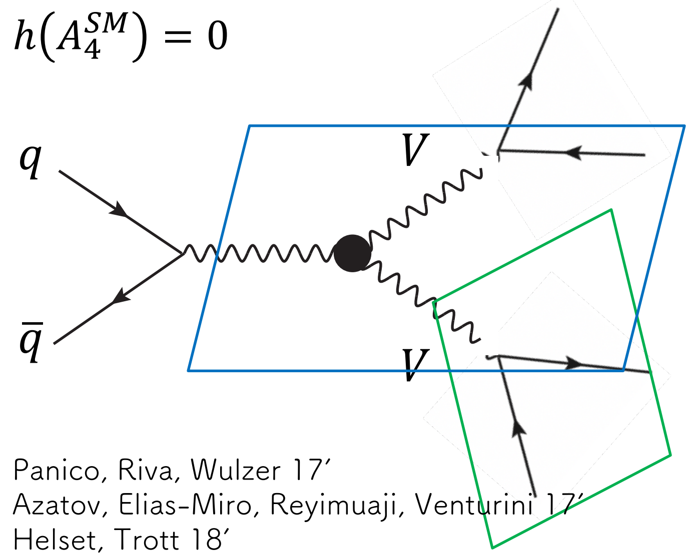
Helicity selection rule: total helicity should match



$h(A_4^{SM}) = 0$ $h(A_4^{BSM}) = 2$ $h(A_4^{SM}) = 0$

The correct picture is that, in fact, they do interfere in a full amplitude





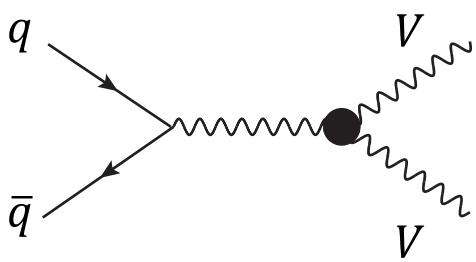
Panico, Riva, Wulzer 17'
Azatov, Elias-Miro, Reyimuaji, Venturini 17'
Helset, Trott 18'
Aoude, Shepherd 19'
+ ⋯

$$\int d\phi\, \underbrace{(\mathcal{M}^*_{SM}\mathcal{M}_{BSM} + h.c.)}_{\neq 0} = 0$$

: suggests us to look into differential distributions of angular variable

Noninterference in VV process

2 to 2 process, subject to non-interference



SMxdim6 scales like

$$\sim \sigma_{SM}\frac{E^2}{\Lambda^2}\times\left(\frac{m_W}{E}\right)^2 \sim \frac{m_W^2}{\Lambda^2}$$

dim6xdim6 scales like

$$\sim \sigma_{SM}\frac{E^4}{\Lambda^4}$$

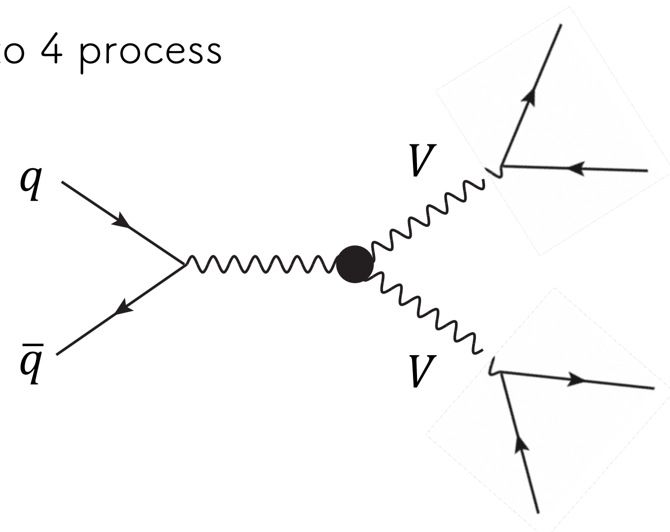
$$\sigma = \sigma^{SM} + \sum\left(\frac{c_i^{(6)}}{\Lambda^2}\cancel{\sigma_i^{(6\times SM)}} + h.c.\right) + \sum\frac{c_i^{(6)}c_j^{(6)*}}{\Lambda^4}\sigma_{ij}^{(6\times 6)} + \cdots$$

- $\Delta c^{(6)} \propto \sqrt{\Delta\sigma}$ (v.s. $\Delta c^{(6)} \propto \Delta\sigma$ in case interference)
- EFT expansion fails, e.g. SMxdim8 ~ dim6xdim6, what if SMxdim8 can interfere without suppression?

E.g. SMxdim8 appears not suppressed

Degrande and Li arXiv:2303.10493

2 to 4 process



Thus, from EFT point of view, naively, power counting goes like

$$\sim \frac{E^2}{\Lambda^2} \qquad\qquad \sim \frac{E^4}{\Lambda^4}$$

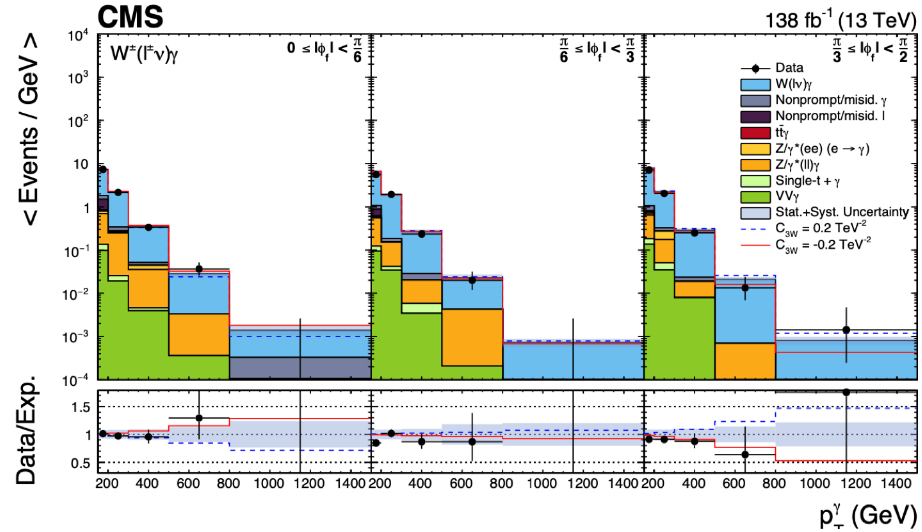
$$\frac{d\sigma/d\phi}{d\sigma_{SM}/d\phi} = 1 + \sum\left(\frac{c_i^{(6)}}{\Lambda^2}\frac{d\sigma_i^{(6\times SM)}/d\phi}{d\sigma_{SM}/d\phi} + h.c.\right) + \sum\frac{c_i^{(6)}c_j^{(6)*}}{\Lambda^4}\frac{d\sigma_{ij}^{(6\times 6)}/d\phi}{d\sigma_{SM}/d\phi} + \cdots$$

Interference resurrection

CMS-SMP-20-005

CERN-EP-2021-219
2022/03/11

Measurement of $W^{\pm}\gamma$ differential cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV and effective field theory constraints



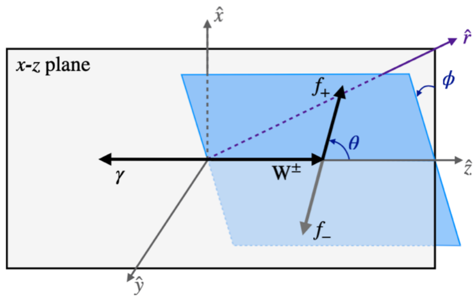
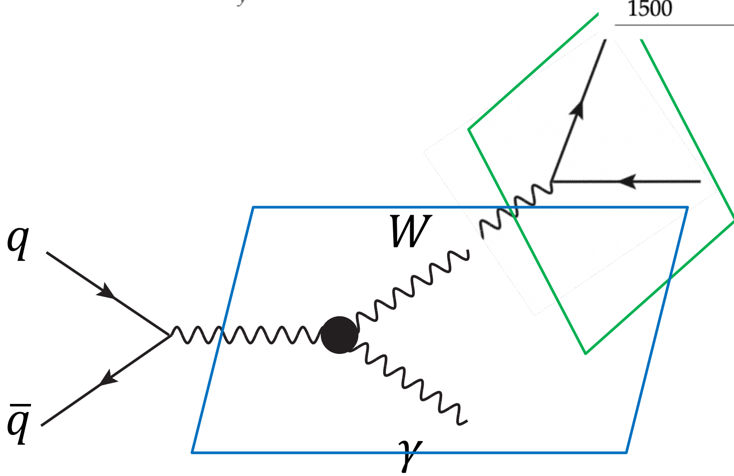


Table 4: Best fit values of C_{3W} and corresponding 95% CL confidence intervals as a function of the maximum p_T^{γ} bin included in the fit.

p_T^{γ} cutoff (GeV)	Best fit C_{3W} (TeV^{-2})		Observed 95% CL (TeV^{-2})		Expected 95% CL (TeV^{-2})	
	SM+int. only	SM+int.+BSM	SM+int. only	SM+int.+BSM	SM+int. only	SM+int.+BSM
200	−0.86	−0.24	[−2.01, 0.38]	[−0.76, 0.40]	[−1.16, 1.27]	[−0.81, 0.71]
300	−0.25	−0.17	[−0.81, 0.34]	[−0.39, 0.28]	[−0.56, 0.60]	[−0.33, 0.33]
500	−0.13	−0.025	[−0.50, 0.25]	[−0.15, 0.12]	[−0.35, 0.38]	[−0.17, 0.16]
800	−0.20	−0.033	[−0.49, 0.11]	[−0.10, 0.08]	[−0.29, 0.31]	[−0.097, 0.095]
1500	−0.13	−0.009	[−0.38, 0.17]	[−0.062, 0.052]	[−0.27, 0.29]	[−0.066, 0.065]

[Also see Talk by **Schmitt**]



$$C_{3W}\epsilon_{ijk}W^{i}_{\mu\nu}W^{j}_{\nu\rho}W^{k}_{\rho\mu}$$

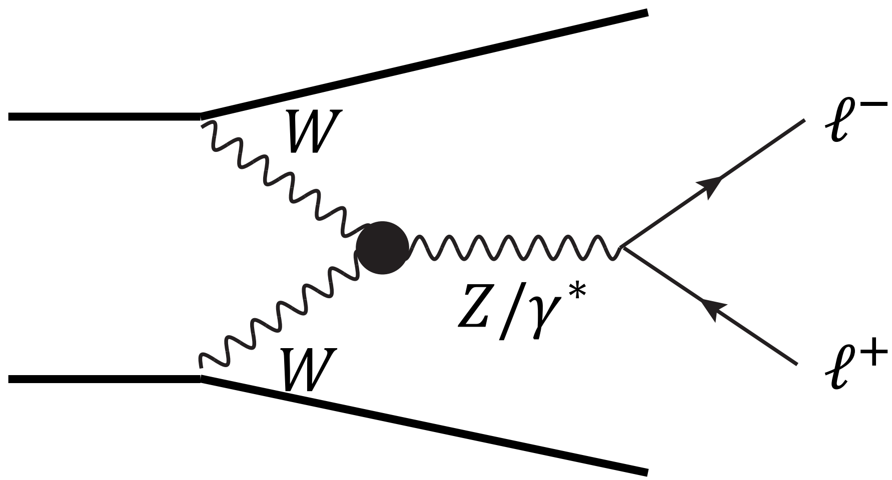
Observed 95% CL (TeV^{-2})	
SM+int. only	SM+int.+BSM
[−0.38, 0.17]	[−0.062, 0.052]

Still quadratic term dominates.

Panico, Riva, Wulzer 17'
CMS collaboration 2111.13948

We newly introduce
2-to-4 dilepton + 2 jets
as a new way of resurrecting interference

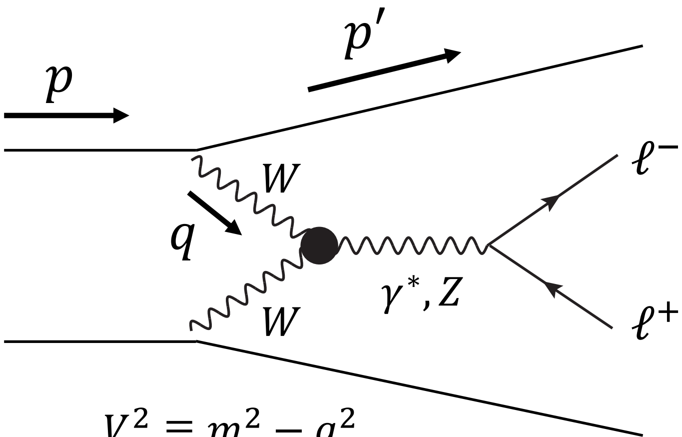
Hwang, Min, Park, **SON**, Yoo JHEP 08 (2023) 069



Interference resurrection in the total cross section

Effective W Approximation (EWA)

: factorization. Total result ~ treating W as on-shell and convolute xsec with W PDF



$$V^2 \equiv m^2 - q^2$$
$$= m^2 - (p - p')^2$$

Time interval during which virtual W can not be distinguished from on-shell W $\quad \Delta t \sim \frac{E}{V^2}$

Interaction scale of hard-process $\quad t \sim \frac{1}{E}$

V : Virtuality of W boson
E : Energy scale of hard-process

Relevant phase space for EWA

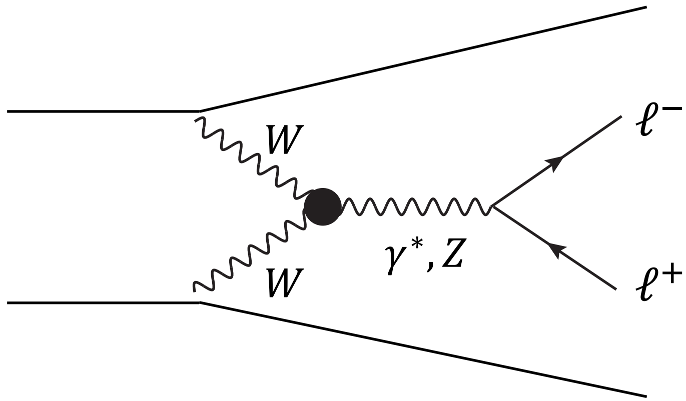
$$xE \sim (1-x)E\ , \quad \delta_m = \frac{m}{E} \ll 1, \quad \delta_\perp = \frac{p_T}{E} \ll 1 \qquad \longrightarrow \qquad \Delta t \sim \frac{E}{V^2} \gg t \sim \frac{1}{E}$$

: factorization can be rigorously proven to work

$$\frac{d\sigma_{EWA}(q_i\bar{q}_j \to q'_i\bar{q}'_j X)}{dx_i dx_j dp_{\perp,i} dp_{\perp,j}} = \sum_{r,s} \frac{C_i^2}{2\pi^2}\frac{C_j^2}{2\pi^2} f_r(x_i, p_{\perp,i}) f_s(x_j, p_{\perp,j}) \times d\sigma(W_r^{q_i} W_s^{q_j} \to X)$$

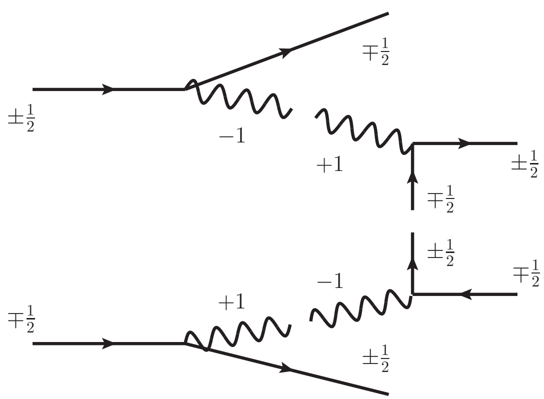
Apparent 2-to-2 process seems to be subject to noninterference.

Interference resurrection



With quark currents attached to both vector bosons, interference seem to be recovered

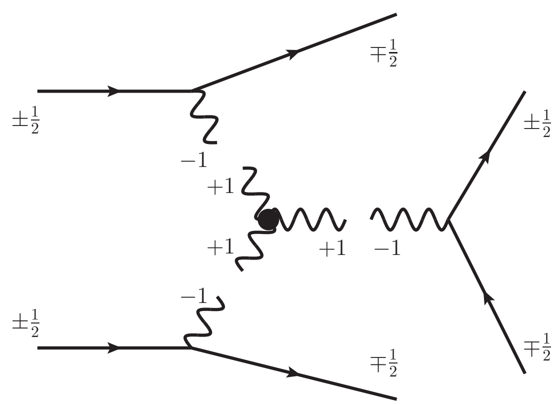
SM diagram unsupposed



Order-one effect from t-channel type (enhanced soft phase space) ?

$+$

BSM diagram

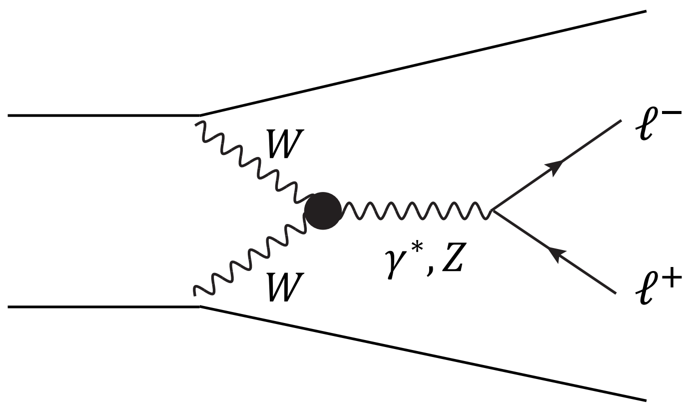


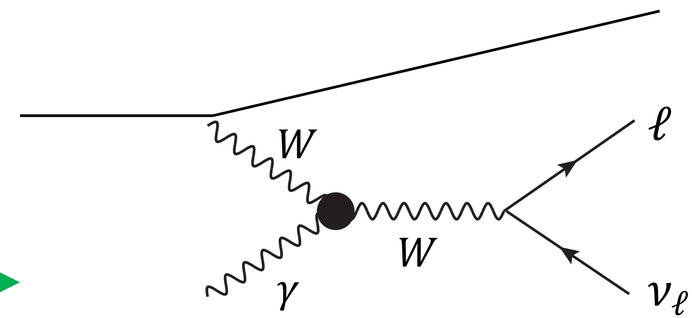
$+ \cdots$

Many radiation type diagrams

Analytic study of resurrection of interference with a toy process

: analytic calculation of 2-to-4 amplitude is extremely challenging, maybe impossible





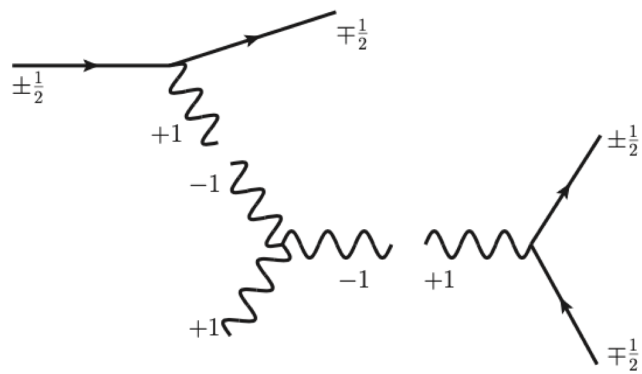
2-to-3 process is analytically calculable

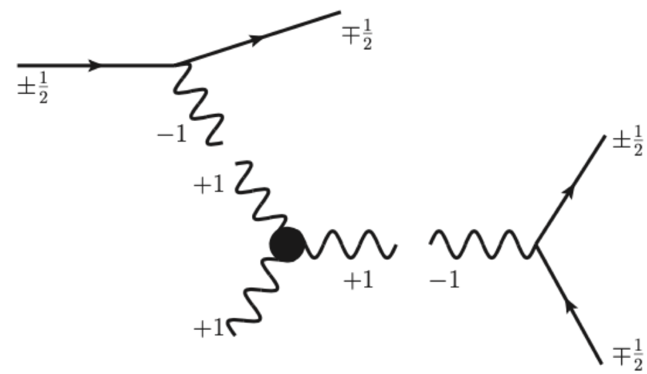
Replace one W with γ for simplicity
→ only one type of the gauge boson

Calculable 2-to-3 toy example

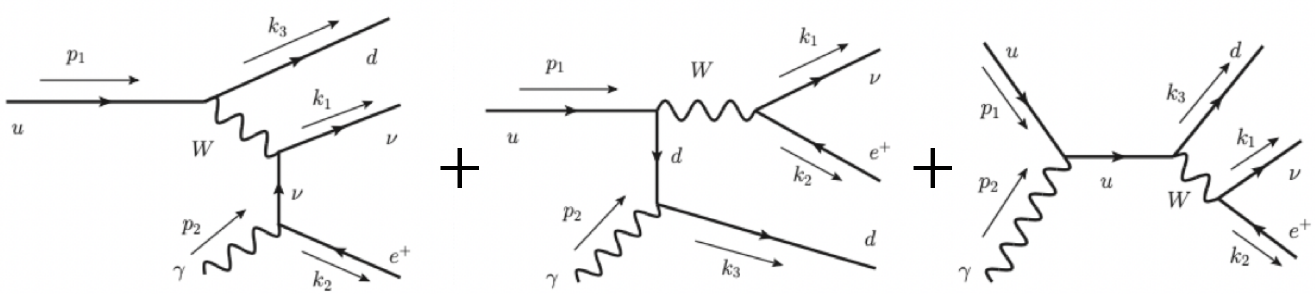
: better to understand structure

SM diagrams | BSM diagrams

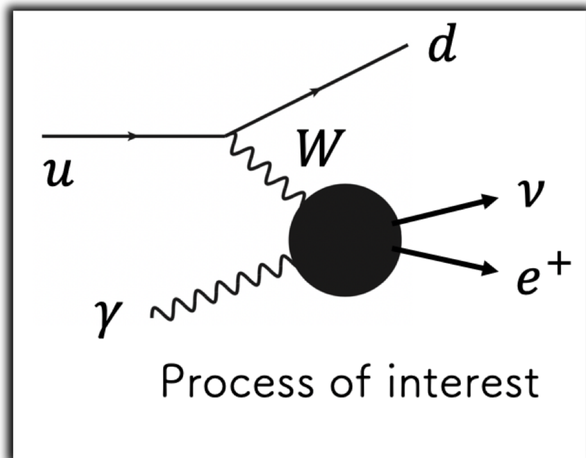


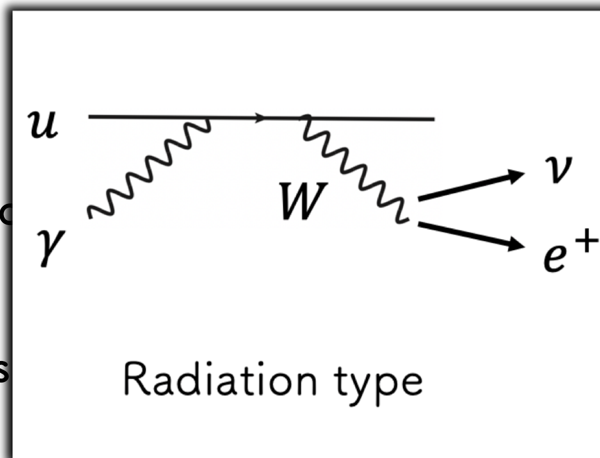


+

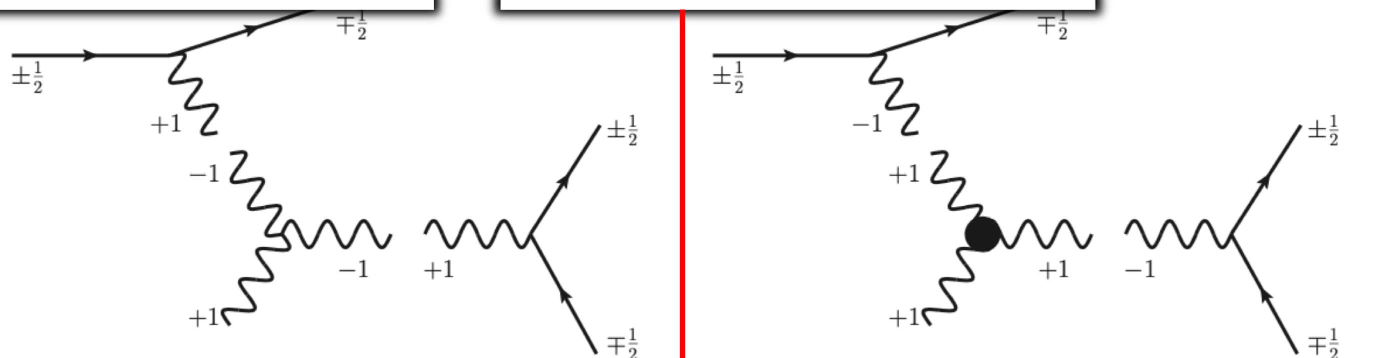


In the unitary gauge

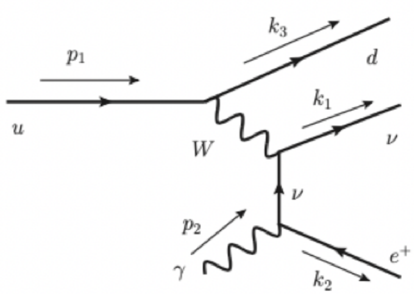




e truc ams iagrams

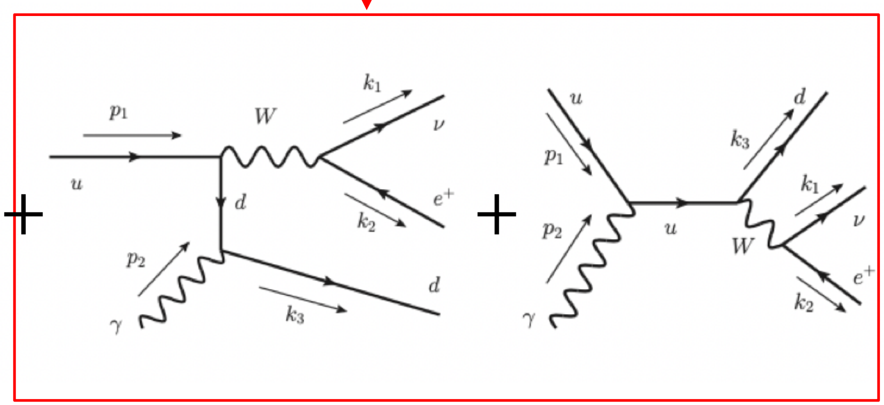


s-channel type +



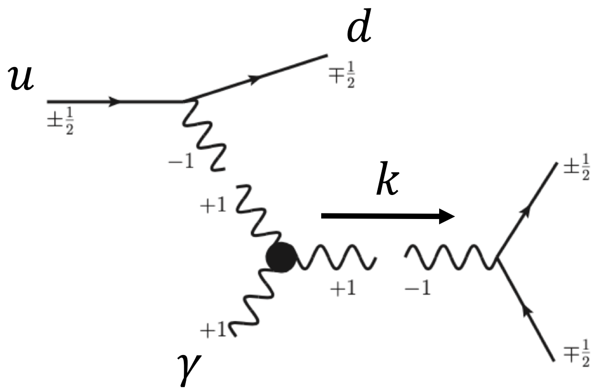
t-channel type

+



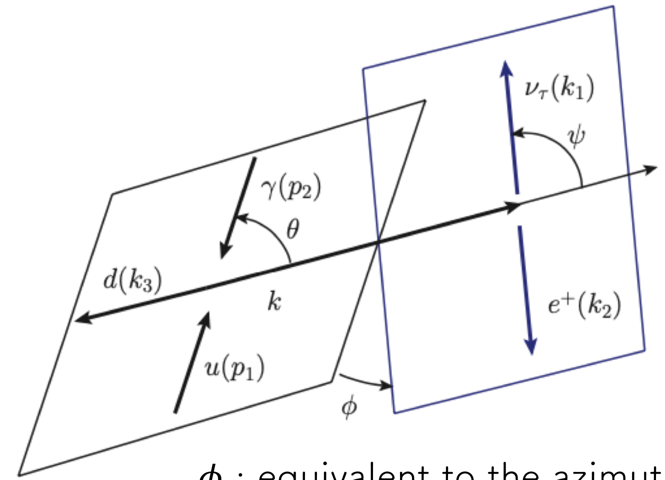
One can choose a gauge where these two diagrams are trashed, but they are important to get correct high E behavior and satisfy Ward identity in general.

Toy Example : 2-to-3



$$k^{\mu} = (\, z\sqrt{\hat{s}}, 0, 0, (1-z)\sqrt{\hat{s}}\,)$$

z : fraction of energy flowing into $\ell\nu$ system

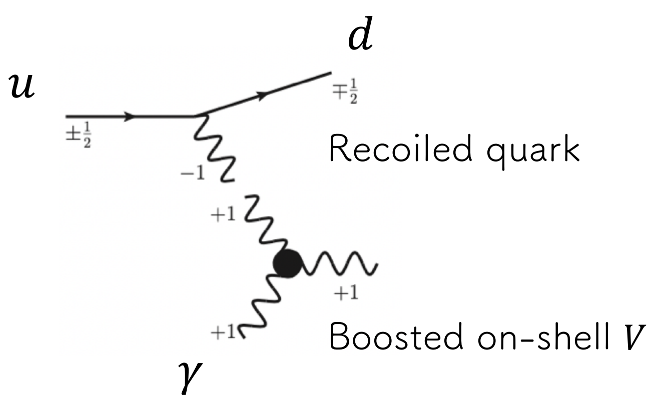


ϕ : equivalent to the azimuthal angle of the forward quark

1. For W mass window

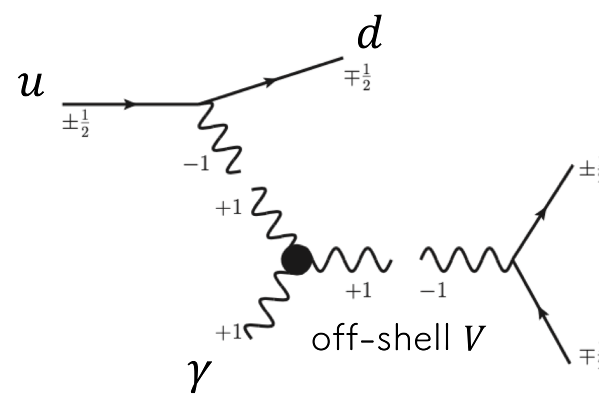
Narrow width approximation applied

$$[\, k^2 = m_{\ell\nu}^2 = (2z-1)\hat{s} \sim m_W^2 \,]$$

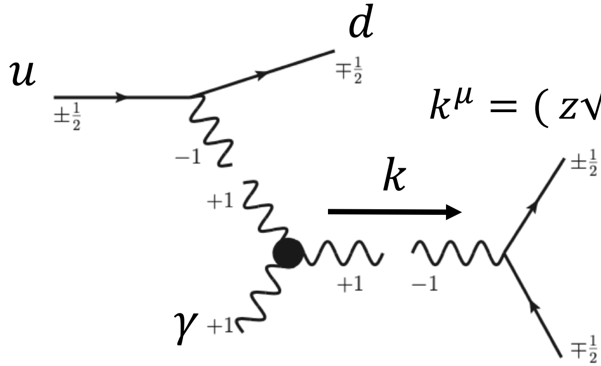


2. Off-shell region away from mass window

$$[\, k^2 = m_{\ell\nu}^2 = (2z-1)\hat{s} \gg m_W^2 \,]$$



Toy Example : 2-to-3



$k^\mu = (\, z\sqrt{\hat{s}}, 0, 0, (1-z)\sqrt{\hat{s}}\,)$

1. For W mass window $[\, k^2 = m_{\ell\nu}^2 = (2z-1)\hat{s} \sim m_W^2 \,]$

   Narrow width approximation applied

   For $\hat{s} \gg m_W^2$

$$\frac{d\hat{\sigma}_{\mathrm{SM}\times\mathrm{BSM}}}{d\phi} \sim \frac{1}{4}\frac{\lambda_z}{512\,\pi^4}\frac{\pi e^2 g^4}{3}\frac{2}{m_W\Gamma_W}\left[\cos(2\phi)\left(2-\log\frac{\hat{s}}{m_W^2}\right)\right]$$

$$\frac{d\hat{\sigma}_{\mathrm{BSM}^2}}{d\phi} \sim \frac{1}{4}\frac{\lambda_z^2}{512\,\pi^4}\frac{\pi e^2 g^4}{6}\frac{\hat{s}}{m_W^3\Gamma_W}$$

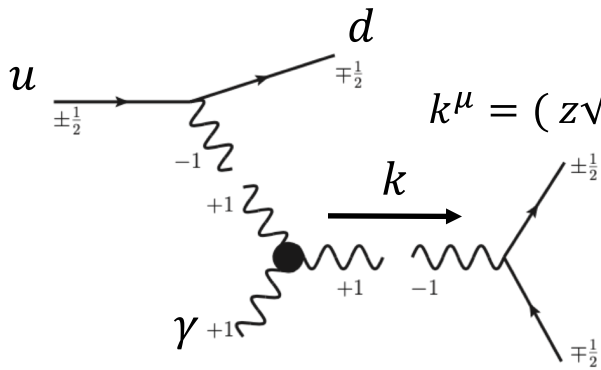
2. Off-shell region away from mass window $[\, k^2 = m_{\ell\nu}^2 = (2z-1)\hat{s} \gg m_W^2 \,]$

   For $\hat{s} \gg m_W^2$

$$\frac{d\hat{\sigma}_{\mathrm{SM}\times\mathrm{BSM}}(u_L\gamma_L \to d\nu e^+)}{d\phi} \sim \frac{\lambda_z}{512\,\pi^4}\frac{e^2 g^4}{m_W^2}\left[-\frac{2}{9}-\frac{\pi^2}{6}\cos\phi+\frac{1}{18}\left(\pi^2-26+22\ln\frac{\hat{s}}{m_W^2}-6\ln^2\frac{\hat{s}}{m_W^2}\right)\cos(2\phi)\right]$$

$$\frac{d\hat{\sigma}_{\mathrm{BSM}^2}(u_L\gamma_L \to d\nu e^+)}{d\phi} \sim \frac{\lambda_z^2}{512\,\pi^4}e^2 g^4\frac{\hat{s}}{m_W^4}\left[\frac{1}{24}\left(-9+4\ln\frac{\hat{s}}{m_W^2}\right)-\frac{\pi^2}{48}\cos\phi-\frac{1}{12}\cos(2\phi)\right]$$

Toy Example : 2-to-3



$$k^\mu = (\, z\sqrt{\hat{s}}, 0, 0, (1-z)\sqrt{\hat{s}} \,)$$

1. For W mass window $[\, k^2 = m_{\ell\nu}^2 = (2z-1)\hat{s} \sim m_W^2 \,]$

   Narrow width approximation applied

   For $\hat{s} \gg m_W^2$

$$\frac{d\hat{\sigma}_{\mathrm{SM\times BSM}}}{d\phi} \sim \frac{1}{4}\frac{\lambda_z}{512\,\pi^4}\frac{\pi e^2 g^4}{3}\frac{2}{m_W \Gamma_W}\Big[\cos(2\phi)\Big(2 - \log \frac{\hat{s}}{\ldots}\Big) \ldots \Big]$$

$$\frac{d\hat{\sigma}_{\mathrm{BSM^2}}}{d\phi} \sim \frac{1}{4}\frac{\lambda_z^2}{512\,\pi^4}\frac{\pi e^2 g^4}{6}\frac{\hat{s}}{m_W^3 \Gamma_W}$$

Suppressed by a factor of $\sim \mathcal{O}\left(\frac{\Gamma_W}{m_W}\right) \times$

A term that survives in the total cross section

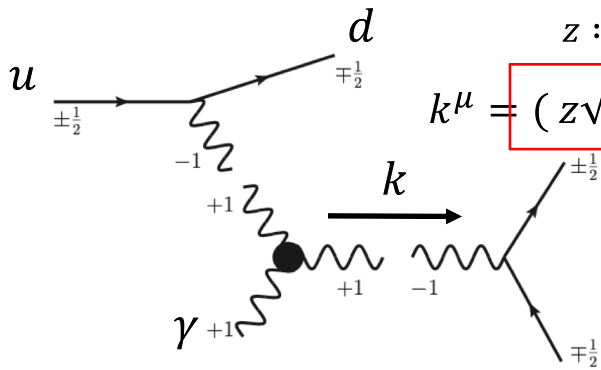
2. Off-shell region away from mass window $[\, k^2 \ldots \gg m_W^2 \,]$

   For $\hat{s} \gg m_W^2$

$$\frac{d\hat{\sigma}_{\mathrm{SM\times BSM}}(u_L \gamma_L \to d\nu e^+)}{d\phi} \sim \frac{\lambda_z}{512\,\pi^4}\frac{e^2 g^4}{m_W^2}\left[-\frac{2}{9} - \frac{\pi^2}{6}\cos\phi + \frac{1}{18}\left(\pi^2 - 26 + 22\ln\frac{\hat{s}}{m_W^2} - 6\ln^2\frac{\hat{s}}{m_W^2}\right)\cos(2\phi)\right]$$

$$\frac{d\hat{\sigma}_{\mathrm{BSM^2}}(u_L \gamma_L \to d\nu e^+)}{d\phi} \sim \frac{\lambda_z^2}{512\,\pi^4} e^2 g^4 \frac{\hat{s}}{m_W^4}\left[\frac{1}{24}\left(-9 + 4\ln\frac{\hat{s}}{m_W^2}\right) - \frac{\pi^2}{48}\cos\phi - \frac{1}{12}\cos(2\phi)\right]$$

Toy Example : 2-to-3



z : fraction of energy flowing into $\ell\nu$ system

$$k^\mu = (\, z\sqrt{\hat s}, 0, 0, (1-z)\sqrt{\hat s}\,)$$

$$\frac{p_T(q)\cosh\eta}{m_{e\nu}} = \frac{1-z}{\sqrt{2z-1}} \leq \frac{1-z_{\min}}{\sqrt{2z_{\min}-1}} = \delta_{\min}$$

$$p_T(q) \leq \delta_{\min}\frac{m_{e\nu}}{\cosh\eta}$$

1. For W mass window [$k^2 = m_{\ell\nu}^2 = (2z-1)\hat s \sim m_W^2$]

Narrow width approximation applied

For $\hat s \gg m_W^2$

$$\frac{d\hat\sigma_{\mathrm{SM\times BSM}}}{d\phi} \sim \frac{1}{4}\frac{\lambda_z}{512\,\pi^4}\frac{\pi e^2 g^4}{3}\frac{2}{m_W\Gamma_W}\left[\cos(2\phi)\left(2 \ldots\right.\right.$$

$$\frac{d\hat\sigma_{\mathrm{BSM^2}}}{d\phi} \sim \frac{1}{4}\frac{\lambda_z^2}{512\,\pi^4}\frac{\pi e^2 g^4}{6}\frac{\hat s}{m_W^3\Gamma_W}$$

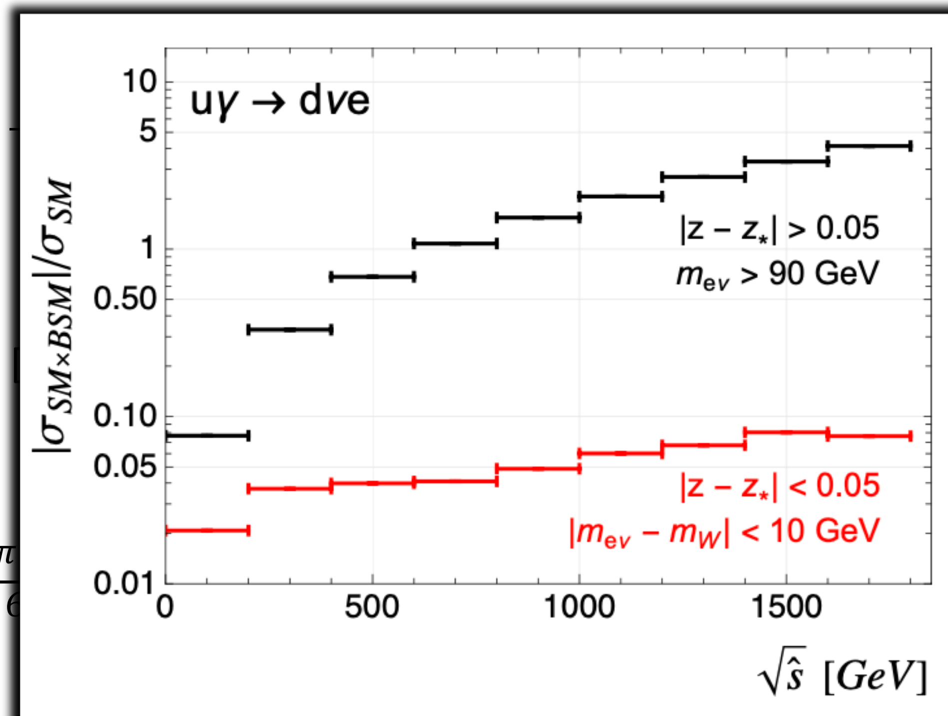
2. Off-shell region away from mass window [

For $\hat s \gg m_W^2$

$$\frac{d\hat\sigma_{\mathrm{SM\times BSM}}(u_L\gamma_L \to d\nu e^+)}{d\phi} \sim \frac{\lambda_z}{512\,\pi^4}\frac{e^2 g^4}{m_W^2}\left[-\frac{2}{9} - \frac{\pi}{6} \ldots\right.$$

$$\frac{d\hat\sigma_{\mathrm{BSM^2}}(u_L\gamma_L \to d\nu e^+)}{d\phi} \sim \frac{\lambda_z^2}{512\,\pi^4} e^2 g^4 \frac{\hat s}{m_W^4}\left[\frac{1}{24}\left(-9 + 4\ln\frac{\ldots}{m_W^2}\right) - \frac{\ldots}{48}\cos\phi - \frac{\ldots}{12}\cos(2\phi)\right]$$

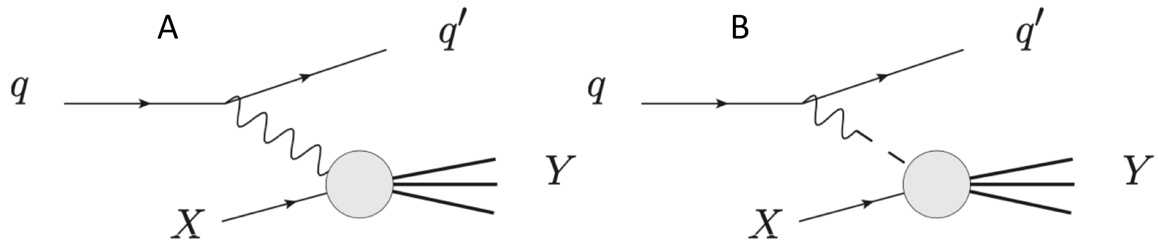
Numerical confirmation



Derivation of EWA : factorization

Borel, Franceschini, Rattazzi, Wulzer 1202.1904

Derivation in the **axial gauge**



$$\mathcal{A}^{\mathrm{sc}-A}_{\mathrm{total}} = -\frac{i}{V^2}\sum_{h=\pm1}\left[J^\mu\left(\varepsilon^h_\mu\right)^*\right]\left[\varepsilon^h_\nu \mathcal{A}^\nu_Q\right] - \frac{i}{V^2}\left[J^\mu\left(\varepsilon^0_\mu\right)^*\right]\left[\left(1-\frac{V^2}{m^2}\right)\varepsilon^0_\nu \mathcal{A}^\nu_Q\right]\left[1+\mathcal{O}(\delta_\perp^2+\delta_m^2)\right]$$

$$\delta_m = \frac{m}{E} \ll 1,\ \delta_\perp = \frac{p_T}{E} \ll 1$$

$$-\frac{i}{V^2}\left[J^\mu\left(\varepsilon^\pm_\mu\right)^*\right] = 2C\frac{p_\perp e^{\pm i\phi}}{V^2}g_\pm(x)\left(1+\mathcal{O}(\delta_\perp^2+\delta_m^2)\right)$$

$$g_\pm(x)\left[\varepsilon^\pm_\nu \mathcal{A}^\nu\right] = \mathcal{A}_\pm = \mathcal{A}^{(0,0)}_\pm + \mathcal{A}^{(1,0)}_\pm \frac{\tilde{p}_\perp}{E} + \mathcal{A}^{(0,1)}_\pm \frac{\tilde{p}^*_\perp}{E} + \cdots$$

Including only transverse polarization ⋯

$$\tilde{p}_\perp \equiv p_1 - ip_2 = p_\perp e^{-i\phi}, \tilde{p}_\perp = p_\perp e^{i\phi}$$

ϕ : azimuthal angle

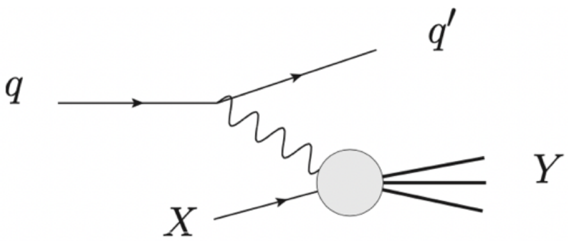
$$\mathcal{A}_{\mathrm{total}} = \frac{2C}{V^2}\left[\tilde{p}_\perp \mathcal{A}_+ + \tilde{p}^*_\perp \mathcal{A}_-\right]$$

$$= \frac{2C}{V^2}\left[\tilde{p}_\perp\left(\mathcal{A}^{(0,0)}_+ + \mathcal{A}^{(1,0)}_+\frac{\tilde{p}_\perp}{E} + \mathcal{A}^{(0,1)}_+\frac{\tilde{p}^*_\perp}{E} + \cdots\right)\right.$$

$$\left. + \tilde{p}^*_\perp\left(\mathcal{A}^{(0,0)}_- + \mathcal{A}^{(1,0)}_-\frac{\tilde{p}_\perp}{E} + \mathcal{A}^{(0,1)}_-\frac{\tilde{p}^*_\perp}{E} + \cdots\right)\right]$$

Borel, Franceschini, Rattazzi, Wulzer 1202.1904

Derivation of EWA : factorization



Including only transverse polarization ⋯

$$\mathcal{A}_{\text{total}} = \frac{2C}{V^2}\Big[\tilde p_\perp \Big(\mathcal{A}_+^{(0,0)} + \mathcal{A}_+^{(1,0)}\frac{\tilde p_\perp}{E} + \mathcal{A}_+^{(0,1)}\frac{\tilde p_\perp^*}{E} + \cdots\Big) + \tilde p_\perp^* \Big(\mathcal{A}_-^{(0,0)} + \mathcal{A}_-^{(1,0)}\frac{\tilde p_\perp}{E} + \mathcal{A}_-^{(0,1)}\frac{\tilde p_\perp^*}{E} + \cdots\Big)\Big]$$

$$\tilde p_\perp \equiv p_1 - ip_2 = p_\perp e^{-i\phi}, \tilde p_\perp = p_\perp e^{i\phi}$$

$$d\sigma(qX \to q'Y)_{\text{EWA}} = \frac{1}{2E_qE_X|1-v_X|}\int_\phi \frac{\left|\mathcal{A}^{(0,0)}\right|^2}{2}\frac{d^3p_{q'}}{2E_{q'}(2\pi)^3} d\Phi_Y (2\pi)^4\delta^4(p_Y + p_{q'} - p_q - p_X)$$

$$\simeq \frac{2C^2}{V^4}\frac{p_\perp dp_\perp x dx}{(2\pi)^2 2(1-x)} \times \left[p_\perp^2\left|\mathcal{A}_+^{(0,0)}\right|^2 + p_\perp^2\left|\mathcal{A}_-^{(0,0)}\right|^2 + \cdots\right] \times \frac{1}{2E_q 2E_W|v_W - v_X|} d\Phi_Y(2\pi)^4\delta^4(p_Y - p_W - p_X)$$

Different polarization is associated with the different total helicity of the sub-amplitude

What if it is subject to the 'helicity selection rule'

$\mathcal{A}_{-,SM}^{(0,0)} \neq 0$ $\quad \mathcal{A}_{-,BSM}^{(0,0)} = 0$

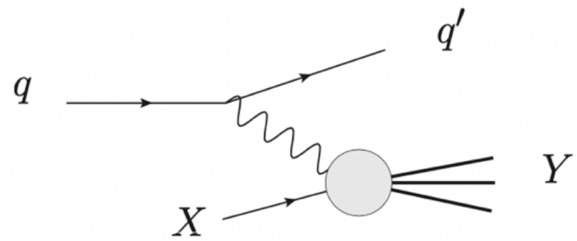
$\mathcal{A}_{+,SM}^{(0,0)} = 0$ $\quad \mathcal{A}_{+,BSM}^{(0,0)} \neq 0$

$$e^{-2i\phi}\mathcal{A}_{-,SM}^{(0,0)*}\mathcal{A}_{+,BSM}^{(0,0)} + h.c.$$

vanishes upon the integration over ϕ

: it meets our usual expectation, or EWA

Beyond the relevant region for EWA



λ_z

Including only transverse polarization ⋯

$$\mathcal{A}_{\text{total}} = \frac{2C}{V^2}\left[\tilde{p}_\perp\left(\mathcal{A}_+^{(0,0)} + \mathcal{A}_+^{(1,0)}\frac{\tilde{p}_\perp}{E} + \mathcal{A}_+^{(0,1)}\frac{\tilde{p}_\perp^*}{E} + \cdots\right) + \tilde{p}_\perp^*\left(\mathcal{A}_-^{(0,0)} + \mathcal{A}_-^{(1,0)}\frac{\tilde{p}_\perp}{E} + \mathcal{A}_-^{(0,1)}\frac{\tilde{p}_\perp^*}{E} + \cdots\right)\right]$$

$$\tilde{p}_\perp \equiv p_1 - ip_2 = p_\perp e^{-i\phi}, \tilde{p}_\perp = p_\perp e^{i\phi}$$

$\mathcal{A}_{-,SM}^{(0,0)} \neq 0$ $\quad$ $\mathcal{A}_{-,BSM}^{(0,0)} = 0$ $\quad$ $\mathcal{A}_{+,SM}^{(0,0)} = 0$ $\quad$ $\mathcal{A}_{+,BSM}^{(0,0)} \neq 0$

[Our computation for the left-handed photon would correspond to (next slide)]

Leading ϕ – independent contributions

$$\left(\frac{\tilde{p}_\perp\tilde{p}_\perp^*}{E^2}\right)^2\left(\mathcal{A}_{-,SM}^{(1,0)*}\mathcal{A}_{+,BSM}^{(0,1)} + h.c.\right)$$

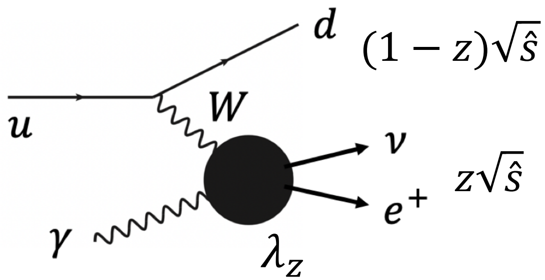
: interference will not be caught in EWA

$$\frac{|\mathcal{A}|^2_{SM\times BSM}}{|\mathcal{A}|^2_{SM}} \propto \lambda_z\left(\frac{\tilde{p}_\perp}{E}\right)^2\frac{E^2}{m^2}$$

$$\left(\frac{\tilde{p}_\perp\tilde{p}_\perp^*}{E^2}\right)\left|\mathcal{A}_{-,SM}^{(0,0)}\right|^2 + \left(\frac{\tilde{p}_\perp\tilde{p}_\perp^*}{E^2}\right)\left|\mathcal{A}_{+,BSM}^{(0,0)}\right|^2$$

$$\frac{|\mathcal{A}|^2_{BSM^2}}{|\mathcal{A}|^2_{SM}} \propto \lambda_z^2\frac{E^4}{m^4}$$

Beyond the relevant region for EWA : our toy process



$$p_T(q) = (1-z)\sqrt{\hat{s}}\sin\theta\ ,\ \ m_{e\nu} = (2z-1)\sqrt{\hat{s}} = E$$

$$p_T(q) = p_\perp \sim E\theta \quad \text{for } \theta \ll 1,\ z \sim \mathcal{O}(1) \ \rightarrow\ \theta \sim \frac{p_\perp}{E}$$

for $\theta \ll 1$

$$\epsilon_L \cdot \mathcal{M} = \sum_m C_m\, e^{\pm i m\phi} \ \rightarrow\ \tilde{\theta}\left(\mathcal{M}_+^{(0,0)} + \mathcal{M}_+^{(1,0)}\tilde{\theta} + \mathcal{M}_+^{(0,1)}\tilde{\theta}^* + \cdots\right)$$

$$+\, \tilde{\theta}^*\left(\mathcal{M}_-^{(0,0)} + \mathcal{M}_-^{(1,0)}\tilde{\theta} + \mathcal{M}_-^{(0,1)}\tilde{\theta}^* + \cdots\right)$$

$$\tilde{\theta} \equiv \theta e^{-i\phi}$$

$\epsilon_L \cdot \mathcal{M}$ in the **unitary gauge**

$$\epsilon_L \cdot \mathcal{M}_{BSM} = \lambda_z \frac{eg^2}{4m_W^2} \frac{\hat{s}^{5/2}\sqrt{(2z-1)(1-z)}\sin\frac{\theta}{2}\, e^{-i\phi}}{[(2z-1)\hat{s} - m_W^2]\,[m_W^2 + \hat{s}(1-z)(1-\cos\theta)]}$$
$$\times \Big[2\sqrt{2z-1}\,\sin\psi\cos\theta - (1-\cos\psi)\sin\theta\, e^{-i\phi}$$
$$+ (2z-1)(1+\cos\psi)\sin\theta\, e^{i\phi}\Big]\ ,$$

$$\epsilon_L \cdot \mathcal{M}_{SM} = -eg^2 \frac{1}{m_W^2 + \hat{s}(1-z)(1-\cos\theta)} \Bigg[\hat{s}^{3/2}\sqrt{\frac{1-z}{2z-1}}(1+\cos\psi)\sec\frac{\theta}{2}$$
$$\times \frac{4(1-z)(2z-1)(1-\cos\theta) - 2(5-4z)\frac{m_W^2}{\hat{s}}}{6\,[(2z-1)\hat{s} - m_W^2]}$$
$$+ \hat{s}^{1/2}\frac{(1-z)^{3/2}}{2z-1}\sin\psi\sec^3\frac{\theta}{2}\sin\theta\, e^{i\phi}$$
$$+ \hat{s}^{1/2}\left(\frac{1-z}{2z-1}\right)^{3/2}\frac{1}{2}(1-\cos\psi)\sec^5\frac{\theta}{2}\sin^2\theta\, e^{2i\phi}$$
$$+ \hat{s}^{1/2}\frac{(1-z)^{3/2}}{(2z-1)^2}\frac{1}{4}(1-\cos\psi)^2\csc\psi\sec^7\frac{\theta}{2}\sin^3\theta\, e^{3i\phi} + \cdots\Bigg]\ ,$$

In this limit, our result can be compared with the result by Borel Franceschini, Rattazzi, Wulzer

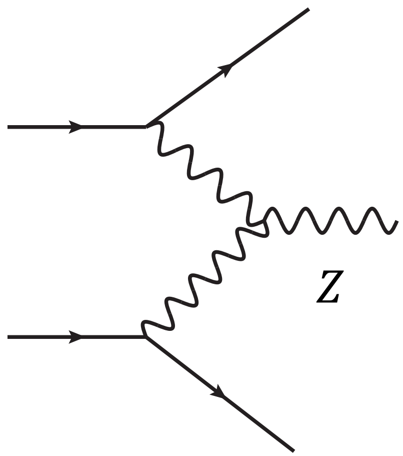
$$\mathcal{M}_{-,\,SM}^{(0,0)} \neq 0 \qquad \mathcal{M}_{-,\,BSM}^{(0,0)} = 0$$

$$\mathcal{M}_{+,\,SM}^{(0,0)} = 0 \qquad \mathcal{M}_{+,\,BSM}^{(0,0)} \neq 0$$

However, our result work for sizable angle which captures the beyond the EWA phase space

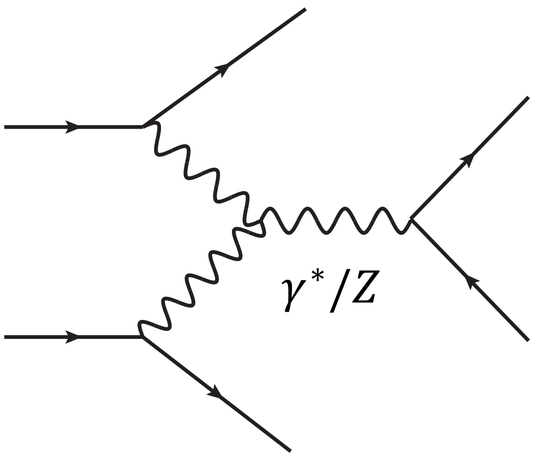
Going back to original
2-to-4 dilepton + 2 jets

1. For Z mass window



Interference may be seen through $\frac{d\sigma/d\phi_{jj}}{d\sigma_{SM}/d\phi_{jj}}$

2. Off-shell region away from Z mass window

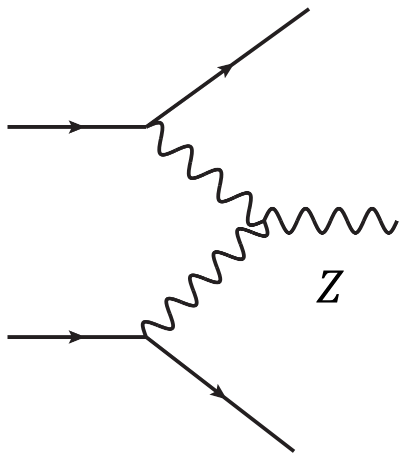


Interference through off-shell effect in total cross section

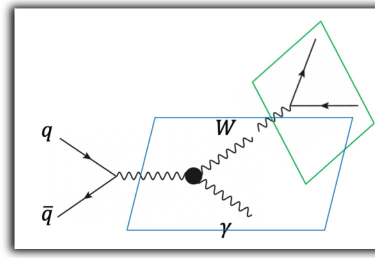
: our new finding

Going back to original 2-to-4 dilepton + 2 jets

1. For Z mass window



[See Talk by **Schmitt** for detail]



CMS $W\gamma$, using 138 fb^{-1} of data

$C_{3W} = [-0.062, 0.052]\ (\mathrm{TeV}^{-2})$@ 95%CL

: dominated by quadratic term

$$C_{3W}\epsilon_{abc}W^a_{\mu\nu}W^b_{\nu\rho}W^c_{\rho\mu}$$

CMS-SMP-16-018 (2017)

Electroweak production of two jets in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration* $\mathcal{L} = 35.9\ \mathrm{fb}^{-1}$

Assuming $\mathcal{L} = 139\ \mathrm{fb}^{-1}$

→ $C_{3W} \sim [-0.13, 0.13]\ (\mathrm{TeV}^{-2})$ @ 95%CL

Our re-analysis 3x weaker

: dominated by quadratic term

Eur. Phys. J. C81 (2021) 163

Differential cross-section measurements for the electroweak production of dijets in association with a *Z* boson in proton–proton collisions at ATLAS

ATLAS Collaboration* $\mathcal{L} = 139\ \mathrm{fb}^{-1}$

$$\frac{d\sigma/d\phi_{jj}}{d\sigma_{SM}/d\phi_{jj}}, \Delta\phi_{jj} = \phi_b - \phi_f$$

→ $C_{3W} = [-0.19, 0.41]\ (\mathrm{TeV}^{-2})$ @ 95%CL

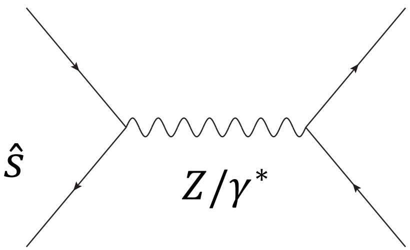
: driven by interference term ✓

2. Off-shell region away from Z mass window

: control Hardness of the process

QCD Drell-Yan

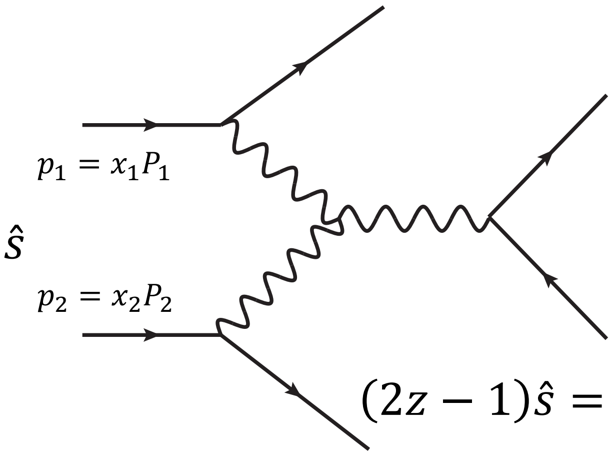
$$x_1 x_2 S_{pp} = \hat{s}$$



$$\hat{s} = m_{\ell\ell}^2$$

EW Drell-Yan

$$x_1 x_2 S_{pp} = \hat{s}$$

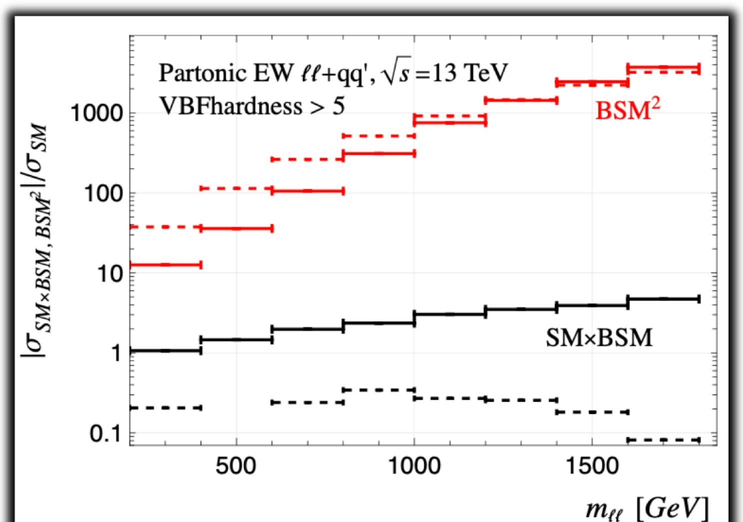


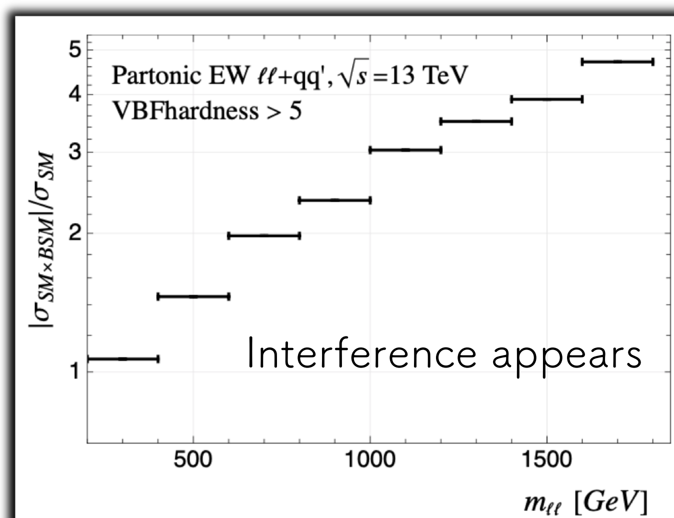
$$z\sqrt{\hat{s}}$$

$$(2z-1)\hat{s} = m_{\ell\ell}^2 - m_{qq'}^2$$

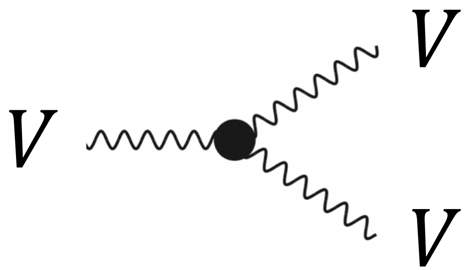
$$VBFhardness = \frac{m_{\ell\ell}^2 - m_{qq'}^2}{p_T^2(qq')\cosh^2\eta_{qq'} + m_{qq'}^2} = \frac{2z-1}{(1-z)^2}$$

: monotonically increasing function





E-growing in Longitudinal polarizations



$$\lambda_z = \lambda_\gamma = c_{WWW} \frac{3g^2 m_W^2}{2\Lambda^2}$$

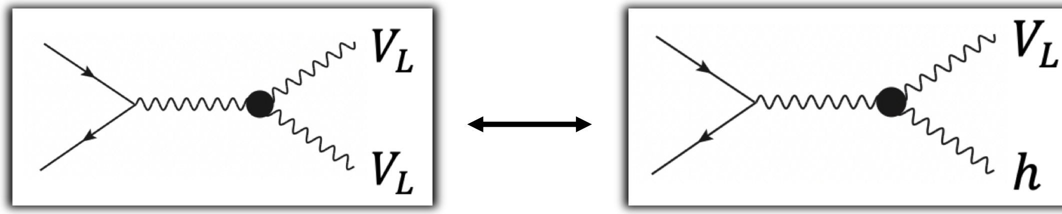
$$\delta\kappa_\gamma = (c_W + c_B) \frac{m_W^2}{2\Lambda^2}$$

$$\delta g_{1,z} = c_W \frac{m_Z^2}{2\Lambda^2}$$

: can be probed by longitudinal polarizations

& linear term dominates

Goldstone boson equivalence theorem



High E-behavior of diboson is parametrized by 4 pars.

→ High Energy Primaries (HEP)

Franceschini, Panico, Pomarol, Riva, Wulzer 18′
Banerjee, Englert, Gupta, Spannowsky 18′
Banerjee, Gupta, Reiness, Seth, Spannowsky 20′
Bishara, Englert, Grojean, Panico, Rossia 22′

$\delta g_{1,z} = [-6.3, 5.8]\times 10^{-3}$, $\delta\kappa_\gamma = [-68, 67]\times 10^{-3}$

Our projection by EW Zjj at HL-LHC

$\delta g_{1,z} = [-1.3, 1.7]\times 10^{-3}$, $\delta\kappa_\gamma = [-7.1, 16.4]\times 10^{-3}$

Projection at HL-LHC using Vh process
by Bishara, Englert, Grojean, Panico, Rossia 22′

Vh is currently statistically limited, but it will outperform at the HL-LHC and will be the most efficient process

Summary

1. EW dilepton process can access a wider phase space beyond the EWA limit and resurrect the interference in the total cross section

: soft-phase space enhanced interference (t-channel)

2. Our toy process provides an explicit analytic understanding of the above feature

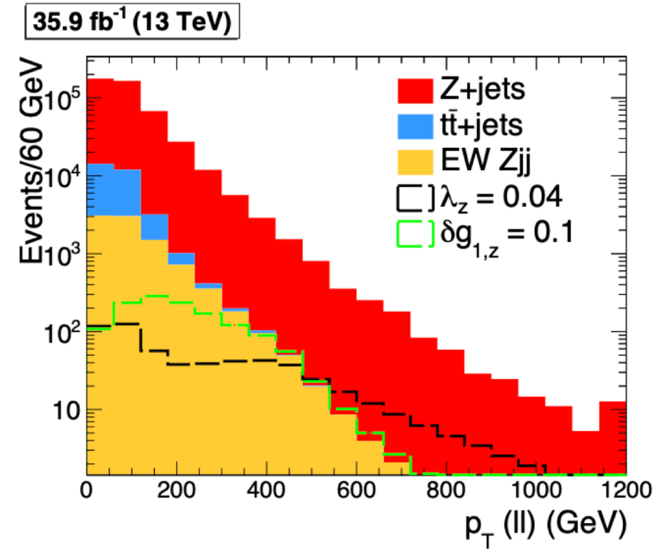
3. We proposed a new variable controlling the hardness of the subprocess, namely VBFhardness, efficiently exploring off-shell region

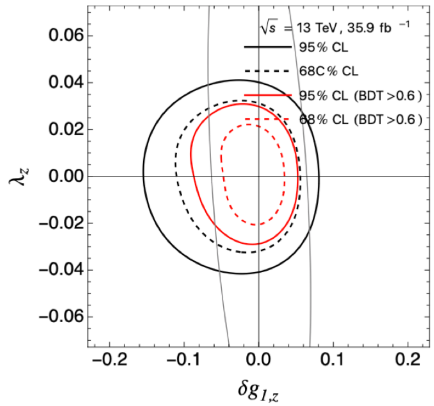
: might be useful for any VBF-process which suffers from non-interference

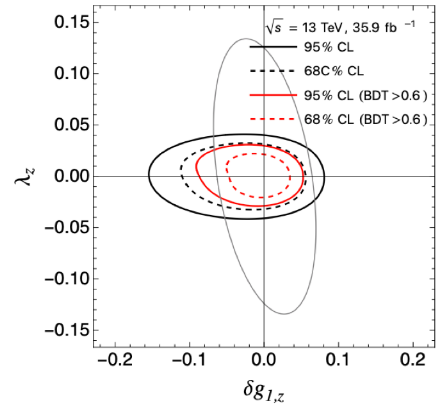
On the sensitivity of aTGC

In Z mass window

$$p_T(\ell_1) > 30 \text{ GeV}\ , \quad p_T(\ell_2) > 20 \text{ GeV}\ , \quad |\eta(\mu)| < 2.4\ , \quad |\eta(e)| < 2.1$$
$$p_T(j_1) > 50 \text{ GeV}\ , \quad p_T(j_2) > 30 \text{ GeV}\ , \quad |\eta(j)| \leq 4.7\ ,$$
$$|m_Z - m_{\ell\ell}| < 15 \text{ GeV}\ , \quad m_{jj} > 200 \text{ GeV}\ .$$

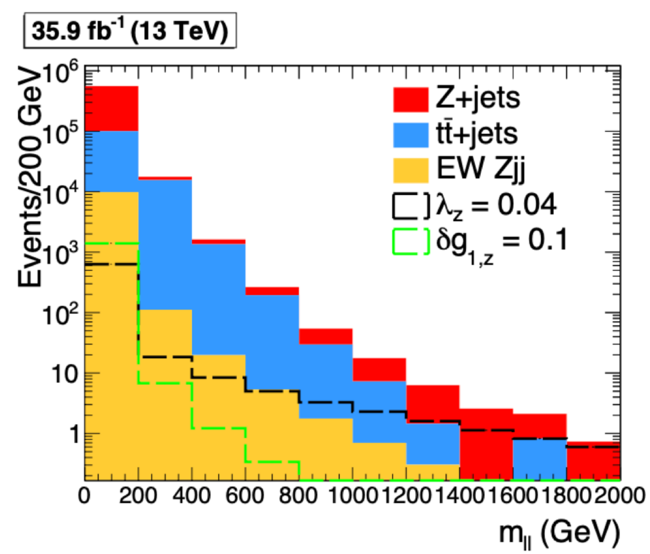


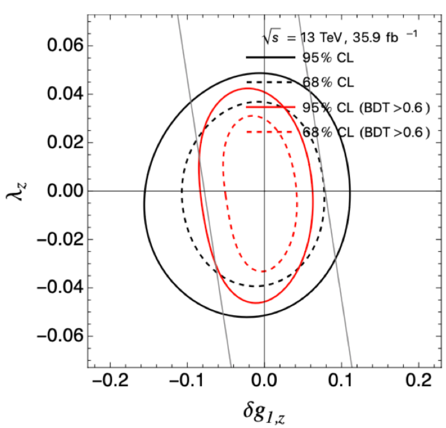


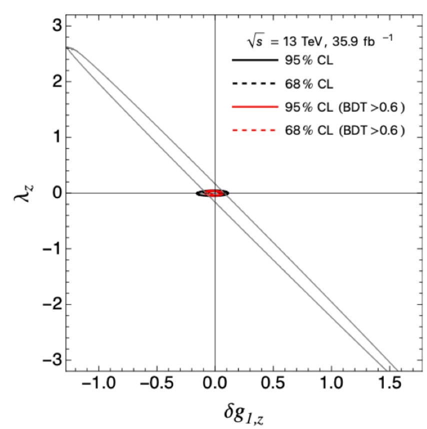


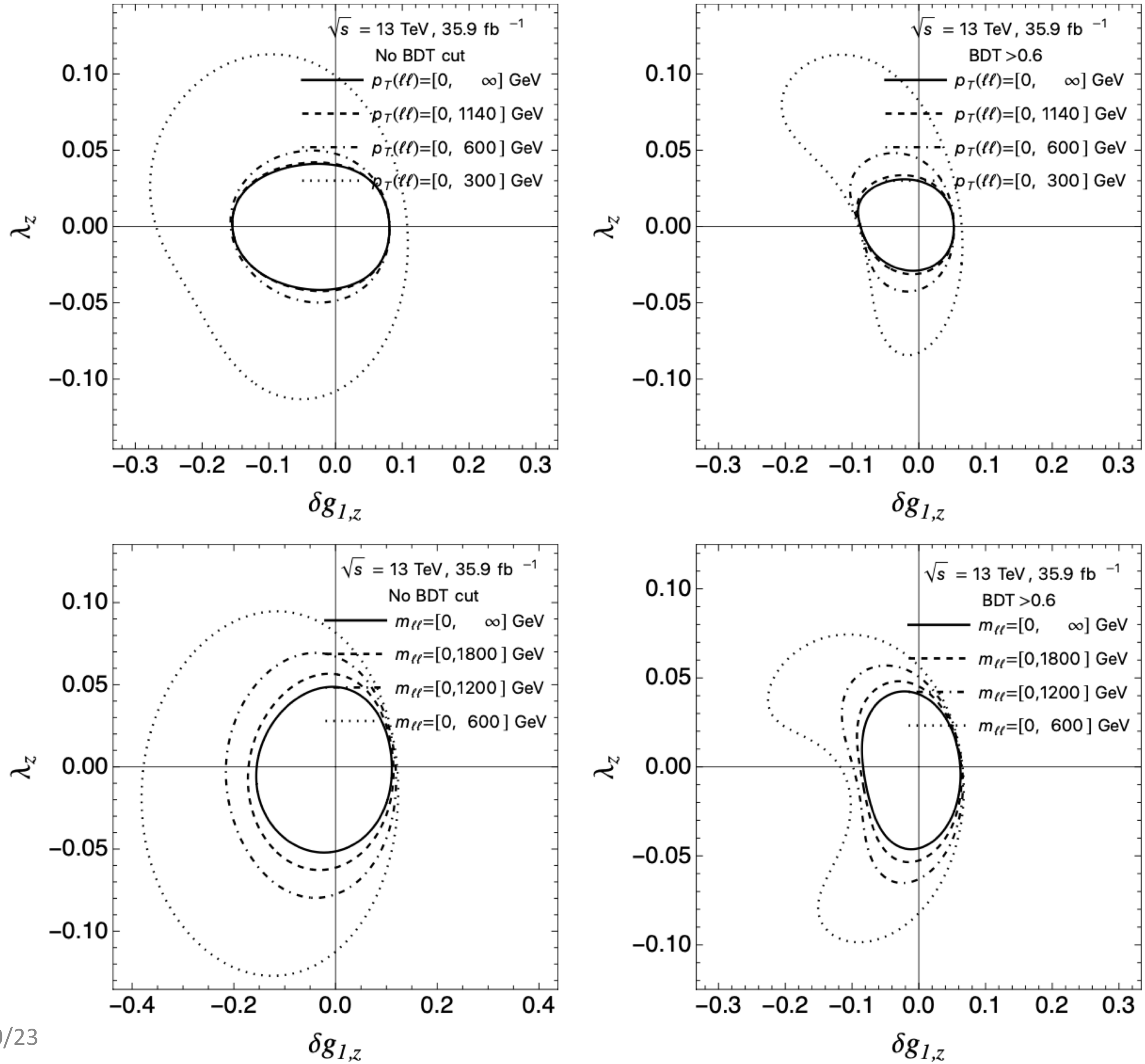
Off-shell region away from Z mass window (only Z mass window is removed wrt CMS)

$$p_T(\ell_1) > 30 \text{ GeV}\ , \quad p_T(\ell_2) > 20 \text{ GeV}\ , \quad |\eta(\mu)| < 2.4\ , \quad |\eta(e)| < 2.1$$
$$p_T(j_1) > 50 \text{ GeV}\ , \quad p_T(j_2) > 30 \text{ GeV}\ , \quad |\eta(j)| \leq 4.7\ ,$$
$$m_{jj} > 200 \text{ GeV}\ .$$








√s = 13 TeV, 35.9 fb⁻¹
No BDT cut
pT(ℓℓ)=[0, ∞] GeV
pT(ℓℓ)=[0, 1140] GeV
pT(ℓℓ)=[0, 600] GeV
pT(ℓℓ)=[0, 300] GeV
√s = 13 TeV, 35.9 fb⁻¹
BDT >0.6
pT(ℓℓ)=[0, ∞] GeV
pT(ℓℓ)=[0, 1140] GeV
pT(ℓℓ)=[0, 600] GeV
pT(ℓℓ)=[0, 300] GeV
√s = 13 TeV, 35.9 fb⁻¹
No BDT cut
mℓℓ=[0, ∞] GeV
mℓℓ=[0,1800] GeV
mℓℓ=[0,1200] GeV
mℓℓ=[0, 600] GeV
√s = 13 TeV, 35.9 fb⁻¹
BDT >0.6
mℓℓ=[0, ∞] GeV
mℓℓ=[0,1800] GeV
mℓℓ=[0,1200] GeV
mℓℓ=[0, 600] GeV
λz
δg1,z