EW precision measurements in diboson production

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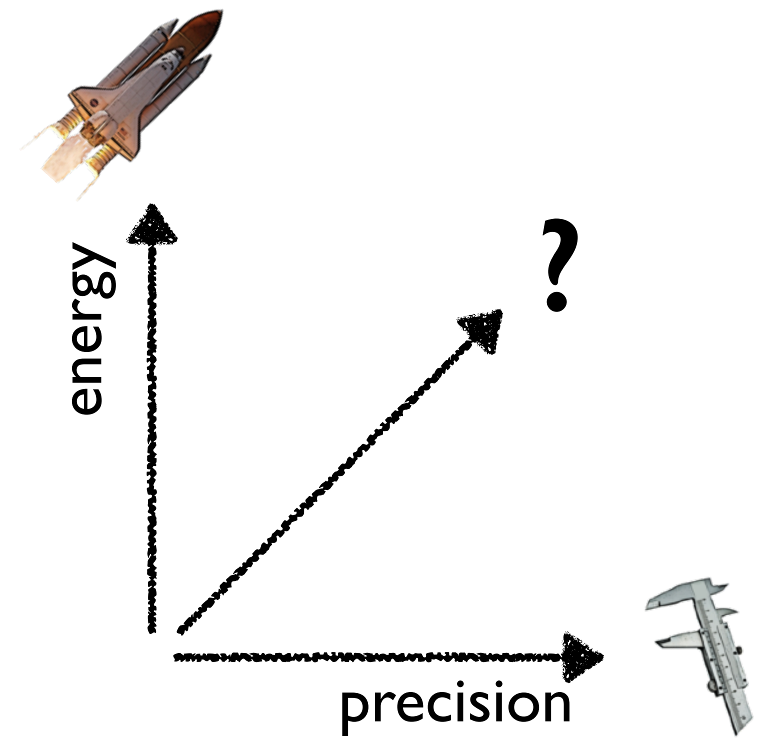
based on work in progress w/ Franceschini, Pomarol, Riva, Wulzer

The precision frontier at LHC

Can we perform “**precision measurements**” at the **LHC**?

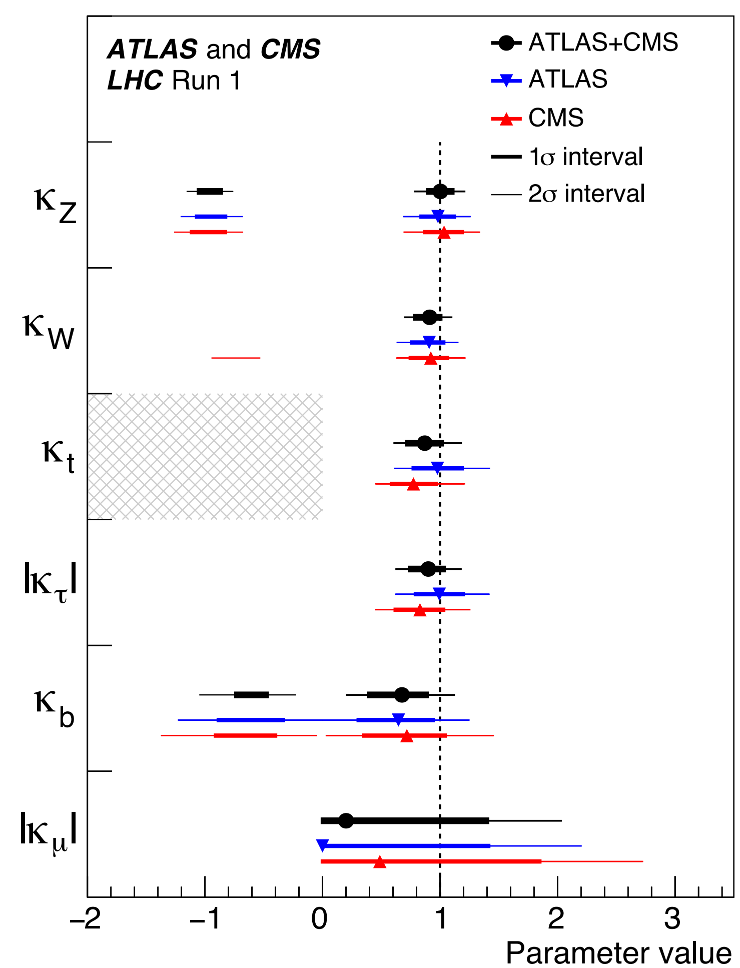


Obvious answer:

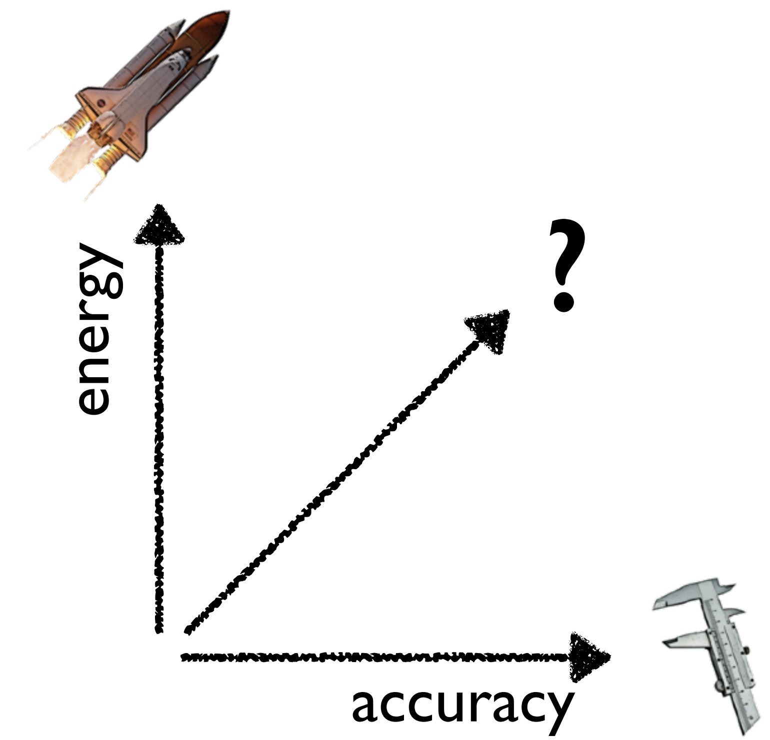
yes, for previously “**untested**” **observables**

Example: precision measurements of the **Higgs couplings**

- deviations expected in several BSM scenarios (eg. SUSY and composite Higgs)
- useful to derive constraints



Energy and accuracy: EW precision



Are there other precision observables we can access at the LHC?

Can we take advantage of high energy to improve **EW precision measurements**?

Which channels for precision?

Which other channels can we exploit for EW precision?

Required features:

- ✦ sizable cross section (low statistical error)
- ✦ small background and good theory understanding (low systematic error)
- ✦ good sensitivity to new physics (enhanced corrections)

Natural candidates: **$2 \rightarrow 2$ scattering processes**

Energy and accuracy: EW precision

If new physics is heavy, low-energy effects are well described by the **EFT language**:

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

leading corrections from dimension-6 operators $\mathcal{O}_i^{(6)}$

- deviations from SM can **grow with energy**

$$\frac{\mathcal{A}_{\rm SM+BSM}}{\mathcal{A}_{\rm SM}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

- LHC could match LEP sensitivity by going at **high energy**

$$0.1\ \% \quad \text{at} \quad 100\ \text{GeV} \quad \longrightarrow \quad 10\ \% \quad \text{at} \quad 1\ \text{TeV}$$

EFT validity

Corrections can not be arbitrarily large

$$\frac{\mathcal{A}_{\mathrm{SM+BSM}}}{\mathcal{A}_{\mathrm{SM}}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

Restrictions:

$$\left.\begin{array}{l} \bullet \text{ necessary condition: } E \lesssim \Lambda \;\Rightarrow\; (E^2/\Lambda^2) \lesssim 1 \\ \bullet \text{ in many cases: } \# < 1 \end{array}\right\} \longrightarrow \frac{\delta\mathcal{A}}{\mathcal{A}_{\mathrm{SM}}} \lesssim 1$$

- ✦ leading effects are linear in BSM (from interference with SM)
- ✦ a meaningful bound can be obtained only if the precision is better than the SM

  ⟶ **clean channels** with low syst. and stat. errors
- ✦ pay attention to the **cut-off!** (restrict analysis to valid region)

Growth vs non-growth

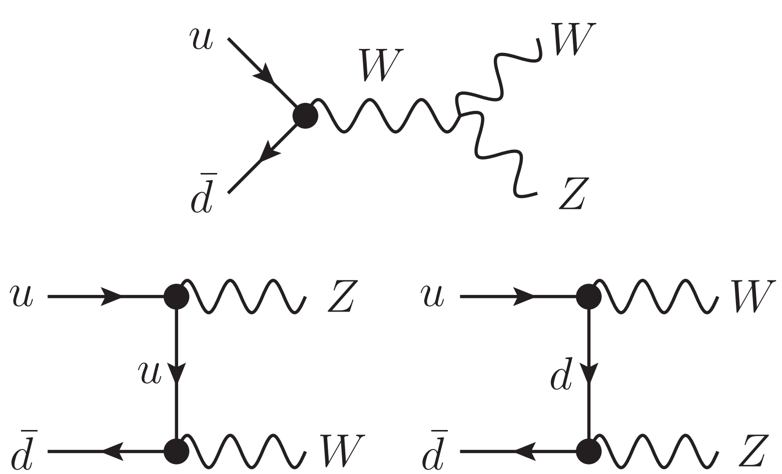
All dim.6 operators induce a growth …but **not** in all channels!

Example: the **WZ channel**

Triplet operator

$$\mathcal{O}_L^3 = (\bar{q}_L \sigma^a \gamma^\mu q_L)(i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$

- corrections to W and Z interactions

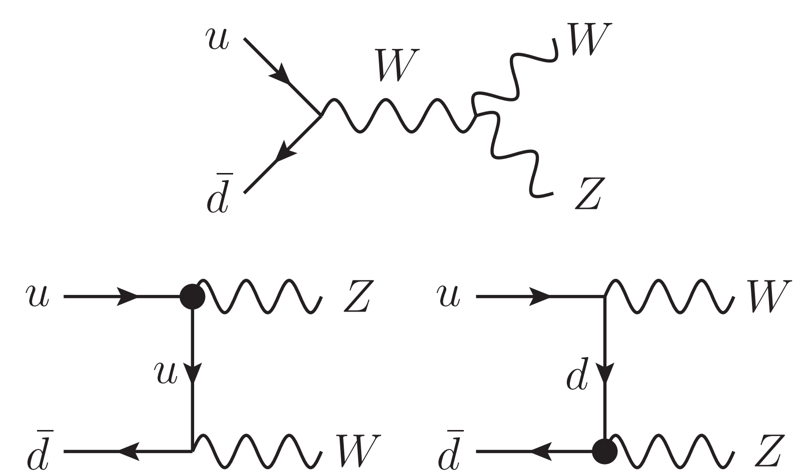


- growth with E^2

Singlet operator

$$\mathcal{O}_L = (\bar{q}_L \gamma^\mu q_L)(i H^\dagger \overleftrightarrow{D}_\mu H)$$

- corrections to Z interactions



- **no growth!**

✦ difficult to guess the growth/no-growth in unitary gauge

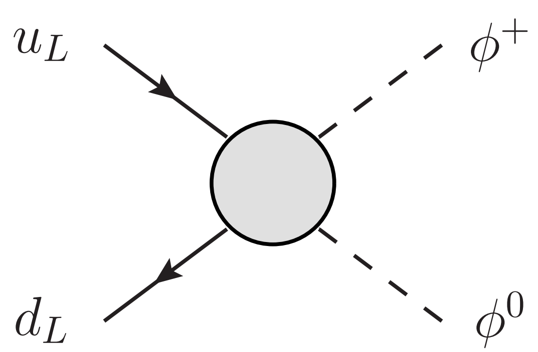
Growth vs non-growth

Easier to understand growth with equivalence theorem:

- at **high energy** gauge fields can be "traded" for Higgs **Goldstones**

Triplet operator

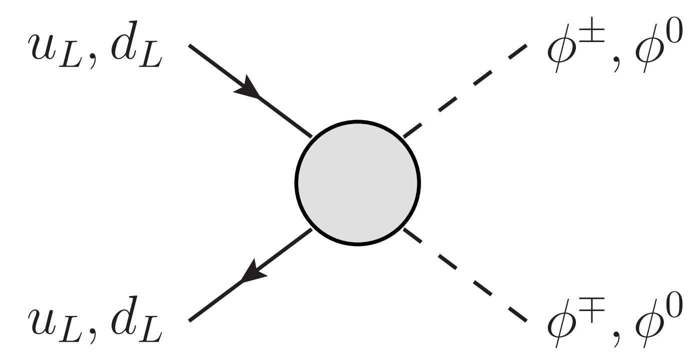
$$\mathcal{O}_L^3 = (\bar{q}_L \sigma^a \gamma^\mu q_L)(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$



- contributes to p p → W Z

Singlet operator

$$\mathcal{O}_L = (\bar{q}_L \gamma^\mu q_L)(iH^\dagger \overleftrightarrow{D}_\mu H)$$



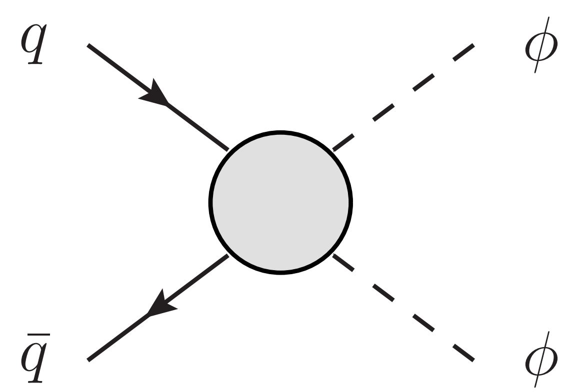
- does **not** contribute to p p → W Z
  (contributes only to neutral channels WW and ZH)

Growth vs non-growth

Easier to understand growth with equivalence theorem:

- at **high energy** gauge fields can be "traded" for Higgs **Goldstones**

- probing diboson at high-energy is a way to test **the Higgs dynamics!**

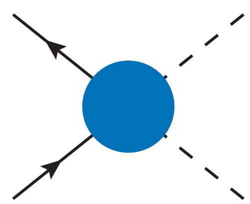


Limitations: non-interference

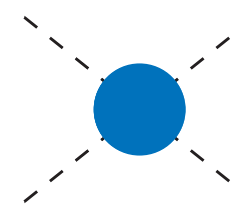
<u>Limitation:</u> at high-energy interference of dim.-6 with SM only in few helicity channels [Azatov, Contino, Machado, Riva '16]

✦ Only **<u>longitudinal</u>** channels interfere at **LO** in $(\varepsilon_{\rm V})^0 = (m_{\rm V}/E)^0$

$\psi\overline{\psi}V_L V_L$



$V_L V_L V_L V_L$



- **growth** at high energy

N.B. amplitudes with longitudinal modes accidentally suppressed

$$\sigma_{\rm SM}(\psi\overline{\psi} \to V_L V_L) \sim 0.002\ \sigma_{\rm SM}(\psi\overline{\psi} \to V_T V_T)$$

$$\sigma_{\rm SM}(V_L V_L \to V_L V_L) \sim 0.1\ \sigma_{\rm SM}(V_T V_T \to V_T V_T)$$

✦ Transverse channels interfere only at subleading order

eg. $\mathcal{A}_{\rm SM}(\psi\overline{\psi}V_{(+)}V_{(-)}) \sim \varepsilon_{\rm V}^0 \qquad \mathcal{A}_{{\rm BSM}_6}(\psi\overline{\psi}V_{(+)}V_{(-)}) \sim \varepsilon_{\rm V}^2$

- no growth at high energy

Which operators in diboson?

Operators inducing **growth with energy**:

$$\begin{cases} \mathcal{O}_L^3 = (\bar{q}_L \sigma^a \gamma^\mu q_L)(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H) \\ \mathcal{O}_L = (\bar{q}_L \gamma^\mu q_L)(iH^\dagger \overleftrightarrow{D}_\mu H) \end{cases}$$

$$\begin{cases} \mathcal{O}_R^u = (\bar{u}_R \gamma^\mu u_R)(iH^\dagger \overleftrightarrow{D}_\mu H) \\ \mathcal{O}_R^d = (\bar{d}_R \gamma^\mu d_R)(iH^\dagger \overleftrightarrow{D}_\mu H) \\ \mathcal{O}_R^{ud} = (\bar{u}_R \gamma^\mu d_R)(i\widetilde{H}^\dagger \overleftrightarrow{D}_\mu H) + \text{h.c.} \end{cases}$$

$$\boxed{\begin{aligned} &WZ,\ WH:\ c_L^{(3)}, c_R^{ud} \\ &WW,\ ZH:\ c_L^{(3)}, c_L, c_R^u, c_R^d \end{aligned}}$$

Amplitudes	Warsaw basis	Primaries
$\bar{u}_L d_L \to W_L Z_L, W_L H$	$-4c_L^{(3)}$	$\delta g_{uL}^Z,\ \delta g_{dL}^Z,\ \delta g_1^Z$
$\bar{u}_R d_R \to W_L Z_L, W_L H$	$-4c_R^{ud}$	δg_R^W
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L H$	$2c_L + 2c_L^{(3)}$	$\delta\kappa_\gamma,\ \delta g_1^Z,\ \delta g_{dL}^Z$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L H$	$2c_L - 2c_L^{(3)}$	$\delta\kappa_\gamma,\ \delta g_1^Z,\ \delta g_{uL}^Z$
$\bar{f}_R f_R \to W_L W_L, Z_L H$	$2c_R^f$	$\delta\kappa_\gamma,\ \delta g_1^Z,\ \delta g_{fR}^Z$

- The $\mathcal{O}_{3W} = \frac{1}{6} g \epsilon_{abc} W_\mu^{a\nu} W_{\nu\rho}^b W^{c\rho\mu}$ operator only interferes at subleading order with the energy-suppressed $++$ and $--$ helicity channels. Only relevant if it has large coefficient and BSM^2 terms are big.

Challenges

Diboson channels may offer sensitivity to new physics but…

challenges:

- ✦ large new-physics effects in subleading helicity channels
- ✦ SM can play the role of "background" (WW and WZ channels)
- ✦ complex final states (eg. neutrinos from W decay)

Rough estimate of reach

Estimate of the reach on c_{HW} $[\times 10^3]$ in the diboson channels

$$O_{HW} = \frac{c_{HW}}{m_W^2} ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

equivalent to $O_L^{(3)}$ at high energy

channel	bounds no bkg.	bounds with bkg.
WH	$[-0.15, 0.15]$	$[-0.5, 0.5]$
ZH	$[-0.5, 0.5]$	$-$
WW	$[-0.3, 0.3]$	$[-0.7, 0.6]$
WZ	$[-0.2, 0.2]$	$[-0.3, 0.3]$

boosted Higgs analysis from [Butterworth et al. 1506.04973]
main bkgs.: Wbb, tt, Wt, WZ

only events with longitudinal polarizations

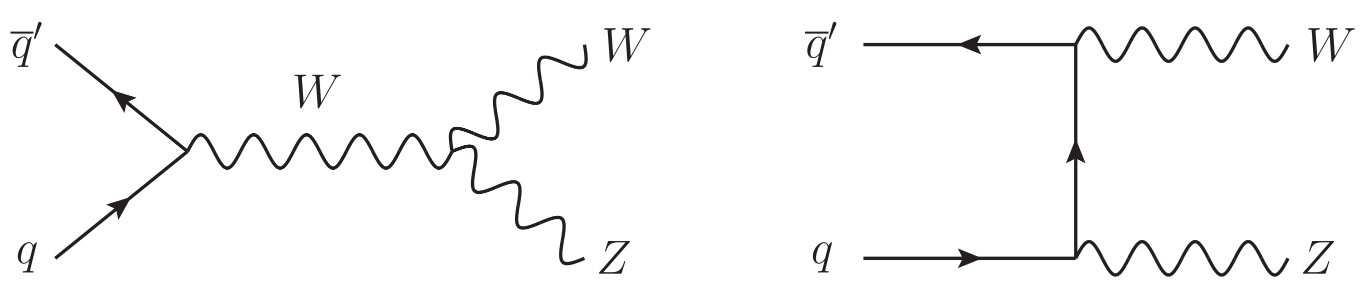
bkg. estimate includes only transverse polarizations

- WZ channel more promising, followed by WH

A promising channel: the WZ process

in progress w/ Franceschini, Pomarol, Riva, Wulzer

WZ production



Clean fully-leptonic final state: $q\bar{q} \to WZ \to (\ell\nu)(\ell\ell)$

- ✦ small background
- ✦ systematic uncertainties under control ($\lesssim$ few %)

[ATLAS Phys. Rev. D 93 (2016)]

Energy enhanced new-physics effects in **longitudinal channel**
(no enhancement in transverse channels due to non-interference theorem)

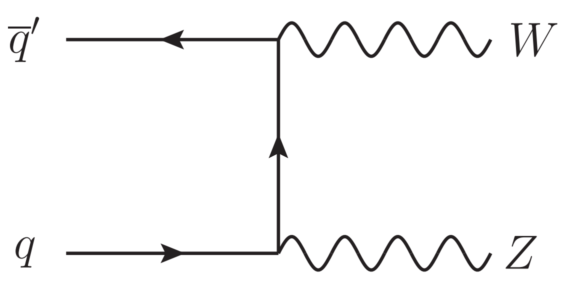
$$\mathcal{O}_L^{(3)} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\overline{q}_L \sigma^a \gamma^\mu q_L) \quad \longrightarrow \quad \frac{\mathcal{A}_{00}^{\mathrm{SM+BSM}}(q\bar{q} \to WZ)}{\mathcal{A}_{00}^{\mathrm{SM}}(q\bar{q} \to WZ)} = 1 + 4\frac{s}{\Lambda^2} c_L^{(3)}$$

leading correction from interference with SM

WZ production

… but **transverse** channels **dominate** the SM cross section

large cross section
due to t-channel singularity
(only there for transverse)



cross sections with standard acceptance cuts:

	σ_{tot}	σ_{LL}	σ_{LL}/σ_{tot}
8 TeV	12 pb	0.73 pb	6%
13 TeV	25 pb	1.5 pb	

(BR for fully-leptonic decay not included $\mathrm{BR}(WZ \to (\ell\nu)(\ell\ell)) \simeq 1.5\%$)

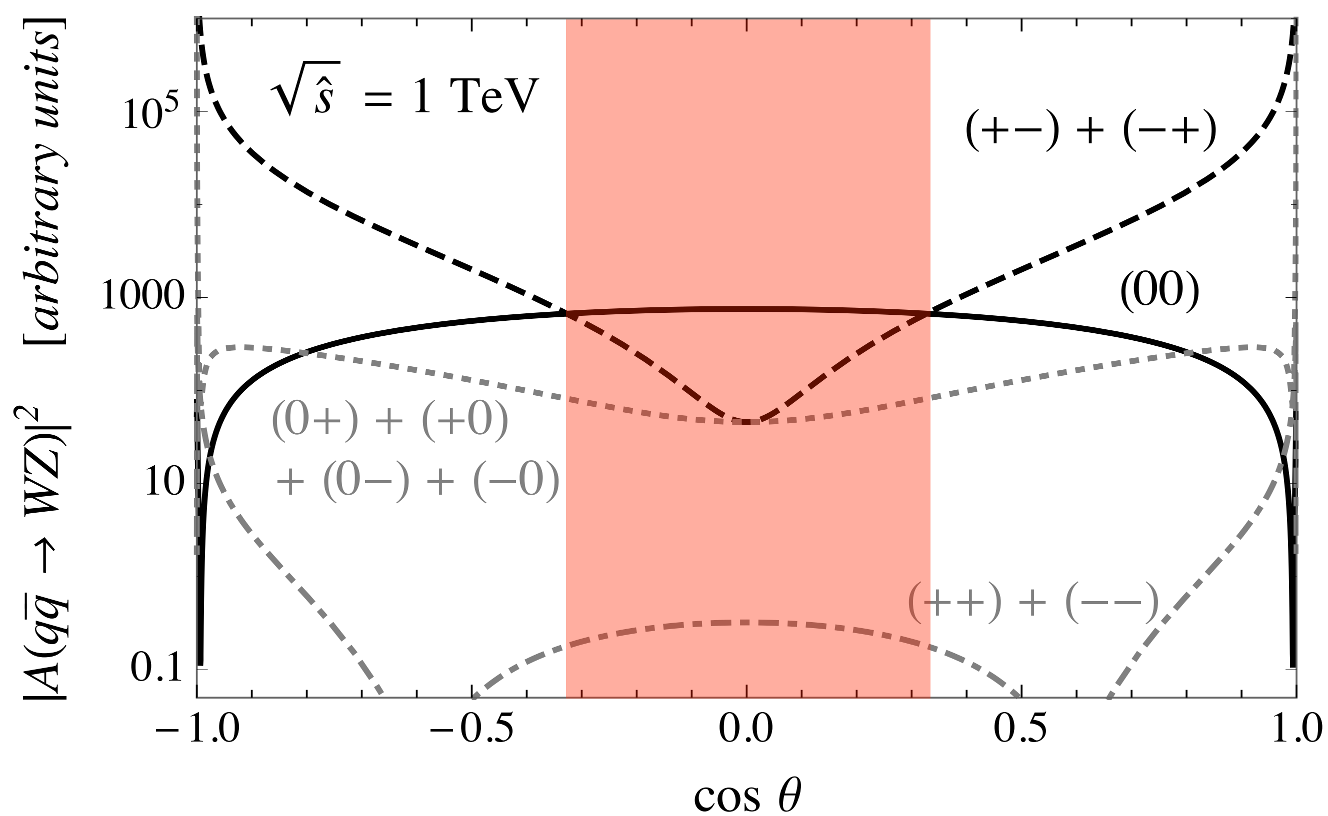
Extracting the longitudinal channel

Transverse amplitudes vanish for (nearly) central scattering

[Baur, Han, Ohnemus '94]

$$A_{(+-)}(u\bar{d} \to WZ)\,, \quad A_{(-+)}(u\bar{d} \to WZ) \propto \cos\theta - \frac{1}{3}\tan\theta_{\mathrm{W}}$$

- longitudinal amplitude dominates for $\theta \sim 90^\circ$
- cuts in $\hat{s}$ and $\cos\theta$ can be used to isolate the longitudinal channel



13 TeV	σ_{tot}	σ_{LL}	σ_{LL}/σ_{tot}
$\lvert\cos\theta\rvert < 0.5 \quad \sqrt{\hat{s}} > 300$ GeV	630 fb	230 fb	37%
$\lvert\cos\theta\rvert < 0.5 \quad \sqrt{\hat{s}} > 500$ GeV	80 fb	34 fb	42%

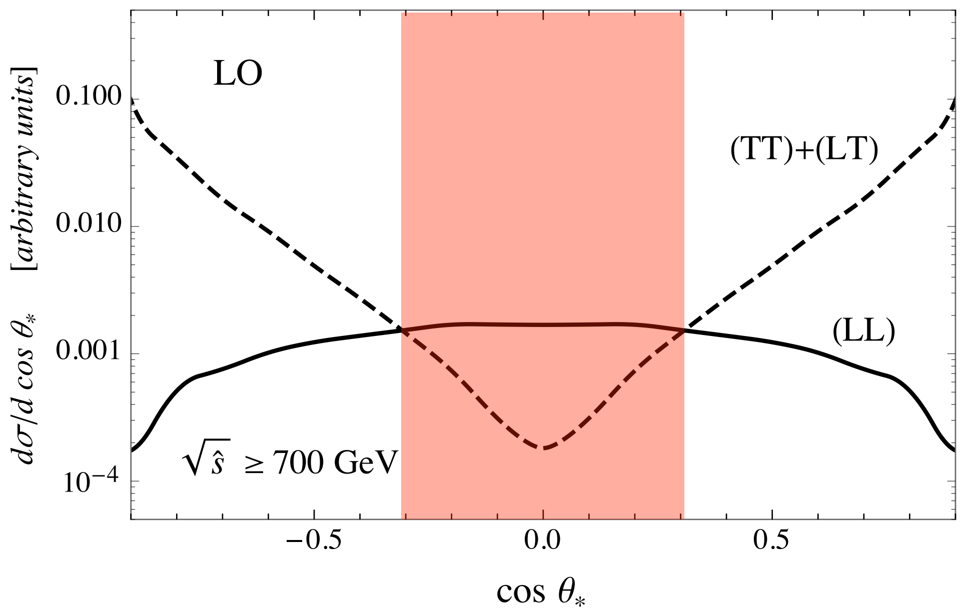
Sensitivity to new physics

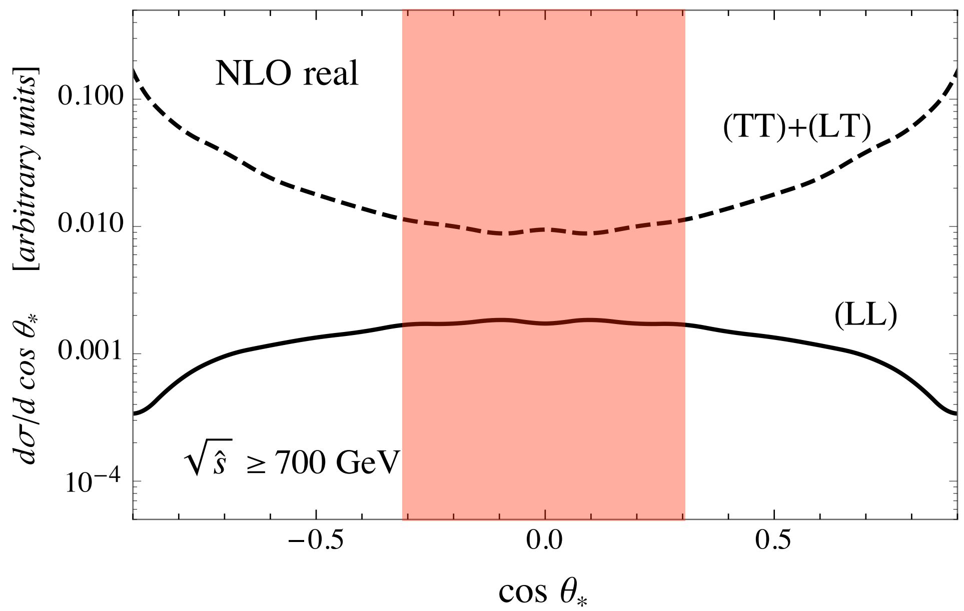
Good sensitivity to new physics: $$\frac{c_L^{(3)}}{(1\ \mathrm{TeV})^2}(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\overline{q}_L\sigma^a\gamma^\mu q_L)$$

13 TeV	$\sqrt{\hat{s}} > 300$ GeV			$\sqrt{\hat{s}} > 500$ GeV		
$(\lvert\cos\theta\rvert < 0.5)$	σ_{LL}	σ_{LL}/σ_{tot}	$\delta\sigma_{tot}$	σ_{LL}	σ_{LL}/σ_{tot}	$\delta\sigma_{tot}$
SM	230 fb	37%		34 fb	42%	
$c_L^{(3)} = 0.05$	290 fb	43%	6%	46 fb	52%	10%
$c_L^{(3)} = 0.5$	470 fb	61%	24%	92 fb	82%	40%

A realistic analysis

✦ NLO corrections partially spoil the LO zeroes



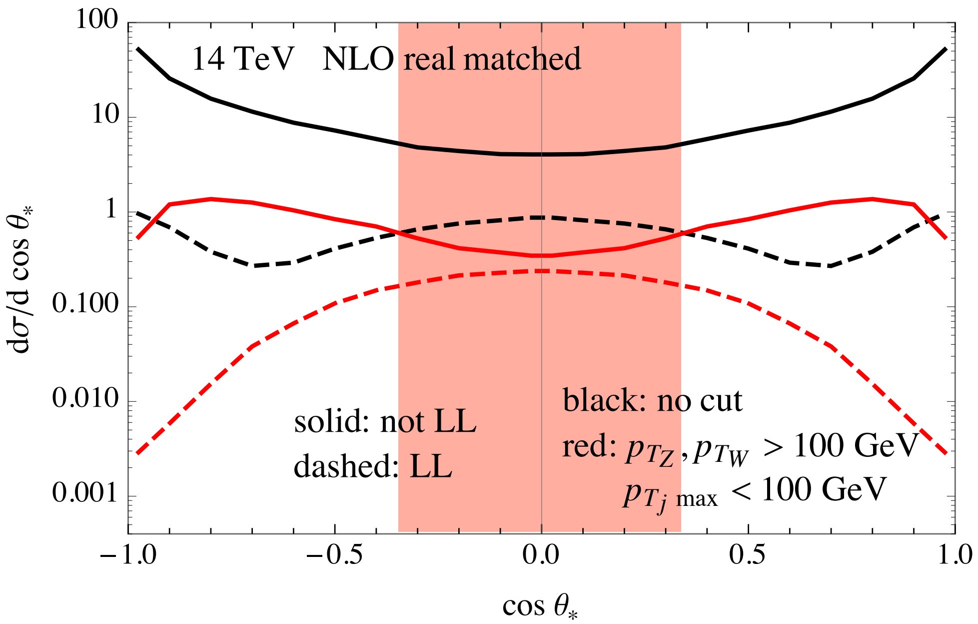


→ NLO effects can be kept under control by jet veto

possible choice:

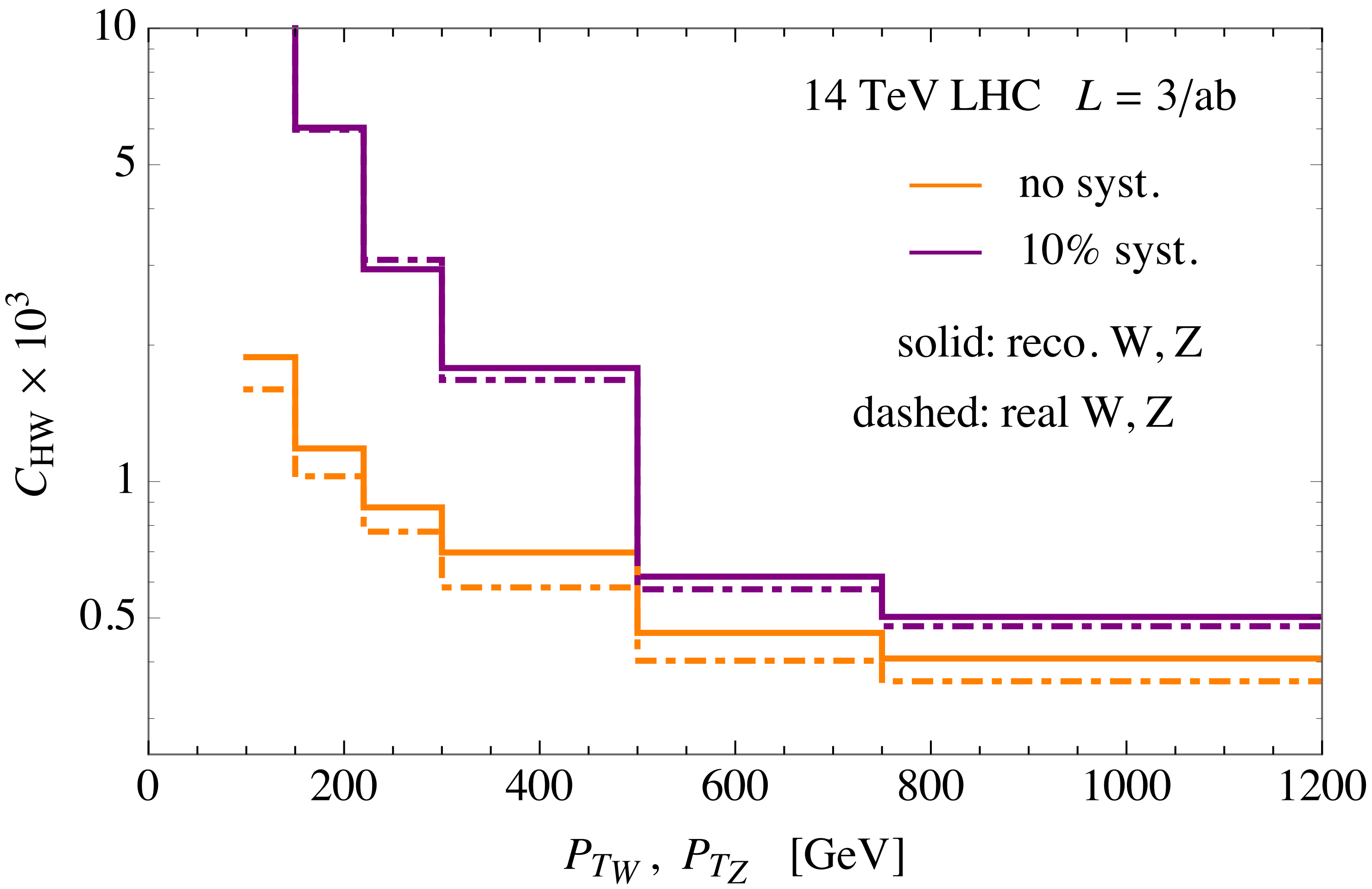
$$p_{T_Z}, p_{T_W} > 100 \text{ GeV}$$

$$p_{T_j max} < 100 \text{ GeV}$$



The reach

Estimates of the bounds on $O_{HW} = \frac{c_{HW}}{m_W^2} ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$



- ✦ impact of systematics can be important (10% estimate in the plot)
- ✦ smaller impact from neutrino reconstruction

“Interference Resurrection”: The $W\gamma$ process

in progress w/ Franceschini, Pomarol, Riva, Wulzer

“Interference Resurrection”

The **non-interference theorem** applies only if we are dealing with final states with definite helicity

when the gauge bosons decay helicities get “mixed”

↓

interference between transverse and longitudinal channels gives rise to **azimuthal correlations!**

<u>Important features:</u>

- interference affects only the **exclusive** cross section:
  it modifies only the **azimuthal distribution** of the decay products
- interference is erased by integrating over the decay angles

Wγ production

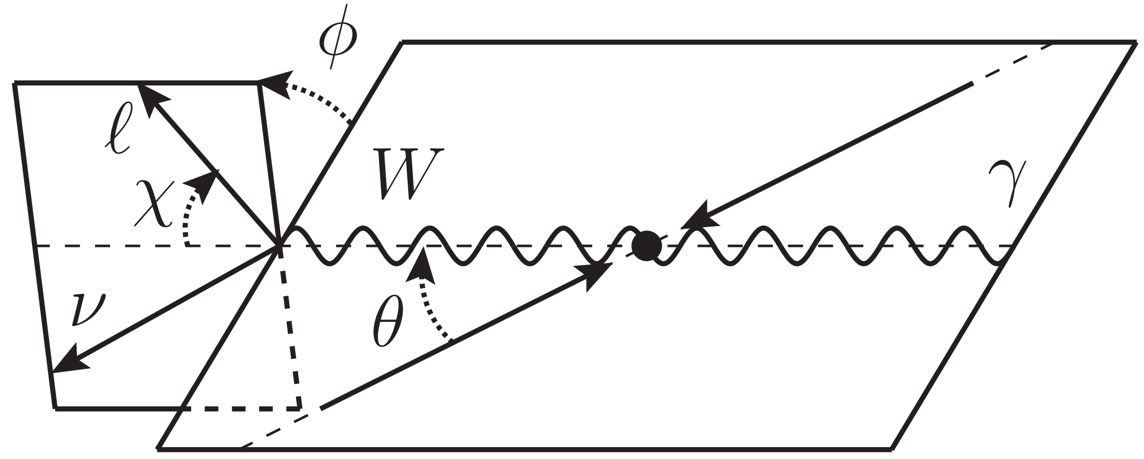
A simple process to explore interference is $W\gamma$ production

Polarized **production**:

$$\begin{cases} \mathcal{A}^{\rm SM}_{(+-)}\,, \mathcal{A}^{\rm SM}_{(-+)} \sim 1 \\ \mathcal{A}^{\rm SM}_{(0\pm)} \sim \dfrac{m_{\rm W}}{E} \\ \mathcal{A}^{\rm SM}_{(++)}\,, \mathcal{A}^{\rm SM}_{(--)} \sim \dfrac{m^2_{\rm W}}{E^2} \end{cases}$$

Polarized W **decay**:

$$\begin{cases} \mathcal{A}_{(+)} \sim (1+\cos\chi)\, e^{i\phi} \\ \mathcal{A}_{(-)} \sim (-1+\cos\chi)\, e^{-i\phi} \\ \mathcal{A}_{(+)} \sim -\sqrt{2}\sin\chi \end{cases}$$



- azimuthal phase depending on W polarization

Wγ production: the amplitude

Total amplitude:

$$|\mathcal{A}_{tot}|^2 \sim (1+c_\chi)^2|\mathcal{A}_{(+\pm)}|^2 + (1-c_\chi)^2|\mathcal{A}_{(-\pm)}|^2 + 2s_\chi^2|\mathcal{A}_{(0\pm)}|^2$$

no interference

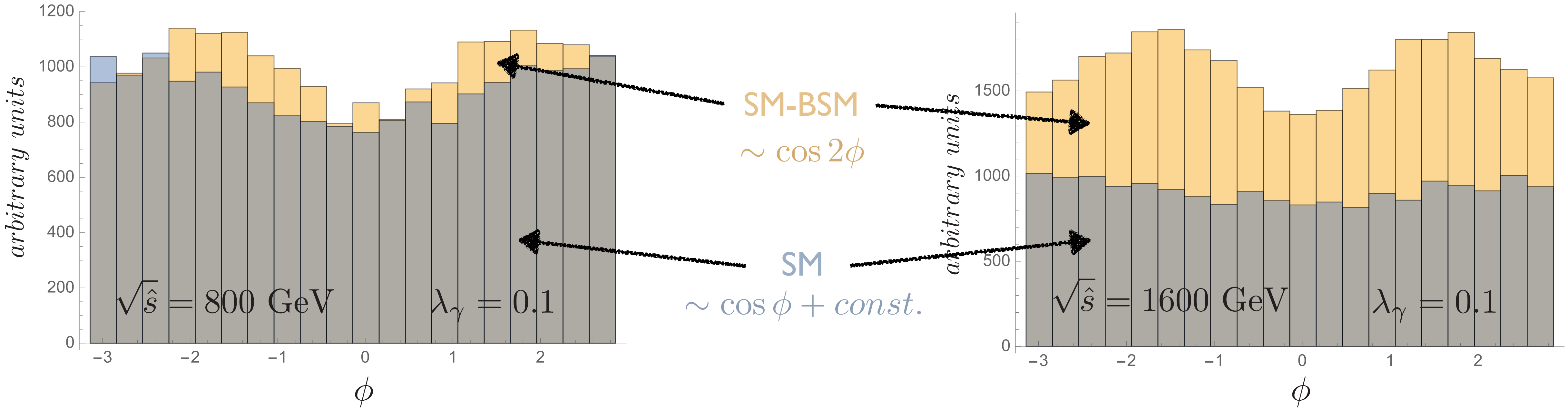
$$-2s_\chi^2\,\mathrm{Re}[\mathcal{A}_{(+\pm)}\mathcal{A}^*_{(-\pm)}e^{2i\phi}]$$
$$-2\sqrt{2}(1+c_\chi)s_\chi\,\mathrm{Re}[\mathcal{A}_{(+\pm)}\mathcal{A}^*_{(0\pm)}e^{i\phi}]$$
$$+2\sqrt{2}(1-c_\chi)s_\chi\,\mathrm{Re}[\mathcal{A}_{(-\pm)}\mathcal{A}^*_{(0\pm)}e^{-i\phi}]$$

interference:
azimuthal correlations

→ interference terms lead to non-trivial dependence on ϕ

Wγ production: TGC corrections

Example: corrections to TGC's: $\frac{ie}{m_{\mathrm{W}}^2}\lambda_\gamma W_\mu^{+\nu} W_\nu^{-\rho} A_\rho{}^\mu$



In progress:

- ✦ extraction of bounds on TGC's
- ✦ application to other processes (eg. WZ)?

Conclusions

Conclusions

Hadron colliders can be used to get **precision EW measurements**

- exploit energy growth of new-physics effects

Challenges:

- accessing **high-energy tails**, good statistics (eg. $2 \to 2$ scattering)
- **accuracy**, low systematic uncertainties (eg. leptonic final states)

Precision in **diboson channels:**

- new-physics effects give growth in **longitudinal channels**
- most promising processes: WZ and WH
- WZ can lead to good sensitivity due to suppression of transverse channel for central scattering