Interference resurrection

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Fundamental physics at colliders

The main goal of the collider program is to deepen our knowledge of fundamental physics

In practical terms, this means **testing the SM**

looking for its possible **failures** → evidence of **New Physics** (BSM)

The roadmap to precision

Complementarity

devising different strategies to test the SM predictions
and to cover different types of new physics

Optimality

improve and optimize the new-physics probes to achieve better sensitivity

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HL-LHC and future colliders will provide a huge amount of data

↓

Fine details of the SM can be tested with high precision

The EFT approach

The **Effective Field Theory** (**EFT**) description can be used to parametrize new-physics effects 'away' from direct production (i.e. for heavy new physics)

Terms in the EFT Lagrangian can be organized in an expansion in E/Λ

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \frac{1}{\Lambda^2}\mathscr{L}_6 + \frac{1}{\Lambda^4}\mathscr{L}_8 + \cdots$$

energy dimension ≤ 4   dim = 6   dim = 8

- **only SM particles** appear in the EFT
- **SM symmetries** are respected

→ "small" number of new operators

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leading corrections

- **only SM particles** appear in the EFT
- **SM symmetries** are respected

→ "small" number of new operators

The leading new-physics effects

- Deviations from SM typically **grow with energy**

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

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- Where to look to optimize the sensitivity

$$\sigma \sim |\mathcal{A}_{\rm SM} + \mathcal{A}_{\rm BSM}|^2 \sim g_{\rm SM}^2 + \# g_{\rm SM} g_{\rm NP} \frac{E^2}{\Lambda^2} + \# g_{\rm NP}^2 \frac{E^4}{\Lambda^4}$$

squared SM contribution — **Interference** — **squared BSM contribution**

  - Squared BSM contribution dominant when $|\mathcal{A}_{\rm BSM}| > |\mathcal{A}_{\rm SM}|$
    (i.e. when BSM corrections are $\gtrsim 100\%$ of SM)
  - Interference becomes dominant when BSM corrections are small
    → important when we can measure the SM with high precision

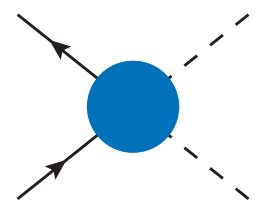
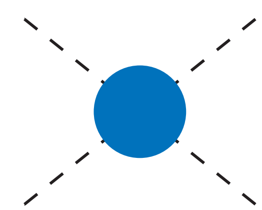
Limitations: non-interference

Limitation:

[Azatov, Contino, Machado, Riva '16]

at high-energy interference of dim-6 operators with SM happens only in few helicity channels

- Eg. in **di-boson production** interference between the SM and new-physics (from dim-6 ops.) happens only in **longitudinal channels**

$\psi\bar{\psi}V_L V_L$  $V_L V_L V_L V_L$ 

  - **growth** at high energy

- Transverse channels interfere only at subleading order in $\varepsilon_V = m_V/E$

  eg. $\mathcal{A}_{\rm SM}(\psi\bar{\psi}V_{(+)}V_{(-)}) \sim \varepsilon_{\rm V}^0$ $\mathcal{A}_{\rm BSM_6}(\psi\bar{\psi}V_{(+)}V_{(-)}) \sim \varepsilon_{\rm V}^2$

  - no growth at high energy

→ Interference resurrection "trick"

The Interference Resurrection trick

GP, Riva, Wulzer '17

“Switching on” the interference

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

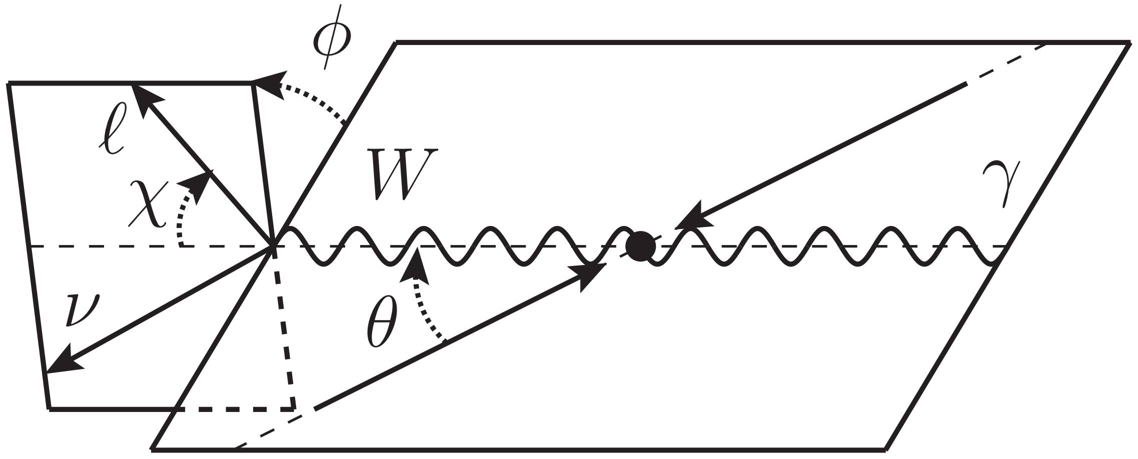
A simple process to explore interference is $W\gamma$ production

Polarized **production**:

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

Polarized W **decay**:

$$\begin{cases} \mathcal{A}_{(+)} \sim (1+\cos\chi)e^{i\phi} \\ \mathcal{A}_{(-)} \sim (-1+\cos\chi)e^{-i\phi} \\ \mathcal{A}_{(0)} \sim -\sqrt{2}\sin\chi \end{cases}$$



- ✦ azimuthal phase depending on W polarization

Wγ production: the amplitude

Total amplitude:

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

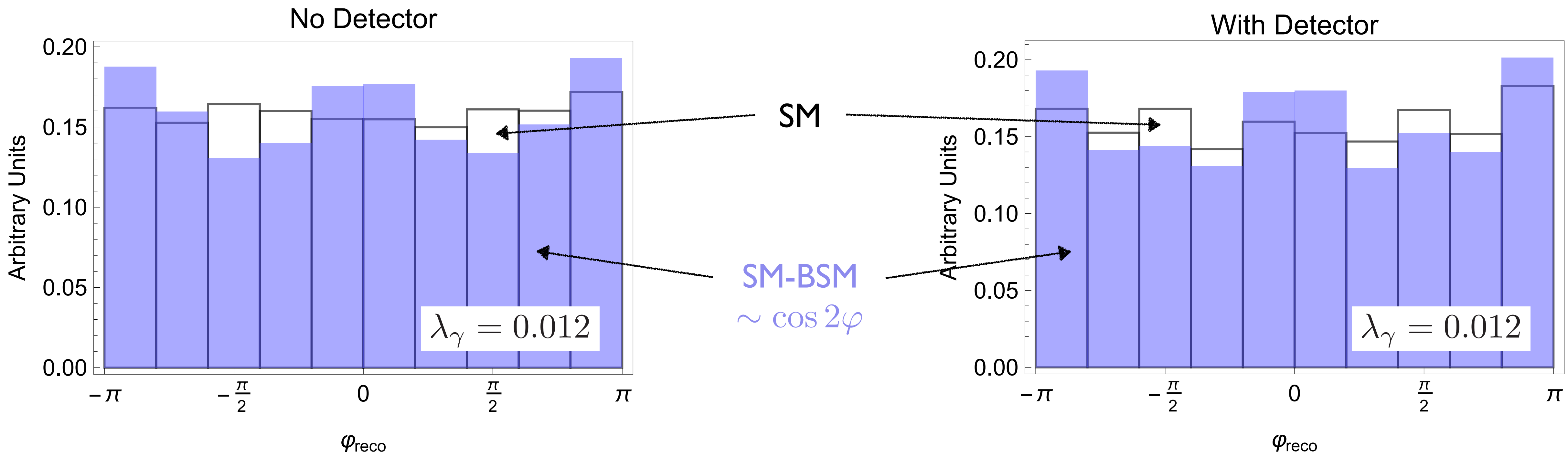
no interference (first line)

interference: **azimuthal correlations** (remaining lines)

→ interference terms lead to non-trivial dependence on ϕ

Wγ production: TGC corrections

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

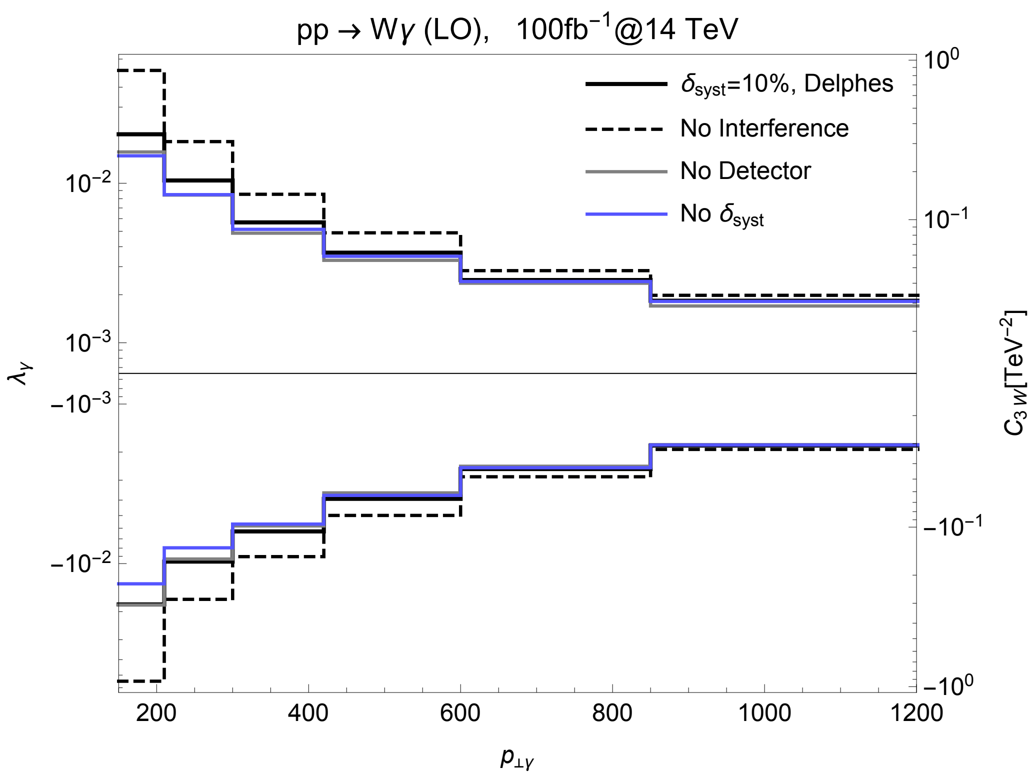


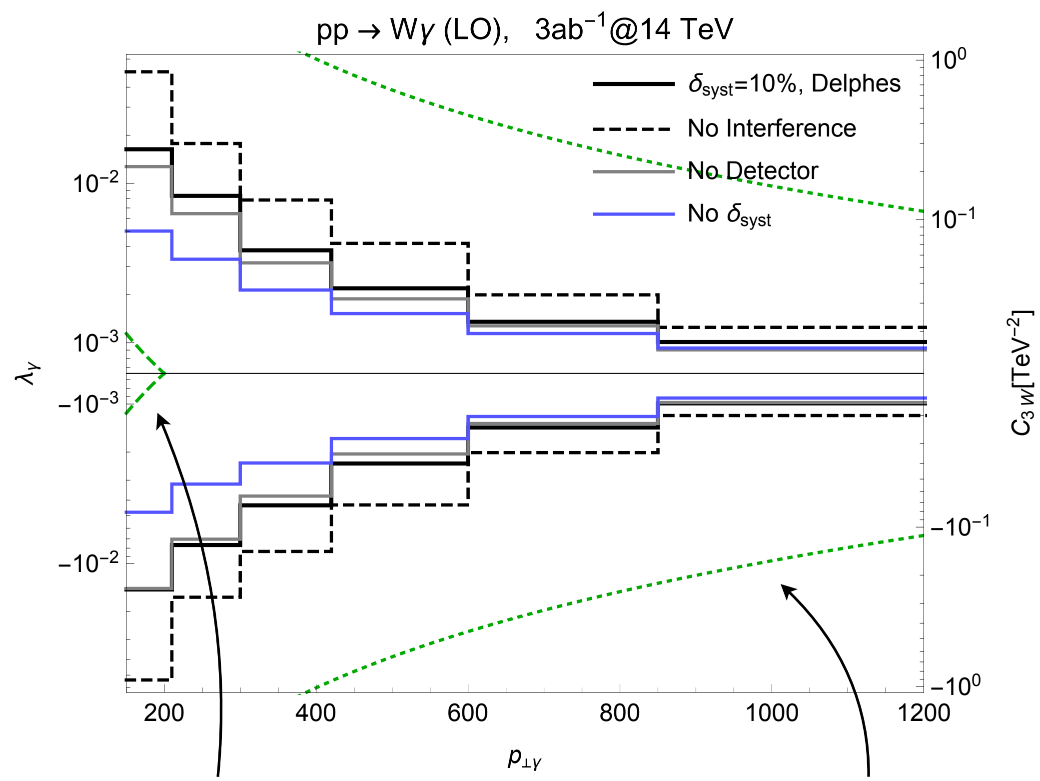
✦ BSM effects from interference clearly visible

- neutrino reconstruction induces small uncertainty
- detector effects under control

Sensitivity reach

"Interference resurrection" improves the bounds at LHC





one-loop new-physics

$\lambda_\gamma \sim 6g^2/(16\pi^2)\, m_W^2/\Lambda^2$

weakly-coupled new-physics

$\lambda_\gamma \sim 6\, m_W^2/\Lambda^2$

- ✦ largest effects in low-energy bins (factor ~2 improvement)
- ✦ significant improvement also on overall bound at HL-LHC

$$|\lambda_\gamma| < 1.0 \times 10^{-3}$$

$|\lambda_\gamma| < 1.3 \times 10^{-3}$ w/o interference

$|\lambda_\gamma| < 0.9 \times 10^{-3}$ no syst. error

- ✦ sensitive to tree-level weakly-coupled new physics

Where to go next

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Interference resurrection is a broad idea
that can be applied to several precision channels

Rule of thumb: **the more differential the better**

- Integrating over some variables can cancel the interference
- SM and BSM distribution often differ in several kinematical variables
- measuring the full differential distributions optimizes the sensitivity to new physics

Where to go next

- **<u>Wγ production</u>**
  - so far we only considered the azimuth decay angle distributions (and a binning in energy)
  - study the impact of measuring also the scattering angle and the polar decay angle
  - CP-odd operators particularly challenging $\varepsilon^{ijk} W_{\mu}^{i\nu} W_{\nu}^{j\rho} \widetilde{W}_{\rho}^{k\mu}$
    - interference naively cancels because of neutrino reconstruction ambiguity
    - can we improve with fully-differential analysis?

Where to go next

- <u>Muon radiation</u>
  - interference resurrection can also be obtained through splitting
    eg. $\mu \to \mu\,\gamma$ can change the muon helicity
  - can we exploit this effect?
  - example: measurement of Z couplings
    (interference between L- and R-handed couplings, deformations via EFT ops.)