Study of CP violating EFT bosonic operators with the ATLAS detector

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Contents

CP violation and effective field theories

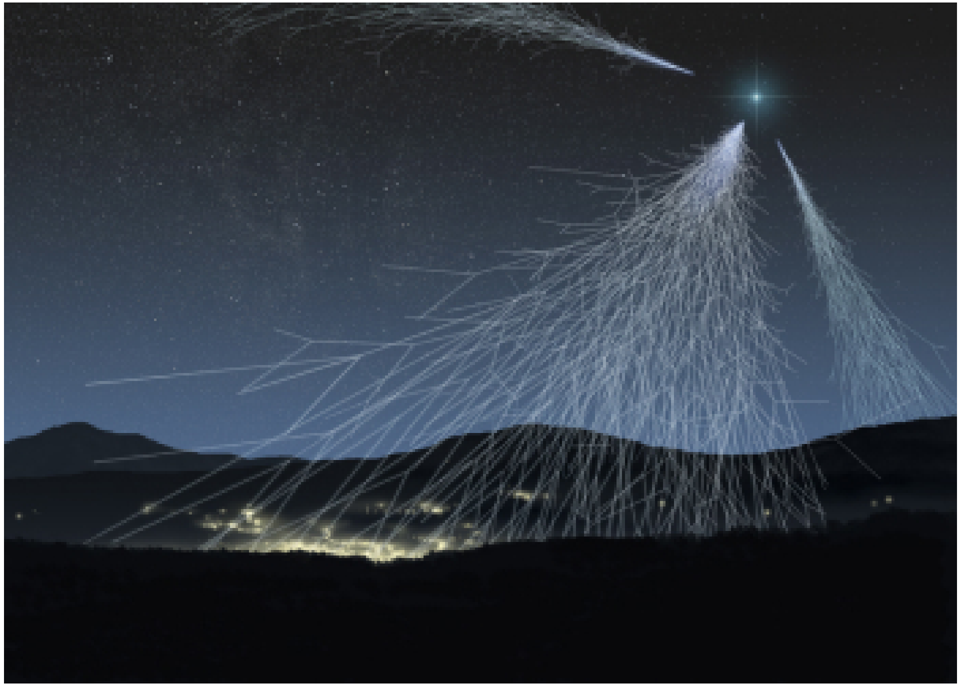
Matter – antimatter asymmetry

Big Bang should have created equal amounts of matter and antimatter in the early universe.

Measurements on cosmic rays :

$$\frac{n(\bar{p})}{n(p)} = 10^{-4}$$

→ **no ambient antiprotons**



Cosmic rays detectors for education

Sakharov's conditions

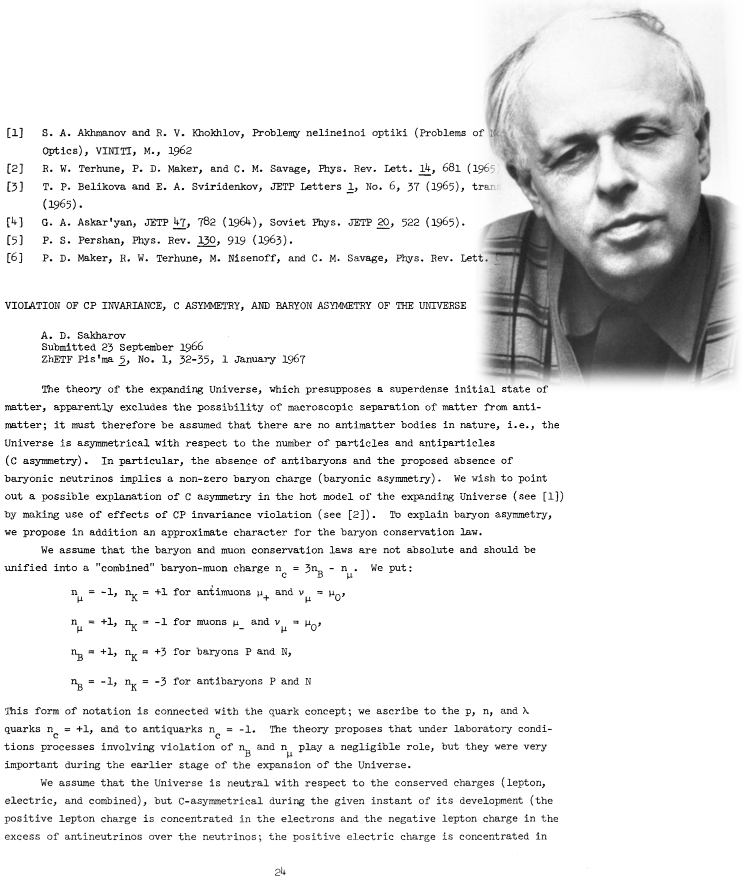
Even if in equal amount initially, such asymmetry can arise if **Sakharov's conditions** are verified :

1 – Violation of baryonic number B

2 – Universe out of thermal equilibrium

3 – Violation of C invariance and CP symmetry

$$\psi \begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix} \xrightarrow{C} \bar{\psi} \begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix} \xrightarrow{P} \bar{\psi} \begin{pmatrix} E \\ -p_x \\ -p_y \\ -p_z \end{pmatrix}$$



[1] S. A. Akhmanov and R. V. Khokhlov, Problemy nelineinoi optiki (Problems of
Optics), VINITI, M., 1962

[2] R. W. Terhune, P. D. Maker, and C. M. Savage, Phys. Rev. Lett. 14, 681 (1965

[3] T. P. Belikova and E. A. Sviridenkov, JETP Letters 1, No. 6, 37 (1965), tran
(1965).

[4] G. A. Askar'yan, JETP 47, 782 (1964), Soviet Phys. JETP 20, 522 (1965).

[5] P. S. Pershan, Phys. Rev. 130, 919 (1963).

[6] P. D. Maker, R. W. Terhune, M. Nisenoff, and C. M. Savage, Phys. Rev. Lett.

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

We assume that the baryon and muon conservation laws are not absolute and should be unified into a "combined" baryon-muon charge $n_c = 3n_B - n_\mu$. We put:

$n_\mu = -1$, $n_K = +1$ for antimuons μ_+ and $\nu_\mu = \mu_0$,

$n_\mu = +1$, $n_K = -1$ for muons μ_- and $\nu_\mu = \mu_0$,

$n_B = +1$, $n_K = +3$ for baryons P and N,

$n_B = -1$, $n_K = -3$ for antibaryons P and N

This form of notation is connected with the quark concept; we ascribe to the p, n, and λ quarks $n_c = +1$, and to antiquarks $n_c = -1$. The theory proposes that under laboratory conditions processes involving violation of n_B and n_μ play a negligible role, but they were very important during the earlier stage of the expansion of the Universe.

We assume that the Universe is neutral with respect to the conserved charges (lepton, electric, and combined), but C-asymmetrical during the given instant of its development (the positive lepton charge is concentrated in the electrons and the negative lepton charge in the excess of antineutrinos over the neutrinos; the positive electric charge is concentrated in

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CPV in the Standard Model

Standard Model Lagrangian :

Gauge bosons

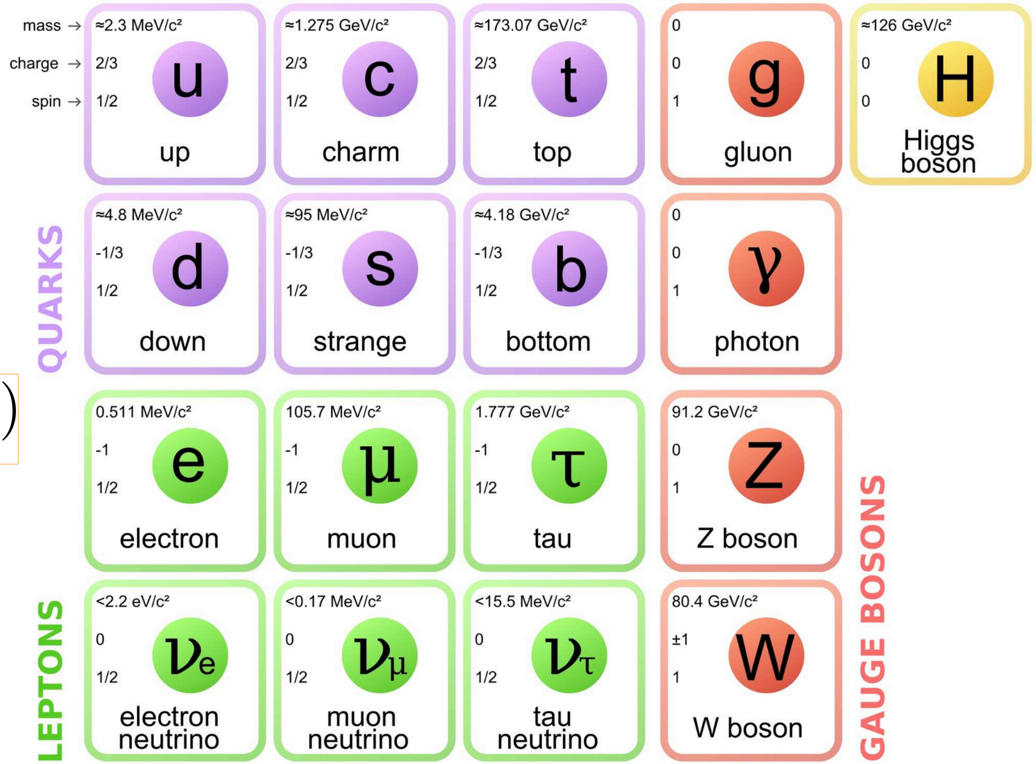
Fermions

$$\mathcal{L}_{SM} = \boxed{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} + \boxed{i\bar{\psi}\gamma_\alpha D^\alpha\psi}$$

$$+\boxed{\psi_i\mathcal{Y}_{ij}\psi_j\phi + h.c.} + \boxed{|D\phi|^2 - V(\phi)}$$

Higgs

Yukawa couplings, only source of Std Model CPV (CKM matrix complex phase)



≈2.3 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈173.07 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c² 0 0 H Higgs boson
≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	
0.511 MeV/c² -1 1/2 e electron	105.7 MeV/c² -1 1/2 μ muon	1.777 GeV/c² -1 1/2 τ tau	91.2 GeV/c² 0 1 Z Z boson	
<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	80.4 GeV/c² ±1 1 W W boson	

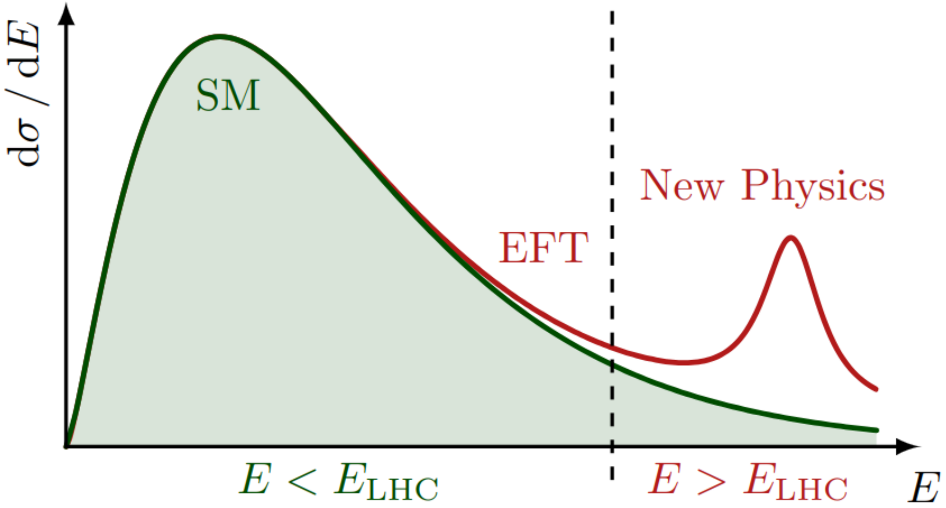
Effective theories to look for new CPV

→ SM allows CP breaking, but predicted effects are not large enough

→ new CPV must occur beyond explored energy range

→ Effective field theory approach

Differential cross section



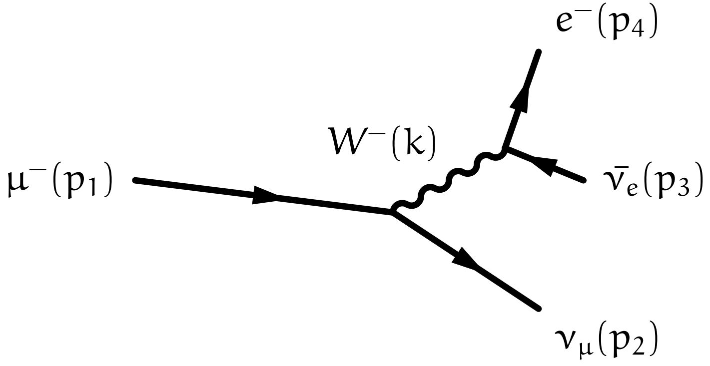
How do EFT work ?

Historical example: muon decay (μ → v_μ e v_e) and Fermi’s 4-point interaction

Muon lifetime τ ~ 1/Γ with $\Gamma \simeq \int \mathcal{M} \mathrm{d}\Phi$

Decay matrix element

Phase space



$$i\mathcal{M} = J^\mu(p_1,p_2)\, i\,\frac{-g_{\mu\nu} - \frac{k_\mu k_\nu}{m_W^2}}{k^2 - m_W^2}\, J^\nu(p_3,p_4)$$

$$i\mathcal{M} = J^\mu(p_1,p_2) P_{\mu\nu}(k) J^\nu(p_3,p_4)$$

How do EFT work ?

Historical example: muon decay and Fermi's 4-point interaction

Low energy limit **$k < p_1 << m_W$**

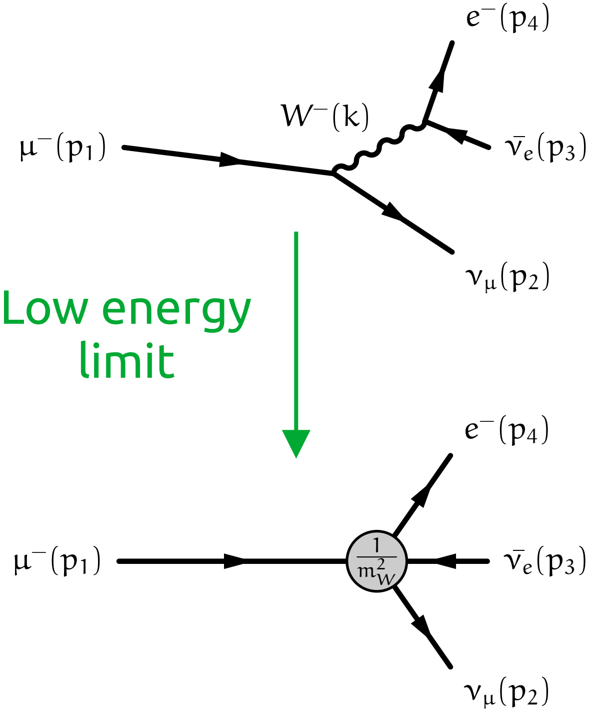
$$i\frac{-g_{\mu\nu} - \frac{k_\mu k_\nu}{m_W^2}}{k^2 - m_W^2} \to -i\frac{g_{\mu\nu}}{m_W^2}$$

$$i\mathcal{M} \to J^\mu(p_1, p_2)P'_{\mu\nu}J^\nu(p_3, p_4)$$

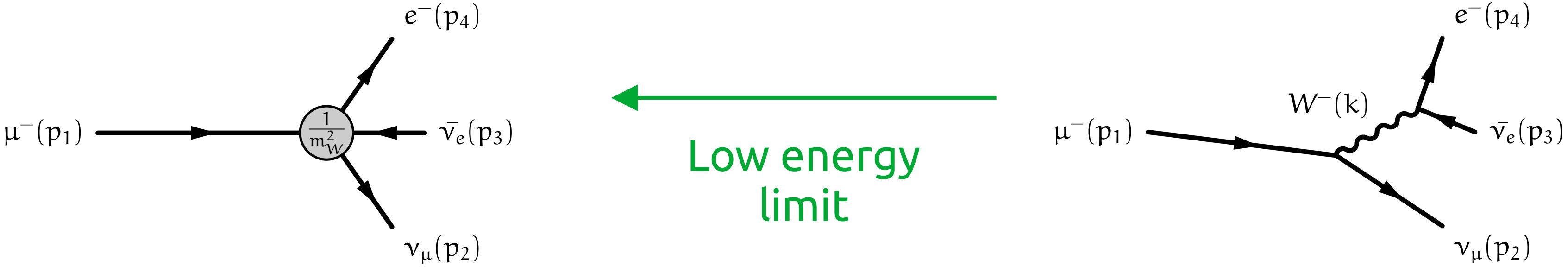
Effective propagator

No more dependence on the W boson kinematics
W mass as part of the **effective coupling**

Fermi's 4-point interaction



How do EFT work ?



Low energy limit

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma_\alpha D^\alpha\psi$$
$$+\psi_i\mathcal{Y}_{ij}\psi_j\phi + h.c. + |D\phi|^2 - V(\phi)$$

Low energy limit

$$\mathcal{L}_{BSM} = ?$$

More complete theory of particle physics

New Lagrangian

- Assumes only existence of SM fields
- Operators of dimension > 4
- BSM fields integrated out in new physics constant **Λ**

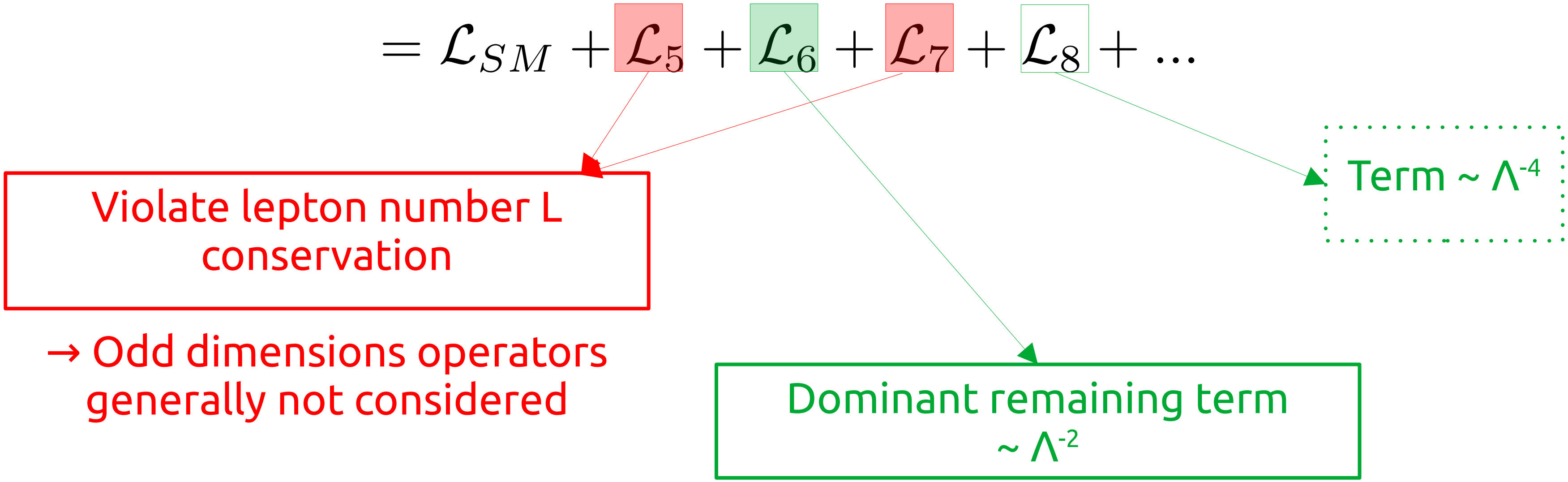
Wilson coefficient

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{\boxed{c_{d,i}}}{\Lambda^{d-4}} \mathcal{Q}_{d,i}$$

Standard Model Effective Field Theory (SMEFT)

Standard Model EFT Lagrangian

$$\begin{aligned}\mathcal{L}_{SMEFT} &= \mathcal{L}_{SM} + \sum_{d>4}\sum_{i} \frac{c_{d,i}}{\Lambda^{d-4}}\mathcal{Q}_{d,i} \\ &= \mathcal{L}_{SM} + \sum_{d>4}\mathcal{L}_d \\ &= \mathcal{L}_{SM} + \boxed{\mathcal{L}_5} + \boxed{\mathcal{L}_6} + \boxed{\mathcal{L}_7} + \boxed{\mathcal{L}_8} + \ldots \end{aligned} \tag{1}$$



Violate lepton number L conservation

→ Odd dimensions operators generally not considered

Dominant remaining term ~ Λ^{-2}

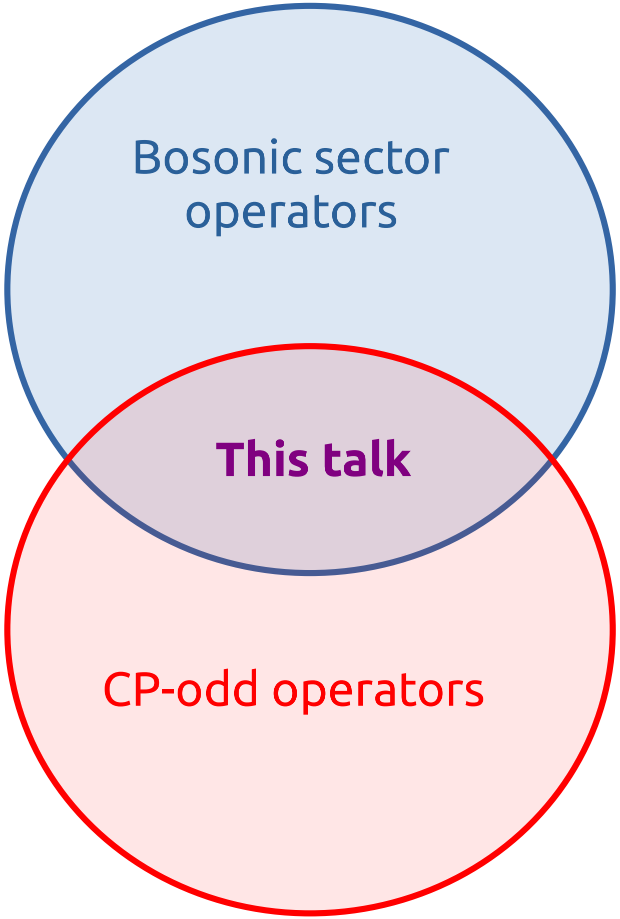
Term ~ Λ^{-4}

CP violation from bosonic operators

Processes involving couplings between bosons abundantly produced at LHC

CP conservation often assumed in most analyses

Specific CP-odd operators challenges,
e.g. almost no modification of the cross section



Standard Model EFT: dim 6 in Warsaw basis

Among those, 6 CP odd operators that include dual tensors

$$\tilde{X}_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma} X^{\rho\sigma}$$

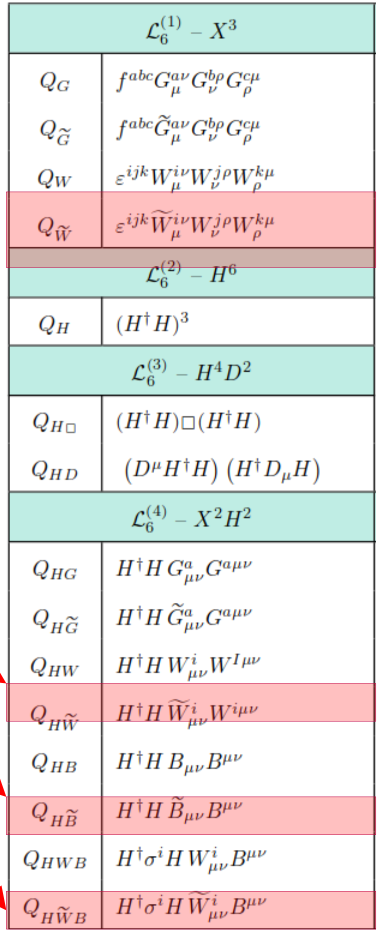
In the electroweak sector, 4 remain:

$$\boxed{\mathcal{Q}_{\tilde{W}}, \mathcal{Q}_{H\tilde{W}}, \mathcal{Q}_{H\tilde{B}}, \mathcal{Q}_{H\tilde{W}B}}$$

Sources of anomalous triple gauge coupling (aTGC)

- V → VH
- V → VV

(V = W or Z boson)



$\mathcal{L}_6^{(1)} - X^3$	
Q_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$
$Q_{\widetilde{G}}$	$f^{abc}\widetilde{G}_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$
Q_W	$\varepsilon^{ijk}W_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk}\widetilde{W}_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$
$\mathcal{L}_6^{(2)} - H^6$	
Q_H	$(H^\dagger H)^3$
$\mathcal{L}_6^{(3)} - H^4D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(D^\mu H^\dagger H\right)\left(H^\dagger D_\mu H\right)$
$\mathcal{L}_6^{(4)} - X^2H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^a G^{a\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^a G^{a\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^i W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^i W^{i\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$
Q_{HWB}	$H^\dagger\sigma^i H\, W_{\mu\nu}^i B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\, \widetilde{W}_{\mu\nu}^i B^{\mu\nu}$

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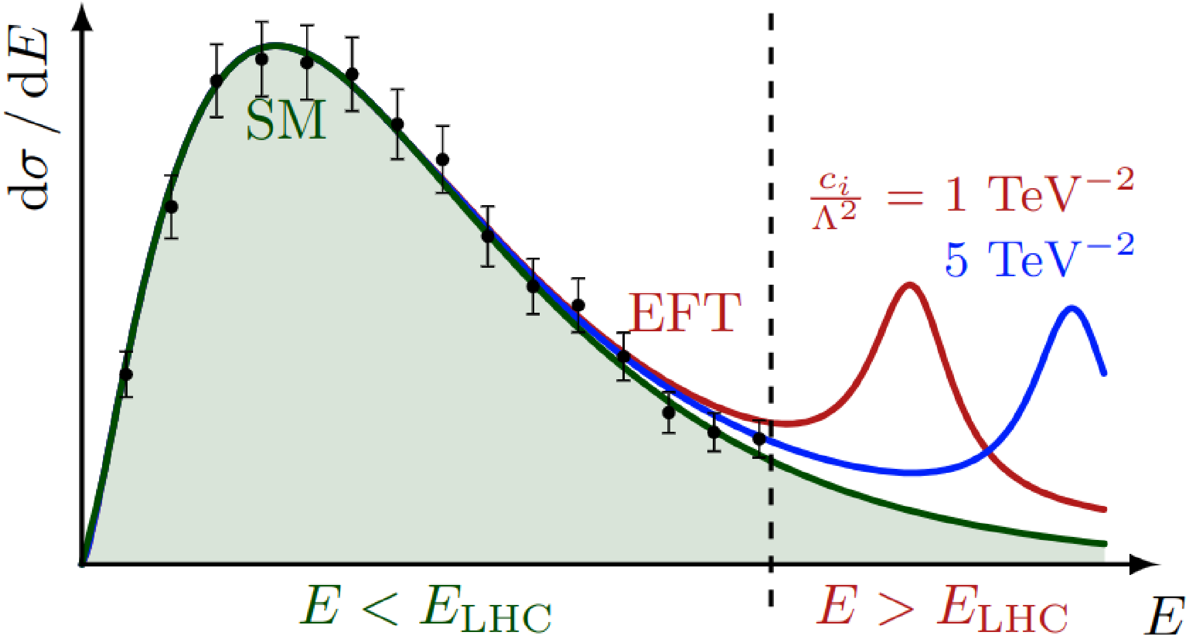
Constraints on Wilson coefficients



At low energies, modifying scale c_i/Λ is equivalent to **scaling** EFT effects

- MC generation for fixed Λ
- Wilson coefficient set floating

Summing MC predictions of SM + EFT and compare with data

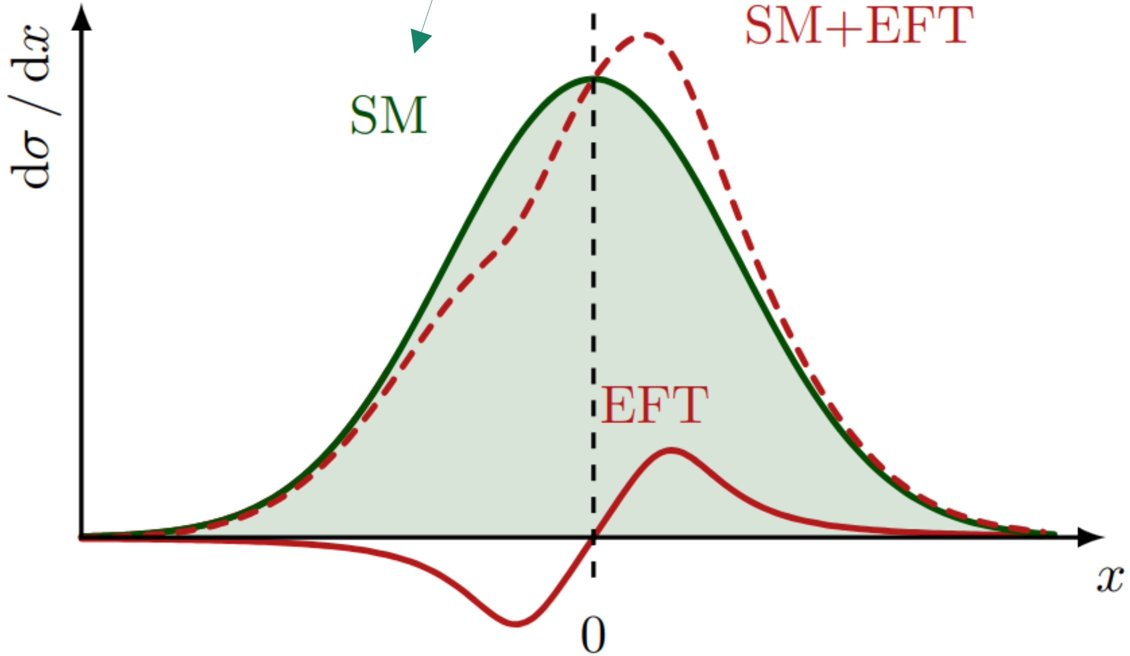
CP odd operators

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM} + \mathcal{M}_6|^2 = |\mathcal{M}_{SM}|^2 + 2\Re(\mathcal{M}^*_{SM}\mathcal{M}_6) + |\mathcal{M}_6|^2$$

CP-even

Linear term
CP-odd

(Quadratic term
CP-even)

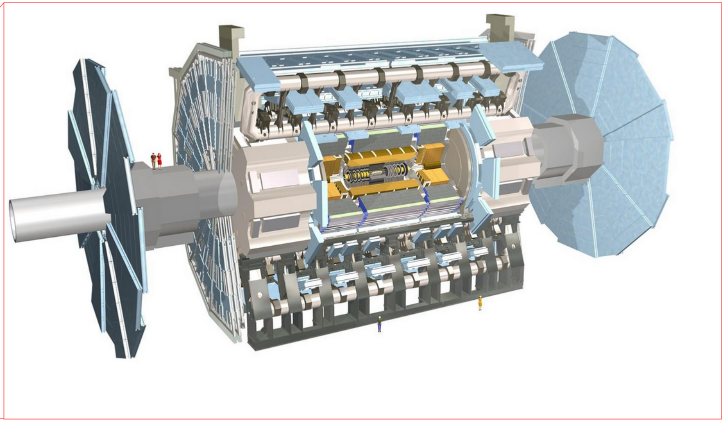


CP-odd observable

The Large Hadron Collider
And
The ATLAS experiment

The LHC and ATLAS

ATLAS detector



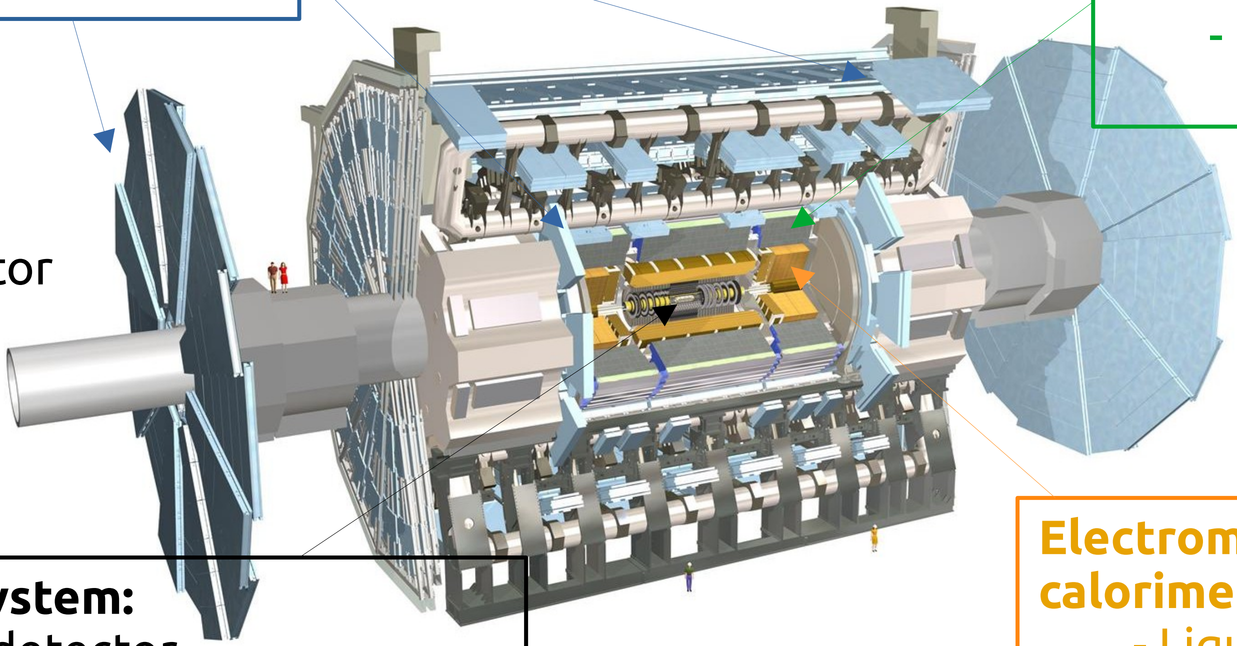
27 km circular collider

proton-proton collisions

Energy available in center of mass frame:

$\sqrt{s}$ = 13.6 TeV

The LHC and ATLAS



Muon spectrometers:
- Drift chambers

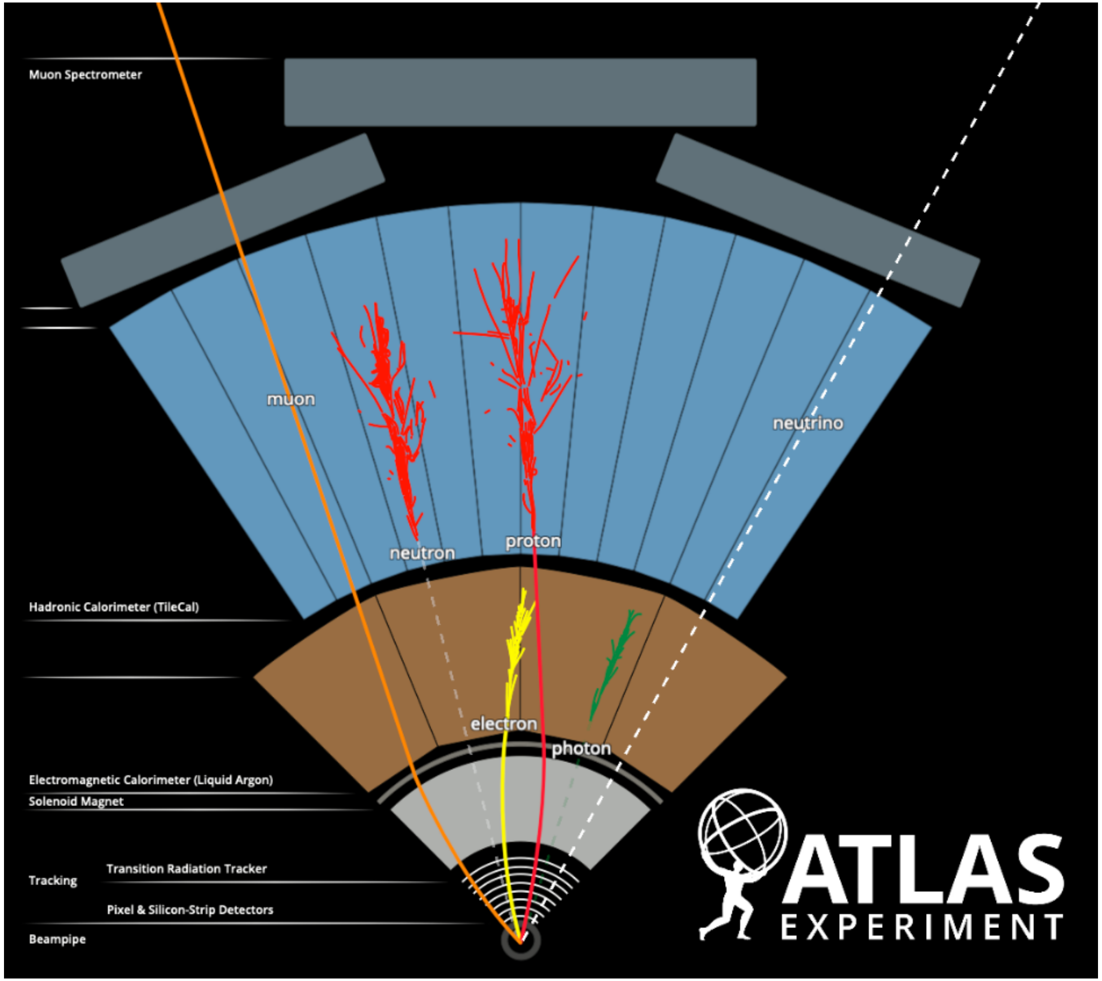
Hadronic calorimeters:
- Tiles + steel
- Liquid Ar + steel

(almost) 4π detector

Electromagnetic calorimeters:
- Liquid Ar + Pb

Tracking system:
- Pixel detector
- Silicon Tracker
- Transition Radiation Tracker

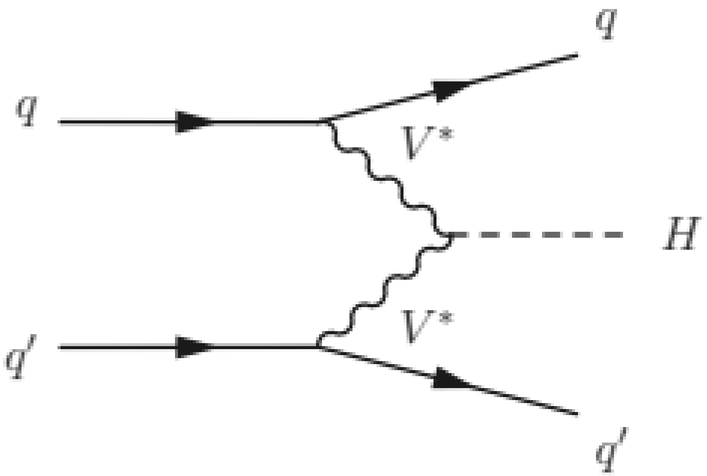
The LHC and ATLAS

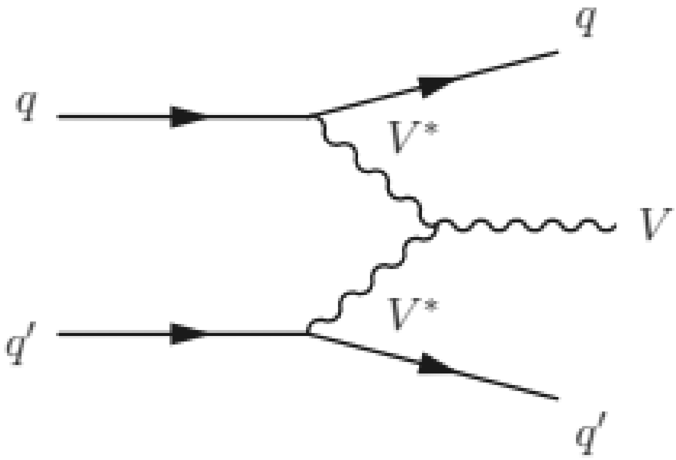


Multi purpose detector

Large variety of final states accessible

Vector Boson Fusion processes





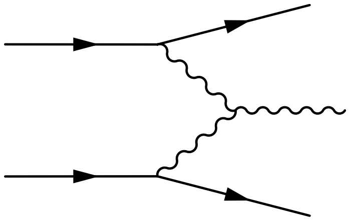
* **H jj** : HVV coupling

- H → γγ
- H → ττ
- H → WW

* **V jj** (V= W,Z) : VVV coupling

- W → $e\nu_e$ or $\mu\nu_\mu$
- Z → ee or μμ

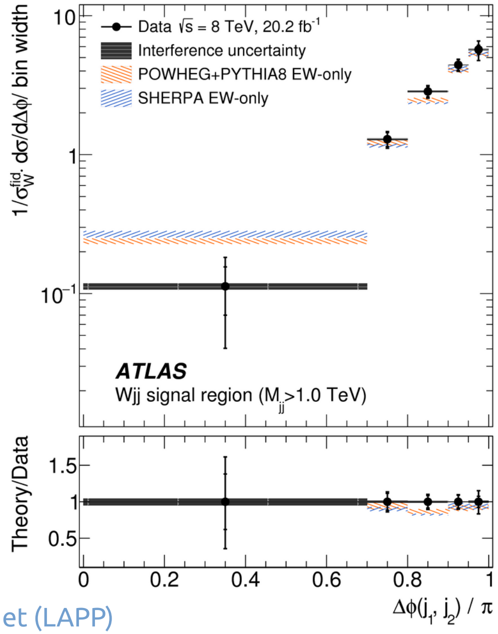
VBF Wjj @ √s = 8 TeV (first in ATLAS)



Challenging analysis in a p-p collider:

- Neutrino of W→lν decay (l = e or μ) only reconstructed as missing E_T

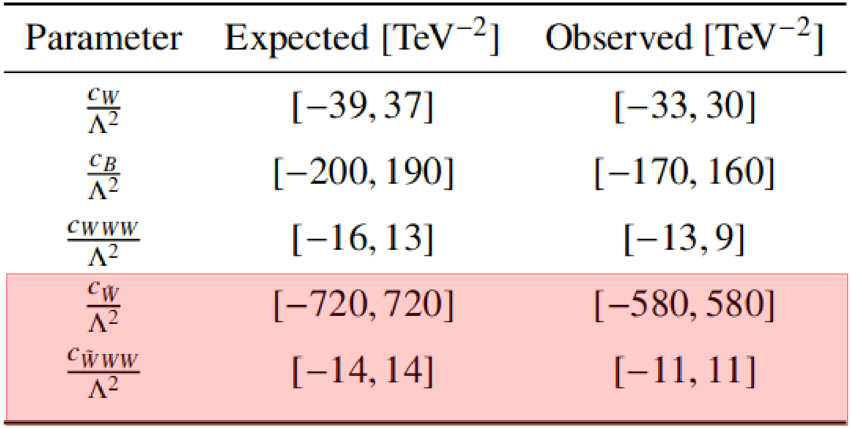
-Important background contamination (expected fraction of 78% of the events)



Eur. Phys. J. C77 (2017)

Fit on **azimuthal angle difference between jets ΔΦ(j_1,j_2)**

$$\Delta\Phi(j_1, j_2) = |\Phi_{j1} - \Phi_{j2}|$$



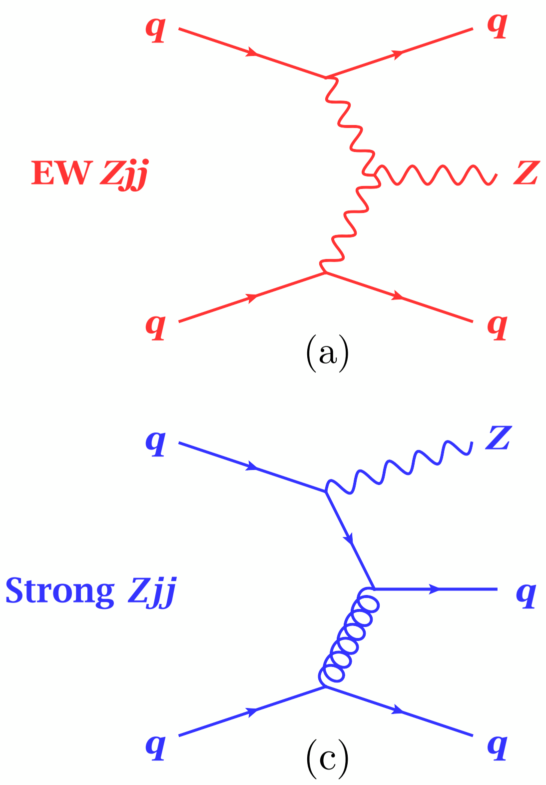
Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
$\frac{c_W}{\Lambda^2}$	[−39, 37]	[−33, 30]
$\frac{c_B}{\Lambda^2}$	[−200, 190]	[−170, 160]
$\frac{c_{WWW}}{\Lambda^2}$	[−16, 13]	[−13, 9]
$\frac{c_{\tilde{W}}}{\Lambda^2}$	[−720, 720]	[−580, 580]
$\frac{c_{\tilde{W}WW}}{\Lambda^2}$	[−14, 14]	[−11, 11]

VBF Zjj (√s = 13 TeV)

- Increased √s (8→13 TeV)
- Full Run 2 statistics (20 → 139 fb^{-1})

Two leptons final state, well reconstructed

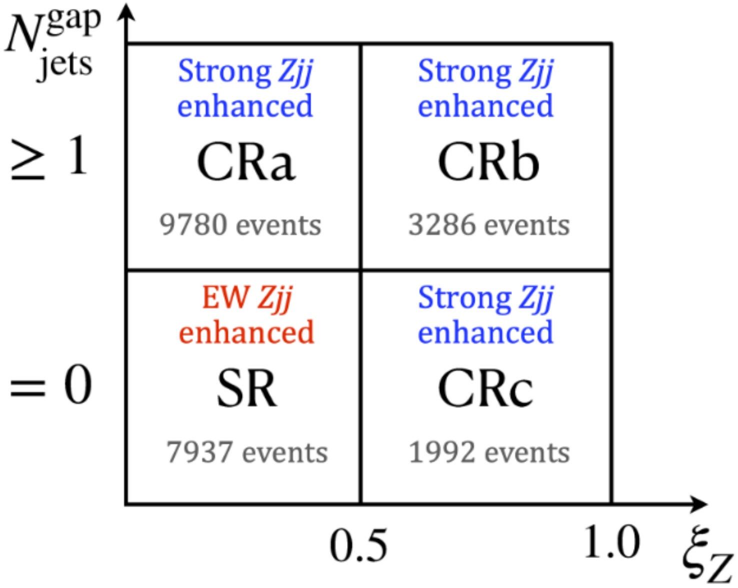
Main challenge: **extract EW component**
→ **VBF topology** related variables



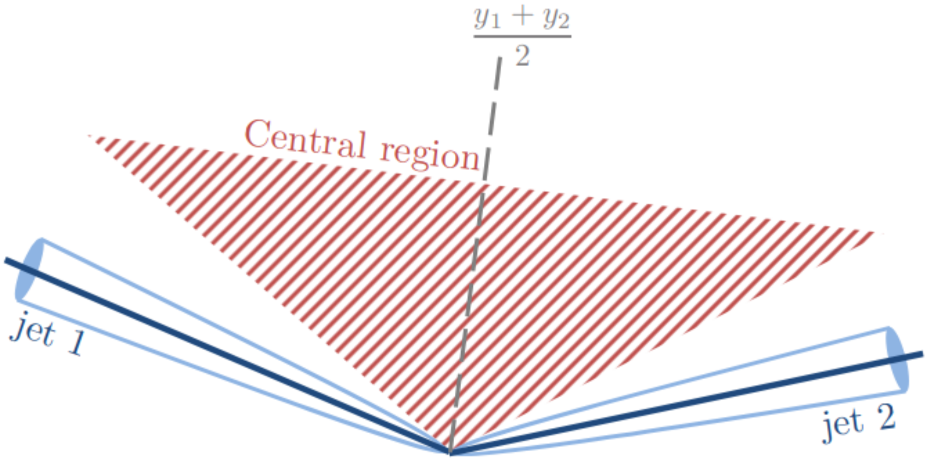
Eur. Phys. J. C 81 (2020)

VBF Zjj ($\sqrt{s}$ = 13 TeV)

Eur. Phys. J. C 81 (2020)



≥ 1	Strong *Zjj* enhanced CRa 9780 events	Strong *Zjj* enhanced CRb 3286 events
$= 0$	EW *Zjj* enhanced SR 7937 events	Strong *Zjj* enhanced CRc 1992 events



$$\xi_Z = \left|y_{ll} - \frac{y_{j1} + y_{j2}}{2}\right| / |y_{j1} - y_{j2}|$$

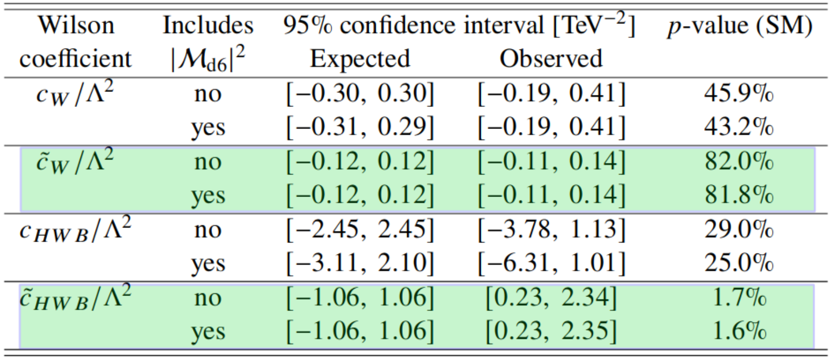
Gap jets = jets with rapidity y such as

$\min(y_{j1},y_{j2}) < y < \max(y_{j1},y_{j2})$

VBF Zjj ($\sqrt{s}$ = 13 TeV)

Full **$\Delta\Phi(j_1,j_2)$** range : [-π,π]

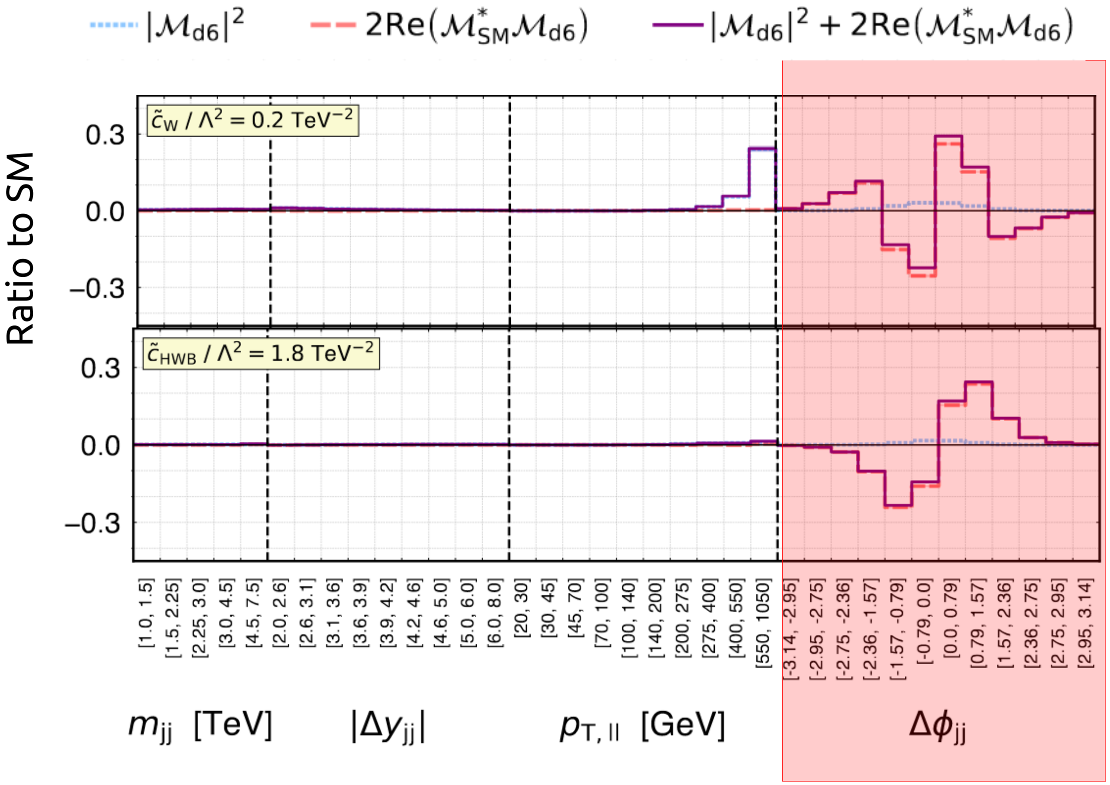
Angular variable → negligeable impact of quadratic term



Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

Most competitive limits to this day

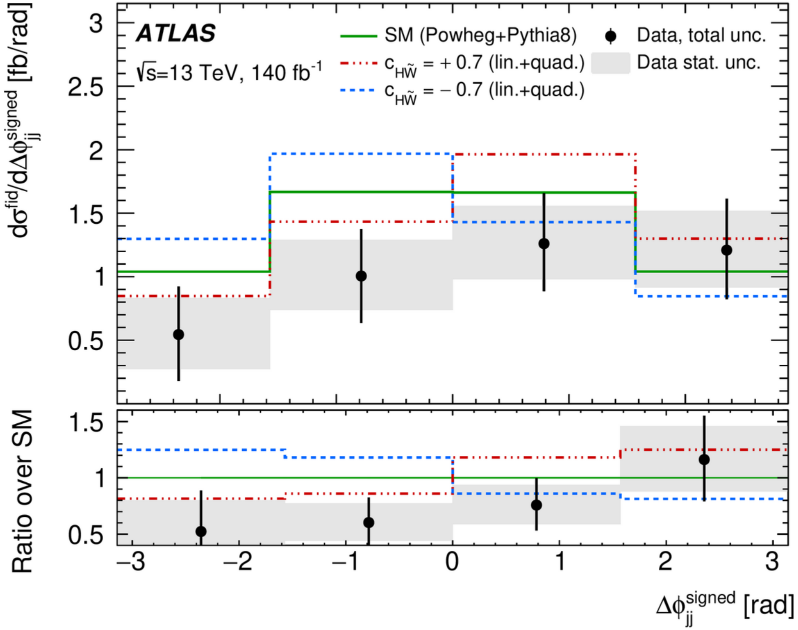
Eur. Phys. J. C 81 (2020)



VBF H → ττ and γγ

Sensitive to $Q_{HB\sim}$ and $Q_{HW\sim}$ complementarily to Vjj

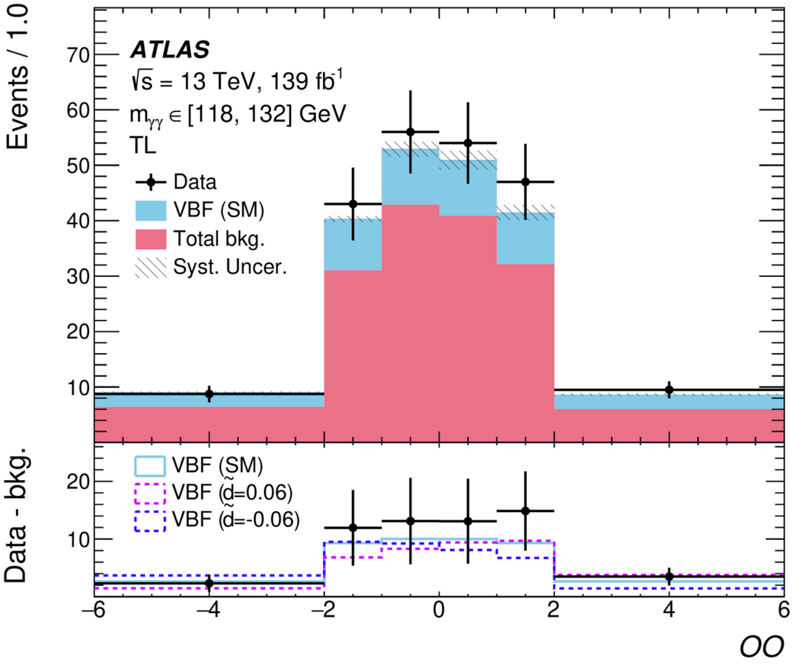
H → ττ: $\Delta\Phi(j_1,j_2)$



http://arxiv.org/abs/2407.16320

H → γγ: Optimal observable

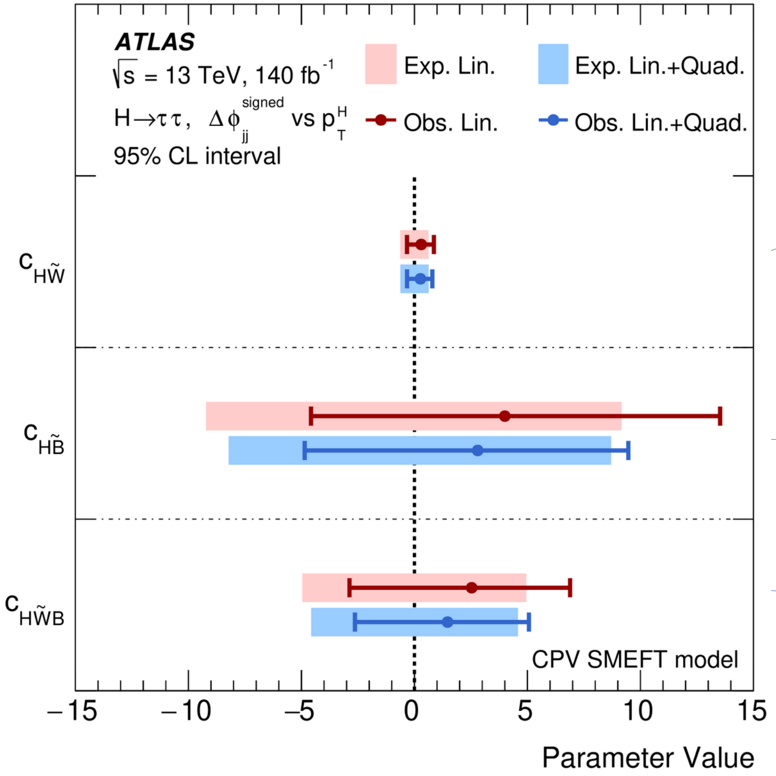
$$OO = \frac{2\Re(\mathcal{M}^*_{SM}\mathcal{M}_6)}{|\mathcal{M}_{SM}|^2}$$



Phys. Rev. Lett. 131 (2023)

VBF H → ττ and ɣɣ

H → ττ



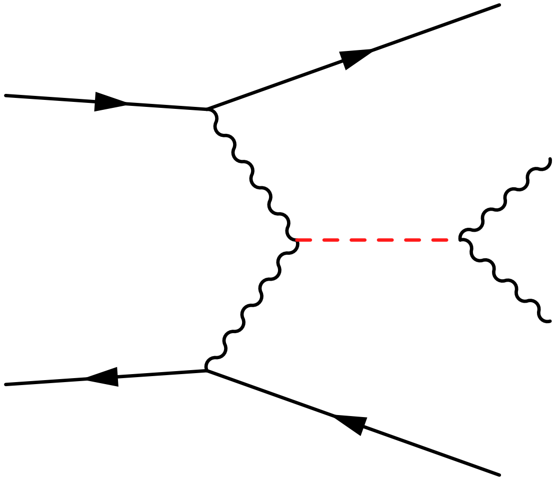
Observed 95 % CI best to date on $c_{HW\sim}$ with $\Delta\Phi(j_1,j_2)$: [-0.31, 0.88]

VBF H →ɣɣ : [-0.55, 1.07] TeV^{-2}

Expected to have small effect

Not as constraining as VBF with EW bosons

VBF H→WW*



- VBF process with two bosons in final states
  → Two HVV vertices (both production and decay)

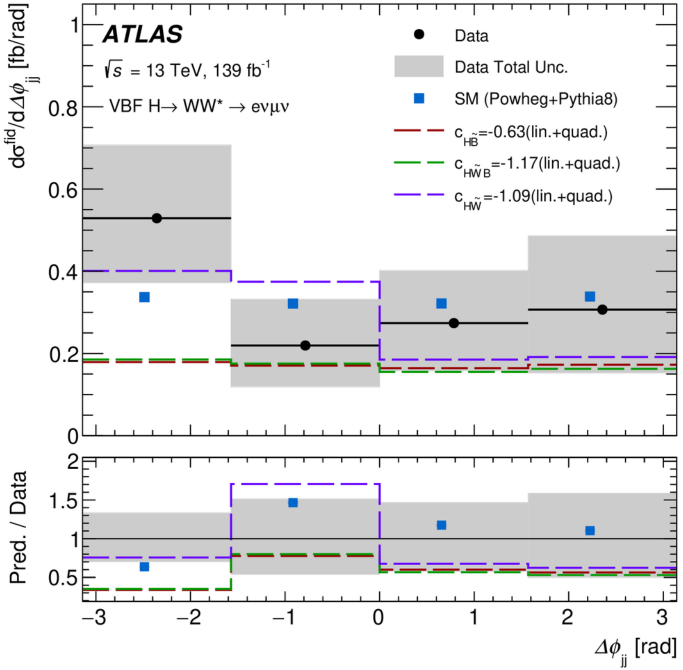
- Higgs boson has higher probability to decay into WW* rather than ττ or γγ

Experimental challenges:

- Two final state neutrinos

- Important backgrounds

VBF H→WW*

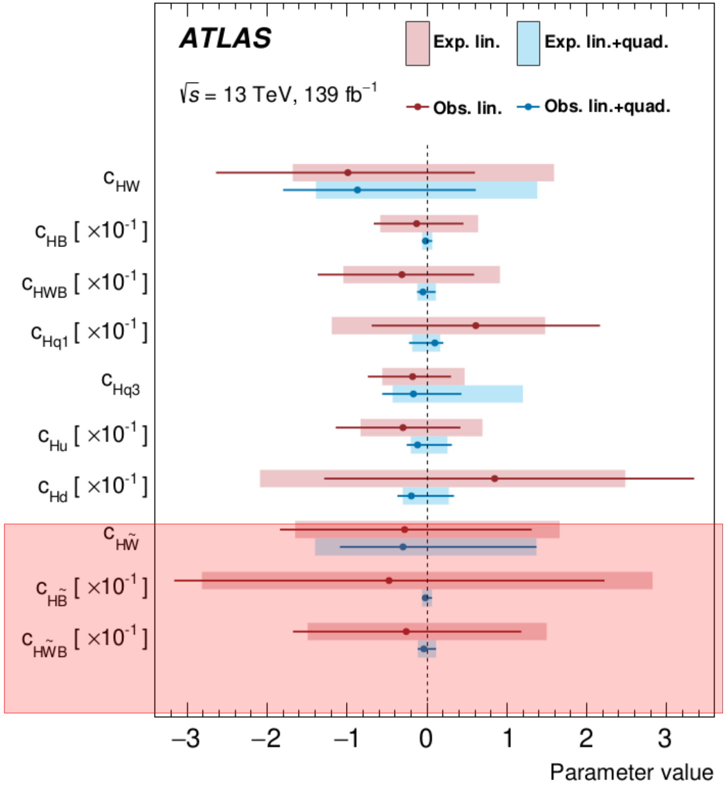


Increased sensitivity to the quadratic term

Expected limits (lin→lin+quad) :

$C_{HB\sim}$ [-28,28] → [-0.62,0.62]
$C_{HW\sim B}$ [-15,15] → [-1.2,1.1]

(competitive with VBF Zjj)



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VBF summary

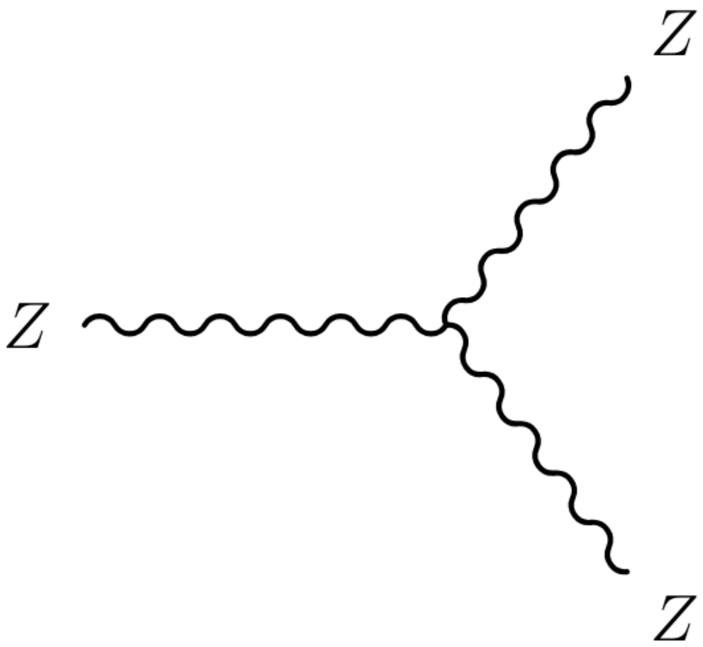
- Single angular observable $\Delta\Phi(j_1,j_2)$ gives stringent constraints for CP-odd c_i

- $Q_{W\sim WW}$ and $Q_{HW\sim B}$ well constrained by EW bosons VBF

- $Q_{HW\sim}$ and $Q_{HB\sim}$ better constrained by Higgs VBF

- Impact of quadratic term negligeable when using angular variables except in VBF H → WW channel
  → exploit additional variables sensitive to quadratic term

Anomalous Neutral Triple Gauge couplings (aNTGC)



CP violating aNTGC

Neutral TGC e.g. in inclusive ZZ production i.e. qq → ZZ + X → ll l'l' + X' (l,l' = e or μ)

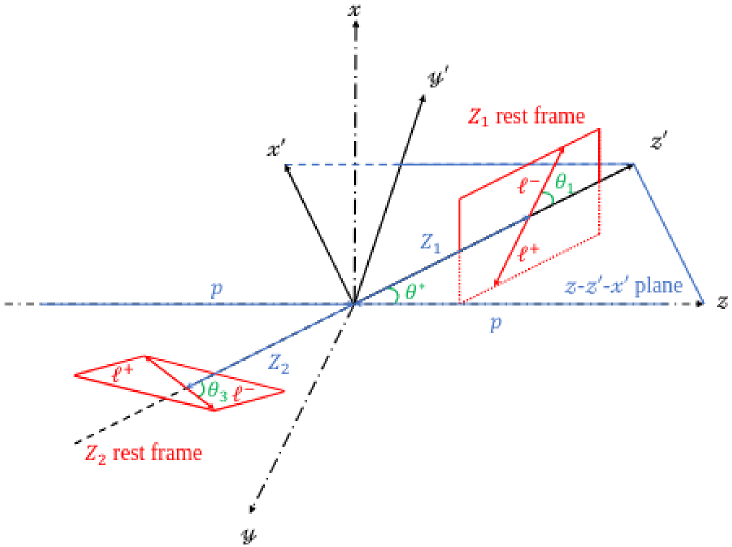
$$\mathcal{L}_{VZZ} \supset -\frac{e}{m_Z^2} f_V^4 (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta)$$

(V = A, Z)

CP-odd observable built from polar and azimuthal angles

$$\mathcal{O}_{T_{yz,1}T_{yz,3}} = (\sin\varphi_1 \times \cos\theta_1) \times (\sin\varphi_3 \times \cos\theta_3)$$

aNTGC parameter	Interference only		Full	
	Expected	Observed	Expected	Observed
f_Z^4	[−0.16, 0.16]	[−0.12, 0.20]	[−0.013, 0.012]	[−0.012, 0.012]
f_γ^4	[−0.30, 0.30]	[−0.34, 0.28]	[−0.015, 0.015]	[−0.015, 0.015]



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Including quadratic term improves limits by a factor >10

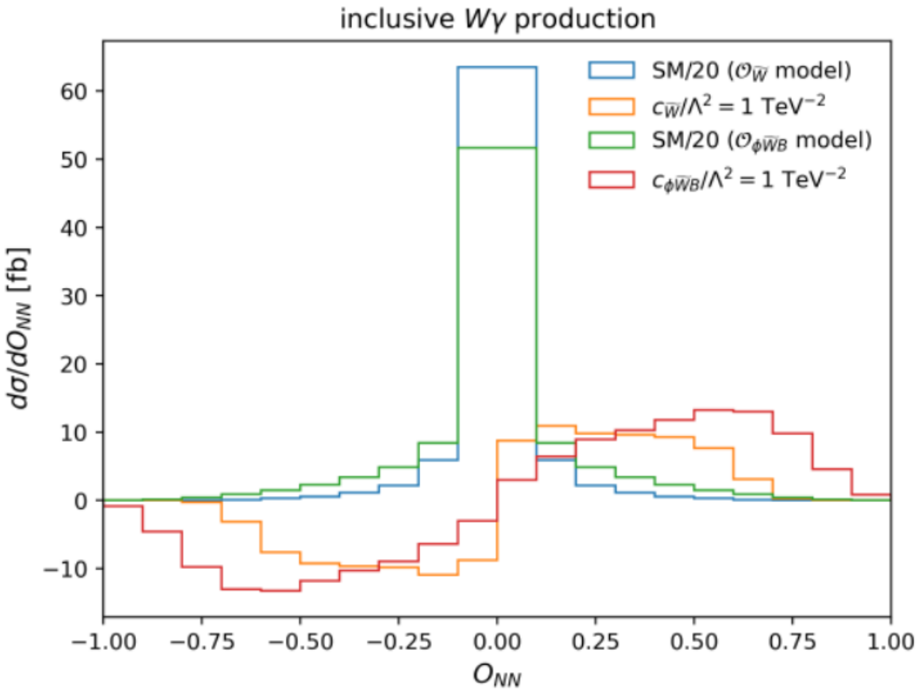
Conclusion & outlook

- Vjj and Hjj analyses **complementary** to constrain dim 6 CP-odd SMEFT bosonic operators
- Constraints on CPV are also put via aNTGC searches

- Combine additional observables, including **angular** and **energy** related observables (ML)

- Exploit additional final states:
    - inclusive diboson final states (WZ, Wy)
    - VBS for dimension 8 operators

In progress …



Phys Rev D 107, 016008 (2023)

Thank you for your attention

Standard Model EFT: dim 6 in Warsaw basis

In the Warsaw basis [1] there are
3 types of dim 6 bosonic operators:

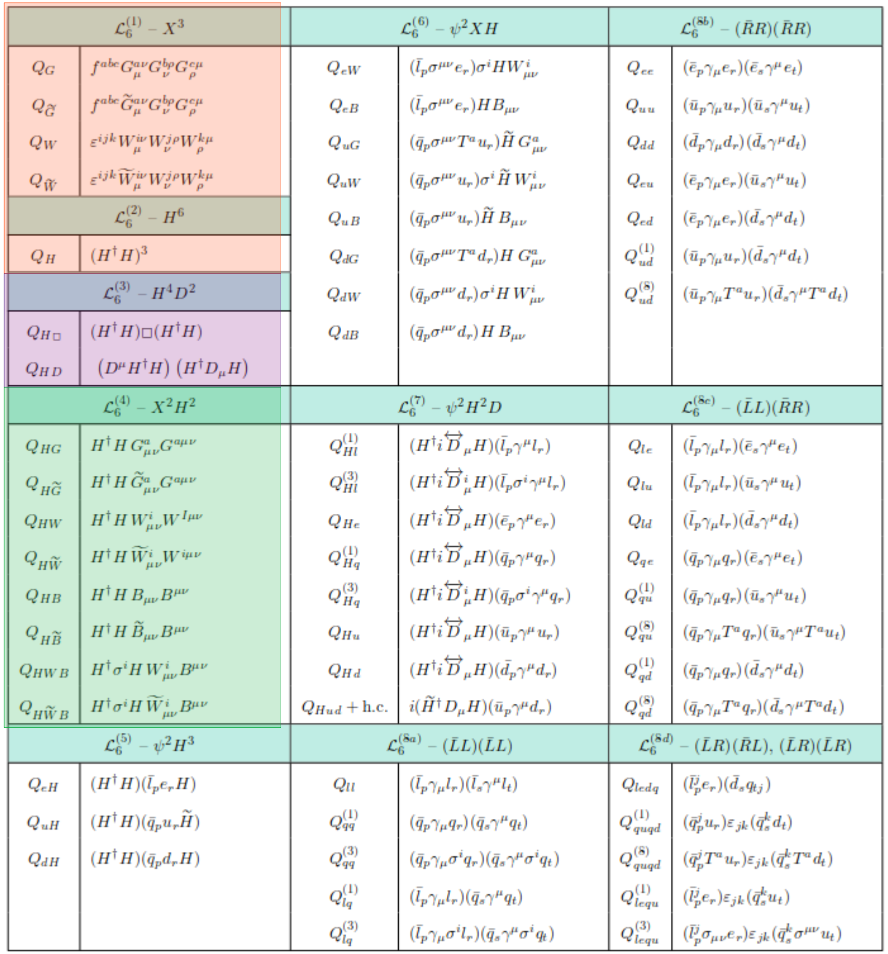
* Boson self-coupling (X^3 or H^6)

* Higgs propagator (H^4D^2)

* Higgs-gauge (X^2H^2)

X : field strength tensor (dim 2)
H : Higgs field (dim 1)
D : Covariant derivative (dim 1)

→ 5 + 2 + 8 = **15 operators**



$\mathcal{L}_6^{(1)} - X^3$	
Q_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$
$Q_{\widetilde{G}}$	$f^{abc}\widetilde{G}_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$
Q_W	$\varepsilon^{ijk}W_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk}\widetilde{W}_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$
$\mathcal{L}_6^{(2)} - H^6$	
Q_H	$(H^\dagger H)^3$
$\mathcal{L}_6^{(3)} - H^4D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(D^\mu H^\dagger H\right)\left(H^\dagger D_\mu H\right)$
$\mathcal{L}_6^{(4)} - X^2H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^a G^{a\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^a G^{a\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^i W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^i W^{i\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$
Q_{HWB}	$H^\dagger\sigma^i H\, W_{\mu\nu}^i B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\, \widetilde{W}_{\mu\nu}^i B^{\mu\nu}$
$\mathcal{L}_6^{(5)} - \psi^2H^3$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$\mathcal{L}_6^{(6)} - \psi^2XH$		$\mathcal{L}_6^{(8b)} - (\bar{R}R)(\bar{R}R)$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\sigma^i H W_{\mu\nu}^i$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^a u_r)\widetilde{H}\, G_{\mu\nu}^a$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\sigma^i\widetilde{H}\, W_{\mu\nu}^i$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^a d_r)H\, G_{\mu\nu}^a$	$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\sigma^i H\, W_{\mu\nu}^i$	$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^a u_r)(\bar{d}_s\gamma^\mu T^a d_t)$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$		
$\mathcal{L}_6^{(7)} - \psi^2H^2D$		$\mathcal{L}_6^{(8c)} - (\bar{L}L)(\bar{R}R)$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{l}_p\sigma^i\gamma^\mu l_r)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{q}_p\sigma^i\gamma^\mu q_r)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^a q_r)(\bar{u}_s\gamma^\mu T^a u_t)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$	$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^a q_r)(\bar{d}_s\gamma^\mu T^a d_t)$
$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$		$\mathcal{L}_6^{(8d)} - (\bar{L}R)(\bar{R}L), (\bar{L}R)(\bar{L}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\sigma^i q_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$	$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^a u_r)\varepsilon_{jk}(\bar{q}_s^k T^a d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\sigma^i l_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$	$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$

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Constraints on Wilson coefficients

Perform maximal likelihood fit on relevant observable

Example: Gaussian likelihood (typically for diboson)

$$\mathcal{L}(c_i|\theta) = \frac{1}{\sqrt{(2\pi)^k|C|}} \exp\Big(-\frac{1}{2}(\boxed{\vec{x}_{data}} - \boxed{\vec{x}_{pred}}(c_i|\theta))^T C^{-1}(\boxed{\vec{x}_{data}} - \boxed{\vec{x}_{pred}}(c_i|\theta))\Big) \times \prod_i^{n_{syst}} f_i(\theta_i)$$

Floating Wilson coefficient

Nuisance parameters (systematics, theory uncertainties, etc.)

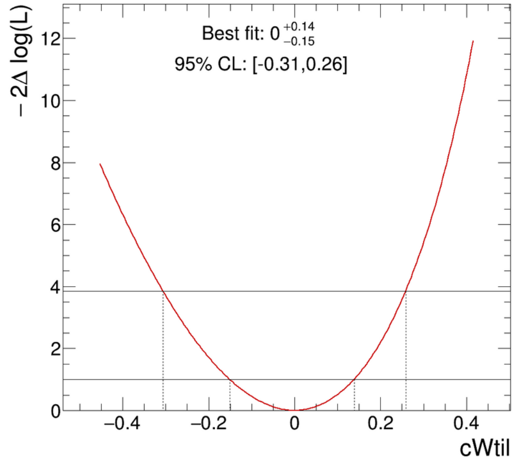
Covariance matrix

Measurement

MC prediction

$x_{pred} = x_{SM} + x_{int}(c_i) + x_{quad}(c_i^2)$

$$-2\Delta\log\mathcal{L}(c_i) = -2\log\left(\frac{\mathcal{L}(c_i)}{\mathcal{L}(\hat{c}_i)}\right)$$



95 % CI

68 % CI

Poisson likelihood

Alternative to the Gaussian likelihood, used for instance in Higgs EFT analyses

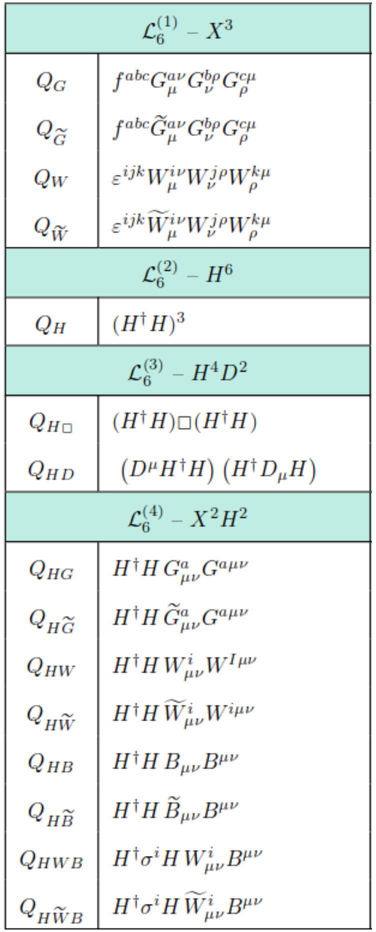
$$\mathcal{L}(x;\mu,\theta) = \prod_{c}^{N_{cat}} \Bigg(\prod_{k}^{N_{bin}} \mathrm{Pois}(\sum_{s} N_c^s + \sum_{b} N_c^b, n_{obs,k}) \Bigg) \times \prod_{i}^{n_{syst}} f_i(\theta_i)$$

Data

MC events (sig + bkg)

Nuisance parameters

Operators definitions



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Q_H	$(H^\dagger H)^3$
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$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^a G^{a\mu\nu}$
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$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^i W^{i\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \sigma^i H\, W_{\mu\nu}^i B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}_{\mu\nu}^i B^{\mu\nu}$

$$W_\mu^{i,\nu} = \partial_\mu W^{i,\nu} - \partial^\nu W_\mu^i - g\varepsilon^{ijk}W_\mu^j W^{k,\nu}$$

$$B^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu$$

$$\mathrm{H} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

HISZ and Warsaw basis

HISZ

$$\mathcal{O}_{\tilde{B}} = (D_\mu H)^\dagger \tilde{B}^{\mu\nu} (D_\nu H)$$

$$\mathcal{O}_{\tilde{W}} = (D_\mu H)^\dagger \tilde{W}^{\mu\nu} (D_\nu H)$$

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}(W_{\mu\nu} W^{\nu}_{\rho} \tilde{W}^{\rho\mu})$$

Warsaw

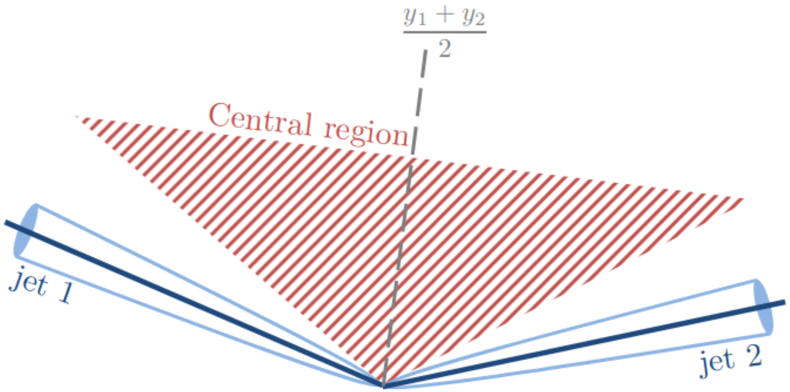
$$\mathcal{Q}_{H\tilde{W}} = \phi^\dagger \phi \tilde{W}^{i}_{\mu\nu} W^{i,\mu\nu}$$

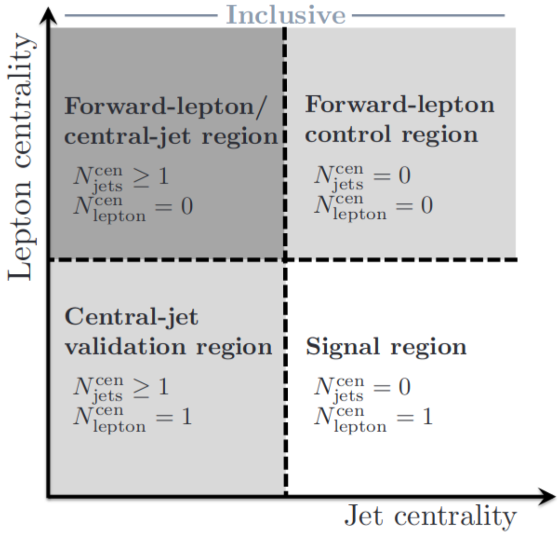
$$\mathcal{Q}_{H\tilde{B}} = \phi^\dagger \phi \tilde{B}_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{Q}_{\tilde{W}WW} = \varepsilon_{ijk} \tilde{W}^{i,\nu}_{\mu} W^{j,\rho}_{\nu} W^{k,\mu}_{\rho}$$

$$\mathcal{Q}_{H\tilde{W}B} = \phi^\dagger \sigma^i \phi \tilde{W}^{i}_{\mu\nu} B^{\mu\nu}$$

Wjj control, validation, signal regions





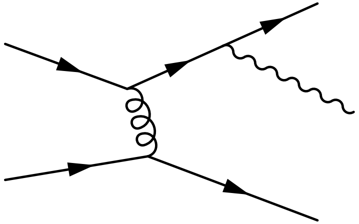
Forward-lepton/ central-jet region
$N^{\text{cen}}_{\text{jets}} \geq 1$
$N^{\text{cen}}_{\text{lepton}} = 0$

Forward-lepton control region
$N^{\text{cen}}_{\text{jets}} = 0$
$N^{\text{cen}}_{\text{lepton}} = 0$

Central-jet validation region
$N^{\text{cen}}_{\text{jets}} \geq 1$
$N^{\text{cen}}_{\text{lepton}} = 1$

Signal region
$N^{\text{cen}}_{\text{jets}} = 0$
$N^{\text{cen}}_{\text{lepton}} = 1$

QCD Wjj



EFT fit region :

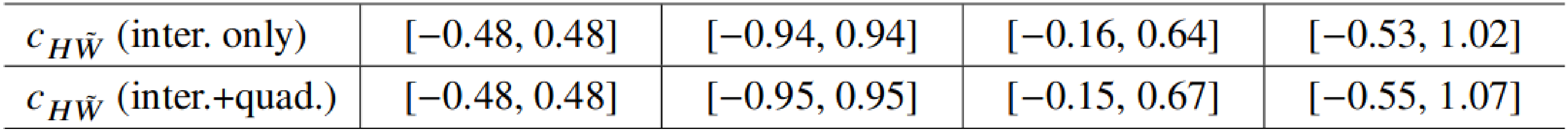
Dedicated high energy SR to increase EFT/SM ratio
→ m_{jj} > 1 TeV, leading jet p_T > 600 GeV

Only accounting for SM-dim6 interference term

Quadratic term impact in VBF H → γγ

$$OO = \frac{2\Re(\mathcal{M}^*_{SM}\mathcal{M}_6)}{|\mathcal{M}_{SM}|^2}$$

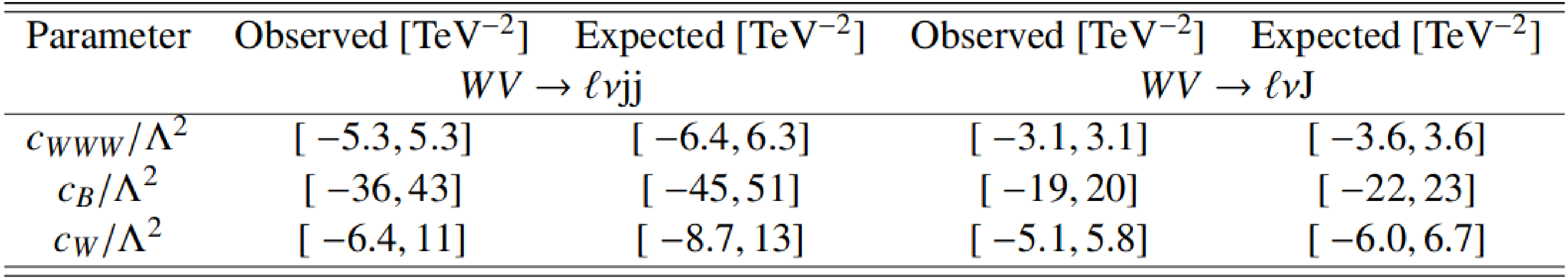
By definition only accounting for interference, not sensitive to quadratic term



$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]

CP even counterparts and constraints

WW/WZ → lvqq' (Eur. Phys. J. C77 (2017) 563)



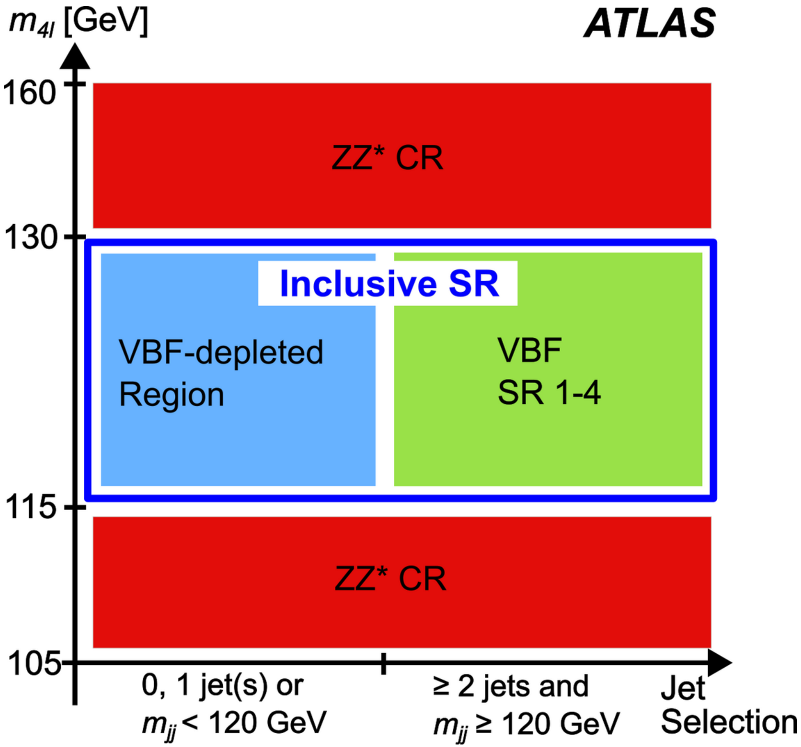
Parameter	Observed [TeV^{-2}]	Expected [TeV^{-2}]	Observed [TeV^{-2}]	Expected [TeV^{-2}]
	$WV \to \ell\nu jj$		$WV \to \ell\nu J$	
c_{WWW}/Λ^2	$[-5.3, 5.3]$	$[-6.4, 6.3]$	$[-3.1, 3.1]$	$[-3.6, 3.6]$
c_B/Λ^2	$[-36, 43]$	$[-45, 51]$	$[-19, 20]$	$[-22, 23]$
c_W/Λ^2	$[-6.4, 11]$	$[-8.7, 13]$	$[-5.1, 5.8]$	$[-6.0, 6.7]$

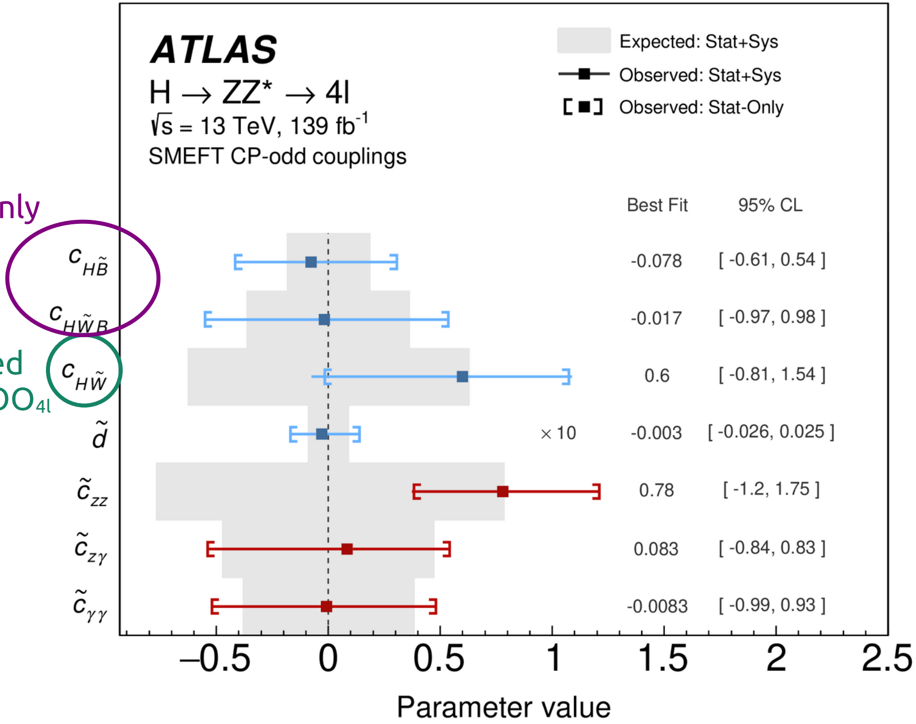
In HISZ basis

Higgs → ZZ* → 4l

Considering **VBF enriched signal region**, using optimal observable for both

1. H **production** vertex **OO_{jj}**
2. H **decay** vertex **OO_{4l}**





OO_{4l} only

Combined OO_{jj} and OO_{4l}

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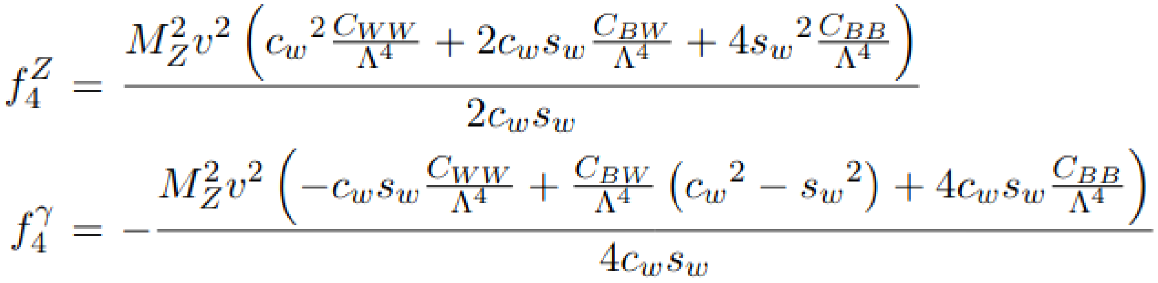
Wilson coefficients from aNTGC

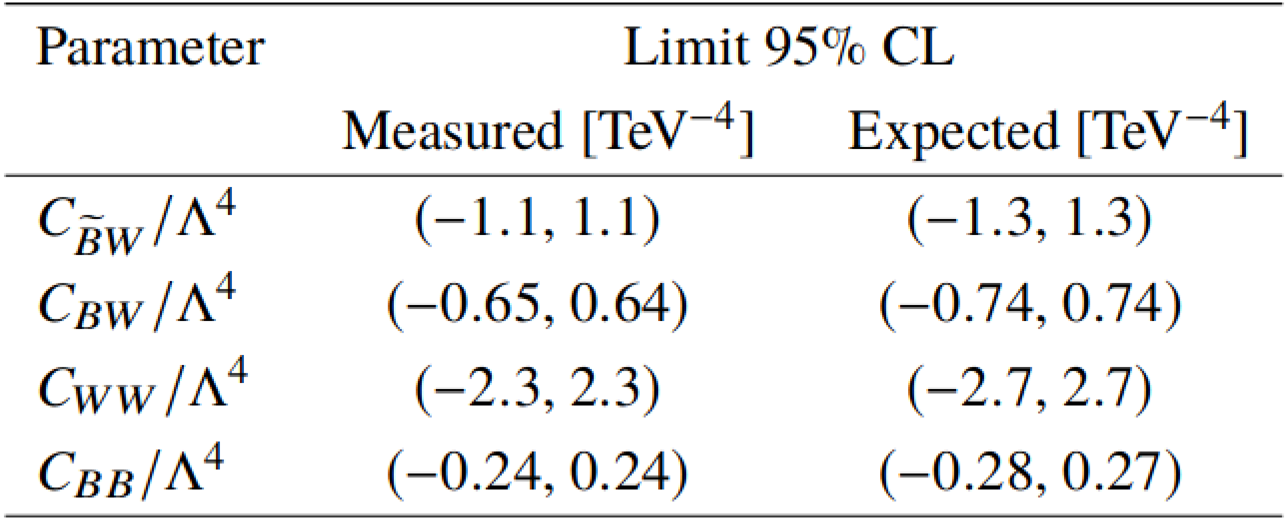
Linear combination of aNTGC parameters gives EFT Wilson coefficients



$$f_4^Z = \frac{M_Z^2 v^2 \left({c_w}^2 \frac{C_{WW}}{\Lambda^4} + 2 c_w s_w \frac{C_{BW}}{\Lambda^4} + 4 {s_w}^2 \frac{C_{BB}}{\Lambda^4} \right)}{2 c_w s_w}$$

$$f_4^\gamma = - \frac{M_Z^2 v^2 \left(- c_w s_w \frac{C_{WW}}{\Lambda^4} + \frac{C_{BW}}{\Lambda^4} \left({c_w}^2 - {s_w}^2 \right) + 4 c_w s_w \frac{C_{BB}}{\Lambda^4} \right)}{4 c_w s_w}$$

arXiv:1308.6323v2

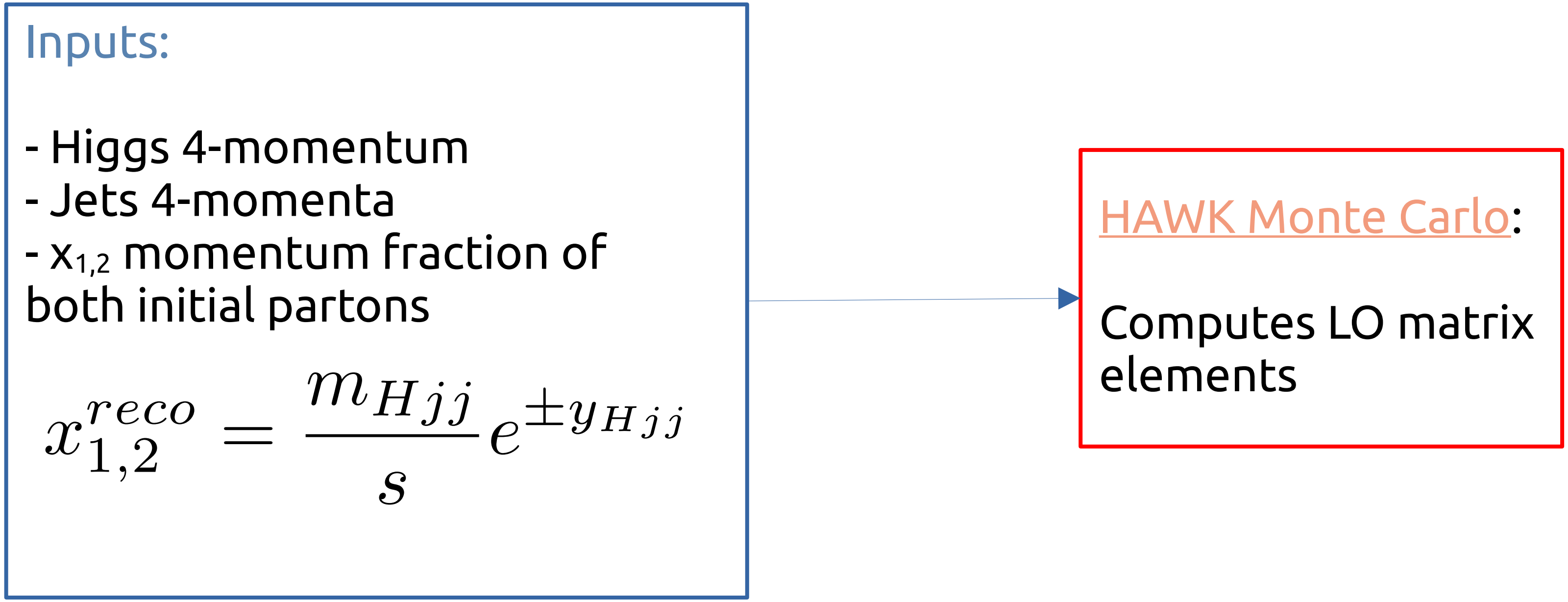


Parameter	Limit 95% CL	
	Measured [TeV^{-4}]	Expected [TeV^{-4}]
$C_{\widetilde{B}W}/\Lambda^4$	(−1.1, 1.1)	(−1.3, 1.3)
C_{BW}/Λ^4	(−0.65, 0.64)	(−0.74, 0.74)
C_{WW}/Λ^4	(−2.3, 2.3)	(−2.7, 2.7)
C_{BB}/Λ^4	(−0.24, 0.24)	(−0.28, 0.27)

From Zɣ → ννɣ

Optimal Observable in Hjj

$$OO = \frac{2\Re(\mathcal{M}^*_{SM}\mathcal{M}_6)}{|\mathcal{M}_{SM}|^2}$$



Inputs:

- Higgs 4-momentum
- Jets 4-momenta
- $x_{1,2}$ momentum fraction of both initial partons

$$x_{1,2}^{reco} = \frac{m_{Hjj}}{s} e^{\pm y_{Hjj}}$$

HAWK Monte Carlo:

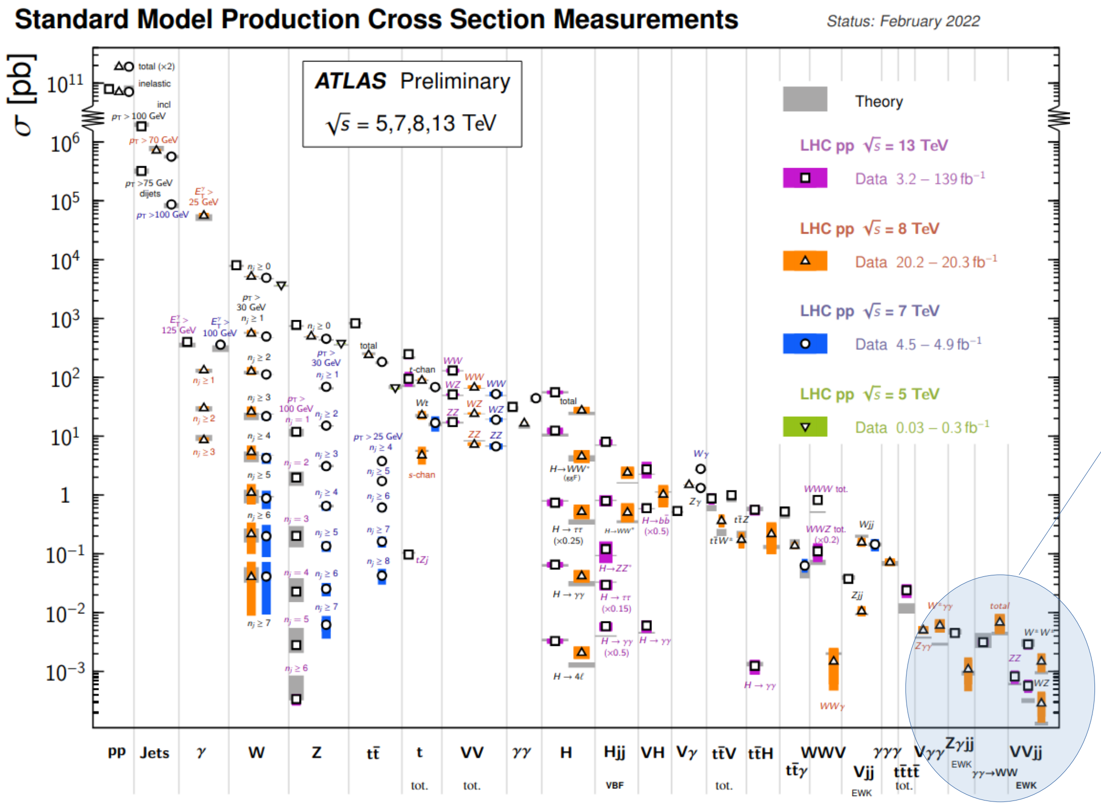
Computes LO matrix elements

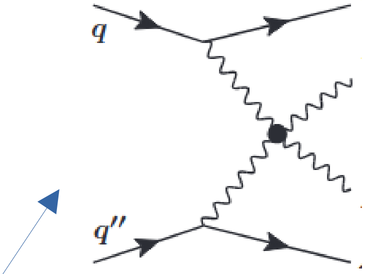
Phys Let B 805 (2020) 135426

What about Vector Boson Scattering ?

aQGC probed in VBS processes → cross section ~ fb → low statistics

ATLAS Std Model summary





Interference
~ Λ^{-4}

Existing VBS analyses considered so far only dim 8 CP-even operators within Eboli's model

e.g. Wγjj or WZjj or Zγjj