Summary of
Multi-Boson Intereactions 2023

C.-P. Yuan
Wu-Ki Tung Endowed Professor
Michigan State University

September 1, 2023 @ UCSD

The 10th MBI international conference

What a relief!

- Thanks to all the speakers for making many excellent presentations.
- Hence, there is no need for me to "repeat" what has been presented in their talks.
- I shall only common on a few physics topics in my "summary" which by no means are the most important results presented by the individual speaker in this conference.
- Hence, you are encouraged to review the posted talk files to find out all the presented results.

Speakers of MBI 2023

ATLAS & CMS:

Aram Apyan
Michael Schmitt
Prachi Atmasiddha
Ulascan Sarica

Theory:

Linda Carpenter
Samuel Homiller
Julie Pages
Minho SON
Haoyang Li
Daniel Whiteson
Antonio Vagnerini

ATLAS:

Bing Zhou
Joseph Earl Lambert
Christophe Pol A Roland
Abraham Tishelman-Charny

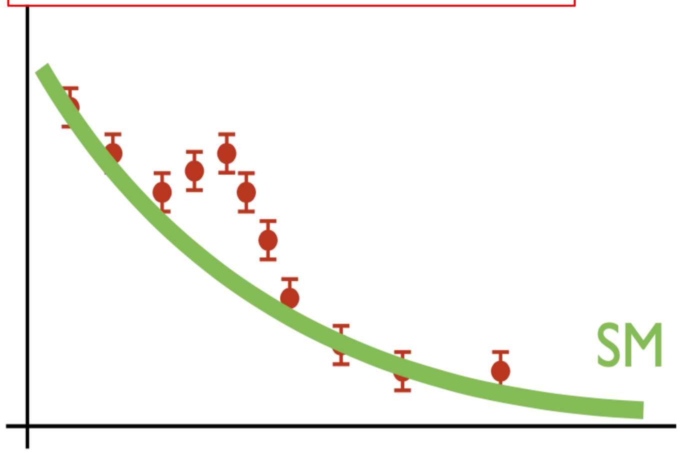
CMS:

Ulascan Sarica
Andrew Michael Levin
Garyfallia Paspalaki

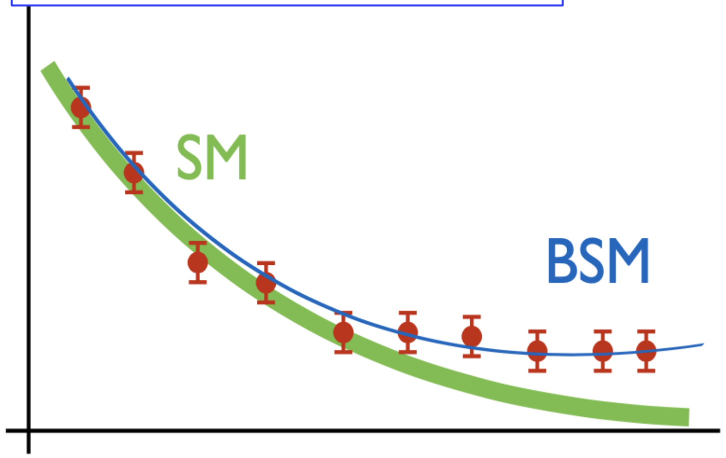
The physics goals of the LHC

- Test the Standard Model (SM)
- Search for physics beyond the SM (BSM)

Resonance search



Deviation search



This conference focus on multi-boson final states, with N=1,2,3,… for boson= W, Z, H, photon,…

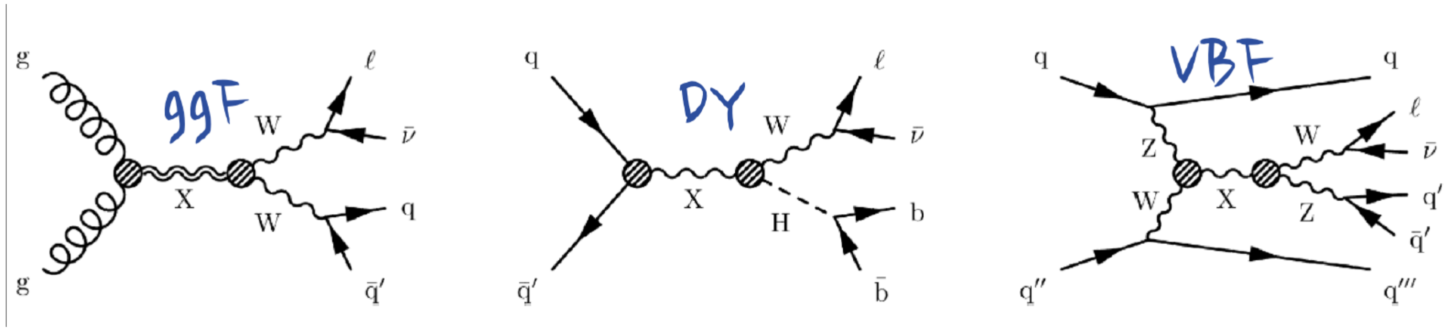
Test the Standard Model

Talk by Bing Zhou

- Need precision QCD and EW calculations. Higher order corrections are important for reaching a better agreement with experimental data.
- Comparing to various differential cross sections can provide more detailed tests of the SM.
- Comparing exclusive and inclusive measurements, such as W+W- production in di-lepton mode, with or without jet veto. Requiring jet veto usually leads to a larger theoretical error.

Search For New Physics

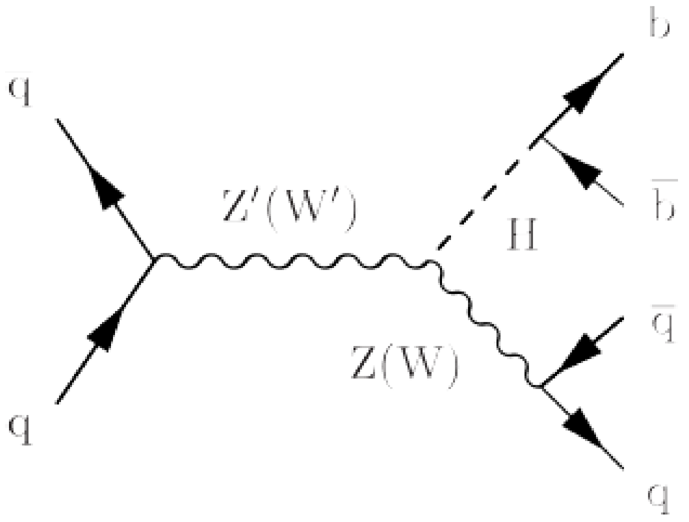
Top-down



Talk by Aram Apyan

- ➢ **Consider some specific model**
- ➢ **Assume narrow width**
- ➢ **Simultaneous analysis of various production channels**
- ➢ **Can do search in fully hadronic final state**
  - ❖ **Highly boosted bosons**
  - ❖ **Use large-radius jets (R=0.8 with large pT)**

(I will comment on this process later.)



Bottom-up

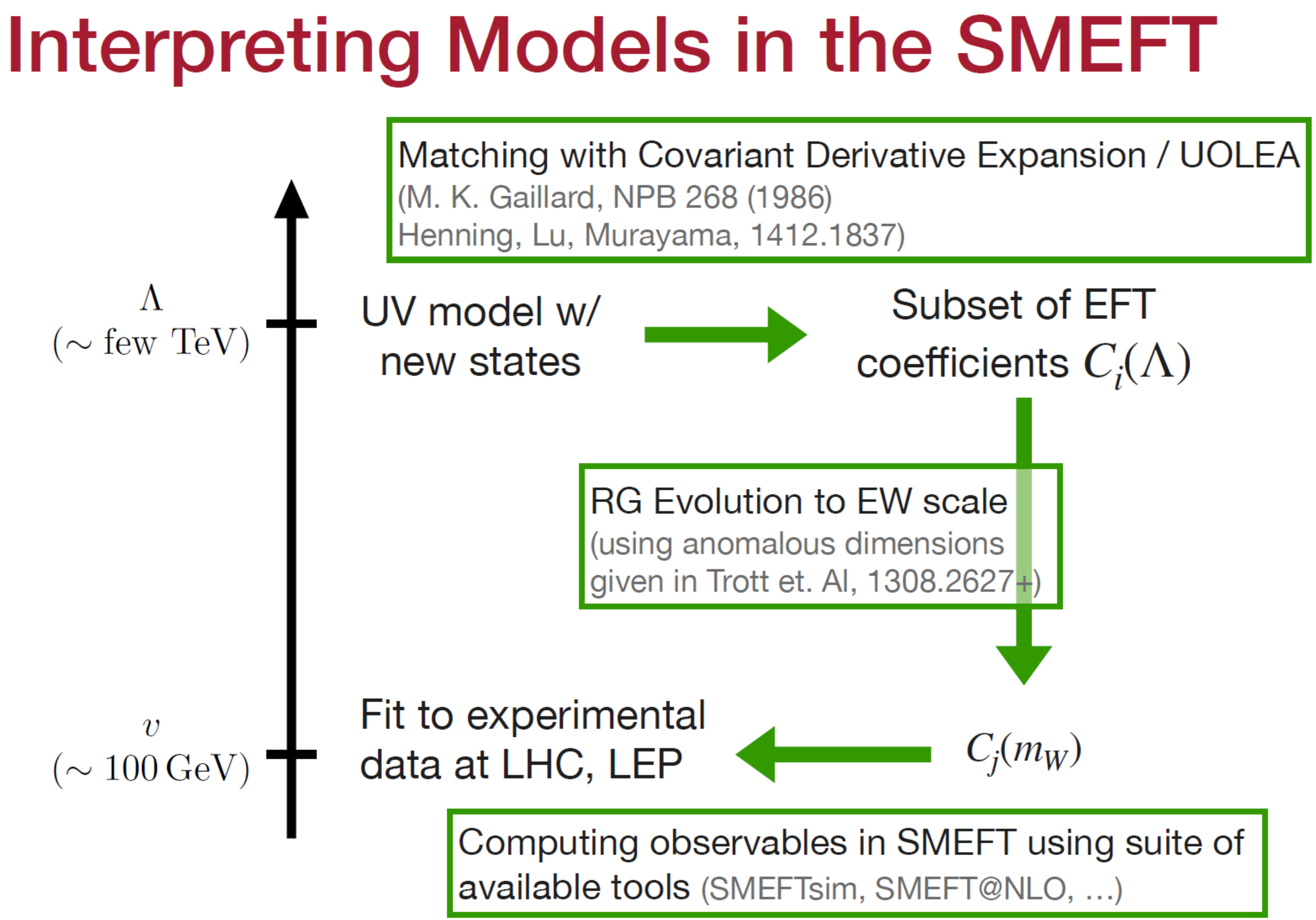
(to be discussed later)

Search For New Physics

Bottom-up

Talk by Samuel Homiller

- In the SMEFT framework



Interpreting Models in the SMEFT

Matching with Covariant Derivative Expansion / UOLEA
(M. K. Gaillard, NPB 268 (1986)
Henning, Lu, Murayama, 1412.1837)

Λ
$(\sim \text{few TeV})$

UV model w/ new states → Subset of EFT coefficients $C_i(\Lambda)$

RG Evolution to EW scale
(using anomalous dimensions given in Trott et. Al, 1308.2627+)

v
$(\sim 100\,\text{GeV})$

Fit to experimental data at LHC, LEP ← $C_j(m_W)$

Computing observables in SMEFT using suite of available tools (SMEFTsim, SMEFT@NLO, …)

In the SMEFT framework

Talk by Samuel Homiller

- Lessons learned from studying some simple UV models about the importance of “higher-order” effects:
  - ❖ **One-loop matching effects**
  - ❖ **RGE-induced (new) contributions**
  - ❖ **Higher order QCD and EW corrections**

- Given a UV model, some EWPO requires the inclusion of the square of dim-6 contribution $(1/\Lambda^4)$ in the SMEFT prediction to agree with the full UV model prediction. Some others even require the inclusion of dim-8 operator contribution.

➡ **This information is generally not known from the bottom-up approach.**

In the SMEFT framework

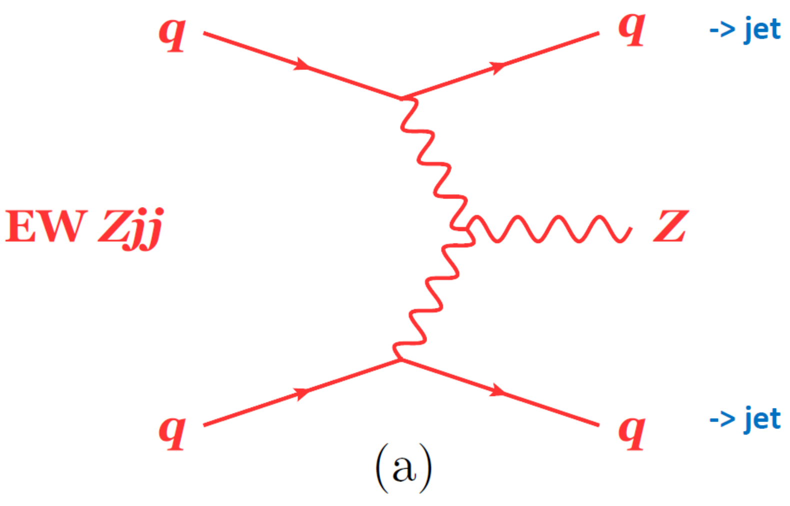
- Automated one-loop matching tools (**Talk by Julie Pages)**
- Multi-boson production sensitivity to dim-6 and dim-8 operators (**Talk by Antonio Vagnerini)**
- Experimental searches in multi-boson final states (**Talk by Michael Schmitt)**

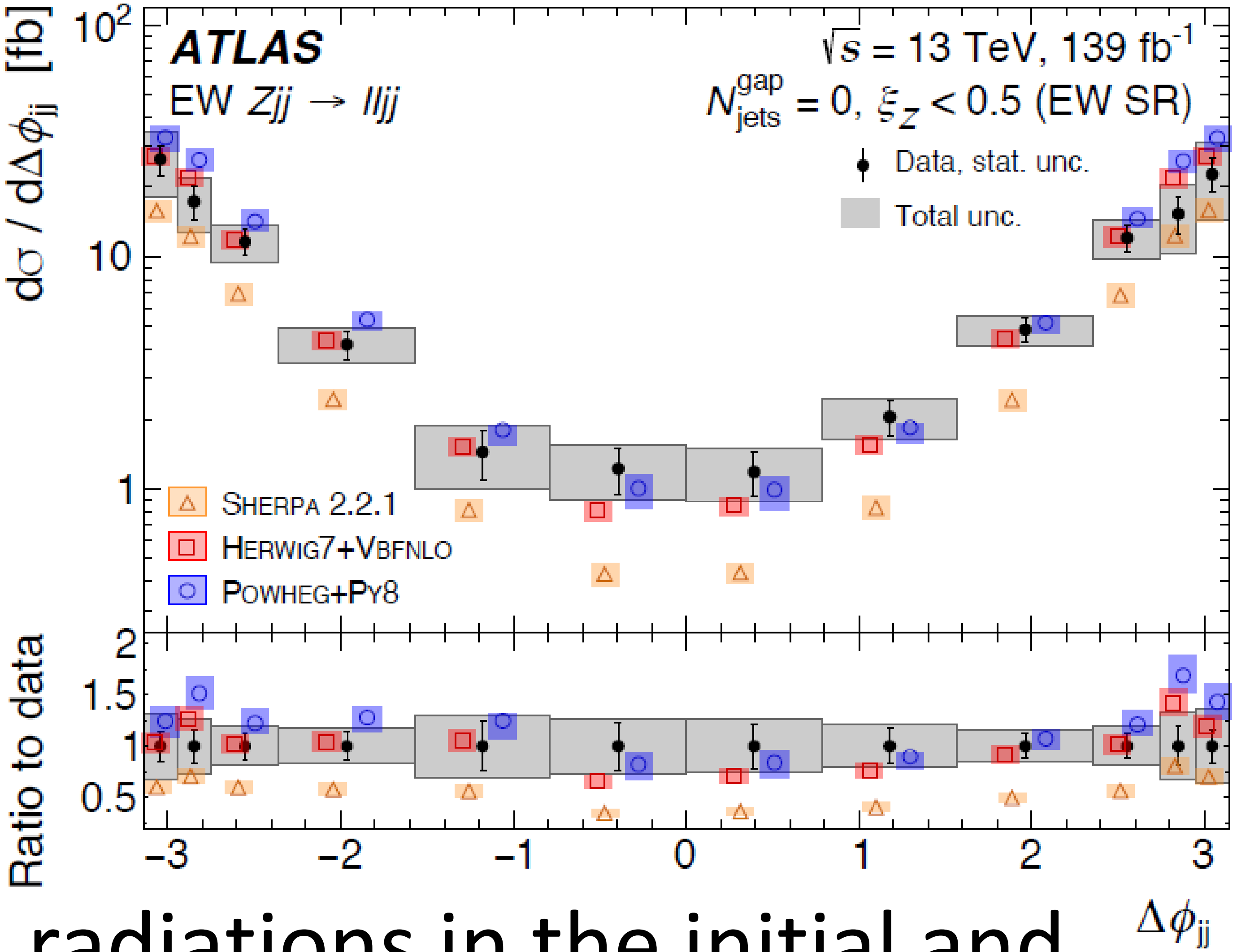
1. dim-6 and the impact of differential cross sections
2. trying to deal with unitarity violation
3. dealing with dim-8 when dim-6 is unknown
4. global combined fits

The power of polarization (or correlation) observables

(See talk by Michael Schmitt)

- EW Zjj production



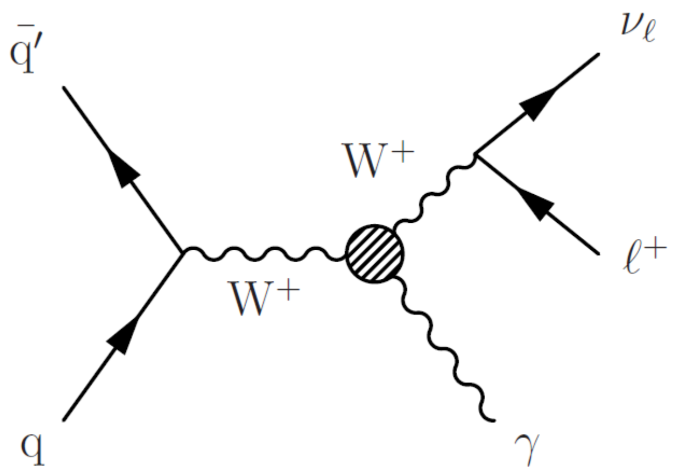


- Effects of QCD soft gluon radiations in the initial and final states are important for predicting $\Delta\phi_{jj}$.

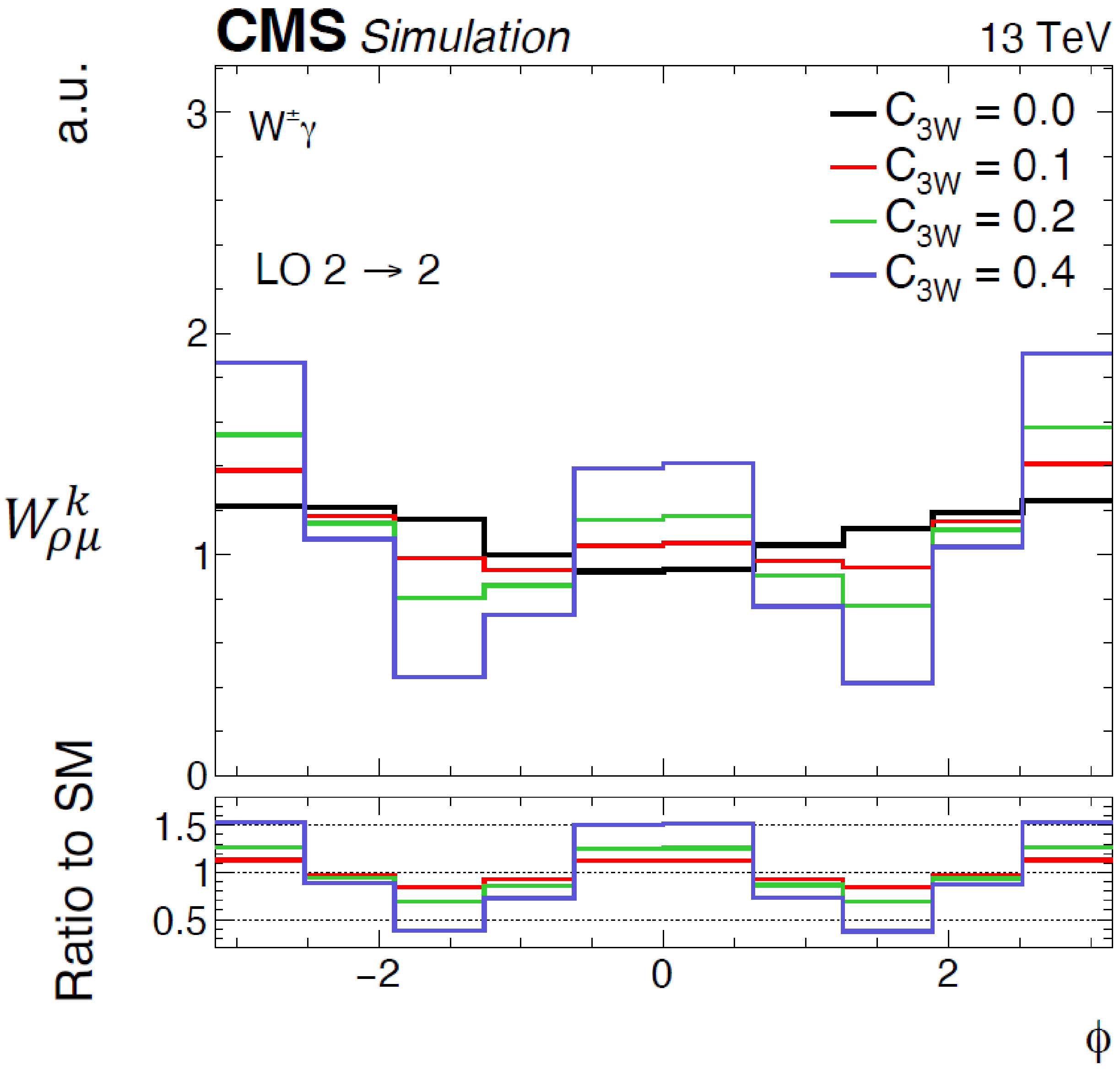
- The QCD showering of event generators does not model the full color coherence effects of the event.
(arXiv:1802.02980)

The power of polarization (or correlation) observables

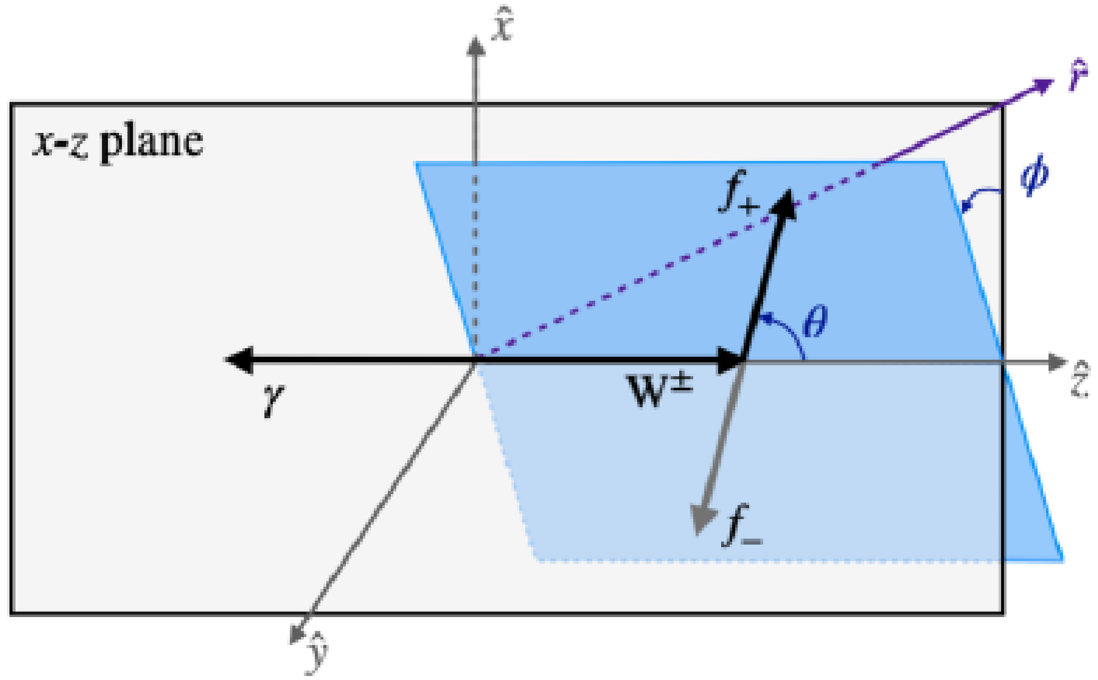
(See talk by Michael Schmitt)



$$C_{3W}\epsilon_{ijk}W^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$$



(See talk by Minho Son)

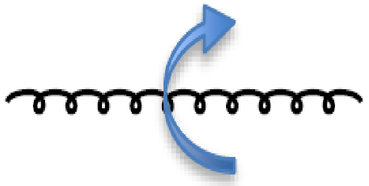


What caused this ϕ dependence?

Polarization observables in bosonic final states

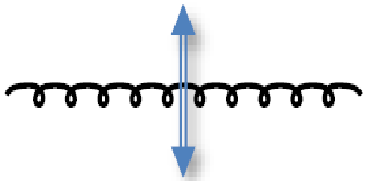
☐ Linear polarization vs. helicity/circular polarization

helicity pol.



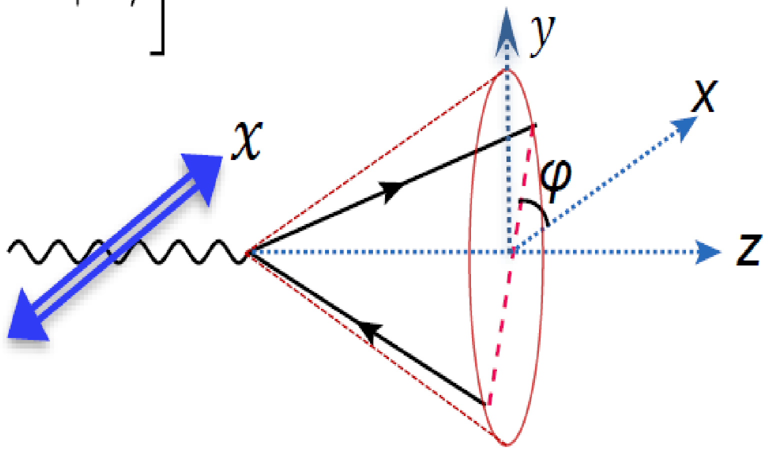
$|\pm 1\rangle$

linear pol.



$$|x\rangle = -\frac{1}{\sqrt{2}}\Big[|+\rangle - |-\rangle\Big], \quad |y\rangle = \frac{i}{\sqrt{2}}\Big[|+\rangle + |-\rangle\Big]$$

$$|e^{+i\phi} \pm e^{-i\phi}|^2 \rightarrow 2(1 \pm \cos 2\phi)$$



Interference of helicity λ_1 and λ_2 causes azimuthal distributions

$$\cos(\lambda_1 - \lambda_2)\phi, \quad \sin(\lambda_1 - \lambda_2)\phi$$

CP even **CP odd**

Useful probes of new physics

Azimuthal dependence

Production of a particle → Decay of this particle (has azimuthal dependence)

- **Decay amplitude:**

$$\langle \mathrm{D}, \phi | \lambda \rangle = \langle \mathrm{D}, 0 | U^{\dagger}(R_z(\phi)) | \lambda \rangle = e^{i\lambda\phi} \langle \mathrm{D}, 0 | \lambda \rangle = A_\lambda(D) e^{i\lambda\phi}$$

$$|\mathrm{D}, \phi\rangle = \text{state of decay products with an overall azimuthal angle } \phi$$

- **Unstable particle V can be thought of an intermediate state that decays into D:**

$$\mathcal{M}(D, \phi) = \langle D, \phi | i \rangle = \sum_\lambda \langle D, \phi | V_\lambda \rangle \langle V_\lambda | i \rangle = \sum_\lambda e^{i\lambda\phi} \mathcal{M}_\lambda(V) A_\lambda(D)$$

- **Azimuthal distribution results from the interference of V_{λ_1} and V_{λ_2}**

$$|\mathcal{M}(D, \phi)|^2 = \sum_\lambda |\mathcal{M}_\lambda(V) A_\lambda(D)|^2 + 2 \sum_{\lambda_1 < \lambda_2} \underline{\mathrm{Re}\left\{ e^{i(\lambda_1 - \lambda_2)\phi} \mathcal{M}_{\lambda_1}(V) A_{\lambda_1}(D) \mathcal{M}^*_{\lambda_2}(V) A^*_{\lambda_2}(D) \right\}}$$

$$\mathrm{Re}\left[\mathcal{M}_{\lambda_1}(V) A_{\lambda_1}(D) \mathcal{M}^*_{\lambda_2}(V) A^*_{\lambda_2}(D)\right] \cos(\lambda_1 - \lambda_2)\phi - \mathrm{Im}\left[\mathcal{M}_{\lambda_1}(V) A_{\lambda_1}(D) \mathcal{M}^*_{\lambda_2}(V) A^*_{\lambda_2}(D)\right] \sin(\lambda_1 - \lambda_2)\phi$$

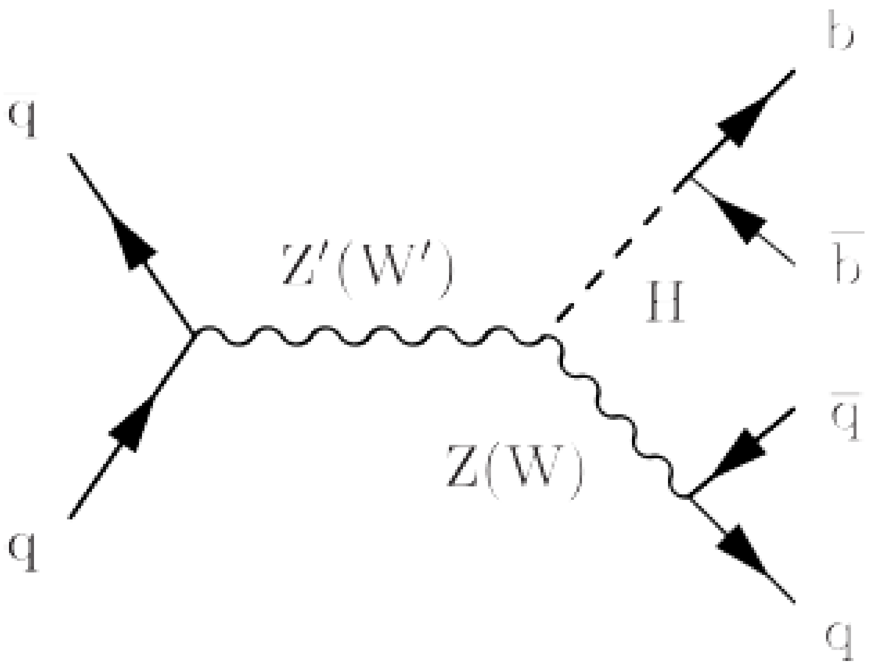
More details: Zhite Yu, Ph.D. Thesis, MSU, arXiv: 2308.13080

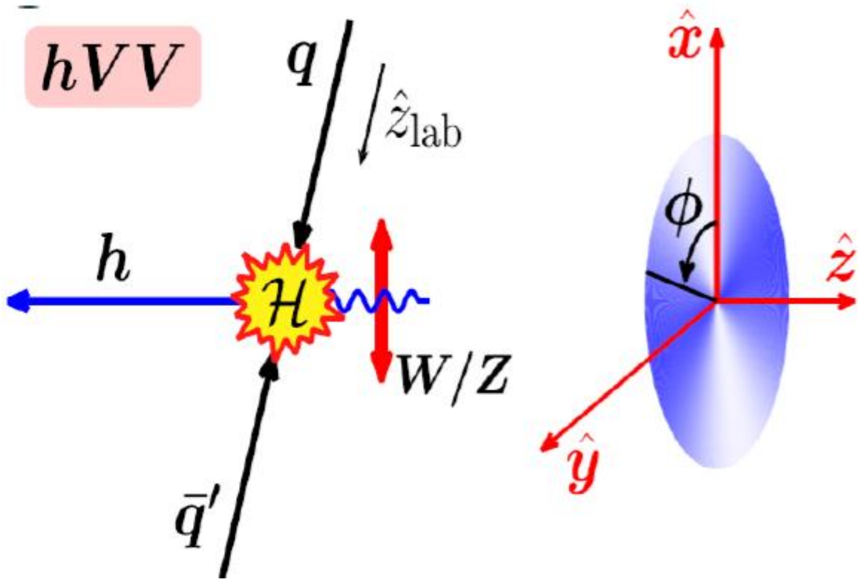
Search in fully hadronic final state

Talk by Aram Apyan

Talk by Daniel Whiteson:
Jet substructure, taggers, and Machine Learning

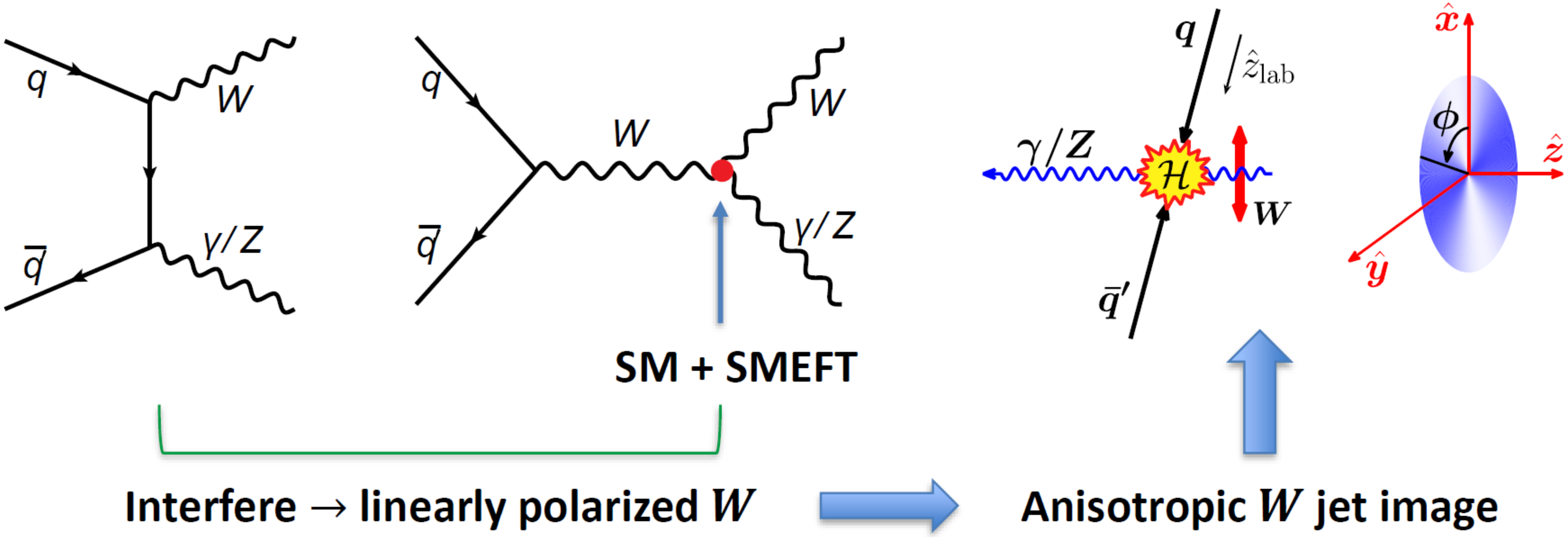
- ❖**Highly boosted bosons**
- ❖**Use large-radius jets (R=0.8 with large pT)**





- ➢ **Hadronic mode energy deposition is $\cos 2\phi$ for CP-even and $\sin 2\phi$ for CP-odd SMEFT operator.**

W/Z polarization and VVV coupling



SM + SMEFT

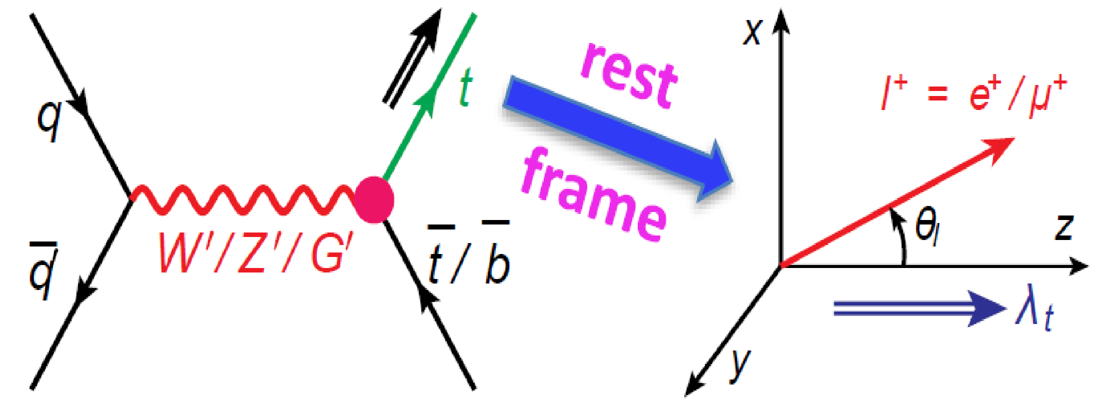
Interfere → linearly polarized W

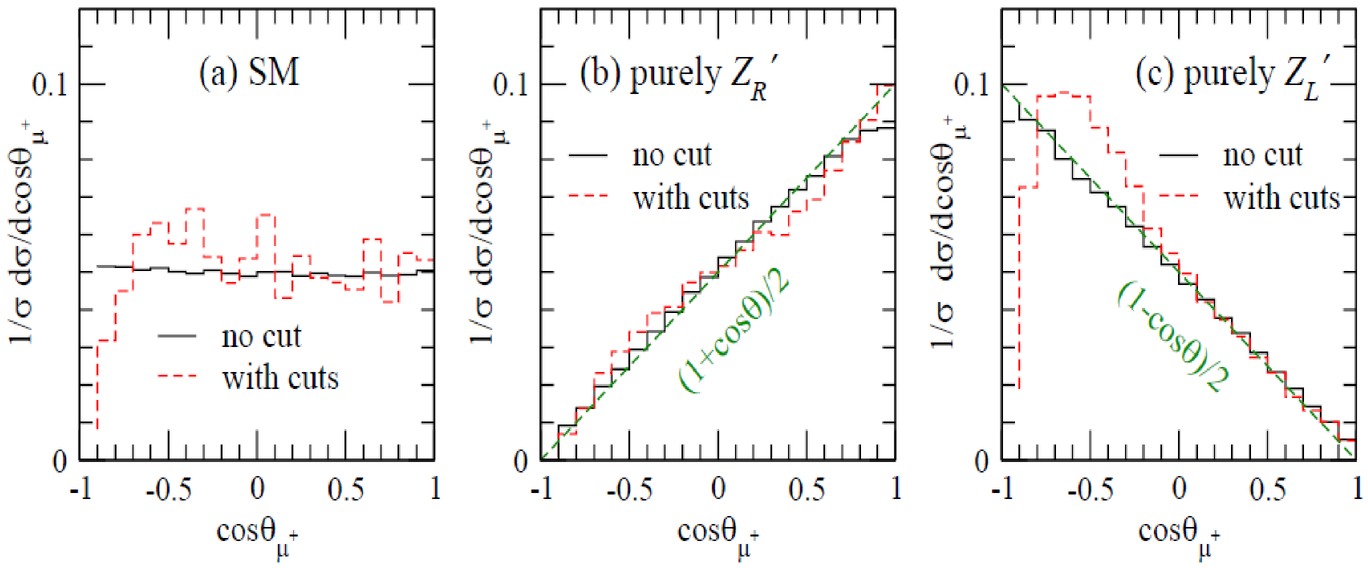
Anisotropic W jet image

- **Hadronic mode energy deposition is $\cos 2\phi$ for CP-even and $\sin 2\phi$ for CP-odd SMEFT operator.**
- **The square of dim-6 operator can only come from the s-channel diagram which does not lead to $\cos 2\phi$ distribution.**

W boson polarization in boosted tops

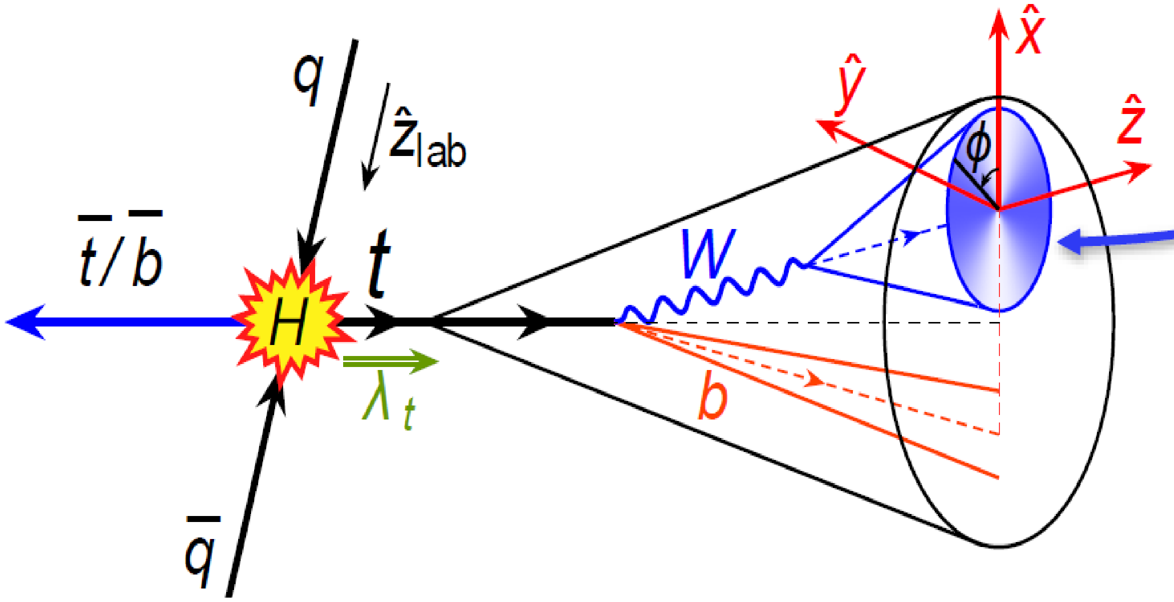
- ❑ **Example:** $pp \to (W', Z', G') \to t\,\bar{t}/t\,\bar{b}$ [Berger et. al. PRD 83, 114026 (2011)]





$$d\Gamma_t/d\cos\theta_l \propto 1 + \lambda_t \cos\theta_l \rightarrow \lambda_t$$

- ❑ **Boosted top quark (hadronic mode)** [Yu & Yuan, PRL 129, 112001 (2022)]



$$\frac{dE}{d\phi} = \frac{E_{\rm tot}}{2\pi}\left[1 + \xi \cos 2\phi\right]$$ **Infrared safe**

Boosted limit: $\xi = \xi(\lambda_t) = 0.145(\lambda_t - 1)$

[Assuming SM tbW coupling]

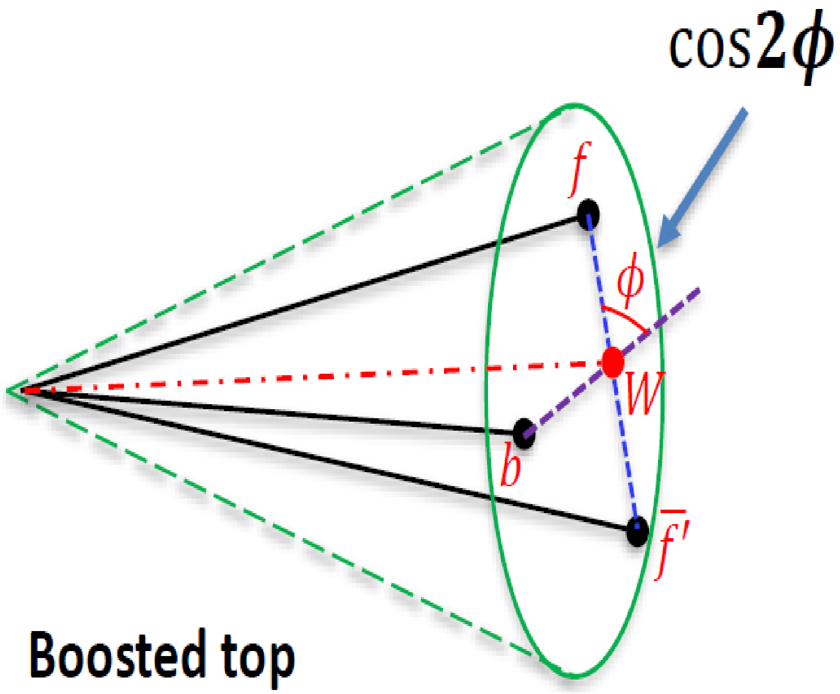
Azimuthal correlation

→ **Boosted top polarization**

A New Boosted Top Jet Substructure

❑ A new observable for boosted top quark jet

- $\cos 2\phi$ angular correlation
- Only exists in boosted top frame
- Due to W linear polarization
- Asymmetry of azimuthal energy deposits



❑ Phenomenological significance

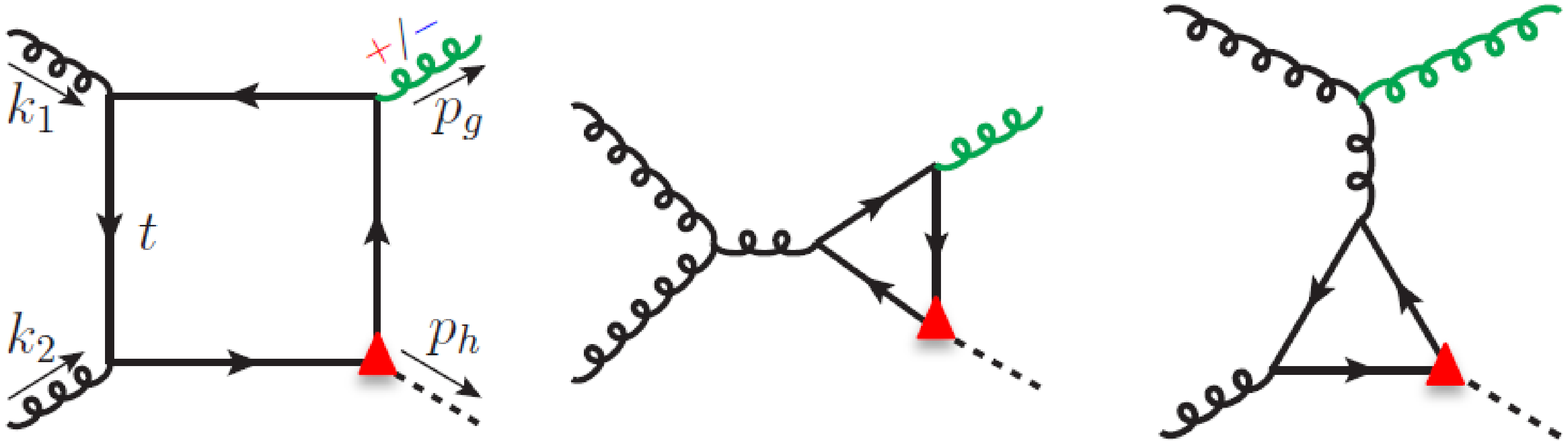
- Measuring longitudinal polarization of boosted top
- New top tagger against QCD jets

Gluon is also a Boson!

- Consider $gg \to h\,g$
- How to make use of the polarization of gluon for probing new physics?

Linearly polarized gluon jet in $gg \to hg$ process

SM + *CP*-odd

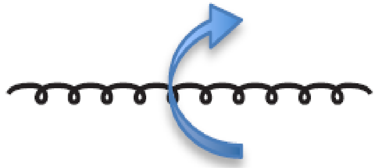


$$\mathcal{L} \supset -\frac{m_t}{v}\, h\, \bar{t}\,(\kappa + i\,\tilde{\kappa}\,\gamma_5)\,t$$

Linear polarization of a gluon

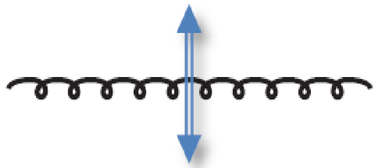
- ☐ **Linear polarization vs. helicity/circular polarization**

helicity pol.



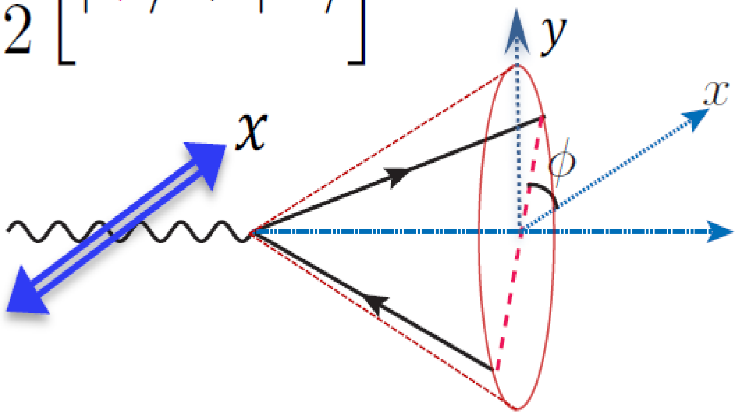
$|\pm 1\rangle \quad \Rightarrow \quad \left|e^{\pm i\phi}\right|^2 = 1$

linear pol.



$$|x\rangle = -\frac{1}{\sqrt{2}}\Big[|+\rangle - |-\rangle\Big], \quad |y\rangle = \frac{i}{\sqrt{2}}\Big[|+\rangle + |-\rangle\Big]$$

$$\Rightarrow \quad |e^{+i\phi} \pm e^{-i\phi}|^2 \to 2(1 \pm \cos 2\phi)$$



- ☐ **Gluon polarization density matrix**

$$\rho_{\lambda\lambda'} = \frac{1}{2}(1 + \boldsymbol{\xi}\cdot\boldsymbol{\sigma})_{\lambda\lambda'} = \frac{1}{2}\begin{array}{c} \begin{array}{cc} + & - \end{array} \\ \left(\begin{array}{cc} 1+\xi_3 & \xi_1 - i\,\xi_2 \\ \xi_1 + i\,\xi_2 & 1-\xi_3 \end{array}\right) \end{array} \begin{array}{c} + \\ - \end{array}$$

$\xi_3 = \rho_{++} - \rho_{--}$ **net helicity**

$\xi_{1,2} \sim \rho_{+-}$ **helicity *interference*** → **Two independent linear pol. dof**

Gluon polarization and $ht\bar{t}$ coupling

Gluon polarization and $ht\bar{t}$ coupling

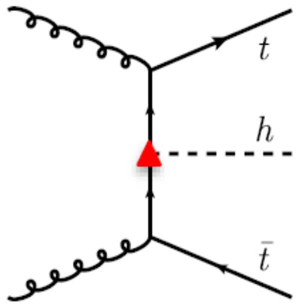
[See also: CMS PRL 125, 061801 (2020), 2208.02686, ATLAS 2303.05974]

- Example: *CP* property of $ht\bar{t}$ coupling

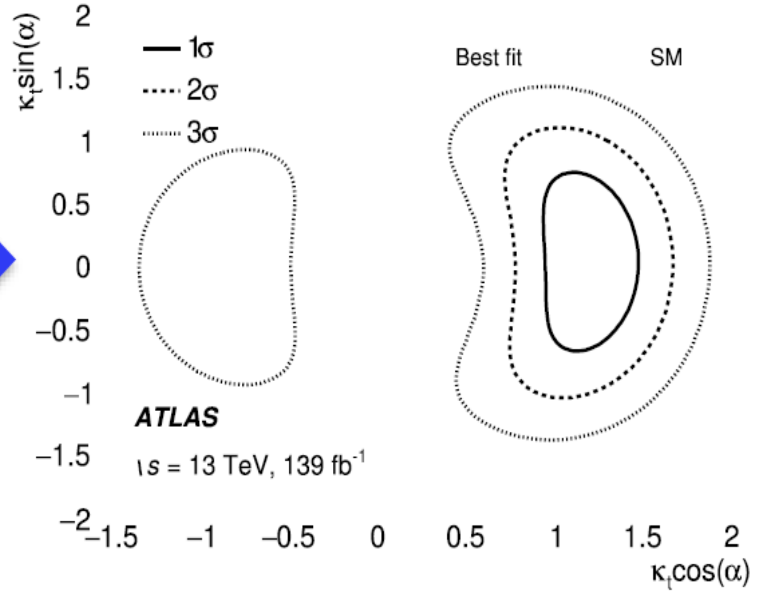
$$\mathcal{L} \supset -\frac{m_t}{v}\, h\, \bar{t}\,(\kappa + i\,\tilde{\kappa}\,\gamma_5)\, t$$

$$= -\kappa_t \frac{m_t}{v}\, h\, \bar{t}\,(\cos\alpha + i \sin\alpha\, \gamma_5)\, t$$

with $\kappa_t = \sqrt{\kappa^2 + \tilde{\kappa}^2}\,, \quad \alpha =$ *CP* phase



ATLAS, PRL 125, 061802 (2020)



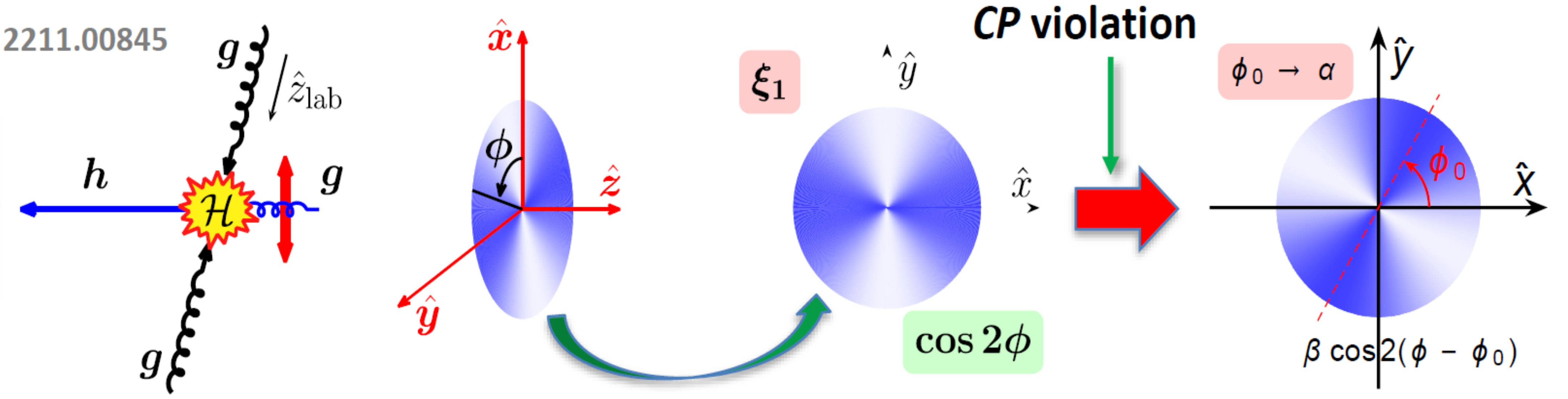
- "Missing" observable in $h + g$ production

Yu, Mohan, Yuan, 2211.00845

$\hat{z} \parallel \boldsymbol{p}_g$

$\hat{y} \parallel \hat{z}_{\rm lab} \times \hat{z}$

$\hat{x} \parallel \hat{y} \times \hat{z}$

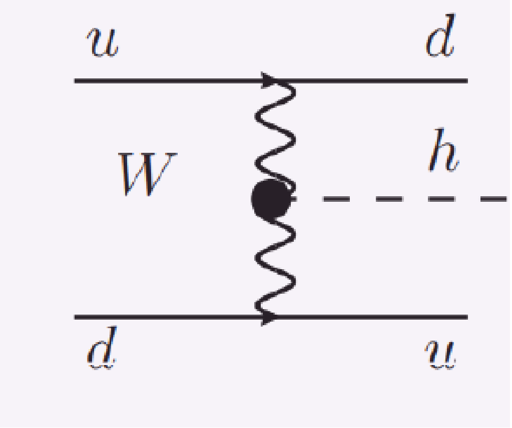


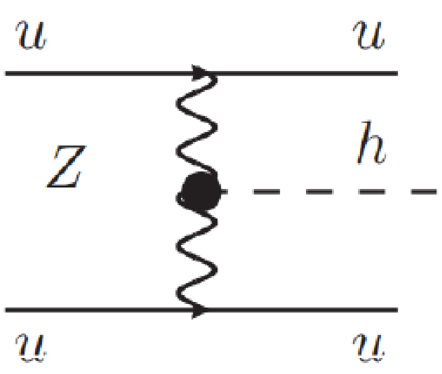
$$\xi_1(\alpha)\cos 2\phi + \xi_2(\alpha)\sin 2\phi$$

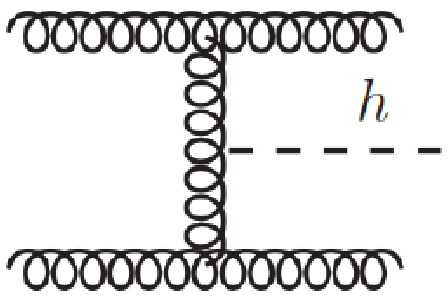
CP phase $=$ rotation of anisotropy axis

A novel tool to discriminate Higgs production mechanisms

Discriminating W-boson fusion, Z-boson fusion and gluon fusion Higgs production





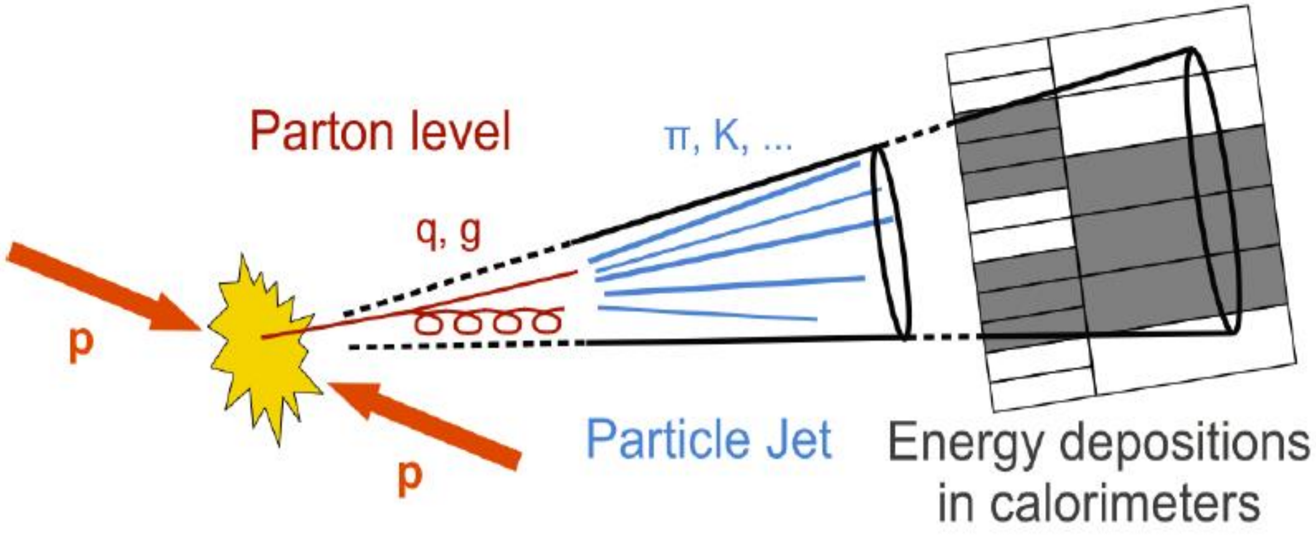


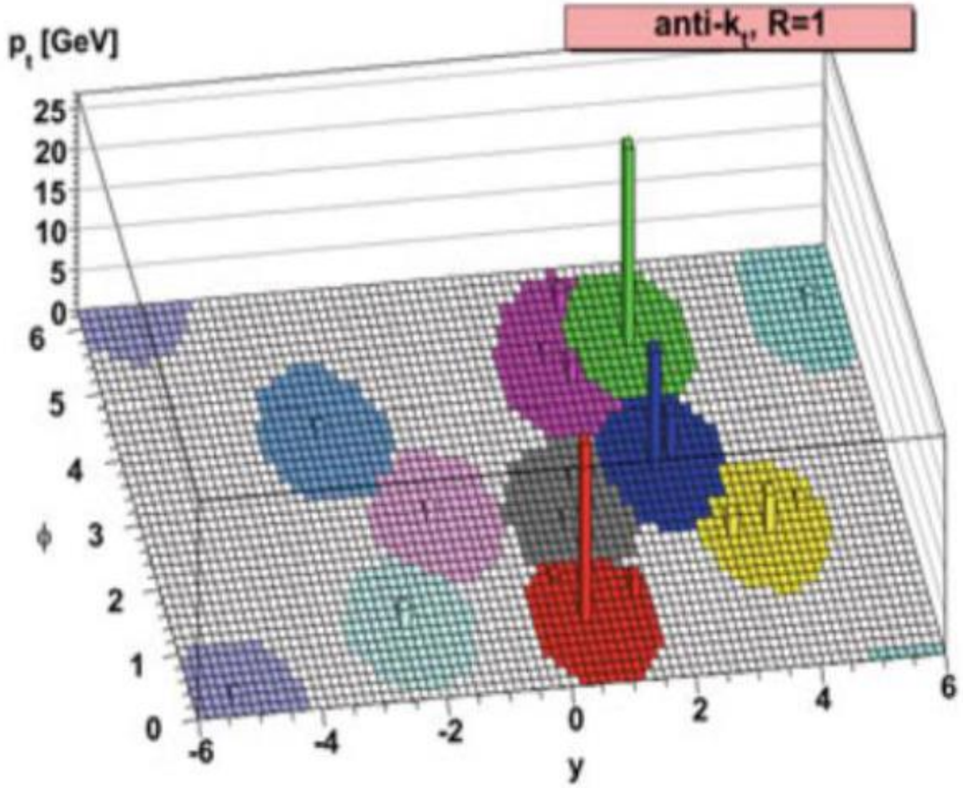
Hai Tao Li, Bin Yan, C.-P. Yuan, PRL, 2023

Separating the W boson's contribution from the VBF Higgs production is an important task for determining the Higgs gauge coupling

The key observable: Jet Charge
W: opposite sign for the two jet charges
Z: same or opposite sign for the two jet charges
G: the sign of the jet charge is arbitrary

Jet charge definition





Transverse-momentum-weighting scheme:

$$Q_J = \frac{1}{(p_T^j)^\kappa} \sum_{i \in jet} Q_i (p_T^i)^\kappa, \ \kappa > 0$$

$$d_{ij} = \min\left(\frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2}\right) \frac{\Delta R_{ij}^2}{R^2}$$

K: To regulate the sensitivity of the soft gluon radiation

R.D. Field and R.P. Feynman, NPB136,1(1978)

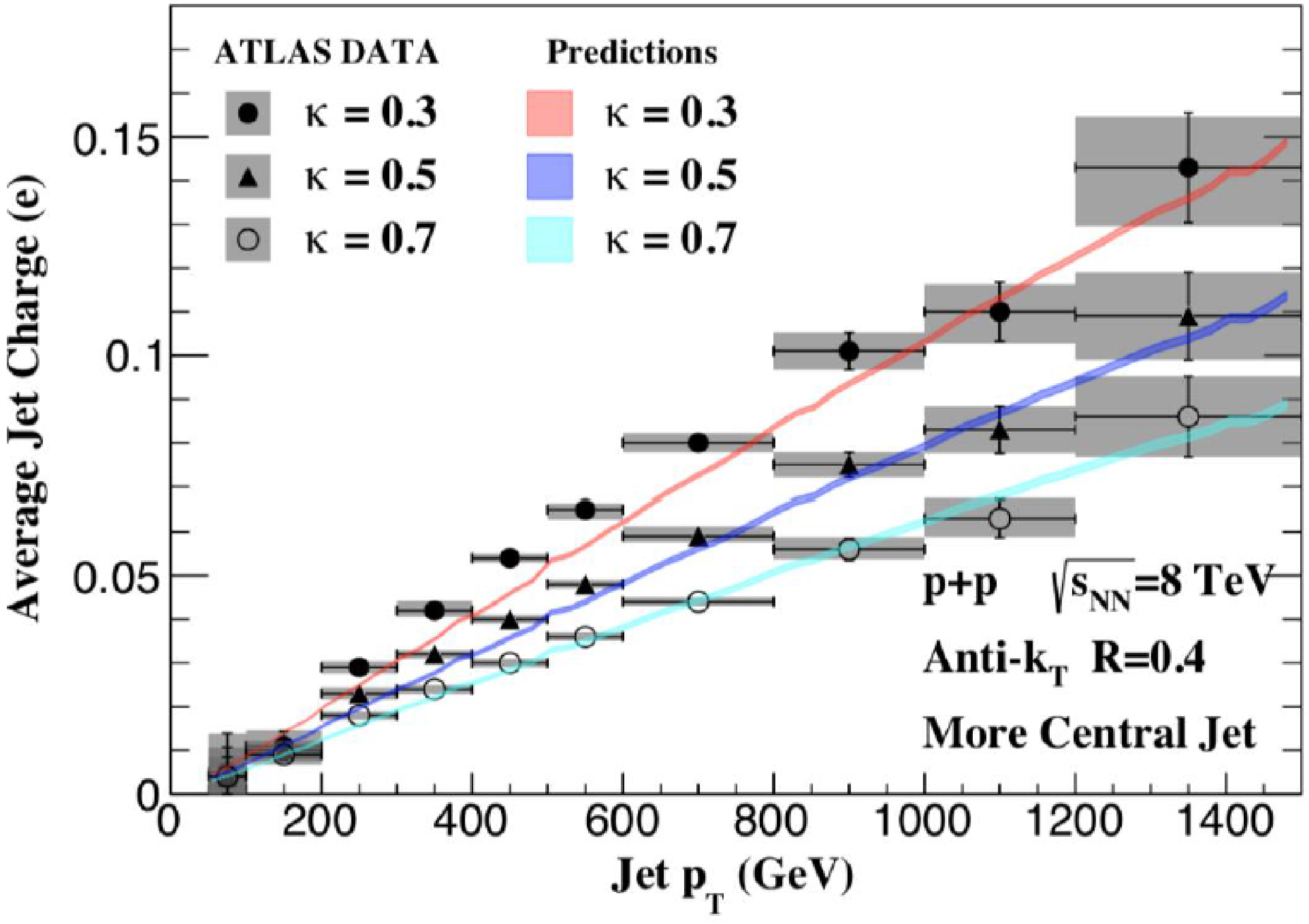
Jet charge @ LHC

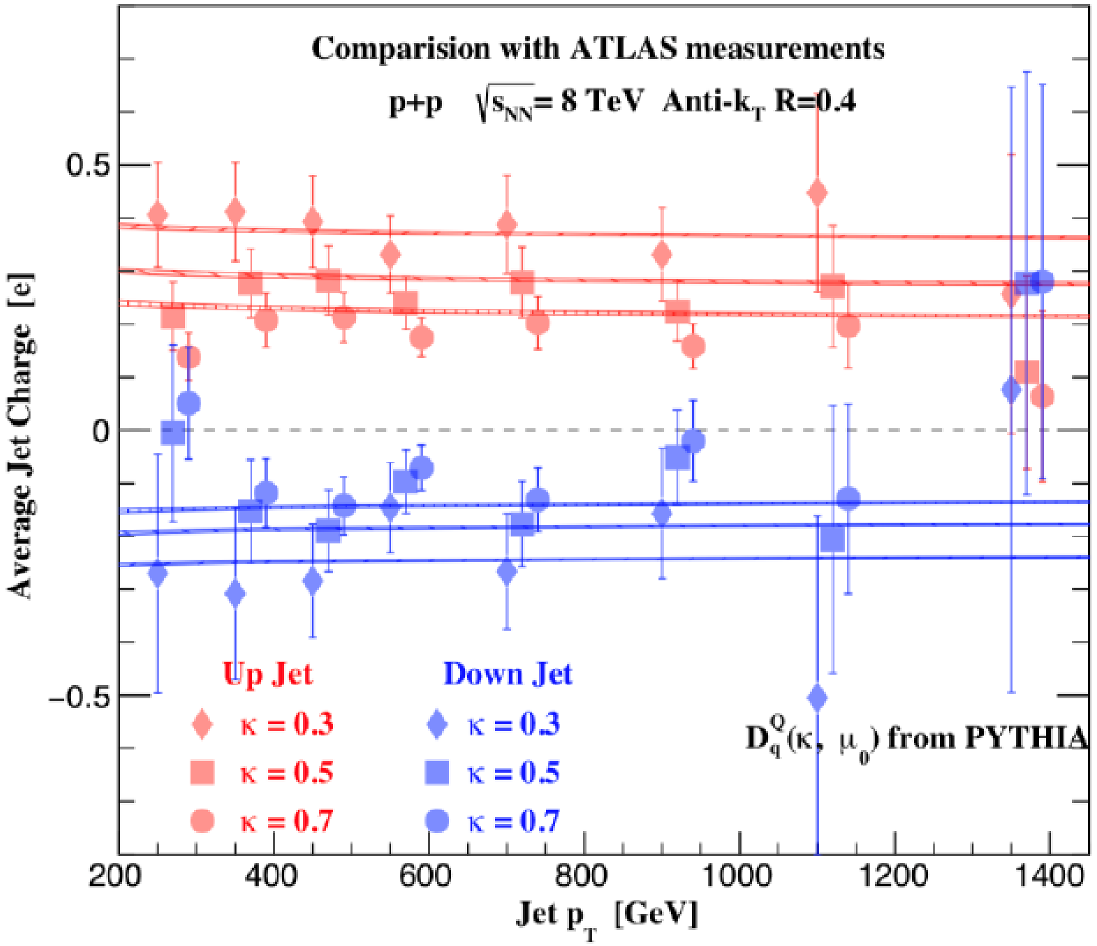
$$\langle Q_k^q \rangle = \frac{1}{\sigma_{q-jet}} \int d\sigma_{q-jet} Q_\kappa(\sigma_{q-jet})$$

D. Krohn, M. D. Schwartz, T. Lin, W.J. Waalewijn, PRL 110(2013)21,212001

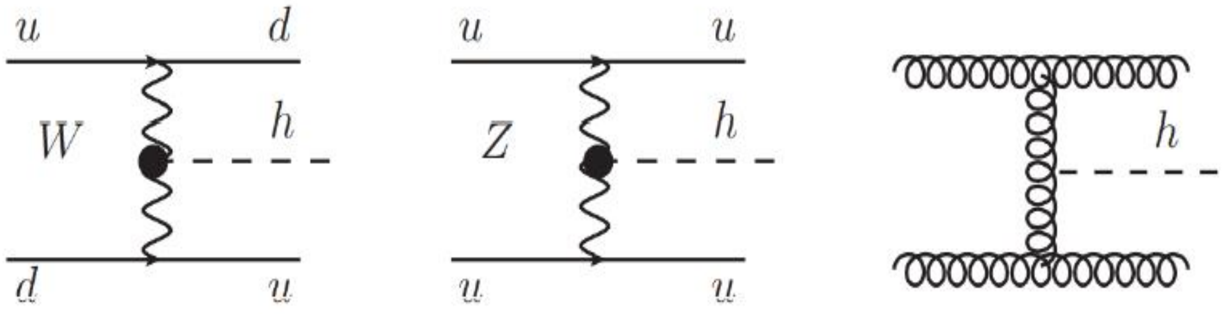
W.J.Waalewijn, PRD86(2012)094030

H. T. Li and I. Vitev, PRD 101(2020)076020

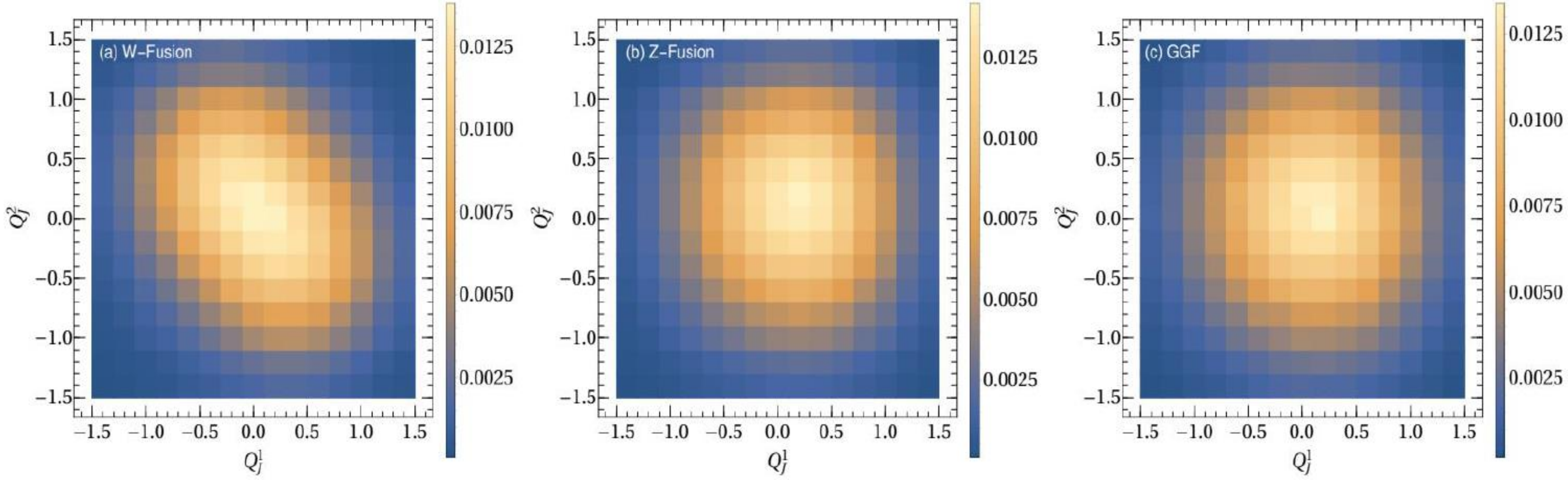




Various Higgs production mechanisms



$$p_T^j > 30\ \text{GeV}, \qquad 1 < |\eta_j| < 4.5,$$
$$m_{jj} > 120\ \text{GeV}, \qquad |\Delta\eta_{jj}| > 3.5, \qquad |\eta_h| < 2.5$$

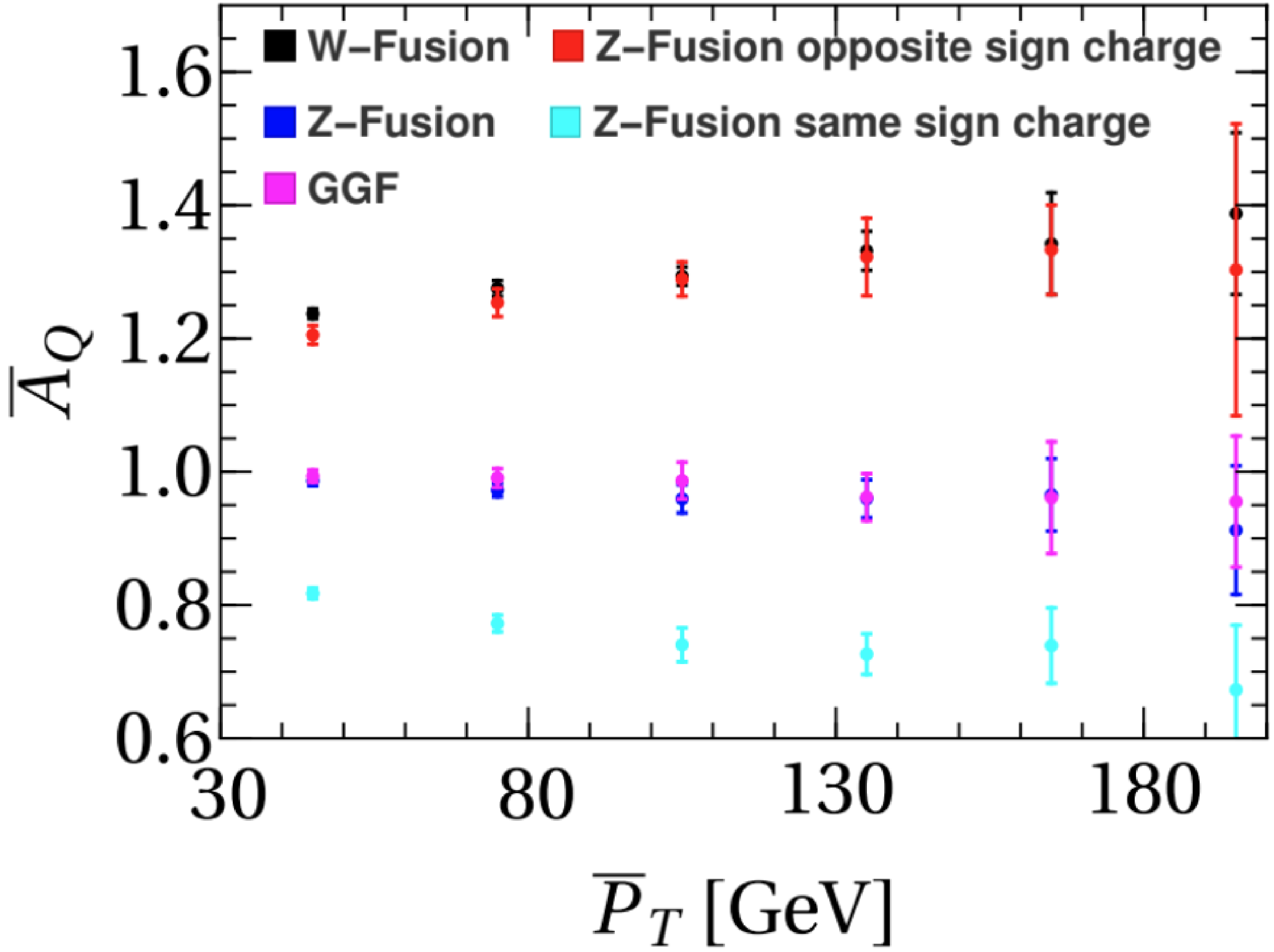


opposite sign for the two jet charges

same or opposite sign

the sign of the jet charge is arbitrary

Jet charge asymmetry



$$\mathcal{L} = 300\ \mathrm{fb}^{-1}$$

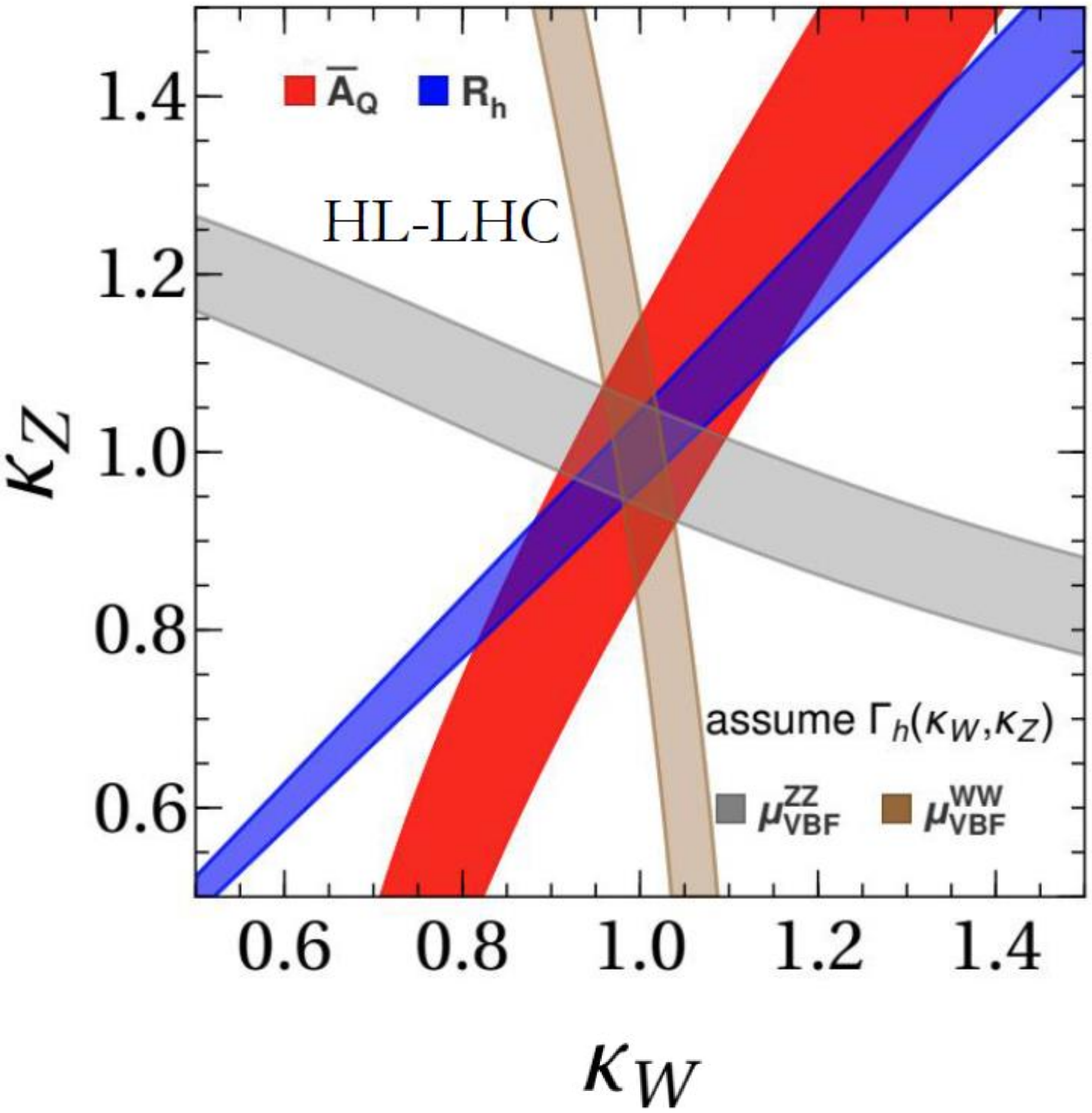
<Q> means the Average value

$$\overline{A}_Q = \frac{\langle |Q_J^1 - Q_J^2| \rangle}{\langle |Q_J^1 + Q_J^2| \rangle}$$

$$\bar{P}_T = \frac{p_T^1 + p_T^2}{2}$$

Various Higgs production mechanisms

$h \to 4\ell/2\ell 2v_\ell$



$$\overline{A}_Q^{\rm tot} = \frac{f_W\langle Q^-\rangle_W + f_Z\langle Q^-\rangle_Z + f_G\langle Q^+\rangle_G}{f_W\langle Q^+\rangle_W + f_Z\langle Q^-\rangle_Z + f_G\langle Q^+\rangle_G}$$

$$R_h = \frac{\mu(gg \to h \to WW^*)}{\mu(gg \to h \to ZZ^*)} = \frac{\kappa_W^2}{\kappa_Z^2}$$

$$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{\rm SM}}$$

The limits from R_h and jet charge asymmetry do not depend on the assumption of the Higgs boson width.

Di-Higgs and HHH productions

(Talk by Abraham Tishelman-Charny)

- Important for measuring hhh and hhhh couplings

➡ to probe Higgs potential

- Challenging in experimental measurements

➡

use transformer to optimize reconstruction efficiency for both resolved and boosted cases **(Talk by Haoyang Li)**

➡

How to distinguish a boosted $h \to bb$ from $g \to bb$ using jet substructure?

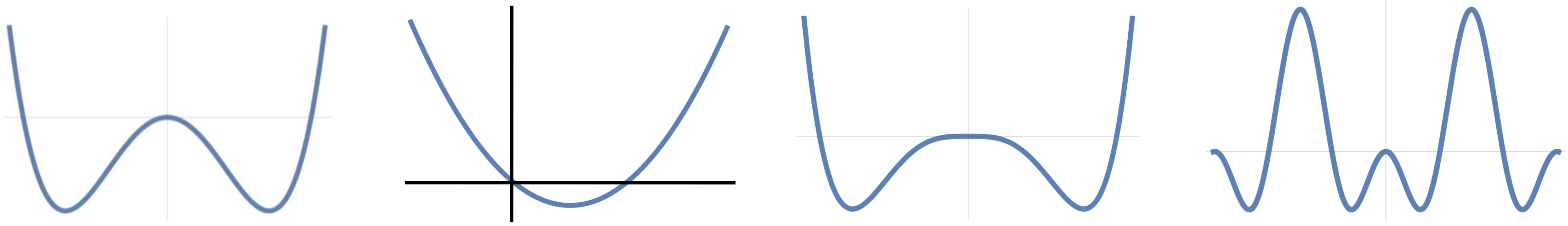
(Talk by Daniel Whiteson)

Li, Li, Yuan, PRL 107 (2011)
Isaacson, Li, Li, Yuan, PLB 771 (2017)

Which EFT for New Physics?

Next mission: probing the nature of Higgs Boson!

To find out the Higgs potential!



Landau-Ginzburg Higgs

$$V(\phi) = -m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

Fundamental particle

Tadpole-induced Higgs

$$V(\phi) = -\mu^3\sqrt{\phi^\dagger\phi} + m^2\phi^\dagger\phi$$

Partial Fundamental (condensate)

Coleman Weinberg Higgs

$$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2 \log\frac{\phi^\dagger\phi}{\mu^2}$$

Conformal particle

Pseudo-Goldstone Higgs

$$V(\phi) = -a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

Composite particle

Not all of these scenarios can be described in SMEFT

➡ **Need to use hEFT**

[Agrawal, Saha, Xu, **Yu**, Yuan, 1907.02078]

SMEFT vs Higgs EFT

Standard model EFT

SU(3) x SU(2) x U(1)

$$\boxed{\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{C_i^{(5)}}{\Lambda_{NP}} Q_i^{(5)} + \frac{C_i^{(6)}}{\Lambda_{NP}^2} Q_i^{(6)} + \cdots}$$

approximate custodial symmetry
SU(2) x SU(2)

$$\langle \Sigma \rangle = \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix} \neq 0$$

$$\Sigma \equiv (\Phi^c, \Phi) = \begin{pmatrix} \Phi^{0*} & \Phi^+ \\ -\Phi^- & \Phi^0 \end{pmatrix} \to g_L \, \Sigma \, g_R^\dagger$$

EW Chiral Lagrangian

$$\Phi \equiv \frac{1}{\sqrt{2}} \vec{\sigma} \cdot \vec{\varphi} = \begin{pmatrix} \frac{1}{\sqrt{2}} \varphi^0 & \varphi^+ \\ \varphi^- & -\frac{1}{\sqrt{2}} \varphi^0 \end{pmatrix}$$

SM fields and Goldstone

CCWZ formalism

EFT Framework

UV model

$$\mathcal{L} = \mathcal{L}^{\text{eff}}_{\text{Gravity}} + \underbrace{\mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{EW}}}_{\mathcal{L}_{SM}} + \mathcal{L}^{NP}_{\text{heavy}}$$

Integrate out TeV heavy states

SMEFT

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{C_i^{(5)}}{\Lambda_{NP}} Q_i^{(5)} + \frac{C_i^{(6)}}{\Lambda_{NP}^2} Q_i^{(6)} + \cdots$$

Electroweak symmetry breaking

Higgs EFT

$$\begin{aligned}\mathcal{L} = {} & \frac{1}{2}(\partial_\mu h)^2 - V(h) \\ & + \frac{v^2}{4}\mathrm{Tr}\left[(\partial_\mu U)^\dagger \partial^\mu U\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right) \\ & - \frac{v}{\sqrt{2}}\left(\bar{t}_L, \bar{b}_L\right) U \left(1 + c_1\frac{h}{v} + c_2\frac{h^2}{v^2} + \cdots\right)\begin{pmatrix} y_t t_R \\ y_b b_R \end{pmatrix} + \text{h. c.}\end{aligned}$$

m_W

LEFT

$$\mathcal{L}_{\text{LEFT}} = \mathcal{L}_{\text{QED+QCD}} + \frac{C_i^{(5)}}{M_W} O_i^{(5)} + \frac{C_i^{(6)}}{M_W^2} O_i^{(6)} + \cdots$$

Multiboson SMEFT/hEFT

SMEFT

$$\mathcal{F}(h) = 1 + 2\frac{h}{v} + \frac{h^2}{v^2}$$

Dim-6

$$\widetilde{B}_{\mu\nu}\langle D^\mu D_\alpha W^{\alpha\beta} W_\beta{}^\nu\rangle$$
$$\widetilde{B}_{\mu\nu}\langle D_\beta D_\alpha W^{\alpha\mu} W^{\beta\nu}\rangle$$
$$\widetilde{B}_{\mu\nu}\langle D_\alpha W^{\alpha\mu} D_\beta W^{\beta\nu}\rangle$$
$$\widetilde{B}_{\mu\nu}\langle D_\alpha W^{\alpha\beta} D_\beta W^{\mu\nu}\rangle$$
$$\widetilde{B}_{\mu\nu}\langle D_\alpha W^{\alpha\beta} D^\mu W_\beta{}^\nu\rangle$$

Dim-8

$$\mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger\, D^\beta\Phi\right]$$
$$[B_{\mu\nu}B^{\mu\nu}] \times \left[(D_\beta\Phi)^\dagger\, D^\beta\Phi\right]$$
$$\left[(D_\mu\Phi)^\dagger\, \widehat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\left[(D_\mu\Phi)^\dagger\, \widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu} D^\nu\Phi\right]$$

$$\mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger\, D^\mu\Phi\right]$$
$$[B_{\mu\nu}B^{\nu\beta}] \times \left[(D_\beta\Phi)^\dagger\, D^\mu\Phi\right]$$
$$\left[(D_\mu\Phi)^\dagger\, \widehat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} + \mathrm{h.c.}$$

HEFT

$$\mathcal{F}(h) = 1 + a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots$$

P4

$$\mathrm{Tr}[V^\mu V_\mu]\mathrm{Tr}[V^\nu V_\nu]\mathcal{F}_6(h)$$
$$\mathrm{Tr}[V^\mu V^\nu]\mathrm{Tr}[V_\mu V_\nu]\mathcal{F}_{11}(h)$$
$$\mathrm{Tr}[V^\mu V_\mu](\mathrm{Tr}[TV_\nu])^2\mathcal{F}_{23}(h)$$
$$\mathrm{Tr}[V^\mu V^\nu]\mathrm{Tr}[TV_\mu]\mathrm{Tr}[TV_\nu]\mathcal{F}_{24}(h)$$
$$(\mathrm{Tr}[TV_\mu]\mathrm{Tr}[TV_\nu])^2\mathcal{F}_{26}(h)$$

P6

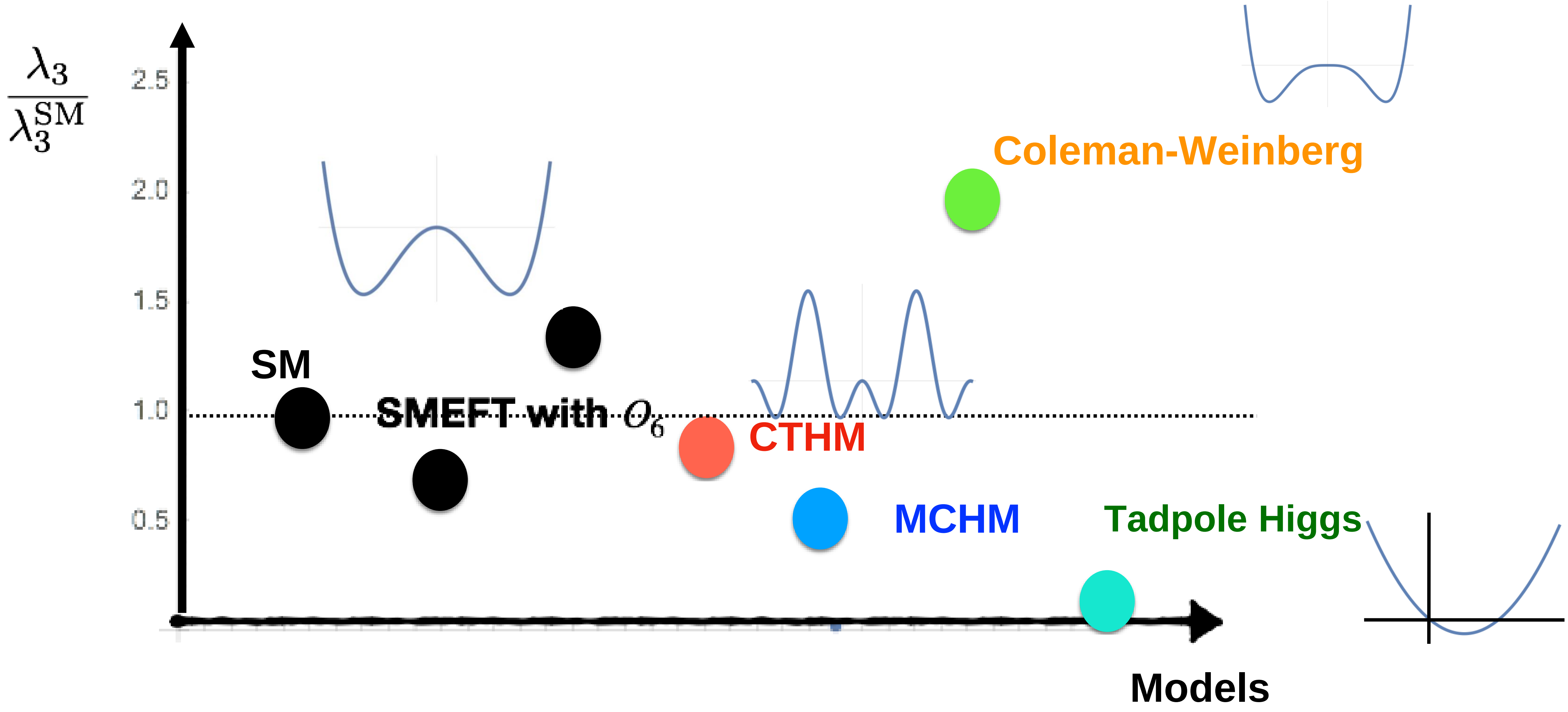
$$\mathrm{Tr}[T\mathcal{D}_{\mu\nu}]\mathrm{Tr}[T\mathcal{D}^{\mu\nu}]\mathrm{Tr}[TV^\alpha]\mathrm{Tr}[TV_\alpha]$$
$$\mathrm{Tr}[T\mathcal{D}^\mu_\mu]\mathrm{Tr}[T\mathcal{D}^\nu_\nu]\mathrm{Tr}[TV^\alpha]\mathrm{Tr}[TV_\alpha]$$
$$-g^2\,\mathrm{Tr}[T\widehat{W}_{\mu\nu}]\mathrm{Tr}[T\widehat{W}^{\mu\nu}]\mathrm{Tr}[TV^\alpha]\mathrm{Tr}[TV_\alpha]$$
$$i\,g\,Tr[T\widehat{W}_{\mu\nu}]\mathrm{Tr}[T\mathcal{D}^{\mu\alpha}]\mathrm{Tr}[TV^\nu]\mathrm{Tr}[TV_\alpha]$$
$$-g'^2\,B_{\mu\nu}B^{\mu\alpha}\mathrm{Tr}[TV^\nu]\mathrm{Tr}[TV_\alpha]$$
$$-gg'\,B_{\mu\nu}\mathrm{Tr}[T\widehat{W}^{\mu\nu}]\mathrm{Tr}[TV^\alpha]\mathrm{Tr}[TV_\alpha]$$

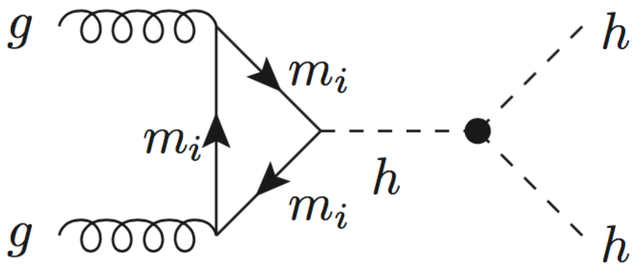
Dim-8 of SMEFT are partially included in p4 of hEFT.

Higgs Self Coupling

[Agrawal, Saha, Xu, **Yu**, Yuan, **2020**]

Make use of large difference in Higgs self coupling





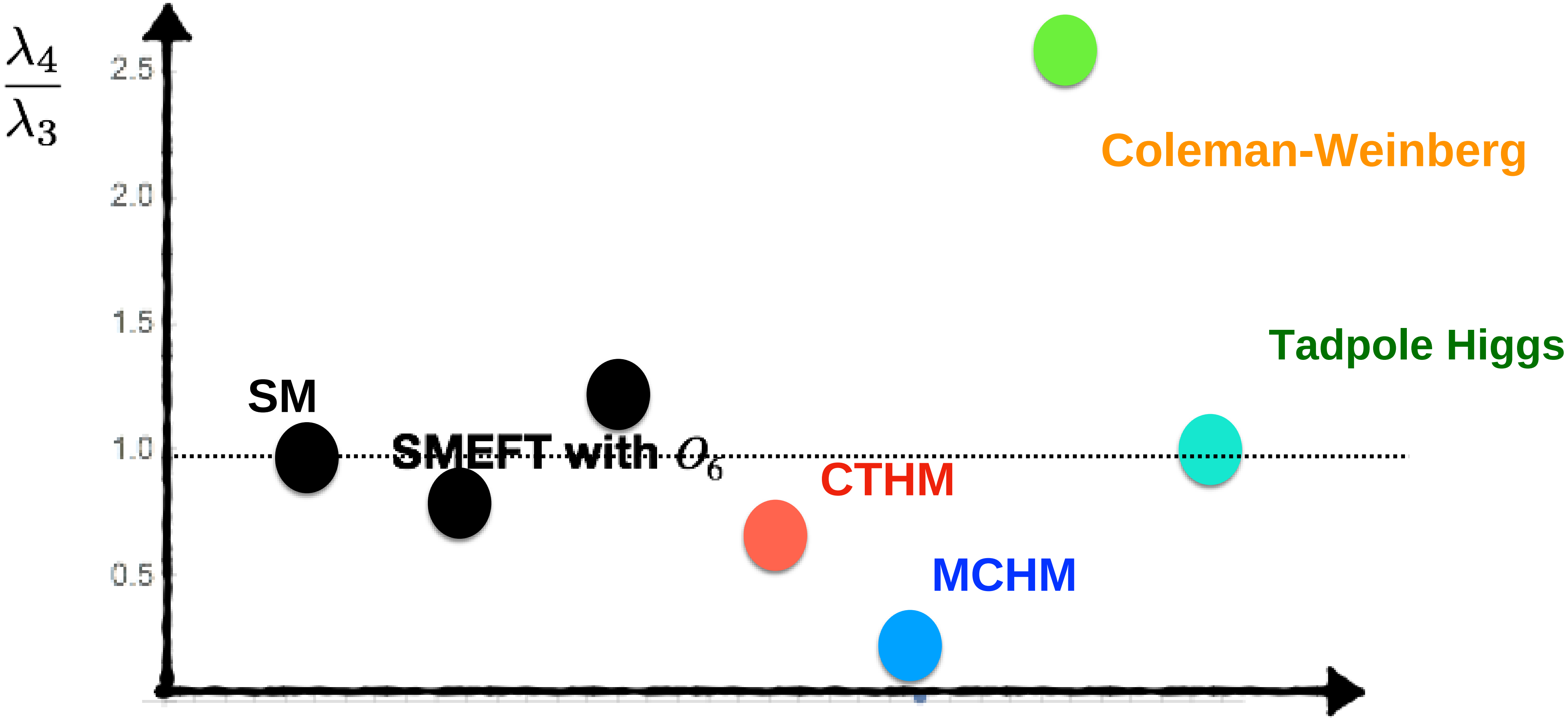
Di-Higgs production

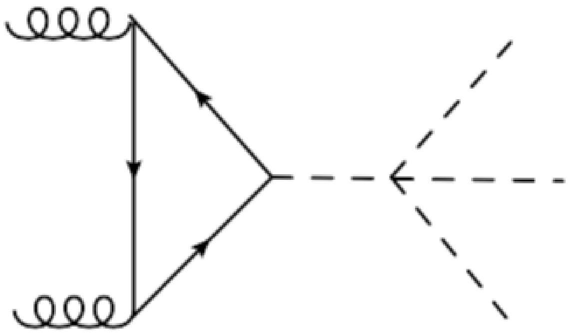
Quartic Higgs Coupling

[Agrawal, Saha, Xu, **Yu**, Yuan, **2020**]

Confirm quartic coupling

Further determine shape of Higgs potential





tri-Higgs production

SMEFT vs. hEFT

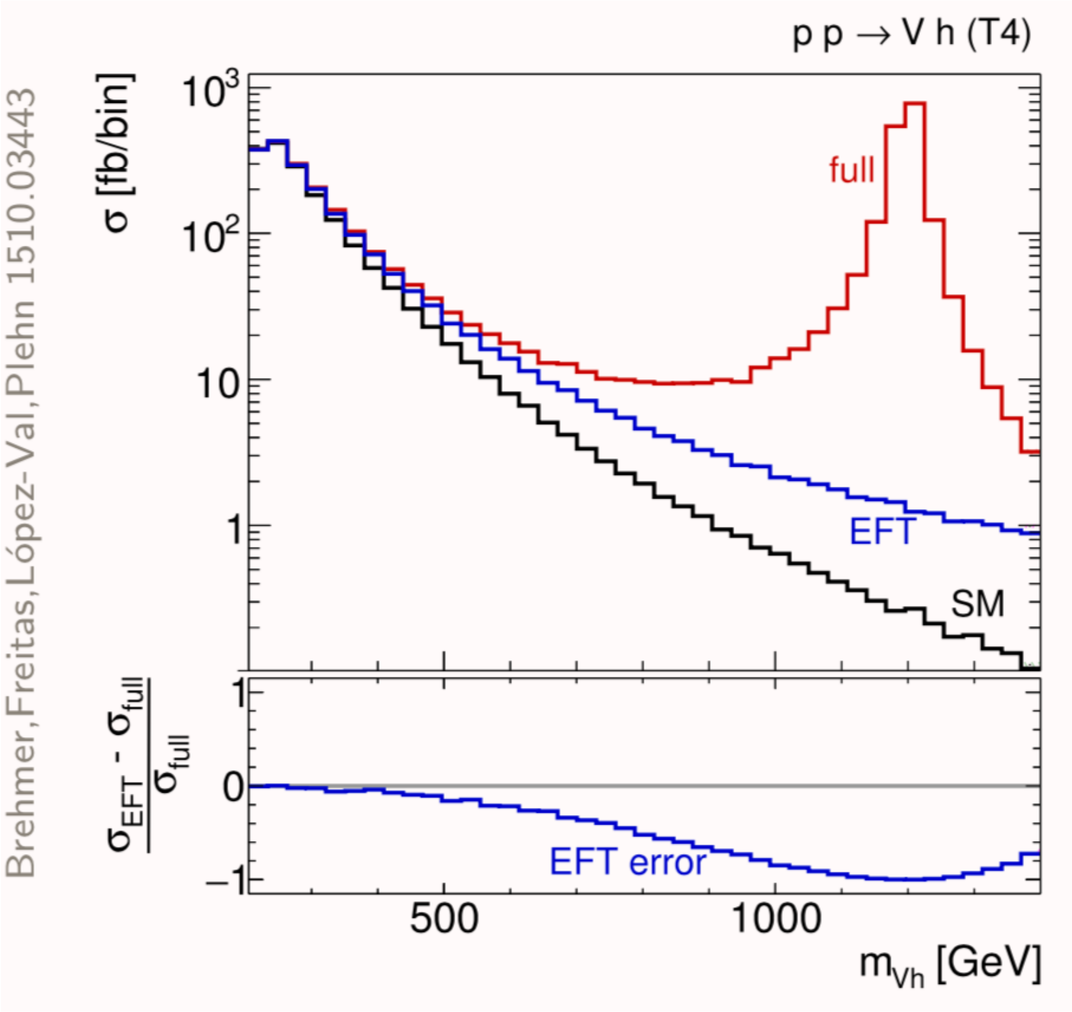
- In SMEFT, h is contained in SU(2) doublet, same as SM.
- hEFT is useful for probing non-SM Higgs potential
- hEFT is more useful for global combination – including studying hhh and hhhh couplings.

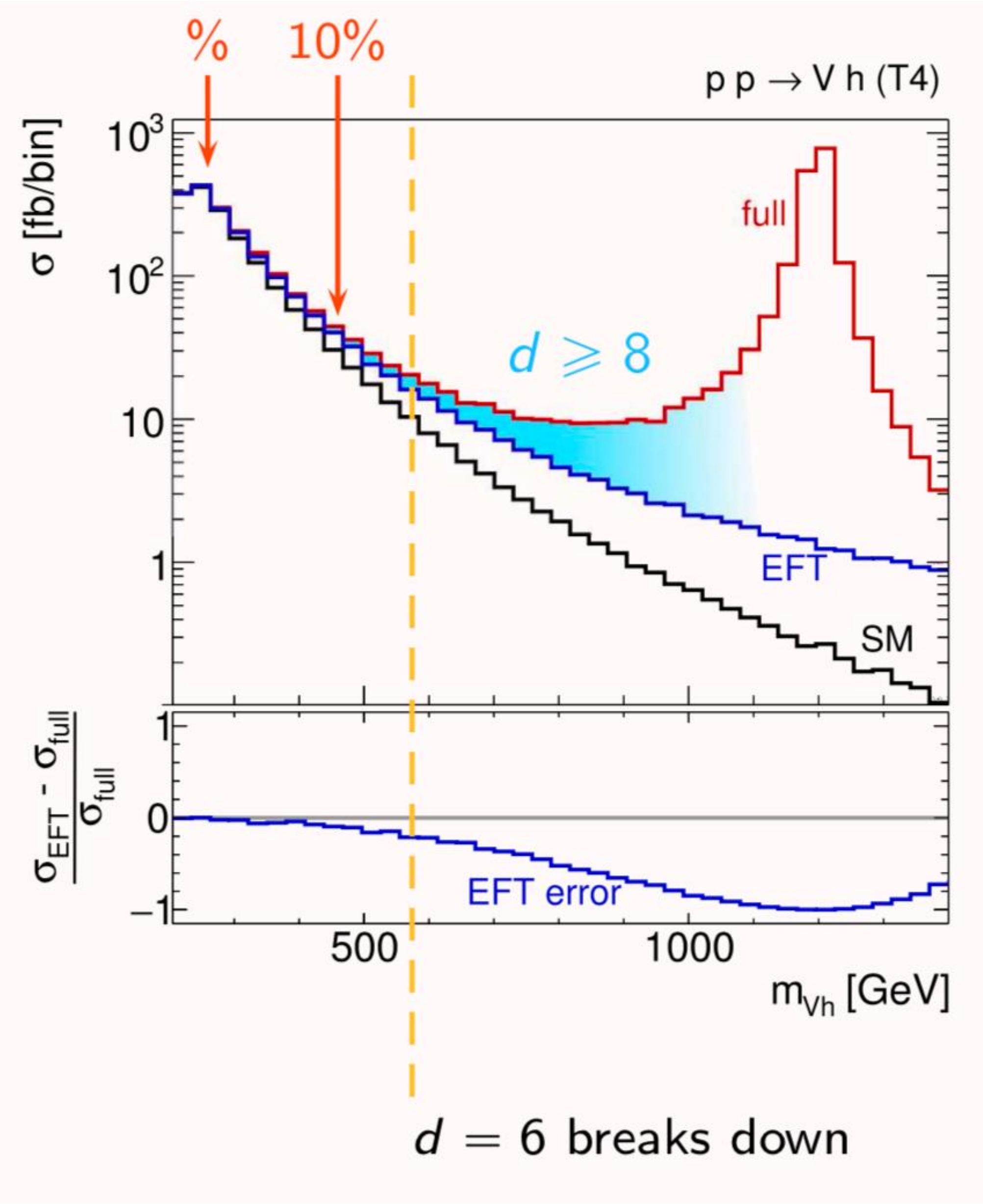
(Talk by Abraham Tishelman-Charny)

What if data sees a fast growing $VV \rightarrow VV$ cross sections in the high energy region, maybe induced by some broad resonances of UV models?

Need Dim-8 of SMEFT for Broad Resonances

Close to resonances, dim-8 contribution becomes important.



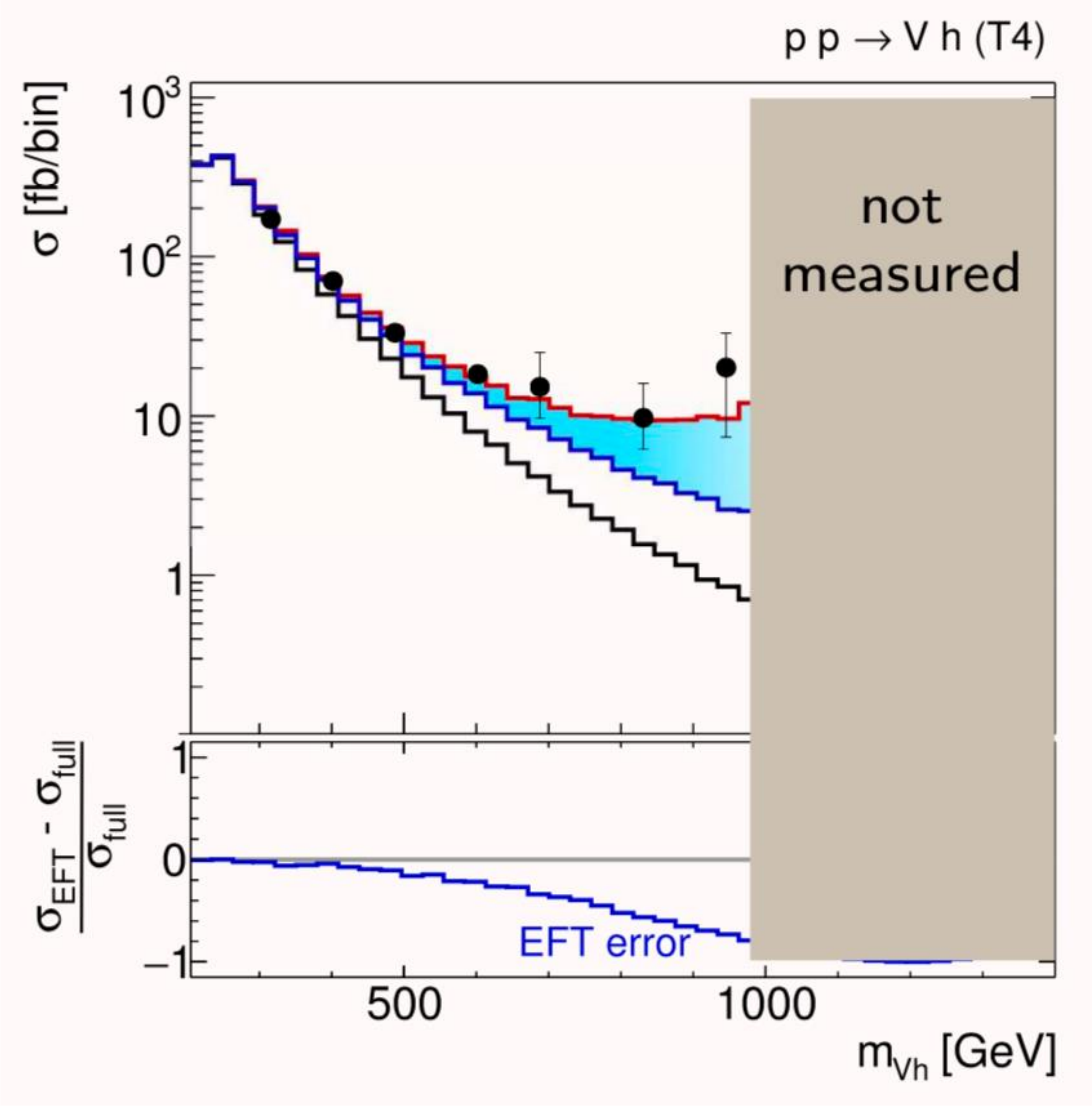


Brehmer,Freitas,L´opez-Val,Plehn 1510.03443

(Add a vector triplet under SU(2), couples to a scalar and fermion currents, and kinetically mixes with the weak gauge bosons of the SM.)

Need Dim-8 of SMEFT for Broad Resonances

Add dim-8 contribution to extend the validity range.



Given a UV model, some experimental observables require the inclusion of the square of dim-6 contribution ($1/\Lambda^4$) in the SMEFT prediction to agree with the full UV model prediction. Some others even require the inclusion of dim-8 operator contribution.

→

This information is generally not known from the bottom-up approach.

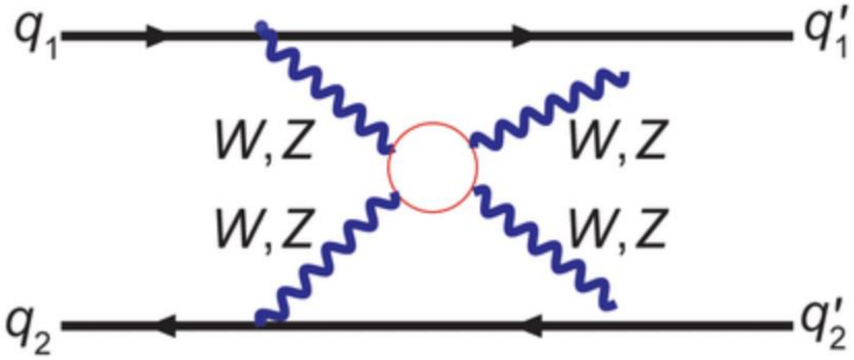
Similar to the EWPO study in the Talk by Samuel Homiller

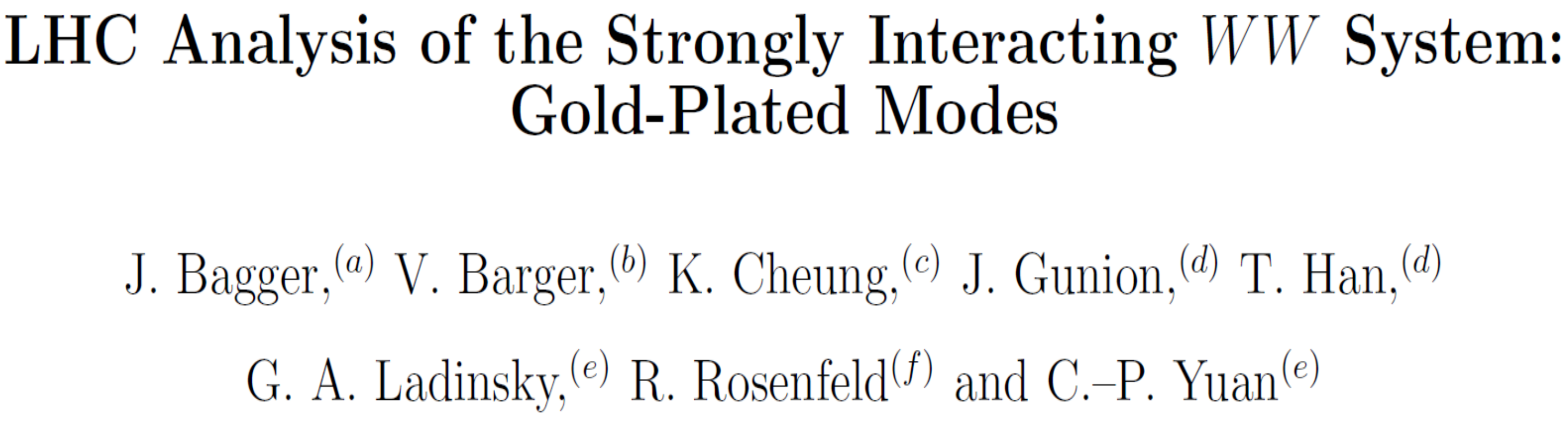
Sharing some thoughts

- Analyzing data using both SMEFT and hEFT.
- If they can describe data equally well, then the SMEFT (and hEFT) result is valid for interpreting the data.
- If they give different predictions of the data, then it is likely that higher order contributions, from the square of dim-6 operators and some dim-8 operators of SMEFT, need to be included. The result of hEFT should also be reported to compare to the data.
- Yet, it would generally be challenging to find out which dim-8 operators of SMEFT to be included without knowing the underlying UV physics?
- Yet, problems related to unitarity breakdown remain.
- Hence, it is important to keep in mind the top-down approach, based on some UV models, when data shows different agreement with SMEFT and hEFT analyses.
- Most likely, a novel idea is needed in this case.

Recall an old study

hep-ph/9504426





LHC Analysis of the Strongly Interacting WW System:
Gold-Plated Modes

J. Bagger,[a] V. Barger,[b] K. Cheung,[c] J. Gunion,[d] T. Han,[d]
G. A. Ladinsky,[e] R. Rosenfeld[f] and C.–P. Yuan[e]

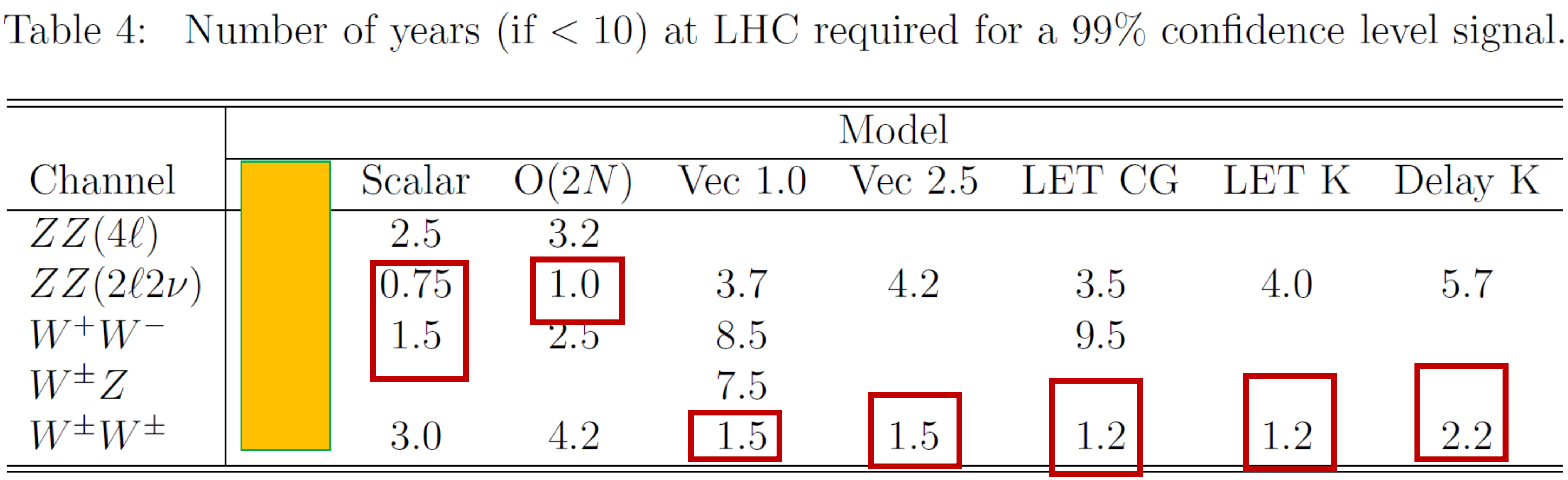


Table 4: Number of years (if < 10) at LHC required for a 99% confidence level signal.

	Model						
Channel	Scalar	O($2N$)	Vec 1.0	Vec 2.5	LET CG	LET K	Delay K
$ZZ(4\ell)$	2.5	3.2					
$ZZ(2\ell 2\nu)$	0.75	1.0	3.7	4.2	3.5	4.0	5.7
W^+W^-	1.5	2.5	8.5		9.5		
$W^\pm Z$			7.5				
$W^\pm W^\pm$	3.0	4.2	1.5	1.5	1.2	1.2	2.2

- ➢ Maybe, one can extend that “old” study with today’s higher order calculations and machine learning tools, etc., for studying broad resonances with certain spin and isospin.

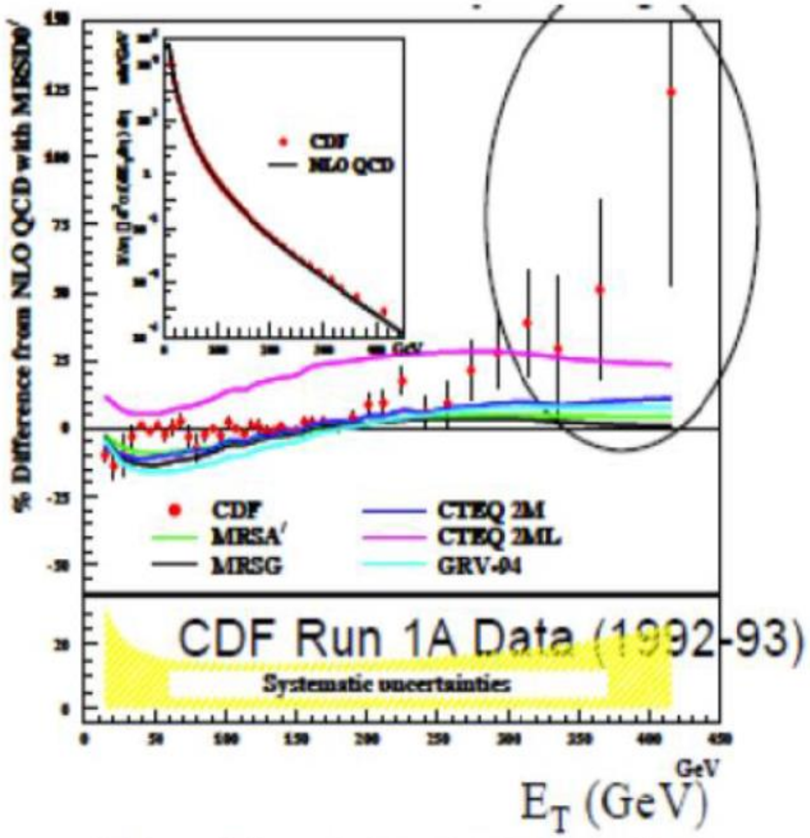
PDF matters!

- Paron distribution functions (PDFs) are needed for making theory predictions to compare with high pT data at the LHC.
- The error estimate of PDFs obtained from global analysis is important for predicting uncertainty of theory predictions induced by PDFs.

More details: See talk by C.-P. Yuan @ Pheno 2023

C T E Q

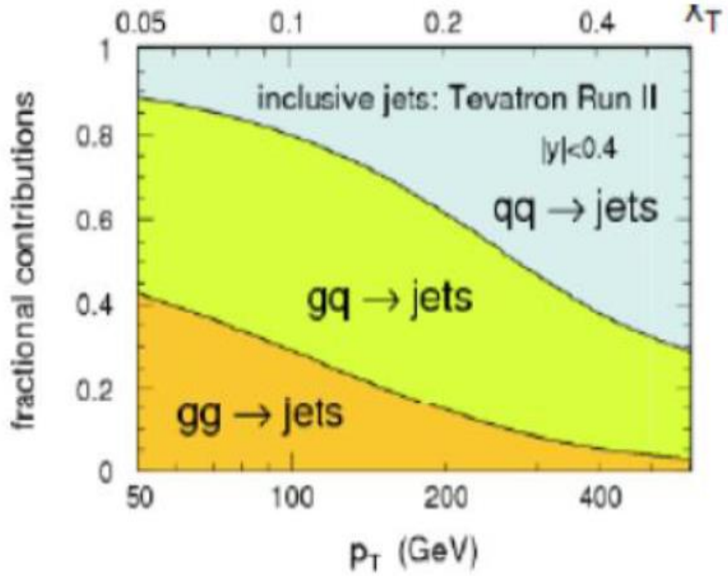
New Physics Found (in 1996) ?

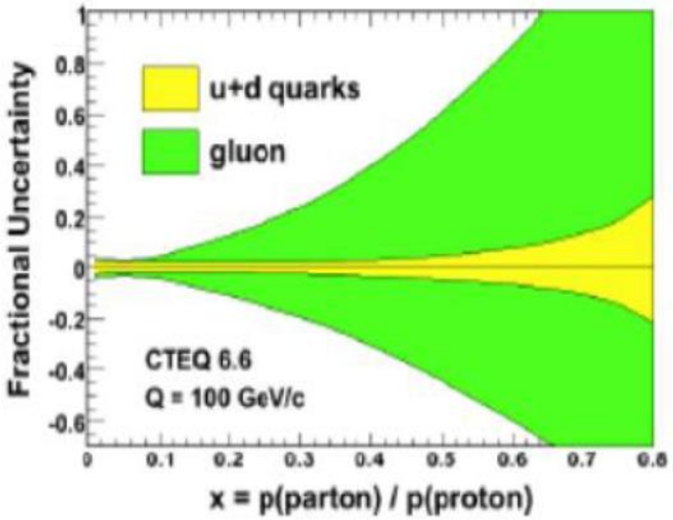


Phys. Rev. Lett. 77, 438 (1996)

High-x gluon not well known

...can be accommodated in the Standard Model





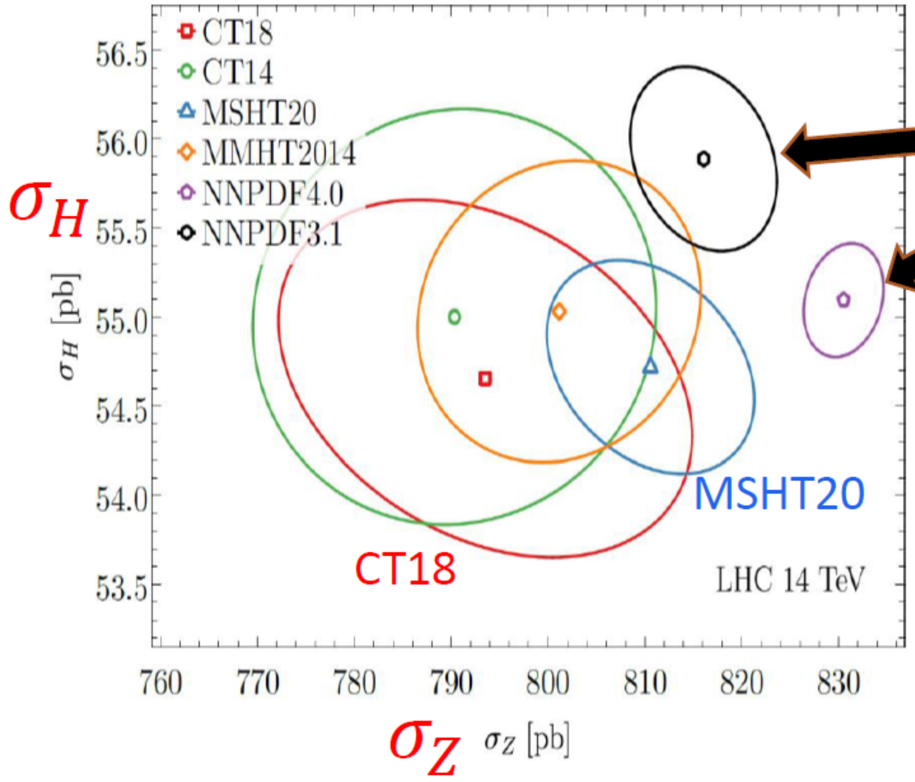
Explained by having better determined PDFs from global analysis;
no need for NP scenario yet.

J. Huston, E. Kovacs, S. Kuhlmann, J.L. Lai, J.F. Owens, D. Soper, W.K. Tung , Phys. Rev. Lett. 77 (1996) 444.

Comparing predictions from various QCD global analysis groups

C T E Q

The PDF-induced errors @ 68% CL in $gg \to h$ and $q\,\bar{q} \to Z$ NNLO cross sections



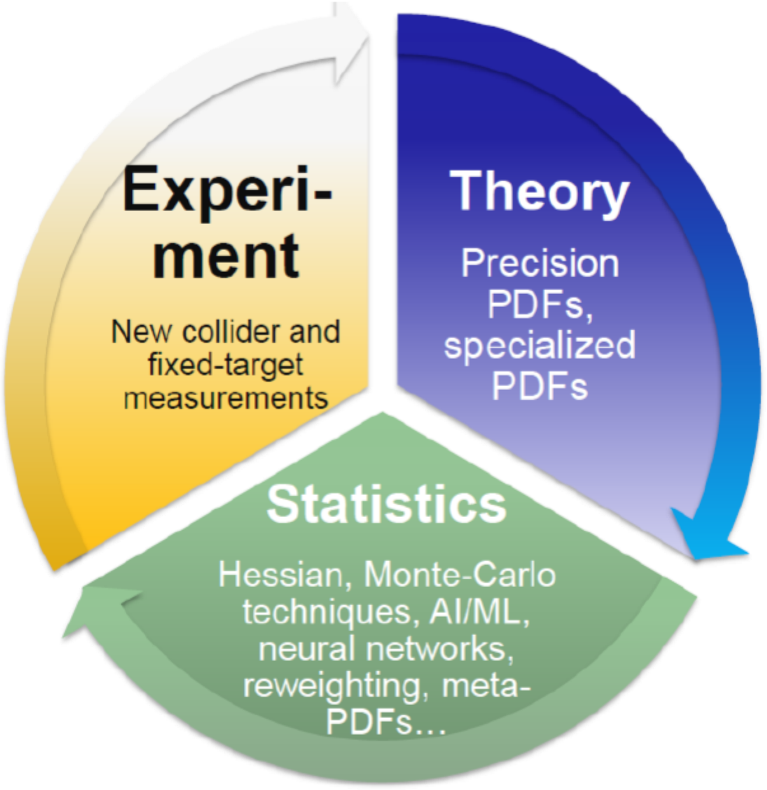
NNPDF3.1

NNPDF4.0

Their predictions do not overlap at 1σ level.

Snowmass 2021, 2203.13923

Due to different choices of


Experi-ment

New collider and fixed-target measurements

Theory

Precision PDFs, specialized PDFs

Statistics

Hessian, Monte-Carlo techniques, AI/ML, neural networks, reweighting, meta-PDFs…

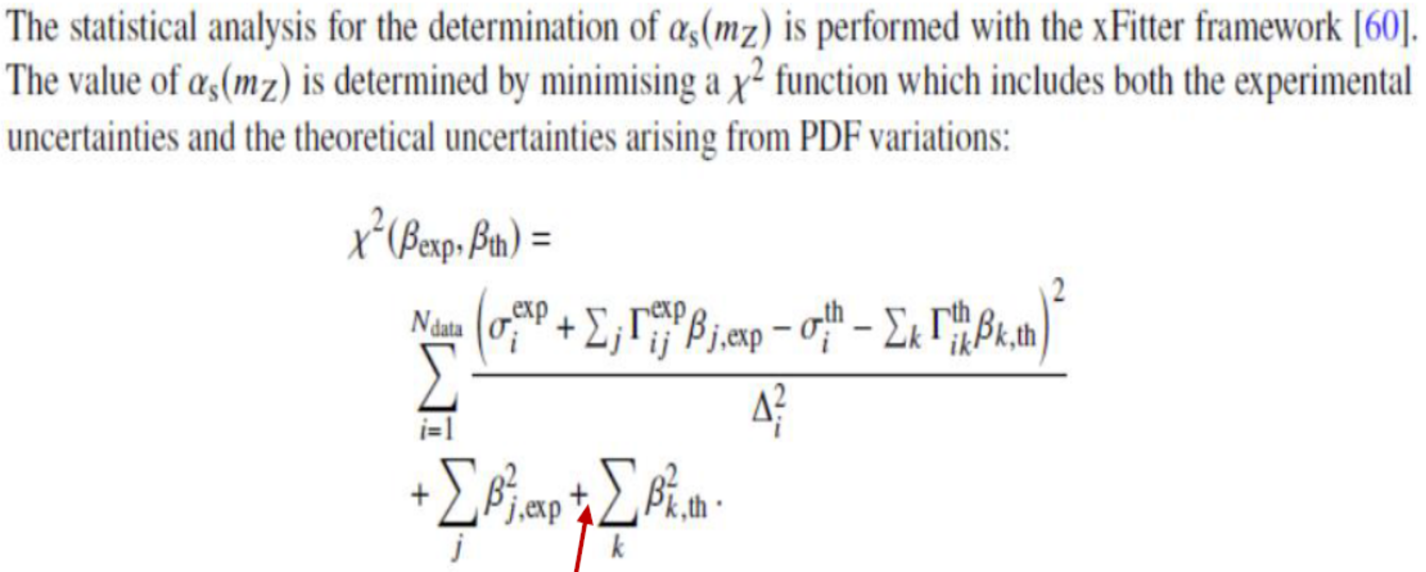
Components of a global QCD fit

Different (though mostly consistent) predictions on

- central values and error estimates of PDFs,
- parton luminosities,
- physical cross sections, and
- various correlations among PDFs and data …

Hessian profiling of CT and MSHT PDFs cannot use $\Delta\chi^2 = 1$

ATLAS-CONF-2023-015



The statistical analysis for the determination of $\alpha_s(m_Z)$ is performed with the xFitter framework [60]. The value of $\alpha_s(m_Z)$ is determined by minimising a χ^2 function which includes both the experimental uncertainties and the theoretical uncertainties arising from PDF variations:

$$\chi^2(\beta_{\rm exp},\beta_{\rm th}) = \sum_{i=1}^{N_{\rm data}} \frac{\left(\sigma_i^{\rm exp} + \sum_j \Gamma_{ij}^{\rm exp}\beta_{j,\rm exp} - \sigma_i^{\rm th} - \sum_k \Gamma_{ik}^{\rm th}\beta_{k,\rm th}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\rm exp}^2 + \sum_k \beta_{k,\rm th}^2 .$$

arXiv: 1907.12177

arXiv:1912.10053

- xFitter profiling uses $\Delta\chi^2 = 1$, by default.
- For CT (or MSHT) PDFs, using $\Delta\chi^2 = 1$ in profiling is equivalent to assigning a weight of about 30 (or 10) to the new data included in the fit. Hence, it will overestimate the impact of new data.
- CT: $T^2 \sim 30$; MSHT: $T^2 \sim 10$

profiling of CT and MSHT PDFs requires to include a tolerance factor $T^2 > 10$ as in the ePump code

When profiling a new experiment with the prior imposed on PDF nuisance parameters $\lambda_{\alpha,th}$:

$$\chi^2(\vec\lambda_{\rm exp},\vec\lambda_{\rm th}) = \sum_{i=1}^{N_{pt}} \frac{\left[D_i + \sum_\alpha \beta_{i,\alpha}^{\rm exp}\lambda_{\alpha,\rm exp} - T_i - \sum_\alpha \beta_{i,\alpha}^{\rm th}\lambda_{\alpha,\rm th}\right]^2}{s_i^2} + \sum_\alpha \lambda_{\alpha,\rm exp}^2 + \sum_\alpha T^2\lambda_{\alpha,\rm th}^2 .$$

$$\beta_{i,\alpha}^{\rm th} = \frac{T_i(f_\alpha^+) - T_i(f_\alpha^-)}{2},$$

new experiment

priors on expt. systematics and PDF params

Machine Learning in CTEQ-TEA analysis: SMEFT

It is a simultaneous fit of PDFs and SMEFT couplings.

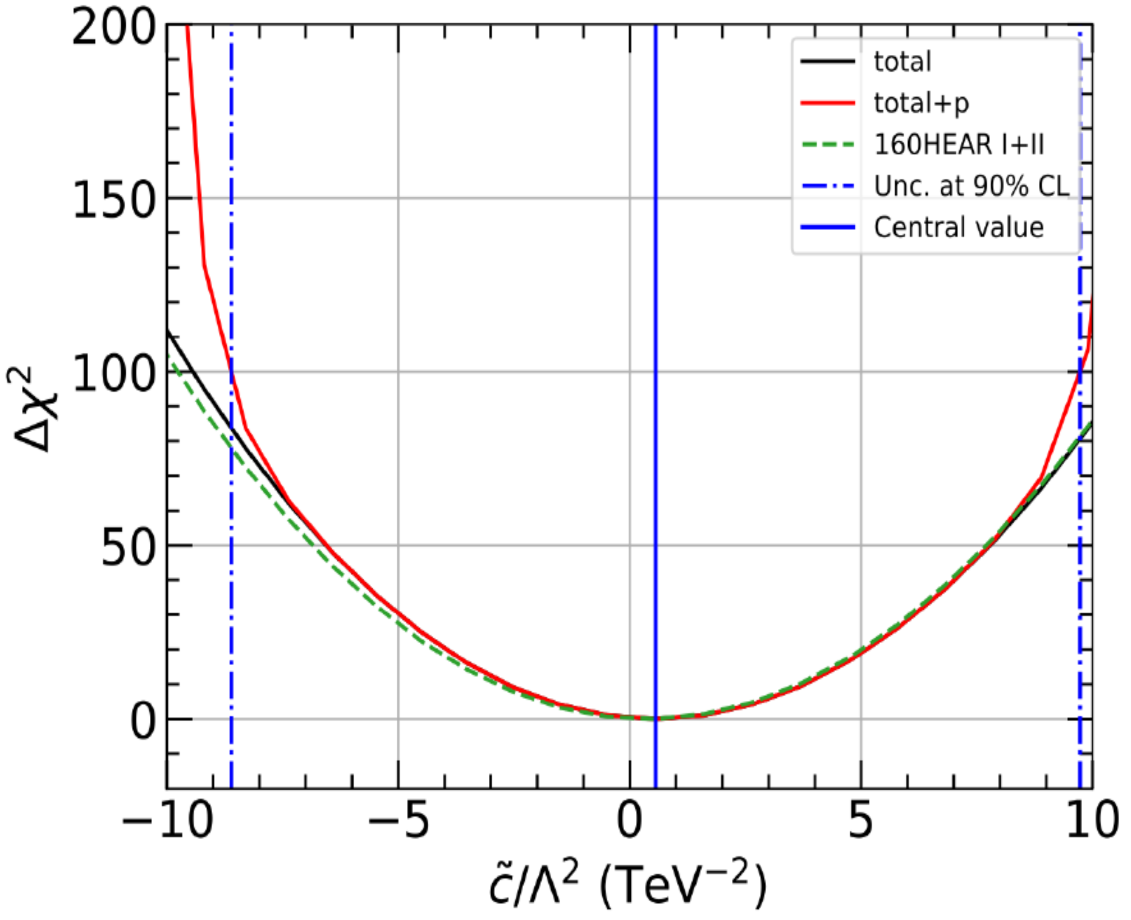
The machine-learning (ML) approach ensures efficient scans over the full PDF parameter space, especially the Lagrange Multiplier scans of χ^2, as demonstrated for a study on the constraint of SMEFT couplings.

arXiv:2201.06586

Lepton-quark contact interactions of SMEFT

$$\begin{aligned}\mathcal{L}_{\mathrm{SMEFT}} &= \mathcal{L}_{\mathrm{SM}} + \sum_{i,j} \frac{c_{ij}}{\Lambda^2} (\bar{q}_i \gamma_\mu q_i)(\bar{l}_j \gamma^\mu l_j) \\ &= \mathcal{L}_{\mathrm{SM}} + \frac{\tilde{c}}{\Lambda^2} \sum_{i,j} e_{q_i} e_{l_j} (\bar{q}_i \gamma_\mu q_i)(\bar{l}_j \gamma^\mu l_j)\end{aligned}$$

LM scans on SMEFT couplings



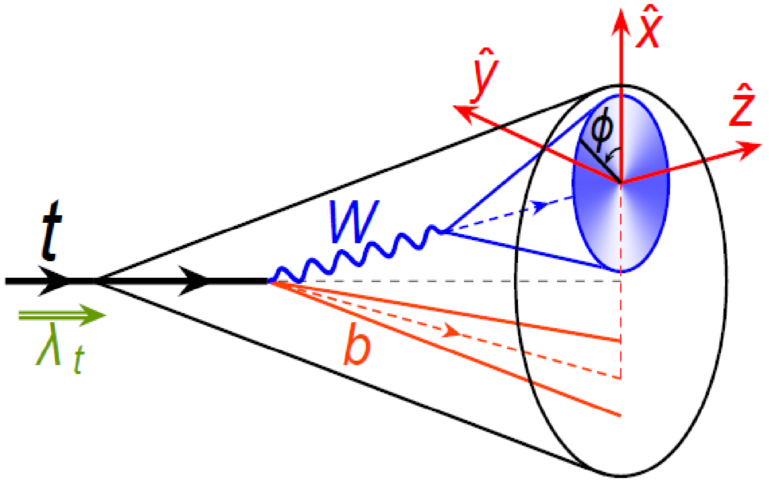
Final remarks

- This is a very productive conference – with plenty of discussions, and many well-prepared talks which not only nicely present the results of recent data and/or theory predictions, but also many well-thought-out physics questions.
- Thanks again to all the speakers.
- Special thanks go to the organizers who brought us together at this beautiful site of UCSD!

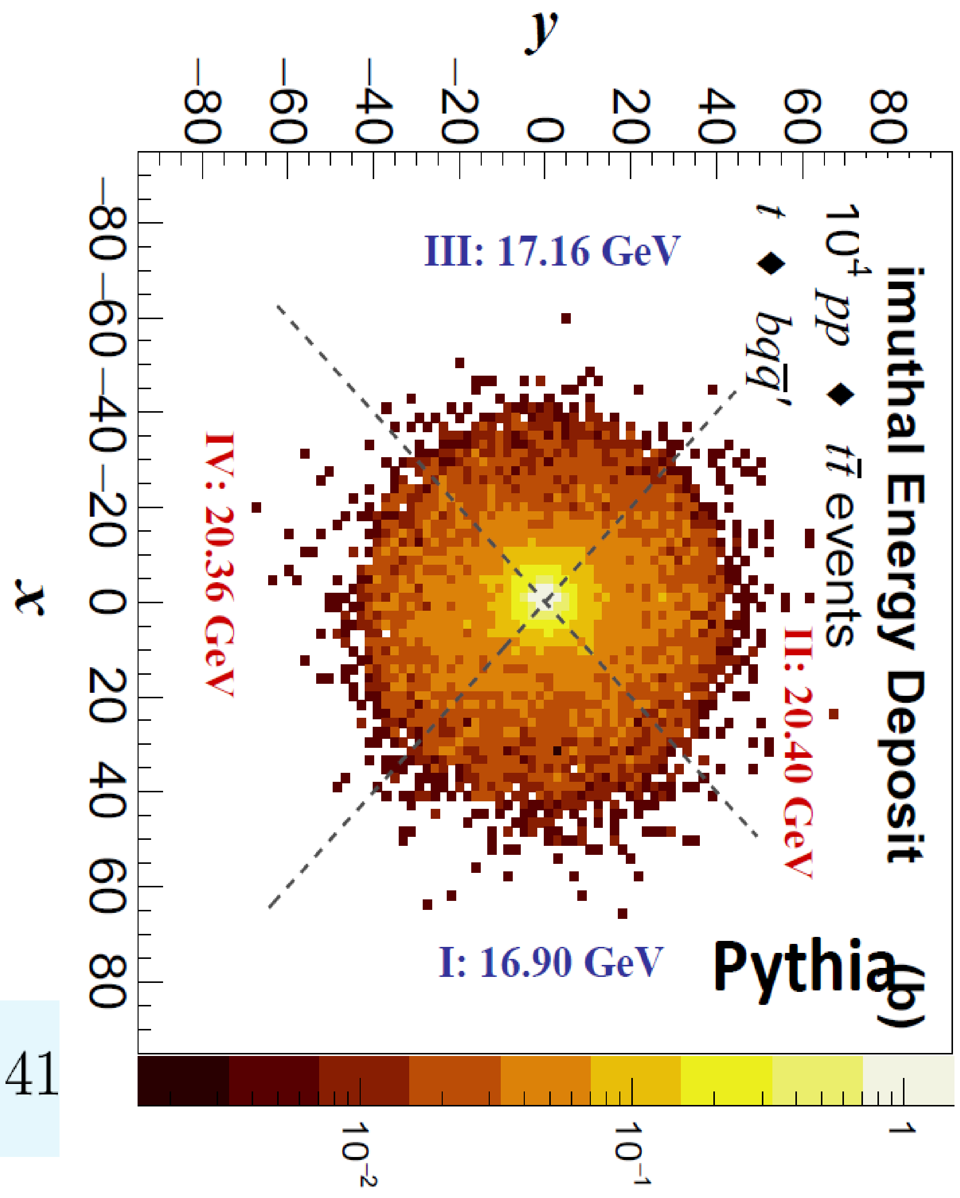
Backup slides

Pythia simulation

Pythia simulation: $pp \to t\bar{t}$ production (unpolarized top)



$$\frac{\mathrm{d}E}{\mathrm{d}\phi} = \frac{E_{\text{tot}}}{2\pi}\left[1 + \xi \cos 2\phi\right]$$



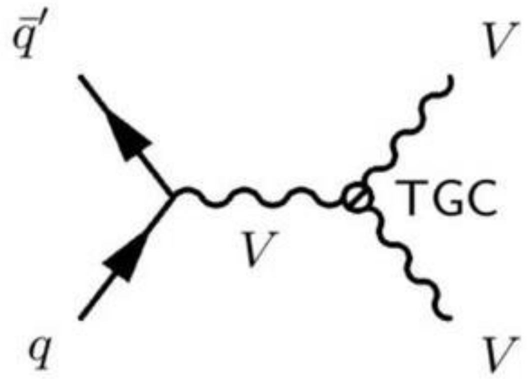
SM prediction: $\xi = \xi(\lambda_t) = 0.145(\lambda_t - 1)$

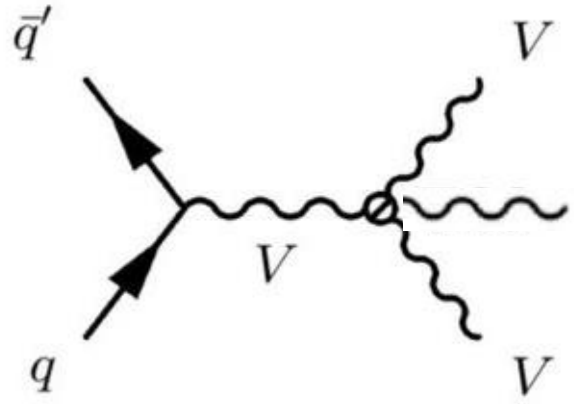
Pythia simulation: $\xi = \frac{\pi}{2} \cdot \frac{(E_1 + E_3) - (E_2 + E_4)}{(E_1 + E_3) + (E_2 + E_4)} = -0.141$

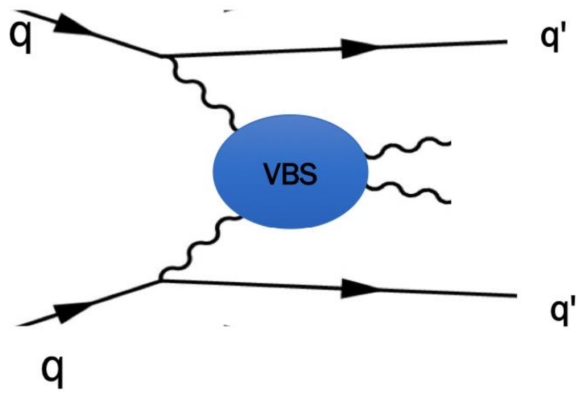
Agrees with SM prediction for $\lambda_t = 0$: unpolarized top

New Physics for Multiboson

Various new physics models







Extended gauge sector

- U(1) extensions
- G221
- Pati-Salam
- …

Extended Higgs sector

- Higgs Singlet
- Higgs Doublet
- Higgs Triplet
- …

Naturalness scenarios

- MSSM
- Randall-Sundrum
- Composite Higgs

Higher Dim SMEFT Operators

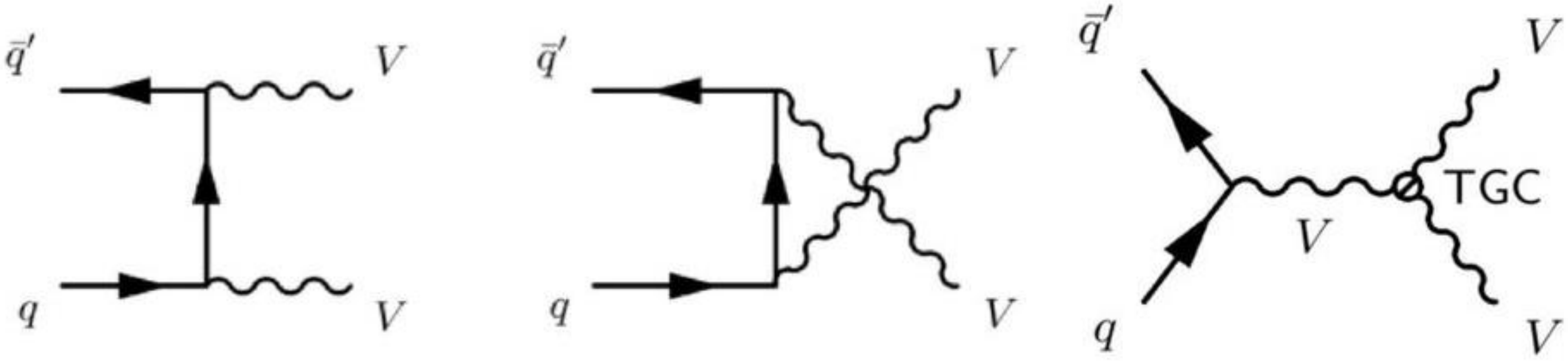
Expect much smaller effects for dim > 7

$$|\mathcal{A}|^2 \sim \left| A_{\rm SM} + \frac{A_{\rm dim-6}}{\Lambda^2} + \frac{A_{\rm dim-8}}{\Lambda^4} + \ldots \right|^2$$

$$\sim \boxed{|A_{\rm SM}|^2 + \frac{2}{\Lambda^2} A_{\rm dim-6} A^*_{\rm SM}} + \frac{1}{\Lambda^4} |A_{\rm dim-6}|^2 + \frac{2}{\Lambda^4} A_{\rm dim-8} A^*_{\rm SM}$$

Some LHC data start to probe dim-8.

Leading operators appear as dim-8 in some processes.



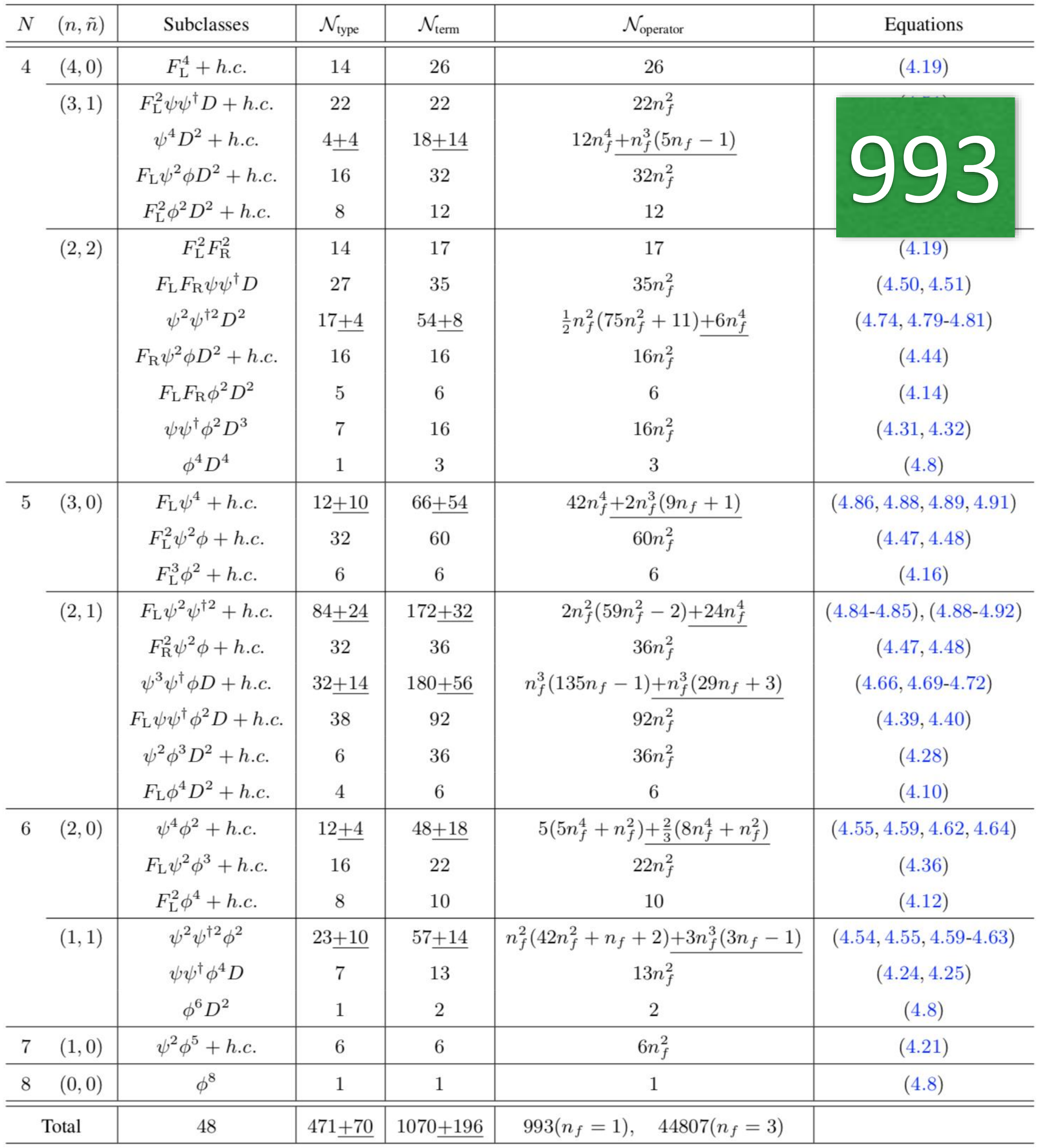
Neutral triple gauge boson ZZZ, ZZA, ZAA couplings

Dim-8 SMEFT

Complete/independent dim-8 operator basis

[Li, Ren, Shu, Xiao, Yu, Zheng, 2005.00008]

[Murphy, 2005.00059]



N	$(n,\tilde{n})$	Subclasses	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$	$\mathcal{N}_{\text{operator}}$	Equations
4	$(4,0)$	$F_{\rm L}^4+h.c.$	14	26	26	(4.19)
	$(3,1)$	$F_{\rm L}^2\psi\psi^\dagger D+h.c.$	22	22	$22n_f^2$	[illegible]
		$\psi^4D^2+h.c.$	$4\underline{+4}$	$18\underline{+14}$	$12n_f^4\underline{+n_f^3(5n_f-1)}$	[illegible]
		$F_{\rm L}\psi^2\phi D^2+h.c.$	16	32	$32n_f^2$	[illegible]
		$F_{\rm L}^2\phi^2D^2+h.c.$	8	12	12	[illegible]
	$(2,2)$	$F_{\rm L}^2F_{\rm R}^2$	14	17	17	(4.19)
		$F_{\rm L}F_{\rm R}\psi\psi^\dagger D$	27	35	$35n_f^2$	(4.50, 4.51)
		$\psi^2\psi^{\dagger2}D^2$	$17\underline{+4}$	$54\underline{+8}$	$\frac{1}{2}n_f^2(75n_f^2+11)\underline{+6n_f^4}$	(4.74, 4.79-4.81)
		$F_{\rm R}\psi^2\phi D^2+h.c.$	16	16	$16n_f^2$	(4.44)
		$F_{\rm L}F_{\rm R}\phi^2D^2$	5	6	6	(4.14)
		$\psi\psi^\dagger\phi^2D^3$	7	16	$16n_f^2$	(4.31, 4.32)
		ϕ^4D^4	1	3	3	(4.8)
5	$(3,0)$	$F_{\rm L}\psi^4+h.c.$	$12\underline{+10}$	$66\underline{+54}$	$42n_f^4\underline{+2n_f^3(9n_f+1)}$	(4.86, 4.88, 4.89, 4.91)
		$F_{\rm L}^2\psi^2\phi+h.c.$	32	60	$60n_f^2$	(4.47, 4.48)
		$F_{\rm L}^3\phi^2+h.c.$	6	6	6	(4.16)
	$(2,1)$	$F_{\rm L}\psi^2\psi^{\dagger2}+h.c.$	$84\underline{+24}$	$172\underline{+32}$	$2n_f^2(59n_f^2-2)\underline{+24n_f^4}$	(4.84-4.85), (4.88-4.92)
		$F_{\rm R}^2\psi^2\phi+h.c.$	32	36	$36n_f^2$	(4.47, 4.48)
		$\psi^3\psi^\dagger\phi D+h.c.$	$32\underline{+14}$	$180\underline{+56}$	$n_f^3(135n_f-1)\underline{+n_f^3(29n_f+3)}$	(4.66, 4.69-4.72)
		$F_{\rm L}\psi\psi^\dagger\phi^2D+h.c.$	38	92	$92n_f^2$	(4.39, 4.40)
		$\psi^2\phi^3D^2+h.c.$	6	36	$36n_f^2$	(4.28)
		$F_{\rm L}\phi^4D^2+h.c.$	4	6	6	(4.10)
6	$(2,0)$	$\psi^4\phi^2+h.c.$	$12\underline{+4}$	$48\underline{+18}$	$5(5n_f^4+n_f^2)\underline{+\frac{2}{3}(8n_f^4+n_f^2)}$	(4.55, 4.59, 4.62, 4.64)
		$F_{\rm L}\psi^2\phi^3+h.c.$	16	22	$22n_f^2$	(4.36)
		$F_{\rm L}^2\phi^4+h.c.$	8	10	10	(4.12)
	$(1,1)$	$\psi^2\psi^{\dagger2}\phi^2$	$23\underline{+10}$	$57\underline{+14}$	$n_f^2(42n_f^2+n_f+2)\underline{+3n_f^3(3n_f-1)}$	(4.54, 4.55, 4.59-4.63)
		$\psi\psi^\dagger\phi^4D$	7	13	$13n_f^2$	(4.24, 4.25)
		ϕ^6D^2	1	2	2	(4.8)
7	$(1,0)$	$\psi^2\phi^5+h.c.$	6	6	$6n_f^2$	(4.21)
8	$(0,0)$	ϕ^8	1	1	1	(4.8)
Total		48	$471\underline{+70}$	$1070\underline{+196}$	$993(n_f=1),\quad 44807(n_f=3)$	

993

TGC/QGC relevant operators

$$\widetilde{B}_{\mu\nu}\langle D^\mu D_\alpha W^{\alpha\beta}W_\beta{}^\nu\rangle$$

$$\widetilde{B}_{\mu\nu}\langle D_\beta D_\alpha W^{\alpha\mu}W^{\beta\nu}\rangle$$

$$\widetilde{B}_{\mu\nu}\langle D_\alpha W^{\alpha\mu}D_\beta W^{\beta\nu}\rangle$$

$$\widetilde{B}_{\mu\nu}\langle D_\alpha W^{\alpha\beta}D_\beta W^{\mu\nu}\rangle$$

$$\widetilde{B}_{\mu\nu}\langle D_\alpha W^{\alpha\beta}D^\mu W_\beta{}^\nu\rangle$$

$$\mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right]\times\left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$[B_{\mu\nu}B^{\mu\nu}]\times\left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}D^\mu\Phi\right]\times B^{\beta\nu}$$

$$\left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu}D^\nu\Phi\right]$$

$$\mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right]\times\left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$[B_{\mu\nu}B^{\nu\beta}]\times\left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}D^\nu\Phi\right]\times B^{\beta\mu}+\mathrm{h.c.}$$

C.-P. Yuan @ MBI2023

SMEFT is not Enough

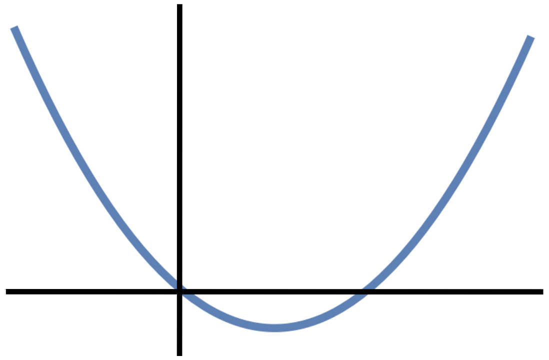
Not all of these scenarios can be described in SMEFT

[Agrawal, Saha, Xu, **Yu**, Yuan, 1907.02078]

Also [Falkowski, Rattazzi 2019]
[Cohen, Craig, Lu, Sutherland, 2021]
[Gomez-Ambrosio, etc, 2022]

- Electroweak symmetry breaking by Higgs mechanism or not?

Tadpole-induced Higgs

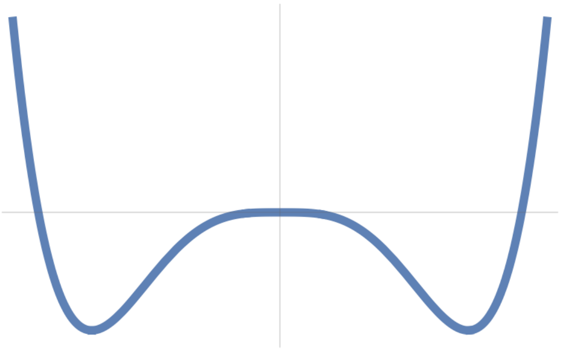


$$V(\phi) = -\mu^3\sqrt{\phi^\dagger\phi} + m^2\phi^\dagger\phi$$

Partly by Condensation

- Non-decoupling: New particle obtains mass from Higgs VEV or not?

Coleman Weinberg Higgs



$$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2\log\frac{\phi^\dagger\phi}{\mu^2}$$

Classical scale invariance

Similarly, 2HDM non-decoupling scenarios

Higgs EFT

EW chiral Lagrangian | EWChL with light Higgs | Higgs EFT

LO and NLO boson

2012

NLO fermion sector

Full NLO and NNLO

LO Lagrangian

[Weinberg, 1979]

NLO Bosonic Lagrangian

[Appelquist, Bernard, 1980]

[Longhitano, 1980, 1981]

[Feruglio, 1993]

NLO Fermionic Lagrangian

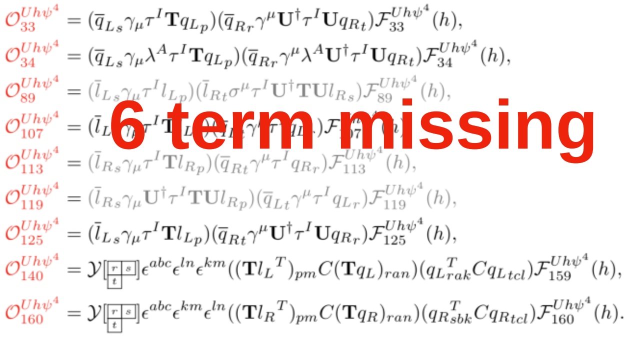
[Buchalla, Cata, Krause, 2014]

[Pich, Rosell, Santos, Sanz-Cillero, 2015, 2018]

Complete NLO Lagrangian (p4)

237 (8595) operators for one (three)

[Sun, Xiao, **Yu**, 2206.07722]



$$\mathcal{O}_{33}^{Uh\psi^4} = (\bar{q}_{L_s}\gamma_\mu\tau^I\mathbf{T}q_{L_p})(\bar{q}_{R_r}\gamma^\mu\mathbf{U}^\dagger\tau^I\mathbf{U}q_{R_t})\mathcal{F}_{33}^{Uh\psi^4}(h),$$

$$\mathcal{O}_{34}^{Uh\psi^4} = (\bar{q}_{L_s}\gamma_\mu\lambda^A\tau^I\mathbf{T}q_{L_p})(\bar{q}_{R_r}\gamma^\mu\lambda^A\mathbf{U}^\dagger\tau^I\mathbf{U}q_{R_t})\mathcal{F}_{34}^{Uh\psi^4}(h),$$

$$\mathcal{O}_{89}^{Uh\psi^4} = (\bar{l}_{L_s}\gamma_\mu\tau^I l_{L_p})(\bar{l}_{R_t}\sigma^\mu\tau^I\mathbf{U}^\dagger\mathbf{T}\mathbf{U}l_{R_s})\mathcal{F}_{89}^{Uh\psi^4}(h),$$

$\mathcal{O}_{107}^{Uh\psi^4} = (\bar{l}_{L}$ [illegible]

$$\mathcal{O}_{113}^{Uh\psi^4} = (\bar{l}_{R_s}\gamma_\mu\tau^I\mathbf{T}l_{R_p})(\bar{q}_{R_t}\gamma^\mu\tau^I q_{R_r})\mathcal{F}_{113}^{Uh\psi^4}(h),$$

$$\mathcal{O}_{119}^{Uh\psi^4} = (\bar{l}_{R_s}\gamma_\mu\mathbf{U}^\dagger\tau^I\mathbf{T}\mathbf{U}l_{R_p})(\bar{q}_{L_t}\gamma^\mu\tau^I q_{L_r})\mathcal{F}_{119}^{Uh\psi^4}(h),$$

$$\mathcal{O}_{125}^{Uh\psi^4} = (\bar{l}_{L_s}\gamma_\mu\tau^I\mathbf{T}l_{L_p})(\bar{q}_{R_t}\gamma^\mu\mathbf{U}^\dagger\tau^I\mathbf{U}q_{R_r})\mathcal{F}_{125}^{Uh\psi^4}(h),$$

$$\mathcal{O}_{140}^{Uh\psi^4} = \mathcal{Y}\left[\begin{array}{|c|c|}\hline r & s \\ \hline t & \\ \cline{1-1}\end{array}\right]\epsilon^{abc}\epsilon^{ln}\epsilon^{km}((\mathbf{T}l_L{}^T)_{pm}C(\mathbf{T}q_L)_{ran})(q_{L\,rak}^T C q_{L\,tcl})\mathcal{F}_{159}^{Uh\psi^4}(h),$$

$$\mathcal{O}_{160}^{Uh\psi^4} = \mathcal{Y}\left[\begin{array}{|c|c|}\hline r & s \\ \hline t & \\ \cline{1-1}\end{array}\right]\epsilon^{abc}\epsilon^{km}\epsilon^{ln}((\mathbf{T}l_R{}^T)_{pm}C(\mathbf{T}q_R)_{ran})(q_{R\,sbk}^T C q_{R\,tcl})\mathcal{F}_{160}^{Uh\psi^4}(h).$$

6 term missing

Complete NNLO Lagrangian (p5, p6)

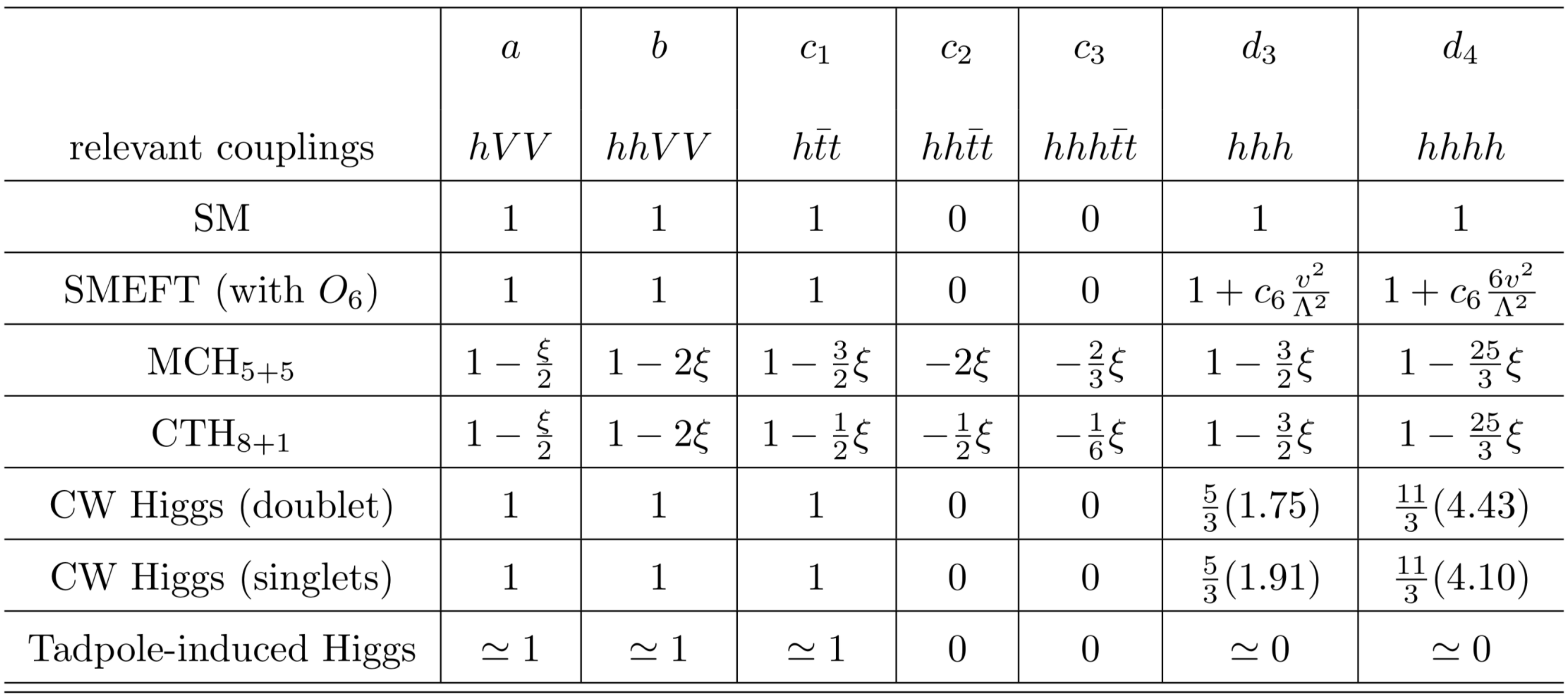
11506(1927574) NNLO operators with flavor number 1(3).

[Sun, Xiao, **Yu**, 2110.14939]

SMEFT vs HEFT

- Correlation between tri-/quartic couplings

[Agrawal, Saha, Xu, **Yu**, Yuan, 1907.02078]



	a	b	c_1	c_2	c_3	d_3	d_4
relevant couplings	hVV	$hhVV$	$h\bar{t}t$	$hh\bar{t}t$	$hhh\bar{t}t$	hhh	$hhhh$
SM	1	1	1	0	0	1	1
SMEFT (with O_6)	1	1	1	0	0	$1+c_6\frac{v^2}{\Lambda^2}$	$1+c_6\frac{6v^2}{\Lambda^2}$
MCH_{5+5}	$1-\frac{\xi}{2}$	$1-2\xi$	$1-\frac{3}{2}\xi$	-2ξ	$-\frac{2}{3}\xi$	$1-\frac{3}{2}\xi$	$1-\frac{25}{3}\xi$
CTH_{8+1}	$1-\frac{\xi}{2}$	$1-2\xi$	$1-\frac{1}{2}\xi$	$-\frac{1}{2}\xi$	$-\frac{1}{6}\xi$	$1-\frac{3}{2}\xi$	$1-\frac{25}{3}\xi$
CW Higgs (doublet)	1	1	1	0	0	$\frac{5}{3}(1.75)$	$\frac{11}{3}(4.43)$
CW Higgs (singlets)	1	1	1	0	0	$\frac{5}{3}(1.91)$	$\frac{11}{3}(4.10)$
Tadpole-induced Higgs	$\simeq 1$	$\simeq 1$	$\simeq 1$	0	0	$\simeq 0$	$\simeq 0$

- Curvature in Higgs field space

[Alonso, Jenkins, Manohar, **2016**]

[Cohen, Craig, Lu, Sutherland, **2020**]