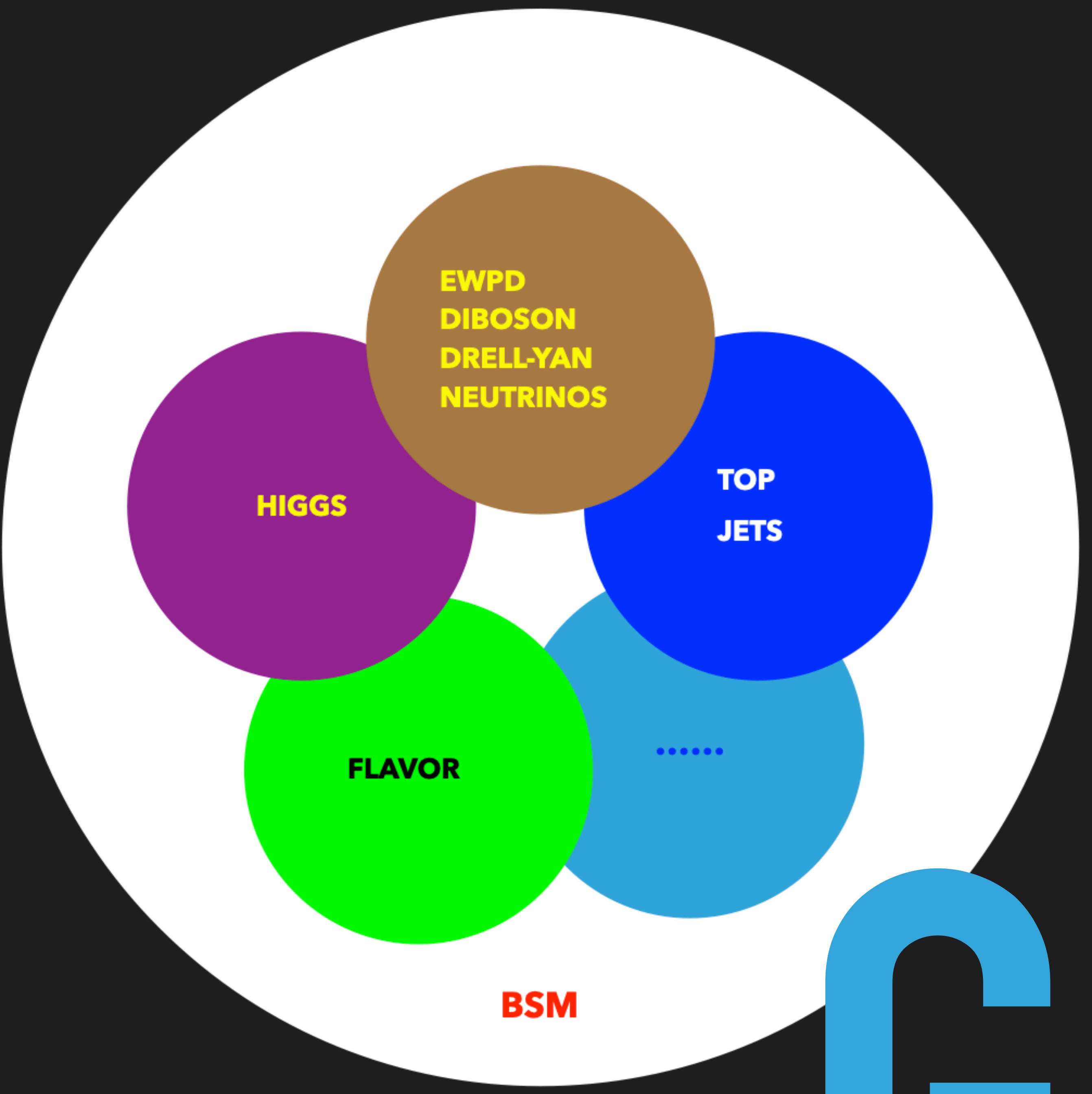


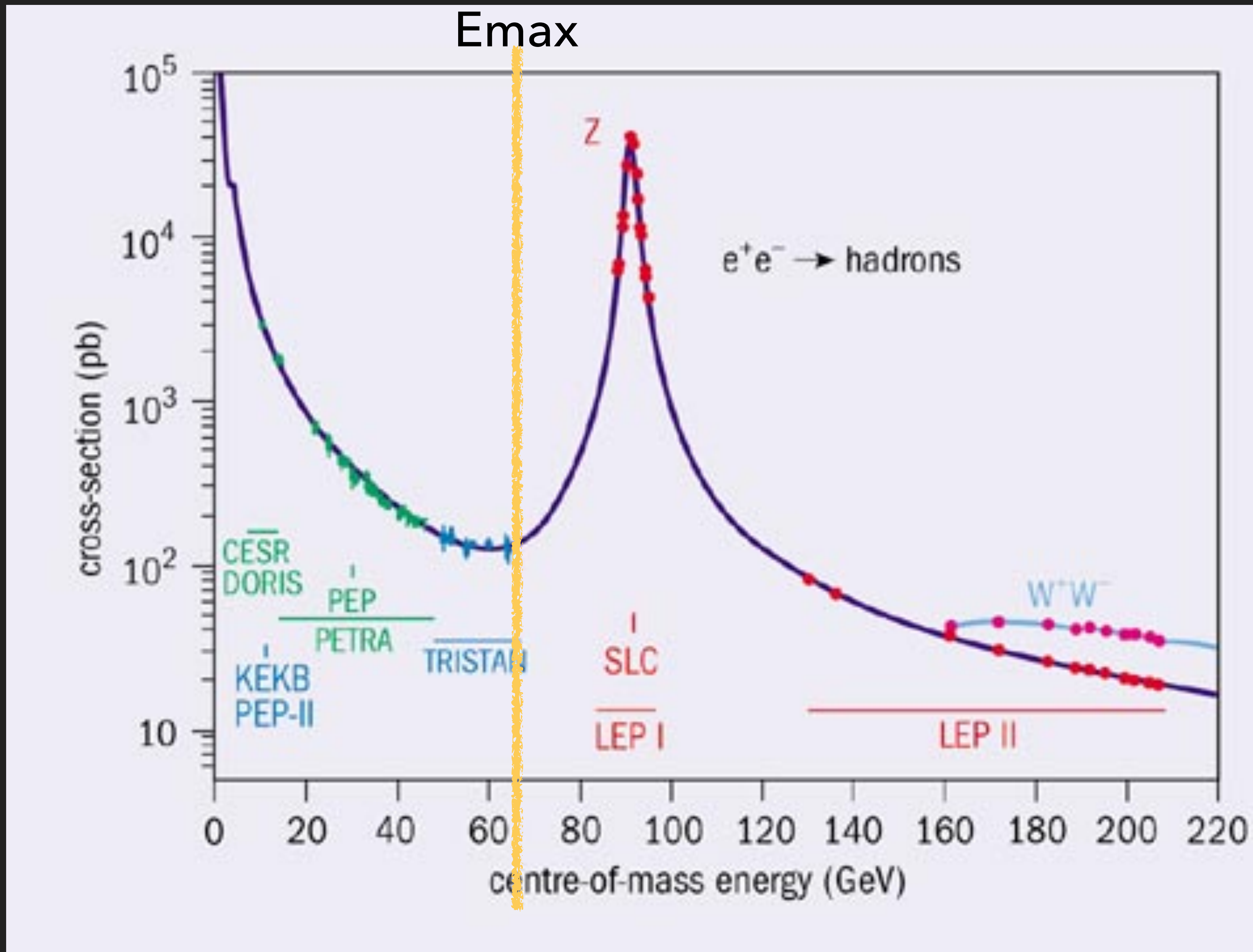
GLOBAL FITS

OSCAR ÉBOLI

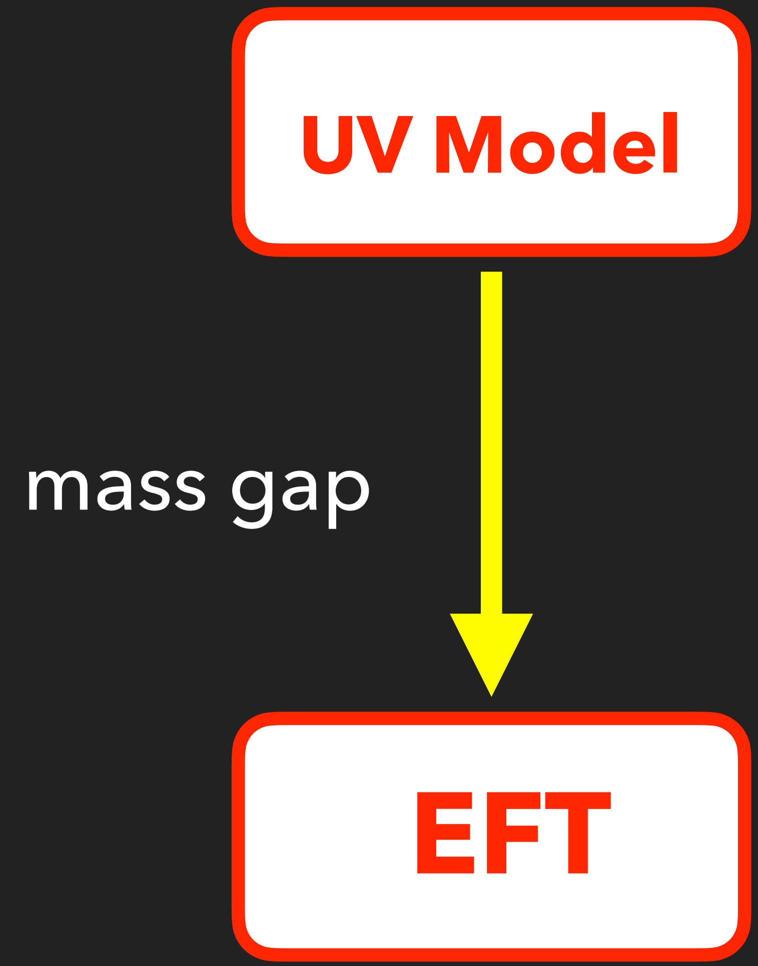
UNIVERSIDADE DE SÃO PAULO

October 29, 2020

- We have the Higgs and no clear sign of new physics
- Hypothesis: there is a large mass gap
- To look for footprints of the UV model we can use EFT



- Hypothesis: the SM gauge symmetry is realized linearly
- At "low energies" we write $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{j\geq 5} \frac{f_{j,k}}{\Lambda^{j-4}} \mathcal{O}_j^{(k)}$



- SMEFT is a consistent QFT
- SMEFT: model independent analysis (bottom-up approach)
- Linear realization of symmetry leads to correlations between anomalous couplings

$(D^\mu\Phi)^\dagger W^a_{\mu\nu}\sigma^a D^\nu\Phi$ gives rise to vertices HVV, VVV, VVVV, ...

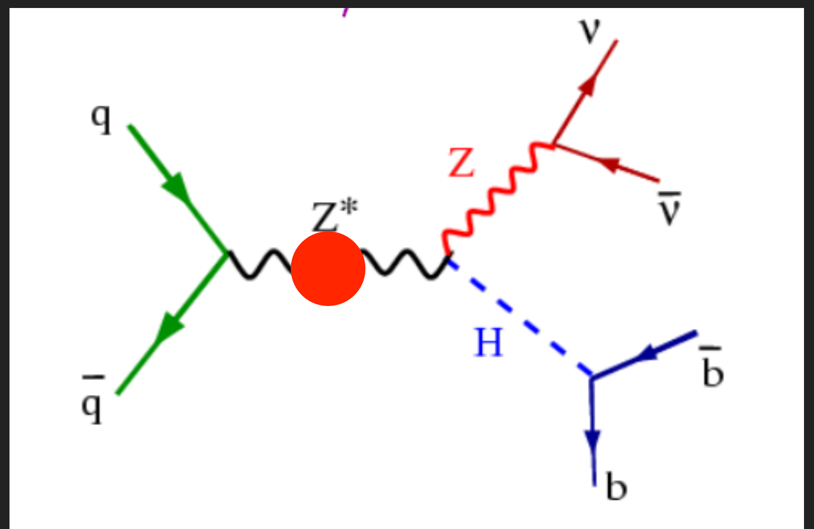
- The truncation of the series is decided by the (th&exp) precision
- For the LHC: focus on dimension-six operators (lowest one)
- To ensure a systematic coverage of BSM models we need to include all operators

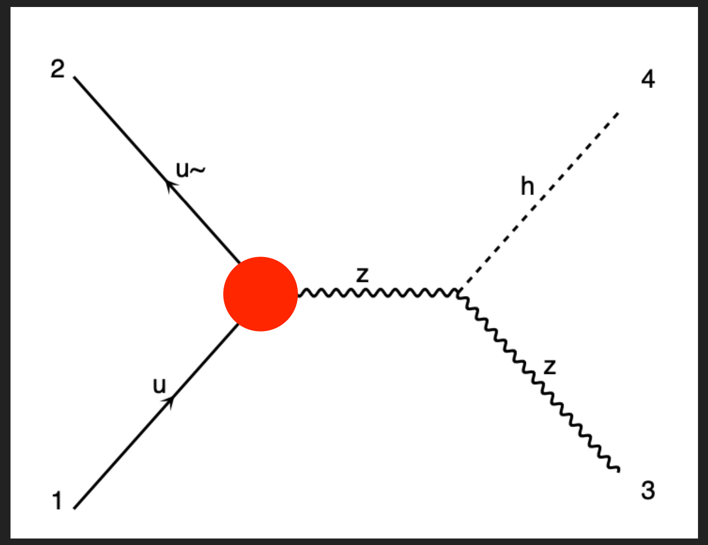
- Example: let's add an extra scalar singlet
- At the matching small, $\mathcal{O}_H$, $\mathcal{O}_{H\Box}$ are generated at tree level [Warsaw basis]
- After running to the weak scale there are also $\mathcal{O}_{HD}$, $\mathcal{O}_{HQ}^{(1)}$, $\mathcal{O}_{HQ}^{(3)}$
- $\mathcal{O}_{H\Box}$ constrained by EWPO

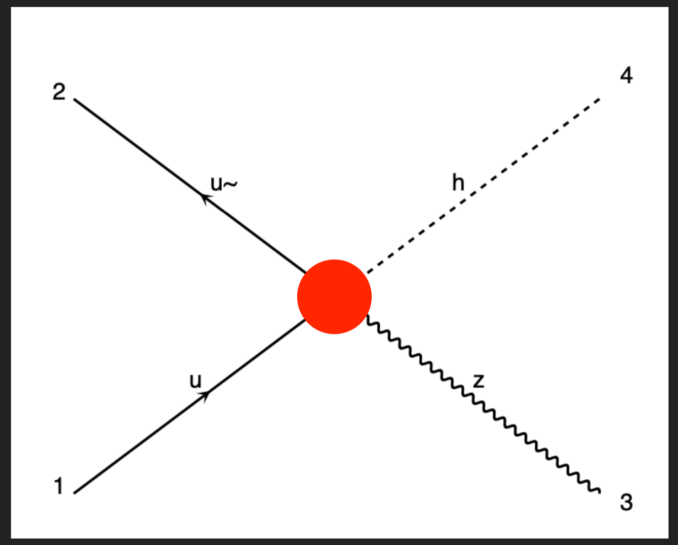
- We need to choose a basis of operators : Warsaw, SILH, HISZ, HIGGS
- Change of basis via the use of the equations of motion

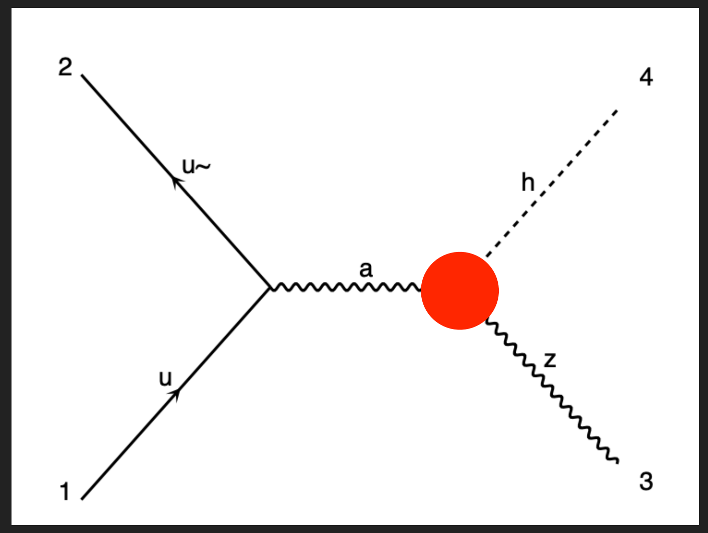
$$(\partial_\mu B^{\mu\nu})^2 \simeq c_1(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)^2 + \sum_\psi c_\psi (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\ \bar\psi\gamma^\mu\psi + \sum_{\psi,\psi'} c_{\psi,\psi'}(\bar\psi\gamma^\mu\psi)(\bar\psi'\gamma^\mu\psi')$$

lead to same S matrix elements









- Warsaw basis has the minimum number of bosonic operators [Grzadkowski et al. arXiv:1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r\varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r\widetilde\varphi)$
Q_{3W}	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r\varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

- plus 4-fermion operators leading to 59 structures not taking flavor into account

- HISZ basis [Hagiwara-Ishihara-Szalapski-Zeppenfeld PRD48 (1993) 2182] trades $\mathcal{O}^{(1)}_{H\ell,ii}$, $\mathcal{O}^{(3)}_{H\ell,ii}$ by

$$\mathcal{O}_W = (D^\mu \Phi)^\dagger W^a_{\mu\nu} \sigma^a D^\nu \Phi \;\; , \;\; \mathcal{O}_B = (D^\mu \Phi)^\dagger B_{\mu\nu} D^\nu \Phi \;\; ,$$

- SILH basis [1303.3876] trades fermonic operators and $\mathcal{O}_{HWB}$, $\mathcal{O}_{HW}$ by

$$\mathcal{O}_W \;\; , \;\; \mathcal{O}_B \;\; , \;\; \mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2 \;\; , \;\; \mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$$

- The HIGGS aimed at Higgs observables [LHCHXSWG-INT-2015-001]
- Translators between bases: Rosetta, JHUGenLexicon, …

- Taking flavor into account the number of operators might get out control!
- Without any flavor symmetry: 1350 (CP-even) and 1149 (CP-odd) = 2499
- Assuming $U(3)_L \times U(3)_\ell \times U(3)_Q \times U(3)_u \times U(3)_d$ there are 85
- Assuming $U(3)_L \times U(3)_\ell \times U(2)_Q \times U(2)_u \times U(2)_d$ there are 270
- Lesson 1: we need to introduce a hypothesis on the flavor symmetry
- Lesson 2: in any case, we need many datasets
- SMEFT has many parameters, so any measurement has blind directions
- Large number of Wilson coefficients and correlations between processes call for a global analysis

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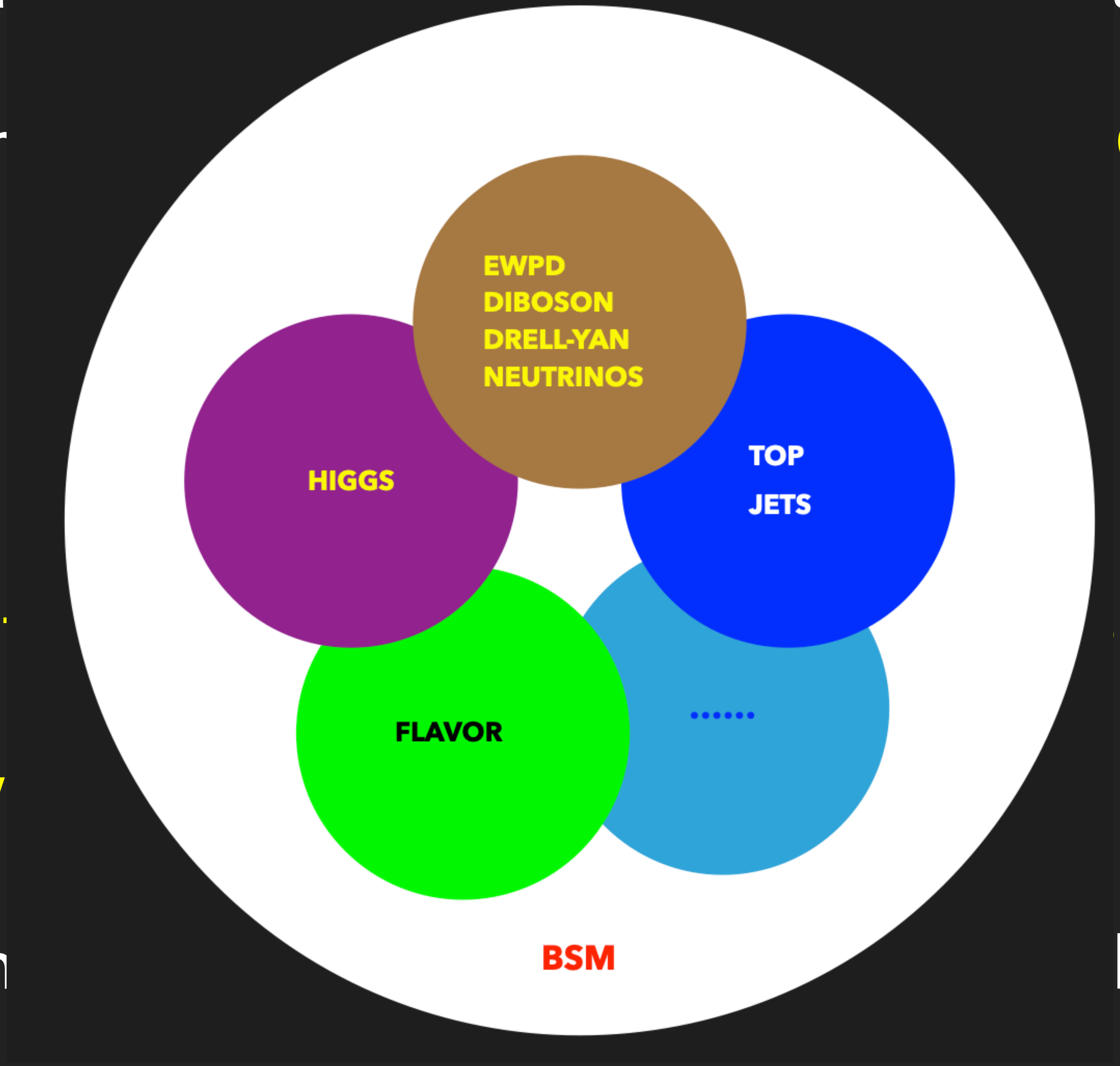
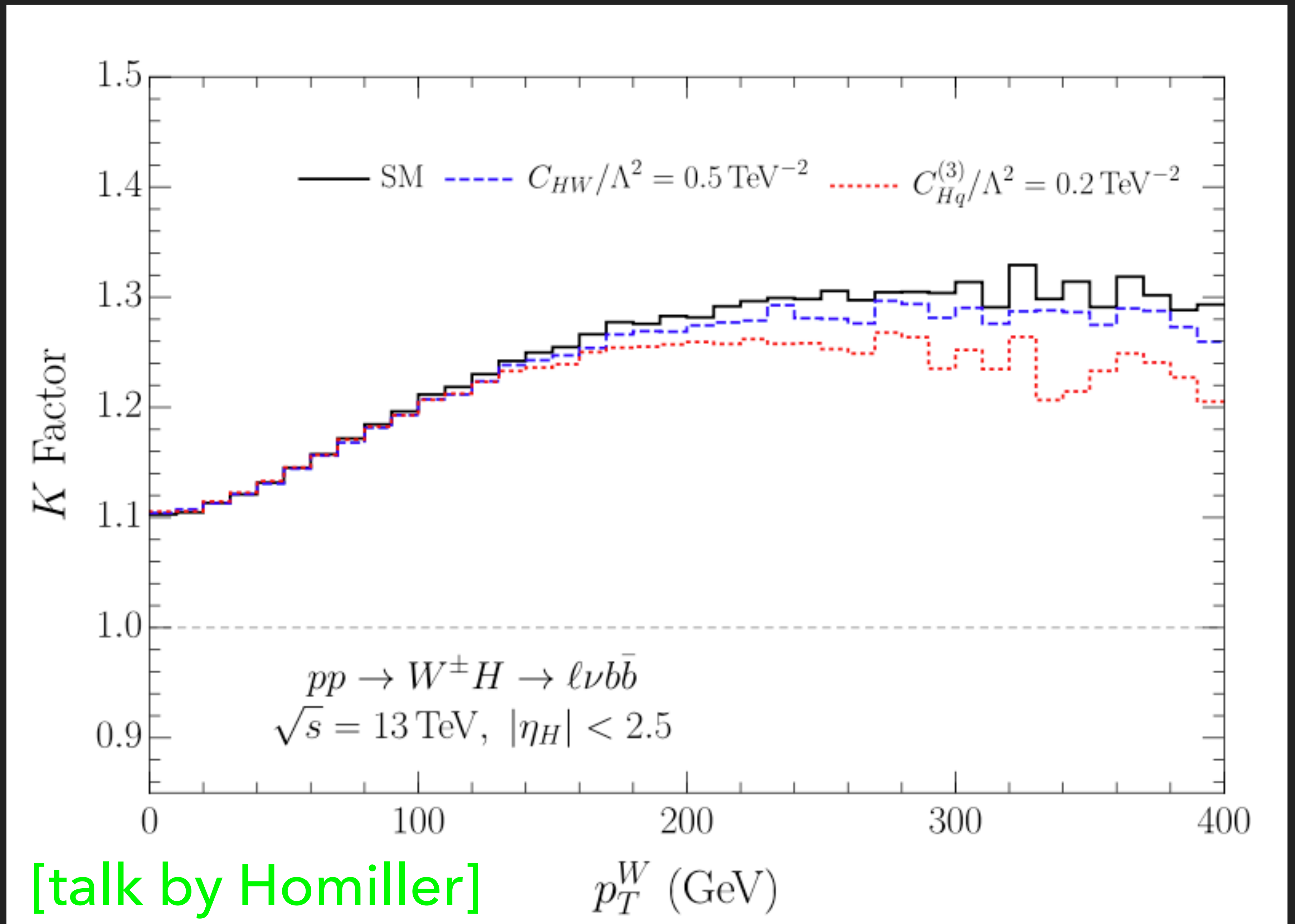


- Large number of Wilson coefficients and correlations between processes call for a global analysis

- Many groups are already doing it
    - Corbett et al. 1207.1344 1211.4580 1304.1151 1411.5026 1505.05516
    - Englert,Freitas,Mullheitner,Plehn,Rauch,Spira,Walz 1403.7191
    - Ellis,Sanz,You 1404.3667 1410.7703 1803.03252
    - Falkowski et al. 1411.0669 1508.00581 1609.06312
    - Englert,Kogler,Schulz,Spannowsky 1511.05170
    - Butter,OE,Gonzalez-Fraile,Gonzalez-Garcia,Plehn,Rauch 1604.03105
    - Freitas,Lopez-Val,Plehn 1607.08251
    - Krauss,Kuttimalai,Plehn 1611.00767
    - Almeida et al. 1812.01009
    - Biekotter,Corbett,Plehn 1812.07587
    - HEPfit 1710.05402 1910.14012
    - Bravo et al. 1910.03606
    - TopFitter, CKMfitter, and many more
- There is a global ongoing TH+EXP effort for precision
- Certainly, global analyses will benefit from HL-LHC and future machines

WHAT IS NEEDED

- precise knowledge of the SM background: NLO, NNLO, .. (QCD+EW)
- there are many higher order tools available: POWHEG, MCFM, MATRIX, FEWZ, JHUGen, VBFNLO, aMC@NLO…
- precise SMEFT predictions: LO UFO for many bases
- precise SMEFT predictions: SMEFT@NLO[Degrande et al. 2008.11743] POWHEG, etc



[talk by Homiller]

+ distributions, control uncertainties, …

- Theoretical uncertainties [de Florian, Lindert, Vryonidou…….LHCHXSWG]
- TH: we need to have input parameters under control (measurements assume SM)
- Information on the validity of the approximation: unitarity, perturbativity, etc
- To the lowest order $M = M_{\rm SM} + \frac{1}{\Lambda^2} M^{(6)}_{\rm EFT} + \ldots \quad \Longrightarrow \quad \sigma \simeq \frac{1}{s}\left(|M_{\rm SM}|^2 + \frac{1}{\Lambda^2} M^\star_{\rm SM} M^{(6)}_{\rm EFT} + \ldots \right)$
- there is no guarantee that the cross section is positive at lowest order!
- Either new hypothesis to remove the problematic phase space regions
- Or adding $\frac{1}{\Lambda^4}|M^{(6)}_{\rm EFT}|^2$ but neglecting dimension-8 operators departing from systematic EFT or introducing a model dependence.

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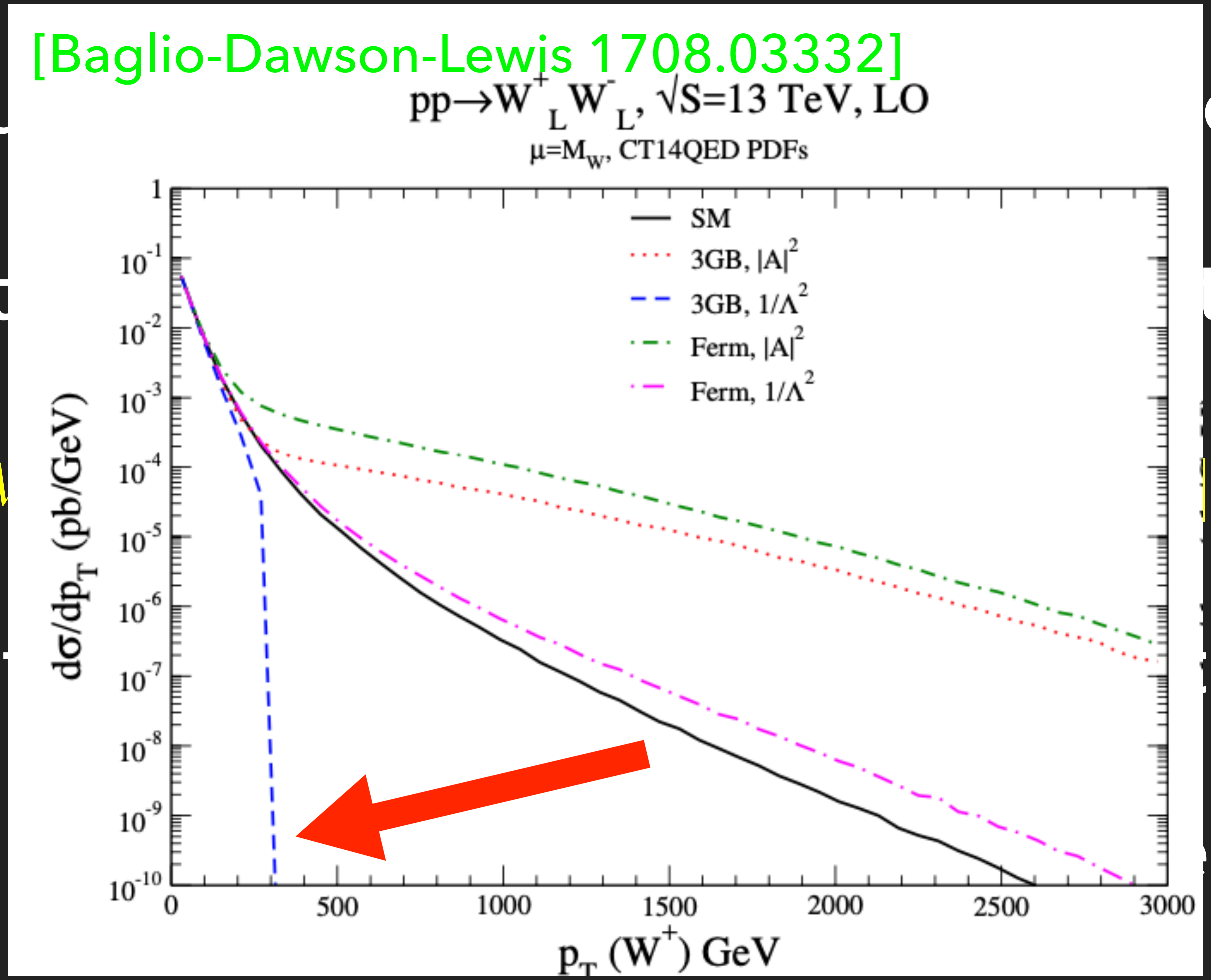

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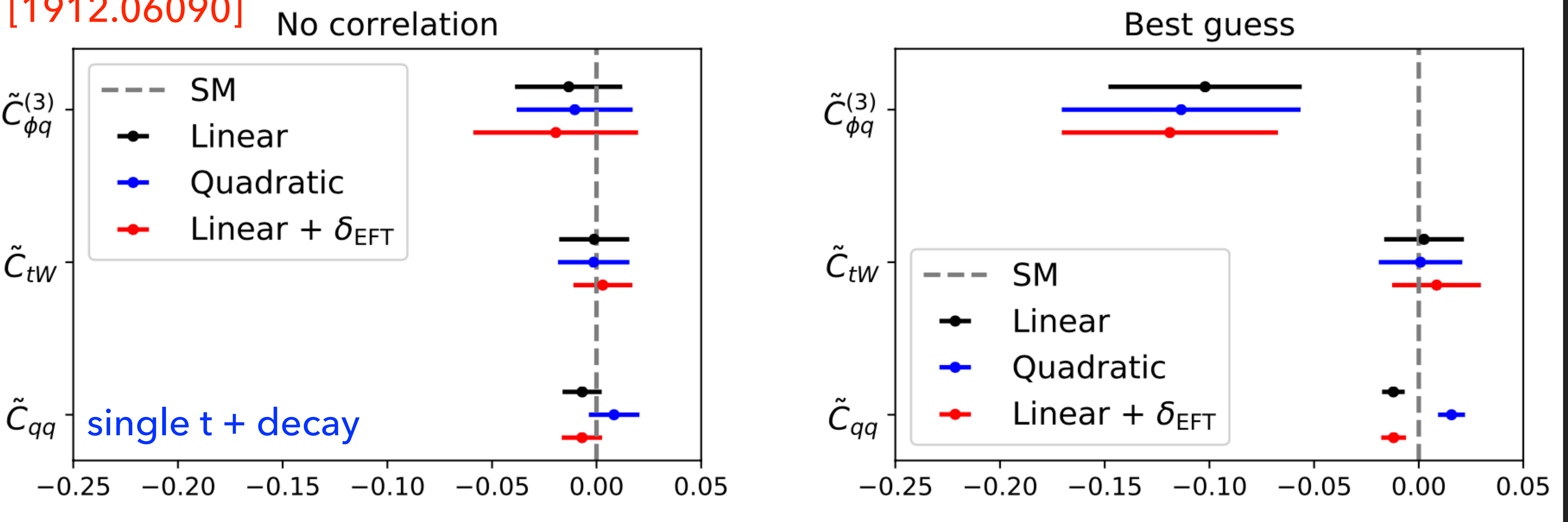
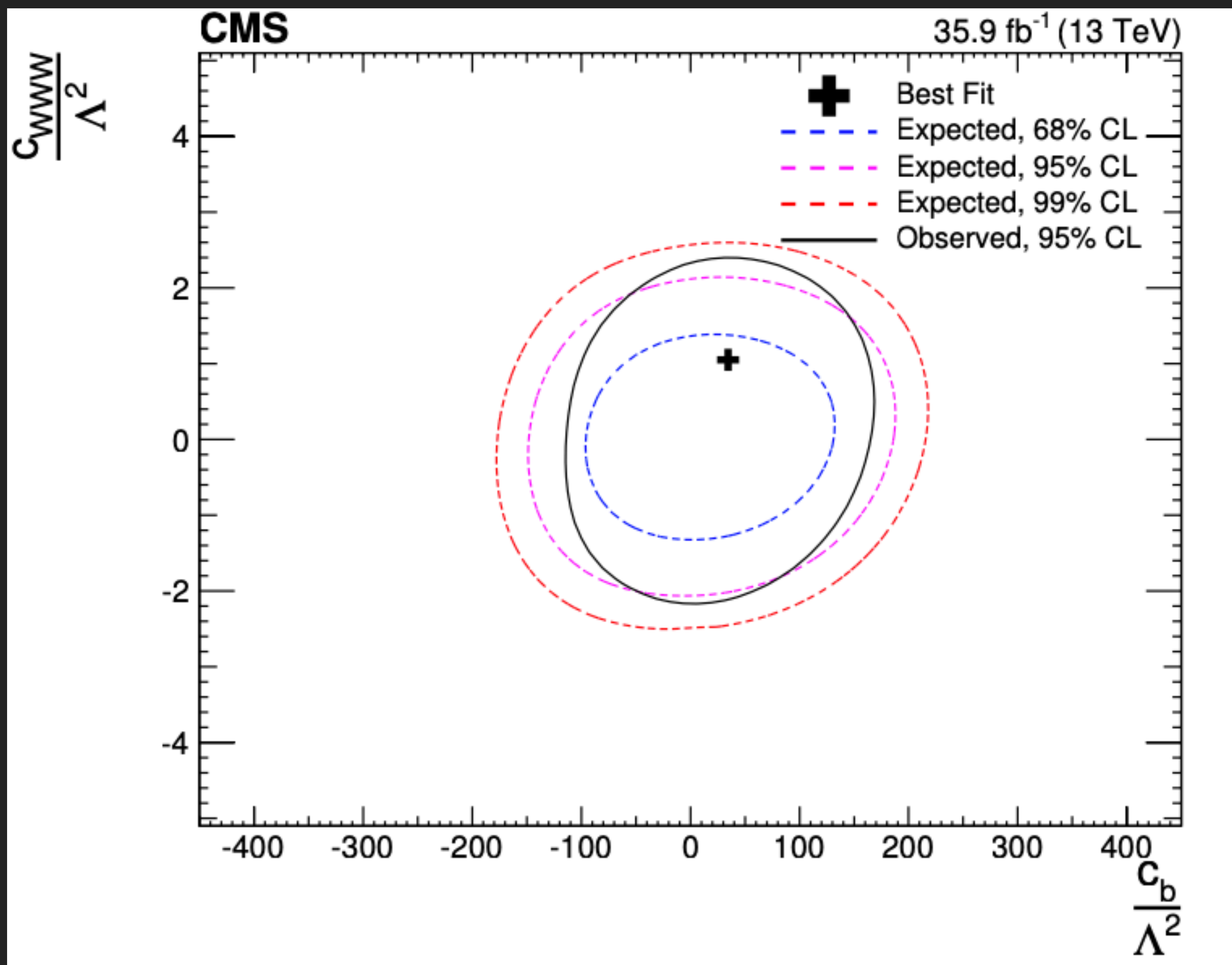
- Information on experimental cut flows, efficiencies
- Information on backgrounds
- Information on results and corresponding correlations (becoming standard)
- Information on the likelihood
- Desirable to have results at particle level, and distributions (STXS or fiducial distr.)

[1912.06090]

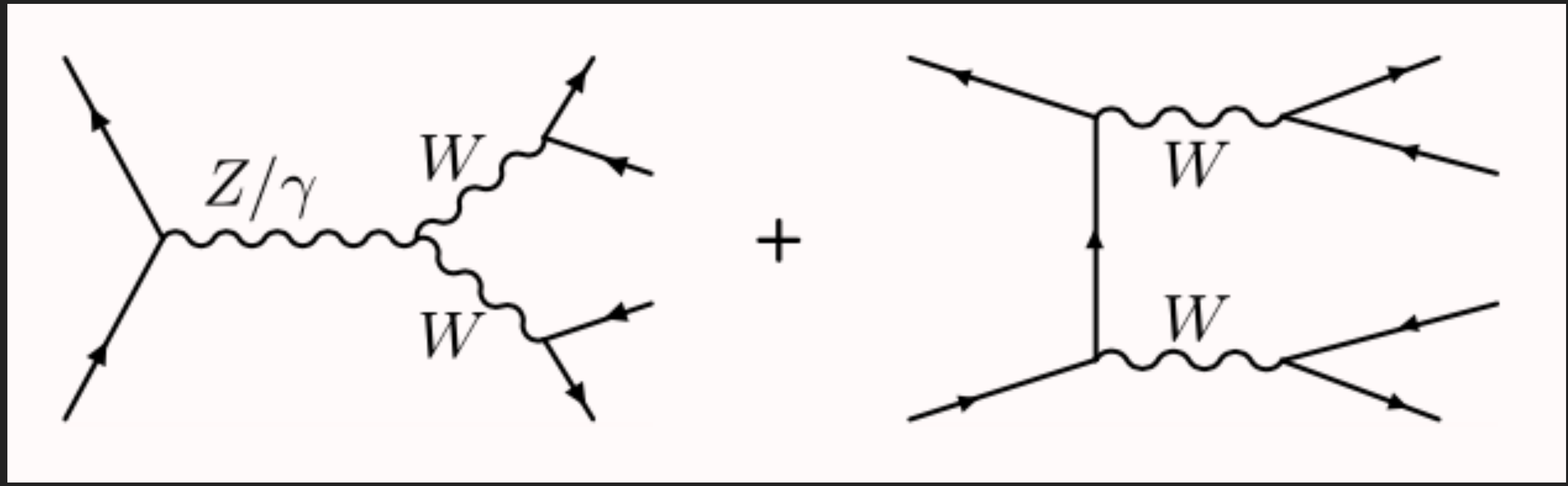




- EWPD Z pole: SM corrections are well under control
- In the Warsaw basis, there are 10 LO parameters and 32 in QCD+EW NLO
  [Dawson-Giardino 1909.02000; Hartmann-Shepherd-Trott 1611.09879]

$$\mathcal{O}_{\ell\ell}\,,\ \mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hu}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}^{(1)}_{HQ}\,,\ \mathcal{O}^{(3)}_{HQ}\,,\ \mathcal{O}^{(1)}_{H\ell}\,,\ \mathcal{O}^{(3)}_{H\ell}$$

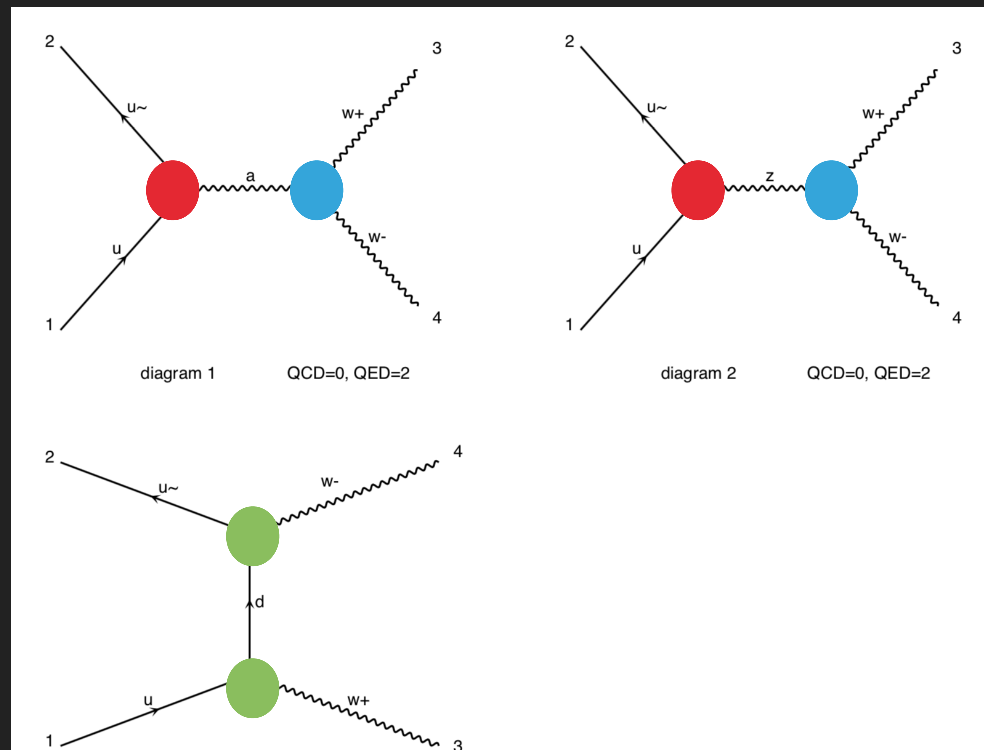
- However, there are 2 blind/flat (LO) directions: more datasets or hypothesis
  [Han-Skiba hep-ph/0412166]
- EWPD Z pole + LEP 2: adding W and fermion pair productions [Berthier et al. 1606.06693]
- 20 operators contribute: 9 additional 4-fermion operators and 1 TGC (O_{3W})
- The WW production lifts the blind direction



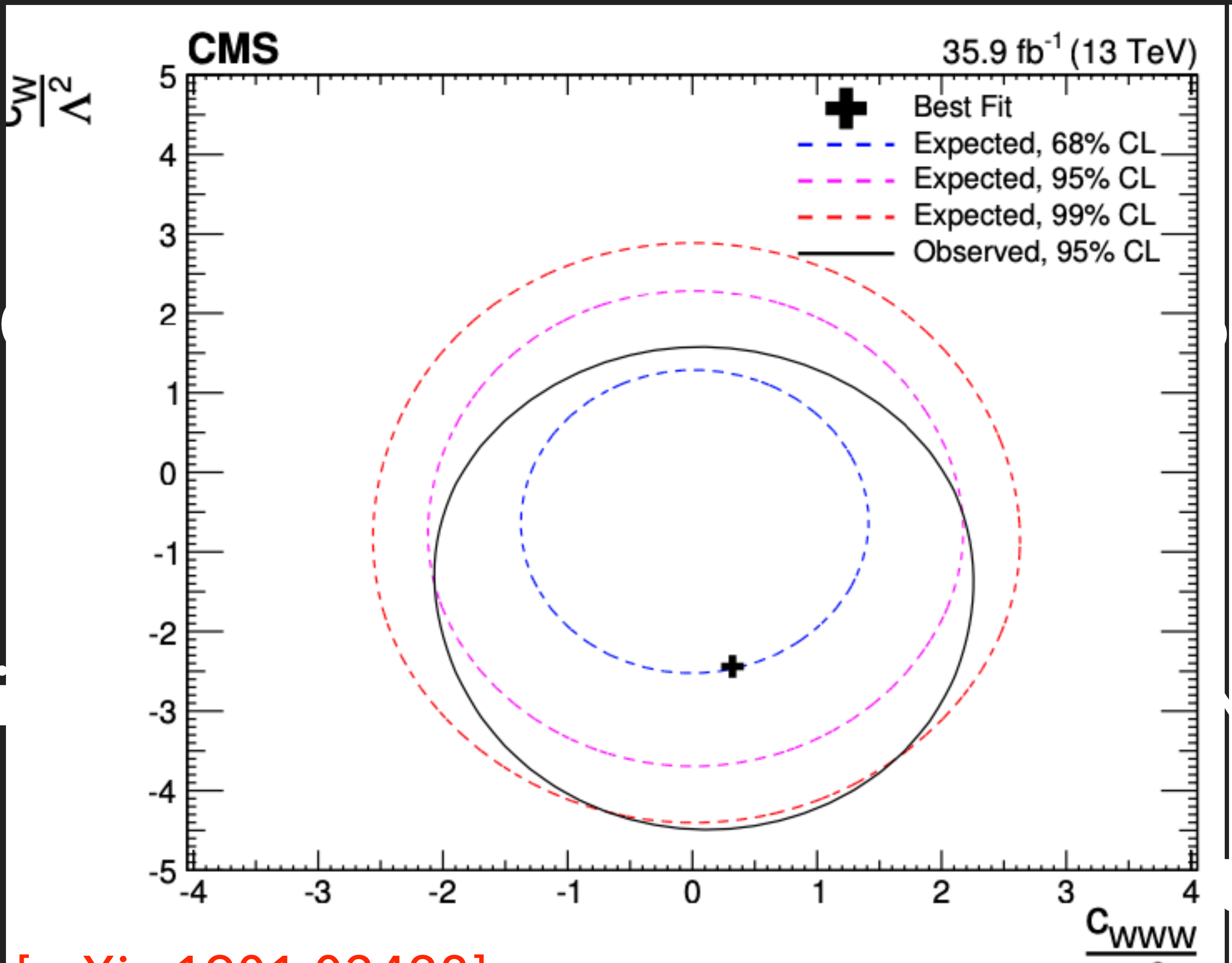
- DIBOSON PRODUCTION: dimension-6 TGC contribute to γW^+W^- , ZW^+W^-

$$\mathcal{O}_{\ell\ell}\ ,\ \mathcal{O}_{HWB}\ ,\ \mathcal{O}_{HD}\ ,\ \mathcal{O}_{3W}\ ,\ \mathcal{O}_{He}\ ,\ \mathcal{O}_{Hu}\ ,\ \mathcal{O}_{Hd}\ ,\ \mathcal{O}_{HQ}^{(1)}\ ,\ \mathcal{O}_{HQ}^{(3)}\ ,\ \mathcal{O}_{H\ell}^{(1)}\ ,\ \mathcal{O}_{H\ell}^{(3)}$$

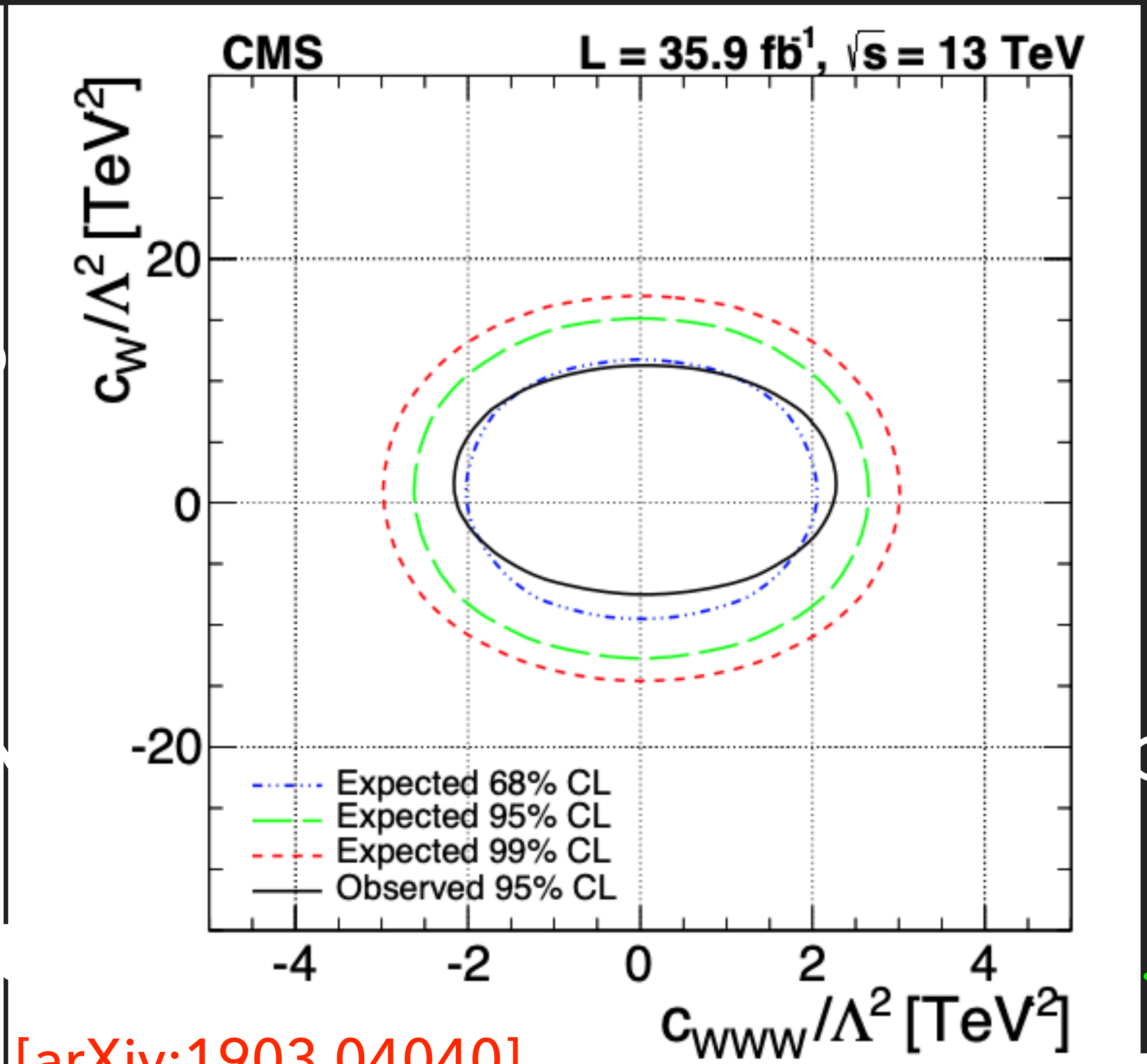
- Neutral TGCs are generated by dimension-8 operators
- Different combinations of couplings
- SM contribution known to NNLO QCD+NLO EW (important at high p_T)
- SMEFT NLO are known but do not solve the problem $\frac{d\sigma}{dp_T} < 0$ [Baglio et al.1708.03332]
- TGC also contribute to VBF jjZ/W production [hep-ph/0405269]
- Experimental results help performing the global fit



- **DIBOSON PRODUCTION:** dimension-6 TGC contribute to γW^+W^- , ZW^+W^-



[arXiv:1901.03428]



[arXiv:1903.04040]

- Neutral T
- Different
- SM contri ... p_T)
- SMEFT N ... .1708.03332]
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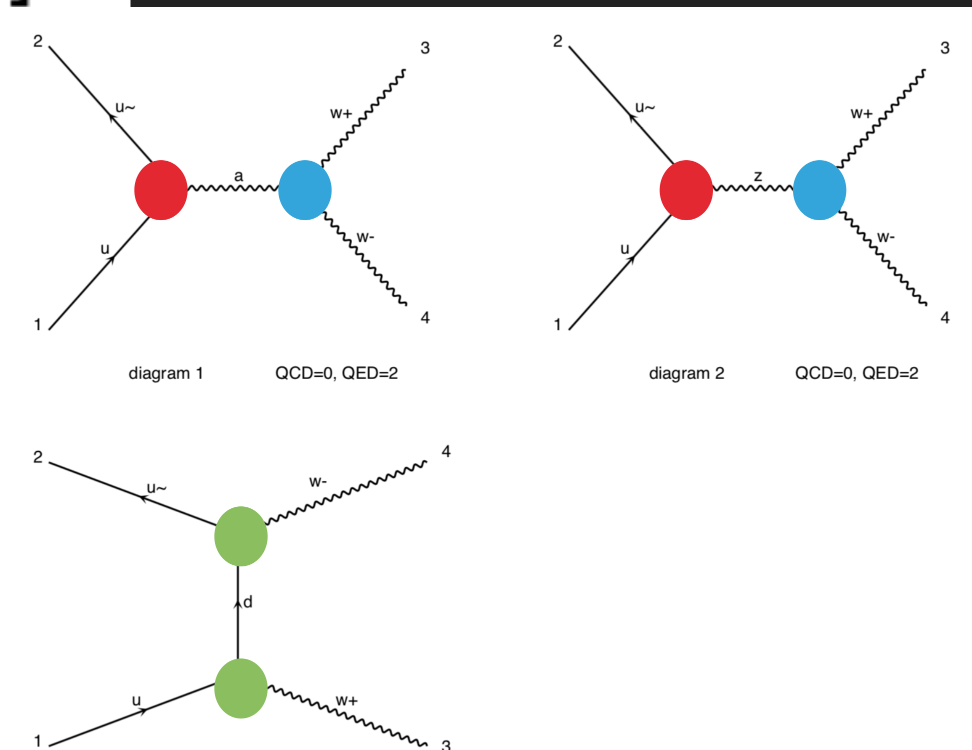
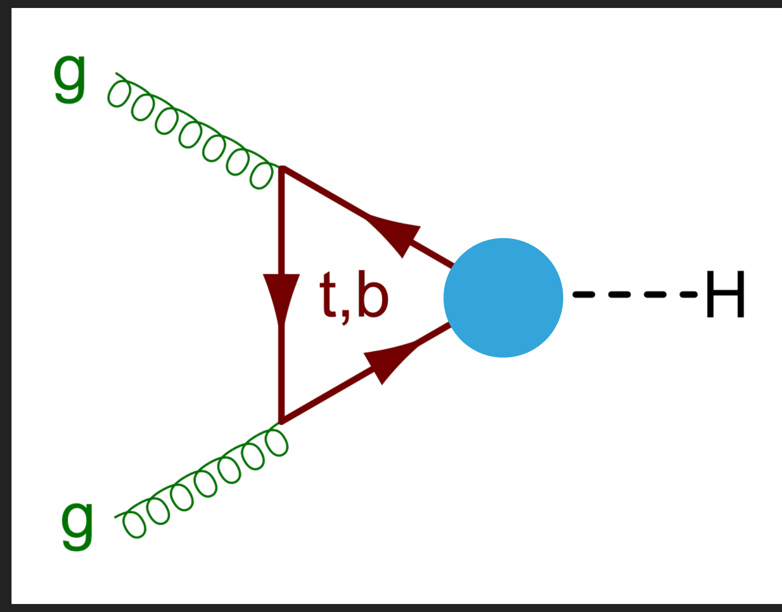
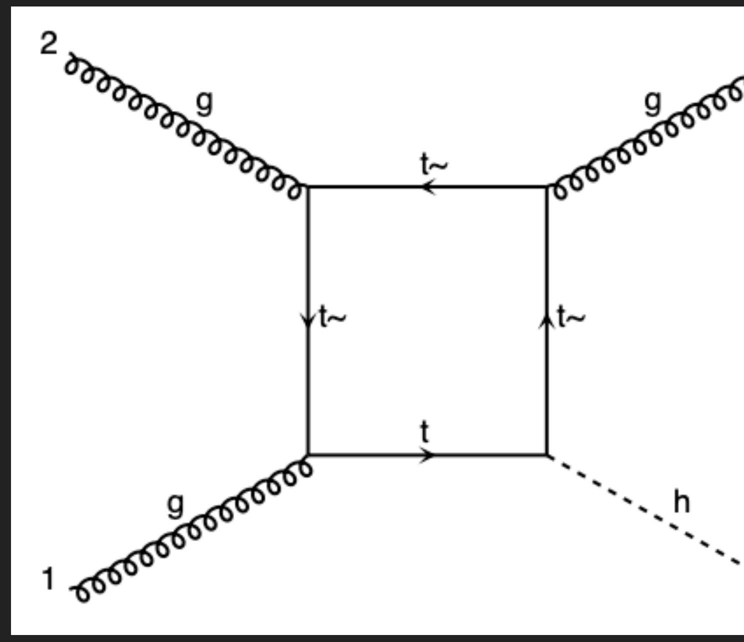


- Higgs production: SMEFT modifies all production and decay modes



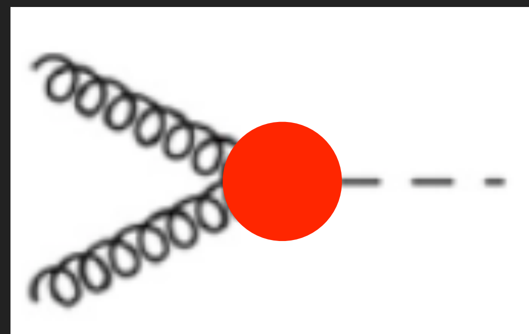
$$\mathcal{O}_{\ell\ell}\ ,\ \mathcal{O}_{HWB}\ ,\ \mathcal{O}_{HD}\ ,\ \mathcal{O}_{He}\ ,\ \mathcal{O}_{Hu}\ ,\ \mathcal{O}_{Hd}\ ,\ \mathcal{O}^{(1)}_{HQ}\ ,\ \mathcal{O}^{(3)}_{HQ}\ ,\ \mathcal{O}^{(1)}_{H\ell}\ ,\ \mathcal{O}^{(3)}_{H\ell}$$
$$\mathcal{O}_{H}\ ,\ \mathcal{O}_{H\Box}\ ,\ \mathcal{O}_{HG}\ ,\ \mathcal{O}_{HW}\ ,\ \mathcal{O}_{HB}\ ,\ \mathcal{O}_{\tau H}\ ,\ \mathcal{O}_{bH}\ ,\ \mathcal{O}_{tH}\ ,\ \ldots$$

- SM predictions: ggH (NNLO+NNLL QCD; 2-loops EW; mixed) ; VBF (full NLO EW+QCD; NNLO QCD) ; VH(NNLO QCD; NLO EW); ttH (NLO QCD); decays (N^3 LO QCD)

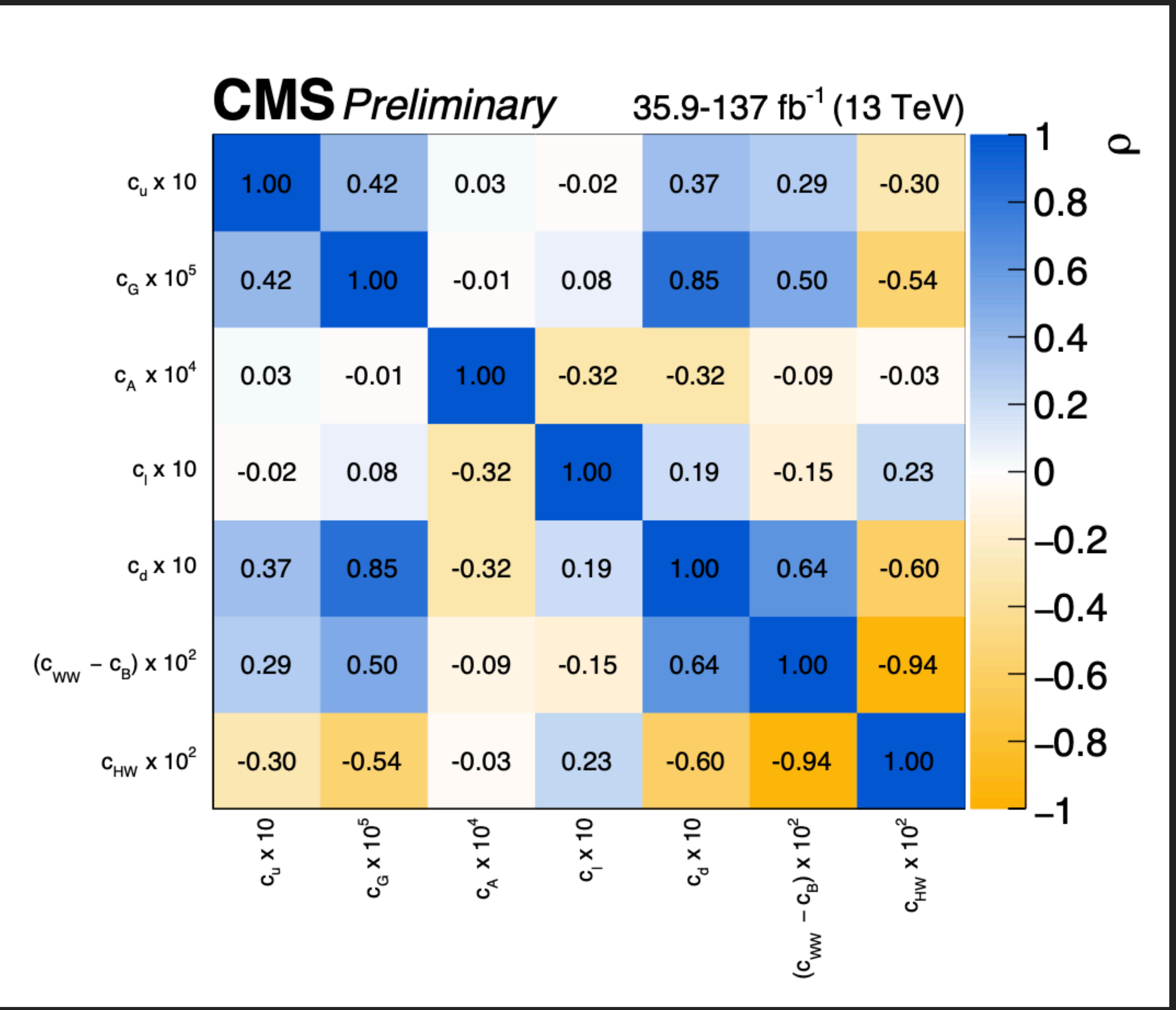


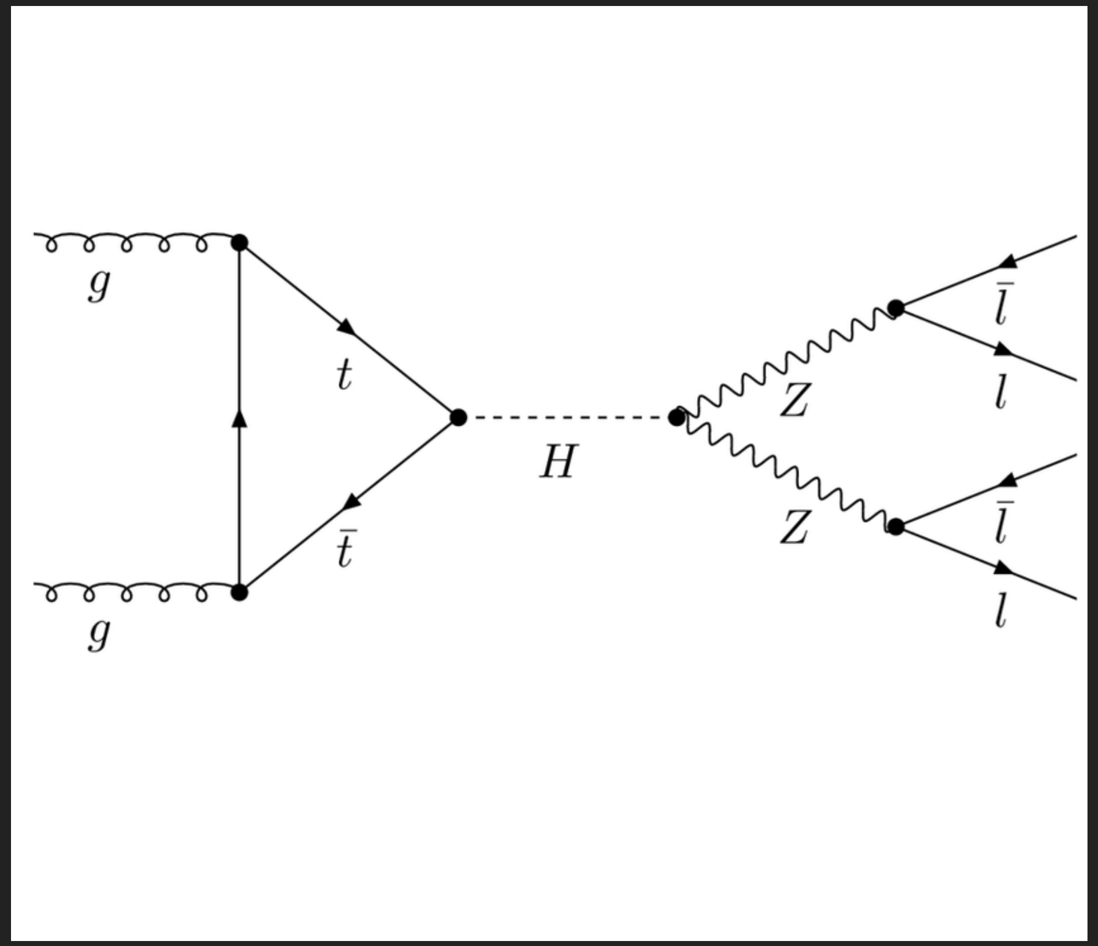
- SMEFT corrections available to NLO QCD
- Tail of distributions enhance SMEFT effects
- Hard gluon emission allows to separate different SMEFT effects [Vryonidou, Lindert this conf.] [Buschmann 1410.5806]

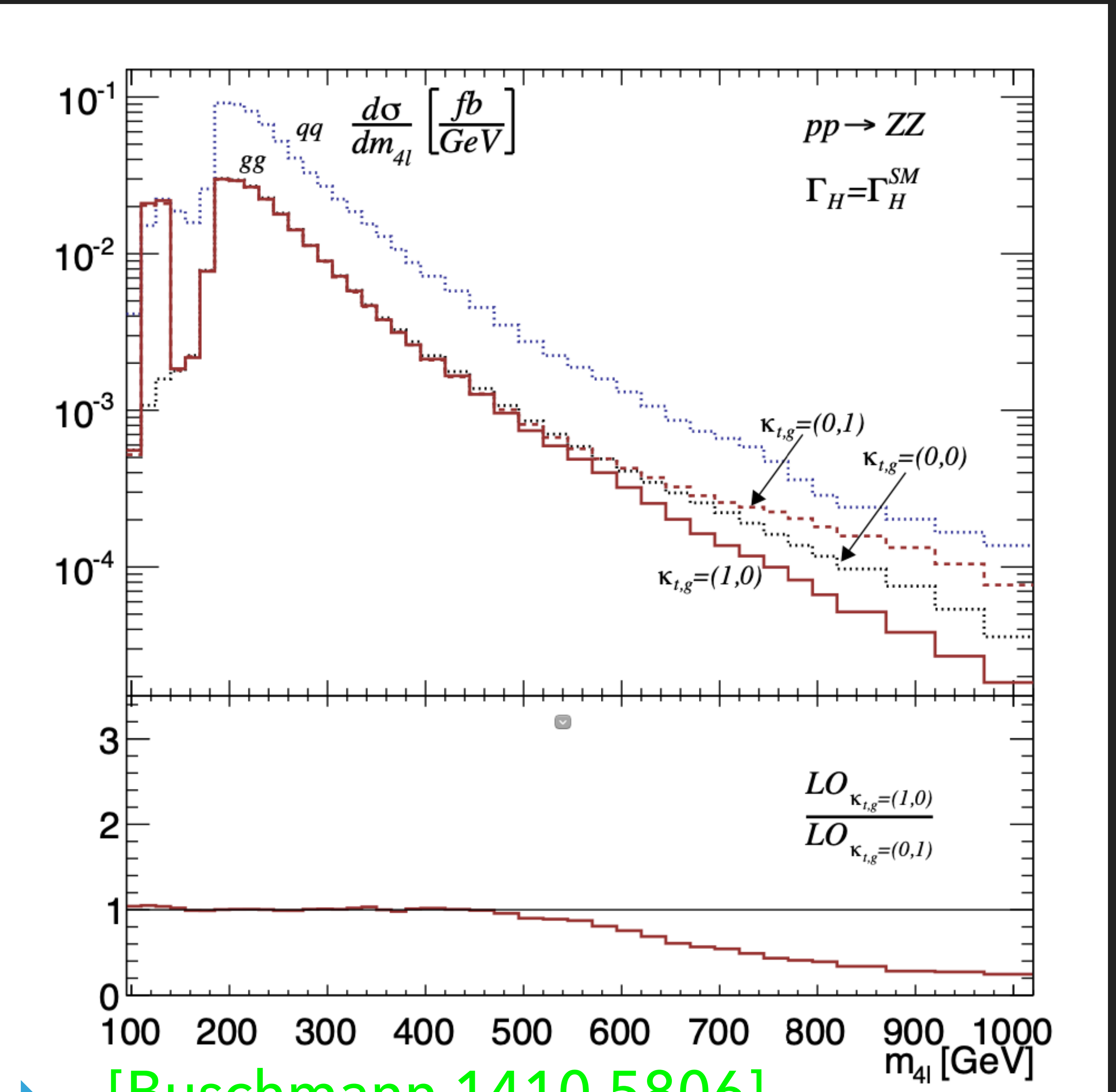
$$\frac{d\sigma}{dp_T^2} \propto \begin{cases} (\kappa_g + \kappa_T)^2 & \text{for } p_T^2 < m_t^2 \\ (\kappa_G + \kappa_T \frac{4m_t^2}{p_T^2})^2 & \text{for } p_T^2 > m_t^2 \end{cases}$$



- Off-shell Higgs production helps to separate different SMEFT effects
- Experimental fits to some SMEFT parameters help to calibrate global fits

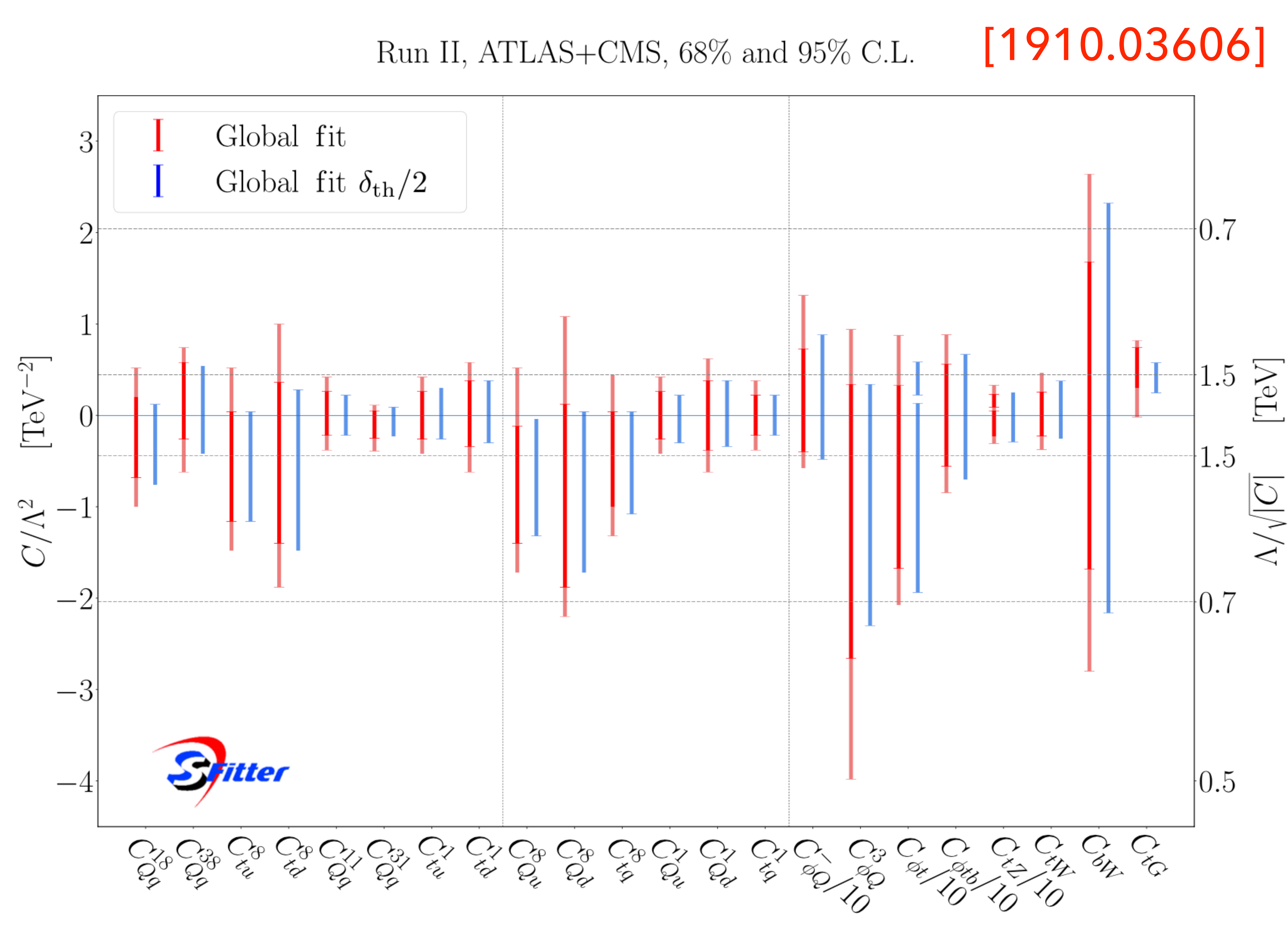






- [Buschmann 1410.5806]

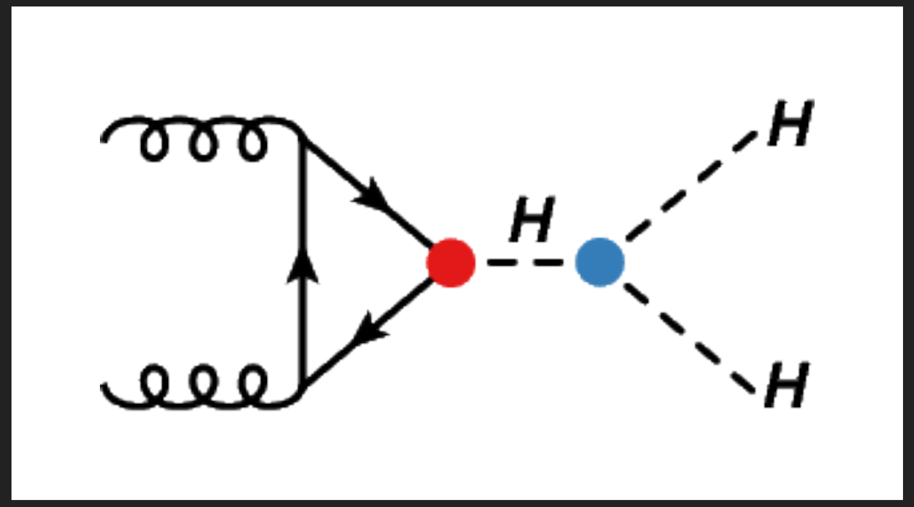
- TT and T productions: 22 operators contribute assuming $U(2)_Q \times U(2)_u \times U(2)_d$ {14 four-fermion operators, 4 dipoles, 4 Vff}
- SM contribution known to NNLO QCD and NLO EW [1701.04105]
- SMEFT contribution known to NLO [SMEFT@NLO]
- There are a large number of available measurements TT, TV, TTZ, TTW
- It is easy to compare measurements with parton level predictions



[1910.03606]

[Similar analyses by TopFitter 1901.03164]

- Jet production allows the study of four-fermion and dipole operators
- Drell-Yan receives contributions from four-fermion and dipole operators
- HH production is a direct probe of the triple Higgs couplings (O_H)
- Low energy + flavor + ……



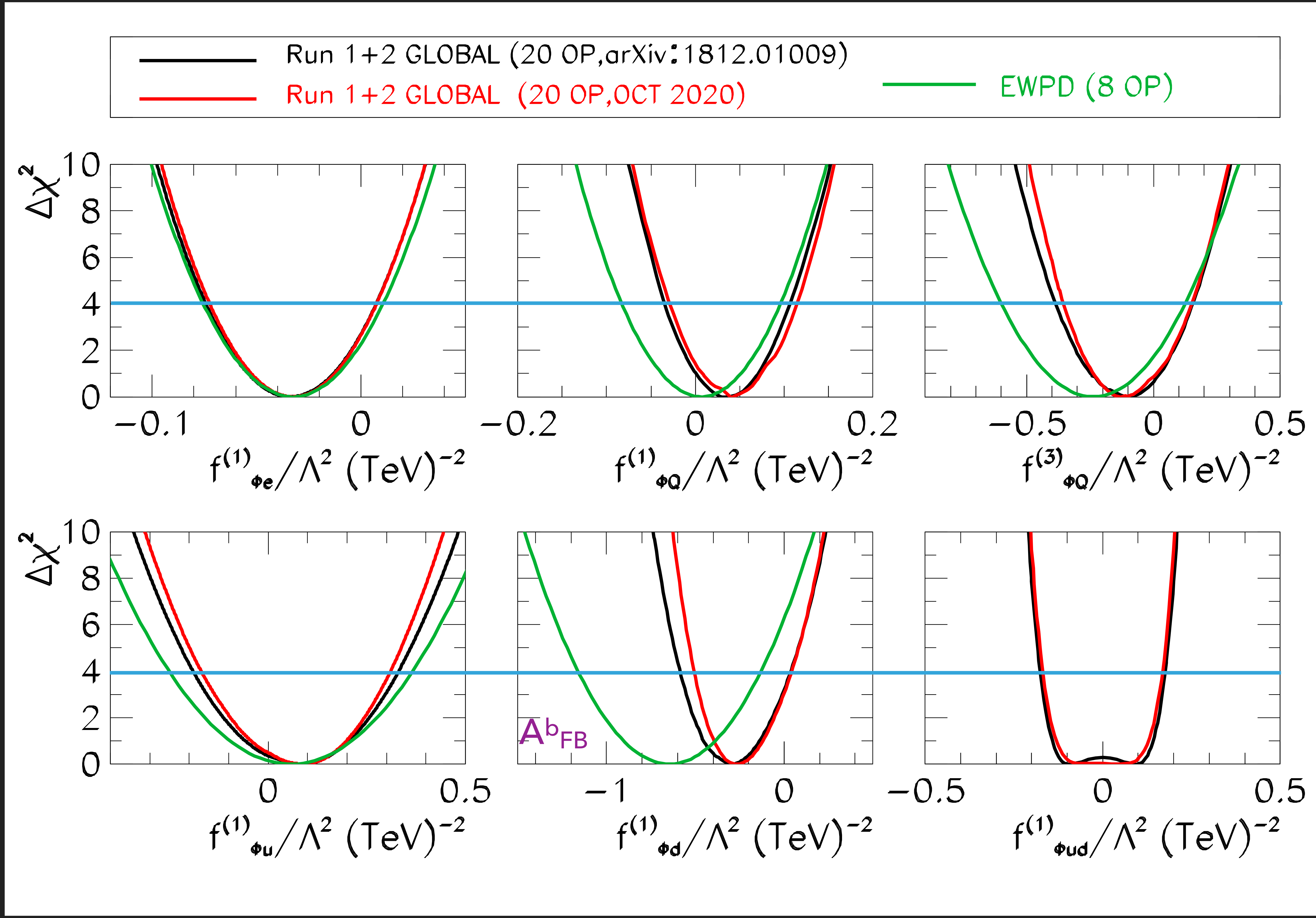
- 20 parameter global analysis using the HISZ [Alves, Almeida, OE, Gonzalez-Garcia, 1812.01009 reloaded

$$\mathcal{O}_{\ell\ell}\,,\ \mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hu}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}^{(1)}_{HQ}\,,\ \mathcal{O}^{(3)}_{HQ}\,,\ \mathcal{O}^{(1)}_{Hud}$$

$$\mathcal{O}_{H}\,,\ \mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{B}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{\tau H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,,\ \mathcal{O}_{\mu H}$$

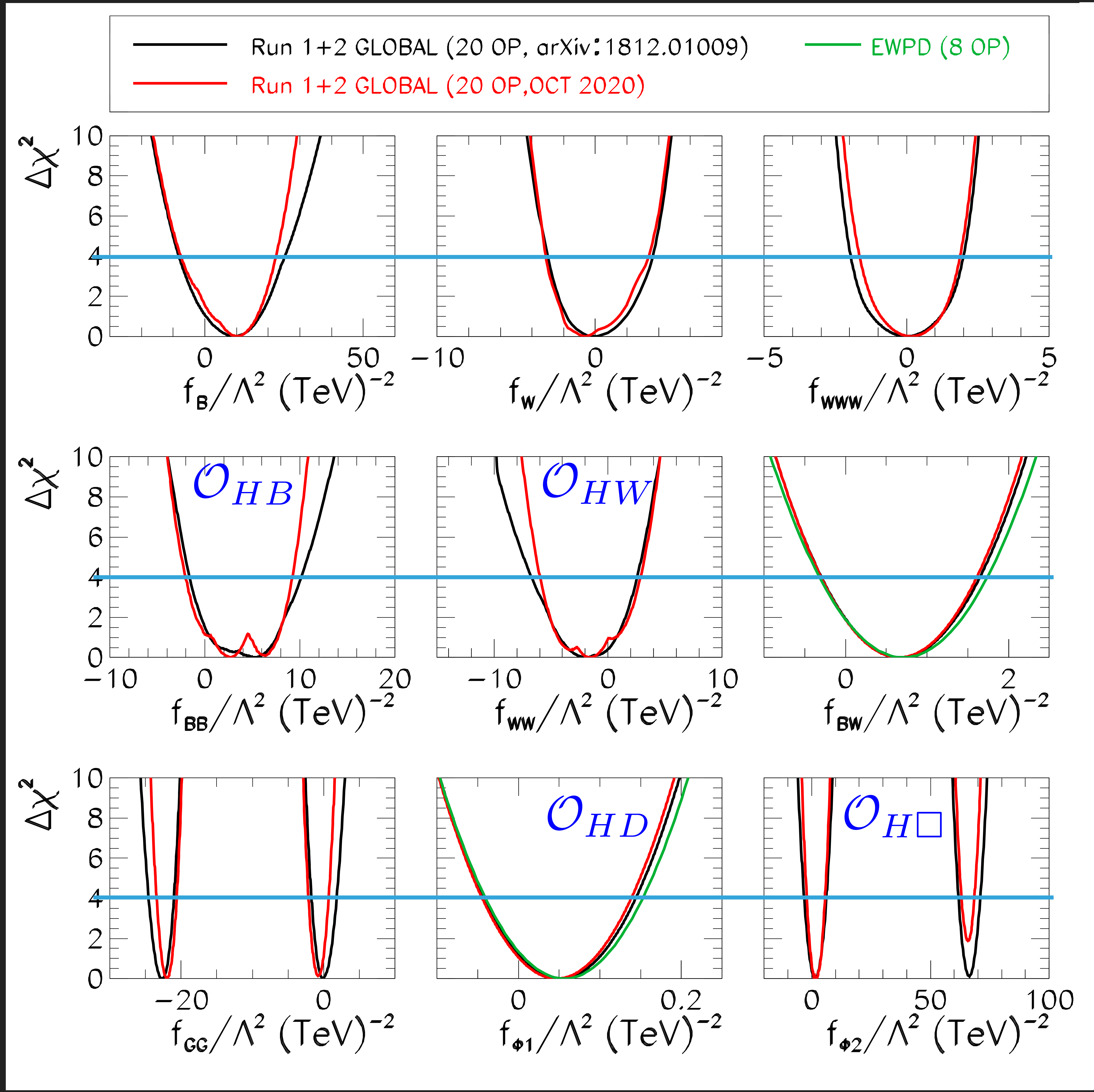
- 20 parameter global analysis using the HISZ
- Datasets:
  - EWPD
  - WW and WZ productions (Run 1 + partial Run 2)
  - Higgs (Run 1 + 2 inclusive)

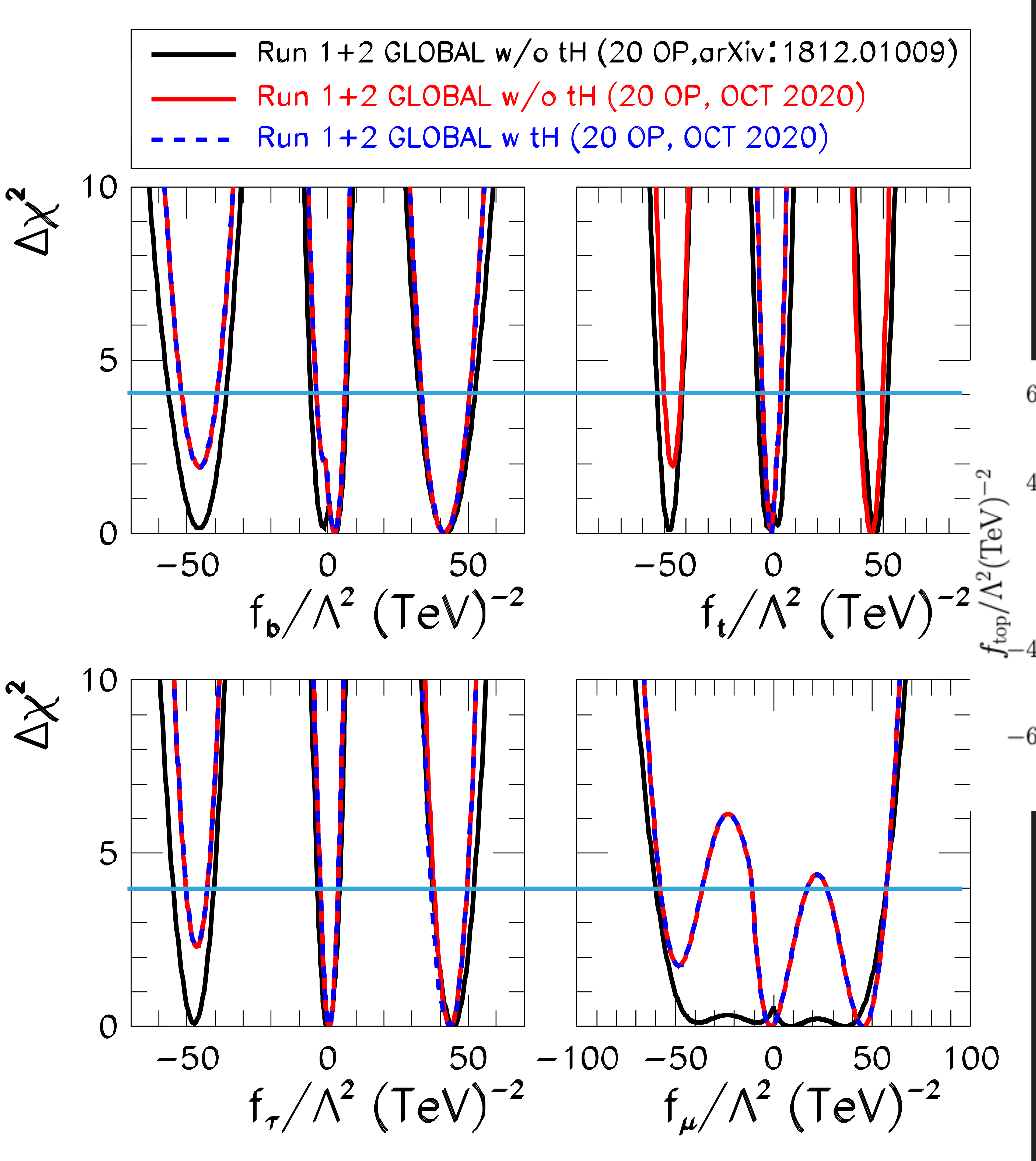
- Operators modifying the coupling of electroweak gauge bosons to fermions

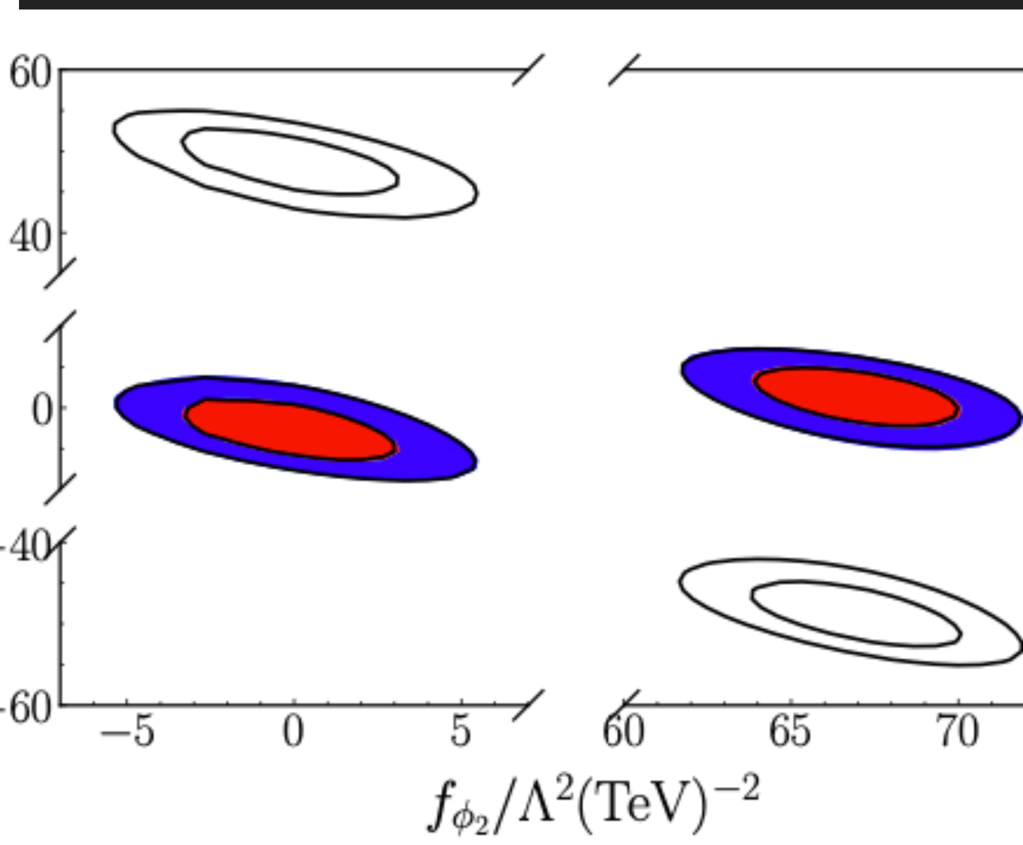


- In the quadratic approximation: small improvement in the agreement with SM

- Bosonic and Yukawa operators

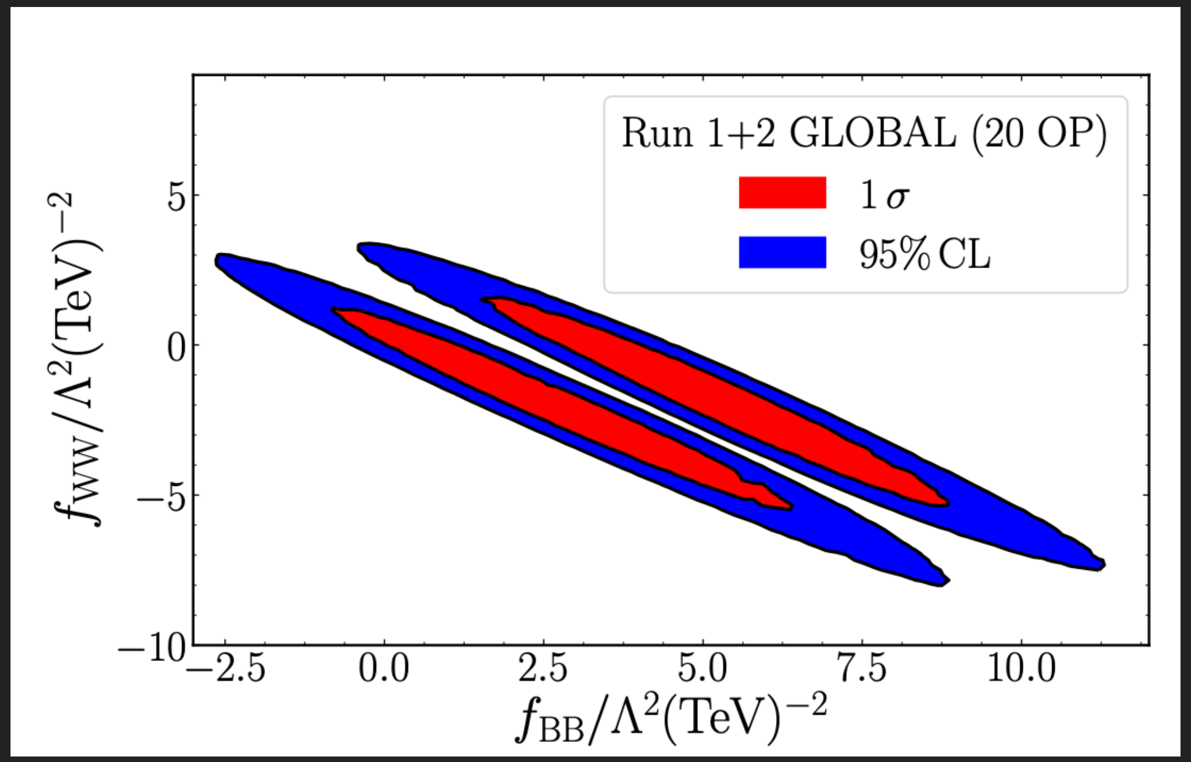


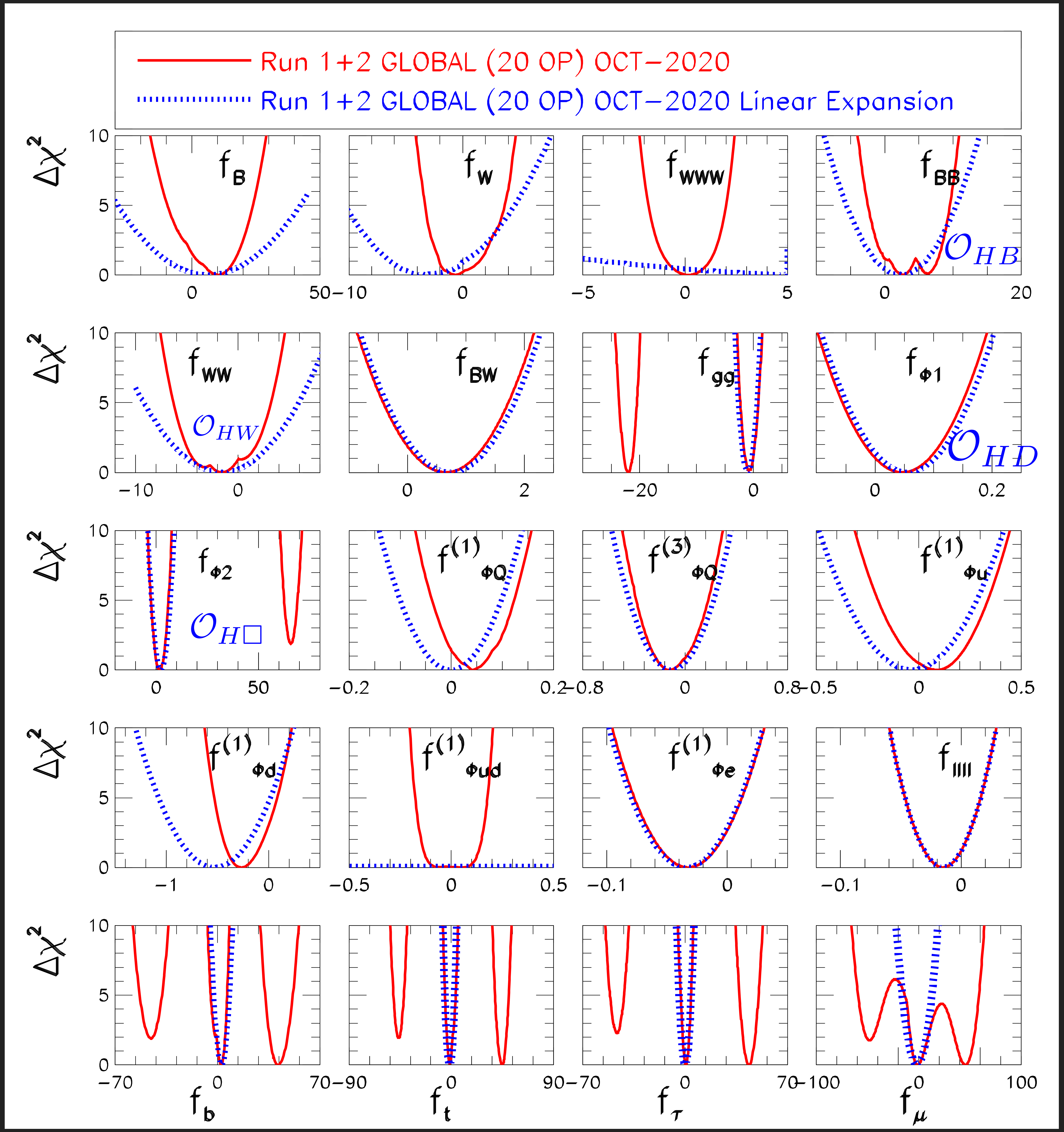




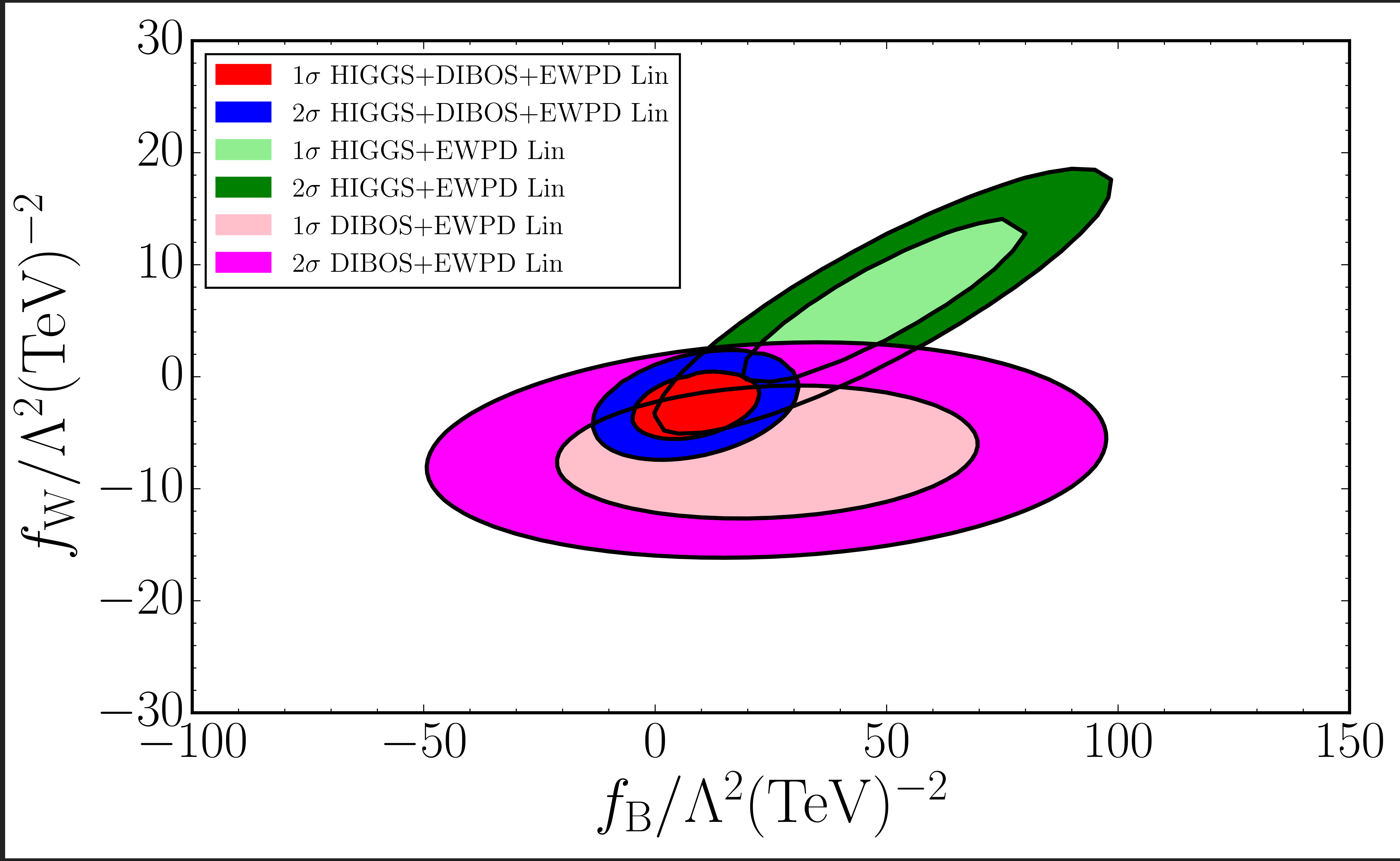
- Good agreement with the SM and some degeneracies remain

- Quadratic versus linear approximation:
- VFF couplings dominated by EWPD
- Small changes in the Higgs couplings
- TGC much less constrained in the linear analysis

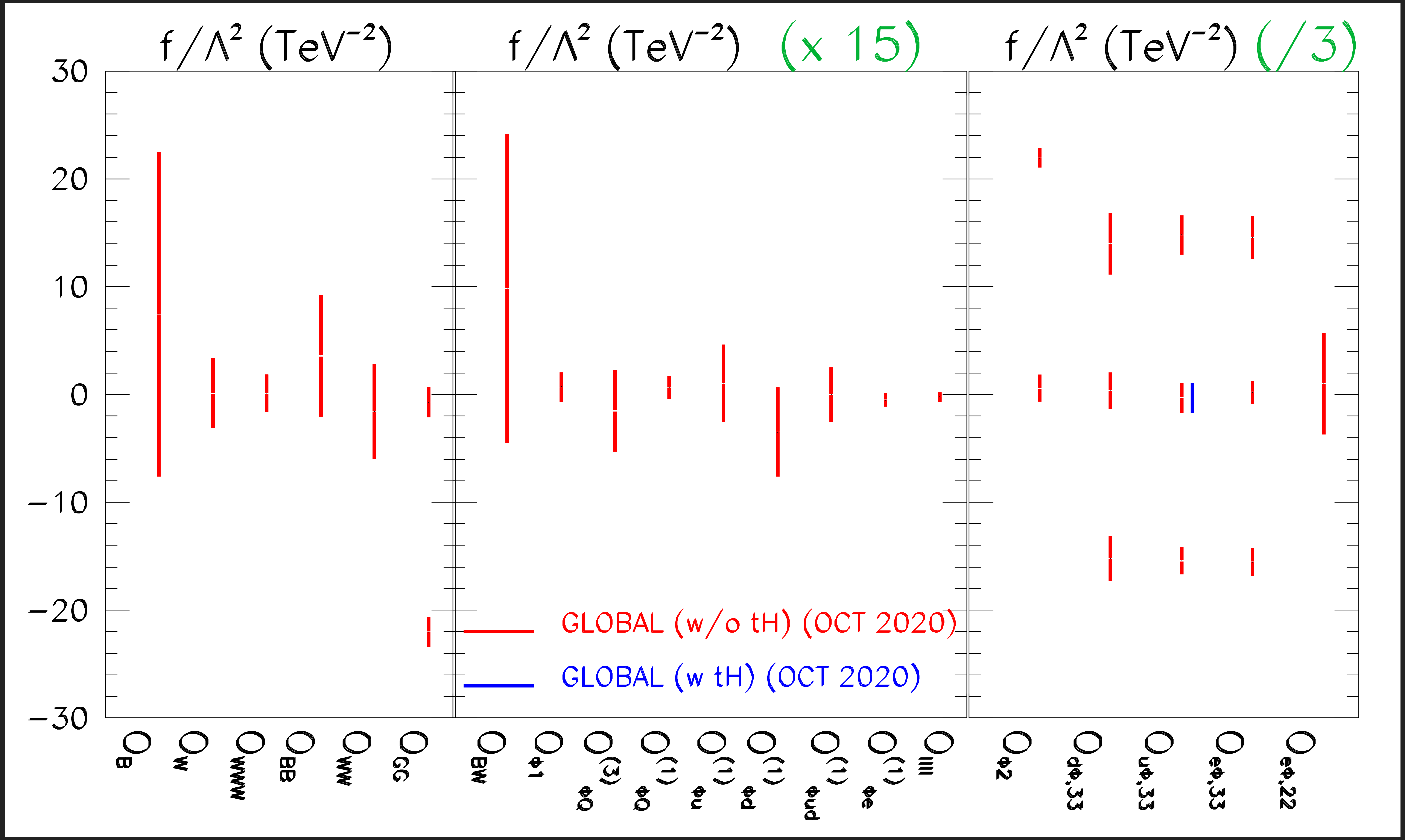




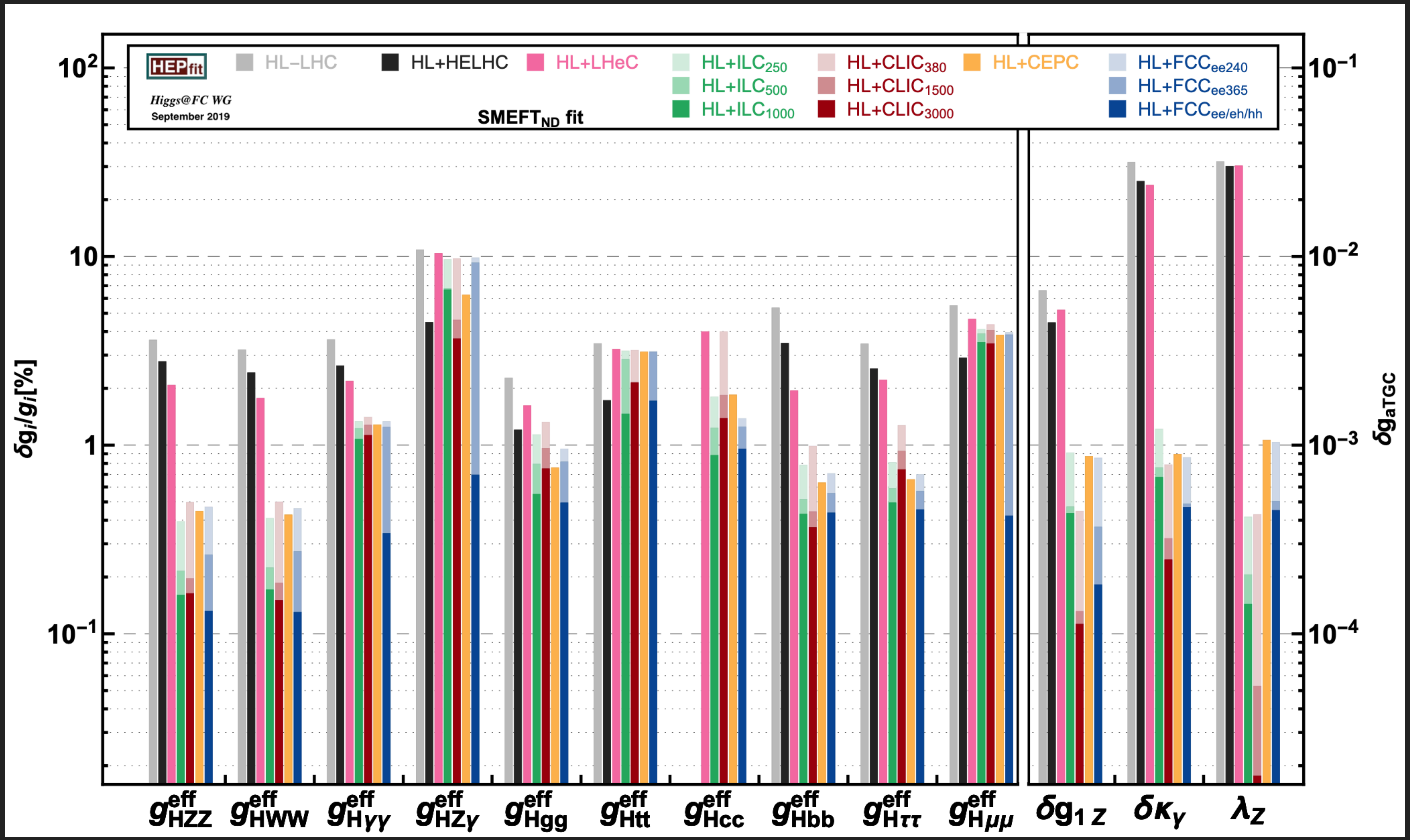
- Higgs dataset has large weight in TGC constraints [1304.1151]



- The 95% C.L. marginalized constraints



- LHC is entering an era of precision measurements with Run 3 and HL-LHC
- There is ongoing effort to guarantee it is success
- This demands a large effort form the experimental and theoretical communities



[1905.03764]

THANK YOU

FINAL REMARKS

$$\delta g_1^Z = \frac{v^2}{\Lambda^2}\frac{1}{c_W^2 - s_W^2}\left(\frac{s_w}{c_w}C_{HWB} + \frac{1}{4}C_{HD} + C_{H\ell}^{(3)} - \frac{1}{2}C_{\ell\ell}\right)$$

$$\kappa^Z = \frac{v^2}{\Lambda^2}\frac{1}{c_W^2 - s_W^2}\left(2s_W c_W C_{HWB} + \frac{1}{4}C_{HD} + C_{H\ell}^{(3)} - \frac{1}{2}C_{\ell\ell}\right)$$

$$\delta\kappa^\gamma = -\frac{v^2}{\Lambda^2}\frac{c_W}{s_W}C_{HBW}$$

$$\lambda^{\gamma/Z} = \frac{3M_W v}{\Lambda^2}C_{3W}$$