The global impact of EW + Higgs SMEFT probe

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The SMEFT

fundamental assumptions:

- new physics nearly decoupled: $\Lambda \gg (v, E)$
- at the accessible scale: **SM** fields + symmetries

a Taylor expansion in canonical dimensions (v/Λ or E/Λ):

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$

C_i free parameters (Wilson coefficients)
→ embed all UV information

$\mathcal{O}_i$ invariant operators that form
a complete, non redundant **basis**
→ embed the IR information

SMEFT at $d = 6$: the Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 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_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^\star \left(\varphi^\dagger D_\mu \varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

SMEFT at $d = 6$: the Warsaw basis

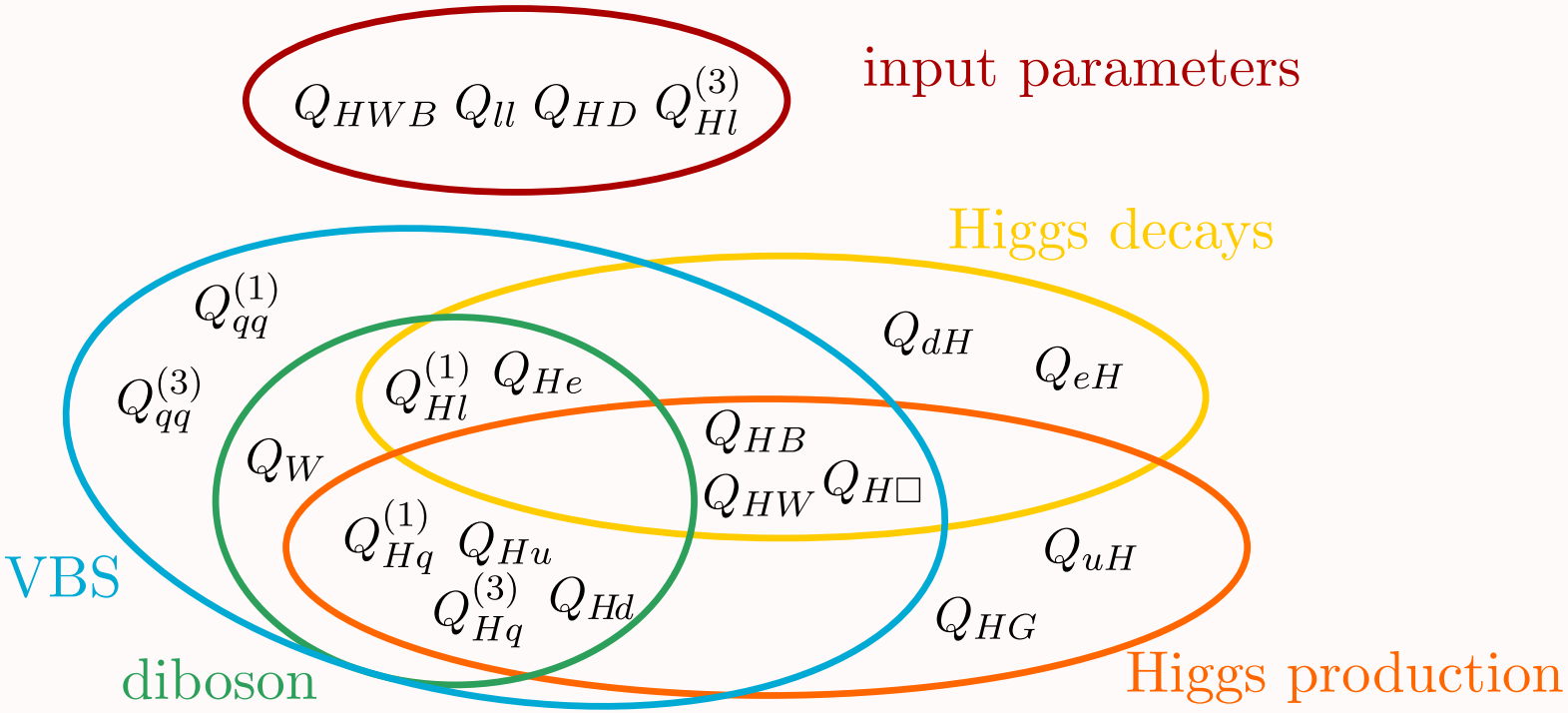
Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

SMEFT for EW and Higgs sectors

leading Warsaw basis operators in Higgs and EW processes: ~ 20



+ CP odd + flavor indices + others entering through loop corrections . . .

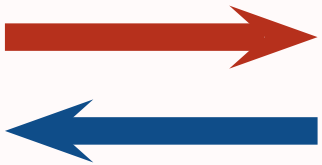
Higgs and EW complementarity

Higgs and gauge bosons are tied together by the **Higgs doublet** structure

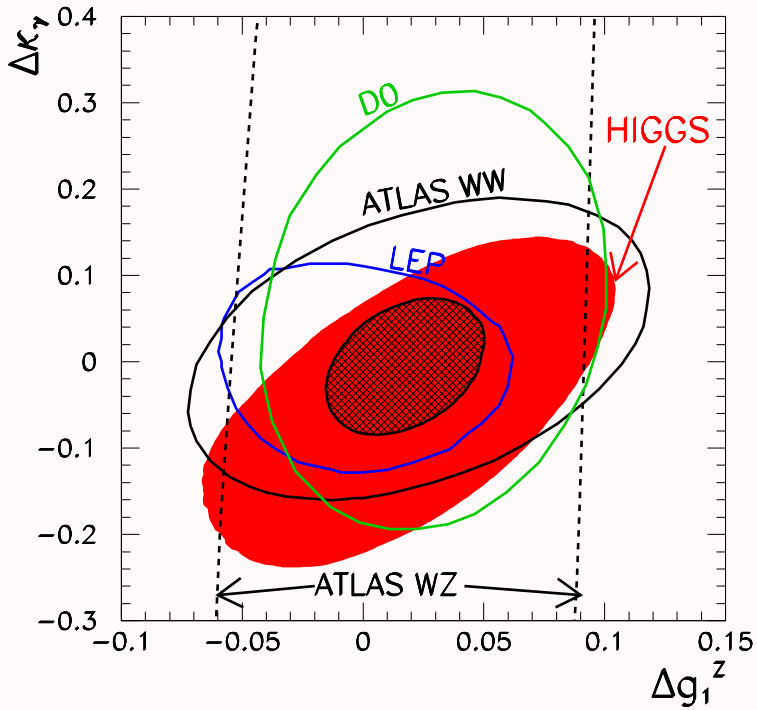
→ cannot be studied separately. rather: take advantage of symmetries
→ testing this relation: probe of Higgs nature / EWSB dynamics

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} i\pi^+ \\ v + h - i\sqrt{2}\pi^0 \end{pmatrix}$$

W_L ↑ $i\pi^+$; h ; $i\sqrt{2}\pi^0$ ↓ Z_L



⇝ Francesco's talk



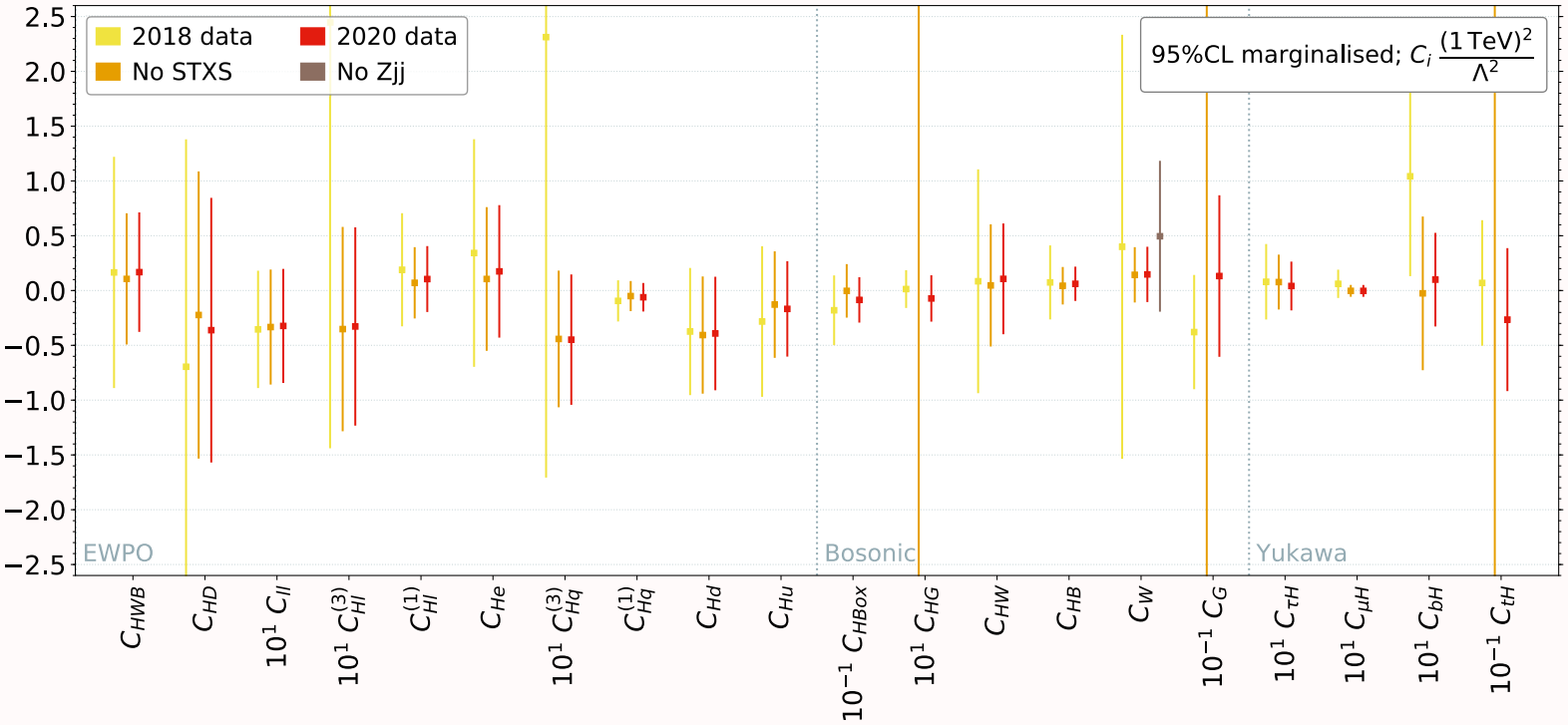
Corbett, Éboli, Gonzalez-Fraile, Gonzalez-Garcia 1304.1151

Higgs + EW interplay has been studied extensively

historically the first two sectors to be combined in **global fits**

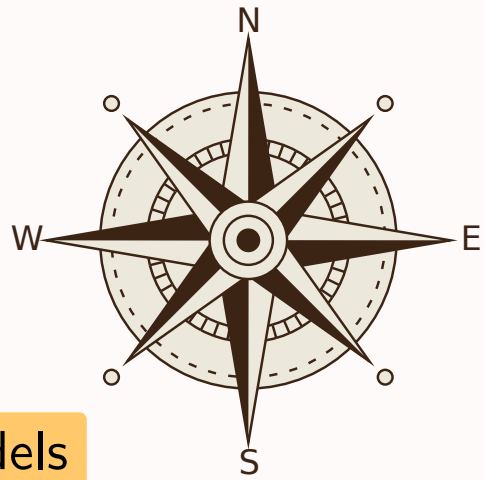
Ellis et al 1803.03252, (+top) **2012.02779**
da Silva Almeida et al 1812.01009
Biekötter et al 1812.07587
de Blas et al 1910.14012
Falkowski, Straub 1911.07866
Dawson,Homiller,Lane 2007.01296
...

typically: EWPO from LEP
+ diboson measurements (LEP2/LHC)
+ Higgs production/decay rates (STXS)



Interesting ingredients for future analyses

- Vector Boson Scattering, triboson, W/Z production in VBF ⇝ Davide's talk
- "more differential" measurements (both Higgs and EW) ⇝ Shanka's talk ⇝ Francesco's talk
- CP probes
- gauge bosons' polarizations
- SMEFT parameterization at NLO QCD and EW
- improved interpretation in terms of concrete BSM models
- relaxing flavor assumptions
  → needed for combination with top and flavor measurements
- ...



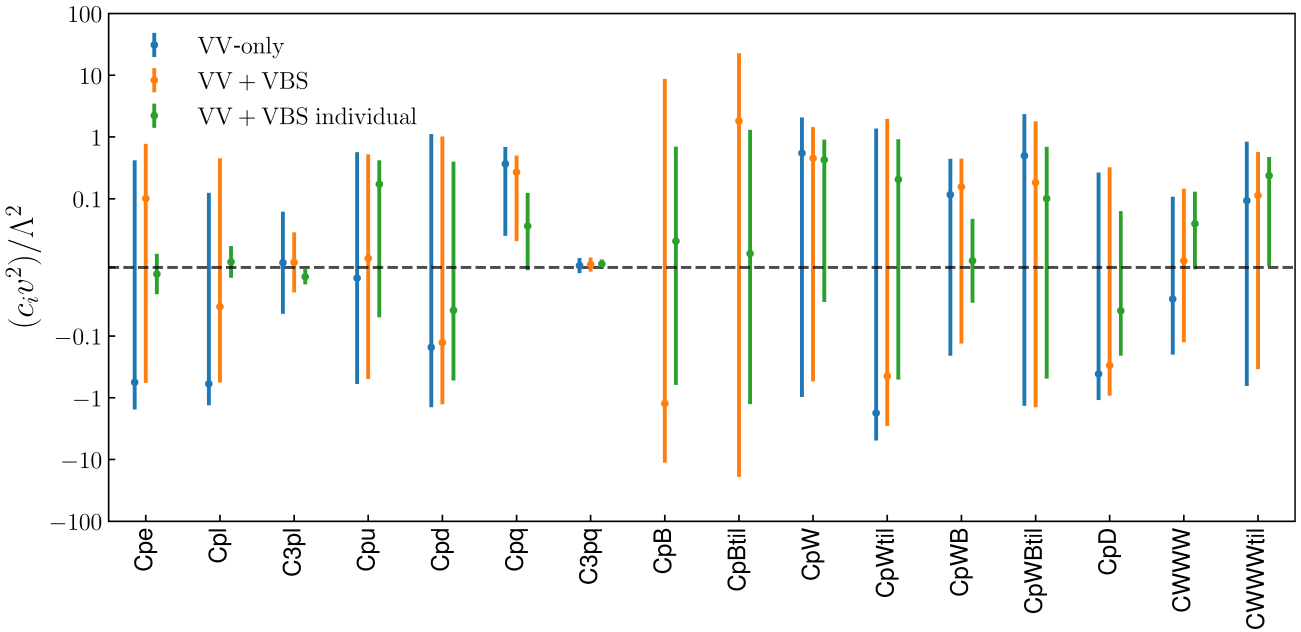
Vector Boson Scattering

SM/exp review: Covarelli,Pellen,Zaro 2102.10991

- directly sensitive to Higgs doublet structure in longitudinal channels
- together with triboson, tree-level probe of aQGC
- $\sim$ new measurements: some channels observed only recently
- historically mostly studied with $d = 8$ operators Eboli,Gonzalez-Garcia,Mizukoshi 0607118

more recently: VBS studies at $d = 6$
not included in global EW+H fits yet

Gomez-Ambrosio 1809.04189
Dedes,Kozow,Szleper 2011.07367
Ethier,Gomez-Ambrosio,Magni,Rojo **2101.03180**
Boldrini et al, in preparation



Vector Boson Scattering at $d = 6$

- strong sensitivity to **4 quark operators**

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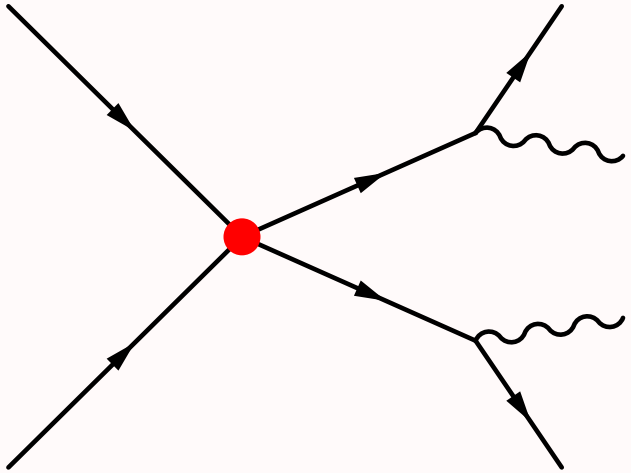
Boldrini et al, in preparation



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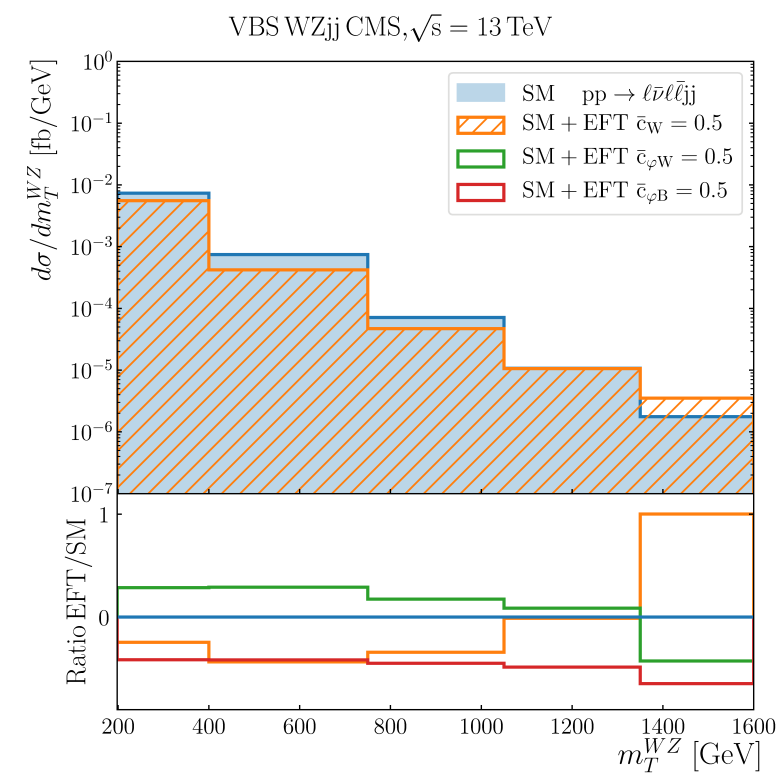
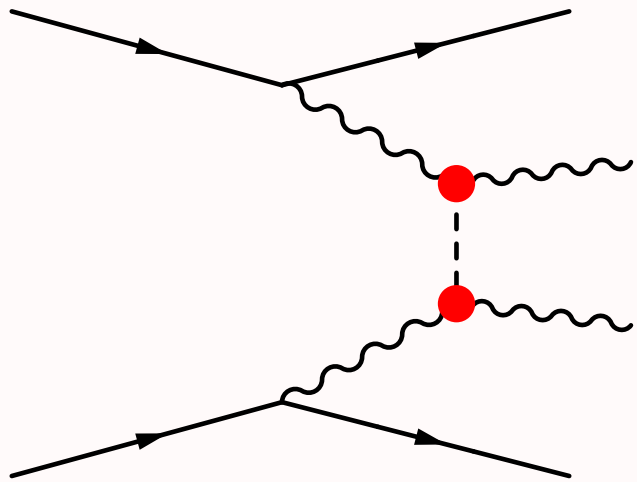
- sensitivity to **Higgs operators**

Gomez-Ambrosio 1809.04189
Boldrini et al, in preparation



Ethier et al 2101.03180



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Gomez-Ambrosio 1809.04189
Boldrini et al, in preparation

- sensitivity to **Higgs operators**
- aQGC at $d = 6$ come from input parameter corrections $+(W_{\mu\nu})^3$

  $\longrightarrow$ correlated to TGC and $Vff, HVV, \ldots$

  $\longrightarrow$ sensitivity to aQGC comes from all other vertices too!

⇝ backup

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Gomez-Ambrosio 1809.04189
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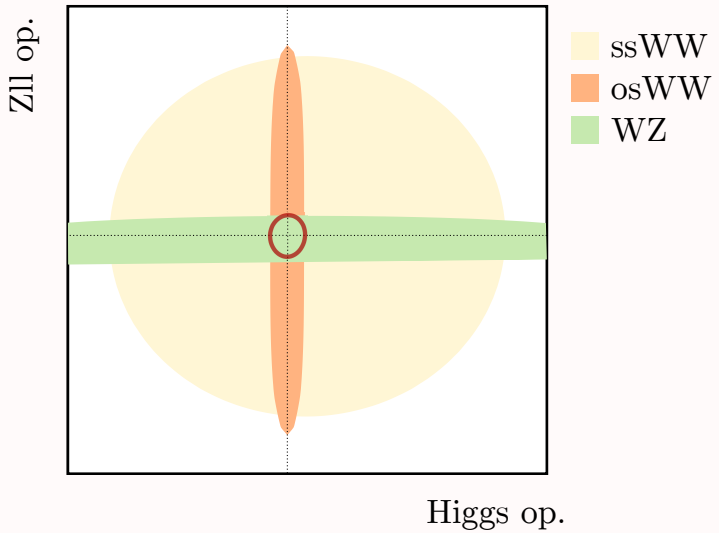
backup

- global analyses largely benefit from combining **several VBS channels**:

$$\{W^\pm W^\pm,\ W^\pm W^\mp,\ WZ,\ ZZ,\ W\gamma,\ Z\gamma\} \times \text{(leptonic/hadronic f. state)}$$



$(\gamma\gamma\ ?)$

More differential information

more statistics → finer binning higher-dim. histograms → better shape analyses interplay of kin. variables

one of the most important improvements for future runs.
not fully accounted for in current projections!

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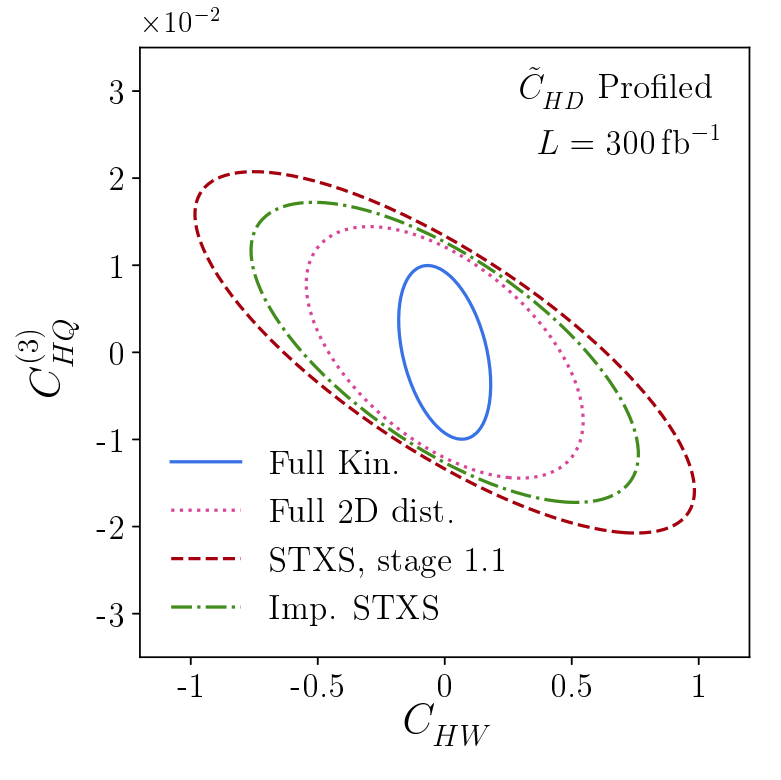

Brehmer,Dawson,Homiller,Kling, Plehn 1908.06980

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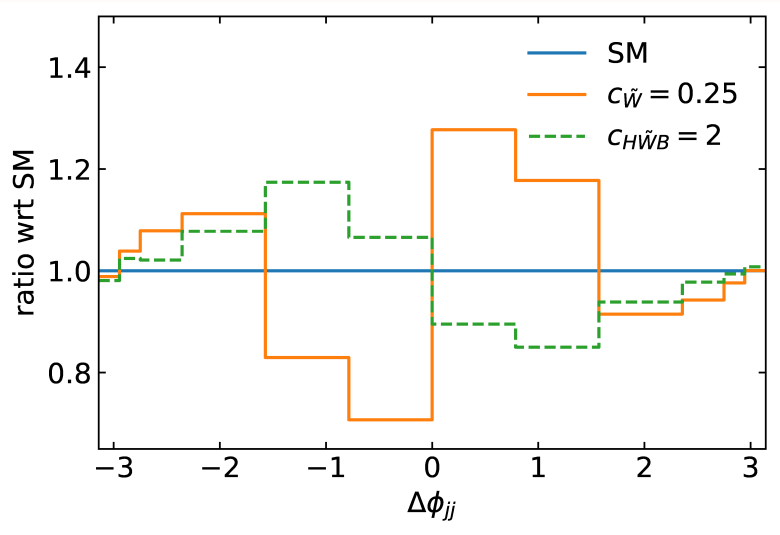
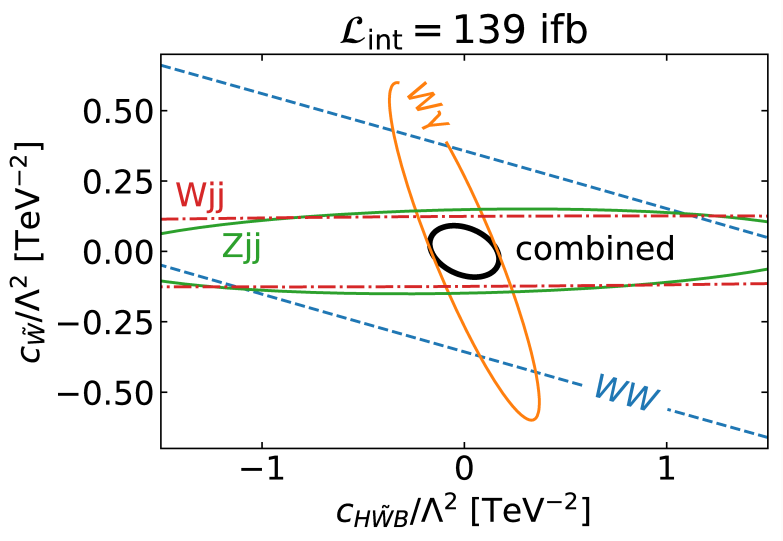
- access to CP properties





Biekötter,Gregg,Krauss,Schönherr 2102.01115

More differential information

more statistics → finer binning, higher-dim. histograms → better shape analyses, interplay of kin. variables

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- extract **more information** from each measurement
- more discriminating power between different shapes → operators
- access to CP properties
- access to polarizations → crucial for VBS, diboson
  → single out Goldstone boson contributions
  → more direct access to EWSB

Inclusion of NLO SMEFT corrections

EW + Higgs observables are sensitive to NLO SMEFT both in QCD and EW

- NLO QCD computed for diboson, EWPO, $h \to \bar{b}b, gg \to h, tth$, VH, VBF

  (Maltoni),Vryonidou,Zhang 1607.05330,1804.09766
  Degrande,Fuks,Matawari,Mimasy,Sanz 1609.04833
  Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460
  Baglio,Dawson,Lewis 1708.03332 1812.00214,1909.11576
  Alioli,Dekens,Mereghetti 1804.07407
  Grazzini,Ilnicka,Spira 1806.08832

  also automated Degrande et al 2008.11743

- NLO EW computed for EWPO, $h \to \gamma\gamma, h \to VV, h \to \bar{f}f$

  Hartmann,(Shepherd),Trott 1505.02646,1407.03568,1611.09879
  Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706
  (Gauld),Cullen,Pecjak,(Scott) 1512.02508,1607.06354,1904.06358,2007.15238
  Dawson,Giardino 1801.01136,1807.11504,1909.02000
  Dawson Ismail 1808.05948
  Dedes,(Paraskevas,Rosiek),Suxho,Trifyllis 1805.00302, 1903.12046

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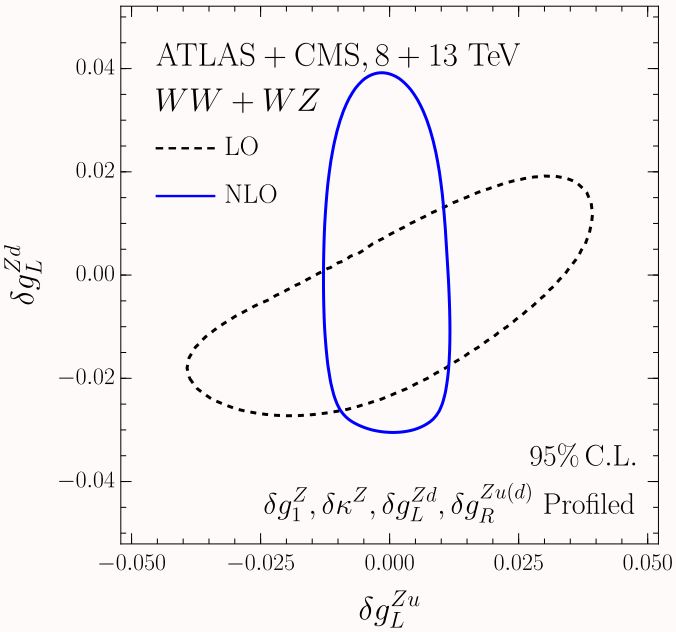
- NLO EW computed for EWPO, $h \to \gamma\gamma, h \to VV, h \to \bar{f}f$

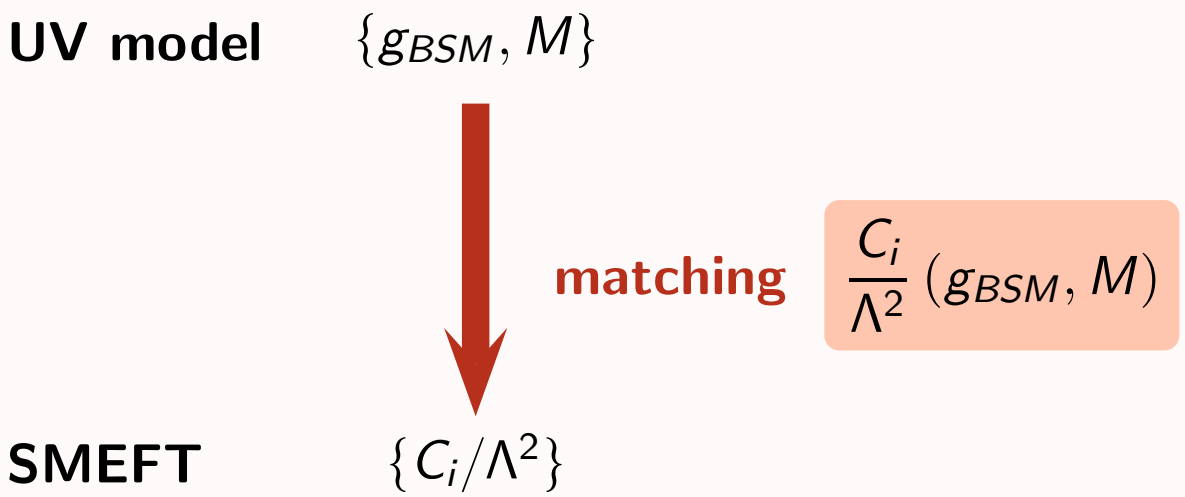
Impact on fits

- introduces dependence on **new operators** (particularly NLO EW)
- **restores some interference terms** that vanish at LO
- NLO QCD generally gives numerically large contributions



Baglio,Dawson,Homiller 1909.11576

Interpretation in terms of models



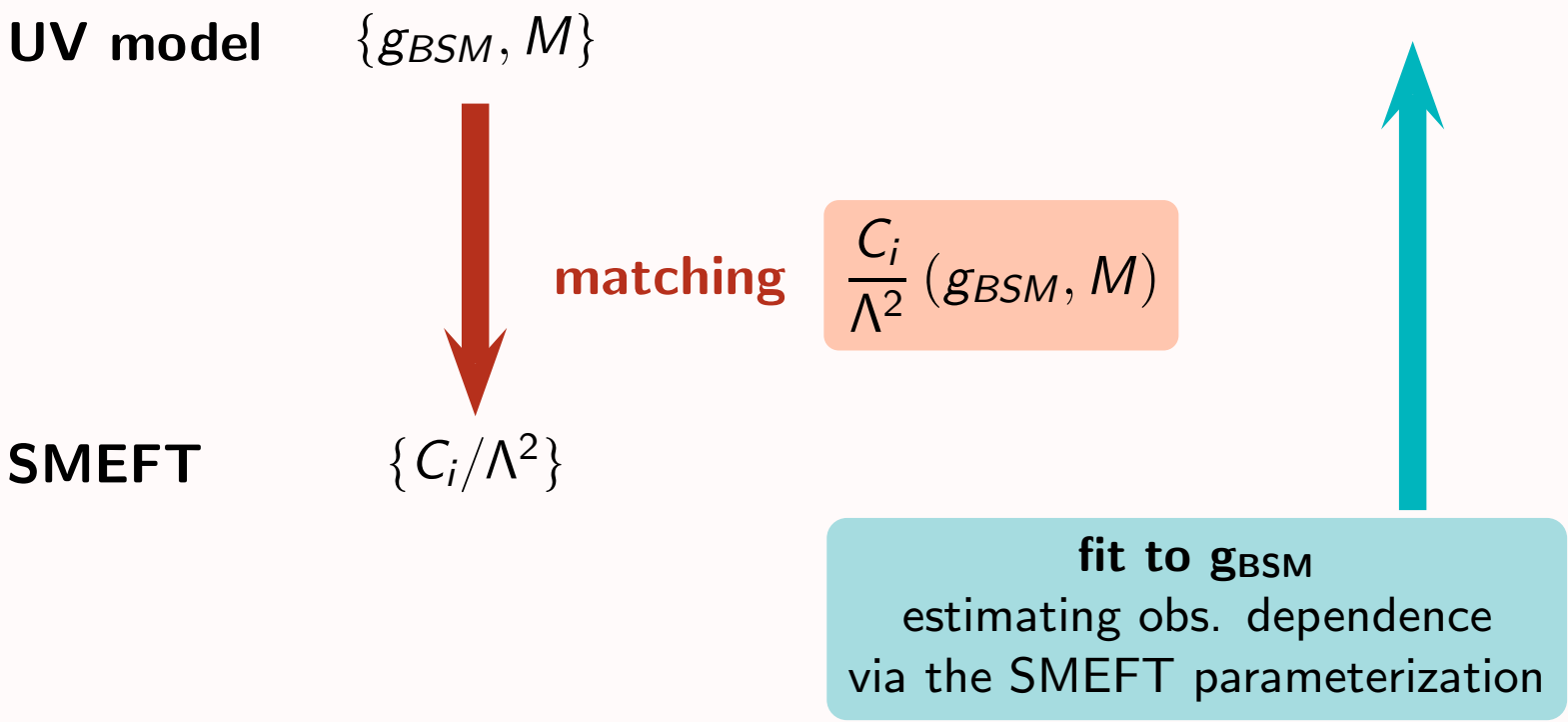
Matching up to 1-loop in UV model via functional methods

Henning,Lu,Murayama 1412.1837,1604.01019, del Aguila,Kunszt,Santiago 1602.00126
Drozd,Ellis,Quevillon,You 1512.03003
Boggia,Gomez-Ambrosio,Passarino 1603.03660
Ellis,Quevillon,(Vuong),You,Zhang 1604.02445,1706.07765,2006.16260
Fuentes-Martin,Portoles,Ruiz-Femenia 1607.02142, Zhang 1610.00710,
Cohen,Lu,Zhang 2011.02484, (Krämer),Summ,Voigt 1806.05171,1908.04798

automated:

Criado 1710.06445, Bashki,Chakrabortty,Kumar Patra 1808.04403
Cohen,Lu,Zhang 2012.07851
Fuentes-Martin,König,Pagès,Thomsen,Wilsch 2012.08506

Interpretation in terms of models

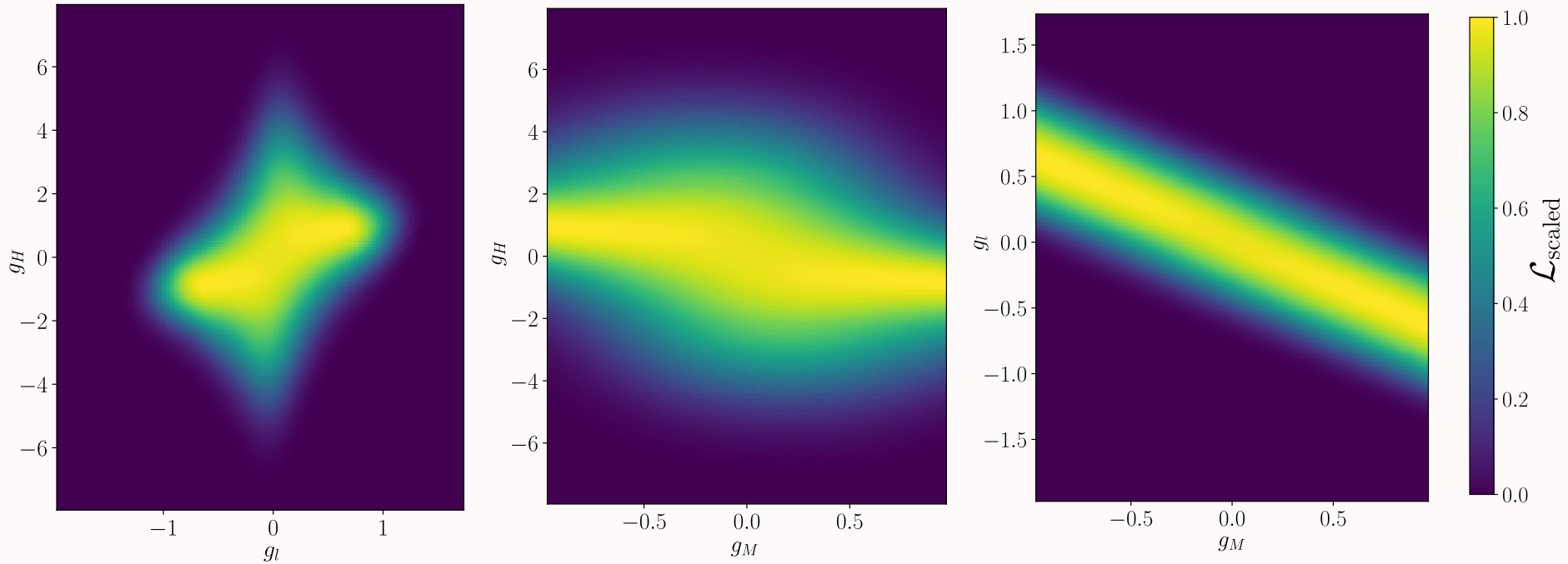


Gorbahn,No,Sanz 1502.07352, Drozd,Ellis,Quevillon,You 1504.02409
Ellis,(Madigan,Mimasu,Murphy),Sanz,You 1803.03252,2012.02779
Dawson,Homiller,Lane 2007.01296,2102.02823
Bakshi,Chakrabortty,Englert,Spannowsky,Stylianou 2009.13394
Anisha,Bakshi,Chakrabortty,Kumar Patra 2010.04088

Example: Heavy Vector Triplet

Brivio,Bruggisser,Geoffray,Luchmann,Krämer,Plehn,Summ in preparation

$$\mathcal{L}_V = -\frac{1}{4} V^i_{\mu\nu} V^{i\mu\nu} - \frac{g_M}{2} V^i_{\mu\nu} W^{i\mu\nu} + \frac{m_V^2}{2} V^i_\mu V^{i\mu} + \frac{g_H}{2} V^i_\mu (H^\dagger i \overleftrightarrow{D}^{i\mu} H) + \frac{g_l}{2} V^-_\mu \bar{\ell} \gamma^\mu \sigma^i \ell + \dots$$



tree-level matching

$m_V = 4$ TeV

all plots PRELIMINARY!

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Brivio,Bruggisser,Geoffray,Luchmann,Krämer,Plehn,Summ in preparation

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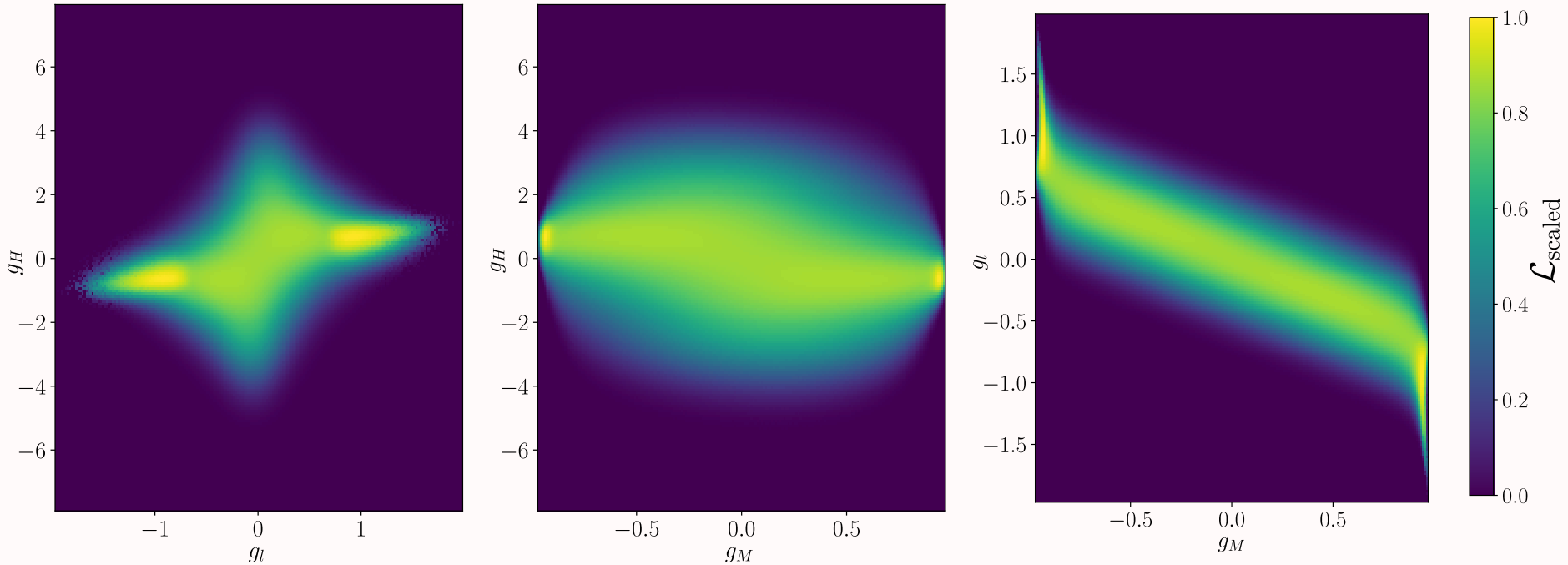

1-loop matching

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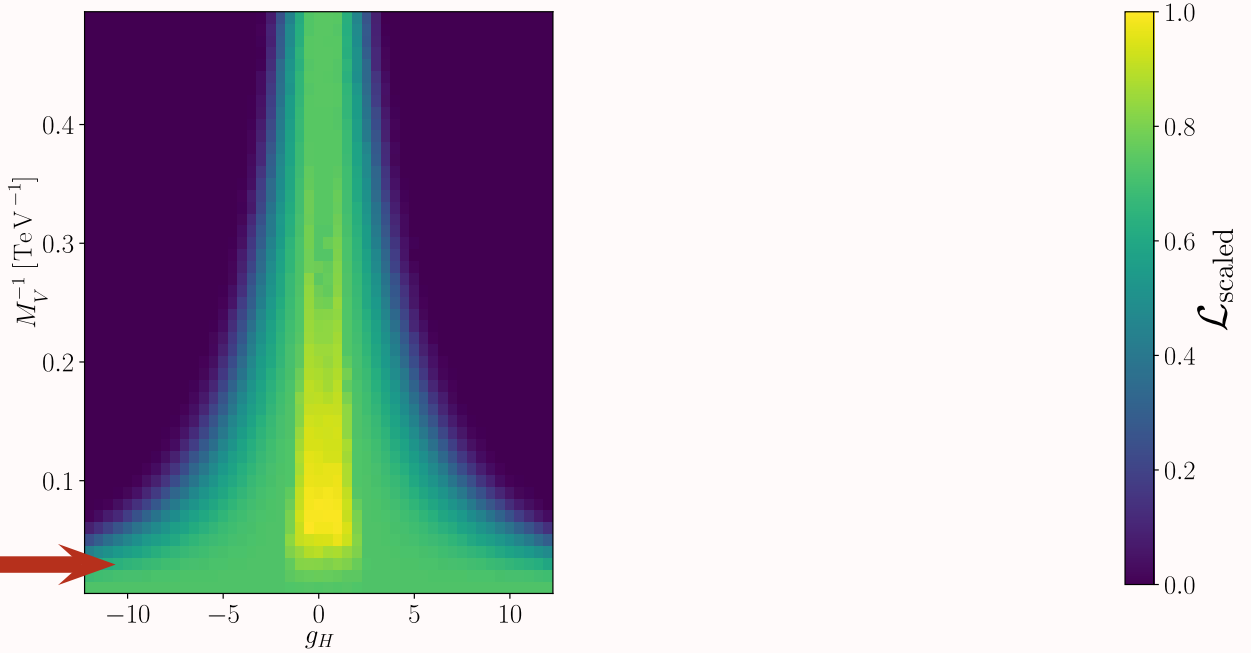
all plots PRELIMINARY!

Example: Heavy Vector Triplet

Brivio,Bruggisser,Geoffray,Luchmann,Krämer,Plehn,Summ in preparation

$$\mathcal{L}_V = -\frac{1}{4} V^i_{\mu\nu} V^{i\mu\nu} - \frac{g_M}{2} V^i_{\mu\nu} W^{i\mu\nu} + \frac{m_V^2}{2} V^i_\mu V^{i\mu} + \frac{g_H}{2} V^i_\mu (H^\dagger i \overleftrightarrow{D}^{i\mu} H) + \frac{g_l}{2} V^-_\mu \bar{\ell} \gamma^\mu \sigma^i \ell + \dots$$



decoupling limit

m_V as a free parameter!

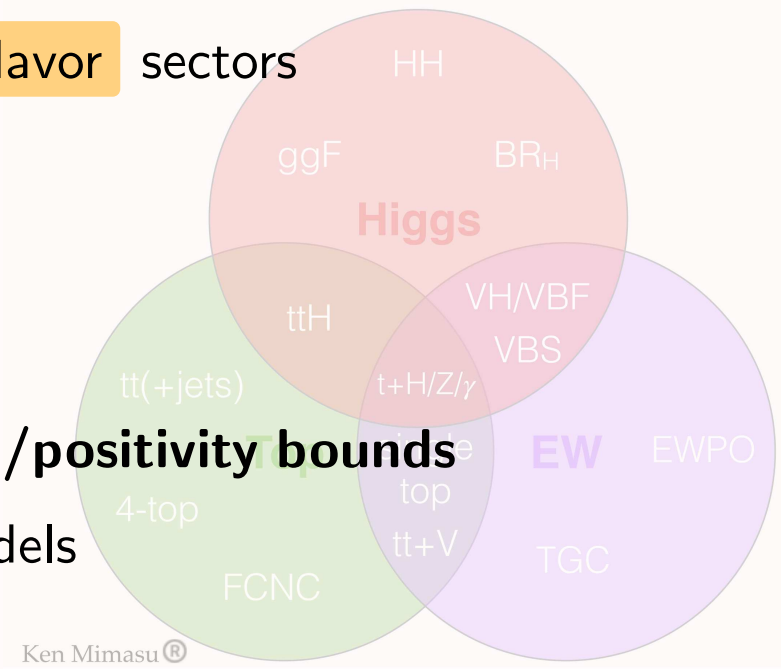
(g_H, m_V^{-1}) projection from 3-param. fit

all plots PRELIMINARY!

Future directions & challenges

Direction and upcoming theory improvements:

- larger fits: combinations with top and flavor sectors
- combined analyses within experiments
- relaxing flavor assumptions
- introducing **SMEFT uncertainties**
- incorporating theory constraints: **unitarity/positivity bounds**
- streamlining interpretation in terms of models



Challenges:

- reduction of TH uncertainties, especially in high-E tails
- polarized measurements
- streamlining SMEFT at NLO EW
- understanding SMEFT in PDFs, hadronization etc
- ...

⇝ Maria's talk