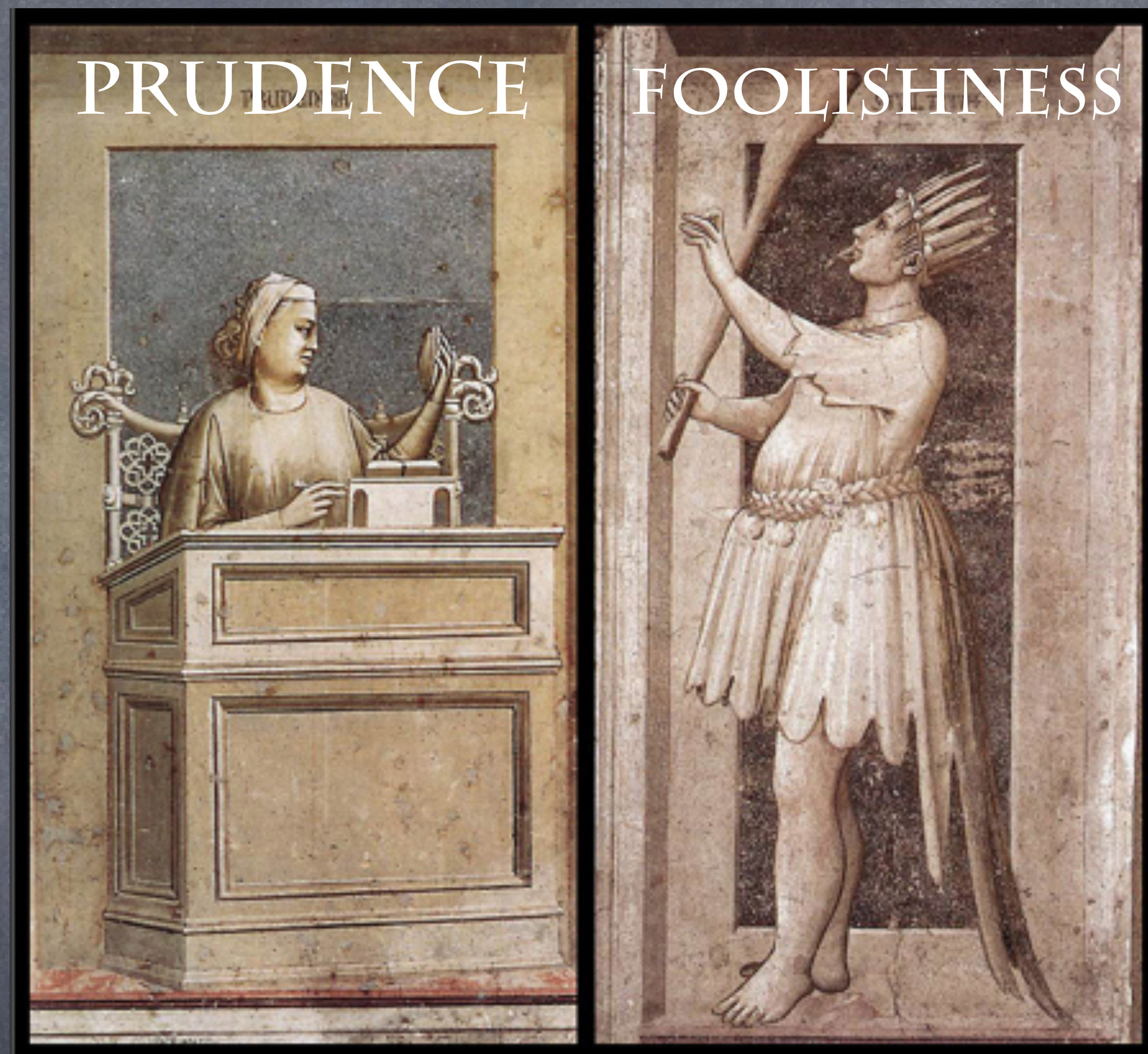
Vices and Virtues of VH/VBF Processes at High-E

$E < M_{cut}$



$E > M_{cut}$

Francesco Riva (EPFL - Lausanne)

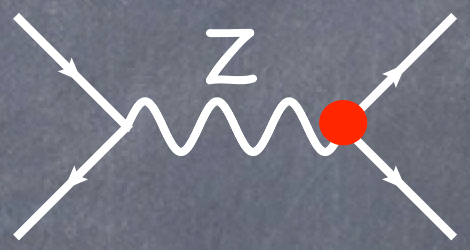
In Collaboration with:
Pomarol, Gupta, Liu, Rattazzi,
Knochel, Biekötter, Krämer

(1308.2803, 1405.0181, 1406.7320, xxx)

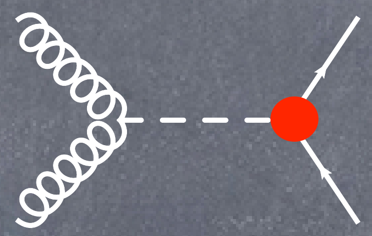
Motivation (an analogy)

1) Resonant processes in the SM

LEP: Z-pole



LHC: h-pole

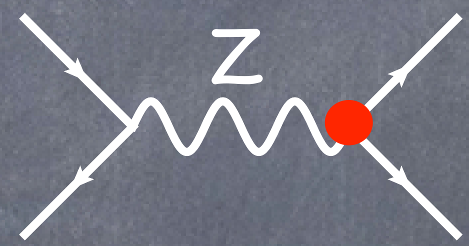


➔ Sensitive to BSM modifications of SM-like vertices

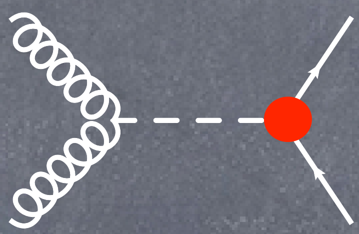
Motivation (an analogy)

1) Resonant processes in the SM

LEP: Z-pole



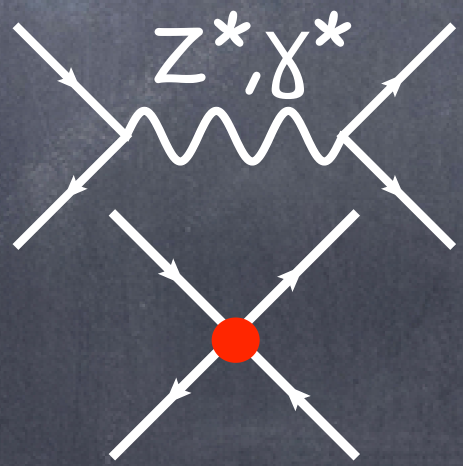
LHC: h-pole



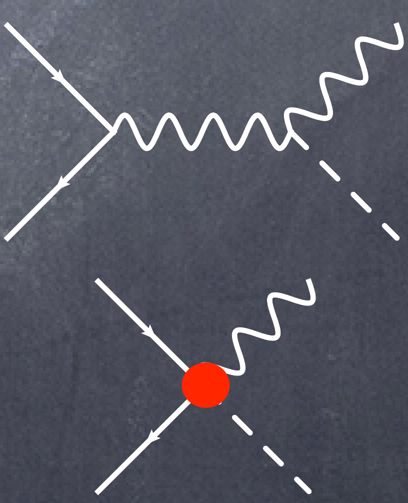
➔ Sensitive to BSM modifications of SM-like vertices

2) Processes that in the SM are off-shell

LEP2: off Z-pole



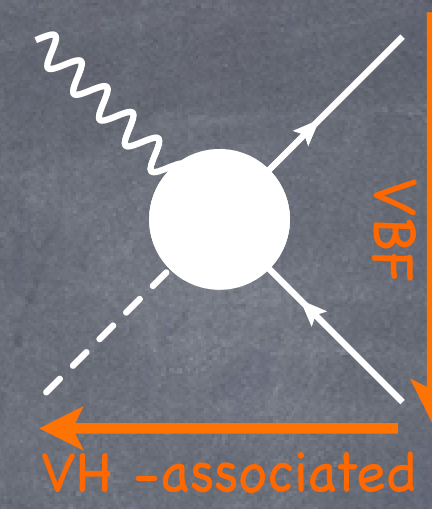
LHC: VH,VBF,h*->ZZ,...



➔ Sensitive to other BSM interactions that affect distributions
Best visible at $E \gtrless m_{h,Z}$

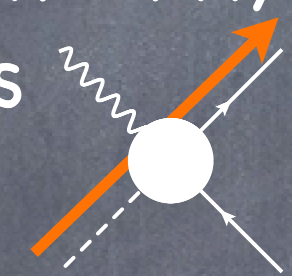
Ellis,Sanz,You'13; Englert,McCullough'13; Artoisenet et al.'13; Isidori,Trott'13; Edezhath'15

EFT



What physics can we learn about in this process?

- Light New Physics better searched using h->Vff, with E<m_h more sensitive to light particles



Isidori,Manohar,Trott'13;
Gonzalez-Alonso,Isidori'14;
Falkowski,Vega-Morales'14

- Heavy New Physics: EFT expansion convenient

$$\mathcal{L}_{\rm eff} = \frac{M_{cut}^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{M_{cut}}\,,\ \frac{g_* H}{M_{cut}}\,,\ \frac{g_* f_{L,R}}{M_{cut}^{3/2}}\,,\ \frac{g F_{\mu\nu}}{M_{cut}^2}\right) \simeq \overset{\text{SM}}{\mathcal{L}_4} + \mathcal{L}_6 + \cdots,$$

$$\mathcal{L}_6 = \sum_i \frac{c_i}{M_{cut}^2}\mathcal{O}_i$$

$$\boxed{\frac{1}{\Lambda_i} \equiv \frac{c_i}{M_{cut}^2}}$$

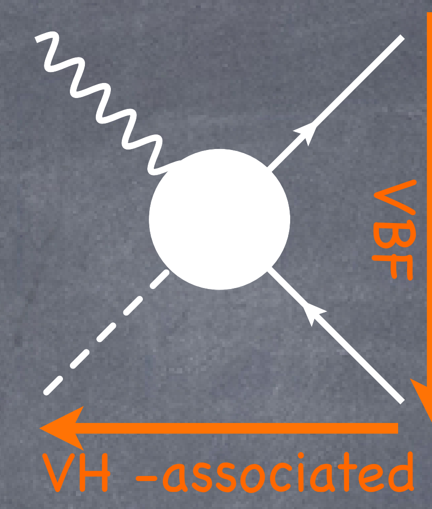
Fermi theory:

$$M_{cut} = m_W$$

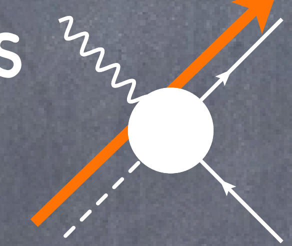
$$\Lambda = v \simeq \frac{M_{cut}}{g}$$

EFT

What physics can we learn about in this process?



- Light New Physics better searched using h->Vff, with E<m_h more sensitive to light particles



Isidori,Manohar,Trott'13;
Gonzalez-Alonso,Isidori'14;
Falkowski,Vega-Morales'14

- Heavy New Physics: EFT expansion convenient

$$\mathcal{L}_{\text{eff}} = \frac{M_{cut}^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{M_{cut}}\,,\ \frac{g_* H}{M_{cut}}\,,\ \frac{g_* f_{L,R}}{M_{cut}^{3/2}}\,,\ \frac{g F_{\mu\nu}}{M_{cut}^2}\right) \simeq \underset{SM}{\mathcal{L}_4} + \mathcal{L}_6 + \cdots,$$

$$\mathcal{L}_6 = \sum_i \frac{c_i}{M_{cut}^2}\mathcal{O}_i$$

$$\boxed{\frac{1}{\Lambda_i} \equiv \frac{c_i}{M_{cut}^2}}$$

Fermi theory:

$M_{cut} = m_W$

$\Lambda = v \simeq \dfrac{M_{cut}}{g}$

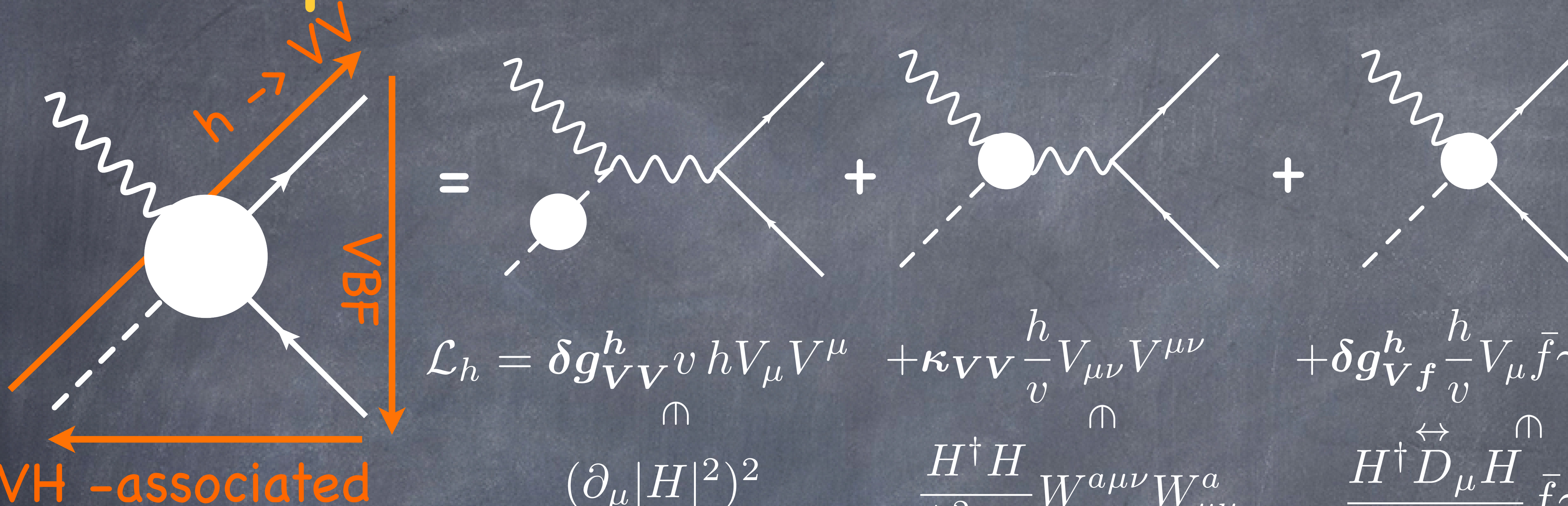
➔ Assume $E \ll M_{cut}$

➔ In some specific cases $\dfrac{M_{cut}}{4\pi} < \Lambda_i < M_{cut}$

Ultimate cutoff: at $E = 4\pi\Lambda$
EFT becomes strongly coupled

e.g. strongly coupled version of
Fermi theory: $\Lambda = \dfrac{m_*}{g_*} \ll m_* = M_{cut}$

EFT parametrization of VH/VBF



$$\mathcal{L}_h = \boldsymbol{\delta g^h_{VV}}\, v\, h V_\mu V^\mu \qquad + \boldsymbol{\kappa_{VV}} \frac{h}{v} V_{\mu\nu} V^{\mu\nu} \qquad + \boldsymbol{\delta g^h_{Vf}} \frac{h}{v} V_\mu \bar{f} \gamma^\mu f$$

$$\Cap \qquad\qquad \Cap \qquad\qquad \Cap$$

$$\frac{(\partial_\mu |H|^2)^2}{\Lambda_H^2} \qquad \frac{H^\dagger H}{\Lambda_{WW}^2} W^{a\mu\nu} W^a_{\mu\nu} \qquad \frac{H^\dagger \overleftrightarrow{D}_\mu H}{\Lambda_{HF}^2} \bar{f} \gamma^\mu f$$

SM rescaling
(like Run1)

Grows with E
Generally not valid at E>M

Grows fast with E
(No V propagator)
Can have $\Lambda < M_{cut}$ if f,H composite
Can have flavor structure

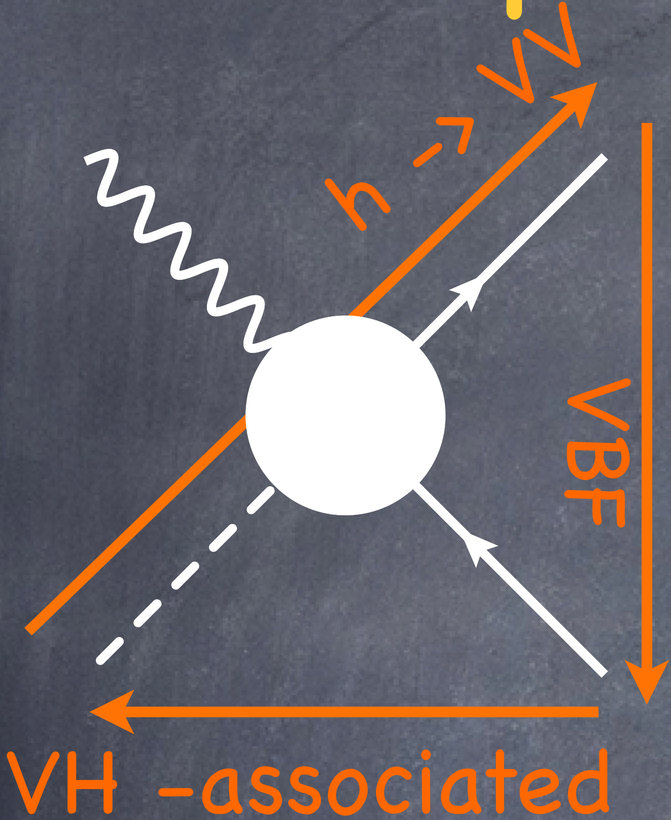
Isidori,Trott'13;
Gupta,Pomarol,FR'13-14-15(to appear)

$\boxed{\bar{q}q \to W^+ h :}$

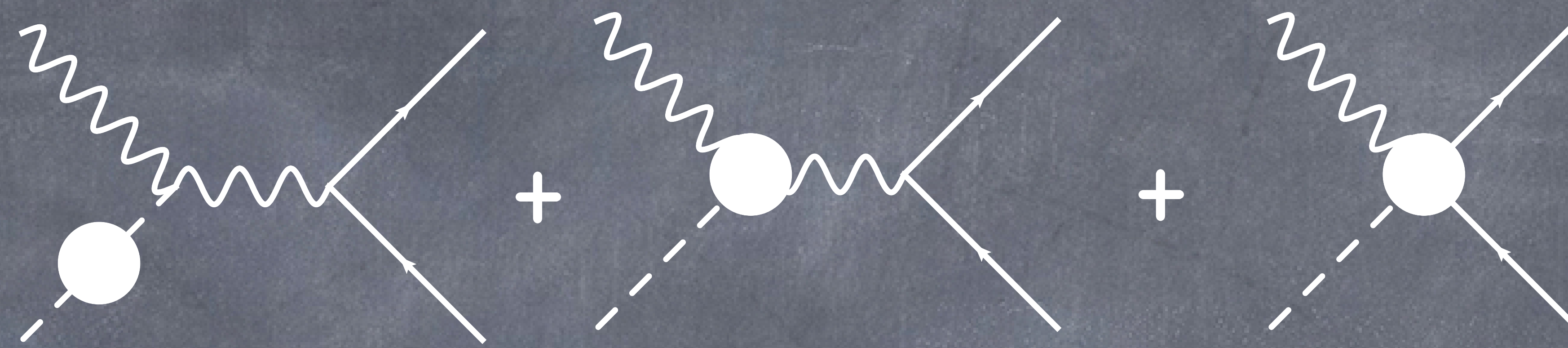
$$\int d\cos\theta |\mathcal{M}_L|^2 \underset{(s \gg m_W)}{\longrightarrow} \frac{g^4}{6}\left(1 - \frac{v^2}{\Lambda_H^2} + 4\frac{\hat{s}}{g^2 \Lambda_{HQ'}^2} + 4\frac{m_W^2}{\Lambda_{WW}^2} + 4\frac{v^2}{\Lambda_{HQ'}^2}\right)^2$$

Biekotter,Knochel,Kramer,Liu,FR'14; Pomarol'14;

EFT parametrization of VH/VBF



=



$$\mathcal{L}_h = \delta g^h_{VV}\, v\, h V_\mu V^\mu \quad + \kappa_{VV}\frac{h}{v}V_{\mu\nu}V^{\mu\nu} \quad + \delta g^h_{Vf}\frac{h}{v}V_\mu \bar f \gamma^\mu f$$

$\cap$ $\frac{(\partial_\mu |H|^2)^2}{\Lambda_H^2}$

SM rescaling
(like Run1)

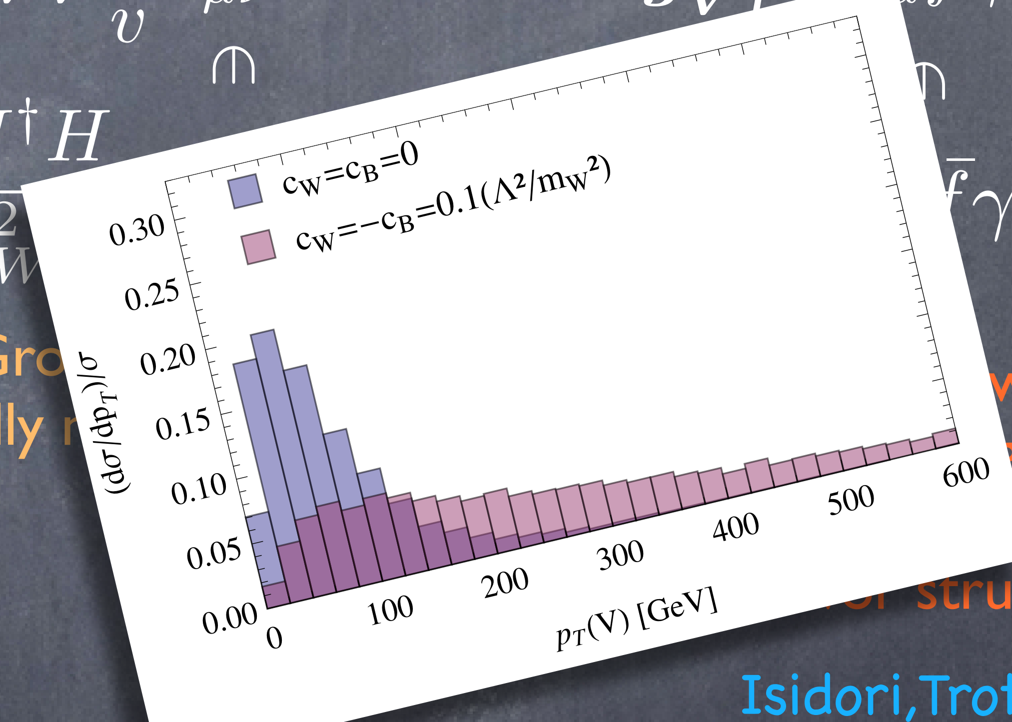
$\cap$ $\frac{H^\dagger H}{\Lambda_W^2}$

Gro

Generally r

$\cap$ $\bar f \gamma^\mu f$

with E
gator)
osite
r structure



Isidori,Trott'13;
Gupta,Pomarol,FR'13-14-15(to appear)

$\boxed{\bar q q \to W^+ h :}$

$$\int d\cos\theta |\mathcal{M}_L|^2 \underset{(s \gg m_W)}{\longrightarrow} \frac{g^4}{6}\left(1-\frac{v^2}{\Lambda_H^2}+4\frac{\hat s}{g^2\Lambda_{HQ'}^2}+4\frac{m_W^2}{\Lambda_{WW}^2}+4\frac{v^2}{\Lambda_{HQ'}^2}\right)^2$$

Biekotter,Knochel,Kramer,Liu,FR'14; Pomarol'14;

Confronting Data

$$\int d\cos\theta |\mathcal{M}|^2 \quad \rightarrow \quad \frac{g^4}{6}\left(1 + 8\frac{\hat{s}}{g^2\Lambda^2_{HQ'}}\right) + \cdots$$

ATLAS-CONF-2013-079

3-jet, 2-tag sample													
	0-lepton			1-lepton					2-lepton				
Process	E_T^{miss} [GeV]			p_T^W [GeV]					p_T^Z [GeV]				
	120-160	160-200	>200	0-90	90-120	120-160	160-200	> 200	0-90	90-120	120-160	160-200	>200
$Z \to \nu\nu$	0.4	0.2	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
$Z \to \ell\ell$	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	0.9	0.3	0.2	0.1	0.1
$W \to \ell\nu$	0.1	0.1	<0.1	2.1	0.6	0.5	0.5	0.6	<0.1	<0.1	<0.1	<0.1	<0.1
VH total	0.5	0.3	0.4	2.2	0.6	0.5	0.5	0.6	0.9	0.3	0.2	0.1	0.1
VH expected	2.7	1.6	1.9	12	3.2	2.6	2.8	3.4	4.9	1.4	1.1	0.6	0.7
Top	169	44	13	4444	1171	592	238	121	114	22	5.5	0.3	<0.1
W+c, light	7.1	2.1	1.2	189	23	11.7	6.8	5.4	<0.1	<0.1	<0.1	<0.1	<0.1
W+b	12	4.7	3.3	318	36	21	14	12	<0.1	<0.1	<0.1	<0.1	<0.1
Z+c, light	6.3	2.8	2.5	8.8	0.9	0.4	0.2	0.1	53	9.6	4.5	1.4	1.2
Z+b	59	26	17	56	6.9	2.5	1.4	0.7	509	91	45	12	7.6
WW	0.2	0.1	0.1	4.0	0.5	0.3	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
VZ	3.7	1.8	2.3	31	4.7	3.1	2.5	3.7	20.1	3.1	1.6	0.9	1.2
Multijet	3.1	0.6	0.4	425	17	5.5	3.0	0.8	<0.1	<0.1	<0.1	<0.1	<0.1
Total Bkg.	260	82	40	5476	1260	637	266	143	696	125	57	15	10
	± 6	± 2	± 1	± 57	± 17	± 11	± 7	± 5	± 16	± 3	± 2	± 1	± 1
Data	287	59	40	5523	1233	639	249	154	734	119	56	13	9
S/B	0.002	0.004	0.009	0.0004	0.0005	0.0008	0.002	0.004	0.001	0.002	0.004	0.008	0.01

Experiments insensitive to small departures from SM

Confronting Data

$$\int d\cos\theta |\mathcal{M}|^2 \quad \rightarrow \quad \frac{g^4}{6}\Bigg(\underbrace{1}_{\text{SM}} + \underbrace{8\frac{\hat{s}}{g^2\Lambda^2_{HQ'}}}_{\text{BSM}} \Bigg) + \cdots$$

ATLAS-CONF-2013-079

3-jet, 2-tag sample													
	0-lepton			1-lepton					2-lepton				
Process	E_T^{miss} [GeV]			p_T^W [GeV]					p_T^Z [GeV]				
	120-160	160-200	>200	0-90	90-120	120-160	160-200	> 200	0-90	90-120	120-160	160-200	>200
$Z \to \nu\nu$	0.4	0.2	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
$Z \to \ell\ell$	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	0.9	0.3	0.2	0.1	0.1
$W \to \ell\nu$	0.1	0.1	<0.1	2.1	0.6	0.5	0.5	0.6	<0.1	<0.1	<0.1	<0.1	<0.1
VH total	0.5	0.3	0.4	2.2	0.6	0.5	0.5	0.6	0.9	0.3	0.2	0.1	0.1
VH expected	2.7	1.6	1.9	12	3.2	2.6	2.8	3.4	4.9	1.4	1.1	0.6	0.7
Top	169	44	13	4444	1171	592	238	121	114	22	5.5	0.3	<0.1
W+c, light	7.1	2.1	1.2	189	23	11.7	6.8	5.4	<0.1	<0.1	<0.1	<0.1	<0.1
W+b	12	4.7	3.3	318	36	21	14	12	<0.1	<0.1	<0.1	<0.1	<0.1
Z+c, light	6.3	2.8	2.5	8.8	0.9	0.4	0.2	0.1	53	9.6	4.5	1.4	1.2
Z+b	59	26	17	56	6.9	2.5	1.4	0.7	509	91	45	12	7.6
WW	0.2	0.1	0.1	4.0	0.5	0.3	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
VZ	3.7	1.8	2.3	31	4.7	3.1	2.5	3.7	20.1	3.1	1.6	0.9	1.2
Multijet	3.1	0.6	0.4	425	17	5.5	3.0	0.8	<0.1	<0.1	<0.1	<0.1	<0.1
Total Bkg.	260 ± 6	82 ± 2	40 ± 1	5476 ± 57	1260 ± 17	637 ± 11	266 ± 7	143 ± 5	696 ± 16	125 ± 3	57 ± 2	15 ± 1	10 ± 1
Data	287	59	40	5523	1233	639	249	154	734	119	56	13	9
S/B	0.002	0.004	0.009	0.0004	0.0005	0.0008	0.002	0.004	0.001	0.002	0.004	0.008	0.01

Experiments insensitive to small departures from SM

..but at high $\sqrt{s} > g\Lambda$ can have BSM>>SM

- The higher the energy (and hence the cutoff M_{cut}), the better the constraint on Λ

Confronting Data

$$\int d\cos\theta|\mathcal{M}|^2 \quad \to \quad \frac{g^4}{6}\left(\underbrace{1}_{\text{SM}}+\underbrace{8\frac{\hat{s}}{g^2\Lambda^2_{HQ'}}}_{\text{BSM}}\right)+\cdots$$

ATLAS-CONF-2013-079

3-jet, 2-tag sample													
	0-lepton			1-lepton					2-lepton				
Process	E_T^{miss} [GeV]			p_T^W [GeV]					p_T^Z [GeV]				
	120-160	160-200	>200	0-90	90-120	120-160	160-200	> 200	0-90	90-120	120-160	160-200	>200
$Z \to \nu\nu$	0.4	0.2	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
$Z \to \ell\ell$	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	0.9	0.3	0.2	0.1	0.1
$W \to \ell\nu$	0.1	0.1	<0.1	2.1	0.6	0.5	0.5	0.6	<0.1	<0.1	<0.1	<0.1	<0.1
VH total	0.5	0.3	0.4	2.2	0.6	0.5	0.5	0.6	0.9	0.3	0.2	0.1	0.1
VH expected	2.7	1.6	1.9	12	3.2	2.6	2.8	3.4	4.9	1.4	1.1	0.6	0.7
Top	169	44	13	4444	1171	592	238	121	114	22	5.5	0.3	<0.1
W+c, light	7.1	2.1	1.2	189	23	11.7	6.8	5.4	<0.1	<0.1	<0.1	<0.1	<0.1
W+b	12	4.7	3.3	318	36	21	14	12	<0.1	<0.1	<0.1	<0.1	<0.1
Z+c, light	6.3	2.8	2.5	8.8	0.9	0.4	0.2	0.1	53	9.6	4.5	1.4	1.2
Z+b	59	26	17	56	6.9	2.5	1.4	0.7	509	91	45	12	7.6
WW	0.2	0.1	0.1	4.0	0.5	0.3	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
VZ	3.7	1.8	2.3	31	4.7	3.1	2.5	3.7	20.1	3.1	1.6	0.9	1.2
Multijet	3.1	0.6	0.4	425	17	5.5	3.0	0.8	<0.1	<0.1	<0.1	<0.1	<0.1
Total Bkg.	260	82	40	5476	1260	637	266	143	696	125	57	15	10
	± 6	± 2	± 1	± 57	± 17	± 11	± 7	± 5	± 16	± 3	± 2	± 1	± 1
Data	287	59	40	5523	1233	639	249	154	734	119	56	13	9
S/B	0.002	0.004	0.009	0.0004	0.0005	0.0008	0.002	0.004	0.001	0.002	0.004	0.008	0.01

Experiments insensitive to small departures from SM

..but at high $\sqrt{s} > g\Lambda$ can have BSM>>SM

- The higher the energy (and hence the cutoff M_{cut}), the better the constraint on Λ

...but $\frac{M_{cut}}{\Lambda} = g_* < 4\pi$ is a measure of how strongly coupled the BSM is

- The higher M_{cut}, the less BSM scenarios can be matched to this analysis

Consistent&Conservative Bounds on Λ

- Information about cutoff $M_{cut} > \sqrt{s}$ (or equivalently g_*) and about observed constraint on Λ, are needed in order to match with explicit BSM

1. Use EFT $\mathcal{L}_{eff} = \sum_i \frac{\mathcal{O}}{\Lambda_i^2}$
2. For different M_{cut} simulate signal with constraint $\sqrt{s} < M_{cut}$

   → produce $\sigma_{\rm signal}(M_{cut}, \Lambda)$

3. Compare with data

$g_* = 4\pi$ (very strongly coupled BSM)

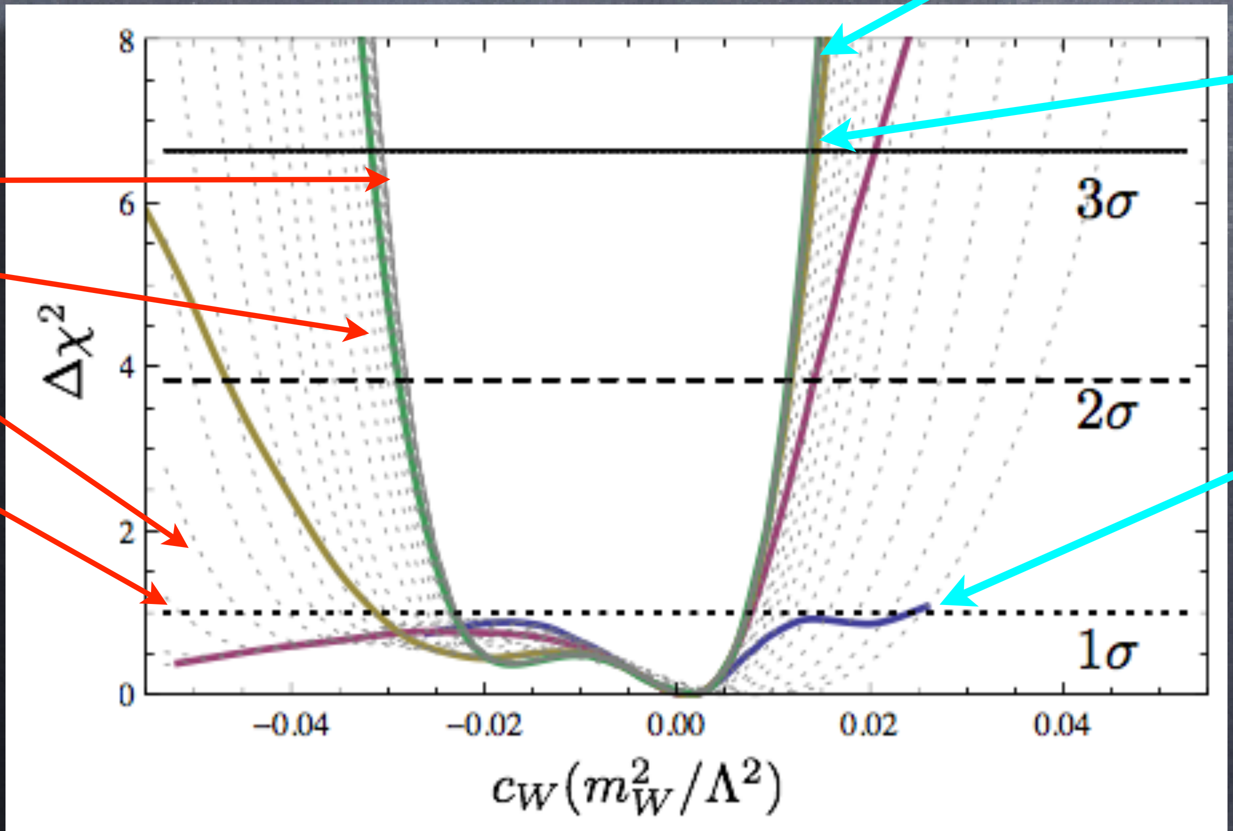
$M_{cut} = \infty$

$1\,\mathrm{TeV}$

$\vdots$

$550\,\mathrm{GeV}$

$500\,\mathrm{GeV}$

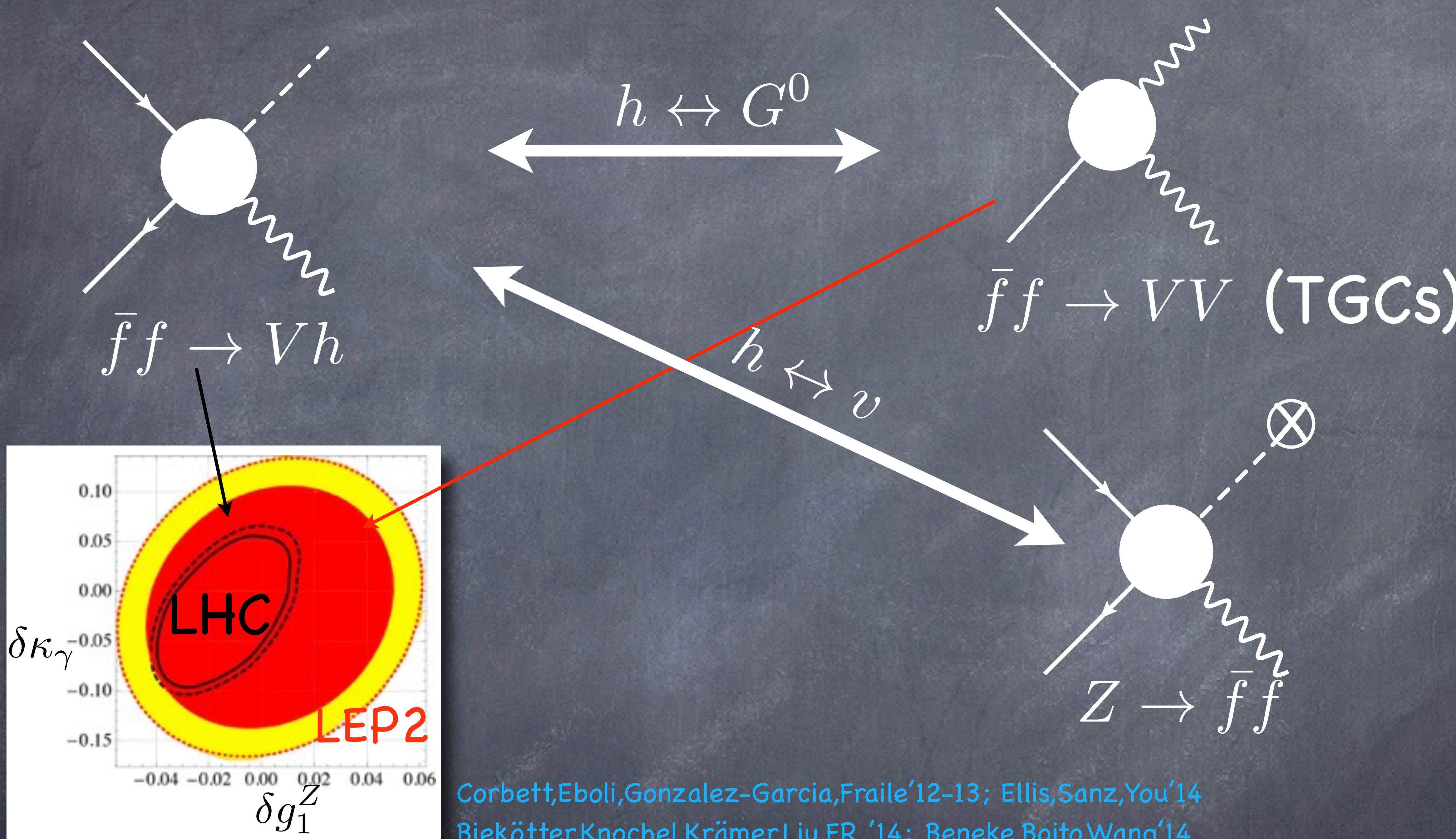


$g_* = 4$
Large-N/Holography
Composite Higgs

$g_* = g_L$
Weakly coupled
Z',...

Biekötter,Knochel,Krämer,Liu,FR '14

Comparison with Other Constraints



Corbett,Eboli,Gonzalez-Garcia,Fraile'12-13; Ellis,Sanz,You'14
Biekötter,Knochel,Krämer,Liu,FR '14; Beneke,Boito,Wang'14

In the extreme case $M_{cut} = 4\pi\Lambda$ LHC analyses can be trusted and can be competitive with and complementary to LEP (valid for all M_{cut}, g_*)

➜ Efforts to improve results at smaller $\sqrt{s}$ improve applicability of results

Conclusions

- VH/VBF can probe BSM effects invisible in h-decays
- At High-E, sensitivity on these (E-growing) effects higher (in particular on $H^\dagger D_\mu H \bar{f}\gamma^\mu f$ structure)
- At High-E, less BSM scenarios have valid EFT description (need strong coupling, e.g. strongly couple H and fermions)
  - Results ideally should be presented with different assumptions about the cutoff M_{cut} or BSM coupling g_*
  - Then, matching to any BSM Straightforward
- Other methods (e.g. dim-8 operators, form-factors that unitarize EFT,...) make BSM matching impossible
- Problem not new: in DM(monojet) searches with EFT description these methods are already used

See Racco,Wulzer,Zwirner'15 and ATLAS 1502.01518