HOW BEST TO USE LHC RESULTS AND EFT TO PROBE PHYSICS ABOVE THE SCALE OF THE LHC

Roberto Contino

EPFL & CERN

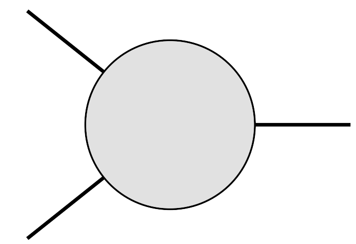
Based on: RC, Falkowski, Goertz, Grojean, Riva JHEP 1607 (2016) 144

Azatov, RC, Machado, Riva arXiv:1607.05236

A First Glance Beyond the Energy Frontier - 5-9 September 2016, Trieste

Looking for New Physics through Precision

- Exploiting the resonant production of a SM state (e.g. Z-pole or single-Higgs production)



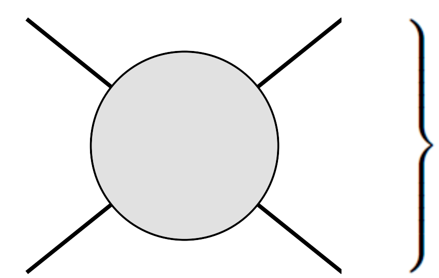
$E = m_h$

$$\frac{\delta c}{c} \sim \frac{g_*^2}{g_{SM}^2}\frac{m_h^2}{\Lambda^2}$$

$\Lambda =$ scale of NP

$g_* =$ coupling strength of the new states with the Higgs boson

- Exploiting the high-energy behavior of non-resonant processes



$E \gg m_h$

$$\frac{\delta \mathcal{A}}{\mathcal{A}} \sim \frac{g_*^2}{g_{SM}^2}\frac{E^2}{\Lambda^2}$$

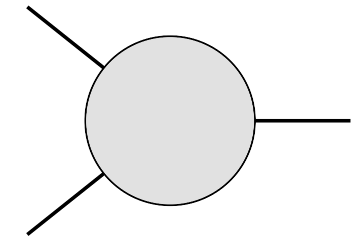
Examples:

- $q\bar{q} \to WV\,(\mathrm{TGC}) + HV \qquad (V = W, Z)$
- Vector boson scattering $VV \to VV$
- Double Higgs production $gg \to HH$
- H+jet associated production

$\vdots$

Looking for New Physics through Precision

- Exploiting the resonant production of a SM state (e.g. Z-pole or single-Higgs production)



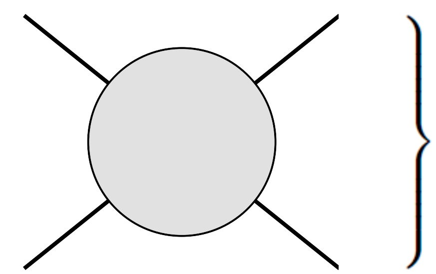
$E = m_h$

$$\frac{\delta c}{c} \sim \frac{g_*^2}{g_{SM}^2} \frac{m_h^2}{\Lambda^2}$$

$\Lambda =$ scale of NP

$g_* =$ coupling strength of the new states with the Higgs boson

- Exploiting the high-energy behavior of non-resonant processes



$E \gg m_h$

$$\frac{\delta \mathcal{A}}{\mathcal{A}} \sim \frac{g_*^2}{g_{SM}^2} \frac{E^2}{\Lambda^2}$$

Examples:
- $q\bar{q} \to WV\,(\mathrm{TGC}) + HV \quad (V = W, Z)$
- Vector boson scattering $VV \to VV$
- Double Higgs production $gg \to HH$
- H+jet associated production

$\vdots$

Sensitivity to NP maximized at large energy (tails of distributions)

☞ challenge for EFT validity

EFT fit to experimental data

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i c_i^{(D)} O_i^{(D)} = \mathcal{L}_{SM} + \Delta\mathcal{L}^{(6)} + \Delta\mathcal{L}^{(8)} + \ldots$$

- **Most effective strategy:**
  Pomarol, Riva JHEP 1401 (2014) 151

Organize data (and group operators) according to how strongly they constrain the effective coefficients

observables	precision
input observables (G_F, α_{em}, m_Z), EDMs, (g-2)	better than 10^{-3}
Z-pole observables at LEP1, W mass	10^{-3}
TGC (LEP2)	10^{-2}
Higgs physics (LHC)	10^{-1}

Typically

$$\boxed{|c_i^{(6)}| \lesssim (0.1 - 10)\,\mathrm{TeV}^{-2}}$$

EFT fit to experimental data

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i c_i^{(D)} O_i^{(D)} = \mathcal{L}_{SM} + \Delta\mathcal{L}^{(6)} + \Delta\mathcal{L}^{(8)} + \dots$$

- Most effective strategy:

  Pomarol, Riva JHEP 1401 (2014) 151

Organize data (and group operators) according to how strongly they constrain the effective coefficients

observables	precision
input observables (G_F, α_{em}, m_Z), EDMs, (g-2)	better than 10^{-3}
Z-pole observables at LEP1, W mass	10^{-3}
TGC (LEP2)	10^{-2}
Higgs physics (LHC)	10^{-1}

Typically

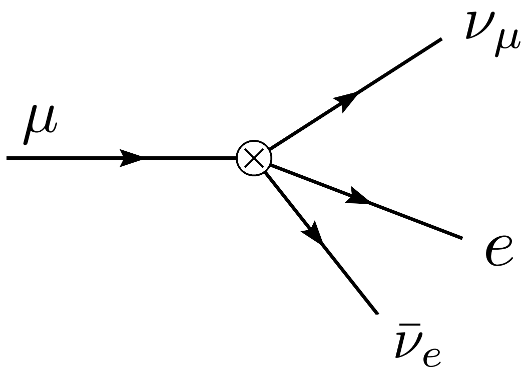
$$\boxed{|c_i^{(6)}| \lesssim (0.1 - 10)\,\mathrm{TeV}^{-2}}$$

Q: *What do the derived limits on $c_i^{(6)}$ imply on the scale Λ of NP ?*

☞ A: *estimate of Λ depends on the kind of UV dynamics*

Example: Fermi theory

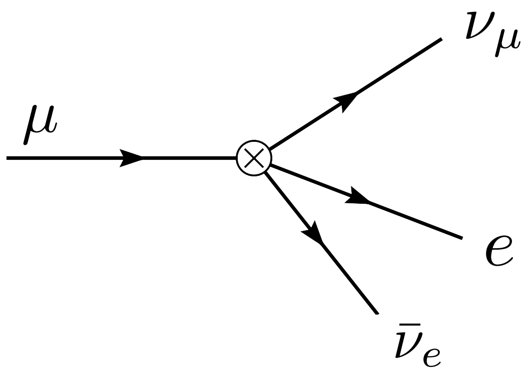
$$\mathcal{L}_{\rm eff} \supset c^{(6)}\,(\bar{e}\gamma_\rho P_L \nu_e)(\bar{\nu}_\mu \gamma_\rho P_L \mu) + \mathrm{h.c.} \qquad c^{(6)} = -\frac{g^2}{2m_W^2}$$



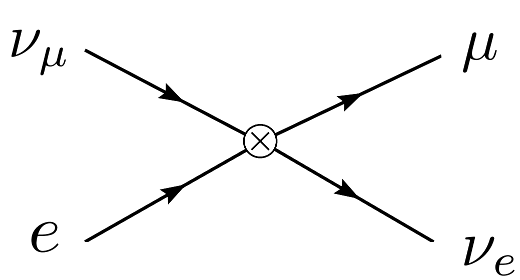
Muon decay measures $c^{(6)} \sim g^2/m_W^2$ → "new physics" scale m_W not directly accessible

Example: Fermi theory

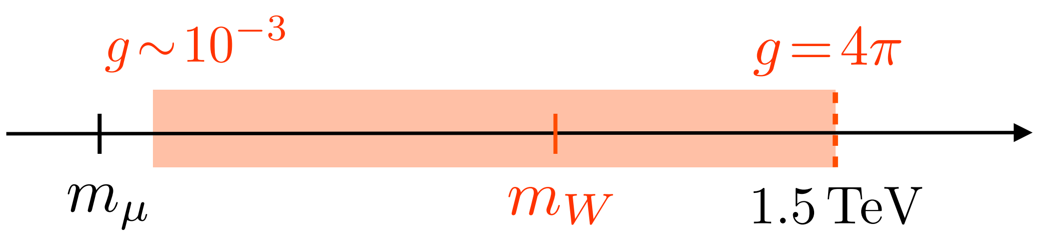
$$\mathcal{L}_{\text{eff}} \supset c^{(6)}\,(\bar{e}\gamma_\rho P_L \nu_e)(\bar{\nu}_\mu \gamma_\rho P_L \mu) + \text{h.c.} \qquad c^{(6)} = -\frac{g^2}{2m_W^2}$$



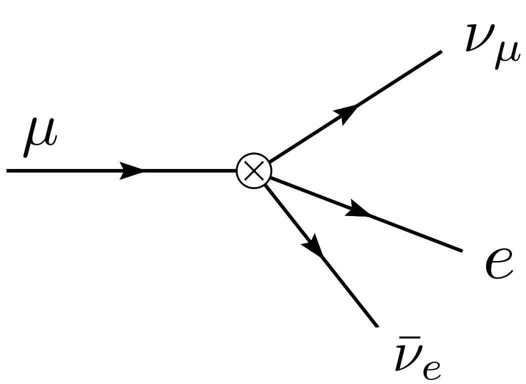
Muon decay measures $c^{(6)} \sim g^2/m_W^2$ → "new physics" scale m_W not directly accessible



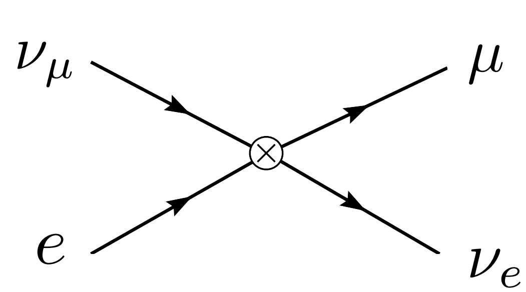
Estimating the scale at which NP shows up (e.g. in neutrino scattering) requires making an assumption on the coupling



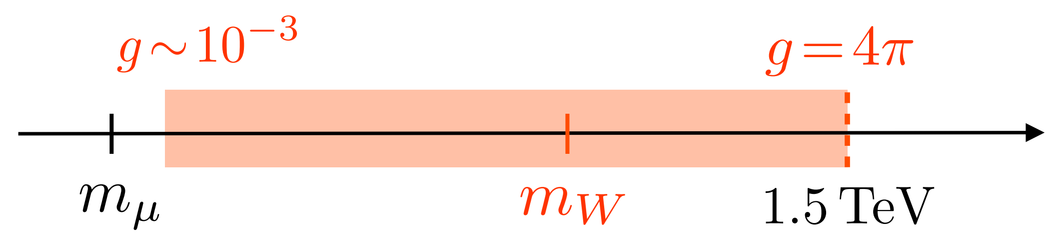
<u>Example</u>: Fermi theory $\mathcal{L}_{\rm eff} \supset c^{(6)} \, (\bar{e}\gamma_\rho P_L \nu_e)(\bar{\nu}_\mu \gamma_\rho P_L \mu) + \text{h.c.}$ $c^{(6)} = -\dfrac{g^2}{2m_W^2}$



Muon decay measures $c^{(6)} \sim g^2/m_W^2$ ⟶ "new physics" scale m_W not directly accessible



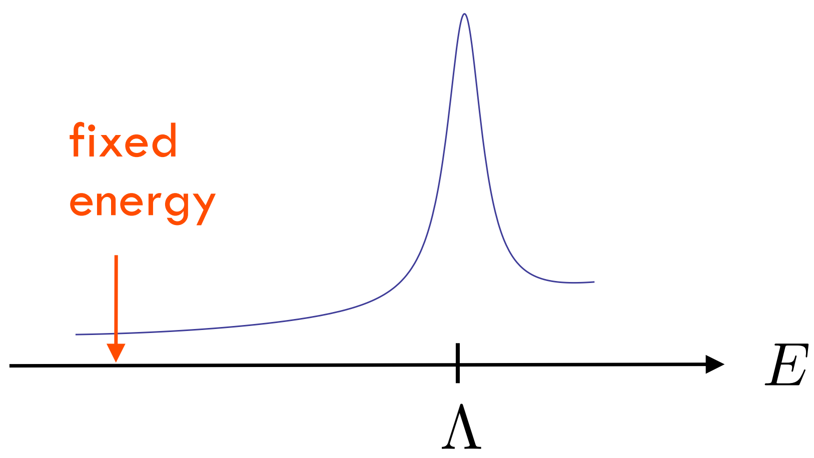
Estimating the scale at which NP shows up (e.g. in neutrino scattering) requires making an assumption on the coupling



☞ *Assessing the validity of the EFT analysis also requires making assumptions of the UV dynamics*

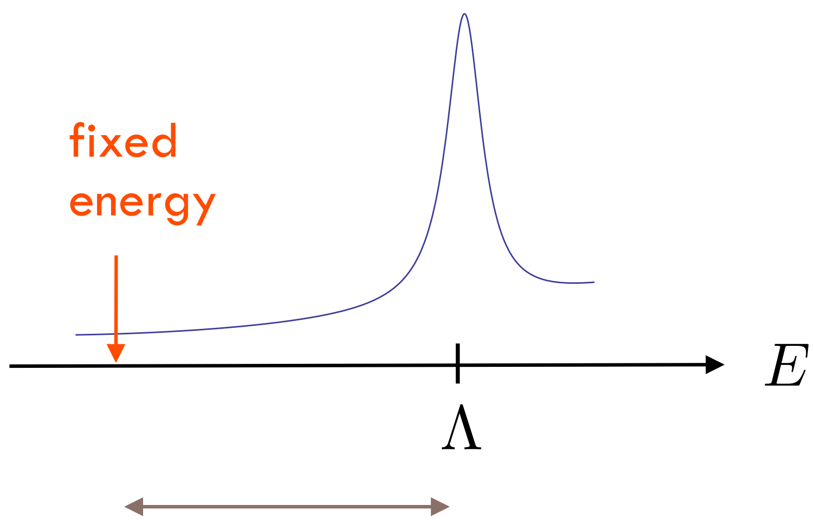
LHC not ideal for an EFT approach

- EFT best suited to fixed-energy, high-precision experiments (ex: LEP, flavor)



LHC not ideal for an EFT approach

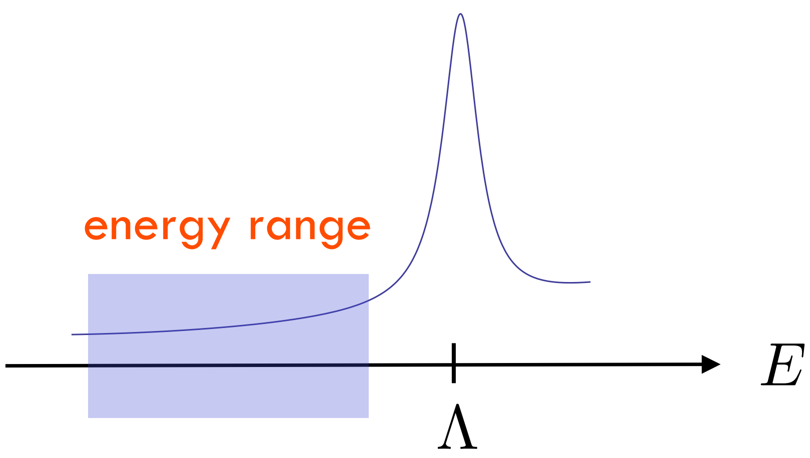
- EFT best suited to fixed-energy, high-precision experiments (ex: LEP, flavor)



large gap of scales requires RG to re-sum large logs

LHC not ideal for an EFT approach

- EFT best suited to fixed-energy, high-precision experiments (ex: LEP, flavor)



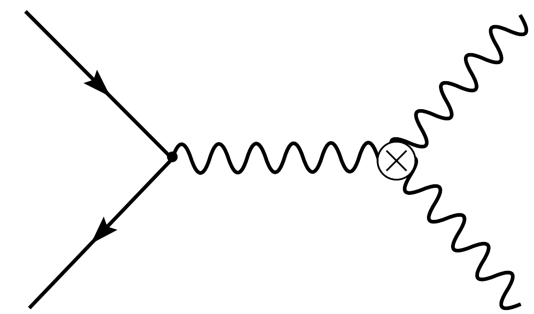
- less suited to low-precision experiments probing an energy range (ex: LHC, hadron machines in general)

EFT fails when max probed energy E_{max} is equal or bigger than physical scale Λ

☞ One can check a posteriori, but *needs to know* E_{max}

TGC measurements: LEP vs LHC

Three dim-6 operators affect TGC



$$O_{HW} = D_\mu H^\dagger W^{\mu\nu} D_\nu H$$

$$O_{HB} = D_\mu H^\dagger B^{\mu\nu} D_\nu H$$

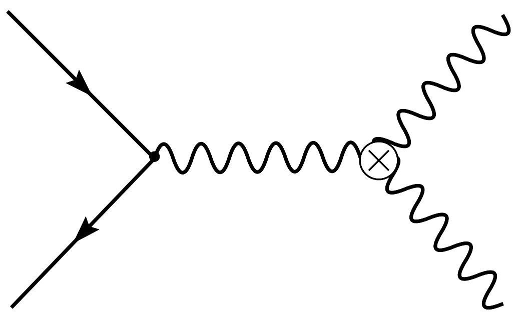
$$O_{3W} = \mathrm{Tr}(W_{\mu\nu} W^{\nu\rho} W_\rho^\mu)$$

TGC measurements: LEP vs LHC

Three dim-6 operators affect TGC

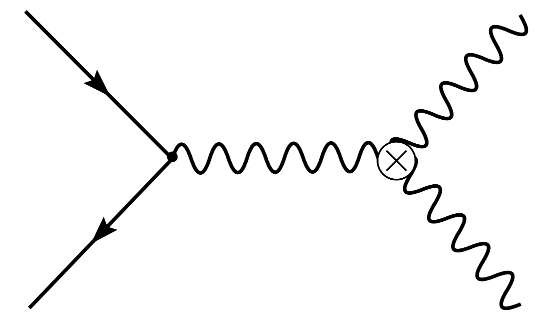
$$O_{HW} = D_\mu H^\dagger W^{\mu\nu} D_\nu H$$
$$O_{HB} = D_\mu H^\dagger B^{\mu\nu} D_\nu H$$
$$\rightarrow V_L V_L$$

$$O_{3W} = \mathrm{Tr}(W_{\mu\nu} W^{\nu\rho} W^\mu_\rho) \rightarrow V_T V_T$$



TGC measurements: LEP vs LHC

Three dim-6 operators affect TGC

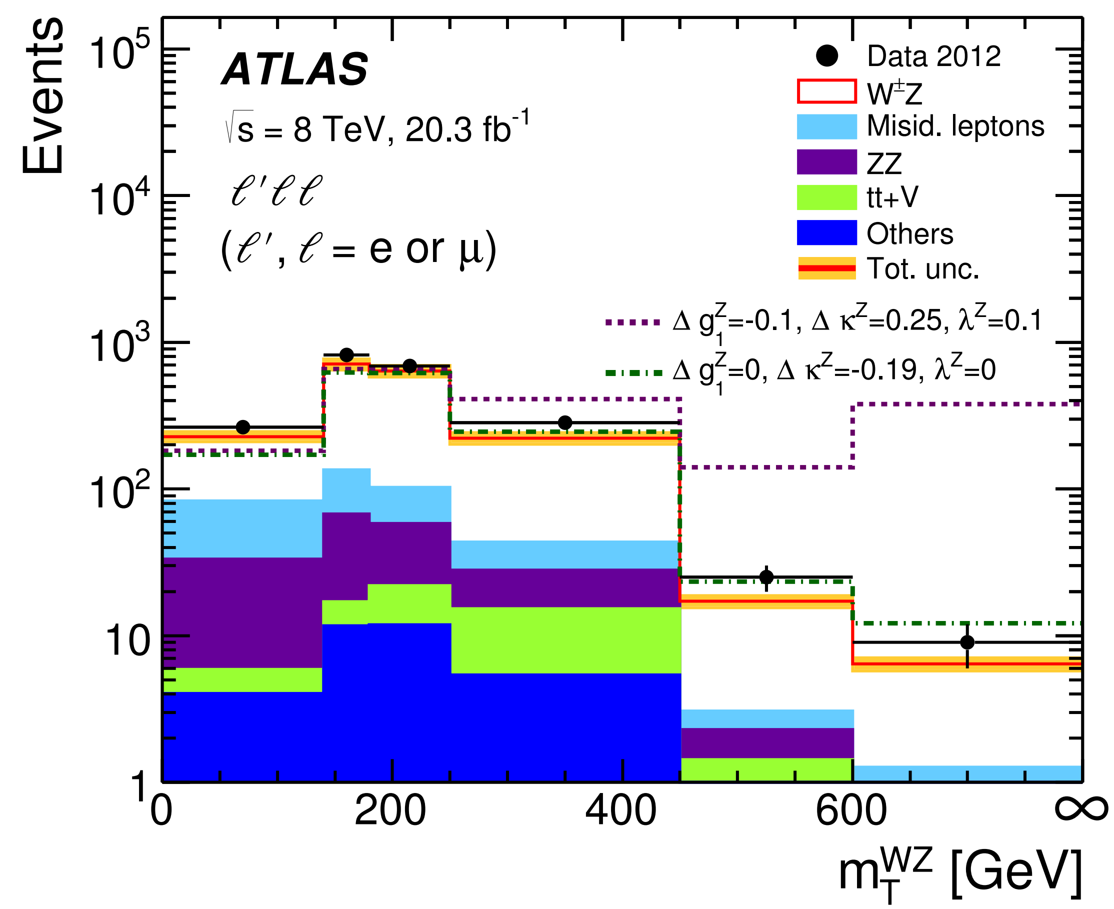


$$O_{HW} = D_\mu H^\dagger W^{\mu\nu} D_\nu H$$
$$O_{HB} = D_\mu H^\dagger B^{\mu\nu} D_\nu H$$
$$\left.\begin{matrix} O_{HW} \\ O_{HB} \end{matrix}\right] \rightarrow V_L V_L$$
$$O_{3W} = \mathrm{Tr}(W_{\mu\nu} W^{\nu\rho} W_\rho^\mu) \rightarrow V_T V_T$$

- LEP2 operated in a narrow range of com energies $\sqrt{s} \sim 200\,\mathrm{GeV}$

- LHC spans a wide energy interval

ATLAS PRD 93 (2016) no.9, 092004

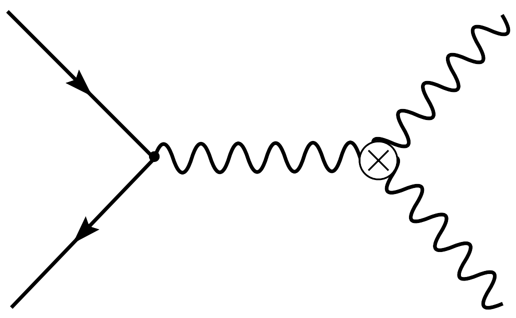


TGC measurements: LEP vs LHC

Three dim-6 operators affect TGC

$$\left.\begin{aligned} O_{HW} &= D_\mu H^\dagger W^{\mu\nu} D_\nu H \\ O_{HB} &= D_\mu H^\dagger B^{\mu\nu} D_\nu H \end{aligned}\right] \rightarrow V_L V_L$$

$$\left. O_{3W} = \mathrm{Tr}(W_{\mu\nu} W^{\nu\rho} W_\rho^\mu) \right] \rightarrow V_T V_T$$

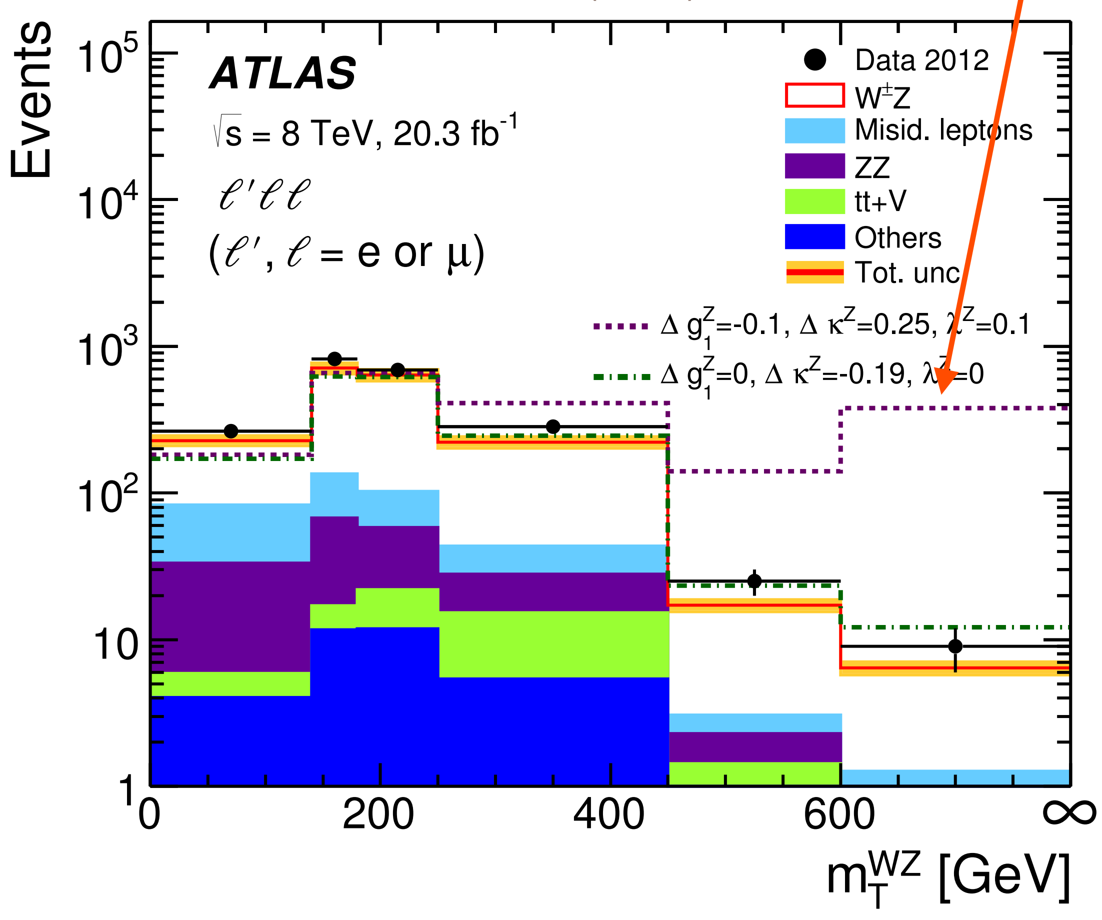


sensitivity on NP mainly comes from bins at large energy

- LEP2 operated in a narrow range of com energies $\sqrt{s} \sim 200\,\mathrm{GeV}$

- LHC spans a wide energy interval

ATLAS PRD 93 (2016) no.9, 092004

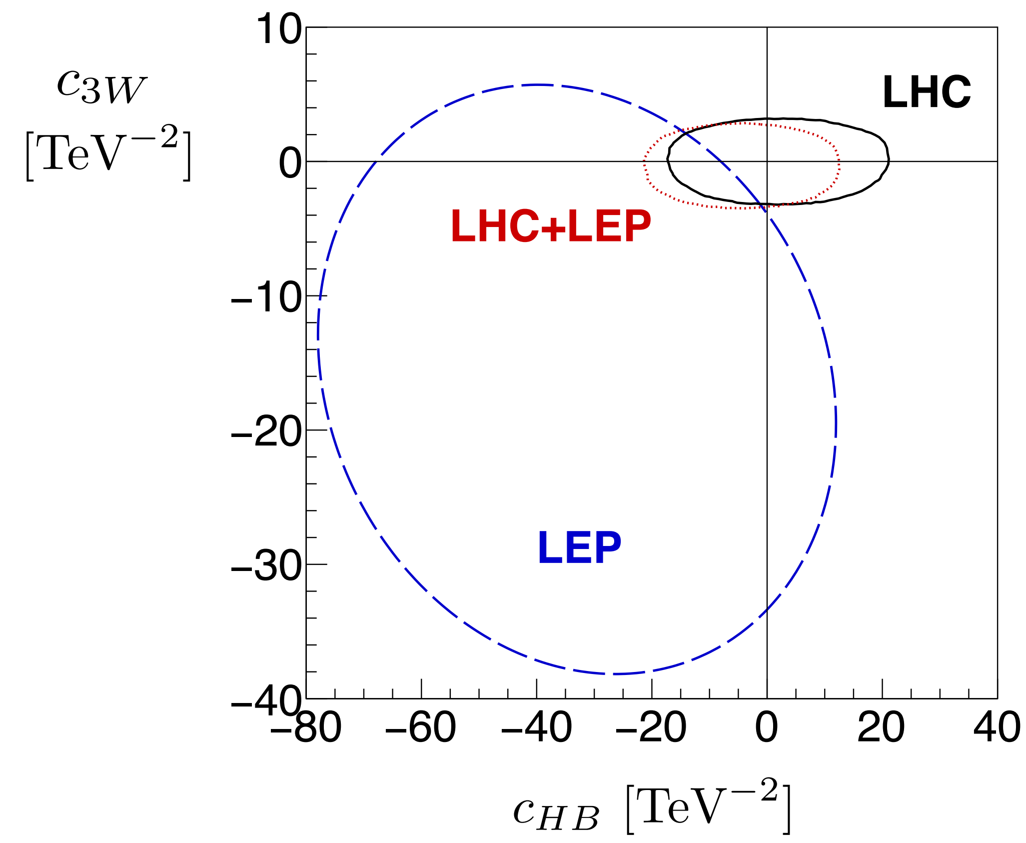


Fit to TGCs

Butter et al. JHEP 1607 (2016) 152

see also:
Falkowski et al. PRL 116 (2016) 011801
Falkowski and Riva JHEP 1502 (2015) 039

$$\sigma = \sigma_{SM}\left(1 + c_i A_i + c_i c_j B_{ij}\right)$$



1-dimensional 95% CL constraints

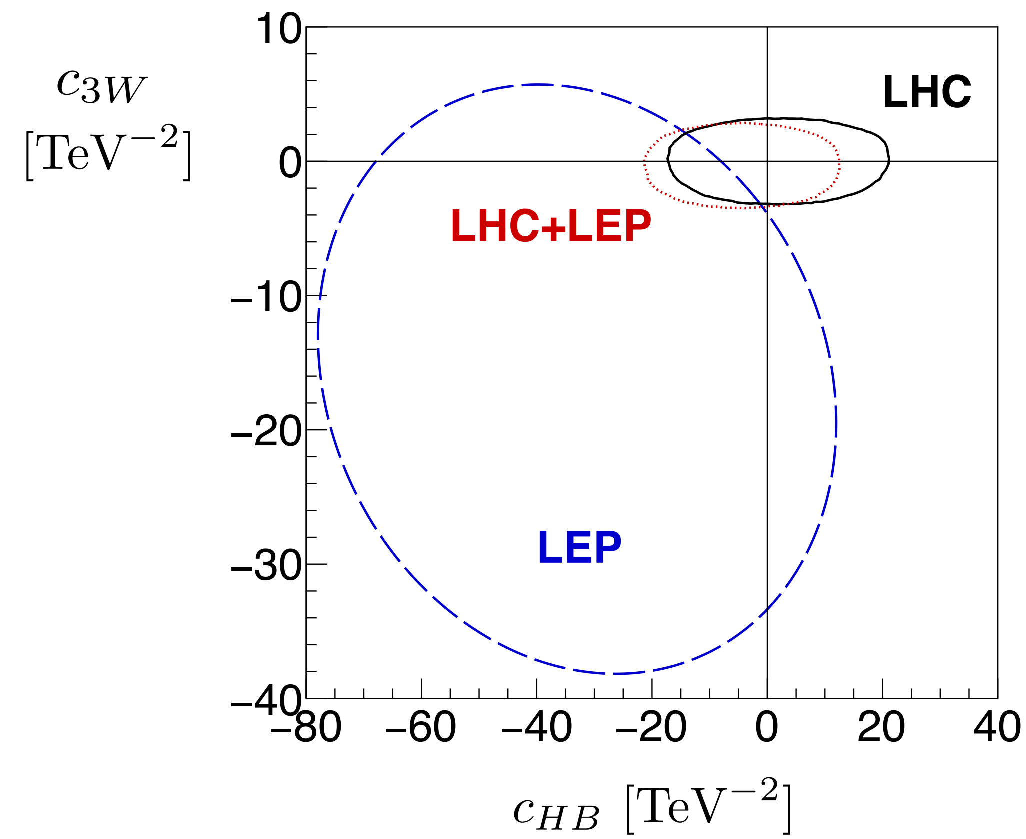
LEP	$c_{HW} \in [-7.6, 19]\ \mathrm{TeV}^{-2}$ $c_{HB} \in [-67, 1.8]\ \mathrm{TeV}^{-2}$ $c_{3W} \in [-32, 3.3]\ \mathrm{TeV}^{-2}$	fit dominated by (D=6) linear terms
LHC	$c_{HW} \in [-1.5, 6.3]\ \mathrm{TeV}^{-2}$ $c_{HB} \in [-14.3, 15.9]\ \mathrm{TeV}^{-2}$ $c_{3W} \in [-2.4, 3.2]\ \mathrm{TeV}^{-2}$	fit dominated by $(D=6)^2$ terms

Fit to TGCs

Butter et al. JHEP 1607 (2016) 152

see also:
Falkowski et al. PRL 116 (2016) 011801
Falkowski and Riva JHEP 1502 (2015) 039

$$\sigma = \sigma_{SM}\left(1 + c_i A_i + c_i c_j B_{ij}\right)$$



1-dimensional 95% CL constraints

LEP

$$c_{HW} \in [-7.6, 19]\ \mathrm{TeV}^{-2}$$
$$c_{HB} \in [-67, 1.8]\ \mathrm{TeV}^{-2}$$
$$c_{3W} \in [-32, 3.3]\ \mathrm{TeV}^{-2}$$

LHC

$$c_{HW} \in [-1.5, 6.3]\ \mathrm{TeV}^{-2}$$
$$c_{HB} \in [-14.3, 15.9]\ \mathrm{TeV}^{-2}$$
$$c_{3W} \in [-2.4, 3.2]\ \mathrm{TeV}^{-2}$$

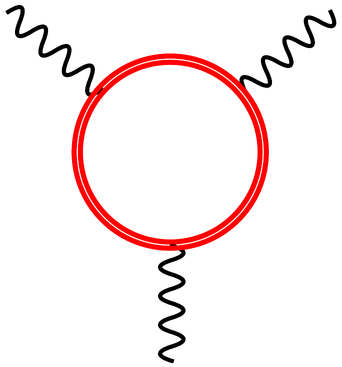
Naively:

- *LHC constraints stronger than LEP ones*
- *c_{3W} slightly more constrained*

Estimating the cutoff scale through SILH power counting (1 coupling, 1 scale):

[Giudice et al. JHEP 0706 (2007) 045]

$$c_{3W} \sim \frac{g}{\Lambda^2}\left(\frac{g^2}{16\pi^2}\right) \qquad c_{HW,HB} \sim \frac{g}{\Lambda^2}\left(\frac{g_*^2}{16\pi^2}\right)$$



1-dimensional 95% CL constraints

LEP

$$c_{HW} \in [-7.6, 19]\,\mathrm{TeV}^{-2}$$

$$c_{HB} \in [-67, 1.8]\,\mathrm{TeV}^{-2}$$

$$c_{3W} \in [-32, 3.3]\,\mathrm{TeV}^{-2}$$

LHC

$$c_{HW} \in [-1.5, 6.3]\,\mathrm{TeV}^{-2}$$

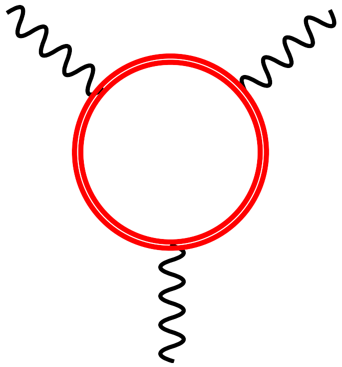
$$c_{HB} \in [-14.3, 15.9]\,\mathrm{TeV}^{-2}$$

$$c_{3W} \in [-2.4, 3.2]\,\mathrm{TeV}^{-2}$$

Estimating the cutoff scale through SILH power counting (1 coupling, 1 scale):

[Giudice et al. JHEP 0706 (2007) 045]

$$c_{3W} \sim \frac{g}{\Lambda^2}\left(\frac{g^2}{16\pi^2}\right) \qquad c_{HW,HB} \sim \frac{g}{\Lambda^2}\left(\frac{g_*^2}{16\pi^2}\right)$$



1-dimensional 95% CL constraints

LEP

$$c_{HW} \in [-7.6, 19]\,\mathrm{TeV}^{-2}$$
$$c_{HB} \in [-67, 1.8]\,\mathrm{TeV}^{-2}$$
$$\rightarrow \Lambda \gtrsim 200\,\mathrm{GeV}\left(\frac{g_*}{4\pi}\right)$$
$$c_{3W} \in [-32, 3.3]\,\mathrm{TeV}^{-2} \rightarrow \Lambda \gtrsim 10\,\mathrm{GeV}$$

LHC

$$c_{HW} \in [-1.5, 6.3]\,\mathrm{TeV}^{-2}$$
$$c_{HB} \in [-14.3, 15.9]\,\mathrm{TeV}^{-2}$$
$$\rightarrow \Lambda \gtrsim 300\,\mathrm{GeV}\left(\frac{g_*}{4\pi}\right)$$
$$c_{3W} \in [-2.4, 3.2]\,\mathrm{TeV}^{-2} \rightarrow \Lambda \gtrsim 20\,\mathrm{GeV}$$

Estimating the cutoff scale through SILH power counting (1 coupling, 1 scale):

[Giudice et al. JHEP 0706 (2007) 045]

$$c_{3W} \sim \frac{g}{\Lambda^2}\left(\frac{g^2}{16\pi^2}\right) \qquad c_{HW,HB} \sim \frac{g}{\Lambda^2}\left(\frac{g_*^2}{16\pi^2}\right)$$

EFT does <u>not</u> quite work, unless the power counting is different

1-dimensional 95% CL constraints

LEP

$$c_{HW} \in [-7.6, 19]\,\mathrm{TeV}^{-2}$$
$$c_{HB} \in [-67, 1.8]\,\mathrm{TeV}^{-2}$$
$$\rightarrow \Lambda \gtrsim 200\,\mathrm{GeV}\left(\frac{g_*}{4\pi}\right)$$

$$c_{3W} \in [-32, 3.3]\,\mathrm{TeV}^{-2} \rightarrow \Lambda \gtrsim 10\,\mathrm{GeV}$$

LHC

$$c_{HW} \in [-1.5, 6.3]\,\mathrm{TeV}^{-2}$$
$$c_{HB} \in [-14.3, 15.9]\,\mathrm{TeV}^{-2}$$
$$\rightarrow \Lambda \gtrsim 300\,\mathrm{GeV}\left(\frac{g_*}{4\pi}\right)$$

$$c_{3W} \in [-2.4, 3.2]\,\mathrm{TeV}^{-2} \rightarrow \Lambda \gtrsim 20\,\mathrm{GeV}$$

Estimating the cutoff scale through SILH power counting (1 coupling, 1 scale):

[Giudice et al. JHEP 0706 (2007) 045]

$$c_{3W} \sim \frac{g}{\Lambda^2}\left(\frac{g^2}{16\pi^2}\right) \qquad c_{HW,HB} \sim \frac{g}{\Lambda^2}\left(\frac{g_*^2}{16\pi^2}\right)$$

EFT does not quite work, unless the power counting is different

for example

Strong dipolar interactions

[Liu, Pomarol, Rattazzi, Riva arXiv:1603.03064]

$$c_{3W} \sim \frac{g_*}{\Lambda^2} \rightarrow \Lambda \gtrsim 2\,\mathrm{TeV}\left(\frac{g_*}{4\pi}\right)^{1/2}$$

95% CL at the LHC

1-dimensional 95% CL constraints

LEP

$$c_{HW} \in [-7.6, 19]\,\mathrm{TeV}^{-2}$$
$$c_{HB} \in [-67, 1.8]\,\mathrm{TeV}^{-2}$$
$$\rightarrow \Lambda \gtrsim 200\,\mathrm{GeV}\left(\frac{g_*}{4\pi}\right)$$

$$c_{3W} \in [-32, 3.3]\,\mathrm{TeV}^{-2} \rightarrow \Lambda \gtrsim 10\,\mathrm{GeV}$$

LHC

$$c_{HW} \in [-1.5, 6.3]\,\mathrm{TeV}^{-2}$$
$$c_{HB} \in [-14.3, 15.9]\,\mathrm{TeV}^{-2}$$
$$\rightarrow \Lambda \gtrsim 300\,\mathrm{GeV}\left(\frac{g_*}{4\pi}\right)$$

$$c_{3W} \in [-2.4, 3.2]\,\mathrm{TeV}^{-2} \rightarrow \Lambda \gtrsim 20\,\mathrm{GeV}$$

Linear vs Quadratic

Notice:

Dominance of quadratic term (over linear ones) is per se neither sufficient nor necessary a condition for the EFT to be valid

Linear vs Quadratic

Notice:

Dominance of quadratic term (over linear ones) is per se neither sufficient nor necessary a condition for the EFT to be valid

✗ Not sufficient

Ex: TGC at LEP2

$$\frac{\delta\sigma}{\sigma} \sim \frac{c_{3W}}{g} E^2 \sim \frac{g^2}{16\pi^2} \frac{E^2}{\Lambda^2}$$

Linear vs Quadratic

Notice: Dominance of quadratic term (over linear ones) is per se neither sufficient nor necessary a condition for the EFT to be valid

✗ Not sufficient Ex: TGC at LEP2 $\frac{\delta\sigma}{\sigma} \sim \frac{c_{3W}}{g} E^2 \sim \underbrace{\frac{g^2}{16\pi^2}}_{small} \frac{E^2}{\Lambda^2}$ *large*

Linear vs Quadratic

Notice: Dominance of quadratic term (over linear ones) is per se neither sufficient nor necessary a condition for the EFT to be valid

✗ Not sufficient   Ex: TGC at LEP2

$$\frac{\delta\sigma}{\sigma} \sim \frac{c_{3W}}{g} E^2 \sim \frac{g^2}{16\pi^2} \frac{E^2}{\Lambda^2}$$

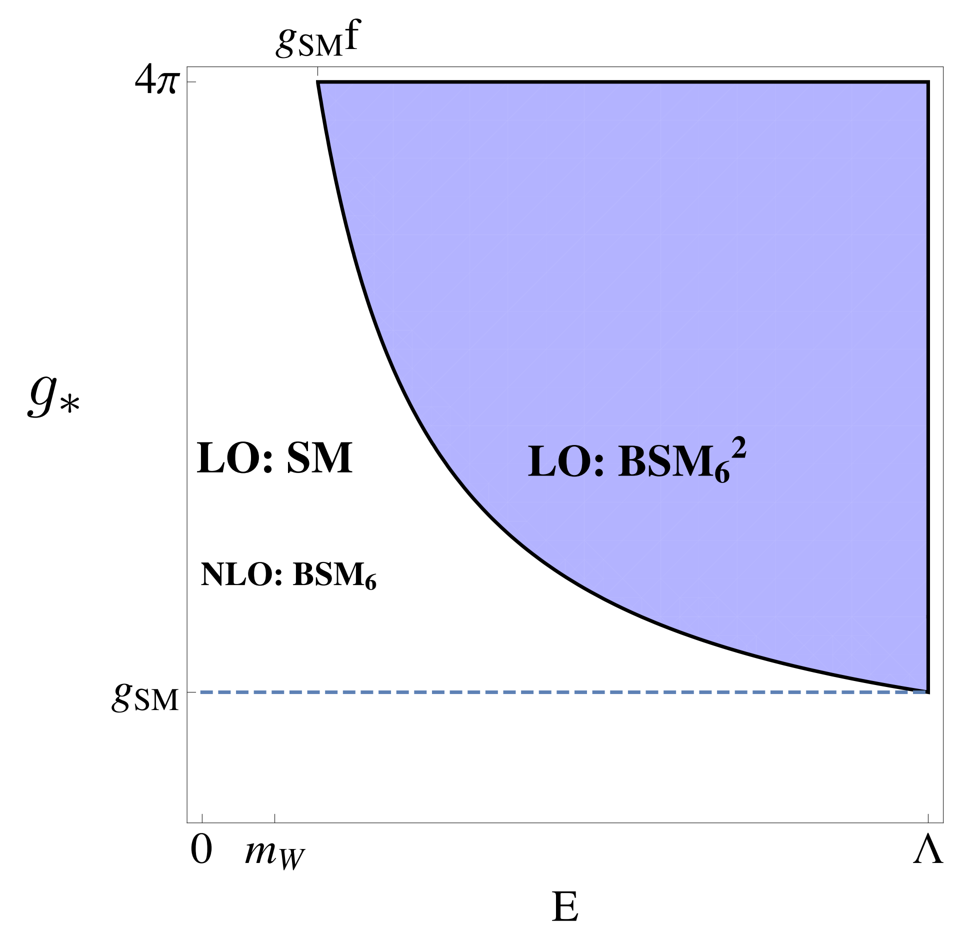
large

small

✗ Not necessary   Ex: $V_L V_L$ scattering

$$O_6 = (H\partial H)^2 \qquad c^{(6)} \sim \frac{g_*^2}{\Lambda^2}$$

$$\sigma(LL \to LL) \sim \frac{g_{\rm SM}^4}{E^2}\Big[1 + \underbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^2}{\Lambda^2}}_{\rm BSM_6 \times\ SM} + \underbrace{\frac{g_*^4}{g_{\rm SM}^4}\frac{E^4}{\Lambda^4}}_{\rm BSM_6{}^2} + \dots\Big]$$



Linear vs Quadratic

Notice: Dominance of quadratic term (over linear ones) is per se neither sufficient nor necessary a condition for the EFT to be valid

✗ Not sufficient   Ex: TGC at LEP2

$$\frac{\delta\sigma}{\sigma} \sim \frac{c_{3W}}{g} E^2 \sim \frac{g^2}{16\pi^2} \frac{E^2}{\Lambda^2}$$

large

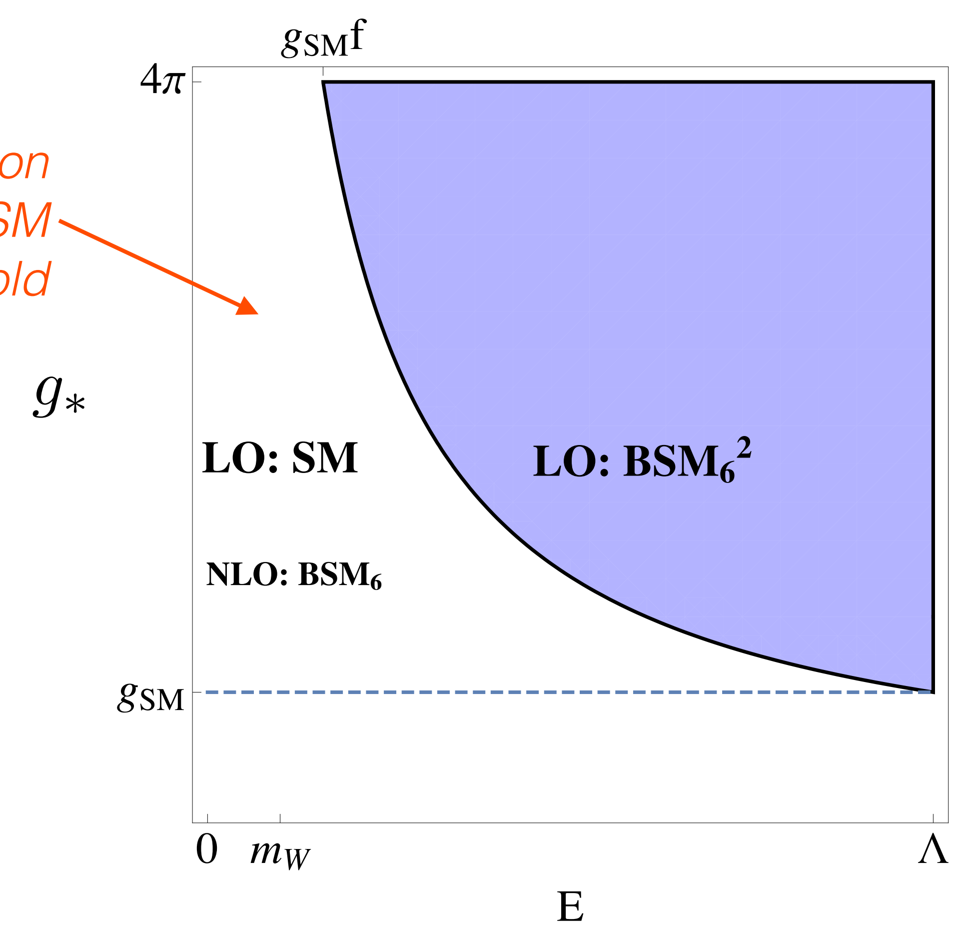
small

✗ Not necessary   Ex: $V_L V_L$ scattering

$$O_6 = (H\partial H)^2 \qquad c^{(6)} \sim \frac{g_*^2}{\Lambda^2}$$

$$\sigma(LL \to LL) \sim \frac{g_{\rm SM}^4}{E^2}\left[1 + \underbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^2}{\Lambda^2}}_{\rm BSM_6 \times\, SM} + \underbrace{\frac{g_*^4}{g_{\rm SM}^4}\frac{E^4}{\Lambda^4}}_{\rm BSM_6{}^2} + \dots\right]$$

NLO correction from dim6-SM close to threshold



Linear vs Quadratic

Notice: Dominance of quadratic term (over linear ones) is per se neither sufficient nor necessary a condition for the EFT to be valid

✗ Not sufficient   Ex: TGC at LEP2

$$\frac{\delta\sigma}{\sigma} \sim \frac{c_{3W}}{g} E^2 \sim \frac{g^2}{16\pi^2} \frac{E^2}{\Lambda^2}$$

large

small

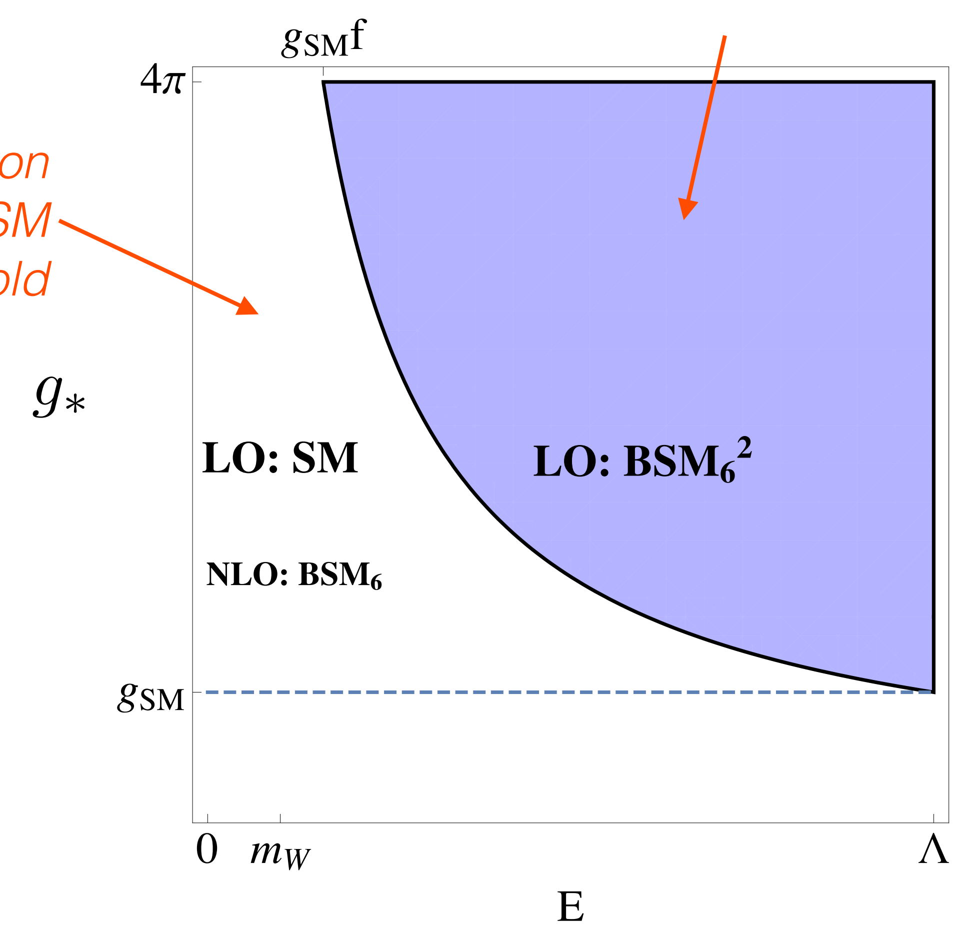
✗ Not necessary   Ex: $V_L V_L$ scattering

$$O_6 = (H\partial H)^2 \qquad c^{(6)} \sim \frac{g_*^2}{\Lambda^2}$$

$$\sigma(LL \to LL) \sim \frac{g_{\rm SM}^4}{E^2}\left[1 + \underbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^2}{\Lambda^2}}_{\rm BSM_6\times\ SM} + \underbrace{\frac{g_*^4}{g_{\rm SM}^4}\frac{E^4}{\Lambda^4}}_{\rm BSM_6{}^2} + \ldots\right]$$

NLO correction from dim6-SM close to threshold

BSM dominates over SM for $\Lambda\, g/g_* < E < \Lambda$



Strategy for a consistent EFT analysis of data

[RC, Falkowski, Goertz, Grojean, Riva JHEP 1607 (2016) 144]

1. Fit of coefficients $c_i^{(6)}$ can be done model independently

   Results should be reported as functions of $M_{\rm cut}$ = max characteristic energy scale

$$c_i^{(6)} < \delta_i^{\rm exp}(M_{\rm cut})$$

Strategy for a consistent EFT analysis of data

[RC, Falkowski, Goertz, Grojean, Riva JHEP 1607 (2016) 144]

1. Fit of coefficients $c_i^{(6)}$ can be done model independently

Results should be reported as functions of $M_{\rm cut}$ = max characteristic energy scale

$$c_i^{(6)} < \delta_i^{\rm exp}(M_{\rm cut})$$

2. Interpretation of results require assumptions on UV dynamics

power counting $\longrightarrow$ $c_i^{(6)} = \dfrac{\tilde{c}_i^{(6)}(g_*)}{\Lambda^2}$

Strategy for a consistent EFT analysis of data

[RC, Falkowski, Goertz, Grojean, Riva JHEP 1607 (2016) 144]

1. Fit of coefficients $c_i^{(6)}$ can be done model independently

   Results should be reported as functions of $M_{\rm cut}$ = max characteristic energy scale

$$c_i^{(6)} < \delta_i^{\rm exp}(M_{\rm cut})$$

2. Interpretation of results require assumptions on UV dynamics

   power counting $\longrightarrow$ $c_i^{(6)} = \dfrac{\tilde{c}_i^{(6)}(g_*)}{\Lambda^2}$

3. Consistent (though conservative) limits through *restriction* of dataset: set $M_{cut} = \kappa\,\Lambda$

$$\boxed{c_i^{(6)} = \frac{\tilde{c}_i^{(6)}(g_*)}{\Lambda^2} < \delta_i^{\rm exp}(\kappa\Lambda)}$$

Strategy for a consistent EFT analysis of data

[RC, Falkowski, Goertz, Grojean, Riva JHEP 1607 (2016) 144]

1. Fit of coefficients $c_i^{(6)}$ can be done model independently

   Results should be reported as functions of $M_{\rm cut}$ = max characteristic energy scale

$$c_i^{(6)} < \delta_i^{\rm exp}(M_{\rm cut})$$

2. Interpretation of results require assumptions on UV dynamics

   power counting $\longrightarrow$ $c_i^{(6)} = \dfrac{\tilde{c}_i^{(6)}(g_*)}{\Lambda^2}$

3. Consistent (though conservative) limits through *restriction* of dataset: set $M_{cut} = \kappa\,\Lambda$

$$\boxed{c_i^{(6)} = \frac{\tilde{c}_i^{(6)}(g_*)}{\Lambda^2} < \delta_i^{\rm exp}(\kappa\Lambda)}$$

$0 < \kappa < 1$ controls the size of the tolerated error due to higher-derivative operators

Strategy for a consistent EFT analysis of data

[RC, Falkowski, Goertz, Grojean, Riva JHEP 1607 (2016) 144]

1. Fit of coefficients $c_i^{(6)}$ can be done model independently

   Results should be reported as functions of $M_{\rm cut}$ = max characteristic energy scale

$$c_i^{(6)} < \delta_i^{\rm exp}(M_{\rm cut})$$

2. Interpretation of results require assumptions on UV dynamics

   power counting $\longrightarrow$ $c_i^{(6)} = \dfrac{\tilde{c}_i^{(6)}(g_*)}{\Lambda^2}$

3. Consistent (though conservative) limits through *restriction* of dataset: set $M_{cut} = \kappa\,\Lambda$

$$\boxed{c_i^{(6)} = \frac{\tilde{c}_i^{(6)}(g_*)}{\Lambda^2} < \delta_i^{\rm exp}(\kappa\Lambda)}$$

$0 < \kappa < 1$ controls the size of the tolerated error due to higher-derivative operators

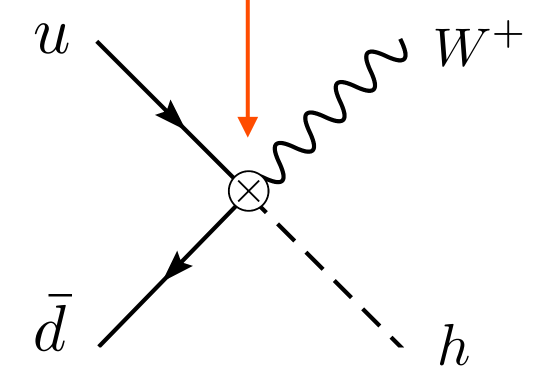
limits on scale Λ set by using data up to $M_{\rm cut} = \kappa\Lambda$

Example of idealized measurement: $u\bar{d} \to W^+ h$

$M_{Wh}[\text{TeV}]$	0.5	1	1.5	2	2.5	3
$\sigma/\sigma_{\text{SM}}$	1 ± 1.2	1 ± 1.0	1 ± 0.8	1 ± 1.2	1 ± 1.6	1 ± 3.0

$$O_{H\psi} = i\,\bar{q}_L \gamma_\mu \sigma^a q_L (H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$

$$c_{H\psi} = -\frac{g_H g_q}{M_V^2}$$



Model of heavy spin-1:

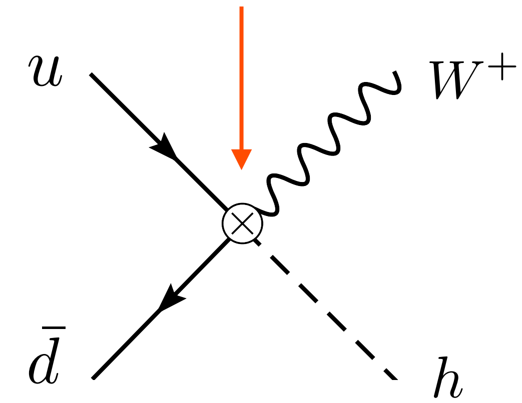
$$\mathcal{L} \supset i g_H V_\mu^i H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + g_q V_\mu^i \bar{q}_L \gamma_\mu \sigma^i q_L$$

Example of idealized measurement: $u\bar{d} \to W^+ h$

$M_{Wh}[\mathrm{TeV}]$	0.5	1	1.5	2	2.5	3
$\sigma/\sigma_{\mathrm{SM}}$	1 ± 1.2	1 ± 1.0	1 ± 0.8	1 ± 1.2	1 ± 1.6	1 ± 3.0

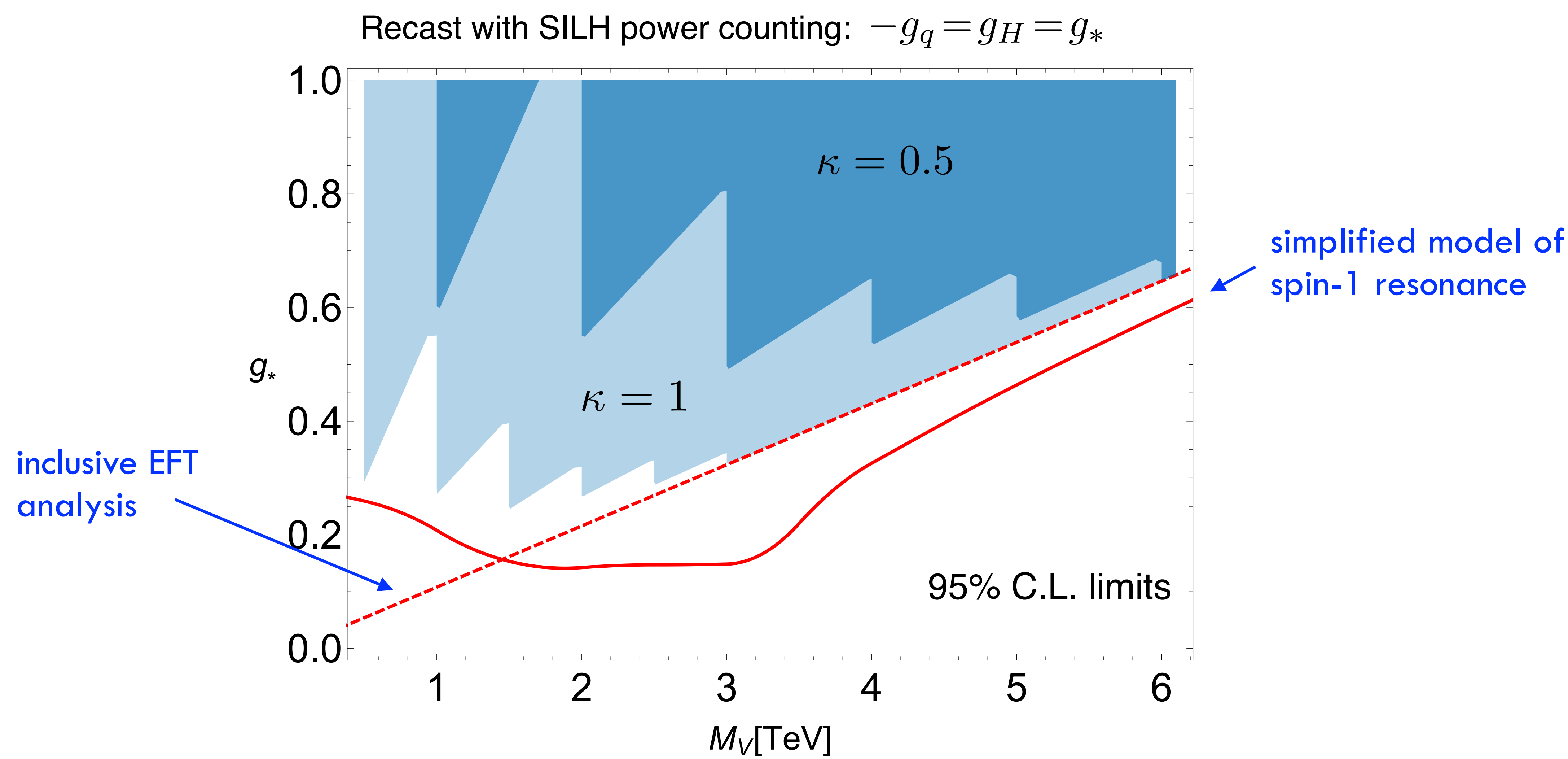
$$O_{H\psi} = i\,\bar{q}_L \gamma_\mu \sigma^a q_L (H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$

$$c_{H\psi} = -\frac{g_H g_q}{M_V^2}$$



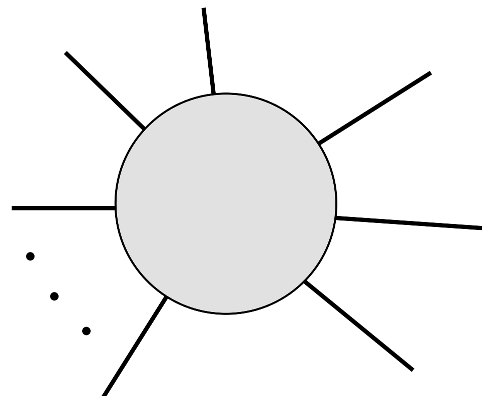
Model of heavy spin-1:

$$\mathcal{L} \supset i g_H V_\mu^i H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + g_q V_\mu^i \bar{q}_L \gamma_\mu \sigma^i q_L$$



Further challenge to EFT: Non-interference from helicity selection rules

[Azatov, RC, Machado, Riva arXiv:1607.05236]



$$h(A) = \sum_i h_i$$

dim-6 and SM interfere only if they contribute to the same helicity amplitude (*the total helicity* $h(A)$ *must be the same*)

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

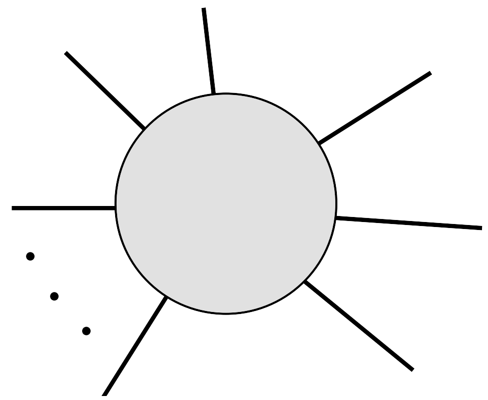
No interference for 4-point amplitudes with at least one transverse boson

<u>Validity</u>:

- at tree-level in the massless (high-energy) limit $E \gg m_W$
- only dim-6 operators
- only 4-point amplitudes

Further challenge to EFT: Non-interference from helicity selection rules

[Azatov, RC, Machado, Riva arXiv:1607.05236]



$$h(A) = \sum_i h_i$$

dim-6 and SM interfere only if they contribute to the same helicity amplitude (*the total helicity* $h(A)$ *must be the same*)

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

No interference for 4-point amplitudes with at least one transverse boson

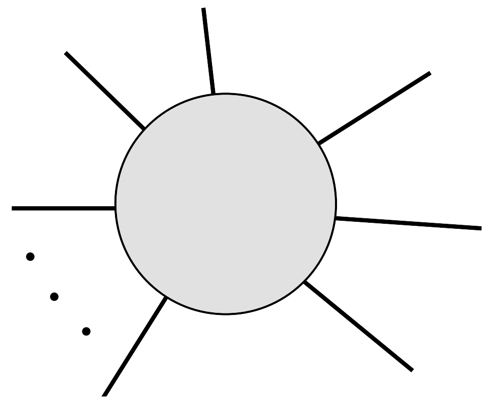
Validity:

- at tree-level in the massless (high-energy) limit $E \gg m_W$
- only dim-6 operators
- only 4-point amplitudes

☞ Interference arises at $O(m_{W,t}^2/\Lambda^2)$ due to mass effects or at $O(\alpha/4\pi)$ due to radiative corrections (real emissions and 1-loop contributions)

Further challenge to EFT: Non-interference from helicity selection rules

[Azatov, RC, Machado, Riva arXiv:1607.05236]



$$h(A) = \sum_i h_i$$

dim-6 and SM interfere only if they contribute to the same helicity amplitude (*the total helicity* $h(A)$ *must be the same*)

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

No interference for 4-point amplitudes with at least one transverse boson

Validity:

- at tree-level in the massless (high-energy) limit $E \gg m_W$
- only dim-6 operators
- only 4-point amplitudes

☞ Interference arises at $O(m^2_{W,t}/\Lambda^2)$ due to mass effects or at $O(\alpha/4\pi)$ due to radiative corrections (real emissions and 1-loop contributions)

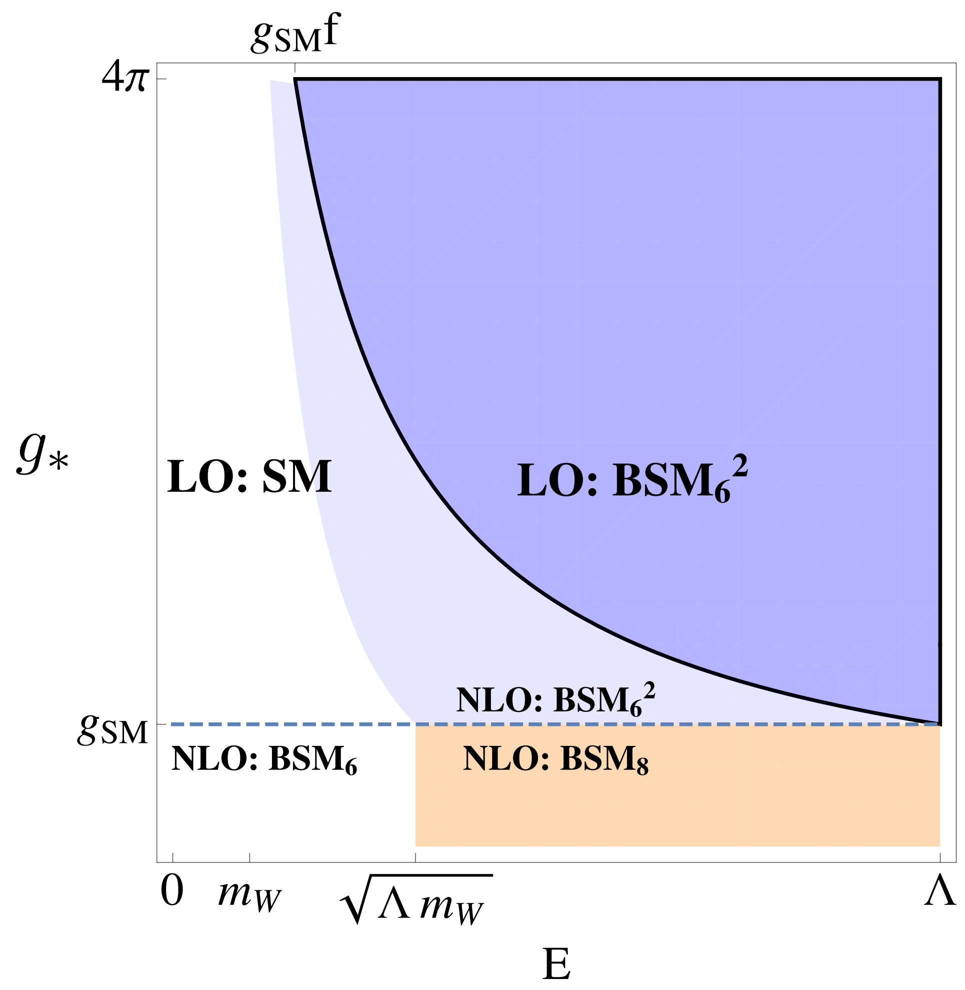
See talk by Riva

Implications of non-interference

Example: $V_L V_L \to V_T V_T$ ($T = \pm$)

$$O_6 = F^2_{\mu\nu} H^\dagger H \qquad c^{(6)} \sim \frac{g_*^2}{\Lambda^2}$$

$$O_8 = F^2_{\mu\nu} H^\dagger H\, D^2 \qquad c^{(8)} \sim \frac{g_*^2}{\Lambda^4}$$



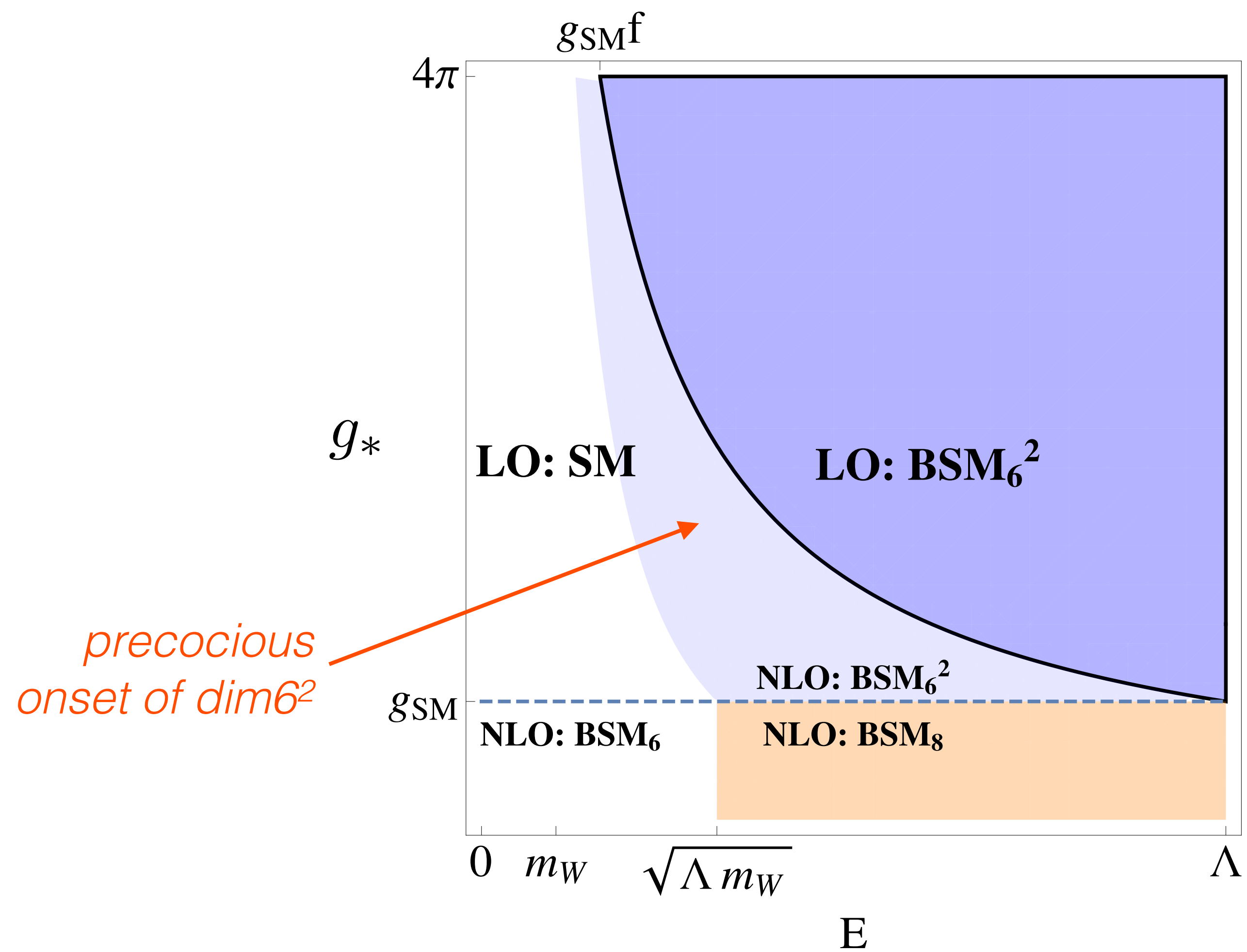
$$\sigma(LL \to TT) \sim \frac{g^4_{\rm SM}}{E^2}\left[1 + \underbrace{\frac{g_*^2}{g^2_{\rm SM}}\frac{m_W^2}{\Lambda^2}}_{\text{BSM}_6\,\times\,\text{SM}} + \underbrace{\frac{g_*^4}{g^4_{\rm SM}}\frac{E^4}{\Lambda^4}}_{\text{BSM}_6{}^2} + \underbrace{\frac{g_*^2}{g^2_{\rm SM}}\frac{E^4}{\Lambda^4}}_{\text{BSM}_8\,\times\,\text{SM}} + \ldots\right]$$

Implications of non-interference

Example: $V_L V_L \to V_T V_T \quad (\, T = \pm \,)$

$$O_6 = F^2_{\mu\nu} H^\dagger H \qquad c^{(6)} \sim \frac{g_*^2}{\Lambda^2}$$

$$O_8 = F^2_{\mu\nu} H^\dagger H\, D^2 \qquad c^{(8)} \sim \frac{g_*^2}{\Lambda^4}$$



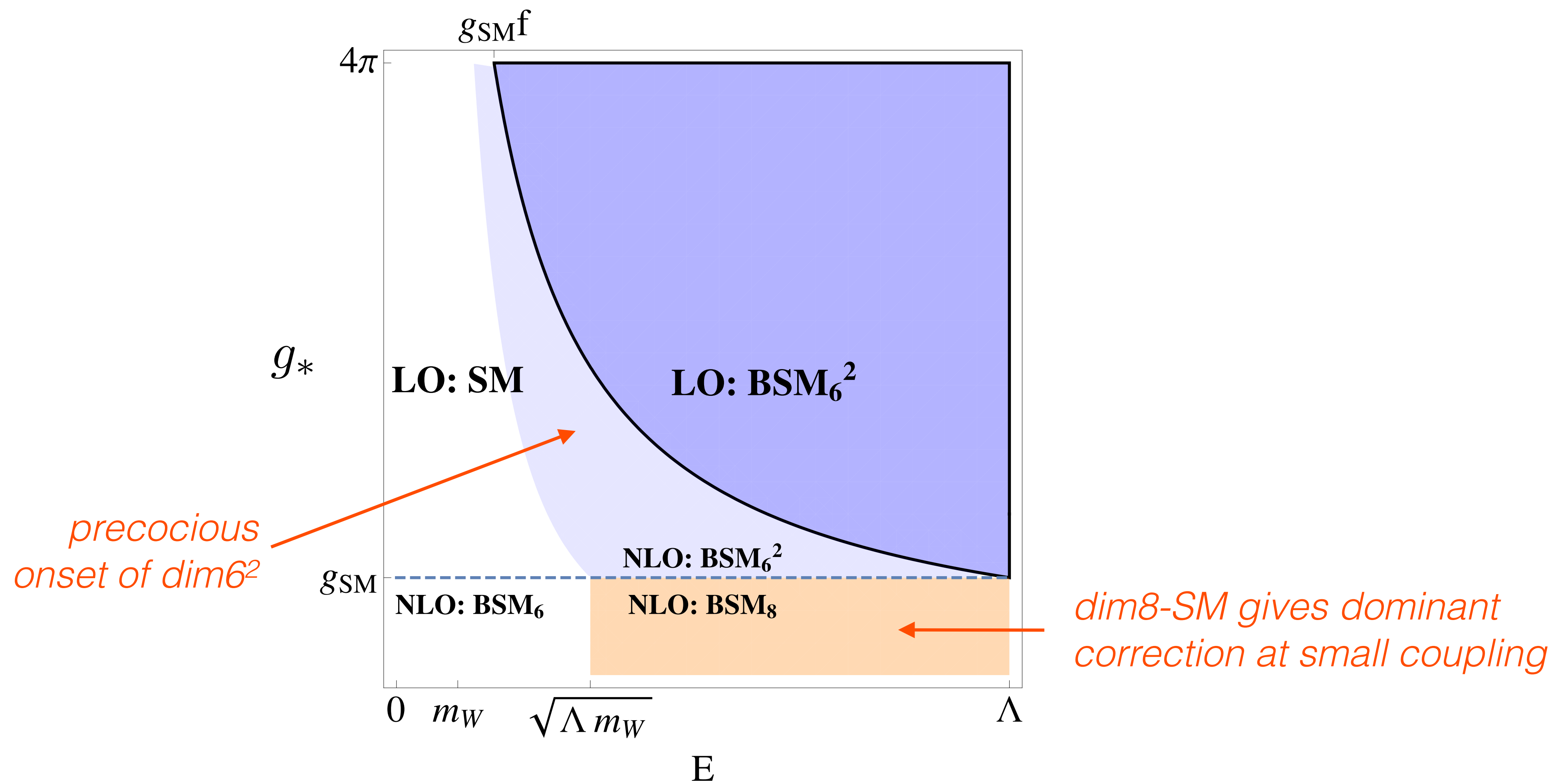
$$\sigma(LL \to TT) \sim \frac{g_{\rm SM}^4}{E^2}\left[1 + \underbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{m_W^2}{\Lambda^2}}_{\mathrm{BSM}_6\,\times\,\mathrm{SM}} + \underbrace{\frac{g_*^4}{g_{\rm SM}^4}\frac{E^4}{\Lambda^4}}_{\mathrm{BSM}_6{}^2} + \underbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^4}{\Lambda^4}}_{\mathrm{BSM}_8\,\times\,\mathrm{SM}} + \ldots\right]$$

Implications of non-interference

Example: $V_L V_L \to V_T V_T$ ($T = \pm$)

$$O_6 = F_{\mu\nu}^2 H^\dagger H \qquad c^{(6)} \sim \frac{g_*^2}{\Lambda^2}$$

$$O_8 = F_{\mu\nu}^2 H^\dagger H\, D^2 \qquad c^{(8)} \sim \frac{g_*^2}{\Lambda^4}$$



$$\sigma(LL \to TT) \sim \frac{g_{\rm SM}^4}{E^2}\left[1 + \underbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{m_W^2}{\Lambda^2}}_{\mathrm{BSM}_6\,\times\,\mathrm{SM}} + \underbrace{\frac{g_*^4}{g_{\rm SM}^4}\frac{E^4}{\Lambda^4}}_{\mathrm{BSM}_6{}^2} + \underbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^4}{\Lambda^4}}_{\mathrm{BSM}_8\,\times\,\mathrm{SM}} + \ldots\right]$$

- D=8 operators can become important in special cases if D=6 ones are suppressed by *symmetries* or *selection rules*

- D=8 operators can become important in special cases if D=6 ones are suppressed by *symmetries* or *selection rules*

Example: Double Higgs production via gluon fusion (assuming Higgs is a pNGB)

[Azatov, RC, Panico, Son PRD 92 (2015) 035001]

$$O_g = H^\dagger H \, G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$c^{(6)} \sim \frac{g_s^2}{16\pi^2} \frac{\lambda^2}{\Lambda^2}$$

(λ = weak spurion breaking the shift symmetry)

$$O_{gD0} = (D_\rho H^\dagger D^\rho H) G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$O_{gD2} = (\eta^{\mu\nu} D_\rho H^\dagger D^\rho H - 4 D^\mu H^\dagger D^\nu H) G^a_{\mu\alpha} G^{a\,\alpha}_{\nu}$$

$$c^{(8)} \sim \frac{g_s^2}{16\pi^2} \frac{g_*^2}{\Lambda^4}$$

- D=8 operators can become important in special cases if D=6 ones are suppressed by *symmetries* or *selection rules*

Example: Double Higgs production via gluon fusion (assuming Higgs is a pNGB)

[Azatov, RC, Panico, Son PRD 92 (2015) 035001]

violates the shift (Goldstone) symmetry

$$O_g = H^\dagger H \, G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$c^{(6)} \sim \frac{g_s^2}{16\pi^2} \frac{\lambda^2}{\Lambda^2}$$

(λ = weak spurion breaking the shift symmetry)

$$O_{gD0} = (D_\rho H^\dagger D^\rho H) G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$O_{gD2} = (\eta^{\mu\nu} D_\rho H^\dagger D^\rho H - 4 D^\mu H^\dagger D^\nu H) G^a_{\mu\alpha} G^{a\,\alpha}_{\nu}$$

$$c^{(8)} \sim \frac{g_s^2}{16\pi^2} \frac{g_*^2}{\Lambda^4}$$

- D=8 operators can become important in special cases if D=6 ones are suppressed by *symmetries* or *selection rules*

Example: Double Higgs production via gluon fusion (assuming Higgs is a pNGB)

[Azatov, RC, Panico, Son PRD 92 (2015) 035001]

violates the shift (Goldstone) symmetry

$$O_g = H^\dagger H \, G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$c^{(6)} \sim \frac{g_s^2}{16\pi^2} \frac{\lambda^2}{\Lambda^2}$$

(λ = weak spurion breaking the shift symmetry)

$$O_{gD0} = (D_\rho H^\dagger D^\rho H) G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$O_{gD2} = (\eta^{\mu\nu} D_\rho H^\dagger D^\rho H - 4 D^\mu H^\dagger D^\nu H) G^a_{\mu\alpha} G^{a\,\alpha}_{\nu}$$

$$c^{(8)} \sim \frac{g_s^2}{16\pi^2} \frac{g_*^2}{\Lambda^4}$$

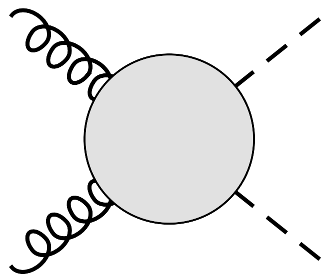
$$A(gg \to hh) \sim \frac{g_s^2}{16\pi^2} \Big(\underbrace{y_t^2}_{\text{SM}} + \underbrace{\lambda^2 \frac{E^2}{\Lambda^2}}_{\text{dim-6}} + \underbrace{g_*^2 \frac{E^4}{\Lambda^4}}_{\text{dim-8}} + \dots \Big)$$

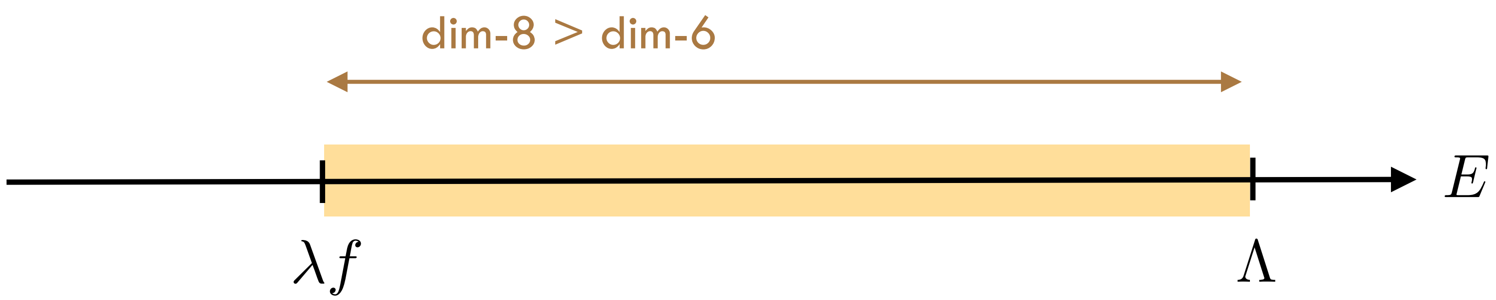
Notice: strong coupling g_* appears only at the dim-8 level

dim-8 dominate over dim-6 for:

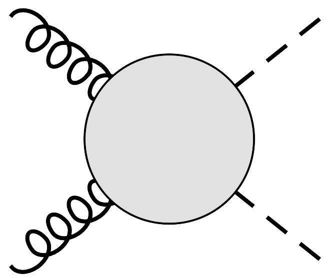
$$\boxed{\lambda f < E < \Lambda}$$

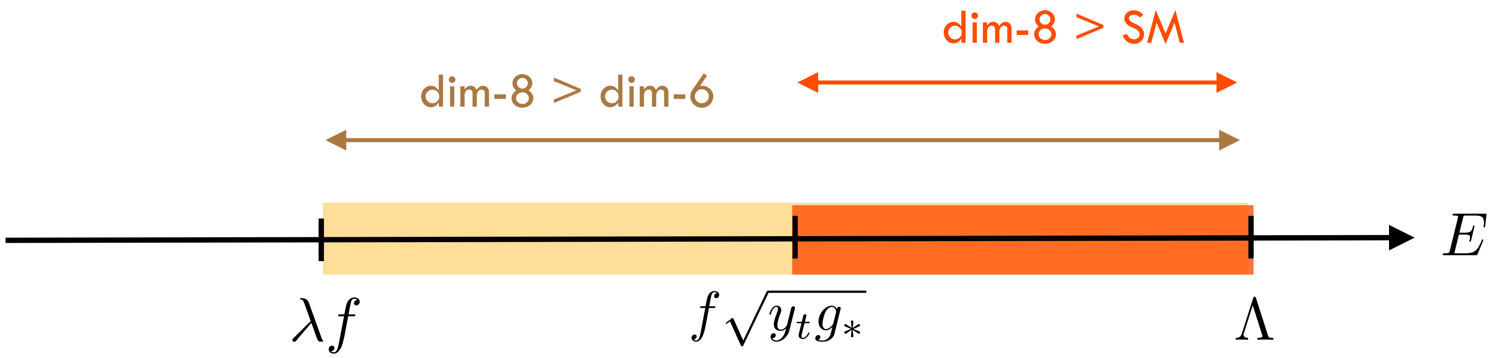
In practice: double Higgs production has a very low rate, dim-8 are unobservable at the LHC unless bigger than SM



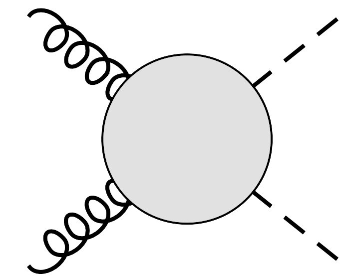


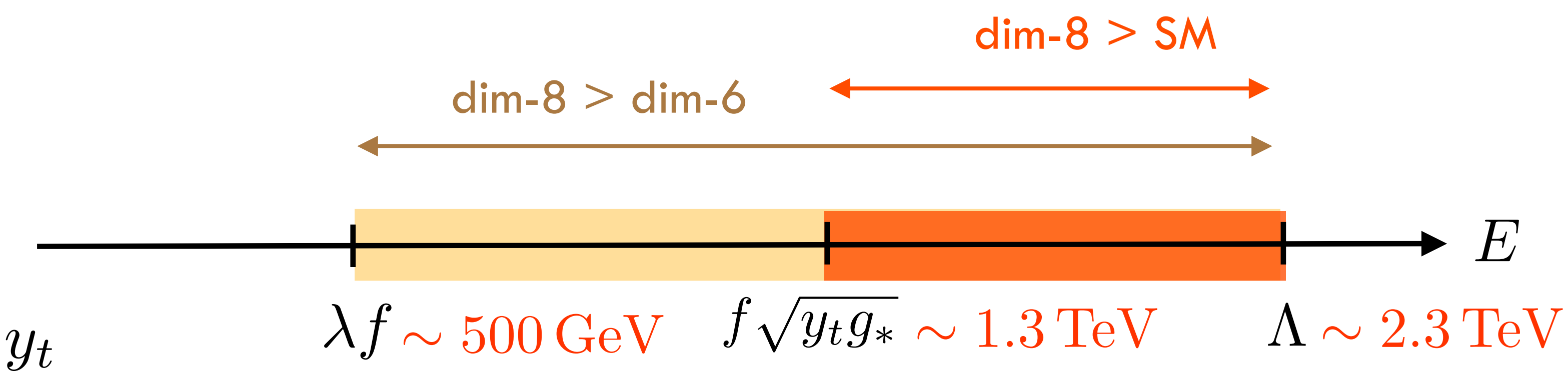
In practice: double Higgs production has a very low rate, dim-8 are unobservable at the LHC unless bigger than SM





In practice: double Higgs production has a very low rate, dim-8 are unobservable at the LHC unless bigger than SM



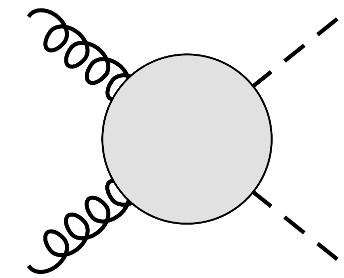


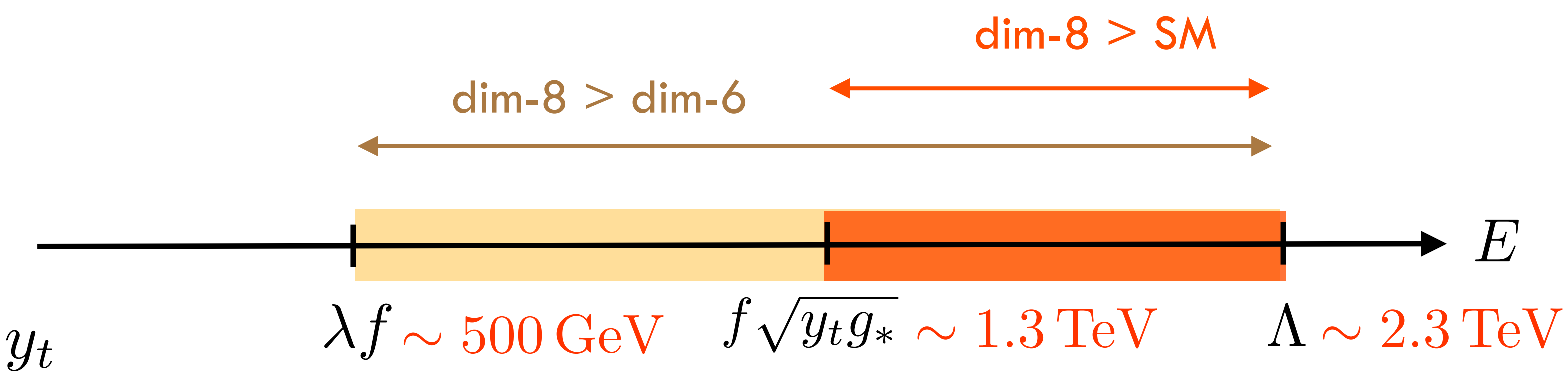
Example: $\lambda = y_t$

$(v^2/f^2) = 0.1$

$g_* = 3$

In practice: double Higgs production has a very low rate, dim-8 are unobservable at the LHC unless bigger than SM





Example: $\lambda = y_t$

$(v^2/f^2) = 0.1$

$g_* = 3$

For a luminosity: $L = 3\,\mathrm{ab}^{-1}$

- requiring at least 5 events
- including 10% efficiency due to kinematic cuts

Largest value of $m(hh)$[GeV]	$b\bar{b}\gamma\gamma$	$4b$
$\sqrt{s} = 14\,\mathrm{TeV}$	550	1550
$\sqrt{s} = 100\,\mathrm{TeV}$	1350	4300

Probing dim-8 operators is very difficult (perhaps impossible) at the LHC

Conclusions / Outlook

Conclusions / Outlook

- Using the EFT in 2→2 processes requires a careful assessment of its validity, to fully exploit the energy reach of the LHC

  Assessing the importance of higher-order operators <u>requires</u> making assumptions on the UV dynamics

Conclusions / Outlook

- Using the EFT in 2→2 processes requires a careful assessment of its validity, to fully exploit the energy reach of the LHC

  Assessing the importance of higher-order operators requires making assumptions on the UV dynamics

- On the experimental side:

  Current EFT analysis of TGC data (both at LEP and LHC) do not constrain any UV theory with simple power counting (like SUSY or CH). EFT validity expected to improve however with higher statistics.

  Current EFT analyses of QGC focusing only on D=8 operators can be partly justified in scenarios with composite W and Z. Neglecting D=6 operators might not be entirely consistent though.

Conclusions / Outlook (II)

- On the experimental side: (continued)

  In general: more synergy between theory and experimental analyses seems required to make fully sense of EFT analyses

  Information on characteristic energy needs to be better disclosed to allow for a proper interpretation of experimental results. It would be desirable to have full information (e.g. likelihood) made public.

Conclusions / Outlook (II)

- On the experimental side: (continued)

  In general: more synergy between theory and experimental analyses seems required to make fully sense of EFT analyses

  Information on characteristic energy needs to be better disclosed to allow for a proper interpretation of experimental results. It would be desirable to have full information (e.g. likelihood) made public.

- On the theory side, improvement is expected on:

  - better determination of SM rates (N^nLO calculations)

  - reducing systematics, e.g. by taking ratios and using data at different energies

  ☞ **See talk by Strassler**

  - EFT at 1-loop (useful only in the case of observed deviations)

Extra slides

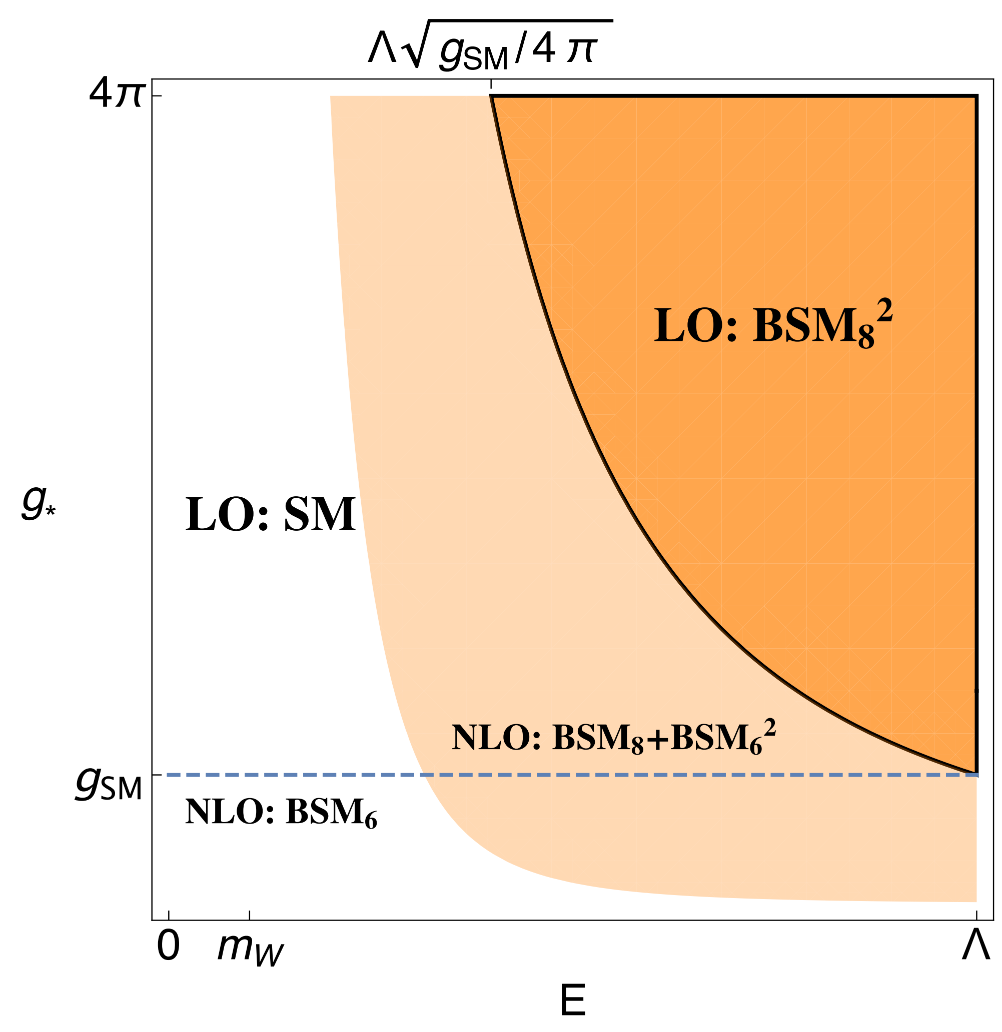
Implications of non-interference (II)

Example: $V_T V_T \to V_T V_T \;\; (T = \pm)$

$$O_6 = F^3_{\mu\nu} \qquad c^{(6)} \sim \frac{g_*}{\Lambda^2}$$

$$O_8 = F^4_{\mu\nu} \qquad c^{(8)} \sim \frac{g_*^2}{\Lambda^4}$$

$$\sigma(TT \to TT) \sim \frac{g_{\rm SM}^4}{E^2}\left[1 + \overbrace{\frac{g_*}{g_{\rm SM}}\frac{m_W^2}{\Lambda^2}}^{\rm BSM_6\times SM} + \overbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^4}{\Lambda^4}}^{\rm BSM_6{}^2} + \underbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^4}{\Lambda^4}}_{\rm BSM_8\times SM} + \underbrace{\frac{g_*^4}{g_{\rm SM}^4}\frac{E^8}{\Lambda^8}}_{\rm BSM_8{}^2} + \dots\right]$$



[similar results for $q\bar{q} \to V_T V_T$]

Implications of non-interference (II)

Example: $V_T V_T \to V_T V_T \;\; (T = \pm)$

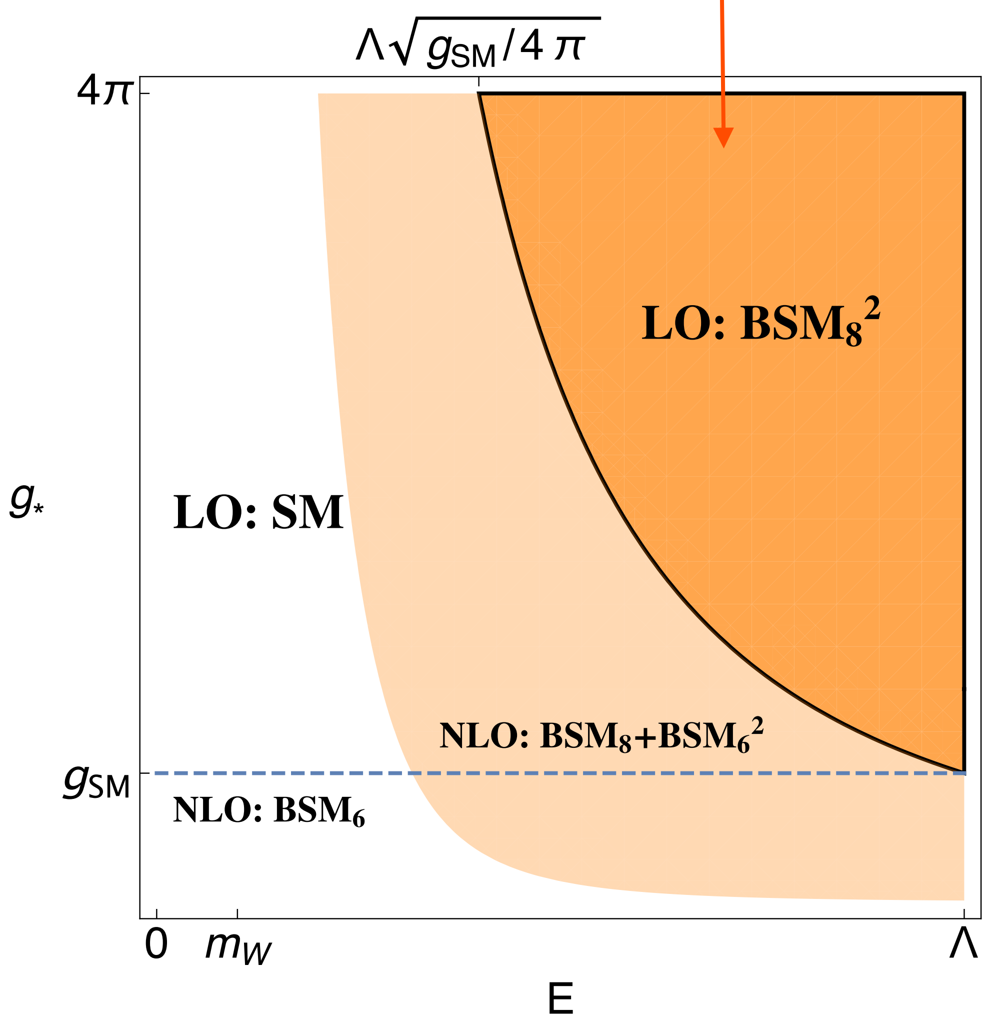
$$O_6 = F^3_{\mu\nu} \qquad c^{(6)} \sim \frac{g_*}{\Lambda^2}$$

$$O_8 = F^4_{\mu\nu} \qquad c^{(8)} \sim \frac{g_*^2}{\Lambda^4}$$

$$\sigma(TT \to TT) \sim \frac{g_{\rm SM}^4}{E^2}\left[1 + \overbrace{\frac{g_*}{g_{\rm SM}}\frac{m_W^2}{\Lambda^2}}^{\rm BSM_6 \times SM} + \overbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^4}{\Lambda^4}}^{\rm BSM_6{}^2} + \underbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^4}{\Lambda^4}}_{\rm BSM_8 \times SM} + \underbrace{\frac{g_*^4}{g_{\rm SM}^4}\frac{E^8}{\Lambda^8}}_{\rm BSM_8{}^2} + \dots\right]$$

dim8² dominates at high energy for strongly-coupled UV dynamics

[Liu, Pomarol, Rattazzi, Riva arXiv:1603.03064]



[similar results for $q\bar{q} \to V_T V_T$]

Implications of non-interference (II)

Example: $V_T V_T \to V_T V_T \;\; (T = \pm)$

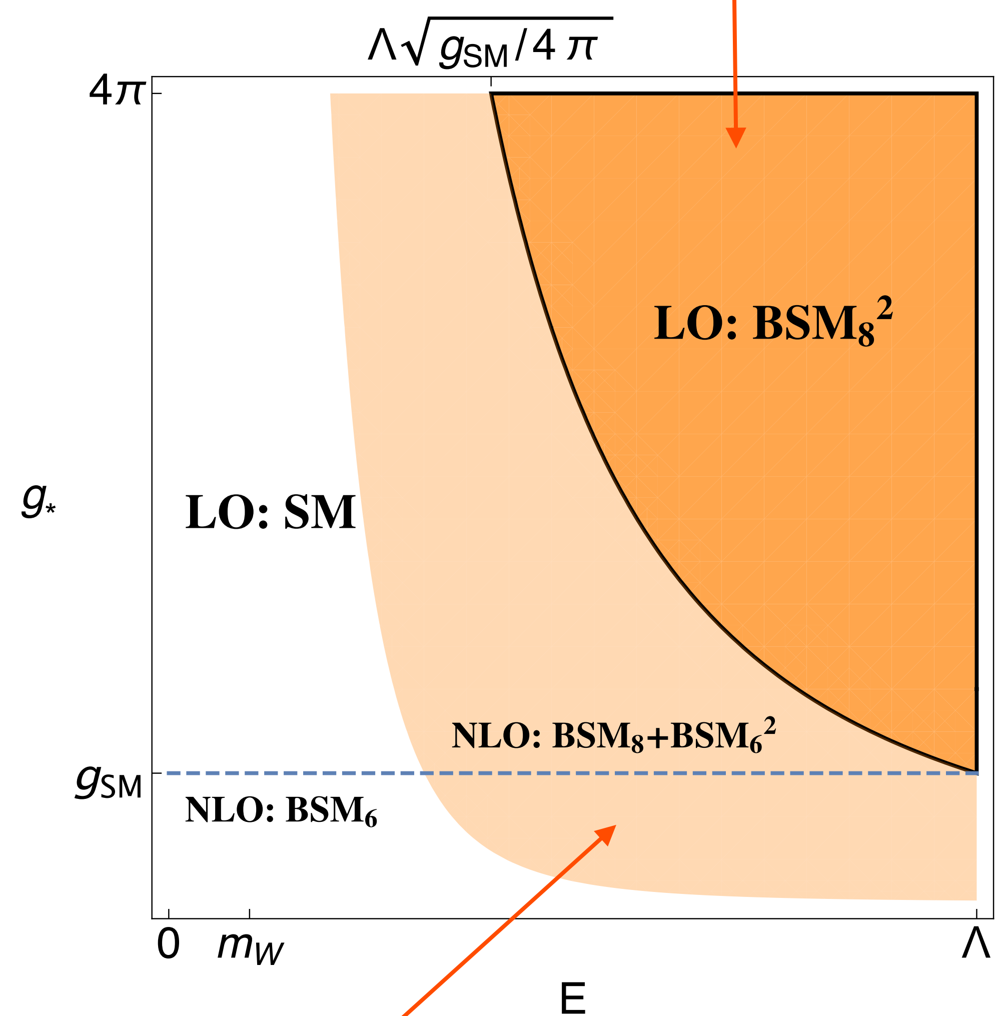
$$O_6 = F^3_{\mu\nu} \qquad c^{(6)} \sim \frac{g_*}{\Lambda^2}$$

$$O_8 = F^4_{\mu\nu} \qquad c^{(8)} \sim \frac{g_*^2}{\Lambda^4}$$

$$\sigma(TT \to TT) \sim \frac{g^4_{\rm SM}}{E^2}\Bigg[1 + \overbrace{\frac{g_*}{g_{\rm SM}}\frac{m_W^2}{\Lambda^2}}^{\rm BSM_6\times SM} + \overbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^4}{\Lambda^4}}^{\rm BSM_6{}^2} + \underbrace{\frac{g_*^2}{g_{\rm SM}^2}\frac{E^4}{\Lambda^4}}_{\rm BSM_8\times SM} + \underbrace{\frac{g_*^4}{g_{\rm SM}^4}\frac{E^8}{\Lambda^8}}_{\rm BSM_8{}^2} + \dots\Bigg]$$

dim8² dominates at high energy for strongly-coupled UV dynamics

[Liu, Pomarol, Rattazzi, Riva arXiv:1603.03064]



precocious onset of dim6² and dim8-SM

[similar results for $q\bar{q} \to V_T V_T$]

Consider: tree-level amplitudes in the massless limit ($E \gg m_W$)

Tools:

- complexified momenta $p \in \mathbb{C}$
- spinor helicity formalism

$$p_\mu (\sigma^\mu)_{a\dot{b}} = -\lambda_a \tilde{\lambda}_{\dot{b}}$$

$$\lambda_a \in (1/2, 0)$$
$$\tilde{\lambda}_{\dot{b}} \in (0, 1/2)$$

$$\bar{u}_+(p) = (\lambda^a, 0)$$
$$\bar{u}_-(p) = (0, \lambda^{\dot{a}})$$

$$\varepsilon_\mu^+ (\sigma^\mu)_{a\dot{b}} = \sqrt{2}\, \frac{\xi_a \tilde{\lambda}_{\dot{b}}}{\langle \xi \lambda \rangle}$$

$$\varepsilon_\mu^- (\sigma^\mu)_{a\dot{b}} = \sqrt{2}\, \frac{\lambda_a \tilde{\xi}_{\dot{b}}}{[\tilde{\lambda}\, \tilde{\xi}]}$$

- Little group scaling

$$\lambda \to t\, \lambda$$
$$\tilde{\lambda} \to t^{-1}\, \tilde{\lambda}$$

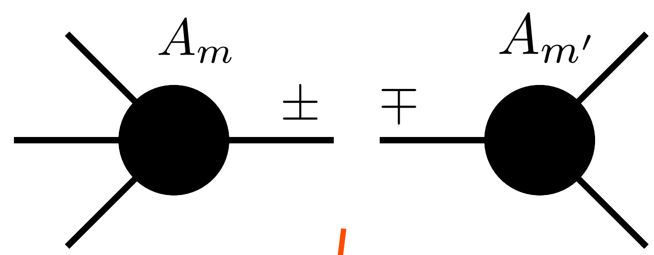
$$A \to t^{-2h(A)} A$$

Well-known results:

1. Helicity addition rule

$$\boxed{h(A_n) = h(A_m) + h(A_{m'})}$$

for any two sub-amplitudes A_m , $A_{m'}$

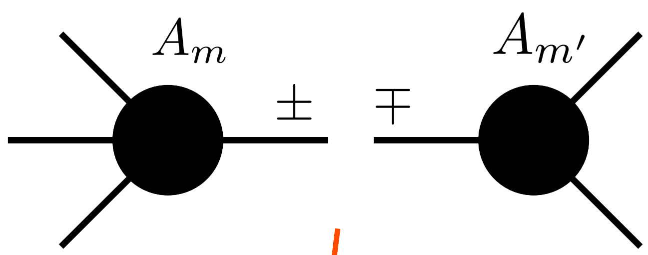


$$m + m' - 2 = n$$

pole for on-shell internal line = factorization into two on-shell sub-amplitudes

Well-known results:

1. Helicity addition rule



$m + m' - 2 = n$

$$\boxed{h(A_n) = h(A_m) + h(A_{m'})}$$

for any two sub-amplitudes A_m , $A_{m'}$

pole for on-shell internal line = factorization into two on-shell sub-amplitudes

2. Helicity of 3-point amplitudes

$$\boxed{h(A_3) = 1 - [g]}$$

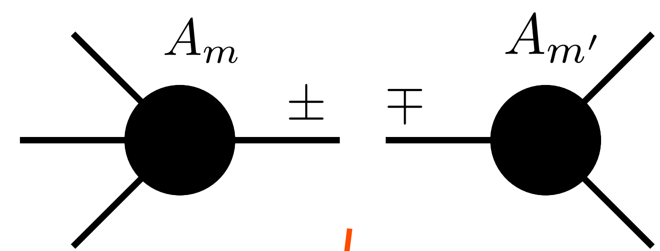
$g =$ cubic coupling

Poincare inv. + Locality + Little group scaling completely fix 3-point amplitudes

In the SM $[g]=0$ gives $h(A_3)= \pm 1$

Well-known results:

1. Helicity addition rule



$$m + m' - 2 = n$$

$$\boxed{h(A_n) = h(A_m) + h(A_{m'})}$$

pole for on-shell internal line = factorization into two on-shell sub-amplitudes

for any two sub-amplitudes A_m , $A_{m'}$

2. Helicity of 3-point amplitudes

$$\boxed{h(A_3) = 1 - [g]}$$

$g =$ cubic coupling

Poincare inv. + Locality + Little group scaling completely fix 3-point amplitudes

In the SM $[g] = 0$ gives $h(A_3) = \pm 1$

3. Selection rule from SUSY Ward Identities

In the SM some 4-point amplitudes with $|h| = 2$ vanish

$$\boxed{\begin{aligned} A(V^+V^+V^+V^-) &= A(V^+V^+\psi^+\psi^-) \\ &= A(V^+V^+\phi\phi) = A(V^+\psi^+\psi^+\phi) = 0 \end{aligned}}$$

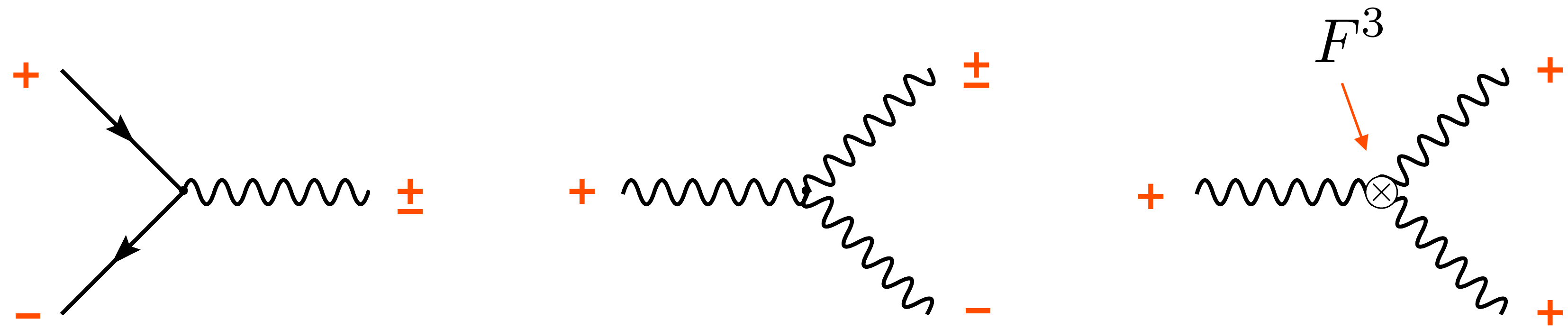
The total helicity of 4-point functions can be determined using these three properties

The total helicity of 4-point functions can be determined using these three properties

$$F_{\mu\nu}\sigma^{\mu}_{\alpha\dot{\alpha}}\sigma^{\nu}_{\beta\dot{\beta}} \equiv F_{\alpha\beta}\bar{\epsilon}_{\dot{\alpha}\dot{\beta}} + \bar{F}_{\dot{\alpha}\dot{\beta}}\epsilon_{\alpha\beta}$$

Example:

Property #2 implies



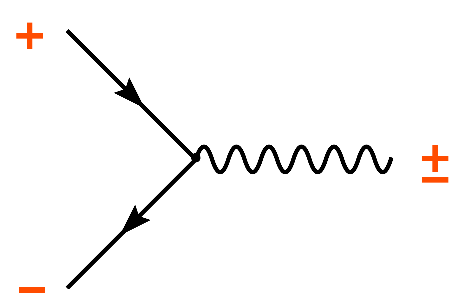
$h(A_3) = \pm 1$ $\qquad$ $h(A_3) = \pm 1$ $\qquad$ $h(A_3) = +3$

The total helicity of 4-point functions can be determined using these three properties

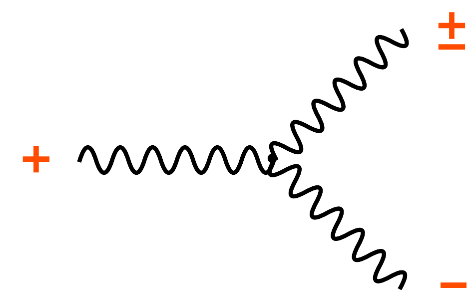
$$F_{\mu\nu}\sigma^{\mu}_{\alpha\dot{\alpha}}\sigma^{\nu}_{\beta\dot{\beta}} \equiv F_{\alpha\beta}\bar{\epsilon}_{\dot{\alpha}\dot{\beta}} + \bar{F}_{\dot{\alpha}\dot{\beta}}\epsilon_{\alpha\beta}$$

Example:

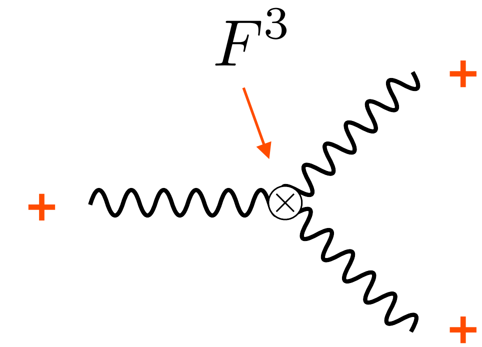
Property #2 implies



$h(A_3) = \pm 1$

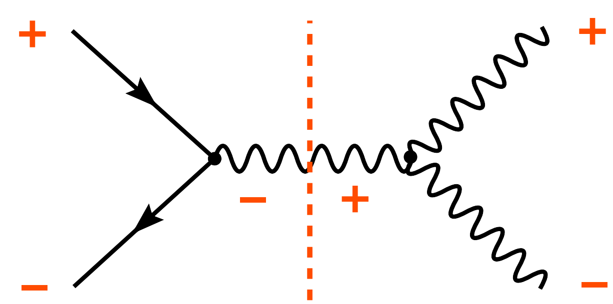


$h(A_3) = \pm 1$

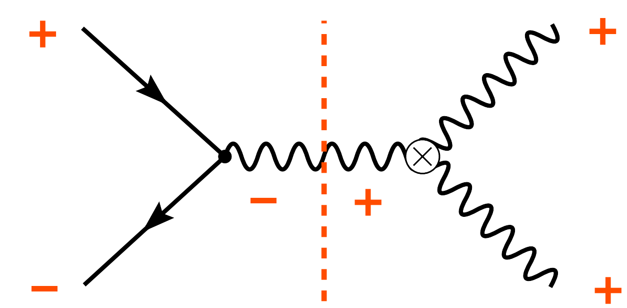


$h(A_3) = +3$

Property #1 implies



$h(A_3) = 0$



$h(A_3) = +2$

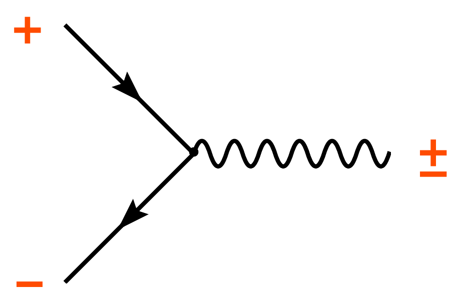
[h=+2 forbidden by Property #3]

The total helicity of 4-point functions can be determined using these three properties

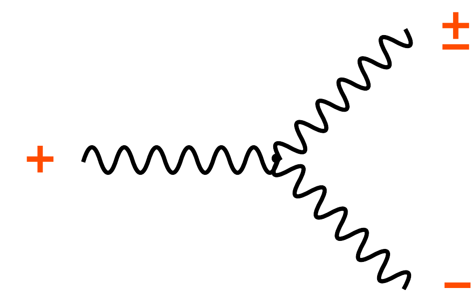
$$F_{\mu\nu}\sigma^{\mu}_{\alpha\dot{\alpha}}\sigma^{\nu}_{\beta\dot{\beta}} \equiv F_{\alpha\beta}\bar{\epsilon}_{\dot{\alpha}\dot{\beta}} + \bar{F}_{\dot{\alpha}\dot{\beta}}\epsilon_{\alpha\beta}$$

Example:

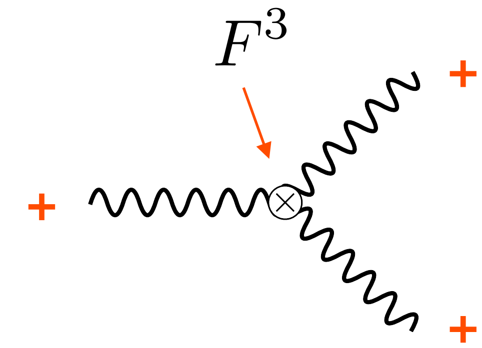
Property #2 implies



$h(A_3) = \pm 1$

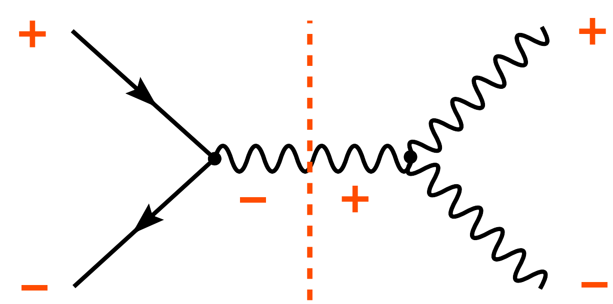


$h(A_3) = \pm 1$

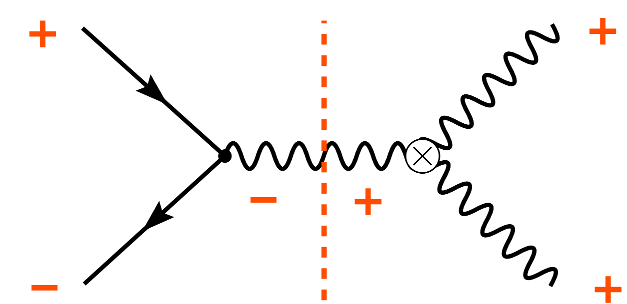


$h(A_3) = +3$

Property #1 implies



$h(A_3) = 0$



$h(A_3) = +2$

[h=+2 forbidden by Property #3]

Generalization to all operators easy through the use of holomorphic and ant-holomorphic weights

$$w(\mathcal{O}) \equiv \min_A\{w(A)\} \qquad \bar{w}(\mathcal{O}) \equiv \min_A\{\bar{w}(A)\}$$

$$w(A) = n(A) - h(A) \qquad \bar{w}(A) = n(A) + h(A)$$

Beyond the leading approximation

- Non-interference in general fails for higher-point amplitudes and at the 1-loop level

  Leading effect arises at $O(\alpha_S/\pi)$ from real emissions (for inclusive processes) and 1-loop virtual corrections (pure EW corrections similar but smaller)

  No log enhancement in the interference due to soft and collinear singularities in real emissions or IR divergences in 1-loop diagrams [see: Dixon and Shadmi NPB 423 (1994) 3]

Beyond the leading approximation

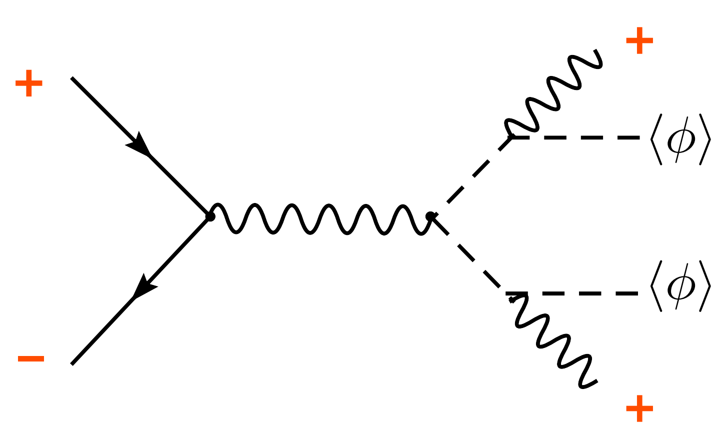
- Non-interference in general fails for higher-point amplitudes and at the 1-loop level

  Leading effect arises at $O(\alpha_S/\pi)$ from real emissions (for inclusive processes) and 1-loop virtual corrections (pure EW corrections similar but smaller)

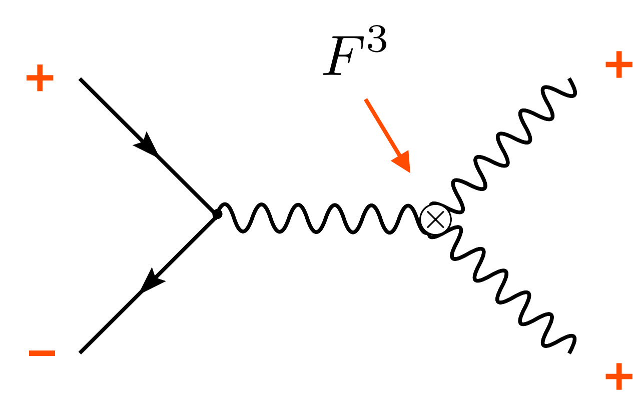
  No log enhancement in the interference due to soft and collinear singularities in real emissions or IR divergences in 1-loop diagrams [see: Dixon and Shadmi NPB 423 (1994) 3]

- Finite-mass effects arise at $O(m^2_{W,t}/E^2)$ and can be determined by considering higher-point amplitudes with Higgs vevs

Ex:



SM: $A_6(\psi^+\psi^-V^+V^+\phi\phi)$



BSM$_6$: $A_6(\psi^+\psi^-V^+V^+)$

- radiative corrections subdominant compared to mass effects except at very high energies $E \gtrsim m_W \sqrt{4\pi/\alpha_S} \sim 1\,\mathrm{TeV}$

Fermion mass insertions usually subdominant except for top quarks (e.g. F^3 interferes at $O(\varepsilon_F^2)$ in $gg \to t\bar{t}$)

- Accessing the $O(1/\Lambda^2)$ corrections from D=6 operators *without relative suppression* is possible by considering $2 \to 3$ processes (i.e. $2 \to 2$ plus extra jet)

ex: constraining F^3 through 3-jet events [Dixon and Shadmi NPB 423 (1994) 3]

Max gain in sensitivity $\sim \sqrt{4\pi/\alpha_S}$ (at the cost of a reduced S/B)

Form of 3-point amplitudes is fixed

for reviews see: Dixon, Boulder 1995 [hep-ph/9601359]
Mangano and Parke Phys. Rept. 200 (1991) 301
Elvang and Huang arXiv:1308.1697

1. By Poincare' invariance any 3-point amplitude can depend on either square *or* angle brackets

$$p_1^\mu + p_2^\mu + p_3^\mu = 0 \quad \longleftrightarrow \quad \langle 12\rangle[12] = 0\,, \quad \langle 23\rangle[23] = 0\,, \quad \langle 31\rangle[31] = 0\,,$$

hence either $\langle 12\rangle = \langle 23\rangle = \langle 31\rangle = 0$ *or* $[12] = [23] = [31] = 0$

Form of 3-point amplitudes is fixed

for reviews see: Dixon, Boulder 1995 [hep-ph/9601359]
Mangano and Parke Phys. Rept. 200 (1991) 301
Elvang and Huang arXiv:1308.1697

1. By Poincare' invariance any 3-point amplitude can depend on either square *or* angle brackets

$$p_1^\mu + p_2^\mu + p_3^\mu = 0 \quad \leftrightarrow \quad \langle 12\rangle[12] = 0\,, \quad \langle 23\rangle[23] = 0\,, \quad \langle 31\rangle[31] = 0\,,$$

hence either $\langle 12\rangle = \langle 23\rangle = \langle 31\rangle = 0$ *or* $[12] = [23] = [31] = 0$

2. Under Little group scaling $A_n \to A_n \times t_i^{-2h_i}$ $\quad |i\rangle \to t_i\, |i\rangle\,, \quad |i] \to t_i^{-1}\, |i]$

Locality implies:

$$A_3 = g \begin{cases} \langle 12\rangle^{r_3} \langle 23\rangle^{r_1} \langle 31\rangle^{r_2} & \text{for } h(A_3) \leq 0 \\ [12]^{\bar{r}_3} [23]^{\bar{r}_1} [31]^{\bar{r}_2} & \text{for } h(A_3) \geq 0 \end{cases}$$

$$r_1 = h_1 - h_2 - h_3$$
$$r_2 = h_2 - h_3 - h_1$$
$$r_3 = h_3 - h_1 - h_2$$
$$\bar{r}_i = -r_i$$

Form of 3-point amplitudes is fixed

for reviews see: Dixon, Boulder 1995 [hep-ph/9601359]
Mangano and Parke Phys. Rept. 200 (1991) 301
Elvang and Huang arXiv:1308.1697

1. By Poincare' invariance any 3-point amplitude can depend on either square *or* angle brackets

$$p_1^\mu + p_2^\mu + p_3^\mu = 0 \quad \longleftrightarrow \quad \langle 12\rangle[12] = 0\,, \quad \langle 23\rangle[23] = 0\,, \quad \langle 31\rangle[31] = 0\,,$$

hence either $\langle 12\rangle = \langle 23\rangle = \langle 31\rangle = 0$ *or* $[12] = [23] = [31] = 0$

2. Under Little group scaling $A_n \to A_n \times t_i^{-2h_i}$ $\quad |i\rangle \to t_i\,|i\rangle\,, \quad |i] \to t_i^{-1}\,|i]$

Locality implies:

$$A_3 = g \begin{cases} \langle 12\rangle^{r_3}\langle 23\rangle^{r_1}\langle 31\rangle^{r_2} & \text{for } h(A_3) \leq 0 \\ [12]^{\bar{r}_3}[23]^{\bar{r}_1}[31]^{\bar{r}_2} & \text{for } h(A_3) \geq 0 \end{cases}$$

$$r_1 = h_1 - h_2 - h_3$$
$$r_2 = h_2 - h_3 - h_1$$
$$r_3 = h_3 - h_1 - h_2$$
$$\bar{r}_i = -r_i$$

3. From Dimensional Analysis it follows: $h(A_3) = 1 - [g]$

similarly: $n - h(A_n) + [g] = even$