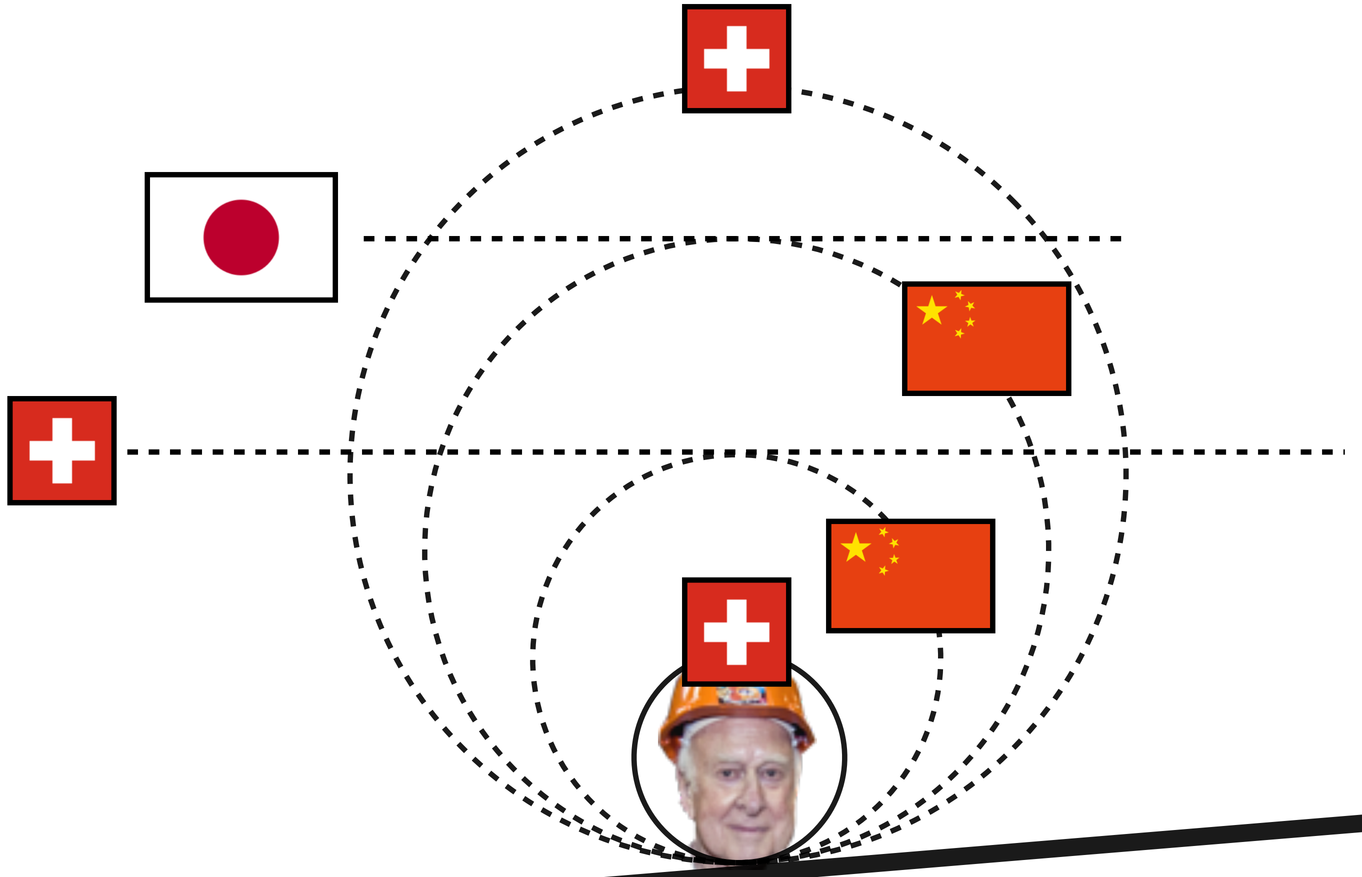
EFT Validity and Interpretation
— BSM Perspective —

EFT Working Group

CERN/Zoom, Jan. 19, 2021



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Can validity of (truncated) EFT be established model-independently?

Contino, Falkowski, Goertz, Grojean, Riva '16

F. Riva, LHCHXSWG '16

Problem: Expansion Validity: E/Λ<<1

Example: Fermi theory $\frac{2}{v^2}\bar\psi_{\nu_\mu}\gamma^\mu\psi_\mu\bar\psi_{\nu_e}\gamma^\mu\psi_e$ is it valid up to v=246 GeV?

No, only to $E = m_W = \frac{g}{2}v \approx 81 \text{ GeV}$ $c_i^6=c_i^8=g^2$

- Weak couplings reduce the validity range of the EFT (as naively expected)
- Strong couplings extend it (for g=4π Fermi theory ok up to E≈3 TeV!)

$$\mathcal{L} = \underbrace{\frac{g^2}{m_W^2}}_{c_6}\psi^4 + \underbrace{\frac{g^2}{m_W^4}}_{c_8}\partial^2\psi^4 + \dots$$

The full knowledge of the Fermi L_{EFT} could then tell us about the cutoff ($c_6/c_8 = m_W^2$)
but this is **model-depend:** one needs to put in some UV assumptions to extract information on the cutoff from the EFT Lagrangian

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Problem: Expansion Validity: E/Λ<<1

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Message #1:
even if we have enough accuracy to reconstruct exactly L_{EFT},
we *cannot* estimate in a model-independent way the EFT truncation errors

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From Observables to L_{EFT}

The question of EFT validity is even more complicated because we don't have directly access to L_{EFT} but only to $|\mathcal{M}|^2, d\sigma \ldots$

observables ⟶ L_{EFT}

can be done only from truncated L_{EFT},
and this truncation induces an error.
We need to make sure that the terms omitted in the truncation
don't affect/spoil too much the determination of the terms kept in L_{EFT}.
To answer this question, one obviously needs to make assumption
on the scaling of the neglected terms as function of the terms that can be measured.

Message #2:
the estimation of the truncation errors also needs UV assumptions
and can be done only a posteriori
once the bounds on the terms kept have been obtained
(not an excuse for not getting the most precise EFT prediction, NLO etc…)

From Amplitudes to L_{EFT}

Let's take the simple example of a single BSM particle of mass M_* exchanged in s-channel and with a coupling g_* to the SM.

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$$\mathcal{A}(\text{SM+SM} \to \text{SM+SM}) = g_{\text{SM}}^2 + \frac{g_*^2 E^2}{E^2 - M_*^2} \approx \underbrace{g_{\text{SM}}^2}_{A_{SM}} - \underbrace{\frac{g_*^2 E^2}{M_*^2}}_{A_6} - \underbrace{\frac{g_*^2 E^4}{M^4}}_{A_8} + \ldots$$

($c_6 = g_*^2/M_*^2, c_8 = g_*^2/M_*^4$ as in the Fermi theory)

EFT benchmark for which the EFT validity/error can be estimated from the knowledge of measurements and UV imprints (g_* or M_*)

"error" (A_8 relative to A_6) is clearly controlled by the energy of the process
EXP should report c_6 as a function of characteristic energy of the measurements

LEP/flavour/early LHC: E is implicitly known
HL-LHC/Future Colliders: E should be reported explicitly

important consequence on the design of the analyses (not always that best sensitivity comes from highest bins → control of the systematics over all energy range…)

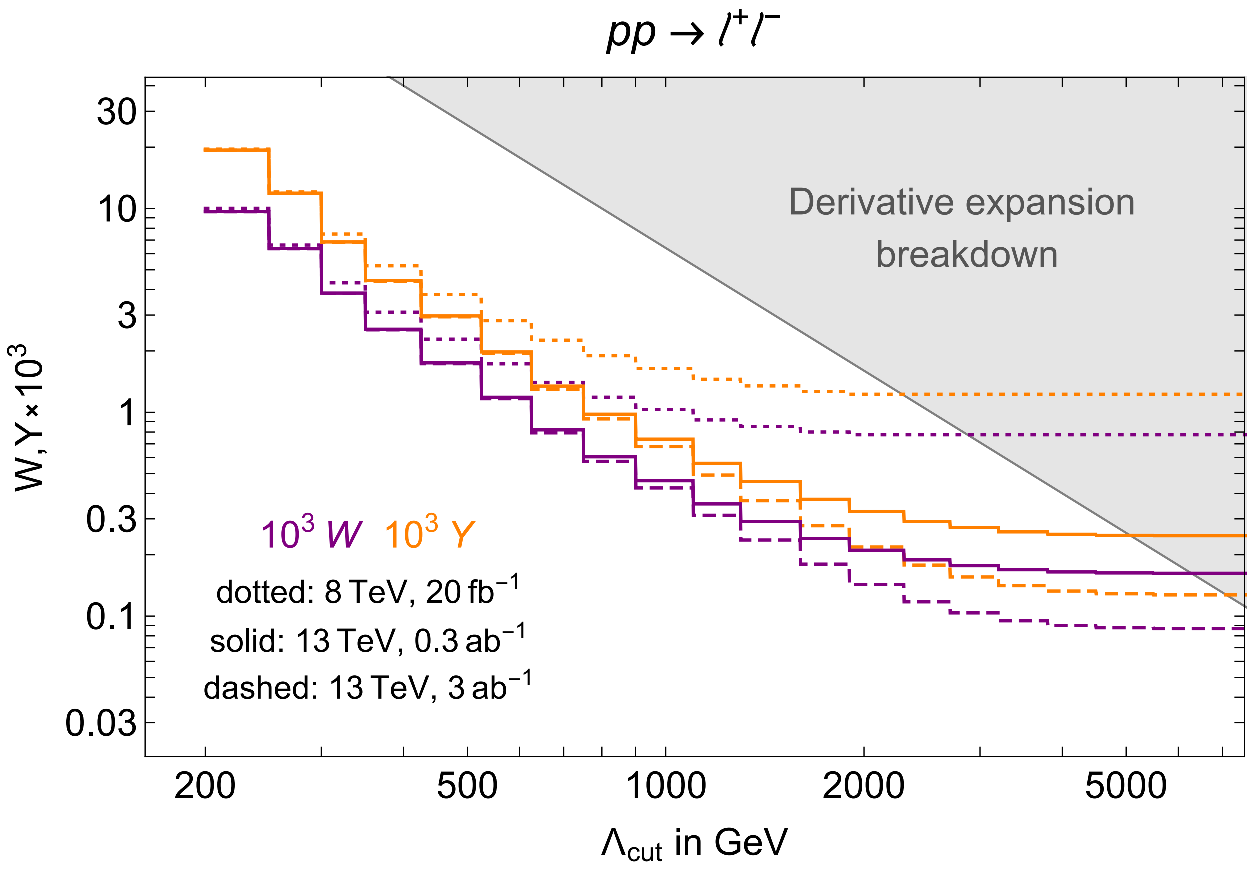
EFT Validity

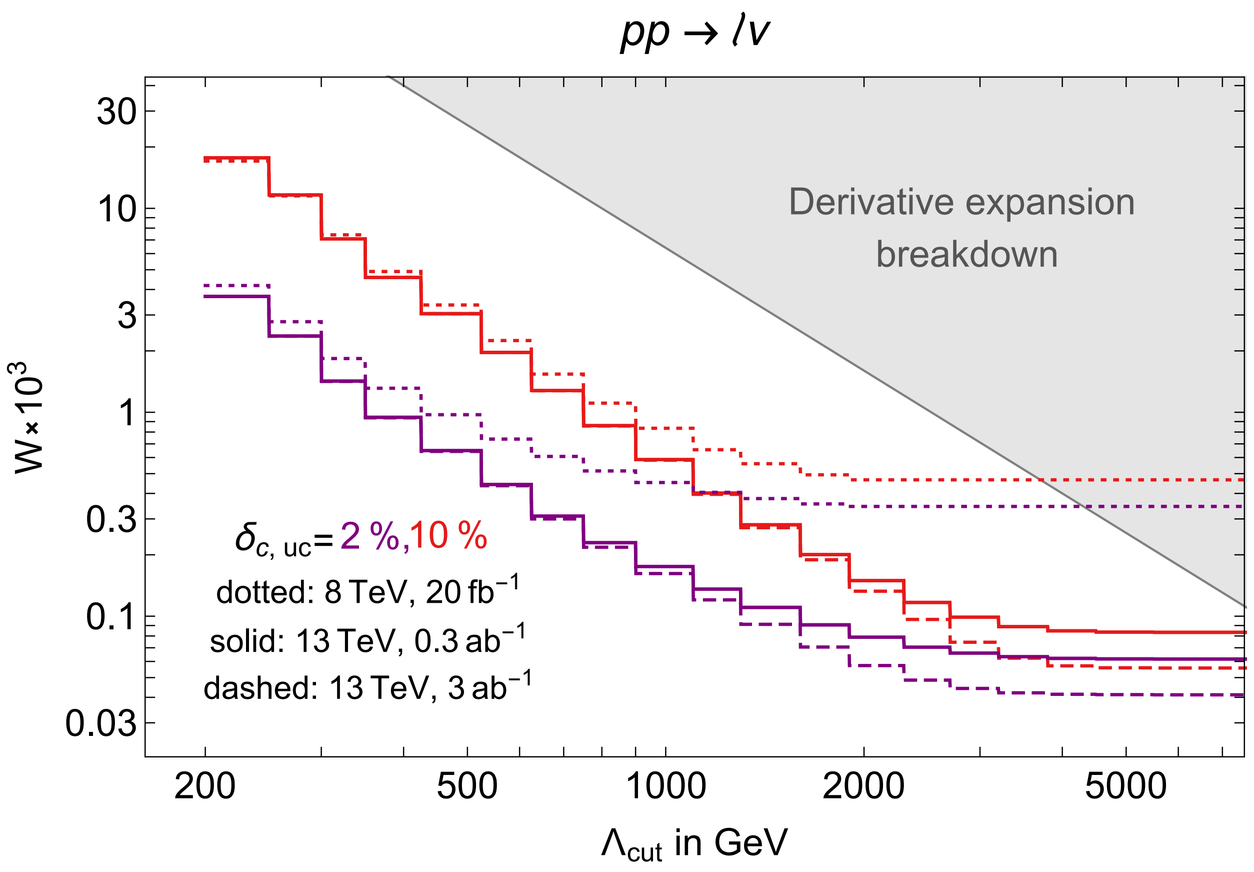
Practical simple recipe #1 in simple EFTs

report the EFT bounds as a function of sliding cut on √š (or equivalent kinematic variable)

$$G_{(6)} < \delta^{\rm exp}(M_{\rm cut})$$

example: Constraints on oblique corrections from Drell-Yan   Farina+ '16   Ricci+ '20





regions where the coupling of NP would be larger than 4π
→ expansion not reliable
i.e. large uncertainty from neglecting higher dimensional operators

The larger the cut, the stronger the constraints. But if it is taken too large, no consistent EFT interpretation.
One cannot exclude that, for some measurements, there is simply no possible consistent EFT interpretation.

|dim-6|² ?

Contino+ '16

Formally |dim-6|² ~ (dim4)*(dim-8) ~ 1/Λ⁴

so |dim-6|² is often, erroneously, taken as a proxy for the truncation error.

$$\mathcal{A} = g_{\rm SM}^2 + \bar{c}_6\, g_*^2 \left(\frac{E}{\Lambda}\right)^2 + \bar{c}_8\, g_*^2 \left(\frac{E}{\Lambda}\right)^4 + \ldots$$

$\bar{c}_6 \sim \bar{c}_8 \sim \mathcal{O}(1)$

$$|\mathcal{A}|^2 = |\mathcal{A}|^2 \left(1 + \frac{g_*^2}{g_{\rm SM}^2}\,\bar{c}_6 \left(\frac{E}{\Lambda}\right)^2 + \left(\frac{g_*^4}{g_{\rm SM}^4}\,\bar{c}_6^2 + \frac{g_*^2}{g_{\rm SM}^2}\,\bar{c}_8\right)\left(\frac{E}{\Lambda}\right)^4 + \ldots\right)$$

- $g_{\rm SM} < g_*$ ➡ $|\mathcal{A}_6|^2 > \mathcal{A}_{\rm SM} \cdot \mathcal{A}_8$
- $g_* < g_{\rm SM}$ ➡ $|\mathcal{A}_6|^2 < \mathcal{A}_{\rm SM} \cdot \mathcal{A}_8$ should we drop $|A_6|^2$ then?

Notice that: $\mathcal{A}_{\rm SM} \cdot \mathcal{A}_6 \sim \frac{g_{\rm SM}^2 g_*^2}{M_*^2} E^2 > \mathcal{A}_{\rm SM} \cdot \mathcal{A}_8$ so interference dim-8 is not dominating

so keeping $|A_6|^2$ or not has no influence on the final bound

Conclusion: either $|A_6|^2$ is important and it should be kept, or it is subdominant and it doesn't hurt to keep it.

|dim-6|^2 ?

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Recipe #2:
Perform a linear and quadratic fits
If the two fits differ: either the reach is dominated by high-energy measurements
or the results are valid only in special UV scenarios (e.g. $g_* > g_{\rm SM}\frac{M}{E}$);
more difficult to make sense of the linear fit.
— Goal of good EFT analysis —
ensure that quadratic and linear fits agree since larger interpretability

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|dim-6|² ?

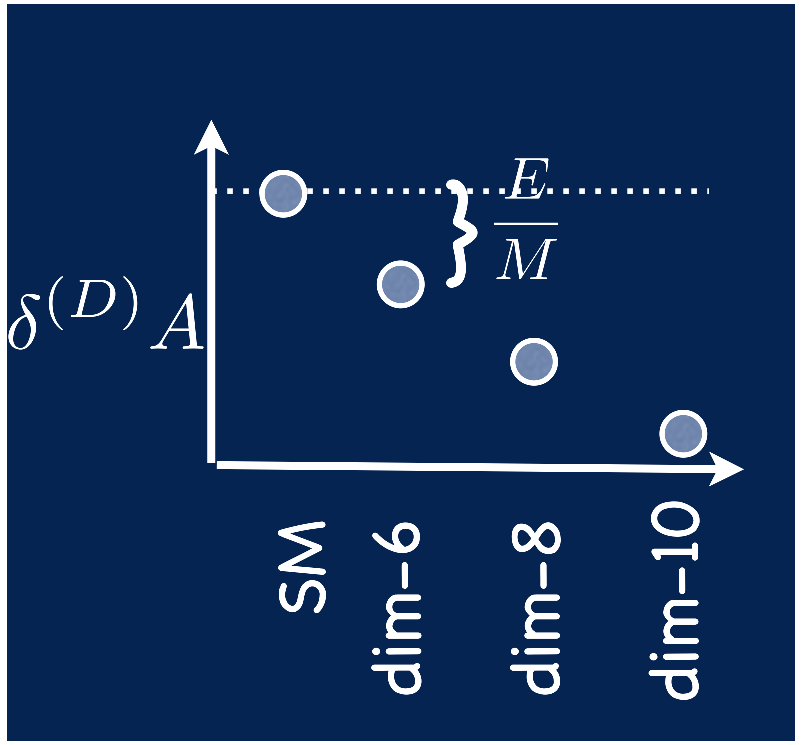
$$A \simeq g^2 \left(1 + \hat{c}\frac{g_*^2}{g^2}\frac{E^2}{\Lambda^2}\right)$$

BSM can be > 1 for g*/g>Λ/E>>1

EFT valid

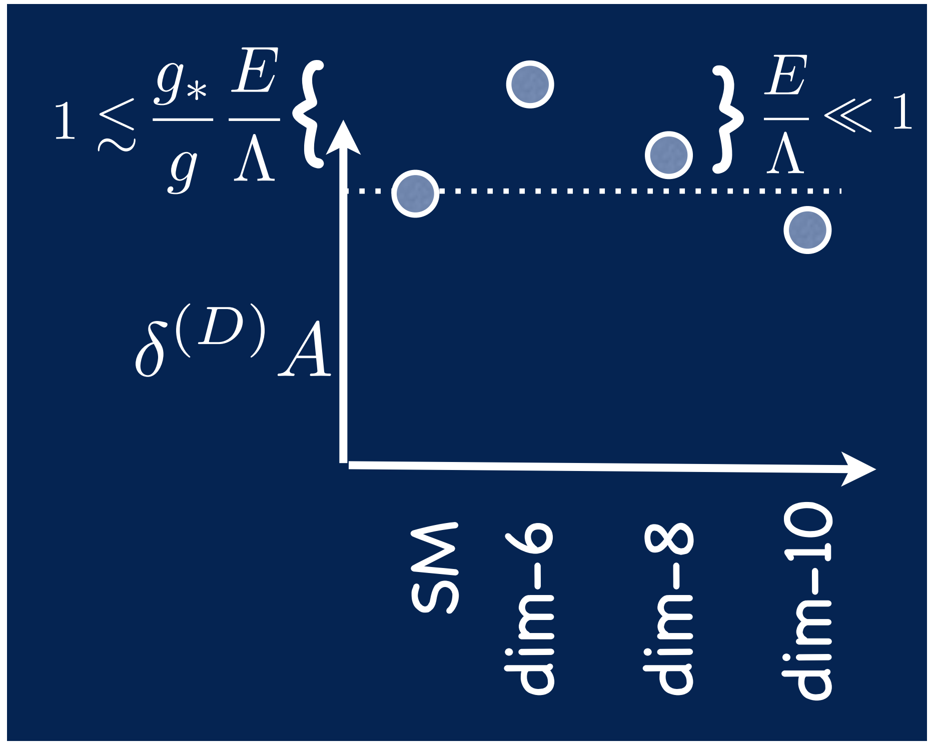
F. Riva, LHCHXSWG '16

Small Deviations from SM



→Interpretation possible for small or large coupling

Large Deviations from SM



Interpretation possible **ONLY** for strong coupling (EFT expansion still valid)

|dim-6|² ?

There can be (many) exception(s) to the simple general scaling rule

- Mixing with operators with weaker bounds
- SM had accidental/structural cancellation: |dim-6|² can dominate over SM*dim-8 even for weakly coupled UV model, e.g. flavour physics
- There is no interference between SM and dim-6 operators, e.g. non-interference theorem, or observable too inclusive (e.g. CP even observable dependence on CP-odd operators): -> need to think of particular observables to “resurrect” the interference!

Azatov+ ‘16

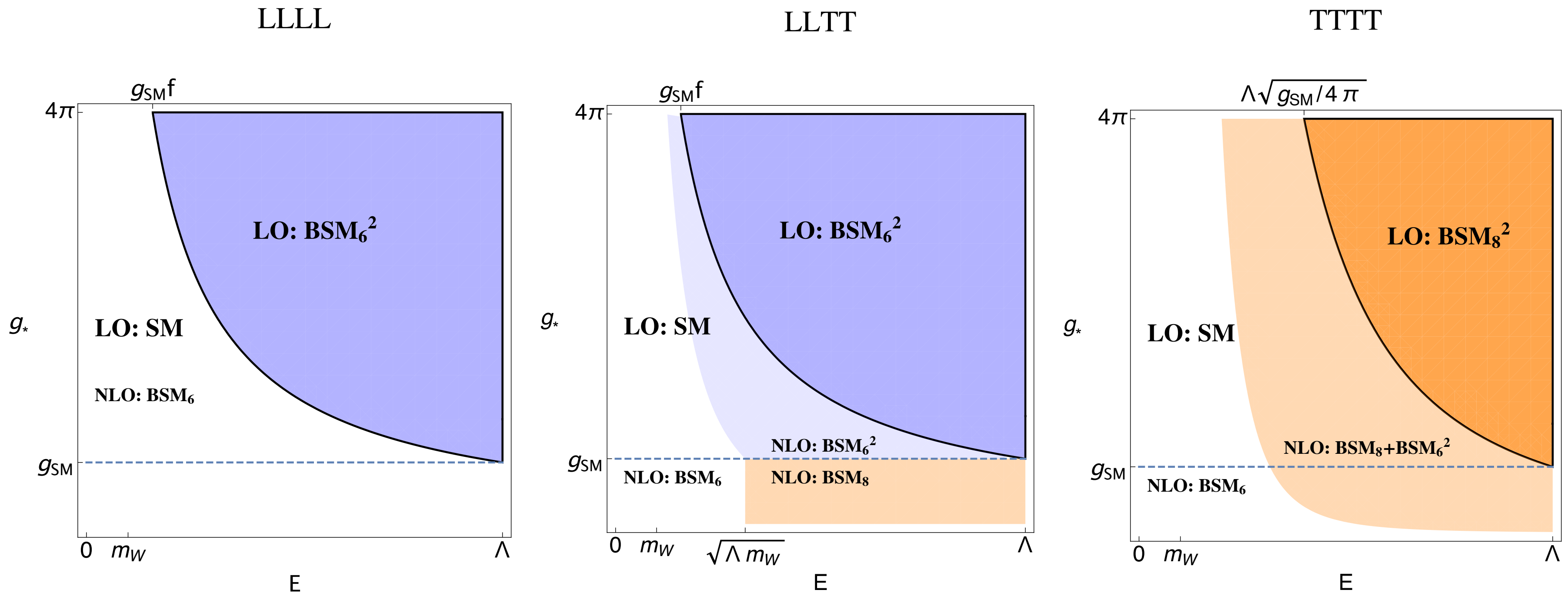
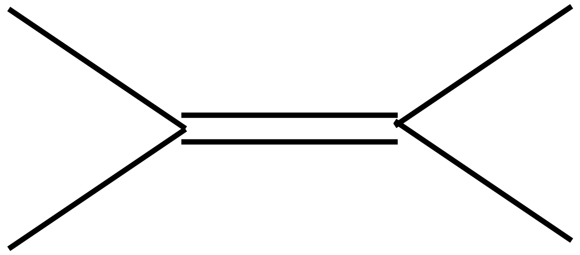
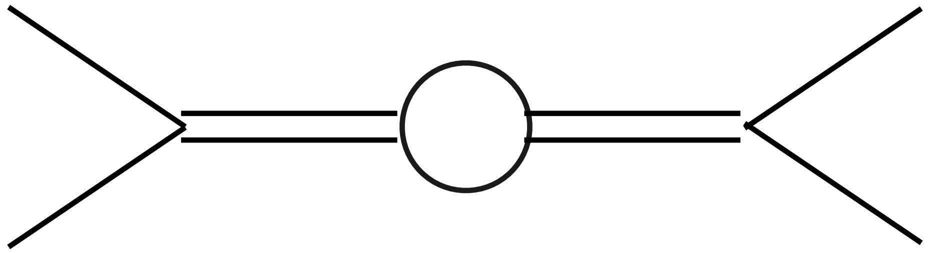


FIG. 2: *A schematic representation of the relative size of different contributions to the VVVV scattering cross sections, with polarization LLLL (left panel), LLTT (central panel) and TTTT (right panel). LO/NLO denote the leading/next-to-leading contributions to the cross section. In the white region the SM dominates and the leading BSM correction comes from the BSM_6-SM interference (denoted as BSM_6). BSM non-interference is responsible for the light-shaded blue and orange regions, where the BSM, although it is only a small perturbation around the SM, is dominated by terms of order E^4/Λ^4, either from $(BSM_6)^2$ or from the BSM_8-SM interference (denoted as BSM_8).*

Double Insertion of BSM vertices in $A_6 A_{SM}$?



$$\frac{g_*^2 E^2}{M^2}$$



$$\frac{1}{16\pi^2}\frac{g_*^4 E^4}{M^4}$$

in general subdominant
except maybe in some particular regions of webspace
or for some analyses with suppression of leading terms

At NLO, double insertions will require dim-8 counter-terms
Change of bases could also require dim-8 operators for consistency

Might become relevant once EFT analyses will enter precision era
Not a priority for now, more urgent actions to be taken now to fully exploit data in an EFT framework

EFT benchmarks: Structural Hypotheses

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots$$

Dimensional arguments impose

$$c_i^{(D)} \sim (\text{coupling})^{n_i-2}$$

n_i=number of fields in operator $\mathcal{O}_i^{(D)}$ (independant of D)

generically, (coupling ~ g_*) coupling of New Physics to SM
but there might exist "selection rules" that lead to other scaling

Examples of symmetries leading to different selection rules

Operator	Naive (maximal) scaling with g_*	Symmetry/Selection Rule and corresponding suppression
$O_{y_\psi} = \|H\|^2 \bar\psi_L H \psi_R$	g_*^3	Chiral: y_f/g_*
$O_T = (1/2)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	g_*^2	Custodial: $(g'/g_*)^2$, $y_t^2/16\pi^2$
$O_{GG} = \|H\|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$ $O_{BB} = \|H\|^2 B_{\mu\nu} B^{\mu\nu}$	g_*^2	Shift symmetry: $(y_t/g_*)^2$ Elementary Vectors: $(g_s/g_*)^2$ (for O_{GG}) $(g'/g_*)^2$ (for O_{BB}) Minimal Coupling: $g_*^2/16\pi^2$
$O_6 = \|H\|^6$	g_*^4	Shift symmetry: λ/g_*^2
$O_H = (1/2)(\partial^\mu \|H\|^2)^2$	g_*^2	Coset Curvature: ϵ_c
$O_B = (i/2)\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}$ $O_W = (i/2)\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right)\partial^\nu W^a_{\mu\nu}$	g_*	Elementary Vectors: g'/g_* (for O_B) g/g_* (for O_W)
$O_{HB} = (i/2)\,(D^\mu H^\dagger D^\nu H)\,B_{\mu\nu}$ $O_{HW} = (i/2)\,(D^\mu H^\dagger \sigma^a D^\nu H)\,W^a_{\mu\nu}$	g_*	Elementary Vectors: g'/g_* (for O_{HB}) g/g_* (for O_{HW}) Minimal Coupling: $g_*^2/16\pi^2$

Contino+ '16

See also, recent HXSWG note 2019-006

These selection rules follow from dynamical principles
that define broad classes of UV models

In all these classes of models, the interpretation of the exp. data
will be different and the validity of the EFT bounds change

The theoretical uncertainty/error induced by dropping dim.8, 10…
scales differently in the different classes of models.

There is no meaning to a model-independent "EFT uncertainty"
(if by EFT uncertainty, you mean the effect of the truncation to dim. 6)

Beware that the scaling might be basis-dependent (e.g. SILH vs Warsaw),
but the suppression applies to physical quantity, e.g. h→γγ , and is robust.
In some bases, the selection rules therefore translate into correlations
among operators rather than in direct scaling of the operators

Conclusions

EFTs are good for { $*$ organising our knowledge; $*$ parametrising our ignorance }

EFT analyses are *not* as model-independent as they looked like or more precisely the interpretation of the bounds & the question of the validity are model-dependent, which is good because they can be used to probe different hypotheses so we can learn about the structure of BSM rather than measuring parameters.

But we have to be careful and be aware of our hypotheses.
It can well be that the real potential of the future colliders projects is mis/under-estimated (LLP, exotics, other interesting UV dynamics…).
So we should stay open-minded and keep *thinking different.*