Motivation

Effective Theories for pedestrians

→ Currently rather "hot" topic in Higgs physics

Why? After discovery of this new boson on 4.7.2012

→ so far, everything consistent with Higgs boson in SM (within current exp. sensitivities)

→ no further convincing sign for new physics at LHC so far

Future plans @ LHC: precise studies of the Higgs boson

→ is it really the SM-Higgs?

→ <u>precise measurement</u> of couplings mandatory!

However: Within SM all Higgs couplings <u>uniquely fixed</u>, can't be varied independently → no fits possible: "compatibility check with SM"

⇒ Possible interpretation of deviations from couplings in SM needs consistent framework beyond SM

Possible frameworks!

a) Choose specific models that have (more) free parameters
   → fits of independent parameters, i.e. couplings, are allowed
   → however, is a model-by-model approach

} e.g. use specific SUSY model

b) temporary framework, how to "interprete" Higgs-boson couplings
   → "κ framework"; use scale factors for couplings, but keep structure as in SM
      ⇒ allows easy fits of size of couplings and consistency checks of the SM
   However: Possible deviations can not directly be interpreted with quantum field theory

c) Effective Field Theory (EFT) approach
   → rather model independent
   → allows fits of parameters
   → allows a kind of consistent perturbative calculations

However: requires that any new physics practically decouples! | strong assumption!
depends on many free parameters, ...

Personal opinion: a) and c) are complementary

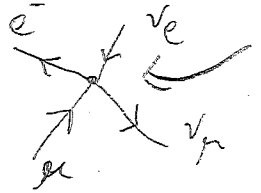
Basics

Let's have a look on EFT - basics

What's the idea? • SM describes current physics results very well
• new physics decouples if new scale is large ≙ basic assumption of EFT's!

By the way: SM is also an "eff. field theory"; valid, however, up to Planck scale, i.e. ~ 10^{19} GeV.

Example from history: Fermi-model for $\mu^- \to e^- \bar{\nu}_e \nu_\mu$



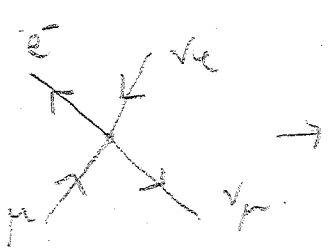
$G_F \sim 10^{-5}\ \text{GeV}^{-2}$

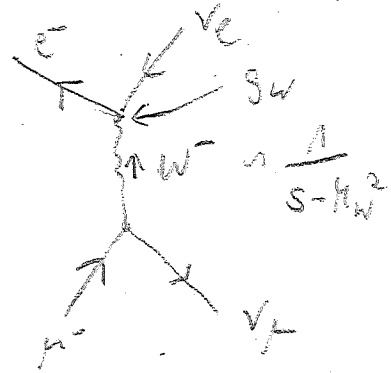
Scattering amplitude $\mathcal{M}(e^- \nu_\mu \to \mu^- \bar{\nu}_e) = \frac{G_F s}{2\sqrt{2}\pi^2}$ (G_F: Fermi-const., $s = (E_{cms})^2$)

→ violates unitarity for $s \leq \frac{\sqrt{2}\pi}{G_F} \triangleq (600\ \text{GeV})^2$

i.e. Fermi-model is effective theory, valid up to specific scale

next step: introduce intermediate boson W^-!





$\Rightarrow \mathcal{M}(e\nu_\mu \to \mu\nu_e) = \frac{g_W^2}{16\pi^2} \frac{s}{M_W^2 - s}$

$= \frac{G_F \cdot s}{2\sqrt{2}\pi^2} \frac{M_W^2}{M_W^2 - s}$

Estimate on couplings g_W: $\rightarrow M_W = \sqrt{\frac{\pi g_W^2}{8 G_F}} = O(100\ \text{GeV})$ $\Rightarrow$ conclusion on scale of M_W

Result: - effective theory applicable if different scales are involved

- validity of EFT up to an energy depending on process/channel

Concrete

EFT more concrete: SM ⊂ EFT

Since SM recovered in low-energy limit: parametrize SM as EFT

$$\mathcal{L}_{eff} = \underbrace{\mathcal{L}_{SM}}_{\text{SM Lagrangian}} + \frac{1}{\Lambda^2} \sum_R \alpha_R O_R$$

O_R ← Operators = eff. vertices, non-perturbative

α_R → "Wilson coefficients" = eff. coupling ≙ perturbative

Λ ← scale of new physics ($\Lambda \gg v$, i.e. H)

Note: validity of EFT assumes $E \ll \Lambda$!

Operators: Different dimensions, often $D=6$ (but also $D=8$ depending on scale Λ)

one example: vertices between eZ: $O_{eZ} = (\bar{l}\, \underbrace{\sigma^{\mu\nu}}\, \tau_I\, e\, \phi)\, Z_{\mu\nu}$ ← Z-boson $D=2$

- $\bar{l}$: Lepton $D=3/2$
- $\sigma^{\mu\nu}$: structure of interaction. Tensor, Vector, etc.
- τ_I
- e: electron $D=3/2$
- ϕ: Higgs $D=1$

$\Rightarrow \geq 60$ different operators to parametrize all possibilities (Remark: if $D=8$ $\Rightarrow$ much larger amount of operators!)

(different Basis: "historical" Buchmüller, Wyler '85; different variants, e.g. "SILH" basis (Strojean involved))

Application

Ongoing Higgs-EFT @ LHC

Crucial question: up to which scale is EFT applicable?
In other words, to which scale is EFT sensitive?

Famous estimate by G. Passarino (2012): EFT in Higgs analyses only sensitive to new scale $\Lambda \in [3\,\text{TeV} - 5\,\text{TeV}]$!

practically beyond direct reach of LHC!
(still under debate)

Conclusions

Take-away

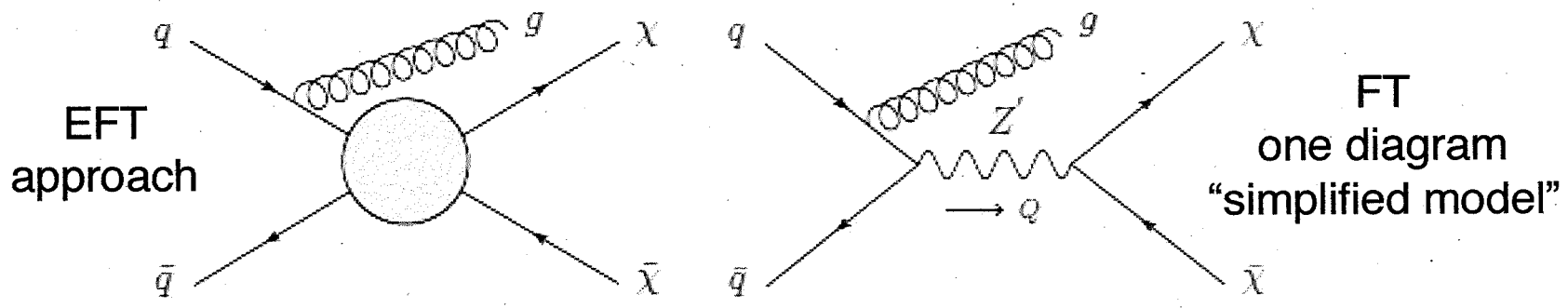
- EFT useful approach if several scales are involved in processes
- EFT provides a model-independent framework <u>if</u> scale of $\Lambda >>$ "process energy"
- validity of EFT depends on process and channel, non-trivial issue!
- one criteria: violation of unitarity
- Concrete: remember O. Buchmüller Desy Colloquium (Oct. 2015) on Dark Matter @ LHC
- Caution: often largest sensitivity to new physics within EFT in boundary regions where EFT is not valid any more!

More info: Talk by A. Denner on EFT, Hamburg Workshop on Higgs Physics, 2014

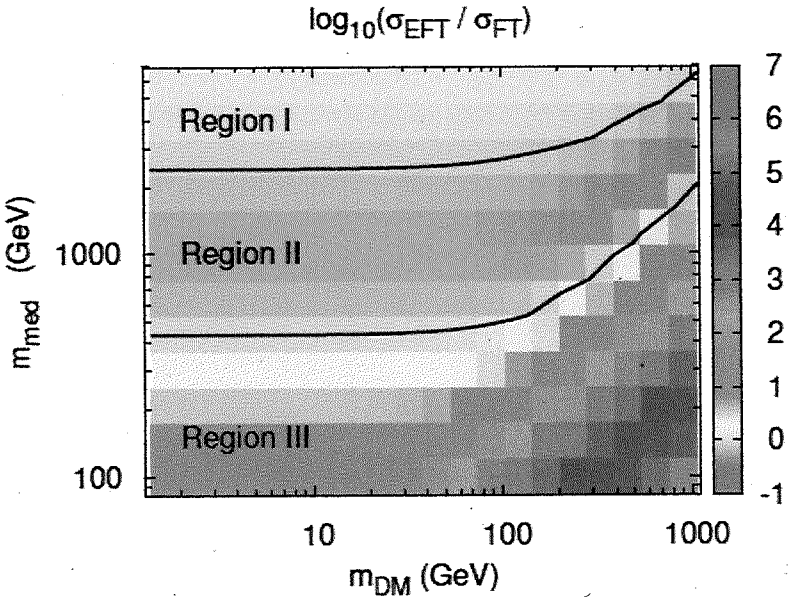
Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)



Use vector and axial-vector mediators (e.g. Z') as example - scalar are similar in conclusion!



Compare prediction of FT with EFT in m_{med} – m_{DM} plane.
Three regions become visible:

Region I: EFT and FT agree better then 20%

- EFT is valid!

Region II: EFT yields significant weaker limits then FT

- EFT limits are too conservative!

Region III: EFT yields significant stronger limits then FT

- EFT limits are too aggressive!

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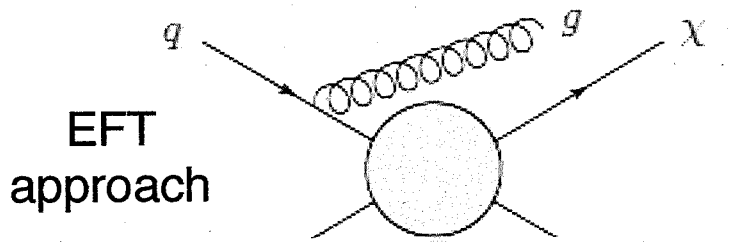
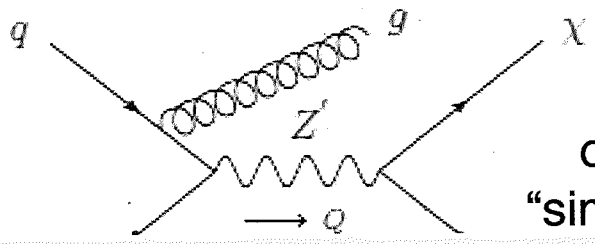


EFT approach

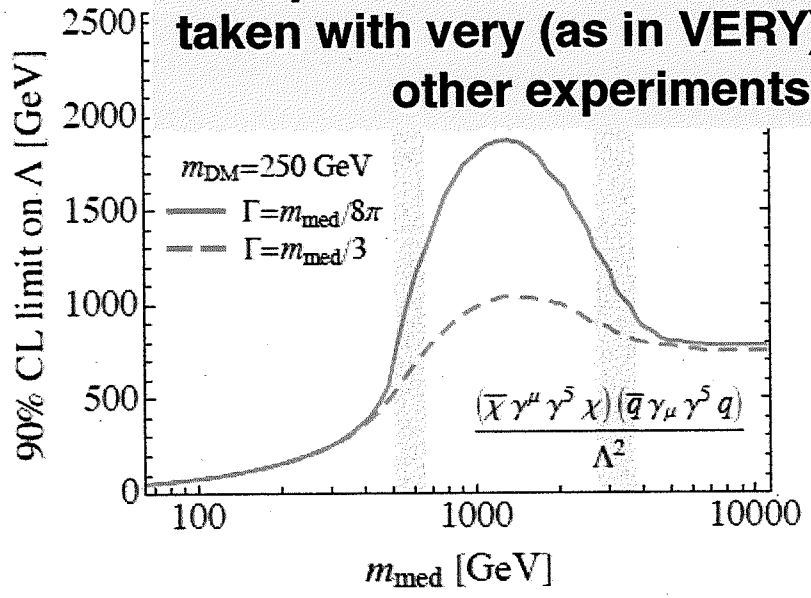


FT
one diagram
"simplified model"

Conclusion:

The EFT is not an appropriate framework for a comprehensive Interpretation of DM searches at colliders and especially must taken with very (as in VERY) special care when comparing with other experiments such as Direct Detection!

Use v … clusion!



Region I: Heavy m_{med}
- EFT is valid!

Region II: Medium m_{med} – Resonant enhancement
- EFT limits are too conservative!

Region III: Low m_{med}
- EFT limits are too aggressive!