Theory Aspects of EFT

Ilaria Brivio (ITP Heidelberg)

on behalf of the WG conveners

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):

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

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

C_i free parameters (Wilson coefficients)
$\to$ embed all UV information

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

Motivations

SMEFT describes **BSM effects @LHC**
in scenarios where BSM is out of collider reach

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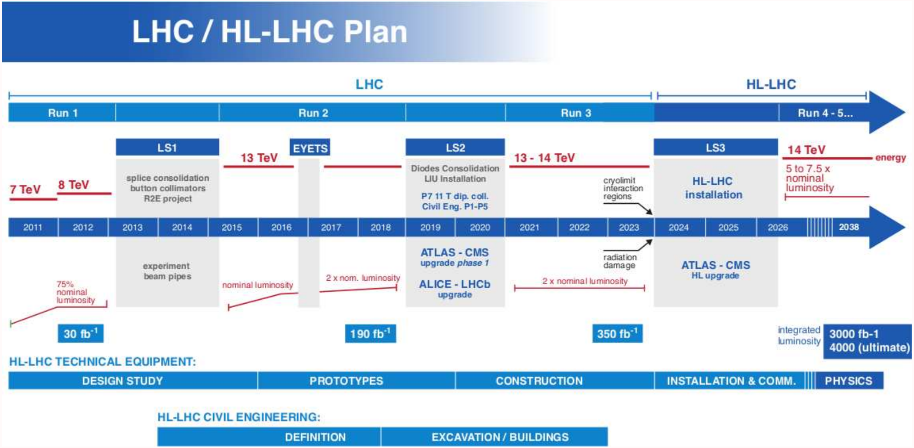
SMEFT describes **BSM effects @LHC**
in scenarios where BSM is out of collider reach

+ a proper QFT :
  renormalizable order by order, well-defined radiative corrections and RGE
+ systematically includes all BSM effects compatible with assumptions
  $\longrightarrow$ largely model-independent
+ the series expansion gives a rationale for the expected size of BSM effects
+ universal language for data interpretation: can connect to other experiments

$\downarrow$

suitable for **a systematic program for indirect searches of NP @LHC**

LHC is entering its precision era



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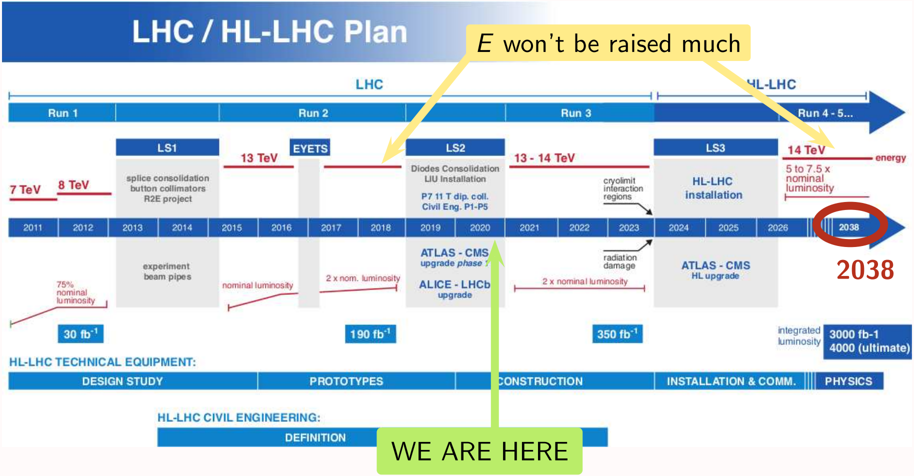

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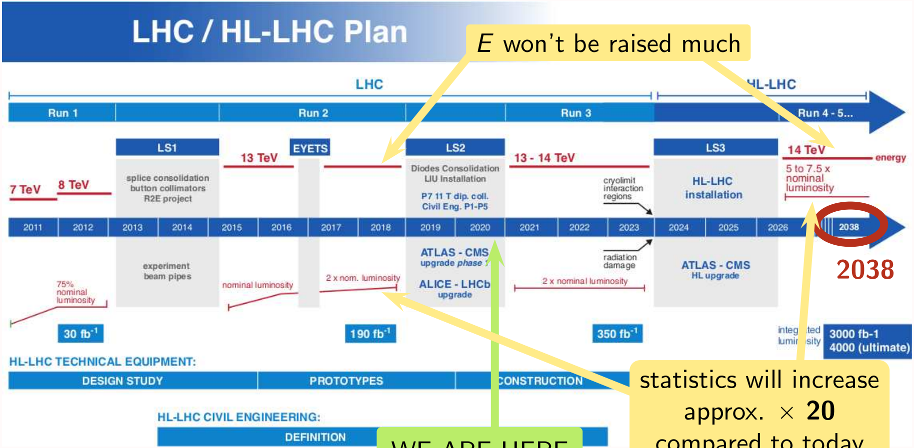


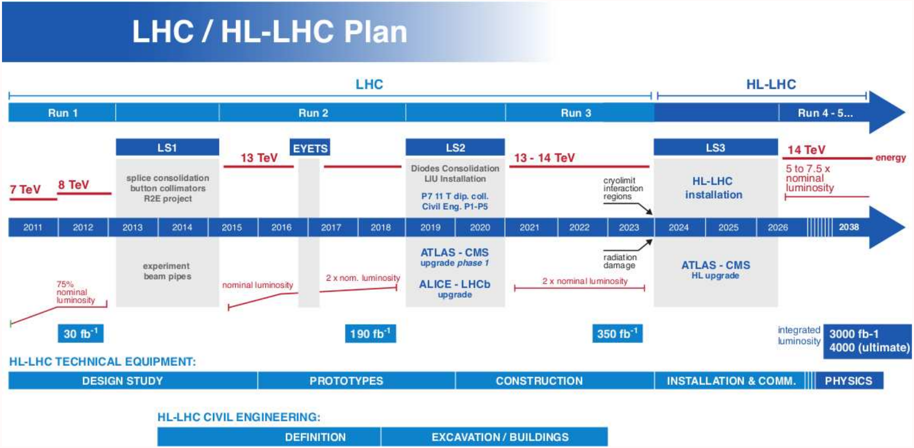
E won't be raised much

2038

WE ARE HERE

statistics will increase approx. $\times$ **20** compared to today

LHC is entering its precision era



in the next years
big opportunities will come
from **precision**

make the most out of data to
complement direct searches with
indirect ones

The need for global analyses

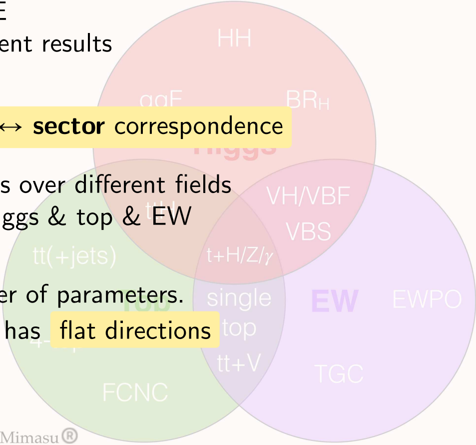
- **systematic** coverage of BSM theories only ensured if all parameters are considered at the same time:

  → most UV models generate multiple operators
  → operators largely mix under RGE
  → necessary to avoid basis-dependent results

- there is no well-defined **operator** ↔ **sector** correspondence

  → reduction to a basis shifts effects over different fields
  → a number of operators enters Higgs & top & EW

- the SMEFT contains a large number of parameters.
  any given measurement necessarily has flat directions



Ken Mimasu®

Goals of the EFT WG

from the mandate `lpcc.web.cern.ch/lhc-eft-wg`

⋮

The LHC EFT WG studies the physics requirements needed to facilitate an interpretation commensurate with the available measurements performed in **a wide range of different processes**

⋮

provides recommendations for the use of EFT by the experiments to interpret their data, and a forum for theoretical discussions of EFT issues

⋮

discusses common uncertainties and combination procedures used by the experiments

⋮

allow **global EFT analyses** *inside and outside experimental collaborations*

⋮

Theory topics for the EFT WG

Outline of WG targets in the **Google doc**

1. EFT Formalism ← mostly lay background for this discussion
2. Predictions and Tools
3. Experimental measurements and observables
4. Fits and related systematics
5. Benchmark scenarios from UV models

Dedicated talks and discussion time <u>tomorrow</u> on each of these areas.

Theory topics for the EFT WG

Outline of WG targets in the **Google doc**

1. EFT Formalism

The starting point for the calculations and fits: what operators, what bases, what perturbation orders, how to combine operators of different dimensions, what constraints to be put in the EFT bases preparation, practical considerations in connection to experimental analyses, flavour and symmetry assumptions. The following issues will be discussed:

- SMEFT bases/notation/normalization/input schemes, etc (***): common conventions, consistency checks among the experiments and streamlining translations among conventions will be required, before any combination is considered. These will be defined on a case by case basis, depending on the specific set of observables included in a given combination.
- Assumptions about the flavour symmetries, and other symmetries like CP
- Definition of scenarios, also for the purposes of doing fit with limited data, and as benchmarks for the presentation of experimental results
- Truncation, quadratic dependences, double insertions, dimension eight contributions, uncertainty prescription, EFT validity (information required from experiments to ensure validity at the interpretation stage) (**)
- TH constraints (unitarity, positivity, etc.) and incorporation into fit results (**)
- Consideration of beyond-SMEFT EFT frameworks, where relevant

Input parameter schemes (finite renormalization)

SM

(pseudo)-observables $\mathcal{O}$

α_s, d_N
m_Z, $\alpha_{\rm em}$
$\mu \to e\nu\nu$, m_h
m_f
meson decay/osc

$\mathcal{L}$ parameters p

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$

analytical / MC
predictions
for any SM process

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→

analytical / MC **predictions** for any SM process

usual procedure

1. choose set $\mathcal{O}$ to define all p unambiguously
2. calculate $\mathcal{O}(p)$ at given order
3. invert the relations $\to p(\mathcal{O})$
4. the renormalized p has a well-defined numerical value

Input parameter schemes (finite renormalization)

SMEFT

(pseudo)-observables $\mathcal{O}$

α_s, d_N
m_Z, $\alpha_{\rm em}$
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→

$\mathcal{L}$ parameters p

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$
EFT	$\mathbf{C_i}$

→

analytical / MC **predictions** for any SM process

SMEFT procedure

1. choose set $\mathcal{O}$ to define all p_{SM} unambiguously
2. calculate $\mathcal{O}(p_{SM}, \mathbf{C_i})$ at given order
3. invert the relations expanding around the SM solution
$$\to p_{SM}(\mathcal{O}) + \delta p(\mathbf{C_i})$$
4. p_{SM} has a numerical value, δp encodes EFT corrections

Input parameter schemes (finite renormalization)

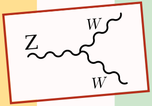
- inputs choice for QCD, Higgs, Yukawa sector is ∼fixed.
- freedom for **EW sector**: $\{g, g', v\} \longleftrightarrow$ 3 among $\{\alpha_{\rm em}, m_Z, m_W, G_F\}$

Sets considered in SMEFT so far:

$\{\alpha_{\rm em}, m_Z, G_F\}$

- γ couplings **not** shifted
- m_W shifted

$$\Delta\kappa_Z \sim C_{HD} + 4C_{Hl}^{(3)} - 2C'_{ll} + 8 s_\theta c_\theta C_{HWB}$$



$\{m_W, m_Z, G_F\}$

- γ couplings shifted
- m_W **not** shifted

$$\Delta\kappa_Z \sim C_{HD} - 4C_{Hl}^{(3)} + 2C'_{ll}$$

avoids EFT-expanding around W pole

Too many parameters?

Numbers depend on

- flavor assumptions
- global symmetry assumptions: CP, custodial, ...
- loop order of the calculation
- EFT order of the calculation
- ...

Each measurement will receive contributions from many parameters

$\rightarrow$ likely unable to disentangle them all

$\rightarrow$ what is the best way to report these results?

Flavor assumptions

assuming a flavor symmetry → **only invariant contractions allowed**

$U(3)^5$

maximal: for each SM field $\psi = \{q_L, u_R, d_R, l_L, e_R\}$:

$$\psi_p \mapsto \Omega_{\psi,pr}\,\psi_r \text{ with } \Omega_\psi \text{ a } 3\times 3 \text{ unitary matrix}$$

Flavor assumptions

assuming a flavor symmetry $\rightarrow$ **only invariant contractions allowed**

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invariants:

eg. $\bar{u}_R\gamma^\mu u_R \rightarrow \bar{u}_{Rp}\gamma^\mu\,(\Omega_u^\dagger)_{ps}(\Omega_u)_{sr}\,u_{Rr} = \bar{u}_{Rp}\gamma^\mu\,\delta_{pr}\,u_{Rr}$ diagonal

$\bar{q}_L\,u_R? \rightarrow \bar{q}_{Lp}\,(\Omega_q^\dagger)_{ps}(\Omega_u)_{sr}\,u_{Rr}$ not invariant!

Flavor assumptions

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$\bar q_L\,u_R? \to \bar q_{Lp}\,(\Omega_q^\dagger)_{ps}(\Omega_u)_{sr}\,u_{Rr}$ not invariant!

Yukawas inserted as spurions: constants transforming under the sym.:

$$Y_u \mapsto \Omega_u\,Y_u\,\Omega_q^\dagger,\quad Y_d \mapsto \Omega_d\,Y_d\,\Omega_q^\dagger,\quad Y_e \mapsto \Omega_e\,Y_e\,\Omega_l^\dagger$$

in this way $(\bar u_R Y_u q_L)$, $(\bar d_R Y_d q_L)$, $(\bar e_R Y_e l_L)$ are allowed

→ all **chirality-changing** currents require inserting a Yukawa

Flavor assumptions

Many options!

$\rightsquigarrow$ see talk by **Gino Isidori** tomorrow

	e.g. $Q_{Hu,pr} = (H i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$		tot
general	$(C_{Hu})_{pr}$	9	2499
$U(3)^5$	$C_{Hu}\,\delta_{pr}$	1	~ 85
$U(3)^5$ + leading corr.	$C^{(0)}_{Hu}\,\delta_{pr} + (\Delta C_{Hu})(Y_u Y_u^\dagger)_{pr}$	2	~ 120
$U(3)^2_{\ell,e} \times U(2)^3_{q,u,d}$	$C_{Hu}\,\delta_{pr},\ \ p,r = 1,2$ $C_{Ht} \qquad p = r = 3$	2	~ 180
$U(1)^3_{\ell+e} \times U(2)^3_{q,u,d}$	$C_{Hu}\,\delta_{pr},\ p,r = 1,2$ $C_{Ht} \qquad p = r = 3$	2	~ 270

Flavor assumptions

Example: EFT recommendations in TOP-WG `1802.07237`

→ **3 staged scenarios** for the quark sector:

baseline

$U(2)_{q+u+d}$ | $U(2)_q \times U(2)_u \times U(2)_d$ | top-philic

more restrictive →

To keep in mind in view of a **combination**:

- symmetries can only be mapped less → more restrictive
- some observables are blind to flavor (eg. in light quarks)

  → symmetric parameterization to encapsulate flat directions?

Global symmetries

- CP

eg. Warsaw basis contains
- 1149/2499 [general] CP odd parameters
- $\sim$ 25/85 $[U(3)^5]$

$\longrightarrow$ generally do not interfere in inclusive measurements: SM CP even at high-E but can give signatures at **differential** level

$\longrightarrow$ not all analyses can be sensitive to them

$\longrightarrow$ at quadratic level, they are **degenerate** with CP even counterparts. both bounded simultaneously:

$$\sigma \sim \left([CP]^2 + [\cancel{CP}]^2\right) < \# \;\Rightarrow\; [CP]^2 < \# \;\text{ and }\; [\cancel{CP}]^2 < \#$$

Global symmetries

- custodial

the SM Higgs potential has a $O(4) \sim SU(2)_L \times SU(2)_R$ global symmetry:

$$\Sigma = \begin{pmatrix} \tilde{H} & H \end{pmatrix}, \qquad \Sigma \mapsto L\,\Sigma\,R^\dagger$$

EWSB breaks it down to the diagonal $SU(2)_{L+R} \equiv$ custodial symmetry

- in the SM, custodial is broken by $g' \neq 0$ and $Y_u \neq Y_d,\ Y_e \neq 0(Y_\nu)$.

$$\updownarrow$$

$$m_Z \neq m_W,\, \theta_W \neq 0,\, \dots$$

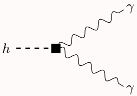
- SMEFT contains BSM sources of custodial violation.
  e.g. in Warsaw basis $O_{HD},\ O_{Hq}^{(1)},\ O_{Hl}^{(1)},\ O_{Hu},\ O_{Hd},\ O_{He}, \dots$
  $\to$ tested eg. by ρ parameter $\sim C_{HD}$

- other symmetries?

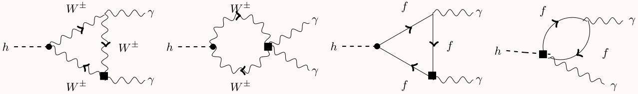
SMEFT calculations at NLO (1 loop)

going to 1-loop generally brings in new operators

eg. $h \to \gamma\gamma$ in Warsaw basis:



$C_{HW}\,,\ C_{HB}\,,\ C_{HWB}$



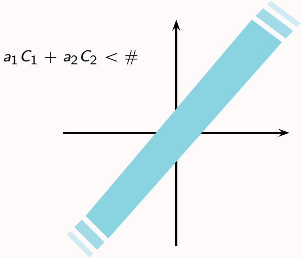
$+\ C_W\,,\ C_{HD}\,,\ C_{eW}\,,\ C_{eB}\,,\ C_{uW}\,,\ C_{uB}\,,\ C_{dW}\,,\ C_{dB}\,,\ C_{eH}\,,\ C_{uH}\,,\ C_{dH}$

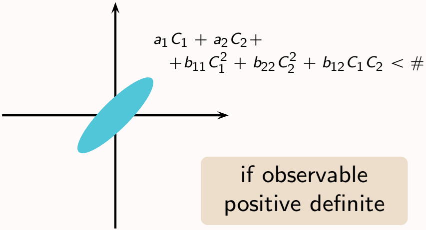
- connected to **tools**: NLO QCD automatized. NLO EW only available from theory calculations of specific processes
- introduce renorm. scheme dependence, etc. that can impact EFT parameterization.
  in a combination, all predictions should have consistent choices

Quadratic and other Λ^{-4} contributions

$$|A_{SMEFT}|^2 = |A_{SM} + A_6|^2 = |A_{SM}|^2 + Re\left[A_{SM} A_6^\dagger\right] + |A_6|^2$$

- restore sensitivity to non-interfering operators (CP odd, dipoles, ...)
- usually increase fit convergence





if observable positive definite

Quadratic and other Λ^{-4} contributions

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- restore sensitivity to non-interfering operators (CP odd, dipoles, ...)
- usually increase fit convergence

Formally are of <u>the same order</u> as

- $\mathscr{L}_8$ - SM interference
- **double** $\mathscr{L}_6$ insertions $\rightarrow$ not renormalizable with $\mathscr{L}_6$ alone
- quadratic terms in the **expansion** of field/parameter redefinitions in $\mathscr{L}_6$ (from kinetic term normalization, inputs)

SMEFT uncertainties

SMEFT predictions come with theory uncertainties that account for

- missing higher orders in the EFT
  - for dim-6 predictions, uncertainties are dominated by $\mathscr{L}_8$ terms, etc.
  - expected to grow with energy, and $\to 100\%$ for $E \to \Lambda$
- missing perturbative orders
- neglected **subdominant** EFT contributions
- unknown SMEFT corrections to extraction of α_s, PDFs, hadronization, etc
- ...

! don't just represent potential variations of prediction's central value, but also potential **extra parameters / fit d.o.f.s**

EFT validity

SMEFT assumes
- no BSM light states
- cutoff $M (\propto \Lambda) \gg E$

$\longleftrightarrow$ the expansion holds

if conditions fail $\rightarrow$ parameterization can **fail to reproduce data**
$\rightarrow$ the **interpretation** can be impaired

How do we check?

Related to, but conceptually distinct from:

Are our measurements probing the physical EFT region?

insufficient exp. precision $\rightarrow$ sensitivity only to **too large values of** $(\boldsymbol{C}/\boldsymbol{\Lambda}^2)$
$\rightarrow$ assuming $C \leqslant 4\pi$, EFT analysis **cannot exclude** $\boldsymbol{M} \gtrsim \boldsymbol{E}$

$\longleftrightarrow$ **unitarity** constraints

EFT consistency constraints

- **Unitarity constraints**

  SMEFT operators can induce corrections that grow with energy.

  → partial wave unitarity violated for sufficiently large $\boldsymbol{C(E/\Lambda)^2}$

  → signals EFT breakdown point ↔ **EFT validity** limits

- **Positivity bounds**

  scattering amplitudes need to respect: analyticity
causality
partial wave unitarity
crossing symmetry
...

  at all orders in the EFT, within the validity region

  → not all regions of EFT parameter space are physical.

  in practice, model-independent limitations mostly apply to $\mathscr{L}_8$

- ...

Connection with BSM models

UV model (parameters $\{\kappa\}$)

EFT (parameters $\{C\}$)

matching procedure

heavy d.o.f.s are "integrated out"

$\downarrow$

operators are **mapped** onto the chosen basis and **run** down to EW scale

$\downarrow$

$C(\kappa)$

can be done efficiently with functional methods, up to 1-loop in the UV model

Connection with BSM models

UV model (parameters $\{\kappa\}$)

EFT (parameters $\{C\}$)

interpretation of EFT measurements

task:
reconstructing UV properties from observed patterns in $\{C\}$

disentangling $\sim$degenerate models

interplay with direct searches
can exploit the complementarity between the two?

Beyond SMEFT

. . . should alternative EFTs be considered?

main example: **Higgs EFT (HEFT)**

$$H \mapsto \frac{v + h}{\sqrt{2}}\,\mathbf{U}, \qquad \mathbf{U} = \exp\left(\frac{i\vec{\sigma}\cdot\vec{\pi}}{v}\right)$$

- less restrictive symmetry assumptions
- order-by-order: more parameters
- in principle can capture a **larger range** of BSM models
- generally more convergent than SMEFT for $\Lambda \lesssim 4\pi v$
  $\to$ can be convenient compared to full dim=8

Summary

theory topics for EFT formalism (and BSM)

- flavor assumptions
- other global symmetries: CP, custodial, ...
- order Λ^{-4} contributions
- SMEFT uncertainties
- EFT validity
- SMEFT calculations at 1-loop
- positivity bounds & unitarity constraints
- connection with BSM models
- beyond SMEFT

Summary

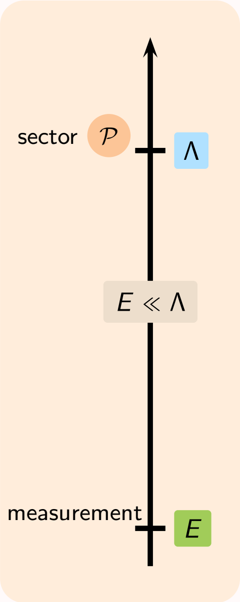
more theory topics within other areas

- predictions & tools
- treatment of unstable particles
- identification of optimal observables, process sensitivities and complementarities
- theory systematics in fits
- statistical analysis and strategies for presentation of fit results
- required precision in SM predictions
- ...

...all to be discussed tomorrow and in future topical meetings

Backup slides

EFTs: basic principles



$\mathcal{P}$ states cannot be produced on-shell at E

$\Rightarrow$ internal lines only, never resonant

$\Rightarrow$ S-matrix contribution is analytical

$\Rightarrow$ can **Taylor expand** in (E/Λ)

Decoupling theorem Appelquist,Carrazzone PRD11 (1975) 2856

Green's functions with internal $\mathcal{P}$ are suppressed by Λ^n

Uncertainty principle

virtual particles of mass M are localized within

$$\Delta x \simeq \frac{1}{\Delta p} = \frac{1}{M}$$

$\mathcal{P}$ effects at $E \ll \Lambda$ are described by
local, **analytic** operators with $\mathbf{1/\Lambda^n}$ **suppressions**

EFTs: basic principles

for $E/\Lambda \to 0$ the $\mathcal{P}$ sector **decouples**

In this limit:

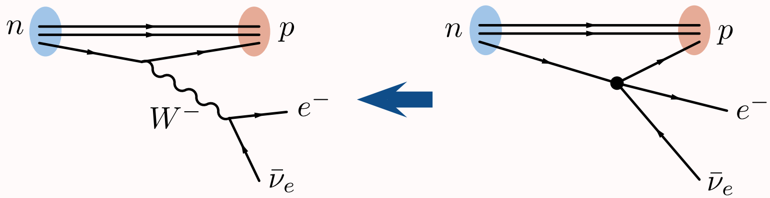
- the $\mathcal{P}$ sector is **not resolved** completely.
  we only see the dominant effects, according to power counting
- the details of $\mathcal{P}$ are irrelevant
- UV divergences in the $\mathcal{P}$ theory are subtracted from low-E physics

same as usual **renormalization**: UV modes can be subtracted out of the physical description, that becomes independent of them.

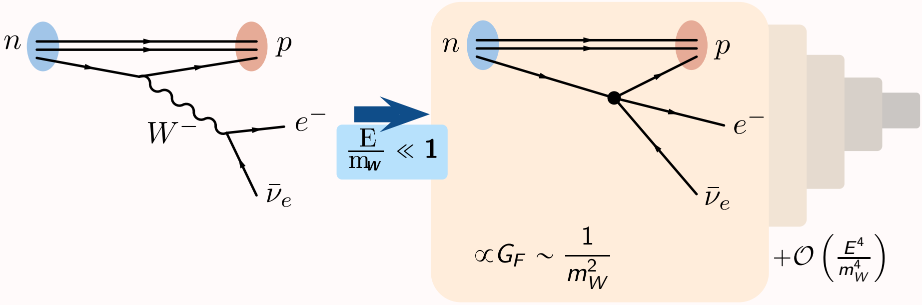
$\to$ we can factor UV and IR components:

$$\mathscr{L} \supset \frac{C_i^{UV}(\mu)}{\Lambda^n} \mathcal{O}_i^{IR}(\mu)$$

An historic example: Fermi interactions



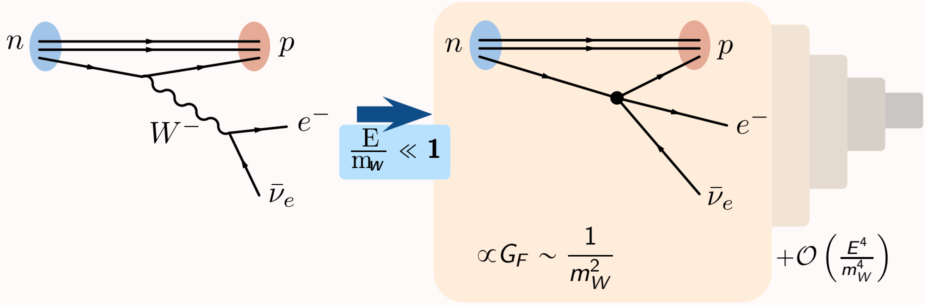
An historic example: Fermi interactions



EFT = QFT valid in a regime $\boldsymbol{E}/\boldsymbol{m}_{\mathrm{W}} \ll \mathbf{1}$ $\longleftrightarrow$ Taylor expansion in $\boldsymbol{E}/\boldsymbol{m}_{\mathrm{W}}$

- **full knowledge** of underlying physics is NOT required
- **hierarchy** of physical effects determined by low-E fields and symmetries

An historic example: Fermi interactions



EW effects at $E \ll m_W$ are described by

local, analytic operators $\propto \frac{1}{m_W^n}$

uncertainty principle

internal lines never on-shell

Decoupling Theorem

Appelquist, Carrazzone PRD11 (1975) 2856

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

d=6: the Warsaw basis

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$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		