Master Topics 2023

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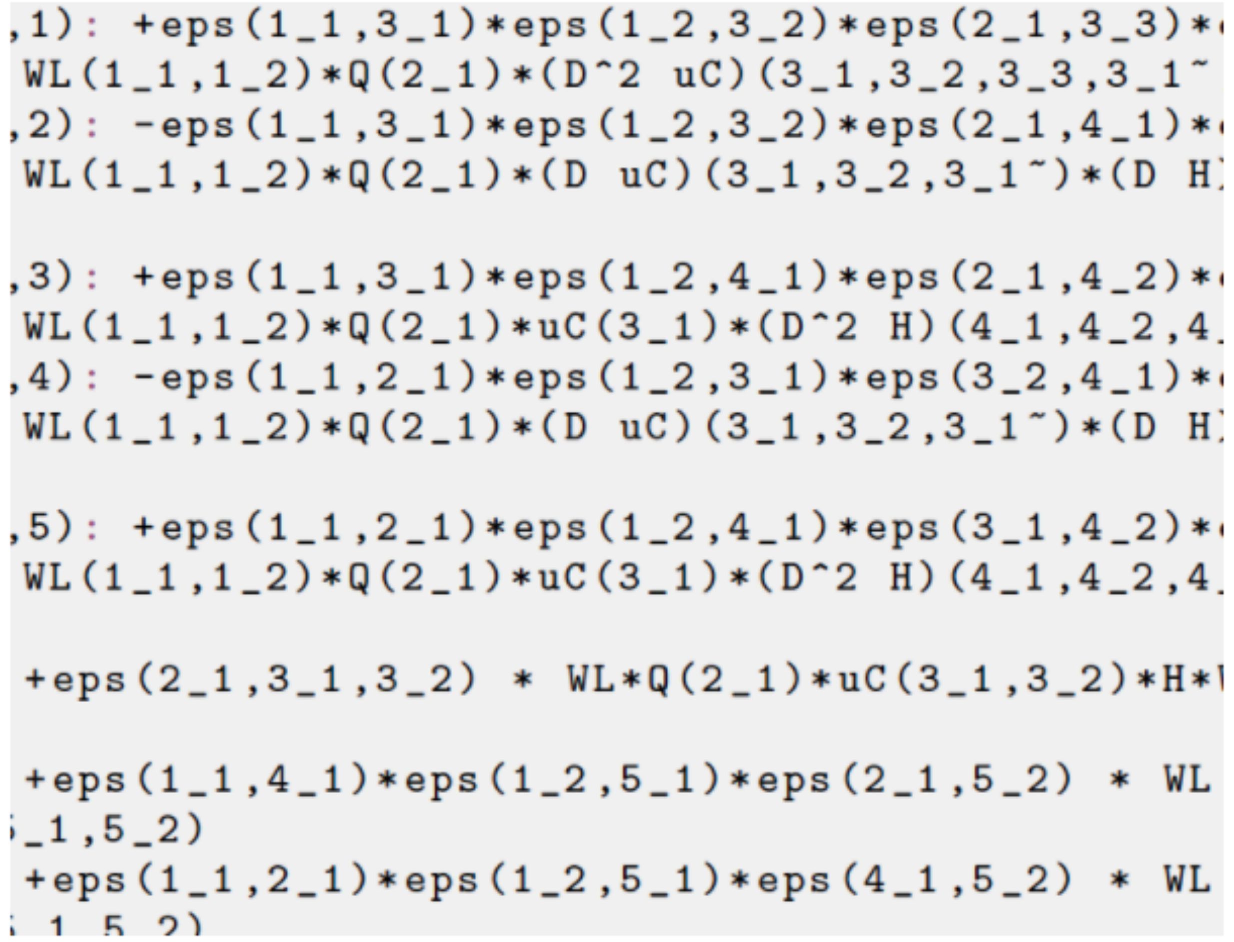
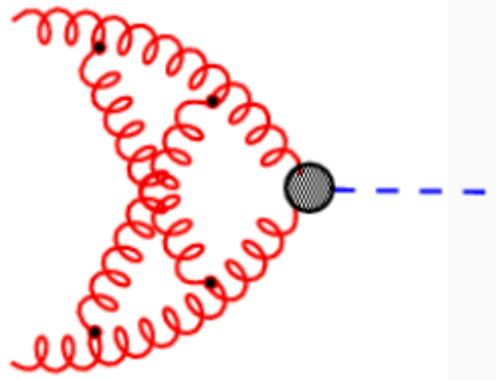
Welcome! (deutsche Version)

[detailed help] multi-search window Submit



What's new? (older news)

- Topics for Master Theses in winter term 2023
  05 Jul 2023
- Listen to the podcast "Blick in unser Universum"
  05 Jun 2023
- New paper on "The end of the particle era?"
  05 Jun 2023
- Outreach article on the makeshift character of the Standard Model
  29 May 2023



One of my favorite Feynman diagrams

I am a professor for theoretical particle physics at RWTH Aachen University.

My main research field is to understand and predict phenomena at particle colliders. Within the last few years, I have been mostly interested in the physics of Higgs bosons in and beyond the Standard Model. Recently, I have also become interested in improving the connection between the perturbative and the lattice approach to quantum field theory through the gradient-flow formalism.

The menu on the left should help you navigate through this page. In particular, you can find a Brief CV, and details about my Research and Teaching activities.

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Master Topics for winter term 2023/2024

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▶ **The gradient-flow beyond QCD**

▶ **Effective field theories and group theory**

▶ **Higgs production at the LHC**

last updated on Jul 05, 2023 by RH

The Gradient Flow beyond QCD

fundamental QCD: $$\mathscr{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a,\mu\nu}$$

$$F_{\mu\nu} = \frac{i}{g}[D_\mu, D_\nu] \qquad D_\mu = \partial_\mu - iT^aA^a_\mu(x)$$

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The Gradient Flow beyond QCD

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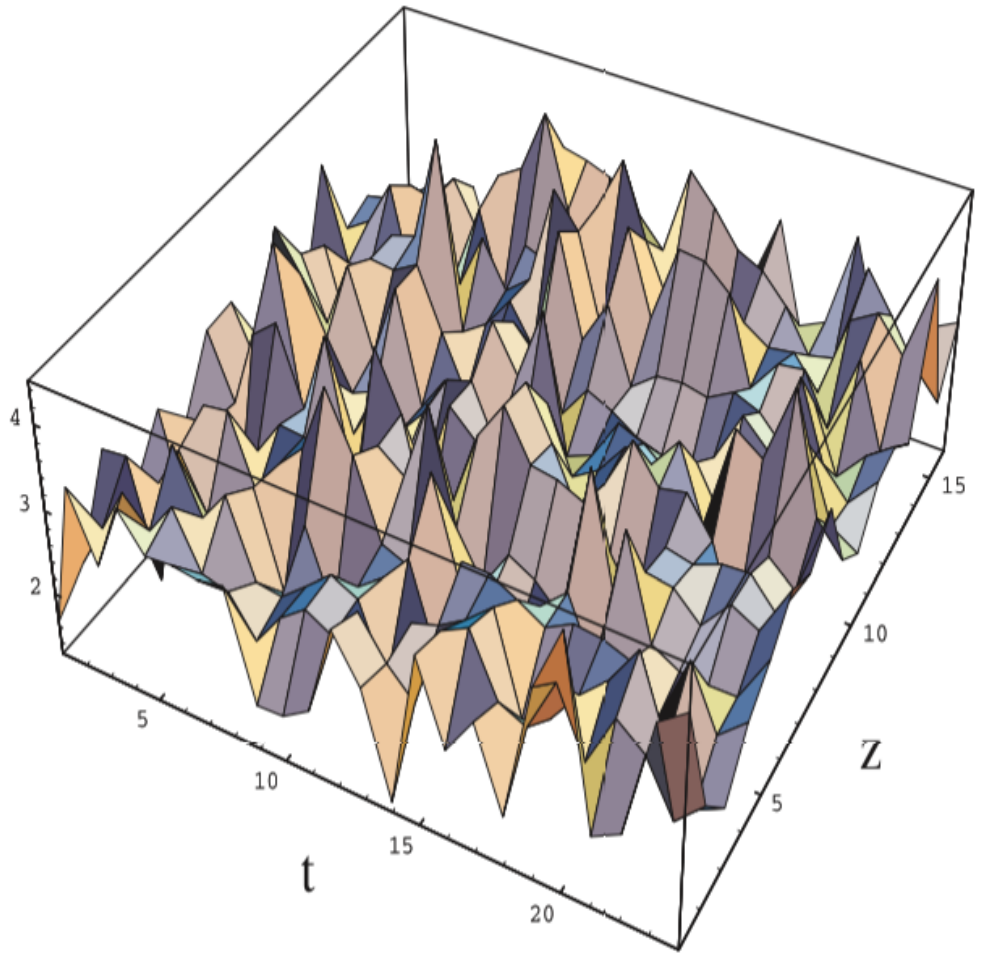
$$F_{\mu\nu} = \frac{i}{g}[D_\mu, D_\nu] \qquad D_\mu = \partial_\mu - iT^a A^a_\mu(x)$$

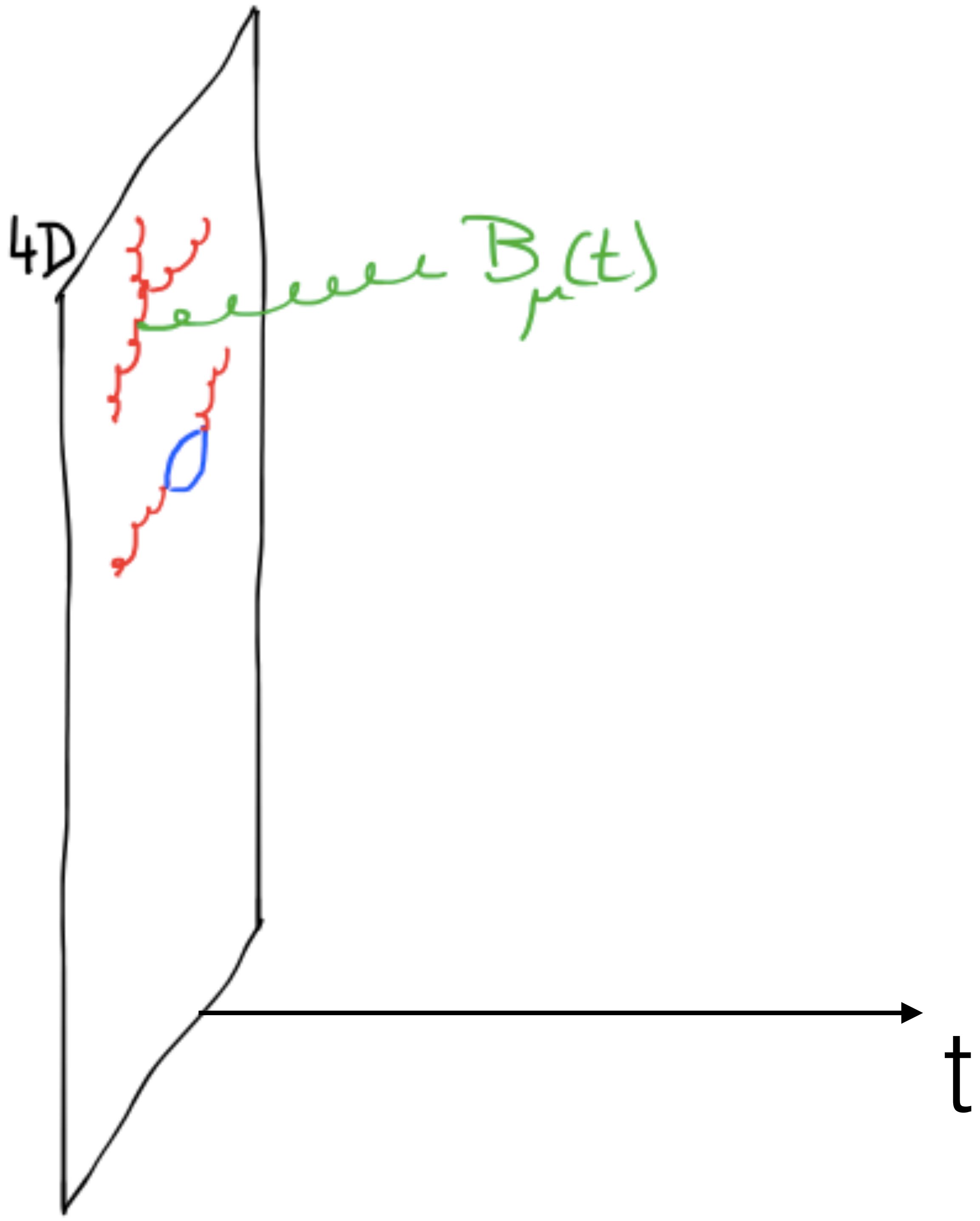
flowed gauge field:

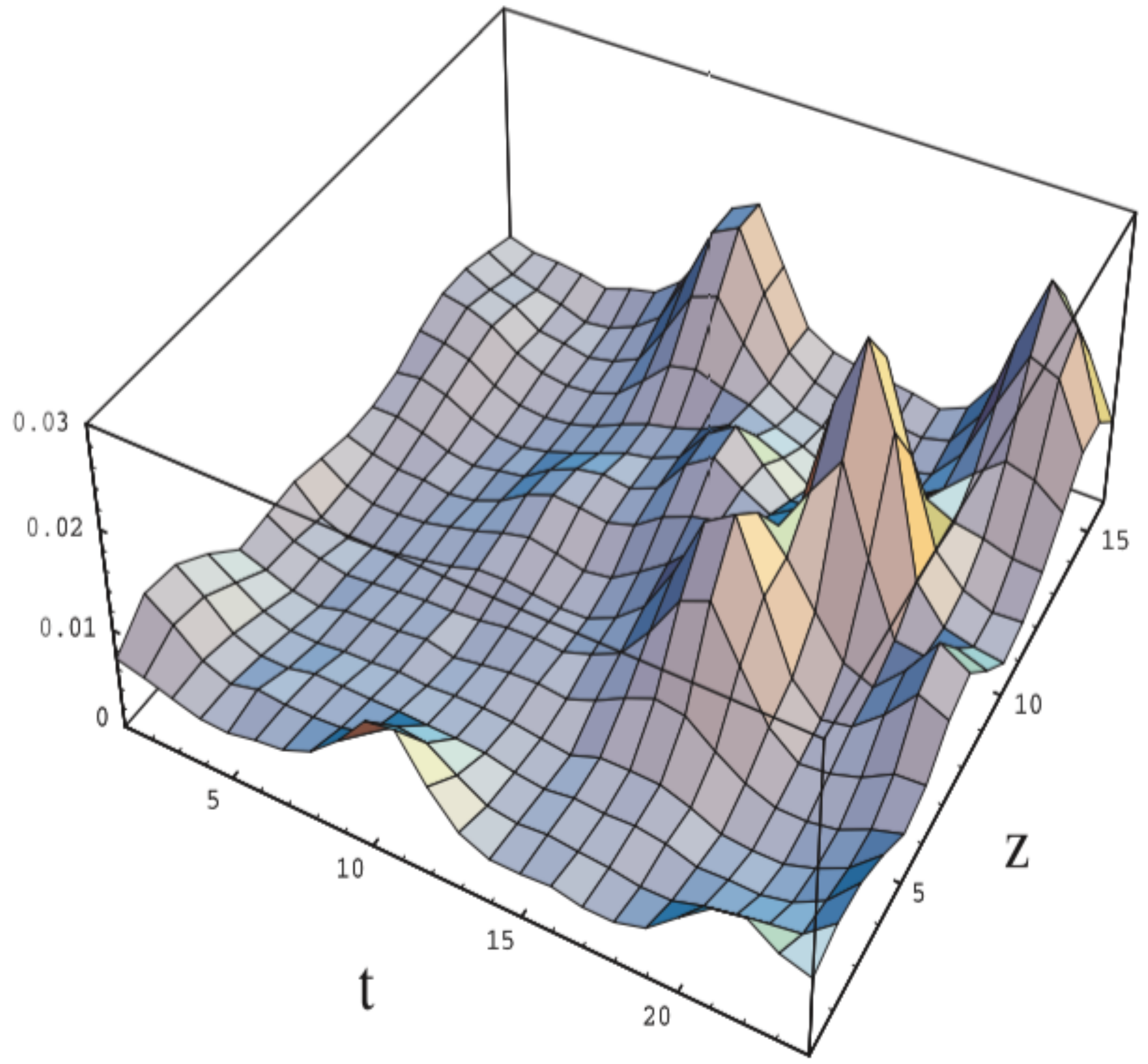
$$\frac{\partial}{\partial t}B_\mu(t,x) = \mathscr{D}_\nu G_{\nu\mu}(t,x)$$

$$B_\mu(t=0,x) = A_\mu(x)$$

The Gradient Flow beyond QCD







The Gradient Flow beyond QCD

- extension to scalar QCD (exists)
- extension to QED (exists)
- extension to the electro-weak theory (new!)

$$\frac{\partial}{\partial t} B_\mu(t,x) = \mathscr{D}_\nu G_{\nu\mu}(t,x)$$

$$B_\mu(t=0,x) = A_\mu(x)$$

Program:

- establish the flow equations
- derive Feynman rules
- calculate simple observables

Application:

Renormalization of Effective Field Theories

The Gradient Flow beyond QCD

Eur. Phys. J. C (2018) 78:944
https://doi.org/10.1140/epjc/s10052-018-6415-7

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Theoretical Physics

The two-loop energy–momentum tensor within the gradient-flow formalism

Robert V. Harlander[a], Yannick Kluth[b], Fabian Lange[c]

Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, 52056 Aachen, Germany

The Gradient Flow beyond QCD

JHEP

Published for SISSA by Springer

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Published: *June 24, 2019*

Results and techniques for higher order calculations within the gradient-flow formalism

Johannes Artz,[a] Robert V. Harlander,[a] Fabian Lange,[a] Tobias Neumann[b,c] and Mario Prausa[d]

-6415-7

The European Physical Journal C

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/–momentum tensor within the gradient-flow

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and Cosmology, RWTH Aachen University, 52056 Aachen, Germany

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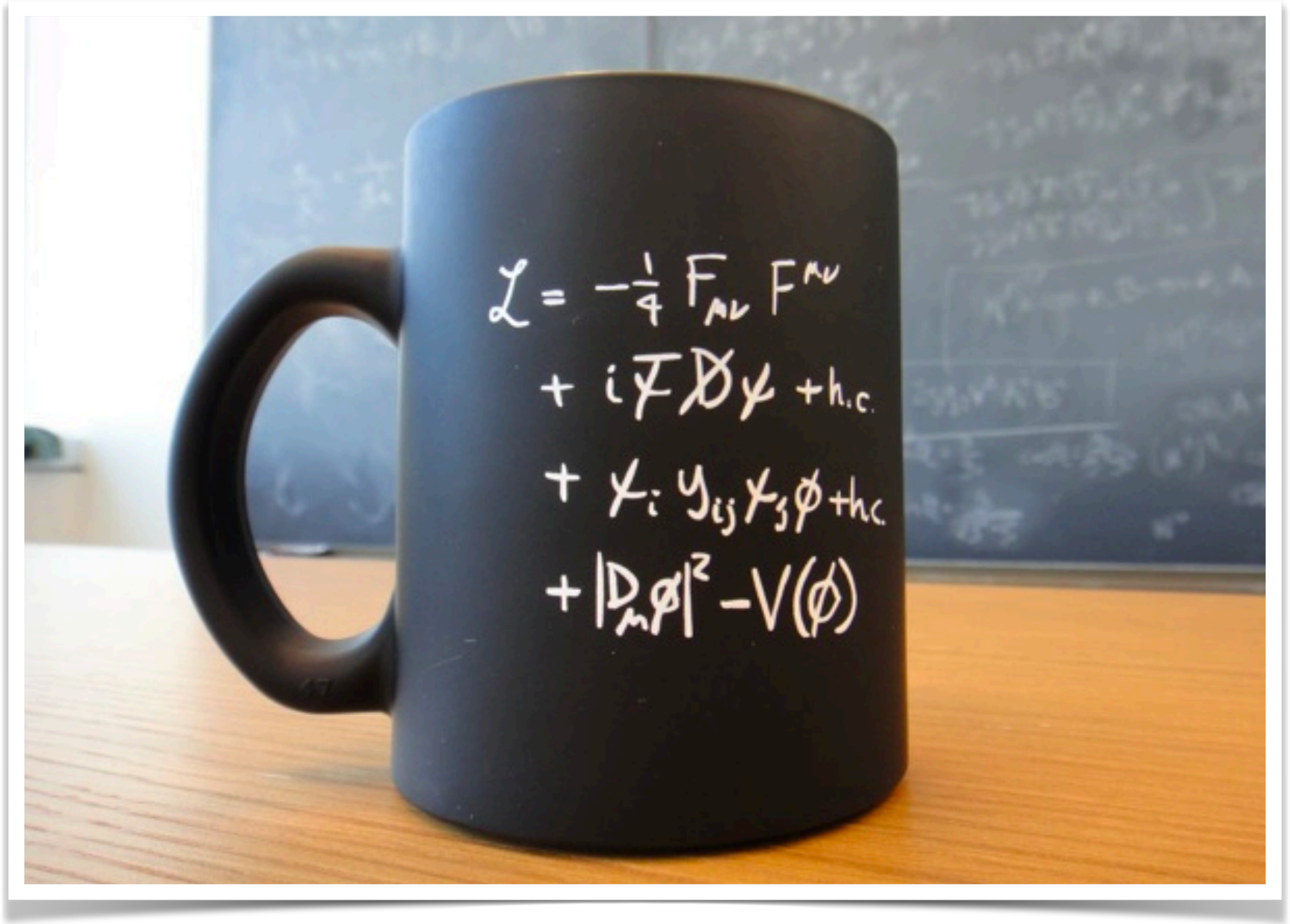
▶ **Effective field theories and group theory**

▶ **Higgs production at the LHC**

last updated on Jul 05, 2023 by RH

Effective Field Theories and Group Theory

Standard Model:



Effective Field Theories and Group Theory

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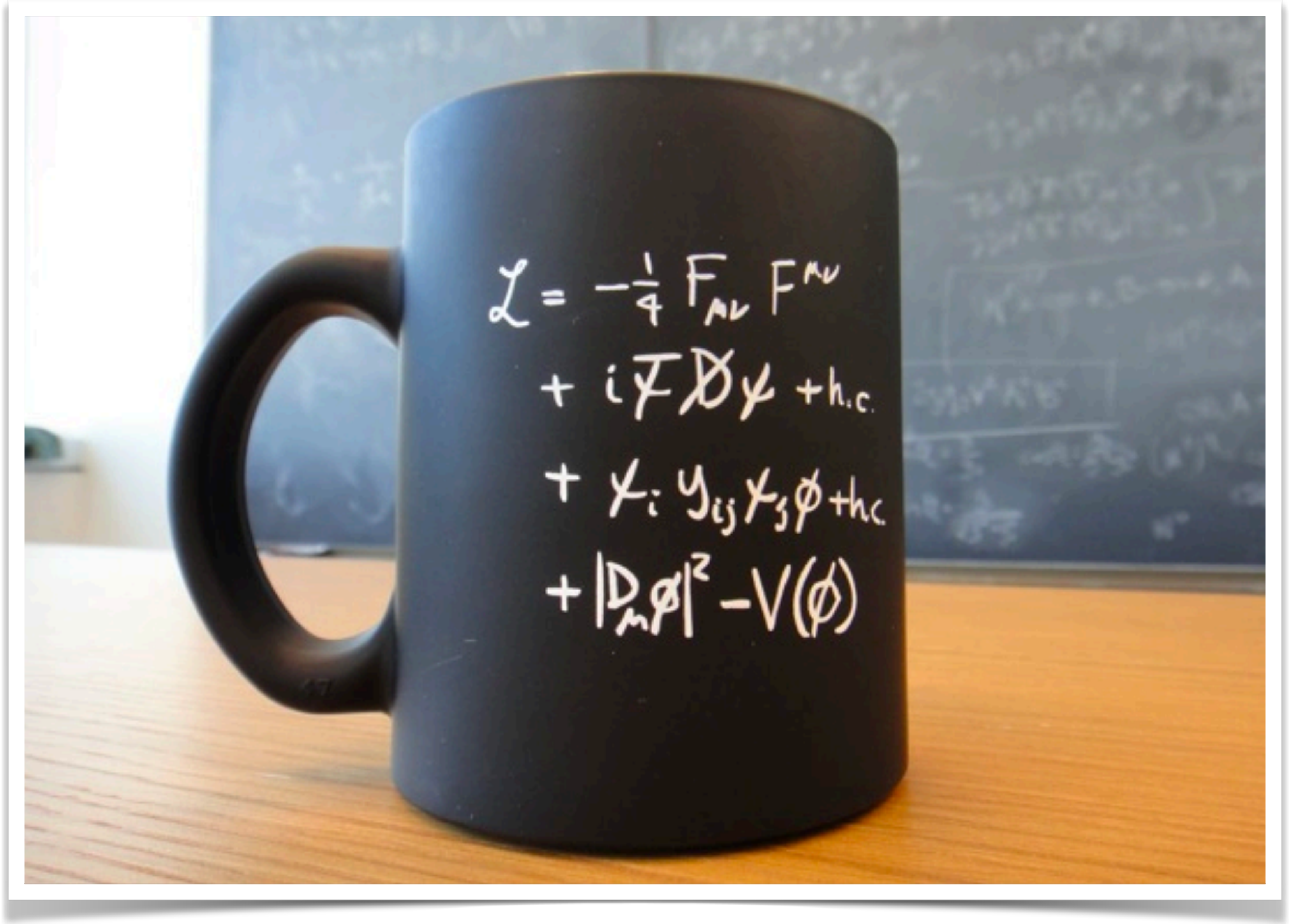

SMEFT

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
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Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
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Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
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Effective Field Theories and Group Theory

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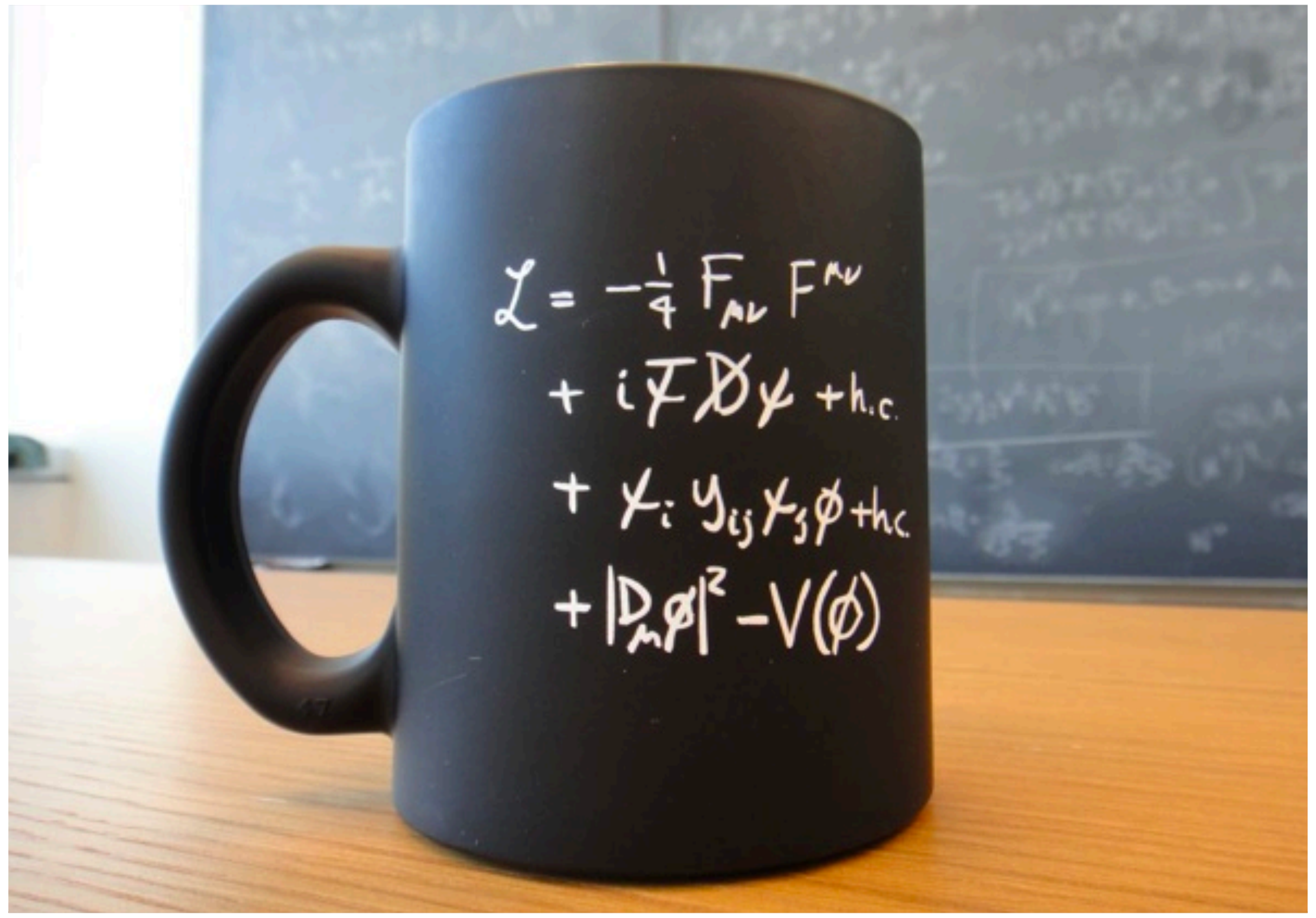

SMEFT @ dim 6

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Effective Field Theories and Group Theory

$$
\begin{array}{llll}
\begin{array}{|c|c|}\hline 2 & 1 \\ \hline 3 & 5 \\ \hline 4 \\ \cline{1-1} \end{array}
& = \begin{array}{|c|c|}\hline 1 & 4 \\ \hline 2 & 5 \\ \hline 3 \\ \cline{1-1} \end{array}
& + \begin{array}{|c|c|}\hline 1 & 2 \\ \hline 3 & 5 \\ \hline 4 \\ \cline{1-1} \end{array}
& - \begin{array}{|c|c|}\hline 1 & 3 \\ \hline 2 & 5 \\ \hline 4 \\ \cline{1-1} \end{array} \,, \\
-\epsilon_{\dot{\alpha}_1\dot{\alpha}_5}\epsilon^{\alpha_1\alpha_5}
& = \epsilon_{\dot{\alpha}_4\dot{\alpha}_5}\epsilon^{\alpha_4\alpha_5}
& +\epsilon_{\dot{\alpha}_2\dot{\alpha}_5}\epsilon^{\alpha_2\alpha_5}
& +\epsilon_{\dot{\alpha}_3\dot{\alpha}_5}\epsilon^{\alpha_3\alpha_5}, \\
-D_\mu\phi_1\phi_2\phi_3\phi_4 D^\mu\phi_5
& = \phi_1\phi_2\phi_3 D_\mu\phi_4 D^\mu\phi_5
& +\phi_1 D_\mu\phi_2\phi_3\phi_4 D^\mu\phi_5
& +\phi_1\phi_2 D_\mu\phi_3\phi_4 D^\mu\phi_5
\end{array}
\tag{3.50}
$$

Group theory, Young tableaux, etc.

AutoEFT 0.0.0

Single Flavor SMEFT: Standard Model Effective Field Theory with a single generation of fermions

Field	Lorentz	SU3_C	SU2_W	U1_Y	nf
GL	-1	[2,1]	[]	0	1
GL+	1	[2,1]	[]	0	1
WL	-1	[]	[2]	0	1
WL+	1	[]	[2]	0	1
BL	-1	[]	[]	0	1
BL+	1	[]	[]	0	1
L	-1/2	[]	[1]	-1/2	1
L+	1/2	[]	[1]	1/2	1
eC	-1/2	[]	[]	1	1
eC+	1/2	[]	[]	-1	1
Q	-1/2	[1]	[1]	1/6	1
Q+	1/2	[1,1]	[1]	-1/6	1
uC	-1/2	[1,1]	[]	-2/3	1
uC+	1/2	[1]	[]	2/3	1
dC	-1/2	[1,1]	[]	1/3	1
dC+	1/2	[1]	[]	-1/3	1
H	0	[]	[1]	1/2	1
H+	0	[]	[1]	-1/2	1

generating operator basis for Single Flavor SMEFT @ d=8

```
AutoEFT 0.0.0
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Single Flavor SMEFT: Standard Model Effective Field Theory with a single genera
tion of fermions
Field | Lorentz | SU3_C | SU2_W | U1_Y | nf
GL    |  -1     | [2,1
GL+   |   1     | [2,1
WL    |  -1     | [
WL+   |   1     | [
BL    |  -1     | [
BL+   |   1     | [
L     | -1/2    | [
L+    |  1/2    | [
eC    | -1/2    | [
eC+   |  1/2    | [
Q     | -1/2    | [1
Q+    |  1/2    | [1,1
uC    | -1/2    | [1,1
uC+   |  1/2    | [1
dC    | -1/2    | [1,1
dC+   |  1/2    | [1]   | []    | -1/3  | 1
H     |   0     | []    | [1]   |  1/2  | 1
H+    |   0     | []    | [1]   | -1/2  | 1

generating operator basis for Single Flavor SMEFT @ d=8
```

```
    ├── #terms=6
    └── #operators=6
----------------------------------------------------------------
• (N=8,nl=0,nr=0)
└── • phi(8)
      ├── H H H H H+ H+ H+ H+
      │   ├── #terms=1
      │   └── #operators=1
      ├── #types=1
      ├── #terms=1
      └── #operators=1
#class=48
#types=521
#terms=993
#operators=993
saved operators in eft/sf_smeft/8/operators
```

AutoEFT 0.0.0
Copyright (C) 2022 Robert V. Harlander, Tim Kempkens, and Magnus C. Schaaf
Single Flavor SMEFT: Standard Model Effective Field Theory with a single generation of fermions

Field	Lorentz	SU3_C	SU2_W	U1_Y	nf
GL	-1	[2,1	[illegible]	[illegible]	[illegible]
GL+	1	[2,1	[illegible]	[illegible]	[illegible]
WL	-1	[	[illegible]	[illegible]	[illegible]
WL+	1	[	[illegible]	[illegible]	[illegible]
BL	-1	[	[illegible]	[illegible]	[illegible]
BL+	1	[	[illegible]	[illegible]	[illegible]
L	-1/2	[	[illegible]	[illegible]	[illegible]
L+	1/2	[	[illegible]	[illegible]	[illegible]
eC	-1/2	[	[illegible]	[illegible]	[illegible]
eC+	1/2	[	[illegible]	[illegible]	[illegible]
Q	-1/2	[1	[illegible]	[illegible]	[illegible]
Q+	1/2	[1,1	[illegible]	[illegible]	[illegible]
uC	-1/2	[1,1	[illegible]	[illegible]	[illegible]
uC+	1/2	[1	[illegible]	[illegible]	[illegible]
dC	-1/2	[1,1	[illegible]	[illegible]	[illegible]
dC+	1/2	[1]	[]	-1/3	1
H	0	[]	[1]	1/2	1
H+	0	[]	[1]	-1/2	1

generating operator basis for Single Flavor SMEFT @ d=8

```
    ├── #terms=6
    └── #operators=6
-----------------------------------------------
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#terms=993
#operators=993
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```

The Standard Model Effective Field Theory up to Mass Dimension 12

R.V. Harlander, T. Kempkens, and M.C. Schaaf

Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, 52056 Aachen, Germany

Effective Field Theories and Group Theory

QFT leads to divergences → dimensional regularization: $D = 4 - 2\epsilon$

Evanescent operators, e.g.

$$(\bar{\psi}\,\gamma^{\mu}\gamma_5\,\psi)(\bar{\psi}\,\gamma_{\mu}\gamma_5\,\psi) \overset{D=4}{\sim} (\bar{\psi}\,\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}\gamma_5\,\psi)(\bar{\psi}\,\gamma_{\mu}\gamma_{\nu}\gamma_{\rho}\gamma_5\,\psi)$$

Program:

- get familiar with field and group theory methods
- understand the origin of evanescent operators
- generalize to arbitrary mass dimension in EFT

Application:

Matching coefficients of EFTs to UV complete theories

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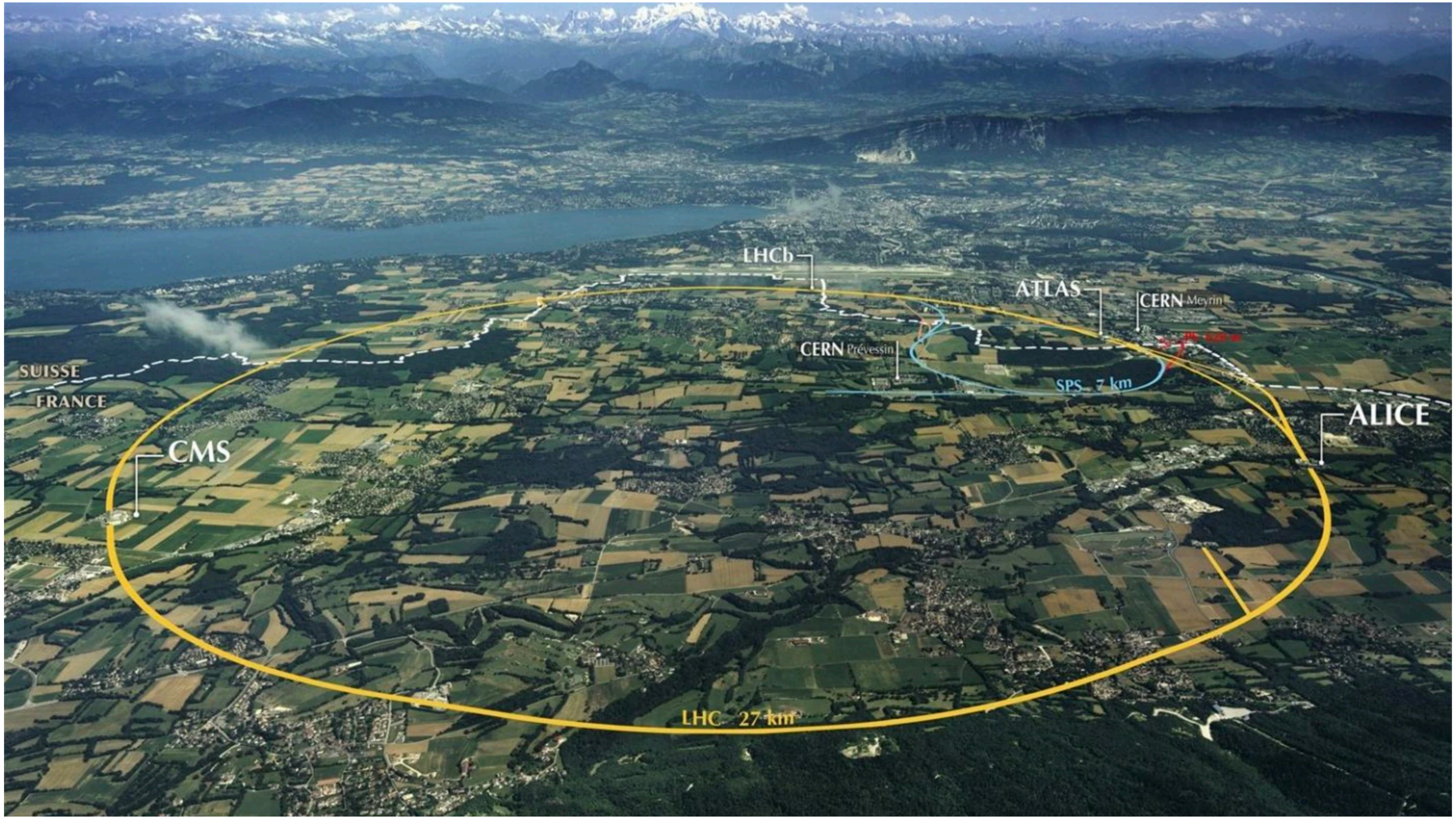
▸ **The gradient-flow beyond QCD**

▸ **Effective field theories and group theory**

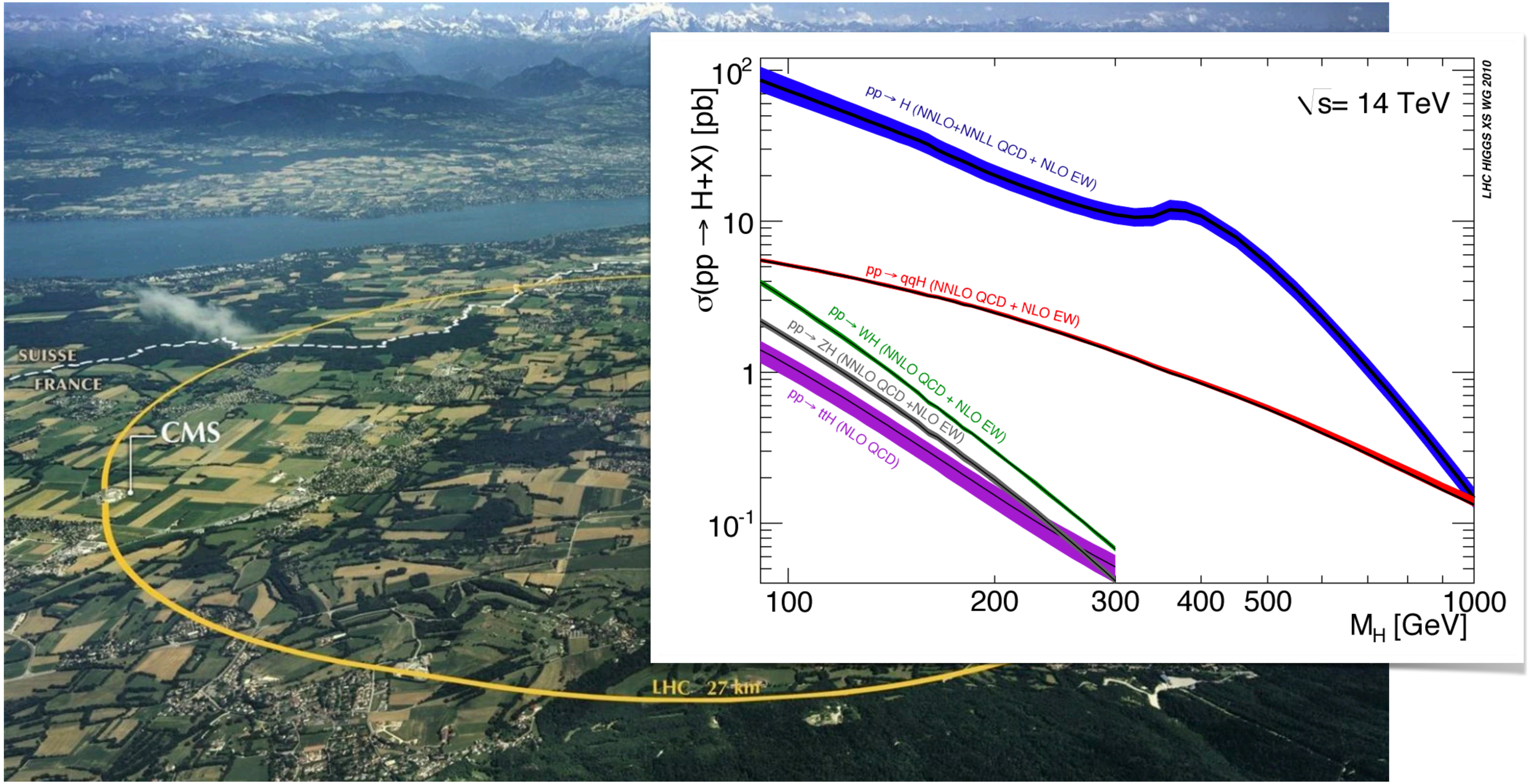
▸ **Higgs production at the LHC**

last updated on Jul 05, 2023 by RH

Higgs production at the LHC



Higgs production at the LHC



Developers

- Robert V. Harlander (RWTH Aachen University)
- Stefan Liebler (KIT)
- Hendrik Mantler

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fans of the MSSM:
to link SusHi to FeynHiggs (FH) by "./configure; make predef=FH"!
to link SusHi to FeynHiggs (FH) including the calculation of interference factors by "./configure; make predef=FHINT"!
to link SusHi to HiggsBounds/HiggsSignals+FH by "./configure; make predef=HB" or "HS"!
fans of the 2HDM:
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SusHi Bento: Beyond NNLO and the heavy-top limit☆

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Robert V. Harlander[a], Stefan Liebler[b,*], Hendrik Mantler[c,d]

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vh@nnlo-v2: new physics in Higgs Strahlung

Robert V. Harlander,[a] Jonas Klappert,[a] Stefan Lieble[b] and Lukas Simon[a]

Higgs production at the LHC

Program:

- get familiar with higher-order perturbative calculations
- get familiar with Higgs phenomenology, BSM, EFTs, etc.
- calculate theoretical predictions in BSM models and EFTs

Application:

Analysis tools for phenomenological studies

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