Theoretical Particle Physics
(Theorie Elementarteilchen)

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Institute of Nuclear Physics & Cluster of Excellence PRISMA,
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Module Topical Courses: “Theoretical Particle Physics”

ID number (JOGU-StINe)	Workload (workload)	Course Duration (laut Studienverlaufsplan)	Designated term (laut Studienverlaufsplan)	Credit Points (LP)
08.128.809	180 h	1	1	6 LP

No.	Courses/Teaching methods	Contact time	Self-study	Credit Points
1.	Lecture with excercises “Theoretical Particle Physics” (WP)		138 h	6 LP
	Lecture (WP)	3 SWS/31.5 h		
	Excercises (WP)	1 SWS/10.5 h		

2. Group sizes

Lecture: unlimited
Excercises: 20

3. Qualification and program goals / Competences

The lecture course “Theoretical Particle Physics” builds upon and continues the lecture course “Relativistic Quantum Field Theory”. The lectures’ program goal is to provide a basic understanding of concepts and methods of quantum field theory which are required for a MA thesis in theoretical particle physics.

4. Course content

Path integral formalism, quantum corrections, renormalization in QED, renormalization group; non-Abelian gauge theories, quantum chromodynamics (QCD), spontaneous symmetry breaking, Higgs mechanism, standard model of particle physics.

5. Applicable to the following programs

MSc. Physics

6. Recommended prerequisites

7. Entry requirements

8. Mode and duration of examinations

8.1 Active participation

successful completion of the exercises

8.2 Course achievements

8.3 Module examination

Common oral examination (30 – 45 Min.) covering two topical courses

9. Weighting of the achievement in the overall grade

6/120

10. Module frequency

Usually every semester

11. Persons responsible for this module and full-time lecturers

Responsible: Prof. Dr. S. Weinzierl
Lecturers: All professors of theoretical high energy physics

12. Auxiliary Information

Course language: English
Literature: Peskin & Schroeder, Ryder, Schwartz, Zee

First glimpse of the Standard Model of Particle Physics

Fundamental constants of the vacuum

$\hbar \simeq 6.58 \times 10^{-16}\,\mathrm{eV\,s}$ $\quad$ $c \simeq 3 \cdot 10^{8}\,\mathrm{m/s}$

quantum physics $\quad$ special relativity

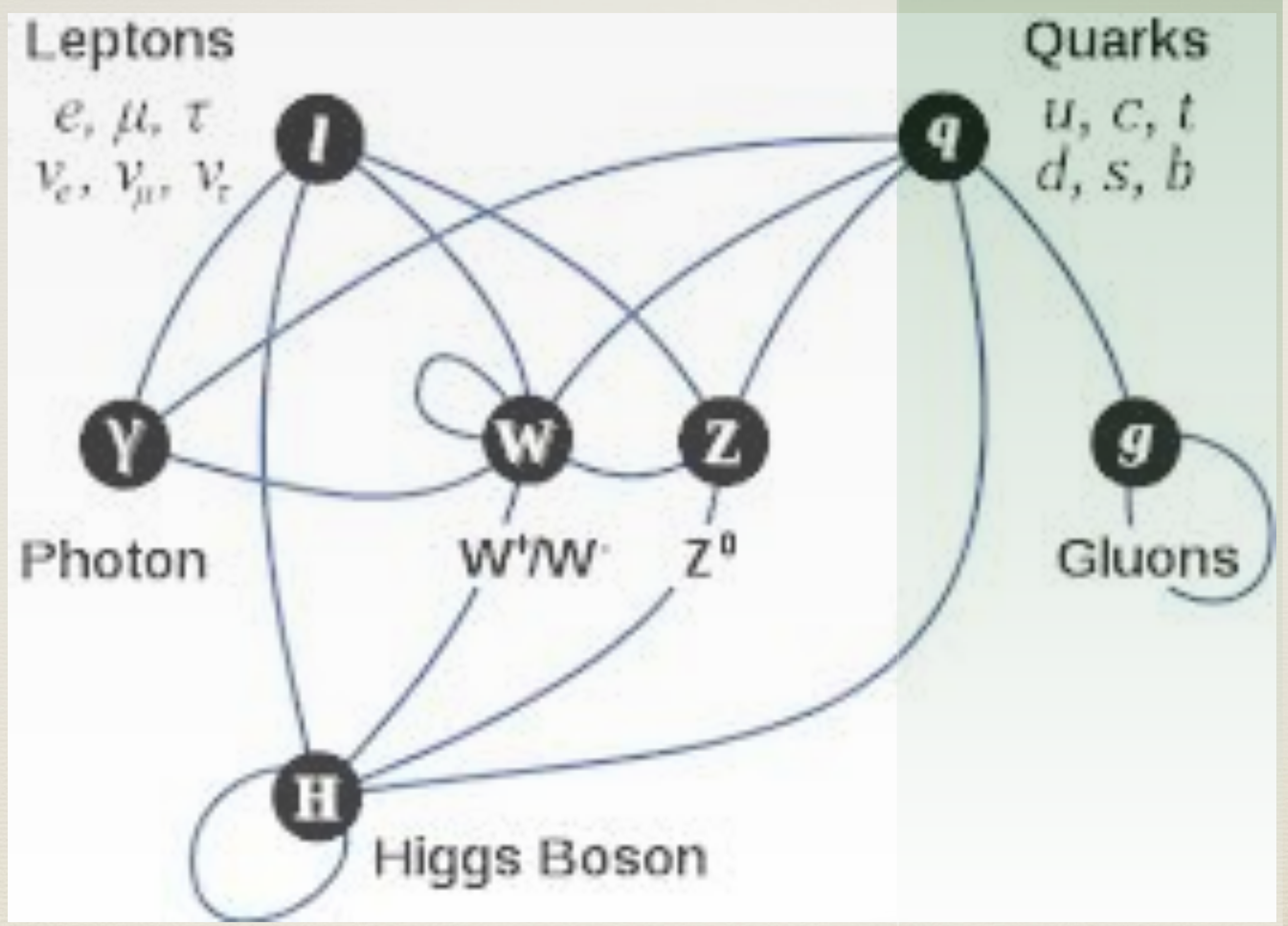
Quantum Field Theory

$\hbar = c = 1$ (Natural Units), $\quad$ e.g. $E = \sqrt{m^2 + p^2}$, $\alpha = \frac{e^2}{4\pi} \simeq \frac{1}{137.036}$

$\hbar c = 0.1973\ldots\ \mathrm{GeV\ fm} = 0.1973\ldots\ \mathrm{eV}\ \mu\mathrm{m}$

Standard Model

Electroweak QCD

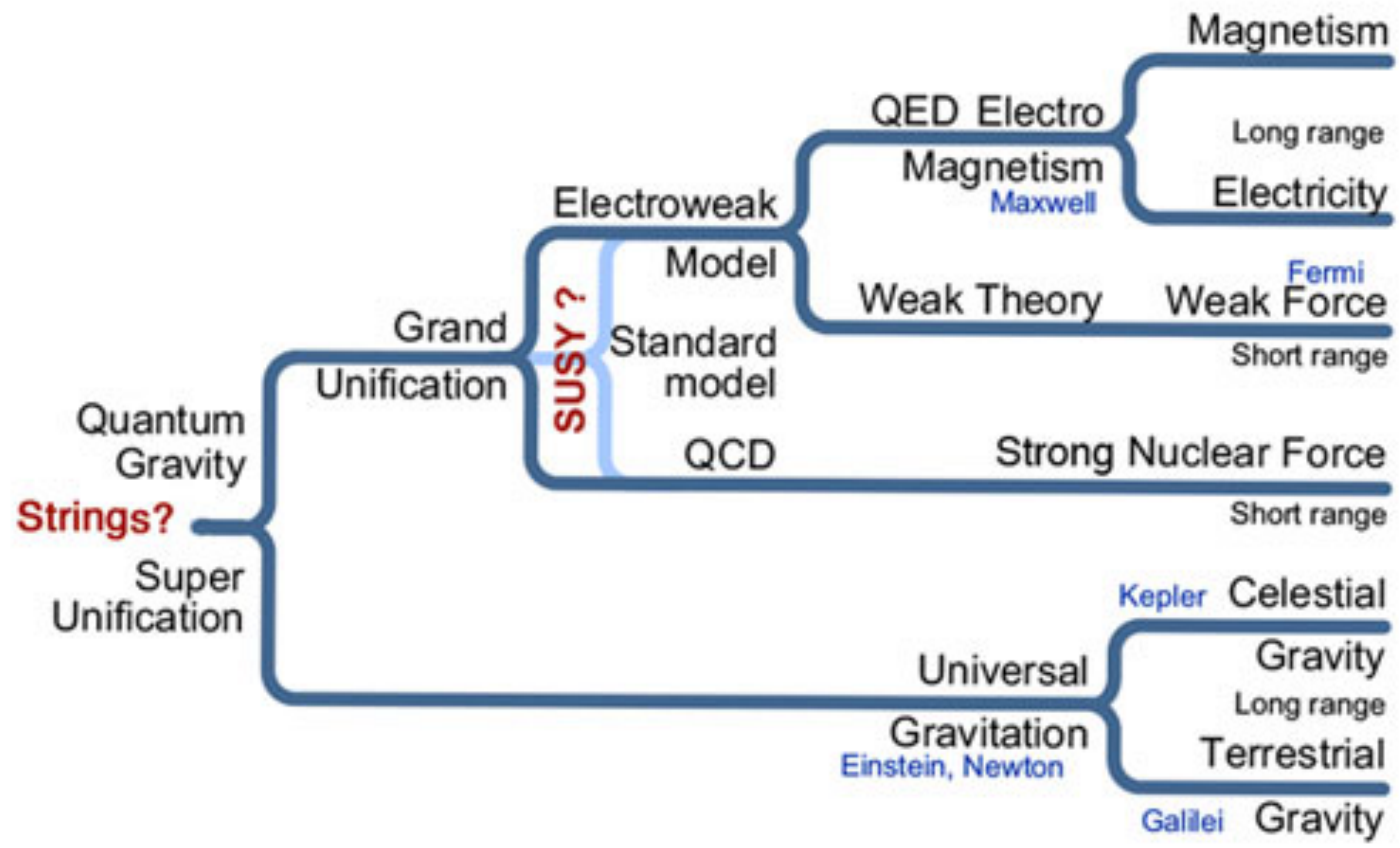


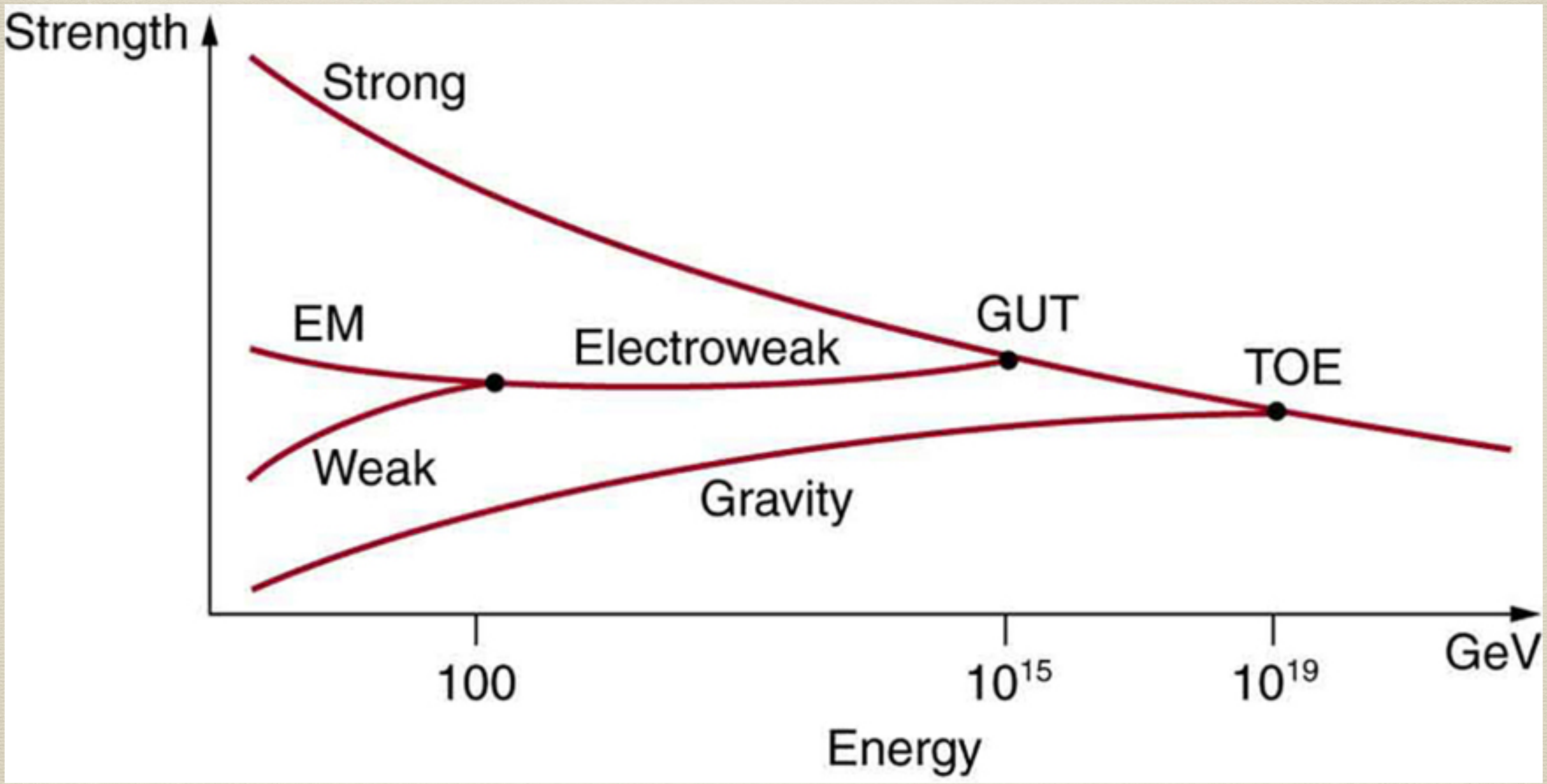
$S = 1/2$, spinor : $\psi^{(\alpha)}(x)$

$S = 1$, vector : $A_\mu(x)$

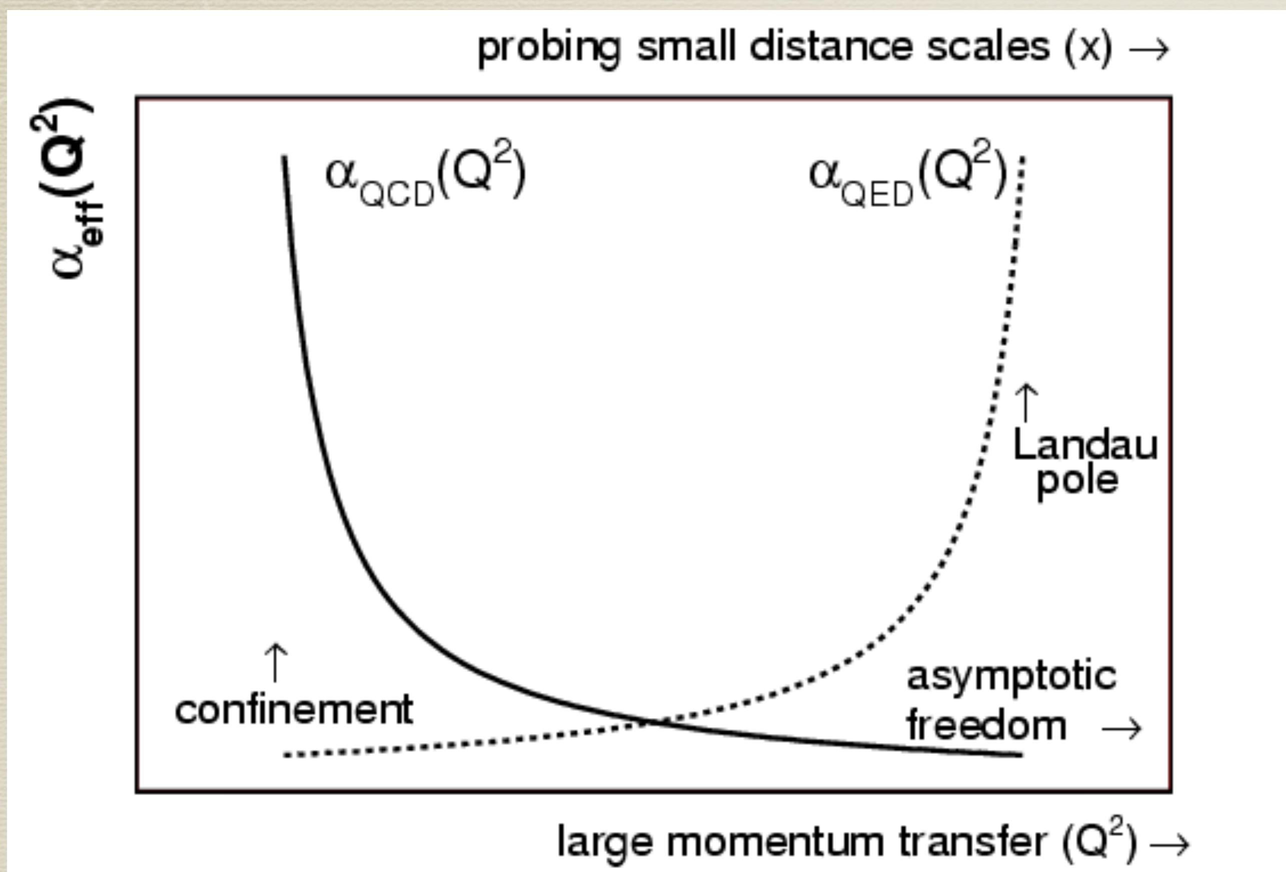
$S = 0$, scalar : $\phi(x)$

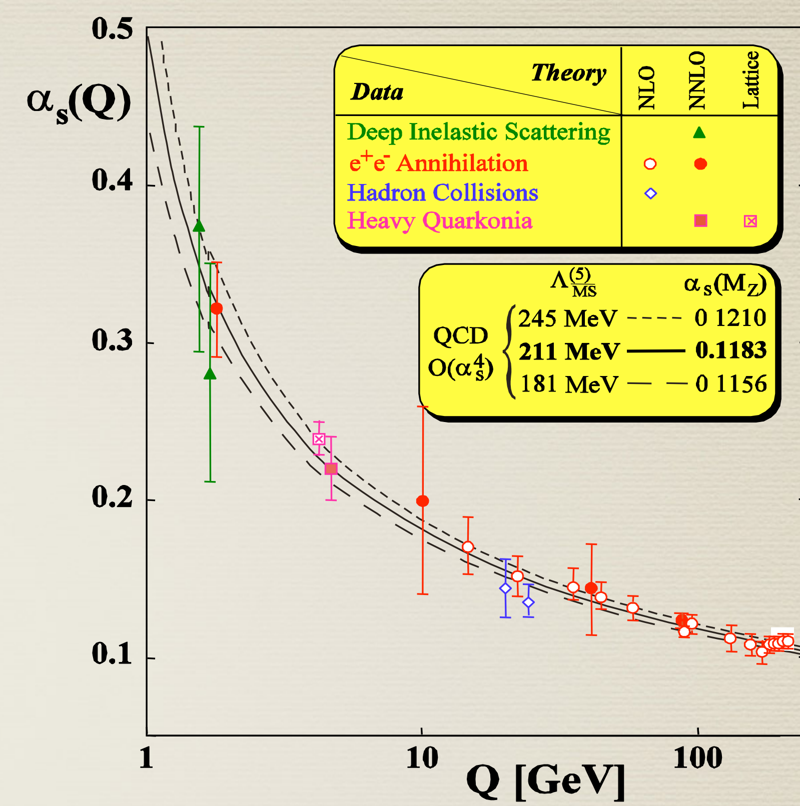
Unification of fundamental interactions




Strength
Strong
EM
Electroweak
GUT
TOE
Weak
Gravity
100
10^15
10^19
GeV
Energy

Running of QCD coupling

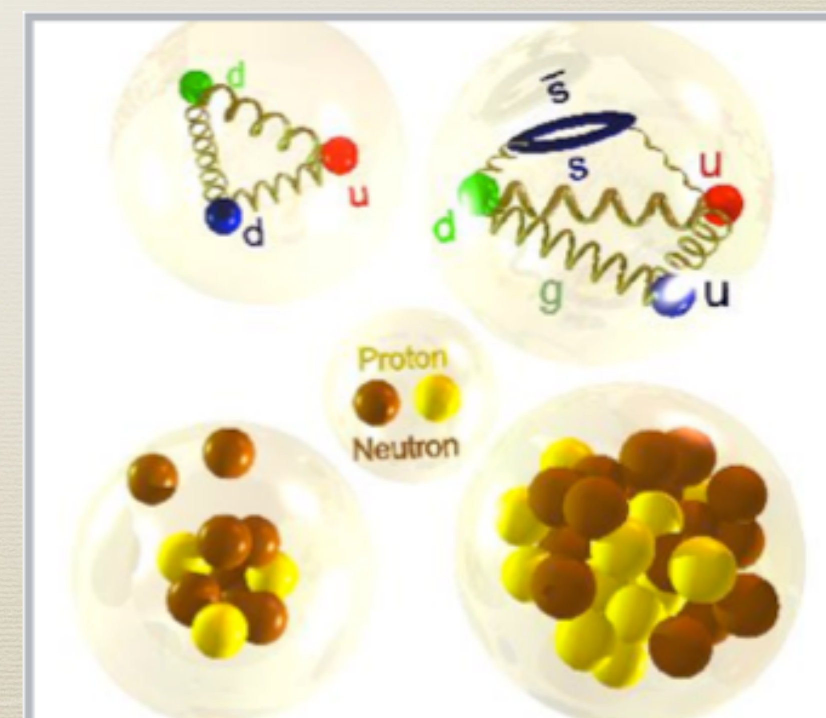




For $Q^2 \to \infty$, $\alpha_s \to 0$: **asymptotic freedom**

For $Q \sim \Lambda_{QCD}$ non-perturbative phenomena:

color confinement,
spontaneous chiral symmetry breaking,
generation of nucleon mass, ...



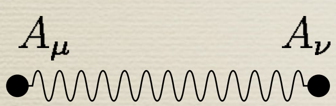
Feynman rules of the SM

[(arXiv: hep-ph/9507456)](arXiv: hep-ph/9507456)

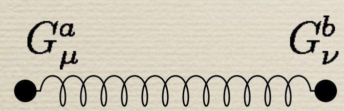
Propagators:

$$\frac{1}{k^2 - M_W^2 + i\varepsilon}\left(g_{\mu\nu} - (1-\xi_W)\,\frac{k_\mu k_\nu}{k^2 - \xi_W\ M_W^2 + i\varepsilon}\right)$$

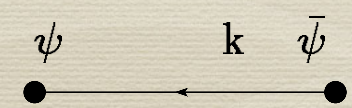
$$\frac{1}{k^2 - M_Z^2 + i\varepsilon}\left(g_{\mu\nu} - (1-\xi_Z)\,\frac{k_\mu k_\nu}{k^2 - \xi_Z M_Z^2 + i\varepsilon}\right)$$



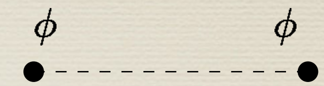
$$\frac{1}{k^2 + i\varepsilon}\left(g_{\mu\nu} - (1-\xi_A)\,\frac{k_\mu k_\nu}{k^2 + i\varepsilon}\right)$$



$$\delta^{ab}\frac{1}{k^2 + i\varepsilon}\left(g_{\mu\nu} - (1-\xi_G)\,\frac{k_\mu k_\nu}{k^2 + i\varepsilon}\right)$$



$$-\frac{\hat{k} + m}{k^2 - m^2 + i\varepsilon} = \frac{\hat{k} + m}{m^2 - k^2 + i\varepsilon}$$



$$-\frac{1}{k^2 - m_H^2 + i\varepsilon}$$

$$-\frac{1}{k^2 - \xi_W\ m_W^2 + i\varepsilon}$$

$$-\frac{1}{k^2 - \xi_Z m_Z^2 + i\varepsilon}$$

$$-\frac{1}{k^2 - \xi_W\ m_W^2 + i\varepsilon}$$

$$-\frac{1}{k^2 - \xi_W\ m_W^2 + i\varepsilon}$$

$$-\frac{1}{k^2 - \xi_Z m_Z^2 + i\varepsilon}$$

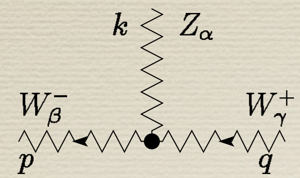
$$-\frac{1}{k^2 + i\varepsilon}$$

$$-\delta_{ab}\frac{1}{k^2 + i\varepsilon}$$

Vertices

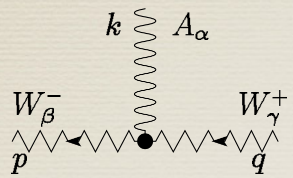
10.4.1 *Gauge Boson Three–vertices*

$\boxed{ZW^+W^-}$



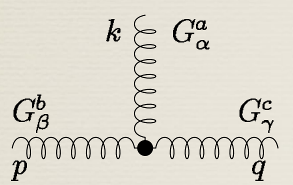
$$e\cot\vartheta_W\left((k-p)^\gamma g^{\alpha\beta}+(p-q)^\alpha g^{\beta\gamma}+(q-k)^\beta g^{\gamma\alpha}\right)$$

$\boxed{AW^+W^-}$



$$e\left((k-p)^\gamma g^{\alpha\beta}+(p-q)^\alpha g^{\beta\gamma}+(q-k)^\beta g^{\gamma\alpha}\right)$$

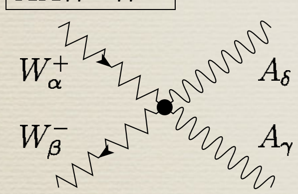
$\boxed{GGG}$



$$ig_s f^{abc}\left((p-k)^\gamma g^{\alpha\beta}+(q-p)^\alpha g^{\beta\gamma}+(k-q)^\beta g^{\gamma\alpha}\right)$$

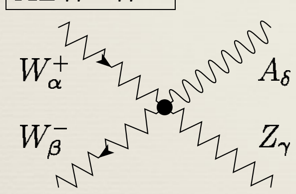
10.4.2 *Gauge Boson Four–vertices*

$\boxed{AAW^+W^-}$



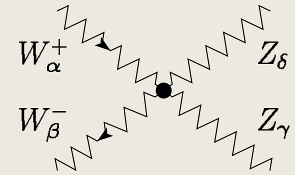
$$e^2(g^{\alpha\gamma}g^{\beta\delta}+g^{\alpha\delta}g^{\beta\gamma}-2g^{\alpha\beta}g^{\gamma\delta})$$

$\boxed{AZW^+W^-}$



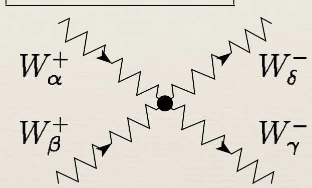
$$e^2\cot\vartheta_W(g^{\alpha\gamma}g^{\beta\delta}+g^{\alpha\delta}g^{\beta\gamma}-2g^{\alpha\beta}g^{\gamma\delta})$$

$\boxed{ZZW^+W^-}$



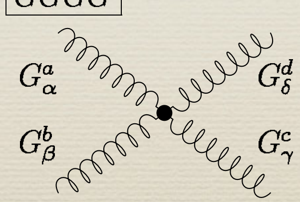
$$e^2\cot^2\vartheta_W(g^{\alpha\gamma}g^{\beta\delta}+g^{\alpha\delta}g^{\beta\gamma}-2g^{\alpha\beta}g^{\gamma\delta})$$

$\boxed{W^+W^-W^+W^-}$



$$-\frac{e^2}{\sin^2\vartheta_W}(g^{\alpha\gamma}g^{\beta\delta}+g^{\alpha\delta}g^{\beta\gamma}-2g^{\alpha\beta}g^{\gamma\delta})$$

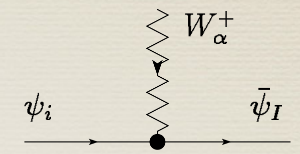
$\boxed{GGGG}$



$$\begin{aligned}-g_s^2\,\big(&f^{rab}f^{rcd}(g^{\alpha\gamma}g^{\delta\beta}-g^{\alpha\delta}g^{\beta\gamma})\\+&f^{rac}f^{rdb}(g^{\alpha\delta}g^{\beta\gamma}-g^{\alpha\beta}g^{\gamma\delta})\\+&f^{rad}f^{rbc}(g^{\alpha\beta}g^{\gamma\delta}-g^{\alpha\gamma}g^{\delta\beta})\ \big)\end{aligned}$$

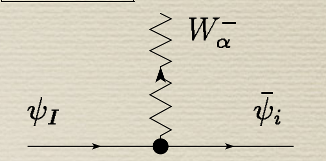
10.4.3 *Gauge–boson–fermion Vertices*

$\boxed{\bar\psi_I\psi_i W^+}$



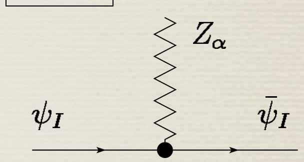
$$\frac{e}{2\sqrt{2}\sin\vartheta_W}V^+_{iI}\gamma^\alpha(1-\gamma^5)$$

$\boxed{\bar\psi_i\psi_I W^-}$



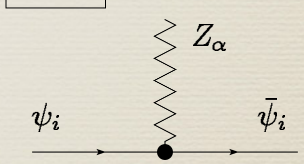
$$\frac{e}{2\sqrt{2}\sin\vartheta_W}V_{iI}\gamma^\alpha(1-\gamma^5)$$

$\boxed{\bar\psi_I\psi_I Z}$



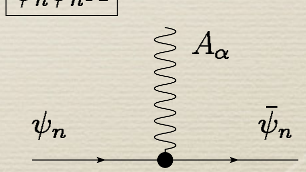
$$\frac{e}{\sin 2\vartheta_W}\gamma^\alpha\left(\frac{1}{2}(1-\gamma^5)-2Q_I\sin^2\vartheta_W\right)$$

$\boxed{\bar\psi_i\psi_i Z}$



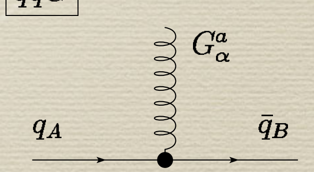
$$\frac{e}{\sin 2\vartheta_W}\gamma^\alpha\left(-\frac{1}{2}(1-\gamma^5)-2Q_i\sin^2\vartheta_W\right)$$

$\boxed{\bar\psi_n\psi_n A}$



$$eQ_n\gamma^\alpha\quad(n=i,I)$$

$\boxed{\bar q qG}$

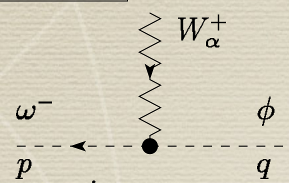


$$g_s\,(t^a)_{BA}\,\gamma^\alpha$$

Vertices (continued)

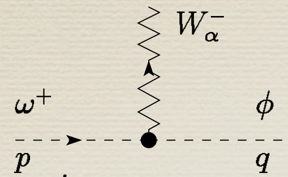
10.4.4 *Gauge–boson–Higgs Three–vertices*

$\phi\, \omega^- W^+$



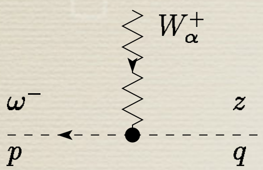
$$\frac{i\, e}{2 \sin \vartheta_W}(p-q)^\alpha$$

$\phi\, \omega^+ W^-$



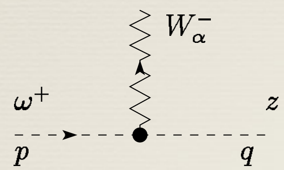
$$\frac{i\, e}{2 \sin \vartheta_W}(p-q)^\alpha$$

$z\, \omega^- W^+$



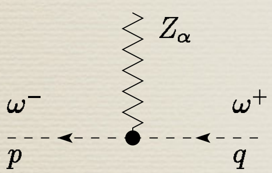
$$\frac{e}{2 \sin \vartheta_W}(p-q)^\alpha$$

$z\, \omega^+ W^-$



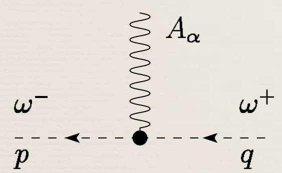
$$-\frac{e}{2 \sin \vartheta_W}(p-q)^\alpha$$

$\omega^+\, \omega^- Z$



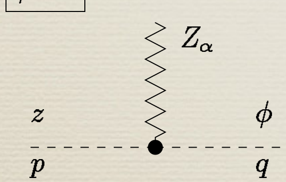
$$-e \cot 2\vartheta_W (p-q)^\alpha$$

$\omega^+\, \omega^- A$



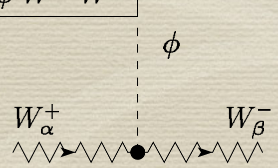
$$-e(p-q)^\alpha$$

$\phi\, z Z$



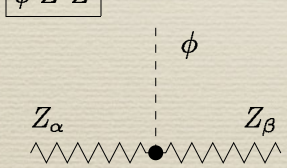
$$\frac{i\, e}{sin 2\vartheta_W}(p-q)^\alpha$$

$\phi\, W^+\, W^-$



$$e \cot \vartheta_W\ M_Z\ g^{\alpha\beta}$$

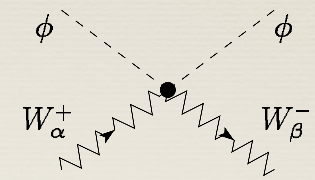
$\phi\ Z\ Z$



$$\frac{2\, e}{\sin 2\vartheta_W} M_Z\ g^{\alpha\beta}$$

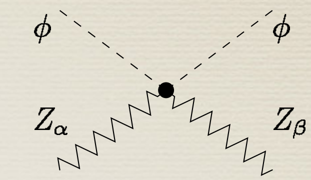
10.4.5 *Gauge–boson–Higgs Four–vertices*

$\phi\ \phi\ W^+\ W^-$



$$\frac{e^2}{2 \sin^2 \vartheta_W} g^{\alpha\beta}$$

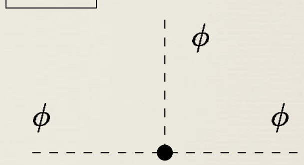
$\phi\ \phi\ Z\ Z$



$$\frac{2\, e^2}{\sin^2 2\vartheta_W} g^{\alpha\beta}$$

10.4.6 *Higgs Three–vertices*

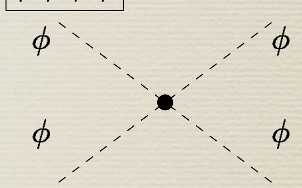
$\phi\ \phi\ \phi$



$$-\frac{3\, e}{\sin 2\vartheta_W}\frac{m_H^2}{M_Z}$$

10.4.7 *Higgs Four–vertices*

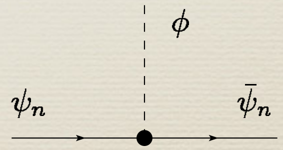
$\phi\ \phi\ \phi\ \phi$



$$-\frac{3\, e^2}{\sin^2 2\vartheta_W}\frac{m_H^2}{M_Z^2}$$

10.4.8 *Higgs–boson–fermion Vertices*

$\bar\psi_n \psi_n \phi$



$$-\frac{e}{\sin 2\vartheta_W}\frac{m_n}{M_Z}$$

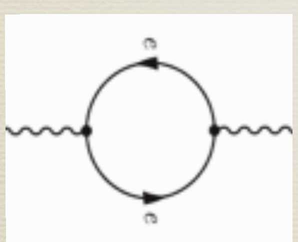
Loops

Finally, every loop integration is performed by the rule

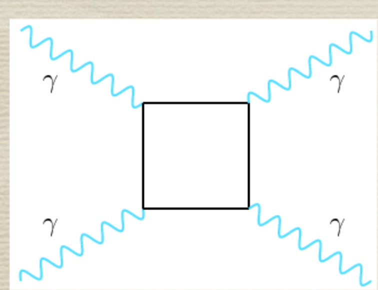
$$\int \frac{d^d\,k}{i\,(2\pi)^d},$$

and with every fermion or ghost loop we associate extra factor (-1).

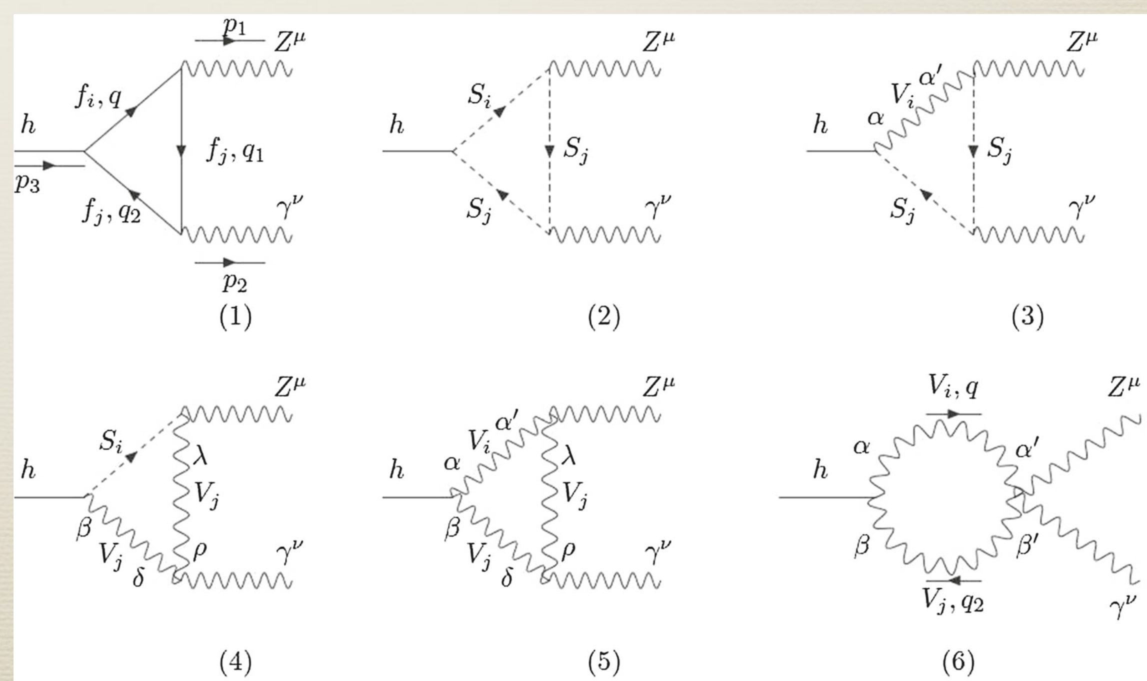
Vacuum polarization



Light-by-light scattering



Higgs decay



Exercise sessions will sometimes involve computer algebra,

i.e., FORM, FeynCalc, LoopTools (Mathematica)

BYOL