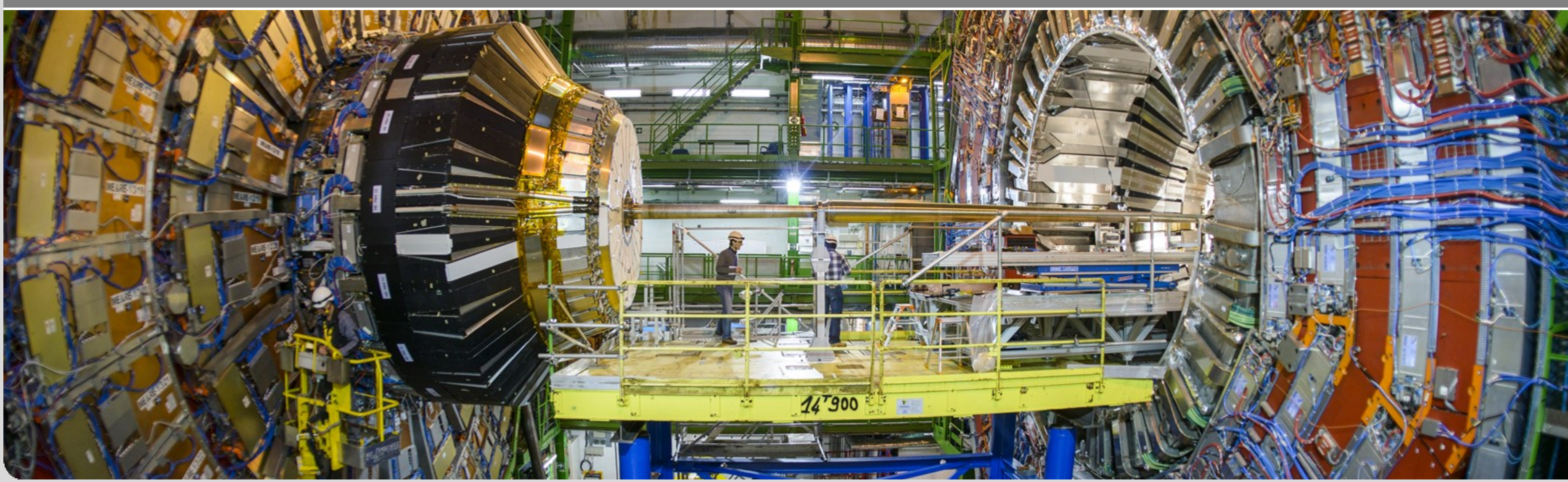
Karlsruhe Institute of Technology

From Lagrangian Density to Observable

Roger Wolf

20. Mai 2015

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY



Schedule for today

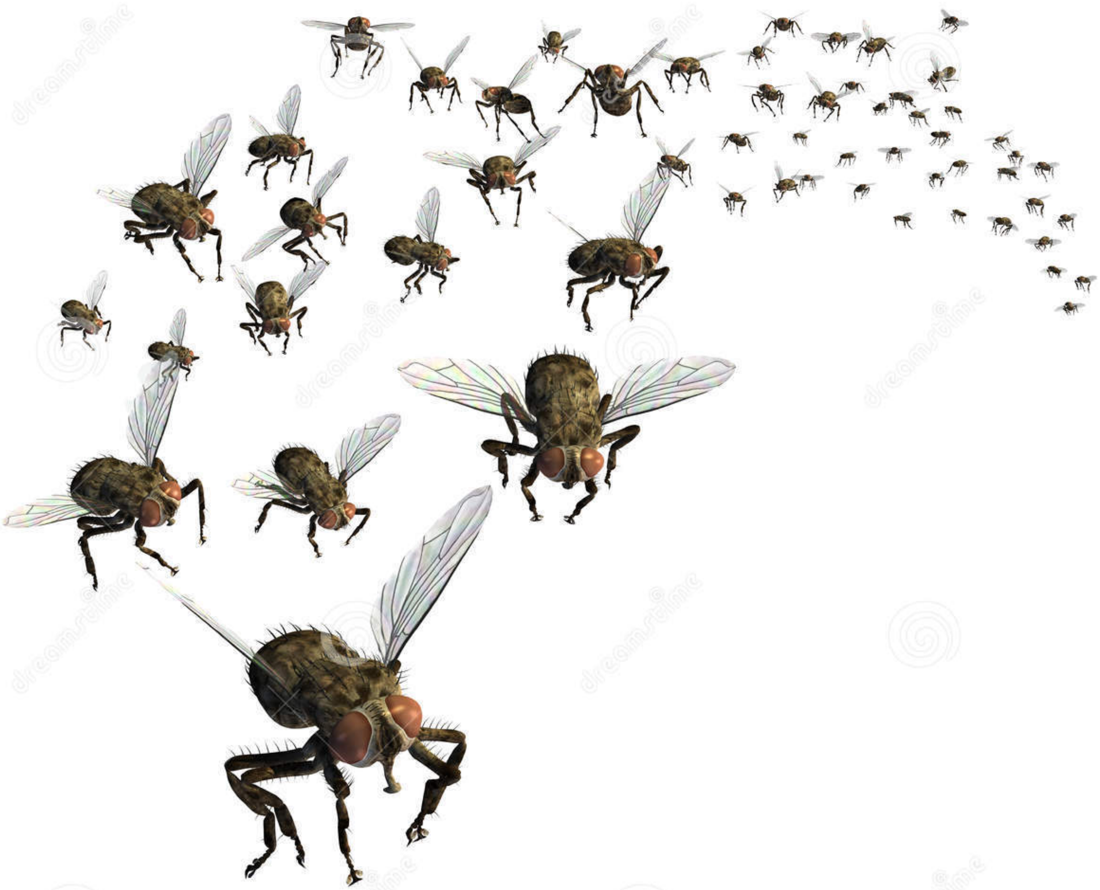
- Does a Feynman diagram have a time direction? If yes, what is it?

3 Intrinsic bounds on the Higgs boson mass in the SM

2 Discussion of higher order effects in perturbation theory

1 Completion of cross section calculation

The perturbative series



The perturbative series

- The integral equation can be solved iteratively:

$$\boxed{\psi_{\text{scat}}(x) = \phi(x) - e\int K(x-x')\gamma^\mu A_\mu(x')\psi_{\text{scat}}(x')\mathrm{d}^4x'}$$

($\phi(x)$ = solution of the homogeneous *Dirac* equation)

- 0th order perturbation theory:

$$\psi^{(0)}(x) = \phi(x)$$

- Just take $\phi(x)$ as solution (→ boring).

- 1st order perturbation theory:

$$\psi^{(1)}(x) = \psi^{(0)}(x) - e\int K(x-x')\gamma^\mu A_\mu(x')\psi^{(0)}(x')\mathrm{d}^4x'$$

- Assume that $\psi^{(0)}(x)$ is close enough to actual solution on RHS.

- 2nd order perturbation theory:

$$\psi^{(2)}(x) = \psi^{(0)}(x) - e\int K(x-x')\gamma^\mu A_\mu(x')\psi^{(1)}(x')\mathrm{d}^4x'$$

- Take $\psi^{(1)}(x)$ as better approximation at RHS to solve inhomogeneous equation.

The perturbative series

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- 0[th] order perturbation theory:

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- 1[st] order perturbation theory:

$$\psi^{(1)}(x) = \psi^{(0)}(x) - e\int K(x-x')\gamma^\mu A_\mu(x')\psi^{(0)}(x')\mathrm{d}^4x'$$

- Assume that $\psi^{(0)}(x)$ is close enough to actual solution on RHS.

- 2[nd] order perturbation theory:

$$\begin{aligned}\psi^{(2)}(x) = \psi^{(0)}(x) &- e\int K(x-x')\gamma^\mu A_\mu(x')\psi^{(0)}(x')\mathrm{d}^4x' \\ &+ e^2\iint K(x-x')\gamma^\mu A_\mu(x')K(x'-x'')\gamma^\mu A_\mu(x'')\psi^{(0)}(x'')\mathrm{d}^4x'\mathrm{d}^4x''\end{aligned}$$

The matrix element $\mathcal{S}_{fi}$

- $\mathcal{S}_{fi}$ is obtained from the projection of the scattering wave ψ_{scat} on $\phi_f = \phi(x_f)$:

$$\boxed{\begin{aligned} \mathcal{S}_{fi} = \int \mathrm{d}^4 x_f \phi_f^\dagger(x_f)\psi_{\text{scat}}(x_f) &= \int \mathrm{d}^4 x_f \phi_f^\dagger(x_f)\mathcal{S}\phi_i(x_f) \\ &= \delta_{fi} + \mathcal{S}_{fi}^{(1)} + \mathcal{S}_{fi}^{(2)} + \dots \end{aligned}}$$

"LO" **"NLO"**

- 1st order perturbation theory:

$$\mathcal{S}_{fi}^{(1)} = -e\int \mathrm{d}^4x' \underbrace{\int \mathrm{d}^4 x_f \phi_f^\dagger(x_f) K(x_f - x')}_{\equiv -i\overline{\phi}_f(x') = -i\overline{\phi}(x_f)} \overbrace{\gamma^\mu A_\mu(x')\phi_i(x')}^{\equiv \phi_f(x_f) = \phi(x_f)}$$

For $E > 0$ and $t_f > t'$ respectively.

$$\phi(x_f) = \ -e\int \mathrm{d}^4x' K(x_f - x')\gamma^\mu A_\mu(x')\phi(x')$$ cf. slide 7

$$\overline{\phi}(x') = i\int \mathrm{d}^3\vec{x}\,\overline{\phi}(x_f)\gamma^0 K(x'-x_f) = -i\int \mathrm{d}^3\vec{x}_f\overline{\phi}(x_f)\gamma^0 K(x_f - x')$$ cf. slide 28

NB: the time integration has already been carried out for the backward evolution from t_f to t' to arrive at the equation of slide 28.

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- 1st order perturbation theory:

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$$\boxed{\mathcal{S}_{fi}^{(1)} = i \cdot \int \mathrm{d}^4 x' \underbrace{e\, \overline{\phi}_f(x')\gamma^\mu A_\mu(x')\phi_i(x')} \qquad \text{(1st order matrix element)}}$$

This corresponds exactly to the IA term in $\mathcal{L}$, including the multiplication by i (cf. Lecture-05 slide 39).

The photon propagator

- The evolution of A_μ happens according to the inhomogeneous wave equation of the photon field (in Lorentz gauge $\partial_\mu A^\mu = 0$)

$$\boxed{\Box A^\mu = eJ^\mu} \quad \text{(++)}$$

- We solve (++) again formally via the *Green's* function $D^{\mu\nu}(x-x')$ with the property:

$$\Box D^{\mu\nu}(x-x') = g^{\mu\nu}\delta^4(x-x')$$

$$A^\mu(x) = e\int \mathrm{d}^4x' D^{\mu\nu}(x-x')J_\nu(x')$$

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$$\Box A^\mu(x) = e\int \mathrm{d}^4x' \underbrace{\Box D^{\mu\nu}(x-x')}_{g^{\mu\nu}\delta^4(x-x')} J_\nu(x') = eJ^\mu(x)$$

Green's function in *Fourier* space (fast forward)

- Check for the concrete form of the *Green*'s function again first in *Fourier* space:

$$D^{\mu\nu}(x-x') = (2\pi)^{-4}\int \mathrm{d}^4q\tilde{D}^{\mu\nu}(q)e^{-iq(x-x')}$$ (*Fourier* transform)

In analogy to the fermion case the defining property of $D^{\mu\nu}(x-x')$ in *Fourier* space

$$\Box D^{\mu\nu}(x-x') = (2\pi)^{-4}\int \mathrm{d}^4q\ (-q^2)\tilde{D}^{\mu\nu}(q)e^{-iq(x-x')} \stackrel{!}{=}$$
$$= (2\pi)^{-4}\int \mathrm{d}^4q\ g^{\mu\nu}e^{-iq(x-x')} = g^{\mu\nu}\delta^4(x-x')$$

(omitting the discussion of integral paths) leads to

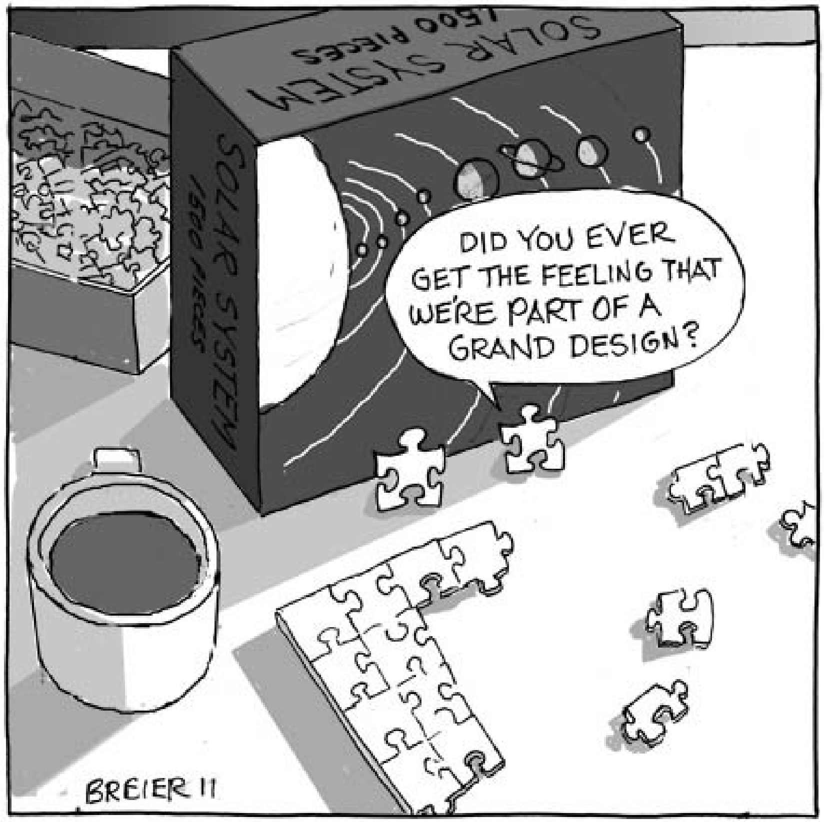
$$\boxed{\tilde{D}^{\mu\nu}(q) = \frac{-g^{\mu\nu}}{q^2+i\epsilon} \qquad \epsilon > 0}$$ (photon propagator)

Green's function in *Fourier* space (fast forward)

- The *Green*'s function can again be obtained from the inverse *Fourier* transform.

$$D^{\mu\nu}(x-x') = (2\pi)^{-4} \int \mathrm{d}^4 q \frac{-g^{\mu\nu}}{q^2+i\epsilon} e^{-iq(x-x')}$$

- We have now collected all pieces of the puzzle to complete the cross section calculation.

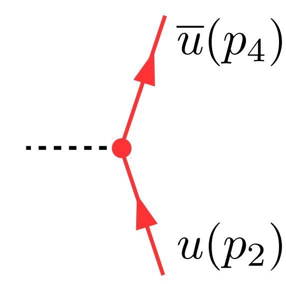


On the way to completion...

- *Ansatz* for target current:

$$\overline{\psi}_f(x'') = \overline{u}(p_4)e^{ip_4x''} \quad \psi_i(x'') = u(p_2)e^{-ip_2x''}$$

$$eJ^\nu(x'') = e\cdot\overline{\psi}_f(x'')\gamma^\nu\psi_i(x'') = e\cdot\overline{u}(p_4)\gamma^\nu u(p_2)e^{i(p_4-p_2)x''}$$



target

- Combination with photon propagator to get the evolution of A_μ:

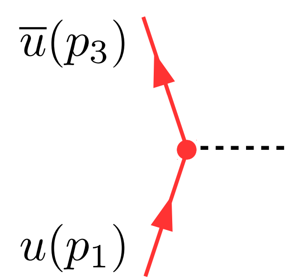
$$A_\mu(x') = e\int \mathrm{d}^4x'' D^{\mu\nu}(x'-x'')J^\nu(x'')$$

$$= e\cdot\int \mathrm{d}^4x''(2\pi)^{-4}\int \mathrm{d}^4q\, \frac{-g_{\mu\nu}}{q^2+i\epsilon}e^{i(p_4-p_2+q)x''}e^{-iqx'}\overline{u}(p_4)\gamma^\nu u(p_2)$$

$$= e\cdot\int \mathrm{d}^4q\frac{-g_{\mu\nu}}{q^2+i\epsilon}\delta^4(p_4-p_2+q)e^{-iqx'}\overline{u}(p_4)\gamma^\nu u(p_2)$$

- *Ansatz* for projectile current:

$$\overline{\phi}_f(x') = \overline{u}(p_3)e^{ip_3x'} \qquad \phi_i(x') = u(p_1)e^{-ip_1x'}$$

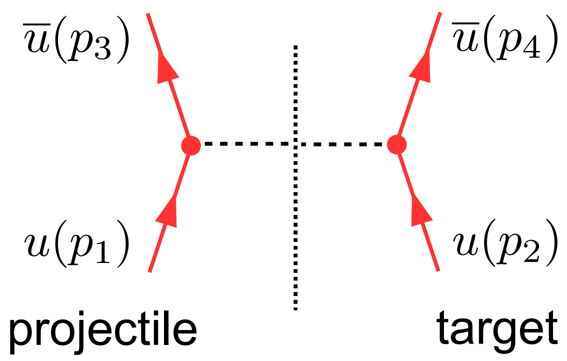


projectile

On the way to completion...

- 1st order matrix element:

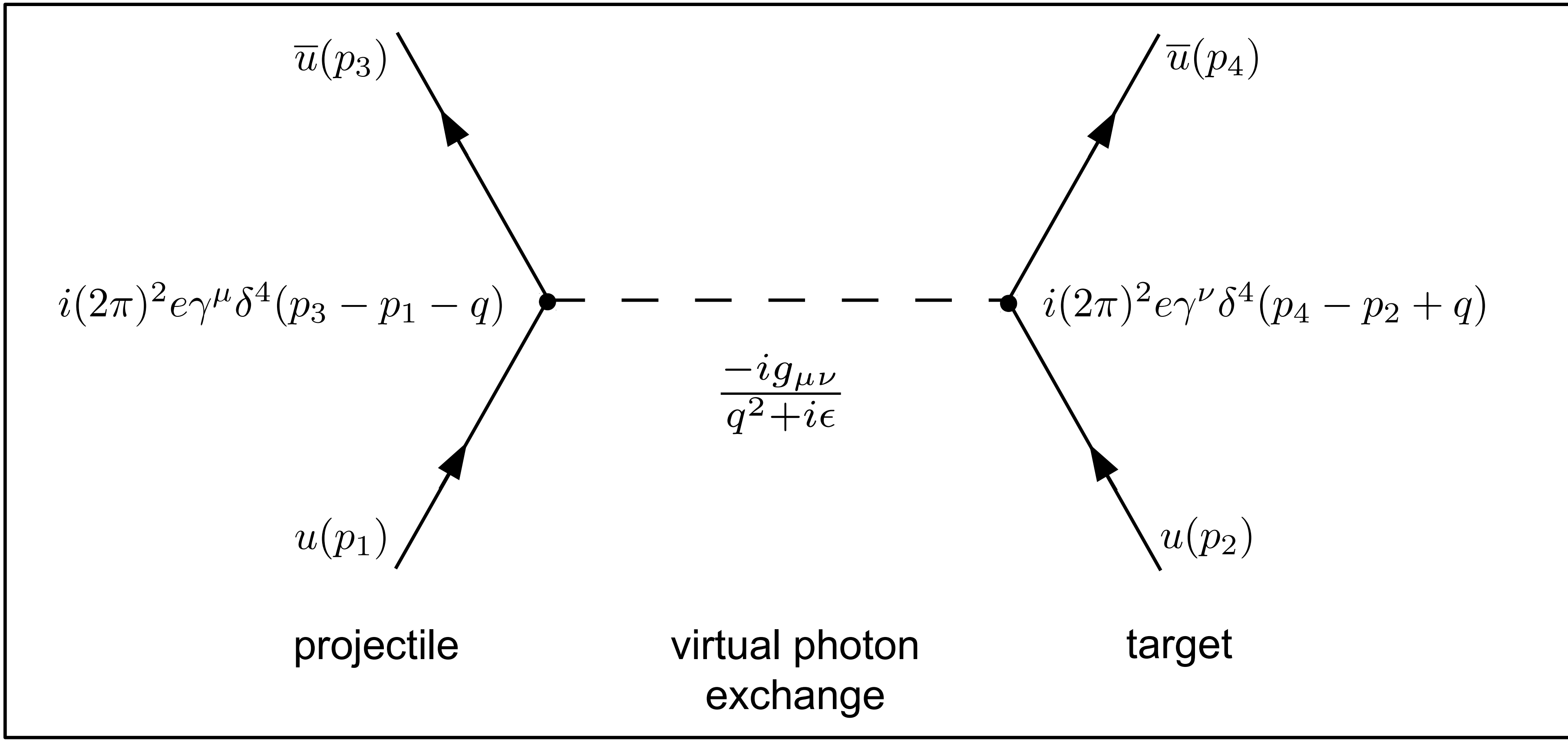
$$\boxed{\begin{aligned} \mathcal{S}_{fi}^{(1)} &= i \cdot \int \mathrm{d}^4x' e\, \overline{\phi}_f(x')\gamma^\mu A_\mu(x')\phi_i(x') \\ \overline{\phi}_f(x') &= \overline{u}(p_3)e^{ip_3x'} \\ \phi_i(x') &= u(p_1)e^{-ip_1x'} \\ A_\mu(x') &= e \cdot \int \mathrm{d}^4q \tfrac{-g_{\mu\nu}}{q^2+i\epsilon}\delta^4(p_4-p_2+q)e^{-iqx'}u(p_4)\gamma^\nu u(p_2) \end{aligned}}$$



$$\mathcal{S}_{fi}^{(1)} = ie^2 \cdot \int \mathrm{d}^4q \underbrace{\int \mathrm{d}^4x'\; e^{i(p_3-p_1-q)x'}}_{(2\pi)^4\delta^4(p_3-p_1-q)} \overline{u}(p_3)\gamma^\mu u(p_1)\frac{-g_{\mu\nu}}{q^2+i\epsilon}\delta^4(p_4-p_2+q)\overline{u}(p_4)\gamma^\nu u(p_2)$$

$$= i\left((2\pi)^2 e\right)^2 \cdot \int \mathrm{d}^4q\; \delta^4(p_3-p_1-q)\overline{u}(p_3)\gamma^\mu u(p_1)\frac{-g_{\mu\nu}}{q^2+i\epsilon}\delta^4(p_4-p_2+q)\overline{u}(p_4)\gamma^\nu u(p_2)$$

The matrix element $\mathcal{S}_{fi}$ (complete picture)



$$\mathcal{S}_{fi}^{(1)} = i\left((2\pi)^2 e\right)^2 \cdot \int \mathrm{d}^4 q \; \delta^4(p_3 - p_1 - q)\overline{u}(p_3)\gamma^\mu u(p_1)\frac{-g_{\mu\nu}}{q^2 + i\epsilon}\delta^4(p_4 - p_2 + q)\overline{u}(p_4)\gamma^\nu u(p_2)$$

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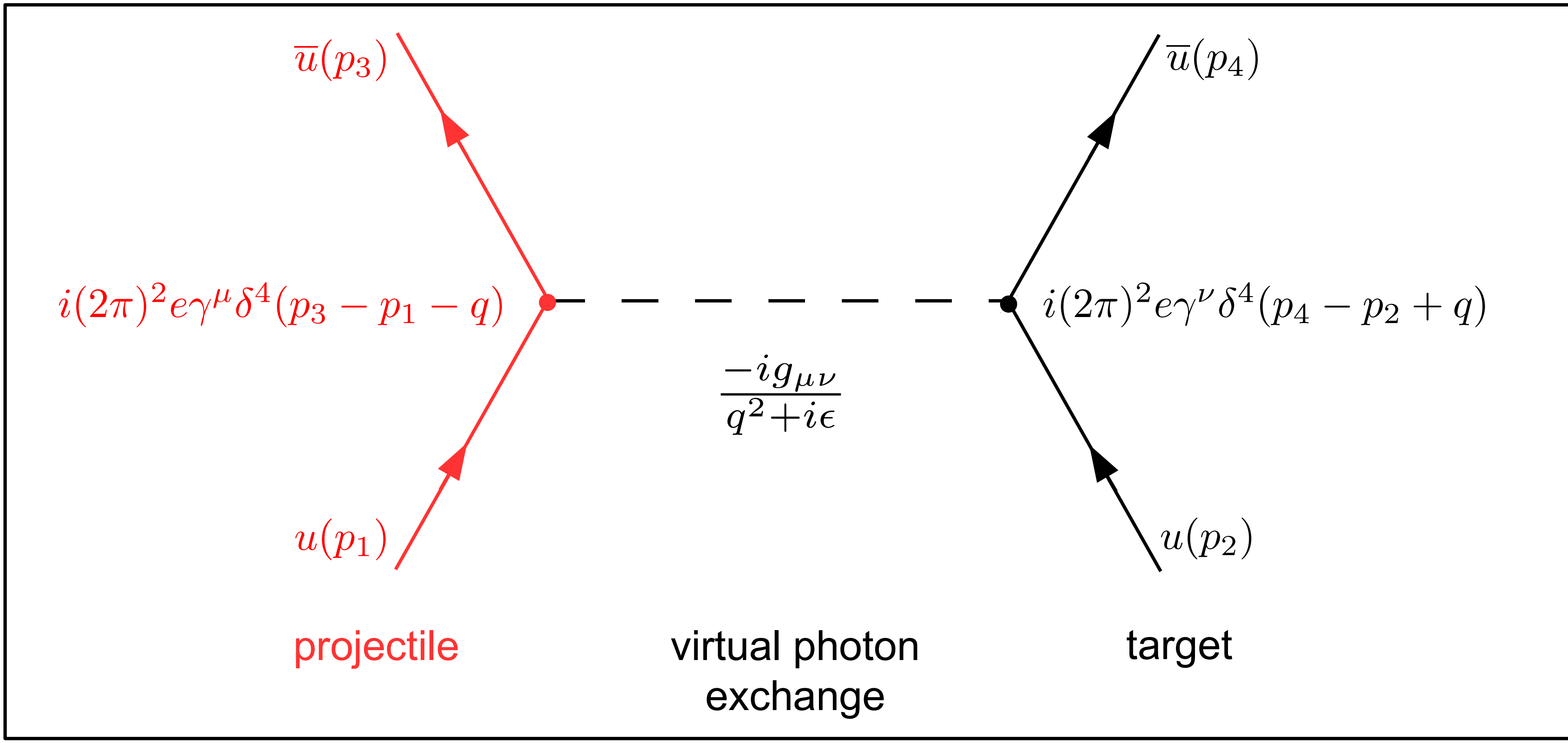

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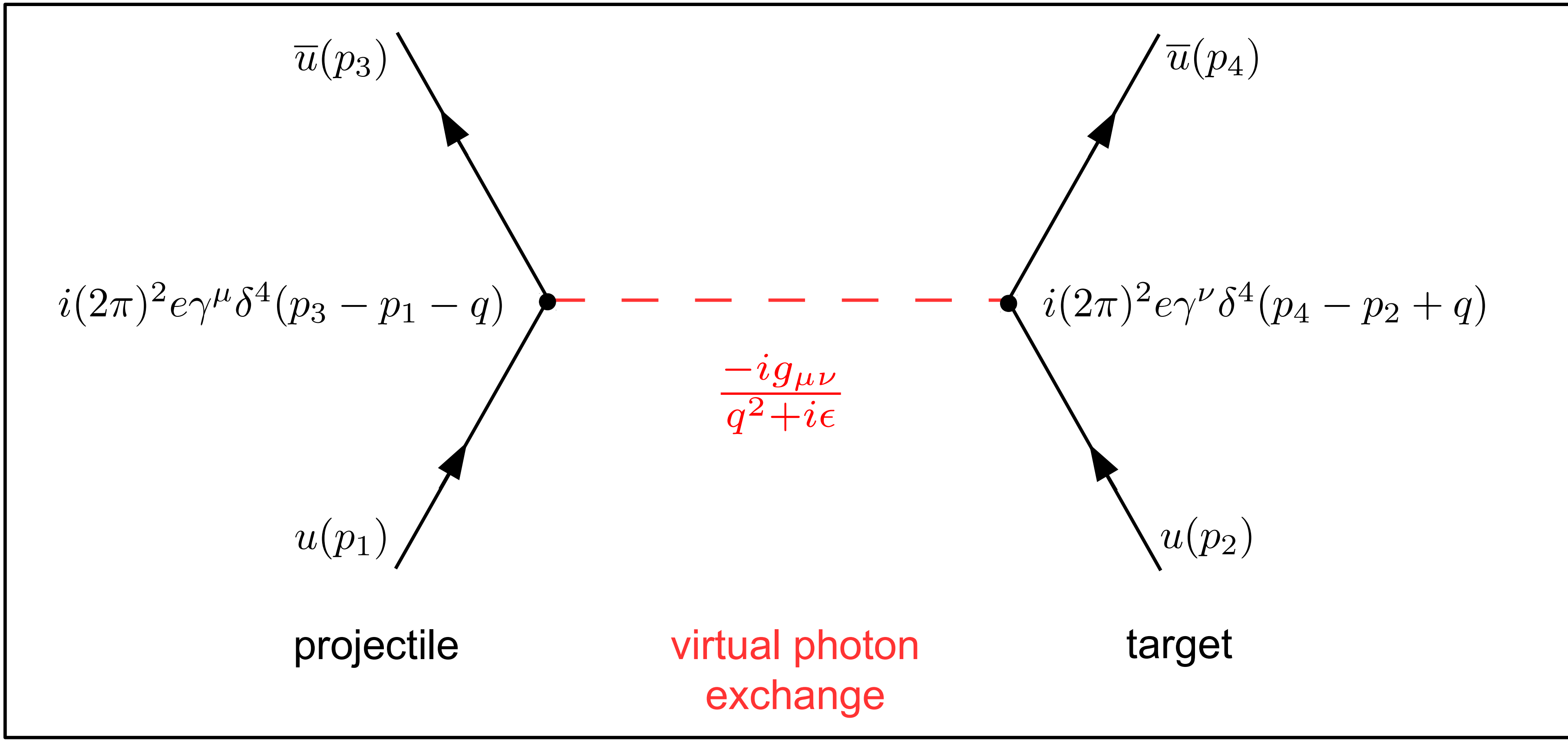

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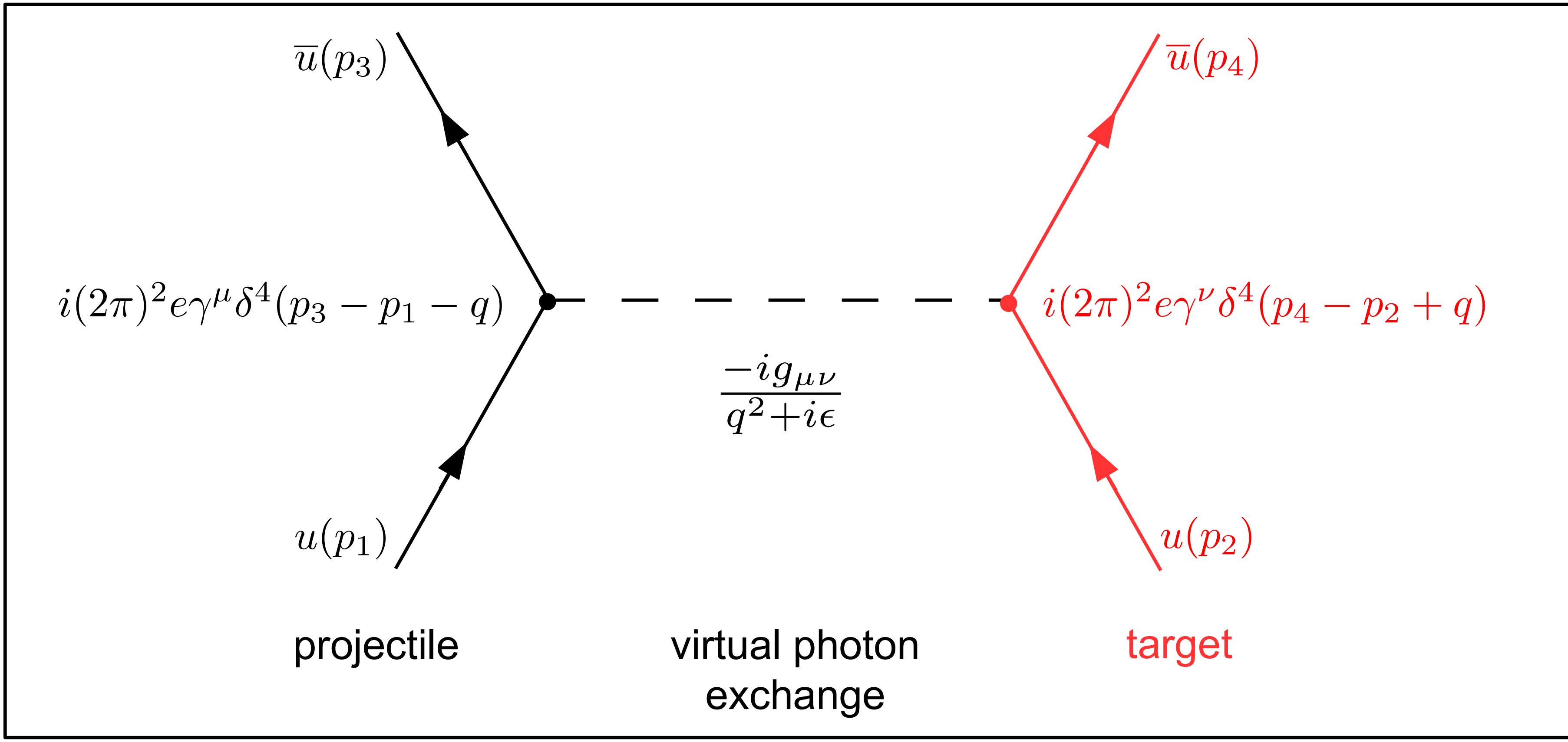

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Feynman Rules (QED)

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- *Feynman* diagrams are a way to represent the elements of the matrix element calculation:

Legs:		
$u(p) \quad (\overline{u}(p))$		• Incoming (outgoing) fermion.
$\epsilon_\mu(k) \quad (\epsilon^*_\mu(k))$		• Incoming (outgoing) photon.
Vertices:		
$i(2\pi)^2 e\gamma^\mu \cdot \delta^4(p_f - p_i - q)$		• Lepton-photon vertex.
Propagators:		
$\frac{i(\gamma^\mu p_\mu + m)}{p^2 - m^2 + i\epsilon}$		• Fermion propagator.
$\frac{-ig^{\mu\nu}}{q^2 + i\epsilon}$		• Photon propagator.
Four-momenta of all virtual particles have to be integrated out.		

Feynman Rules (QED)

- *Feynman* diagrams are a way to represent the elements of the matrix element calculation:

- A *Feynman* diagram:
  - is not just a sketch, it has a strict mathematical correspondence.
  - is drawn in momentum space.
  - does not have a time direction. Only time information is introduced by choice of initial and final state by reader (e.g. t-channel vs s-channel processes).

Higher order

Fixed order calculations

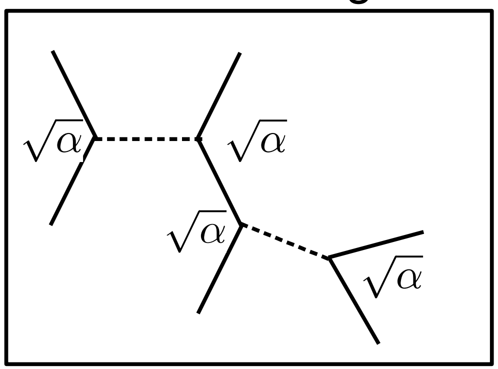
- Scattering amplitude $\mathcal{S}_{fi}$ only known in perturbation theory.
- Works better the smaller the perturbation is:
  - QED: $\alpha \approx \frac{1}{137}$
  - QFD: $\alpha_{\mathrm{w}} = \frac{\alpha}{\sin^2(\theta_W)} \approx 4 \cdot \alpha_{\mathrm{em}}$ $\quad$ $\text{with}\, \theta_W = 28.74°$
  - QCD: $\alpha_s(m_Z) \approx 0.12$
- If perturbation theory works well, the first contribution of the scattering amplitude is already sufficient to describe the main features of the scattering process.
- This contribution is of order "α". It is often called *Tree Level*, *Born Level* or *Leading Order* (LO) scattering amplitude.
- Any higher order of the scattering amplitude in perturbation theory appears at higher orders of "α".

Order α^2 diagrams (QED)

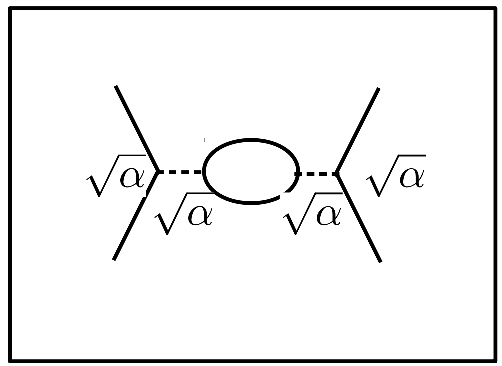
- We have only discussed contributions to $\mathcal{S}_{fi}$, which are of order α^1 in QED. (e.g. LO $ee \to ee$ scattering) .

- Diagrams which contribute to order α^2 would look like this:

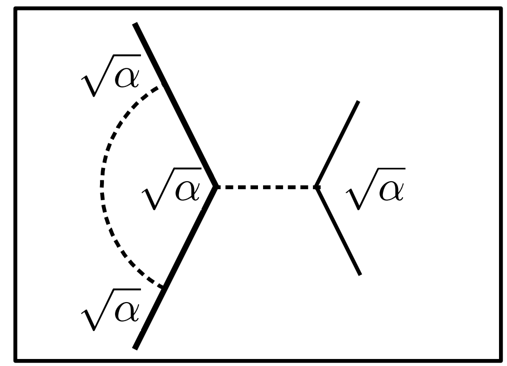
Additional legs:



Loops:



(in propagators or legs)



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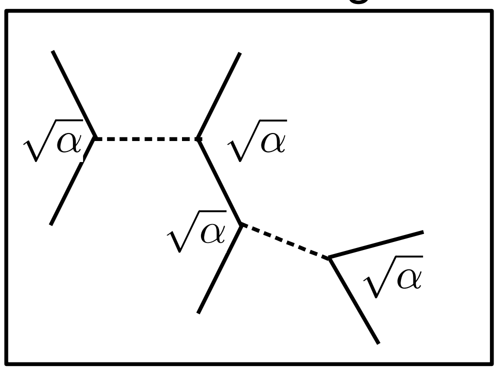

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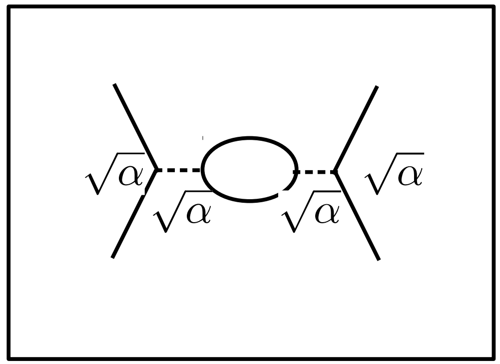

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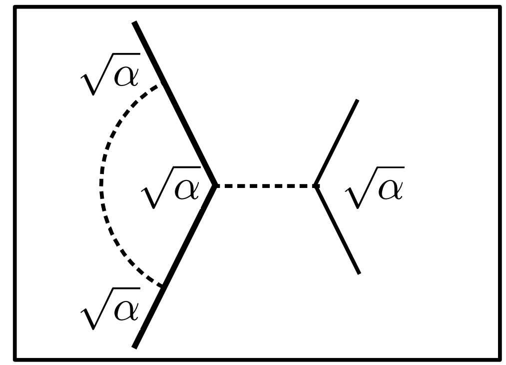

(in vertices)

- LO term for a $2 \to 4$ process.
- NLO contrib. for the $2 \to 2$ process.
- Opens phasespace.

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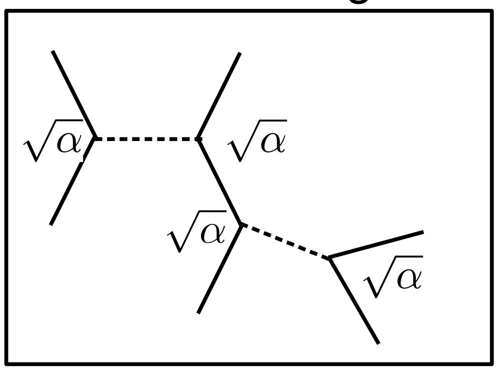

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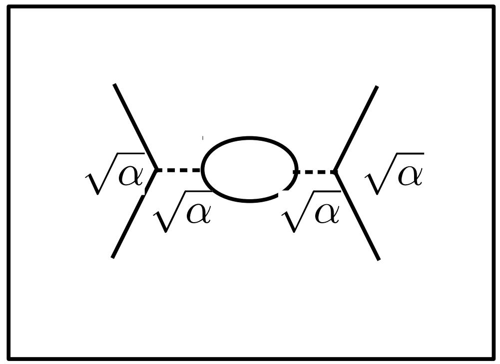

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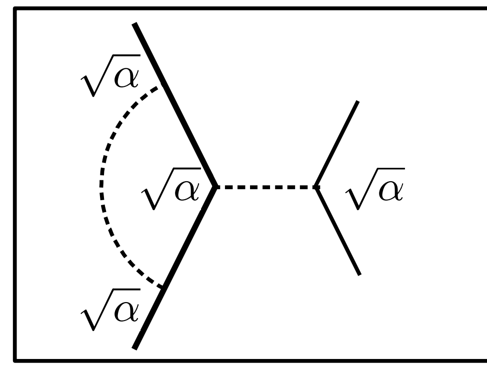

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- Modifies (effective) masses of particles ("running masses").

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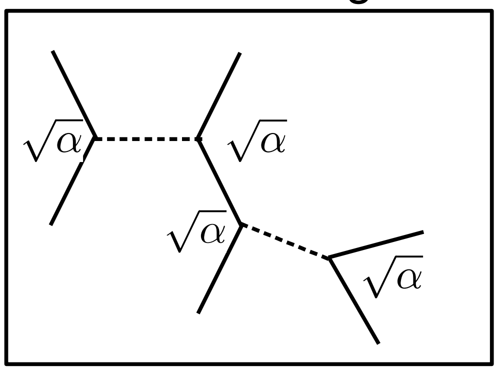

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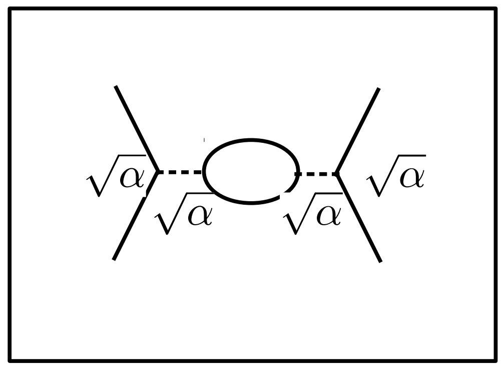

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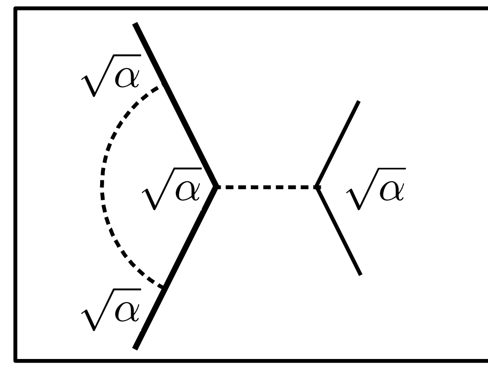

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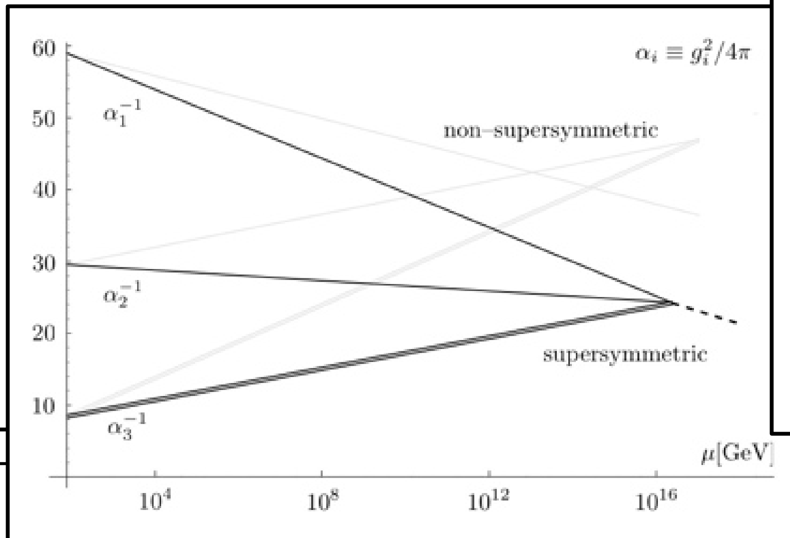
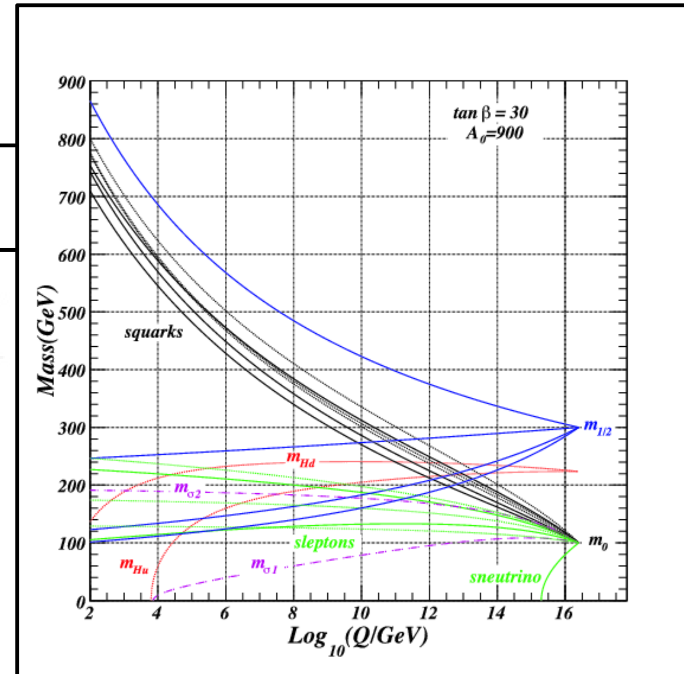
- LO term for a $2 \rightarrow 4$ process.
- NLO contrib. for the $2 \rightarrow 2$ process.
- Opens phasespace.

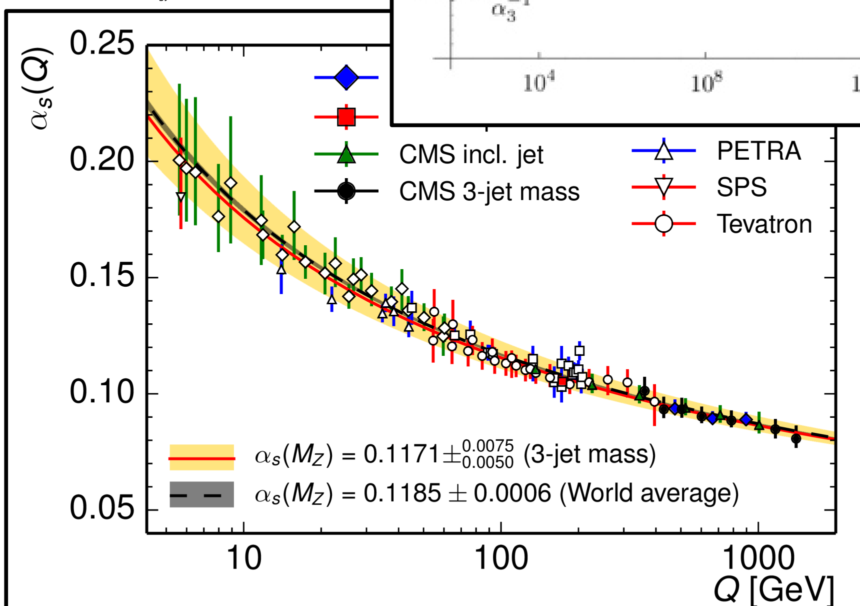
- Modifies (effective) masses of particles ("running masses").

- Modifies (effective) couplings of particles ("running couplings").

Examples for “running constants”







- Running of the constants can be predicted and are indeed observed.
- Coupling needs to be measured at least in one point.
- One usually gives the value at a reference scale (e.g. m_Z).

Effect of higher order corrections

- Change of over all normalization of cross sections (e.g. via change of coupling, but also by kinematic opening of phasespace – large effect).

- Change of kinematic distributions (e.g. harder or softer transverse momentum spectrum of particles)

Effect of higher order corrections

- Change of over all normalization of cross sections (e.g. via change of coupling, but also by kinematic opening of phasespace – large effect).

- Change of kinematic distributions (e.g. harder or softer transverse momentum spectrum of particles)

- In QED effects are usually "small" (correction to LO is already at $\mathcal{O}(1\%)$ level). In QCD effects are usually "large" ($\mathcal{O}(10\%)$). Therefore reliable QCD predictions almost always require (N)NLO calculations.

- Higher orders can be mixed (e.g. $\mathcal{O}(\alpha\alpha_s^2)$).

- In concrete calculations the number of contributing diagrams quickly explodes for higher order calculations, which makes these calculations very difficult.

Boundaries on Higgs mass within the SM

Running of λ in the Higgs potential

- Like the couplings α , α_w and α_s also the self-coupling λ in the Higgs potential is subject to higher order corrections:

$$\mathcal{L}^\mathrm{Higgs} = \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi)$$

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2$$

(Higgs potential)

$$\boxed{\frac{\mathrm{d}\lambda}{\mathrm{d}\log Q^2} = \frac{1}{16\pi^2}\left[\underbrace{12\lambda^2}_{\text{Higgs}} + \underbrace{6\lambda y_t^2 - 3y_t^4}_{\textit{top}\text{ quark}} - \frac{3}{2}\lambda\left(3\alpha^2 + \alpha_\mathrm{w}^2\right) + \ldots\right]}$$

(Renormalization group equation at 1-loop accuracy)

- Since the Higgs boson couples proportional to the mass the high energy behavior of λ will be dominated by the heaviest object in the loop.

Running of λ in the Higgs potential

- First case: large Higgs mass ($m_H \gg Q^2$).

$$\boxed{\frac{\mathrm{d}\lambda}{\mathrm{d}\log Q^2} = \frac{1}{16\pi^2}\left[\underbrace{12\lambda^2}_{\text{Higgs}} + \underbrace{6\lambda y_t^2 - 3y_t^4}_{\textit{top}\text{ quark}} - \frac{3}{2}\lambda\left(3\alpha^2 + \alpha_\mathrm{w}^2\right) + \ldots\right]}$$

$$\Big\downarrow {\scriptstyle m_H \gg Q^2}$$

$$\boxed{\frac{\mathrm{d}\lambda}{\mathrm{d}\log Q^2} = \frac{3}{4\pi^2}\lambda^2(Q^2)} \xrightarrow{\text{solution}} \lambda(Q^2) = \frac{\lambda(v^2)}{1 - \frac{3}{4\pi^2}\lambda(v^2)\log\left(Q^2/v^2\right)}$$

- For $Q^2 \ll v^2 = 246\,\mathrm{GeV}$ we get $\log\left(Q^2/v^2\right) \to -\infty$ and $\lambda(Q^2) \to 0$.

- For increasing Q^2 $\lambda(Q^2)$ will run into a pole and become non-perturbative. This pole is called *Landau* pole. From the pole an upper bound on m_H can be obtained depending on the scale Q.

Triviality bound

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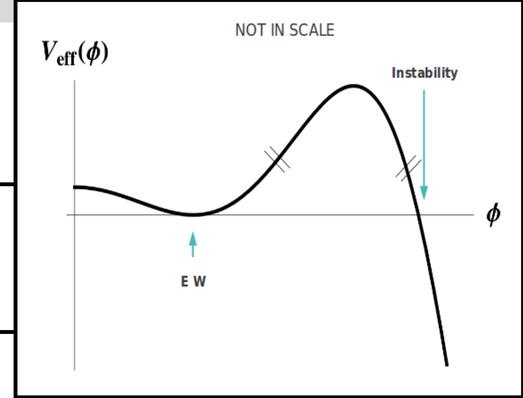
- The upper bound on m_H due to the *Landau* pole is called *triviality bound*:

$$m_H\left(Q = 10^{3}\,\mathrm{GeV}\right) \leq 1.6\,\mathrm{TeV}$$
$$m_H\left(Q = 10^{16}\,\mathrm{GeV}\right) \leq 340\,\mathrm{GeV}$$

(triviality bound)

- NB: here Q indicates up to which scale the SM should be applicable.

The Running of λ in the Higgs Potential



Higgs potential w/ running λ .

- Second case: small Higgs mass ($m_H \ll m_t$)

$$\boxed{\frac{\mathrm{d}\lambda}{\mathrm{d}\log Q^2} = \frac{1}{16\pi^2}\left[\underbrace{12\lambda^2}_{\text{Higgs}} + \underbrace{6\lambda y_t^2 - 3y_t^4}_{\textit{top}\text{ quark}} - \frac{3}{2}\lambda\left(3\alpha^2 + \alpha_{\mathrm{w}}^2\right) + \ldots\right]}$$

$$\Big\downarrow m_H \ll m_t$$

$$\boxed{\frac{\mathrm{d}\lambda}{\mathrm{d}\log Q^2} = -\frac{3}{16\pi^2}y_t^4} \xrightarrow{\text{solution}} \lambda(Q^2) = \lambda(v^2) - \frac{3}{16\pi^2}\frac{m_t^4}{v^4}\log\left(Q^2/v^2\right)$$

(with: $y_t = {}^{m_t}/_{v}$)

- With increasing Q^2 $\lambda(Q^2)$ will turn negative and the Higgs potential will no longer be bound from below. The vacuum turns instable. From this turning point we obtain a lower bound on m_H depending on the scale Q.

Triviality bound & stability bound

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- The upper bound on m_H due to the *Landau* pole is called *triviality bound*:

$$m_H\left(Q = 10^{3}\,\mathrm{GeV}\right) \le 1.6\,\mathrm{TeV}$$
$$m_H\left(Q = 10^{16}\,\mathrm{GeV}\right) \le 340\,\mathrm{GeV}$$

(triviality bound)

- The lower bound on m_H is called *stability bound*:

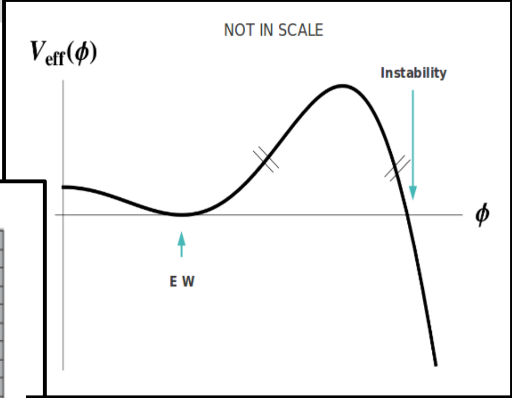
$$m_H\left(Q = 10^{3}\,\mathrm{GeV}\right) \ge 20\,\mathrm{GeV}$$
$$m_H\left(Q = 10^{16}\,\mathrm{GeV}\right) \ge 90\,\mathrm{GeV}$$

(stability bound)

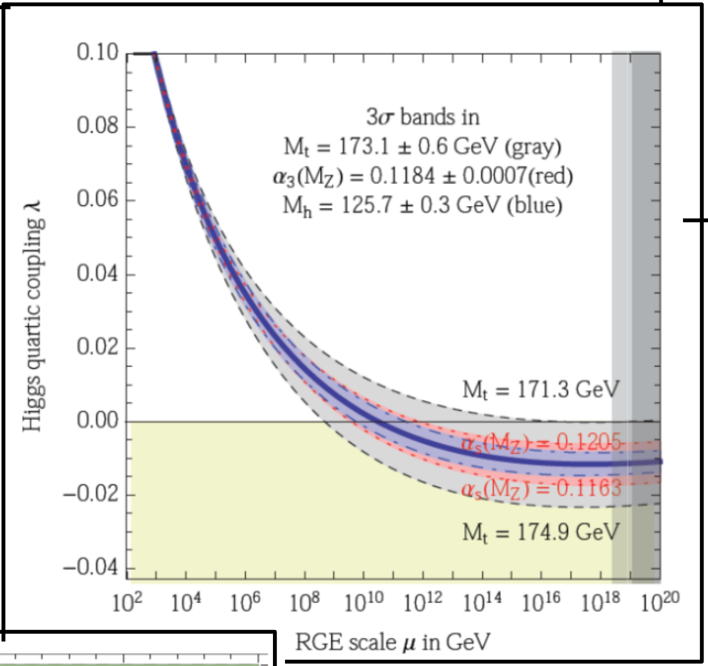
- Indeed the later search window for the SM Higgs boson was in the range of $100 < m_H < 1000\,\mathrm{GeV}$, for these and other reasons.

- NB: here Q indicates up to which scale the SM should be applicable.

Intrinsic bounds on m_H

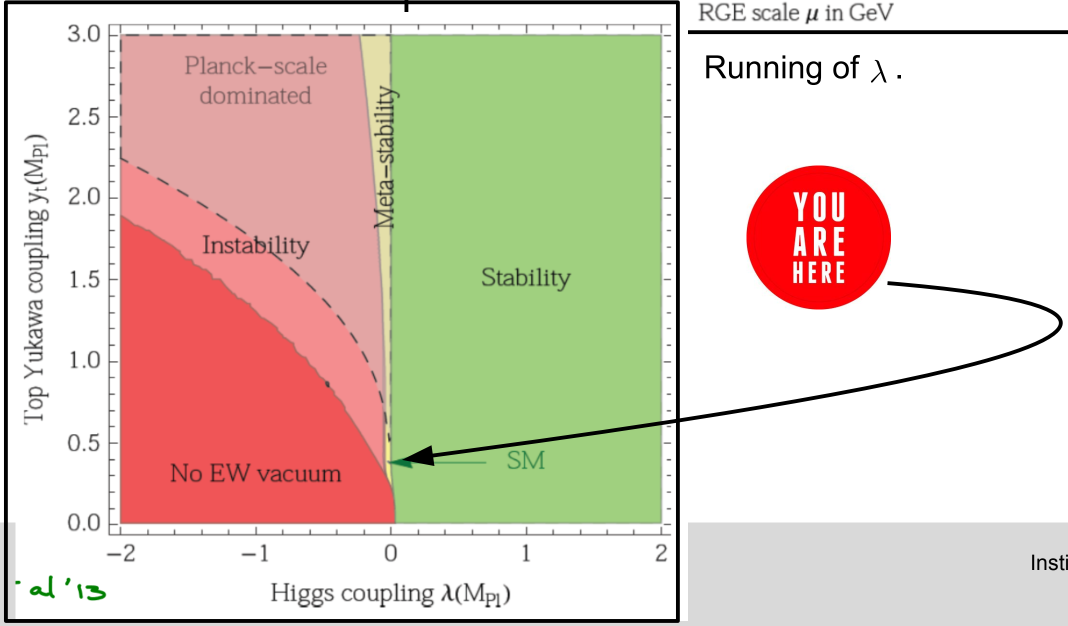


Higgs potential w/ running λ .

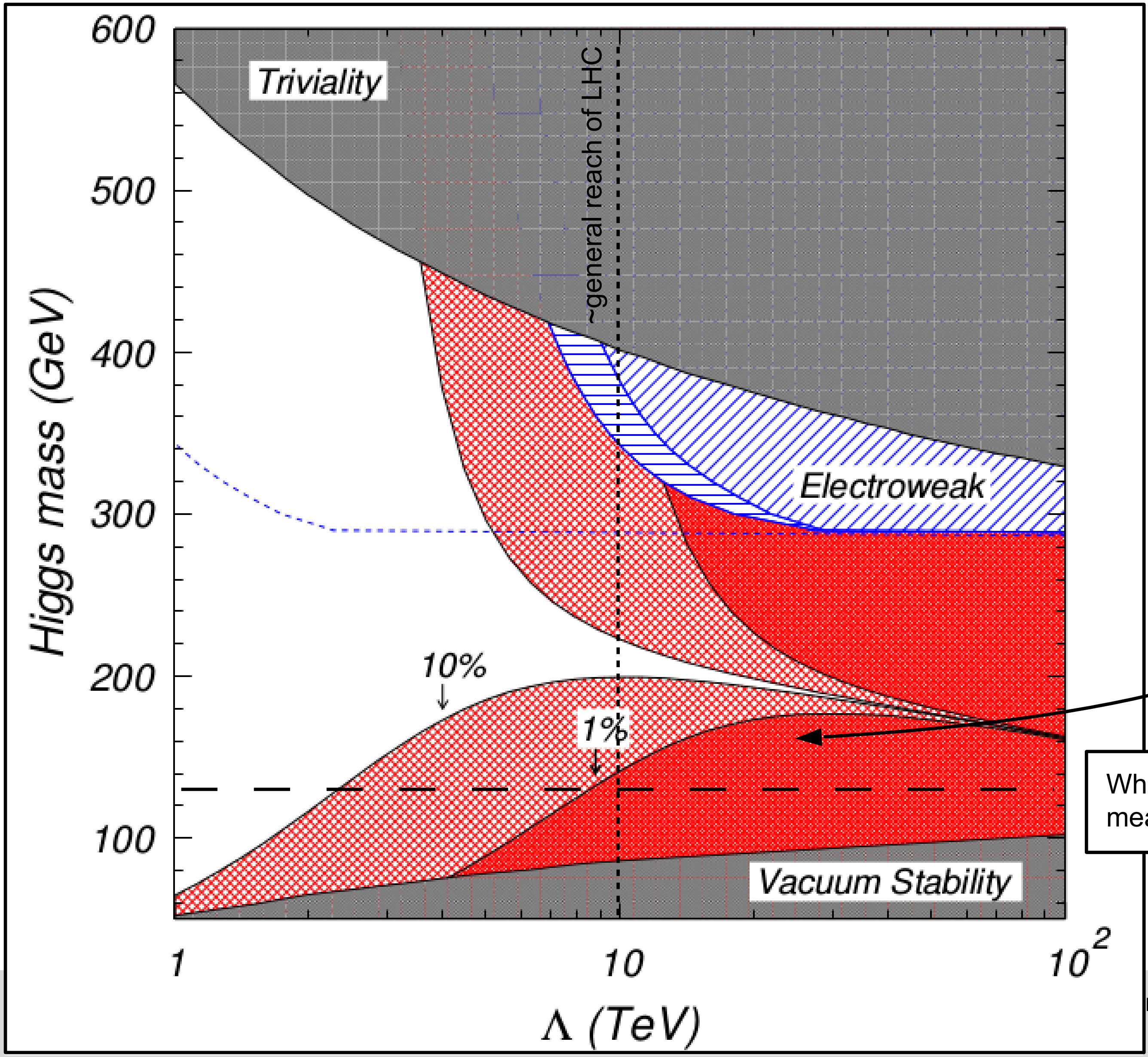


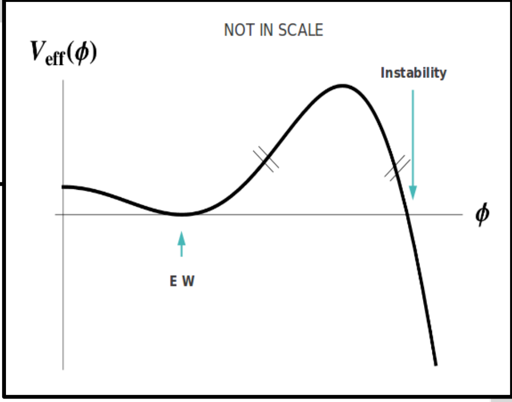
Running of λ .

The SM in the stress field of vacuum stability.



Intrinsic bounds on m_H





Higgs potential w/ running λ .

Different levels of fine tuning in the SM.

What we have found and measured for m_H.

Concluding Remarks

- Reviewed Feynman rules and calculated cross section for simple QED scattering process.
- Briefly discussed effects of higher order corrections in perturbation theory.
- Discussed boundaries on Higgs boson mass immanent to the SM as an application of higher order effects on the Higgs self-coupling.
- Note: on Thursday next week will be holiday. On Friday next week there will be an Exercise session. The week after we will start with the experimental part of the lecture.

Backup