

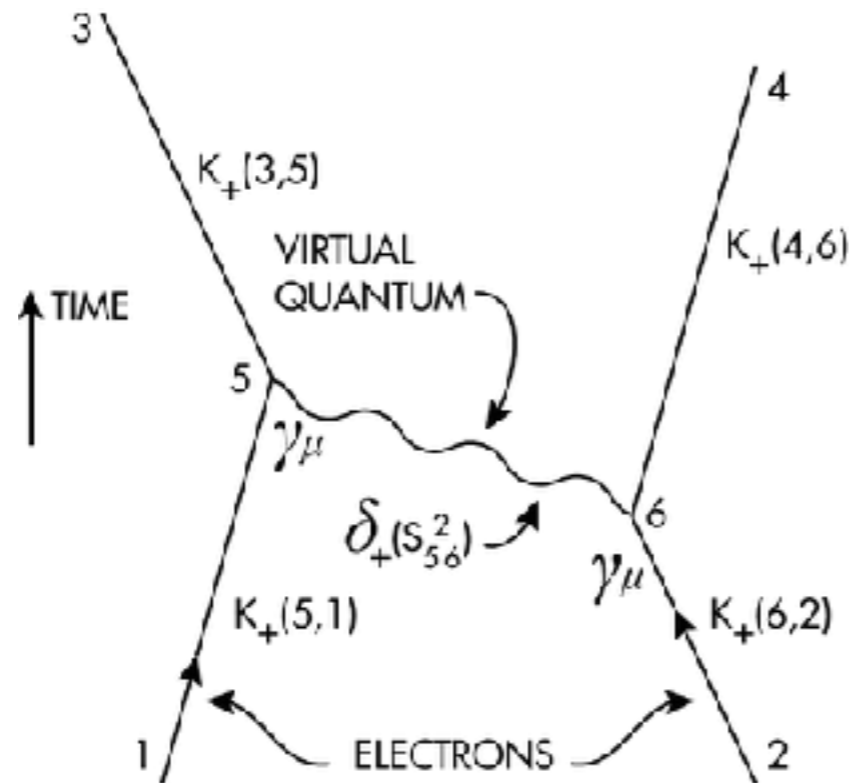
Quantenfeldtheorie

... in 90 Minuten

Robert Harlander

RWTH Aachen University

Ziele

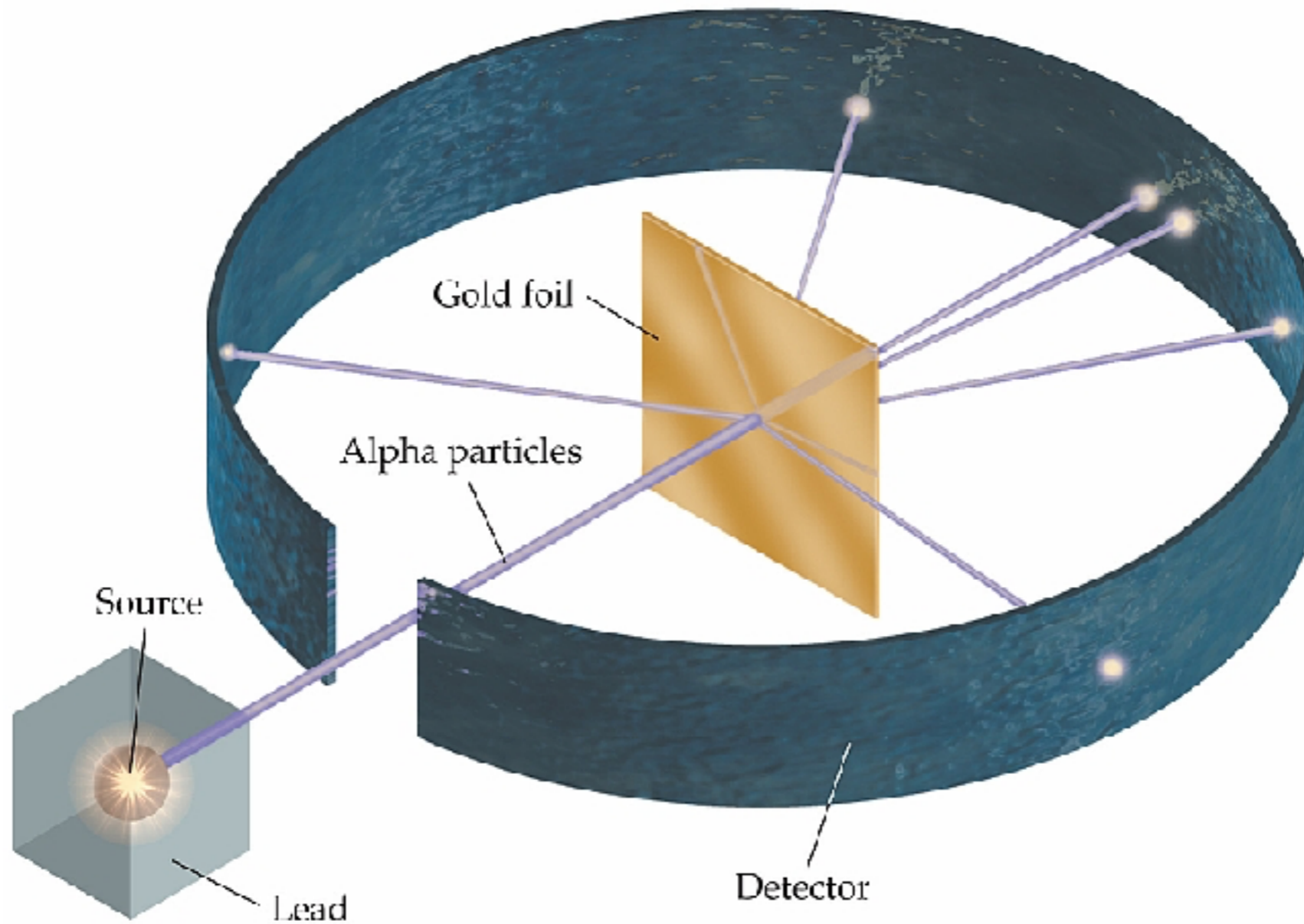


Feynman '49

- Wo kommt das her?
- Was kann man damit machen?
- Wie kann man das interpretieren?

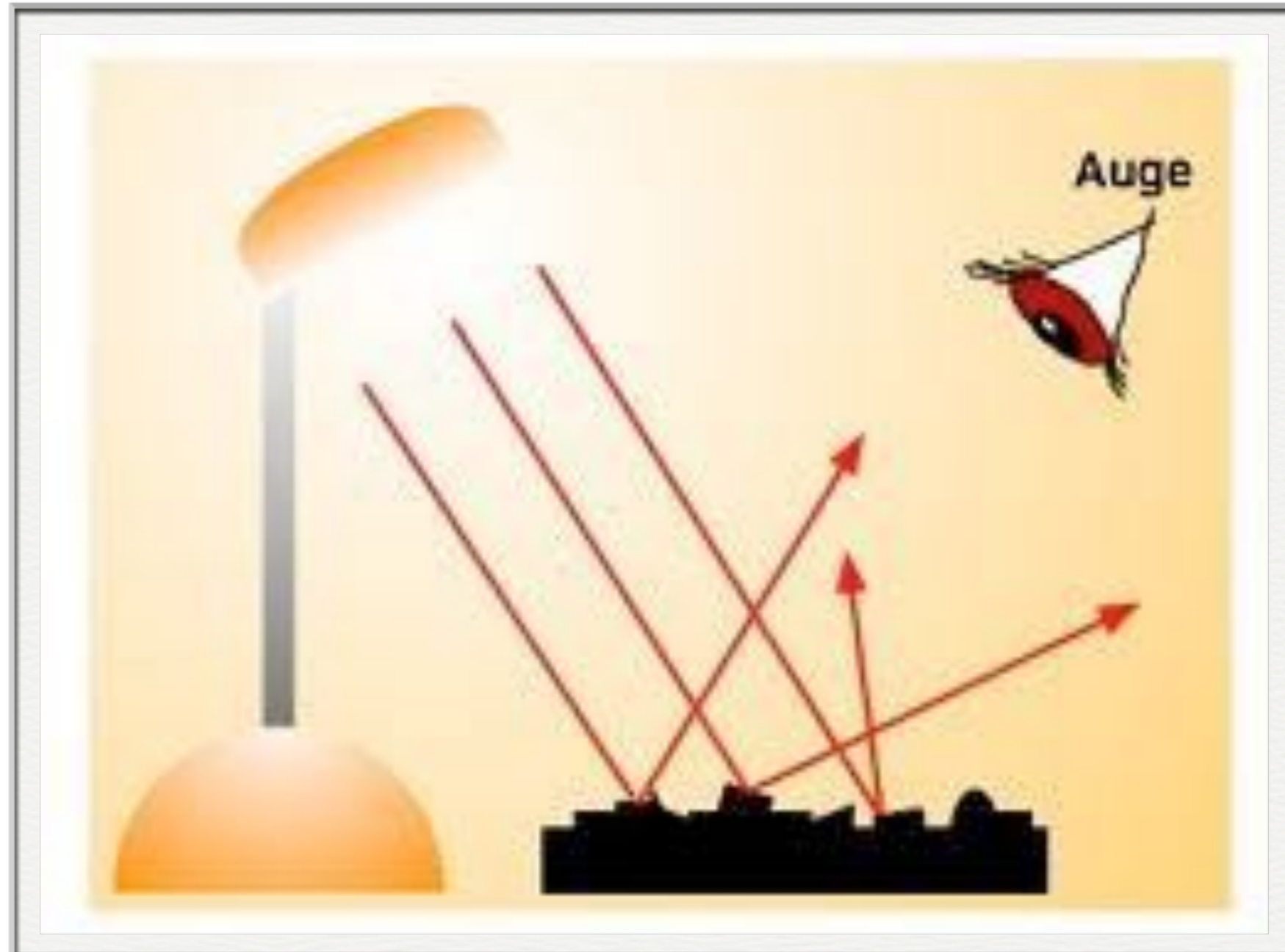
Streuexperiment

Streuexperiment



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Streuexperiment



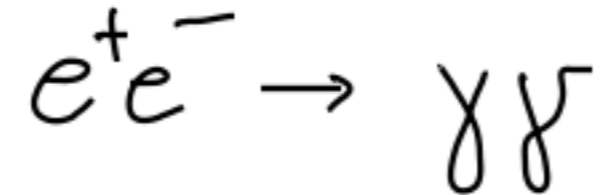
Streuexperiment

z.B. Elektron + Positron \rightarrow Photon + Photon

$$e^+e^- \rightarrow \gamma\gamma$$

Streuexperiment

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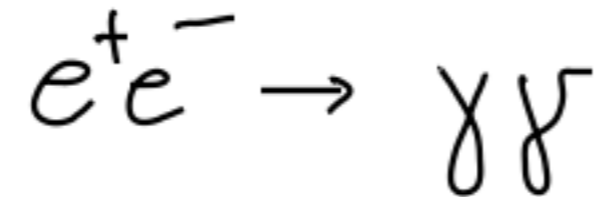


Streuexperiment:

- Wahrscheinlichkeit?
- Photon in Richtung α ?
- ... ?

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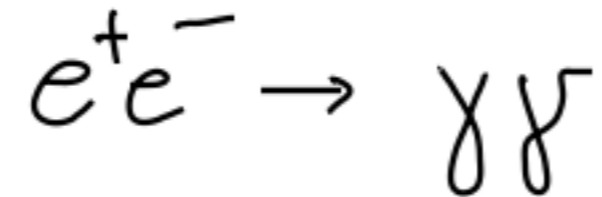
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Gegeben: Anfangszustand ($t \rightarrow -\infty$)

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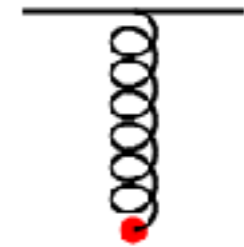
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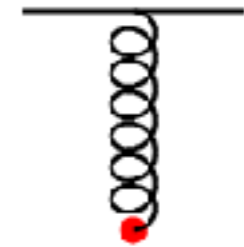
Gesucht: Wahrscheinlichkeit für Endzustand ($t \rightarrow +\infty$)

Harmonischer Oszillator



1 2 3 4 5 6 7 8 9 10 11 12

Harmonischer Oszillator



1 2 3 4 5 6 7 8 9 10 11 12

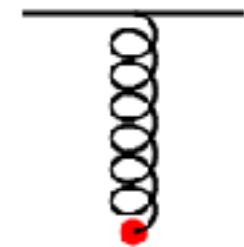
Harmonischer Oszillator

Klassische Mechanik:

$$\ddot{q}(t) + \omega^2 q(t) = 0$$

q : Auslenkung

\ddot{q} : Beschleunigung



Navigation icons: back, forward, search, etc.

Harmonischer Oszillator

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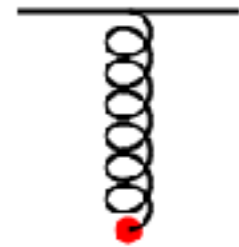
$$\ddot{q}(t) + \omega^2 q(t) = 0$$

q : Auslenkung

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$$q(t) = \tilde{A} \cos(\omega t + \phi)$$

$$E = \frac{1}{2} m \omega^2 \tilde{A}^2$$



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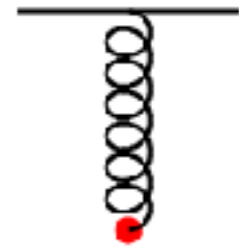
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$$q(t) = \tilde{A} \cos(\omega t + \phi)$$

$$q(t) = A' \cos(\omega t) + B' \sin(\omega t)$$

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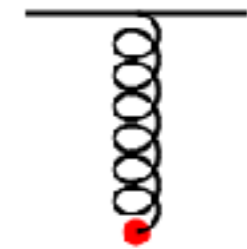
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$$q(t) = A e^{i\omega t} + B e^{-i\omega t}$$

Quantenmechanik

Harmonischer Oszillator

klassisch:

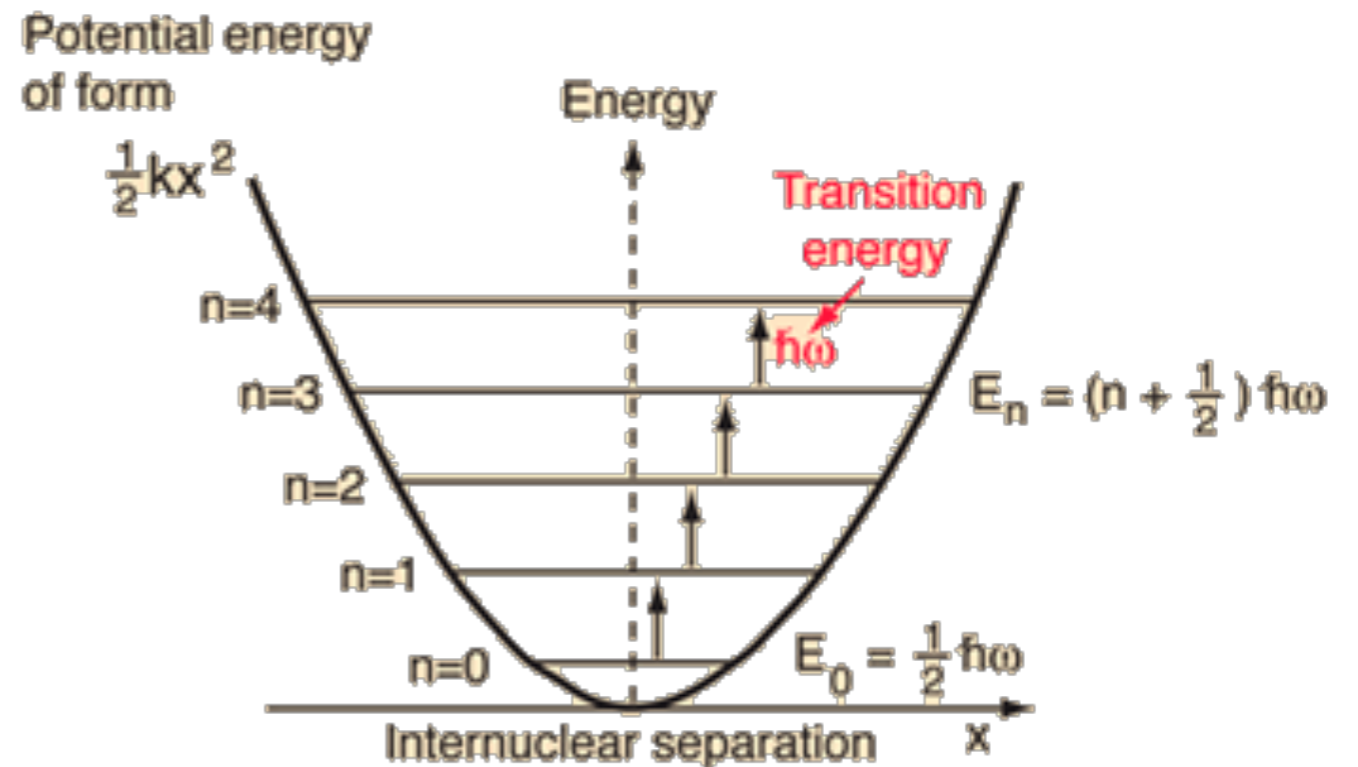
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quantenmechanisch:

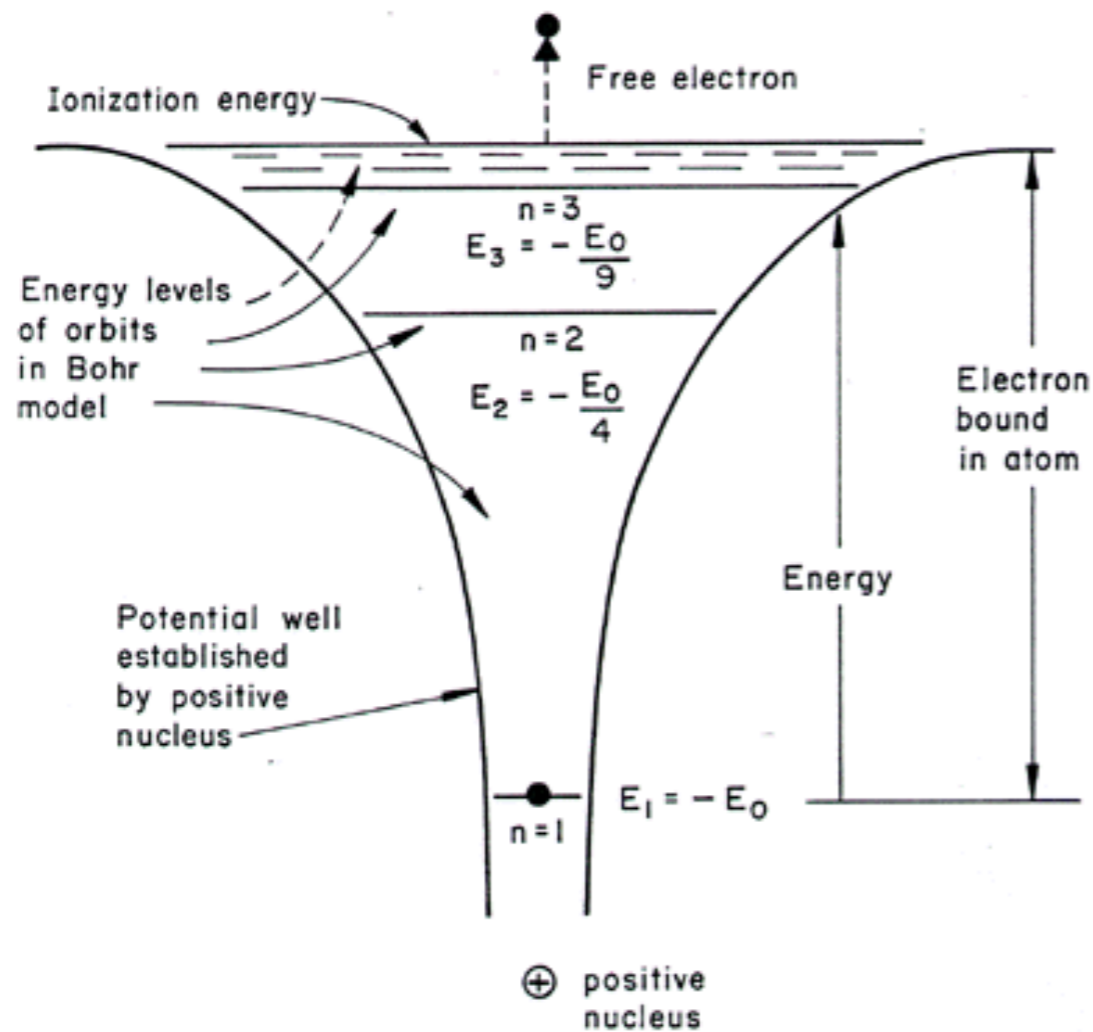
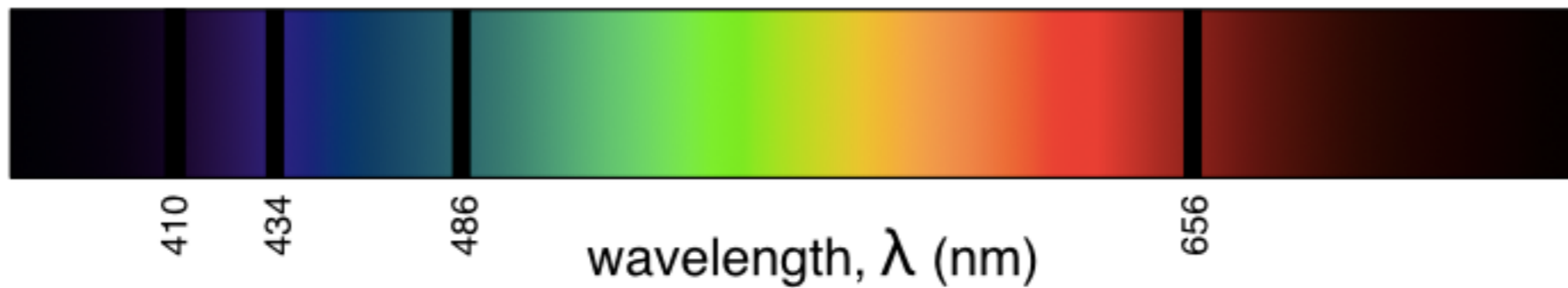
$$E_n = \hbar \omega \left(n + \frac{1}{2} \right)$$

Nullpunktsenergie: $E_0 = \frac{1}{2} \hbar \omega$

Im folgenden: $E_{\text{HO}} = E_1 - E_0 = \hbar \omega$

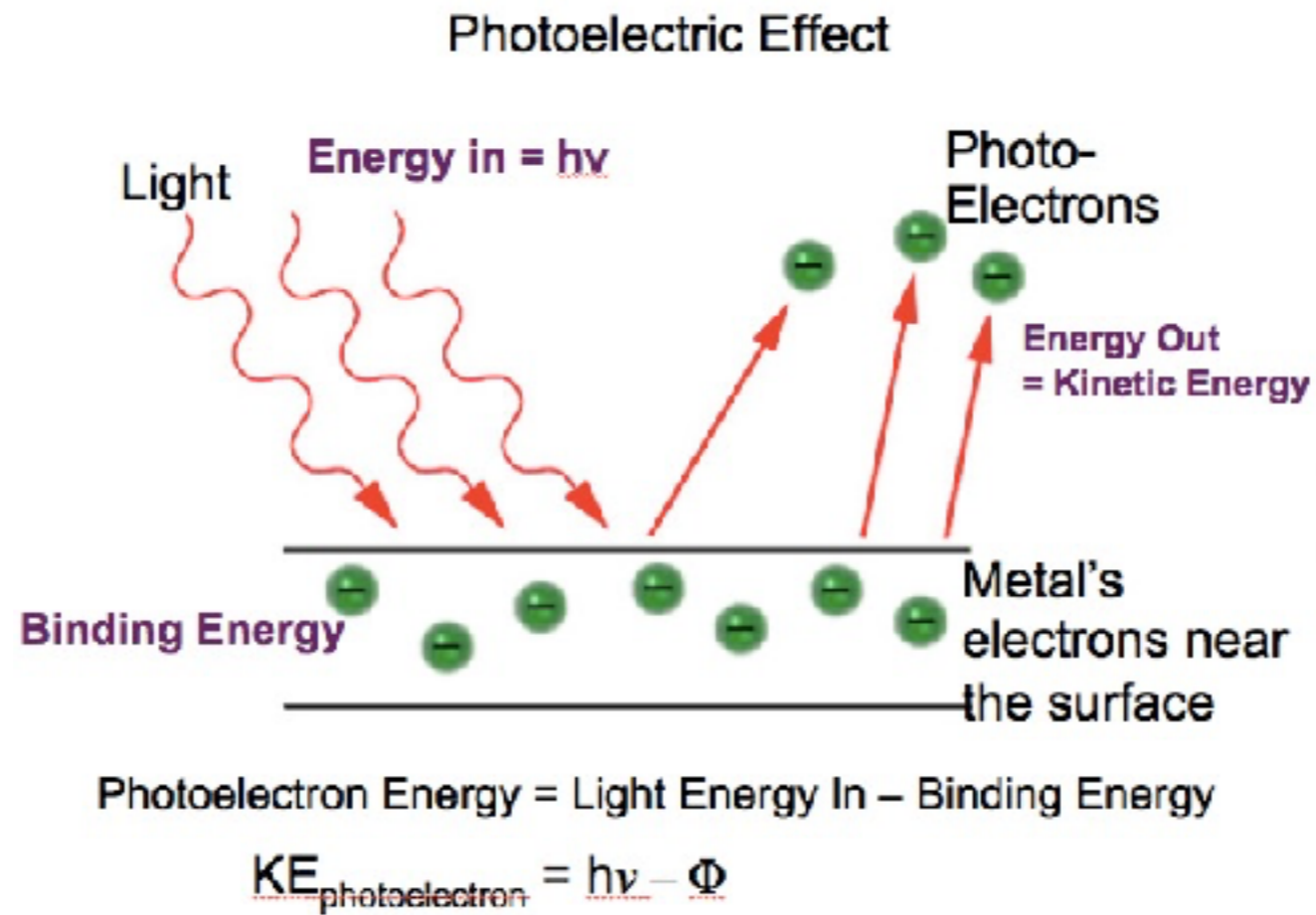


Hydrogen Absorption Spectrum



$$E_n = \frac{-13.6 \text{ eV}}{n^2}$$

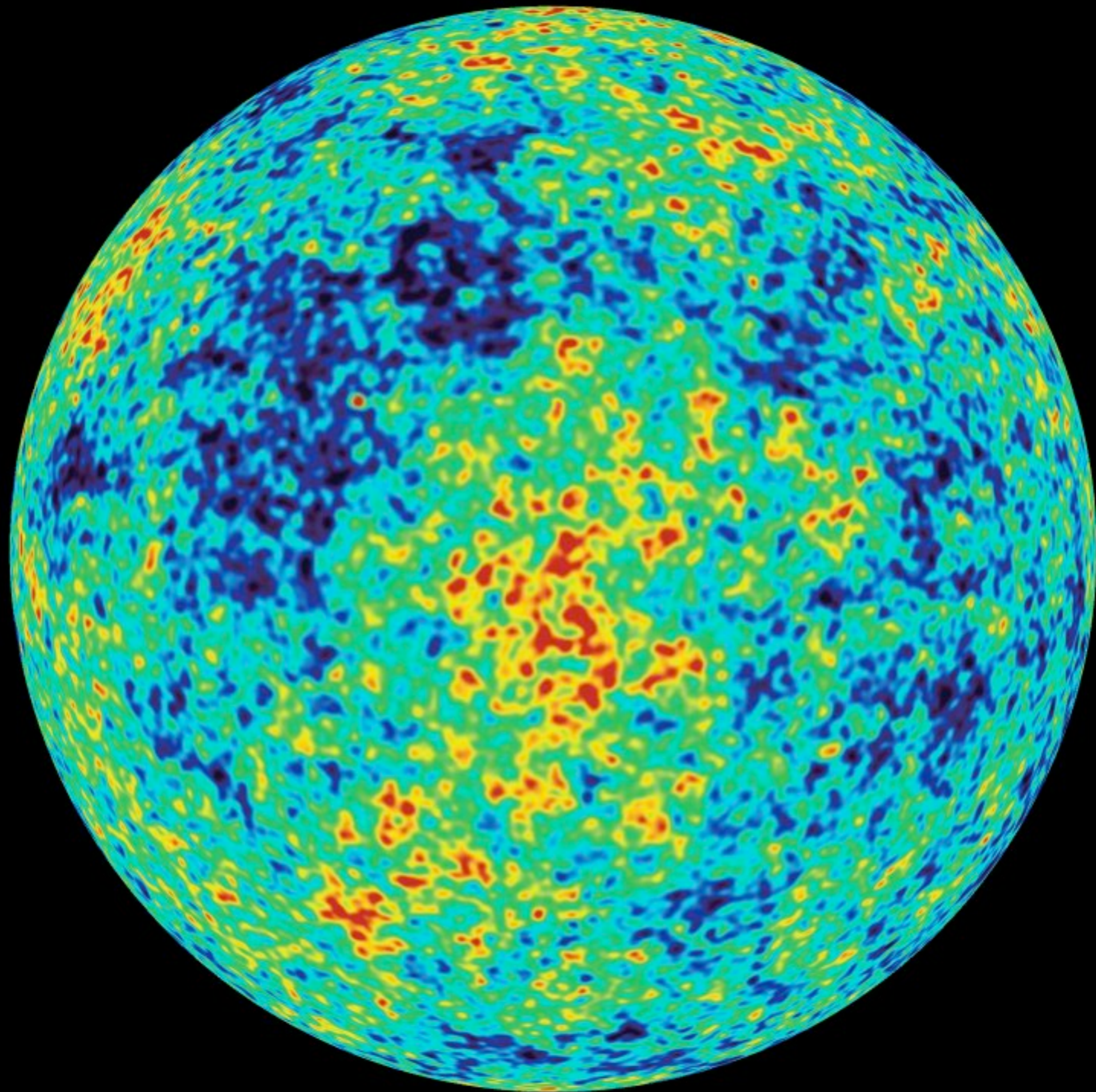
Quanten



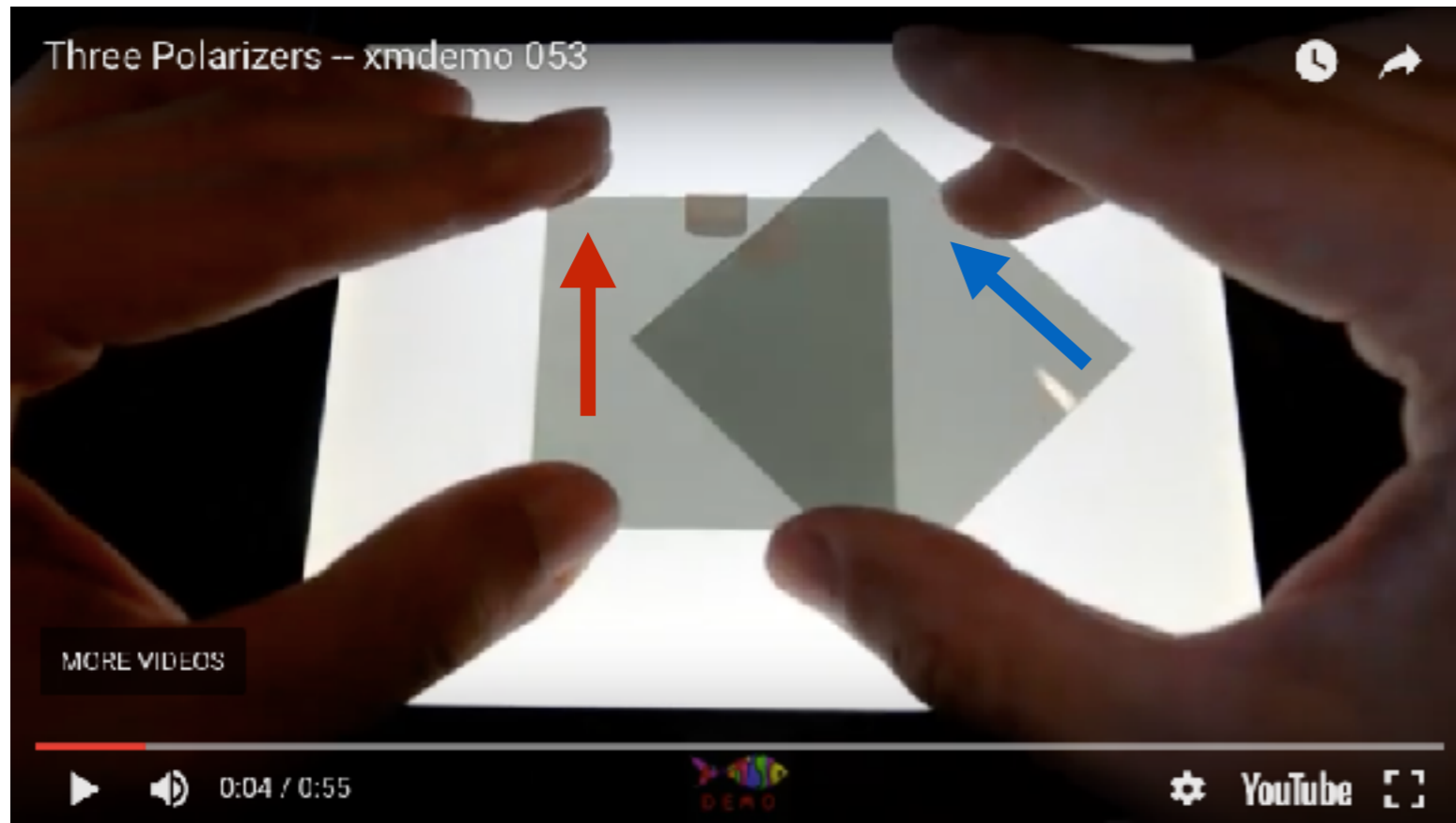
Photon: $E = h\nu$

<https://chemdemos.uoregon.edu/demos/Photoelectric-Effect-Computer-Simulation-PHET>





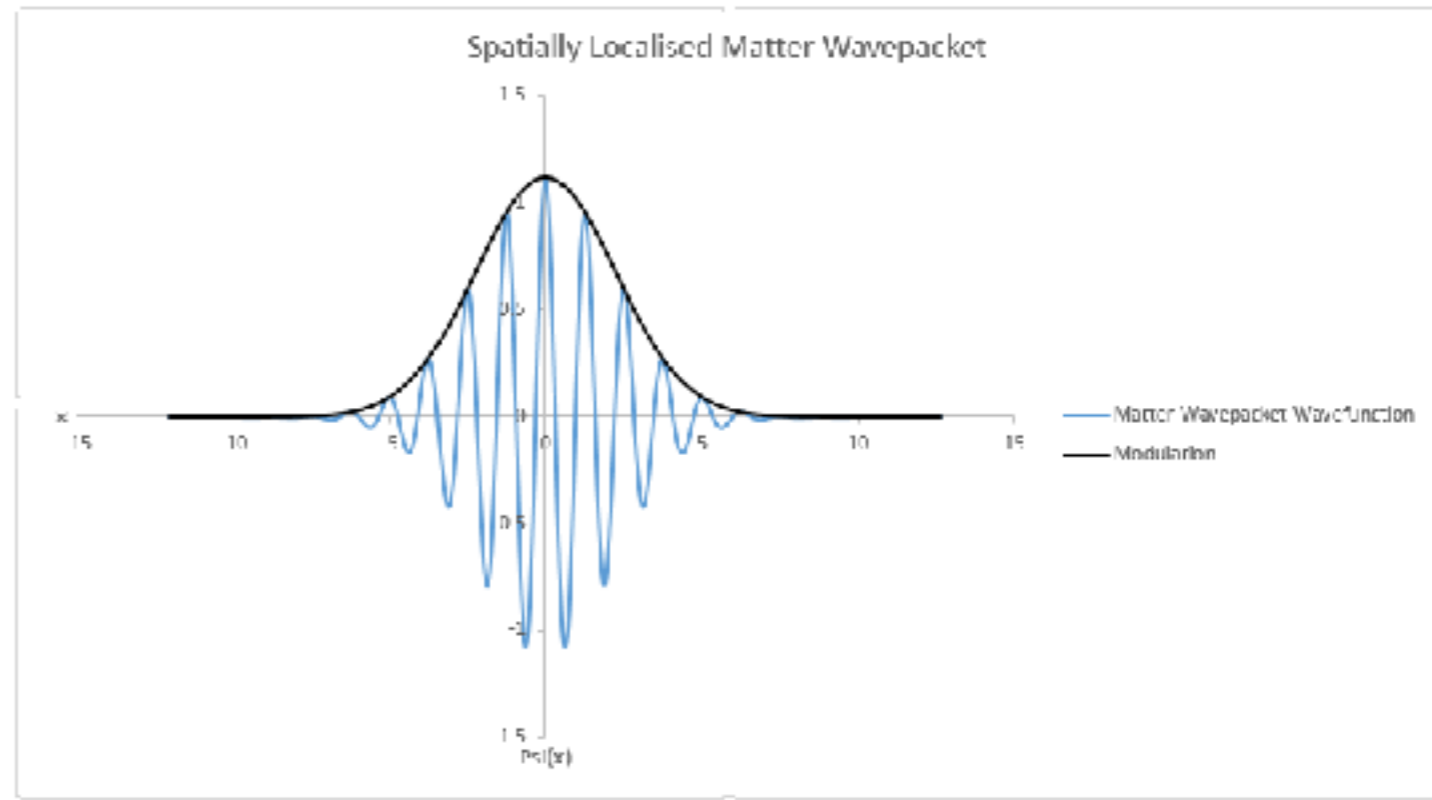
Wahrscheinlichkeiten



... für ein einzelnes Photon?

Formalismus der QM

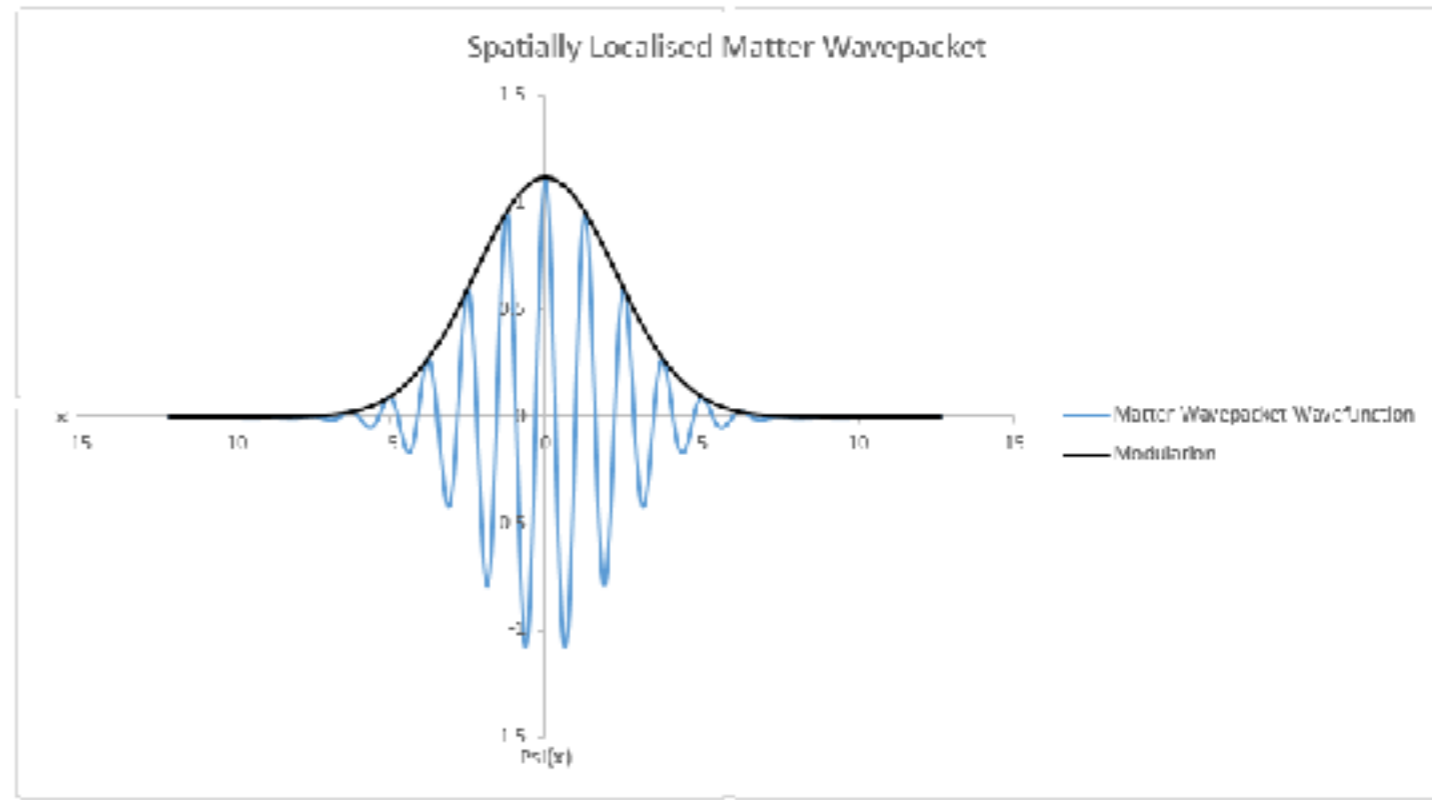
Wellenfunktion: $\psi(x, t)$



Formalismus der QM

Wellenfunktion: $\psi(x, t)$

Messgrößen \leftrightarrow Operatoren

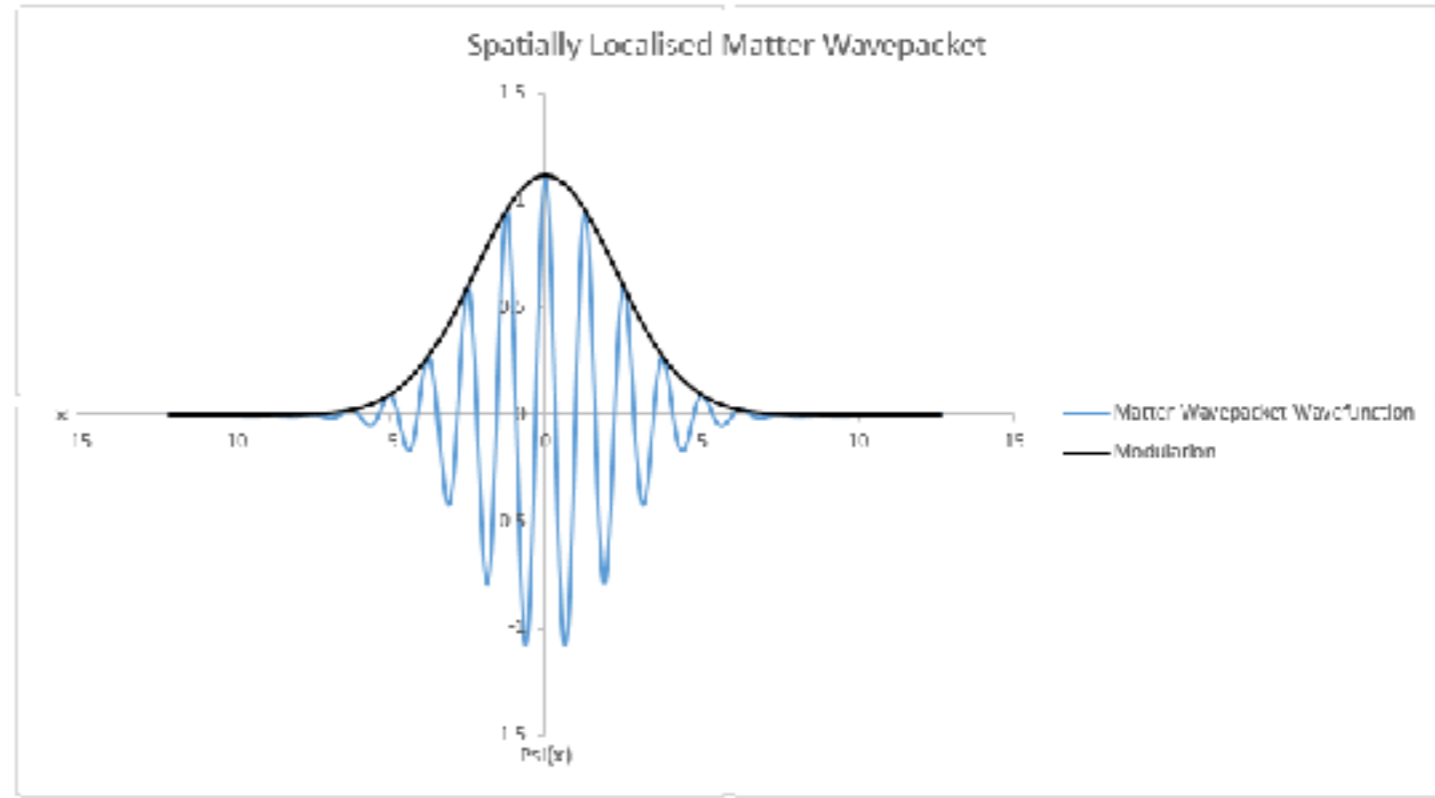


Formalismus der QM

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Messgrößen \leftrightarrow Operatoren

$$\hat{p} = -i\hbar \frac{d}{dx}$$

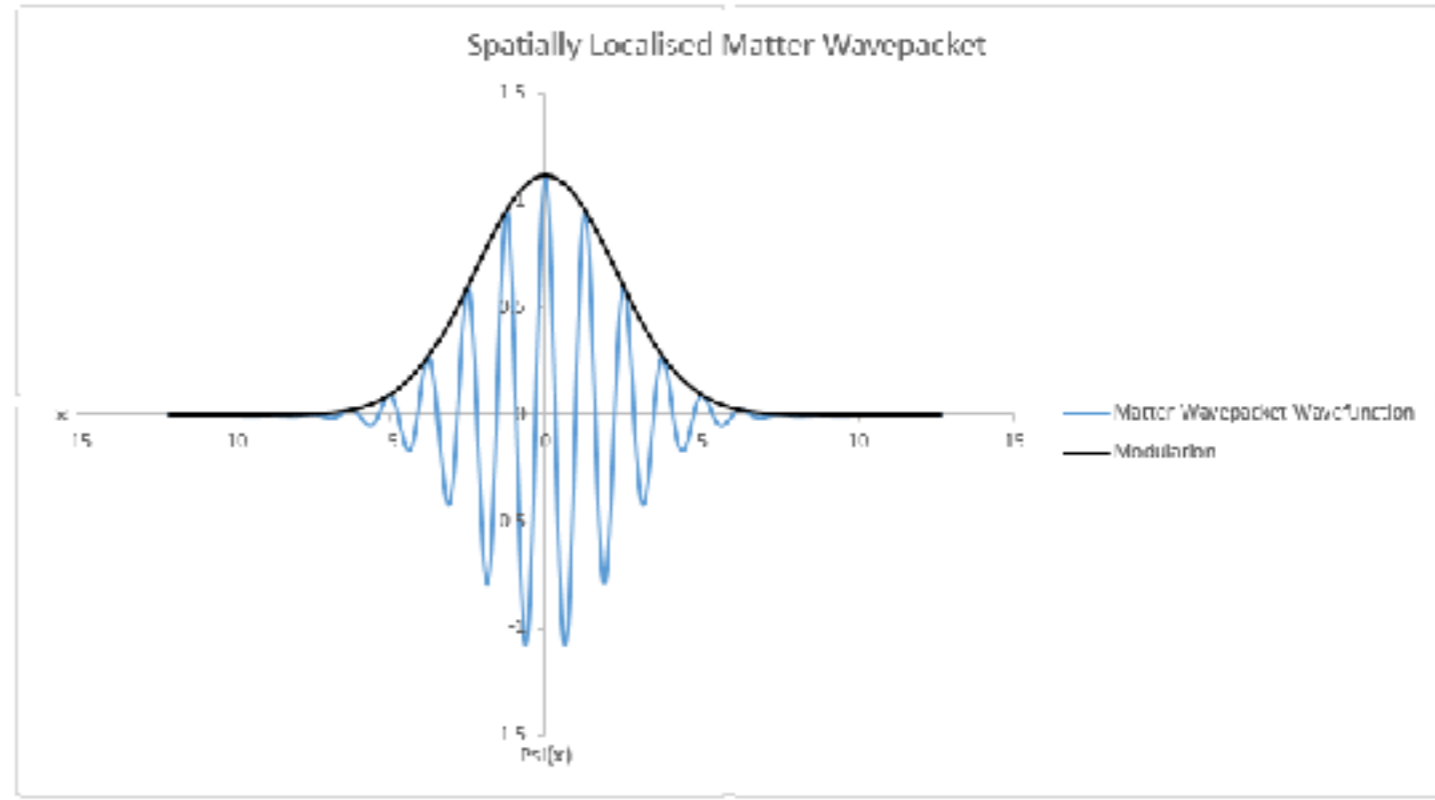


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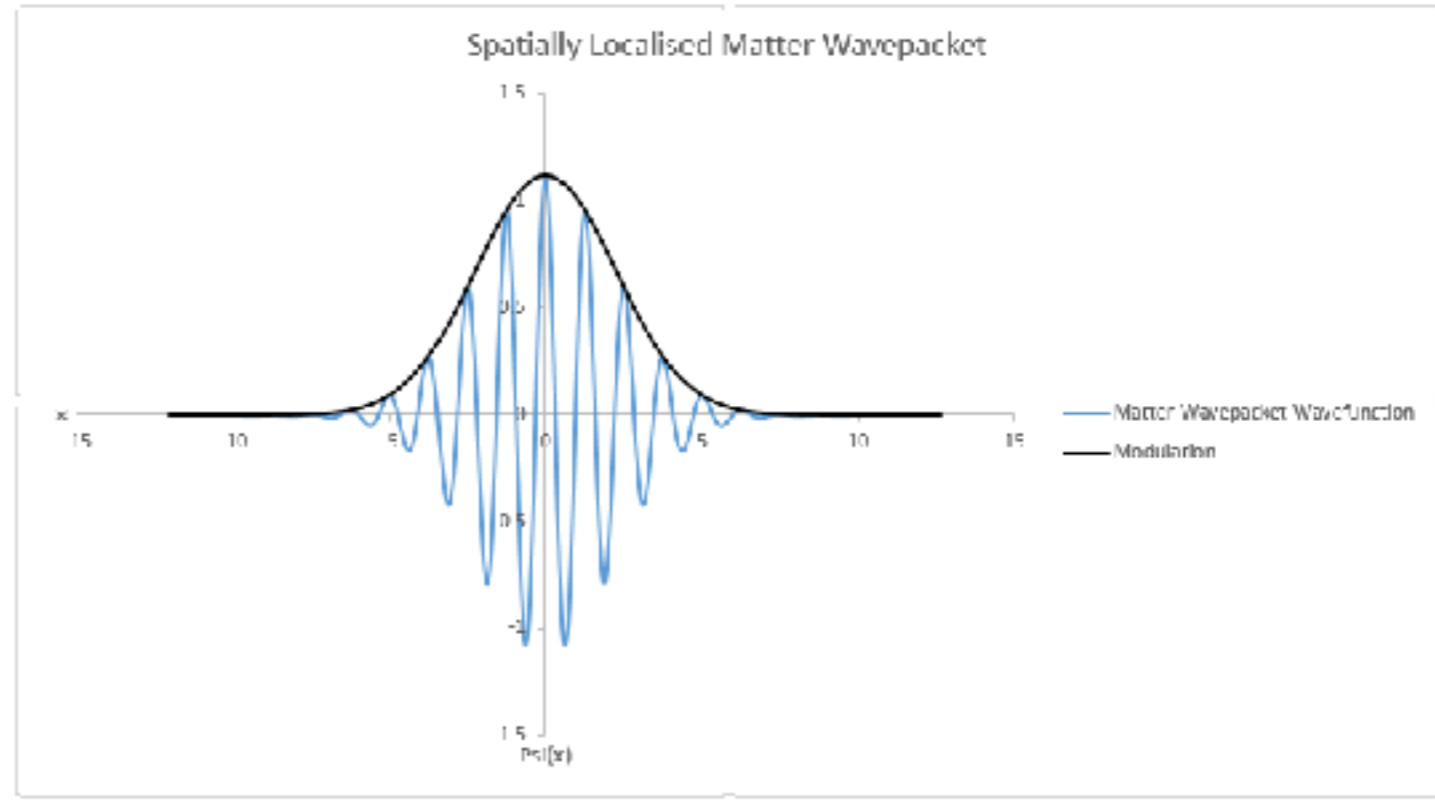


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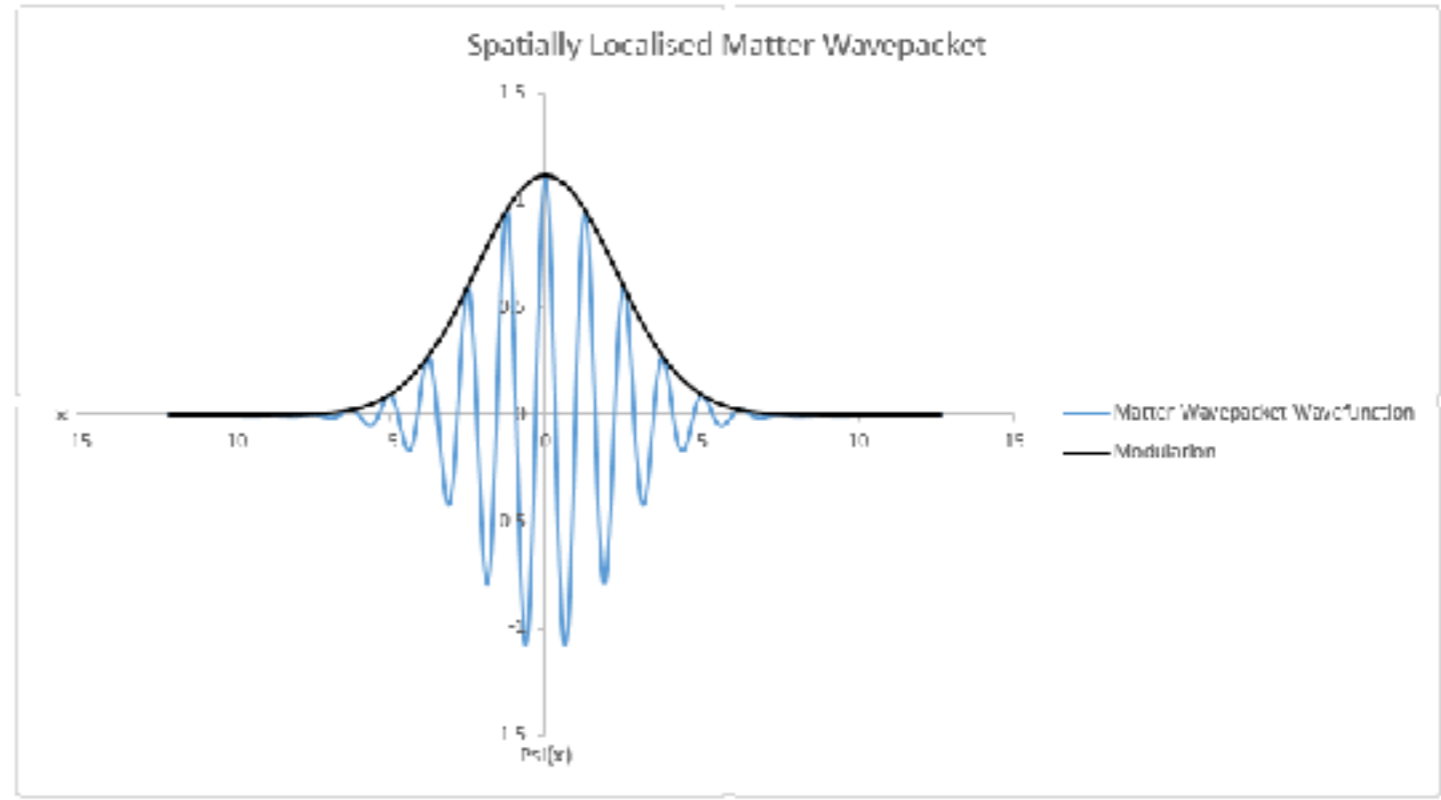
$$\langle \hat{p}(t) \rangle = -i\hbar \int dx \psi^*(x, t) \frac{d}{dx} \psi(x, t)$$

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$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$$

Ebene Welle

$$\psi_p(x, t) = C_p e^{\frac{i}{\hbar}(px - Et)}$$

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unlokalisiertes “Teilchen” mit scharfem Impuls!



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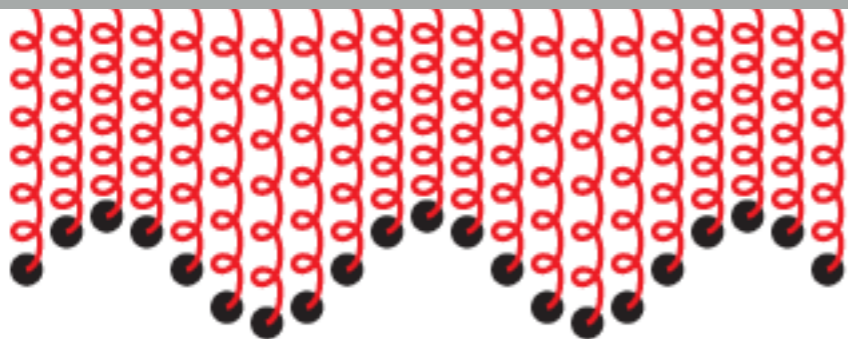
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Quantisiere diese HOs!
“2. Quantisierung”

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4. Interpretiere dies als klassische HOs an jedem Ort x .

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(störungstheoretisches Bild)

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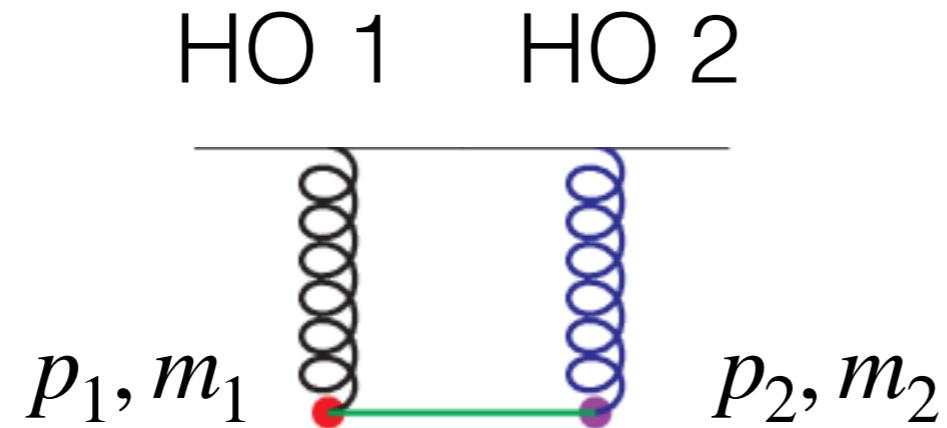
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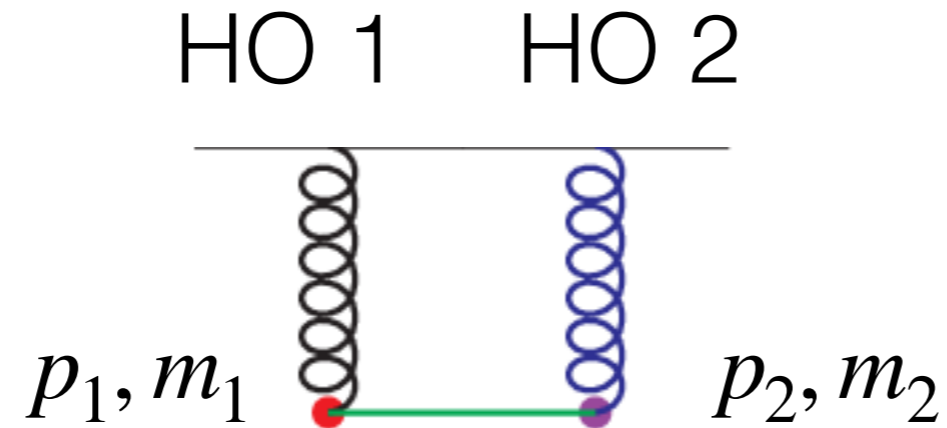
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- angeregt $\hat{=}$ Teilchen
- nicht angeregt $\hat{=}$ kein Teilchen

Wechselwirkung



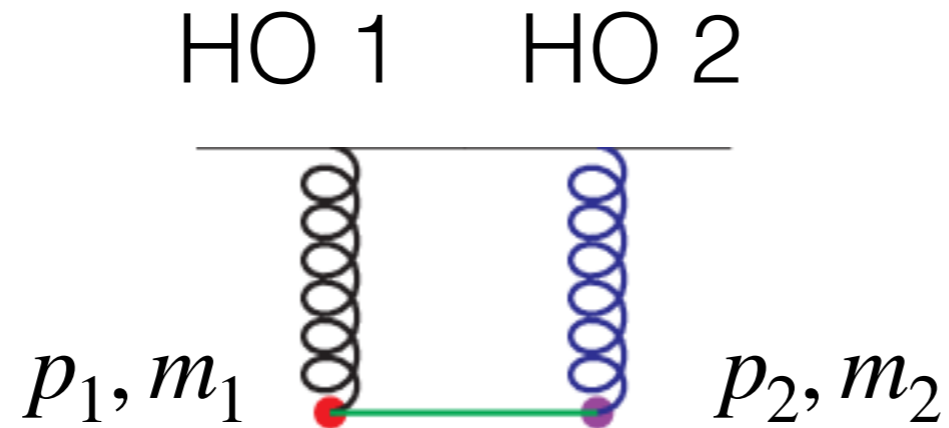
klassisch

Wechselwirkung



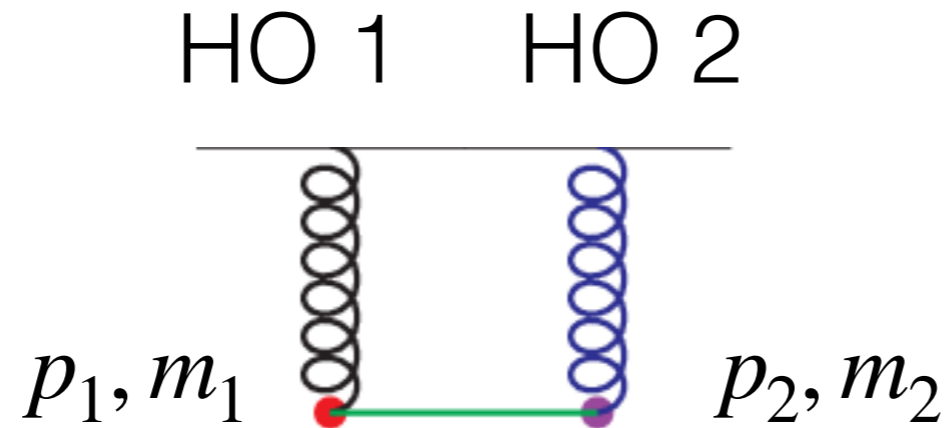
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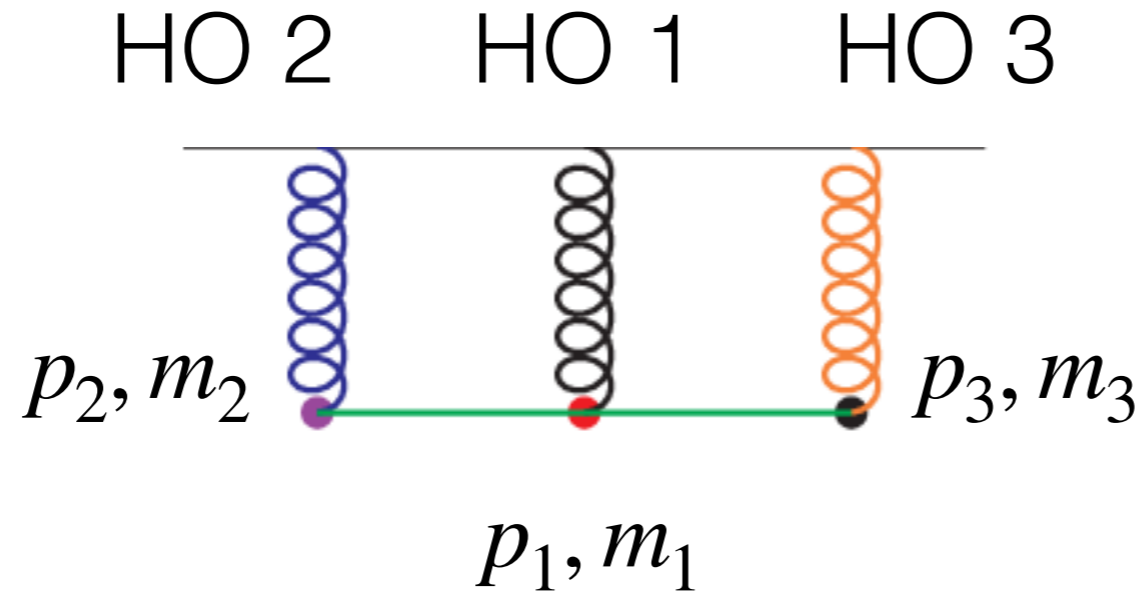
quantenmechanisch

Wechselwirkung



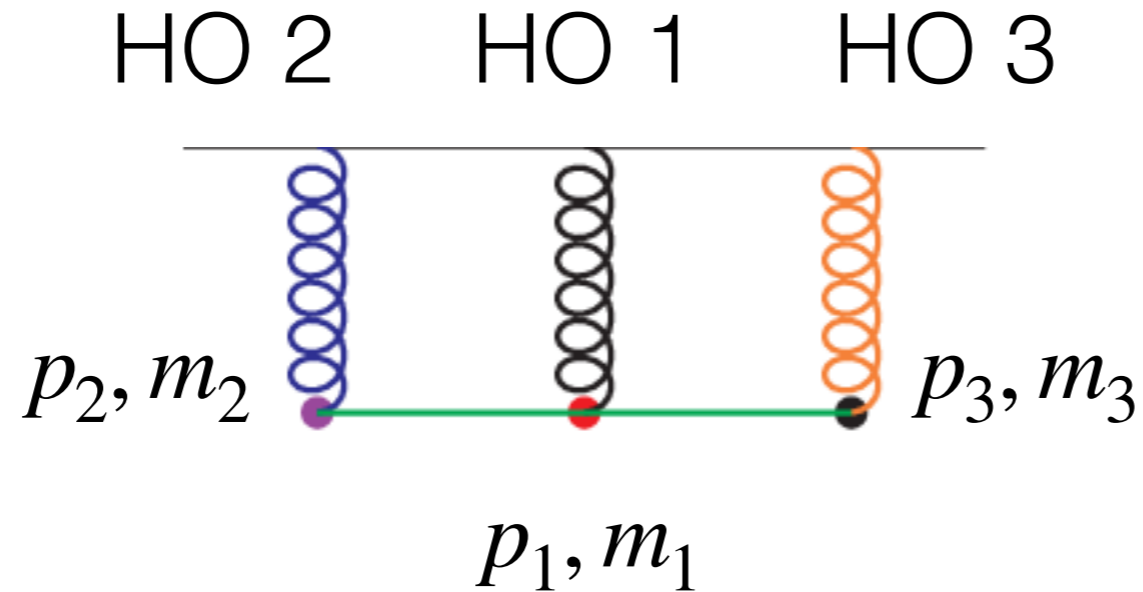
quantenmechanisch

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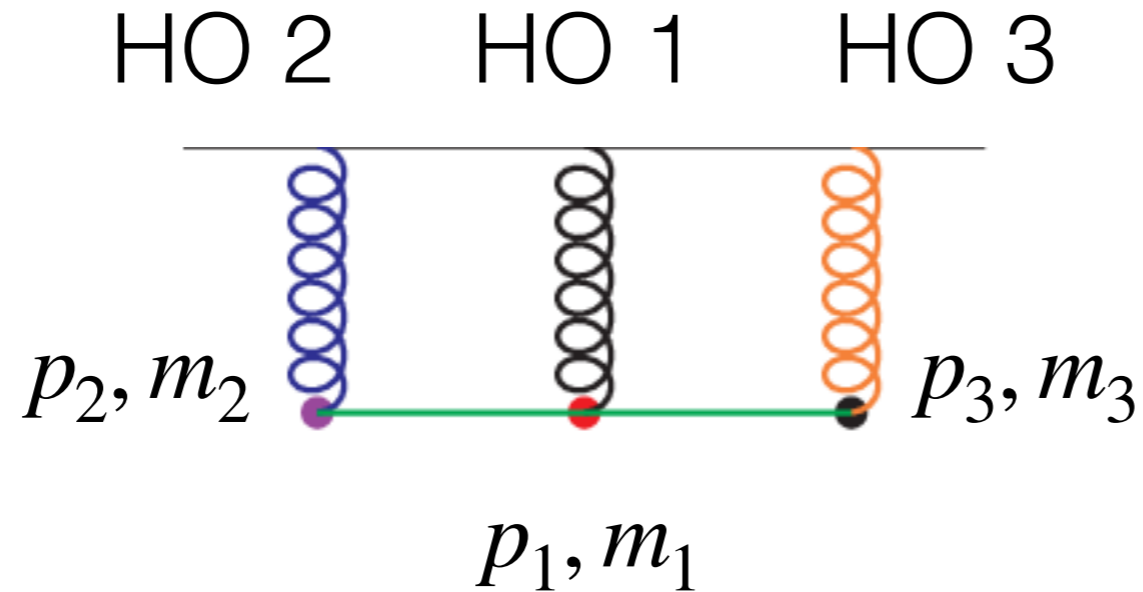
quantenmechanisch

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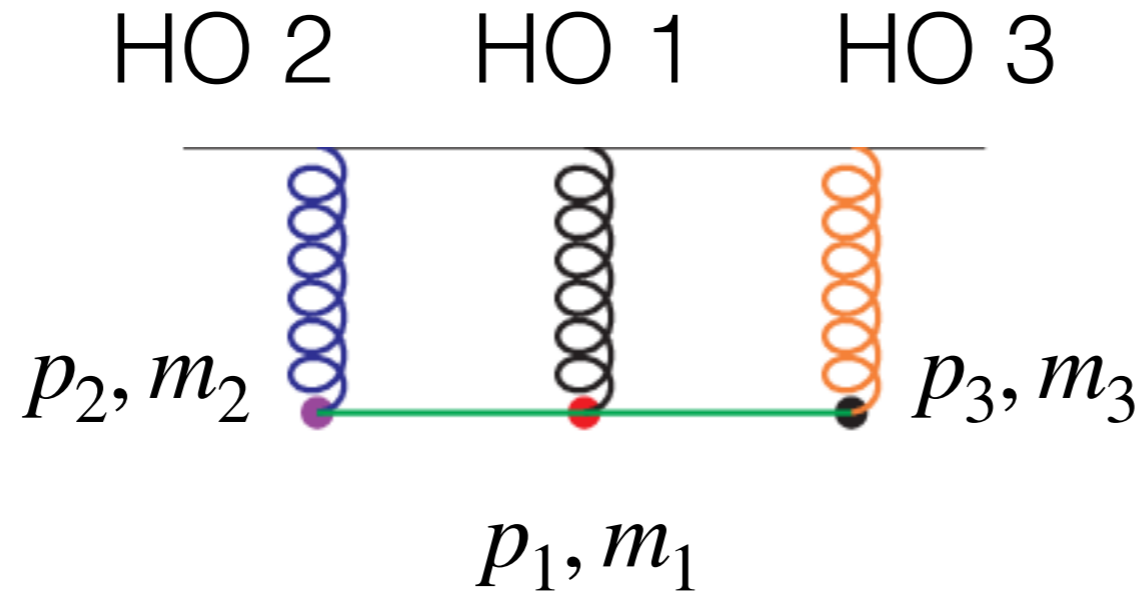
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quantenmechanisch



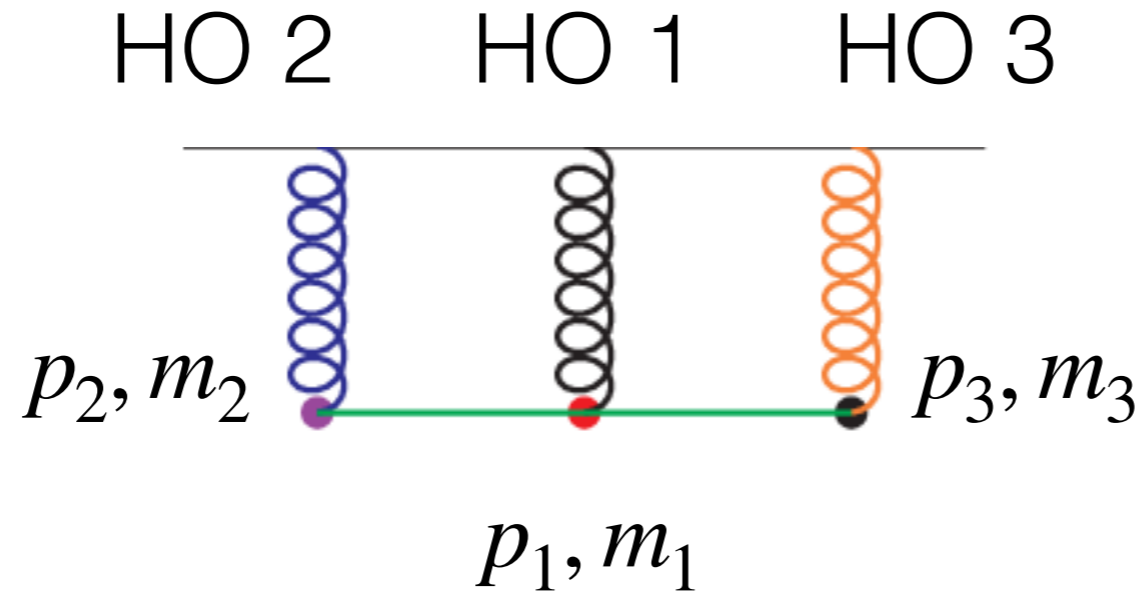
Wechselwirkung



quantenmechanisch



Wechselwirkung

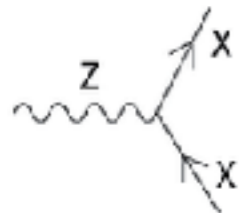


quantenmechanisch

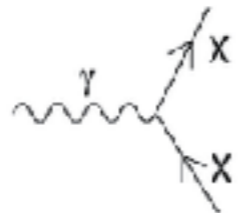
Vertex

Vertices

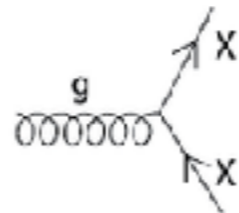
Standard Model Interactions (Forces Mediated by Gauge Bosons)



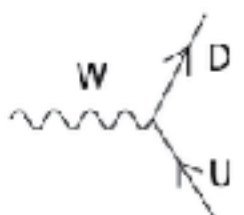
X is any fermion in the Standard Model.



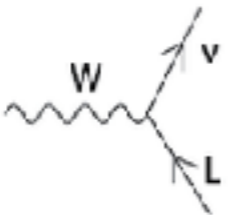
X is electrically charged.



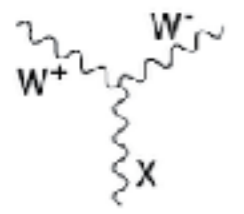
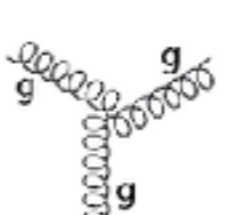
X is any quark.



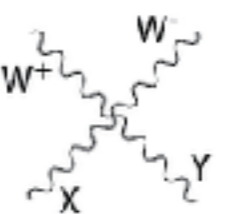
U is a up-type quark;
D is a down-type quark.



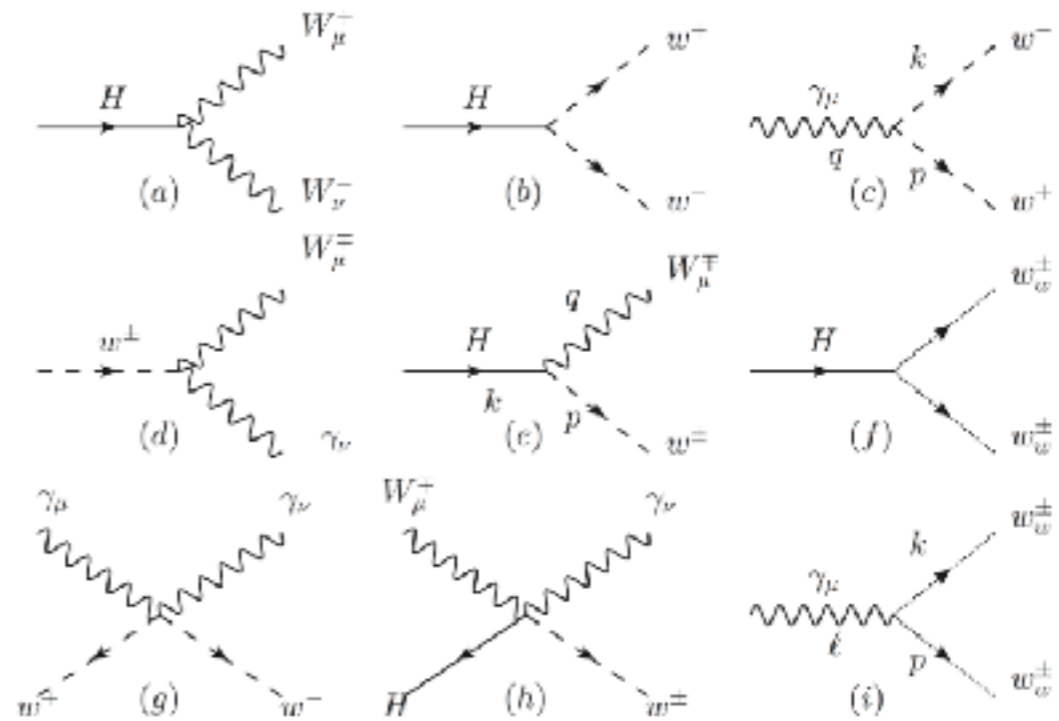
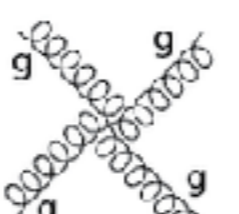
L is a lepton and ν is the corresponding neutrino.



X is a photon or Z-boson.

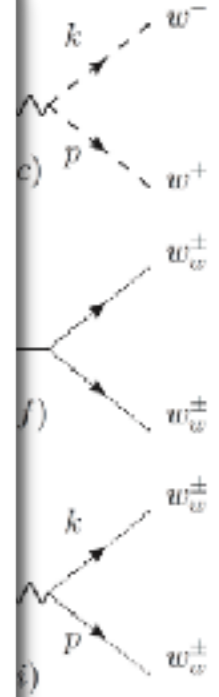
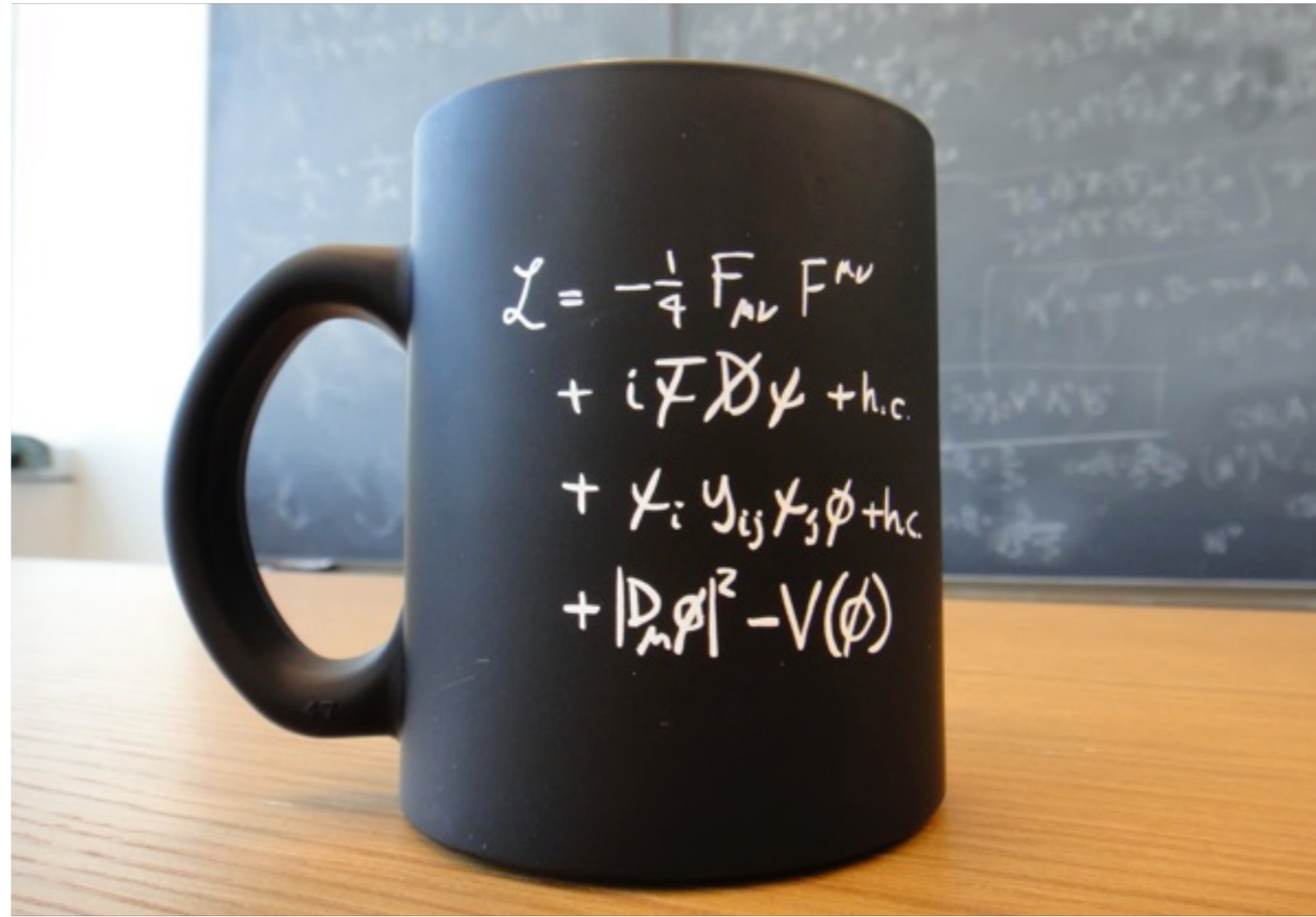
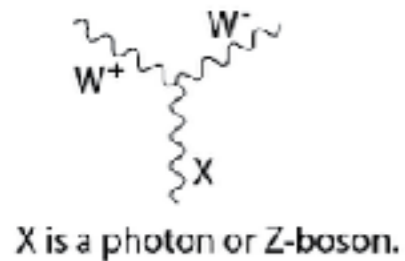
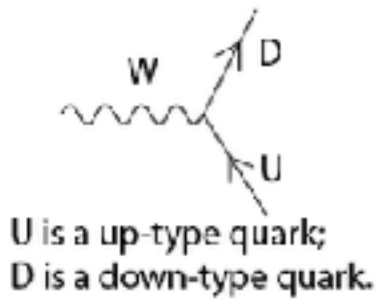
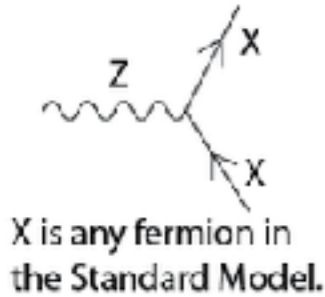


X and Y are any two electroweak bosons such that charge is conserved.

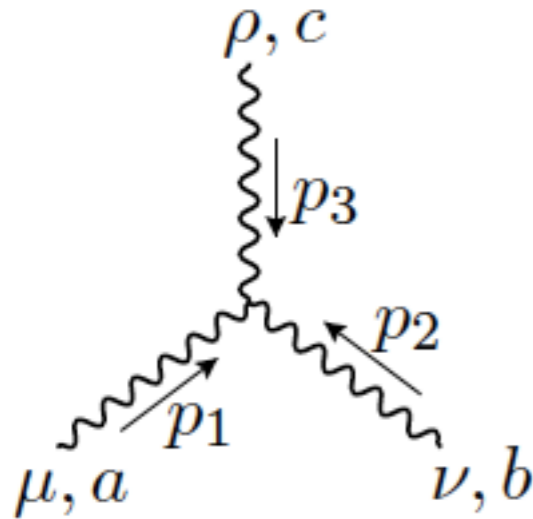


Vertices

Standard Model Interactions (Forces Mediated by Gauge Bosons)

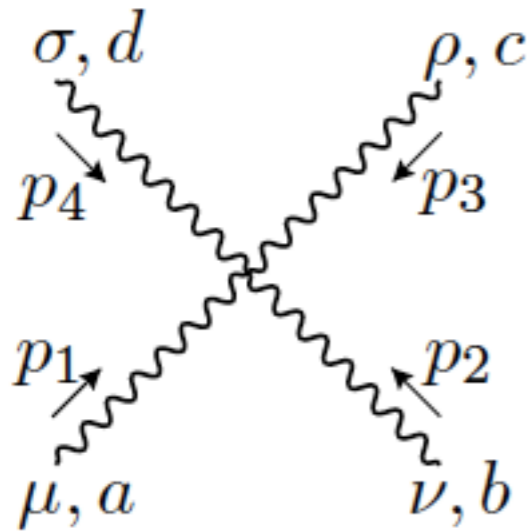


Feynman-Regeln

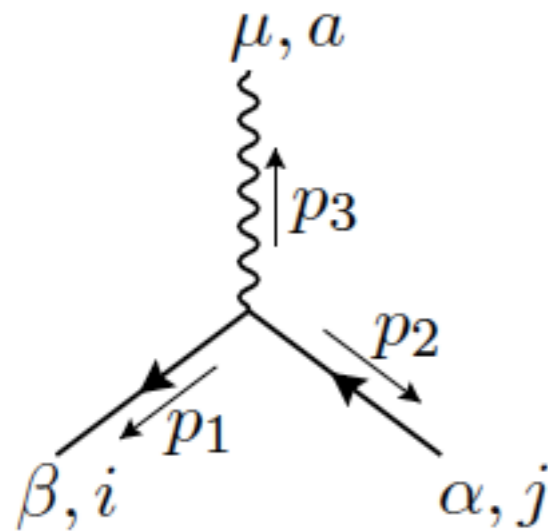


$$gf^{abc} [g^{\mu\nu} (p_1 - p_2)^\rho + g^{\nu\rho} (p_2 - p_3)^\mu + g^{\rho\mu} (p_3 - p_1)^\nu]$$

Feynman-Regeln



$$-ig^2 \left[\begin{aligned} & f_{eab} f_{ecd} (g_{\mu\rho} g_{\nu\sigma} - g_{\mu\sigma} g_{\nu\rho}) \\ & + f_{eac} f_{edb} (g_{\mu\sigma} g_{\rho\nu} - g_{\mu\nu} g_{\rho\sigma}) \\ & + f_{ead} f_{ebc} (g_{\mu\nu} g_{\rho\sigma} - g_{\mu\rho} g_{\nu\sigma}) \end{aligned} \right]$$



$$ig(\gamma^\mu)_{\beta\alpha} T_{ij}^a$$

Myon-Wechselwirkungen



Myon-Wechselwirkungen



Myon-Wechselwirkungen

Myon •

W-Boson

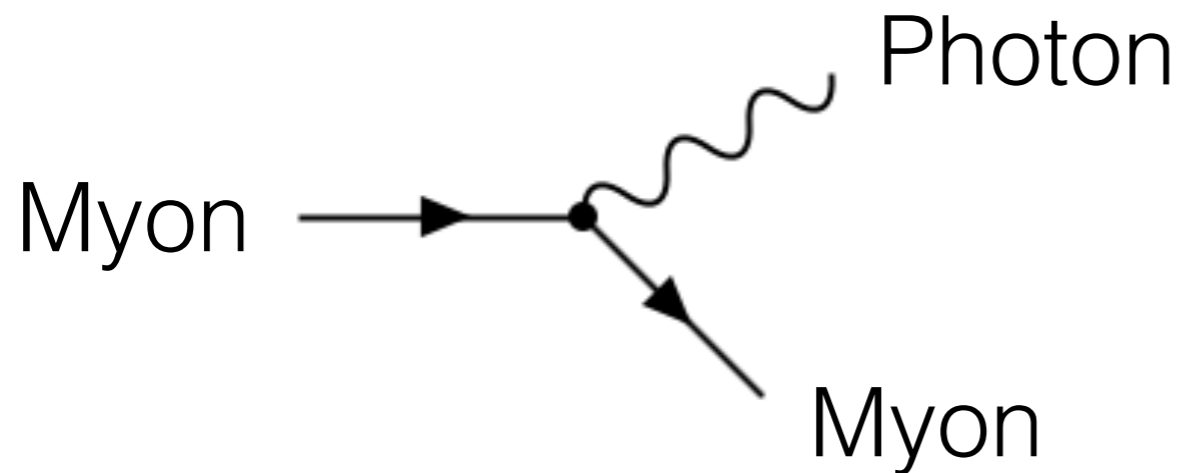
Myon-Neutrino

Myon-Wechselwirkungen

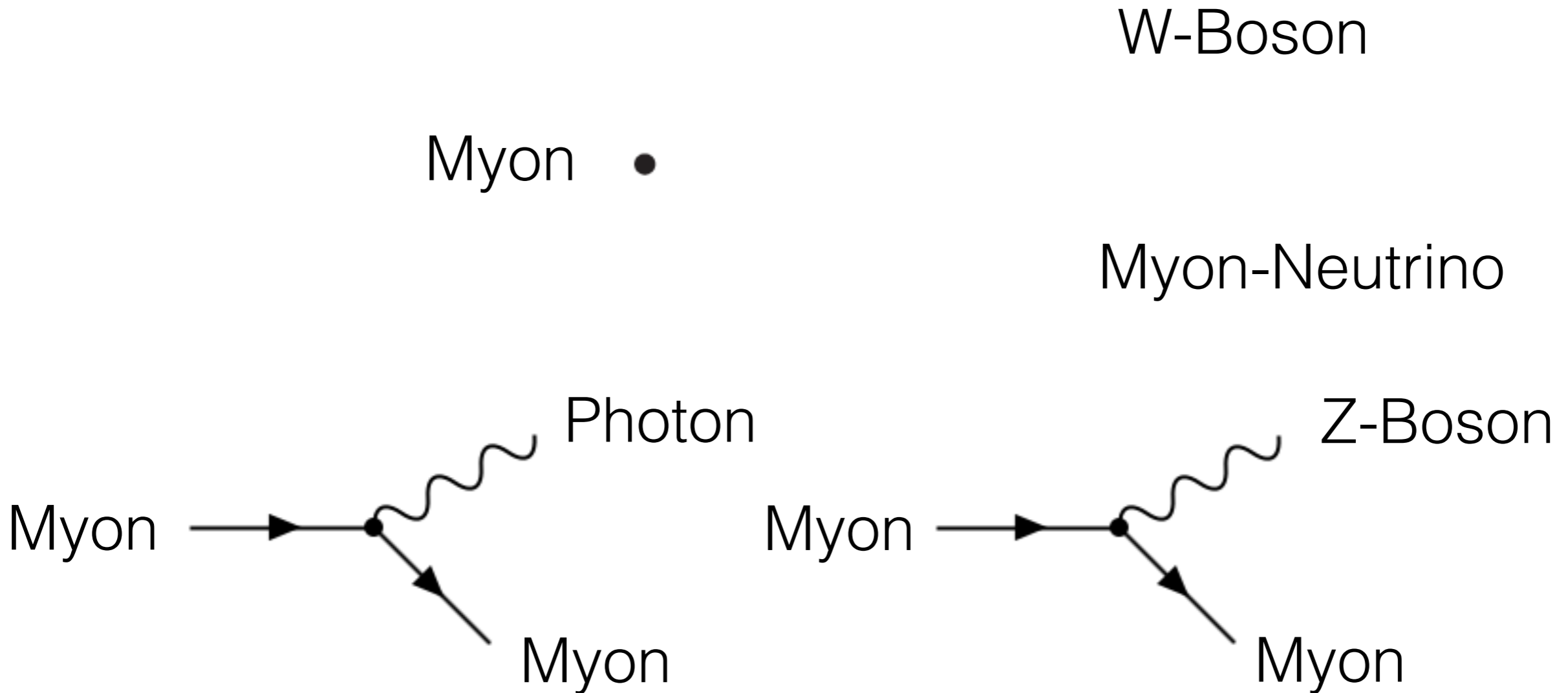
W-Boson

Myon •

Myon-Neutrino



Myon-Wechselwirkungen



Myon-Zerfall?

Myon •

W-Boson

Myon-Neutrino

Myon-Zerfall?

Myon •

W-Boson

Myon-Neutrino

Myon-Zerfall?

Myon •
100 MeV/c²

80.000 MeV/c²

W-Boson

Myon-Neutrino

0 MeV/c²

Myon-Zerfall?

80.000 MeV/c²

W-Boson

Myon •

100 MeV/c²

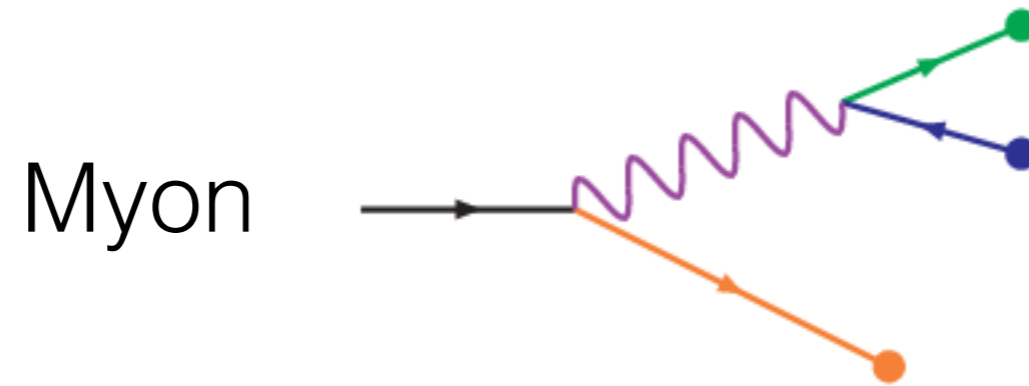
Myon-Neutrino

0 MeV/c²

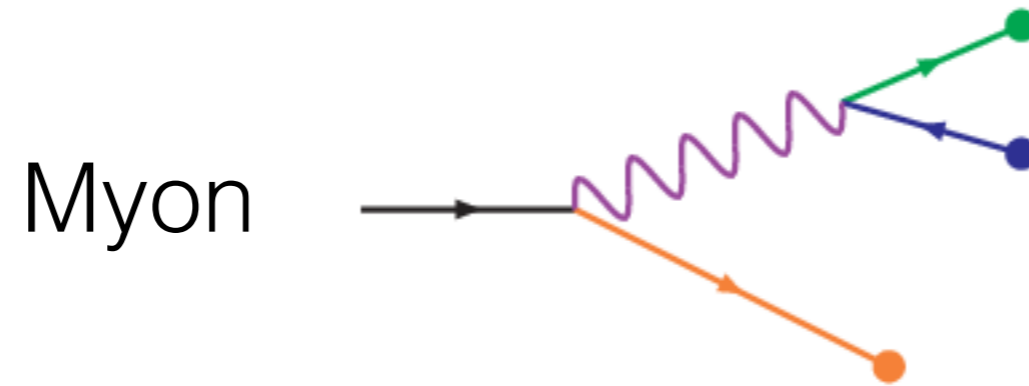
$$\text{QM: } \Delta x \cdot \Delta p \geq \frac{\hbar}{2}$$

$$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$$

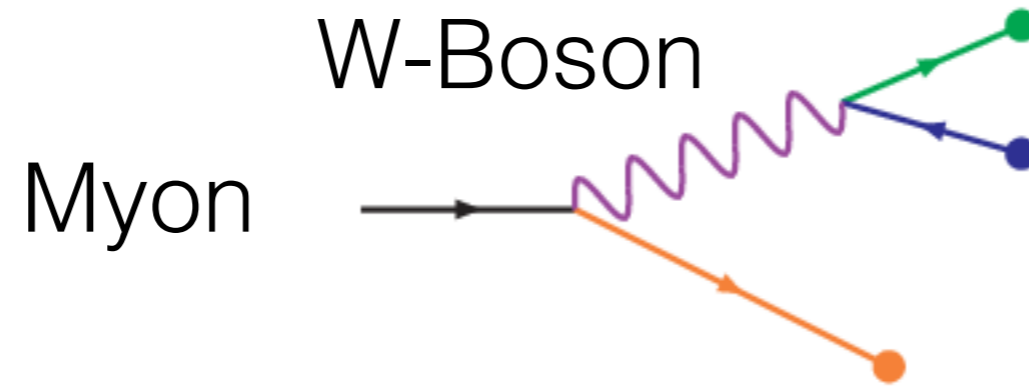
Myon-Zerfall?



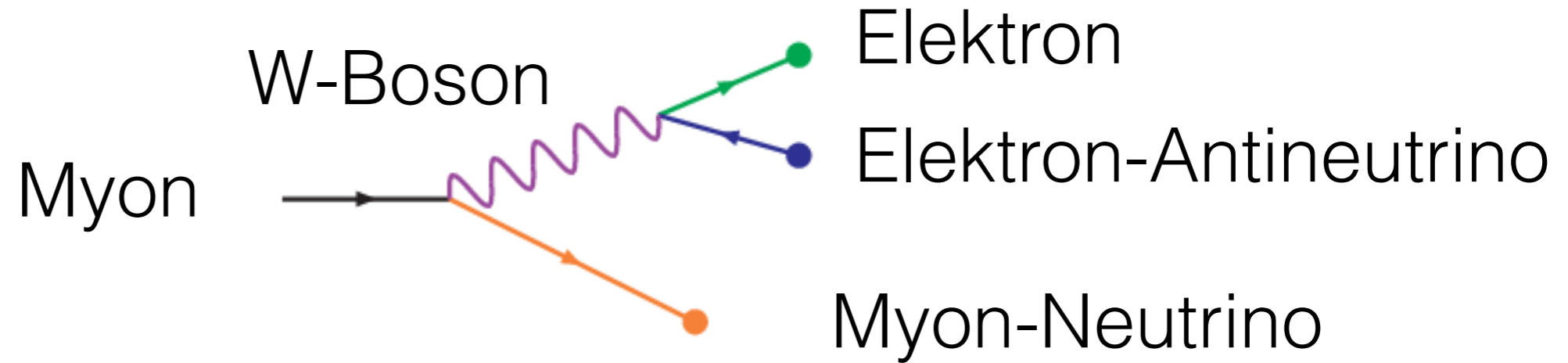
Myon-Zerfall?



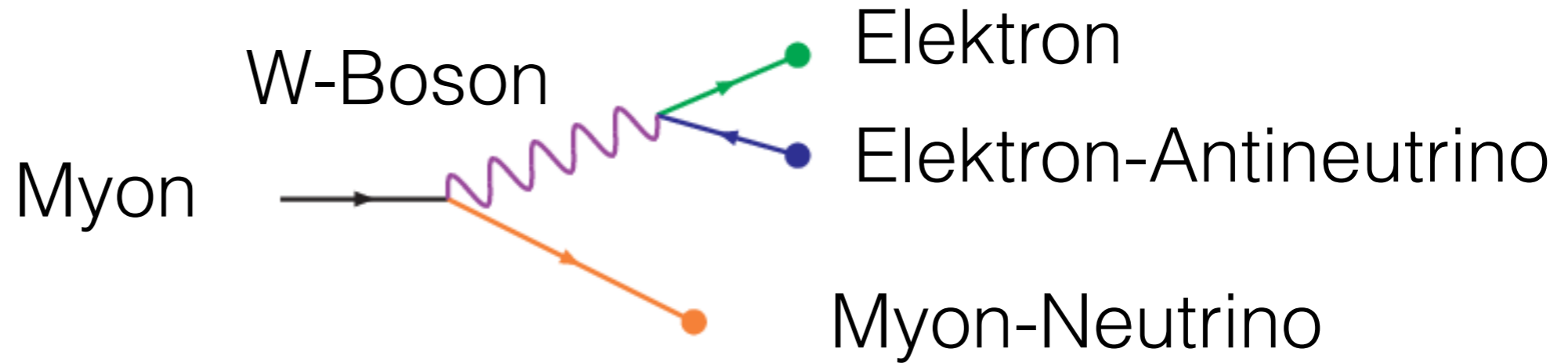
Myon-Zerfall?



Myon-Zerfall?



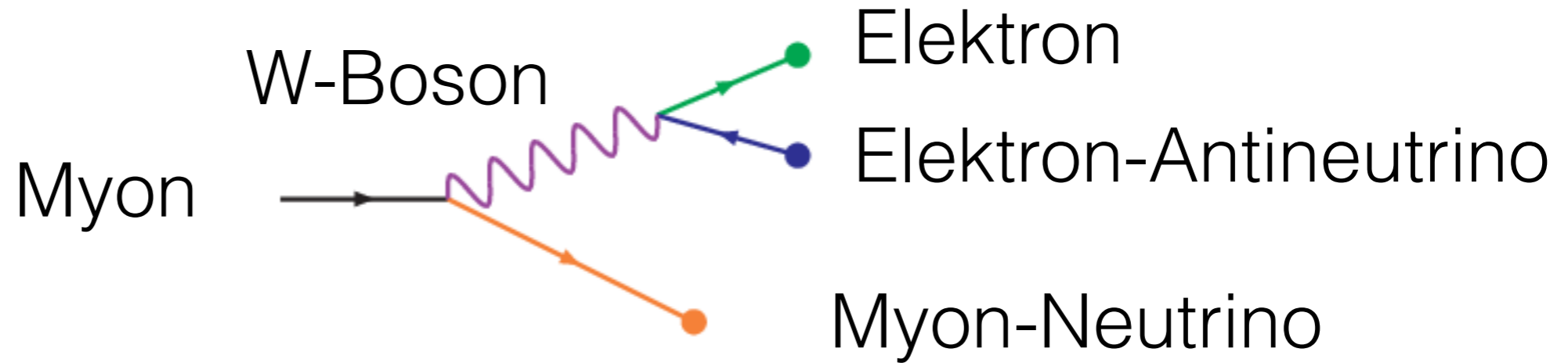
Myon-Zerfall?



W-Boson ist “off-shell”:

$$\Delta E^2 \equiv E^2 - E_W^2 = E^2 - M_W^2 c^4 - p_W^2 c^2 \neq 0$$

Myon-Zerfall?

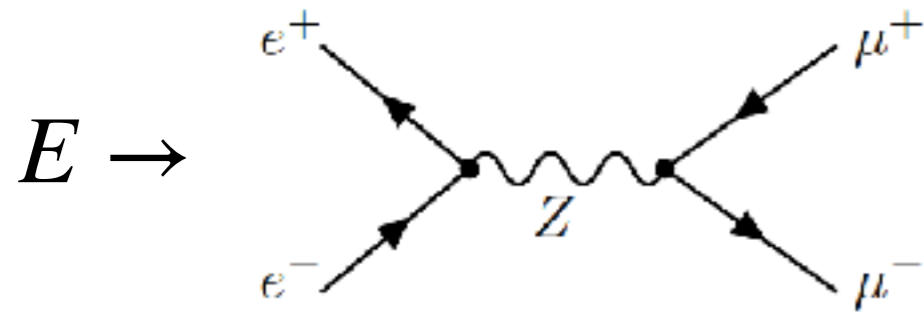


W-Boson ist “off-shell”:

$$\Delta E^2 \equiv E^2 - E_W^2 = E^2 - M_W^2 c^4 - p_W^2 c^2 \neq 0$$

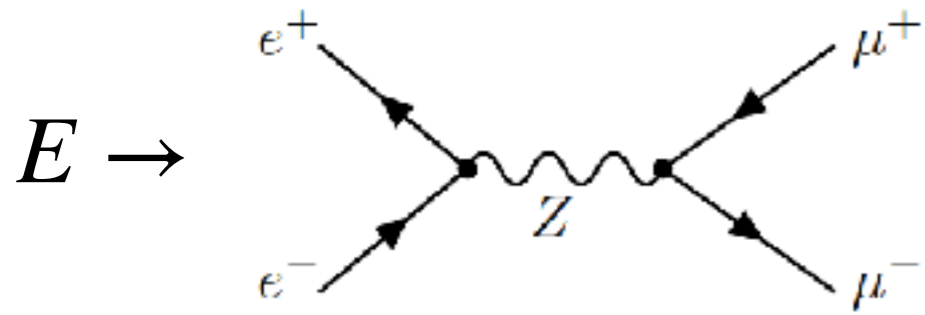
“Off-shellness” unterdrückt mit $1/(\Delta E^2)$

Wirkungsquerschnitte

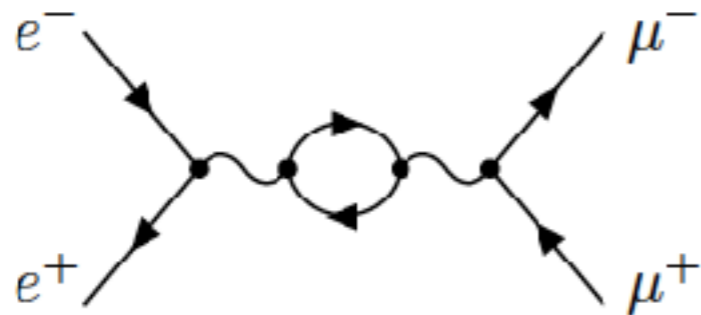


$$\sigma \sim \frac{1}{|E^2 - M_Z^2 c^4|^2}$$

Wirkungsquerschnitte

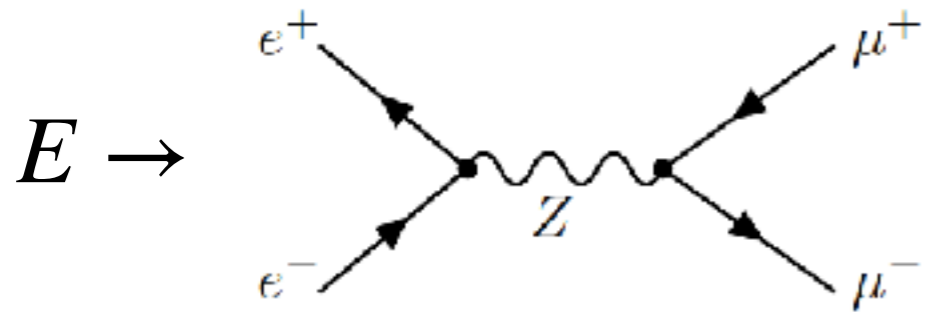


$$\sigma \sim \frac{1}{|E^2 - M_Z^2 c^4|^2}$$

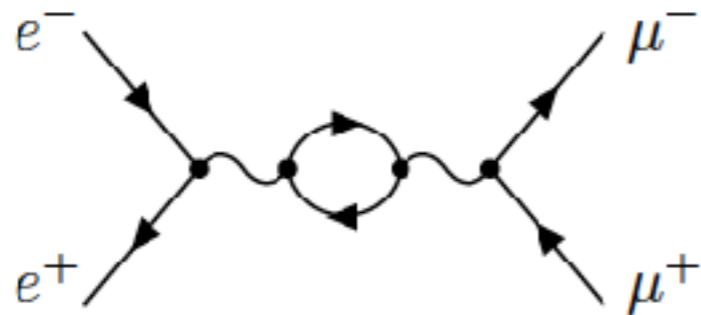


$$\sigma \sim \frac{1}{(E^2 - M_Z^2 c^4)^2 + M_Z^2 \Gamma_Z^2}$$

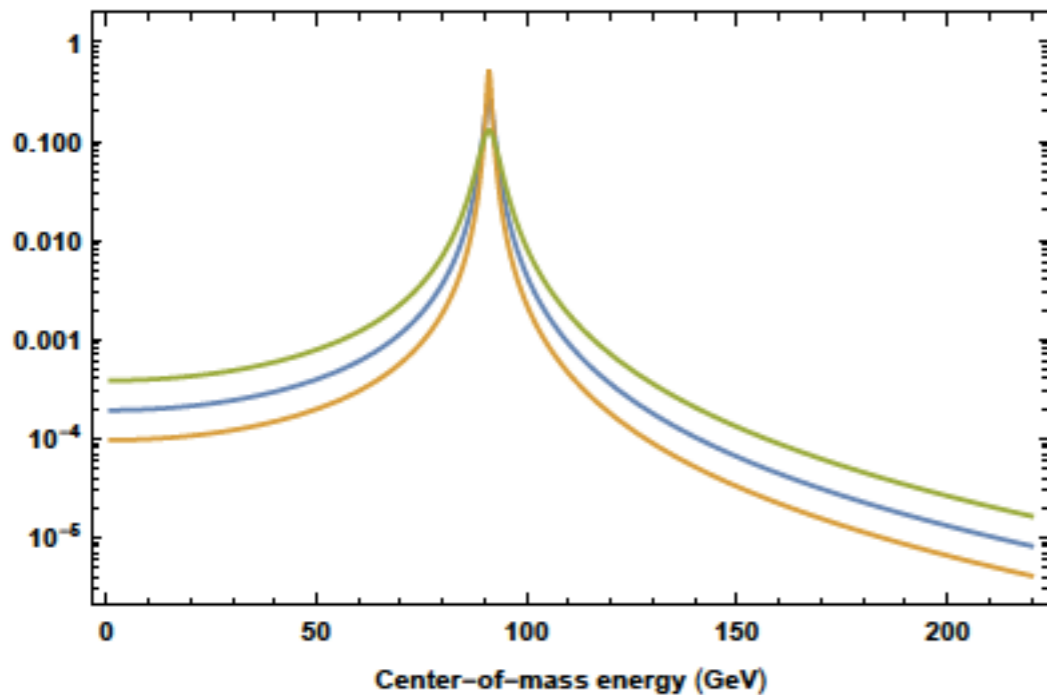
Wirkungsquerschnitte



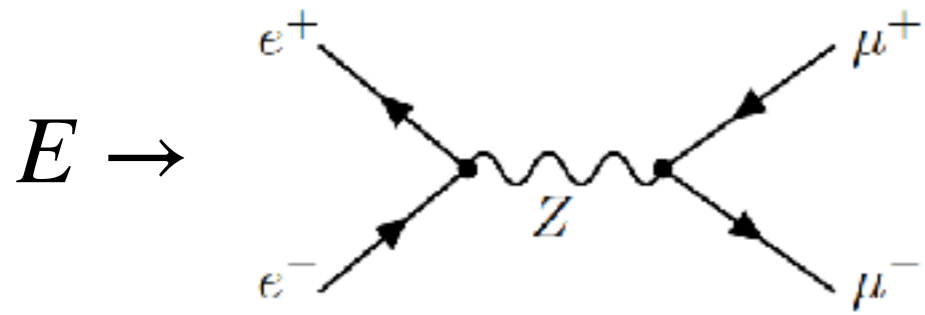
$$\sigma \sim \frac{1}{|E^2 - M_Z^2 c^4|^2}$$



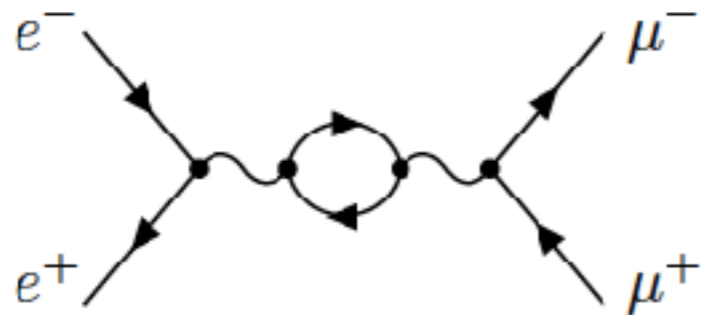
$$\sigma \sim \frac{1}{(E^2 - M_Z^2 c^4)^2 + M_Z^2 \Gamma_Z^2}$$



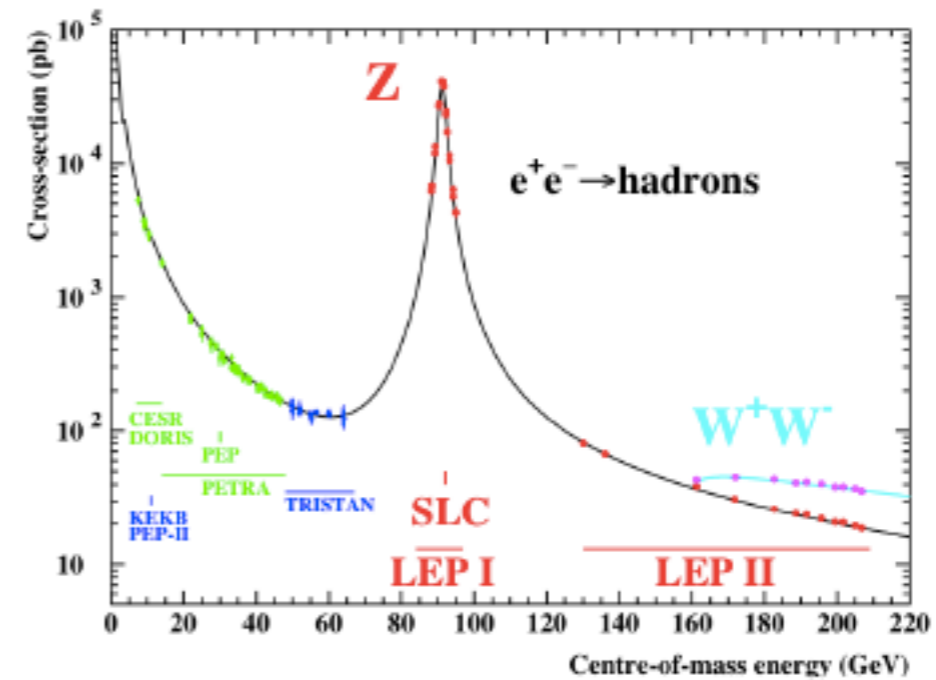
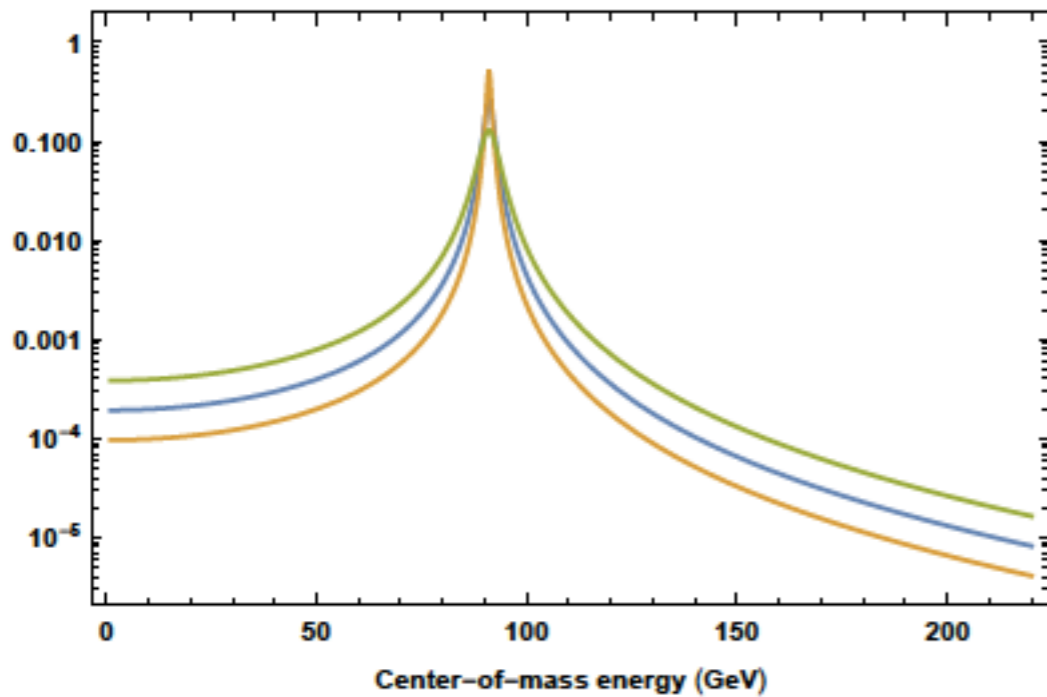
Wirkungsquerschnitte



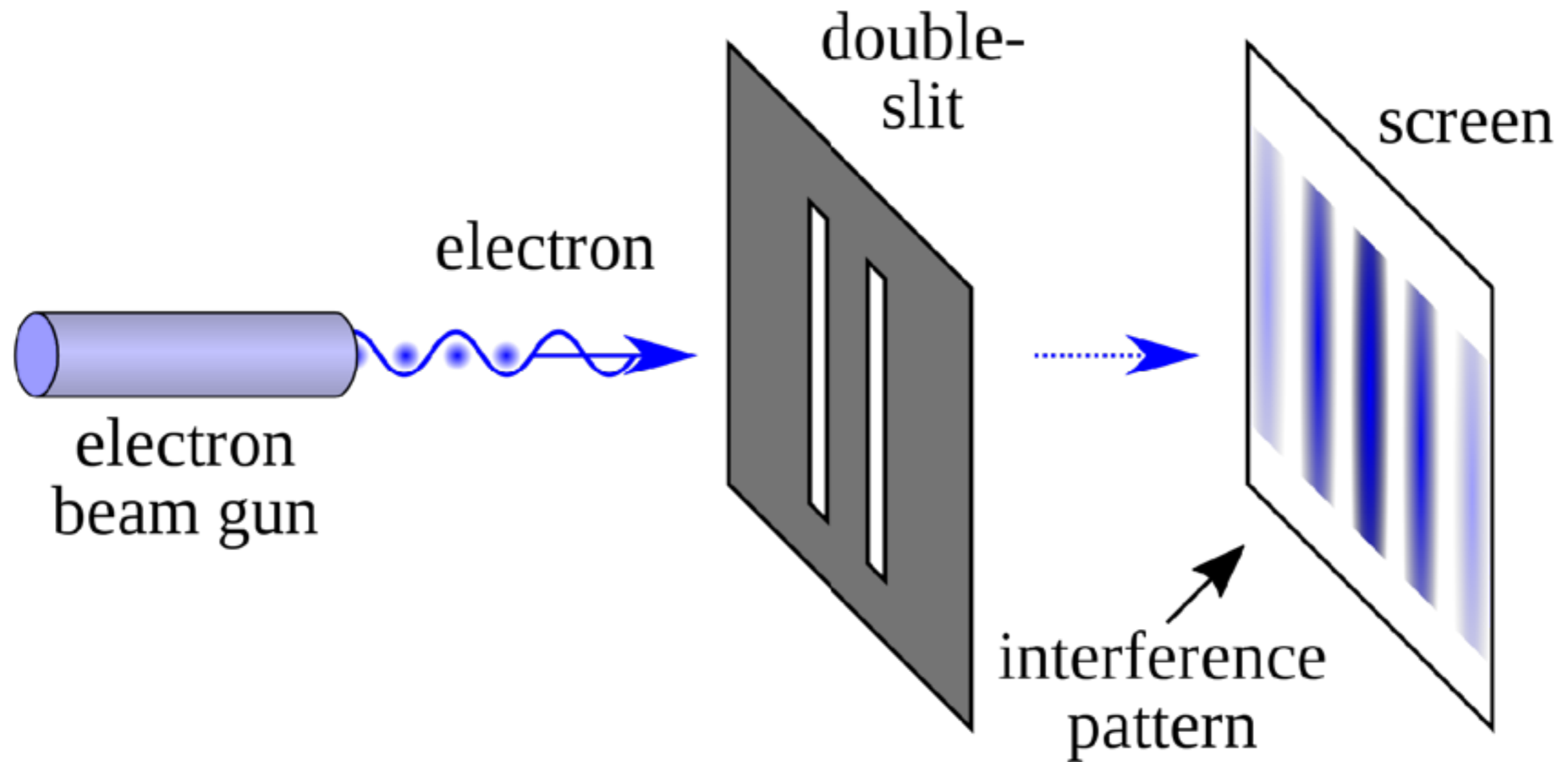
$$\sigma \sim \frac{1}{|E^2 - M_Z^2 c^4|^2}$$



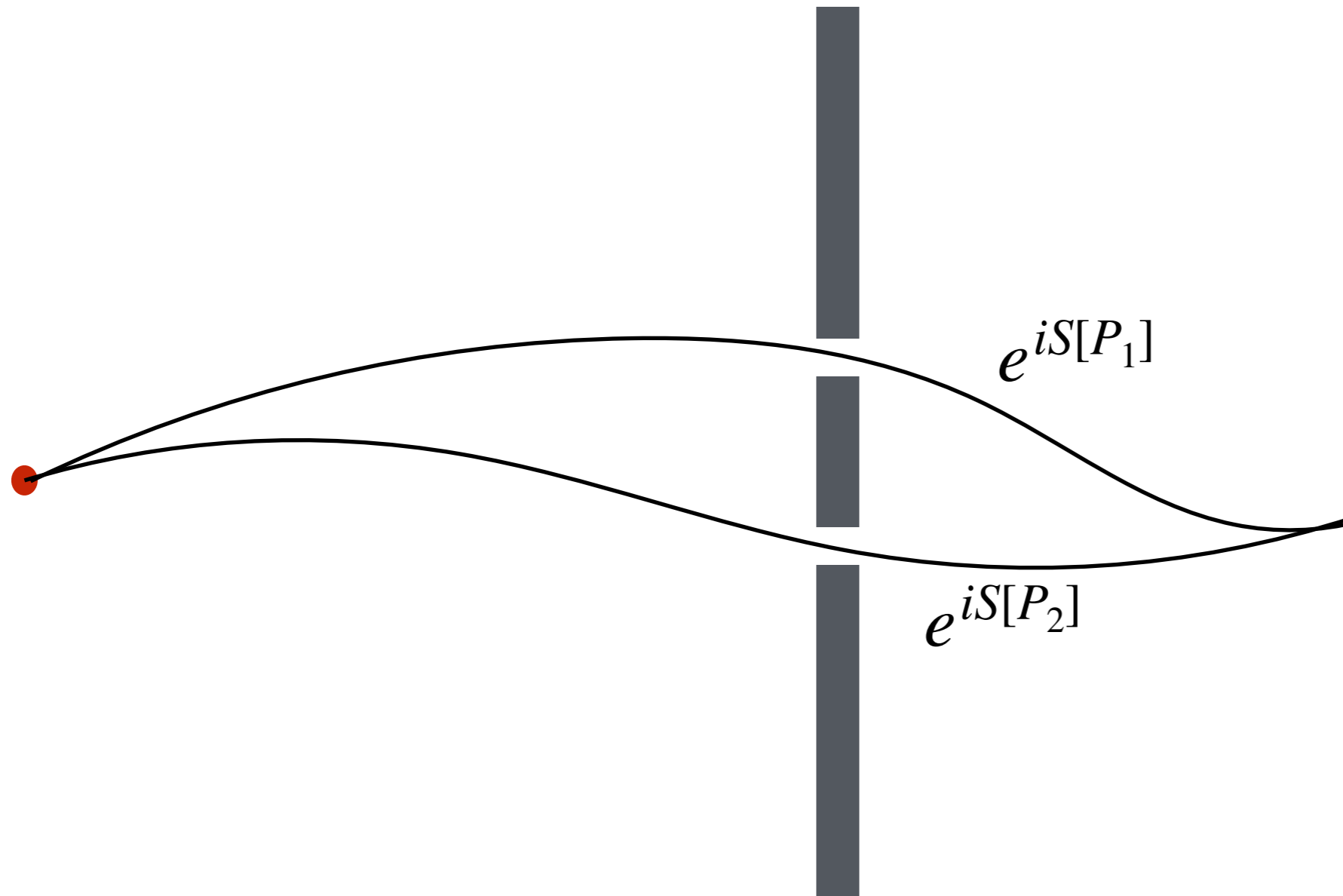
$$\sigma \sim \frac{1}{(E^2 - M_Z^2 c^4)^2 + M_Z^2 \Gamma_Z^2}$$



Intermezzo

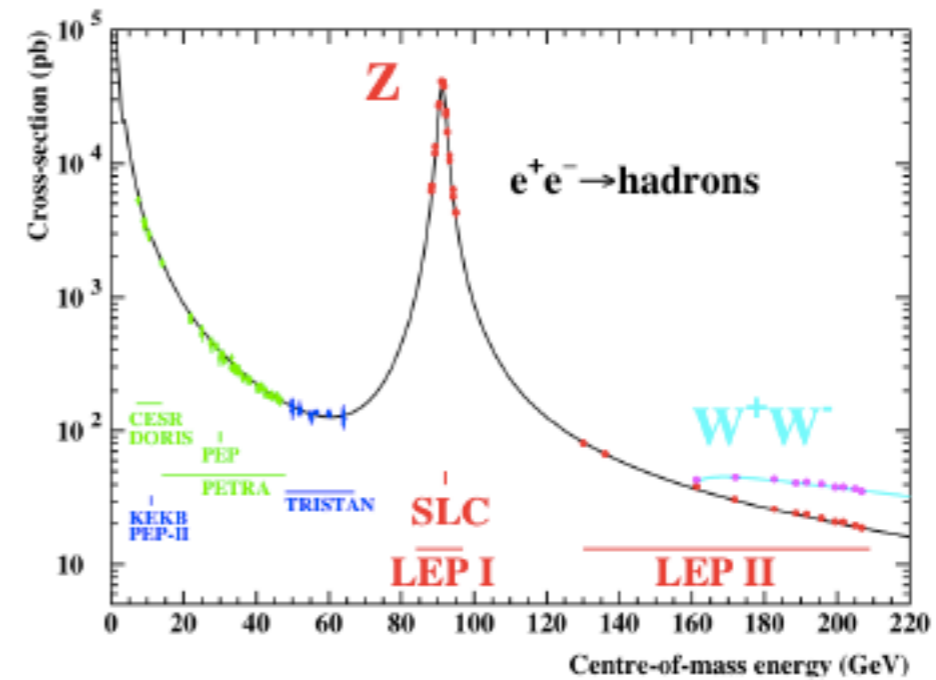
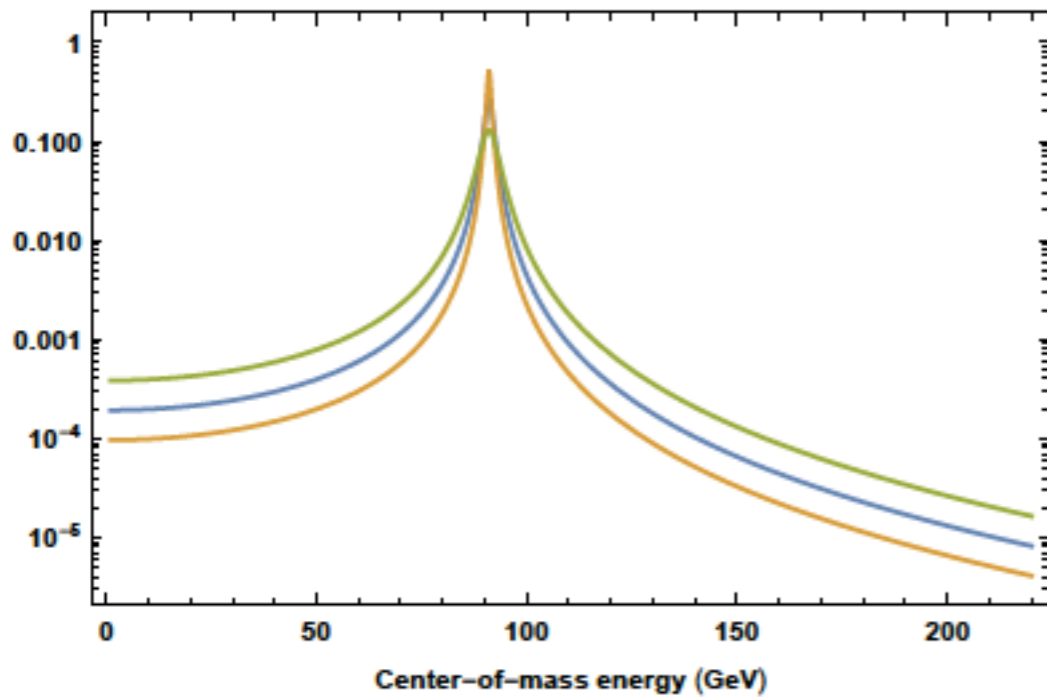
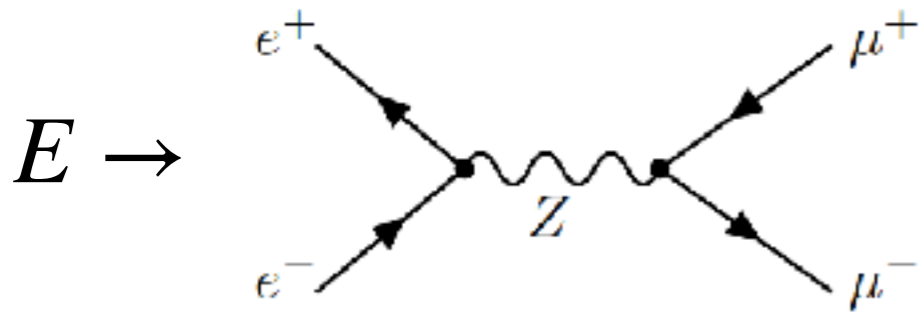


Intermezzo

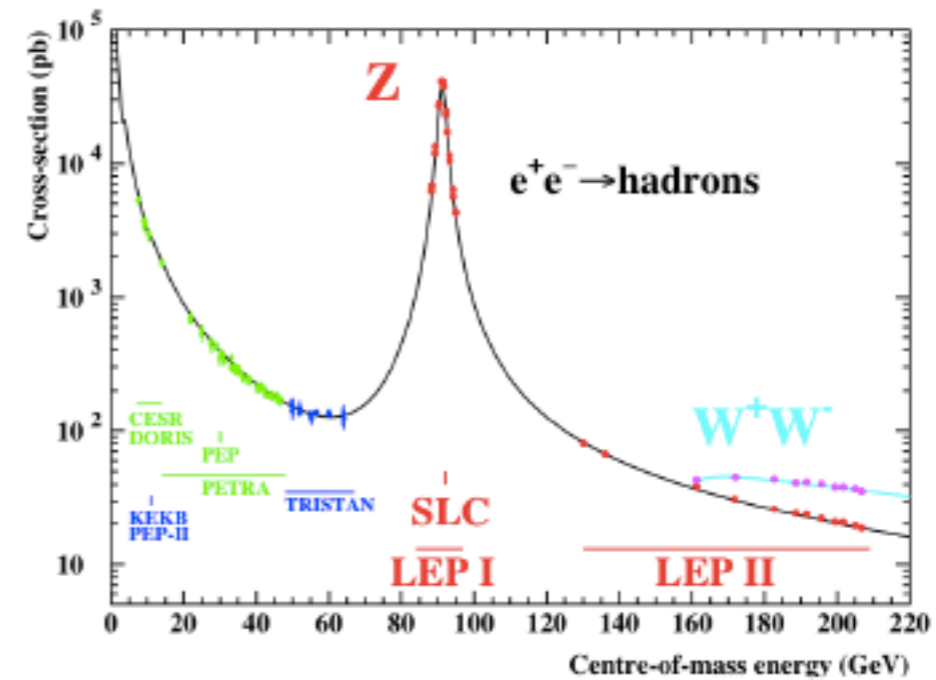
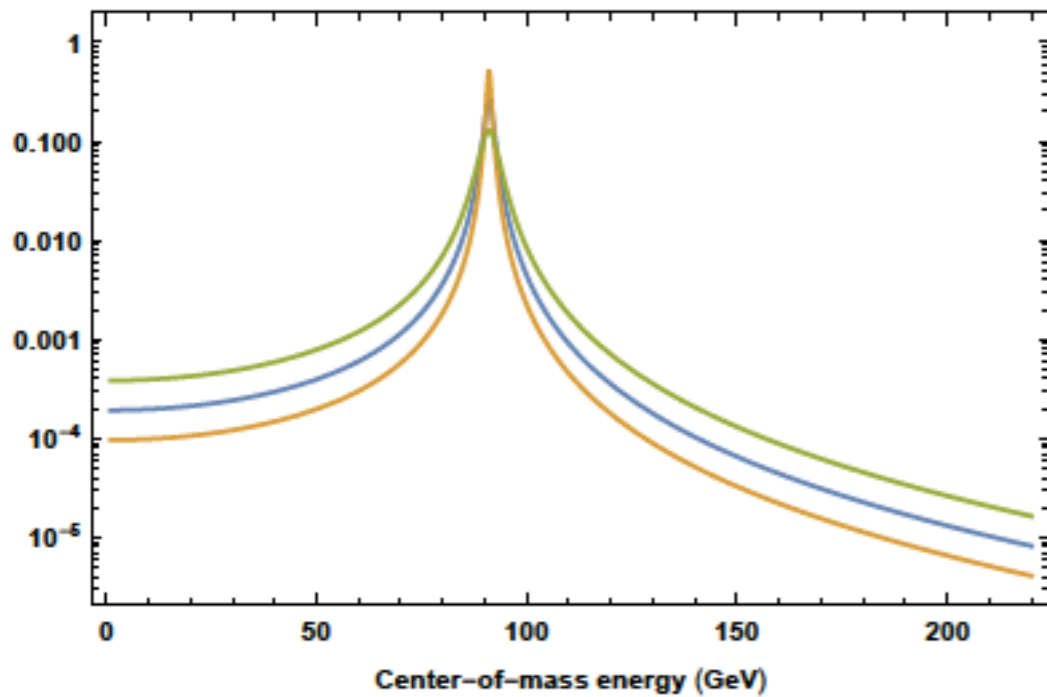
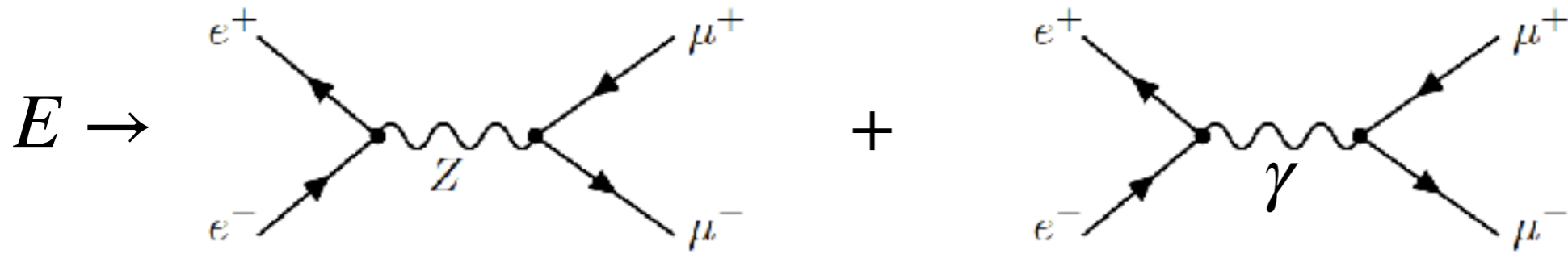


Wahrscheinlichkeit: $\left| e^{iS[P_1]} + e^{iS[P_2]} \right|^2$

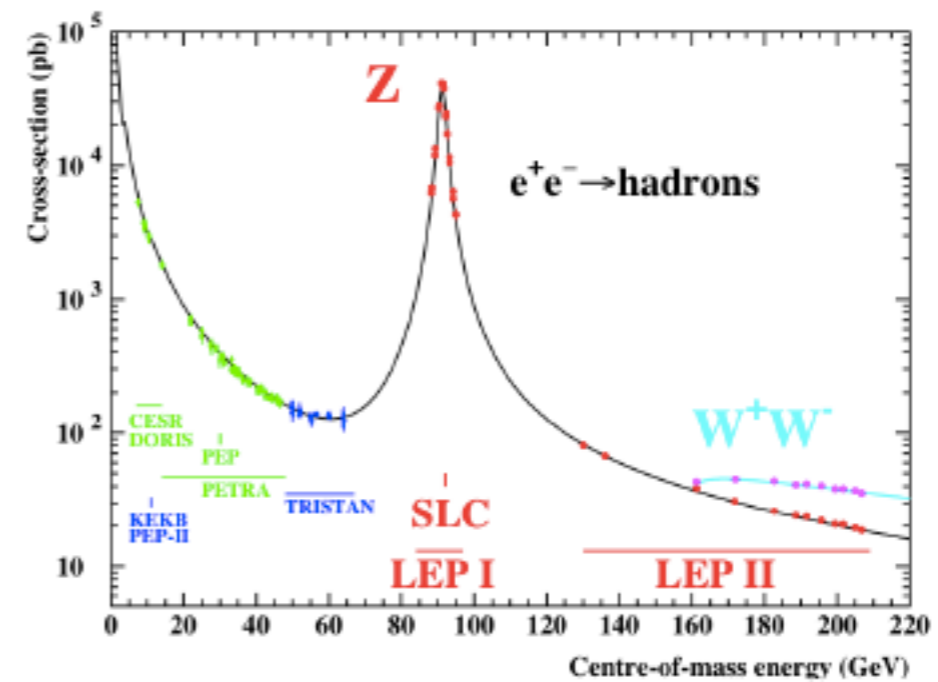
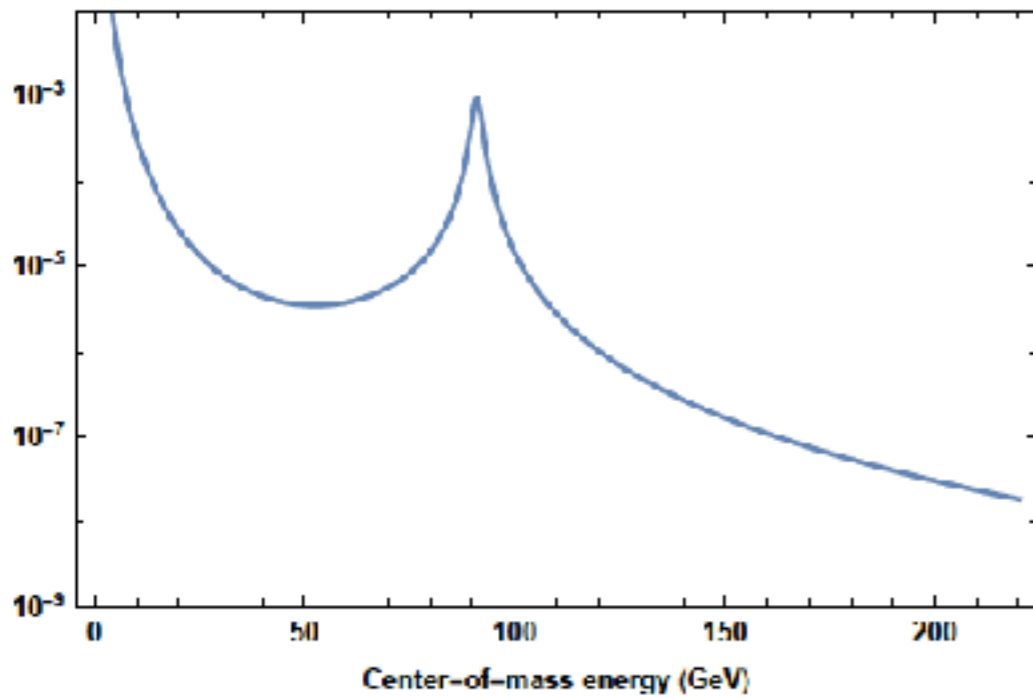
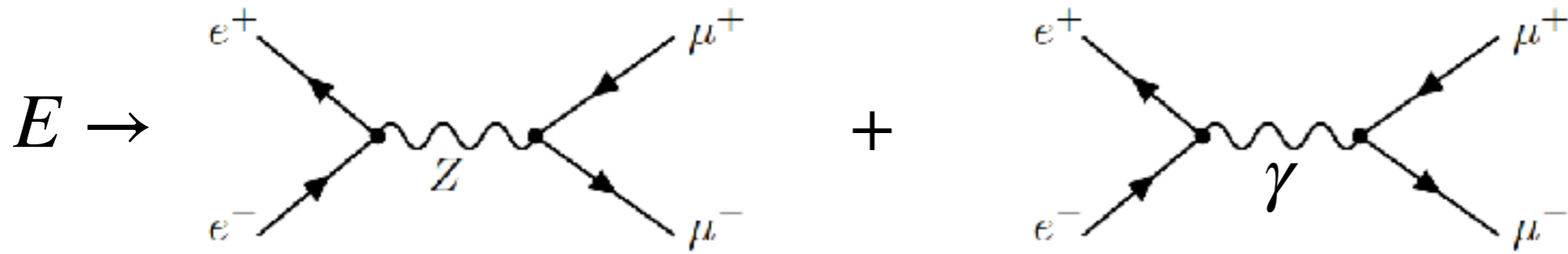
Wirkungsquerschnitte



Wirkungsquerschnitte

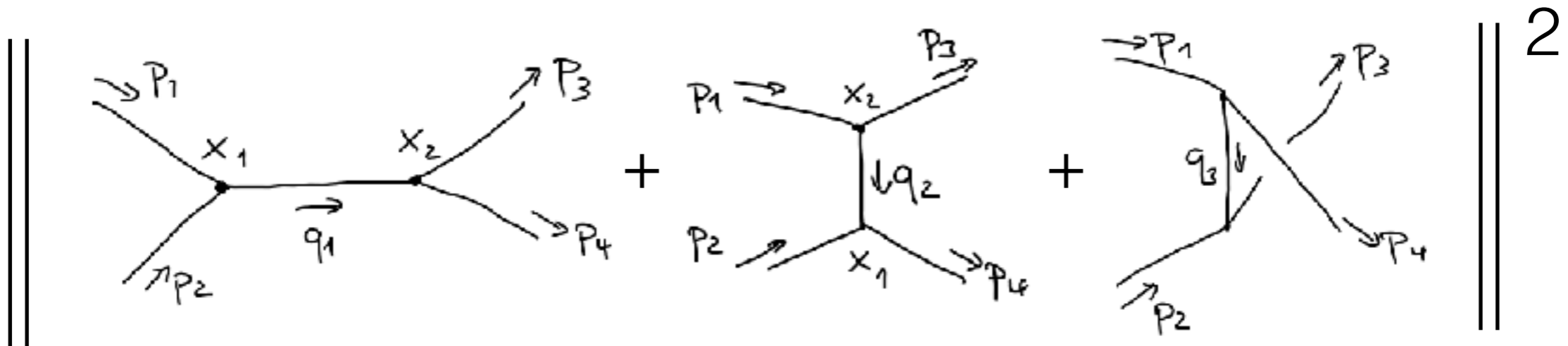


Wirkungsquerschnitte



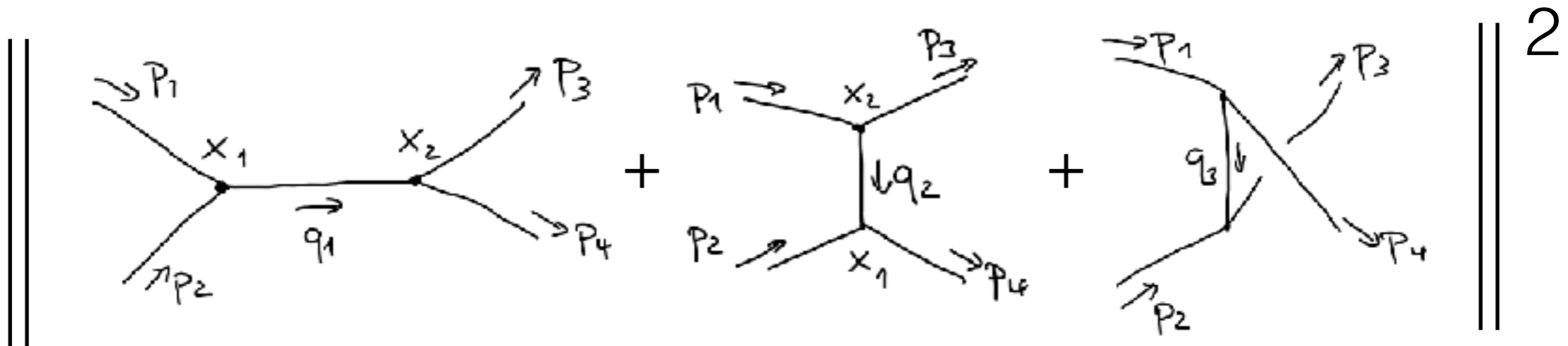
Wirkungsquerschnitte

Summe über Feynman-Diagramme, quadriert



Wirkungsquerschnitte

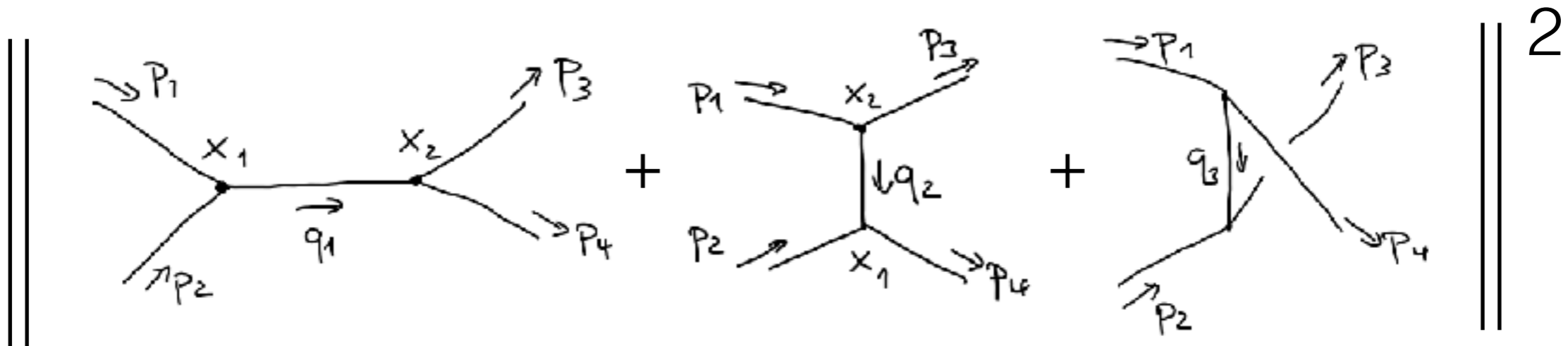
Summe über Feynman-Diagramme, quadriert



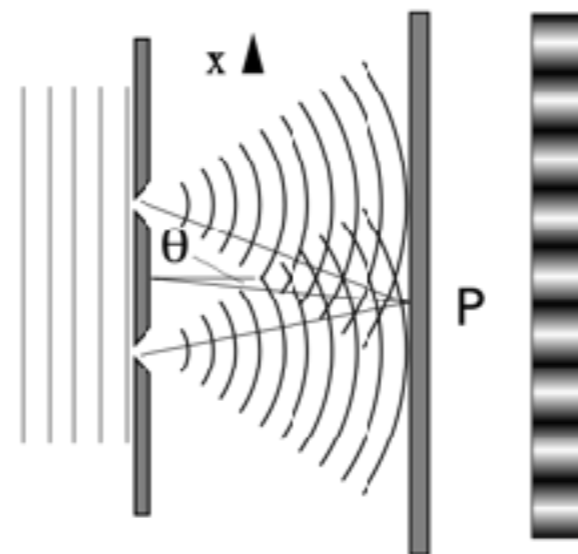
Interferenz-Effekte!

Wirkungsquerschnitte

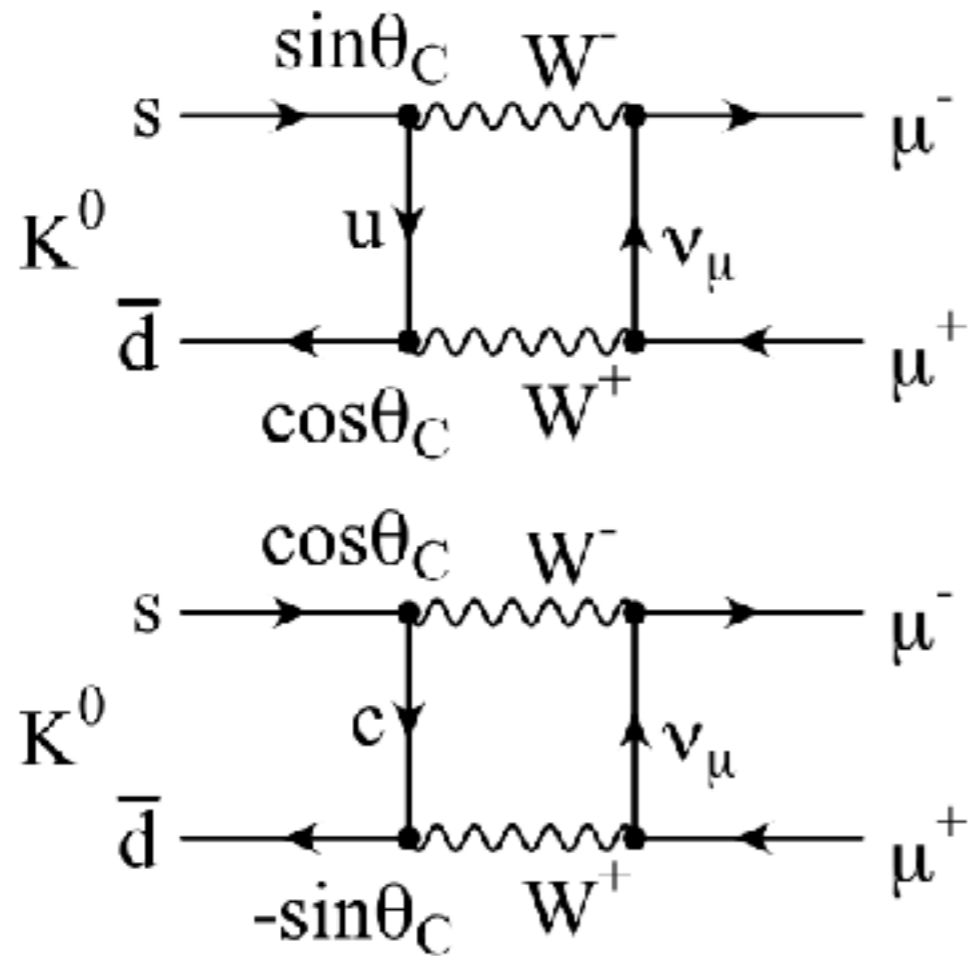
Summe über Feynman-Diagramme, quadriert



Interferenz-Effekte!



Interferenz-Effekte



Flavor-changing neutral currents

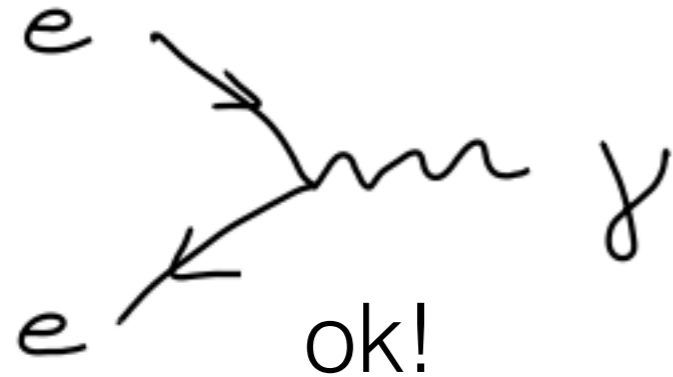
GIM-Mechanismus
(Glashow-Iliopoulos-Maiani)

→ destruktive Interferenz

Vorhersage des Charm-Quarks

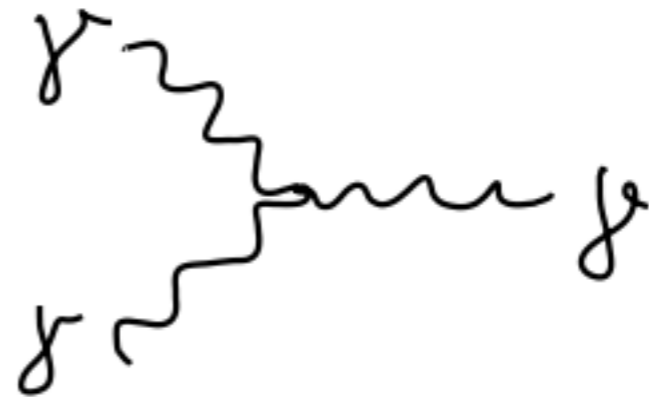
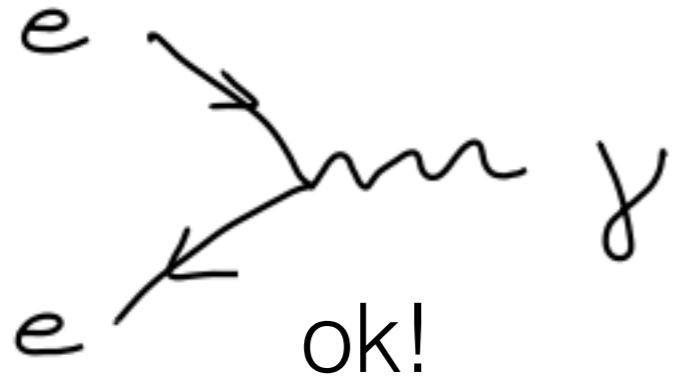
Schleifen-Diagramme

Photonen koppeln an elektrische Ladung



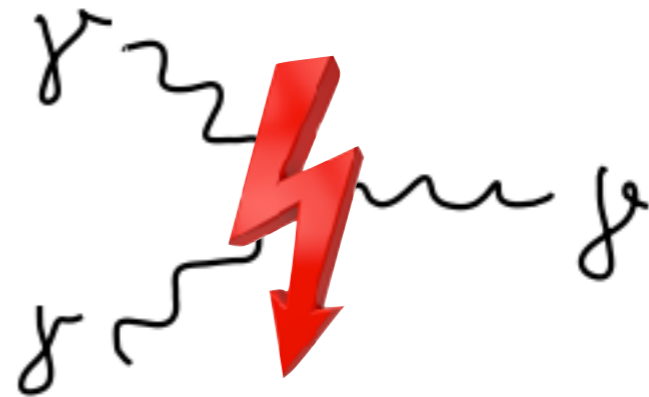
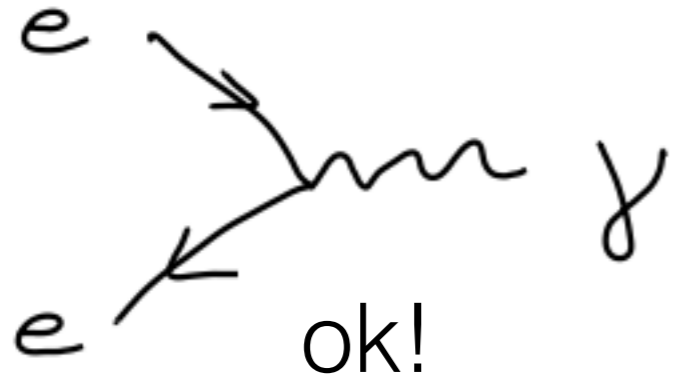
Schleifen-Diagramme

Photonen koppeln an elektrische Ladung



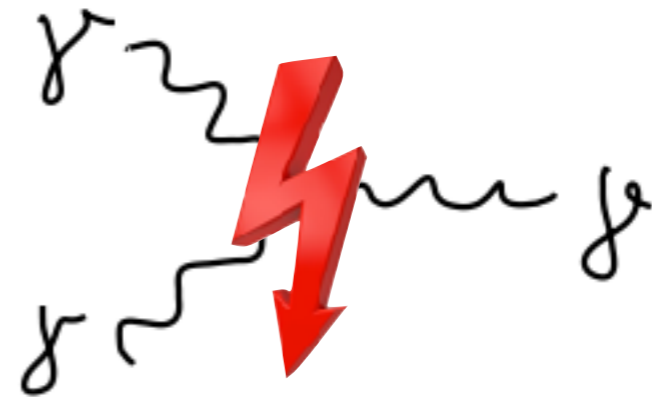
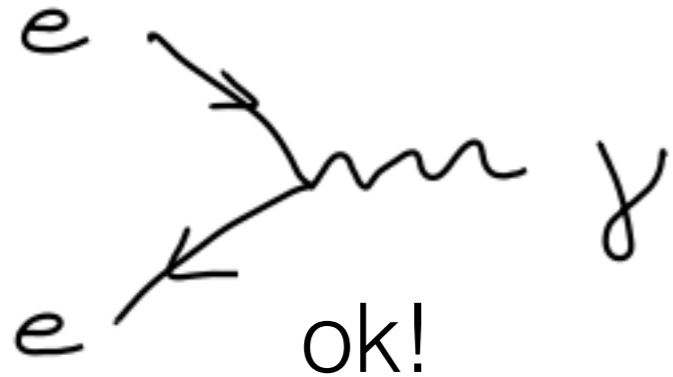
Schleifen-Diagramme

Photonen koppeln an elektrische Ladung



Schleifen-Diagramme

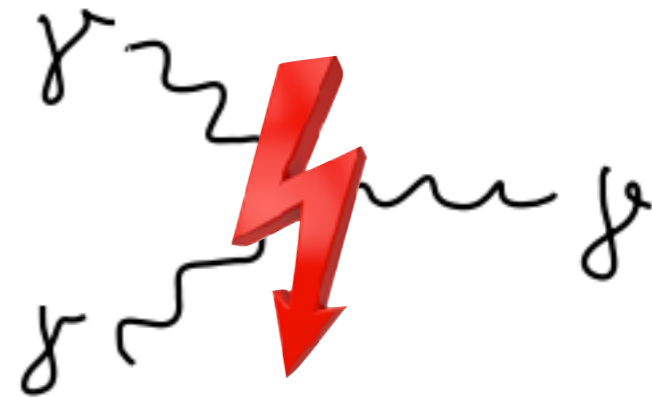
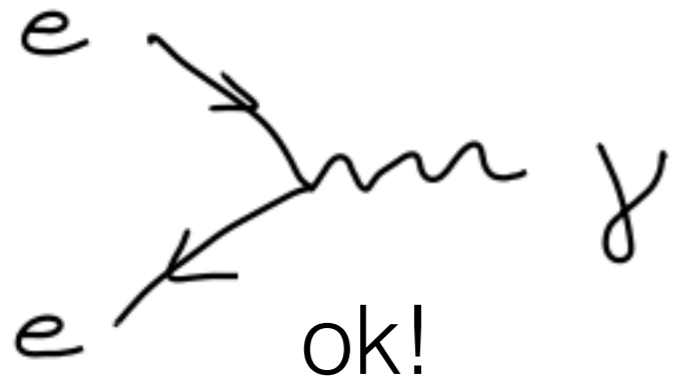
Photonen koppeln an elektrische Ladung



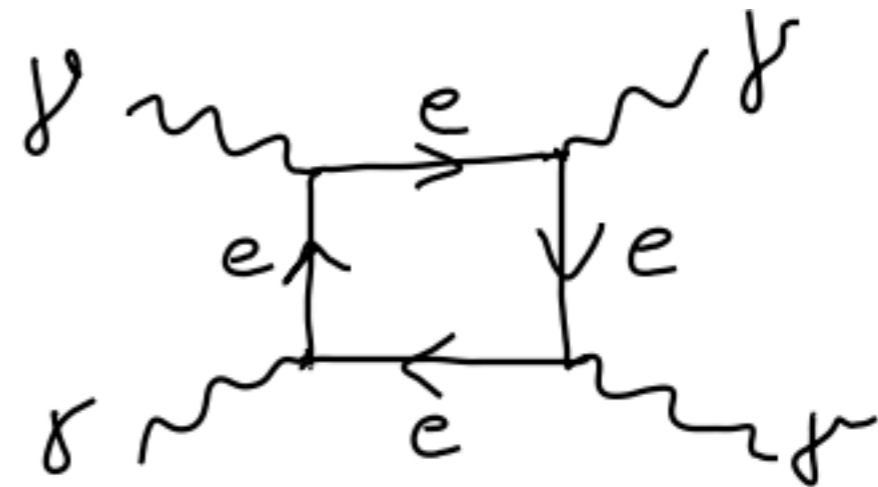
Licht-Licht-Streuung:
Schleifen-induziert!

Schleifen-Diagramme

Photonen koppeln an elektrische Ladung

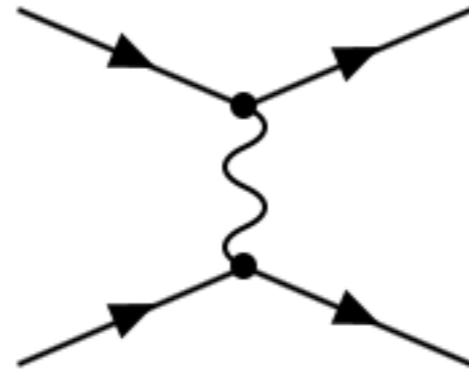


Licht-Licht-Streuung:
Schleifen-induziert!



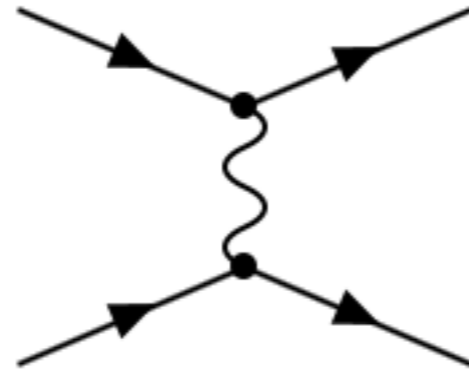
(Fehl?) Interpretation

Betrachte Elektron-Elektron-Streuung:



(Fehl?) Interpretation

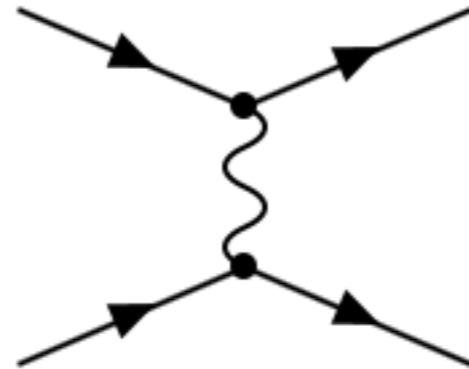
Betrachte Elektron-Elektron-Streuung:



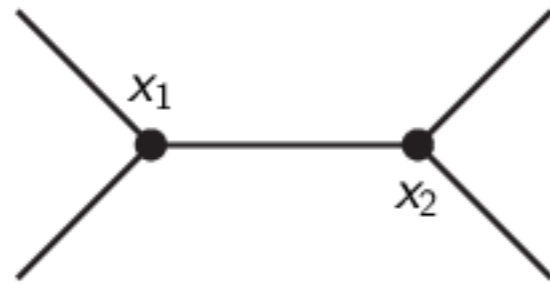
-
-

(Fehl?) Interpretation

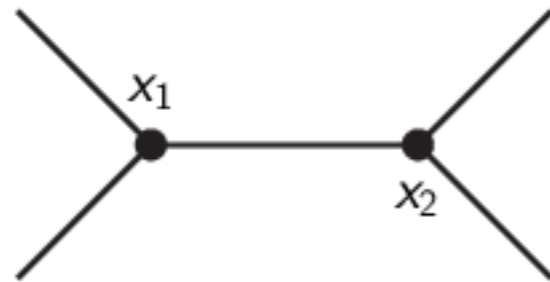
Betrachte Elektron-Elektron-Streuung:



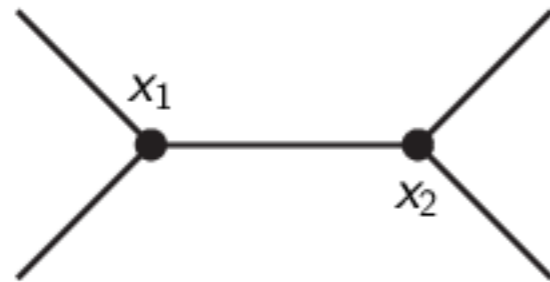
(Fehl?) Interpretation



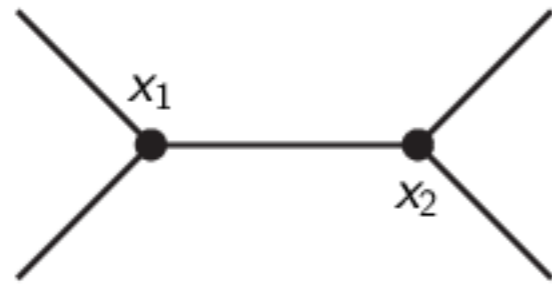
(Fehl?) Interpretation



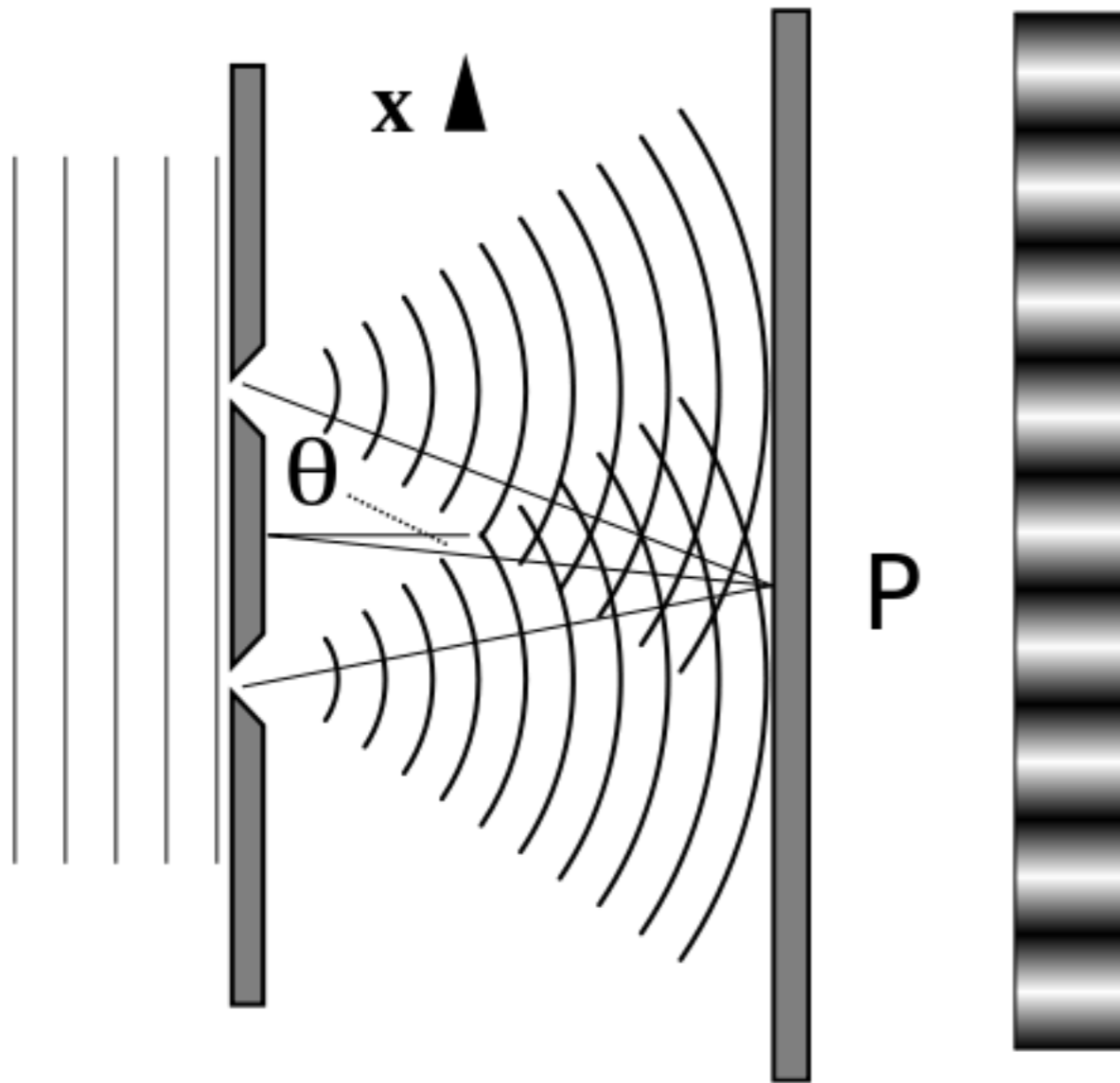
(Fehl?) Interpretation



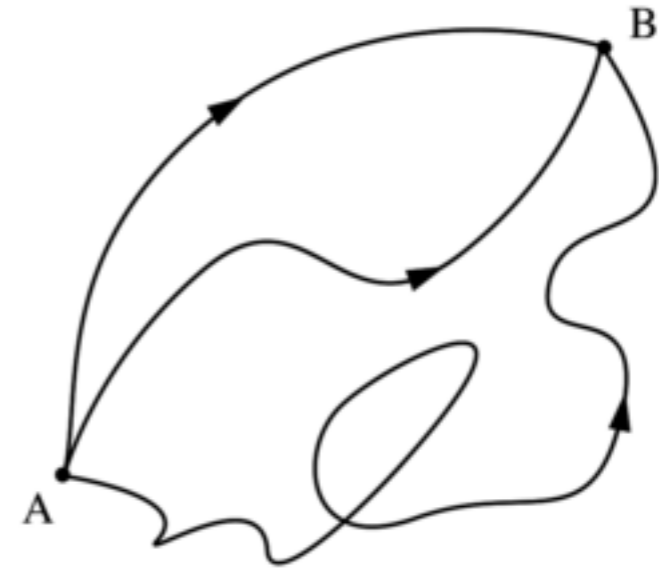
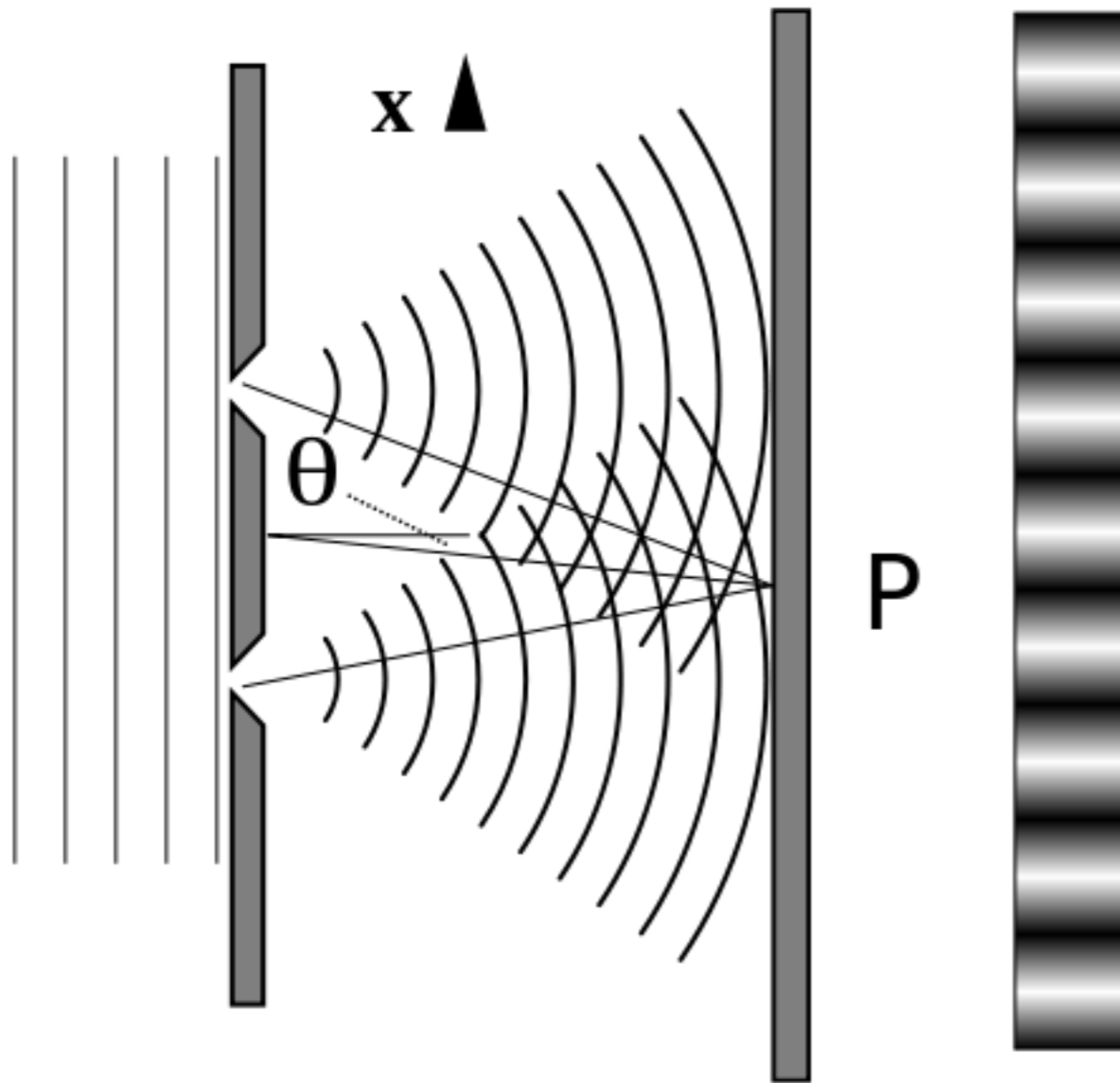
(Fehl?) Interpretation



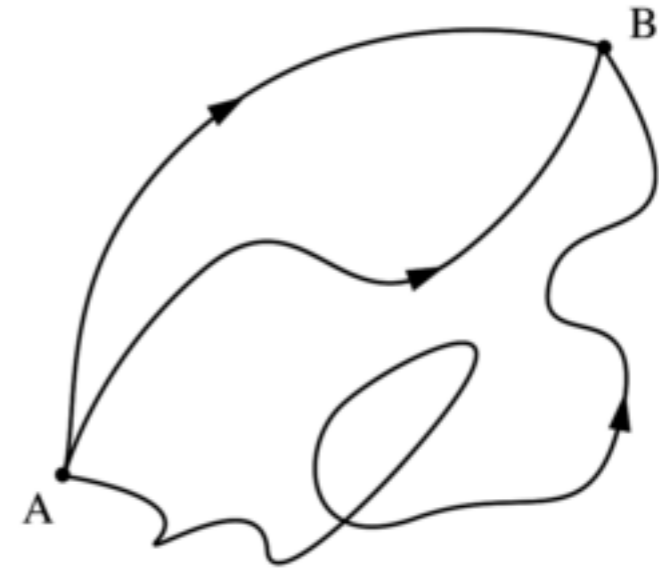
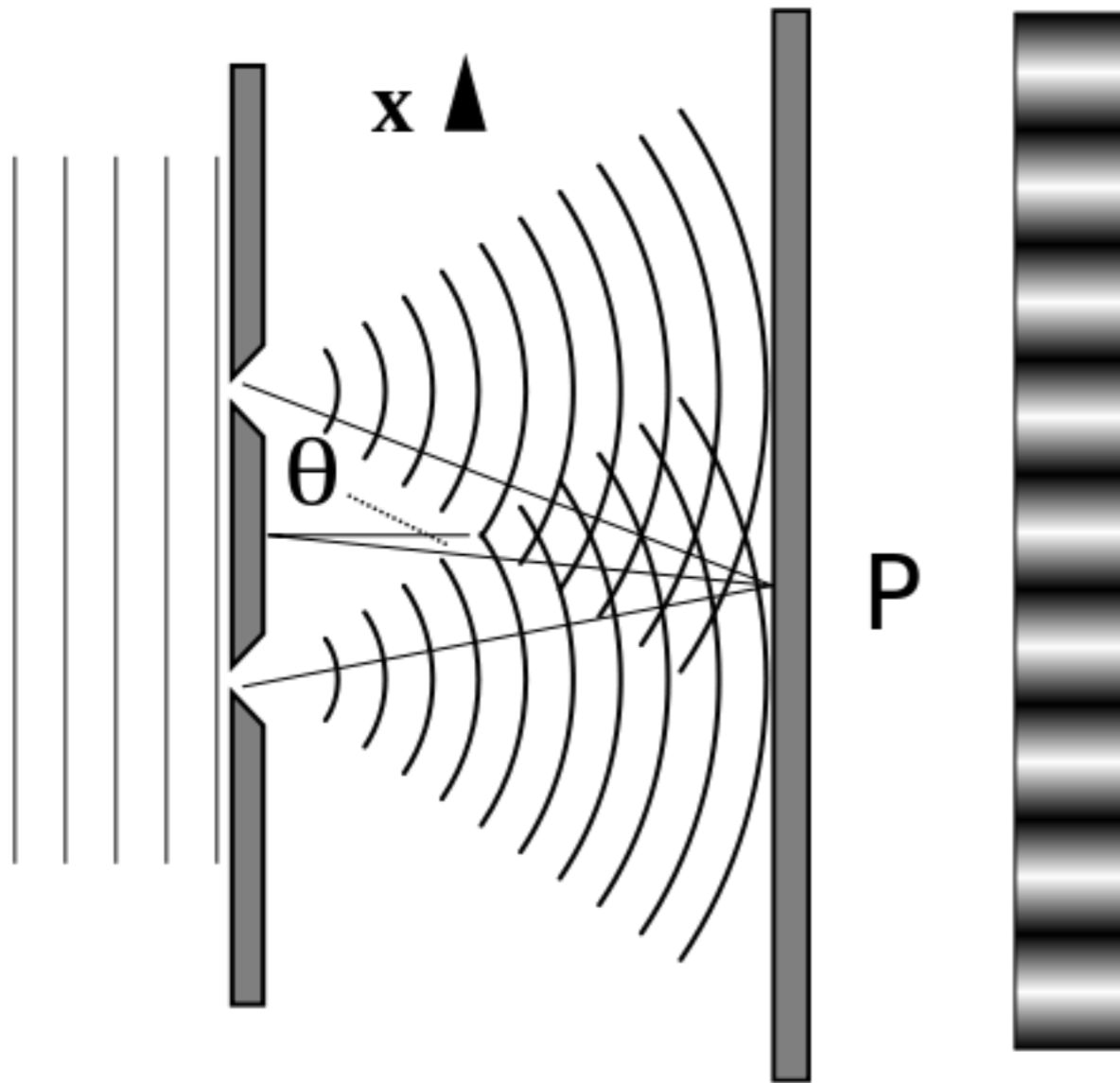
Interpretation



Interpretation



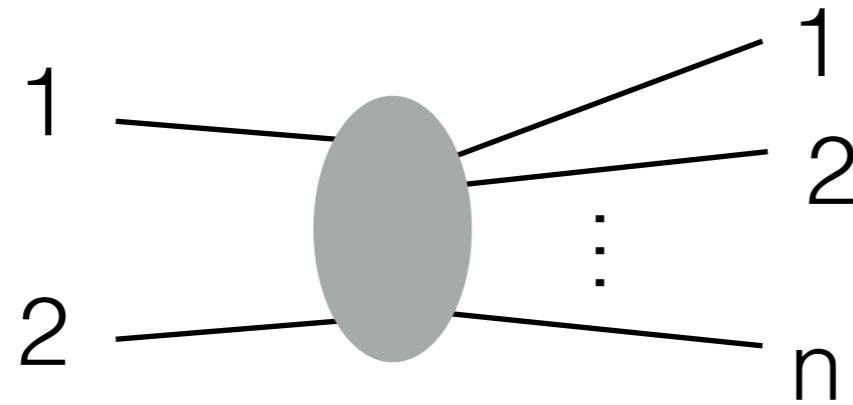
Interpretation



$$Z(B, A) = \mathcal{N} \int \mathcal{D}q \exp\left(\frac{i}{\hbar} S\right)$$

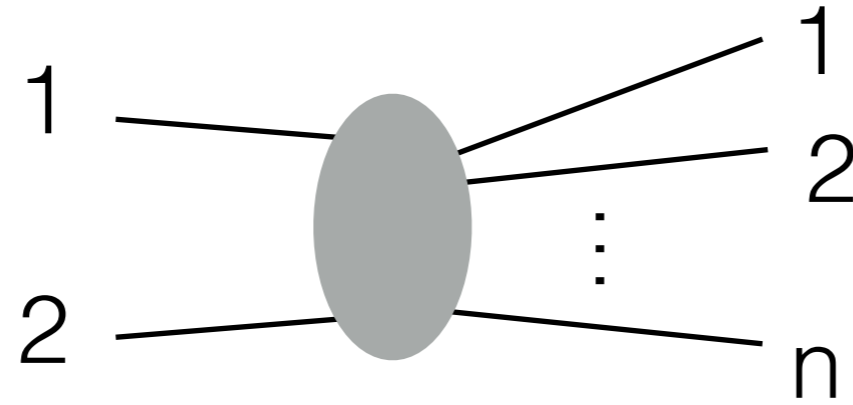
Pfadintegral

Formeln...



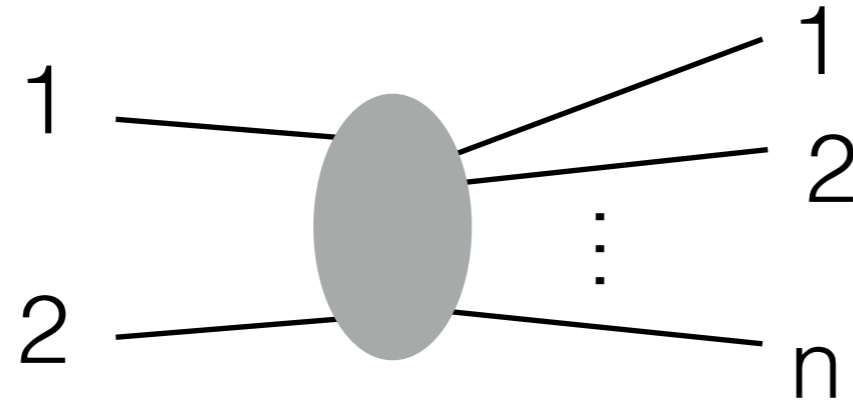
Formeln...

$$P_i = p_1 + p_2$$



Formeln...

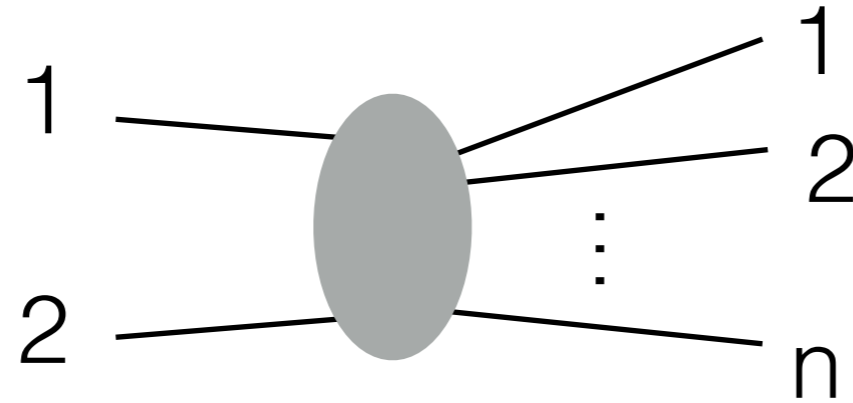
$$P_i = p_1 + p_2$$



$$P_f = p'_1 + p'_2 + \dots + p'_n$$

Formeln...

$$P_i = p_1 + p_2$$



$$P_f = p'_1 + p'_2 + \dots + p'_n$$

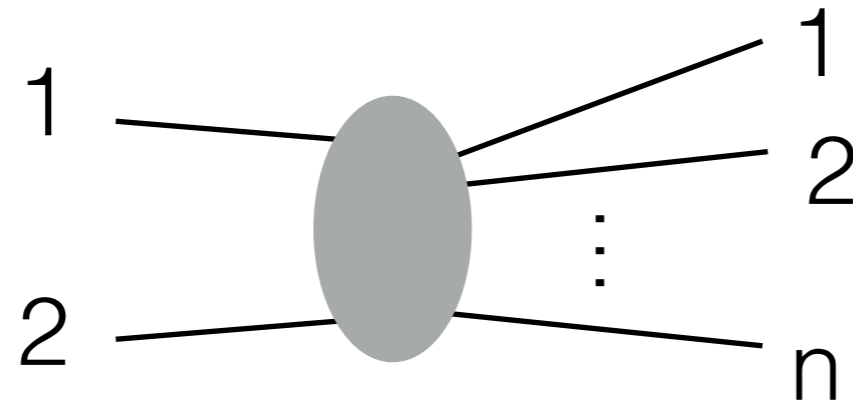
Wirkungsquerschnitt:

$$d\sigma = \frac{1}{4E_1 E_2 |\vec{v}_1 - \vec{v}_2|} |\mathcal{M}_{fi}|^2 d\Gamma_{\text{LIPS}}$$

$$d\Gamma_{\text{LIPS}} = (2\pi)^4 \delta(P_f - P_i) \prod_{j=3}^n \frac{d^3 p_j}{(2\pi)^3 2E_j}$$

Formeln...

$$P_i = p_1 + p_2$$



$$P_f = p'_1 + p'_2 + \dots + p'_n$$

Wirkungsquerschnitt:

$$d\sigma = \frac{1}{4E_1 E_2 |\vec{v}_1 - \vec{v}_2|} |\mathcal{M}_{fi}|^2 d\Gamma_{\text{LIPS}}$$

$$d\Gamma_{\text{LIPS}} = (2\pi)^4 \delta(P_f - P_i) \prod_{j=3}^n \frac{d^3 p_j}{(2\pi)^3 2E_j}$$

$$S = \alpha 1 + i\mathcal{T},$$

$$\langle f | \mathcal{T} | i \rangle = (2\pi)^4 \delta(P_f - P_i) \langle f | \mathcal{M} | i \rangle$$

← \mathcal{M}_{fi}

... mehr Formeln ...

$$\langle \mathcal{F} | S | i \rangle = 2^{n/2} \sqrt{E_1 \cdots E_n} \lim_{T_i \rightarrow \infty} \langle \Omega | \underbrace{a_n a_{n-1} \cdots a_{-1}^+ a_{-2}^+}_{\text{already time-ordered}} | \Omega \rangle = T(\dots)$$

... mehr Formeln ...

$$\langle \mathcal{F} | S | i \rangle = 2^{n/2} \sqrt{E_1 \cdots E_n} \lim_{T_i \rightarrow \infty} \langle \Omega | \underbrace{a_n a_{n-1} \cdots a_{-1}^+ a_{-2}^+}_{\text{already time-ordered}} | \Omega \rangle$$

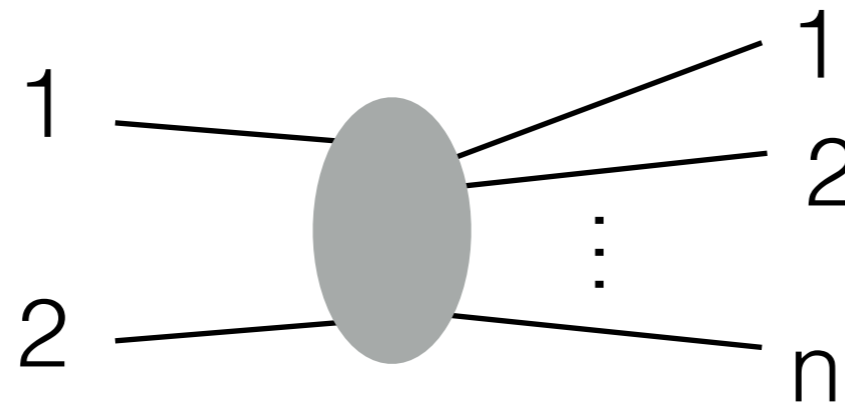
$= T(\dots)$

$$= \left[i \int d^4 x_1 e^{-i p_1 x_1} (\square_1 + m^2) \right] \cdots \left[i \int d^4 x_n e^{+i p_n x_n} (\square_n + m^2) \right]$$
$$\times \langle \Omega | T \phi(x_1) \cdots \phi(x_n) | \Omega \rangle$$

LSZ reduction formula

... noch mehr Formeln ...

$$\langle \Omega | T \phi(x_1) \dots \phi(x_n) | \Omega \rangle =$$
$$= \frac{\langle 0 | T \phi_0(x_1) \dots \phi_0(x_n) \exp(i \int d^4x \mathcal{L}_{int}(\phi_0)) | 0 \rangle}{\langle 0 | T \exp(i \int d^4x \mathcal{L}_{int}(\phi_0)) | 0 \rangle}$$



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