

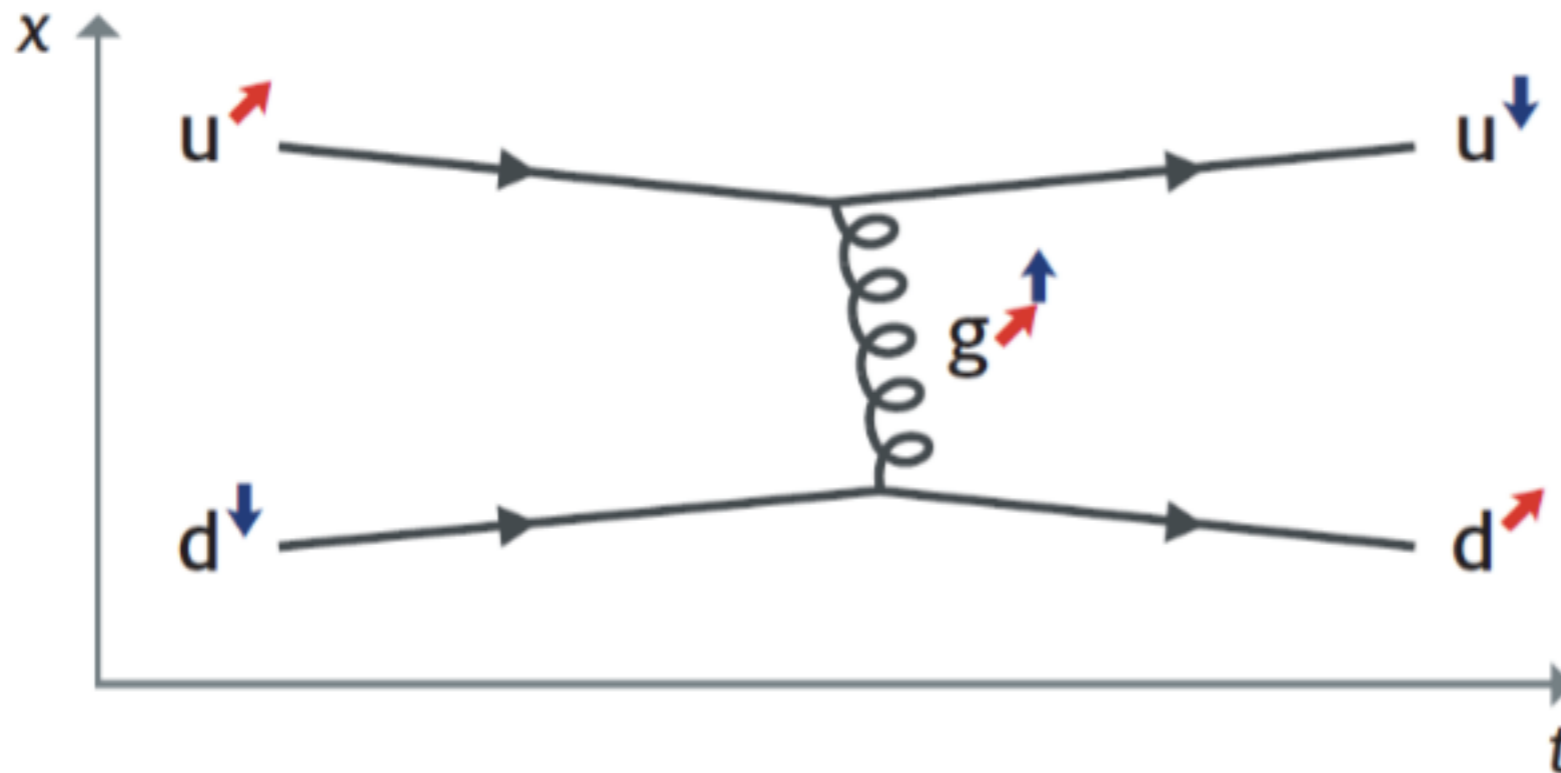
Quantenfeldtheorie

... in 90 Minuten

Robert Harlander

RWTH Aachen University

Ziele



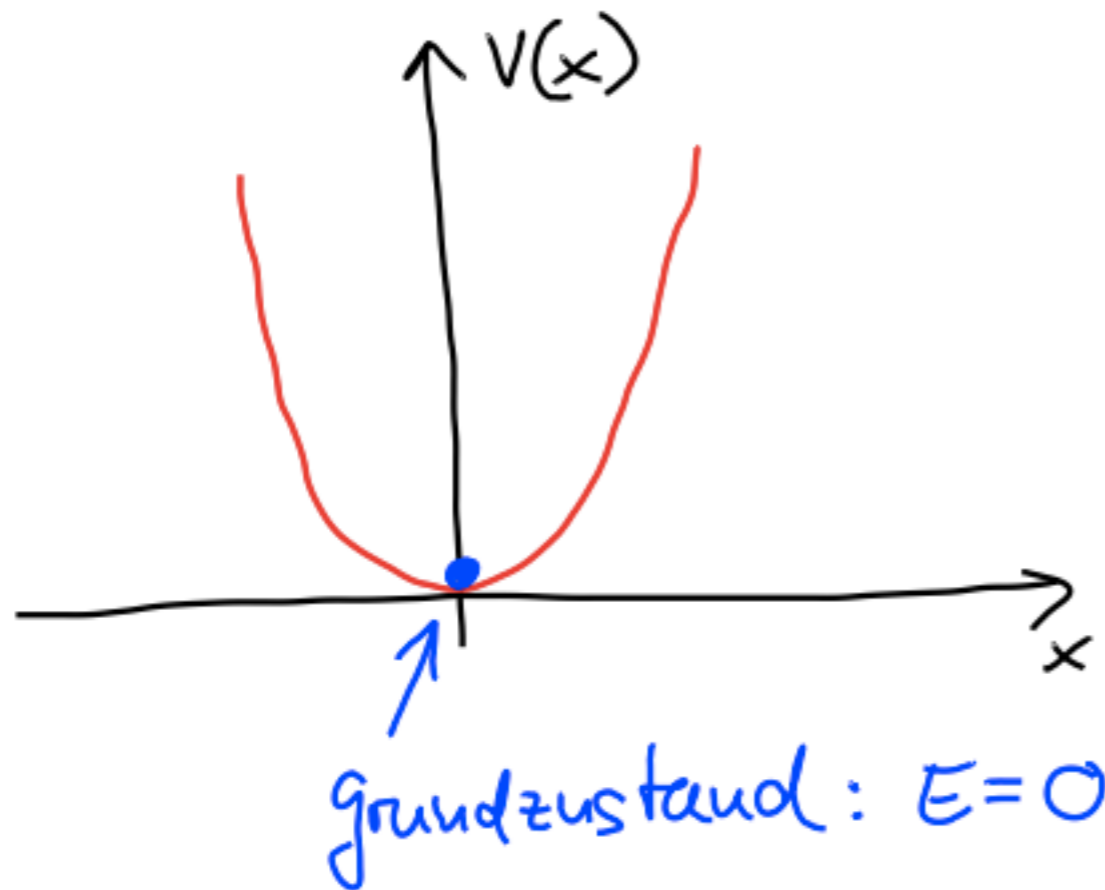
- Wo kommt das her?
- Was kann man damit machen?
- Wie kann man das interpretieren?

Harmonischer Oszillator

klassische Mechanik:

$$V(x) = \frac{1}{2} k x^2 \quad \omega = \sqrt{\frac{k}{M}}$$

$$E = \frac{M}{2} (\dot{x}^2 + \omega^2 x^2)$$



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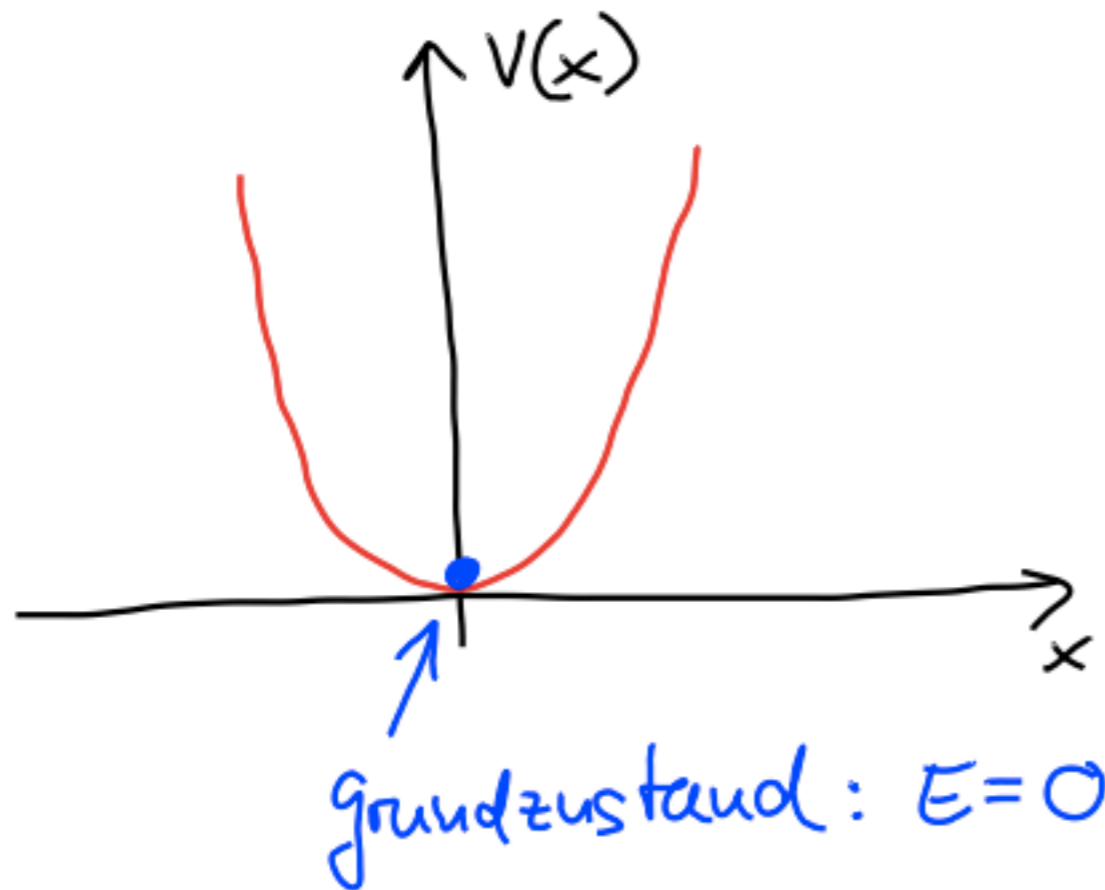
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Lagrangefunktion:

$$L = \frac{M}{2} (\dot{x}^2 - \omega^2 x^2)$$



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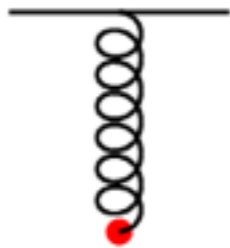
Lösung: $x(t) = A \cos(\omega t + \varphi)$

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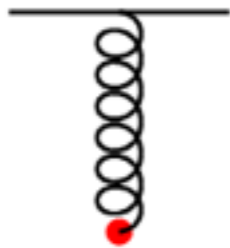
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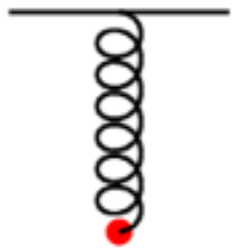
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Quantenmechanik

Hamiltonfunktion

Quantenmechanik

Hamiltonoperator

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Eigenwerte von \hat{H} = mögliche Energiewerte des Systems

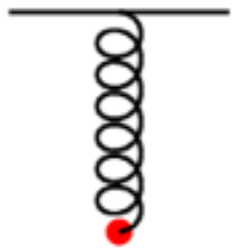
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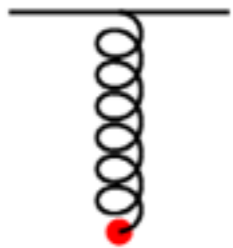
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Definiere:
$$a = \sqrt{\frac{m\omega}{2\hbar}} \left(\hat{X} + \frac{i}{m\omega} \hat{P} \right)$$

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$$\Leftrightarrow [a, a^\dagger] := aa^\dagger - a^\dagger a = 1$$

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$$\hat{H} = \hbar\omega \left(a^\dagger a + \frac{1}{2} \right)$$

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

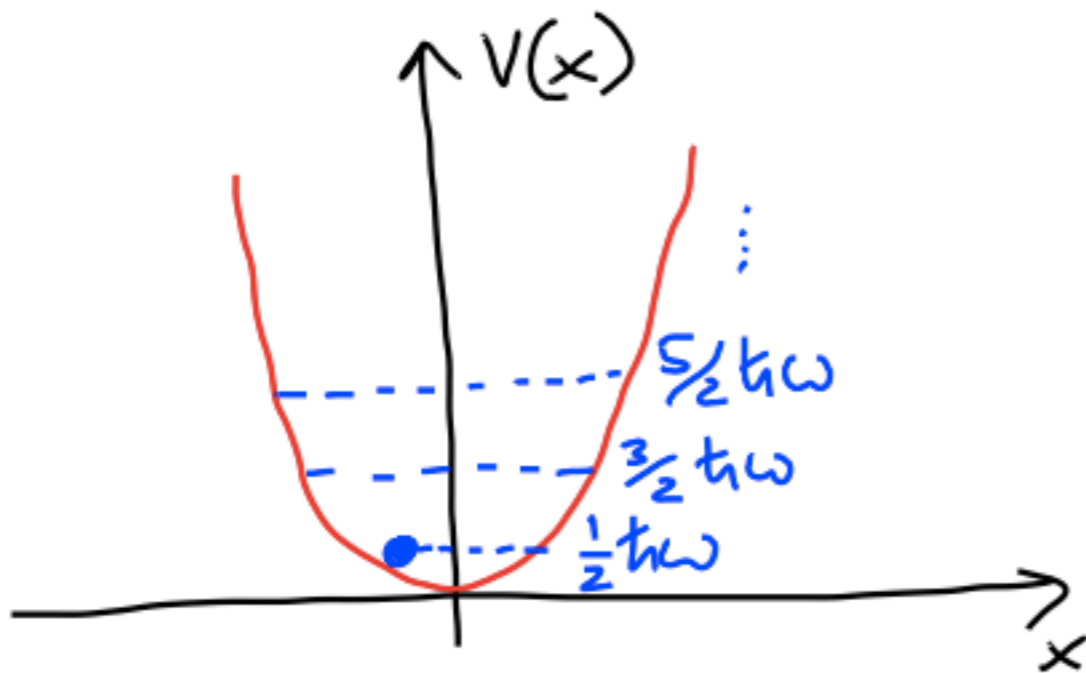
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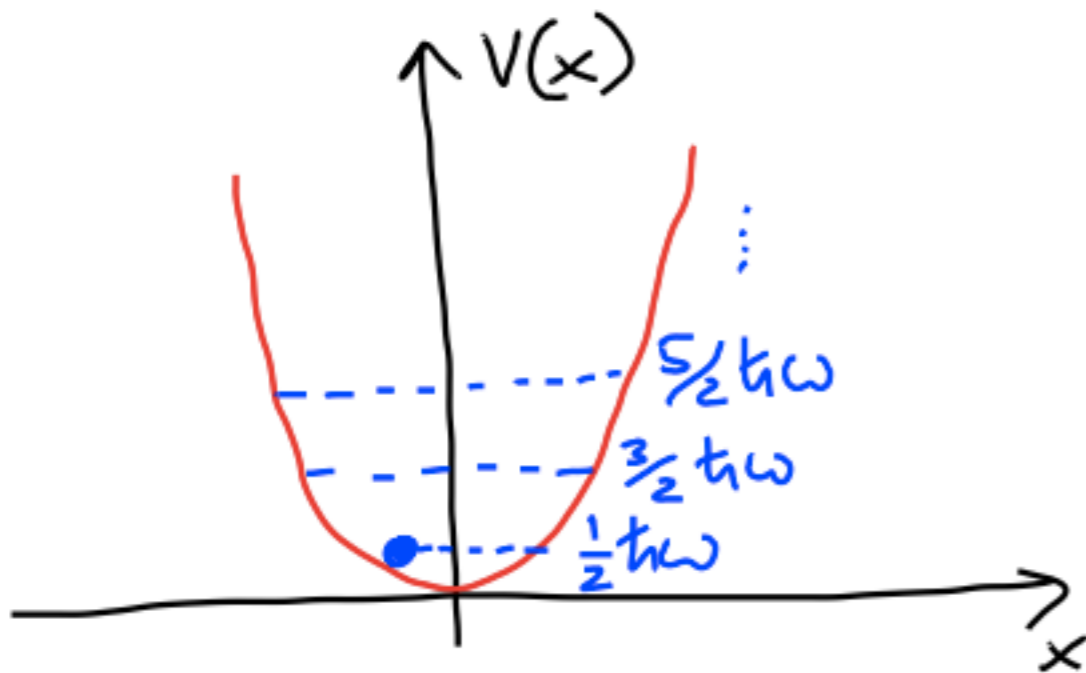
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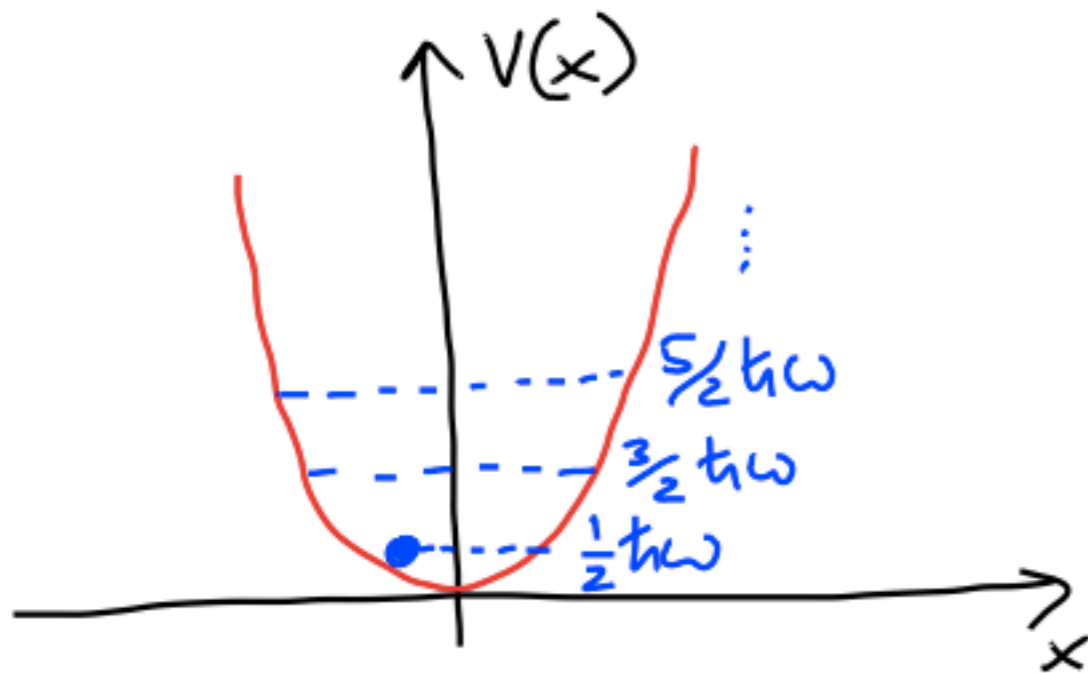
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$$a|n\rangle = \sqrt{n}|n-1\rangle$$

$$a^\dagger|n\rangle = \sqrt{n+1}|n+1\rangle$$

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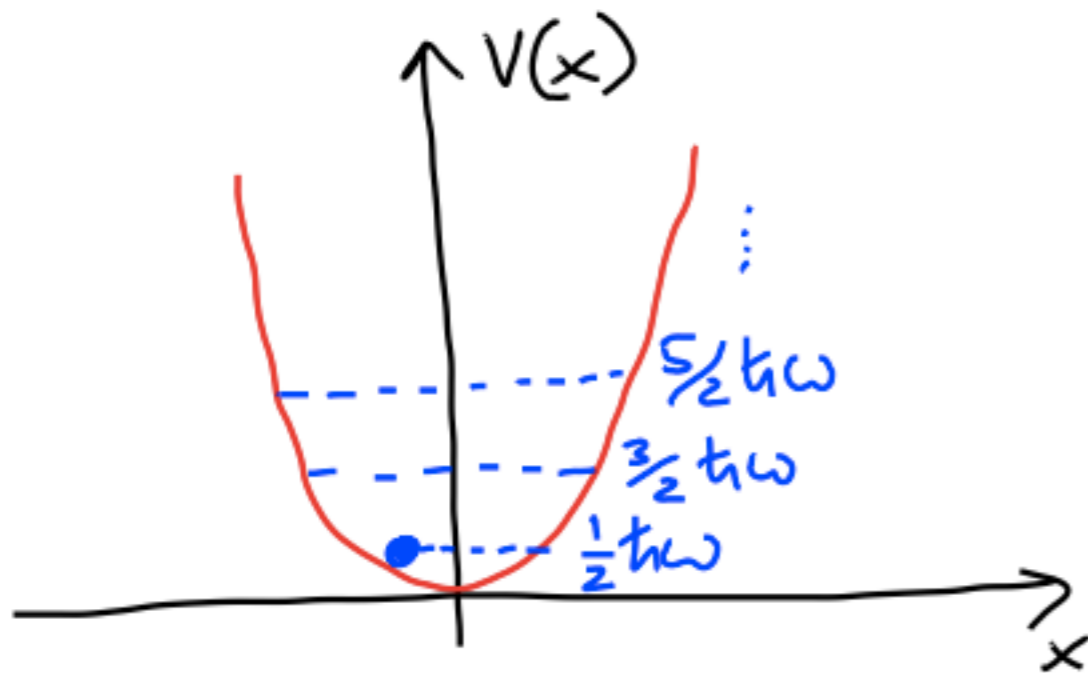
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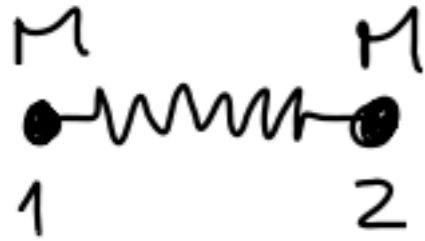
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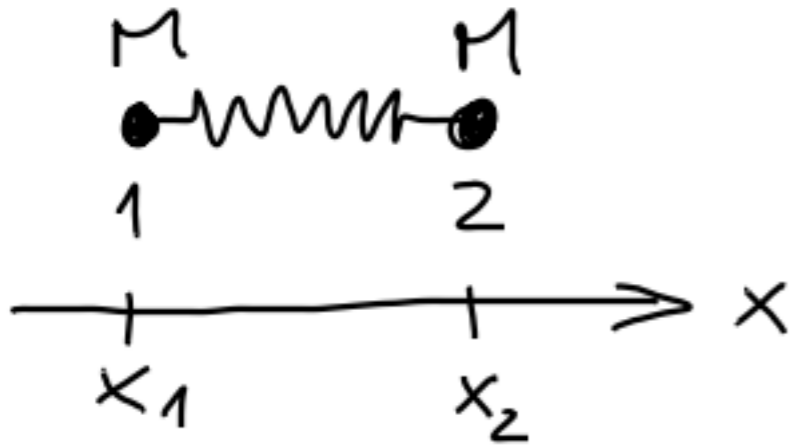
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beachte: $a|0\rangle = 0$

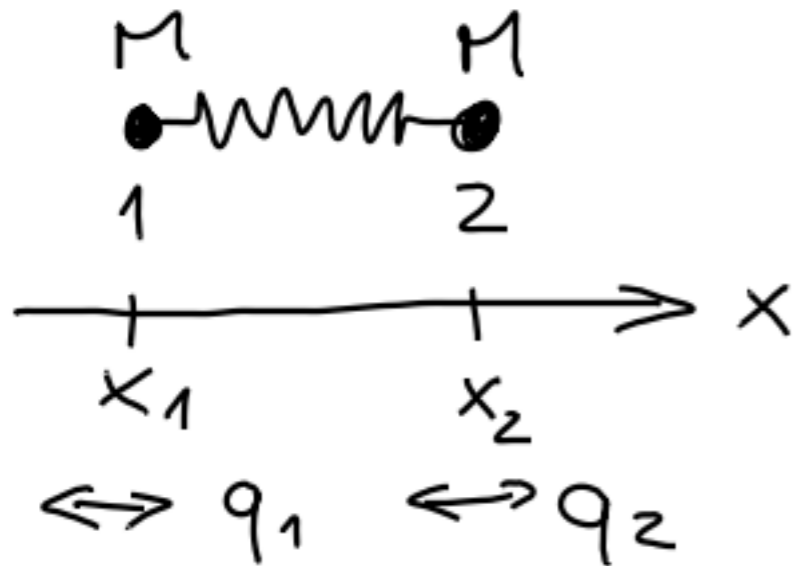
Gekoppelte Massen



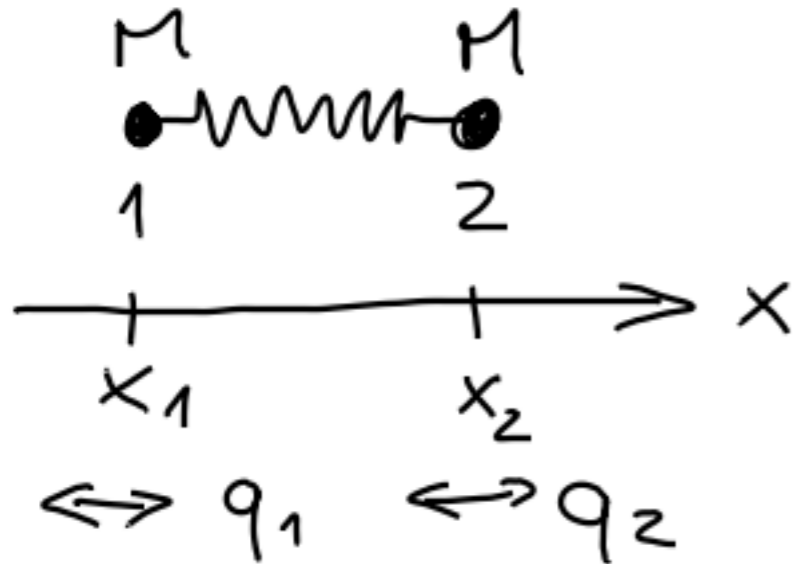
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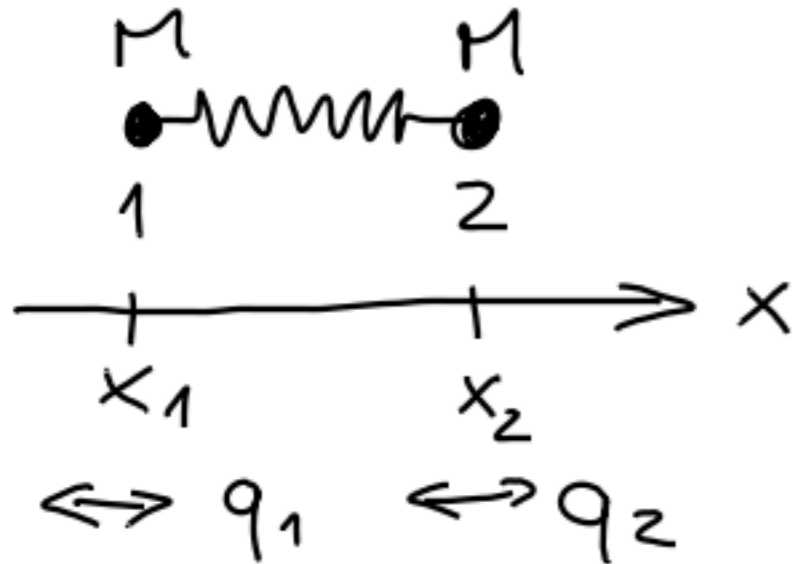


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$$E_{\text{kin}} = \frac{M}{2} (\dot{q}_1^2 + \dot{q}_2^2)$$

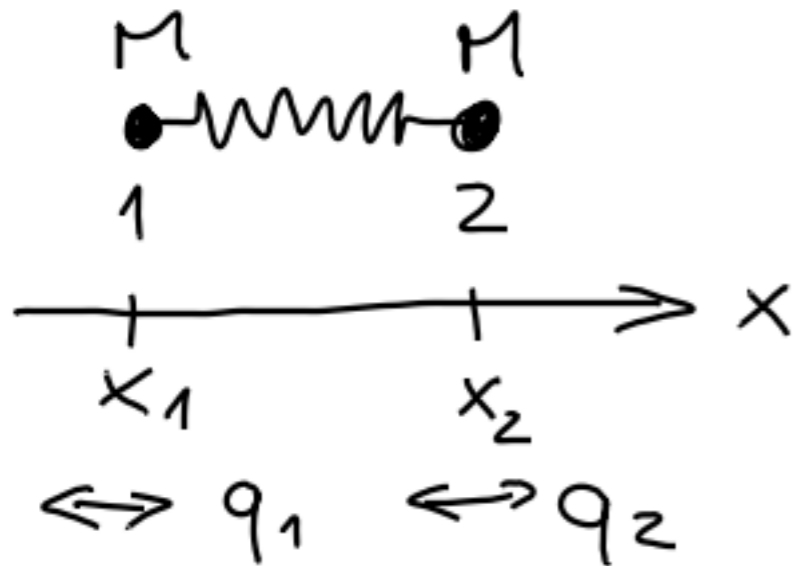
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$$E_{\text{kin}} = \frac{M}{2} (\dot{q}_1^2 + \dot{q}_2^2)$$

$$V = \frac{k}{2} (q_1 - q_2)^2$$

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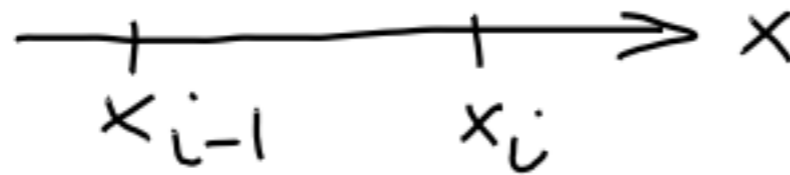
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$$L = E_{\text{kin}} - V = \frac{M}{2} \left[(\dot{q}_1^2 + \dot{q}_2^2) - \omega^2 (q_1 - q_2)^2 \right]$$

$$\omega = \sqrt{\frac{k}{M}}$$

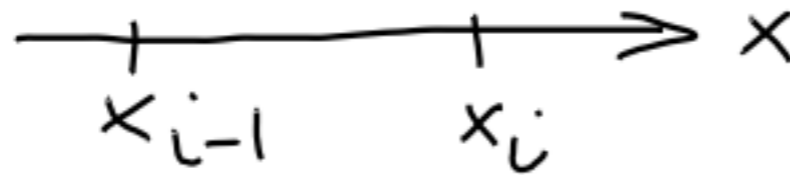
Lineare Kette



$$\Delta x = x_i - x_{i-1}$$

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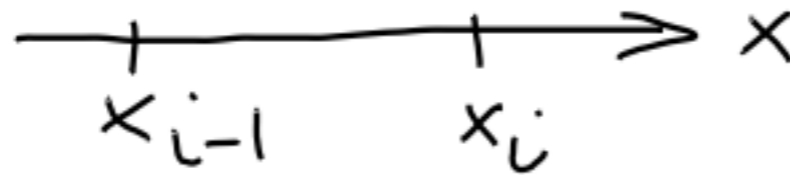


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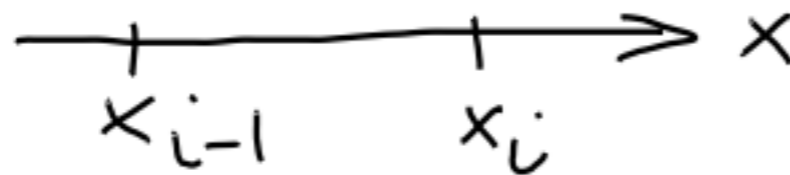
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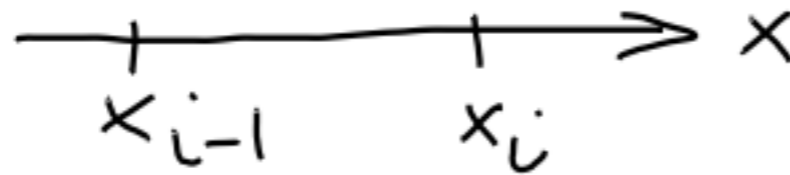
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$$q_i - q_{i-1} = q(x_i) - q(x_i - \Delta x) \xrightarrow{\Delta x \rightarrow 0} \frac{\partial q(x)}{\partial x} dx$$

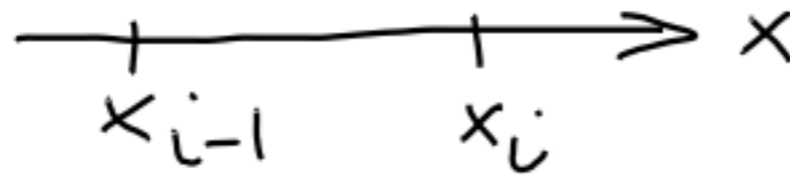
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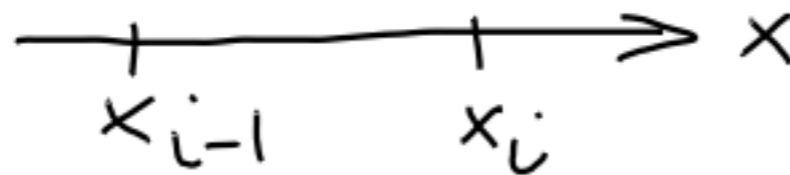


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Lineare Kette



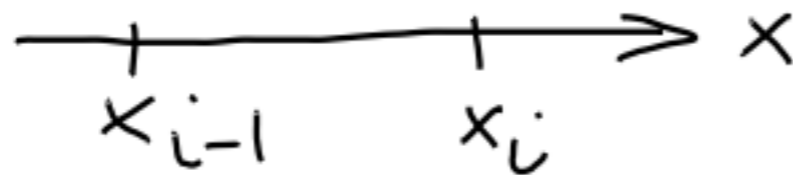
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Lagrangedichte

Lineare Kette



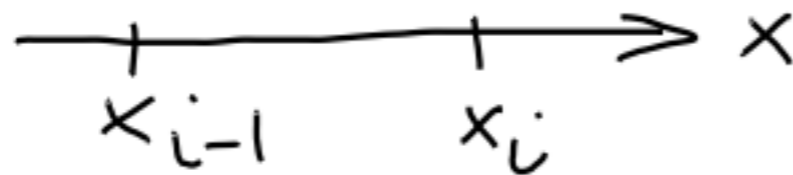
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Lagrangedichte $q(x)$: Feld

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Quantisierung: Quantenfeldtheorie

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Funktion von Koordinaten und Geschwindigkeiten.

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verallgemeinerten

\Rightarrow Relativistische Feldtheorie: $q(x), \partial_\mu q(x)$

Relativistische Felder

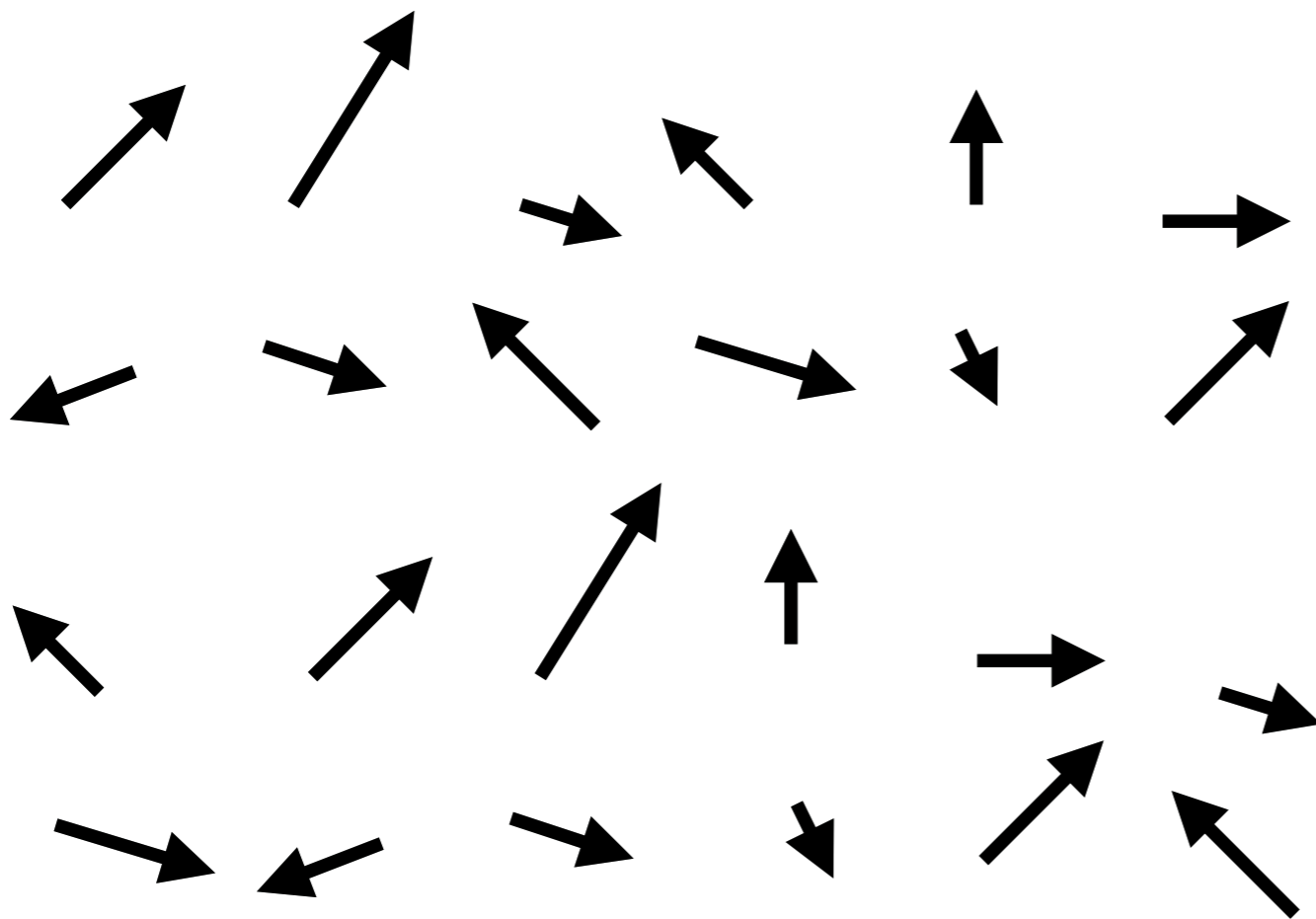
Transformation gemäß irreduzibler Darstellung
der Poincaré-Gruppe

(Drehungen, Boosts, Verschiebungen, Raum/Zeitspiegelungen)

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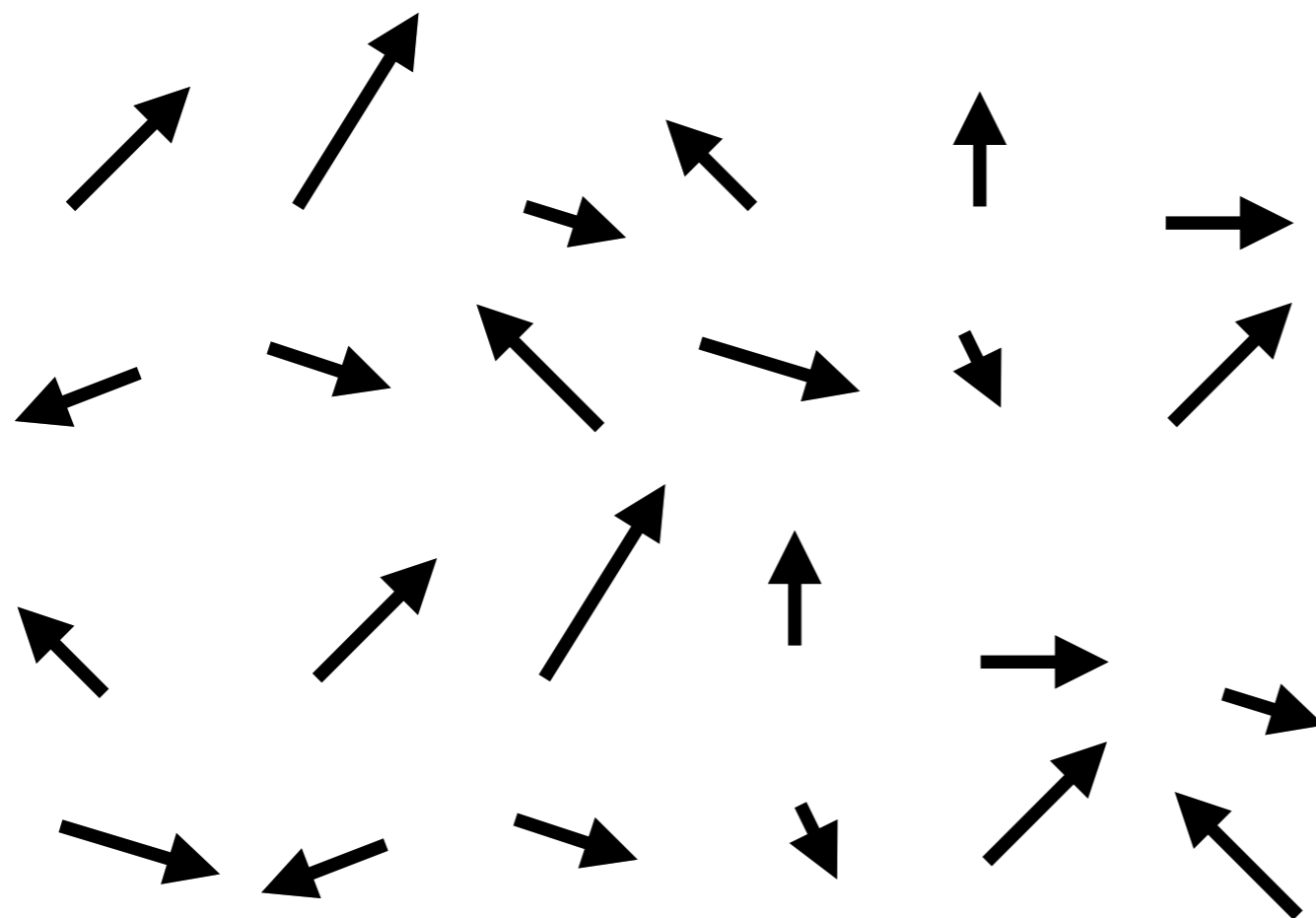
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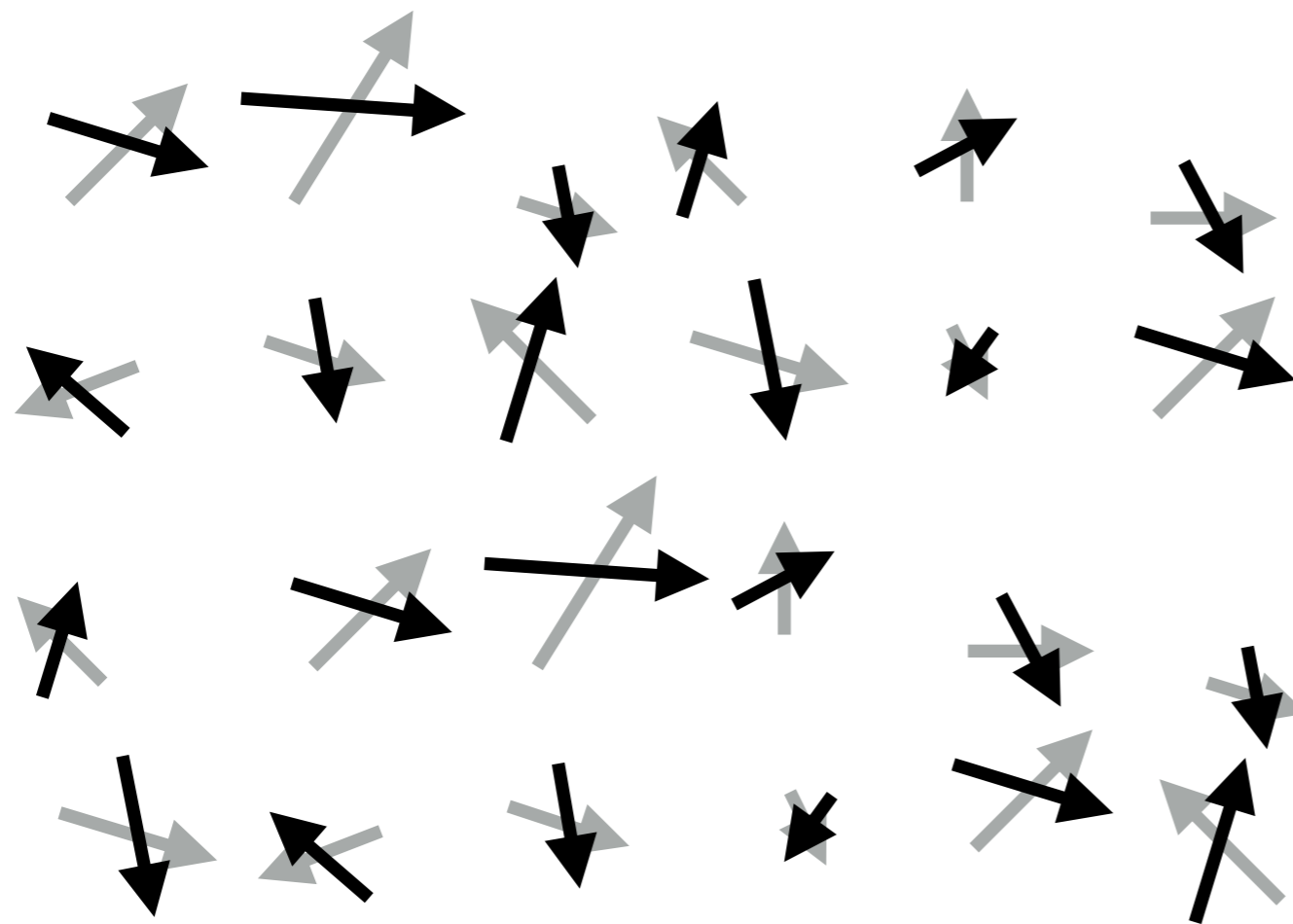


Rotation

Relativistische Felder

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der Poincaré-Gruppe

(Drehungen, Boosts, Verschiebungen, Raum/Zeitspiegelungen)

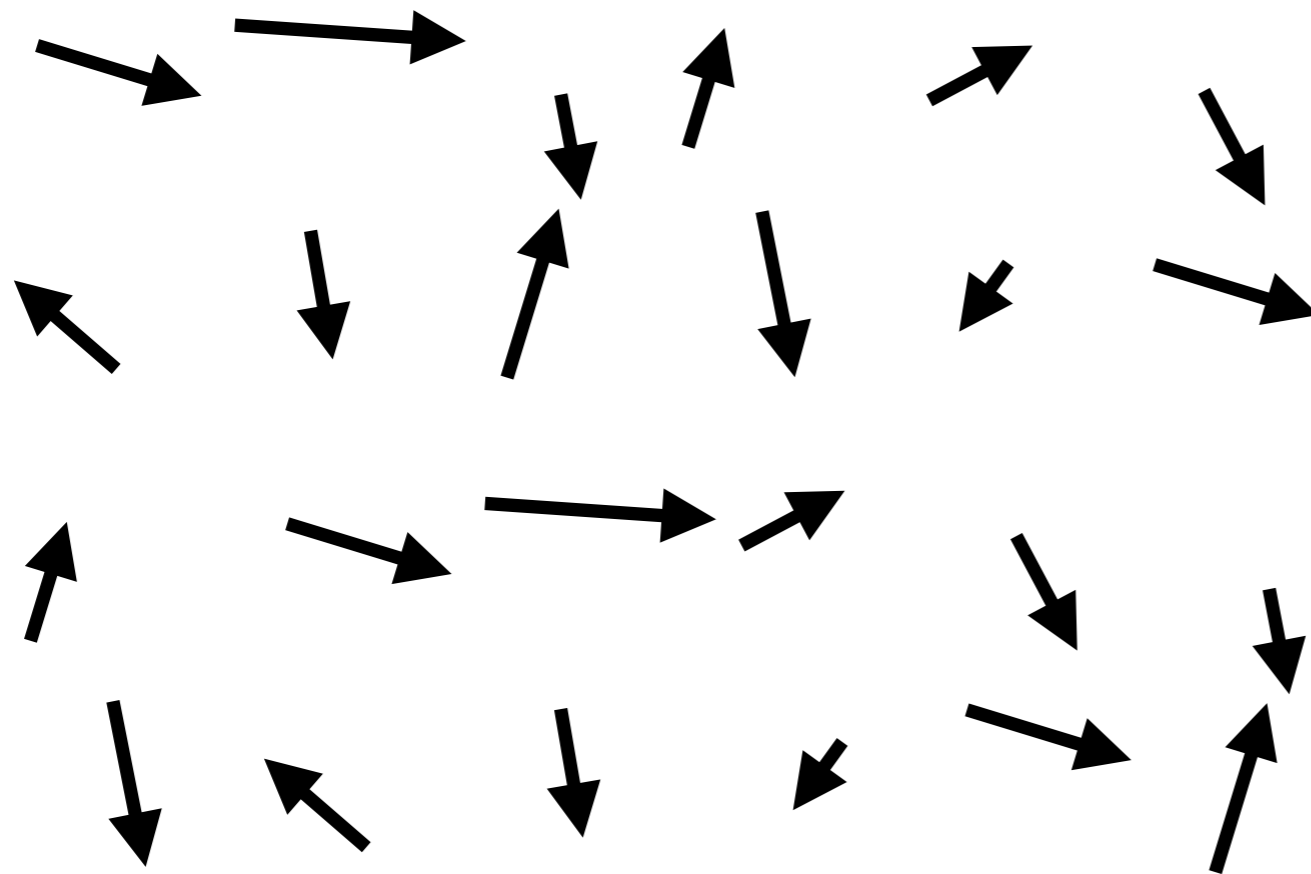


Rotation

Relativistische Felder

Transformation gemäß irreduzibler Darstellung
der Poincaré-Gruppe

(Drehungen, Boosts, Verschiebungen, Raum/Zeitspiegelungen)



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Transformation gemäß irreduzibler Darstellung
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Skalarfelder: $\phi \rightarrow \phi$ Spin 0

Spinorfelder: $\psi \rightarrow \Lambda_{1/2} \psi$ Spin 1/2

Vektorfelder: $A_\mu \rightarrow \Lambda_\mu^\nu A_\nu$ Spin 1

Skalarfeld

$$\mathcal{L} = \frac{1}{2} (\partial_\mu \phi) (\partial^\mu \phi) - \frac{1}{2} m^2 \phi^2 + \frac{\mu}{3} \phi^3 + \frac{\lambda}{4} \phi^4 + \dots$$

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Euler-Lagrange:
$$\frac{\delta \mathcal{L}}{\delta \phi} - \partial_\mu \frac{\delta \mathcal{L}}{\delta (\partial_\mu \phi)} = 0$$

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Freies Feld:
$$(\partial_\mu \partial^\mu + m^2) \phi = 0$$

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Freies Feld:
$$(\partial_\mu \partial^\mu + m^2) \Phi = 0$$

(mit Φ_1 und Φ_2 ist auch $\Phi_1 + \Phi_2$ eine Lösung)

Skalarfeld

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mit $[a(\vec{p}, t), a^\dagger(\vec{p}', t)] = \delta(\vec{p} - \vec{p}')$

Skalarfeld

$$\phi(x) = \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{1}{2\omega} \left[a(\vec{p}) e^{-i\vec{p}\cdot x} + a^\dagger(\vec{p}) e^{+i\vec{p}\cdot x} \right]$$

$$[a(\vec{p}), a^\dagger(\vec{p}')] = \delta(\vec{p} - \vec{p}')$$

Quantenfeld = Harmonische Oszillatoren

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Quantenfeld = Harmonische Oszillatoren

Basiszustände: $|\vec{p}, 0\rangle, |\vec{p}, 1\rangle, |\vec{p}, 2\rangle, \dots$
 \downarrow \downarrow
 $|0\rangle$ $|\vec{p}\rangle = a^\dagger(\vec{p})|0\rangle$

Quantenfeldtheorie

$|0\rangle$: Vakuum

$|\vec{p}\rangle$: 1-Teilchen-Zustand

$|\vec{p}_1, \vec{p}_2\rangle = |\vec{p}_1\rangle \otimes |\vec{p}_2\rangle = 2\text{-Teilchen-Zustand}$

etc.

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Erinnerung: $E_n = \hbar\omega \left(n + \frac{1}{2}\right)$ $n=0, 1, 2, 3, \dots$

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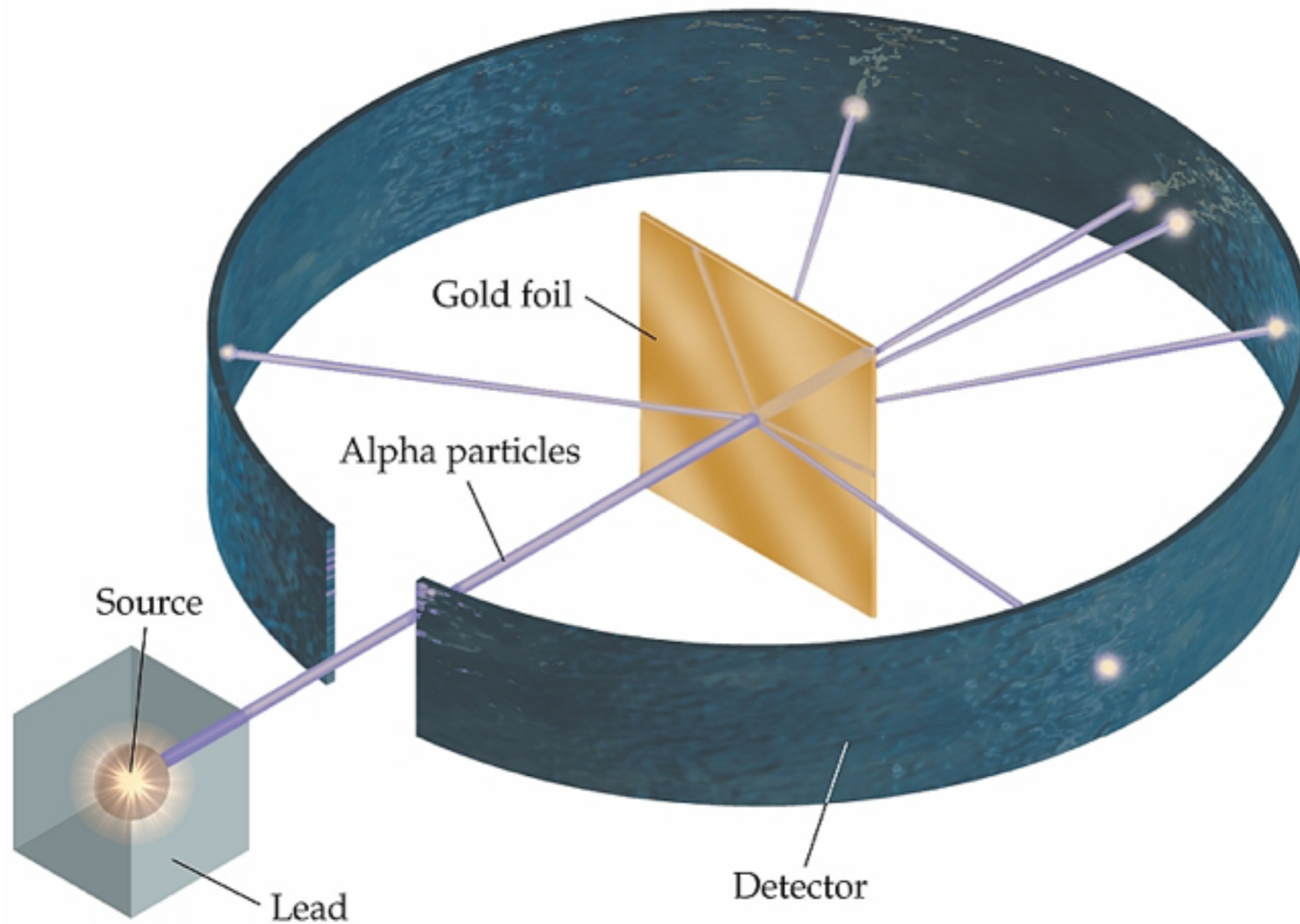
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beachte: $E_0 = \int d^3p \frac{\hbar\omega}{2} = \infty$

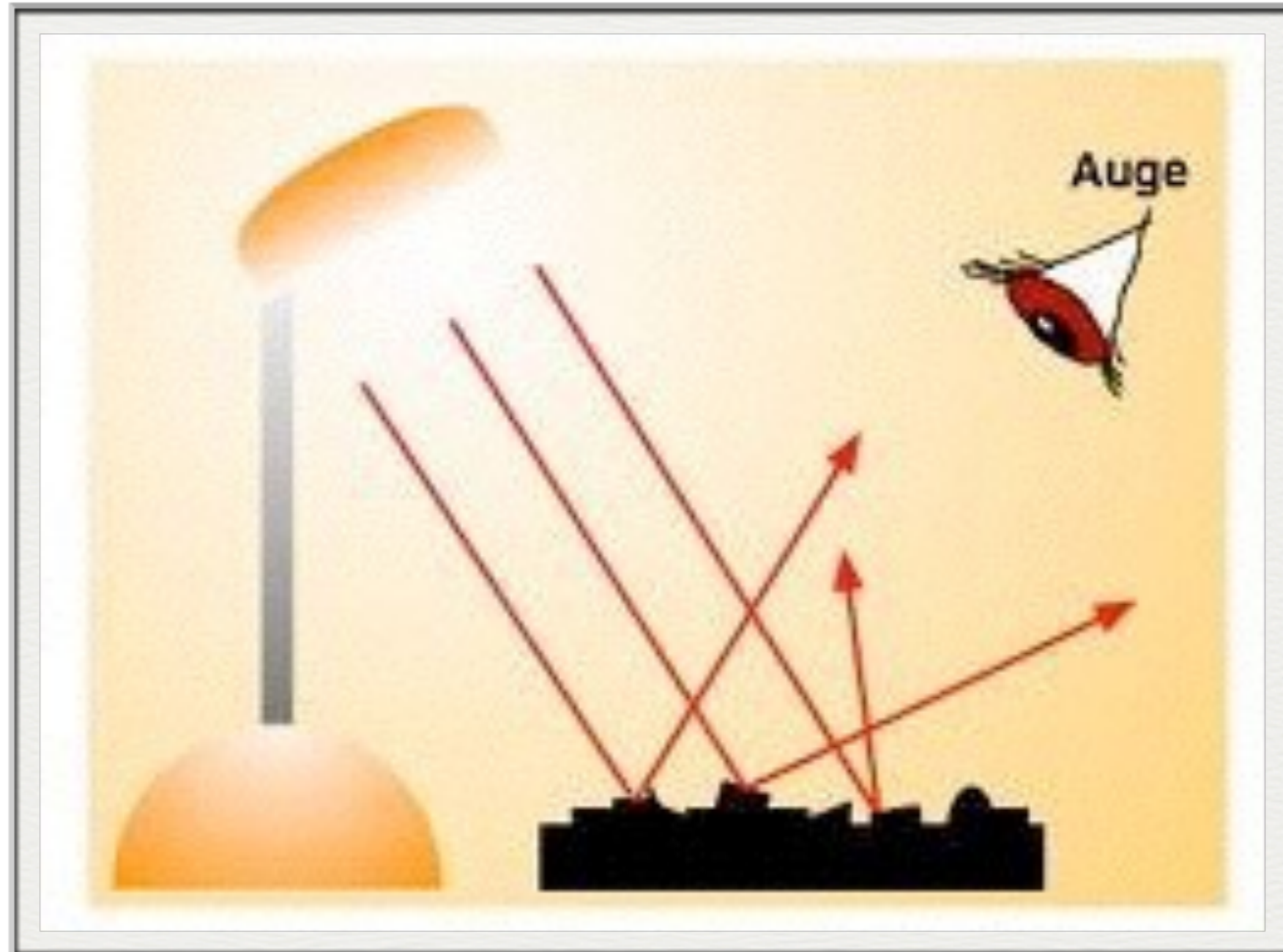
Streuexperiment

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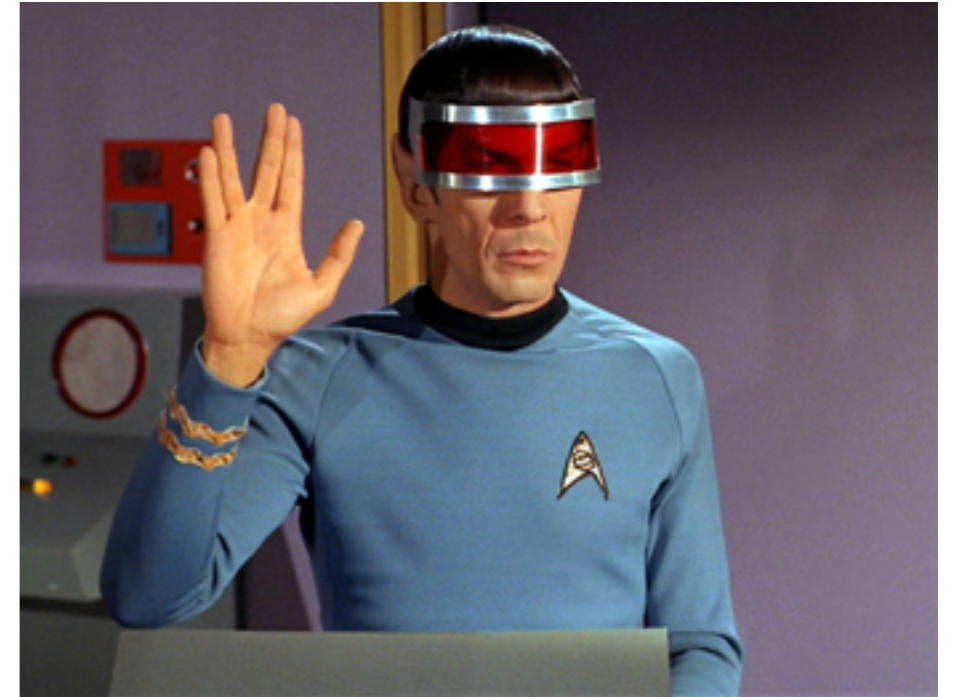
z.B. Elektron + Positron \rightarrow Photon + Photon

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

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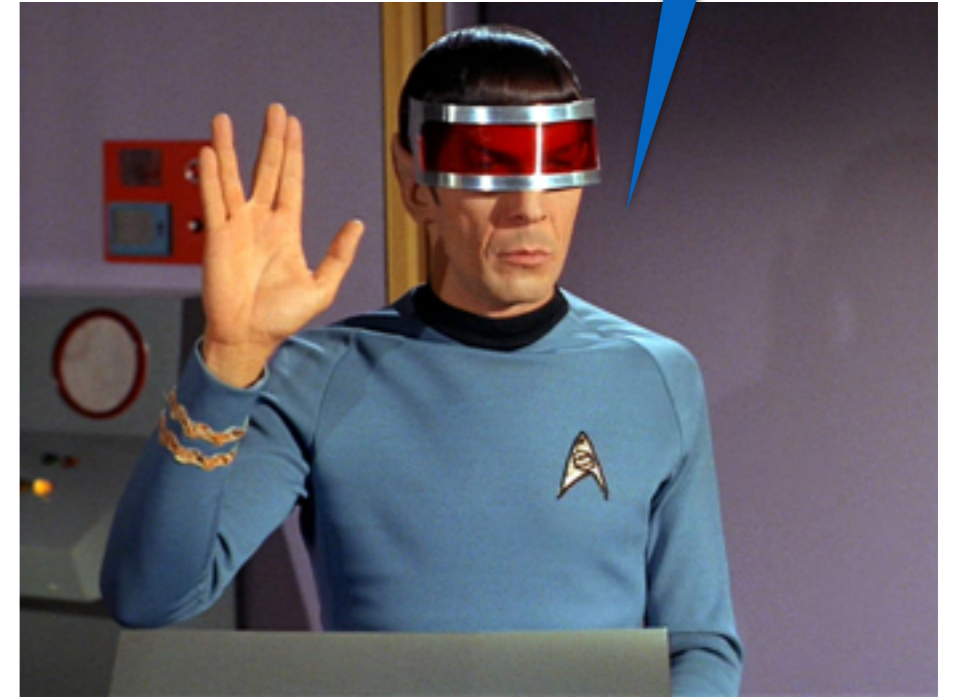


Streuexperiment

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Reine Energie,
Scotty



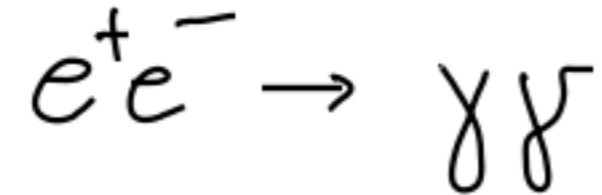
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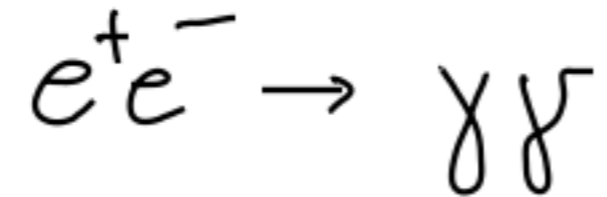


Streuexperiment:

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

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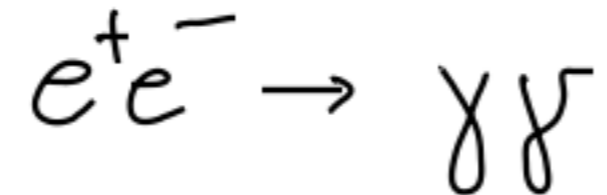
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Gegeben: Anfangszustand ($t \rightarrow -\infty$)

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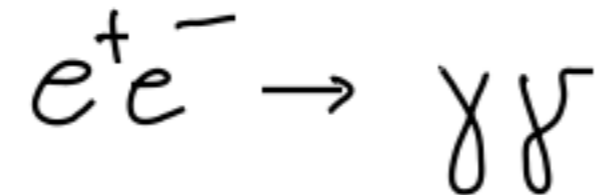
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$|i\rangle$

Streuexperiment

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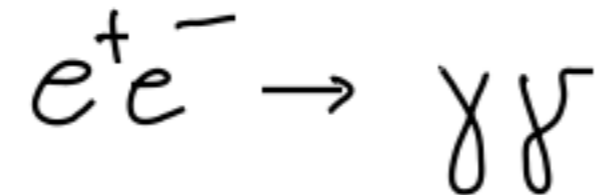
Gegeben: Anfangszustand ($t \rightarrow -\infty$)

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

$$S(t, t_0) |i\rangle$$

Streuexperiment

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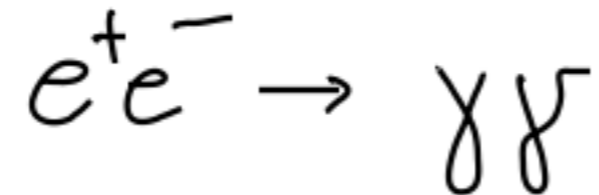
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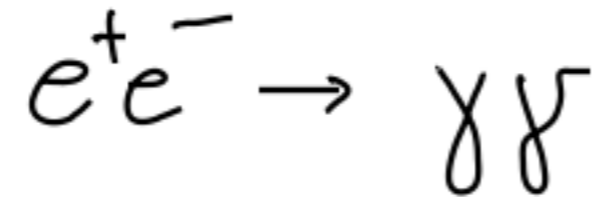
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$$\lim_{t_0 \rightarrow -\infty} \langle f | S(t, t_0) | i \rangle$$

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S-Matrix

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$$|i\rangle = a_1^+ a_2^+ |0\rangle$$

$$|f\rangle = a_3^+ a_4^+ |0\rangle \quad \Leftrightarrow \quad \langle f| = \langle 0| a_4 a_3$$

$S(t, t_0)$: Zeitentwicklungsoperator (S-Matrix)

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Erinnerung: $i\hbar \frac{\partial}{\partial t} |\psi\rangle = \hat{H} |\psi\rangle$

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Wiederholung

$$H = p\dot{x} - L = \frac{p^2}{2M} + \frac{M}{2}\omega^2 x^2$$

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Matrixelement

$$\lim_{t \rightarrow +\infty} \lim_{t_0 \rightarrow -\infty} \langle f | S(t, t_0) | i \rangle$$
$$= \langle f | e^{-\frac{i}{\hbar} \int d^4x \hat{\mathcal{H}}(\dots)} | i \rangle$$

Matrixelement

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$$= \langle f | e^{-\frac{i}{\hbar} \int d^4x \hat{\mathcal{H}}(\dots)} | i \rangle$$

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$$\begin{aligned} \langle f | S | i \rangle &= \langle f | i \rangle + \langle f | -\frac{i}{\hbar} \int d^4x \hat{\mathcal{H}}(x) | i \rangle \\ &+ \langle f | \frac{1}{2} \left(-\frac{i}{\hbar}\right)^2 \int d^4x_1 \int d^4x_2 \hat{\mathcal{H}}(x_1) \hat{\mathcal{H}}(x_2) | i \rangle \\ &+ \end{aligned}$$

Matrixelement

zu berechnen:

Matrixelement

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$$\langle 0 | a^\dagger(p_1) a(p_2) | 0 \rangle = 0$$

$$\langle 0 | \underbrace{a(p_1) a^\dagger(p_2)} | 0 \rangle = \delta(p_1 - p_2)$$
$$= \delta(p_1 - p_2) + a^\dagger(p_2) a(p_1)$$

Matrixelement

zu berechnen: $\langle 0 | \dots a(p) \dots a^\dagger(p') \dots | 0 \rangle$
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$$= \delta(p_1 - p_2) + a^\dagger(p_2) a(p_1)$$

⇒ immer linkes a mit rechtem a^\dagger paaren

Matrixelement

Φ liefert entweder a oder a^+

$$\begin{aligned} & \langle p_3, p_4 | \Phi^3(x) | p_1, p_2 \rangle \\ &= \langle 0 | a_3 a_4 \Phi(x) \Phi(x) \Phi(x) a_1^\dagger a_2^\dagger | 0 \rangle \end{aligned}$$

Matrixelement

Φ liefert entweder a oder a^+

$$\begin{aligned} & \langle p_3, p_4 | \Phi^3(x) | p_1, p_2 \rangle \\ &= \langle 0 | a_3 a_4 \underbrace{\Phi(x) \Phi(x) \Phi(x)}_{\text{[bracketed]}} a_1^\dagger a_2^\dagger | 0 \rangle \end{aligned}$$

Matrixelement

Φ liefert entweder a oder a^+

$$\begin{aligned} & \langle p_3, p_4 | \Phi^3(x) | p_1, p_2 \rangle \\ &= \langle 0 | a_3 a_4 \underbrace{\Phi(x) \Phi(x) \Phi(x)}_{a_1^+ a_2^+} | 0 \rangle \end{aligned}$$

Matrixelement

Φ liefert entweder a oder a^+

$$\begin{aligned} & \langle p_3, p_4 | \Phi^3(x) | p_1, p_2 \rangle \\ &= \langle 0 | \underbrace{a_3 a_4}_{\text{}} \underbrace{\Phi(x) \Phi(x) \Phi(x) a_1^+ a_2^+}_{\text{}} | 0 \rangle \end{aligned}$$

Matrixelement

Φ liefert entweder a oder a^+

$$\begin{aligned} & \langle p_3, p_4 | \Phi^3(x) | p_1, p_2 \rangle \\ &= \langle 0 | a_3 a_4 \underbrace{\Phi(x)} \underbrace{\Phi(x) \Phi(x)} a_1^\dagger a_2^\dagger | 0 \rangle \end{aligned}$$

Matrixelement

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$$\begin{aligned} & \langle p_3, p_4 | \Phi^3(x) | p_1, p_2 \rangle \\ &= \langle 0 | a_3 a_4 \underbrace{\Phi(x)} \underbrace{\Phi(x) \Phi(x)} a_1^\dagger a_2^\dagger | 0 \rangle \\ &= 0 \end{aligned}$$

Matrixelement

Φ liefert entweder a oder a^+

$$\begin{aligned} & \langle p_3, p_4 | \Phi^3(x) | p_1, p_2 \rangle \\ &= \langle 0 | a_3 a_4 \underbrace{\Phi(x)} \underbrace{\Phi(x)} \underbrace{\Phi(x)} a_1^\dagger a_2^\dagger | 0 \rangle \\ &= 0 \end{aligned}$$

$$\begin{aligned} \langle f | S | i \rangle &= \langle f | i \rangle + \langle f | -\frac{i}{\hbar} \int d^4x \hat{\mathcal{H}}(x) | i \rangle \\ &+ \langle f | \frac{1}{2} \left(-\frac{i}{\hbar}\right)^2 \int d^4x_1 \int d^4x_2 \hat{\mathcal{H}}(x_1) \hat{\mathcal{H}}(x_2) | i \rangle \\ &+ \end{aligned}$$

Feynman-Diagramme

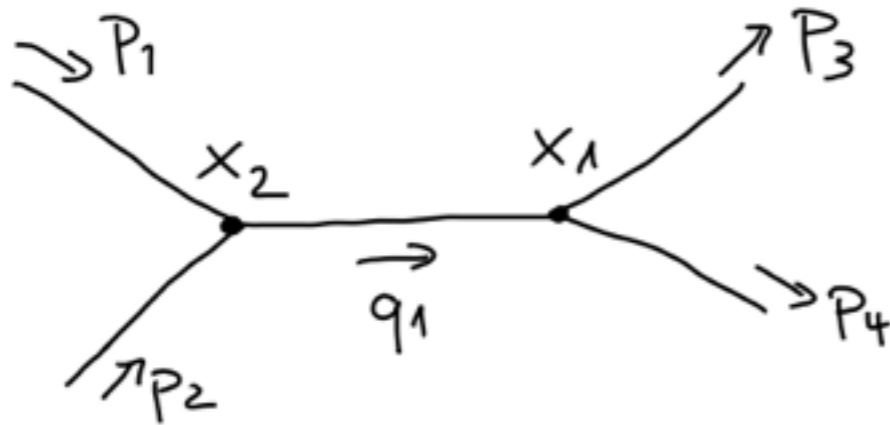
$$\langle 0 | a_3 a_4 \phi(x_1) \phi(x_2) \phi(x_1) \phi(x_2) \phi(x_2) \phi(x_2) a_1^\dagger a_2^\dagger | 0 \rangle$$

Feynman-Diagramme

$$\langle 0 | a_3 a_4 \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_2) \phi(x_2)} a_1^\dagger a_2^\dagger | 0 \rangle$$

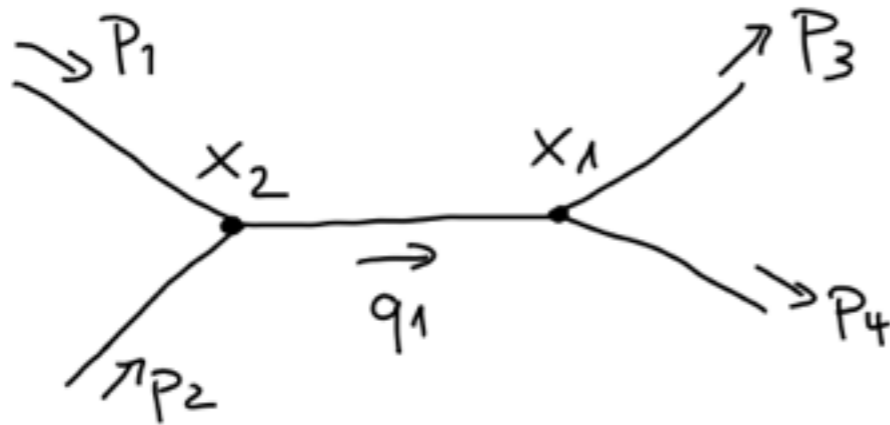
Feynman-Diagramme

$$\langle 0 | a_3 a_4 \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_2) \phi(x_2)} a_1^\dagger a_2^\dagger | 0 \rangle$$



Feynman-Diagramme

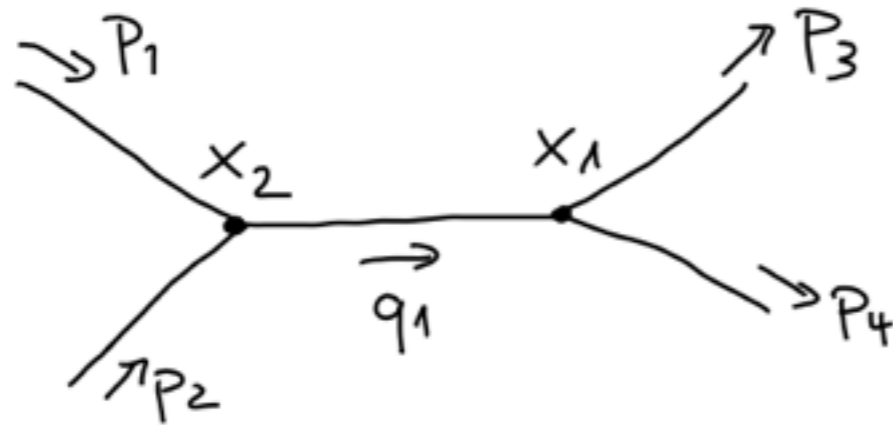
$$\langle 0 | a_3 a_4 \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_2) \phi(x_2)} a_1^\dagger a_2^\dagger | 0 \rangle$$



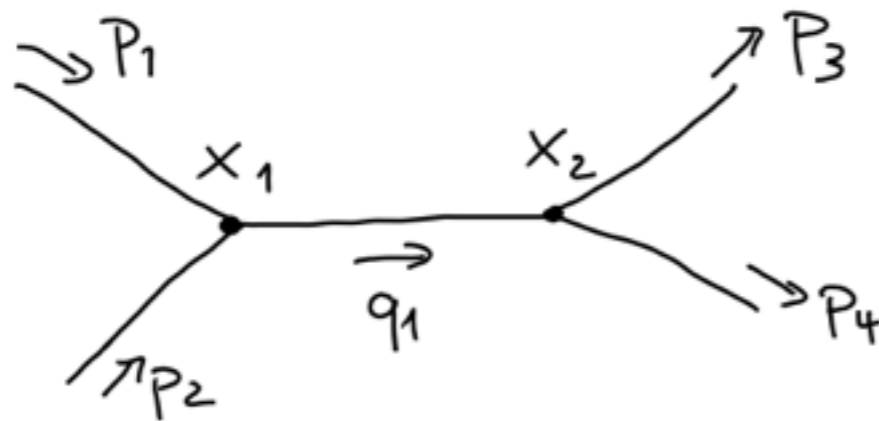
$$q_1 = p_1 + p_2 = p_3 + p_4$$

Feynman-Diagramme

$$\langle 0 | a_3 a_4 \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_2) \phi(x_2)} a_1^\dagger a_2^\dagger | 0 \rangle$$

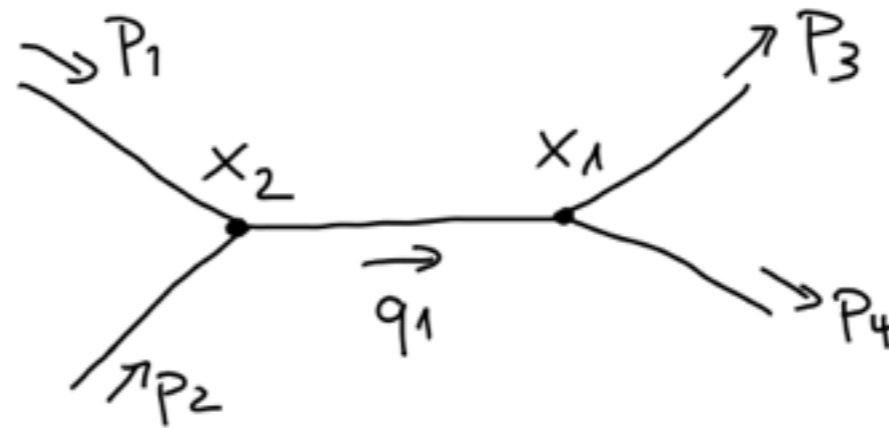


$$q_1 = p_1 + p_2 = p_3 + p_4$$



Feynman-Diagramme

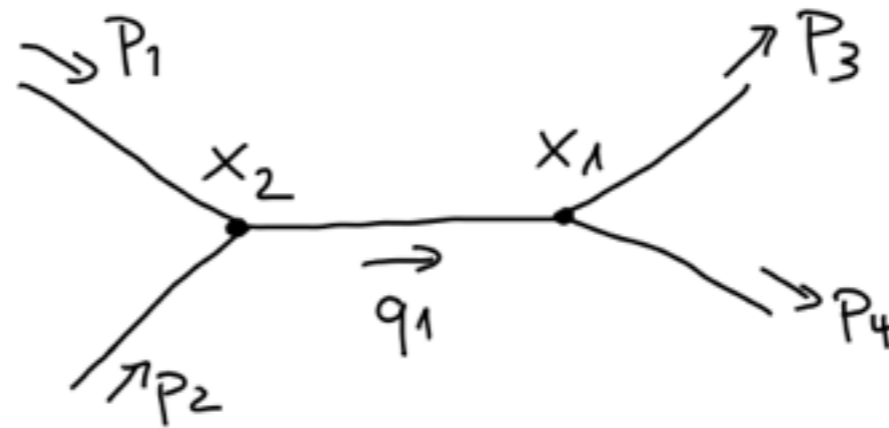
$$\langle 0 | a_3 a_4 \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_2) \phi(x_2)} a_1^\dagger a_2^\dagger | 0 \rangle$$



Feynman-Diagramme

$$\langle 0 | a_3 a_4 \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_2) \phi(x_2)} a_1^\dagger a_2^\dagger | 0 \rangle$$

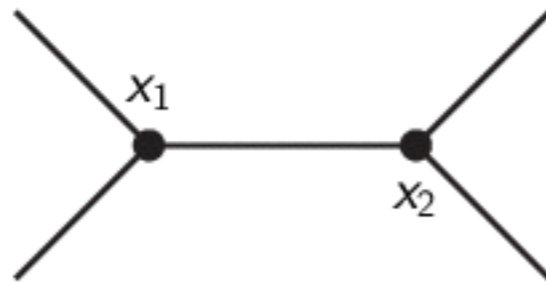
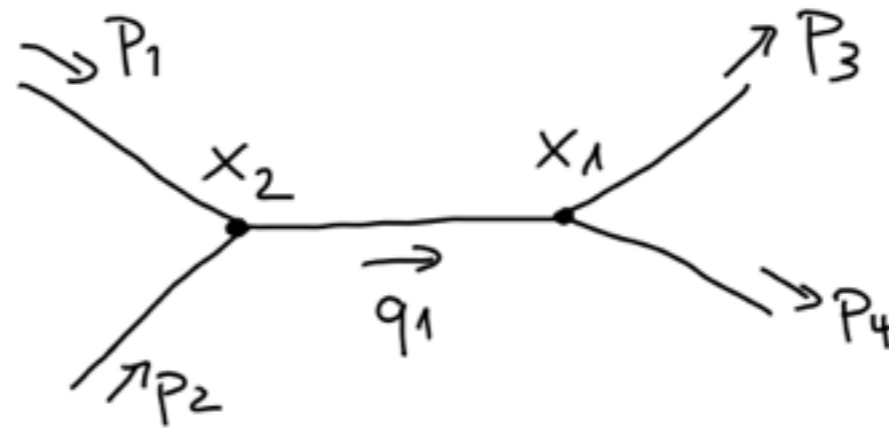
$$\int d^4 x_1 \int d^4 x_2$$



Feynman-Diagramme

$$\langle 0 | a_3 a_4 \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_2) \phi(x_2)} a_1^\dagger a_2^\dagger | 0 \rangle$$

$$\int d^4 x_1 \int d^4 x_2$$

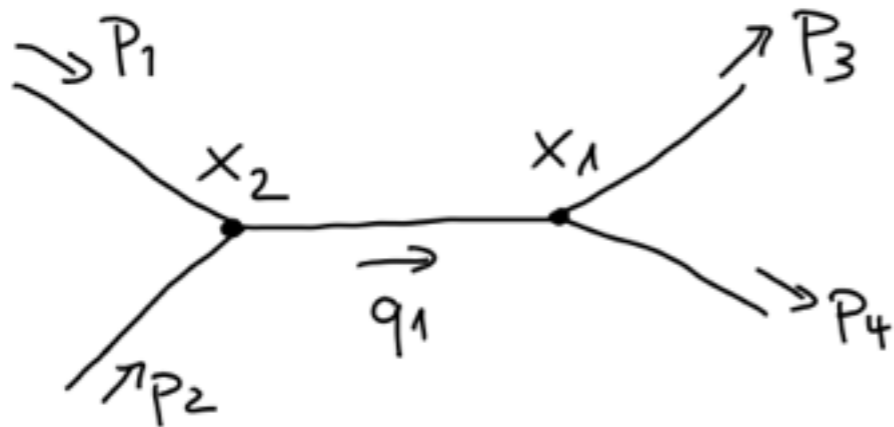


Feynman-Diagramme

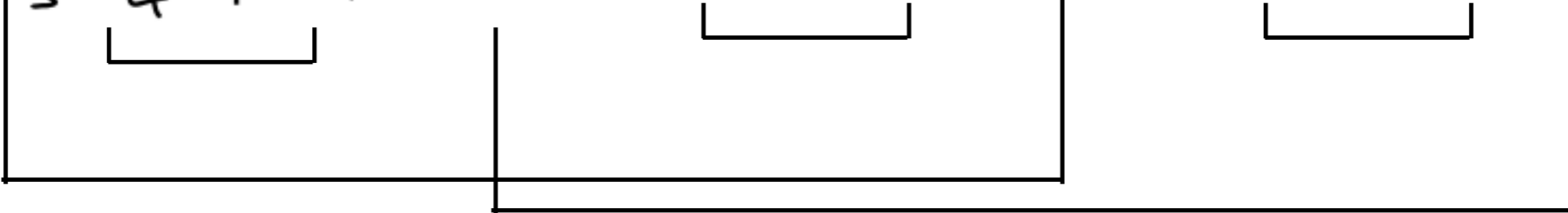
$$\langle 0 | a_3 a_4 \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_2) \phi(x_2)} a_1^\dagger a_2^\dagger | 0 \rangle$$

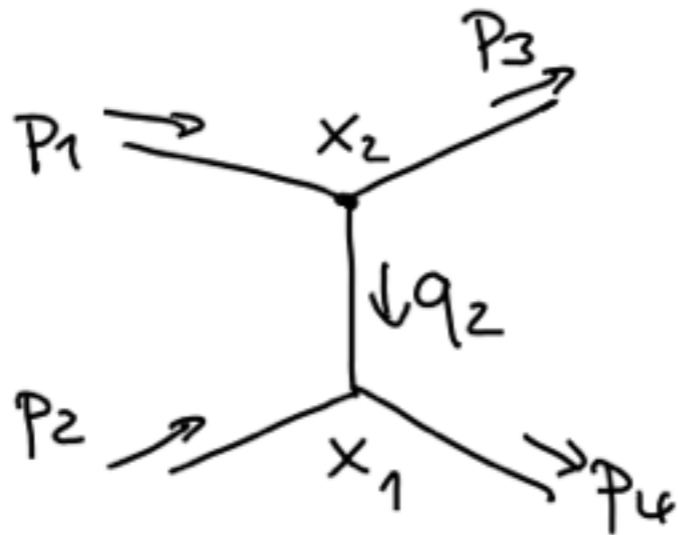
Feynman-Diagramme

$$\langle 0 | a_3 a_4 \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_1) \phi(x_2)} \underbrace{\phi(x_2) \phi(x_2)} a_1^\dagger a_2^\dagger | 0 \rangle$$



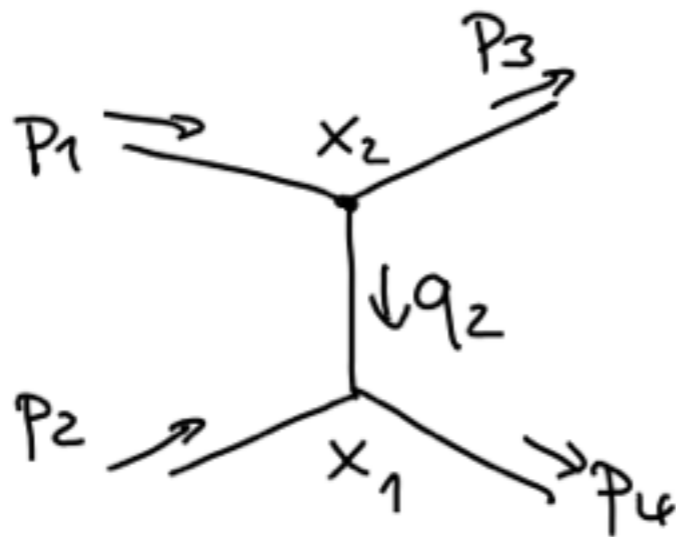
Feynman-Diagramme

$$\langle 0 | a_3 a_4 \underbrace{\phi(x_1) \phi(x_1)} \underbrace{\phi(x_2) \phi(x_2)} \underbrace{\phi(x_2) \phi(x_2)} a_1^\dagger a_2^\dagger | 0 \rangle$$




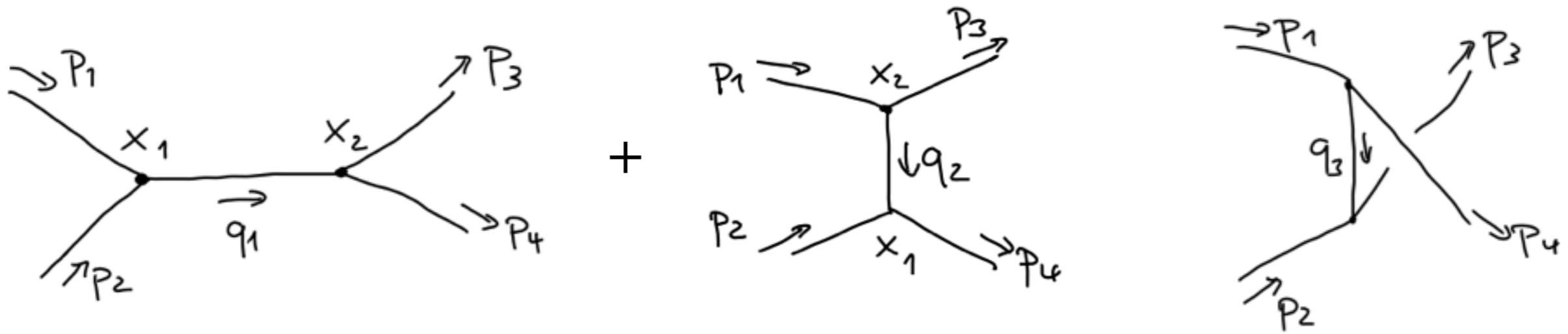
Feynman-Diagramme

$$\langle 0 | a_3 a_4 \phi(x_1) \phi(x_1) \phi(x_1) \phi(x_2) \phi(x_2) \phi(x_2) a_1^\dagger a_2^\dagger | 0 \rangle$$

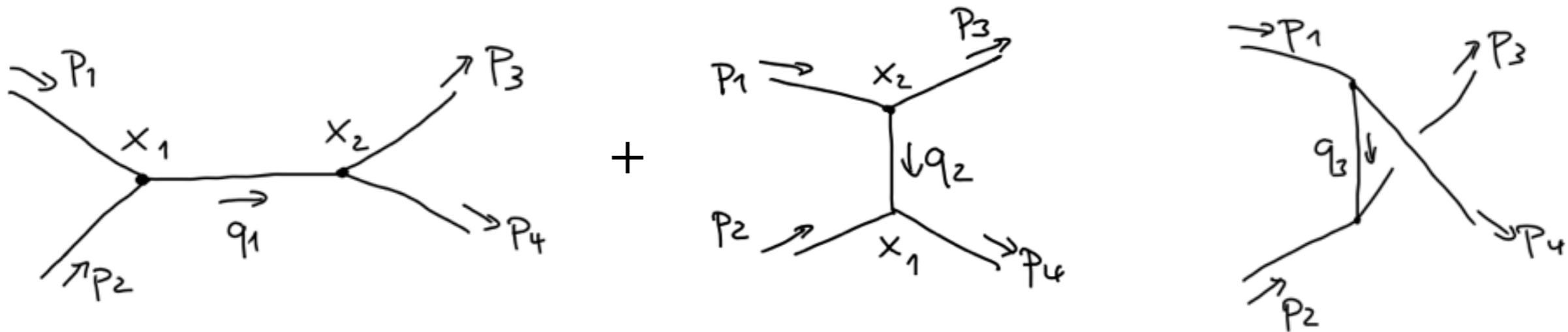


$$q_2 = p_1 - p_3 = p_4 - p_2$$

Feynman-Diagramme

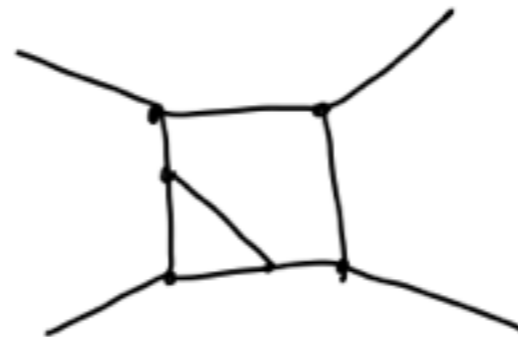
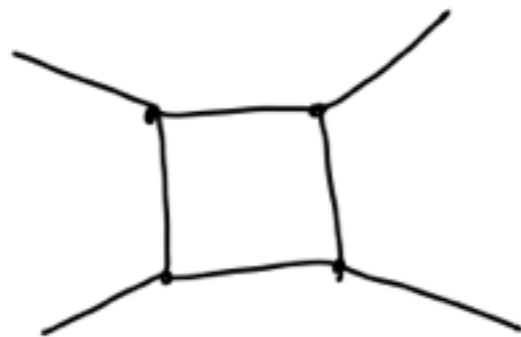
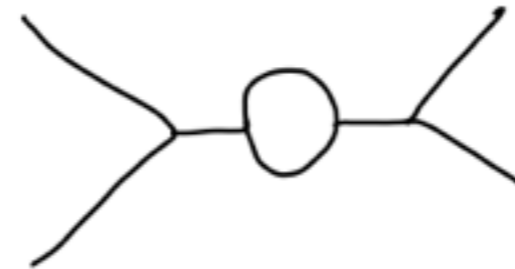
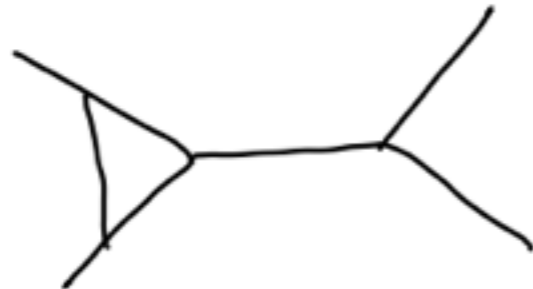


Feynman-Diagramme



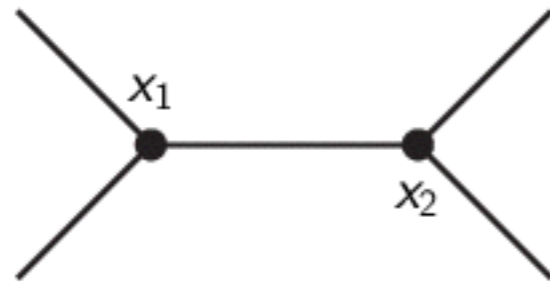
$$\begin{aligned}
 \langle f | S | i \rangle &= \langle f | i \rangle + \langle f | -\frac{i}{\hbar} \int d^4x \hat{\mathcal{H}}(x) | i \rangle \\
 &+ \langle f | \frac{1}{2} \left(-\frac{i}{\hbar}\right)^2 \int d^4x_1 \int d^4x_2 \hat{\mathcal{H}}(x_1) \hat{\mathcal{H}}(x_2) | i \rangle \\
 &+
 \end{aligned}$$

Schleifendiagramme

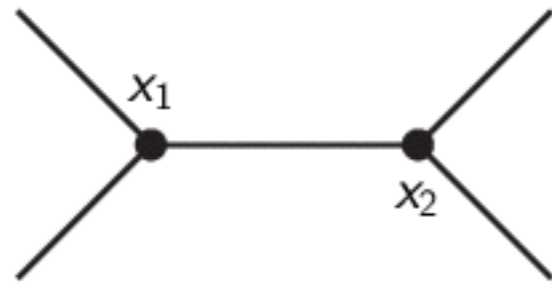


Interpretation

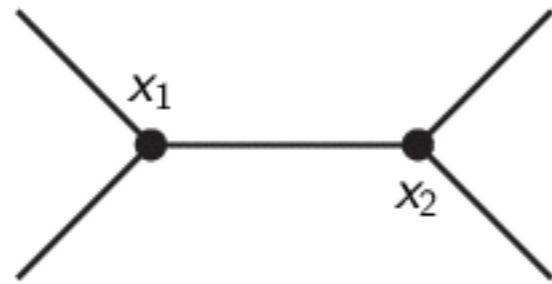
(Fehl-)Interpretation



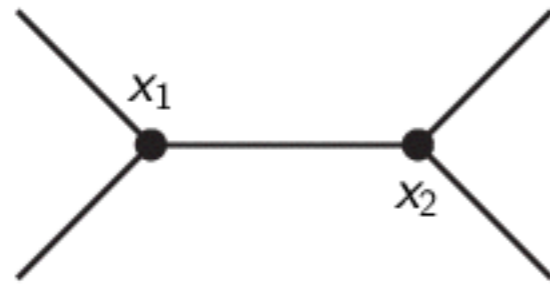
(Fehl-)Interpretation



(Fehl-)Interpretation



(Fehl-)Interpretation



(Fehl-)Interpretation



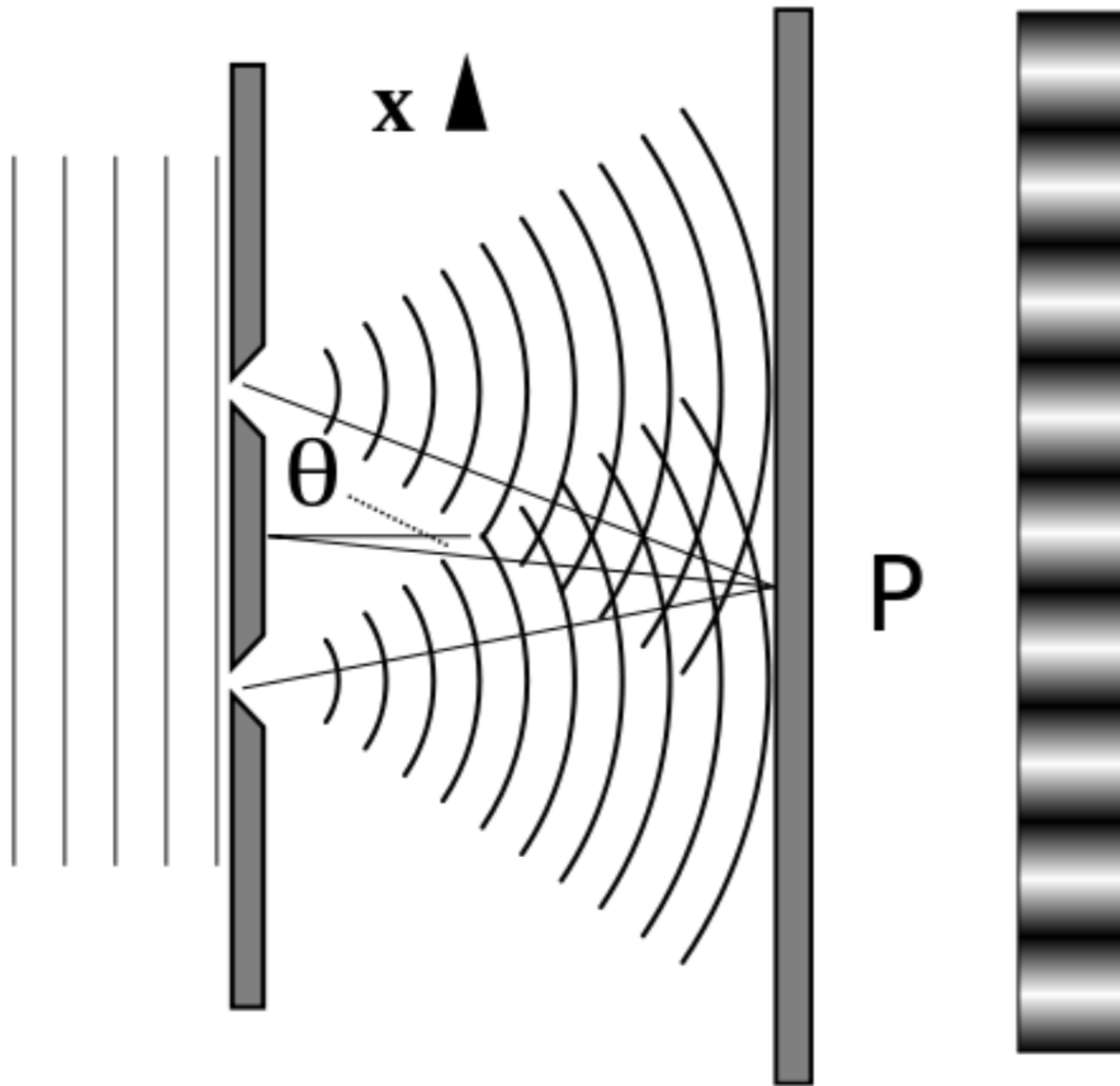
(Fehl-)Interpretation



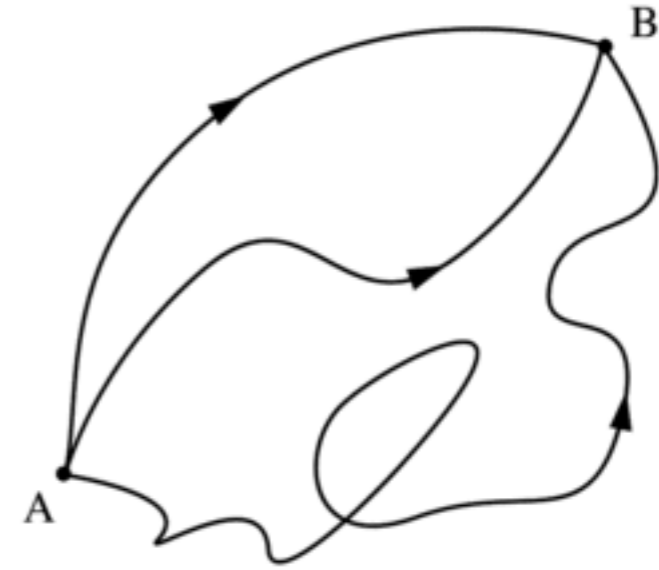
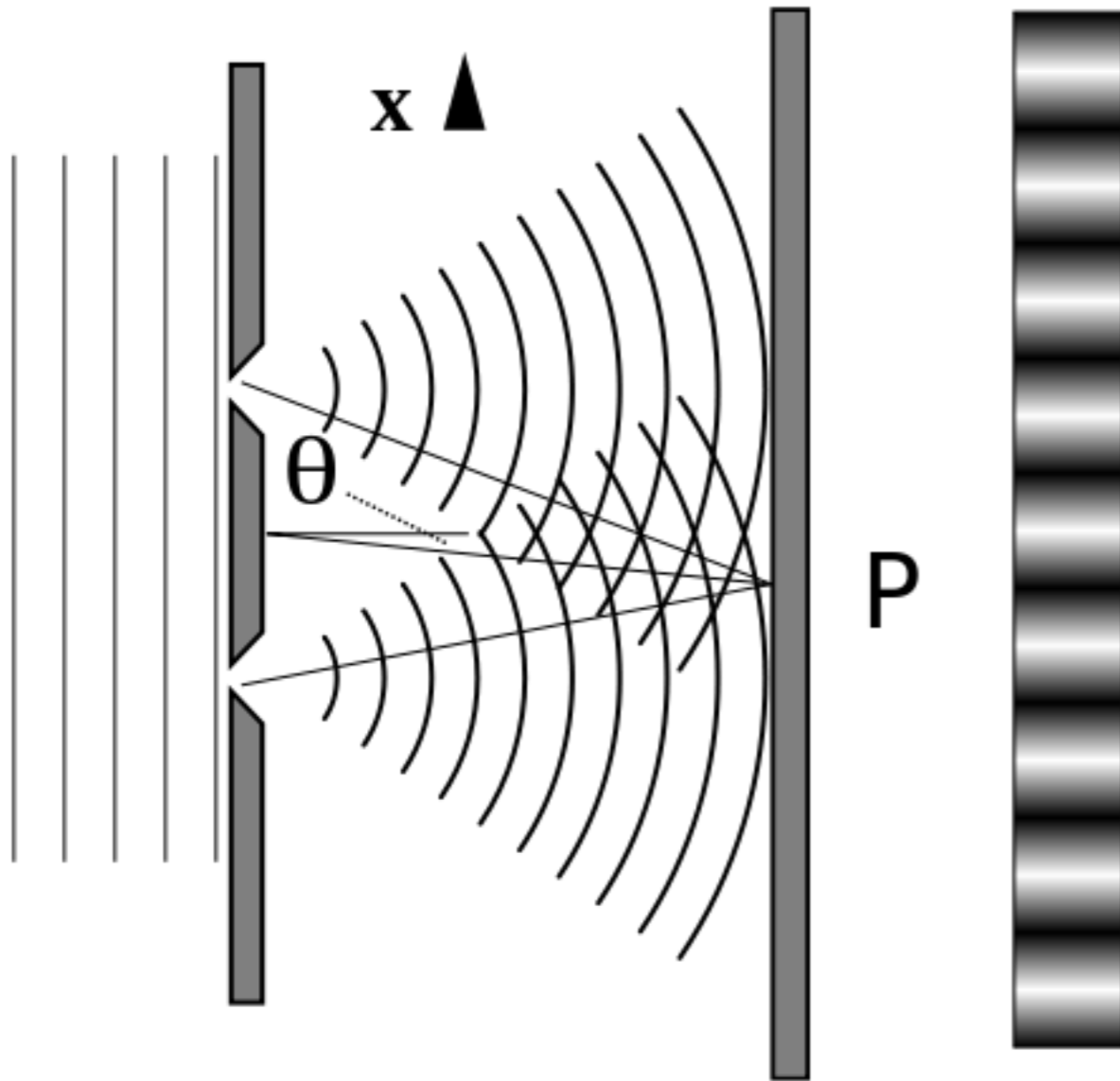
(Fehl-)Interpretation



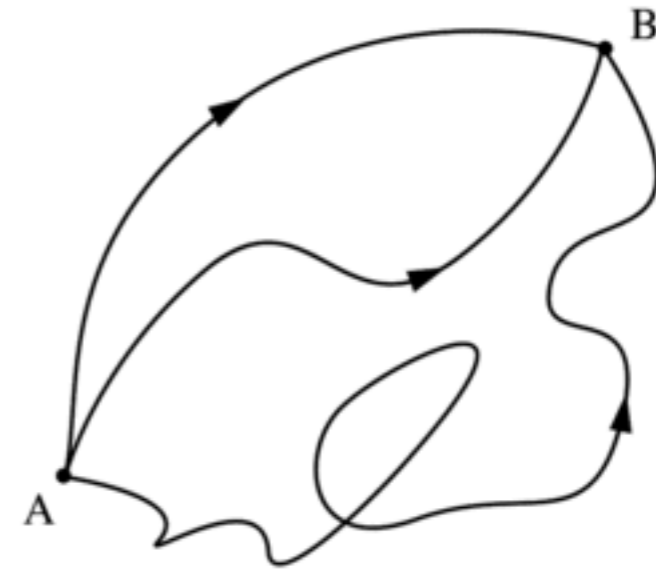
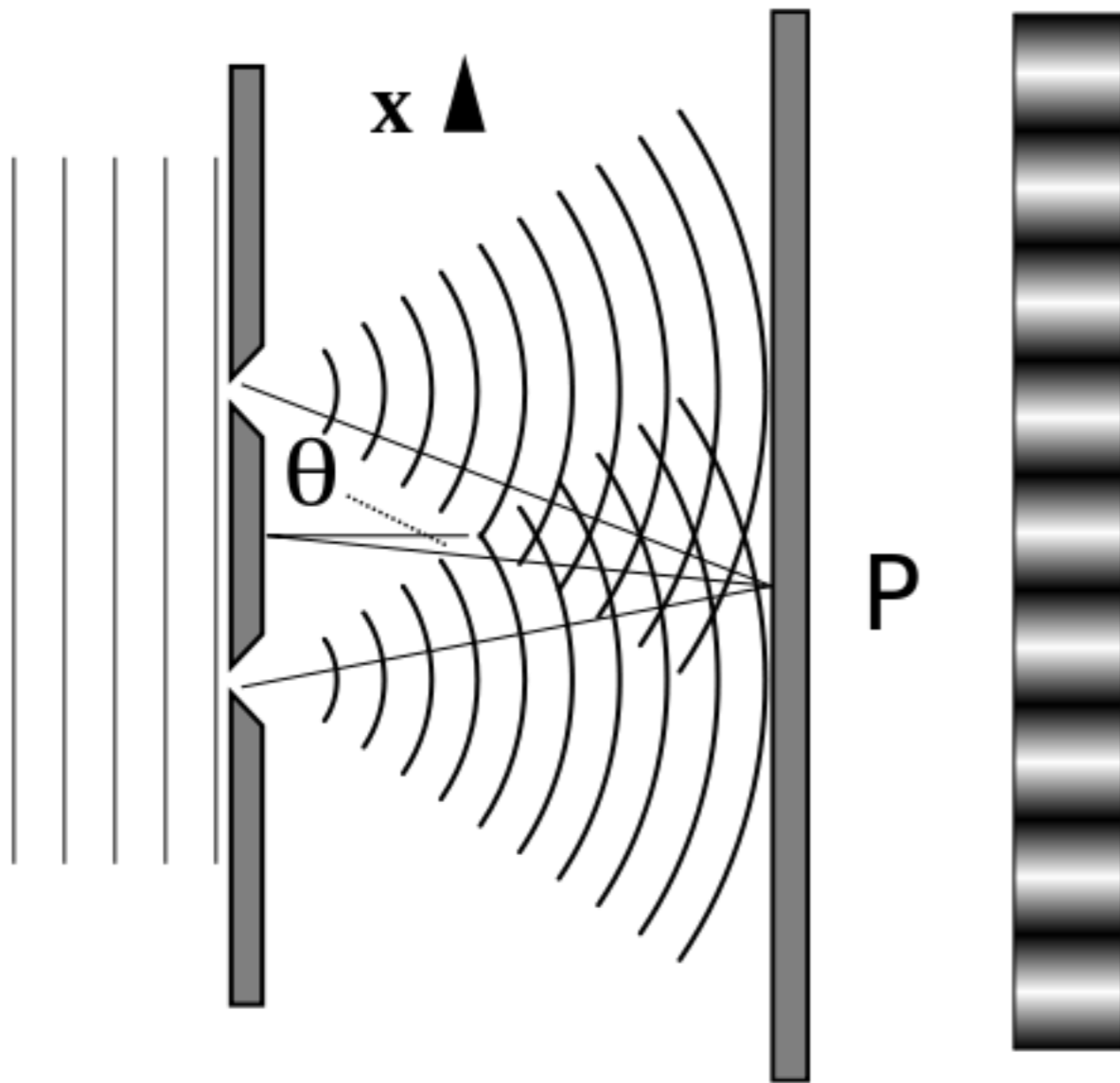
Interpretation



Interpretation



Interpretation



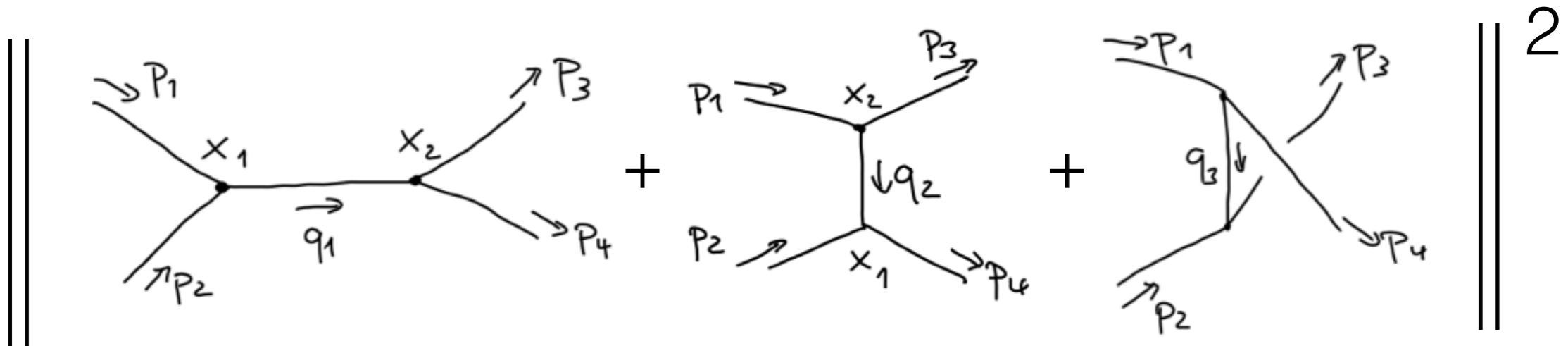
$$Z(B, A) = \mathcal{N} \int \mathcal{D}q \exp\left(\frac{i}{\hbar} S\right)$$

Pfadintegral

Wirkungsquerschnitt

Wahrscheinlichkeit: $\sim \| \langle f|S|i\rangle \|^2$

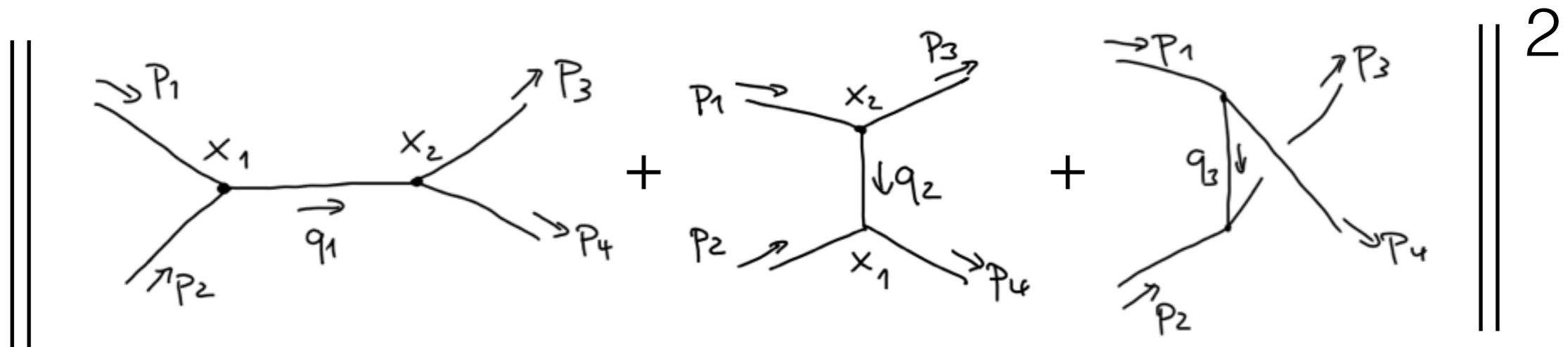
Summe über Feynman-Diagramme, quadriert



Wirkungsquerschnitt

Wahrscheinlichkeit: $\sim \| \langle f|S|i\rangle \|^2$

Summe über Feynman-Diagramme, quadriert

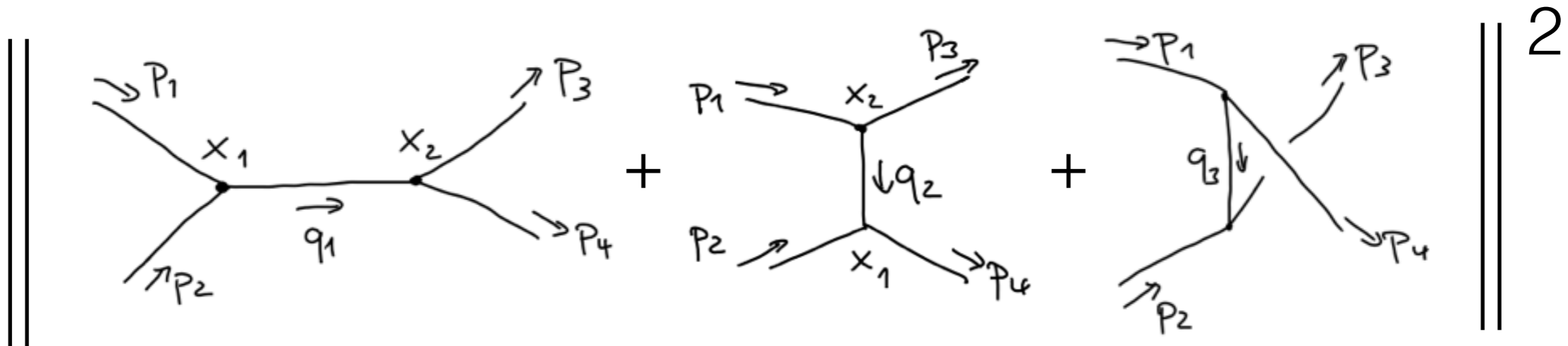


Auslöschungseffekte!

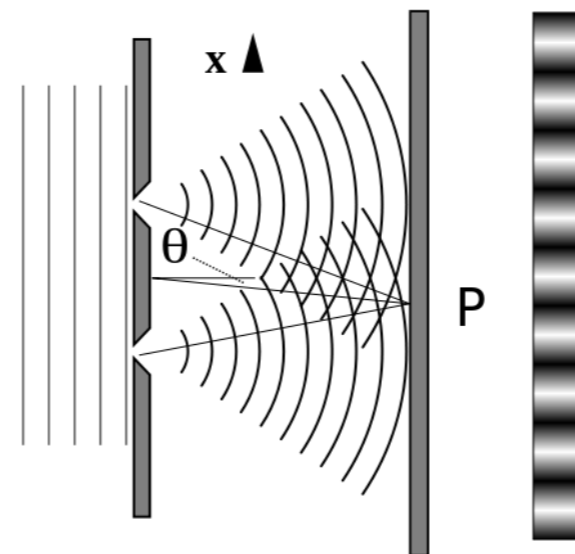
Wirkungsquerschnitt

Wahrscheinlichkeit: $\sim \|\langle f|S|i\rangle\|^2$

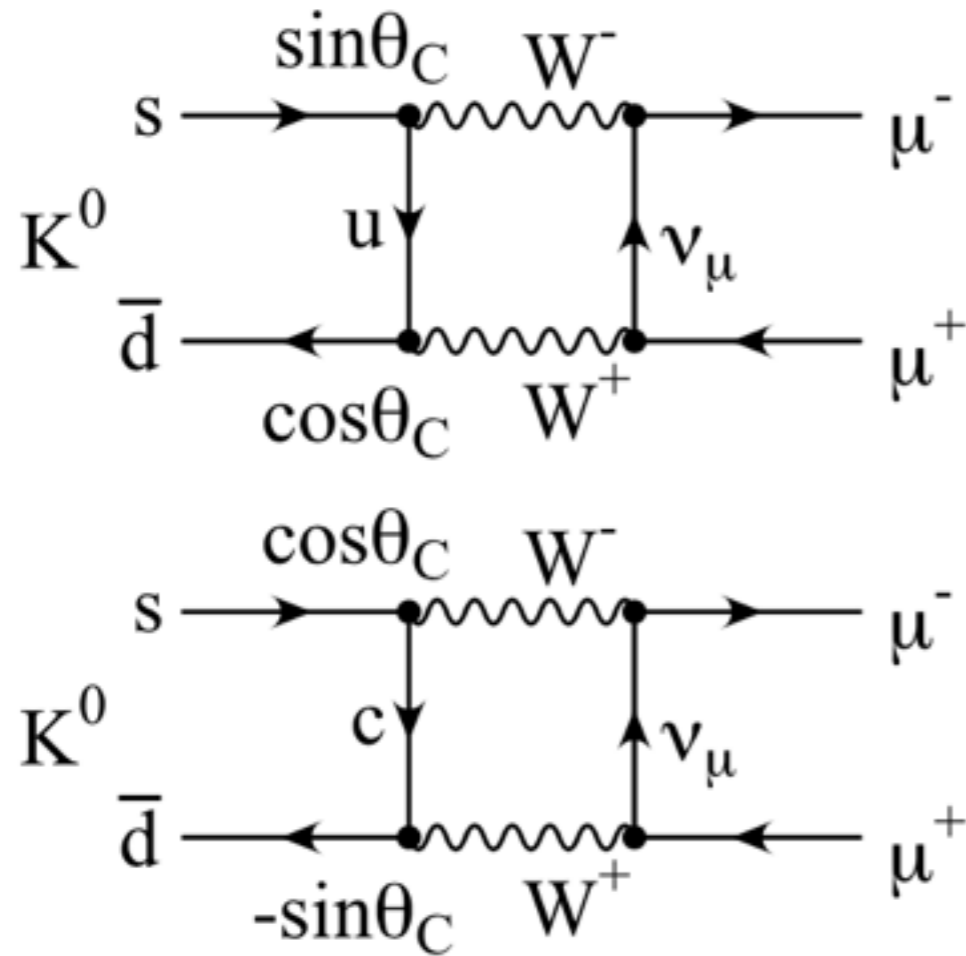
Summe über Feynman-Diagramme, quadriert



Auslöschungseffekte!



Interferenz-Effekte



Flavor-changing neutral currents

GIM-Mechanismus
(Glashow-Iliopoulos-Maiani)

Vorhersage des Charm-Quarks

Higgs



Higgs

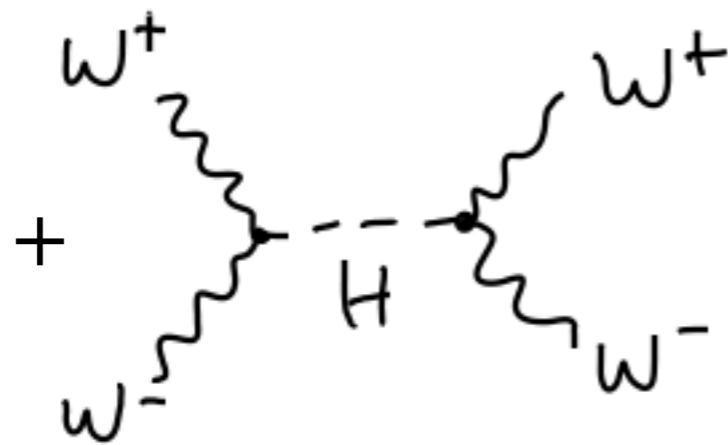


→ Wahrscheinlichkeit $> 100\%$

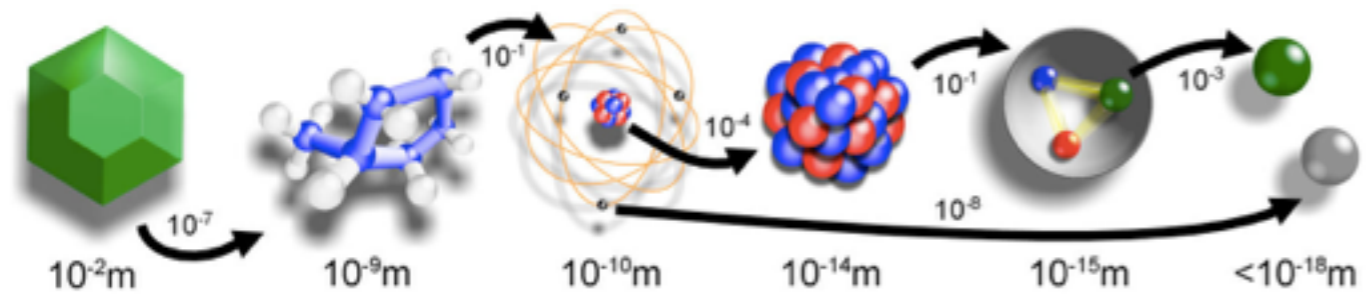
Higgs



→ Wahrscheinlichkeit $> 100\%$

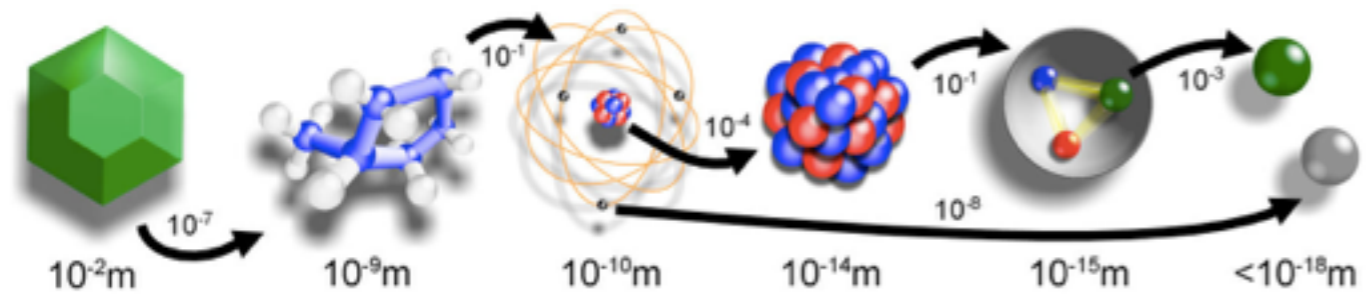


→ Wahrscheinlichkeit $< 100\%$



Drei Generationen der Materie (Fermionen)

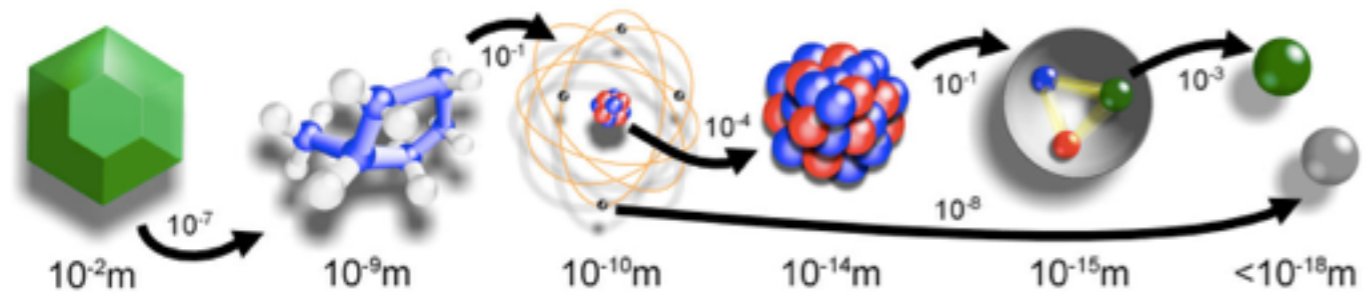
	I	II	III	
Masse	2,4 MeV	1,27 GeV	171,2 GeV	0
Ladung	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
Spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Name	u up	c charm	t top	γ Photon
Quarks	4,8 MeV $-\frac{1}{3}$	104 MeV $-\frac{1}{3}$	4,2 GeV $-\frac{1}{3}$	0
	d down	s strange	b bottom	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptonen	<2,2 eV	<0,17 MeV	<15,5 MeV	91,2 GeV
	0 $\frac{1}{2}$	0 $\frac{1}{2}$	0 $\frac{1}{2}$	0
	ν_e Elektron-Neutrino	ν_μ Myon-Neutrino	ν_τ Tau-Neutrino	Z^0 schwache Kraft
0,511 MeV -1 $\frac{1}{2}$	105,7 MeV -1 $\frac{1}{2}$	1,777 GeV -1 $\frac{1}{2}$	80,4 GeV ± 1 1	
e Elektron	μ Myon	τ Tau	W^\pm schwache Kraft	
			Eichbosonen	



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c.$$

Drei Generationen der Materie (Fermionen)

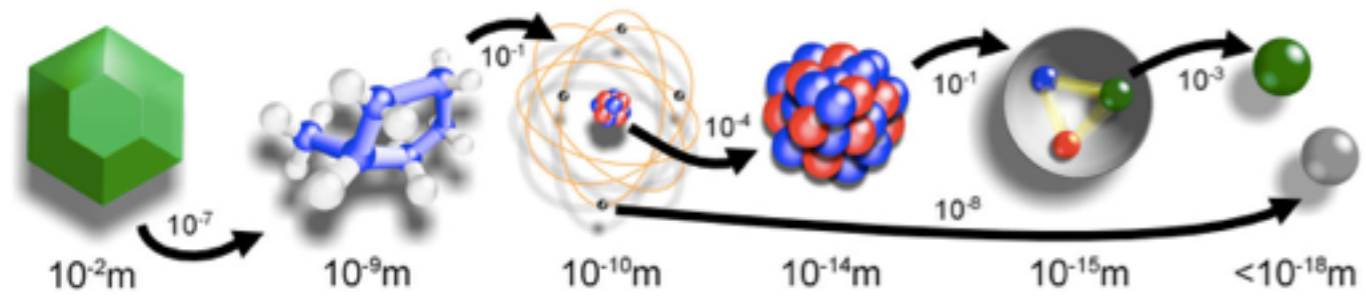
	I	II	III	
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Name	u up	c charm	t top	γ Photon
Quarks	4,8 MeV $-\frac{1}{3}$	104 MeV $-\frac{1}{3}$	4,2 GeV $-\frac{1}{3}$	0 0 1
	d down	s strange	b bottom	g Gluon
	<2,2 eV 0	<0,17 MeV 0	<15,5 MeV 0	91,2 GeV 0
Leptonen	$\frac{1}{2}$ ν_e Elektron-Neutrino	$\frac{1}{2}$ ν_μ Myon-Neutrino	$\frac{1}{2}$ ν_τ Tau-Neutrino	1 Z^0 schwache Kraft
	0,511 MeV -1 $\frac{1}{2}$ e Elektron	105,7 MeV -1 $\frac{1}{2}$ μ Myon	1,777 GeV -1 $\frac{1}{2}$ τ Tau	± 1 1 W^\pm schwache Kraft
				Eichbosonen



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. - \bar{\psi} m \psi + \frac{1}{2} A_{\mu} m^{\mu\nu} A_{\nu}$$

Drei Generationen der Materie (Fermionen)

	I	II	III	
Masse	2,4 MeV	1,27 GeV	171,2 GeV	0
Ladung	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
Spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Name	u up	c charm	t top	γ Photon
Quarks	4,8 MeV $-\frac{1}{3}$	104 MeV $-\frac{1}{3}$	4,2 GeV $-\frac{1}{3}$	0
	d down	s strange	b bottom	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptonen	<2,2 eV	<0,17 MeV	<15,5 MeV	91,2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e Elektron-Neutrino	ν_μ Myon-Neutrino	ν_τ Tau-Neutrino	Z⁰ schwache Kraft
	0,511 MeV	105,7 MeV	1,777 GeV	80,4 GeV
	-1	-1	-1	±1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e Elektron	μ Myon	τ Tau	W[±] schwache Kraft
				Eichbosonen

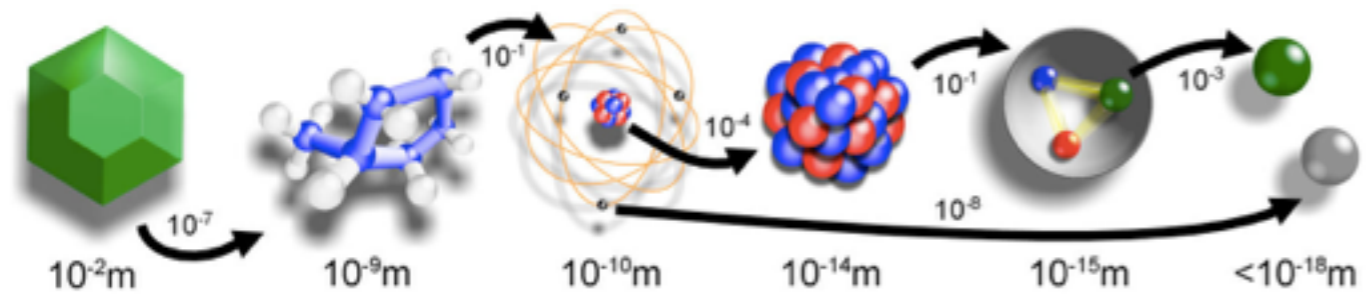


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. - \bar{\psi} m \psi + \frac{1}{2} A_{\mu} m^{\mu\nu} A_{\nu}$$

Drei Generationen der Materie (Fermionen)

	I	II	III	
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	d down	s strange	b bottom	g Gluon
	<2,2 eV 0	<0,17 MeV 0	<15,5 MeV 0	91,2 GeV 0
Leptonen	$\frac{1}{2}$ ν_e Elektron-Neutrino	$\frac{1}{2}$ ν_μ Myon-Neutrino	$\frac{1}{2}$ ν_τ Tau-Neutrino	1 Z⁰ schwache Kraft
	0,511 MeV -1	105,7 MeV -1	1,777 GeV -1	80,4 GeV ±1
	e Elektron	μ Myon	τ Tau	W[±] schwache Kraft
			Eichbosonen	





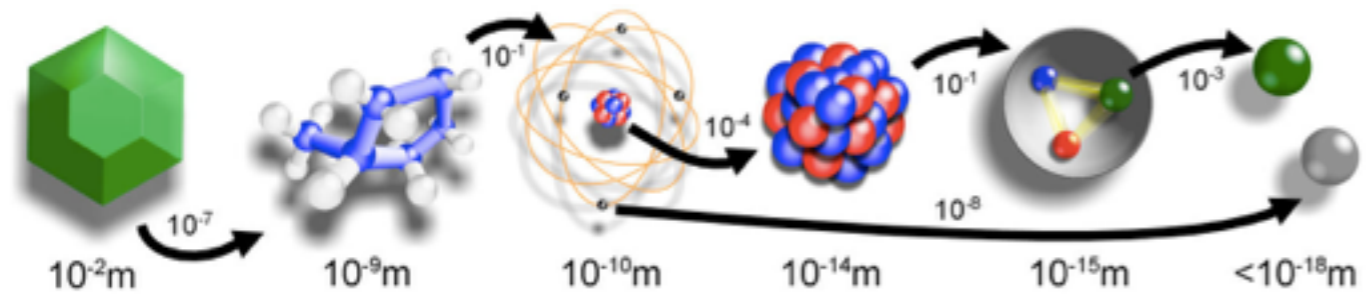
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D}\psi + h.c. - \bar{\psi} m \psi + \frac{1}{2} A_{\mu} m^{\mu\nu} A_{\nu}$$

Drei Generationen der Materie (Fermionen)

	I	II	III	
Masse	2,4 MeV	1,27 GeV	171,2 GeV	0
Ladung	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
Spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Name	u up	c charm	t top	γ Photon
Quarks	4,8 MeV $-\frac{1}{3}$	104 MeV $-\frac{1}{3}$	4,2 GeV $-\frac{1}{3}$	0
	d down	s strange	b bottom	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
			g Gluon	
Leptonen	<2,2 eV	<0,17 MeV	<15,5 MeV	91,2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e Elektron-Neutrino	ν_μ Myon-Neutrino	ν_τ Tau-Neutrino	Z⁰ schwache Kraft
	0,511 MeV	105,7 MeV	1,777 GeV	80,4 GeV
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e Elektron	μ Myon	τ Tau	W[±] schwache Kraft

Eichbosonen





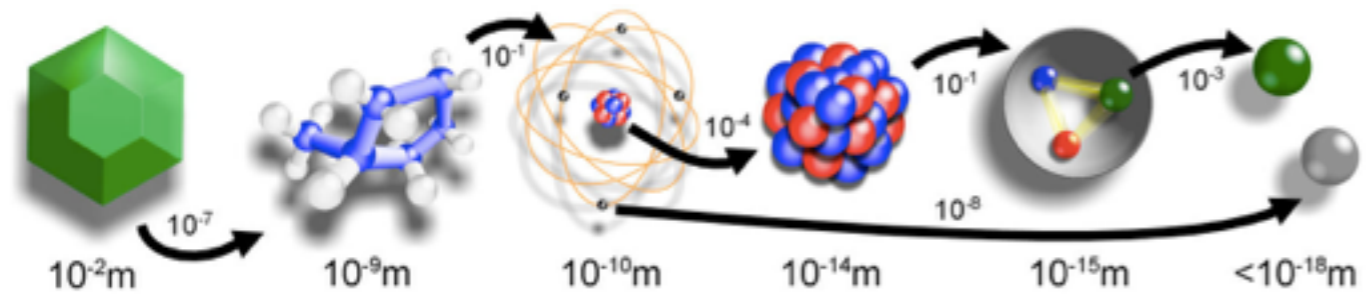
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. - \bar{\psi} m \psi + \frac{1}{2} A_{\mu} m^{\mu\nu} A_{\nu}$$

⇒ Wahrscheinlichkeiten > 1

Drei Generationen der Materie (Fermionen)

	I	II	III	
Masse	2,4 MeV	1,27 GeV	171,2 GeV	0
Ladung	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
Spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Name	u up	c charm	t top	γ Photon
Quarks	4,8 MeV $-\frac{1}{3}$	104 MeV $-\frac{1}{3}$	4,2 GeV $-\frac{1}{3}$	0
	d down	s strange	b bottom	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptonen	<2,2 eV	<0,17 MeV	<15,5 MeV	91,2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e Elektron-Neutrino	ν_μ Myon-Neutrino	ν_τ Tau-Neutrino	Z⁰ schwache Kraft
	0,511 MeV -1	105,7 MeV -1	1,777 GeV -1	±1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e Elektron	μ Myon	τ Tau	W[±] schwache Kraft
				Eichbosonen



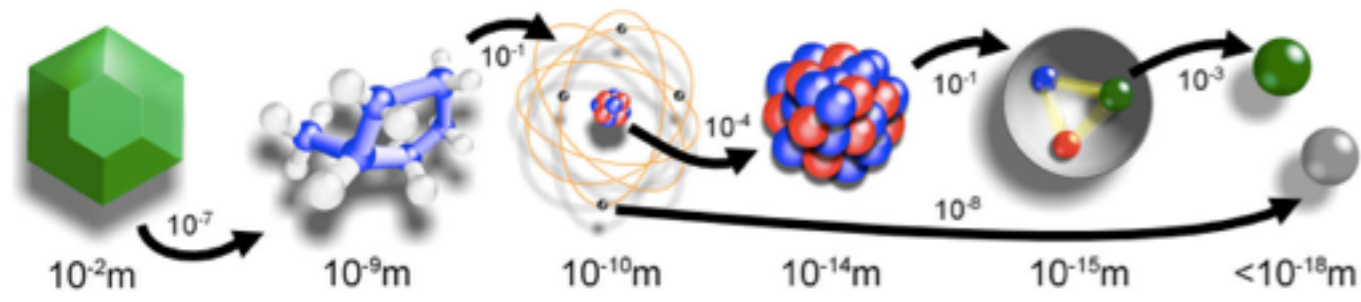


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D}\psi + h.c.$$

Drei Generationen der Materie (Fermionen)

	I	II	III	
Masse	2,4 MeV	1,27 GeV	171,2 GeV	0
Ladung	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
Spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Name	u up	c charm	t top	γ Photon
Quarks	4,8 MeV $-\frac{1}{3}$	104 MeV $-\frac{1}{3}$	4,2 GeV $-\frac{1}{3}$	0
	d down	s strange	b bottom	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptonen	<2,2 eV 0	<0,17 MeV 0	<15,5 MeV 0	91,2 GeV 0
	ν_e Elektron-Neutrino	ν_μ Myon-Neutrino	ν_τ Tau-Neutrino	Z⁰ schwache Kraft
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Eichbosonen	0,511 MeV -1	105,7 MeV -1	1,777 GeV -1	80,4 GeV ±1
	e Elektron	μ Myon	τ Tau	W[±] schwache Kraft
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1

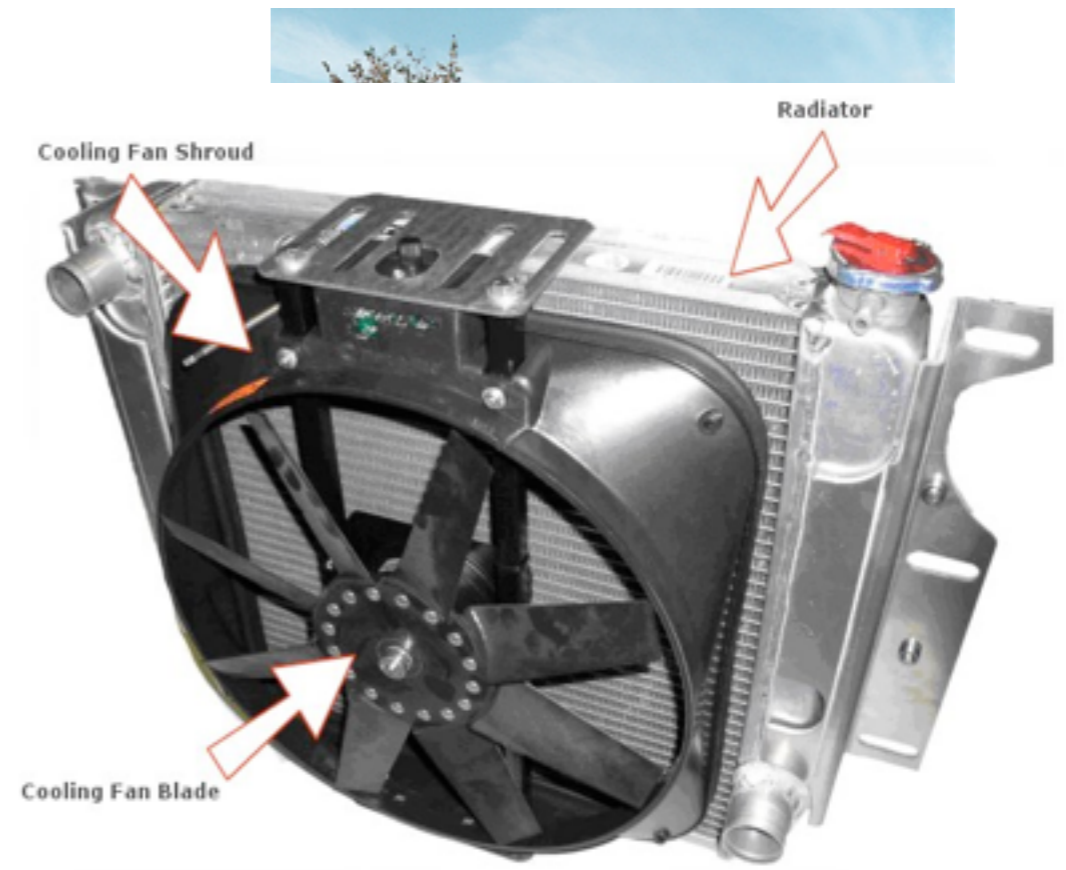


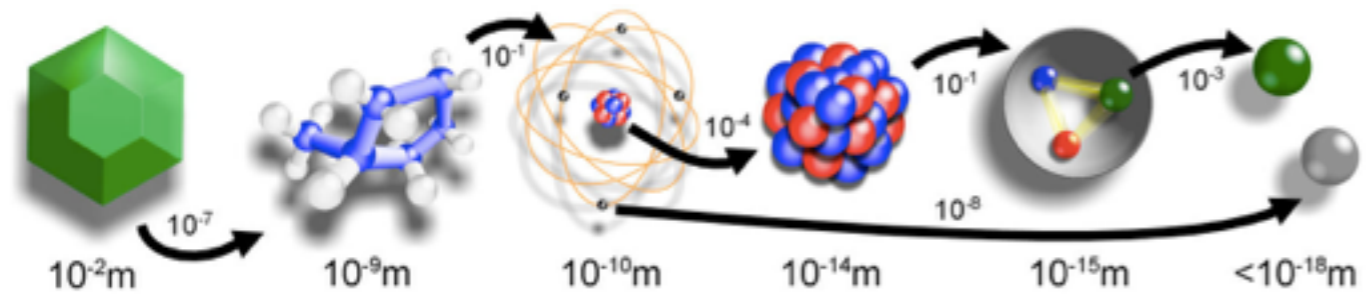


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D}\psi + h.c.$$

Drei Generationen der Materie (Fermionen)

	I	II	III	
Masse	2,4 MeV	1,27 GeV	171,2 GeV	0
Ladung	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
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Name	u up	c charm	t top	γ Photon
Quarks	4,8 MeV $-\frac{1}{3}$	104 MeV $-\frac{1}{3}$	4,2 GeV $-\frac{1}{3}$	0 0 1
	d down	s strange	b bottom	g Gluon
	<2,2 eV 0	<0,17 MeV 0	<15,5 MeV 0	91,2 GeV 0
Leptonen	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e Elektron-Neutrino	ν_μ Myon-Neutrino	ν_τ Tau-Neutrino	Z^0 schwache Kraft
	0,511 MeV -1	105,7 MeV -1	1,777 GeV -1	80,4 GeV ± 1
	e Elektron	μ Myon	τ Tau	W^\pm schwache Kraft
				Eichbosonen



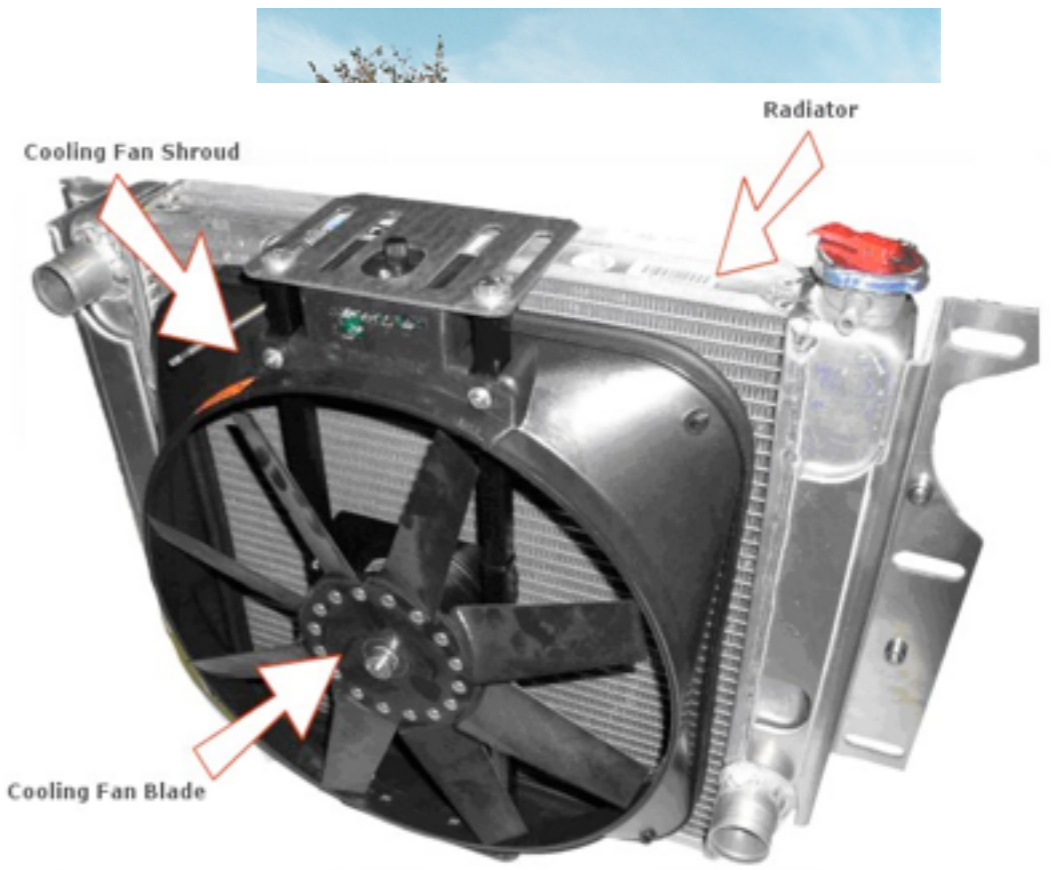


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. - \bar{\psi} \gamma \psi \phi + h.c. + |D_{\mu} \phi|^2 - V(\phi)$$

Drei Generationen der Materie (Fermionen)

	I	II	III	
Masse	2,4 MeV	1,27 GeV	171,2 GeV	0
Ladung	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
Spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Name	u up	c charm	t top	γ Photon
Quarks	4,8 MeV $-\frac{1}{3}$	104 MeV $-\frac{1}{3}$	4,2 GeV $-\frac{1}{3}$	0 0 1
	d down	s strange	b bottom	g Gluon
	<2,2 eV 0	<0,17 MeV 0	<15,5 MeV 0	91,2 GeV 0
Leptonen	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e Elektron-Neutrino	ν_μ Myon-Neutrino	ν_τ Tau-Neutrino	Z⁰ schwache Kraft
	0,511 MeV -1	105,7 MeV -1	1,777 GeV -1	80,4 GeV ±1
	e Elektron	μ Myon	τ Tau	W[±] schwache Kraft

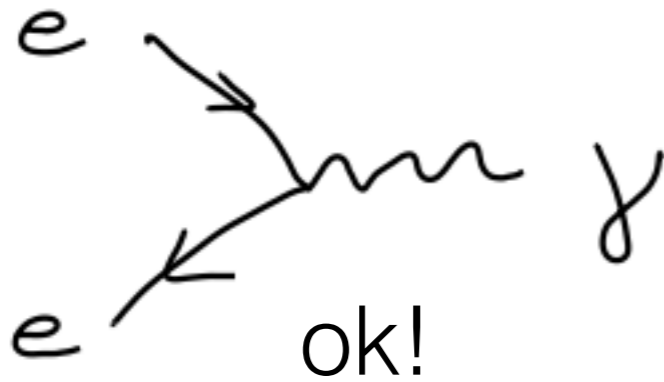
Eichbosonen



Higgs-Produktion

Es koppelt nicht alles an alles!

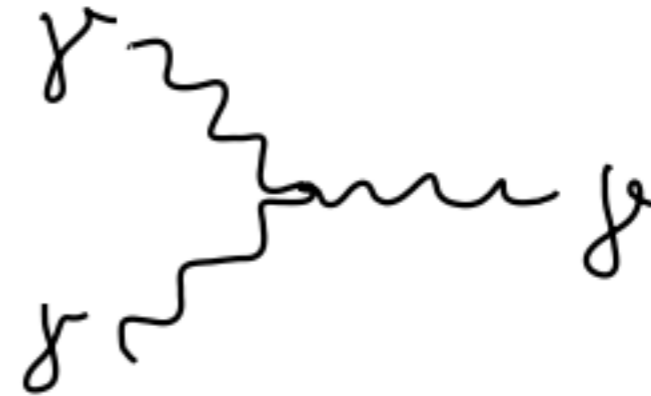
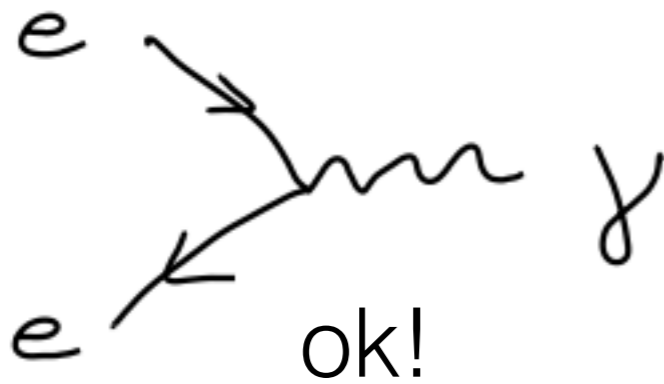
z.B. Photonen koppeln an elektrische Ladung



Higgs-Produktion

Es koppelt nicht alles an alles!

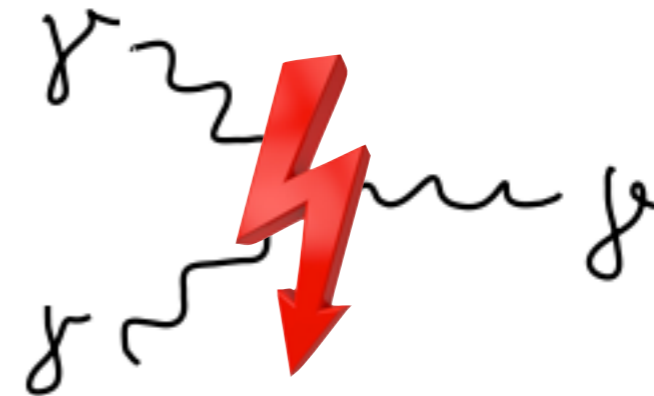
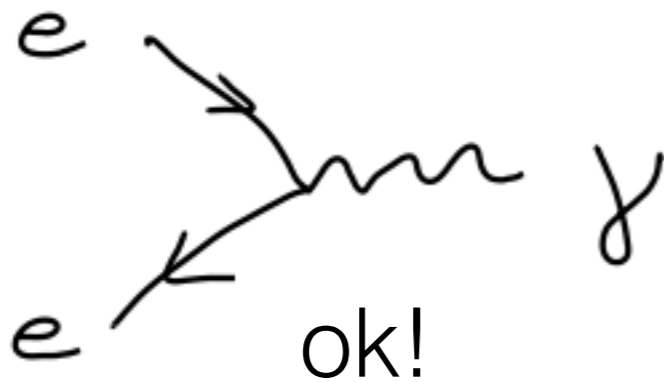
z.B. Photonen koppeln an elektrische Ladung



Higgs-Produktion

Es koppelt nicht alles an alles!

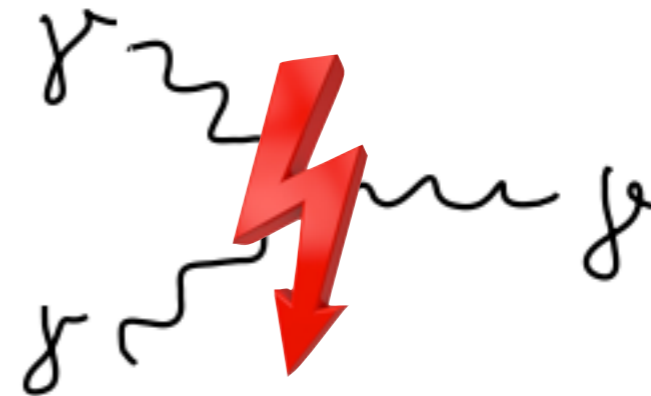
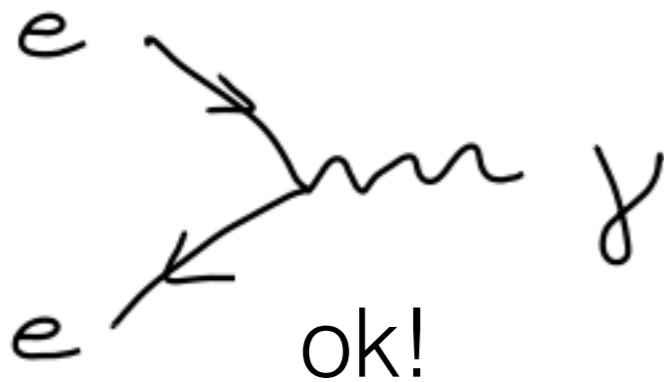
z.B. Photonen koppeln an elektrische Ladung



Higgs-Produktion

Es koppelt nicht alles an alles!

z.B. Photonen koppeln an elektrische Ladung

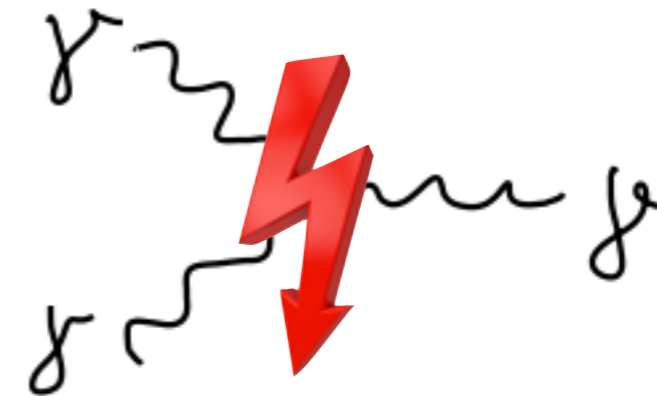
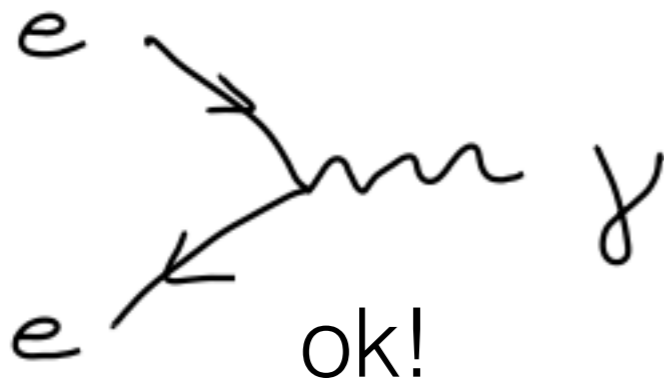


Licht-Licht-Streuung:
Schleifen-induziert!

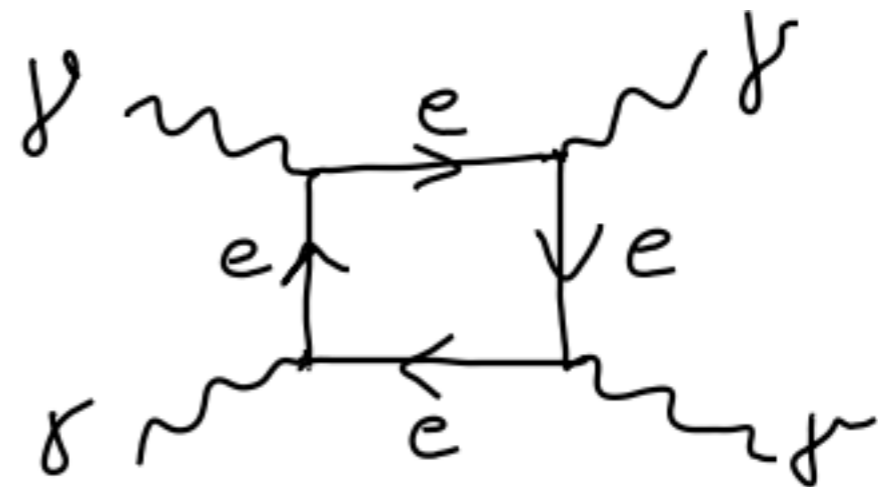
Higgs-Produktion

Es koppelt nicht alles an alles!

z.B. Photonen koppeln an elektrische Ladung



Licht-Licht-Streuung:
Schleifen-induziert!



Higgs-Produktion

Es koppelt nicht alles an alles!

z.B. Higgs koppelt an Masse

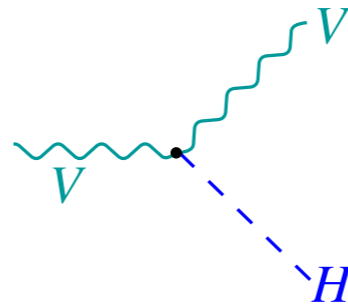
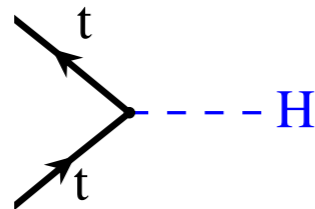
⇒ koppelt am stärksten an Topquark, W- und Z-Boson

Higgs-Produktion

Es koppelt nicht alles an alles!

z.B. Higgs koppelt an Masse

⇒ koppelt am stärksten an Topquark, W- und Z-Boson

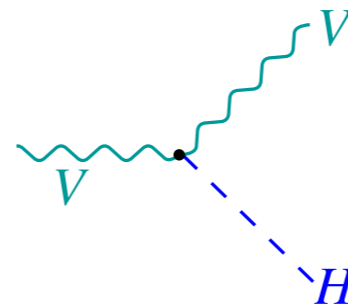
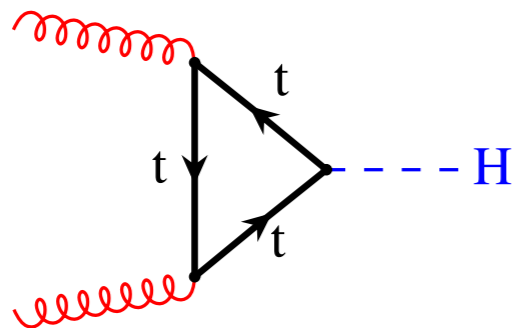


Higgs-Produktion

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z.B. Higgs koppelt an Masse

⇒ koppelt am stärksten an Topquark, W- und Z-Boson

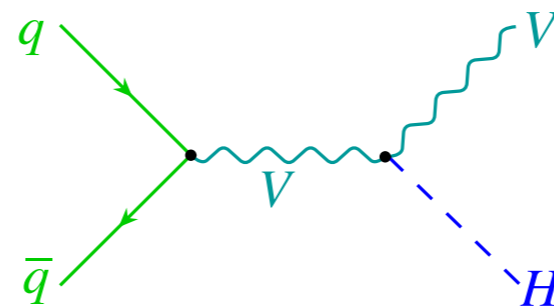
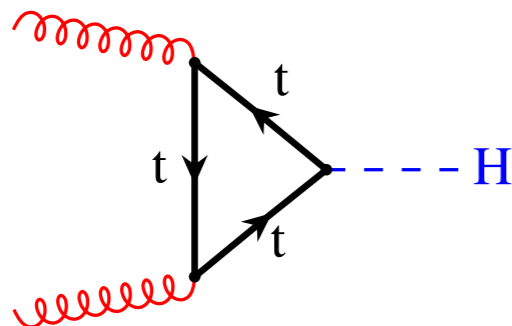


Higgs-Produktion

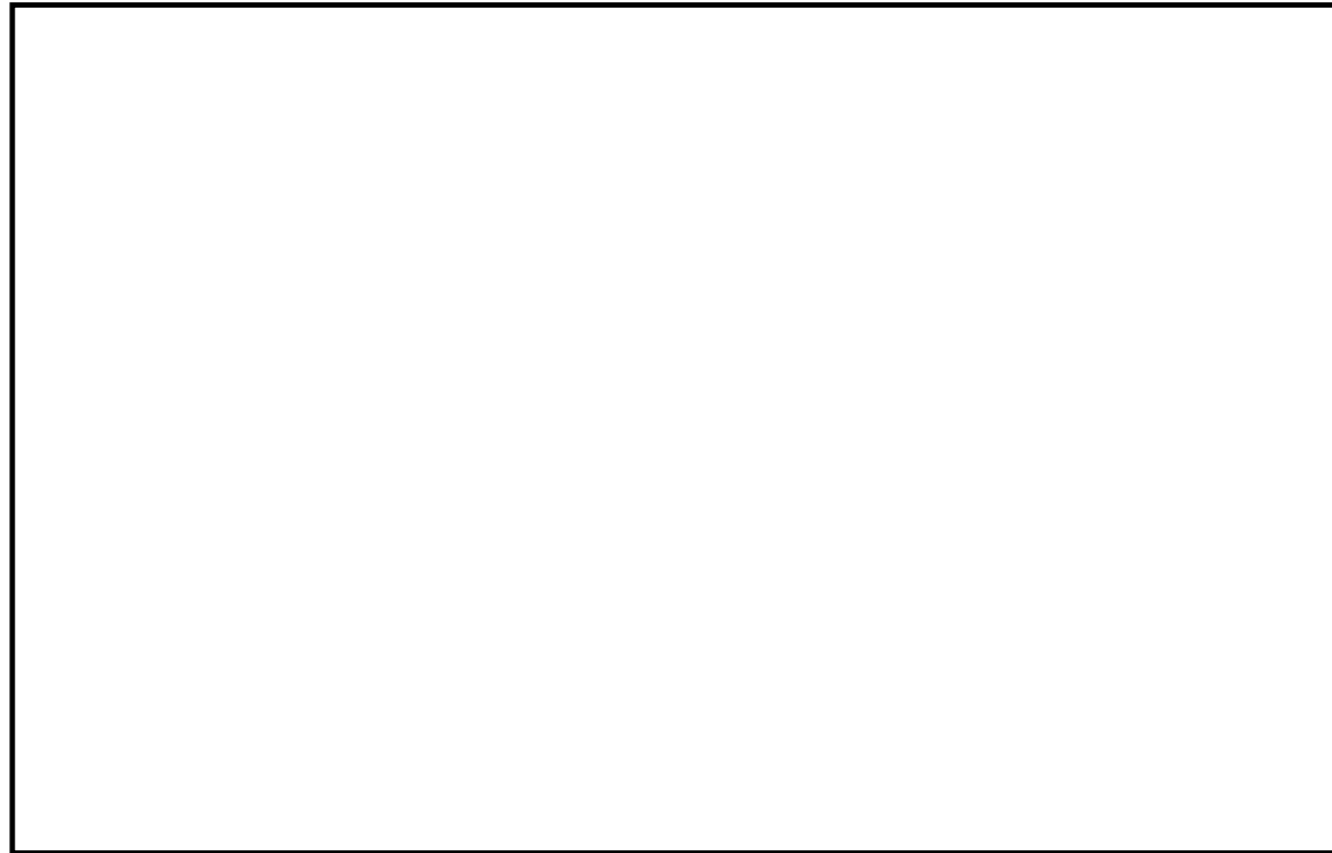
Es koppelt nicht alles an alles!

z.B. Higgs koppelt an Masse

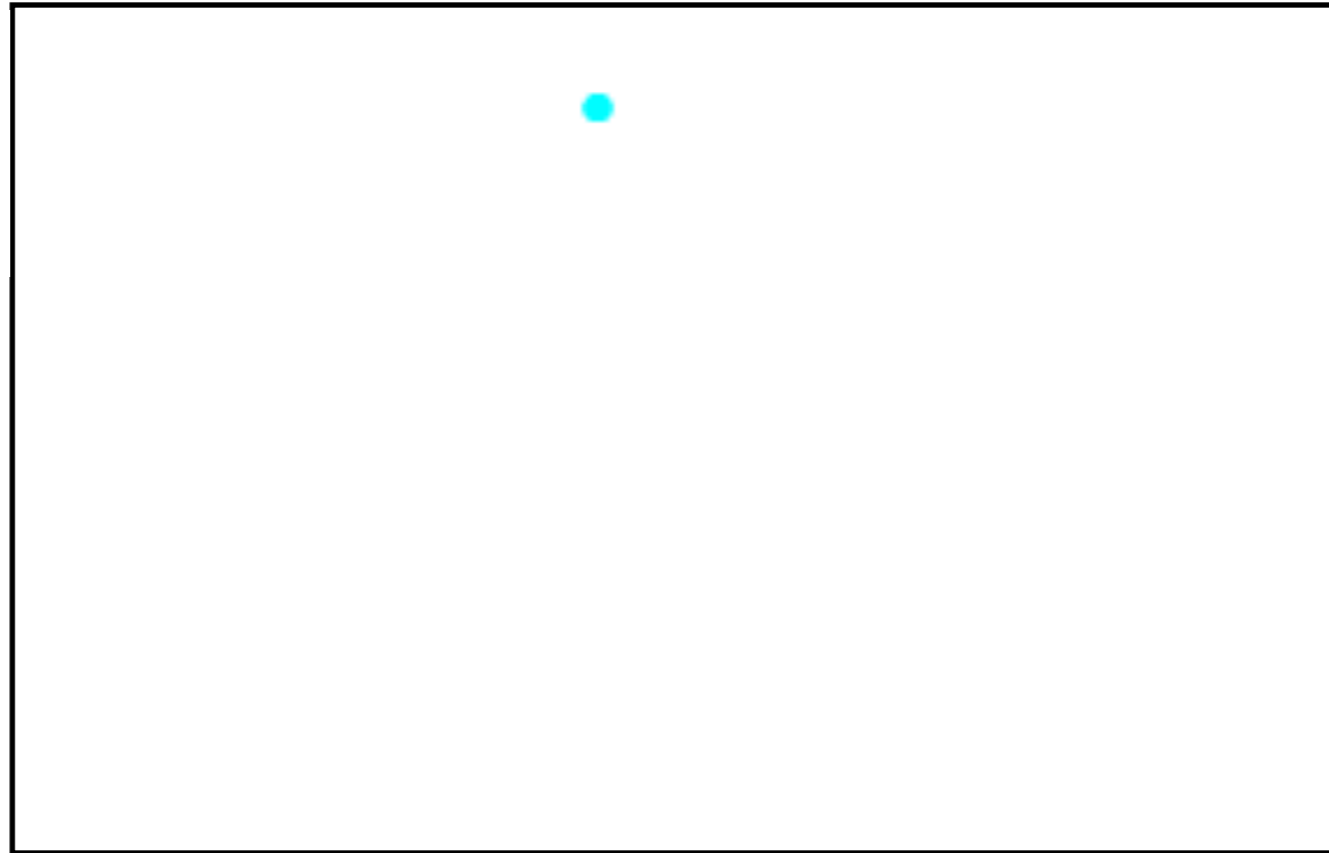
⇒ koppelt am stärksten an Topquark, W- und Z-Boson



The vacuum

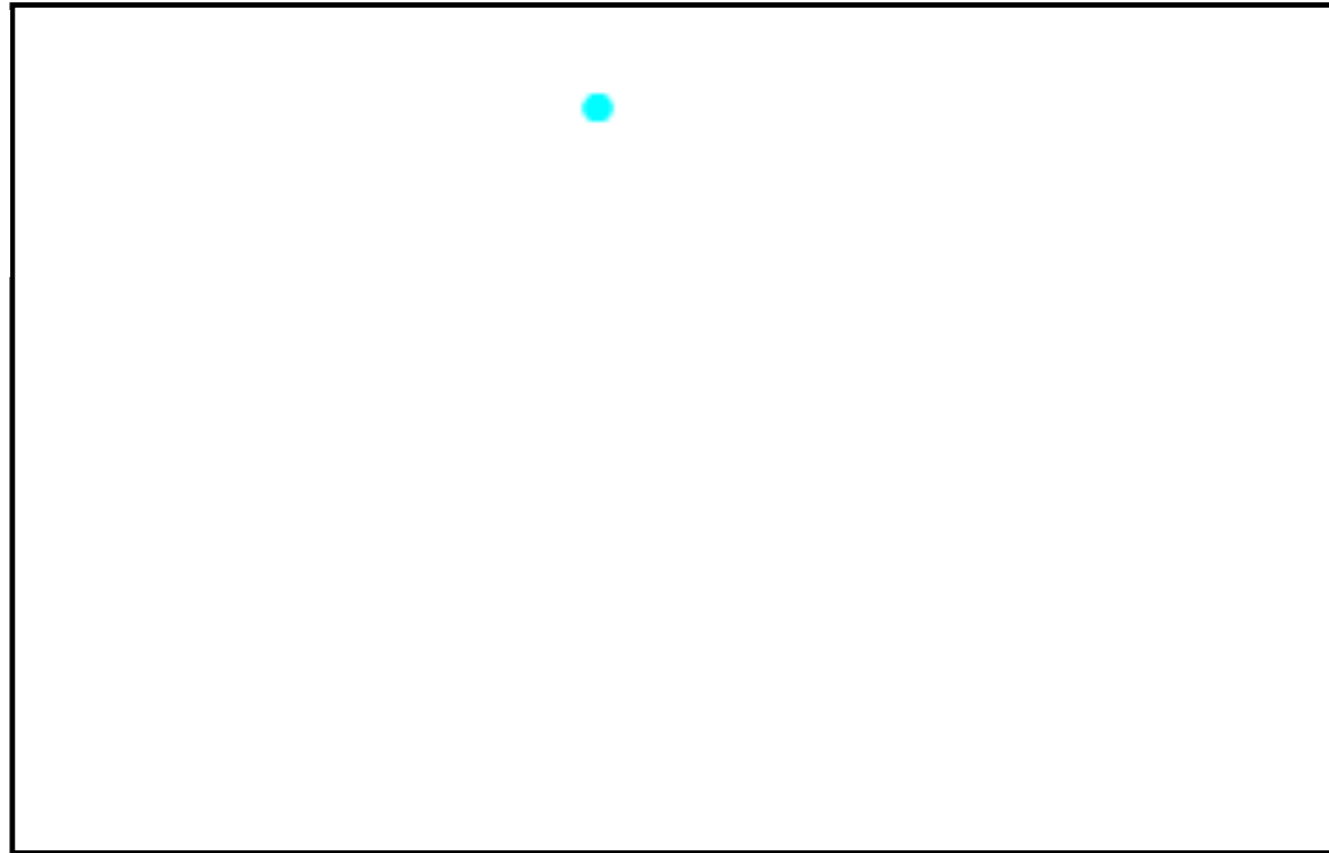


The quantum vacuum



$$\langle 0 | \dots \underbrace{\phi \dots \phi}_{\text{}} \dots | 0 \rangle$$

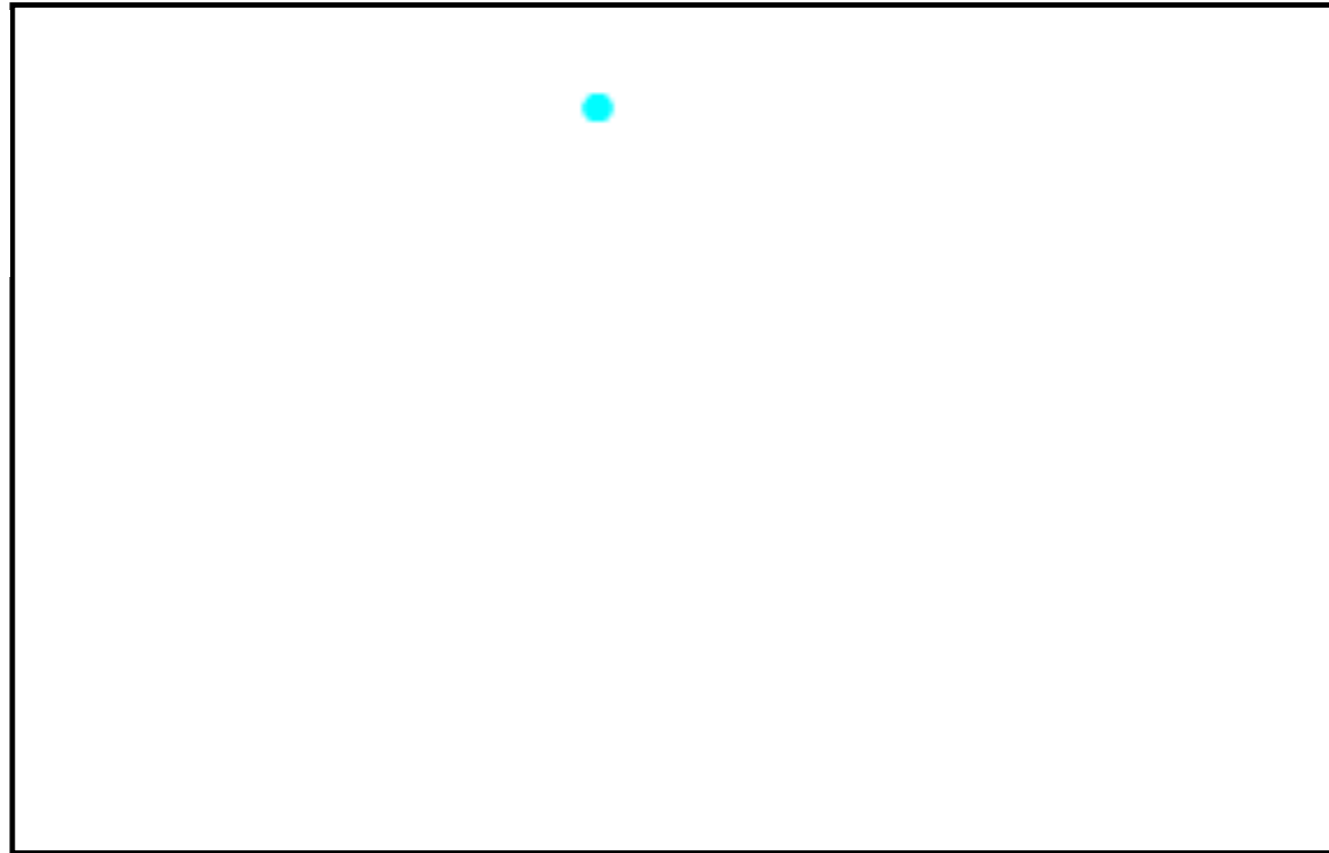
The quantum vacuum



$$\langle 0 | \dots \phi \dots \phi \dots | 0 \rangle$$

└──────────┘

The quantum vacuum



$$\langle 0 | \dots \underbrace{\phi \dots \phi}_{\text{}} \dots | 0 \rangle$$





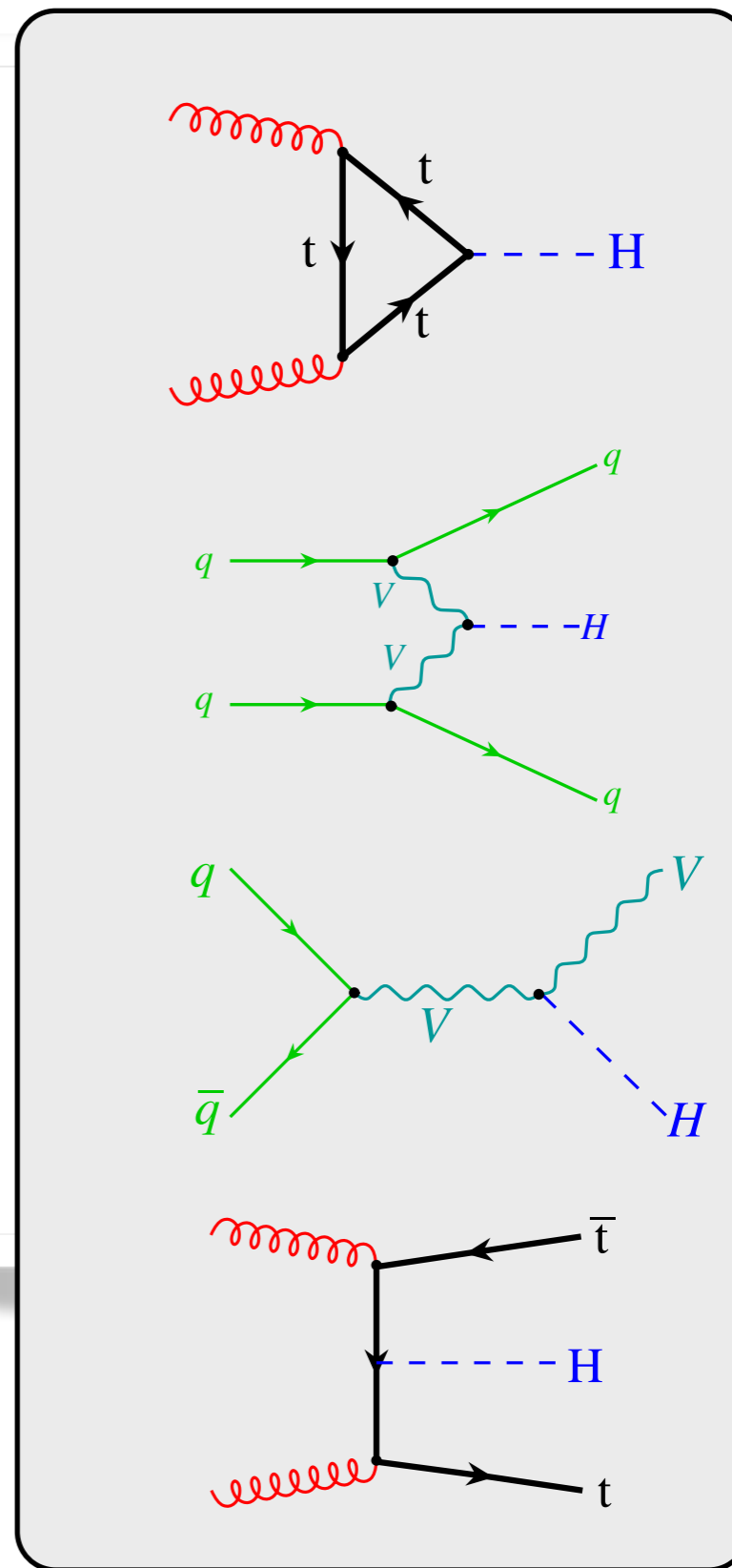
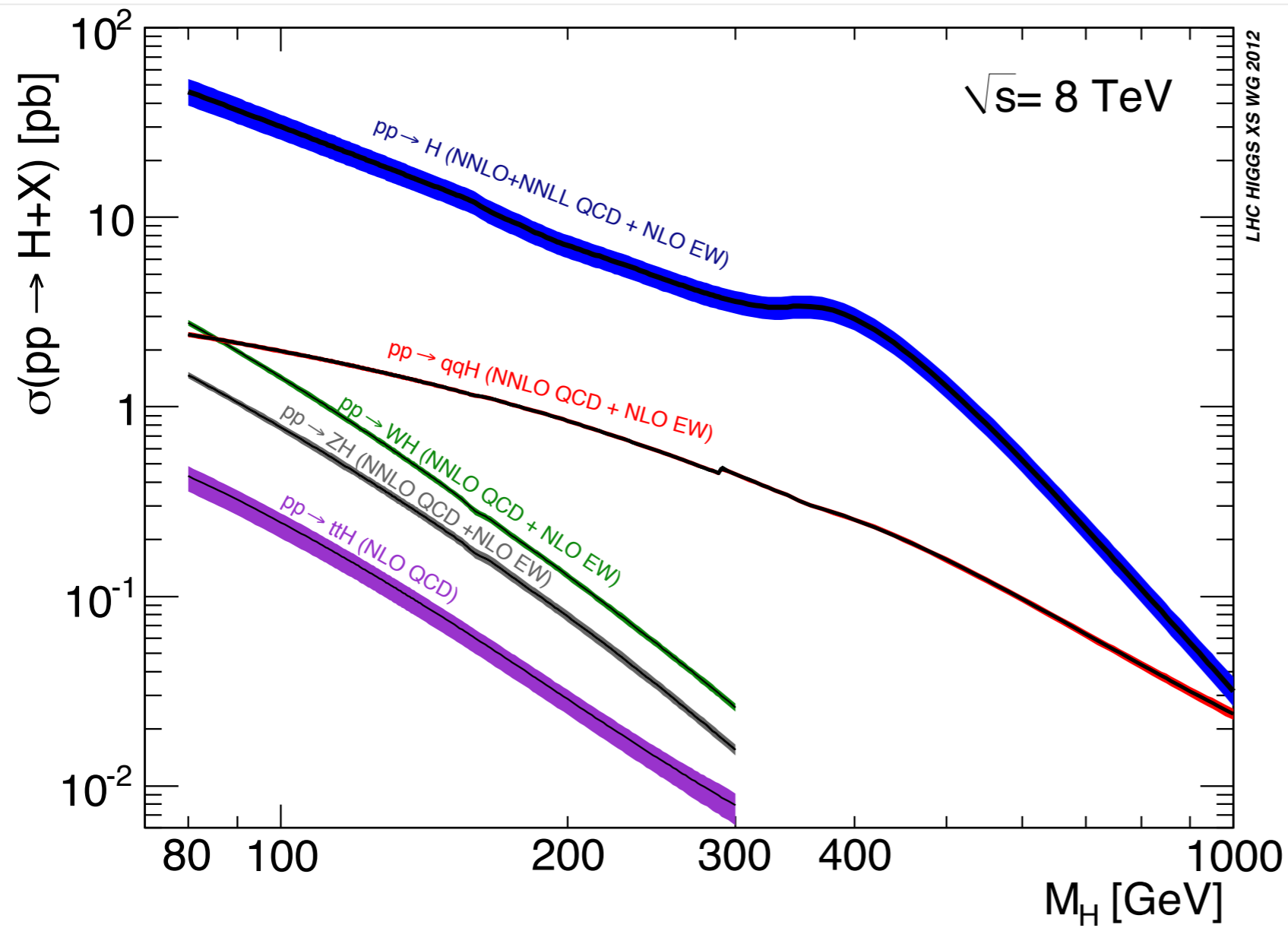












ATLAS Preliminary

$W, Z H \rightarrow bb$

$\sqrt{s} = 7 \text{ TeV: } \int L dt = 4.7 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV: } \int L dt = 13 \text{ fb}^{-1}$

$H \rightarrow \tau\tau$

$\sqrt{s} = 7 \text{ TeV: } \int L dt = 4.6 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV: } \int L dt = 13 \text{ fb}^{-1}$

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

$\sqrt{s} = 7 \text{ TeV: } \int L dt = 4.6 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV: } \int L dt = 20.7 \text{ fb}^{-1}$

$H \rightarrow \gamma\gamma$

$\sqrt{s} = 7 \text{ TeV: } \int L dt = 4.8 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV: } \int L dt = 20.7 \text{ fb}^{-1}$

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

$\sqrt{s} = 7 \text{ TeV: } \int L dt = 4.6 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV: } \int L dt = 20.7 \text{ fb}^{-1}$

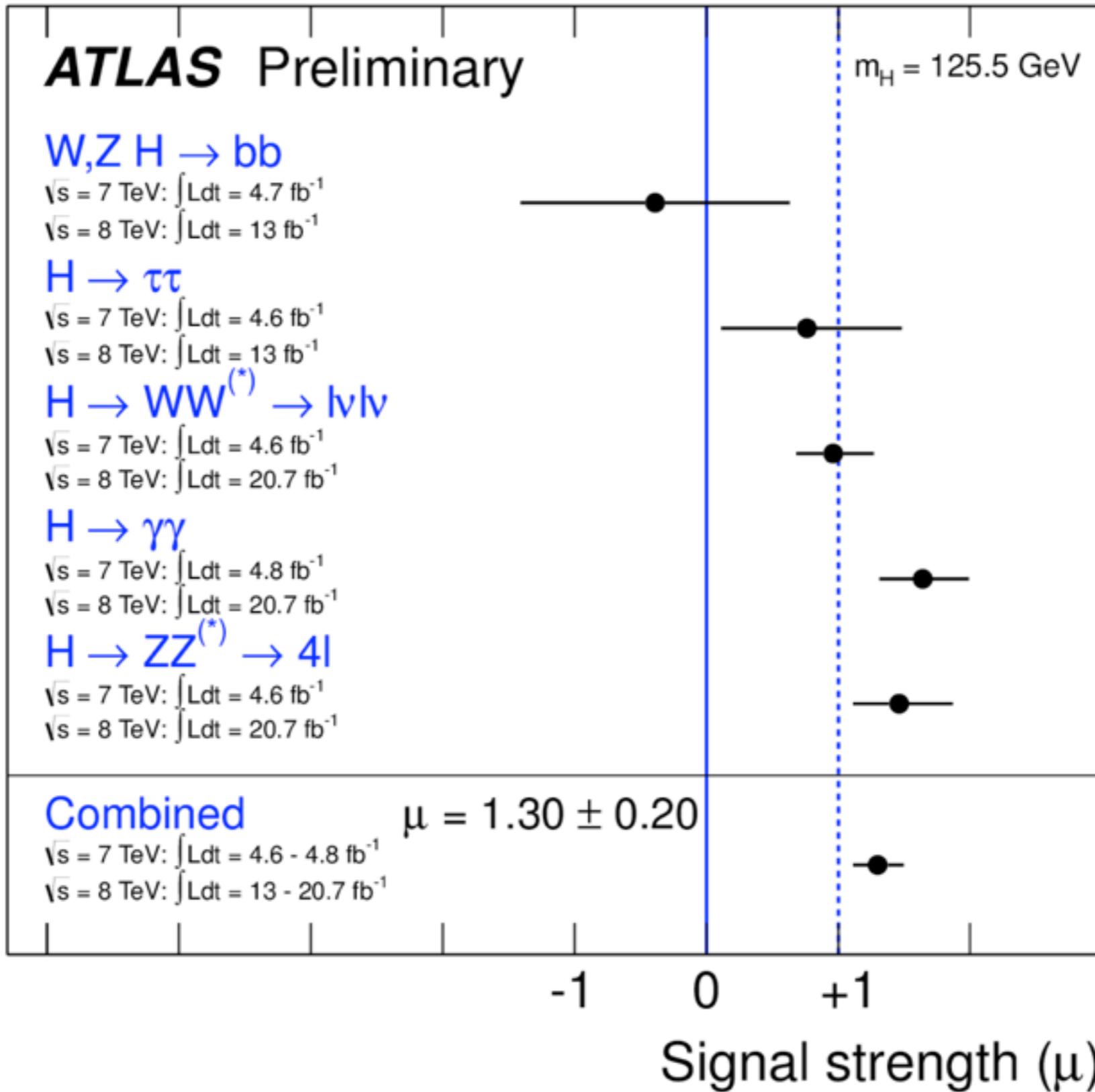
Combined

$\sqrt{s} = 7 \text{ TeV: } \int L dt = 4.6 - 4.8 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV: } \int L dt = 13 - 20.7 \text{ fb}^{-1}$

$$\mu = 1.30 \pm 0.20$$

$m_H = 125.5 \text{ GeV}$



March 2013

$$\int_0^1 dx f_{\text{exp}}(x, a) = 1 + a \frac{13}{36} + a^2 \frac{809}{4050} + a^3 \frac{1927}{14700} + a^4 \frac{234314}{2480625} + a^5 \frac{7803574}{108056025} + \dots$$

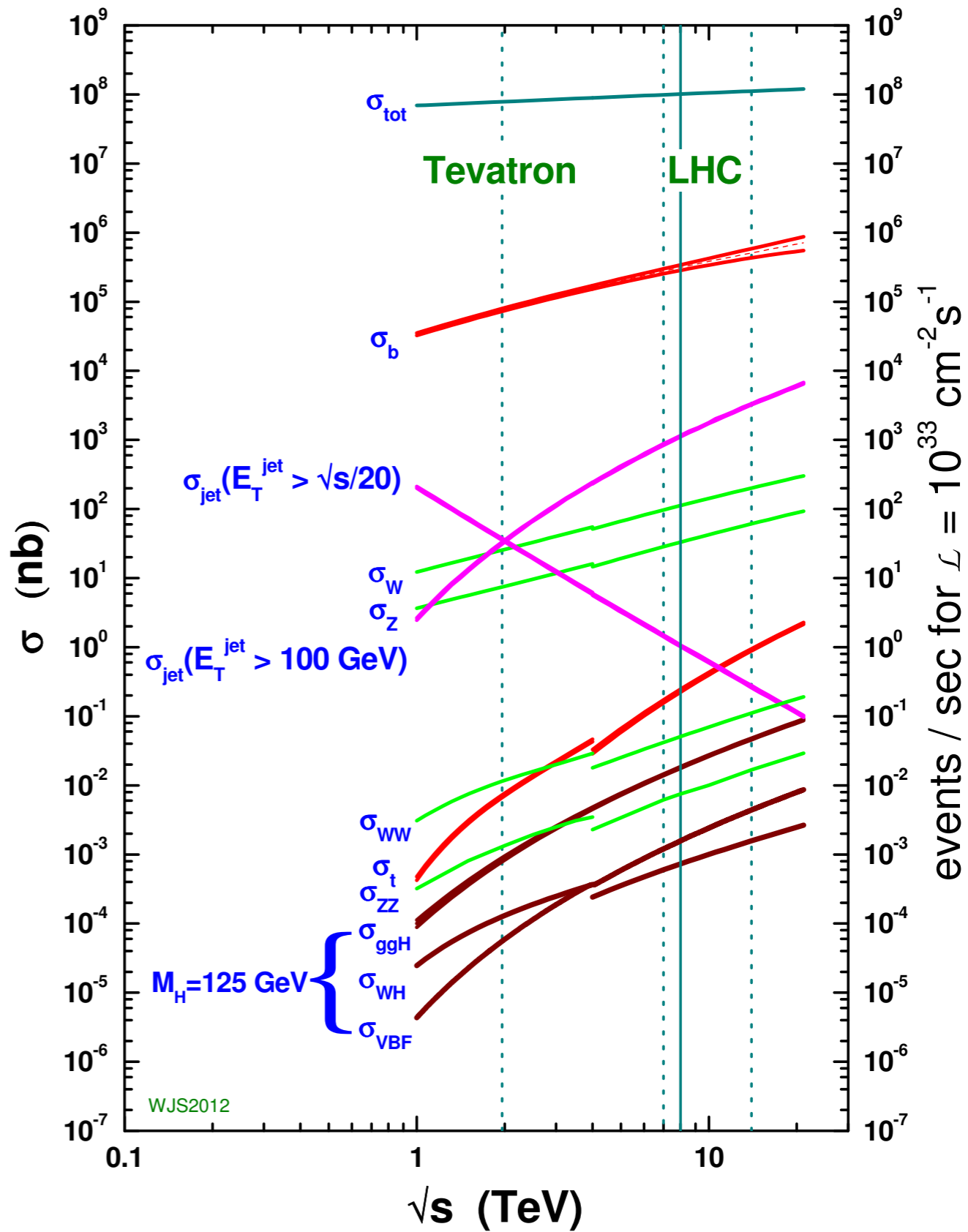
$$\begin{aligned}
\int_0^1 dx f_{\text{exp}}(x, a) &= 1 + a \frac{13}{36} + a^2 \frac{809}{4050} + a^3 \frac{1927}{14700} + a^4 \frac{234314}{2480625} + a^5 \frac{7803574}{108056025} + \dots \\
&+ a^{10} \frac{1056398775221248}{35860111300528515} + \dots \\
&+ a^{20} \frac{2217706582351833455192629609234432}{197020007032219396569654189271817625} + \dots \\
&+ a^{30} \frac{349236466671635422491277237990399242846765692175253504}{55484337187722346543070476479469237573996143089554108125} + \dots \\
&+ a^{40} \frac{61113456056322311744870175064504244192595167719946035127265078613639168}{14745493454562605394456699787099536537401020068836289098341590591777721875} + \dots
\end{aligned}$$

$$\begin{aligned}
\int_0^1 dx f_{\text{exp}}(x, a) &= 1 + a \frac{13}{36} + a^2 \frac{809}{4050} + a^3 \frac{1927}{14700} + a^4 \frac{234314}{2480625} + a^5 \frac{7803574}{108056025} + \dots \\
&+ a^{10} \frac{1056398775221248}{35860111300528515} + \dots \\
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&+ a^{30} \frac{349236466671635422491277237990399242846765692175253504}{55484337187722346543070476479469237573996143089554108125} + \dots \\
&+ a^{40} \frac{61113456056322311744870175064504244192595167719946035127265078613639168}{14745493454562605394456699787099536537401020068836289098341590591777721875} + \dots \\
&+ \dots \\
&+ a^{100} \frac{4583687359778220331319274633011959191579658481277324946765508662514142950473189880}{12361295730895994540334845001986054803298478598756567121146590356726691797785803568} + \dots \\
&+ \dots
\end{aligned}$$

$$\frac{073723510165058975042994651746980177004918909674384605895858111613625485152720257024}{3570376152784851514702163382285502271661099338115463236231206966125740312425543144375} + \dots$$

$$\begin{aligned}
\int_0^1 dx f_{\text{exp}}(x, a) &= 1 + a \frac{13}{36} + a^2 \frac{809}{4050} + a^3 \frac{1927}{14700} + a^4 \frac{234314}{2480625} + a^5 \frac{7803574}{108056025} + \dots \\
&+ a^{10} \frac{1056398775221248}{35860111300528515} + \dots \\
&+ a^{20} \frac{2217706582351833455192629609234432}{197020007032219396569654189271817625} + \dots \\
&+ a^{30} \frac{349236466671635422491277237990399242846765692175253504}{55484337187722346543070476479469237573996143089554108125} + \dots \\
&+ a^{40} \frac{61113456056322311744870175064504244192595167719946035127265078613639168}{14745493454562605394456699787099536537401020068836289098341590591777721875} + \dots \\
&+ \dots \\
&+ a^{100} \frac{4583687359778220331319274633011959191579658481277324946765508662514142950473189880}{12361295730895994540334845001986054803298478598756567121146590356726691797785803568} + \dots \\
&+ \dots
\end{aligned}$$

proton - (anti)proton cross sections



Next-to-Next-to-Leading Order Higgs Production at Hadron Colliders

Robert V. Harlander*

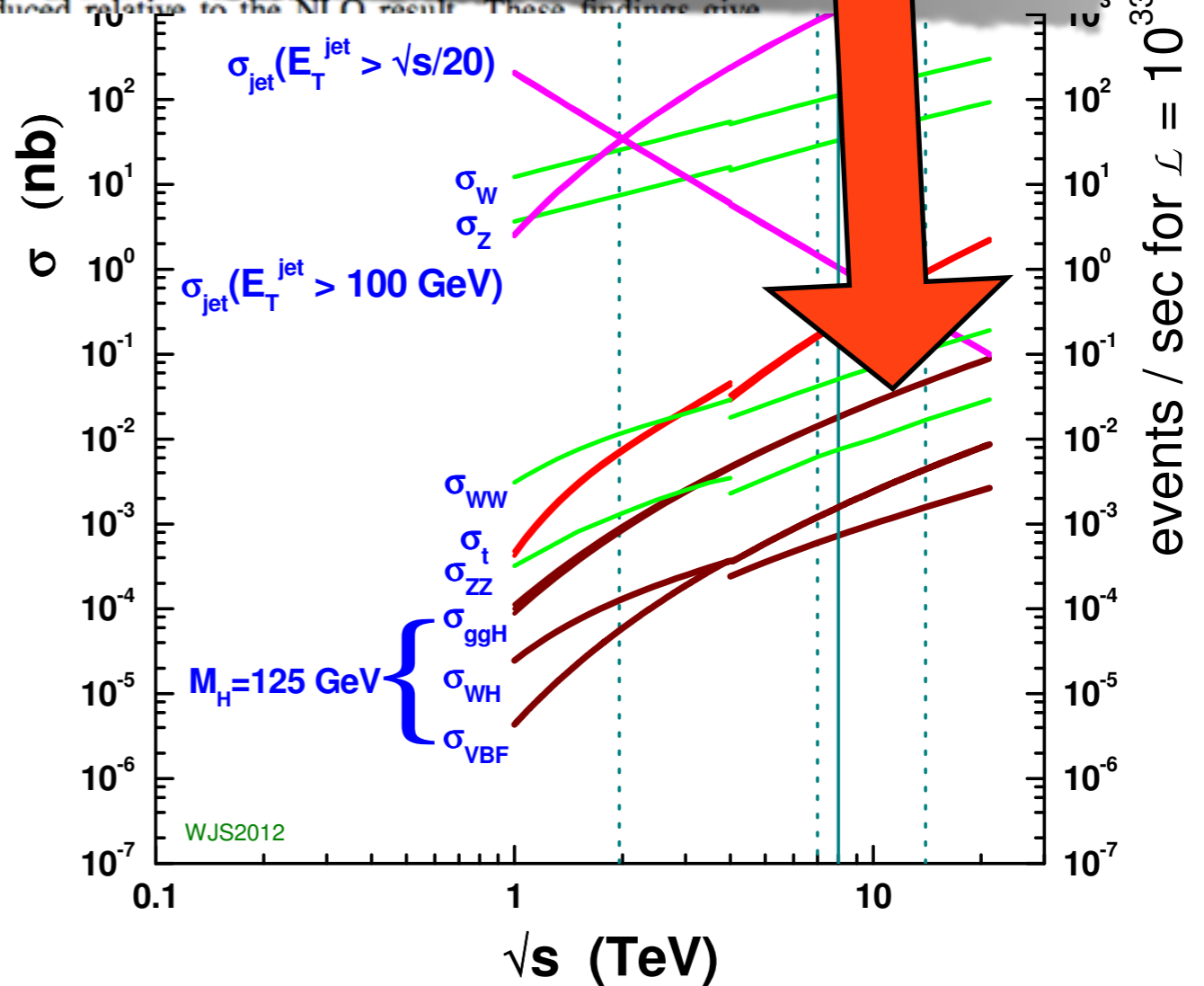
TH Division, CERN, CH-1211 Geneva 23, Switzerland

William B. Kilgore†

Physics Department, Brookhaven National Laboratory, Upton, New York 11973

(Received 22 January 2002; published 6 May 2002)

The Higgs-boson production cross section at pp and $p\bar{p}$ colliders is calculated in QCD at next-to-next-to-leading order (NNLO). We find that the perturbative expansion of the production cross section is well behaved and that scale dependence is reduced relative to the NLO result. These findings give



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Top-quark mediated effects in hadronic Higgs-Strahlung

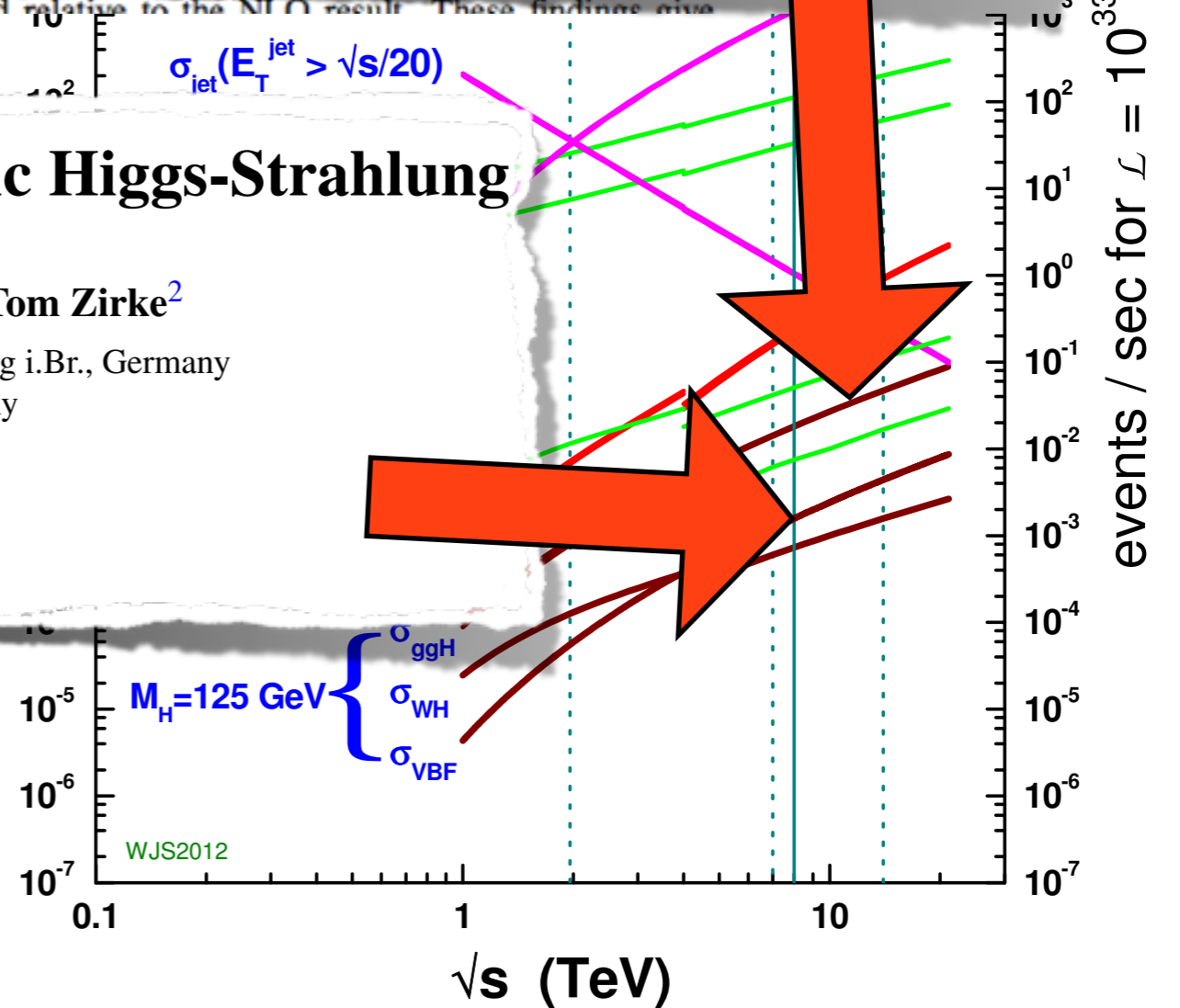
Oliver Brein¹, Robert V. Harlander^{2,a}, Marius Wiesemann², Tom Zirke²

¹Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, 79104 Freiburg i.Br., Germany

²Fachbereich C, Bergische Universität Wuppertal, 42097 Wuppertal, Germany

Received: 18 November 2011

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Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration ☆

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.



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¹⁷⁴ *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*

¹⁷⁵ *Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany*

¹⁷⁶ *Department of Physics, Yale University, New Haven, CT, United States*

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ATLAS Collaboration [☆]

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

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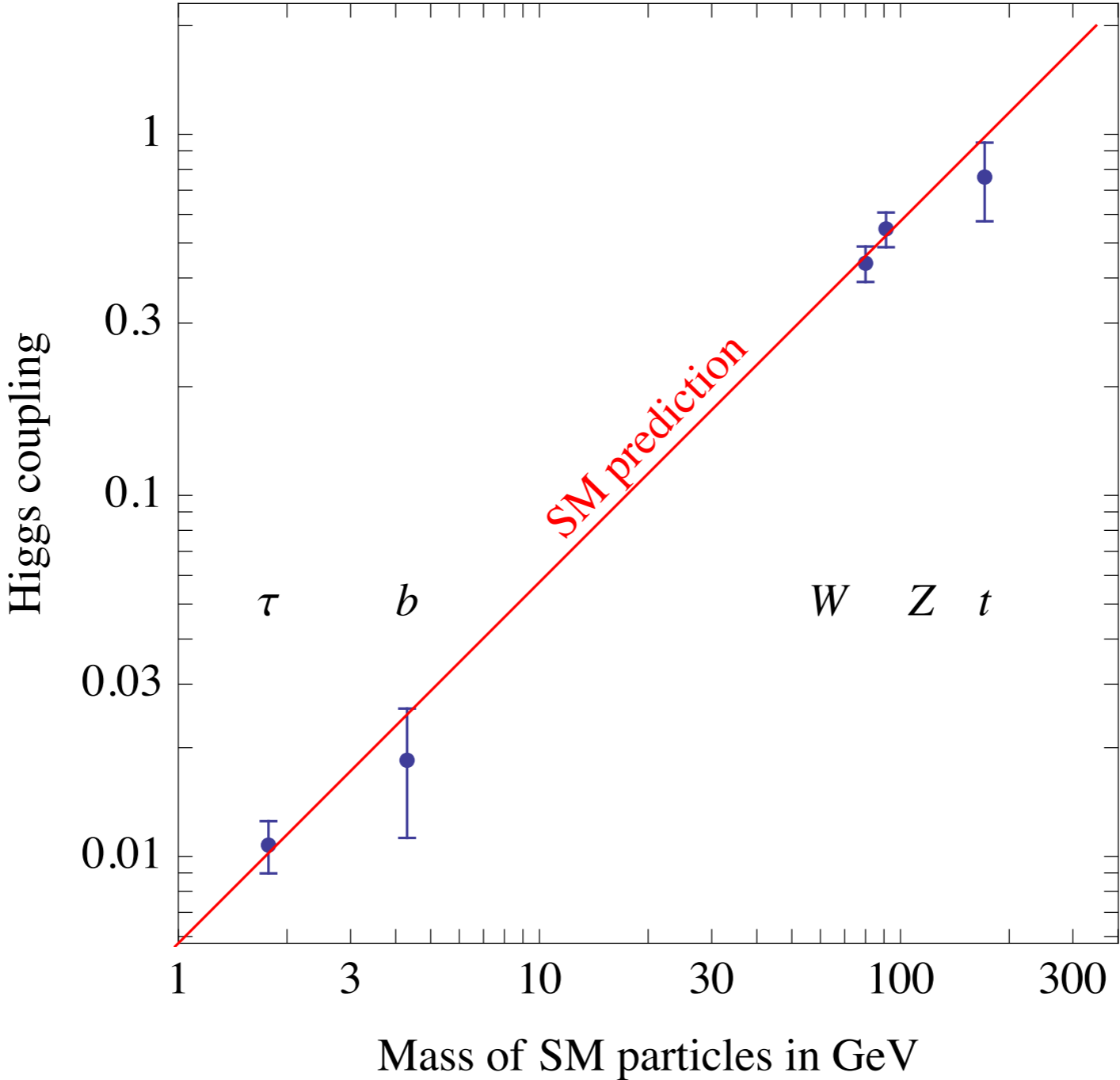
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Fit to Higgs couplings



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und watschelt wie ein Higgs,
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Aber wer weiss?

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