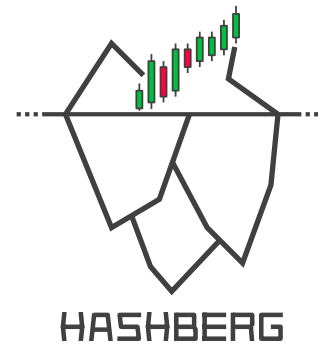


Categorical Semantics for Feynman Diagrams

Razin A. Shaikh and Stefano Gogioso

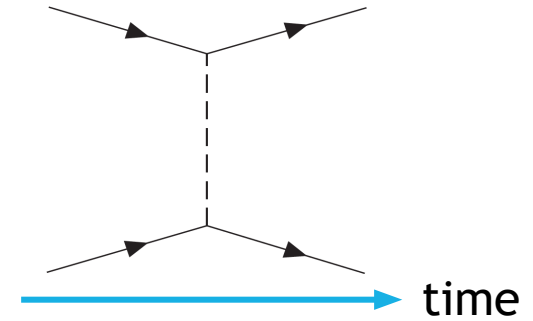


Motivation

Motivation

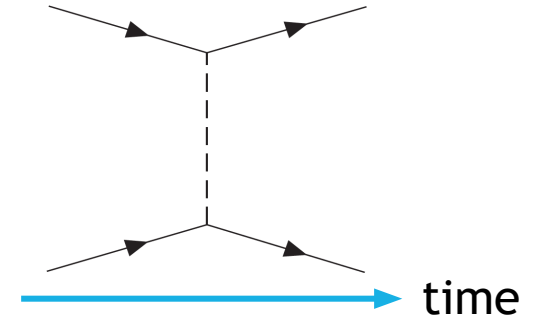
- ▶ Quantum field theory (QFT) provides the best current model of the universe

Motivation



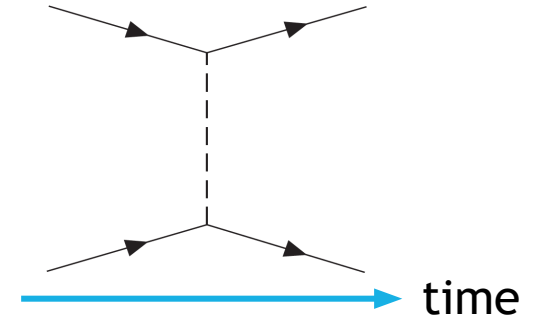
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- ▶ In QFT, Feynman diagrams represent probability amplitudes of interactions

Motivation



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- ▶ In QFT, Feynman diagrams represent probability amplitudes of interactions
- ▶ How do Feynman diagrams formally arise from field operators?

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- ▶ Quantum field theory (QFT) provides the best current model of the universe
- ▶ In QFT, Feynman diagrams represent probability amplitudes of interactions
- ▶ How do Feynman diagrams formally arise from field operators?
- ▶ Can we compose Feynman diagrams?

Overview

- ▶ Categorical quantum fields
- ▶ Categorical Feynman diagrams
- ▶ Composing Feynman diagrams

Scalar Classical Fields

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Simple harmonic oscillators at each point of momentum space

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To quantise the field, quantize the harmonic oscillators

Quantization

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Quantization

- ▶ We cannot use the category \mathbf{Hilb} - no cups, caps or spiders
- ▶ We use $\star\mathbf{fHilb}$ - category of hyperfinite-dimensional Hilbert space
- ▶ $\star\mathbf{fHilb}$ is dagger compact - has cups, caps and spiders
- ▶ The results from $\star\mathbf{fHilb}$ can be transferred to \mathbf{Hilb} using a functor

Quantum Harmonic Oscillator

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- ▶ Described by an object \mathcal{H}^κ , for some hyperfinite natural number κ

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Creation operator

$$a_\kappa^\dagger : \mathcal{H}^\kappa \rightarrow \mathcal{H}^{\kappa+1}$$

$$|n\rangle \mapsto \sqrt{n+1} |n+1\rangle$$

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Annihilation operator

$$a_\kappa : \mathcal{H}^\kappa \rightarrow \mathcal{H}^{\kappa-1}$$
$$|n\rangle \mapsto \sqrt{n} |n-1\rangle$$

Scalar Quantum Fields

Scalar quantum field \rightarrow *quantum* harmonic oscillators at each point of momentum space Ω

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Quantum field $\nearrow \mathcal{H}^{(\tau)} := \bigotimes_{\underline{p} \in \Omega} \mathcal{H}^{\tau_{\underline{p}}} \nwarrow$ Quantum harmonic oscillators

Scalar Quantum Fields

Scalar quantum field \rightarrow *quantum* harmonic oscillators at each point of momentum space Ω

$$\text{Quantum field} \rightarrow \mathcal{H}^{(\tau)} := \bigotimes_{\underline{p} \in \Omega} \mathcal{H}^{\tau_{\underline{p}}} \leftarrow \text{Quantum harmonic oscillators}$$

The Fock basis \rightarrow Particle number for each momentum point:

$$|\beta_{\underline{n}}\rangle := \bigotimes_{\underline{p} \in \Omega} |n_{\underline{p}}\rangle$$

Ingredients required for Feynman diagrams

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- ▶ Creation and annihilation operators of the field

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- ▶ Creation and annihilation operators of the field
- ▶ Feynman propagator

Field Operators

Creation and annihilation operators for fields

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Creation and annihilation operators for fields

$$\begin{aligned} a_{\tau}^{\dagger}(\underline{p}) : \mathcal{H}^{(\tau)} &\longrightarrow \mathcal{H}^{(\tau+\delta_{\underline{p}})} \\ |\beta_{\underline{n}}\rangle &\mapsto \sqrt{\omega_{ir}^3} \sqrt{n_{\underline{p}} + 1} |\beta_{\underline{n}+\delta_{\underline{p}}}\rangle \end{aligned}$$

$$\begin{aligned} \delta_{\underline{p}} : \Omega &\longrightarrow \{0, 1\} \\ \underline{q} &\mapsto \delta_{\underline{p}, \underline{q}} \end{aligned}$$

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$$\begin{aligned} a_{\tau}(\underline{p}) : \mathcal{H}^{(\tau)} &\longrightarrow \mathcal{H}^{(\tau-\delta_{\underline{p}})} \\ |\beta_{\underline{n}}\rangle &\mapsto \sqrt{\omega_{ir}^3} \sqrt{n_{\underline{p}}} |\beta_{\underline{n}-\delta_{\underline{p}}}\rangle \end{aligned}$$

Coherently-controlled Field Operators

We package the field operators into coherently-controlled versions:

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$$\begin{array}{c} \text{---} \\ \text{---} \end{array} \boxed{\gamma^\dagger} \text{---} \quad := \quad \sum_{\underline{p} \in \Omega} \frac{1}{\omega_{ir}^3} \frac{1}{\sqrt{2E_{\underline{p}}}} \quad \begin{array}{c} \text{---} \boxed{a^\dagger(\underline{p})} \text{---} \\ \text{---} \boxed{\chi_{\underline{p}}} \end{array}$$

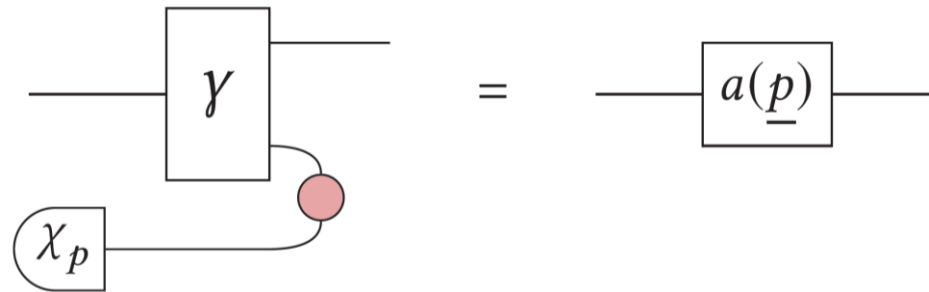
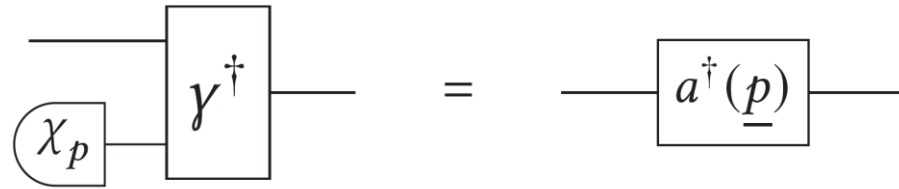
Coherently-controlled Field Operators

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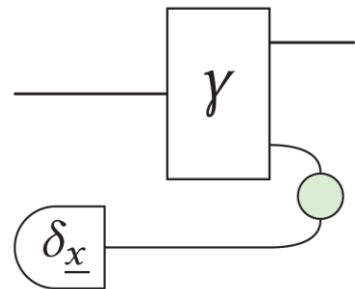
Coherently-controlled Field Operators

Plug in momentum basis state \rightarrow recover original momentum-space field operators



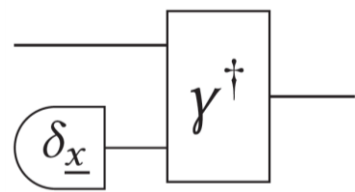
Coherently-controlled Field Operators

Plug in position basis state \rightarrow Fourier transform of momentum-space operators, i.e. position-space operators



A Feynman diagram representing the creation operator. It consists of a rectangular box labeled with the Greek letter γ . An incoming line from the left enters the box. An outgoing line from the right exits the box and connects to a green circular vertex. A second line enters this vertex from below, originating from a box labeled $\delta_{\underline{x}}$.

$$= \sum_{\underline{p}} \frac{1}{\omega_{ir}^3} \frac{1}{\sqrt{2E_{\underline{p}}}} a(\underline{p}) e^{i2\pi \underline{p} \cdot \underline{x}} =: \phi^+(\underline{x})$$



A Feynman diagram representing the annihilation operator. It consists of a rectangular box labeled with γ^\dagger . An incoming line from the left enters the box. An outgoing line from the right exits the box. A second line enters the box from below, originating from a box labeled $\delta_{\underline{x}}$.

$$= \sum_{\underline{p}} \frac{1}{\omega_{ir}^3} \frac{1}{\sqrt{2E_{\underline{p}}}} a^\dagger(\underline{p}) e^{-i2\pi \underline{p} \cdot \underline{x}} =: \phi^-(\underline{x})$$

Feynman propagator

Feynman propagator

Probability of a particle travelling from spacetime point x to y

Feynman propagator

Probability of a particle travelling from spacetime point x to y

$$\Delta_F(x - y) = \text{Diagram 1} = \text{Diagram 2}$$

The image shows two Feynman diagrams representing the Feynman propagator $\Delta_F(x - y)$. Both diagrams are preceded by an equals sign. Each diagram consists of a horizontal line at the top. Below this line, on the left, is a box containing δ_x (top diagram) or δ_y (bottom diagram). A line connects this box to a diamond-shaped vertex labeled ϕ . From the right side of the ϕ vertex, a line curves to a green circular vertex. In the top diagram, the δ_x box is connected to the ϕ vertex, and the δ_y box is connected to the green vertex. In the bottom diagram, the δ_y box is connected to the ϕ vertex, and the δ_x box is connected to the green vertex. The two diagrams are separated by an equals sign.

Feynman propagator

Probability of a particle travelling from spacetime point x to y

$$\Delta_F(x - y) = \begin{array}{c} \text{---} \\ \delta_x \text{---} \diamond \phi \text{---} \text{---} \\ \delta_y \text{---} \text{---} \end{array} = \begin{array}{c} \text{---} \\ \delta_x \text{---} \text{---} \\ \delta_y \text{---} \diamond \phi \text{---} \end{array}$$

$$\Delta_F(x - y) = \begin{cases} D(x - y) & x_0 > y_0 \\ D(y - x) & y_0 > x_0 \end{cases}$$

$$D(x - y) := [\phi^+(x), \phi^-(y)]$$

Overview

- ▶ Categorical quantum fields
- ▶ **Categorical Feynman diagrams**
- ▶ Composing Feynman diagrams

Scalar Yukawa Theory

- ▶ Simplified version of the theory of strong force between nucleons

Scalar Yukawa Theory

- ▶ Simplified version of the theory of strong force between nucleons
- ▶ We adopt the following notation:

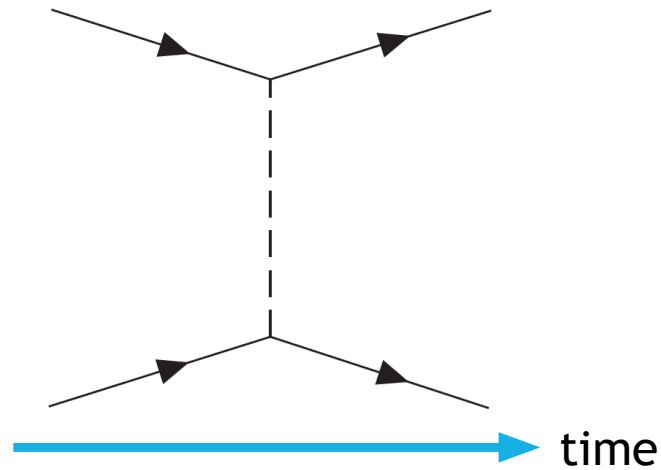
n_+ nucleons 

n_- anti-nucleons 

m mesons 

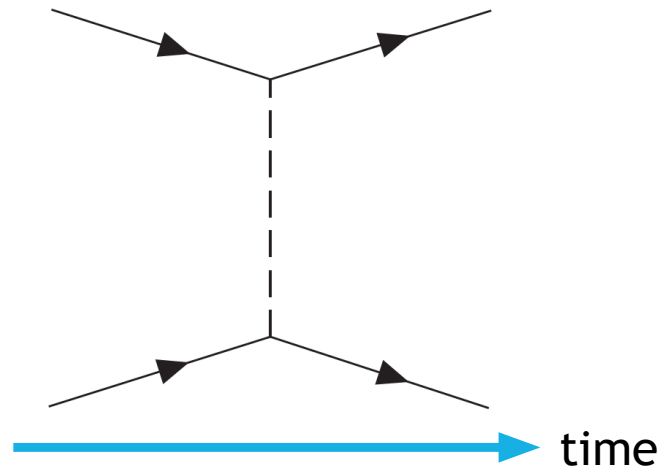
Example 1: Nucleon-Nucleon Scattering

Interaction of two nucleons mediated by a virtual meson:



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Interaction of two nucleons mediated by a virtual meson:



Corresponding Wick's expansion term:

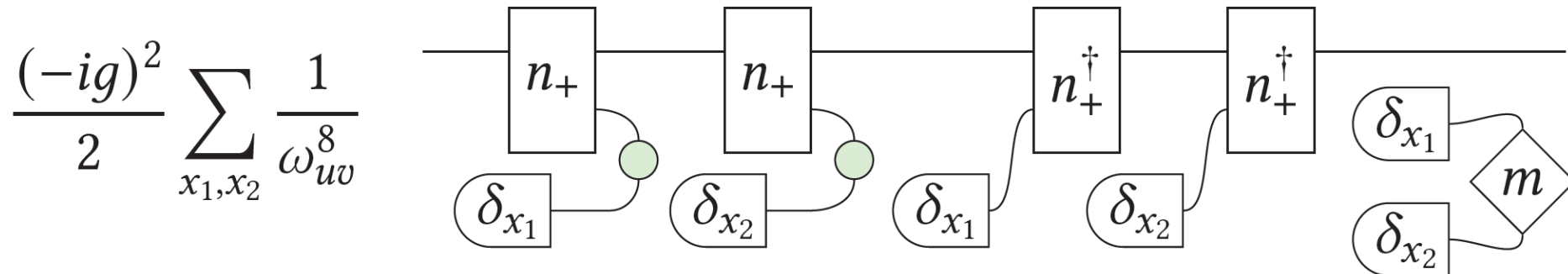
$$\frac{(-ig)^2}{2} \sum_{x_1, x_2} \frac{1}{\omega_{uv}^8} n_{+}^{\dagger}(x_1) n_{+}^{\dagger}(x_2) n_{+}(x_1) n_{+}(x_2) \overline{m(x_1) m(x_2)}$$

Example 1: Nucleon-Nucleon Scattering

$$\frac{(-ig)^2}{2} \sum_{x_1, x_2} \frac{1}{\omega_{uv}^8} n_+^\dagger(x_1) n_+^\dagger(x_2) n_+(x_1) n_+(x_2) \overline{m(x_1) m(x_2)}$$

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Split and Merge maps

Split and Merge maps

$$| \underline{n} \rangle \mapsto \sqrt{\langle \underline{n} | \underline{n} \rangle} \sum_{\underline{i} \in \Theta_n^k} \bigotimes_{j=1}^k \frac{1}{\sqrt{\langle \underline{i}_j | \underline{i}_j \rangle}} | \underline{i}_j \rangle$$

$$\Theta_{\underline{n}}^k := \text{all ways of partitioning particles of } |\underline{n}\rangle \text{ in } k \text{ partitions}$$

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$$\begin{array}{c}
 \text{Diagram 1:} \quad \text{A multi-input fusion gate with } k \text{ inputs on the left and one output on the right.} \\
 : \underbrace{\mathcal{H}^{(\tau)} \otimes \dots \otimes \mathcal{H}^{(\tau)}}_k \rightarrow \mathcal{H}^{(\tau)} \\
 \\
 \text{Diagram 2:} \quad \bigotimes_{j=1}^k \underline{|i_j\rangle} \mapsto \left(\prod_{j=1}^k \sqrt{\langle \underline{i_j} | \underline{i_j} \rangle} \right) \frac{1}{\sqrt{\langle \underline{n} | \underline{n} \rangle}} \underline{|n\rangle}
 \end{array}$$

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Split and Merge Maps

For our Feynman diagrams, we need three properties:

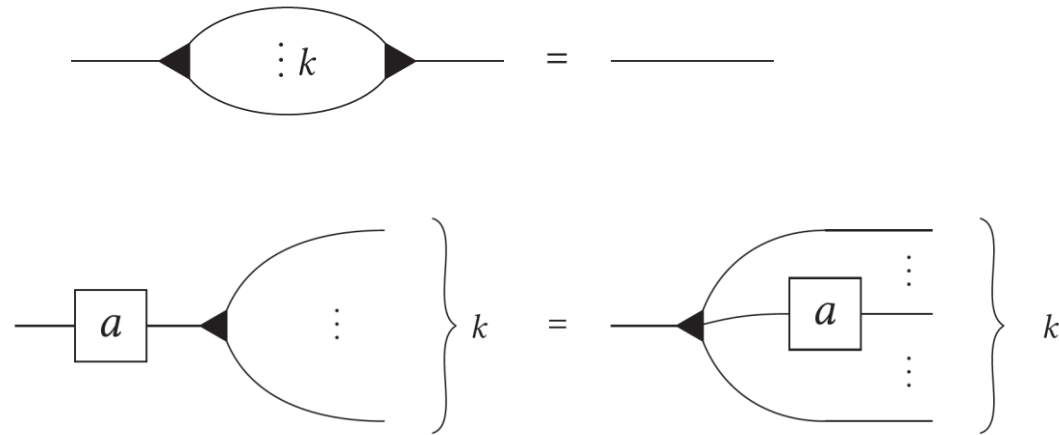
Split and Merge Maps

For our Feynman diagrams, we need three properties:

$$\text{Diagram with a bubble containing } \vdots k \text{ and two external lines} = \text{Diagram with two external lines}$$

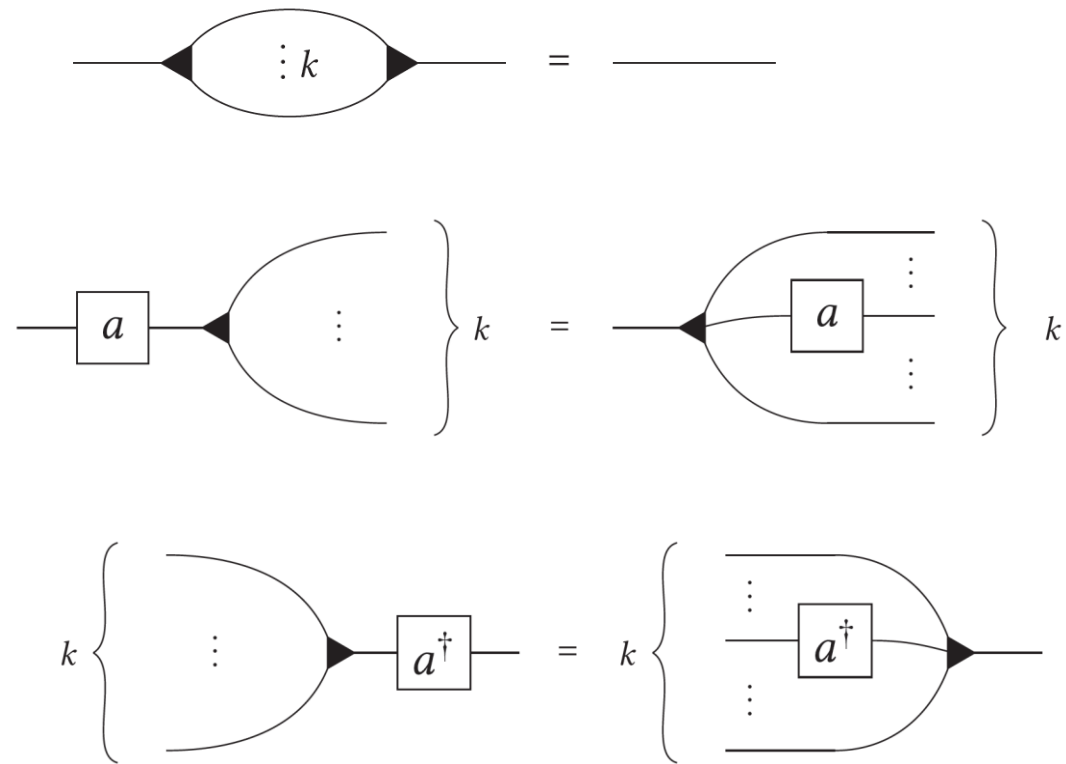
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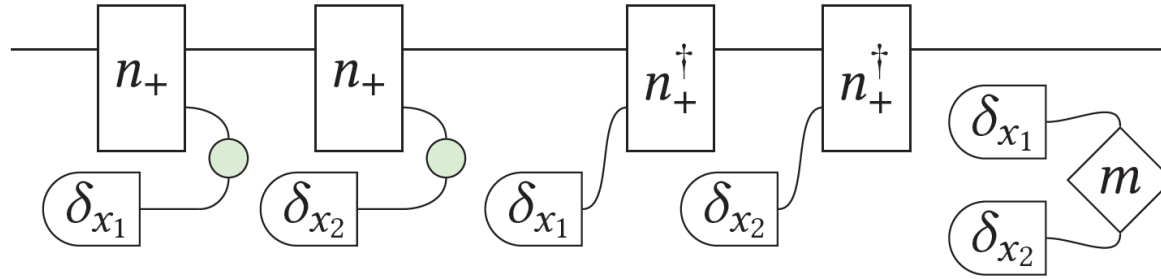
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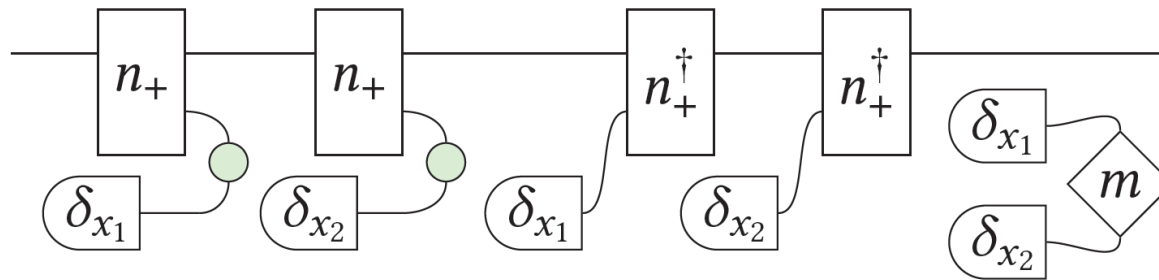


Example 1: Nucleon-Nucleon Scattering

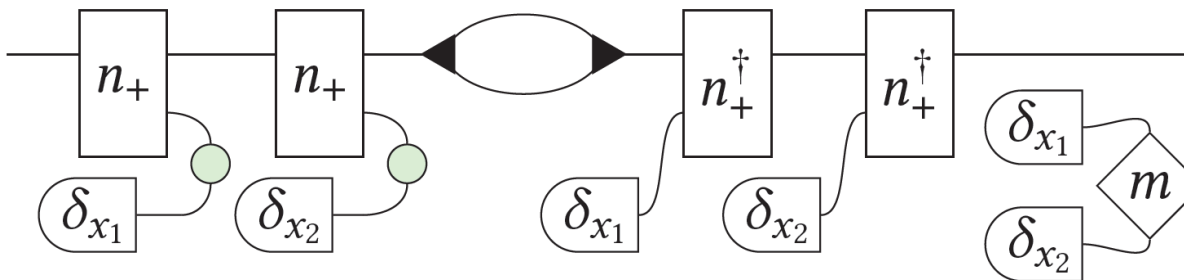
$$\frac{(-ig)^2}{2} \sum_{x_1, x_2} \frac{1}{\omega_{uv}^8}$$



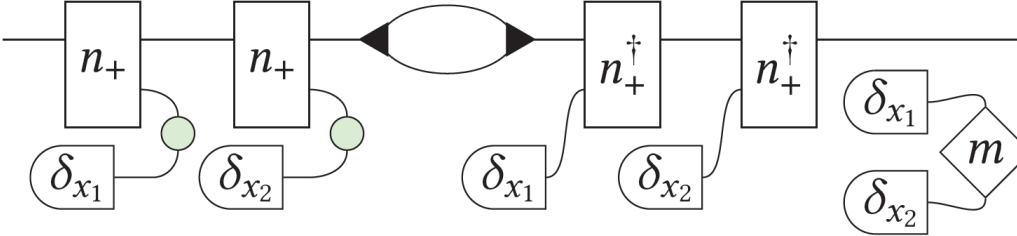
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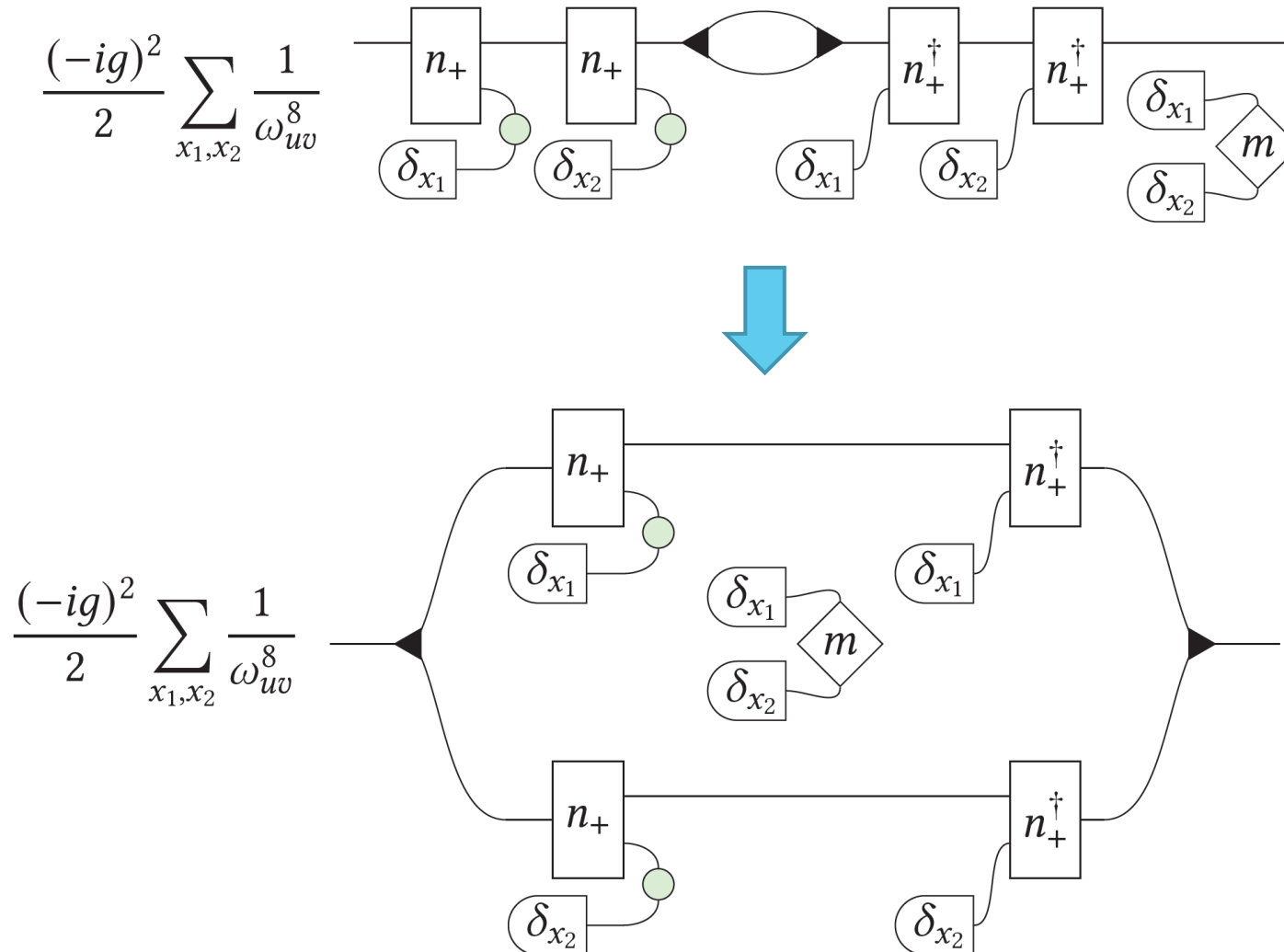
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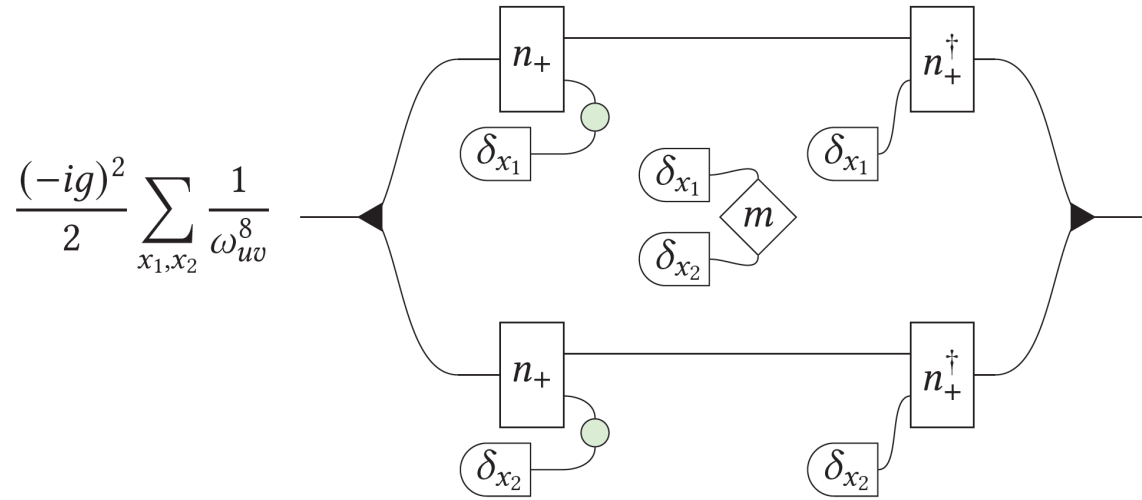
$$\frac{(-ig)^2}{2} \sum_{x_1, x_2} \frac{1}{\omega_{uv}^8}$$


The diagram illustrates a nucleon-nucleon scattering process. It features two incoming nucleons on the left, each represented by a box labeled n_+ . These nucleons interact via a central exchange particle, depicted as a horizontal oval with two black triangular vertices. The outgoing nucleons on the right are represented by boxes labeled n_+^\dagger . The diagram includes four external lines, each associated with a delta function: δ_{x_1} and δ_{x_2} for the incoming lines, and δ_{x_1} and δ_{x_2} for the outgoing lines. The outgoing lines are connected to a diamond-shaped box labeled m , which represents the mass of the nucleons. The entire diagram is enclosed in a rectangular frame.

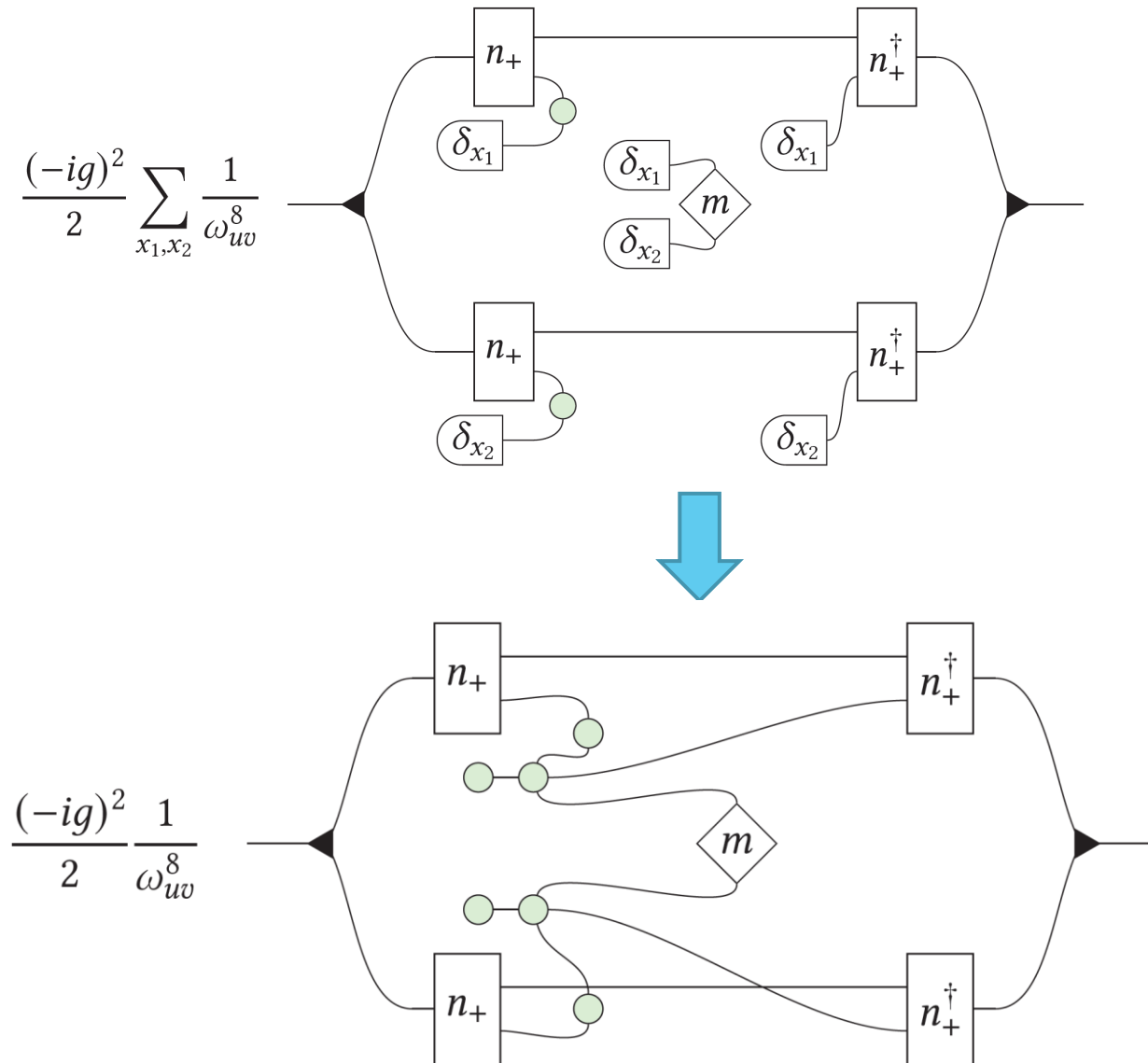
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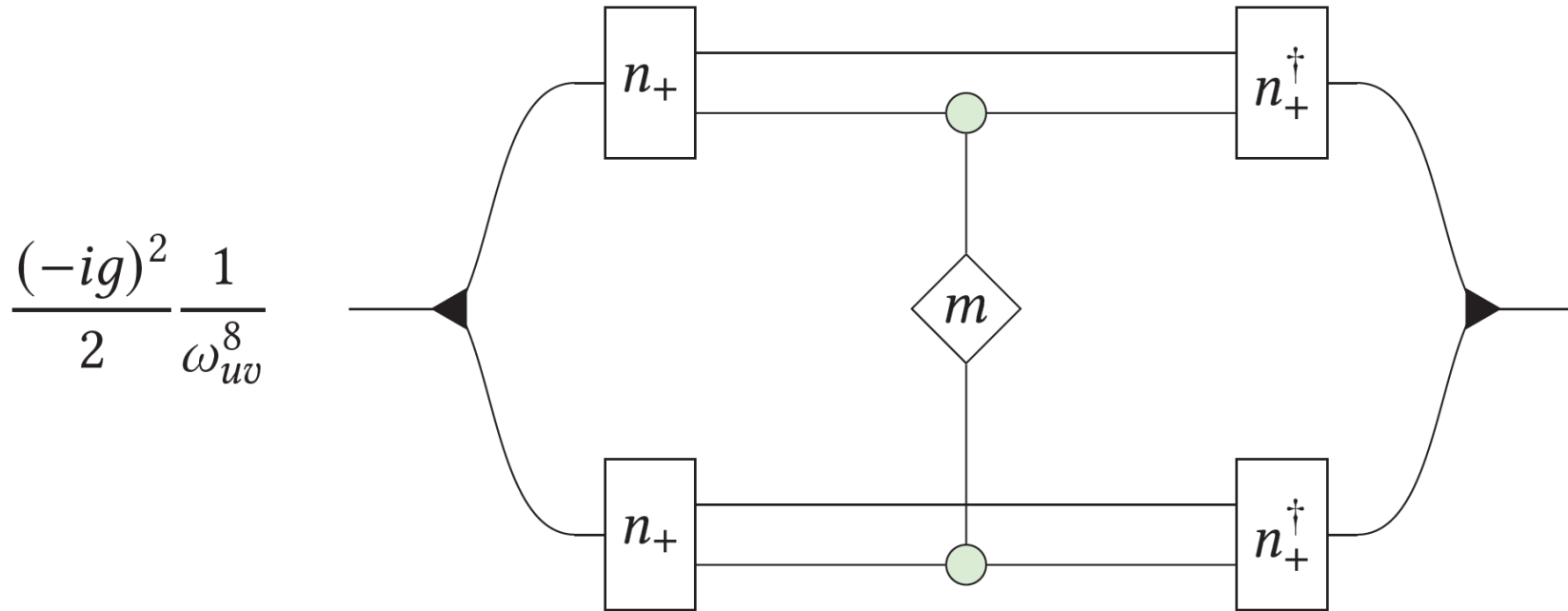
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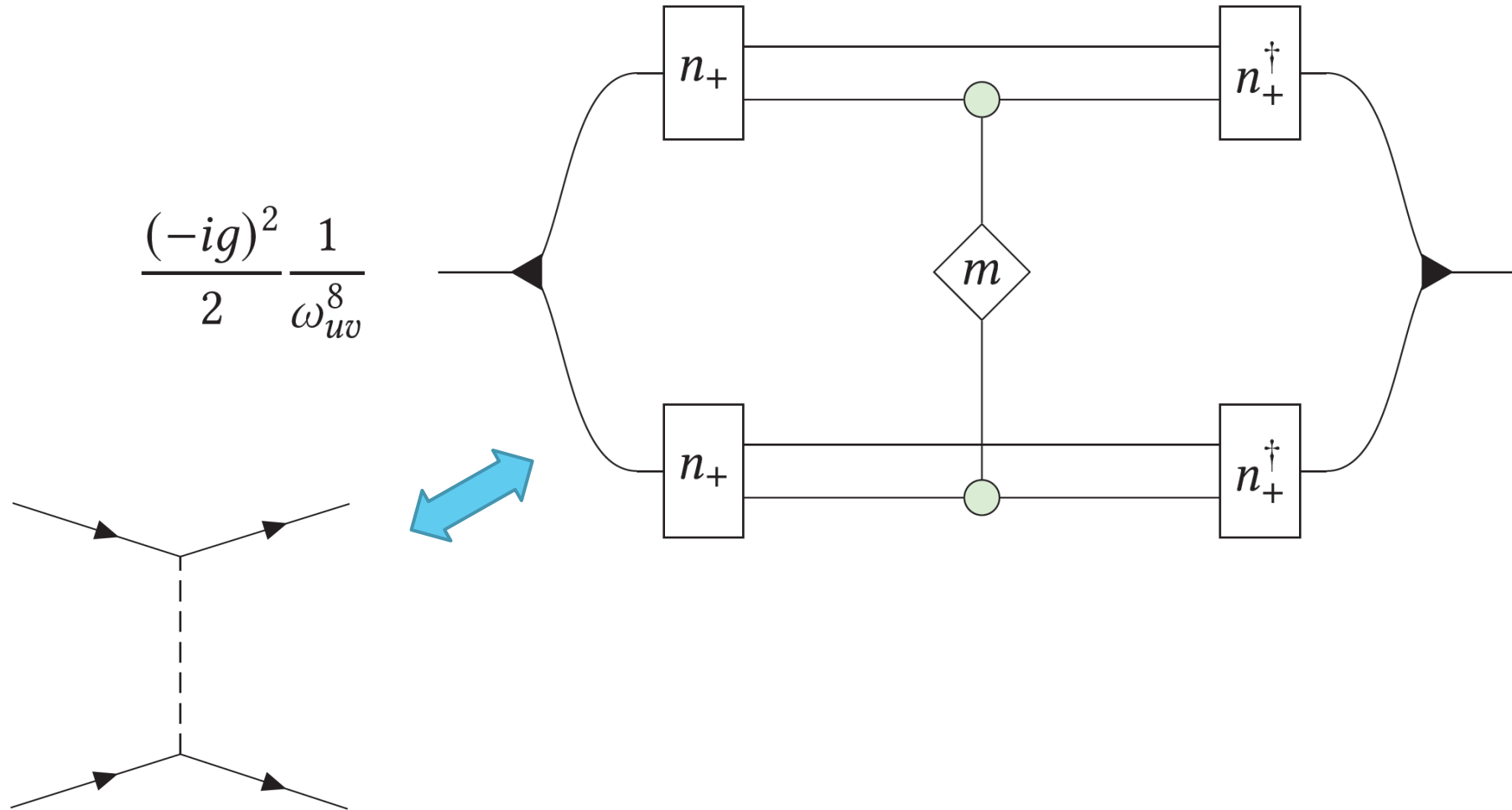
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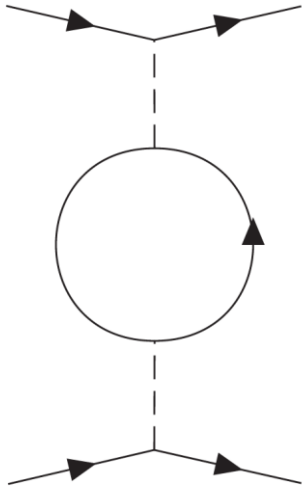
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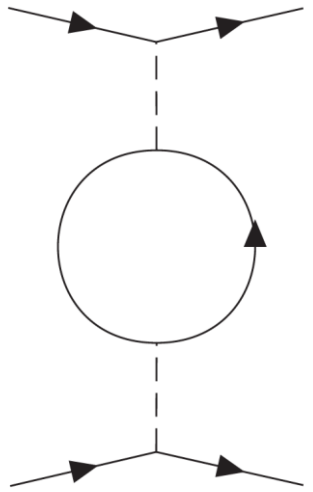
Example 1: Nucleon-Nucleon Scattering



Example 2: NN Scattering with Loop



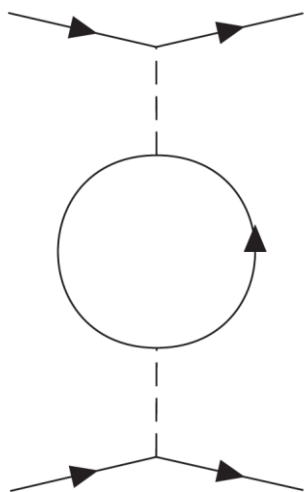
Example 2: NN Scattering with Loop



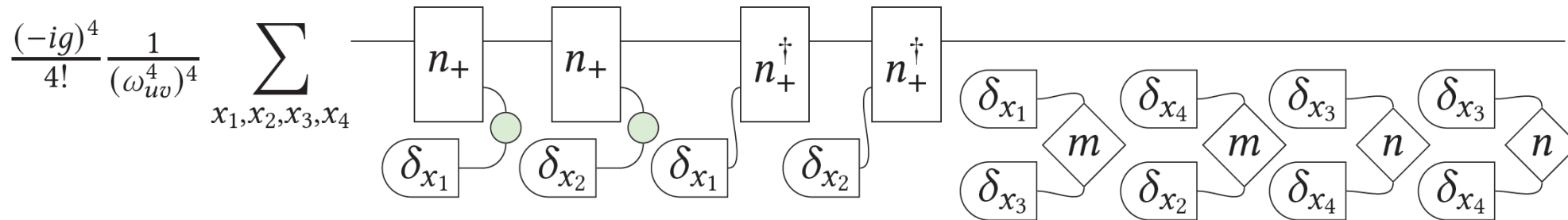
A Feynman diagram representing a loop process. It consists of a central circle with a clockwise arrow. Two dashed lines extend vertically from the top and bottom of the circle. Each dashed line connects to a vertex where two fermion lines meet. The top vertex has two outgoing fermion lines, and the bottom vertex has two outgoing fermion lines. A blue arrow points from the diagram to the right, indicating the corresponding mathematical expression.

$$\frac{(-ig)^4}{4!} \frac{1}{(\omega_{uv}^4)^4} \sum_{x_1, x_2, x_3, x_4} \left(\begin{array}{c} n_+^\dagger(x_1) n_+^\dagger(x_2) n_+(x_1) n_+(x_2) \\ \overbrace{\phi(x_1) \phi(x_2) \phi(x_3) \phi(x_4)} \\ \overbrace{\psi^\dagger(x_3) \psi(x_3) \psi^\dagger(x_4) \psi(x_4)} \end{array} \right)$$

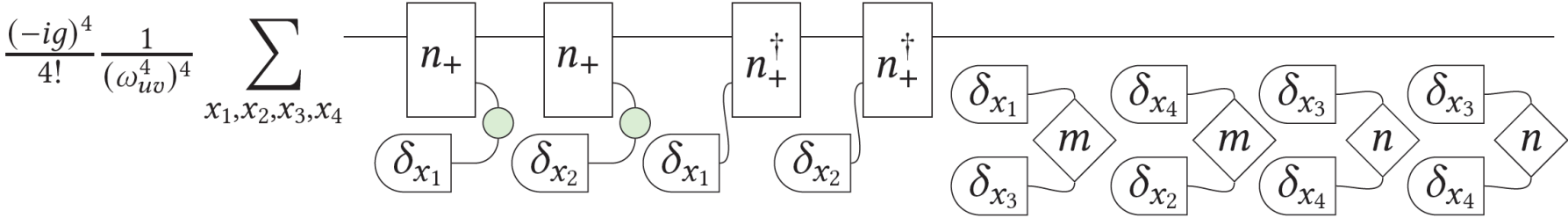
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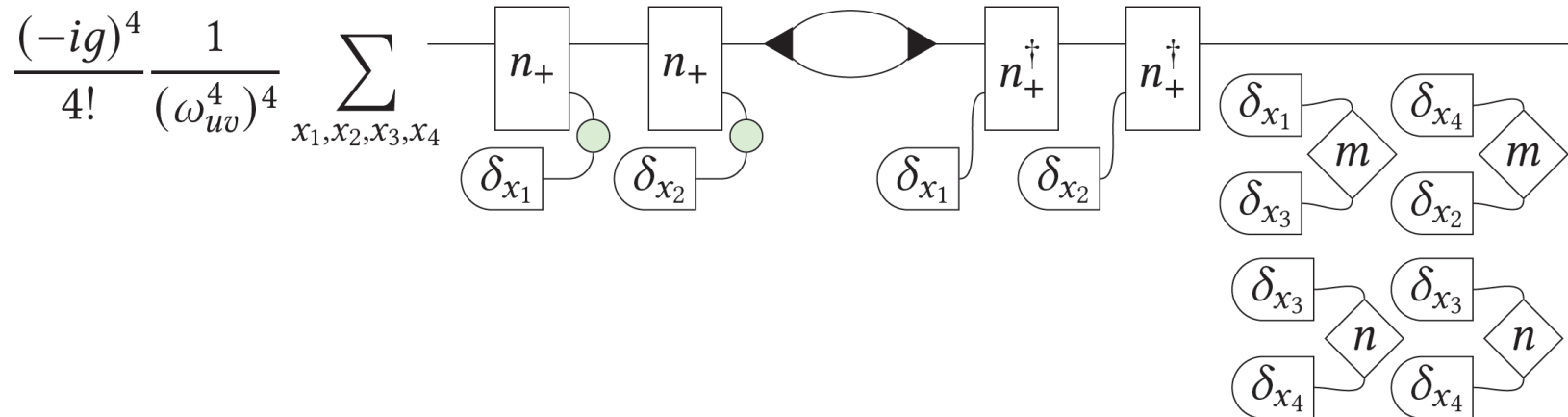
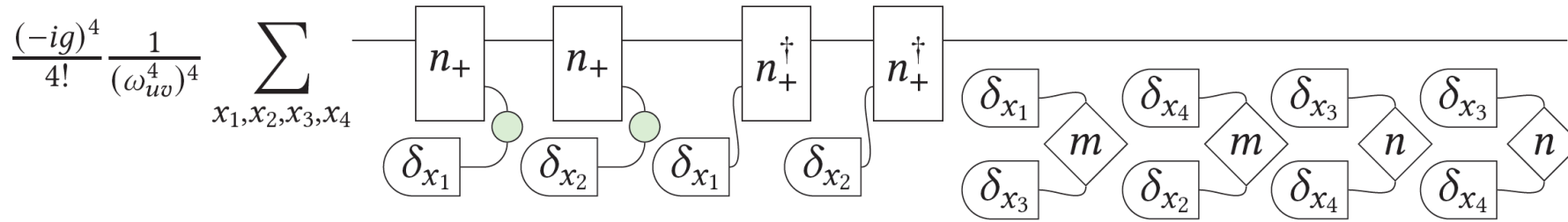
$$\frac{(-ig)^4}{4!} \frac{1}{(\omega_{uv}^4)^4} \sum_{x_1, x_2, x_3, x_4} \begin{pmatrix} n_+^\dagger(x_1) n_+^\dagger(x_2) n_+(x_1) n_+(x_2) \\ \overbrace{\phi(x_1) \phi(x_2) \phi(x_3) \phi(x_4)} \\ \underbrace{\psi^\dagger(x_3) \psi(x_3) \psi^\dagger(x_4) \psi(x_4)} \end{pmatrix}$$



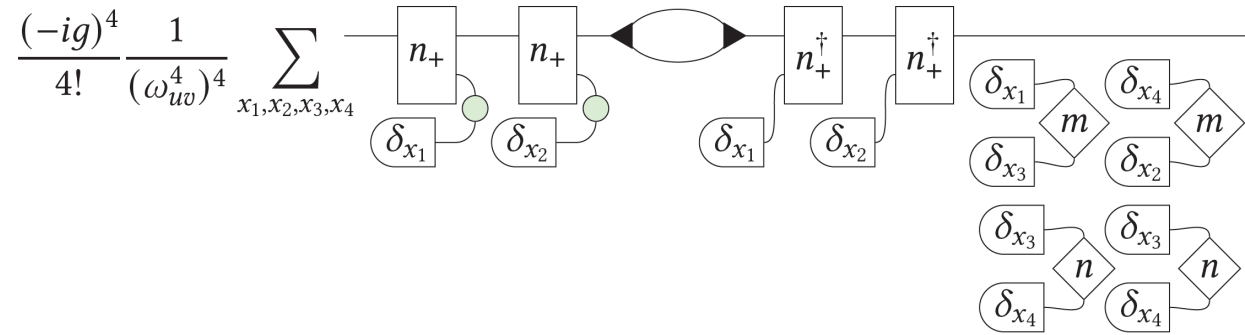
Example 2: NN Scattering with Loop



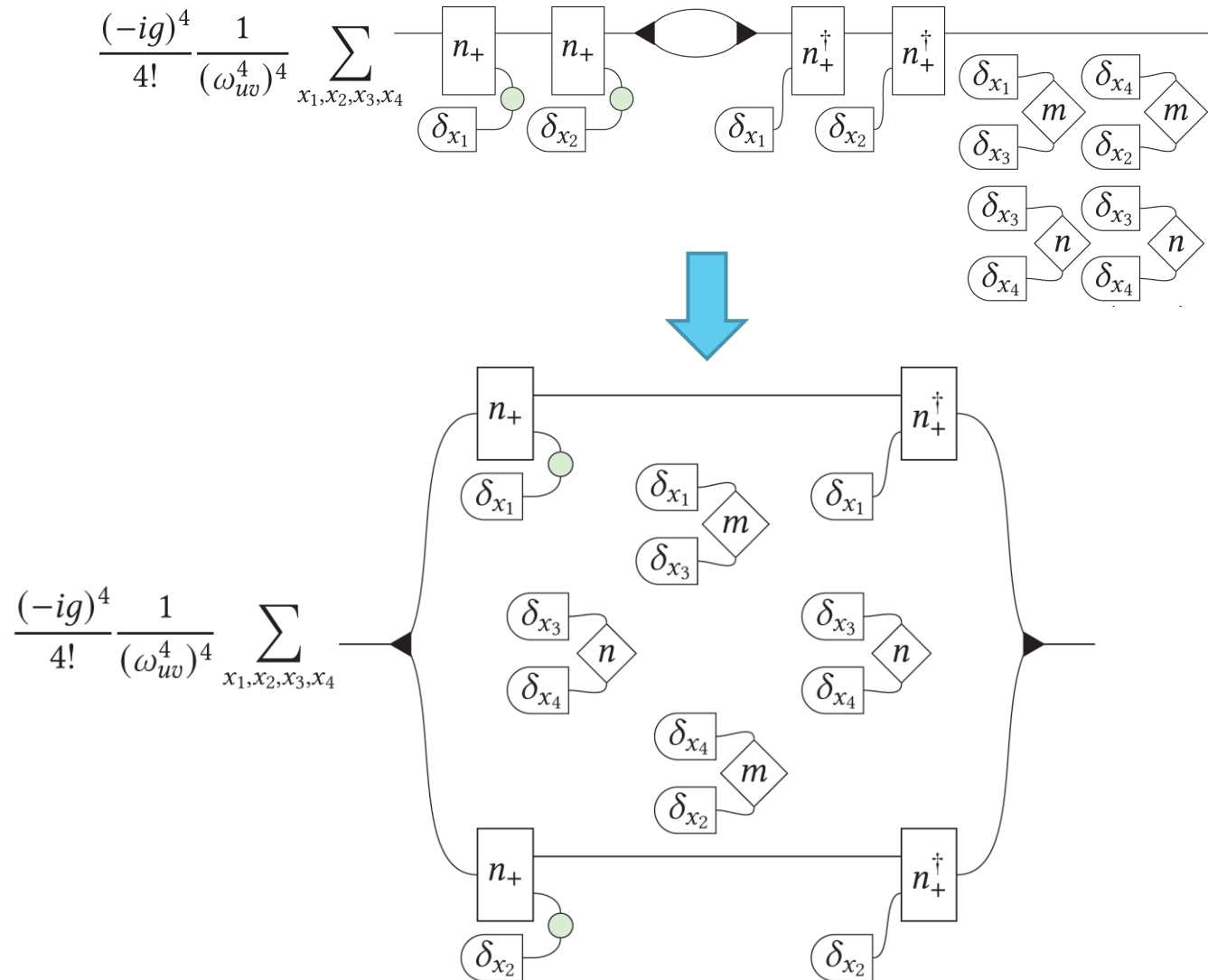
Example 2: NN Scattering with Loop



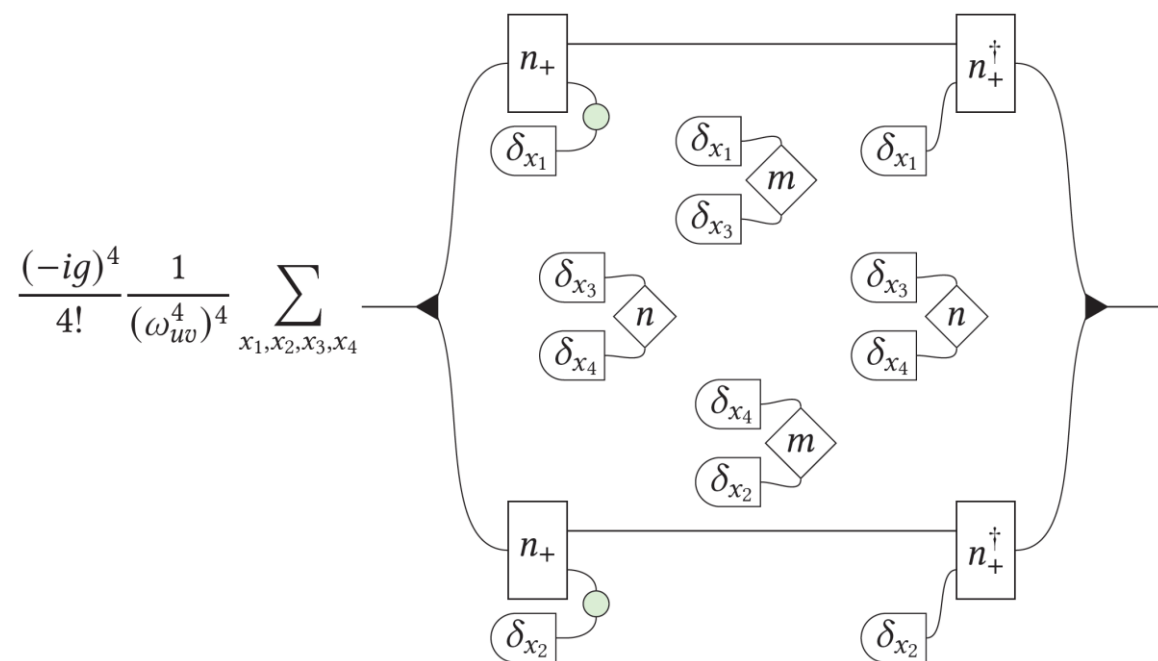
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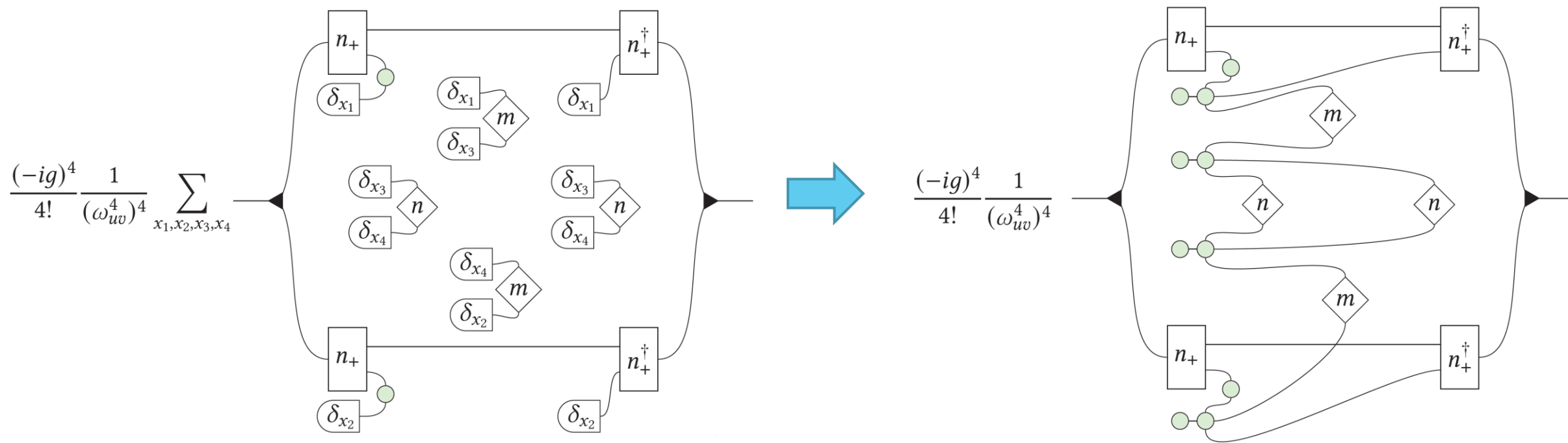
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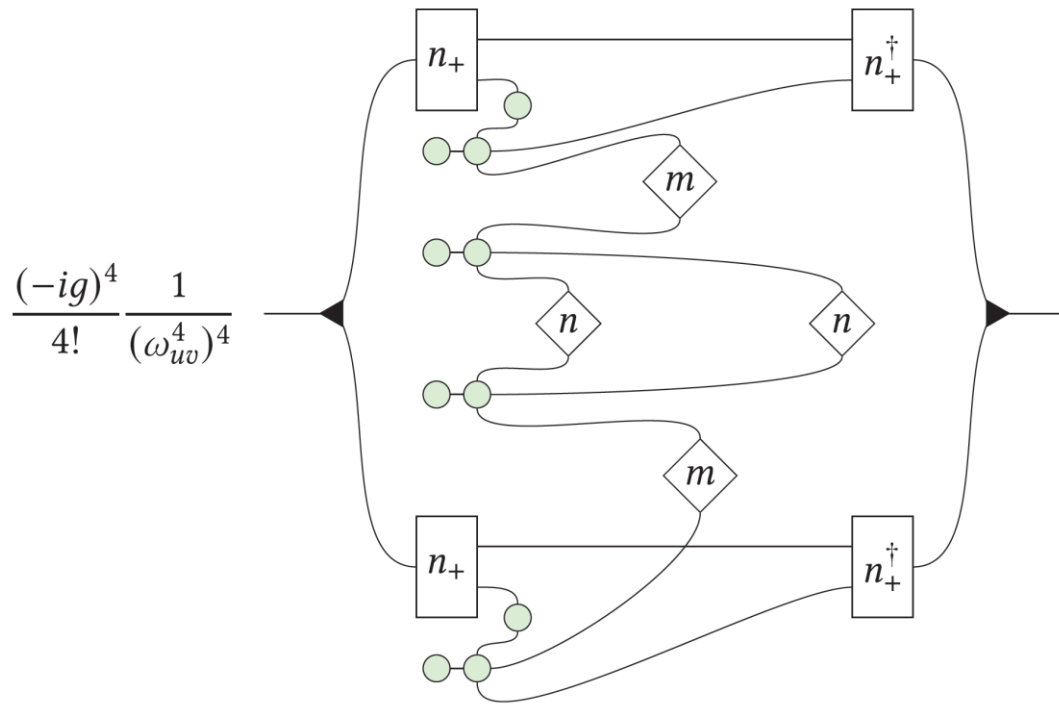
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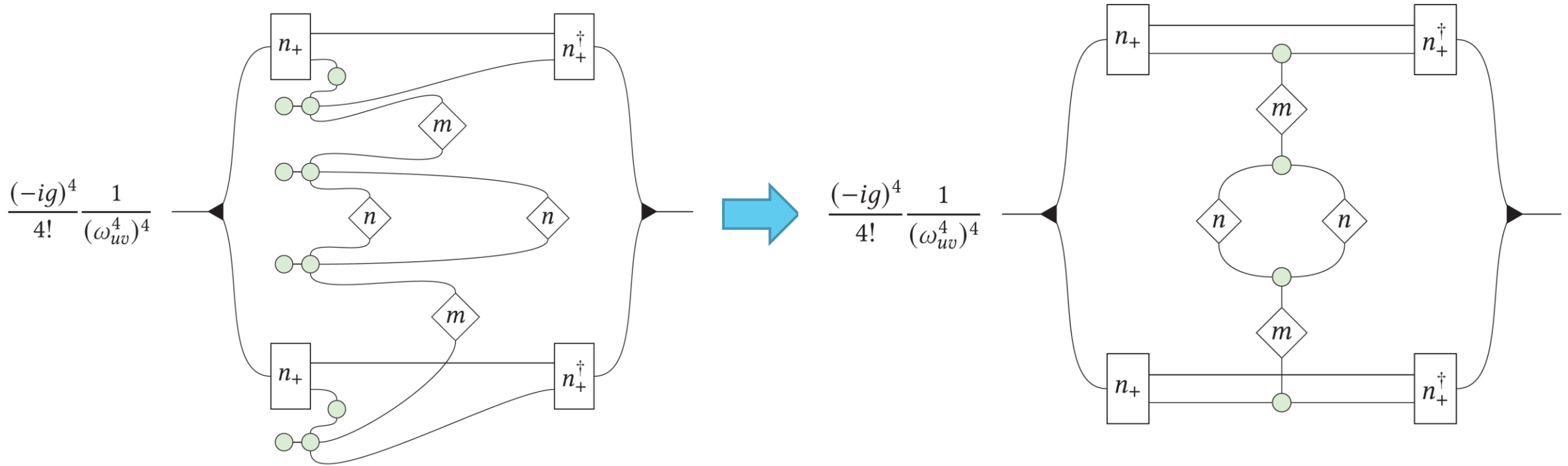
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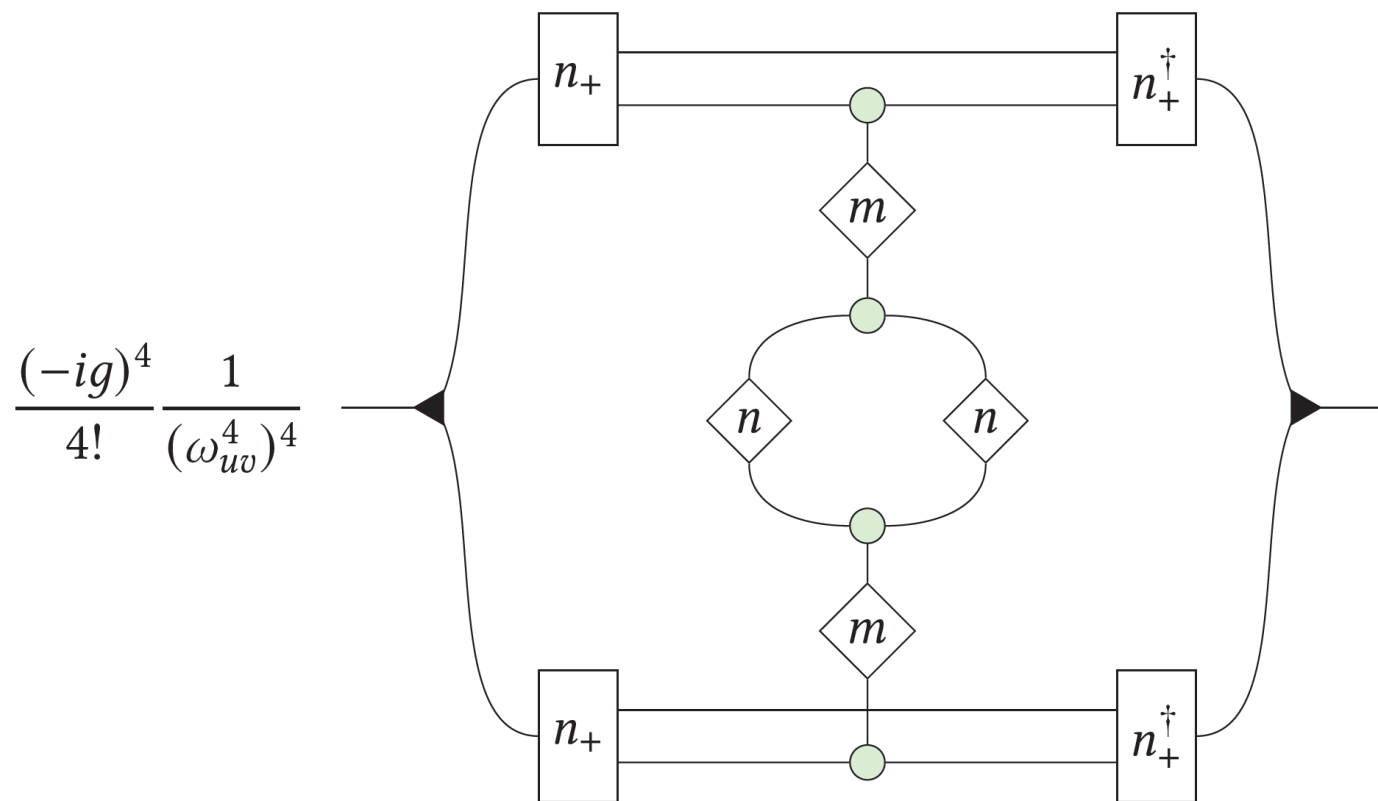
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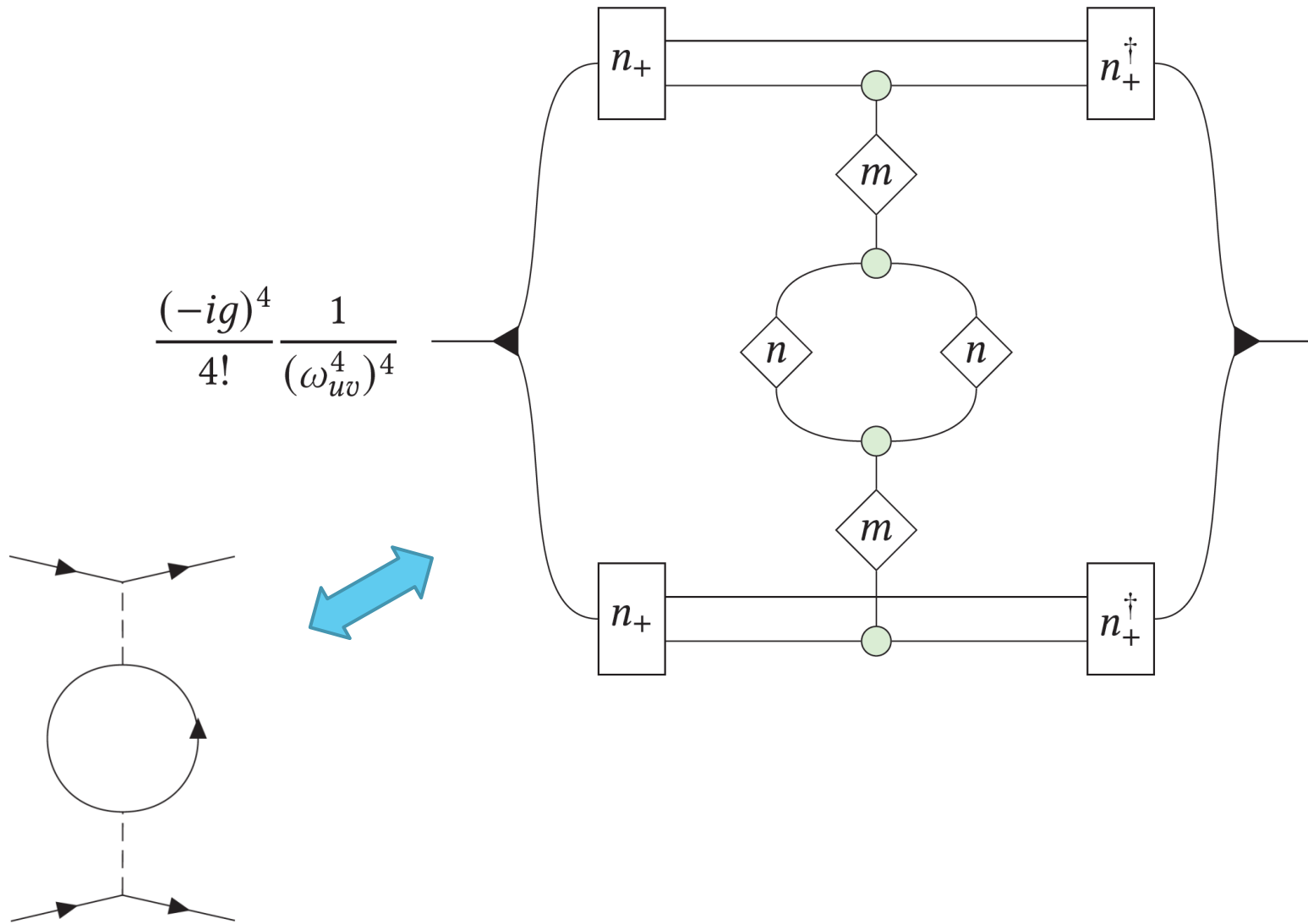
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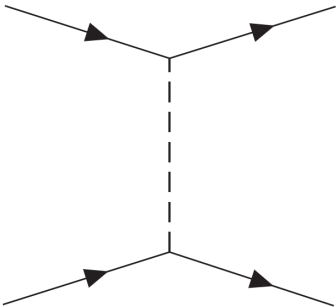
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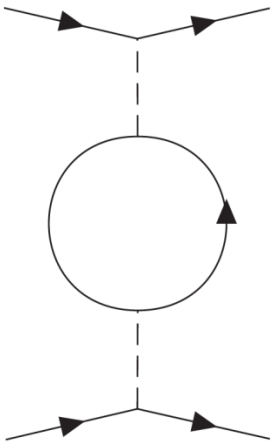
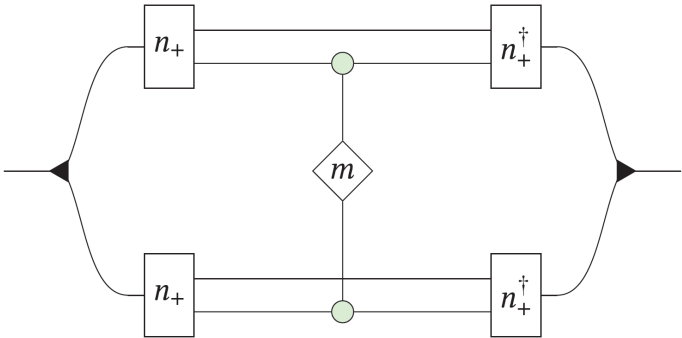
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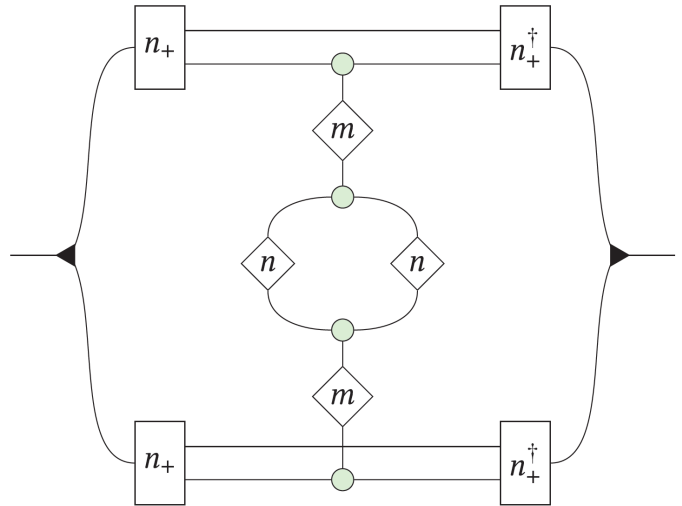
Example Gallery



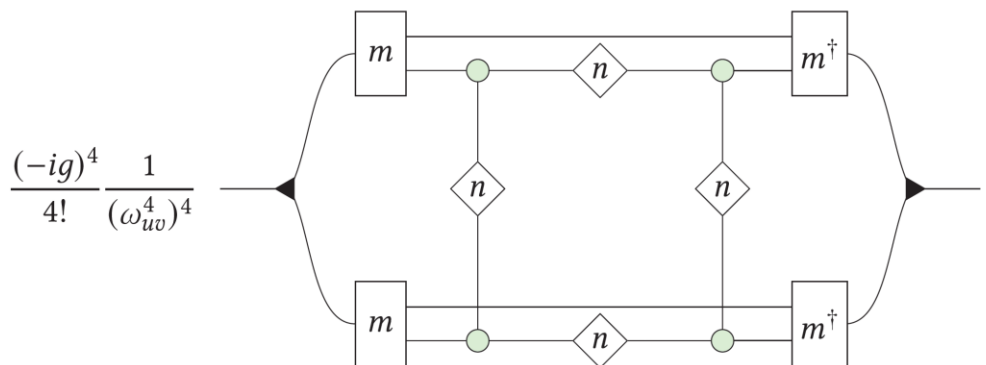
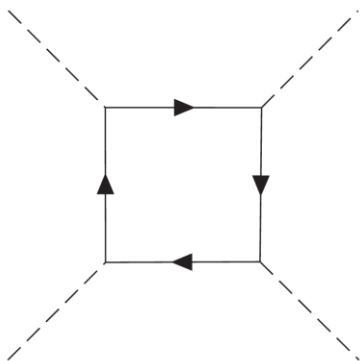
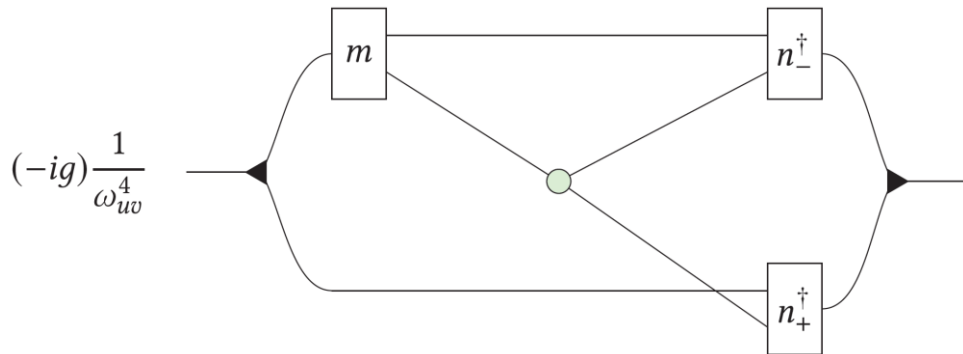
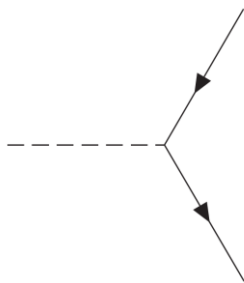
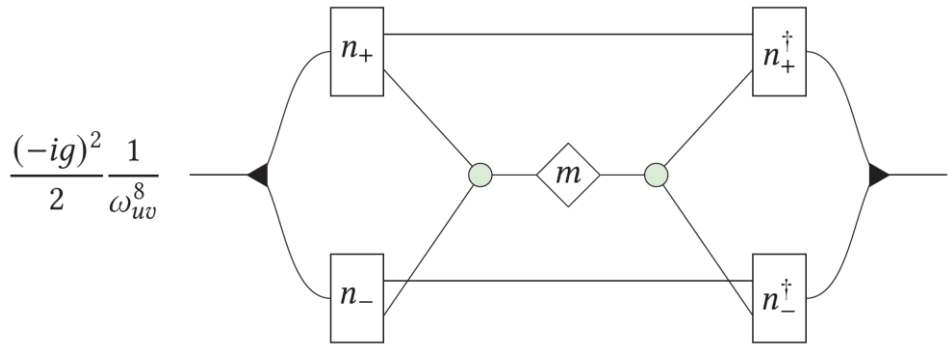
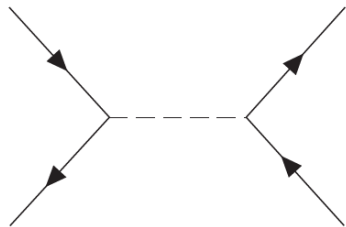
$$\frac{(-ig)^2}{2} \frac{1}{\omega_{uv}^8}$$



$$\frac{(-ig)^4}{4!} \frac{1}{(\omega_{uv}^4)^4}$$



Example Gallery

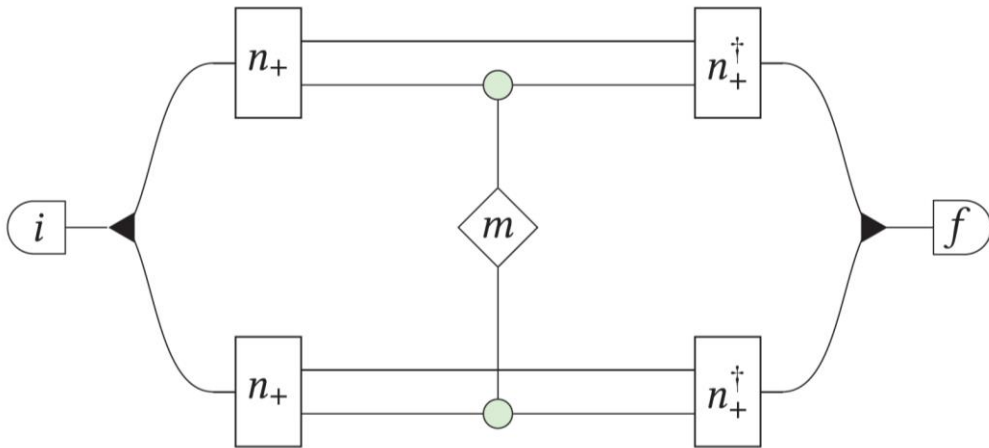


Computing Amplitudes

Computing Amplitudes

$$|i\rangle = |p_1, p_2\rangle = n_+^\dagger(p_1)n_+^\dagger(p_2)|0\rangle$$

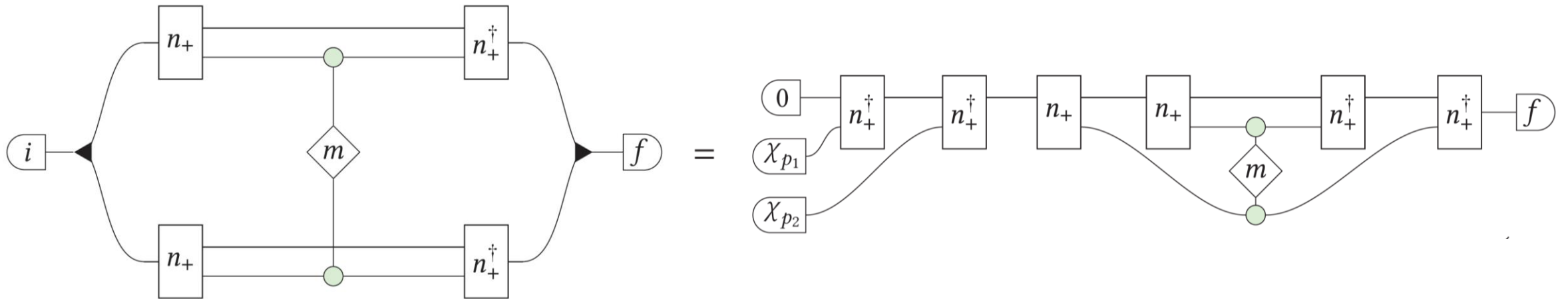
$$|f\rangle = |p'_1, p'_2\rangle = n_+^\dagger(p'_1)n_+^\dagger(p'_2)|0\rangle$$



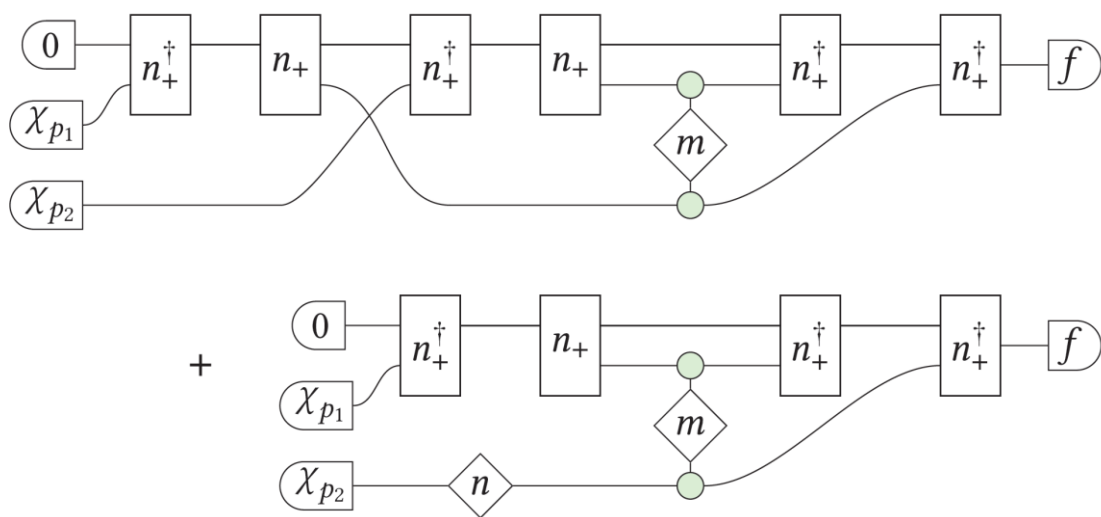
Computing Amplitudes

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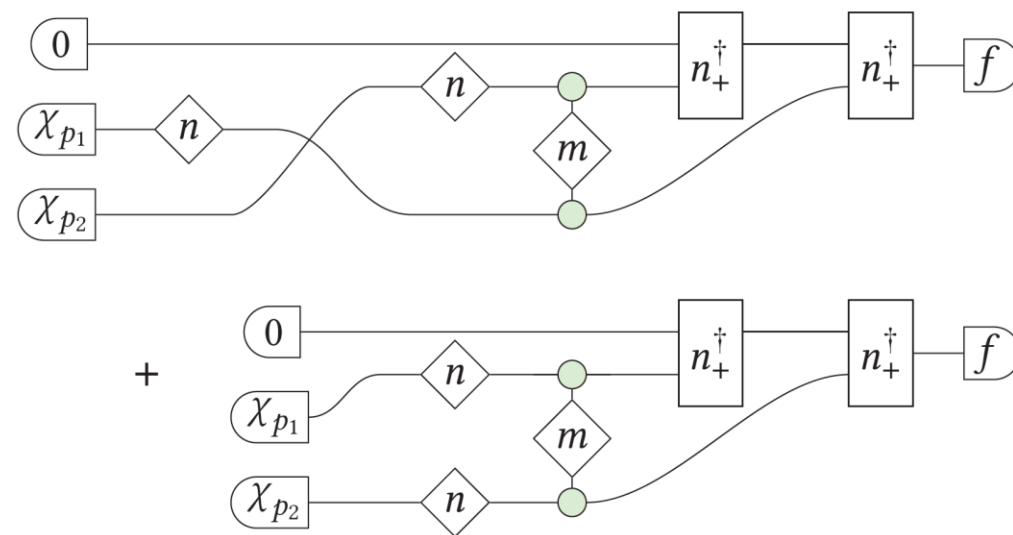
$$|f\rangle = |p'_1, p'_2\rangle = n_+^\dagger(p'_1)n_+^\dagger(p'_2)|0\rangle$$



Computing Amplitudes



=



Computing Amplitudes

$$(-ig)^2 \frac{1}{\omega_{uv}^8} \left(\begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \right) + \left(\begin{array}{c} \text{Diagram 3} \\ \text{Diagram 4} \end{array} \right)$$

$$(-ig)^2 \frac{1}{\omega_{uv}^8} \sum_{x_1, x_2} \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \end{array}$$

$$\begin{array}{c} \chi_p \\ \downarrow n \\ \delta_x \end{array} = e^{i2\pi p \cdot x}$$

$$(-ig)^2 \sum_{x_1, x_2} \frac{1}{\omega_{uv}^8} e^{-i2\pi p_1 \cdot x_1} e^{-i2\pi p_2 \cdot x_2} e^{i2\pi p'_1 \cdot x_1} e^{i2\pi p'_2 \cdot x_2} \sum_k \frac{1}{\omega_{ir}^4} \frac{ie^{-i2\pi k \cdot (x_1 - x_2)}}{k^2 - m^2 + i\epsilon}$$

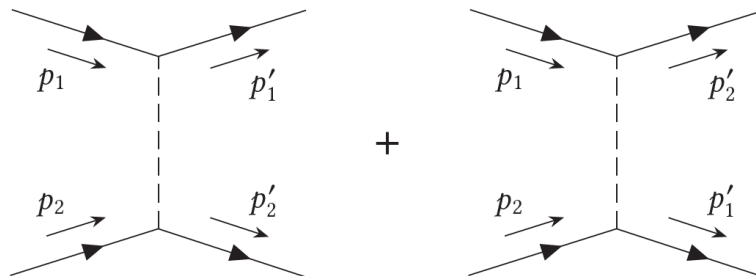
Computing Amplitudes

$$(-ig)^2 \frac{1}{\omega_{uv}^8} \left(\begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \right)$$

The diagrams inside the parentheses represent two Feynman diagrams for a process involving two incoming particles (labeled χ_{p_1} and χ_{p_2}) and two outgoing particles (labeled $\chi_{p'_1}$ and $\chi_{p'_2}$). The diagrams are connected by a plus sign. The first diagram shows a central vertex (green circle) connected to four external lines (squares labeled n). The second diagram shows a central vertex (green circle) connected to four external lines (squares labeled n), with an additional internal line (diamond labeled m) connecting the two vertices.



$$i\mathcal{A} = (-ig)^2 \left[\frac{i}{(p_1 - p'_1)^2 - m^2 + i\epsilon} + \frac{i}{(p_1 - p'_2)^2 - m^2 + i\epsilon} \right]$$

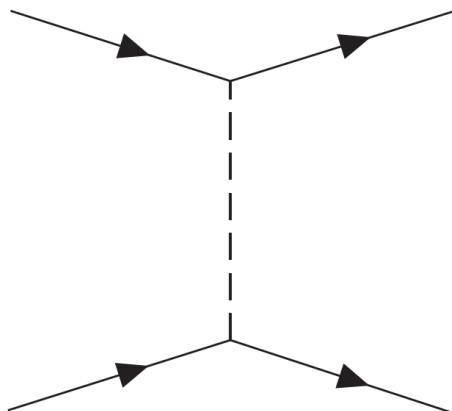


Overview

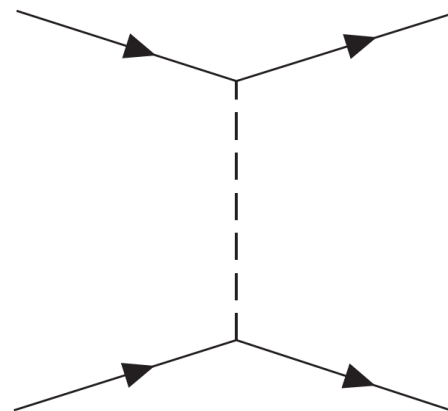
- ▶ Categorical quantum fields
- ▶ Categorical Feynman diagrams
- ▶ Composing Feynman diagrams

Composing Feynman Diagrams

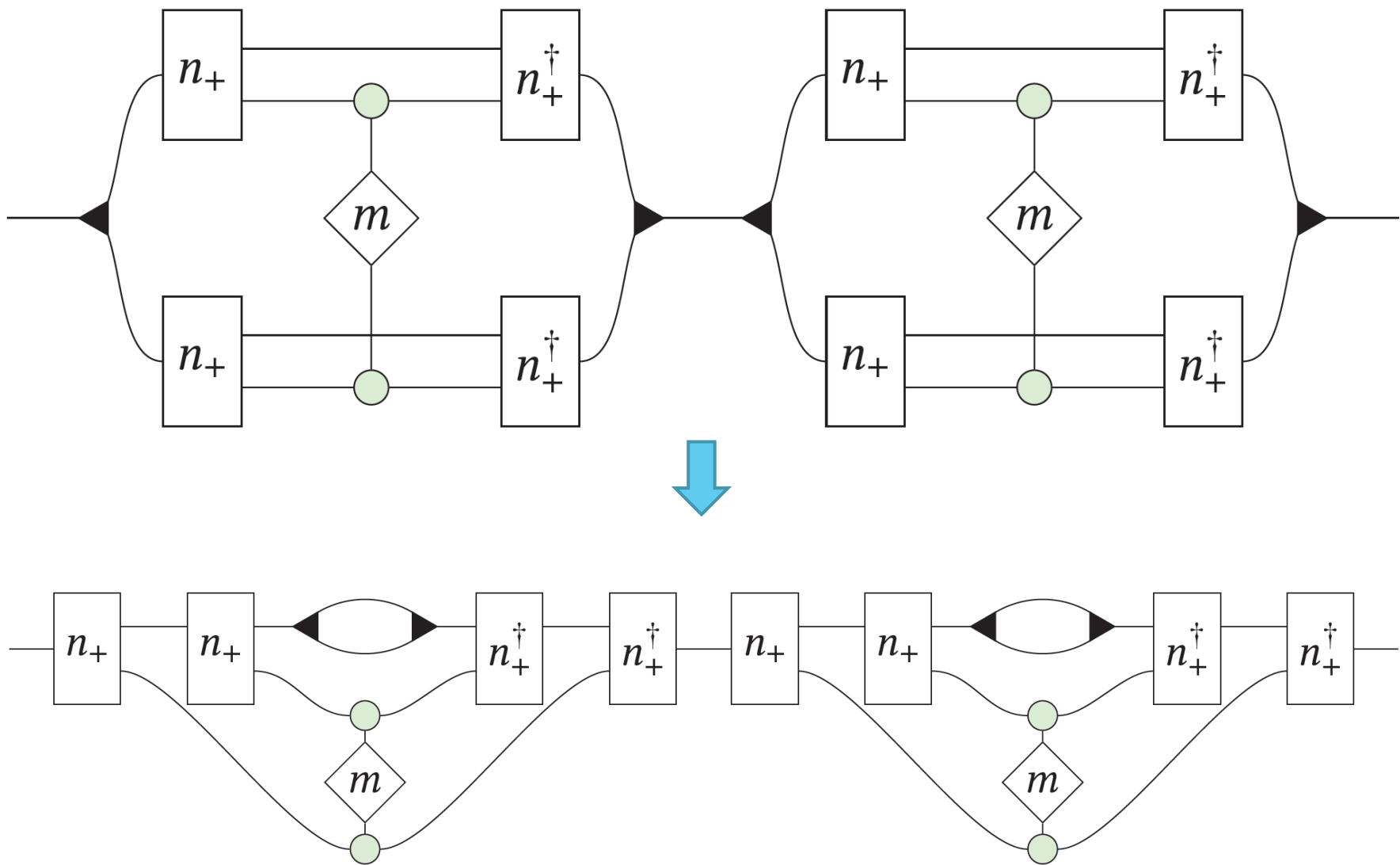
We compose categorical versions of



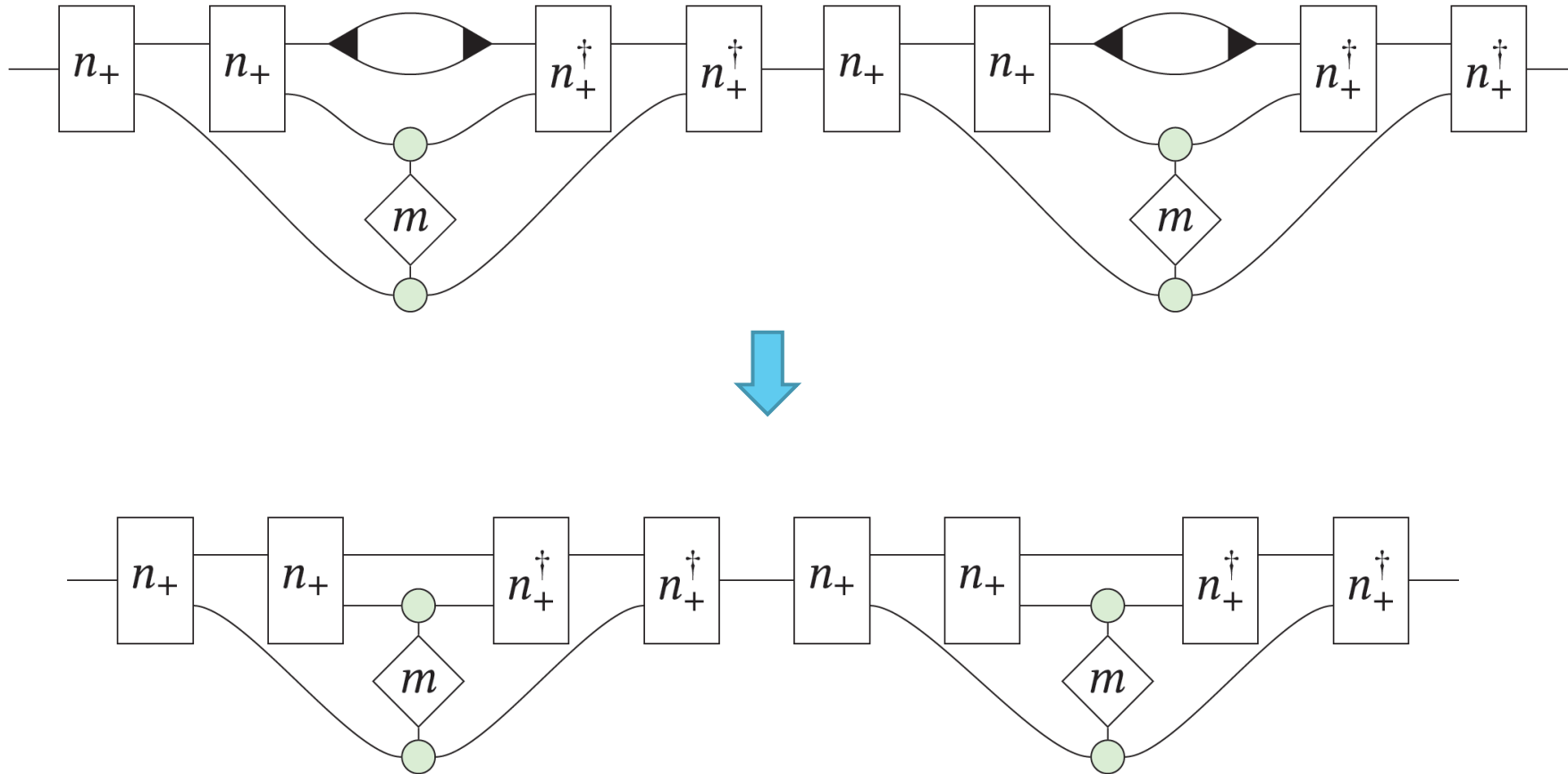
and



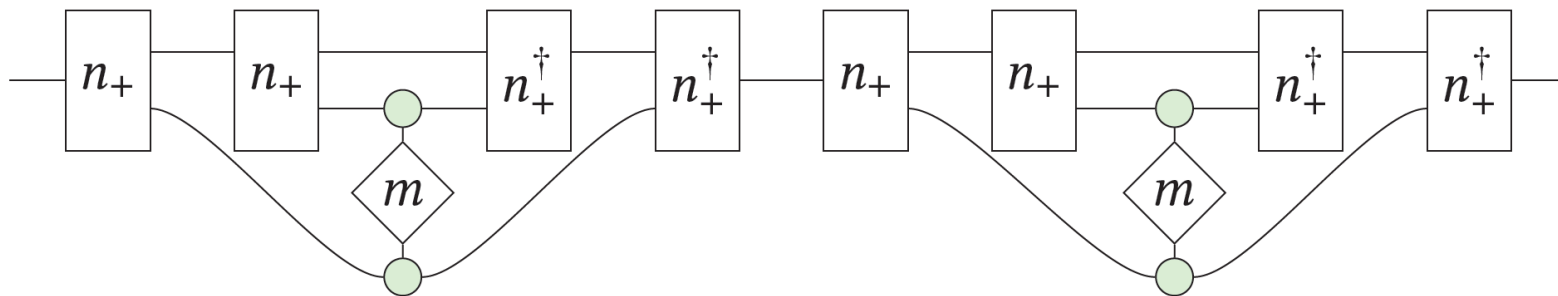
Composing Feynman Diagrams



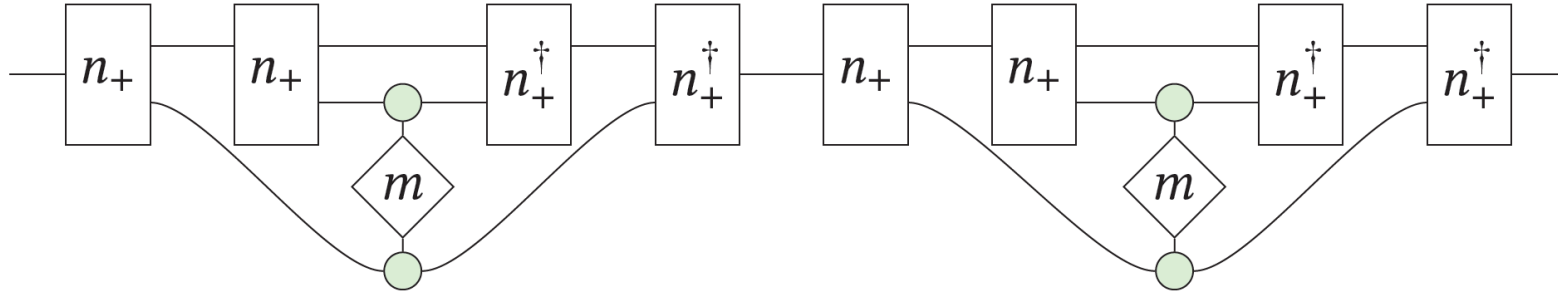
Composing Feynman Diagrams



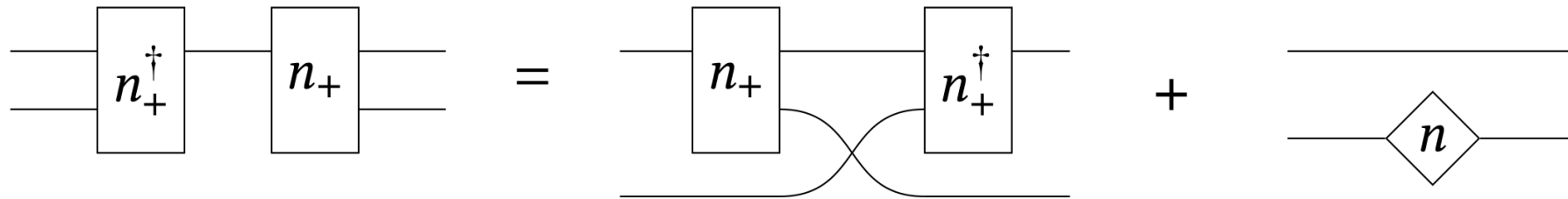
Composing Feynman Diagrams



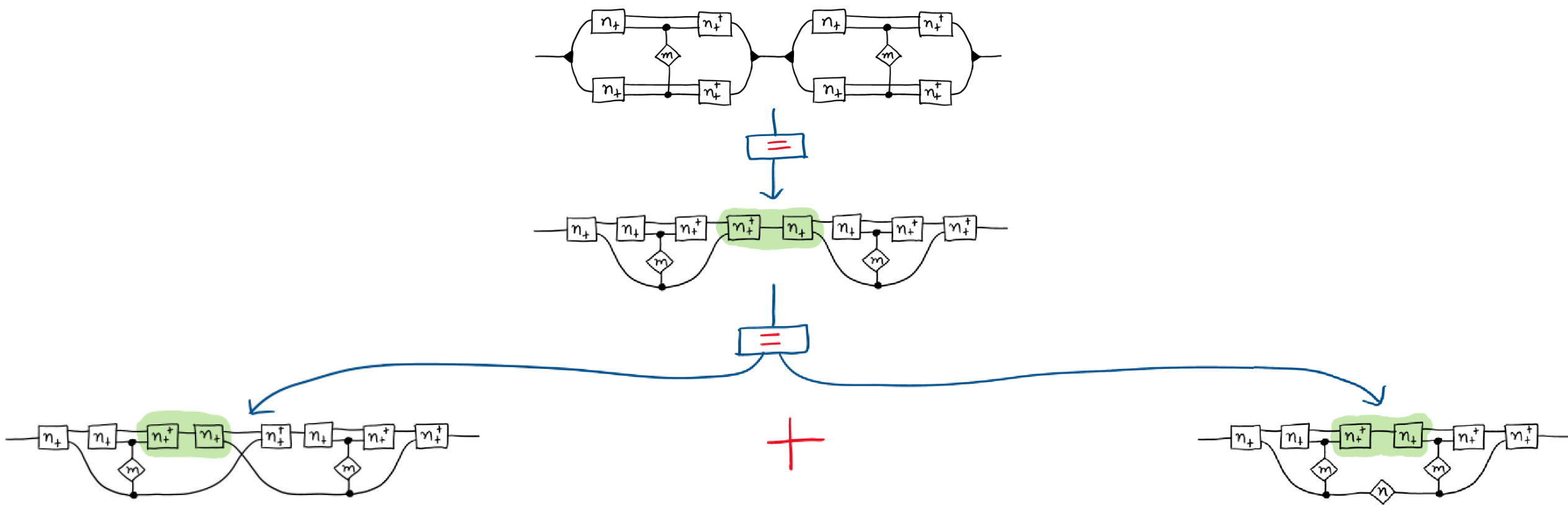
Composing Feynman Diagrams



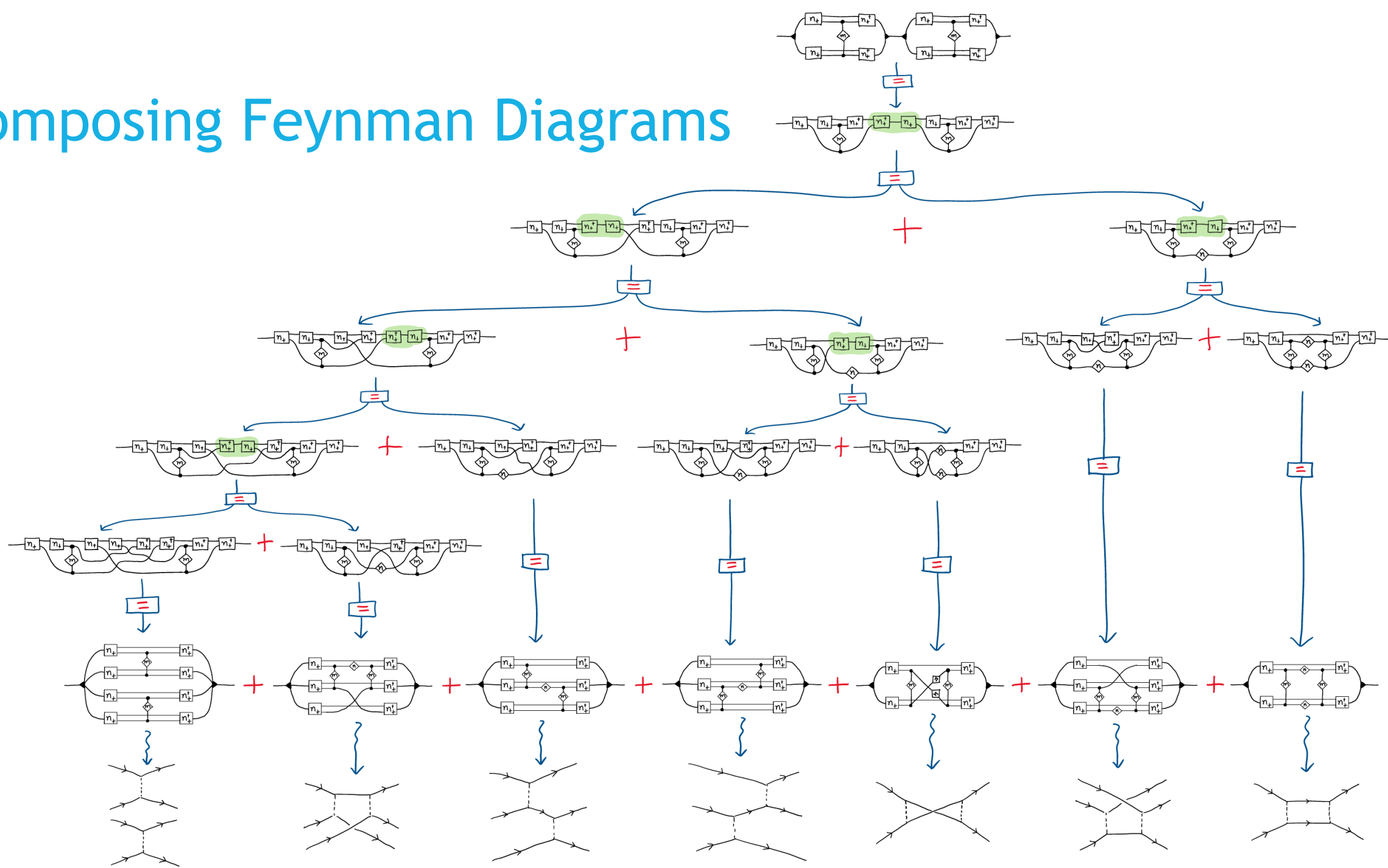
Apply commutation rule:



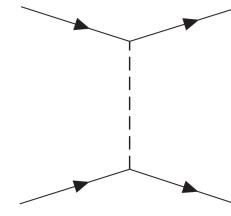
Composing Feynman Diagrams



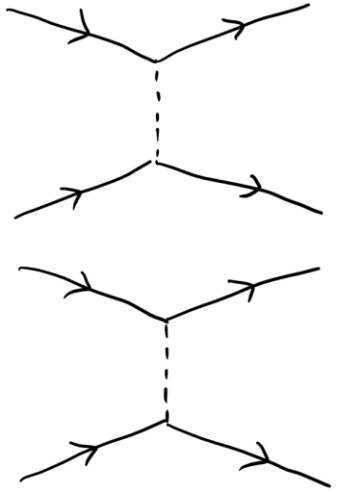
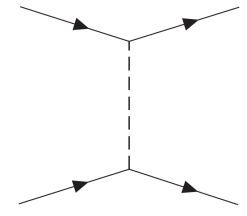
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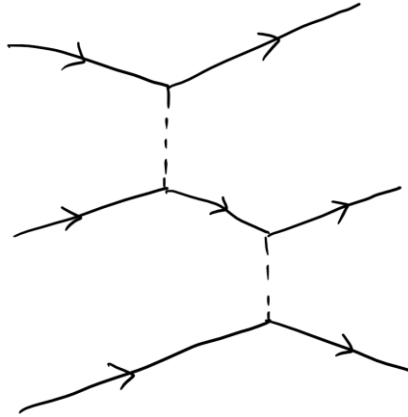
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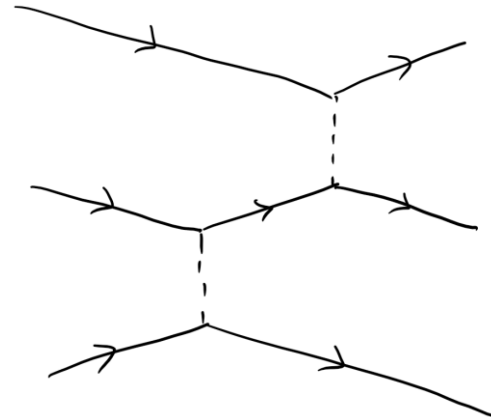
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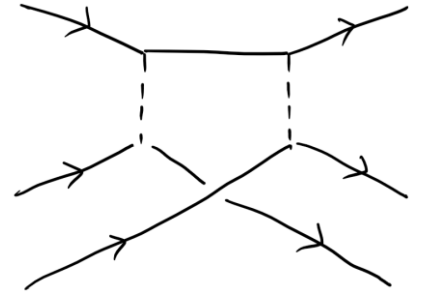
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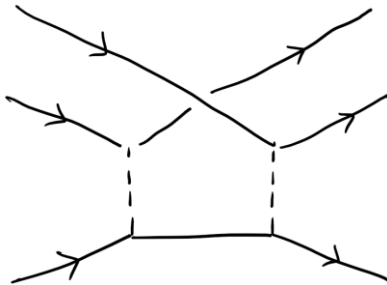
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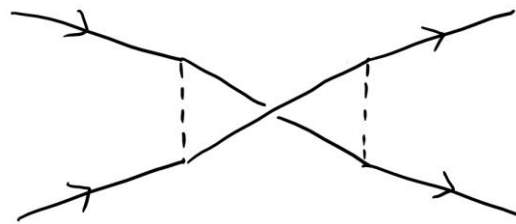
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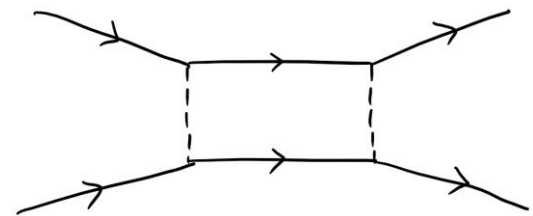
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Conclusion

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Conclusion

- ▶ Categorical Feynman diagrams represent interaction processes instead of amplitudes
- ▶ Amplitudes can be obtained by plugging in initial and final states
- ▶ Shift from *syntactic*, graph-theoretic compositionality to *semantic*, categorical-diagrammatic compositionality
- ▶ Composition of categorical diagrams gives the superposition of all graph-theoretic combinations

Future work

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- ▶ Quantum simulation of particle physics
 - ▶ Compile categorical Feynman diagrams to quantum circuits

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Thanks for listening!