Electromagnetic currents of the pion-nucleon system

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Introduction

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  - Good: such approaches respect (at least) 2-body **unitarity**
  - Bad: **symmetries broken** (crossing, gauge invariance, PCAC. . .) in the process
- Here I present an approach that sums the perturbation series in a different way, so that **symmetries are preserved**

Gauging equations method

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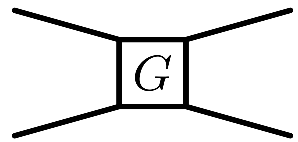
- Equation describing the interaction of this system with an external EM field
- Resulting EM currents are **gauge invariant**

Gauging the two-body Green function

- Given the Bethe-Salpeter equation

$$G = G_0 + G_0 V G \qquad (1)$$

$=$



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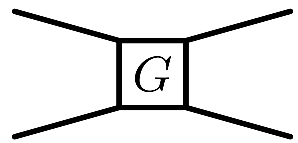

- add μ everywhere in Eq. (1):

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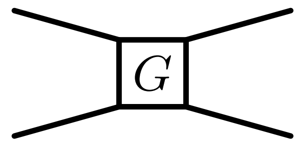
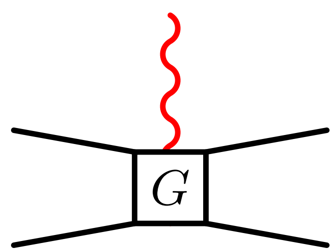


- add μ everywhere in Eq. (1):

$$G^\mu = G_0^\mu + G_0^\mu V G + G_0 V^\mu G + G_0 V G^\mu$$

- this attaches a photon **everywhere** in G and gives the 5-point function

$G^\mu =$



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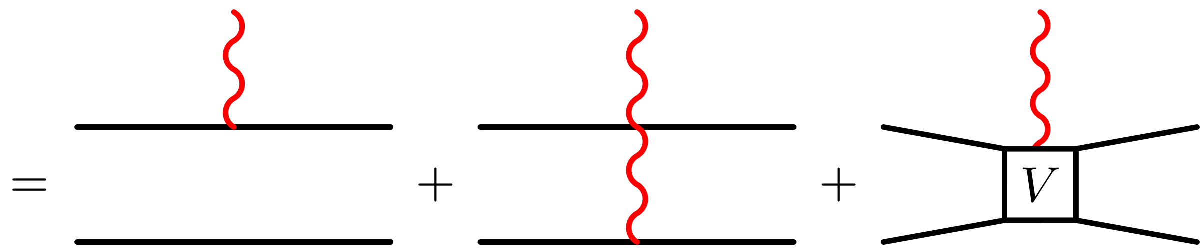
- simple algebra gives

$$G^{\mu} = G\,\Gamma^{\mu}\,G$$

$$\Gamma^{\mu} = G_0^{-1} G_0^{\mu} G_0^{-1} + V^{\mu}$$



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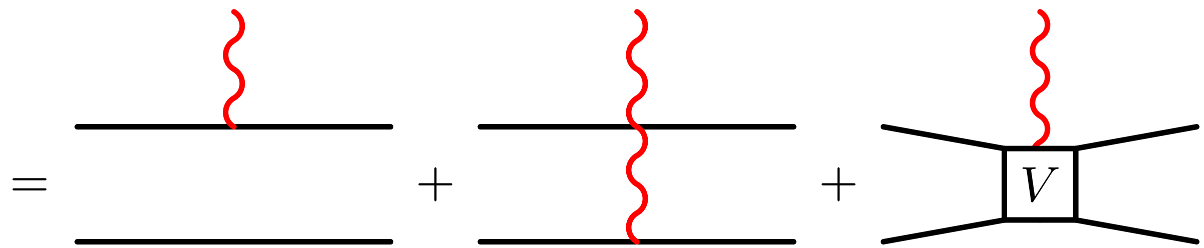

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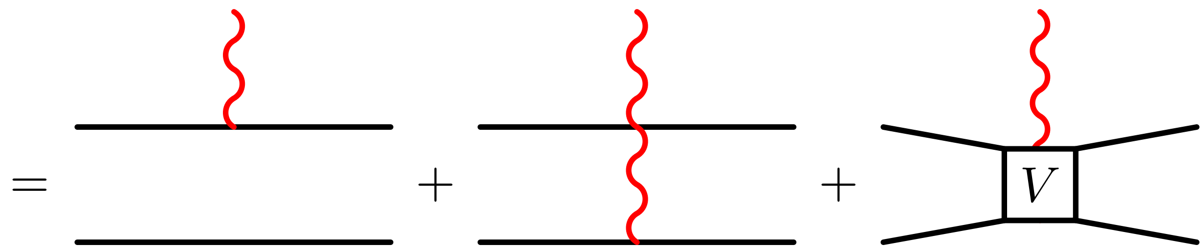

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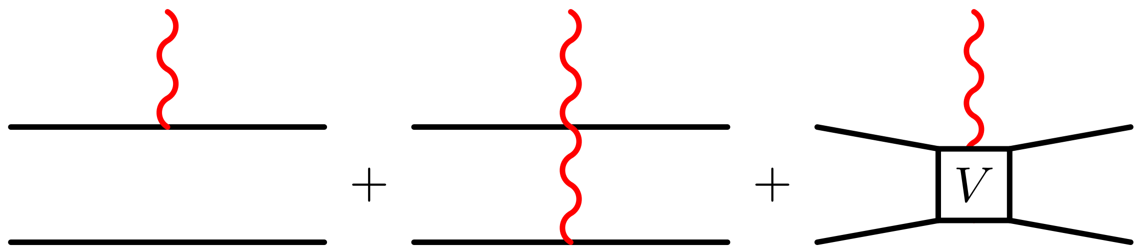
$=$ 

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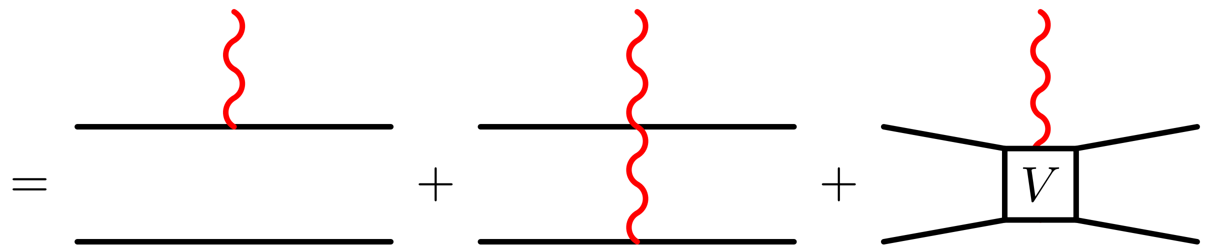

- Gauge invariance is guaranteed since photon is attached everywhere
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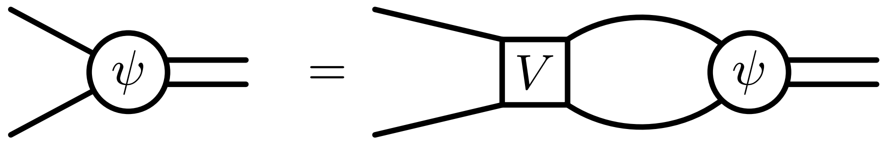
  - then output G^{μ} satisfies the Ward-Takahashi identity

Gauging the bound state wave function

- The two-body bound state equation:

$$\psi = G_0 V \psi \tag{2}$$



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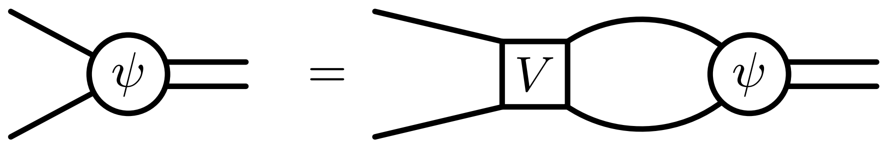

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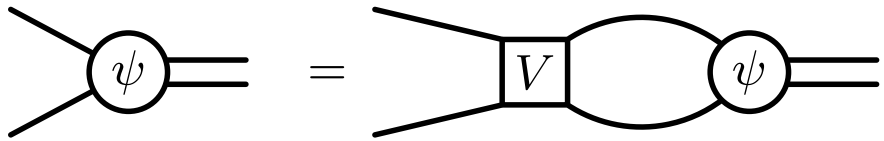

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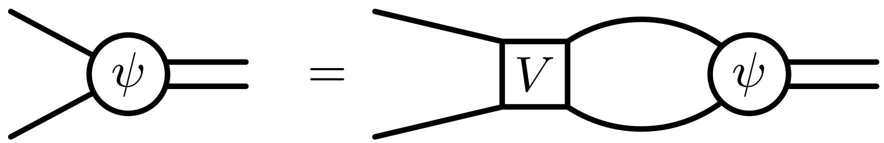

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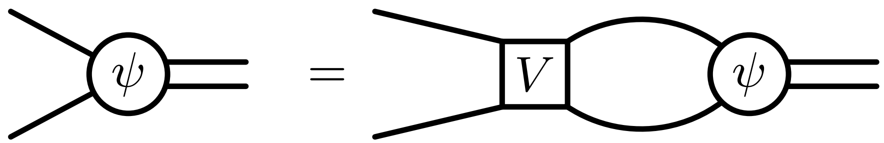

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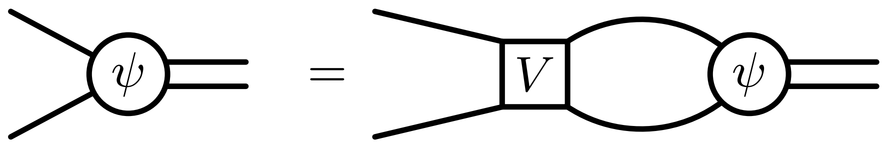

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- The "deuteron" photodisintegration amplitude is then $\boxed{G_0^{-1} \psi^{\mu} \epsilon_{\mu}}$

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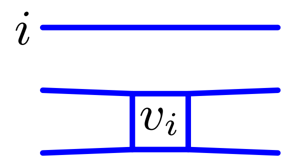
- Again

$$G = G_0 + G_0 V G$$

$$G^{\mu} = G\left(G_0^{-1} G_0^{\mu} G_0^{-1} + V^{\mu}\right) G$$

but now (neglecting 3-body forces)

$$V = \sum_i$$



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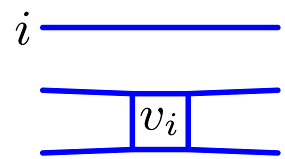

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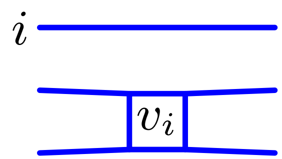

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- Subtraction term
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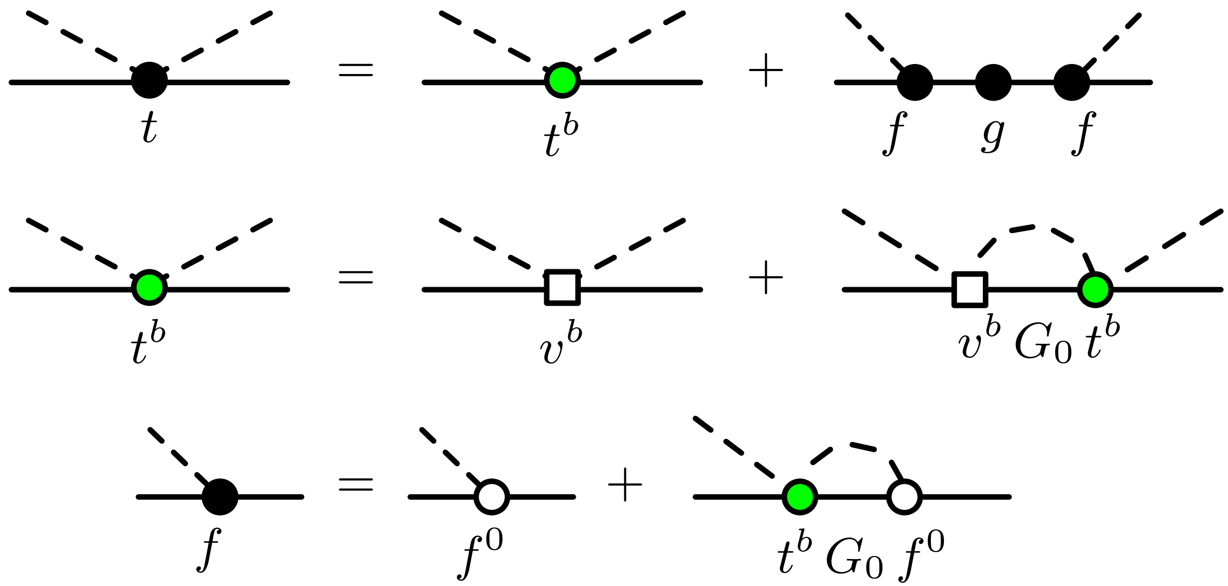
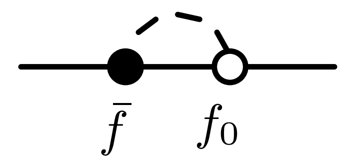
Standard description of πN scattering



$$g^{-1} = g_0^{-1} - \Sigma \qquad \Sigma =$$



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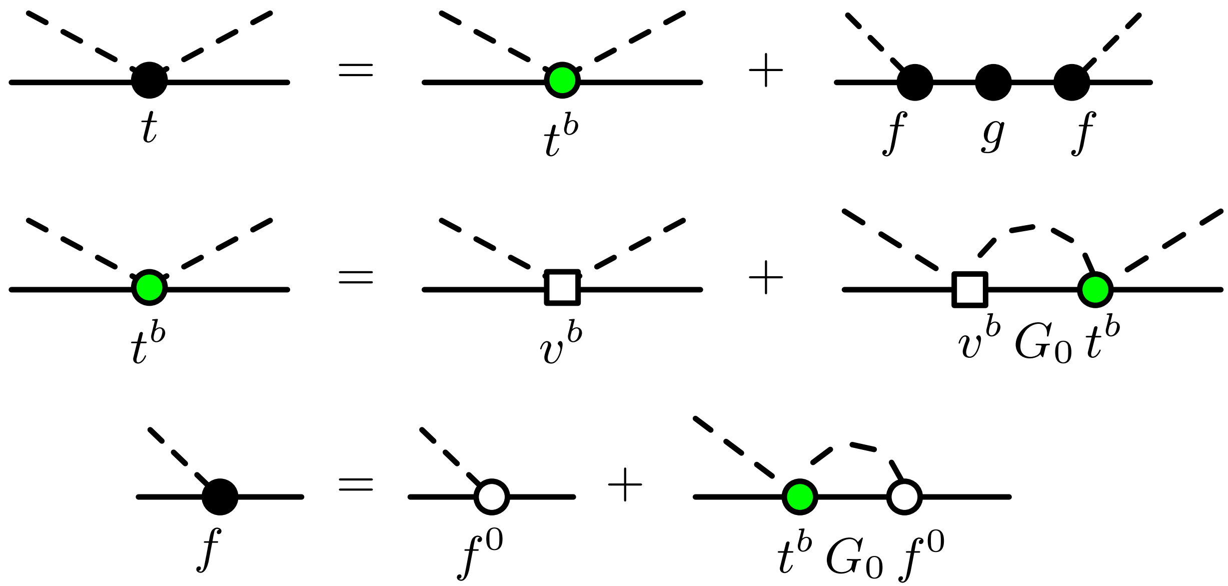

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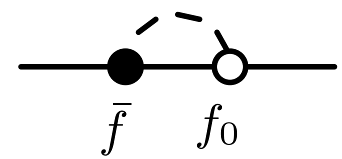

- Good: two-body unitarity
- Bad: **No crossing symmetry** once v^b approximated, no PCAC

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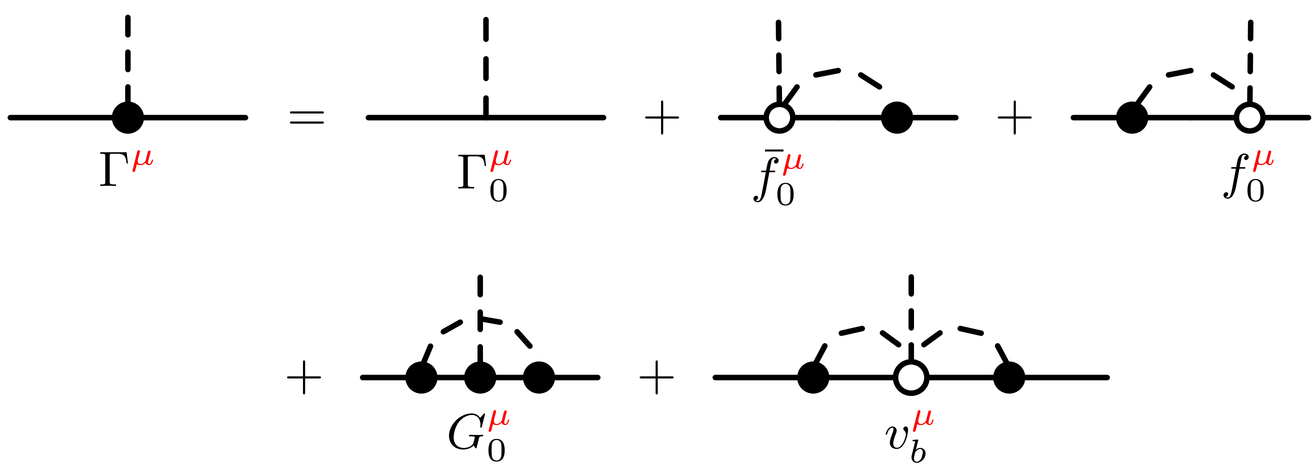
$$g^\mu = g\,\Gamma^\mu g \qquad\qquad \Gamma^\mu = \Gamma_0^\mu + \Sigma^\mu$$

$$\Gamma^\mu = \Gamma_0^\mu + \bar{f}_0^\mu G_0 f + \bar{f} G_0 f_0^\mu + \bar{f} G_0^\mu f + \bar{f} G_0 v_b^\mu G_0 f$$



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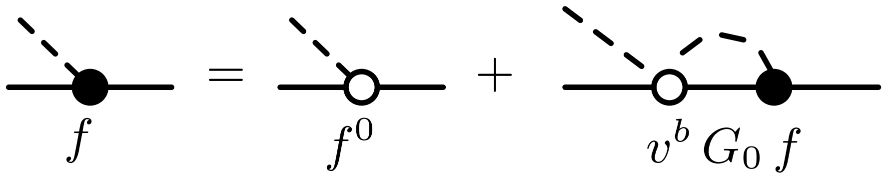

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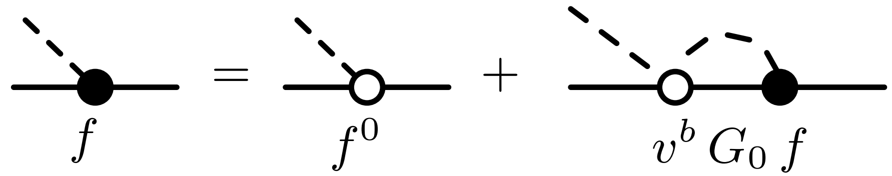

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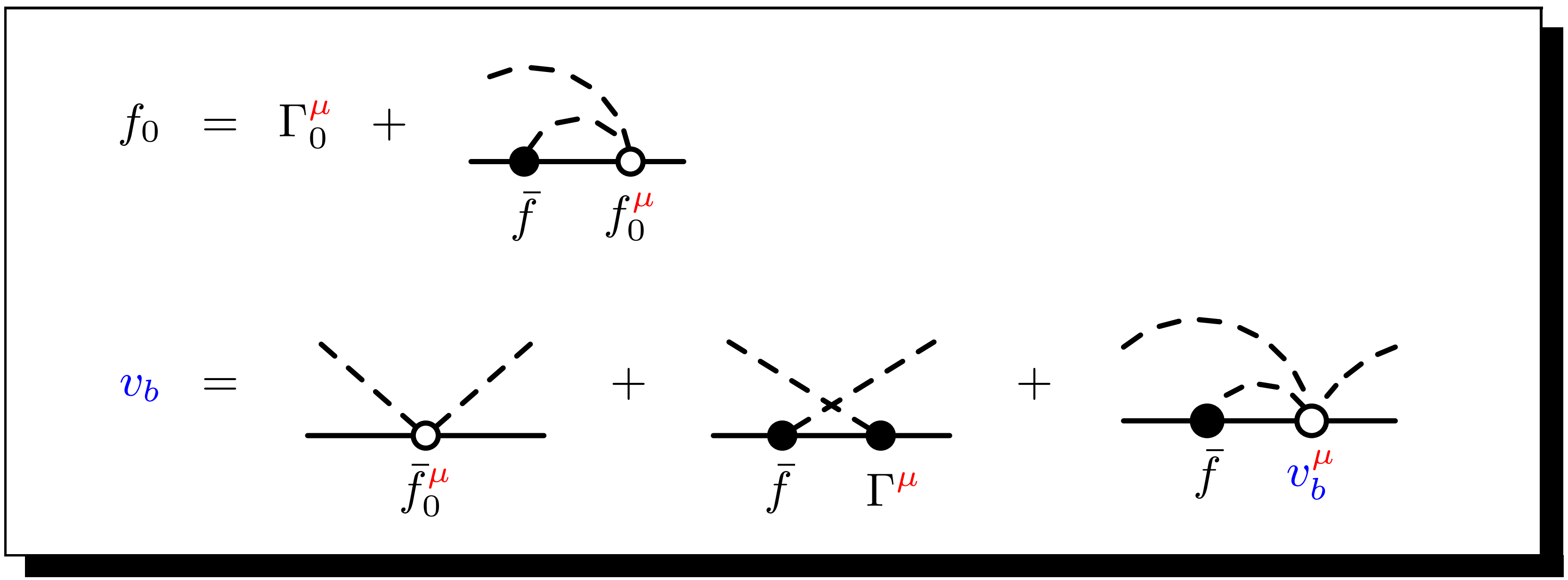

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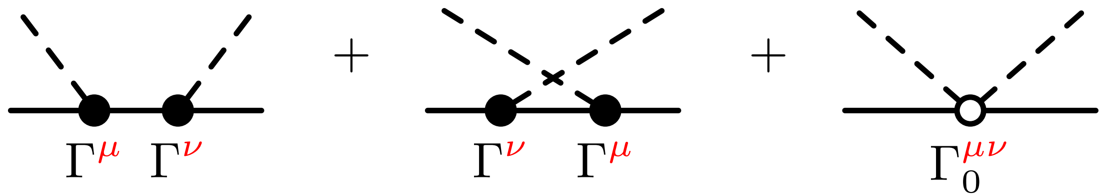
$$T_{\pi N} = \Gamma^{\mu} g \Gamma^{\nu} + \Gamma^{\nu} g \Gamma^{\mu} + \Gamma_0^{\mu\nu} + \Sigma^{\mu\nu}$$

$T_{\pi N} =$



$+ \ \Sigma^{\mu\nu}$

$$\begin{aligned}\Sigma^{\mu\nu} &= \bar{f}_0^{\mu\nu} G_0 f + \bar{f} G_0 f_0^{\mu\nu} + \bar{f} G_0 \Delta^{\mu\nu} G_0 f \\ &+ \bar{f}_0^{\mu} G \Delta^{\nu} G_0 f + \bar{f} G_0 \Delta^{\nu} G f_0^{\mu} + (\mu \leftrightarrow \nu) \\ &+ \bar{f}_0^{\mu} G f_0^{\nu} + \bar{f} G_0 \Delta^{\mu} G \Delta^{\nu} G_0 f + (\mu \leftrightarrow \nu)\end{aligned}$$

$$\Delta^{\mu} = \Gamma^{\mu} g_{\pi}^{-1} + v_b^{\mu}, \qquad G = G_0 + G_0 t_b G_0$$

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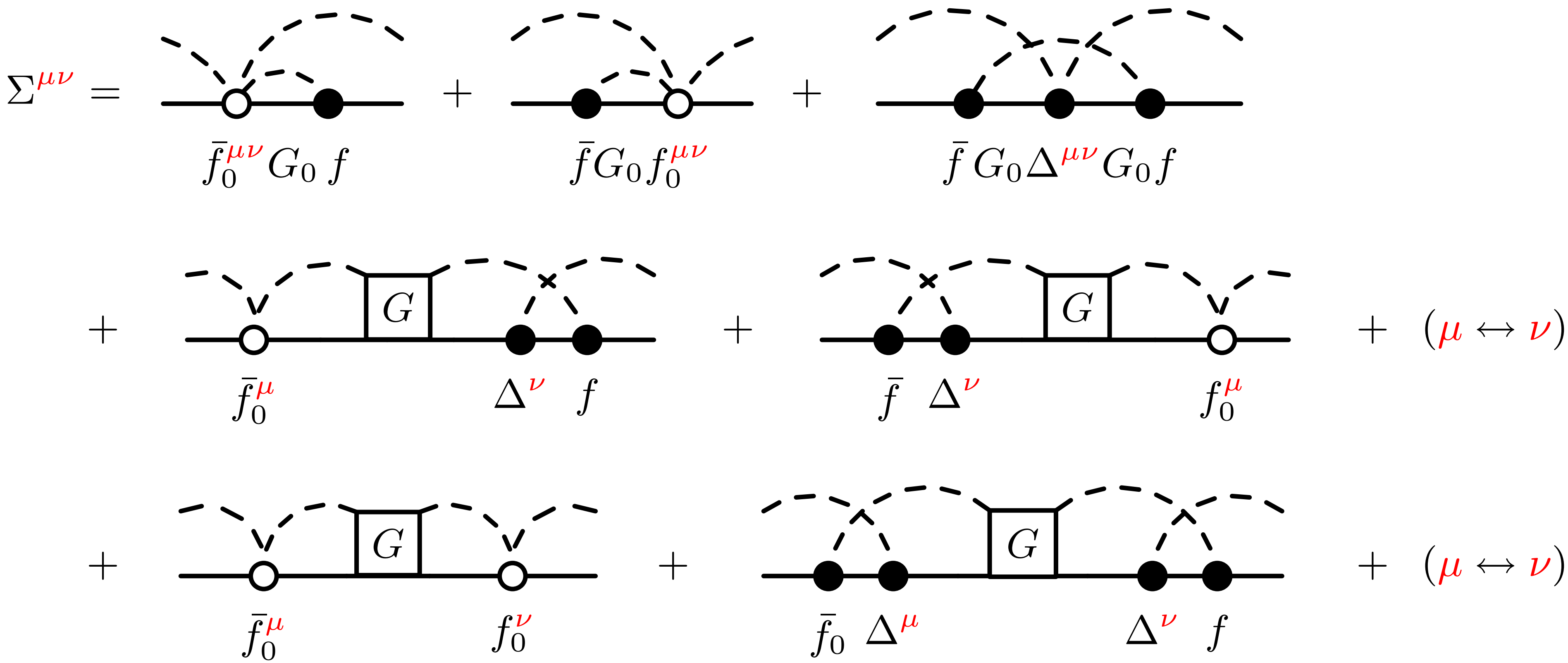

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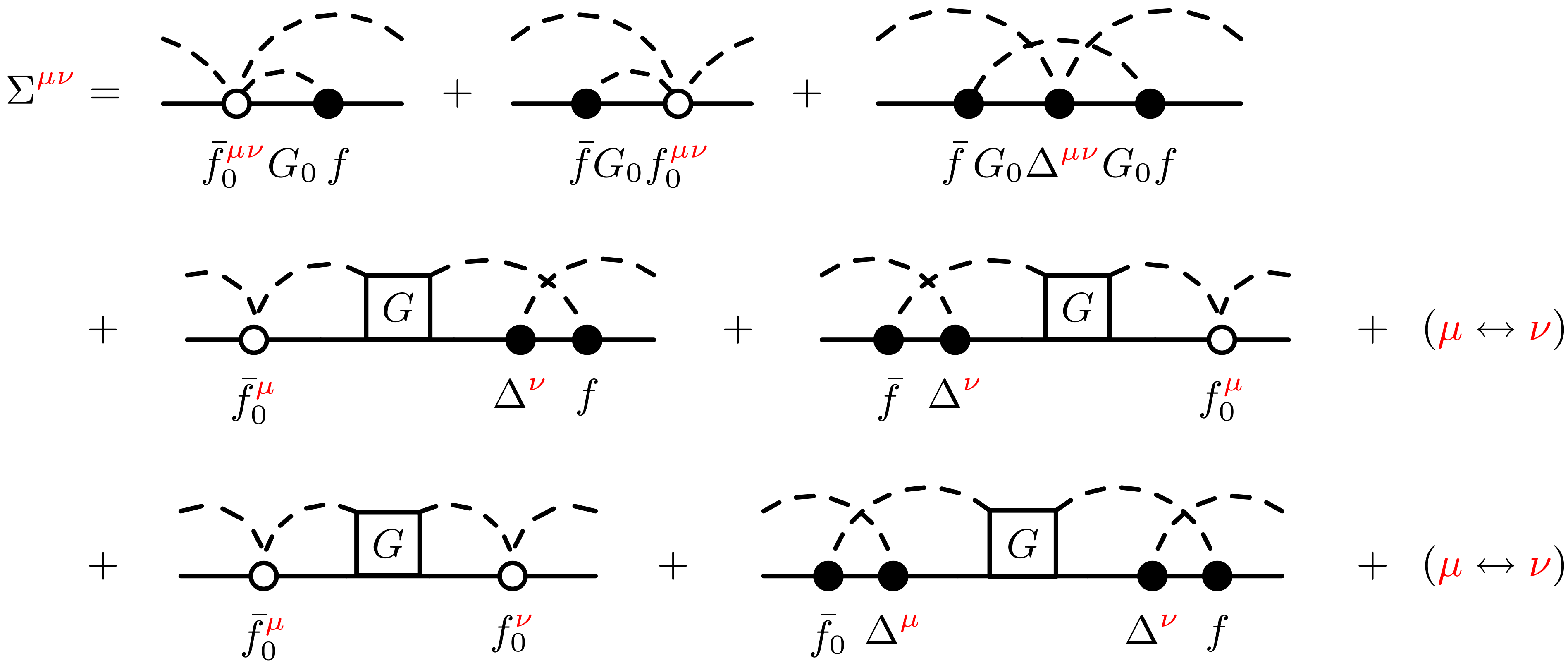

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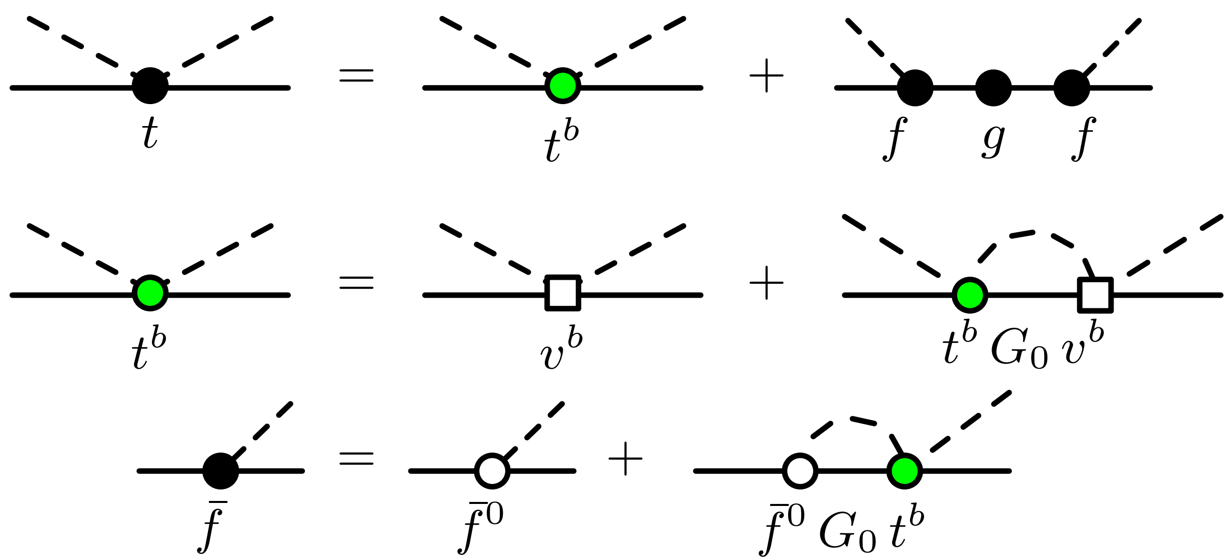
- Good: **Obeys crossing symmetry**, PCAC a possibility

Standard description of pion photoproduction



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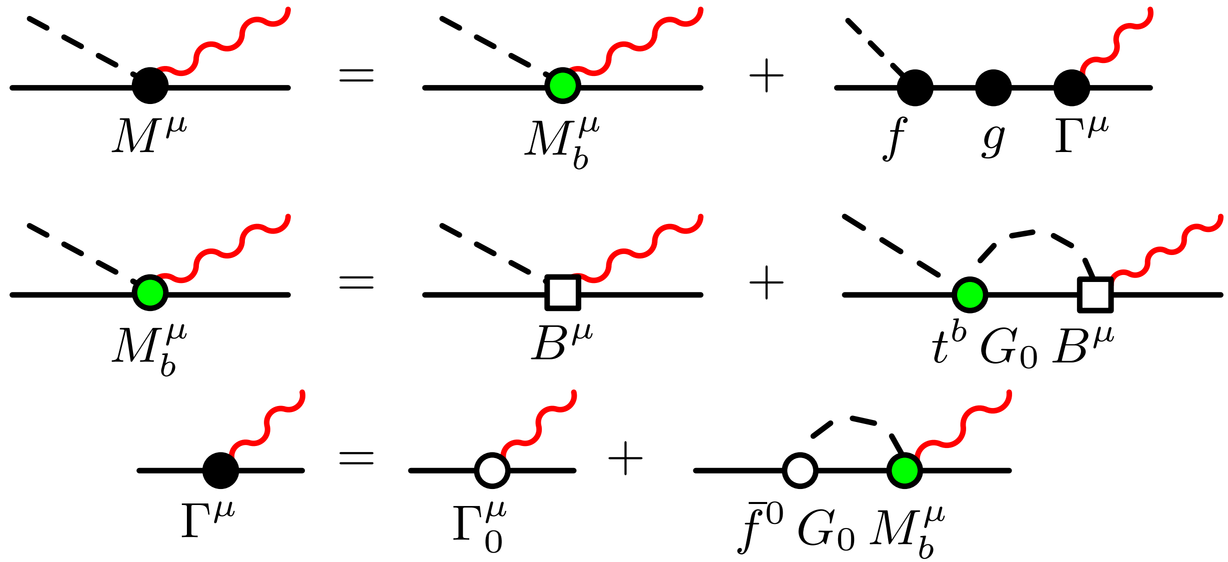

- Good: two-body unitarity guaranteed (Watson's theorem)

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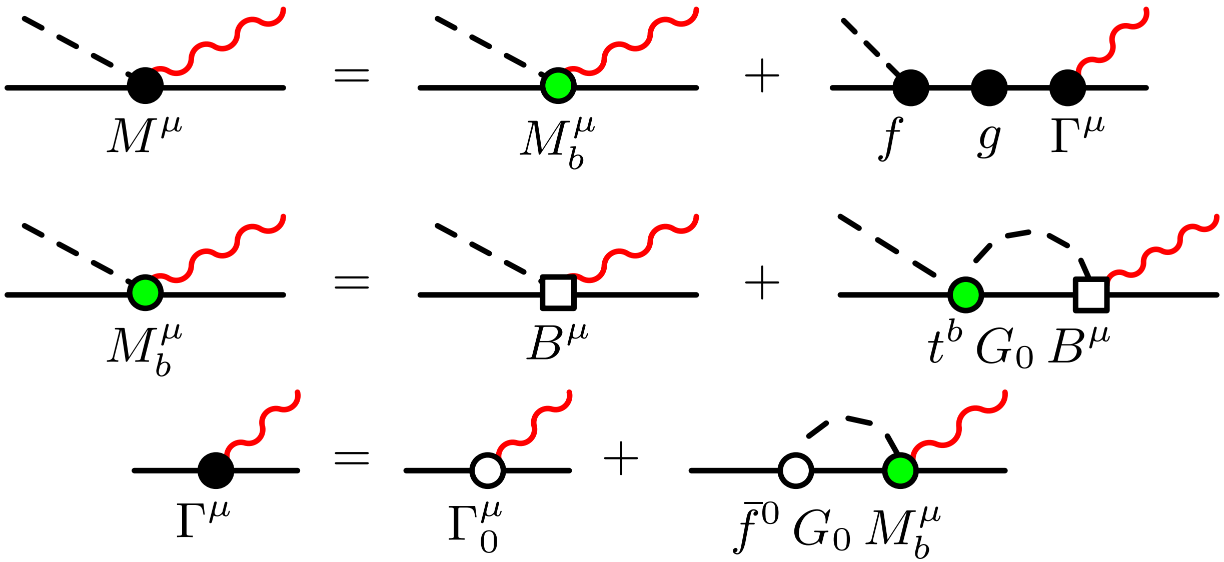

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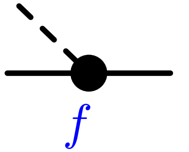
- Bad: not gauge invariant

Gauge invariant pion photoproduction

- Start with the dressed πNN vertex 

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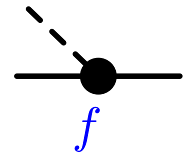
- Start with the dressed πNN vertex 

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- Then gauge the equation for $G_0 f g$ since

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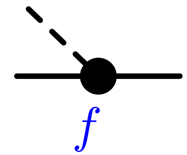
- Start with the dressed πNN vertex 

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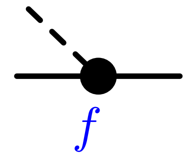
- Start with the dressed πNN vertex 

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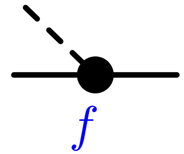
  - $(G_0 f g)^{\mu} = (G_0 f_0 g)^{\mu} + (G_0 v_b G_0 f g)^{\mu}$

$$= (G_0 f_0 g)^{\mu} + (G_0 v_b)^{\mu} + (G_0 f g)^{\mu}$$

Gauge invariant pion photoproduction

- Start with the dressed πNN vertex 

 of the standard πN description
- Then gauge the equation for $G_0 f g$ since

$$M^\mu = G_0^{-1} (G_0 f g)^\mu g^{-1}$$

is the pion photoproduction amplitude

  - $f = f_0 + v_b G_0 f$:
  - $(G_0 f g)^\mu = (G_0 f_0 g)^\mu + (G_0 v_b G_0 f g)^\mu$

$$= (G_0 f_0 g)^\mu + (G_0 v_b)^\mu + (G_0 f g)^\mu$$

$$\boxed{M^\mu = f g \Gamma^\mu + (1 + t G_0)\left(f_0^\mu + \Gamma_0^\mu G_0 f + v_b^\mu G_0 f\right)}$$

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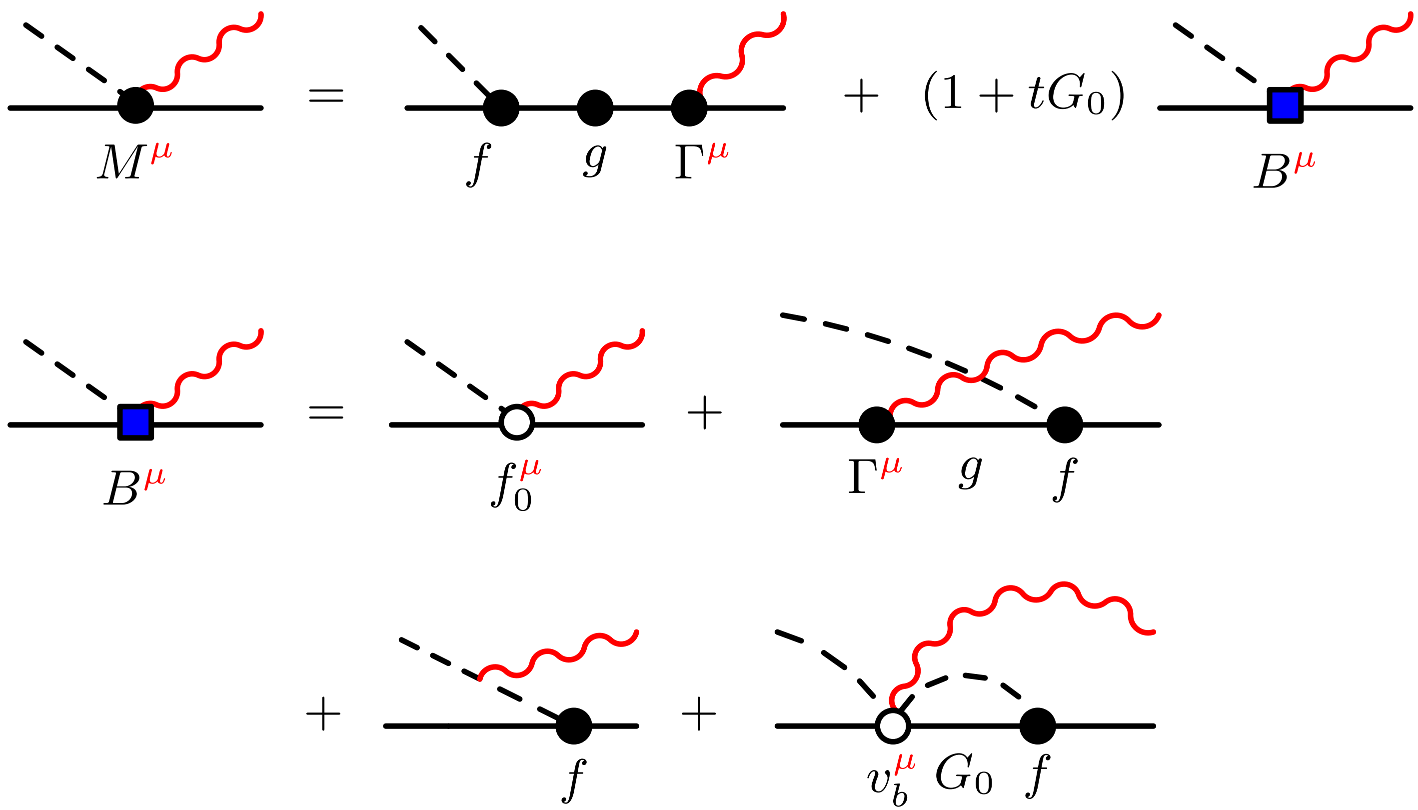
- The derived pion photoproduction amplitude is:



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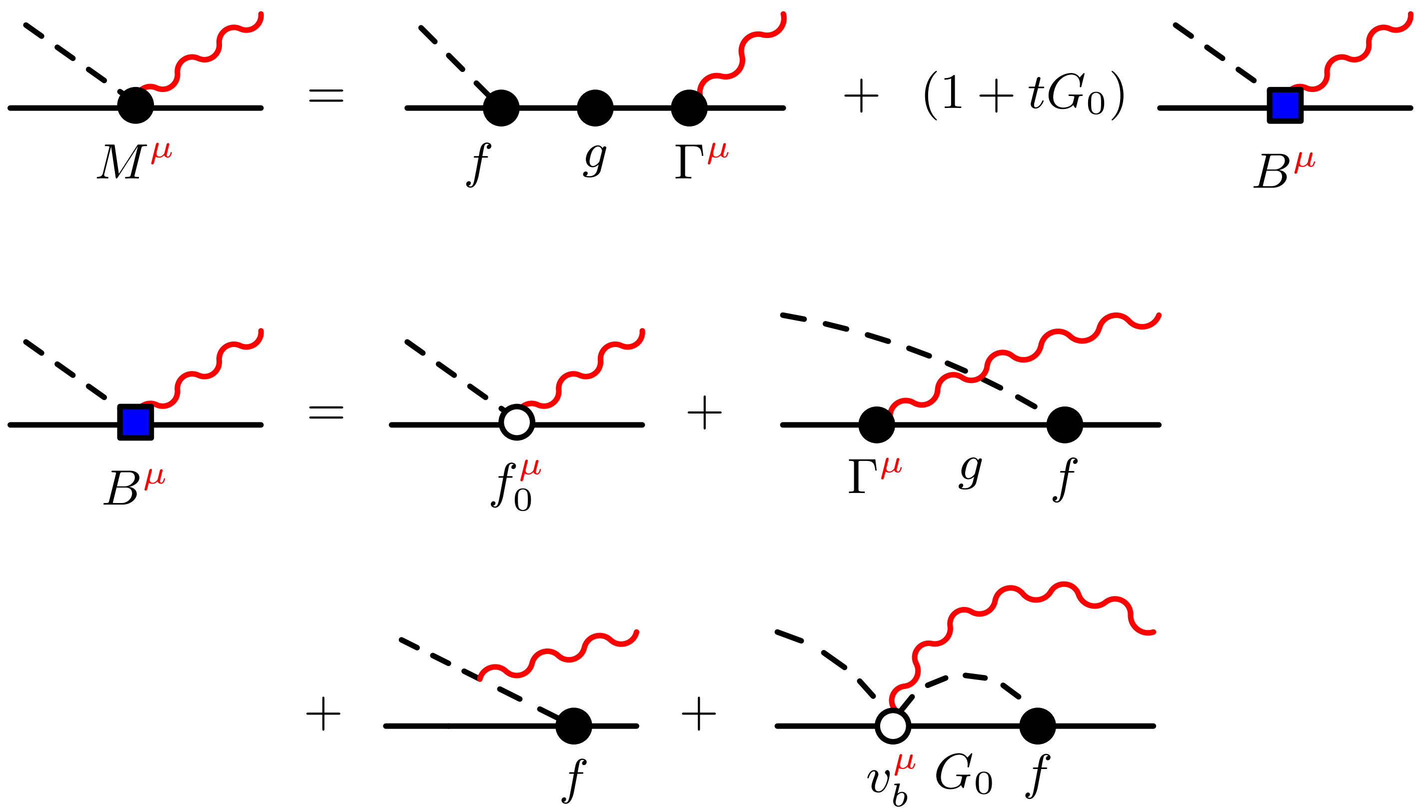

- The amplitude M^μ is gauge invariant as long as the gauged inputs Γ^μ, f_0^μ, and v_b^μ satisfy Ward-Takahashi identities.

Gauge invariant pion photoproduction

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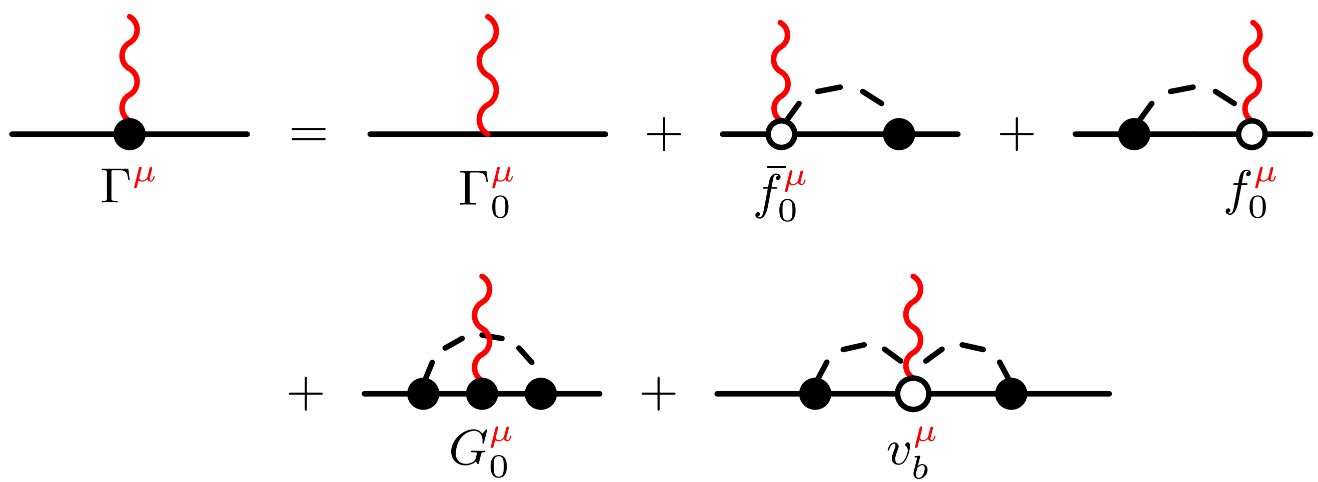
- But Γ^μ must be constructed by gauging the dressed propagator g:

$$g^\mu = g\,\Gamma^\mu g \qquad\qquad \Gamma^\mu = \Gamma_0^\mu + \Sigma^\mu$$

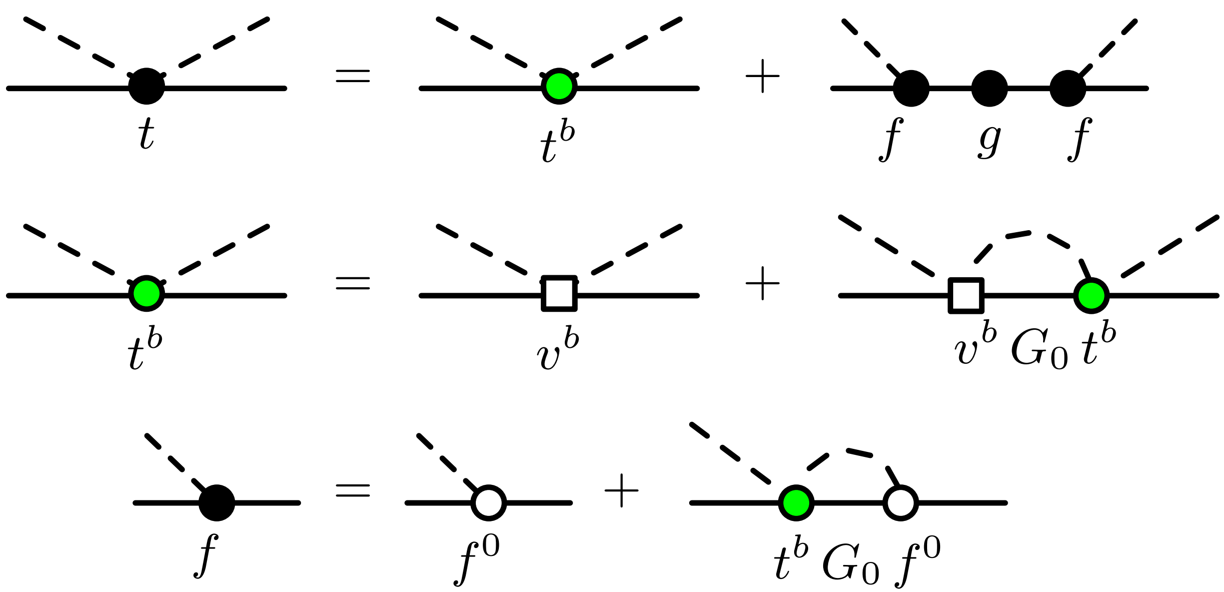
$$\Gamma^\mu = \Gamma_0^\mu + \bar{f}_0^\mu G_0 f + \bar{f} G_0 f_0^\mu + \bar{f} G_0^\mu f + \bar{f} G_0 v_b^\mu G_0 f$$



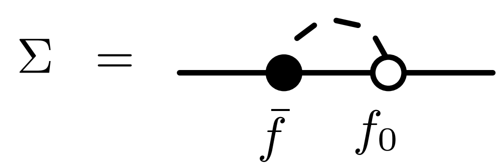
Pion photoproduction in the spectator model

- For the standard description of πN scattering we follow the approach of Gross and Surya (PRC 47, 703 (1993)):

$$g_\pi(k) = \frac{i}{k^2 - \mu^2 + i\epsilon} \qquad \rightarrow \qquad \delta_\pi(k) = 2\pi\delta^+(k^2 - \mu^2)$$



$$g^{-1} = g_0^{-1} - \Sigma$$



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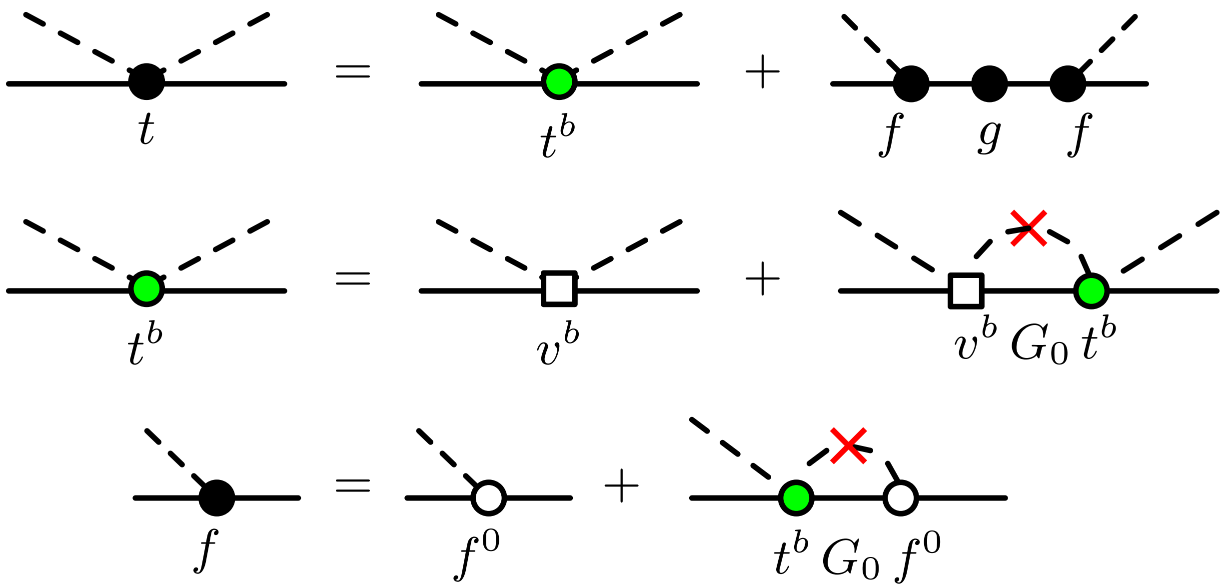

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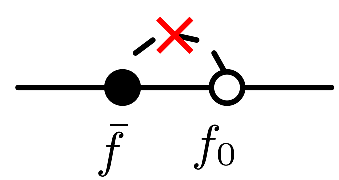

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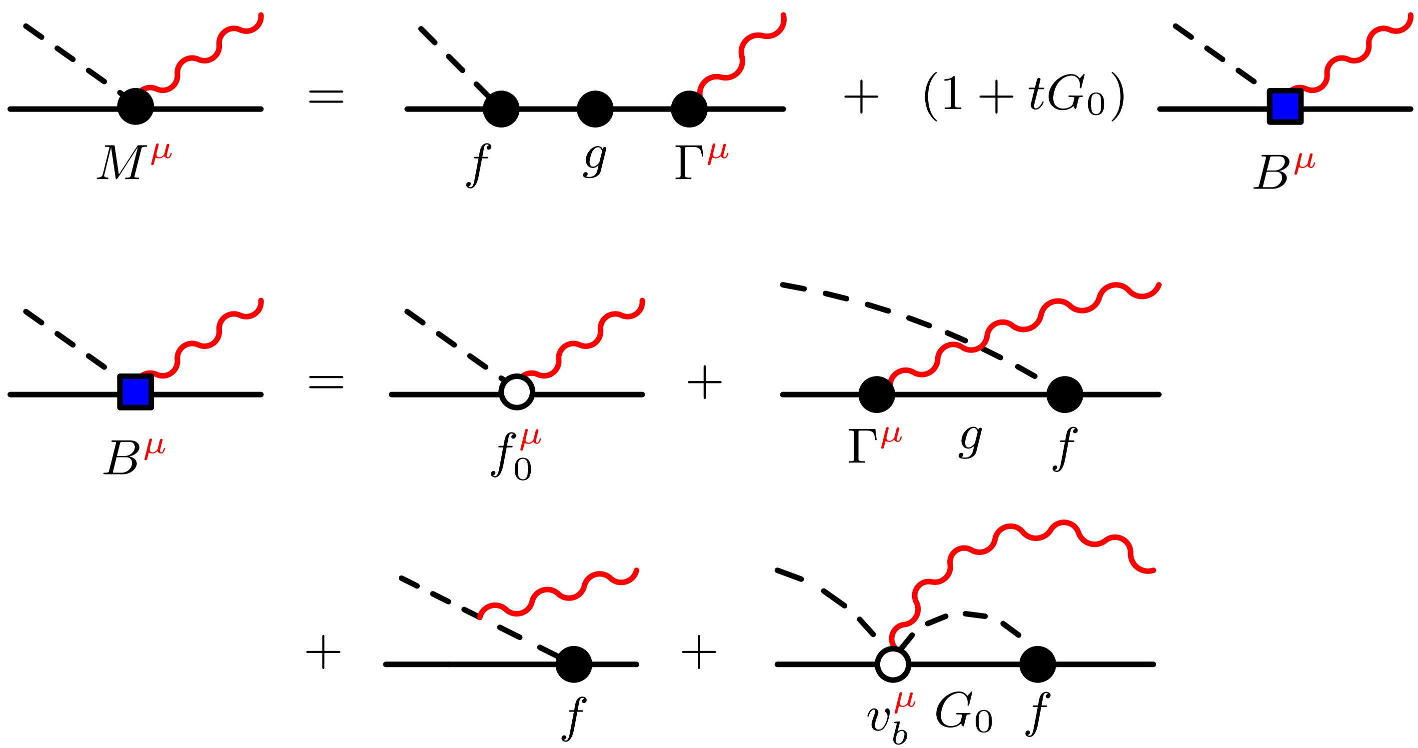

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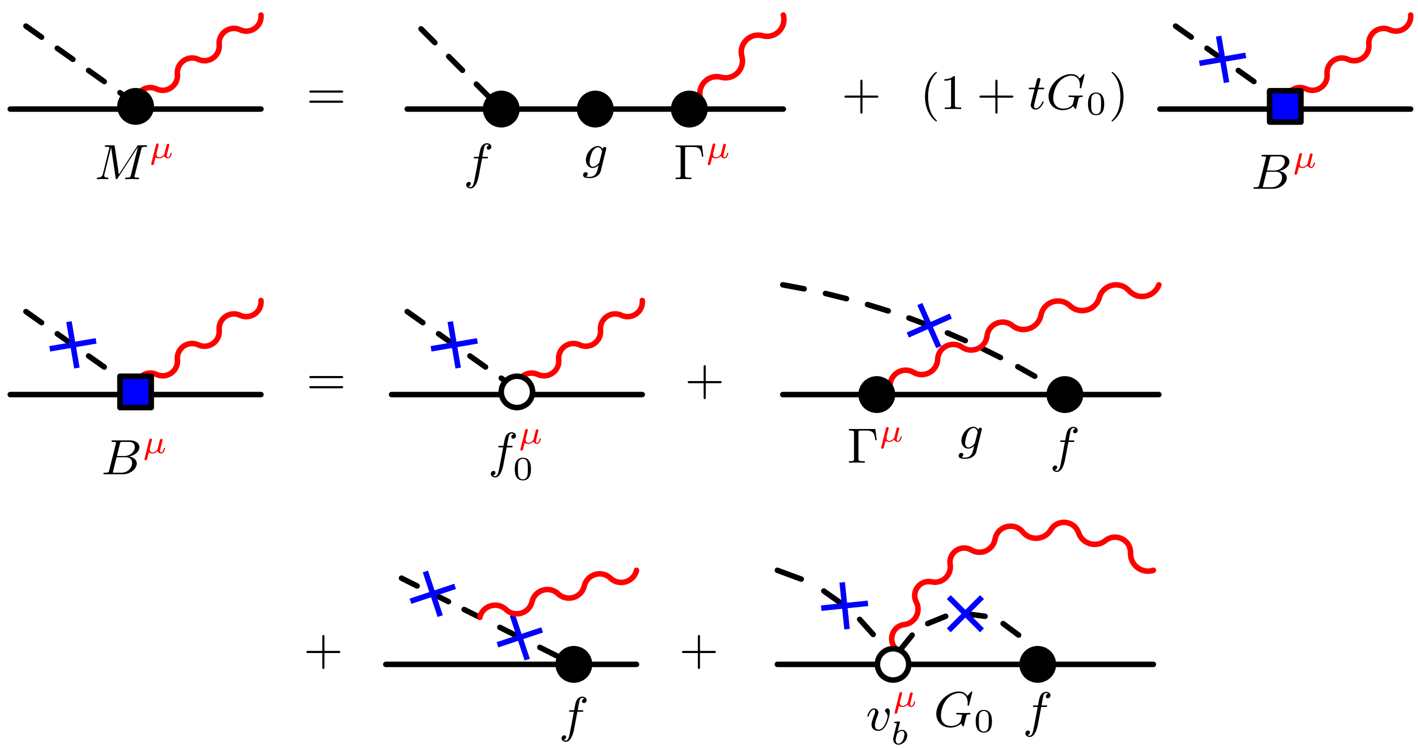

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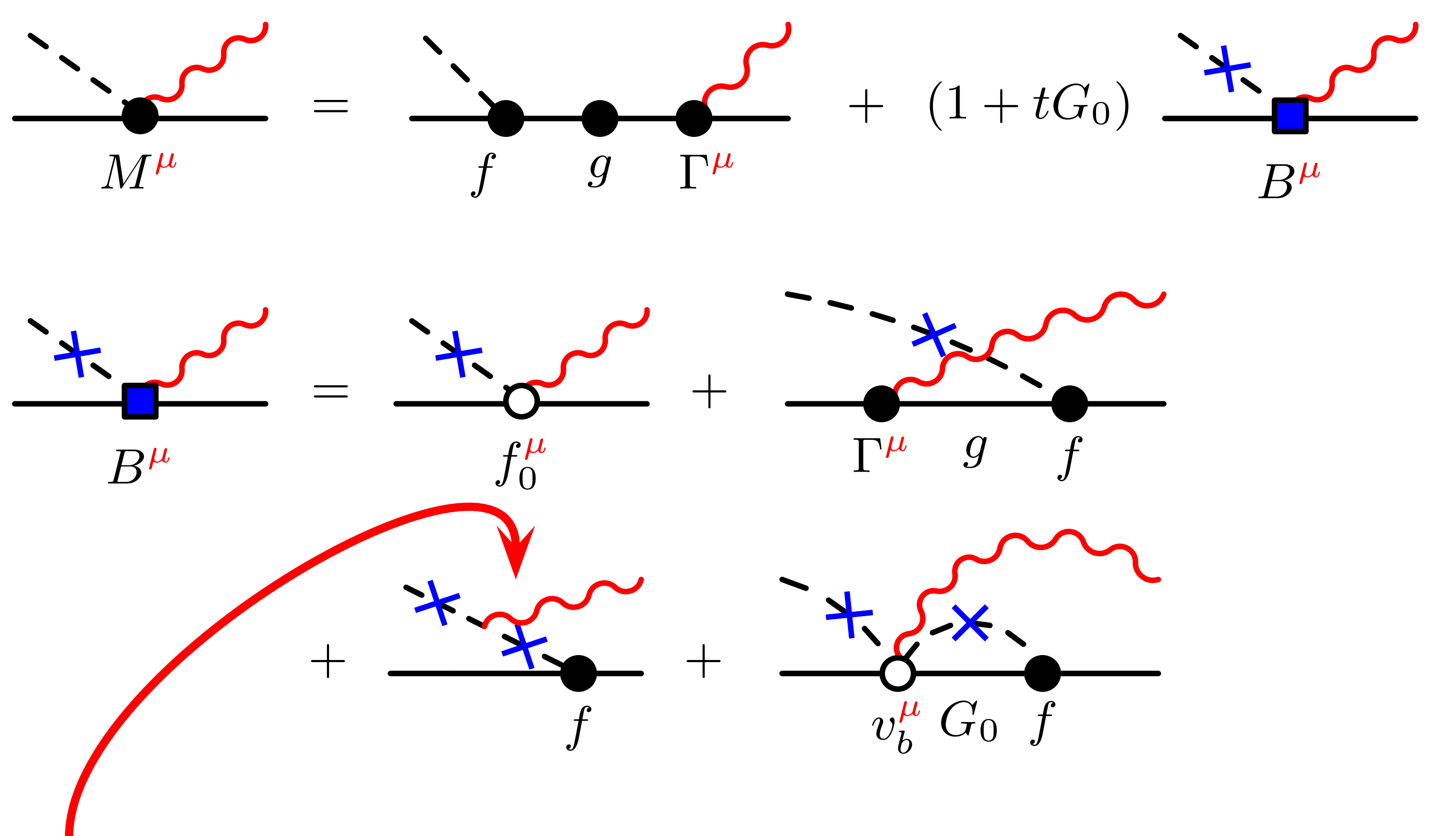

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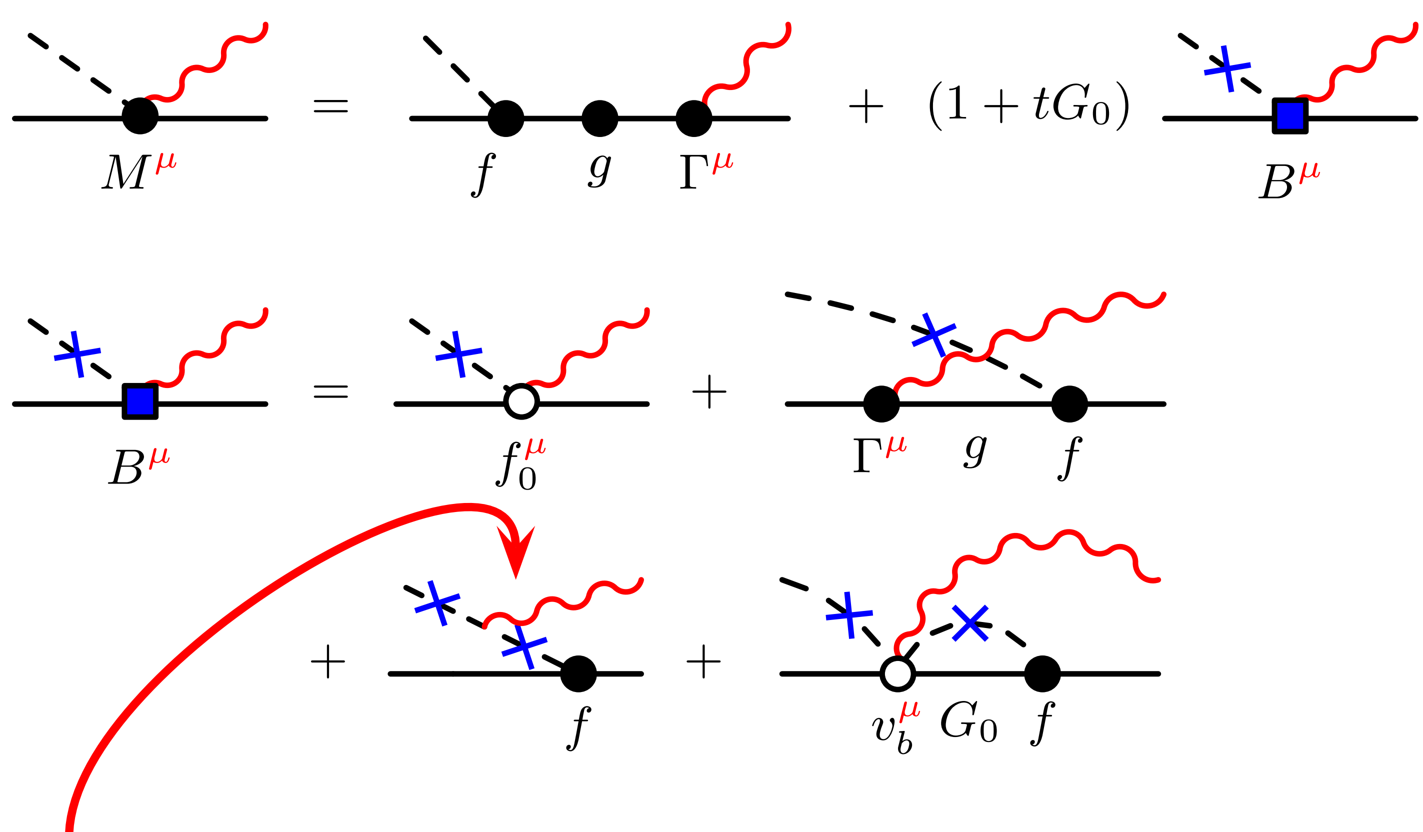
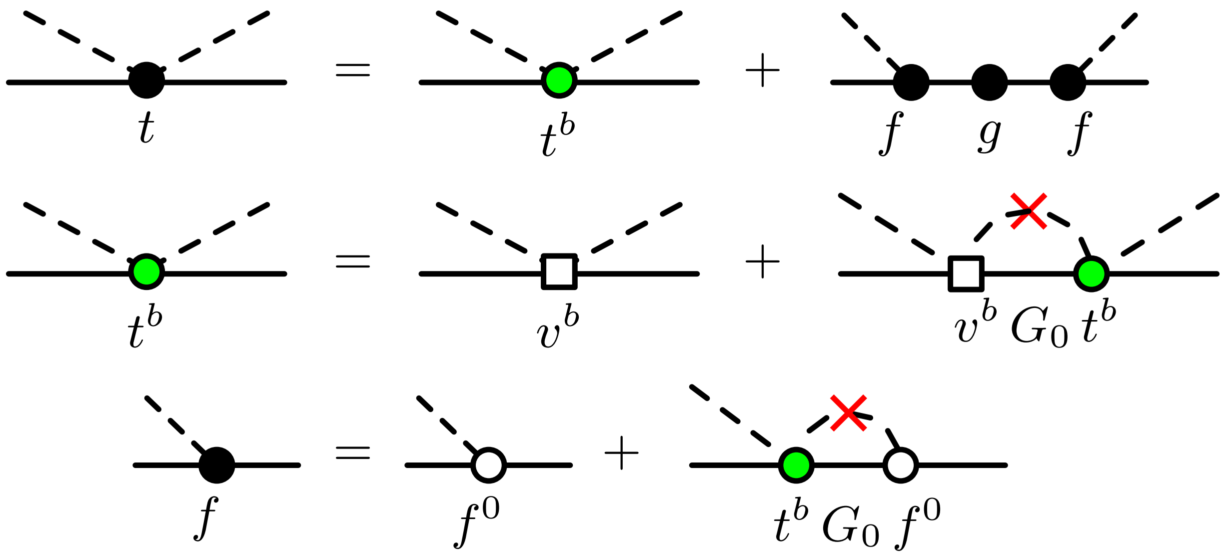


- What to do? In any case, gauge invariance will be lost

Pion photoproduction in the spectator model

- **2.** Gauge the 3D spectator equations:



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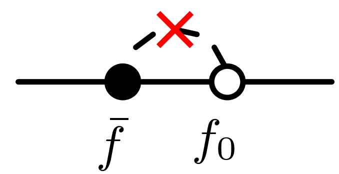

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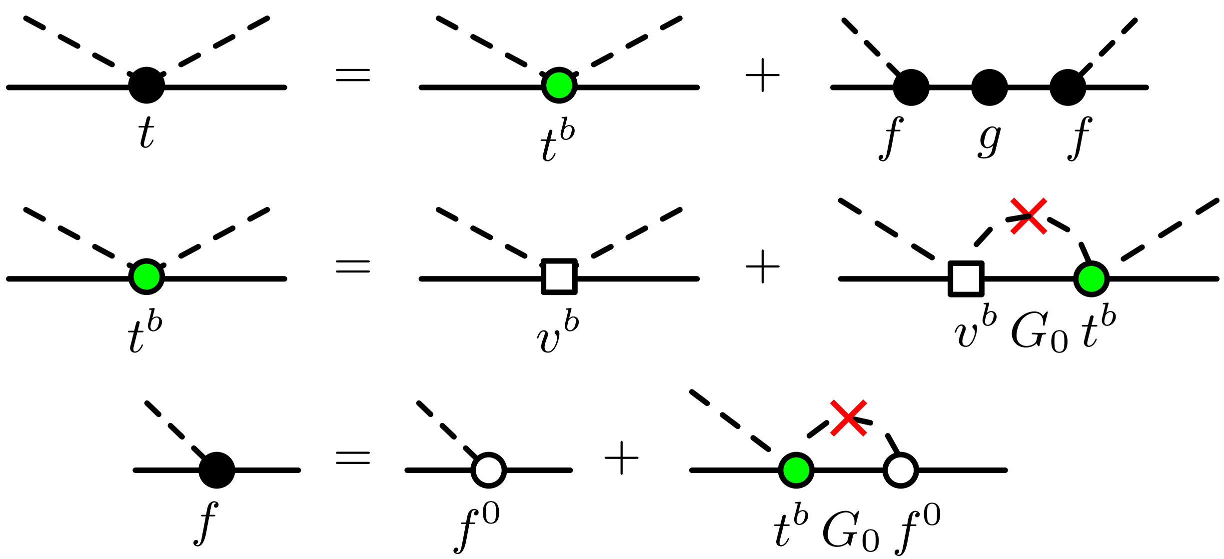

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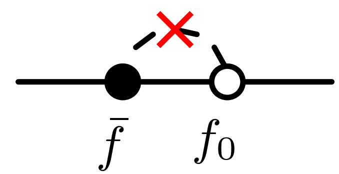
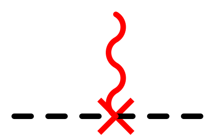


- In this case one is faced giving meaning to δ_π^μ:

$$\delta_\pi^\mu =$$



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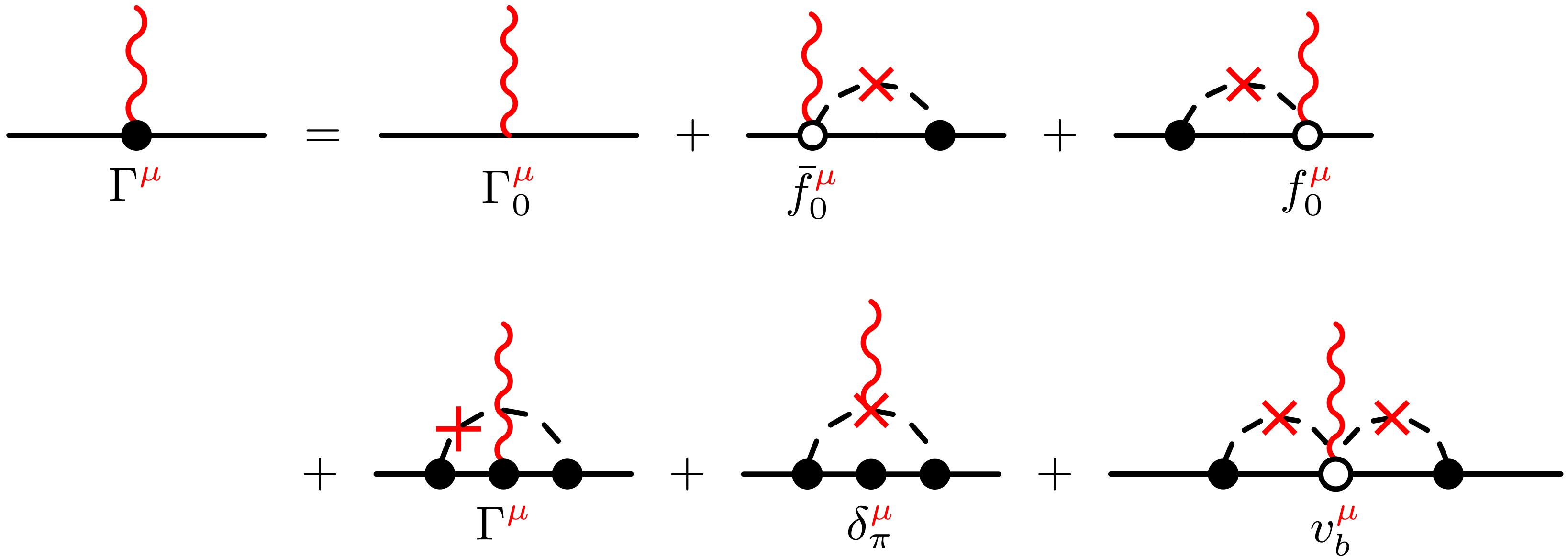
  - reduce a d^4k integral to a d^3k integral
- Such a δ_π^μ is provided by the Ansatz

$$\boxed{\delta_\pi^\mu(k',k) = 2\pi i e_\pi (k'^\mu + k^\mu)\frac{\delta^+(k'^2-\mu^2) - \delta^+(k^2-\mu^2)}{k^2 - k'^2}}$$

Pion photoproduction in the spectator model

- The nucleon EM vertex in the gauged spectator model is



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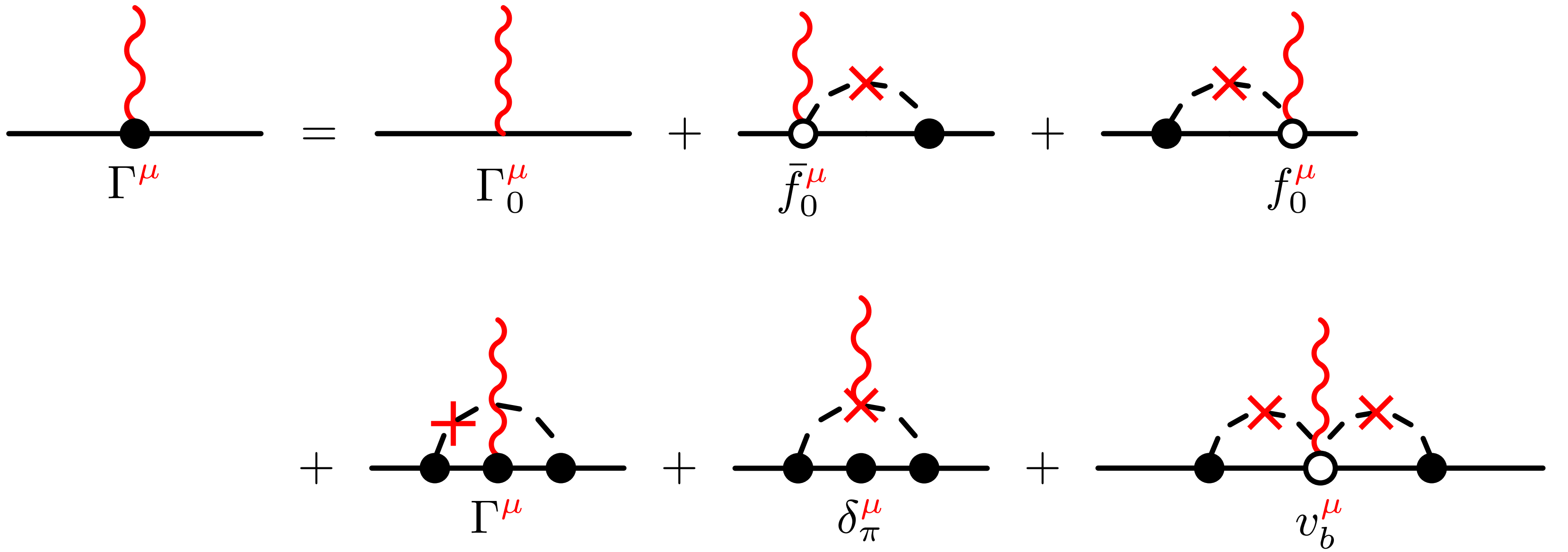

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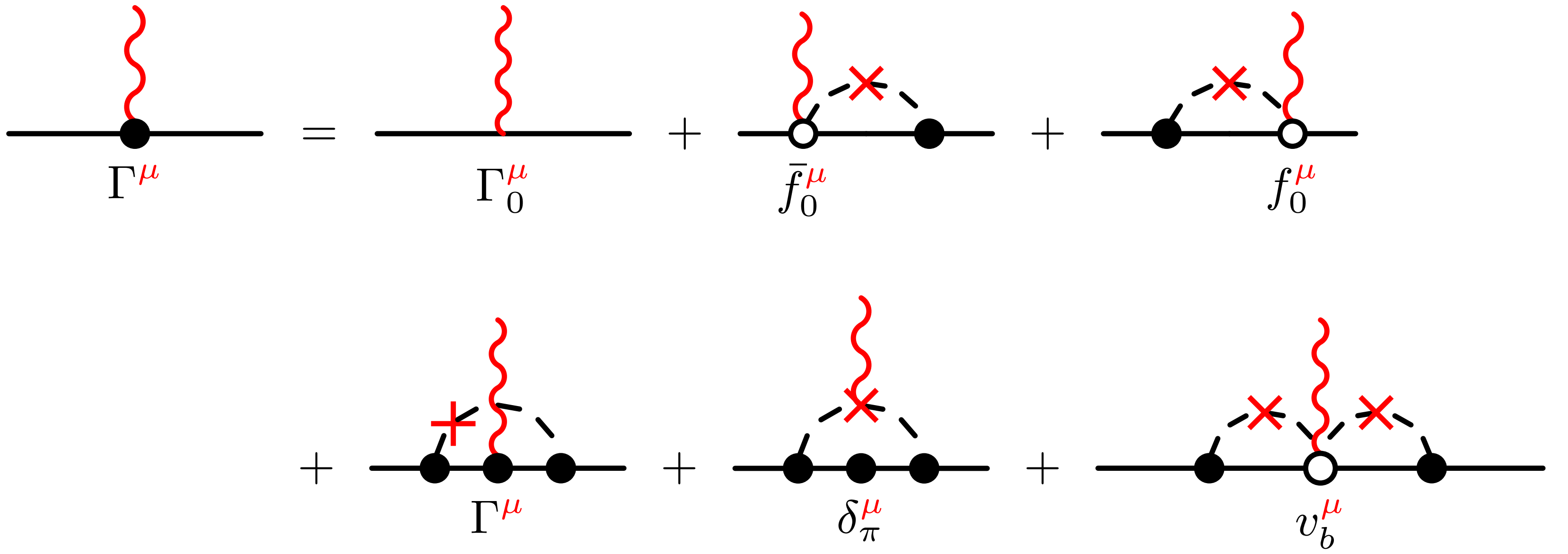

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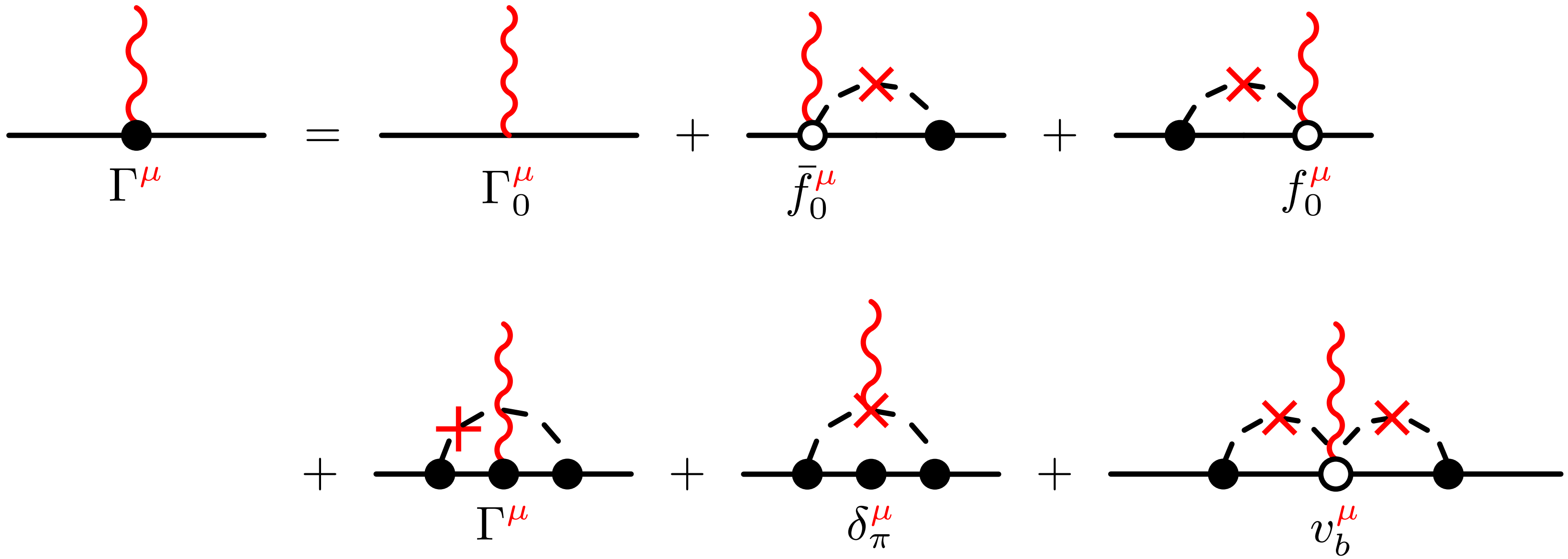

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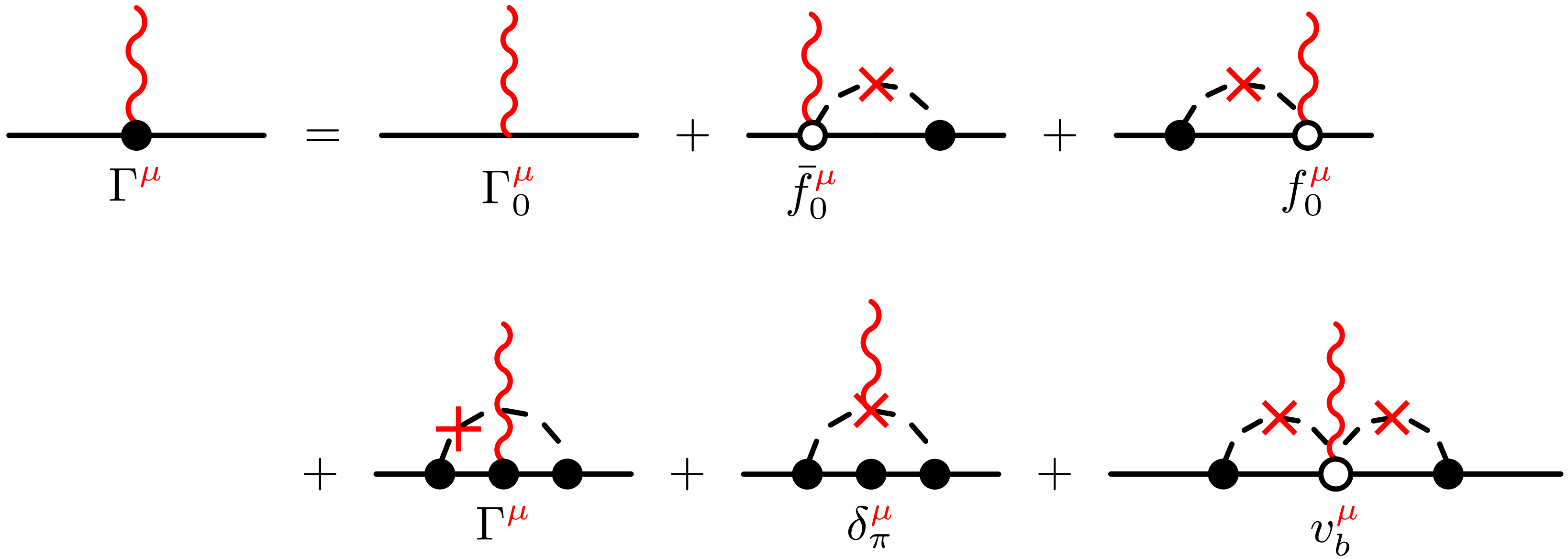

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πN equations:

- Gauging the dressed nucleon propagator g with one pion leads to an interesting "self consistency" equation for the πN potential v_b.
- Gauging g with two pions gives a πN amplitude that is crossing symmetric
- Complete pion attachment is a necessary first step towards PCAC

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- Happy Birthday Tony!