Renormalizability Criteria
in Nuclear Chiral EFT

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Outline

Motivation: explicit renormalization in chiral EFT

Motivation: finite (of the order of the hard scale) cutoff scheme

Renormalizability of the **NN amplitude at NLO**. Counterexamples

Renormalizability in the nonperturbative regime. Counterexamples

Summary

Renormalization in chiral EFT

Expansion parameter: (soft scale)/(hard scale) $Q = \dfrac{q}{\Lambda_b}$

$$q \in \{ |\vec{p}| \, , M_\pi \} \, , \qquad \Lambda_b \sim M_\rho$$

"Perturbative" calculation of observables

Renormalization in chiral EFT

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"Perturbative" calculation of observables

$$\mathcal{L}_{\rm eff} = \mathcal{L}_\pi^{(2)} + \mathcal{L}_{\pi N}^{(1)} + \mathcal{L}_{NN}^{(0)} + \mathcal{L}_{NN}^{(2)} + \ldots$$

Bare parameters of the Lagrangian

Renormalization:
power counting for
renormalized quantities

Implicit renormalization

$T = T_0$ fit bare $C_i^{(0)}$

$T = T_0 + T_2$ (re)fit bare $C_i^{(0)},\ C_i^{(2)}$

$T = T_0 + T_2 + T_4$ (re)fit bare $C_i^{(0)},\ C_i^{(2)},\ C_i^{(4)}$

$\ldots$

Balancing at the border of phenomenology

Implicit renormalization

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$\ldots$

Balancing at the border of phenomenology

Explicit renormalization

$$T = \mathbb{R}(T_0) + \mathbb{R}(T_2) + \mathbb{R}(T_4) + \ldots$$

$C_i = C_i^r + \delta C_i$ bare =renormalized + counter term
(absorb divergent and power counting breaking contributions)

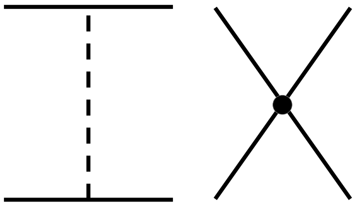
Identify each term individually, or at least prove this is possible

Justifies theoretical error estimation!

Power counting for NN chiral EFT: LO and NLO

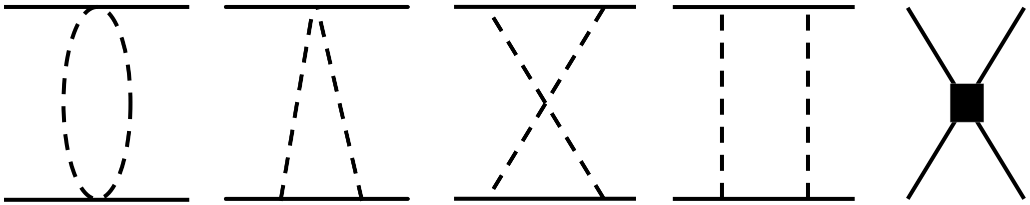
Weinberg, S., **NPB363**, 3 (1991)

$\mathcal{O}(Q^0)$

$V_{\rm LO} = V_0$  +...

$$|V_0(p',p)| \leq V_{\rm max} \times 1$$

$\mathcal{O}(Q^2)$

$V_{\rm NLO} = V_2$ 

$$|V_2(p',p)| \leq V_{\rm max} \frac{p^2 + p'^2}{\Lambda_b^2} \log \frac{p^2 + p'^2}{M_\pi^2}$$

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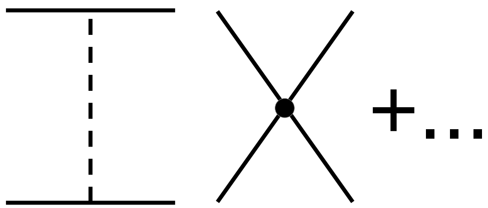

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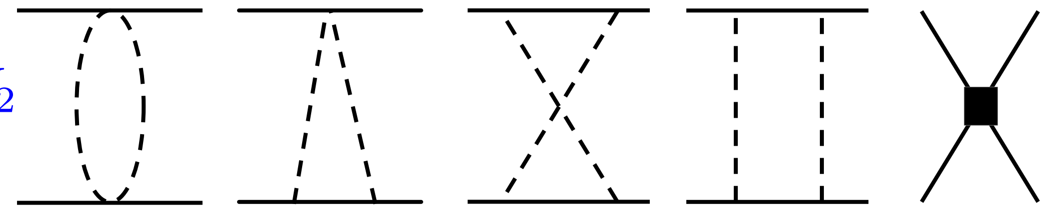

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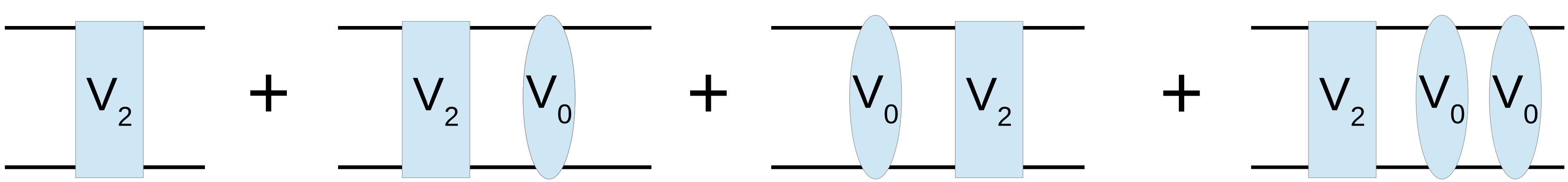
LO potential has to be iterated (resummed):

$$T_2 = V_2 + V_2 G V_0 + V_0 G V_2 + V_2 G V_0 G V_0 + \ldots$$



Motivation: Finite cutoff scheme

Rob Timmermans: If you cannot go with the cutoff above the breakdown scale, what, at all, are you doing?

Answer: The finite cutoff scheme is the most well grounded approach to date (with nonperturbative pions)

$$\text{LO: } T_0^{[n]} = V_0 (G V_0)^n \sim \mathcal{O}(Q^0)$$

We cannot absorb all positive powers of Λ.
Absorb only those that are not compensated by the inverse powers of Λ_b

Expectation: $\Lambda \approx \Lambda_b : \int \frac{p^{n-1} dp}{(\Lambda_b)^n} \sim \left(\frac{\Lambda}{\Lambda_b}\right)^n \sim \left(\frac{\Lambda_b}{\Lambda_b}\right)^n \sim \mathcal{O}(Q^0)$

G. P. Lepage, nucl-th/9706029
J. Gegelia, **JPG25**, 1681 (1999)

$$\text{NLO: } T_2^{[m,n]} = (V_0 G)^m \, V_2 \, (G V_0)^n \sim \mathcal{O}(Q^0) \neq \mathcal{O}(Q^2)$$

Power-counting violating contributions from large loop momenta: $p \sim \Lambda \,, p' \sim \Lambda$ in $V_2(p', p)$

Expectation: power-counting breaking contributions can be absorbed by lower order contact (counter) terms

Variation of the cutoff

$$\delta T_\Lambda = (\mathbb{1} + T_0 G)\delta V_\Lambda(\mathbb{1} + G T_0)$$

$$\triangle T_\Lambda = (\mathbb{1} + T_0 G)\triangle V_\Lambda(\mathbb{1} + G T_0) \approx |T_0|^2 m_N \Lambda \frac{\triangle\Lambda}{\Lambda}$$

Not small If T_0 is enhanced (S-waves): $T_0 \sim Q^{-1}$

After renormalization: adjusting counter terms

$$\triangle\mathbb{R}(T_\Lambda) = (\mathbb{1} + T_0 G)(\triangle V_{\mathrm{CT}} + \triangle V_\Lambda)(\mathbb{1} + G T_0) \approx |T_0|^2 m_N \Lambda \frac{\triangle\Lambda}{\Lambda}\frac{p^2}{\Lambda^2}$$

nontrivial!

Effective Lagrangian and the regulator

$$\mathcal{L} = \mathcal{L}_{\mathrm{LO}} + \mathcal{L}_{>\mathrm{LO}}$$

-RG-invariance

$$\mathcal{L}_{\mathrm{LO}} \Longrightarrow V_{\mathrm{LO}} = V_{\Lambda}^{(0)}$$ → regulated potential

$V_{>\mathrm{LO}} = V - V_{\mathrm{LO}}$ contains $\delta_{\Lambda} V^{(0)} = V_{\Lambda}^{(0)} - V_{\Lambda=\infty}^{(0)}$

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Lagrangian and amplitude are **formally** cutoff (regulator) independent

$$\frac{d\mathcal{L}}{d\Lambda} = 0 \longrightarrow \frac{dT}{d\Lambda} = 0$$

Λ specifies the non-perturbative regime (the renormalization scheme)

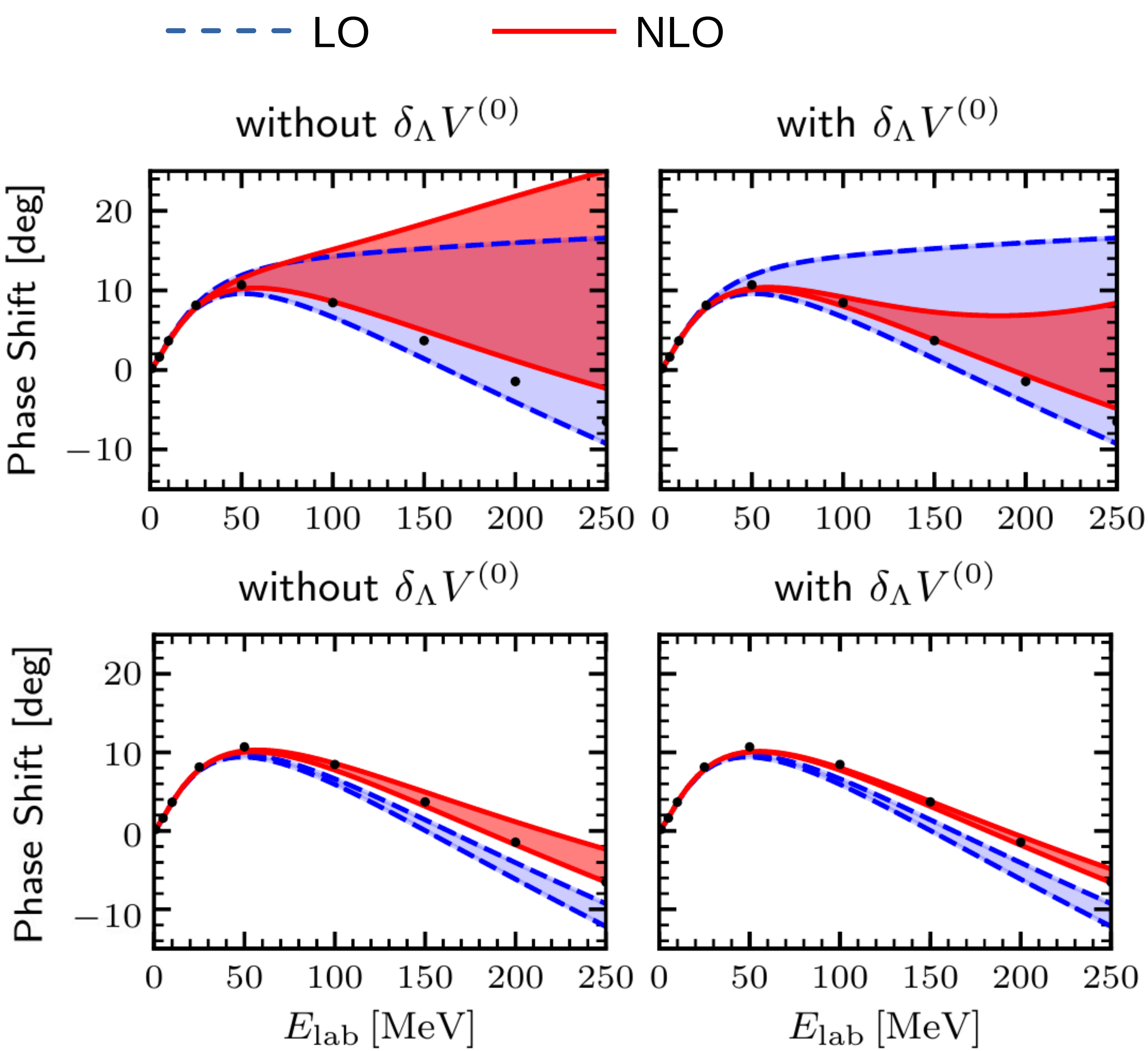
Nonperturbative effects (bound states) cannot be generated this way

The remaining Λ-dependence is removed perturbatively by expansion δV_Λ

For locally regulated long-range potentials, $\delta_\Lambda V^{(0)}$ can be expanded in 1/Λ
and absorbed by contact interactions,
or can be kept explicit to access lower values of the cutoff

Explicit inclusion of the regulator corrections $\delta V_{\Lambda}^{(0)}$, ${}^3P_0$

AG, E.Epelbaum, **PRC107**, 044002 (2023)



$\Lambda_{1\pi} \in (300, 450)\,\text{MeV}$

$\Lambda_{1\pi} \in (450, 800)\,\text{MeV}$

Misconceptions: RG-invariance in Perturbative QFT

S-matrix is renormalization scale μ independent (only formally and up to higher order)

Perturbation theory converges equally well for all μ:

QED: Landau pole

QCD:

> effective coupling constant. Given a scheme, our procedure automatically determines the coupling-constant scale appropriate to a particular process. This leads to a new criterion for the convergence of perturbative expansions in QCD. We examine a number of well known reactions in QCD, and

Brodsky, Lepage, Mackenzie, **PRD28 (1)**, 228 (1983)

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for $\Lambda_1, \Lambda_2 > \bar{\Lambda}_{\text{EFT}}$:

$$\frac{\mathcal{O}(k, p_{\text{typ}}; \Lambda_1) - \mathcal{O}(k, p_{\text{typ}}; \Lambda_2)}{\mathcal{O}(k, p_{\text{typ}}; \Lambda_1)} = \left(\frac{k, p_{\text{typ}}}{\overline{\Lambda}_{\text{EFT}}}\right)^{n+1} \times \ldots$$

H. Grießhammer, **EPJA 56 (4)**, 118 (2020)

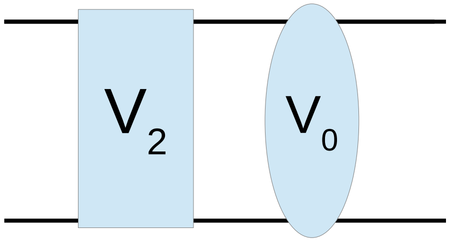
$$\not\Updownarrow$$

$$\frac{\Lambda}{T^{(\mathcal{V})}(Q,\Lambda)} \frac{\mathrm{d}T^{(\mathcal{V})}(Q,\Lambda)}{\mathrm{d}\Lambda} = \mathcal{O}\left(\frac{Q^{\mathcal{V}+1}}{M_{\text{hi}}^{\mathcal{V}}\Lambda}\right)$$

H. W. Hammer, S. König, U. van Kolck,
Rev. Mod. Phys. 92(2), 025004 (2020)

None of these criteria can be fulfilled (exceptional cutoffs), but this is not necessary

Technicalities of renormalization: estimating integrals using bounds on potentials



$$T_2^{[0,1]} = \int_0^\infty \frac{p''^2 dp''}{(2\pi)^3} V_2(p', p'') G(p''; p_{\text{on}}) V_0(p'', p)$$

LO potential: $V_0 \sim 1$

NLO potential: $V_2 \sim \frac{p^2}{\Lambda_b^2} \log \frac{p^2}{M_\pi^2}$

2-nucleon Green's function: $G \sim \frac{1}{p^2}$

Integral converges at $p \sim \Lambda$ (regulator) ⟶ $T_2^{[0,1]} \sim \frac{\Lambda^3}{\Lambda_b^3} \log \frac{\Lambda}{M_\pi} \neq \mathcal{O}(Q^2)$

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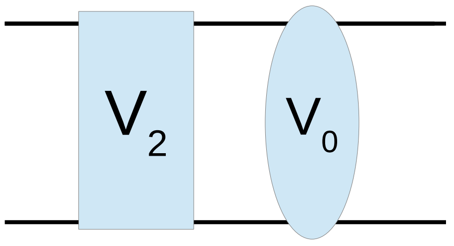

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Integral converges at $p \sim \Lambda$ (regulator) $\longrightarrow$ $T_2^{[0,1]} \sim \frac{\Lambda^3}{\Lambda_b^3} \log \frac{\Lambda}{M_\pi} \neq \mathcal{O}(Q^2)$

Renormalization → Subtraction → Counter term δC_0

Structure of the interaction in chiral EFT

Interaction obtained from chiral EFT: $V(\vec{p}\,', \vec{p}) = V_{\rm short}(\vec{p}\,', \vec{p}) + V_{\rm long}(\vec{p}\,', \vec{p})$

$$V_{\rm short}(\vec{p}\,', \vec{p}) = \text{Polynomial}(\vec{p}\,', \vec{p})\, F_\Lambda(\vec{p}\,', \vec{p})$$

$$V_{\rm long}(\vec{p}\,', \vec{p}) = V_L(\vec{q} = \vec{p}\,' - \vec{p})\, \tilde{F}_\Lambda(\vec{p}\,', \vec{p}), \qquad V_L = V_{1\pi} + V_{2\pi} + \ldots$$

Subtractions: $\left| V(p', p) - V(p', 0) \right| \leq \left| \frac{p}{p'} \right| \times (\ldots) \text{ if } |p'| > |p|$

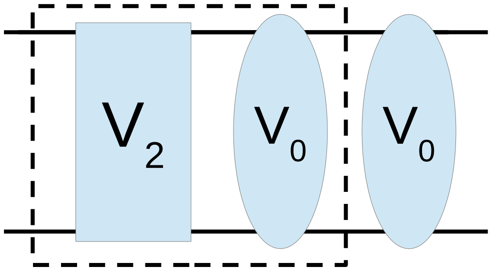
$$\left| V(p', p) - \sum_{i=0}^{n} \frac{\partial^i V(p', p)}{i! (\partial p)^i} \bigg|_{p=0} p^i \right| \leq \left| \frac{p}{p'} \right|^{n+1} \times (\ldots) \text{ if } |p'| > |p|$$

AG, E.Epelbaum, **PRC 105**, 024001 (2022)

→ Large loop momenta are suppressed

→ Renormalizability

More iterations of V_0



LO potential: $V_0 \sim 1$

Renormalized NLO amplitude: $\mathbb{R}\left(T_2^{[0,1]}\right) \sim \frac{p^2}{\Lambda_b^2}\frac{\Lambda}{\Lambda_b}\log\frac{\Lambda}{M_\pi}$

2-nucleon Green's function: $G \sim \frac{1}{p^2}$

Integral converges at $p \sim \Lambda$ $\longrightarrow$ $T_2^{[0,2]} \sim \frac{\Lambda^4}{\Lambda_b^4}\log\frac{\Lambda}{M_\pi} \neq \mathcal{O}(Q^2)$

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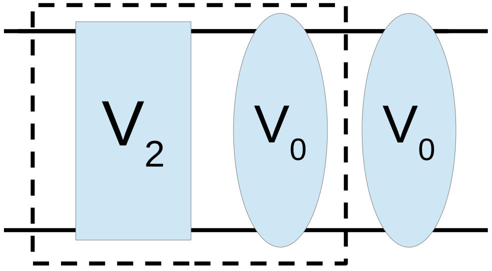

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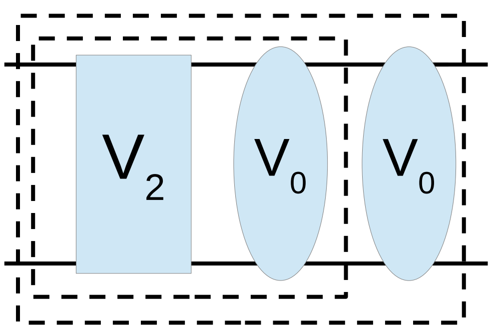
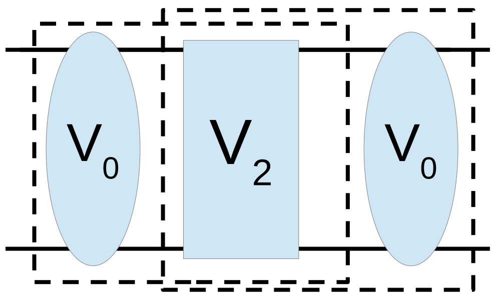
One more subtraction The same form of a counter term δC_0

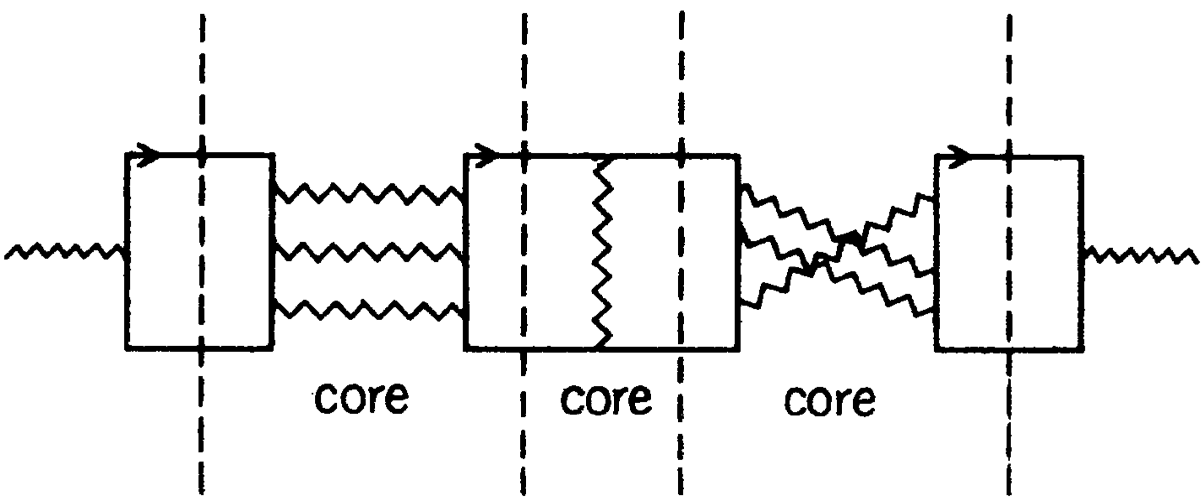


$$\mathbb{R}\left(T_2^{[0,2]}\right) \sim \frac{p^2}{\Lambda_b^2}\frac{\Lambda^2}{\Lambda_b^2}\log\frac{\Lambda}{M_\pi}$$

Overlapping diagrams



Early history of QFT. Using tricks: Ward identities, derivatives w.r.t external momenta



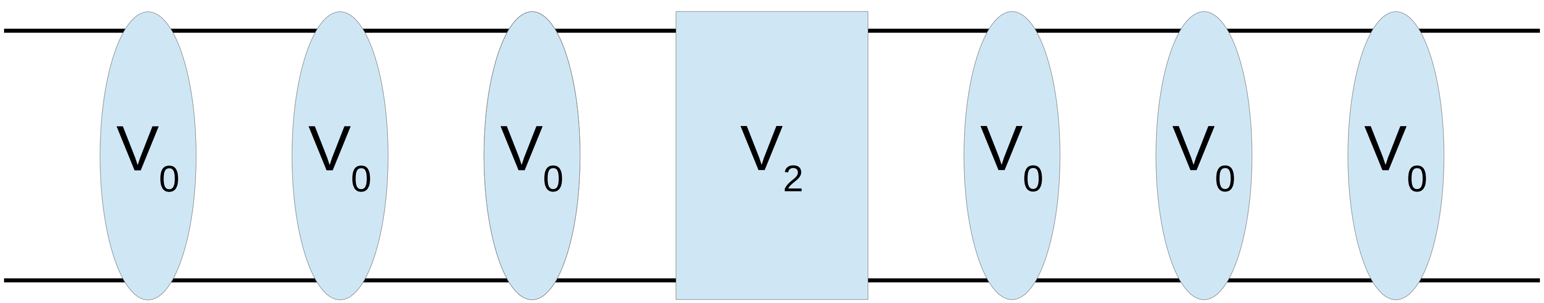
Mills, Yang, **Prog.Theor.Phys.Suppl. 37** (1966)

For this 16-th order diagram
tricks do not work

General method. BPHZ scheme:
subtractions in all possible nested sets of diagrams (forests)

N. N. Bogoliubov, O. S. Parasiuk, **AM97**, 227 (1957); K. Hepp, **CMP2**, 301 (1966); W. Zimmermann, **CMP15**, 208 (1969)

General case, BPHZ



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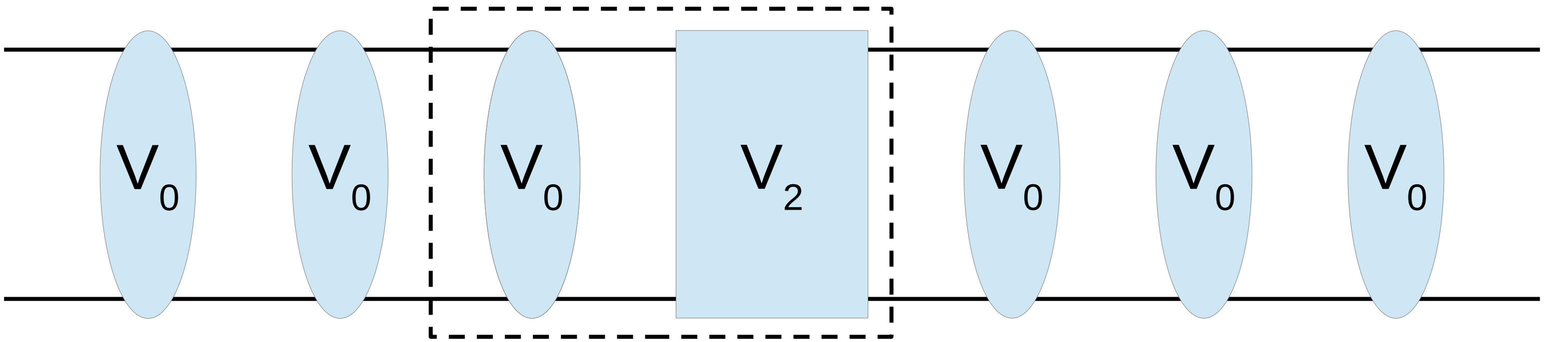

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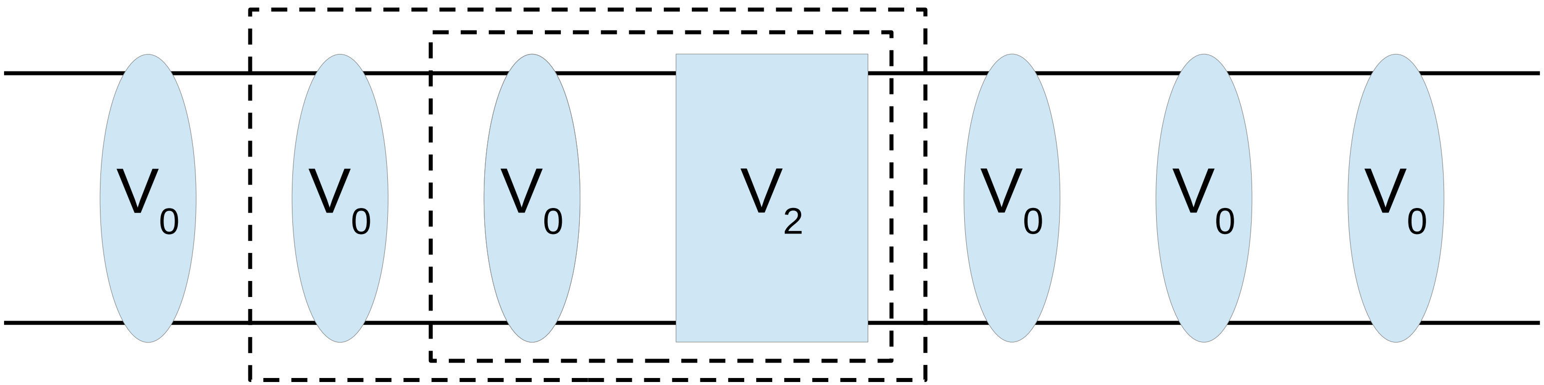

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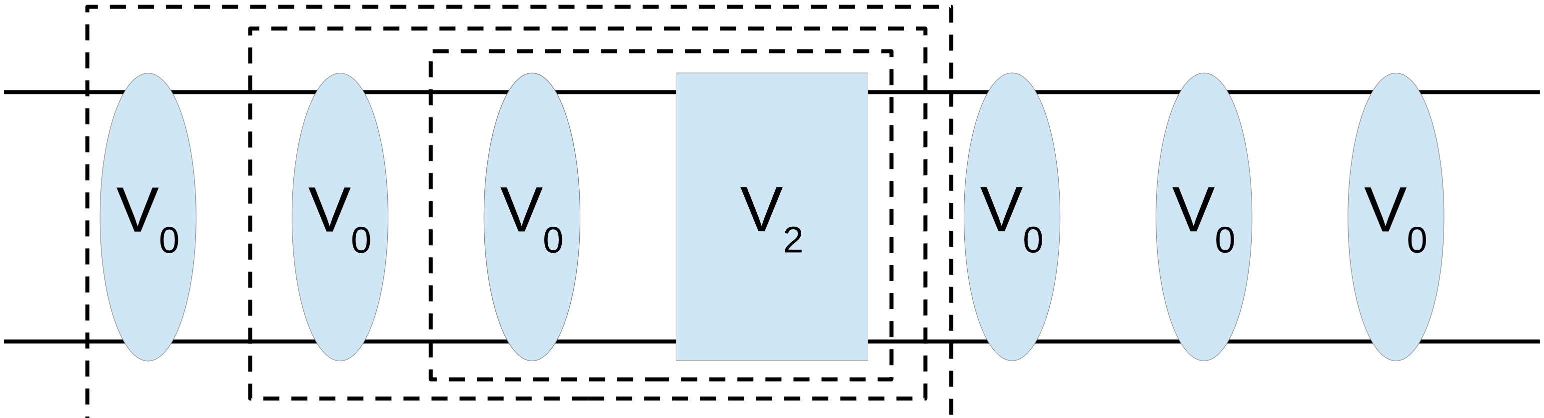

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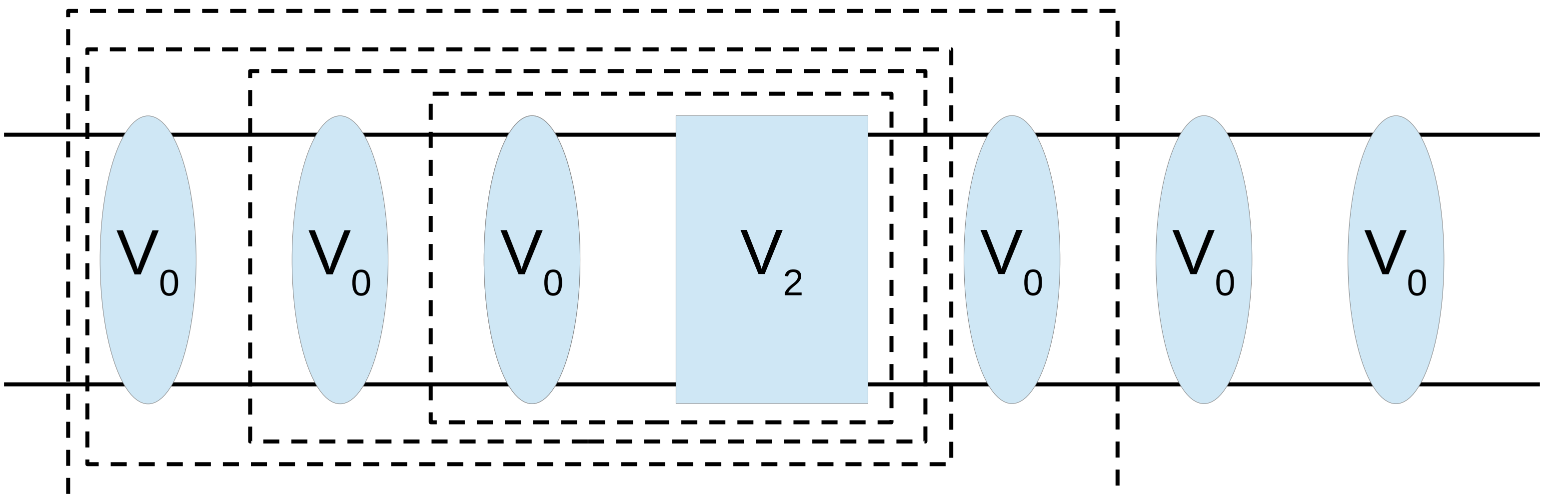

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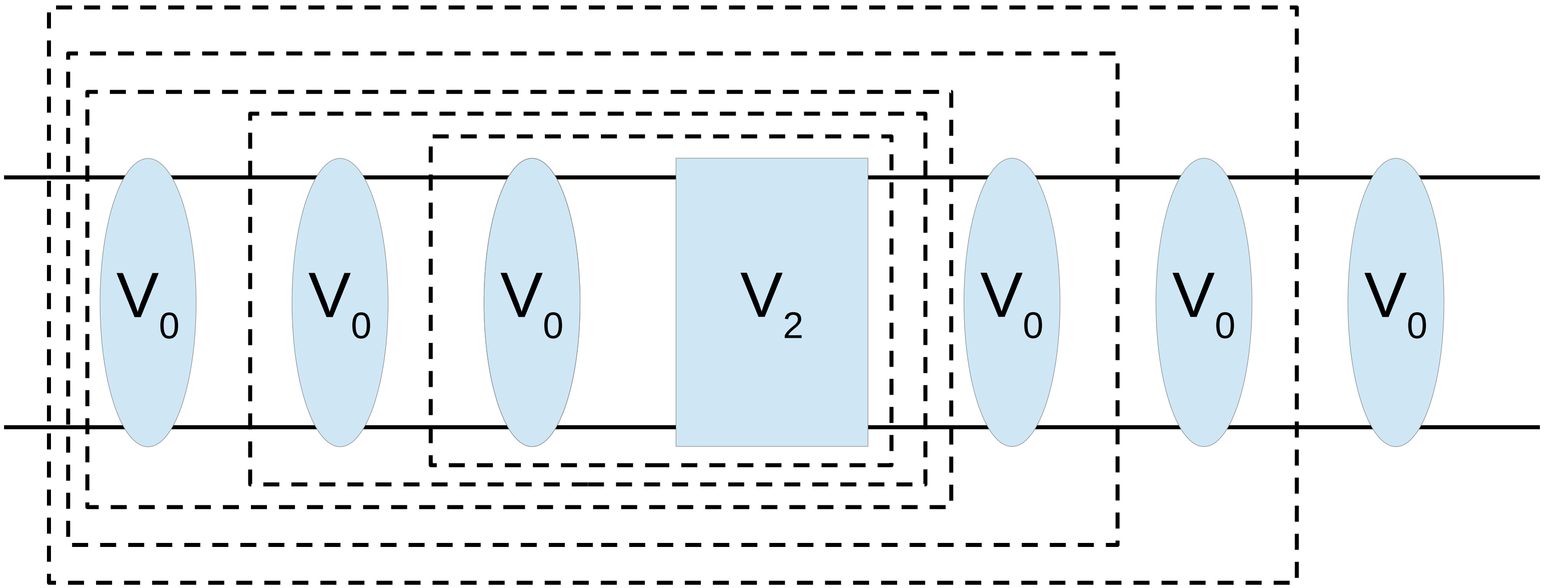

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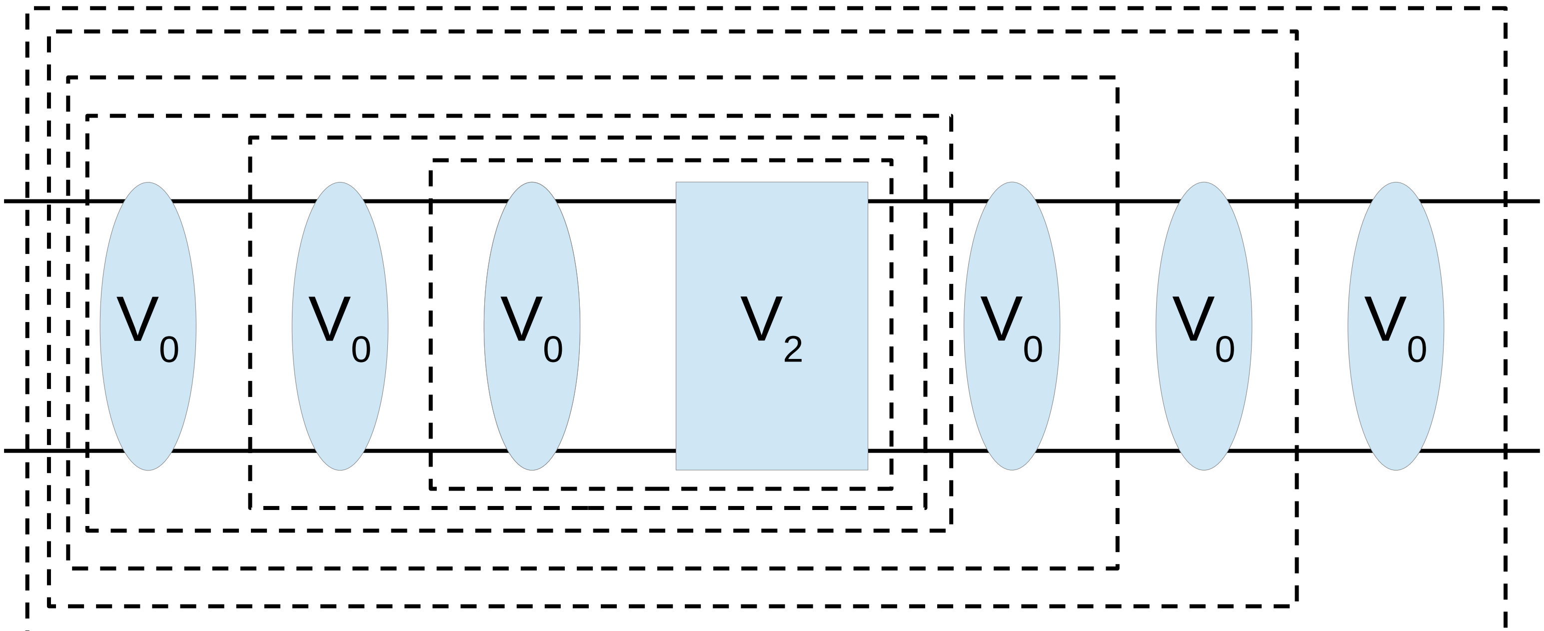

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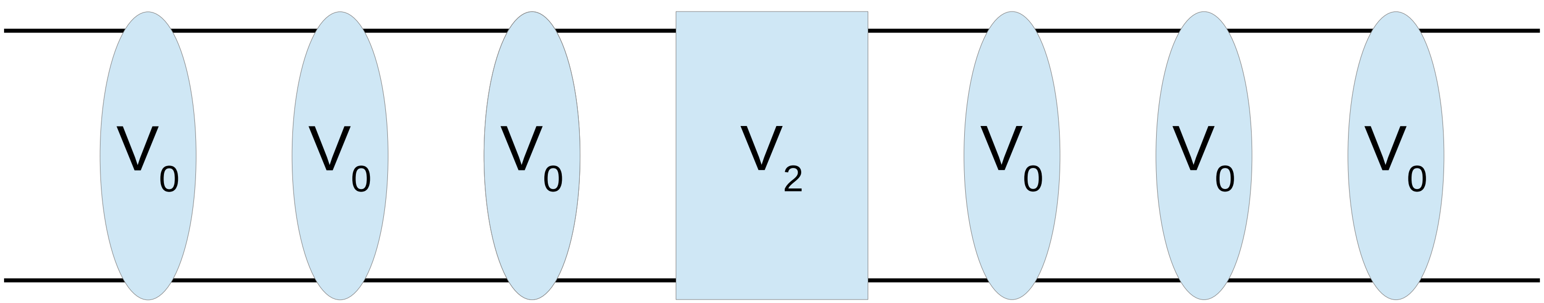
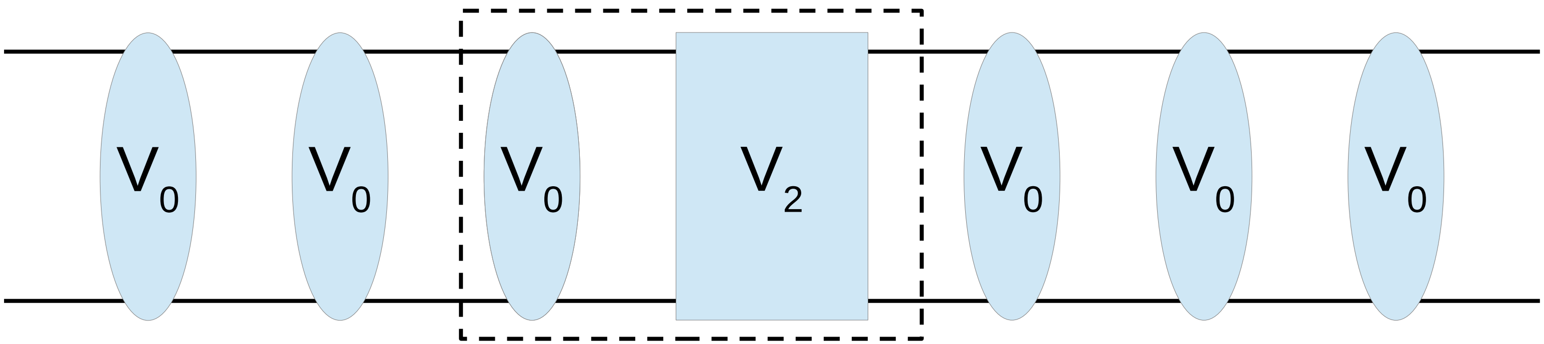


General case, BPHZ



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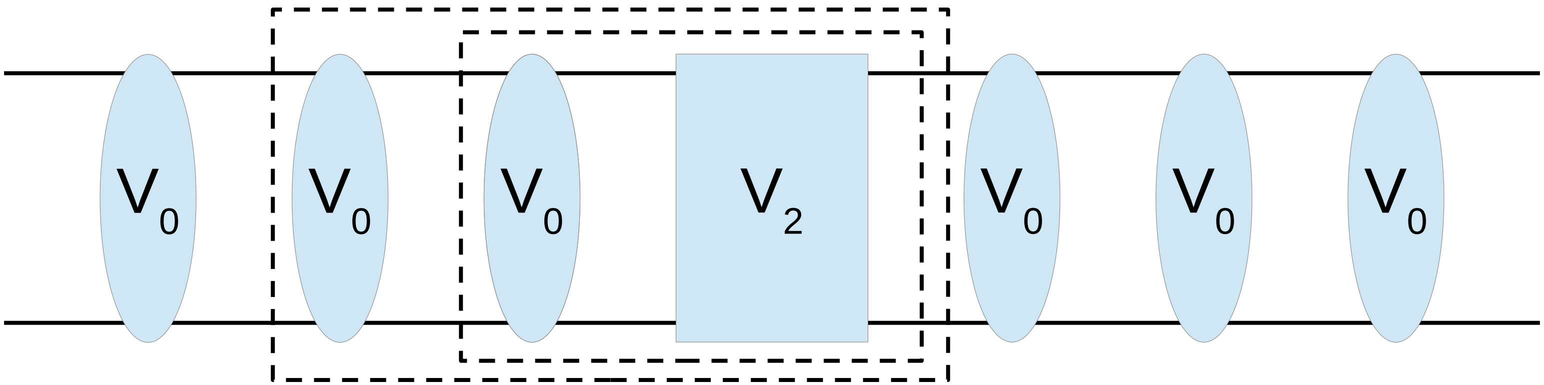

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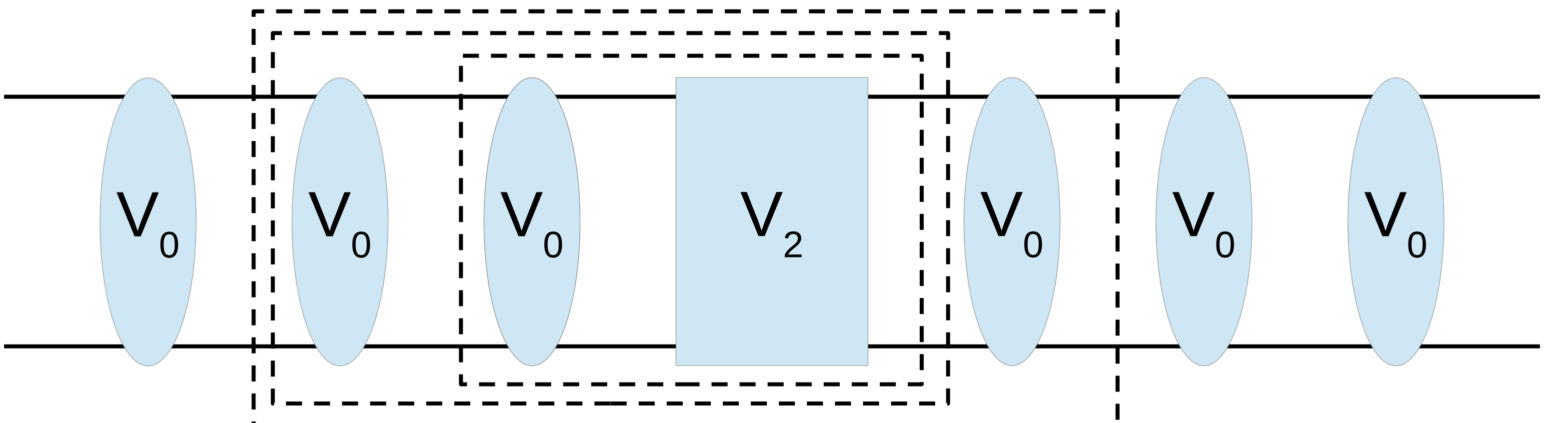

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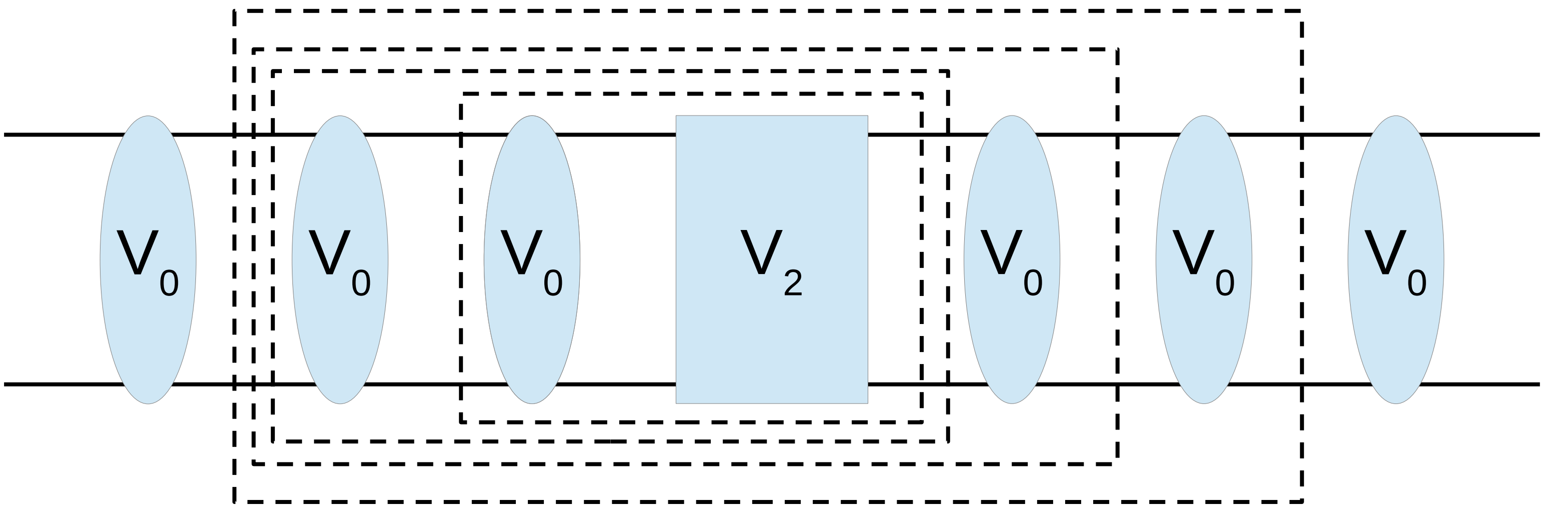

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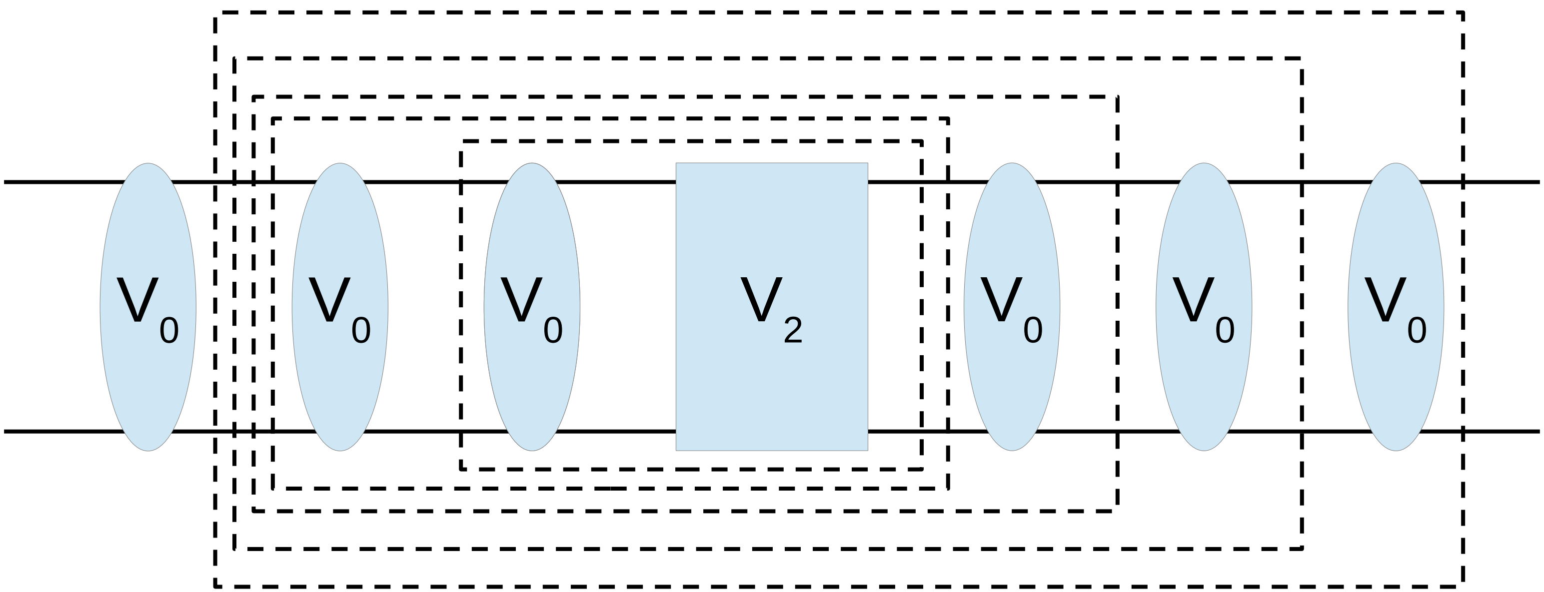

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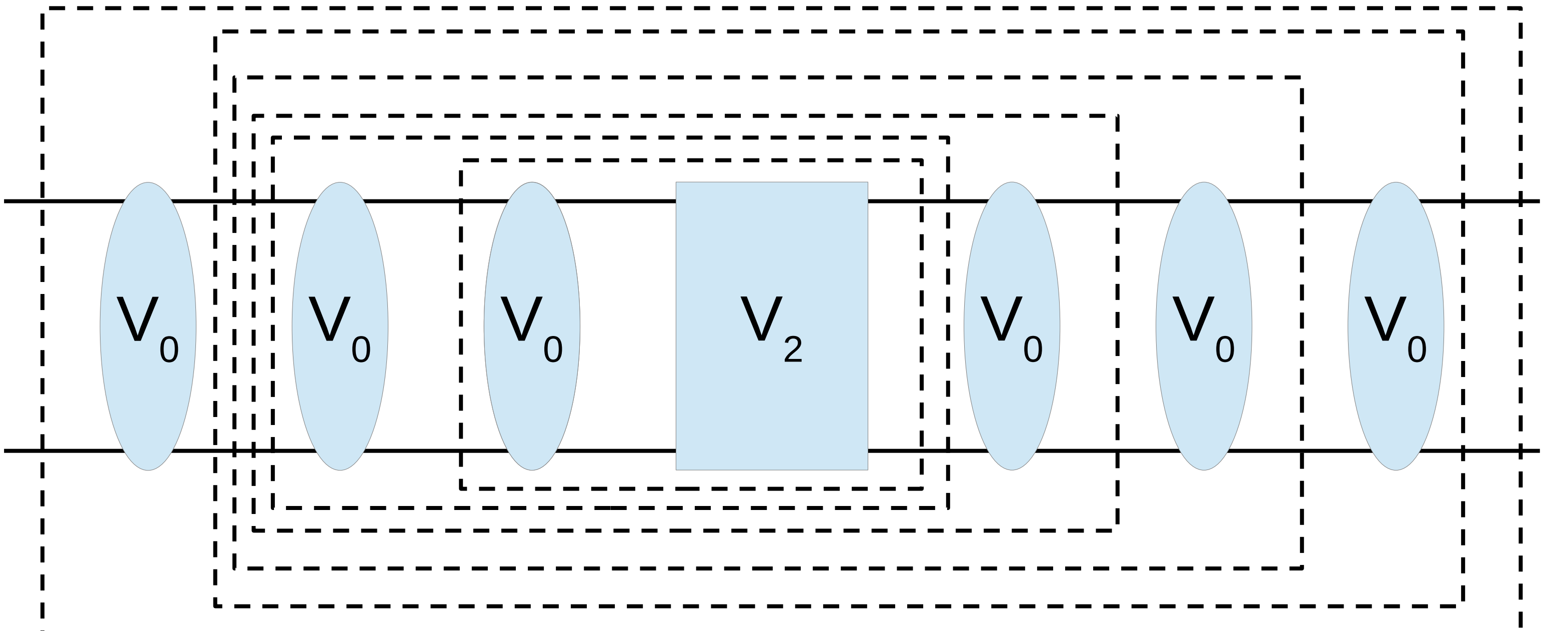

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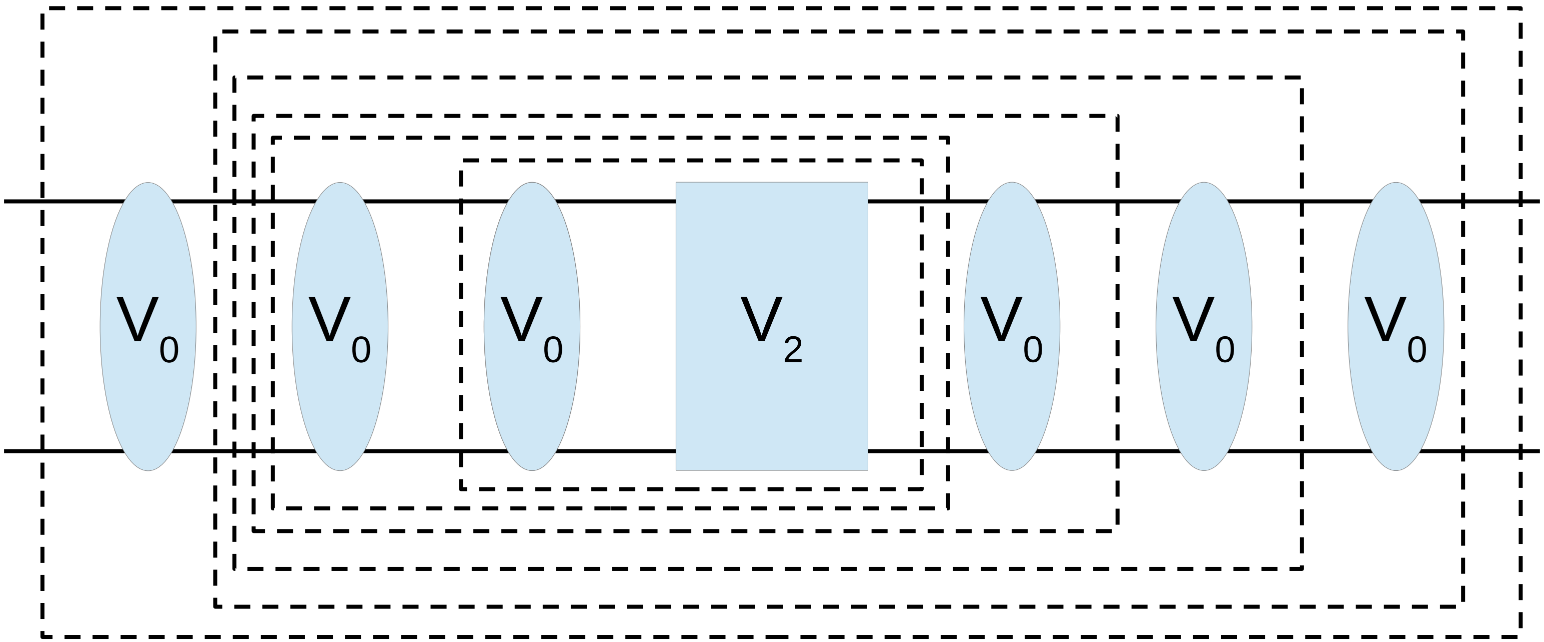

Partition integrations over p_i into sectors to avoid double counting

All counter terms add up to a single counter term δC_0

Power counting in the finite-cutoff scheme, NLO

AG, E.Epelbaum, **PRC 105**, 024001 (2022)

Renormalized amplitude:

$$\mathbb{R}\left(T_2\right) = \sum_{m,n=0}^{\infty} \mathbb{R}\left(T_2^{[m,n]}\right)$$ -Perturbative (convergent) sum

$$\mathbb{R}(T_2^{[m,n]})(p) \sim \frac{p^2}{\Lambda_b^2}\left(\frac{\Lambda}{\Lambda_b}\right)^{m+n} \log \Lambda/M_\pi$$

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$$\Lambda \approx \Lambda_b$$

$$\mathbb{R}(T_2^{[m,n]})(p) = \mathcal{O}(Q^2)$$

Non-local separable long-range interaction

AG, E.Epelbaum, N.Jacobi, in preparation

$$V_0 = C_0 F_\Lambda(p') F_\Lambda(p) + \ldots,$$

$$V_2 = C_2 \frac{p'^2 + p^2}{\Lambda_b^2} \frac{p'^2 p^2}{(M_\pi^2 + p'^2)(M_\pi^2 + p^2)} F_\Lambda(p') F_\Lambda(p).$$

two-pion exchange

$$F_\Lambda(p) = \frac{\Lambda^2}{(\Lambda^2 + p^2)}$$

$$V_0 G V_2 \sim \frac{\Lambda^2}{\Lambda_b^2} \frac{p^2}{(M_\pi^2 + p^2)} \sim O(Q^0)$$

$$\int dp', \qquad p' \sim \Lambda$$

$$\left| V(p', p) - V(p', 0) \right| \not\leq \left| \frac{p}{p'} \right| \times (\ldots) \text{ if } |p'| > |p|$$

→ Long-range power-counting-breaking terms

→ Nonrenormalizability (in terms of local counter terms)

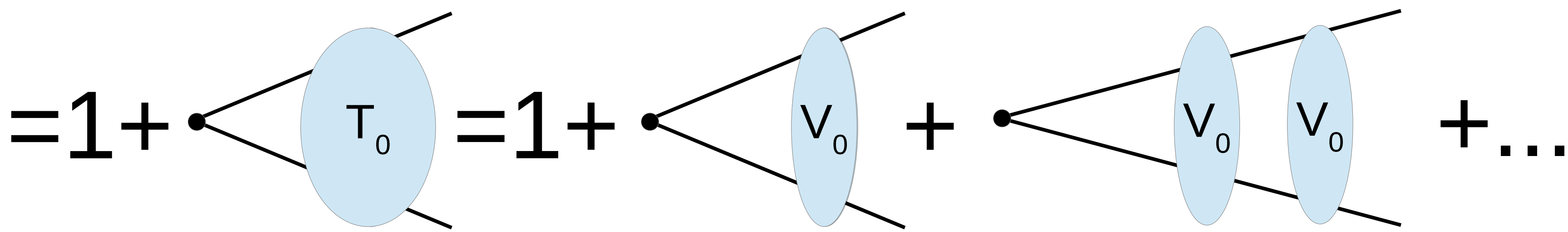
Renormalization in the non-perturbative regime

AG, E.Epelbaum, **PRC107**, 044002 (2023)

The series for ***$R(T_2^{[m,n]})$*** can be summed explicitly:

$$\mathbb{R}\left(T_2\right)(p) = \sum_{m,n=0}^{\infty} \mathbb{R}\left(T_2^{[m,n]}\right)(p) = T_2(p) + \delta C_0\, \psi_p(0)^2, \qquad \delta C_0 = -\frac{T_2(0)}{\psi_0(0)^2}$$

$\psi_p(0)$



Using Fredholm formula to match to the perturbative regime

$$T_2(p) = (1 + T_0 G) V_2 (1 + G T_0) = \frac{N_2(p)}{D(p)^2}$$

$D(p)$-Fredholm determinant

Convergent series in V_0: $N_2 = \sum_{i=0}^{\infty} N_2^{[i]}\ ,\ D = \sum_{i=0}^{\infty} D^{[i]}$

The same for the counter terms:

$$\delta T_2 = (1 + T_0 G) \delta V_0^{ct} (1 + G T_0) = \delta C_0 \left[\psi_p(0)\right]^2$$

$$\psi_p(0) = \frac{\nu(p)}{D(p)} \qquad \nu(p) = \sum_{i=0}^{\infty} \nu^{[i]}(p)$$

Renormalizability constraints

$$\mathbb{R}\left(T_2\right)(p) = \frac{1}{D(p)^2}\left[N_2(p) + \delta C_0\, \nu(p)^2\right], \qquad \delta C_0 = -\frac{N_2(0)}{\nu_0^2}$$

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Renormalizability constraints on (the short-range part of) the LO potential.
The simplest formulation: LECs must be of natural size (If $\Lambda \sim \Lambda_b$).

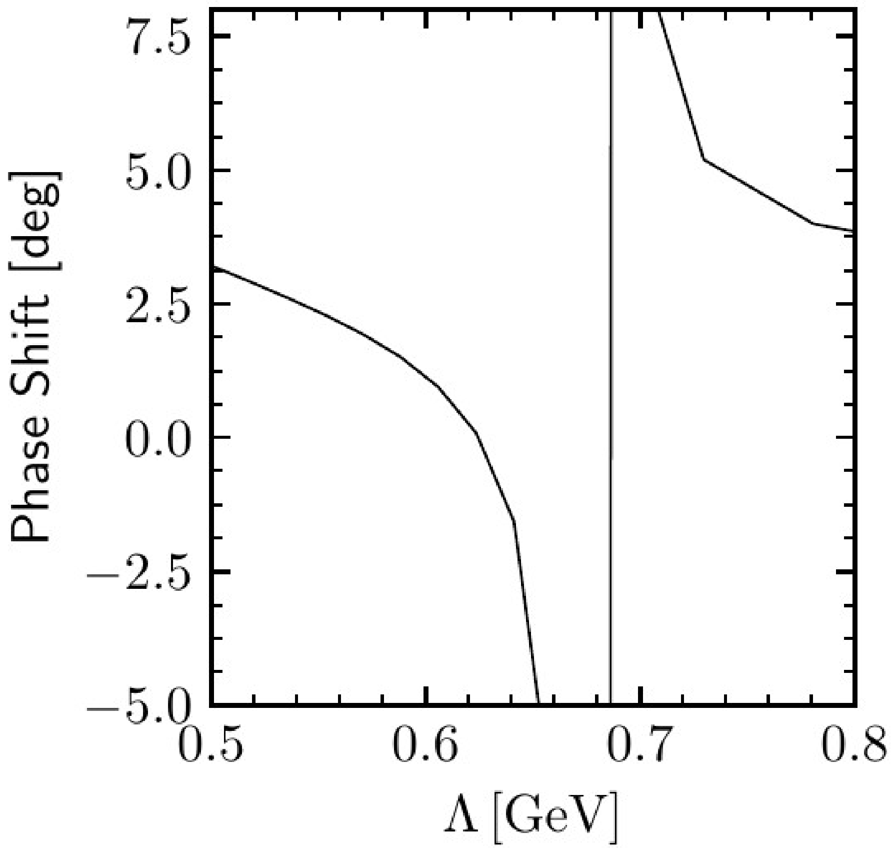
Constraints on the choice of the cutoff are not driven by data!

For realistic interactions works well for Λ<650-750 MeV

Failure of renormalizability for $\Lambda > \Lambda_b, {}^3P_0$

AG, E.Epelbaum, **PRC107**, 034001 (2023)

T_{lab}=130MeV



Sharp cutoff, harder than smooth regulators
0.7 GeV → above 1 GeV

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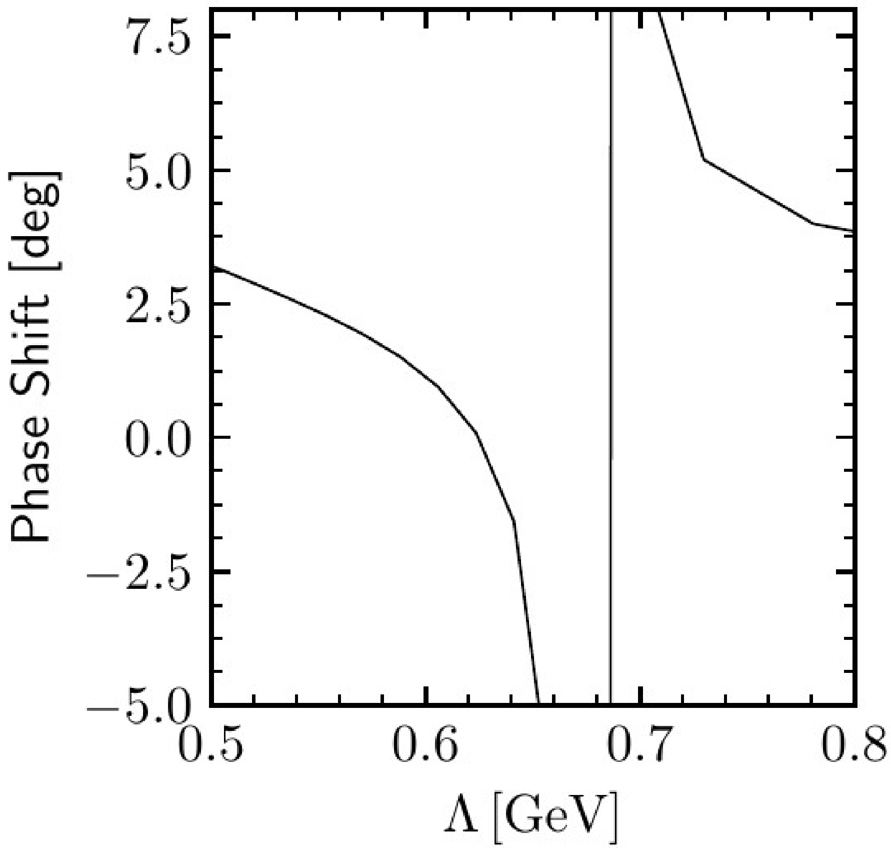


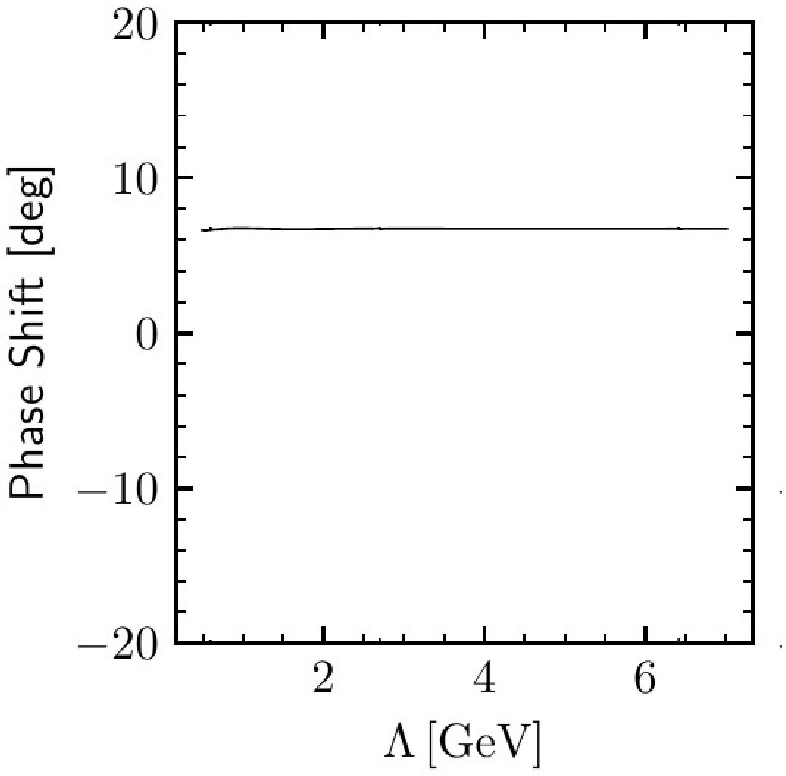
Sharp cutoff, harder than smooth regulators
0.7 GeV → above 1 GeV

Adding one more counter term at NLO to reduce cutoff dependence: “RG-invariance”

B. Long, C. J. Yang, **PRC84**, 057001 (2011)

AG, E.Epelbaum, **PRC107**, 034001 (2023)

R. Peng, B. Long, F. Xu, 2407.08342 (2024)



Exceptional cutoffs

B. Long, C. J. Yang, **PRC84**, 057001 (2011)

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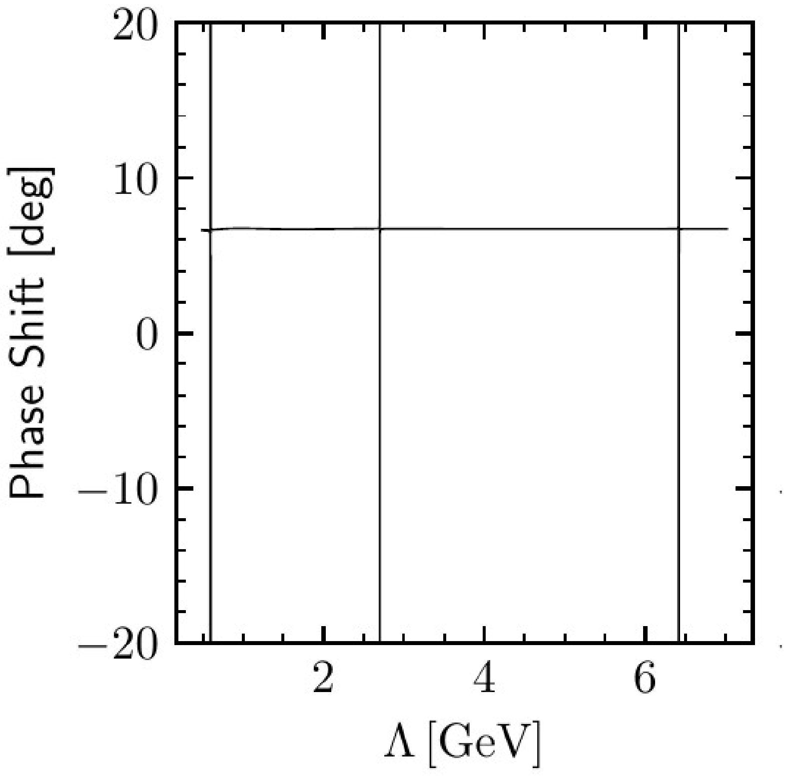

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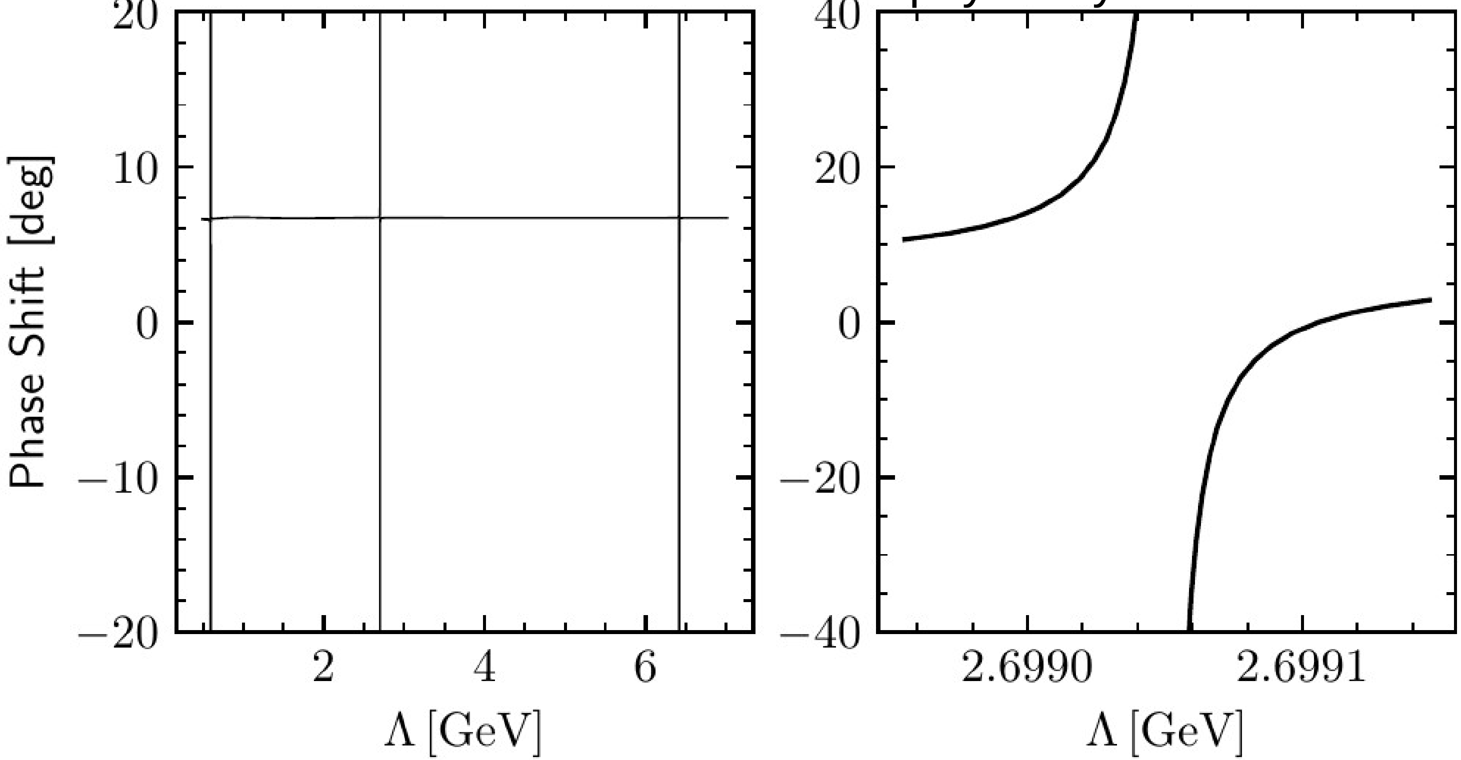
“physically measure zero”



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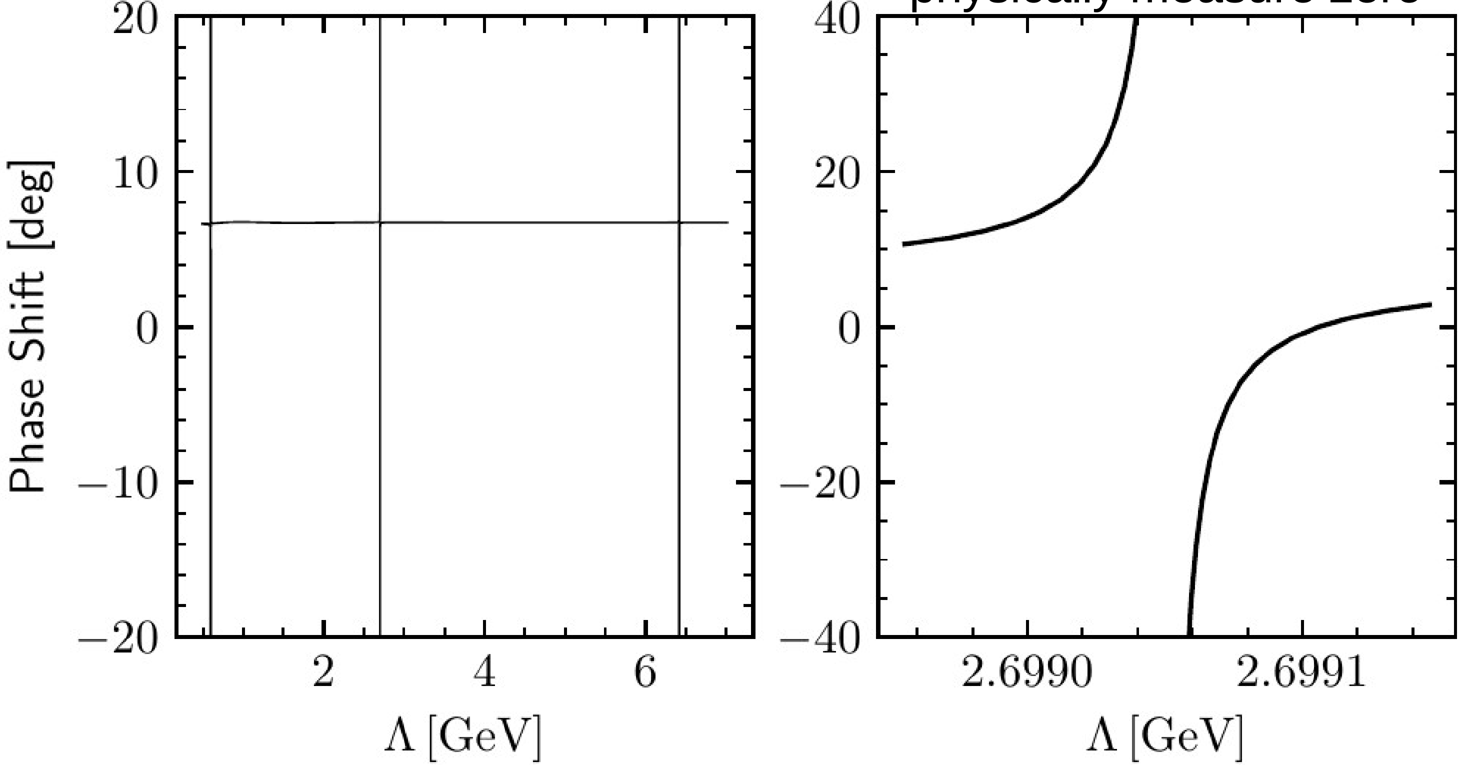

The poles of the S-matrix is a set of measure zero
→ neglect them?

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B. Long, C. J. Yang, **PRC84**, 057001 (2011)

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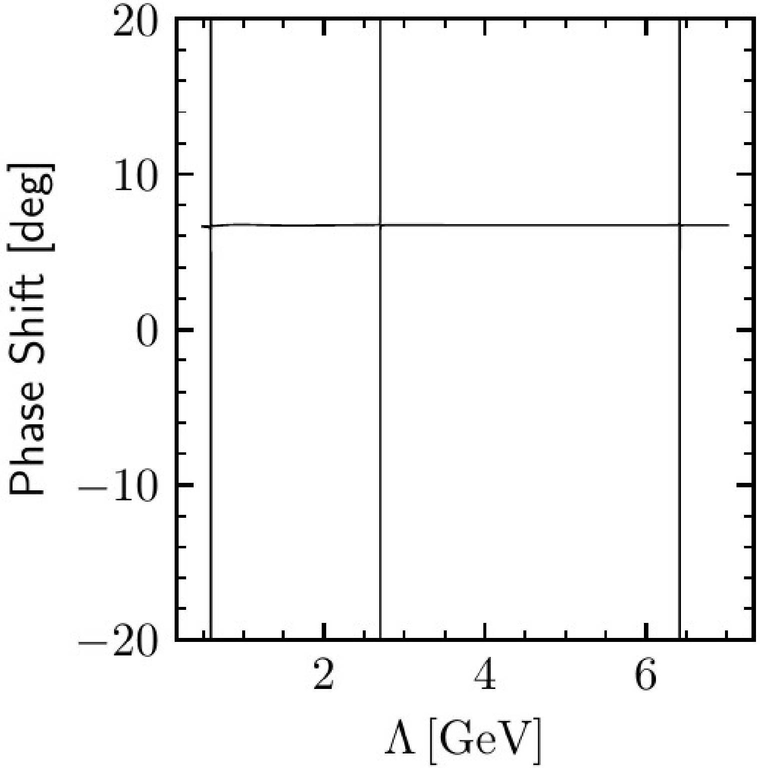

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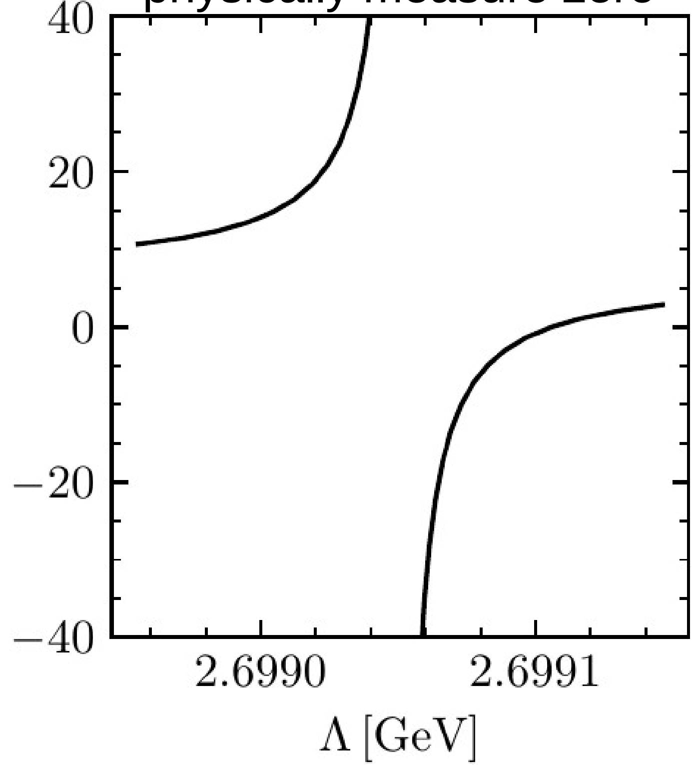

The poles of the S-matrix is a set of measure zero
→ neglect them?

Relying on numerical simulations without a deeper understanding of the physics might be dangerous

(In)Consistency of Weinberg power counting and its modifications

Large cutoff arguments are irrelevant in the finite cutoff scheme:
Divergencies → positive (uncompensated) power powers of Λ

$^{1}S_0 : M_\pi^2 \log M_\pi/\Lambda \sim O(Q^2)$ for $\Lambda \sim \Lambda_b$

Mismatch of ultraviolet divergencies and infrared power counting is typicall:
covariant ChPT in the 1-nucleon sector, especially Δ-full
→scheme dependence as a higher order effect

Consistent in the EFT sense: systematic expansion preserving symmetries

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$^3P_0$: cutoff variation is a higher order effect, it is phenomenologically enhanced (reduce g_A by a factor of 2)

The scheme is inefficient → promote some contact terms: $^1S_{0,}$ $^3P_0$

Analogy in perturbative EFT: promotion of the Q^5 contact term in γN→γN ChPT

H. Griesshammer, J. McGovern, D. Phillips, **Eur.Phys.J. A 52** (2016) 5, 139

Going to larger cutoff values: “RG-invariance”

H. W. Hammer, S. König, U. van Kolck,
Rev. Mod. Phys. 92(2), 025004 (2020)

However, while in analytical calculations Eq. (...) can be verified explicitly, in numerical calculations varying the regulator parameter widely above the breakdown scale is usually the only tool available to check RG invariance.

After renormalization, when the contribution from momenta of the order of the large cutoff have been removed, the dominant terms in loop integrals come from momenta of O(Q).

What about momenta of order Λ_b ?

Large cutoffs do not solve any problems of finite cutoffs

Price:
Promoting many (∞) counter terms
to make the amplitude insensitive (independent) of the cutoff
Relying on purely (potentially dangerous) numerical analysis

Summary

Explicit renormalization of an EFT provides a justified systematic expansion of observables and theoretical error estimate

Sufficient conditions for renormalizability:

(1) Locality of the long-range forces

(2) Cutoff of the order of the hard scale $\Lambda \approx \Lambda_b$

(3) Naturalness of the counter terms

(1)+(2) in most cases imply (3): (1)+(2) $\rightarrow$ (3)

Questions

Should we insist on cutoff insensitivity of a scheme for $\Lambda > \Lambda_b$
by promoting many (∞) counter terms
and
relying on semi-phenomenological (potentially dangerous) numerical analysis

or

should we stick to the practically more affordable
and better justified fundamentally
finite cutoff scheme ?