A Saga of the Weak and the Strong

Hadronic Parity Violation

Brian Tiburzi

5 April, 2012

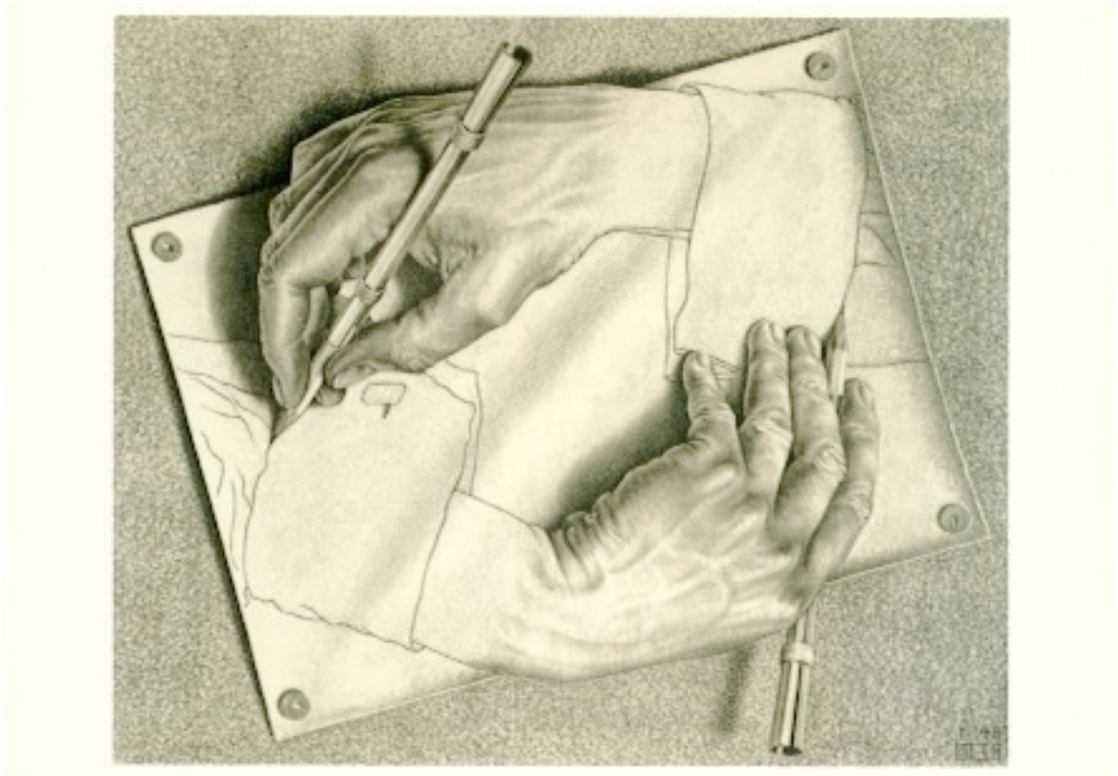
BT, PRD **85** 054020 (2012)

The Saga of Parity Violation

- **Parity Violation, Nuclear Parity Violation, Hadronic Parity Violation**
  Weak interactions between quarks

- **New Experiments, New Motivation**
  Fundamental neutron physics beamline

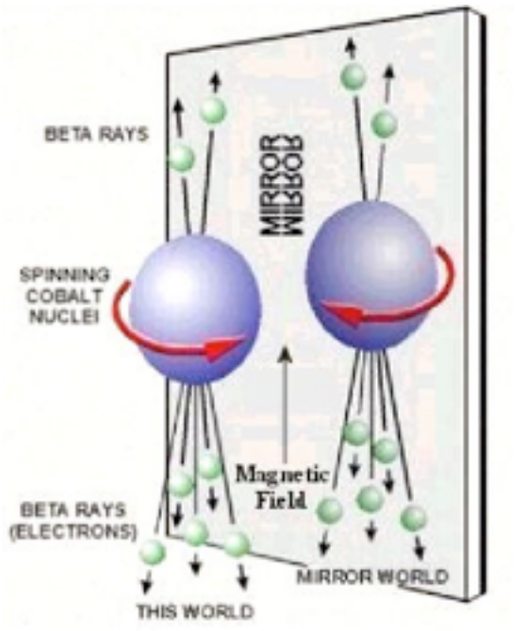
- **From Quarks to Nuclei**
  ~~Impossibility~~ in non-perturbative QCD
  Opportunity



Disclaimer: P odd and CP even processes

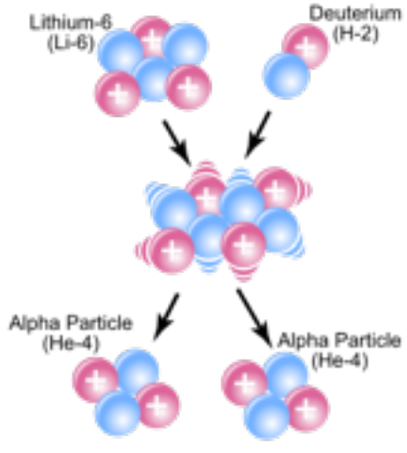
Historical Introduction

- **Parity Violation in the Weak Interaction ca. 1956**



Maximal violation 100%

- **Parity Violation in Nuclear Interactions**



Parity in Nuclear Reactions*

NEIL TANNER

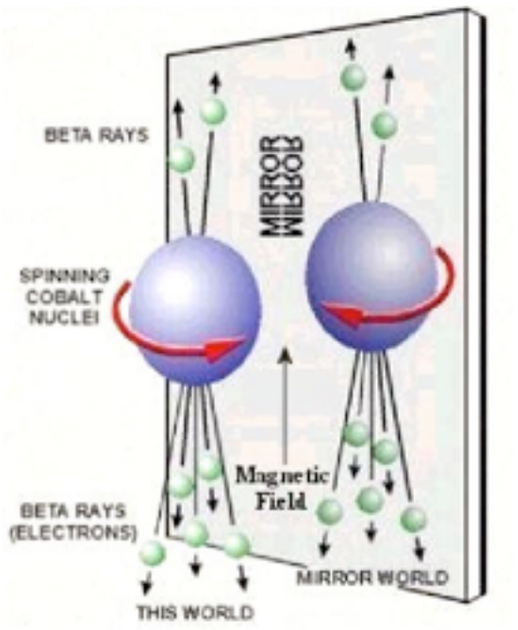
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

(Received June 26, 1957)

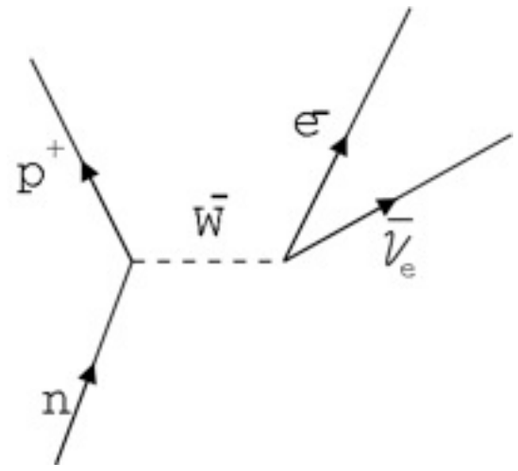
THE failure of parity conservation recently observed in β decay has raised the question of how accurately parity is conserved in nuclear reactions. A quite sensitive test is to be found in certain (p,α) reactions which are rigorously forbidden by angular momentum and parity conservation. The particular

55 Years Later: Standard Model

- Parity Violation in the Weak Interaction



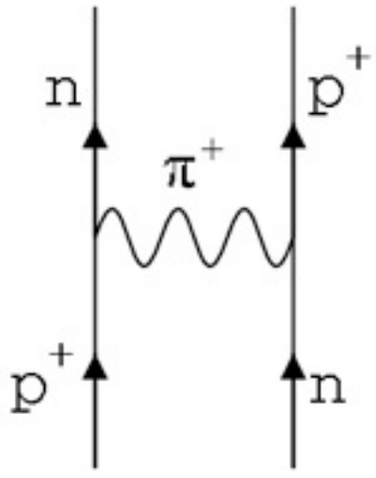
$$G_F = \frac{\sqrt{2} g^2}{8 M_W^2} = 10^{-5}/\mathrm{GeV}^2$$



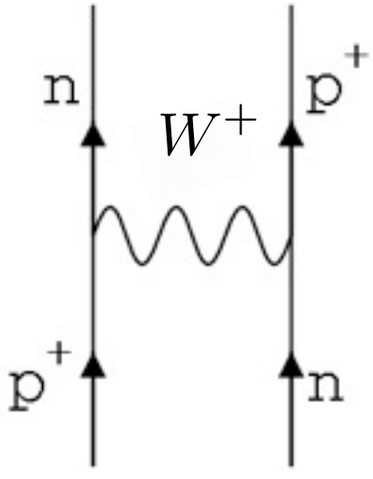
$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \left(\overline{u}_L \gamma_\mu d_L\right) \left(\overline{\nu}_L \gamma^\mu e_L\right)$$

$$\langle p|V|n\rangle \sim g_V \qquad \langle p|A|n\rangle \sim g_A$$

- Nuclear Force from Strong Interactions



$$\sim \left(\frac{g_A}{f_\pi}\right)^2 \frac{q\cdot\sigma_1\, q\cdot\sigma_2}{q^2 + m_\pi^2} \qquad G_F$$



Nucleon-Nucleon Weak Interactions

$$G_F f_\pi^2 \sim 10^{-7}$$

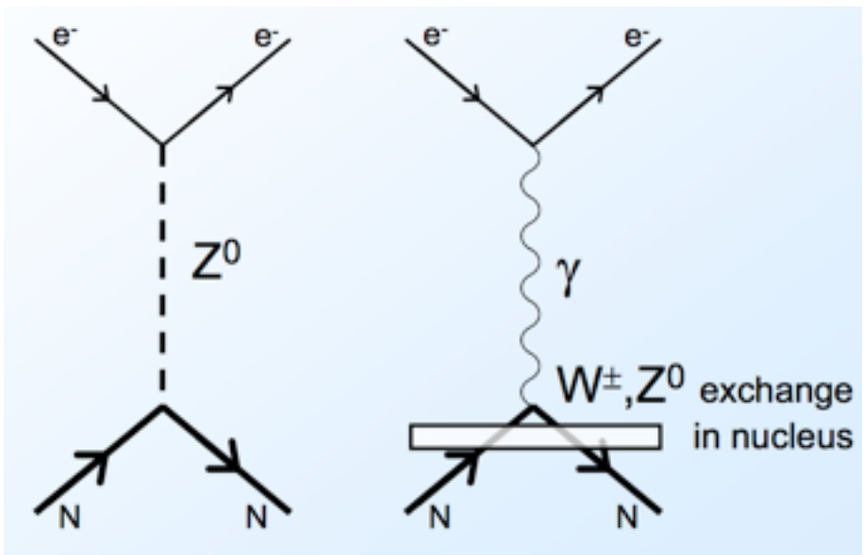
Nuclear Parity Violation

Violate strong interaction symmetries to see weak nuclear force

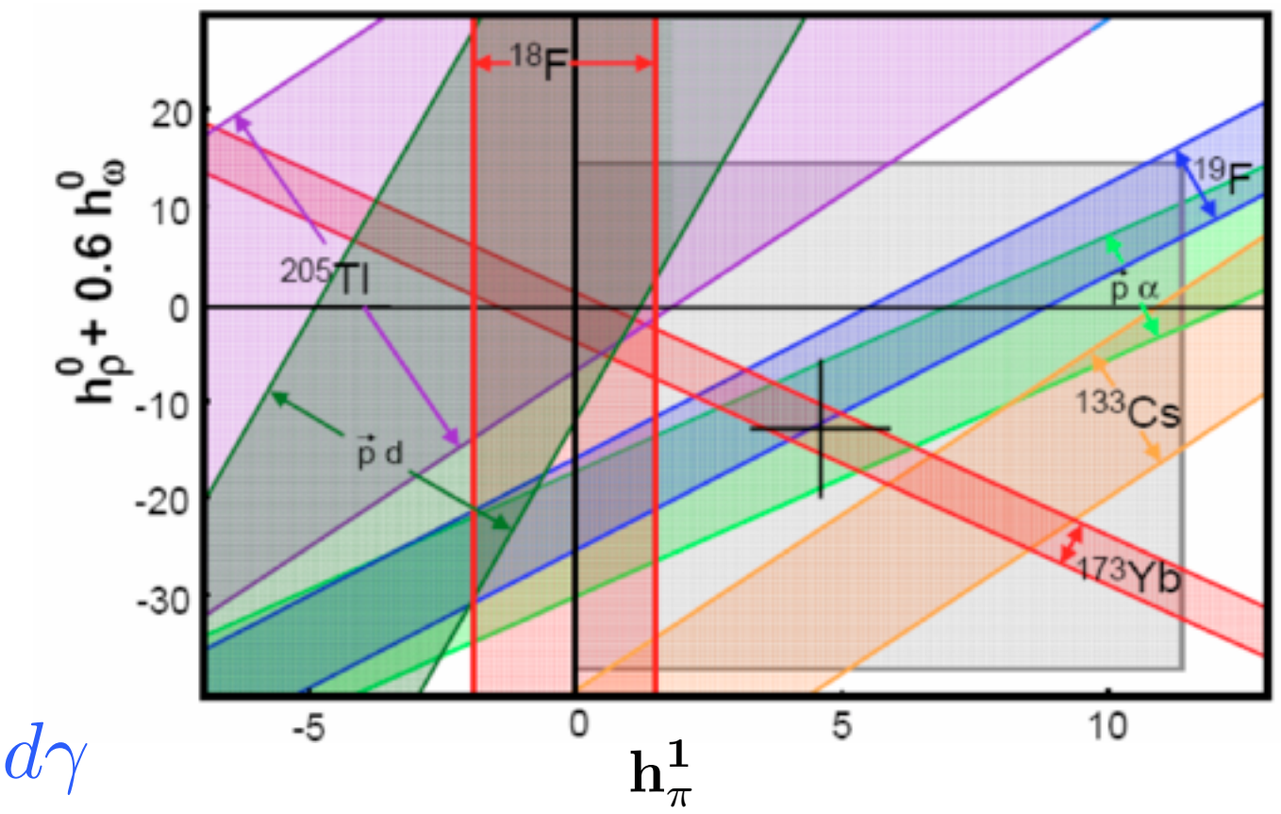
- **(Many) Parity Violating Nuclear reactions have been seen starting in 1967**
- **1989** From one in ten million to one in ten... $^{139}\mathrm{La}$ $|P_+\rangle \longrightarrow |P_+\rangle + \epsilon|P_-\rangle$

$$\epsilon = \langle P_+|\frac{1}{E_+ - E_-}\mathcal{H}_{PV}|P_-\rangle \qquad \Delta E/E \sim 10^{-6} \quad \text{for} \quad \Delta E \sim 0.7\,\mathrm{keV}$$

- Same ideas are being applied in **Atomic Parity Violation** expts. atoms, molecules, solids



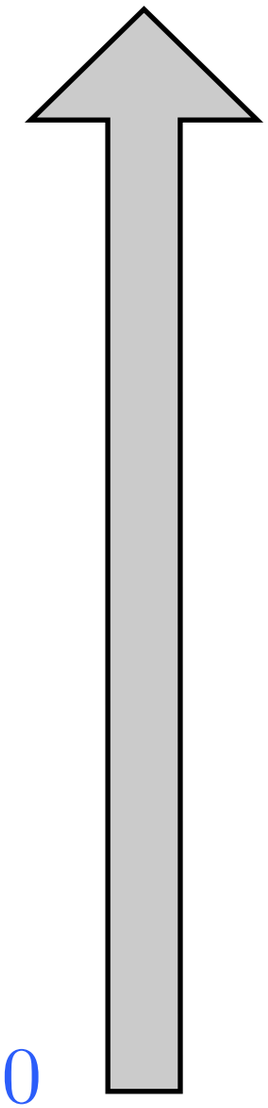
Parity Violating Nuclear Force



- **Forthcoming:** $n + {}^4\mathrm{He} \quad \vec{n}p \to d\gamma$

Panoply of Parity Violation

- PV nuclear transitions, PV photo-nuclear transitions (anapole moment), PV nucleon-nucleon interaction, PV nucleon-meson couplings, ... , ...
- **Organize with Effective Theory mindset**



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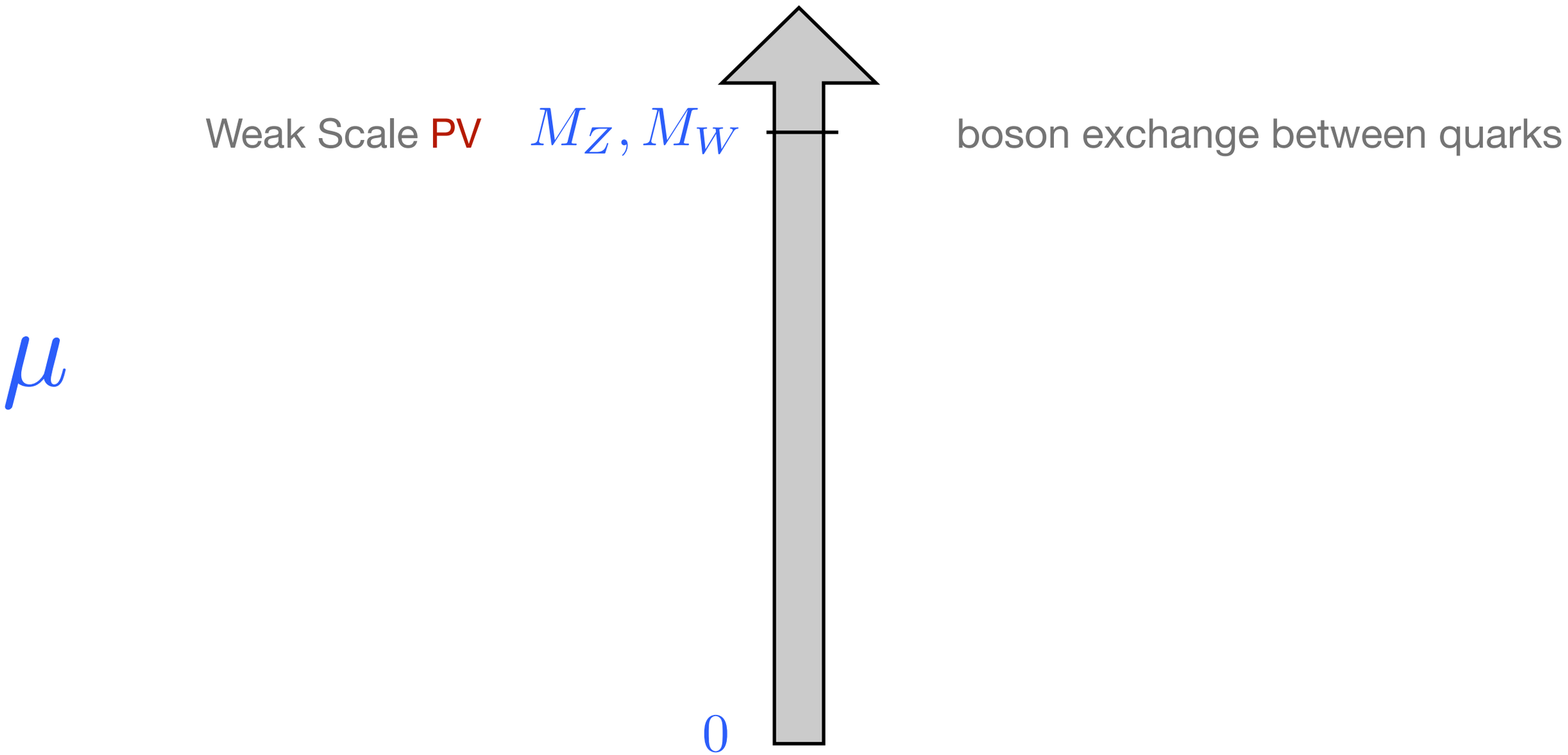

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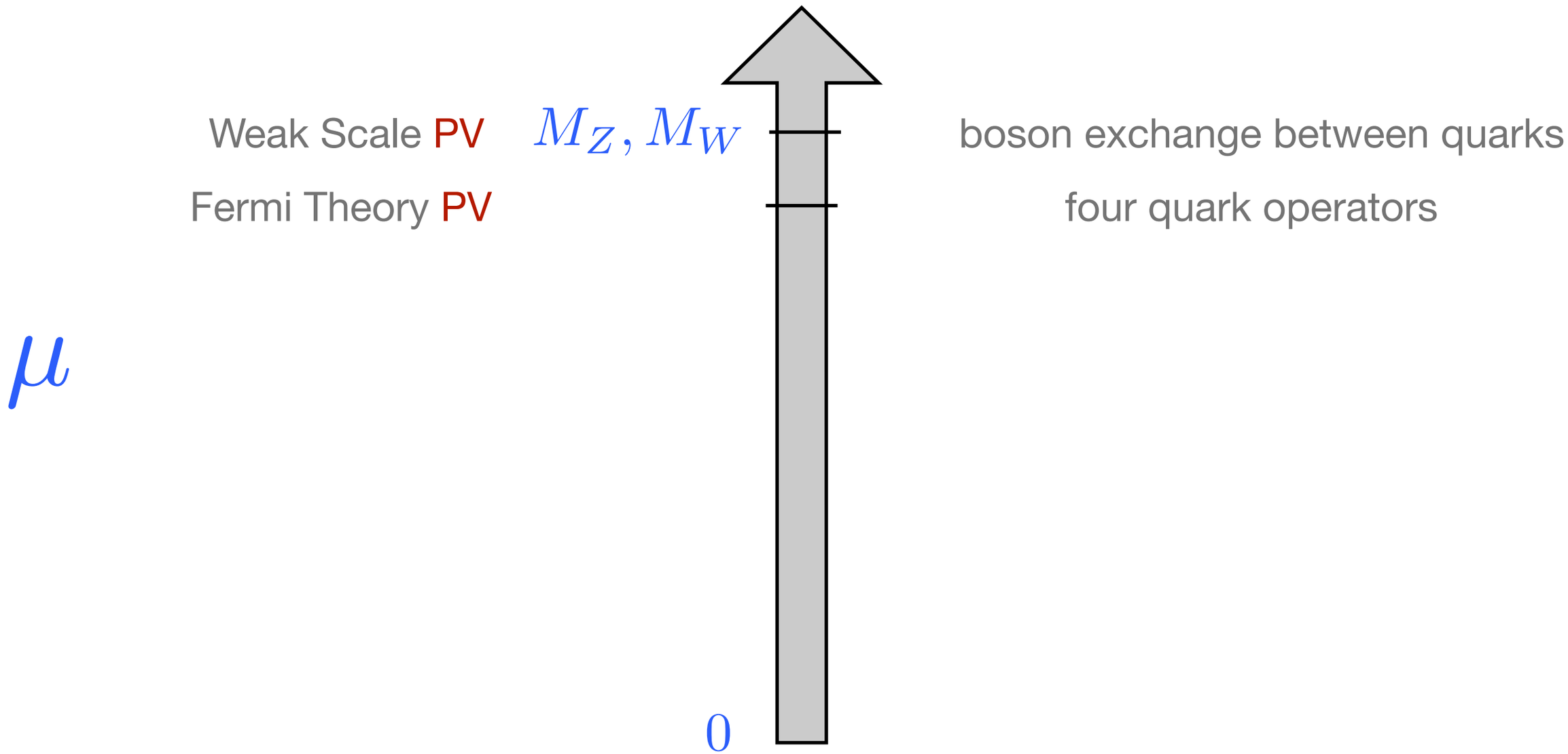

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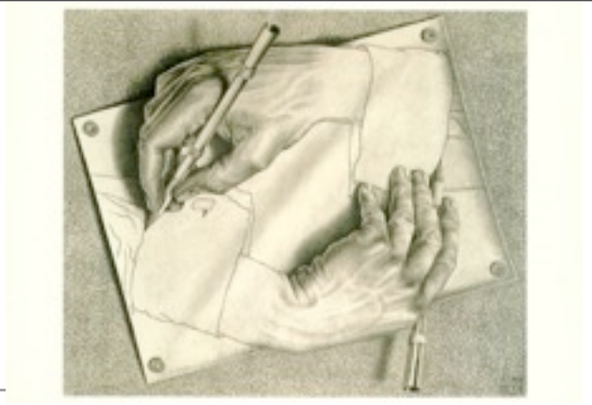

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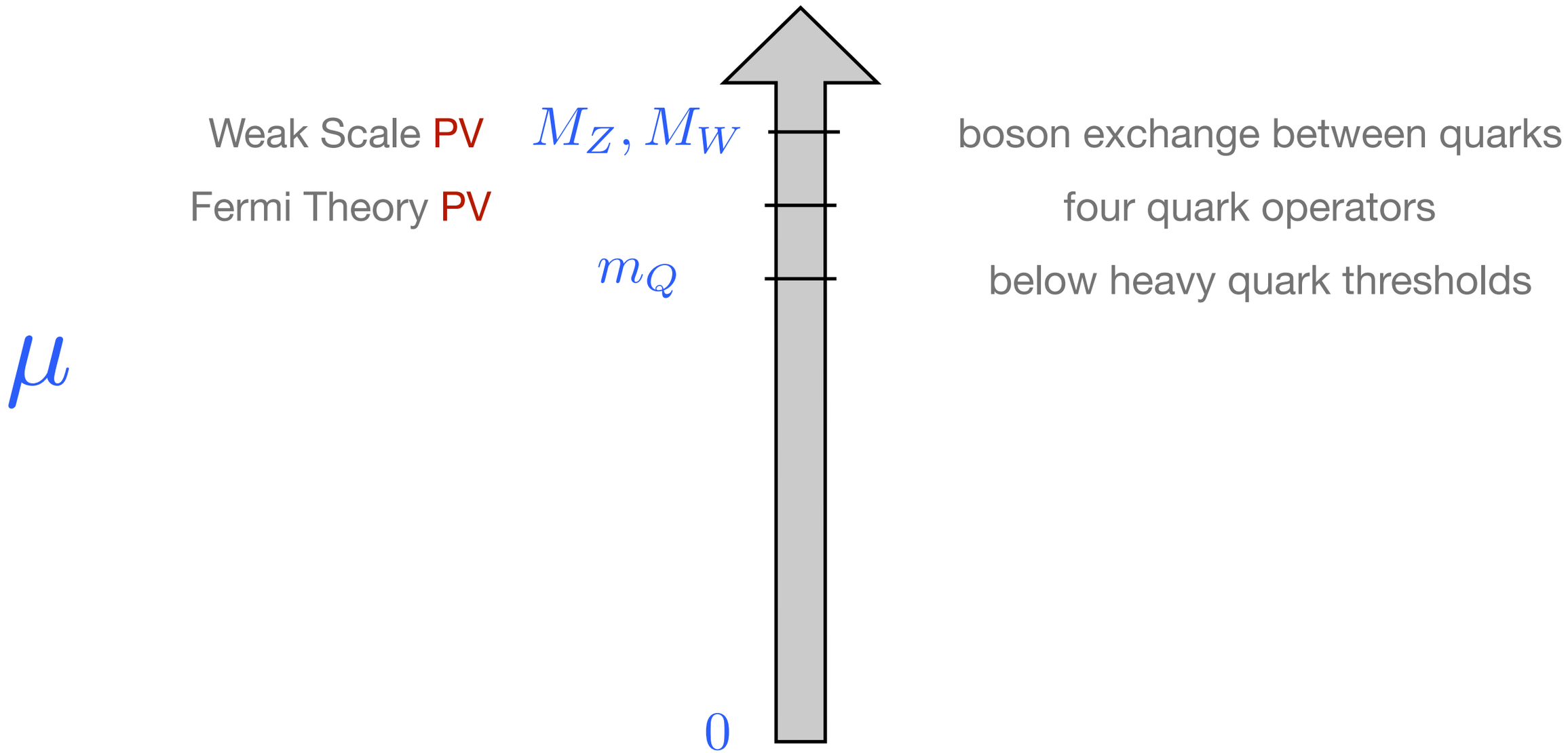

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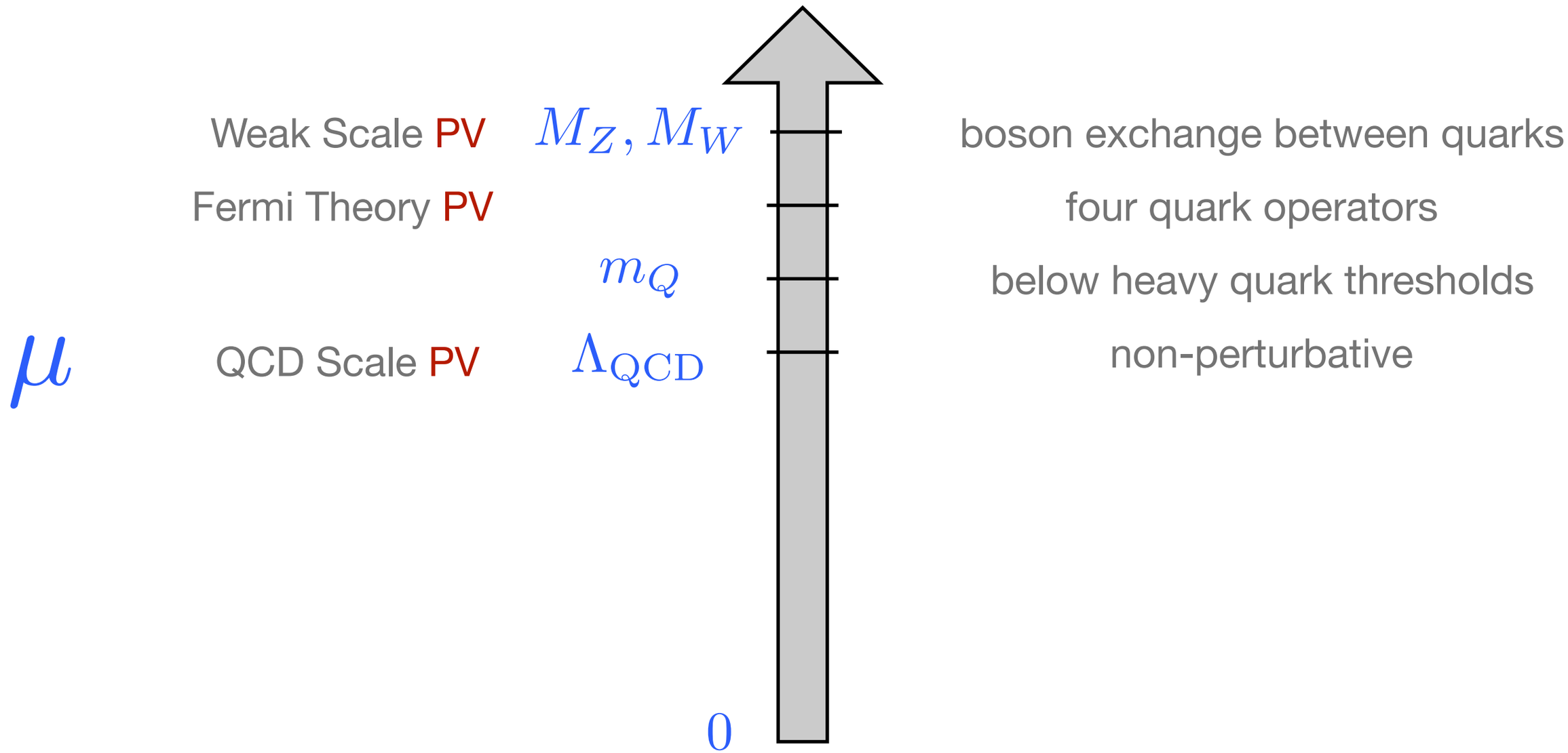

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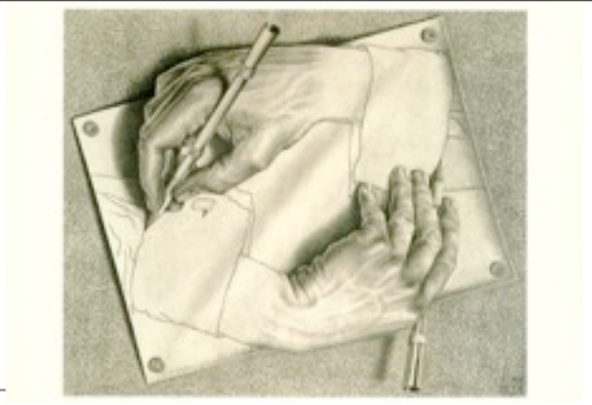

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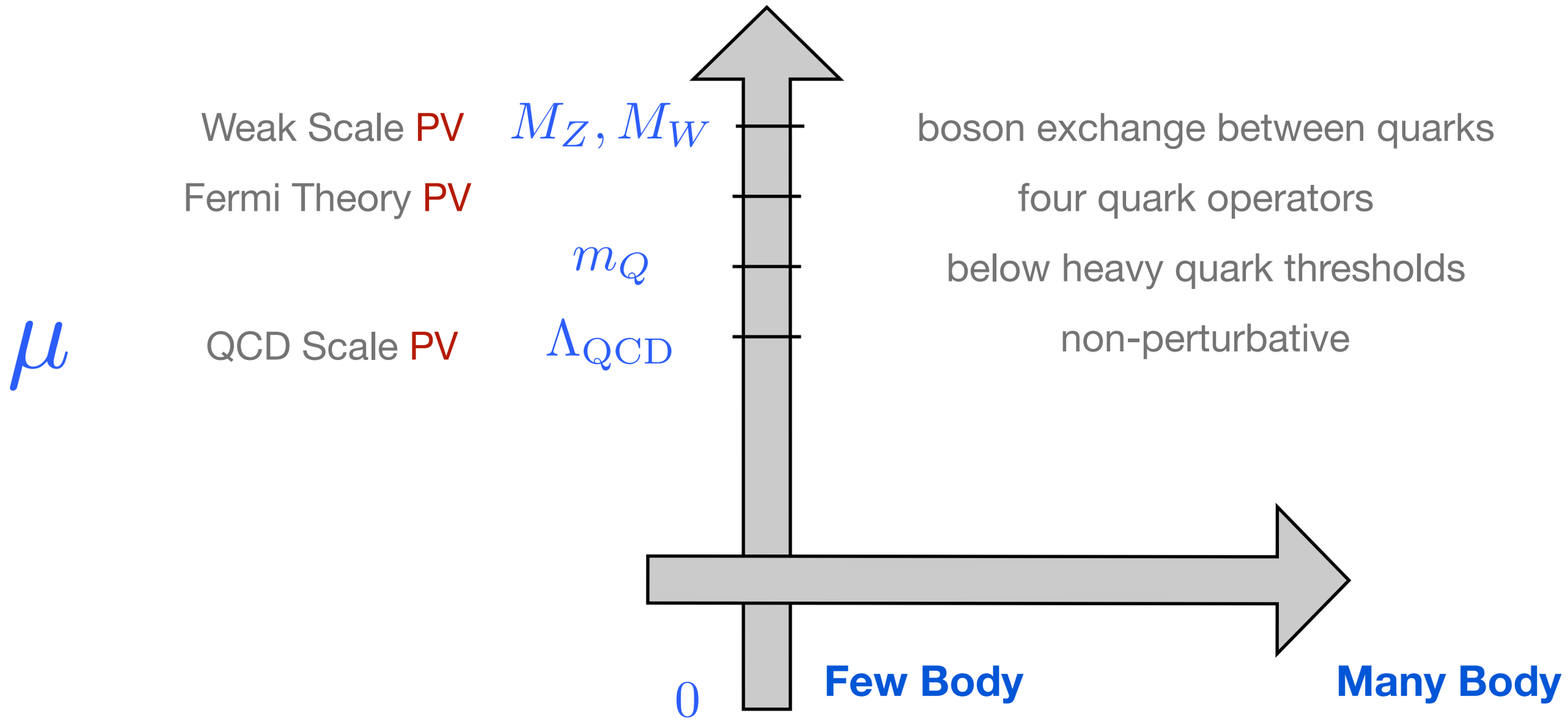

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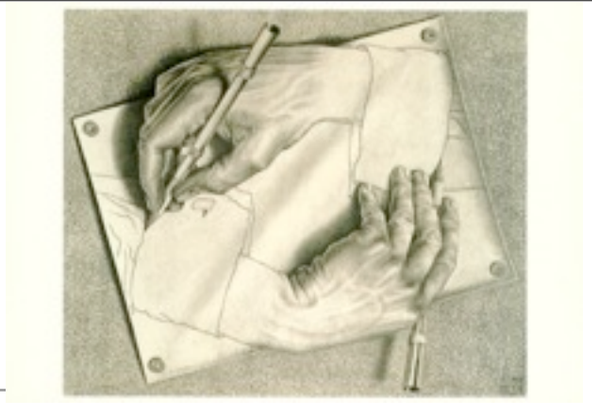

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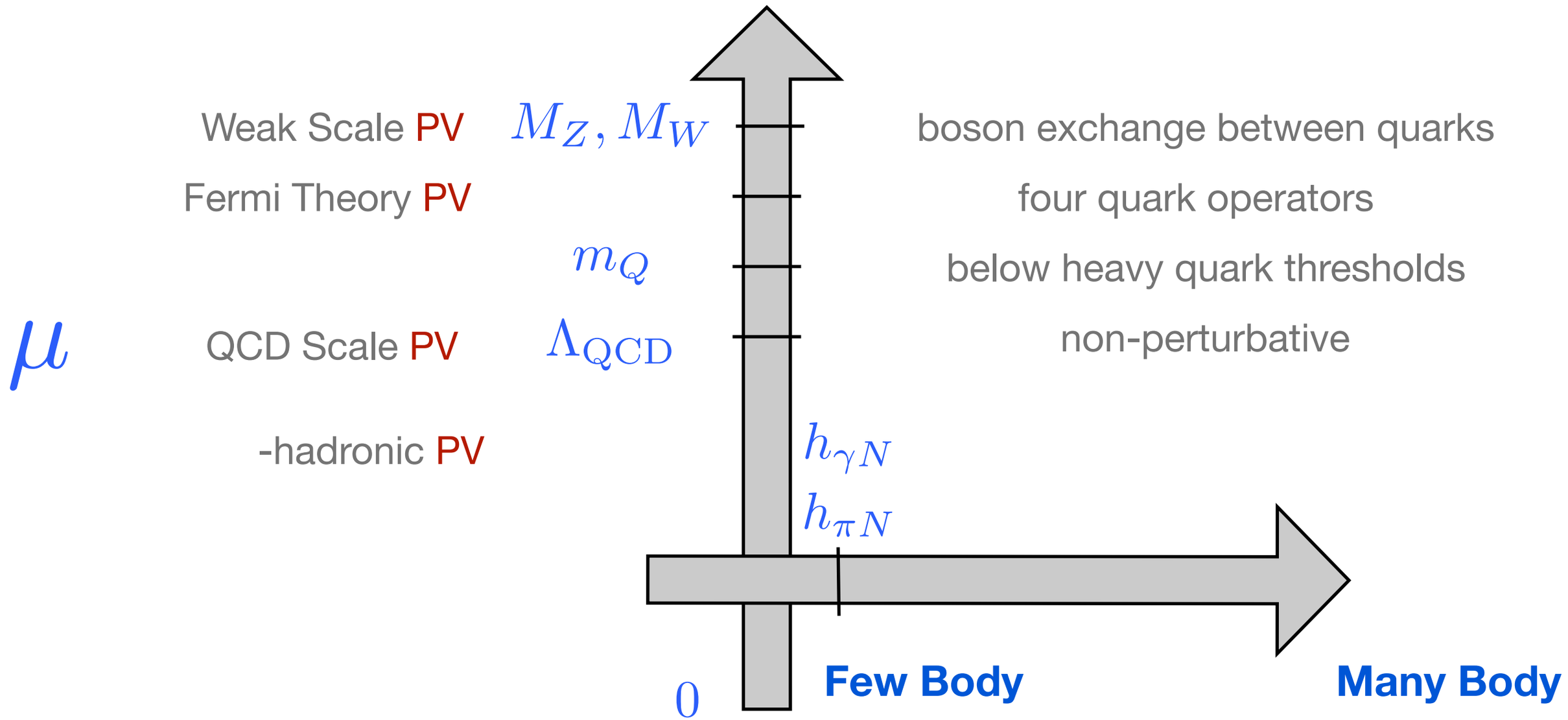

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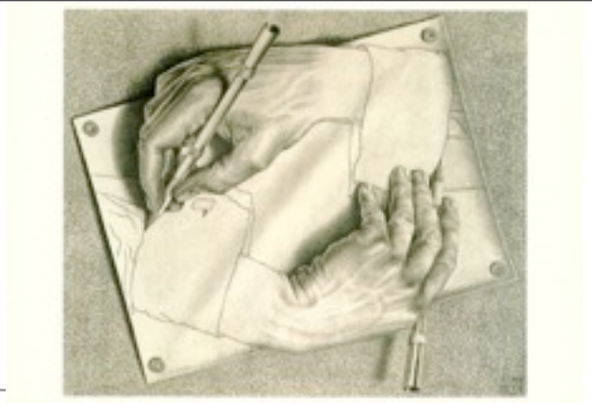

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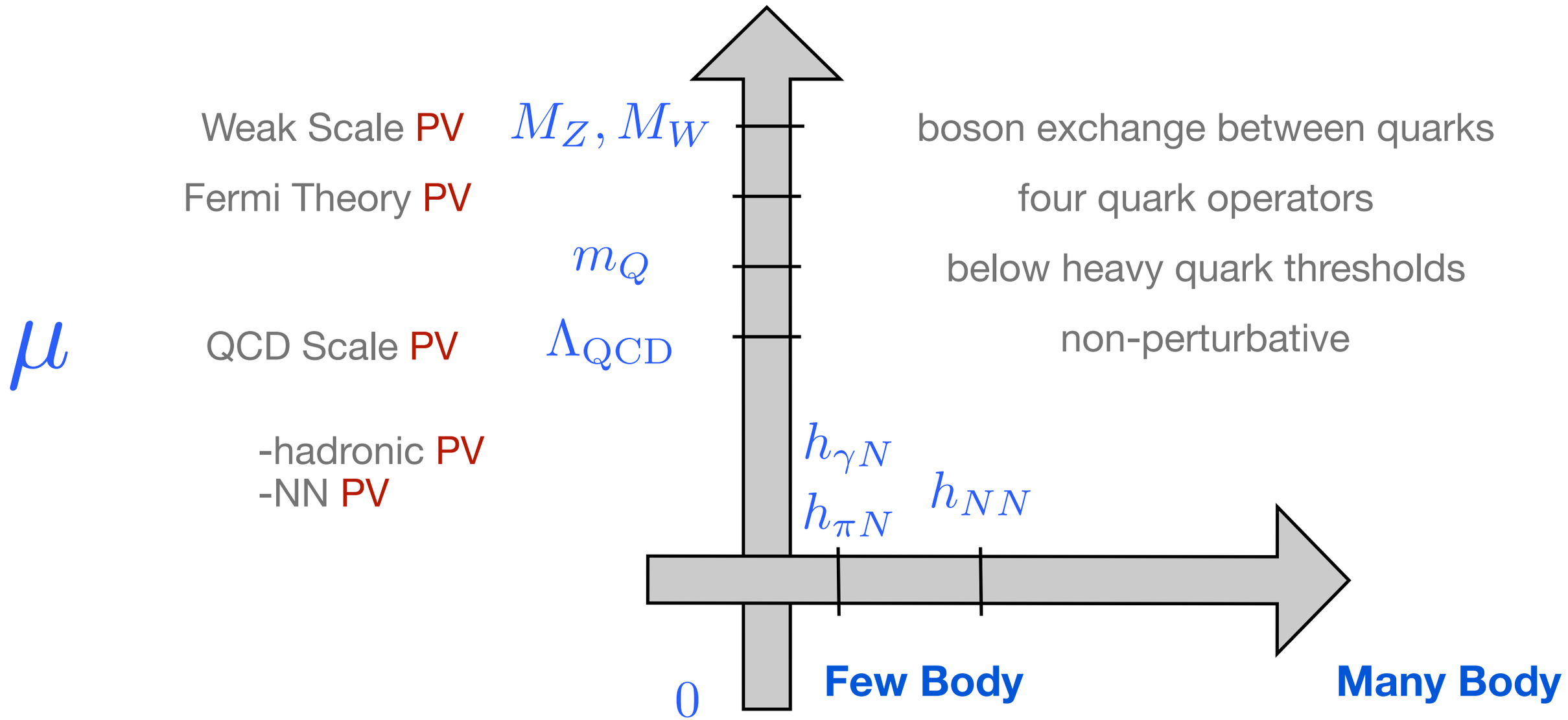

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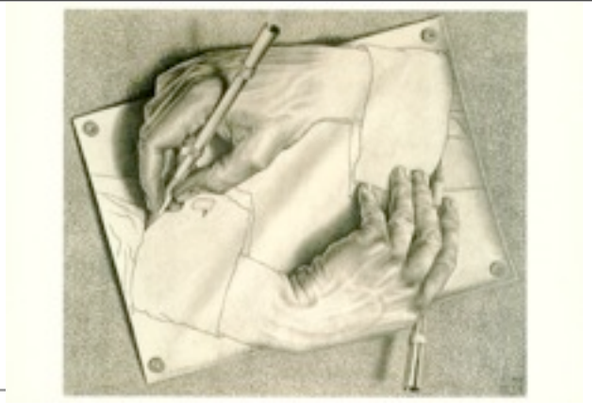

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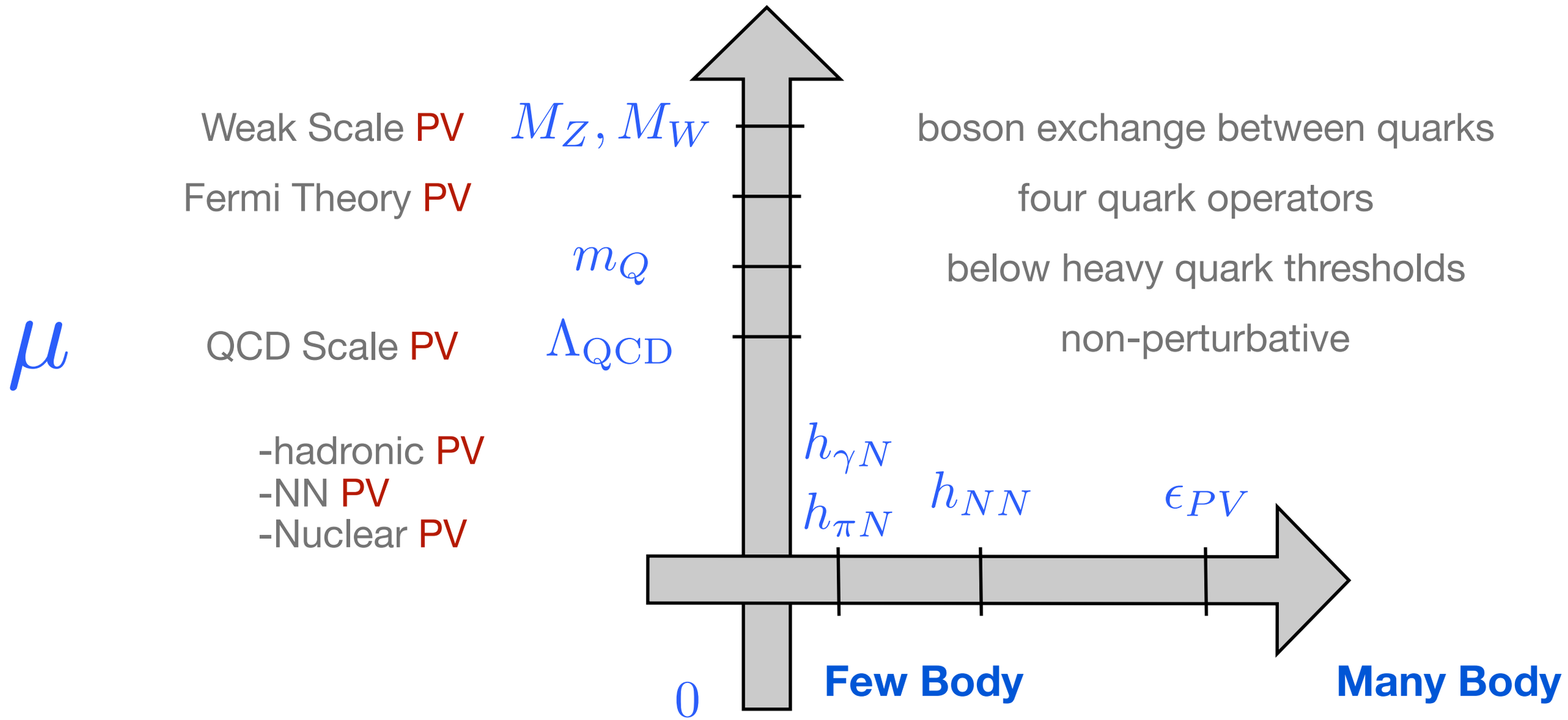
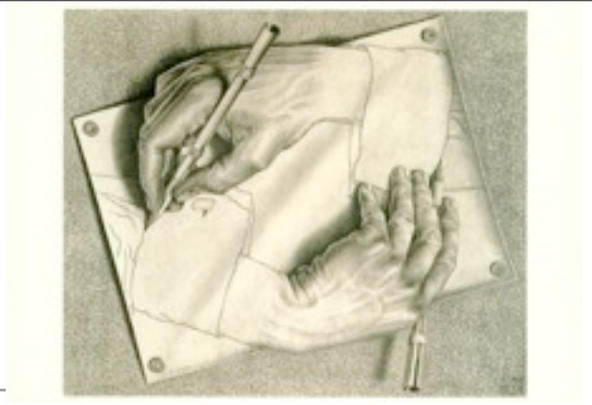


Parallel to Parity Violation



Lattice QCD: Connect Quarks to Hadrons, Few Body

Quantum Many Body: Connect Few Body to Nuclei

- **Organize with Effective Theory mindset**

-hadronic PC
-NN PC
-Nuclear PC

g_V g_A ϵ_d $\epsilon_{\mathcal{N}}$

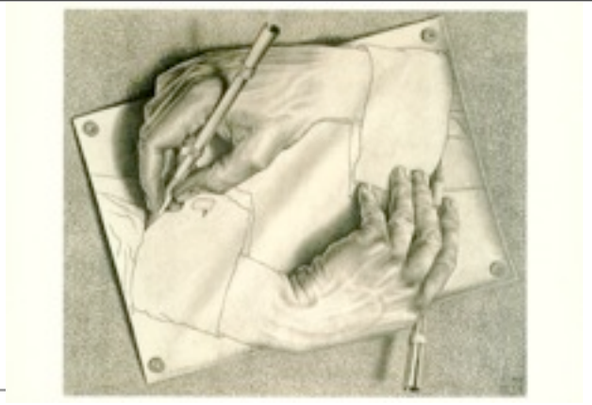
μ QCD Scale PV $\Lambda_{\rm QCD}$ non-perturbative

-hadronic PV
-NN PV
-Nuclear PV

$h_{\gamma N}$ $h_{\pi N}$ h_{NN} ϵ_{PV}

Few Body **Many Body**

Parallel to Parity Violation



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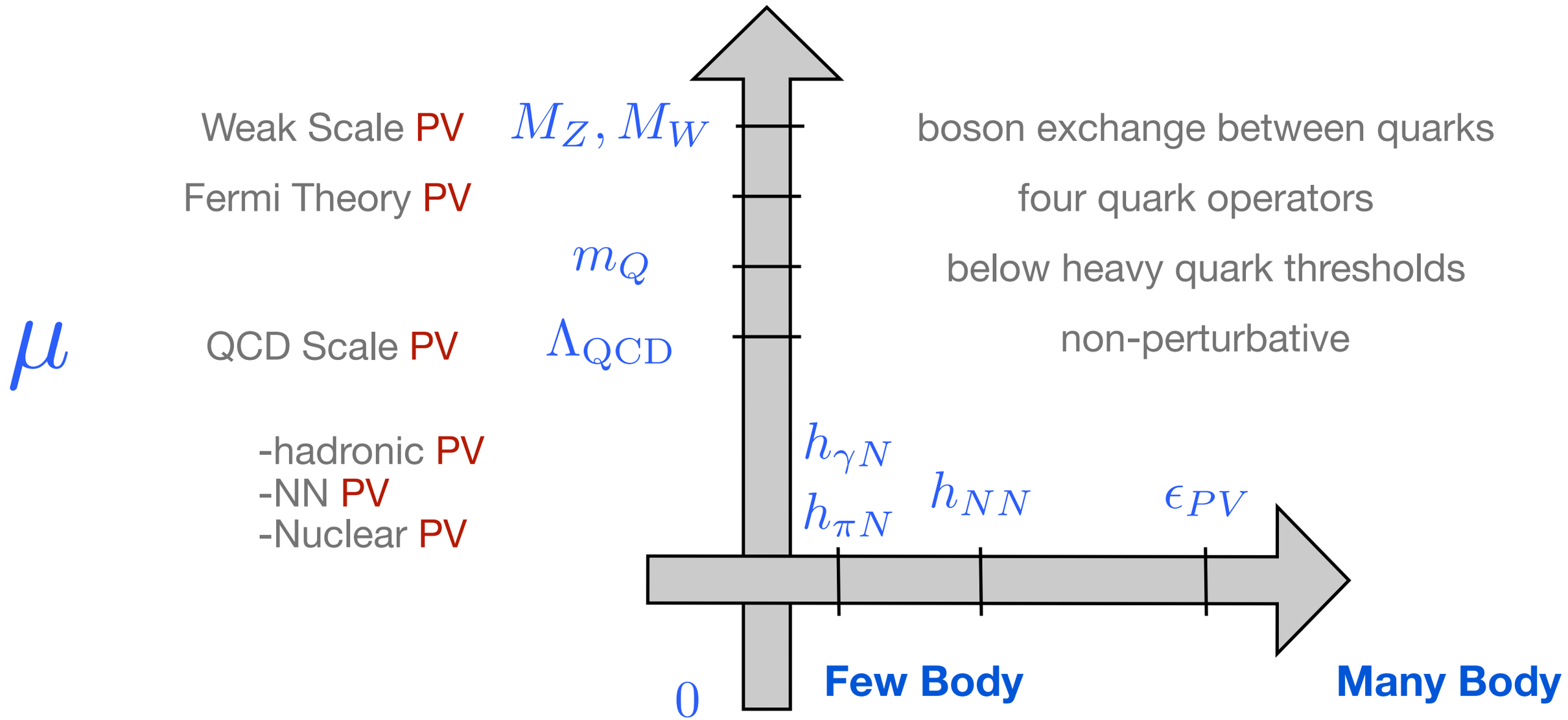
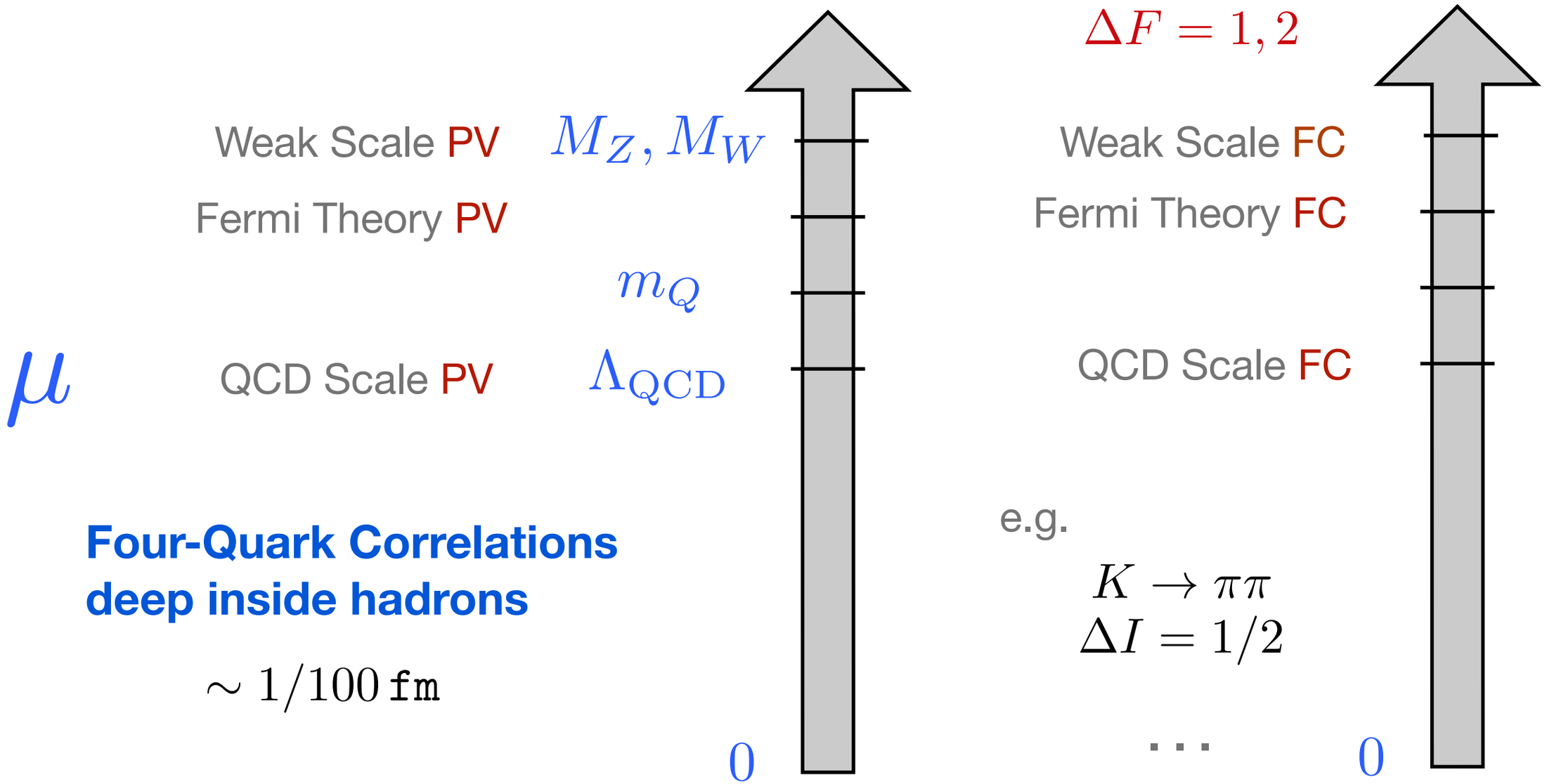


Parallel to Parity Violation

Perturbative QCD: Connect Standard Model to QCD scale

Lattice QCD: Connect Four Quark Ops. to Observables

- **Organize with Effective Theory mindset**



Four-Quark Correlations deep inside hadrons

$\sim 1/100\,\mathtt{fm}$

Hadronic Parity Violation in QCD

Perturbative QCD: Connect Standard Model to QCD scale

Lattice QCD: Connect Four Quark Ops. to Observables

- **QCD renormalization of PV**

$$\mathcal{L}_{\rm PV}^{I=1} = \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

B Tiburzi, PRD **85** 054020 (2012)

- **(First) Lattice QCD calculation of PV**

$$\langle p|\mathcal{L}_{\rm PV}^{I=1}|\pi n\rangle = h_\pi^1$$

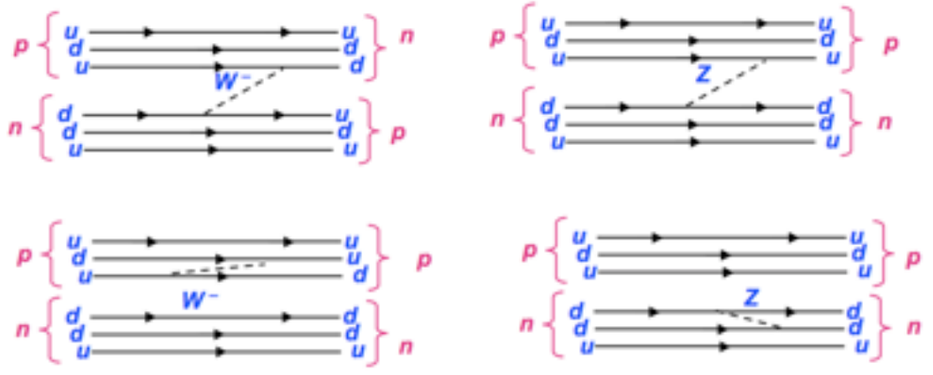
J Wasem, PRC **85** 022501(R) (2012)

- **In tandem: program to remove model dependence in NN, NNN, ...**

  Zhu Maekawa Holstein Ramsey-Musolf van Kolck, Phillips Schindler Springer Grießhammer, Shin Ando Hyun, Vanasse, . . .

Isovector Parity Violation in QCD

Why Isovector?



- **QCD renormalization of PV**
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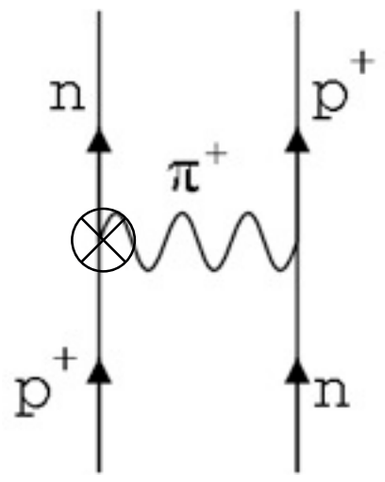
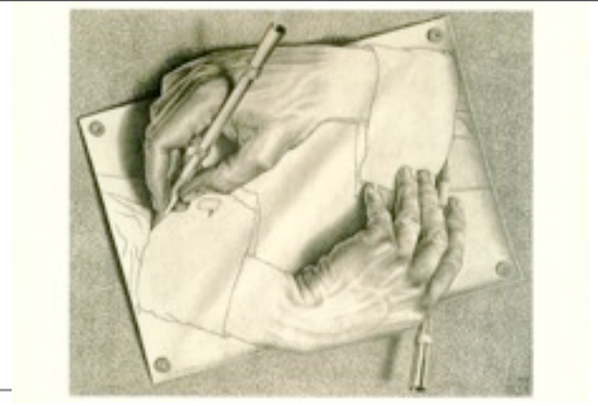


$$\sim \frac{h_\pi^1 g_A}{f_\pi^2}\frac{\sigma\cdot q}{q^2+m_\pi^2}$$

Alleged: Longest range piece of PV NN interaction

Isovector Parity Violation in QCD



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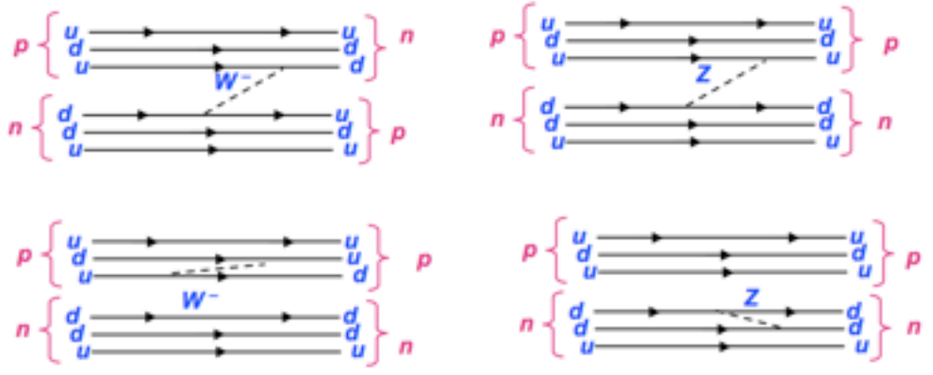


- **QCD renormalization of PV**
- **(First) Lattice QCD calculation of PV**

$$\mathcal{L}_{\rm PV}^{I=1} = \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

$$\langle p|\mathcal{L}_{\rm PV}^{I=1}|\pi n\rangle = h_\pi^1$$

$$W^\pm : \Delta I = 0, 2 \propto |V_{ud}|^2$$
$$\Delta I = 1 \quad \propto |V_{us}|^2$$
$$Z^0 : \Delta I = 0, 1, 2$$

$$J_\mu^{W^-} = \overline{U}_L \gamma_\mu V D_L$$

$$J_\mu^{Z^0} = \overline{\Psi}_L \gamma_\mu \left(T_3 - s_W^2 Q\right) \Psi_L$$

Alleged: 95% probe of hadronic neutral current

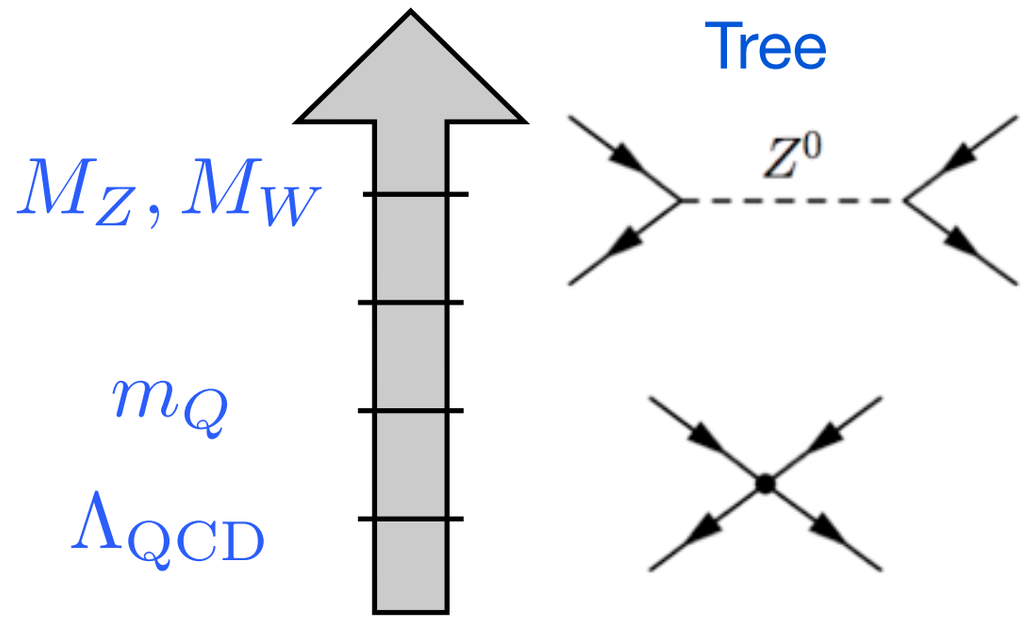
QCD Renormalization of Isovector Parity Violation

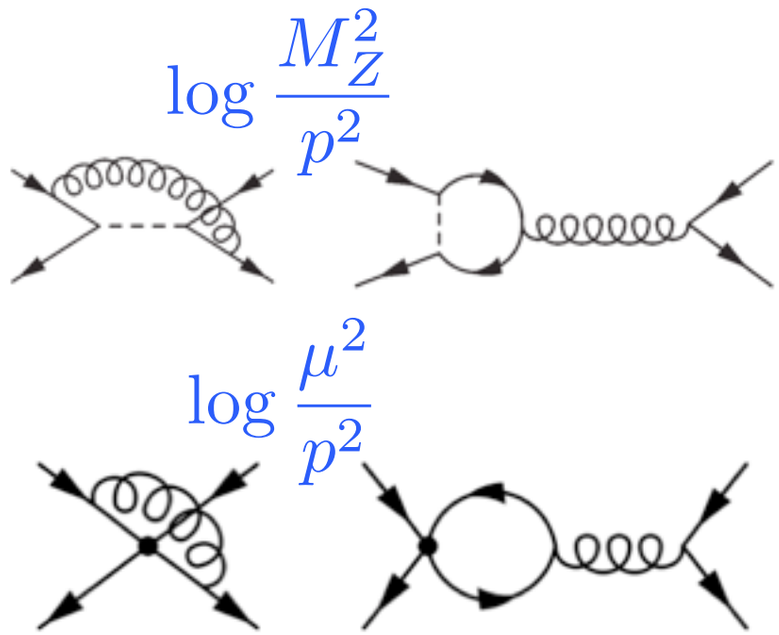
Alleged: 95% probe of hadronic neutral current

Weak Scale PV

Fermi Theory PV

QCD Scale PV





$$\mathcal{L}_{\rm PV}^{I=1} = \frac{G_F}{\sqrt{2}} \frac{1}{3} s_W^2 \, (\bar{u}u - \bar{d}d)_A (\bar{u}u + \bar{d}d)_V$$

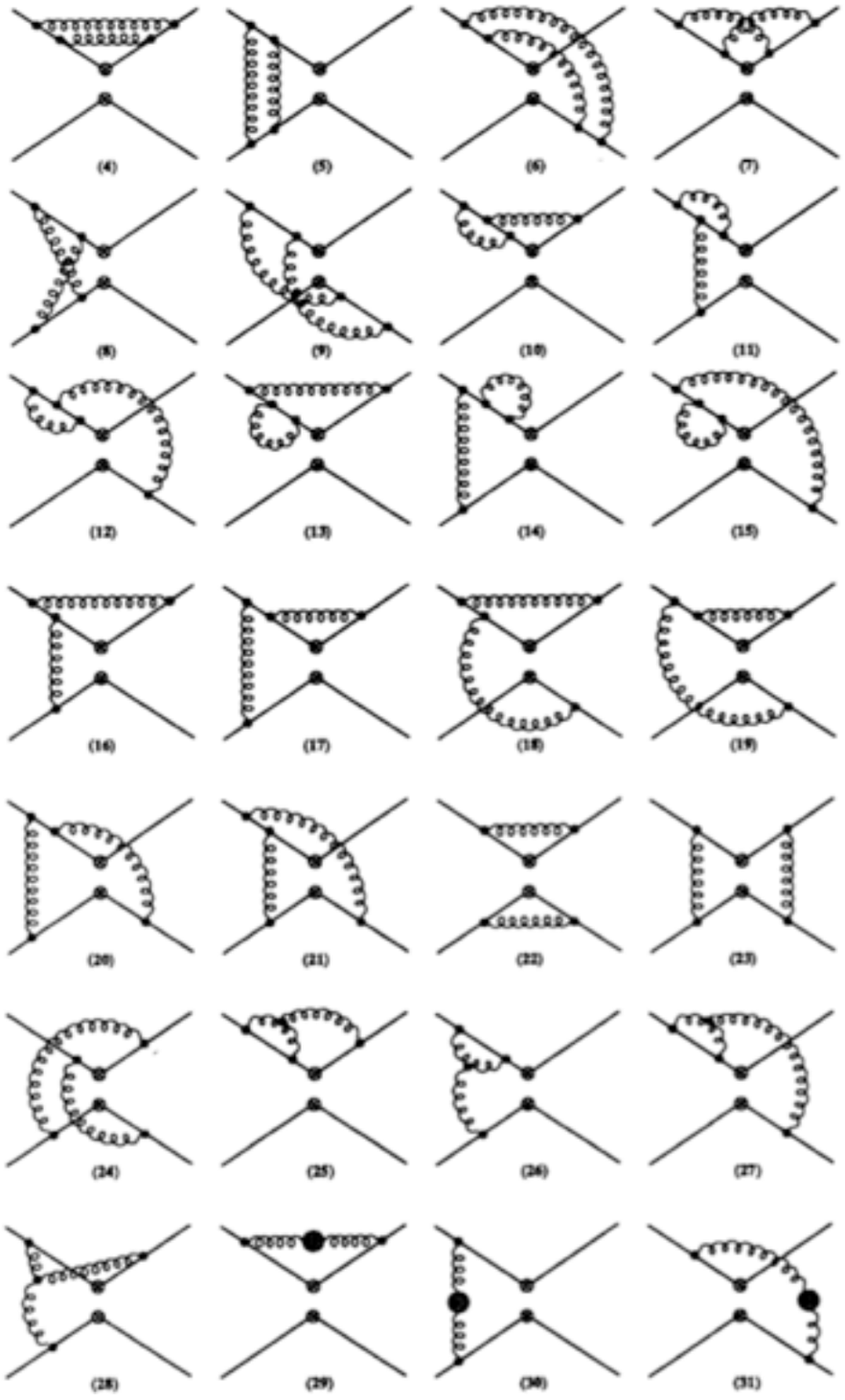
$$\log \frac{M_Z^2}{p^2} = \log \frac{\mu^2}{p^2} - \log \frac{\mu^2}{M_Z^2}$$

$$\mathcal{L}_{\rm PV}^{I=1} = \sum_i C_i(\mu) \mathcal{O}_i(\mu) \qquad C(\mu) \sim -\log \frac{\mu^2}{M_Z^2}$$

Sum leading logs $\quad \mu \frac{d}{d\mu} \vec{C} = \frac{\alpha_s}{4\pi} \gamma^T \cdot \vec{C}$

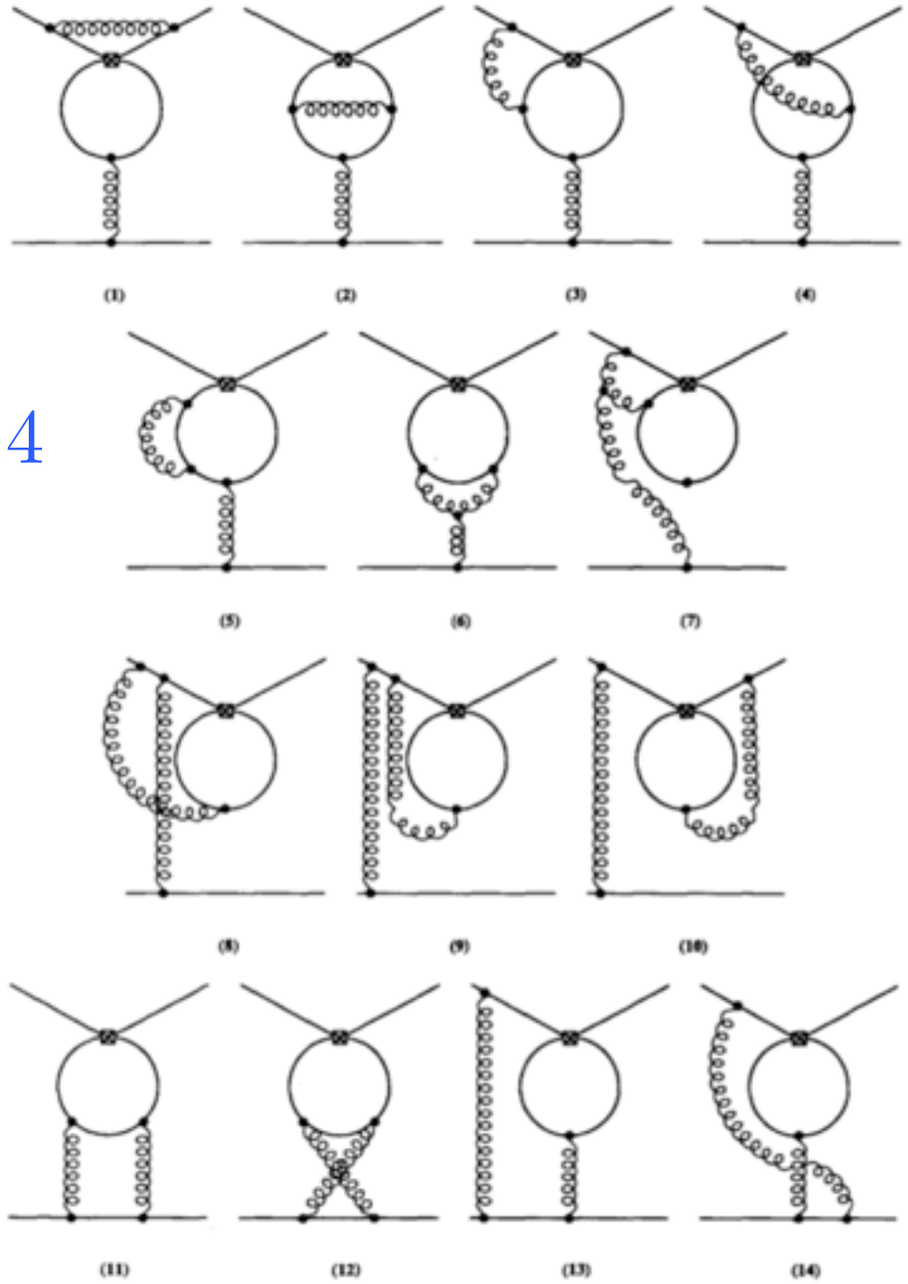
70's Donoghue, McKellar, . . . , 90's Dia Savage Liu Springer, Kaplan Savage

QCD Renormalization of Isovector Parity Violation



$\alpha_s(1\,\mathtt{GeV}) \sim 0.4$

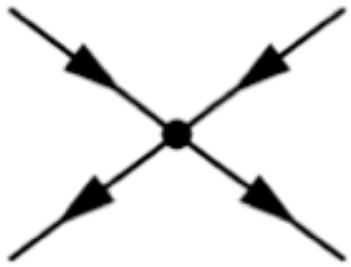
Sum LL to NLO



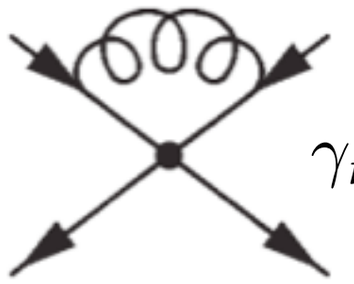
... renormalization scheme dependence (Good!)

QCD Renormalization of Isovector Parity Violation

Renormalization scheme: dimensional regularization



$\gamma_\mu\gamma_5 \otimes \gamma^\mu$



$\gamma_\nu\gamma_\rho\gamma_\mu\gamma_5 \otimes \gamma^\nu\gamma^\rho\gamma^\mu$

Four dimensions affords simplification $\gamma_\nu\gamma_\rho\gamma_\mu = g_{\nu\rho}\gamma_\mu - g_{\nu\mu}\gamma_\rho + g_{\rho\mu}\gamma_\nu - i\varepsilon_{\nu\rho\mu\sigma}\gamma^\sigma\gamma_5$

Enlarge operator basis to include mixing with evanescent operators

$\Delta F \neq 0$ Experts: Buras Jamin Lautenbacher Weisz, Ciuchini Franco Lubicz Martinelli Reina Scimemi Silvestrini

(PV in Lattice QCD requires different scheme than dim reg... work in progress)

QCD Renormalization of Isovector Parity Violation

Renormalization scheme: dimensional regularization

E.g.

$\Delta S = 1$ $\quad Q_1 = (\overline{s}d)_{V-A}(\overline{u}u)_{V-A}$ Mass independent scheme & QCD flavor blind!

W-exchange

U-spin

$(\overline{s}s - \overline{d}d)_{V-A}(\overline{u}u)_{V-A}$

V-spin

$(\overline{u}u - \overline{d}d)_{V-A}(\overline{s}s)_{V-A}$

Parity invariance

$\Delta I = 1$ $\quad \mathcal{O} = (\overline{u}\gamma_\mu u - \overline{d}\gamma_\mu d)_L(\overline{s}\gamma^\mu s)_L - (\overline{u}\gamma_\mu u - \overline{d}\gamma_\mu d)_R(\overline{s}\gamma^\mu s)_R$

Z-exchange

$\Delta I = 1$ follows from $\Delta S = 1$ including QED penguins, and BSM operators

. . . just different initial conditions in evolution

QCD Renormalization of Isovector Parity Violation

Results ('t Hooft-Veltman scheme)

$$\mathcal{L}_{\mathrm{PV}}^{I=1} = \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

$$O_1 = (\bar{u}u - \bar{d}d)_A(\bar{u}u + \bar{d}d)_V,$$
$$O_2 = (\bar{u}u - \bar{d}d]_A[\bar{u}u + \bar{d}d)_V,$$
$$O_3 = (\bar{u}u - \bar{d}d)_V(\bar{u}u + \bar{d}d)_A,$$
$$O_4 = (\bar{u}u - \bar{d}d]_V[\bar{u}u + \bar{d}d)_A,$$

Non-Strange vs. Strange

$$O_5 = (\bar{u}u - \bar{d}d)_A(\bar{s}s)_V, \qquad O_6 = (\bar{u}u - \bar{d}d]_A[\bar{s}s)_V,$$
$$O_7 = (\bar{u}u - \bar{d}d)_V(\bar{s}s)_A, \qquad O_8 = (\bar{u}u - \bar{d}d]_V[\bar{s}s)_A.$$

Fierz constraint

- 2 ops in chiral basis

$$L \otimes L - R \otimes R$$

Alleged: 95% probe of hadronic neutral current

$\sin^2\theta_W$ Non-Strange

vs.

1 Strange

80 - 100% Dynamical Question!

$C_i(\mu = 1\,\mathrm{GeV})$

i	LO [18]	LO	NLO (Z)	NLO (Z + W)
1	0.403	0.264	−0.054	−0.055
2	0.765	0.981	0.803	0.810
3	-0.463	−0.592	−0.629	−0.627
4	0	0	0	0
5	5.61	5.97	4.85	5.09
6	−1.90	−2.30	−2.14	−2.55
7	4.74	5.12	4.27	4.51
8	−2.67	−3.29	−2.94	−3.36

[18] Kaplan Savage, NUPHA **556** (1993) B Tiburzi, PRD **85** 054020 (2012)

Summarizing the Saga

- New neutron experiments will constrain PV in few-body systems
- Connecting few-body PV to many-body PV stringent test of methods NMB/NNEFT
- Connecting PV four quark operators to PV couplings between hadrons: test of non-pQCD
- Connection of nuclear PV to Standard Model

"Parity Violation"