Towards Exploring Parity Violation with Lattice QCD

Brian Tiburzi
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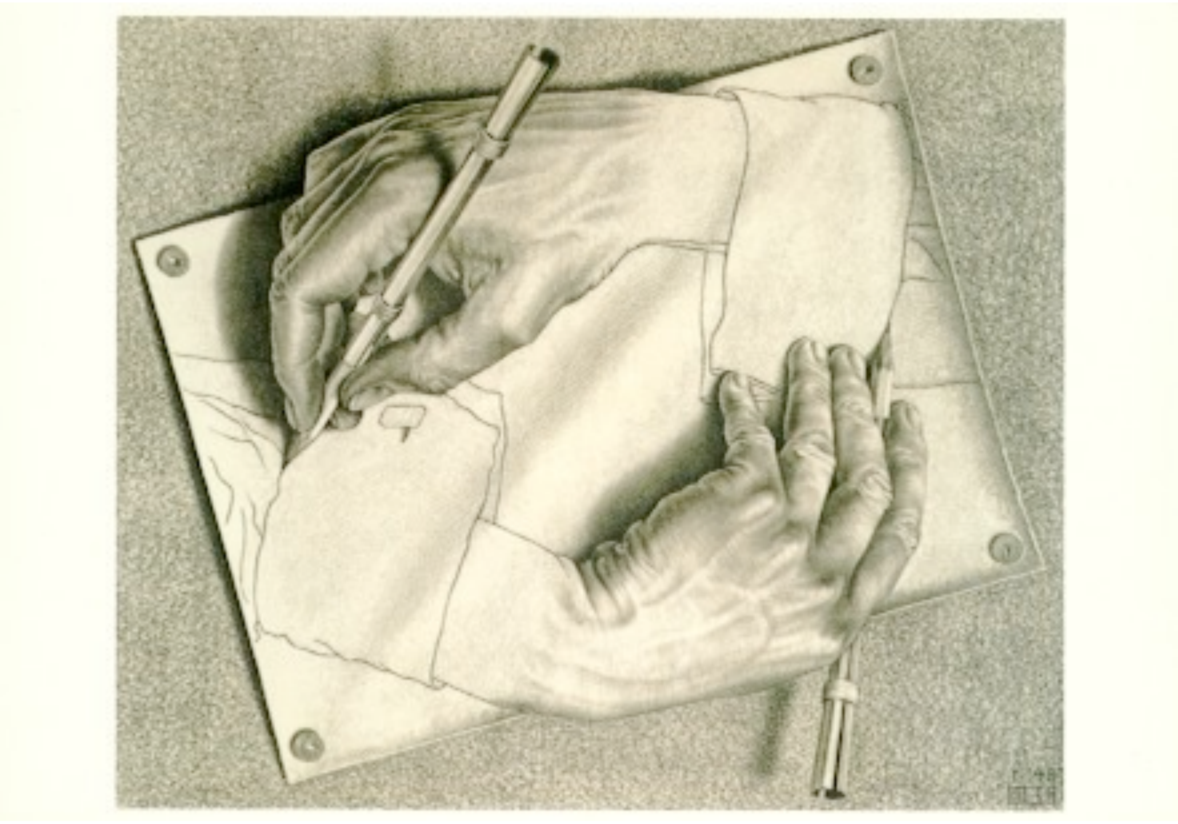
The City College of New York
RIKEN BNL Research Center
CUNY

Towards Exploring Parity Violation with Lattice QCD

- **Hadronic Weak Interactions**
- **Lattice QCD calculations**
- **Hadronic Parity Violation**
  isovector and isotensor



Goal: provide a sense of what challenges lattice QCD computations must confront

Quark Interactions to Hadronic Couplings

Ken Wilson
1936-2013

- **Textbook**: gauge theories defined in perturbation theory
- **QCD**: short distance perturbative, long distance non-perturbative

$$\overline{\psi}\,(\not{D} + m_q)\,\psi + \frac{1}{4} G_{\mu\nu} G_{\mu\nu}$$

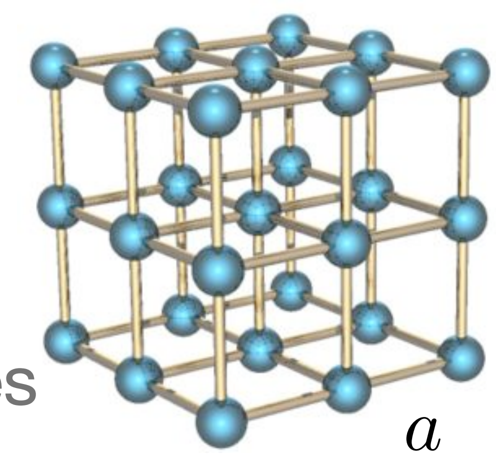
Many Technicalities →

$M_N \quad \epsilon_b(D)$

$\delta_{NN}(k)$

Wilson Lattice Action
Wilson Fermions

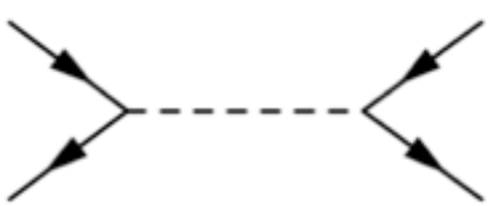
Non-perturbative definition of asymptotically free gauge theories



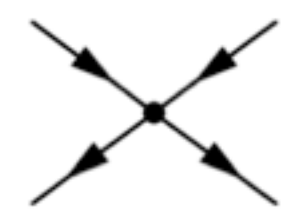
Spectrum
Interactions

Strong interaction observables

- **Quarks couple to other fundamental interactions**: e.g. weak interaction



$$J(x)D(x,0)J(0) = \sum_i C_i(\mu)\mathcal{O}_i(x,\mu)$$

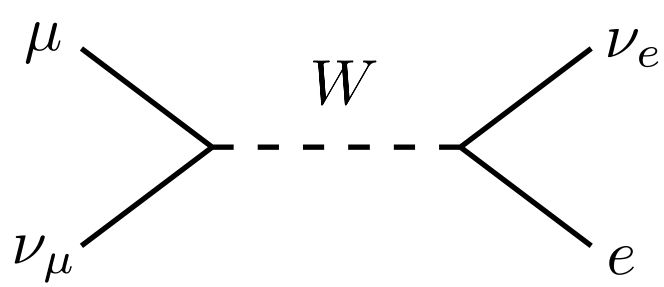


Wilson Operator Product Expansion, Wilson Coefficients, Wilson Renormalization Group

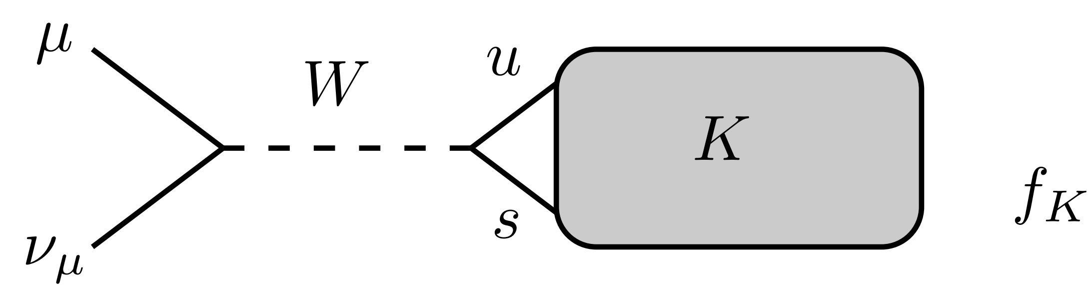
- **Hadronic weak (& *BSM*) interactions require all the Wilson brand names**

Weak Interactions

- Leptonic weak interaction

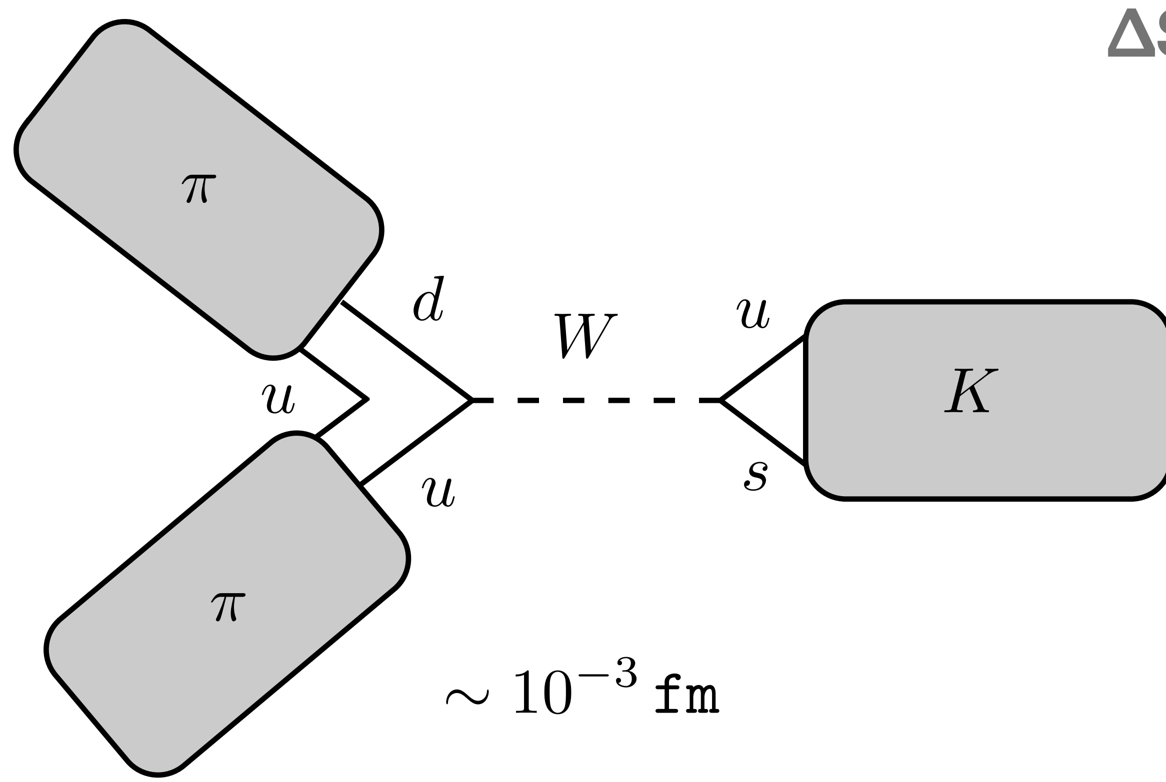


- Semi-leptonic weak interaction



- Non-leptonic (hadronic) weak interaction

ΔS = 1



Example: K→ππ and ΔI = 1/2 Rule

- **Old Puzzle**: **I** = 0 weak decay channel experimentally observed ~500x over **I** = 2
- Amplitude level: A0 / A2 ~ 22.5
  pQCD contributes a factor of ~2
  Rest non-perturbative?

$$\mathcal{A} = \sum_i C_i(\mu)\langle\pi\pi|\mathcal{O}_i(\mu)|K\rangle_{\texttt{Lattice}}$$

PRL 110, 152001 (2013)

Emerging understanding of the $\Delta I = 1/2$ Rule from Lattice QCD

P.A. Boyle,[1] N.H. Christ,[2] N. Garron,[3] E.J. Goode,[4] T. Janowski,[4] C. Lehner,[5] Q. Liu,[2] A.T. Lytle,[4] C.T. Sachrajda,[4] A. Soni,[6] and D. Zhang[2]
(The RBC and UKQCD Collaborations)

- **Almost There?**

$$\mathcal{A}_0/\mathcal{A}_2(m_\pi = 330\,\texttt{MeV}) = 12.0(1.7)$$

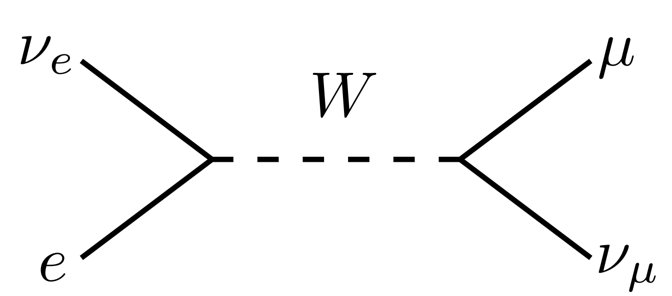
- **Theoretical Challenges ΔS = 1 Processes**

Usual Suspects: pion mass, lattice spacing, lattice volume		**underway**
Additional Challenges:	Physical Kinematics	**underway**
	Multi-Hadron States and Normalization	✓
	Operator Renormalization & Scale Invariance	✓
	Statistically Noisy Operator Self-Contractions	✓

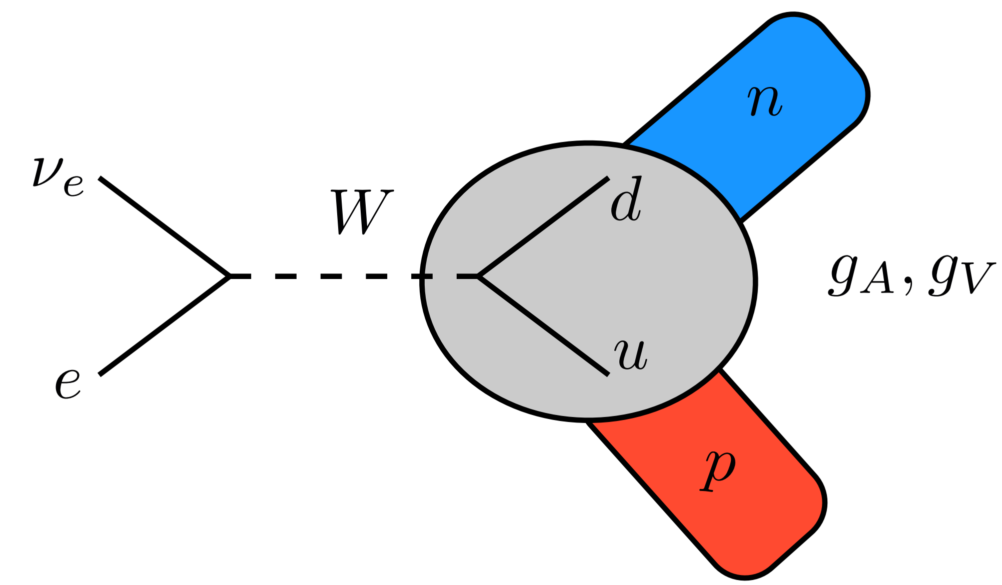
- **Can such success carry over to weak nuclear processes?**

Dirtiest Corner of Standard Model

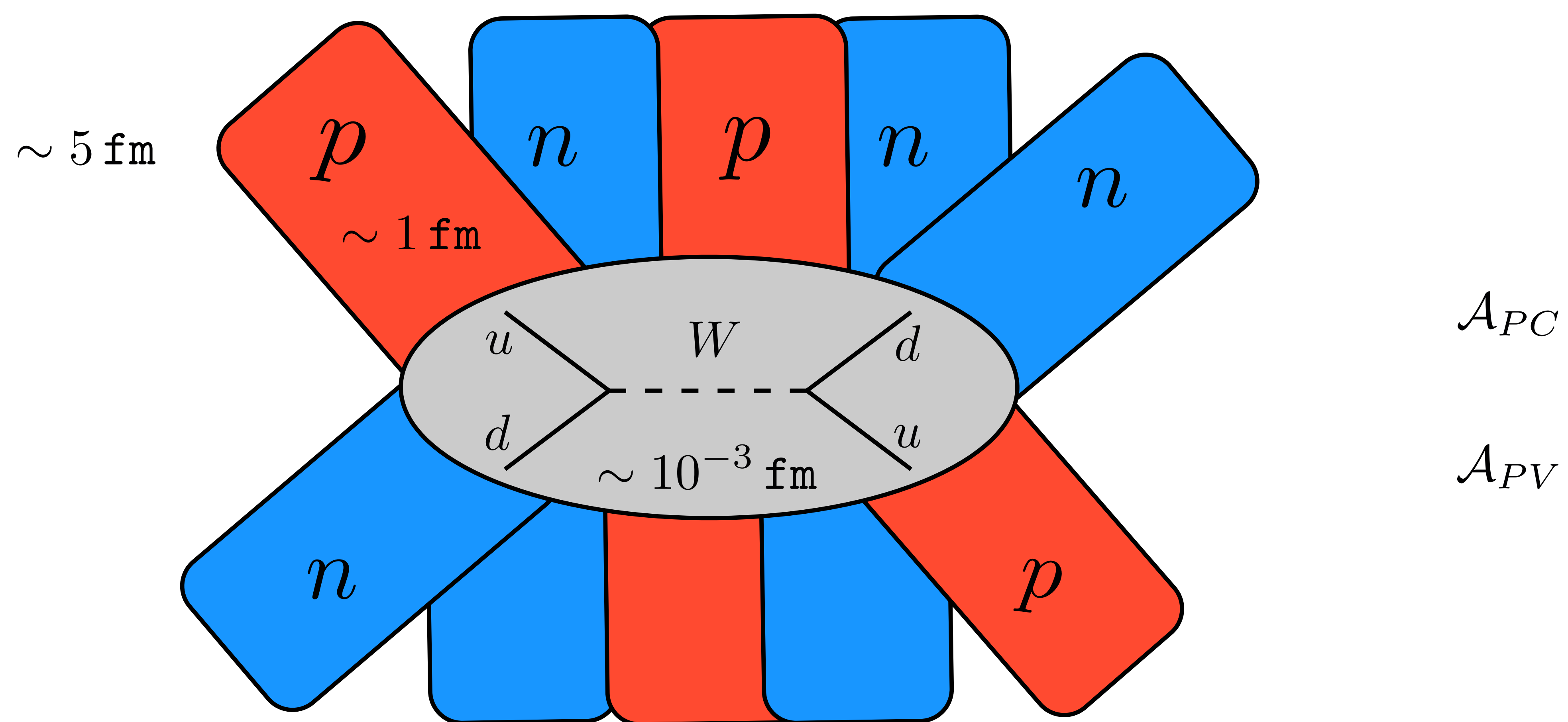
- Leptonic weak interaction



- Semi-leptonic weak interaction

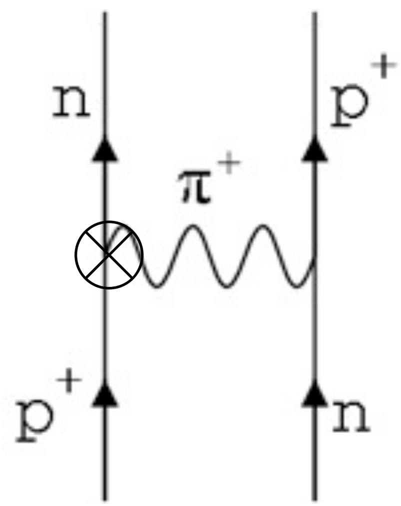


- Hadronic weak interaction



Example: N→(Nπ)$_S$ and ΔI = 1 Parity Violation

- **Old Problem**: hadronic neutral weak interaction is the least constrained SM current
- **New experiments**: parity violation in few-body systems, map out NN weak interaction?



$$\mathcal{A} = \sum_i C_i(\mu)\langle(\pi N)_s|\mathcal{O}_i(\mu)|N\rangle_{\rm Lattice}$$

Lattice QCD Calculation of Nuclear Parity Violation

Joseph Wasem **PRC 85, 022501 (2012)**

Signal Found $h^1_{\pi NN} = 1.1(5) \times 10^{-7} \pm ??$

- **Theoretical Challenges ΔI = 1 Processes**

Usual Suspects: pion mass, lattice spacing, lattice volume — **to be done**

Additional Challenges:

	Physical Kinematics	**largely solved**
	Multi-Hadron States and Normalization	**to be done**
	Operator Renormalization & Scale Invariance	**to be done**
	Statistically Noisy Operator Self-Contractions	**to be done**

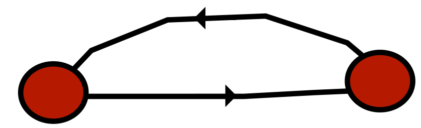
- **How many lattice advances carry over to weak nuclear processes?**

Particle Physics (B=0) vs. Nuclear Physics (B>0)

Statistical nature of lattice QCD two-point correlation functions (*Parisi, Lepage*)

Pion Correlation Function

Signal $\sum_{\{A_\mu\}} \langle q\overline{q}(t) q\overline{q}(0)\rangle \sim e^{-m_\pi t}$

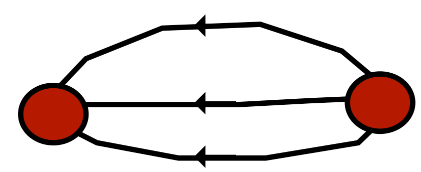


Noise^2 $\sum_{\{A_\mu\}} \langle q\overline{q}(t) q\overline{q}(t) q\overline{q}(0) q\overline{q}(0)\rangle \sim e^{-2m_\pi t}$

Signal/Noise $\sim \text{const}$

Nucleon Correlation Function

Signal $\sum_{\{A_\mu\}} \langle qqq(t)\overline{qqq}(0)\rangle \sim e^{-Mt}$



Noise^2 $\sum_{\{A_\mu\}} \langle qqq(t)\overline{qqq}(t) qqq(0)\overline{qqq}(0)\rangle \sim e^{-3m_\pi t}$

Signal/Noise $\sim e^{-(M-\frac{3}{2}m_\pi)t}$

Baryons are statistically noisy.... nuclear physics has an extra hurdle

Higher statistics

Optimal operators

(Un)Physical Kinematics in N→(Nπ)$_s$

- Lattice states are created on-shell

$$G(\tau) = \sum_{\vec{x}} e^{i\vec{p}\cdot\vec{x}} \langle N(\vec{x},\tau) N^\dagger(0,0)\rangle = Z e^{-\sqrt{\vec{p}^2 + M_N^2}\,\tau} + \cdots$$ **ground-state saturation**

- Hadronic transition matrix elements have energy insertion

$$E_N = M_N$$
$$E_{(\pi N)_s} = M_N + m_\pi$$

⇒

$$\langle (\pi N)_s | \mathcal{O}_i(\mu) | N \rangle_{\mathrm{Lattice}} = h^1_{\pi NN}(\Delta E)$$

- Partial solution implemented (due to Beane, Bedaque, Parreno, Savage, **NUPHA:747,** 55 (2005))

$p \to n\pi^+$ $\quad h^1_{\pi NN}(m_\pi)$

T-invariance

$n\pi^+ \to p$ $\quad h^1_{\pi NN}(-m_\pi)$

⇒

$$h^1_{\pi NN} = \frac{1}{2}\left[h^1_{\pi NN}(m_\pi) + h^1_{\pi NN}(-m_\pi)\right] + \mathcal{O}(m_\pi^2)$$

Consequence: remove via chiral extrapolation but then only can determine chiral limit coupling

Likely small: only~10% at 400 MeV pion mass.
Precision demands in nuclear physics typically not as great as particle physics

- Full solution: determine energy dependence, extrapolate to zero, e.g. TwBCs

Example: $N \to (N\pi)_S$ and $\Delta I = 1$ Parity Violation

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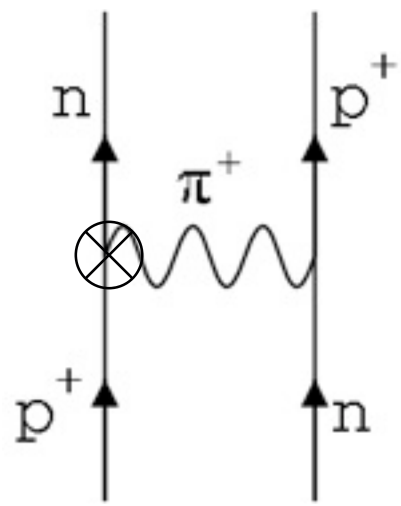

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Multi-Hadron States and Normalization

- Multi-Hadron operator not used... Matrix element evaluated by a trick

$$G^*(\tau) = \langle 0|N^*(\tau)N^{*\dagger}(0)|0\rangle = Ze^{-E_{(N\pi)_s}\tau} + \cdots$$

— $M_{N^*} > M_N + m_\pi$

ground-state saturation — $(N\pi)_s$

three-quark operator for odd-parity N

four-quarks + antiquark

Method requires this condition to hold for lattice parameters

$$= Ze^{-E_{(N\pi)_s}\tau} + Z'e^{-E^*\tau} + \cdots$$

Unfortunately likely Z << Z'

... requires extremely long time to resolve ground state

- Finite volume and infinite volume states have different normalizations

Lellouch, Lüscher, **Commun. Math. Phys. 291,** 31 (2001)

$$|1\rangle_\infty = N_1|1\rangle_V$$
$$|2\rangle_\infty = N_2|2\rangle_V$$

$${}_\infty\langle n|n\rangle_\infty = N_n^2 \, {}_V\langle n|n\rangle_V = N_n^2 e^{-E_n\tau}$$

Not needed for spectrum

$${}_\infty\langle 2|\mathcal{O}|1\rangle_\infty = N_2 N_1 \, {}_V\langle 2|\mathcal{O}|1\rangle_V = N_2 N_1 (h^1_{\pi NN})_V$$

Lellouch-Lüscher factor requires two-particle energy **Not Computed** **Computed**

Lellouch-Lüscher Factor

- **Single Particle Energy Quantization:** $E = \sqrt{\vec{p}^2 + M^2}$ $\vec{p} = \frac{2\pi}{L}\vec{n}$

- **Two Particle Energy Quantization:** $E_{\text{total}} = \sqrt{k^2 + M^2} + \sqrt{k^2 + m^2}$ $\vec{P} = 0$

$$n\pi - \delta_0(k) = \phi(k)$$

(known function for a torus)

$$\rho_V(E) = \frac{dn}{dE} = \frac{\phi'(k) + \delta'(k)}{4\pi k} E$$

$$|2\rangle_\infty = 4\pi\sqrt{\frac{V E \rho_V(E)}{k}}\,|2\rangle_V$$

- **One-to-Two Particle Amplitude:**

$$|\mathcal{M}_\infty|^2 = \frac{8\pi V^2 M E_{\text{total}}^2}{k^2}\left[\delta'(k) + \phi'(k)\right]|\mathcal{M}_V|^2$$

Not Computed

Computed $|(h^1_{\pi NN})_V|^2$

Generalization for energy insertion:

Lin, Martinelli, Pallante, Sachrajda, Villadoro **NuPhB:**650, 301 (2003)

Kim, Sachrajda, Sharpe **NuPhB:**727, 218 (2005)

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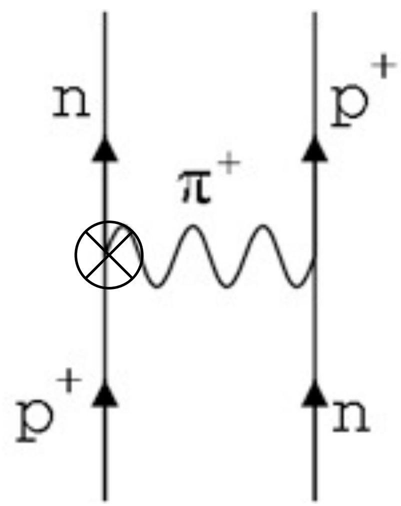

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Operator Renormalization and Scale Invariance

$$\mathcal{A} = \sum_i C_i(\mu)\langle(\pi N)_s|\mathcal{O}_i(\mu)|N\rangle$$

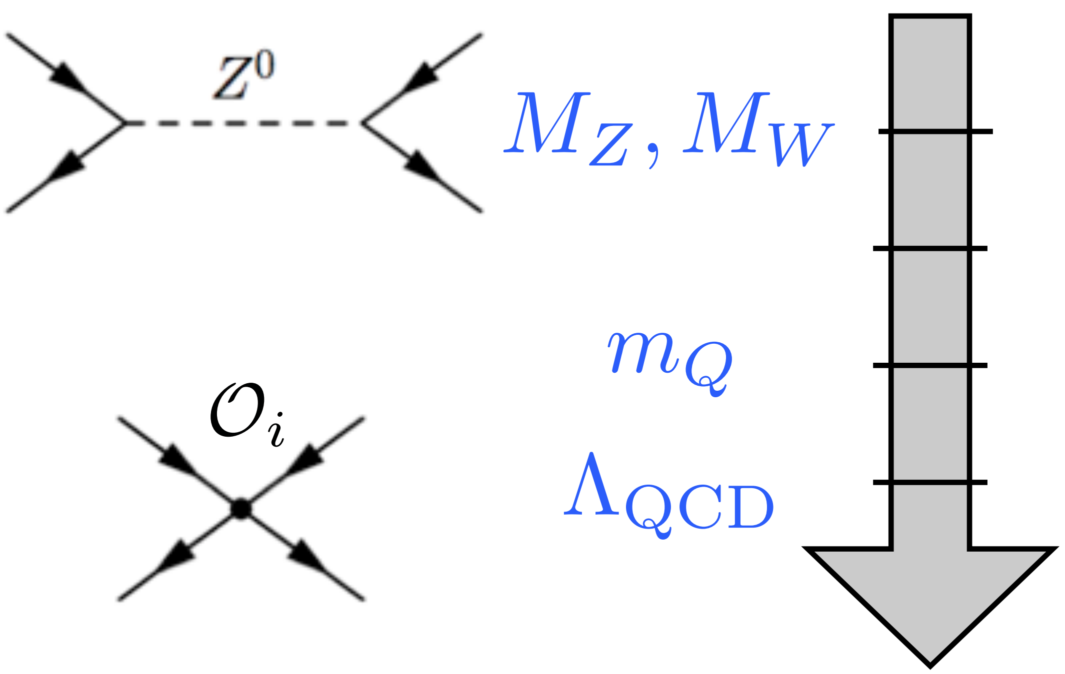
$\mu = 90\,\texttt{GeV}$

computable in pQCD at high scale

$\mu = 1-2\,\texttt{GeV}$

computable on lattice at low scale

Tree Level



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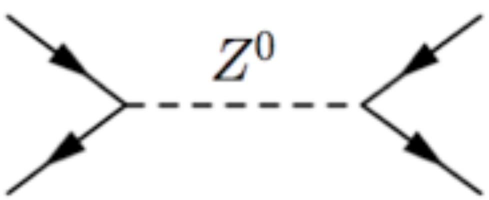
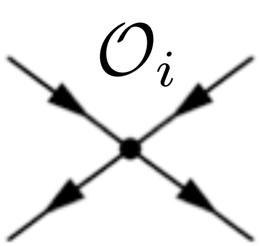
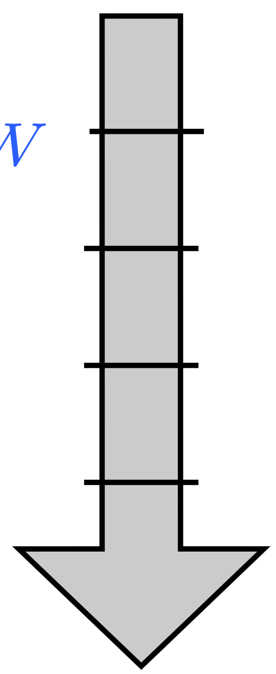


M_Z, M_W

m_Q

$\Lambda_{\rm QCD}$





One Loop

$\log \frac{M_Z^2}{p^2}$

$\log \frac{\mu^2}{p^2}$

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

$$\delta C(\mu) \sim -\alpha_s(\mu) \log \frac{\mu^2}{M_Z^2}$$

70’s Donoghue, McKellar, . . . , 90’s Dia Savage Liu Springer

Operator Renormalization and Scale Invariance

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

Tree Level

$\sin^2\theta_W$ Non-Strange

1 vs. Strange

One Loop Results

$O_1 = (\bar{u}u - \bar{d}d)_A(\bar{u}u + \bar{d}d)_V,$

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

$O_3 = (\bar{u}u - \bar{d}d)_V(\bar{u}u + \bar{d}d)_A,$

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

$O_5 = (\overline{u}u - \overline{d}d)_A(\overline{s}s)_V$

$O_6 = (\overline{u}u - \overline{d}d]_A[\overline{s}s)_V$

$O_7 = (\overline{u}u - \overline{d}d)_V(\overline{s}s)_A$

$O_8 = (\overline{u}u - \overline{d}d]_V[\overline{s}s)_A$

$C_i(\mu = 1\,\texttt{GeV}) \,/\, C_1^{\rm Tree}$

i	LO		LO
1	0.403		0.264
2	0.765		0.981
3	-0.463		−0.592
4	0	(Fierz)	0
5	5.61		5.97
6	−1.90		−2.30
7	4.74		5.12
8	−2.67		−3.29

- Discrepancies

DSLS provide only ratios

$\alpha_s(m_c)/\alpha_s(m_b) = 1.44$

Using their ratios, I get their values

No heavy quark masses quoted in 1990 **PDG**

Dia, Savage, Liu, Springer PLB **271**, 403 (1991)

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

Operator Renormalization and Scale Invariance

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i	LO		LO	LO: 1992 **PDG**
1	0.403		0.264	0.54(4)
2	0.765		0.981	0.55(6)
3	-0.463		−0.592	−0.35(3)
4	0	(Fierz)	0	0
5	5.61		5.97	5.35(7)
6	−1.90		−2.30	−1.57(10)
7	4.74		5.12	4.45(8)
8	−2.67		−3.29	−2.12(15)

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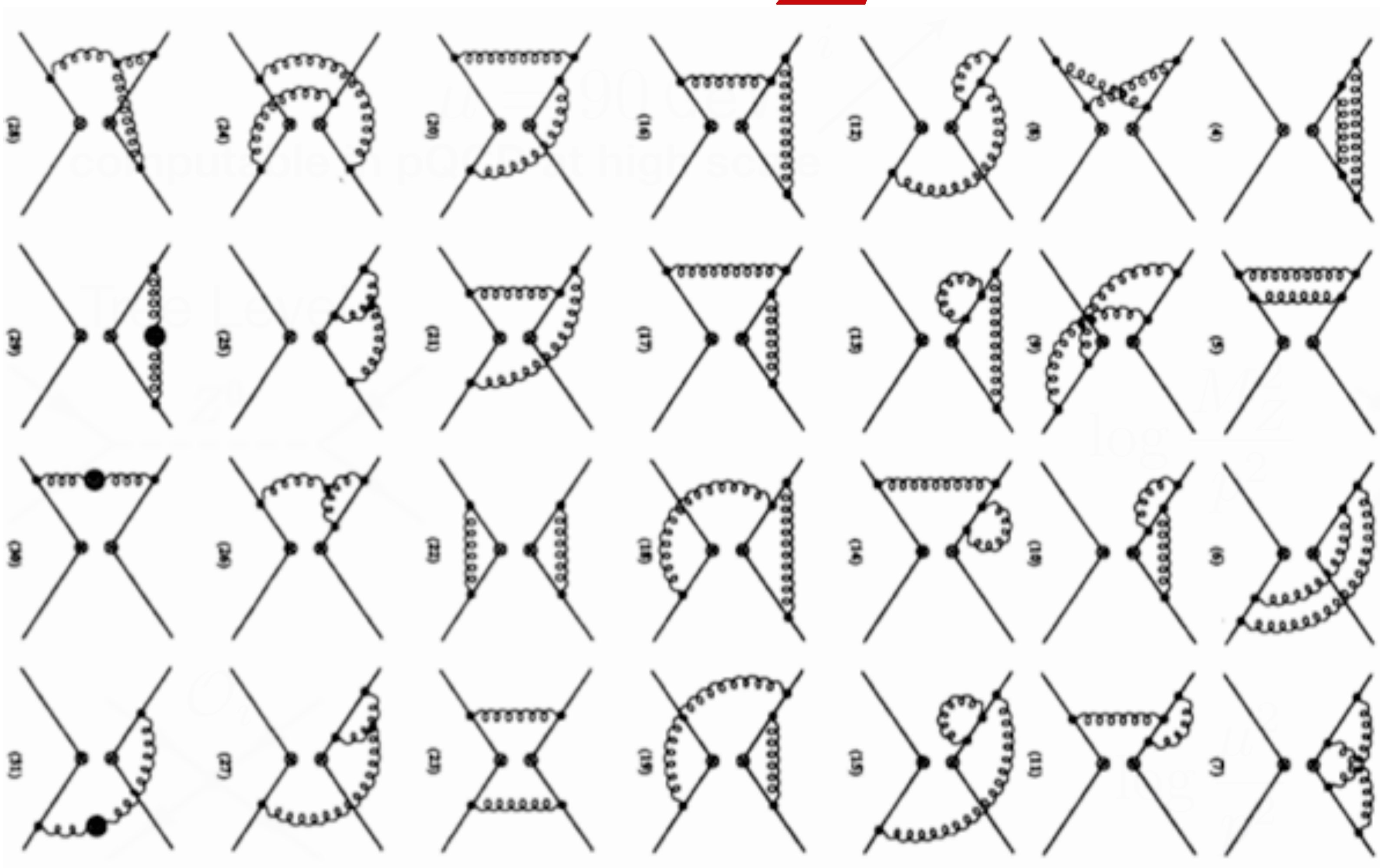

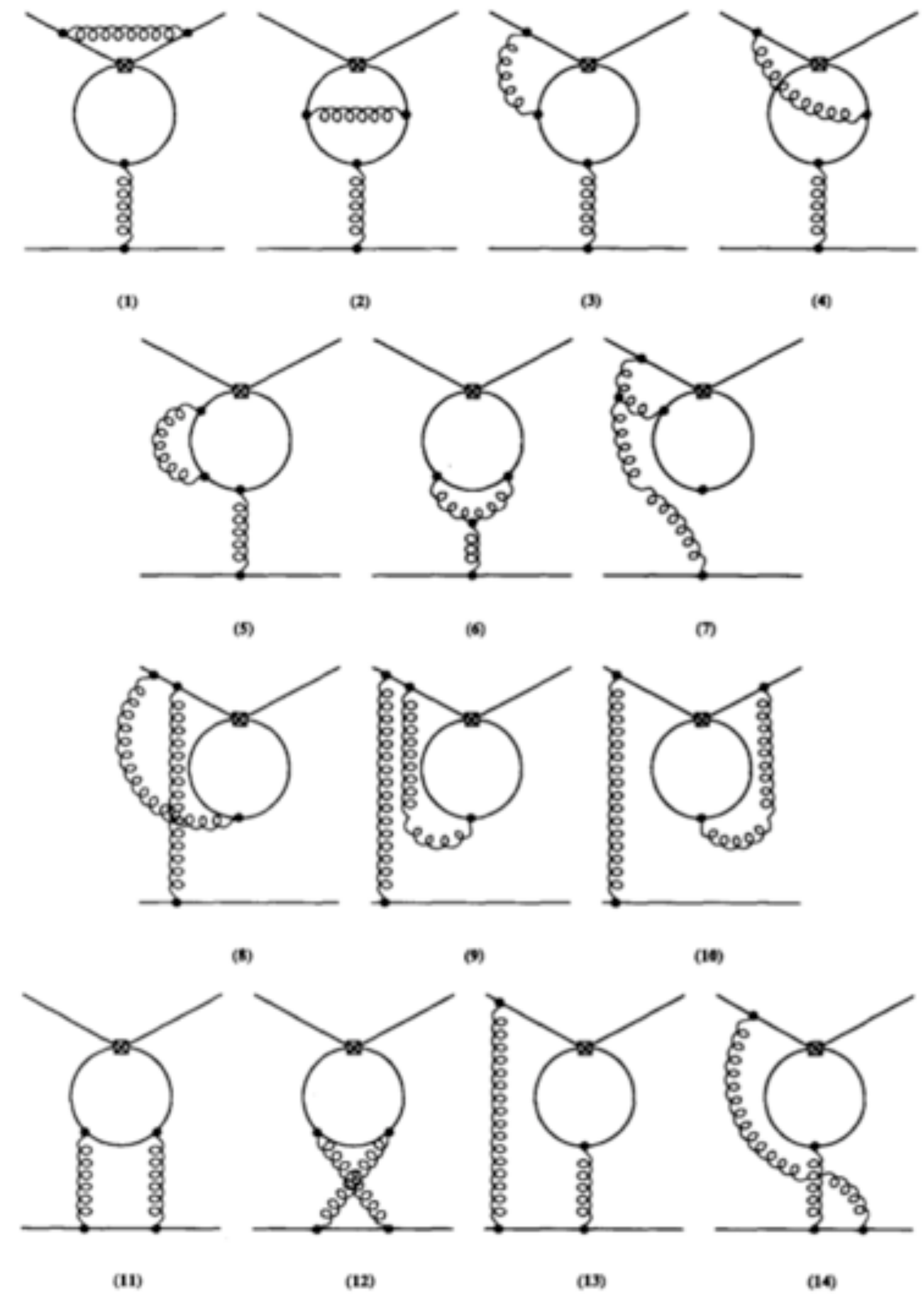

Two Loop

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

QCD Renormalization of Isovector Parity Violation

Results ('t Hooft-Veltman scheme)

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

ΔI = 1

Alleged: 95% probe of hadronic neutral current

$\sin^2\theta_W$ Non-Strange

vs.

1 Strange

80 - 100% Dynamical Question!

$C_i(\mu = 1\,\mathtt{GeV})\,/\,C_1^{\mathrm{Tree}}$

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4	0	(Fierz)	0	(Fierz)	0	(Fierz)	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

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

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Results ('t Hooft-Veltman scheme)

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

$\Delta I = 1$

Additional finding:
chiral basis reveals only **5** independent operators
(consequence of non-singlet chiral symmetry)

$L \otimes L - R \otimes R$

$L \otimes R - R \otimes L$

Alleged: 95% probe of hadronic neutral current

$\sin^2\theta_W$ Non-Strange

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computable on lattice at low scale

- Scale Invariance: requires same renormalization scheme

pQCD ‘t Hooft-Veltman scheme

5 independent PV operators in chiral basis

Anisotropic Lattice Regularization + Wilson Fermions

14 independent PV operators

Unphysical + unphysical chiral mixing

- Matching calculation required...

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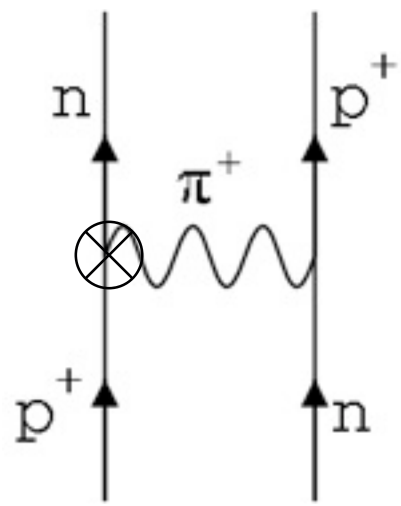

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Joseph Wasem **PRC 85, 022501 (2012)**

Signal Found $h^1_{\pi NN} = 1.1(5)\times 10^{-7} \pm ??$

- **Theoretical Challenges ΔI = 1 Processes**

Usual Suspects: pion mass, lattice spacing, lattice volume **to be done**

Additional Challenges: ~~Physical Kinematics **largely solved**~~

~~Multi-Hadron States and Normalization **to be done**~~

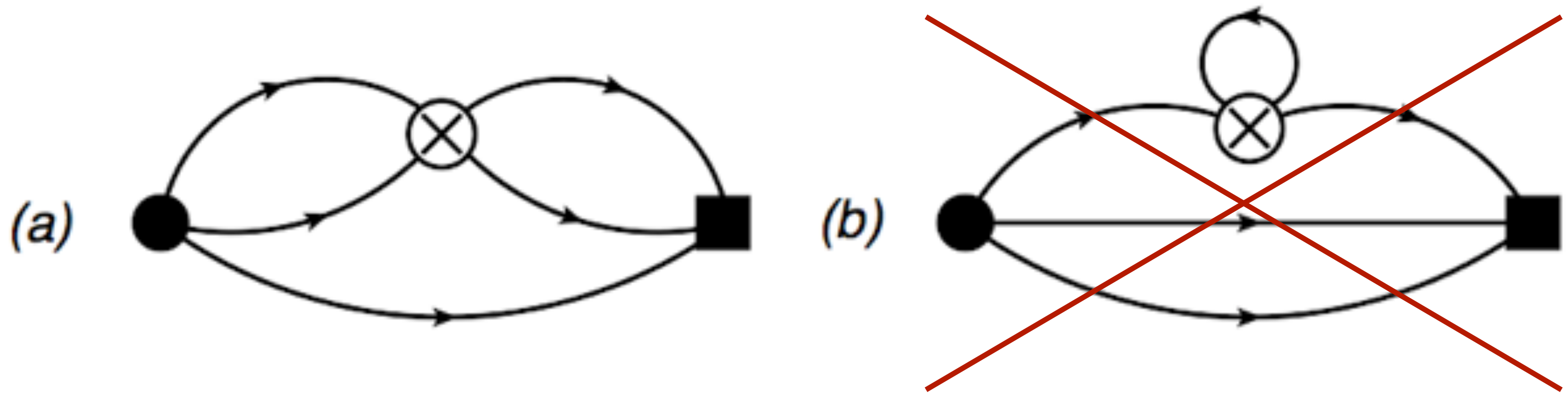
~~Operator Renormalization & Scale Invariance **to be done**~~

Statistically Noisy Operator Self-Contractions **to be done**

- **How many lattice advances carry over to weak nuclear processes?**

Statistically Noisy Operator Self-Contractions

$$G(\tau', \tau) = \langle 0 | N(\tau') \mathcal{O}_i(\tau) N^{*\dagger}(0) | 0 \rangle$$



Vector and Axial-Vector self-contractions

$\sin^2\theta_W$

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

$(a) + (b)$

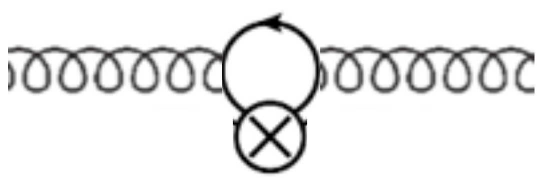
1

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

(b)

Wilson coeffs.

Another notorious difficulty



quark disconnected diagrams

Flavor dependence? $\sim m_q$

Extend to SU(3) + chiral corrections?

Utilize Fierz redundancy?

$\bar{s}s$ $\bar{s}\gamma_\mu s$

small nucleon strangeness

$$\langle \bar{s}\gamma_\mu s \rangle \ll \langle \bar{q}\gamma_\mu q \rangle ?$$

0.16 from Adelaide

Isotensor Parity Violation

$$\mathcal{O} = (\overline{q}\tau^3 q)_A (\overline{q}\tau^3 q)_V - \frac{1}{3}(\overline{q}\vec{\tau}\, q)_A \cdot (\overline{q}\vec{\tau}\, q)_V$$

- Only **one** operator & **without** self-contractions

$$\mathcal{L}_{PV}^{\Delta I=2} = \frac{G_F}{\sqrt{2}} C(\mu)\mathcal{O}(\mu)$$

Operator Renormalization

Tiburzi, PRD**86:** 097501 (2012)

LO	$C(1\,\mathtt{GeV})/C^{(0)}$
LO [15]	0.79
LO	0.70
NLO	$C(1\,\mathtt{GeV})/C^{(0)}$
't Hooft-Veltman	0.58
Naïve Dim. Reg.	0.74
RI/MOM	0.77
RI/SMOM($\gamma_\mu, \not{q}$)	0.67
RI/SMOM(γ_μ, γ_μ)	0.75
RI/SMOM($\not{q}, \not{q}$)	0.73
RI/SMOM($\not{q}, \gamma_\mu$)	0.81

1992 PDG
0.78(1)

[15] Kaplan Savage, NuPhA **556** (1993)

Wilson fermions still to do...

Better proving ground for Lattice QCD?

$$\mathcal{L}_{NN} = [\vec{\nabla} p^\dagger \cdot \vec{\sigma}\, \sigma_2\, p^*] \cdot [n^T \sigma_2\, n] + \ldots$$

s- to p-wave **NN** interaction

Operator matrix element between 2 hadrons
(one step beyond multi-hadron calculations done)

πN interactions

$$\mathcal{L}_{\pi\pi N} + \mathcal{L}_{\pi\gamma N}$$

External fields could ``substitute” for pions

πPV

Isotensor 3 pion interaction exists

Easier for lattice compute parameters in DDH model?

Summary

- **Lattice QCD**: Wilsonian machinery turns high-scale interactions (both SM & *Beyond*) into QCD-scale hadronic couplings
- After decades of dedicated work, trustworthy results emerging e.g. **$K \to \pi\pi$**
- **Some of this success will carry over to weak nuclear processes!**

Challenges = Opportunity

- **Hadronic Parity Violation**:
  πN-coupling more or less challenging than $K \to \pi\pi$?
  Use external axial fields for coupling to pions?
  Develop technology for isotensor NN-interaction?
  Isovector parity-violating lattices from auxiliary fields?