Ground State → Ground State Reactions

CEvNS And Coherent π Production

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Caltech

Neutrino Theory Network

PART 1

COHERENCE

- Why are coherent reactions simple?
- When do the GS→GS transitions dominate?
- How do we profit from kinematics?

PART 2

LOW ENERGY

- Coherence from limited kinematics.
- Elastic neutrino and electron scattering on nuclei.
- Higher order corrections & their uncertainties.

PART 3

PION PROD.

- Coherent-π production.
- Comparison vs $\nu e \to \nu e$ & CCQE.
- Proposal for future work + feedback solicitation.

Coherent Scattering

How Coherence Arises

$$\lim_{Q\to 0} \int \mathrm{d}x \;\; \mathrm{e}^{\mathrm{i}Q\cdot x} \, \langle B \,|\, J_\mu(x) \,|\, A \rangle \propto v_\mu \times (\text{some \#})$$

$$v^\mu J_\mu(x) = \rho(x) \qquad\qquad \int \mathrm{d}x \; \hat{\rho}(x) = \hat{Q}$$

$$(\text{some \#}) = \langle A \,|\, \hat{Q} \,|\, B \rangle = Q_A \, \langle B \,|\, A \rangle$$

How Coherence Arises

- Matrix elements are proportional to the charge of a particle in the point-like limit.
- An inherently low-q^2 expansion.

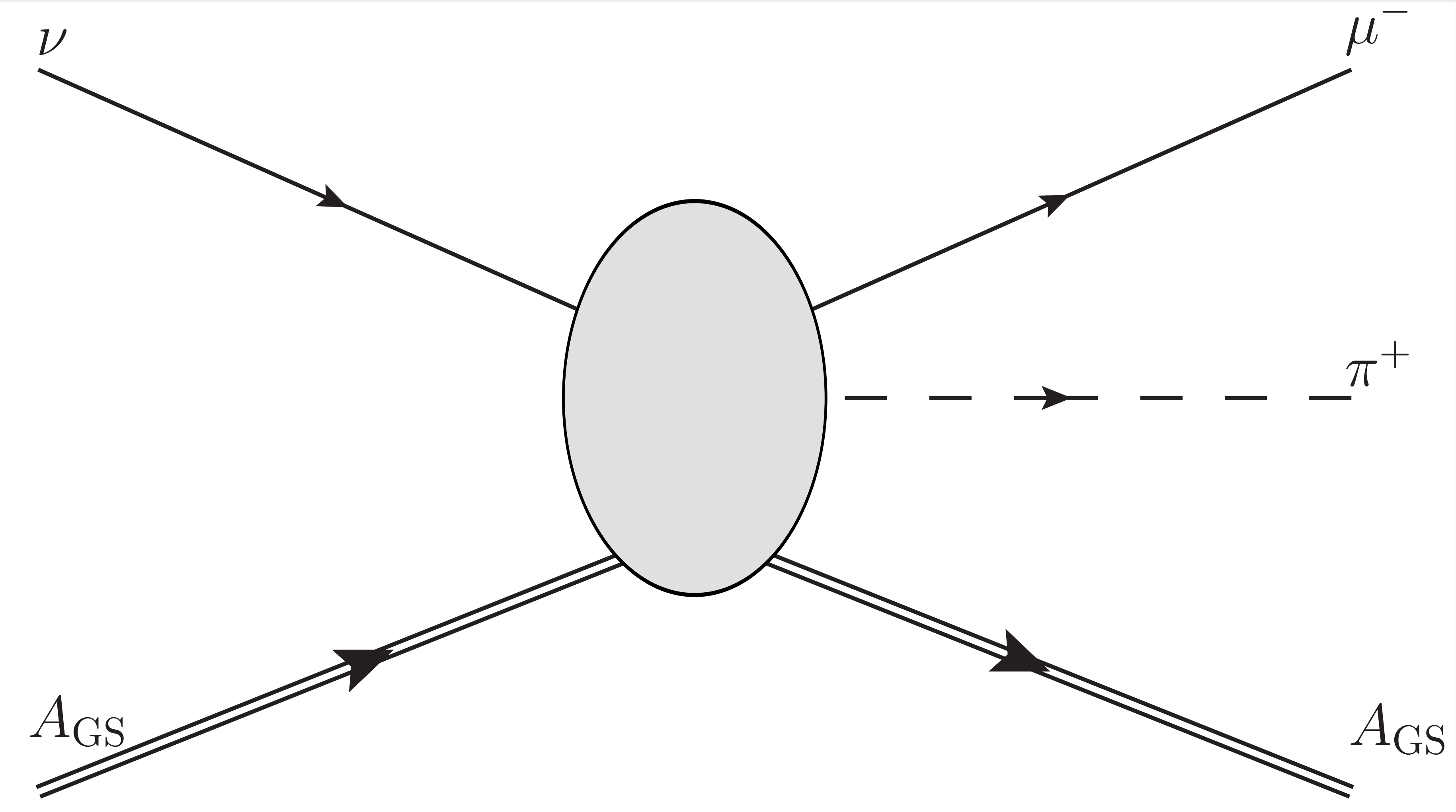
$$\lambda \gtrsim R$$

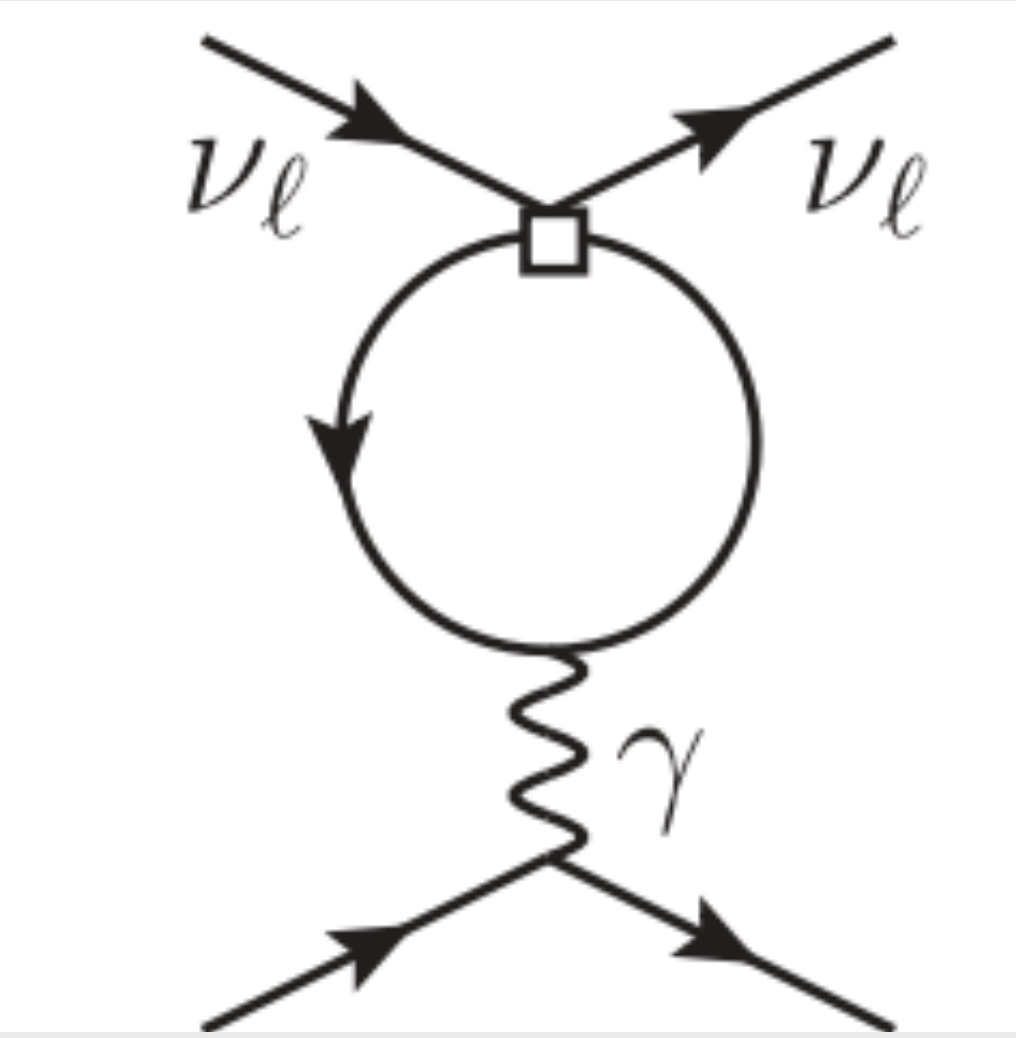
$$Q_A \, \langle B \,|\, \tilde{\rho}(q^2) \,|\, A \rangle$$

- "Static" matrix elements

Ground State → Ground State

- Matrix elements are simpler in the low-q^2 limit.
- Coherence enhances elastic final states.
  Dominates cross section in the relevant phase space.





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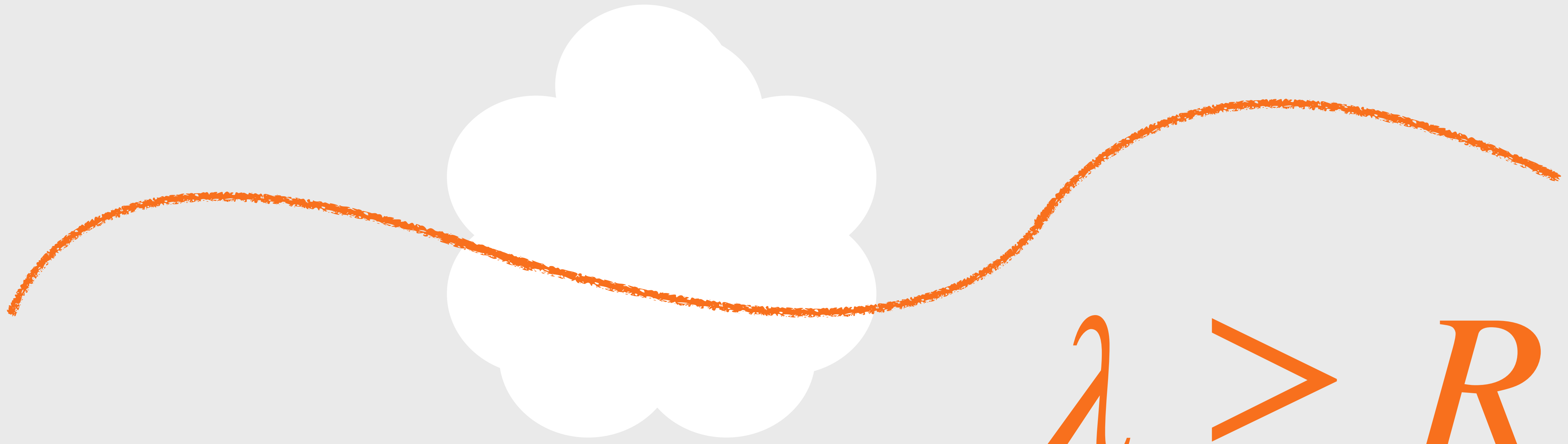

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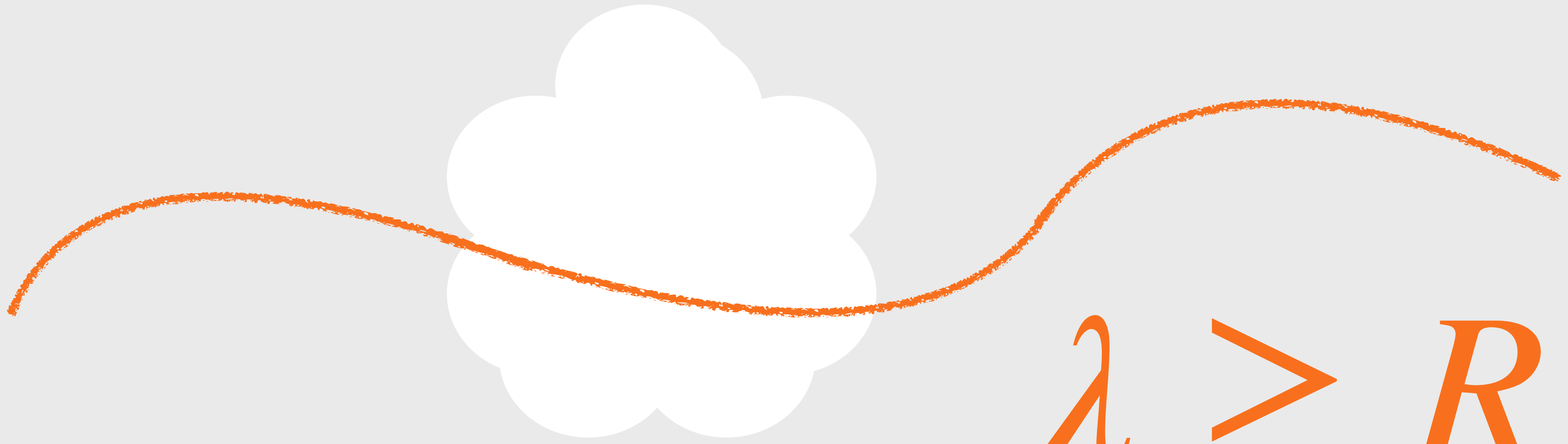

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QED Corrections To CEvNS At $O(\alpha)$

ARXIV:2011.05960

Simplest Coherent Process

$$\nu\, A_{\mathrm{GS}} \to \nu\, A_{\mathrm{GS}}$$

$$\frac{\mathrm{d}\sigma_{\nu_\ell}}{\mathrm{d}T} = \frac{\mathrm{G_F^2} M_\mathrm{A}}{4\pi}\left(1 - \frac{T}{E_\nu} - \frac{M_\mathrm{A} T}{2E_\nu^2}\right)\mathrm{F_W}\left(Q^2\right)$$

TREE LEVEL RESULT

STATIC MATRIX ELEMENT

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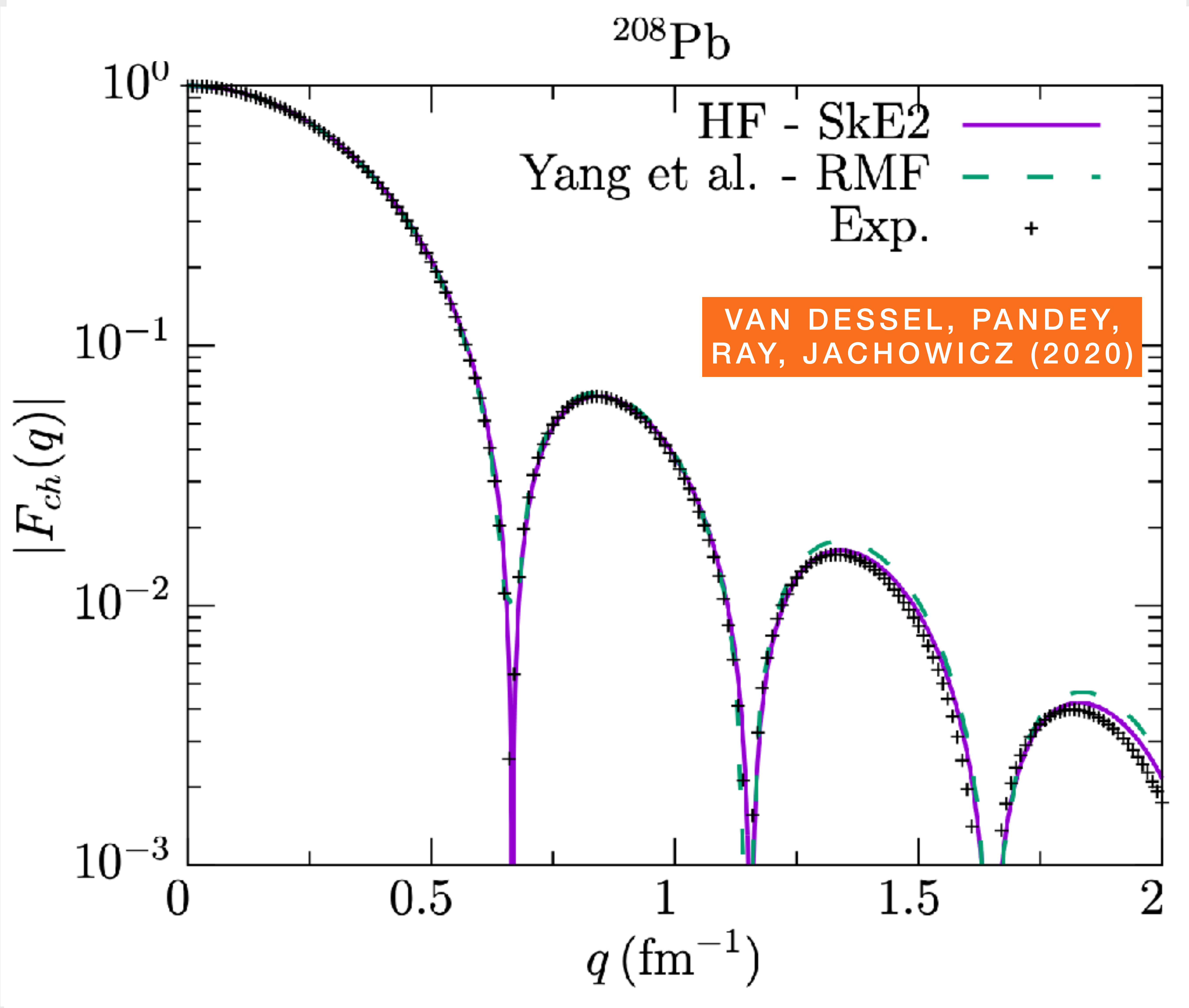
Weak Form Factor

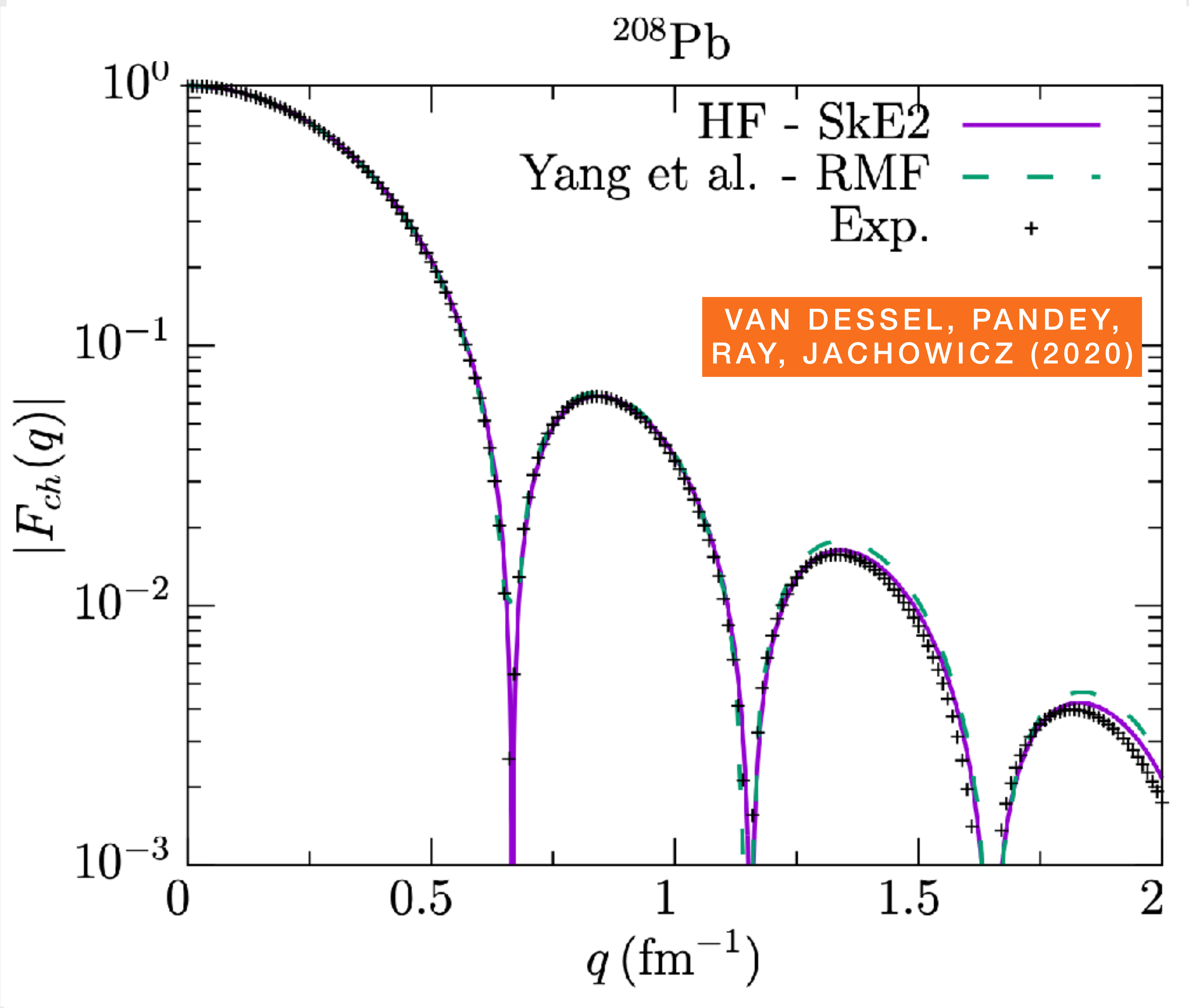


$$F_W(Q^2)$$

STATIC MATRIX ELEMENT

- Precise predictions available in literature.
- Charge form factor data reproduced extremely well.

Weak Form Factor



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Radiative Corrections

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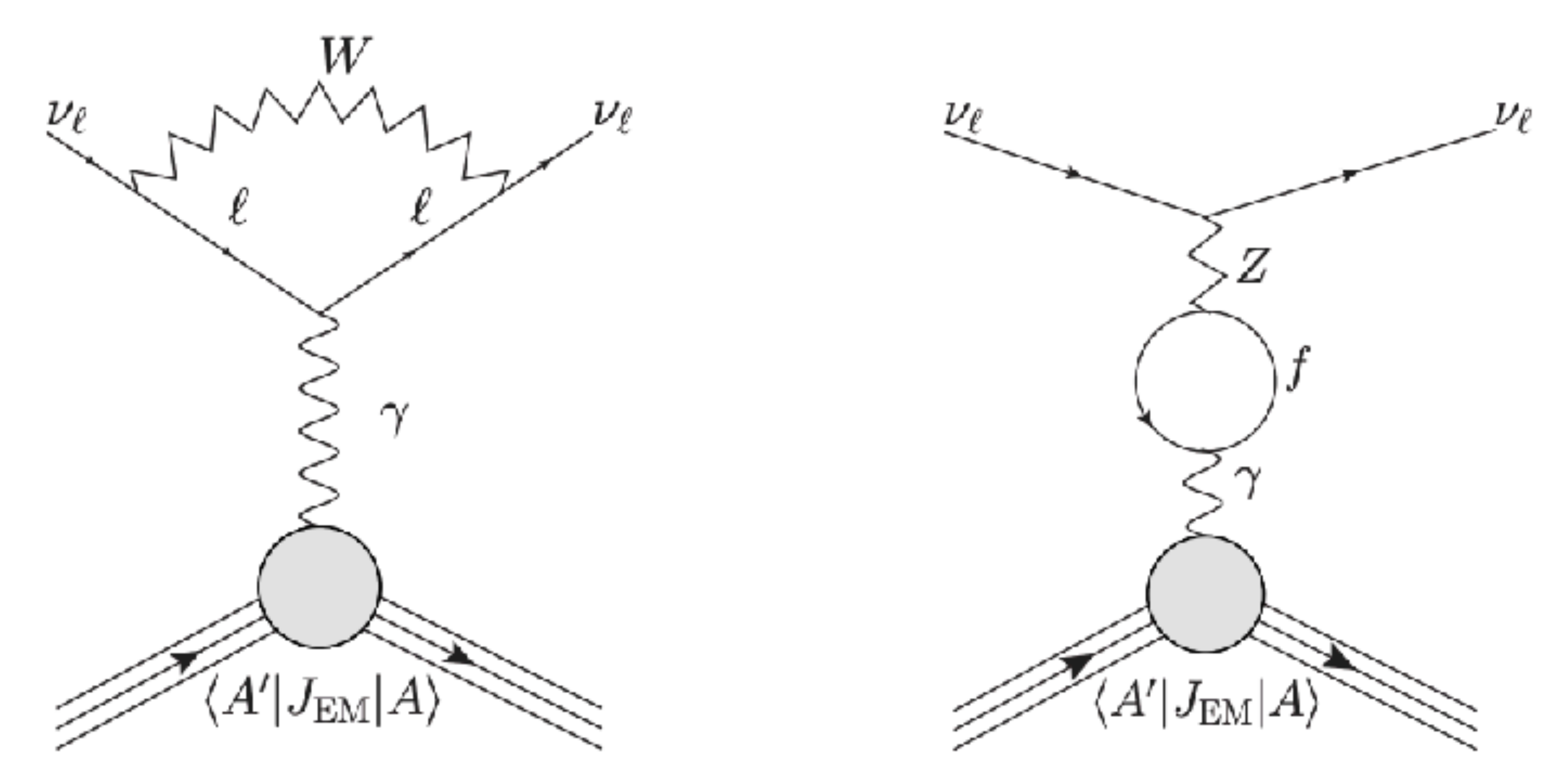
1-LOOP RESULT

- New matrix element needed at 1-loop.
- But it's the nuclear charge form factor.

STATIC MATRIX ELEMENTS



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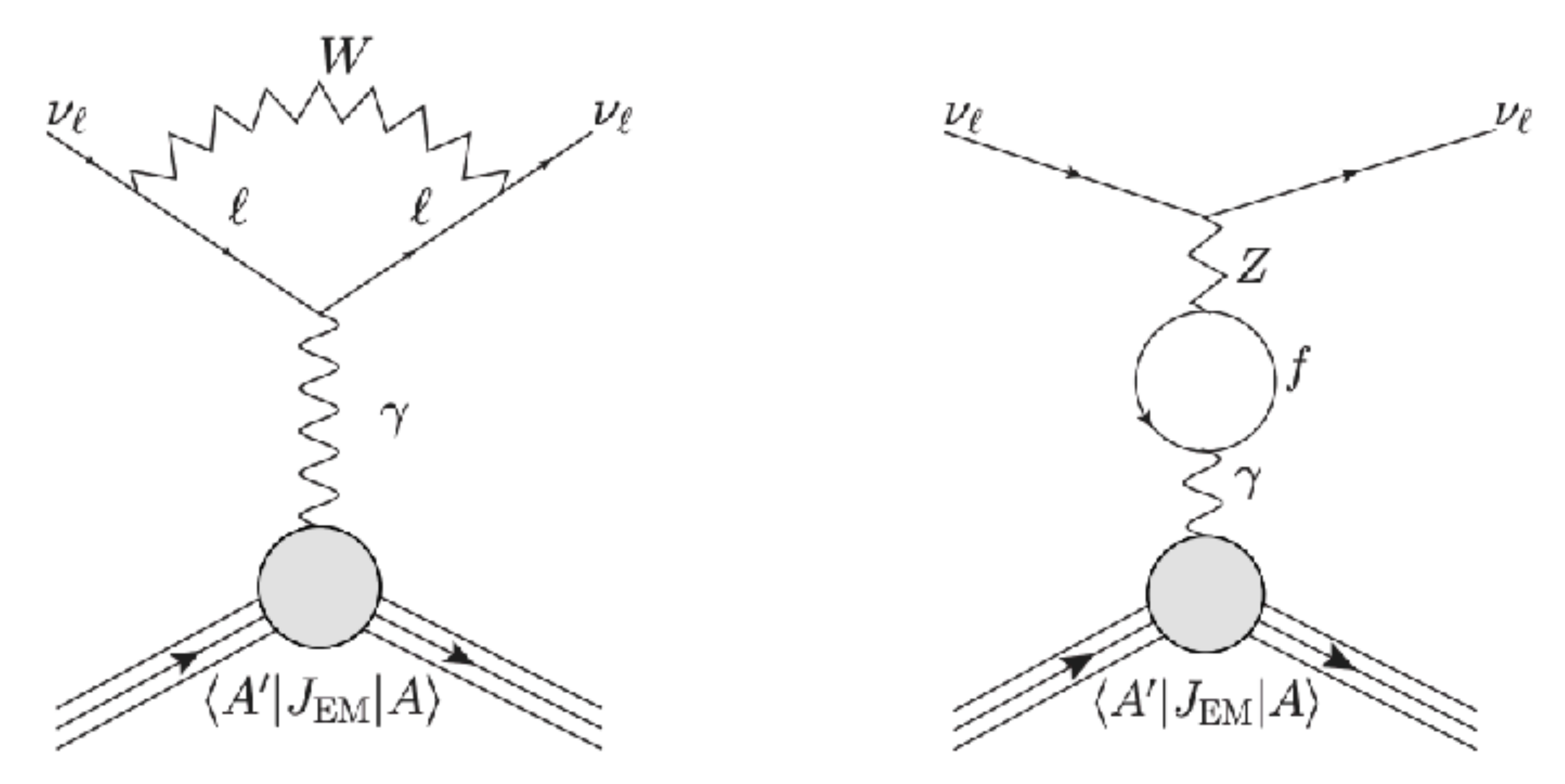

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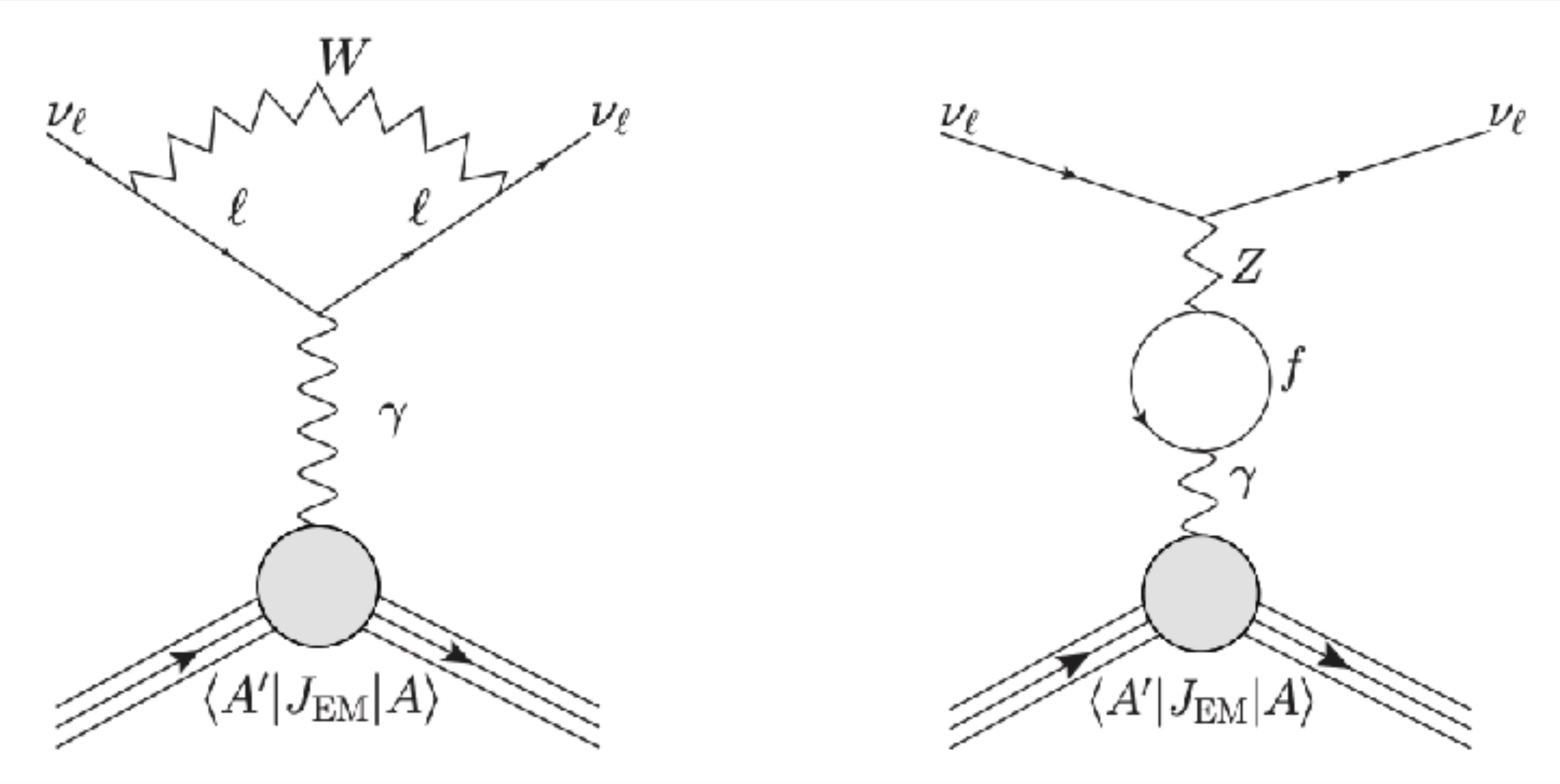

Results For Monoenergetic Neutrino

ARXIV:2011.05960

E_ν, MeV	$10^{40} \cdot \sigma_{\nu_\mu}$, cm^2	$10^{40} \cdot \sigma^0_{\nu_\mu}$, cm^2
50	34.64(1.36)	32.05
30	15.37(0.25)	14.23
10	1.91(0.01)	1.77

- Big $\sim 10\,\%$ corrections.
- Dominated by RG-running.

Construction Of Error Budget

E_ν, MeV	Nuclear	Nucleon	Hadronic	Quark	Pert.	Total	$10^{40} \cdot \sigma_{\nu_\mu}$, cm^2	$10^{40} \cdot \sigma^0_{\nu_\mu}$, cm^2
50	4.	0.06	0.56	0.13	0.08	4.05	34.64(1.36)	32.05
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- At small Q^2 we use nuclear radii & Taylor series.
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- Use uncertainties on charge/magnetic radii

$$\mathrm{G}^i_{\mathrm{E,M}}\left(Q^2\right) = \mathrm{G}^i_{\mathrm{E,M}}(0)\left[1 - \frac{\left(r^i_{\mathrm{E,M}}\right)^2}{6}Q^2 + \mathrm{O}\left(Q^4\right)\right]$$

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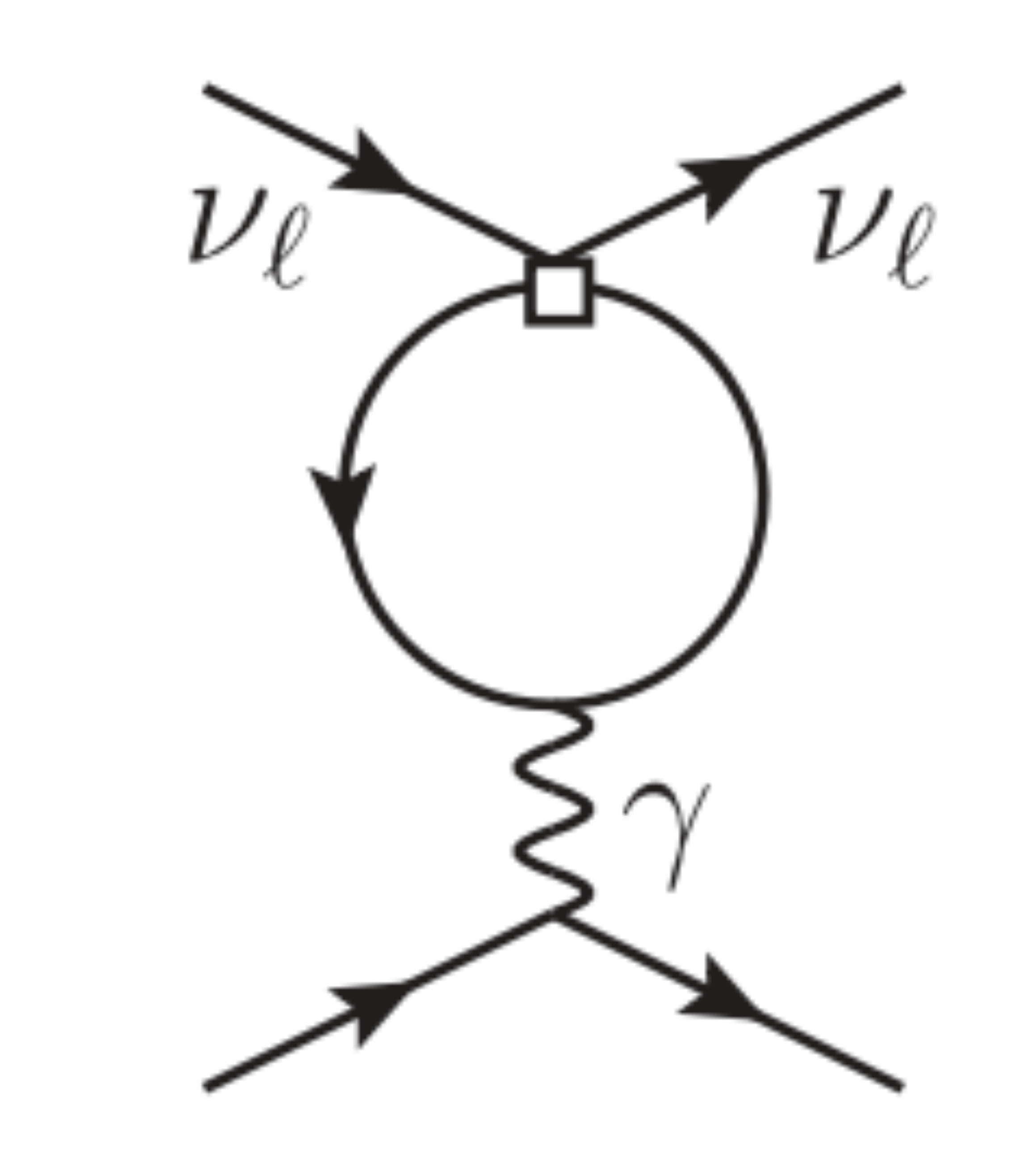

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- SU(3) symmetric estimate with large (ad hoc) 20% error

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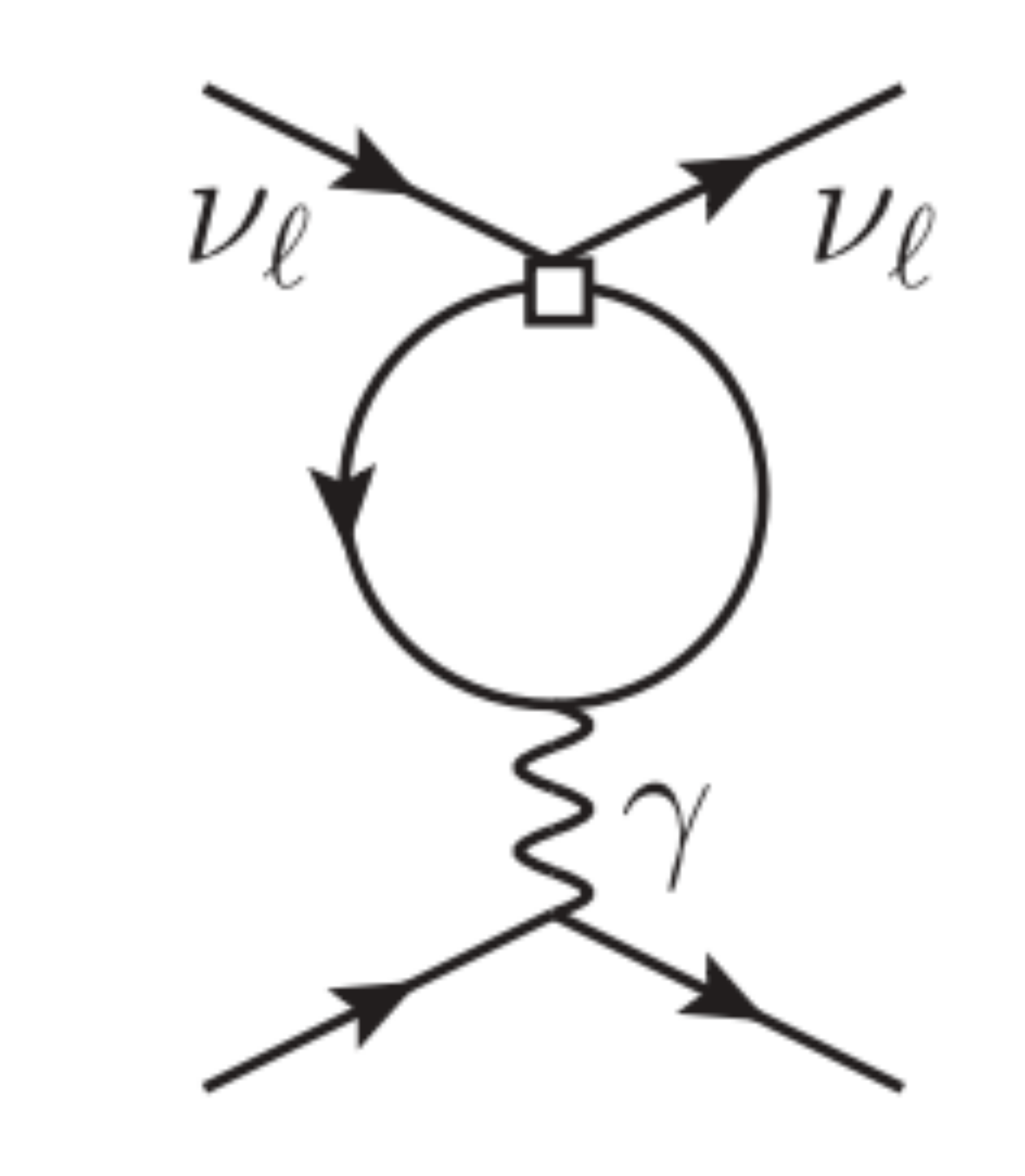

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- Variation of input parameters.
- Solve RG eq's.
- Add in quadrature.

LOW-SCALE
WILSON COEFFICIENTS

$c_{\rm L}^{\nu_\ell \ell'}$, $\ell = \ell'$	$c_{\rm L}^{\nu_\ell \ell'}$, $\ell \neq \ell'$	$c_{\rm R}^{\nu_\ell \ell'}$	$c_{\rm L}^{u}$	$c_{\rm R}^{u}$	$c_{\rm L}^{d}$	$c_{\rm R}^{d}$
2.39818(33)	−0.90084(32)	0.76911(60)	1.14065(13)	−0.51173(38)	−1.41478(12)	0.25617(20)
2.412	−0.887	0.763	1.141	−0.508	−1.395	0.254

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- Estimate of higher order logarithmic contributions.
- Well established procedure (with good empirical results) in EFT/pQCD literature

$$1 + \alpha(\mu)(\log \mu + \#)$$

$$+\alpha^2(\mu)(\log^2 \mu + \log \mu + \#)$$

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Coulomb Corrections To CEvNS

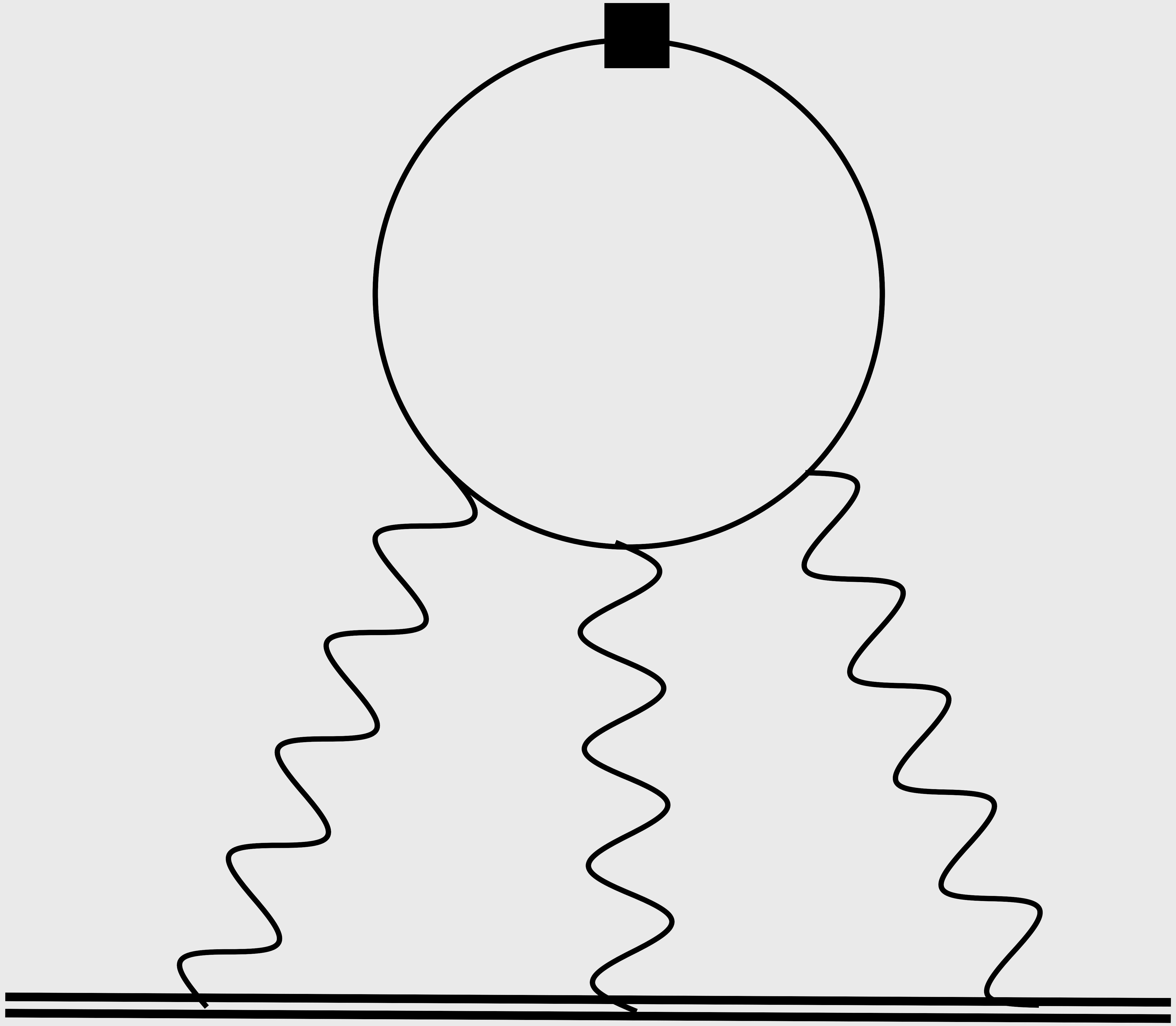
ARXIV:2304.09241

Radiative Corrections For Precision CEvNS

- Separation of scales and point-like expansion offers clean SM prediction.
- COHERENT aims for a future percent level measurement.
- Natural question: are we missing anything?

Coulomb Corrections & CEvNS

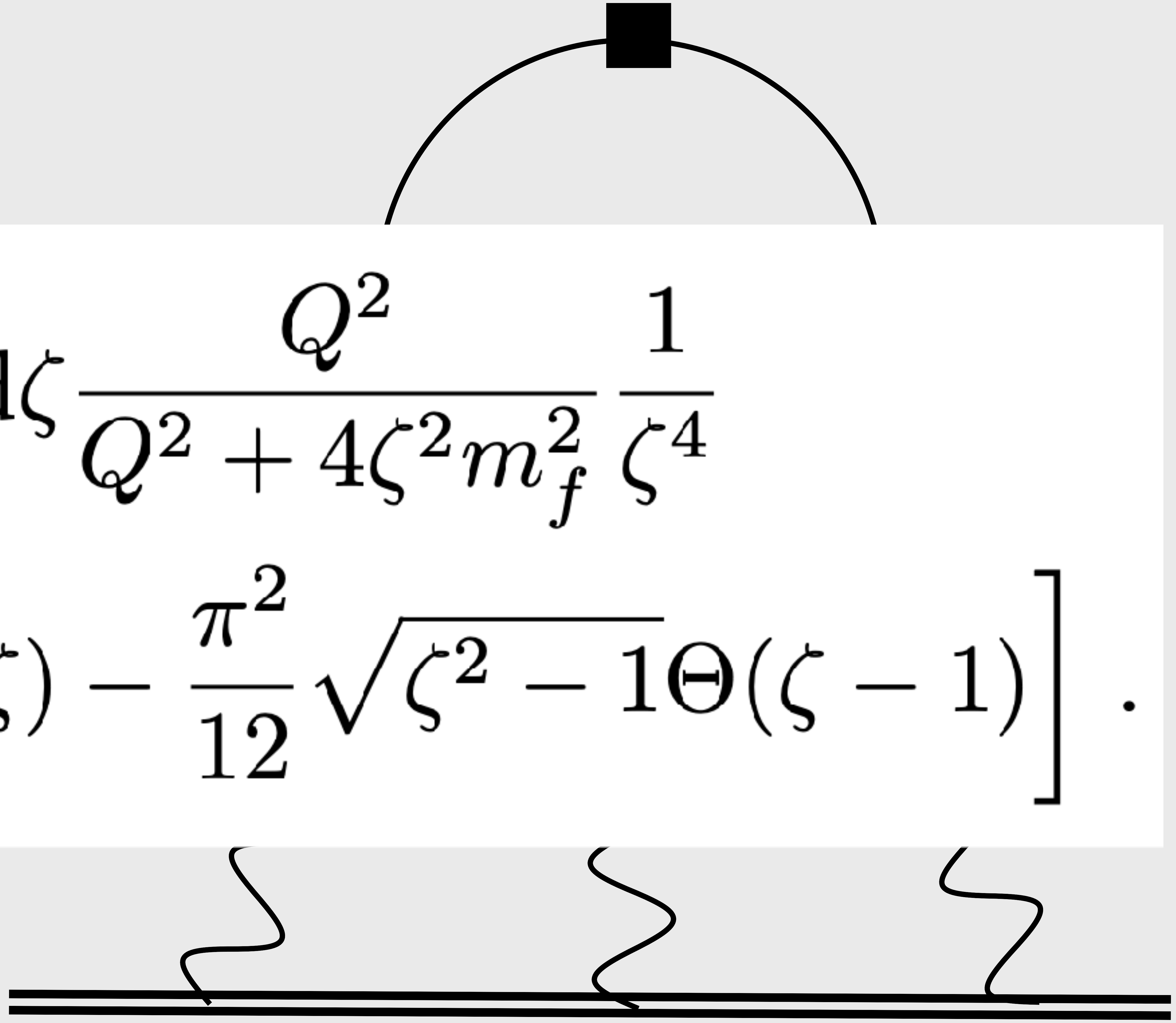
- Nature of observable requires using heavy nuclei with large Z.
- Higher orders in $Z\alpha$ are not necessarily small.
- This is a 3-loop effect. Not included in RG-running etc. of EFT analysis.



Coulomb Corrections & CEvNS

- Nature of observable

$$\Pi_{\mathrm{WK}}(Q^2, m_f) = \frac{1}{2}\int_0^\infty \mathrm{d}\zeta \frac{Q^2}{Q^2 + 4\zeta^2 m_f^2}\frac{1}{\zeta^4}\left[F(\zeta) - \frac{\pi^2}{12}\sqrt{\zeta^2 - 1}\,\Theta(\zeta - 1)\right].$$



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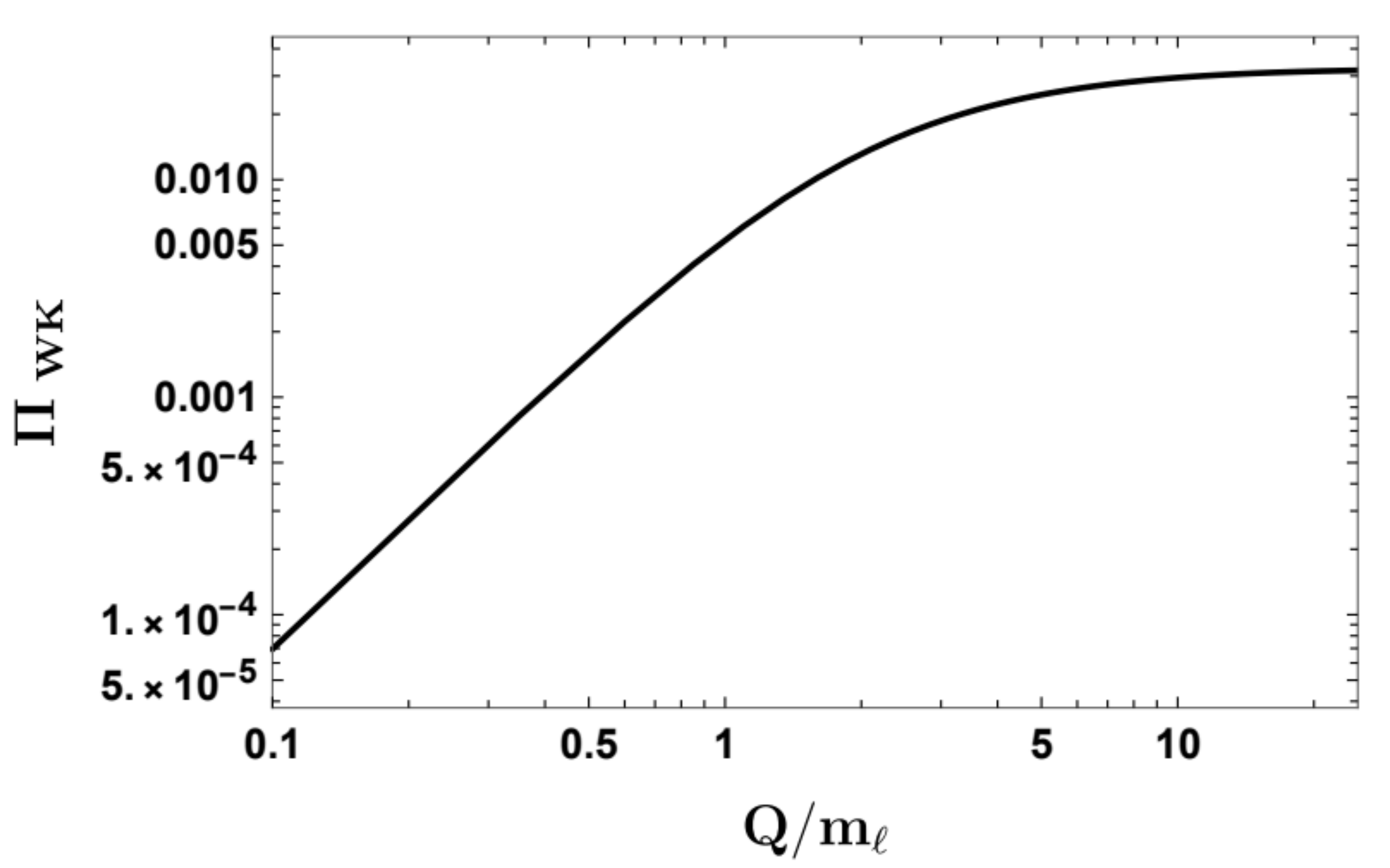
- included in RG-running etc. of EFT analysis.

Results For CEvNS

- Result is very small.
- Not obvious. Numerical cancellation of large numbers.



$$\lim_{Q\to\infty} \Pi_{\mathrm{WK}}(Q/m_\ell) = \frac{1}{2}\left[\frac{\pi^2}{6} - \frac{2}{3}\zeta(3) - \frac{7}{9}\right] \approx 0.03 \ .$$

Results For CEvNS

- Coefficient of $(Z\alpha)^2$ turns out to be ~100 times smaller than the 1-loop coefficient.
- Negligible for any realistic analysis.

Q	Asymmetry	$\mathcal{A}^{(0)}_{\ell,\ell'}$	$\mathcal{A}^{(1)}_{\ell,\ell'}$
1 MeV	$\ell = e \quad \ell' = \mu$	3.36	0.02
	$\ell = e \quad \ell' = \tau$	5.24	0.02
	$\ell = \mu \quad \ell' = \tau$	1.88	—
10 MeV	$\ell = e \quad \ell' = \mu$	2.12	0.03
	$\ell = e \quad \ell' = \tau$	4.00	0.03
	$\ell = \mu \quad \ell' = \tau$	1.88	—
30 MeV	$\ell = e \quad \ell' = \mu$	1.40	0.03
	$\ell = e \quad \ell' = \tau$	3.28	0.03
	$\ell = \mu \quad \ell' = \tau$	1.88	—

Other Necessities For Precision CEvNS

Radiative Corrections To Neutrino Spectra

- Pion and muon decays also modified by radiative corrections.
- Effects are calculated by O. Tomalak in arXiv:2112.12395.
- Small effects ~0.5% due to lack of logarithmic enhancements.

Inelastic Backgrounds

- Subdominant due to absence of coherence.
- Need to be "invisible" channels.
- See talk by V. Pandey and arXiv:2206.08590

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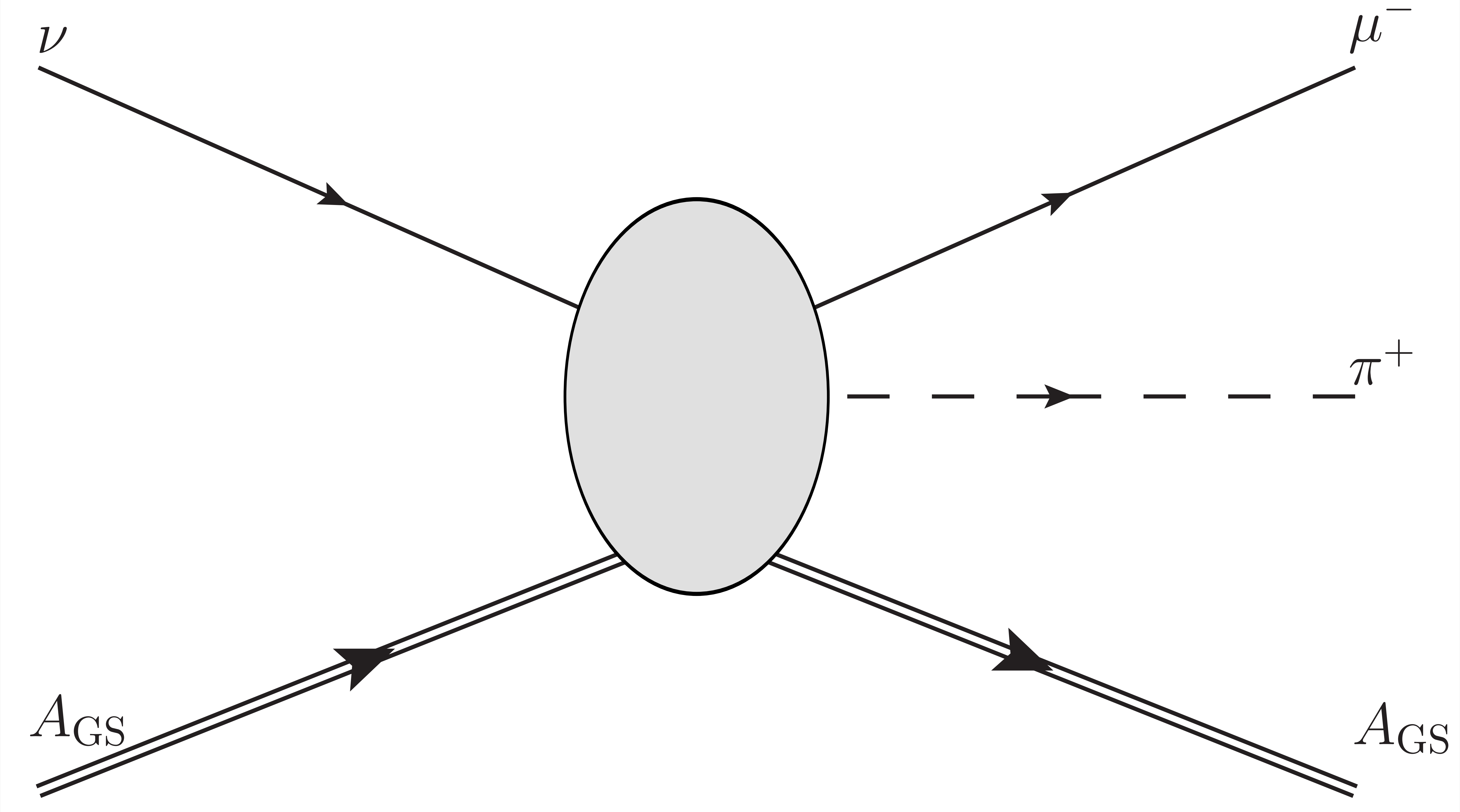
Coherent Pion Production

$$\nu \; A_{\mathrm{GS}} \rightarrow \ell \; \pi \; A_{\mathrm{GS}}$$

$$\nu\, A_{GS} \rightarrow \ell\ \pi\ A_{GS}$$

HADRONIC → NAIVELY COMPLICATED



COMPELLING FOR E_ν

- Pion and muon reconstructable.
- Minimal energy transfer to nucleus.

This Channel Is Worth Pursuing

- In the chiral limit, $m_\pi^2 = 0$, amplitude is related to $\pi\, A_{\rm GS} \to \pi\, A_{\rm GS}$ elastic scattering.
- Corrections to this limit are controlled by small parameters e.g. m_π^2/E_ν^2.
- Amplitude can be systematically expanded (in terms of hadronic matrix elements).

Discalaimer: Work In Progress. No Warranty Implied

This Part Of The Talk Is Propaganda

GOALS

- Convince you that a *bonafide* prediction of coherent pion production is possible within a systematic framework.
- Motivate experimental interest in:
    1. Do flux measurements with coherent pion production.
    2. Measure elastic pion scattering (differential in Q^2)
- Motivate theory work for necessary hadronic modeling.

1) Kinematics

$$E_\ell + E_\pi + T_A = E_\nu \implies p_\nu = (E_\nu, 0, 0, E_\nu)$$

$$p^\mu_{\pi\ell} = p^\mu_\pi + p_\ell \implies m^2_{\pi\ell}$$

$$m^2_{\pi\ell} \;\&\; \mathbf{p}_{\pi\ell} \;\&\; \mathbf{p}_\nu \implies \mathbf{Q}^2 = (\mathbf{p}'_A - \mathbf{p}_A)^2$$

FULLY RECONSTRUCTABLE KINEMATICS!

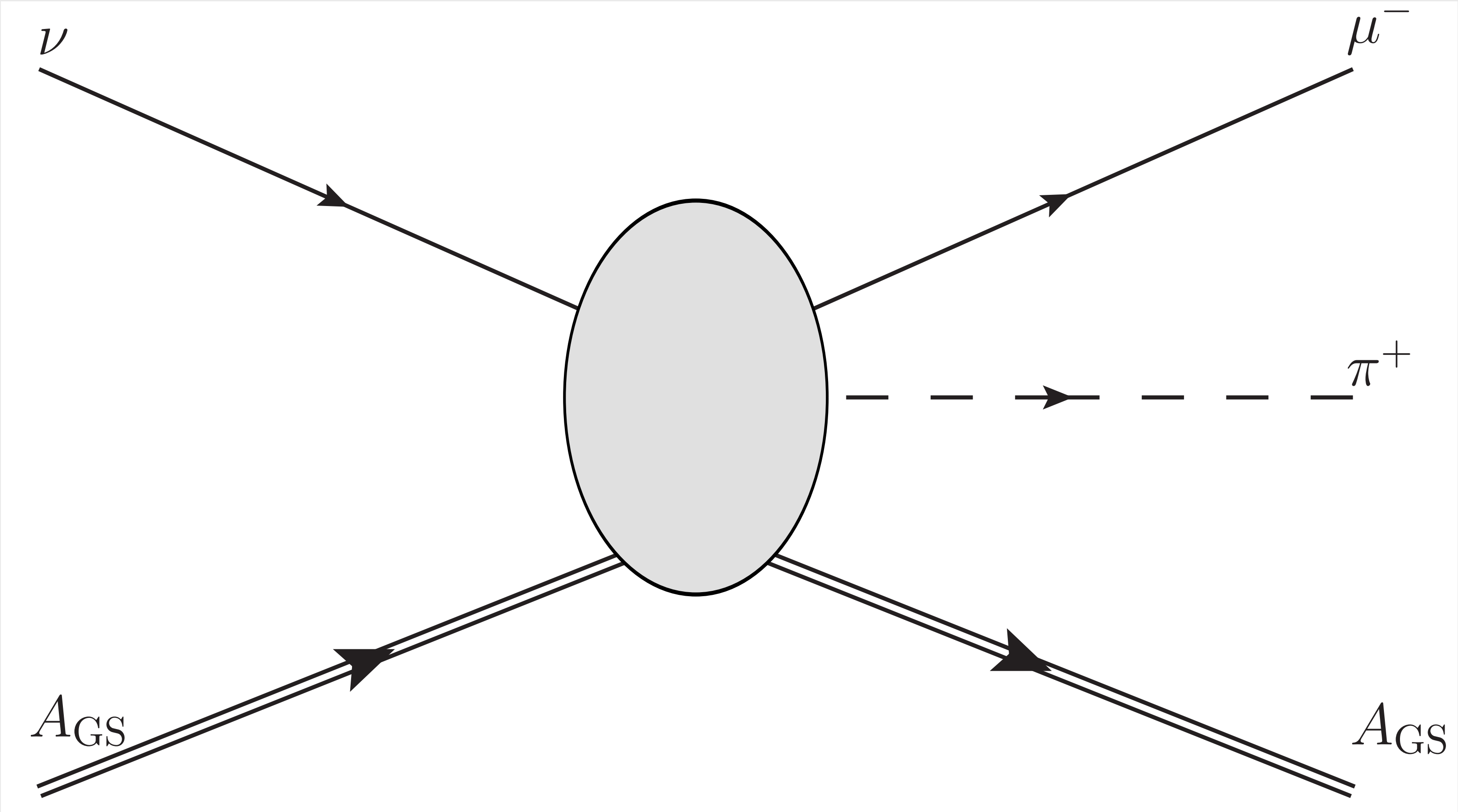
2) Statistics

- A good "standard candle" has two features:
    1. Good statistics.
    2. "Precision" theory.

Number of events

	$\nu e \to \nu e$	$\nu A \to \ell \pi A$	$\nu A \to \ell\ X$
	$E_\nu \sigma \sim 10^{-42}\ \mathrm{cm}^2\ \mathrm{GeV}$	$E_\nu \sigma \sim 10^{-40}\ \mathrm{cm}^2\ \mathrm{GeV}$	$E_\nu \sigma \sim 10^{-38}\ \mathrm{cm}^2\ \mathrm{GeV}$
Events DUNE	$\sim 3 \times 10^3$ /yr	$\sim 3 \times 10^5$ /yr	$\sim 10^8$ /yr

3) Chiral Symmetries



- Matrix element dominated by longitudinal axial current

$$\langle \pi A | J^A_\mu | A \rangle \epsilon^\mu_L = \epsilon^\mu_L A^{\mathrm{reg}}_\mu$$

- In chiral limit

$$\langle \pi A | J^A_\mu | A \rangle = \frac{f_\pi \kappa_\mu}{\kappa^2} T_{A\pi} + A^{\mathrm{reg}}_\mu$$

$$\kappa^\mu A^{\mathrm{reg}}_\mu = f_\pi T_{A\pi}$$

$$\epsilon^\mu_L \kappa_\mu = 0$$

- For $|\mathbf{Q}| \ll |\mathbf{p}_\pi|$

$$\epsilon^\mu_L A^{\mathrm{reg}}_\mu \approx \kappa^\mu A^{\mathrm{reg}}_\mu$$

ADLER (1964) , RHEIN & SEHGAL (1983), KARTAVTSEV, PASCHOS & GOUNARIS (2006)

Elastic Pion Nucleus Scattering

- At leading order in m_π^2/E_ν^2 we need data-driven input.
- Therefore need ***pion-<u>nucleus</u>*** elastic scattering data.
- Must match relevant experimental targets.

USE NEW DATA FROM EMPHATIC & NA61/SHINE

EXPRESION OF INTEREST

Measurements of kaon and pion scattering in the WCTE facility at CERN

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Safe Vs Dangerous Phase Space

$$\sigma_{\text{safe}}(E_\nu) = \int_{\text{safe}} d\Pi \sum_{\text{spins}} |\mathcal{M}|^2$$

SAFE := WHERE APRROX. WORK

$$\sigma_{\text{safe}}(E_\nu) \leq \sigma(E_\nu)$$

$$\Phi(E_\nu) = N_{\text{safe}}(E_\nu)/\sigma_{\text{safe}}(E_\nu)$$

Safe Phase Space

- Both lepton and pion should be forward going.
- Small opening angles.

$$E_\pi^2 \gg m_{\ell\pi}^2 \gg Q^2 \qquad \theta_{\ell\pi} \lesssim \frac{(200\ \mathrm{MeV})}{E_\nu}$$

- Small momentum transfers.

Summary Of The Propaganda

- A *bonafide* prediction of coherent pion production is possible within a systematic framework.
- I think there should be experimental interest in:
    1. Flux measurements with coherent pion production.
    2. Measure elastic pion scattering (differential in Q^2).
- More theory work is needed.