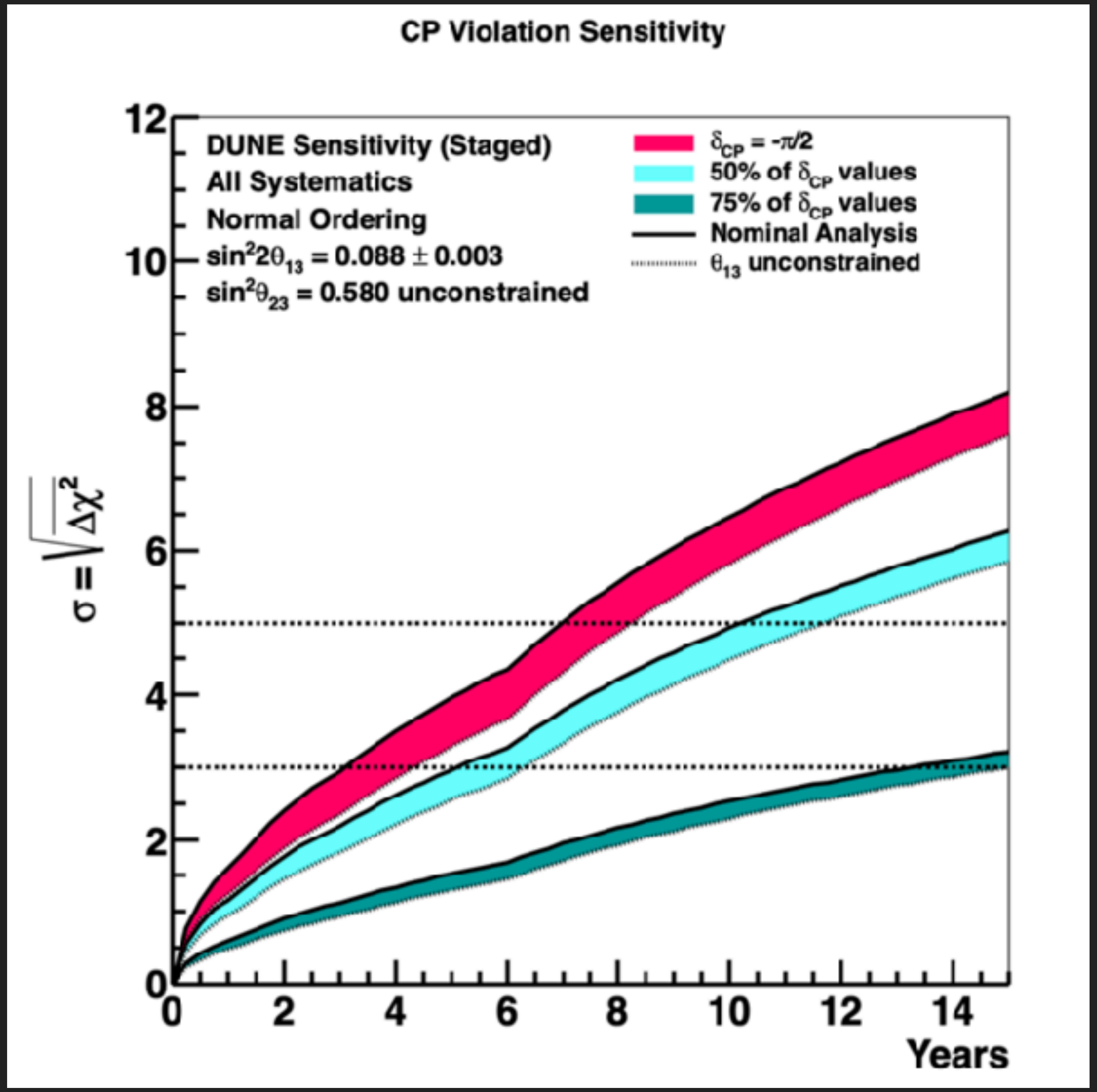
EUROPEAN PHYSICAL SOCIETY | HEP MEETING 2021

JULY 30 2021 | RYAN PLESTID | UNIVERSITY OF KENTUCKY (AND FNAL)

NEUTRINOS NUCLEI & QED

MOTIVATION

- Let us take DUNE as a ``flagship'' example.
- Expects $\sim O(10^8)$ CC events in near detector
- Absent near detector, must deal with O(10%) uncertainty on (cross section) x (flux)
- Require percent level predictions.
- Systematic issue: near beam is all muon neutrinos, far beam is oscillated.

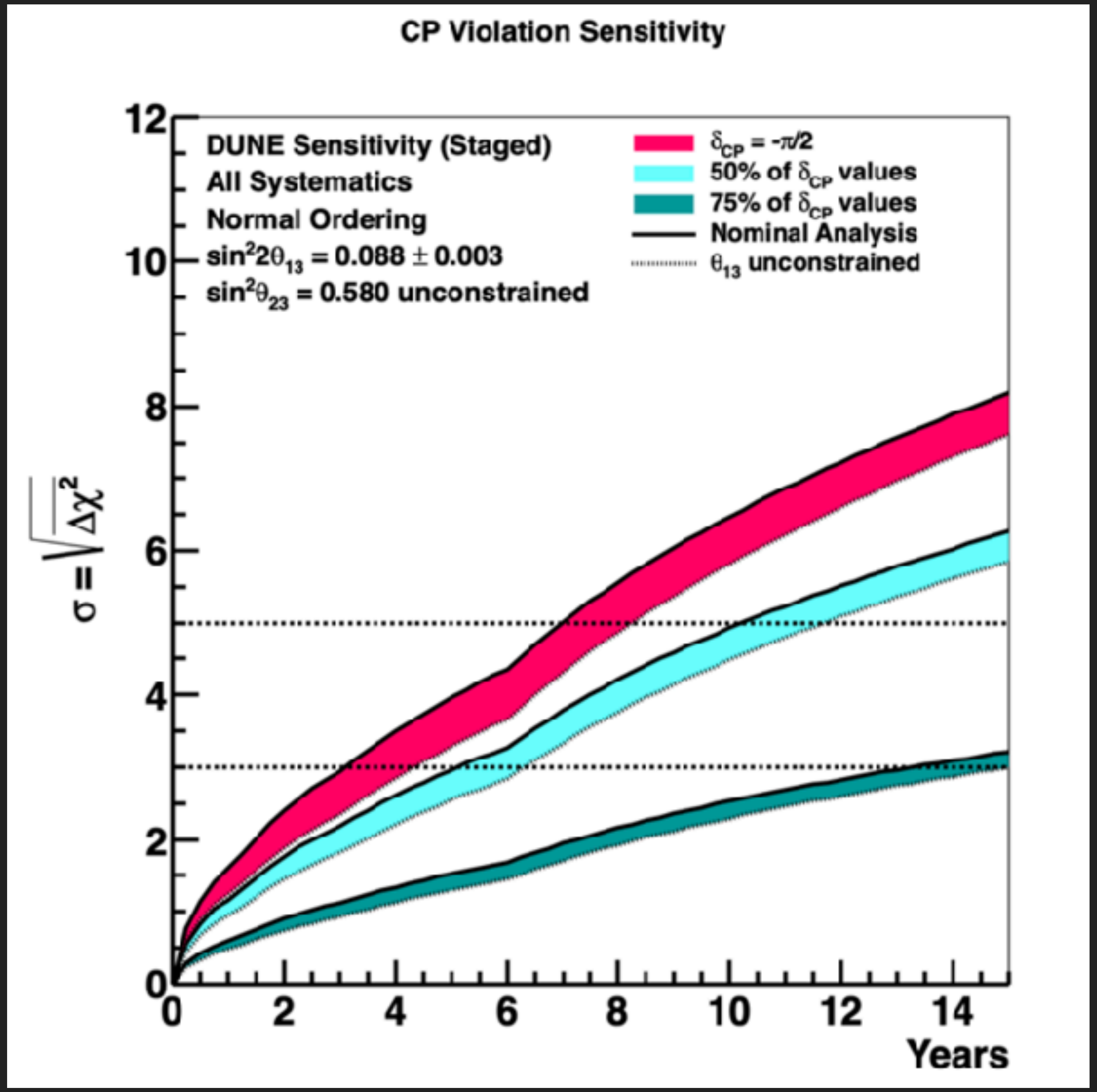


5.5 The Near Detector Simulation and Reconstruction

Oscillation parameters are determined by comparing observed charged-current event spectra at the FD to predictions that are, *a priori*, subject to uncertainties on the neutrino flux and cross sections at the level of tens of percent as described in the preceding sections. To achieve the required few percent precision of DUNE, it is necessary to constrain these uncertainties with a highly capable ND suite. The ND is described in more detail in Volume I, Introduction to DUNE.

MOTIVATION

- Systematic issue:
  - Near beam is all muon neutrinos
  - Far beam is oscillated.
- QED effects depend on lepton mass.
- Lepton mass induces ***flavor dependent neutrino cross sections.***



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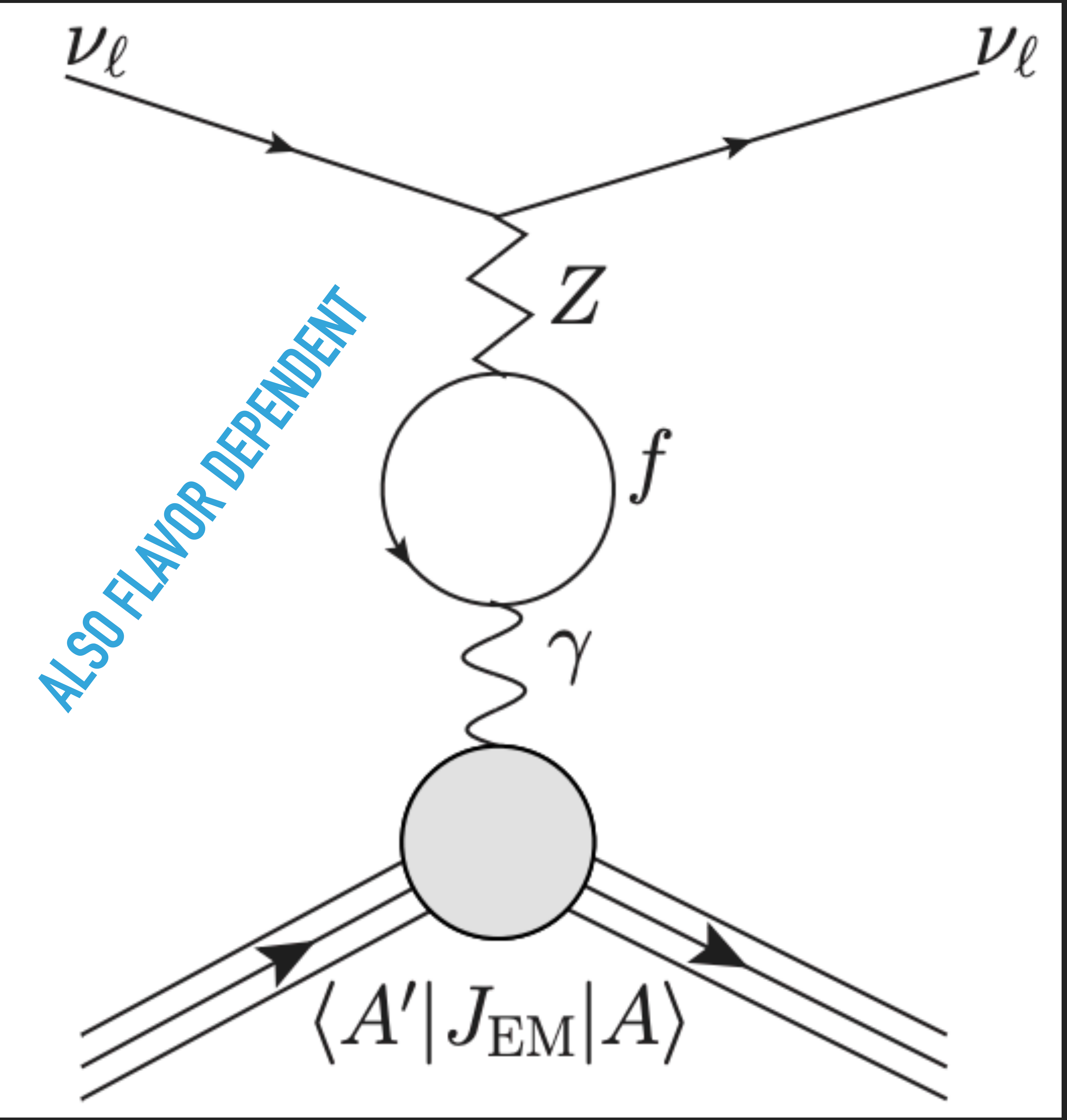
WHAT THIS TALK IS ABOUT?

- Neutrinos and leptons talking to photons.
- QED corrections to standard neutrino cross sections.
- Importance of QED corrections at the intensity frontier for percent-level precision.



THREE INPUTS FOR CROSS SECTIONS

- Nucleon level inputs. Form factors etc. ← Flavour blind
- Nuclear response (including FSI). ← Flavour blind
- Radiative corrections. ← Flavour depdendent

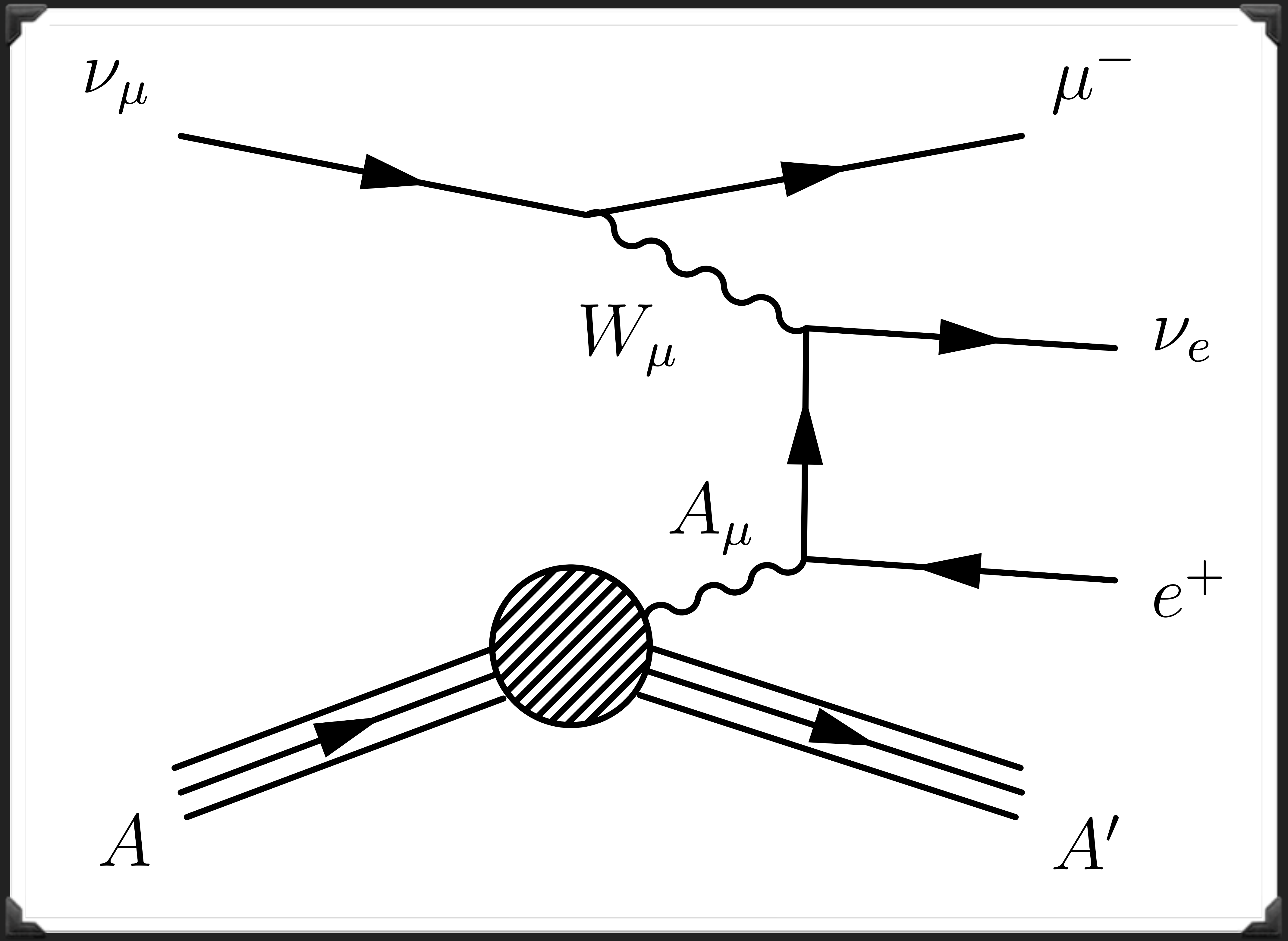
$$\frac{\alpha}{\pi}\log(E_\nu/m_\ell) \qquad \pm\frac{\pi Z\alpha}{v}$$

NEUTRINO TRIDENT PRODUCTION

$$\sigma \sim G_F^2 \times \alpha^2 Z^2 \log(m_\ell/E)$$

$$\nu\, Z \to \nu_i\, \ell_j^+\, \ell_k^-\ \ Z$$

- Can pick up a coherent enhancement in the small Q^2 regime.
- Same regime yields a log-enhancement.
- This is roughly speaking the smallest SM cross section with reasonable statistics at next generation facilities.



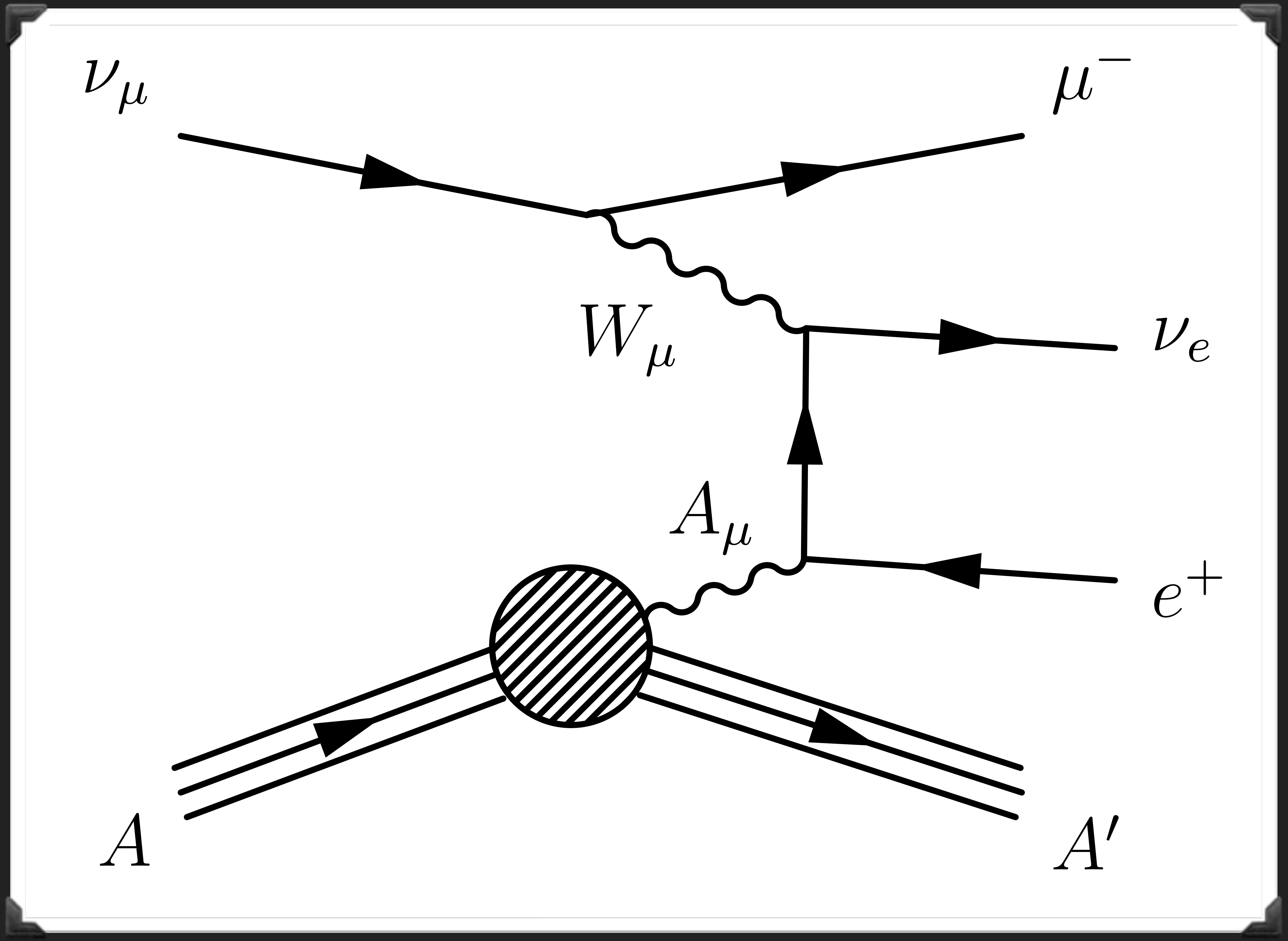
ESTIMATING THE SIZE OF QED EFFECTS

$$\sigma \sim G_F^2 \times \alpha^2 Z^2 \; \log(m_\ell/E)$$

- All neutrino processes must pay a penalty of G_F^2.
- QED corrections interference with tree-level

$$\left[G_F\left(1+\frac{\alpha}{\pi}\delta_{RC}\right)\right]^2 \sim G_F^2 + \frac{\alpha}{\pi}\, G_F^2$$

- Soft-regions see a coherent effect $\alpha \to Z\alpha$
- Soft & collinear regions yield large logarithms L .
- Kinematic/phase space factors can also enhance rates.

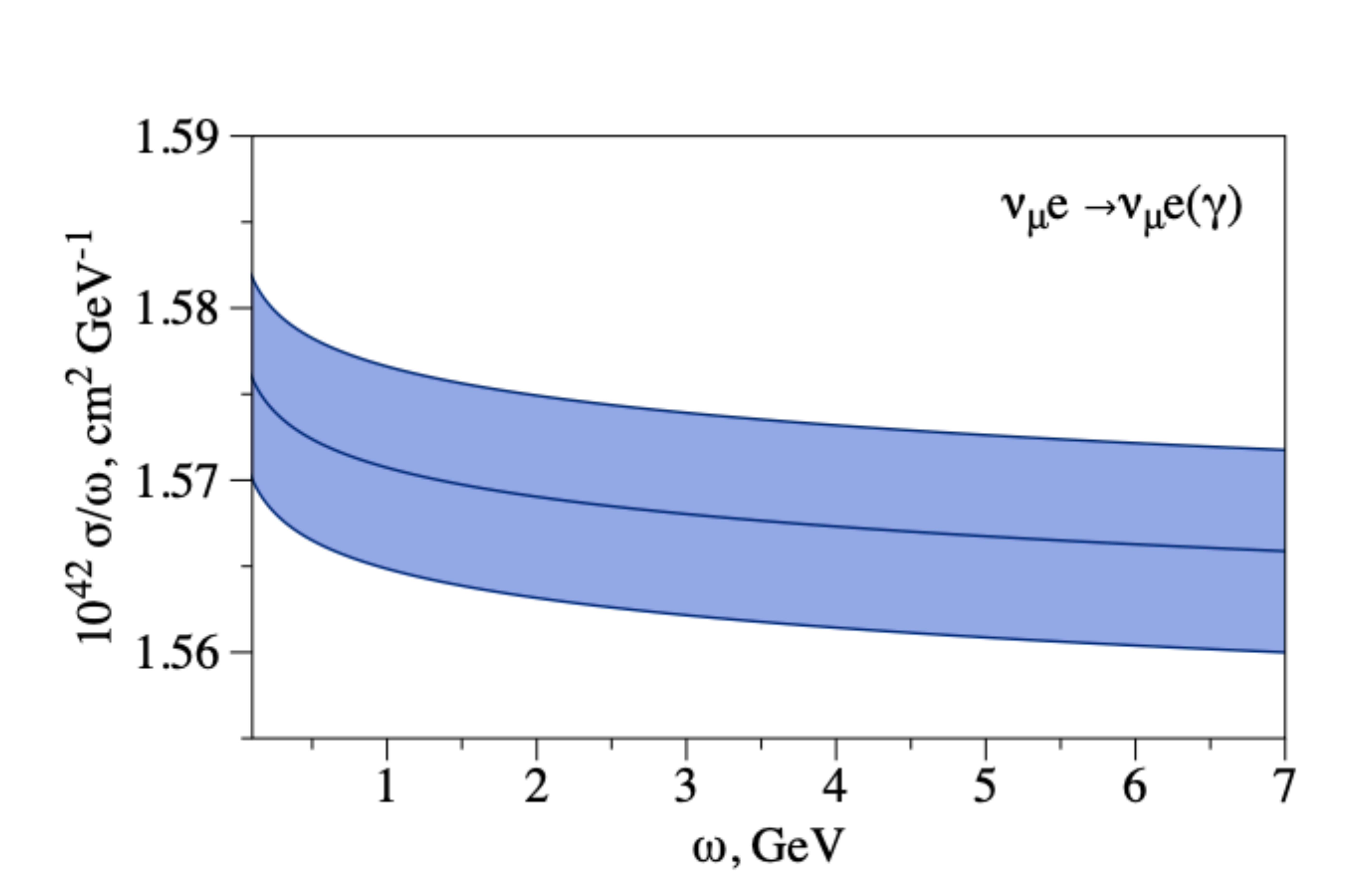


RECENT WORK WORTH HIGHLIGHTING

- Neutrino-Electron scattering at NLO in α

Tomalak & Hill 2019

arXiv:1907.03379



RECENT WORK WORTH HIGHLIGHTING

- CCQE. at NLO in α

  Tomalak, Chen, Hill, McFarland 2021

  arXiv:2105.07939

  (see also arXiv:1206.6745 Day & McFarland 2012)

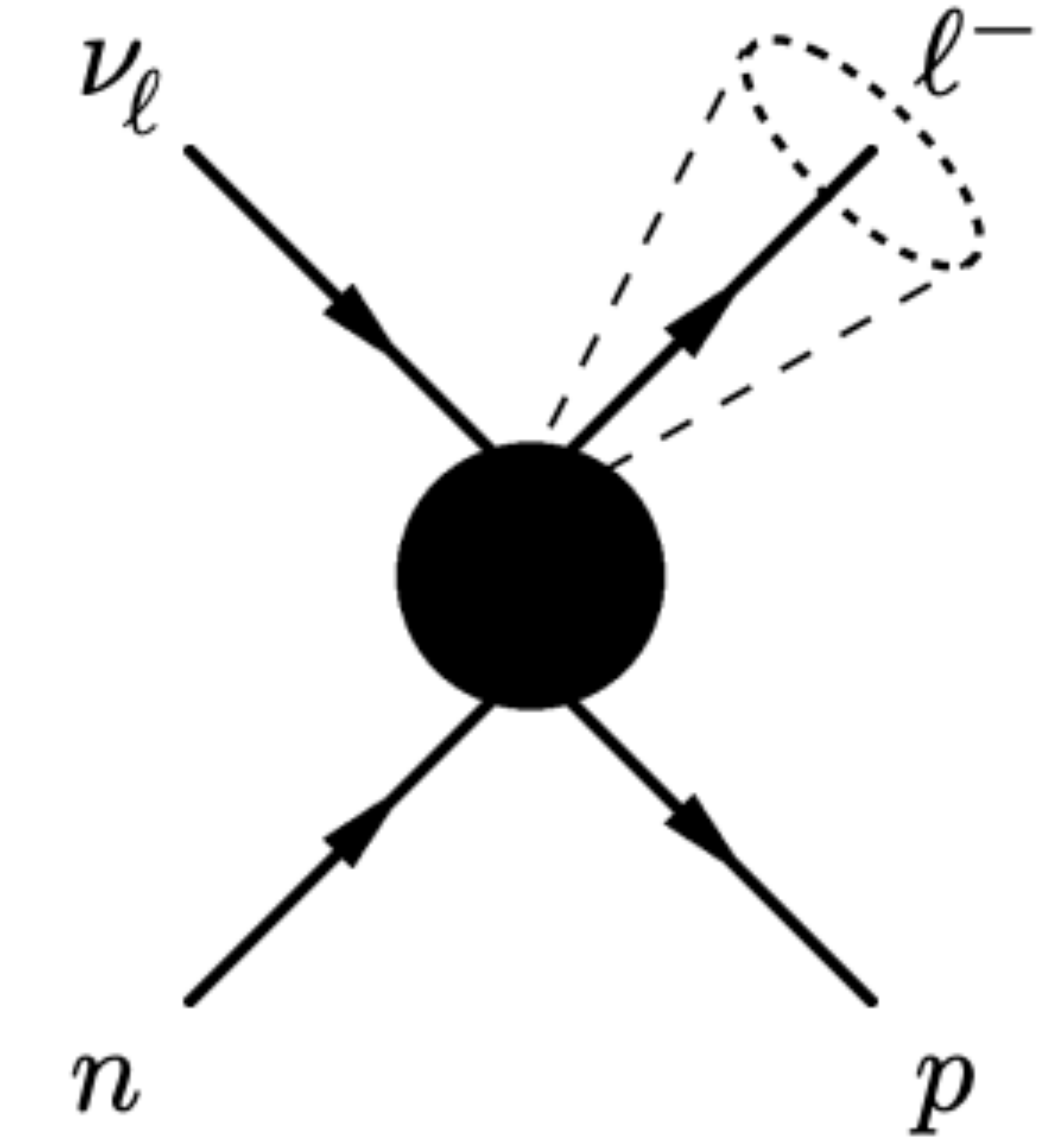


FIG. 1: Schematic representation of charged current eastic event. Photons that are within an angle $\Delta\theta$ of the charged lepton, or that have energy below ΔE, are included in the cross section.

RADIATIVE CORRECTIONS FOR CEVNS

BASED ON ARXIV:2011.05960

OLEKSANDR TOMALAK, PEDRO MACHADO & VISHVAS PANDEY

RELATED WORK FOR $\nu\, e^- \rightarrow \nu\, e^-$

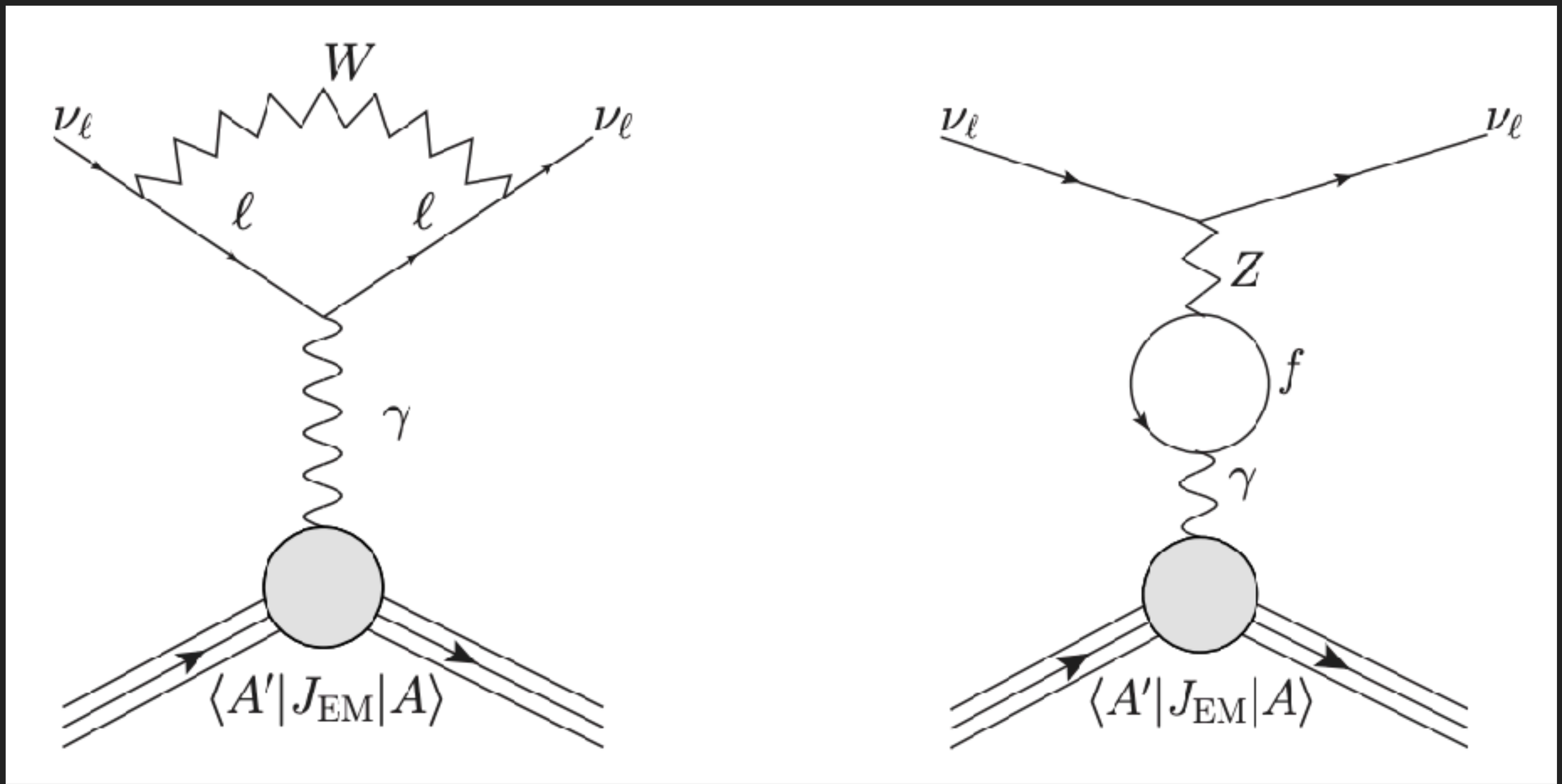
ARXIV:1911.01493 & ARXIV:1911.01493

OLEKSANDR TOMALAK & RICHARD J. HILL

EFT APPROACH TO CEVNS IN THE SM

- CEvNS involves many scales in principle.
  - Scale of nuclear coherence
  - W & Z boson
  - Heavy & light quarks
  - Leptons
- Do we work with quarks or hadrons?
- What about box diagrams?

Use EFT to separate scales



EW Scale

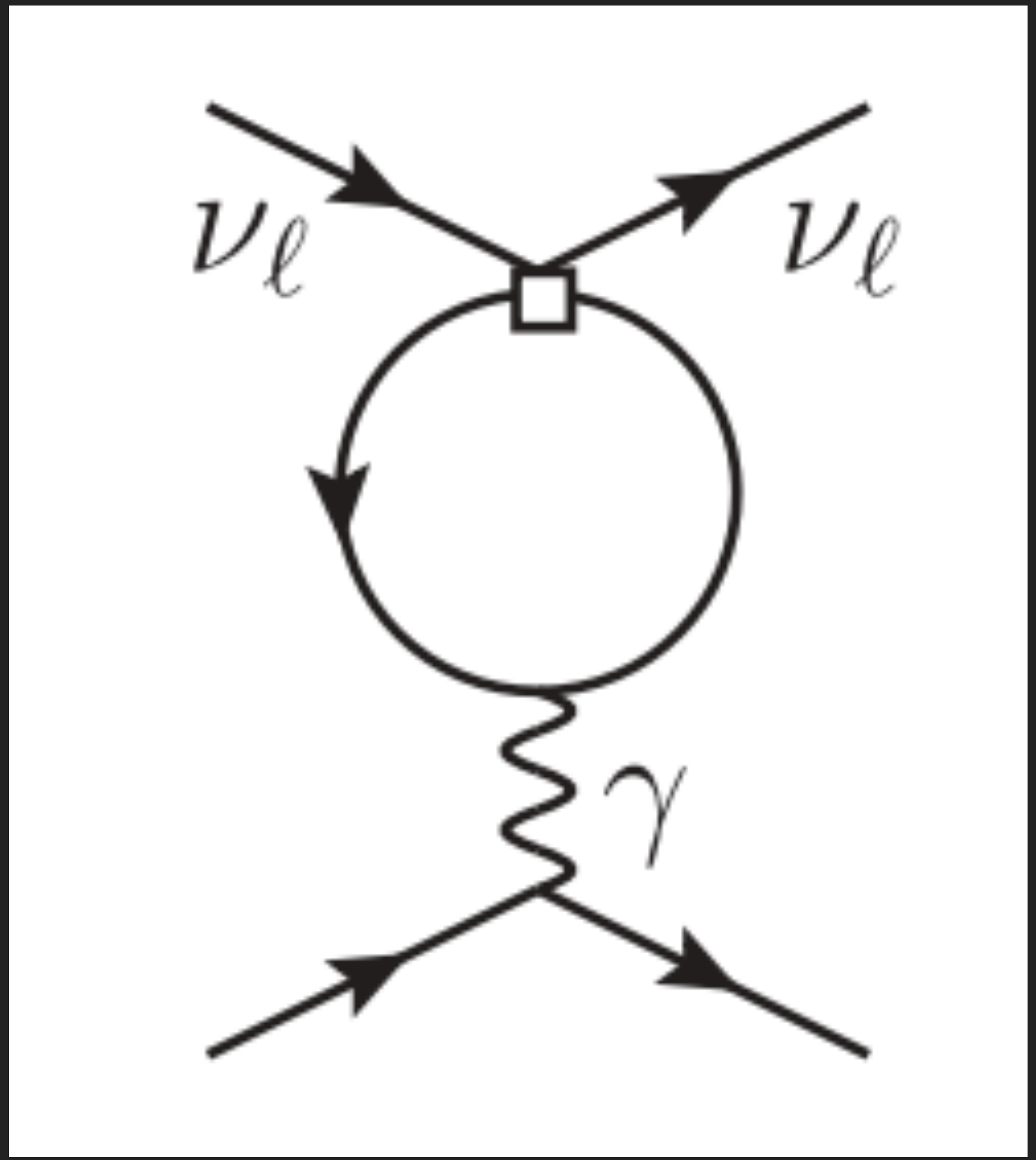
4-Fermi Theory

Decouple heavy quarks

2-GeV — Wilson coefficients

Dynamical light leptons & non-perturbative light-quark QCD { 2-GeV … 50 MeV

50 MeV — CEvNS



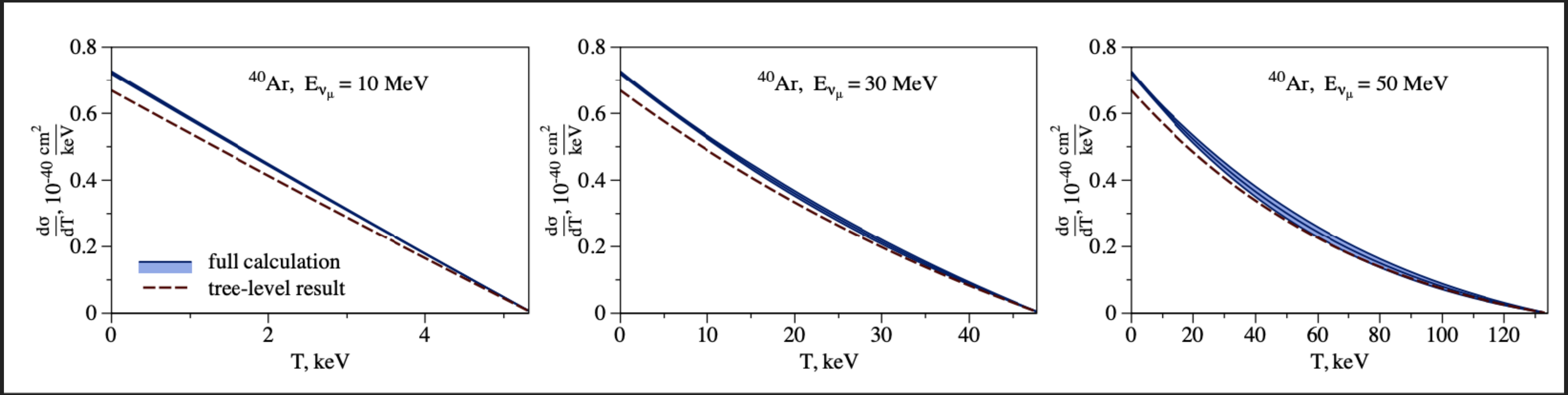
EFT APPROACH TO CEVNS IN THE SM

$$\delta^{\nu_\ell} = \frac{c_{\mathrm{L}}^{\nu_\ell e} + c_{\mathrm{R}}^{\nu_\ell e}}{\sqrt{2}\mathrm{G_F}} \Pi\left(Q^2, m_e; \mu\right) + \frac{c_{\mathrm{L}}^{\nu_\ell \mu} + c_{\mathrm{R}}^{\nu_\ell \mu}}{\sqrt{2}\mathrm{G_F}} \Pi\left(Q^2, m_\mu; \mu\right) + \frac{c_{\mathrm{L}}^{\nu_\ell \tau} + c_{\mathrm{R}}^{\nu_\ell \tau}}{\sqrt{2}\mathrm{G_F}} \Pi\left(0, m_\tau; \mu\right)$$

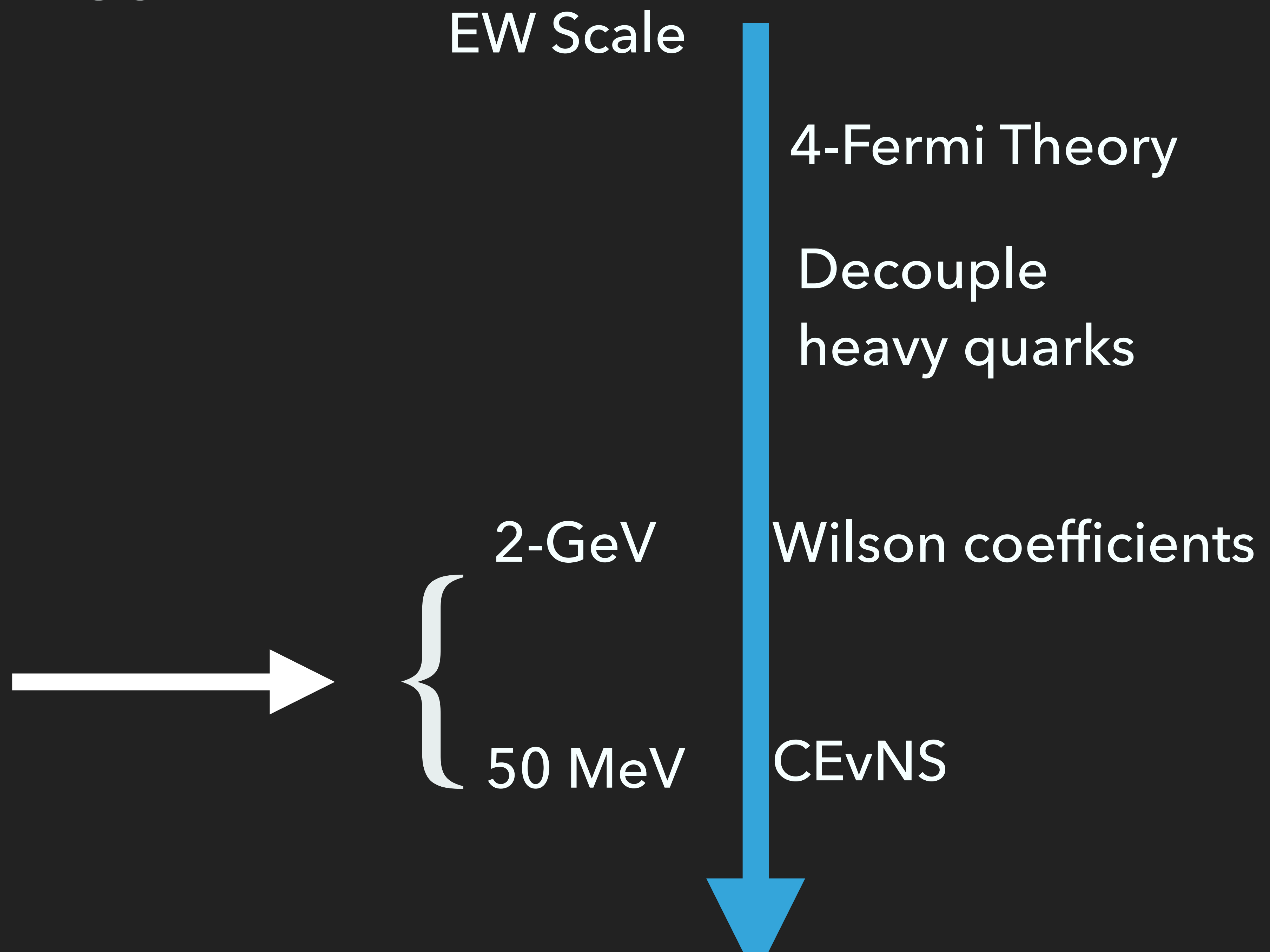
$$\Pi\left(Q^2, m_f; \mu\right) = \frac{1}{3}\ln\frac{\mu^2}{m_f^2} + \frac{5}{9} - \frac{4m_f^2}{3Q^2} + \frac{1}{3}\left(1 - \frac{2m_f^2}{Q^2}\right)\sqrt{1 + \frac{4m_f^2}{Q^2}}\ln\frac{\sqrt{1+\frac{4m_f^2}{Q^2}} - 1}{\sqrt{1+\frac{4m_f^2}{Q^2}} + 1}$$

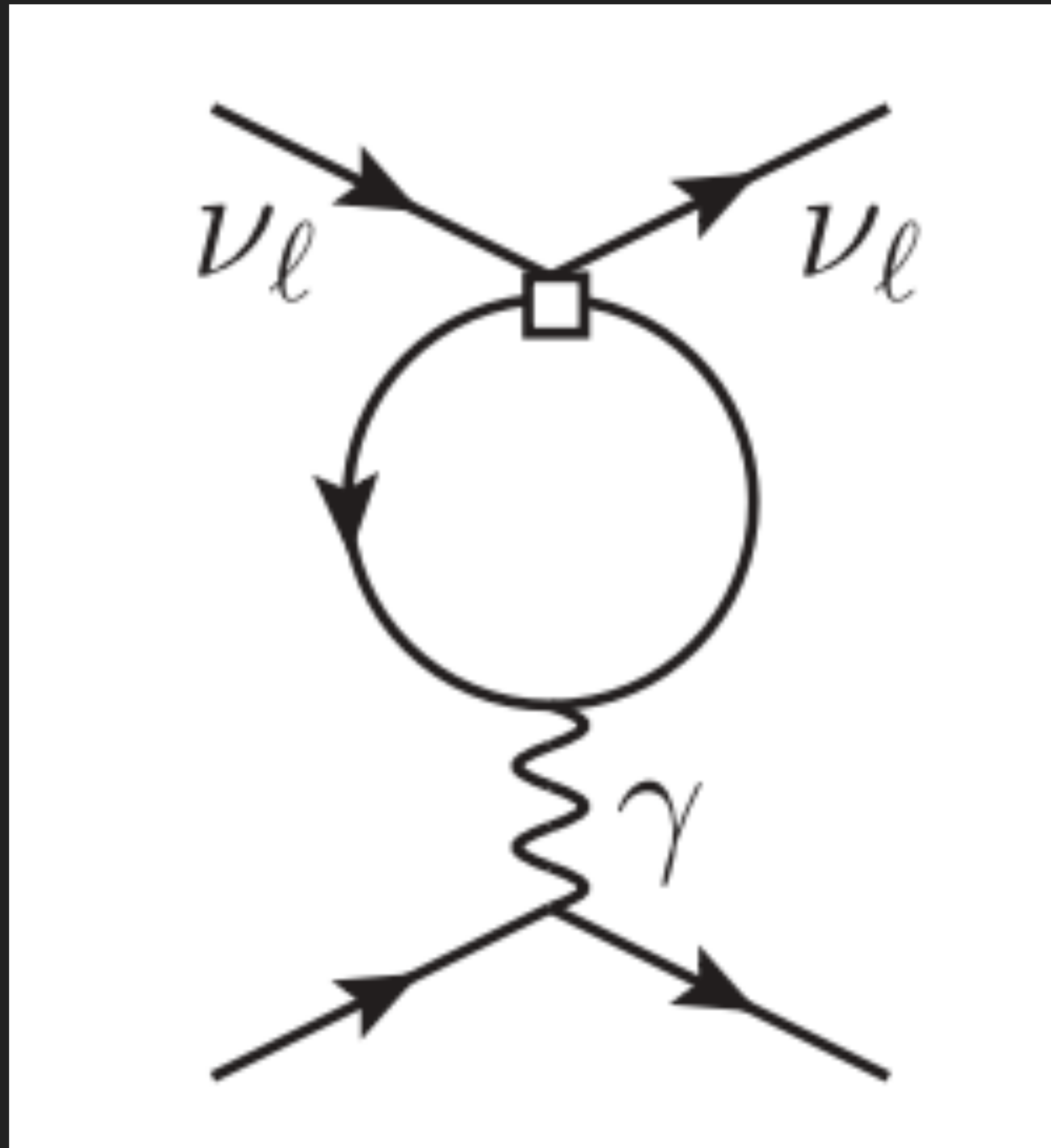
- Electrons an muons running in loops introduce ***kinematical dependence*** through vacuum polarization. This is often overlooked in the literature.
- Lepton masses introduce flavor dependence into cross section.

EFT APPROACH TO CEVNS IN THE SM



- Work with effective Lagrangian defined at a scale $\mu = 2$ GeV with pQCD.
  - 4-Fermi theory
  - Light quarks
  - All leptons & photons
- Hadronic scales treated with non-perturbative QCD correlators.





EFT APPROACH TO CEVNS IN THE SM

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
30	1.5	0.014	0.56	0.13	0.03	1.65	15.37(0.25)	14.23
10	0.04	0.001	0.56	0.13	0.004	0.58	1.91(0.01)	1.77

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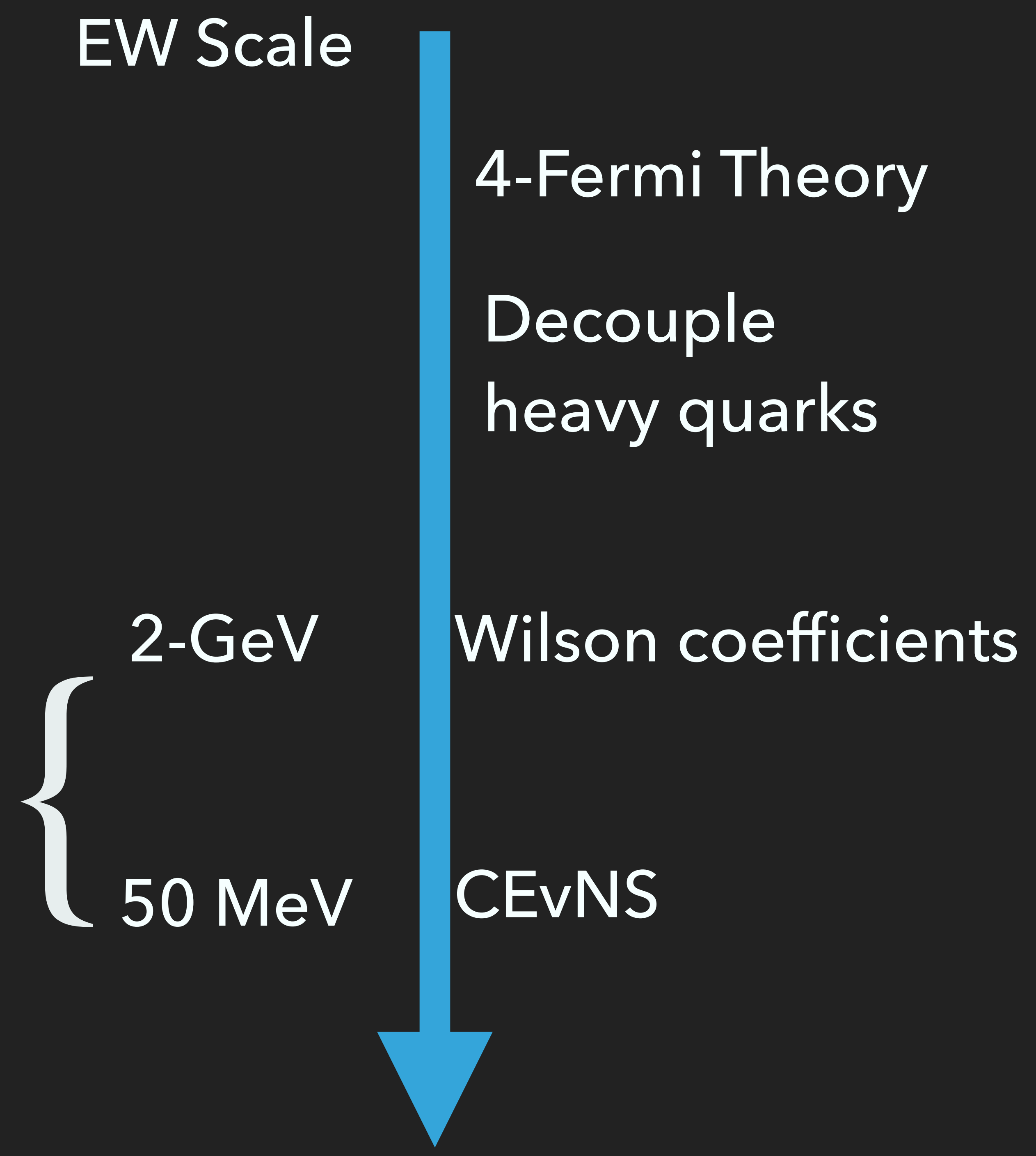

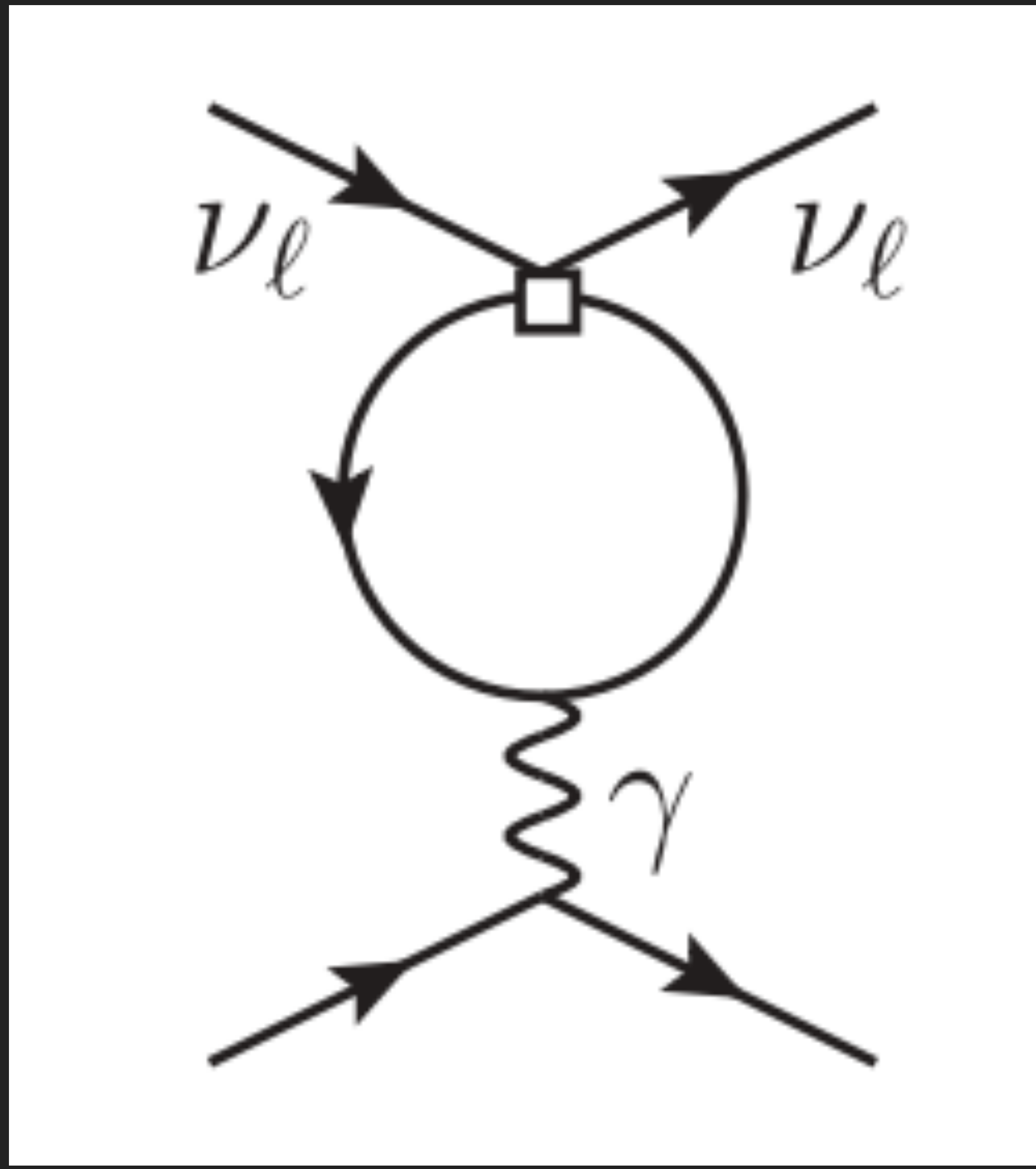

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EW Scale — 4-Fermi Theory

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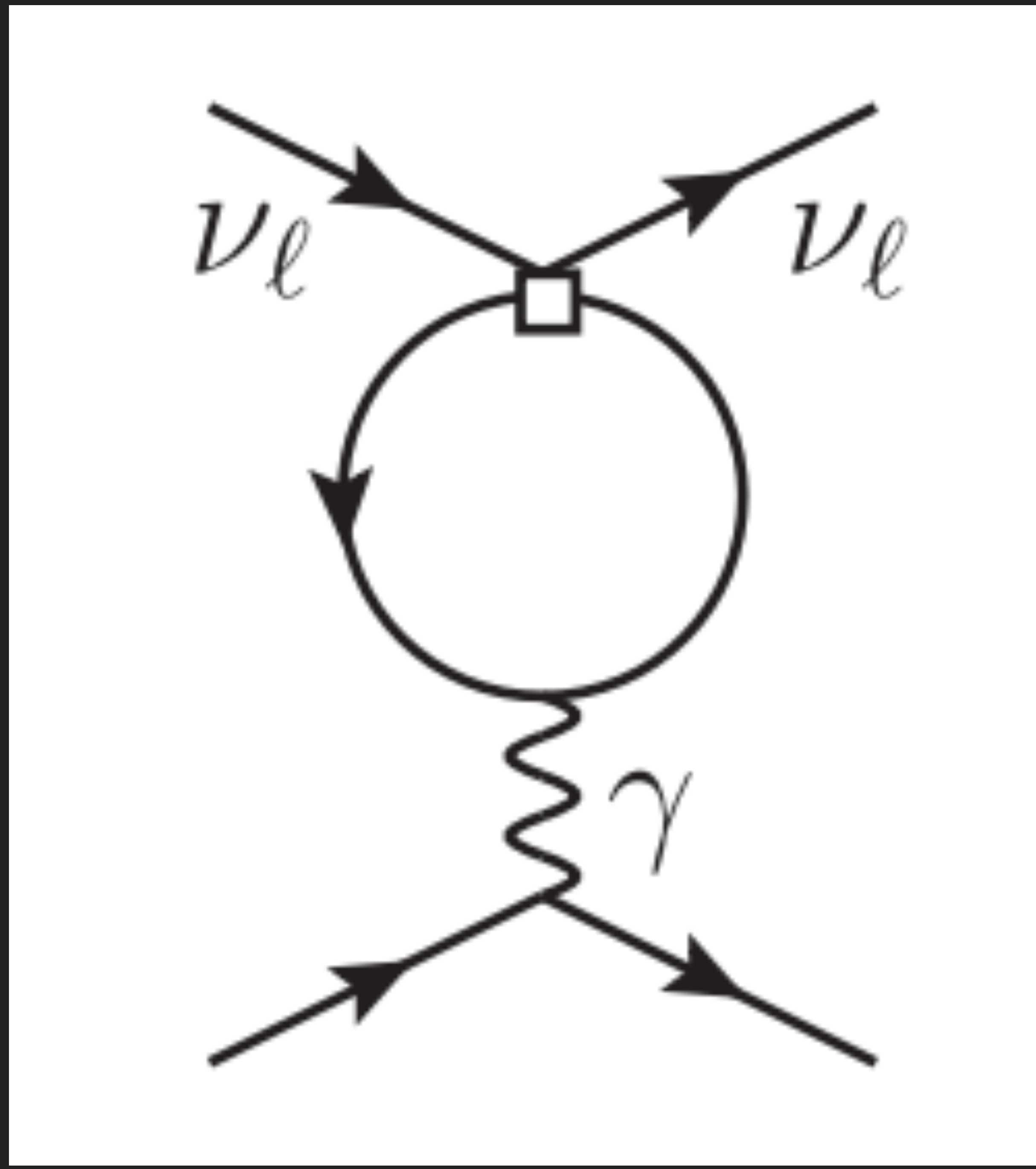

EFT APPROACH TO CEVNS IN THE SM

Same dominant error as in
$\nu_\ell\, e \to \nu_\ell\, e$

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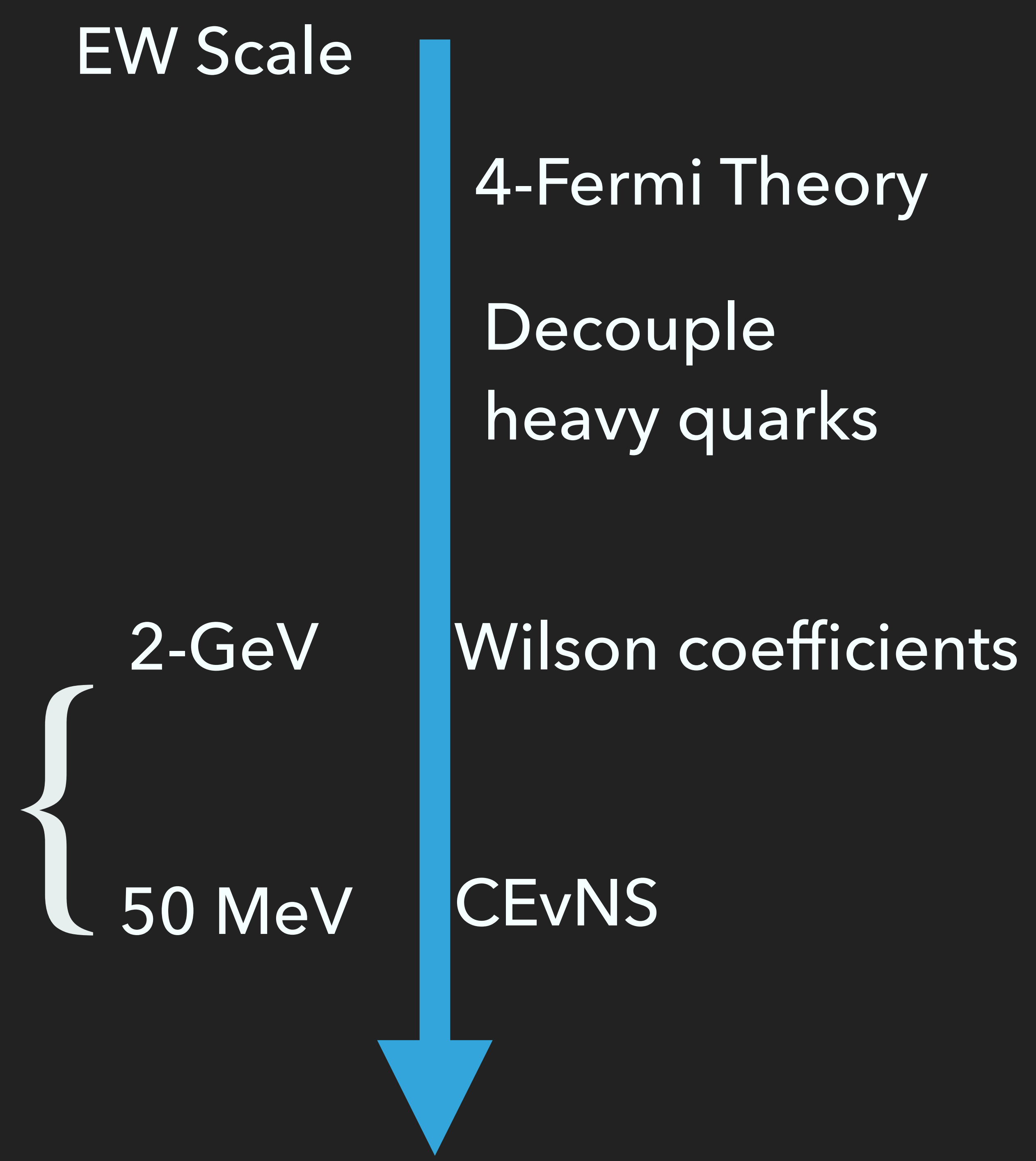
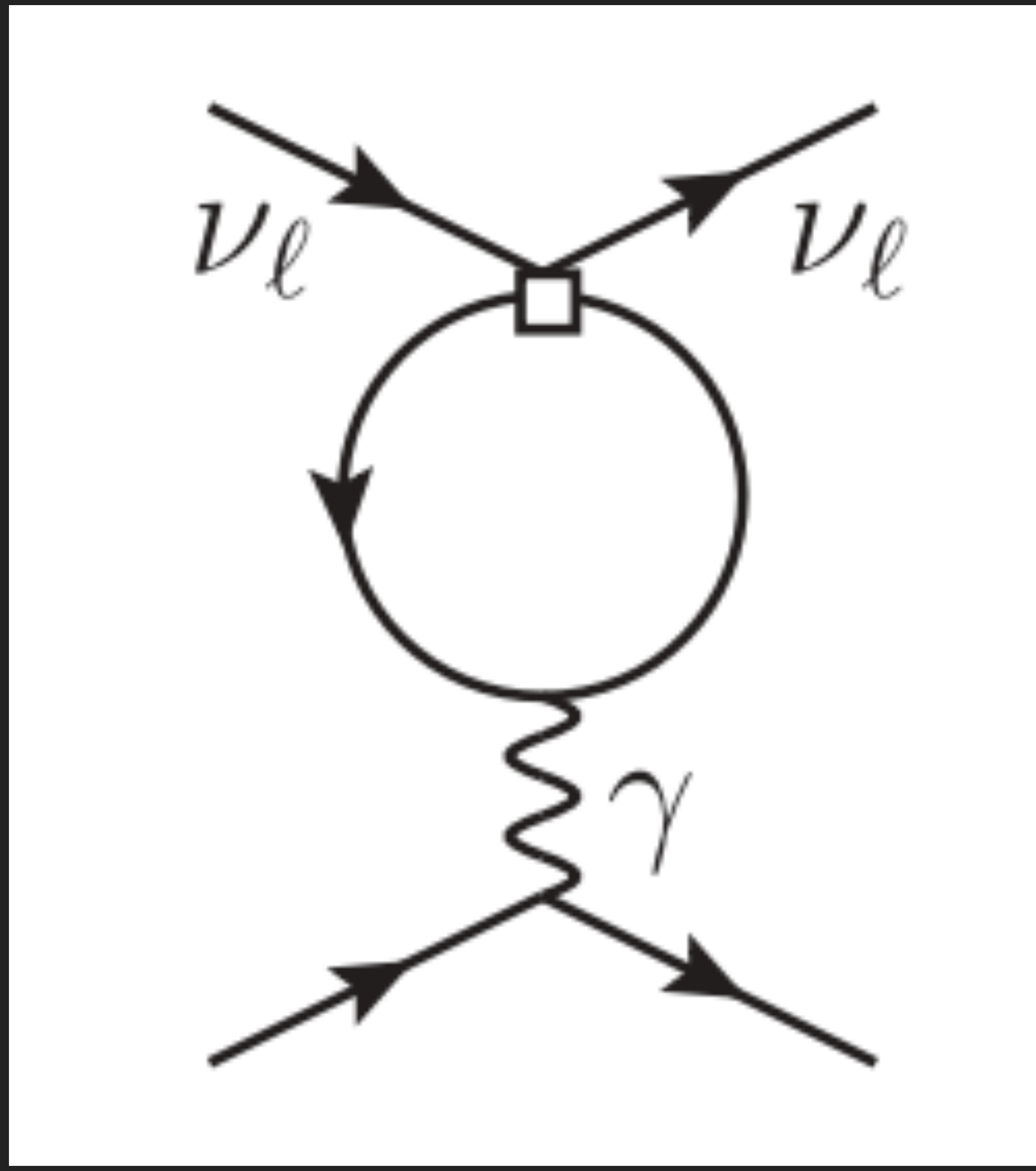
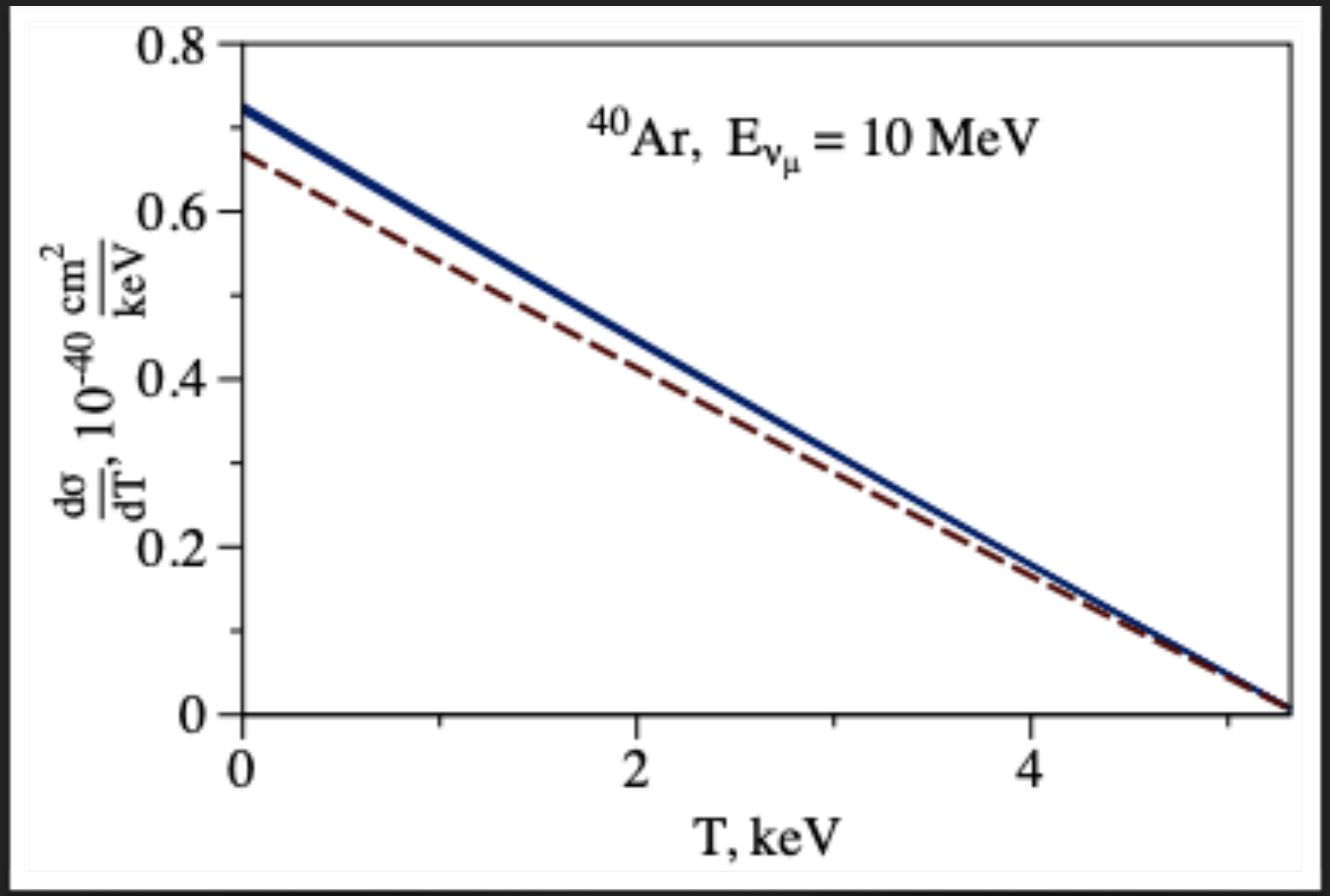
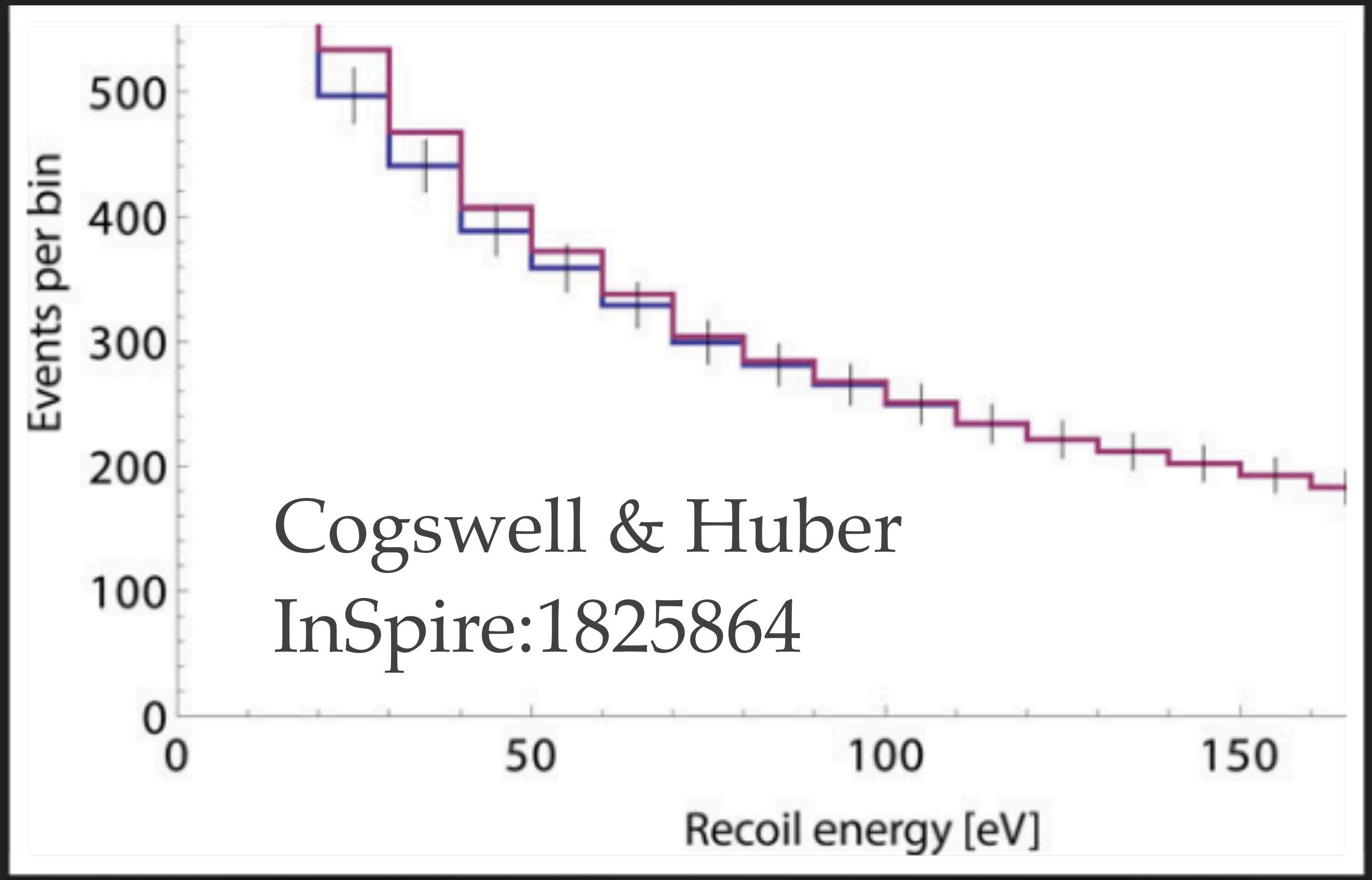




APPLICATIONS OF PRECISION CEVNS: BREEDING BLANKETS

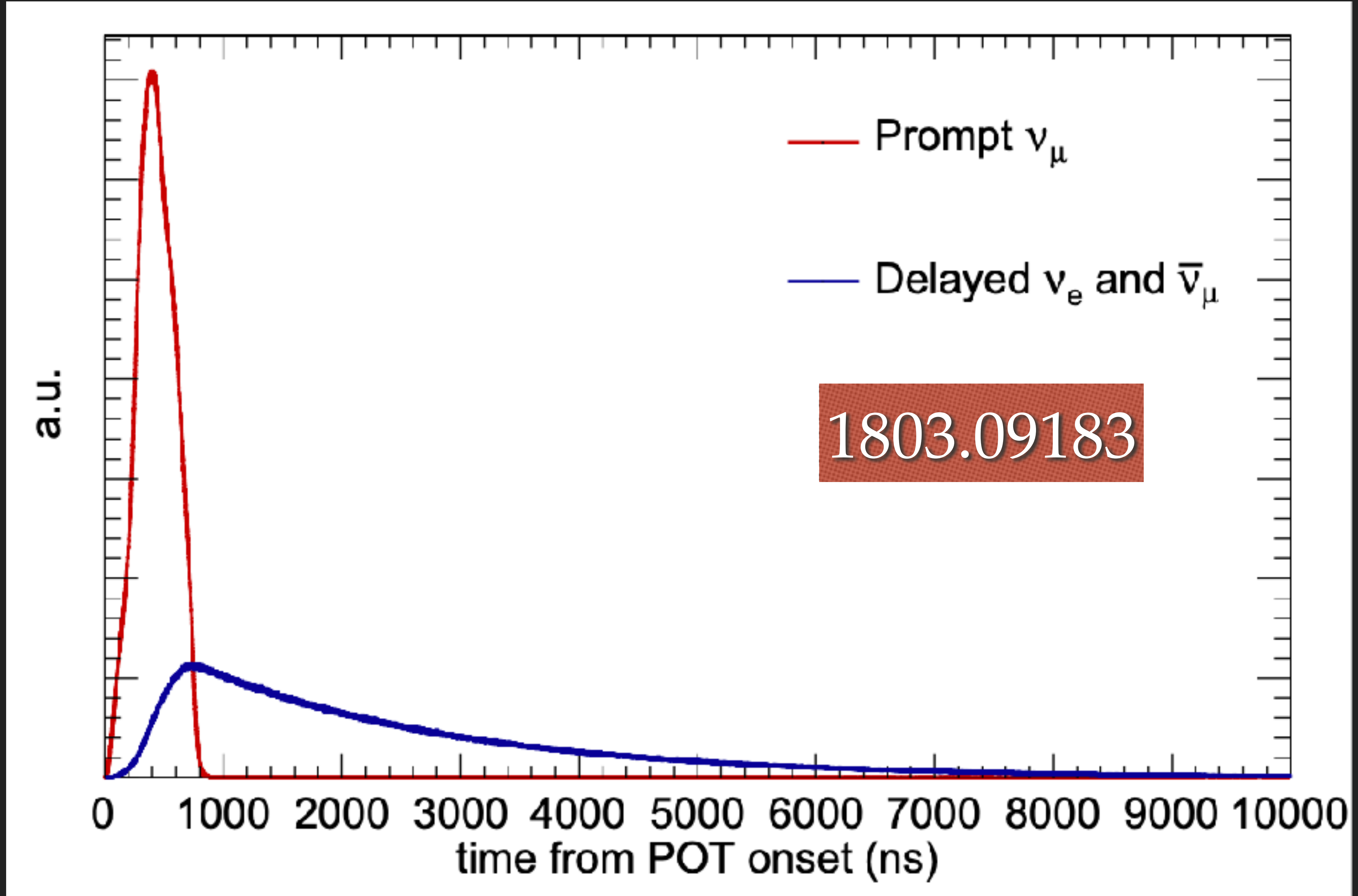
- Kinematic dependence from lepton loops is largest when momentum transfer is small.
- This corresponds to small nuclear recoil.
- The Q^2 dependence steepens the IR behaviour of the cross section at the level of 4%.
- Similar to the signature of plutonium breeding blankets proposed in Cogswell & Huber (2018).





APPLICATIONS OF PRECISION CEVNS: PROMPT DELAY RATIO FOR NSI

- One ``handle" on flavor content with piDAR is the prompt vs delayed signal.
- Very well understood, naive 2:1 ratio assuming perfect cut + LO cross section.
- Flavor dependent radiative corrections break naive prediction.
- COHERENT collaboration includes some radiative corrections, but they are not published. Will be good to compare.



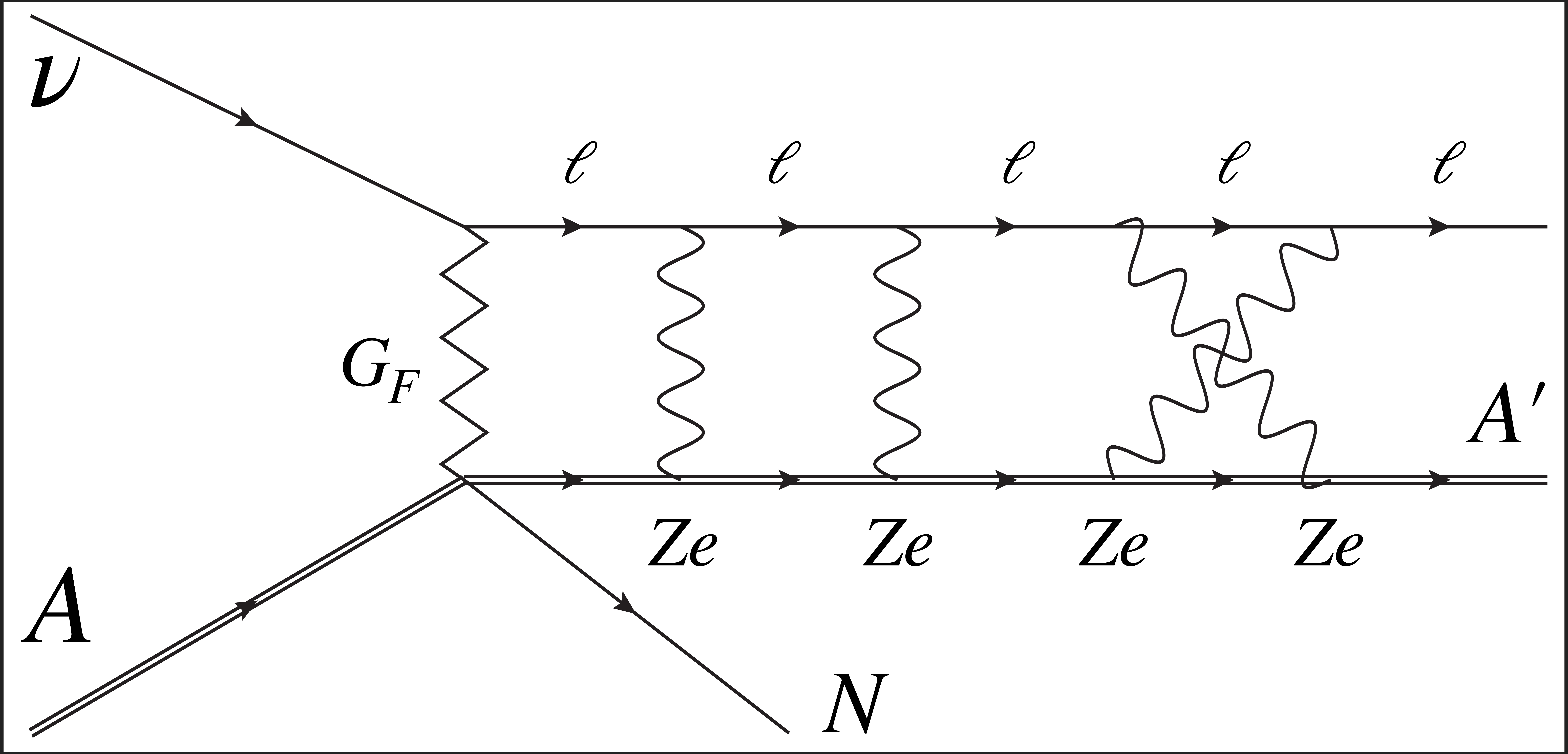
(b) SNS neutrino timing distribution.

COULOMB CORRECTIONS FOR CHARGED CURRENTS

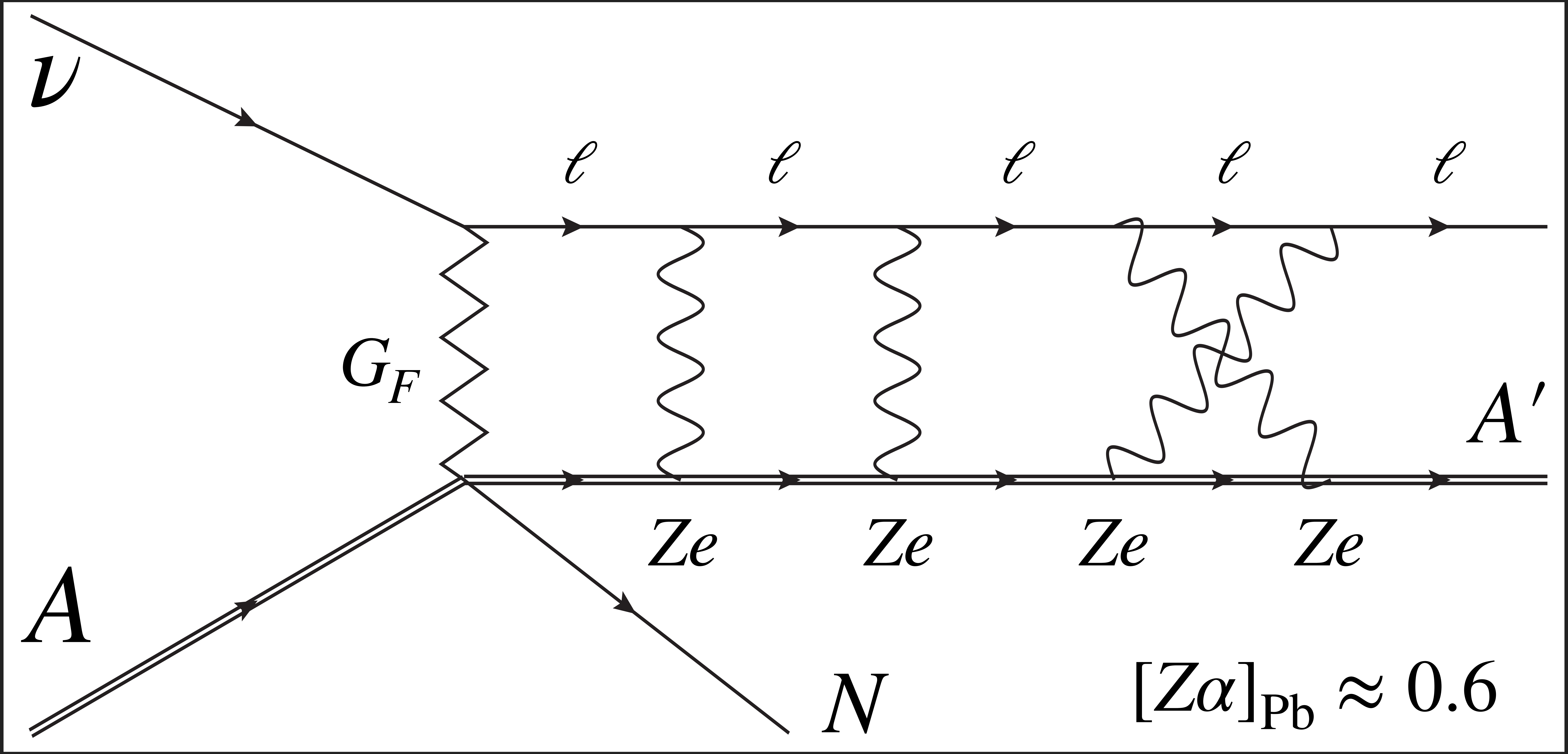
BASED ON ONGOING WORK WITH

OLEKSANDR TOMALAK & RICHARD J. HILL

SOFT PHOTON EXCHANGE WITH NUCLEUS



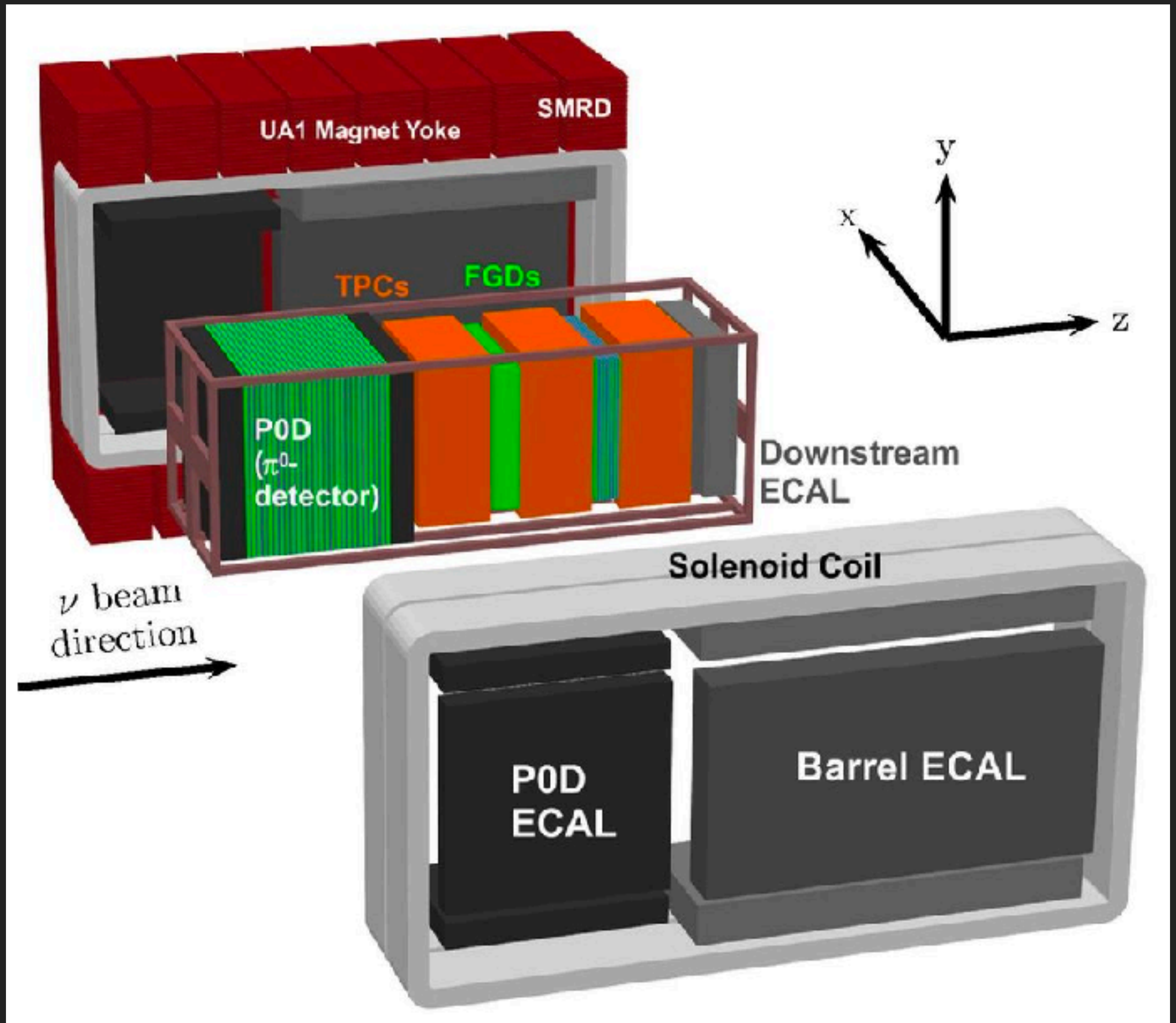
SOFT PHOTON EXCHANGE WITH NUCLEUS



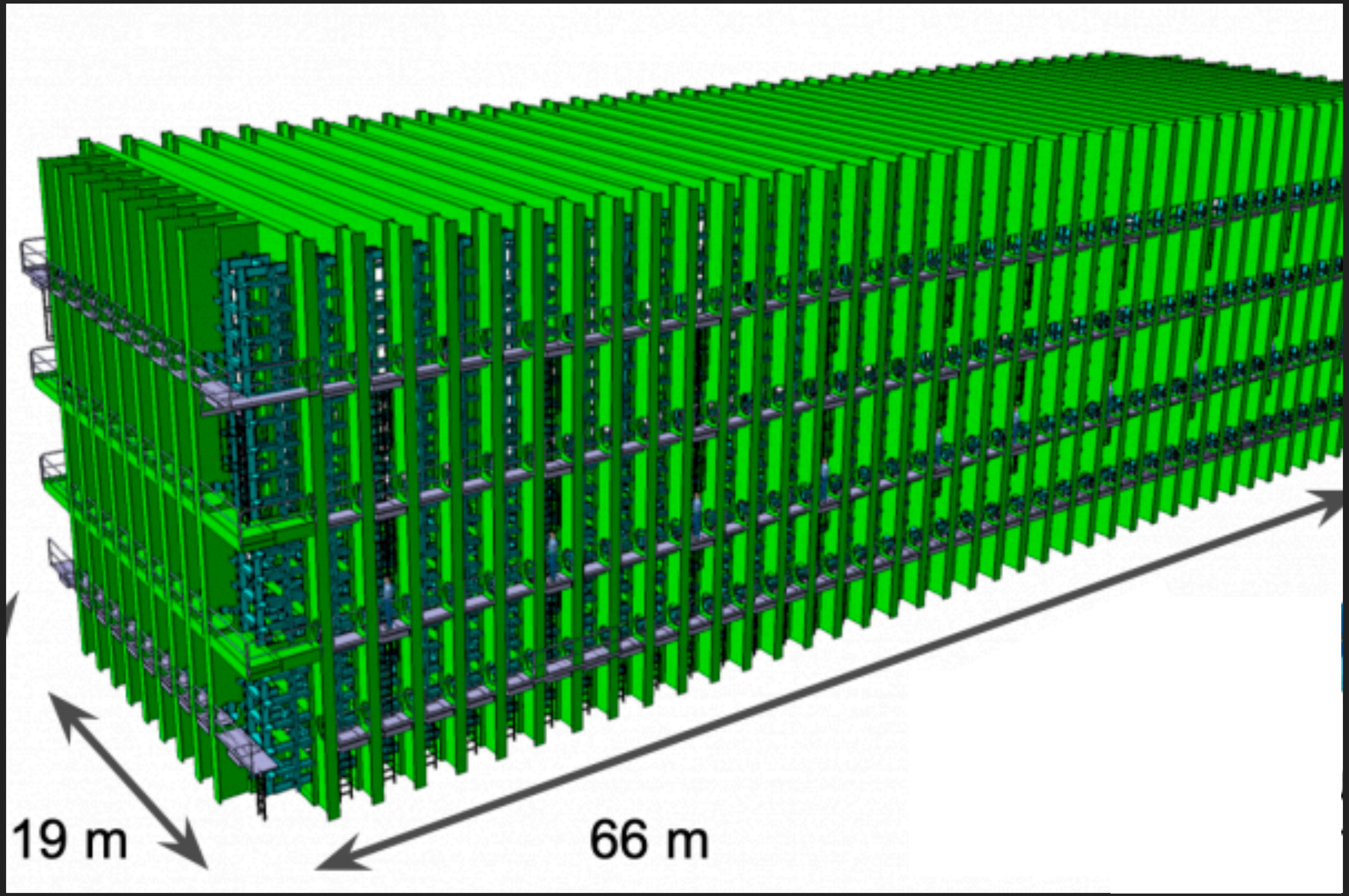
MOTIVATION

- Coulomb corrections must be controlled for percent level observables.

ND 280 @ T2K: Z=82 for Pb

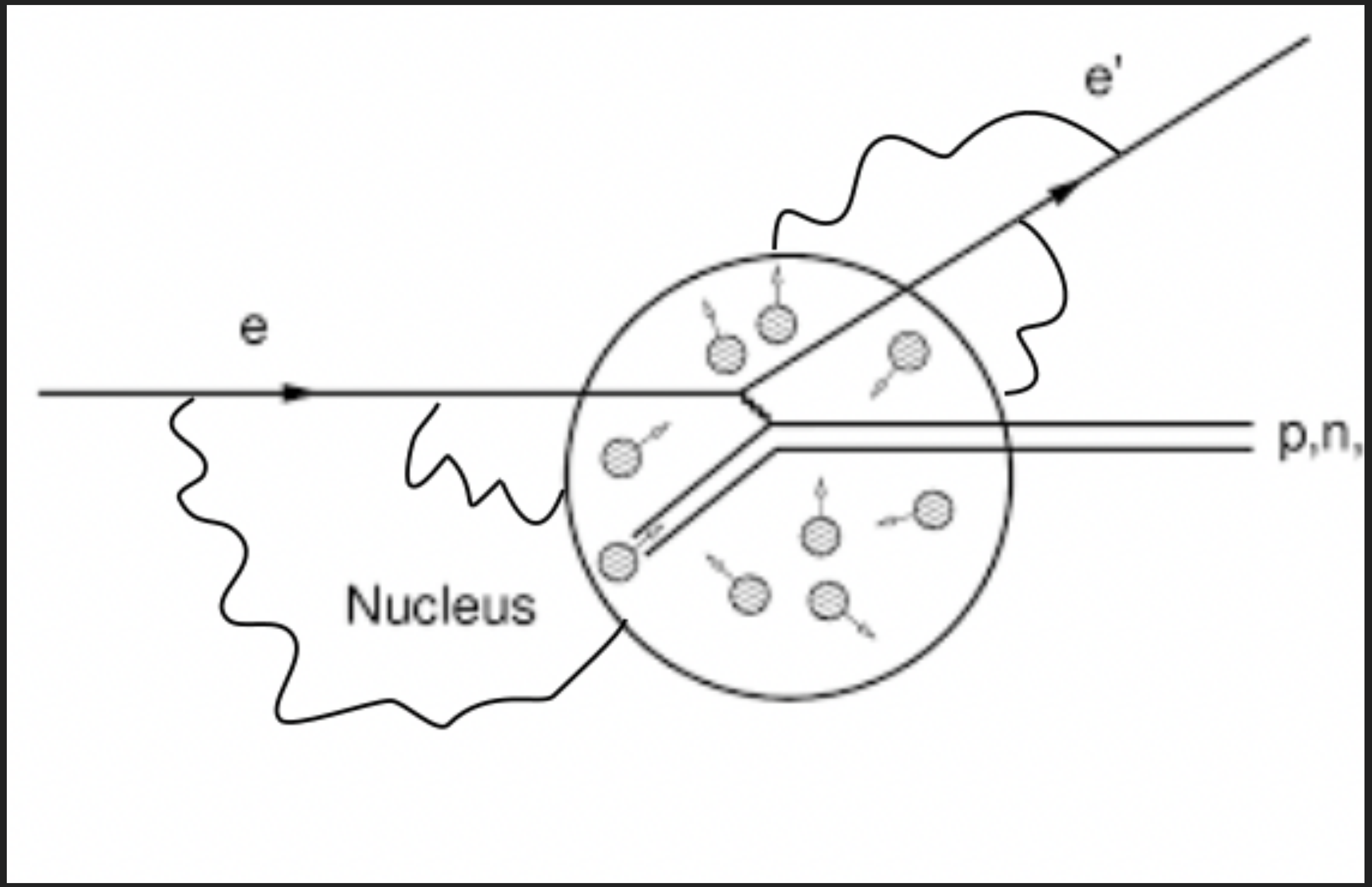


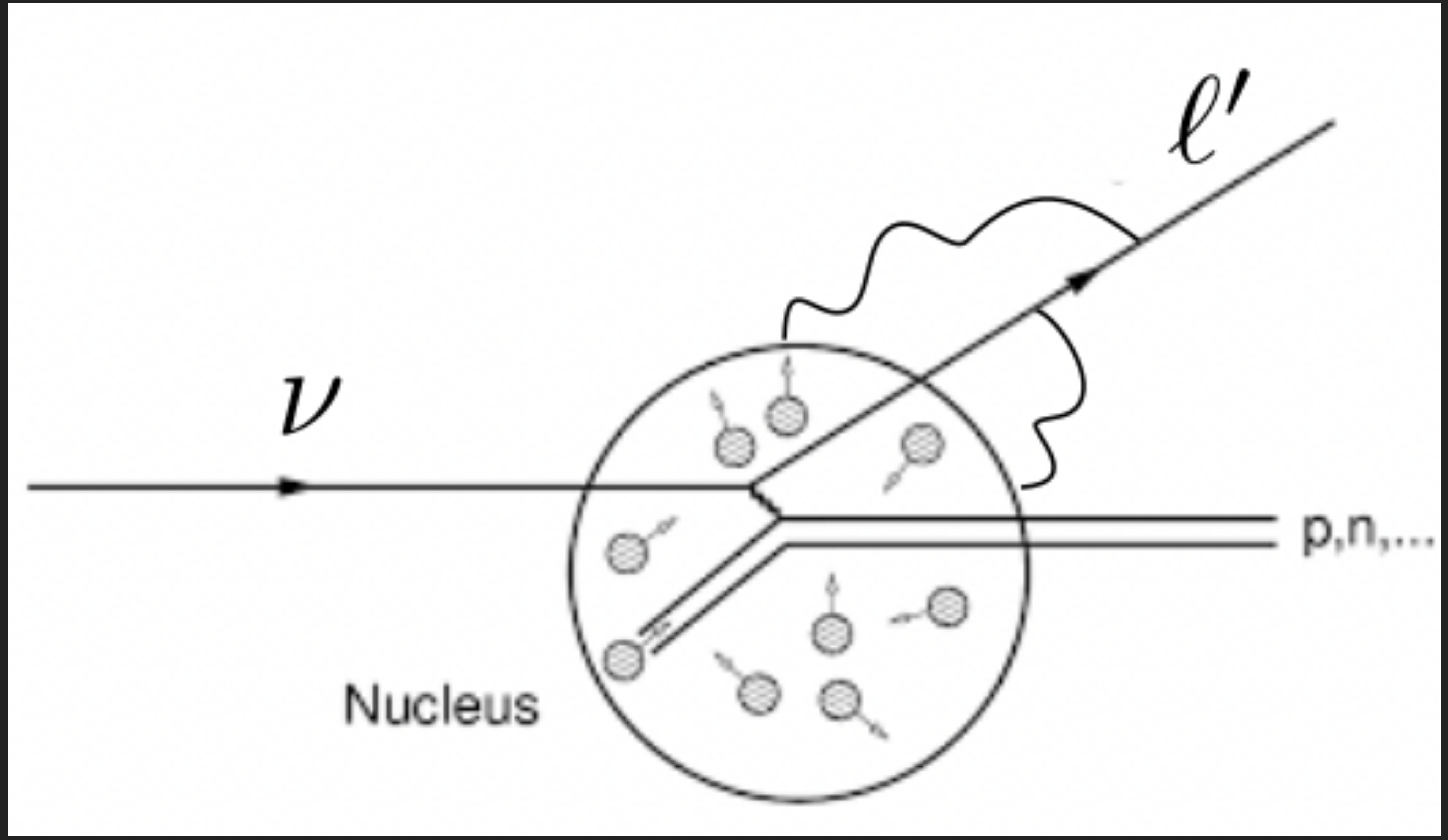
DUNE ND & FD, Z=18 for Ar



MOTIVATION

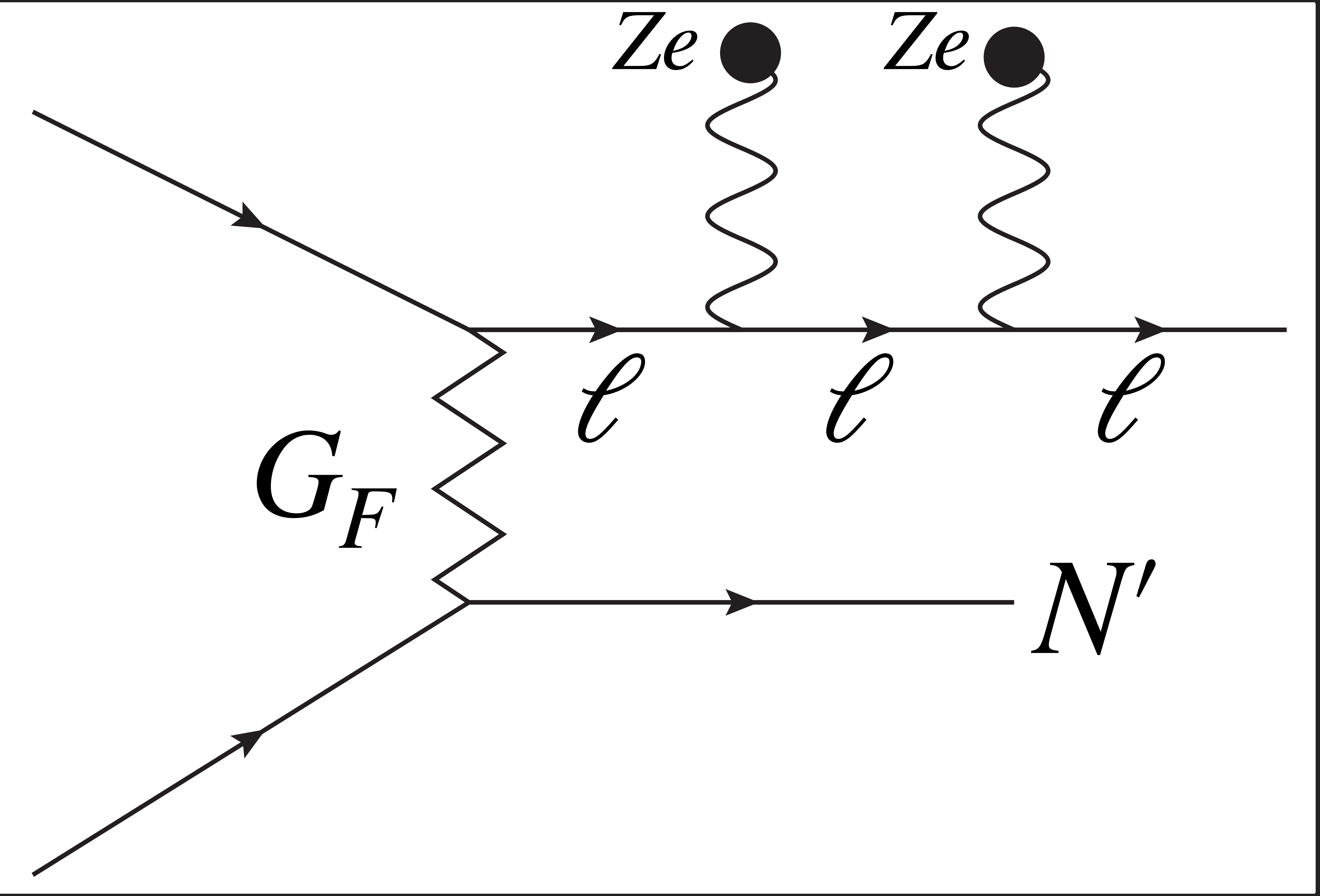
- Coulomb corrections differ between (e, e') scattering and (ν, ℓ') scattering





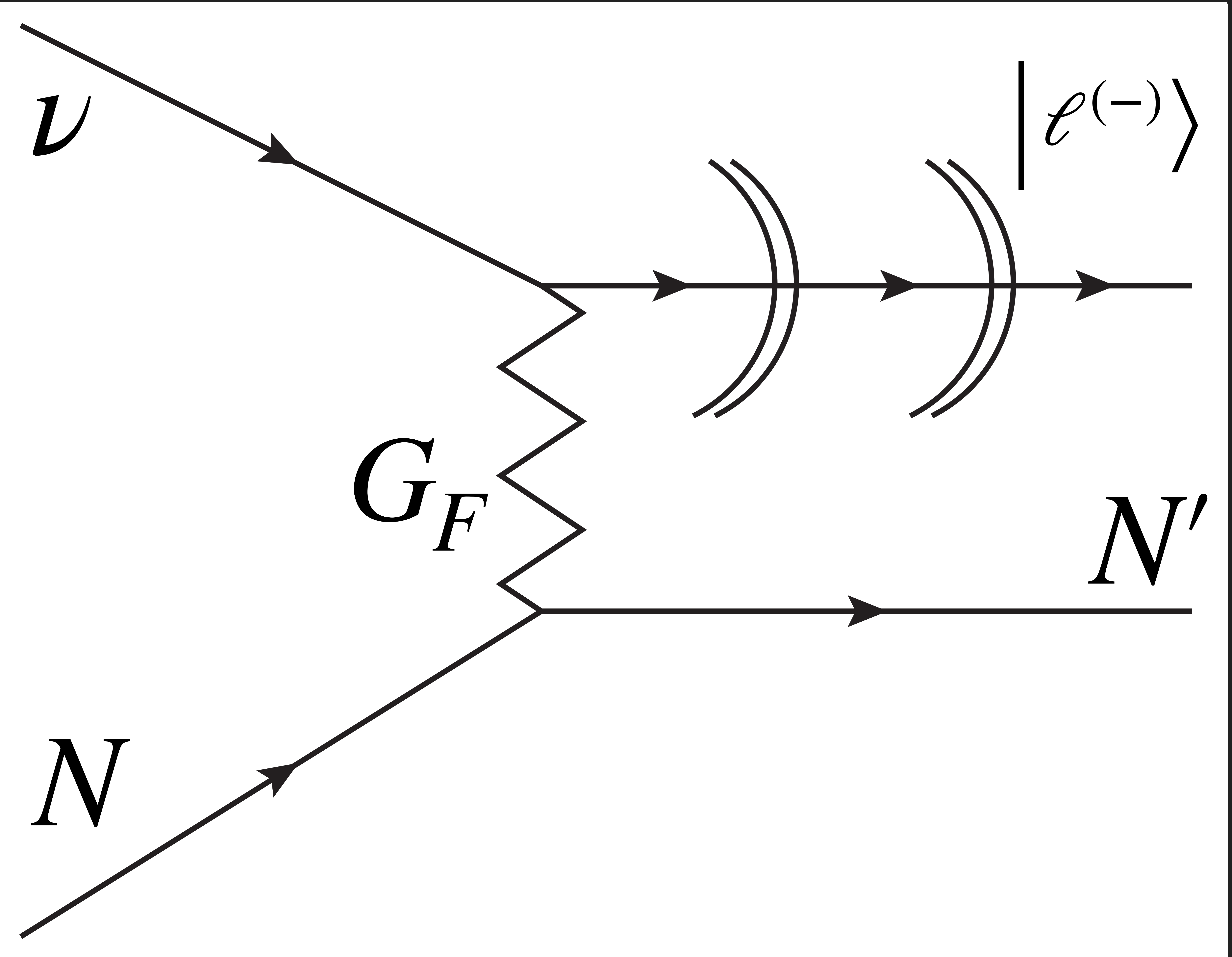
- Final and initial state feel Coulomb field
- Only final state feels Coulomb field

EXTERNAL FIELD APPROXIMATION



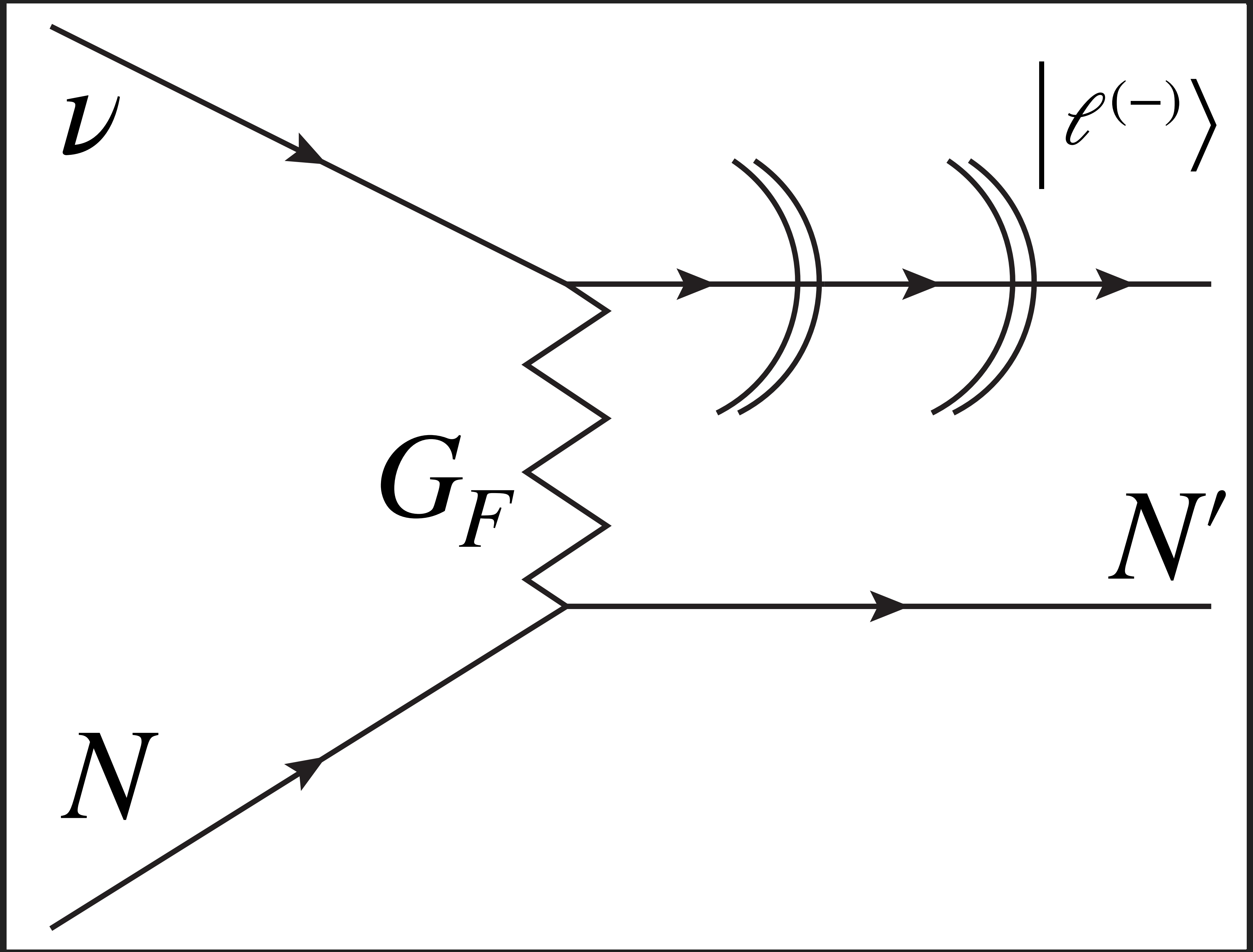
- Spectator nucleus becomes a background field.
- Coulomb field distorts lepton.
- In this talk we will ignore nucleon FSI.

DISTORTED WAVE BORN SERIES



- Use out-state solution of Coulomb scattering problem.
- S-matrix does not conserve momentum.
- Loss of plane wave leads to loss of $(2\pi)^3\delta^{(3)}(\Sigma P)$.

DISTORTED WAVE BORN SERIES



- Use out-state solution of Coulomb scattering problem.
- Loss of plane wave leads to loss of $(2\pi)^3\delta^{(3)}(\Sigma P)$

$$e^{ik'x}\bar{u}_{k'}\,\gamma_\mu(1-\gamma_5)u_k e^{-ikx} \rightarrow \bar{\mathcal{U}}_{k'}(x)\,\gamma_\mu(1-\gamma_5)u_k e^{-ikx}$$

“MODIFIED” EFFECTIVE MOMENTUM APPROXIMATION

ENGEL & EMA / MEMA

arXiv:nucl-th/9711045

PHYSICAL REVIEW C VOLUME 57, NUMBER 4 APRIL 1998

Approximate treatment of lepton distortion in charged-current neutrino scattering from nuclei

Jonathan Engel
Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27599-3255
(Received 18 November 1997)

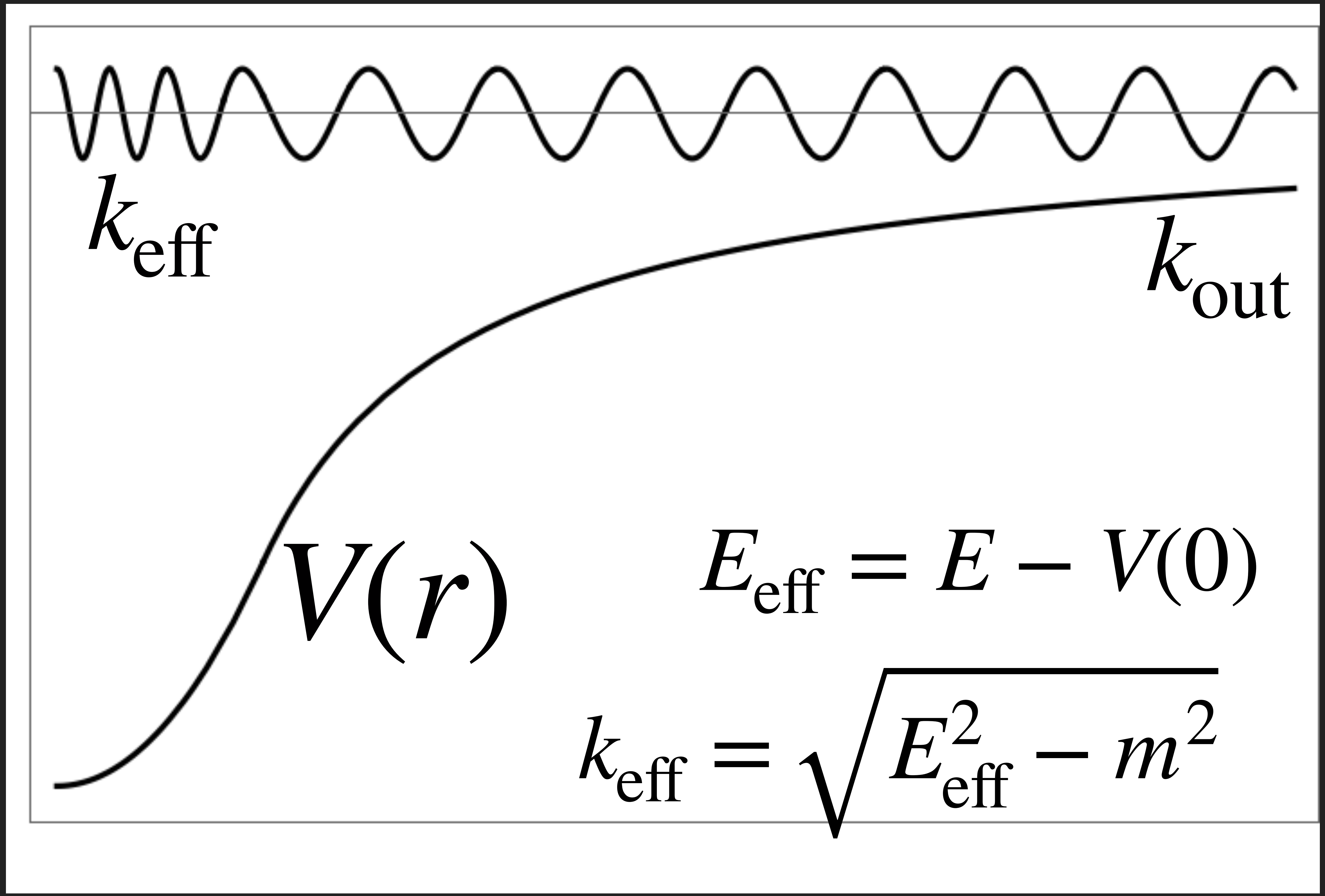
The partial-wave expansion used to treat the distortion of scattered electrons by the nuclear Coulomb field is simpler and considerably less time-consuming when applied to the production of muons and electrons by low- and intermediate-energy neutrinos. For angle-integrated cross sections, however, a modification of the ‘‘effective-momentum’’ approximation seems to work so well that for muons the full distorted-wave treatment is usually unnecessary, even at kinetic energies as low as 1 MeV and in nuclei as heavy as lead. The method does not work as well for electron production at low energies, but there a Fermi function often proves perfectly adequate. Scattering of electron neutrinos from muon decay on iodine and of atmospheric neutrinos on iron is discussed in light of these results. [S0556-2813(98)04804-3]

PACS number(s): 25.30.Pt, 11.80.Fv

- Advocates for a effective momentum approximation.
- Validates against toy model with vector current.

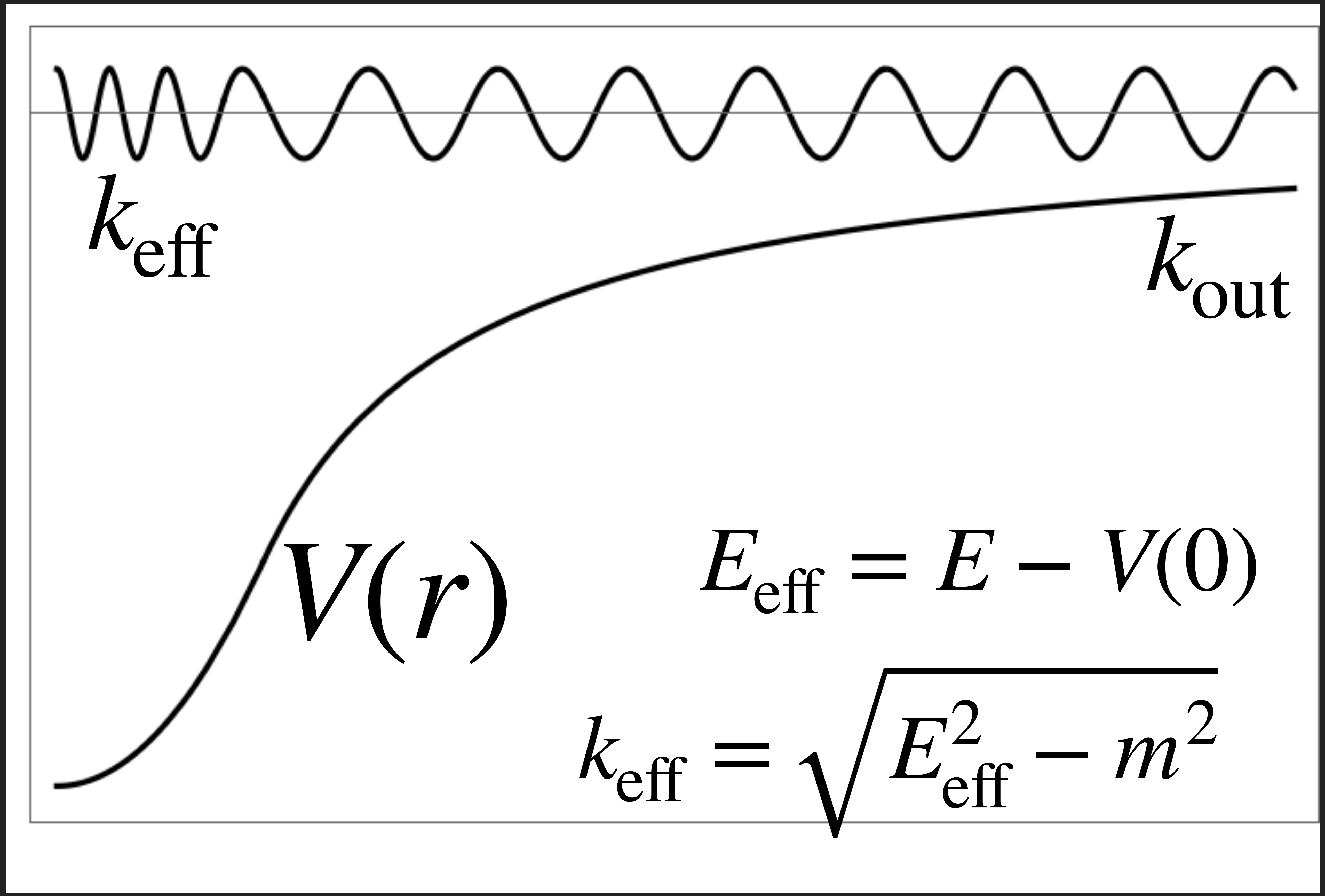
EFFECTIVE MOMENTUM

arXiv:nucl-th/9711045



- Effective momentum near nucleus.
- Re-scaled wave amplitude by $\sqrt{kE/k_{\rm eff}E_{\rm eff}}$.
- Effective momentum still conserved in phase space.
- Advocates for a effective momentum approximation
- This is what is inside GENIE.

EFFECTIVE MOMENTUM



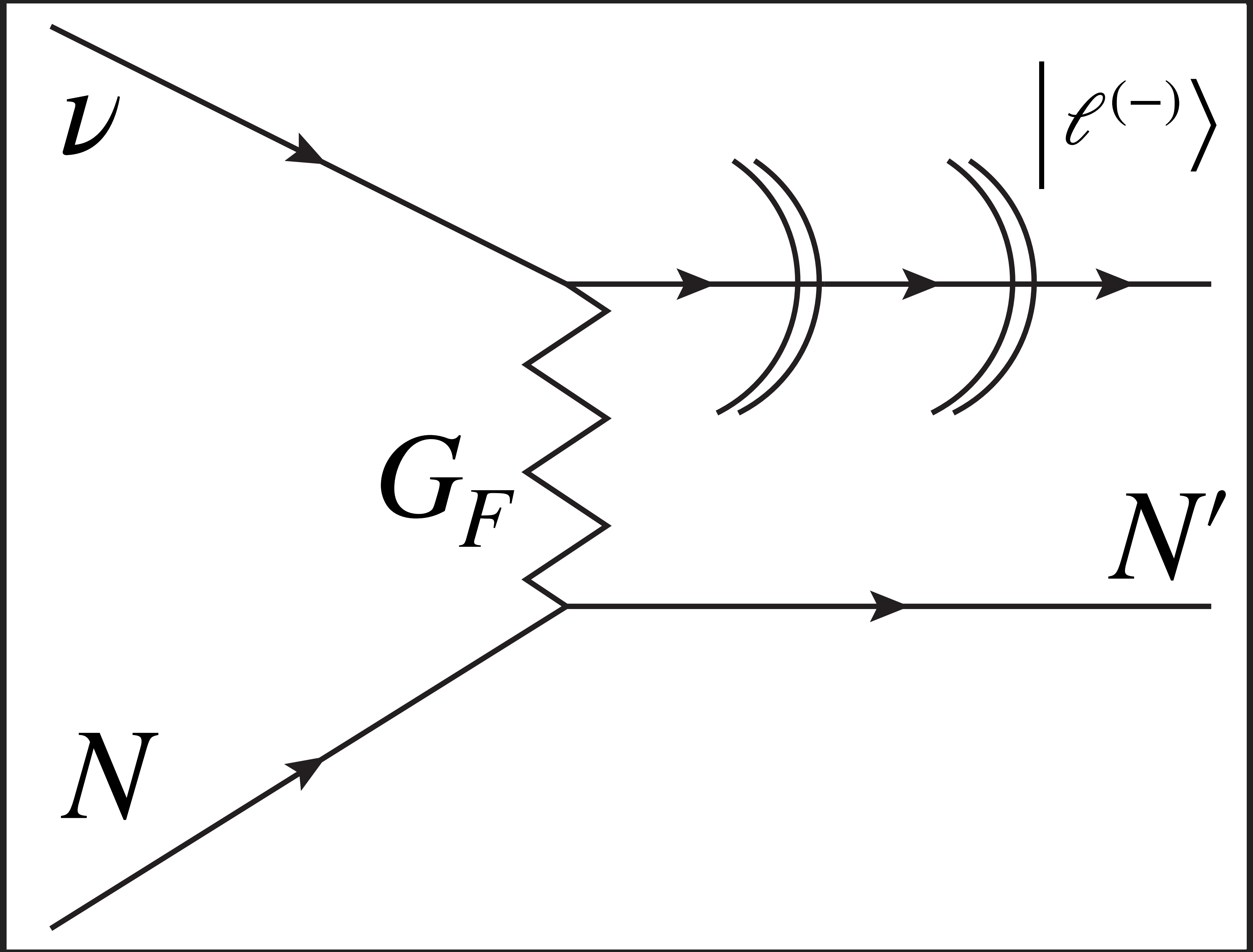
- This is what is inside GENIE.

QUESTIONS THAT SHOULD BUG YOU

- What controls the approximation?
- Can this be systematically extended?
- Is this accurate enough for the future of neutrino physics?

SYSTEMATIC DERIVATION WITH CORRECTIONS

DISTORTED WAVE BORN SERIES



- Use out-state solution of Coulomb scattering problem.
- Loss of plane wave leads to loss of $(2\pi)^3\delta^{(3)}(\Sigma P)$

$$\mathrm{e}^{\mathrm{i}k'x}\bar{u}_{k'}\,\gamma_\mu(1-\gamma_5)u_k\mathrm{e}^{-\mathrm{i}kx} \rightarrow \bar{\mathcal{U}}_{k'}(x)\,\gamma_\mu(1-\gamma_5)u_k\mathrm{e}^{-\mathrm{i}kx}$$

EIKONAL APPROXIMATION — DIRAC EQUATION

$$\mathscr{U}_k^{(\pm)}(x) = \mathrm{e}^{-\mathrm{i}\omega t}\ \mathrm{e}^{\mathrm{i}kx}\mathrm{e}^{\mathrm{i}\chi^{(\pm)}(x)}\ u_\beta(k)$$

Solve Dirac equation with Coulomb field iteratively

$$\chi^{(\pm)} = \chi_0^{(\pm)} + \frac{1}{|\mathbf{k}|}\chi_1^{(\pm)} + \frac{1}{|\mathbf{k}|^2}\chi_2^{(\pm)} + \ldots$$

EIKONAL APPROXIMATION — DIRAC EQUATION

$$\chi_0^{(+)} = -\frac{1}{v}\int_{-\infty}^{z} \mathrm{d}z\ V(z,b) \quad (\text{for } \hat{z}\cdot\hat{k} = 1)$$

Solve Dirac equation with Coulomb field iteratively

$$\chi^{(\pm)} = \chi_0^{(\pm)} + \frac{1}{|\mathbf{k}|}\chi_1^{(\pm)} + \frac{1}{|\mathbf{k}|^2}\chi_2^{(\pm)} + \ldots$$

COMPUTING MATRIX ELEMENTS

With wavefunctions we compute matrix elements

$$e^{ik'x}\bar{u}_{k'}\,\gamma_\mu(1-\gamma_5)u_k e^{-ikx} \to \bar{\mathscr{U}}_{k'}(x)\,\gamma_\mu(1-\gamma_5)u_k e^{-ikx}$$

COMPUTING MATRIX ELEMENTS

With wavefunctions we compute matrix elements

$$\int \mathrm{d}^4x \, \langle f | J_\mu(x) | i \rangle \quad \bar{u}_{k'} \gamma_\mu P_L u_k \mathrm{e}^{\mathrm{i}Qx}$$

$$\rightarrow \int \mathrm{d}^4x \, \langle f | J_\mu(x) | i \rangle \quad \underline{\mathrm{e}^{\mathrm{i}\chi(x)}} \quad \bar{u}_{k'} \gamma_\mu P_L u_k \mathrm{e}^{\mathrm{i}Qx}$$

Spoils momentum conservation, lepton can "straggle" off Coulomb potential

POWER COUNTING — MATRIX ELEMENTS

$$\mathscr{M} \sim \int \mathrm{d}^3x \; \mathrm{e}^{\mathrm{i}\mathbf{Q}\cdot\mathbf{x}} \; \mathrm{e}^{\mathrm{i}\chi(x)} \; \langle A' | \, J_\mu(x) \, | A \rangle L^\mu$$

We need a scheme by which to reliably estimate the size of different terms from wavefunction to matrix element.

$$\mathbf{x} \sim O(1/Q) \sim O(1/E)$$

POWER COUNTING — MATRIX ELEMENTS

$$\mathscr{M} \sim \int \mathrm{d}^3x \; \mathrm{e}^{\mathrm{i}\mathbf{Q}\cdot\mathbf{x}} \; \mathrm{e}^{\mathrm{i}\chi(x)} \; \langle A' | J_\mu(x) | A \rangle L^\mu$$

Note rapidly oscillating integrand

Powers of x are power suppressed $\quad \mathbf{x} \sim O(1/Q)$

Justifies series expansion of Eikonal phase

EIKONAL APPROXIMATION — TO O(1/E²) — TAYLOR EXPAND

$$\chi^{(\pm)} = \chi_0^{(\pm)} + \frac{1}{E}\chi_1^{(\pm)} + \frac{1}{E^2}\chi_2^{(\pm)} + \ldots$$

Work to 2nd order in Taylor expansion

Work to 1st order in Taylor expansion

Work to zeroth order in Taylor expansion

Note imaginary parts contribute at one lower order in 1/E.

Imaginary part at zero changes amplitude, real part is irrelevant phase.

TOY NUCLEAR MODEL

ANTI-NEUTRINO + BOUND PROTON $\longrightarrow$ ANTI-LETPTON + FREE NEUTRON

$$|\bar{\nu}\rangle + |\phi\rangle \rightarrow |\ell^{+}_{\text{out}}\rangle + |n\rangle$$

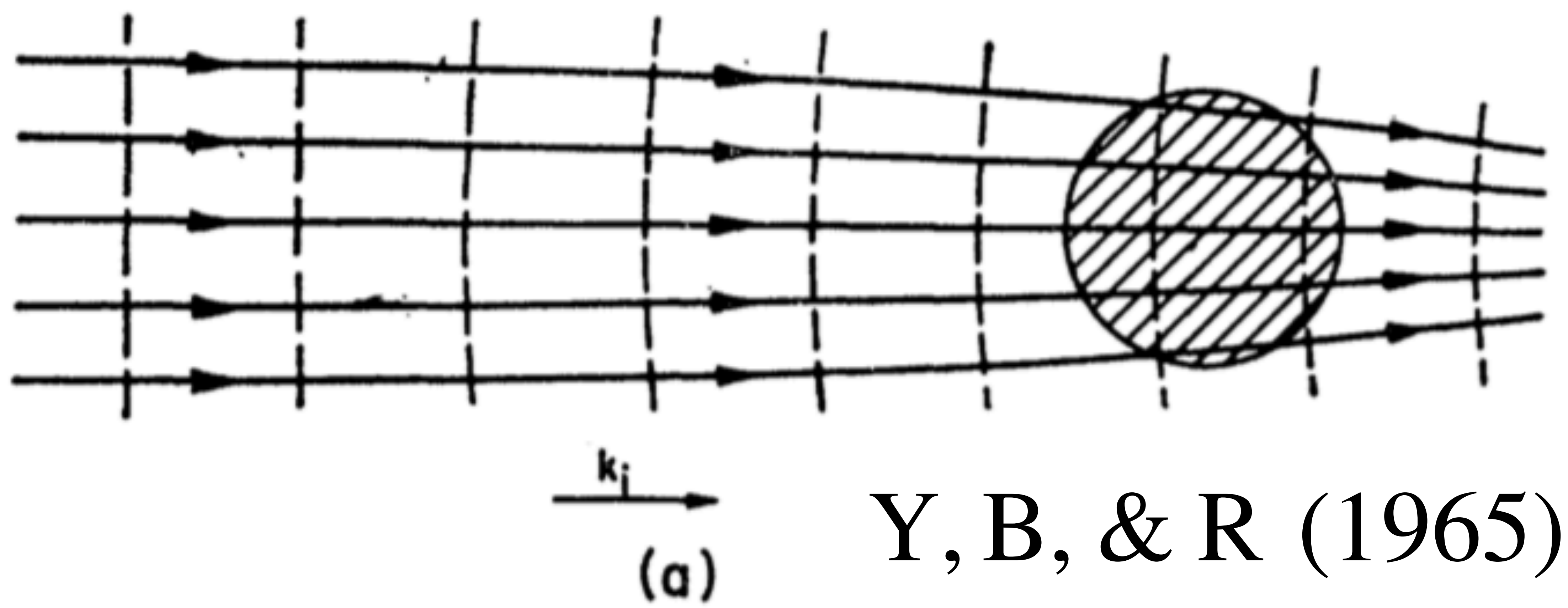
$$\phi(p) \sim \frac{1}{r_A^3} e^{-r_A^2 p^2}$$

$$e^{i\chi_0(x)}$$

ANTI-NEUTRINO + BOUND PROTON $\longrightarrow$ ANTI-LETPTON + FREE NEUTRON

$$e^{i\chi_0(x)}$$

Focussing in transverse plane



Y, B, & R (1965)

$$\sigma_\perp^2 = \frac{Z\alpha}{4\pi}\left\langle \frac{1}{r^2} \right\rangle$$

$$\chi_0(x) \approx \delta k \times z \; + \; \frac{1}{2}\sigma_\perp^2 \times b^2 + \ldots$$

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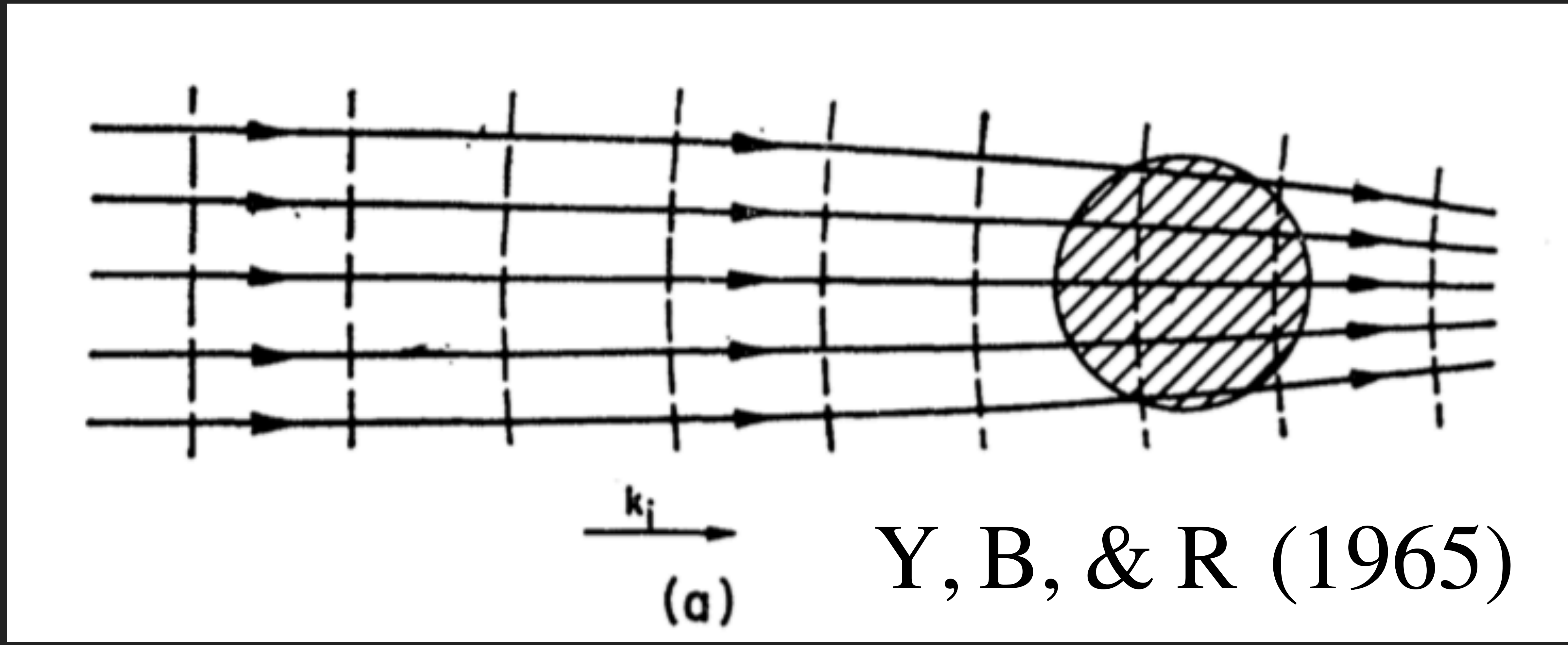

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$$\mathrm{d}\sigma \sim \mathrm{d}\sigma_{\mathrm{PW}} \; / \, . \; k_z \to k_z^{\mathrm{eff}} \; / \, . \; \delta^{(2)}(P_\perp) \to \mathrm{e}^{-P_\perp^2/\sigma_\perp^2}$$

Transverse Momentum Fluctuations

ANTI-NEUTRINO + BOUND PROTON $\longrightarrow$ ANTI-LETPTON + FREE NEUTRON

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In general this factor has nuclear model-dependence

Work ongoing to understand general case

ANTI-NEUTRINO + BOUND PROTON $\longrightarrow$ ANTI-LETPTON + FREE NEUTRON

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In general this factor has nuclear model-dependence

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WORK ONGOING

SUMMARY & OUTLOOK

- Engel's mEMA can be systematically derived.
- Sub-leading corrections are ***analytically*** calculable.
- Effects include overall shift of wavefunction nomalization, and transverse momentum fluctuations.

- Asymmetry between neutrino- and anti-neutrino.