neutrino physics and HEP: lecture 2

frontiers in neutrino interactions: experiments, simulation, and theory

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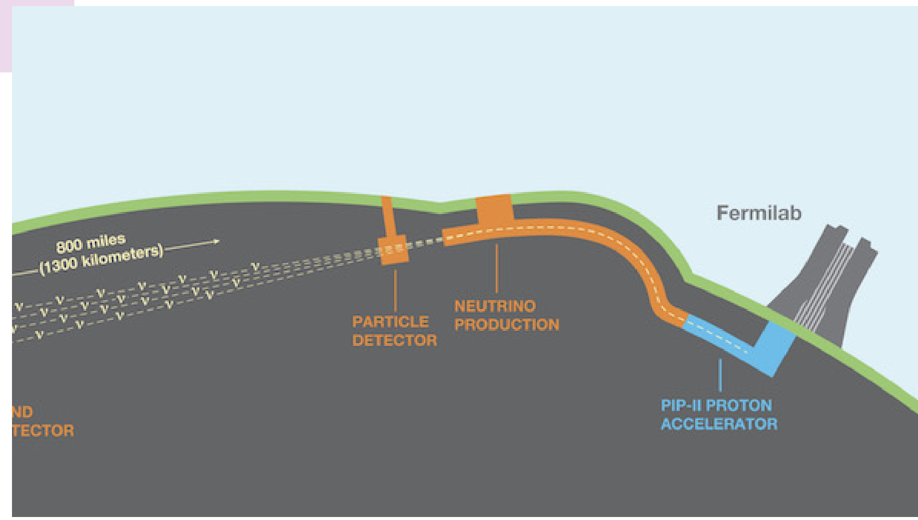
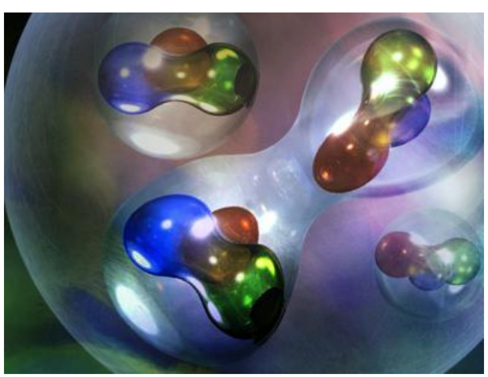
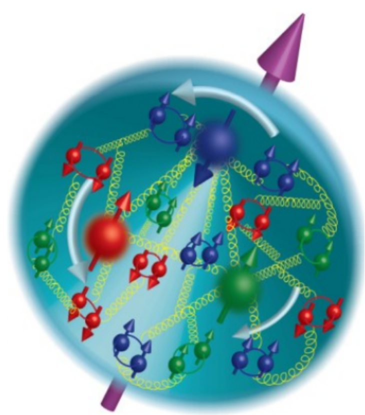
15th July 2022

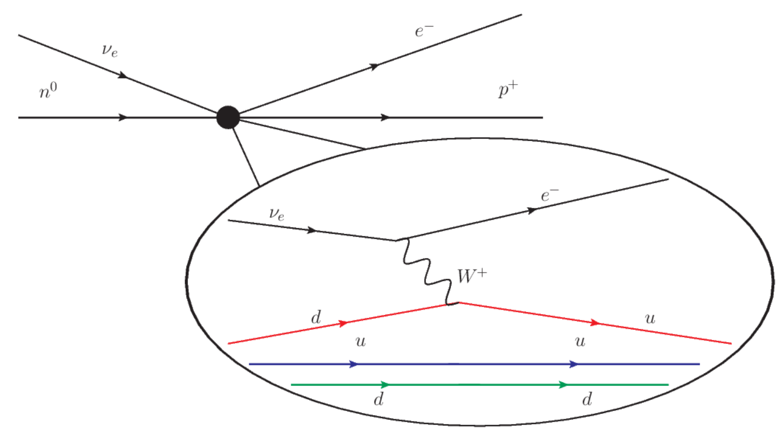


Special thanks to Fermilab colleagues:
Minerba Betancourt, Jorge Morfin, Steven Gardiner, …

and, of course, CTEQ colleagues!

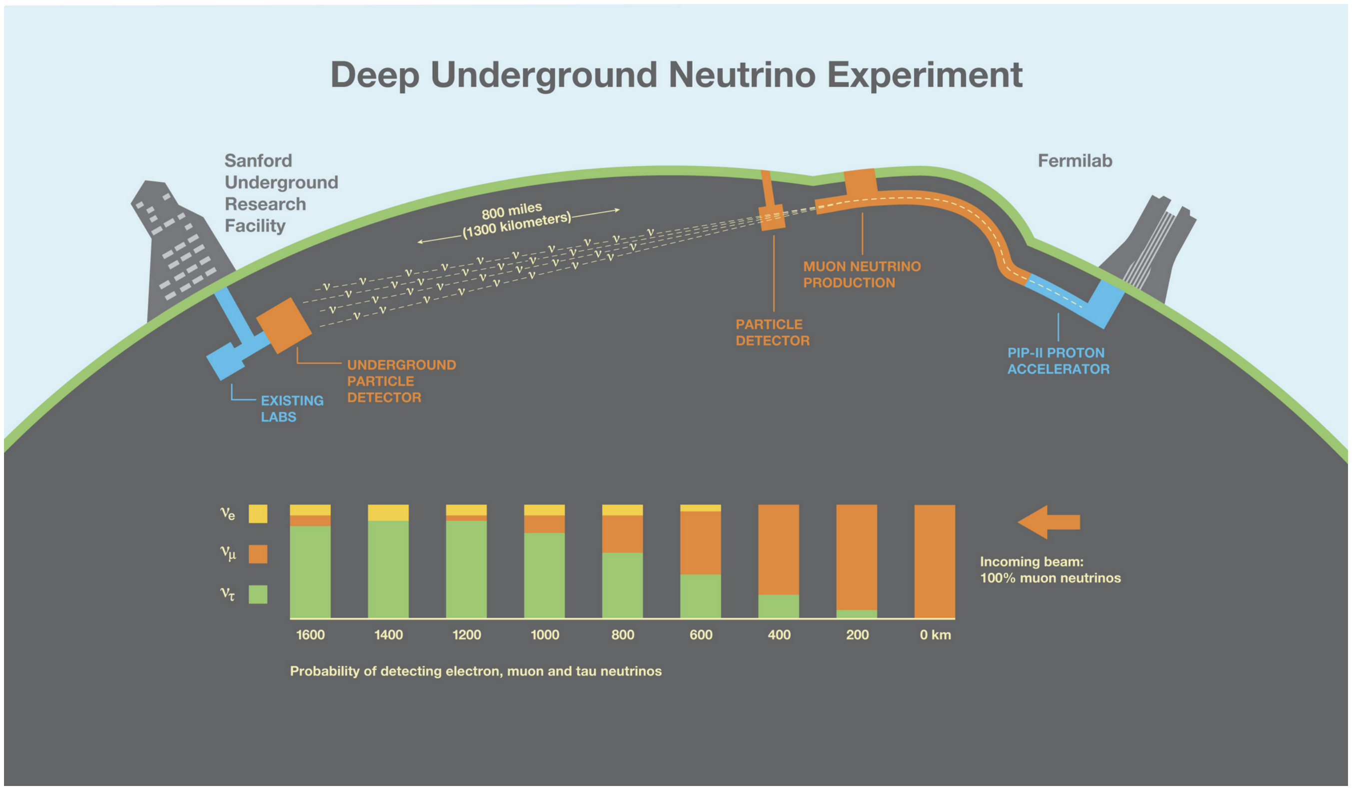






yesterday: neutrino experiments in broader context of HEP

- neutrino expts (think: **flavor oscillation** searches) occupy important place in SM tests



- requires knowledge of the νA cross section, $\sigma(E_\nu)$, to extract neutrino disappearance signature from near-, far-detectors

→ theory inaccuracies translate into limits in experimental precision

hampers sensitivity to: neutrino masses; hierarchy; BSM signatures; …

caution! measured neutrino flux must be unfolded (tomorrow)

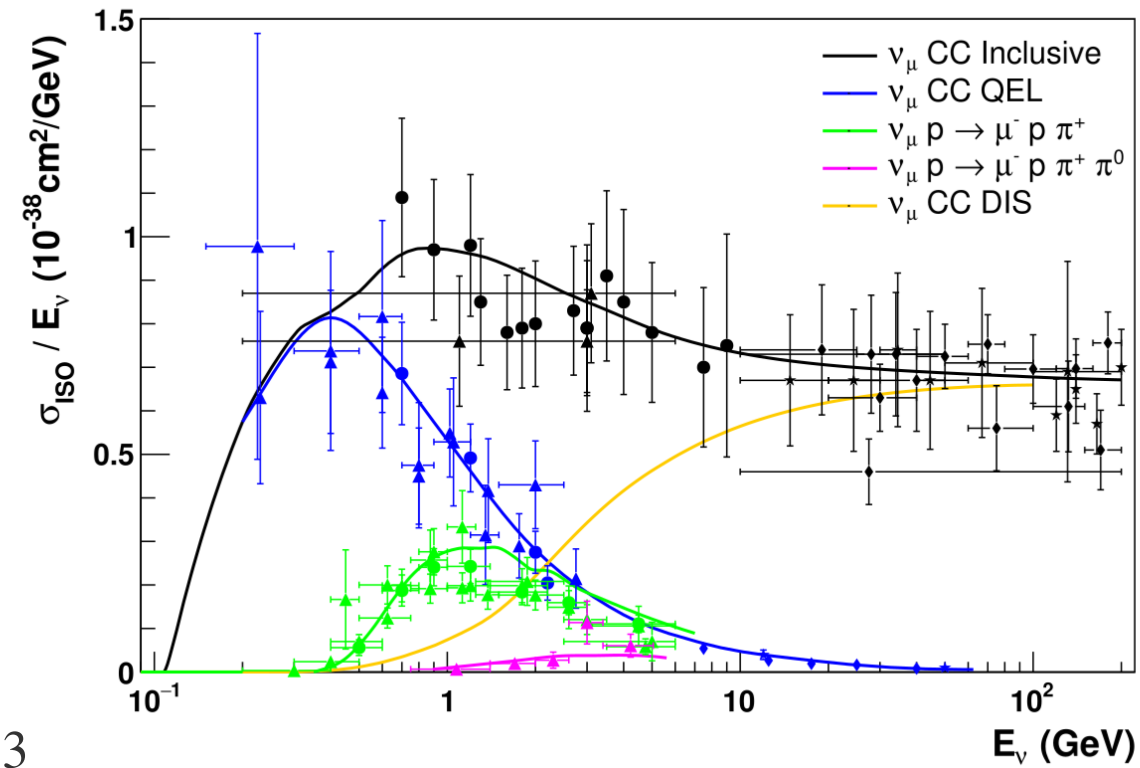
- oscillation searches require near/far fluxes; unfolding depends on $\sigma(E_\nu)$

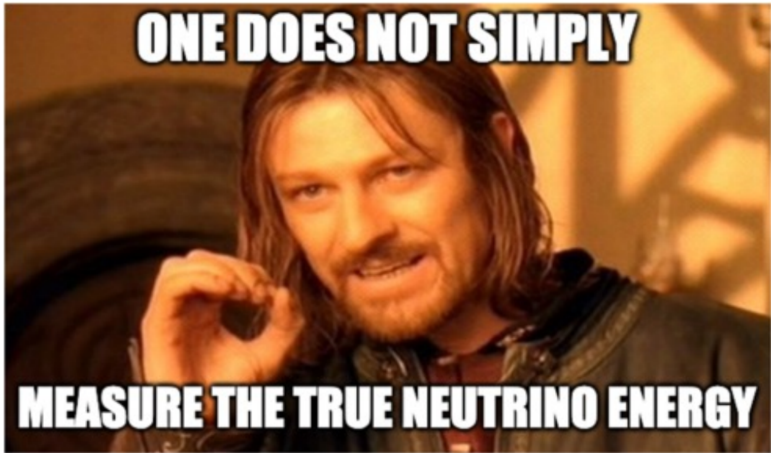
$$N_i(E_\nu^{\rm rec}, L) \sim \sum_k \int dE_\nu\, \Phi_i(E_\nu, L)\sigma_k(E_\nu) f_{\sigma_k}(E_\nu, E_\nu^{\rm rec})$$

$\Phi_i(E_\nu, L)$: neutrino flux, i^{th} flavor → want this

$\sigma_k(E_\nu)$: total cross section, process k

$f_{\sigma_k}(E_\nu, E_\nu^{rec})$: smearing matrix → need to know these





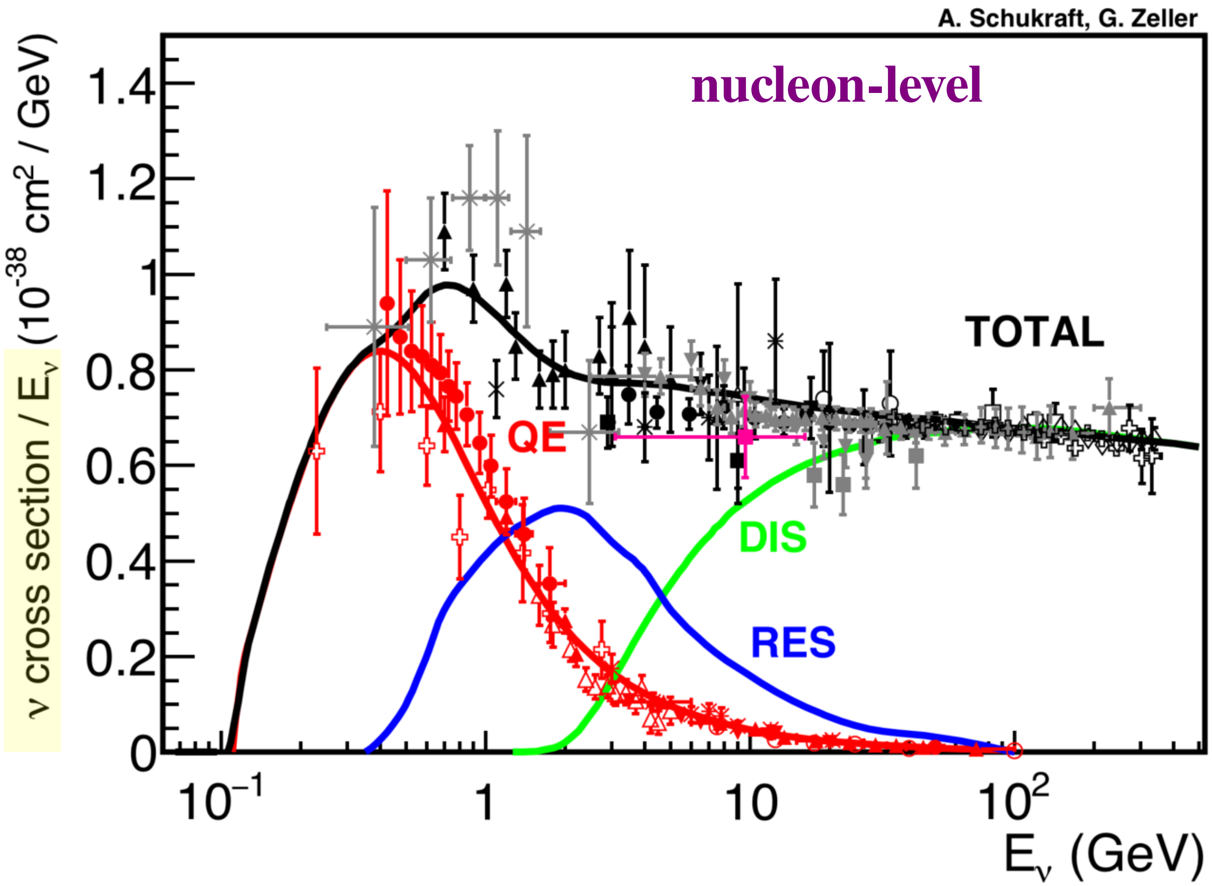
Shirley Li

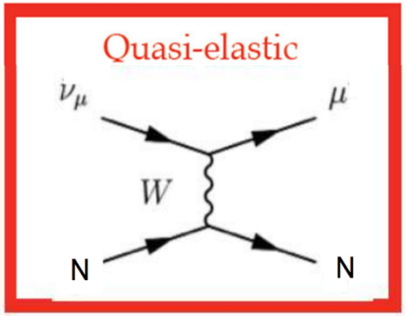
today: the **νA cross section** – connections to QCD, nuclear dynamics

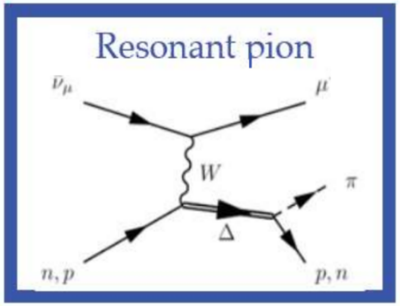
- **anatomy of νA interactions**: the integrated cross section
- νA theory meets experiments: **neutrino generators**
- **neutrino DIS**: quark-level neutrino scattering
- **open issues** in νA physics

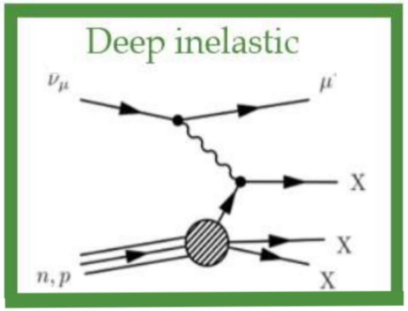
neutrino cross sections are <u>complicated</u>!

- full, integrated cross section emerges from various constituent sub-processes









- for nucleon scattering, three distinct mechanisms; unique empirical signatures
  → distinct QCD/nuclear processes; predominate at very different kinematics

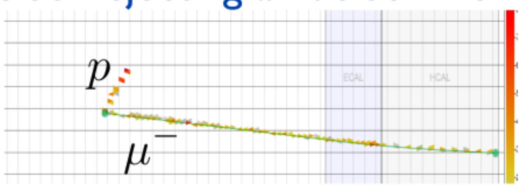
neutrino cross sections are <u>complicated</u>!

- experimentalists search for characteristic signals

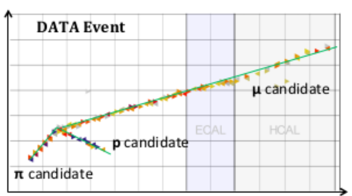
empirical

theoretical

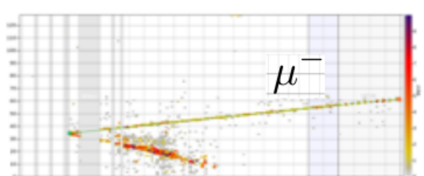
The neutrino scatters elastically off the nucleon ejecting a nucleon from the target

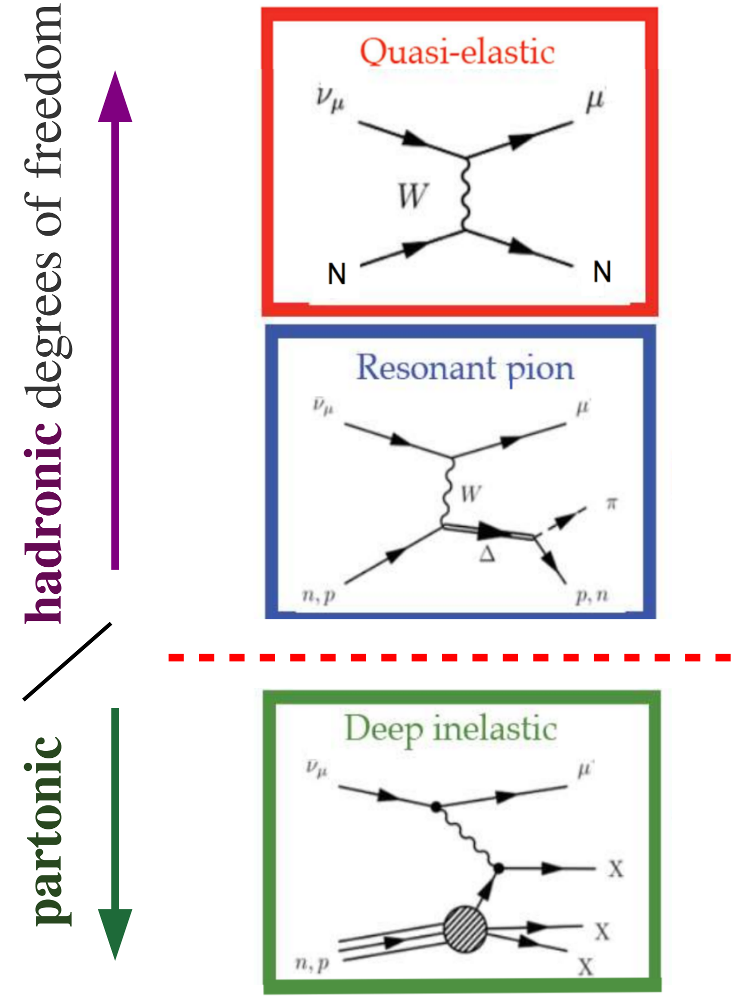


The neutrino can excite the target nucleon to a resonance state



The neutrino scatters off a quark in the nucleon producing a hadronic system in the final state





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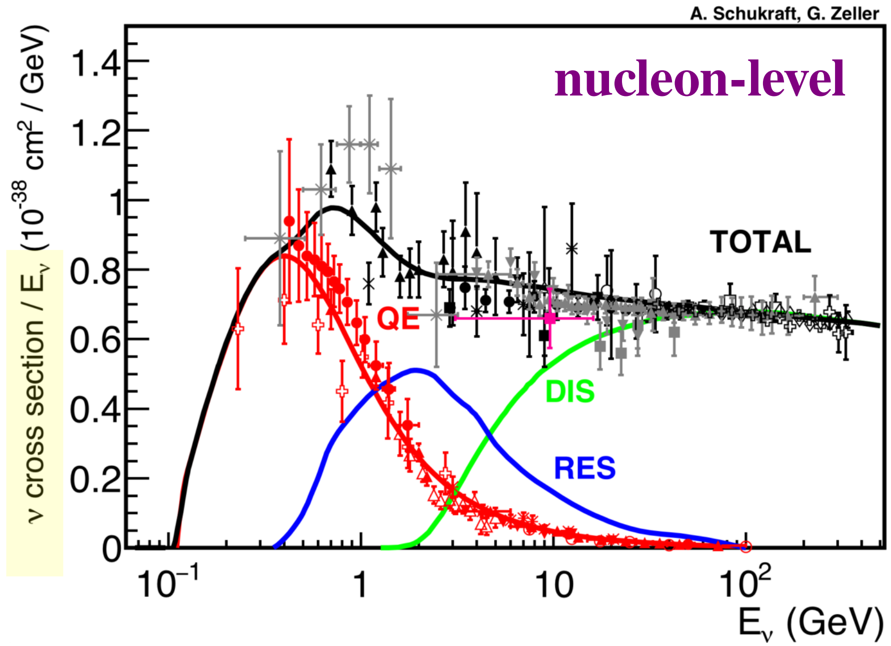
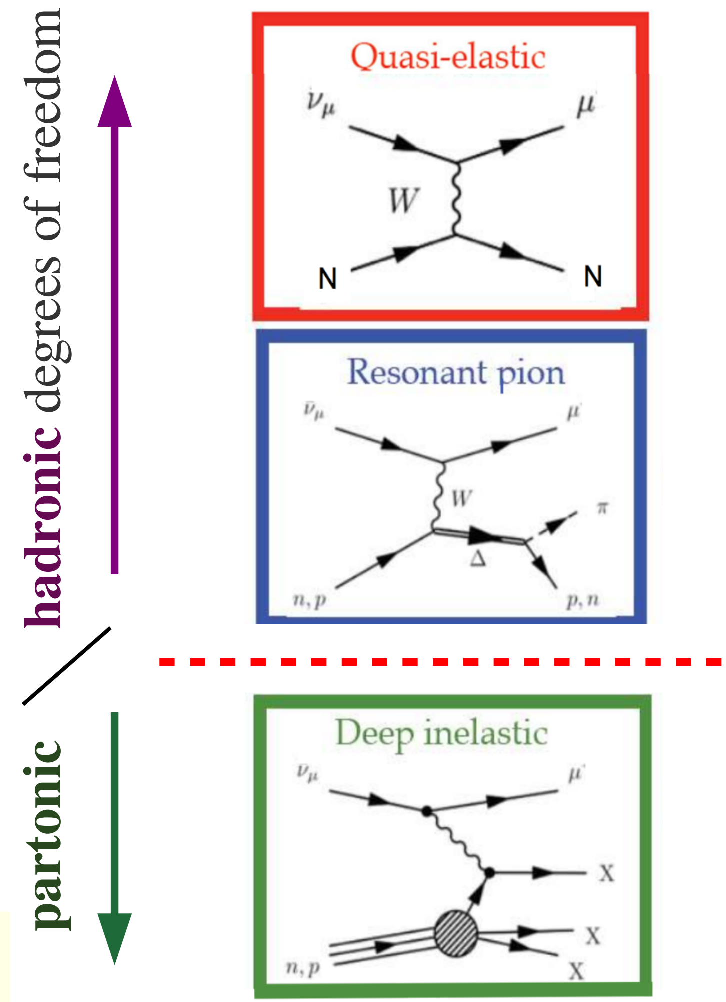
neutrino cross sections are <u>complicated</u>!

- full, integrated cross section emerges from various constituent sub-processes





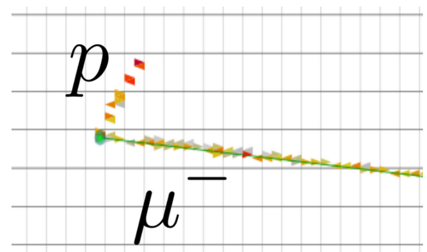
- <u>note</u>: these processes traverse the boundary between perturbative and nonperturbative dynamics;

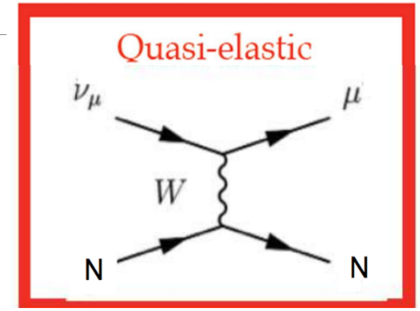
  → **closely tied up with confinement** ("grand challenge")

- for nucleon scattering, three distinct mechanisms; unique empirical signatures

  → distinct QCD/nuclear processes; predominate at very different kinematics

quasi-elastic scattering dominates low-energy cross section





- Using Llewellyn-Smith formalism:

$$\frac{d\sigma}{dQ^2_{QE}} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\left\{A(Q^2) \pm B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

Q^2-dependent factors depend (A, B, C) on single-nucleon information

→ vector, axial-vector form factors: $F_{1,2}(Q^2)$, $F_A(Q^2)$

$$A(Q^2) = \frac{m_\mu^2 + Q^2}{M^2}\Big\{(1+\frac{Q^2}{4M^2})F_A^2 - (1-\frac{Q^2}{4M^2})F_1^2 + \frac{Q^2}{4M^2}(1-\frac{Q^2}{4M^2})(\xi F_2)^2$$
$$+\frac{Q^2}{M^2}Re(F_1^*\xi F_2) - \frac{Q^2}{M^2}(1+\frac{Q^2}{4M^2})(F_A^3)^2$$
$$-\frac{m_\mu^2}{4M^2}\left[|F_1+\xi F_2|^2 + |F_A + 2F_P|^2 - 4(1+\frac{Q^2}{4M^2})((F_V^3)^2 + F_P^2)\right]\Big\}$$

$$B(Q^2) = \frac{Q^2}{M^2}Re\left[F_A^*(F_1+\xi F_2)\right] - \frac{m_\mu^2}{M^2}Re\left[(F_1 - \tau\xi F_2)F_V^{3*} - (F_A^* - \frac{Q^2}{2M^2}F_P)F_A^3\right]$$

$$C(Q^2) = \frac{1}{4}\left\{F_A^2 + F_1^2 + \tau(\xi F_2)^2 + \frac{Q^2}{M^2}(F_A^3)^2\right\}$$

especially limiting

how to describe nucleon form factor inputs?

→ historically, a single-parameter dipole ansatz used:

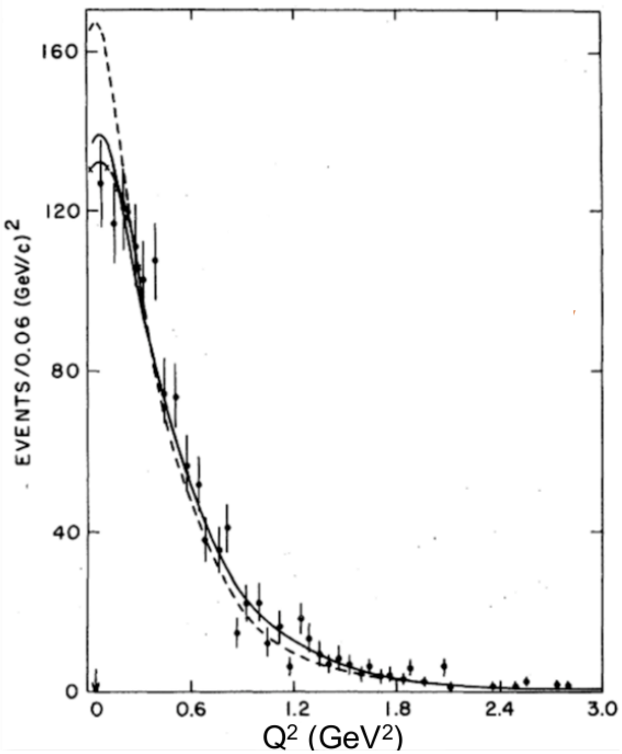
$$G_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

…but is this adequate?

- low-Q^2 shape is nontrivial: more flexible approaches necessary

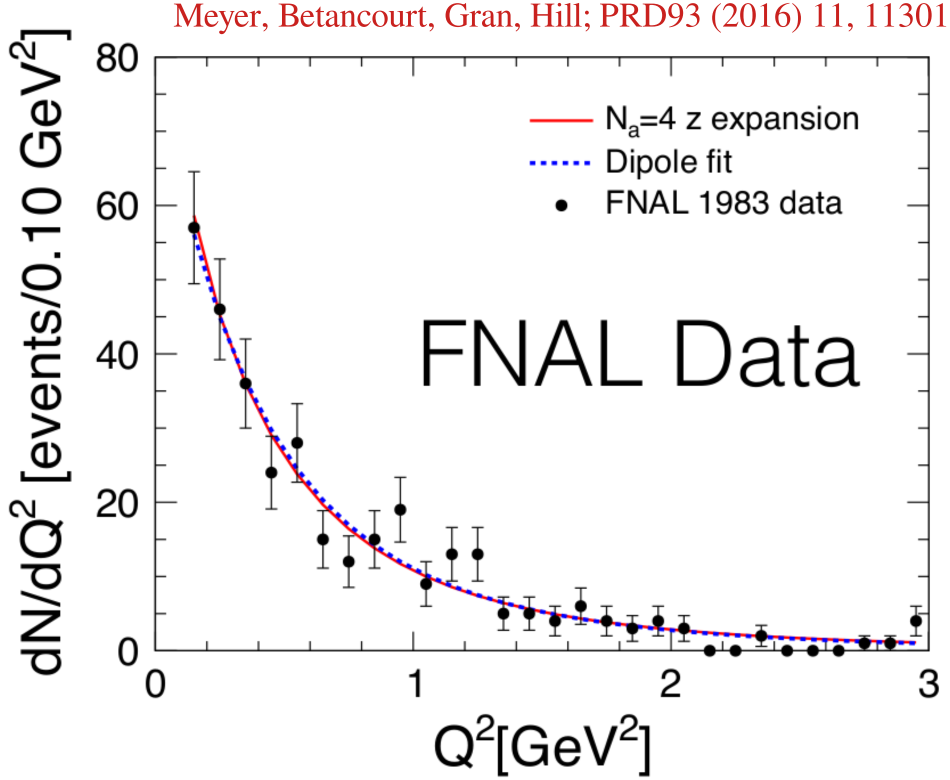
$$F_A(q^2) = \sum_{k=0}^{k_{\max}} a_k z(q^2)^k$$

$M_A = 1.07 \pm 0.06 GeV$



Baker, PRD 23, 2499 (1981)

Meyer, Betancourt, Gran, Hill; PRD93 (2016) 11, 113015



$$\langle p'_N \lambda'_N; N | J^\mu_A(0) | p_N, \lambda_N; N\rangle \qquad G_A \equiv \widetilde{F}_{1N}$$

$$= \overline{u}(p'_N, \lambda'_N)\left[\widetilde{F}_{1N}\gamma^\mu\gamma_5 + \widetilde{F}_{2N}\,\frac{q^\mu\gamma_5}{2M}\right]\frac{\boldsymbol{\tau}}{2}u(p_N, \lambda_N)$$

we can build a physical (relativistic quark) model for nucleon's axial structure:

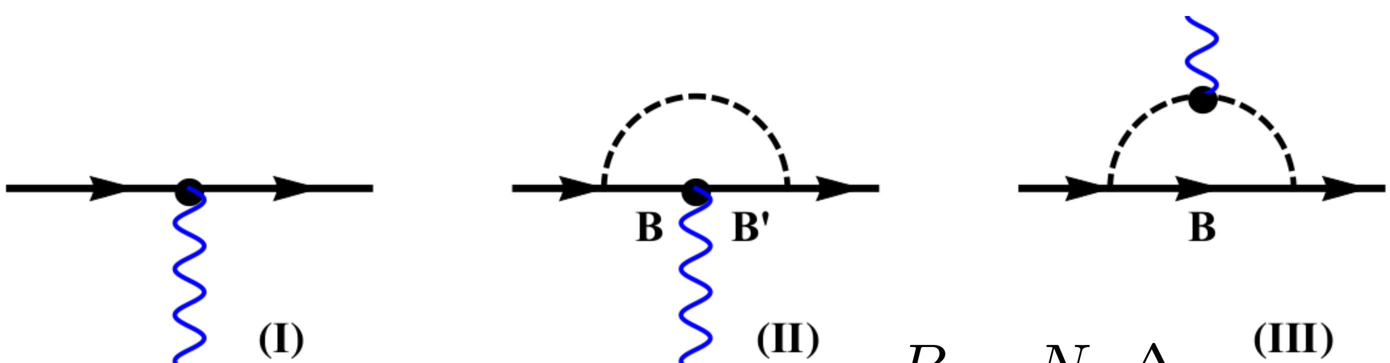
model EM and axial form factors light-front wave functions for *bare* quark+diquark core

$$|p_N^+, \lambda_N; N\rangle^{ss} = \int \frac{dx d\vec{k}_\perp}{16\pi^3 x(1-x)} \sum_{\lambda_q} \phi^{\lambda_N}_{\lambda_q}(x, \vec{k}_\perp)|x, \vec{k}_\perp, \lambda_q; q, d = s\rangle$$

$$|p_N^+, \lambda_N; N\rangle^{st} = \int \frac{dx d\vec{k}_\perp}{16\pi^3 x(1-x)} \sum_{\lambda_q, \lambda_d} \phi^{\lambda_N}_{\lambda_q\lambda_d}(x, \vec{k}_\perp)|x, \vec{k}_\perp, \lambda_q, \lambda_d; q, d = a\rangle$$

… include pion `cloud' contributions via chiral lagrangians with relativistic vertex factors:

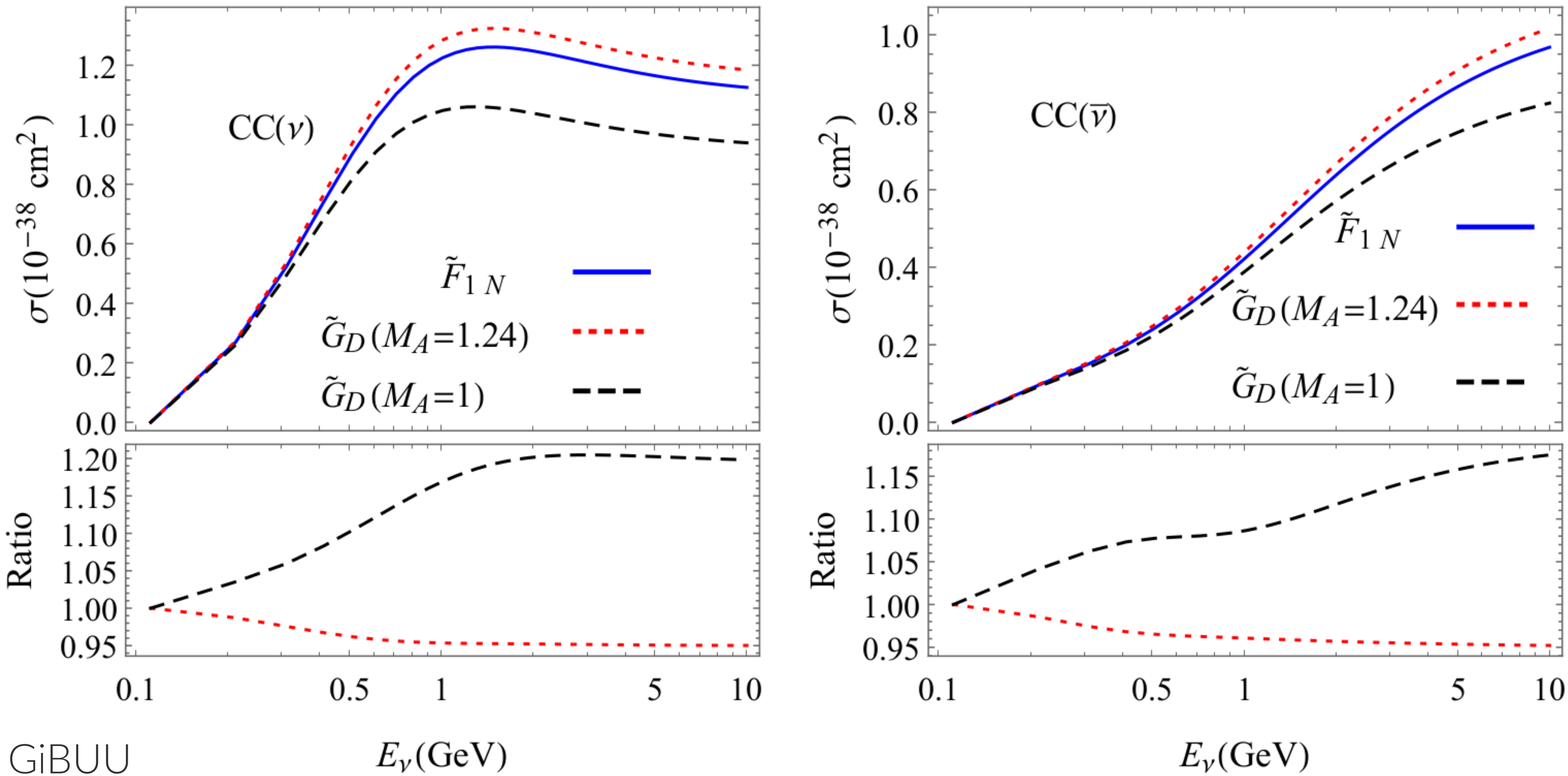
Zhang, TJH, Miller



$B = N,\ \Delta$

form factor models → QE → total cross section

variations in axial form factor Q^2 dependence influence cross section

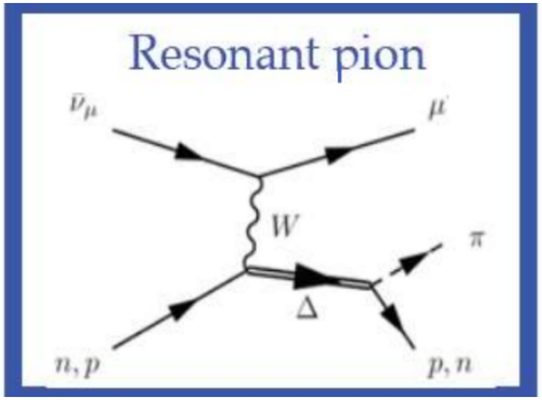


GiBUU

Argon cross sections in DUNE peak-flux region shift by **>5-10%**

→ **needs more data; concerted theory effort!**

resonance region: subtle mix of hadronic, QCD dynamics



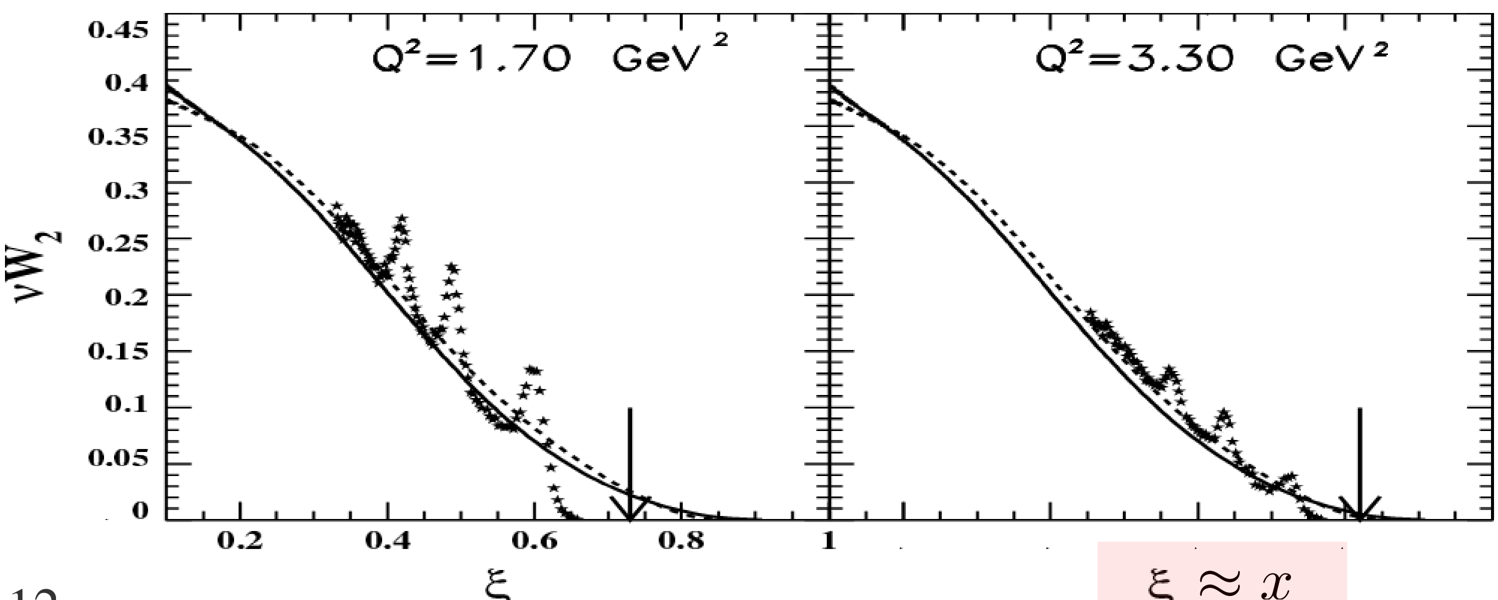
$$W^2 = (p+q)^2 = M_N^2 + Q^2\left(\frac{1}{x} - 1\right)$$

[low W $\rightarrow x \sim 1$]

$$x = Q^2/2p\cdot q$$

- more 'exclusive' processes involving production of definite nucleon excitations

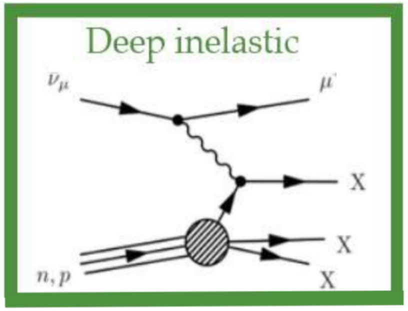
$\langle\Delta|T|N\rangle \rightarrow$ computed from quark models (*e.g.*, Berger-Sehgal, …)



$\xi \approx x$

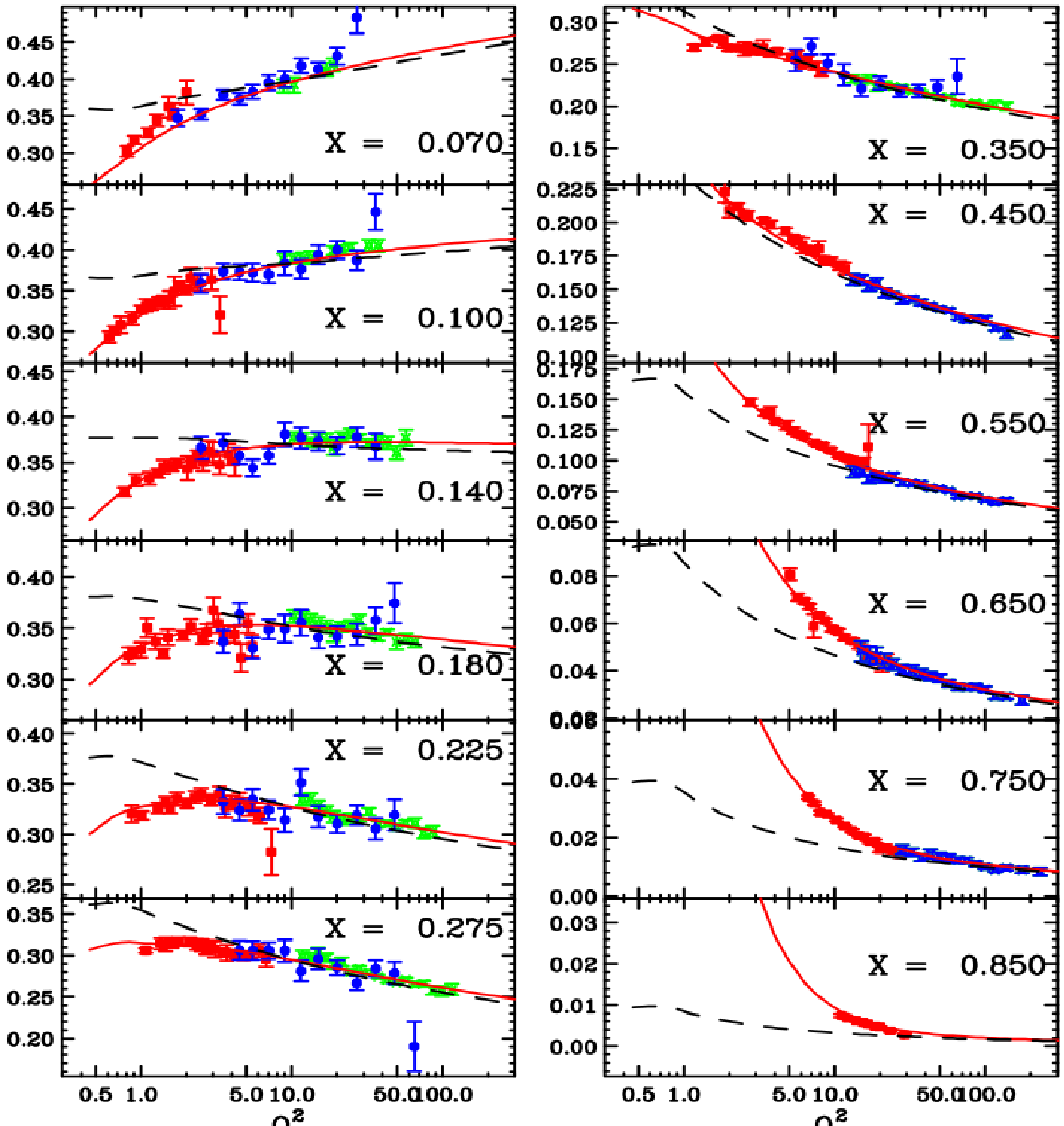
- important point: model-computed resonances fluctuate about smooth high-energy background;
- consistent description of RES, DIS is challenging!

DIS for neutrino programs



...interactions at quark level...

- need to cover DIS from very high energies down to low W, Q^2



- strong reliance on tunable phenomenological models; *e.g.*, Bodek-Yang

LO PDFs, $q(x) \to q(\xi_w)$

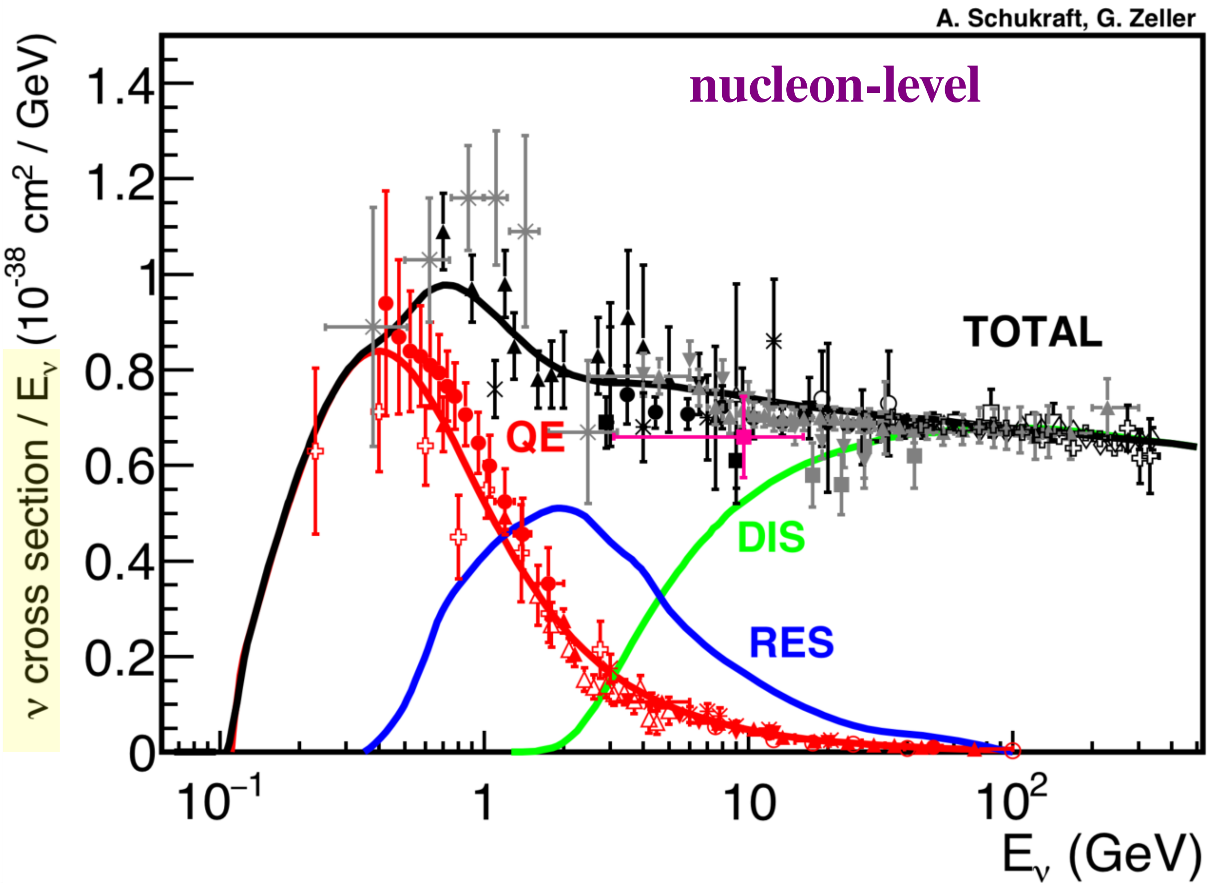
$$\xi_w = \frac{Q^2 + {M_f}^2 + B}{M\nu[1 + \sqrt{1 + Q^2/\nu^2}] + A}$$

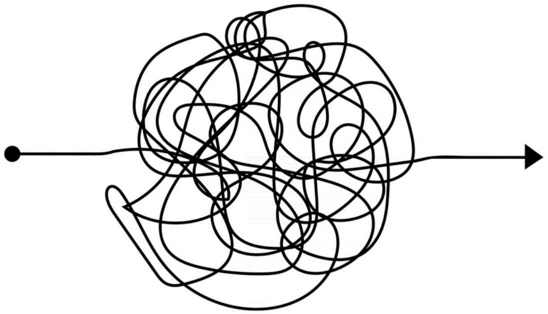
- together with low-Q^2 K-factors, meant to simulate missing [non]perturbative QCD dynamics

(will revisit later...)

neutrino-**nucleus** cross sections are (still more) complicated!

- again, each of these sub-processes is determined in conjunction with the others



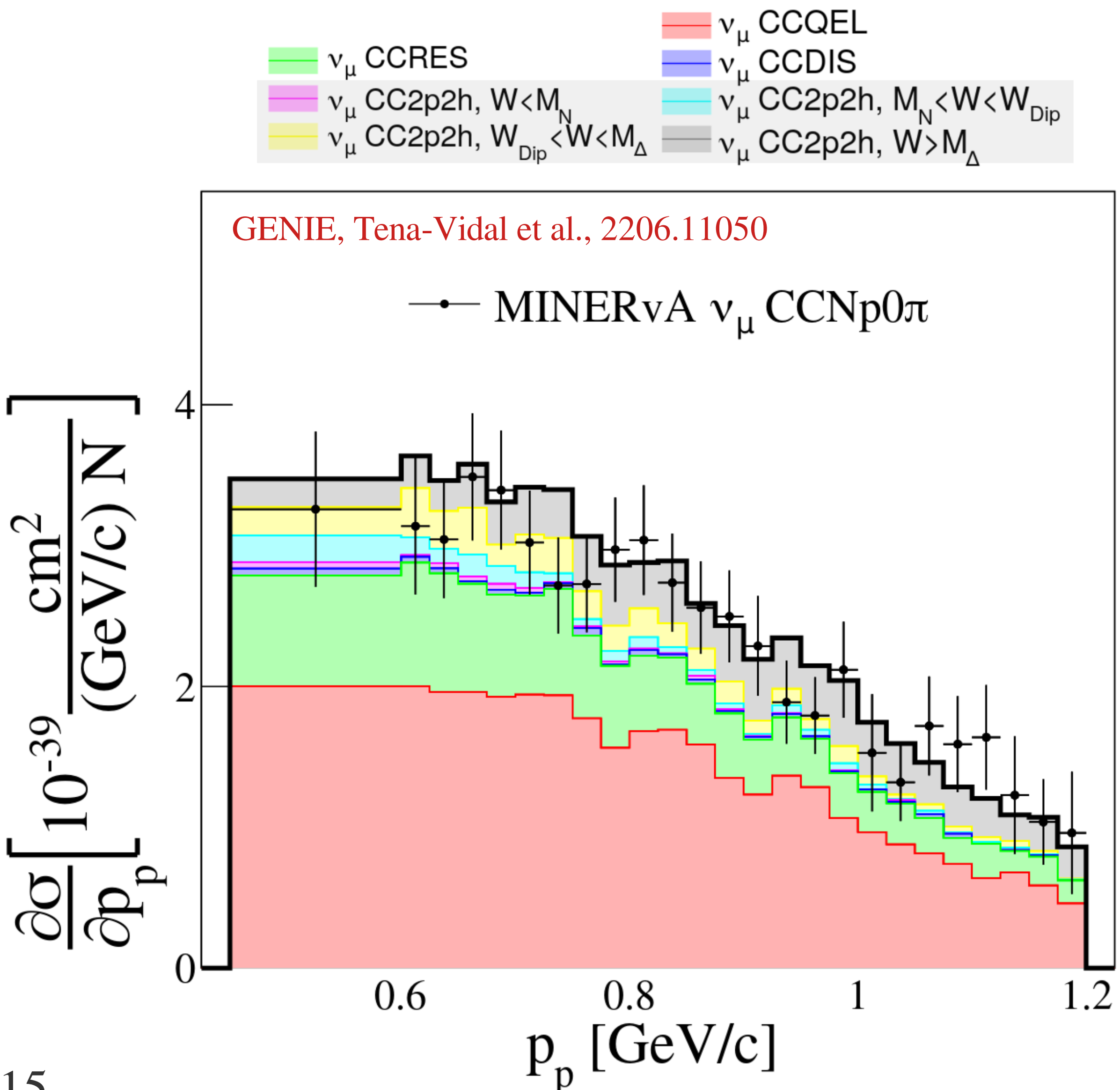


- above: νN → incorporating nuclear effects (νA) further complicates things

… introduces more processes to be modeled...

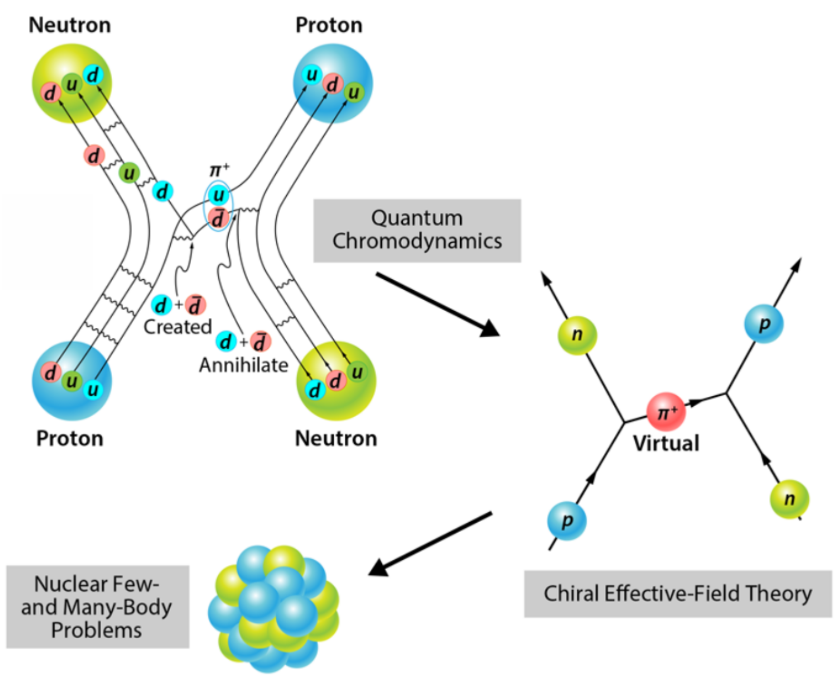
nuclear models like '2p2h' are necessary for νA

- low-energy data (few-GeV and below) generally require explicit nuclear models

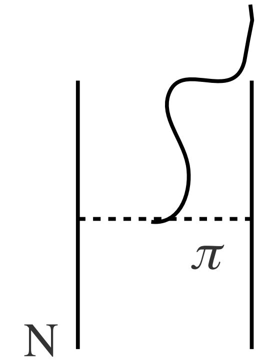


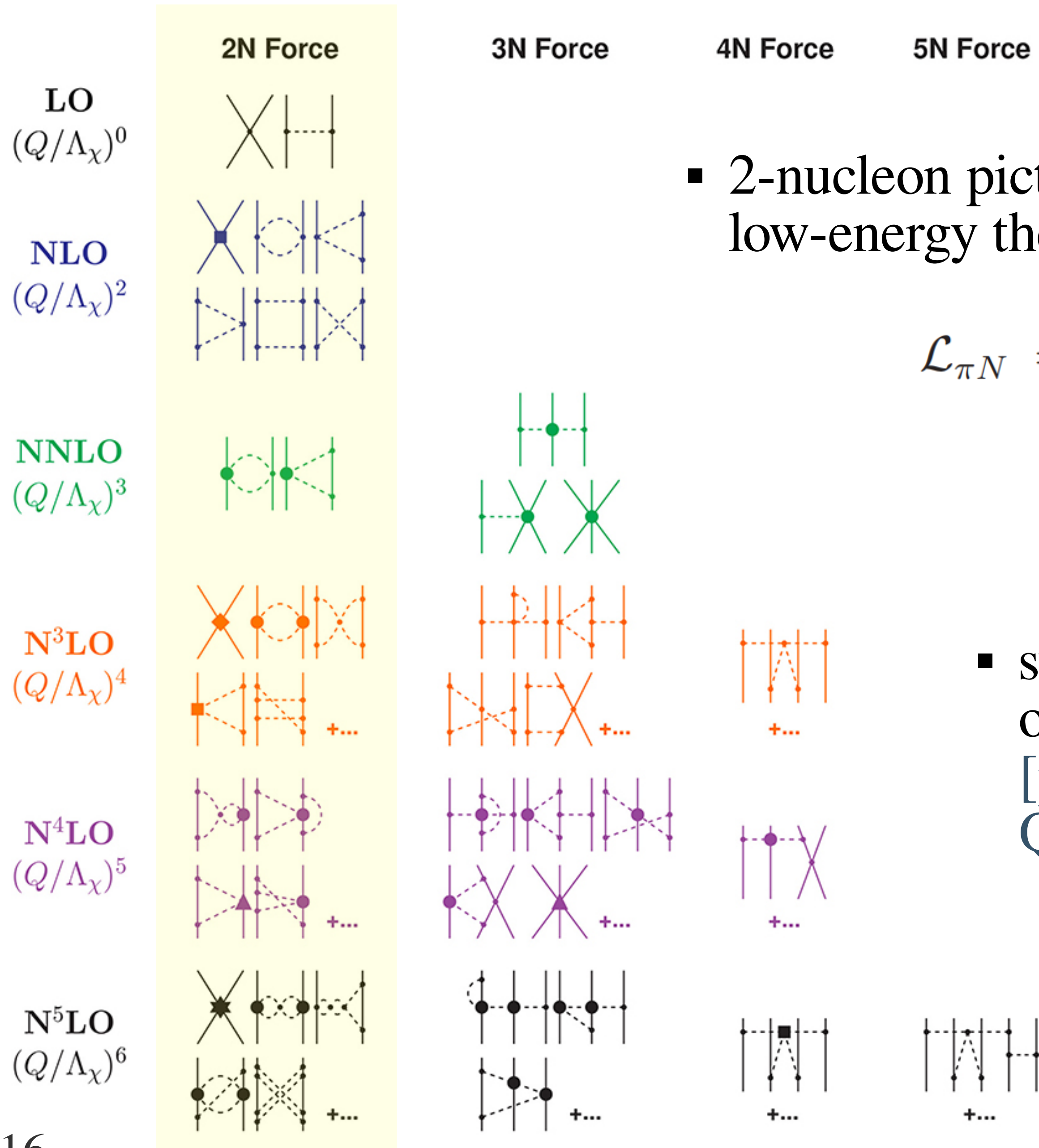
- the nuclear medium offers novel (QCD) interactions unavailable in scattering from free nucleons

e.g., scattering from 2-nucleon states



meson (pion) exchange dominant low-energy mechanism





- 2-nucleon picture has basis in formal low-energy theory

$$\mathcal{L}_{\pi N} = \frac{g_A}{2f_\pi}\bar{\psi}_N\gamma^\mu\gamma_5\,\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}\,\psi_N - \frac{1}{(2f_\pi)^2}\bar{\psi}_N\gamma^\mu\,\boldsymbol{\tau}\cdot(\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi})\,\psi_N$$

- systematically improvable to higher orders, particle interactions [perturbation theory not just for QCD, EW theory!]

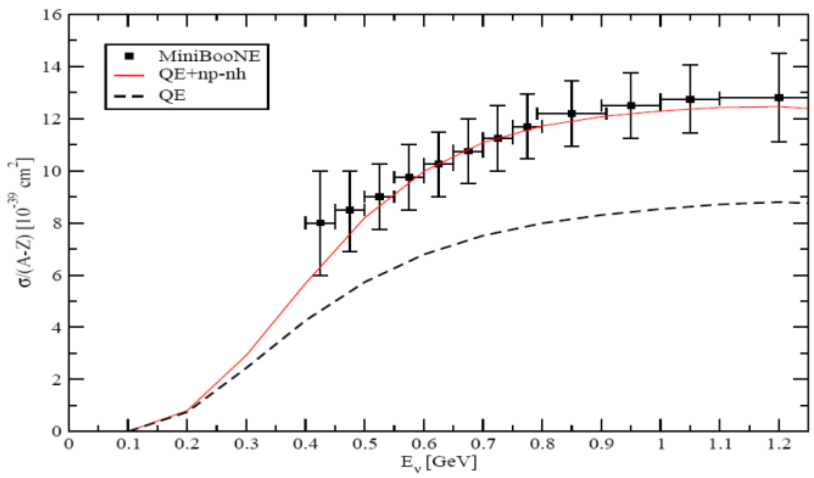
nuclear physics produces multi-2 (and higher)-nucleon correlations; external bosons scatter from these

modern neutrino calculations implement phenemenological models

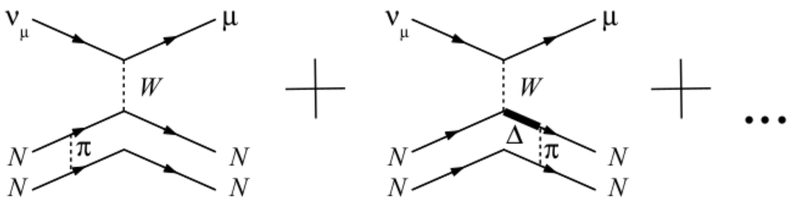
- still require freedom to **parametrically tune** to describe date; implement models derived from 2-nucleon scattering mechanism

- Inclusion of the multi nucleon emission channel (np-nn) gives better agreement with data

Model compared to MiniBooNE data

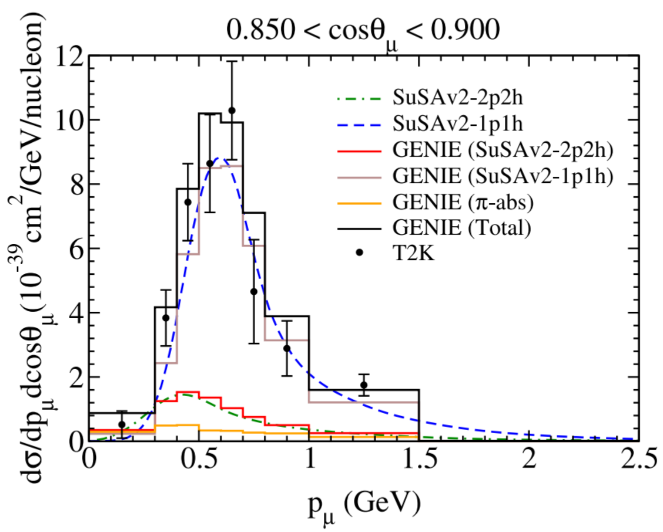


M. Martini, M. Ericson, G. Chanfray, J. Marteau *Phys. Rev. C 80 065501 (2009)*



other models: SuperScaling Approximation (SUSA)

Phys. Rev. D 101, 033003 (2020)



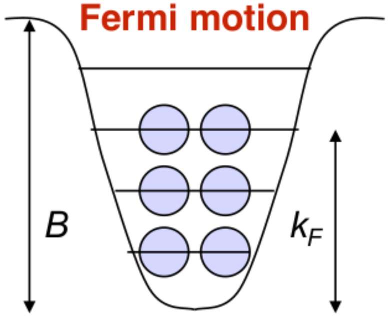
- We are using one of the theoretical predictions and latest GENIE implementation of Valencia model for QE-like 2p2h, arXiv:1601.02038, PRC 70, 055503 (2004), PRC 83, 045501 (2011)

2-nucleon ('2p2h') effects are **merely one example**

- large, multi-nucleon system introduces many considerations

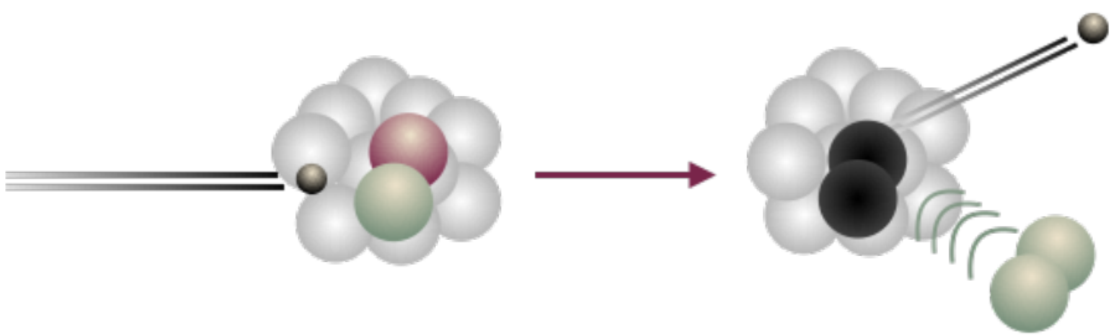
- Fermi motion: In a nucleus, the target nucleon has a momentum. Modeled as Fermi gas that fills up all available state until some Fermi momentum
- Pauli blocking: Pauli exclusion principle ensures that states cannot occupy states that are already filled
- Multi nucleon interactions
- Final state interactions

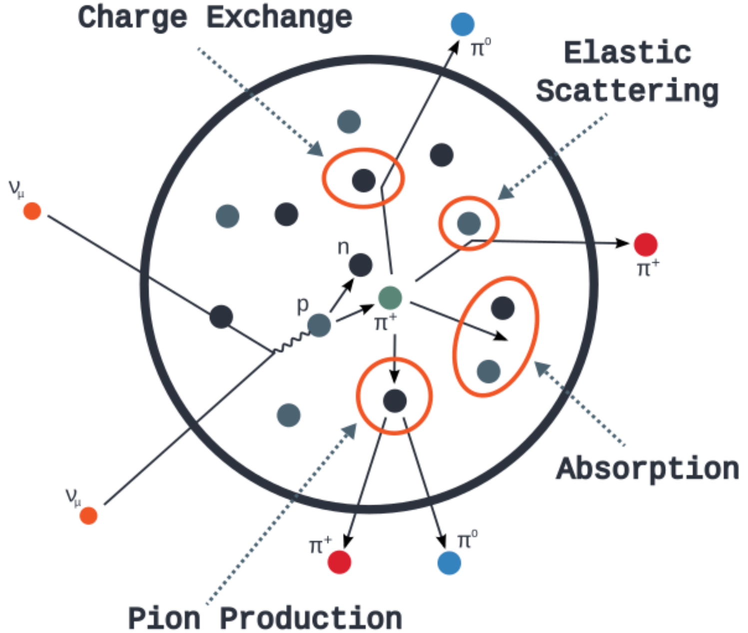
Fermi motion



Final State Interactions (FSI)

Multi nucleon interactions



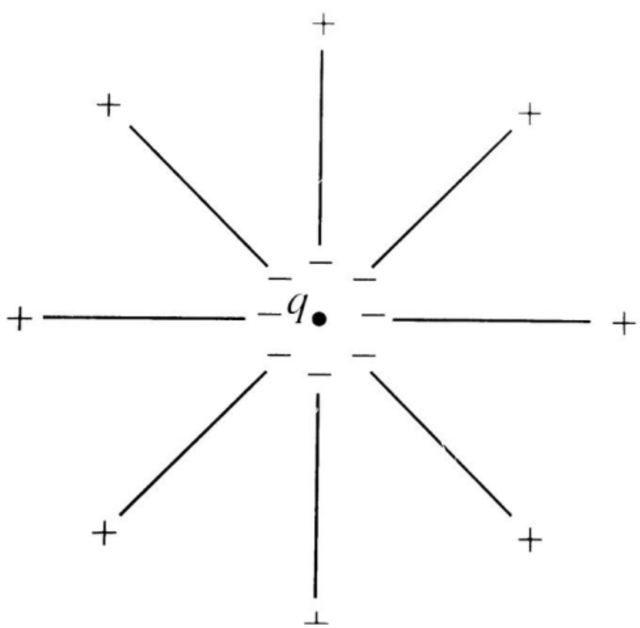


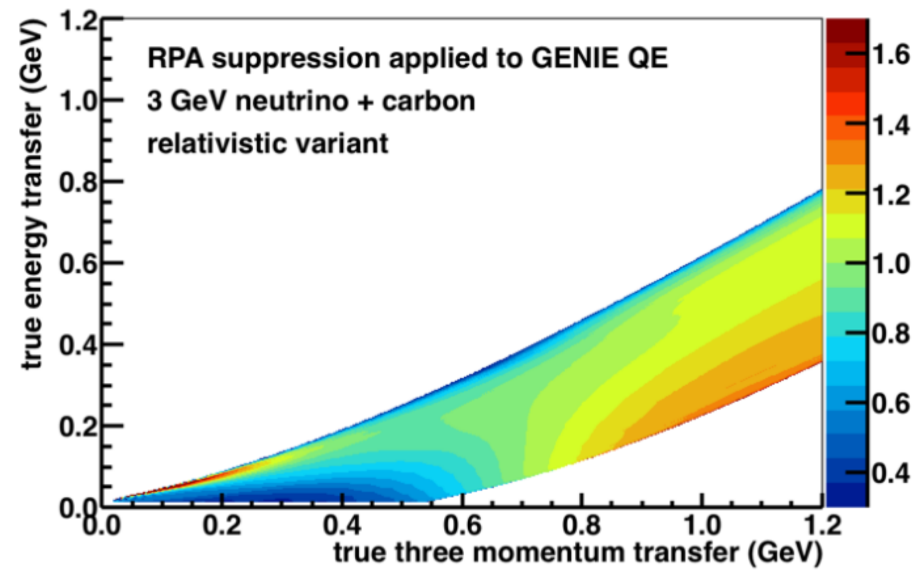
in contrast to few-nucleon, collective nuclear effects as well

- low-energy cross sections (QE) subject to **long-distance correlations**

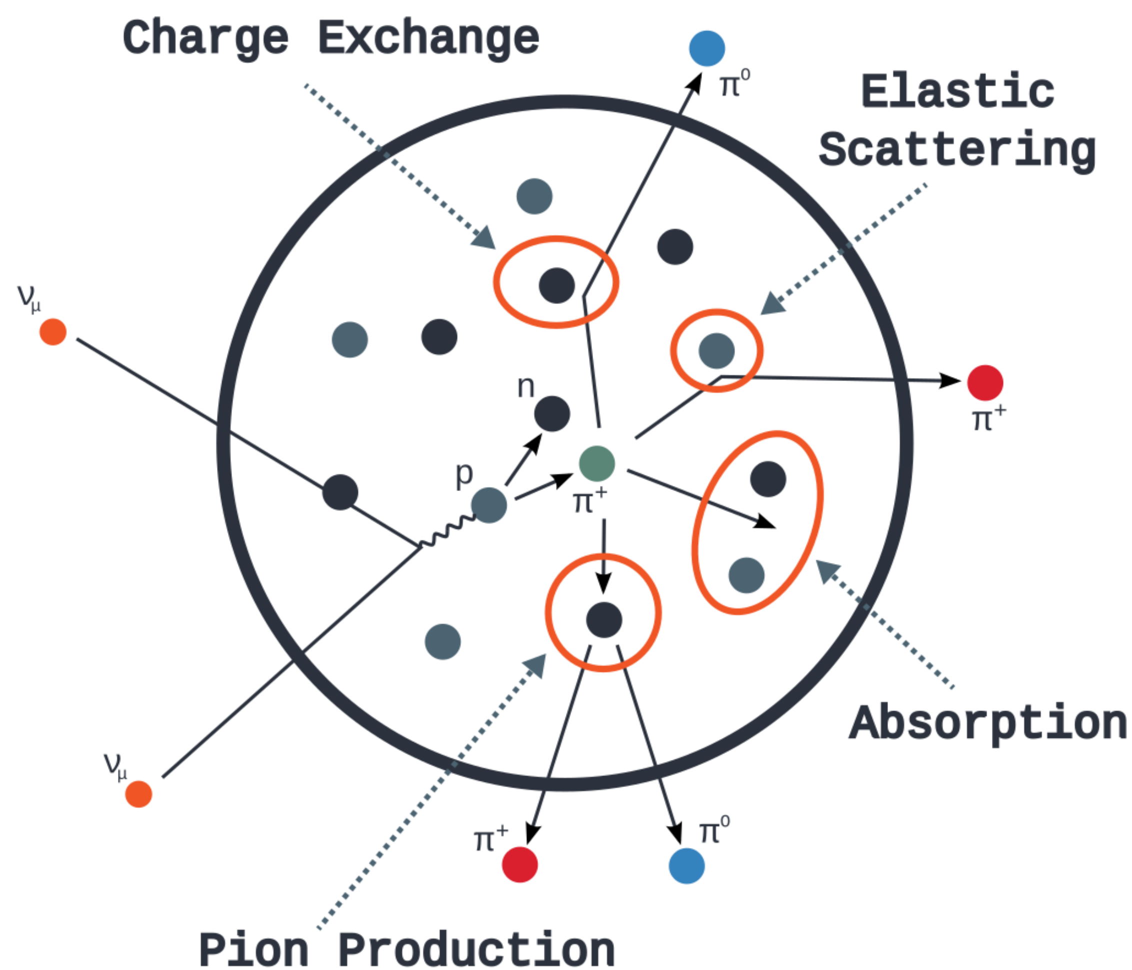
- Analogous to screening of electric charge in a dielectric
- For neutrino scattering in a nucleus, imagine the W as having a weak charge and polarizing the nuclear medium
- Calculated using Random phase approximation (RPA), PRC 70, 055503 (2004)
- We add the RPA to GENIE by reweighting the QE events
- Suppress cross sections at low four momentum transfer Q^2

$$\sigma^{\mathrm{QEL}} = \omega_{\mathrm{RPA}} \cdot \sigma^{\mathrm{QEL}}_{\mathrm{RPA}} + \omega_{\mathrm{No\,RPA}} \cdot \sigma^{\mathrm{QEL}}_{\mathrm{No\,RPA}}$$





lastly, final-state interactions (**FSI**) influence kinematic distributions



- hadrons produced in 'primary interactions' must traverse nuclear medium

models

→ intranuclear cascade: semi-classical propagation b/t successive re-scatters

→ hadron transport: adapted from heavy-ion; solve Kadanoff-Baym

merely a *sampling* of the types of nuclear models

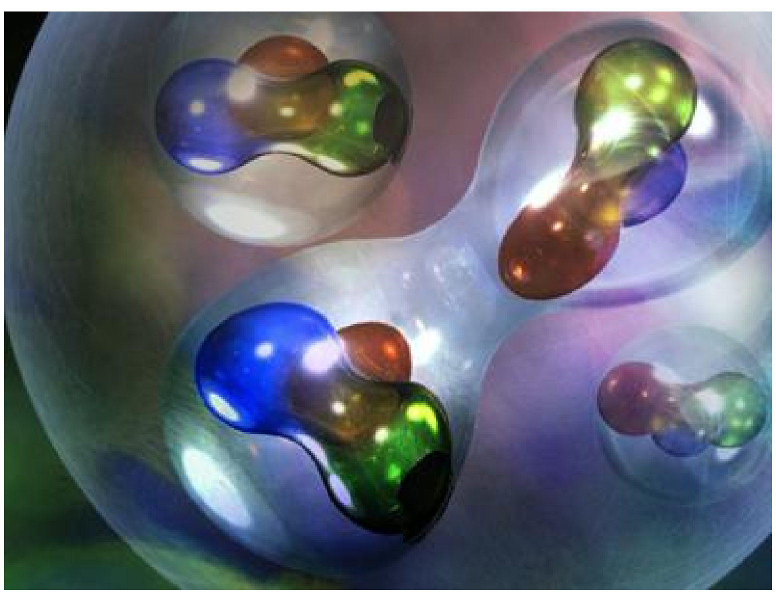
- these nuclear corrections are generally felt at low energies

$$E_\nu \lesssim 1\,\mathrm{GeV},\ \text{probing correlation lengths} \gtrsim 1\,\mathrm{fm}$$

- nuclear medium is complex soup of strongly-correlated fields, QCD *d.o.f.*

→ natural to expect corrections at higher energies

→ deeply fascinating: how does QCD produce dynamics of nuclear environment?



OR: what are the partonic implications of placing a nucleon in the nucleus?

→ focus of nuclear DIS programs;

→ vital for νA precision predictions

...more soon!

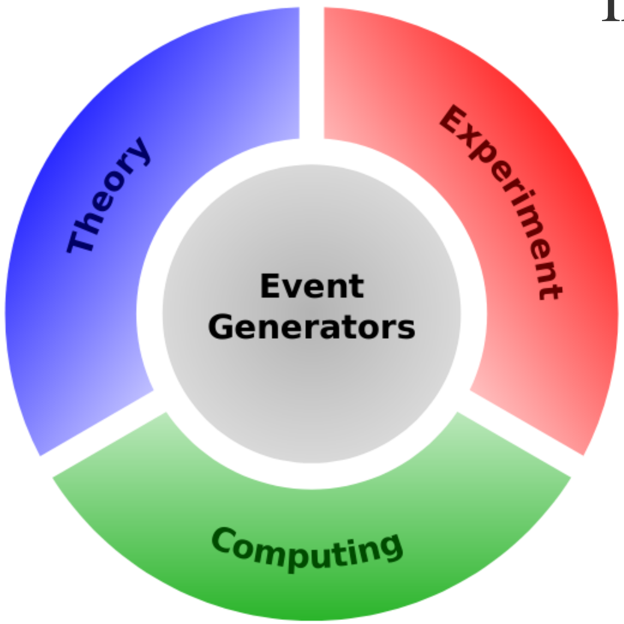
- clear that the νA cross section involves interplay of various models

  → prescription/model/parametrization uncertainties are an important limitation

- conversely, high-quality neutrino (or other) data may be sensitive to model choices

  → can be used to constrain tunable parameters; test model assumptions

  → need systematic approach to include theory ingredients simultaneously

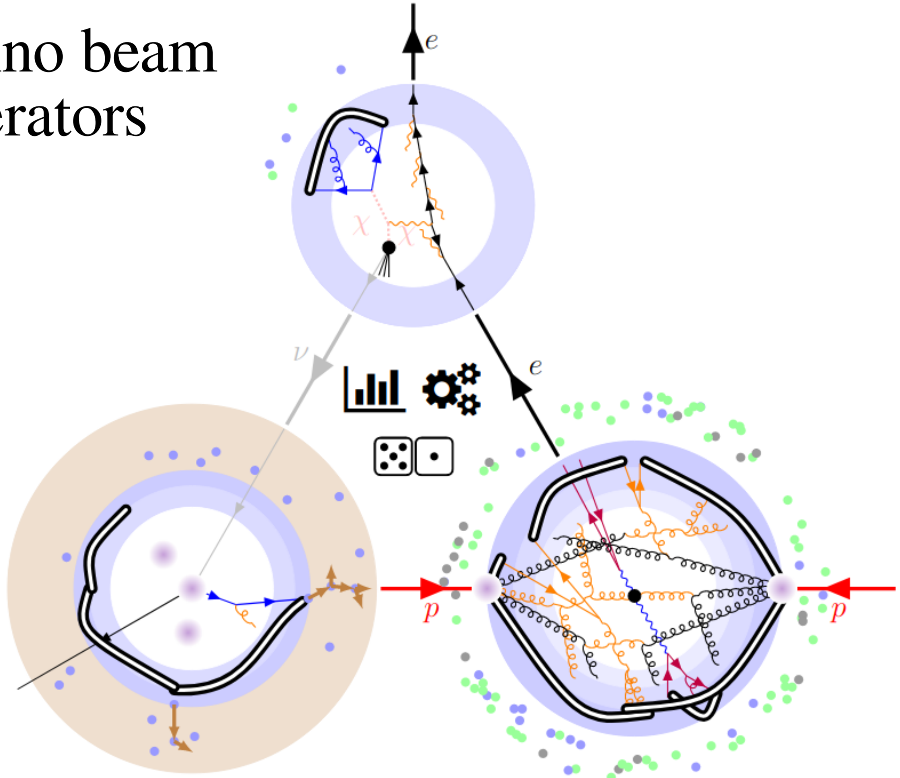


ingredients come together in event generators

- neutrino events must ultimately be simulated in Monte Carlo generators to understand systematics

  → frameworks rest at interface of theory, computation, and experiment

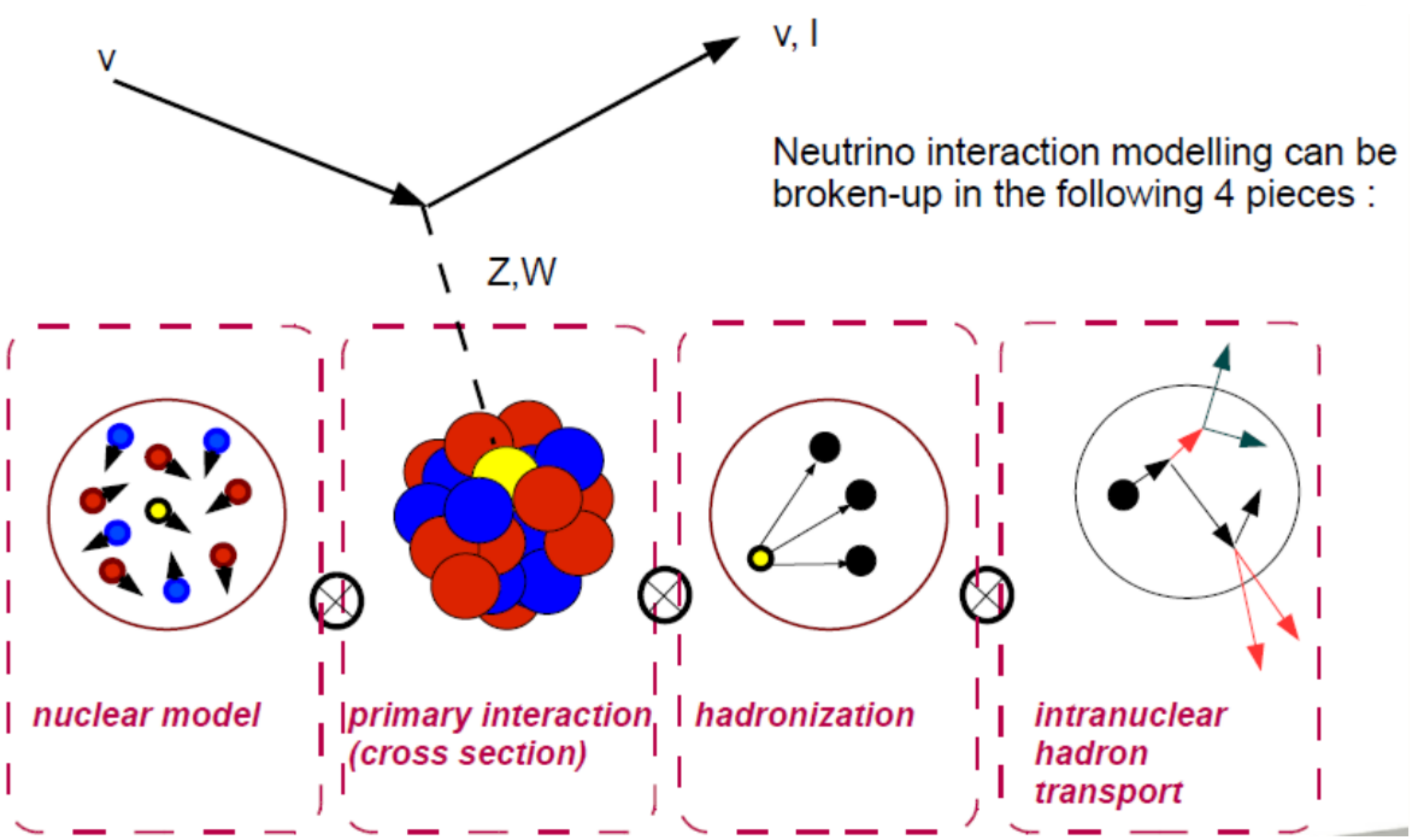
- again, impracticability of determining neutrino beam energy implies sensitive dependence on generators for event-by-event reconstruction



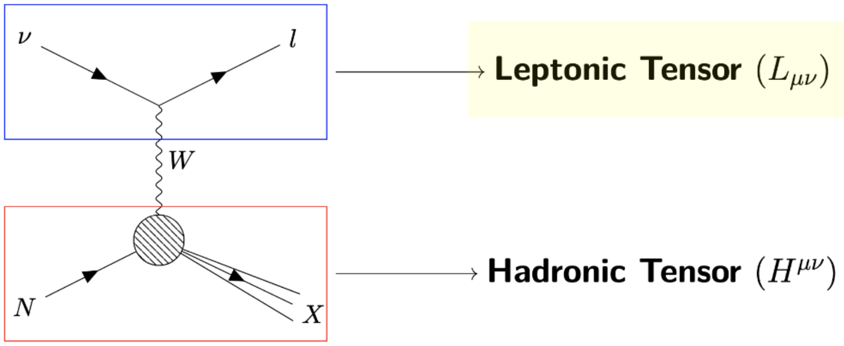
for DUNE, need **percent-level precision** or better; past this, sensitivity to CP-violation, mixing degrades substantially

central development effort

generators systematize the physics ingredients discussed above



- aspiration: structure neutrino generators for easier BSM modifications



[predominant locus of BSM scenarios]

- recent developments: Achilles generator

Isaacson et al., 2205.06378

ecosystem of neutrino generators

- must stress: **generators occupy vital place bridging experiments ↔ theory**

- commonly used generator packages implement different mixes of theory models; approaches to hadron transport

GiBUU

Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

NuWro
Wroclaw Neutrino Event Generator

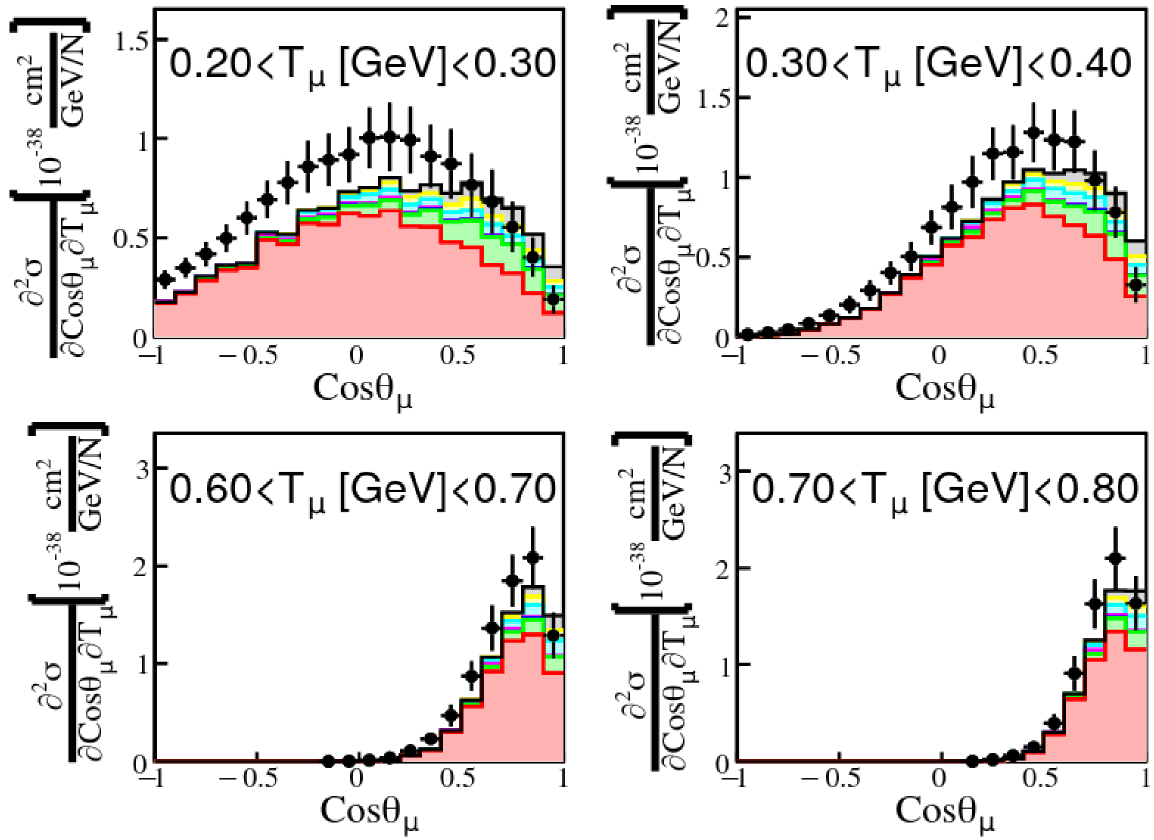
→ on-going effort to standardize theory interfaces; input/output conventions; interoperability

[lessons from collider efforts useful]

generator tunings

- neutrino generators accompanied by global analyses of available parameters

Simulation domain	Model
Nuclear model	Local Fermi Gas [14]
QEL and 2p2h	Valencia [13, 15]
QEL Charm	Kovalenko [16]
QEL $\Delta S = 1$	Pais [17]
RES	Berger-Sehgal [18]
SIS/DIS	Bodek-Yang [19]
DIS $\Delta S = 1$	Aivazis-Tung-Olness [20]
Coherent π production	Berger-Sehgal [18]
Hadronization	AGKY [21]
FSI	INTRANUKE hA [22]

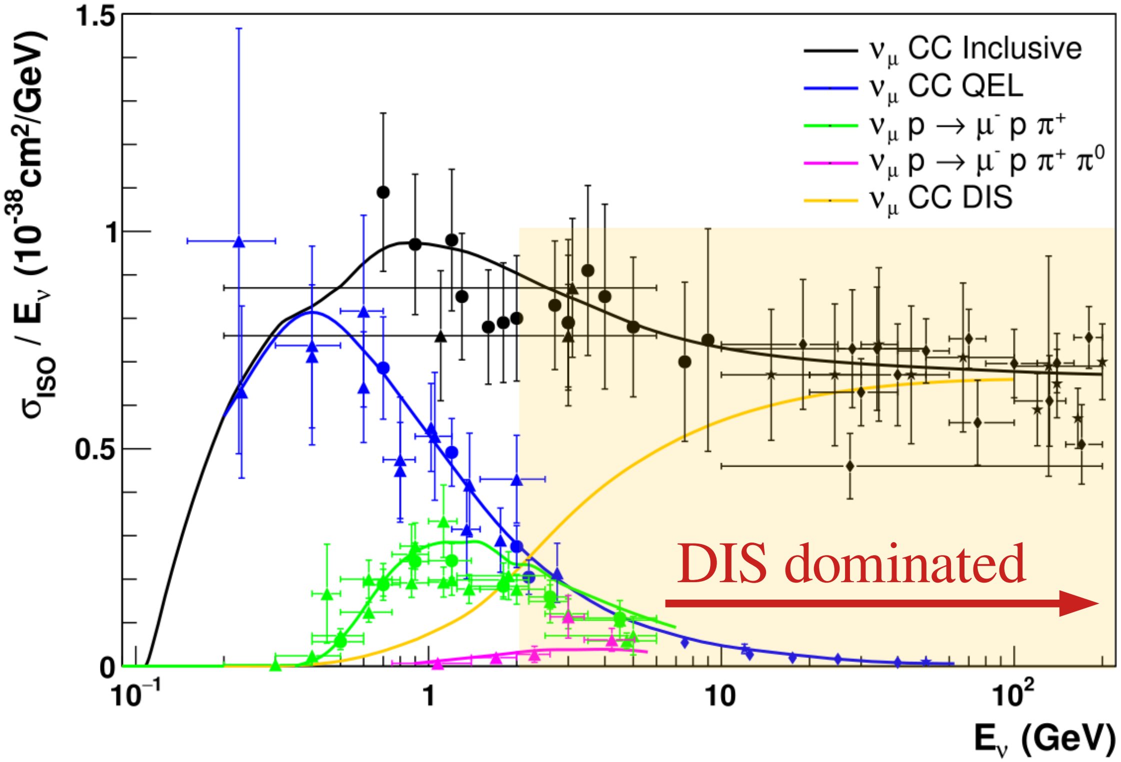


→ physical compatibility of models in tunes is an open topic

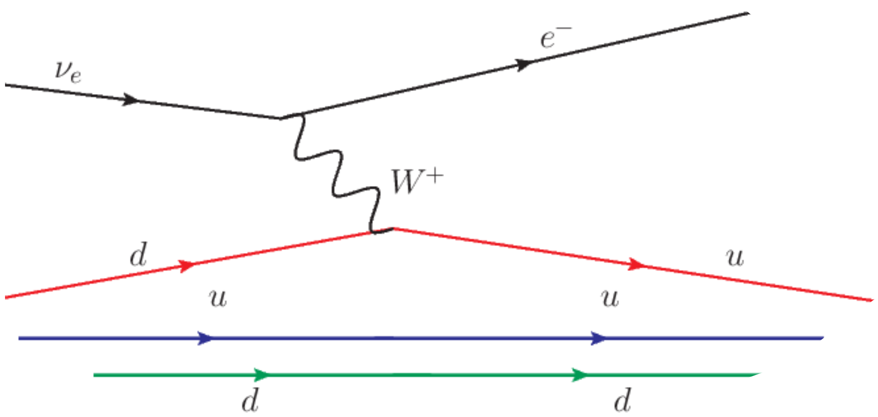
→ **complicated correlations and patterns of tensions**

- given strong model dependence, strong value to QCD-based input…

neutrino-nuclear DIS is a problem of special interest



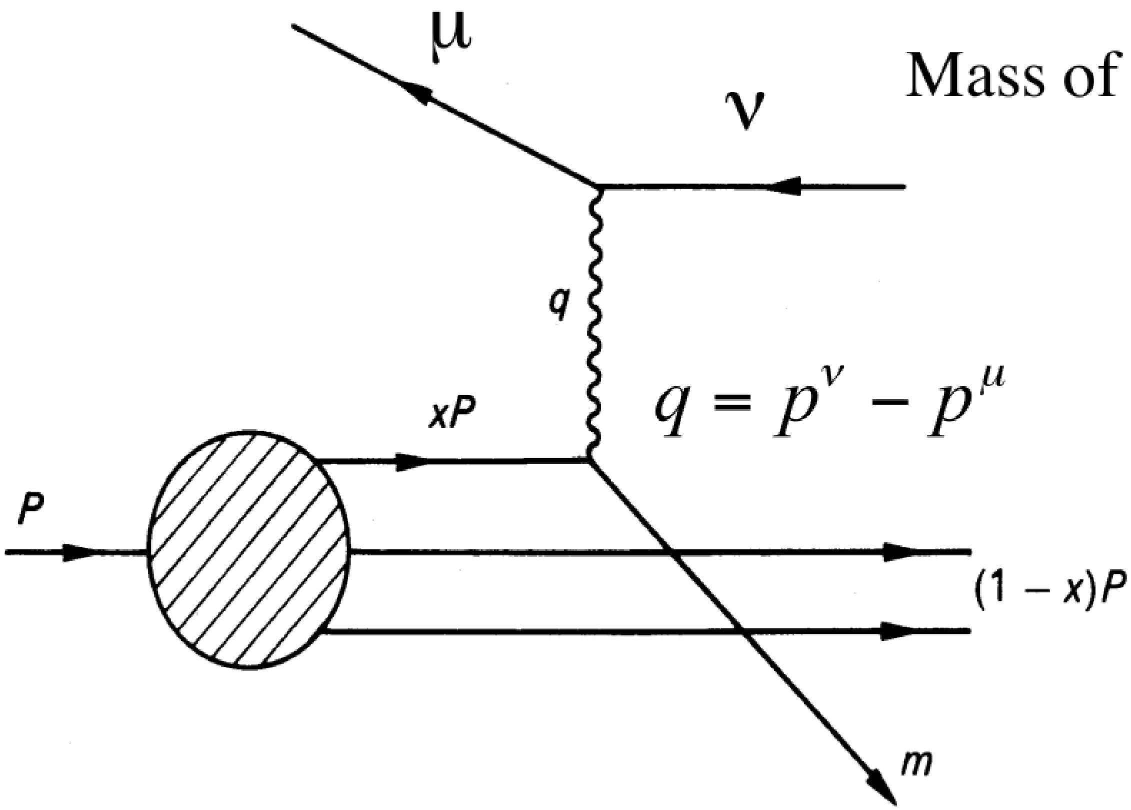
→ most formulable in terms of active QCD degrees of freedom



- high energy scattering dominated DIS
  - → provides context to systematically improve QCD theory
  - → unique access to hadron, nuclear flavor structure
    - $\sim \langle \gamma_\mu \gamma_5 \rangle$ CC operator structure selects uniqe parton-level flavor currents
- critical contribution in few-GeV region for DUNE, Phase-1, 2

neutrino DIS closely resembles EM analogue

Mass of target quark $m_q^{\,2} = x^2 P^2$



Mass of final state quark

$$m_{q'}^{\,2} = (xP + q)^2$$

$$q = p^{\nu} - p^{\mu}$$

In "infinite momentum frame", x is momentum of partons inside the nucleon

$$x = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{2M_T \nu}$$

Neutrino scatters off a point-like parton inside the nucleon. Valid picture at high energies

neutrino-nucleon interactions in the quark model

- charge-current structure restricts flavors "felt" by external boson

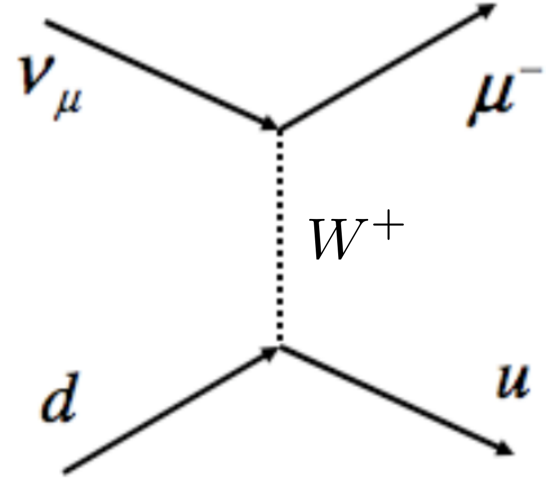
recitation yesterday: point-like scattering!

- Scattering off proton:

$$\frac{d\sigma_{CC}(\nu_\mu p)}{dxdy} = \frac{G_F^2 ME}{\pi} 2x\left\{\left[d(x)+s(x)\right]+\left[\bar{u}(x)+\bar{c}(x)\right](1-y)^2\right\}$$

$$\frac{d\sigma_{CC}(\bar{\nu}_\mu p)}{dxdy} = \frac{G_F^2 ME}{\pi} 2x\left\{\left[u(x)+c(x)\right](1-y)^2+\left[\bar{d}(x)+\bar{s}(x)\right]\right\}$$

- Structure functions:



$$F_2^{\nu p}(x) = 2x\left[d(x)+\bar{u}(x)+s(x)+\bar{c}(x)\right]$$
$$xF_3^{\nu p}(x) = 2x\left[d(x)-\bar{u}(x)+s(x)-\bar{c}(x)\right]$$
$$F_2^{\bar{\nu} p}(x) = 2x\left[u(x)+c(x)+\bar{d}(x)+\bar{s}(x)\right]$$
$$xF_3^{\bar{\nu} p}(x) = 2x\left[u(x)+c(x)-\bar{d}(x)-\bar{s}(x)\right]$$

- Neutron (isospin symmetry):

$$F_2^{\nu n}(x) = 2x\left[u(x)+\bar{d}(x)+s(x)+\bar{c}(x)\right]$$
$$xF_3^{\nu n}(x) = 2x\left[u(x)-\bar{d}(x)+s(x)-\bar{c}(x)\right]$$

nuclear scattering involves systems with mixed isospin

- simplications occur in quark model for isoscalar nucleons, $N = (p+n)/2$

  - Scattering off isoscalar target (equal number neutrons and protons):

$$q \equiv u + d + s + c \qquad \bar{q} \equiv \bar{u} + \bar{d} + \bar{s} + \bar{c}$$

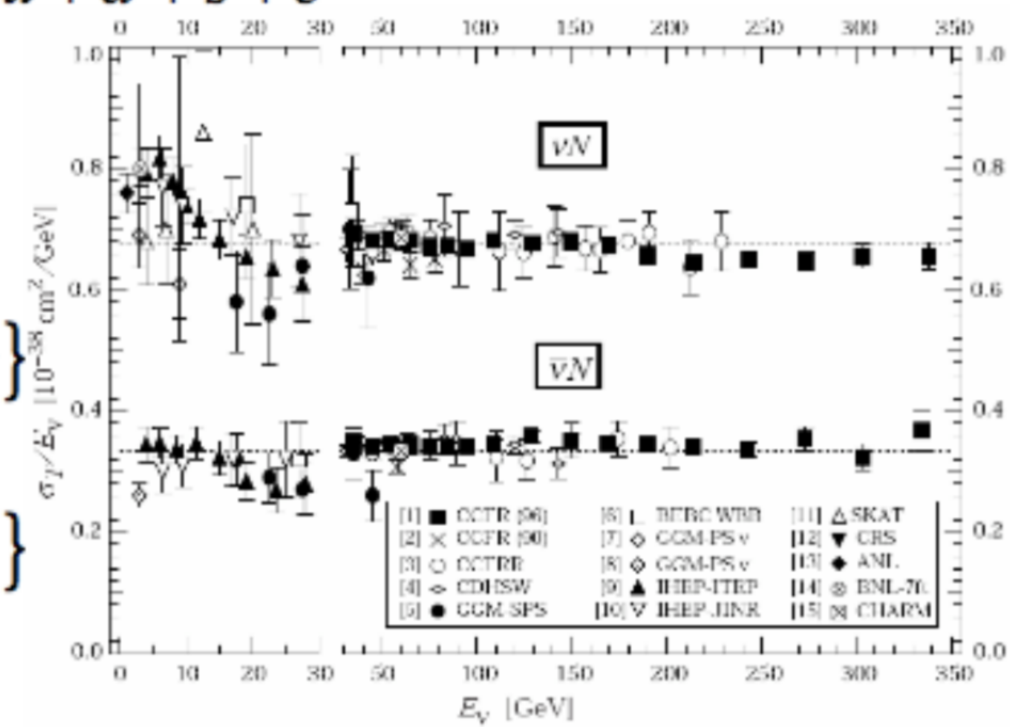
$$F_2^{\nu N}(x) = x\left[q(x) + \bar{q}(x)\right]$$

$$xF_3^{\nu N}(x) = x\left[q(x) - \bar{q}(x) + 2\left(s(x) - c(x)\right)\right]$$

$$xF_3^{\bar{\nu} N}(x) = x\left[q(x) - \bar{q}(x) - 2\left(s(x) - c(x)\right)\right]$$

$$\frac{d\sigma_{CC}(\nu_\mu N)}{dxdy} = \frac{G_F{}^2 ME}{\pi} x\left\{q(x) + \bar{q}(x)\,(1-y)^2\right\}$$

$$\frac{d\sigma_{CC}(\bar{\nu}_\mu N)}{dxdy} = \frac{G_F{}^2 ME}{\pi} x\left\{q(x)(1-y)^2 + \bar{q}(x)\right\}$$



  - Total cross-section:

$$\sigma_{CC}(\nu_\mu N) = \frac{G_F{}^2 s}{2\pi}\left[\langle Q\rangle + \frac{1}{3}\langle\bar{Q}\rangle\right] = (0.677 \pm 0.014)\times 10^{-38}\, cm^2/GeV \times E(GeV)$$

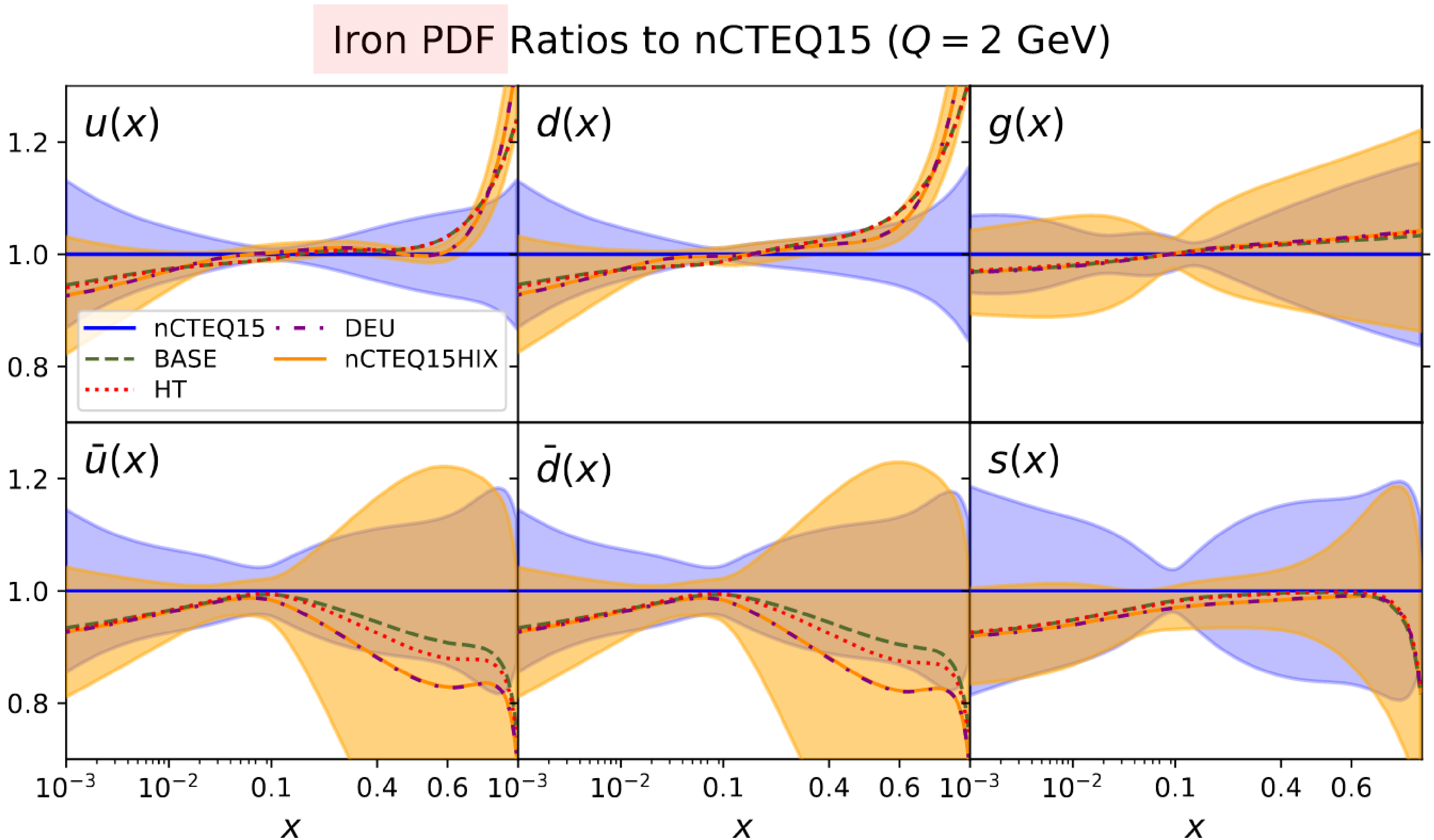
$$\sigma_{CC}(\bar{\nu}_\mu N) = \frac{G_F{}^2 s}{2\pi}\left[\frac{1}{3}\langle Q\rangle + \langle\bar{Q}\rangle\right] = (0.334 \pm 0.008)\times 10^{-38}\, cm^2/GeV \times E(GeV)$$

ultimately, need freely-fitted **nuclear PDFs**

→ multitude of nuclear effects impact the partonic content of nuclei vs. proton

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}$$

(anti)shadowing; long, short-distance correlations; collective effects; ...

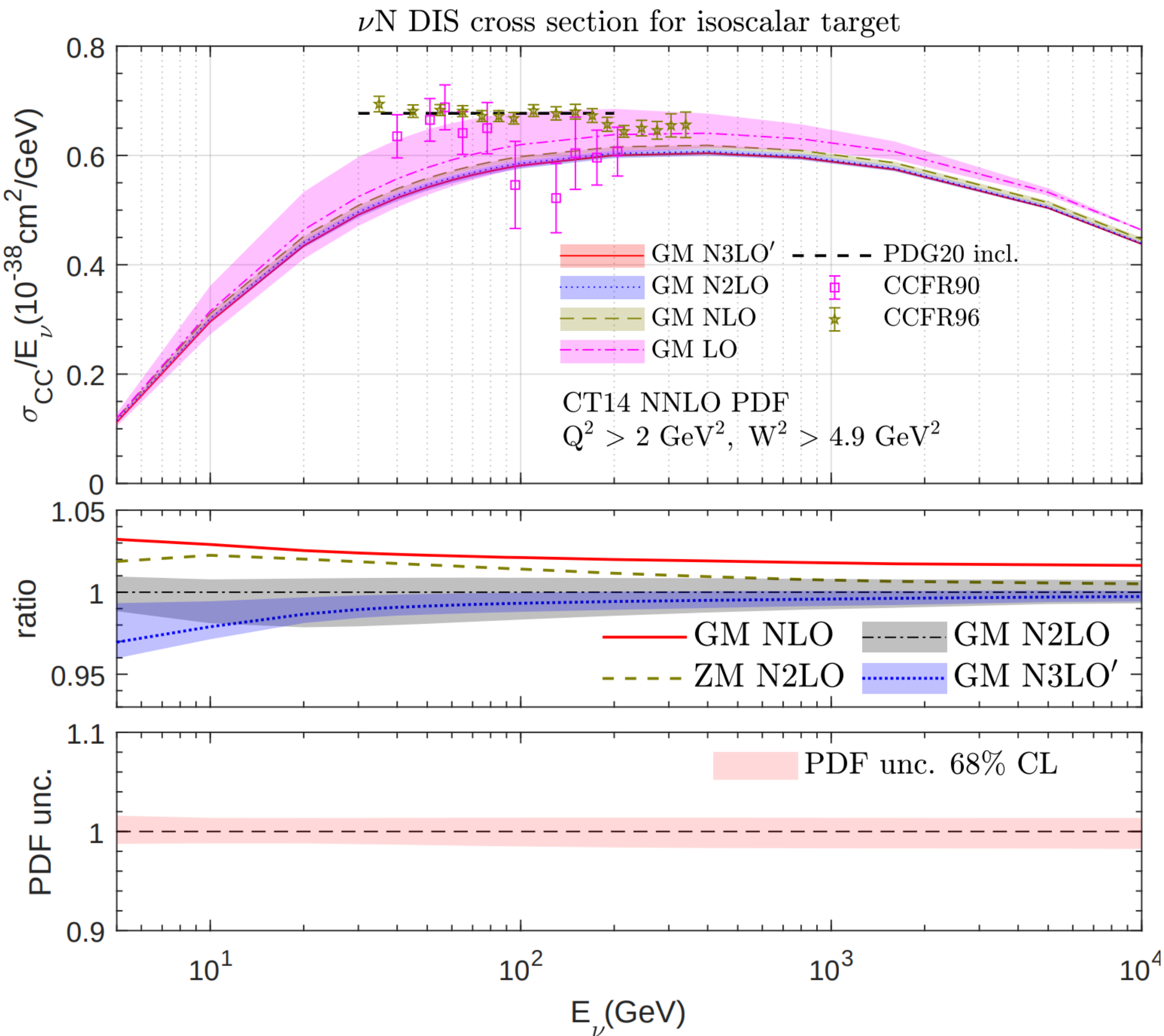


but this is all LO! … higher orders are important (and challenging)

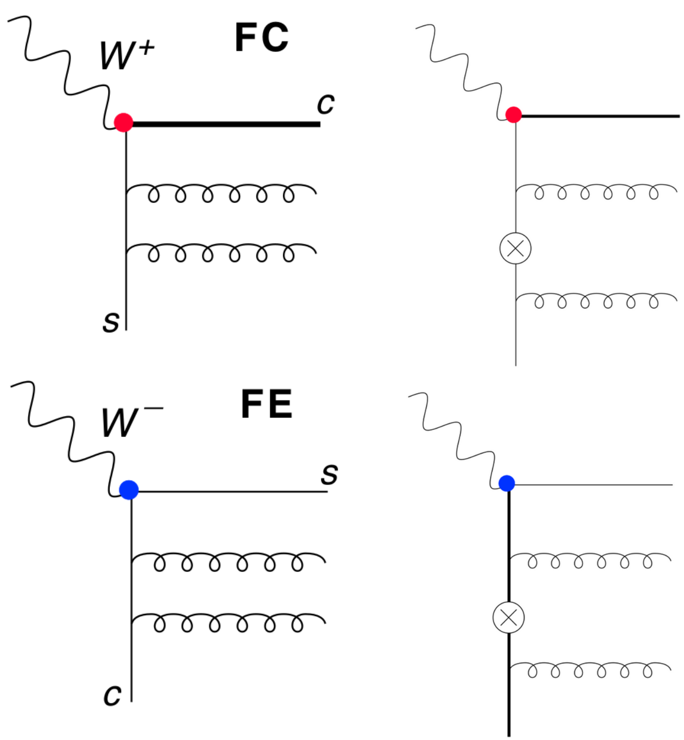
- computing NNLO corrections is very non-trivial, especially given heavy-quark mass scales

Phys. Rev. D**105** (2022) 1, **L**011503

$$F_i^{\mathrm{CC}}(x,Q^2) = \sum_a \int_x^1 \frac{dy}{y}\, C_i^a(y)\Phi_a\left(\frac{x}{y}\right) \;+\; \mathcal{O}\left(\frac{M_N^2}{Q^2}\right)$$



→ at higher energies, significant impact on sensitivity of forward-physics program at FASERν (~100s GeV); neutrino telescopes (>TeV)

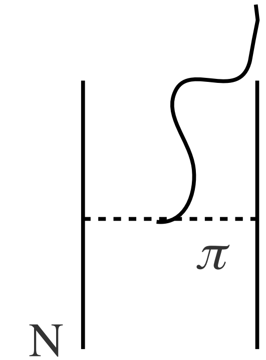


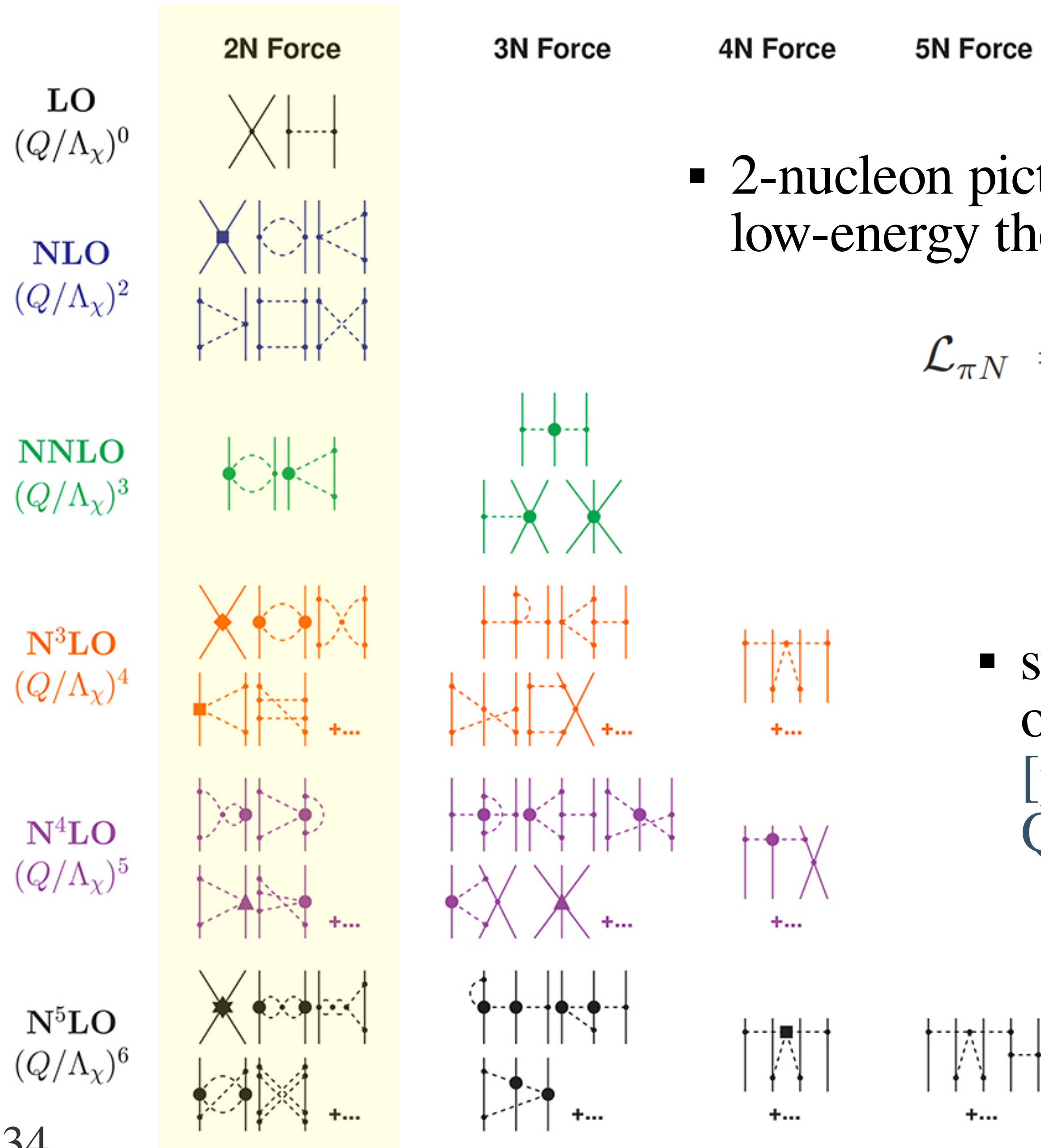
some open questions

- exciting topics; YOU may be the one to solve or advance these…

again, must disclaim that this is my own very limited (and biased) selection!

earlier: showed χ_{PT} description of nuclear interactions



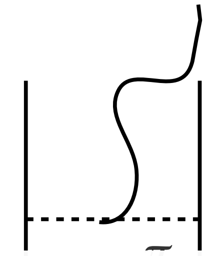


- 2-nucleon picture has basis in formal low-energy theory

$$\mathcal{L}_{\pi N} = \frac{g_A}{2f_\pi}\bar{\psi}_N\gamma^\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}\,\psi_N - \frac{1}{(2f_\pi)^2}\bar{\psi}_N\gamma^\mu\boldsymbol{\tau}\cdot(\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi})\,\psi_N$$

- systematically improvable to higher orders, particle interactions [perturbation theory not just for QCD, EW theory!]

nuclear physics produces multi-2 (and higher)-nucleon correlations; external bosons scatter from these based on the non-linear realization of chiral symmetry



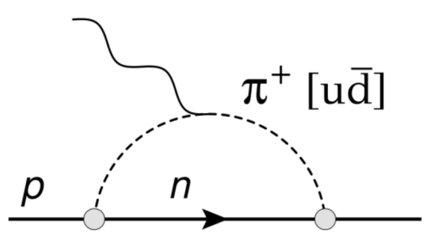
- <u>deep question</u>: the pion is the pseudo-Nambu-Goldstone boson associated with chiral symmetry breaking…

→ how does this work at quark-level? the symmetries of QCD must be reflected in the symmetries of the hadronic effective theory

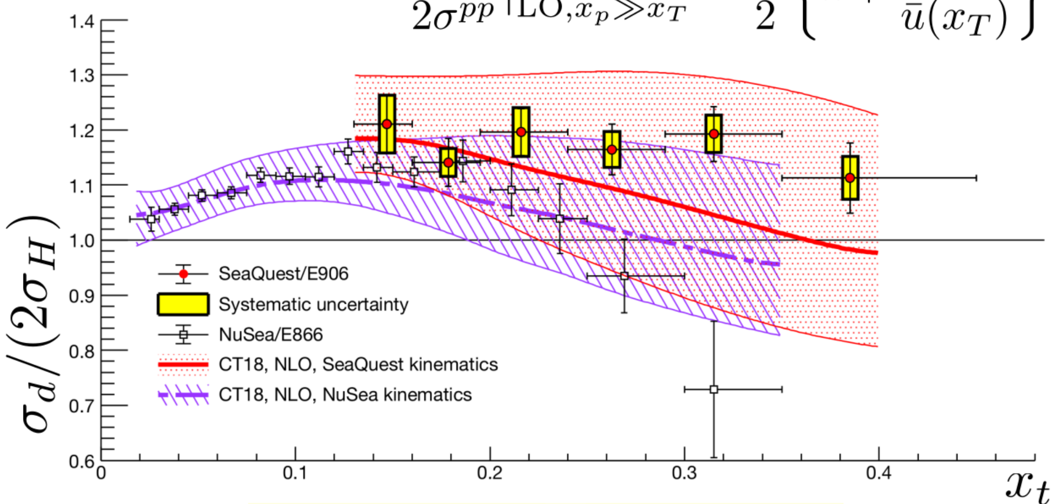
→ **relevant for understanding QCD, modeling νA**

The Fermilab SeaQuest (E906) experiment may be sensitive to the high-x fraction of $\bar{d}$ vs. $\bar{u}$

→ many nonpert. models favor $\bar{d}/\bar{u} > 1$



$$\frac{\sigma^{pd}}{2\sigma^{pp}}\Big|_{\mathrm{LO},x_p\gg x_T} \sim \frac{1}{2}\left\{1+\frac{\bar{d}(x_T)}{\bar{u}(x_T)}\right\}$$



CT18 NNLO, $\chi^2_E/N_{pt} = 0.82$

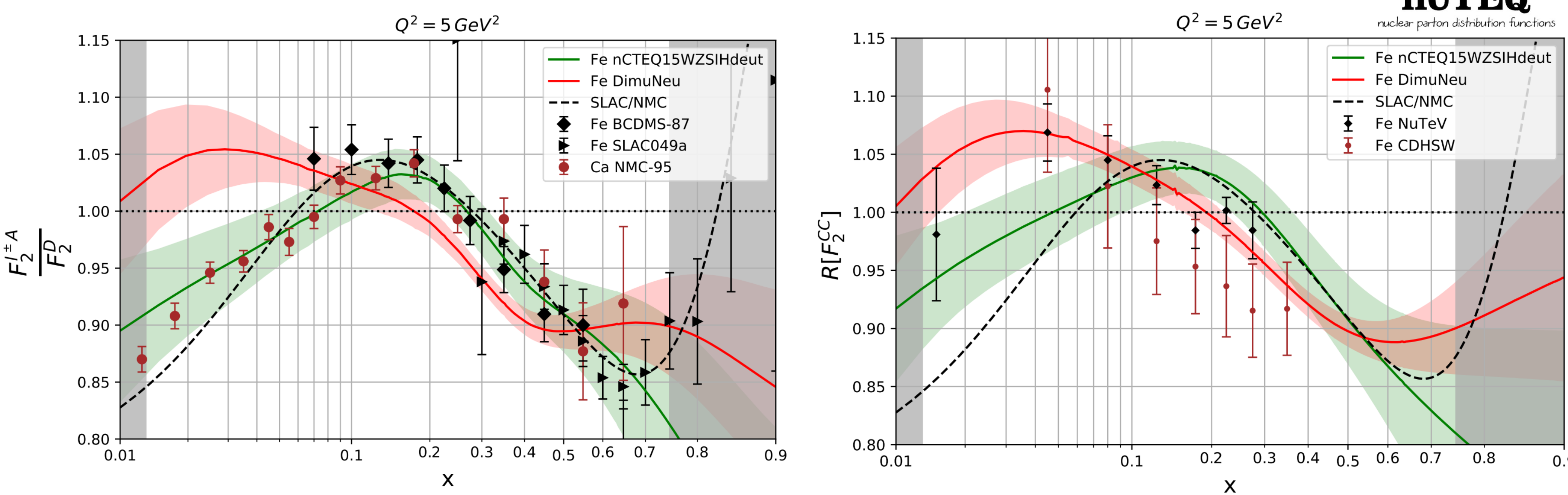
must better understand QCD in nuclei

- require knowledge of nuclear corrections; these directly fitted by nPDF analyses

  → better control over x, A dependence can benefit flavor separations

- require knowledge of nuclear corrections; these directly fitted by nPDF analyses

ongoing questions of statistical compatibility of **neutrino**-, **charged-lepton** scattering:



Muzakka et al., 2204.13157

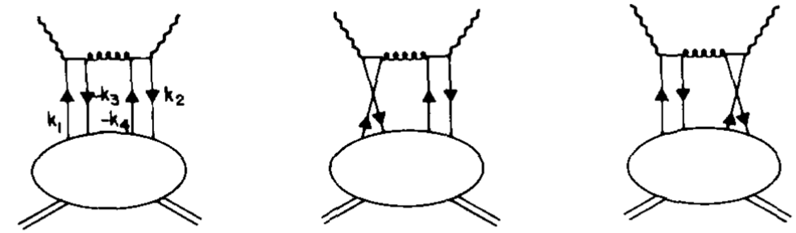
$$F_i^{\rm CC}(x,Q^2) = \sum_a \int_x^1 \frac{dy}{y}\, C_i^a(y)\Phi_a\left(\frac{x}{y}\right) \;+\; \mathcal{O}\left(\frac{M_N^2}{Q^2}\right)$$

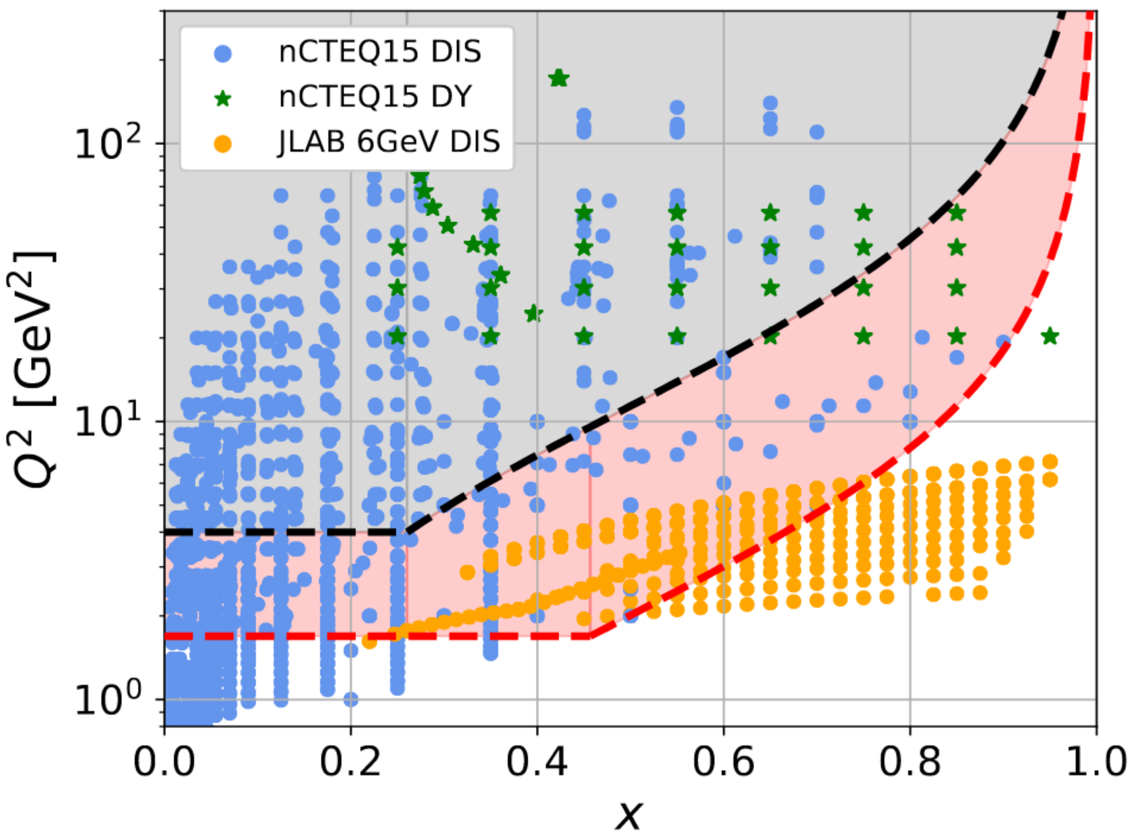
- tests of nuclear factorization would be valuable; **how do EW probes see nuclei?**

how far can we extend formal QCD into DIS/SIS regime?

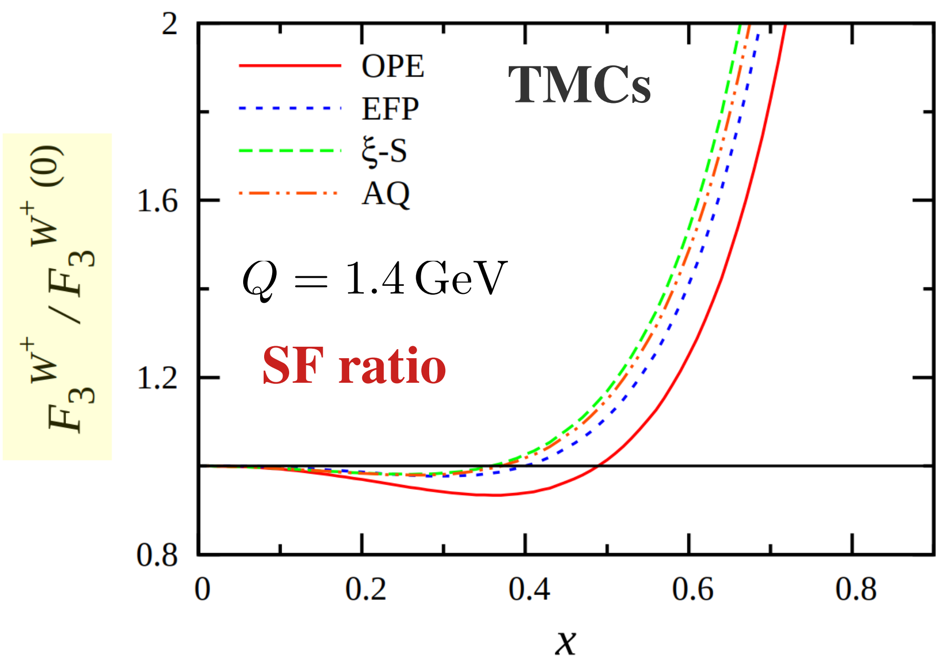
- can answer phenomenologically → systematically lower reach of QCD analysis to lower Q^2, W^2

HTs





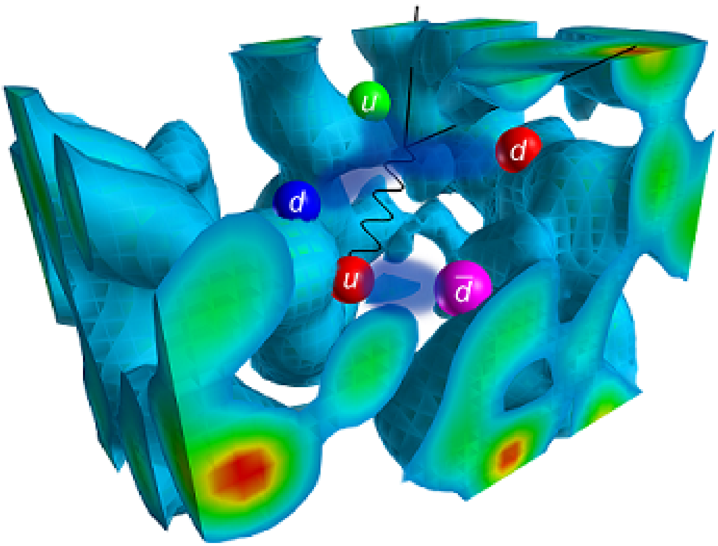
Brady, Accardi, TJH, Melnitchouk: PRD**84** (2011) 9, 074008



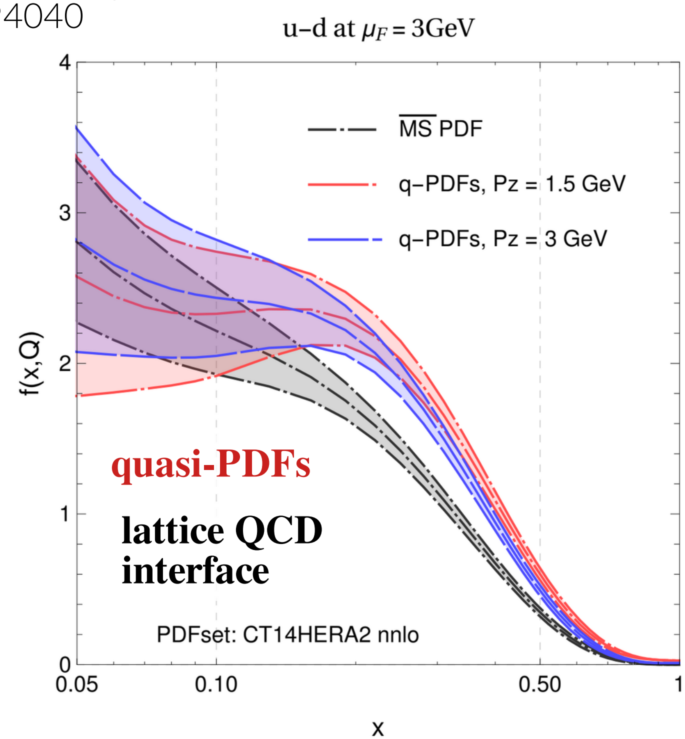
- encounter finite-Q^2 effects: multi-parton interactions ("higher twist"); nonperturbative mass effects (TMCs)

→ **requires** careful treatment in few-GeV region ...currently absent.

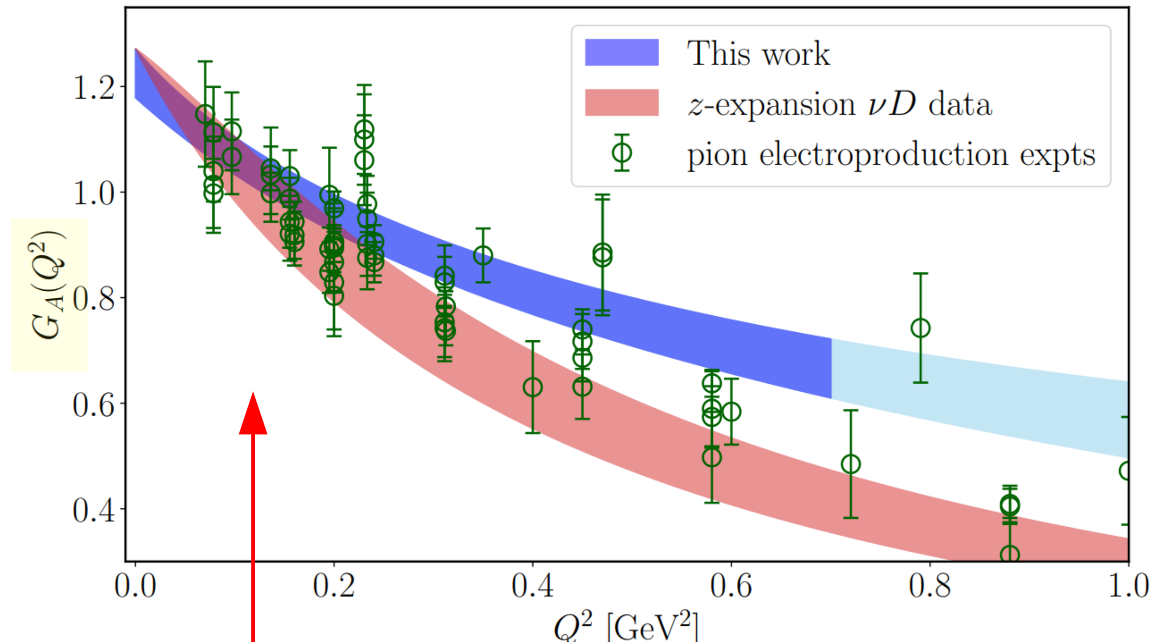
what might lattice QCD, *ab initio* methods achieve?



TJH, Wang, Nadolsky, Olness: PRD100 (2019) 9, 094040



- many limiting QCD inputs discussed earlier may be calculable on the **lattice**



2207.03440

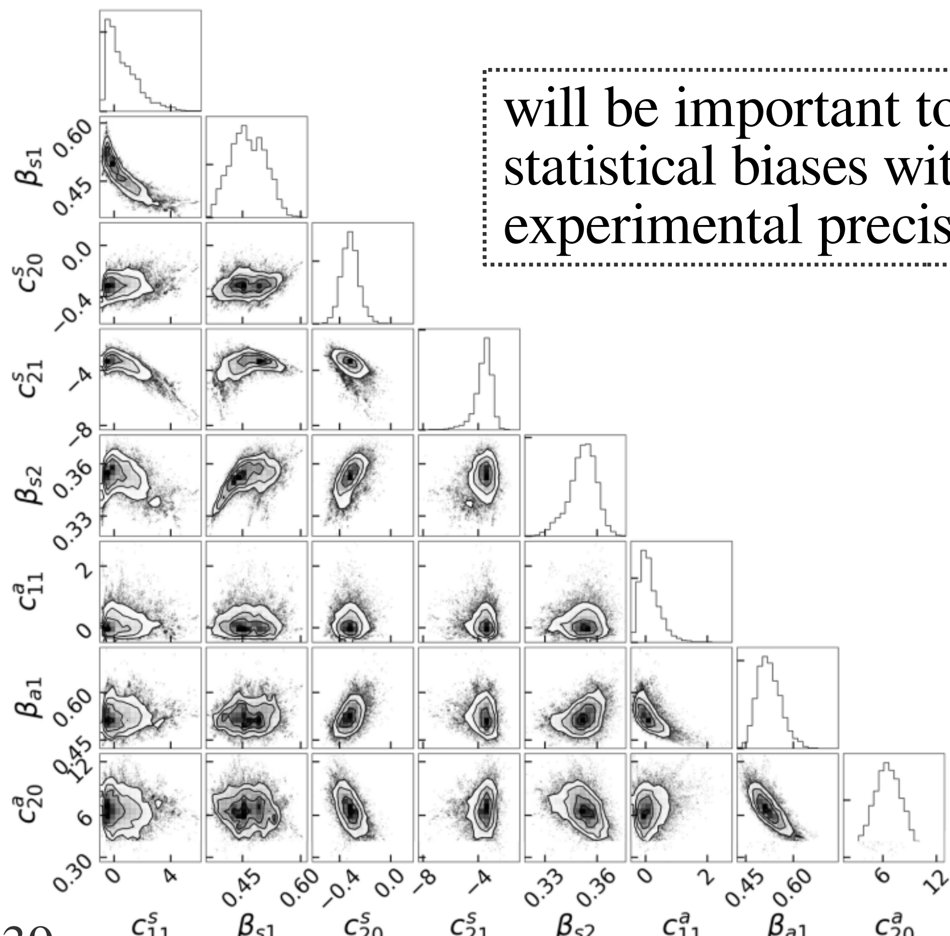
e.g., useful for quasi-elastic neutrino cross section

- synergies with QCD analyses possible

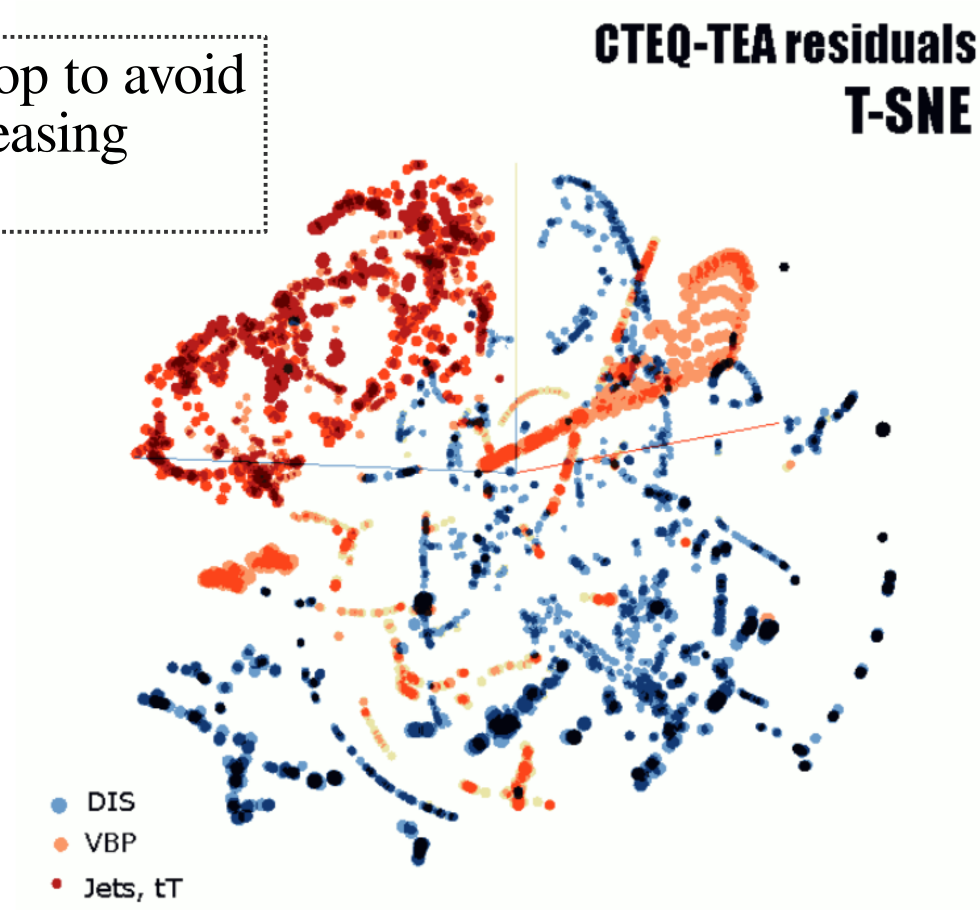
$$G_A(Q^2 = 0) = g_A = \int_0^1 dx\, \Delta u(x) - \Delta d(x)$$

can we improve the model tunings inside event generators?

- emphasized that generator tunings must contend with internal correlations
  - → Bayesian methods (*e.g.*, MCMC) helpful for disentangling
  - → dimensionality reduction techniques can encapsulate dominant pulls

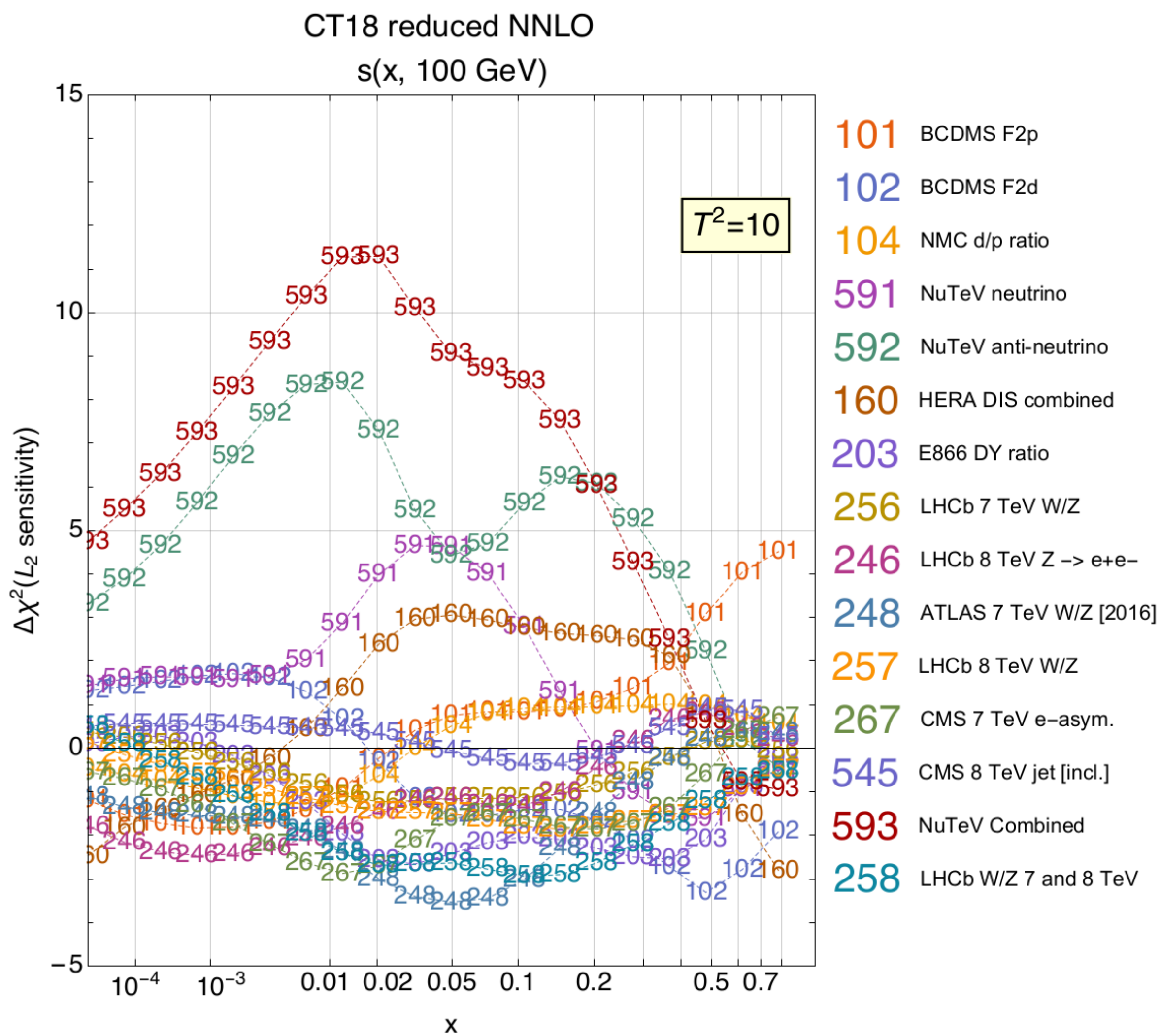


will be important to develop to avoid statistical biases with increasing experimental precision

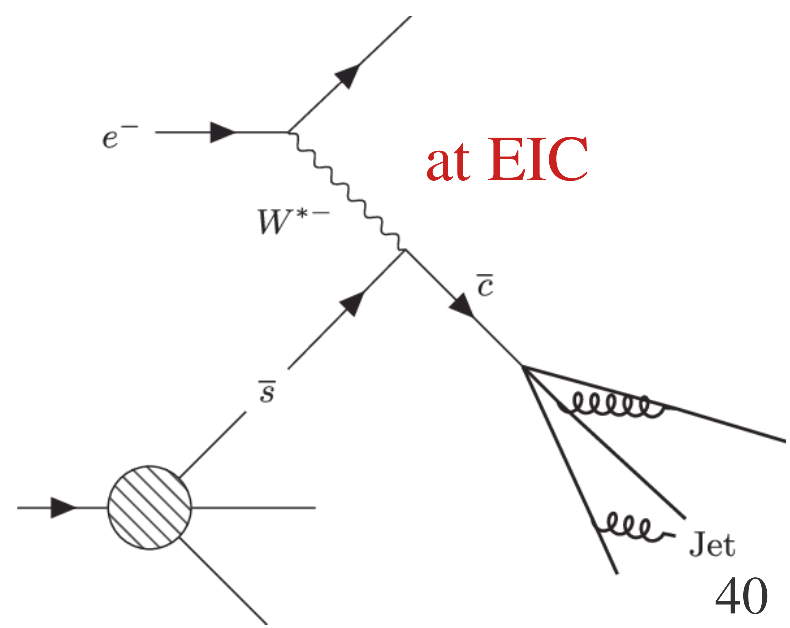


connections to other experiments?

- CC nuclear DIS has an important place in PDF analyses



- would be valuable to better under understand relationships to other influential hadronic data
  - analogous charged-lepton measurements at EIC; parity-violation at JLab



- data from LHC, EIC, JLab, RHIC, ...

exciting times: many problems, many opportunities

- understanding the neutrino sector is inextricably linked to understanding QCD

  → many interesting **calculations**, **measurements** await your effort

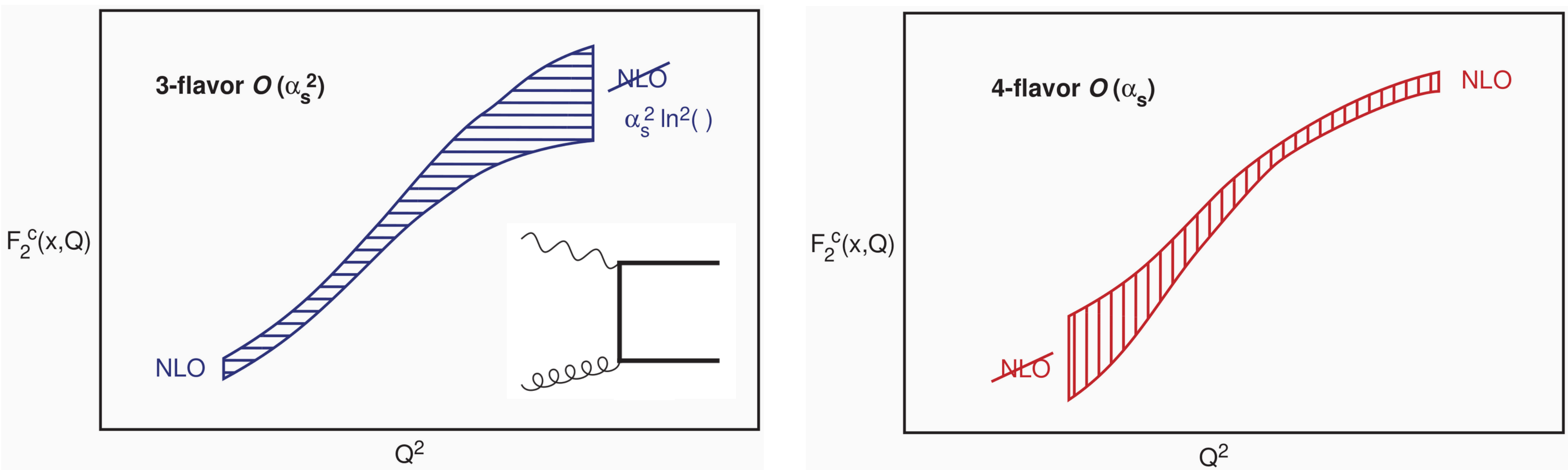
  → all strike at **core HEP objectives**

Many thanks! ☺ please reach out with questions: thobbs@fnal.gov

supplementary material

evolution schemes as general problem in QCD

- higher order(s) in pQCD: improved accuracy in Wilson coeff., control over scale dependence
- at given fixed order, nontrivial relationship with chosen heavy-quark (HQ) scheme



→ fixed flavor-number (FFN): $Q \gtrsim M_Q$; flavor-creation (FC) processes with $n_f = 3$

→ zero-mass (ZM) variable flavor-number: $Q \gg M_Q$; flavor-excitation (FE) processes with $n_f = 4$

- 2 paradigms adapted to different regimes w.r.t. HQ mass scale; ∃ **interpolation scheme**?

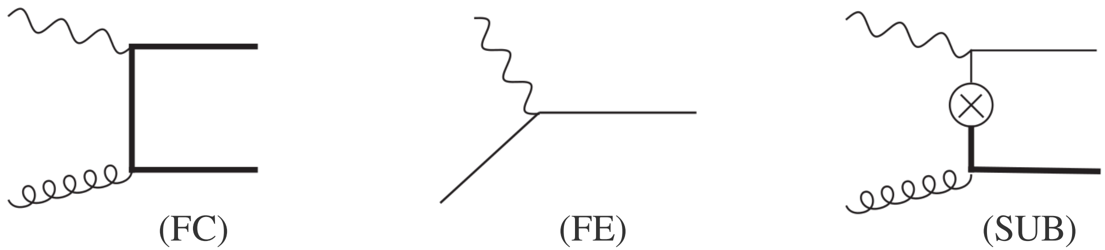
general-mass schemes: S-ACOT-χ

- variable flavor-number scheme to interpolate between ZM and FFN regimes: **ACOT**

  Aivazis, Collins, Olness, Tung; PRD**50** (1994) 3085-3118

  → systematic approach to incorporating HQ mass dependence

- introduce subtraction term(s) to eliminate double counting between FC/FE contributions:



$$\begin{cases} Q \gtrsim M_Q \implies \text{(SUB)} \approx \text{(FE) such that } n_f = 3 \text{ FC dominates} \\ Q \gg M_Q \implies \text{(SUB)} \approx \text{(FC) such that } n_f = 4 \text{ FE dominates} \end{cases}$$

$$\chi(x, Q, M_Q) = x\left(1 + \frac{1}{Q^2}[\sum_{\text{F.S.}} M_Q]^2\right)$$

  - "simplified" ACOT (S-ACOT): neglect full HQ mass dependence in FE graphs
  - S-ACOT-χ: smooth HQ thresholds, include approx. HQ mass dependence: $C_i(x) \to C_i(\chi)$

- formulation necessitates careful tracking of diagrams to organize calculation correctly

template calculation: NC DIS at NNLO

Guzzi, Nadolsky, Lai, Yuan Phys. Rev. D**86**, 053005 (2012) [arXiv: 1108.5112]

- at structure-function level, factorization allows separation of coeff. functions, PDFs:

$$F(x,Q) = \sum_{i=1}^{N_f^{fs}} e_i^2 \sum_{a=0}^{N_f} \left[C_{i,a} \otimes \Phi_{a/p} \right](x,Q) \qquad (F = F_{2,L})$$

- compute S-ACOT-χ coeff. functions: expand in α_s each term in auxiliary partonic struct. func.:

$$F_{i,b}(\widehat{x},Q) = \sum_{a=0}^{N_f} \left[C_{i,a} \otimes \Phi_{a/b} \right](\widehat{x},Q)$$

→ matching terms order-by-order,

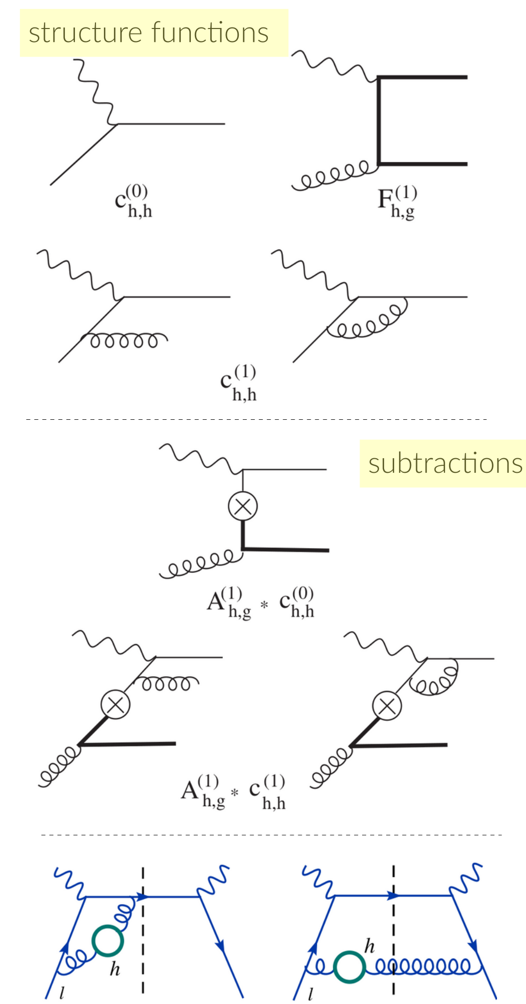
$$\begin{cases} C_{i,b}^{(0)}(\widehat{x}) &= F_{i,b}^{(0)}(\widehat{x}) \\ C_{i,b}^{(1)}(\widehat{x}) &= F_{i,b}^{(1)}(\widehat{x}) - \left[C_{i,a}^{(0)} \otimes A_{ab}^{(1)} \right](\widehat{x}) \\ C_{i,b}^{(2)}(\widehat{x}) &= F_{i,b}^{(2)}(\widehat{x}) - \left[C_{i,a}^{(0)} \otimes A_{ab}^{(2)} \right](\widehat{x}) - \left[C_{i,a}^{(1)} \otimes A_{ab}^{(1)} \right](\widehat{x}) \end{cases}$$

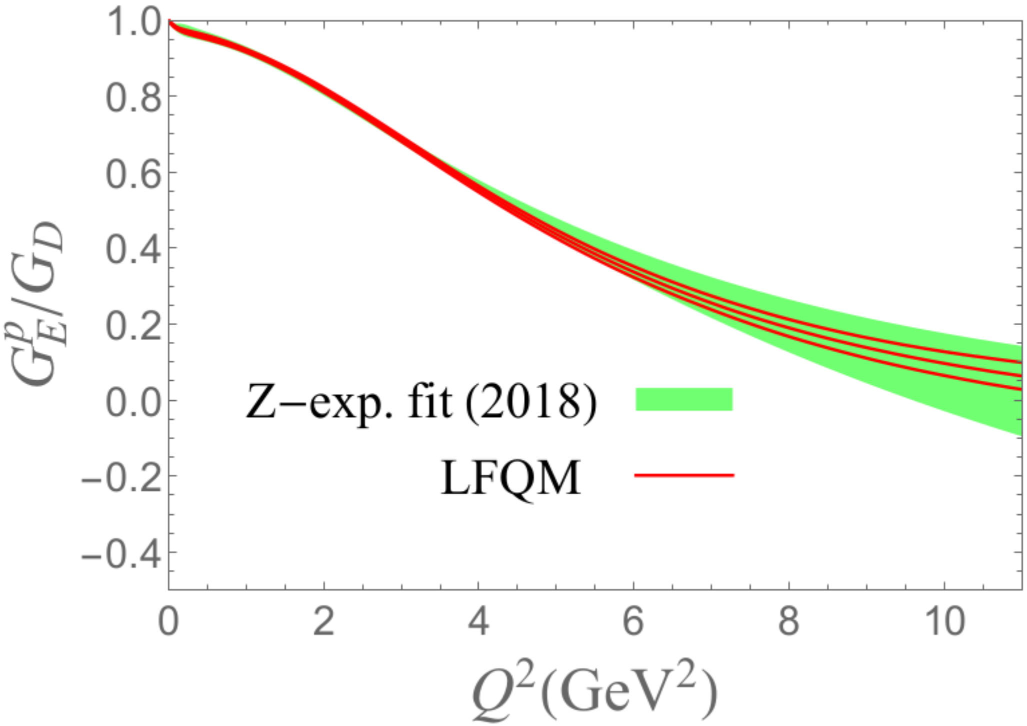
- organize into heavy-, light-quark pieces: $F = \sum_{l=1}^{N_l} F_l + F_h$

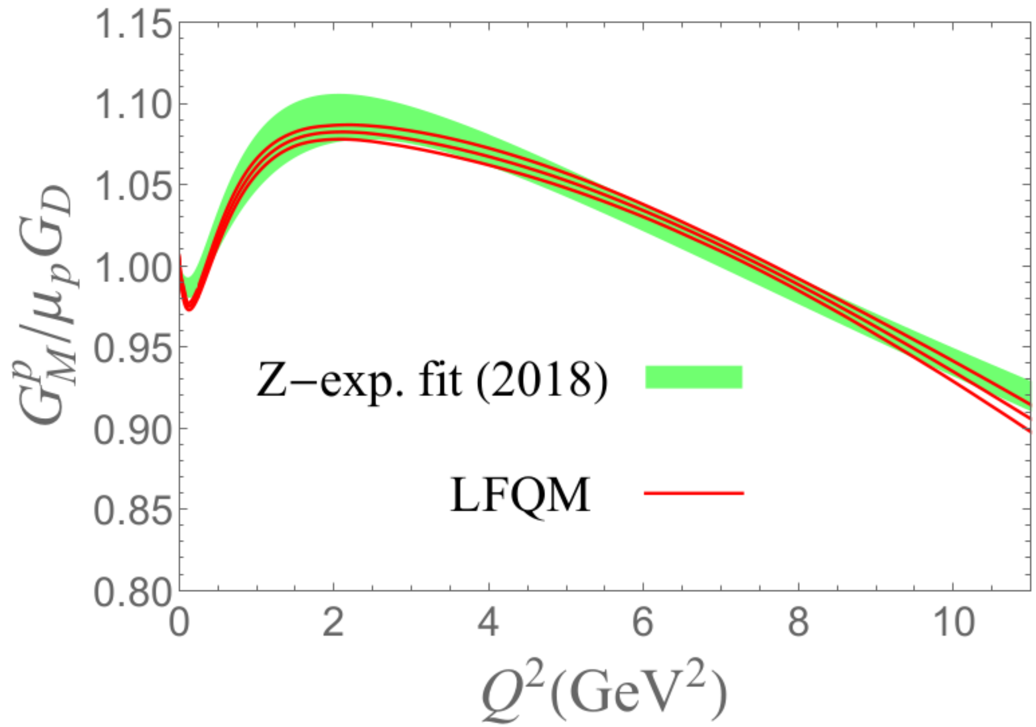
$$C_{h,g}^{(2)} = \widehat{F}_{h,g}^{(2)} - A_{hg}^{(2)} - c_{h,h}^{(1)} \otimes A_{hg}^{(1)}$$

S-ACOT-χ: massless FE, χ-rescaled

→ light-quark SFs: additional flavor non-sing. (NS) *disconnected* graphs:

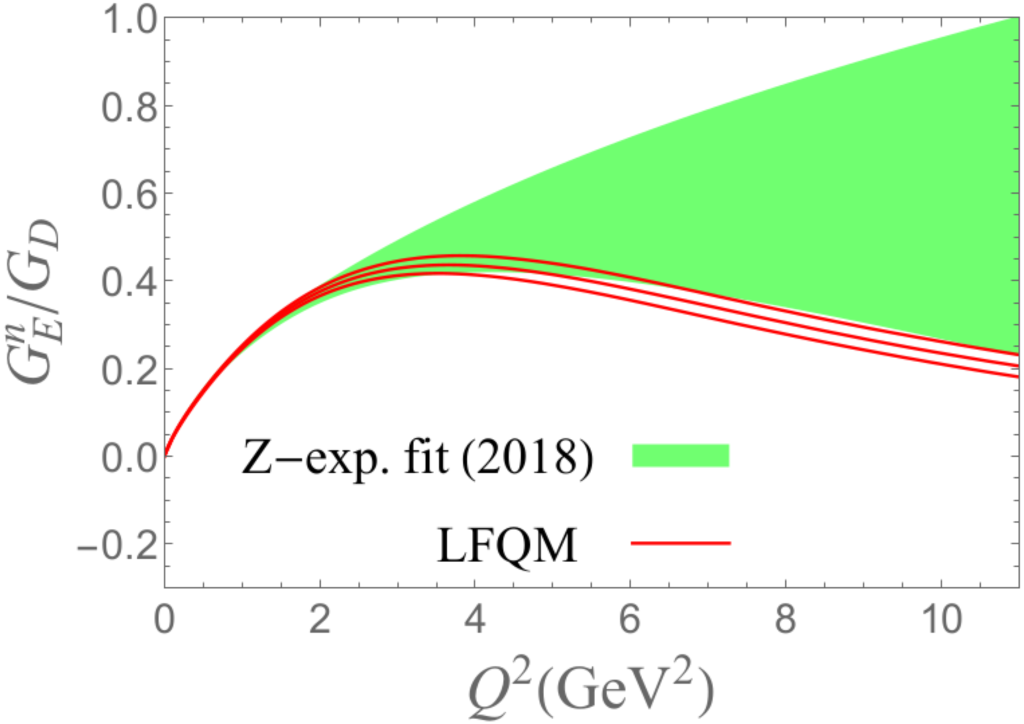


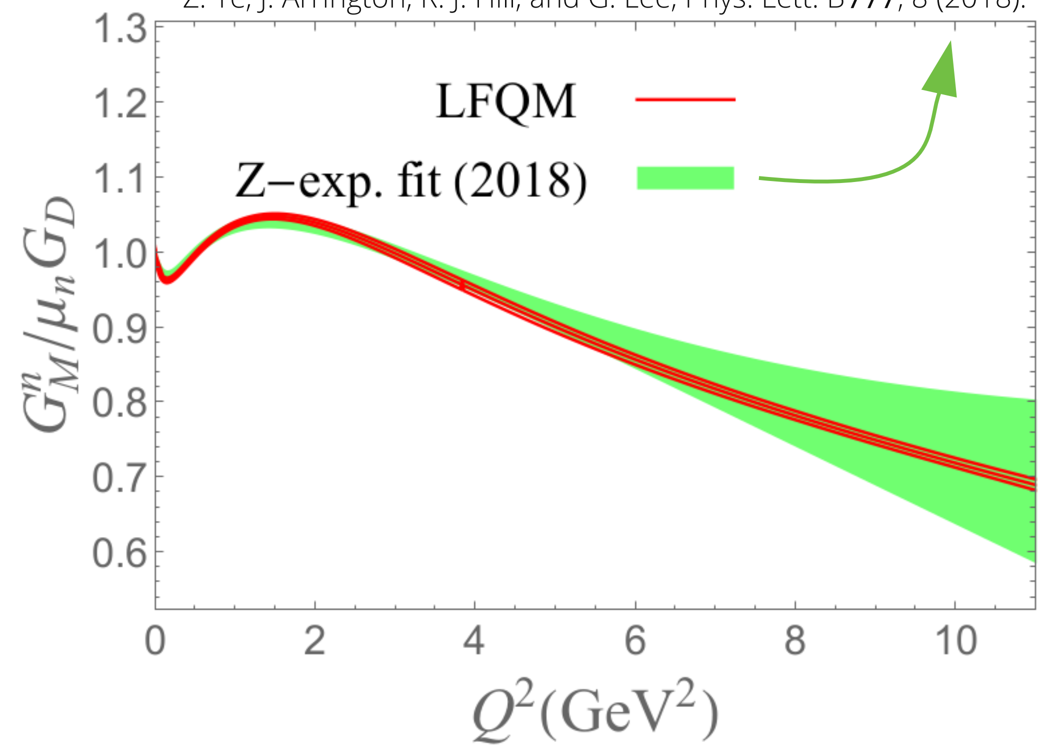




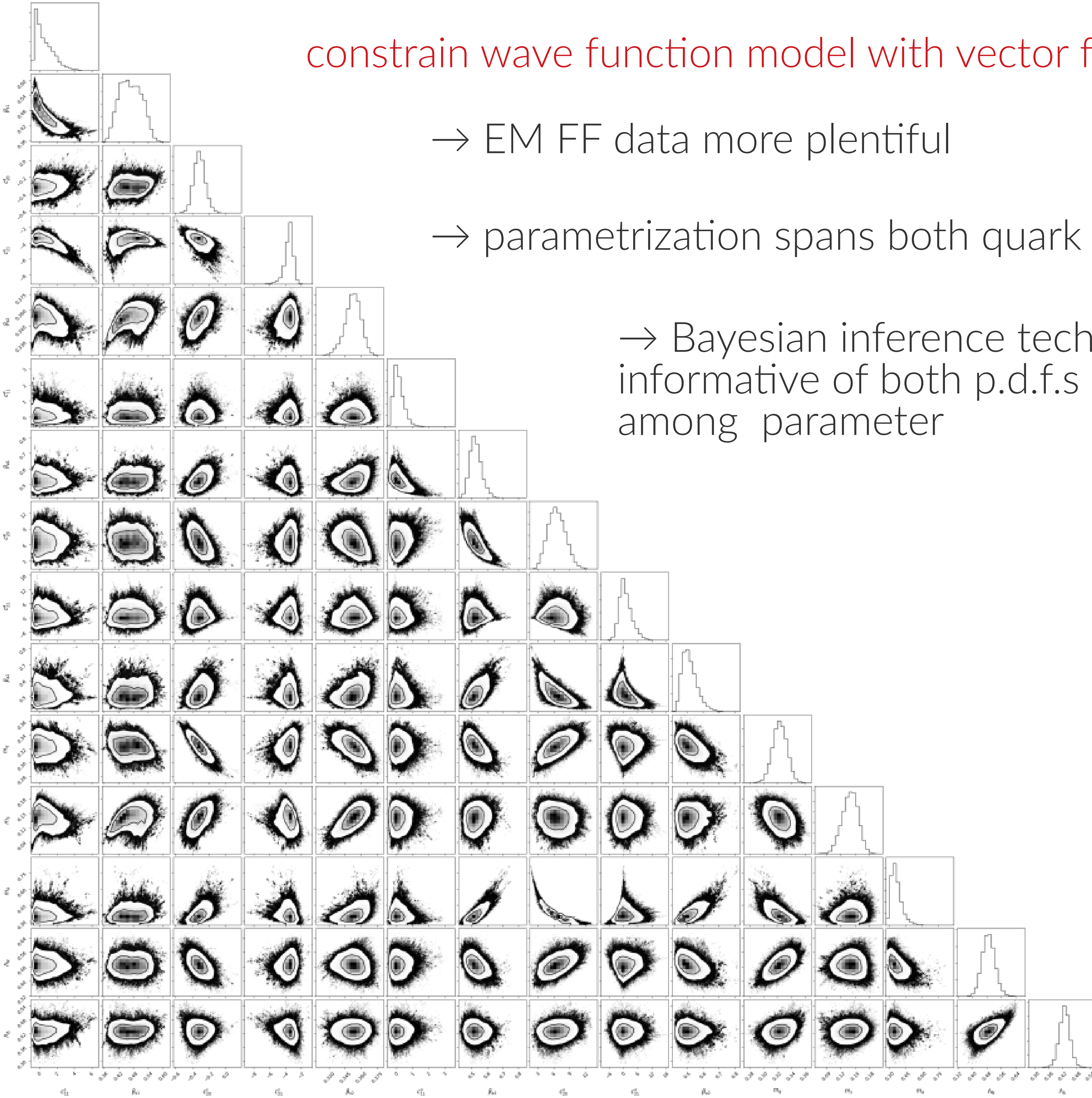
➞ tune the model to fit EM form factors

Z. Ye, J. Arrington, R. J. Hill, and G. Lee, Phys. Lett. B**777**, 8 (2018).





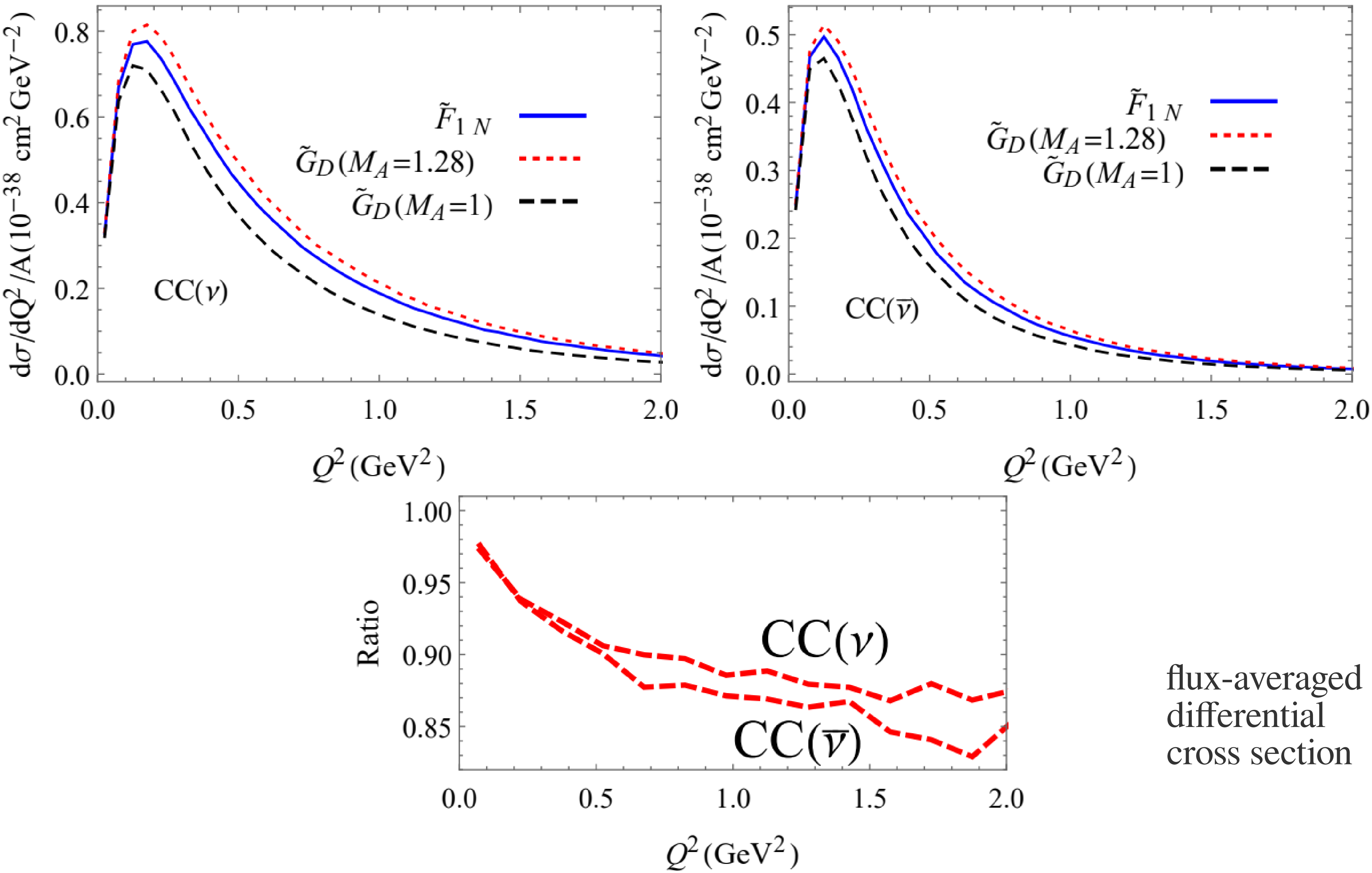
constrain wave function model with vector form factor data



→ EM FF data more plentiful

→ parametrization spans both quark and pion sectors

→ Bayesian inference techniques are informative of both p.d.f.s and correlations among parameter the behavior of the axial form factor has a large impact in nuclear cross sections! → input into GiBUU transport code for $\nu(\overline{\nu}) - {}^{40}\mathrm{Ar}$



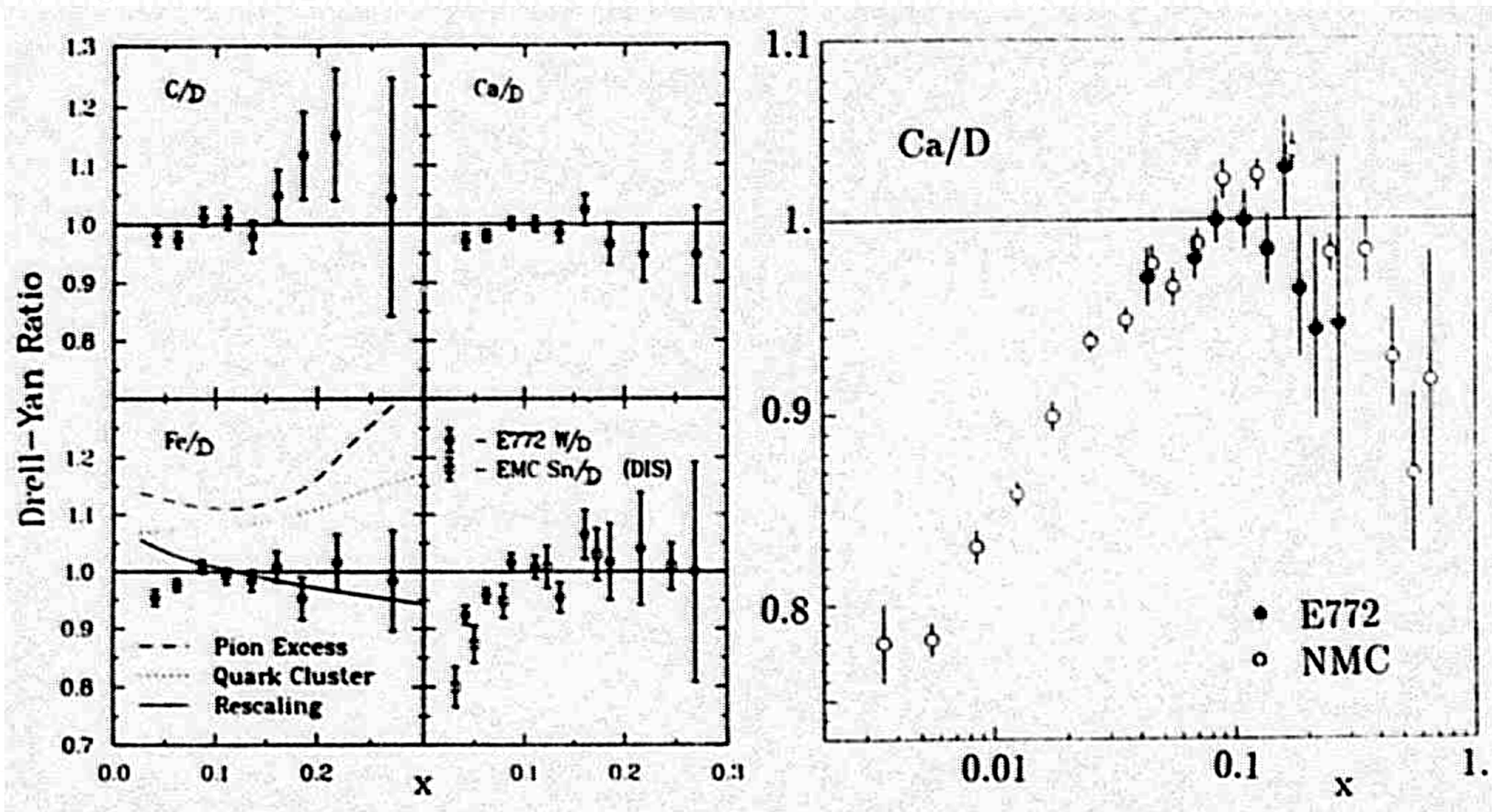
flux-averaged differential cross section

~5-10% deviation from naive 1-parameter dipole ansatz!

important relationship between deuteron / heavy nucl. data

- since CTEQ6: phenomenological nuclear correction factors, *e.g.*,

Rondio, Nucl. Phys. **A553** (1993) 615c-624c



8	nu-A incl. DIS	CDHSW F_2	108
		CDHSW xF_3	109
		CCFR F_2	110
		CCFR xF_3	111
9	ttbar production	CMS 8 TeV 19.7 fb^{-1} , $t\bar{t}$ norm. top p_T and y cross sec.	573
		ATLAS 8 TeV 20.3 fb^{-1}, $t\bar{t}$ p_T^t, $m_{t\bar{t}}$ abs. spectrum	580
10	nu-A dimuon SIDIS	NuTeV $\nu\mu\mu$ SIDIS	124
		NuTeV $\nu\bar{\mu}\mu$ SIDIS	125
		CCFR $\nu\mu\mu$ SIDIS	126
		CCFR $\nu\bar{\mu}\mu$ SIDIS	127

→ deserves dedicated, consistent study; heavy-nuclear corrections can be $\lesssim 5\%$