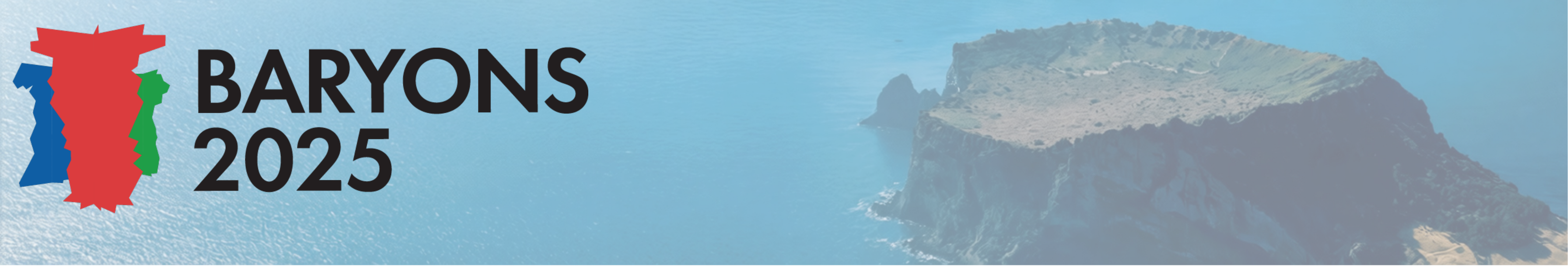

Flavor asymmetry from the non-perturbative nucleon sea

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Based on:
Duan et al, PRC 2024
(2404.07755)

In collaboration with :
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Baryons 2025, Jeju Island, Korea, Nov. 10-14, 2025

Gottfried sum rule

[Gottfried '67]

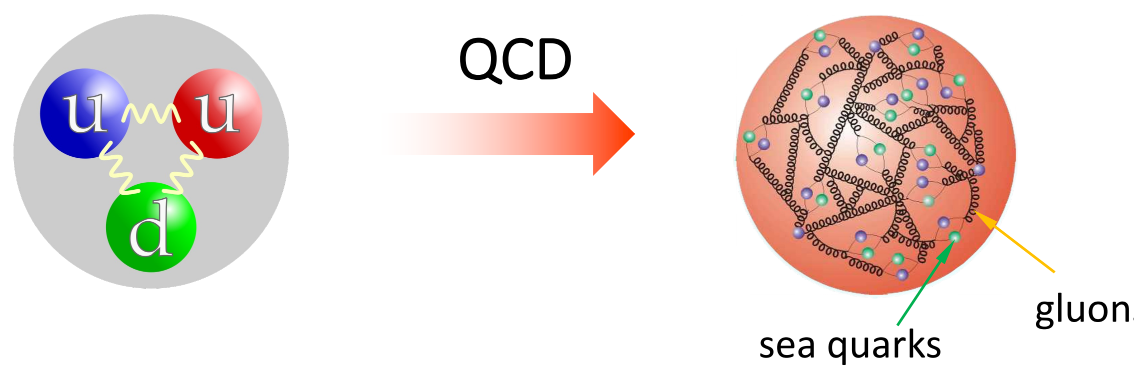
Flavor asymmetry probes the non-perturbative structure of the nucleon

$$\int_0^1 \frac{dx}{x}\left[F_2^p(x,Q^2) - F_2^n(x,Q^2)\right] = \frac{1}{3} + \frac{2}{3}\int_0^1 dx\left[\bar{u}(x,Q^2) - \bar{d}(x,Q^2)\right]$$

= 0 in pQCD

- Perturbative QCD: generation of sea quark due to gluon splitting → flavor blind
- Violation of GSR: non-perturbative QCD effects
  - Pion cloud model
  - Pauli blocking
  - Chiral quark model
  - Instantons
  - Statistical parton distributions

[e.g. Ross '79 , Thomas '83, Basso '16]

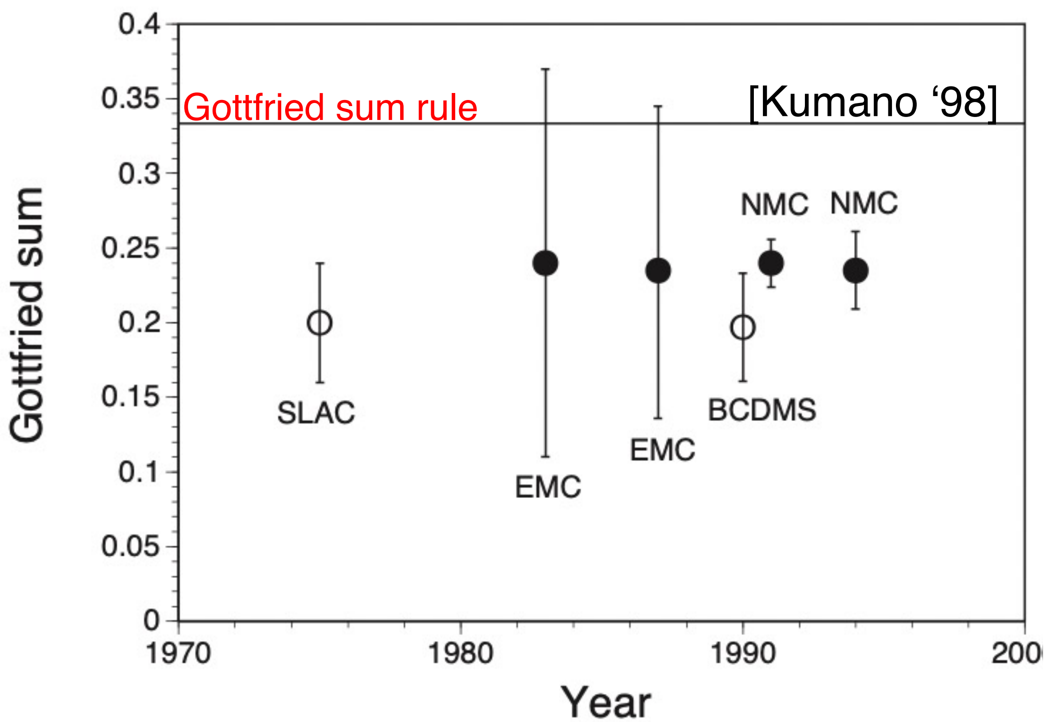


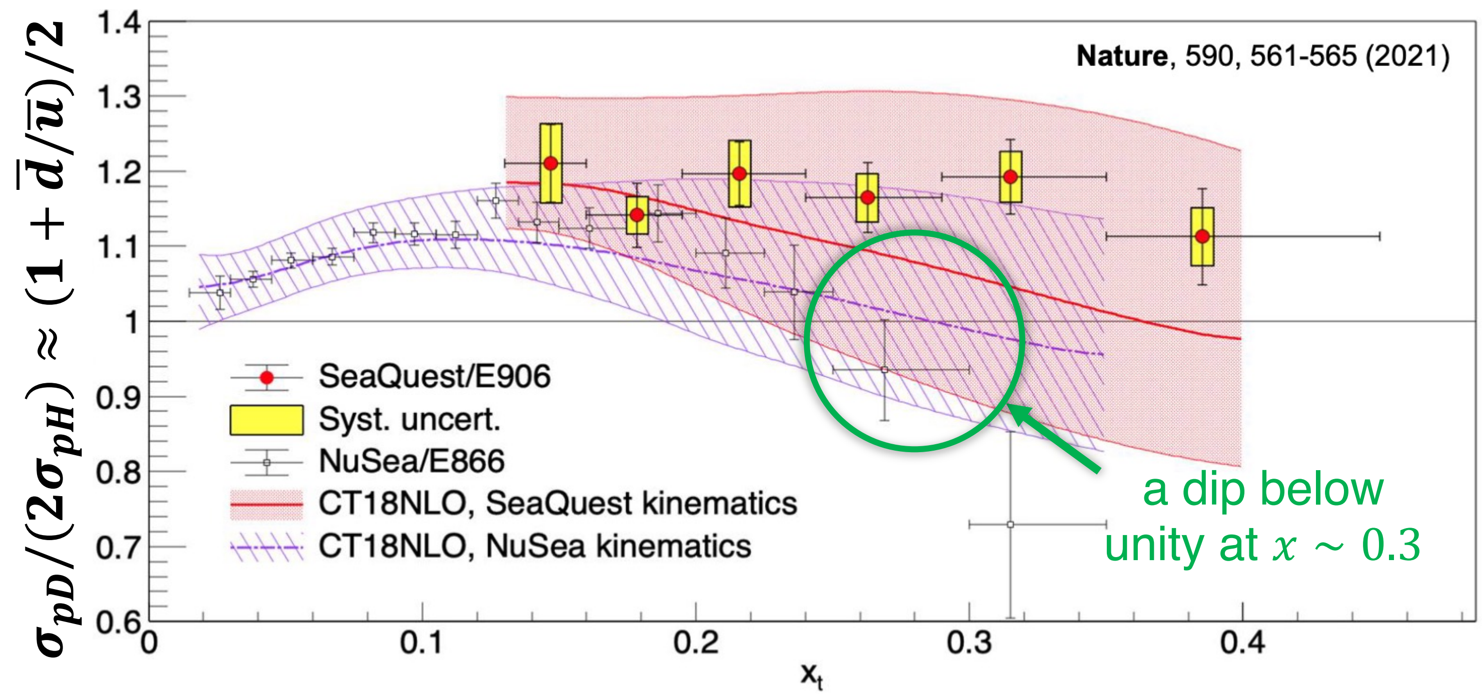
- Not well constrained in global fitting

Experimental measurements

- Experimental measurements from DIS and Drell-Yan reveal a striking flavor asymmetry of the anti-quarks at moderate x [NA51 ‘94, NuSea ’98 & ’01, SeaQuest ‘23]
- SeaQuest results shows a dramatic discrepancy with the NuSea data at large x
  - Assumptions: isospin symmetry, nuclear effect neglected

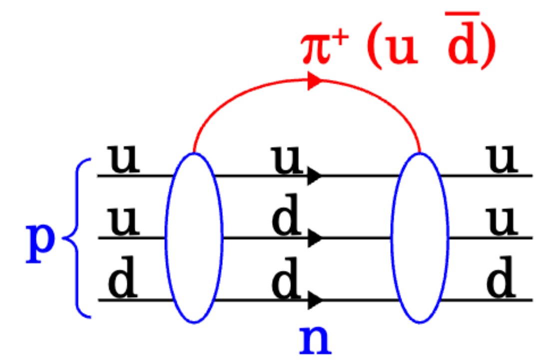
$$\frac{d^2\sigma_{AB}}{dx_1 dx_2} = \frac{4\pi\alpha}{9x_1x_2}\sum_{i\in u,d,s,\cdots} e_i^2[q_i^A(x_1)\bar{q}_i^B(x_2) + \bar{q}_i^A(x_1)q_i^B(x_2)] \quad \Rightarrow \quad \frac{\sigma_{pD}}{\sigma_{pH}} \approx 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}$$





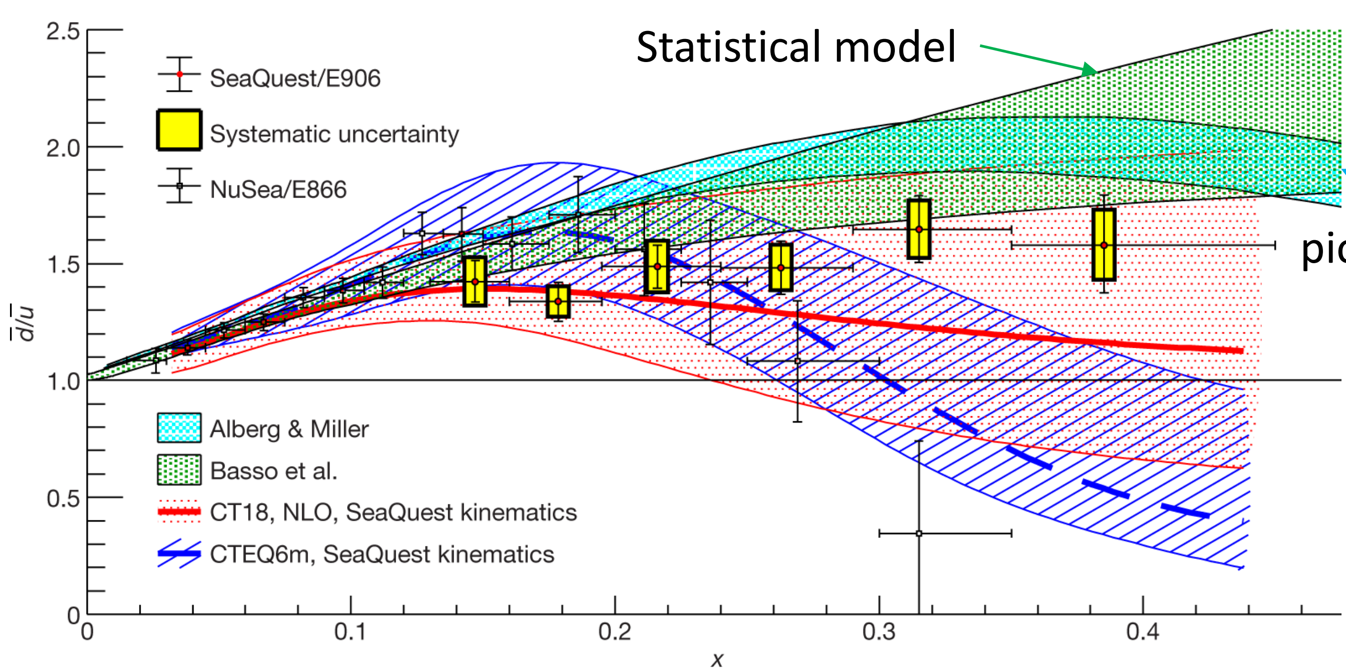
Pion cloud model

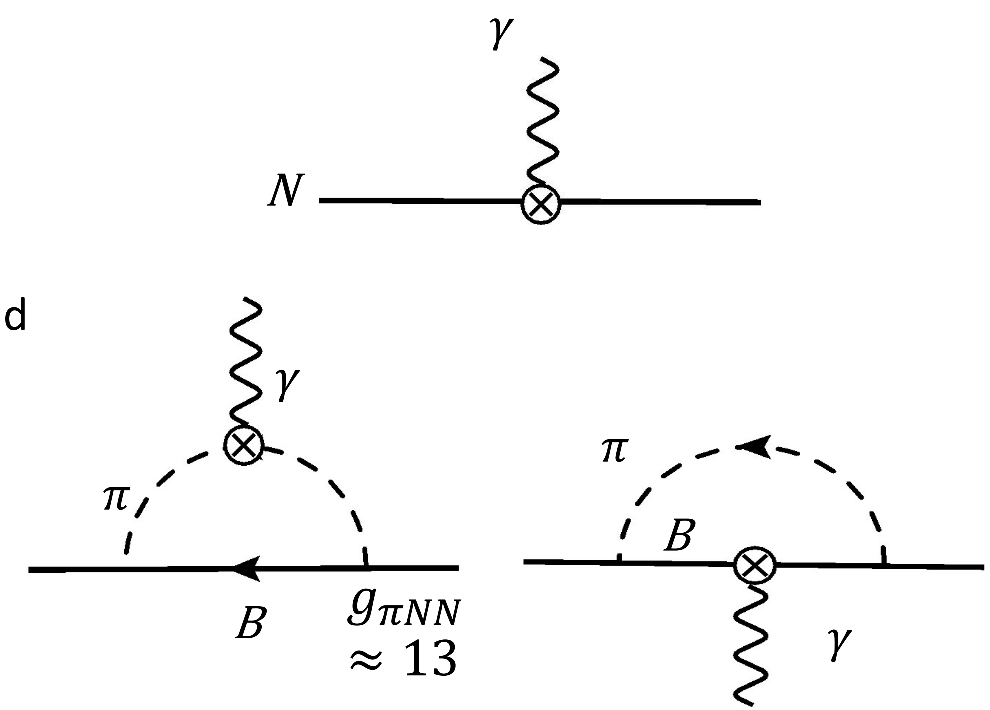
- Reasonably described by two theoretical predictions:
  - Pion cloud model [Ji et. al. '13, Alberg et. al '21]
  - Statistic model [Basso et. al '16]
- Both models slightly overshoot the SeaQuest data



- Assumption in the Alberg & Miller's model: light-cone perturbation theory (LCPT)

$$|p\rangle_{\rm ph} = |p\rangle + |n\pi^+\rangle + |\Delta\pi^-\rangle + |\Lambda K\rangle + |B\pi\pi\rangle + \cdots$$





A simplified pion cloud model

[YL, Karmanov & Vary '15]

$$\mathcal{L}_{int} = g_0 N^\dagger N \pi + g_{\pi N \Delta} \Delta^\dagger N \pi + g_{\pi N \Delta} N^\dagger \Delta \pi$$

$$m_N = 0.94\text{GeV}, m_\Delta = 1.23\text{GeV}, \mu = 0.14\text{GeV}, \alpha_{\pi NN} = 0.8, \alpha_{\pi N\Delta} = 0.95, \alpha = \frac{g^2}{16\pi m_B^2}$$

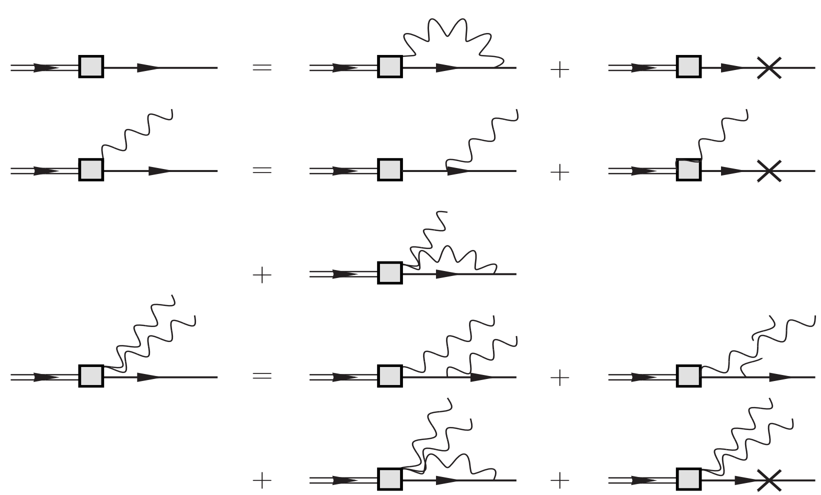
- Scalar constituents with Yukawa type interaction
- Non-perturbative solution: light cone Hamiltonian eigenvalue equation

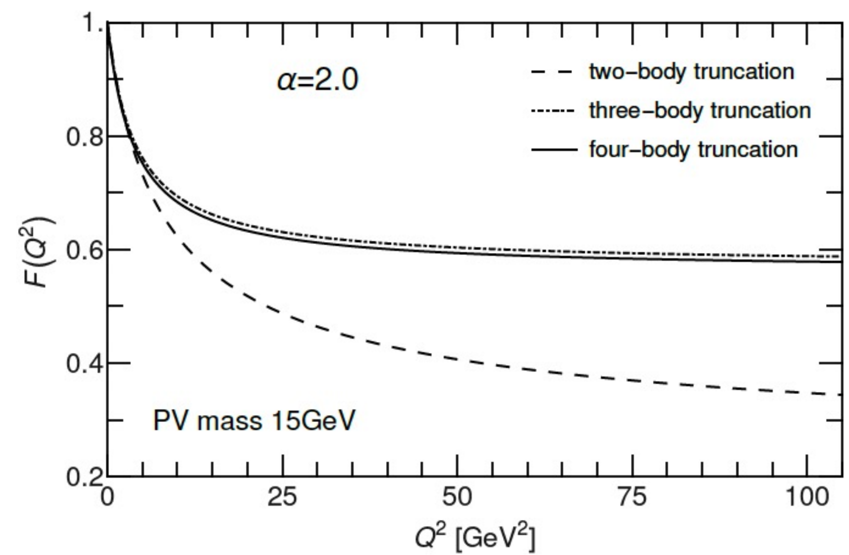
$$H_{\mathrm{LC}}|\psi\rangle = M^2|\psi\rangle$$

- Fock sector convergence up to $|N\pi\pi\rangle$

beyond perturbative one-pion physics

$$|N\rangle_{\mathrm{ph}} = |N\rangle + |N\pi\rangle + |\Delta\pi\rangle + |N\pi\pi\rangle + |\Delta\pi\pi\rangle + |N\pi\pi\pi\rangle + |\Delta\pi\pi\pi\rangle + \cdots$$

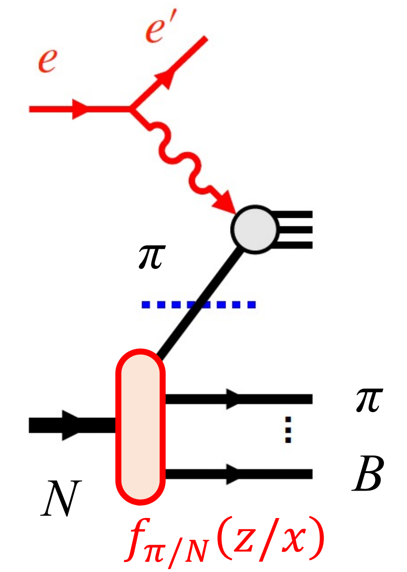




Convolution formula

$$q(x) = \sum_h \int \frac{dz}{z} f_{h/H}(z/x) q_h^{(0)}(z) \equiv f_{h/H} \otimes q_h^{(0)}$$

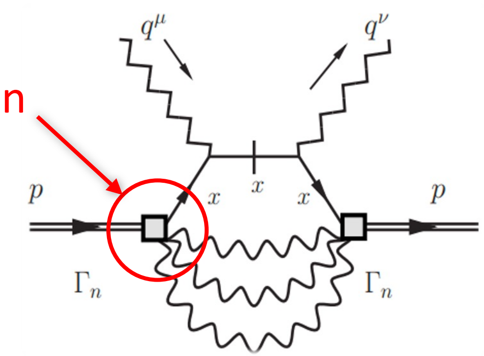
where $f_{h/H}$ is the h longitudinal momentum distribution (LMD) in H, and $q_h^{(0)}$ represents quark PDF in bare hadron h



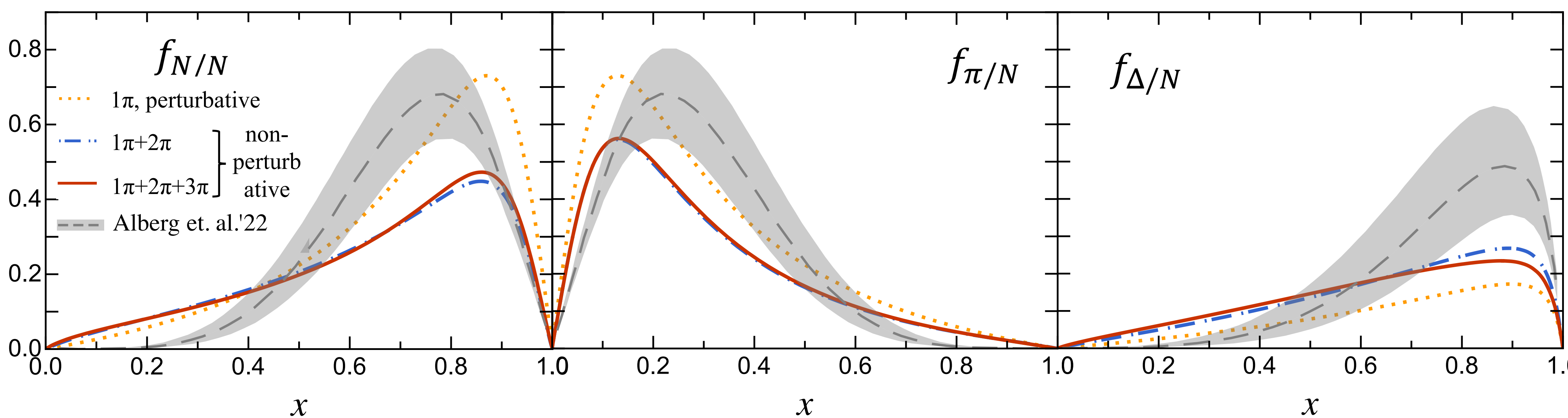
- Non-perturbative LMD:

$$f_{h/H}(x) = \int [dx_i d^2 k_{i\perp}]_n \sum_{j \in h} \delta(x - x_j) \left| \psi_{n/H}(\{x_i, \vec{k}_{i\perp}\}) \right|$$

light-front wave function



- Non-perturbative LMD show sizeable deviation from the perturbative LMD, indicating an important multi-pion sea contribution



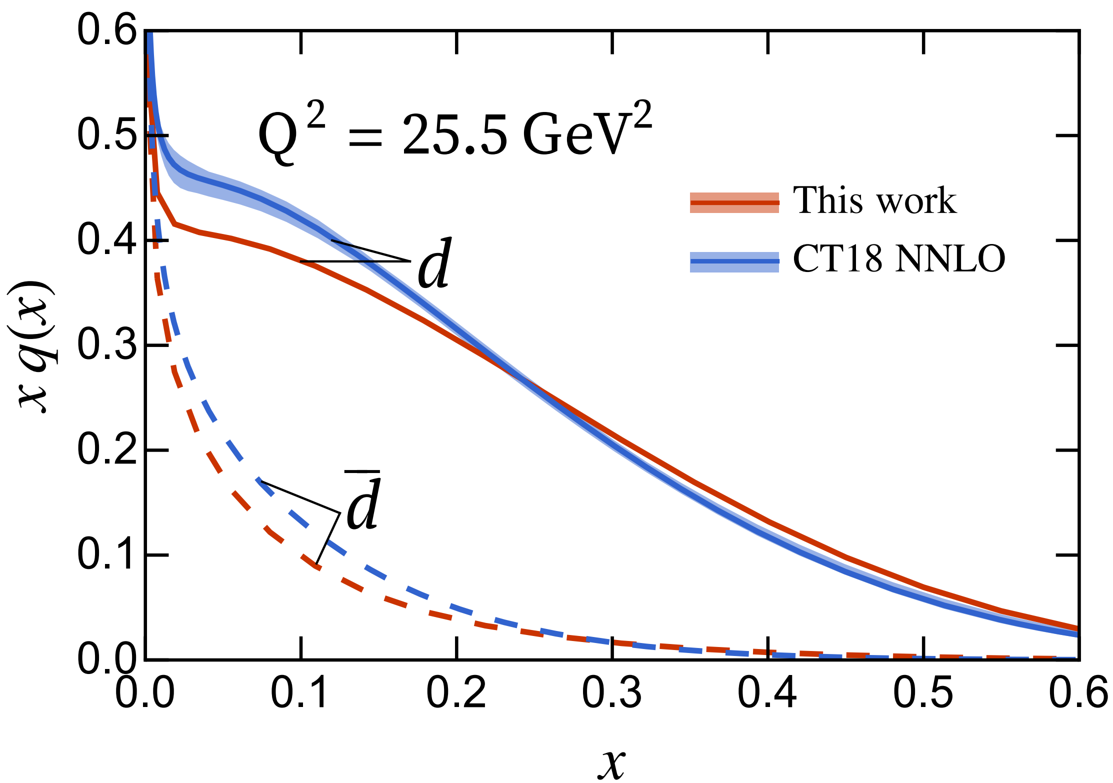
Quark PDFs in pion cloud model

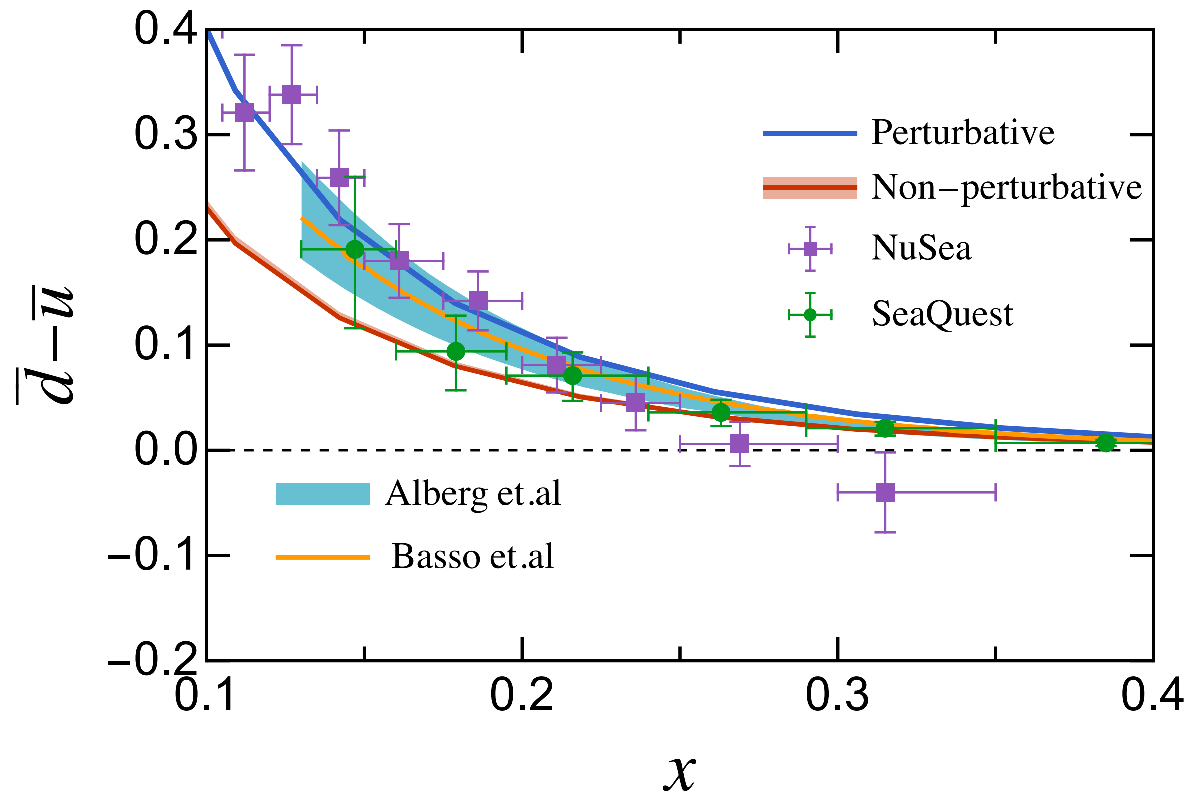
$$\bar{d}(x) = \left(\frac{5}{6} f_{\pi N} + \frac{1}{3} f_{\pi \Delta}\right) \otimes q_\pi^v + \sum_B f_{\pi B} \otimes q_\pi^s + \sum_B f_{B\pi} \otimes q_B^s + Z q_N^s(x)$$

where $f_{\pi N}(x)$ is the π LMD within $|N\pi\rangle$ sector, $f_{\pi\Delta}(x)$ is the π LMD within $|\Delta\pi\rangle$, $q_\pi^{v/s}$ represents valence/sea quark PDF in pion, Z is the bare nucleon probability

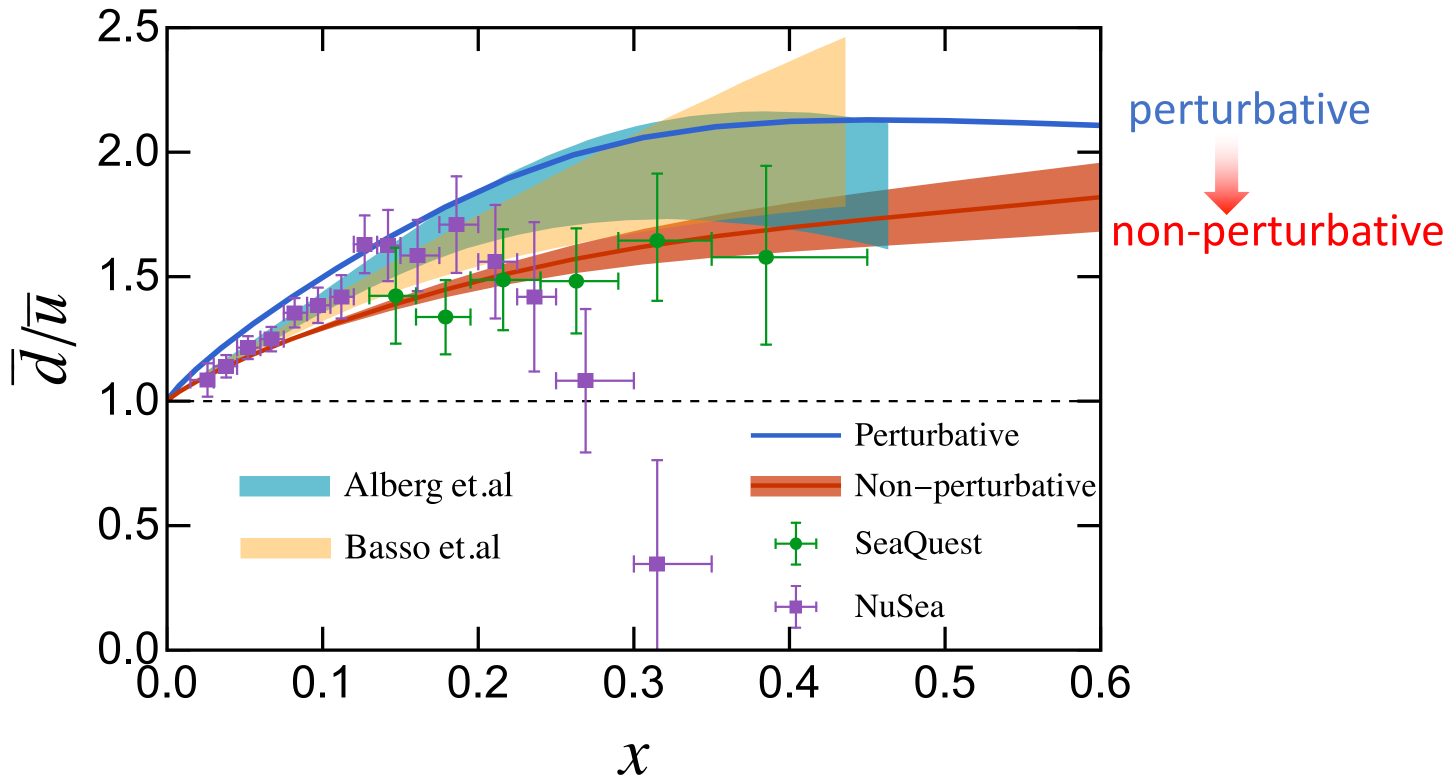
[Holtmann et al. '97]

- Non-perturbative xd and $x\bar{d}$ are in reasonable agreement with CT18 NNLO





Flavor asymmetry of the nucleon sea



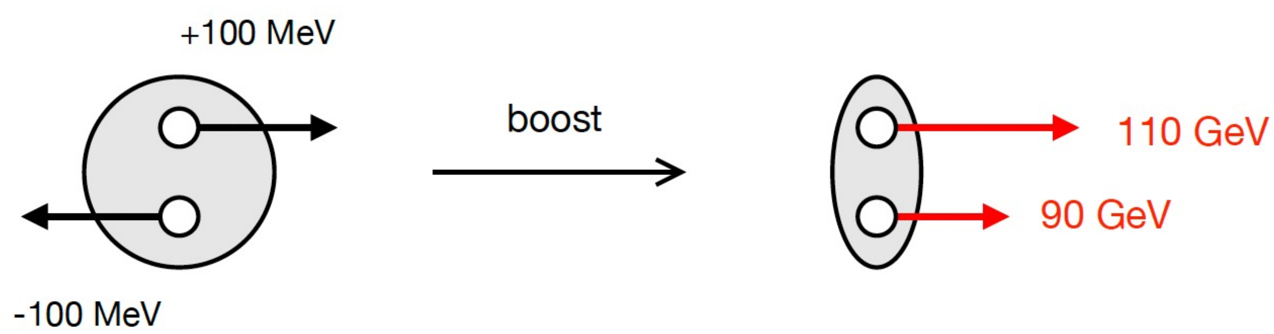
- Both our perturbative and non-perturbative results follow the same trend as Alberg & Miller's pion cloud model based on LCPT
- Adding multi-pion contributions lower the flavor asymmetry $\bar{d}/\bar{u}$, and show better agreement with the SeaQuest data

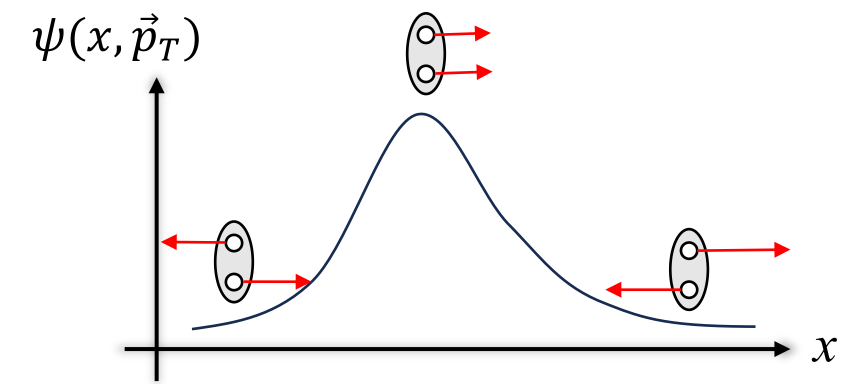
Gottfried sum

	$[x_{min}, x_{max}]$	$\int_{x_{min}}^{x_{max}} (\bar{d} - \bar{u}) \mathrm{d}x$
NMC	[0, 1]	0.15±0.04
NuSea*	[0, 1]	0.118±0.012
SeaQuest	[0.13, 0.45]	0.0159±0.0060
This work (perturbative)	[0.13, 0.45]	0.0212
This work (non-perturbative)	[0.13, 0.45]	0.0122±0.0007

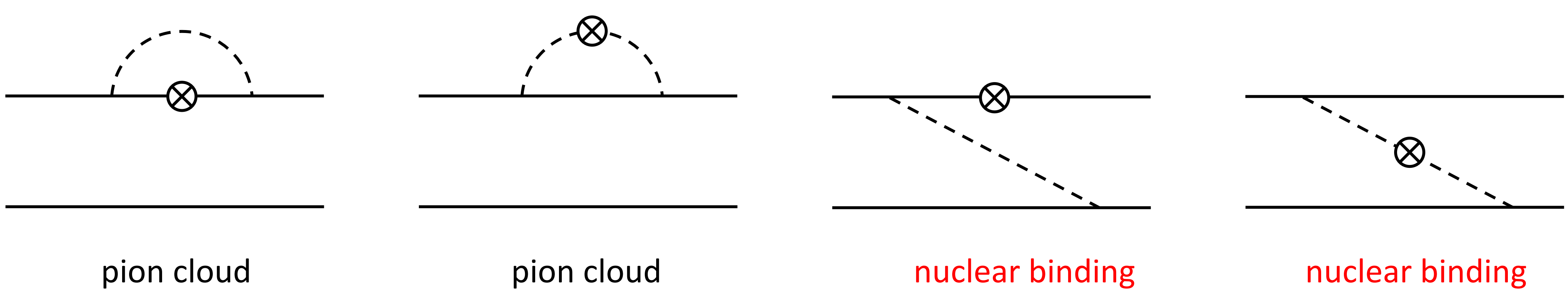
* Extrapolated from [0.015, 0.3]

Nuclear effects





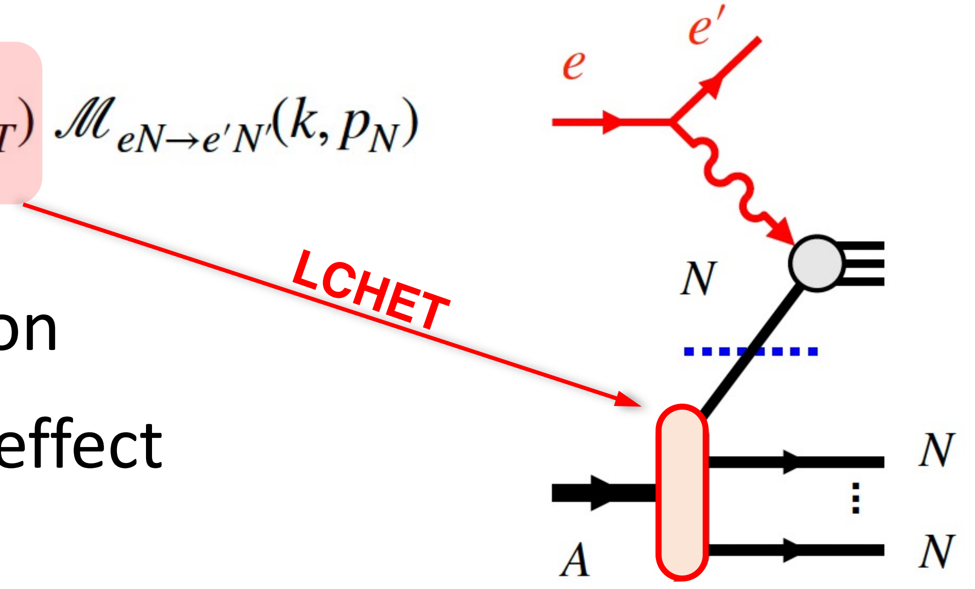
- Nuclear effects are not negligible in a prori
- Consistent treatment of the proton-deuteron Drell-Yan should also include the nuclear binding induced by the pion exchange
- Light-cone Hamiltonian effective theory (LCHET)



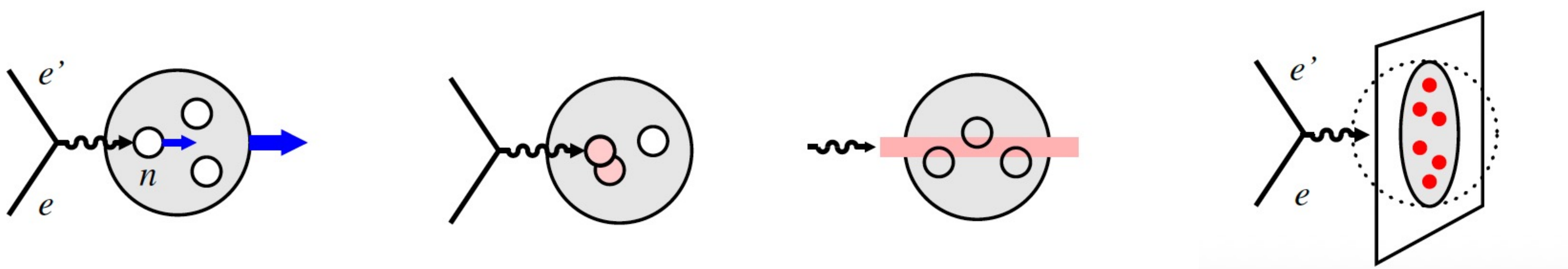
LCHET for EIC

See also C.-R. Ji's plenary talk on Friday

$$\mathcal{M}_{eD\to e'N'S'}(k,p_D) = \int \frac{d\alpha_N}{\alpha_N}\int d^2p_{NT}\,\mathrm{Flux}(\alpha_N)\,\Psi(\alpha_N,\mathbf{p}_{NT})\,\mathcal{M}_{eN\to e'N'}(k,p_N)$$



- Neutron structures and flavor decomposition
- Nuclear interaction at short distance, EMC effect
- Nuclear shadowing and diffraction
- Nuclear parton distributions



Taken from C. Weiss

Summary and outlooks

- We investigate the non-perturbative nucleon sea flavor asymmetry within the pion cloud model using a light-front Hamiltonian approach
- We show that the non-perturbative sea is not negligible: it improves the perturbative results towards the recent SeaQuest measurement
- Consistent treatment of the proton-deuteron Drell-Yan (e.g. SeaQuest) should also incorporate the nuclear effects, which can be treated in the same LCHET framework

Thank You!