Flavor asymmetry from the non-perturbative nucleon sea

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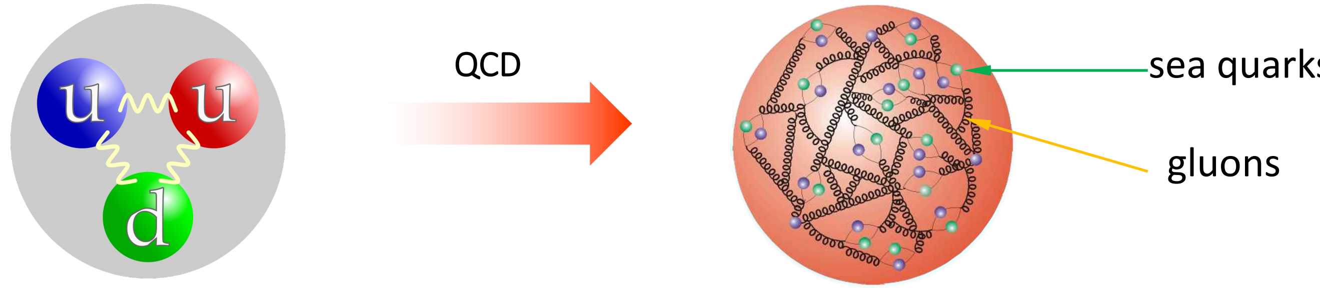
Perturbative sea quarks in nucleon

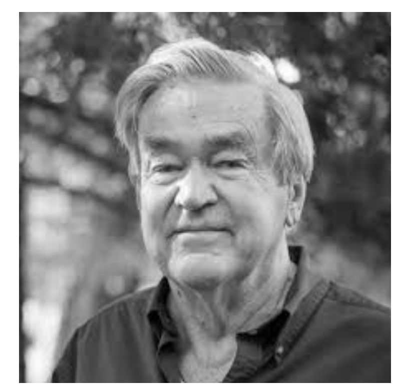




- Parton model of nucleon :

  1. Valence part : 3 quarks compose a nucleon, such as p(uud) [Feynman '69, Bjorken et. al '69]

  2. Sea part : gluon splitting ($\bar{d} = \bar{u} = d = u$)

Asymmetry in nucleon sea

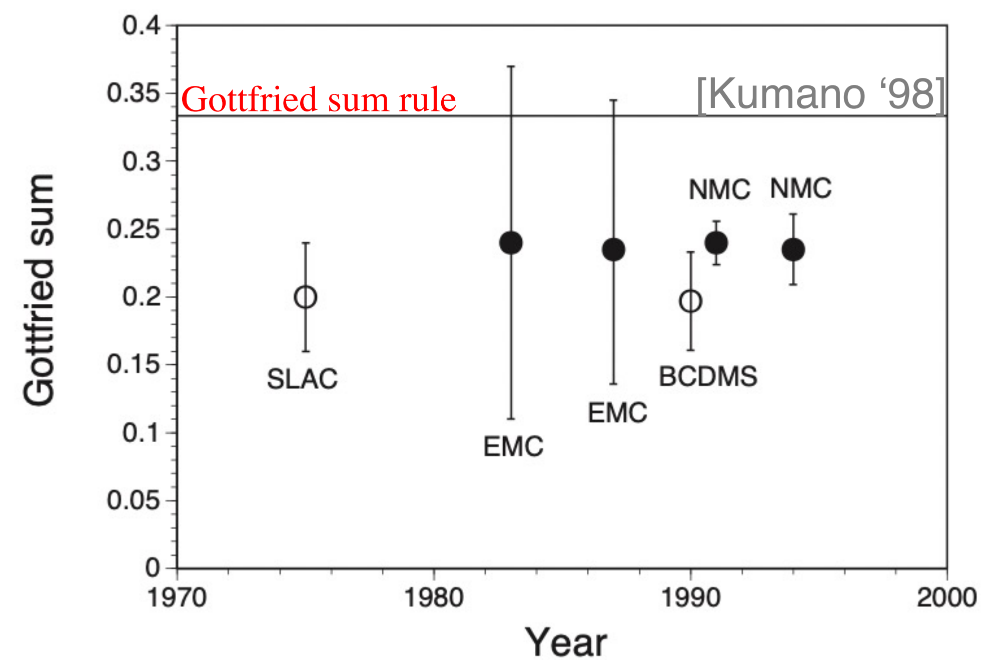
Gottfried sum rule (GSR): [Gottfried '67]

0 in perturbative QCD

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

where F_2^p represents proton structure function and F_2^n represents neutron structure function

- Experimental tests of Gottfried sum rule
  - DIS
  - SIDIS
  - Drell-Yan
- Violation of GSR: non-perturbative effects

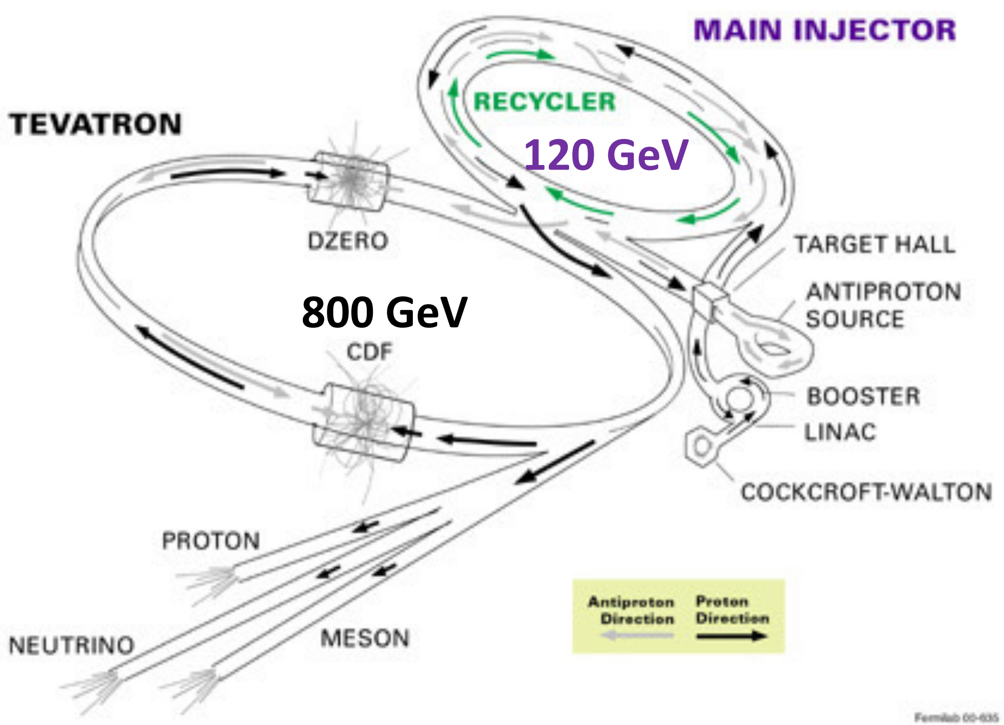


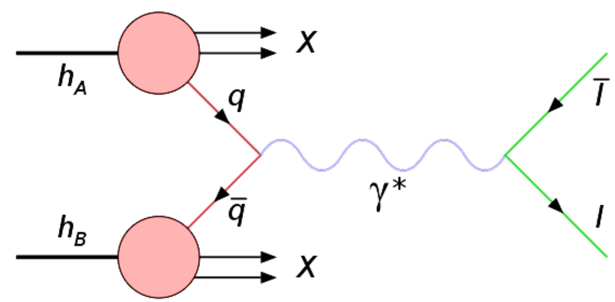
Fix-target Drell-Yan experiments at Fermilab [NuSea '98 & '01, SeaQuest '23]

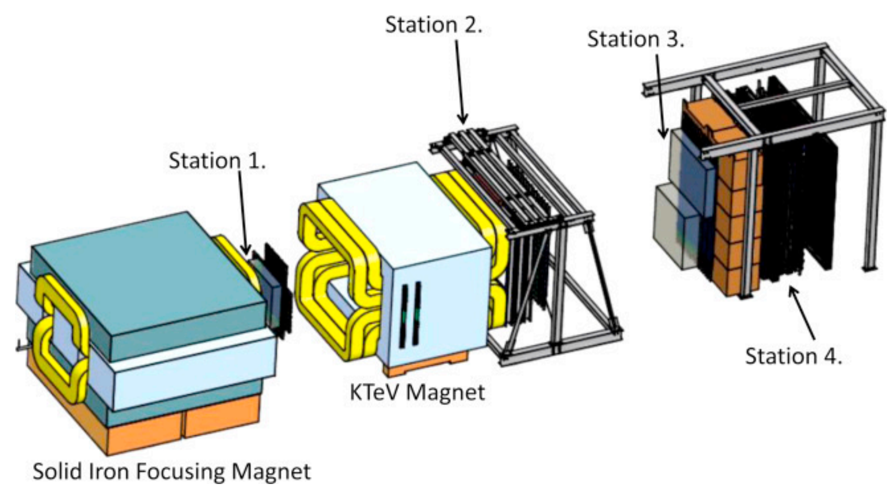
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_1 dx_2} = \frac{4\pi\alpha}{9x_1x_2} \sum_{i\in u,d,s,\cdots} e_i^2[q_i^A(x_1)\bar{q}_i^B(x_2) + \bar{q}_i^A(x_1)q_i^B(x_2)]$$

$$\Rightarrow \frac{\sigma_D}{\sigma_H} \approx 1 + \frac{\bar{d}_p(x_t)}{\bar{u}_p(x_t)}$$

- NuSea/E866: 800 GeV proton beam from Tevatron bombarding liquid H/D target
- SeaQuest/E906: 120 GeV proton beam from injector bombarding liquid H/D target





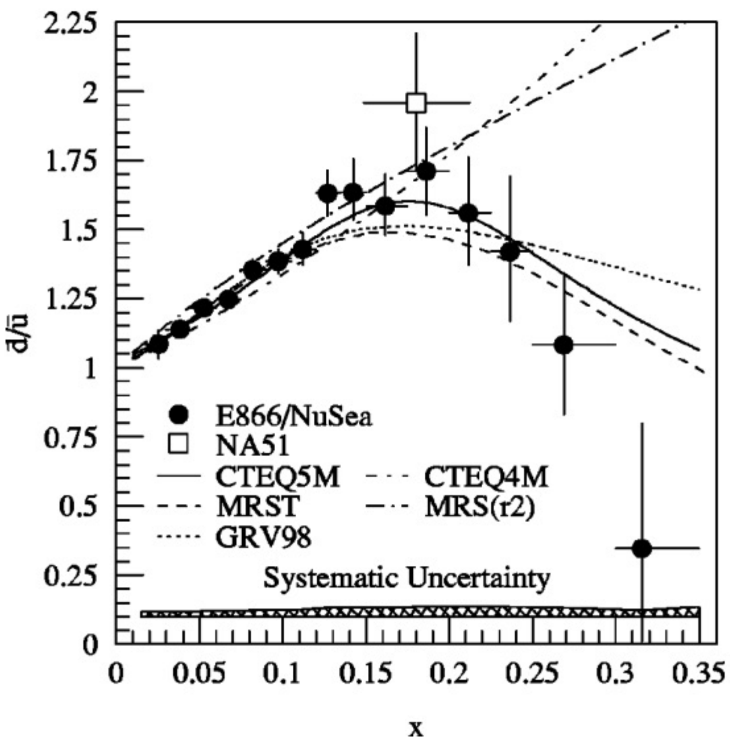


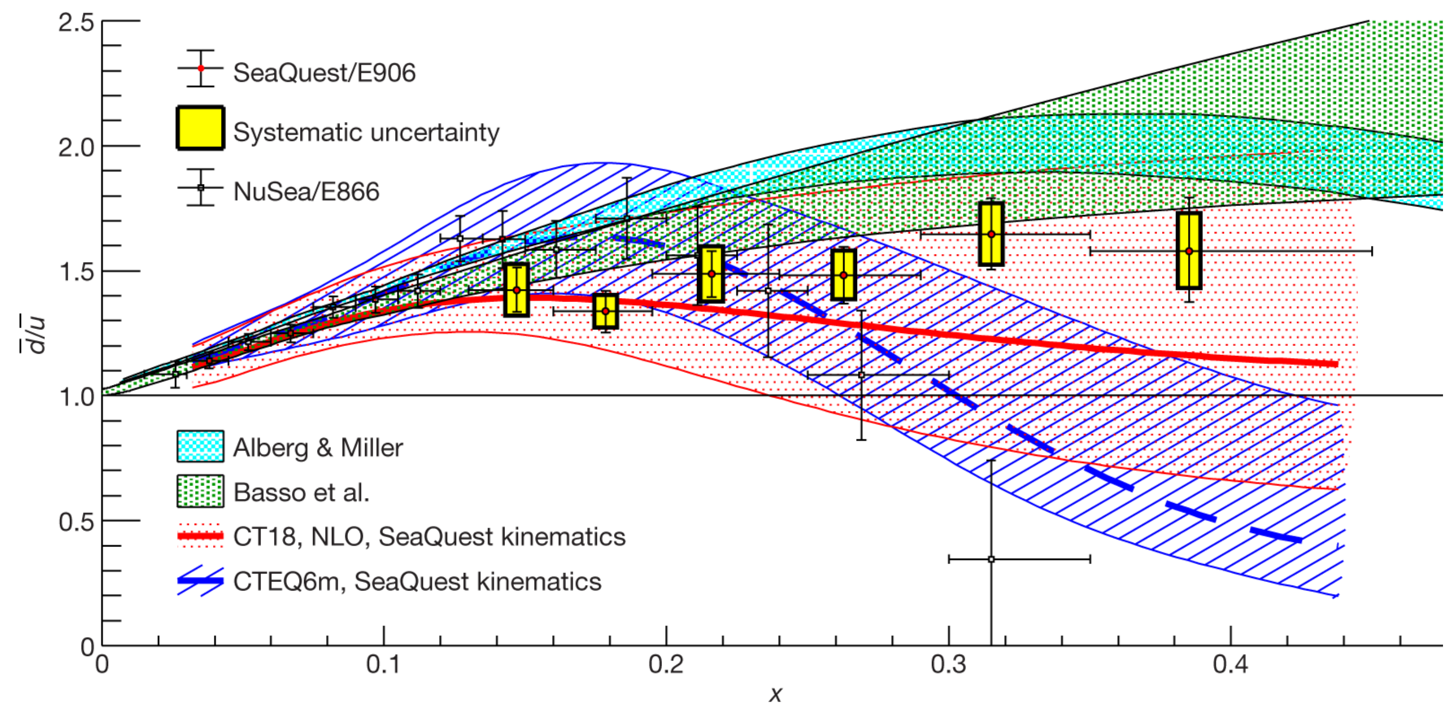
Flavor asymmetry from Drell-Yan

[NA51 ‘94, NuSea ’98 & ’01, SeaQuest ‘23]

- Discrepancy of the sea asymmetry $\bar{d}/\bar{u}$ at large x region
  - NuSea data sketch a dip below unity at $x \sim 0.3$

- Theoretical interpretations:
  - Pauli-Blocking: only few percent effect [Ross et. al ‘79]
  - Meson cloud model [Thomas et. al. ‘83, Alberg et. al ‘21]
  - Statistic model [Basso et. al ‘16]





Pion cloud model

[Theberge et. al. ‘80, Thomas et. al. ’83]

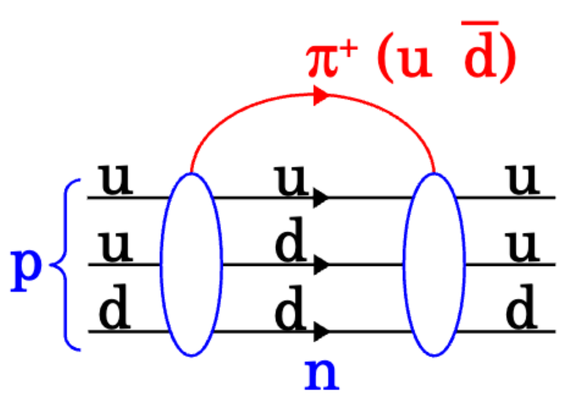
- Nucleon sea from non-perturbative QCD fluctuation into baryon-meson states:

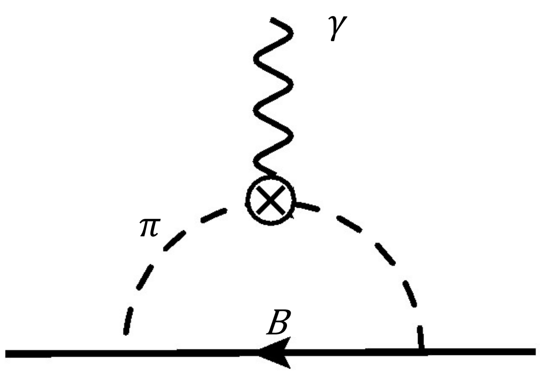
$$|p\rangle_{\mathrm{ph}} = |p\rangle + |n\pi^+\rangle + |\Delta\pi^-\rangle + |\Lambda K\rangle + \cdots$$

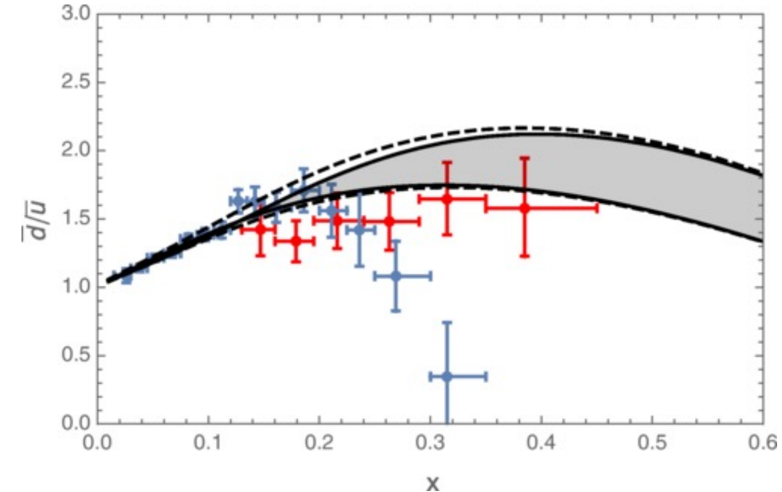
- Pion cloud from light-cone chiral effective field theory [Alberg et. al ‘22]

$$\mathcal{L}_{int} = -\frac{g_A}{2f_\pi}\bar{\psi}\gamma_\mu\gamma_5\tau^a\psi\partial_\mu\pi^a - \frac{1}{f_\pi^2}\bar{\psi}\gamma_\mu\tau^a\psi\epsilon^{abc}\pi^b\partial_\mu\pi^c - \frac{g_{\pi N\Delta}}{2M}(\bar{\Delta}_\mu^i g^{\mu\nu}\psi\partial_\nu\pi^i + \mathrm{H.C.})$$

  - No free parameter
  - Solved in light-cone perturbation theory with a Fock sector truncation up to one-pion $|B\pi\rangle$
  - Good agreement with NuSea data at small x
  - Consistent but slightly overshoot SeaQuest data at large x
- What about effects of the non-perturbative sea, e.g. multi-pion?







Non-perturbative scalar pion cloud

[Li, Karmanov & Vary '15]

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

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

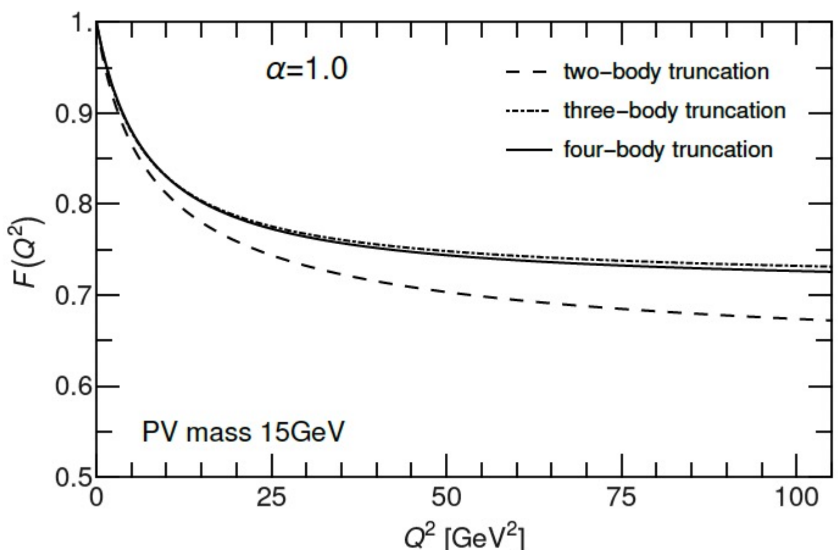
- Non-perturbative light cone Hamiltonian approach

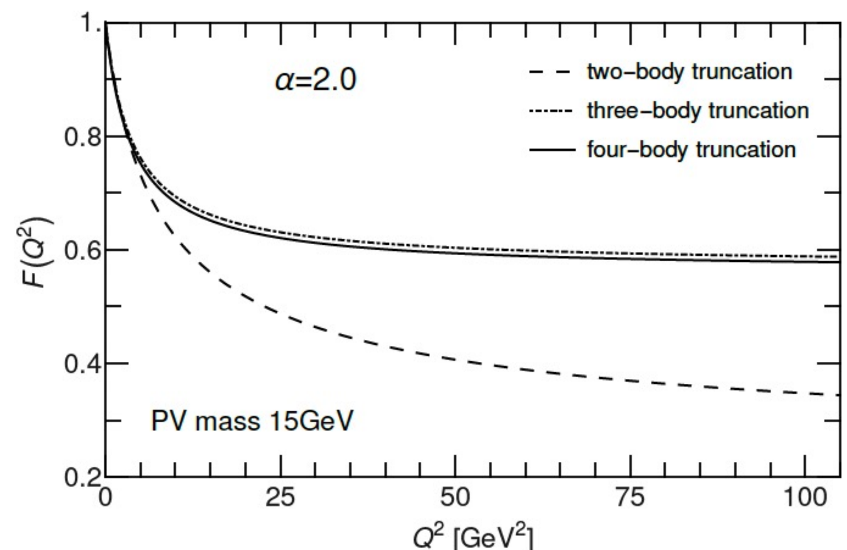
$$H_{LC}|\psi\rangle = M^2|\psi\rangle$$

- Systematic Fock sector expansion and truncation: solved with up to $|N\pi\pi\pi\rangle$ sector at non-perturbative couplings

$$|\psi\rangle = \boxed{|N\rangle + |N\pi\rangle + |N\pi\pi\rangle + |N\pi\pi\pi\rangle} + |\Delta\pi\rangle + |\Delta\pi\pi\rangle + |\Delta\pi\pi\pi\rangle \cdots$$

- Observed numerical convergence of Fock sector expansion up to $|N\pi\pi\rangle$ sector



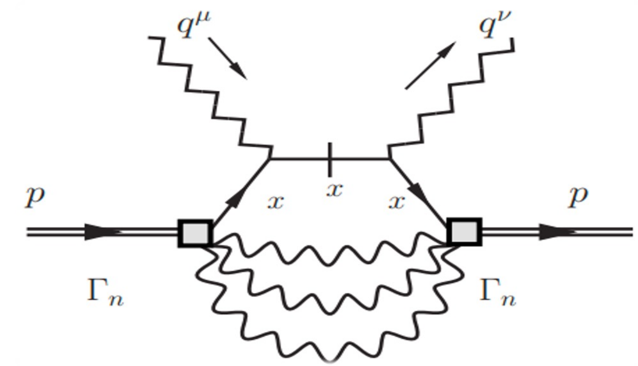


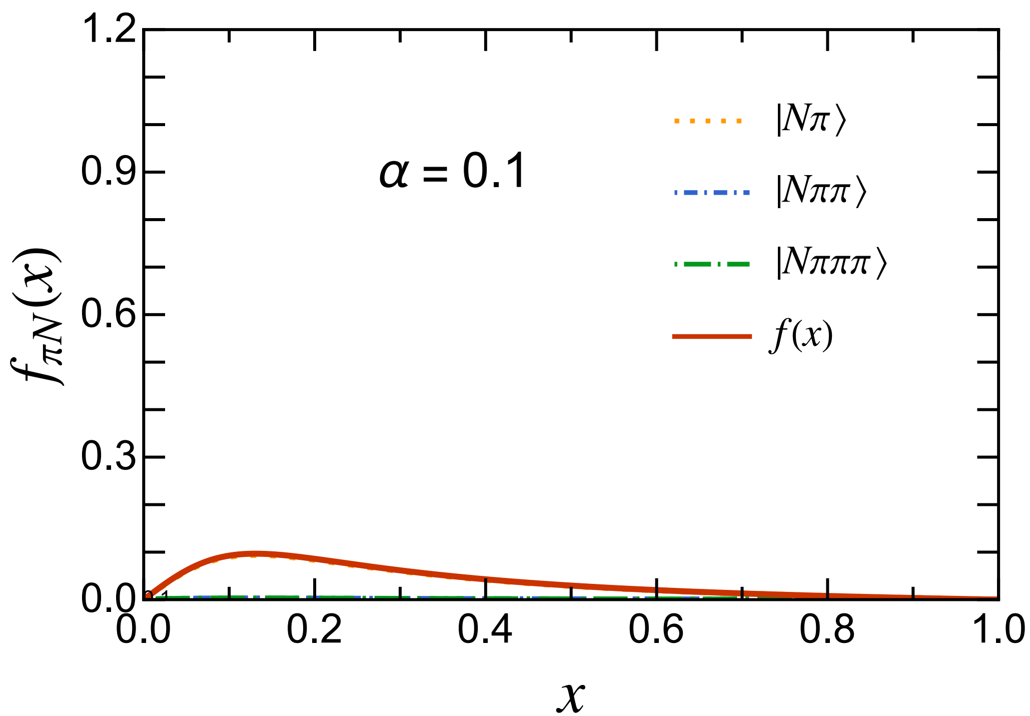
Longitudinal momentum distribution (LMD)

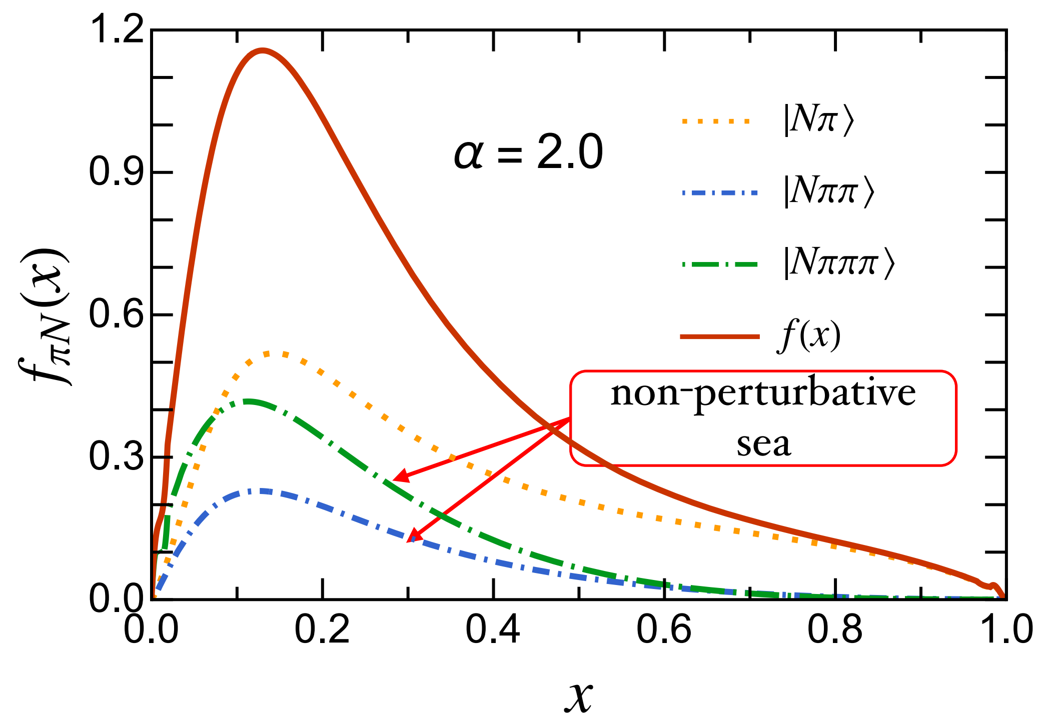
$$p_i(x,\mu) = \frac{k^+}{2}\int dz^- e^{\frac{i}{2}(1-x)p^+z^-}\left\langle p\left|\psi_i^\dagger\left(-\frac{z}{2}\right)\psi_i\left(\frac{z}{2}\right)\right|p\right\rangle\Big|_{z^+=z_\perp=0,\mu}$$

where $i = \pi, N, \Delta$

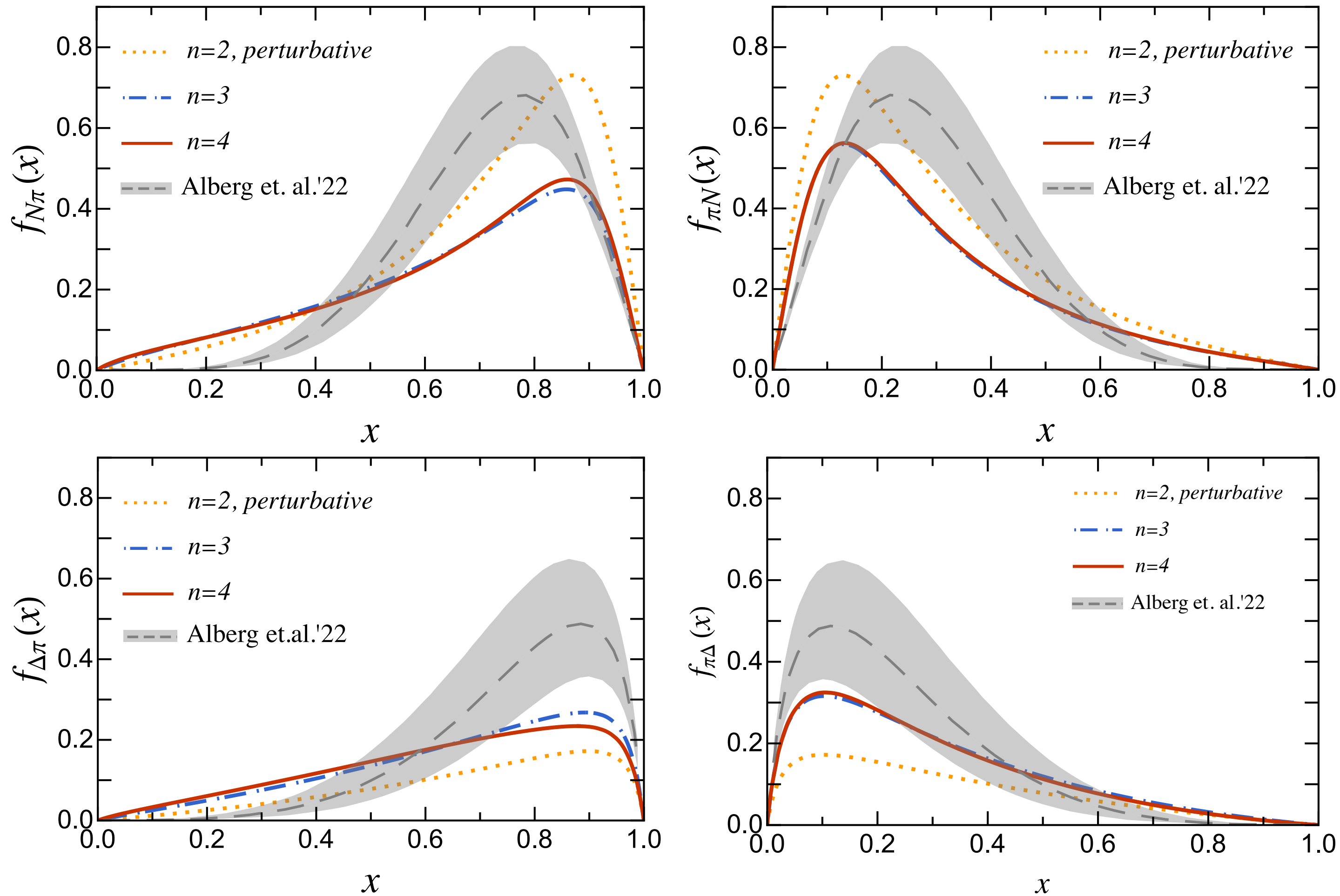
- Scalar theory is super-renormalizable and we can take $\mu \to \infty$
- Perturbative sea is dominant at small α
- Multi-pion sea contribution is significant at larger α







LMDs within the physical nucleon



- Parameters $\alpha_{\pi NN} = 0.8, \alpha_{\pi N\Delta} = 0.95$ chosen to fit the SeaQuest data
- Fock sector convergence
- Violation of the perturbative ansatz: $f_{\pi B}(x) = f_{B\pi}\,(1-x)$

Anti-quark PDFs in pion cloud model

$$\bar{d}(x) = \left(\frac{5}{6} f_{\pi N} + \frac{1}{3} f_{\pi\Delta}\right) \otimes q_\pi^v + \bar{q}_{sym}(x)$$

$$\bar{u}(x) = \left(\frac{1}{6} f_{\pi N} + \frac{2}{3} f_{\pi\Delta}\right) \otimes q_\pi^v + \bar{q}_{sym}(x)$$

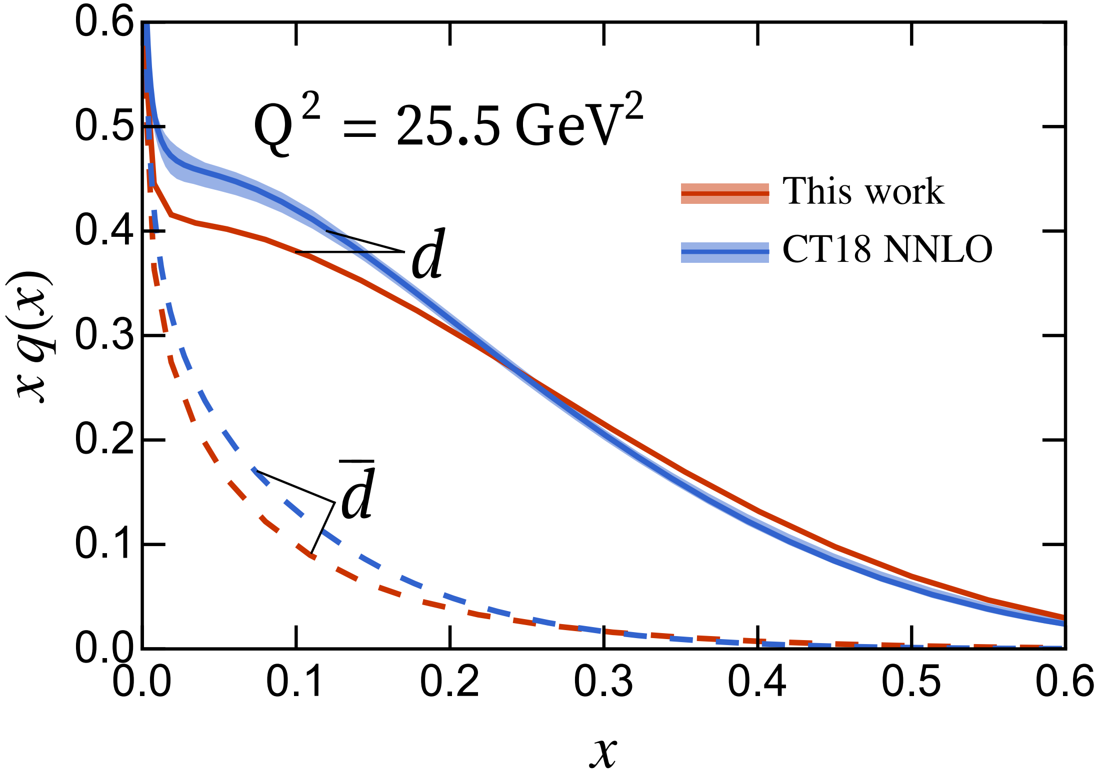
$$\bar{q}_{sym}(x) \equiv \sum_B f_{\pi B} \otimes q_\pi^s + \sum_B f_{B\pi} \otimes q_B^s + Z q_N^s(x)$$

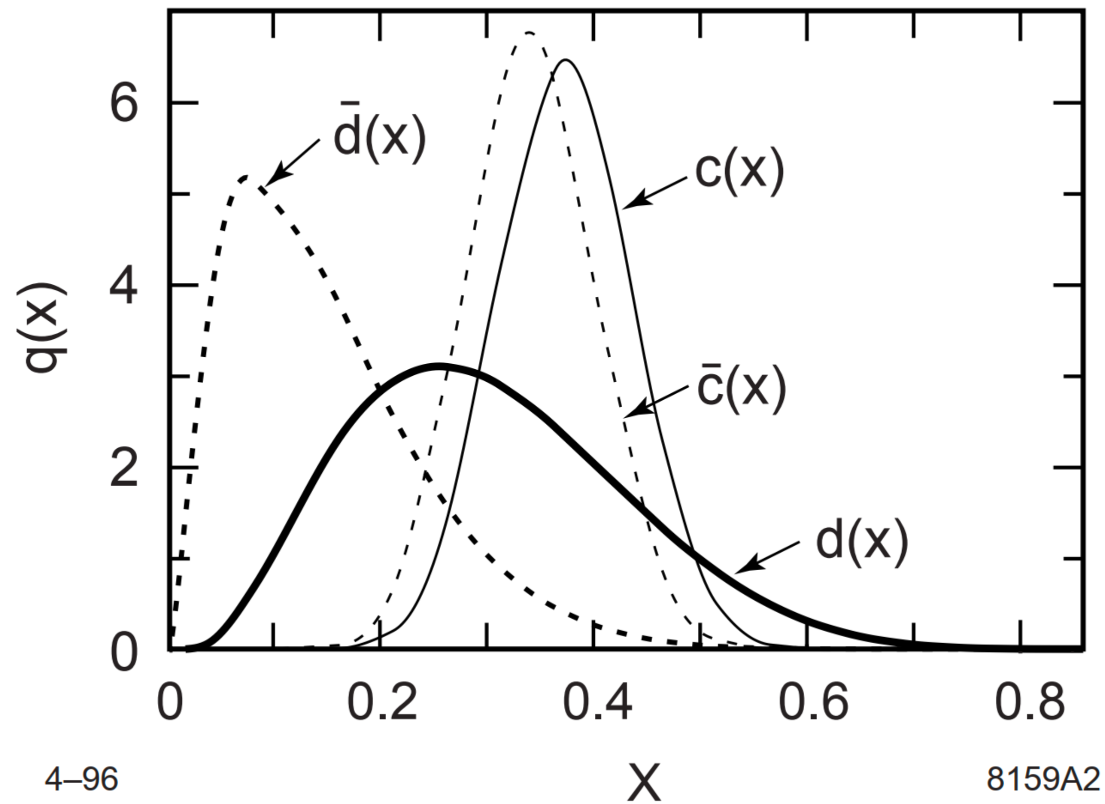
where $f_{\pi N}(x)$ is the π LMD within N, $f_{\pi\Delta}(x)$ is the π LMD within Δ, $q_\pi^{v/s}$ represents valence/sea quark PDF in pion, Z is the bare nucleon probability

- Following Alberg & Miller, we adopt bare nucleon PDFs from Holtmann [Holtmann et al. '97]
- Scale of the quark PDF evolved to $Q^2 = 25.5\ \text{GeV}^2$ by NLO DGLAP

Quark anti-quark asymmetry

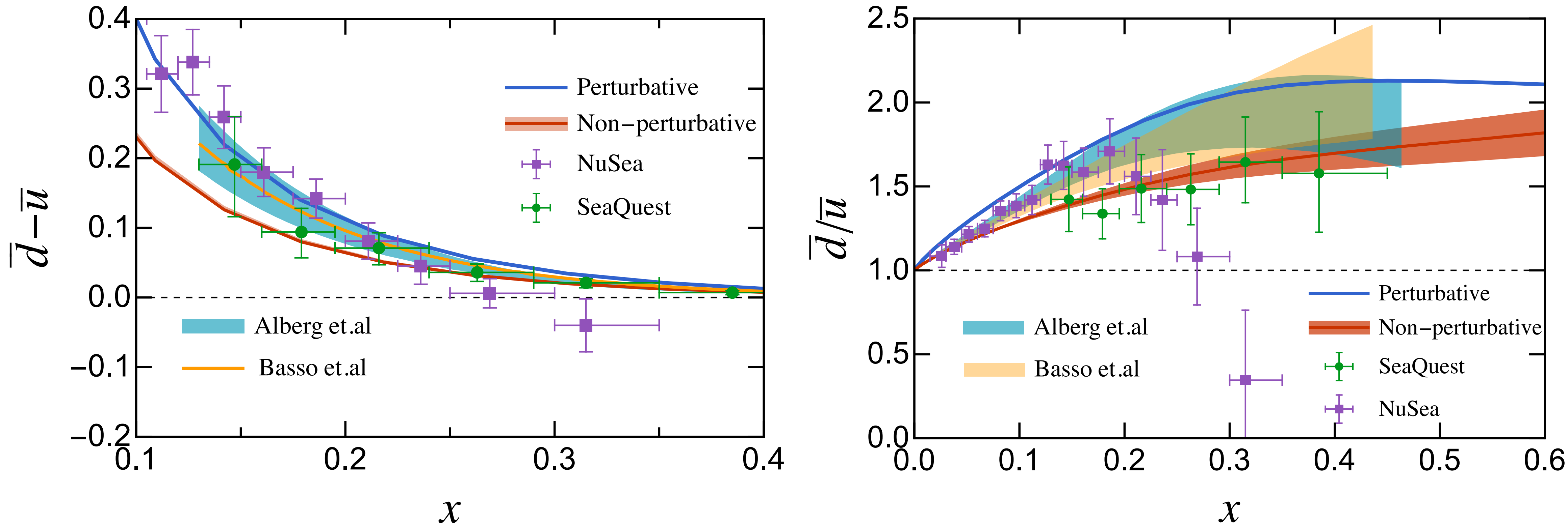
[Brodsky & Ma '96]





- Non-perturbative $xd(x)$ and $x\bar{d}$ are in reasonable agreement with CT18 NNLO
- In principle can be used to investigate quark-antiquark sea asymmetry, such as nucleon strangeness and intrinsic charm, as shown by Brodsky et. al.

Anti-quark flavor asymmetry



- Both perturbative and non-perturbative results are consistent with the trend of Alberg et. al.'s predictions as well as the SeaQuest data
- Our perturbative results are in rough agreement with Alberg et. al.'s perturbative results
- Our non-perturbative results are lower than the perturbative results, indicating a significant multi-pion sea

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
This work (perturbative)	[0, 1]	0.112
This work (non-perturbative)	[0, 1]	0.064 ± 0.002

* Obtained from extrapolating results within $[0.015, 0.3]$

Summary

- We calculated the longitudinal moment distribution of a strongly-coupled scalar nucleon using light-front Hamiltonian formalism and apply it to the pion cloud model to investigate the nucleon sea quark PDFs
- Within our model, the non-perturbative results improve the perturbative results and show good agreement with the recent SeaQuest measurement
- Our work indicates there may be large non-perturbative contributions to nucleon sea, originated from the multi-pion Fock sector

Thank You