Measurement of $p+d$ / $p+p$ Cross-Section Ratio of Drell-Yan Process at FNAL-SeaQuest

HAWAII 2023

2023/Nov/30, F06.7

Kenichi Nakano

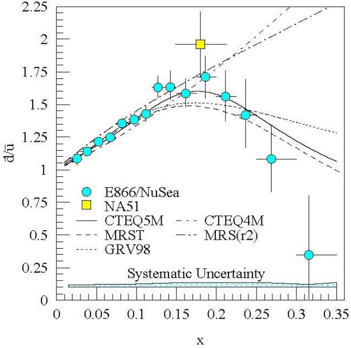
University of Virginia

Outline

1. Aim & method of experiment
    - $\bar{d}(x)/\bar{u}(x)$ = Flavor asymmetry of light-quark sea in the proton
    - Method of measuring $\bar{d}(x)/\bar{u}(x)$ via Drell-Yan process
2. SeaQuest experiment
    - Beam, target & spectrometer
    - Data taking & analysis
3. Measurement of $\bar{d}(x)/\bar{u}(x)$
    - Two methods of extracting cross-section ratio ($\sigma^{pd}/2\sigma^{pp}$)
    - Result of cross-section ratio: Phys. Rev. C **108**, 035202 (2023)
    - Results of $\bar{d}(x)/\bar{u}(x)$ & $\bar{d}(x) - \bar{u}(x)$
4. Conclusions

Anti-Quark Flavor Asymmetry: $\bar{d}/\bar{u}$

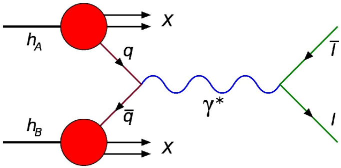
- Symmetric in gluon splitting: $g \to u\bar{u}$ or $d\bar{d}$
- CERN NMC ('90): deep inelastic muon scattering
  - Gottfried Sum: $S_G = 0.235 \pm 0.026 < 1/3$
  - $\int_0^1 \bar{d}(x)dx - \int_0^1 \bar{u}(x)dx = 0.147 \pm 0.039$ — Asymmetry!
- Measurement of x dependence of $\bar{d}(x)/\bar{u}(x)$: Drell-Yan process
  - CERN NA51 ('94): $\bar{d} > \bar{u}$ at $x \sim 0.18$
  - FNAL E866/NuSea ('98): $\bar{d}(x)/\bar{u}(x)$ for $x \in (0.015, 0.35)$



70% asymmetry!

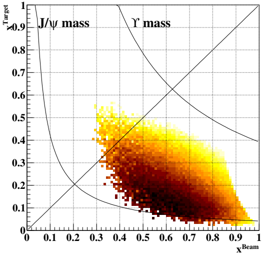
A few % expected

Measurement of $\bar{d}(x)/\bar{u}(x)$ with Drell-Yan Process



- Drell-Yan process: $p + p \to \gamma^* \to \mu^+ + \mu^-$
  - Virtual photon
    - Invariant mass: $M^2 = x_1 x_2 s$
    - Rapidity: $\exp Y = \sqrt{x_1/x_2}$
  - Beam $x_1 = \frac{M}{\sqrt{s}} e^Y$, Target $x_2 = \frac{M}{\sqrt{s}} e^{-Y}$
  - Cross section at LO:

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum_{q=u,d} e_q{}^2 \left\{q_{beam}(x_1)\bar{q}_{target}(x_2) + \bar{q}_{beam}(x_1)q_{target}(x_2)\right\}$$

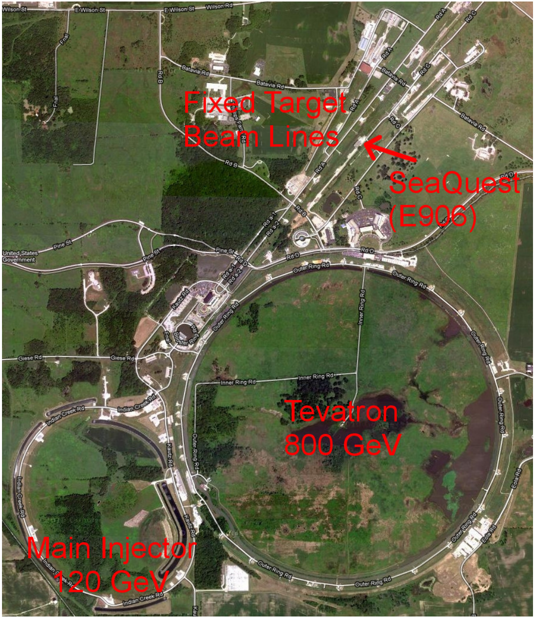


  - Only "$q_{beam}(x_1)\bar{q}_{target}(x_2)$" survives @ forward rapidity, i.e. quark in beam & anti-quark in target
- Ratio of cross sections with LH2 & LD2 targets

$$\frac{\sigma_{pd}(x_2)}{2\sigma_{pp}(x_2)} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right)$$

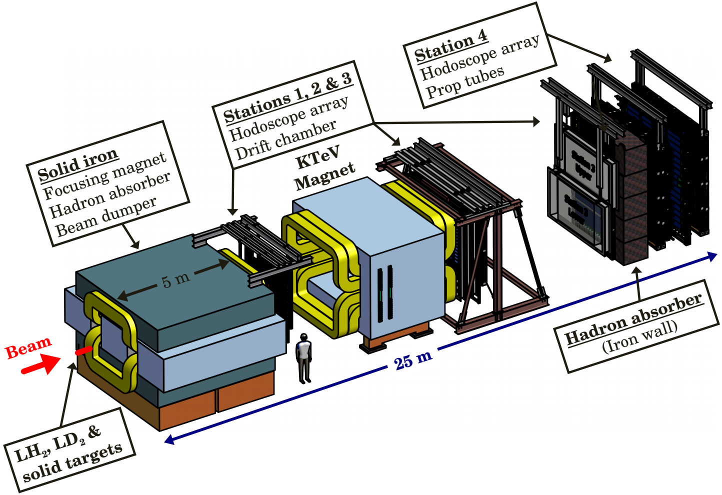
- SeaQuest measures the x dependence of $\bar{d}(x)/\bar{u}(x)$ particularly at high x ($0.15 \lesssim x \lesssim 0.45$)

Fermilab Proton Beam



- Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)
- Duty cycle
  - 5 sec for E906
  - 55 sec for ν exp.
- Bunch
  - Length: 1 nsec
  - Interval: 19 nsec (53 MHz)
  - 10^{13} protons in 5 sec in spot size

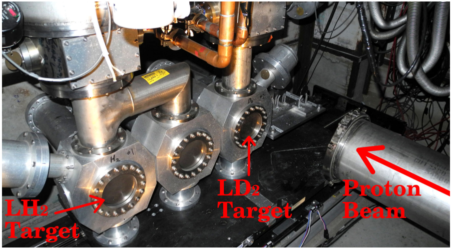
E906/SeaQuest Spectrometer

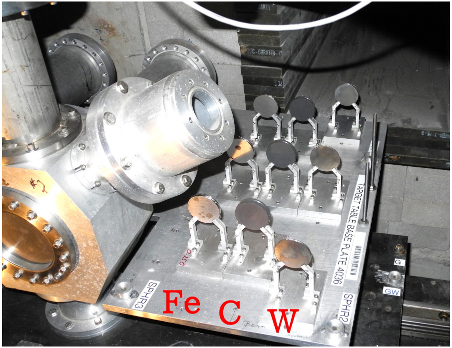


- Targets: LH_2, LD_2, C, Fe, W
- Focusing magnet (FMag) & Tracking magnet (KMag)
- Iron inside FMag, as hadron absorber & beam dump

SeaQuest Targets

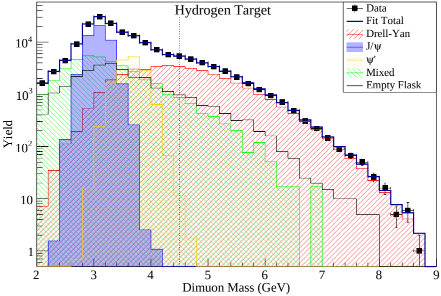
- LH_2, LD_2
  - 50.8 cm $\sim$ 0.1 interaction lengths
- Iron, Carbon, Tungsten





Reconstruction & Identification of Drell-Yan Events

- Physics data were taken in 2013-2017
  - Unlike-sign muon pairs were triggered and reconstructed
  - The 1st half was used for this study
- Distribution of dimuon mass



  - Drell-Yan, J/ψ & ψ' events from simulation
  - Events on non-target materials from empty-target data
  - Random-coincidence BGs from real data via event mixing
- Origins of measured dimuons well understood
- Dominated by Drell-Yan at $M > 4.5$ GeV

Two Methods of Extracting Cross-Section Ratio

$$\frac{\sigma_{pd}(x_2)}{2\sigma_{pp}(x_2)} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right)$$

- To crosscheck the extracted result
- Dimuon rates in p+p & p+d at $M > 4.5$ GeV

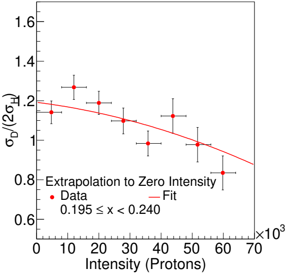
$$Y_{H,D}(x_2, I) = \frac{N_{H,D}(x_2, I)}{L_{H,D}} - \frac{N_{Empty}(x_2, I)}{L_{Empty}}$$

  - Normalized by relative luminosity (L)
  - Corrected for non-target-material events

1. Intensity extrapolation (IE) method — Nature 590, 561
   - Random BG & reco. inefficiency $\to 0$ when beam intensity (I) $\to 0$

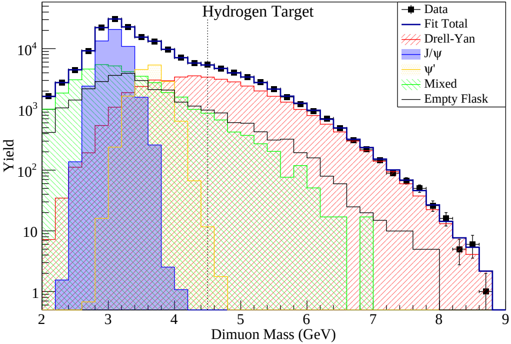
$$\frac{Y_D(x_2, I)}{2Y_H(x_2, I)} = \frac{\sigma_{pd}(x_2)}{2\sigma_{pp}(x_2)} + a\,I + b\,I^2$$

   - Data-driven correction



2. Mass fit (MF) method — PRC 108, 035202

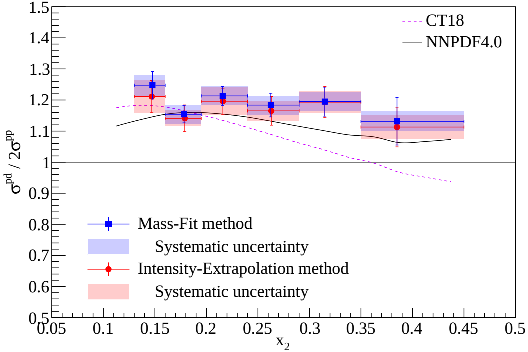
- Random BG
  - Mixed events normalized via the mass fit
- Reconstruction inefficiency
  - Embedding of detector hits into MC dimuon events
  - As function of detector occupancy (= rate dependence)
- Optimization of simulation & analysis cut
  $\Longrightarrow$ Reasonable agreement between real data & simulation



Cross-Section Ratio: $\sigma_{pd}/2\sigma_{pp}$

- Versus x_2 with two extraction methods

PRC 108, 035202



  - The data set is common to the two methods
  - Systematic error of the MF method
    - Beam flux normalization
    - Efficiency correction
    - Simulation-parameter dependence
    - Mostly uncorrelated with the IE method
  - Excellent agreement between the two methods

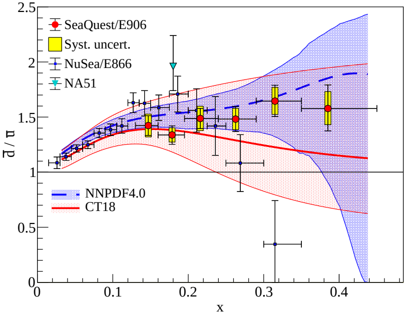
Anti-Quark Flavor Asymmetry: $\bar{d}(x)/\bar{u}(x)$

PRC 108, 035202

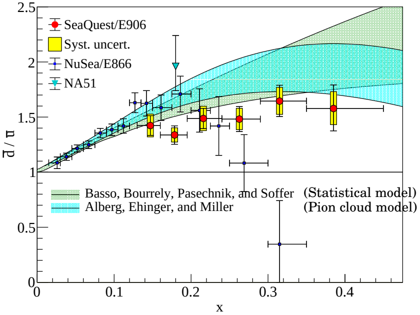
- Derived from the cross-section ratio extracted with the IE method

$$\frac{\sigma_{pd}(x_2)}{2\sigma_{pp}(x_2)} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right)$$

- With PDFs



- With model calculations



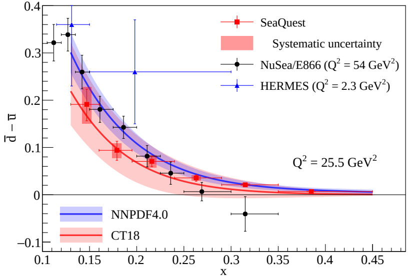
  - Good agreement with calculations
  - The cause of the drop in the E866 data above $x = 0.2$ remains unexplained

Asymmetry in Difference: $\bar{d}(x) - \bar{u}(x)$

PRC 108, 035202

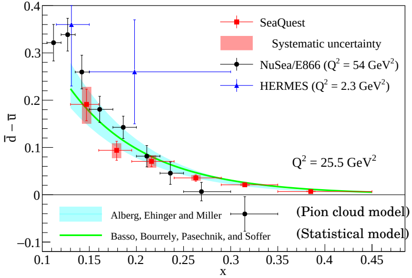
- Direct measure of contribution from nonperturbative processes
  - Determined from $\bar{d}(x)/\bar{u}(x)$ measured in SeaQuest
  - $\bar{d}(x) + \bar{u}(x)$ was taken from CT18 PDF

- With PDFs



  - Good agreement with calculations

- With model calculations



  - Better agreement with calculations than $\bar{d}(x)/\bar{u}(x)$

Conclusions

- Flavor asymmetry of light-quark sea; $\bar{d}(x)/\bar{u}(x)$
  - As large as 70% at $x \sim 0.2$
  - What QCD mechanism generates the asymmetric sea?
- SeaQuest experiment
  - Use of the Drell-Yan process in $p+p$ & $p+d$ at forward rapidity

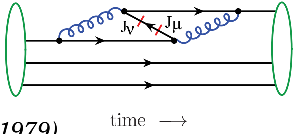
$$\frac{\sigma_{pd}(x_2)}{2\sigma_{pp}(x_2)} \approx \frac{1}{2}\left(1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right)$$

  - With the first half of recorded data
- Measurement of flavor asymmetry — PRC 108, 035202
  - Two methods of extracting $\sigma_{pd}(x_2)/2\sigma_{pp}(x_2)$ resulted in excellent agreement
  - $\bar{d}(x)/\bar{u}(x)$ & $\bar{d}(x) - \bar{u}(x)$ were derived and compared to theory calculations
- Improved analyses are ongoing
  - Better statistics with full dataset & looser cut

Backup Slides

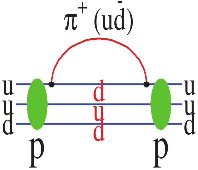
Theories of $\bar{d}/\bar{u}$ Asymmetry (1)

- Mass difference between u & d ($\sim$2 & 5 MeV) in $g \to q\bar{q}$
  - Very small and even results in $\bar{d} < \bar{u}$

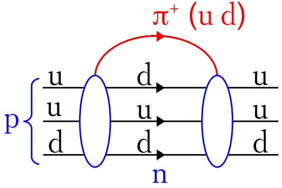


- Pauli blocking ... *PRD15, 2590 (1977)*
  - $Prob(g \to u\bar{u}) < Prob(g \to d\bar{d})$ since $p = uud$
  - Cannot explain the measured size ... *NPB149, 497 (1979)*
  - Even $\bar{d} < \bar{u}$ via connected sea (at high x)? ... *PLB736, 411 (2014)*

- Chiral quark model ... *PRD59, 034024 (1999)*
  - Effective interaction between Goldstone boson (π) & constituent quark
  - $|q_{\text{constituent}}\rangle = \left(1 - \frac{3a}{2}\right)|q\rangle + \frac{3a}{2}|q\pi\rangle$



Theories of $\bar{d}/\bar{u}$ Asymmetry (2)

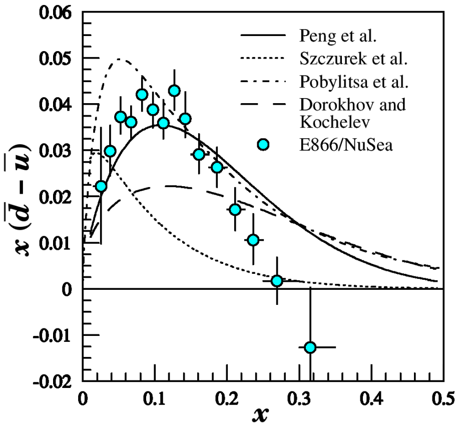


- Meson cloud model ... *PRD58, 092004 (1998)*
  - $|p\rangle = (1-a-b)|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle$
  - More $\bar{d}$ in π^+ as $|n\pi^+\rangle$ etc.
  - Less $\bar{u}$ in π^- as $|\Delta^{++}\pi^-\rangle$ etc.
  - Predict non-zero $L_{q,\bar{q}}$ like "meson tornado" (need $L = 1$ of π to make $J^P = 1/2^+$ of proton, as parity of π is $J^P = 0^-$)

- Statistical model ... *NPA941, 307 (2015)*
  - Based on the Fermi & Bose statistics
  - Predict $\bar{d}(x) - \bar{u}(x) = -\left[\Delta\bar{d}(x) - \Delta\bar{u}(x)\right]$

- Global understandings together with $\Delta\bar{q}(x)$ & $L_{\bar{q}}$ are anticipated

Comparison of Theories to Measurements



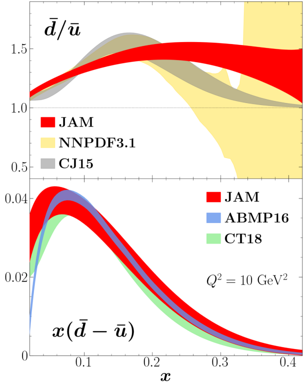
Meson cloud model: PRD58, 092004
Chiral quark model: NPA596, 397
Chiral quark model: PRD59, 034024
Instanton model: PLB304, 167
(Updated calculations exist)

- The x dependence of $\bar{d}(x)/\bar{u}(x)$ is the key to develope/examine models
  - Sharp drop at $x \sim 0.3$. Even go down to $\bar{d} < \bar{u}$?
- Reveal what QCD mechanism generates the asymmetric sea!

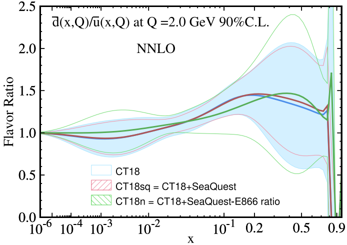
Theoretical Calculations about $\bar{d}/\bar{u}$

- The SeaQuest data have been analyzed, together with the RHIC-STAR $W^{\pm}$ data, including but not limited to

- JAM
  PRD 104, 074031

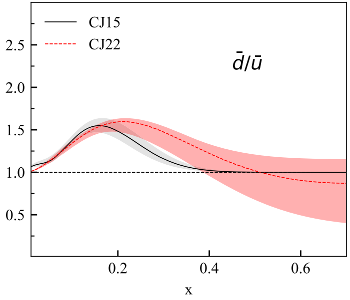


- CT18sq
  arXiv:2108.06596



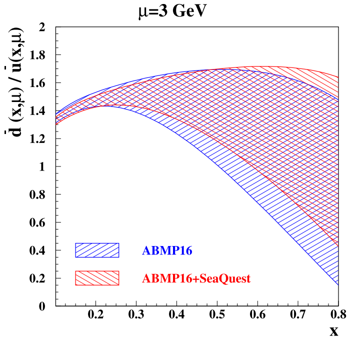
- CJ22

  PRD 107, 113005



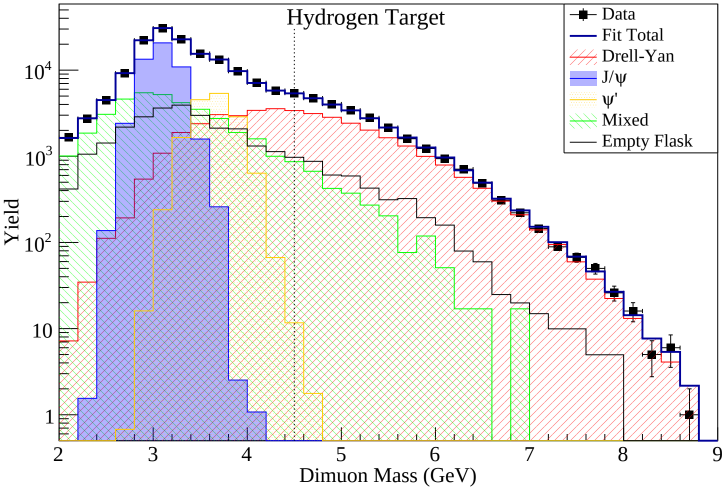
- ABMP16+SeaQuest

  arXiv:2306.01918



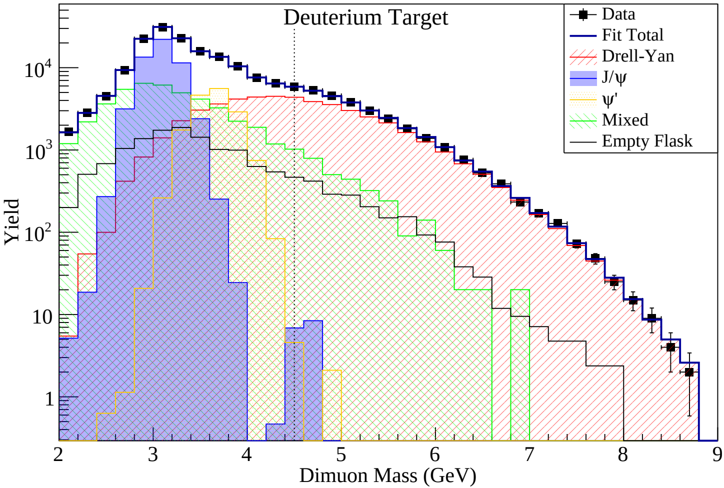
Mass Distribution — LH2

PRC 108, 035202



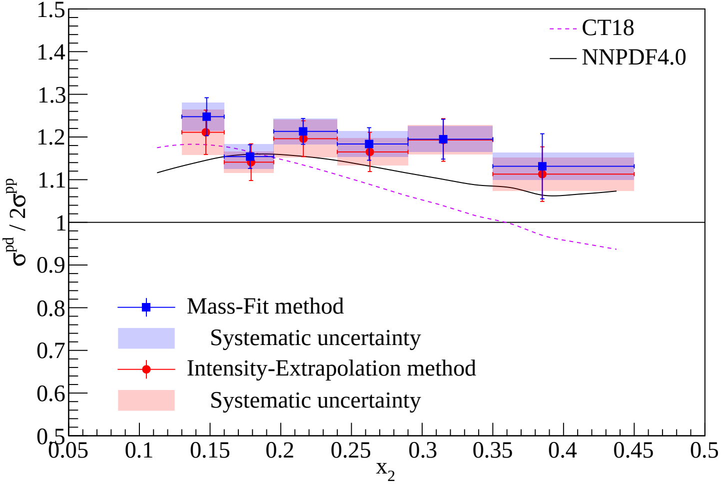
Mass Distribution — LD2

PRC 108, 035202



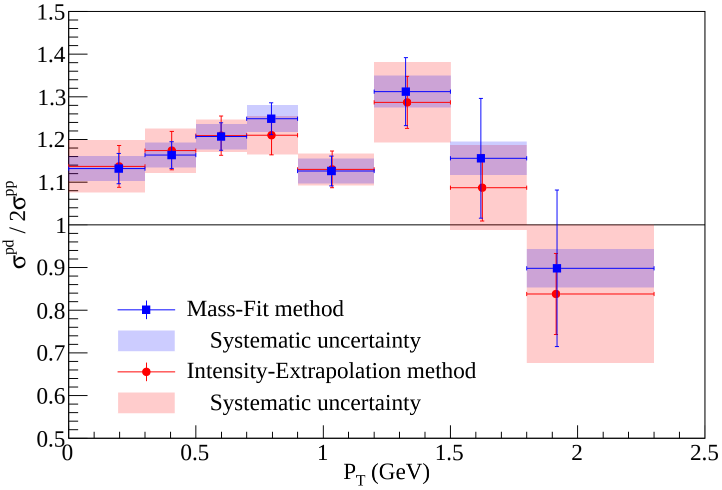
Cross-Section Ratio ($\sigma_{pd}/2\sigma_{pp}$) vs x_2

PRC 108, 035202



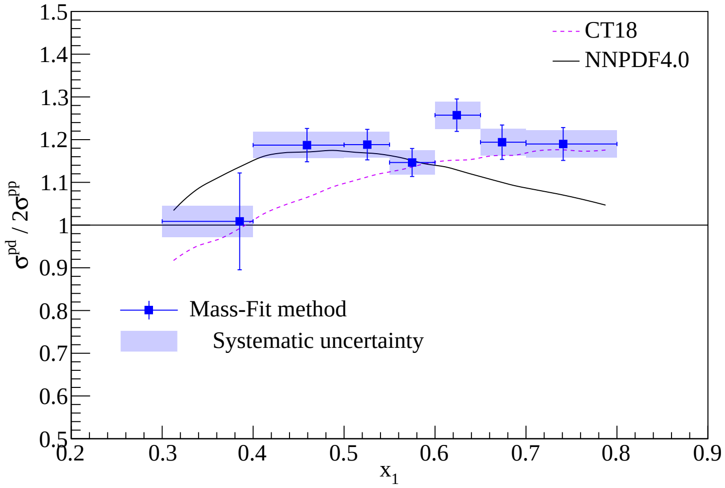
Cross-Section Ratio ($\sigma_{pd}/2\sigma_{pp}$) vs Dimuon p_T

PRC 108, 035202



Cross-Section Ratio ($\sigma_{pd}/2\sigma_{pp}$) vs x_1

PRC 108, 035202



Cross-Section Ratio ($\sigma_{pd}/2\sigma_{pp}$) vs x_F

PRC 108, 035202