MARATHON experiment

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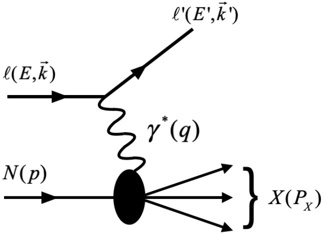
PVDIS workshop 2022

Outline

- Experiment overview
- Data analysis and cross section ratio results
- F_2^n/F_2^p results and d/u

MARATHON experiment

- Inclusive electron deep inelastic scattering on ^{3}He, ^{3}H, ^{2}H, ^{1}H



$$Q^2 = -q^2 = 4EE' sin^2(\frac{\theta}{2})$$
$$\nu = E - E'$$
$$x = \frac{Q^2}{2M\nu} \quad \textbf{(Bjorken x)}$$
$$W^2 = (q+p)^2 = M^2 + Q^2(\frac{1}{x} - 1)$$

- Physics observables: cross section ratios between different targets
- Determine the F_2^n/F_2^p over the range from x=0.195 to x=0.825
- Put constraints on d/u quark ratio at high x
- Measure the ^{3}He, ^{3}H EMC ratio

Cross Section and Structure functions

- Cross section for inelastic electron-nucleon scattering:

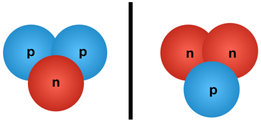
$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 (E')^2}{Q^4} cos^2(\frac{\theta}{2})[\frac{F_2(\nu, Q^2)}{\nu} + \frac{2F_1(\nu, Q^2)}{M} tan^2(\frac{\theta}{2})]$$

$$F_1 = \frac{F_2(1 + Q^2/\nu^2)}{2x(1 + R)} \quad \rightarrow \quad \boldsymbol{\sigma \propto F_2}$$

The measurements of $R = \sigma_L/\sigma_T$ show no A dependence at high Q^2 and R $\ll$ 1.

F_2^n/F_2^p from $\sigma(^3\mathrm{H})/\sigma(^3\mathrm{He})$

Perform inclusive DIS on mirror nuclei ^3H, ^3He



$$\frac{F_2^{^3H}}{F_2^{^3He}} = \frac{\sigma(^3H)}{\sigma(^3He)}$$

- ^3H and ^3He EMC type ratios:

$$R(^3He) = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \qquad R(^3H) = \frac{F_2^{^3H}}{F_2^p + 2F_2^n} \tag{1}$$

define the "super-ratio" of EMC ratios in ^3H and ^3He:

$$\mathcal{R} = \frac{R(^3He)}{R(^3H)} \tag{2}$$

- Free neutron to proton structure functions:

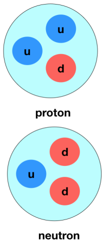
$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

- measure $F_2^{^3He}/F_2^{^3H}$
- $\mathcal{R}$ is determined by theory

F_2^n/F_2^p and d/u

Quark-Parton Model:

$$F_2^p(x) = x[(\frac{2}{3})^2(u^p + \overline{u}^p) + (-\frac{1}{3})^2(d^p + \overline{d}^p) + (-\frac{1}{3})^2(s^p + \overline{s}^p)]$$
$$F_2^n(x) = x[(\frac{2}{3})^2(u^n + \overline{u}^n) + (-\frac{1}{3})^2(d^n + \overline{d}^n) + (-\frac{1}{3})^2(s^n + \overline{s}^n)]$$



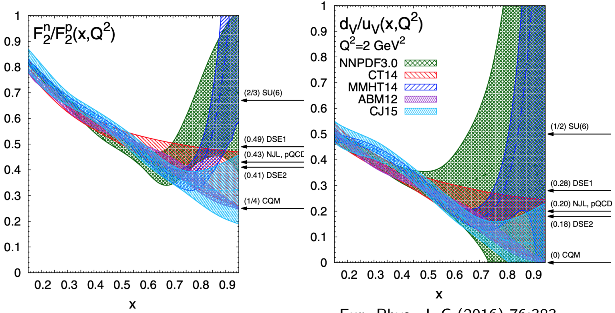
Assume isospin symmetry and neglect sea quark distributions:

$$u^p(x) = d^n(x) \equiv u(x) \qquad d^p(x) = u^n(x) \equiv d(x)$$

$$\frac{F_2^n}{F_2^p} = \frac{1 + 4\boldsymbol{d/u}}{4 + \boldsymbol{d/u}}$$

F_2^n/F_2^p is one of the best methods to determine the d/u ratio.

Large x issue



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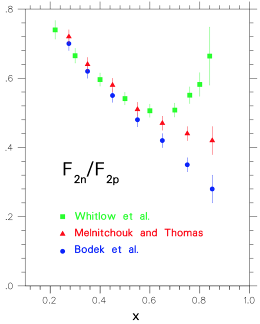
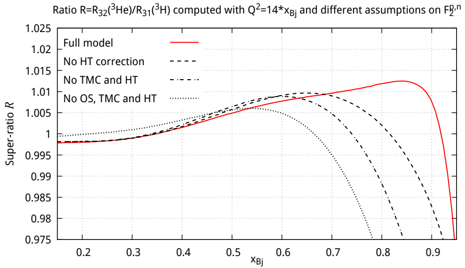


F_2^n/F_2^p extracted from SLAC d/p DIS data using different nuclear corrections

- Since there is no free neutron target, inclusive DIS on the deuteron has been used to extract F_2^n for decades
- However, the nuclear corrections inside deuteron are model dependent.

Super-ratio $\mathcal{R}$

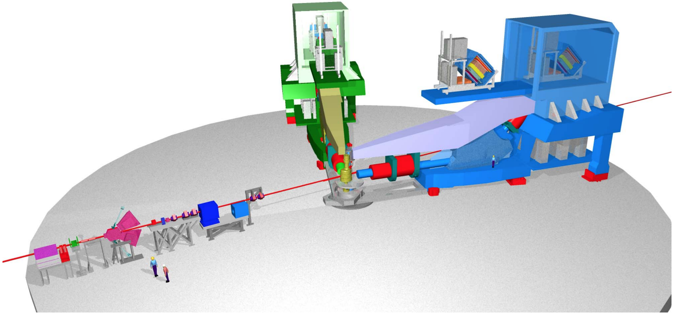
- ^3H and ^3He are mirror nuclei. The nuclear corrections should be similar.
- $\mathcal{R}$ has been calculated in theory to deviate from 1 up about 1% by taking into account all possible effects

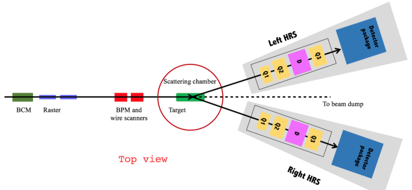


Super-ratio $\mathcal{R}$ calculated by S. Kulagin and R. Petti

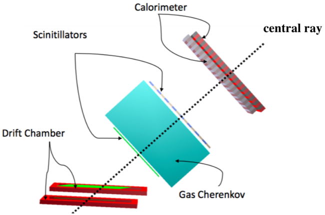
- An iterative procedure could eliminate the nucleon structure function dependence in the F_2^n/F_2^p extraction.

Hall A High Resolution Spectrometers (HRS)



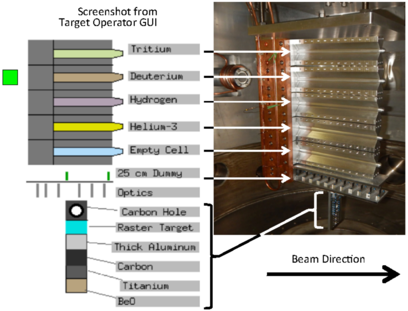


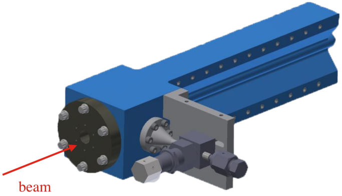
HRS top view



Detector package

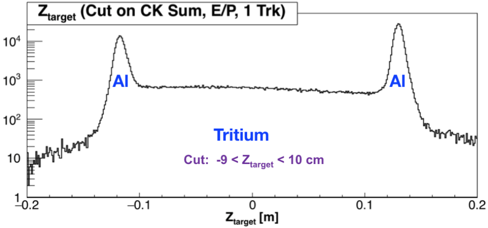
Targets





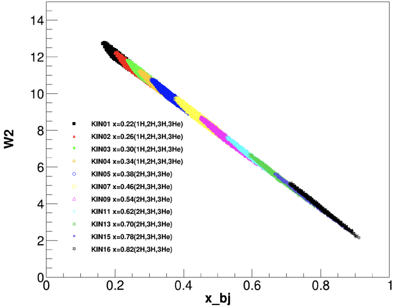
Tritium target

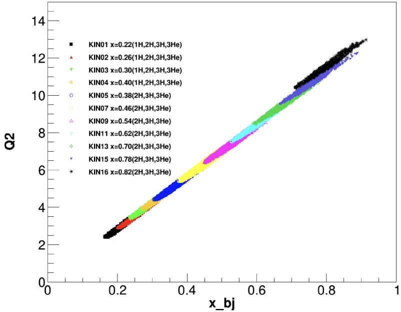
- Low activity ($\sim$ 1k Ci)
- Sealed cell
- 40K gas
- Beam current $\leq 22.5\ uA$



MARATHON Kinematics

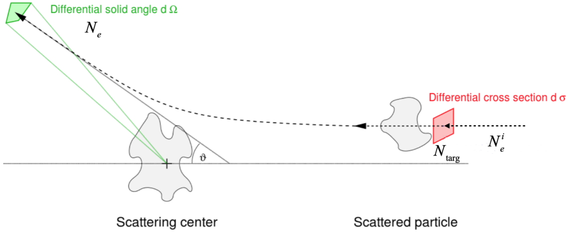
- Experiment ran on January-April 2018;
- Beam energy 10.6 GeV;
- Average current $\sim$ 20 uA
- Scattering angle: 17 $^\circ$ - 36 $^\circ$
- Cover the Bjorken x range $0.19 < x < 0.83$ ($W^2 > 3GeV^2$)
- Took DIS data on ^3H, ^3He, ^2D, ^1H





Cross section ratio extraction

- Cross section:
$$\frac{d\sigma}{d\Omega dE'} \approx \frac{Yield}{\Delta E' \Delta\Omega}$$
- When bin different σ_A in same bins, the ratio of the cross sections is equal to the ratio of yields: $\sigma_{A1}/\sigma_{A2} = Yield_{A1}/Yield_{A2}$
- Data yield:
$$Yield = \frac{N_e}{N_e^i \cdot N_{targ}}$$



N_e: number of scattered electrons detected;
N_{targ}: number of target particles;
N_e^i: number of incident electrons;

Yield and yield ratio

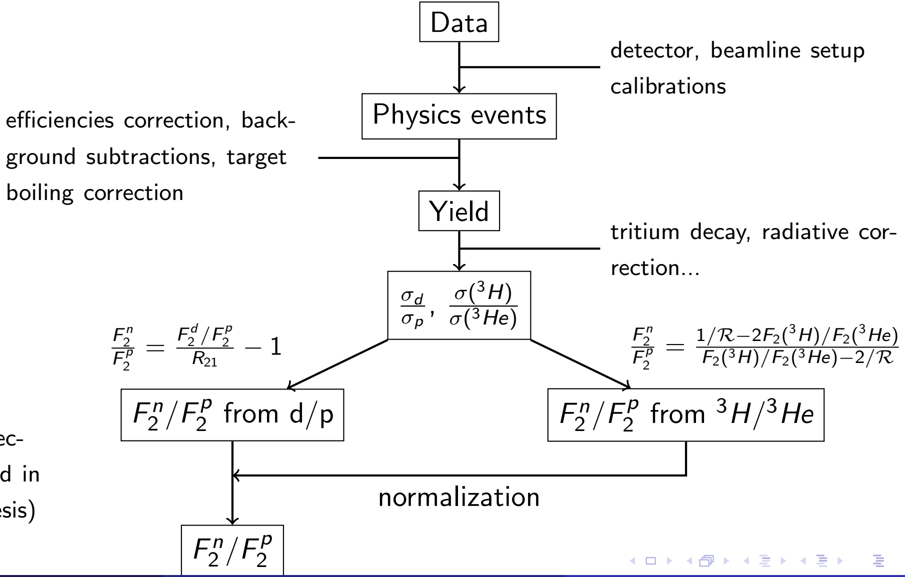
$$Yield = \frac{N_e}{N_e^i \cdot N_{targg}}$$

- $N_e = (N_e^{raw} - N_{e^+} - N_{EC}) \cdot C_{eff} \cdot C_{DT} \cdot ACC(E', \theta)$
  - N_{e^+}: charge symmetric background;
  - N_{EC}: target end cap background;
  - C_{eff}: the efficiencies of detectors;
  - C_{DT}: DAQ deadtime correction;
  - $ACC(E', \theta)$: the spectrometer acceptance function;
  - C_{eff}, $ACC(E', \theta)$ are canceled in the yield ratio
- $N_{targ} \propto \frac{\tau}{m_A}$

  target thickness τ changes when beam is on $\rightarrow$ target boiling correction

- $N_e^i = I \cdot t$

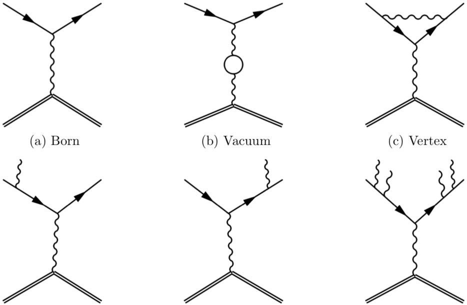
Analysis procedure



(Absolute cross sections can be found in Jason Bane's Thesis)

Radiative correction

- The yield extracted from data does not correspond to the born process
- There are higher order QED processes:
  - External radiations: when electrons pass through materials, they lose energy due to ionization and bremsstrahlung
  - Internal radiations: during scattering, higher order Feynman diagrams contribute



(a) Born (b) Vacuum (c) Vertex

(d) Bremsstrahlung (e) Bremsstrahlung (f) Soft photon emission

Radiative correction

$$\sigma_{rad}(E_s, E_p) = \int_0^T \frac{dt}{T} \int_{E_{s\,min(E_p)}}^{E_s} dE'_s \int_{E_p}^{E_p\,max(E'_s)} dE'_p I(E_s, E'_s, t)\sigma_r(E'_s, E'_p) I(E'_p, E_p, T-t)$$

(Mo. & Tsai method, SLAC-PUB-848 (1971).)

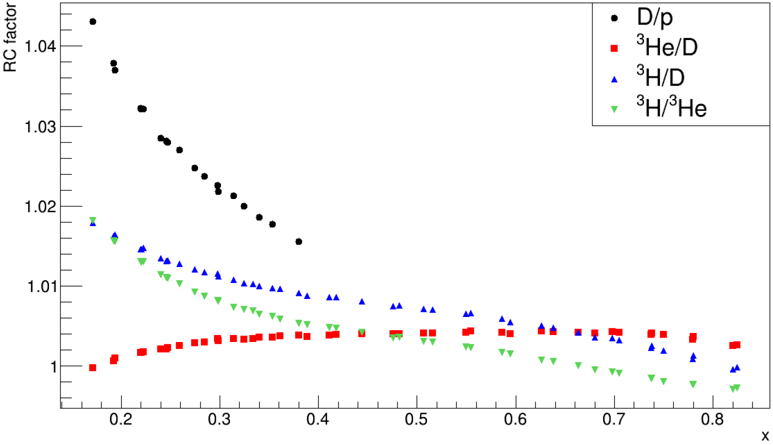
- $I(E, E', t)$: the probability of energy loss due to the external radiation.
- T: total path length before and after scattering.
- $\sigma_r = \sigma_r^{DIS} + \sigma_r^{quasi-elastic} + \sigma_r^{elastic} \Leftarrow$ require a cross section input

$$\Rightarrow \quad RC = \frac{\sigma_{born}^{model}}{\sigma_{rad}^{model}} \quad \Rightarrow \quad \sigma_{born}^{data} = \sigma_{rad}^{data} \cdot RC$$

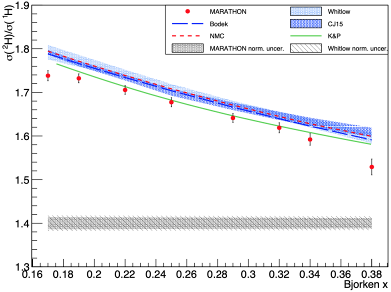
- For ^3H and ^3He born cross section model, we use F_2^d from Bodek *et al.* [1] and the EMC model ($F_2(^3He)/F_2^d$) from S. Kulagin and R. Petti (KP) [2]
- RC error is the deviation caused by using different cross section models

[1] Phys. Rev. D20, 1471 (1979)
[2] Nucl Phys A765 (2006) 126

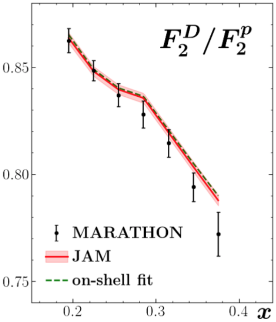
Radiative correction



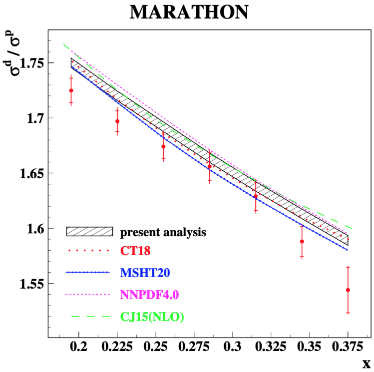
σ^d/σ^p from MARATHON



Hanjie Liu's thesis (2020)
normalization: 0.79%



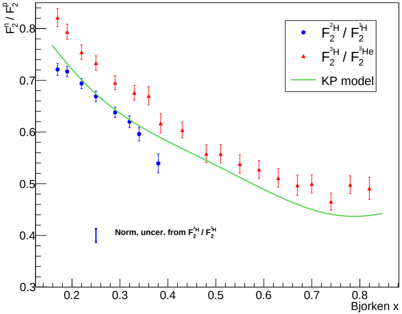
JAM (Phys. Rew. L 127, 242001 (2021))
Fitted normalization: 1.9%



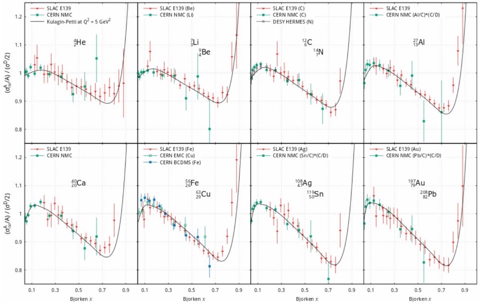
AKP (arXiv:2203.07333 (2022))
Fitted normalization: 1.4%

F_2^n/F_2^p extraction - Experimental method

- $R(d) = \frac{F_2^d}{F_2^n + F_2 p}$ from K&P model is used to extract F_2^n/F_2^p from σ^d/σ^p
- Super-ratio $\mathcal{R}_{ht}$ from K&P model is used to extract F_2^n/F_2^p from $\sigma(^3He)/\sigma(^3H)$



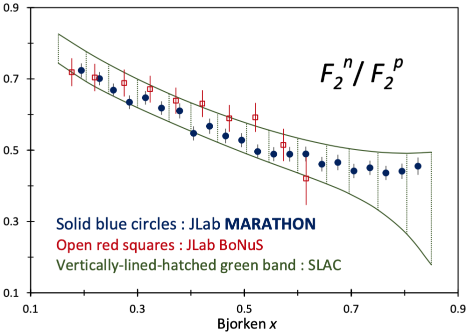
Compilation of EMC Effect Data by S. Kulagin and R. Petti
SLAC E139-CERN



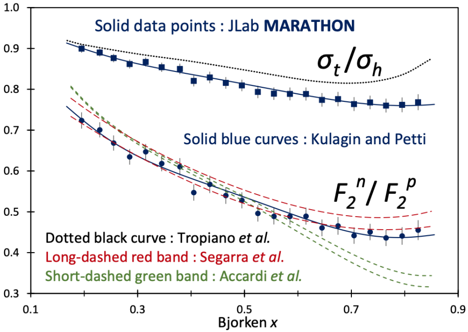
Nuclear effects are minimal around $x = 0.3$

F_2^n/F_2^p Result - Experimental method

- In order to match the F_2^n/F_2^p extracted from σ_h/σ_t to that from σ_d/σ_p at $x = 0.31$, σ_h/σ_t ratio at x $= 0.31$ had to be normalized by a multiplicative factor of 1.025 ± 0.007



Phys. Rew. L 128, 132003 (2022)

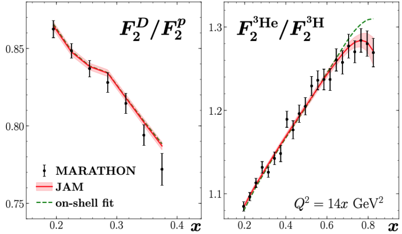


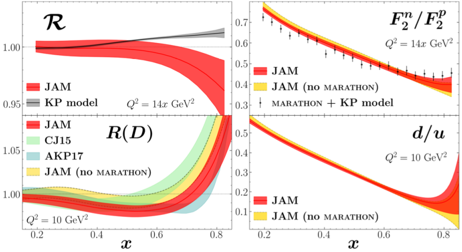
no need for iteration

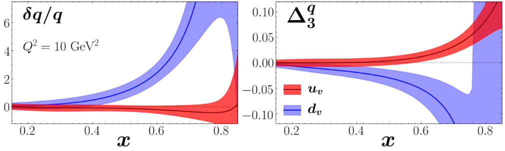
F_2^n/F_2^p and d/u Result - Global fitting

Global fitting with MARATHON data (based on JAM) Phys. Rew. L 127, 242001 (2021)

- Off-shell effect is implemented at PDFs level and isospin dependent
- Off-shell effect is different for different nuclei
- The 1.025 normalization on σ_h/σ_t is removed

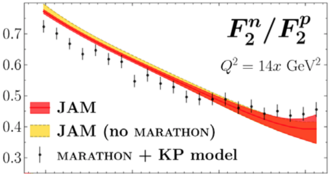


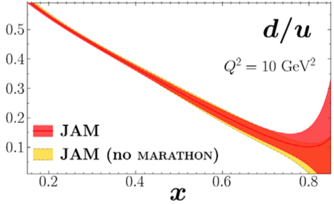




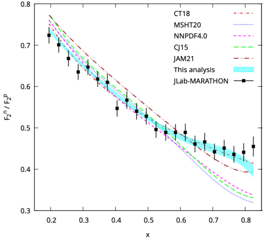
Discussions on F_2^n/F_2^p and d/u Result

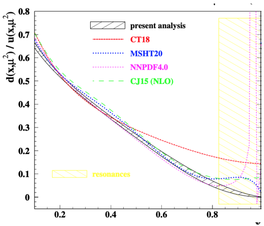
- **JAM: MARATHON data included in the fitting** (Phys. Rew. L 127, 242001 (2021))





- **AKP: MARATHON data not included in the fitting** (arXiv:2203.07333 (2022))





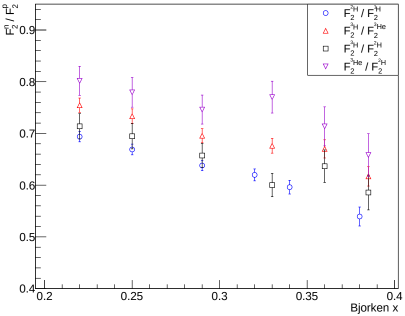
Summary

- The MARATHON σ_d/σ_p measurements agree with the model but slightly lower
- $R(d)$ and $\mathcal{R}_{ht}$ from Kulagin and Petti model are used in the F_2^n/F_2^P extraction
- $^3H/^3He$ data is scaled down by 2.5%
- The extracted F_2^n/F_2^p agrees well with the KP model
- Combining the information from JAM and AKP global analysis, MARATHON data gives more insight on nuclear effects than constraining the PDFs.
- The EMC ratio of ^3H and ^3He will be published in a separate paper

backup

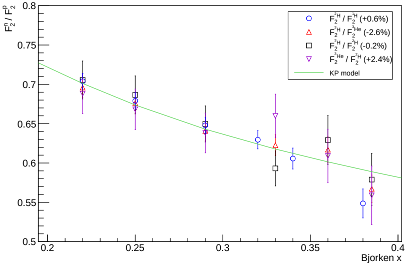
Normalization

- The EMC ratios for different nuclei all cross 1 around $x = 0.3$
  $\rightarrow$ the nuclear effects are about 0 around $x = 0.3$
  $\rightarrow$ F_2^n/F_2^p extracted from different nuclei should be same around $x = 0.3$
- Extract F_2^n/F_2^p from $\sigma(^3H)/\sigma_d$ and $\sigma(^3He)/\sigma_d$ at $x = 0.3$



Normalization

- The EMC ratios for different nuclei all cross 1 around $x = 0.3$
  $\rightarrow$ the nuclear effects are about 0 at $x = 0.3$
  $\rightarrow$ F_2^n/F_2^p extracted from different nuclei should be same around $x = 0.3$
- Extract F_2^n/F_2^p from $\sigma(^3H)/\sigma_d$ and $\sigma(^3He)/\sigma_d$ at $x = 0.3$



Ratio	Normalization
$F_2^{^2H}/F_2^{^1H}$	+0.6%
$F_2^{^3H}/F_2^{^2H}$	-0.2%
$F_2^{^3He}/F_2^{^2H}$	+2.4%
$F_2^{^3H}/F_2^{^3He}$	-2.6%

- $F_2^{^3He}$ needs to be normalized by 2.4%

(This is from my thesis. They're not exactly the same as the published paper. Please use the published number.)