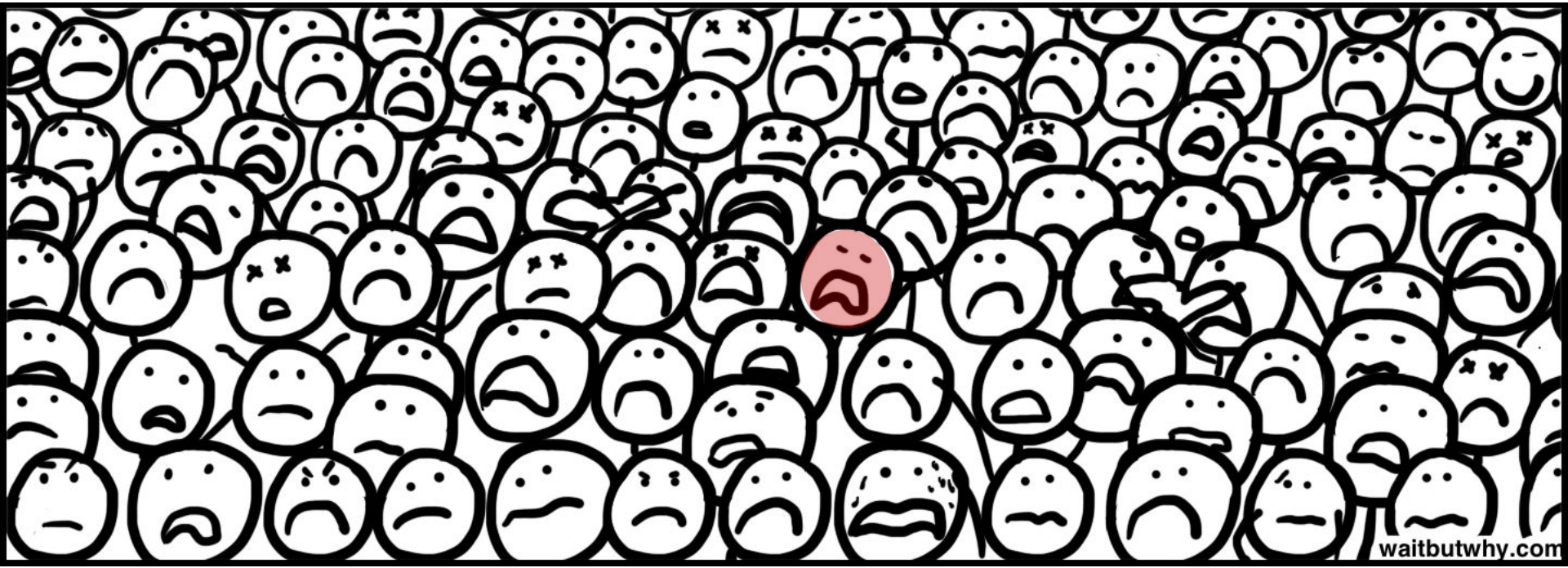
The SeaQuest Experiment

Michelle M. Medeiros

for the SeaQuest Collaboration

49th Fermilab Users Meeting - Jun. 15, 2016

Argonne NATIONAL LABORATORY


waitbutwhy.com

What is the **QUEST** for?

Nucleons → valence quarks + gluons + **sea quarks** } PARTONS

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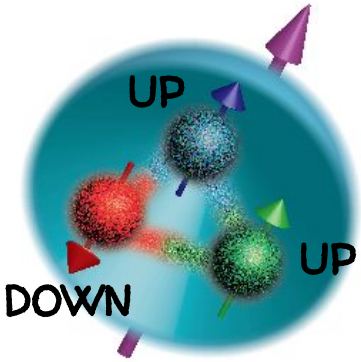

proton

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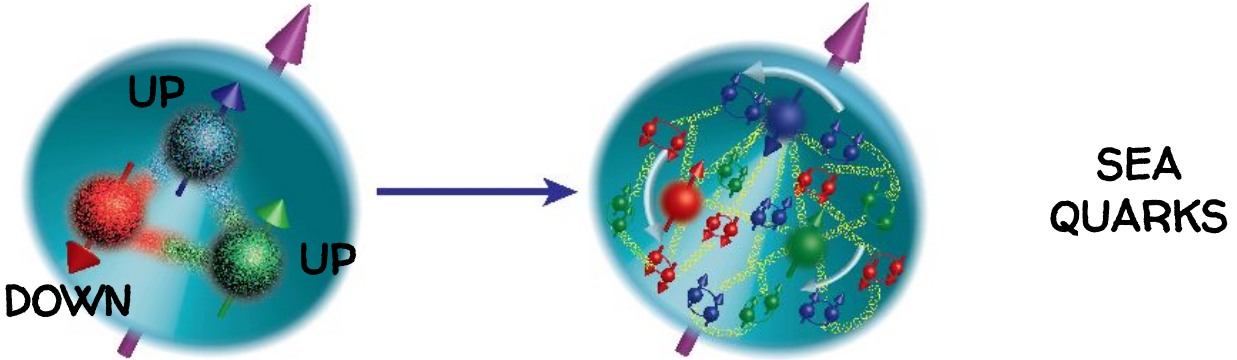
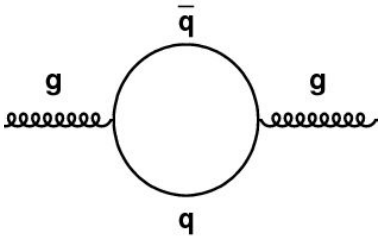


proton



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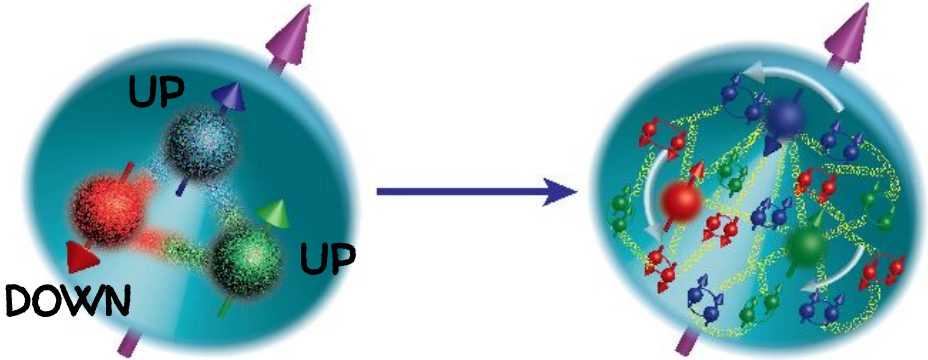

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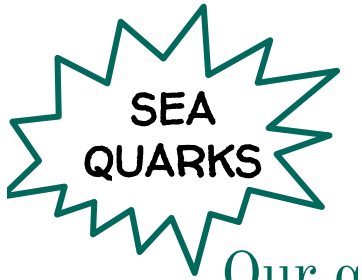
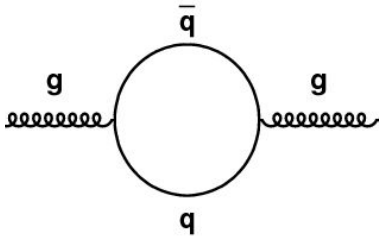


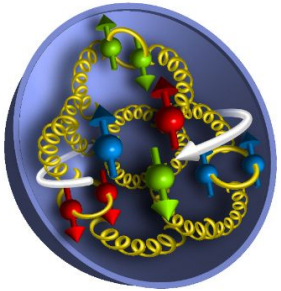
Our quest!

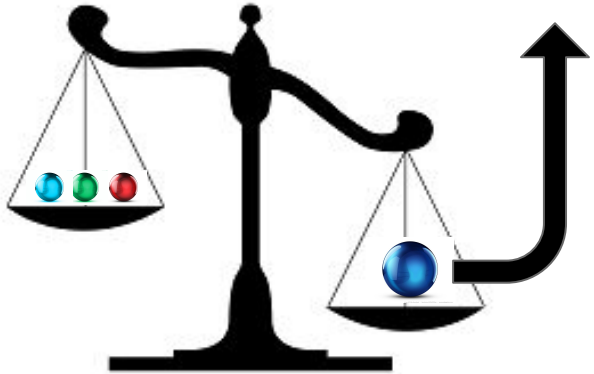


The Nucleon Structure

Up quark: 2.3 MeV/c^2 x 2
Down quark: 4.8 MeV/c^2

9.4 MeV/c^2



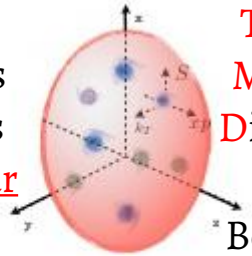


938 MeV/c^2

The Nucleon Structure

What contributes to the spin?

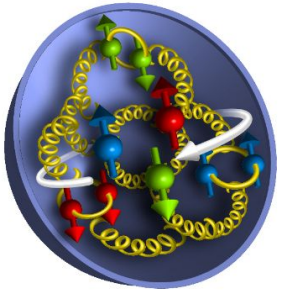
- spin of quarks
- spin of gluons
- orbital angular momentum



$\int \mathrm{TMDs}(x,k_T) \ldots dk_T$

Transverse Momentum Distributions

Boer-Mulders & Sivers



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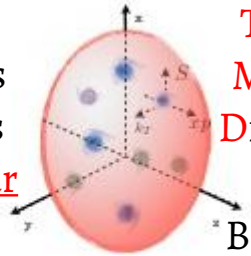

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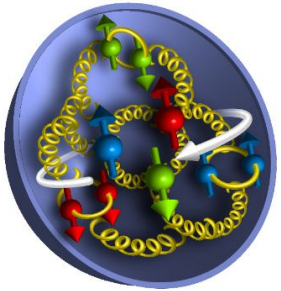
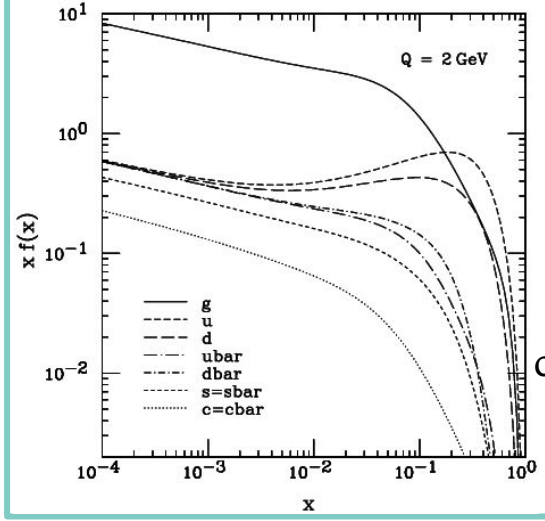


What are nucleons composed of?



Structure functions

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fraction of hadron momentum carried by each quark:

x

The Nucleon Structure

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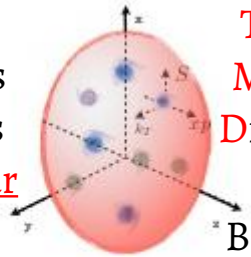

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Transverse Momentum Distributions

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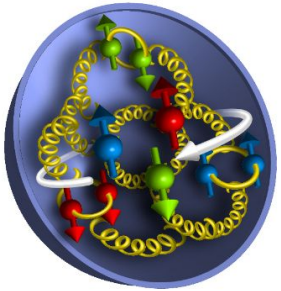

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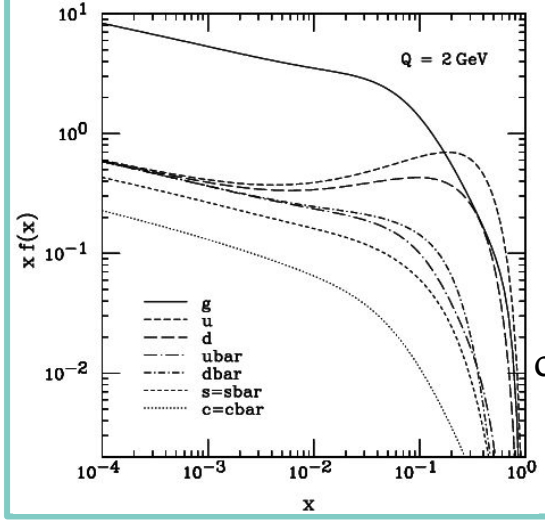

Structure functions

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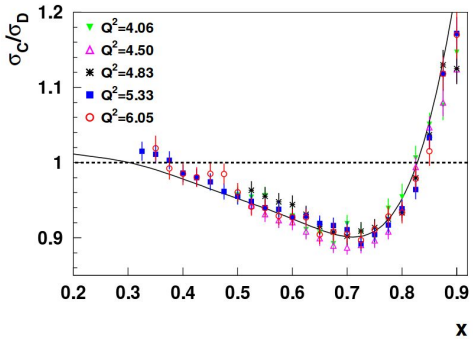
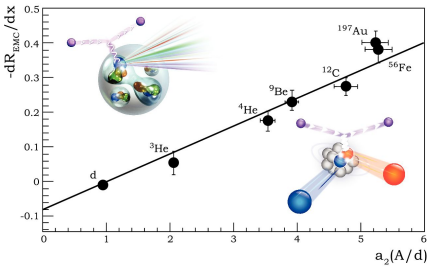
Partons in bounded nucleon *vs.* free nucleon



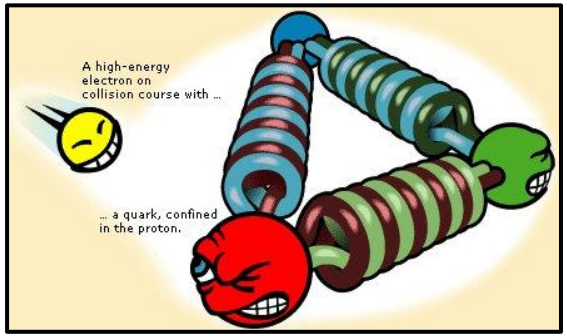
EMC effect

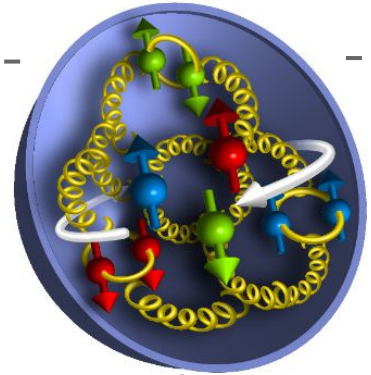
- nuclear dependence of the structure function
- nuclear dependence of the EMC effect
- "Everyone's Model is Cool"

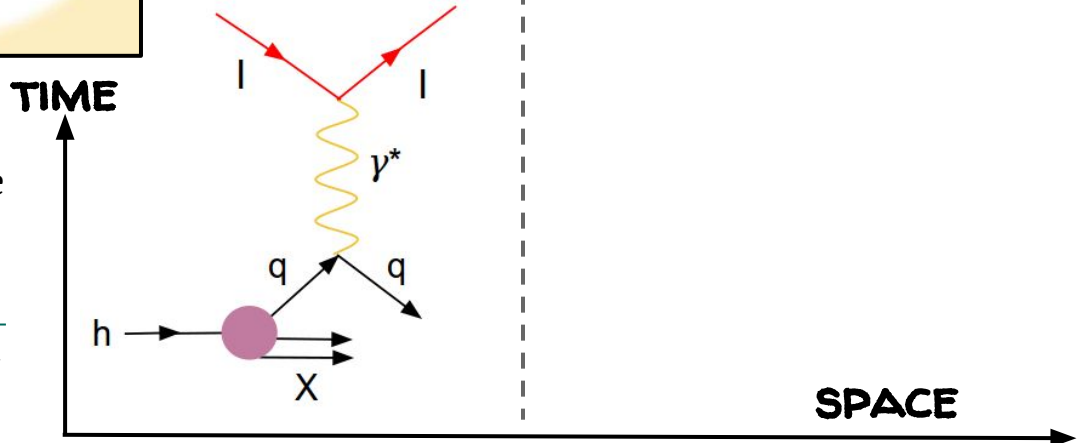


Probing the Nucleon Sea

Deep Inelastic Scattering (DIS)







- Strong final state interactions
- Does not distinguish q & $\overline{q}$

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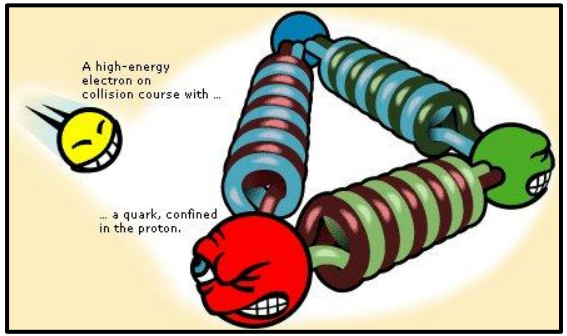

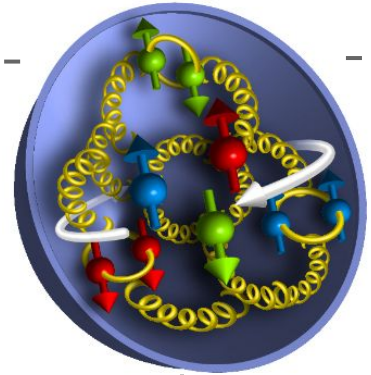

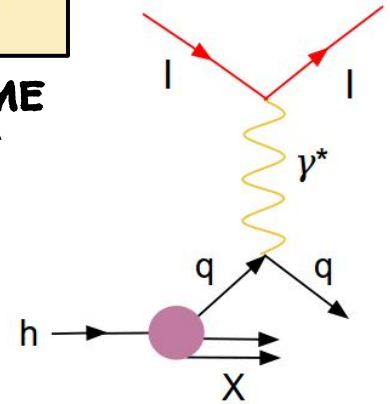

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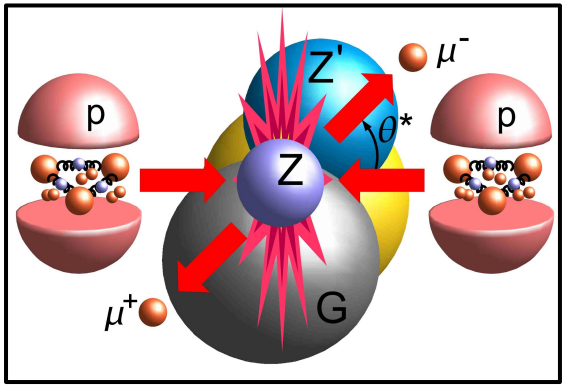
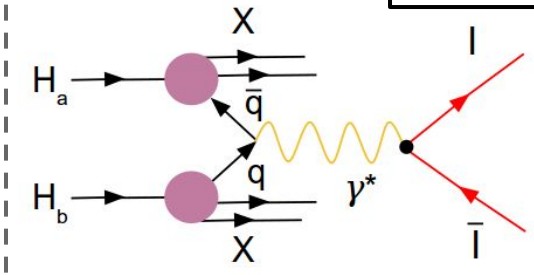
Drell-Yan Process (DY)





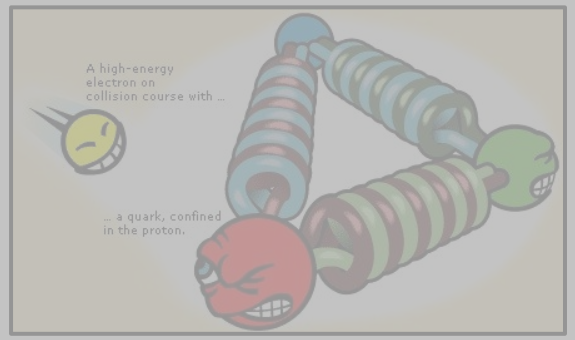
- Sensitivity to $\bar{q}$
- Pair of lepton-antilepton as final state

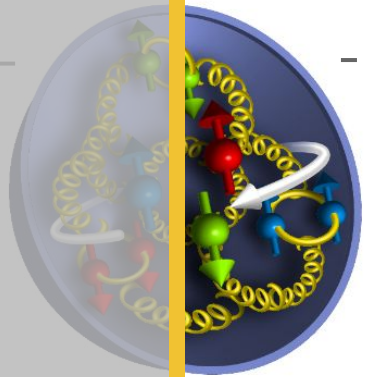
TIME

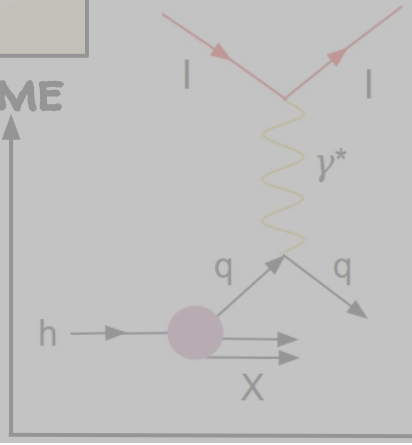
SPACE

Probing the Nucleon Sea

Deep Inelastic Scattering (DIS)







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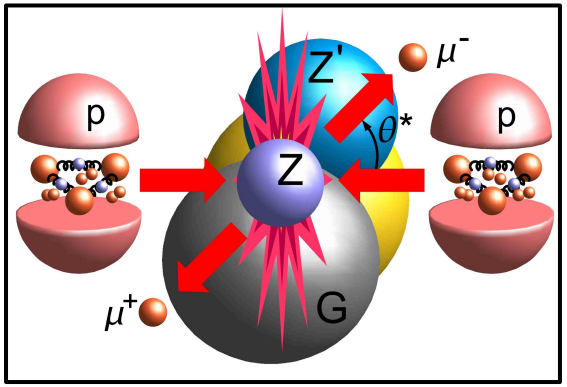

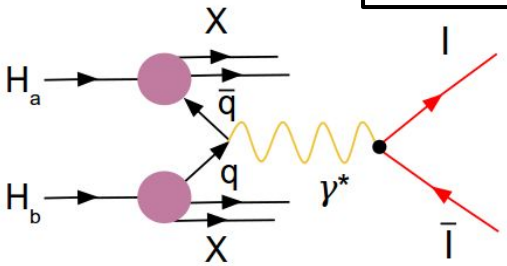

- Sensitivity to $\overline{q}$
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Drell-Yan Process

Cross-section:

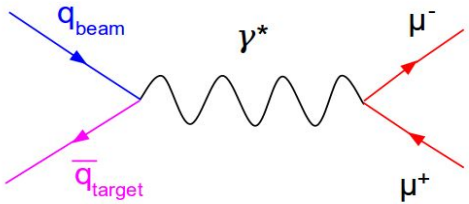
$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_t(x_t)q_b(x_b) + \bar{q}_b(x_b)q_t(x_t)\right]$$

Can extract relative number of $\bar{\mathbf{d}}$ and $\bar{\mathbf{u}}$ in the sea by comparing cross-sections of proton beam with hydrogen (pp) and deuterium (pd).

$$\left.\frac{\sigma_{pd}}{2\sigma_{pp}}\right|_{x_{beam}>>x_{target}} \approx \frac{1}{2}\left[1 + \frac{\bar{d}_{target}}{\bar{u}_{target}}\right]$$

- Deuterium → free proton + free neutron.
- Proton and neutron → isospin particles:

$$\sigma_{pd} \approx \sigma_{pn} + \sigma_{pp}$$



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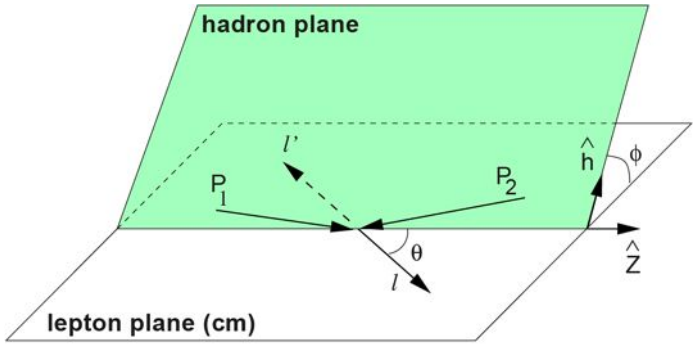
Angular distribution:



$$\frac{d\sigma}{d\Omega} \propto 1 + \gamma\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

Does the pair l^+l^- has angular preference?

If YES.....

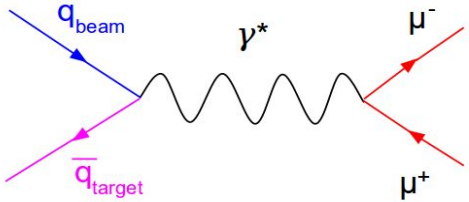
Able to deduce:

→ OAM of quarks inside the proton with polarized target:

Sivers Function

→ polarization of non-collinear partons inside the proton:

Boer-Mulders Function



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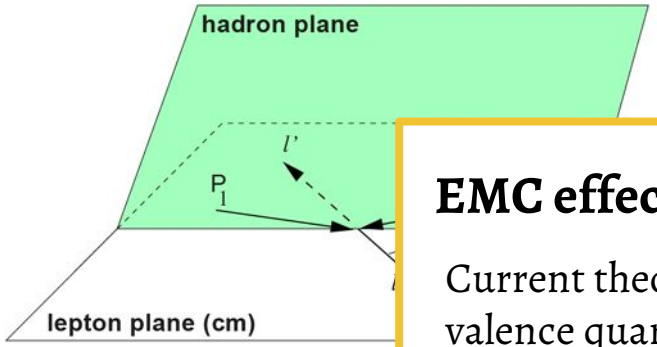

$$\frac{d\sigma}{d\Omega} \propto 1 + \gamma\cos^2\theta + \mu\sin 2\theta\, c$$

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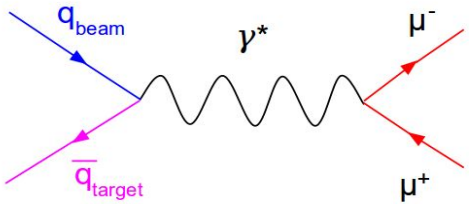

EMC effect:

Current theories attribute it to high-momentum valence quarks (2N-SRC)

Drell-Yan with different nuclei targets **should not** see an effect.

Drell-Yan Process

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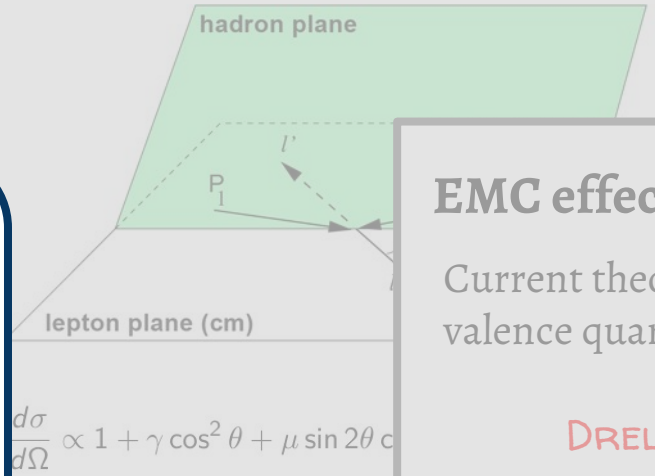

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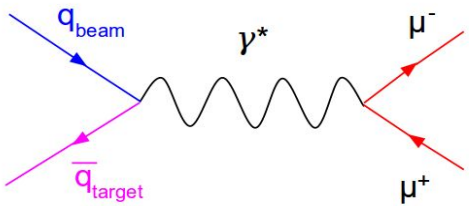
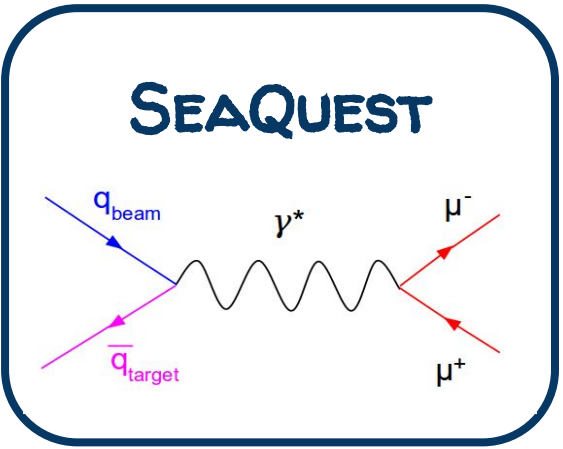
SeaQuest



Measurements in SeaQuest

- Cross-section in different nuclei targets
- Dimuon angular distribution → Boer-Mulders
- EMC effect in different nuclei targets

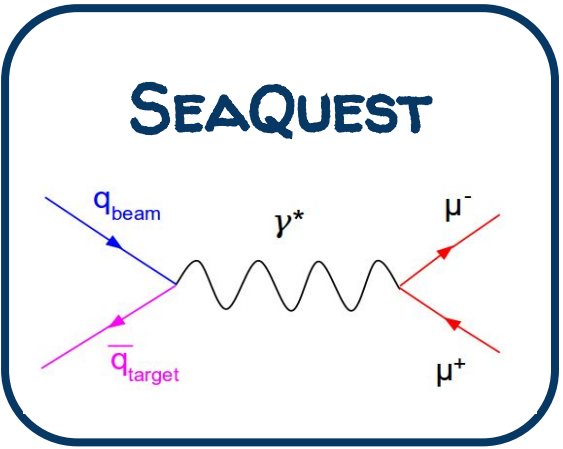


$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t}\frac{1}{s}$$

$$\sum_q e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + \cancel{\bar{q}_b(x_b) q_t(x_t)} \right] \sim 0$$

Measurements in SeaQuest

- Cross-section in different nuclei targets
- Dimuon angular distribution → Boer-Mulders
- EMC effect in different nuclei targets
- Fast colored parton interactions in cold nuclear matter
- Dark photon search



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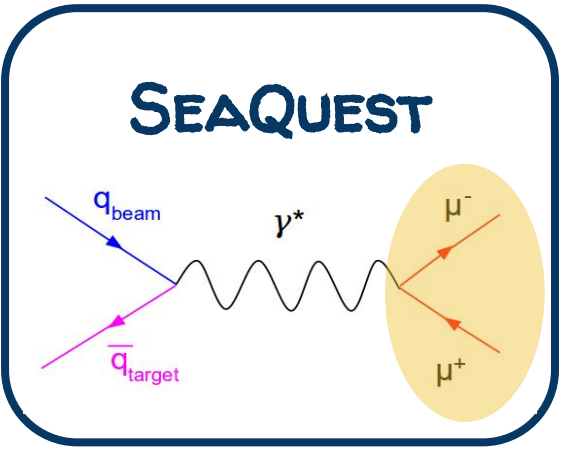
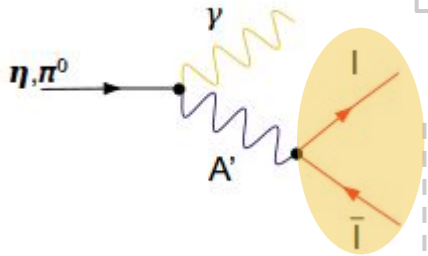
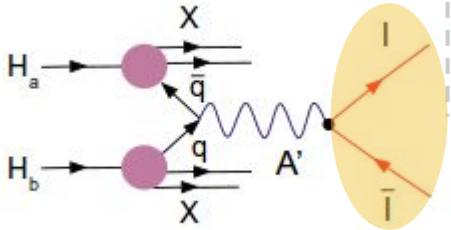
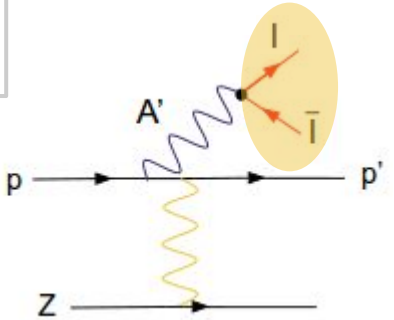




Eta decay



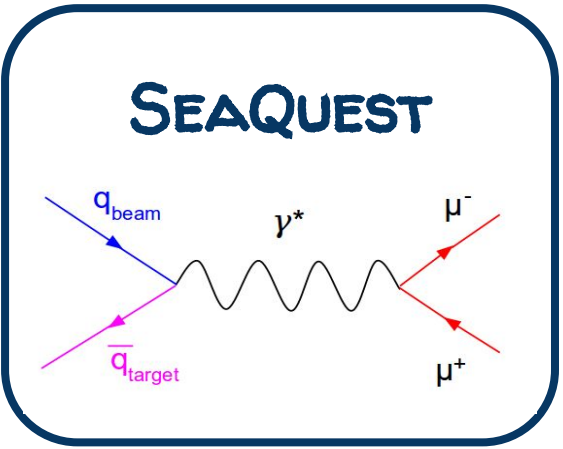
Dark Drell-Yan



Proton Bremstrahlung

Measurements in SeaQuest

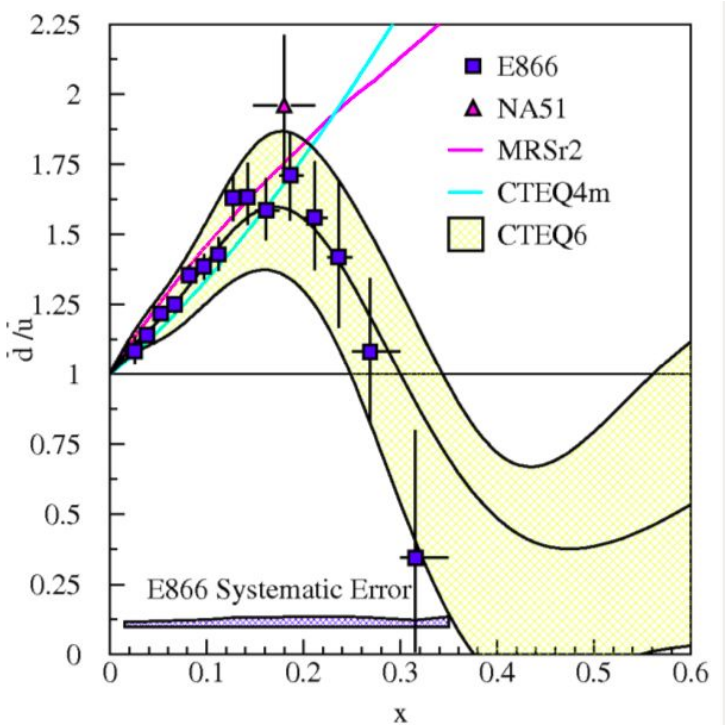
- Cross-section in different nuclei targets
- Dimuon angular distribution → Boer-Mulders
- EMC effect in different nuclei targets
- Fast colored parton interactions in cold nuclear matter
- Dark photon search
- Flavor asymmetry in the sea



$$\bar{d} \neq \bar{u}$$

Non-perturbative effect

Previous Flavor Asymmetry Results



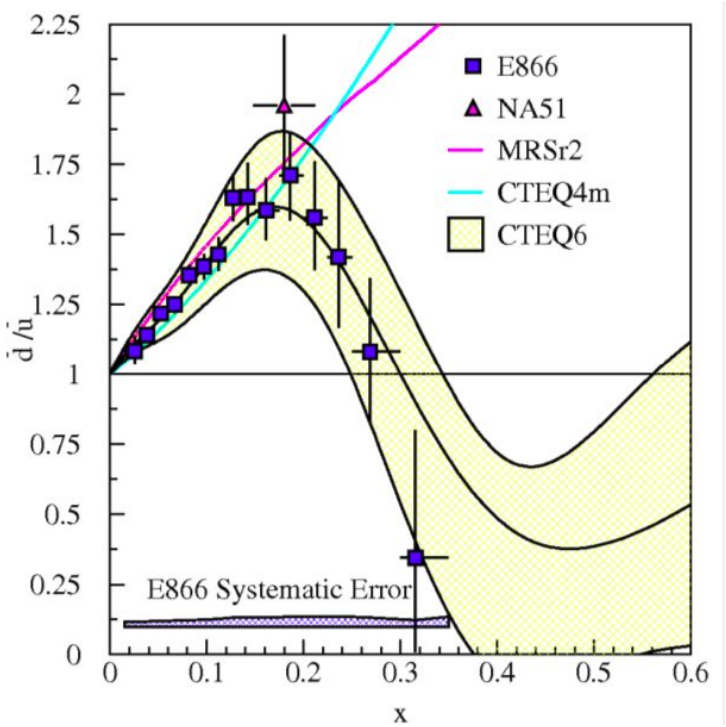
Possible Explanations...

Pauli blocking:

u > d in the proton

⬇

more $\bar{d}$ in the sea



Possible Explanations...

Pauli blocking:

u > d in the proton

more $\bar{d}$ in the sea

Instanton model:

$u\uparrow + I \rightarrow u\downarrow + d\bar{d}(s\bar{s})$

Possible Explanations...

Pauli blocking:

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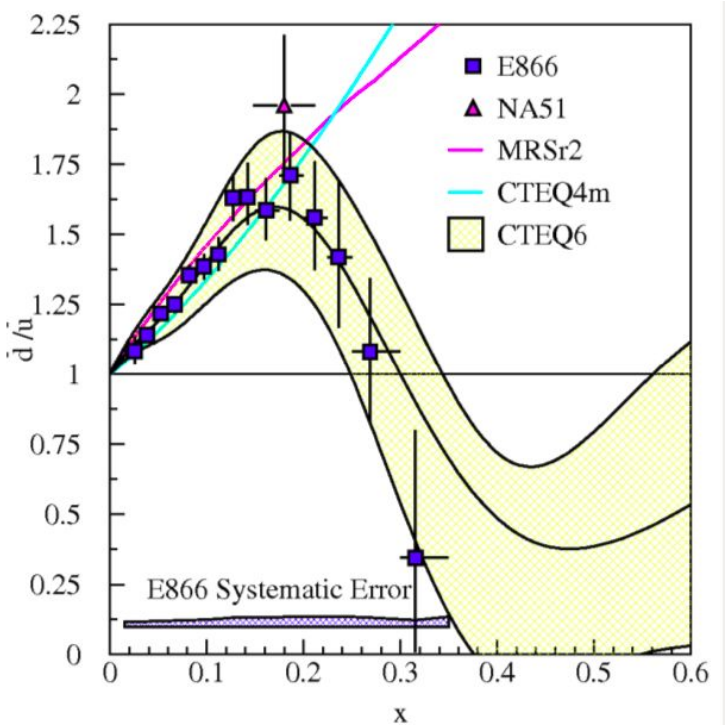

Instanton model:

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Chiral quark model:

Goldstone bosons ⟷ Valence quarks

Possible Explanations...

Pauli blocking:

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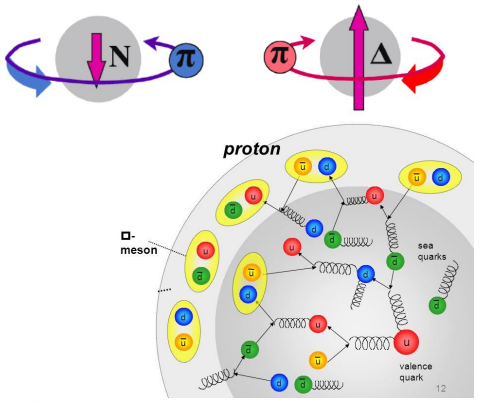
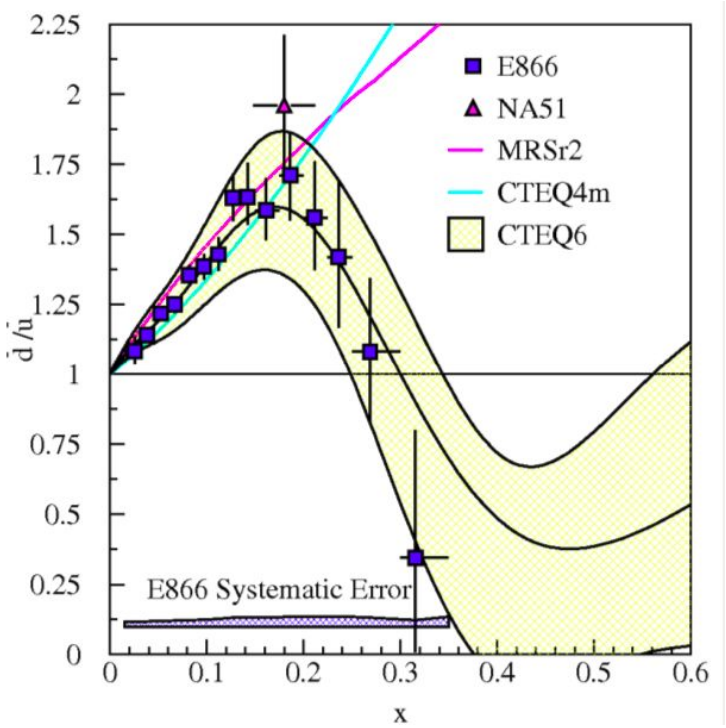
⬇

more $\bar{d}$ in the sea

Meson cloud:





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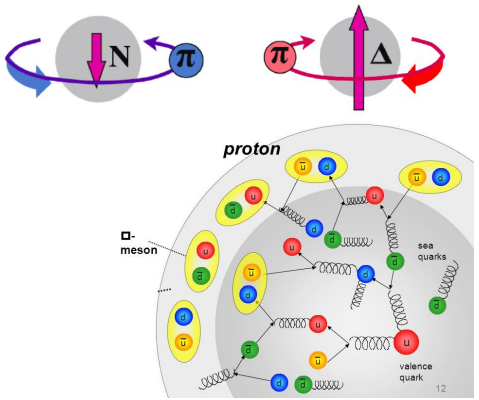
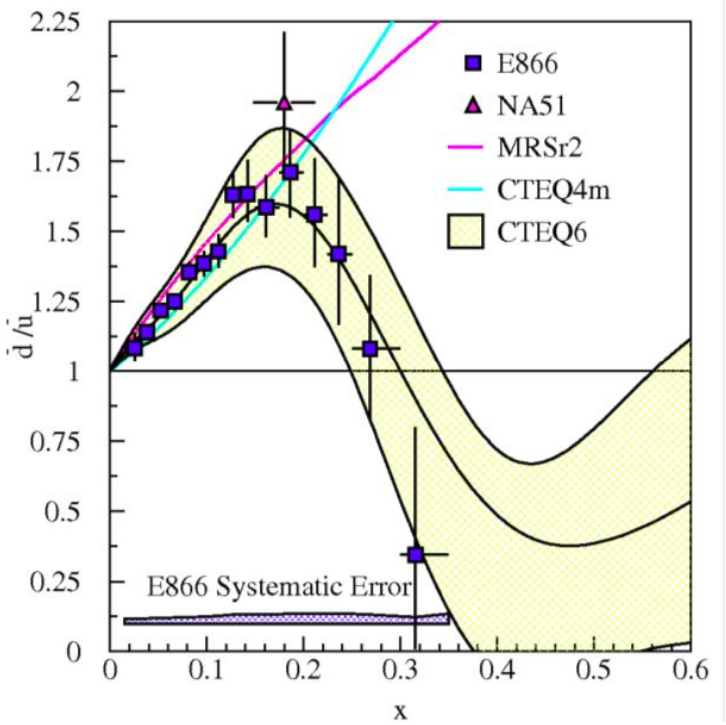




Instanton model:

$u\uparrow + I \rightarrow u\downarrow + d\bar{d}\,(s\bar{s})$

Hybrid model:

Non-perturbative + perturbative

Chiral quark model:

Goldstone bosons ⟷ Valence quarks

Possible Explanations...

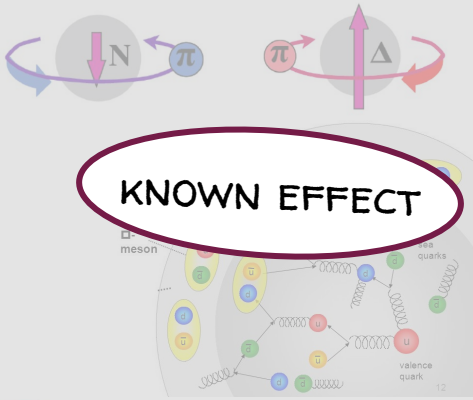
Pauli blocking:

$u > d$

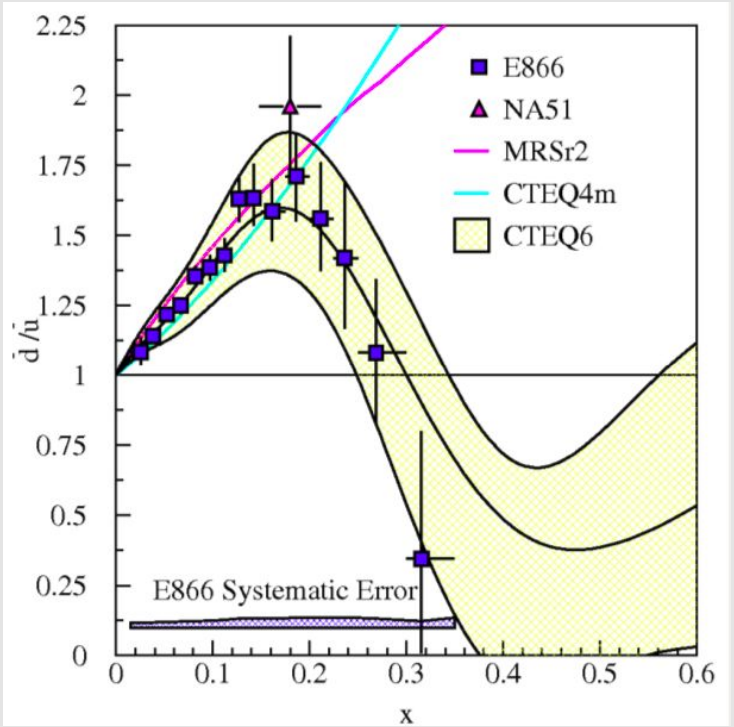
more $\bar{d}$ in the sea

SMALL EFFECT

Meson cloud:



KNOWN EFFECT



Instanton model:

$u\uparrow + \bar{u}\downarrow$

RATIO → 4, HIGH X

H

DOES NOT ACCOUNT FOR HIGH X RESULTS

Ch… quark model:

Goldst… …ce bosons … quarks

RATIO < 1.58, ANY X

Possible Explanations...

No model predicted $\bar{d}/\bar{u} < 1$, for any x.

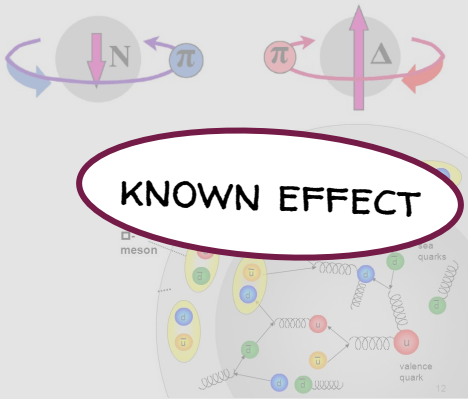
Pauli blocking:

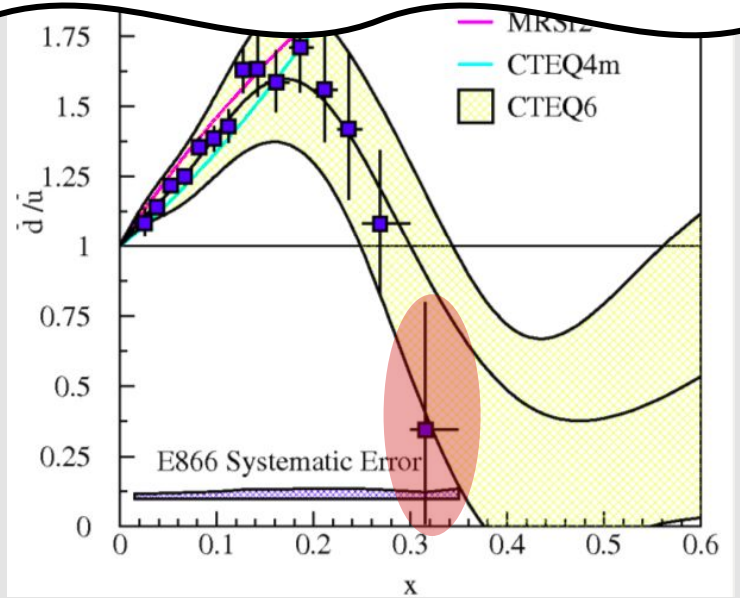
$u > d$

SMALL EFFECT

more $\bar{d}$ in the sea

Meson cloud:





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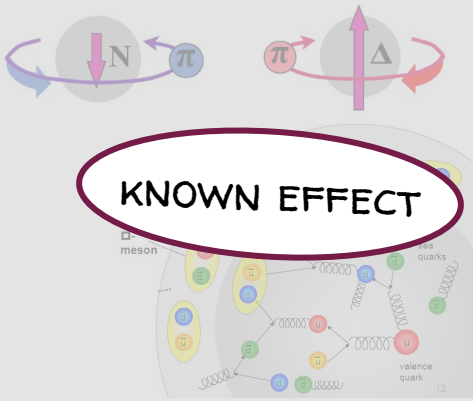
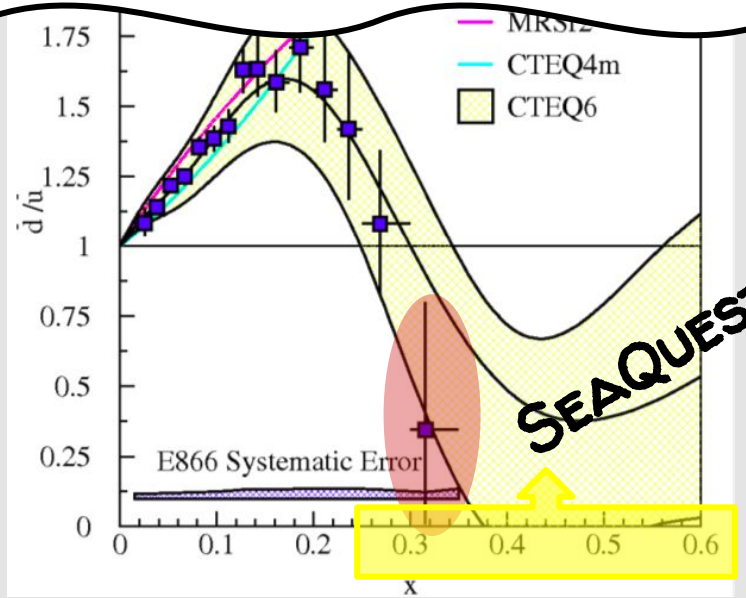


KNOWN EFFECT



Instanton model:

$u\uparrow + \bar{u}\downarrow$

RATIO → 4, HIGH X

H...

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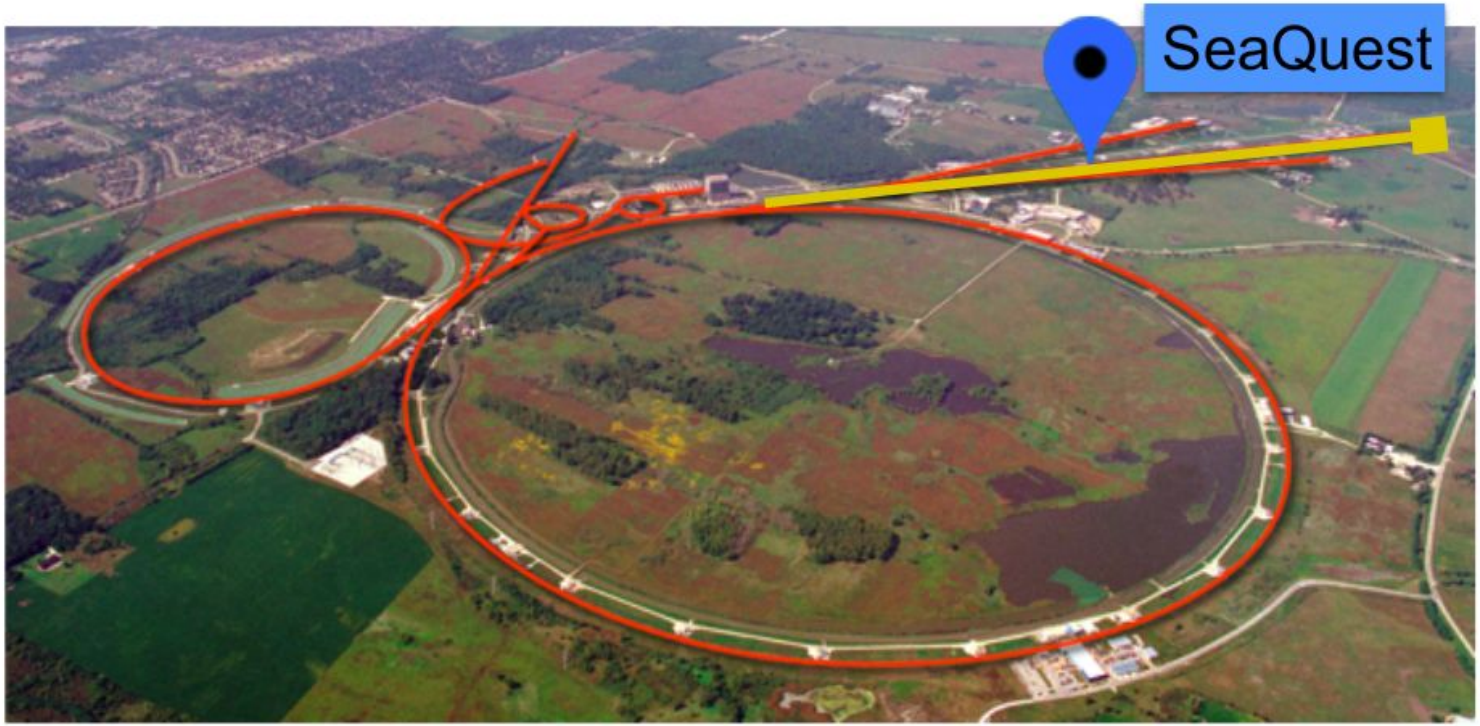
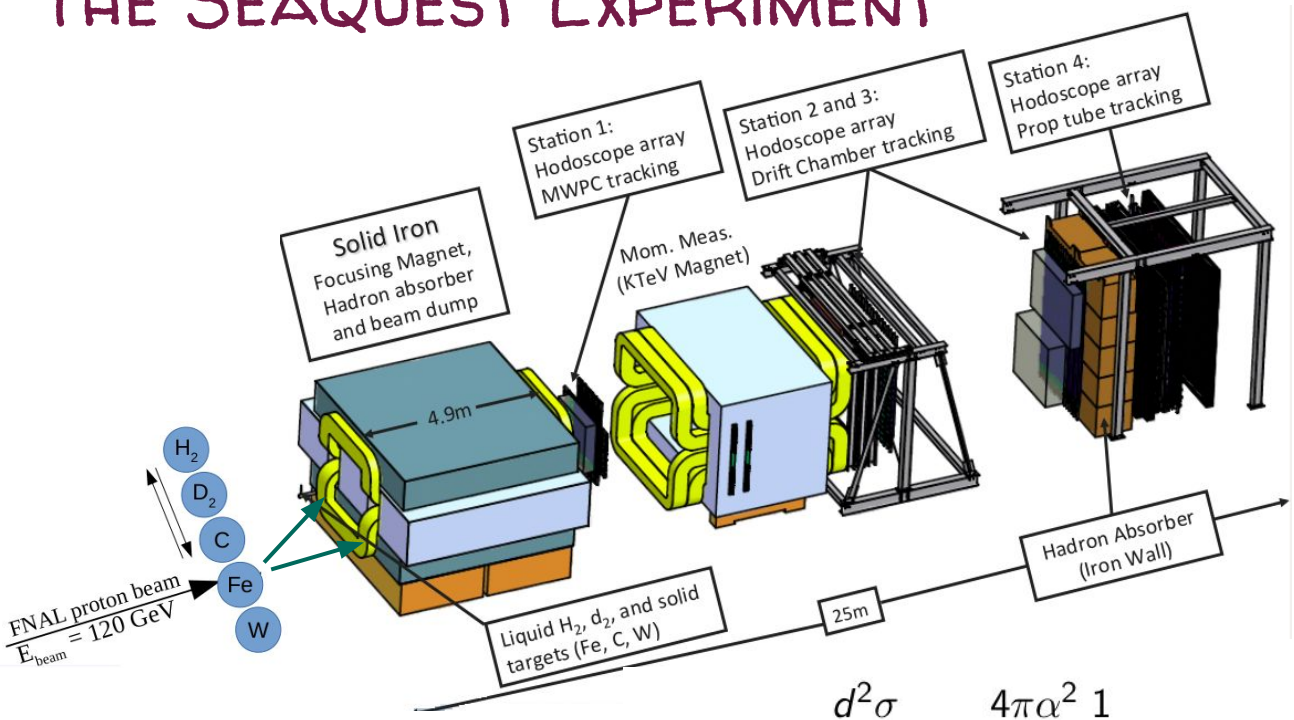
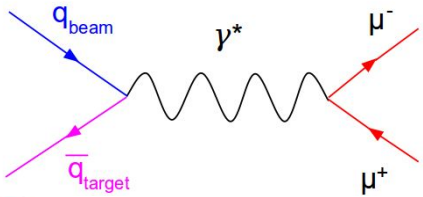
RATIO < 1.58, ANY X

The SeaQuest Experiment



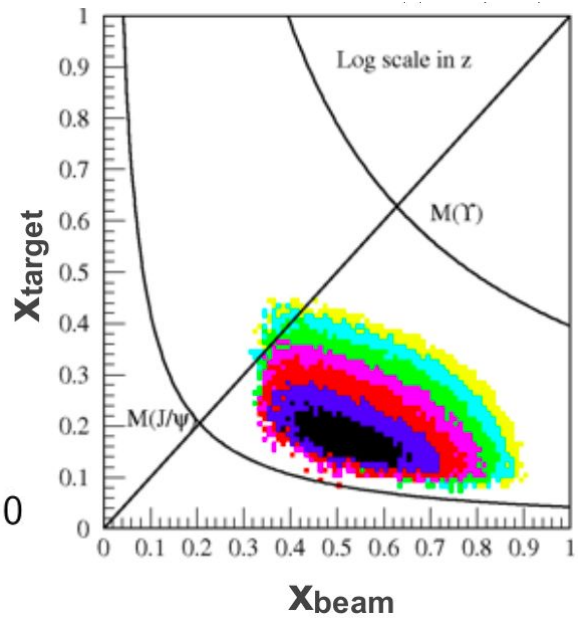
The SeaQuest Experiment





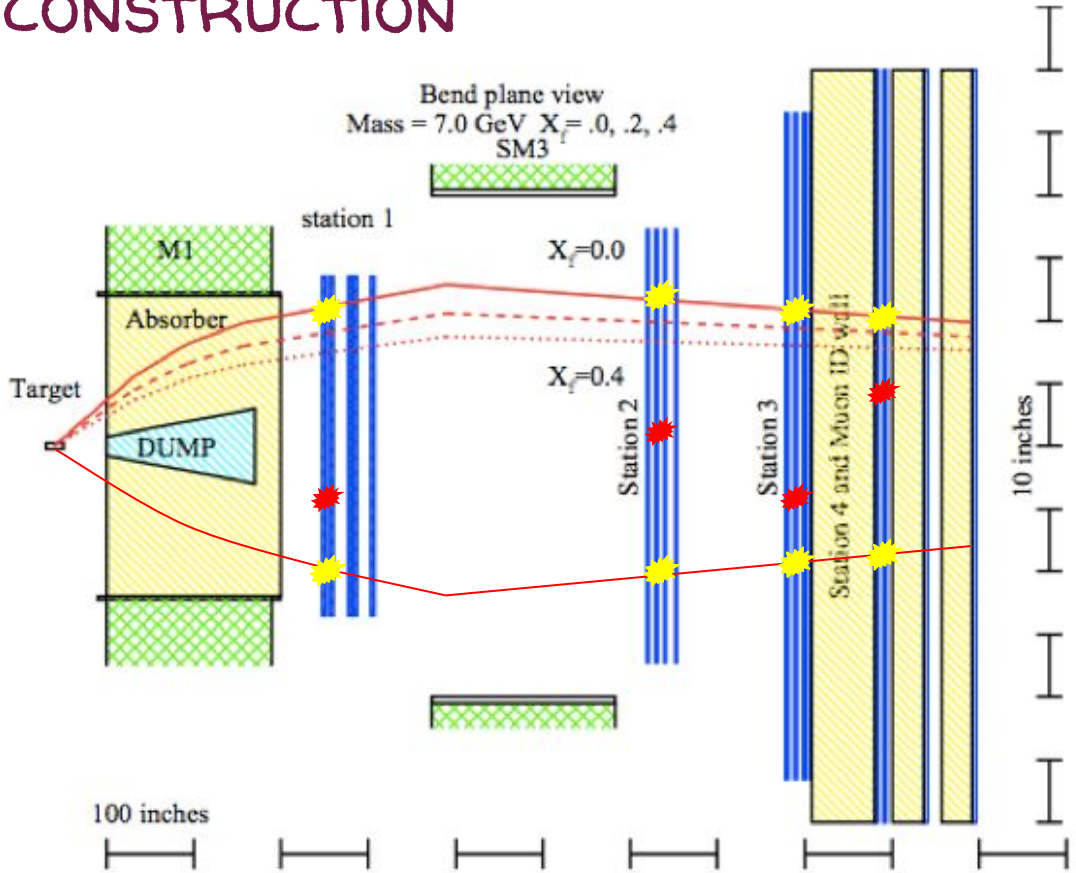
$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t}\frac{1}{s}$$

$$\sum_q e_q^2 \left[\bar{q}_t(x_t)q_b(x_b) + \bar{q}_b(x_b)q_t(x_t)\right] \sim 0$$

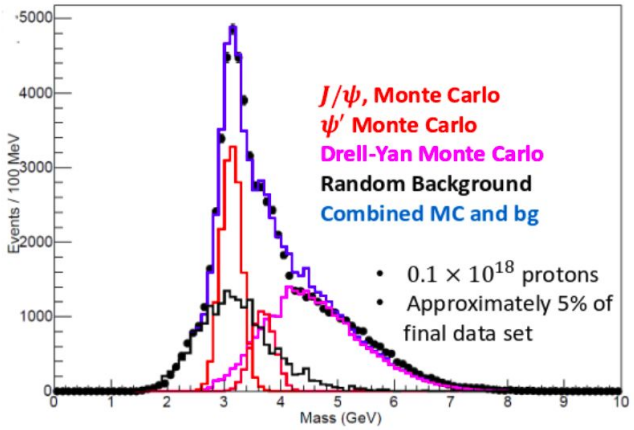


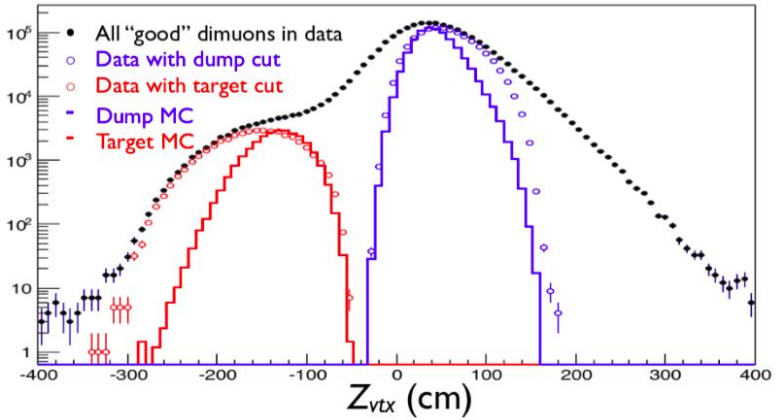
Event Selection & Reconstruction

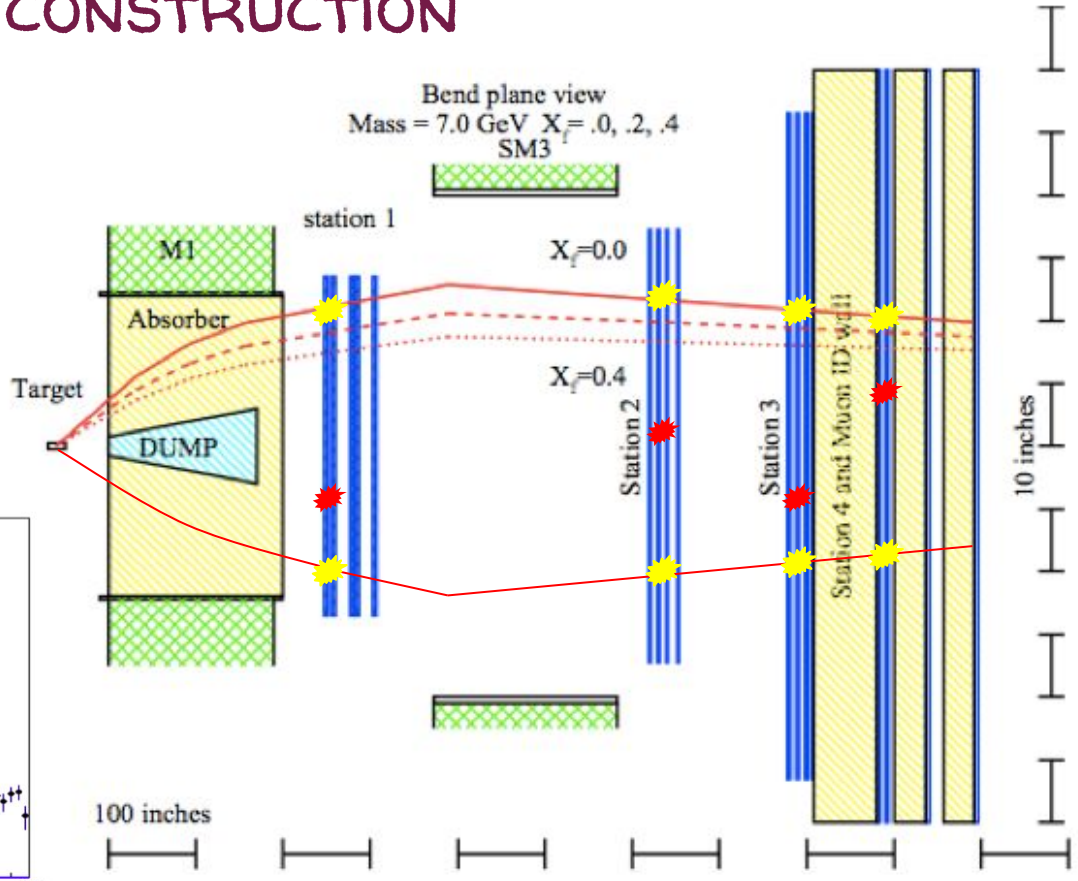
"Roadsets" of possible dimuons coming from Drell-Yan interactions in the target.



Event Selection & Reconstruction



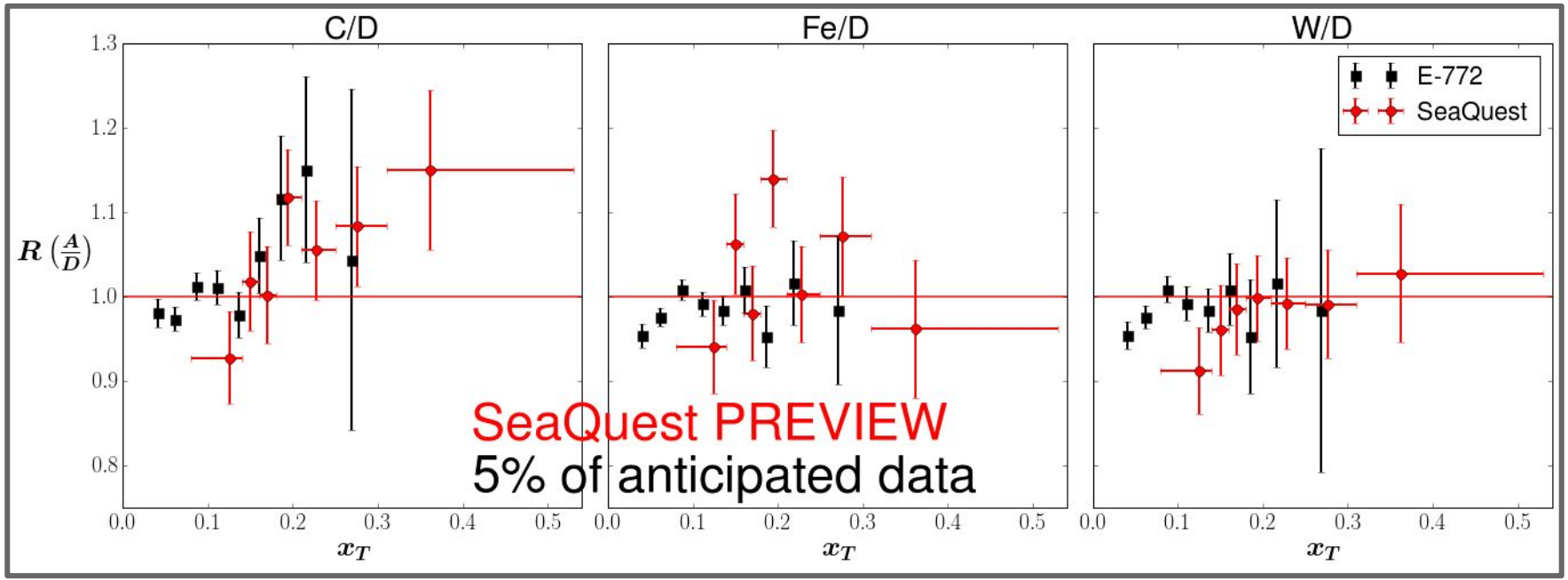




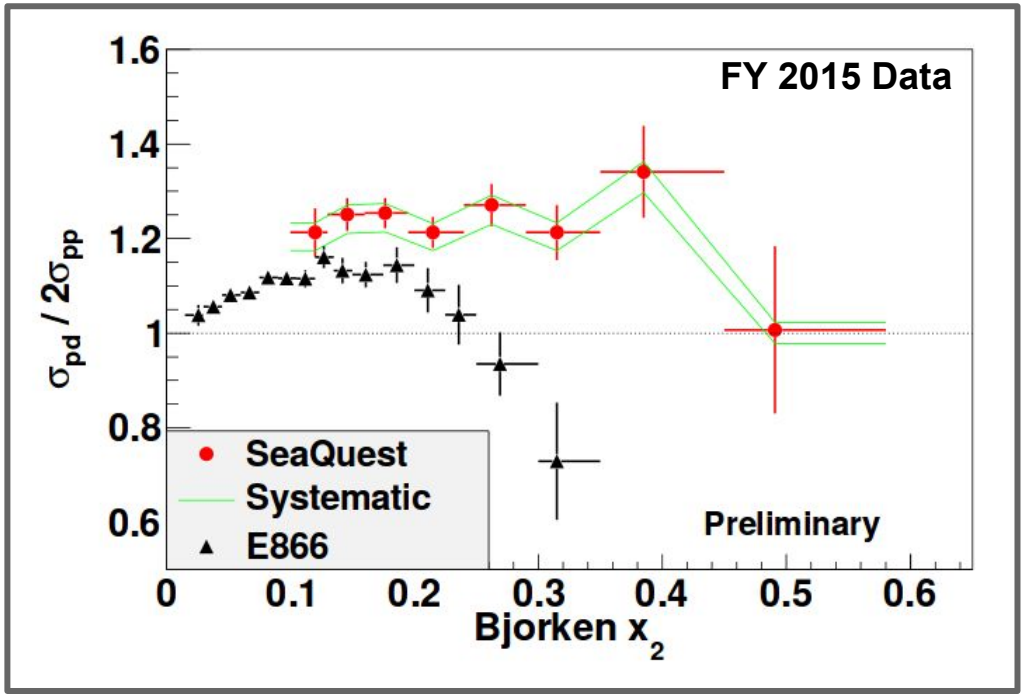
The Cool Stuff...

(Preliminary Results)

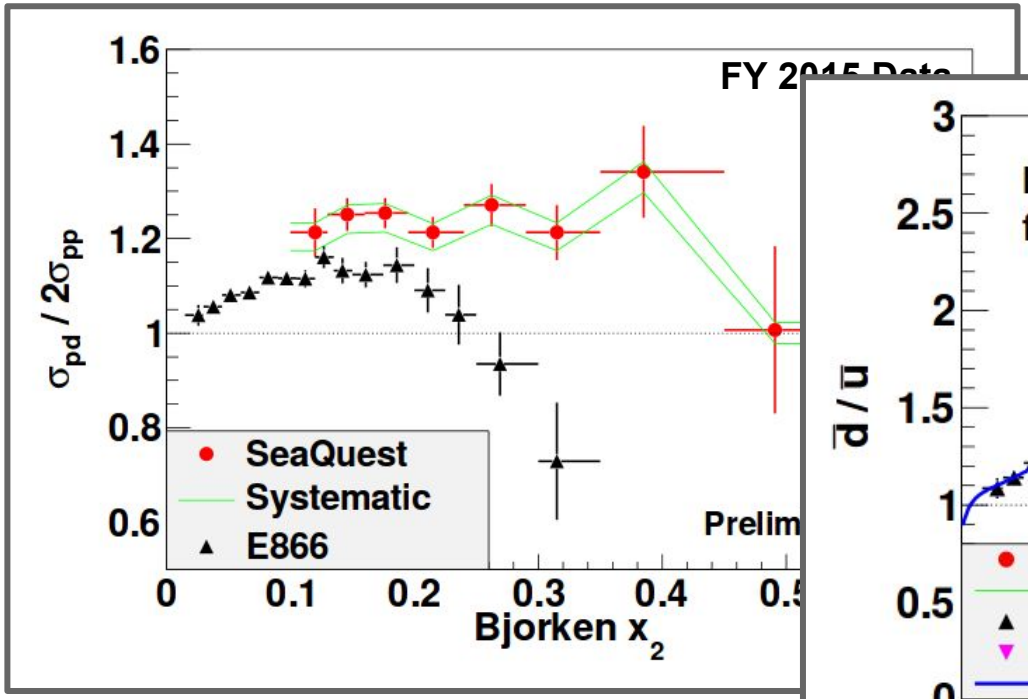
EMC Ratio

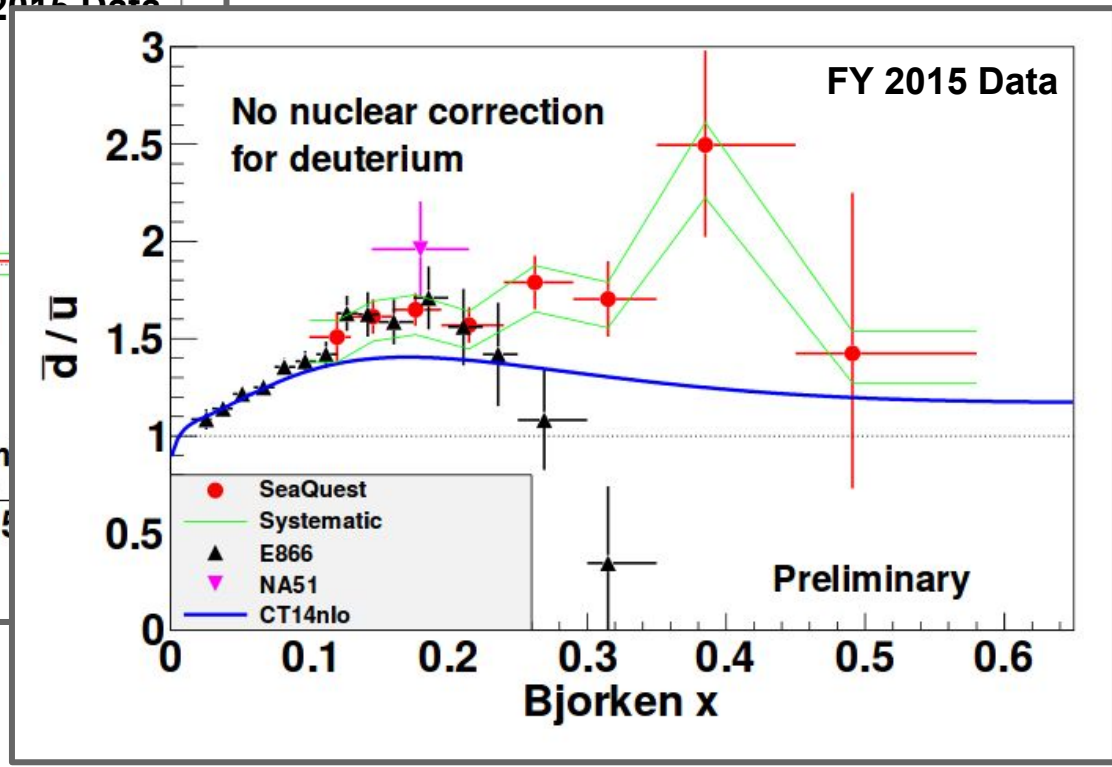

C/D
Fe/D
W/D
E-772
SeaQuest
$R\left(\frac{A}{D}\right)$
x_T
SeaQuest PREVIEW
5% of anticipated data

Cross-Section



Cross-Section & Flavor Asymmetry





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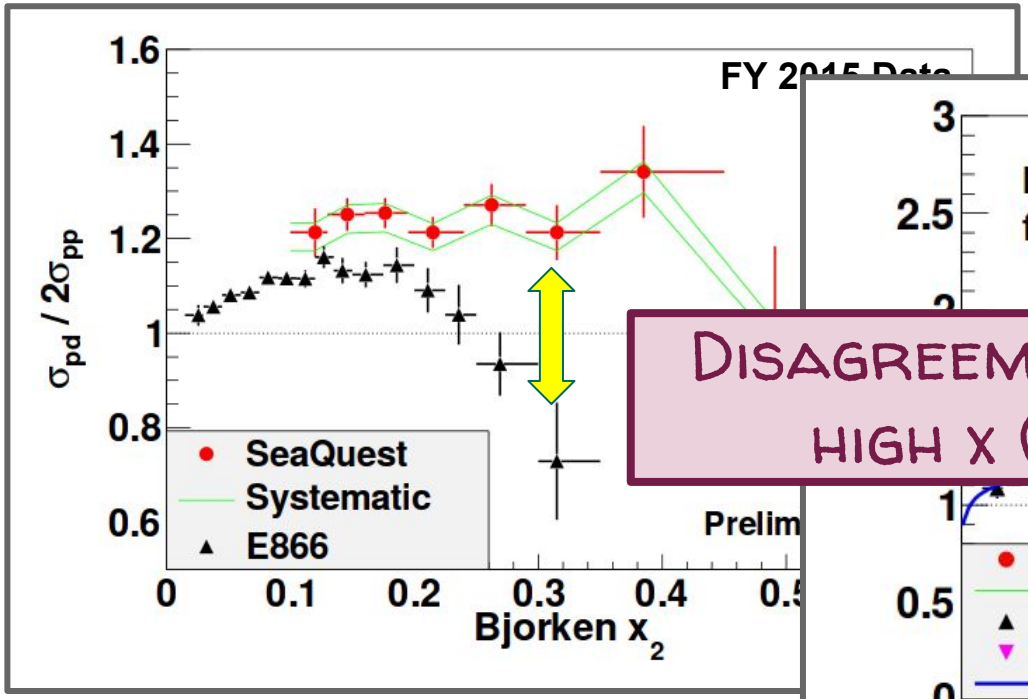
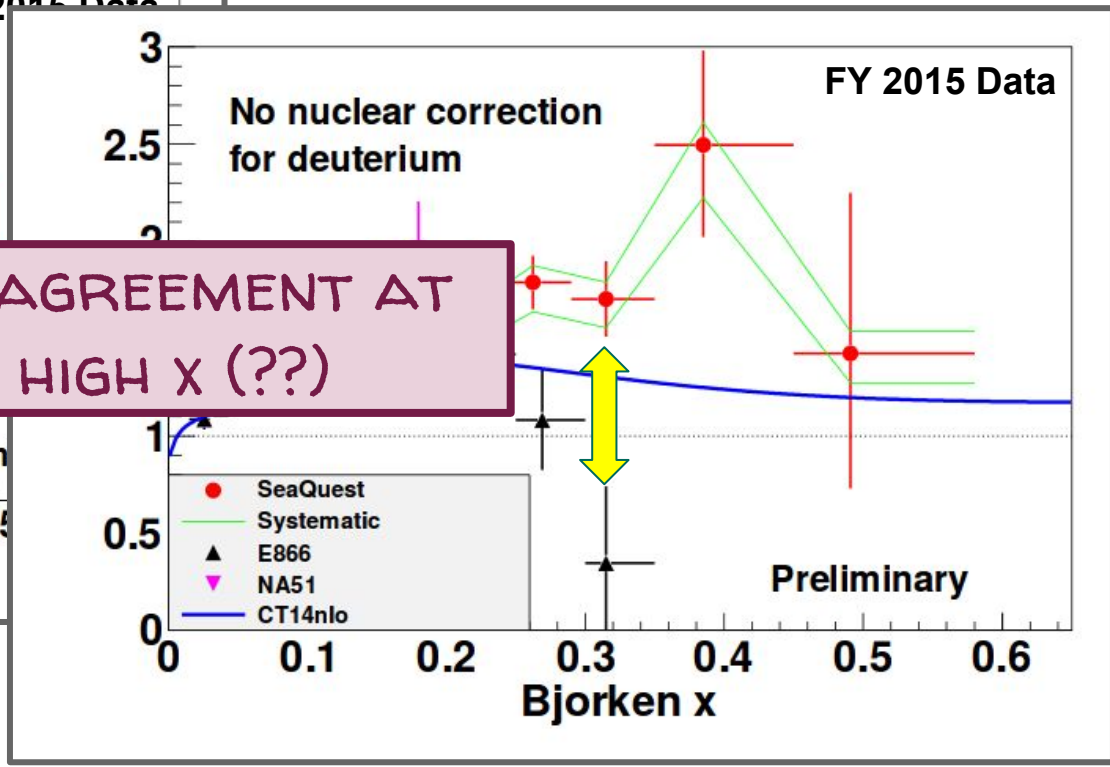
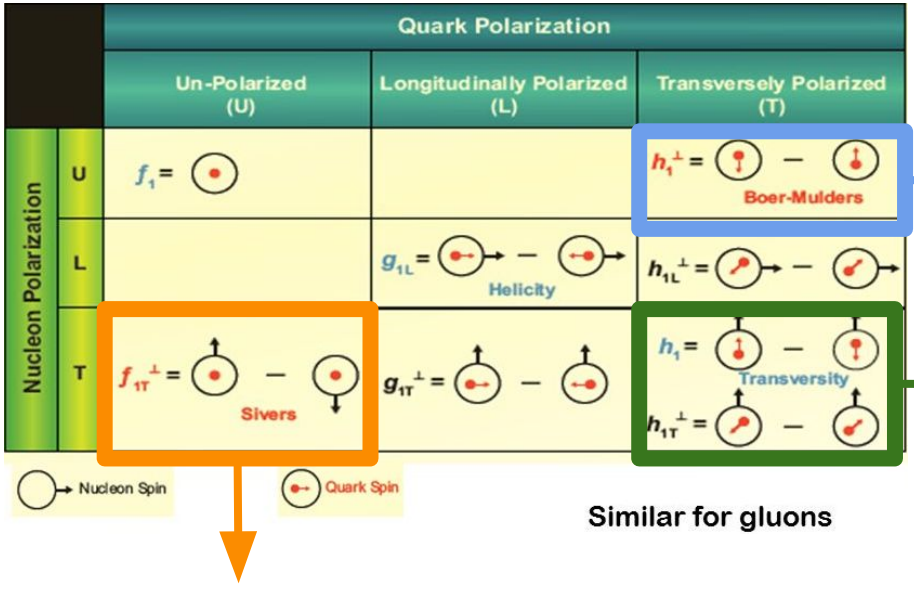




Disagreement at high x (??)

Beyond SeaQuest: Polarized Drell-Yan



Similar for gluons

SeaQuest

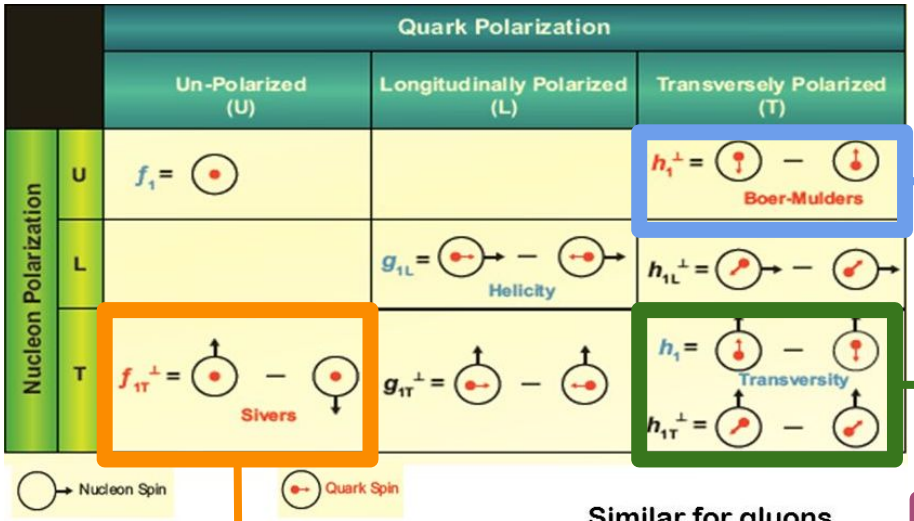
E1027

Polarized beam (+ Polarized target)

E1039

Polarized target

Beyond SeaQuest: Polarized Drell-Yan



SeaQuest

E1027

Polarized beam (+ Polarized target)

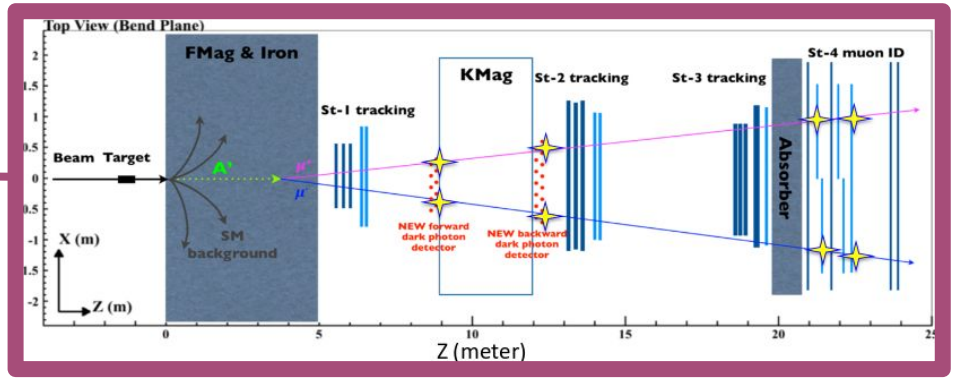
Similar for gluons

E1039

Polarized target

E1067

Upgrade for dark photon & dark higgs search

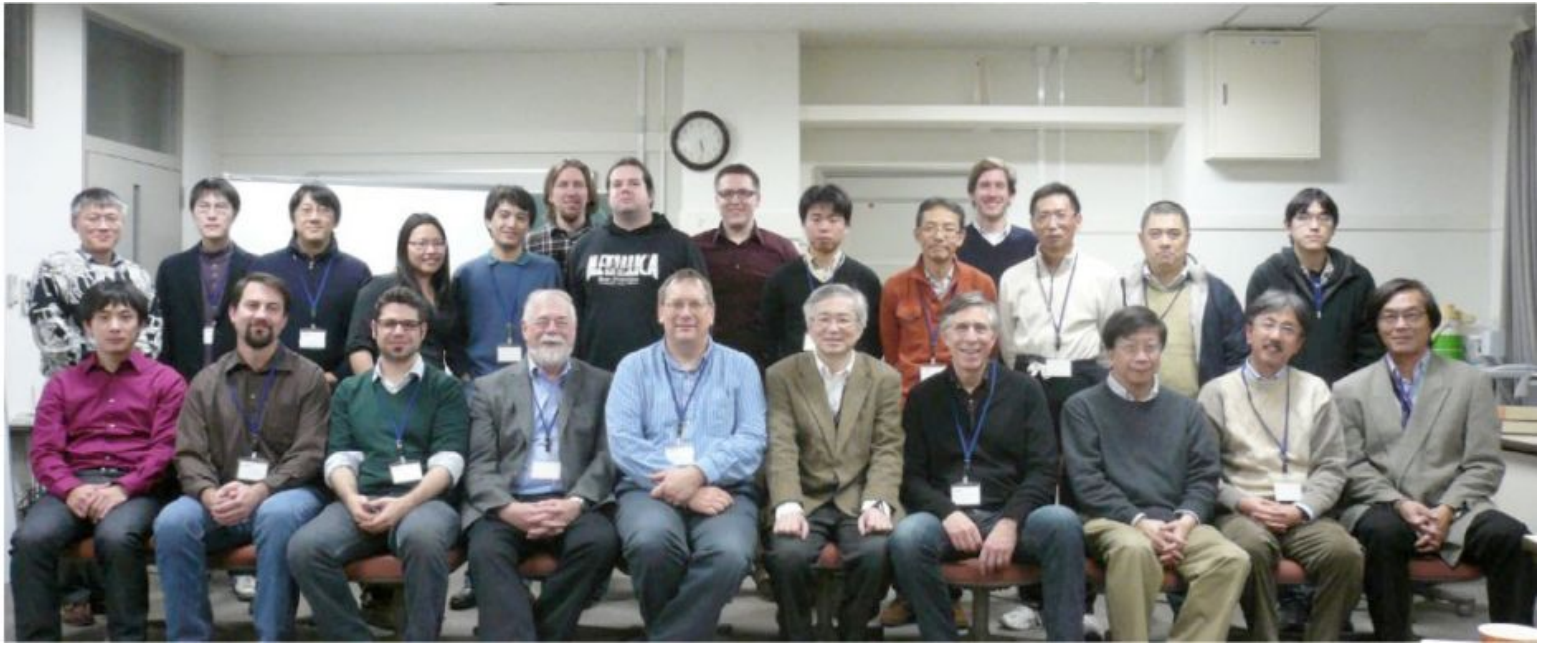


Summary

- Drell-Yan process has sensitivity to the structure of sea quarks inside nucleons.
- SeaQuest uses Drell-Yan to study sea antiquarks inside protons.
- Different physics/measurements being studied.
- Latest results show:
  - No significant EMC effect for sea antiquarks.
  - Flavor asymmetry $\bar{d}/\bar{u} > 1$, for any x → interesting differences with previous results at high x.

Exciting time ahead with SeaQuest!

THANK YOU.



BACKUP

Timeline of SeaQuest

March 2012 — I

REST

Nov 2013 — II

REST

Nov 2014 — III

REST

IV

July 2016 — V

Main injector upgrades

Commissioning run
- All detector subsystems work
- Issues and upgrades addressed

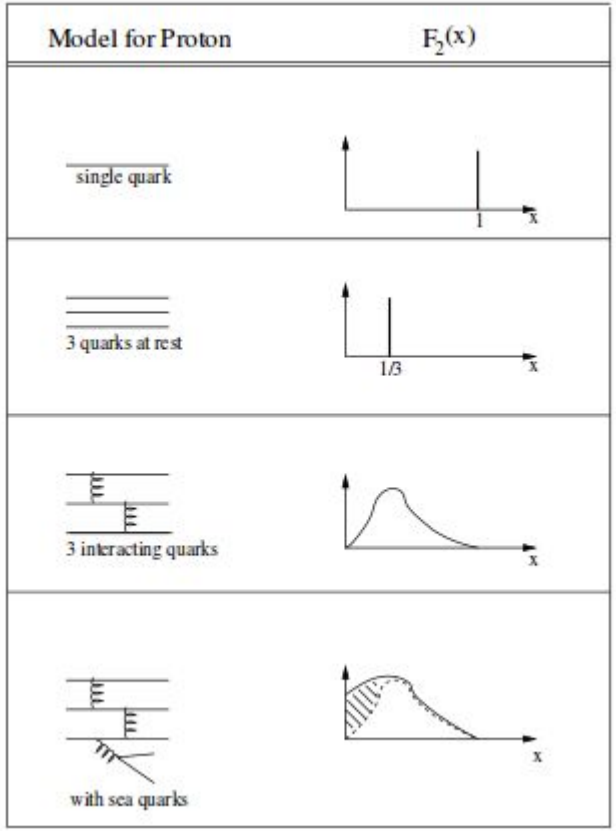
- Stable operation of all detector sub systems
- Dark photon road sets included into the trigger system
- New St3- installed

- Improved duty factor
- Continue data taking

- Installation of new St 1 drift chamber
- Scheduled accelerator maintenance

Slide from Arun Tadepalli

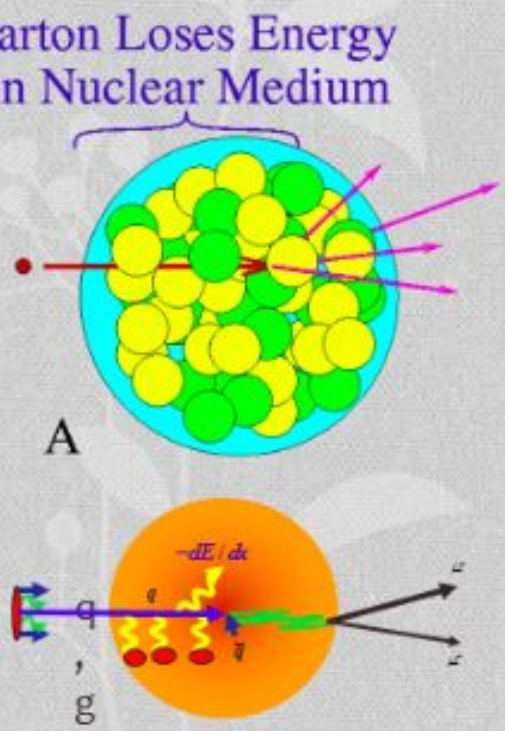
Model for the proton



(Phys 741) Quarks, Nuclei, and the Cosmos: A Modern Introduction to Nuclear Physics, Prof. Xiangdong Ji

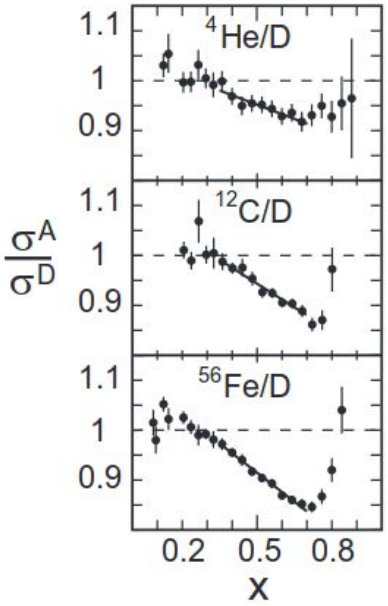
Parton energy loss in cold nuclear matter

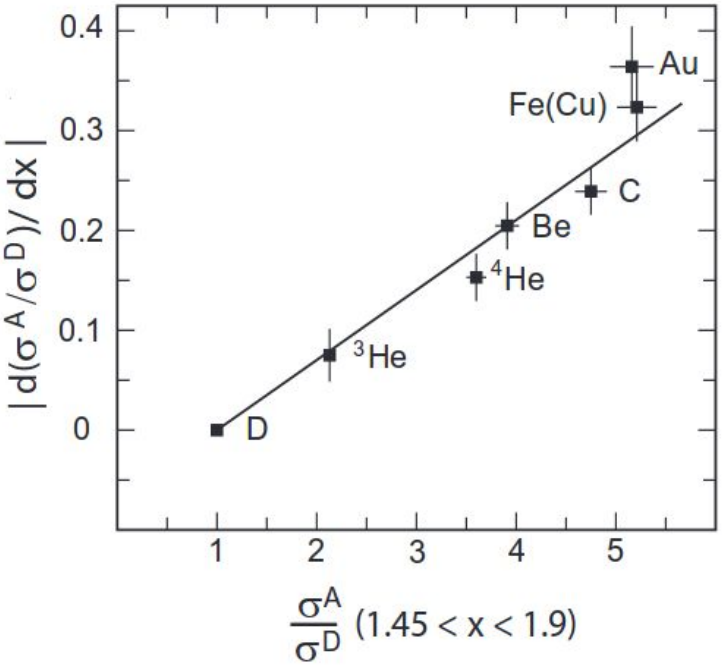
- QCD partons (are thought to) lose energy while decelerating in a strongly interacting medium
- Drell Yan process is an ideal tool to study the interactions of fast partons traversing cold nuclei
- The dilepton pair doesn't interact strongly with the nuclear medium
- Significant implications for physics of relativistic heavy ion collisions (RHIC)

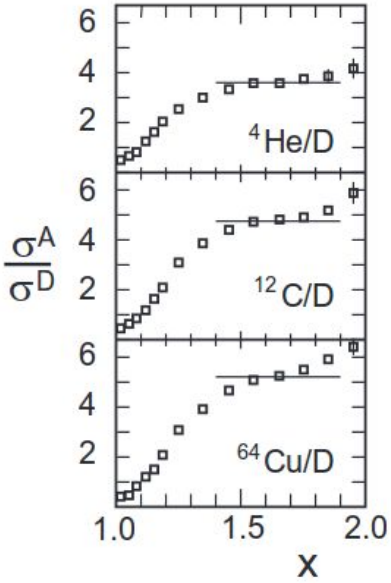


Slide from Arun Tadepalli

The EMC effect







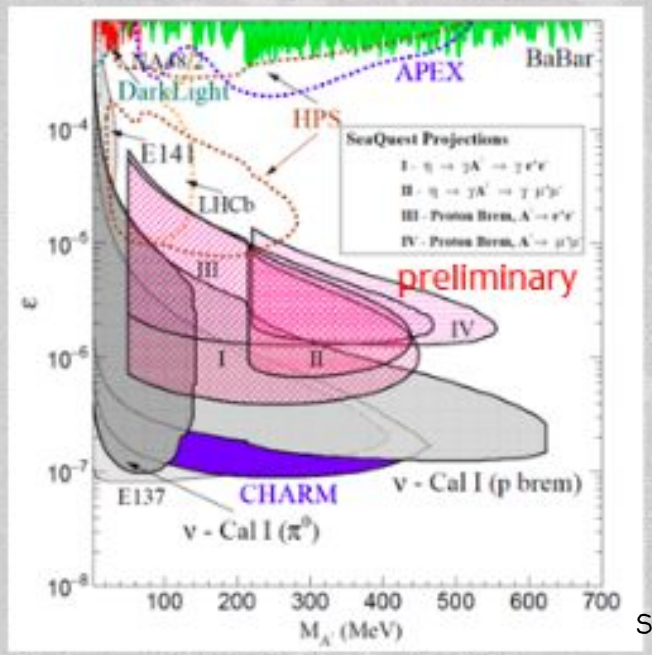
A' sensitivity region for SeaQuest

2E12 ppp
200 days
10 event contours

$$l_o \approx \frac{0.8cm}{N_{eff}}\left(\frac{E_o}{10\,GeV}\right)\left(\frac{10^{-4}}{\varepsilon}\right)^2\left(\frac{100\,MeV}{m_{A'}}\right)^2$$

J. D. Bjorken et al, PRD **80** (2009) 075018

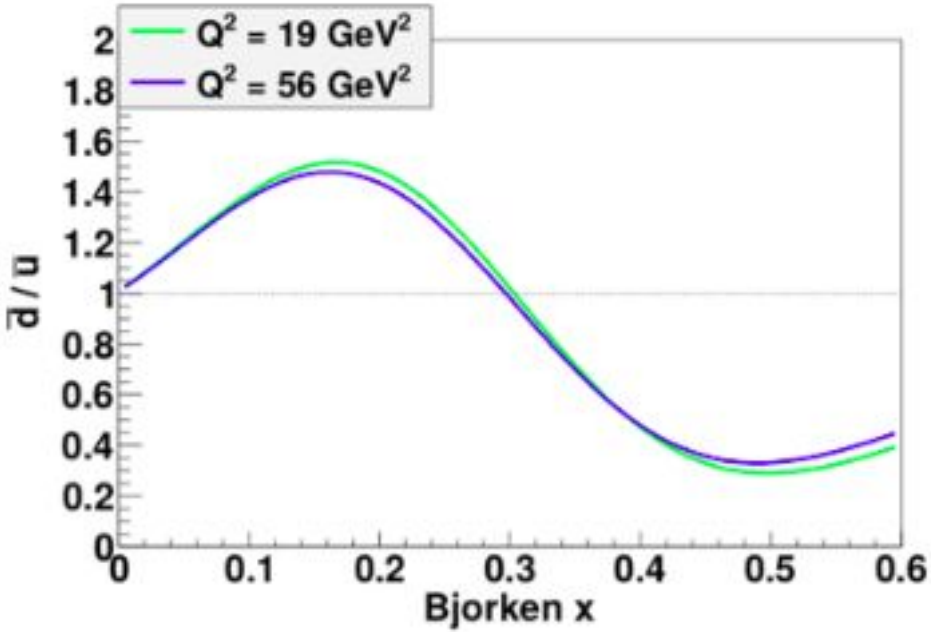
- E_o = energy of the A'
- N_{eff} = no. of available decay products
- l_o = distance that A' travels before decaying
- ε = coupling constant between standard model and dark sector
- $m_{A'}$ = mass of A'



S. Gardner, R. J. Holt, A. Tadepalli, arXiv 1509.00050

Slide from Arun Tadepalli

Q^2 evolution



- Differences in Q^2 according to CT10
- Difference between SeaQuest and E866 because of Q^2 evolution is small

Slide from Arun Tadepalli

Background and Systematics

- Background rejection:
  - $m_{\mu\mu} < 4.5$ GeV $\rightarrow$ J/Ψ events
  - $9.0 < m_{\mu\mu} < 10.7$ GeV $\rightarrow$ Y ressonance events.
- Systematic uncertainties:
  - empty target correction.
  - PDFs uncertainties.
  - hydrogen contamination of the deuterium target.
  - sources of rate dependence.

Bjorken x

Fraction of longitudinal momentum (p_L) of the hadron carried by a given parton in the overall center of mass frame.

Consider lepton + hadron interaction.

Definition of x:

$$x = \frac{-q^2}{2p.q} = \frac{Q^2}{2M(E - E')}$$

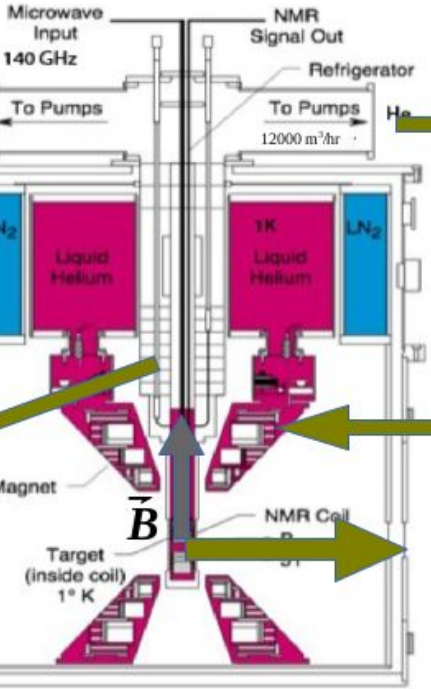
- $0 < x < 1$
- q→ four momentum transfer between lepton and target nucleon.
- p→ incident nucleon four momentum.
- elastic scattering: $(p + q)^2 = M^2 \rightarrow x=1$.
- deep inelastic scattering: $Q^2 \gg M^2 \rightarrow x<1$.

Calculation of $\bar{d}/\bar{u}$

Iterative process in each bin of x_{target}:

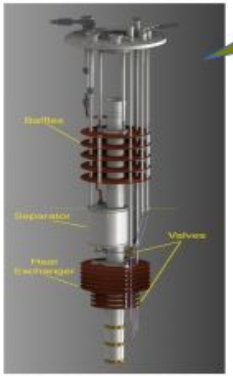
1. Measurement of cross-section ratio from data:
   - $R_{data} = \sigma_{pd}/\sigma_{pp}$
2. Calculate a prediction from cross-section ratio:
   - Based on estimation of $\bar{d}/\bar{u}$.
   - Uses CT10 PDFs for other quarks and anitquarks.
   - Uses PDFs to fix $\bar{d} + \bar{u}$.
   - Call it R_{pred}
3. Adjust estimate oof $\bar{d}/\bar{u}$ based on R_{data} - R_{pred}.
4. Repeat 2 and 3 until $R_{data} = R_{pred}$.

Polarized Target System (E1039)



Roots pump system used to pump on liquid ^{4}He vapor pressure to reach **1K**

Cryostat



Superconducting Coils for Magnet: **5T**

Target Material: Irradiated NH_3

$P_{(s=1/2,p)} = 0.5\,\%$

Slide from David Kleijan