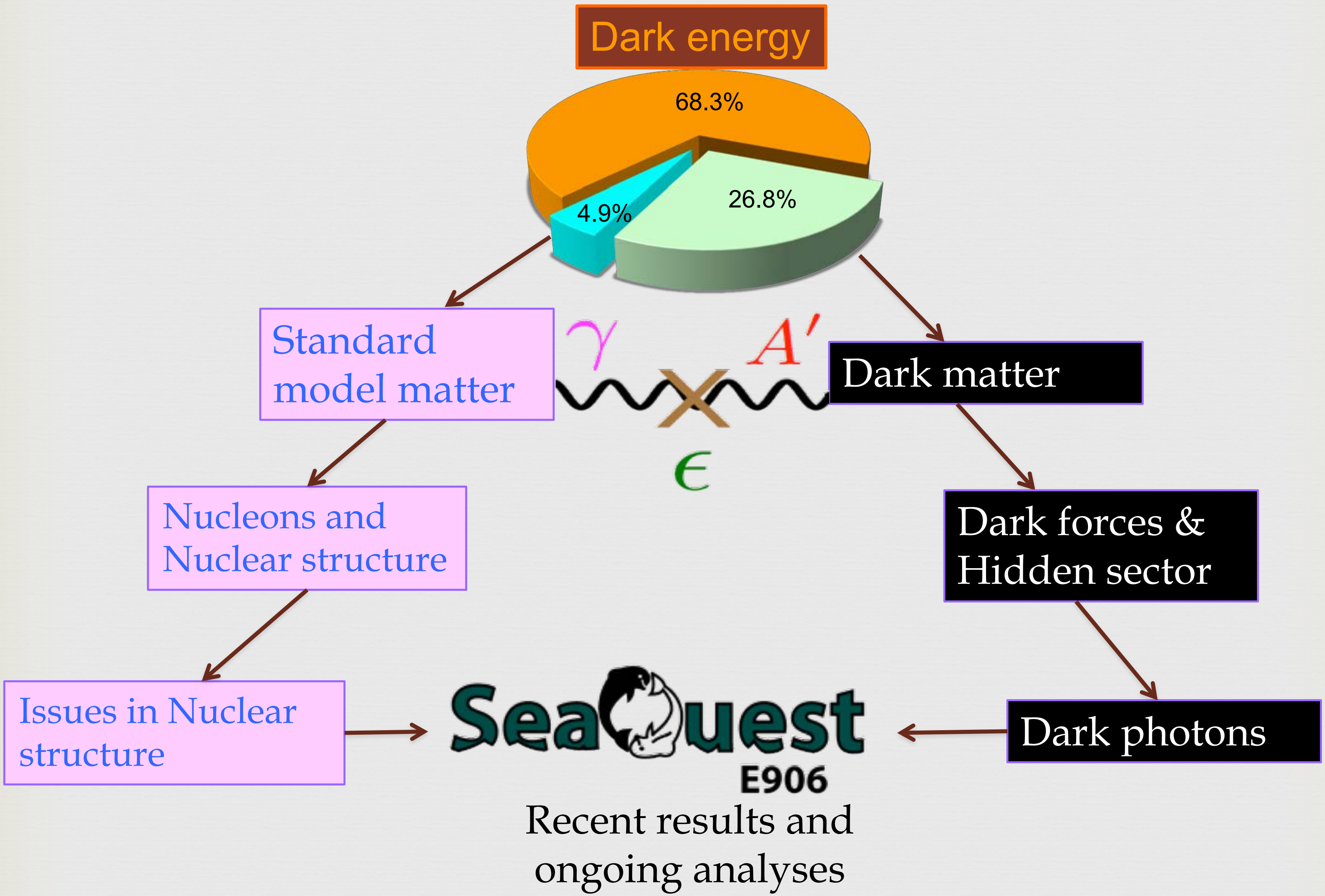
Exploring the light Anti-Quark flavor asymmetry in the nucleon sea

Arun Tadepalli - Jefferson Lab
(on behalf of the SeaQuest E906 collaboration)

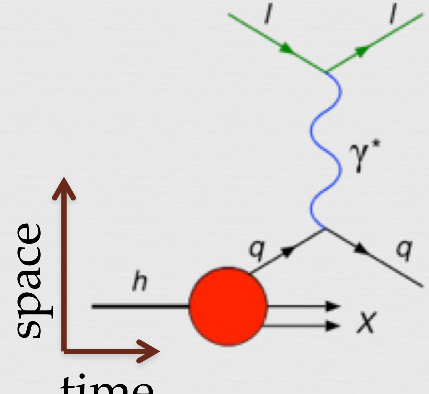
Contents of the talk/Universe



Rich Drell-Yan and *J/ψ* program

1. Light Anti-Quark Flavor Asymmetry
2. Absolute cross sections on pp and pD collisions
3. Nuclear dependence of Anti-Quarks in the Nuclei
4. Transverse momentum broadening of DY dimuons
5. Parton energy loss in cold nuclear matter
6. Search for dark photons
7. Many other interesting J/ψ physics topics

Experimental toolbox



At SeaQuest, we use the Drell-Yan process which has unique sensitivity to the antiquark structure of nucleon and nuclei

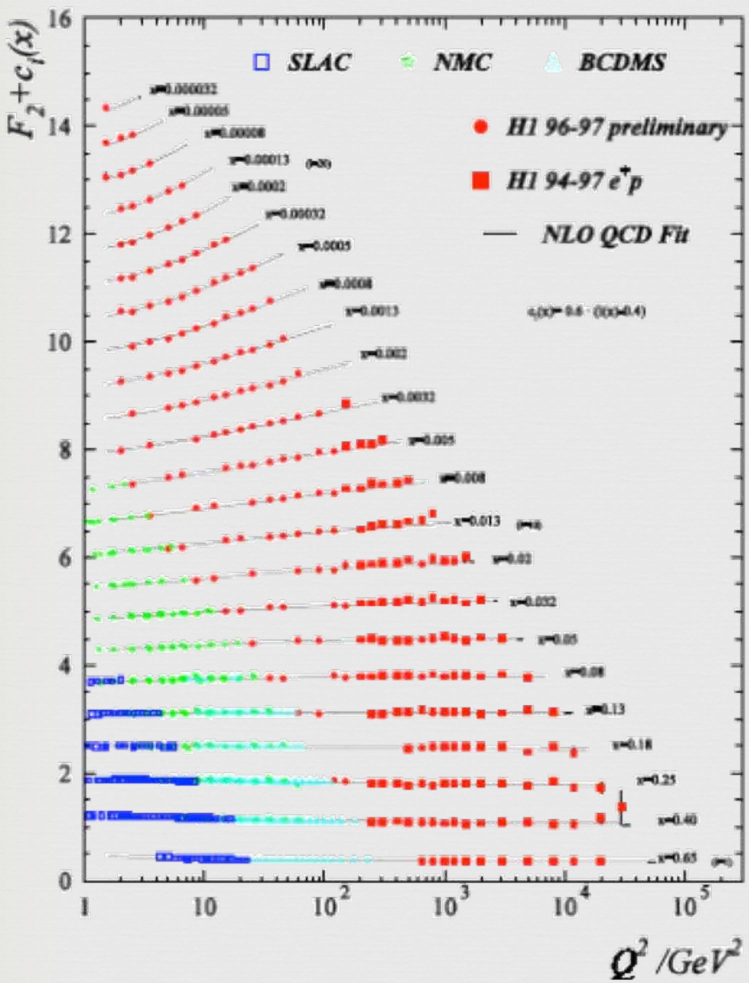
DEEP INELASTIC SCATT

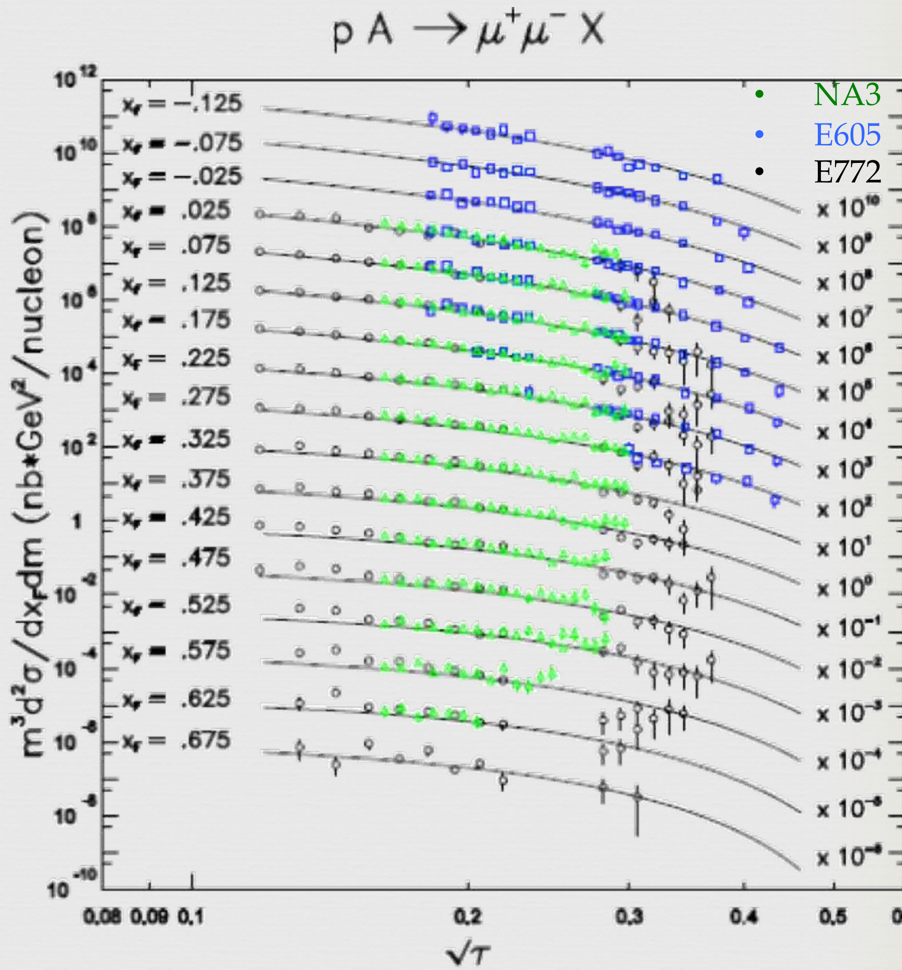
- Lepton scatters f
- Exchang
- E n (or
- tiate between ntiquark

N PROCESS

- uark from hadron annihilates with antiquark from another hadron
- Virtual photon is created
- Decays into a lepton + antilepton
- Unique sensitivity to the anti-quark distributions

DIS & DY – complementary!





McGaughey, Moss, Peng Ann.Rev. Nucl.Part.Sci.49 (1999) 217

What is the Drell-Yan process?

Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 8 September 1970)

Muon pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/c^2 have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32}/m_{\mu\mu}^5$ cm^2 (GeV/c)$^{-2}$ and exhibits no resonant structure. The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

..bel prize winning

Two prominent features observed

- Shoulder between 3 – 4 GeV
- Underlying continuum (DY dimuons)

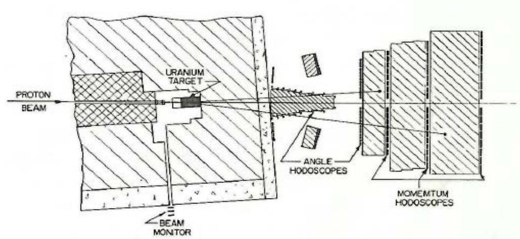
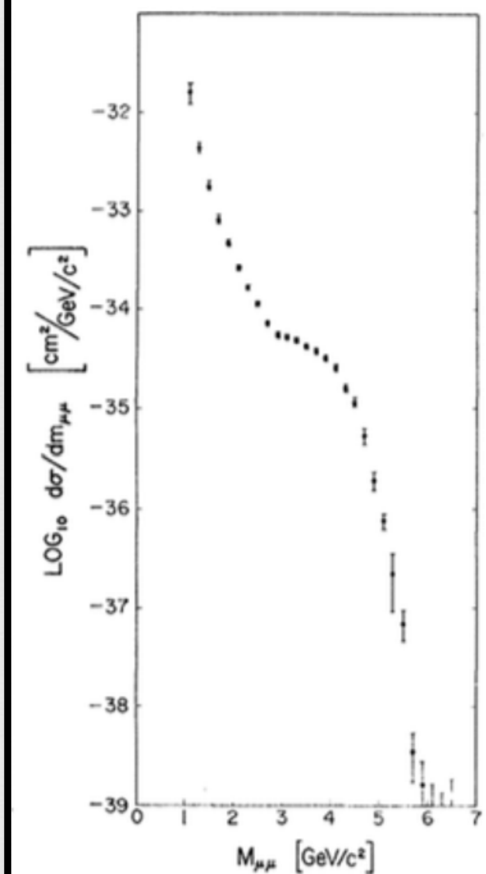


FIG. 1. Plan view of the apparatus.



Phys.Rev.Lett. 25 (1970) 1523-1526

Explanation by Drell and Yan

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.

Underlying continuum explained in the framework of the parton model

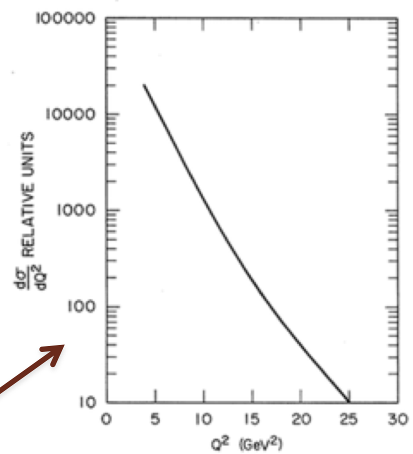
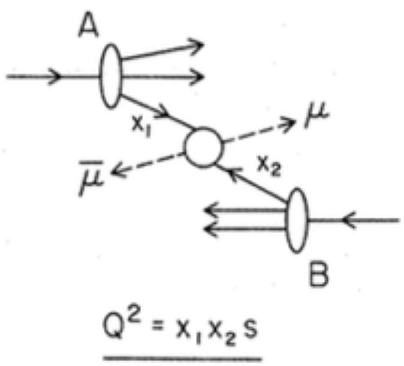


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.

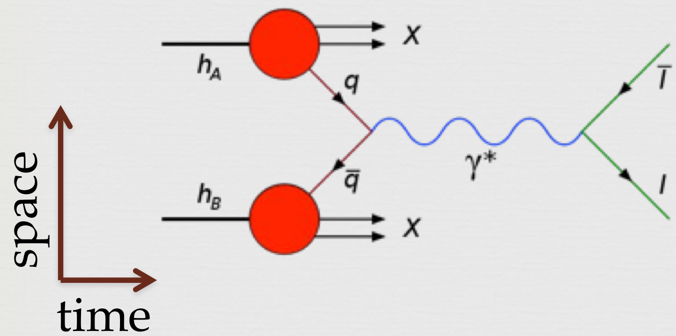


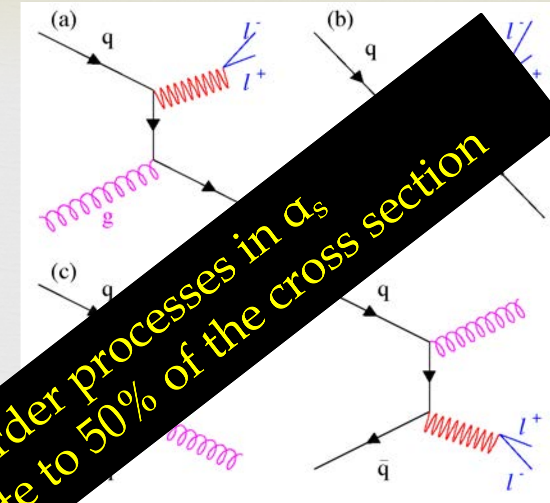
Model explained only part of the cross section

parton annihilates with an anti-parton

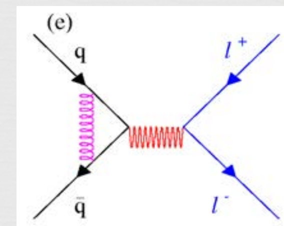
Phys.Rev.Lett 25.902 (1970)

Leading Order Drell Yan cross-section formula





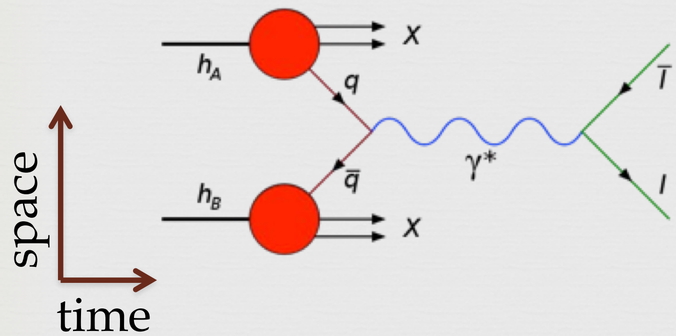
*Higher order processes in α_s contribute to 50% of the cross section

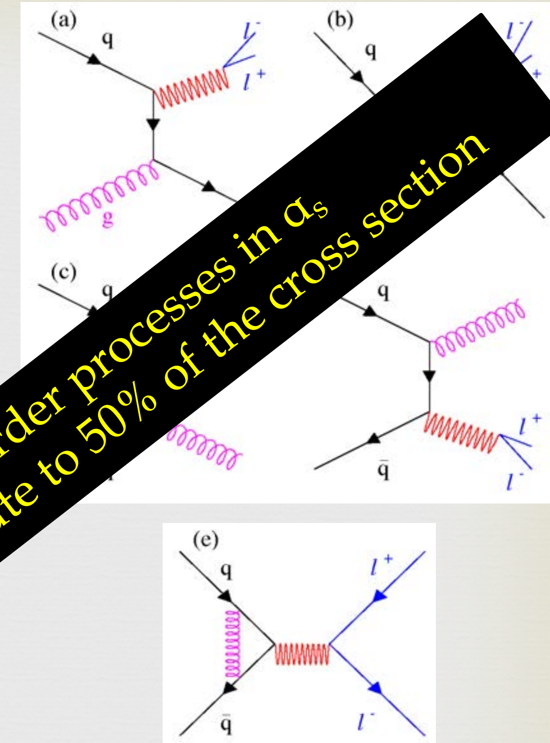


$$\frac{d^2\sigma}{dx_{targ}dx_{beam}} = \frac{4\pi\alpha^2}{9sx_{targ}x_{beam}}\sum_i \varepsilon_i^2\left[q_{beam}(x_{beam})\,\bar{q}_{targ}(x_{targ}) + q_{targ}(x_{targ})\,\bar{q}_{beam}(x_{beam})\right]$$

- Drell-Yan cross section
- Fine structure constant
- Charge weighted summation over all quark flavors
- PDF of a quark of flavor i in the beam
- PDF of anti quarks of flavor i in the target
- Center of mass energy squared
- momentum fraction of antiquark in the target
- momentum fraction of quark in the beam

Leading Order Drell Yan cross-section formula





*Higher order processes in α_s contribute to 50% of the cross section

$$\frac{d^2\sigma}{dx_{targ}dx_{beam}} = \frac{4\pi\alpha^2}{9sx_{targ}x_{beam}} \sum_i \varepsilon_i^2 [q_{beam}(x_{beam})\,\bar{q}_{targ}(x_{targ}) + q_{targ}(x_{targ})\,\bar{q}_{beam}(x_{beam})]$$

Acceptance of the spectrometer can be tuned to study antiquark distributions

Term negligible compared to the first term

Accessing the anti-quark distributions

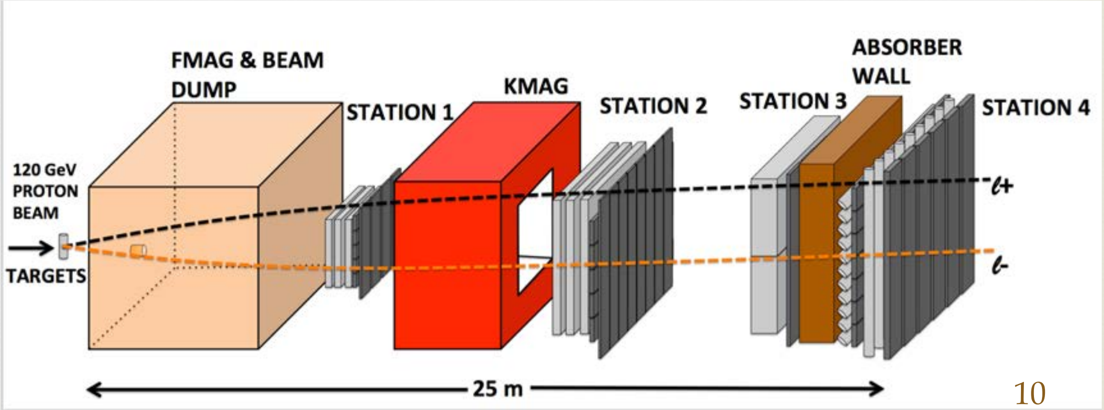
Detector acceptance tuned to study the antiquark distributions of the target

x_{target} x_{beam}

$$\frac{d^2\sigma}{dx_{targ}dx_{beam}} = \frac{4\pi\alpha^2}{9sx_{targ}x_{beam}}\sum_i \varepsilon_i^2 [q_{beam}(x_{beam})\bar{q}_{targ}(x_{targ}) + q_{targ}(x_{targ})\bar{q}_{beam}(x_{beam})]$$

Ratio of cross sections of p-p and p-A reactions is the key to probing the sea structure

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{(x_{beam}>>x_{targ})} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_{targ})}{\bar{u}(x_{targ})}\right]$$



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The SeaQuest Experiment

E906

- 120 GeV/c proton beam from the Main Injector at Fermilab
- Fixed target experiment that uses several cryogenic and solid targets
- Takes advantage of the Drell-Yan process to probe anti-quark distributions
- Optimized for detecting such Drell-Yan dimuons

Advantages of 120 GeV Main Injector

The (very successful) past:

Fermilab E866/NuSea

- Data in 1996-1997
- ^{1}H, ^{2}H, and nuclear targets
- 800 GeV proton beam

The present:

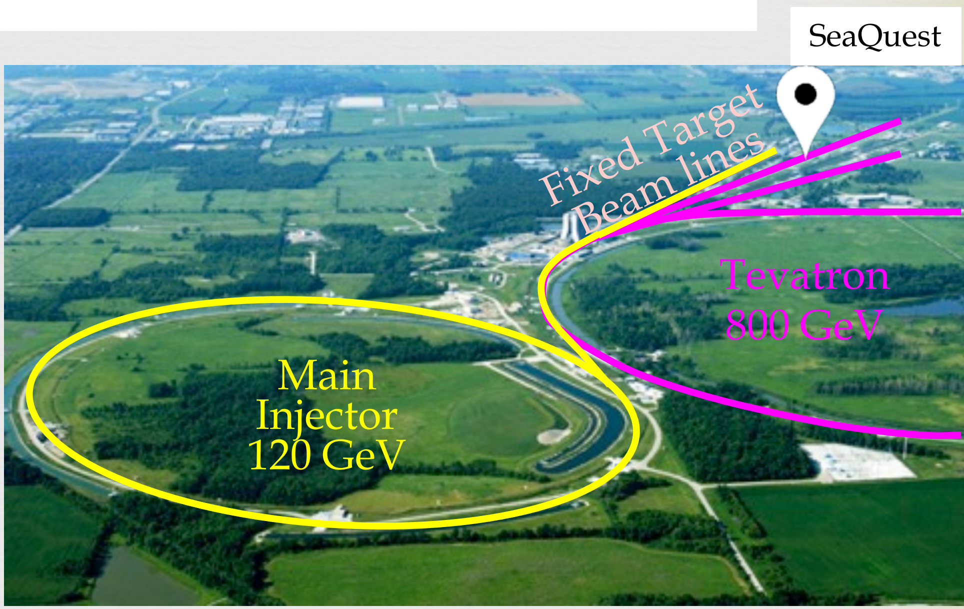
Fermilab E906

- Data in 2013 - 2017
- ^{1}H, ^{2}H, and nuclear targets
- 120 GeV proton Beam

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

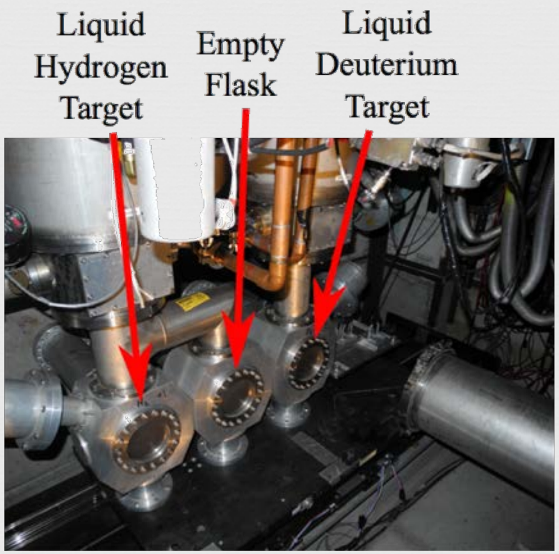
- Cross section scales as 1/s
  - *7 x that of 800 GeV beam*
- Backgrounds, primarily from J/ψ decays scale as s
  - *7 x Luminosity for same detector rate as 800 GeV beam*

Improved statistics!!



TARGETS

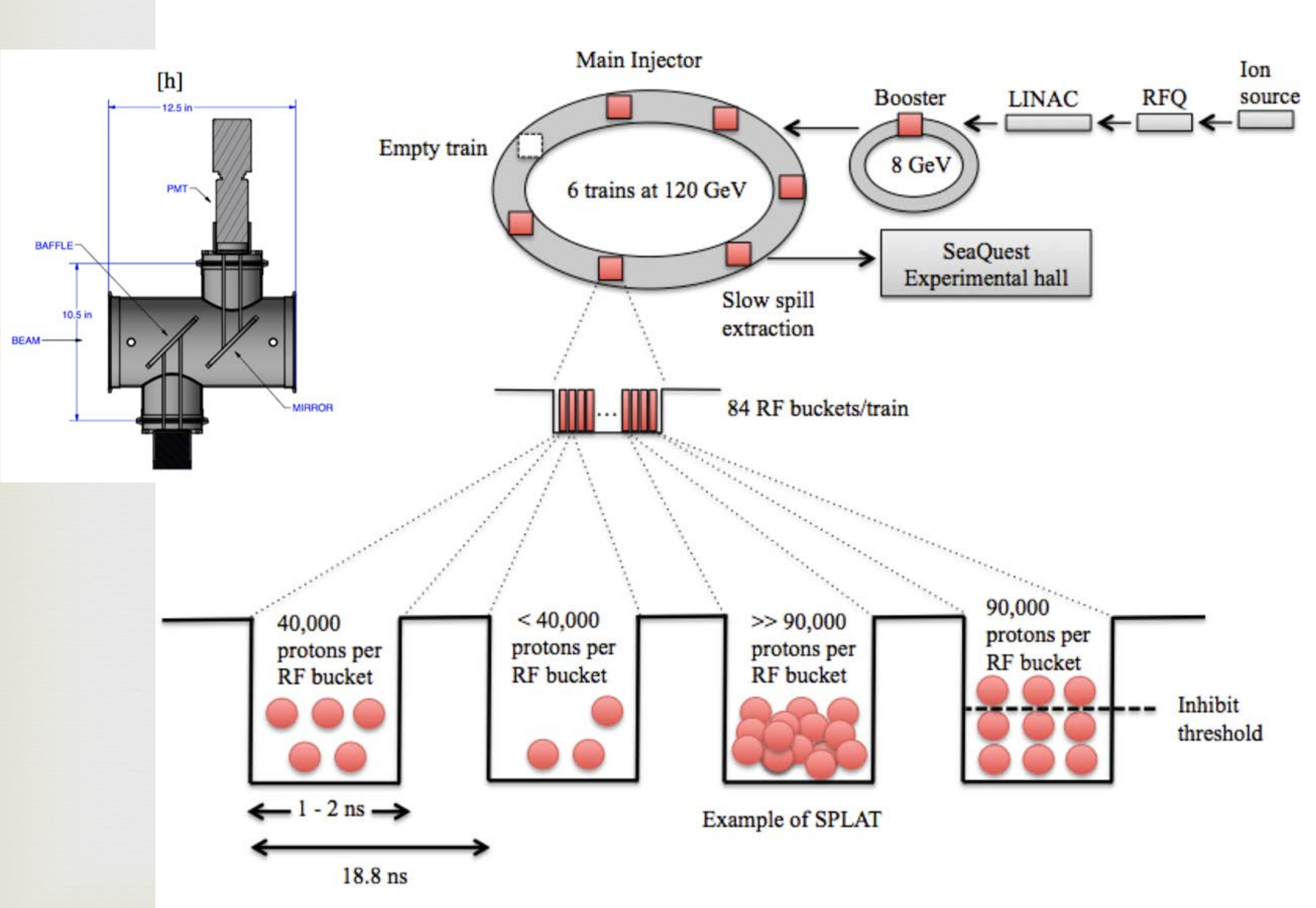
- 2 liquid targets: hydrogen and deuterium
  - 20″ long, 3″ diameter flasks
- 3 solid targets:
  - carbon, iron, tungsten
- Background subtraction:
  - empty flask, nothing
- All targets <15% interaction length
- Beam time split roughly:
  - LH2 – 44%
  - LD2 – 22%
  - C, Fe, W – 17%
  - random background - 17%



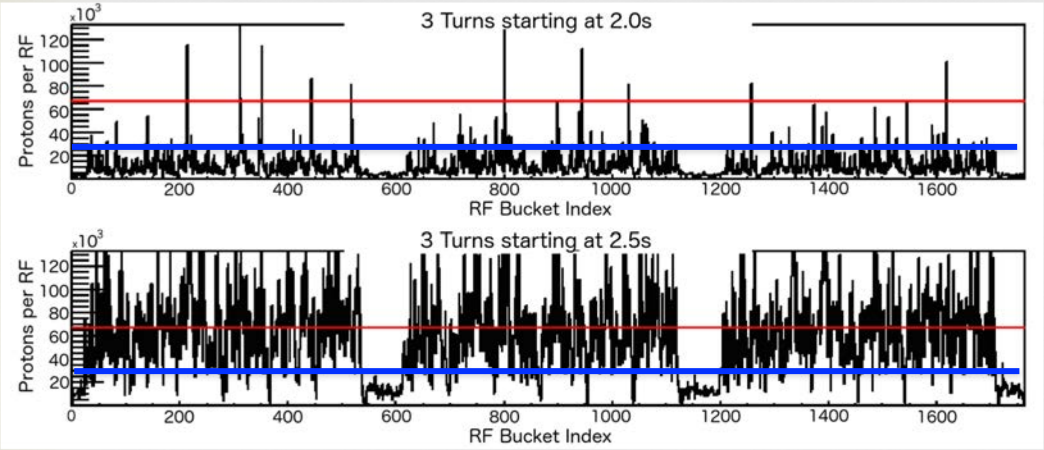
For anti-quark flavor asymmetry studies

For Nuclear dependence studies

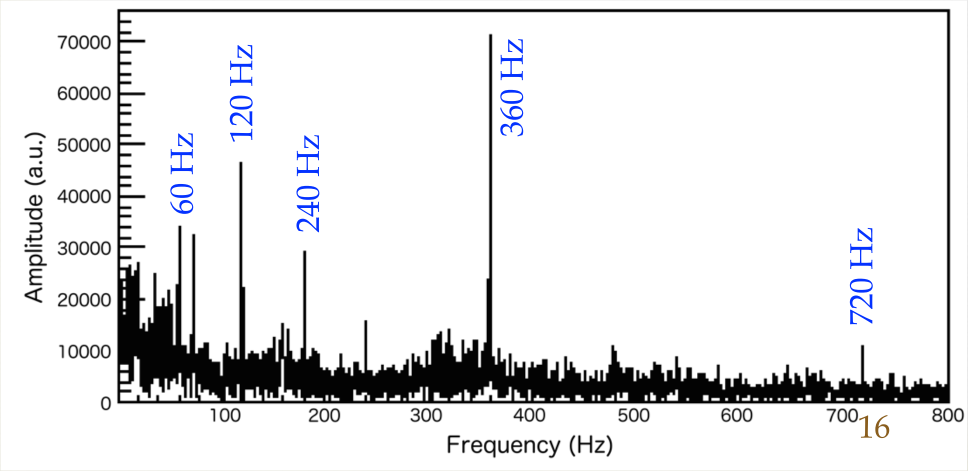
Beam microstructure



Randomly chosen Beam Intensity profile



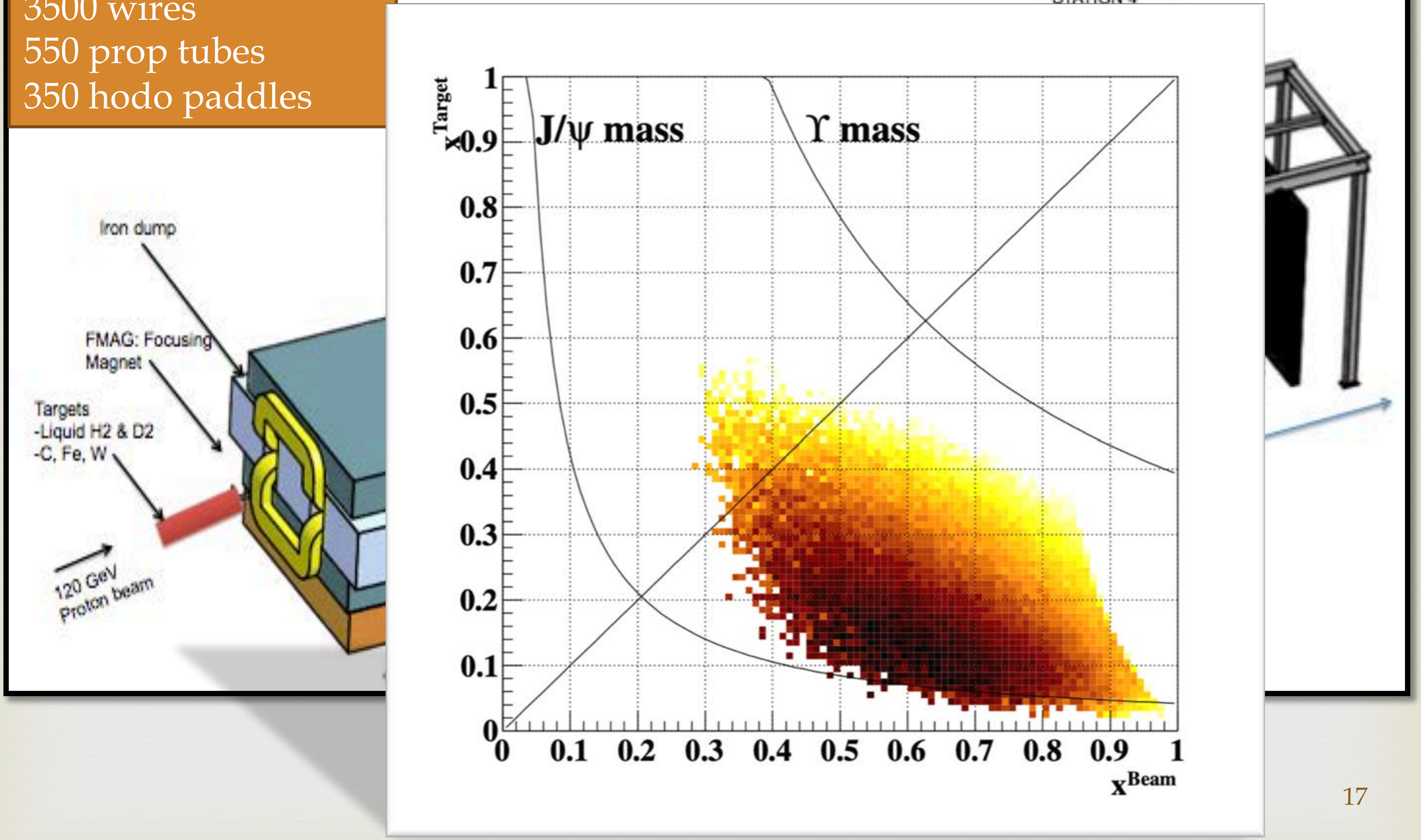
- Each bin is a 19 ns bucket
- Veto Level
- Even beam distribution



FOURIER TRANSFORM

The SeaQuest Spectrometer

3500 wires
550 prop tubes
350 hodo paddles



Timeline of SeaQuest

Stony Brook University

PVDIS workshop

March 2012

I

Shutdown

Nov 2013

II

Shutdown

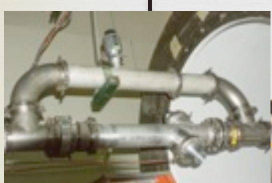
Nov 2014

III

Shutdown

IV & V & VI

FINISH



Main injector upgrades

DAQ upgrade

Commissioning run

- All detector subsystems work
- Issues and upgrades addressed

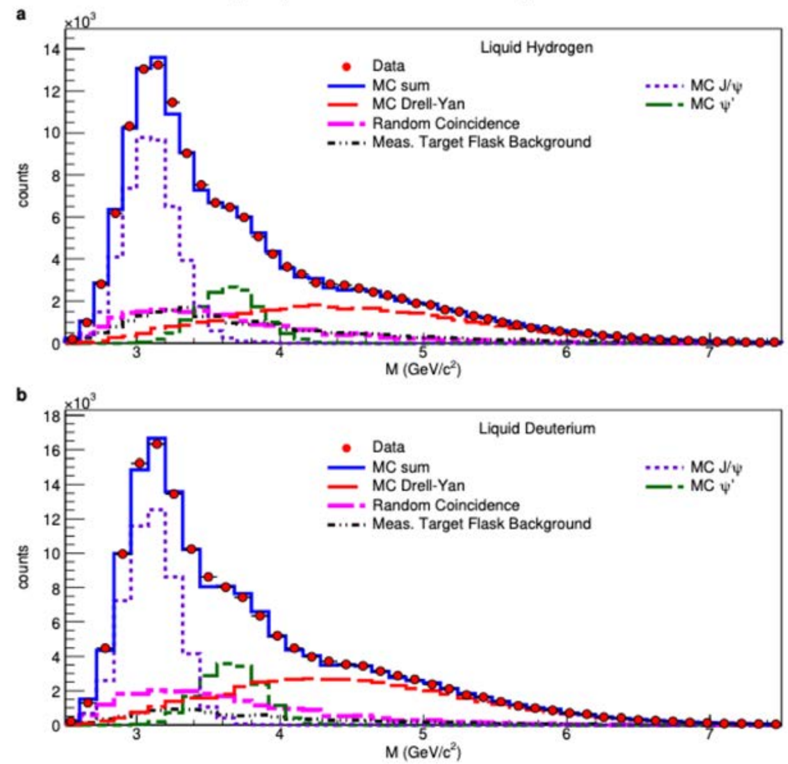
- Stable operation of all detector sub systems
- Dark photon road sets included into the trigger system
- New St3- installed

- Improved duty factor
- Continue data taking

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

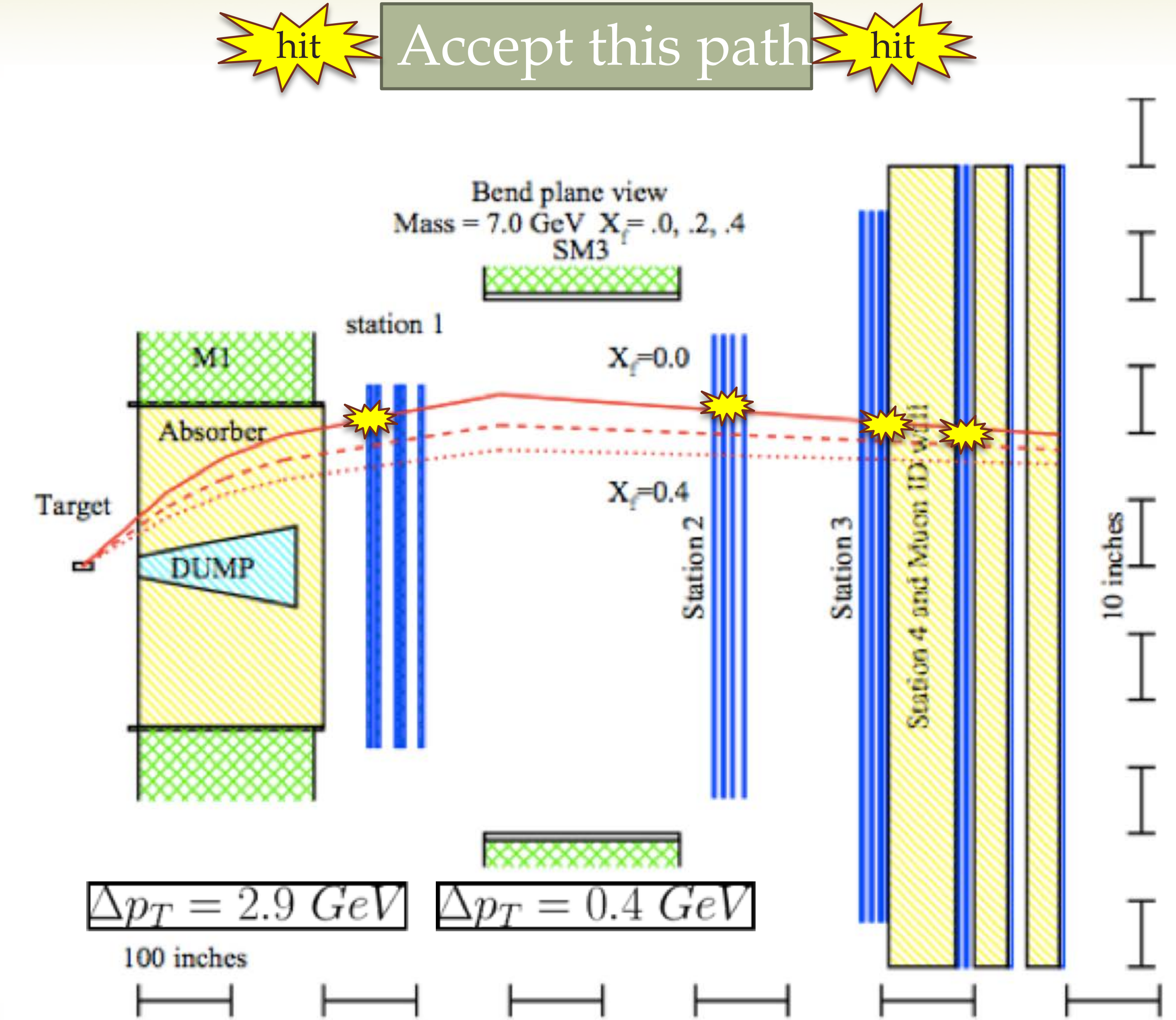
Event selection and reconstruction

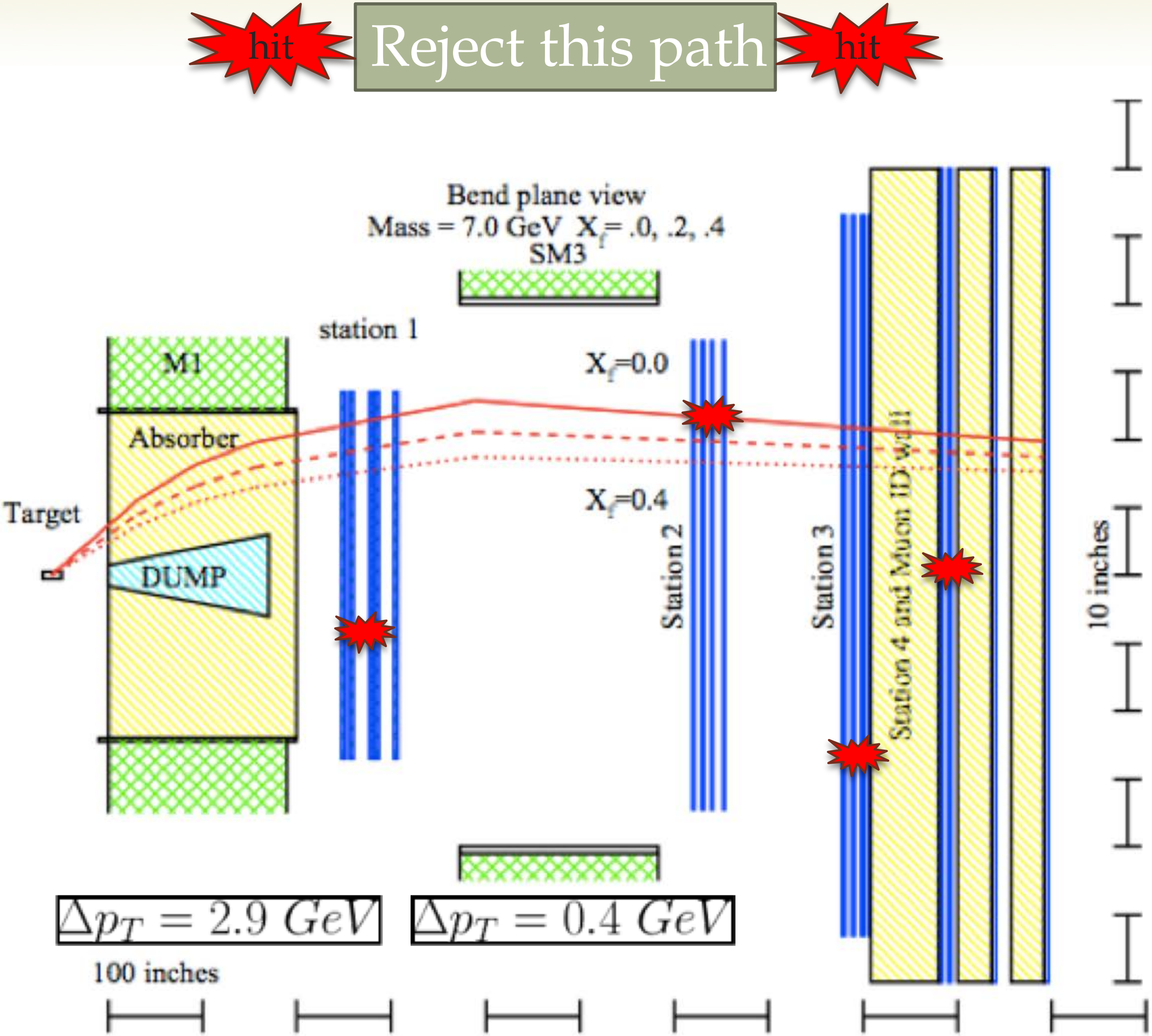
- Invariant mass spectrum for FY 2015 data
- 30% of anticipated data
- Data agrees well with Monte Carlo (spectrometer works as expected)
- Data with Mass > 4.5 GeV are mostly dimuons coming from the Drell-Yan process



The reconstructed muon pair invariant mass spectra for the liquid hydrogen (a) and liquid deuterium (b) targets. In the lower mass region, the predominant signal is produced by $J/\psi \rightarrow \mu^+\mu^-$ decay, followed by the $\mu^+\mu^-$ decay of the ψ'. The prominence of the J/ψ provides a calibration point for the absolute field of the solid iron magnet. At invariant masses above 4.5 GeV/c^2 the Drell-Yan process becomes the dominant feature. The data are shown as red points. Additionally, Monte Carlo (MC) simulated distributions of Drell-Yan, J/ψ, and ψ' along with measured random coincidence and empty target backgrounds are shown. The sum of these is shown in the blue solid curve labeled MC sum. The normalizations of the Monte Carlo and the random background were from a fit to the data.

Accept this path

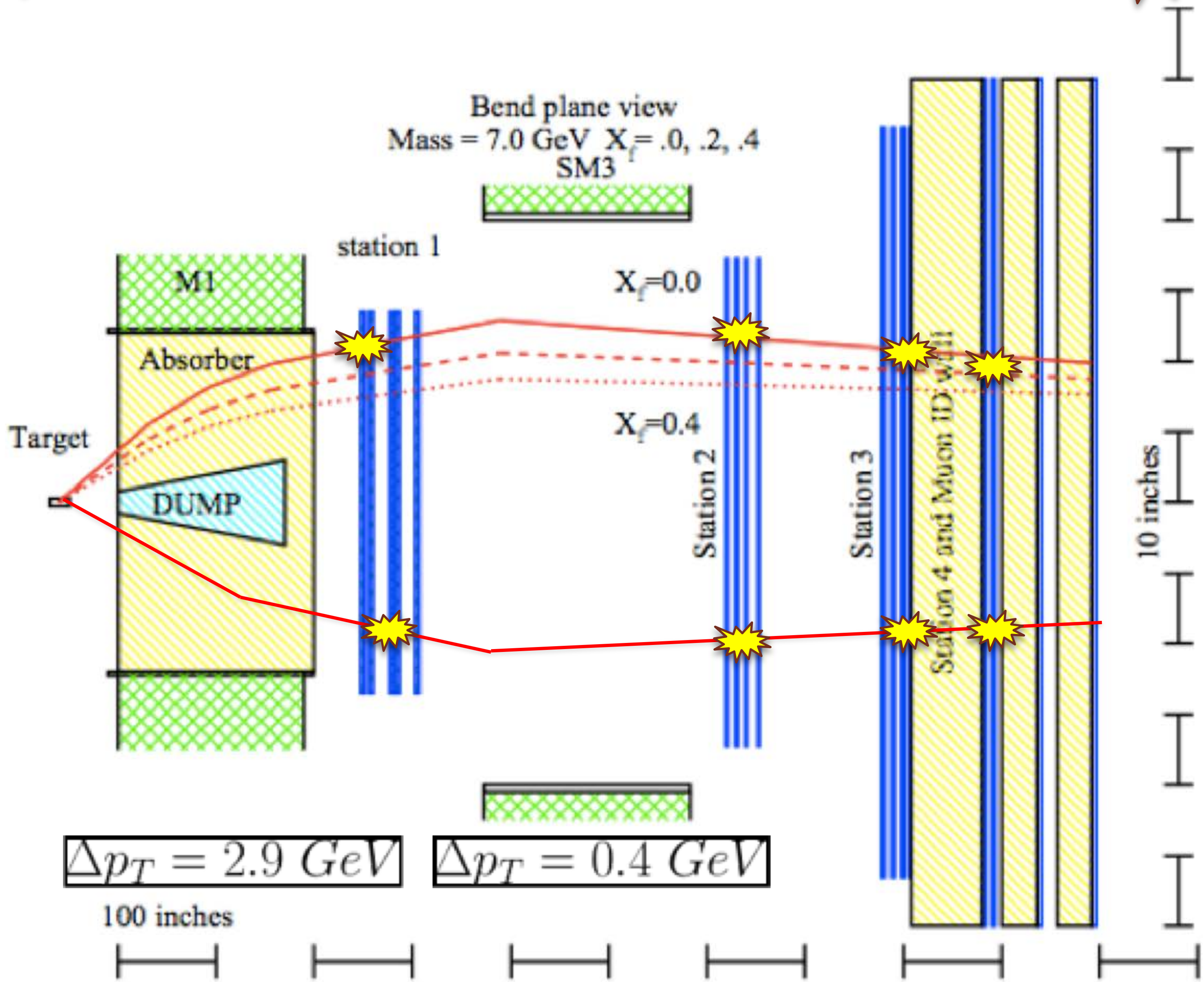



hit
Reject this path
hit
Bend plane view
Mass = 7.0 GeV X_f = .0, .2, .4
SM3
station 1
M1
Absorber
Target
DUMP
X_f=0.0
X_f=0.4
Station 2
Station 3
Station 4 and Muon ID wall
10 inches
Δp_T = 2.9 GeV
Δp_T = 0.4 GeV
100 inches

Signal is a coincidence of μ^+ & μ^- paths

hit

hit



$\Delta p_T = 2.9\ GeV$

$\Delta p_T = 0.4\ GeV$

SeaQuest asks important questions!

Absolute cross sections

What is the origin of the nucleon sea?

J/ψ and ψ′ suppressed after generated in cold nuclear matter?

Light Quark flavor asymmetry in the nucleon sea

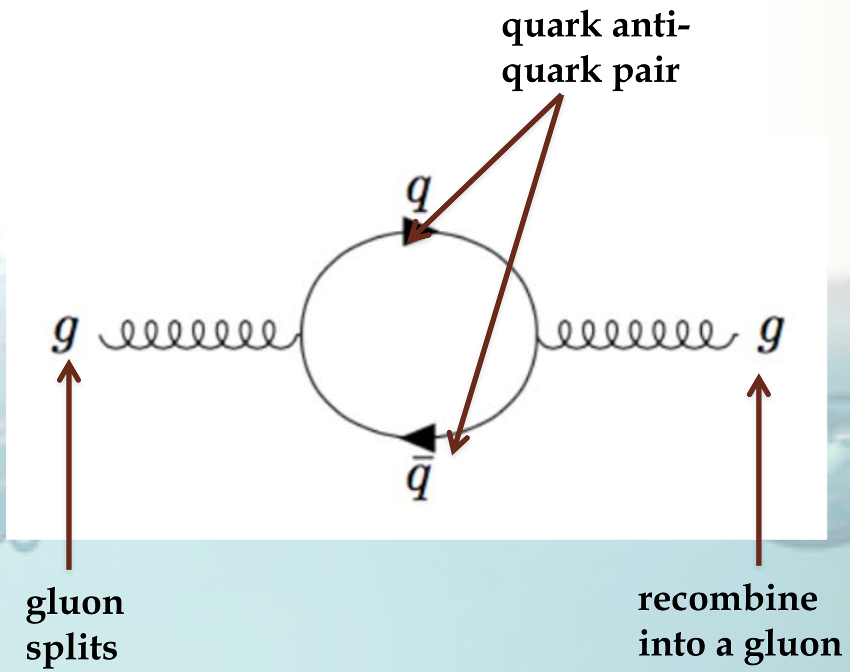
Anti shadowing and EMC effect observed in anti-quarks in nuclei?

How much energy do partons lose while traversing cold nuclear matter?

Did you just say dark photons??

Nucleon sea (Flavor symmetric?)

- Nucleon sea naively assumed to be flavor symmetric
- Gluons don't couple to flavor
- Masses of u and d quarks are small and similar, compared to QCD scale



Perturbative contributions calculated to be small!

D. A. Ross and C. T. Sachrajda, Nucl. Phys. B149, 497 (1979)

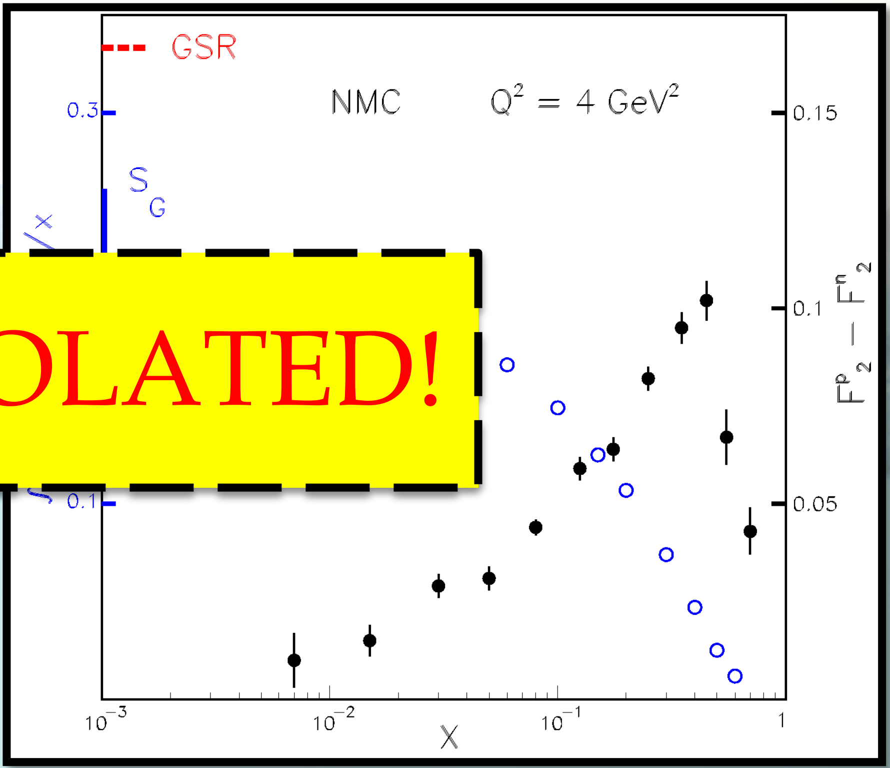
NMC (1991)

- Gottfried Sum Rule gives insight into the relative light quark flavor content of the nucleon

$$S_G = \frac{1}{3} + \int_0^1 \frac{2}{3}(\bar{u}^p(x) - \bar{d}^p(x))\,dx$$

- Symmetric sea i
- NMC experime GeV and 280 GeV muon beam)

GSR VIOLATED!



$$S_G = \int_{0.004}^{0.8} (F_2^p - F_2^n)\,dx/x$$

$$= 0.221 \pm 0.008 \pm 0.019$$

Amaudruz *et. al.* Phys. Rev. D 66, 21
Arneodo *et. al.* Phys. Rev. D 50, 1

- After extrapolation to 0 and 1

$$= 0.235 \pm 0.026$$

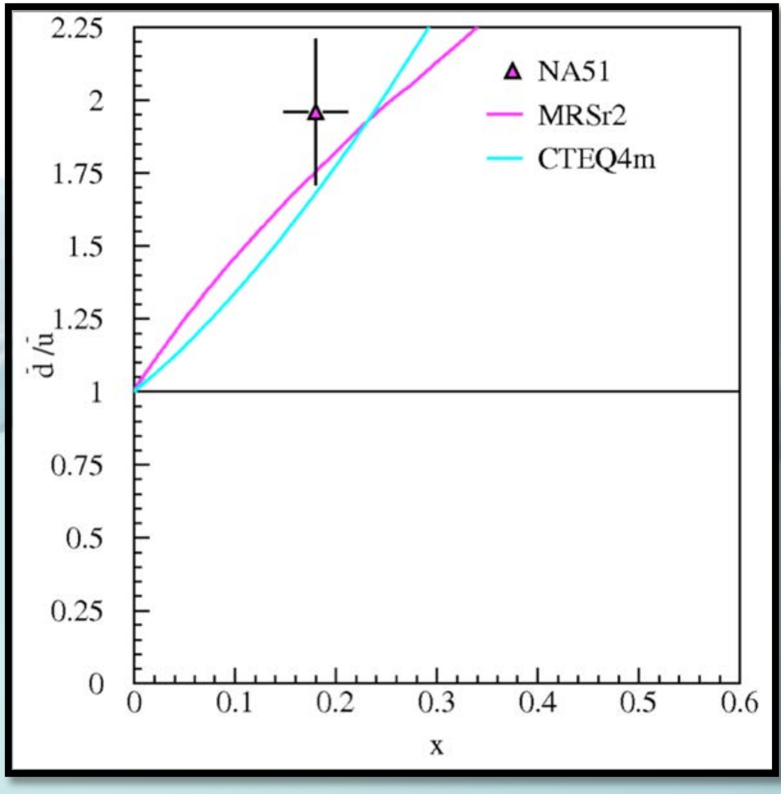
NA51 (1994)

- 450 GeV proton beam, LD2, LH2 targets

$$A_{DY} = \frac{\sigma_{pp} - \sigma_{pn}}{\sigma_{pp} + \sigma_{pn}} = 2\frac{\sigma_{pp}}{\sigma_{pd}} - 1$$

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

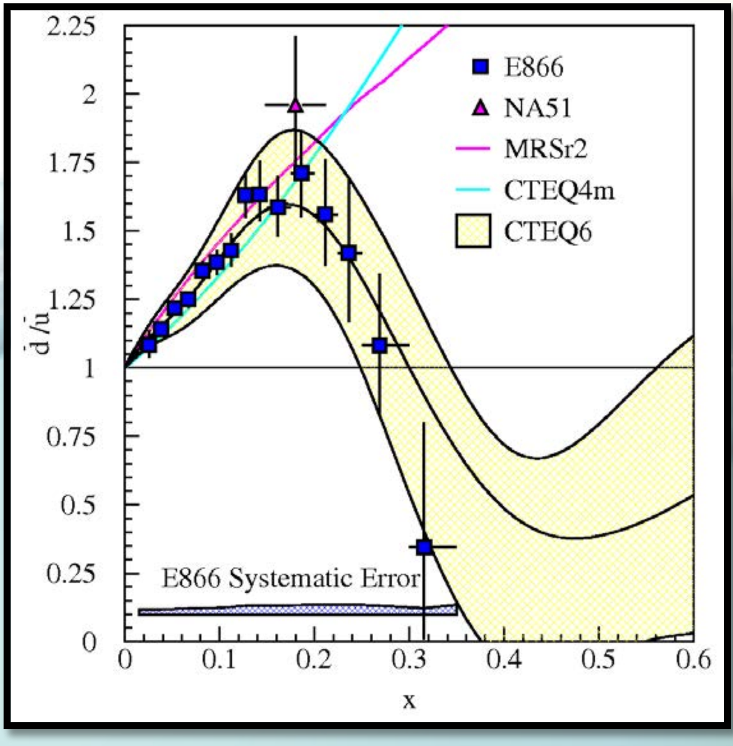
$$\left.\frac{\bar{d}}{\bar{u}}\right|_{\langle x \rangle = 0.18} = 1.96 \pm 0.15 \pm 0.05$$



Baldit *et. al.* Phys. Lett. B 332, 244-250

E866 (1998)

- Mapped out the x dependence
- Overturn at 0.2
- Drop in the ratio below 1 at x_B = 0.25 (limited statistical uncertainty and bin on edge of acceptance)
- This asymmetry has to come from a non-perturbative origin!



R.S. Towell *et. al*. Phys. Rev. D 64, 244-250

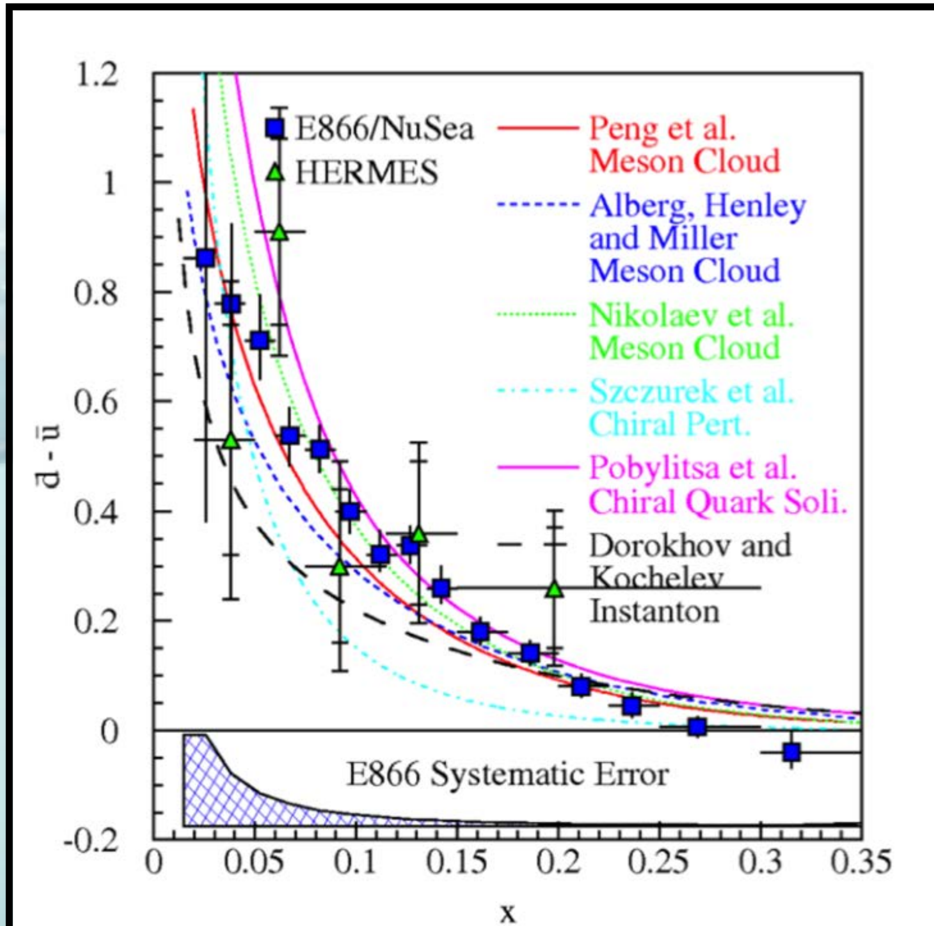
Origin of the nucleon sea

- Symmetric (perturbative and non-perturbative) component cancels away in the difference
- Non-perturbative models are motivated to explain the observed difference

x_{min}	x_{max}	$\int_{x_{min}}^{x_{max}} (\bar{d} - \bar{u})dx$	Q^2 (GeV^2)	Source	Ref.
0.0	1.0	0.147 ± .026	4	NMC	[8]
0.015	0.35	0.080 ± 0.011	54	NUSEA	[12]
0.0	1.0	0.118 ± 0.012	54	NUSEA	[12]
0.001	1.0	0.165	54	CT66nlo	[31]
0.001	1.0	0.114	54	CT10nlo	[16]
0.001	1.0	0.116	2	CT10nlo	[16]
0.01	1.0	0.090	54	CT14nlo	[17]
0.001	1.0	0.086	1	Stat. Mod.	[32]
0.	1.0	0.13	?	Det. Bal.	[33]
0.02	0.345	0.108	54	Chiral Soliton	[34]
0.0	1.0	0.13 ± 0.07	?	Lattice	[35]

Table I. Integrals of $(\bar{d} - \bar{u})$ from x_{min} to x_{max} from experiment (NMC and NUSEA) and from several global fits (CTEQ6.6, CTEQ10, CTEQ14), calculations (Lattice), and models (Statistical and Detailed Balance). The weak variation of the integral to the choice of scale is illustrated with the CTEQ10 comparison at 2 and 54 GeV^2. The scales of the detailed balance and lattice calculations are not explicitly reported in those references.

Peng *et al.* Phys. Rev. D 58 092004

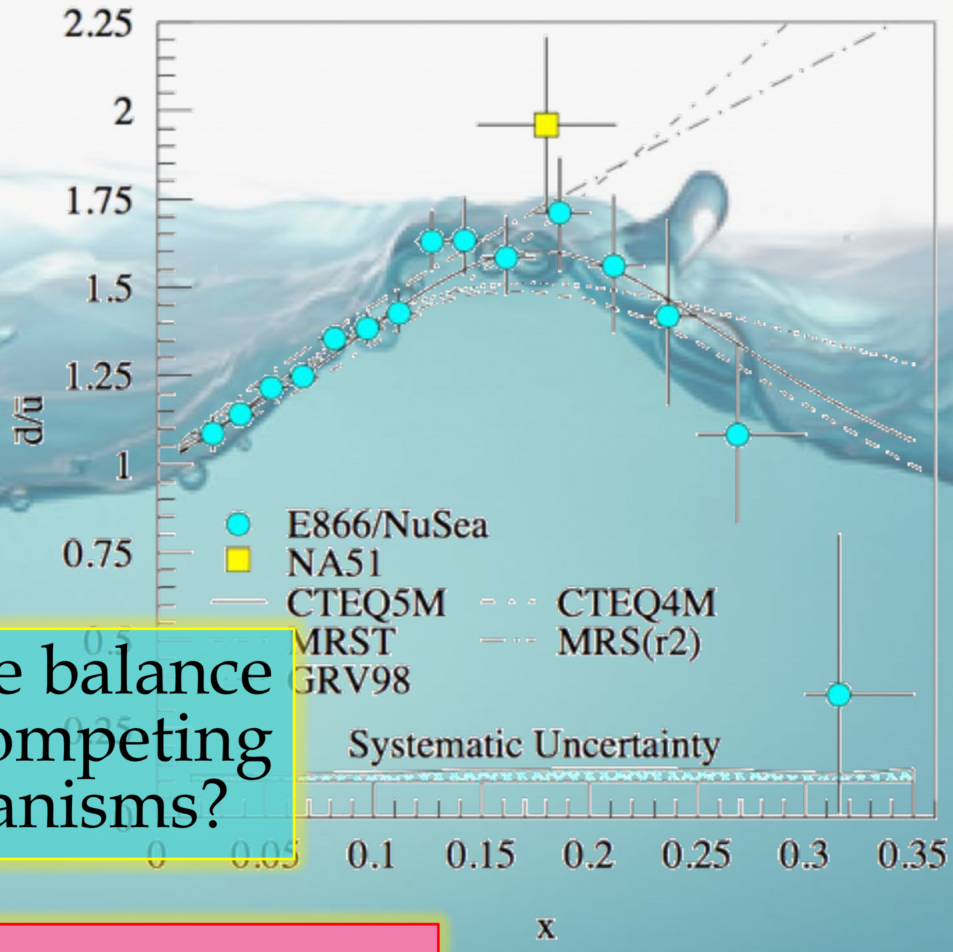


D.F. Geesaman, P.E. Reimer Rept.Prog.Phys. 82 (2019) 4, 046301

How is the nucleon sea generated?

Meson Cloud model?

Chiral Quark Soliton model?



Delicate balance of all competing mechanisms?

Connected-sea partons?

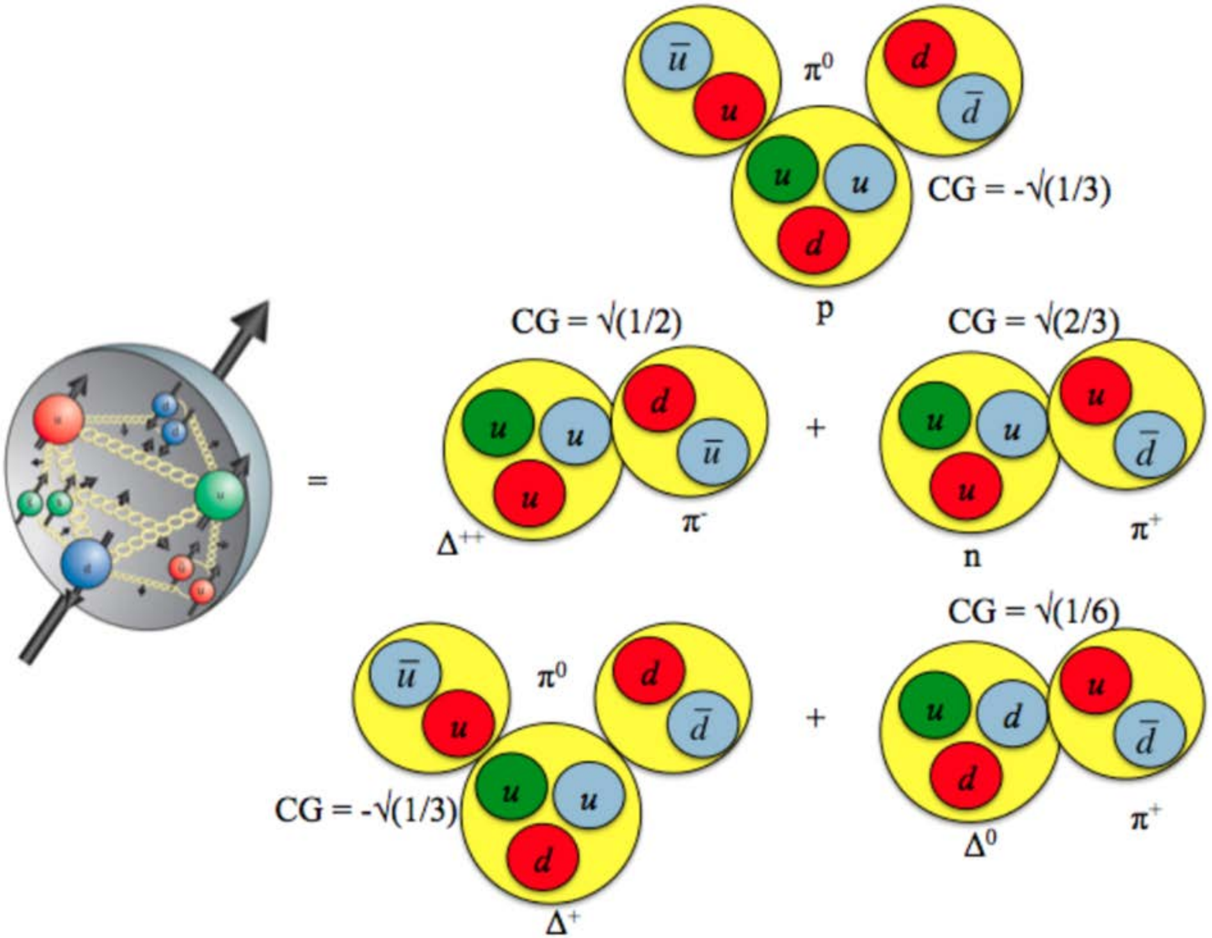
Instanton model?

Hybrid model?

Statistical parton distribution functions?

Naïve meson cloud model

Look at the Clebsch-Gordan coefficients…



Pauli blocking + meson cloud

- Attempts to explain the suppression of a certain flavor of quark antiquark pair
- Presence of an additional u valence quark suppresses $u\bar{u}$ as compared to $d\bar{d}$
- Not fully blocked as newly created antiquark can exist with other antiquarks with a different color

Dynamics of light antiquarks in the proton

W. Melnitchouk*
Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany

J. Speth†
Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany

A. W. Thomas‡
Department of Physics and Mathematical Physics, and Special Research Centre for the Subatomic Structure of Matter, University of Adelaide, Adelaide 5005, Australia
(Received 4 June 1998; published 8 December 1998)

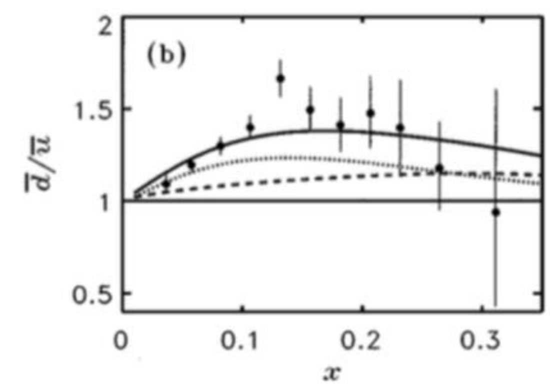
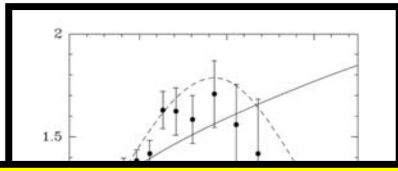
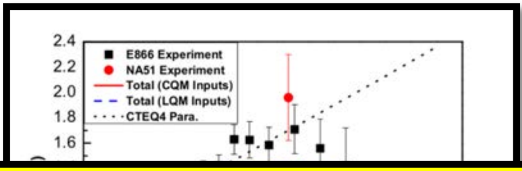


FIG. 11. Contributions from pions with $\Lambda_{\pi N} = 1$ GeV and $\Lambda_{\pi\Delta} = 1.3$ GeV (dashed) and from antisymmetrization (dotted) to the (a) $\bar{d} - \bar{u}$ difference and (b) $\bar{d}/\bar{u}$ ratio, and the combined effect (solid).

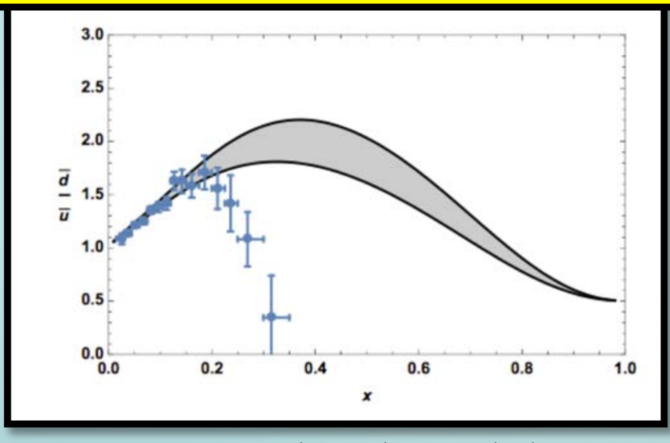
Phys. Rev. D 59, 014033 (1998)
Phys. Rev. D 15, 2590

Many models…
none predict drop below 1 at x = 0.25

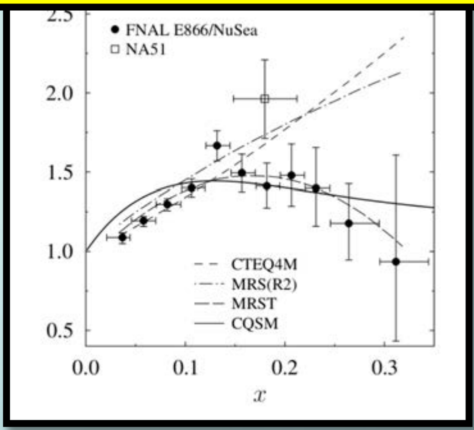




A model that captures the correct non-perturbative physics that generates the nucleon sea will account for the observed flavor asymmetry!



Meson cloud model



Chiral Quark Soliton model

QUANTUM PHYSICS

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Article

The asymmetry of antimatter in the proton

https://doi.org/10.1038/s41586-021-03282-z

Received: 2 June 2020

Accepted: 15 December 2020

Published online: 24 February 2021

Check for updates

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The nuclear physicist Paul Reimer (left) amid SeaQuest, an experiment at Fermilab ... out of used parts.

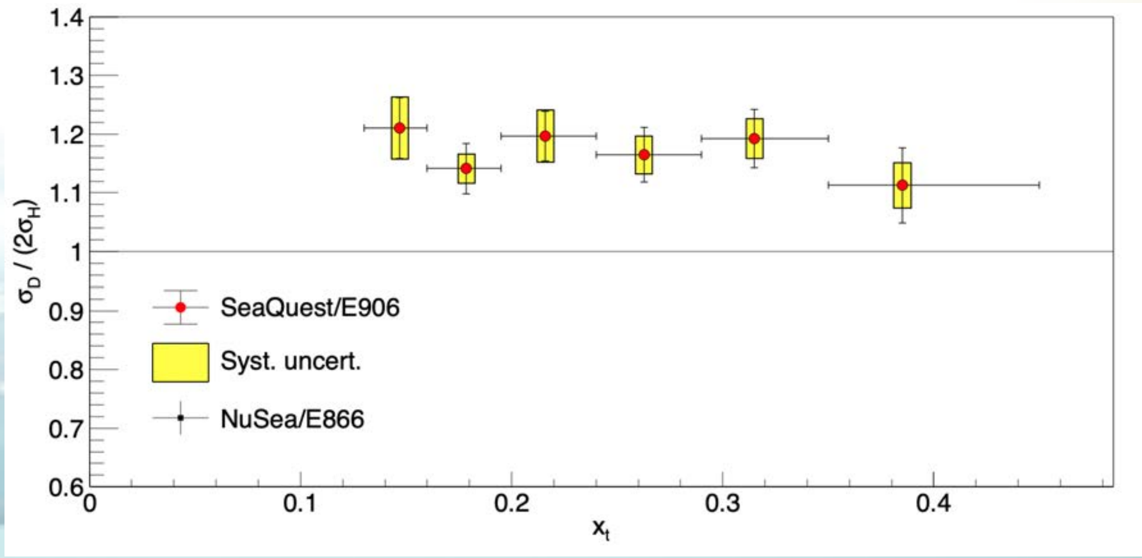
Protons are messy on the inside. Made ... constantly shifting collection of transient quarks and antiquarks ... and gluons (squiggles) that bind the quarks together.

$\frac{\sigma_{pd}}{2\sigma_{pp}}$ Cross section ratio results

- ~30% of the anticipated data

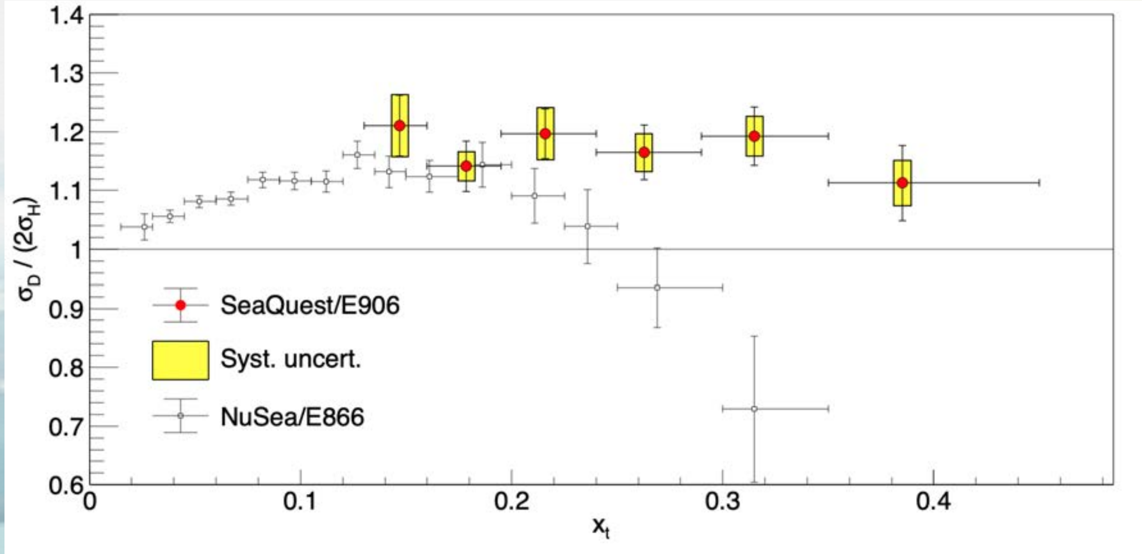
- Ratio of cross-sections of LD2 and LH2

Dove et.al. Nature 590, 561 – 565 (2021)



$\frac{\sigma_{pd}}{2\sigma_{pp}}$ Cross section ratio results

Dove et.al. Nature 590, 561 – 565 (2021)

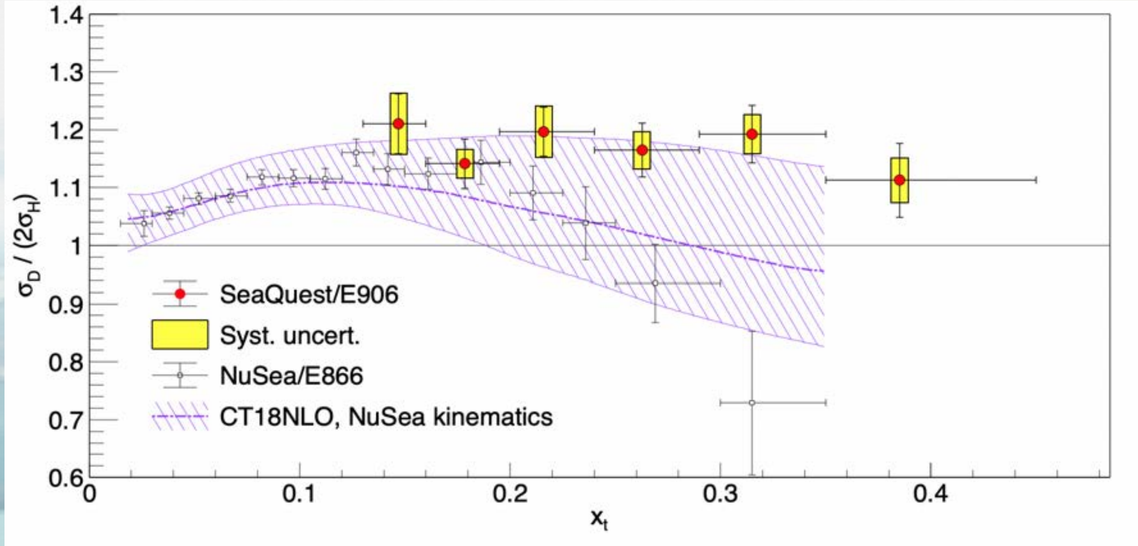


- Comparison with E866/NuSea
- Some differences are expected as the experiments have different
  - beam energies
  - acceptance
  - x_B distributions for a given x_T value

$$\frac{\sigma_{pd}}{2\sigma_{pp}}$$

Cross section ratio results

Dove et.al. Nature 590, 561 – 565 (2021)



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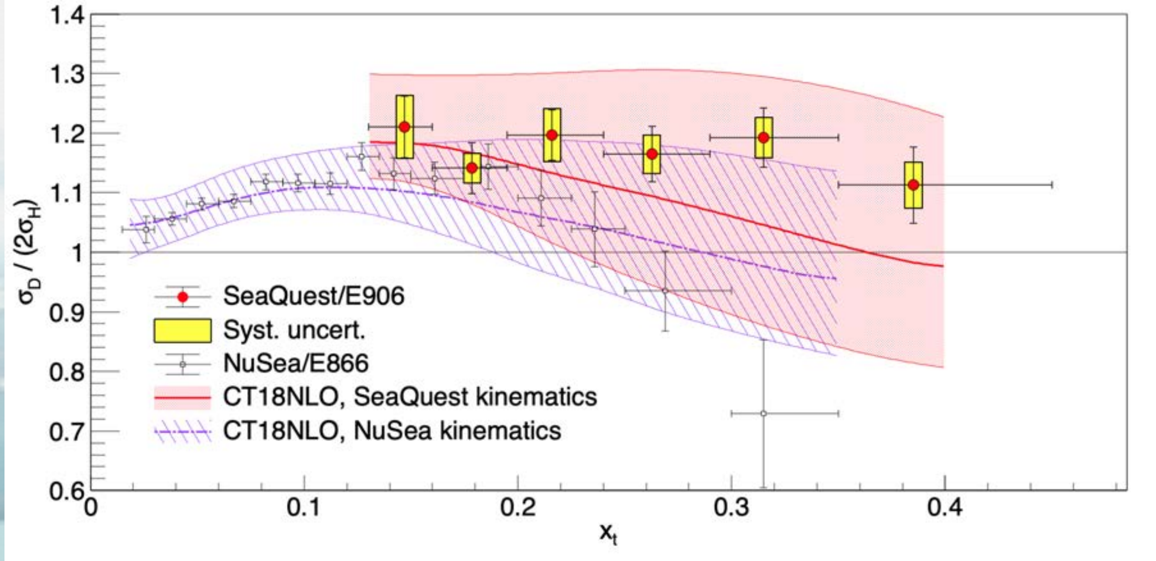
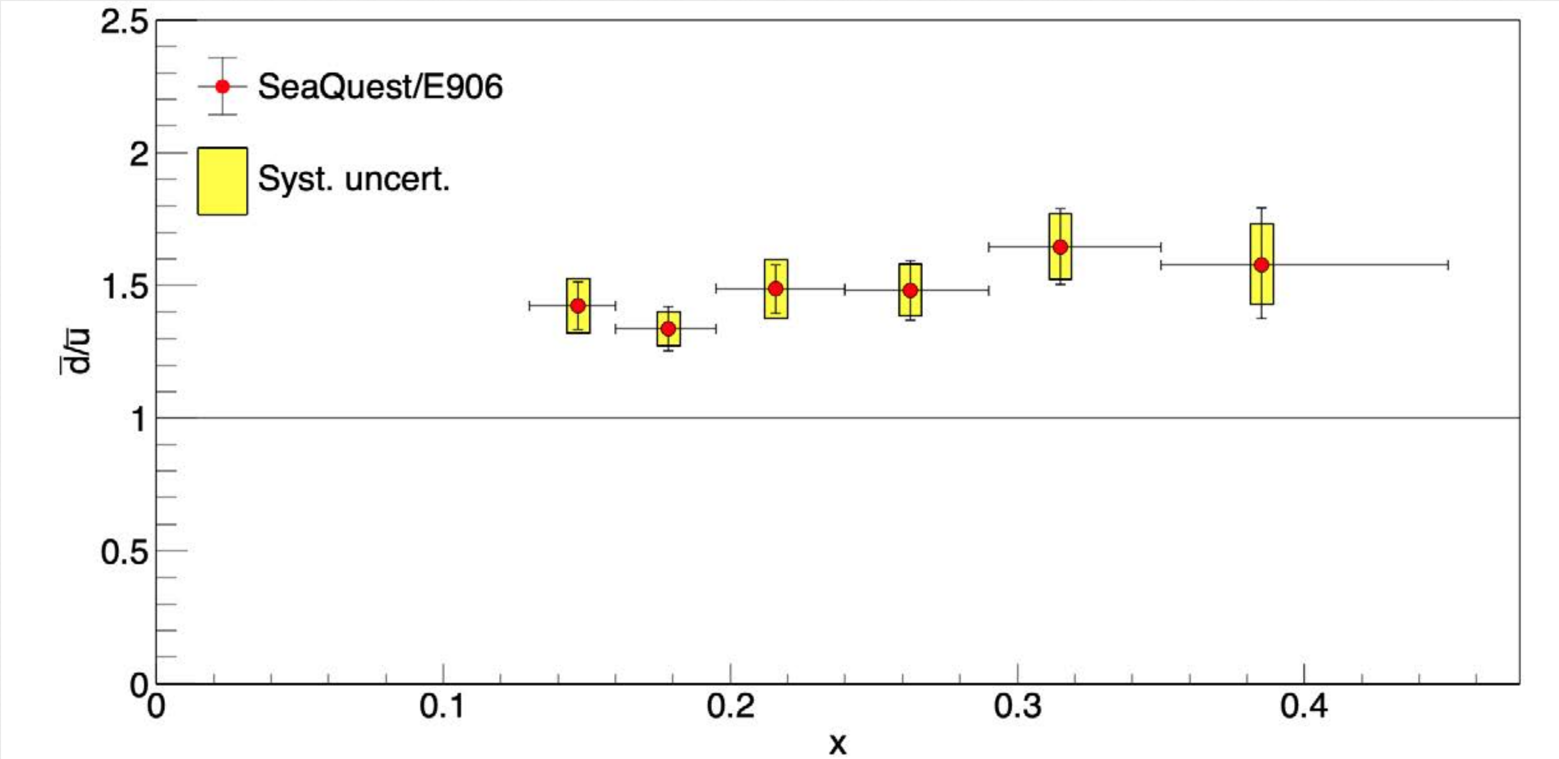


- Comparison with E866/NuSea
- Some differences are expected as the experiments have different
  - beam energies
  - acceptance
  - x_B distributions for a given x_T value

$$Q^2 = x_1 x_2 s$$

$\bar{d}(x)/\bar{u}(x)$ - results

Dove et.al. Nature 590, 561 – 565 (2021)

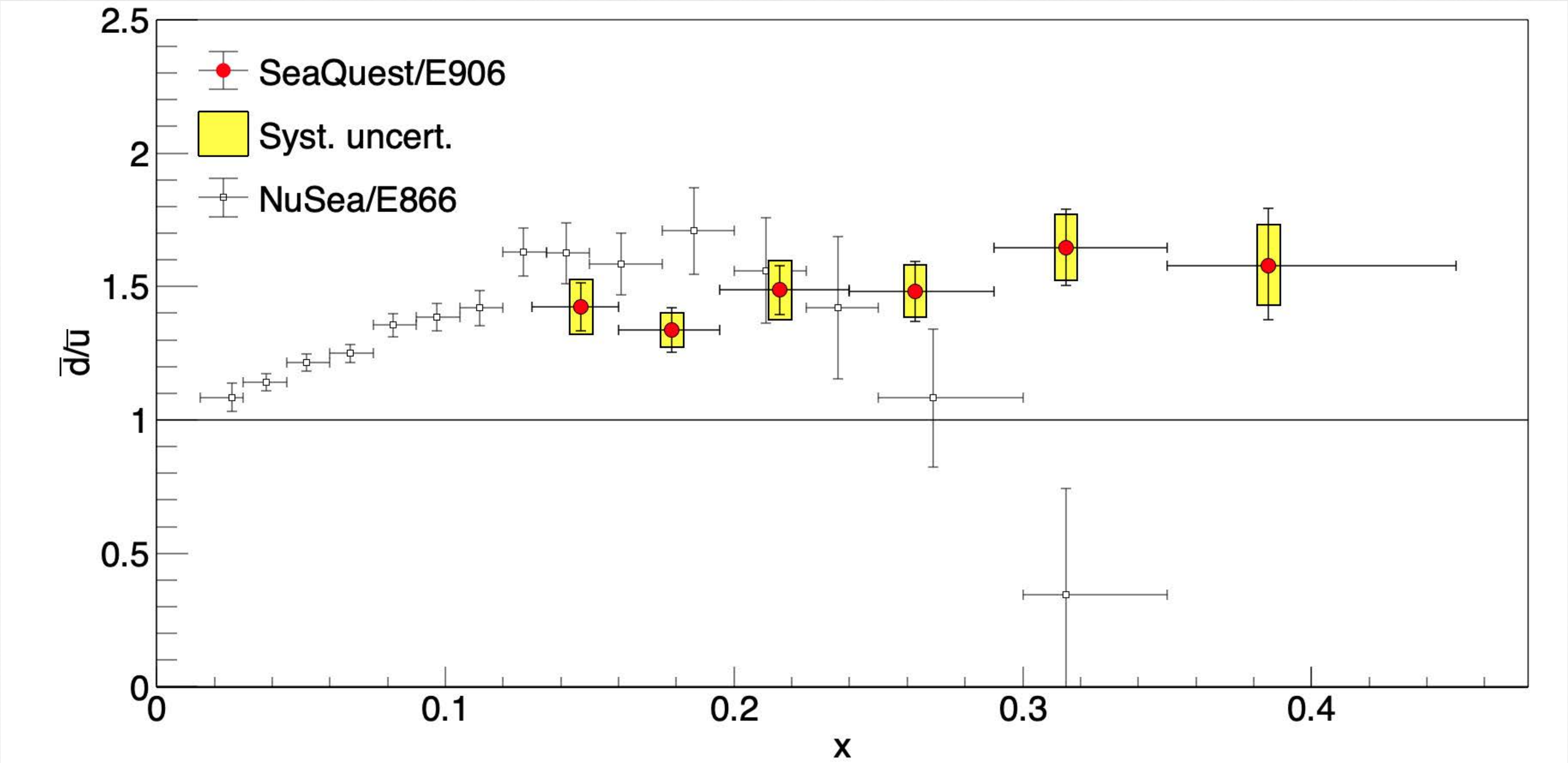


*NLO analysis

- SeaQuest data points show that nature prefers anti-down over anti-up in the proton!

$\bar{d}(x)/\bar{u}(x)$ - results

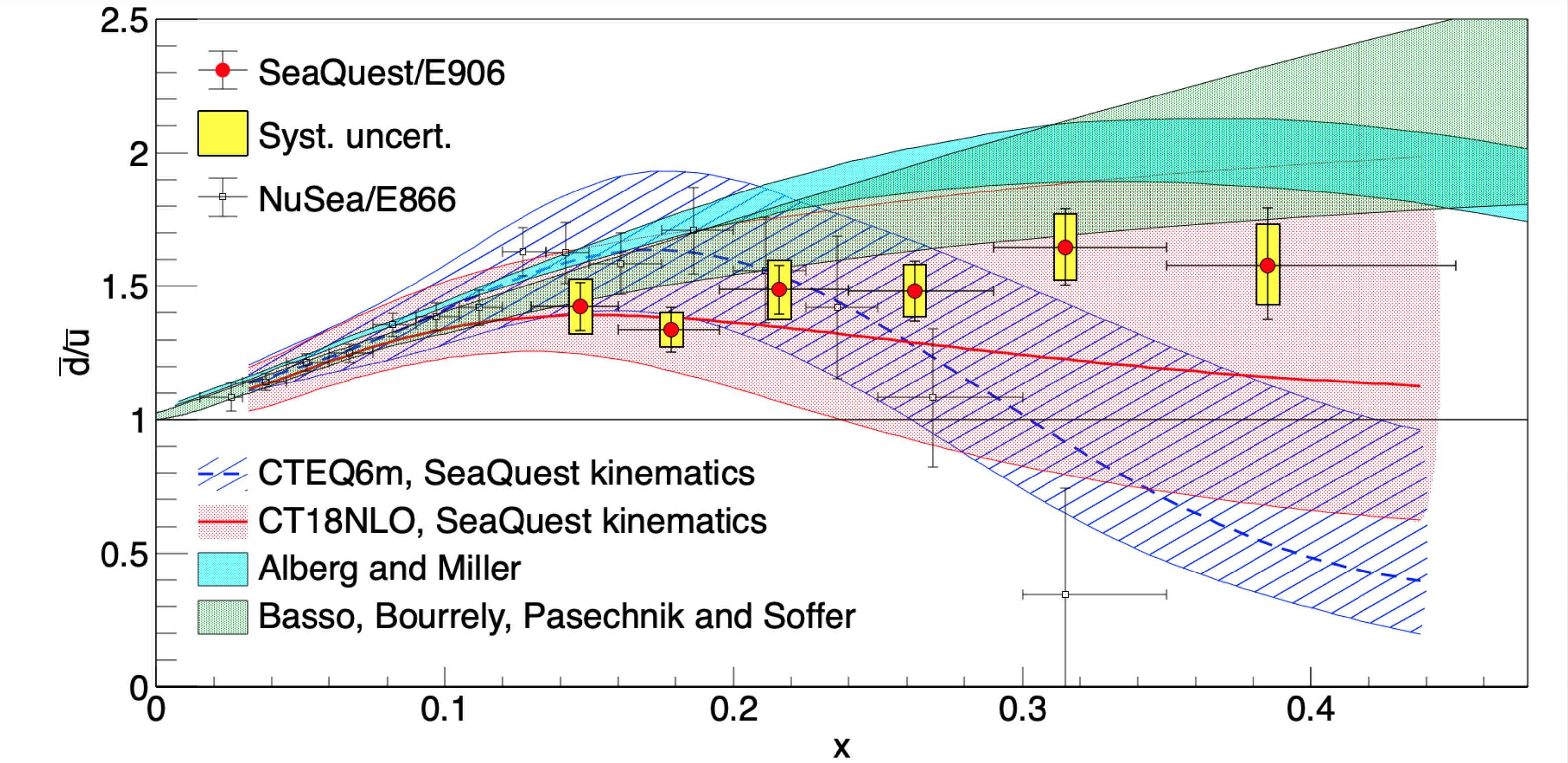
Dove et.al. Nature 590, 561 – 565 (2021)



- Higher statistical precision compared to NuSea in the intermediate x region
- SeaQuest data points stay above 1 for all of the measured range of x

$\bar{d}(x)/\bar{u}(x)$ - results

Dove et.al. Nature 590, 561 – 565 (2021)



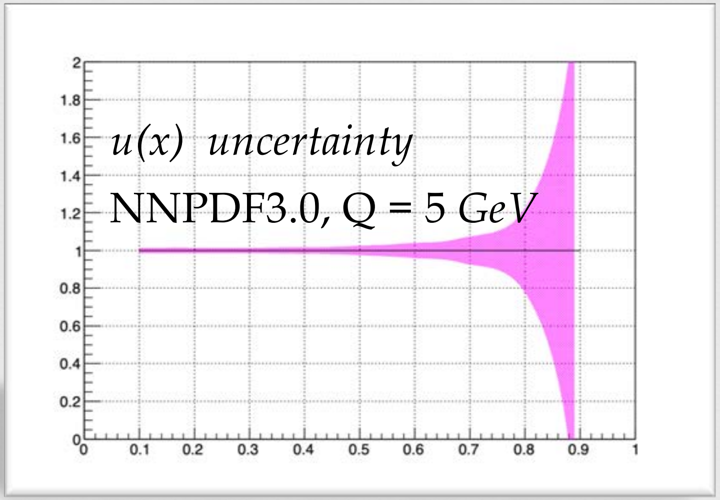
- Good agreement with Alberg and Miller, and Basso et al.

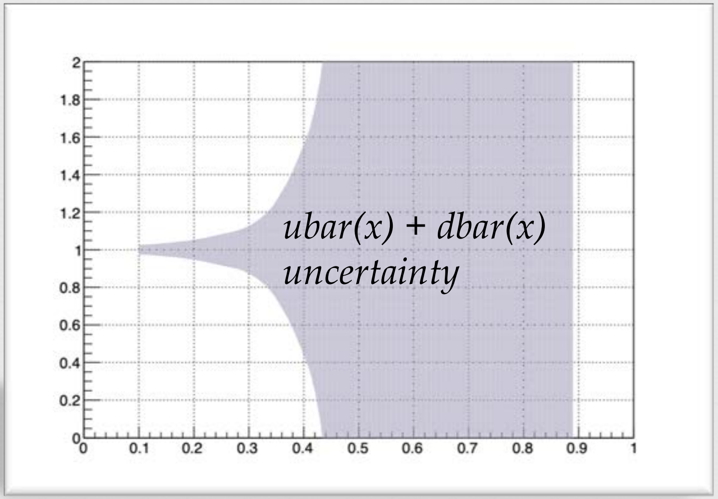
Absolute cross sections from p+d interactions

- The proton deuterium data can be used to look into *ubar(x)* + *dbar(x)* at intermediate *x*, where the sea quark distribution is poorly known.

- In order to calculate *dbar(x)* - *ubar(x)* from *dbar(x)/ubar(x)*, knowledge of *dbar(x)* + *ubar(x)* is required

- *u(x)* well known at intermediate-x . On the contrary *ubar(x) + dbar(x)* has huge uncertainties for x>0.3





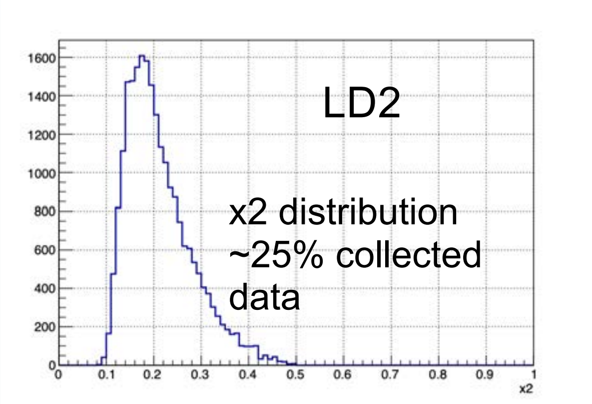
$$\sigma_{pd} = \sigma_{pp} + \sigma_{pn}$$

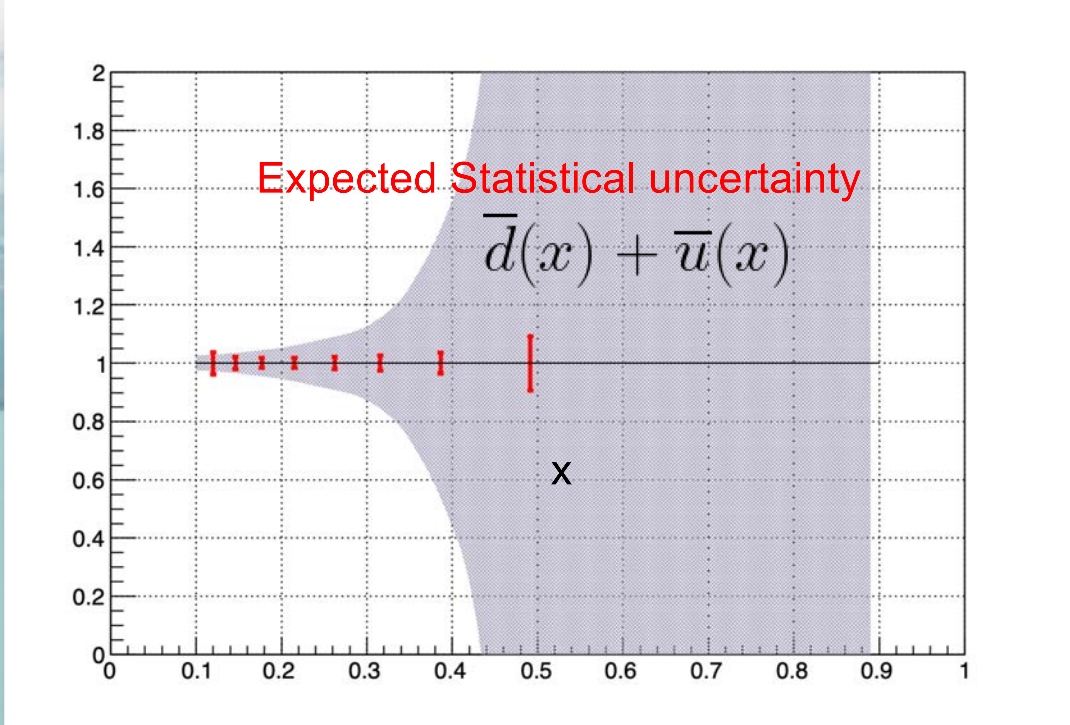
$$\left.\frac{d^2\sigma_{pd}}{dM^2 dx_F}\right|_{x1>x2} \approx \frac{4\pi\alpha^2}{9M^4}\frac{x_1 x_2}{x_1+x_2}\left(\frac{4u(x_1)+d(x_1)}{9}\right)\left(\bar{d}(x_2)+\bar{u}(x_2)\right)$$

Slide credit: Shivangi Prasad

$\overline{d}(x) + \overline{u}(x)$ from SeaQuest

- Data taken on LD2 target
- Analysis in progress





Slide credit: Shivangi Prasad

Bayesian Monte Carlo extraction of sea asymmetry with SeaQuest and STAR data

C. Cocuzza,[1] W. Melnitchouk,[2] A. Metz,[1] and N. Sato[2]

[1] *Department of Physics, SERC, Temple University, Philadelphia, Pennsylvania 19122, USA*
[2] *Jefferson Lab, Newport News, Virginia 23606, USA*

Jefferson Lab Angular Momentum (JAM) Collaboration

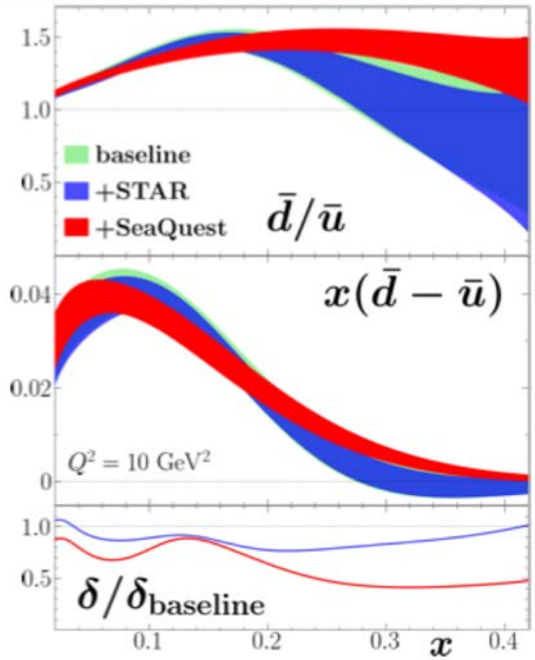


FIG. 5. Impact on the $\bar{d}/\bar{u}$ ratio (top panel) and the asymmetry $x(\bar{d}-\bar{u})$ (middle panel) of the W-lepton data from STAR [39] (blue bands) and the Drell-Yan measurement from SeaQuest [38] (red bands) relative to the "baseline" (green bands) which contains all data except these. The STAR and SeaQuest data are added in succession. The uncertainty on $\bar{d}/\bar{u}$ for these two scenarios normalized to that of the baseline are shown in the bottom panel. All bands represent 1σ uncertainty.

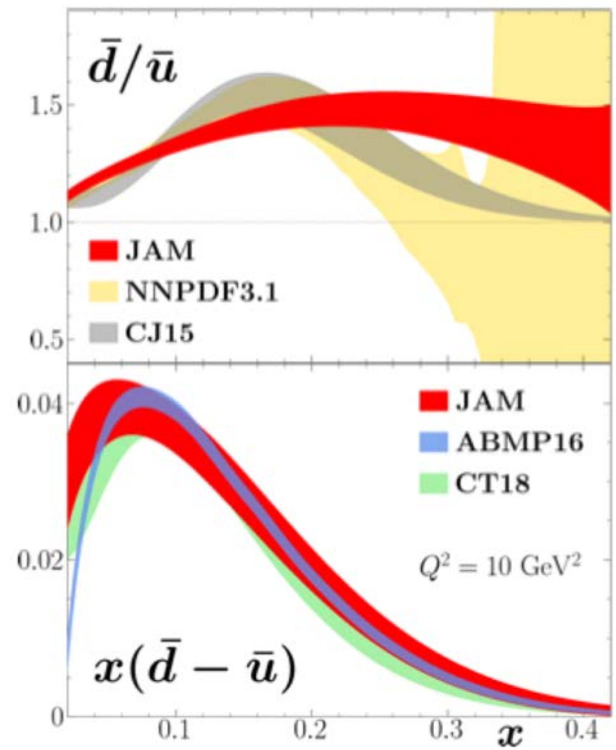
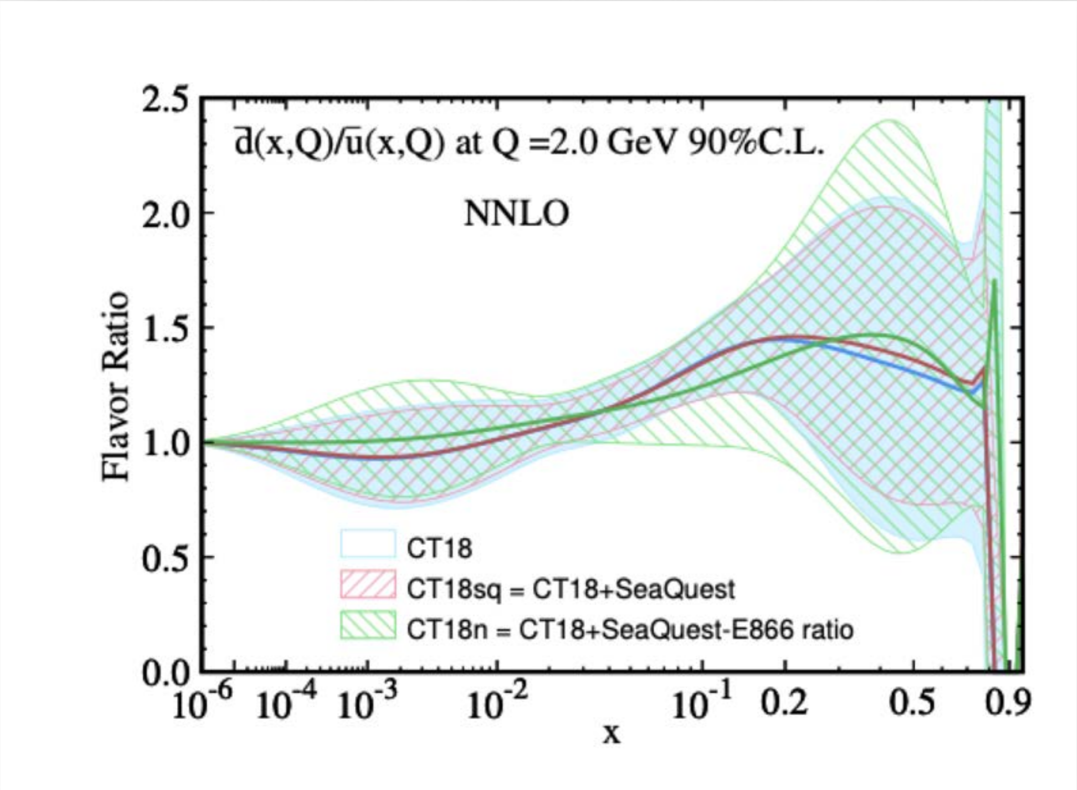


FIG. 6. Comparison of the JAM $\bar{d}/\bar{u}$ and $x(\bar{d}-\bar{u})$ PDFs (red bands) with the NLO parametrizations from NNPDF3.1 [75] (gold), ABMP16 [76] (blue), CJ15 [77] (gray), and CT18 [78] (green) at the scale $Q^2 = 10$ GeV^2. All bands represent 1σ uncertainty.

Slide courtesy: Chris Cocuzza et al

NNLO constraints on proton PDFs from the SeaQuest and STAR experiments and other developments in the CTEQ-TEA global analysis



https://arxiv.org/abs/2108.06596

CJ15 – Sanghwa Park, Alberto Accardi, Xiaoxian, J.F. Owens

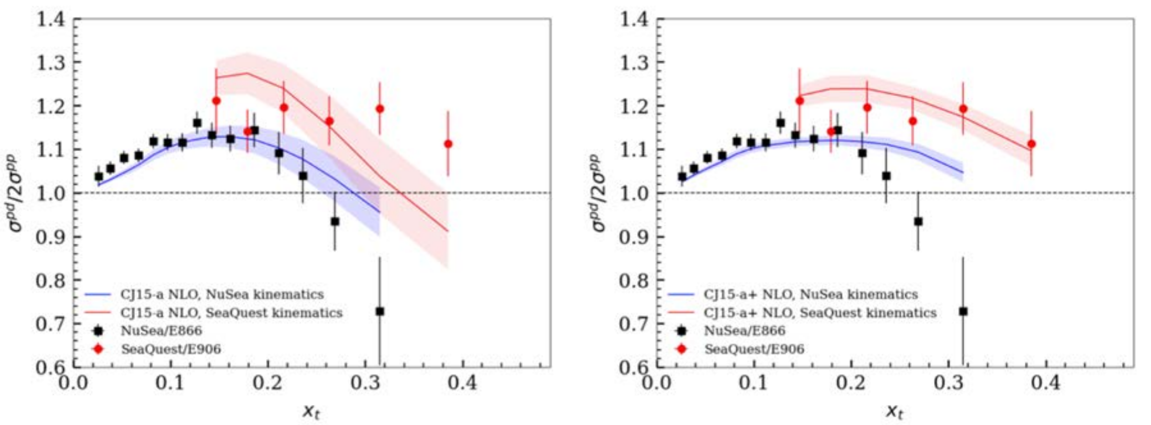


Figure 2: Cross section ratio of Drell-Yan lepton pair production in $p + d$ and $p + p$ collisions by E866 and SeaQuest experiments compared with CJ15 NLO calculations before (left) and after (right) including the SeaQuest and STAR data.

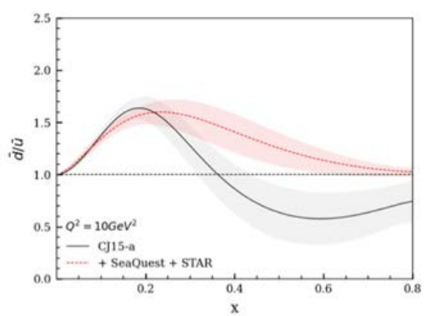
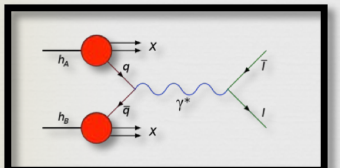


Figure 3: $\bar{d}$ over $\bar{u}$ ratio at $Q^2 = 10$ GeV^2 extracted from the CJ15 PDF fits before (CJ15-a, black solid line) and after (CJ15-a+, red solid line) adding the STAR W lepton charge ratio data in $p+p$ collisons and the SeaQuest Drell-Yan lepton pair production ratio in $p+p$ and $p+d$ collisions on top of the data sets used for the standard CJ15 PDF analysis.

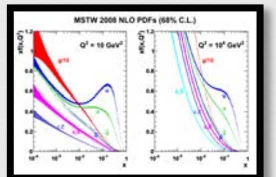
https://arxiv.org/abs/2108.05786

Recap - I

Drell-Yan process

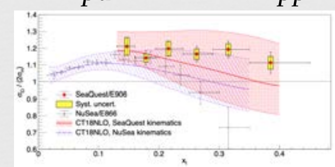


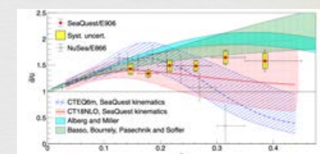
→ Anti-quark distributions in the nucleon



→ SeaQuest E906

$\sigma_{pd}(x)/2\sigma_{pp}(x)$

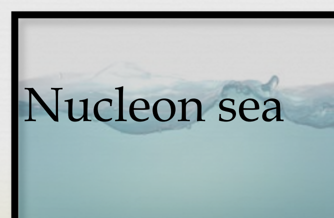




$\bar{d}(x)/\bar{u}(x)$

*unpolarized

Constraints on various non perturbative models that attempt to explain nucleon sea at high-*x*



W.-C. Chang, J.-C. Peng / Progress in Particle and Nuclear Physics 79 (2014) 95–135

Table 5

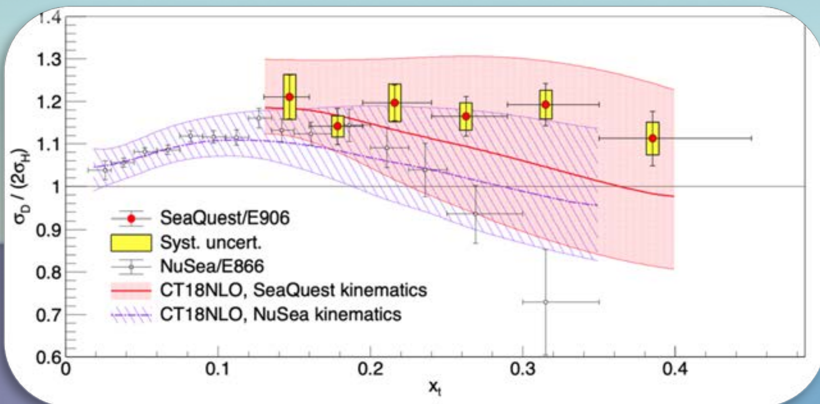
Prediction of various theoretical models on the integral $I_\Delta = \int_0^1[\Delta\bar{u}(x) - \Delta\bar{d}(x)]dx$.

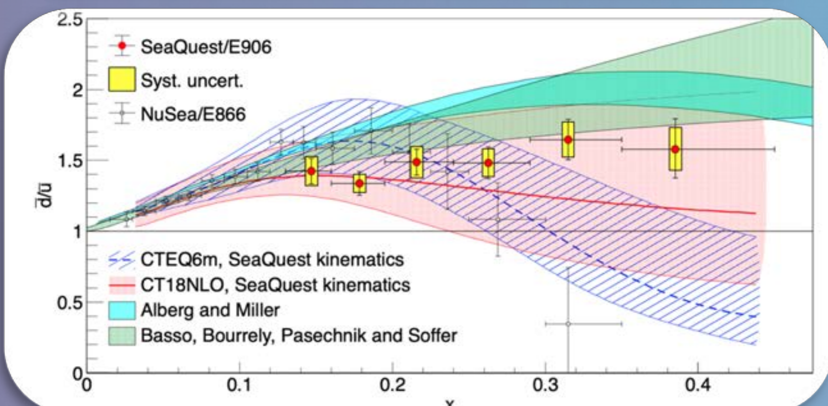
Model	I_Δ prediction	Ref.
Meson cloud (π-meson)	0	[31,127]
Meson cloud (ρ-meson)	$\simeq -0.0007$ to -0.027	[117]
Meson cloud ($\pi - \rho$ interf.)	$= -6\int_0^1 g^p(x)dx$	[118]
Meson cloud (ρ and $\pi - \rho$ interf.)	$\simeq -0.004$ to -0.033	[119]
Meson cloud (ρ-meson)	<0	[120]
Meson cloud ($\pi - \sigma$ interf.)	$\simeq 0.12$	[132]
Pauli-blocking (bag-model)	$\simeq 0.09$	[119]
Pauli-blocking (ansatz)	$\simeq 0.3$	[128]
Pauli-blocking	$= \frac{5}{3}\int_0^1[\bar{d}(x) - \bar{u}(x)]dx \simeq 0.2$	[129]
Chiral-quark soliton	0.31	[130]
Chiral-quark soliton	$\simeq \int_0^1 2x^{0.12}[\bar{d}(x) - \bar{u}(x)]dx$	[131]
Instanton	$= \frac{5}{3}\int_0^1[\bar{d}(x) - \bar{u}(x)]dx \simeq 0.2$	[123]
Statistical	$\simeq \int_0^1[\bar{d}(x) - \bar{u}(x)]dx \simeq 0.12$	[41]
Statistical	$> \int_0^1[\bar{d}(x) - \bar{u}(x)]dx > 0.12$	[126]

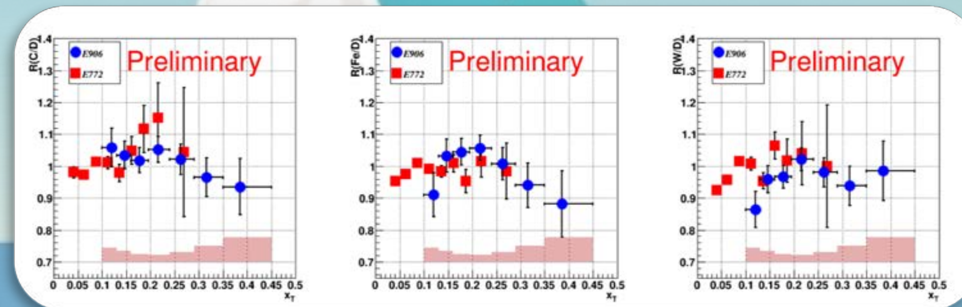
Spin contributions of anti-quarks

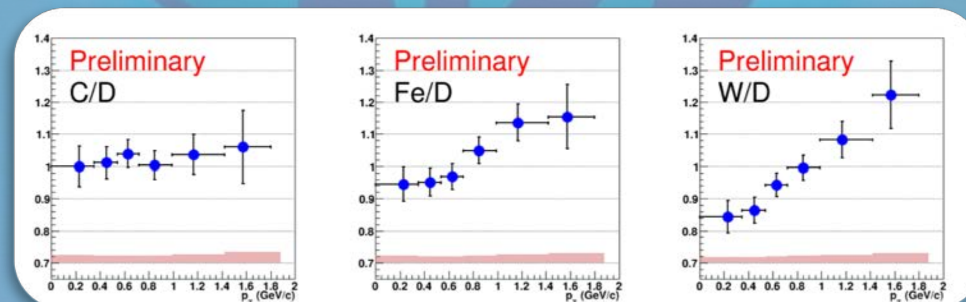
Summary

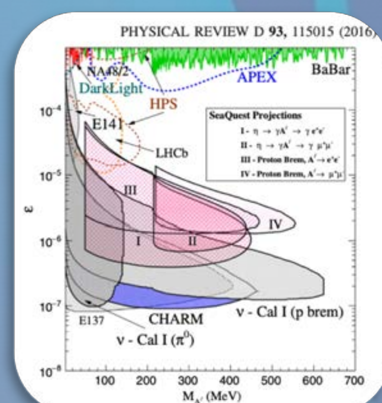
Dove et. al. Nature 590, 561 – 565 (2021)

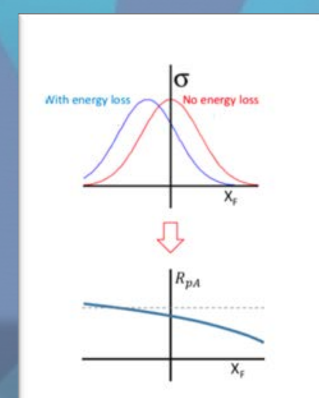












Stay tuned for more exciting results and publications in the near future!

Exploring the Light Anti-Quark Flavor Asymmetry in the Nucleon Sea using Semi Inclusive Charged Pion Production in Hall C

A Letter of Intent for PAC50

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LOI submitted to PAC50

Old proposal: PR 12-06-111
LOI: 12-22-01
Reader: Alessandro Bachetta