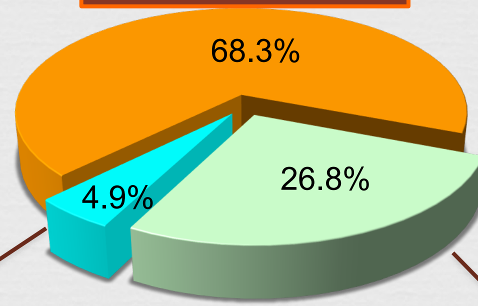
The SeaQuest Experiment

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

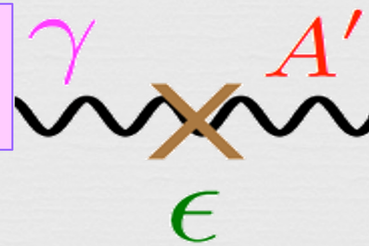
Fermilab is a fantastic place!

Contents of the talk/Universe

Dark energy



Standard model matter



Dark matter

Nucleons and Nuclear structure

Dark forces & Hidden sector

Issues in Nuclear structure

SeaQuest E906

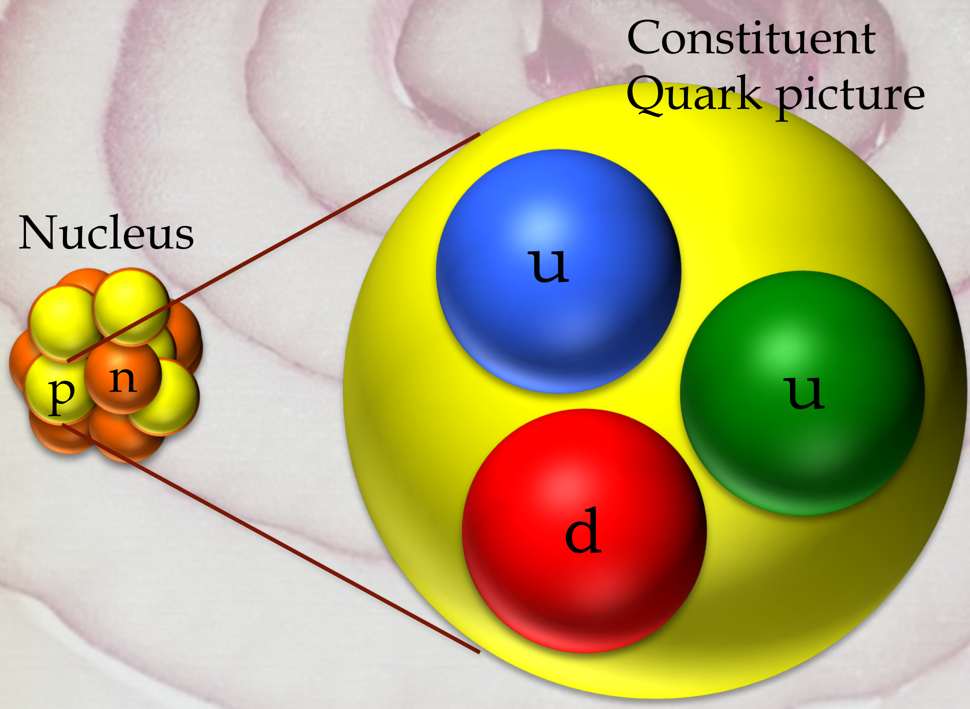
Dark photons

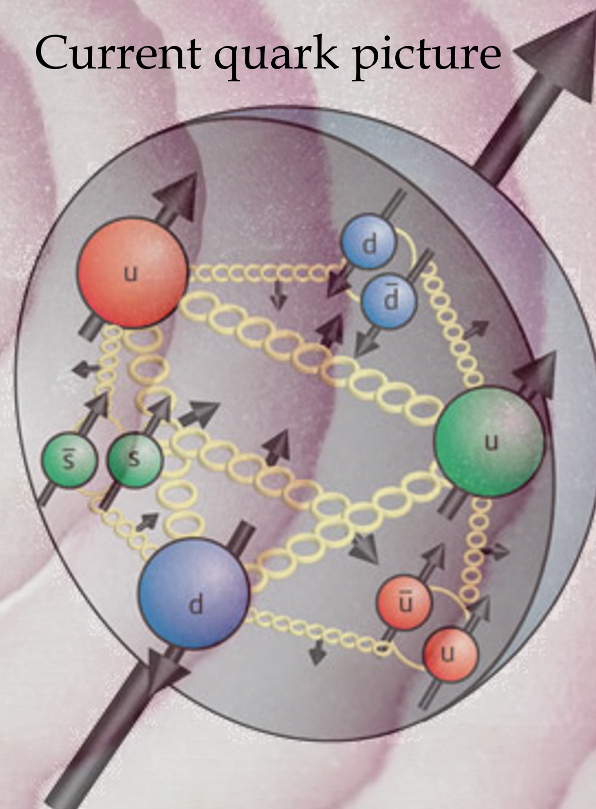
Recent results and ongoing analyses

Rich Drell-Yan and *J/ψ* program

1. Light Anti-Quark Flavor Asymmetry
2. Absolute cross sections from 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

Standard Model



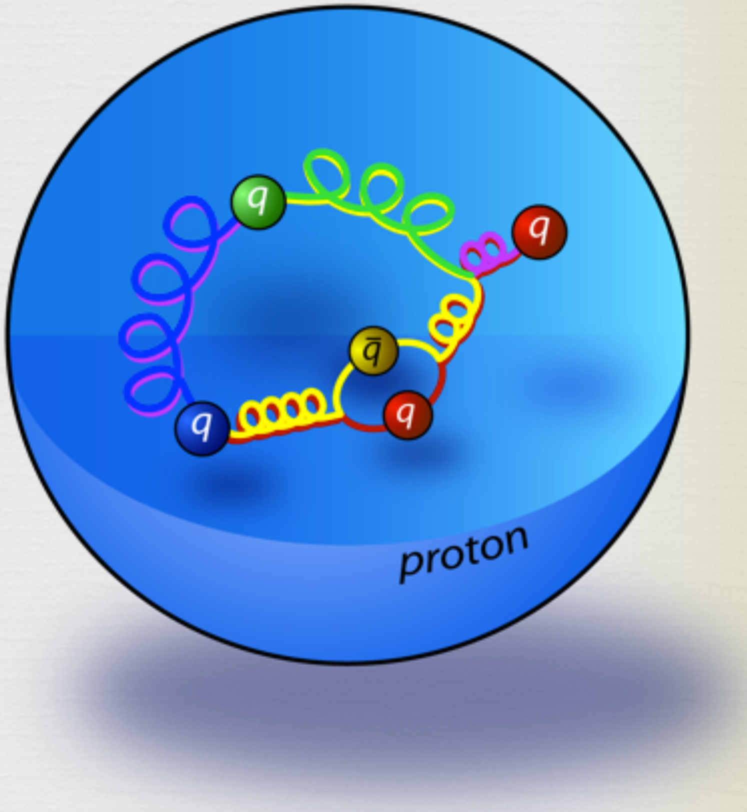


Experiments all over the world continue to peel the layers of the rich inner substructure!

Goal: Study nucleon and nuclear structure

- Dynamical QCD quantum systems
  - Valence quarks
  - Gluons
  - Sea quark anti-quark pairs

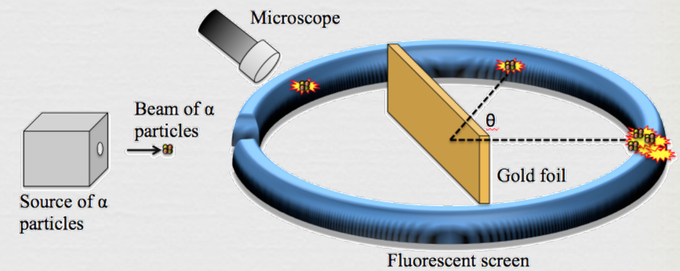
- SeaQuest's goal is to study quark gluon dynamics in nucleons and nuclei in particular the sea structure

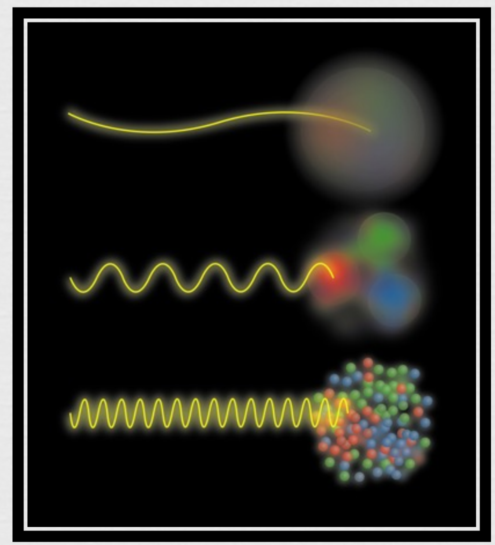


How to probe the nucleus?

- Wealth of information obtained from scattering experiments
  - Beam of known particle type, momentum, spin etc.
  - Incident on target
  - Hits recorded using detectors
  - Tracks reconstructed and physics extracted

Rutherford's gold foil experiment





Inner structure reveals itself with higher resolution!

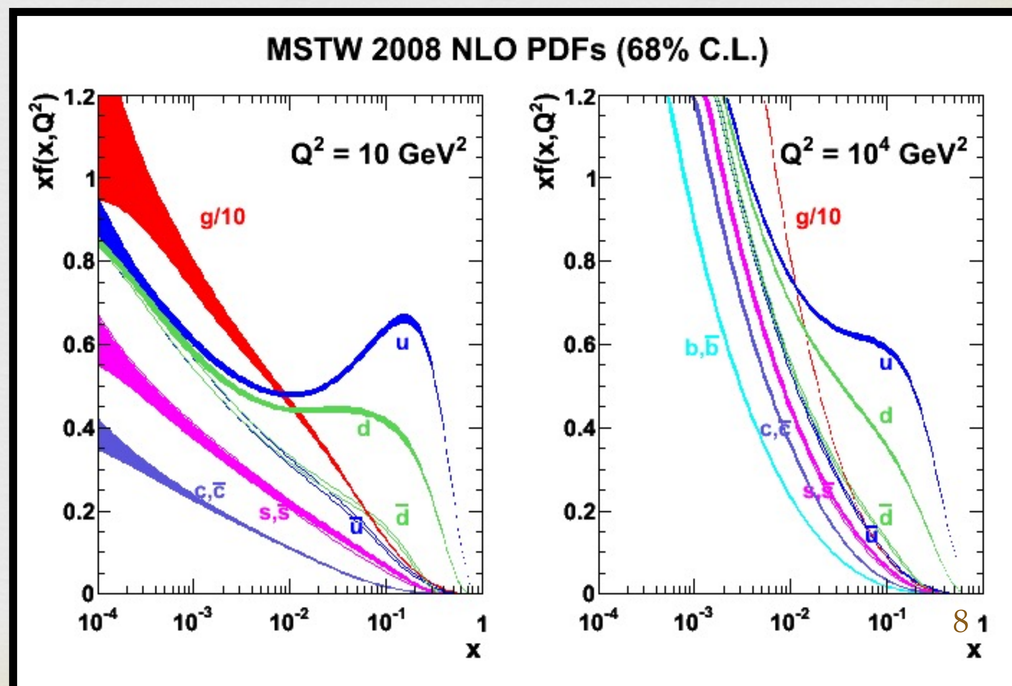
Viewpoint: Quark Parton model

J.D. Bjorken PhysRev.179.1547
R. Feynman Phys. Rev. Lett 23, 1415-

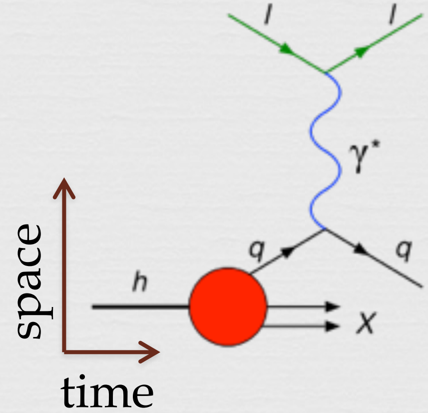
- Nucleon consists of partons (quarks and gluons)
- Partons carry a fraction x_{Bj} of the nucleon's longitudinal momentum in the infinite momentum frame
- Nucleon longitudinal structure can be given as an incoherent sum of the interactions of the various "free partons" under impulse approximation

Richard Feynman

James Bjorken



Experimental toolbox



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

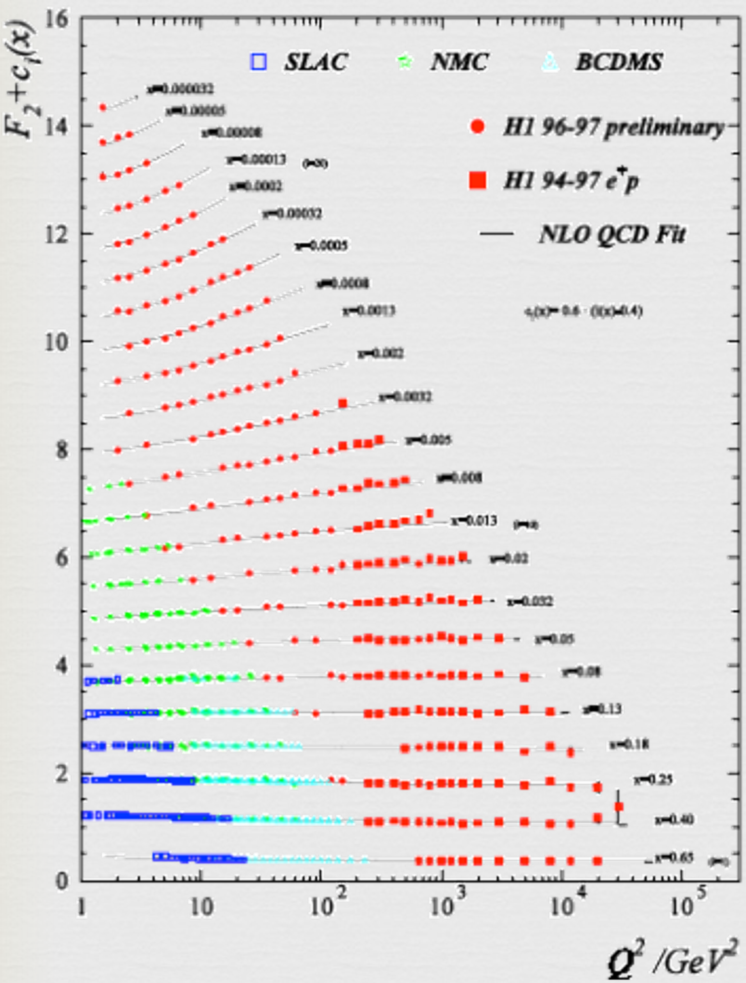
DEEP INELASTIC SCATT

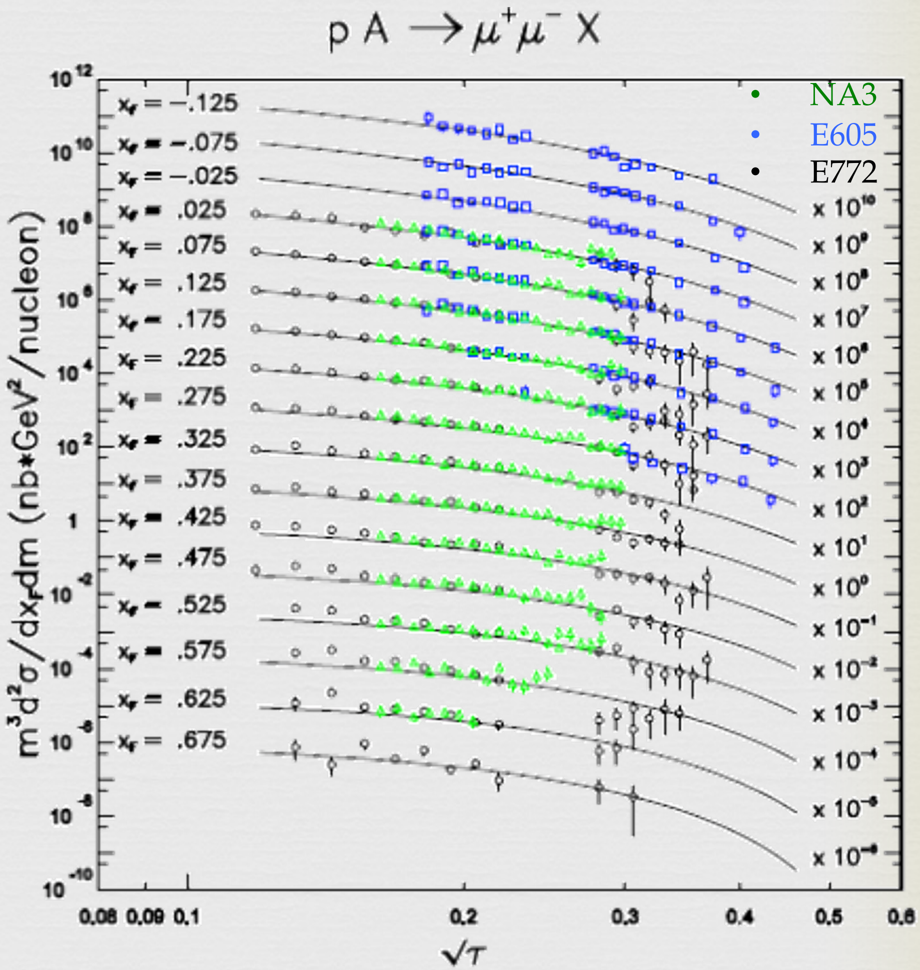
- Lepton scatters f
- Exchang
- E n (or
- tiate between ntiquark

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

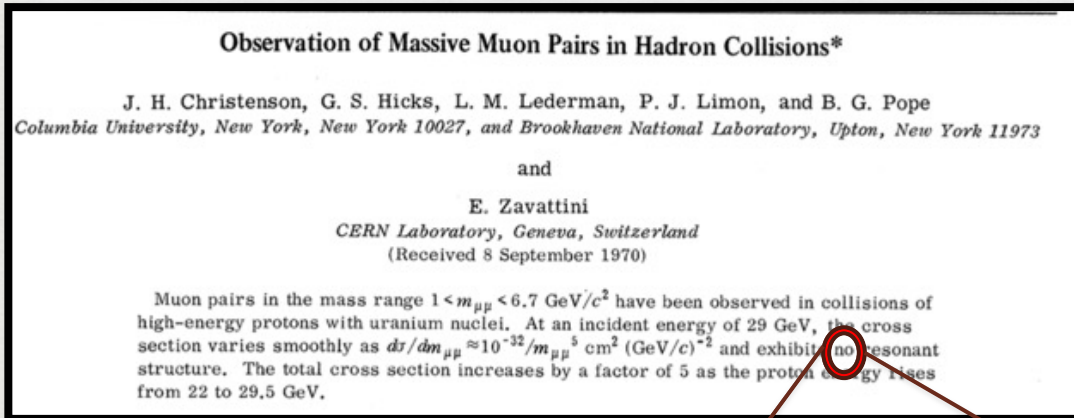
DIS & DY – complementary!





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)

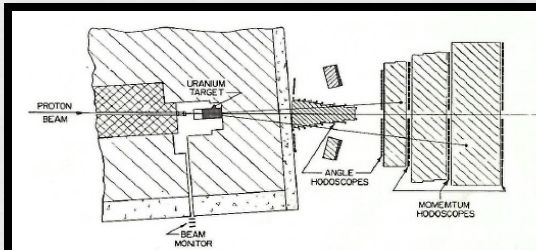
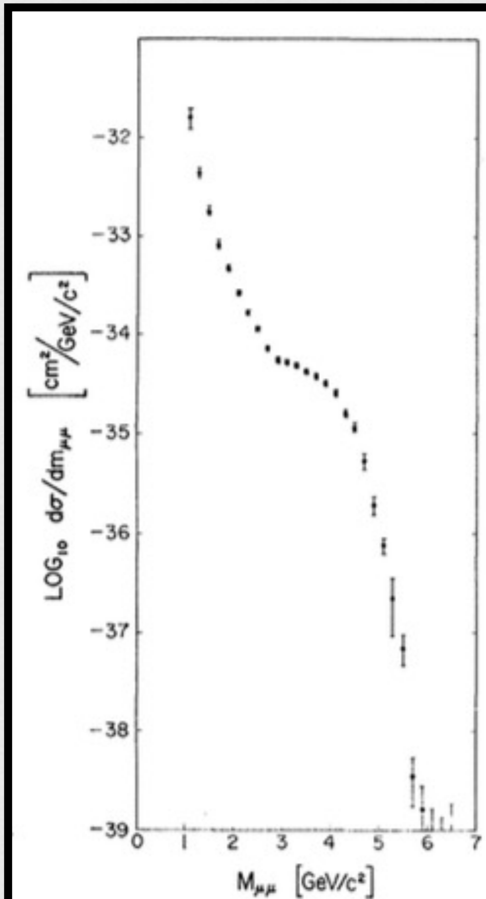


FIG. 1. Plan view of the apparatus.



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

Model explained only part of the cross section

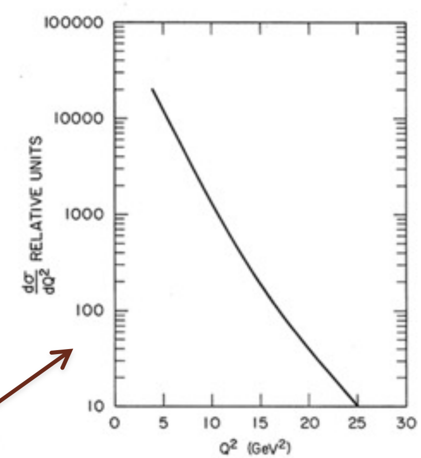
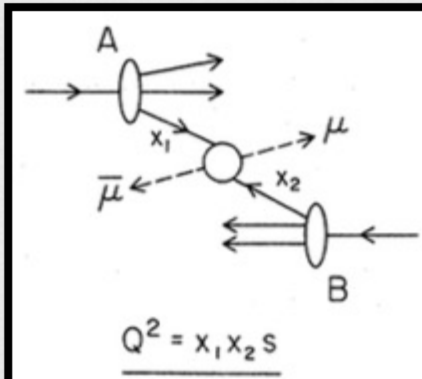


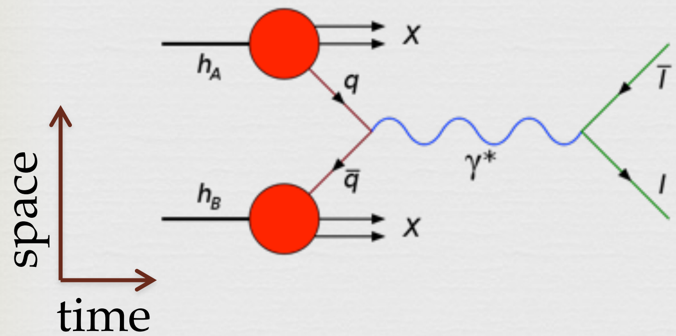
FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.

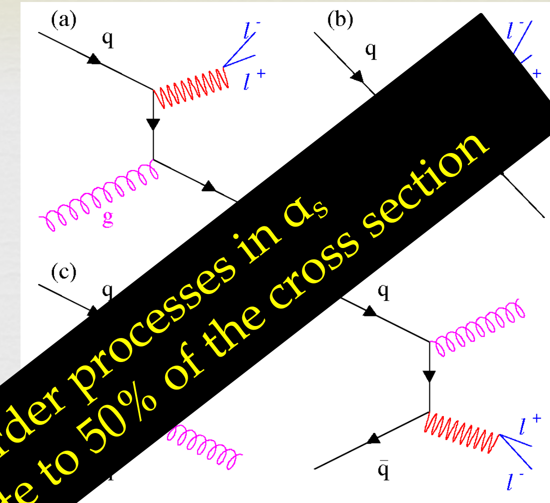
Phys.Rev.Lett 25.902 (1970)



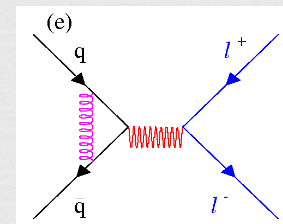
parton annihilates with an anti-parton

Leading Order Drell Yan cross-section formula





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



Drell-Yan cross section

Fine structure constant

Charge weighted summation over all quark flavors

PDF of a quark of flavor i in the beam

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

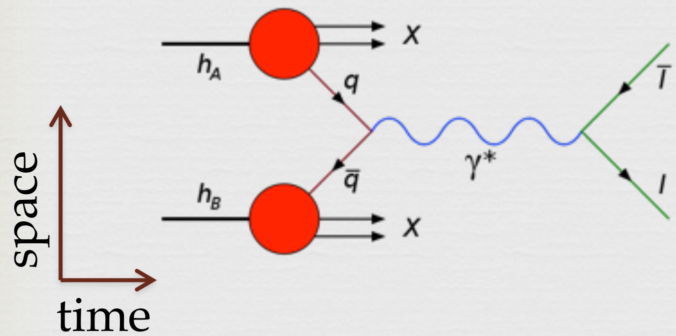
Center of mass energy squared

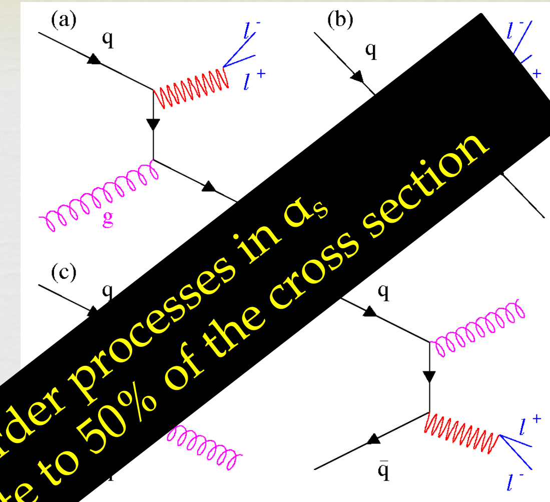
momentum fraction of antiquark in the target

momentum fraction of quark in the beam

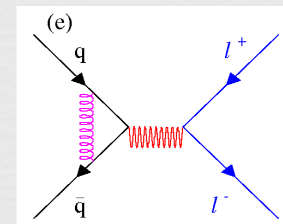
PDF of anti quarks of flavor i in the target

Leading Order Drell Yan cross-section formula





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



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

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

D

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•

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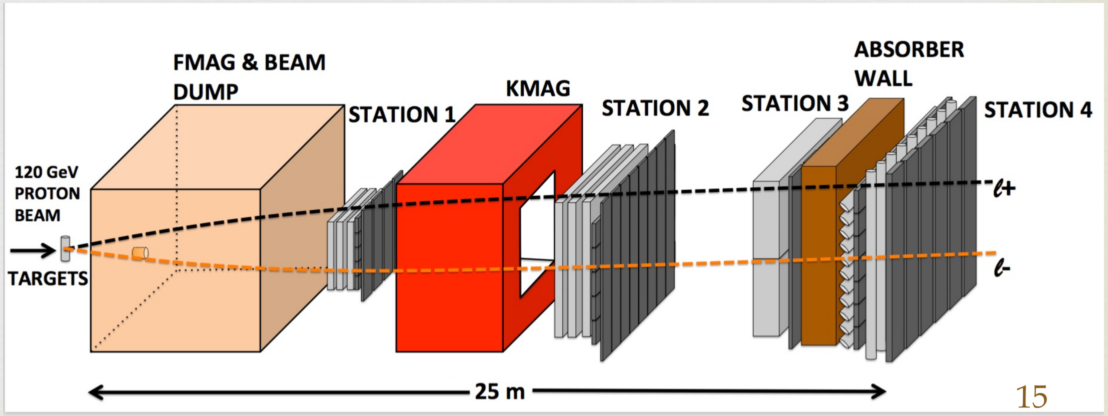
x_{target} x_{beam}

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

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

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



Fermilab E906/SeaQuest Collaboration

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Gerry Garvey, Xiaodong Jiang, Andreas Klein, David Kleinjan,
Mike Leitch, Kun Liu, Ming Liu, Pat McGaughey

*Co-Spokespersons

The SeaQuest E906 Experiment

- 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

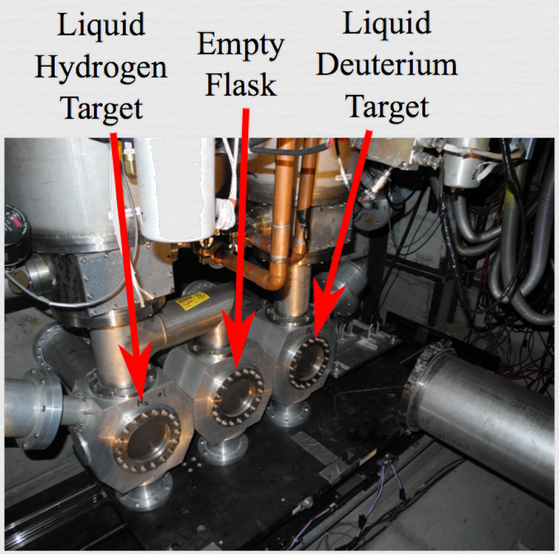
$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

- 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*

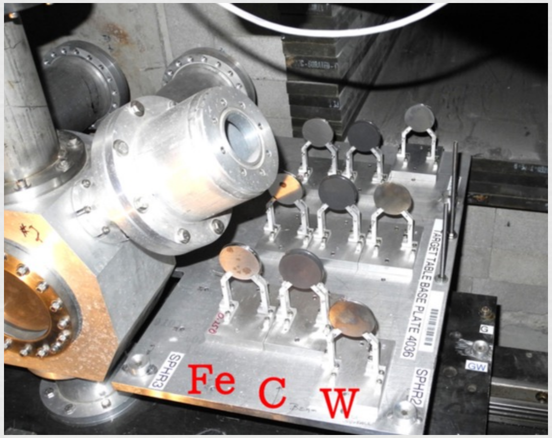
Improved statistics!!

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%

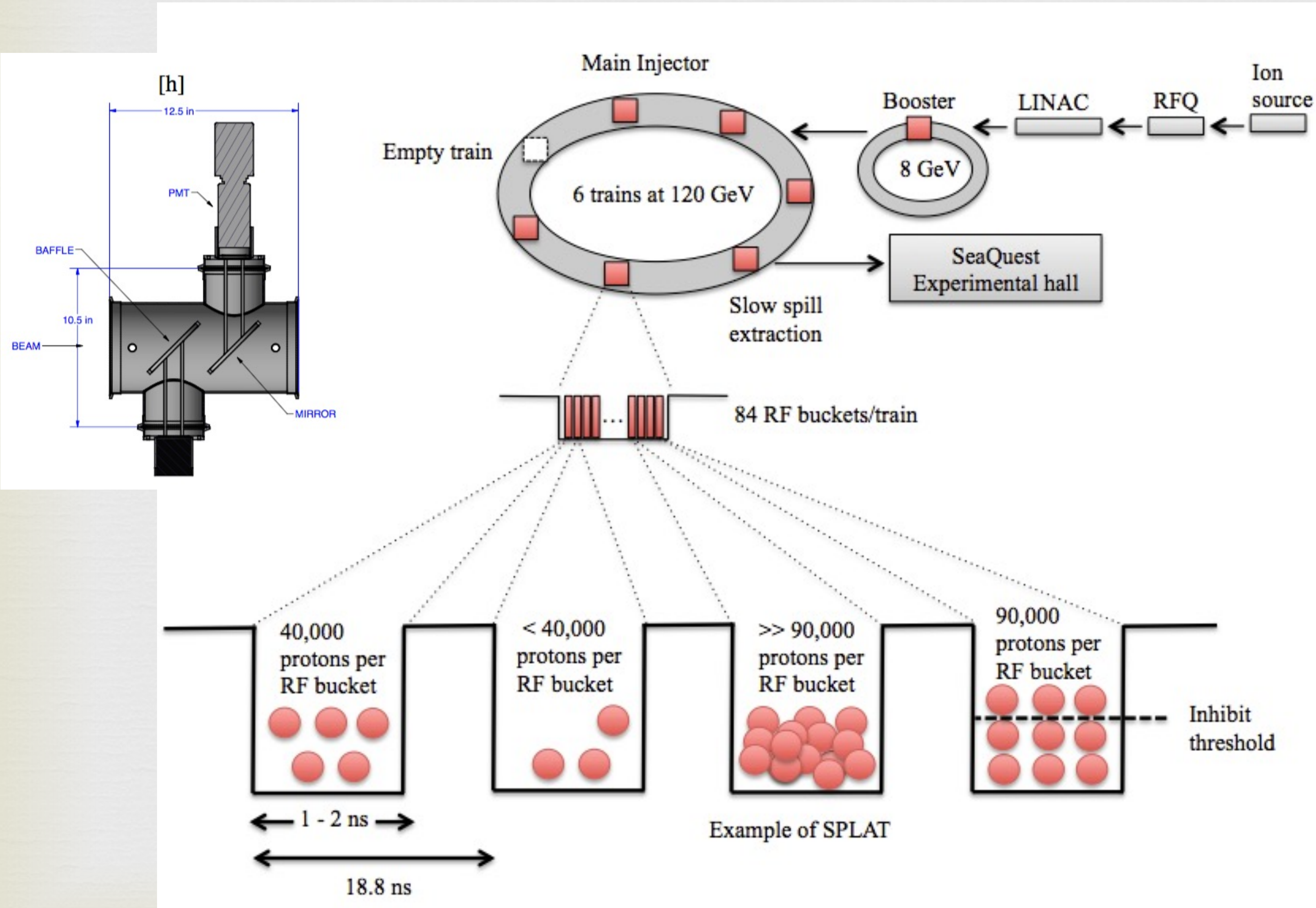


For anti-quark flavor asymmetry studies

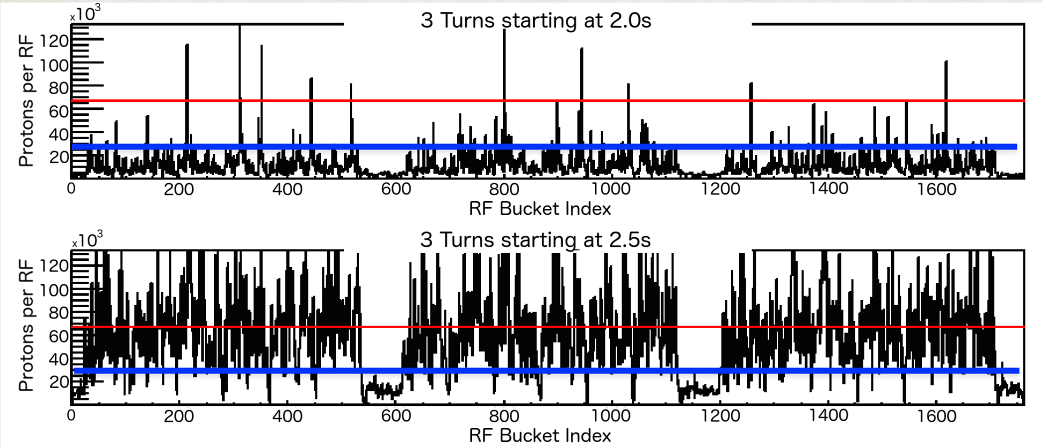


For Nuclear dependence studies

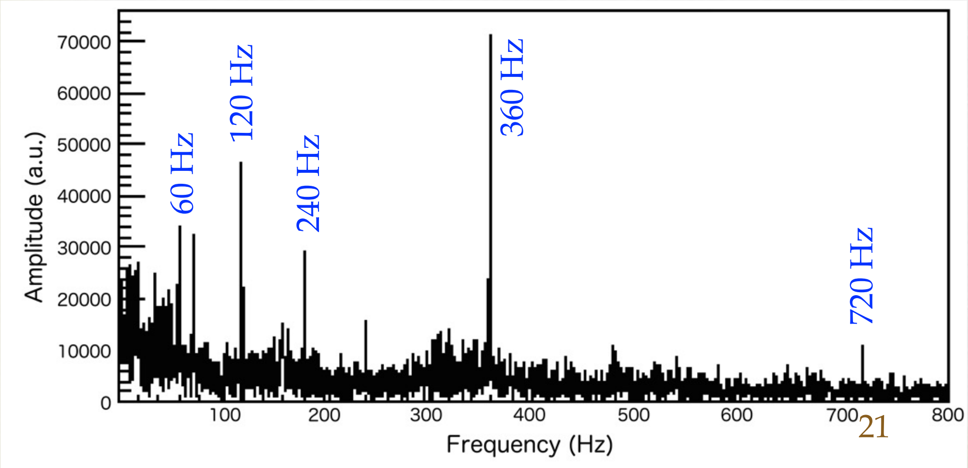
Beam microstructure



Randomly chosen Beam Intensity profile



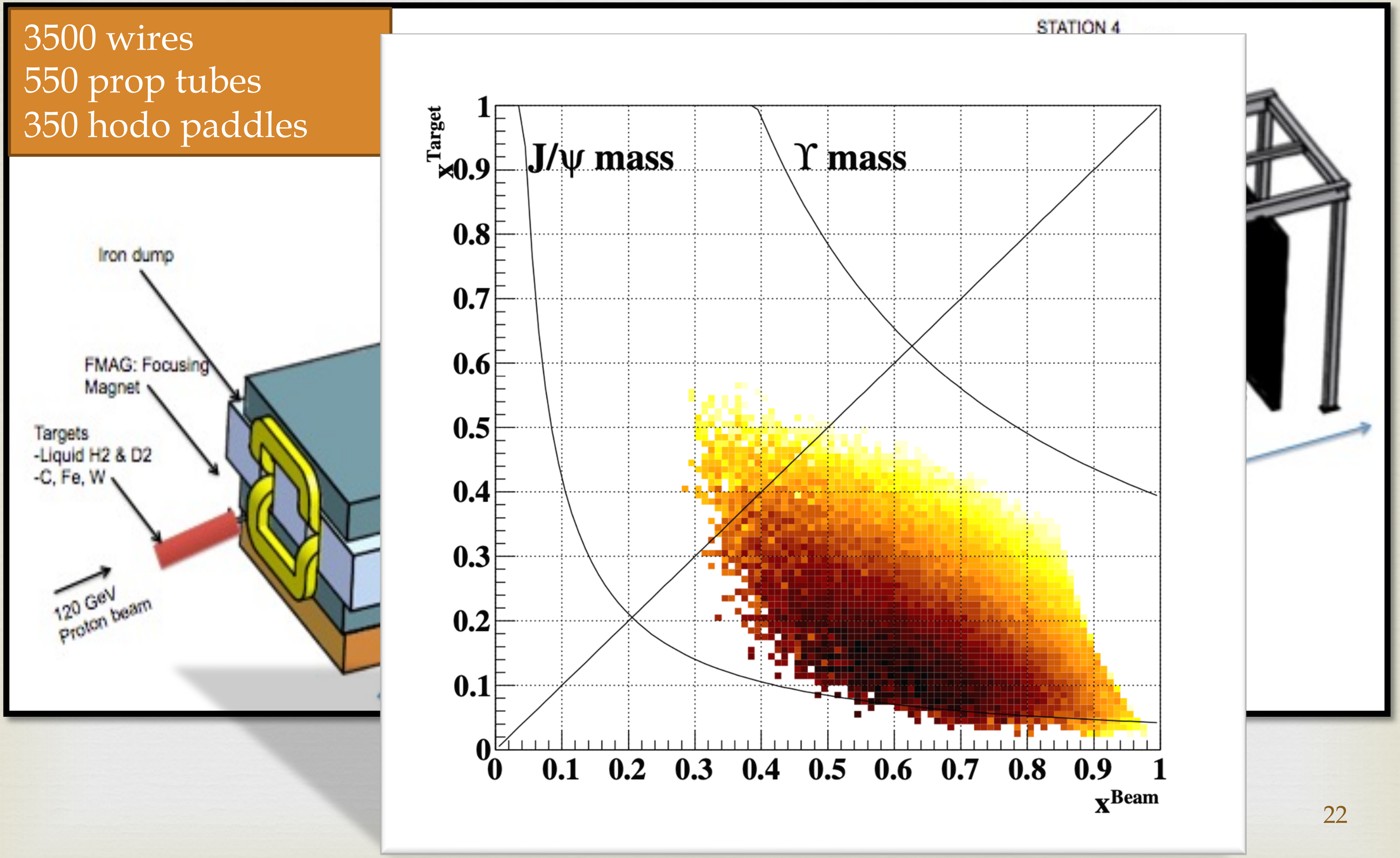
- Each bin is a 19 ns bucket
- Veto Level
- Even beam distribution



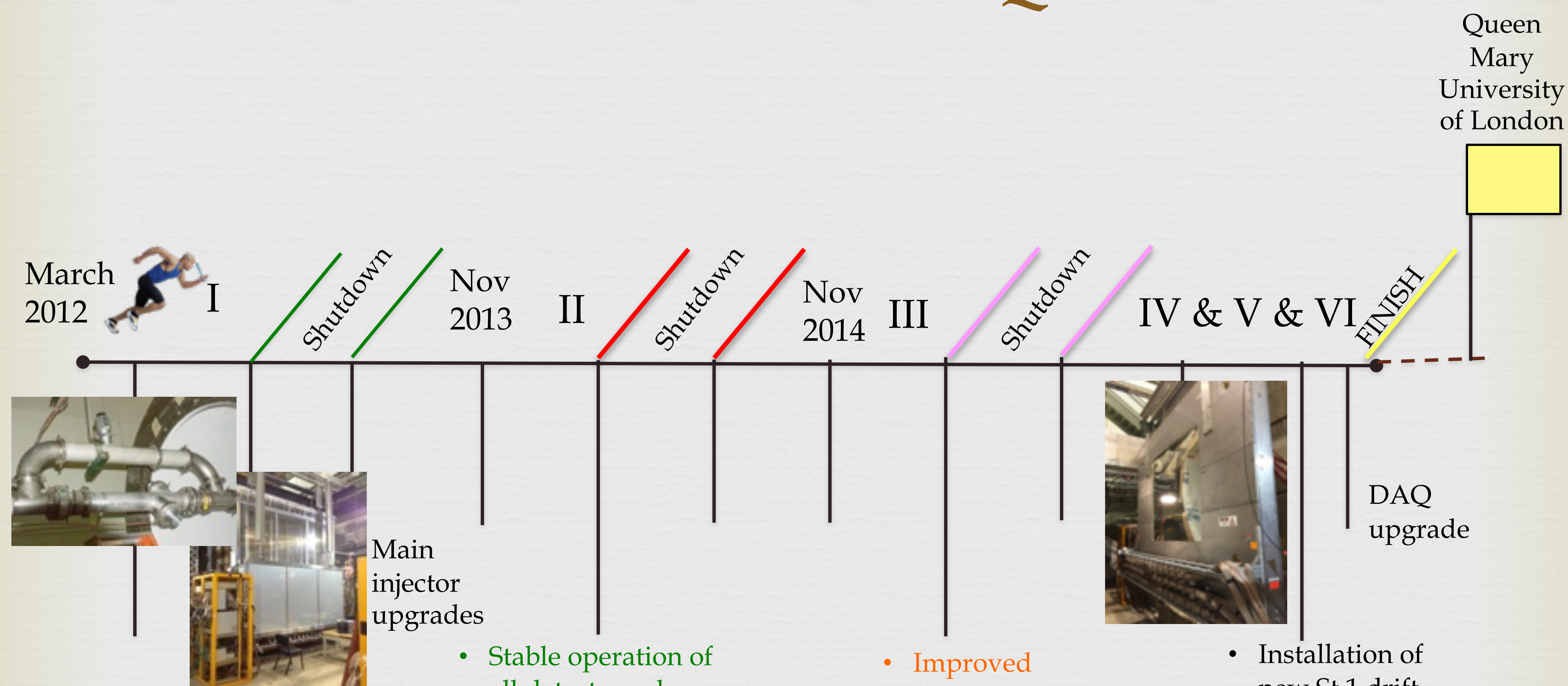
FOURIER TRANSFORM

The SeaQuest Spectrometer

3500 wires
550 prop tubes
350 hodo paddles



Timeline of SeaQuest



Commissioning run

- All detector subsystems work
- Issues and upgrades addressed

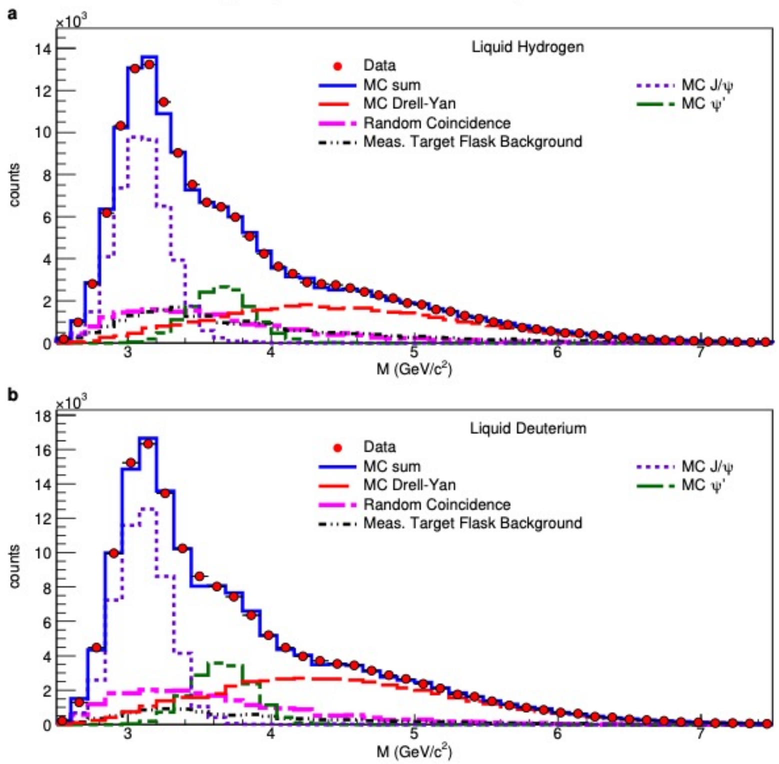
- Stable operation of all detector sub systems
- Dark photon road sets included into the trigger system
- New St3- installed

- Improved duty factor
- Continue data taking

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

Event selection and reconstruction

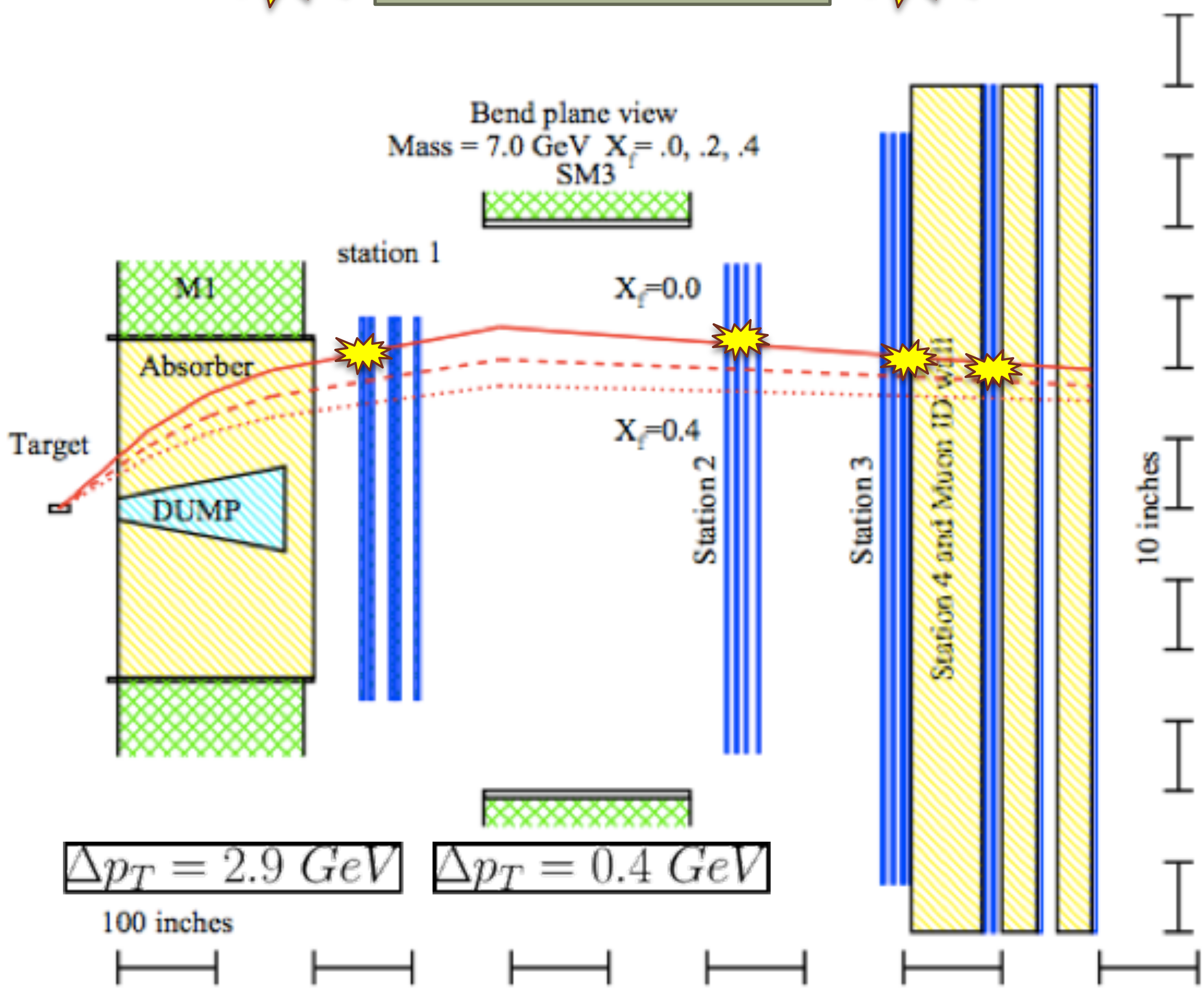
- Invariant mass spectrum for FY 2015 data
- 30% of anticipated data
- Data agrees well with Monte Carlo (spectrometer works as expected)
- Data with Mass > 4.5 GeV are mostly dimuons coming from the Drell-Yan process



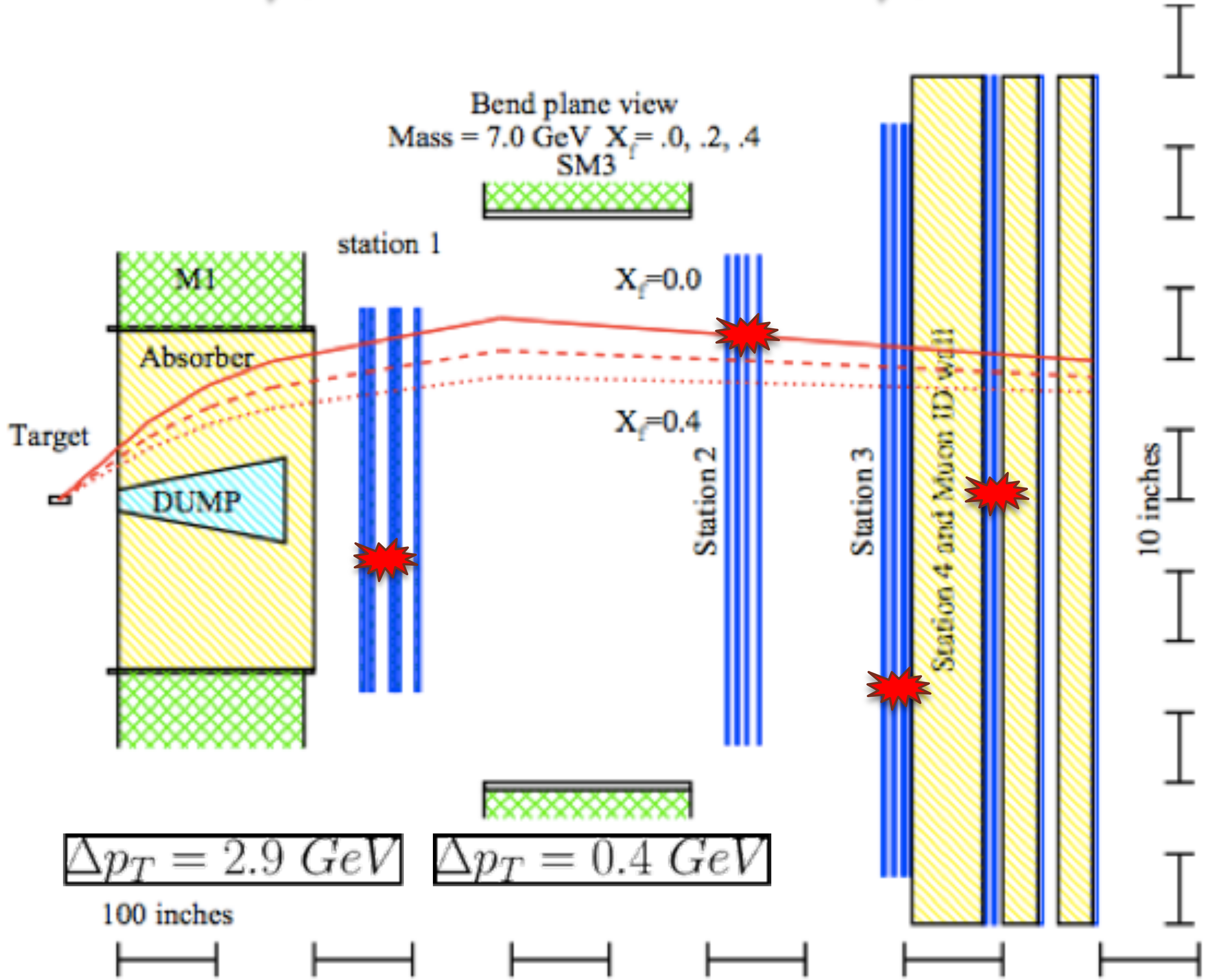
The reconstructed muon pair invariant mass spectra for the liquid hydrogen (a) and liquid deuterium (b) targets. In the lower mass region, the predominant signal is produced by $J/\psi \rightarrow \mu^+\mu^-$ decay, followed by the $\mu^+\mu^-$ decay of the ψ'. The prominence of the J/ψ provides a calibration 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.

Random background from FPGA4 events

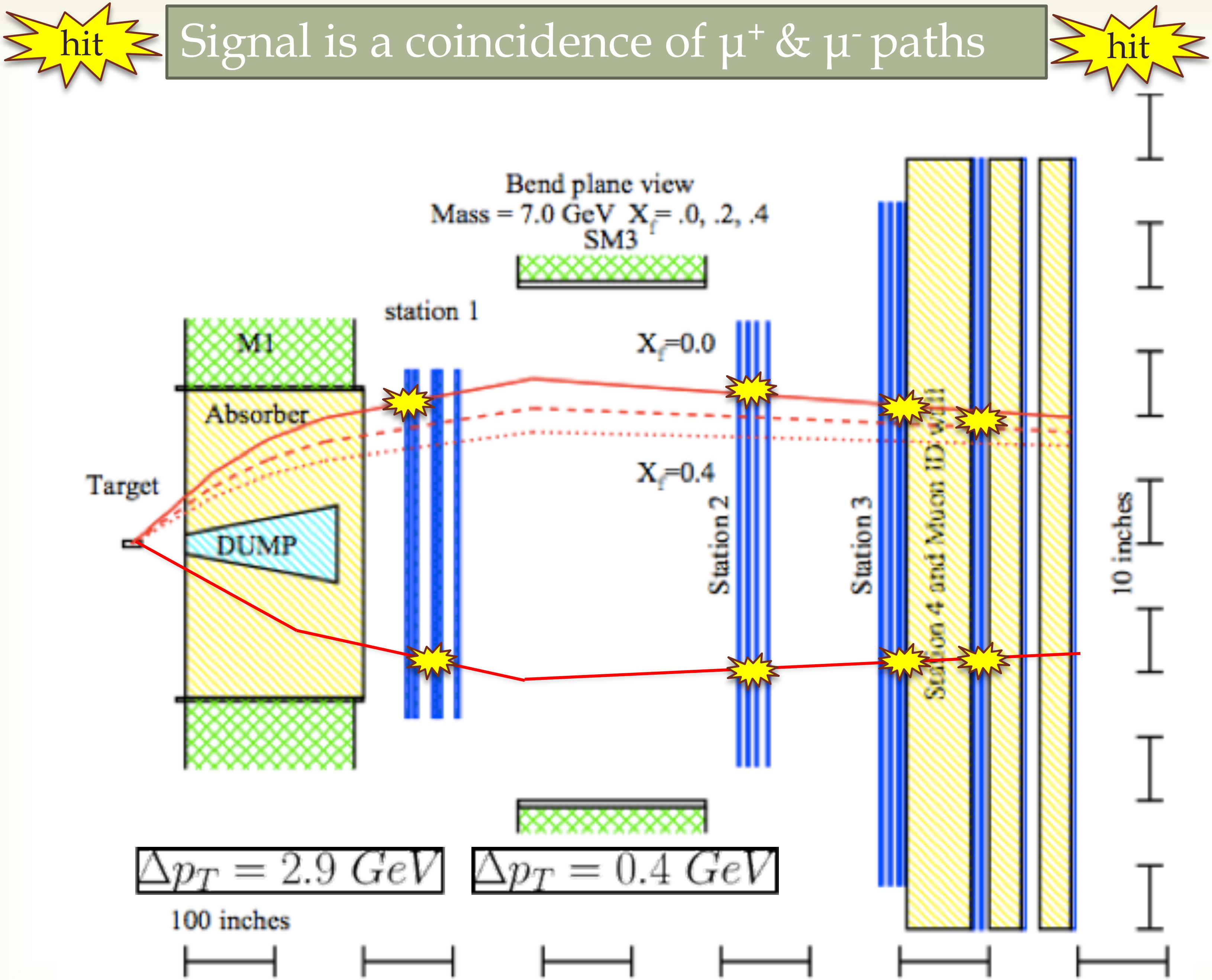
Accept this path



Reject this path



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



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

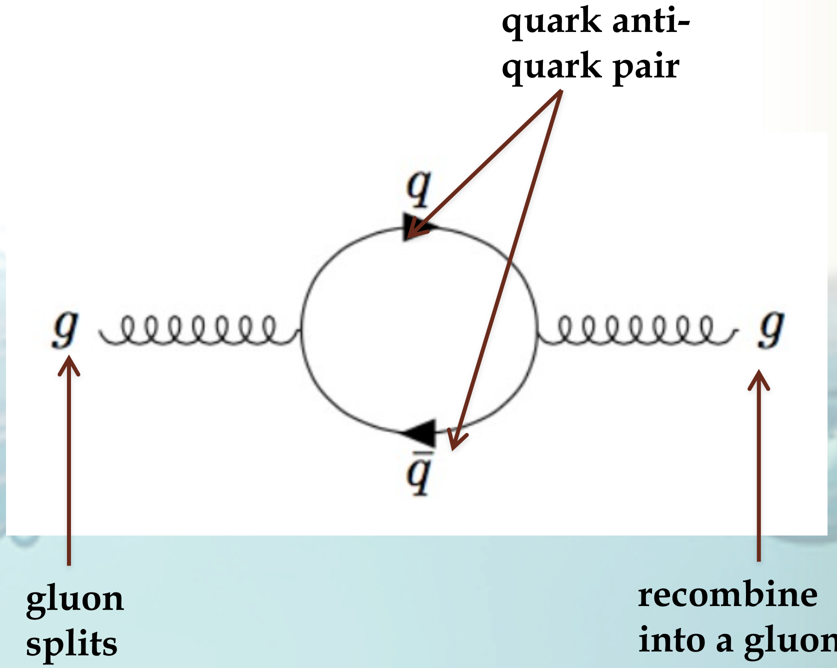
Anti shadowing and EMC effect observed in anti-quarks in nuclei?

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

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

- Symmetric sea i

- NMC experime
GeV and 280 GeV muon beam)

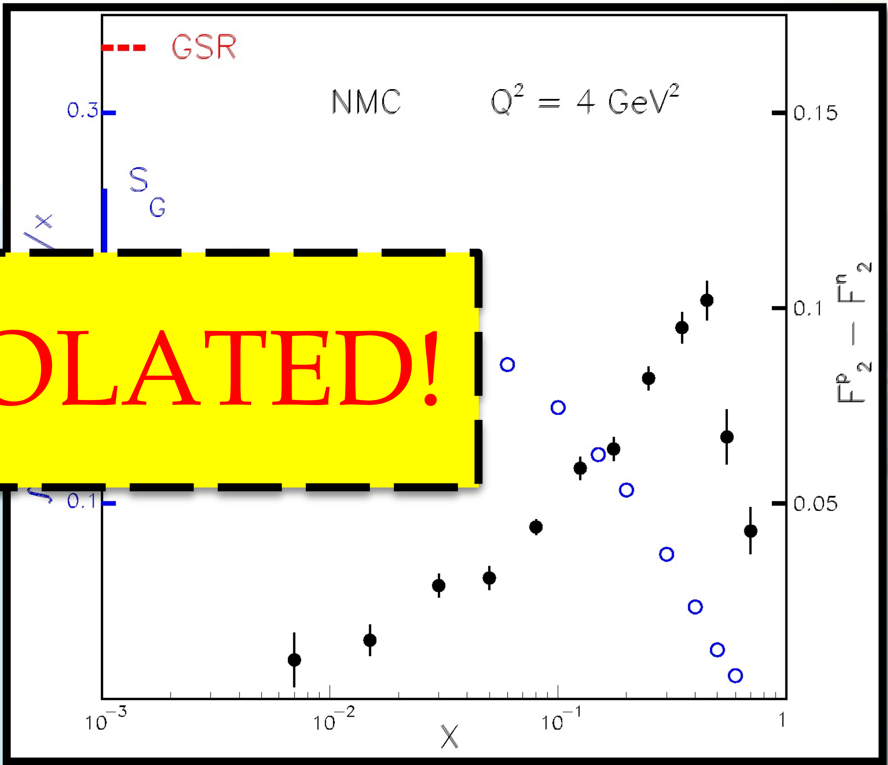
$$S_G = \int_{0.004}^{0.8} (F_2^p - F_2^n)\, dx / x$$

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

- After extrapolation to 0 and 1

$$= 0.235 \pm 0.026$$

GSR VIOLATED!



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

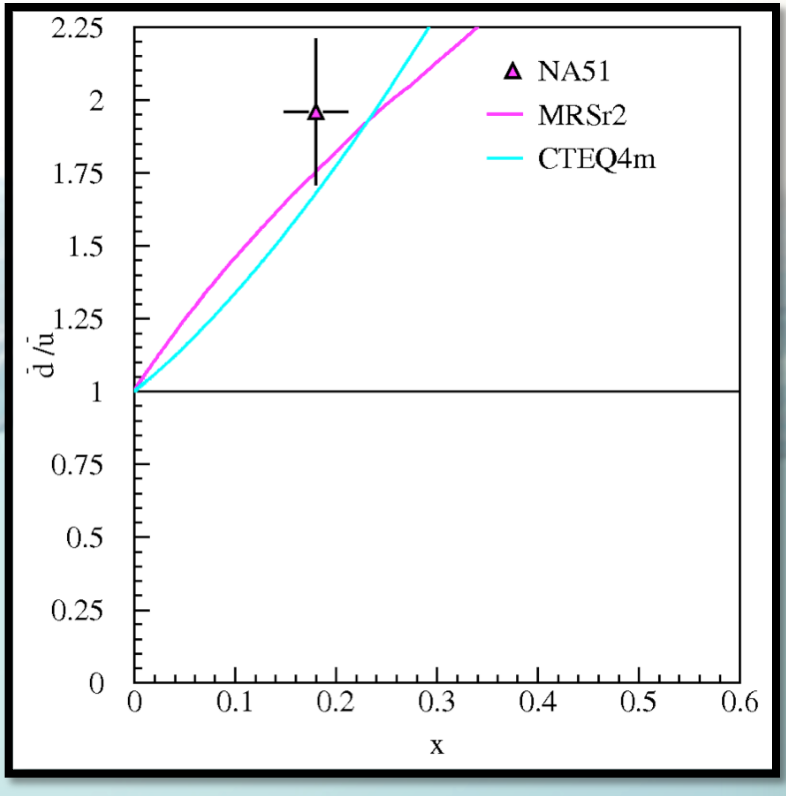
NA51 (1994)

- 450 GeV proton beam, LD2, LH2 targets

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

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

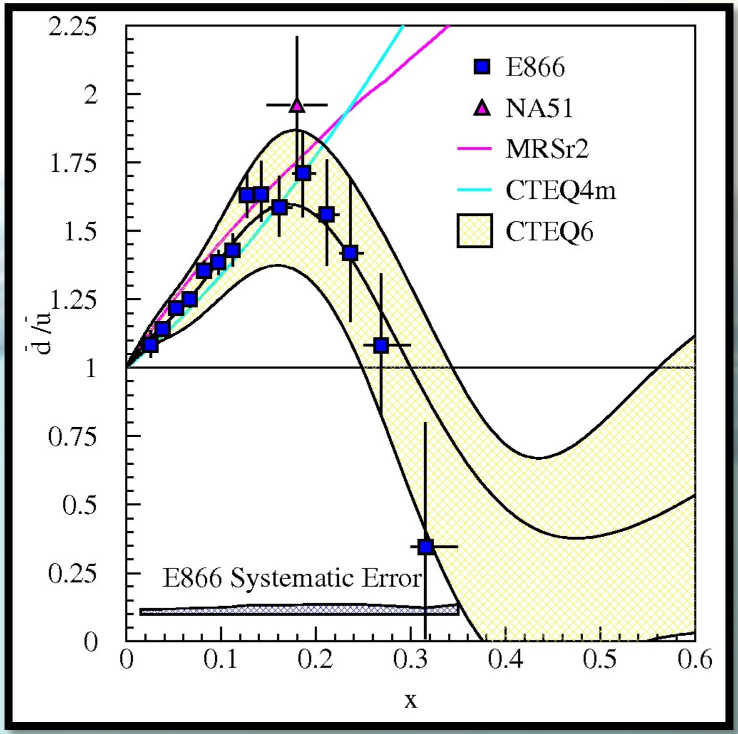
$$\left.\frac{\bar{d}}{\bar{u}}\right|_{\langle x\rangle = 0.18} = 1.96 \pm 0.15 \pm 0.05$$



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

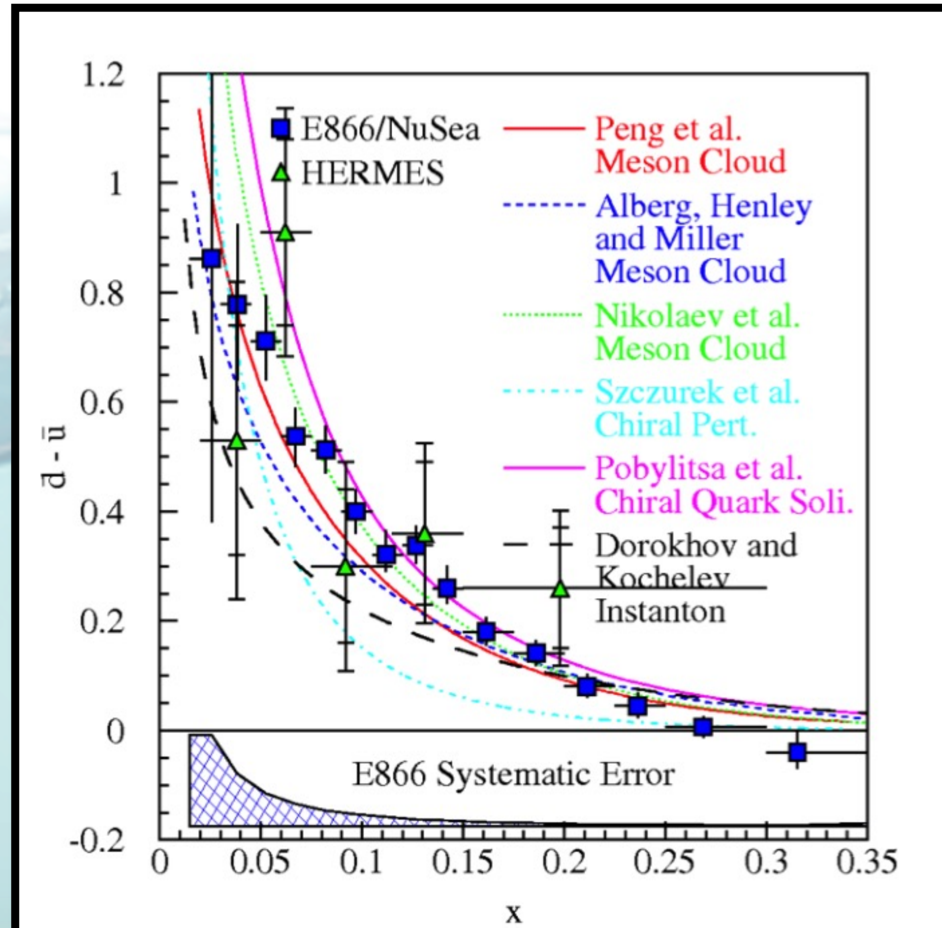
- Symmetric (perturbative and non-perturbative) component cancels away in the difference
- Non-perturbative models are motivated to explain the observed difference

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]

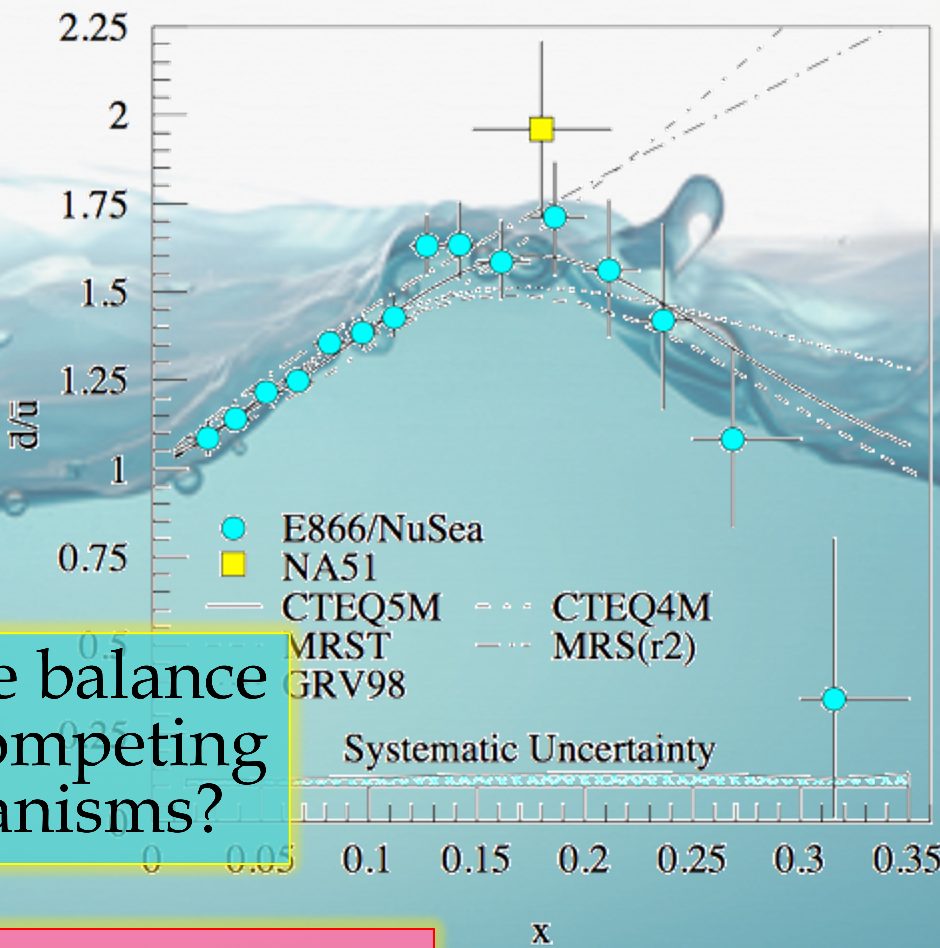
Table I. Integrals of $(\bar{d}-\bar{u})$ from x_{min} to x_{max} from experiment (NMC and NUSEA) and from several global fits (CTEQ6.6, CTEQ10, CTEQ14), calculations (Lattice), and models (Statistical and Detailed Balance). The weak variation of the integral to the choice of scale is illustrated with 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.

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

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



How is the nucleon sea generated?



Meson Cloud model?

Chiral Quark Soliton model?

Connected-sea partons?

Delicate balance of all competing mechanisms?

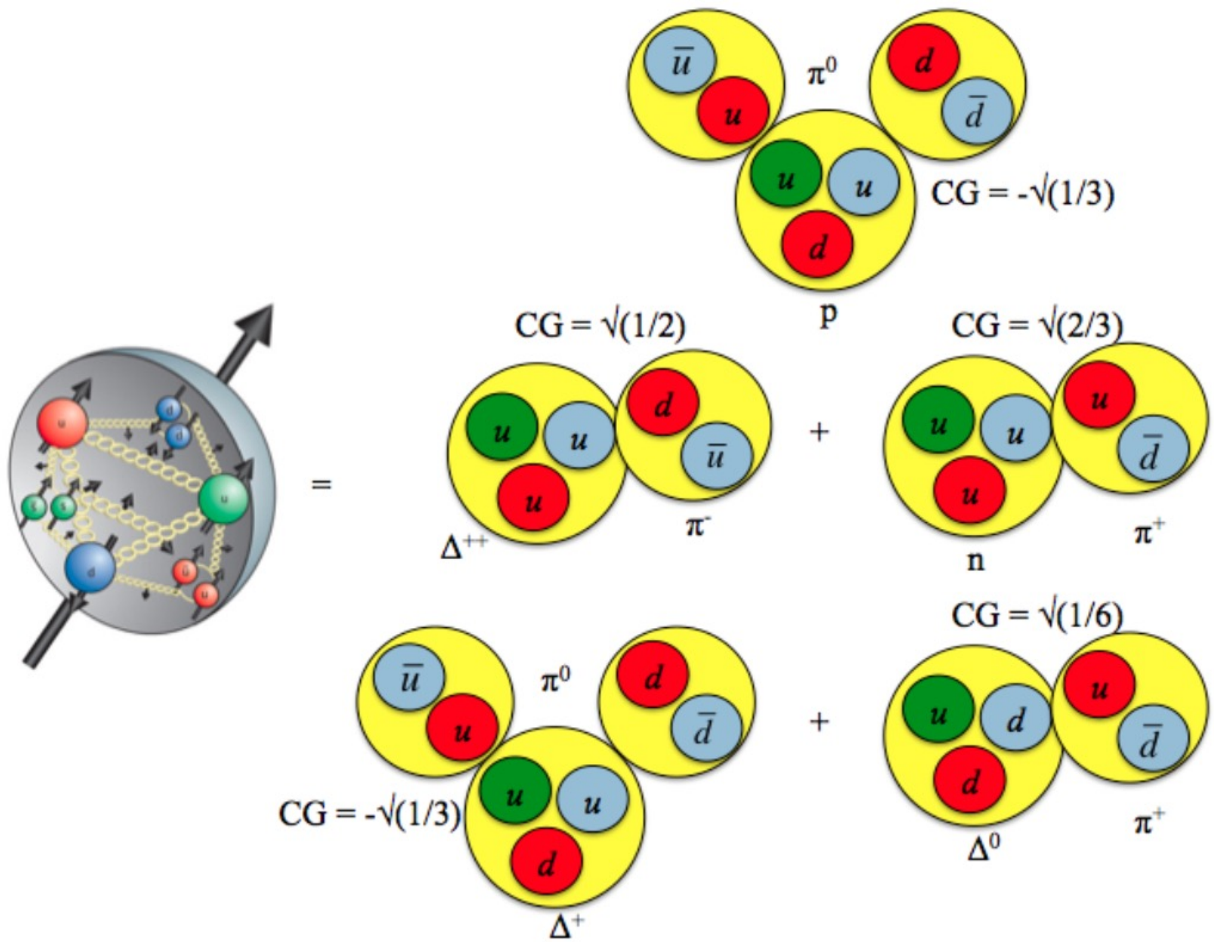
Instanton model?

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

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(Received 4 June 1998; published 8 December 1998)

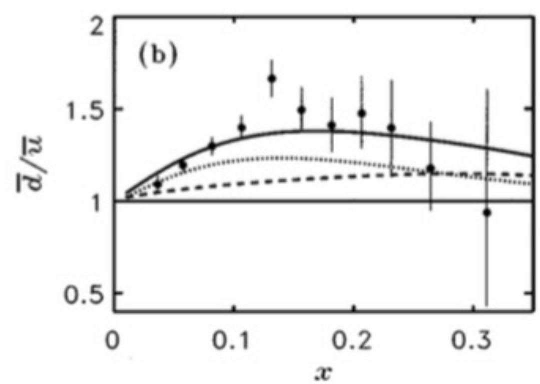
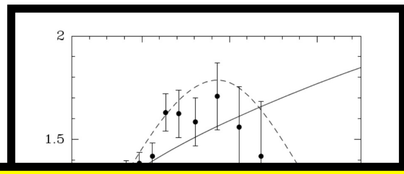
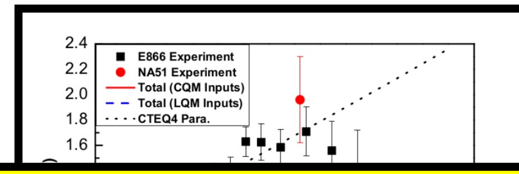


FIG. 11. Contributions from pions with $\Lambda_{\pi N}=1$ GeV and $\Lambda_{\pi\Delta}=1.3$ GeV (dashed) and from antisymmetrization (dotted) to the (a) $\bar{d}-\bar{u}$ difference and (b) $\bar{d}/\bar{u}$ ratio, and the combined effect (solid).

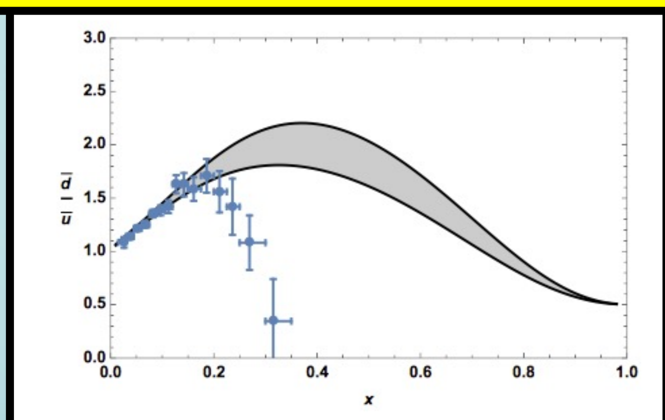
Phys. Rev. D 59, 014033 (1998)
Phys. Rev. D 15, 2590

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

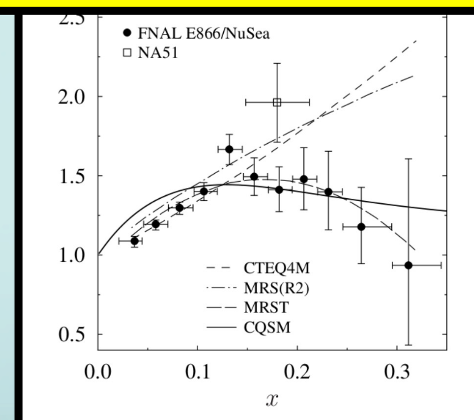




A model that captures the correct non-perturbative physics that generates the nucleon sea will account for the observed flavor asymmetry!



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

J. Dove[1], B. Kerns[1], R. E. McClellan[1,18], S. Miyasaka[2], D. H. Morton[3], K. Nagai[2,4], S. Prasad[1], F. Sanftl[2], M. B. C. Scott[3], A. S. Tadepalli[5,18], C. A. Aidala[3,6], J. Arrington[7,19], C. Ayuso[3,20], C. L. Barker[8], C. N. Brown[9], W. C. Chang[4], A. Chen[1,3,4], D. C. Christian[10], B. P. Dannowitz[1], M. Daugherity[8], M. Diefenthaler[1,18], L. El Fassi[5,11], D. F. Geesaman[7,21], R. Gilman[5], Y. Goto[12], L. Guo[6,22], R. Guo[13], T. J. Hague[8], R. J. Holt[7,23], D. Isenhower[8], E. R. Kinney[14], N. Kitts[8], A. Klein[6], D. W. Kleinjan[6], Y. Kudo[15], C. Leung[1], P.-J. Lin[14], K. Liu[6], M. X. Liu[6], W. Lorenzon[3], N. C. R. Makins[1], M. Mesquita de Medeiros[7], P. L. McGaughey[6], Y. Miyachi[15], I. Mooney[3,24], K. Nakahara[16,25], K. Nakano[2,12], S. Nara[15], J.-C. Peng[1], A. J. Puckett[6,26], B. J. Ramson[3,27], P. E. Reimer[7]✉, J. G. Rubin[3,7], S. Sawada[17], T. Sawada[3,28], T.-A. Shibata[2,29], D. Su[4], M. Teo[1,30], B. G. Tice[7], R. S. Towell[8], S. Uemura[6,31], S. Watson[8], S. G. Wang[4,13,32], A. B. Wickes[6], J. Wu[10], Z. Xi[8] & Z. Ye[7]

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

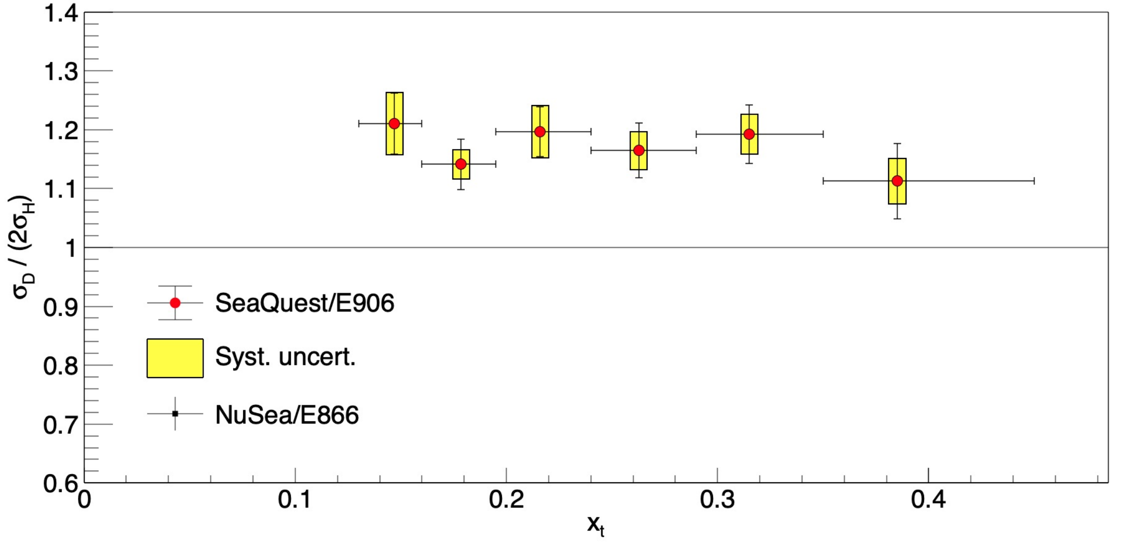
Protons are messy on the inside. Made o... constantly shifting collection of transient quarks and antiquarks ... and gluons (squiggles) that bind the quarks together.

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

Cross section ratio results

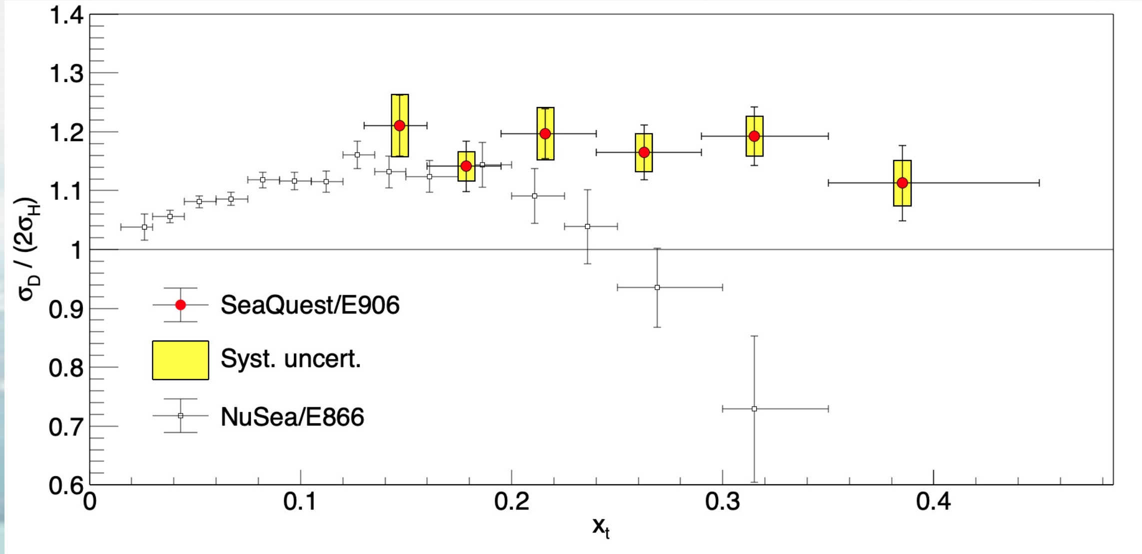
- ~30% of the anticipated data
- Ratio of cross-sections of LD2 and LH2

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)

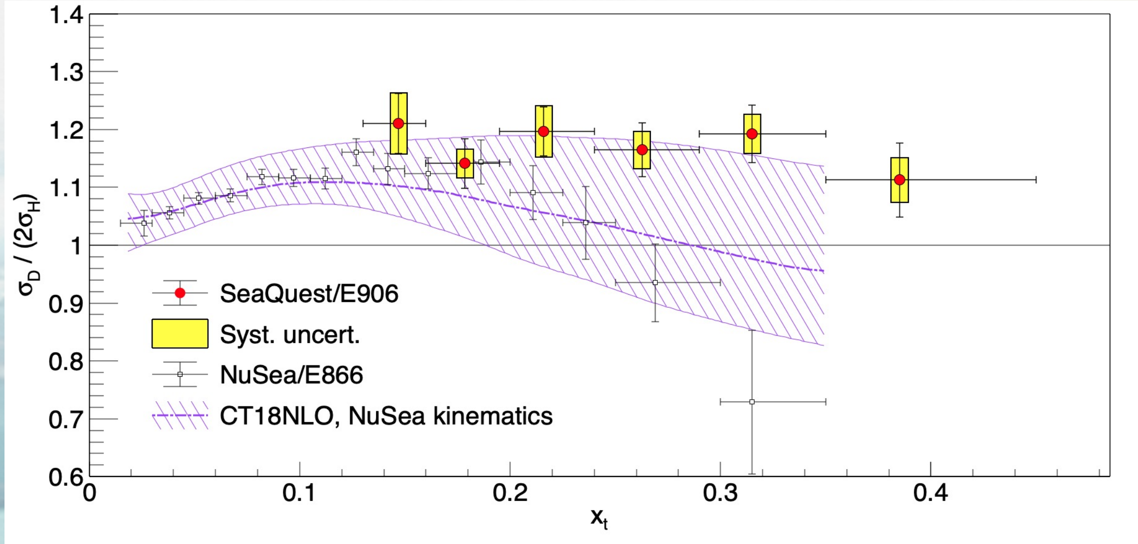


- Comparison with E866/NuSea
- Some differences are expected as the experiments have different
  - beam energies
  - acceptance
  - x_B distributions for a given x_T value

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

Cross section ratio results

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



- Comparison with E866/NuSea
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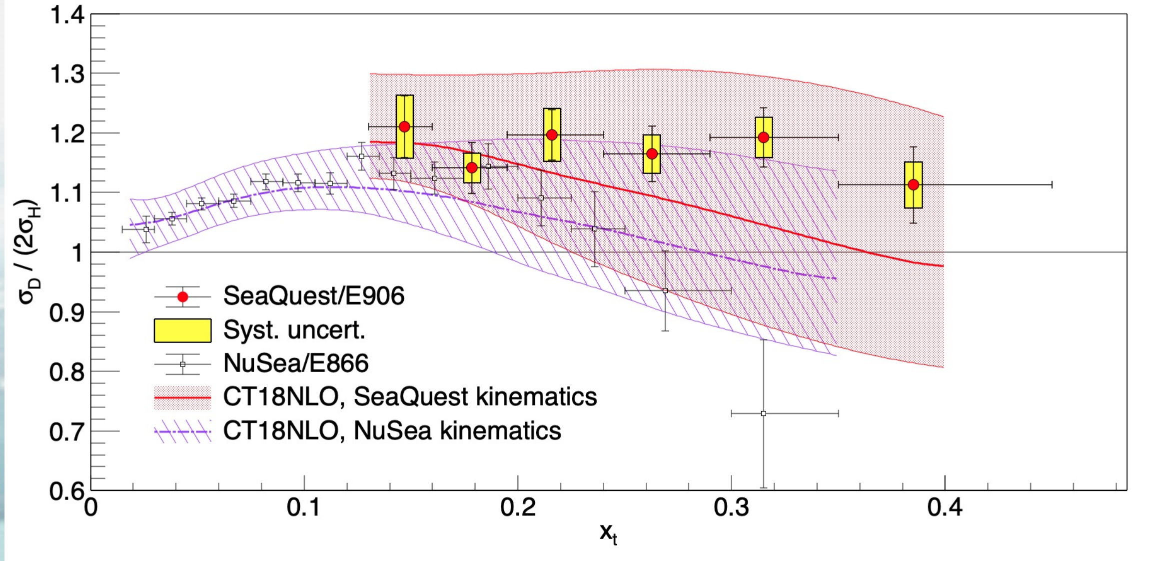
$\frac{\sigma_{pd}}{2\sigma_{pp}}$ Cross section ratio results

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

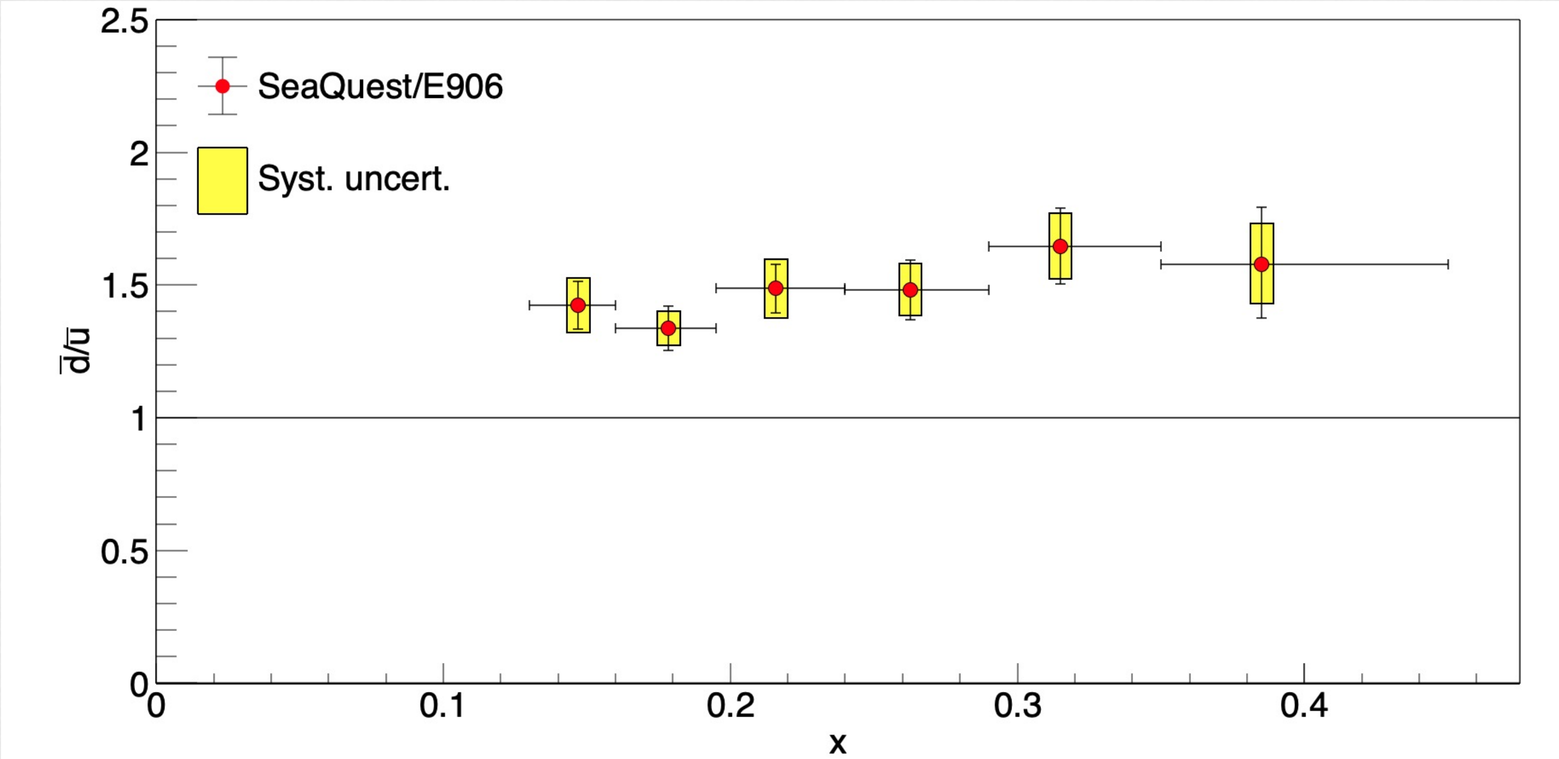


- Comparison with E866/NuSea
- Some differences are expected as the experiments have different
    - beam energies
    - acceptance
    - x_B distributions for a given x_T value

$$Q^2 = x_1 x_2 s$$

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

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

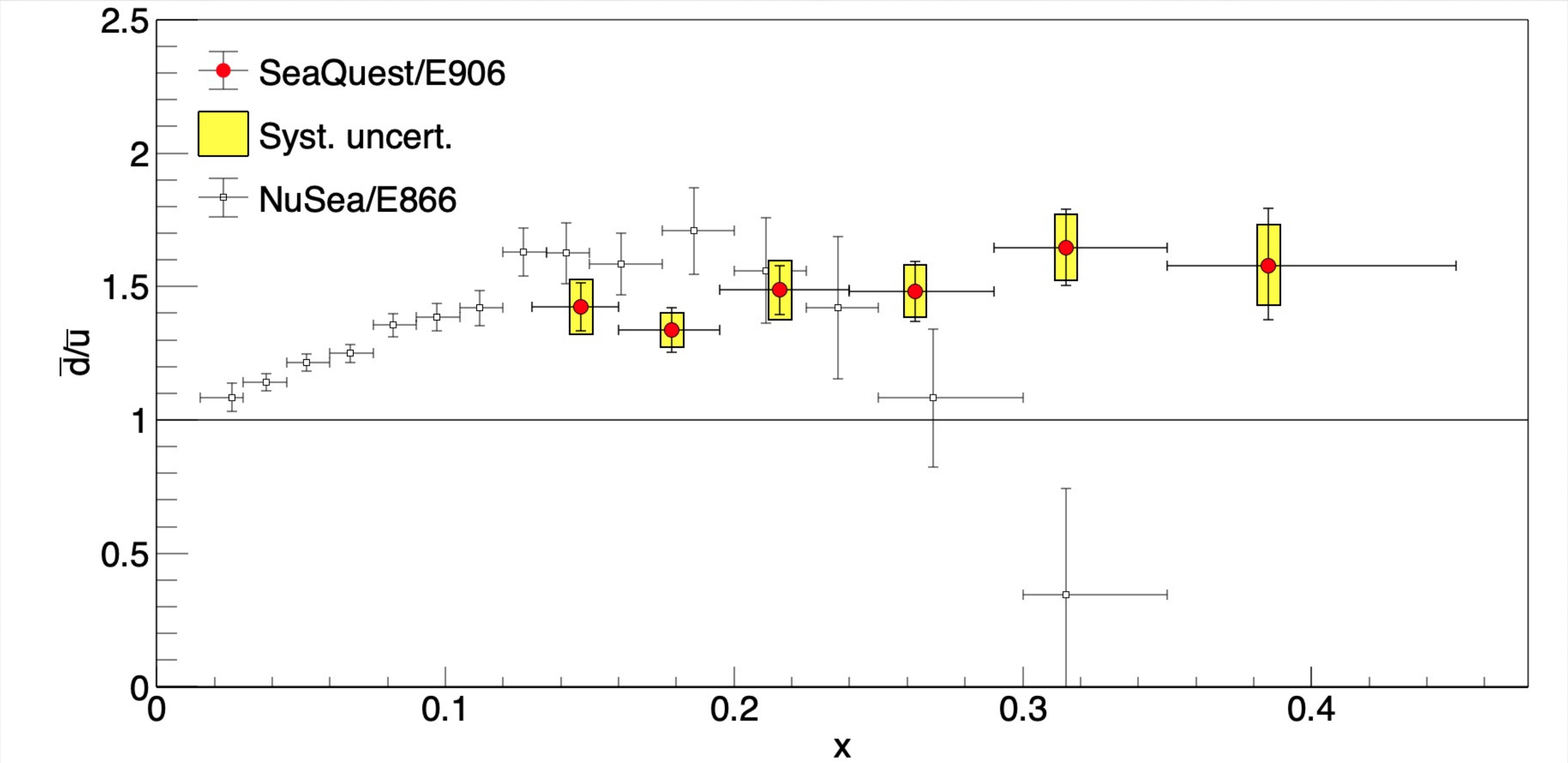


*NLO analysis

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

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

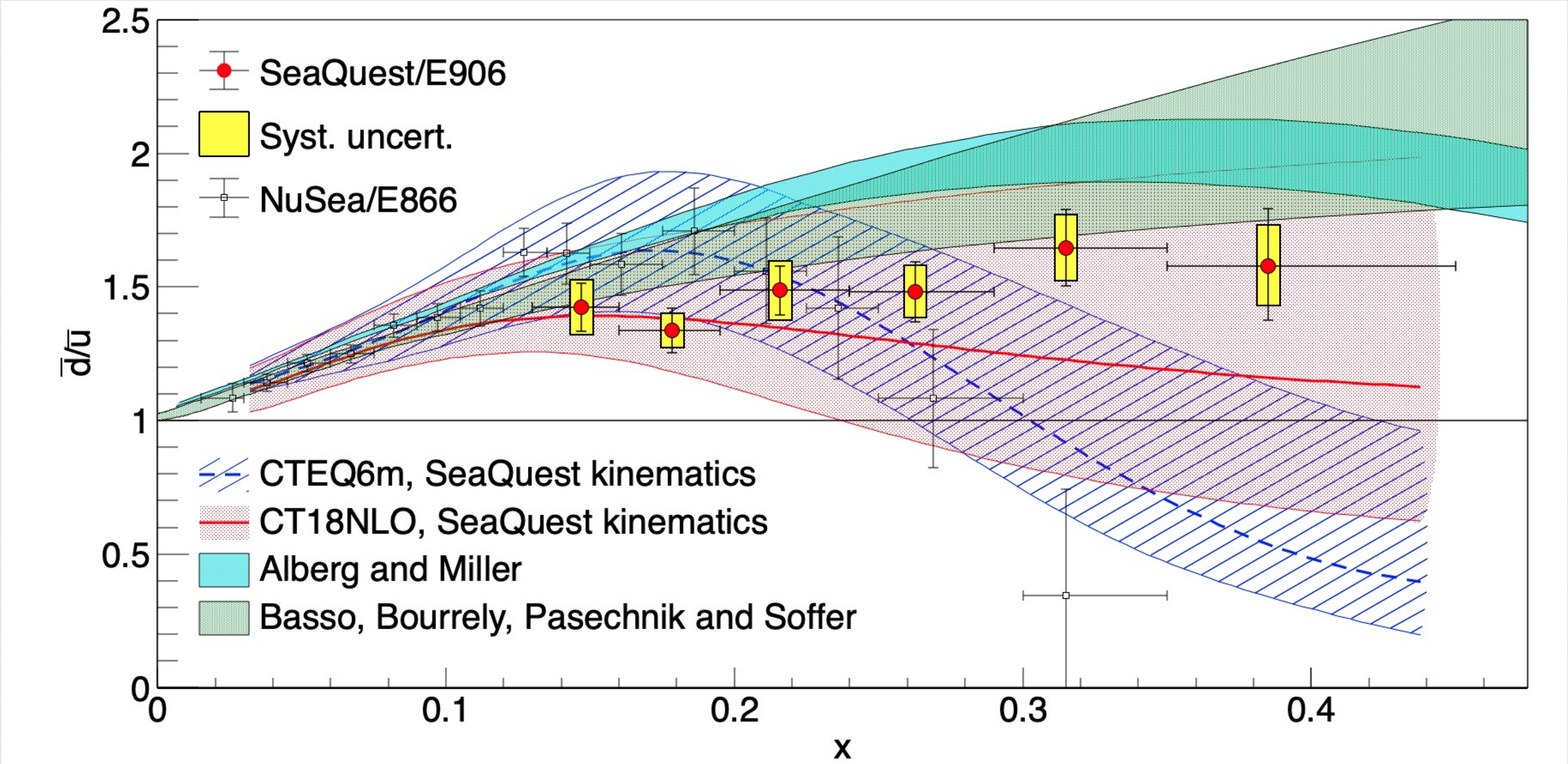
Dove et.al. Nature 590, 561 – 565 (2021)



- 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

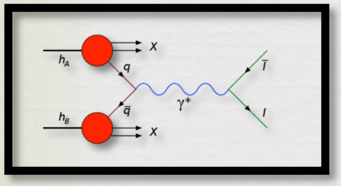
Dove et.al. Nature 590, 561 – 565 (2021)



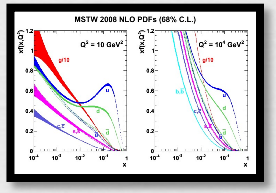
- Good agreement with Alberg and Miller, and Basso et al.

Recap - I

Drell-Yan process

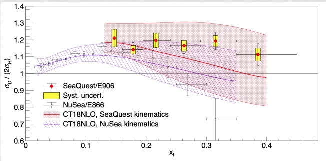


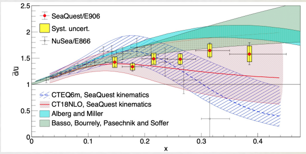
Anti-quark distributions in the nucleon



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

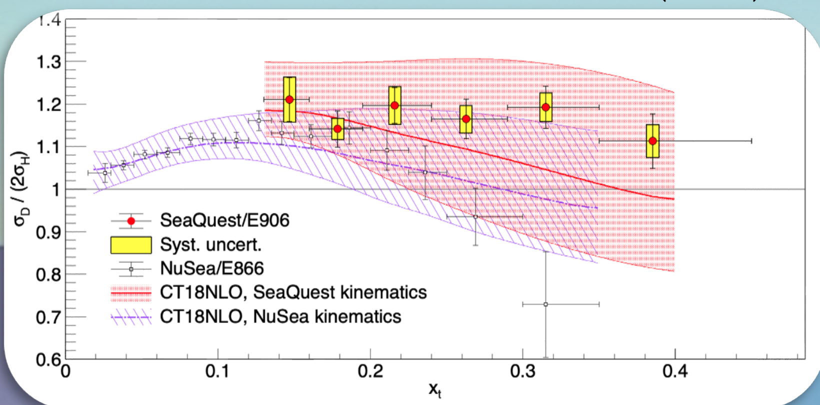
Prediction of various theoretical models on the integral $I_\Delta = \int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]dx$.

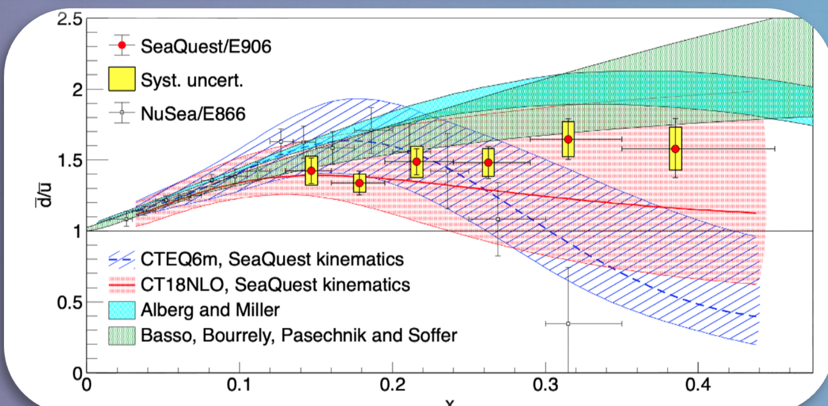
Model	I_Δ prediction	Ref.
Meson cloud (π-meson)	0	[31,127]
Meson cloud (ρ-meson)	$\simeq -0.0007$ to -0.027	[117]
Meson cloud ($\pi - \rho$ interf.)	$= -6\int_0^1 g^p(x)dx$	[118]
Meson cloud (ρ and $\pi - \rho$ interf.)	$\simeq -0.004$ to -0.033	[119]
Meson cloud (ρ-meson)	<0	[120]
Meson cloud ($\pi - \sigma$ 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]

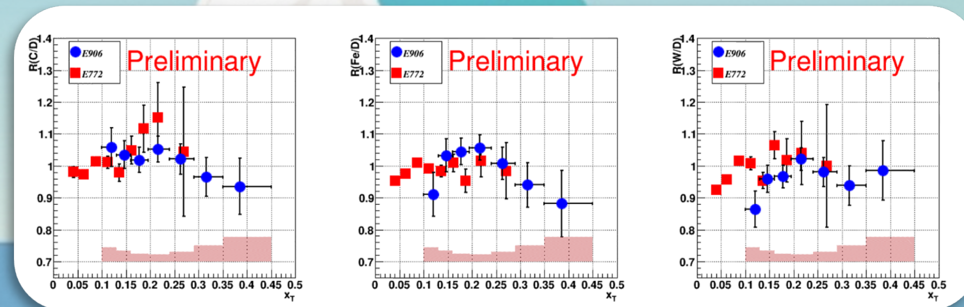
Spin contributions of anti-quarks

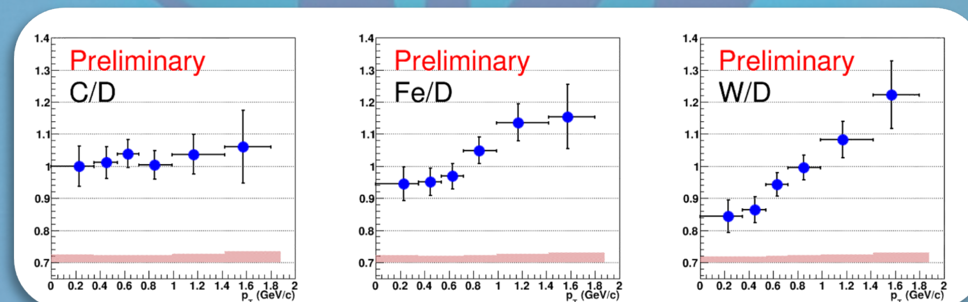
Summary

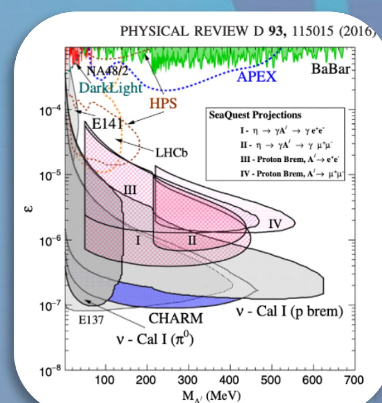
Dove et. al. Nature 590, 561 – 565 (2021)

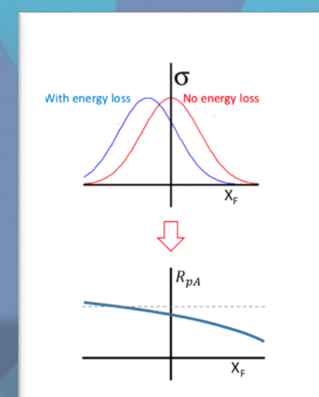












Stay tuned for results from more data and publications in the near future!

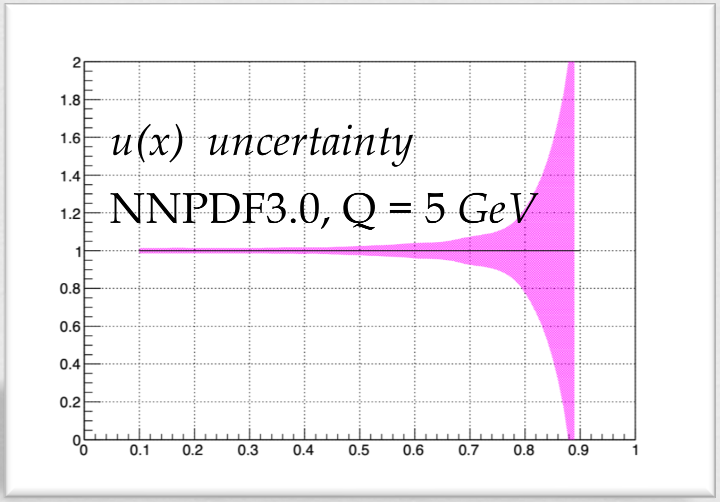
THANK YOU!

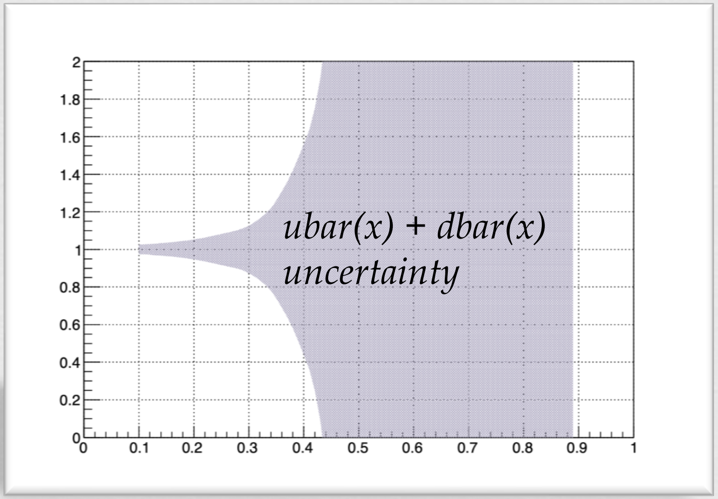
Absolute cross sections from p+d interactions

- 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





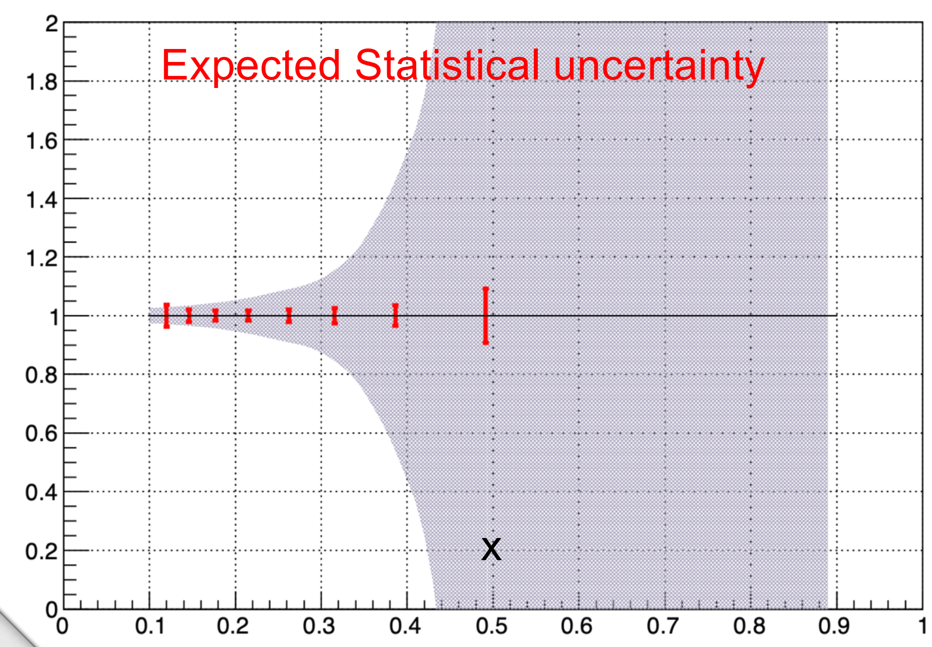
$$\sigma_{pd} = \sigma_{pp} + \sigma_{pn}$$

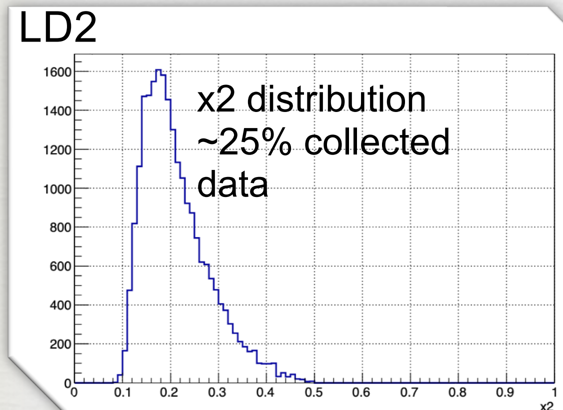
$$\left.\frac{d^2\sigma_{pd}}{dM^2 dx_F}\right|_{x1>x2} \approx \frac{4\pi\alpha^2}{9M^4}\frac{x_1 x_2}{x_1+x_2}\left(\frac{4u(x_1)+d(x_1)}{9}\right)\left(\bar{d}(x_2)+\bar{u}(x_2)\right)$$

Slide credit: Shivangi Prasad

ubar(x)+dbar(x) from SeaQuest

- Data taken on LD2 target
- Analysis in progress





Slide credit: Shivangi Prasad

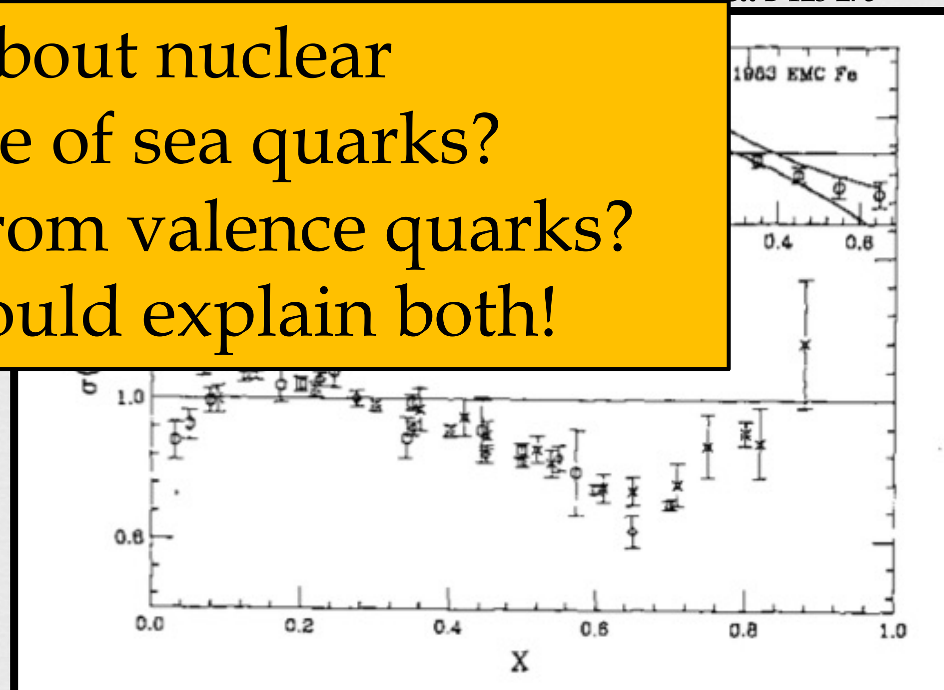
Nuclear dependence in DIS

- Parton d
functions
differ fro
nucleon

- Tremend
experime
theoretical activity
since the discovery

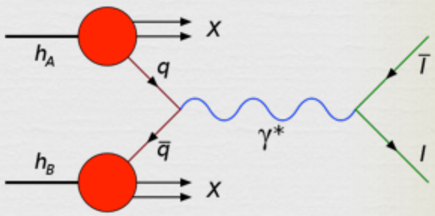
- Region above x = 0.04 is primarily sensitive to valence quarks

J. J. Aubert et. al. PhysLett B 123 275



But what about nuclear dependence of sea quarks?
Different from valence quarks?
Models should explain both!

One prediction…



Phys. Rev. Lett 64, 1342 (1990)

Shadowing and Anti-Shadowing of Nuclear Structure Functions*

STANLEY J. BRODSKY AND HUNG JUNG LU

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

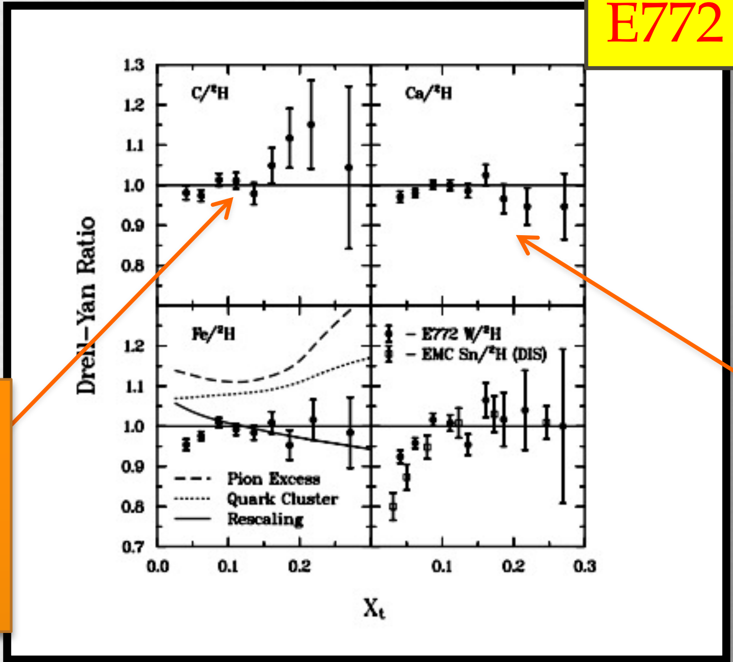
Finally, we note that due to the perturbative QCD factorization theorem for inclusive reactions, the same analysis can be extended to Drell–Yan processes. Thus shadowing and anti-shadowing should also be observable in the nuclear structure function $F_2^A(x_2, Q^2)$ extracted from massive lepton pair production on nuclear target[18] at low x_2.

Drell-Yan process sensitive to anti-quarks distributions in the target!

Nuclear dependence in Drell-Yan

E772 data

Rise not observed in anti-shadowing region (0.1 < x < 0.3) like in DIS but limited by statistical uncertainty for x > 0.2



Alde et. al. E772 Collaboration. Phys. Rev. Lett. 64.2479 (1990)

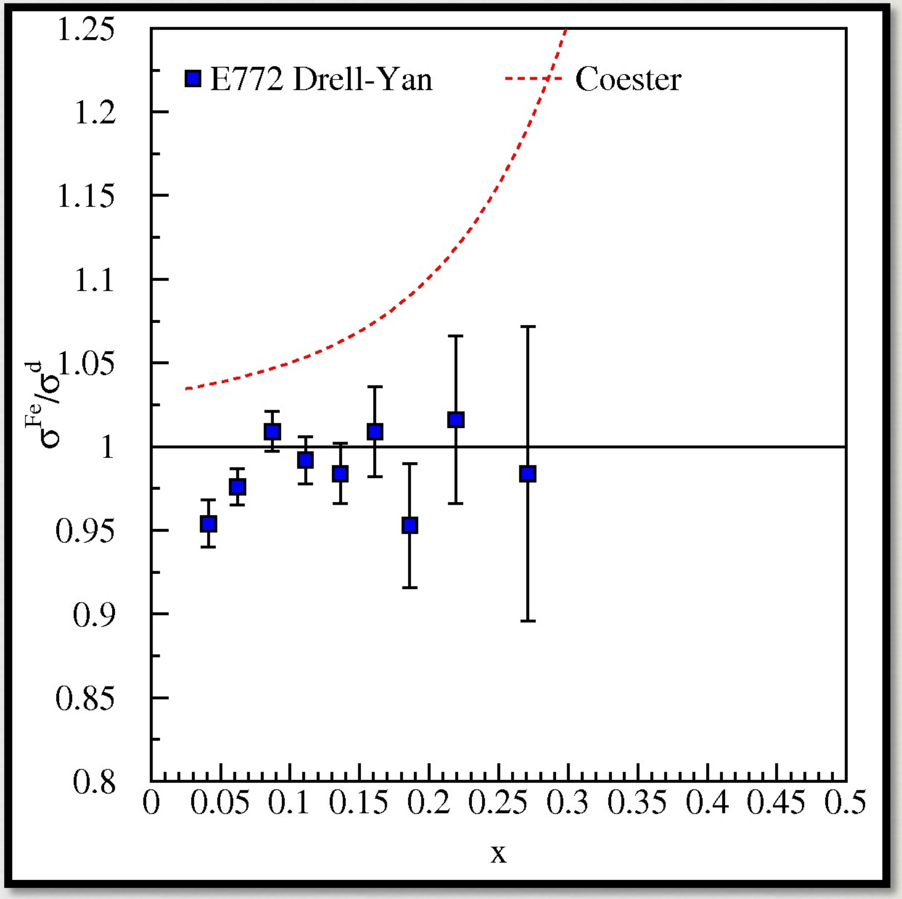
Is there a reduction at larger x (EMC region) in the Drell-Yan process? E772 could not address this region. Their data ends before ratio drops below 1 in DIS

- More precise measurements needed in the anti-shadowing and EMC region!

Nuclear dependence in Drell-Yan

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "nuclear mesons"
- Some models predict an enhancement in the cross section ratio due to the increase of virtual mesons in heavier targets relative to deuterium

*Theoretical predictions for 800 GeV

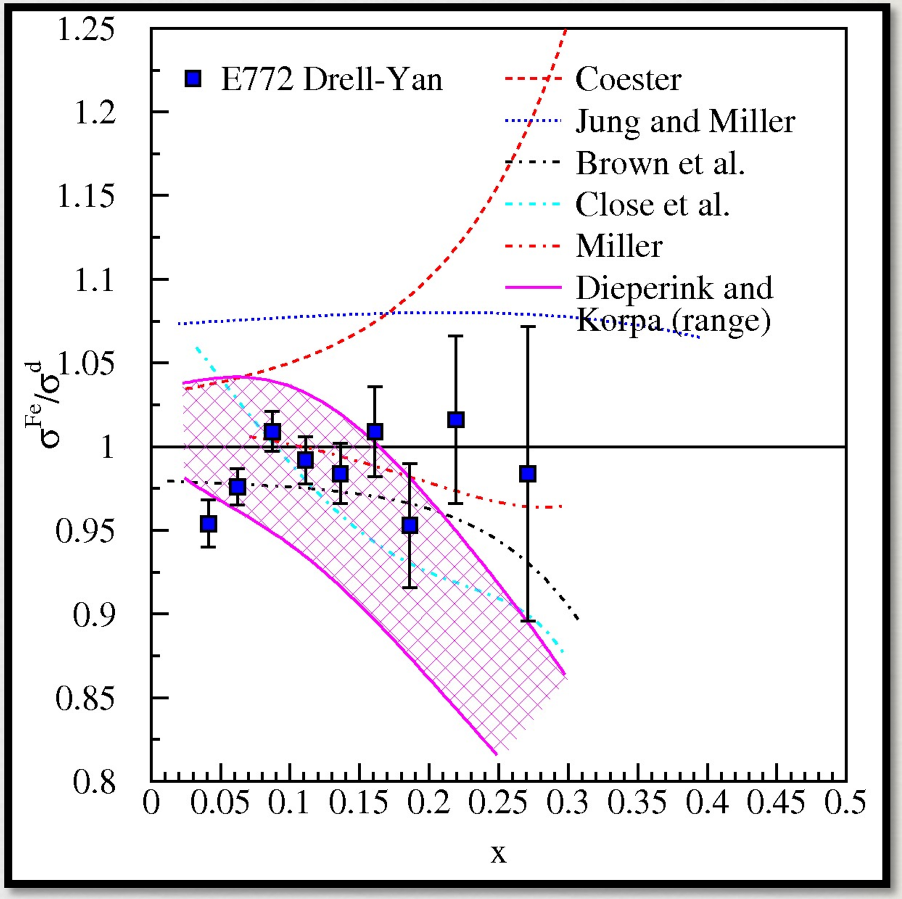


P. Reimer, D. Geesaman, *et al.*, "Drell-Yan Measurements of Nucleon and Nuclear Structure with the Fermilab Main Injector: E906," 2006.

Nuclear dependence in Drell-Yan

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "nuclear mesons"
- Some models predict an enhancement in the cross section ratio due to the increase of virtual mesons in heavier targets relative to deuterium
- Others expect a decrease in the cross section ratio

*Theoretical predictions for 800 GeV



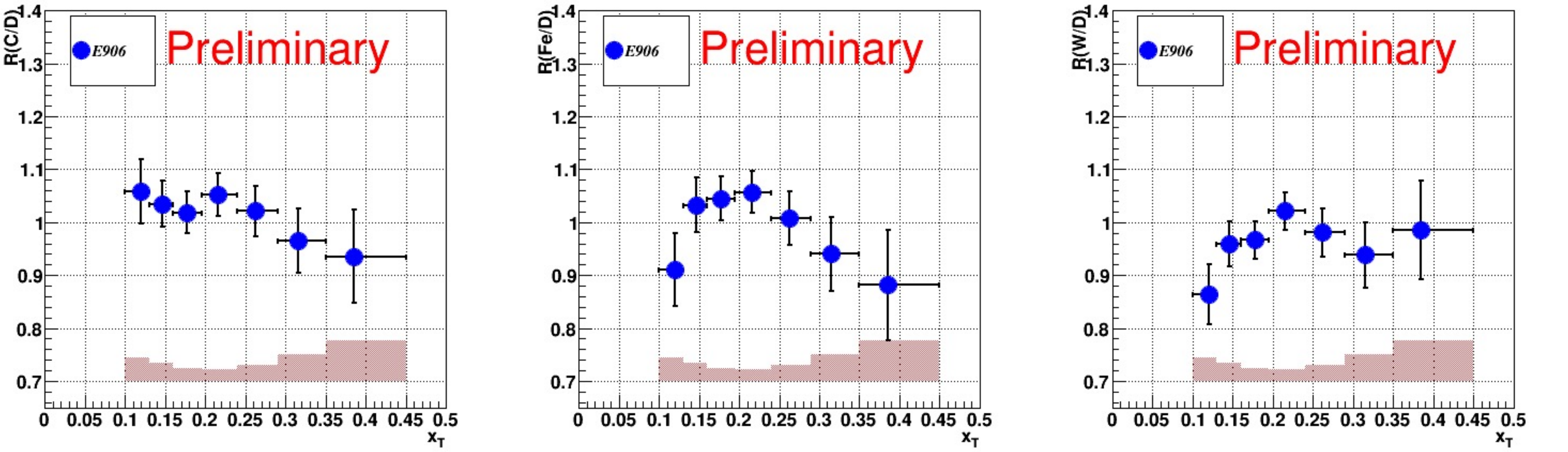
P. Reimer, D. Geesaman, *et al.*, "Drell-Yan Measurements of Nucleon and Nuclear Structure with the Fermilab Main Injector: E906," 2006.

Cross section ratios - R_{pA}

1. Data taken on C, Fe, W, LD2, LH2, empty flask and no target and analysis based on Run II and Run III data
2. Per-nucleon cross section ratios obtained after extrapolating to 0 trigger intensity where rate dependence effects simply vanish
3. No isoscalar corrections applied

*trigger intensity = instantaneous intensity of each triggered RF bucket by beam Cerenkov counter

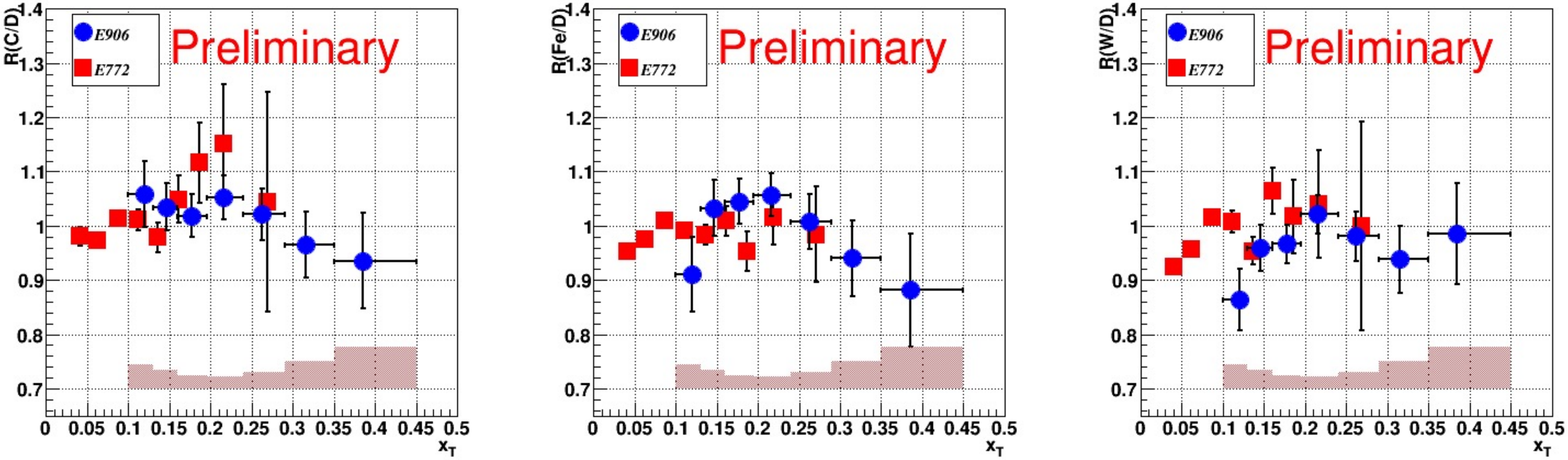
SeaQuest results



- No enhancement seen as in the case of a pion excess model!
- EMC like behavior is displayed but results are consistent with 1

SeaQuest comparison with E772

*E772 systematics not shown



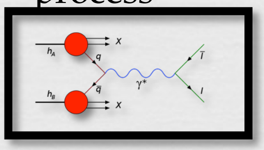
- No enhancement seen as in the case of a pion excess model!
- EMC like behavior is displayed but results are consistent with 1
- Basically in agreement with E772 results in the overlap region

Systematic uncertainties

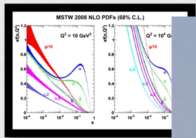
- Extrapolation function fit (major)
- Other sources (minor):
  - J/ψ and ψ' tail contamination into the high mass region
  - Choice of trigger intensity binning and range
  - Liquid deuterium contamination
  - 2% overall normalization and 0.5% beam on solid target correction
  - Difference between LH2 and LD2 target flask lengths

RECAP - II

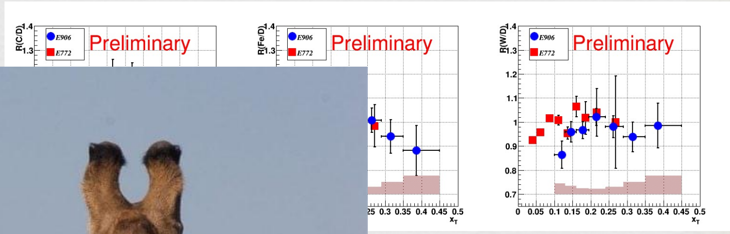
Drell-Yan process

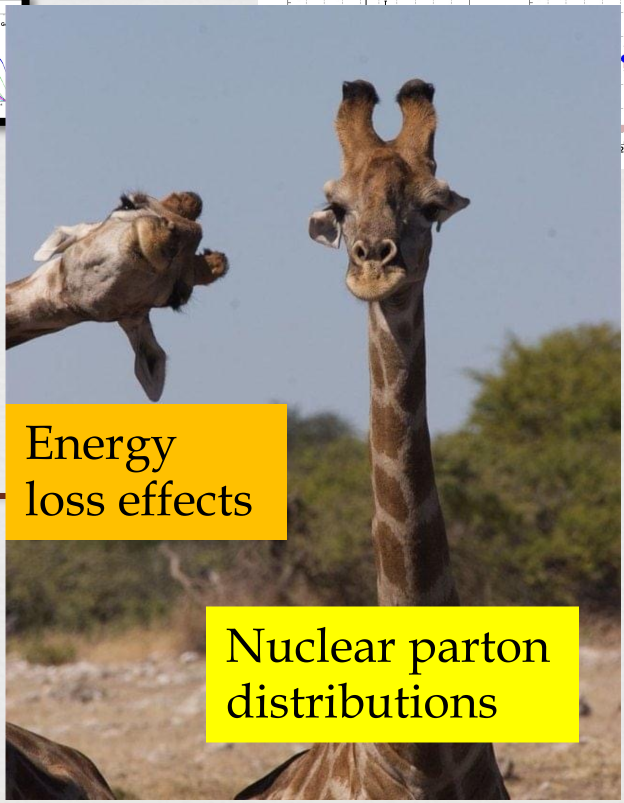


Anti-quark distributions



SeaQuest E906

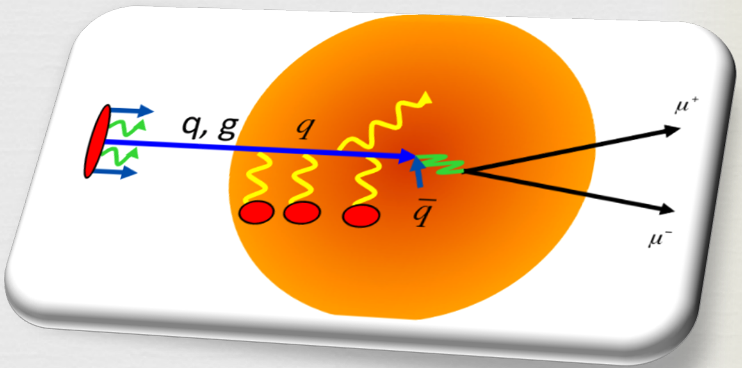


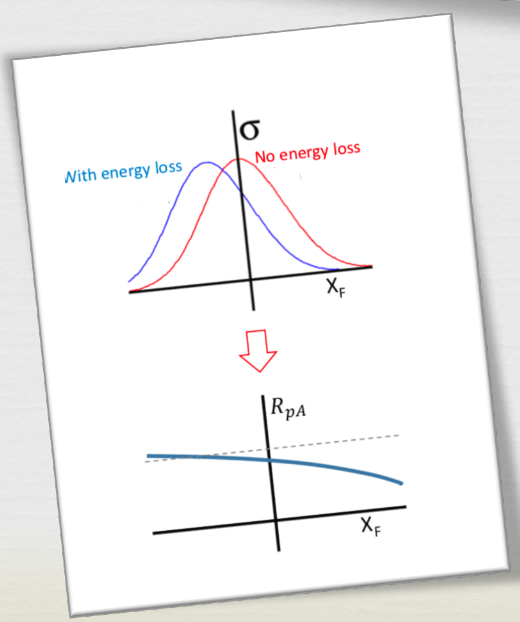


Nuclear dependence in sea anti-quarks

Parton energy loss in cold nuclear matter

- QCD partons are thought to lose energy while strongly interacting with cold nuclear matter
- Drell-Yan process is an ideal probe to study initial state energy loss effects due to no final state interactions of muons
- Has significant implications for RHIC physics in terms of setting the baseline for energy loss in p-A collisions





Motivating theory models

- First model: Gavin and Milana

$$\Delta x_1 = -\kappa_1 x_1 A^{1/3},$$

  - $\Delta x_1 \approx 0.4$ % / fm and k_1 has Q^2 dependence

- Second model: Brodsky and Hoyer

$$\Delta x_1 \approx -\frac{\kappa_2}{s} A^{1/3},$$

  - Energy loss should be ≤ 0.5 GeV/fm

- Third model: Baier et. al.(formulation of model 2 extended)

$$\Delta x_1 \approx -\frac{\kappa_3}{s} A^{2/3}.$$

Definitions:

- Δx_1 - the average change in the incident-parton momentum fraction
- S - square of the nucleon-nucleon center of mass energy
- A - nucleon mass

Measurements of E866

- E866 placed upper limits on the energy loss
- Shadowing could contribute to the drop in the cross section.
- Need for measurements that are not influenced by shadowing region
- SeaQuest is able to measure energy loss at a lower beam energy well out of the shadowing region

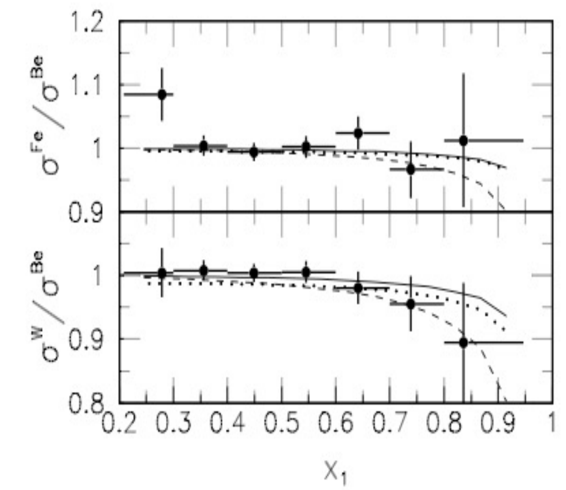
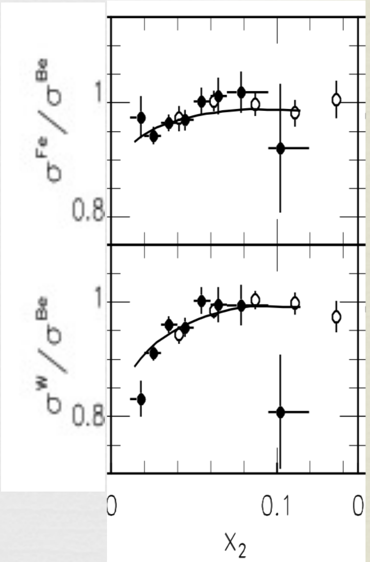
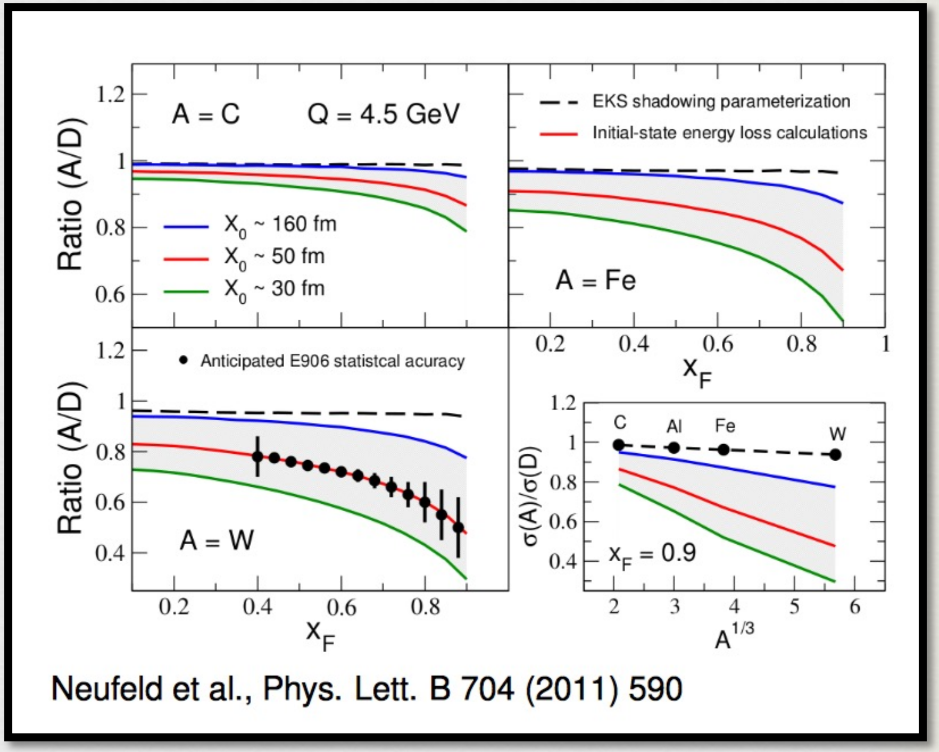


FIG. 4. Ratios of the cross section per nucleon versus x_1 for Fe/Be (upper panel) and W/Be (lower panel), corrected for shadowing. The solid curves are the best fit using the energy loss form (1), and the dashed curves show the 1σ upper limits. The dotted curves show the 1σ upper limits using the energy loss form (3). The 1σ upper limit curves using the energy loss form (2) are essentially identical to those using form (3).



Role of SeaQuest

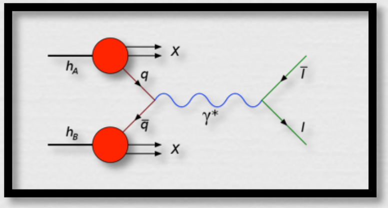
- 120 GeV is expected to be more sensitive to energy loss effects
- SeaQuest measured 0.13 < x < 0.45 which includes region well out of the shadowing region
- Analysis of this data is in progress!

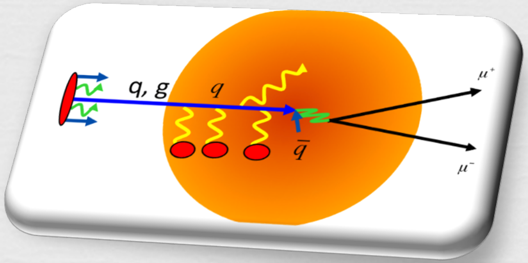


Projections for SeaQuest

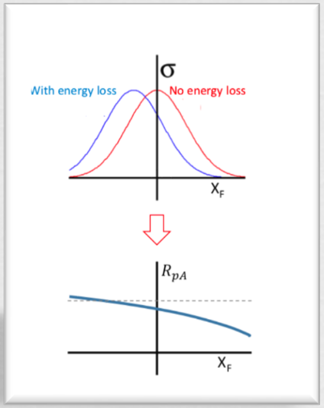
RECAP - III

Drell-Yan process





Ideal probe since there are no final state interactions



Parton energy loss in cold nuclear matter sets a baseline using pA collisions

Constraints on models that explain parton energy loss in cold and perhaps hot nuclear matter

p_T broadening in Drell-Yan dimuons

1. NA10 observed pT broadening for pi's on W and LD_2 Drell-Yan reactions

2. They observed differences for 140 and 286 GeV attributed to parton multiple scattering of the parton in the nuclear medium and also differences in pT distributions at these two energies

3. NA10 used two different target lengths and observed similar broadening (i.e. broadening not coming from the incident pion beam getting scattered along the target but from the parton scattering within the nucleus where DY reaction takes place)

OBSERVATION OF A NUCLEAR DEPENDENCE OF THE TRANSVERSE MOMENTUM DISTRIBUTION OF MASSIVE MUON PAIRS PRODUCED IN HADRONIC COLLISIONS

NA10 Collaboration

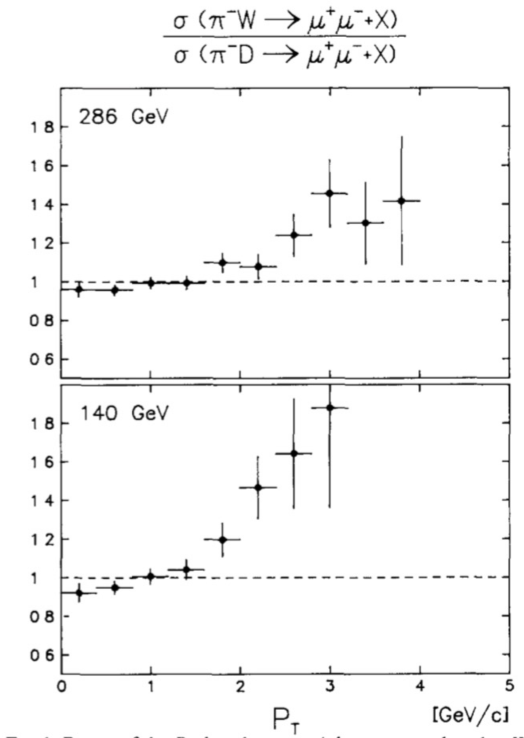
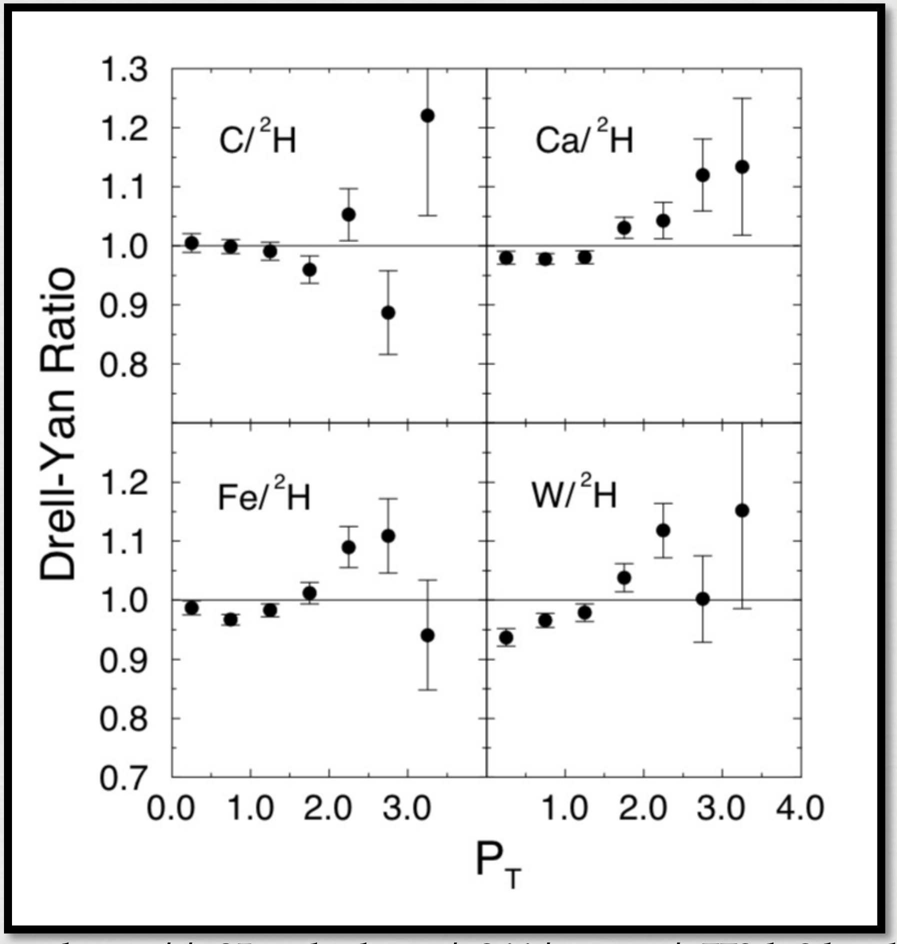


Fig 1 Ratios of the P_T distributions of dimuons produced in W and D The W and D samples are normalized to the same number of events Only statistical uncertainties are shown

E772 observations

1. E772 (unpublished) data shown
2. Ratio rises above 1 for pT > 0.8 GeV/c and slightly earlier for Tungsten
3. Slight reduction in low pT region and a rise in high pT region attributed to multiple scattering



https://p25ext.lanl.gov/e866/papers/e772dy2.html

E866 observations

- Similar observations as E772
- Drop in the low p_T region and rise in the high p_T region
- How does this look like for 120 GeV?

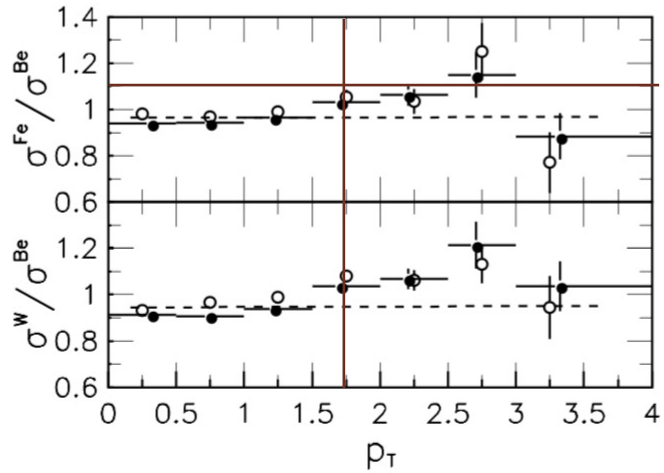


FIG. 3. Ratios of the measured Drell-Yan cross section per nucleon versus p_T. Solid circles show ratios of Fe/Be and W/Be from the present experiment, and open circles show ratios of Fe/C and W/C from E772. The dashed curves are shadowing predictions for the present experiment.

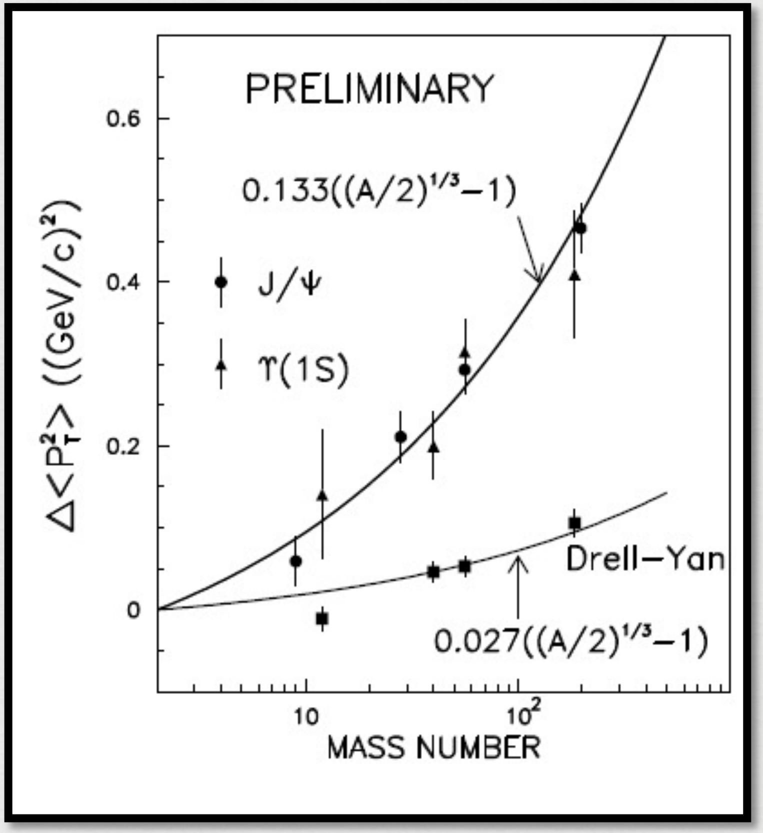
Vasiliev et al PRL 83 12 1999

Energy loss and p_T broadening

- The goal is to eventually get to $< \Delta P_T^2>$ which can be connected to energy loss (in some models) via

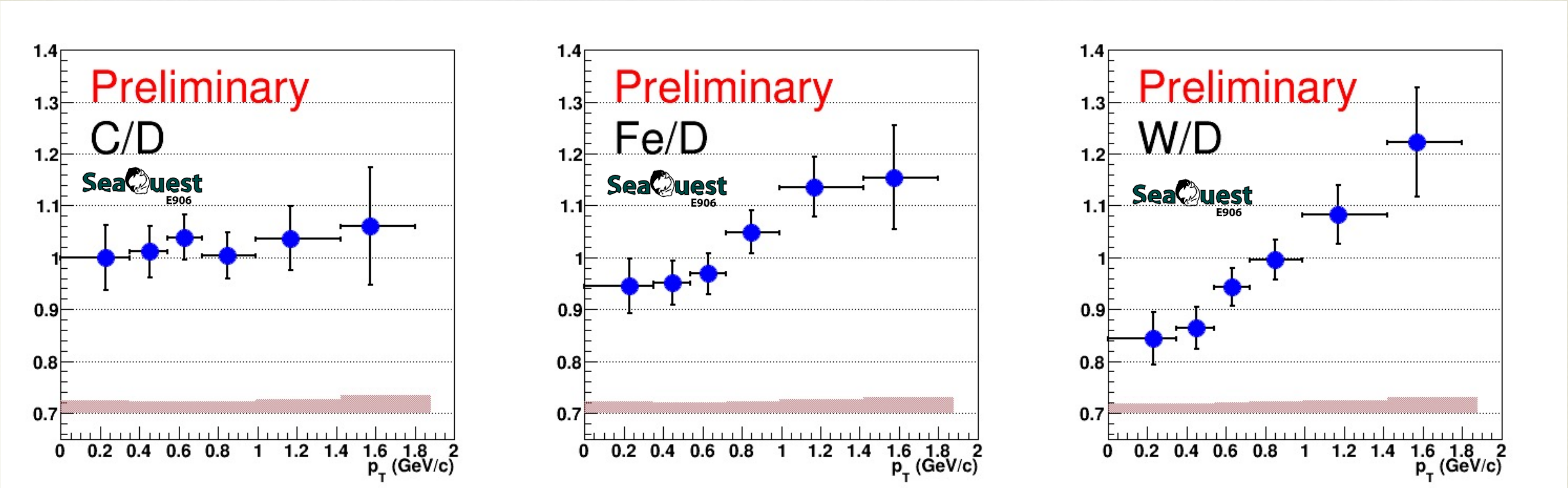
$$-dE/dz = \frac{1}{4}\alpha_s N_c p_t^2,$$

- Also, the interesting question to ask is, do we see the same or different broadening for a lower beam energy?



P. L. McGaughey, J. M. Moss and J. C. Peng, Annu. Rev. Nucl. Part. Sci. 49, 217 (1999); J. C. Peng, arXiv:hep-ph/9912371.

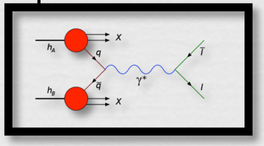
SeaQuest results



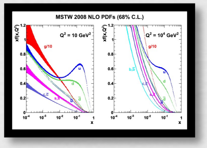
- Ratio consistent with 1 for carbon/LD_2
- Drop in the ratio in low pT region and a slight enhancement in the high pT region observed for Fe/LD_2
- More prominent broadening in the case of W/LD_2

RECAP - IV

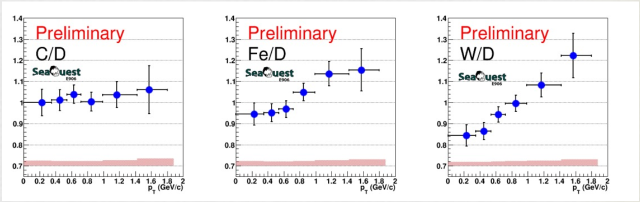
Drell-Yan process



Anti-quark distributions



STAGE 1



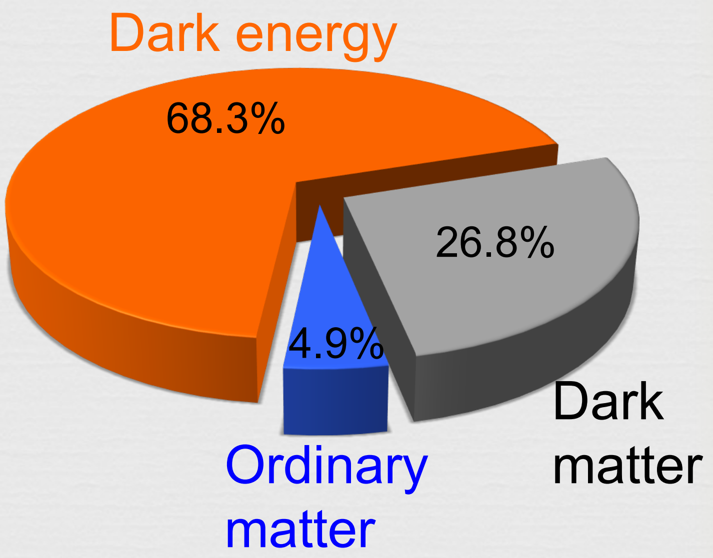
STAGE 2 (in progress)

Extract the ΔP_T^2 from these ratios and LD_2 pT distributions

Constraints on models that explain parton energy loss in cold nuclear matter

What's the matter?

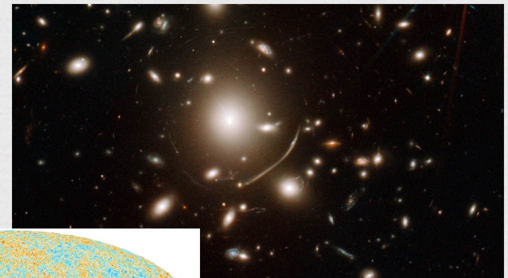
- Dark matter is:
  - one of the greatest unsolved mysteries of modern physics
  - a central element for cosmology and astronomy
  - about 27% of the energy density of the Universe

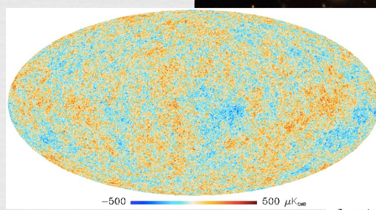


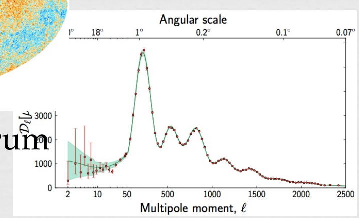
Dark matter - motivation

F. Zwicky, ApJ 86 (1937) 217
Motion of individual galaxies in coma clusters

Gravitational lensing of galaxies

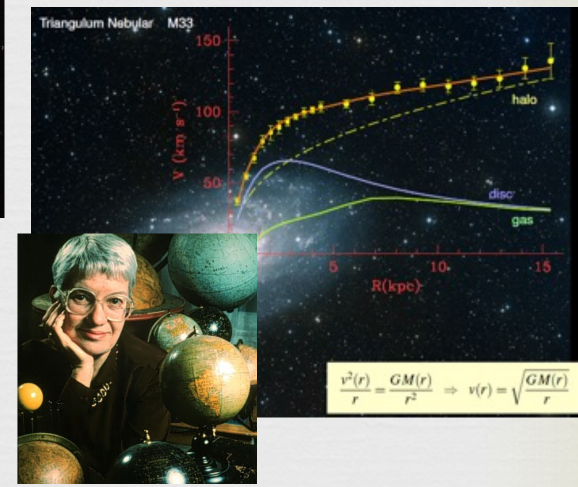






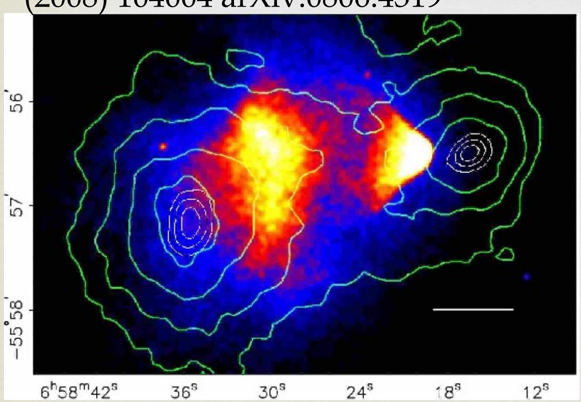
CMB – power spectrum

V. Rubin et al, ApJ 238 (1980) 471
Rotational curves of individual galaxies

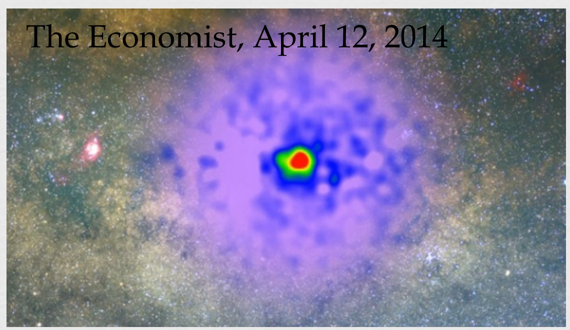


VERA RUBIN

Dai, De-Chang *et al.* Phys.Rev. D78 (2008) 104004 arXiv:0806.4319

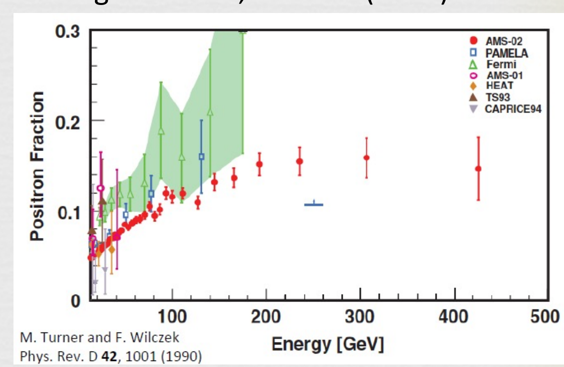


Bullet clusters - aftermath



P. Agrawal et al., arXiv: 1404.1373
T. Daylan et al, arXiv: 1402.6703
Hooper and Linden, PRD, arXiv:1110.0006
B. D. Fields, S. L. Shapiro, J. Shelton, PRL 113 (2014) 151302

M. Aguilar et al., PRL 113 (2014) 121101



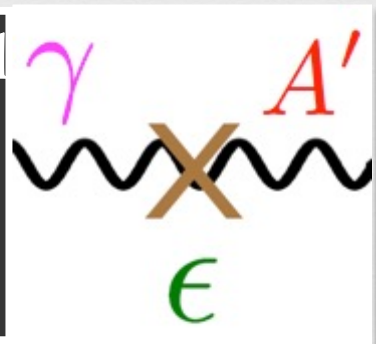
Positron fraction excess

Dark Sector and Standard Model coupling

Standard Model

Quarks, leptons

g W Z γ



Hidden Sector

dark matter

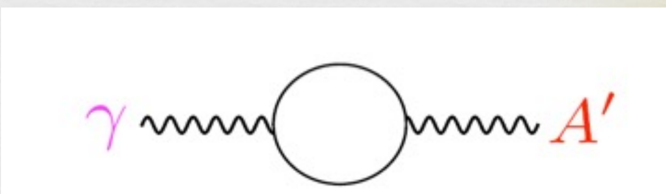
A'

- Dark Sector could interact with the Standard Model sector via a hidden gauge boson (A′ or "dark photon" or "para photon" or "hidden photon")

- Dark photons can provide a portal into the Dark Sector

- Dark photons could couple to Standard Model matter with $\alpha' = \alpha\varepsilon^2$

$$\mathcal{L} \supset -\frac{1}{4}F^{\mathrm{SM}}_{\mu\nu}F^{\mu\nu}_{\mathrm{SM}} - \frac{1}{4}F^{\mathrm{hidden}}_{\mu\nu}F^{\mu\nu}_{\mathrm{hidden}} + \frac{\varepsilon}{2}F^{\mathrm{SM}}_{\mu\nu}F^{\mu\nu}_{\mathrm{hidden}} + m^2_{\gamma'}A^{\mathrm{hidden}}_{\mu}A^{\mu}_{\mathrm{hidden}}$$



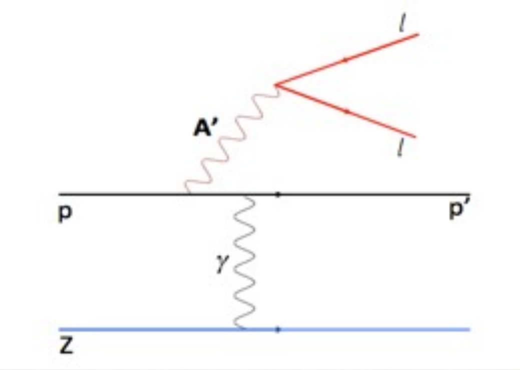
A′ produced via a loop mechanism

B. Holdom, PLB **166** (1986) 196

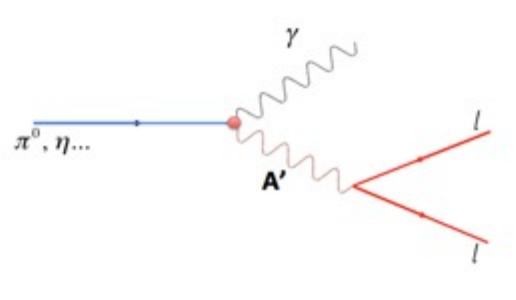
J. D. Bjorken et al, PRD **80** (2009) 075018

Possible A′ production mechanisms

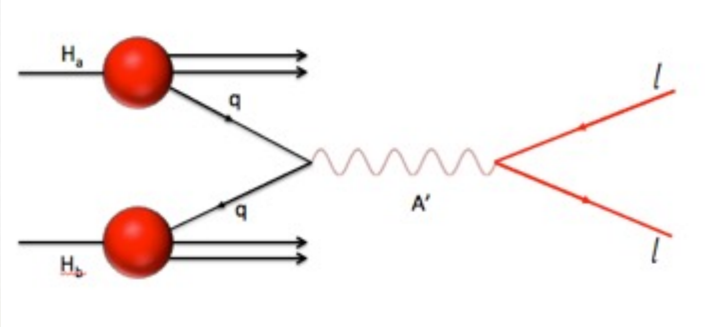
- Proton Bremsstrahlung



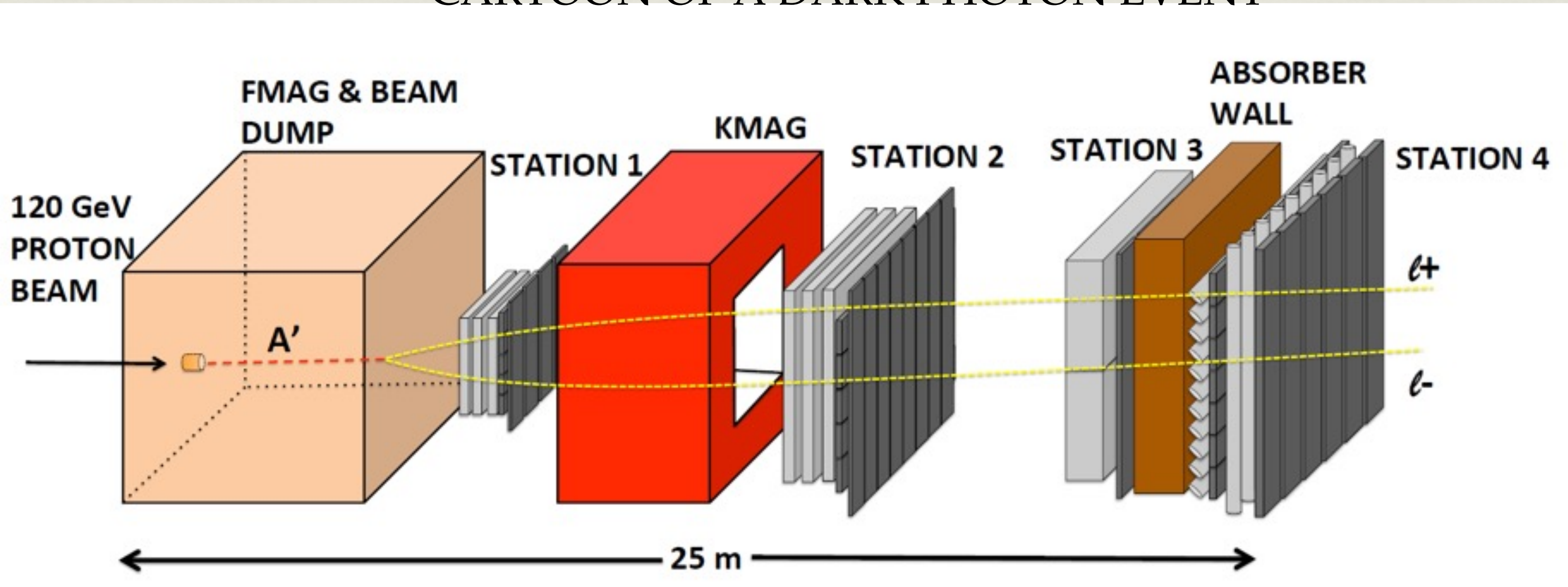
- η … decay



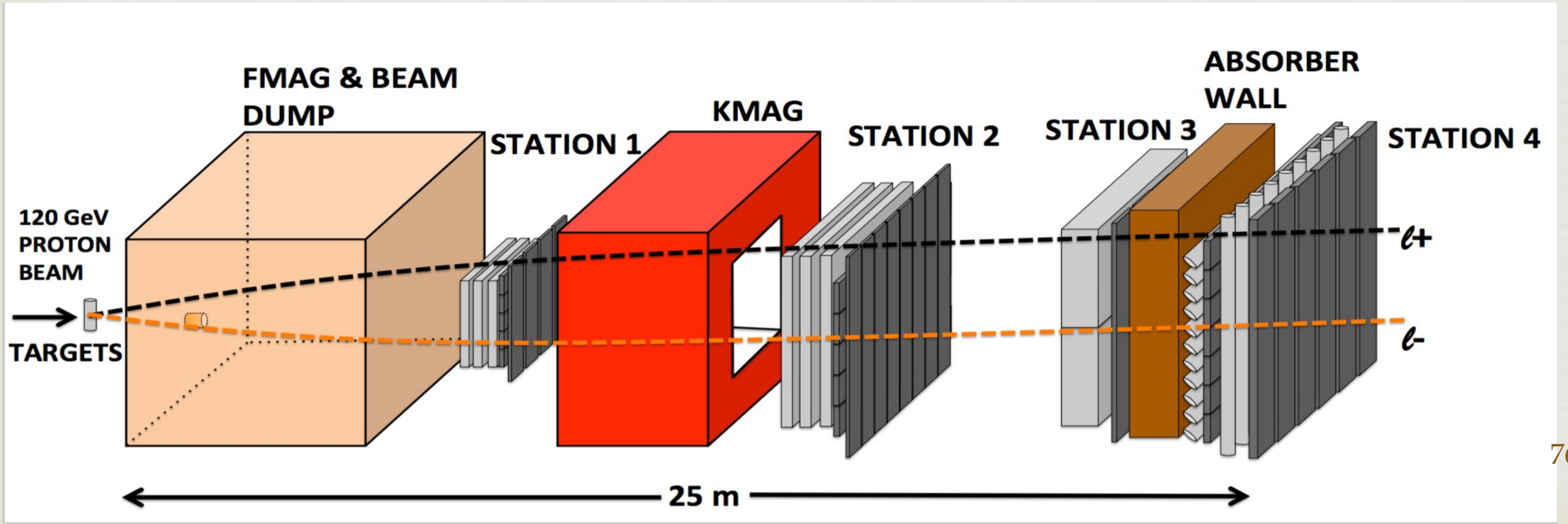
- Dark Drell-Yan process



CARTOON OF A DARK PHOTON EVENT



CARTOON OF A DRELL YAN EVENT



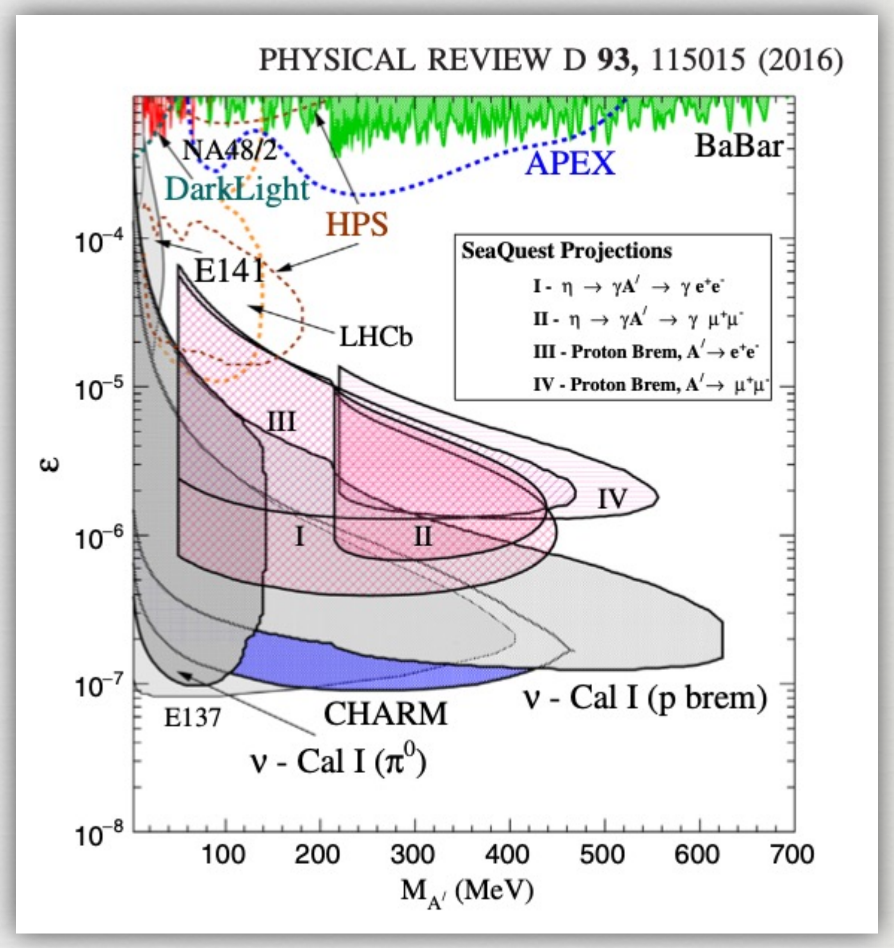
SeaQuest projections

2E12 ppp
200 days
10 event contours

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

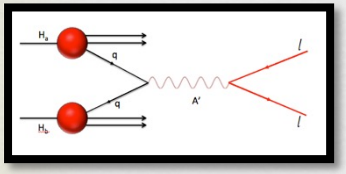
J. D. Bjorken et al, PRD **80** (2009) 075018

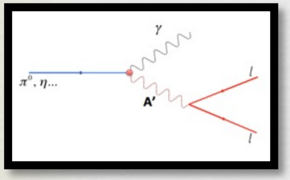
- E_0 = energy of the A′
- N_{eff} = no. of available decay products
- l_0 = distance that A′ travels before decaying
- ε = coupling constant between standard model and dark sector
- $m_{A'}$ = mass of A′

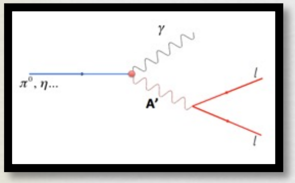


S. Gardner, R. J. Holt, A. Tadepalli,
Phys.Rev.D 93 (2016) 11, 115015 arxiv:1509.00050 [hep-ph]

RECAP - V

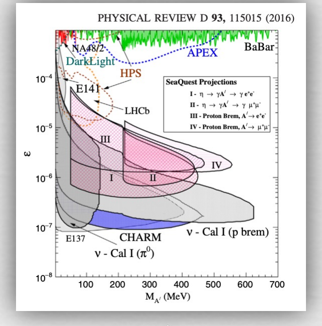






Dark photons

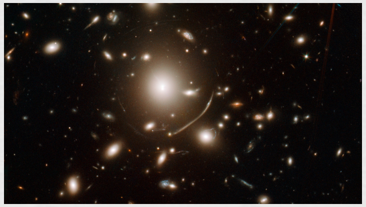
$$l_o \approx \frac{0.8\,cm}{N_{eff}}\left(\frac{E_o}{10\,GeV}\right)\left(\frac{10^{-4}}{\varepsilon}\right)^2\left(\frac{100\,MeV}{m_{A'}}\right)^2$$



SeaQuest
E906

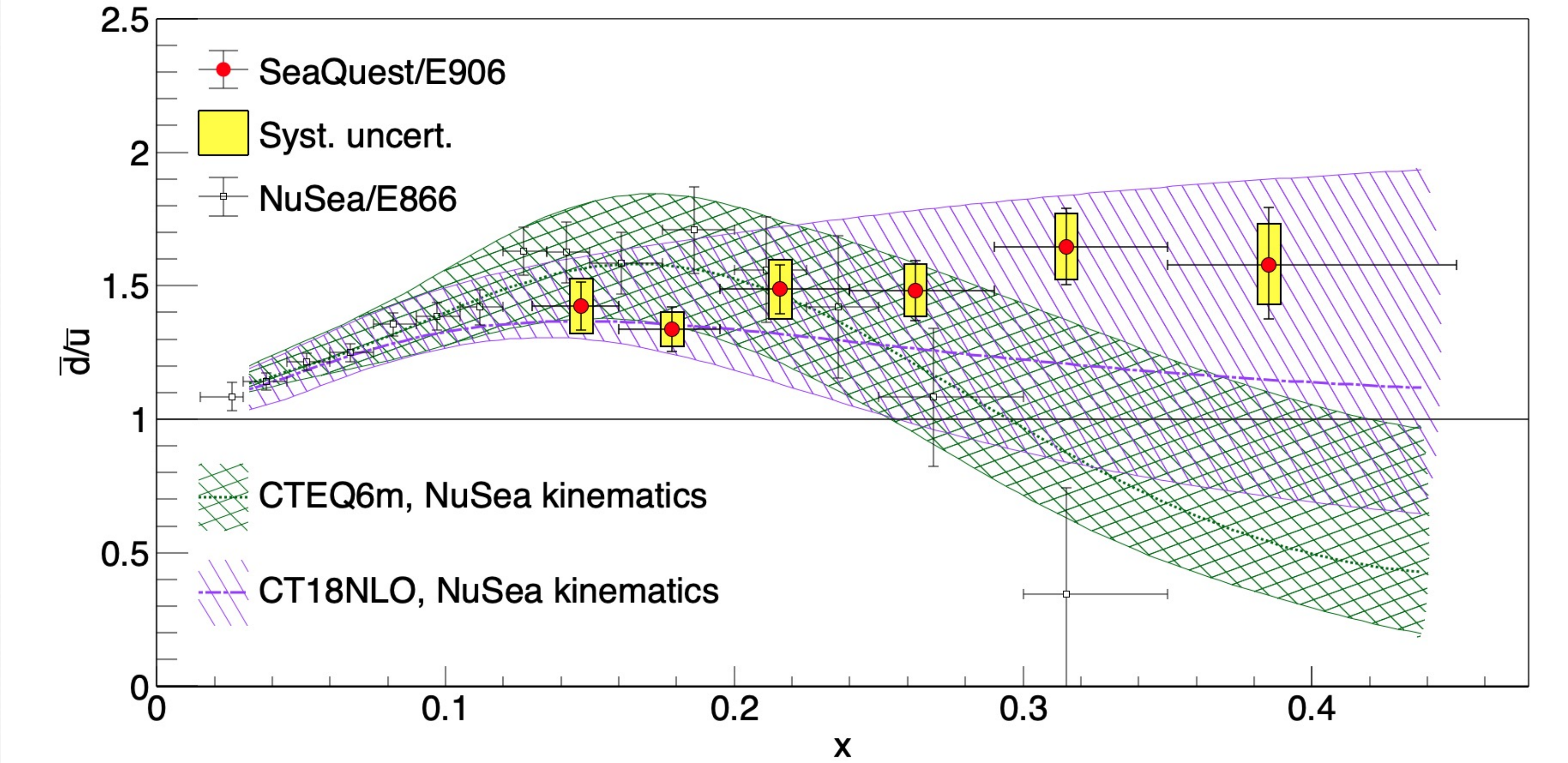
Constraints on mass and ε parameter space

portal



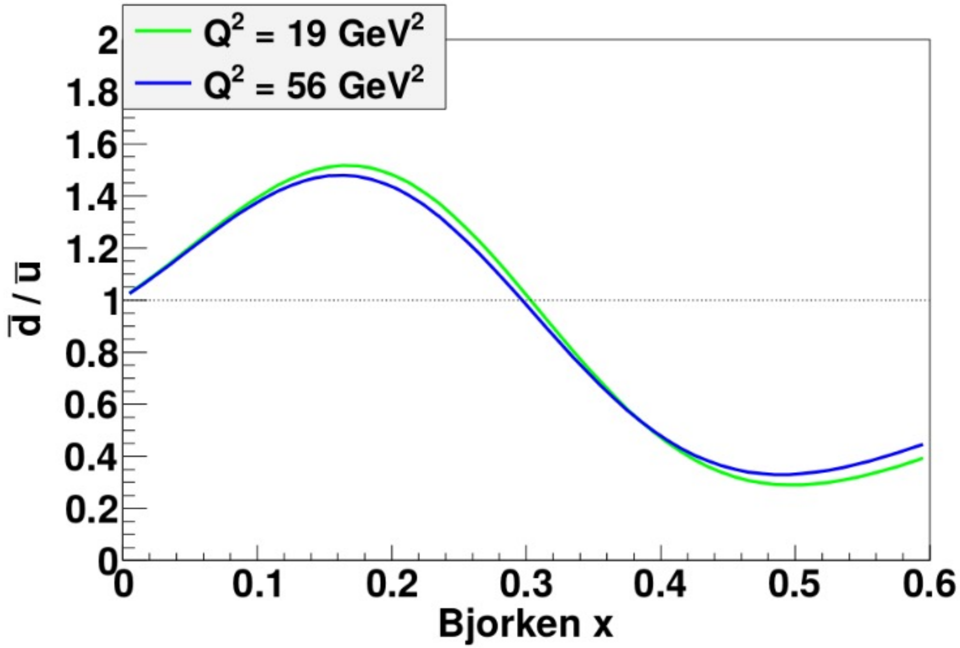
Thank you!

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



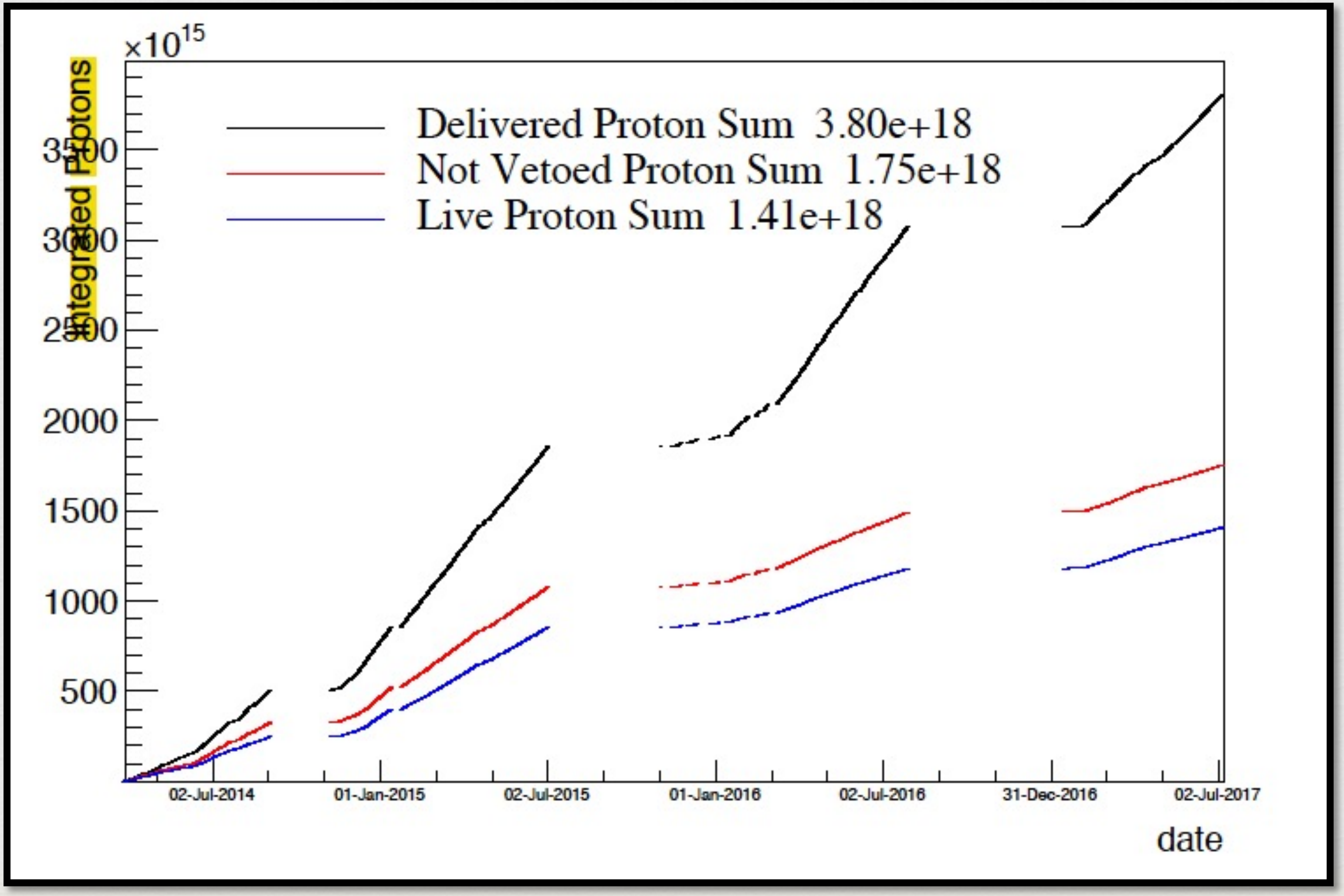
Q^2 evolution of pdfs

Slide taken from Bryan Kerns, APS, 2016

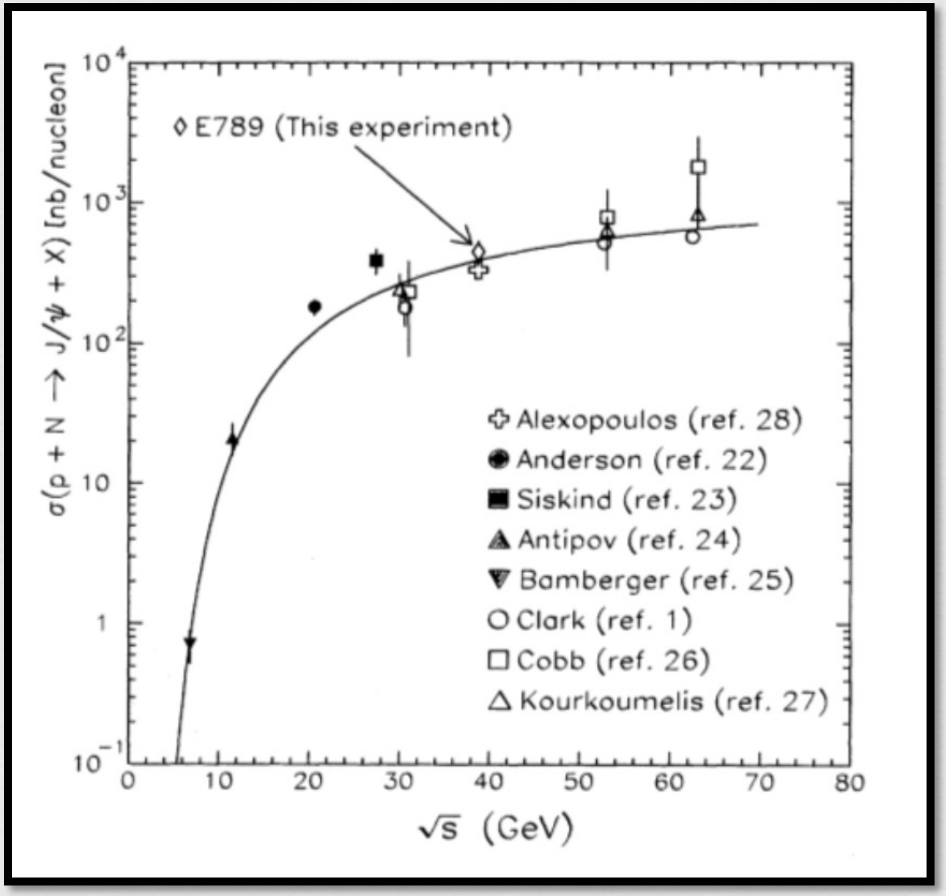


- Differences in Q^2 according to CT10
- Difference between SeaQuest and E866 because of Q^2 evolution is small

Live protons



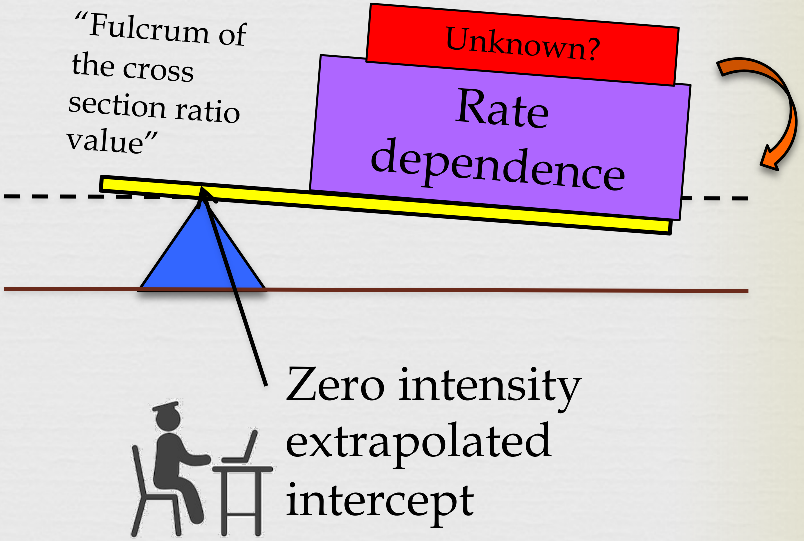
J/psi background scaling



Schub et al. Phys. Rev. D 52 1307, 1995

Extrapolation method

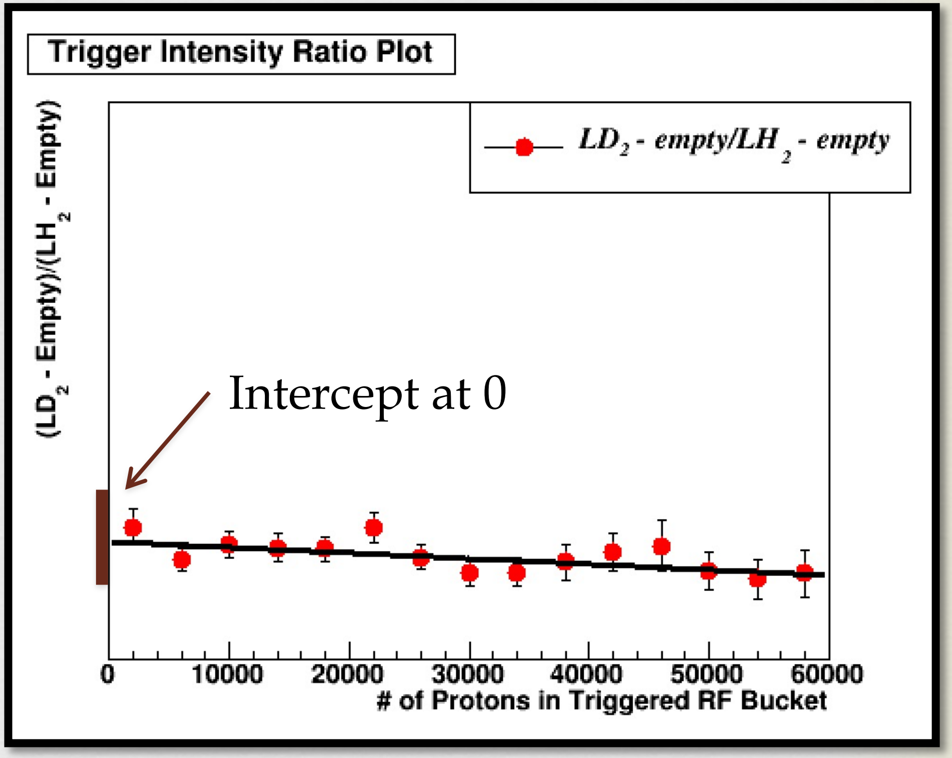
- We calculate the cross sections using hits from detectors
- We plot the ratio of cross sections of two targets as a function of the # of protons in the triggered bucket
- There is a slope for the DY dimuon yield ratio that could be caused by aspects of rate dependence
  - Different accidental backgrounds
  - Relative tracking efficiency difference
  - DAQ dead time differences
- Rate dependence vanishes at beam intensity = 0!



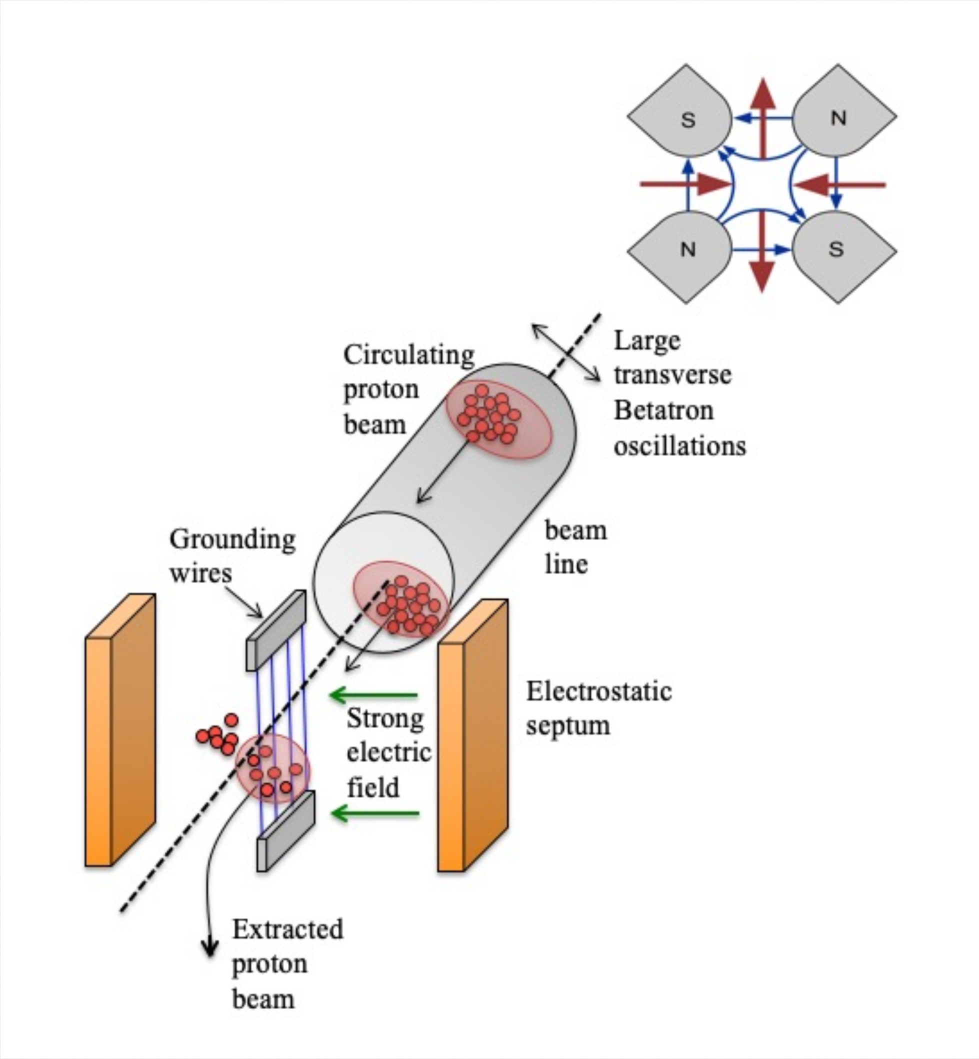
Extrapolation method contd...

- SeaQuest had collected enough statistics to allow a separation of the data into different x_T bins

- Extract intercept at 0 which is free from accidental background and rate dependence!



*Linear fit shown for simplicity!


S
N
N
S
Large
transverse
Betatron
oscillations
Circulating
proton
beam
beam
line
Grounding
wires
Electrostatic
septum
Strong
electric
field
Extracted
proton
beam

Drell-Yan Kinematics

4-vectors: p_{targ}, p_{beam}, $p_{\mu+}$, $p_{\mu-}$

$$p_{cms} = p_{targ} + p_{beam}$$

$$p_{sum} = p_{\mu+} + p_{\mu-}$$

$$x_{beam} = p_{targ}\, p_{sum} / (p_{targ}\, p_{cms})$$

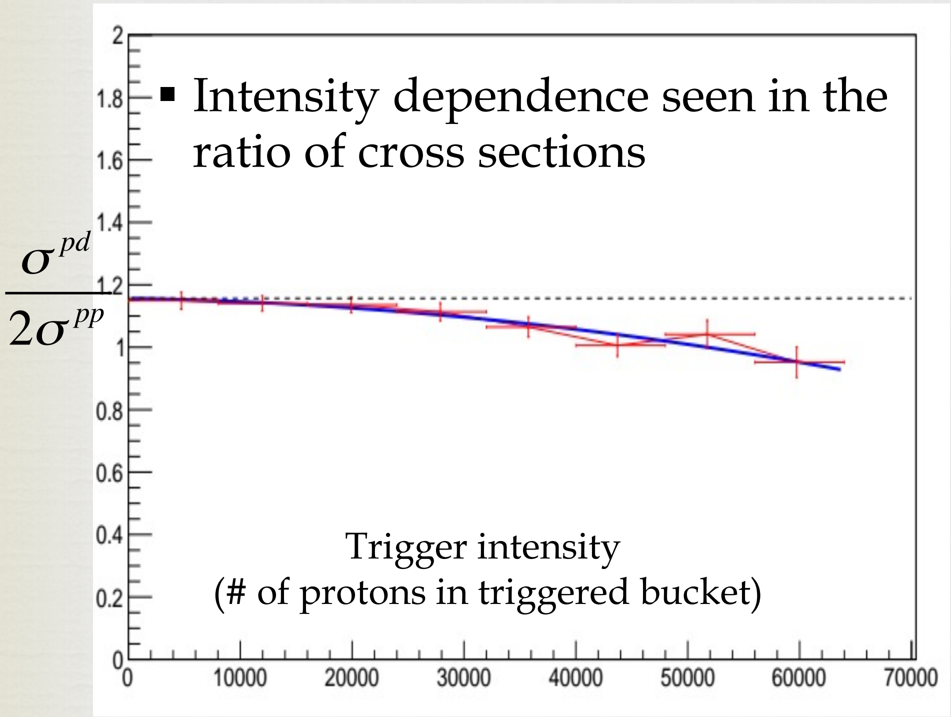
$$x_{targ} = p_{beam}\, p_{sum} / (p_{beam}\, p_{cms})$$

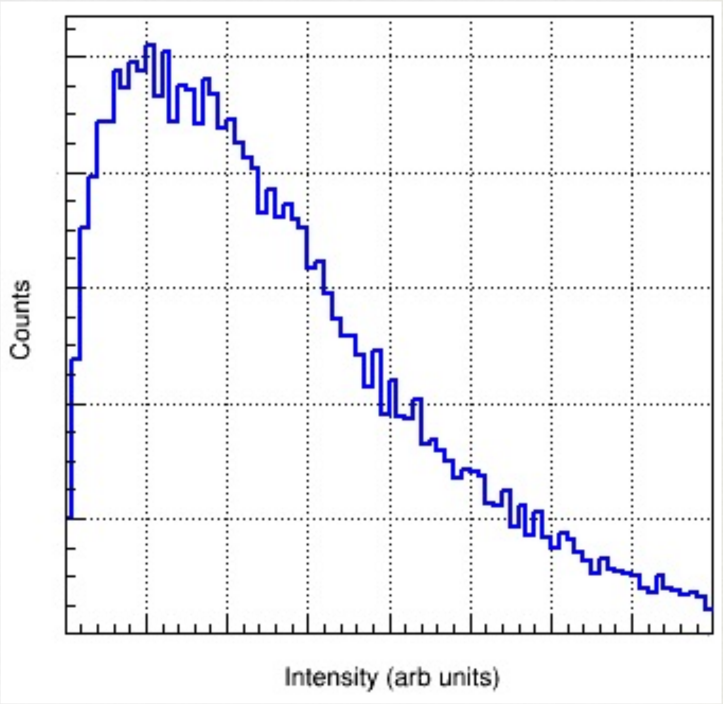
$$M^2_{\gamma} / s = x_{beam}\, x_{targ}$$

$$x_F \sim x_{beam} - x_{targ}$$

Note that the $\mu^+\mu^-$, $p\mu^+$ and $p\mu^-$ planes are not necessarily coplanar - this gives access to p_T.

Intensity Dependence



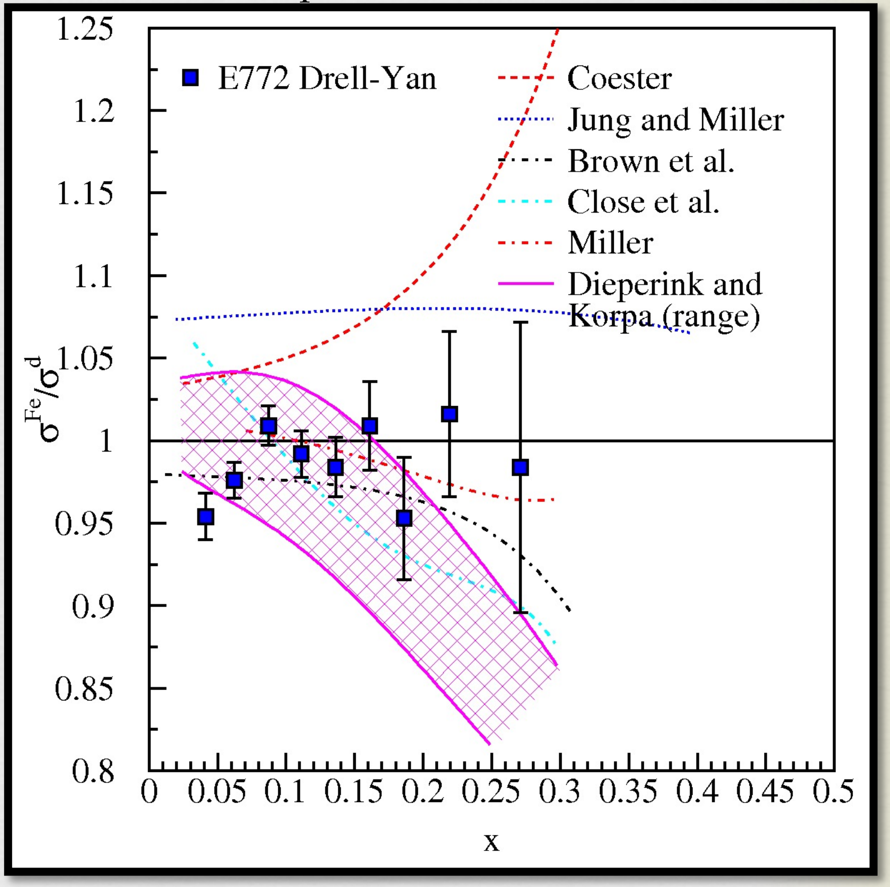


- Extract intercept at 0 which is free from accidental background and rate dependence!

Role of SeaQuest

- SeaQuest explored the high-x region for Drell-Yan reactions
- Higher precision compared to E772

*Theoretical predictions for 800 GeV



P. Reimer, D. Geesaman, *et al.*, "Drell-Yan Measurements of Nucleon and Nuclear Structure with the Fermilab Main Injector: E906," 2006.