The light sea quarks asymmetry in proton from the SeaQuest experiment at Fermilab

Márcia Quaresma - LIP Lisbon

LIP Lisbon Seminar

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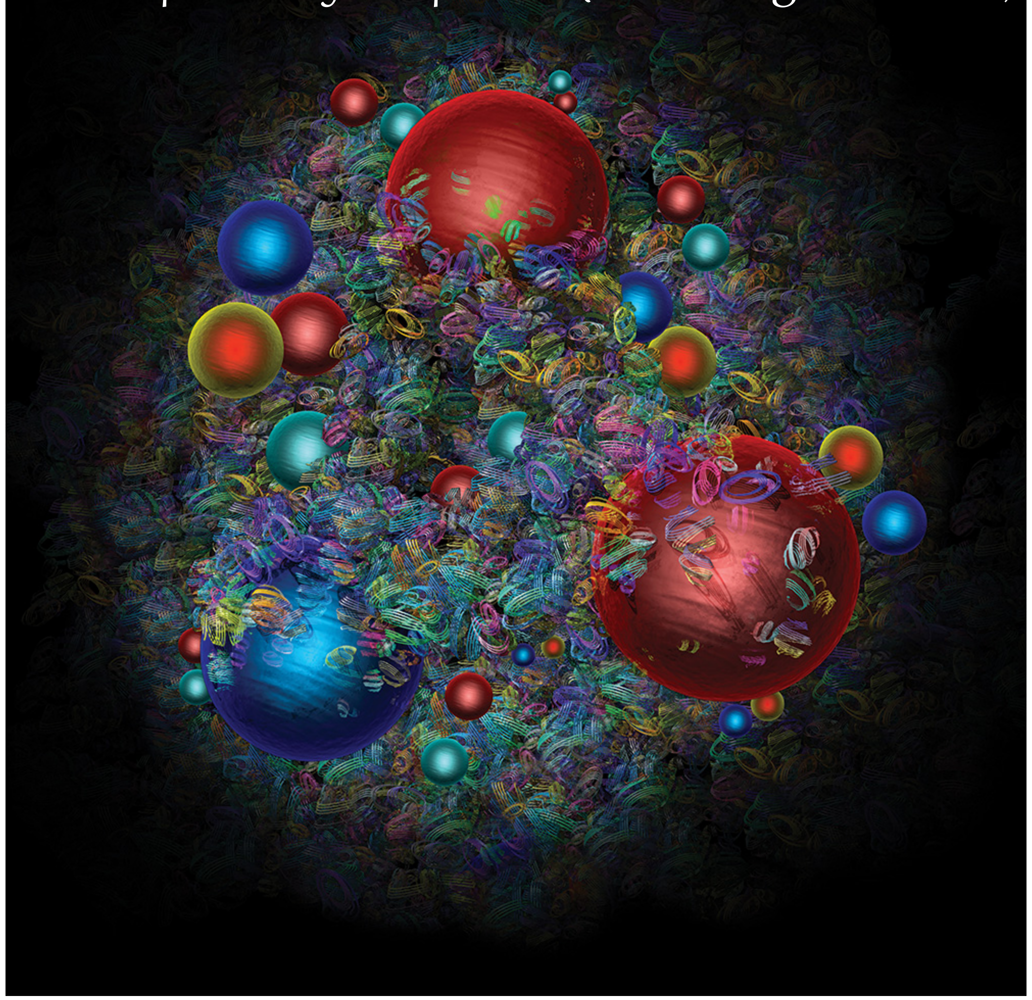
Contents

Structure of the proton


artistic picture of the proton (D Dominguez/CERN)

proton is a very complex object made of:
quarks/anti-quarks and gluons

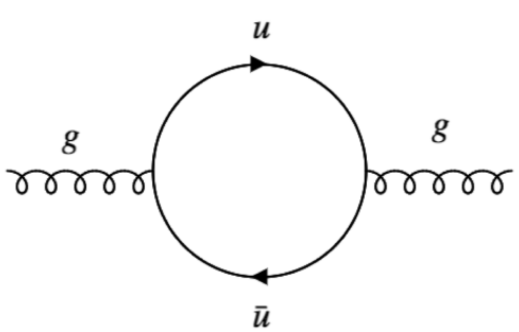
the three valence quarks (uud) are not more than the quark excess w.r.t. the anti-quarks

they carry most of the properties of the proton (such as the charge and the isospin)

But

the strong force (gluons) and
the sea of the quark—anti-quark pairs
are primarily responsible for its mass

What is the origin of the anti-quarks?
gluon splitting fluctuations?



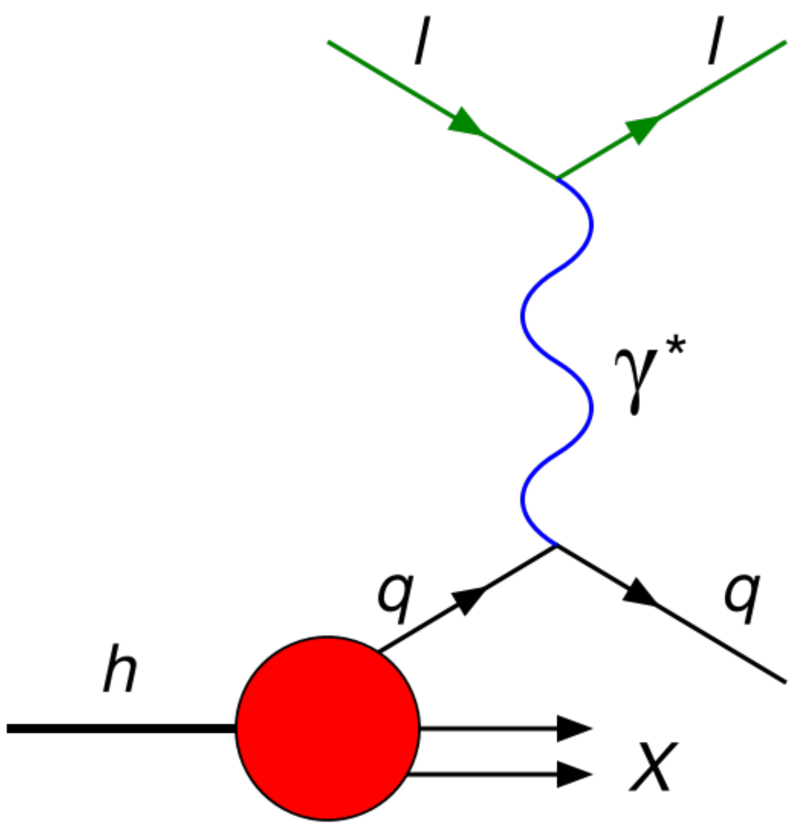
Then

$$\bar{u} = \bar{d}$$

Probing the proton structure

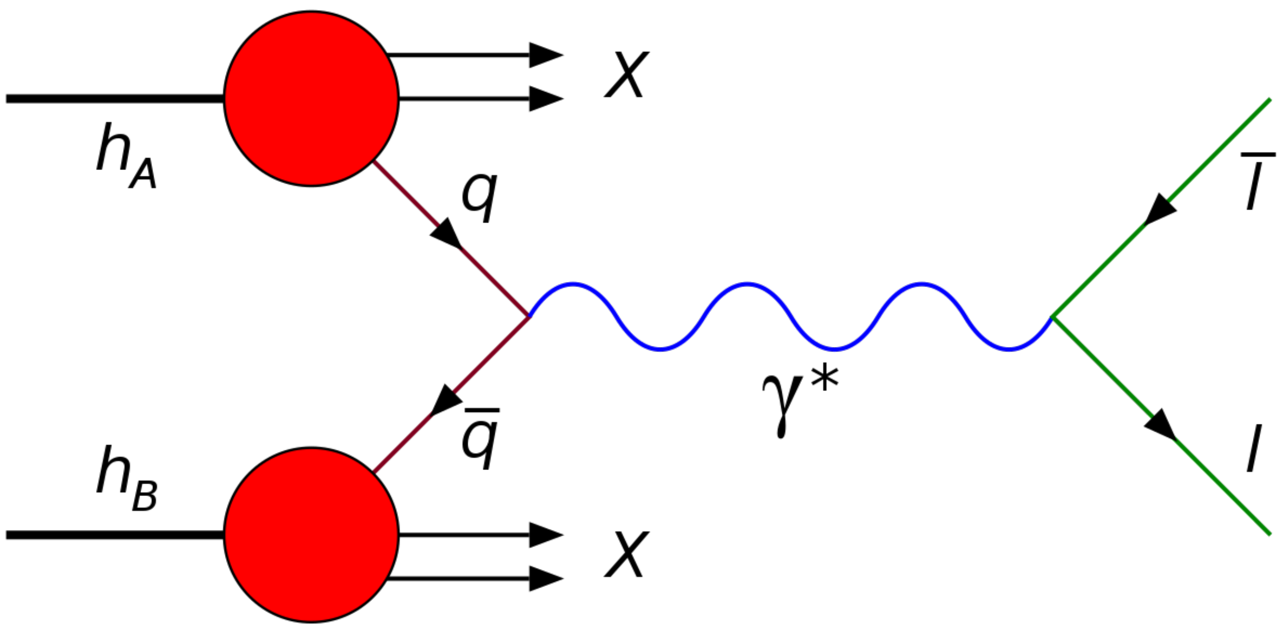
Both DIS and Drell-Yan process are good tools to probe the structure of hadrons

Deep Inelastic Scattering (DIS)



x_{Bj} is the fraction of momentum carried by the target quark

Drell-Yan process



In fixed target experiments:

x_1 is the fraction of momentum carried by the beam quark and x_2 by the target quark

Light sea quarks on proton

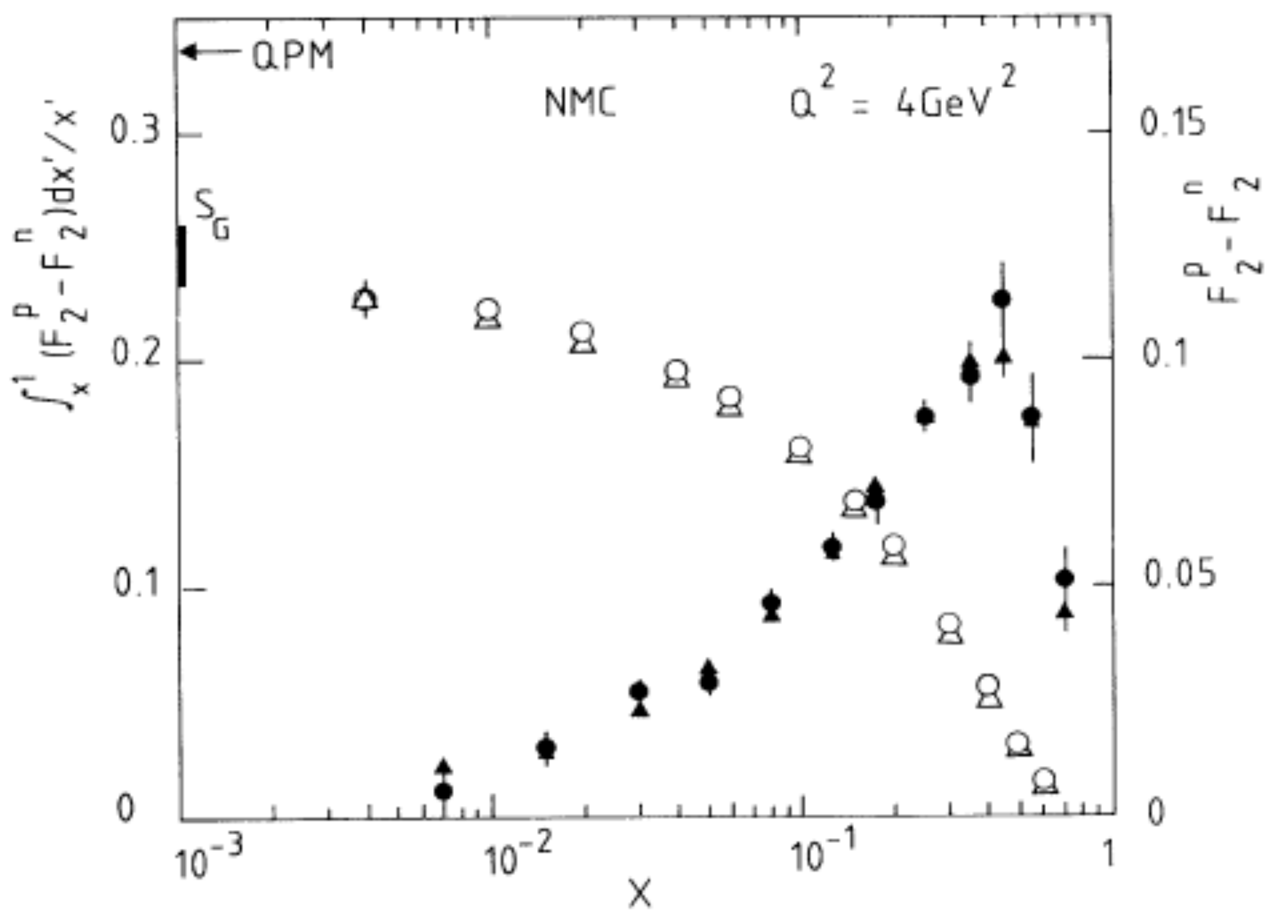
First hint of $\bar{u} \neq \bar{d}$

Gottfried Sum Rule:

$$S_G(QPM) = \int_0^1 dx\, \frac{F_2^p - F_2^n}{x} = \frac{1}{3} + \int_0^1 dx \overset{= 0 \text{ if } \bar{u} = \bar{d}}{\boxed{(\bar{u} - \bar{d})}} = \frac{1}{3}$$

“Prof. Bjorken and I constructed the sum rules in the hope of destroying the quark model”
(Gottfried, 1967)

PRL 66 (1991) 2712



Measured at NMC in 1991:
DIS w/ muon beam on hydrogen and deuterium targets in the range
$0.004 < x < 0.8$
and extrapolated to
$0 < x < 1$

$$S_G = 0.240 \pm 0.016 < \frac{1}{3}$$

$$\int_0^1 dx\, (\bar{d} - \bar{u}) = 0.140 \pm 0.024$$

Different possible explanations:

1. Isospin symmetry breaking in the light quarks sea
2. Change of the parton distributions behaviour at small x

Motivated independent methods to check the $\frac{\bar{d}}{\bar{u}}$ and to measure the x-dependence

NA51 experiment at CERN

Drell-Yan was proposed (by Ellis and Stirling) as a good way to discriminate the origin of the NMC result

The NA51 experiment was made up in a time record (2 months) making use of the existing Drell-Yan dedicated spectrometer used in previous CERN experiments (NA10, NA38)

PLB 256 (1991) 258-264

SCF
CERN SPSLC
92-15

PROPOSAL

STUDY OF THE ISOSPIN BREAKING
IN THE LIGHT QUARK SEA
FROM THE DRELL-YAN PROCESS

M.C. Abreu[3], A. Baldit[1], C. Barrière[1], M. Bedjidian[8], V. Bisi[7],
P. Bordalo[3], J. Castor[1], P. Cerello[7], T. Chambon[1], B. Chaurand[5],
E. Chiavassa[7], D. Contardo[8], G. Dellacasa[7], N. De Marco[7], E. Descroi
A. Devaux[1], O. Drapier[8], B. Espagnon[1], J. Fargeix[1], R. Ferreira[3],
F. Ferrero[7], P. Force[1], L. Fredj[1], J. Gago[3], M. Gallio[7],
C. Gerschel[4], P. Giubellino[7], Ph. Gorodetzky[6], P. Guaita[7], B. Grosdidi
J.Y. Grossiord[8], A. Guichard[8], R. Haroutunian[8], D. Jouan[4], L. Kluber
G. Landaud[1], D. Lazic[6], C. Lourenço[3], F. Malek[8], F. Martelli[7],
A. Marzari[7], M. Masera[7], R. Mazini[6], A. Musso[7], L. Peralta[3],
A. Piccotti[7], J.R. Pizzi[8], C. Racca[6], L. Ramello[7], S. Ramos[3],
L. Riccati[7], A. Romana[5], S. Sartori[7], E. Scomparin[7], S. Silva[3],
P. Sonderegger[2], X. Tarrago[4], J. Varela[3], F. Vazeille[1] and E. Vercellin

important LIP collaboration (~15% of collaborators)

PLB 332 (1994) 244-250

Study of the Isospin Symmetry Breaking in the Light Quark Sea of the Nucleon from the Drell-Yan Process
NA51 Collaboration

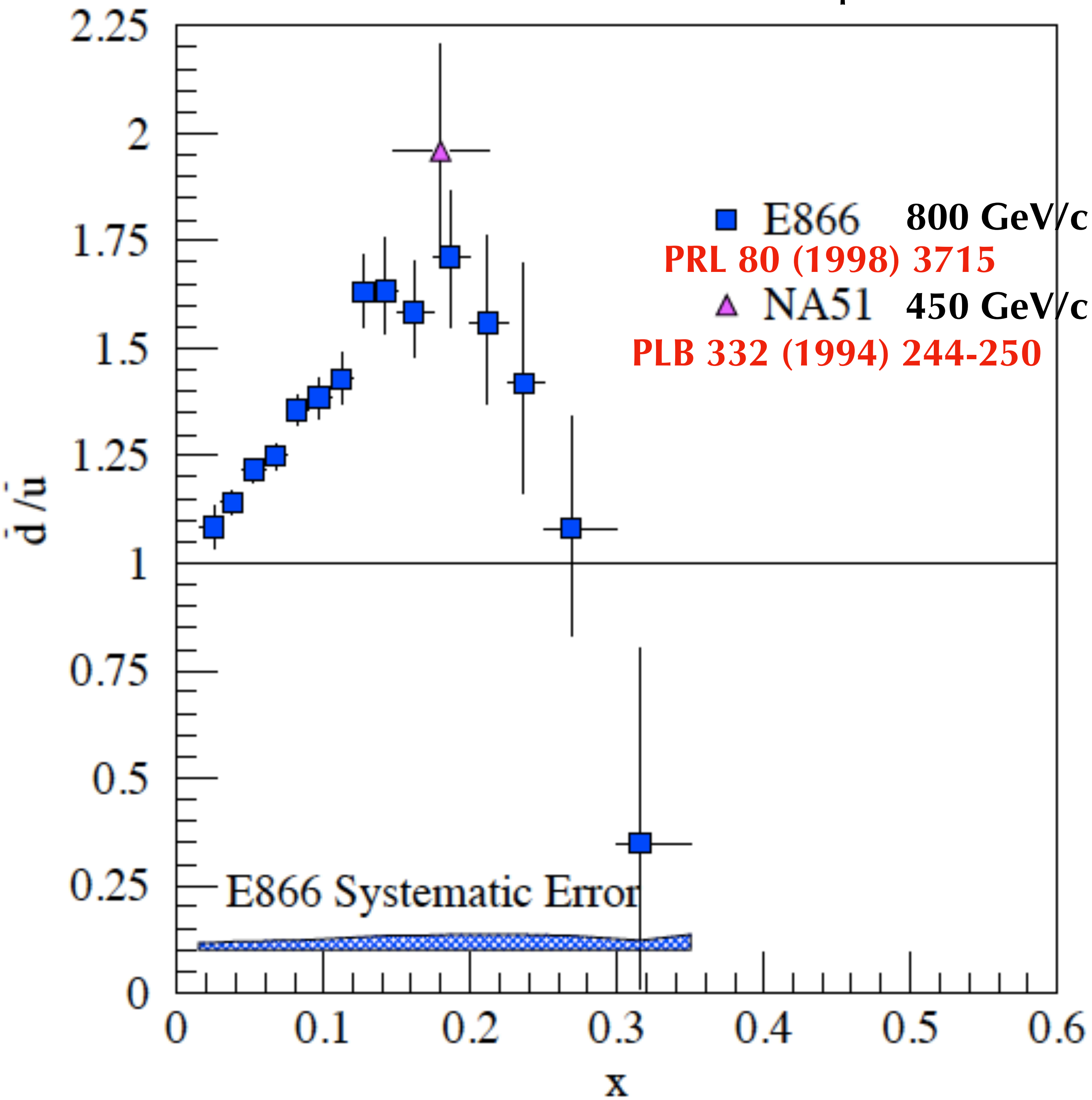
A. Baldit, C. Barrière, J. Castor, T. Chambon, A. Devaux, B. Espagnon, J. Fargeix, P. Force, G. Landaud, P. Saturnini, F. Vazeille
Laboratoire de Physique Corpusculaire de Clermont-Ferrand
IN2P3-CNRS et Université Blaise Pascal, F-63177 Aubière Cedex, France
P. Sonderegger
CERN, CH-1211 Geneva 23, Switzerland
M.C. Abreu[b], P. Bordalo[a], R. Ferreira[c], C. Lourenço[d], S. Ramos[a], S. Silva, J. Varela
LIP, Av. E. Garcia, 14-1, P-1000 Lisbon, Portugal

clear indication of isospin symmetry violation in the light quark sea of the nucleon

$$\frac{\bar{u}}{\bar{d}} = 0.51 \pm 0.04 \pm 0.05 \ \textbf{at} \ \ x = 0.18$$

x-dependence of $\bar{d}/\bar{u}$

The E866/NuSea experiment was proposed at Fermilab in 1993 also making use of the existing Drell-Yan dedicated spectrometer at Fermilab (E772 and E789)



NuSea coverage: $0.015 < x < 0.35$

Striking result:

1. Significant flavour asymmetry at $x \sim 0.2$
2. Symmetric at $x \sim 0.3$
3. $\bar{u}$ becomes dominant at large x?

Large uncertainties
and
puzzling change of behaviour

$\Downarrow$

Motivation for
the SeaQuest experiment
to measure the same quantity
with better precision and
in a wider x range

Models to describe $\bar{u} \neq \bar{d}$

Pauli Blocking:

- $g \rightarrow u\bar{u}$ is suppressed w.r.t. $g \rightarrow d\bar{d}$ since $p(uud)$
- small effect in the asymmetry, **NPB 149 (1979) 497**

Statistical model:

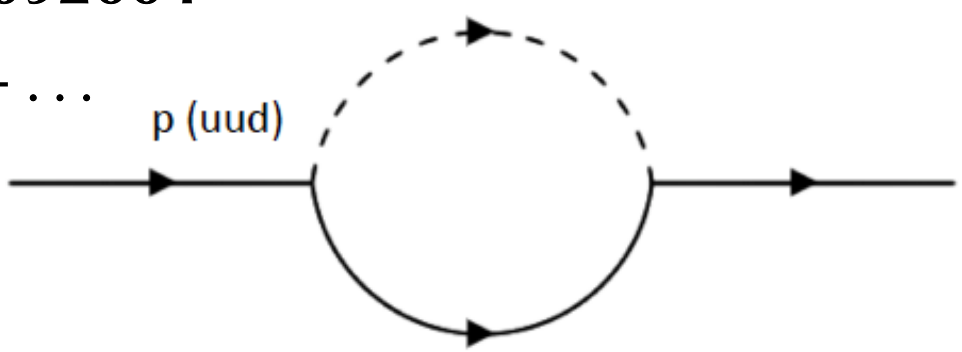
- Fermi (quarks) and Bose (gluons) statistics, **NPA 948 (2016) 63**

Meson cloud model:

- The proton is a superposition of states, **PRD 58 (1998) 092004**

➡ $|p> = |p_0> + \alpha|\underset{\substack{\downarrow \\ (udd)(u\bar{d})}}{n\pi^+}> + \beta|\underset{\substack{\downarrow \\ (uuu)(\bar{u}d)}}{\Delta^{++}\pi^-}> + \gamma|\Lambda^0 K^+> + \ldots$

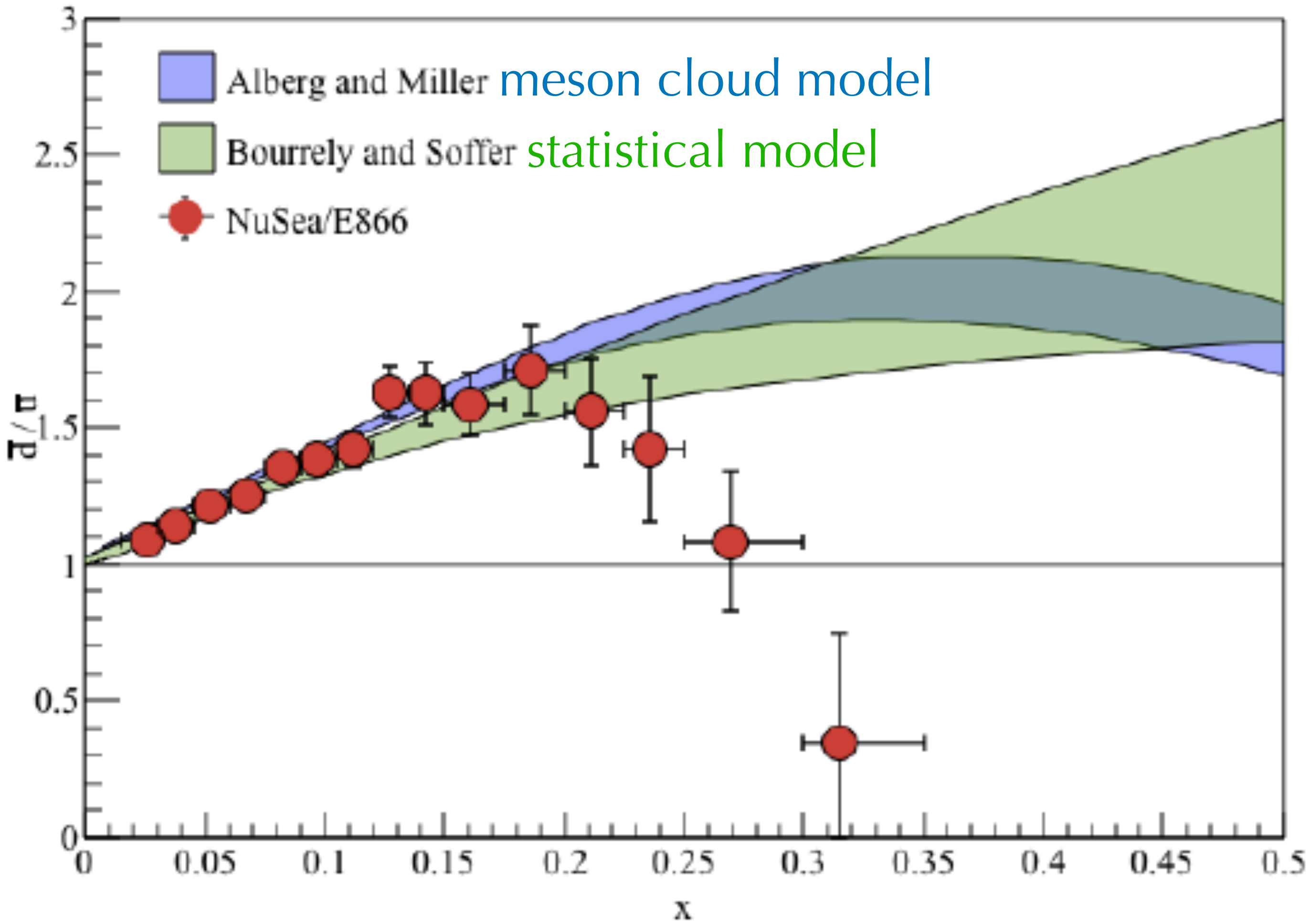
$\alpha > \beta \Rightarrow \bar{d} > \bar{u}$



The list of models could continue...

Models/data agreement

arXiv:1812.10372v1



None of the models available today are able to describe completely the experimental data

No existing models can explain sign-change for $\bar{d} - \bar{u}$ at any value of x

SeaQuest was proposed with the main goal of:

Measuring this asymmetry up to $x \sim 0.45$ and with a better precision

SeaQuest experiment

SeaQuest experiment at Fermilab

Fermilab (Fermi National Accelerator Laboratory)

is located at Batavia, Illinois, US

was established in 1967

was the house of Tevatron:

- One of the largest accelerators (6.3 km perimeter)
- Responsible for the discovery of top quark (1995)
- Was shut down in 2011

currently more focused on neutrino experiments

SeaQuest Collaboration

SeaQuest was proposed in 1999

started the physics data taking in 2013

collaboration of around 100 people

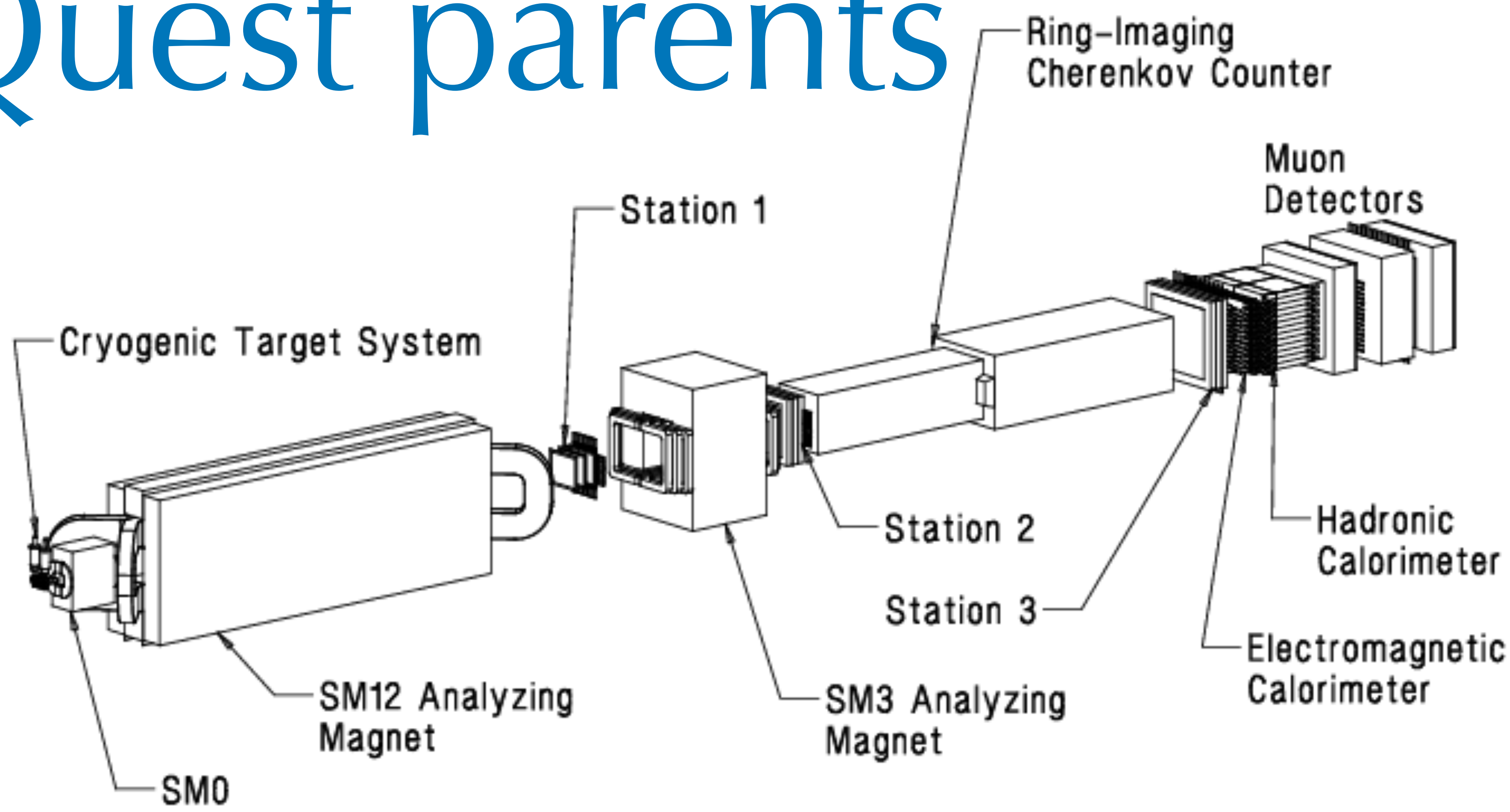
from around 20 institutes

and 3 countries (USA, Taiwan and Japan)

proton induced Drell-Yan fixed target experiment

120 GeV/c proton beam from the main injector

SeaQuest parents



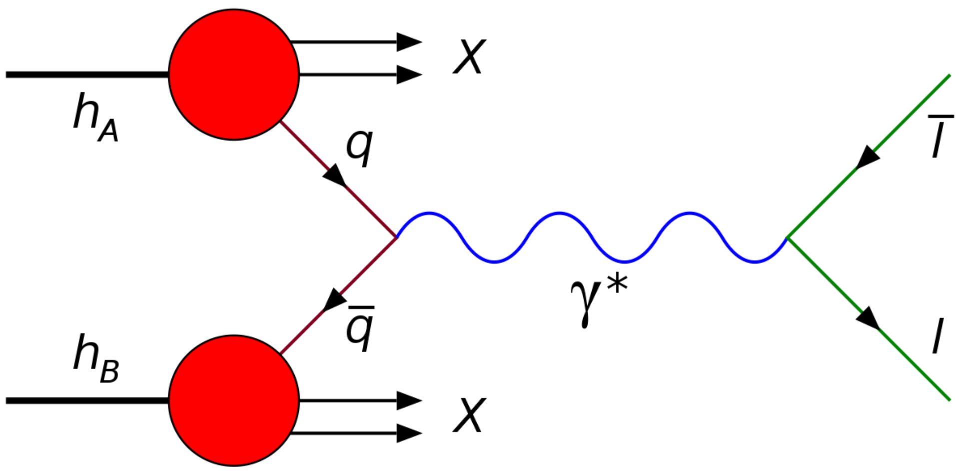
Fermilab dimuon spectrometer used in previous experiments:

1. Fermilab E772 (proposed in 1986 and completed in 1988)
   - "Nuclear Dependence of Drell-Yan and Quarkonium Production"
2. Fermilab E789 (proposed in 1989 and completed in 1991)
   - "Search for Two-Body Decays of Heavy Quark Mesons"
3. Fermilab E866 (proposed in 1993 and completed in 1996)
   - "Determination of $\bar{d}/\bar{u}$ Ratio of the Proton via Drell-Yan"

SeaQuest interests

Through the measurement of the Drell-Yan process, using a proton beam and several targets SeaQuest is able to contribute for more than one physics topic

Drell-Yan process



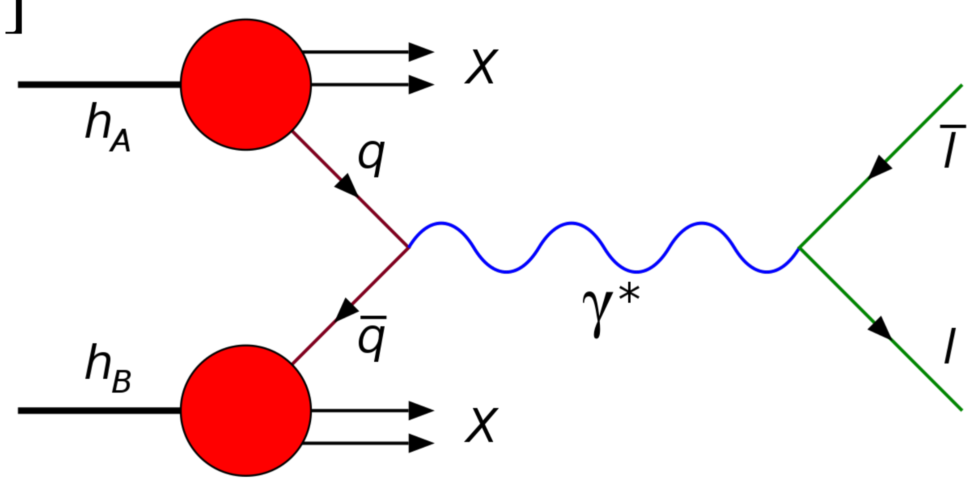
Main physics topic: The measurement of the ratio between the light sea quarks in proton

Other topics:

1. Angular distributions: Parton distribution functions, namely Boer-Mulders TMD PDF
2. Nuclear dependences: EMC effect, Parton energy loss
3. Dark photon search

proton induced Drell-Yan

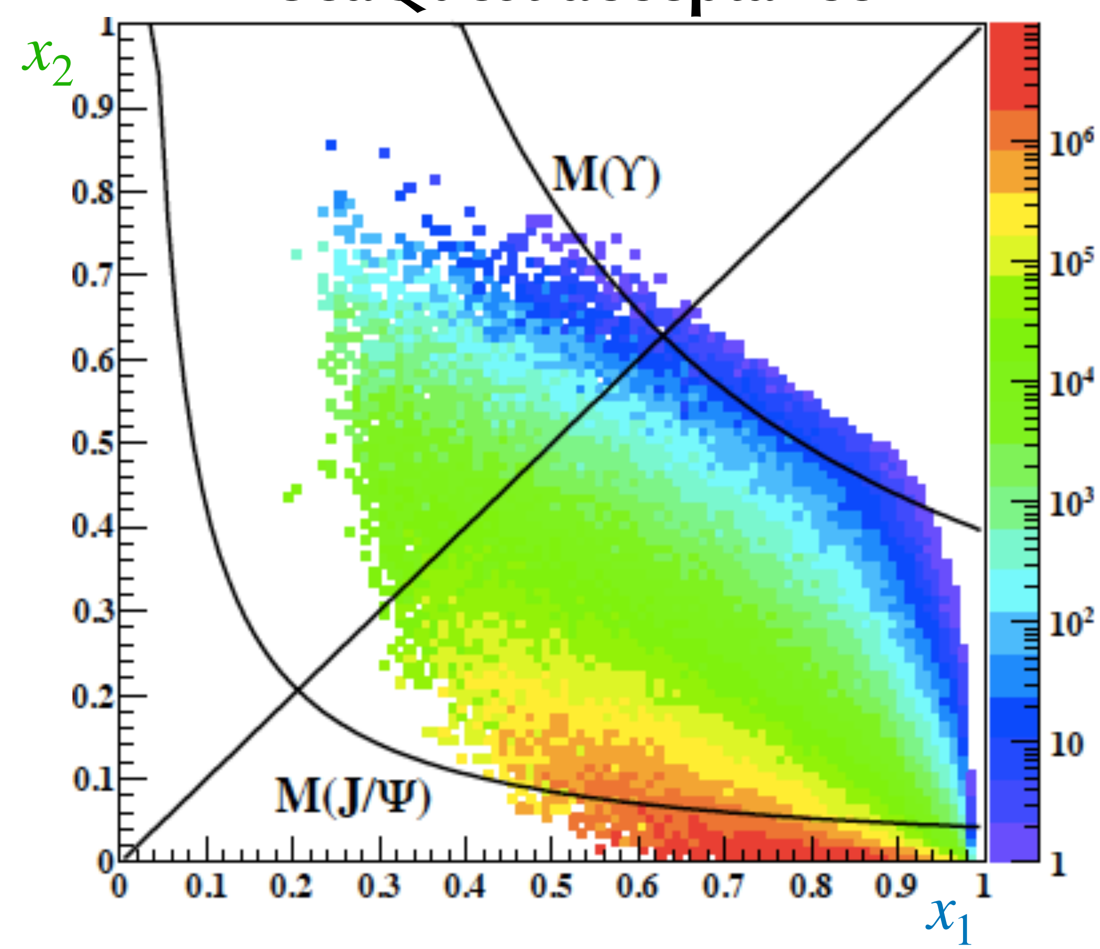
$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_i e_i^2[q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1)q_i(x_2)]$$



- x_1 is the fraction of momentum carried by the beam quark/anti-quark
- x_2 is the fraction of momentum carried by the target quark/anti-quark

The second term in cross-section vanishes in the forward direction (fixed target experiment):

$x_1 \gg x_2 \Rightarrow$ likely to access valence quark from beam $p(uud)$ and the anti-quark from target



SeaQuest accesses sea quarks from target

From NuSea to SeaQuest

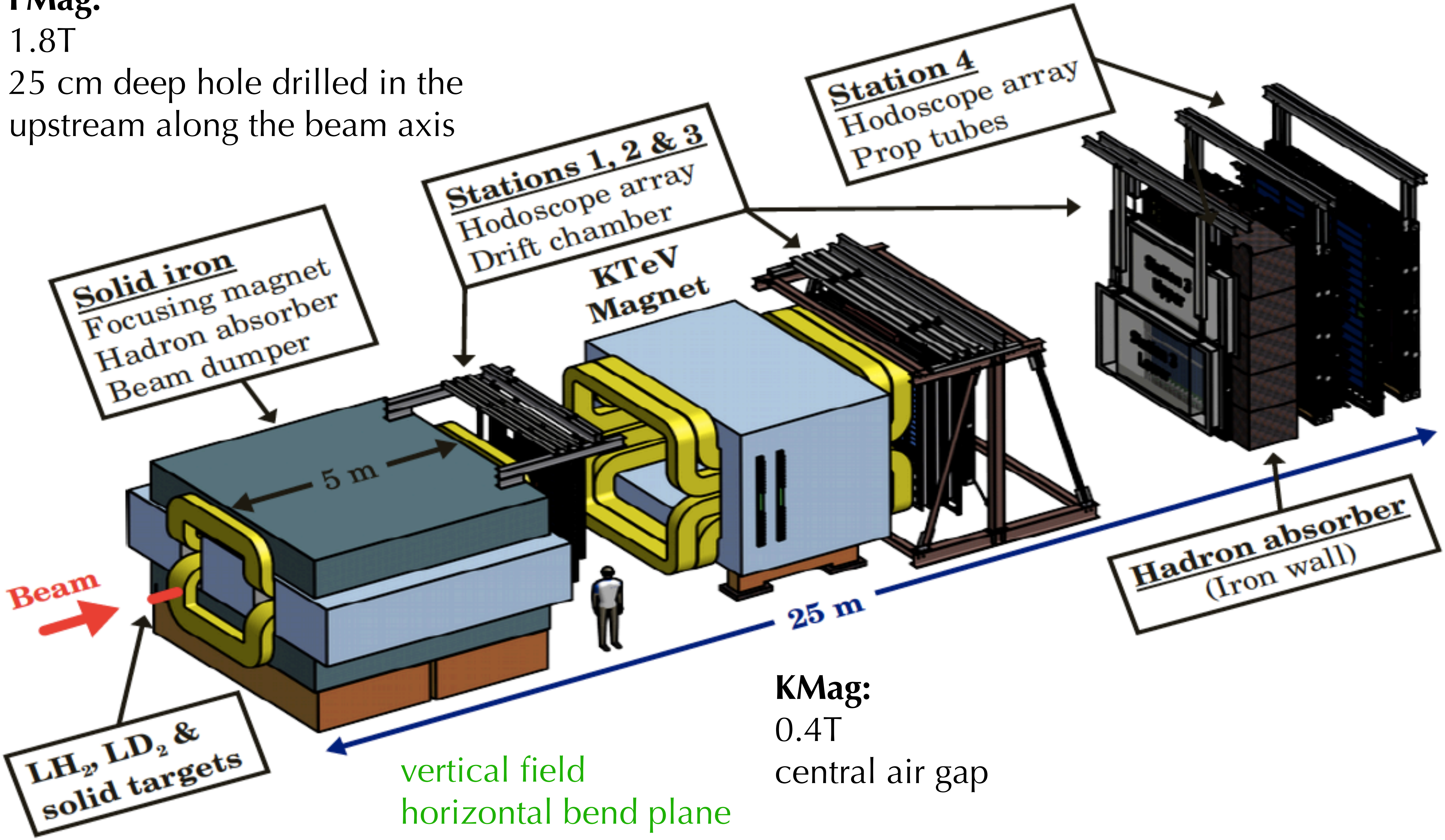
Improvements for the SeaQuest experiment:

* $0.15 < x < 0.45$ instead of $0.015 < x < 0.35$ in NuSea
    * 120 GeV/c proton beam instead of 800 GeV/c proton beam
    * spectrometer was shortened significantly to account for the difference in boost
        * wider acceptance
    * tune of the trigger for large x and large $M^2_{\mu\mu}$
        * Better statistics for Drell-Yan in the region of interest
        * Suppression of background (concentrated at low masses)

Experimental setup

Nucl. Instrum. Methods A 930 (2019) 49-63

FMag:
1.8T
25 cm deep hole drilled in the upstream along the beam axis



KMag:
0.4T
central air gap

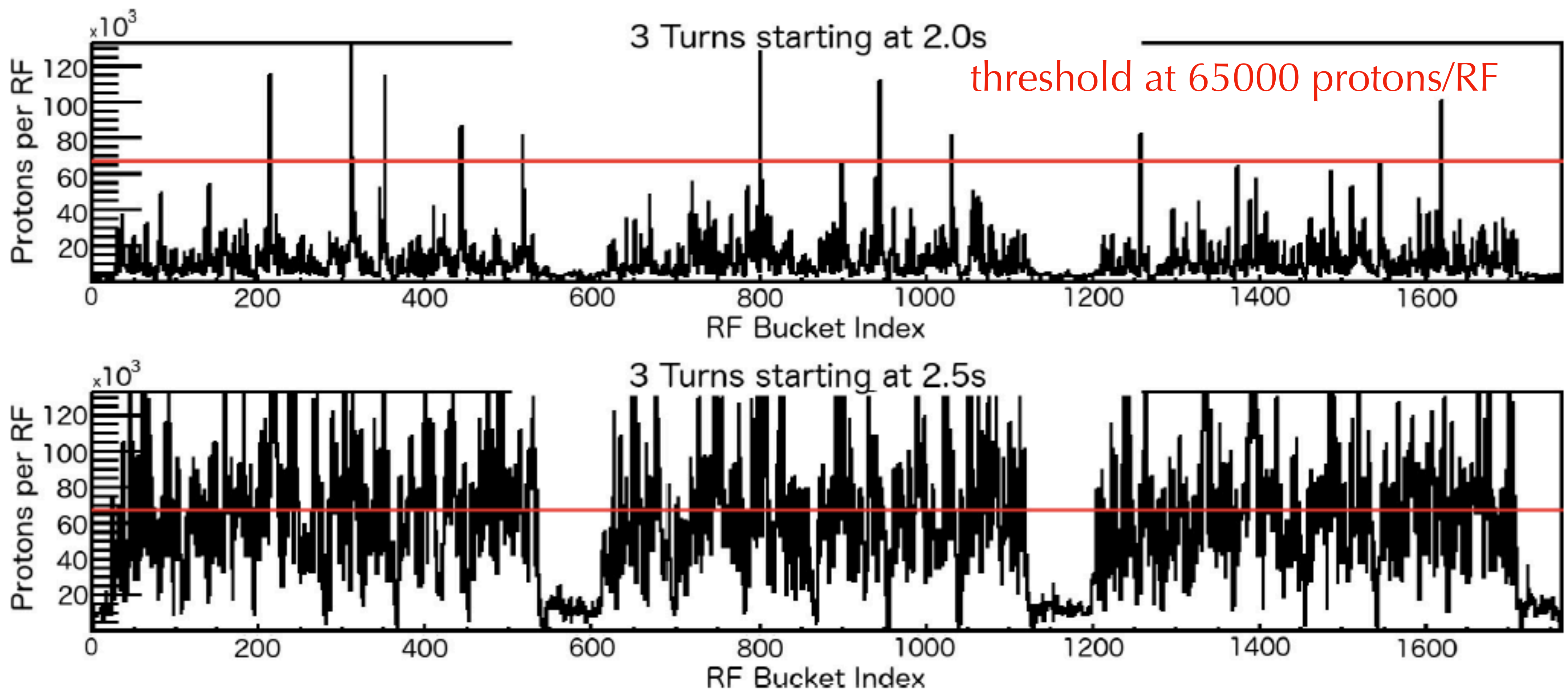
vertical field
horizontal bend plane

Proton beam

120 GeV/c proton beam:

- spill~4s every 1 minute
- the other ~56s are used to swap the target if needed
- frequency = 53.1 MHz (just like the structure from the main injector) = 18.8 ns
- each “RF bucket” comes every 18.8 ns and last for ~2ns
- the beam intensity (~ 5×10^{12} p/spill) is measured for every beam bucket

Variation of the beam intensity

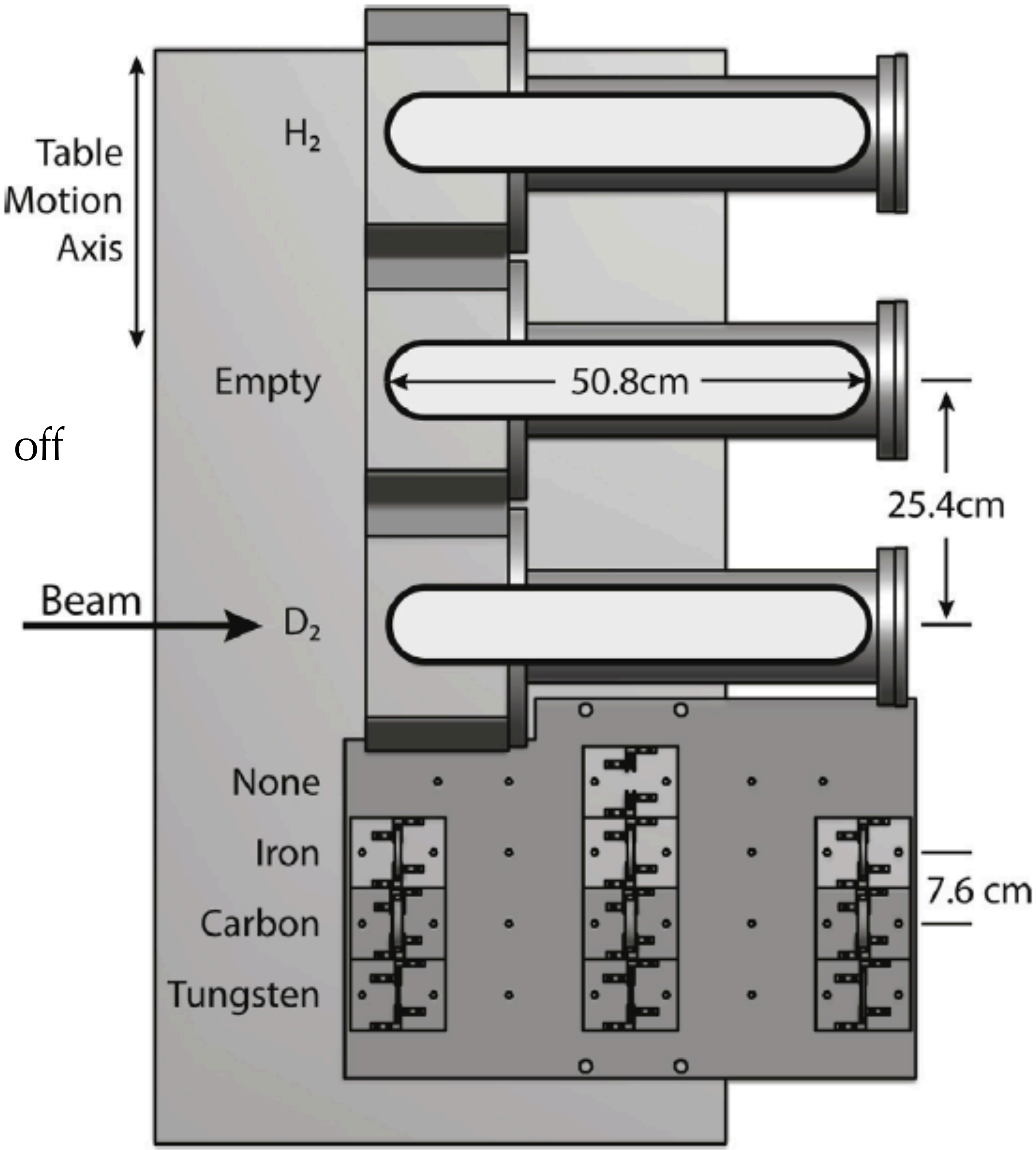


Targets

- 2 liquid targets positions
- 3 solid targets positions
- 1 empty target position
- 1 none target position
- the target is moved during the beam off

Typical configuration

Target	Spills/cycle
H_2	10
Empty flask	2
D_2	5
No target	2
Iron	1
Carbon	2
Tungsten	1



Trigger

- signals from hodoscopes
- optimised to accept high mass dimuons (from 4 to 10 GeV/c2) from target
  - other sources, as J/ψ, are suppressed
  - in order to keep the trigger rate low enough and maintain an acceptable DAQ dead time
- 5 different triggers:

Name	Side	Charge	Notes
Matrix 1	TB/BT	+-/-+	Main physics trigger
Matrix 2	TT/BB	+-/-+	Same-side trigger
Matrix 3	TB/BT	++/- -	Like-charge trigger
Matrix 4	T/B	+/-	All single triggers
Matrix 5	T/B	+/-	High-pT single triggers (pT>3 GeV/c)

used to estimate the combinatorial background

pairs of uncorrelated muons from pion/kaon decays identified as dimuons (mainly present at low masses)

Timeline

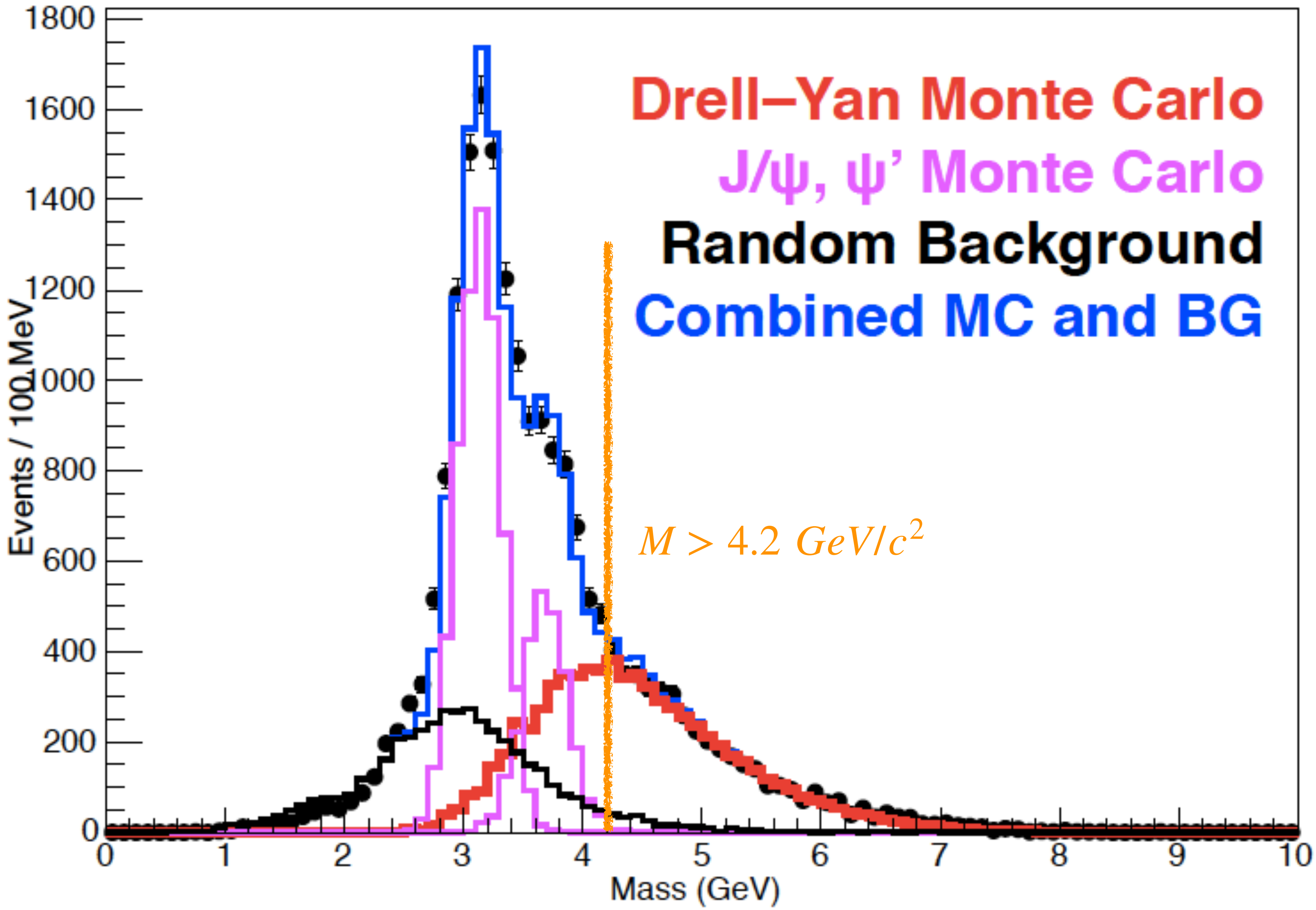
Data set	Dates	Comments
1	Mar.-Apr. 2012	Commissioning
2	Nov. 2013 - Sep. 2014	New station 3 (lower) drift chamber
3	Nov. 2014 - Jul. 2015	improvements in stations 1 and 2 photomultipliers
4	Nov. 2015 - Feb. 2016	New station 1 drift chamber
5	Mar. 2016 - Jul. 2016	Both drift chambers in station one (the old and the new)
6	Nov. 2016 - Jul. 2017	DAQ upgrade

essentially 4 years of physics data taking, with some improvements/changes

✓ 1.4×10^{18} protons on target

Data analysis of $\bar{d}/\bar{u}$

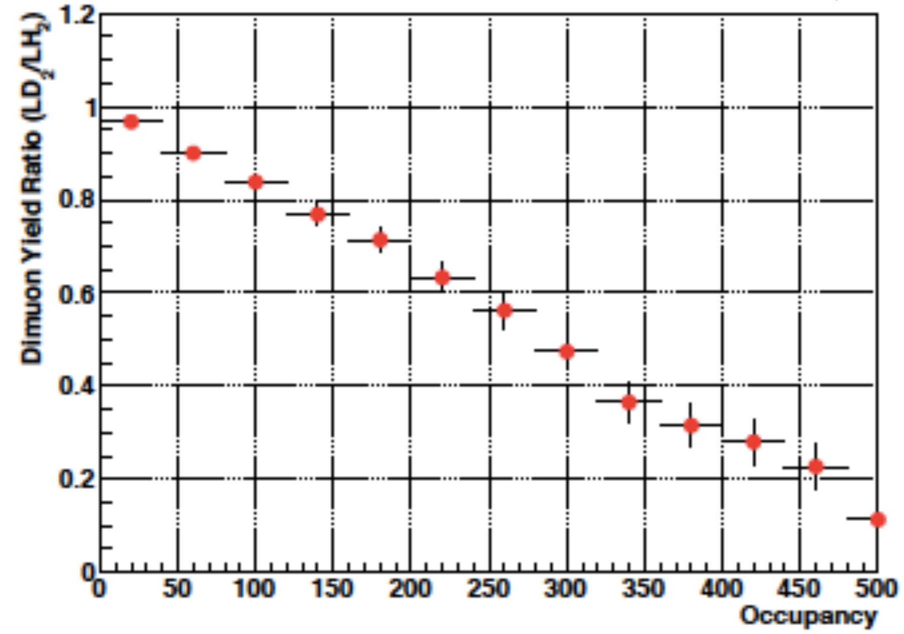
Mass distribution

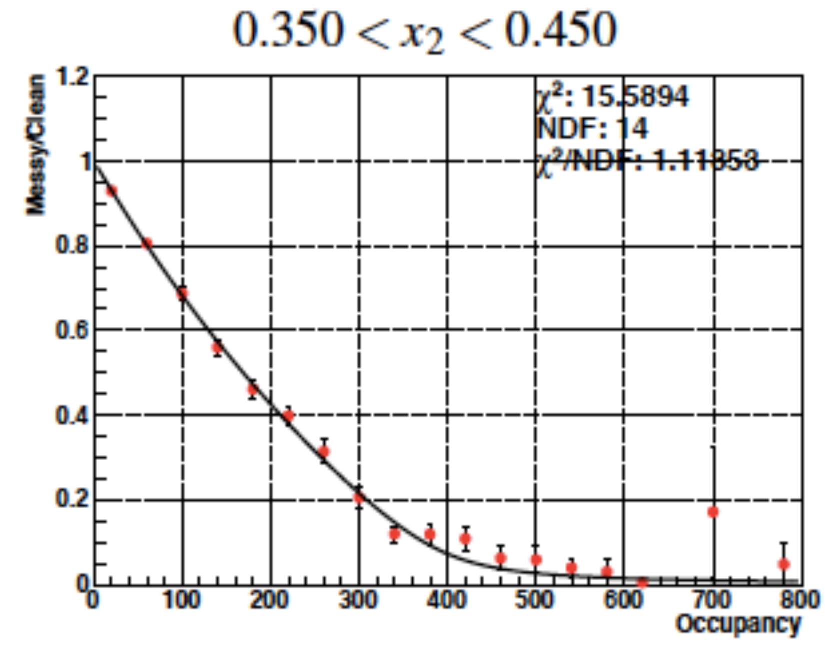


- Drell-Yan, J/ψ and ψ' distributions obtained from MC
- **Combinatorial background** was obtained **from data**

Extract cross-section ratio

Data from 2014 and 2015, FERMILAB-THESIS-2017-05





$$\frac{\sigma_{pd}}{2\sigma_{pp}} = \frac{\frac{N_D\ C_D}{I_D\ T_D}}{2\frac{N_H\ C_H}{I_H\ T_H}}$$

Obtained from MC using:
Messy/clean MC in function of the occupancy of the detectors

$N_{D(H)}$ is the number of dimuons

$C_{D(H)}$ is the correction factor due to the tracking efficiency (beam intensity dependent) and due to the background subtraction

$I_{D(H)}$ is the integrated intensity

$T_{D(H)}$ is the number of nucleons on target

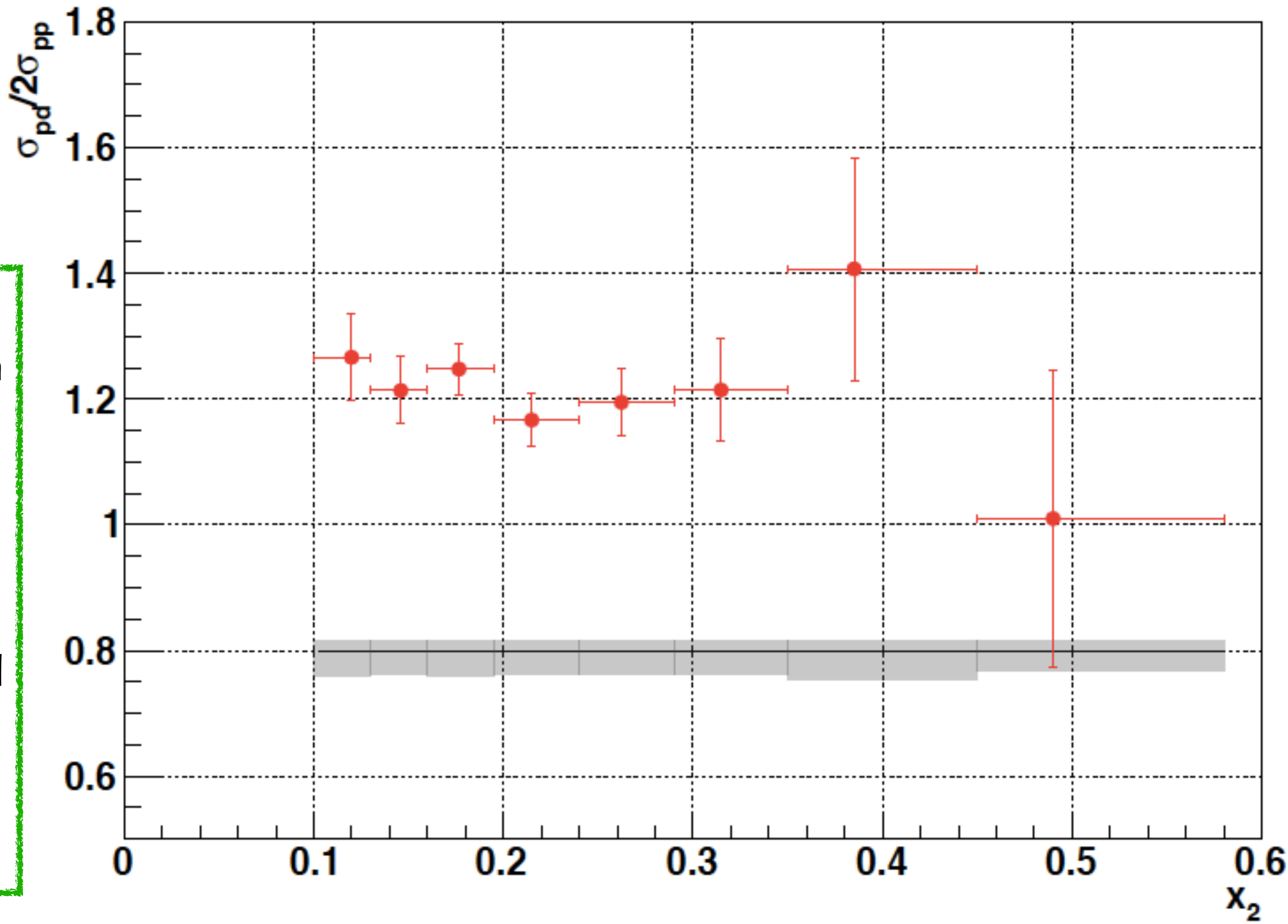
No acceptance correction needed

Background
from combinatorial background
and
from dimuons generated in the target container

Cross-section ratio

after all the corrections applied

Data from 2014 and 2015, FERMILAB-THESIS-2017-05



Systematics:

- Hydrogen contamination of deuterium target (between 1% and 5%)
- Background estimation (depending on the method/sample used and on the intensity)
- Rate dependence of dimuon yields

Extract $\bar{d}/\bar{u}$

When $x_1 \gg x_2$

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

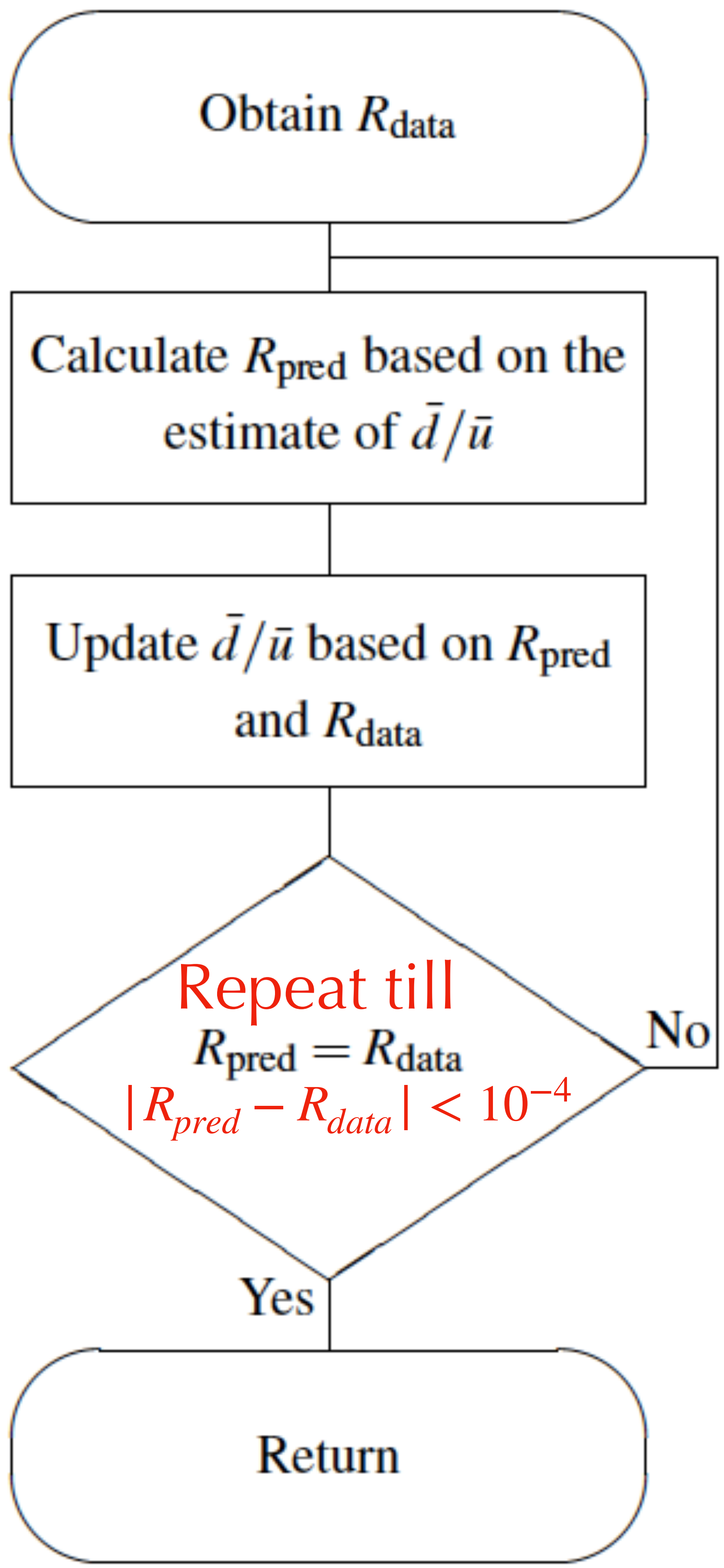
But this is just approximated:

To convert the cross-section ratio into $\bar{d}/\bar{u}$ an iterative analysis is preformed using the cross-section at LO:

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9 s x_1 x_2} \sum_i e_i^2 [q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1) q_i(x_2)]$$

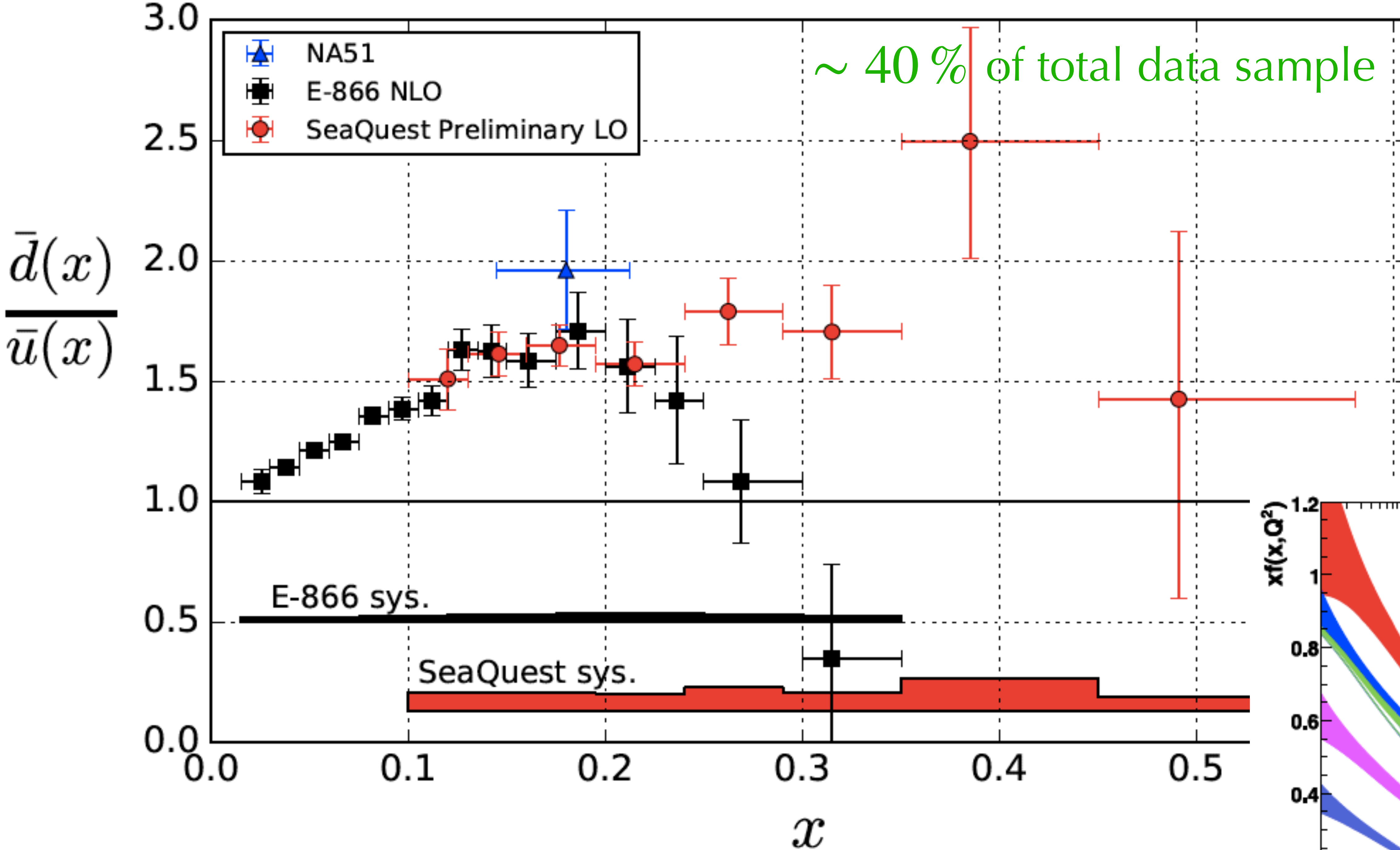
$\bar{d}/\bar{u} = 1$ In the first iteration

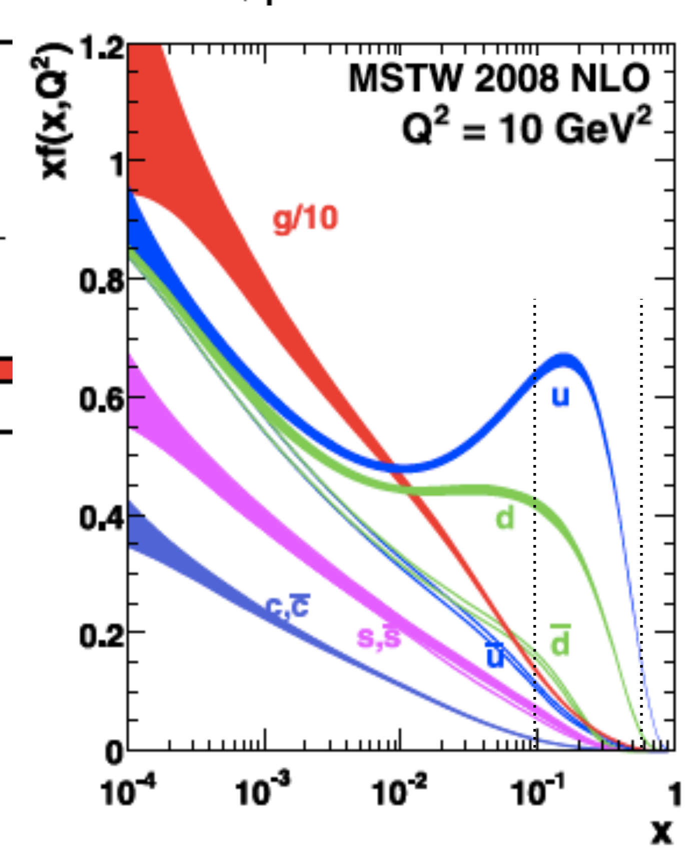
And calculate the Rpred using the cross-section formula and CT10LO PDF set



Preliminary result

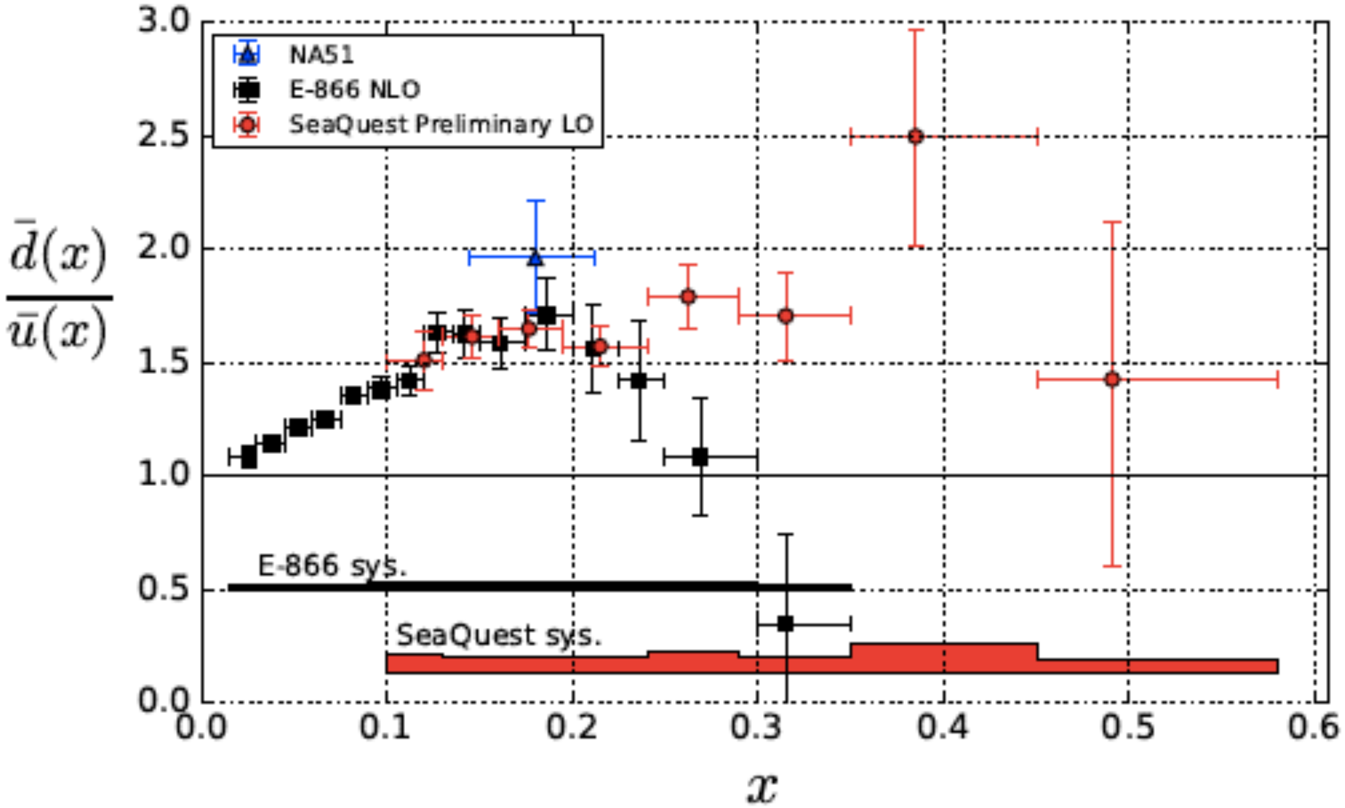
PoS (DIS 2018) 033



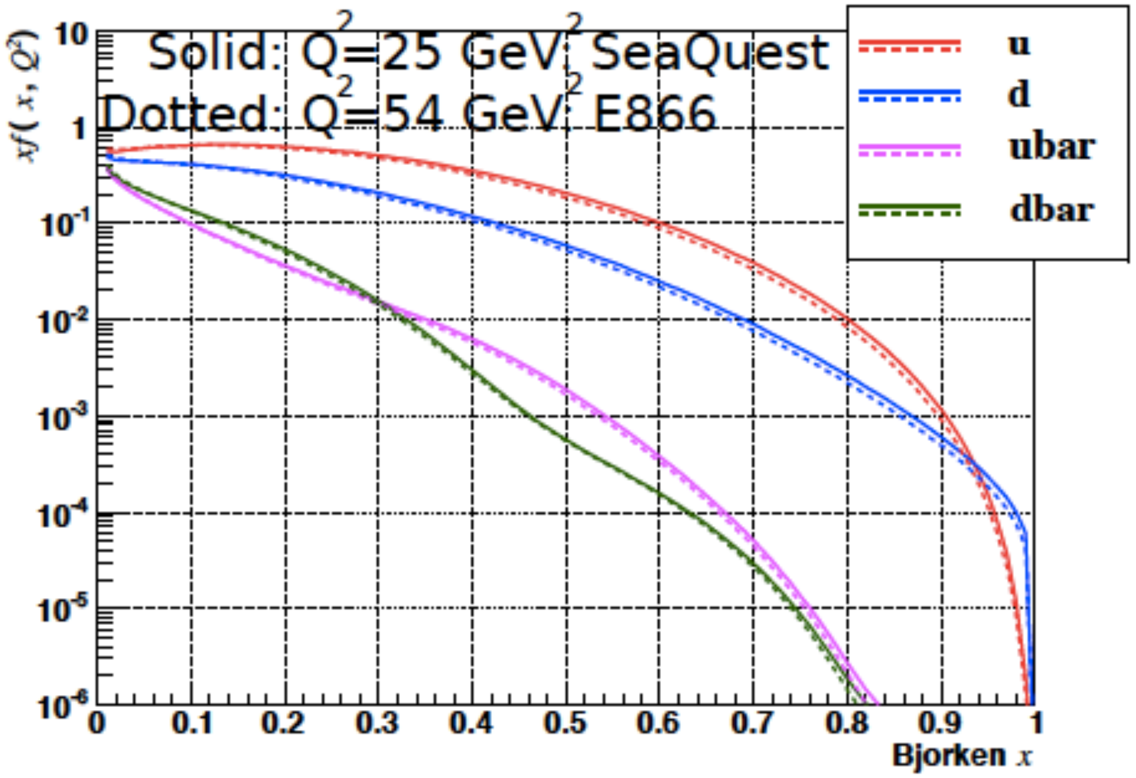


Same systematics as for cross-section ratio plus systematics from uncertainties on PDFs

Results compatibility



How are the PDFs affected by the different $Q^2 \equiv M^2_{\mu\mu}$ of NuSea and SeaQuest?



The two experiments cover a different acceptance

$\Downarrow$

average x_1 is different

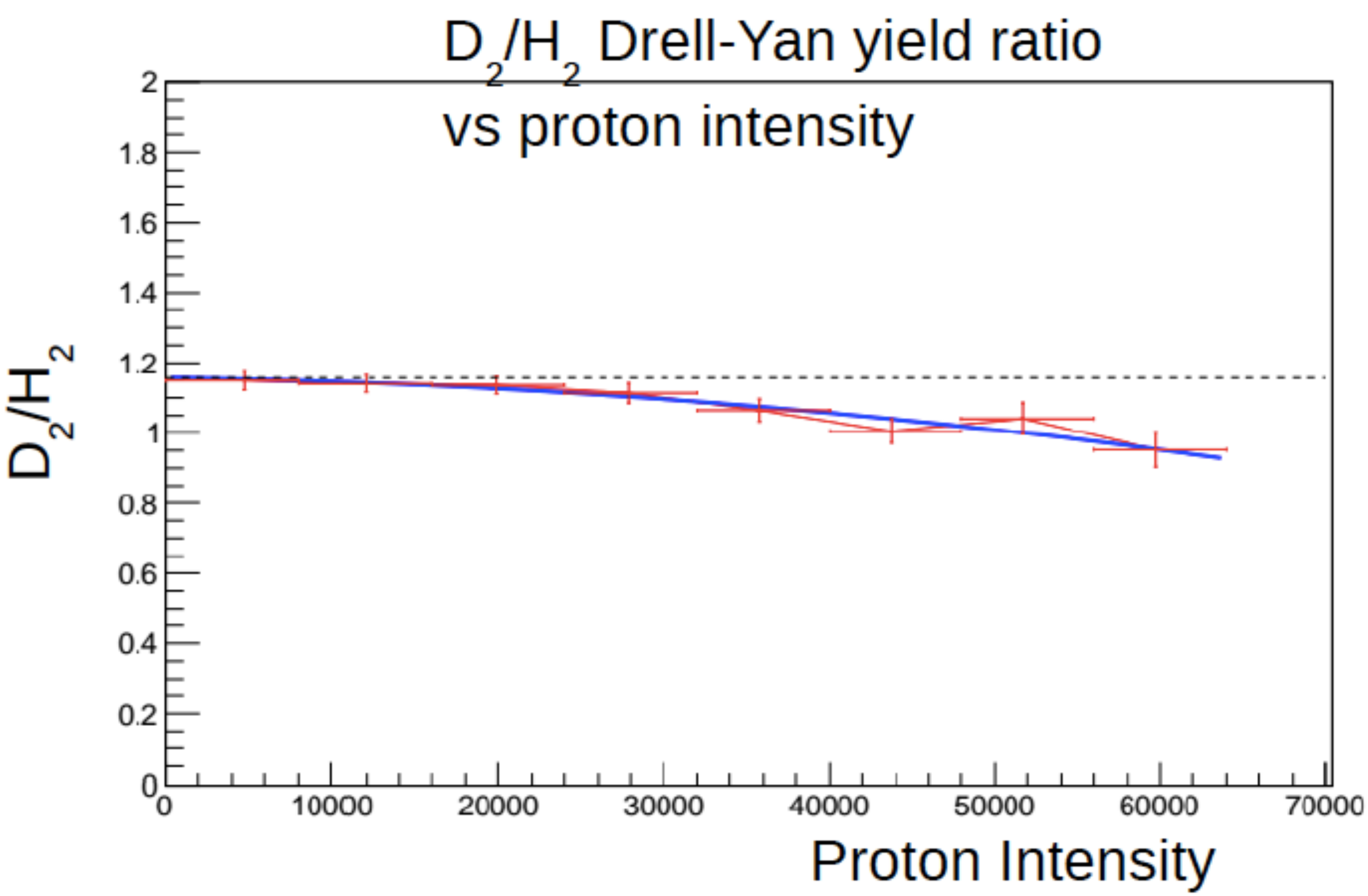
Are the systematics quoted by NuSea too optimistic?

Different method to extract cross-section ratio

By extrapolating the ratio to zero intensity, all forms of rate dependence can be removed

$$\lim_{Intensity \to 0} D_2/H_2$$

- No reconstruction efficiency effect
- No combinatorial background



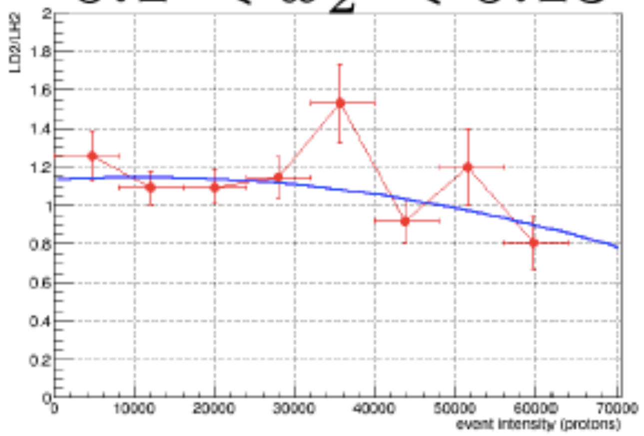
Which fitting function?

Is this method valid?

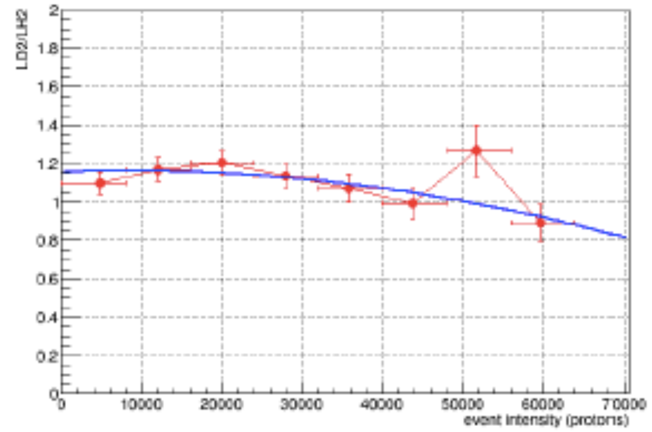
Extrapolation method

DIS 2019 conference

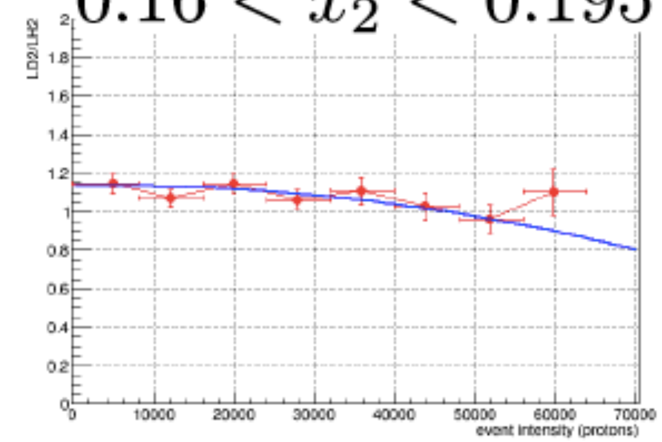
$0.1 < x_2 < 0.13$



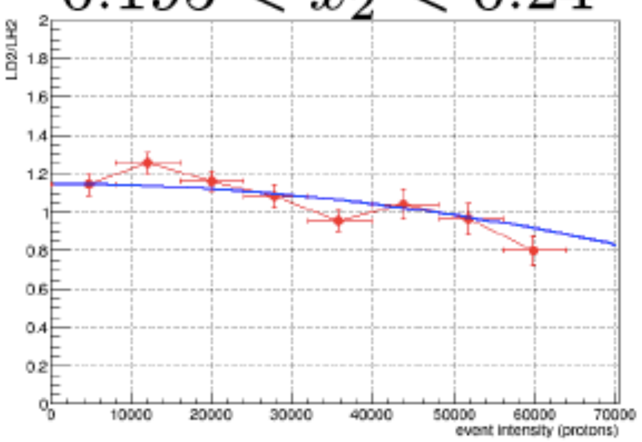
$0.13 < x_2 < 0.16$



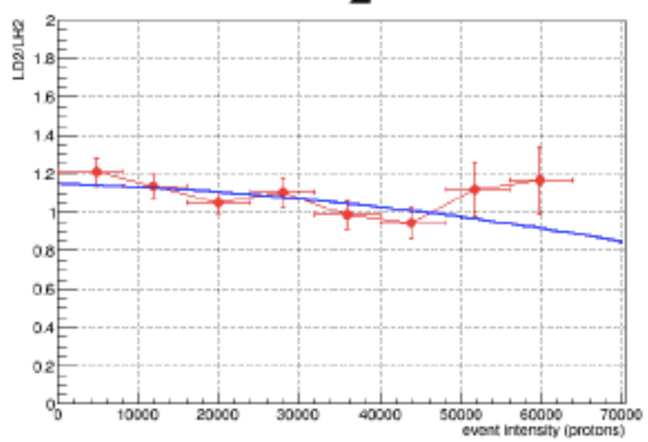
$0.16 < x_2 < 0.195$



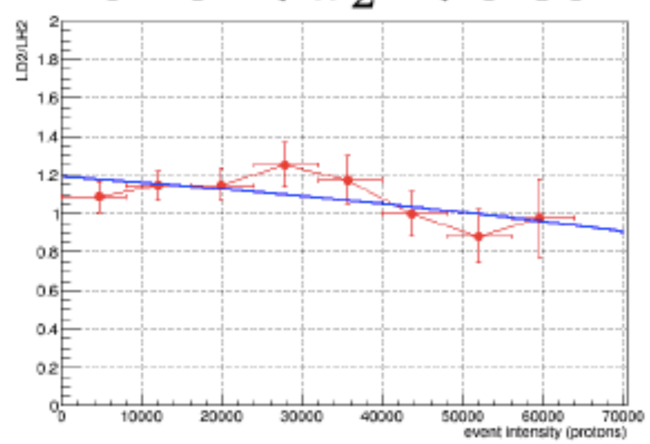
$0.195 < x_2 < 0.24$



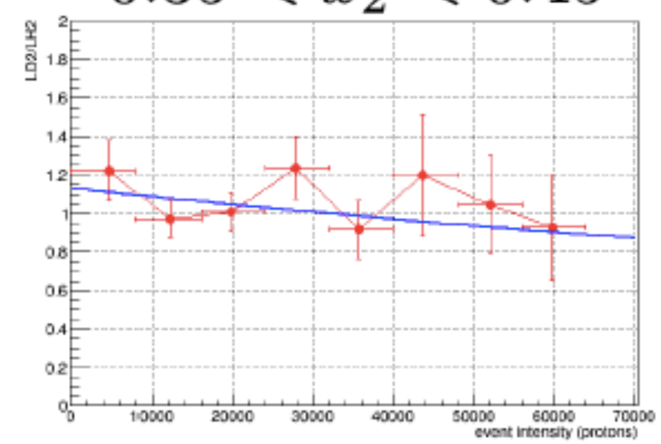
$0.24 < x_2 < 0.29$



$0.29 < x_2 < 0.35$



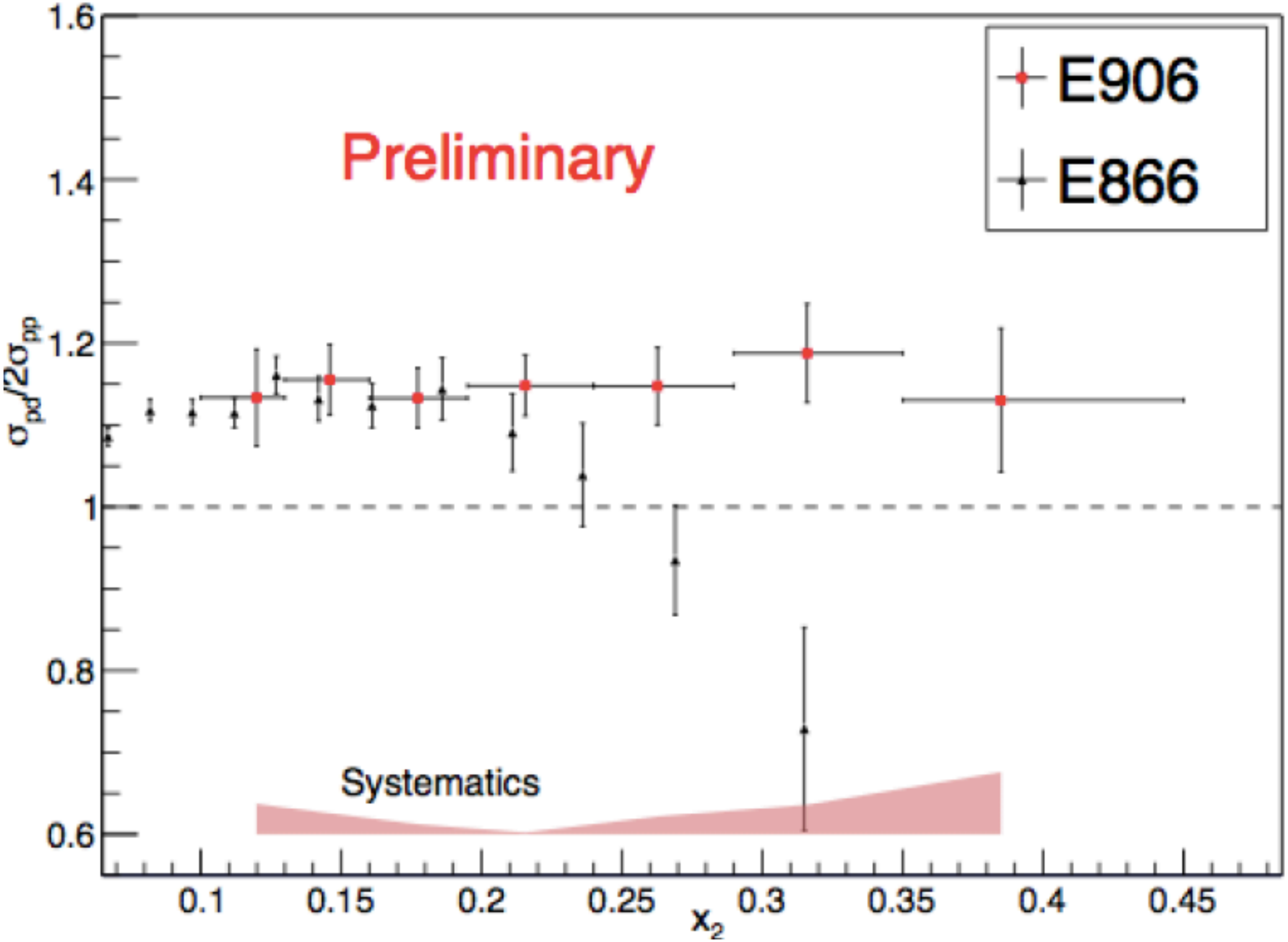
$0.35 < x_2 < 0.45$



<u>Main source of systematics:</u> Extrapolation function

Extrapolation method

DIS 2019 conference



The result is compatible with the previous method (with mass fitting and reconstruction efficiency correction from MC)

More analyses

Angular distributions

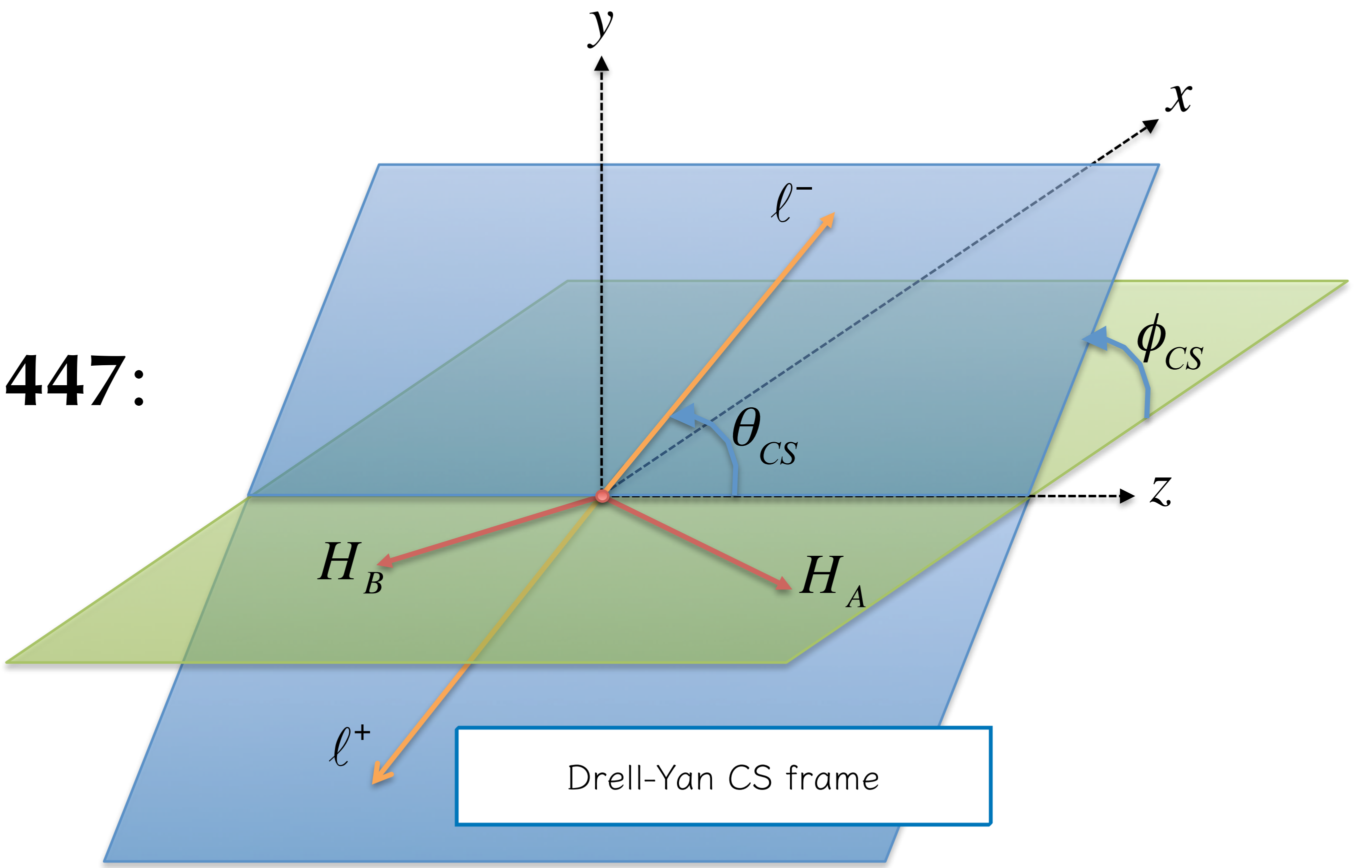
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

Naive LO process: $\lambda = 1,\ \mu = \nu = 0$

The Lam-Tung relation **PRD 18 (1978) 2447**:

$1 - \lambda - 2\nu = 0$

should be valid when we include higher order corrections



Past experiments

$$\nu \propto BM_{beam} \otimes BM_{target}$$

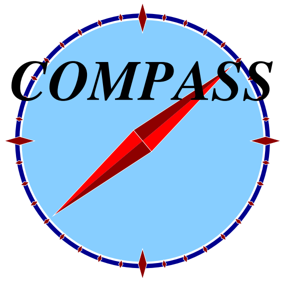
Boer-Mulders arises from the:

Correlation between the transverse spin of the quarks and its transverse motion

In **pion** induced DY:

BM from pion beam valence quark

BM from proton target valence quark

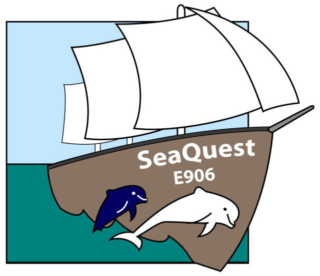


COMPASS results highly expected

In **proton** induced DY:

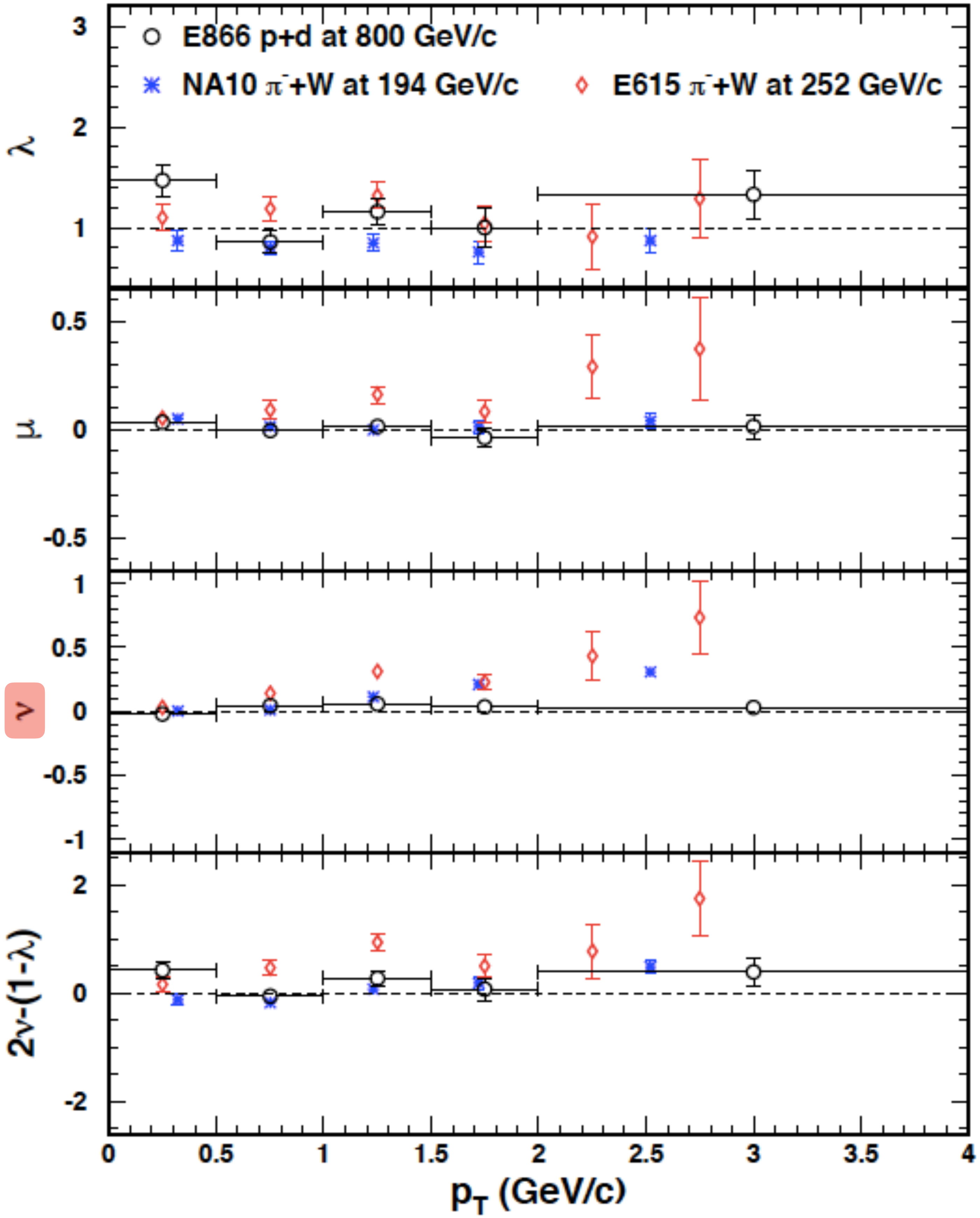
BM from proton beam valence quark

BM from proton target sea anti-quark



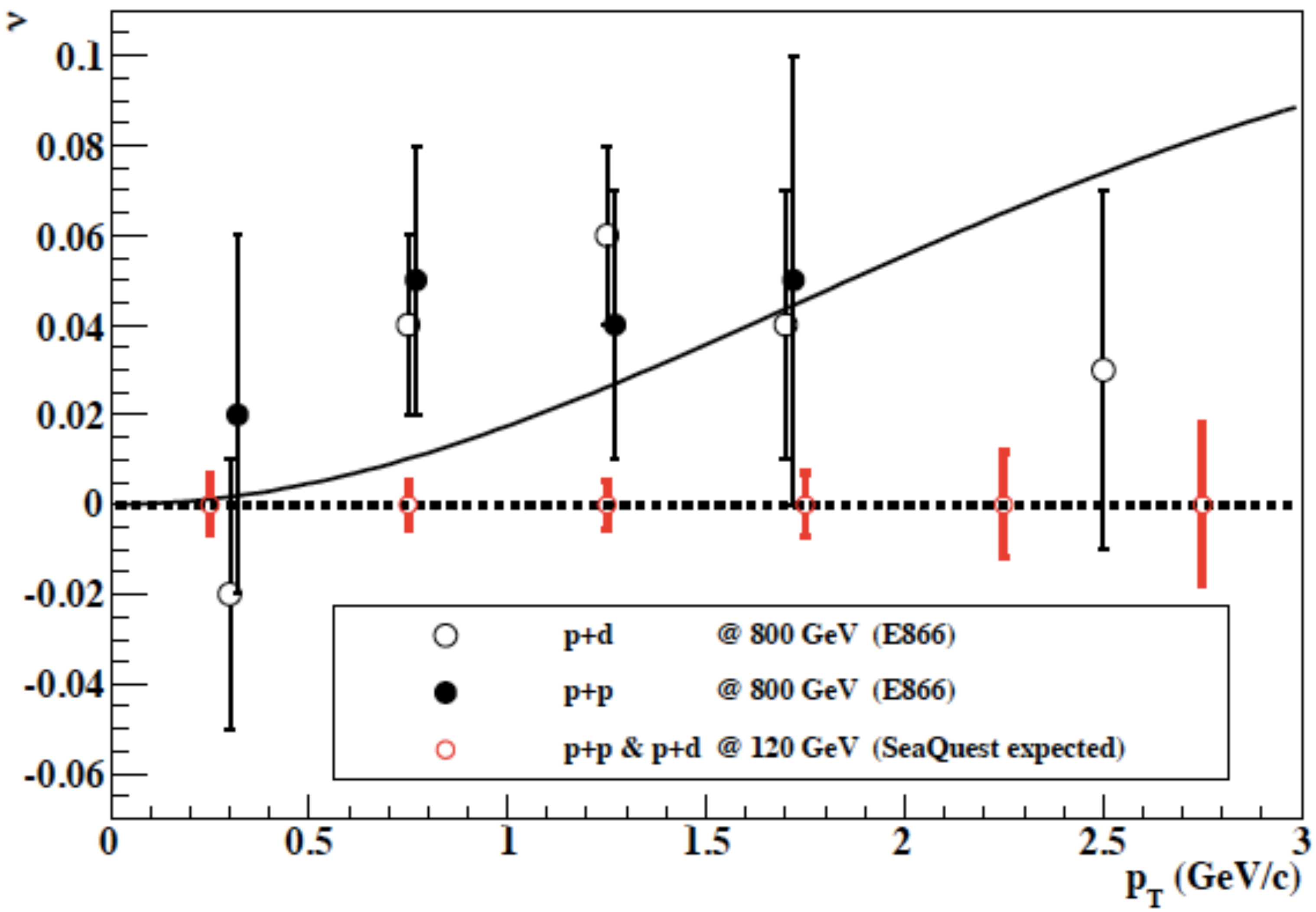
SeaQuest results highly expected

PRL 99 (2007) 082301



Expected statistics

DIS 2018 conference



Clear improvement with respect NuSea

Partonic energy loss

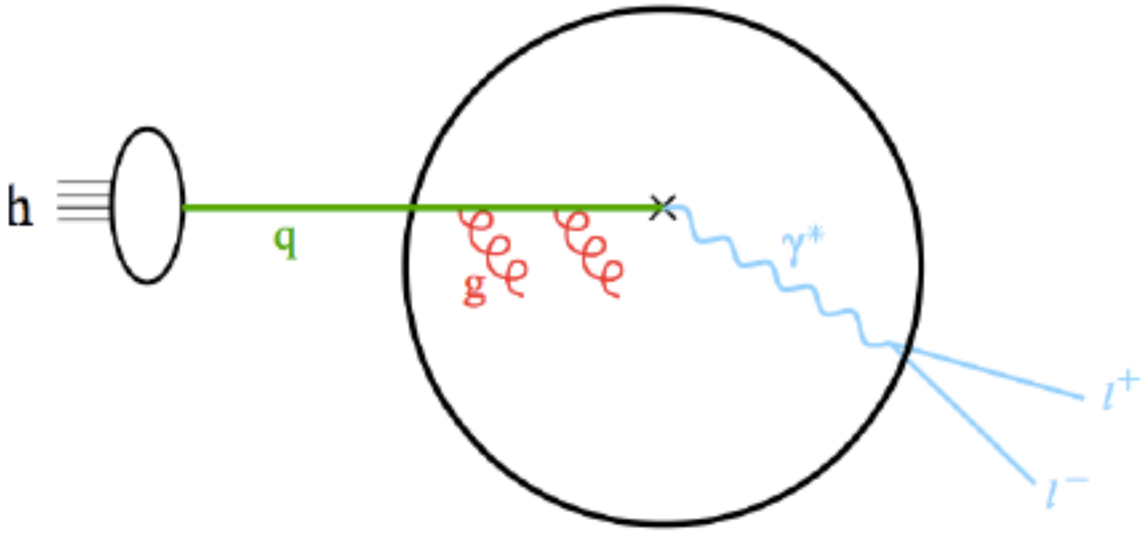
Parton multiple scattering in nuclei induces gluon radiation

Energy-loss in cold nuclear matter

Can be studied through different processes

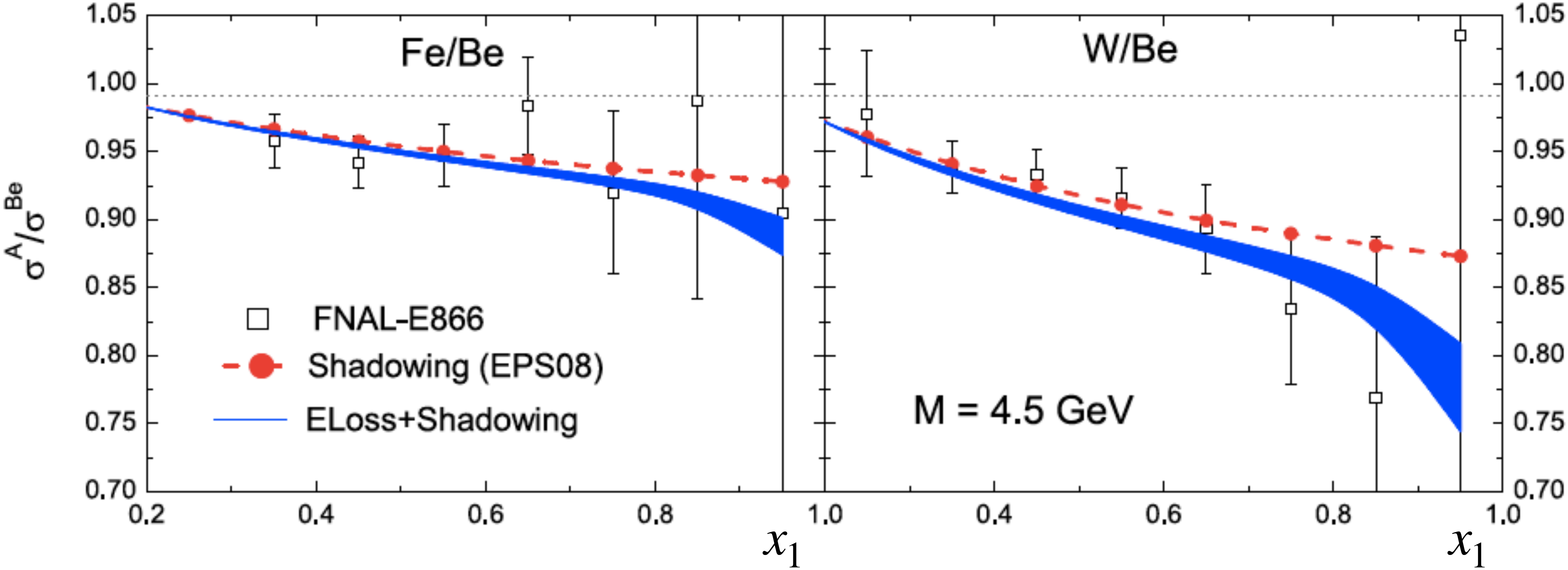
In **Drell-Yan** is an initial state effect

$$R(x_{beam}) = \frac{\frac{1}{A_A}\sigma_{pA}}{\frac{1}{A_C}\sigma_{pC}}$$



Past experiments an models

FERMILAB-THESIS-2017-18



In heavy nucleus, some nucleons are shadowed by the nucleons in the front and are less likely to participate in the interaction

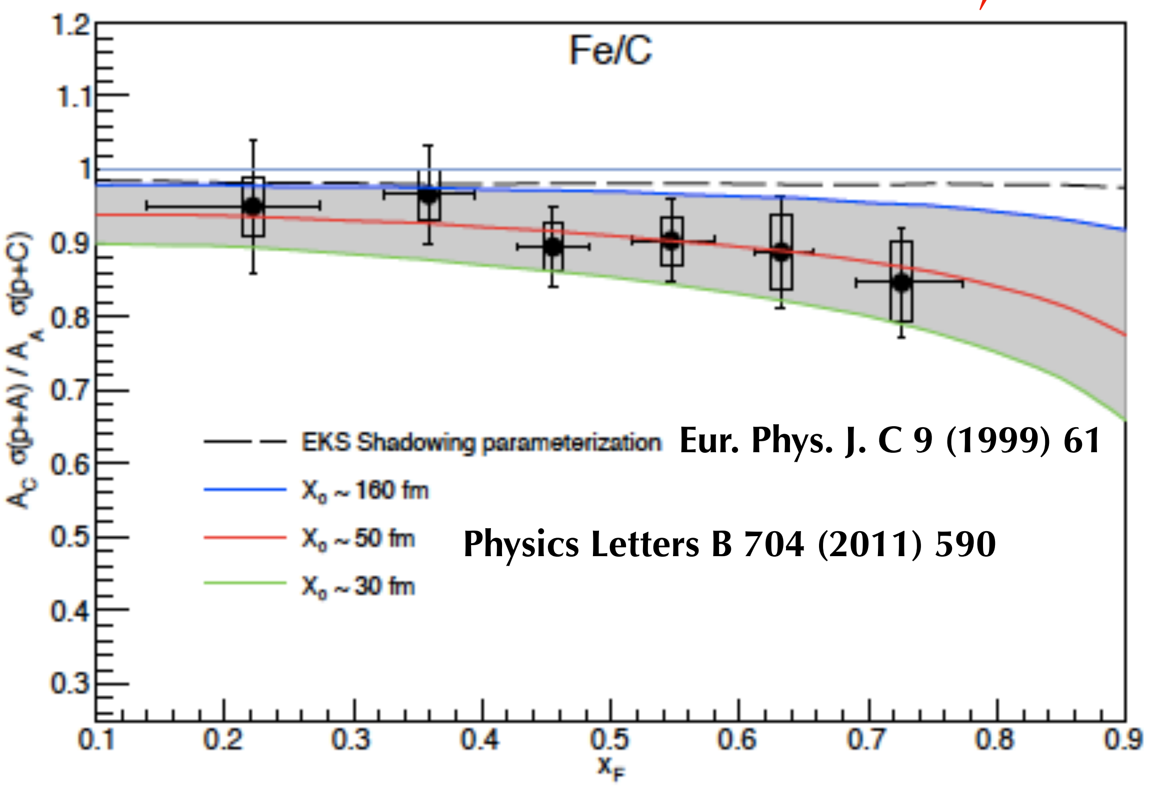
Can the shadowing effect alone explain the results?

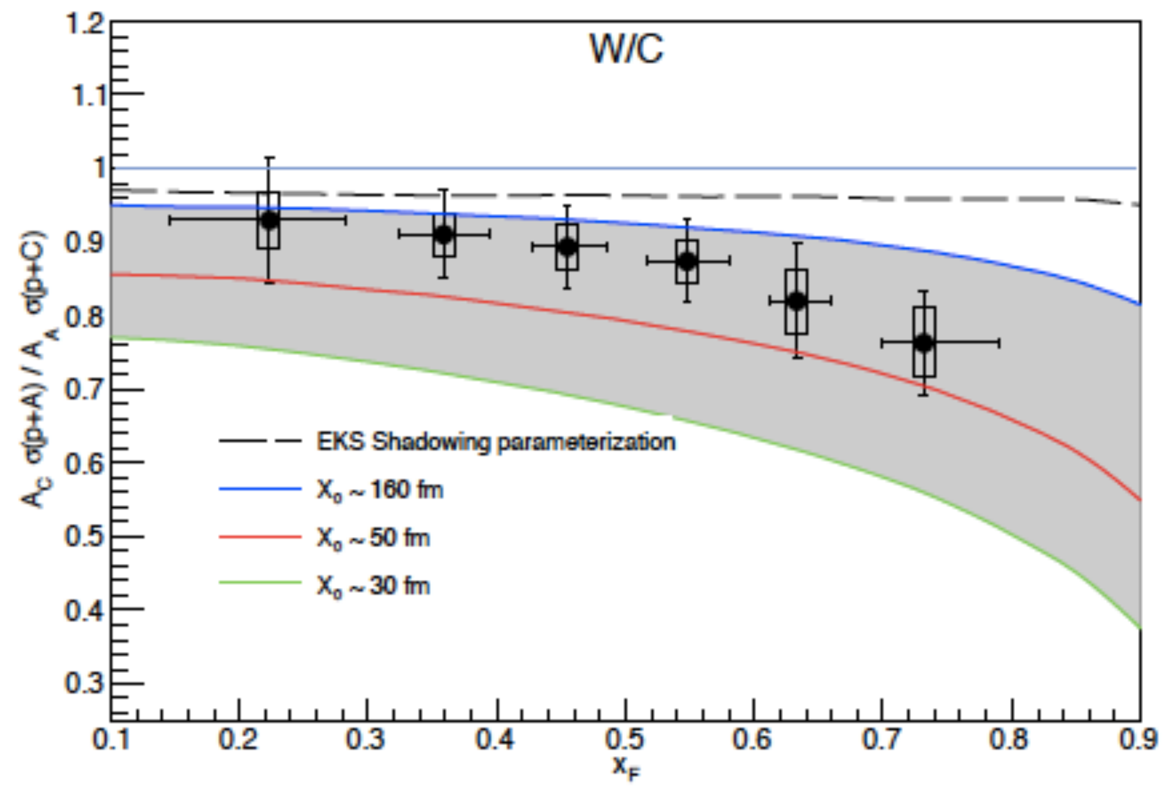
E866 covers mainly the shadowing region $x_2 < 0.1$

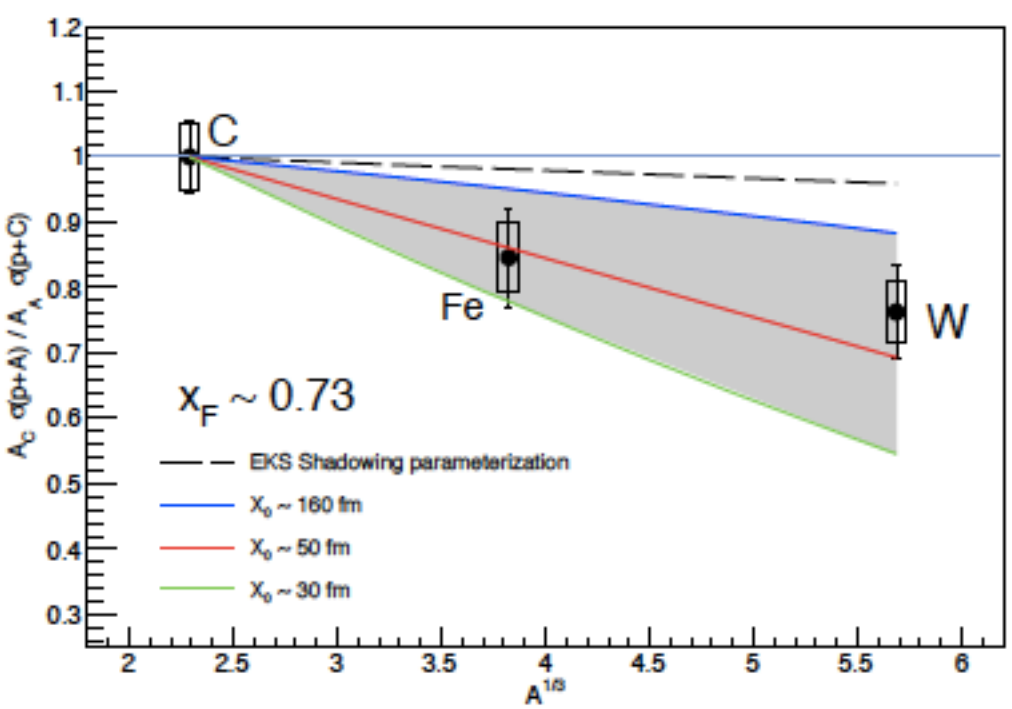
SeaQuest covers a wider region than the shadowing region

Preliminary results from SeaQuest

Data from 2014, FERMILAB-THESIS-2017-18







Three possibilities for the quark radiation length X_0 (from past experiments it was estimated to be between 50 fm and 100 fm)

Clear effect of the energy loss according to the models considered

Linear dependence with $A^{1/3}$ at high x_F as predicted

Drell-Yan dedicated measurements at Fermilab after SeaQuest

SeaQuest son: E1039/SpinQuest

SeaQuest with a polarised target

Main goal: Measure the Sivers function of $\bar{u}$ and $\bar{d}$

↓

Correlation between the transverse spin of the nucleon and the transverse motion of its partons

Non-zero quark orbital angular momentum

Second stage of approval by Fermilab in 2018:

➡ Decommissioning of E906/SeaQuest

➡ Commissioning of E1039/SpinQuest

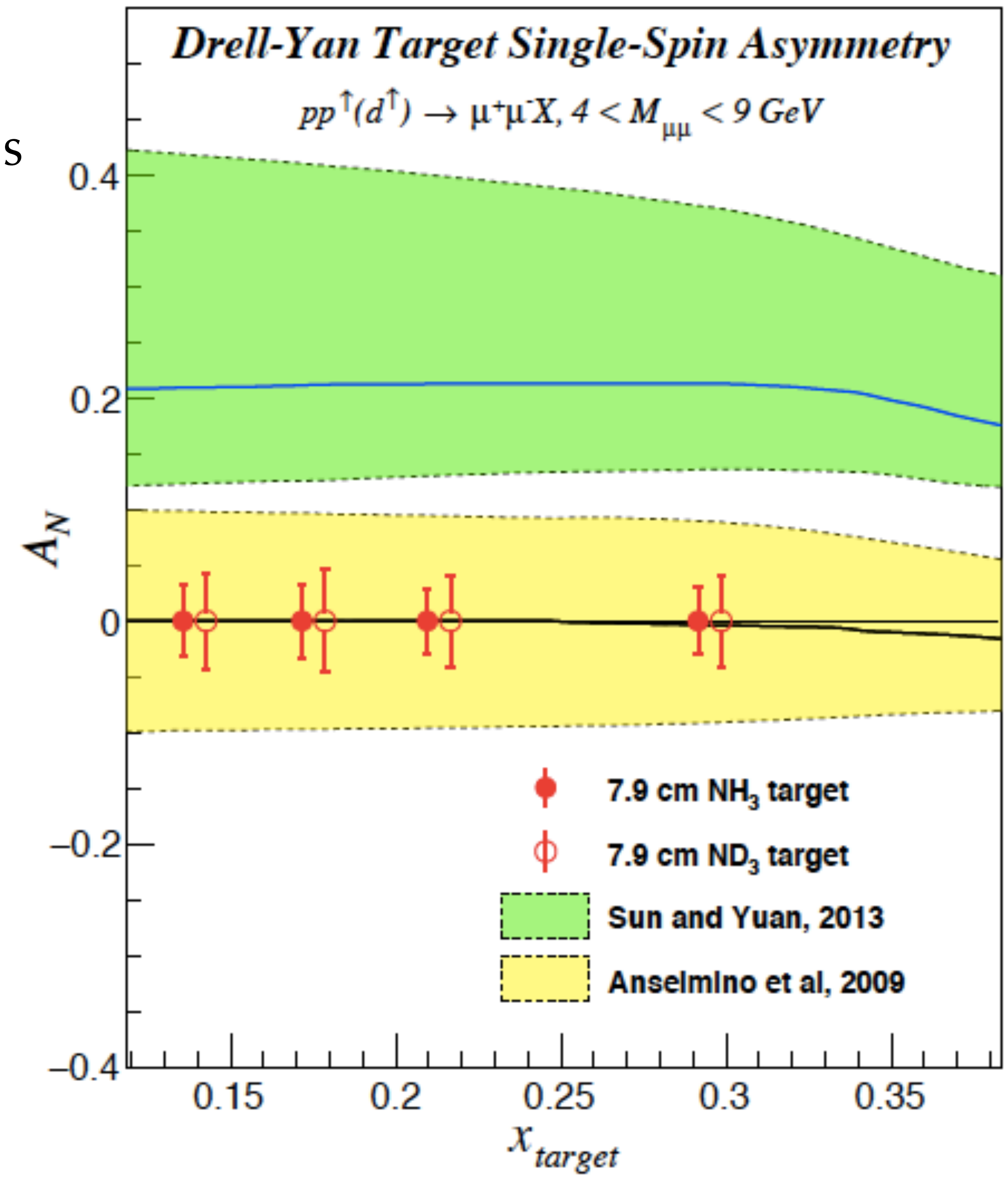
➡ New shielding and target platform

➡ Detectors maintenance and repair

In 2019:

➡ Polarised target installation

Statistical projections



Summary

- SeaQuest finished the data taking in 2017
- Some preliminary results using part of the data are released
- The preliminary result for the light sea quarks asymmetry is compatible with the previous experiments up to x~0.25 and then deviates from the existing data
- The final analysis is ongoing, using the final and complete data set
- Other analyses are also progressing and the results should become available soon
- Part of the SeaQuest community is now also involved on the SpinQuest experiment, to measure the Sivers function for sea quarks

Thank you for your attention!