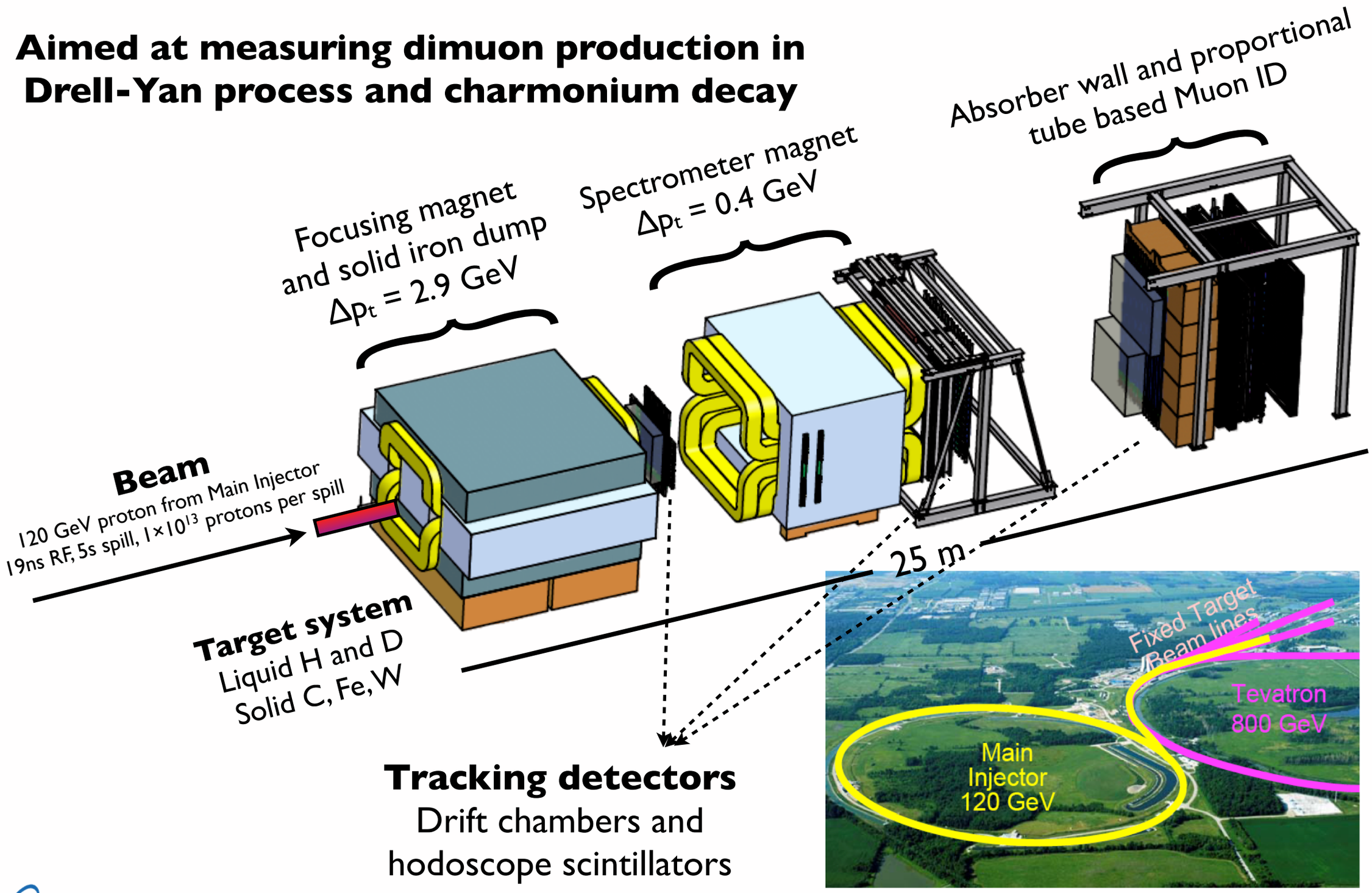
Flavor Asymmetry in Light Quark Sea and Quark Energy Loss at Fermilab E906/SeaQuest Experiment

Kun Liu (on behalf of E906/SeaQuest collaboration)
Los Alamos National Laboratory

XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2015)
Dallas, TX, April 27 - May 1, 2015

E906/SeaQuest experiment at Fermilab

Aimed at measuring dimuon production in Drell-Yan process and charmonium decay



Los Alamos NATIONAL LABORATORY EST. 1943

E906/SeaQuest Collaboration

Abilene Christian University
Ryan Castillo, Michael Daugherity, Donald Isenhower, Noah Kitts, Lacey Medlock, Noah Shutty, Rusty Towell, Shon Watson, Ziao Jai Xi

Academia Sinica
Wen-Chen Chang, Ting-Hua Chang, Shiu Shiuan-Hao

Argonne National Laboratory
John Arrington, Don Geesaman*, Kawtar Hafidi, Roy Holt, Harold Jackson, David Potterveld, Paul E. Reimer*, Brian Tice

University of Colorado
Ed Kinney, Joseph Katich, Po-Ju Lin

Fermi National Accelerator Laboratory
Chuck Brown, Dave Christian, Su-Yin Wang, Jin-Yuan Wu

University of Illinois
Bryan Dannowitz, Markus Diefenthaler, Bryan Kerns, Hao Li, Naomi C.R Makins, Dhyaanesh Mullagur R. Evan McClellan, Jen-Chieh Peng, Shivangi Prasad, Mae Hwee Teo, Mariusz Witek, Yangqiu Yin

KEK
Shin'ya Sawada

Los Alamos National Laboratory
Gerry Garvey, Xiaodong Jiang, Andreas Klein, David Kleinjan, Mike Leitch, Kun Liu, Ming Liu, Pat McGaughey, Joel Moss

Mississippi State University
Lamiaa El Fassi

University of Maryland
Betsy Beise, Yen-Chu Chen, Kazutaka Nakahara

University of Michigan
Christine Aidala, McKenzie Barber, Catherine Culkin, Vera Loggins, Wolfgang Lorenzon, Bryan Ramson, Richard Raymond, Josh Rubin, Matt Wood

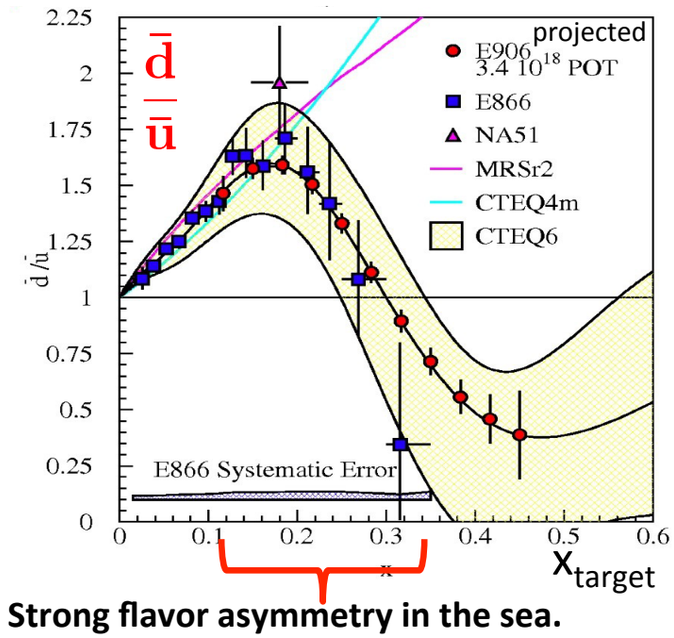
National Kaohsiung Normal University
Rurngsheng Guo, Su-Yin Wang

RIKEN
Yoshinori Fukao, Yuji Goto, Atsushi Taketani, Manabu Togawa

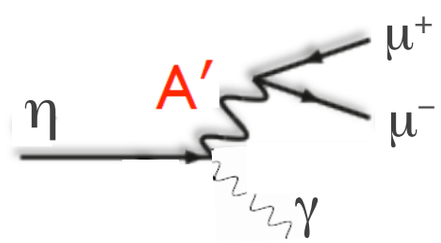
Rutgers, The State University of New Jersey
Ron Gilman, Ron Ransome, Arun Tadepalli

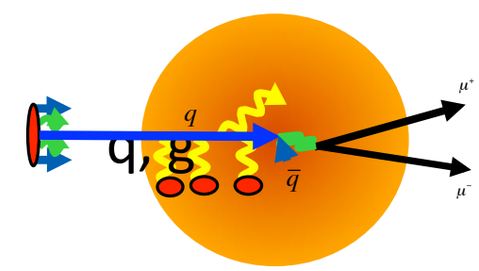
Tokyo Tech
Shou Miyaska, Kei Nagai, Kenichi Nakano, Shigeki Obata, Florian Sanftl, Toshi-Aki Shibata

Yamagata University
Yuya Kudo, Yoshiyuki Miyachi, Shumpei Nara



Strong flavor asymmetry in the sea.



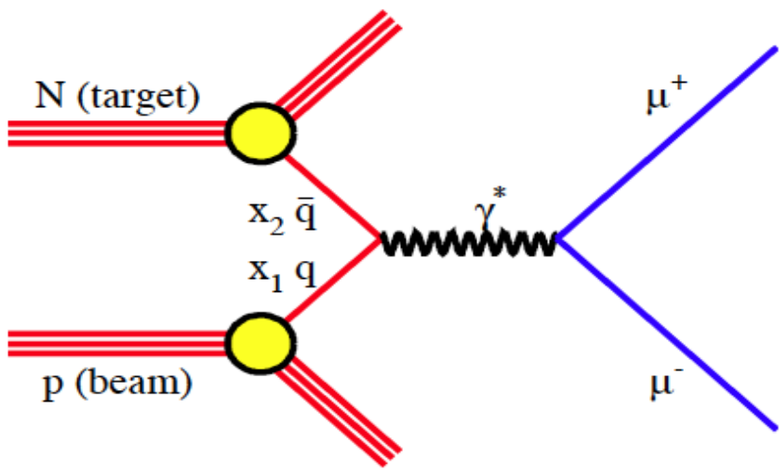


2009 @ Los Alamos

2013 @ Tokyo Tech

E906 kinematic coverage

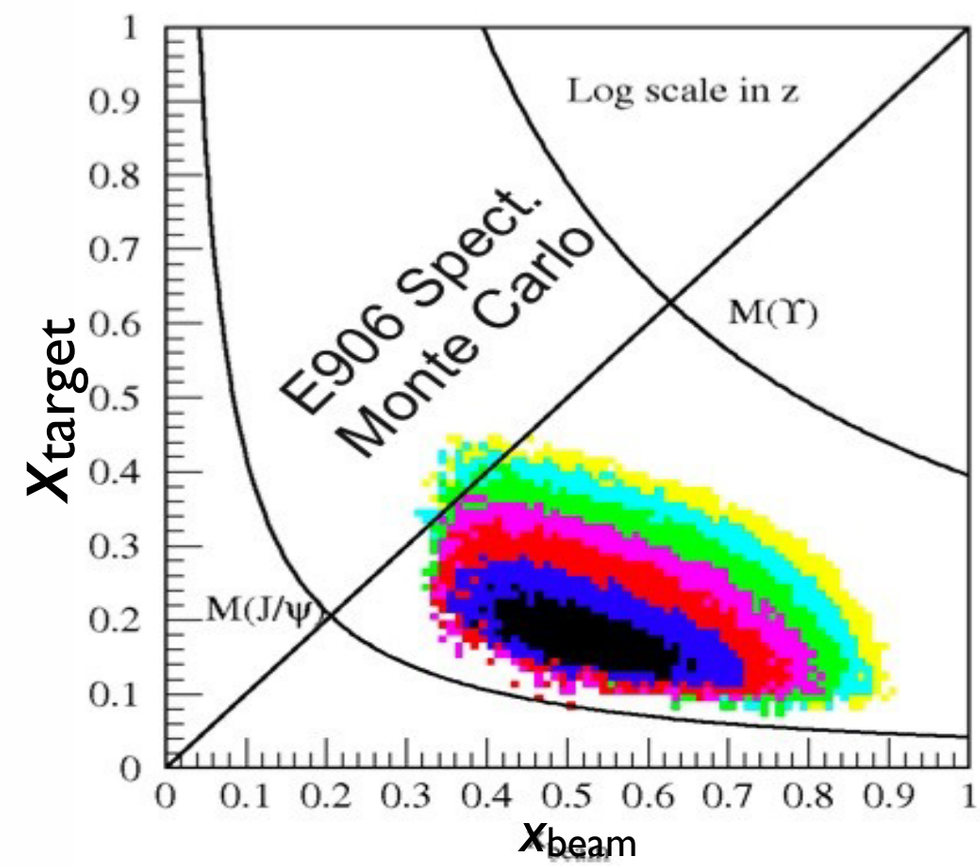
The Drell-Yan process:

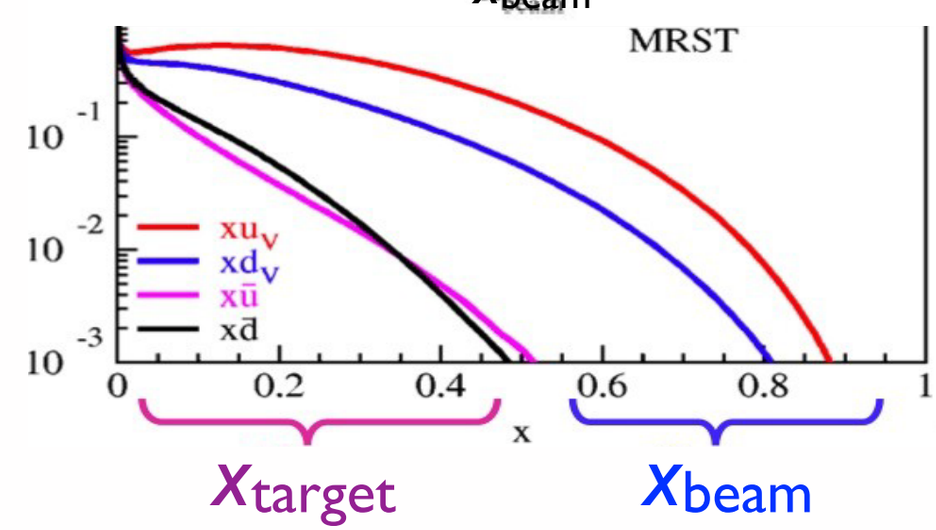


$$\frac{d^2\sigma}{dx_b\,dx_t} = \frac{4\pi\alpha^2}{9x_b\,x_t}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_t(x_t)q_b(x_b) + \cancel{q_t(x_t)\bar{q}_b(x_b)}\right]$$

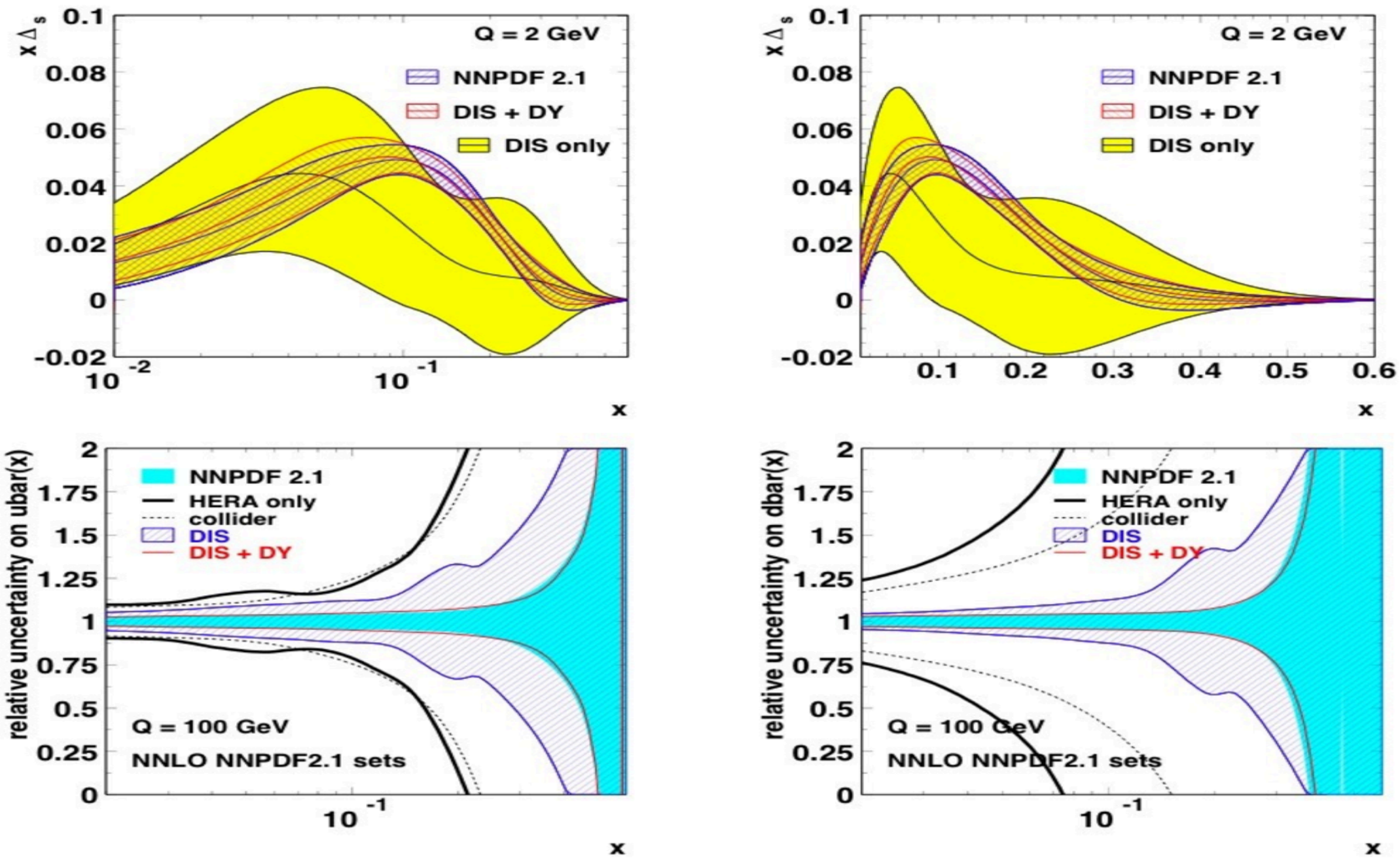
small

$\bar{q}_t(x_t)$: target sea quark at low/intermediate x
$q_b(x_b)$: beam valence quark at high x

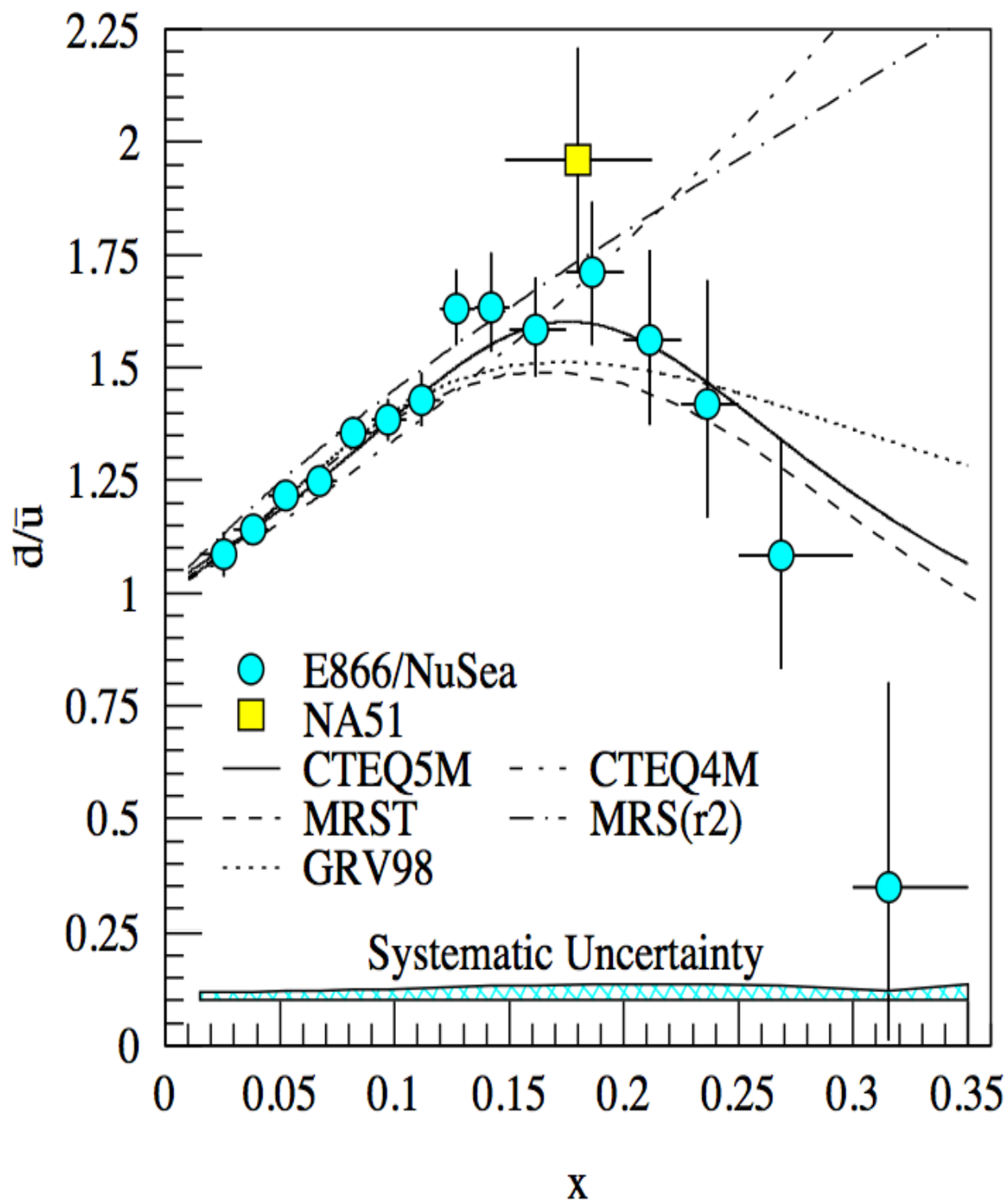




DY vs. DIS on sea quark sensitivity



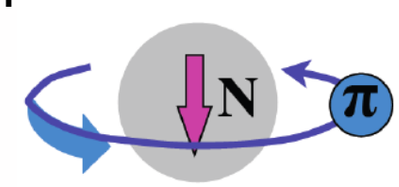
Flavor asymmetry in light quark sea

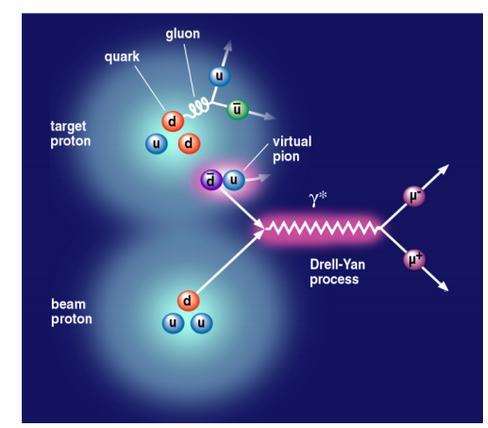


- Assuming charge symmetry, ignoring nuclear effects of deuterium and heavy quark contributions:

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right].$$

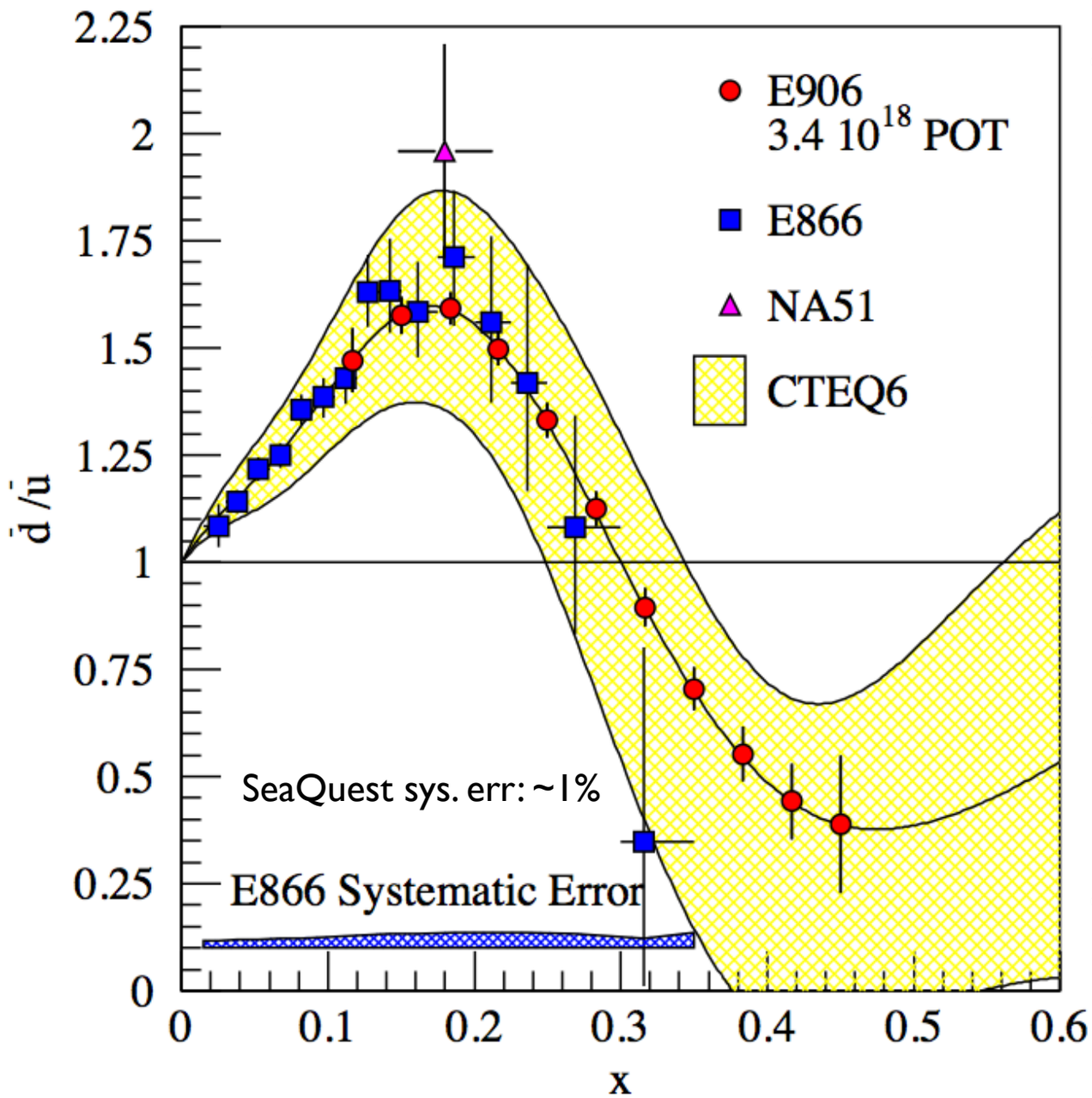
- Naively we would expect flavor symmetry between $\bar{u}$ and $\bar{d}$
- E866/NuSea experiment reveals a striking asymmetry in the sea distributions at moderate x
- Caused by virtual pions?





- Important constraints on light sea polarization
- No models until recently (Peng *et al*, PLB 736 2014, 411) could incorporate the sign change at $x > 0.25$

Measurement of $\bar{d}/\bar{u}$ at E906/SeaQuest



- E906 is based on 120 GeV proton beam from Main Injector compared with 800 GeV beam of E866 ⟹ much lower $\sqrt{s}$

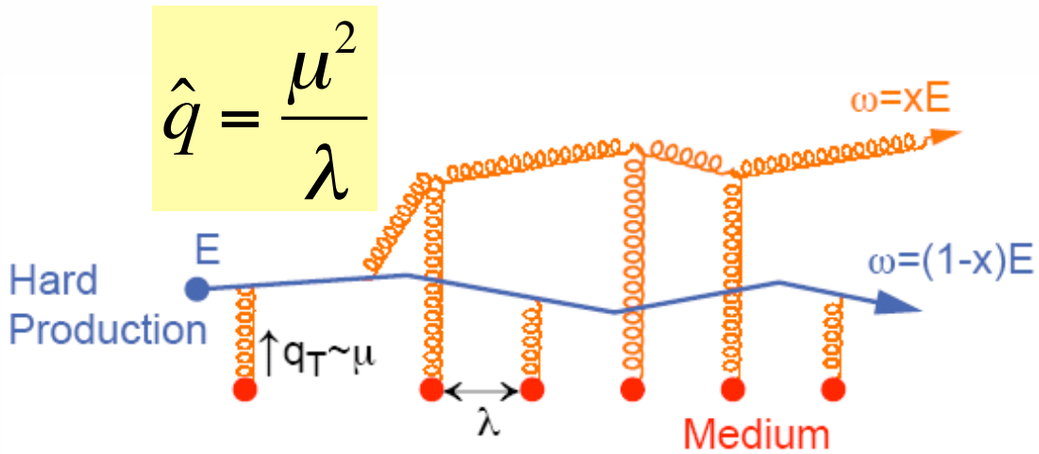
- Drell-Yan cross section scales as $1/s$
- J/ψ cross section scales as s

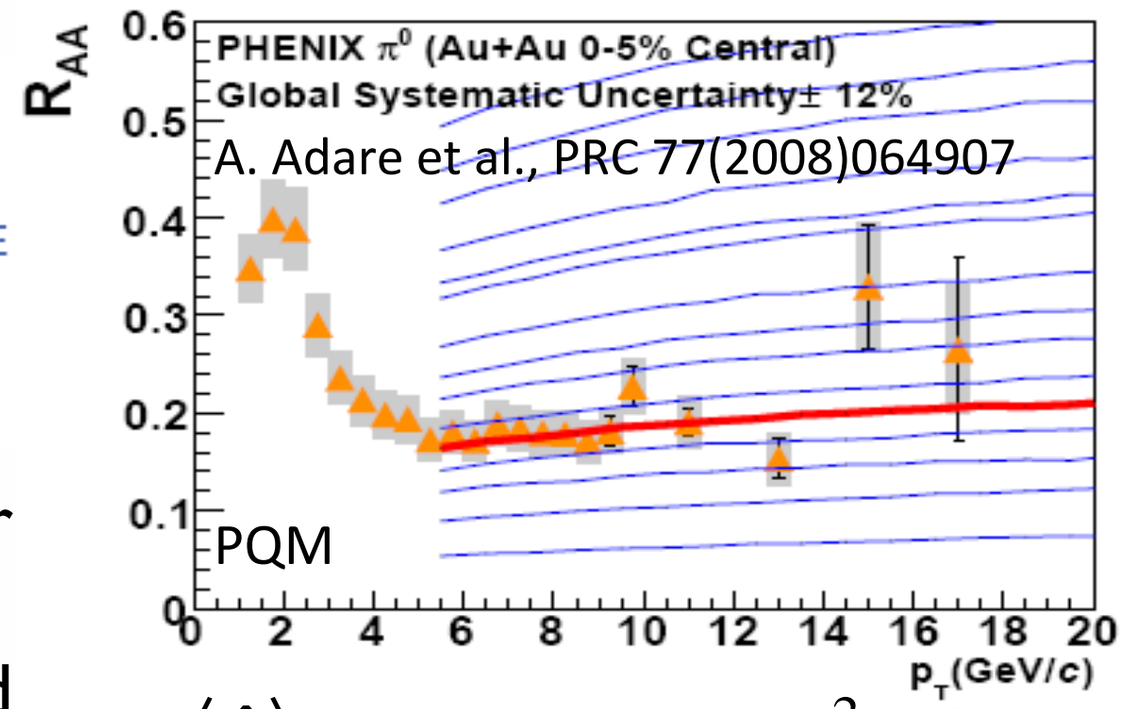
⇩

50x improvement of precision

- Common x coverage with E866 and E772, and extend to higher region

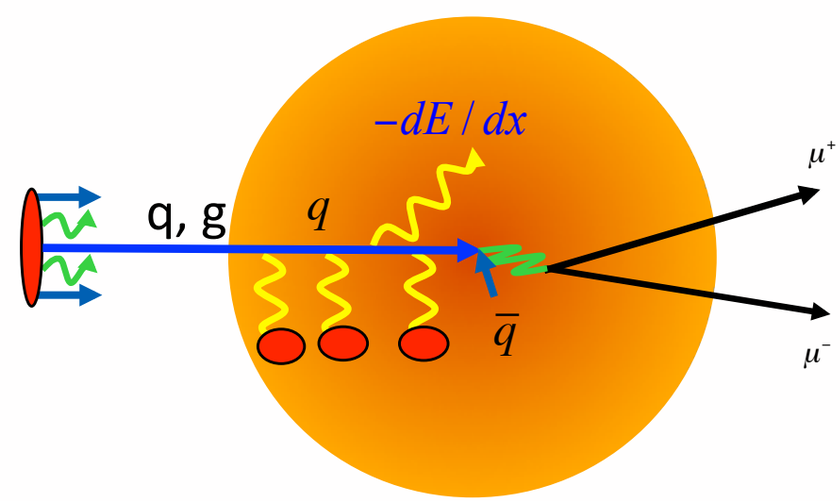
Partonic energy loss in Drell-Yan process



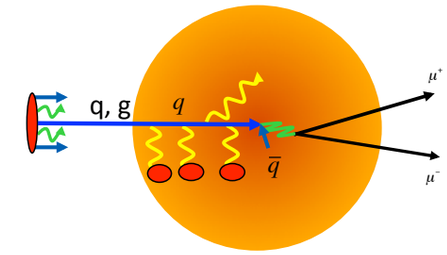


- Fundamental probe to study matter properties
- Accessing energy loss from hard scattering in hot and dense medium in heavy ion physics:
  - nuclear modification R_{AA} << 1 at high p_T
  - very model-dependent
- Drell-Yan process provides a clean baseline calibration since there is only minimal final state interactions

→ $\langle \hat{q} \rangle = 2 \sim 20\ \mathrm{GeV}^2 / \mathrm{fm}$



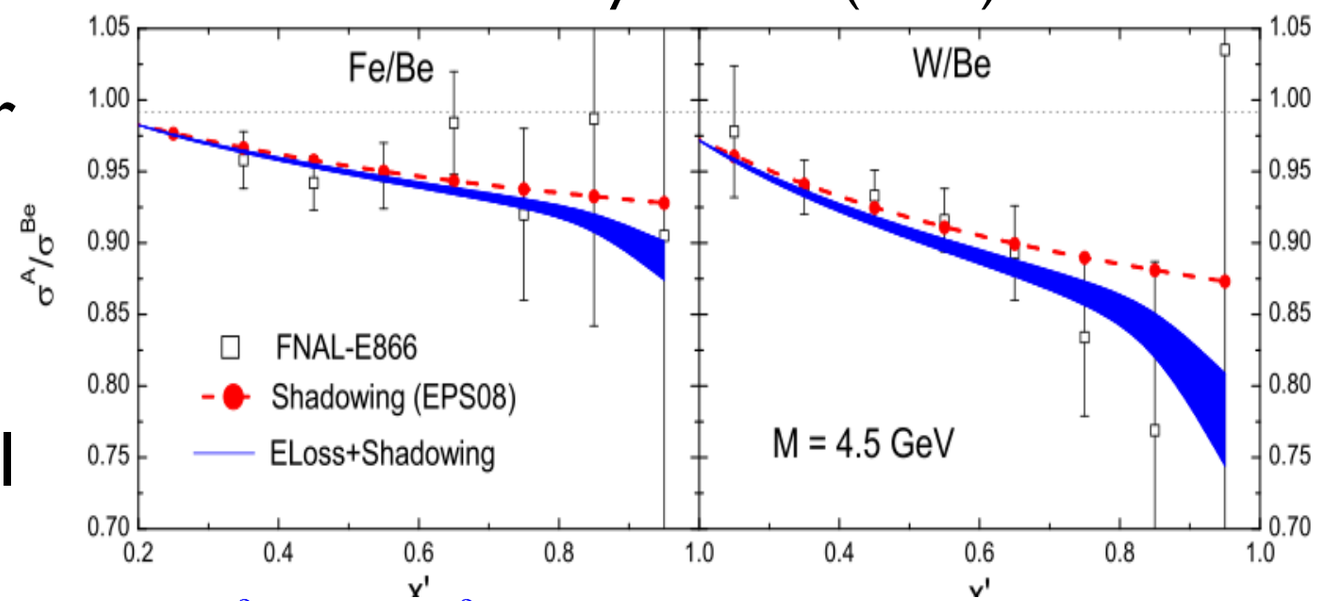
Early data from E866 @ Fermilab



- Energy loss vs. shadowing
  - Correction must be made for shadowing effects
    - Garvey & Peng PRL 90 (2003)
  - NO partonic energy loss if all effects from shadowing
    - Vasiliev *et al.*, PRL 83 (1999)
  - Significant parton energy loss, ~1.2 GeV/fm if all from energy loss
    - Johnson *et al.*, PRC 65 025203 (2002)

Both yield 20~30% effects in R_{pA}

Nucl. Phys. A 879 (2012)



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

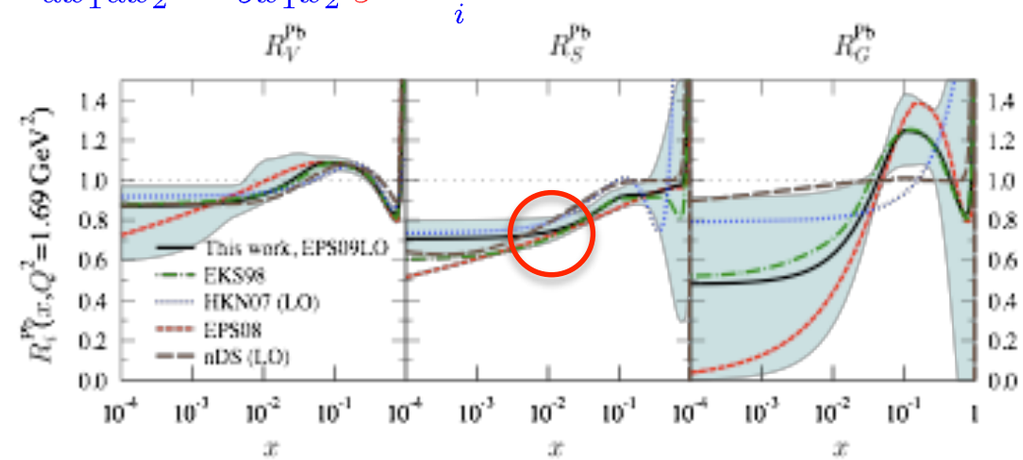


Figure 11: Comparison of the average valence and sea quark, and gluon modifications at $Q^2 = 1.69\,\mathrm{GeV}^2$ for Pb nucleus from LO global DGLAP analyses EKS98 [1, 2], EKPS [3], nDS [6], HKN07 [5], and this work EPS09LO.

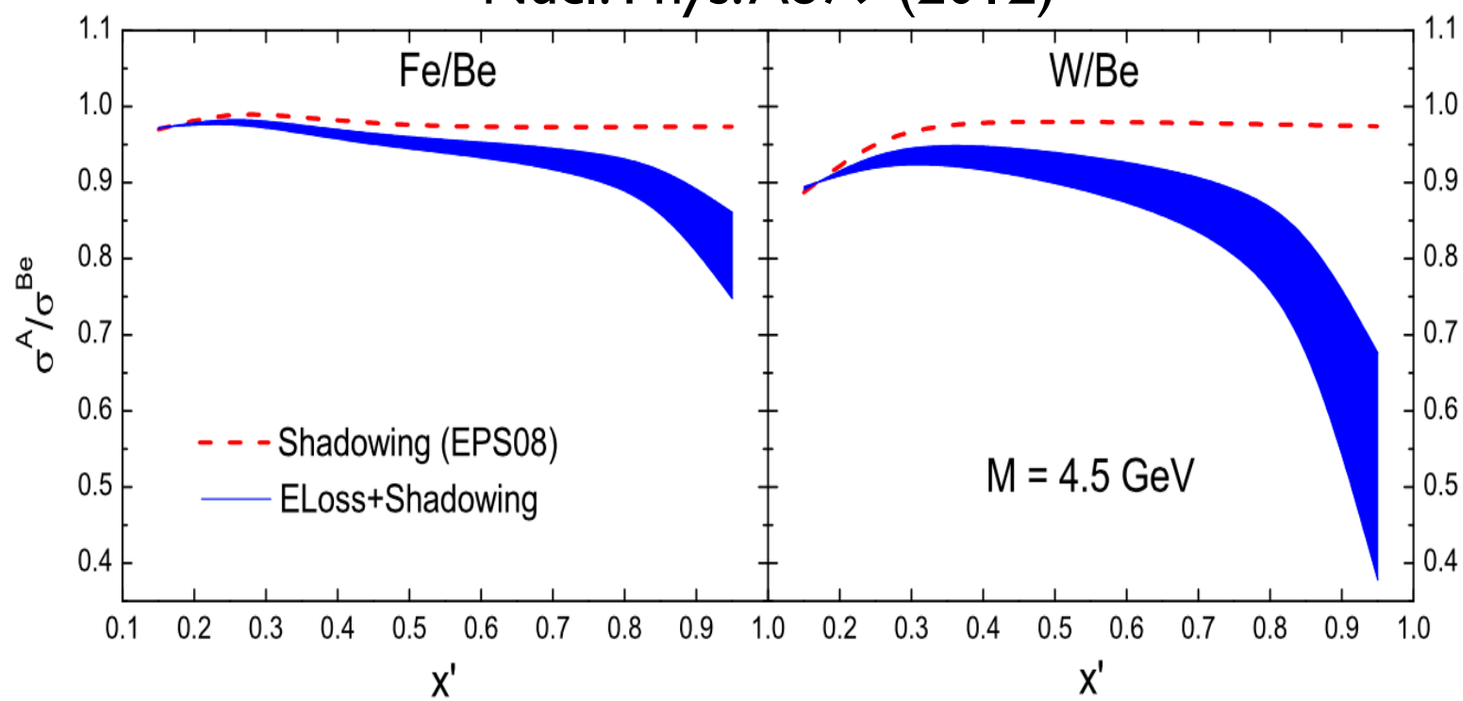
arXiv: 0802.0139

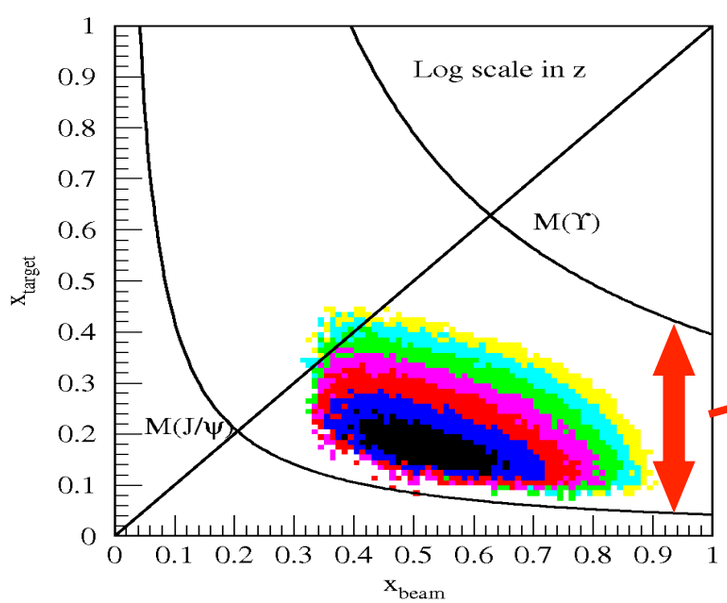
E906 Drell-Yan dimuon acceptance

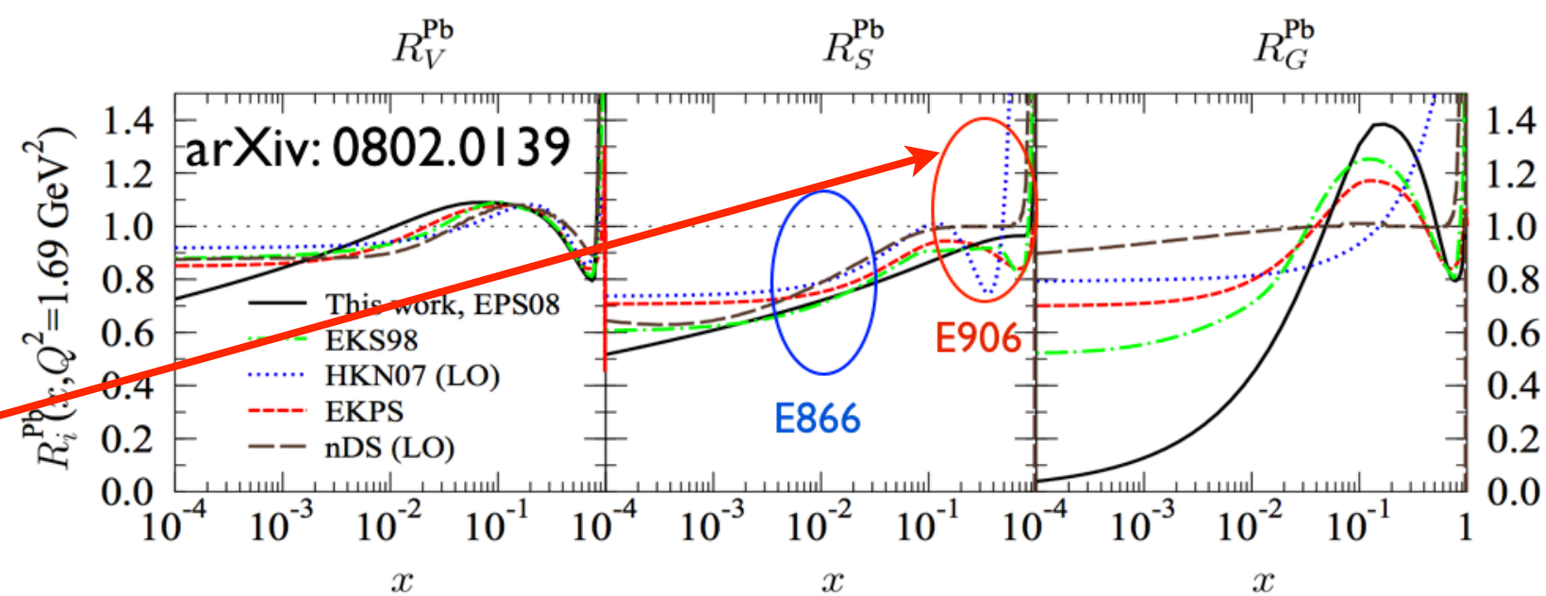
- Parton initial energy: 30 - 120 GeV (relevant to RHIC and LHC parton energy)
- Direct test on various models:
  - Gavin and Milana: $\Delta x_1 = -\kappa_1 x_1 A^{\frac{1}{3}}$
  - Brodsky and Hoyer: $\Delta x_1 = -\frac{\kappa_2}{s} A^{\frac{1}{3}}$
  - Baier *et al*: $\Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}$

- Sea quark x = 0.1 ~ 0.3
- Minimal shadowing
- *1/s* enhanced dE/dx effect

Nucl. Phys. A879 (2012)





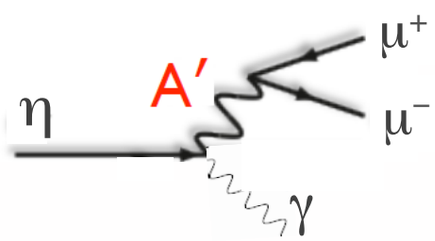


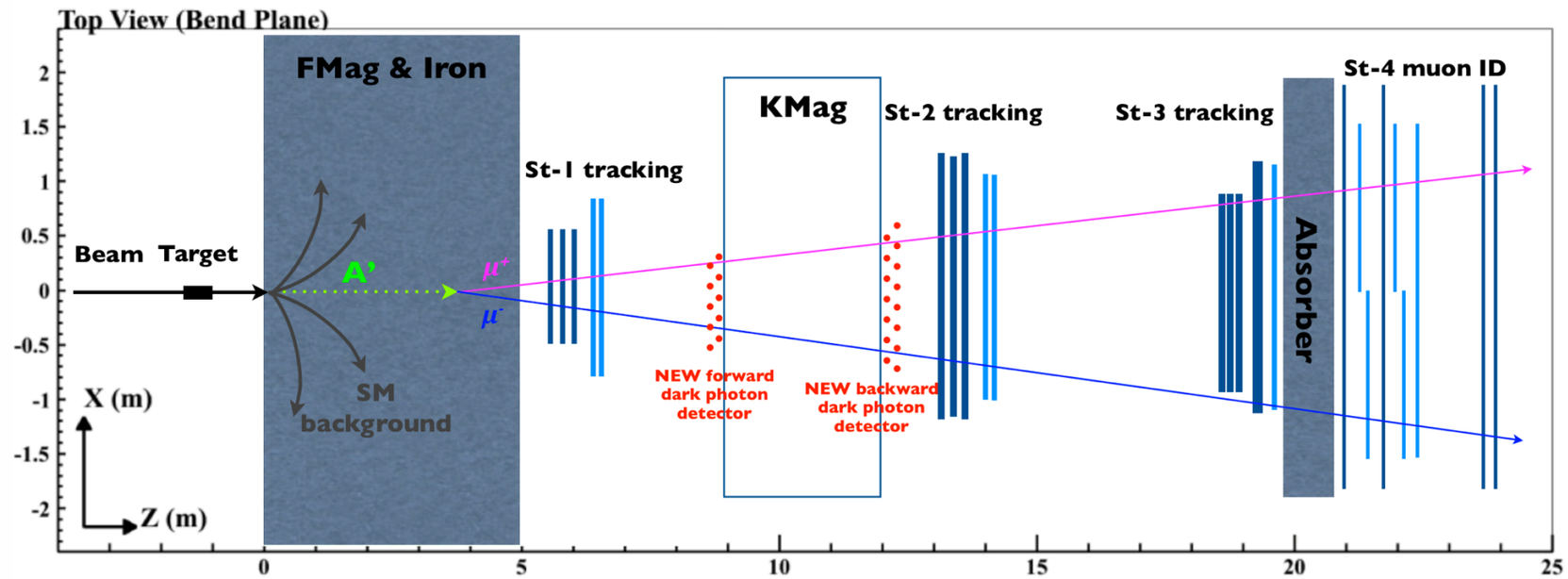
First unambiguous determination of dE/dx in CNM

Dark photon search

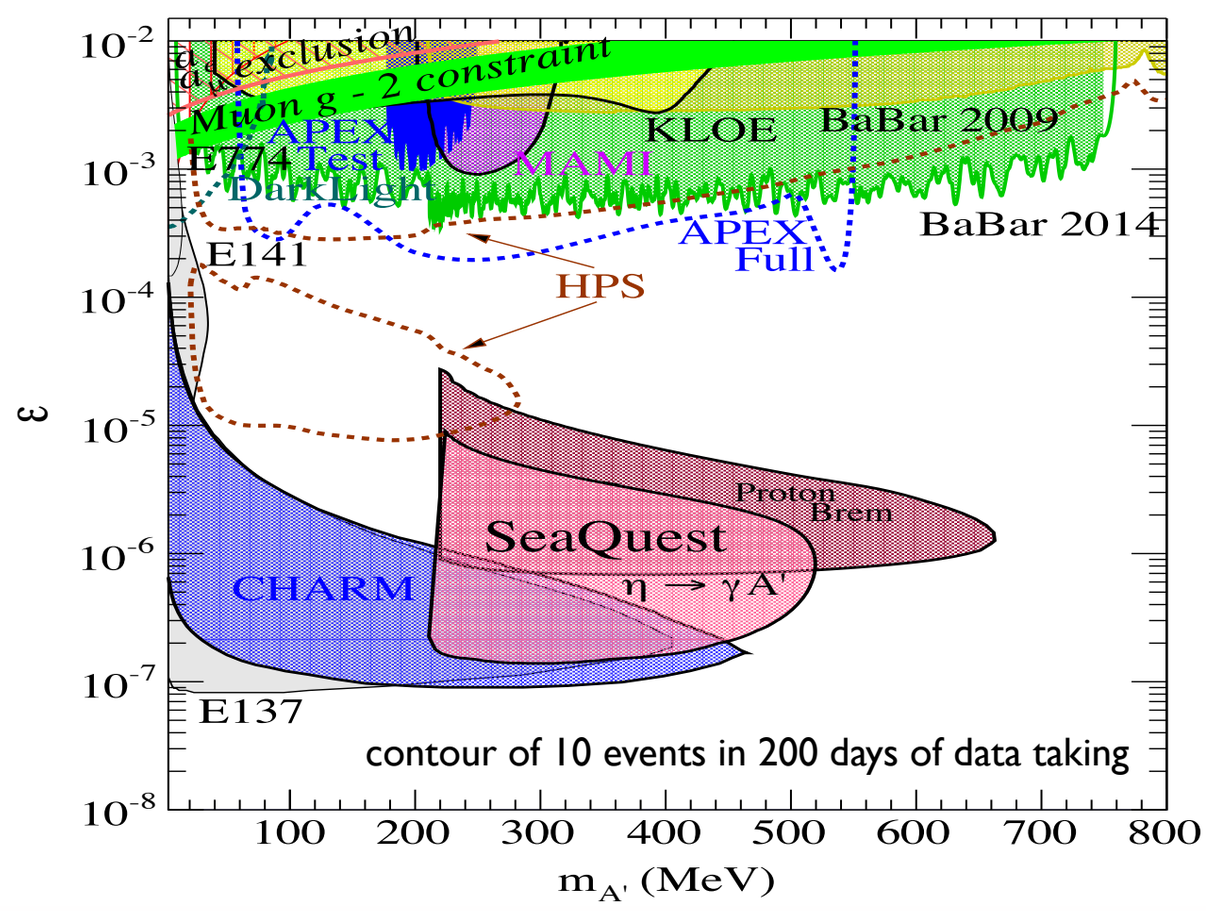
Dark photon (A'):

- gauge boson of the U(1) extension to SM
- dark photon - SM fermion coupling strength $\alpha' = \varepsilon^2\alpha$

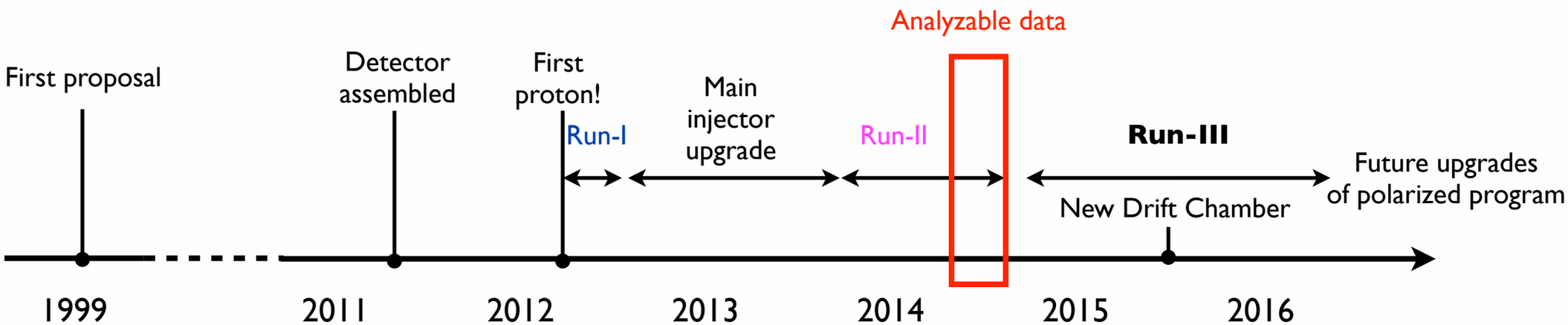




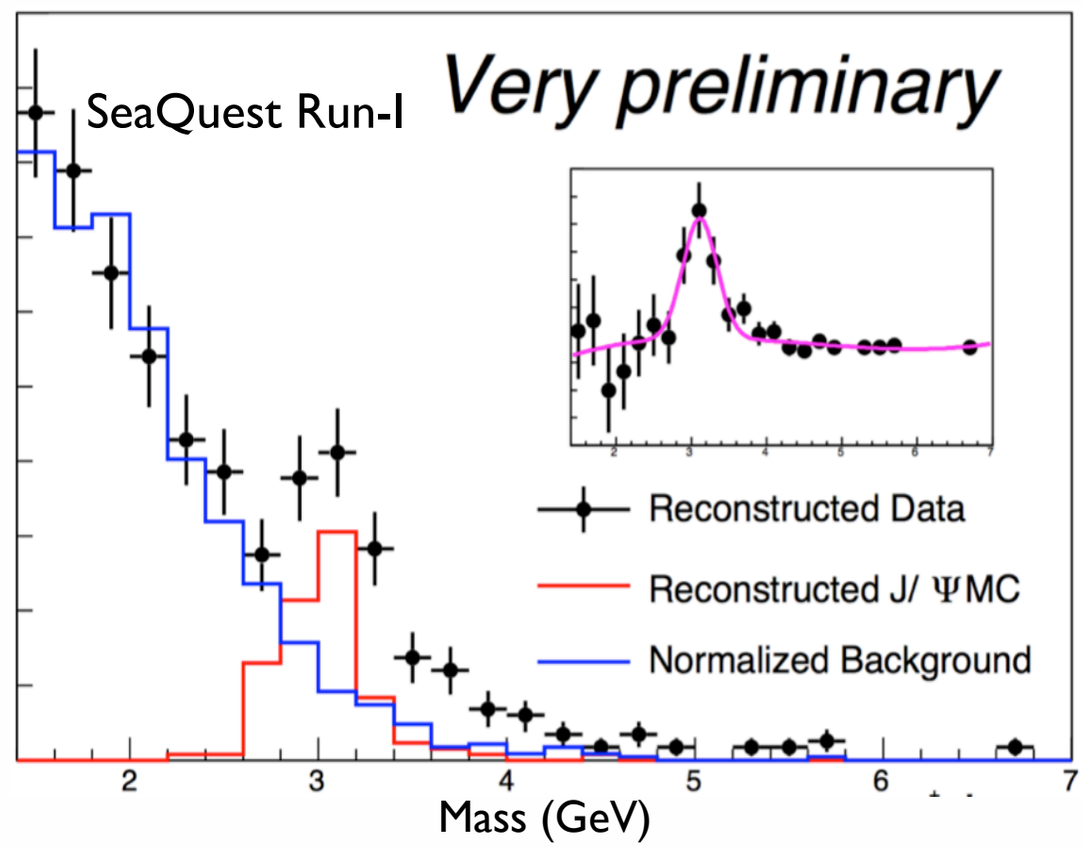
- Sensitive to $10^{-7} < \varepsilon < 10^{-5}$, 220 MeV $< m_{A'} <$ 550 MeV
- Primary limiting factor:
  - displaced vertex
  - detector acceptance at large angle
- New proposals under discussion to extend our sensitivity region



Timeline and milestones of SeaQuest

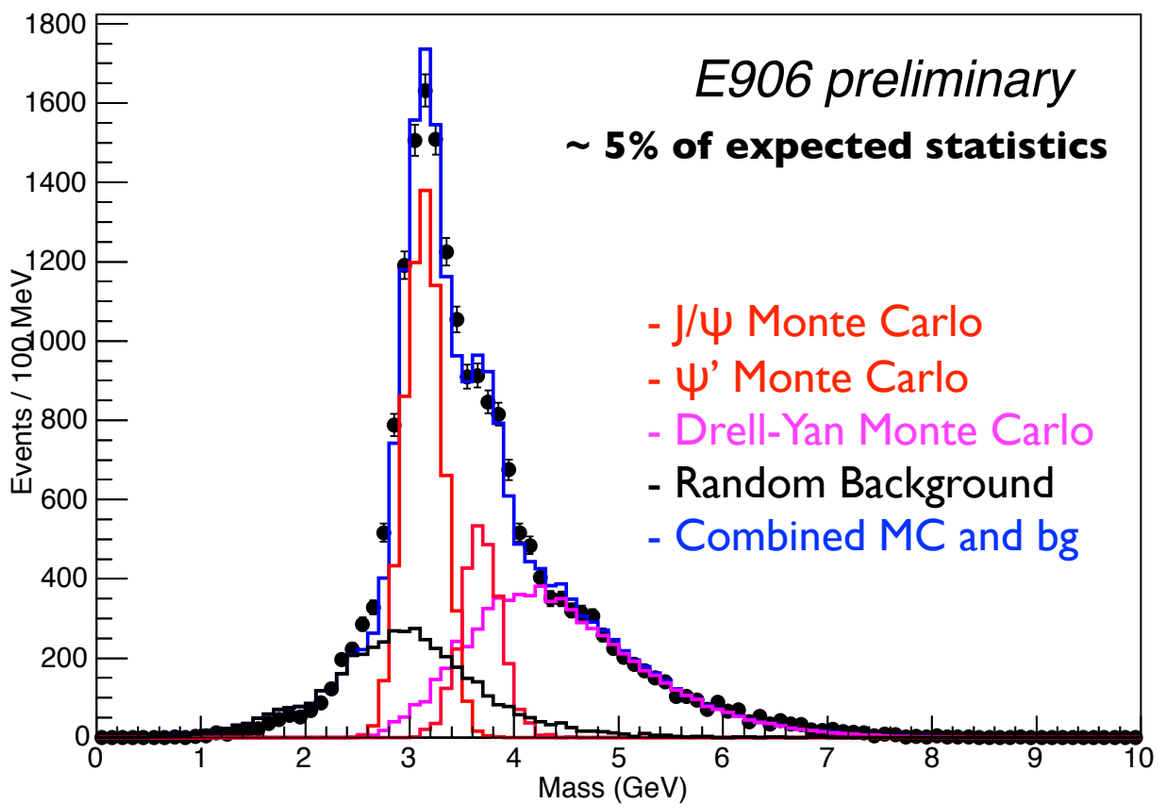


- Due to various delays, only a very short 2-month commissioning Run-I was taken in early 2012
- In the longer Run-II, we solved almost all the problems discovered in Run-I
- After a short 2-month accelerator maintenance, we started a 2-yr Run-III
- New station-1 drift chamber will be installed soon to extend the x_2 coverage
- Polarized projects (target and/or beam) will take over in summer 2016



Dr. Markus Diefenthaler, Polarized Drell-Yan measurement at Fermilab: The future of the SeaQuest experiment, WG7, Apr. 30

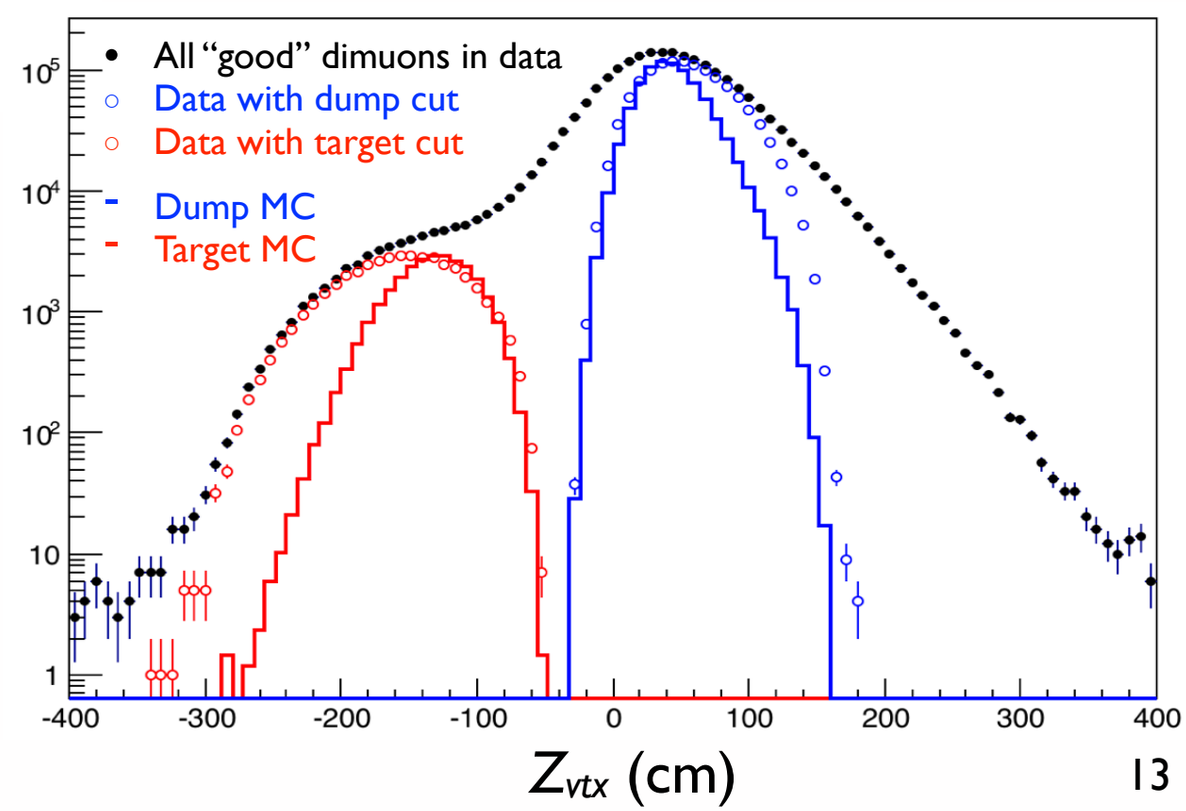
Data from FY 2014 (Run-II)



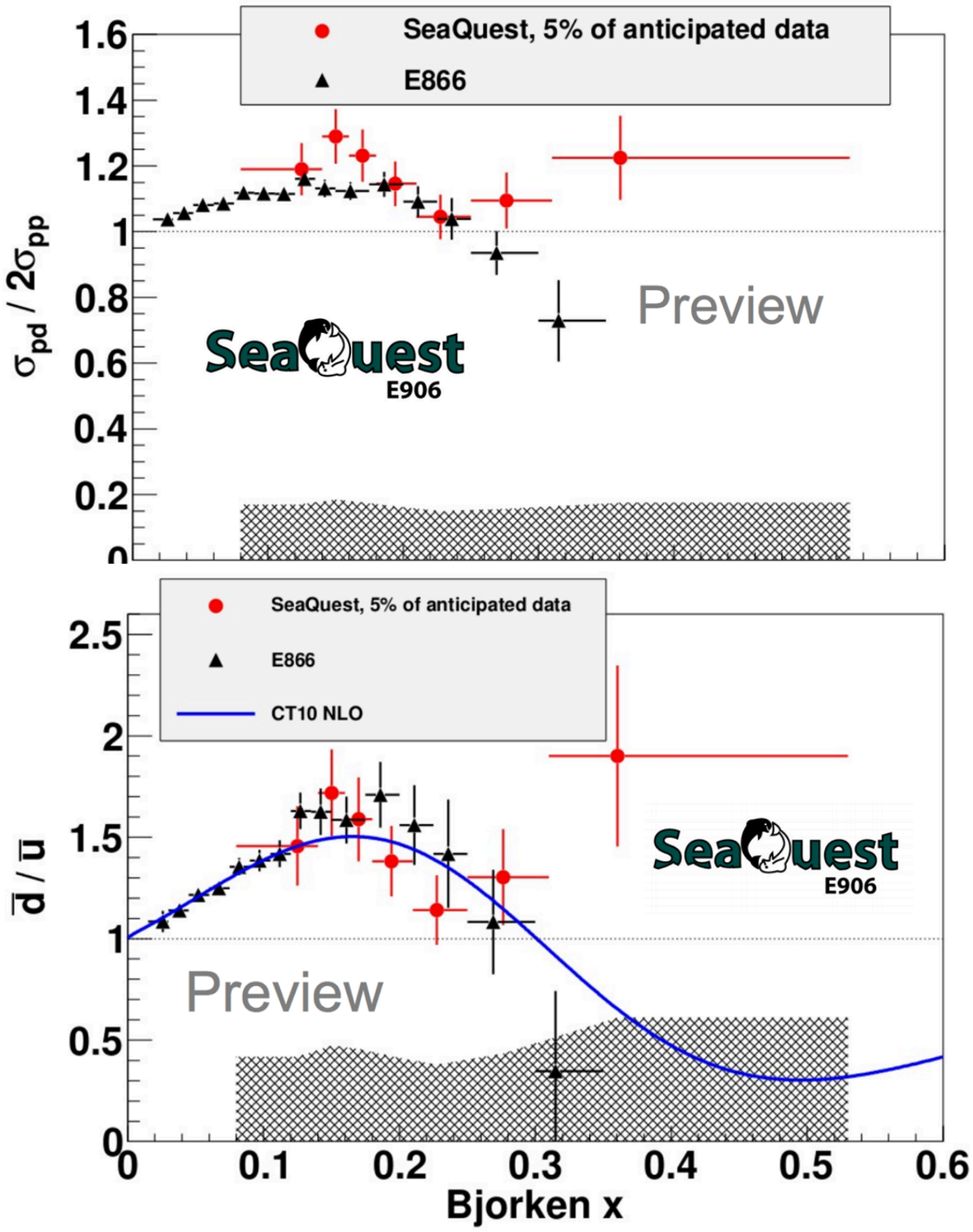
- Monte Carlo describe data well
- Resolution better than expected
  - $\sigma_M(J/\psi) \sim 180$ MeV, $\sigma_M(DY) \sim 220$ MeV
  - J/ψ ψ' separation
  - Cleaner DY sample
- Good target/beam dump separation

- Beam quality worse than expected (instantaneous rate much higher than average)
  - live time of spectrometer greatly reduced by the 'super' RF buckets
  - Reconstruction efficiency lower than expected because of the high detector occupancy

- Entire beam interacts upstream of SeaQuest spectrometer
- Pointing resolution very poor along beam axis
- Dominated by random coincidences

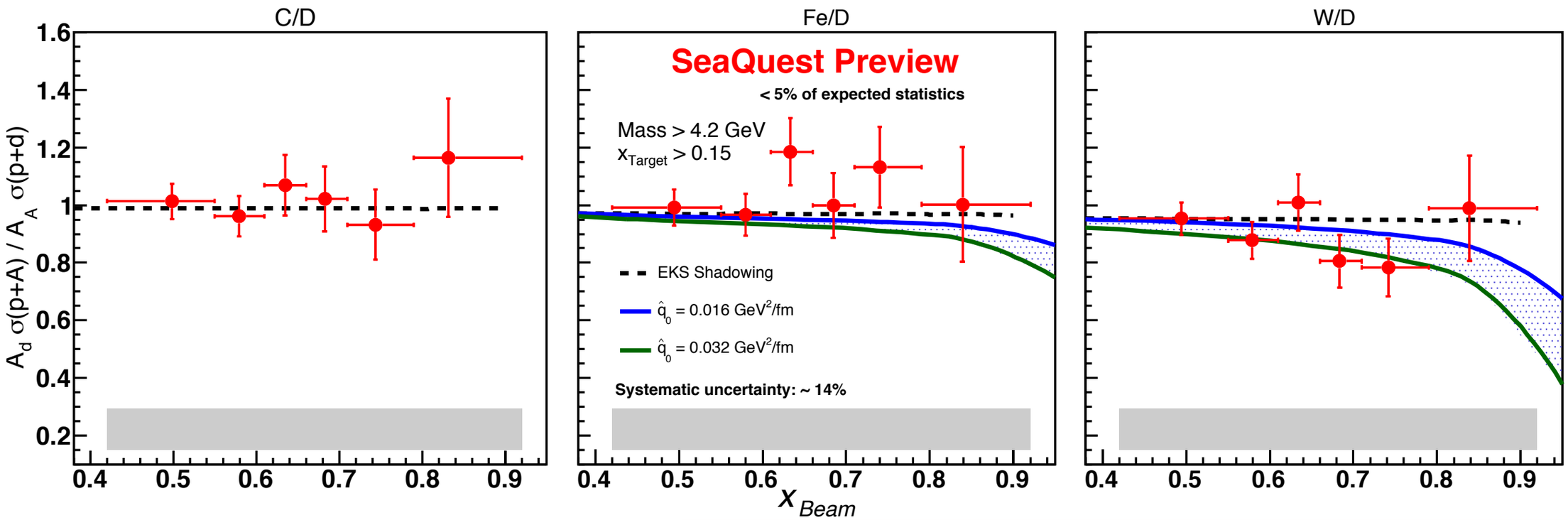


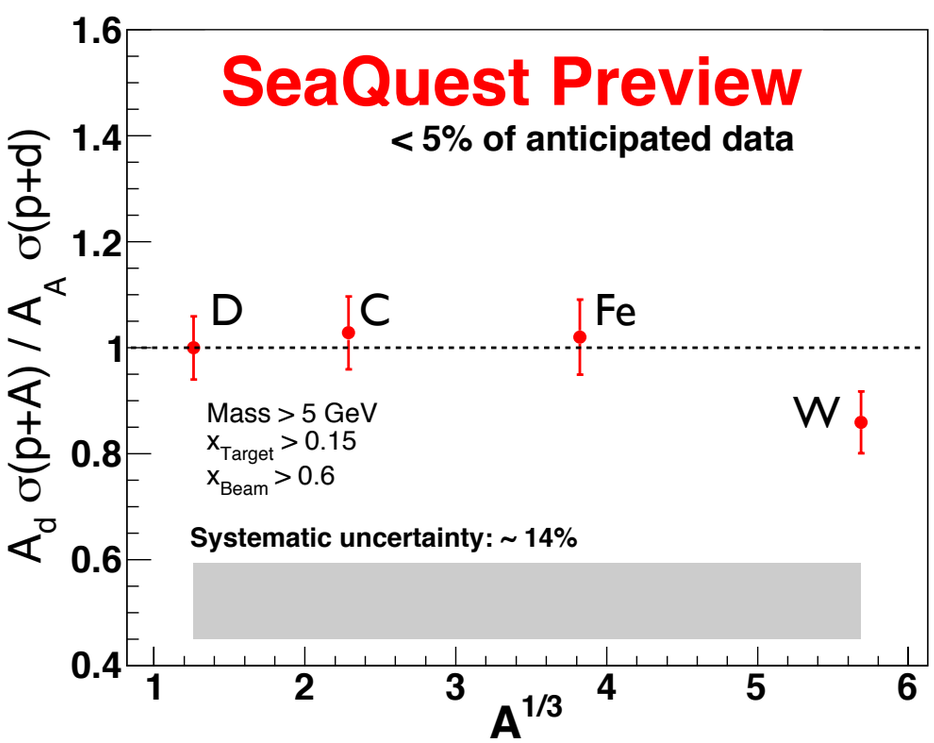
E906 preview measurements on $\bar{d}/\bar{u}$



- Only consists of 5% of the total expected statistics
- Well consistent with E866 results at low x_2
- Interesting behavior at high x_2, with large statistical uncertainties. New larger drift chamber and more statistics will help us pin down this point.
- Current systematic error mainly comes from LD_2 impurity and unresolved rate-dependence. We expect final systematic uncertainty to be ~1%

Quark energy loss at E906





- Too early to make any conclusion on p+Fe as limited by the statistics
- A consistently negative slope beyond the shadowing strength is observed in p+W data.
- With 20x more statistics, we will be able to clearly distinguish between:
  - ➢ $-dE \propto A^{1/3}$ (or $\propto L$)
  - ➢ $-dE \propto A^{2/3}$ (or $\propto L^2$)

Los Alamos NATIONAL LABORATORY EST. 1943

Summary

Run-II: 5% of total statistics:

- confirmed the large light sea quark asymmetry at $x_2 \sim 0.15$, while the sign change at $x_2 > 0.3$ still waits for more statistics
- observed a negative slope beyond the extent of shadowing

Ongoing Run-III: ~20x of Run-II statistics

Other ongoing physics analysis:

- EMC effect in Drell-Yan
- Transverse momentum broadening
- Difference between J/ψ and ψ' suppression in pA
- Search for double J/ψ production
- Search for dark photons
- ...