Drell-Yan Process: Most Recent Results and Open Issues

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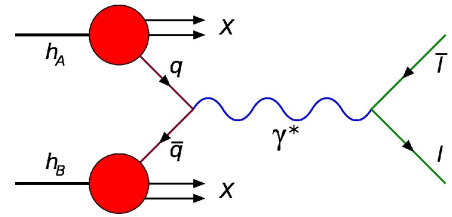
Outline

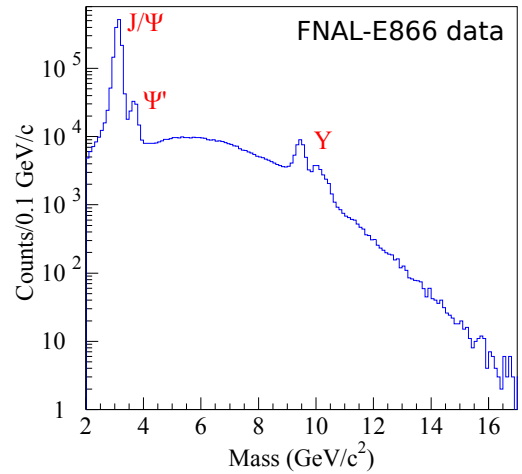
1. Drell-Yan process for studying nucleon structure
2. Drell-Yan Measurement @ SeaQuest
3. Physics topics (mostly related to SeaQuest)
   - Flavor asymmetry of anti-quarks ($\bar{d}(x)/\bar{u}(x)$)
   - Parton energy loss in cold nuclear matter
   - Angular distribution (Boer-Mulders function?)
4. Summary

Drell-Yan for PDF Measurements

- Cross section of $p + p$ D-Y @ LO

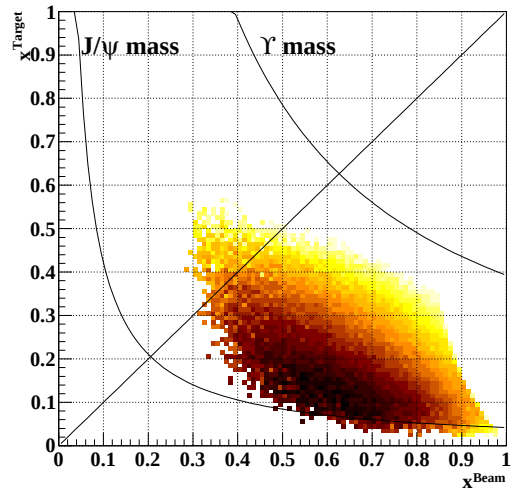
$$\frac{d^2\sigma}{dx_{Beam}dx_{Target}} = \frac{4\pi\alpha^2}{9x_{Beam}x_{Target}}\frac{1}{s}\sum_i {e_i}^2 \cdot$$
$$\{q_i(x_{Beam})\bar{q}_i(x_{Target}) + \bar{q}_i(x_{Beam})q_i(x_{Target})\}$$



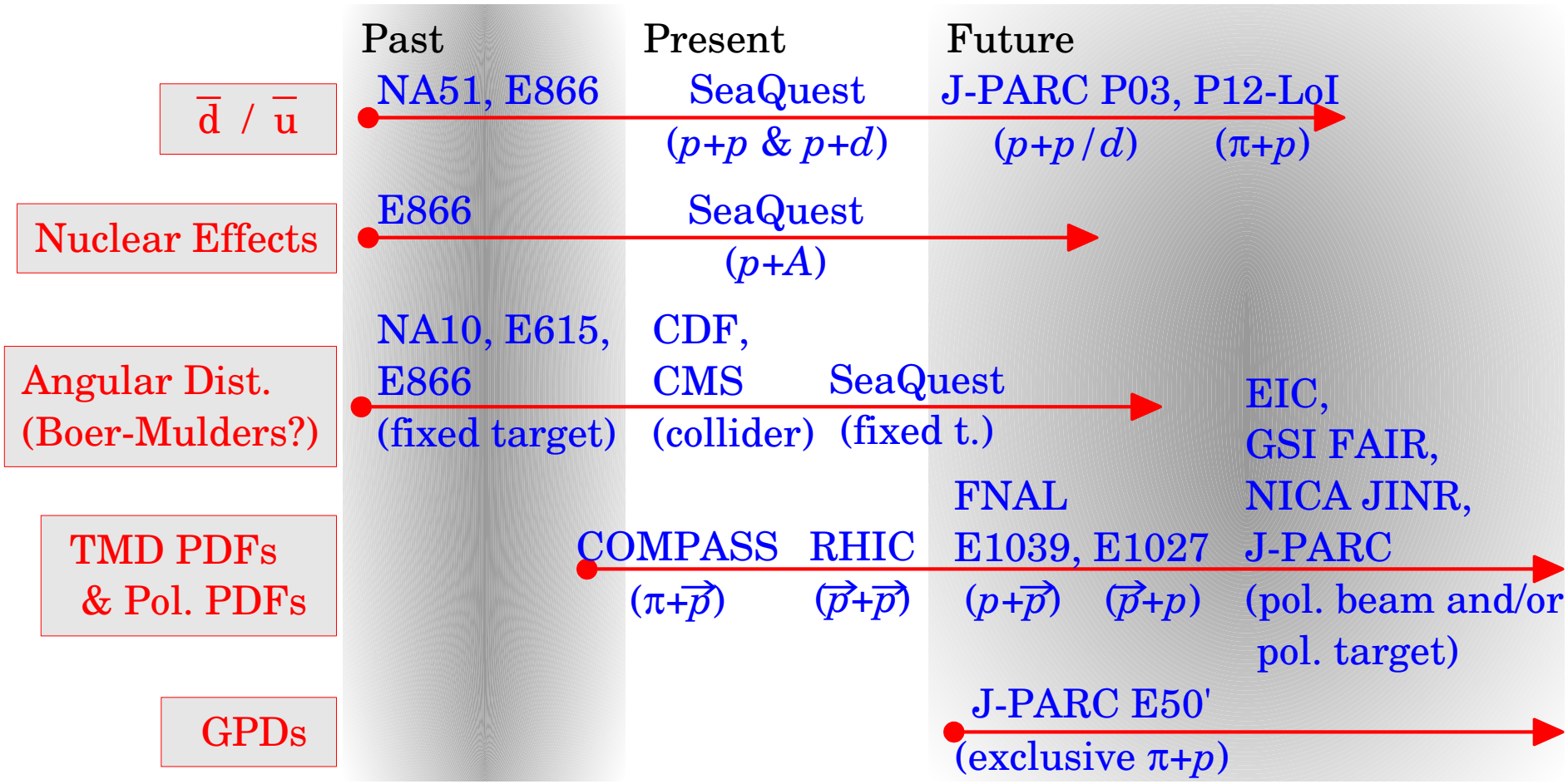


  - "$q_i(x_{Beam})$ $\bar{q}_i(x_{Target})$" survives @ forward rapidity
  - q w/ x_{Beam} & $\bar{q}$ w/ x_{Target} are distinguishable event-by-event

- Specialty
  - Sensitivity to $\bar{q}$
  - Similarity to SIDIS
    - TMD sign change
    - Angular distribution
  - No strong interaction in final state (vs heavy-ion collision)

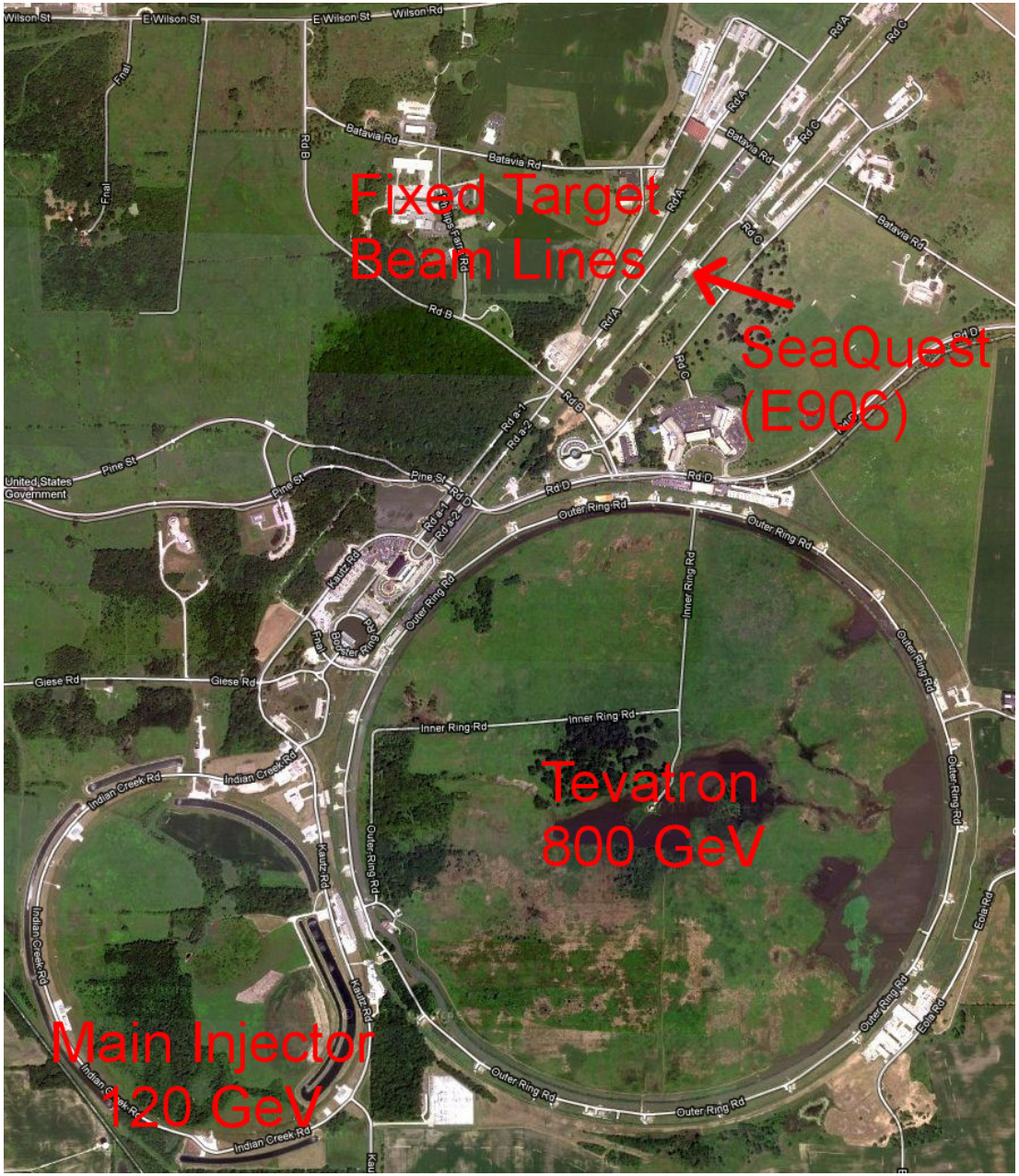


Physics Topics & Drell-Yan Experiments



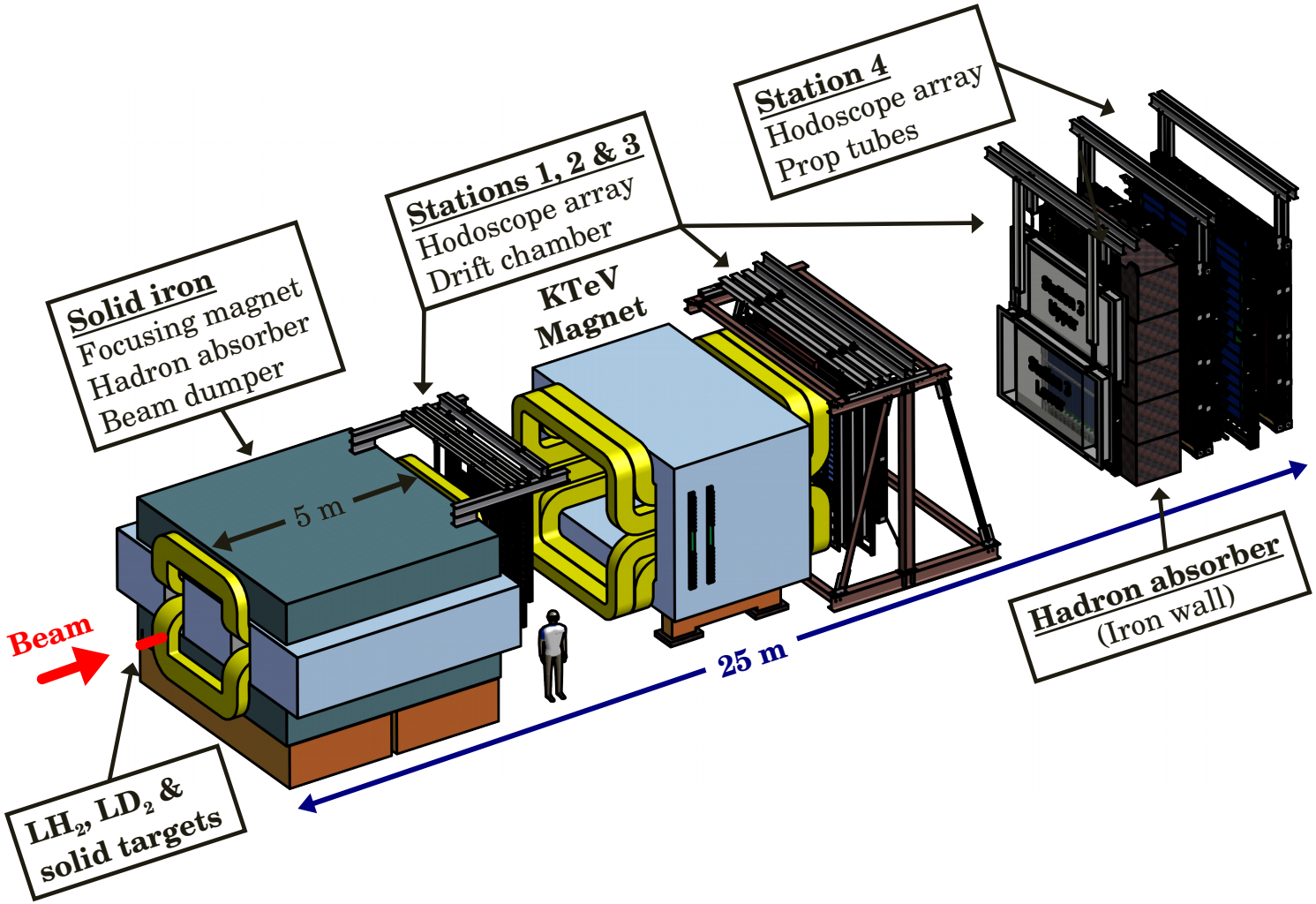
Measurement of Drell-Yan Process @ SeaQuest

Fermilab Proton Beam



- Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)
- Duty cycle
  - 5 sec for E906
  - 55 sec for ν exp.
- Bunch
  - Length: 1 nsec
  - Interval: 19 nsec (53 MHz)
  - 10^{13} protons in 5 sec in spot size

E906/SeaQuest Spectrometer



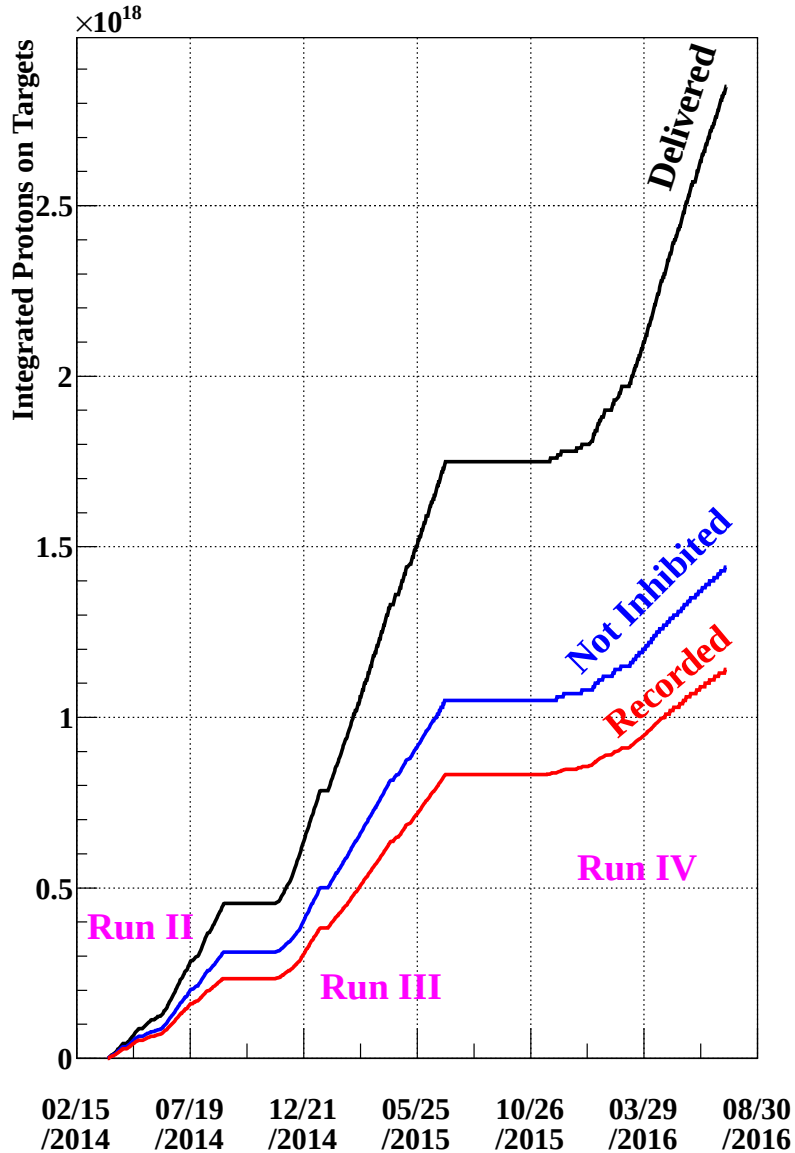
- Targets: LH_2, LD_2, C, Fe, W
- Focusing magnet (FMag) & Tracking magnet (KMag)
- Iron inside FMag, as hadron absorber & beam dump

Status of SeaQuest Data Taking

- Events

Year	Month	Event
2008	12	Fermilab Stage-2 approval
2011	08	End of spectrometer construction
2012	03-04	1st data taking (commissioning)
	05-	Detector & DAQ upgrade
2013	11-	2nd data taking (10 months)
2014	11-	3rd data taking (8 months)
2015	10-	4th data taking (10 months)
2016	11-	5th data taking

- Beam protons on targets
  - 1.1×10^{18} recorded up to FY2016
  - 0.6×10^{18} analyzed for preliminary $\bar{d}/\bar{u}$
- Data taking continues in FY2017
  - Another 0.4×10^{18} to be recorded (1.5×10^{18} in total)
  - Wider chamber acceptance at St. 1
  - Faster DAQ
  - Smarter trigger logic

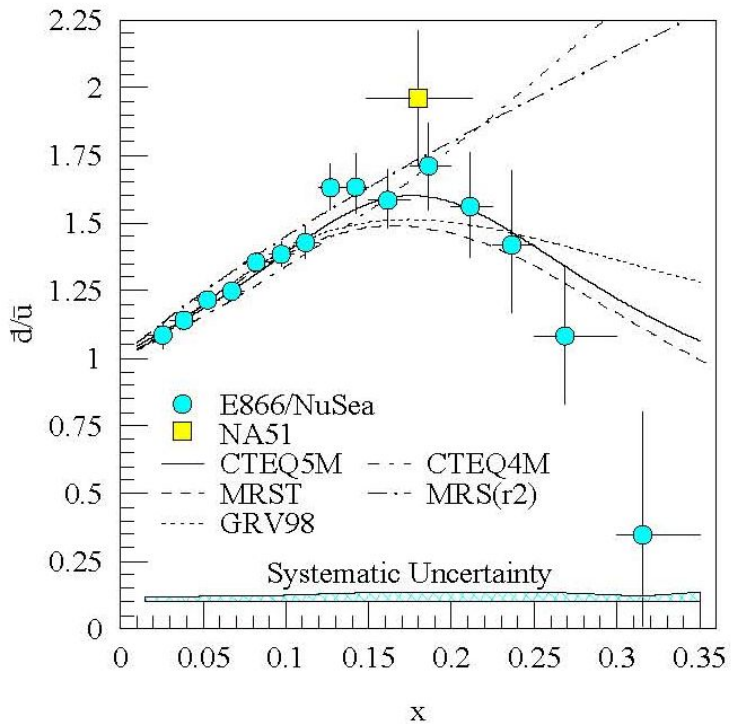


Anti-Quark Flavor Asymmetry:

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

Past Measurements of Flavor Asymmetry

- Symmetric in gluon splitting ($g \to u\bar{u}$ or $d\bar{d}$)
- CERN NMC ('90): deep inelastic muon scattering
  - Gottfried Sum: $S_G = 0.2281(65) < 1/3$
  - $\int \bar{d}(x)dx > \int \bar{u}(x)dx$ ... discovery of flavor asymmetry of anti-quarks in proton
- Measurement of x dependence of $\bar{u}(x)$ & $\bar{d}(x)$: Drell-Yan process
  - CERN NA51 ('94): $\bar{d} > \bar{u}$ at $x \sim 0.18$
  - FNAL E866/NuSea ('98): $\bar{d}(x)/\bar{u}(x)$ for $x \in (0.015, 0.35)$



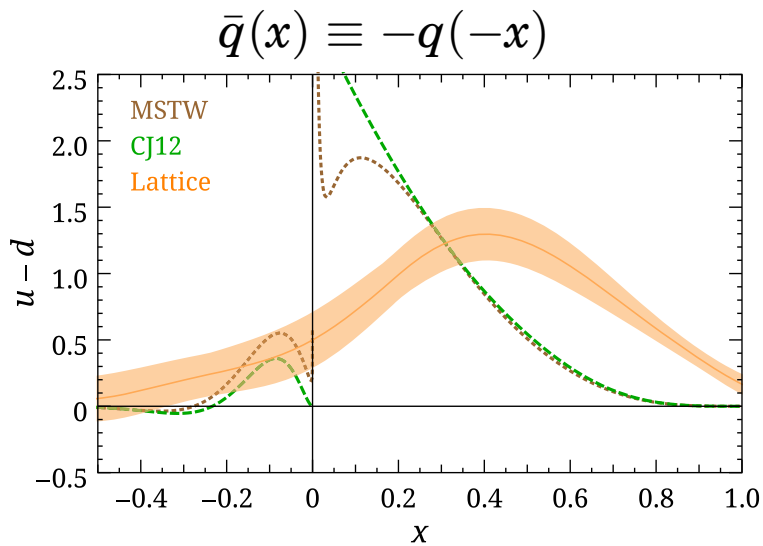
70% asymmetry!

Theories of $\bar{d}/\bar{u}$ Asymmetry (1)

- Mass difference between u & d ($\sim$2 & 5 MeV) in $g \to q\bar{q}$
  - Very small and even results in $\bar{d} < \bar{u}$

- Pauli blocking ... *PRD15, 2590 (1977)*
  - $Prob(g \to u\bar{u}) < Prob(g \to d\bar{d})$ since $p = uud$
  - Cannot explain the measured size ... *NPB149, 497 (1979)*
  - Even $\bar{d} < \bar{u}$ via connected sea (at high x)? ... *PLB736, 411 (2014)*

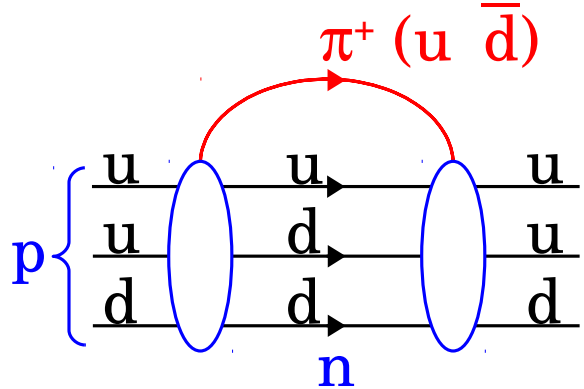
- Lattice-QCD calculation with LaMET ... *PRD91, 054510 (2015)*
  - As large as the measured size
  - Room to improve pion mass & lattice size



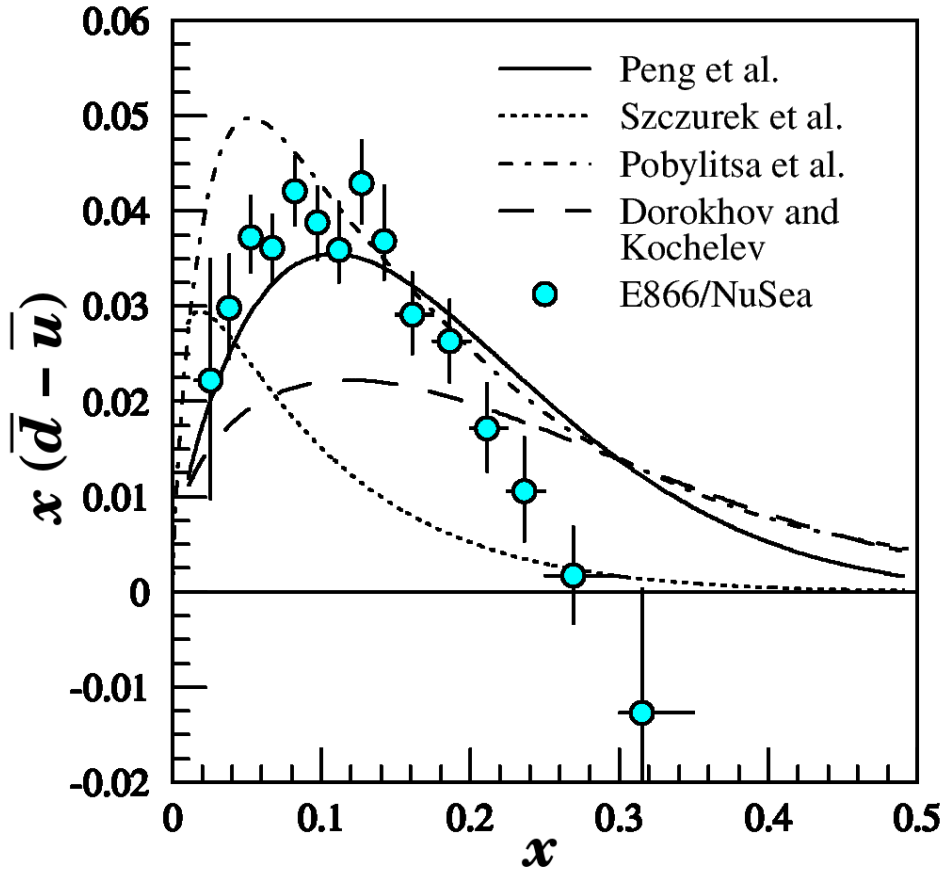
Theories of $\bar{d}/\bar{u}$ Asymmetry (2)

- Statistical model ... *NPA941, 307 (2015)*
  - Based on the Fermi & Bose statistics
  - Predicts $\bar{d}(x) - \bar{u}(x) = \Delta\bar{u}(x) - \Delta\bar{d}(x)$

- Meson cloud model ... *PRD58, 092004 (1998)*
  - $|p\rangle = (1-a-b)|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle$
  - More $\bar{d}$ in π^+ as $|n\pi^+\rangle$ etc.
  - Less $\bar{u}$ in π^- as $|\Delta^{++}\pi^-\rangle$ etc.
  - Predict non-zero $L_{q,\bar{q}}$ like "meson tornado" (need $L = 1$ of π to make $J^P = 1/2^+$ of proton, as parity of π is $J^P = 0^-$)



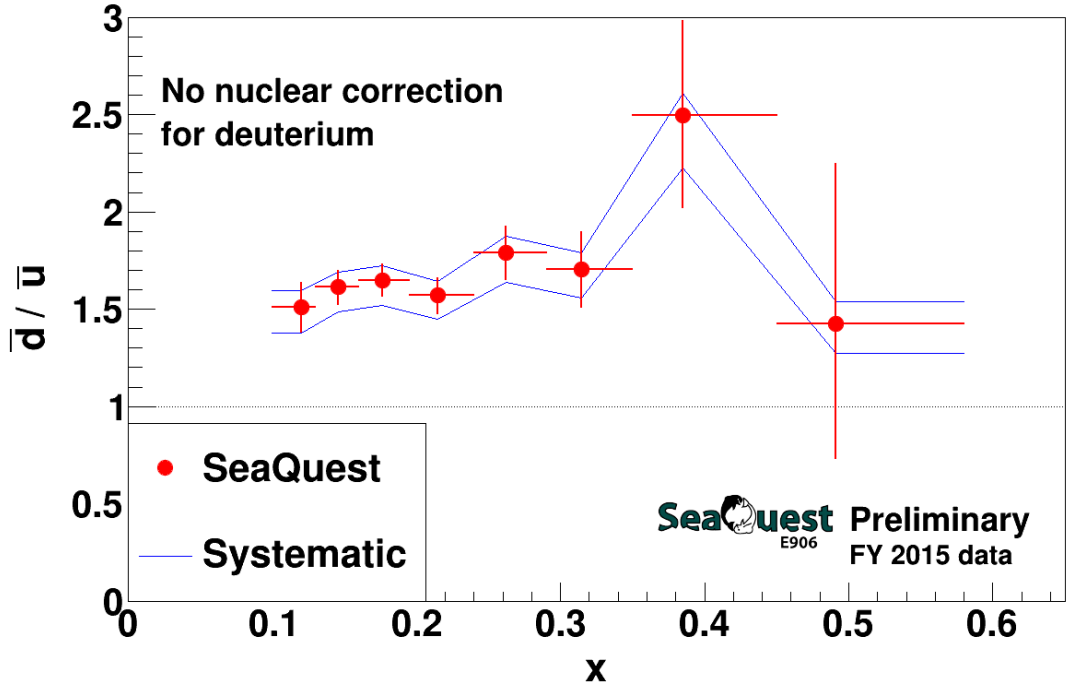
Comparison of Theories to Measurements



- The x dependence of $\bar{d}(x)/\bar{u}(x)$ is the key to develope/examine models
  - Drop sharply at $x \sim 0.3$? Go down to $\bar{d} < \bar{u}$?

Anti-Quark Flavor Asymmetry: $\bar{d}/\bar{u}$

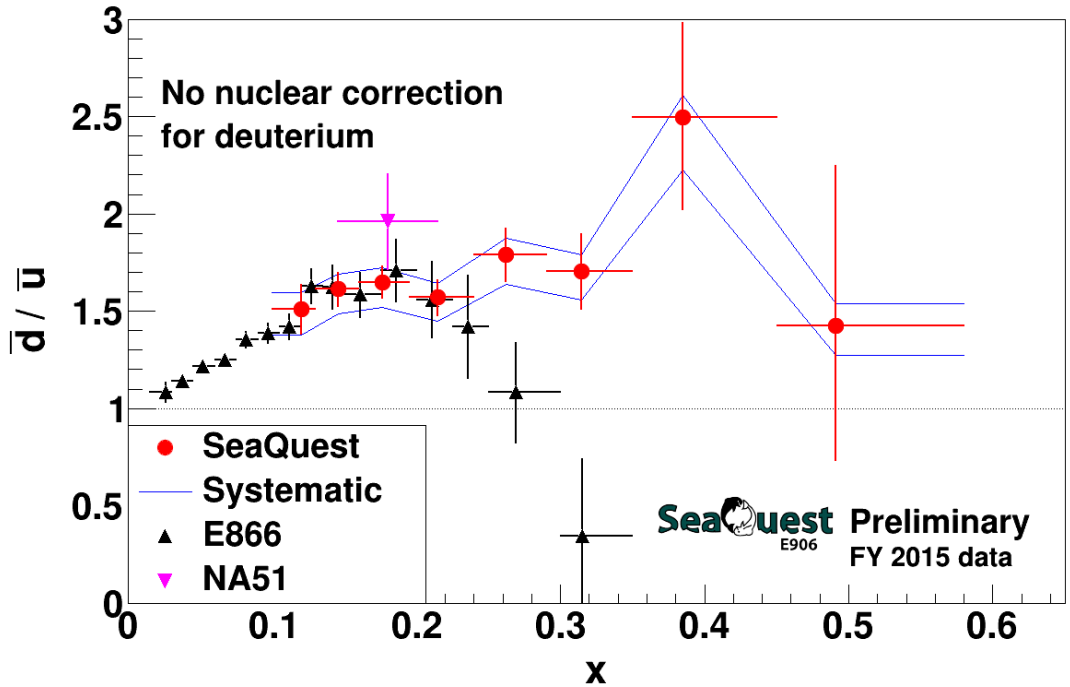
- Preliminary result with 6×10^{17} PoTs



- Systematic errors
  - Errors of cross-section ratio
  - Errors of CT10 PDF
  - $\bar{d}/\bar{u}$ outside the measured x range
- $\bar{d}/\bar{u} > 1$ at high x also

Anti-Quark Flavor Asymmetry: $\bar{d}/\bar{u}$

- Comparison with other measurements

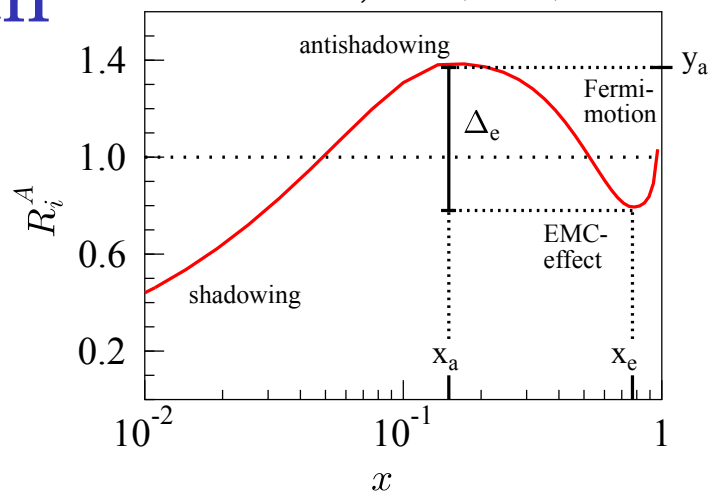


  - All agree at small x
  - $\bar{d}/\bar{u}$ at $x \sim 0.3$ seems higher by SeaQuest
    ... Physical reasons for this difference are being investigated

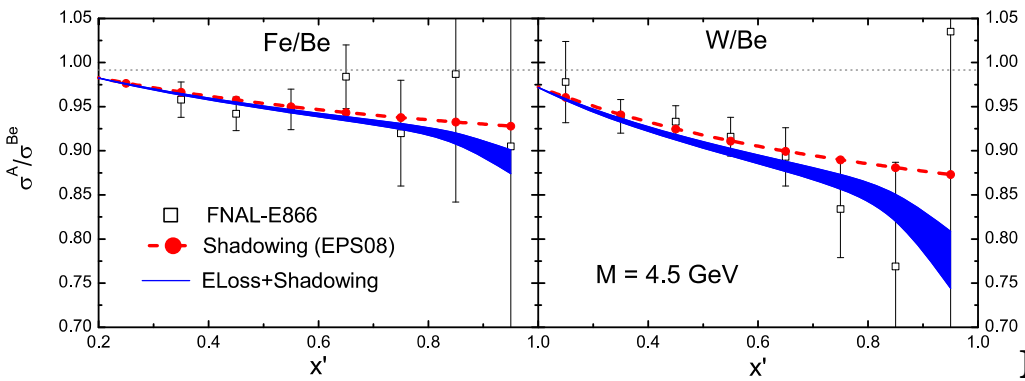
Parton Energy Loss in Cold Nuclear Matter

Nuclear Effects in $p + A$ Drell-Yan

JHEP 0807, 102 (2008)



- Modification of PDF inside nucleus A:
  $R_i^A(x) \equiv f_i^A(x)/f_i^p(x)$
  - Shadowing & anti-shadowing
  - EMC effect ... PLB 123, 275 (1983)
  - Fermi motion
- Interaction of parton in p going into nucleus
  - Parton energy loss (in cold nuclear matter)
    $\Longleftrightarrow$ In QGP at RHIC/LHC
- Measurement of $\hat{\sigma}^{p+A}(x)/\hat{\sigma}^{p+p}(x)$ with Drell-Yan
  - Result of FNAL-E866 @ $E_{beam} = 800$ GeV, $\sqrt{s} = 39$ GeV

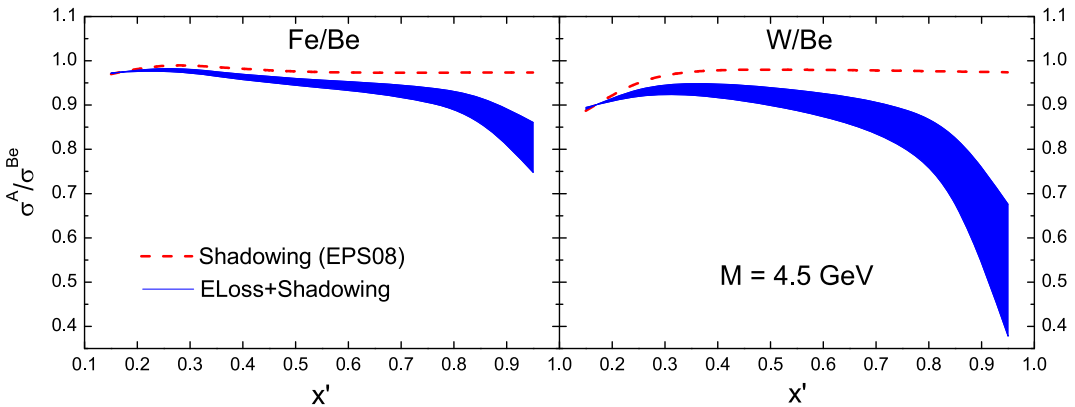


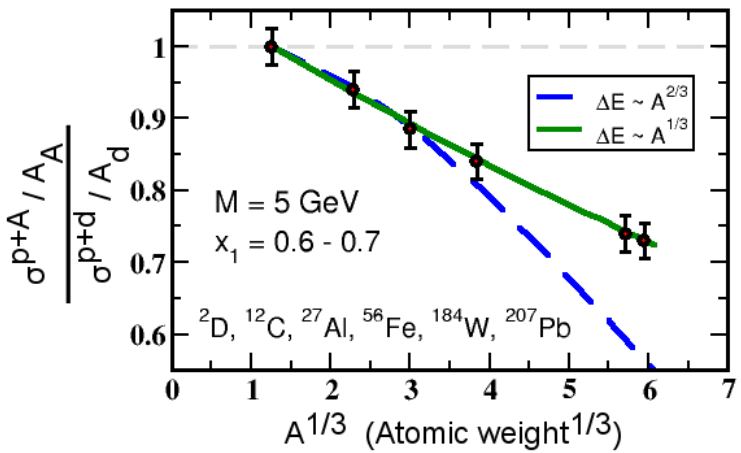
Nucl. Phys. A879, 77 (2012)

  - Shadowing on $\bar{q} \sim$ parton energy loss on q
  - Either alone can reproduce the measured size

Measurement by SeaQuest

- Measurement at smaller $\sqrt{s}$ ($= 15$ GeV) & larger x ($\gtrsim 0.3$)
  - Shadowing gets smaller & parton energy loss gets larger by $1/s$
  - Direct extraction of parton energy loss in cold nuclear matter





- Theory prediction: Change of x by parton energy loss
  - $\Delta x = -\kappa_1 \, x \, A^{1/3}$ ... Gavin & Milana (PRL68, 1834)
  - $\Delta x = -\frac{\kappa_2}{s} \, A^{1/3}$ ... Brodsky & Hoyer (PLB298, 165)
  - $\Delta x = -\frac{\kappa_2}{s} \, A^{2/3}$ ... Baier et al. (NPB531, 403)
  - Measure with several targets (A) to select the right model
- Plan to measure at small x to study shadowing etc.
- Plan to measure p_T broadening ... arXiv:hep-ph/9912371

Present SeaQuest Result

- Select where parton energy loss dominates ... $x_{Target} > 0.15, x_{Beam} > 0.6$
- With 5×10^{17} PoTs

(Preview plots are not archived)

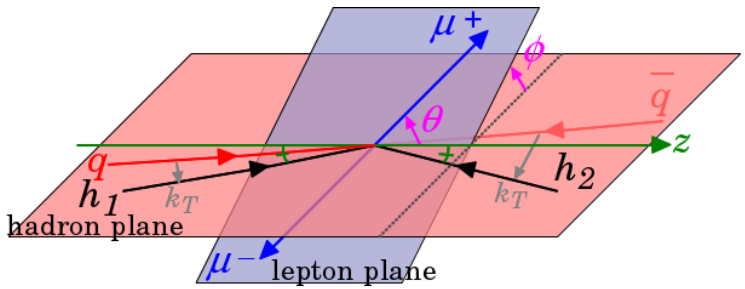
- Systematic error $\approx$ uncertainty of tracking efficiency

Angular Distribution (Boer-Mulders Effect?)

Lam-Tung Relation

- Drell-Yan angles in Collins-Soper frame

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$



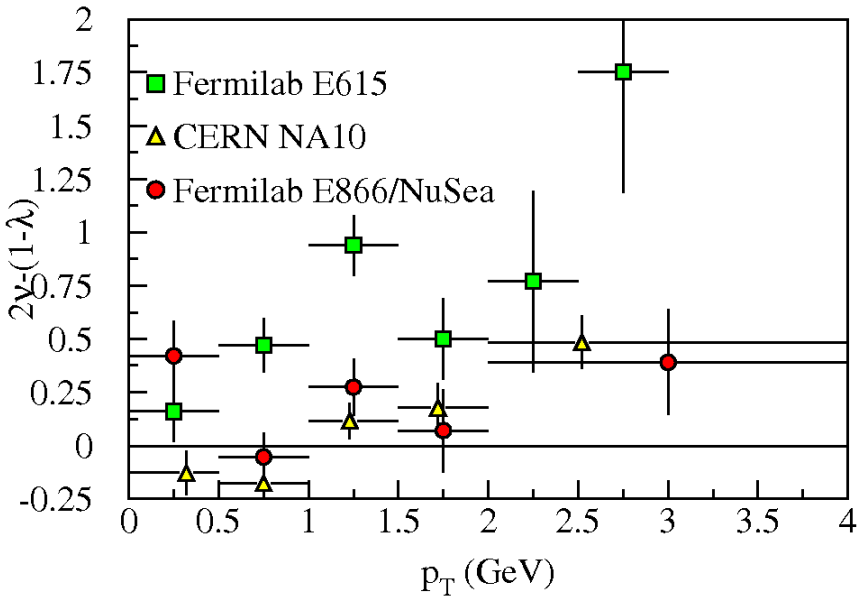
- Lam-Tung relation:

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

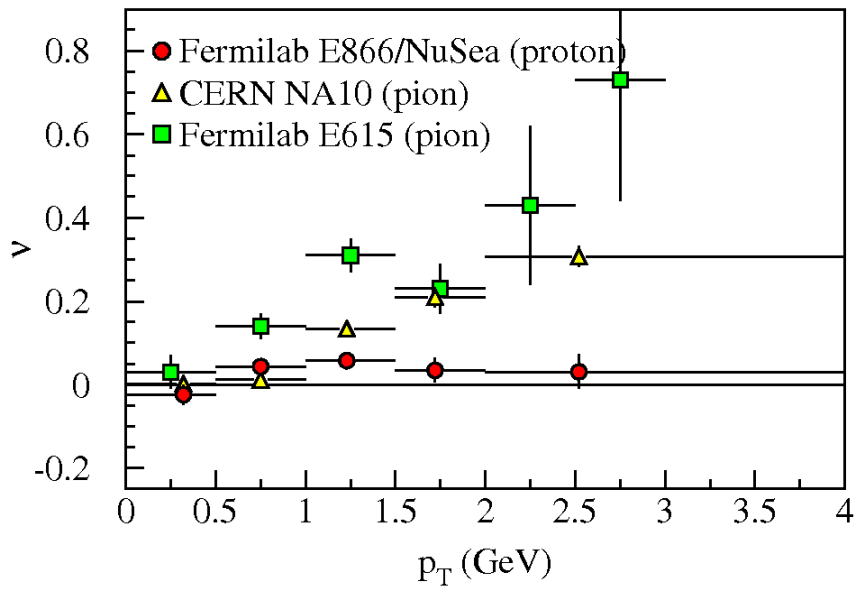
  - Spin-1/2 nature of quarks ... analogous to Callen-Gross relation in DIS
  - No NLO corrections ($\mathcal{O}(\alpha_s)$)
  - Small NNLO corrections ($\mathcal{O}(\alpha_s^2)$)

Measurements @ Fixed-Target Experiments

- $2\nu - (1 - \lambda)$



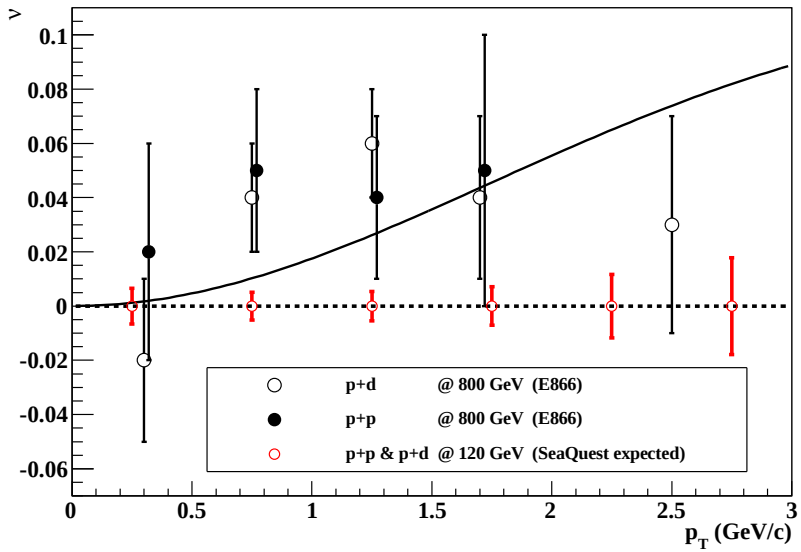
- ν ... $\cos 2\phi$ dependence



- With π beam
  - Lam-Tung relation violated!
  - Large ν
  - Large $h_1^\perp$ of q
- With p beam
  - Lam-Tung relation violated weakly?
  - Small ν
  - Small $h_1^\perp$ of $\bar{q}$

Anticipated Result by SeaQuest

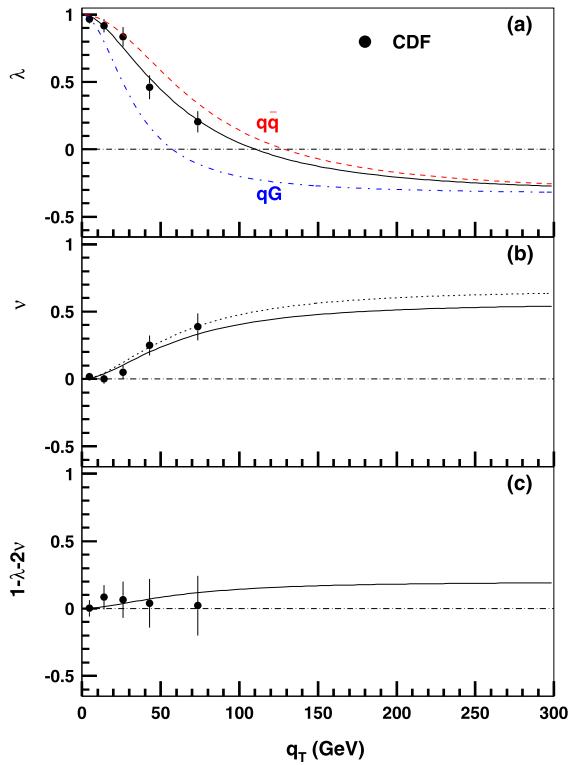
- SeaQuest measures the Drell-Yan angular distribution in p+p & p+d
  - ν = size of $\cos(2\phi)$ modulation
  - Probably small as past measurements indicate small $h_1^\perp$ of $\bar{q}$
  - Better accuracy is anticipated

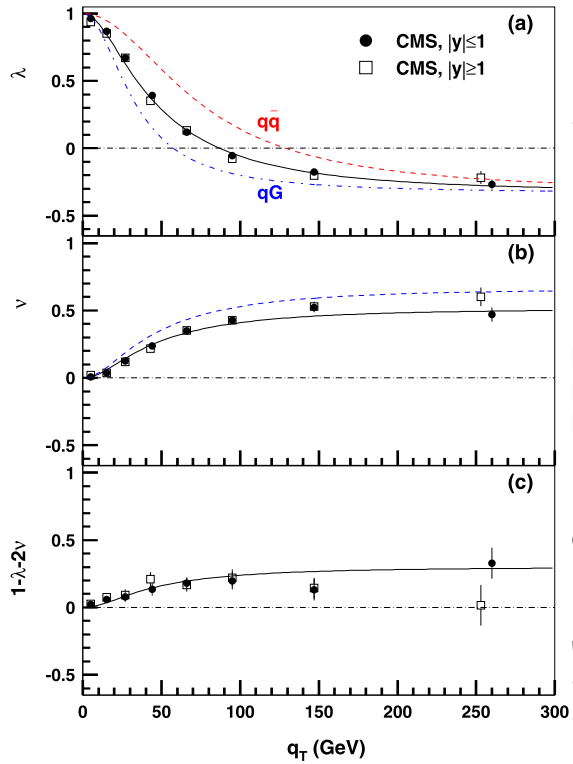


- Convolution of two Boer-Mulders functions:
  $\nu \propto \left[h_1^\perp \text{ of } \bar{q} \right] \times \left[h_1^\perp \text{ of } q \right]$
- Extraction of $h_1^\perp$ from p+p & p+d Drell-Yan (E866)
  ... PRD 81, 034023 (2010), PRD 82, 114025 (2010)

Measurements @ Collider Experiments

- CDF (PRL 106, 241801)
  - $p + \bar{p} \to Z \to e^+ + e^-$ @ $\sqrt{s} = 2$ TeV
- CMS (PLB 750, 154)
  - $p + p \to Z \to \mu^+ + \mu^-$ @ 8 TeV





(plots from PLB 758, 384)

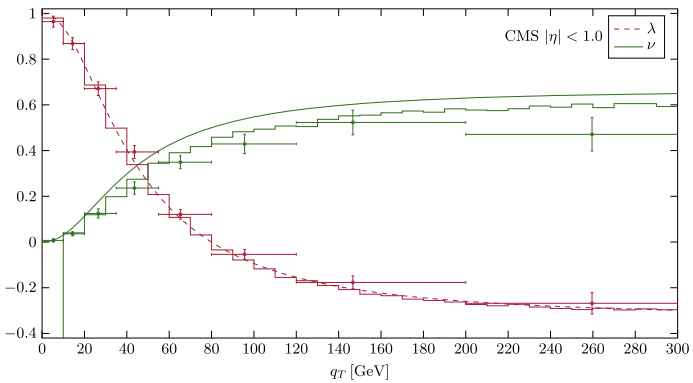
- No violation of Lam-Tang relation
- Violation! Why different?

Calculations of Higher-Order Terms

- Without intrinsic k_T (i.e. Boer-Mulders effect)
- Terms
  - LO: $q + \bar{q} \to \gamma$
  - $\mathcal{O}(\alpha_s)$: $q + \bar{q} \to \gamma + g$ & $q + g \to q + \gamma$
  - $\mathcal{O}(\alpha_s^2)$: $q + \bar{q} \to \gamma + g + g$ etc.
- Studies
  - PRD 51, 4891 (1995) ... evaluation at $\mathcal{O}(\alpha_s^2)$ for CDF
  - PRD 76, 074006 (2007) ... evaluation at $\mathcal{O}(\alpha_s)$ with resummation
  - PLB 758, 384 (2016) ... evaluation at $\mathcal{O}(\alpha_s)$ & insight about $\mathcal{O}(\alpha_s^2)$
  - PRD 93, 114013 (2016) ... evaluation at $\mathcal{O}(\alpha_s^2)$ for NA10 thru CMS
    - No soft-gluon resummation ... little effect to angular coefficients
    - No higher-twist terms
  - and quite more

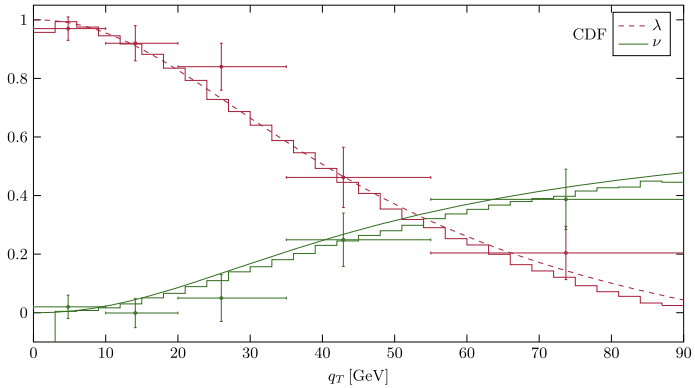
Calculated Results — CMS & CDF

- CMS @ $|\eta| < 1.0$



  - $\mathcal{O}(\alpha_s)$ term holds $1 - \lambda = 2\nu$
  - $\mathcal{O}(\alpha_s^2)$ term does violate it!
  - Well reproduced λ & ν measured

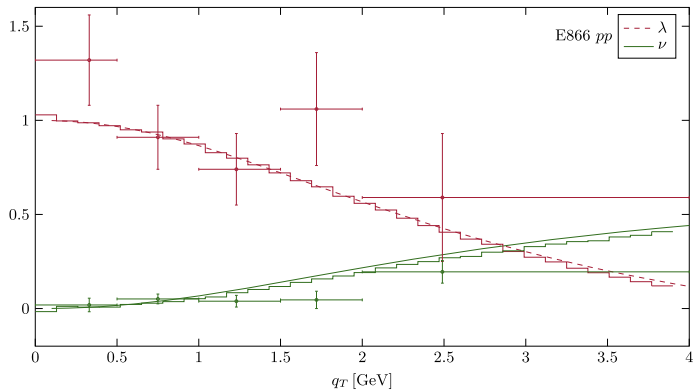
- CDF



  - Well reproduced λ & ν measured also
  - Smaller $\mathcal{O}(\alpha_s^2)$ term because of less g radiation in $q + \bar{q}$ than $q + g$

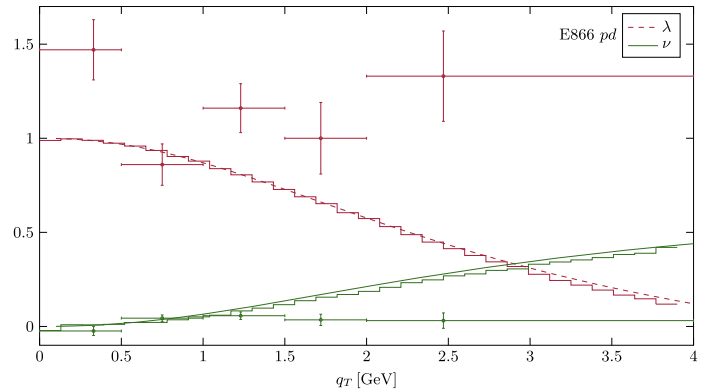
Calculated Results — E866

- E866 $p + p$ ($E_p = 800$ GeV)



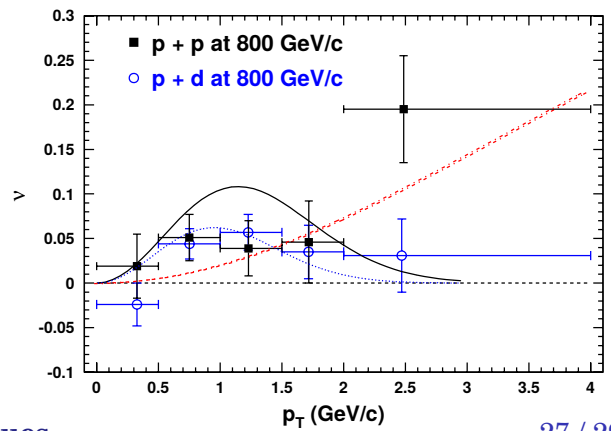
  - Calculation $\sim$ measurement

- E866 $p + d$



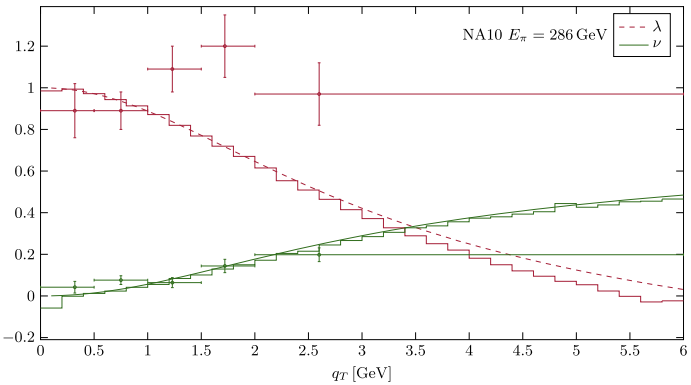
  - Calculation $\neq$ measurement!
  - λ measured seems out of positivity limit (≤ 1)

- Calculation in E866 paper (PRL 102, 182001)
  - With soft-gluon resummation ($\nu = \frac{2p_T^2}{2Q^2+3p_T^2}$)
  - As small as the measured $p + d$ size. Because of resummation? Or kinematic bias in measurement?



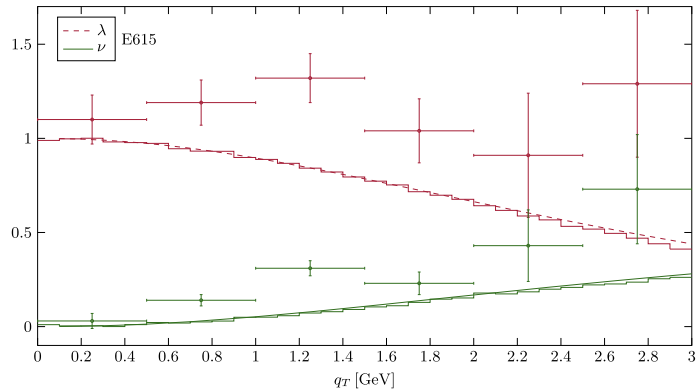
Calculated Results — NA10 & E615

- NA10 ($E_\pi = 286$ GeV)



  - Calculation $\sim$ measurement
  - λ measured too large

- E615 ($E_\pi = 252$ GeV)



  - Calculation $\neq$ measurement!
  - λ measured too large

- Overall: The higher-order calculation works fine (without the Boer-Mulders effect)
  - For p- & π-induced D-Y together
  - Change by $\sim$50% due to soft-gluon resummation?
  - Exceptions are E866 $p + d$ &E615 $\pi + W$. Kinematic bias?

Summary

- The Drell-Yan process is a sharp tool to explore the nucleon structure
- $\bar{d}(x)/\bar{u}(x)$
  - SeaQuest found $\bar{d}(x)/\bar{u}(x) > 1$. Final result is awaited
  - Other quantities like $\Delta\bar{d}(x)$ vs $\Delta\bar{u}(x)$ & $L_{q,\bar{q}}$ can/should be examined together to understand the right mechanism of flavor asymmetry
  - New experiments are planned, which depend on the SeaQuest result
- Parton-enery loss in cold nuclear matter
  - SeaQuest found $\sigma_{p+A}/\sigma_{p+p} < 1$ at high x
  - Fundamental input to understand QGP at RHIC/LHC
- Angular distribution
  - The $\mathcal{O}(\alpha_s^{1,2})$ term was found large enough to reproduce the measurements (except E866 $p+d$, E615 $\pi+W$ and the resummation effect?)
  - New results of COMPASS, RHIC, SeaQuest, etc. are valuable