Drell-Yan experiments at Fermilab/RHIC/J-PARC

QCD Frontier 2013

Jefferson Lab

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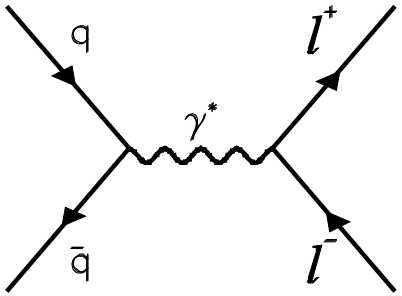
Yuji Goto (RIKEN)

Outline

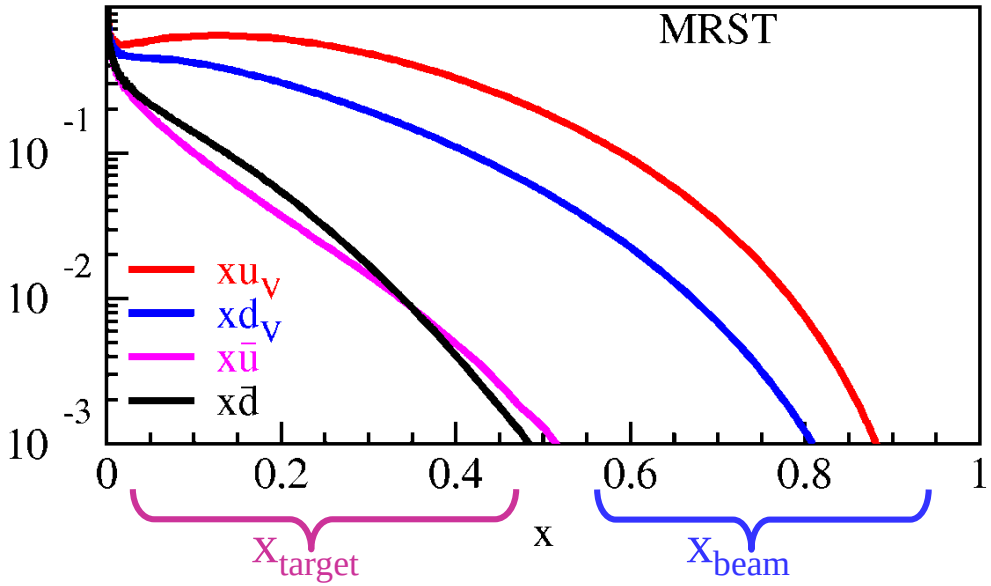
- Fermilab Drell-Yan experiments
  - Unpolarized program
    - Flavor asymmetry of sea-quark distribution
    - Boer-Mulders distribution
- Polarized Drell-Yan experiments
  - Polarized Drell-Yan proposals of Fermilab program
  - PHENIX upgrade program at RHIC
  - Possible J-PARC program

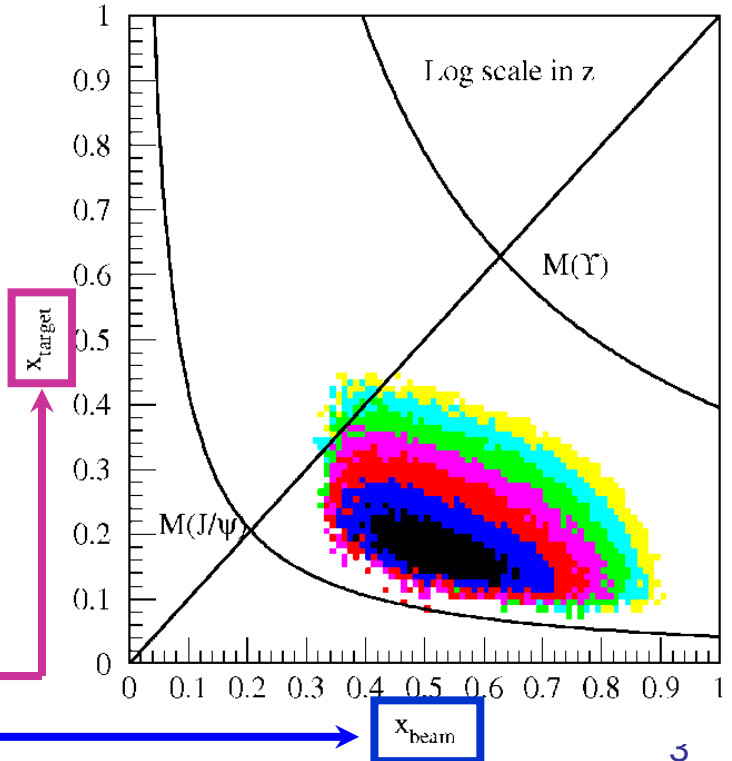
Drell-Yan experiments



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

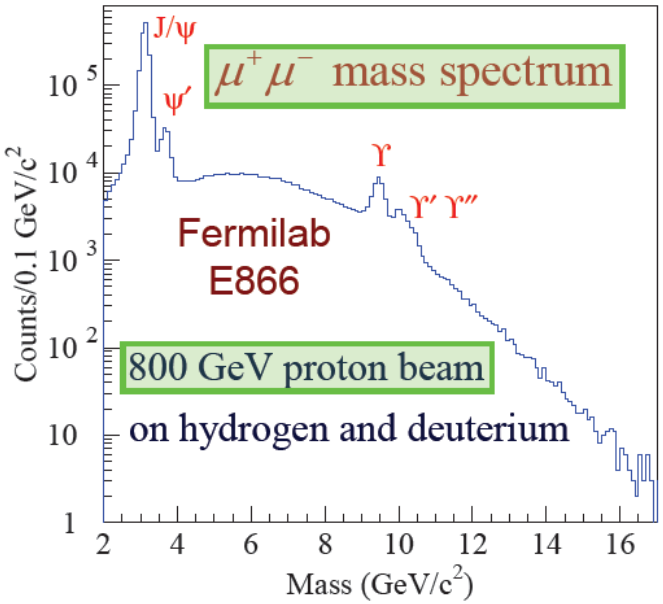
- Fixed target experiment (e.g. at Fermilab)
  - forward detector acceptance chooses large x_b and small x_t

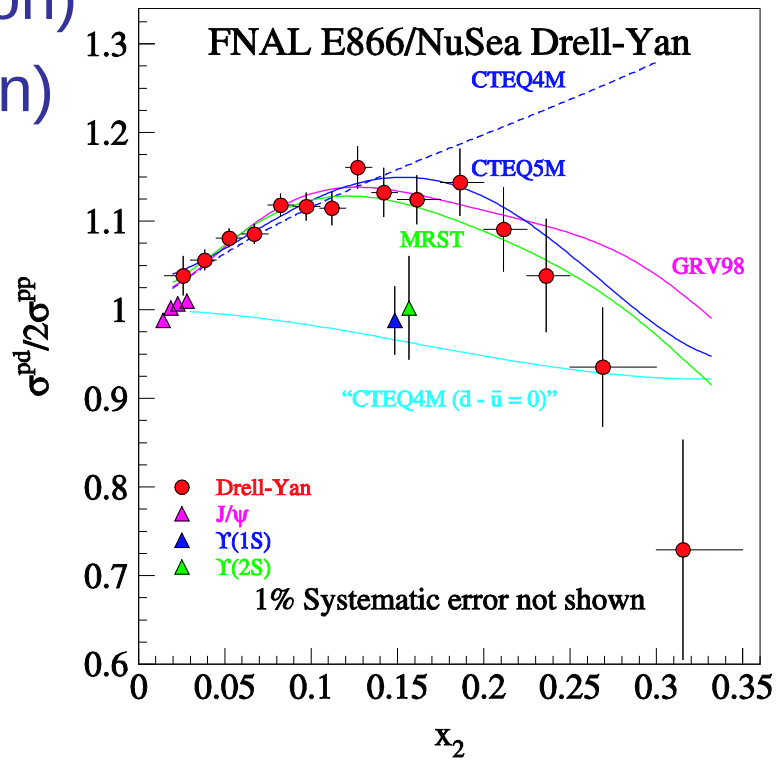




Flavor asymmetry of sea-quark distribution

- Fermilab-E866/NuSea experiment
  - E_{beam} = 800 GeV (from Tevatron)
  - x = 0.01 – 0.35 (valence region)





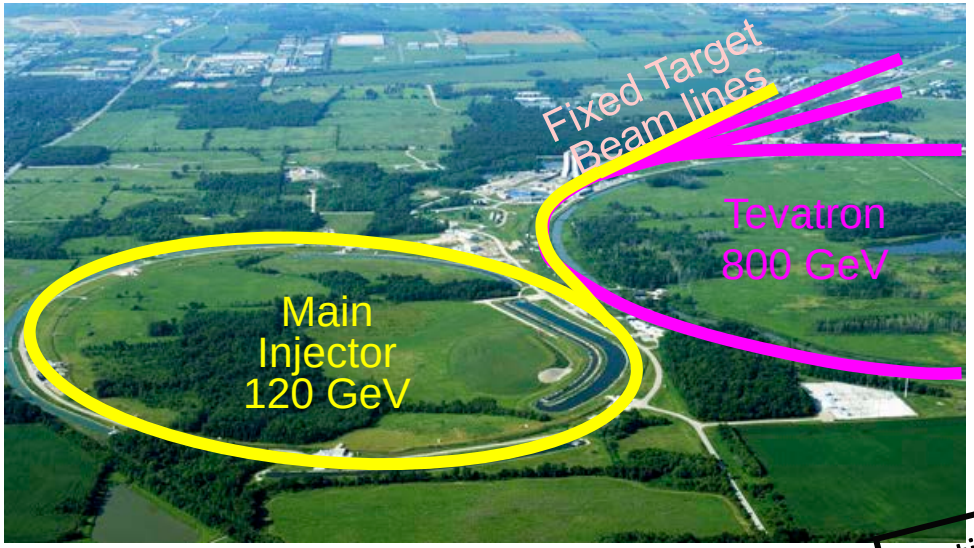
$$\frac{\sigma^{pd}}{2\sigma^{pp}} \sim \frac{1}{2}\left[1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

with CTEQ5M

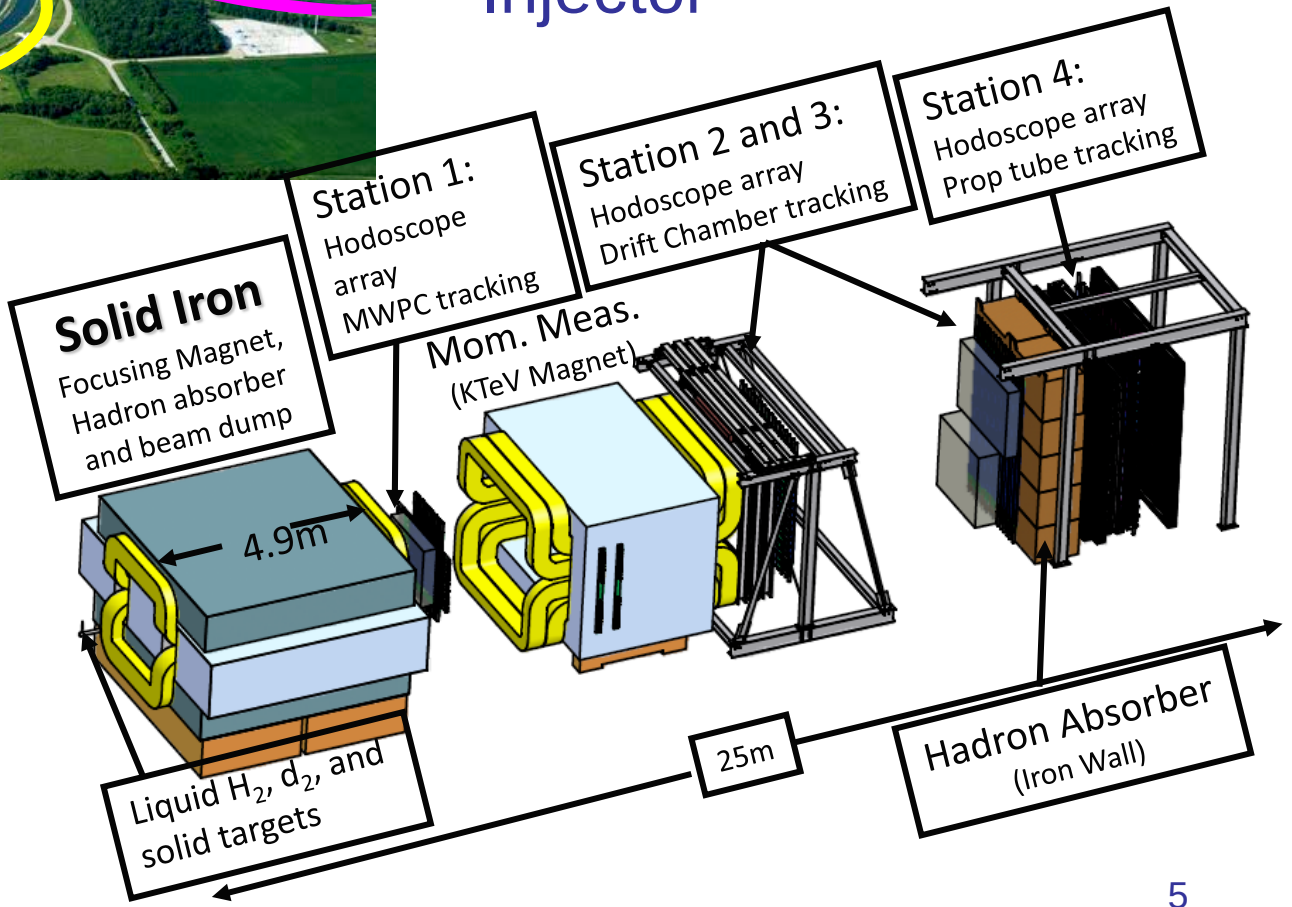
$$\int_{0.015}^{0.35} dx[\bar{d}(x)-\bar{u}(x)] = 0.0803 \pm 0.011$$

$$\int_{0}^{1} dx[\bar{d}(x)-\bar{u}(x)] = 0.118 \pm 0.012$$

Fermilab-E906/SeaQuest experiment



- Dimuon measurement from Drell-Yan process
- 120-GeV proton beam from the Fermilab Main Injector

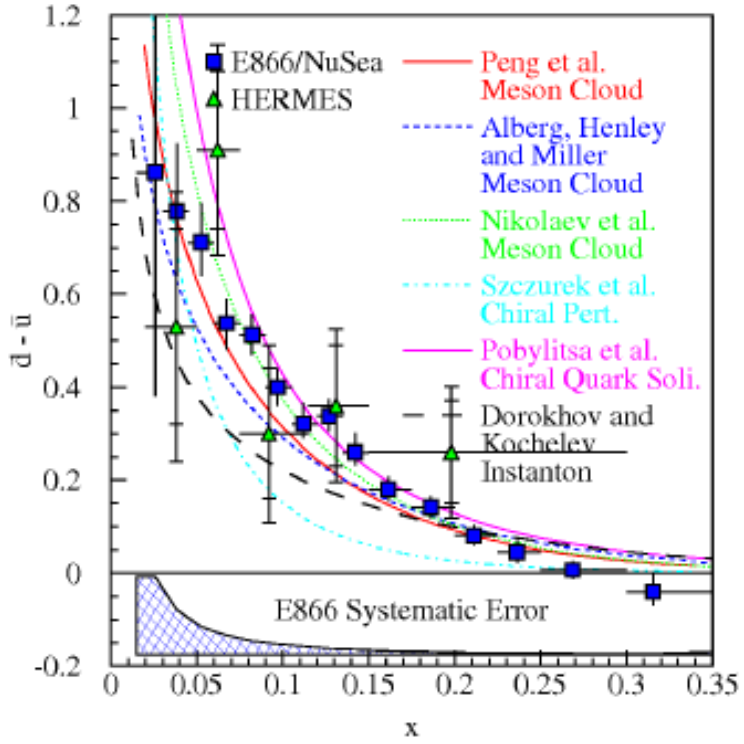


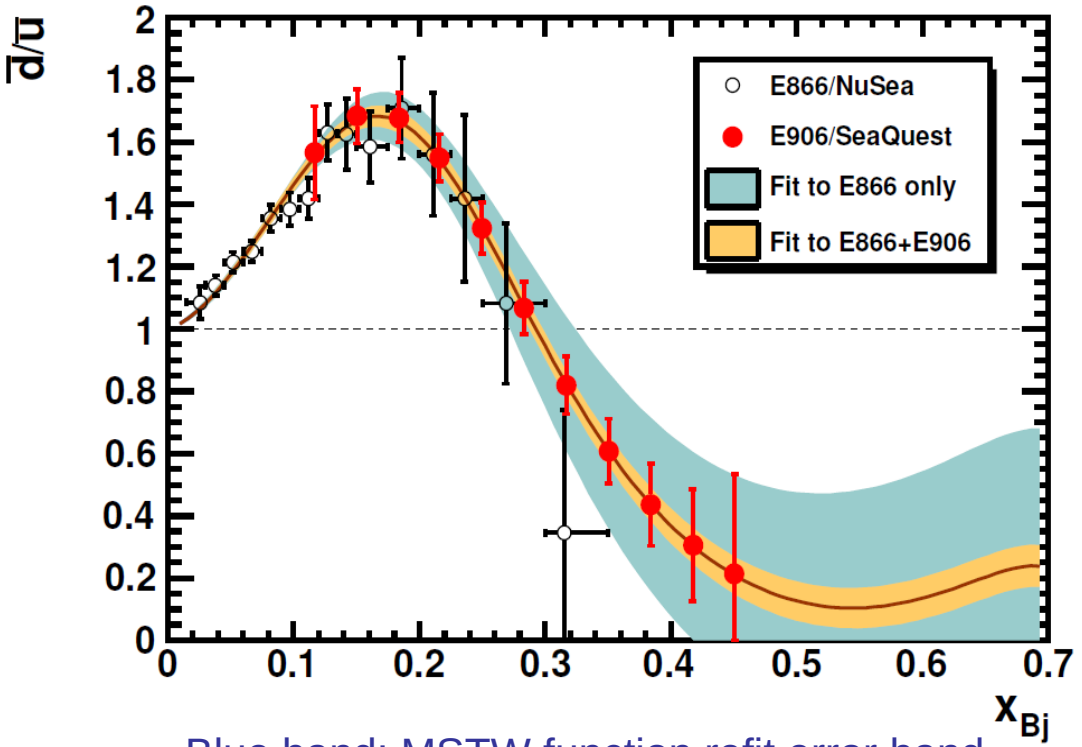
Fermilab-E906/SeaQuest experiment

- Nucleon structure
  - With hydrogen and deuterium targets
  - Select anti-quark distributions in hadrons
    - Flavor asymmetry of sea-quark distributions
    - Boer-Mulders distribution
- Cold Nuclear Matter (CNM)
  - With nuclear targets
    - Partonic energy loss
    - EMC effect

Flavor asymmetry of sea-quark distribution

- Fermilab-E906/SeaQuest experiment
  - E_{beam} = 120 GeV (from Main Injector)
  - x = 0.1 – 0.45

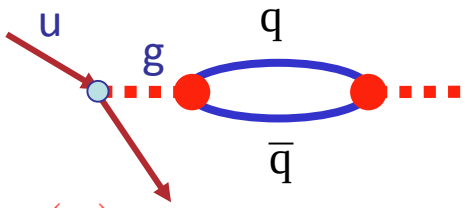




Blue band: MSTW function refit error band with E866 data
Yellow band: error band with E866 data + E906 expected statistics

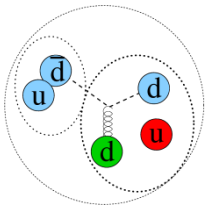
Flavor asymmetry of sea-quark distribution

- Competition between
  - perturbative QCD
    - gluon dissociation $\bar{d}_{\rm split}(x) = \bar{u}_{\rm split}(x) = \bar{q}_{\rm split}(x)$



  - non-perturbative contributions
    - Meson cloud model

$$|p\rangle = (1-a-b)\,|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle + \ldots$$



    - Chiral quark model

$$\langle q|\bar{q}\rangle = \left[1-\frac{3a}{2}\right]\langle q|\bar{q}\rangle + \frac{3a}{2}\langle q\pi|\bar{q}\pi\rangle \qquad \int_0^1 \left[\bar{d}(x)-\bar{u}(x)\right]dx = \frac{2a}{3}$$

    - Instanton model

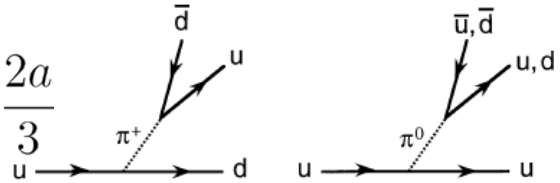


Fig. 17. Valence u quark splitting.

- π^+ in the proton as an origin of anti-d quark
  - pseudo-scaler meson should have orbital angular momentum in the proton…

Drell-Yan decay angular distributions

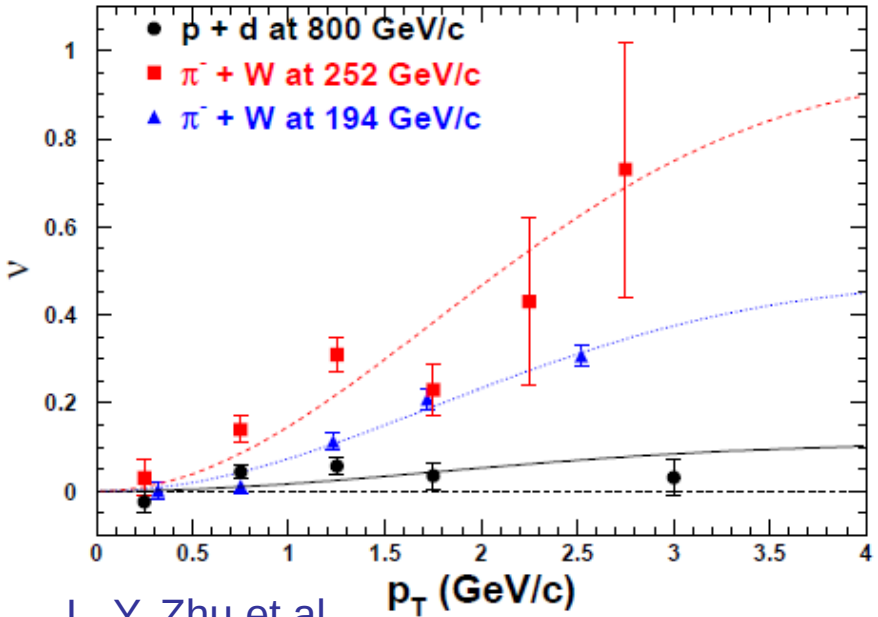
- A general expression for Drell-Yan decay angular distributions

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

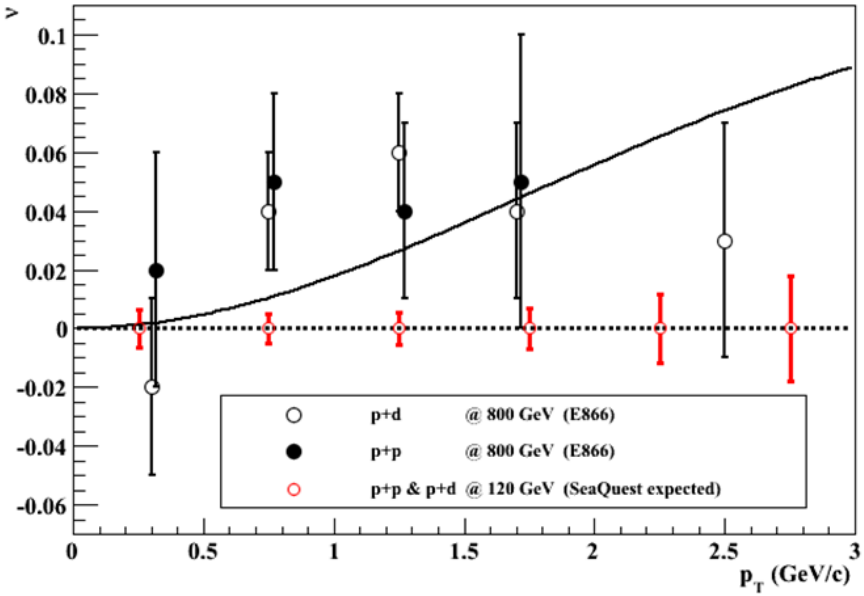
  - λ can differ from 1, but should satisfy $1-\lambda=2\nu$ (Lam-Tung relation)
  - Reflect the spin-1/2 nature of quarks (analog of the Callan-Gross relation in DIS)
  - Insensitive to QCD corrections
- Violation of the Lam-Tung relation
  - $\nu\neq 0$ and ν increases with p_T
  - Violation of the Lam-Tung relation suggests new mechanisms with non-perturbative origin

Drell-Yan decay angular distributions

- Boer-Mulders function $h_1^{\perp}$
  - Transverse-momentum dependence of transversely-polarized partons inside the (unpolarized) nucleon
- Small ν is observed for p+d and p+p
  - π^-+W: [valence $h_1^{\perp}(\pi)$]⊗[valence $h_1^{\perp}(p)$]
  - p+d and p+p: [valence $h_1^{\perp}(p)$]⊗[sea $h_1^{\perp}(p)$]



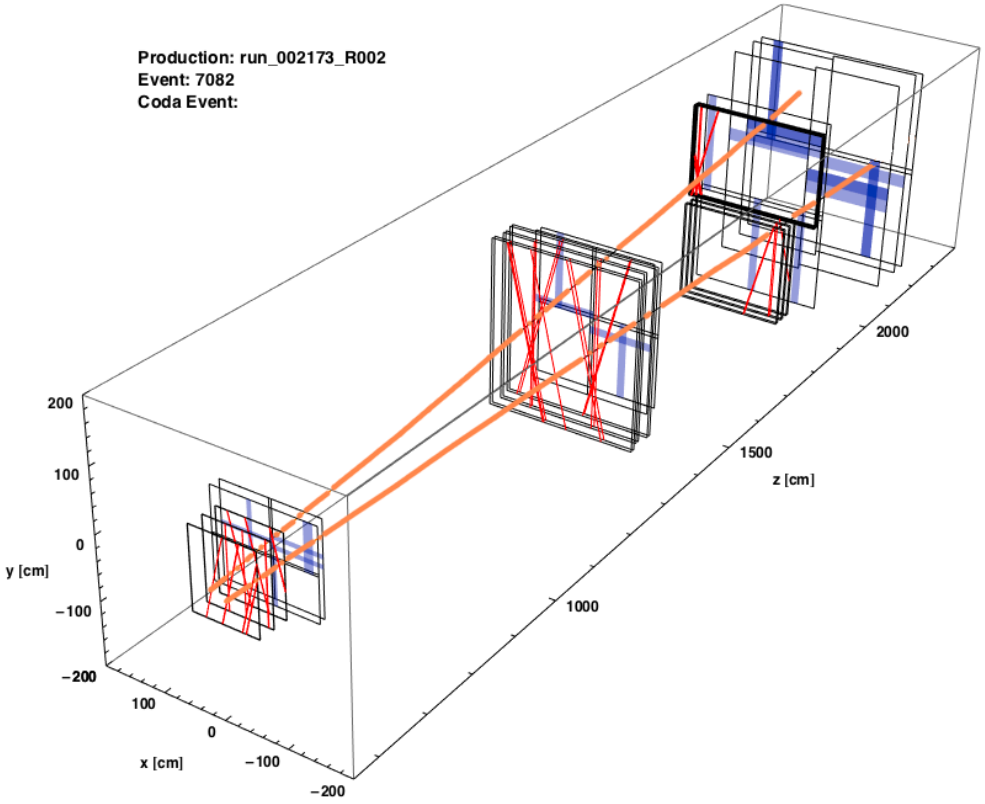
L. Y. Zhu et al.,
Phys. Rev. Lett. 99 (2007) 082301
Phys. Rev. Lett. 102 (2009) 182001



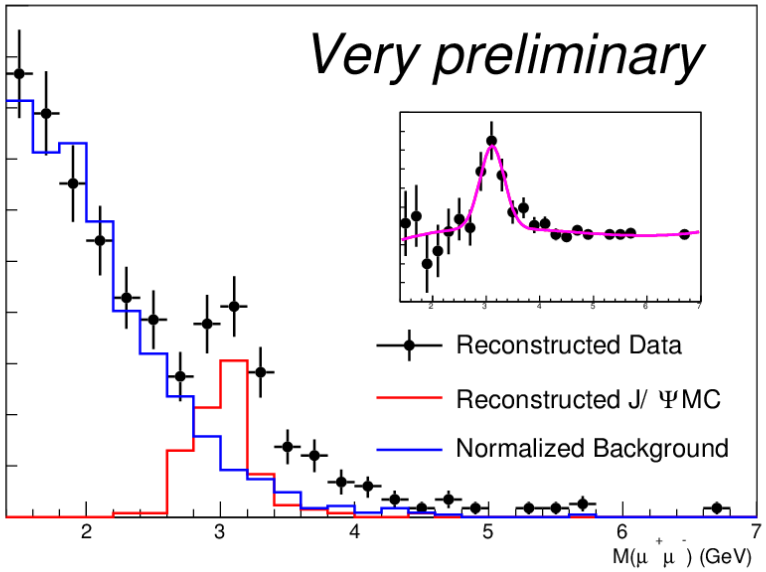
Error profile for SeaQuest statistics

SeaQuest commissioning run

- February 22nd – April 30th, 2012
  - 120 GeV/*c* proton beam, 19 ns interval (53 MHz)
  - Beam intensity: 1.0×10^{12} proton/spill (5 s spill at 1 minute interval)
  - Target: H_2, empty flask, D_2, Fe, C, W
- Unstable beam bunch intensity
  - Feedback control of the beam extraction magnet (accelerator group under construction)
  - Trigger veto against high intensity bunch (prototype test)



- Commissioning run
  - Dimuon mass distribution
  - Mass resolution at J/ψ peak ~0.3 GeV/c^2 almost consistent with hardware specification
  - Improvement of the track reconstruction algorithm underway
- Coming physics run
  - Main injector upgraded
  - Extraction beam line commissioning ongoing
  - Beam to the SeaQuest experiment late October, 2013
  - 2 year data accumulation (2013-2015) for 1.0×10^{19} protons on target
  - Beam intensity: 1.0×10^{13} protons/spill (5s spill at 1 minute interval)



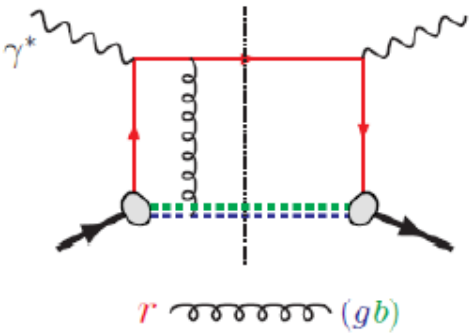
Polarized Drell-Yan experiment

- Toward understanding of the “Spin Puzzle” with extended picture of the nucleon structure
  - 3-dimensional description of the nucleon structure
    - Quantum many-body correlation of quarks and gluons
    - Transverse quark-gluon distribution inside the nucleon
  - TMD (Transverse-Momentum Dependence) factorization and collinear higher-twist factorization
    - Transverse-momentum distribution inside the nucleon
- Single transverse-spin asymmetry
  - Sivers function
  - Transversity
  - Boer-Mulders function
- Double transverse-spin asymmetry
  - Transversity (quark⊗antiquark for p+p collisions)
- Double helicity asymmetry
  - Flavor asymmetry of sea-quark polarization

Non-universality of TMD distribution function

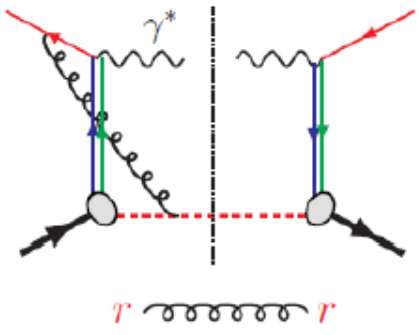
- Opposite-sign contribution of TMD distribution function to SSA in semi-Inclusive DIS (SIDIS) process and Drell-Yan process

SIDIS



attractive

Drell-Yan



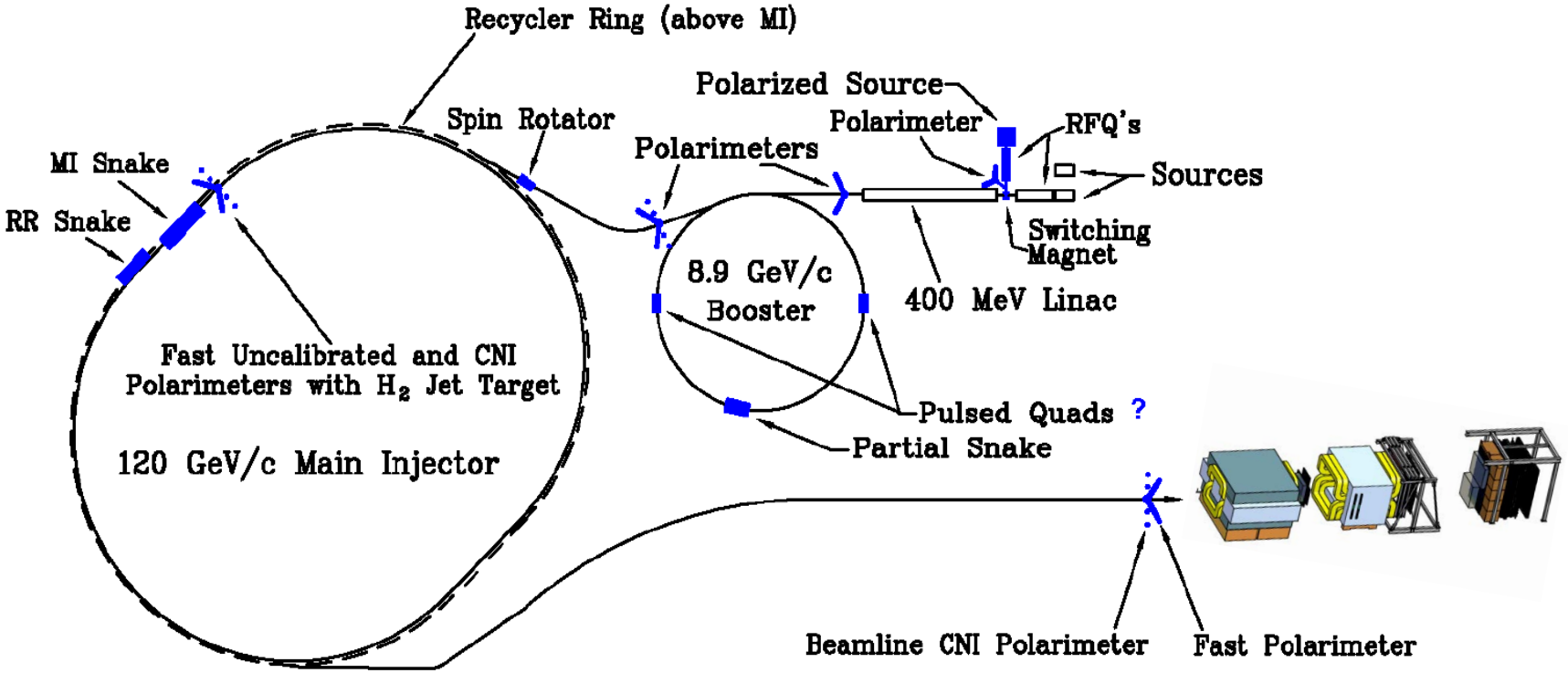
repulsive

$$f_{1T}^{\perp q}|_{\mathrm{SIDIS}} = -f_{1T}^{\perp q}|_{\mathrm{DY}}$$

- Fundamental property based on gauge invariance of QCD
- Experimental verification required
  - Understanding in wide kinematic range from fixed target experiments to collider experiments
  - Polarized Drell-Yan experiments
    - COMPASS, SeaQuest, RHIC(, GSI-FAIR, NICA, …)
  - Polarized SIDIS experiments
    - EIC

Polarized Drell-Yan experiment P1027

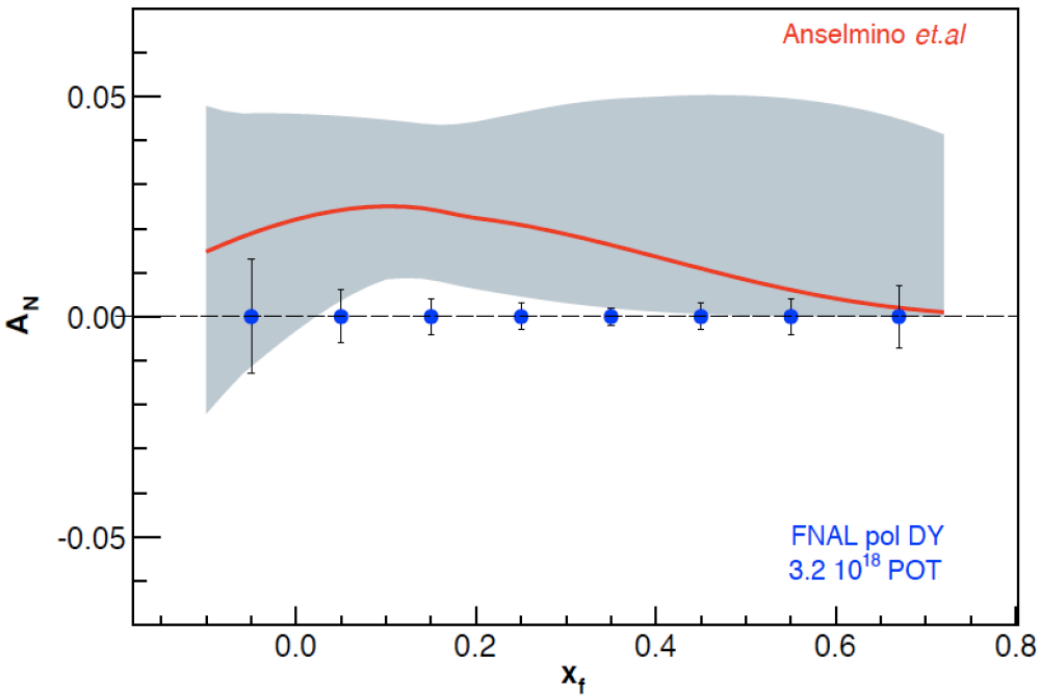
- Polarized beam experiment
  - May 18th, 2012 proposal submitted
  - November 14th, 2012 stage-1 approval



Polarized Drell-Yan experiment P1027

- Clean measurement of sign and shape of Sivers distributions to compare DIS and Drell-Yan
- 3.2×10^{18} POT
- Red curve: prediction from SIDIS data (HERMES & COMPASS)

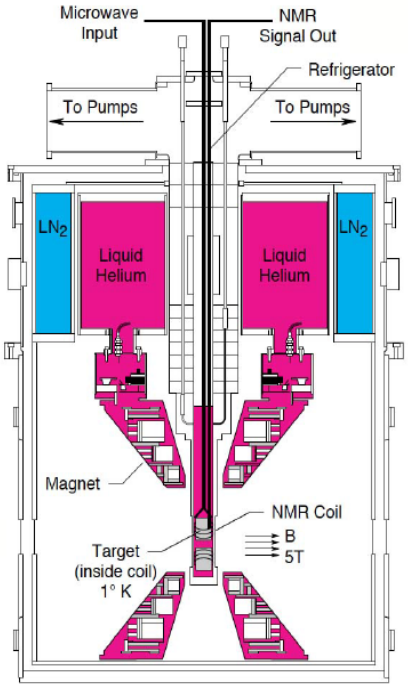
$$A_N \equiv \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \propto \frac{f_{1T}^{\perp,u}(x_B) \cdot \bar{u}(x_T)}{u(x_B) \cdot \bar{u}(x_T)}$$

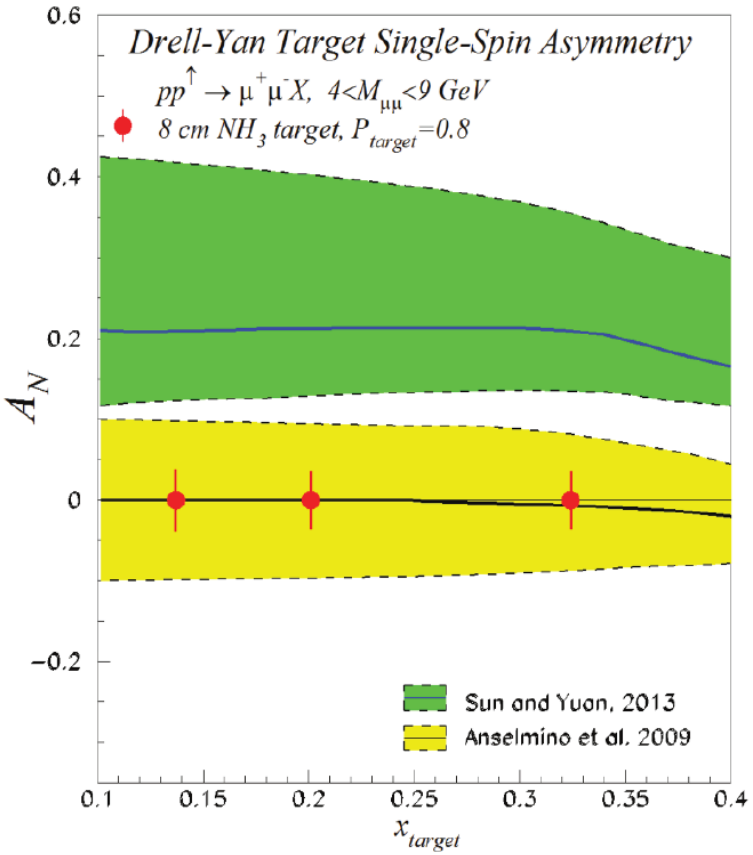


Polarized Drell-Yan experiment P1039

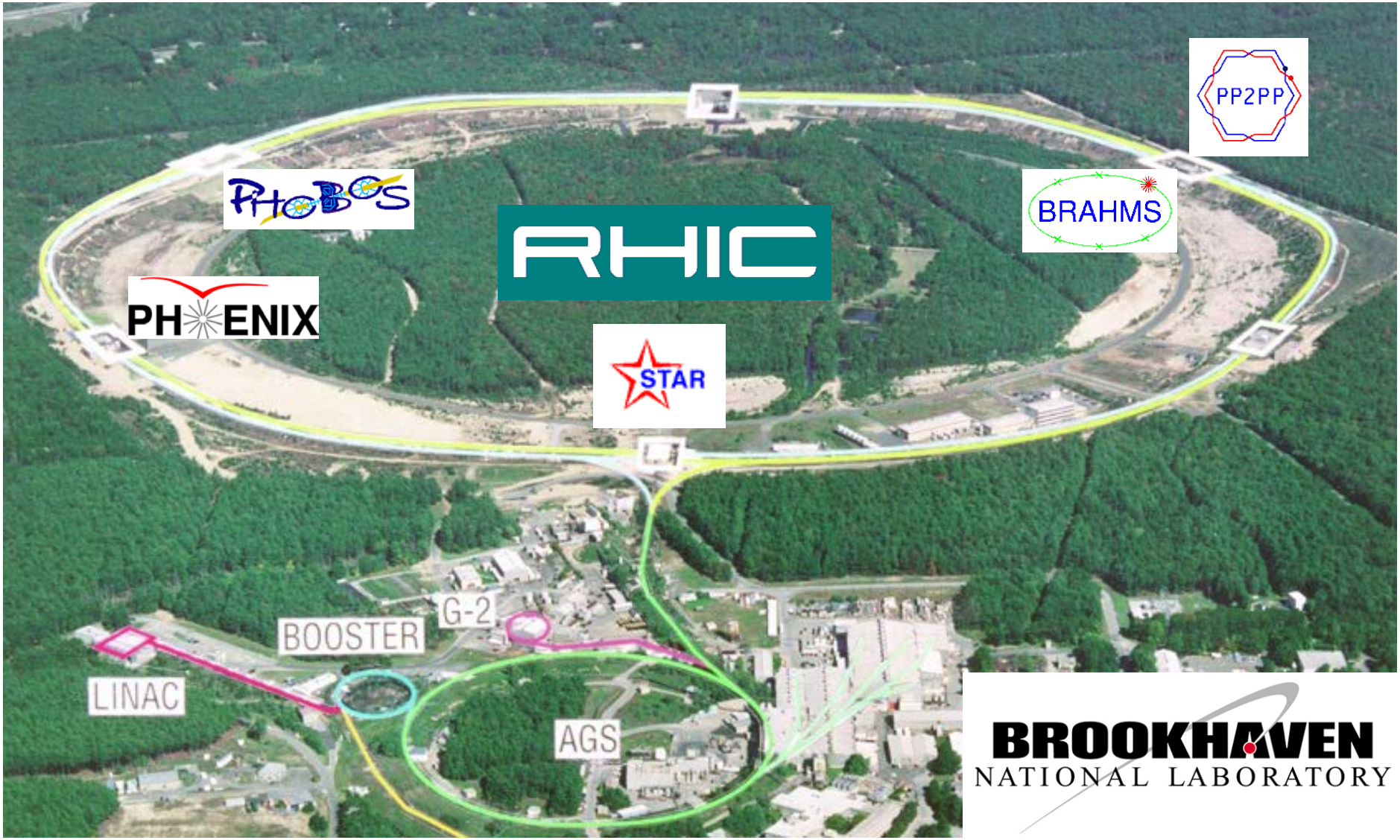
- Polarized target experiment
  - May 6th, 2013 LoI submitted
  - June 26th, 2013 stage-1 approval
- Polarized target R&D at LANL
  - LANL LDRD project FY2013-2016

$$A_N \equiv \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \propto \frac{u(x_B) \cdot f_{1T}^{\perp,\bar{u}}(x_T)}{u(x_B) \cdot \bar{u}(x_T)}$$



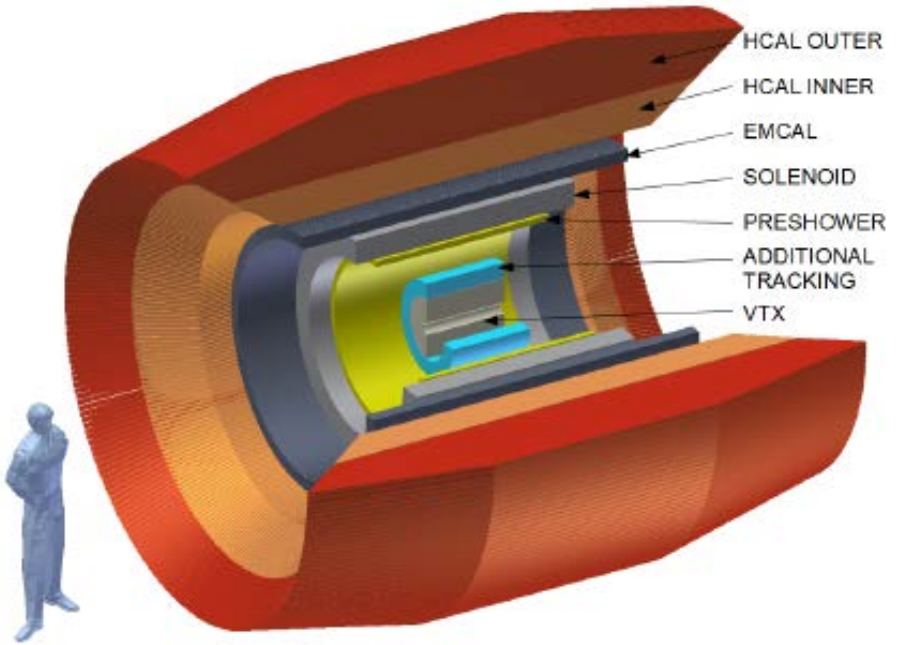


RHIC


PP2PP
PHOBOS
BRAHMS
RHIC
PHENIX
STAR
G-2
BOOSTER
LINAC
AGS
BROOKHAVEN
NATIONAL LABORATORY

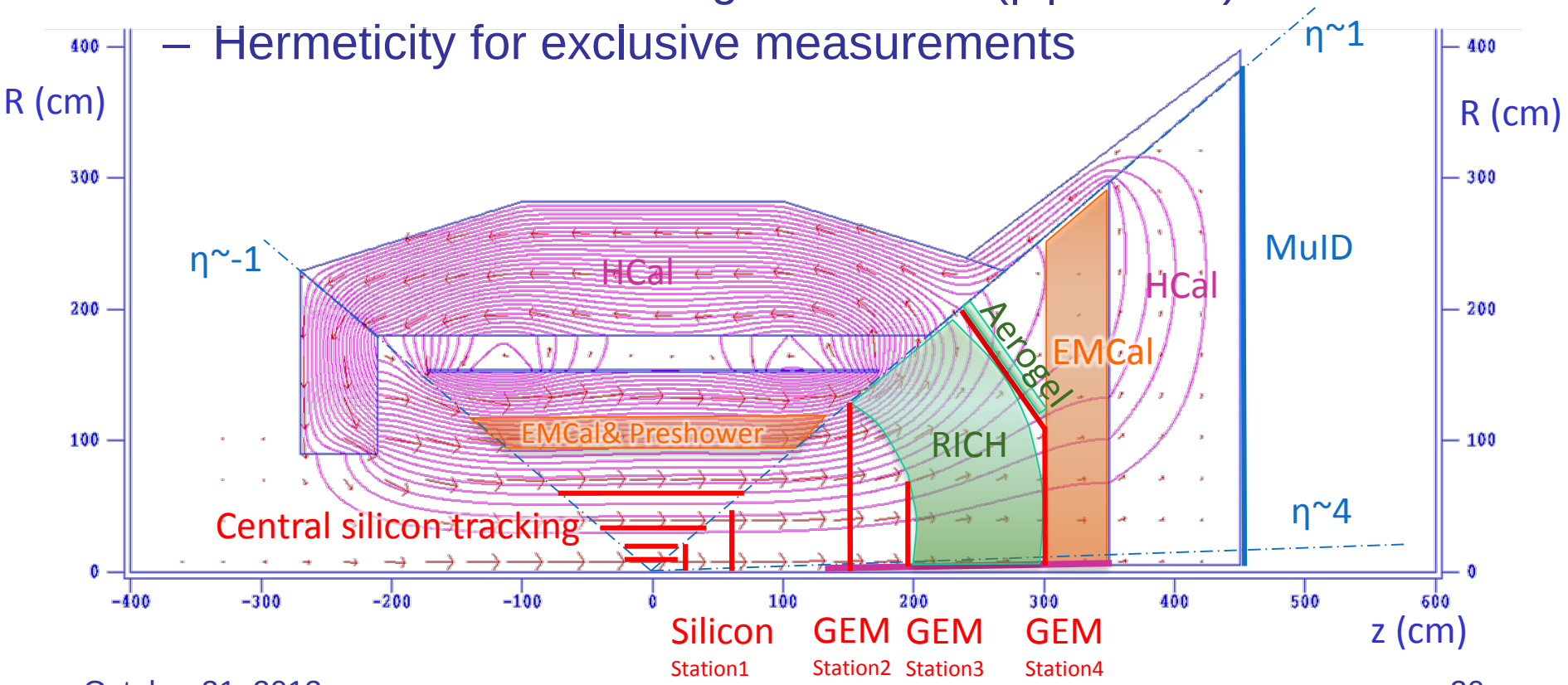
Detector upgrade project at PHENIX

- sPHENIX
  - Barrel upgrade
    - Compact jet detector
    - Extension of tracking layers and preshower detector
  - Forward upgrade
  - Partial installation and commissioning in 2018-2019
  - Completion and experiment in 2021-2022
- ePHENIX at eRHIC
  - Transition to eRHIC in 2023-2024
  - Commissioning and experiment start in 2025



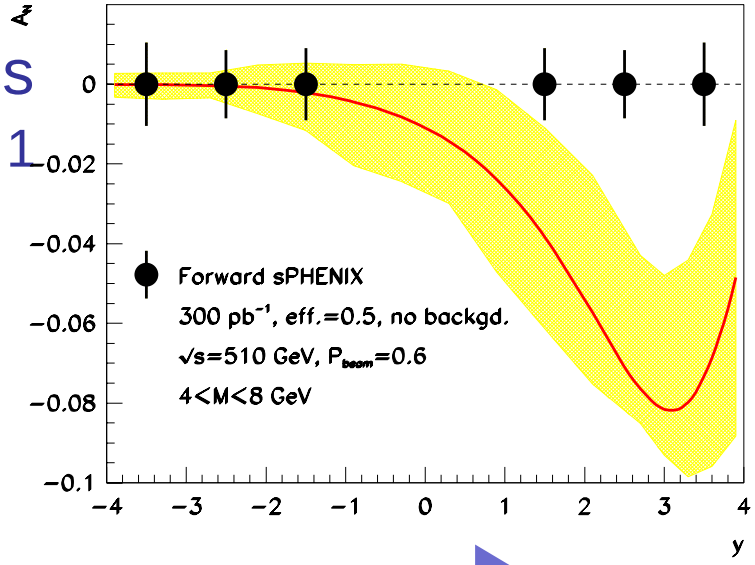
sPHENIX forward upgrade

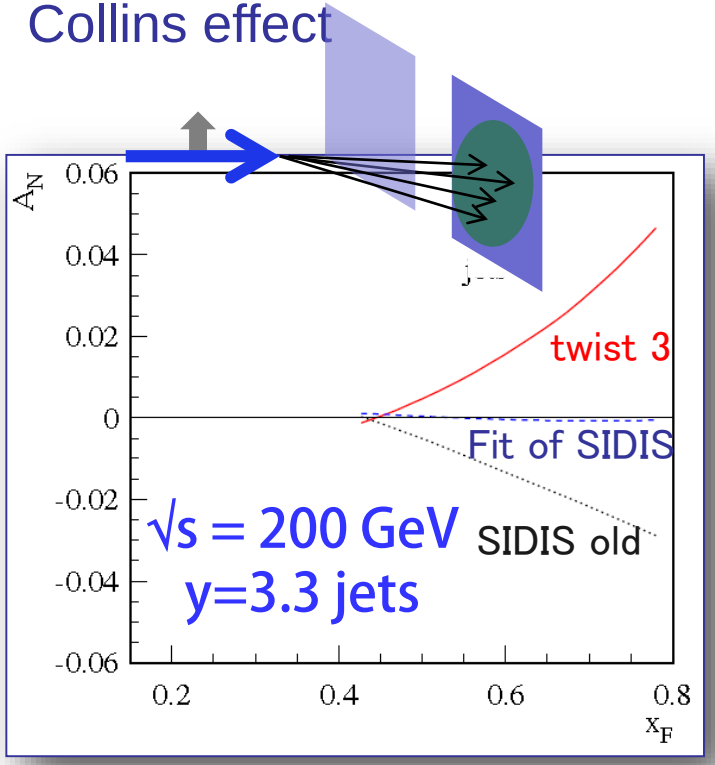
- Open geometry
  - Wide kinematic coverage of photon, jet, leptons and identified hadrons
- Compatible design for eRHIC detector (ePHENIX)
  - Constraint from IR design of eRHIC (|z| < 4.5m)
  - Hermeticity for exclusive measurements

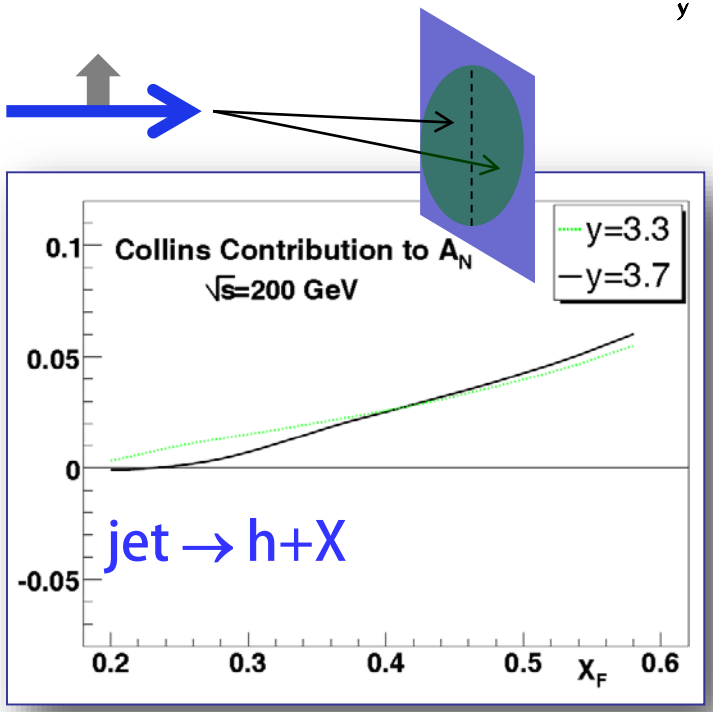


sPHENIX forward upgrade

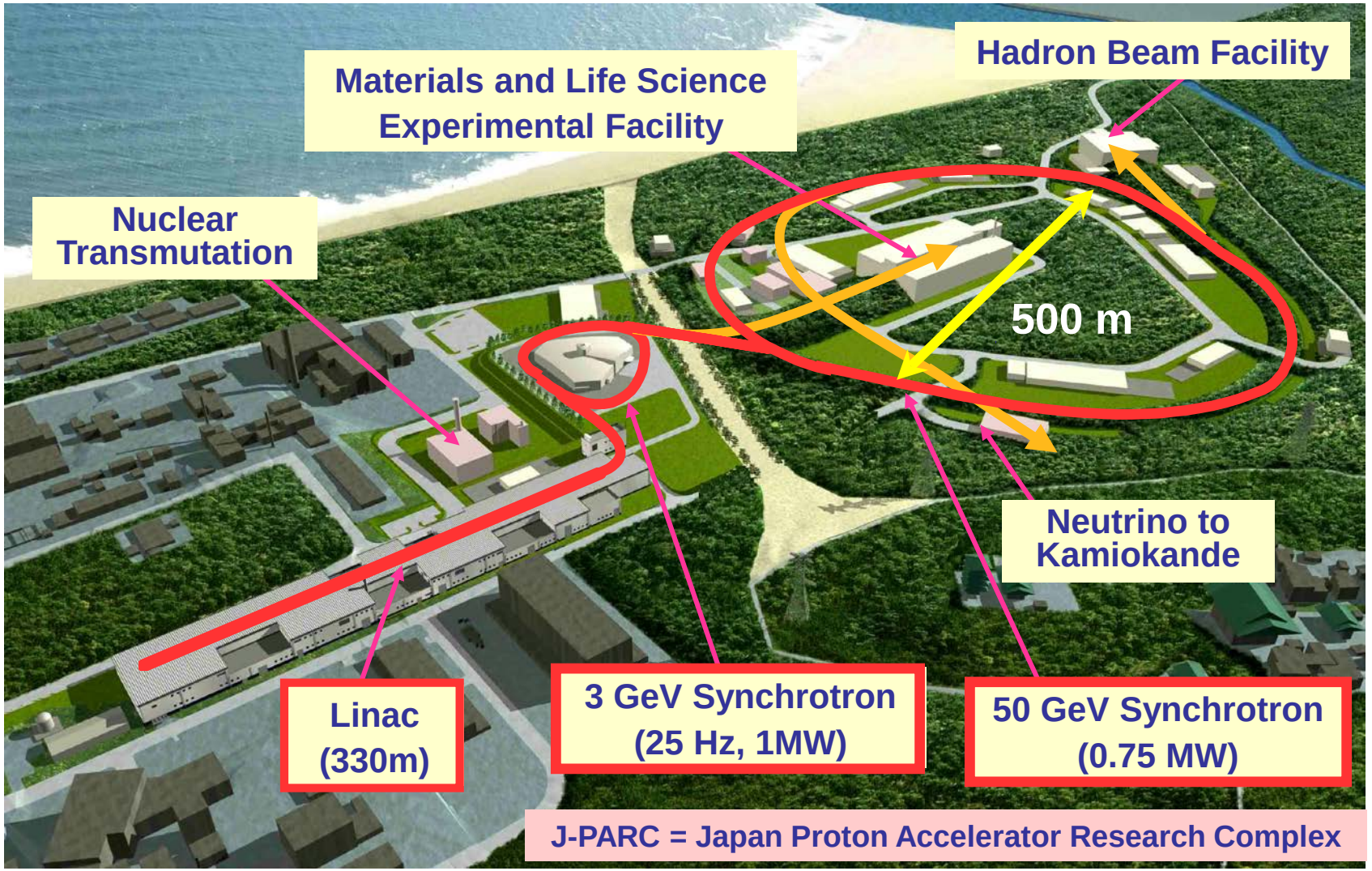
- Sivers effect in Drell-Yan process
  - Valence quark region at x~0.2 with $1 < \eta < 4$ coverage
- Jet asymmetry
  - Sivers effect or higher-twist effect
- Asymmetry inside of jets
  - Collins effect







J-PARC facility



Joint Project between KEK and JAEA

J-PARC proposal/LoI

- P04: measurement of high-mass dimuon production at the 50-GeV proton synchrotron
  - “deferred”
- P12-LoI: study of parton distribution function of mesons via Drell-Yan process at J-PARC at high-p beamline
- P24: polarized proton acceleration at J-PARC
  - “no decision”

- Possible stage-1?
  - 30 GeV unpolarized proton beam & 5-20 GeV π/K beam + polarized target

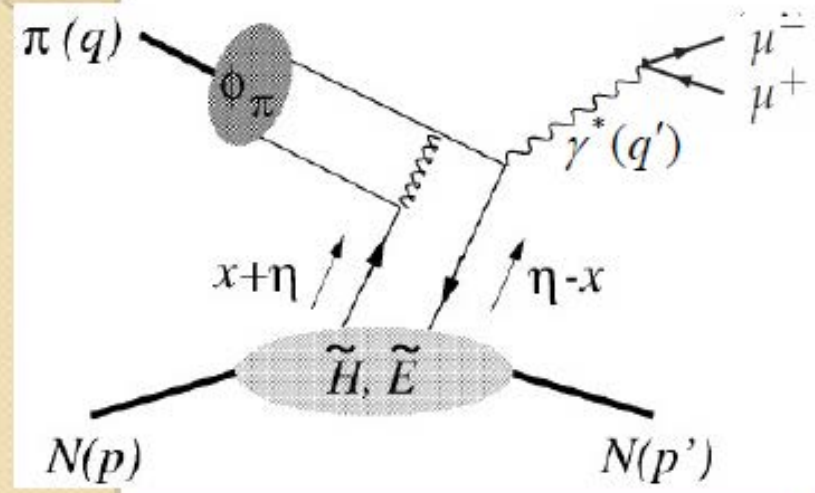
Slide by W. Chang

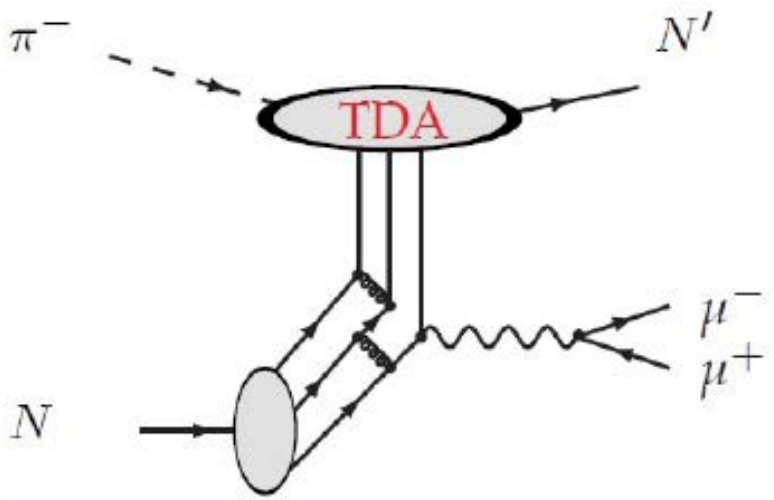
Exclusive Pion-Induced Drell-Yan Process

Bernard Pire , IWHS2011

small $t = (q - q')^2$

large $t = (q - q')^2$





ϕ_π : pion distritribution amplitude (DA)

- DA characterizes the minimal valence Fock state of hadrons.
- DA of pion are also explored by pion-photon transition form factor in Belle and Barbar Exps.

TDA : π-N transistion distritribution amplitude

- TDA characterizes the next-to-minimal valence Fock state of hadrons.
- TDA of pion-nucleon is related to the pion cloud of nucleons.

Summary

- Fermilab SeaQuest experiment
  - Unpolarized program
    - Flavor asymmetry of sea-quark distribution
    - Boer-Mulders distribution
    - Cold Nuclear Matter (CNM) effect
  - Physics run will start in late October (this month)
- Polarized Drell-Yan experiments
  - Polarized Drell-Yan proposals of Fermilab program
    - P1027 polarized beam experiment (stage-1 approval)
    - P1039 polarized target experiment (stage-1 approval)
  - PHENIX upgrade program at RHIC
    - sPHENIX barrel and forward detector upgrade under discussion
  - Possible J-PARC program
    - Exclusive Drell-Yan measurement under development