Sea-quark spin/flavor with Drell-Yan experiments

INT Workshop

"Orbital Angular Momentum in QCD"

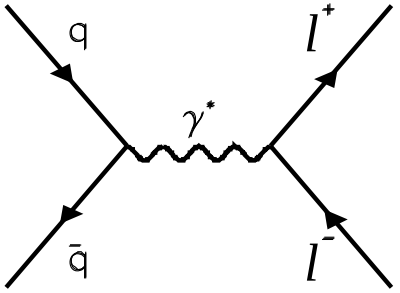
February 15, 2012

Yuji Goto (RIKEN)

Outline

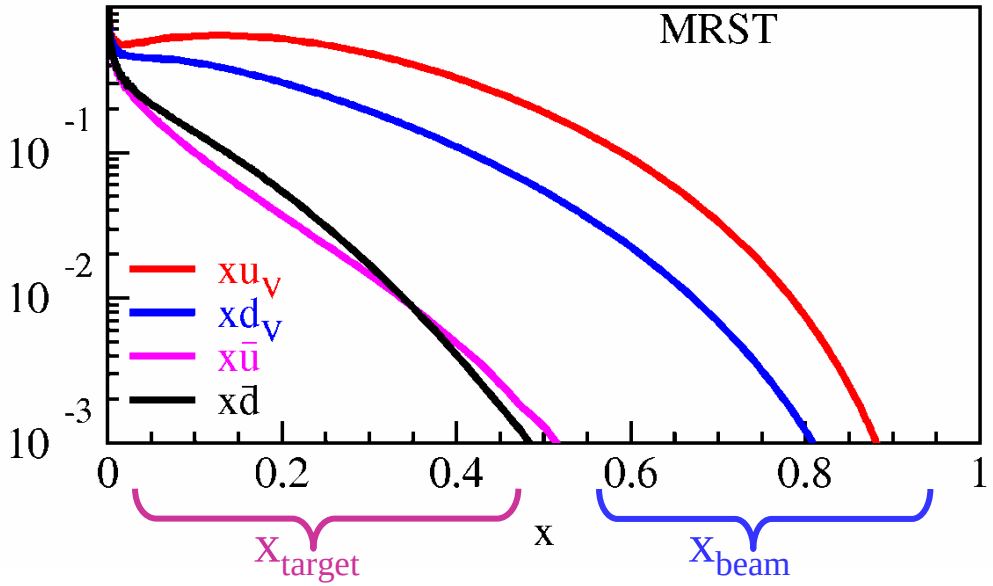
- Fermilab Drell-Yan experiments
  - Unpolarized program
    - Flavor asymmetry of sea-quark distribution
    - Boer-Mulders distribution
- Polarized Drell-Yan experiments
  - RHIC polarized programs (Bland's talk on Feb.10)
    - Sivers distribution
  - Other programs (possible extension of Fermilab program)

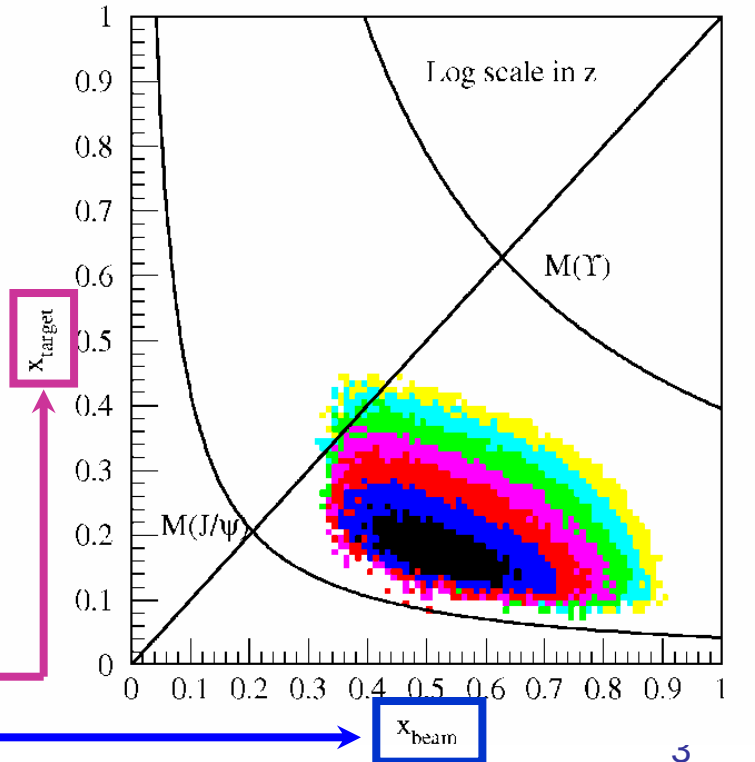
Drell-Yan experiments



$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s}\sum_{q\in\{u,d,s,\ldots\}} e_q^2\left[\bar{q}_{\mathrm{t}}\left(x_{\mathrm{t}}\right)q_{\mathrm{b}}\left(x_{\mathrm{b}}\right)+\bar{q}_{\mathrm{b}}\left(x_{\mathrm{b}}\right)q_{\mathrm{t}}\left(x_{\mathrm{t}}\right)\right]$$

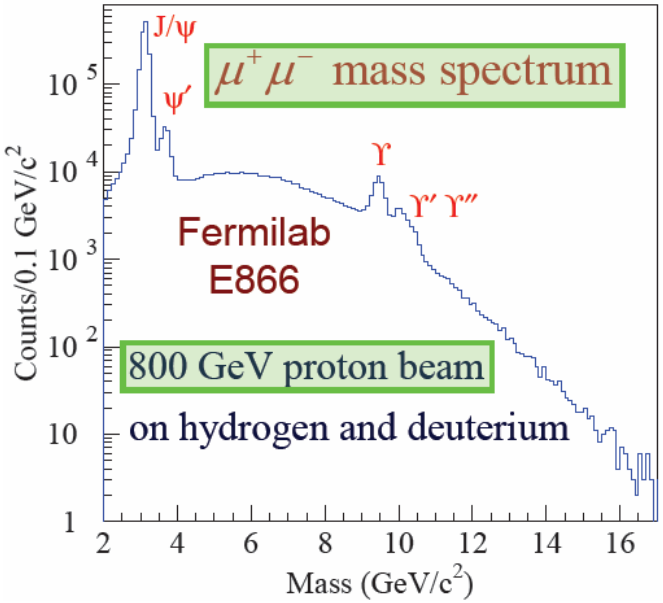
- Fixed target experiment (e.g. at Fermilab)
  - forward detector acceptance chooses large x_b and small x_t

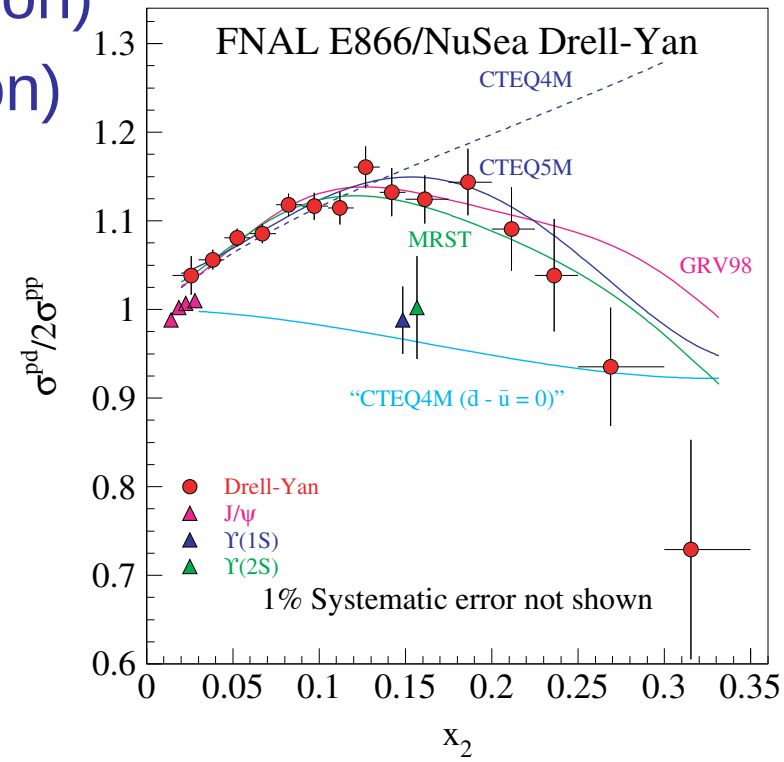




Flavor asymmetry of sea-quark distribution

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





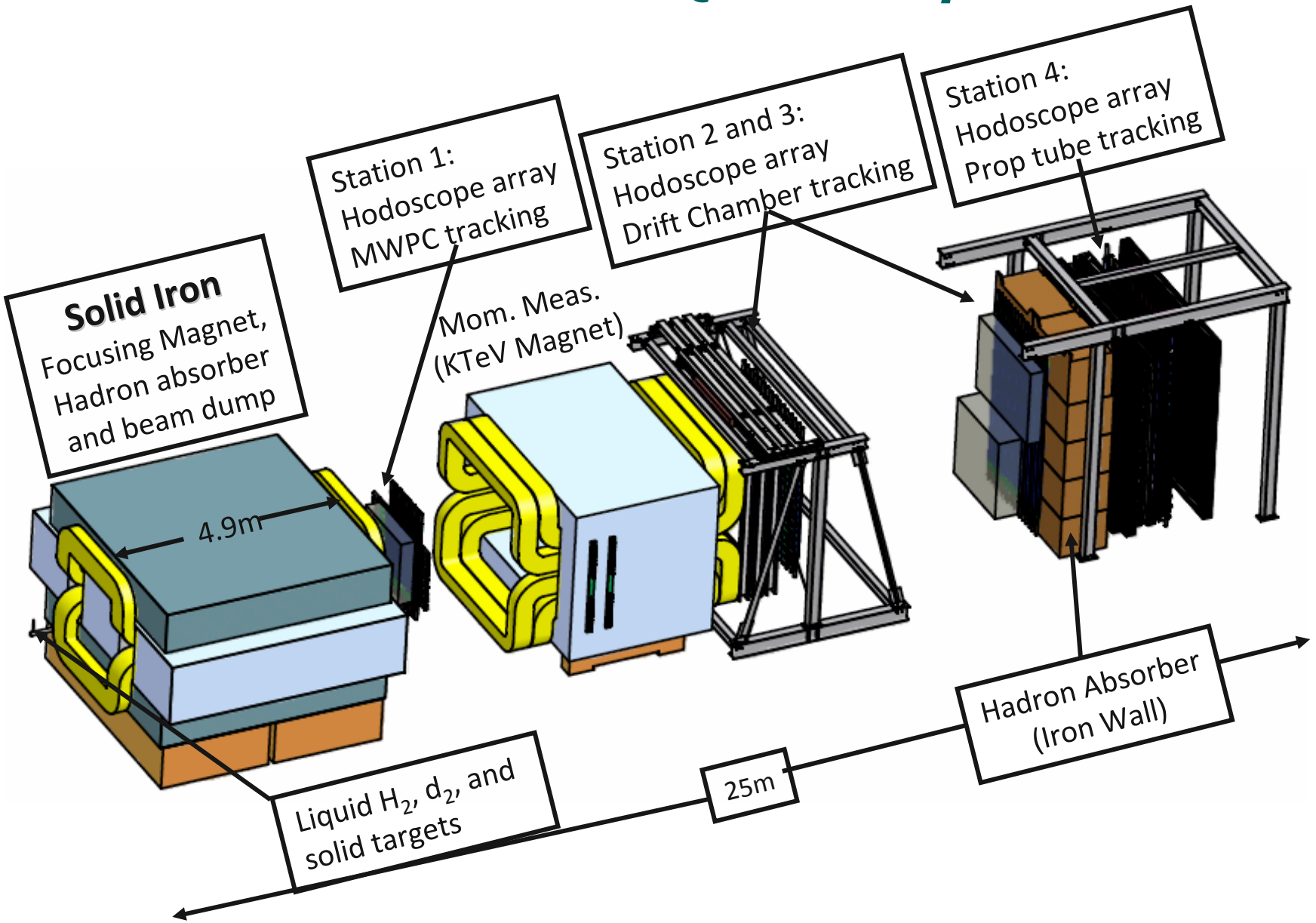
$$\frac{\sigma^{pd}}{2\sigma^{pp}} \sim \frac{1}{2}\left[1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

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

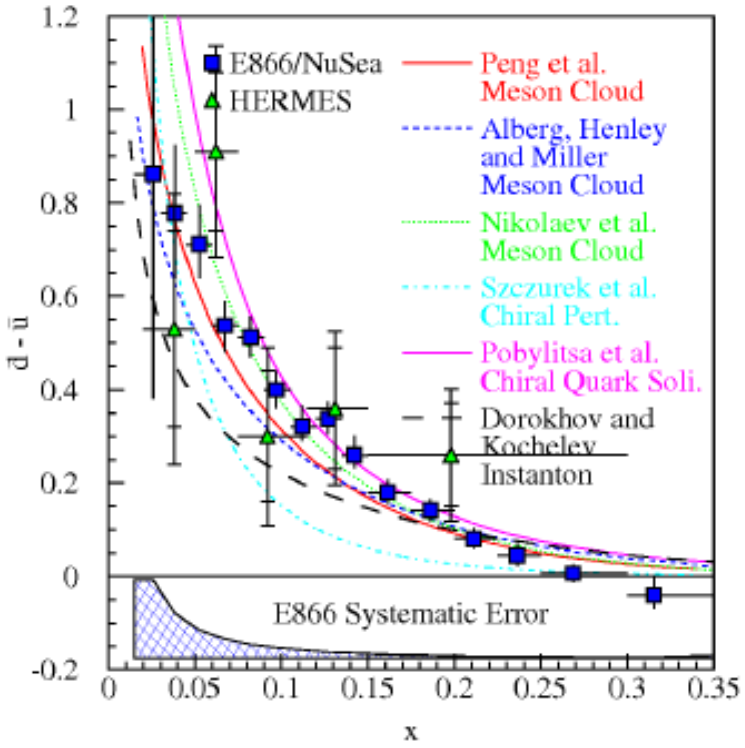


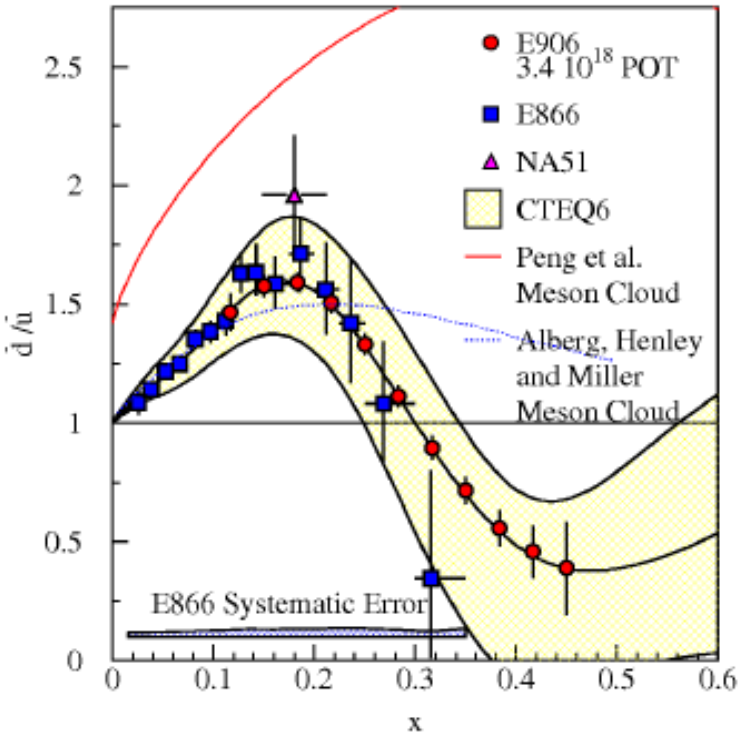
Fermilab-E906/SeaQuest experiment

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

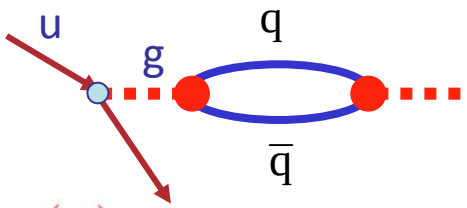
Flavor asymmetry of sea-quark distribution

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



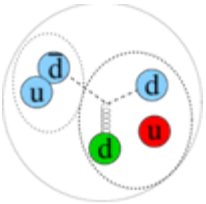


Flavor asymmetry of sea-quark distribution



- 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

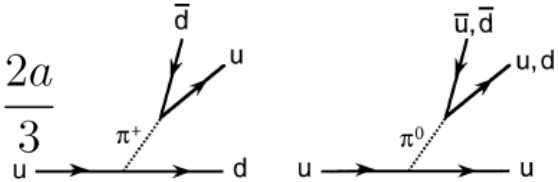
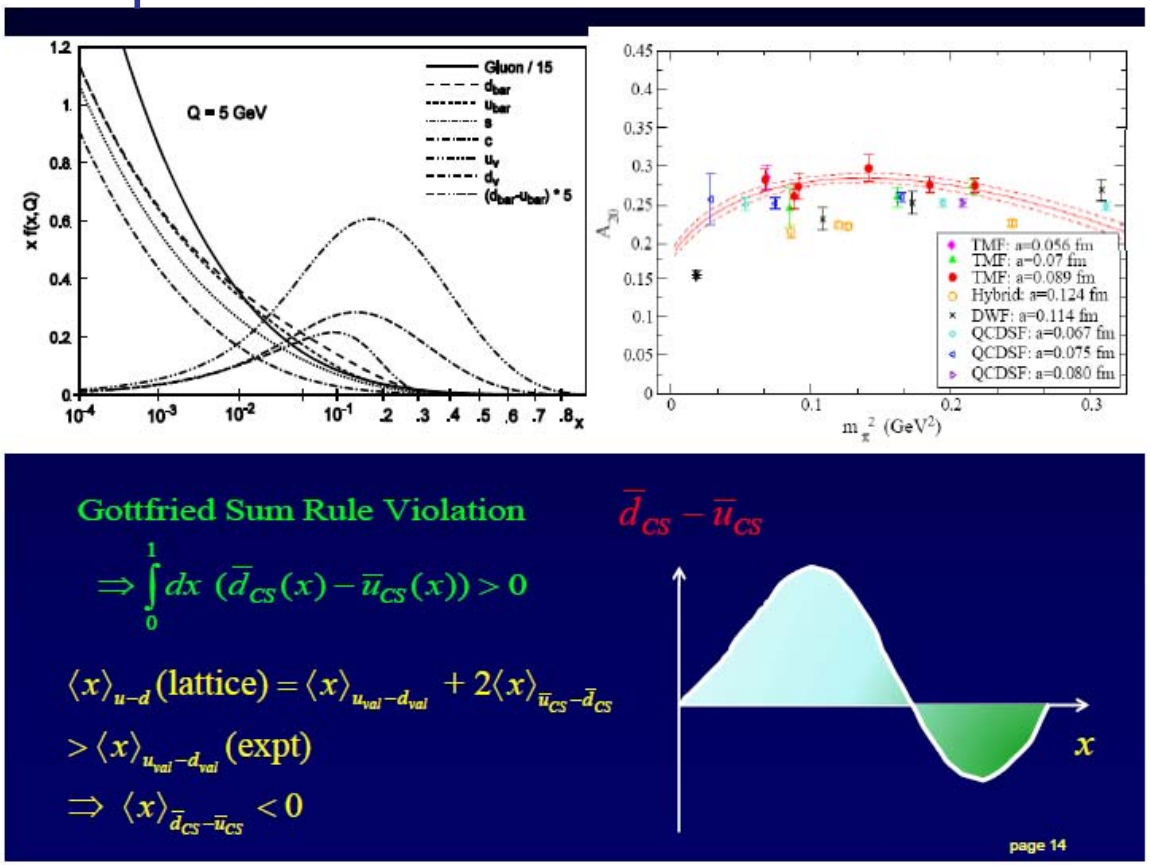


Fig. 17. Valence u quark splitting.

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

Flavor asymmetry of sea-quark distribution

- Liu's talk on Feb.6 $\bar{d} - \bar{u} < 0$?
  - In lattice calculation, connected sea component should be d-bar – u-bar < 0
  - But, this component doesn't contribute to OAM…



Drell-Yan decay angular distributions

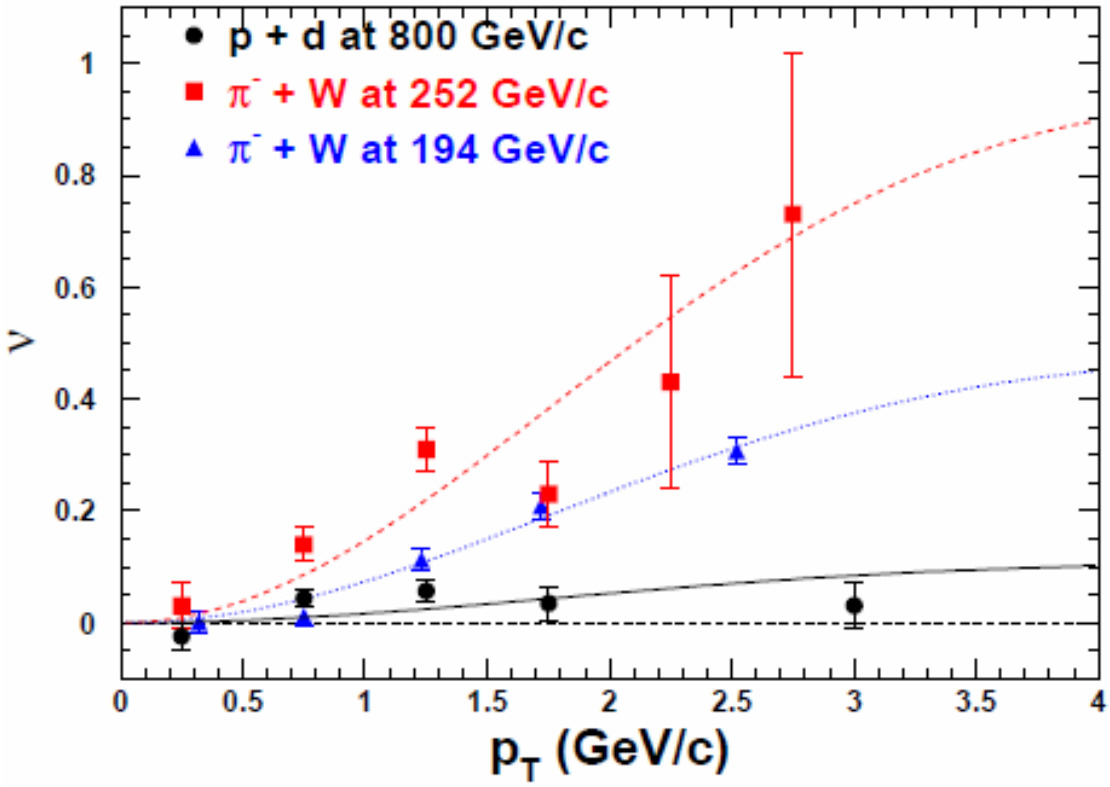
- A general expression for Drell-Yan decay angular distributions

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

  - $\lambda=1$, $\mu=\nu=0$ for non-zero p_T in Collins-Soper frame
  - 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

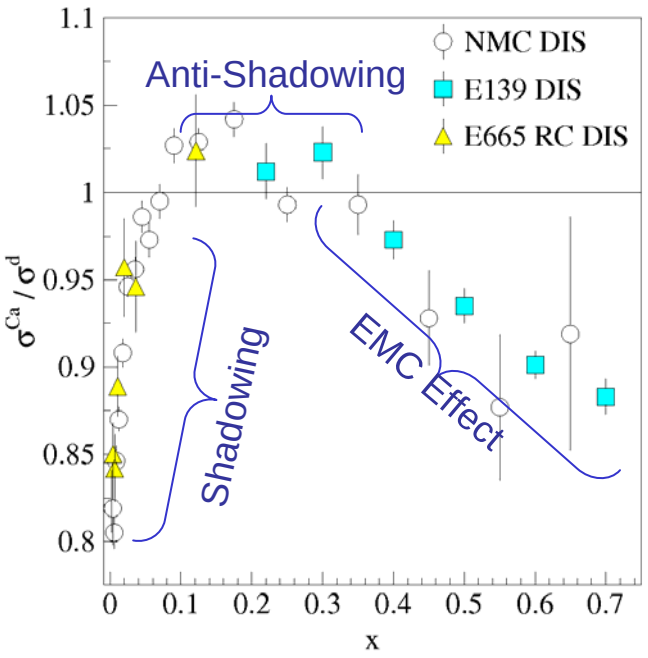
- Boer-Mulders function $h_1^{\perp}$
  - Small ν is observed for p+d and p+p
  - π^-+W: [valence $h_1^{\perp}(\pi)$]⊗[valence $h_1^{\perp}(p)$]
  - p+d and p+p: [valence $h_1^{\perp}(p)$]⊗[sea $h_1^{\perp}(p)$]

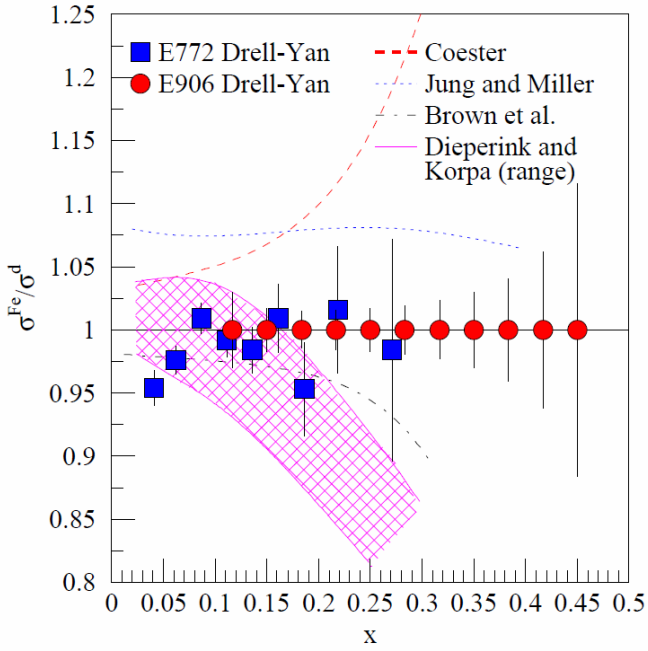


L. Y. Zhu et al.,
Phys. Rev. Lett. 99 (2007) 082301
Phys. Rev. Lett. 102 (2009) 182001

EMC effect

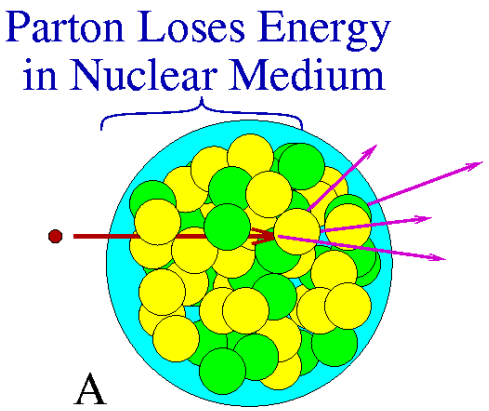
- Discovered by the EMC collaboration from muon DIS experiments in 1983
- Modification of the antiquark distributions in nuclei relative to the nucleon
  - Virtual meson exchange modifies the antiquark distributions of the nuclei
  - Present Drell-Yan data suggests no modification

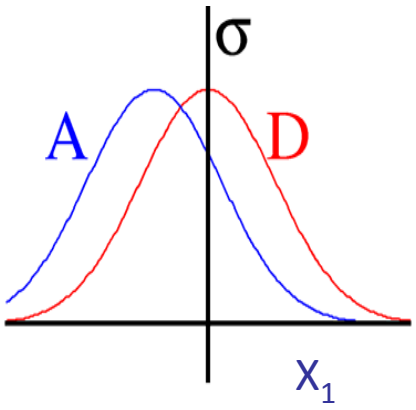


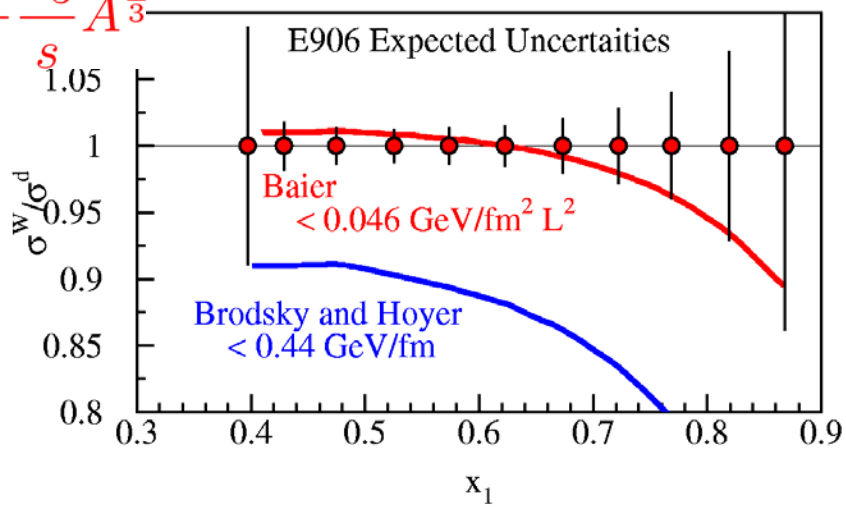


Parton energy loss

- Energy loss in cold nuclear matter
  - Prior to annihilation
  - No apparent shift in x_1 found so far
  - Important to understand energy loss in hot nuclear matter
  - Models
    - Galvin 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. $\Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}$

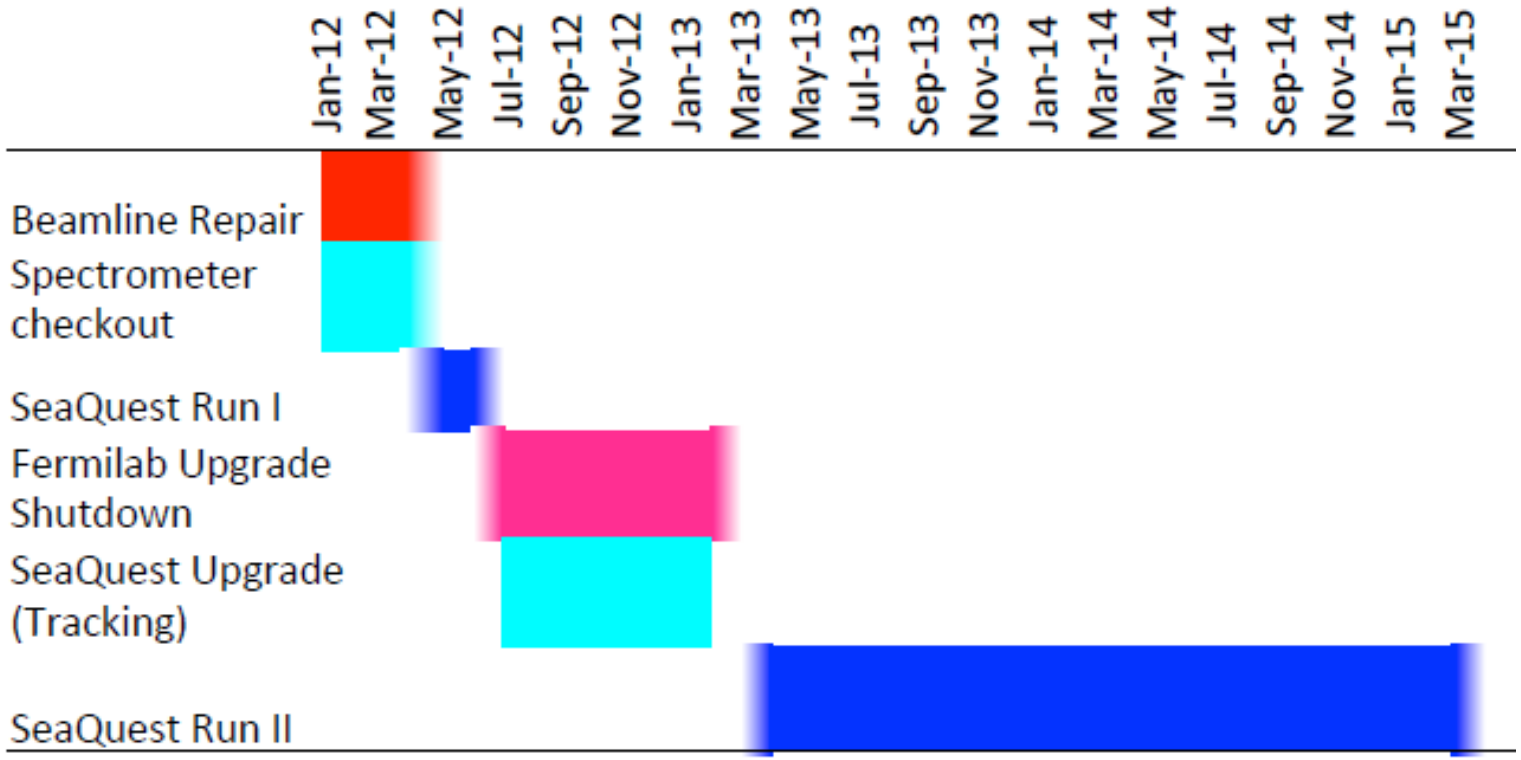






Fermilab-E906/SeaQuest experiment

- Status
  - Present critical path is a repair of beam line vacuum
  - Experiment is ready to run
  - Run (> 2 months) before Fermilab maintenance break

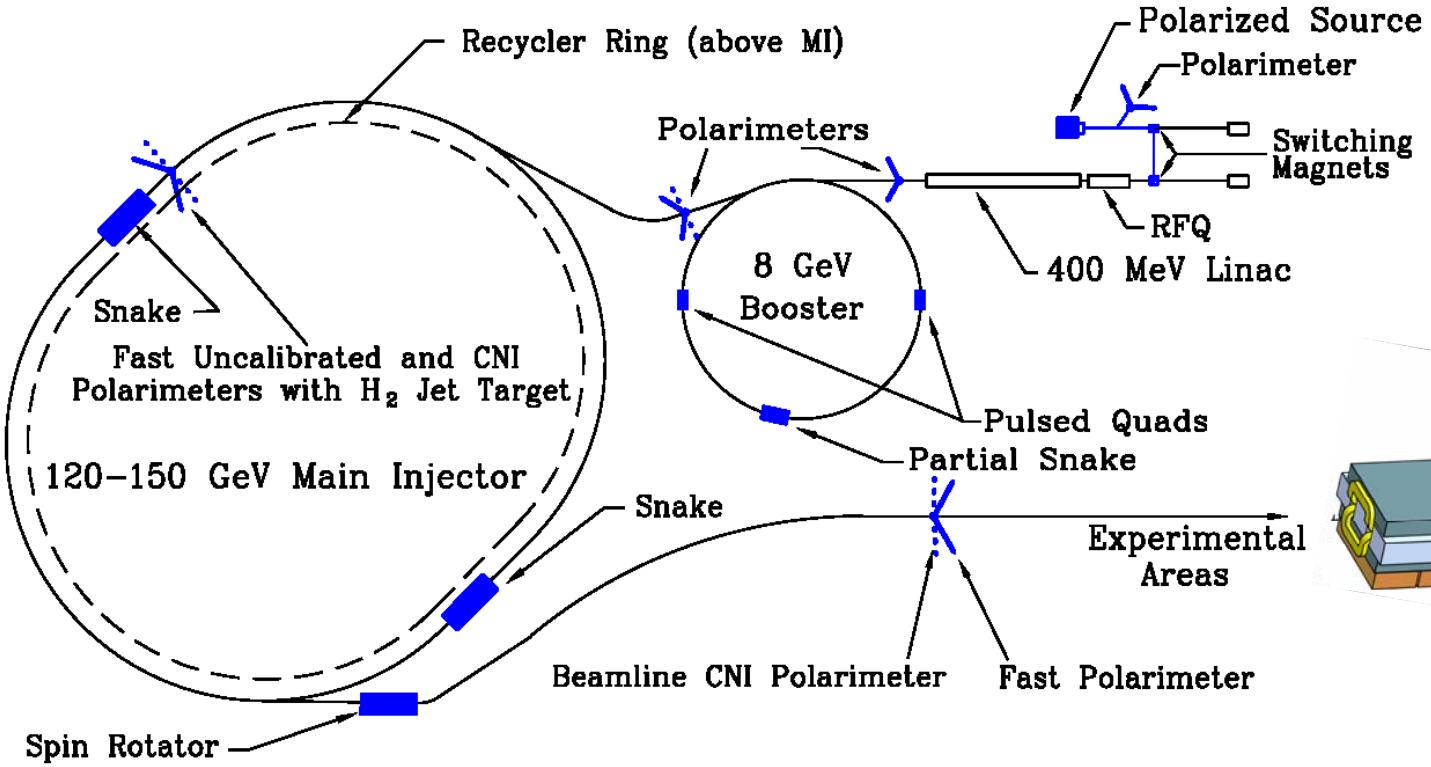


Polarized Drell-Yan experiment

- Many new inputs for remaining proton-spin puzzle
- Single transverse-spin asymmetry
  - Sivers function measurement
  - Transversity
  - Boer-Mulders function
- Double transverse-spin asymmetry
  - Transversity (quark⊗antiquark for p+p collisions)
- Double helicity asymmtry
  - Flavor asymmetry of sea-quark polarization

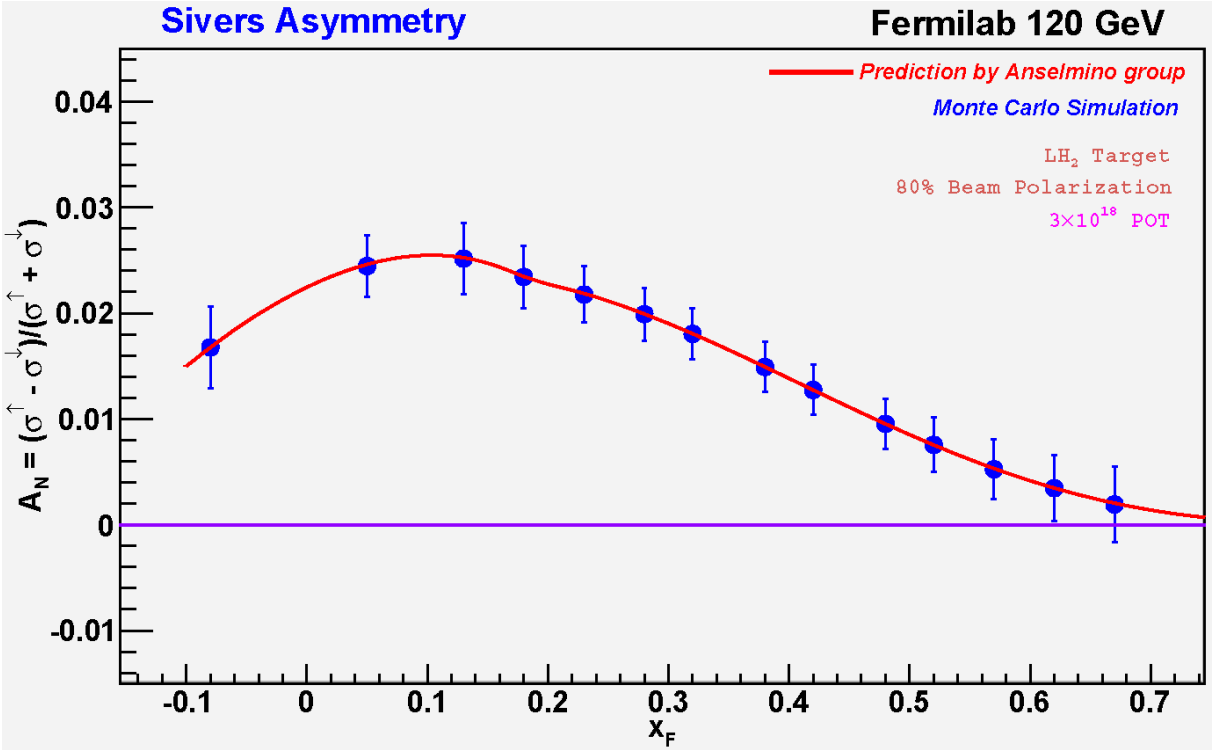
Polarized Drell-Yan experiment

- Polarized beam
- Polarized Fermilab Main Injector study completed: arXiv:1110.3042
- Approx. $4M+
- Physics proposal to Fermilab in June 2012



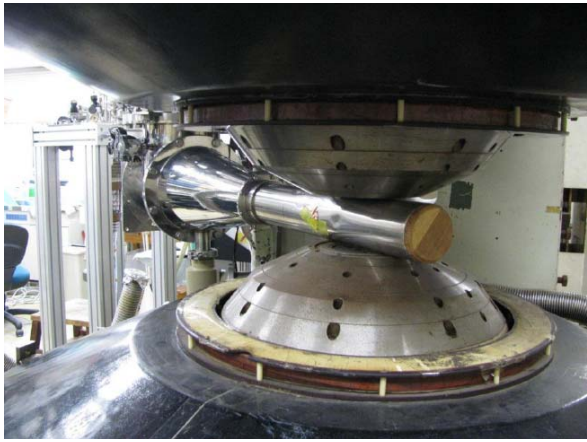
Polarized Drell-Yan experiment

- Clean measurement of sign and shape of Sivers distributions to compare DIS and Drell-Yan
- Luminosity
  - L_{av} = 2 x 10^{35} $cm^{-2}s^{-1}$ (10% of available beam time: I_{av} = 15 nA)
  - 100 fb^{-1} for 5 x 10^5 min: (= 2 yrs at 50% efficiency)



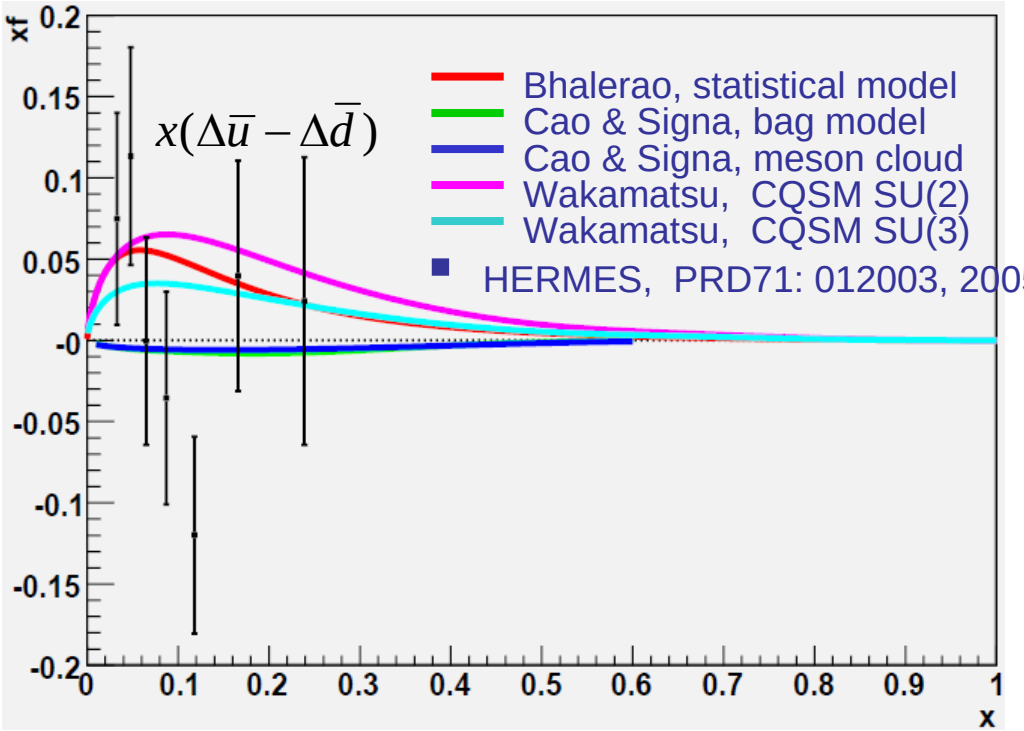
Polarized Drell-Yan experiment

- Polarized target R&D
- KEK
  - Rebuilding “Michigan” target @ North-CH/K5
    - Irradiated-NH3
    - 5-T magnet & 1-K cryostat
  - Vacuum & cryostat system made
    - But damaged by the earthquake
  - 213 MHz NMR to be tested (2011)
  - Microwave 140GHz EIO to be purchased (2011-12)
  - Sample test to be done (2012)
- Yamagata Univ.
  - Material R&D
  - Polyethylene fiber
    - Large surface area
    - Large cooling power
    - Deformation performance
  - To be tested with a new cryostat (2011-12)
    - Cooling test underway



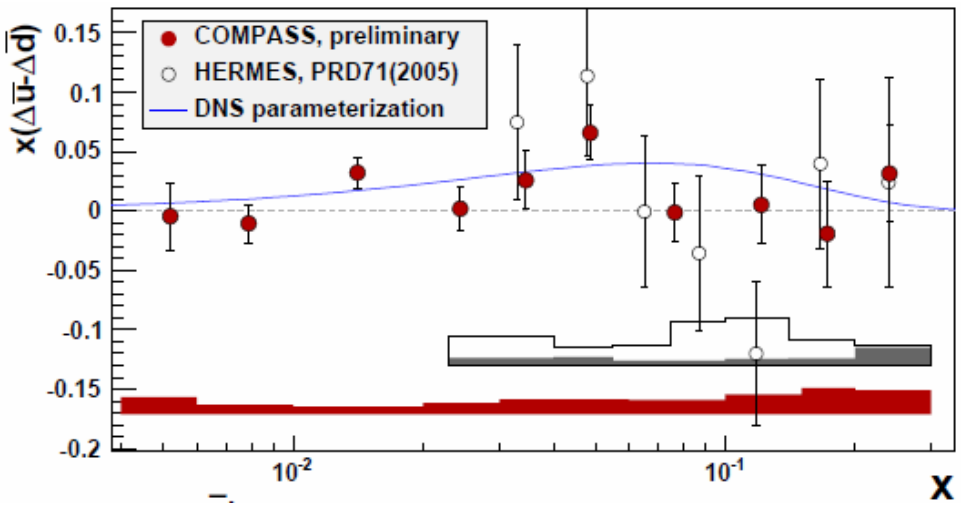
Polarized Drell-Yan experiment

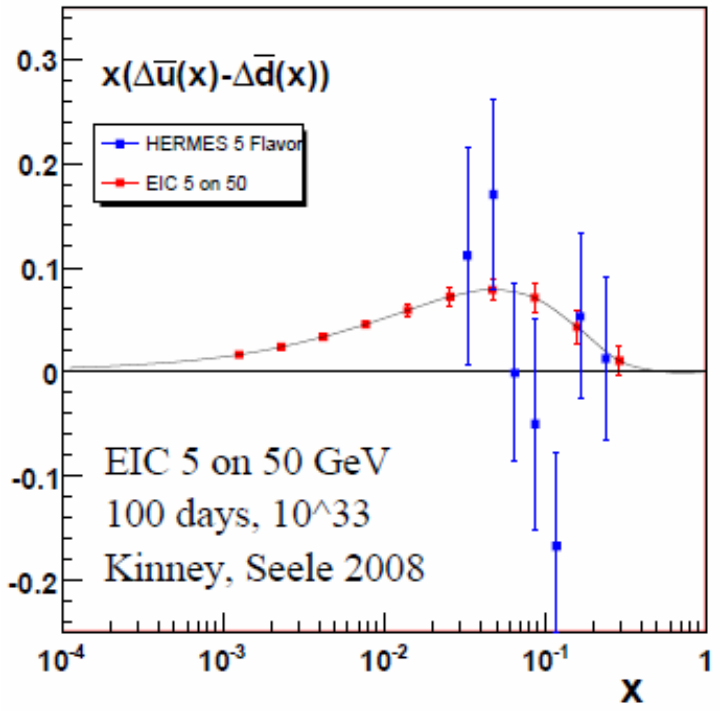
- Double helicity asymmetry
  - A_{LL} measurement
  - Flavor asymmetry of sea-quark polarization
  - High luminosity accumulation is very important



Polarized Drell-Yan experiment

- Flavor asymmetry of sea-quark polarization
  - SIDIS data from HERMES, and new COMPASS data available
  - W data from RHIC will be available in the near future
  - Polarized Drell-Yan data will be able to cover higher-x region





Polarized Drell-Yan experiment

- Options with SeaQuest apparatus after the unpolarized experiment
  - At RHIC with internal target (unpolarized)
  - At J-PARC (unpolarized & polarized programs)
- Many other programs in the world

experiment	particles	energy	x1 or x2	luminosity
COMPASS	$\pi^{\pm}$+ p$\uparrow$	160 GeV $\sqrt{s}$ = 17.4 GeV	x2 = 0.2 – 0.3	2 × 10^{33} $cm^{-2}s^{-1}$
COMPASS (low mass)	$\pi^{\pm}$+ p$\uparrow$	160 GeV $\sqrt{s}$ = 17.4 GeV	x2 ~ 0.05	2 × 10^{33} $cm^{-2}s^{-1}$
PAX	p$\uparrow$ + pbar	collider $\sqrt{s}$ = 14 GeV	x1 = 0.1 – 0.9	2 × 10^{30} $cm^{-2}s^{-1}$
PANDA (low mass)	pbar + p$\uparrow$	15 GeV $\sqrt{s}$ = 5.5 GeV	x2 = 0.2 – 0.4	2 × 10^{32} $cm^{-2}s^{-1}$
J-PARC	p$\uparrow$ + p	50 GeV $\sqrt{s}$ = 10 GeV	x1 = 0.5 – 0.9	10^{35} $cm^{-2}s^{-1}$
NICA	p$\uparrow$ + p	collider $\sqrt{s}$ = 20 GeV	x1 = 0.1 – 0.8	10^{30} $cm^{-2}s^{-1}$
RHIC PHENIX Muon	p$\uparrow$ + p	collider $\sqrt{s}$ = 500 GeV	x1 = 0.05 – 0.1	2 × 10^{32} $cm^{-2}s^{-1}$
RHIC Internal Target phase-1	p$\uparrow$ + p	250 GeV $\sqrt{s}$ = 22 GeV	x1 = 0.2 – 0.5	2 × 10^{33} $cm^{-2}s^{-1}$
RHIC Internal Target phase-2	p$\uparrow$ + p	250 GeV $\sqrt{s}$ = 22 GeV	x1 = 0.2 – 0.5	3 × 10^{34} $cm^{2}s^{1}$

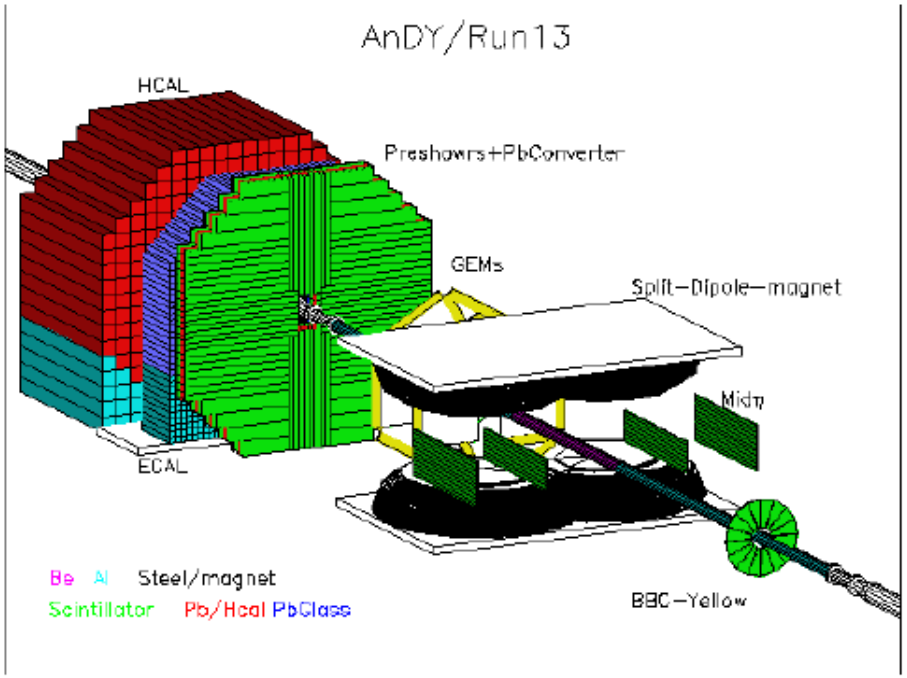
RHIC experiments: AnDY

- Bland's talk on Feb.10

2.10.2012 31

Goal of A_NDY Project

Measure the analyzing power for forward Drell-Yan production to test the predicted change in sign from semi-inclusive deep inelastic scattering to DY associated with the Sivers function

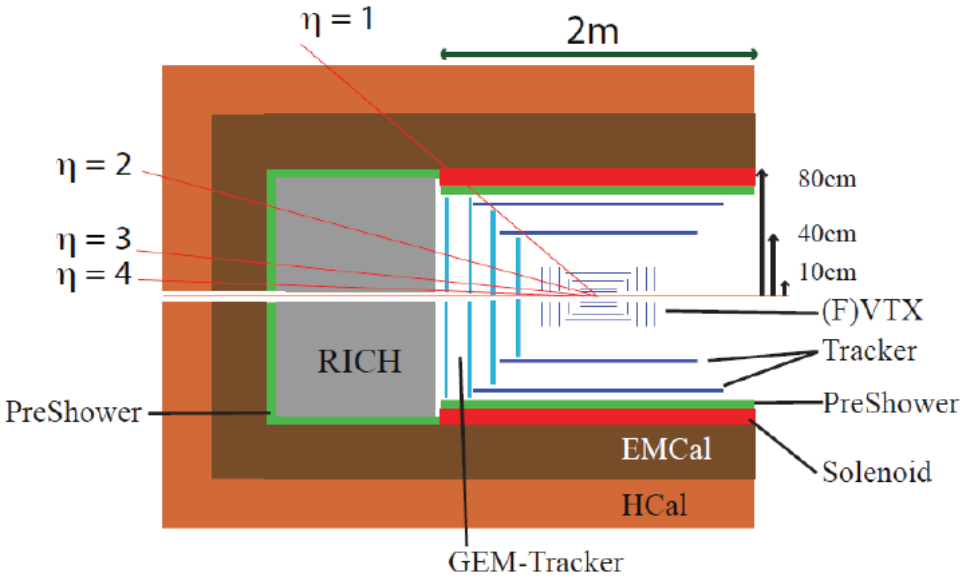


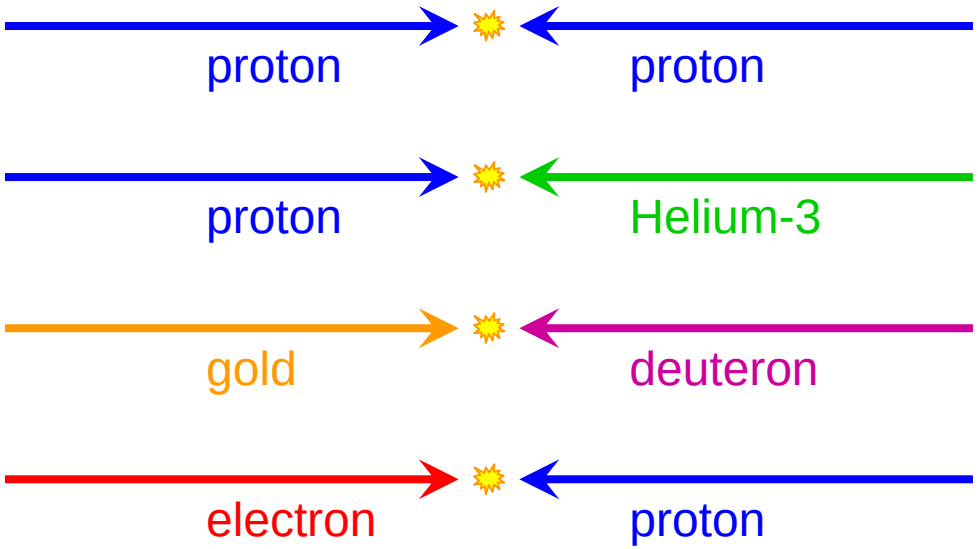
GEANT model of proposed A_NDY apparatus (run-13)

RHIC experiments: sPHENIX upgrade

- Spin physics highlights with forward upgrade
  - Transverse spin program
    - Jet
    - Drell-Yan process
  - Longitudinal
    - ΔG via jets, γ-jet (correlation measurement)
  - Polarized Helium-3 and RHIC energy upgrade
- Cold nuclear matter
- Low-x gluon saturation

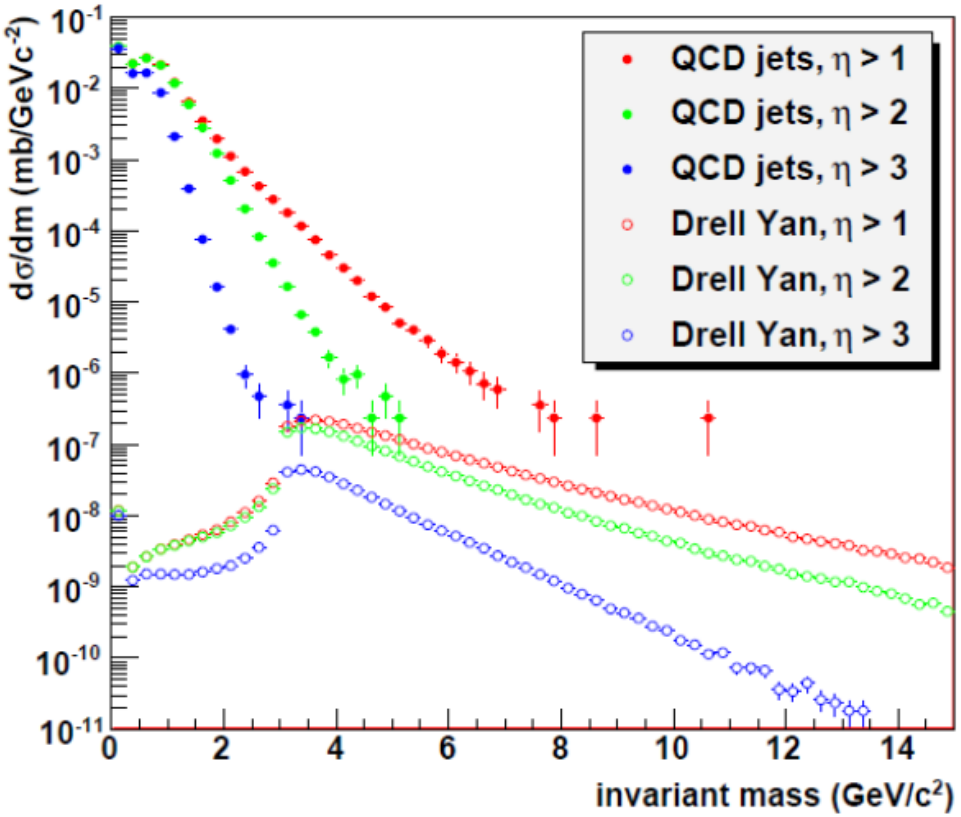
RHIC experiments: sPHENIX upgrade





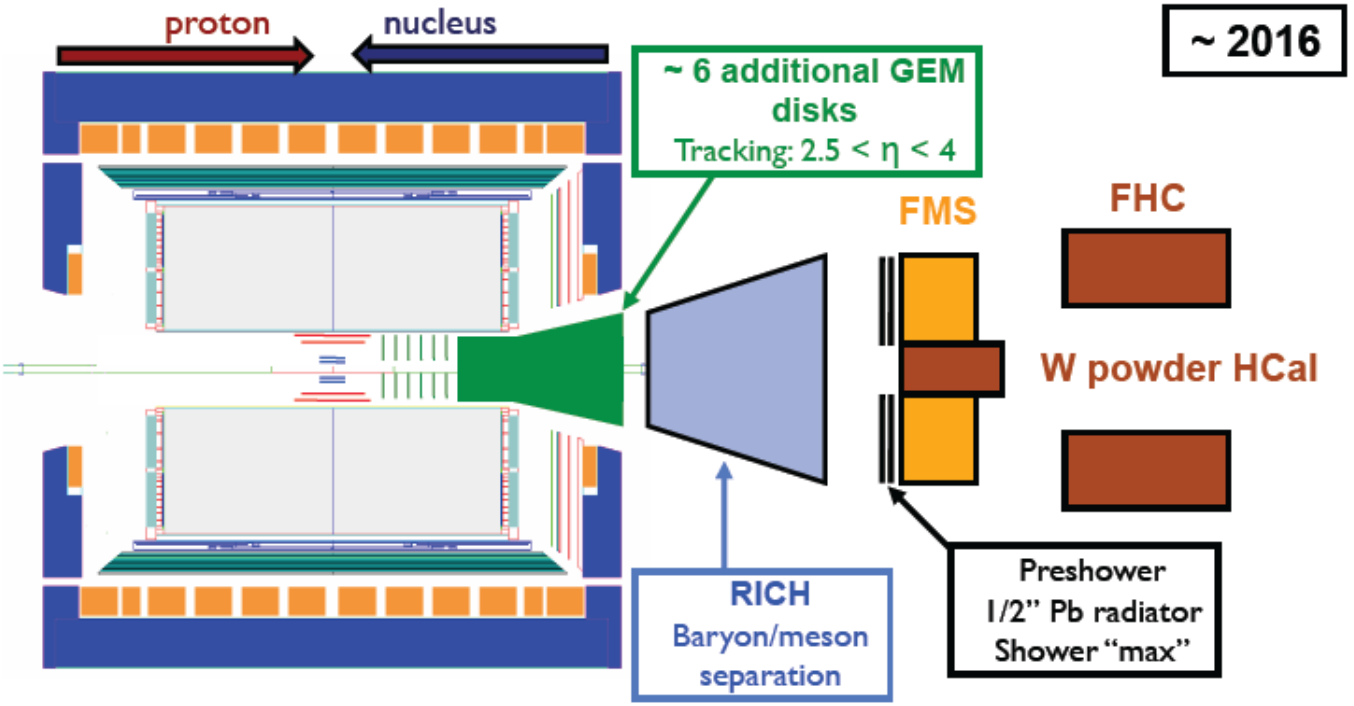
RHIC experiments: sPHENIX upgrade

- Drell-Yan S/N w.r.t. QCD backgrounds
  - Drell-Yan signal 4-10 GeV/c^2
  - Energy cut E1,E2 > 2 GeV
  - Forward rapidities
    - Effectively no background left
    - Statistically limited



RHIC experiments: STAR upgrade

STAR moving forward: instrumentation upgrade



- Forward instrumentation optimized for **p+A** and **transverse spin** physics
  - Charged-particle tracking
  - e/h and γ/π^0 discrimination
  - Baryon/meson separation
- The upgrade can be utilized for forward (hadronic side) in e+p, e+A

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RHIC experiments: STAR upgrade

STAR Upgrades and physics: Nucleon spin and Cold nuclear matter

year	near term (11-13)	mid-decade (14-16)	long term (17-19)
Colliding system	p+p	p+p, p+^{3}He	p+p, p+A
Upgrade	FGT,FHC,DAQ10K, Trigger	HFT,MTD,Trigger, RP phase II	Forward Detectors,Trigger
Nucleon spin structure	W A_L jet and di-jet A_{LL}, intra-jet correlation, Λ D_{LL}/D_{TT}	W A_L with polarized ^{3}He	A_N in p+p, p+A
QCD beyond collinear factorization	Forward A_N	Forward A_N with ^{3}He (Flavor separation)	Drell-Yan, Forward-Forward corr.
Exotic particles		exotic mesons,baryons	exotic mesons,baryons
Properties of initial states			Charm corr. Drell-Yan J/Ψ. F-Fcorr. ,Λ

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RHIC upgrades: Helium-3

- Polarized Helium-3 acceleration

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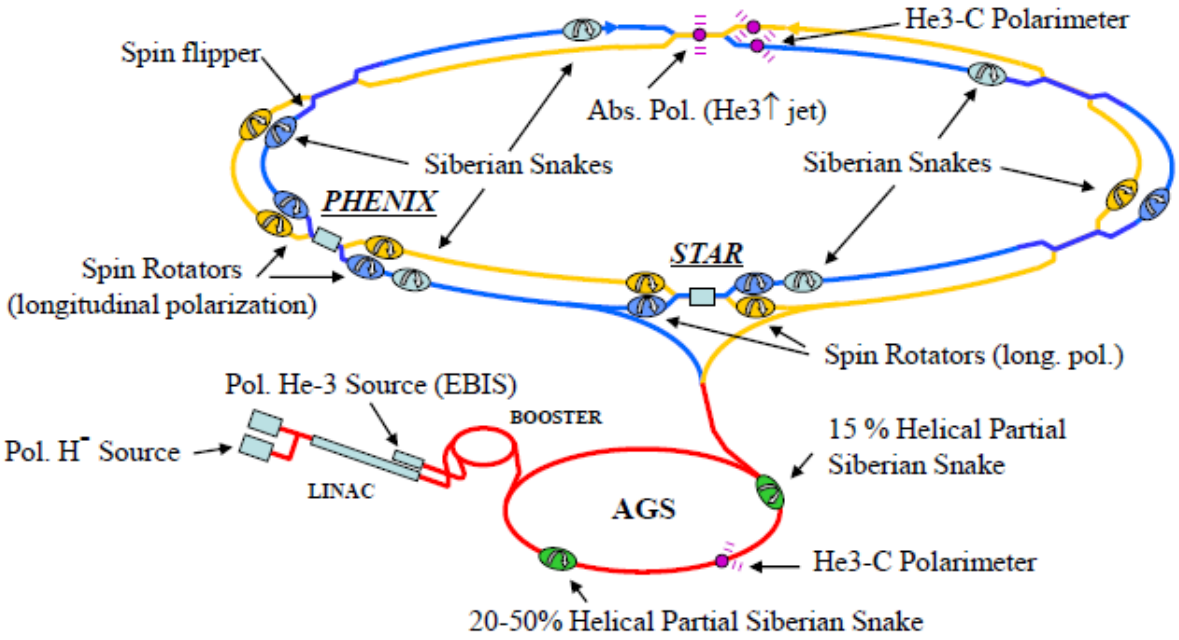
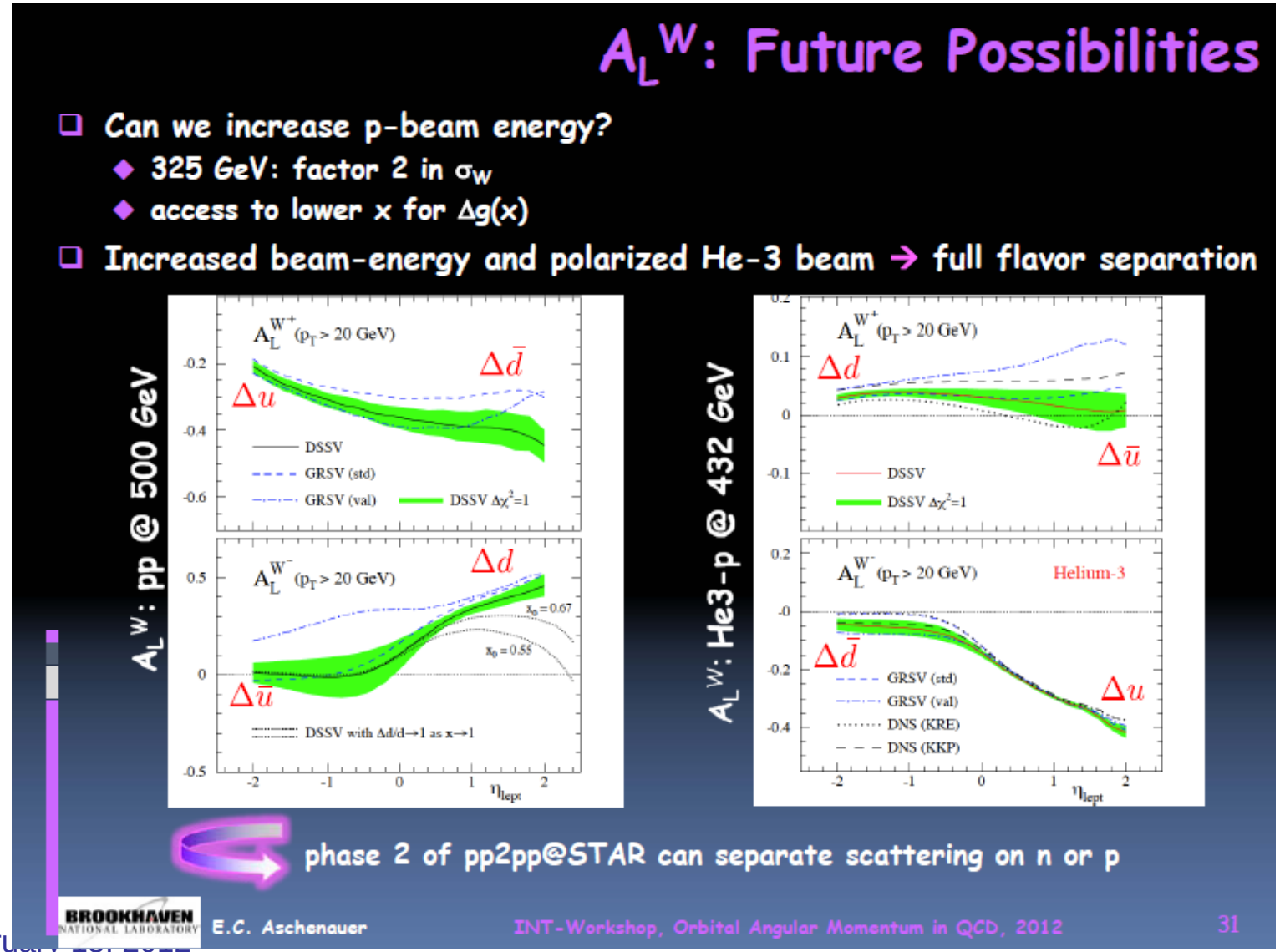
Polarized He-3 in RHIC

- Resent workshop to review status and R&D needs for polarized He-3 acceleration
- Polarized He-3 from new EBIS; test soon possibly starting with unpolarized He-3
- Polarimetry:
  - Relative: He3-C CNI polarimeter;
  - Absolute: He3-He3 CNI polarimeter using polarized He-3 jet
- Depolarizing resonances are stronger; no depolarization expected with six snakes in RHIC
- Physics from polarized p-He3? High luminosity may be possible (see below)



RHIC upgrades: Helium-3

- Aschenauer's talk on Feb.6



RHIC upgrades: Luminosity

- High luminosity
  - Coherent electron cooling

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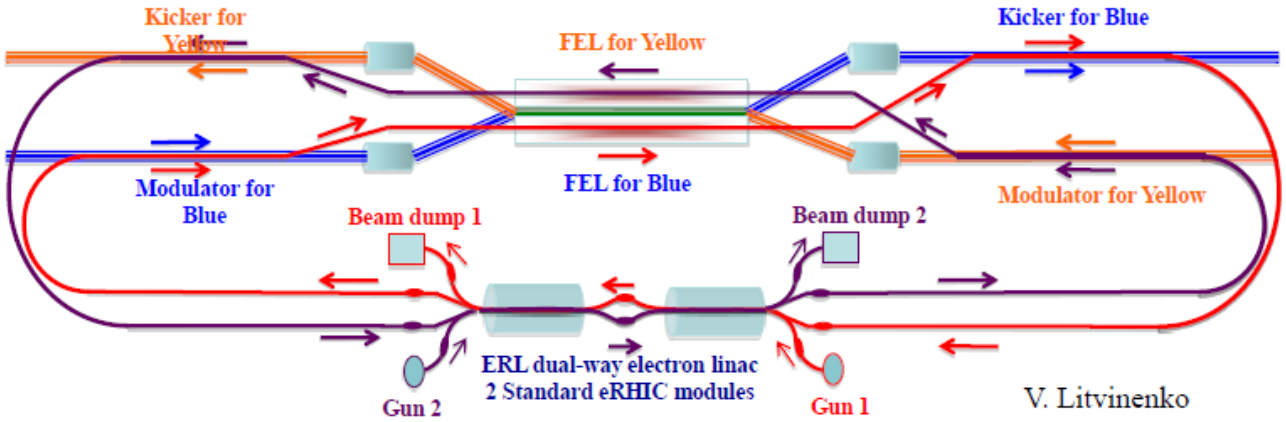
Coherent electron Cooling for RHIC

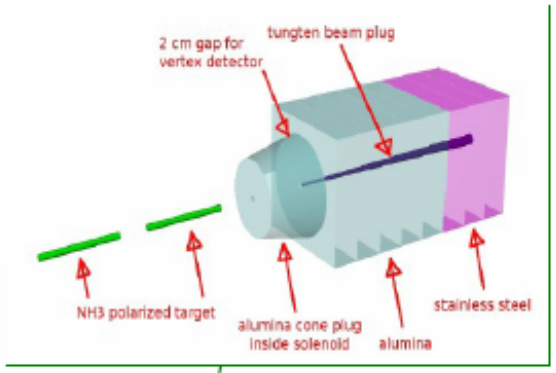
- RHIC: overlap length ~ 10 cm, ε_n (95%) ~ 1 π μm , β* ~ 10 cm □ ~ x10 luminosity increase
- Together with eLens beam-beam compensation 5 x10^{33} cm^{-2} s^{-1} might be possible for 500 GeV pp (~ 25 interactions per crossing)
- LHC demonstrated 30 interactions per crossing is OK, planning for 200!
- Effect of long range beam-beam?
- Possible layout in RHIC IP of CeC driven by a single linac:



COMPASS experiment

- COMPASS-II polarized Drell-Yan

COMPASS II: Drell-Yan

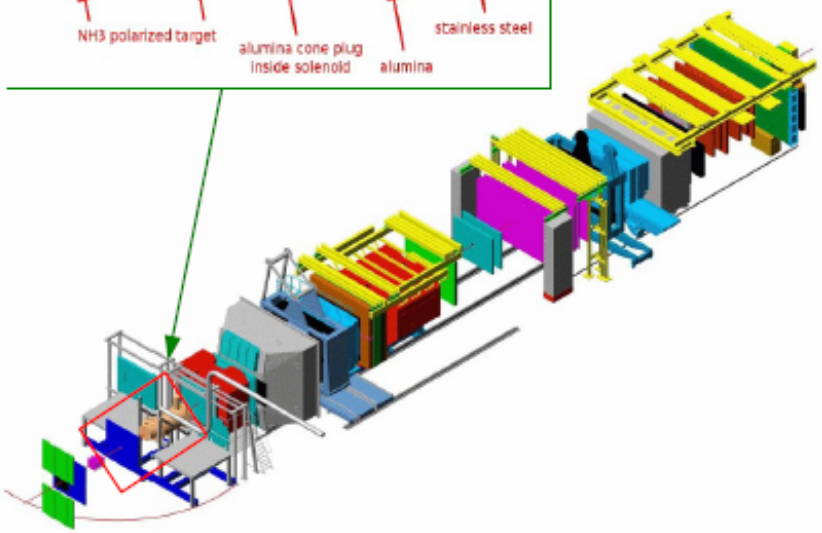


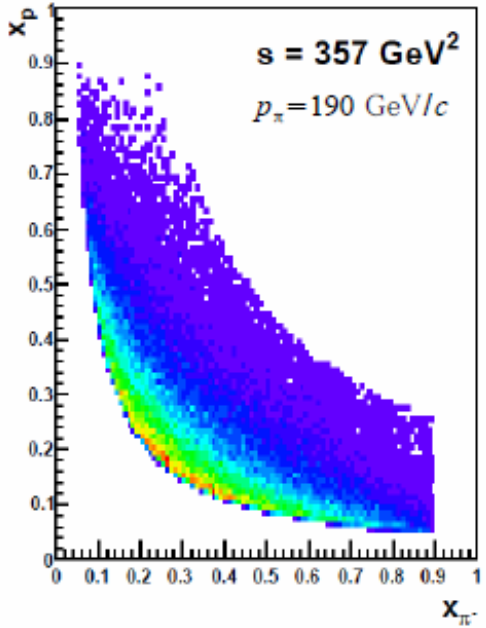
190 GeV/c pion beam

Pol. NH3

Single polarized

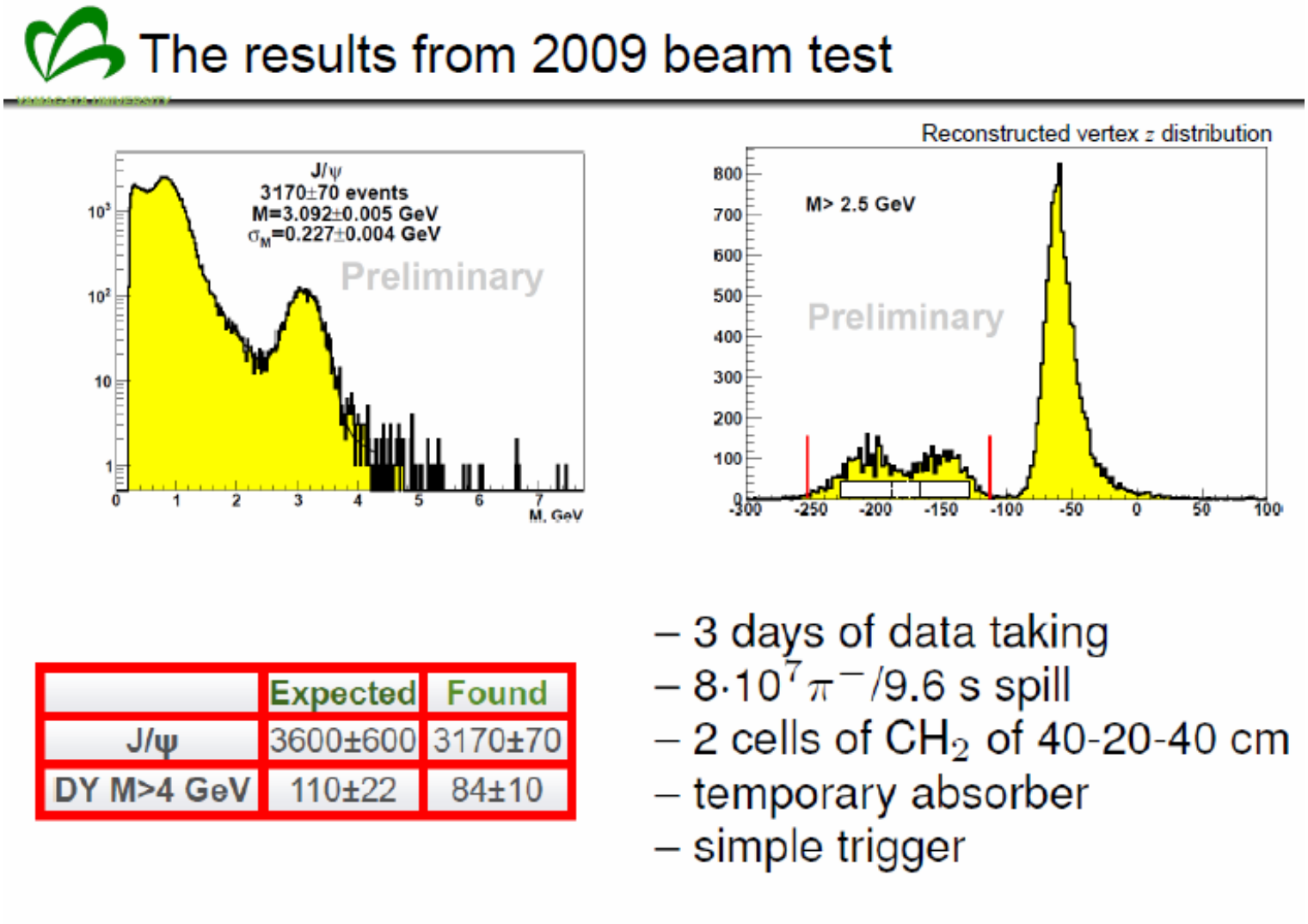
π-p Drell-Yan





COMPASS experiment

- COMPASS-II polarized Drell-Yan



	Expected	Found
J/ψ	3600±600	3170±70
DY M>4 GeV	110±22	84±10

COMPASS experiment

- COMPASS-II polarized Drell-Yan

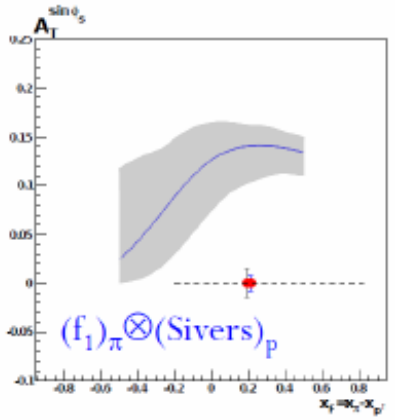
Projections for azimuthal asymmetries

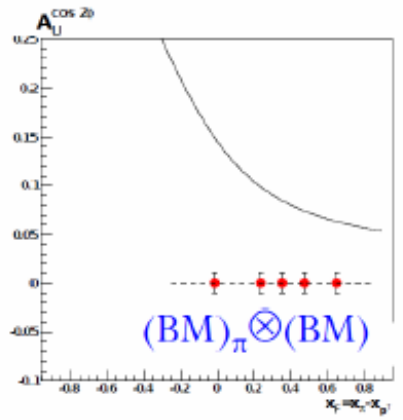
projections with
2 years of data
$6 \cdot 10^8$ π spill (9.6 s)
1.1 m pol. NH_3

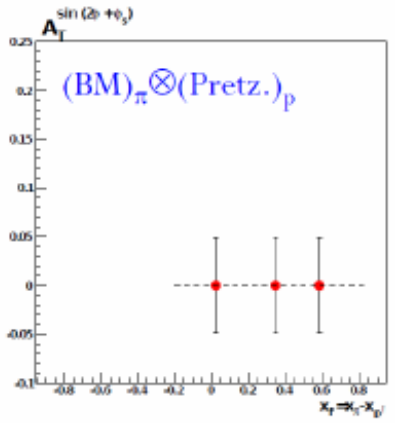
$$p_\pi = 190 \text{ GeV}/c$$

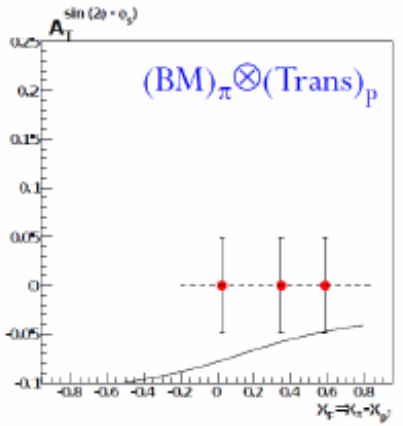
$$4 < M_{\mu\mu} < 9 \text{ GeV}/c^2$$

Asymmetry	Dimuon mass (GeV/c^2)		
	$2 < M_{\mu\mu} < 2.5$	J/ψ region	$4 < M_{\mu\mu} < 9$
$\delta A_U^{\cos 2\phi}$	0.0020	0.0013	0.0045
$\delta A_T^{\sin \phi_S}$	0.0062	0.0040	0.0142
$\delta A_T^{\sin(2\phi+\phi_S)}$	0.0123	0.008	0.0285
$\delta A_T^{\sin(2\phi-\phi_S)}$	0.0123	0.008	0.0285







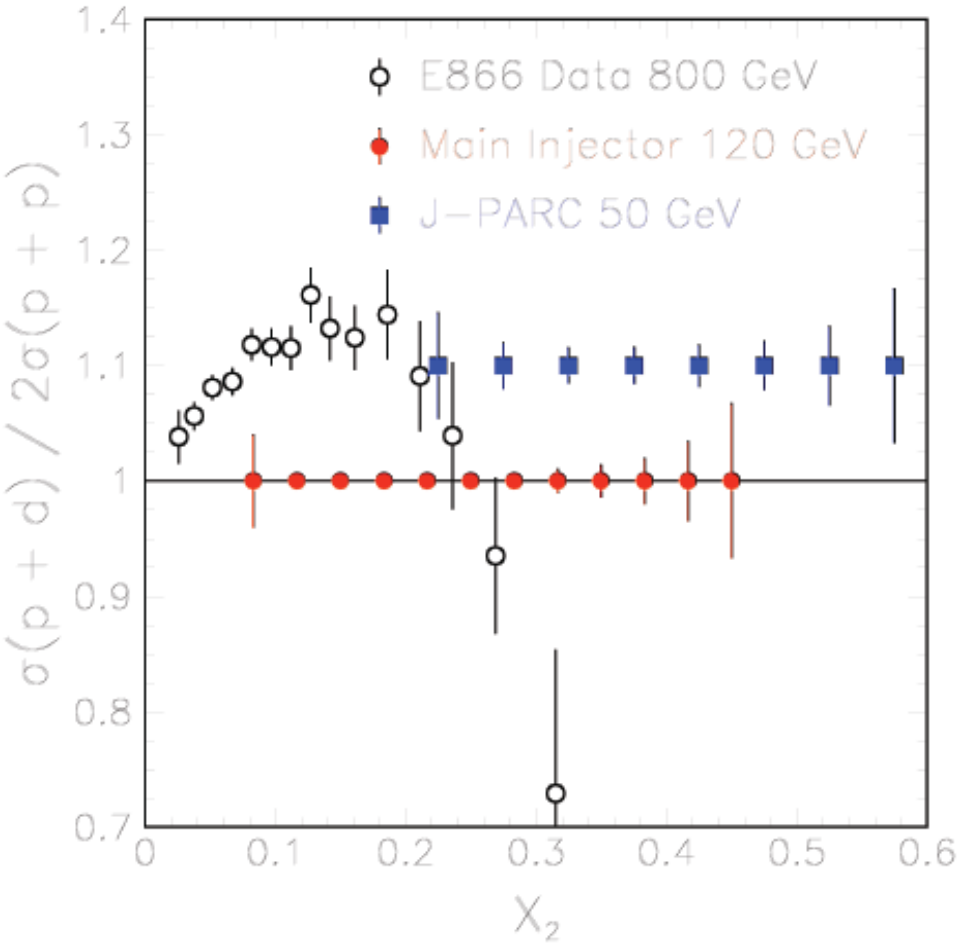


J-PARC proposal/LoI

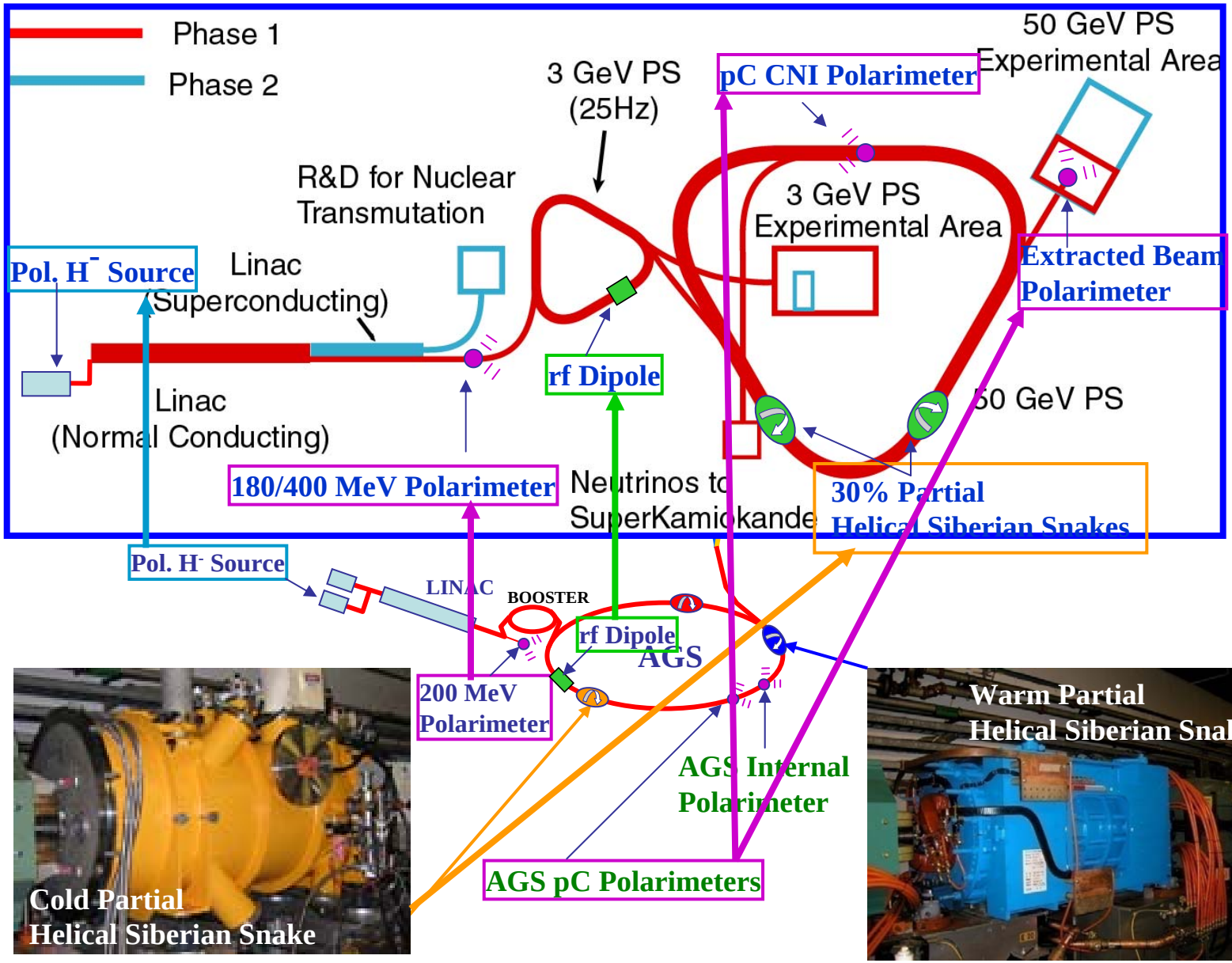
- P04: measurement of high-mass dimuon production at the 50-GeV proton synchrotron
  - spokespersons: Jen-Chieh Peng (UIUC) and Shinya Sawadas (KEK)
  - “deferred”
- P12-LoI: study of parton distribution function of mesons via Drell-Yan process at J-PARC at high-p beamline
  - spokesperson: Seonho Choi (Seoul National University)
- P24: polarized proton acceleration at J-PARC
  - contact persons: Yuji Goto (RIKEN) and Hikaru Sato (KEK)
  - “no decision”

J-PARC P04 proposal

- Flavor asymmetry of sea-quark distribution
- Unpolarized Drell-Yan
  - Higher-x coverage
  - 10^{12} protons per spill (3s)
  - 50-cm long LH2/LD2 targets
  - 60-day runs for each targets
  - Assuming 50% efficiency



Polarized proton acceleration at J-PARC



Summary

- Fermilab SeaQuest experiment
  - Flavor asymmetry of sea-quark distribution
    - Spatial distribution of sea-quarks in the nucleon $\leftrightarrow$ OAM
  - Boer-Mulders distribution
  - Nuclear matter
- Polarized Drell-Yan experiments
  - Sivers distribution
    - AnDY/COMPASS/…
  - RHIC polarized programs
    - Detector/accelerator upgrades
  - possible future extension of SeaQuest experiment
    - Polarized beam/target at Fermilab
    - RHIC/J-PARC
  - Flavor asymmetry of sea-quark polarization
    - High luminosity accumulation is very important