Discussions at PKU: New Spin Physics Results

JLab: a New Paper on Physical Review Letters

RHIC/PHENIX: a New Surprise from p↑+A Run2015

Xiaodong Jiang (Los Alamos) 10/15/2015

A New Paper on Phys. Rev. Lett. (in print, arXiv:1502.02636).

- First measurement of a new observable for nucleon structure, forbidden at the leading-order.
- 10x improvements over the last measurement (SLAC-1970).

A New Surprise from RHIC/PHENIX p↑+A Run2015 (preliminary)

- First measurement of forward neutron spin asymmetry in p↑+A.
- Very surprising asymmetry behavior in p↑+p, vs p↑+AL, p↑+Au.

Drell-Yan Experiments with Polarized Targets at Fermilab:

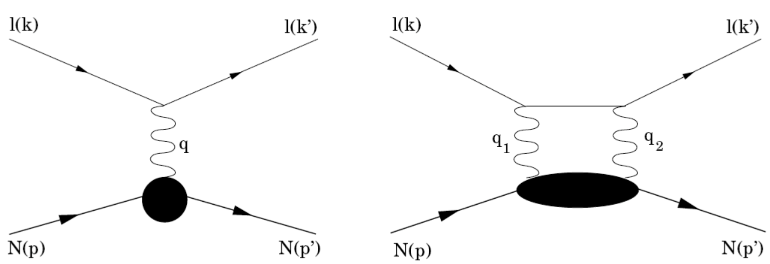
- Polarized target D-Y spin-asymmetry measurements (E1039).
- (Search for Dark-Photons/Higgs through di-muon production.)

Can electrons tell left-right in elastic scattering on a nucleon ?

$$N^{\uparrow}(e, e')N$$

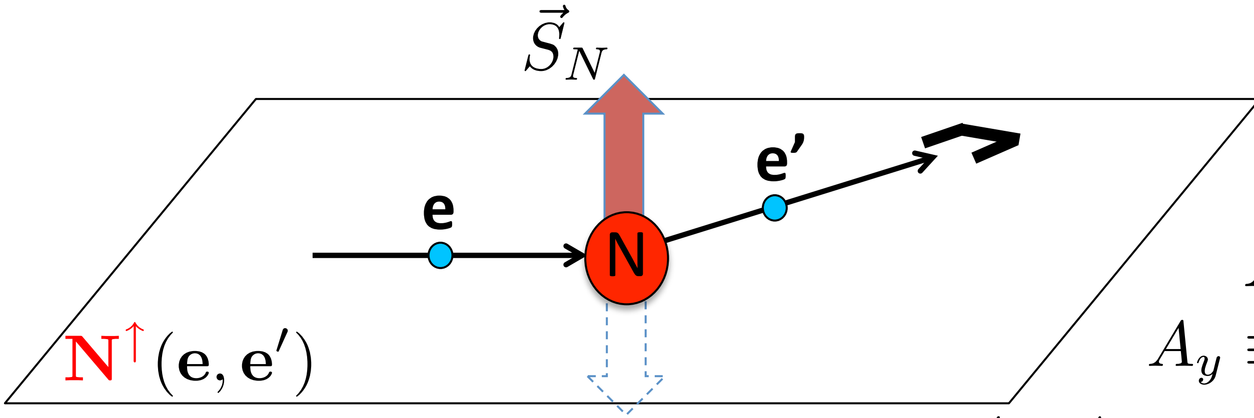
Not allowed, if only one-photon exchange, no imaginary piece in the scattering amplitude.

Yes, from interference between one- and two-photon exchange amplitudes.



Experiment E05-015 @ Jefferson Lab Hall A

Target Single-Spin Asymmetry in $\mathbf{N}^{\uparrow}(\mathrm{e}, \mathrm{e}')$



$$A_y = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$$A_y \propto (\vec{e} \times \vec{e'}) \cdot \vec{S}_N$$

$$A_y \equiv 0 \text{ under } 1\gamma \text{ exchange}$$

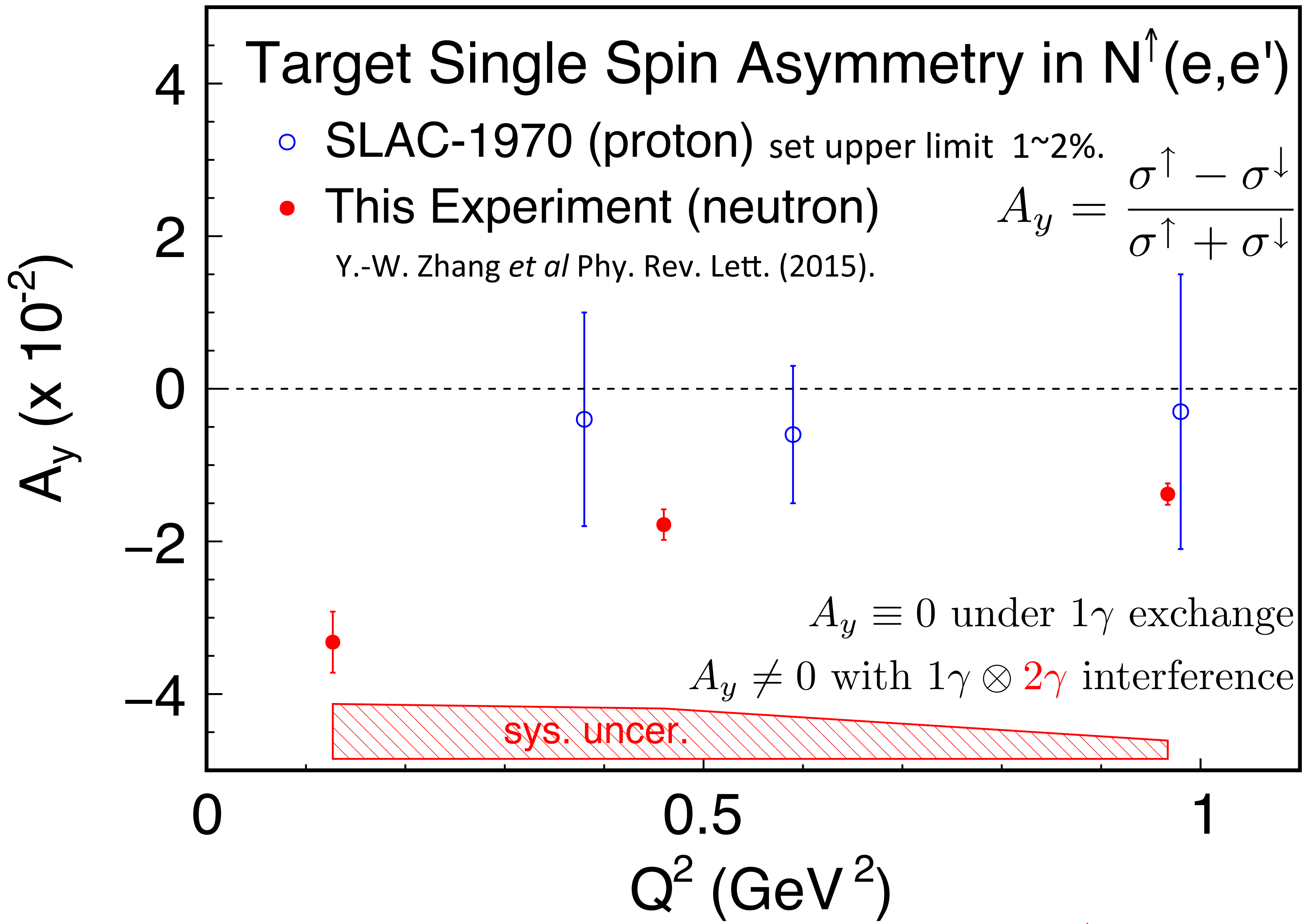
$$A_y \neq 0 \text{ with } 1\gamma \otimes 2\gamma \text{ interference}$$

Q: any difference in electron's scattering probability between target spin-Up vs spin-Down ?

A: **Yes. Definitely !!!**

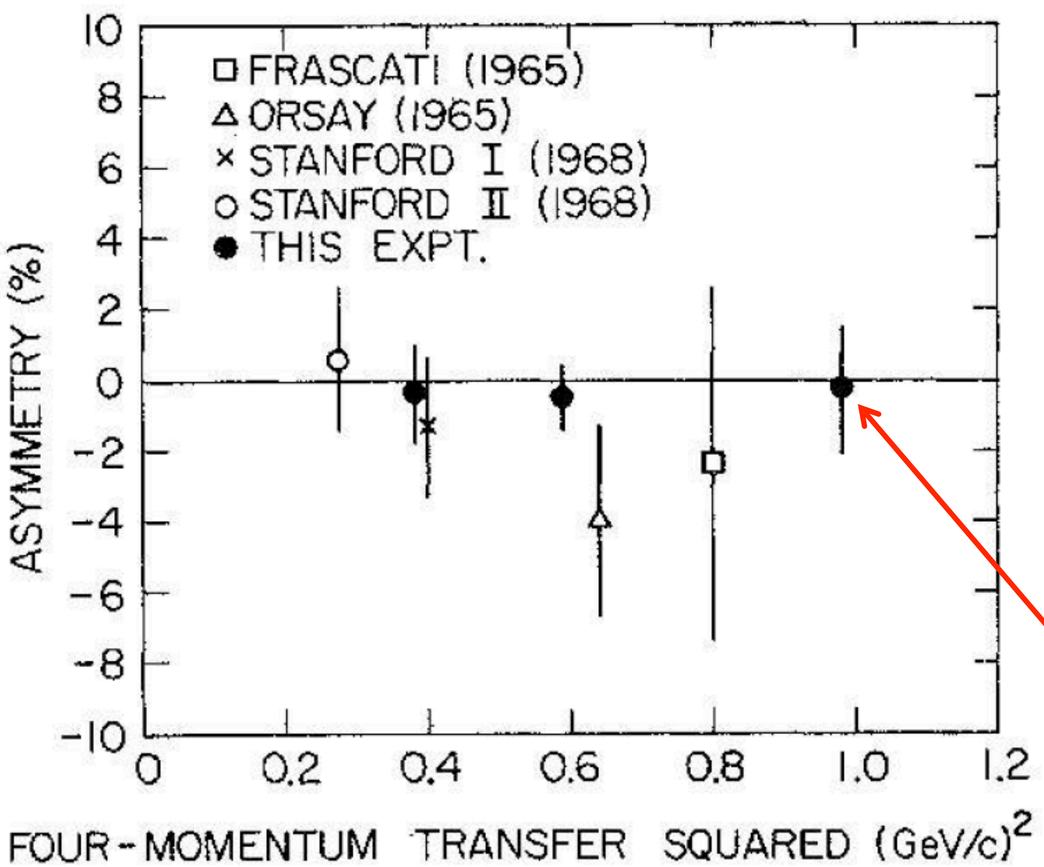
- Time-Reversal Odd observable, forbidden at the leading-order.
- Non-zero A_y has never been measured.
- New precision tool to study the fundamental sub-structure of nucleon, provides access to the moments of nucleon's Generalized-Parton-Distributions (GPDs).

- The last experiment was in 1970, set an upper limit of 1~2%. T. Powell *et al*, PRL 753, **24** (1970).
- Jefferson Lab E05-015: Y.-W. Zhang Ph.D. Rutgers (2013). Co-PI: T. Averett (W&M), J.-P. Chen (JLab), X. Jiang (LANL).



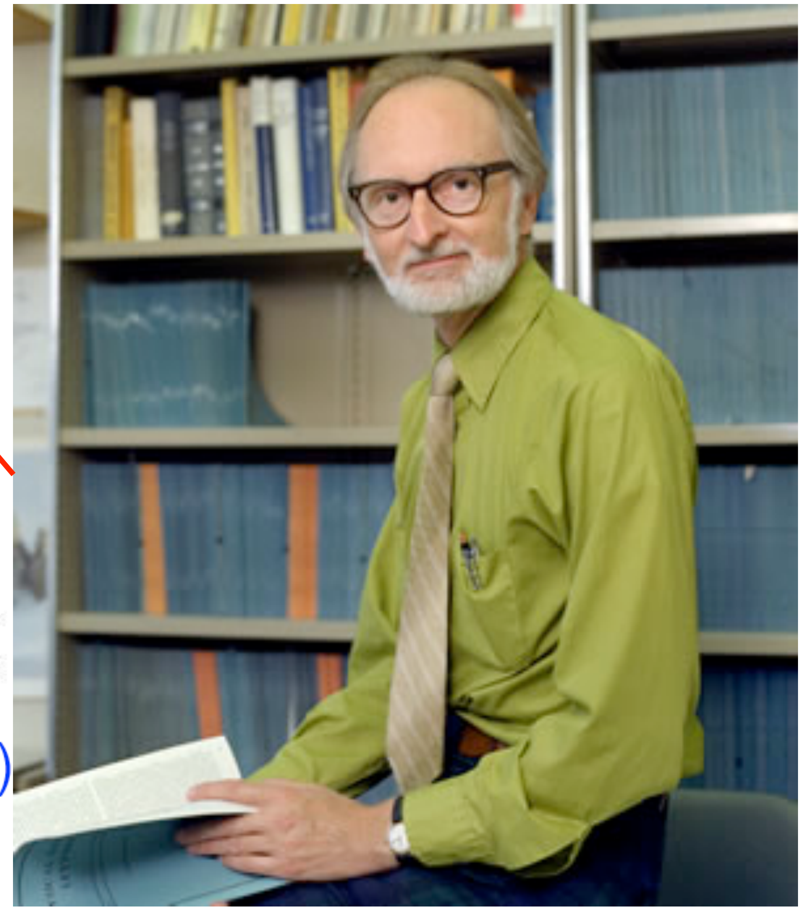
- First observation of a non-zero target single-spin asymmetry in $\mathbf{N}^{\uparrow}(\mathbf{e}, \mathbf{e}')$
- The last measurement was SLAC-1970, led by O. Chamberlain (Nobel 1959, discovered $\overline{p}$).
- Polarized ^{3}He as an effective polarized neutron target, in quasi-elastic kinematics.

A non-vanishing inclusive A_y has never been observed



SLAC, T. Powell *et al.*, PRL **24**, 753 (1970)

The last effort was made at Stanford in 1969, black dots. Set an upper limit: A_y<2% for proton.



Owen Chamberlain (1920-2006)
Nobel physics 1959.

Control of Systematic Uncertainties

Many things could change between target spin flips

- Beam intensity, beam charge…
- Target density…
- Detector responses, DAQ dead time…
- Background. Track reconstruction Eff. …

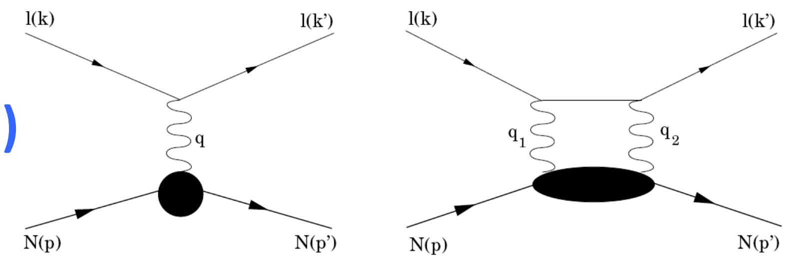
Each term caries its own correction factor

$$A_{meas} = \frac{\frac{N^{\uparrow}}{\mathcal{L}^{\uparrow}} - \frac{N^{\downarrow}}{\mathcal{L}^{\downarrow}}}{\frac{N^{\uparrow}}{\mathcal{L}^{\uparrow}} + \frac{N^{\downarrow}}{\mathcal{L}^{\downarrow}}} = \frac{N^{\uparrow} - N^{\downarrow} \cdot \frac{\mathcal{L}^{\uparrow}}{\mathcal{L}^{\downarrow}}}{N^{\uparrow} + N^{\downarrow} \cdot \frac{\mathcal{L}^{\uparrow}}{\mathcal{L}^{\downarrow}}}$$

➔Need to control raw false asymmetry.

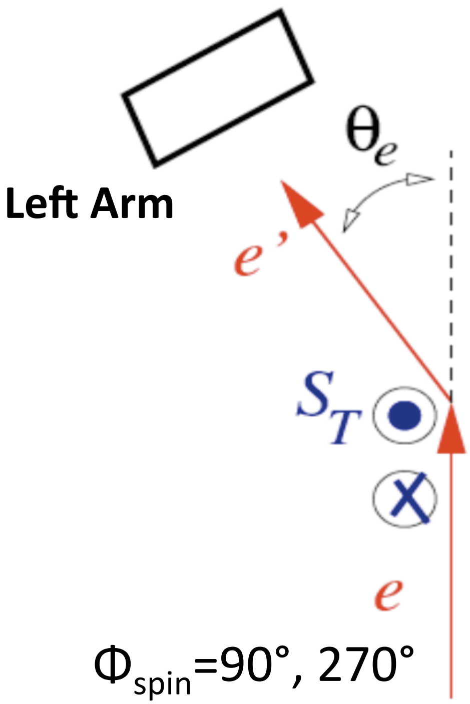
Clearly demonstrate the physics signal .

Example: Target Single-Spin Asymmetry in inclusive $^3He^{\uparrow}(e,e')$ scattering (Quasi-Elastic)

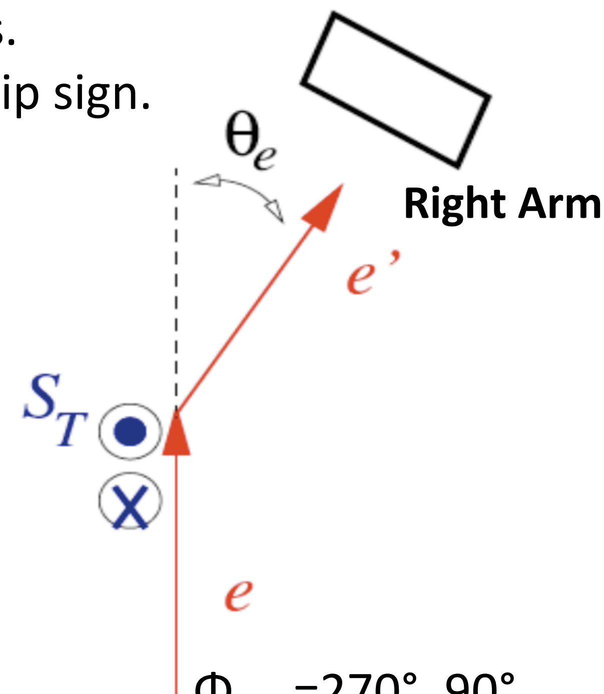


A_y arises from interference of one- and two-photon exchange, provides access to weighted moments of GPD E and H.

Two independent measurements.
Real physics asymmetry should flip sign.



$$A_y = \frac{N_\uparrow - N_\downarrow \cdot \frac{\mathcal{L}_\uparrow}{\mathcal{L}_\downarrow}}{N_\uparrow + N_\downarrow \cdot \frac{\mathcal{L}_\uparrow}{\mathcal{L}_\downarrow}}$$



Φ_{spin}=90°, 270°

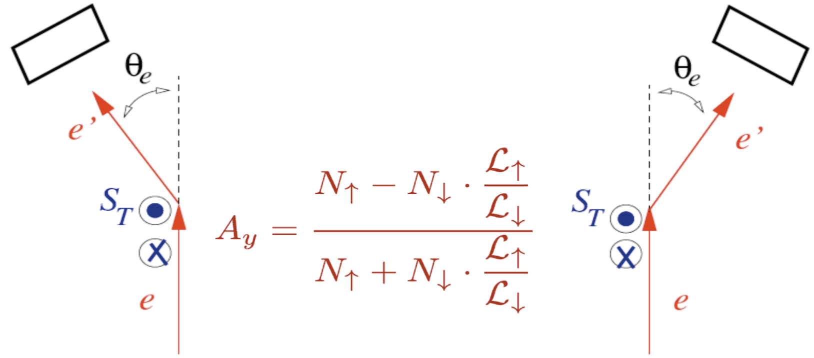
$$(\vec{e} \times \vec{e}\,') \bullet \vec{S}_T > 0$$

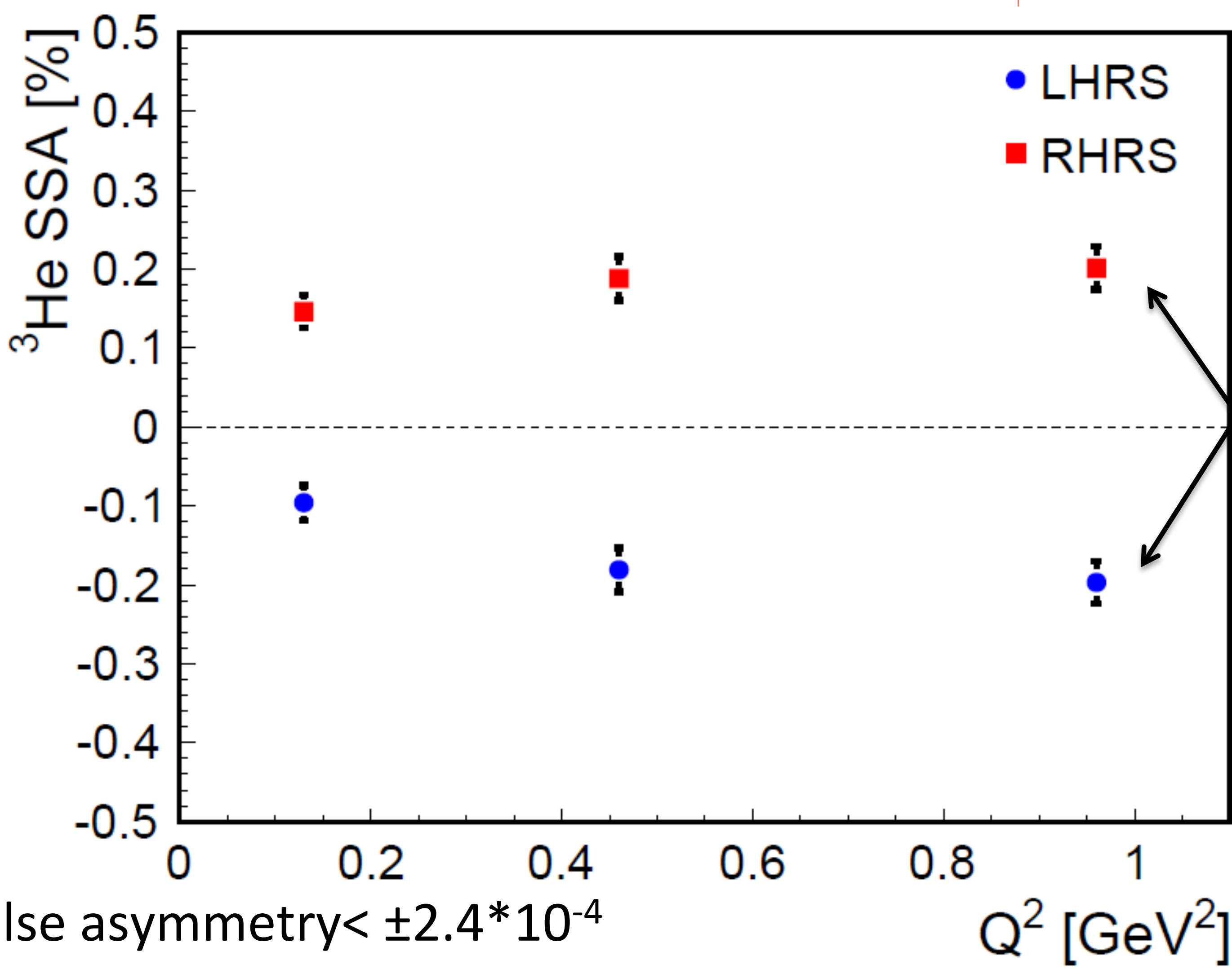
Φ_{spin}=270°, 90°

$$(\vec{e} \times \vec{e}\,') \bullet \vec{S}_T < 0$$

$^{3}He^{\uparrow}(e,e')$

Q^2 = 0.13, 0.46 and 0.98 GeV^2 , Quasi-Elastic





Φ_{spin}=90°, 270°

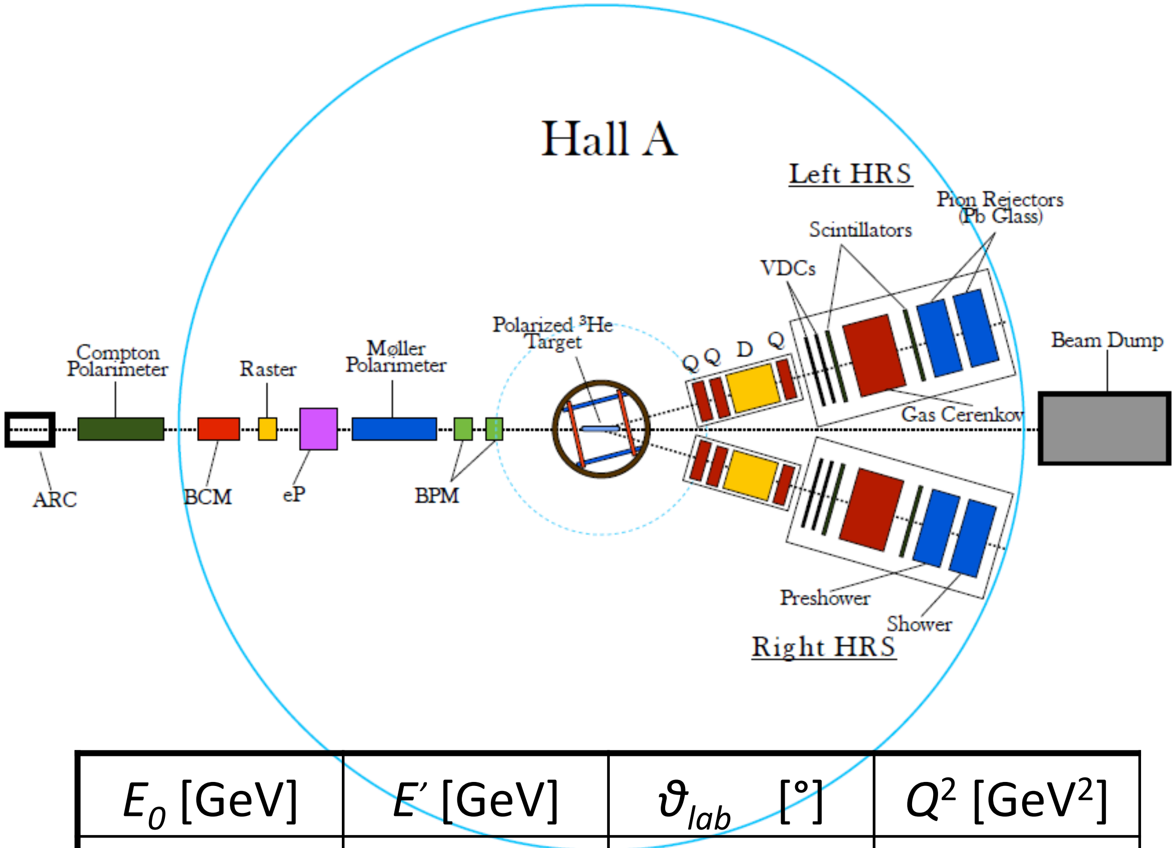
Physics SSA flip signs between two independent measurements.

Φ_{spin}=270°, 90°

False asymmetry< ±2.4*10^{-4}

The Measurements

Jefferson Lab Hall A.

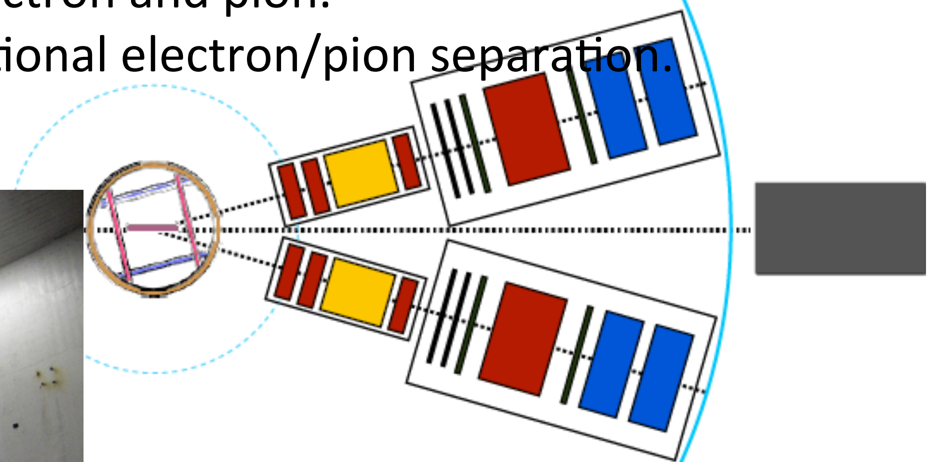


E_0 [GeV]	E' [GeV]	ϑ_{lab} [°]	Q^2 [GeV^2]
1.25	1.17	17	0.13
2.43	2.17	17	0.46
3.61	3.07	17	0.97

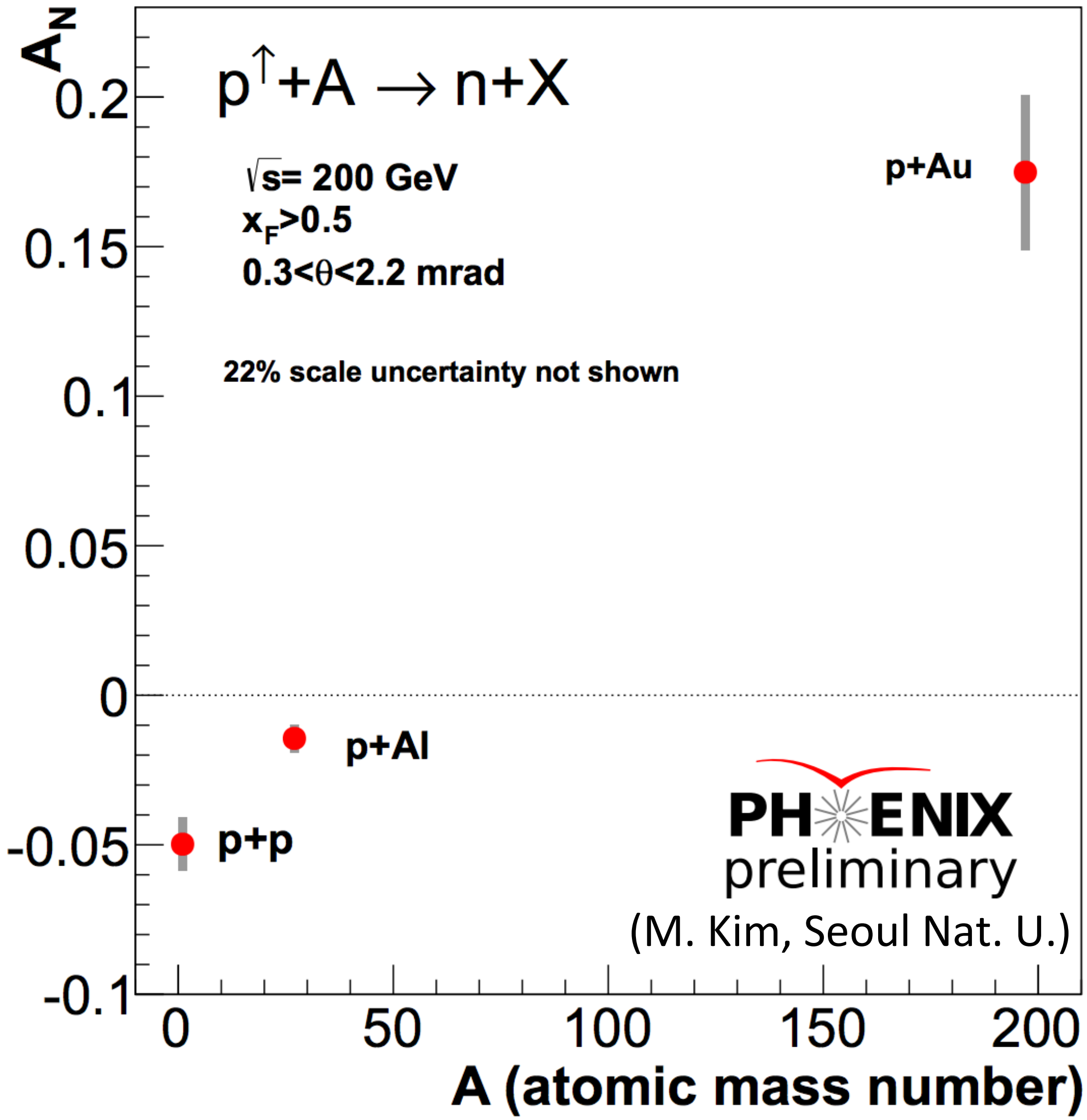
The Measurements

High Resolution Spectrometers (HRSs): Detects scattered electrons from $^{3}He(e,e')$

- Vertical Drift Chambers (VDCs): Determine the trajectory of the particles.
- Trigger Scintillators: Generate the trigger information.
- A Gas Cherenkov: Separate electron and pion.
- Lead-Glass Calorimeters: Additional electron/pion separation.



A New Surprise from RHIC/PHENIX p↑+A Run-2015



Single-spin asymmetry reveals left-right bias of neutrons:

- Favor the right side of proton spin vector in p↑+p.
- Favor the right-side of proton spin vector in p↑+Au.

Expecting more surprises from LANL group's spin analysis efforts:

- Forward hadrons and muons.
- Forward J/Ψ, and final state spin-orientations.
- Particles and reaction-plane correlations in p↑+A

- First measurement of forward neutron spin asymmetry in p↑+A.

At Fermilab: Fixed Target Drell-Yan Experiments

Two approved NEW experiments:

- Polarized proton target single-spin asymmetry (E1039): p+p↑ -> γ* (μ+ μ-) + X
- Search of Dark-Photon Dark-Higgs signal (P1067): p+p -> γ-Dark (μ+ μ-) + X

Currently running (E906, will be finishing in 2016):

- Proton/Deuteron target ratio (dbar/ubar): p+p (D) -> γ* (μ+ μ-) + X
- Nuclear target (quark energy loss): p+A -> γ* (μ+ μ-) + X

Can be expand into **(New Proposals with expanded Collaboration in 2016)**:

- 3He/4He target yield ratio (dbar/ubar in dense nuclear medium): p+3He (4He) -> γ* (μ+ μ-) + X
- Polarized Deuteron target single-spin asymmetry: p+D↑ -> γ* (μ+ μ-) + X

Introduction: single-spin asymmetry in $p\,p^{\uparrow} \rightarrow \pi X$

E704 √s =20 GeV.
PLB 264 (1991) 462.

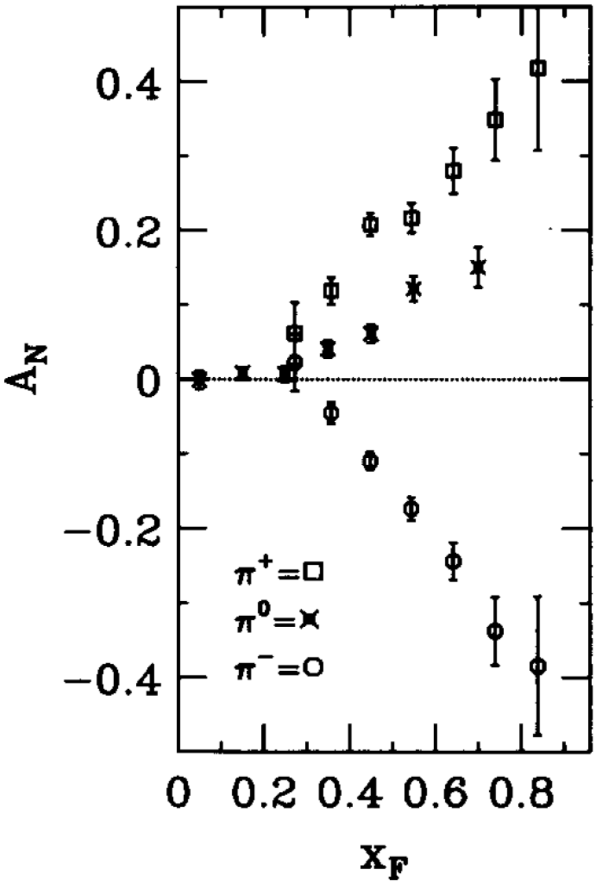
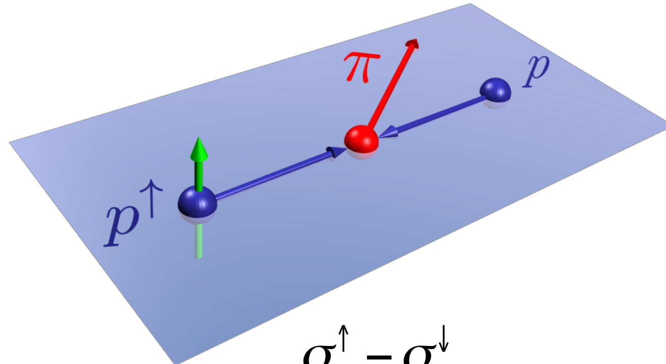


Fig. 4. A_N versus x_F for π^+, π^- and π^0 data.



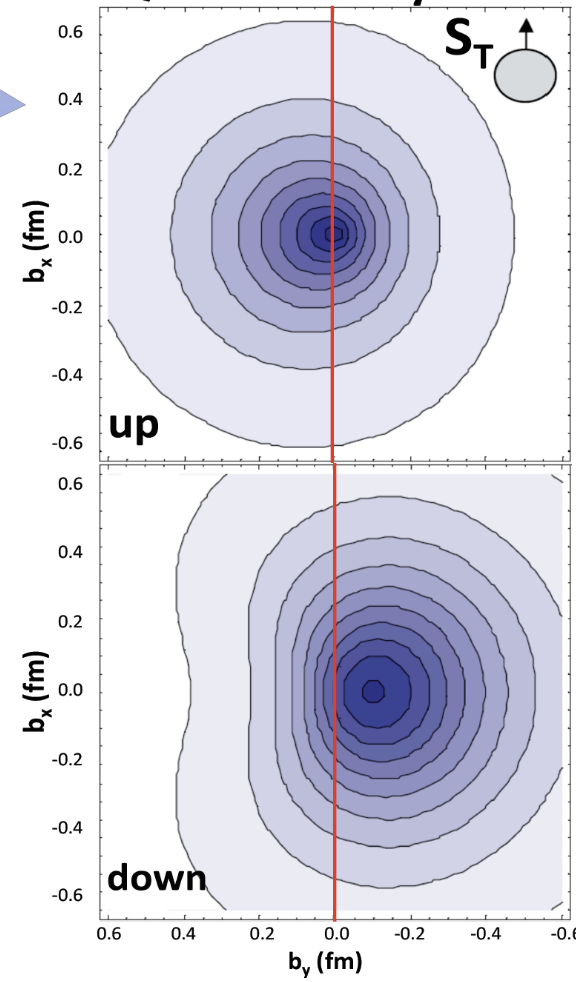
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$\pi^+ \, (u\bar{d})$ favors left

$\pi^- \, (d\bar{u})$ favors right

One possible explanation (Sivers effect): quark transvers motion generates a left-right bias.

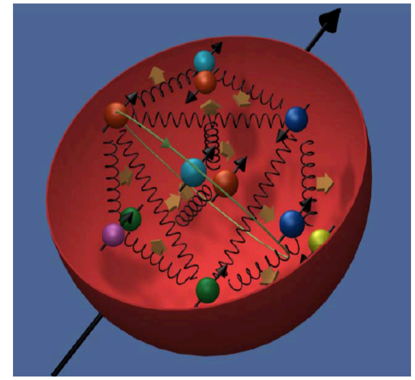
Quark Density in 2D



Lattice QCD PRL98:222001,2007.

Quarks in a transversely polarized nucleon can tell left-right, up-quarks favor left, down-quarks favor right.

Quark Orbital Momentum and the Sivers Function

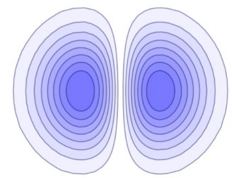


The Sivers function is the distribution of unpolarized quarks in a transversely polarized proton

$$\vec{L} = \vec{b} \times \vec{k}$$

$$f_{q/P^{\uparrow}}(x, \mathbf{k}_{\perp}, S) = f_1(x, \mathbf{k}_{\perp}^2) - \frac{\mathbf{S} \cdot (\hat{\mathbf{P}} \times \mathbf{k}_{\perp})}{M} f_{1T}^{\perp}(x, \mathbf{k}_{\perp}^2)$$

quark density 

 Sivers distribution

Sivers distribution was believed to vanish until 2002!

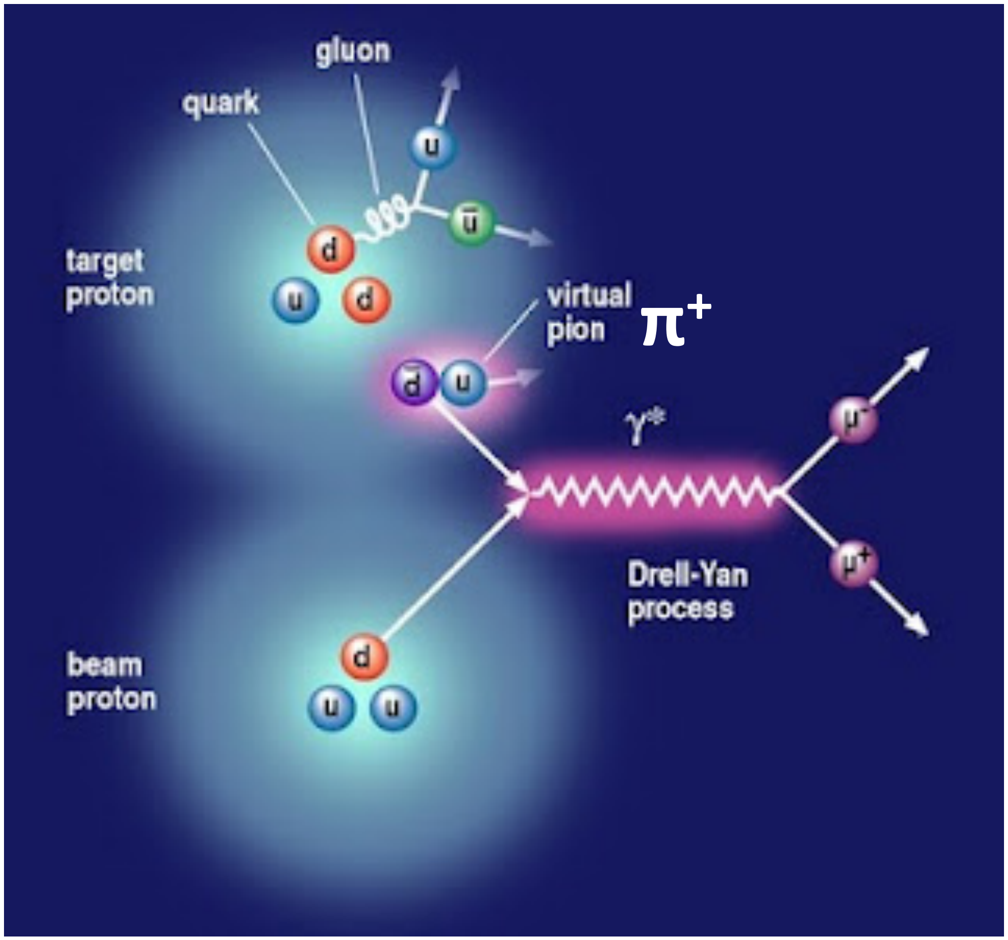
- Naive T-odd, not allowed for collinear quarks. Transverse Mom. Dep. parton distributions (TMD).
- Imaginary piece of interference $L_q=0$ ✖ $L_q=1$ quark wave functions.

Sivers function = 0 ⇔ $L_q=0$

Sea quark Sivers function =0 ?

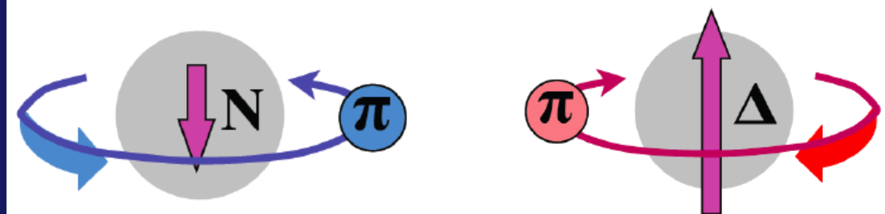
The meson cloud model explains the flavor asymmetry in the sea, and requires quarks to carry angular momentum.

$|p\rangle = p + N\pi + \Delta\pi + \ldots$



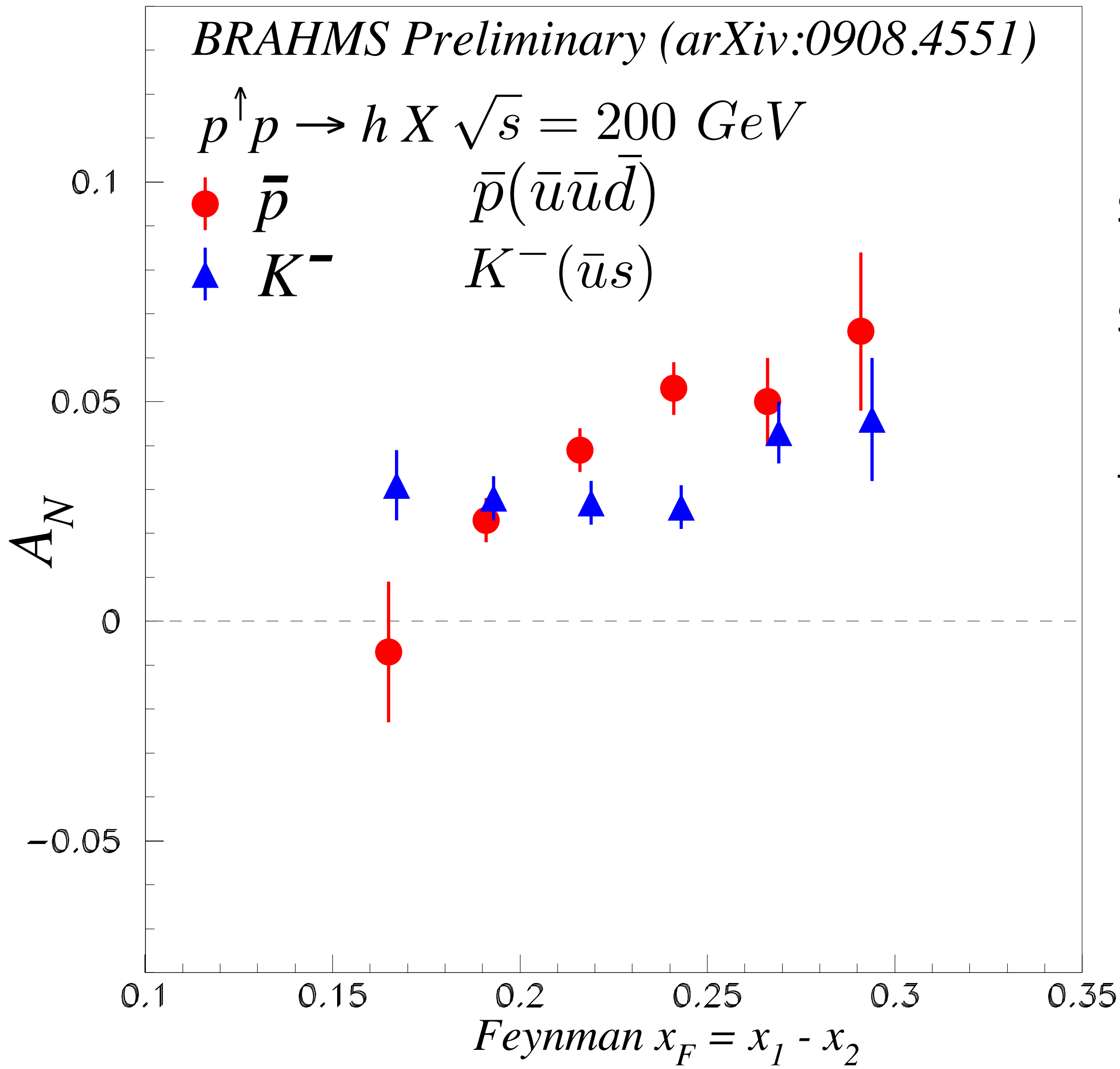
Pions $J^p=0^-$ Negative Parity

Need **L=1** to get proton's $J^p=½^+$



Sea quarks should carry orbital angular momentum.

Hints of Non-Vanishing Sea Quark Sivers Distribution ?

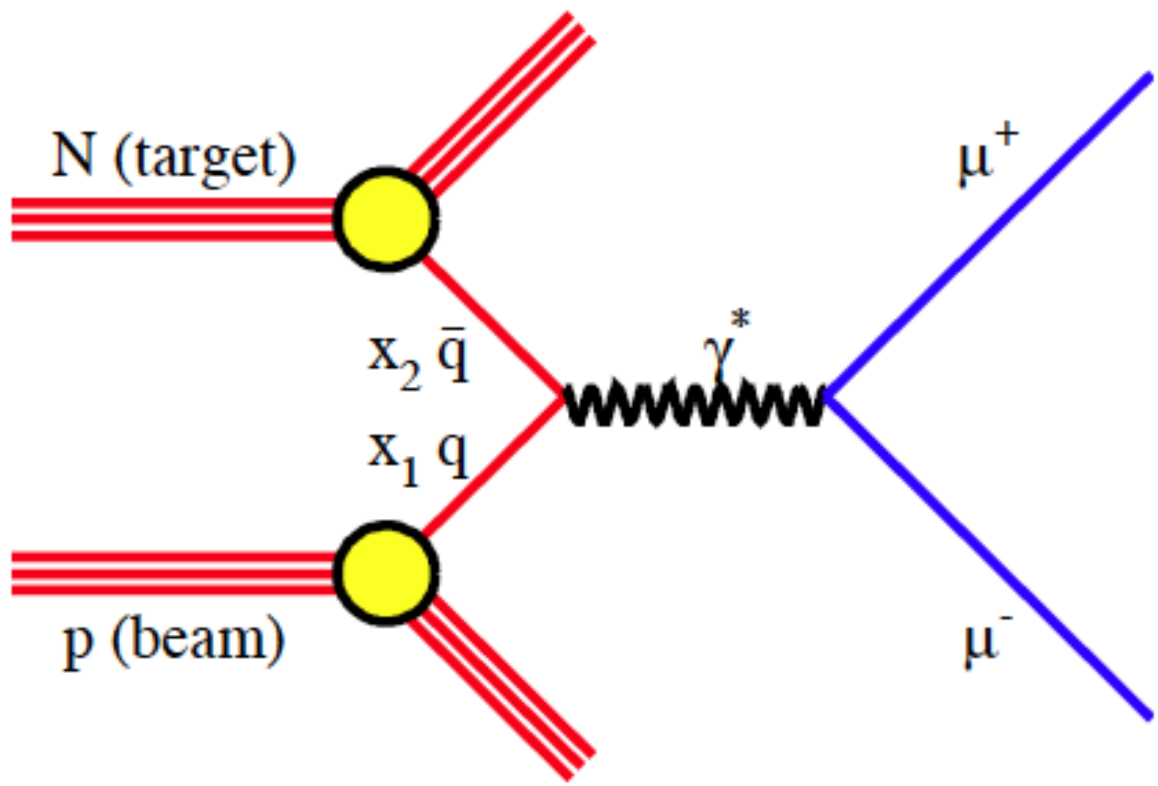


Sea quark generates left-right bias ?

Secondary string-breaking ?

Left-right bias generated through fragmentation process ?

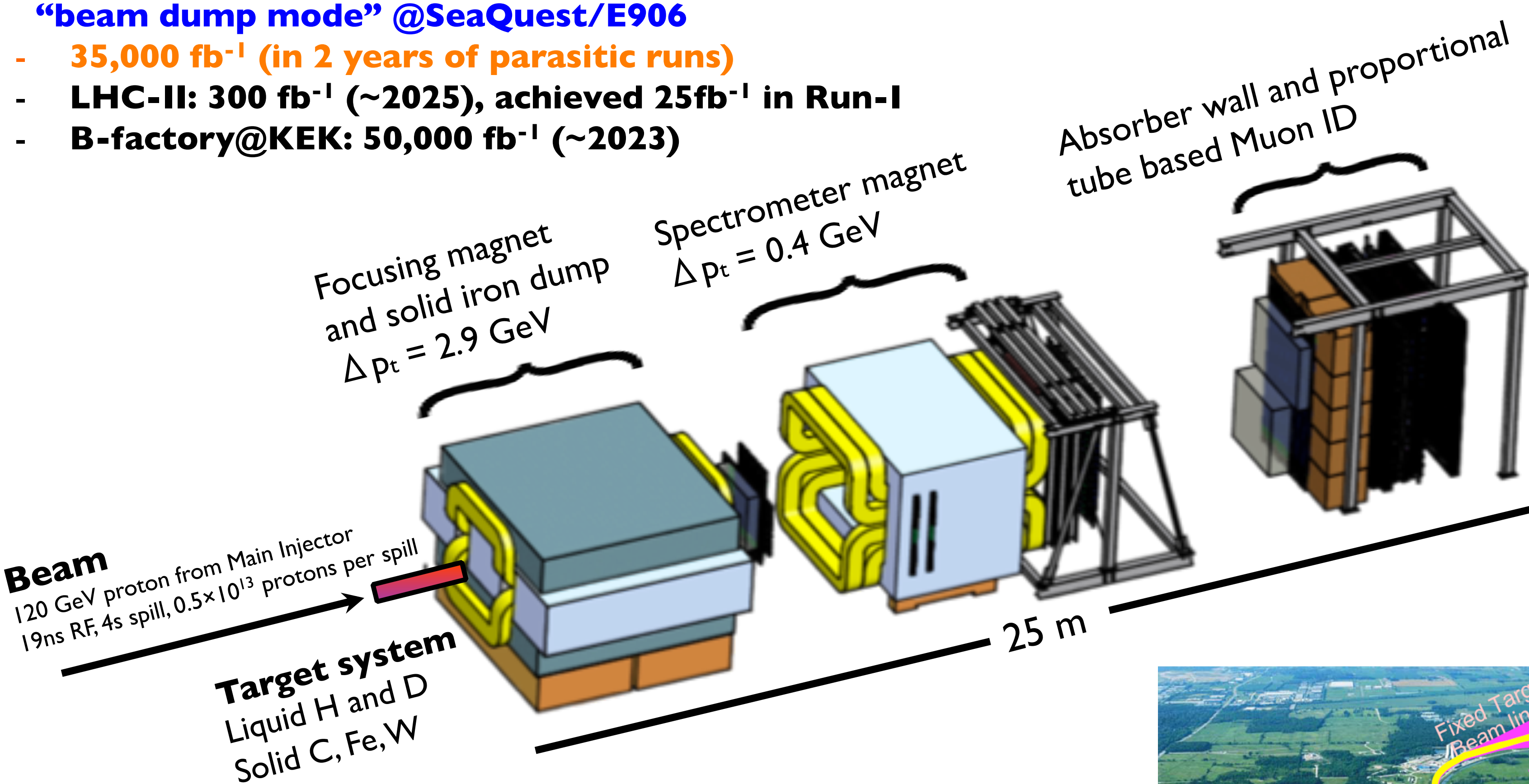
Drell-Yan Reaction Provides Access to Sea Quark Information



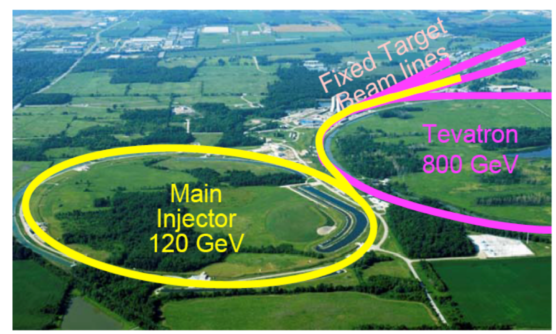
Intensity Frontier at Fermilab: 120 GeV Beam

World's highest intensity high energy proton beam:
"beam dump mode" @SeaQuest/E906

- **35,000 fb^{-1} (in 2 years of parasitic runs)**
- **LHC-II: 300 fb^{-1} (~2025), achieved 25fb^{-1} in Run-I**
- **B-factory@KEK: 50,000 fb^{-1} (~2023)**

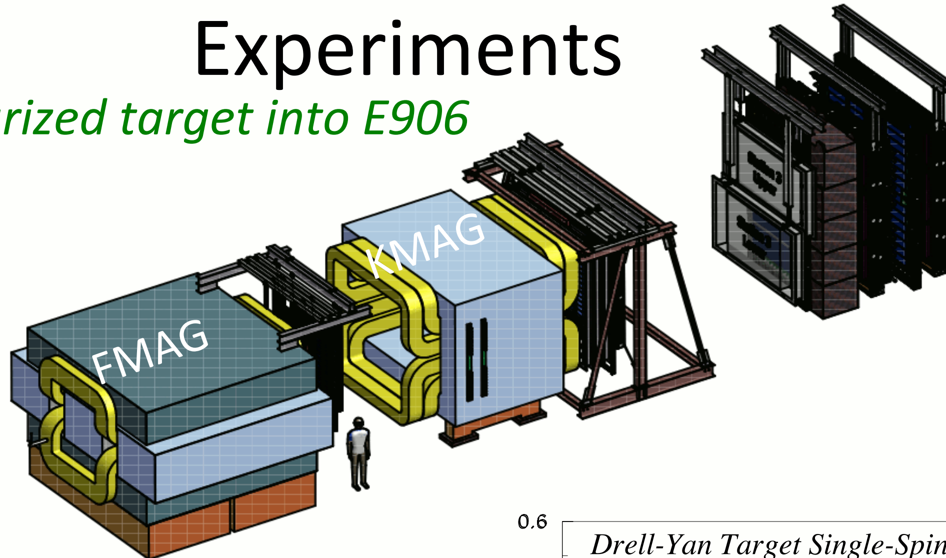


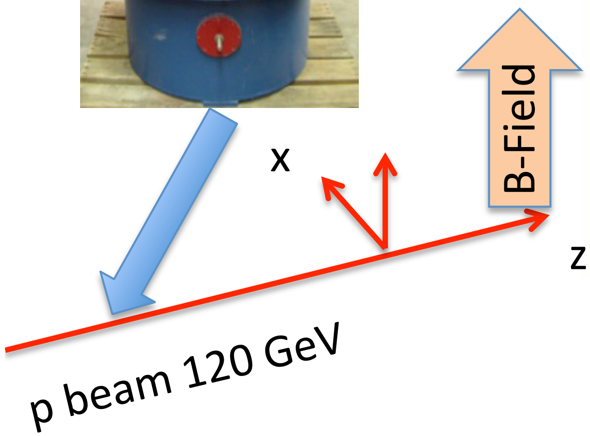
- Capture most beam in beam dump mode: p+Fe collisions!
- Parasitic run mode possible with other experiments, E1039/E1027

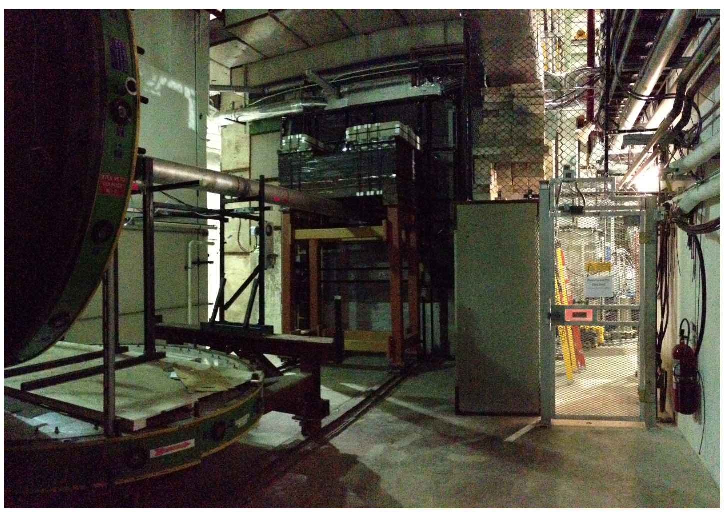


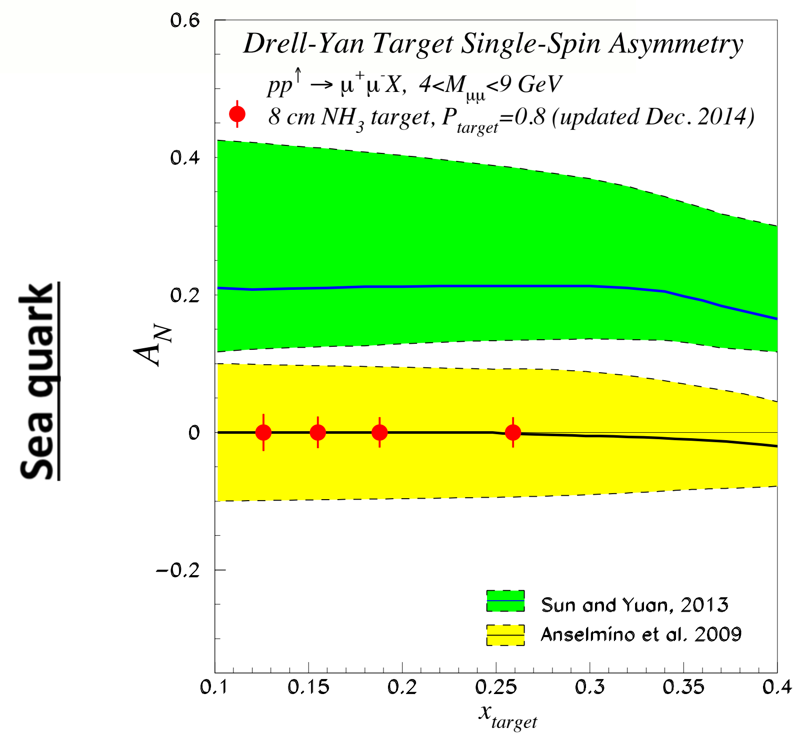
Fermilab E1039: Fixed Target Drell-Yan Experiments

Install polarized target into E906

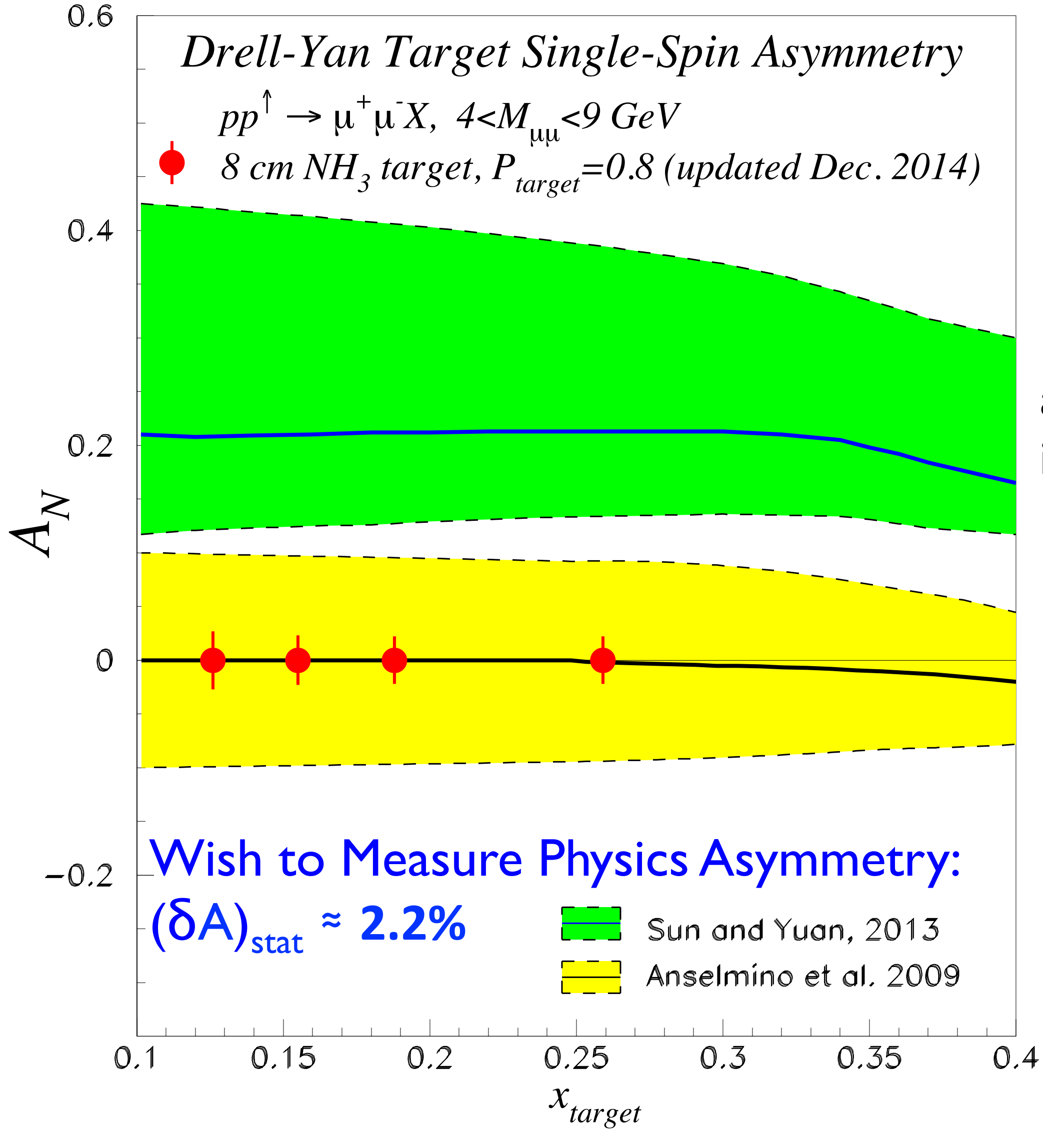








The Goal of E1039: Projected Precisions



$$A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$$

Sivers function = 0 ⇔ L_q=0

Existing data do not constrain sea quark's angular motion (Sivers distribution), neither in sign nor in value.

If $A_N \neq 0$, a major discovery:

- "Smoking Gun" evidence for $L_{ubar} \neq 0$
- Strong impacts to physics at EIC.

If $A_N = 0$, a major puzzle:

- L_{ubar}=0, spin puzzle more dramatic ?
- Contradict to Lattice QCD and Meson Cloud Model.

Need to control physics asymmetry systematics to: $(\delta A)_{sys} \approx 1.0$ %

Statistics shown for one calendar year of running:
$\mathcal{L} = 5.2*10^{42}/cm^2$ ⇔ POT = $7.8*10^{17}$

Approved for two calendar years of beam time. Installation Fall 2016

In reality, everything changes... between the 8-hour target spin flip

- Beam pulse intensity, duty factor, charge profile, halo…
- Target contents, Helium level, polarization…
- Trigger Eff. detector responses, DAQ dead time…
- Background. Track reconstruction Eff. …

Each term caries its own correction factor

$$A_{meas} = \frac{\frac{N^{\uparrow}}{\mathcal{L}^{\uparrow}} - \frac{N^{\downarrow}}{\mathcal{L}^{\downarrow}}}{\frac{N^{\uparrow}}{\mathcal{L}^{\uparrow}} + \frac{N^{\downarrow}}{\mathcal{L}^{\downarrow}}} = \frac{N^{\uparrow} - N^{\downarrow} \cdot \frac{\mathcal{L}^{\uparrow}}{\mathcal{L}^{\downarrow}}}{N^{\uparrow} + N^{\downarrow} \cdot \frac{\mathcal{L}^{\uparrow}}{\mathcal{L}^{\downarrow}}}$$

➔Need to control raw false asymmetry: $\delta(\mathbf{A})_{\mathbf{raw}} \approx \mathbf{0.1\%}$

Do sea quarks carry any longitudinal spin (helicity) of the proton ?

A clear probe to access sea quarks' polarization: Drell-Yan beam-target double-spin asymmetry A_{LL}

If we have **a polarized proton beam and a polarized proton target**.

Longitudinal-Longitudinal A_{LL}: access sea quark helicity.
(Transverse-Transverse A_{TT}: access sea quark transversity)

We define Drell-Yan longitudinally polarized beam-target double-spin asymmetry A_{LL} as:

$$A_{LL}^{DY} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Delta\sigma_{DY}}{\sigma_{DY}}$$

i.e, the ratio of the difference over the sum (or asymmetry) between the spin-aligned and spin-anti-aligned Drell-Yan cross sections, at the Leading Order, we have:

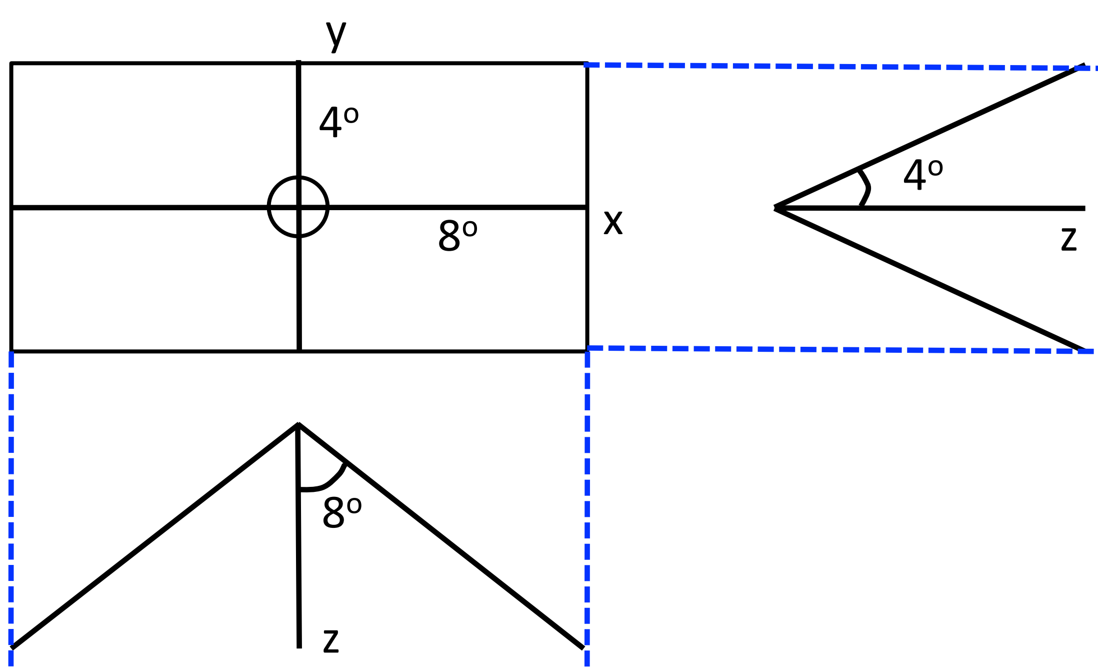
$$A_{LL}^{DY} = -\frac{\sum_q e_q^2\{\Delta q(x_1)\Delta\bar{q}(x_2) + \Delta\bar{q}(x_1)\Delta q(x_2)\}}{\sum_q e_q^2\{q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\}}$$

$$A_{pp} \approx -\frac{\Delta u_1}{u_1}\frac{\Delta\bar{u}_2}{\bar{u}_2} \qquad A_{pn} \approx -\frac{\Delta u_1}{u_1}\frac{\Delta\bar{d}_2}{\bar{d}_2}$$

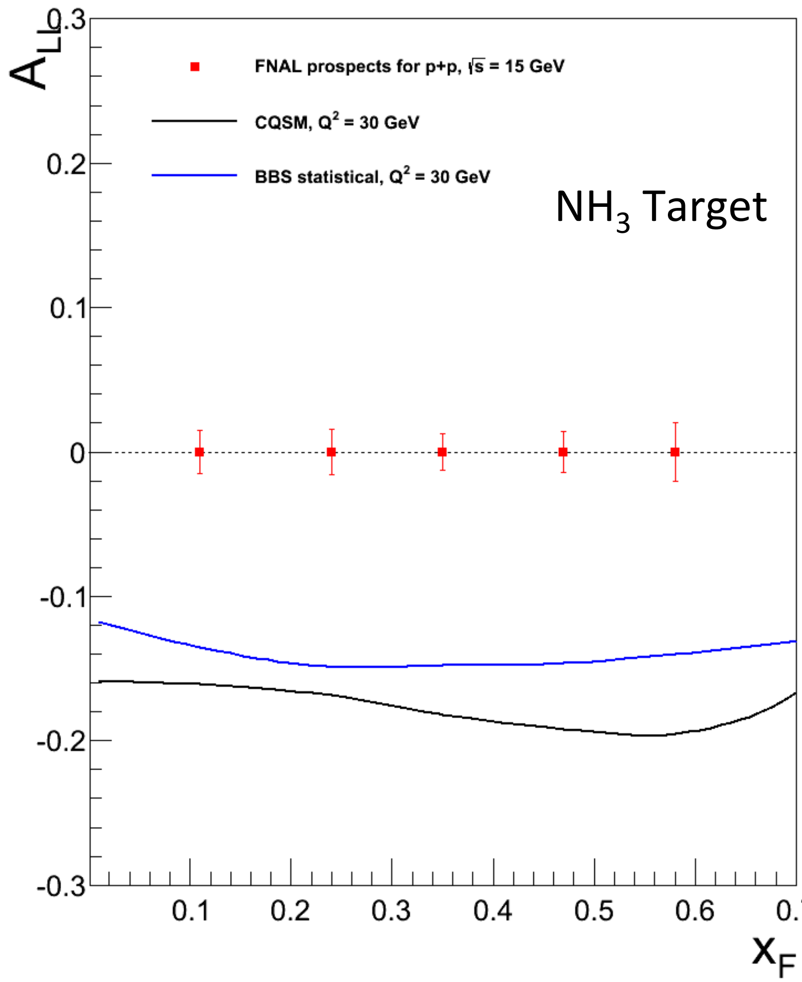
if anti-quarks carry no spin ➔ $A_{LL}^{DY} \equiv 0$!!!

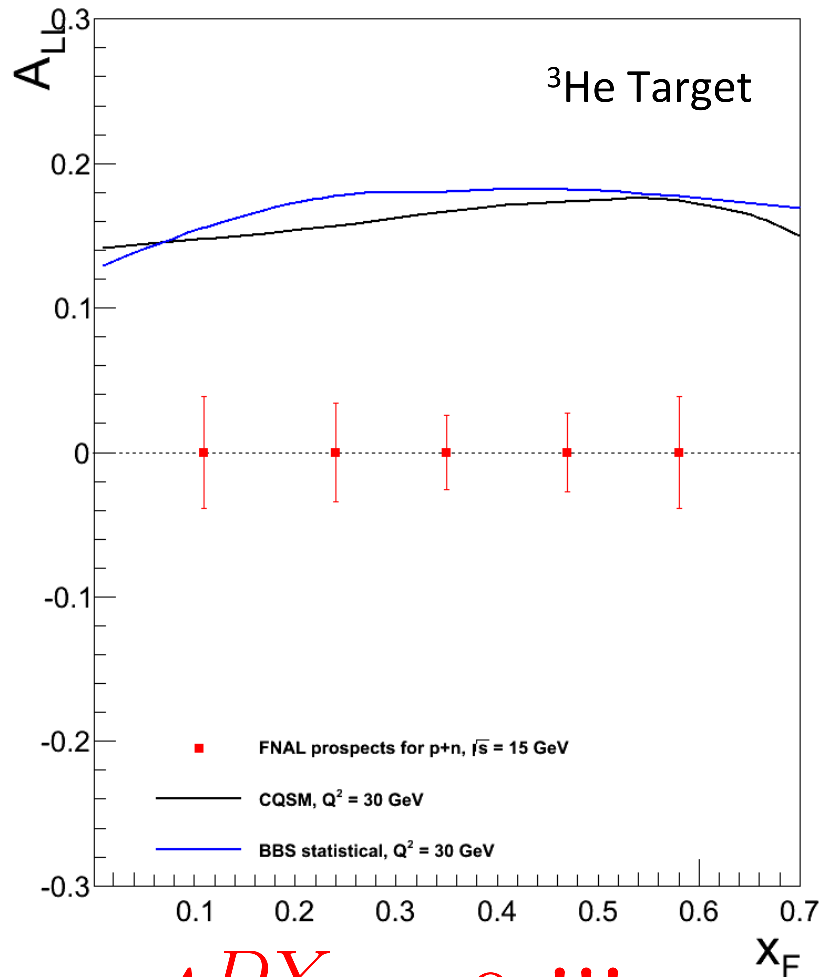
Geometry of an "ideal" spectrometer for FNAL Drell-Yan

- Vertical acceptance ±4 degree
- Horizontal acceptance ±8 degree
- Beam line ±1 degree



FNAL "prospected data" vs. theory predictions





if anti-quarks carry no spin ➔ $A_{LL}^{DY} \equiv 0$!!!

Chiral Quark Soliton Model: Wakamatsu, 2010. BBS statistical model: Soffer et al 2004.

A_{TT} to Access Transversity

$$A_{TT}^{DY} = \frac{\sin^2\theta\cos 2\phi}{1+\cos^2\theta} \cdot \frac{\sum_q e_q^2\{\delta q(x_1)\delta\bar{q}(x_2) + \delta\bar{q}(x_1)\delta q(x_2)\}}{\sum_q e_q^2\{q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\}}$$

where θ is the polar angle of either lepton in the rest frame of the virtual photon, and ϕ is the azimuthal angle between the direction of the polarization and the normal to the plane of the di-lepton decay.

$\langle\cos(2\phi)\rangle \approx 2/\pi$, i.e. almost cover all DY azimuthal angles.

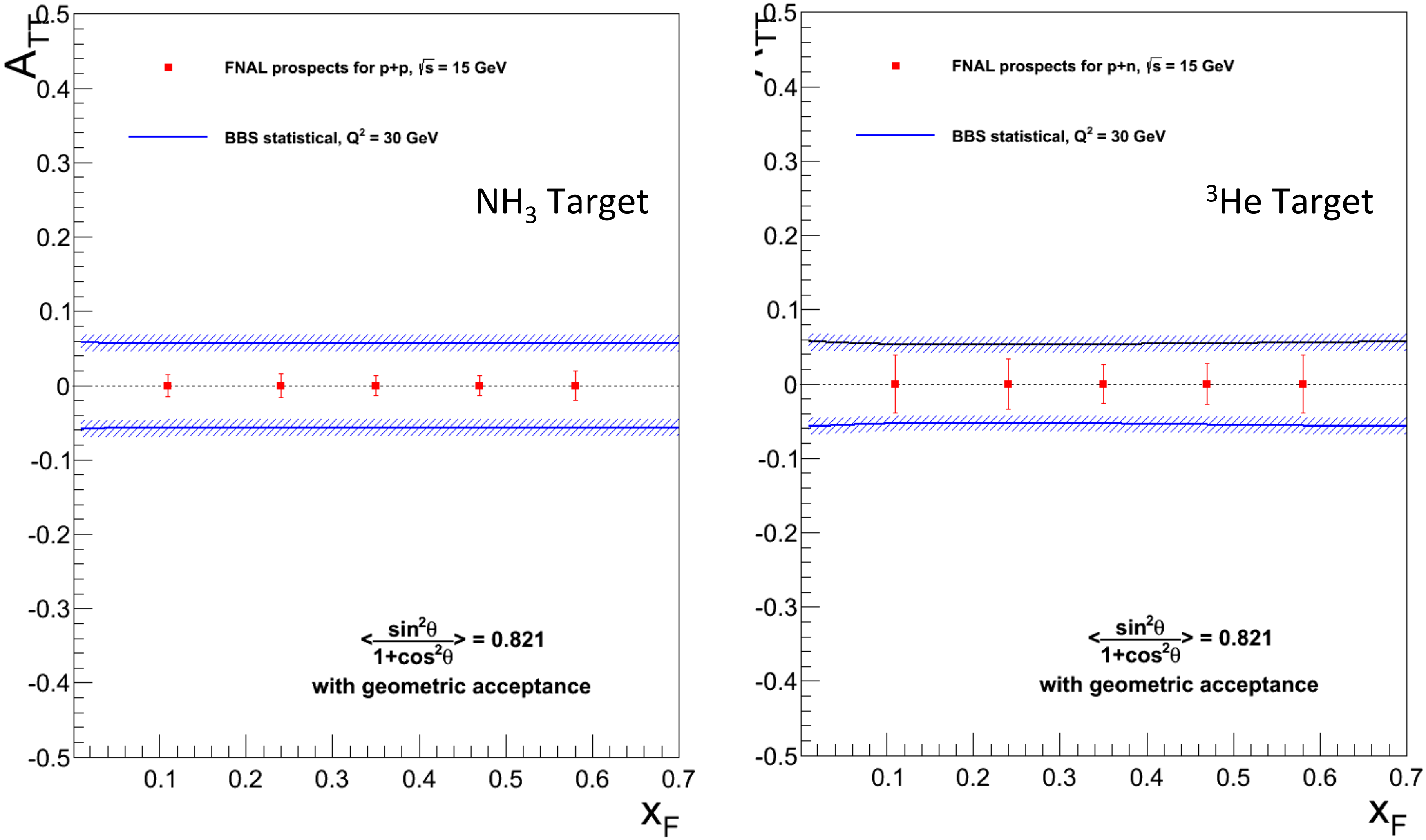
$$\left\langle \frac{\sin^2\theta}{1+\cos^2\theta} \right\rangle = 0.414$$ if cover all θ, peak at 1.0 for θ=90°.

Lacking knowledge on transversity, we took the Soffer (positivity) bounds for both quark and anti-quark, i.e:

$$\delta q(x) \leq \frac{1}{2}|q(x) + \Delta q(x)| \qquad \delta\bar{q}(x) \leq \frac{1}{2}|\bar{q}(x) + \Delta\bar{q}(x)|$$

We can also try Anselmino group's fits results of quark transversity, later.

A_{TT} FNAL "prospected data" vs. theory predictions



A Short Summary

Polarized Drell-Yan reaction can be used to access:

- Sea quarks' angular motion: Sivers distribution. A_{UT}
- Sea quarks' helicity distribution. A_{LL}
- Sea quarks' transverse spin (transversity) distribution. A_{TT}

Questions:

What are the (known) limits of:

- **sea quarks' Sivers distributions ?**
- **sea quarks' helicity distributions ?**
- **sea quarks' transversity distributions ?**

Model Predictions ???

Especially Model Predictions on:

$$\frac{f_{1T}^{\perp \bar{u}}}{\bar{u}}; \qquad \frac{f_{1T}^{\perp \bar{u}+\bar{d}}}{\bar{u}+\bar{d}}$$

At x=0.1~0.3
Where we can make good measurements

Backup Slides:

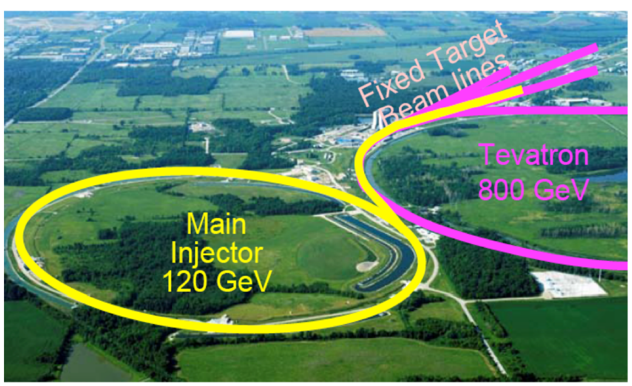
Fermilab experiment On Dark Photon Search

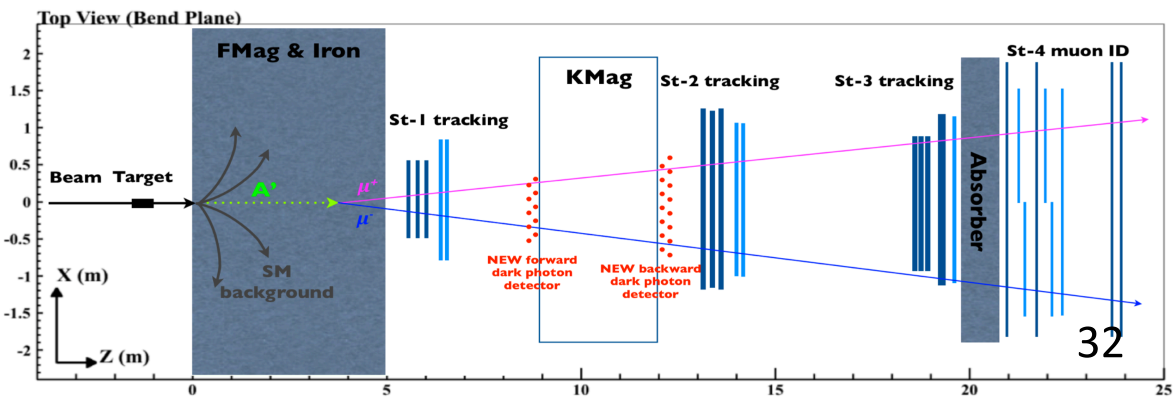
Also at Fermilab, while taking data for E1039 on spin asymmetry measurement:

A Direct Search for Dark Photon and Dark Higgs Particles with the SeaQuest Spectrometer in Beam Dump Mode at Fermilab

PI: Ming X. Liu (Los Alamos) and Paul E. Reimer (Argonne)

P1067 Collaboration

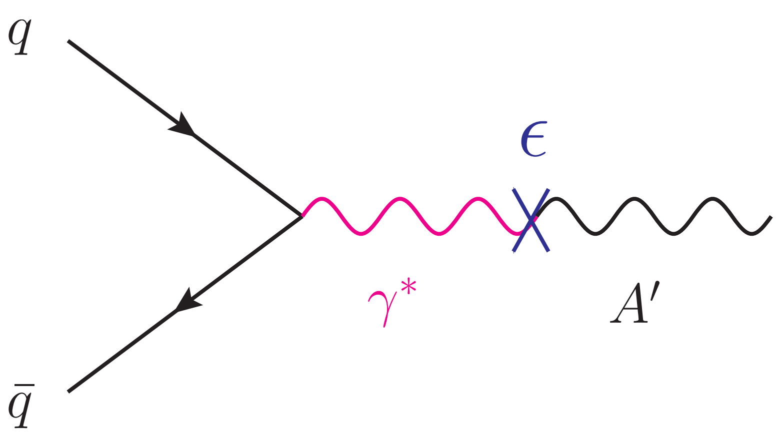




Direct Productions of Dark Photons and Dark Higgs in p+Fe at Fermilab

Photon portal: "vector"

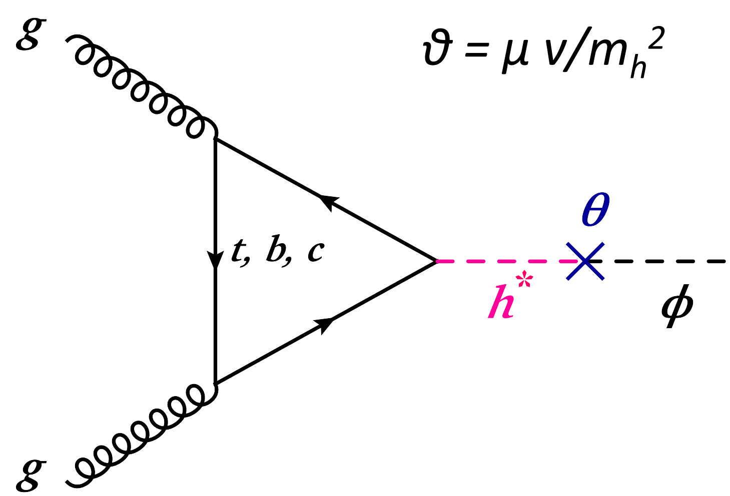
$$\mathcal{L}_{\rm mix} = \frac{\epsilon}{2} F^{\rm QED}_{\mu\nu} F^{\mu\nu}_{\rm Dark}$$



Higgs portal: "scalar"

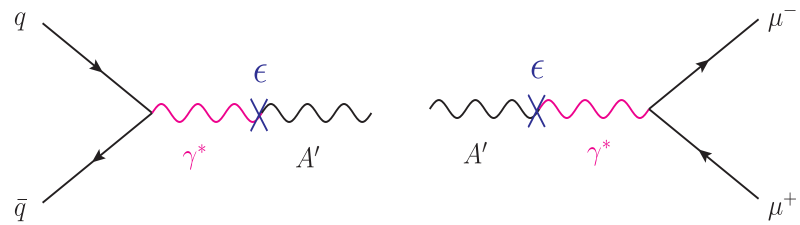
$$\mathcal{L}_{\rm mix} = \mu\phi|H^\dagger H|$$

$\vartheta = \mu\, v/m_h^2$

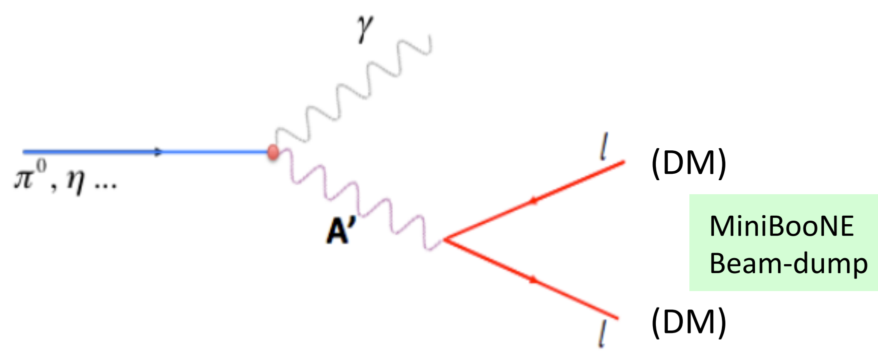


Dark Photon Search in Dimuon Channel at SeaQuest in Beam Dump Mode (p+Fe)

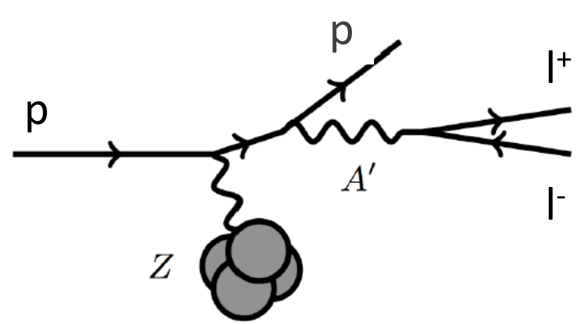
1. Drell-Yan like



2. π^0, η, … decay



3. Bremsstrahlung



Dark Photon Sensitivity: Summary

POT:1.4x10^{18} (parasitic w/ E1039)

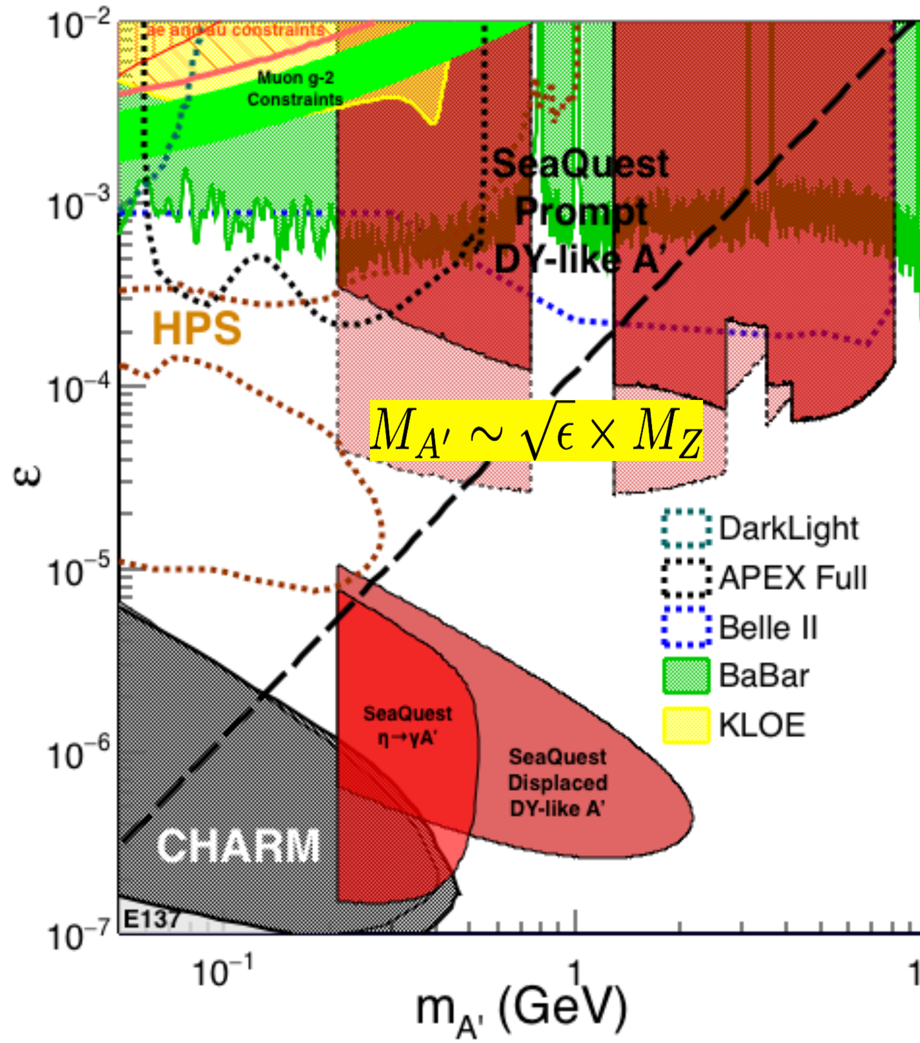
Signals considered:

- Drell-Yan like
- Eta decays
- Bremsstralung

Covers a wide range of unexplored parameter phase space

- Displaced dimuons
  - Minimal SM background
- Prompt dimuons
  - Excellent coverage over BELLE-II projection
  - Possible dedicated runs later to fully restore mass < 3GeV (Phase-II)
- ***Phase-II with upgrades***

  Access below 200MeV with di-electrons (add EMCal)



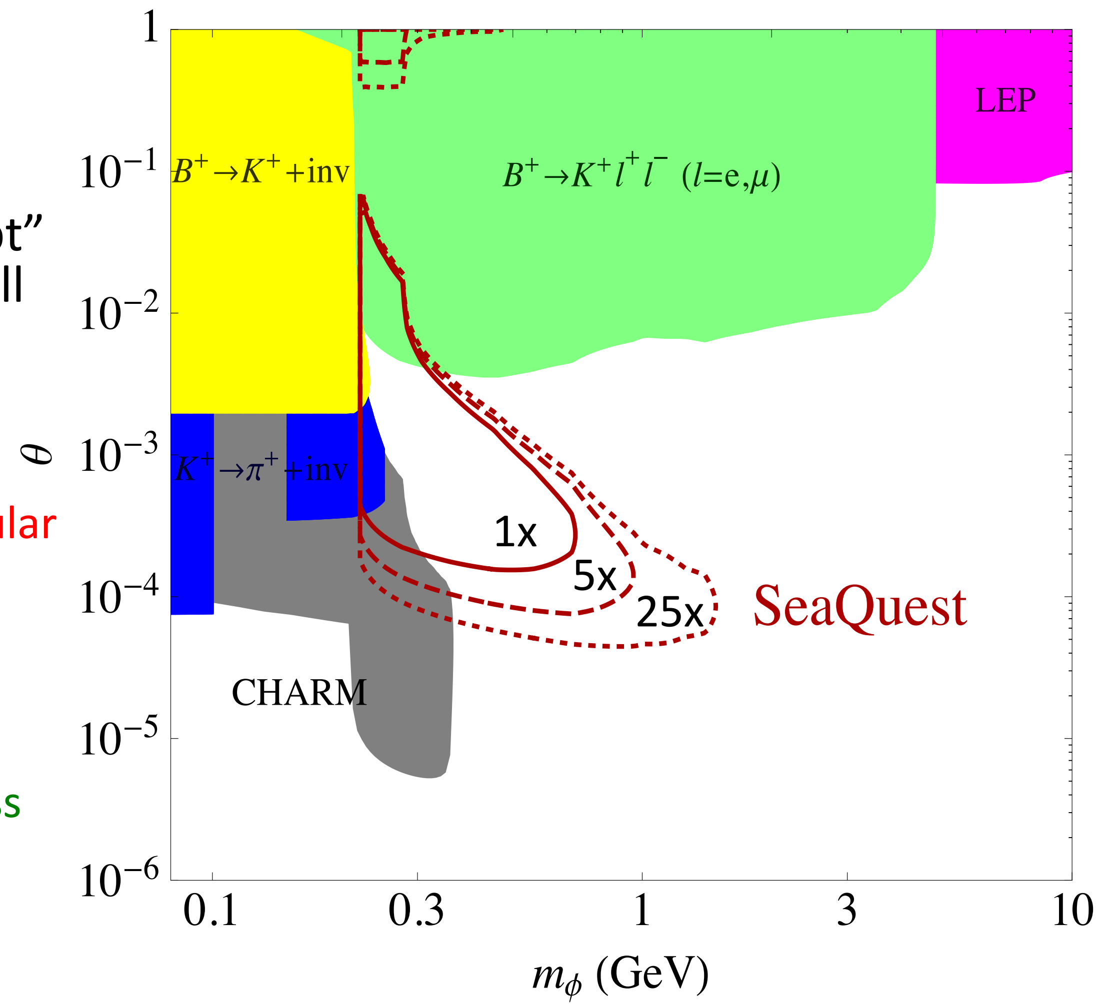
(2017?)
(2016?)
(~2023)

SeaQuest Dark Higgs Sensitivity

POT:1.4x10^{18} (Phase-I)

Y. Zhang (2015)

- Dimuons with downstream displaced decay vertices
- Limited sensitivity to "prompt" large mixing case due to small cross-section
- Dark Higgs or dark photons?
  - Dimuon kinematic and angular distributions
- Phase-II
  - Dedicated high luminosity runs optimized for low mass acceptance, mass<3GeV

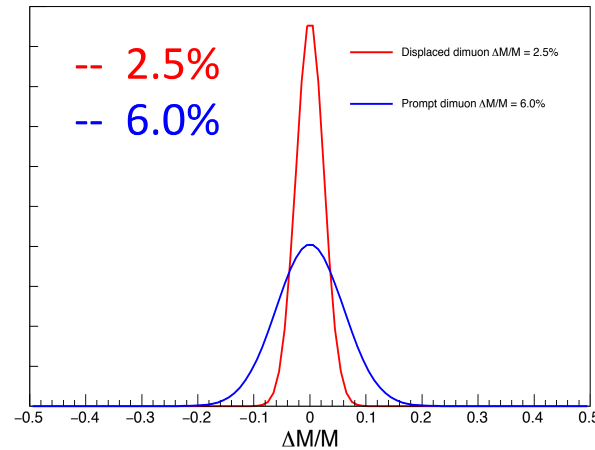


New Collaborators are very much welcome:

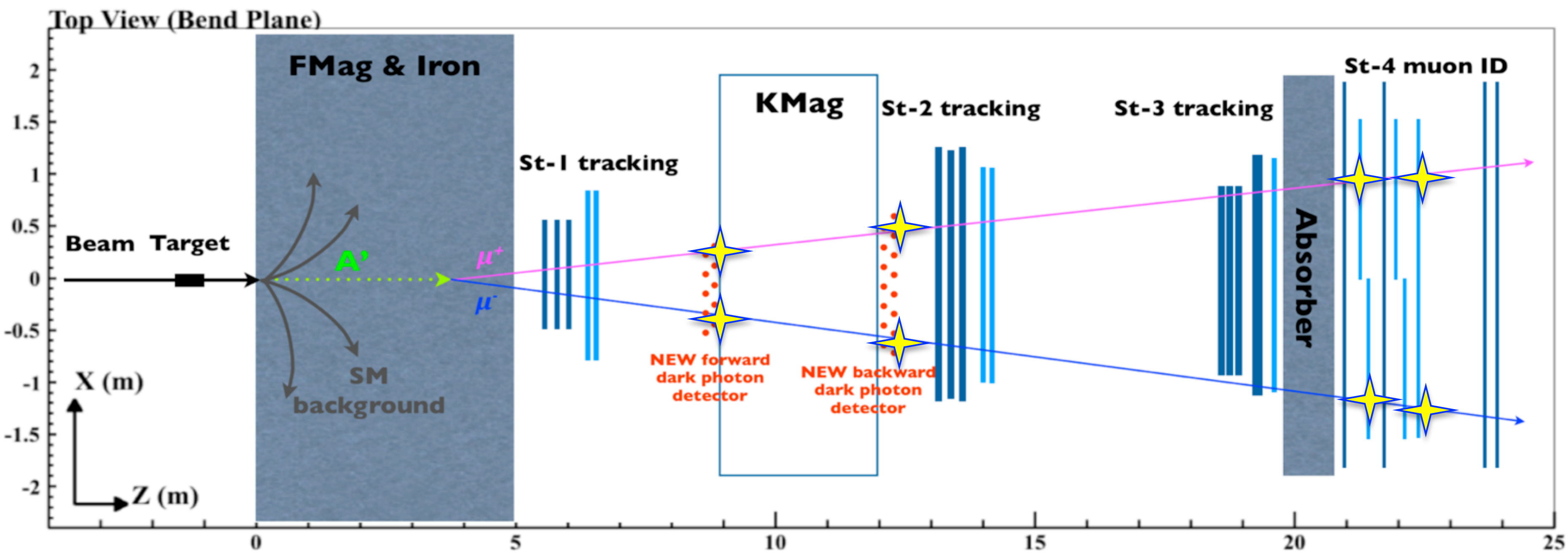
- Physics interests
- Detectors, trigger, DAQ developments
- Taking data, running the experiments
- Physics analysis, final physics results.
- Expanding into new physics.
- New Collaborators from Chinese Institutions (???).

Proposed Experimental Measurements

- Dark photon trigger upgrade
  1. Add a fine-granularity scintillating strip based trigger/tracking to tag dimuons from the same decay Z-vertex
  2. A new trigger for events with displaced down-stream dimuons
- Unique signals
  1. Displaced dimuon decay vertex for long-lived particles
  2. Invariant mass peak in dimuon mass spectrum
- Beam time
  1. Run parasitically with E1039 (2017-2019)
  2. Possible dedicated runs later with upgraded ($e^{+/-}$, $h^{+/-}$)



Dimuon mass resolution



Z (meter)

A New High-Granularity Displayed Dimuon Vertex Trigger

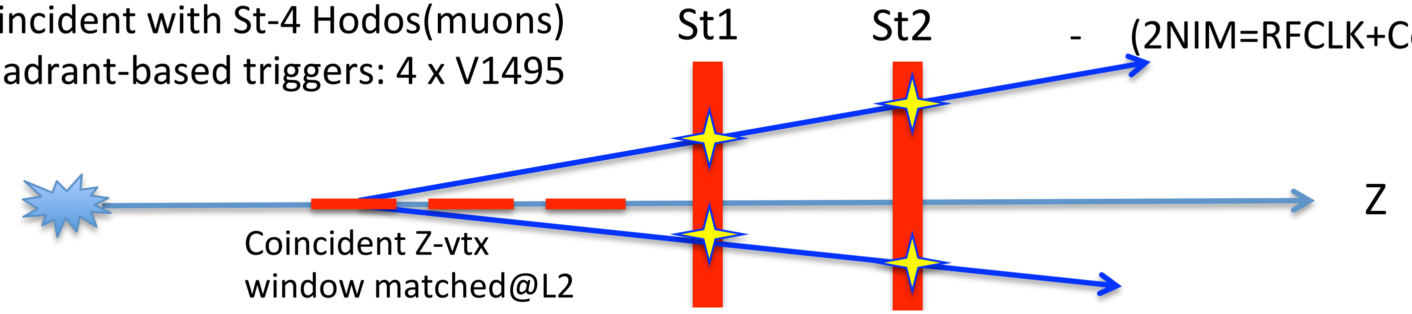
High rejection power, very low rate, << 1 kHz(E906 DAQ limit)

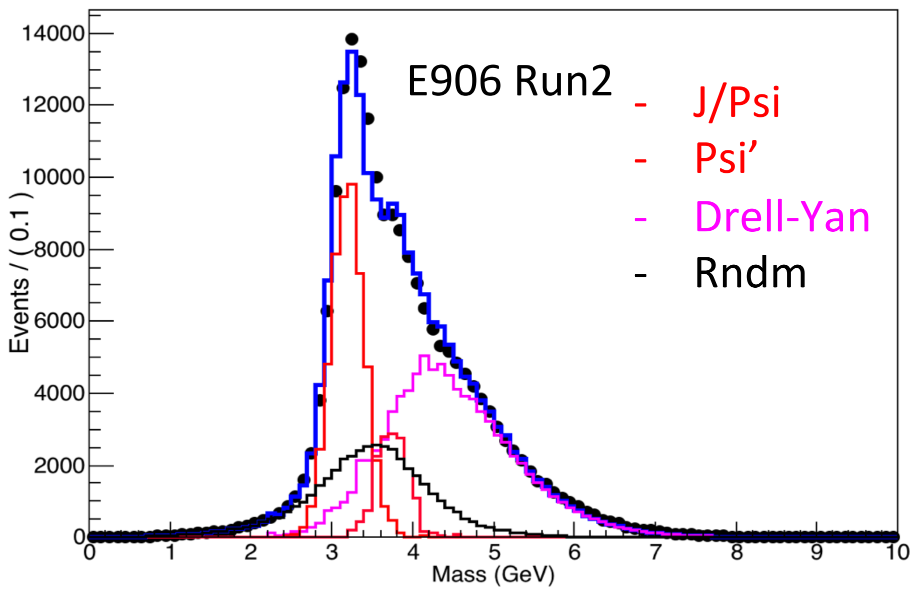
Y-Plane Trigger:

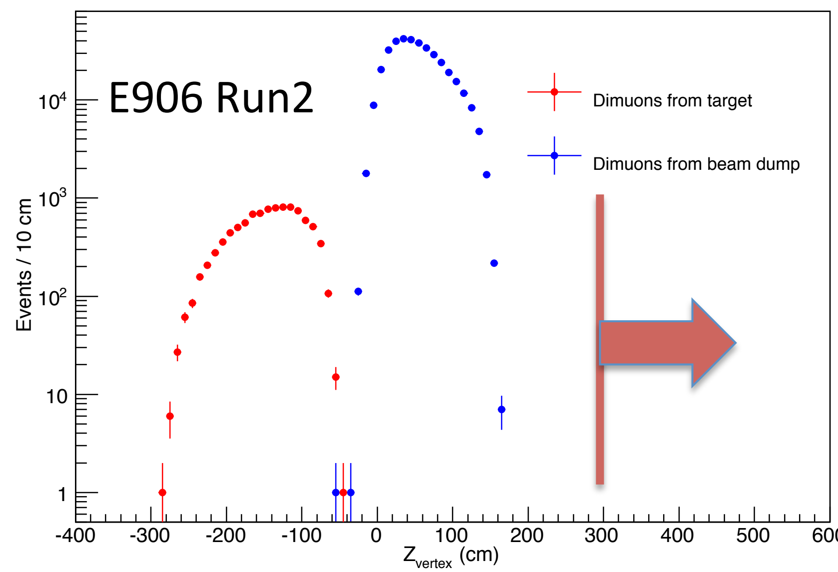
- A quadrant panel: 40 x 40 cm^2, 1cm thinck
  - 40 x 1cm x 40 cm scintillating strips, SiPM readout
- Straight line projection, 30cm Z-vertex resolution
- Displaced z-vertex, mostly low mass < 3GeV
- Coincident with St-4 Hodos(muons)
- Quadrant-based triggers: 4 x V1495

Y-channels per quadrant:

- 1x V1495
- 40(St1) + 40(St2) + 8x2 (St4-Y1,2) = 96
- 96+64 = 160 possible
  - 72+72+16 = 160 (possible)
  - (2NIM=RFCLK+ComSTOP)







Dimuon Z-vertex (cm)