Deep Exclusive π^- Production with transversely polarized He3 using SoLID

A run-group proposal with E12-10-006

Zhihong Ye, ANL

On behalf of Co-Spokespeople:

Garth Huber (contact), Zafar Ahmed, *from Univ. of Regina*

and Zhihong Ye

05/07/2016

Drafted proposal:
https://userweb.jlab.org/~yez/Work/solid/solid_neutron_DEMP.pdf

Physics Motivation

▪ Generalized Parton Distribution:

- GPDs give the 3D spatial distributions of quarks and gluons in a nucleon
- GPDs interrelate the longitudinal and transverse momentum structure of partons within a fast moving hadron.

$H^{q,g}(x,\xi,t)$ spin avg. no heli. flip	$E^{q,g}(x,\xi,t)$ spin avg. helicity flip
$\tilde{H}^{q,g}(x,\xi,t)$ spin diff. no heli. flip	$\tilde{E}^{q,g}(x,\xi,t)$ spin diff. helicity flip

- At leading twist-2, four quark chirality conserving GPDs for each quark, gluon type.
- Because quark helicity is conserved in the hard scattering regime, the produced meson acts as a helicity filter.

  - Leading order QCD predicts:
  - Vector meson production sensitive to unpolarized GPDs, H and E.
  - Pseudoscalar mesons sensitive to polarized GPDs, $\tilde{H}$ and $\tilde{E}$.

Physics Motivation

- **Generalized Parton Distribution:**

➢ Integral of transverse components reduces GPDs into one-dimensional PDF

➢ Access to Angular Momenta of quarks & gluons.

➢ First moments of GPDs are related to nucleon elastic form factors through model-independent sum rules:

$$\sum_q e_q \int_{-1}^{+1} dx H^q(x,\xi,t) = F_1(t)$$

$$\sum_q e_q \int_{-1}^{+1} dx E^q(x,\xi,t) = F_2(t)$$

Dirac and Pauli elastic nucleon form factors.
t -dependence fairly well known.

$$\sum_q e_q \int_{-1}^{+1} dx \widetilde{H}^q(x,\xi,t) = G_A(t)$$

Isovector axial form factor.
t –dep. poorly known.

$$\sum_q e_q \int_{-1}^{+1} dx \widetilde{E}^q(x,\xi,t) = G_p(t)$$

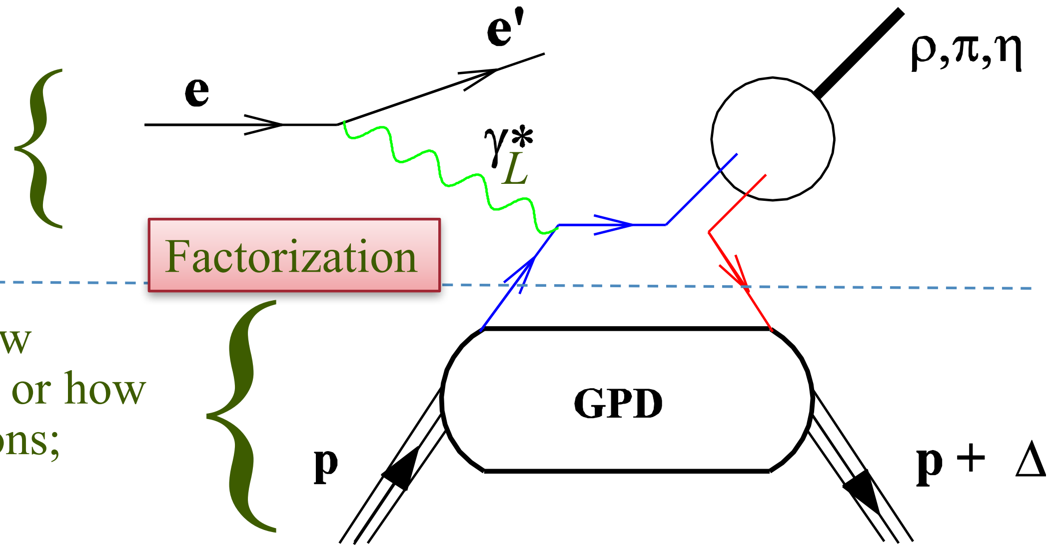
Pseudoscalar form factor.
Very poorly known.

Physics Motivation

- Factorization of Hard Reactions:

➢ Hard probe creates a small size $q\bar{q}$ or gluon configuration (or a real photon in DVCS); (described by pQCD)

➢ Non-perturbative part describes how hadron reacts to this configuration, or how the probe is transformed into hadrons; (parameterized by GPDs).



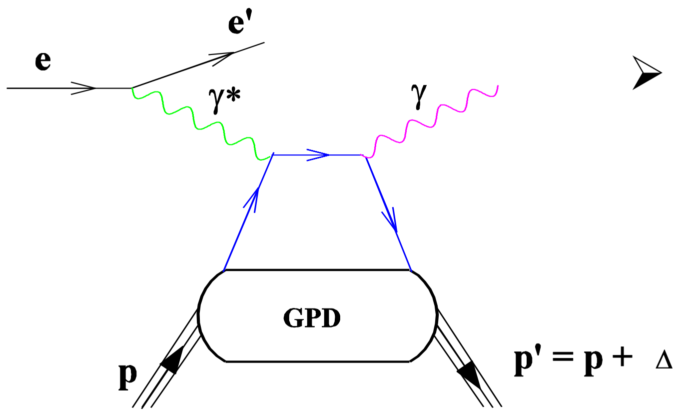
✓ Hard exclusive meson electroproduction first shown to be factorizable by Collins, Frankfurt & Strikman [PRD 56(1997)2982].

✓ Factorization applies when the γ* is longitudinally polarized.

  ✓ corresponds to small size configuration compared to transversely polarized γ*.

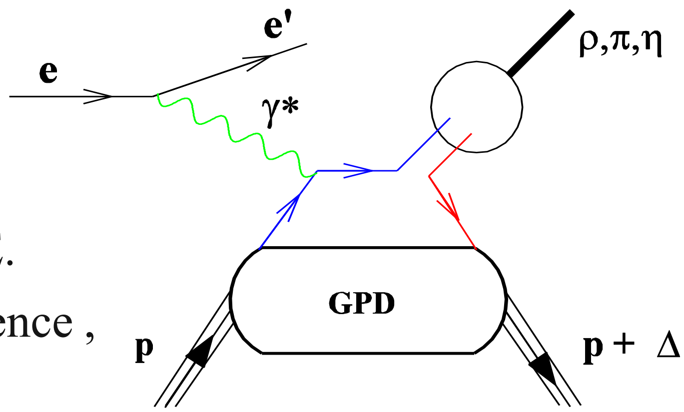
Physics Motivation

- Exclusive Hard Processes to probe GPDs:



- Deeply Virtual Compton Scattering (DVCS):
  - ✓ Sensitive to all four GPDs.

- Deep Exclusive Meson Production (DEMP):
  - ✓ Vector mesons sensitive to spin-average H, E.
  - ✓ Pseudoscalar mesons sensitive to spin-difference , $\widetilde{H}$ and $\widetilde{E}$.



- Need a variety of Hard Exclusive Measurements to disentangle different GPDs.

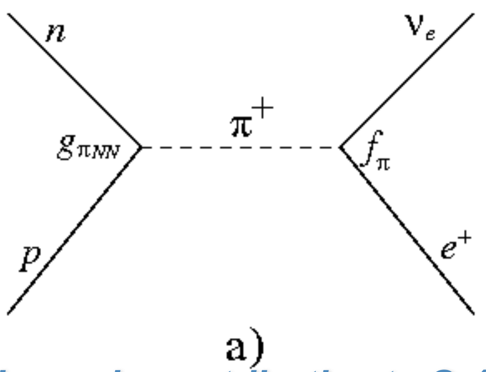
Physics Motivation

- Probe GPD-$\tilde{E}$ with DEMP: $$\sum_q e_q \int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = G_p(t)$$

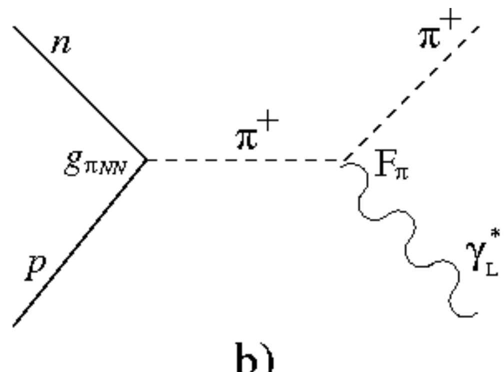
✓ GPD-$\tilde{E}$ is not related to an already known parton distribution.

✓ Experimental information can provide new nucleon structure info unlikely to be available from any other source.

✓ $G_P(t)$, which is highly uncertain, receives contributions from $J^{PG}=0^{--}$ states, and contains an important pion pole contribution.



Pion pole contribution to $G_P(t)$



Pion pole contribution to meson electroproduction at low –t.

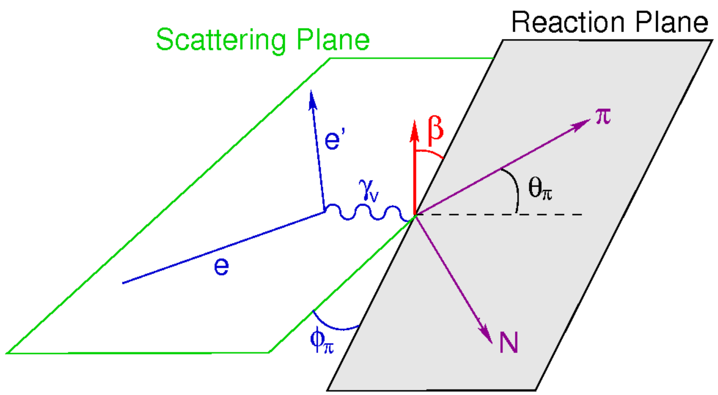
For this reason, a pion pole-dominated ansatz is typically assumed:

$$\tilde{E}^{ud}(x,\xi,t) = F_\pi(t)\frac{\theta(\xi > |x|)}{2\xi}\phi_\pi\left(\frac{x+\xi}{2\xi}\right),$$

where F_π is the pion FF and ϕ_π the pion PDF.

Physics Motivation

- Target Single Spin Asymmetry in DEMP:



- Asymmetry with transversely polarized target and longitudinally polarized virtual phone

$$\mathbf{A_L^\perp} = \frac{\int_0^\pi \mathbf{d}\beta \frac{\mathbf{d}\sigma_\mathbf{L}^{\pi^-}}{\mathbf{d}\beta} - \int_\pi^{2\pi} \mathbf{d}\beta \frac{\mathbf{d}\sigma_\mathbf{L}^{\pi^-}}{\mathbf{d}\beta}}{\int_0^{2\pi} \mathbf{d}\beta \frac{\mathbf{d}\sigma_\mathbf{L}^{\pi^-}}{\mathbf{d}\beta}}$$

$d\sigma_\pi{}^L$ = exclusive π cross section for longitudinal γ*
β = angle between transversely polarized target vector and the reaction plane.

- Unpolarized Cross section

$$2\pi \frac{d^2\sigma}{dt d\phi} = \epsilon \frac{d\sigma_\mathrm{L}}{dt} + \frac{d\sigma_\mathrm{T}}{dt} + \sqrt{2\epsilon(\epsilon+1)} \frac{d\sigma_\mathrm{LT}}{dt} \cos\phi + \epsilon \frac{d\sigma_\mathrm{TT}}{dt} \cos 2\phi$$

- Polarized cross section has additional components

$$\sigma_t = -P_\perp \sin\beta \, [\sigma_{TT}^y + 2\epsilon \, \sigma_L^y]$$
$$- P_\perp \sin\beta \, [\epsilon(\cos 2\phi_s \cos 2\beta + \sin 2\phi_s \sin 2\beta) \, \sigma_{TT'}^y]$$
$$- P_\perp \sin\beta \left[\sqrt{2\epsilon(1+\epsilon)} (\cos\phi_s \cos\beta + \sin\phi_s \sin\beta) \, \sigma_{LT}^y\right]$$
$$- P_\perp \cos\beta \left[\sqrt{2\epsilon(1+\epsilon)} (\sin\phi_s \sin\beta - \cos\phi_s \cos\beta) \, \sigma_{LT}^x\right]$$
$$- P_\perp \cos\beta \, [\epsilon(\sin 2\phi_s \sin 2\beta - \cos 2\phi_s \cos 2\beta) \, \sigma_{TT}^x]$$

L/T Separation

sin β module

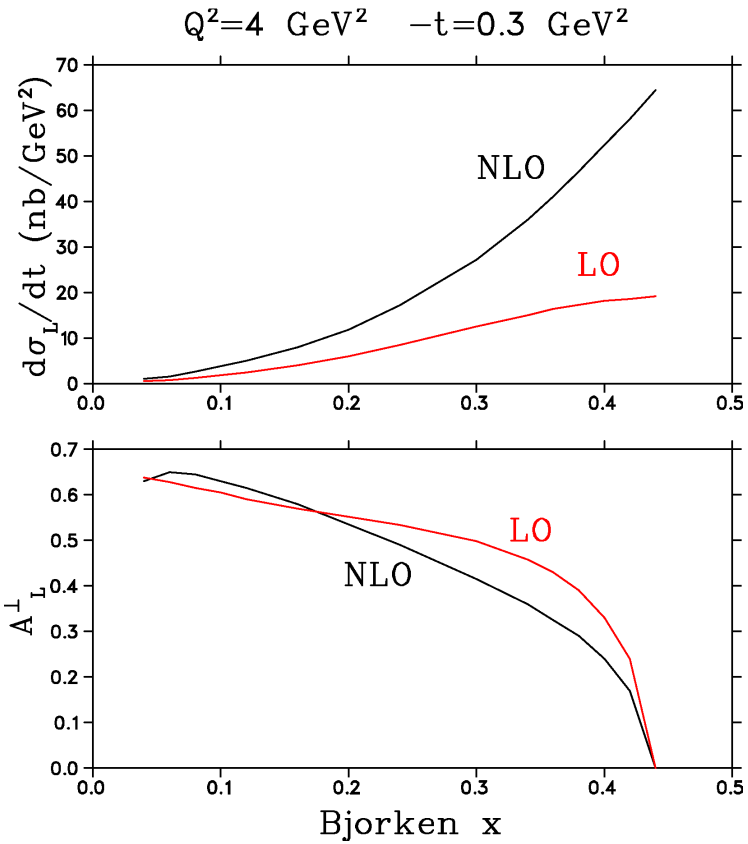
$$A_\perp = \frac{1}{P_\perp} \frac{2}{\pi} \frac{2\sigma_L^y}{\sigma_L}$$

Physics Motivation

- Target Single Spin Asymmetry in DEMP:

➢ Frankfurt et al. have shown $A_L^{\perp}$ vanishes if $\tilde{E}$ is zero [PRD 60(1999)014010].

- If $\tilde{E} \neq 0$, the asymmetry will display a $\sin\beta$ dependence.
- Higher order corrections, which may be significant at low Q^2 for σ_L, likely cancel in $A_L^{\perp}$.



➢ Belitsky and Müller calculations:

✓ At Q^2=10 GeV^2, NLO effects can be large, but cancel in $A_L^{\perp}$ (PL B513(2001)349).

✓ At Q^2=4 GeV^2, higher twist effects even larger in σ_L, but still cancel in the asymmetry (CIPANP 2003).

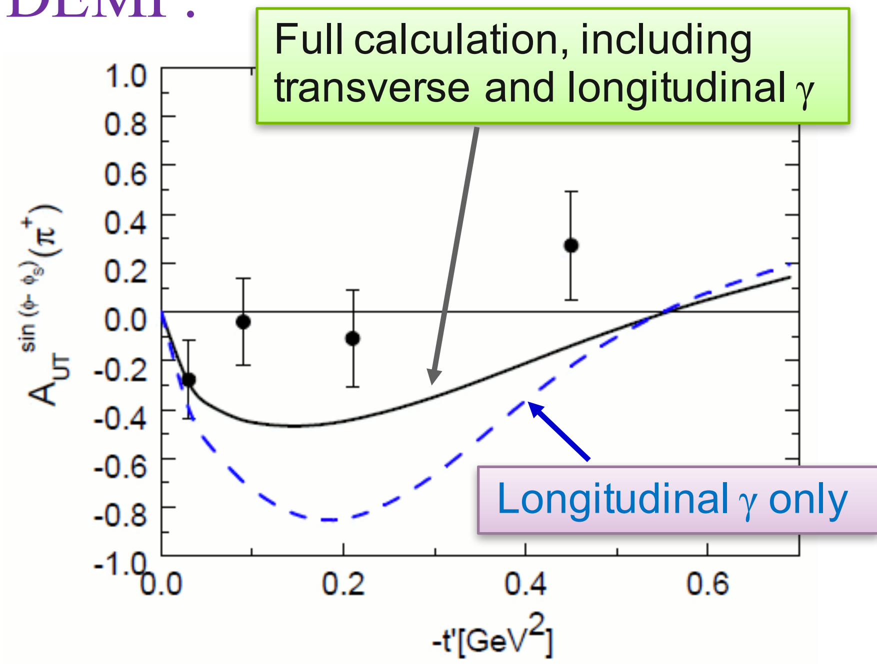
This relatively low value of Q^2 for the expected onset of precocious scaling is important, because it is experimentally accessible at JLab 12 GeV.

Physics Motivation

- Target Single Spin Asymmetry in DEMP:

HERMES Data:

- Exclusive π^+ production by scattering 27.6 GeV positrons or electrons from transverse polarized ^1H without L/T separation. [PLB 682(2010)345]
- $\langle x_B \rangle$=0.13, $\langle Q^2 \rangle$=2.38 GeV^2, $\langle -t \rangle$=0.46 GeV^2.



- ✓ Goloskokov and Kroll indicate the HERMES results have significant contributions from transverse photons, as well as from L and T interferences. [Eur Phys.J. C65(2010)137]
- ✓ Because no factorization theorems exist for exclusive π production by transverse photons, these data cannot be simply interpreted in terms of GPDs.

Physics Motivation

▪ Target Single Spin Asymmetry in DEMP:

➢ The study of $A_L^{\perp}$ is also important for the reliable extraction of F_π from $p(e,e'\pi^+)n$ data at high Q^2. [Frankfurt, Polyakov, Strikman, Vanderhaeghen PRL 84(2000)2589].

- Non-pion pole contributions need to be accounted for in order to reliably extract F_π from σ_L data at low -t.
- 12 GeV Pion Form Factor experiment restricted to Q^2=6 GeV^2 to keep non-pole contributions to an acceptable level ($-t_{min}$<0.2 GeV^2).

➢ $A_L^{\perp}$ is an interference between pseudoscalar and pseudovector contributions.

- Help constrain the non-pole contribution to $p(e,e'\pi^+)n$.
- Assist the more reliable extraction of the pion form factor.
- Possibly extend the kinematic region for F_π measurements.

➢ To cleanly extract $A_L^{\perp}$, we need:

- Target polarized transverse to γ^* direction.
- Large acceptance in π azimuthal angle (i.e. φ, β).
- Measurements at multiple beam energies and electron scattering angles.
  ε dependence (L/T separation); controlled systematic uncertainties

Physics Motivation

- Complementarity of SoLID and SHMS+HMS Experiments

SHMS+HMS:

- HMS detects scattered e'.

  SHMS detects forward, high momentum π.
- Expected small systematic uncertainties to give reliable L/T separations.
- Good missing mass resolution to isolate exclusive final state.
- Multiple SHMS angle settings to obtain complete azimuthal coverage up to 4^o from q-vector.
- It is not possible to have complete azimuthal coverage at larger –t, where $A_L^{\perp}$ is largest.
- **PR12-12-005 by GH, D. Dutta, D. Gaskell, W. Hersman.**

SoLID:

- Complete azimuthal coverage, polar angle θ= 8^o up to 24^o for e and π
- High luminosity, particle ID and vertex resolution capabilities well matched to the experiment.
- **L/T separation is not possible**, the asymmetry is "diluted" by T, TT contributions.
- The measurement is valuable as it is the only practical way to obtain $A_{UT}^{\sin(\varphi-\varphi_s)}$ over a wide kinematic range.
- Complementary to Hall C measurement.

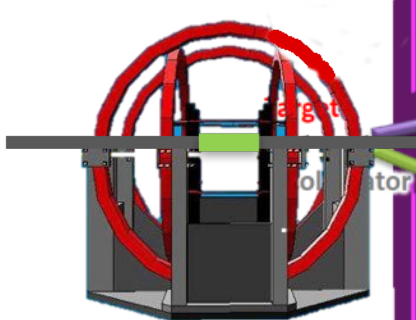
Measure DEMP with SoLID-SIDIS

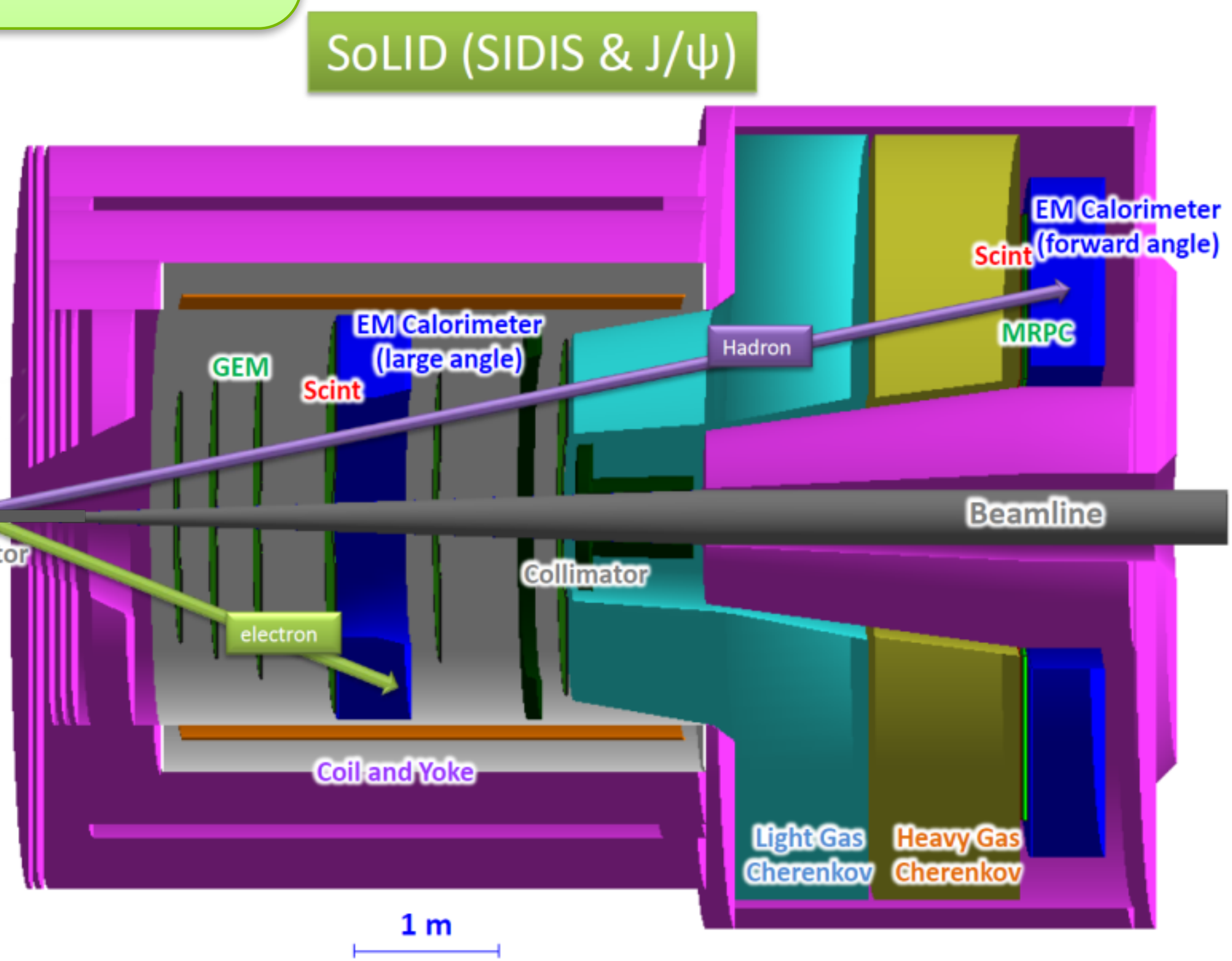
$\vec{n}(e, e'\pi^-)p$:with transversely polarized He3

$$< A_{UT} >= \frac{1}{P \cdot \eta_n \cdot f} \frac{N^+ - N^-}{N^+ + N^-}$$

Run in parallel with E12-10-006:
E0 = 11.0 GeV (48 days)
Luminosity = 10^{36} cm^{-2} s^{-1} (per nucleon)

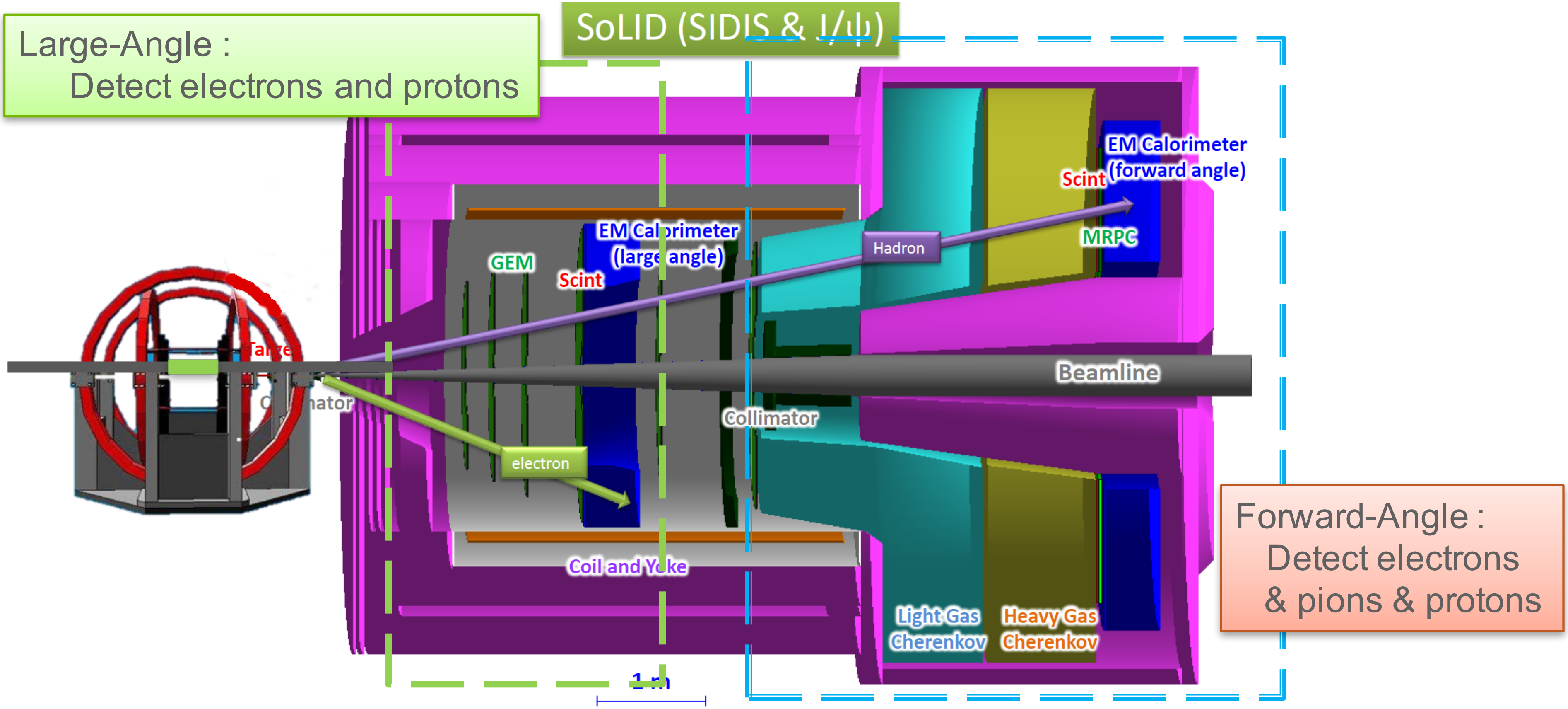
Coil	Inner Diameter (m)
Inner	1.27
Outer	1.45
Vertical	1.83





Note: The target size is roughly close to real but the location is estimated.

Measure DEMP with SoLID-SIDIS



e/$\pi^{\pm}$ Coverage: →Forward Acceptance: ϕ: 2π, θ: 8°-14.8° , P: 1.0 – 7.0 GeV/c, for e/$\pi^{\pm}$

→Large Acceptance: ϕ : 2π, θ: 16°-24° , P: 3.5 – 7.0 GeV/c, for e only

Proton Coverage : →same to e/pi at FA and LA, except the momentum-range can be much lower

Resolution: δP/P ~ 2%, θ ~ 0.6mrad, ϕ ~ 5mrad

Online Coincidence Trigger: Electron Trigger + Hadron Trigger
Offline Analysis: Identify protons and form triple-coincidence

Proton Recoil Detector

- A Conceptual Design:

✓ Cover angles of 24° to 50°

2π on the azimuthal angle

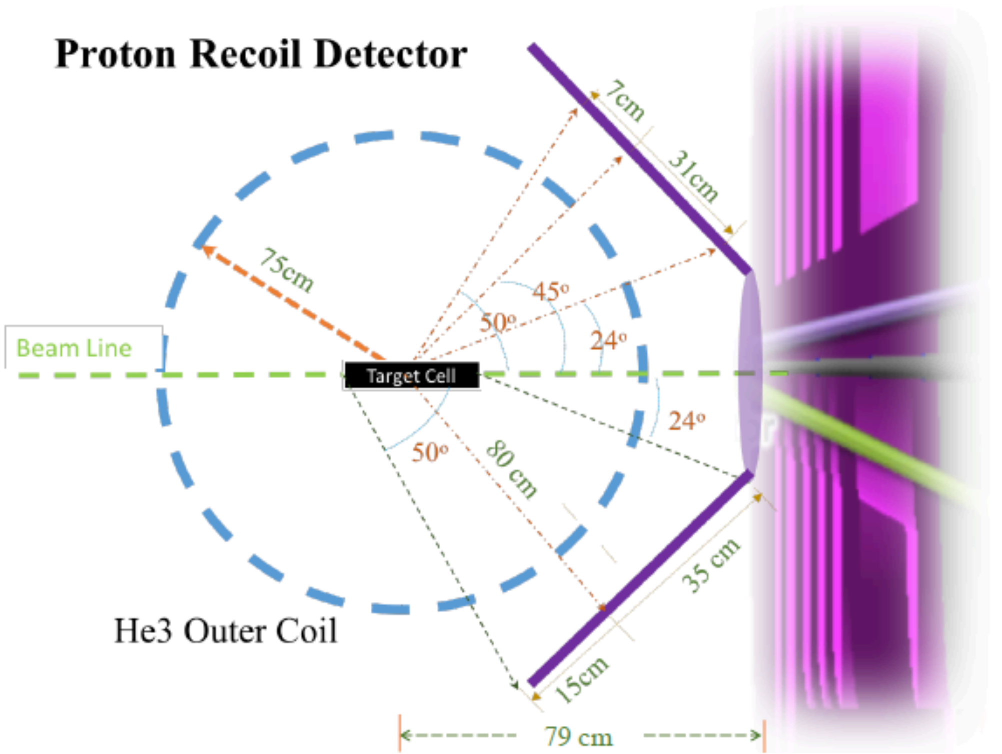
✓ Inner Radius=32 cm

Outer Radis = 67 cm

Detector Length = 50 cm

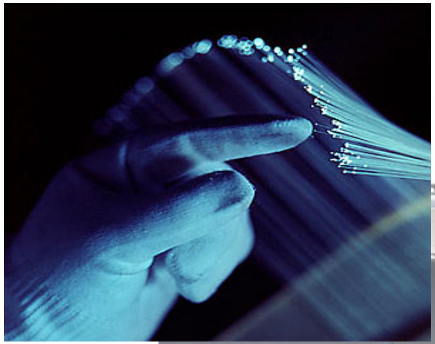
✓ Distance from Target = 79cm

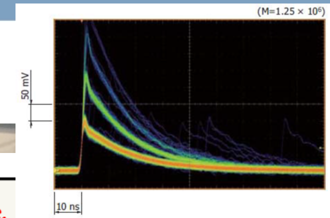
(far end touches the magnet)

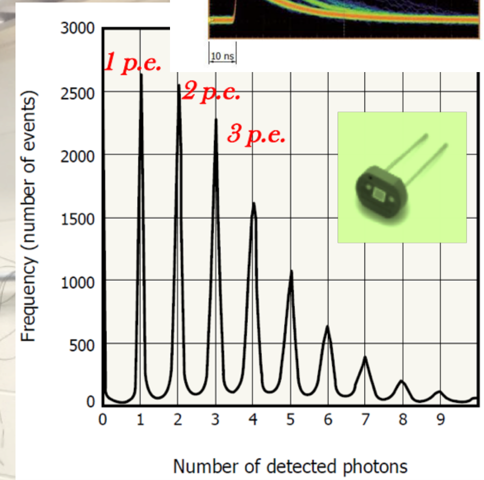


- Need good timing resolution (<60~ps)
- Need fine segments due to huge low energy backgrounds
  (An aluminum foil cover can block most of low energy electrons)
- Need to provide angle information for offline background suppression
- Photon-Detectors need to work in strong magnetic fields from target & solenoid
- A good candidate: Scintillating Fiber Tracker
- Geant4 Simulation is undergoing

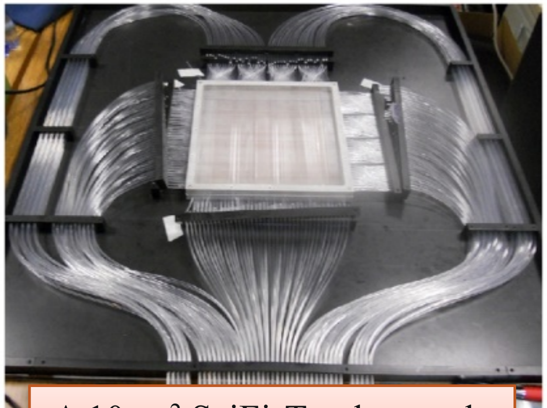
Scintillating Fiber Tracker





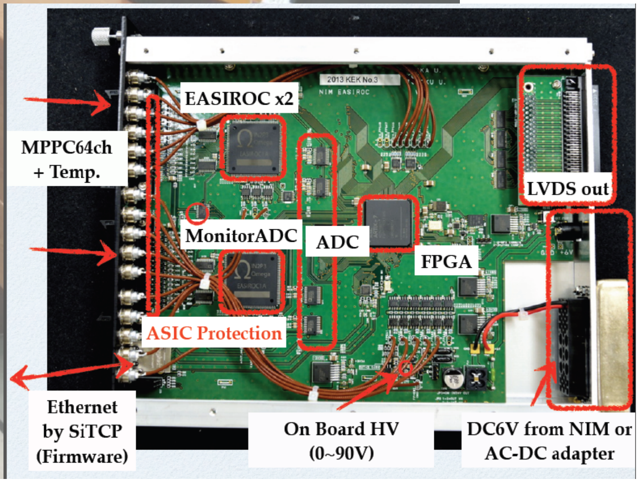


SiPM → Avalanche Photodiode (APD) pixels working in Geiger-mode



A 10cm² SciFi-Tracker made by a medical group

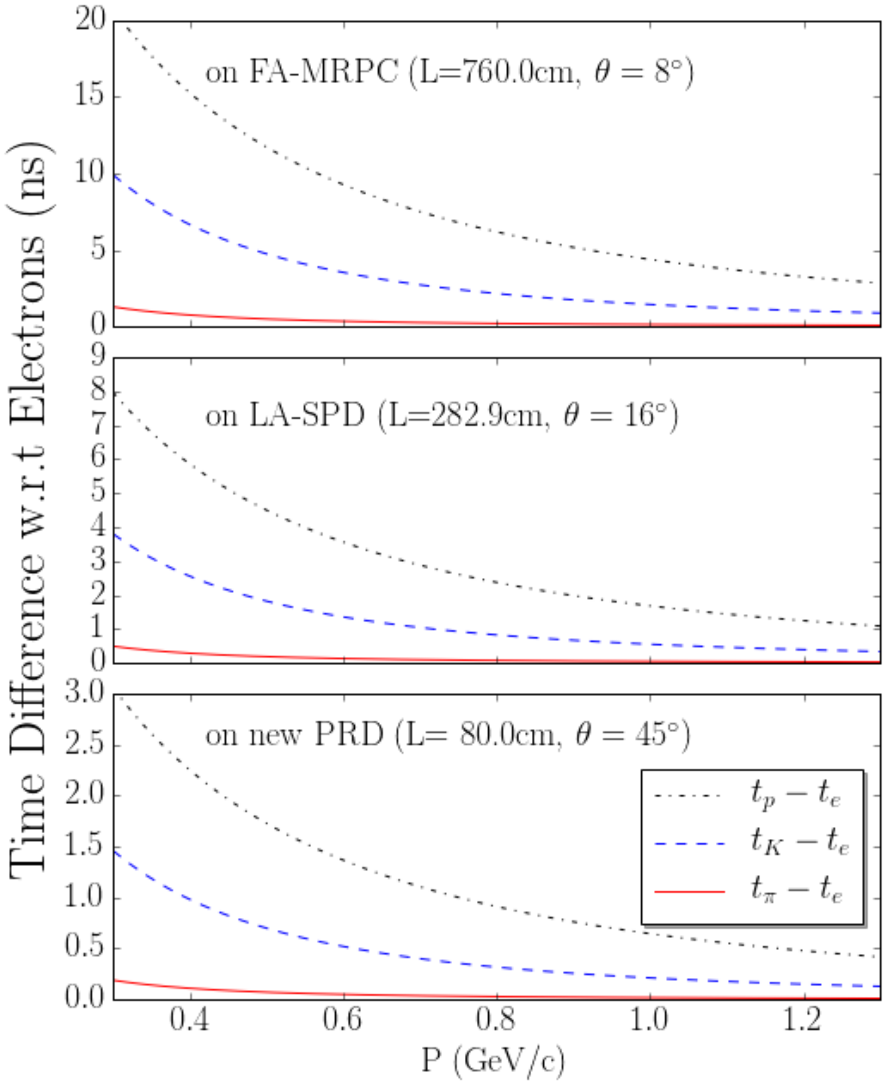
A prototype project funded by JSA 2014 Postdoc Prize



EASIROC+SiPM ("portable"!)

Proton Detection

- Using Time-Of-Flight as Proton-PID:



Need >5σ timing resolution to identify protons from other charged particles.

- Existing SoLID Timing Detectors:
  - ✓ Timing + Momentum Info
  - ✓ MRPC & FASPD at Forward-Angle

    cover $8^0 \sim 14.8^0$; >3ns separation
  - ✓ LASPD at Large-Angle

    cover $14^0 \sim 24^0$; >1ns separation

- A new Proton Recoil Detector:

No momentum info; Only reply on 1D TOF cuts

  - ✓ Cover $14^0 \sim 24^0$;
  - ✓ Good separation from electrons/pions

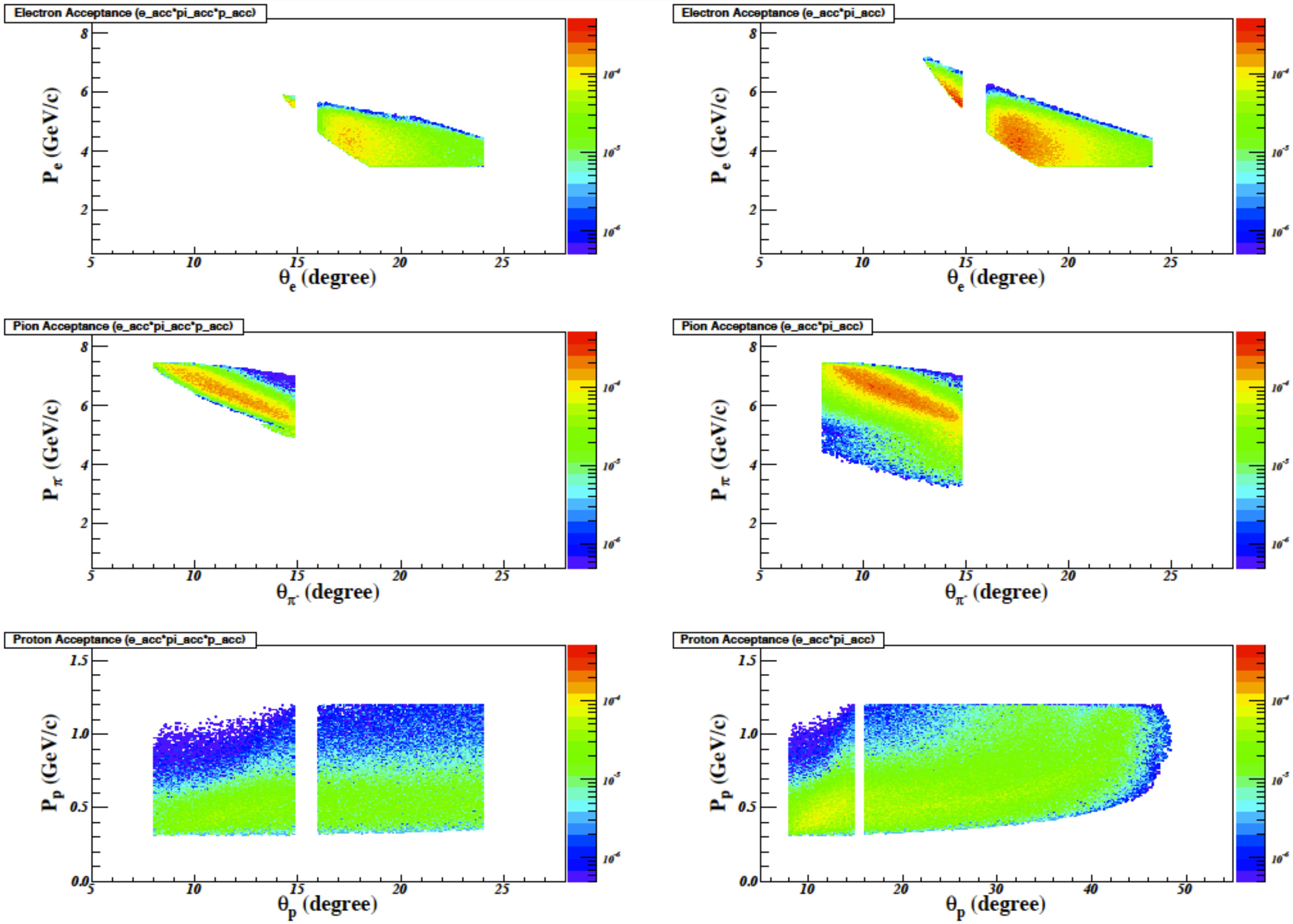
    (lowP π^-– highP p >=0.3ns,

    need σ < 60ps)
  - Hard to separate kaons from protons

    low-P K *mixed with high-P* p

Projection

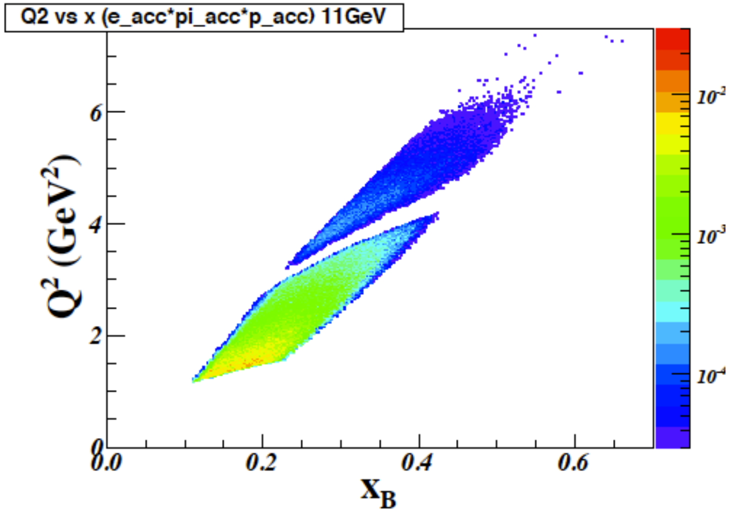
- Acceptance: (Cuts on Q2>4 GeV^2 and W>2 GeV)



(a) w/o PRD (b) w/ PRD

Projection

- Kinematic & Rates:



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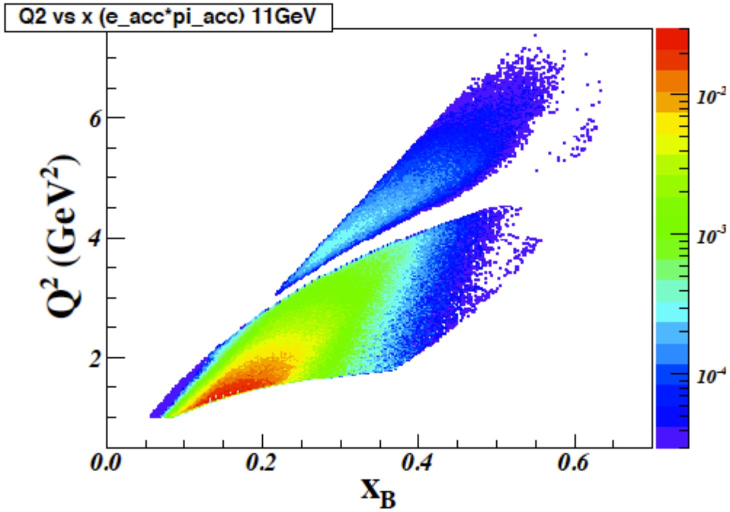


(b) w PRD

$1< Q^2 <4$ GeV^2	$Q^2 >4$ GeV^2	Total
DEMP: $\vec{n}(e,e'\pi^- p)$ Triple-Coincidence (Hz)		
23.91 (6.21)	0.59 (0.28)	24.50 (6.49)
SIDIS: $\vec{n}(e,e'\pi^-)X$ Double-Coincidence (Hz)		
1388.85	35.77	1424.62

- Rates were estimated with a model developed by Garth & Zafar.
- Good physics rates are at Q^2>4GeV^2:
  0.53 Hz (or 0.31 Hz w/o PRD)
- Dominated background are SIDIS events

Projection

- Asymmetry Binning:

➢ 1D binning on –t
(May further binning on Q^2)

➢ Asymmetries are diluted due to not doing L/T separation:

from model:

$$A_{UT} = -f_{L/T} \cdot A_L^{\perp,model}$$

$$f_{L/T} = \frac{\epsilon\sigma_L}{\sigma_T + \epsilon \cdot \sigma_L},$$

$$\epsilon = 1/(1 + \frac{2\nu}{Q^2} tan^2(\theta))$$

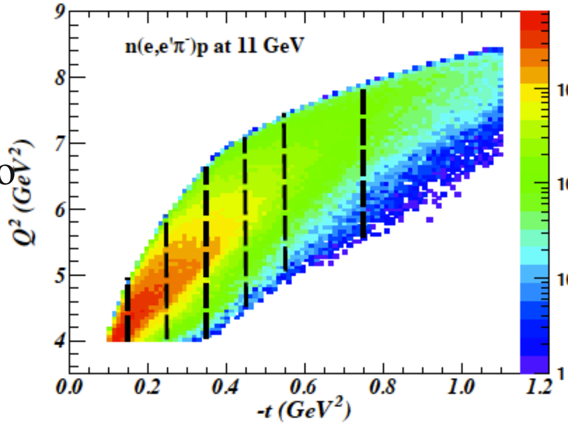
➢ Stat. Error is given as:

$$\delta A_{UT} = \frac{1}{P \cdot \eta_n \cdot f} \sqrt{\frac{1 - (P \cdot < A_{UT} >)^2}{N_i^+ + N_i^-}},$$

P → He3 polarization 60%

η_n → Effective neutron 0.865

f → Dilution from protons (0.9 estimated)



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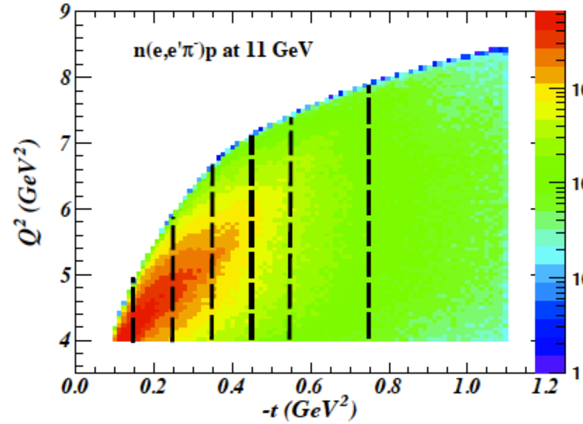

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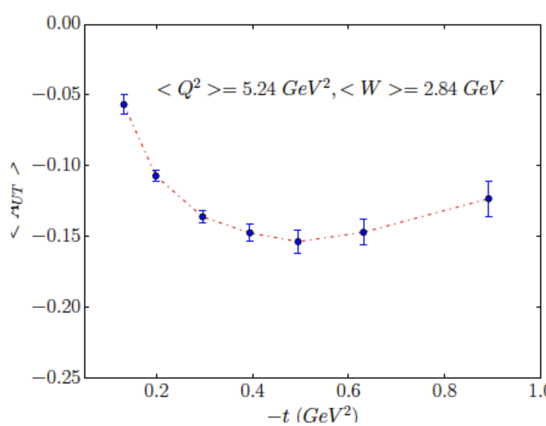

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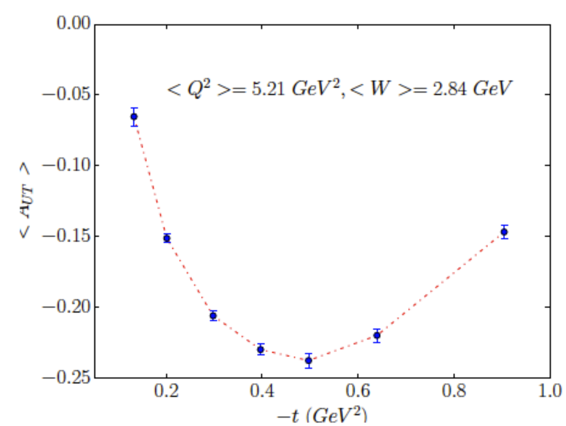

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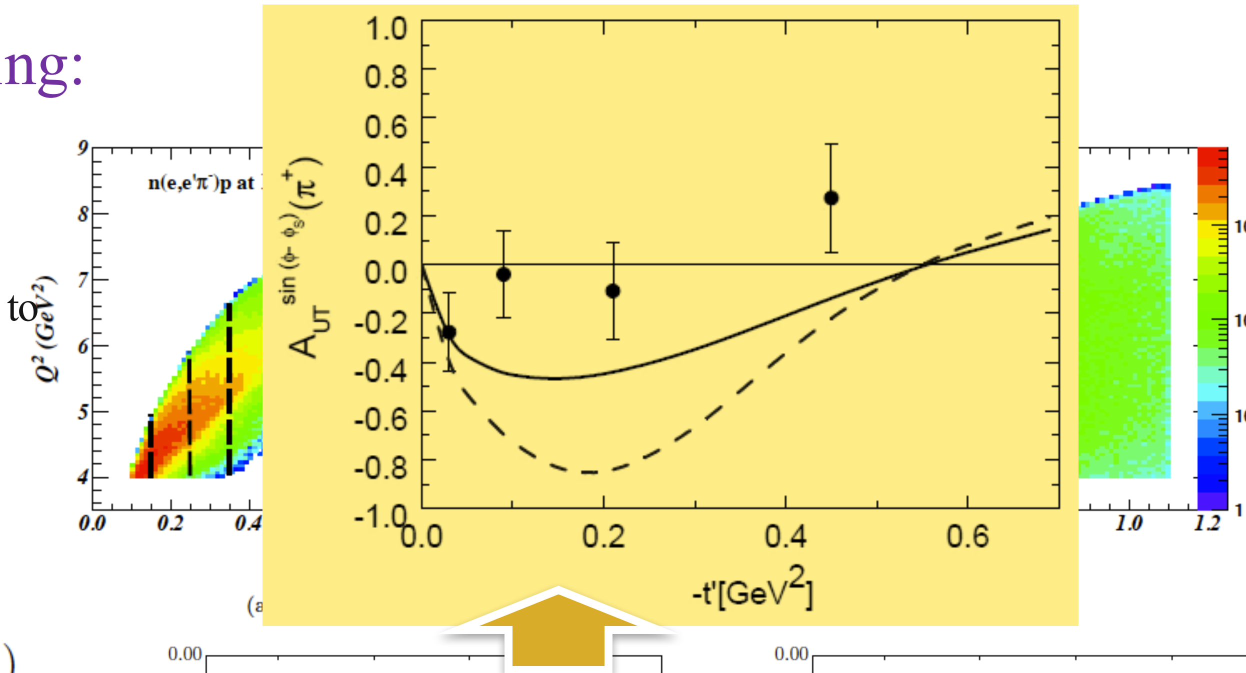
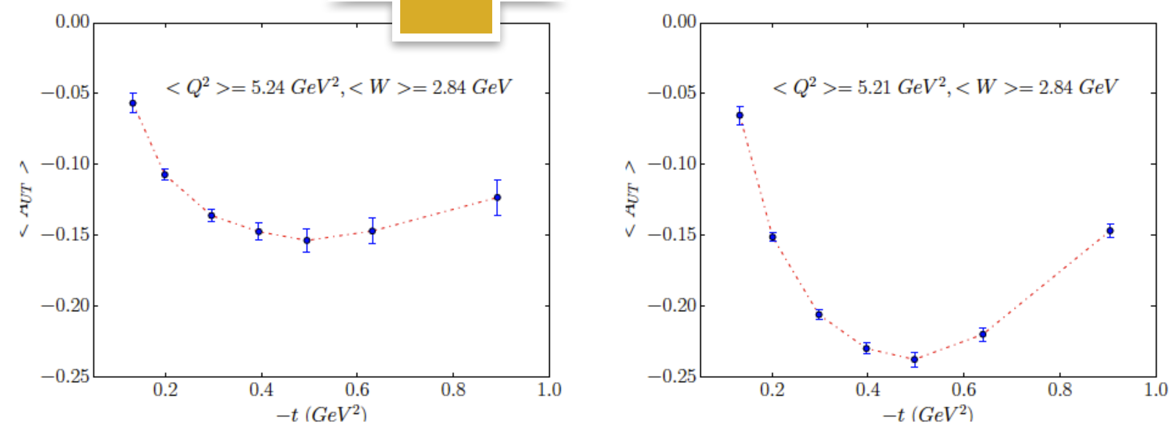




(a) w/o PRD

(b) w/ PRD

Missing Mass

- Exclusivity of DEMP Events

  - With Proton detection, most of background events can be suppressed
  - Major background would be SIDIS events

    from (a) Protons in "X",

    (b) Accidental coincidence of SIDIS events with protons in all background sources

  - Reconstructing Missing Momentum and Missing Mass to further suppress background during offline analysis.

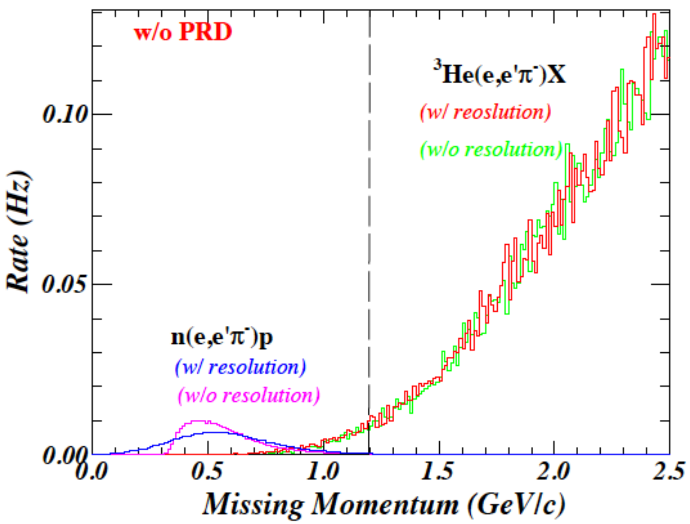
✓ Assuming all "X" in SIDIS contain protons (hard to estimate the real branching-ratio)

✓ Fold in detector resolutions: $\frac{\delta P}{P} = \frac{2\%}{\sqrt{E}}, \delta\theta = 0.6\ mrad, \delta\phi = 5\ mrad$

✓ Nucleus-Effect, Fermi Motion and Radiative Effect are not considered yet but some of them are expected to be small in the asymmetry extraction.

Missing Mass

- Exclusivity of DEMP Events



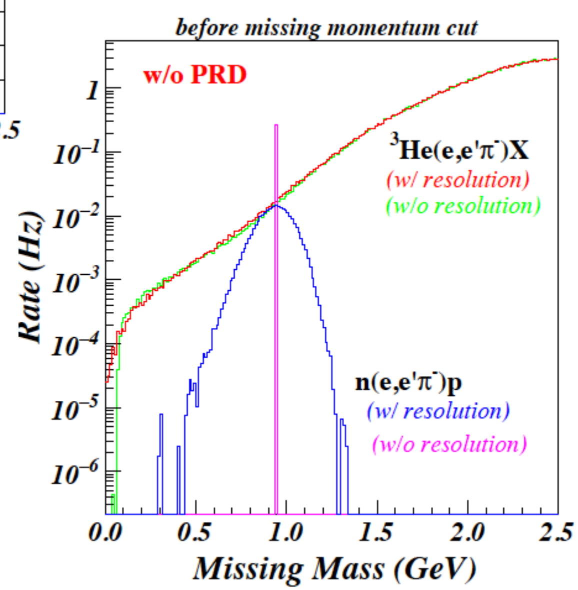
✓ Missing Momentum are well separated for SIDIS and DEMP.

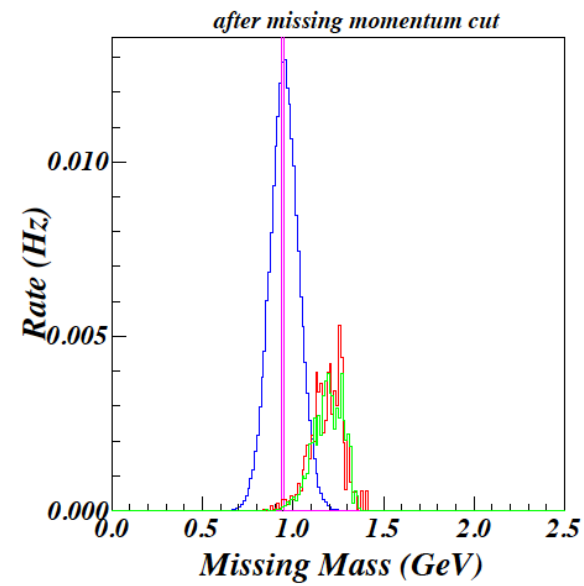
✓ Cutting P_{miss}<1.2 GeV/c, reject most of SIDIS background

✓ Background is expected to be even smaller, since SIDIS rate are overestimated

✓ Other backgrounds will be more uniform in the MM, asymmetries of which can be evaluated and corrected.

✓ Rest of random background will largely suppressed in the asymmetry.





SIDIS rate is still overestimated for safety

Systematic Uncertainties

- Detector-wide, DEMP measurement shares the same systematic uncertainties with SIDIS experiments:

Sources	Relative Value
Beam Polarization	2%
Target Polarization	3%
Acceptance	3%
Other Contamination	$< 5\%$
Radiation Correction	1%

- Other sources of uncertainties are still under estimation.

To-Do-List

- Projections were made by assuming a free neutron. We are implementing Fermi-Motion and Radiative Effect in the generator.
- Optimizing the projections, e.g. further binning on Q^2
- Further designing and evaluating the Proton-Recoil-Detector
- Study more background situation
- Evaluating more systematic errors
- Double check of all calculations

Summary

- GPDs provide new information of the 3D spatial distributions of quarks and gluons; connect 1D-PDF, Form-Factors and so on. *(Four GPDs for each quark flavor or gluon: H, E, $\tilde{H}$ and $\tilde{E}$)*
- DEMP can measure $\tilde{H}$ and $\tilde{E}$; It is an unique process to probe $\tilde{E}$, which gets access to pion form factors.
- Target Single-Spin Asymmetry of DEMP has relatively low requirement on the Q^2

  (Higher order effects are largely cancelled even at Q^2~4 GeV^2).
- Using SoLID-SIDIS configuration and transversely polarized He3, we can measure asymmetries of neutron DEMP

  Complementary to the Hall-C experiment with limited coverage but doing L/T separation
- Run in-parallel with SIDIS experiments; No new beam time; No configuration change needed except potentially adding a new proton recoil detector
- Expect to have very good statistical errors over wide –t coverage
- Proton Detection will help us to maintain the Exclusivity. Missing Momentum and Missing Mass cuts can further reject most background.

Backup Slides

DEMP TSSA Connection to GPDs

L. Frankfurt *et. al.* , PRD 60 014010 (1999):

- Charge Pion Production:

$$\mathcal{A}=\frac{1}{|S_\perp|}\frac{\int_0^{\pi} d\beta|\mathcal{M}(\beta)|^2-\int_{\pi}^{2\pi} d\beta|\mathcal{M}(\beta)|^2}{\int_0^{2\pi} d\beta|\mathcal{M}(\beta)|^2}=\frac{2\sigma_1}{\pi\sigma_0}$$

$$\sigma=\sigma_0+\sigma_1([\vec{p}_\perp{}' ,\vec{S}_\perp]\cdot\vec{e}_z)/|\vec{p}_\perp{}'|=\sigma_0+\sigma_1|\vec{S}_\perp|\sin\beta,$$

$$\mathcal{A}_{+,0}=\frac{|\Delta_\perp|}{\pi M_N}\frac{\xi\,\mathrm{Im}(A_{+,0}B^*_{+,0})}{|A_{+,0}|^2\left(1-\frac{\xi^2}{4}\right)-|B_{+,0}|^2\frac{t\xi^2}{16M_N^2}-\frac{\xi^2}{2}\mathrm{Re}(A_{+,0}B^*_{+,0})}$$

$$A_+=\int_{-1}^{1} d\tau\tilde{H}^{(3)}(\tau,\xi,t)(3\alpha^-(\tau)-\alpha^+(\tau))$$

$$B_+=\int_{-1}^{1} d\tau\tilde{E}^{(3)}(\tau,\xi,t)(3\alpha^-(\tau)-\alpha^+(\tau)),$$

$$\tilde{H}^{(3)}(\tau,\xi,t)=\tilde{H}_u(\tau,\xi,t)-\tilde{H}_d(\tau,\xi,t),$$

$$\tilde{E}^{(3)}(\tau,\xi,t)=\tilde{E}_u(\tau,\xi,t)-\tilde{E}_d(\tau,\xi,t),$$

$$\alpha^{\pm}(\tau)=\frac{1}{\tau+\frac{\xi}{2}-i0}\pm\frac{1}{\tau-\frac{\xi}{2}+i0},$$

Acceptance w/ Q2>1GeV^2 Cut