High luminosity experiments in Hall A and C

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U.S. DEPARTMENT OF ENERGY | Office of Science

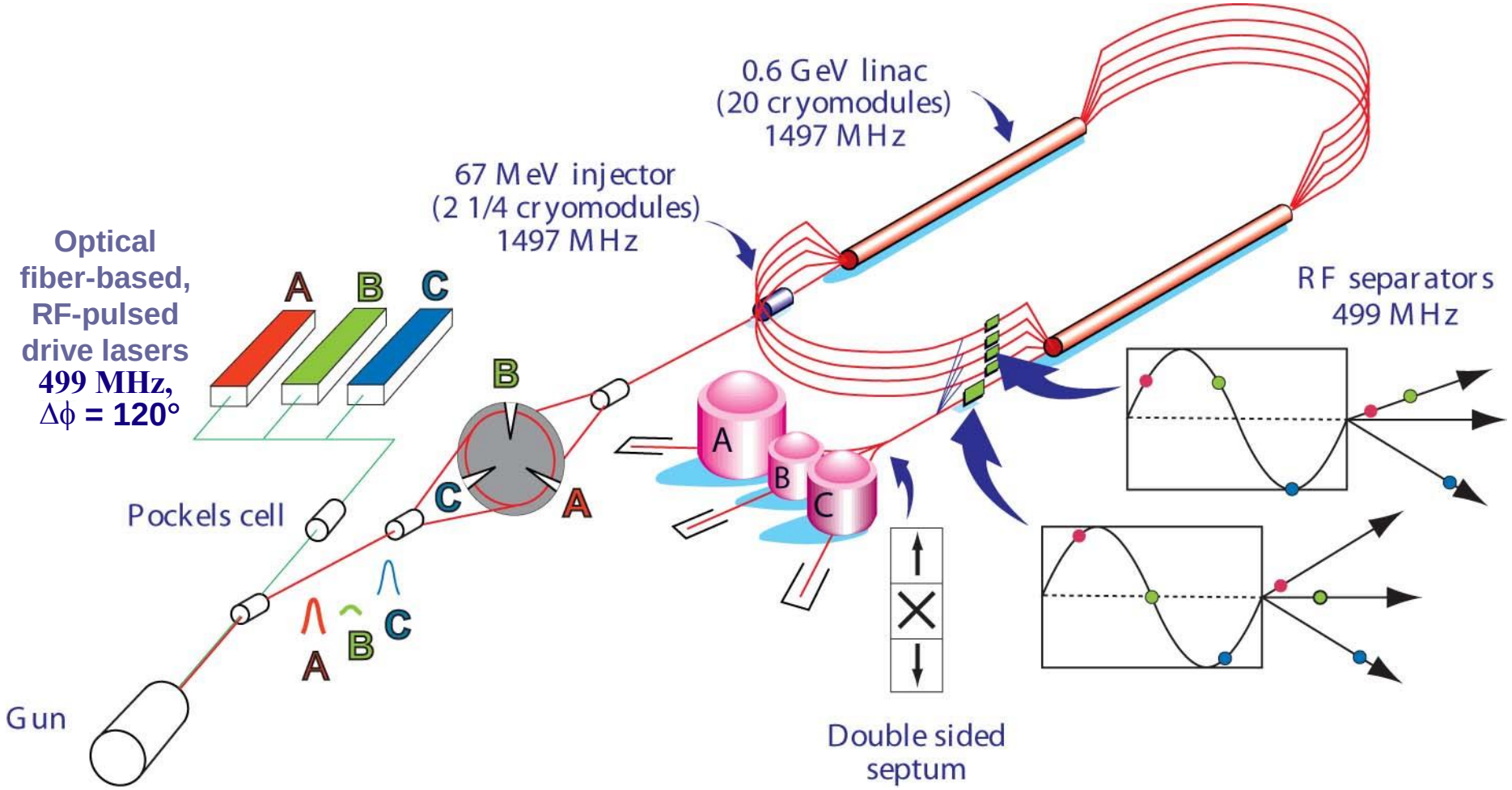
Jefferson Lab
Thomas Jefferson National Accelerator Facility

JSA

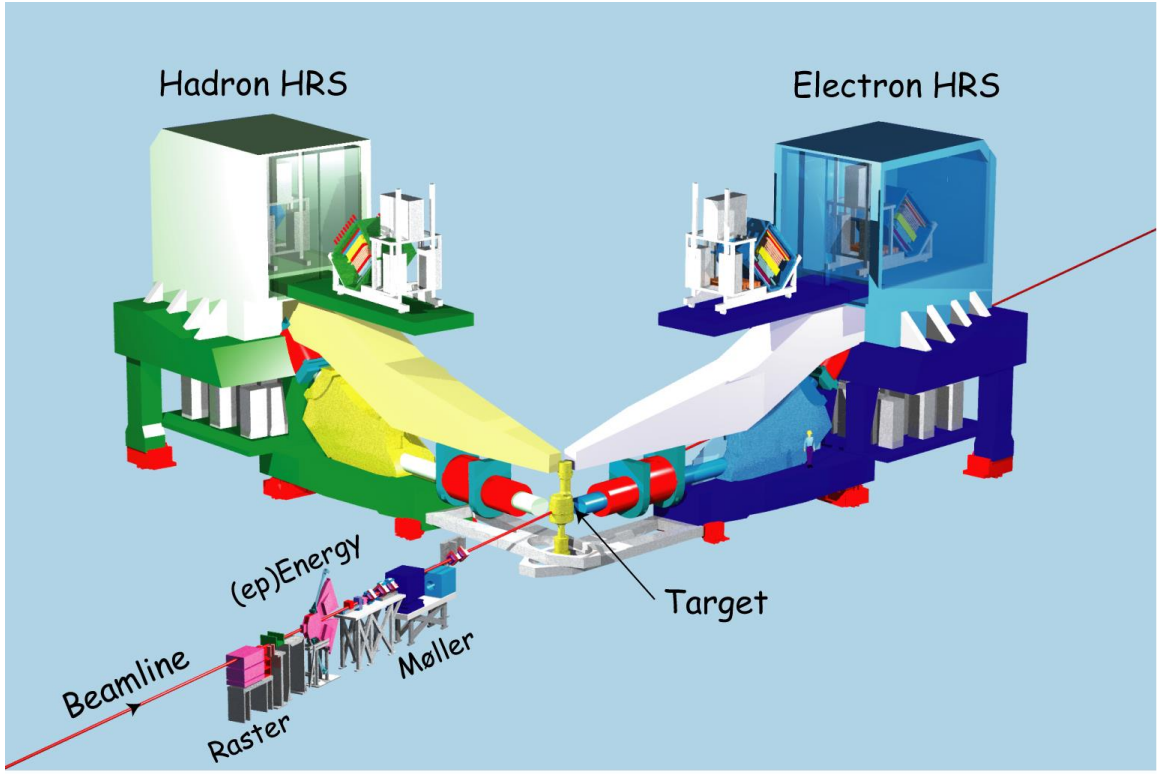
Outline

- Hall A/C overview
- Previous experiments
- SuperBigBite
  - GMn
  - GEp
  - SIDIS setup
  - TDIS setup
- SoLID
  - Overview
  - J/Psi
- SoLID DDVCS setup
- Moller
- Conclusion

Continuous Electron Beam Accelerator Facility



Hall A Infrastructure



HRS Spectrometers	FWHM
Max. momentum	4.2 GeV/c
Momentum acceptance	± 4.5%
Momentum resolution	1.10^{-4}
Angular acceptance	6 msr
Angular resolution	1 mrad
Vertex acceptance	± 5 cm
Vertex reconstruction	1 mm

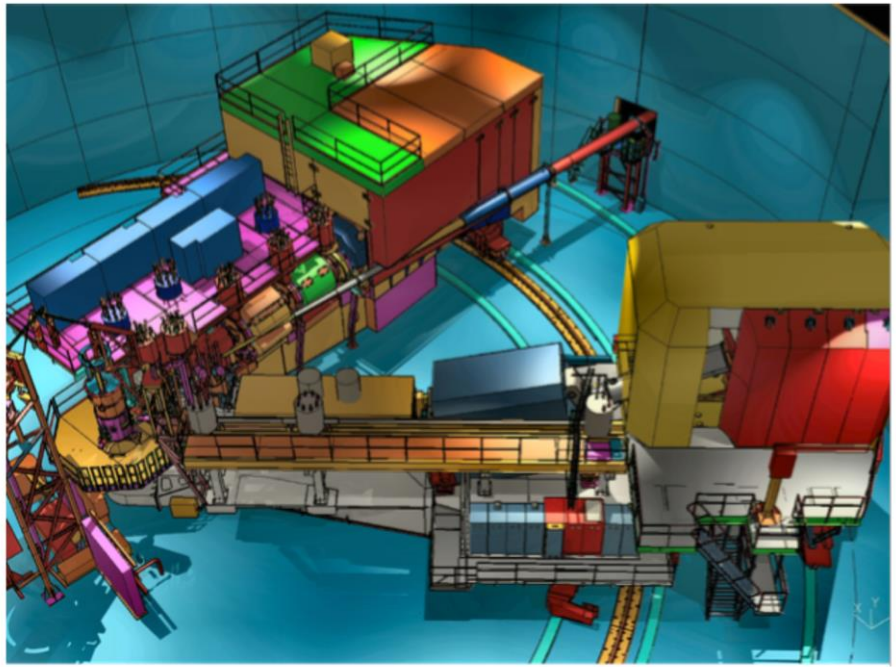
Focal-Plane Detectors

- Scintillator trigger
- MWDC tracking
- Pb-glass preshower/shower
- Gas Cherenkov
- Aerogel Cherenkovs
- Ring Imaging CHerenkov

Auxiliary Instrumentation

- Møller Polarimeter
- Compton Polarimeter
- Polarized ^{3}He Target
- Cryo-target : 15 cm (2.10^{38} cm^{-2}.s^{-1} at 60 uA) to 1 m target
- BigBite spectrometer
- Large on-floor detector arrays for neutrons and photons

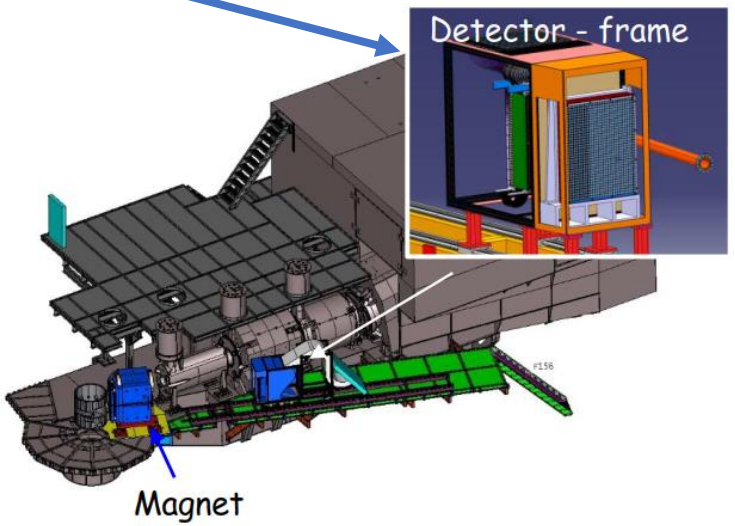
Hall C



Parameter	*HMS Performance*	*SHMS Specification*
Range of Central Momentum	0.4 to 7.4 GeV/c	2 to 11 GeV/c
Momentum Acceptance	±10%	-10% to +22%
Momentum Resolution	0.1% – 0.15%	0.03% – 0.08%
Scattering Angle Range	10.5° to 90°	5.5° to 40°
Target Length Accepted at 90°	10 cm	25 cm
Horizontal Angle Acceptance	±32 mrad	±18 mrad
Vertical Angle Acceptance	±85 mrad	±45 mrad
Solid Angle Acceptance	8.1 msr	4 msr
Horizontal Angle Resolution	0.8 mrad	0.5 – 1.2 mrad
Vertical Angle Resolution	1.0 mrad	0.3 – 1.1 mrad
Target resolution (y_{tar})	0.3 cm	0.1 - 0.3 cm
Maximum Event Rate	2000 Hz	10,000 Hz
Max. Flux within Acceptance	~ 5 MHz	~ 5 MHz
e/h Discrimination	>1000:1 at 98% efficiency	>1000:1 at 98% efficiency
π/K Discrimination	100:1 at 95% efficiency	100:1 at 95% efficiency

Plan to run the NPS experiments in July 2023 – Mar 2024

- Install Neutral Particle Spectrometer (NPS) during March 2023 to July 2023 down
- Magnet with calorimeter
  - 1080 Lead-Tungstate blocks in Calorimeter to detect γ and π^0
  - Remove the SHMS HB magnet



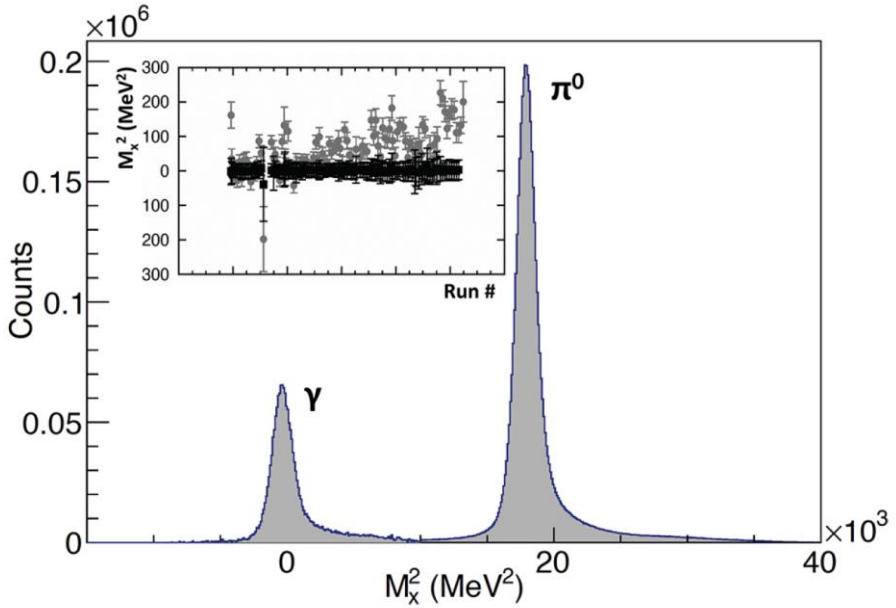
- Experiments
  - E12-13-010 is two concurrent experiments
    - Exclusive Deeply Virtual Compton on proton
    - SIDIS p(e,e',π^0) cross section. Map the transverse momentum dependence.
    - 53 PAC days.
  - E12-06-114 is completion of Hall A DVCS experiment
    - 35 PAC days.
  - *Note that new proposal for Neutron DVCS could change the schedule*
  - Two experiments with photon beam running concurrently
    - E12-14-003 : Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies (18 PAC days)
    - E12-14-005 :Wide Angle Exclusive Photoproduction of pi-zero Mesons

nDelta experiments

- Detect electron and proton and select pi0 with missing mass
- Hall A
  - E91-011: Recoil polarization measurements for neutral pion electroproduction at $Q^2 = 1$ (GeV/c)^2 near the Delta resonance

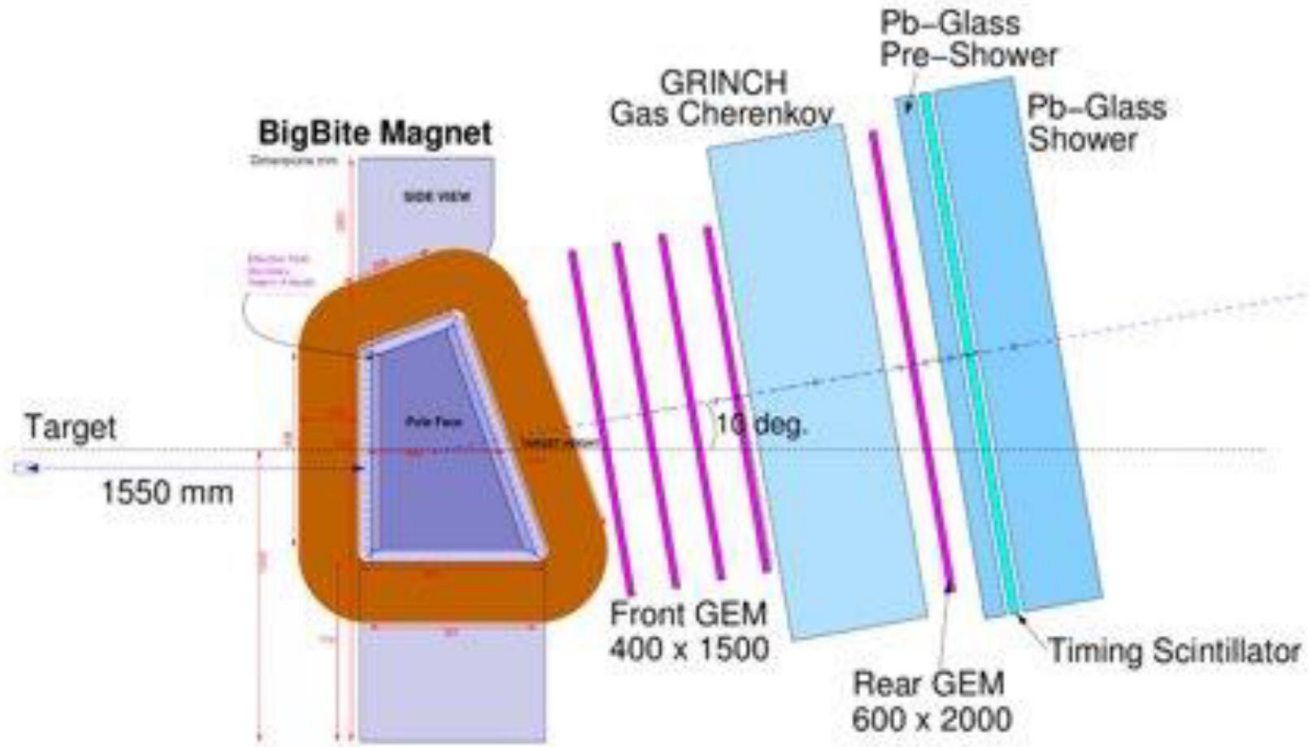
Phys.Rev.C 75 (2007) 025201 • e-Print: nucl-ex/0509004 [nucl-ex]

  - E08-010 N-Delta Measurement of the Coulomb quadrupole amplitude in the γ* p → Δ (1232) reaction in the low momentum transfer region
    Phys.Lett.B 760 (2016) 267-272 (2015)
    https://arxiv.org/pdf/1509.00780.pdf
- Hall C
  - PR12-22-001 Measurement of the N to Delta Transition Form Factors at low four momentum transfers



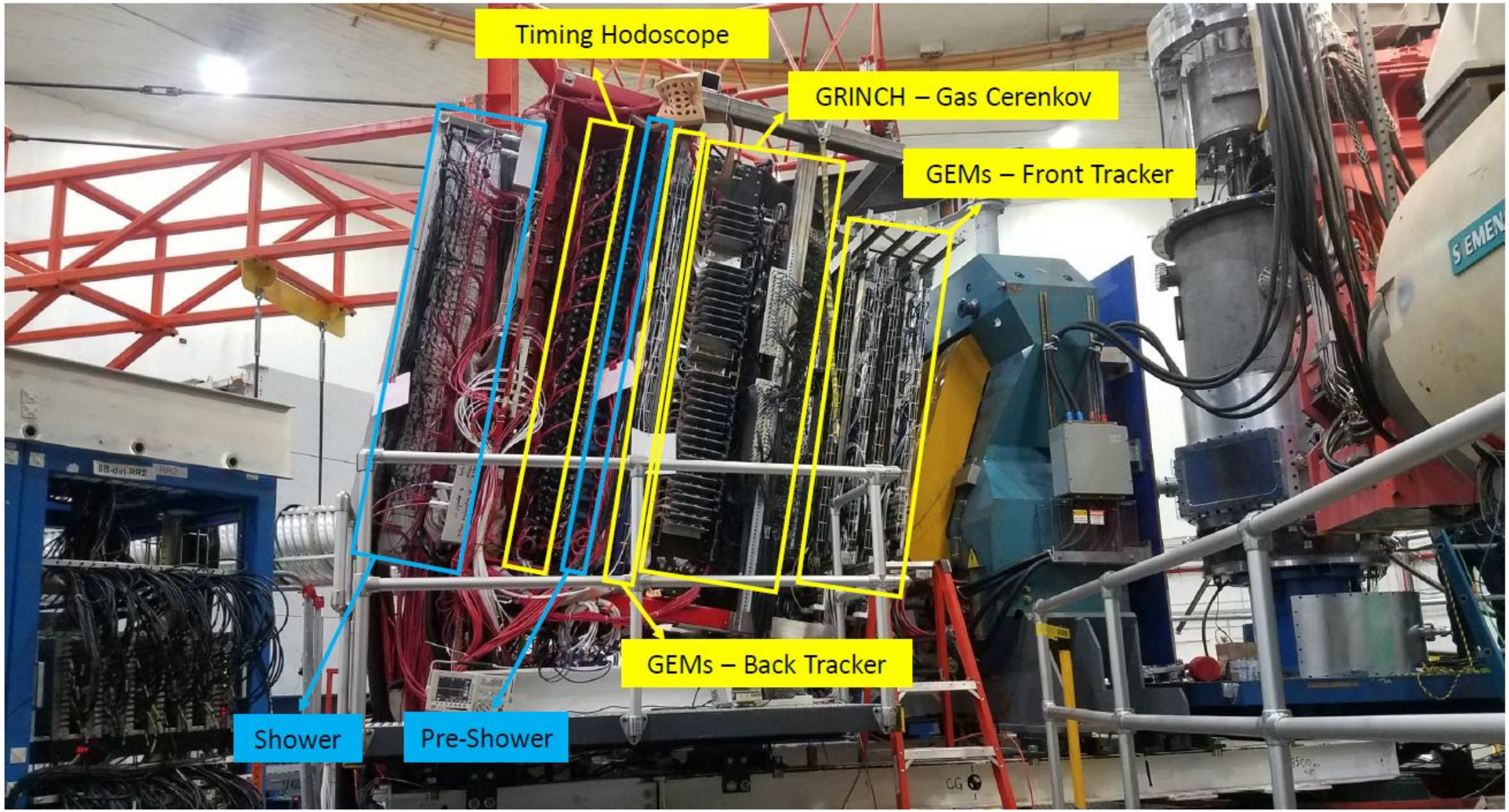
Bigbite Electron Spectrometer - BB

- A non-focusing, large momentum and angular acceptance spectrometer
- The spectrometer consists of a single dipole magnet and a detection system
- Current detection system includes:
  - 5 layers of GEM detectors (UVa, INFN)
  - GRINCH gas Cerenkov detector (W&M, JMU, NC A&T)
  - A shower and preshower (JLab, UConn, Yerevan)
  - A timing Hodoscope plane (Glasgow U, JLab)
- High background rates due to open configuration
- GEM detectors to handle high rate



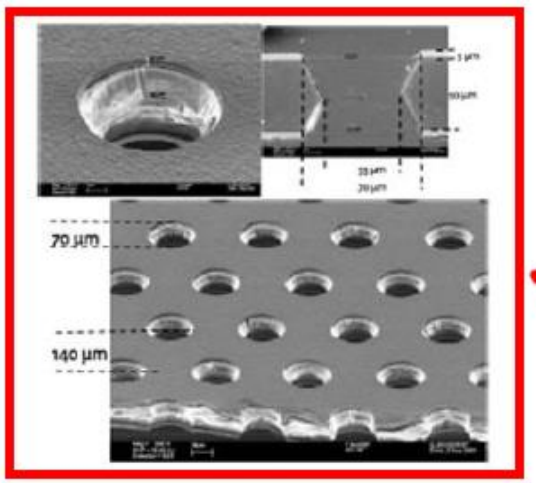
BB Electron Arm

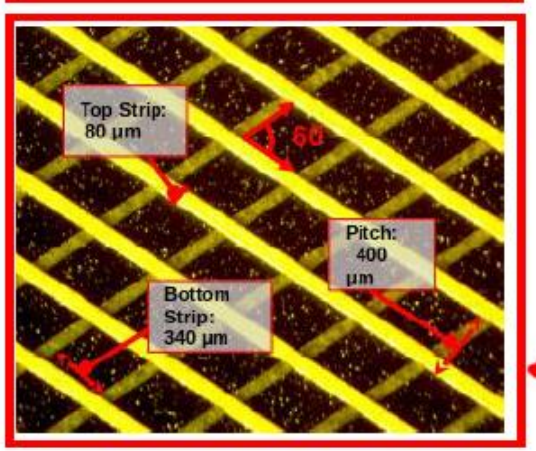
Bigbite Spectrometer in GMn Experiment

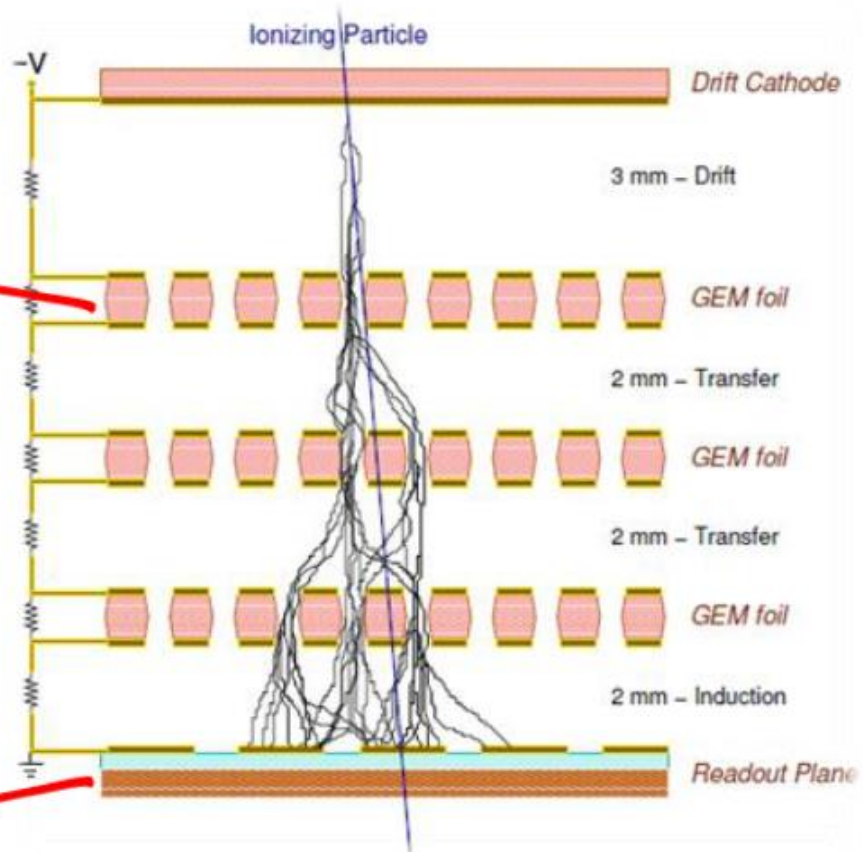


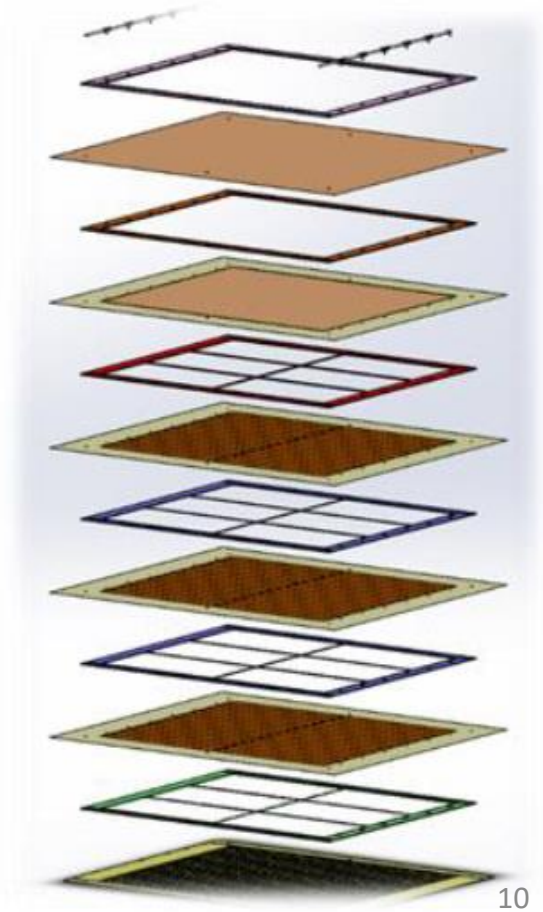
GEM Detector

- GEM (Gas Electron Multiplier) detectors consist of GEM foils and a **2D** readout plane
- Compass triple foil structure
- High Rate (2 MHz/cm^2), high space resolution (70 um)







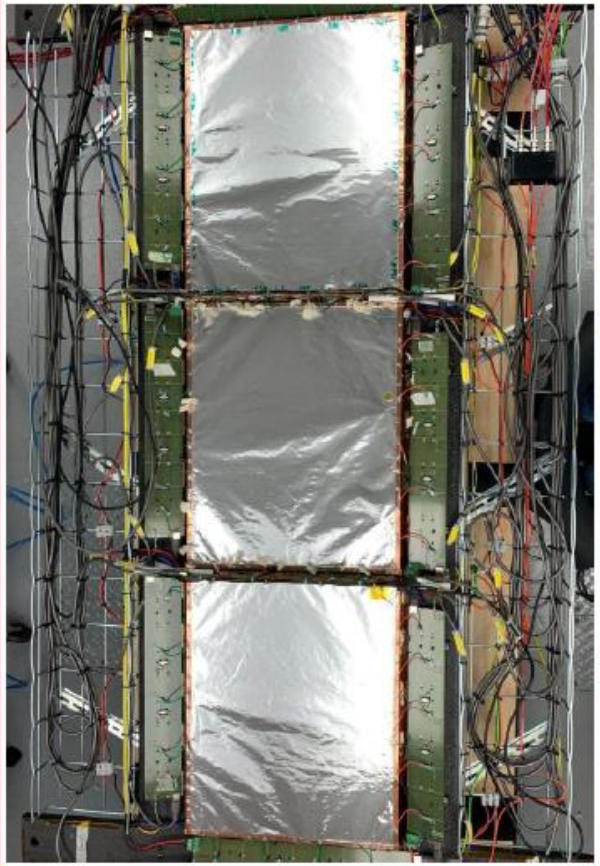


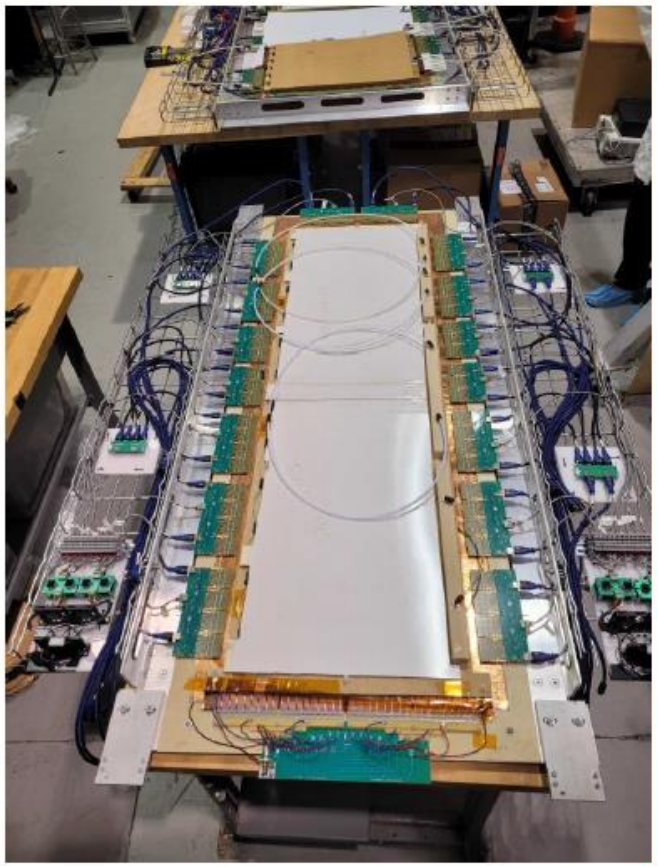
GEM Detectors in Bigbite

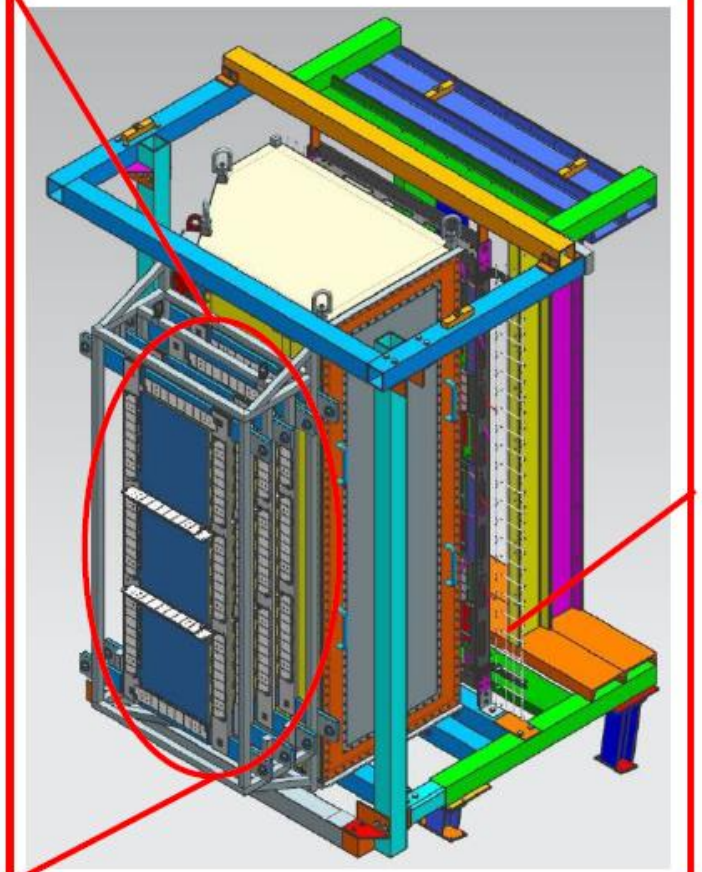
40X150 cm^2 layers, made of 3 40X50 GEM modules

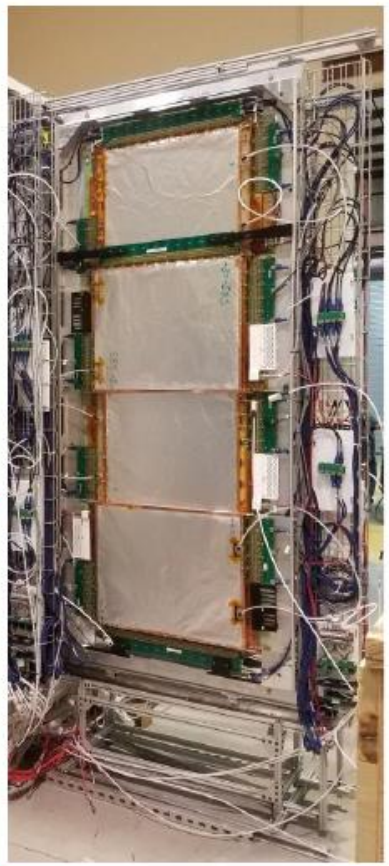
40X150 cm^2 layer, made of a single module, no dead area in active area

60X200 cm^2 layers, made of 4 60X50 GEM modules







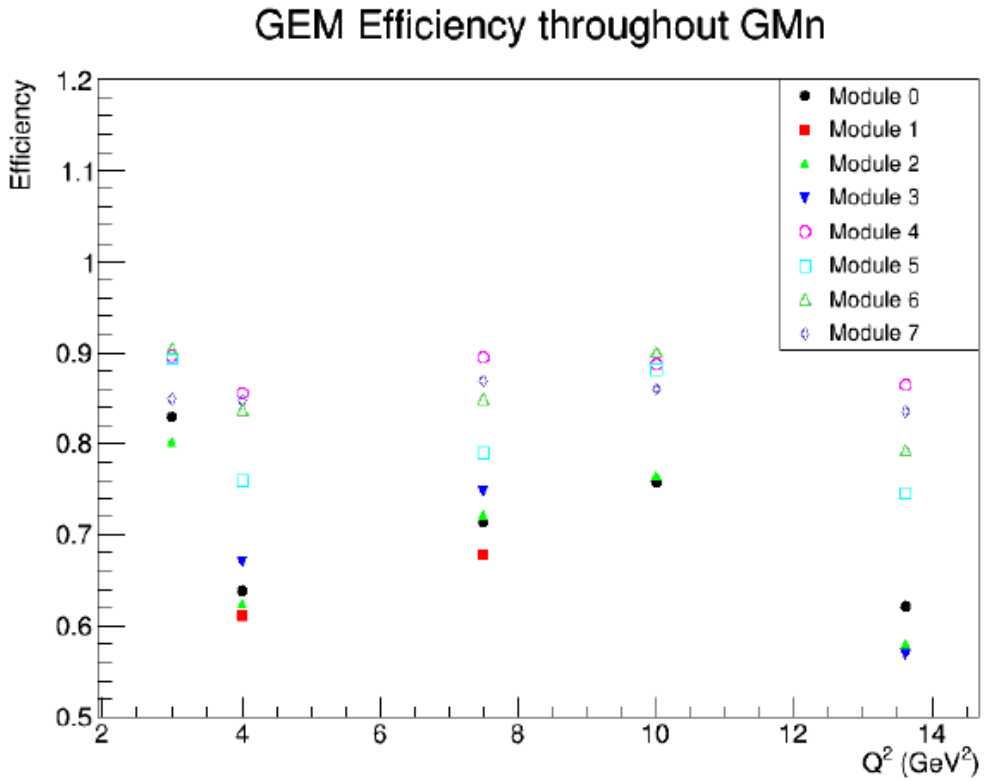


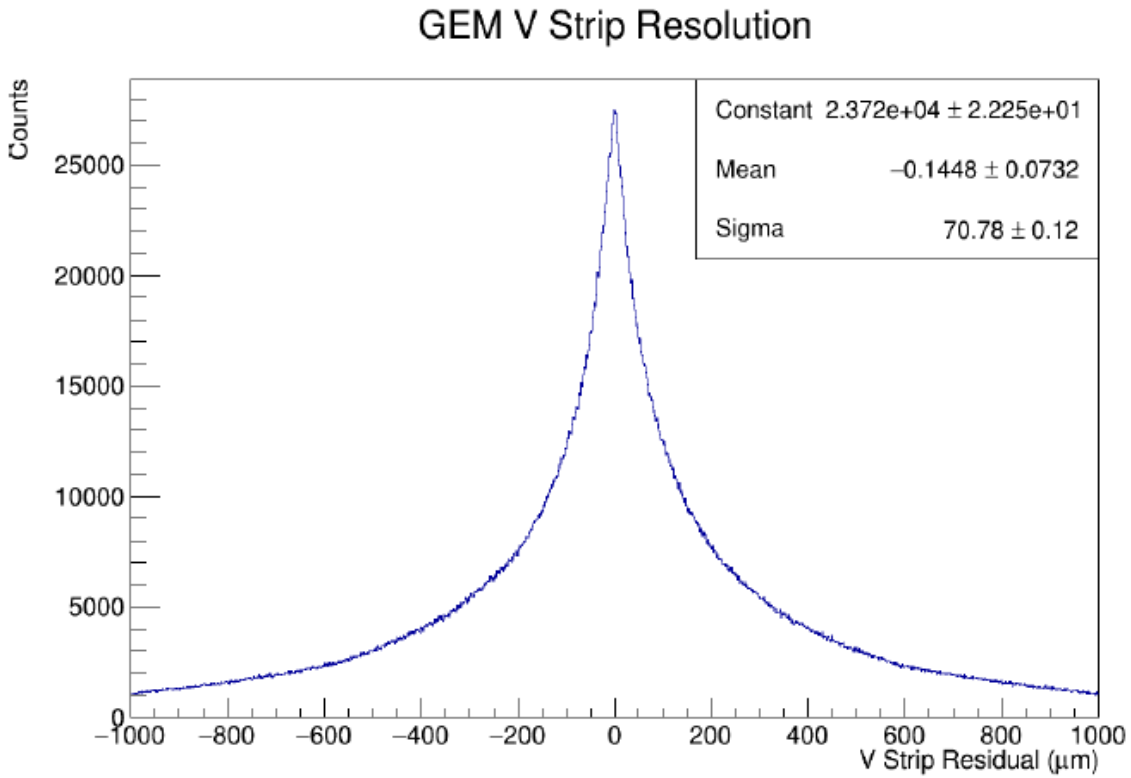
INFN XY **UVa UV** **Bigbite Detectors** **UVa XY**

These layers are among the largest GEM layers ever built

GEM Detector Performance in GMn

- Efficiency varies from module to module due to different rates seen by different modules
- Backtrackers has consistently higher efficiency due to low rates
- Position resolution around 70 um





Plot courtesy of Sean Jeffas

Tracking Algorithm

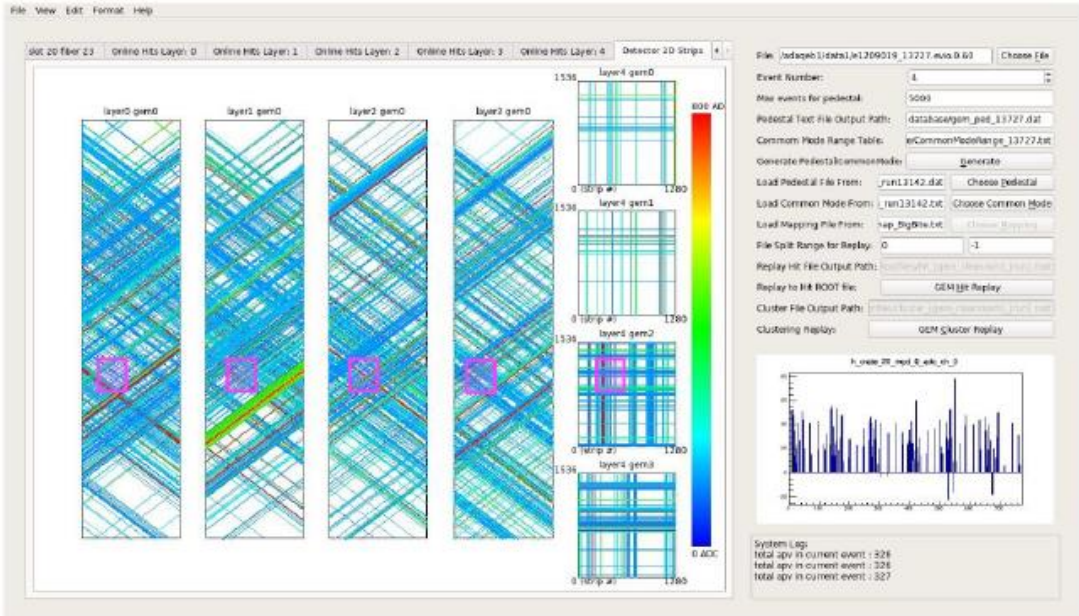
- 5 GEM layers out of electromagnetic field, high rate, large quantity of combinations

Tracking algorithm in a nutshell:

- Perform 1D clustering of strips along each dimension in each GEM chamber
- Form all possible 2D combinations within calorimeter-defined region
- Divide each tracking layer into a uniform 2D rectangular grid, accumulate a list of 2D hit candidates in each grid bin (bin size 1 x 1 cm^2)
- Loop all possible combinations from hits in outermost layers (within search region)
- Form straight-line projection
- Loop all possible combinations from each inner layer (minimum 3 layers)
- Find the hit combination with best X^2/ndf

Tracking algorithm credit goes to **Prof. Andrew Puckett and Dr. Weizhi Xiong**

What we're up against, II (run 13727, 12 uA LD2, $Q^2 = 4.5\ GeV^2, E = 4\ GeV$)



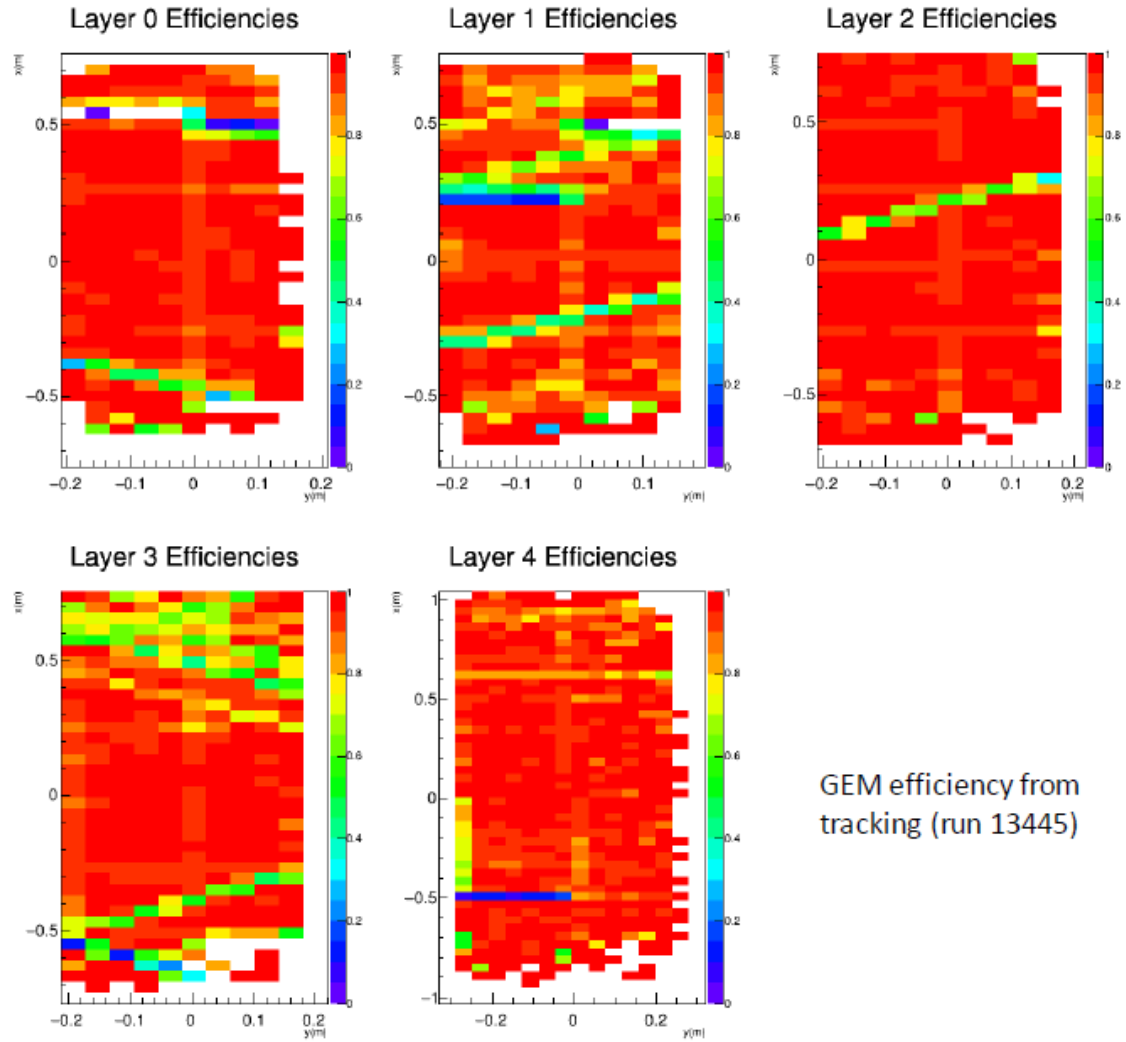
- This is the same event as previous slide, but requiring max ADC sample on a strip greater than 100, a typical offline threshold for cluster maxima that is higher than online threshold

□ = approximate size of calorimeter-constrained track search region at each layer

Slide courtesy of Prof. Andrew Puckett

Tracking Performance

- **Average > 90% under low occupancy, > 60% under high occupancy in GMn**
- Low efficiency area due to dead channels on GEM detectors and APV chips
- While occupancy increases, efficiency drops
  - GEM gain drop due to high voltage system design
  - Larger number of possible 2D combinations, more fake tracks
  - More noise hits due to negative signals, common mode sagging towards the lower side under high occupancy – offline correction developed (Sean Jeffas from UVa)
- We took a set of high beam current (high occupancy) runs to study this effect, the analysis work is in progress, further improvements will be made in future



GEM efficiency from tracking (run 13445)

Estimated Rates in GMn

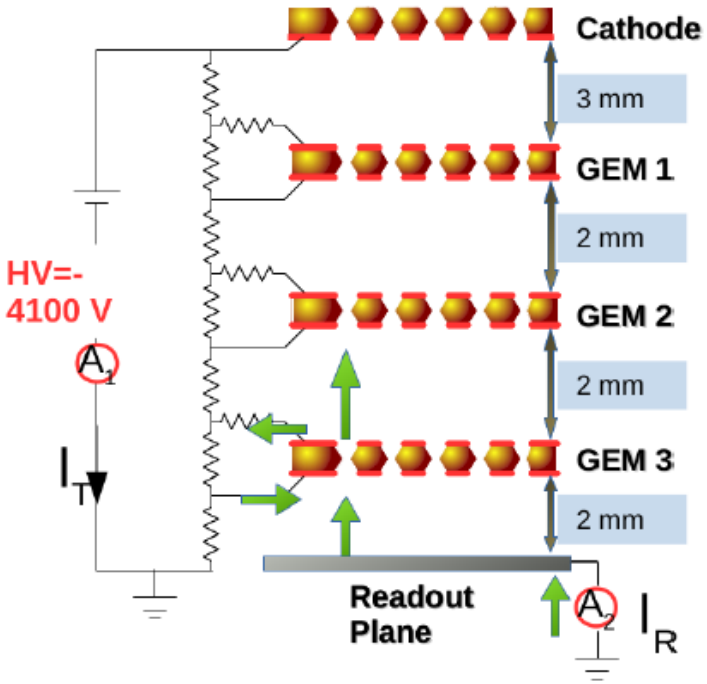
- Background comes from: beamline structure, target window...
- A majority background rate comes from low energy photons, less than 1% conversion rate, can be rejected by tracking
- Estimated from GEM gain factor measurement, not precise
- Rates are about a factor of 2 – 3 times higher than expected

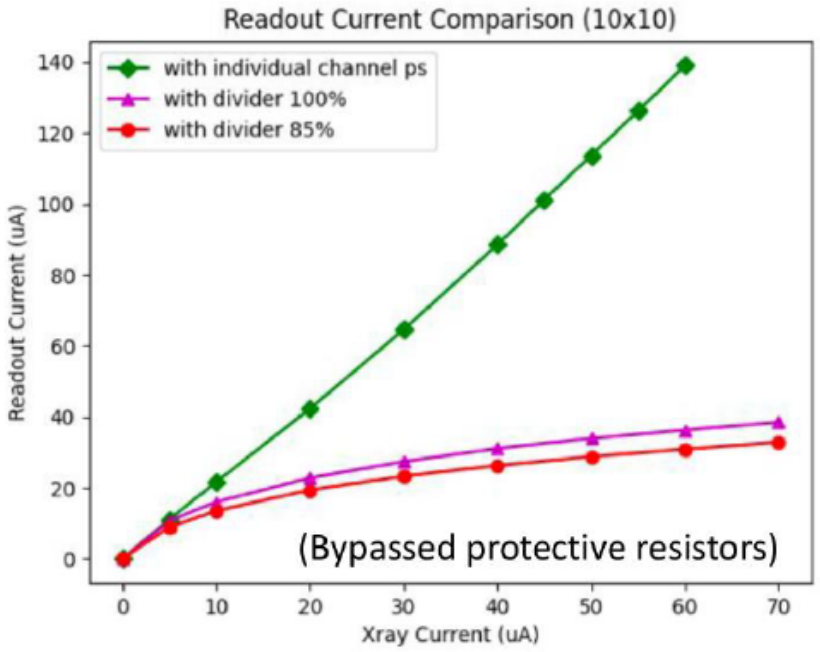
SBS Period	Target	E_beam (GeV)	Beam Current (uA)	BB Angle (Deg)	BB Distance (m)	Q^2 $(GeV/c)^2$	Extrapolated I_excess	Rate
SBS-4	LD2	3.728	1.75/3.75/7/10	36	1.8	3.0	(R. 28) E. 28	159.6 KHz/cm²
SBS-7	LH2	7.906	1/2/4/8/10	40	1.85	9.8	(R. 38) E. 40	228 KHz/cm²
SBS-8	LH2	5.965	1/2/3/4/5/8	26.5	2.0	4.5	(R. 40) E. 48	273.6 KHz/cm²
SBS-11	LD2	9.91	2/4/8/10/11/12	42	1.55	13.5	(R. 71) E. 105	598.5 KHz/cm²
SBS-14	LD2	5.965	1/2/7.5/8/10	46.5	1.85	7.4	(R. 42) E. 49	279.3 KHz/cm²

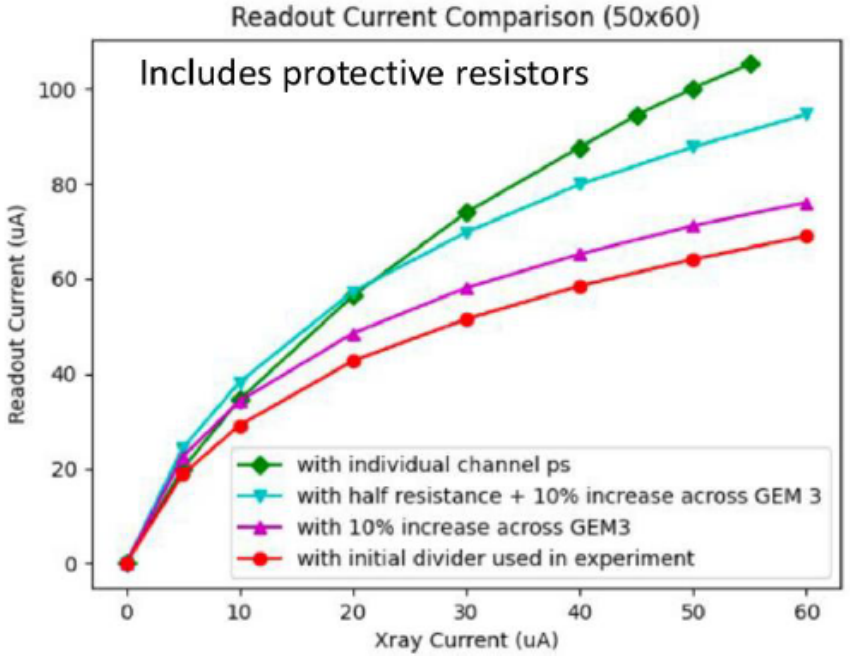
12 uA on LD2 ~ 8.10^{37}

Further Improvement for High Rate

- Under high rate, the large current flowing through GEM detector will change the HV distribution on each GEM foils
- A HV drop on 3rd GEM foil was observed
- Increased the HV distributor resistor for GEM3 by 10% before GMn
- A new solution using a parallel HV unit to provide HV for each GEM foil separately





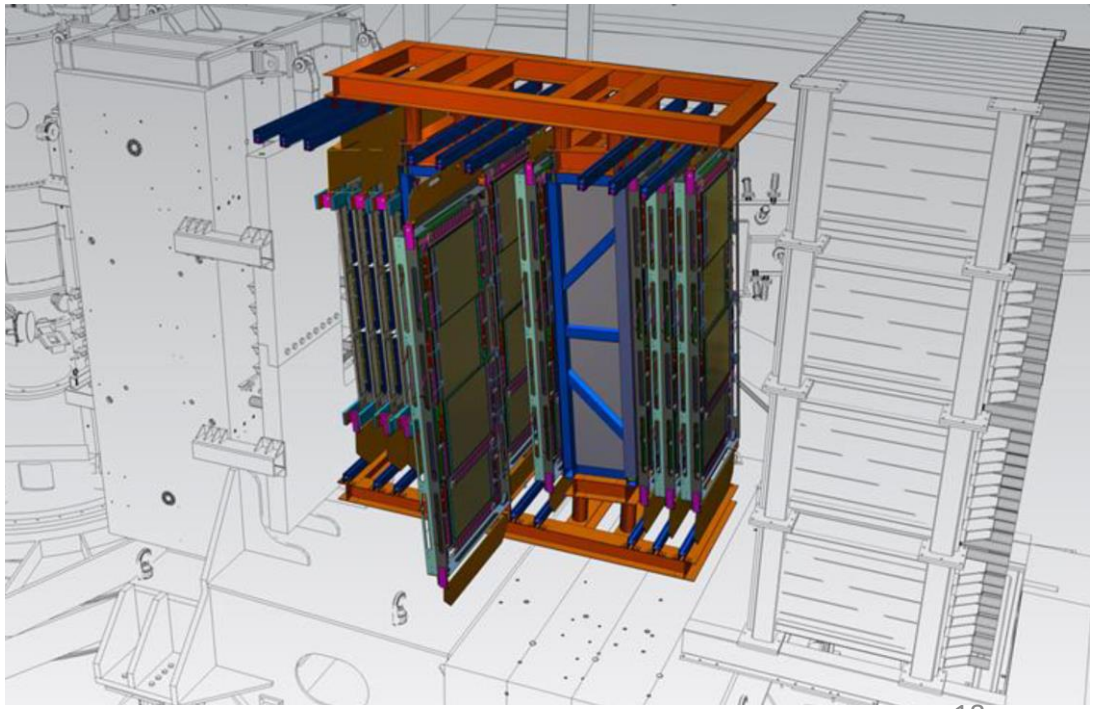


Physics Programs with SBS/BB

- Major measurements of nucleon form factors using SBS/BB Spectrometers
  - GMn (E12-09-019): Precision Measurement of the Neutron Magnetic Form Factor at up to Q^2 = 18 $(GeV/c)^2$. Data collection **completed February 2022 (see Eric's talk)**
  - nTPE (E12-20-010): Measurement of the Two-Photon Exchange Contribution to the Electron-Neutron Elastic Scattering Cross Section. Data collection **completed February 2022**
  - GEn-II (E12-09-016): Measurement of the Neutron Electromagnetic Form Factor Ratio GEn/GMn at High Q^2. Scheduled **this coming fall**
  - GEn-RP (E12-17-004): Measurement of the Ratio GEn/GMn by the double polarized $^2H(e, e'n)$ Reaction
  - GEp-V (E12-07-109): Large Acceptance Proton Form Factor Ratio Measurements at 13 and 15 $(GeV/c)^2$ Using Recoil Polarization Method

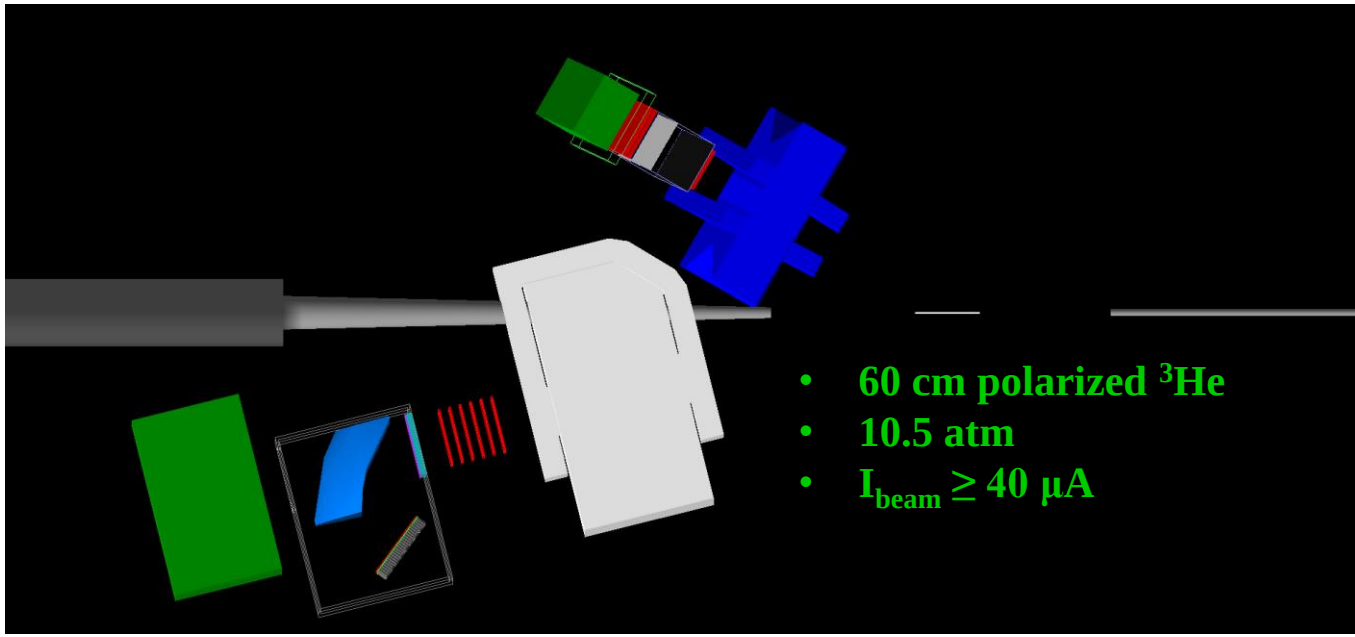
SBS Gep proton polarimeter arm

- GEM tracker after SBS magnet
- GEM trackers before and after CH2 analyzer for recoil proton measurement
- HCAL for coincidence trigger with electron arm ECAL (Lead Glass)

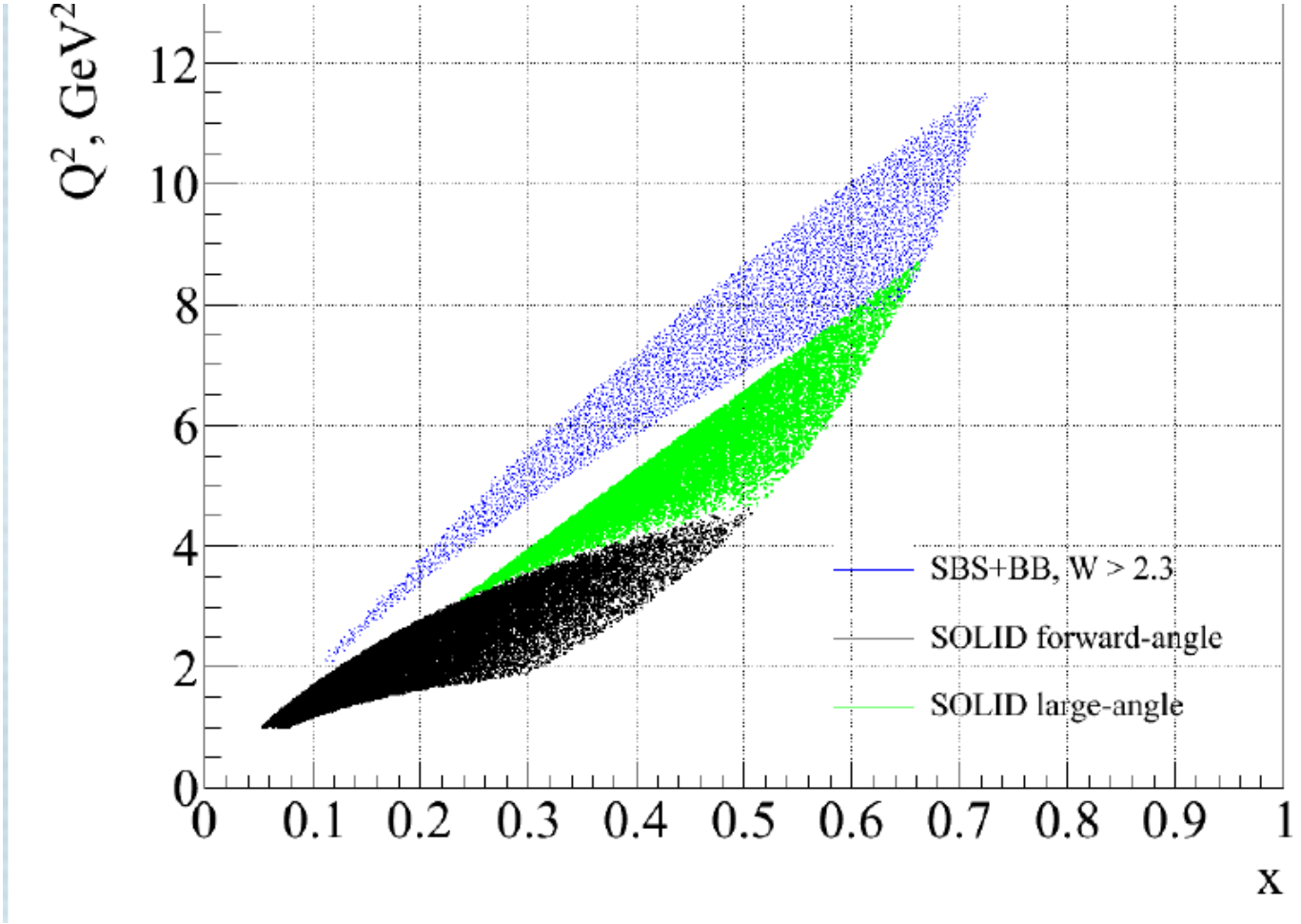


SBS SIDIS experiment E12-09-018

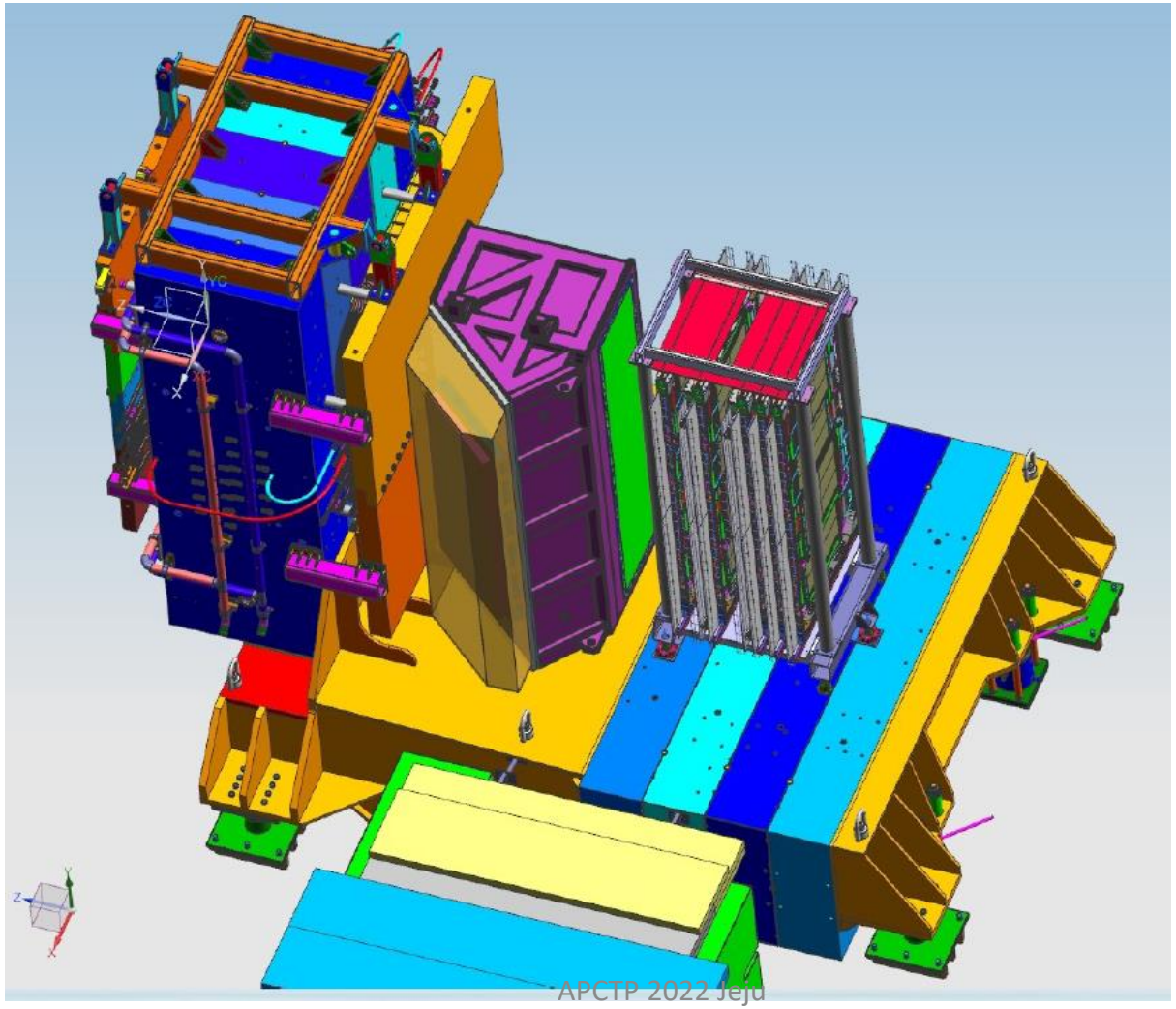
- He3 target
- Bigbite as electron arm at 30 degrees ~45 msrd
- SBS magnet with HERMES RICH GEM and HCAL as hadron arm at 14 degrees
- Very-high luminosity (~5x1036 cm-2s-1)
- polarized 3He target, capable of rapid spin-flips in either the vertical or horizontal directions



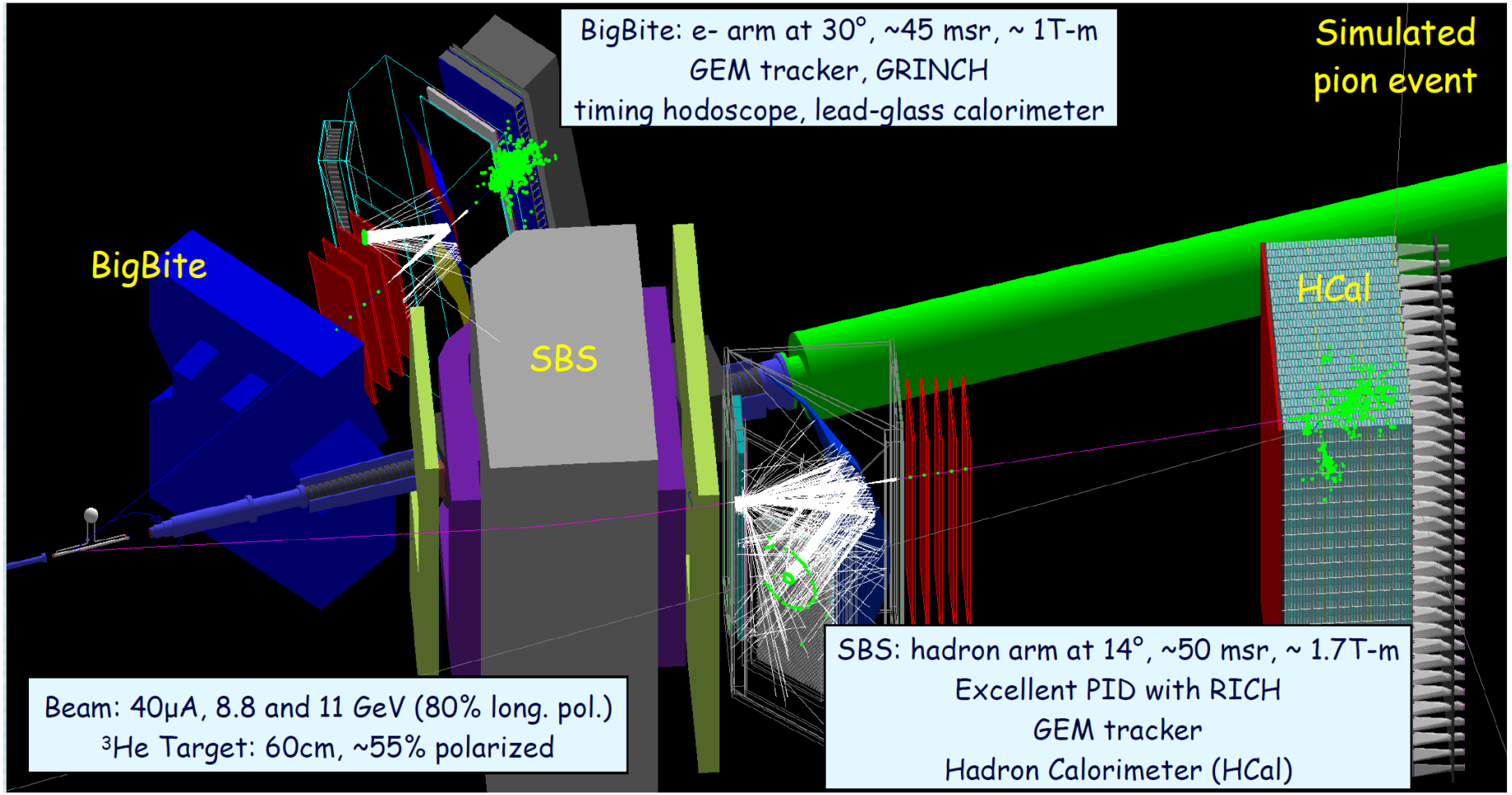
Kinematical coverage SBS SIDIS



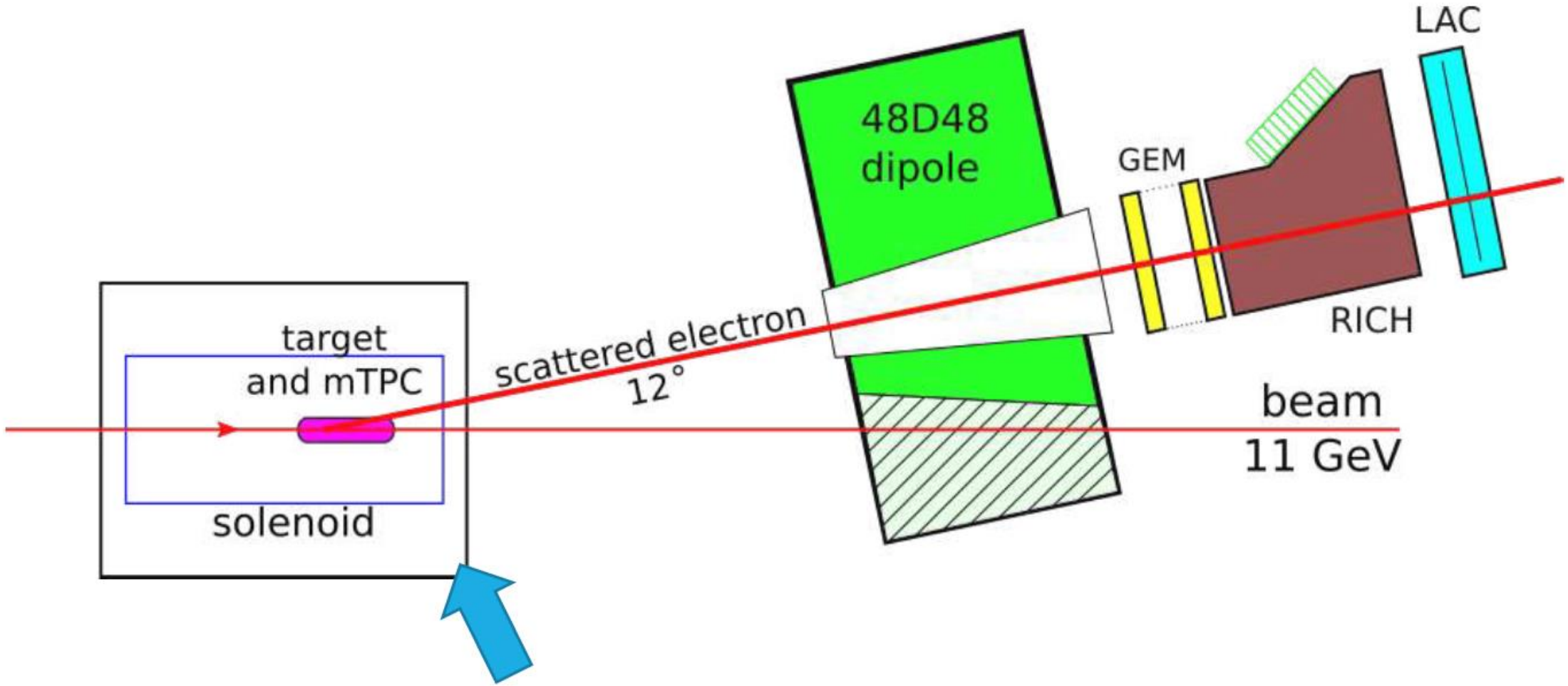
SBS SIDIS hadron arm



SBS SIDIS


BigBite: e- arm at 30°, ~45 msr, ~ 1T-m
GEM tracker, GRINCH
timing hodoscope, lead-glass calorimeter
Simulated
pion event
BigBite
SBS
HCal
Beam: 40μA, 8.8 and 11 GeV (80% long. pol.)
³He Target: 60cm, ~55% polarized
SBS: hadron arm at 14°, ~50 msr, ~ 1.7T-m
Excellent PID with RICH
GEM tracker
Hadron Calorimeter (HCal)

TDIS in Hall A: Experimental layout

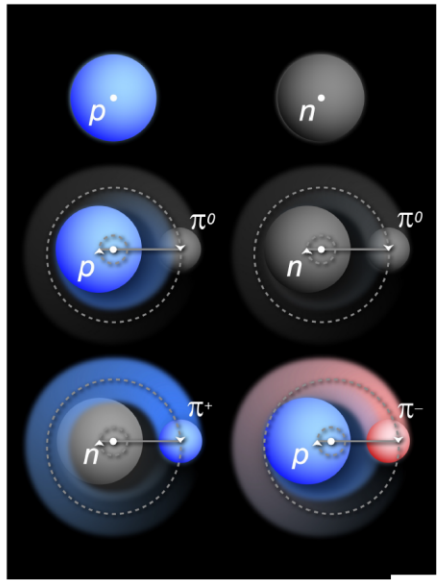


A new detector → mTPC: multi-Time Projection Chamber to measure low-momentum recoil protons

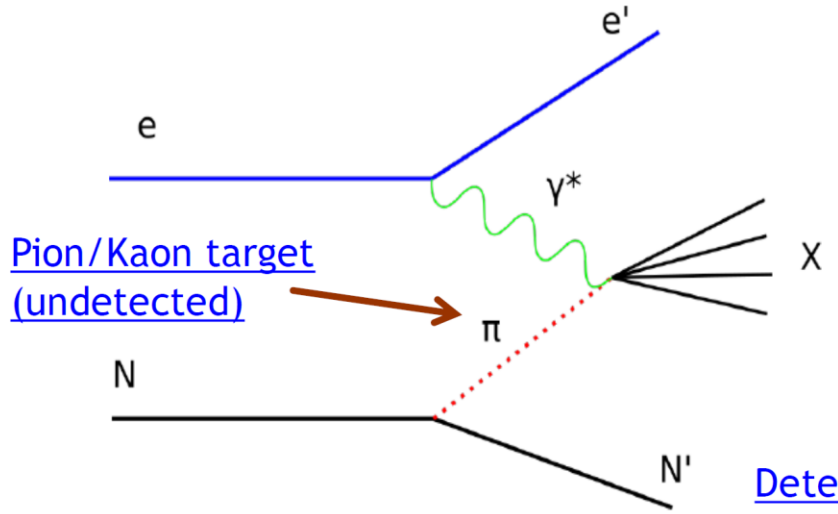
SBS TDIS

Physics Objects for Pion/Kaon Structure Studies

Sullivan process – scattering from nucleon-meson fluctuations



Detect scattered electron



DIS event - reconstruct x, Q^2, W^2, also M_X (W_π) of undetected recoiling hadronic system

Detect "tagged" proton/neutron/lambda

$$F_2^{LP(3)} = \sum_i \left[\int_{t_0}^{t_{min}} f_i(z,t)dt\right] F_2^i(x_i, Q^2) \qquad i = \pi,\ \rho,\ \ldots$$

"Flux factor"

Tagged Deep Inelastic Scattering (TDIS) in Hall A

DIS experiment:
11 GeV electron beam

+

We need to detect low momentum protons:

60 – 400 MeV/c

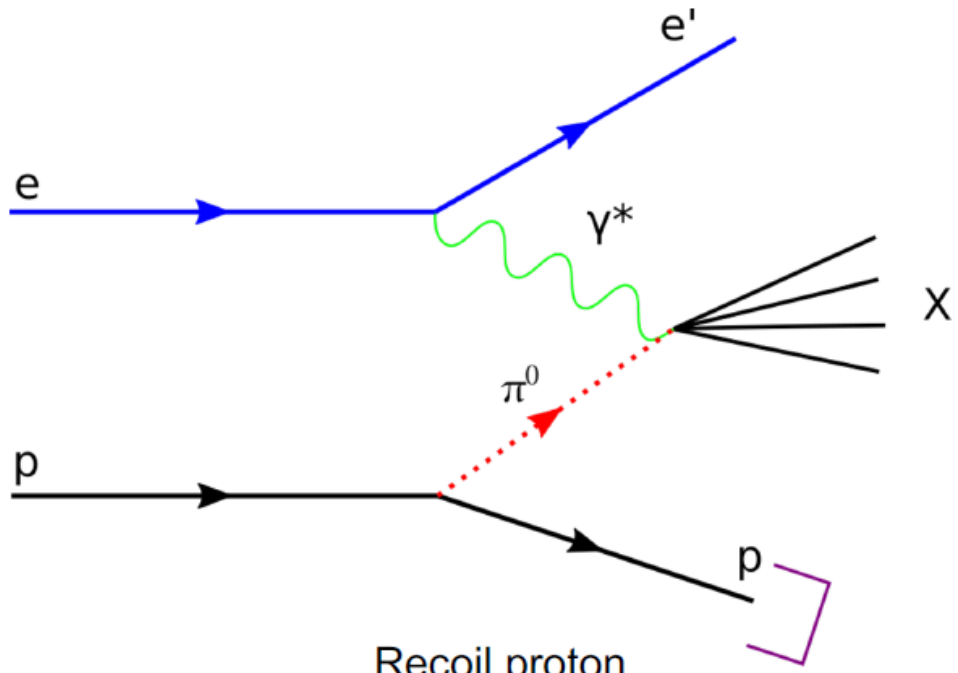
- eH → 1 proton
- eD → 2 protons with common vertex

Under these kinematics:

$8 < W^2 < 18\ GeV^2$
$1 < Q^2 < 3\ (GeV/c)^2$
$0.05 < x < 0.2$

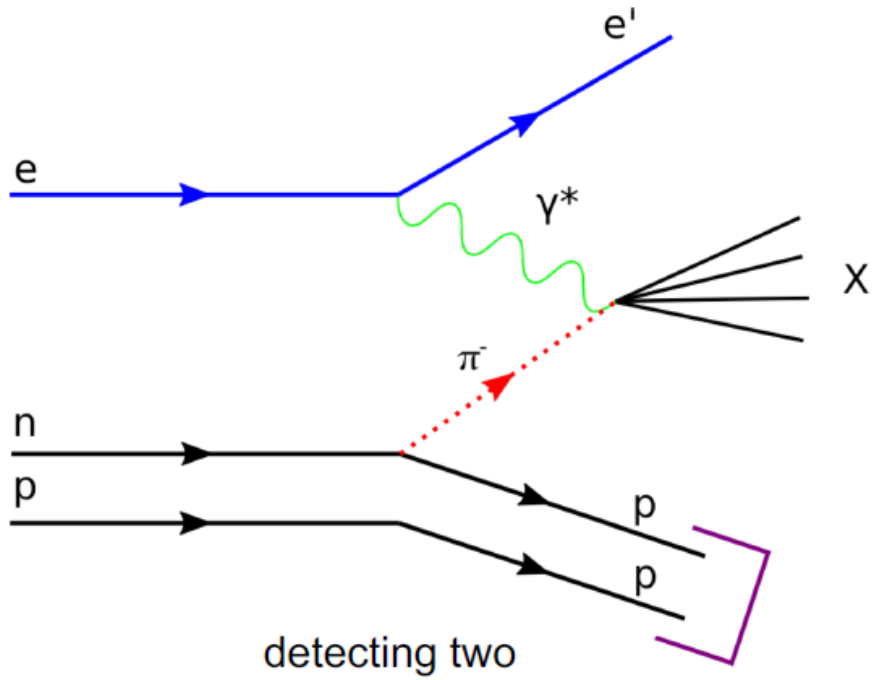
High luminosity is required $\sim 10^{36}$ Hz/cm

Pion structure from Sullivan process: TDIS



Recoil proton (backward going slow proton) **TAG**

- Effective π^0 target



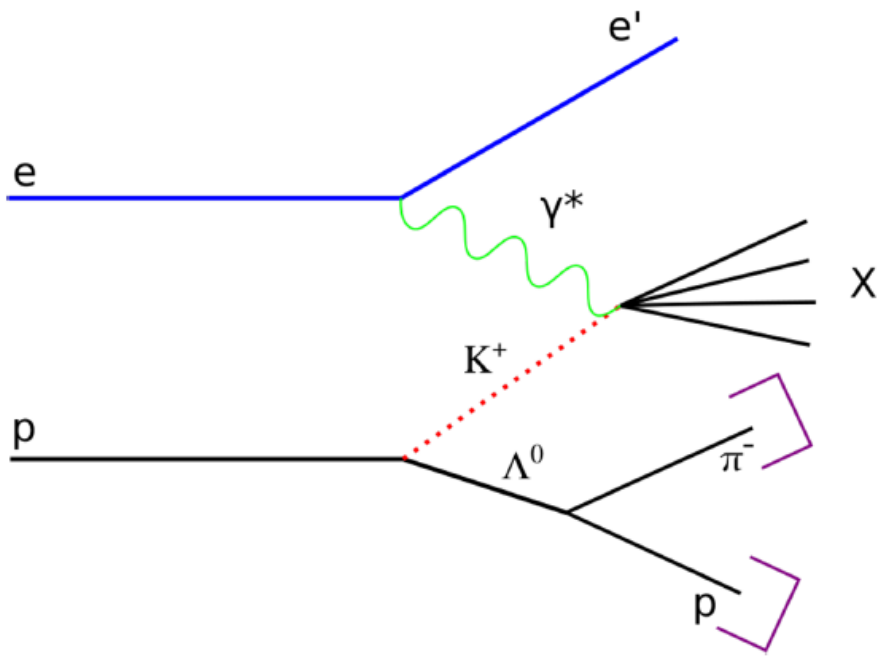
detecting two protons with common vertex Spectator proton

- Effective π^- target

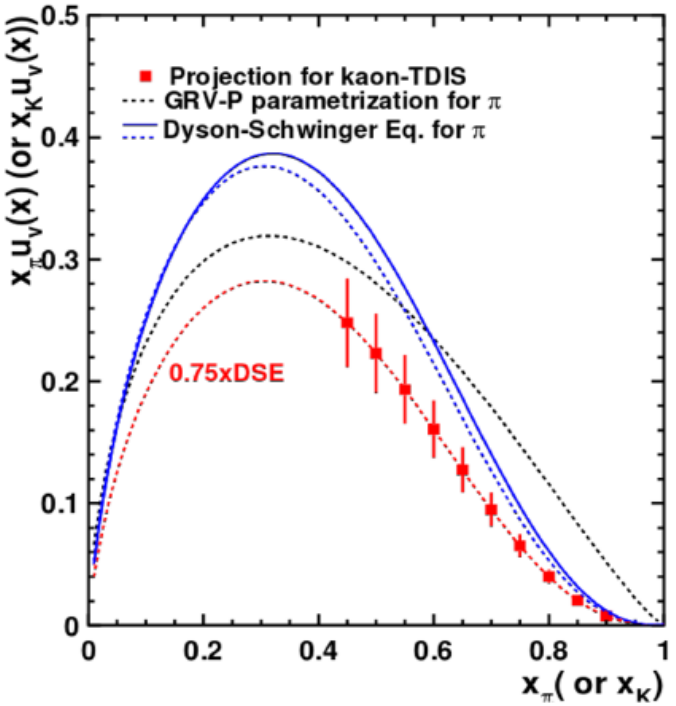
Run Group Addition: Kaon TDIS (C12-15-006A)

Kaon Tagged Deep Inelastic Scattering (TDIS)

C12-15-006A

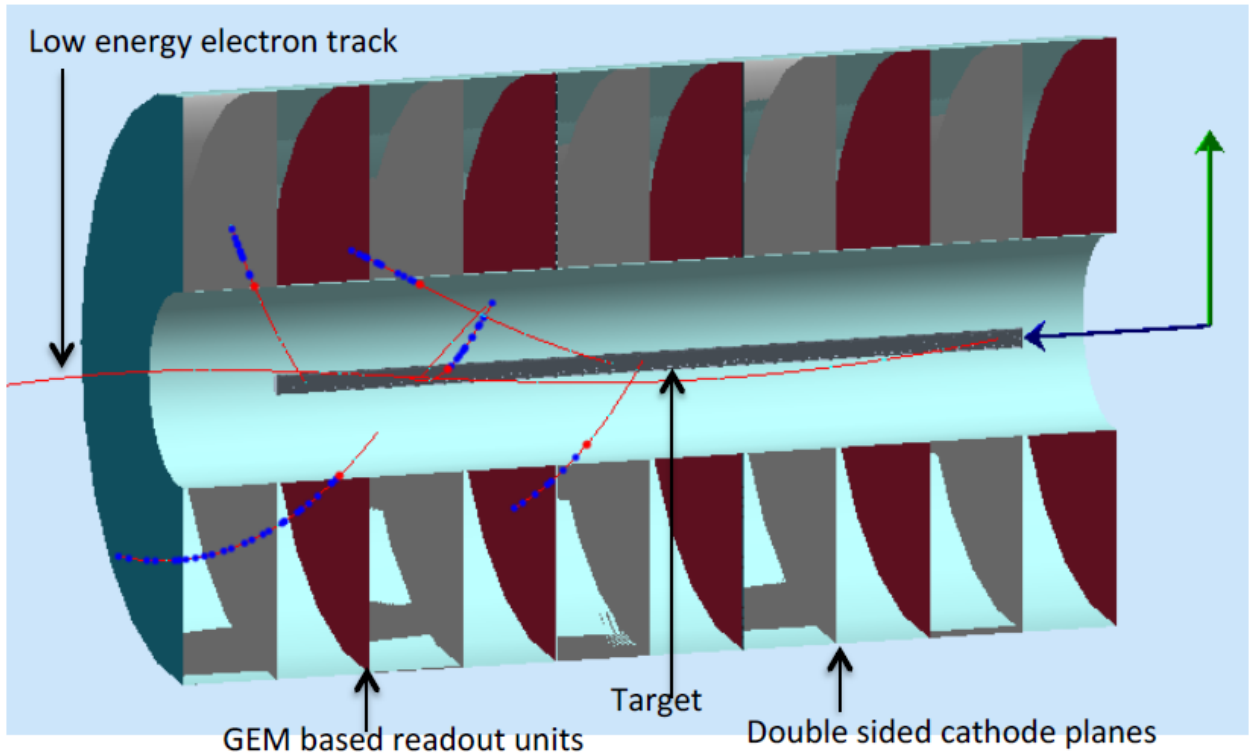


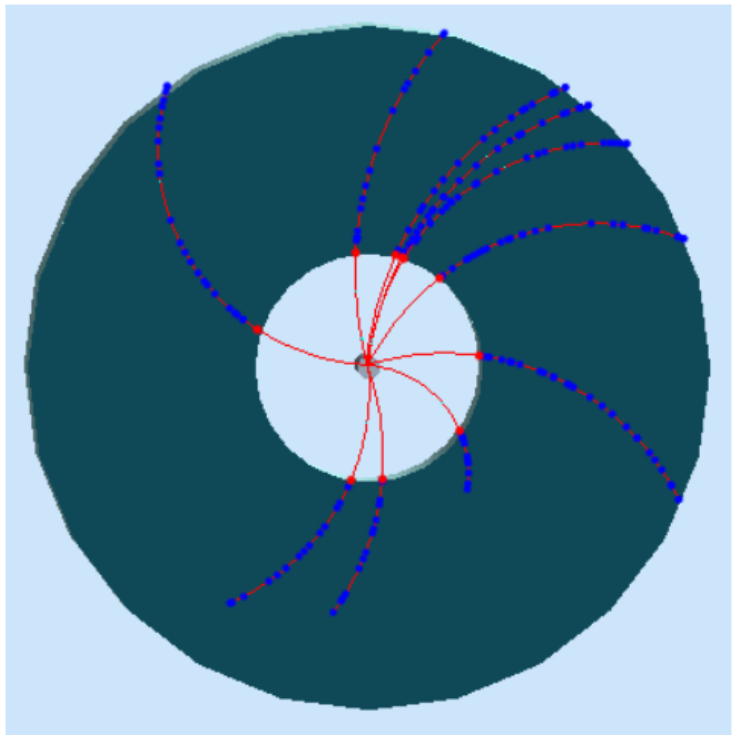
- TDIS run group proposal accepted PAC45 July 2017 Conditionally approved, as pion TDIS (same set-up/27-day beam time)
- **Mesonic content/flux factors unknown, both pion and kaon TDIS measurements will be extremely useful experimental tests**
- Kaon TDIS gives background measurement for pion TDIS



The multiple-Time Projection Chamber (mTPC) in TDIS

- Will be placed in the bore of the UVa superconducting solenoid magnet (L=152.7 cm, $\vec{B}$= 4.7 T) to fit the requirement of strong magnetic field parallel to $\vec{E}$
- Consist of 10 TPC modules to form one composite mTPC → takes care of high rates compared to single/radial TPC



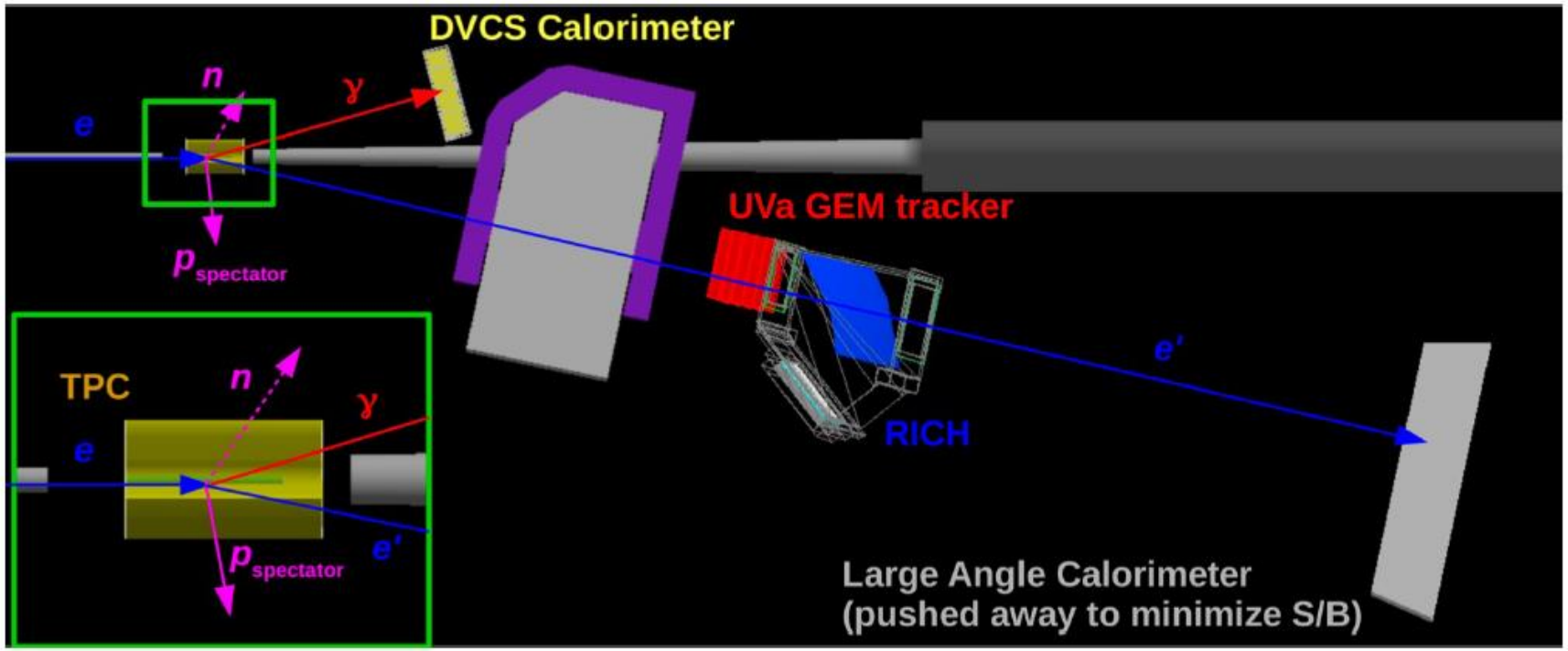


Ptcl tracks

Dimensions : 55 cm long, Inner (outer) radii = 5 cm (15 cm)

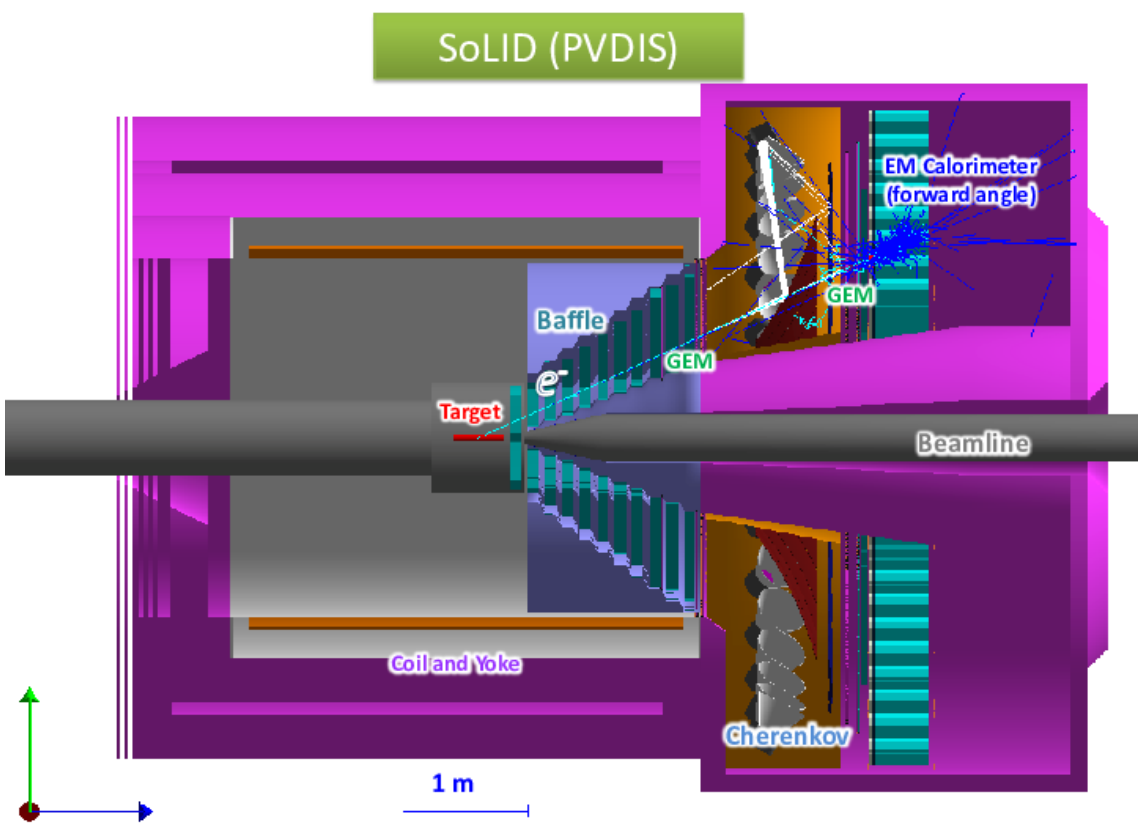
More spectator tagged physics: nDVCS using TDIS setup

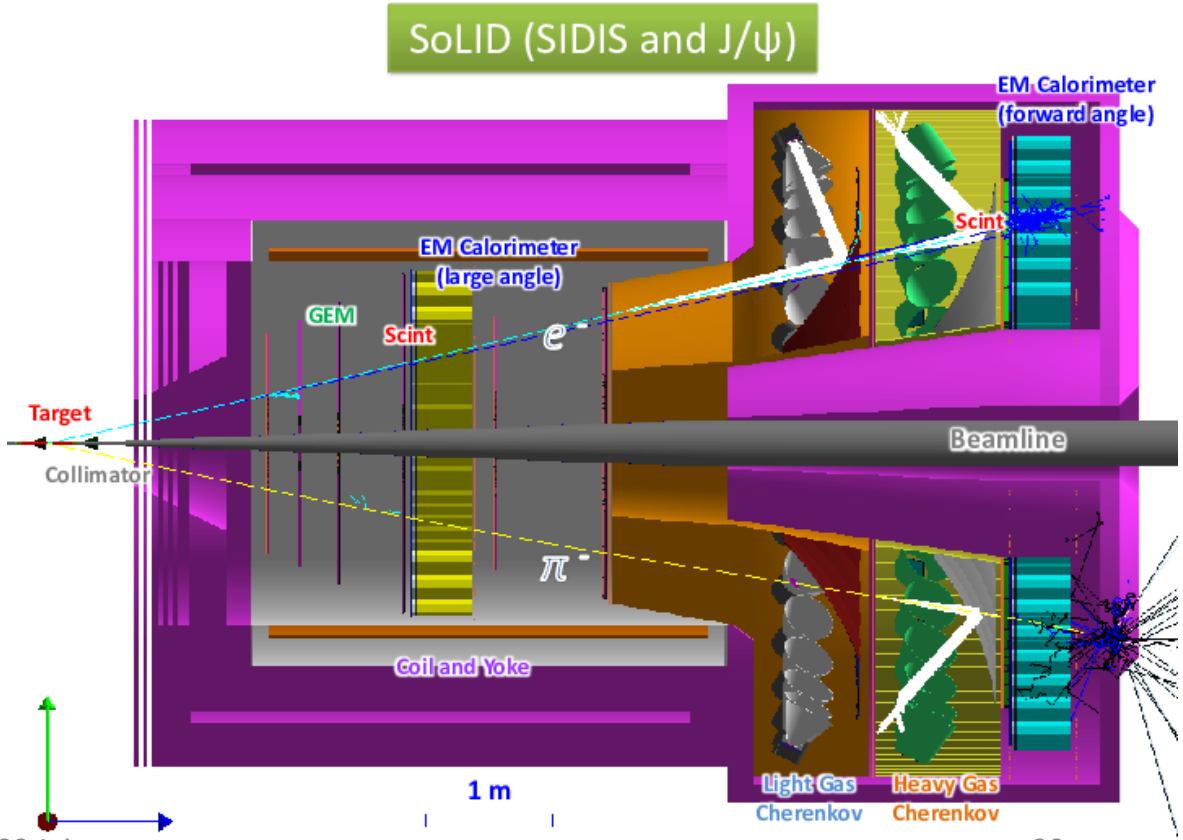
- Measure exclusive photon and neutral pion electroproduction on deuterium, with identification of the spectator proton $D(e, e' \gamma p_{spec})n$ and $D(e, e' \pi^0 p_{spec})n$, in the valence region ($x > 0.1$) and deep inelastic regime: $Q^2 > 1\ GeV^2$, $W^2 > 2\ GeV^2$
  - Addition of electromagnetic calorimeter to TDIS experimental setup (photon detection)
  - mTPC will detect spectator proton → allow PID of nDVCS events
  - SBS will detect e'



SoLID program

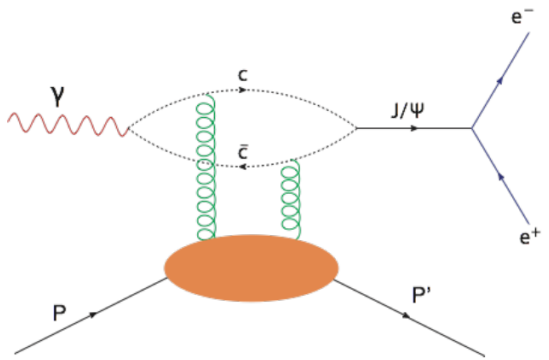
- SoLID detector : CLEO magnet + GEM trackers + Cerenkov + ECal
- 2 detector setup : PVDIS 60 uA, SIDIS 15 uA He3, J/Psi 3uA 15 cm LH2 target

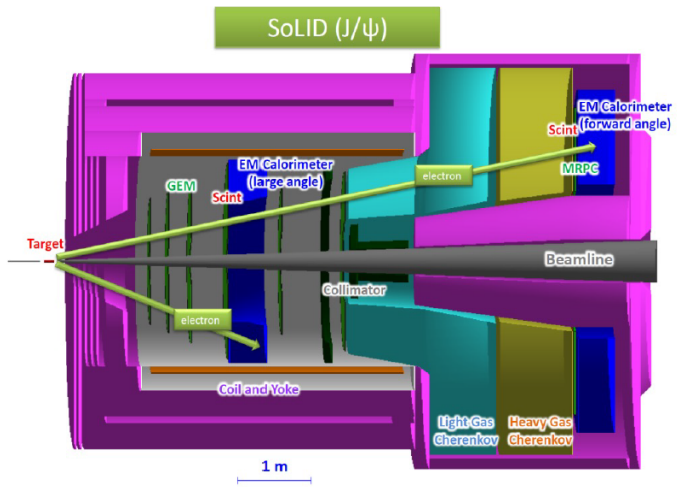


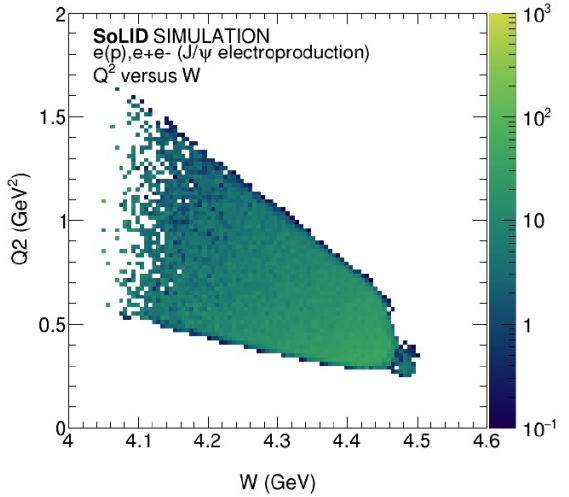


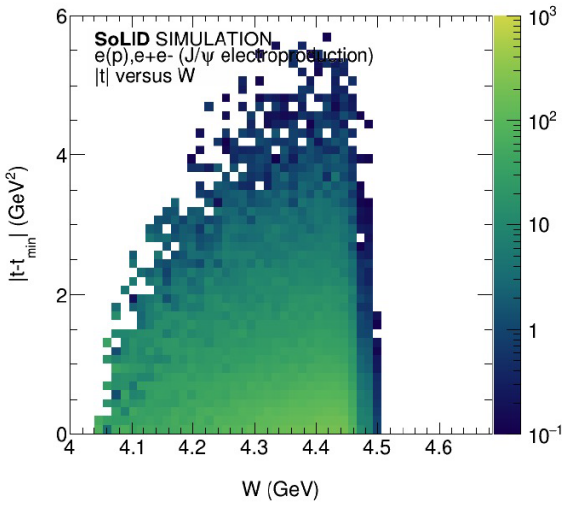
SoLID Experiment Overview

- 50 days of $3\,\mu A$ beam on a 15 cm long LH_2 target at $1 \times 10^{37} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - 10 more days include calibration/background run
- SoLID configuration overall compatible with SIDIS
  - **Electroproduction trigger**: 3-fold coincidence of e, e^-e^+
  - **Photoproduction trigger:** 3-fold coincidence of p, e^-e^+
  - **Additional trigger:** 4-fold coincidence of ep, e^-e^+
  - And (inclusive) 2-fold coincidence e^+e^-







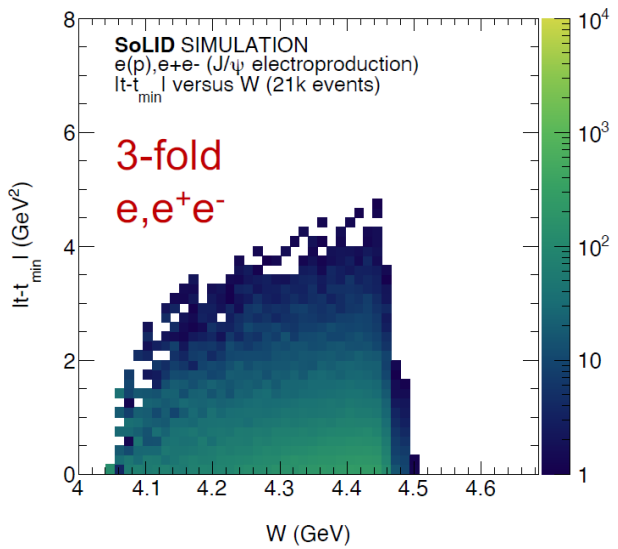


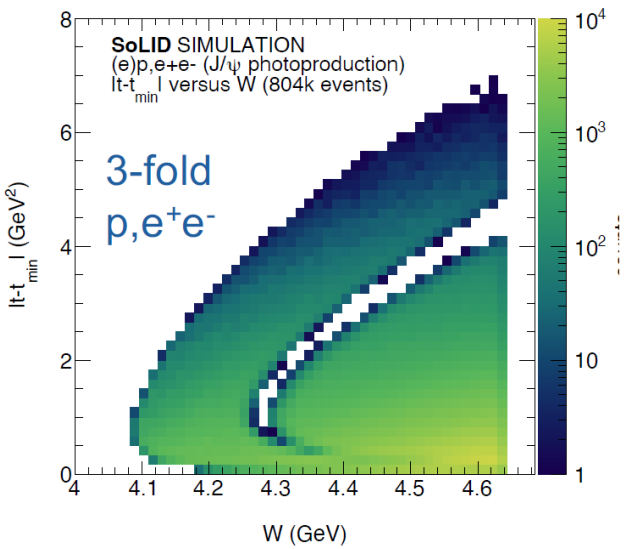
$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

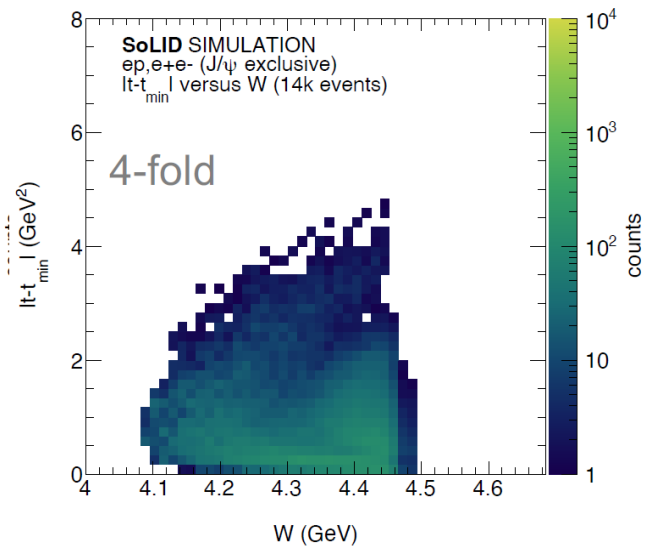
Event Counts @ 1x10^{37} in 50 days

- 4-fold coincidence: ep,e$^+$e$^-$
  - **280-400** events/day
- 3-fold (electroproduction): e,e$^+$e$^-$
  - **415-594** events/day
- 3-fold (photoproduction): p,e$^+$e$^-$
  - **16k-23k** events/day
- 2-fold (inclusive): e$^+$e$^-$
  - 26k-37k events/day

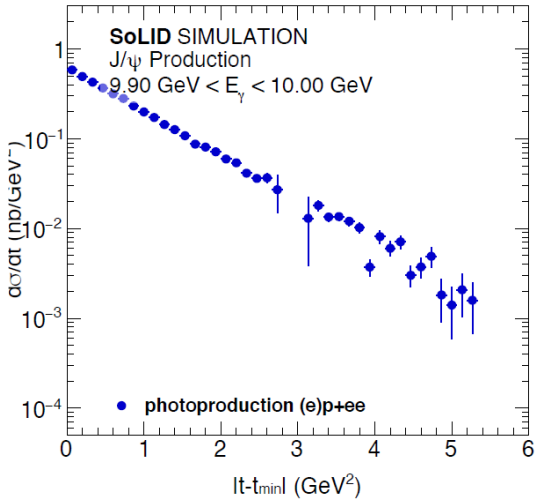
	Time (Hour)	Time (Day)
LH_2 at 11 GeV	**1200**	**50**
Dedicated Al dummy run	**72**	**3**
Optics and detector check out	**72**	**3**
Special low luminosity	**96**	**4**
Total	**1440**	**60**

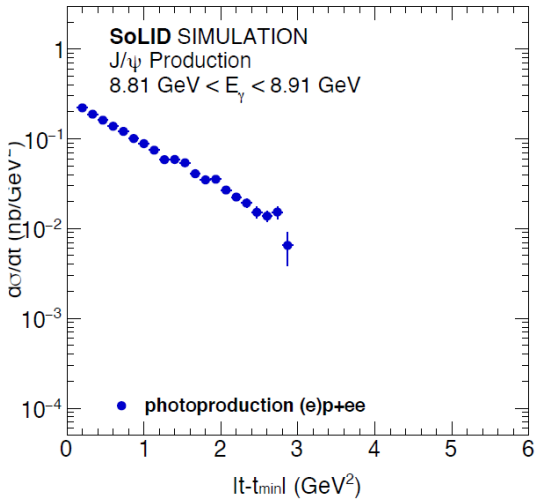


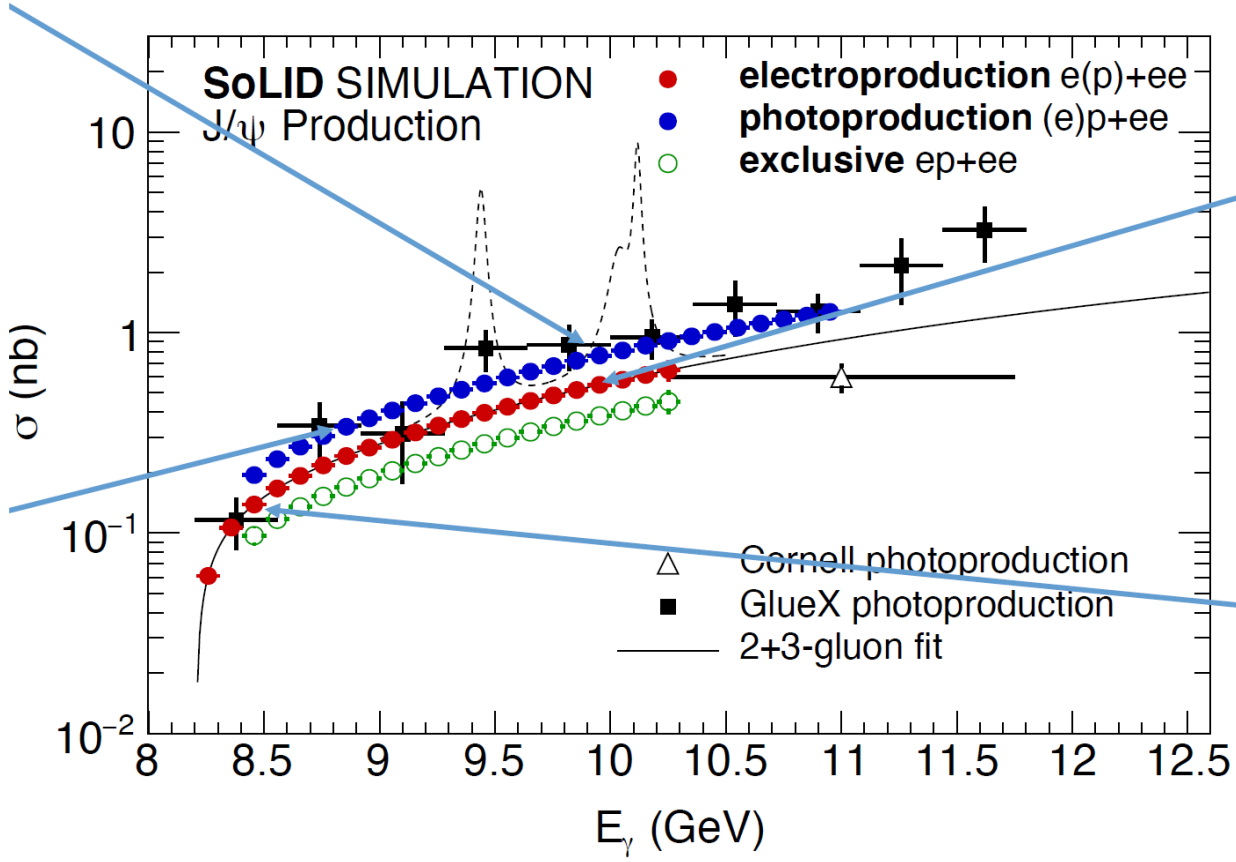


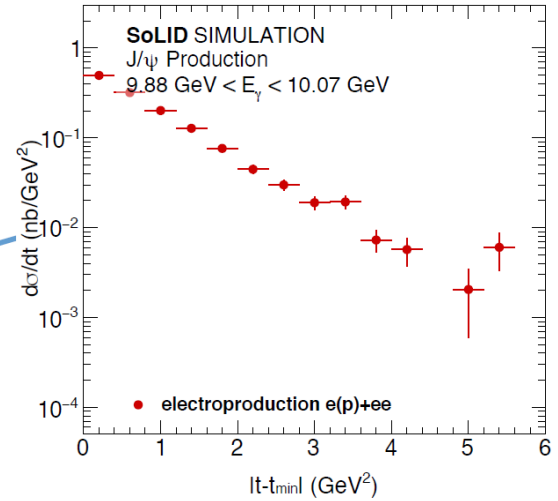


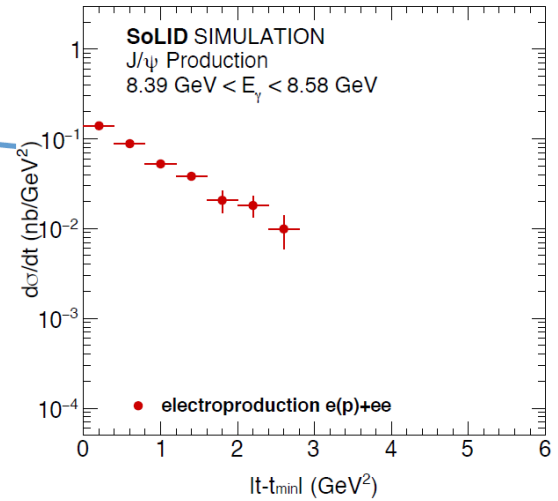
J/Psi Experiment E12-12-006 @ SoLID (C4)



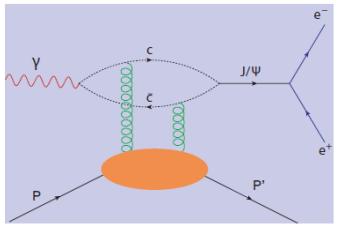




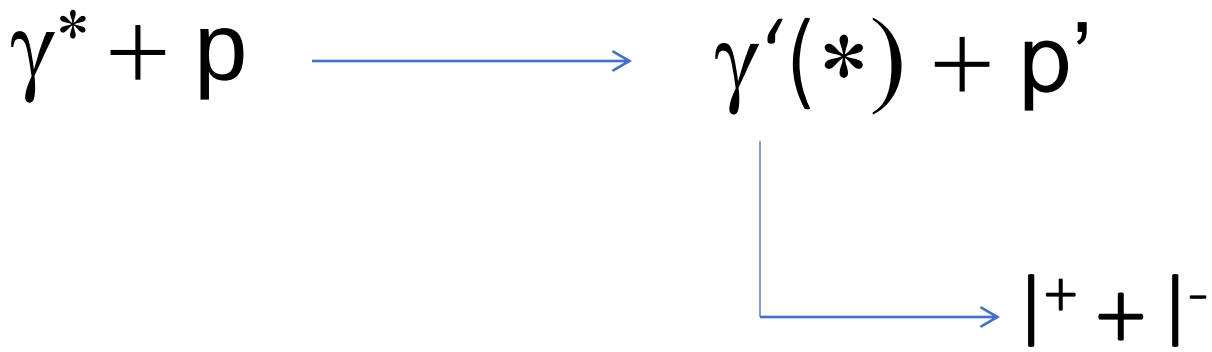




Sensitivity at threshold at about 10^{-3} nb!

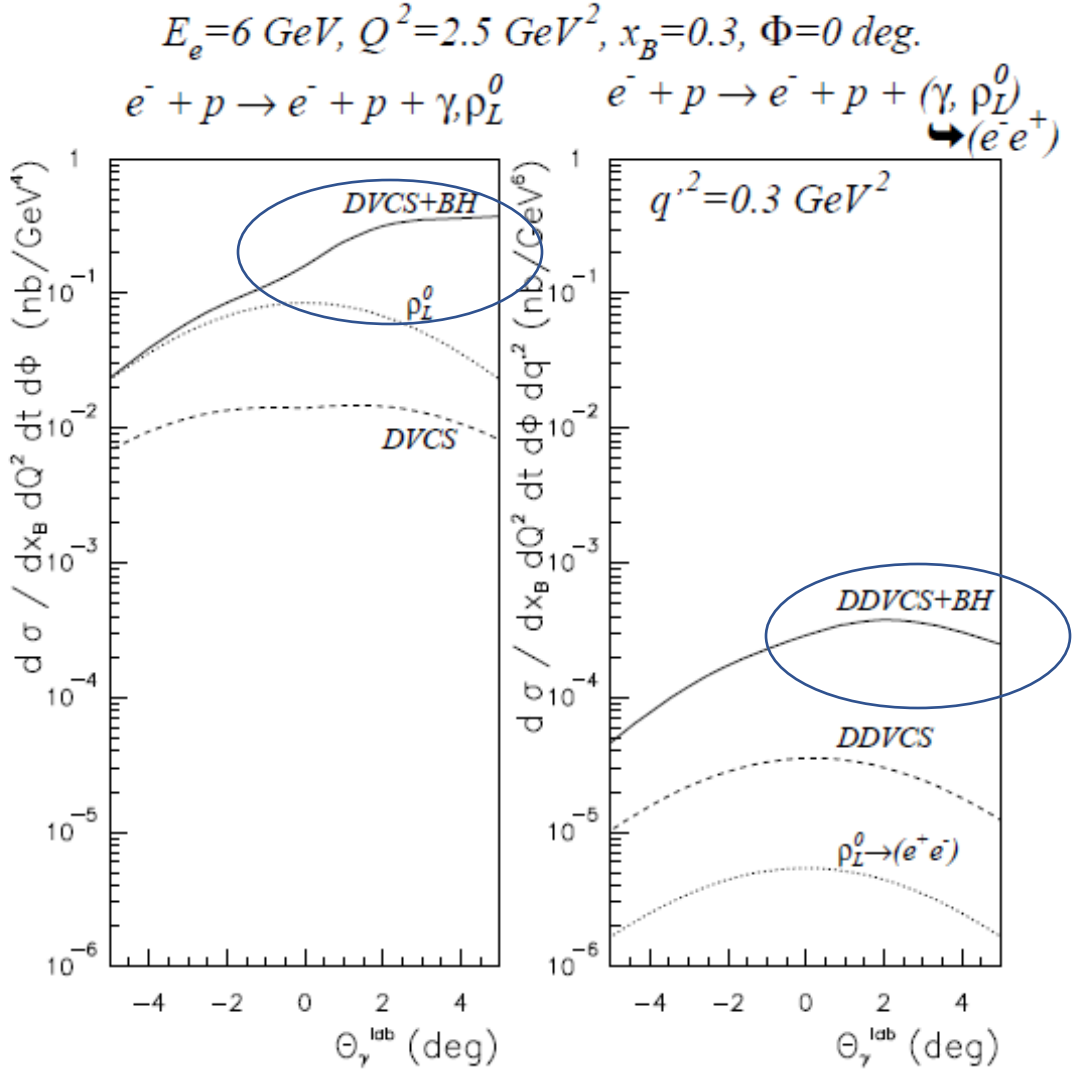


DVCS / Double DVCS



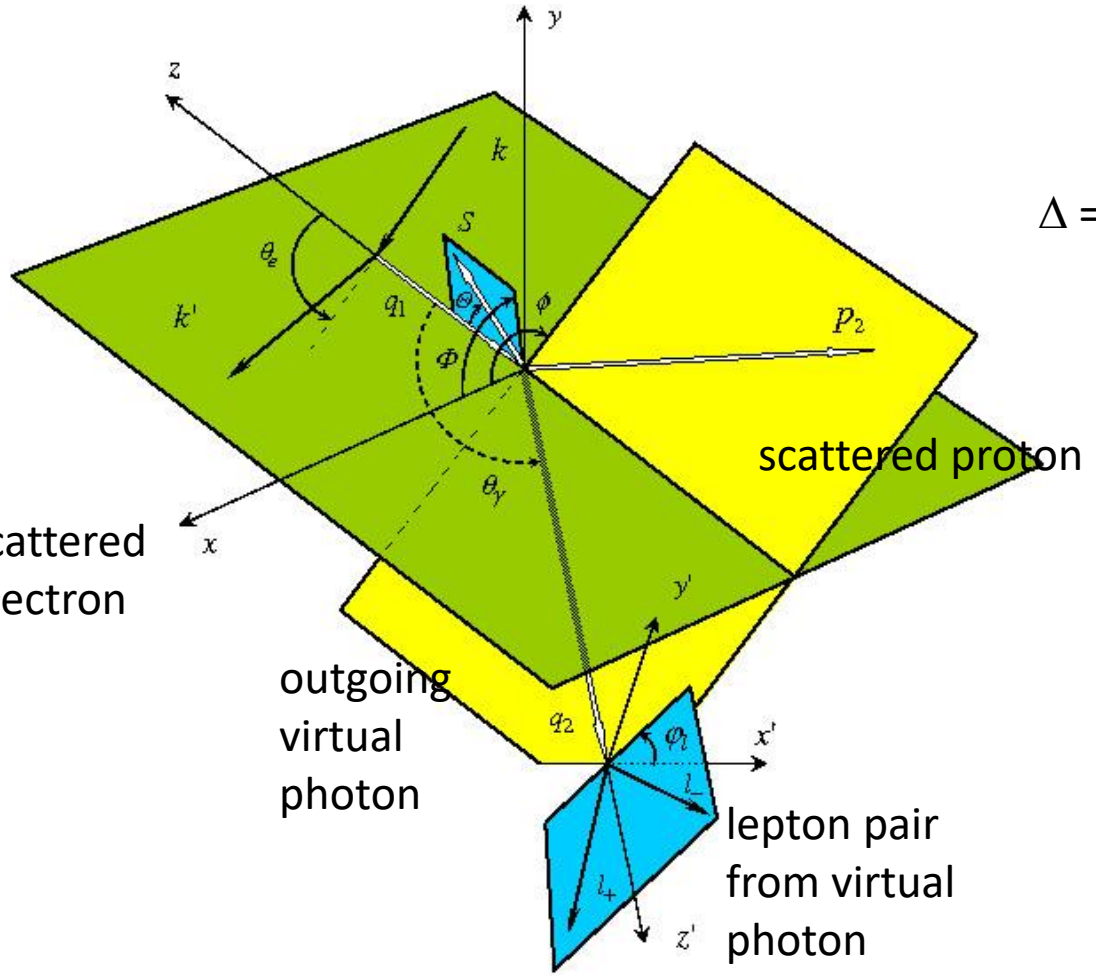
Guidal and Vanderhaegen : Double deeply virtual Compton scattering off the nucleon (arXiv:hep-ph/0208275v1 30 Aug 2002)
Belitsky Radyushkin : Unraveling hadron structure with generalized parton distributions (arXiv:hep-ph/0504030v3 27 Jun 2005)

DDVCS cross section



- VGG model
- Order of ~0.1 pb = 10^{-36}cm^2
- About 100 to 1000 smaller than DVCS
- Virtual Beth and Heitler
- Interference term enhanced by BH
- Contributions from mesons small when far from meson mass

Double Deeply Virtual Compton Scattering



scattered proton

scattered electron

outgoing virtual photon

lepton pair from virtual photon

Δ = p1-p2 = q2-q1

p = p1+p2

q = ½ (q1+q2)

$Q^2 = -q^2$

$\xi = \frac{Q^2}{2p.q}$ $\eta = \frac{\Delta.q}{p.q}$

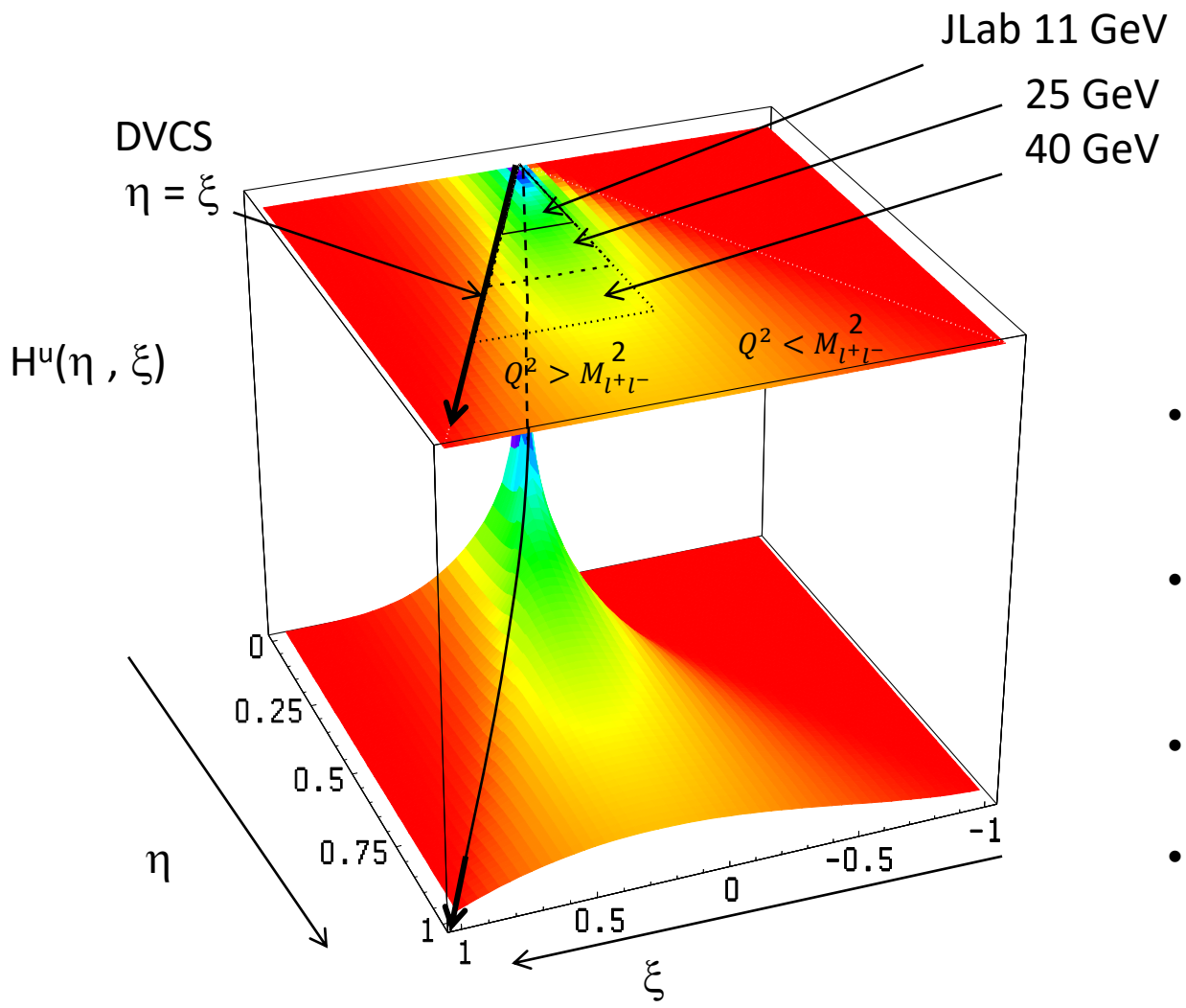
$Q^2 = -(k-k')^2$ $x_{bj} = \frac{Q^2}{2p_1q_1}$

Belitsky Radyushkin : Unraveling hadron structure with generalized parton distributions (arXiv:hep-ph/0504030v3 27 Jun 2005)

$$\left\{ \begin{array}{c} A_{\rm LU}^{\sin\phi} \\ A_{\rm LU}^{\sin\varphi_\mu} \end{array} \right\} = \frac{1}{\mathcal{N}} \int_{\pi/4}^{3\pi/4} d\theta_\mu \int_0^{2\pi} d\varphi_\mu \int_0^{2\pi} d\phi \left\{ \begin{array}{c} 2\sin\phi \\ 2\sin\varphi_\mu \end{array} \right\} \frac{d^7\overrightarrow{\sigma} - d^7\overleftarrow{\sigma}}{dx_B\, dy\, dt\, d\phi\, dQ'^2\, d\Omega_\mu}$$

$$\propto \Im\mathrm{m} \left\{ F_1\mathcal{H} - \frac{t}{4M_N^2} F_2\mathcal{E} + \xi(F_1+F_2)\widetilde{\mathcal{H}} \right\},$$

Kinematical coverage

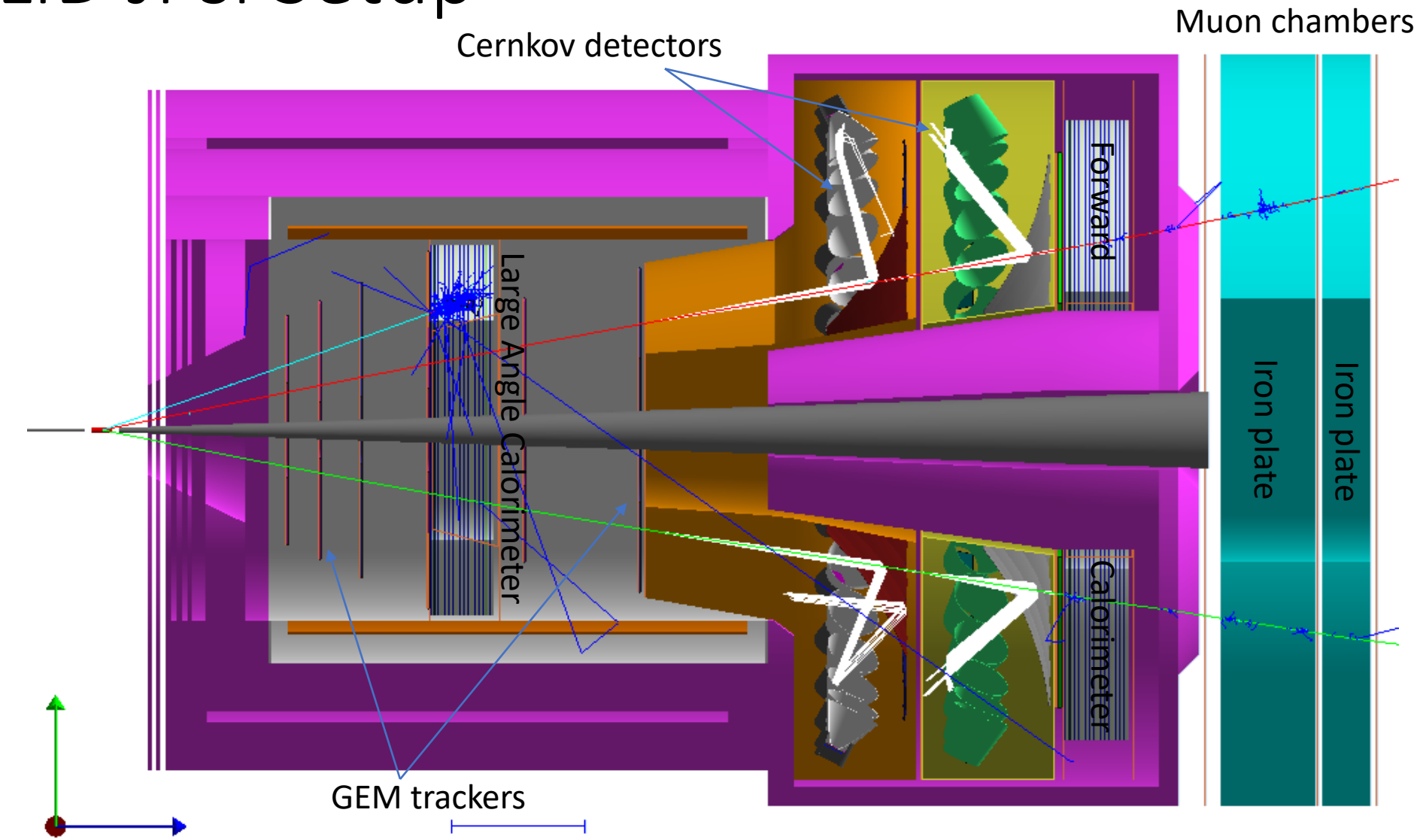


- DVCS only probes η = ξ line
- Example with model of GPD H for up quark
- Jlab : $Q^2>0$
- Kinematical range increases with beam energy (larger dilepton mass)

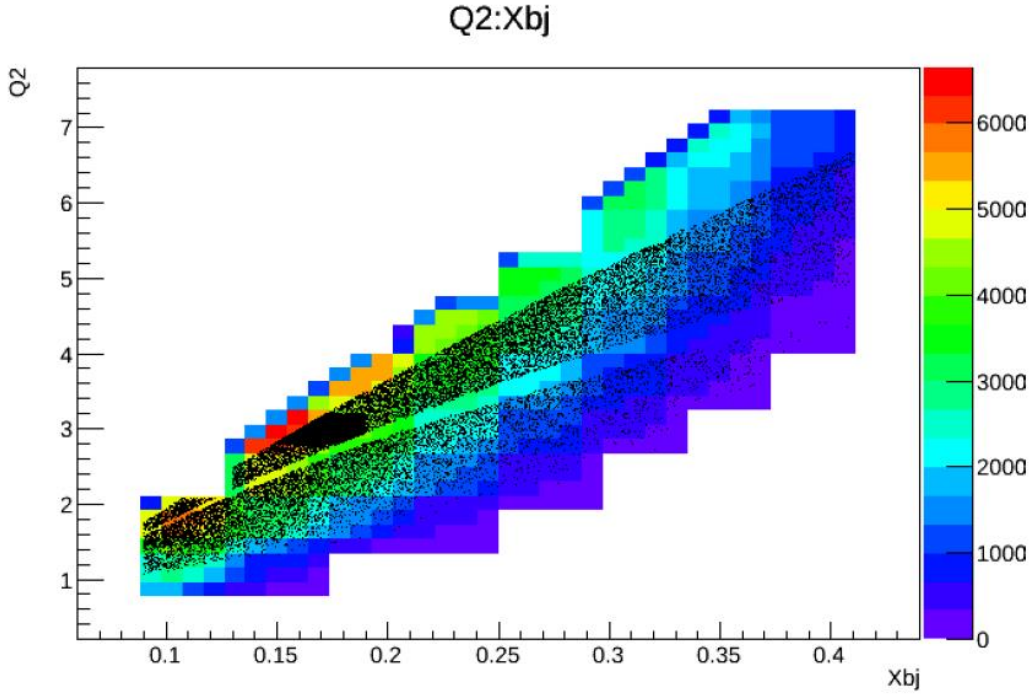
DDVCS LOI

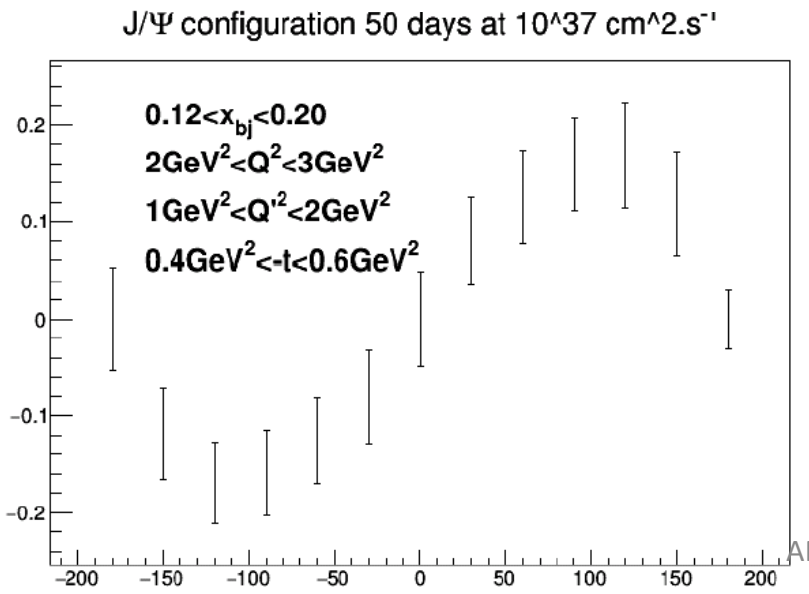
- PAC 43 : Measurement of Double Deeply Virtual Compton Scattering (DDVCS) in the di-muon channel with the SoLID spectrometer
  (Boer,Camsonne,Gnanvo,Sparveri,**Voutier**,Zhao)

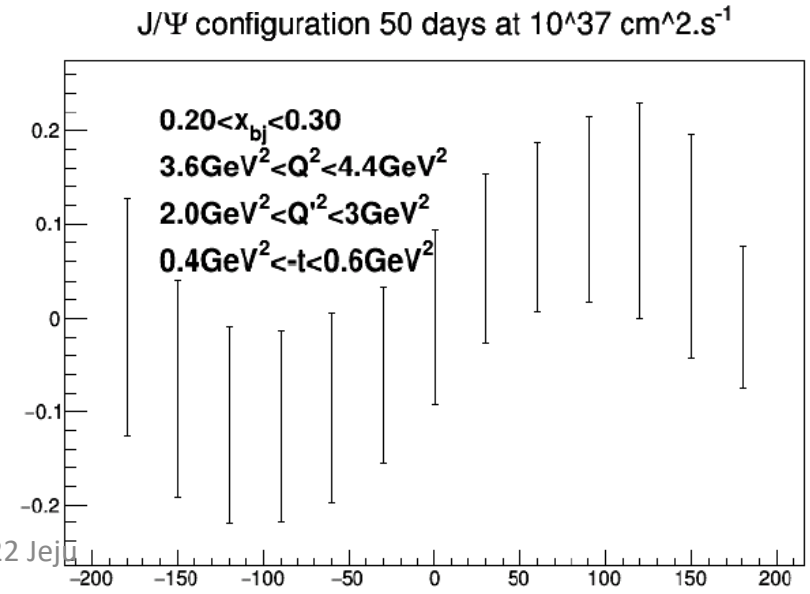
SoLID JPsi Setup



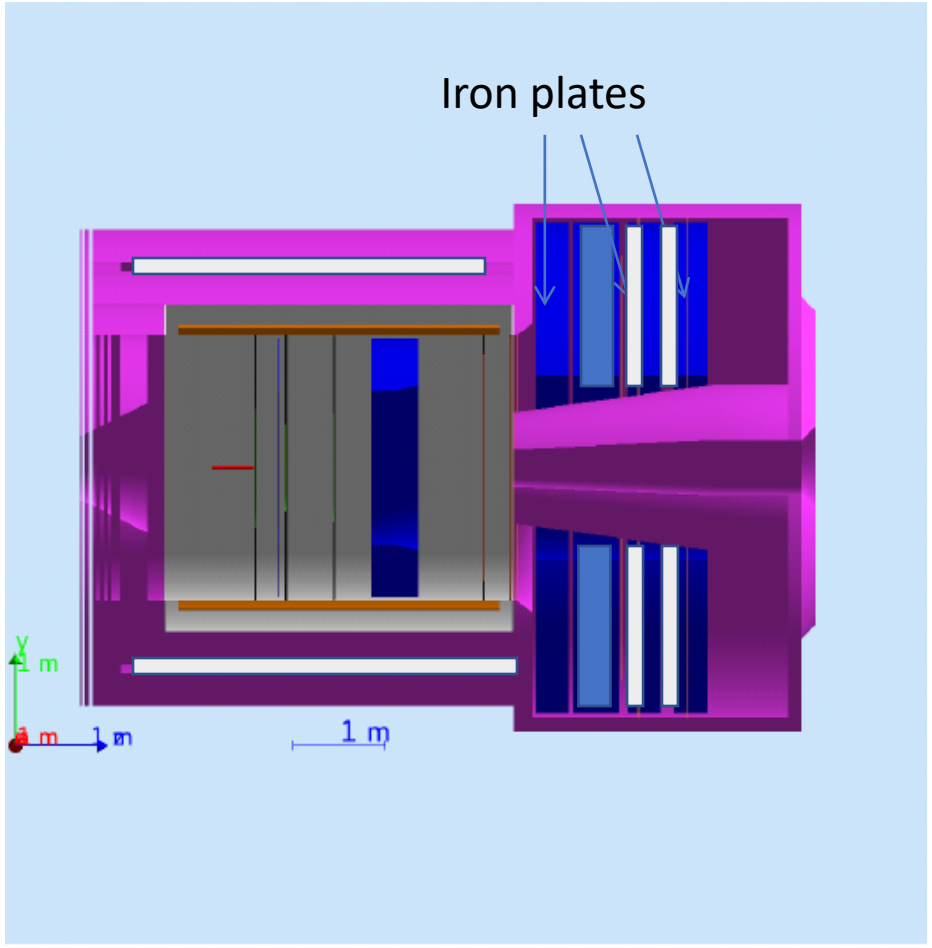
Counts J/psi setup 60 days at 10^37 $cm^{-2}s^{-1}$







Dedicated setup

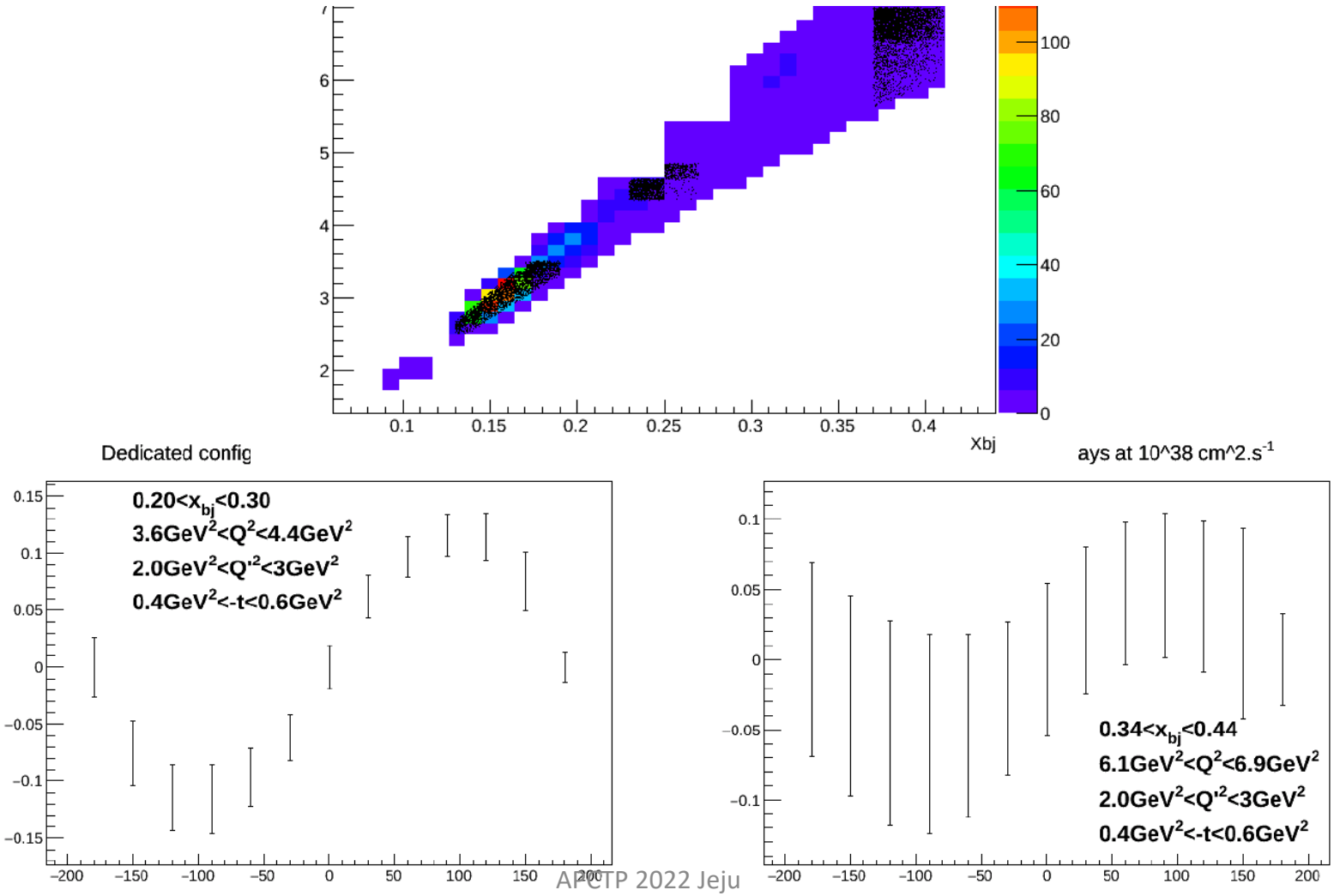


- Target moved 2m from Jpsi position inside and switch to 45 cm target
- Iron plate from 3rd layer yoke in front and behind calorimeter

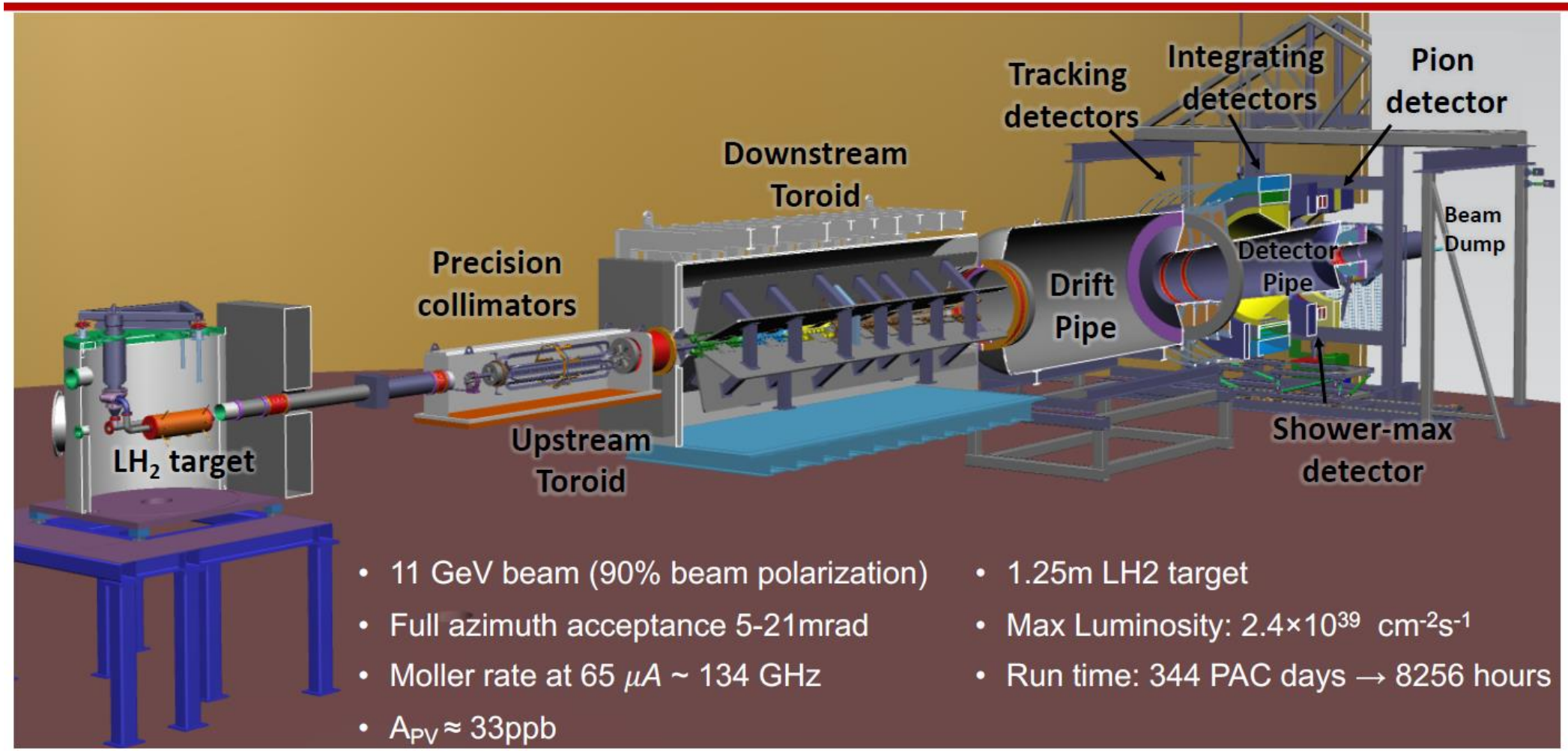
- Remove Gas Cerenkov

- Try to reach 10^{38} $cm^{-2}s^{-1}$
- 10 uA on 45 cm target

Expected accuracy dedicated setup 90 days at 10^{38} $cm^{-2}s^{-1}$



Moller experiment



Higher luminosity ?

- Current could go up to 80 uA
- Target length up to 1.25 meter ~ 2.4.10^39 cm-2.s-1
- Tracker occupancy and photon background
  - Reduce amount of Copper in GEM
  - Micromegas option
  - Build smaller chambers and add more channels
  - Study complement with 2D pad readout
  - Superconducting tracker option
- Calorimetry
  - Study liquid scintillator and cryogenics calorimeter option
  - Superconducting detector to replace PMT
  - MCP PMT or LAPPD
- Cerenkov
  - Superconducting detector to replace PMT
  - MCP PMT or LAPPD
  - HBD type Cerenkov for Large Angle calorimeter

With existing 40 cm and 60 uA ~ 5. 10^38 $cm^{-2}s^{-1}$ technically doable mostly matter of cost

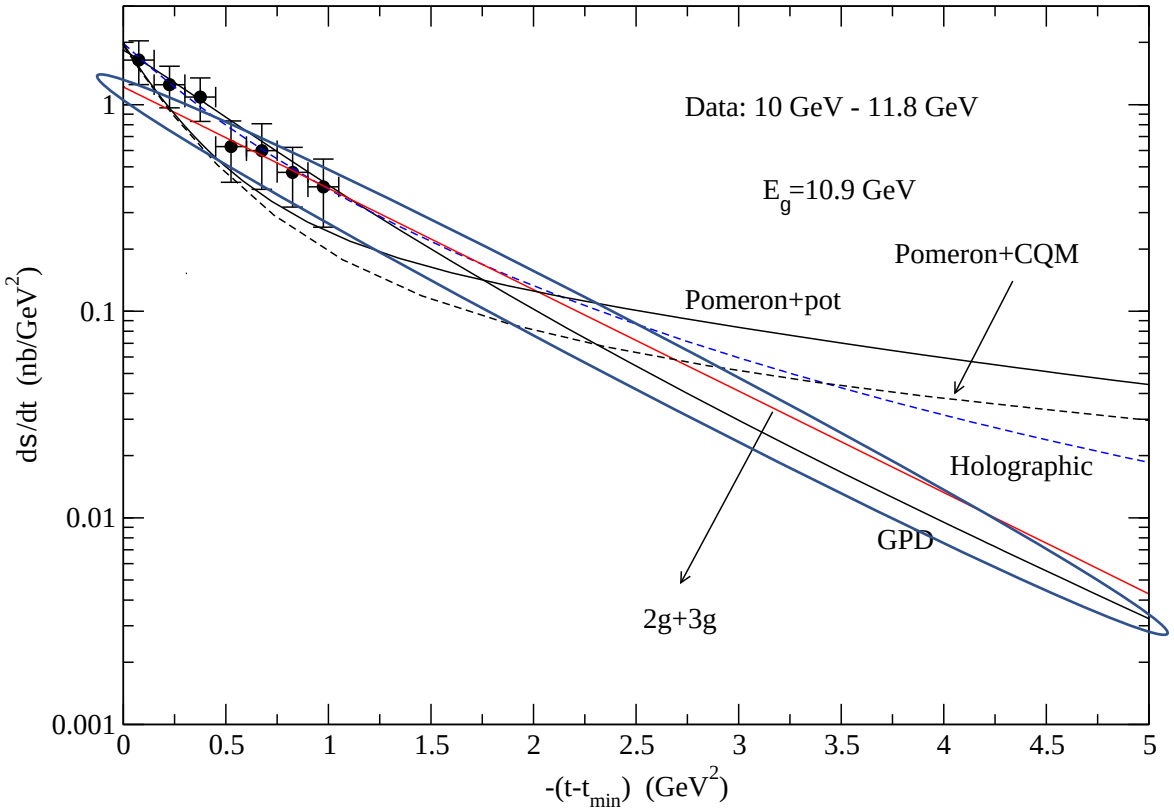
Complementarity with CLAS12

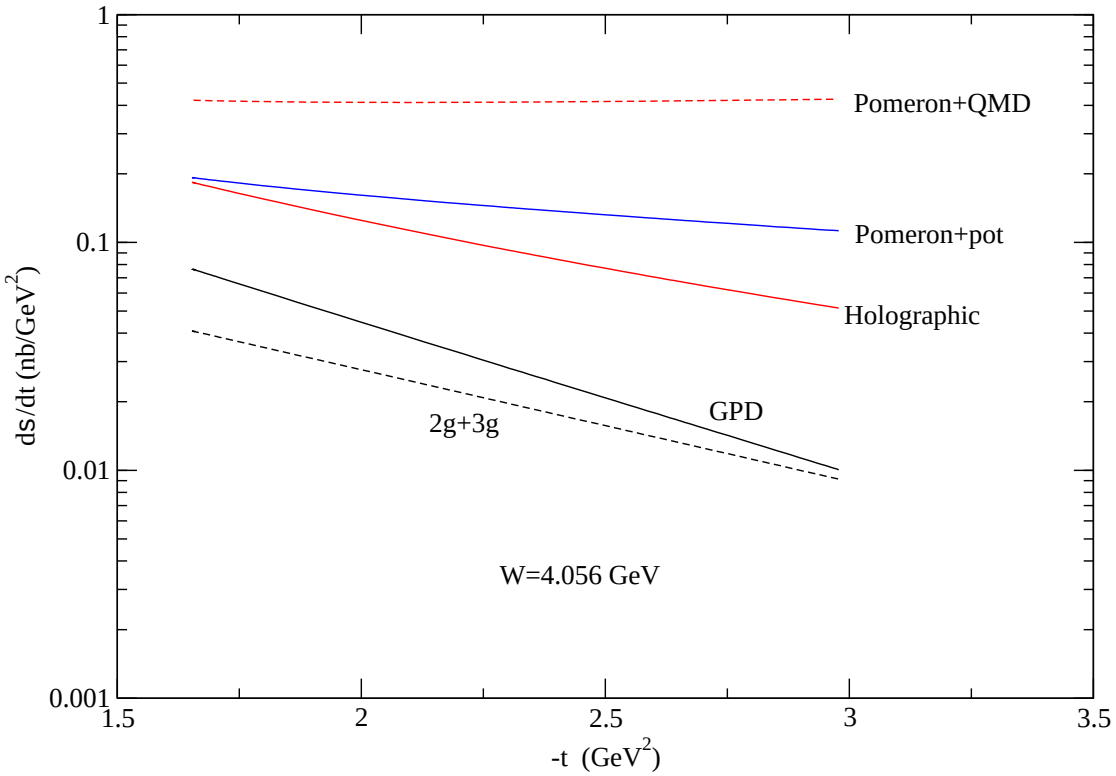
- Not as good as CLAS12 for complex final states
- Could be complementary for processes within acceptances such as large Q2 and large t for one pion production
- Background for (D)VCS measurement, check acceptance for pions
- Background to DDVCS

$\gamma^{*}N \longrightarrow N\pi^{+}\pi^{-}$

- Kinematic range might be limited due to trigger : possible dedicated measurements
- Investigating feasibility of streaming readout : remove bias of trigger and allow to record additional processes parasitically

From TS Harry Lee Talk Monday





All are comparable to the available JLab data

Prediction at W=4.056 MeV (Near threshold)

Conclusion

- Hall A and C high luminosity halls luminosity ranging from 10^{36} up to 5.10^{38} $cm^{-2}.s^{-1}$
- Few simple measurements using small acceptance spectrometers
- Larger acceptance detectors available such as SuperBigBite
- Large acceptance detector like SoLID striving to keep running at highest luminosity
  - Approved experiments SIDIS and J/Psi
  - Future possible experiment DDVCS
- Focus on deep inelastic but could have dedicated experiment in resonance or might be able to record parasitically if streaming readout is implemented