GPD studies at Jefferson Lab Hall A/C

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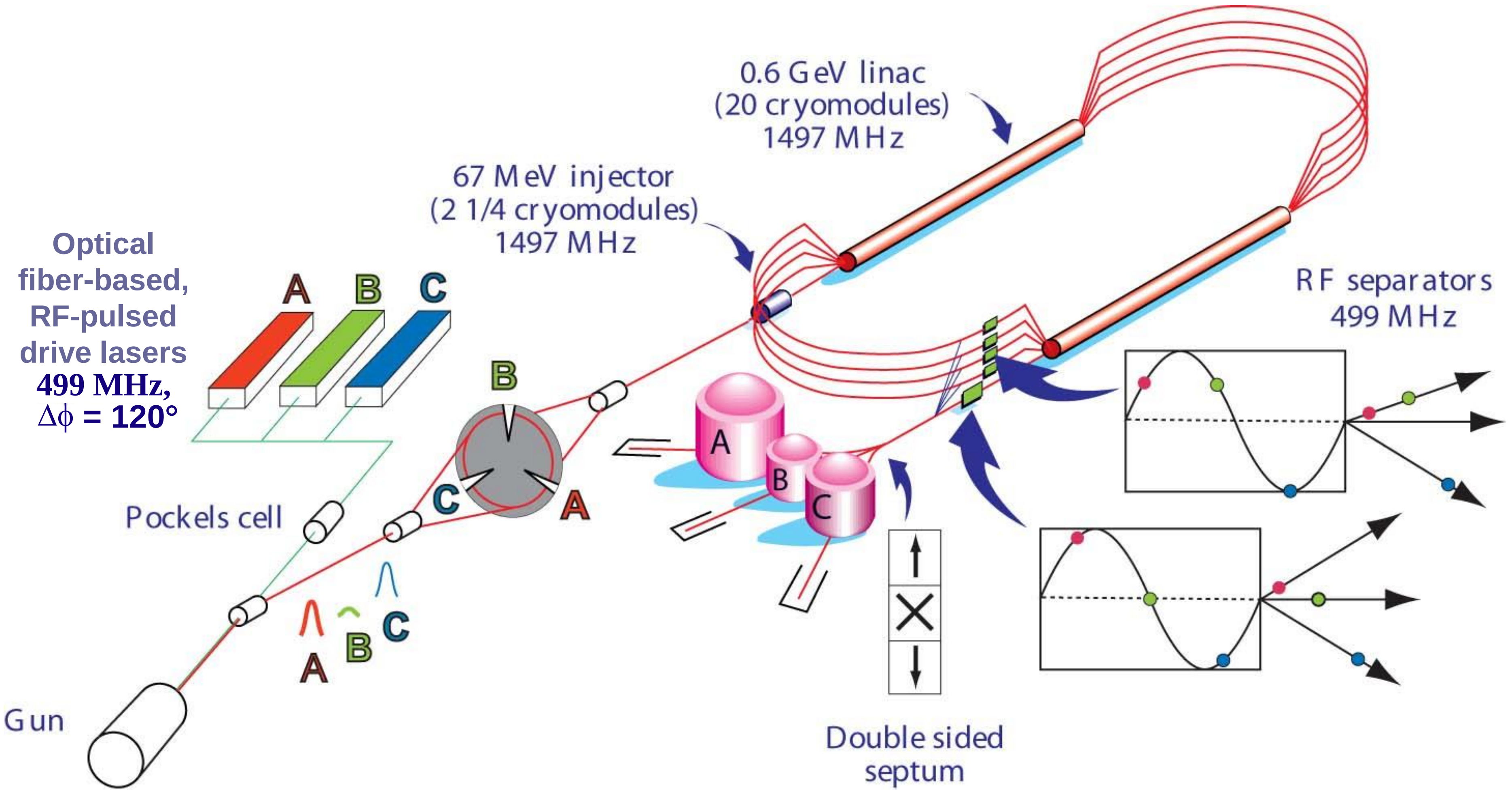
Jefferson Laboratory Hall A

APCPT GPD workshop
Incheon, South Korea
June 24th 2024

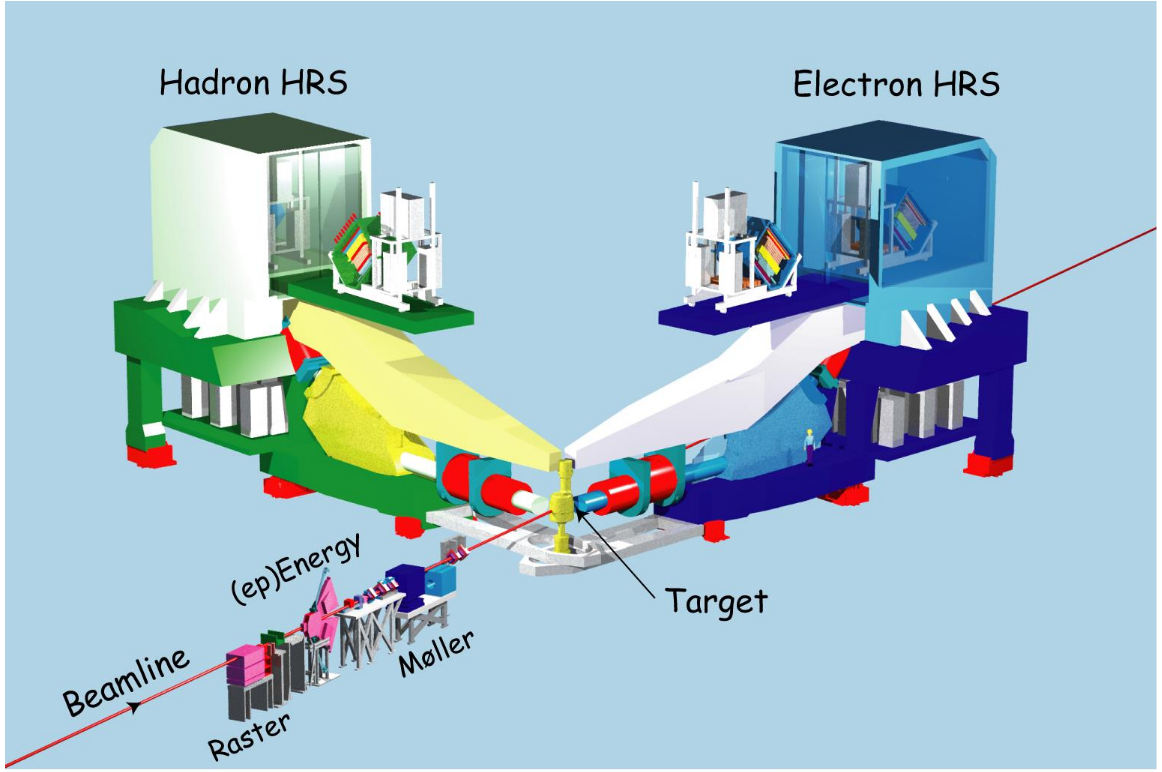
Outline

- Hall A/C overview
- Hall C NPS
- Hall A SuperBigBite
  - TDIS setup
- Hall A SoLID DDVCS setup
- Hall C TCS
- Hall C DVCS with recoil polarization
- Conclusion

Continuous Electron Beam Accelerator Facility



Hall A Infrastructure



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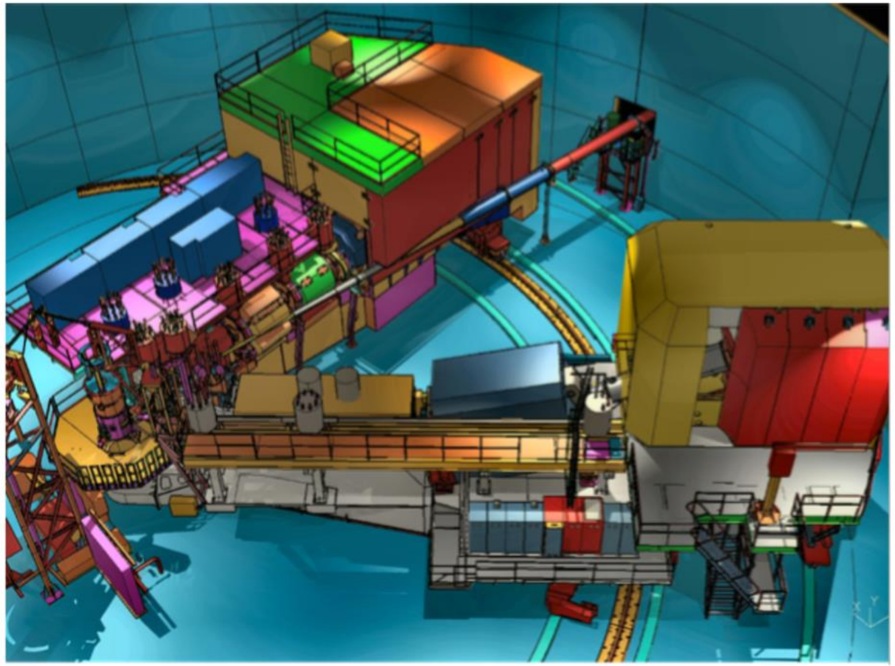
HRS Spectrometers	FWHM
Max. momentum	4.2 GeV/c
Momentum acceptance	± 4.5%
Momentum resolution	1.10^{-4}
Angular acceptance	6 msr
Angular resolution	1 mrad
Vertex acceptance	± 5 cm
Vertex reconstruction	1 mm

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

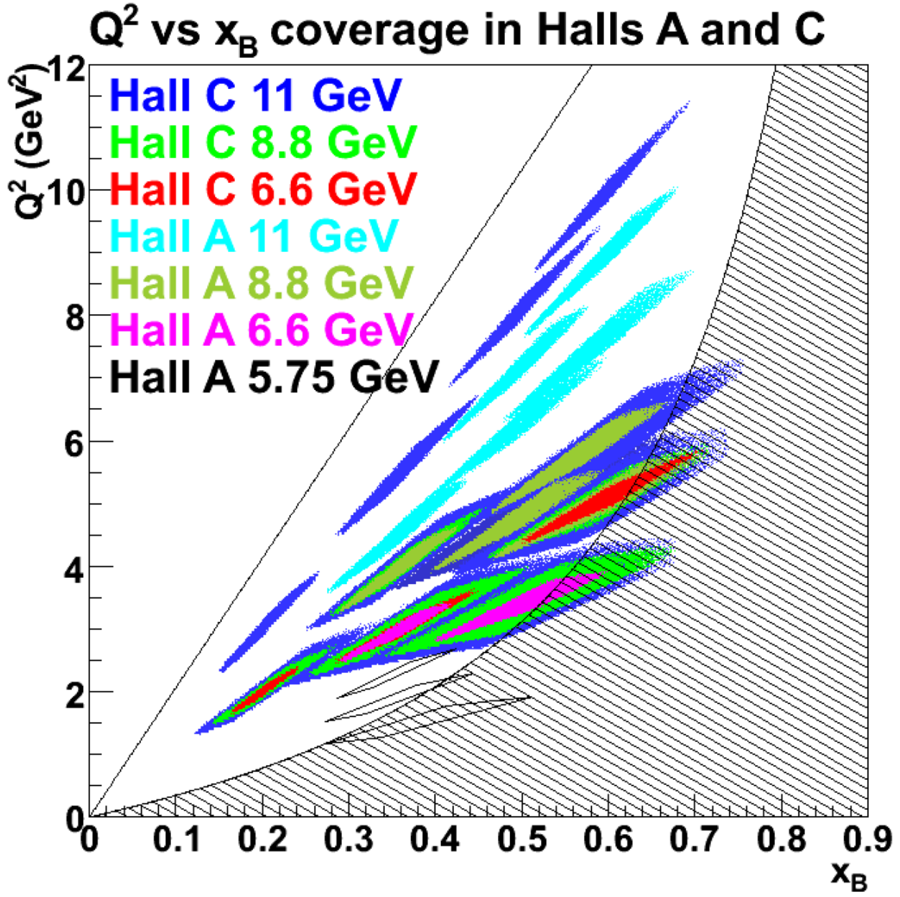


Parameter	*HMS Performance*	*SHMS Specification*
Range of Central Momentum	0.4 to 7.4 GeV/c	2 to 11 GeV/c
Momentum Acceptance	±10%	-10% to +22%
Momentum Resolution	0.1% – 0.15%	0.03% – 0.08%
Scattering Angle Range	10.5° to 90°	5.5° to 40°
Target Length Accepted at 90°	10 cm	25 cm
Horizontal Angle Acceptance	±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

NPS experiments from September 2023 – May 2024

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

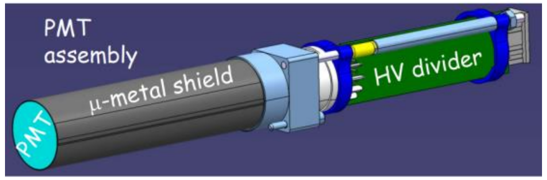
- Experiments
  - E12-13-010 is two concurrent experiments
    - Exclusive Deeply Virtual Compton on proton
    - SIDIS p(e,e',π^0) cross section. Map the transverse momentum dependence.
    - 53 PAC days.
  - E12-06-114 is completion of Hall A DVCS experiment
    - 35 PAC days.
  - Two experiments with 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
  - Positron experiment
    - E12+23-006: Deeply Virtual Compton Scattering using a positron beam in hall C

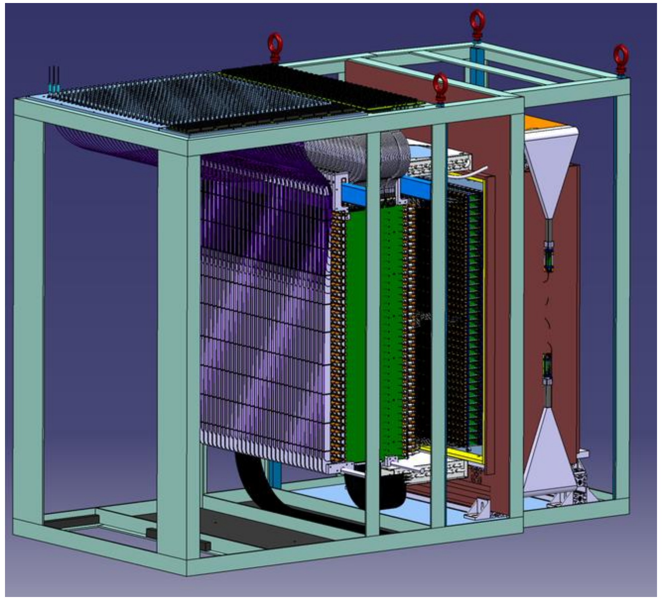


Jefferson Lab

NPS Calorimeter

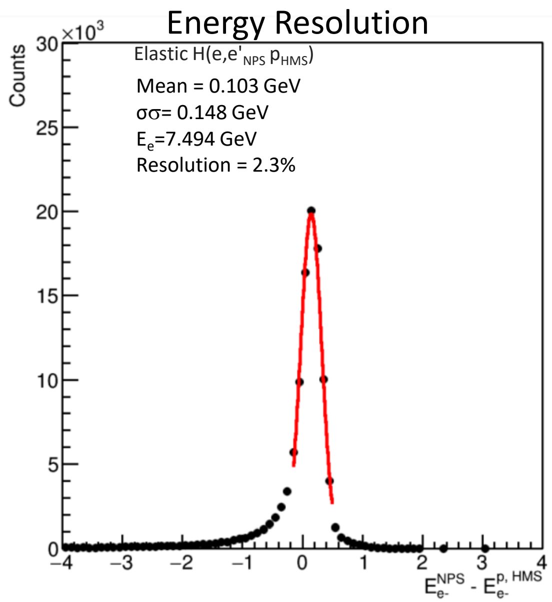
- 1080 $PbWO_4$ blocks
  - High energy resolution
  - High light yield
  - RadHard
- Temperature controlled frame
- Hamamatsu 4125 PMTs
- HV divider and amplifier to reduced HV requirements
- LED system for curing and gain monitoring
- HV, LV, and LED signals distributed to an entire column through distribution board

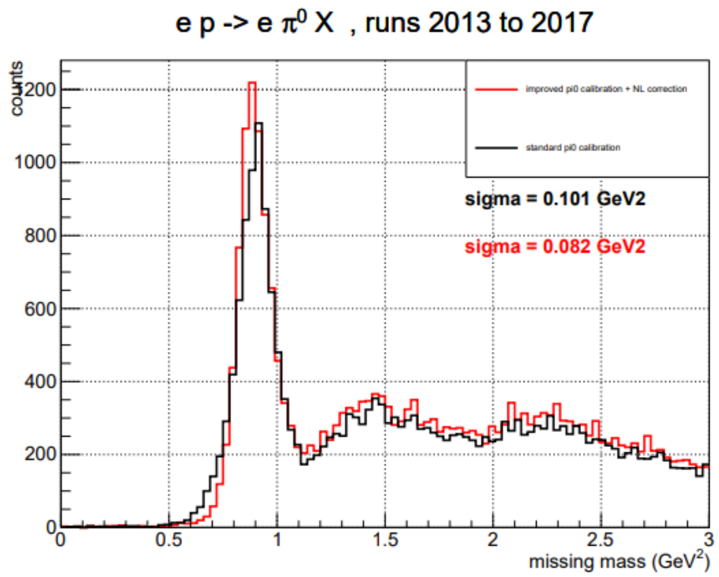




Energy Resolution

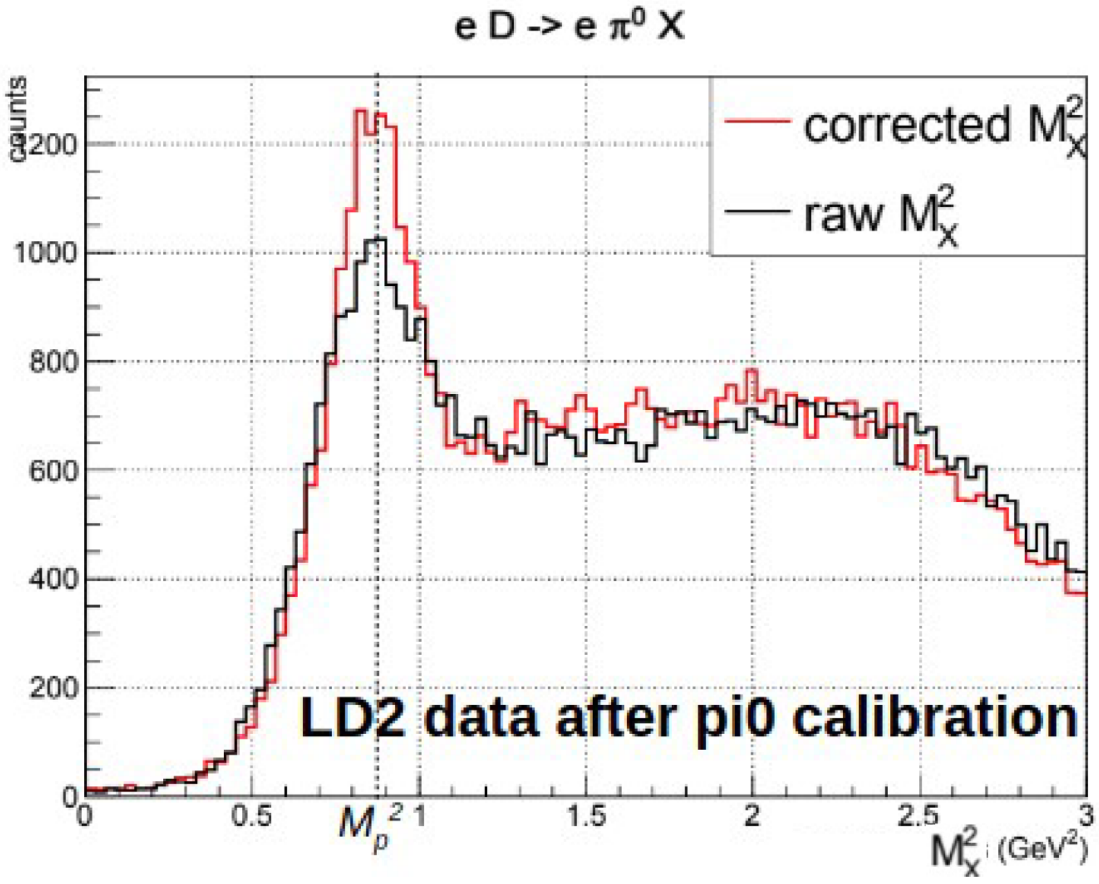
- Exclusivity of the reaction is determined by the missing mass technique
- Missing mass resolution is dominated by the energy resolution of the calorimeter
- Energy resolution from elastic calibration ~2.3% at E_e=7.494 GeV
- Missing mass resolution from π^0 calibration 82MeV
  - Hear Hao's talk for more details on calibrations



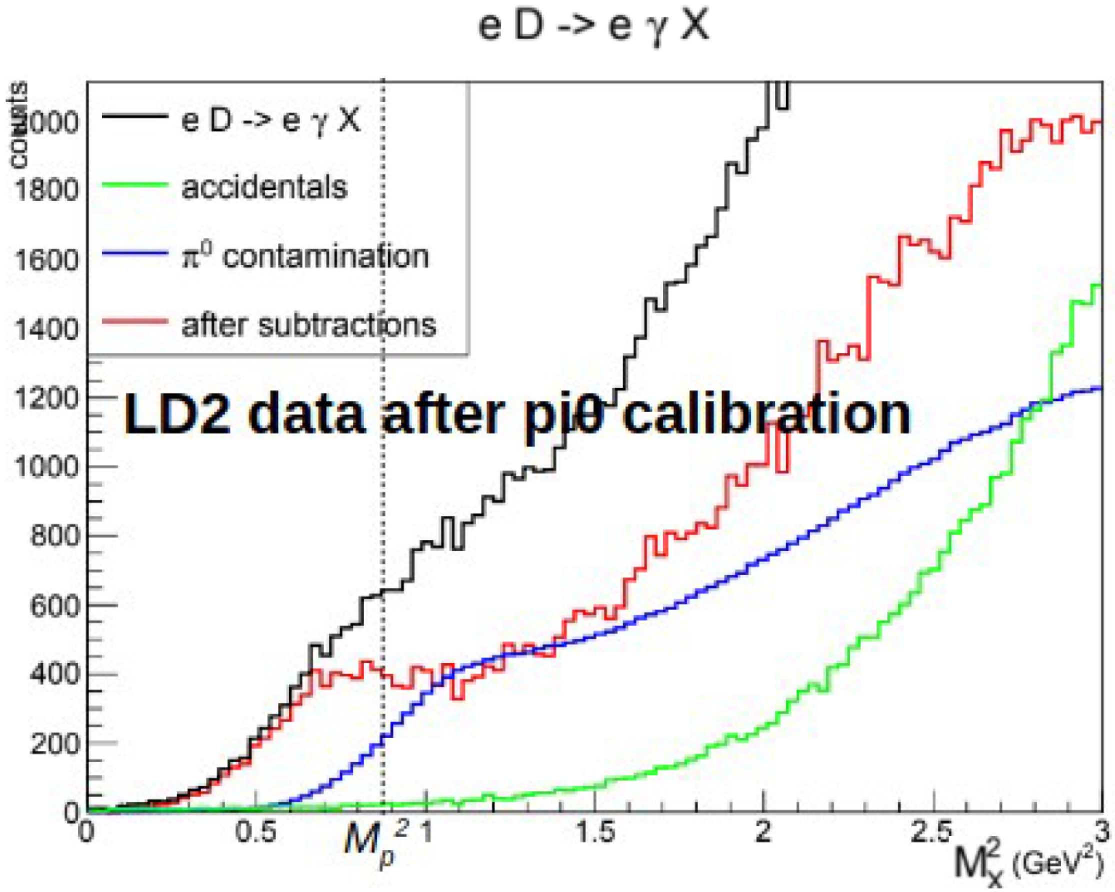


nDVCS Very preliminary physics plots

- Missing mass squared corrected by the correlation between the missing mass squared and the invariant mass

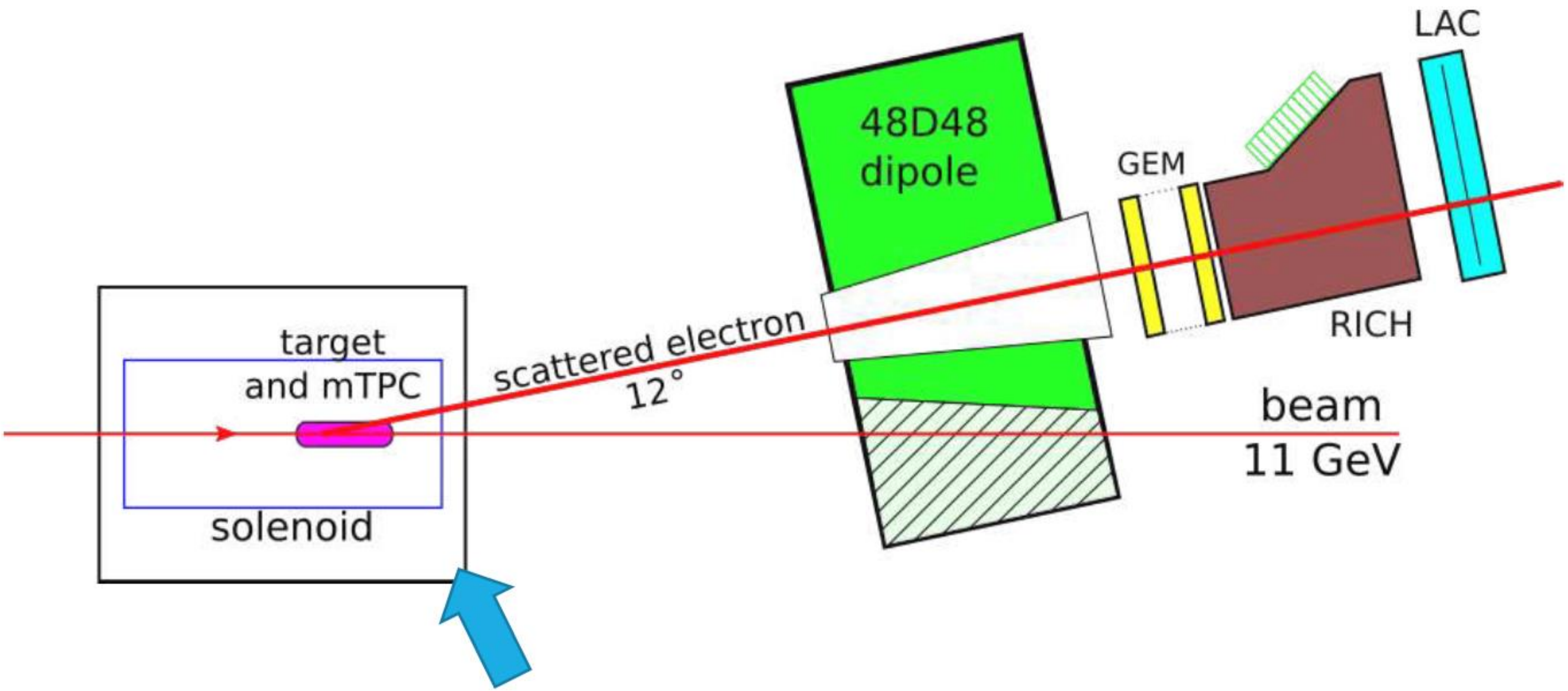


- Subtraction of Pi0 and accidentals



Future experiments

TDIS in Hall A: Experimental layout

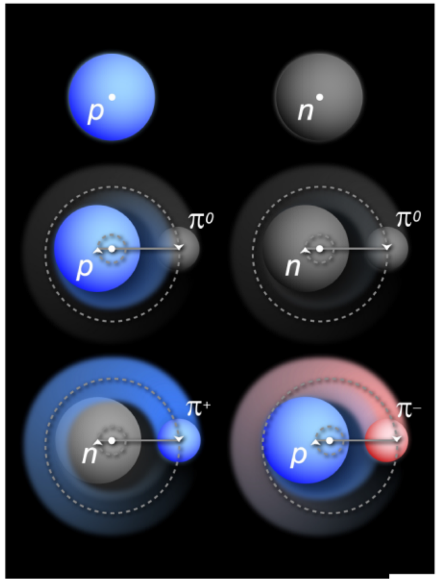


A new detector → mTPC: multi-Time Projection Chamber to measure low-momentum recoil protons

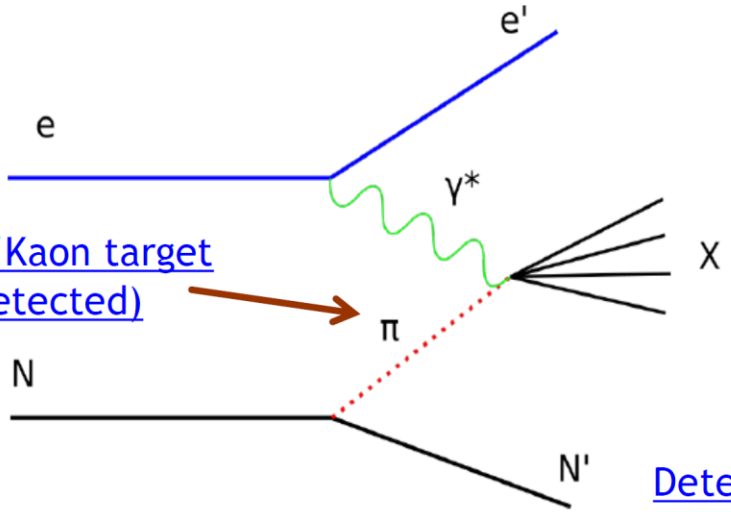
SBS TDIS

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

Pion/Kaon target (undetected)

Detect “tagged” proton/neutron/lambda

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

i = π, ρ, …

“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

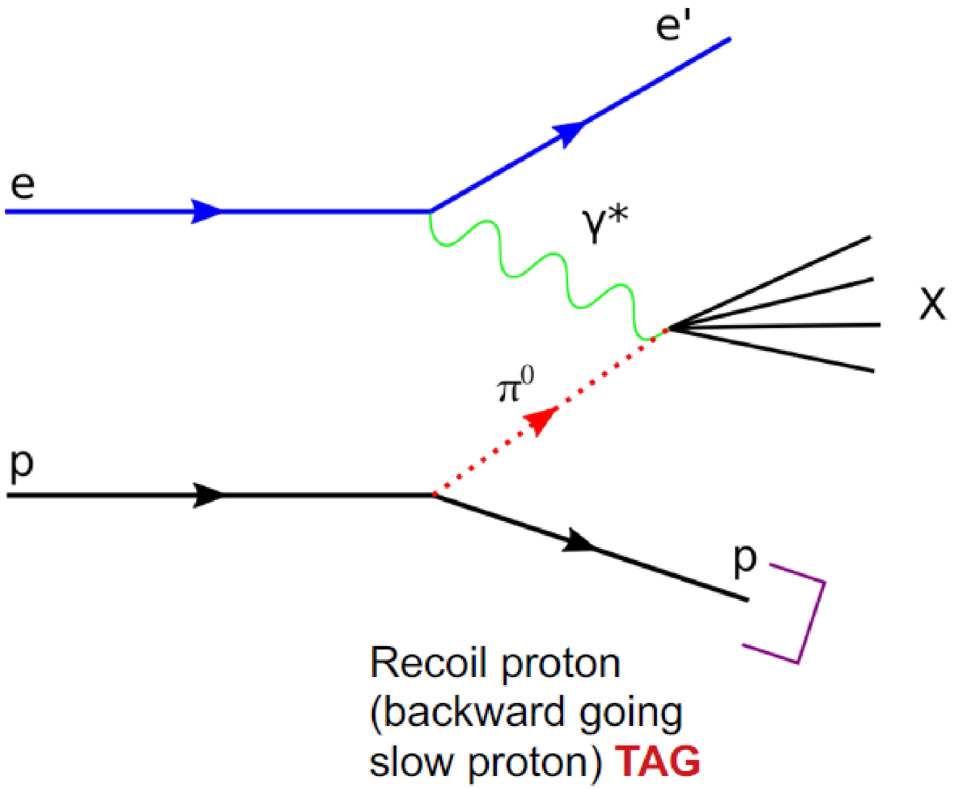
- eH → 1 proton
- eD → 2 protons with common vertex

Under these kinematics:

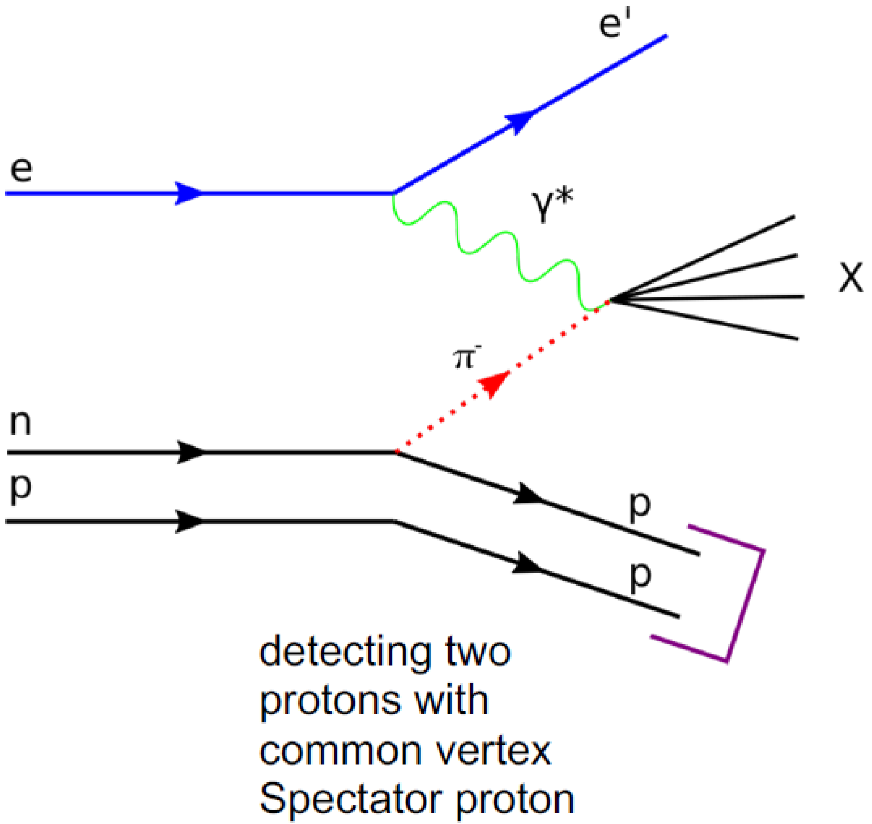
$8 < W^2 < 18\ GeV^2$
$1 < Q^2 < 3\ (GeV/c)^2$
$0.05 < x < 0.2$

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

Pion structure from Sullivan process: TDIS



- Effective π^0 target

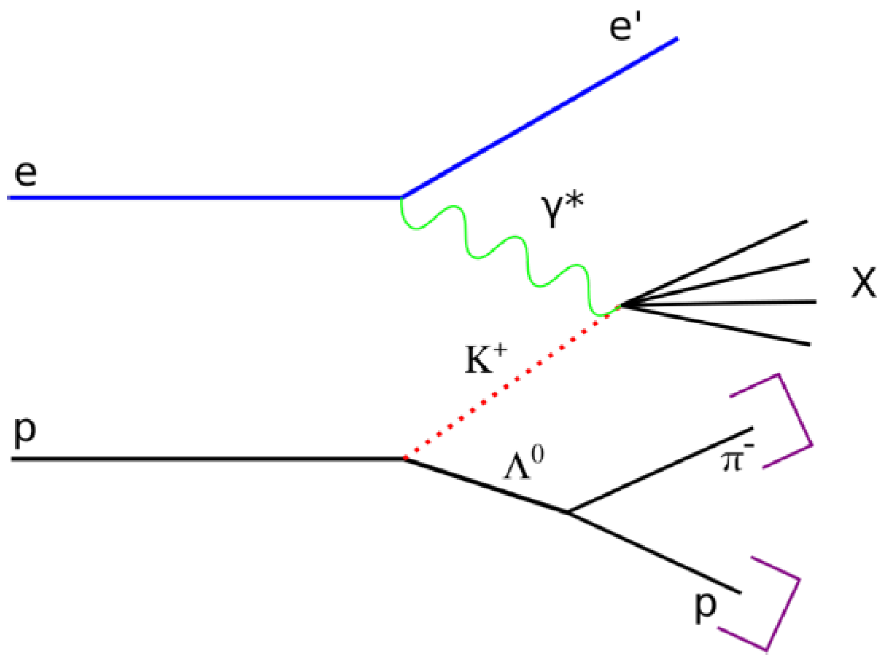


- Effective π^- target

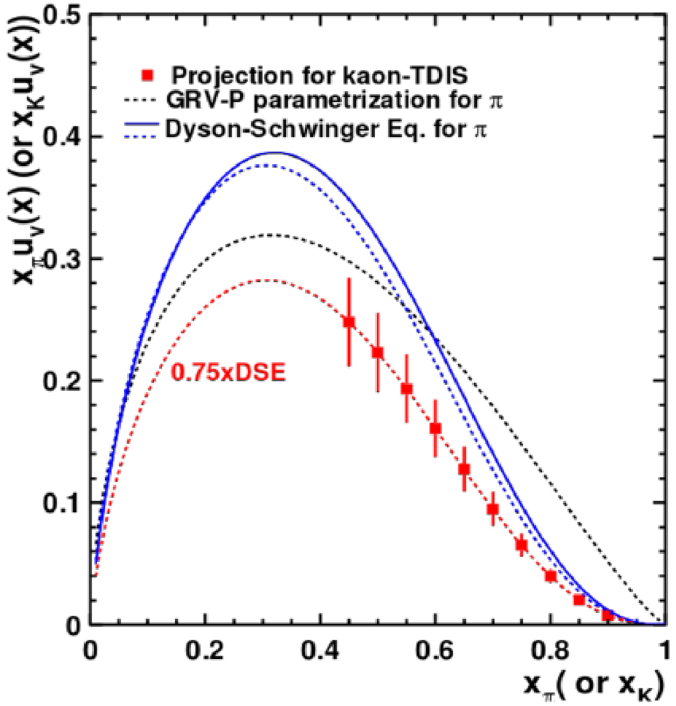
Run Group Addition: Kaon TDIS (C12-15-006A)

Kaon Tagged Deep Inelastic Scattering (TDIS)

C12-15-006A

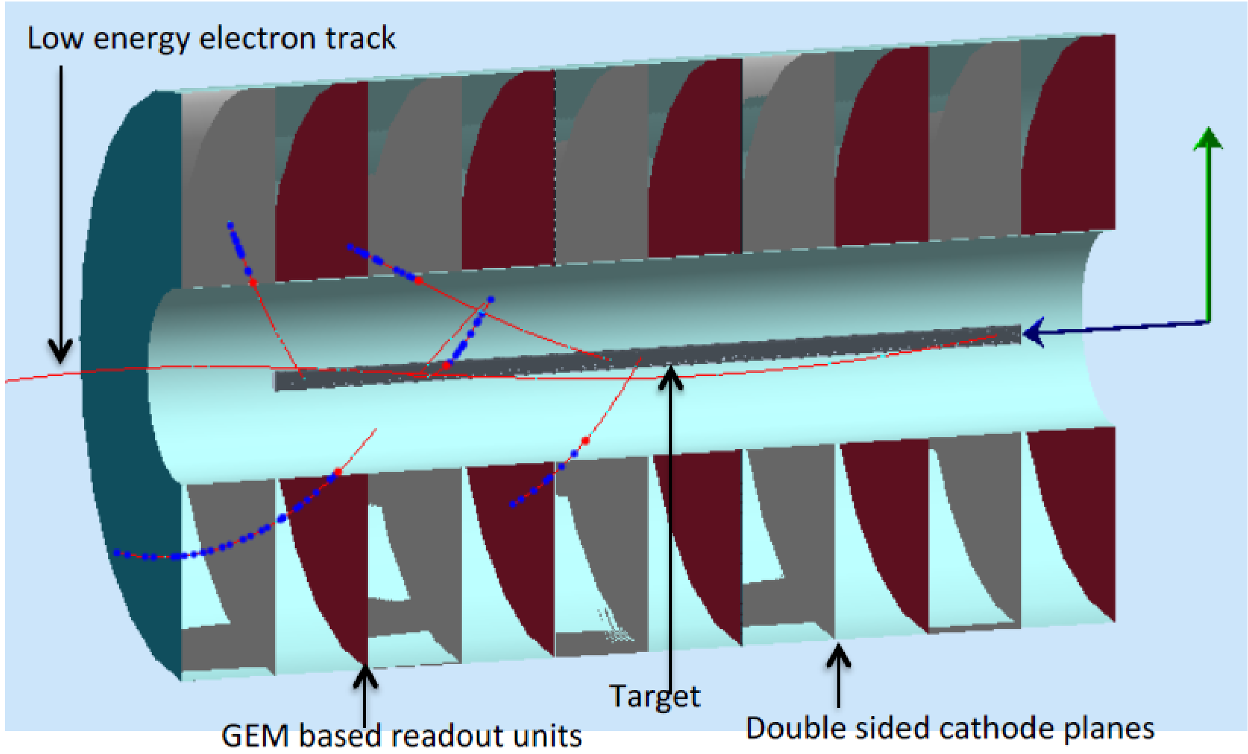


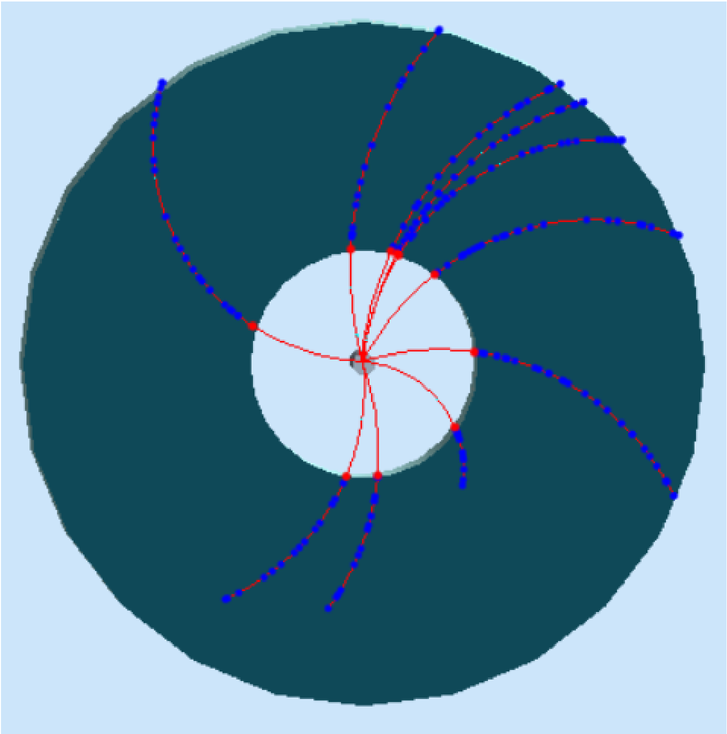
- TDIS run group proposal accepted PAC45 July 2017 Conditionally approved, as pion TDIS (same set-up/27-day beam time)
- **Mesonic content/flux factors unknown, both pion and kaon TDIS measurements will be extremely useful experimental tests**
- Kaon TDIS gives background measurement for pion TDIS



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



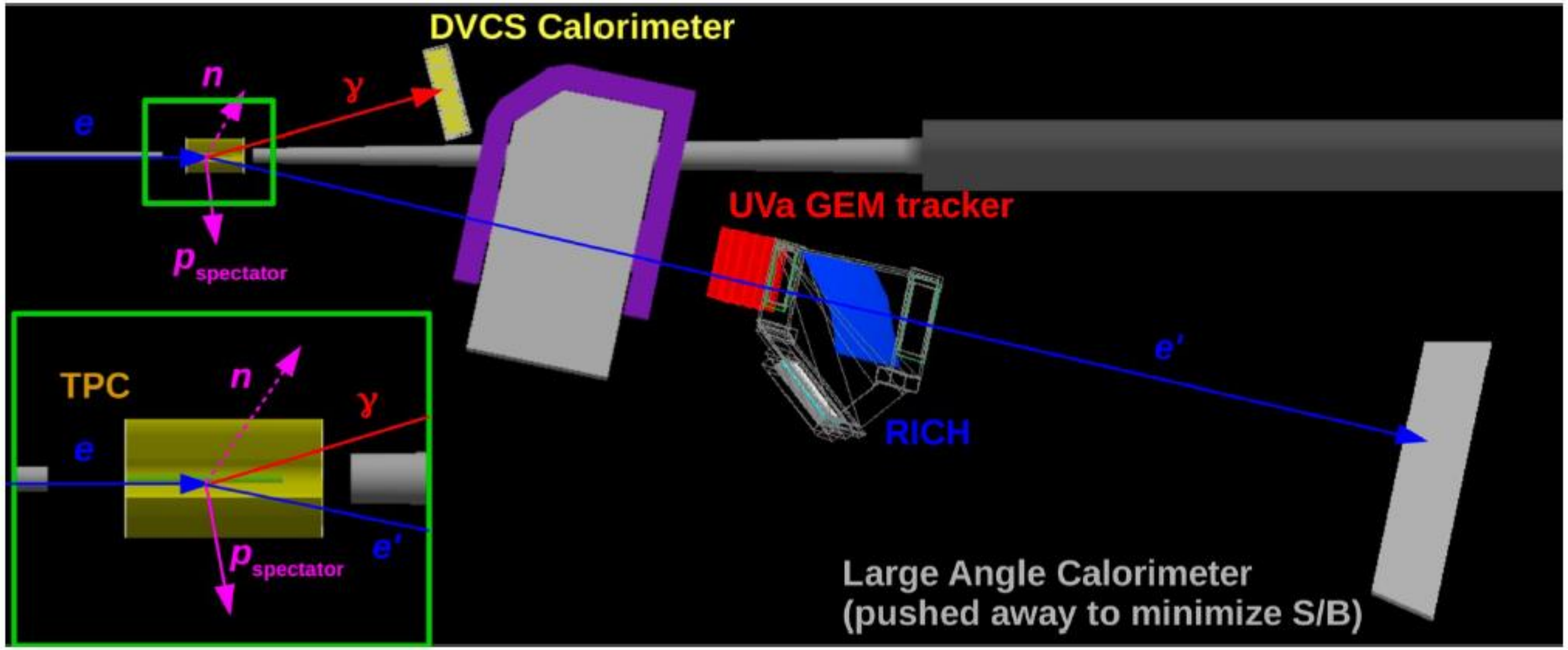


Ptcl tracks

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

More spectator tagged physics: nDVCS using TDIS setup

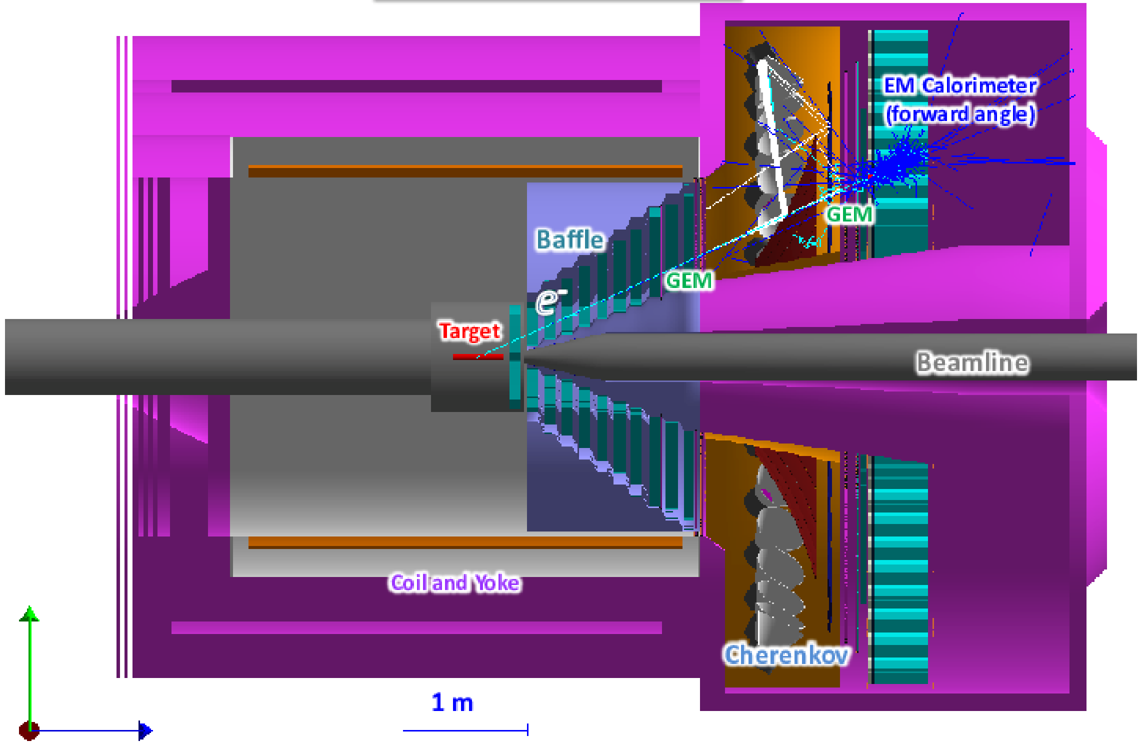
- Measure exclusive photon and neutral pion electroproduction on deuterium, with identification of the spectator proton $D(e, e' \gamma p_{spec})n$ and $D(e, e' \pi^0 p_{spec})n$, in the valence region ($x > 0.1$) and deep inelastic regime: $Q^2 > 1$ GeV^2 , $W^2 > 2$ GeV^2
  - Addition of electromagnetic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



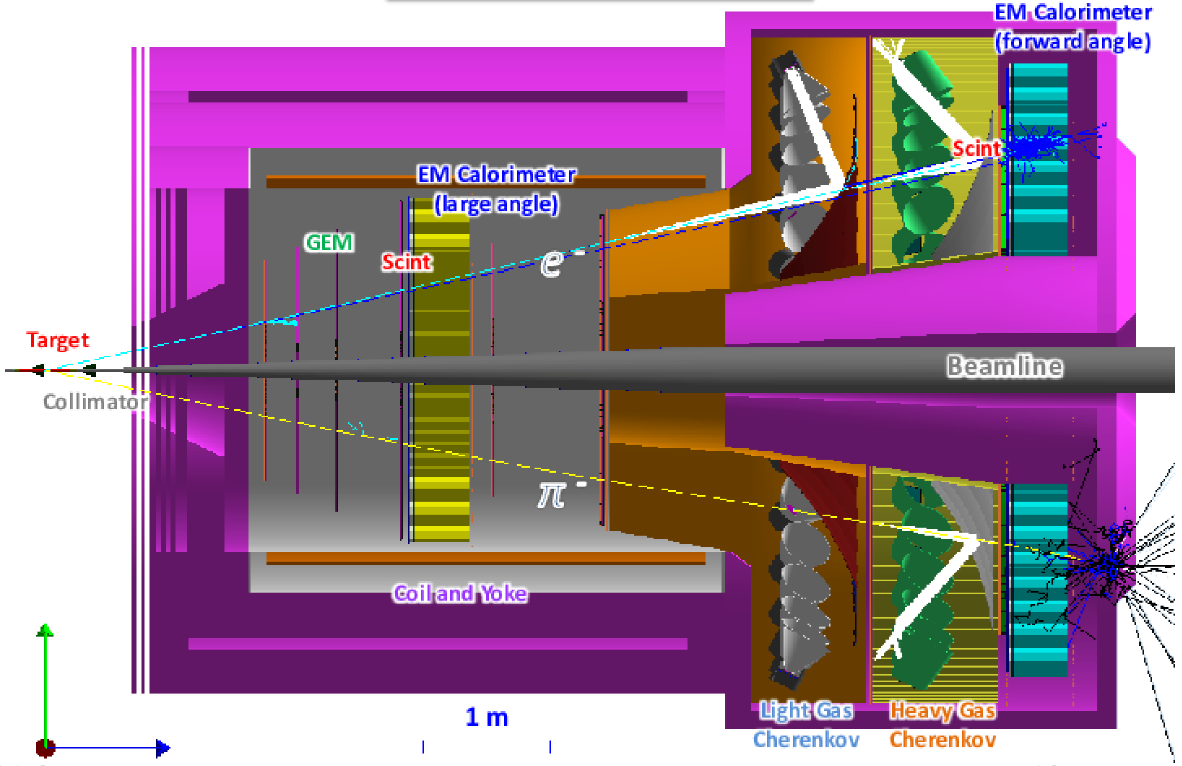
SoLID program

- 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 (PVDIS)

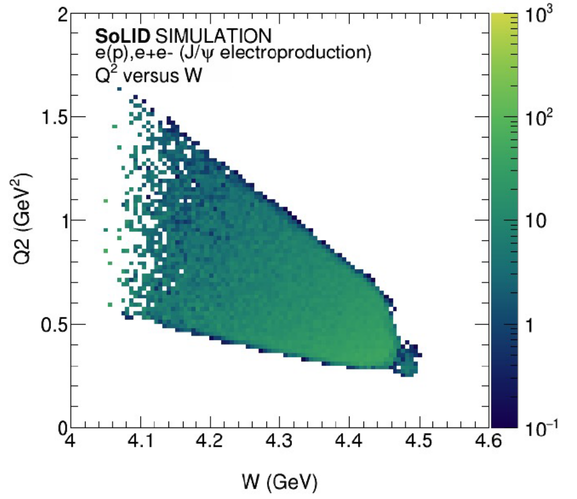


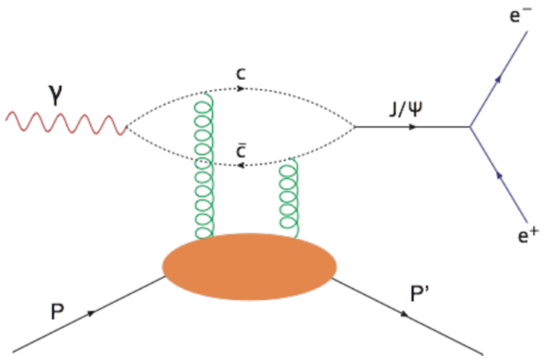
SoLID (SIDIS and J/ψ)

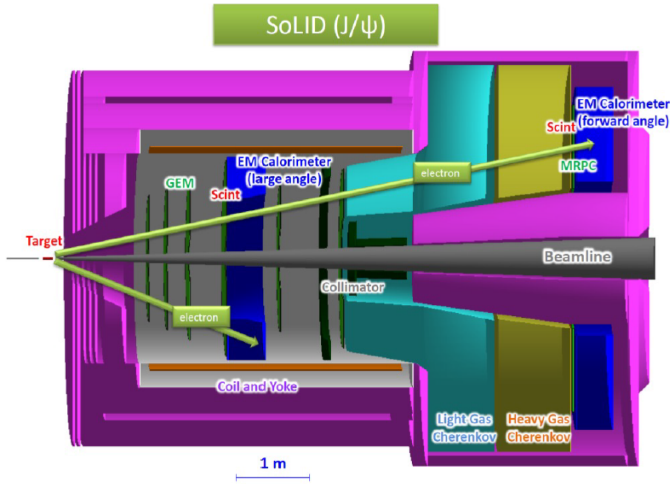


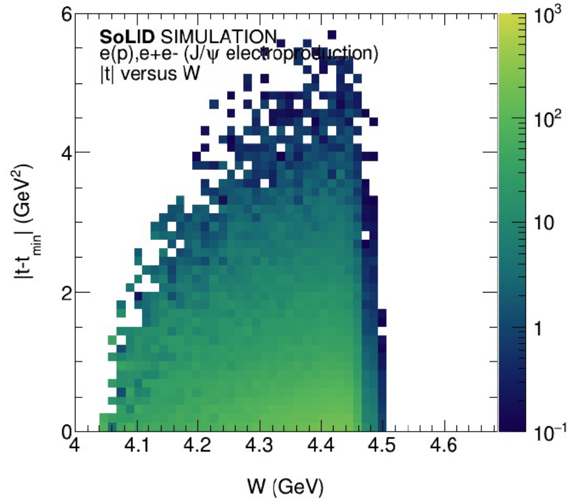
SoLID Experiment Overview

- 50 days of $3\,\mu\mathrm{A}$ 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^-







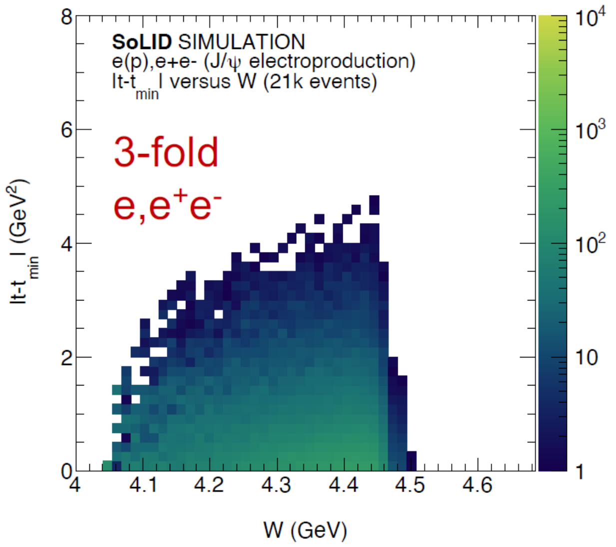


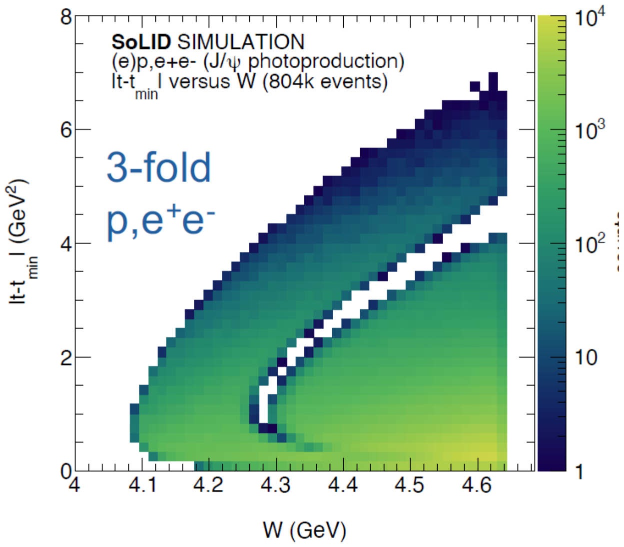
$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

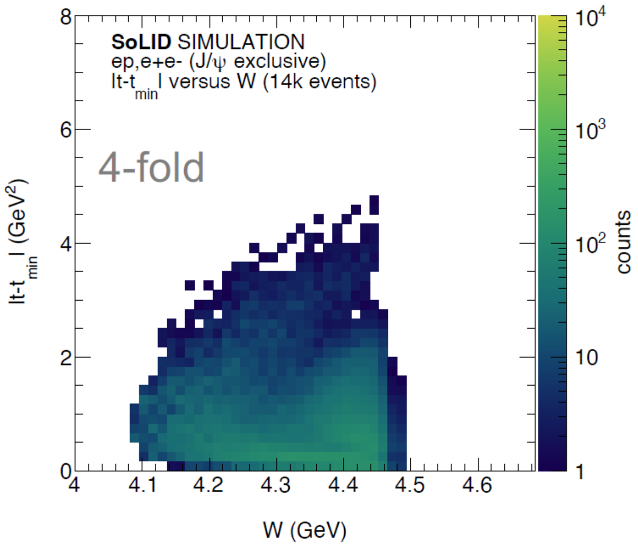
Event Counts @ $1x10^{37}$ in 50 days

- 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

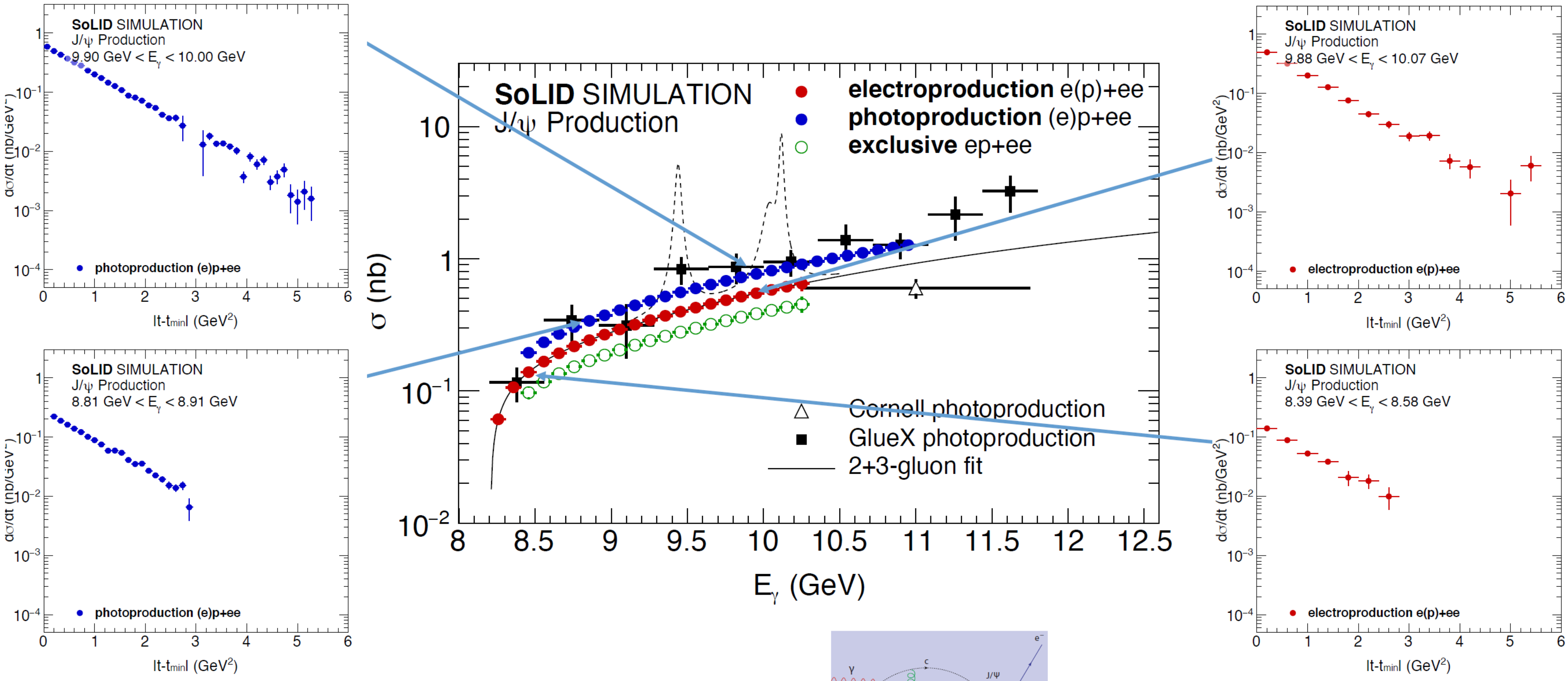
	Time (Hour)	Time (Day)
LH_2 at 11 GeV	**1200**	**50**
Dedicated Al dummy run	**72**	**3**
Optics and detector check out	**72**	**3**
Special low luminosity	**96**	**4**
Total	**1440**	**60**



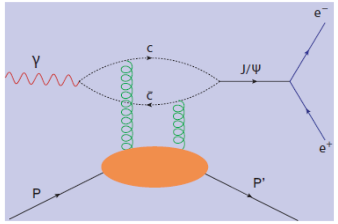




J/Psi Experiment E12-12-006 @ SoLID (C4)



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



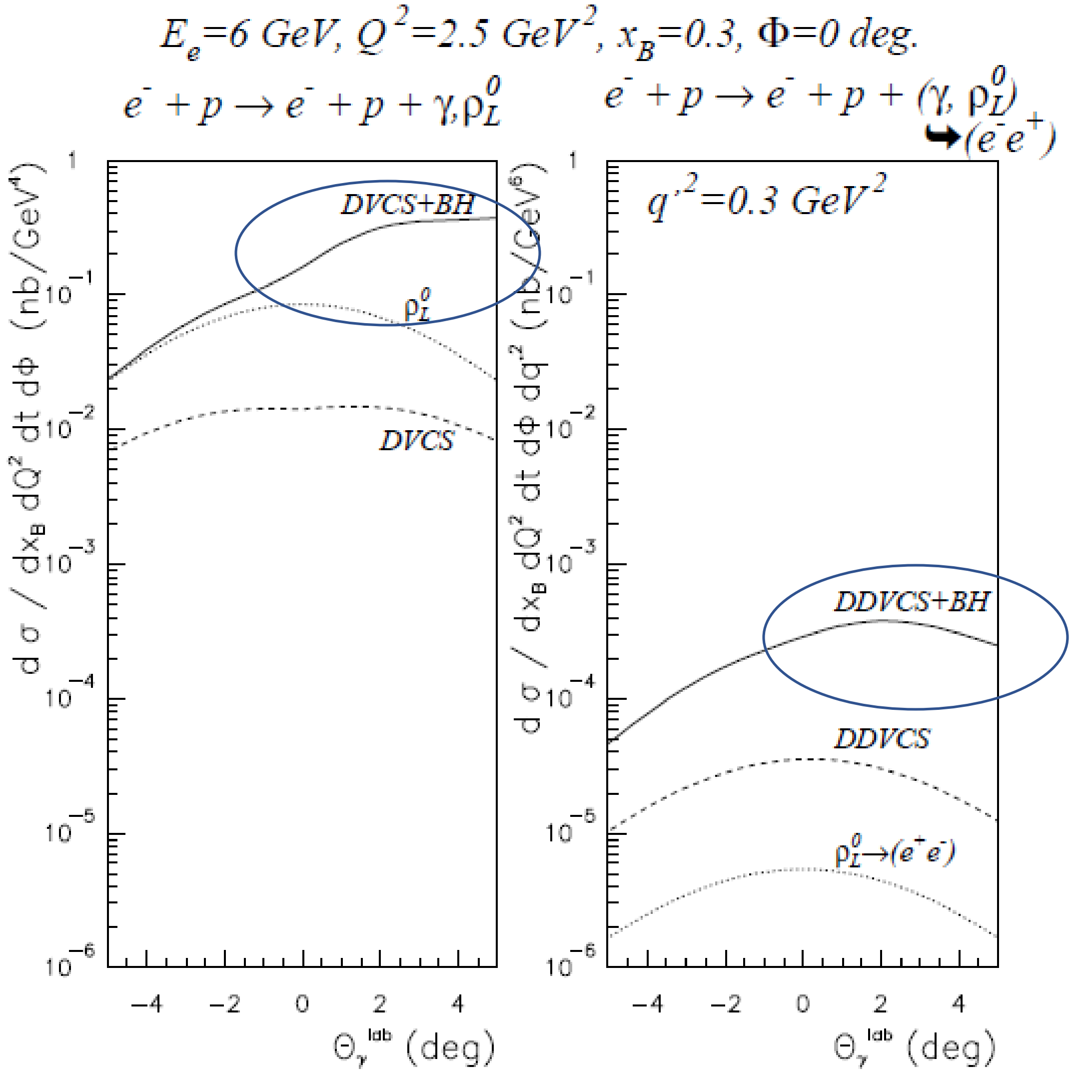
DVCS / Double DVCS

$$\gamma^* + p \longrightarrow \gamma'(*) + p'$$

$$\gamma'(*) \longrightarrow l^+ + l^-$$

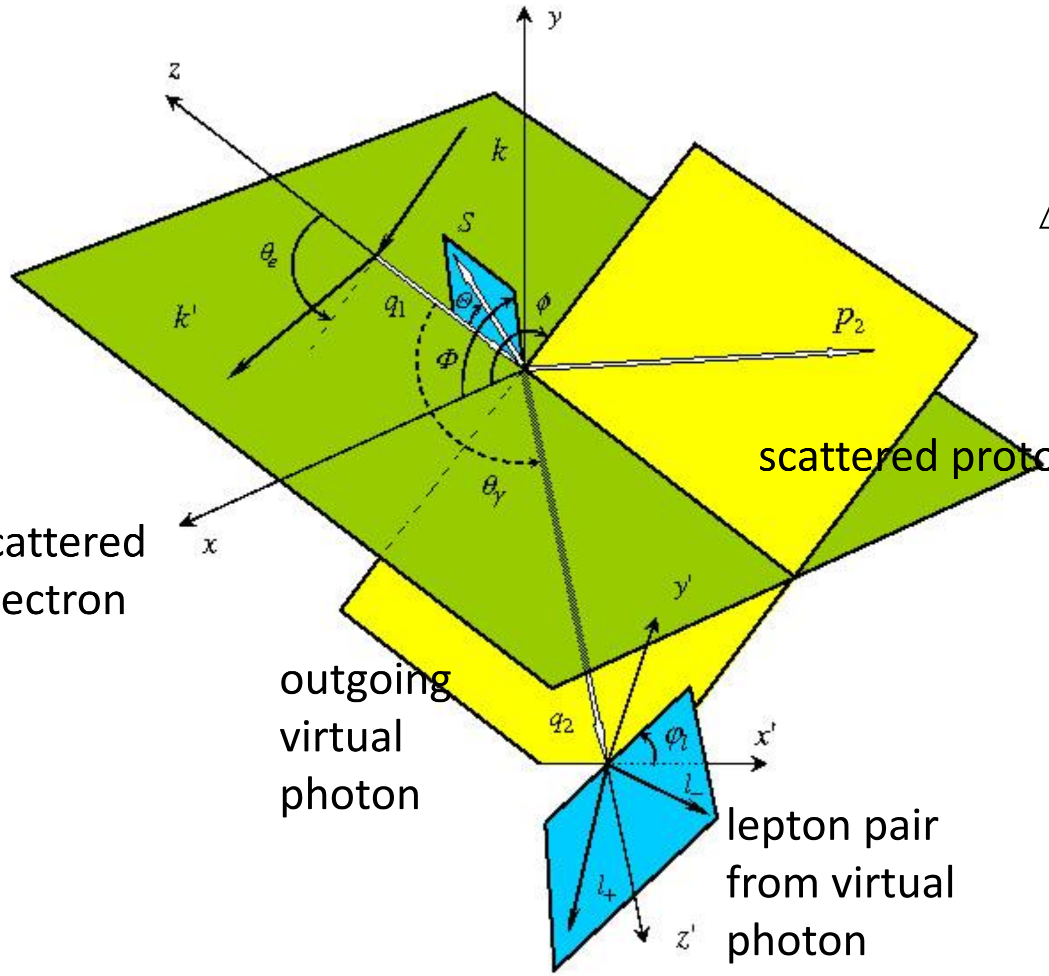
Guidal and Vanderhaegen : Double deeply virtual Compton scattering off the nucleon (arXiv:hep-ph/0208275v1 30 Aug 2002)
Belitsky Radyushkin : Unraveling hadron structure with generalized parton distributions (arXiv:hep-ph/0504030v3 27 Jun 2005)

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



Δ = p1-p2 = q2-q1

p = p1+p2

q = ½ (q1+q2)

$Q^2 = -q^2$

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

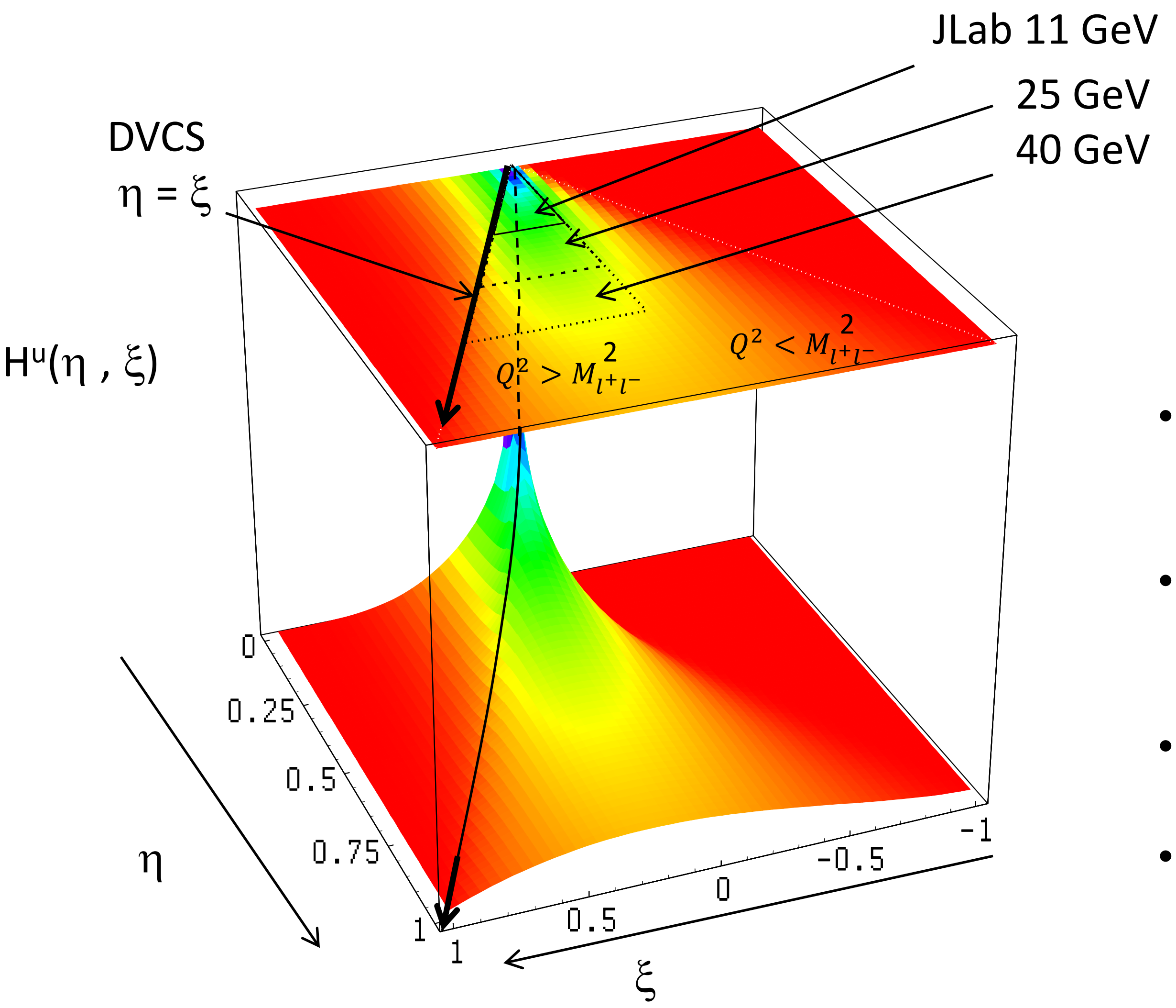
$$Q^2 = -(k-k')^2 \qquad x_{bj} = \frac{Q^2}{2p_1q_1}$$

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

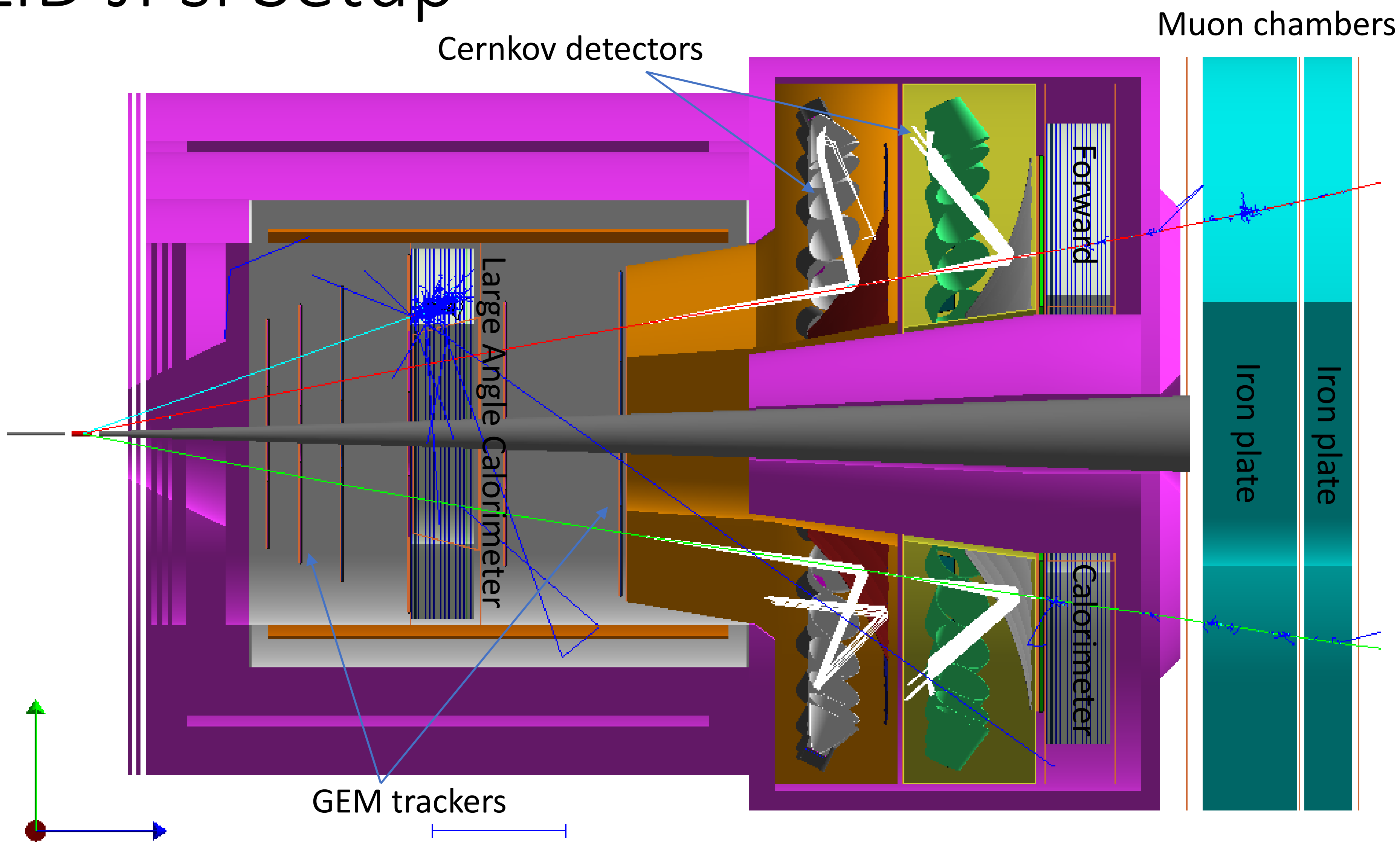


- DVCS only probes η = ξ line
- Example with model of GPD H for up quark
- Jlab : $Q^2>0$
- Kinematical range increases with beam energy (larger dilepton mass)

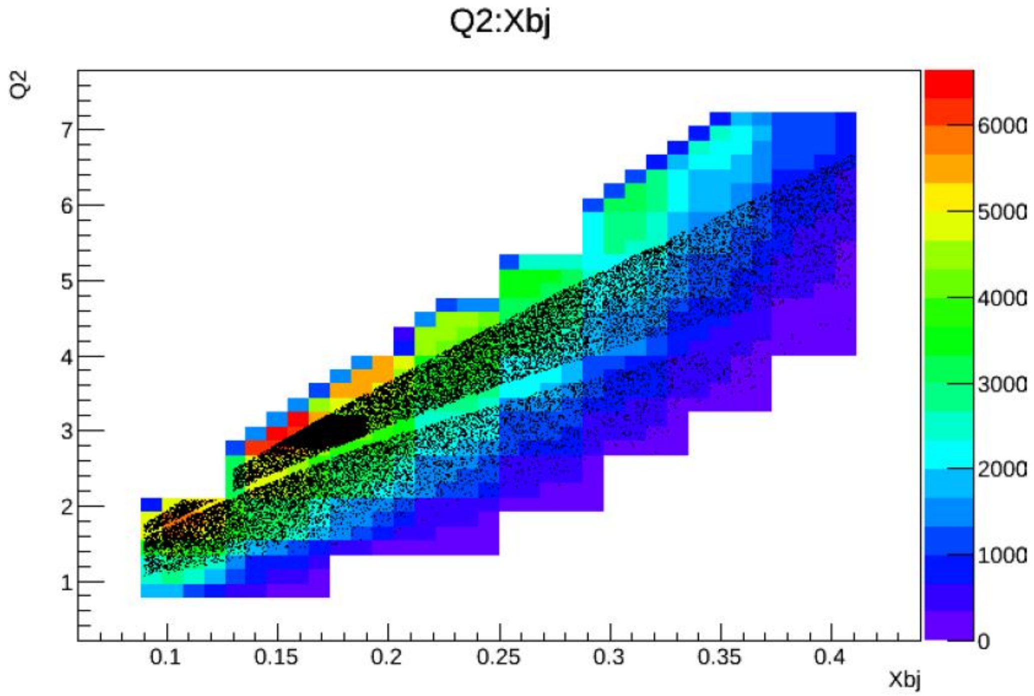
DDVCS LOI

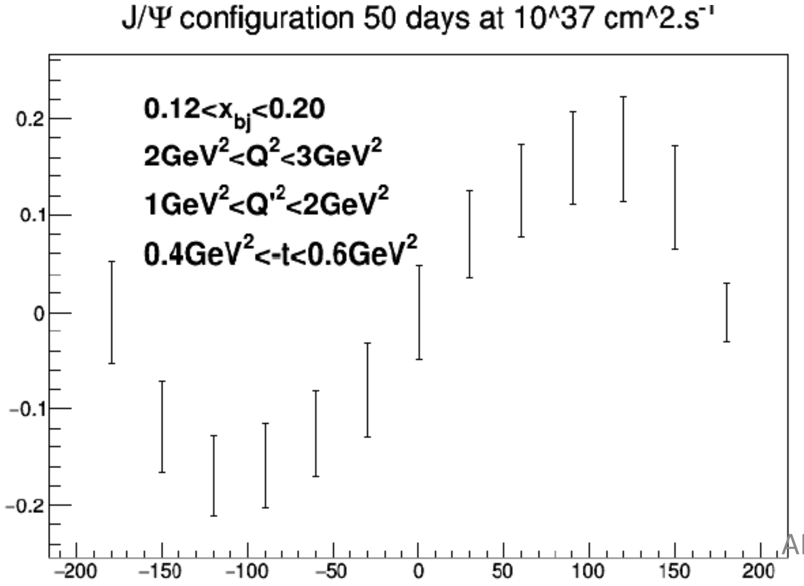
- PAC 43 : Measurement of Double Deeply Virtual Compton Scattering (DDVCS) in the di-muon channel with the SoLID spectrometer (Boer,Camsonne,Gnanvo,Sparveri,**Voutier**,Zhao)

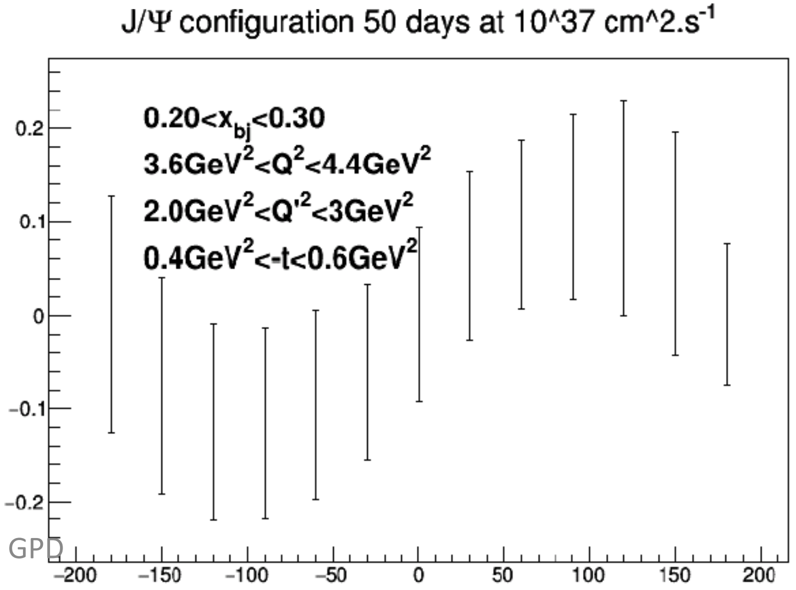
SoLID JPsi Setup



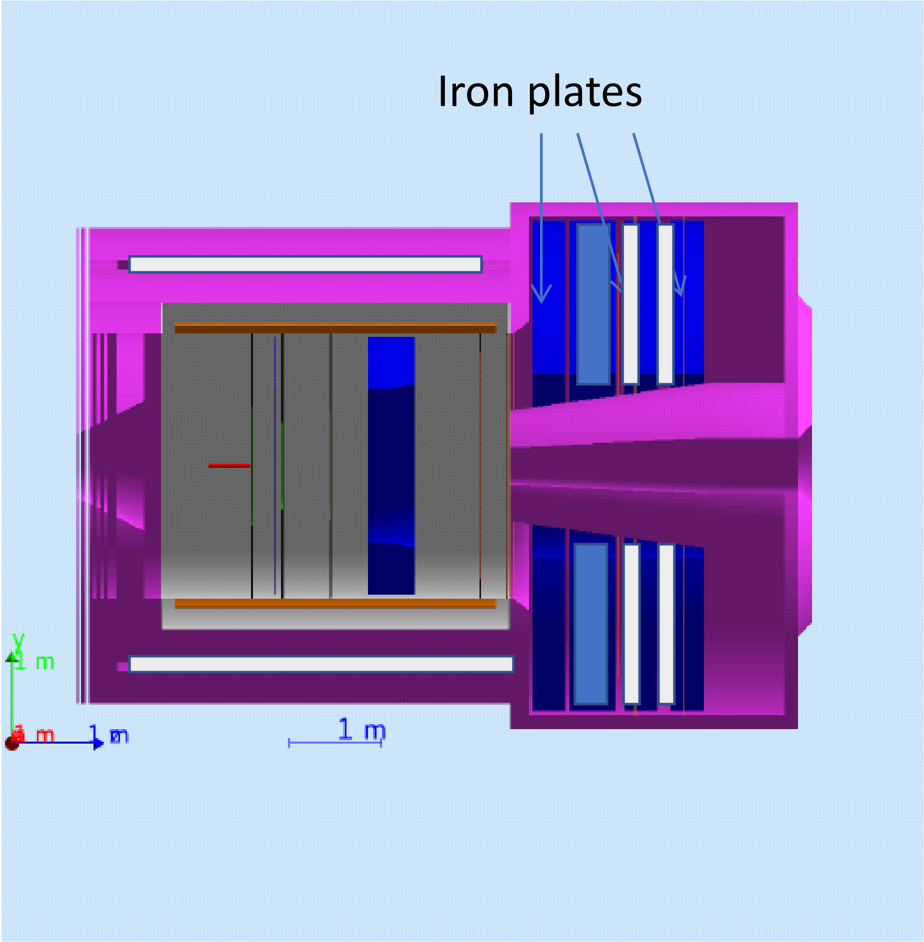
Counts J/psi setup 60 days at 10^{37} $cm^{-2}s^{-1}$







Dedicated setup

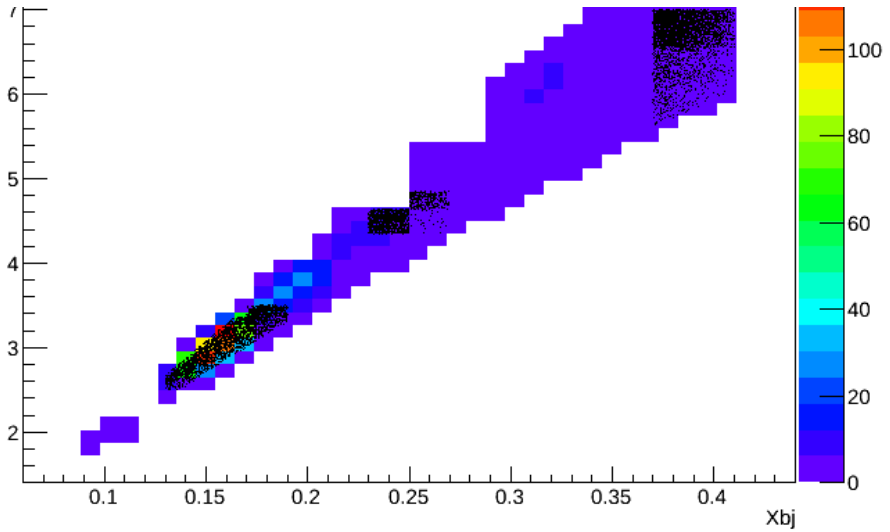


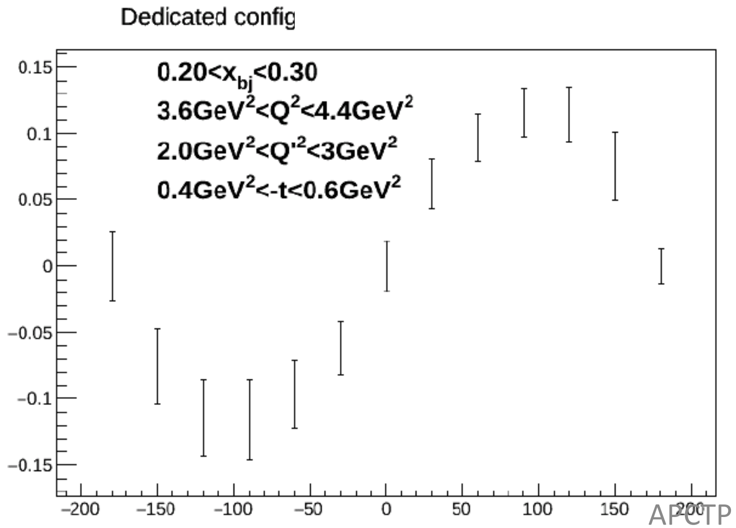
- Target moved 2m from Jpsi position inside and switch to 45 cm target
- Iron plate from 3rd layer yoke in front and behind calorimeter

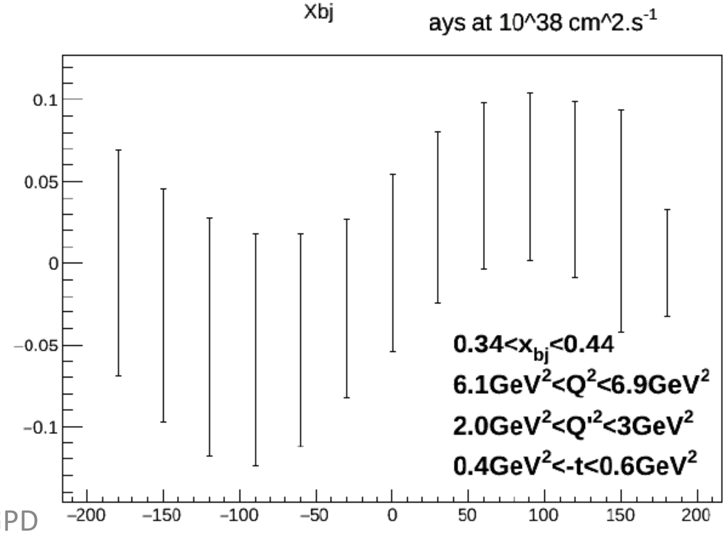
- Remove Gas Cerenkov

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

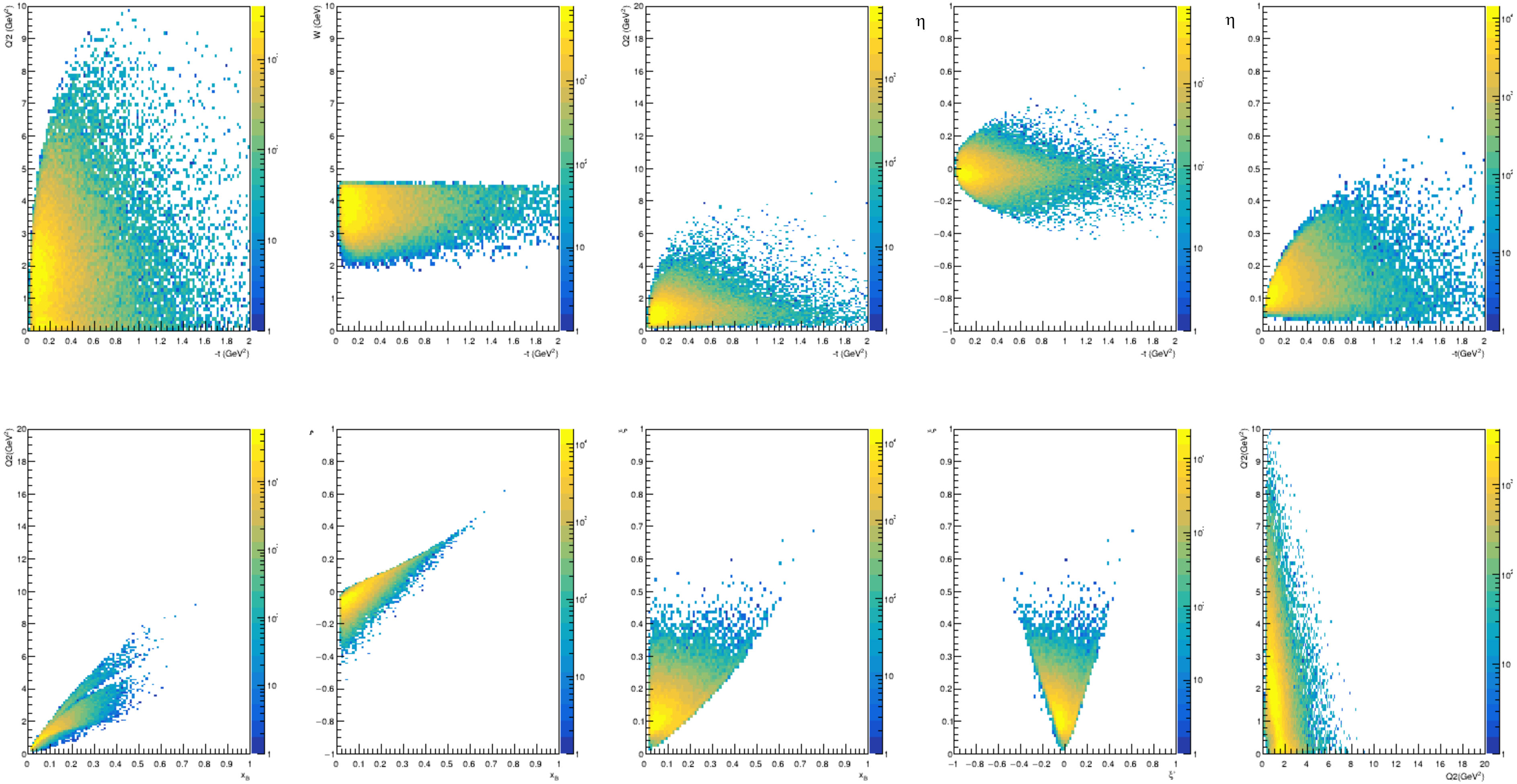
Expected accuracy dedicated setup
90 days at 10^{38} $cm^{-2}s^{-1}$





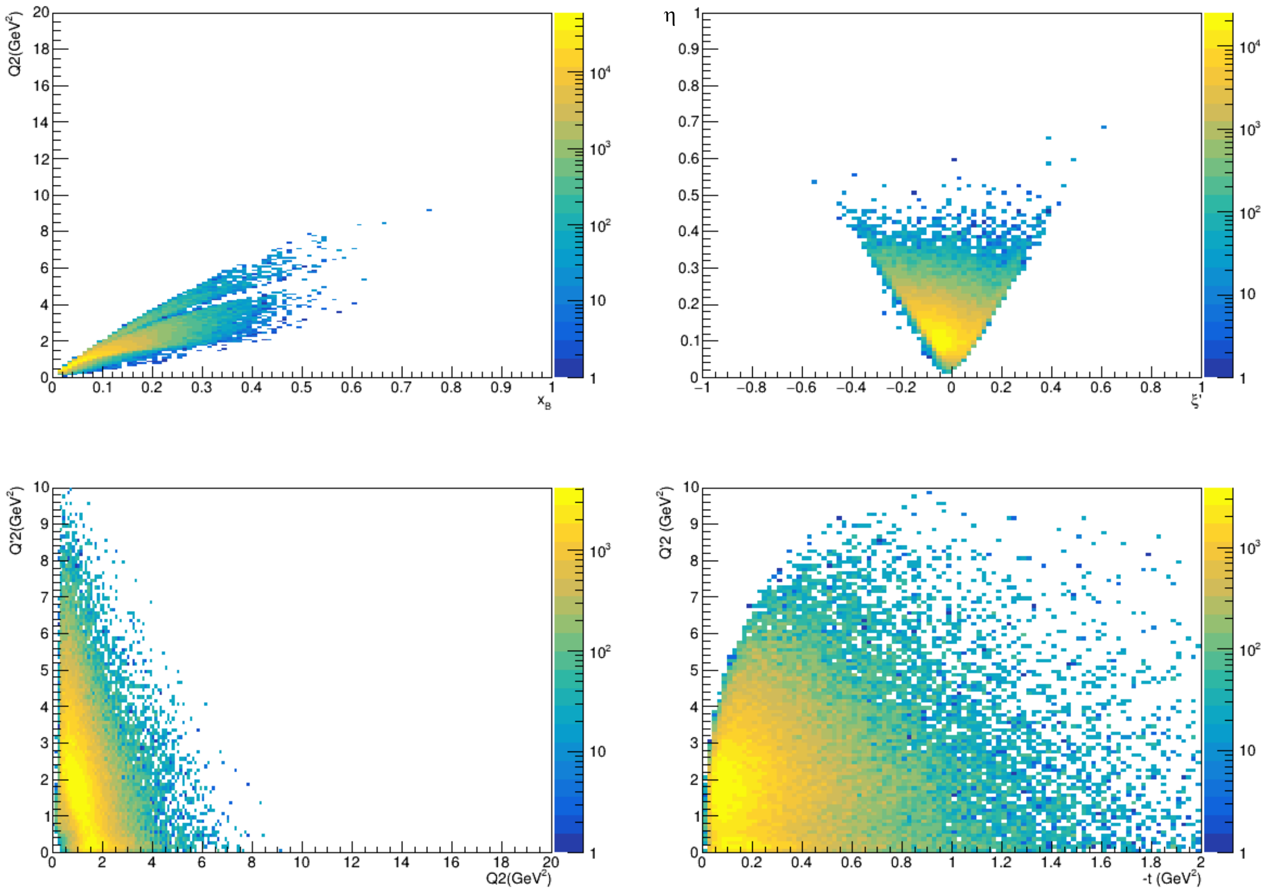


Kinematical coverage 11 GeV



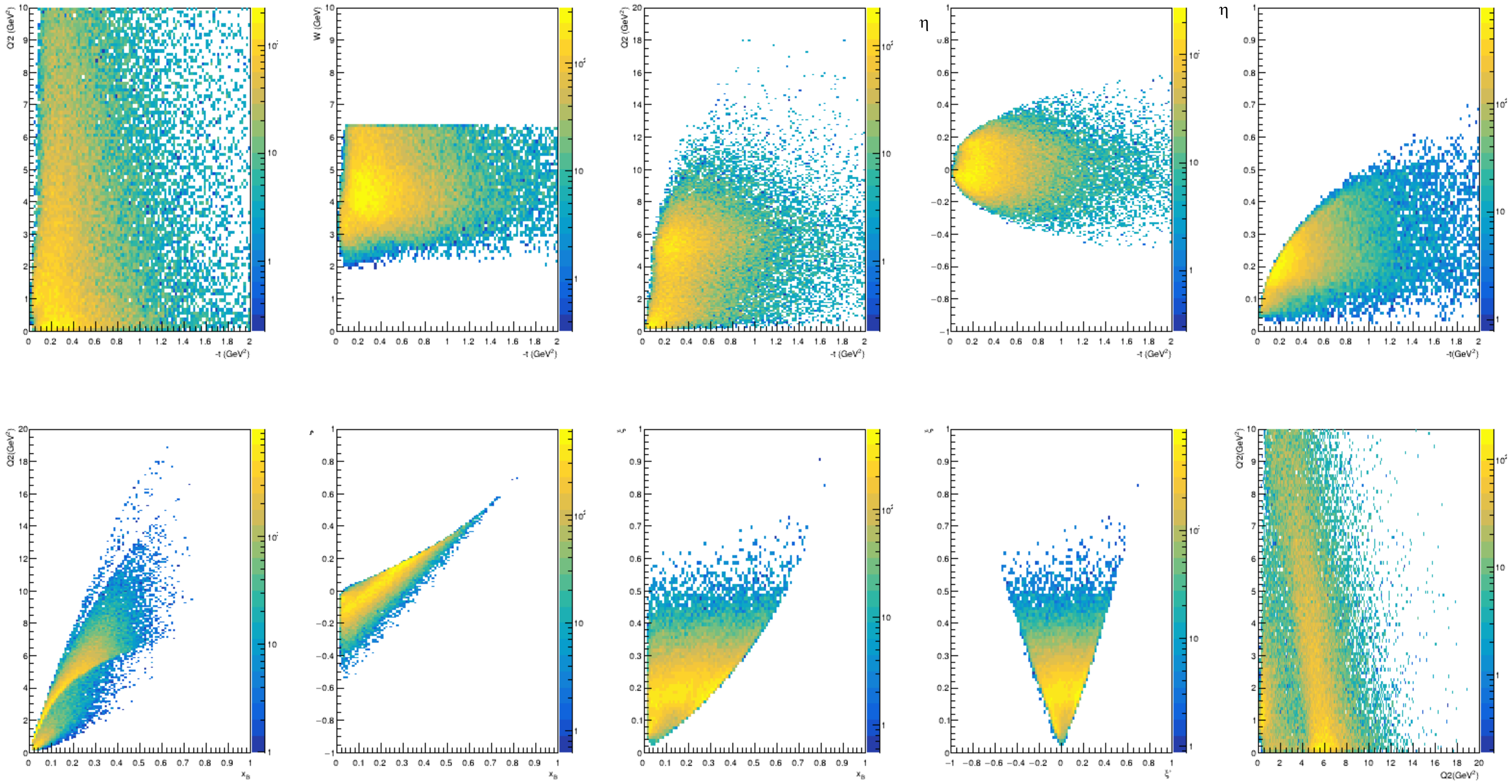
Zhiwen Zhao (GRAPE)

Kinematical coverage 11 GeV



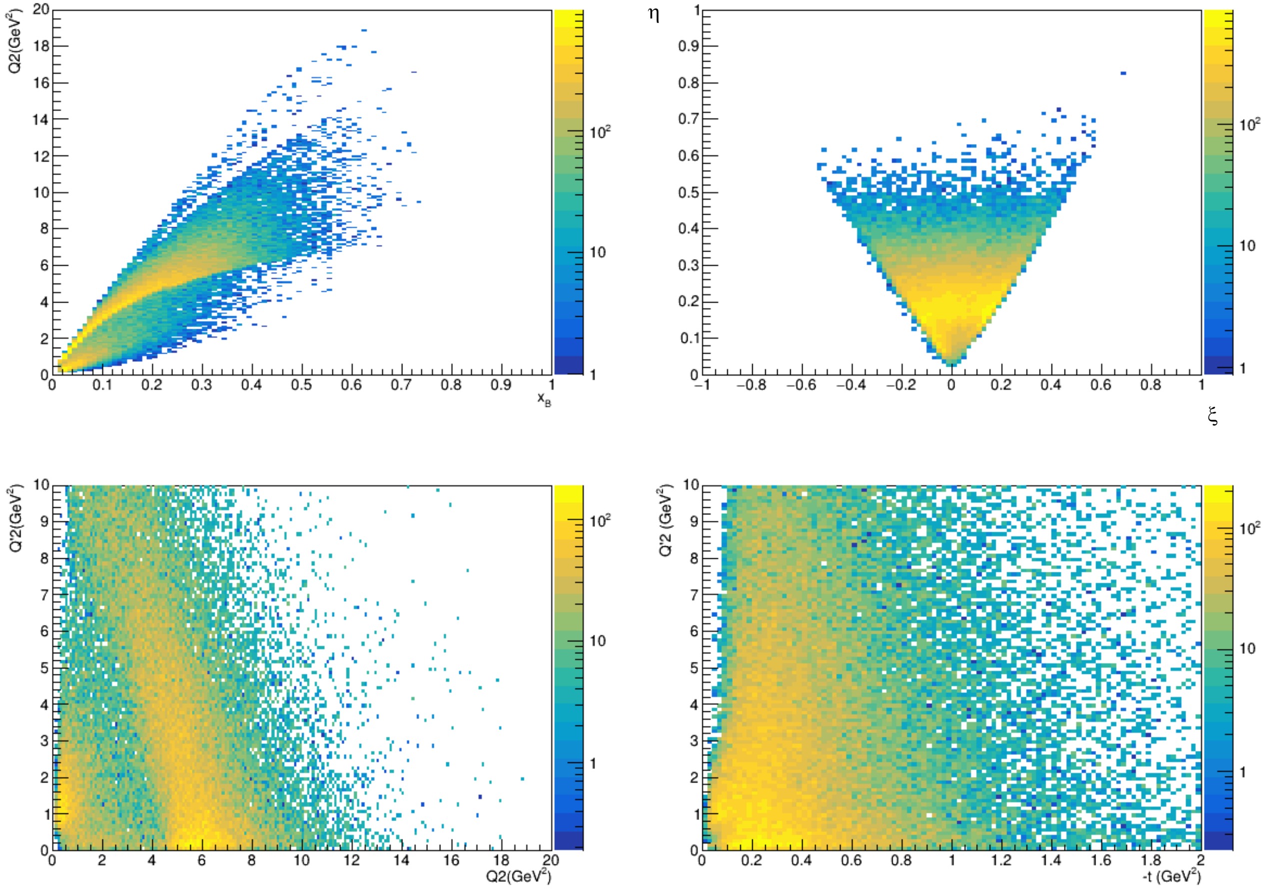
Zhiwen Zhao (GRAPE)

Kinematical coverage 22 GeV



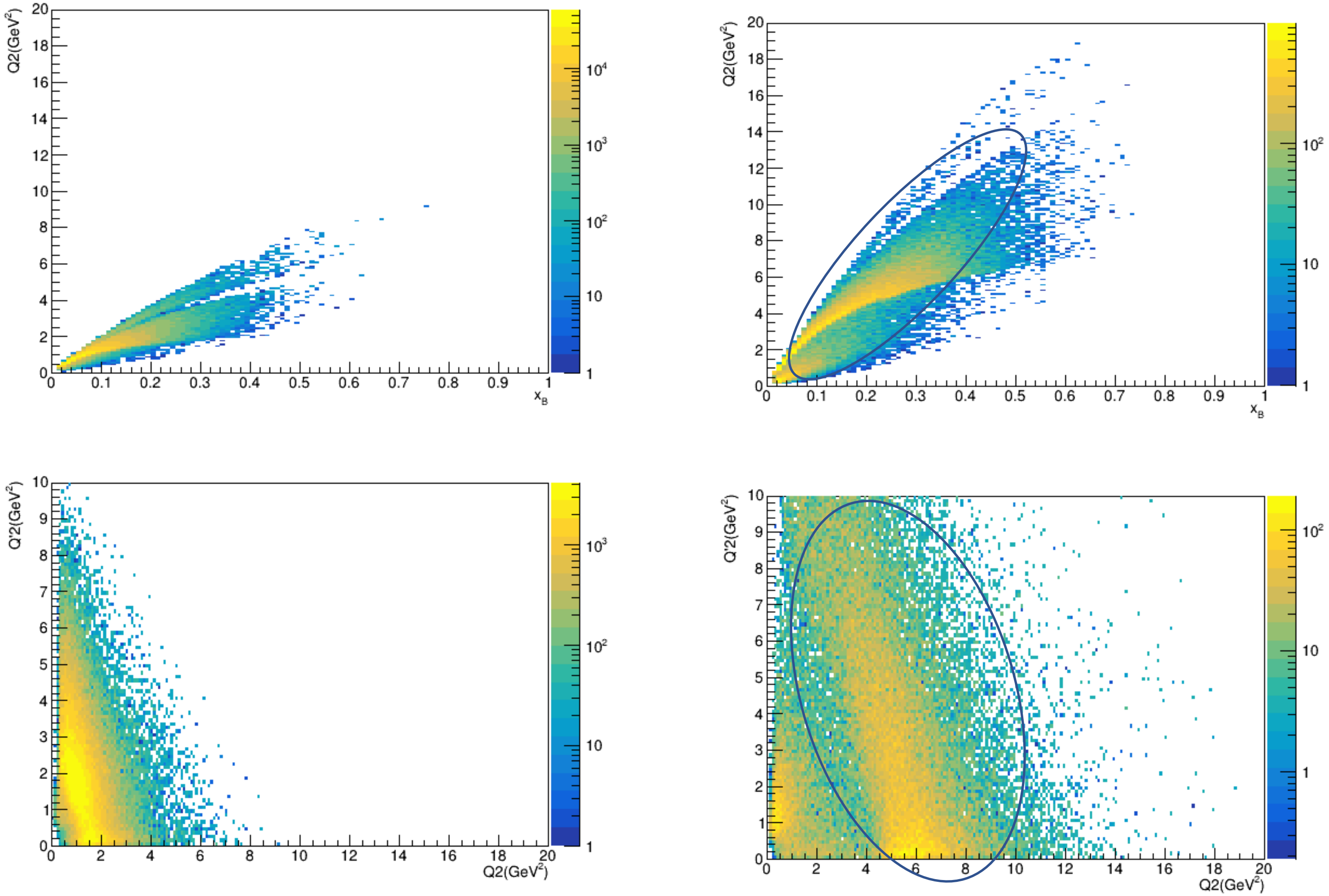
Zhiwen Zhao (GRAPE)

Kinematical coverage 22 GeV

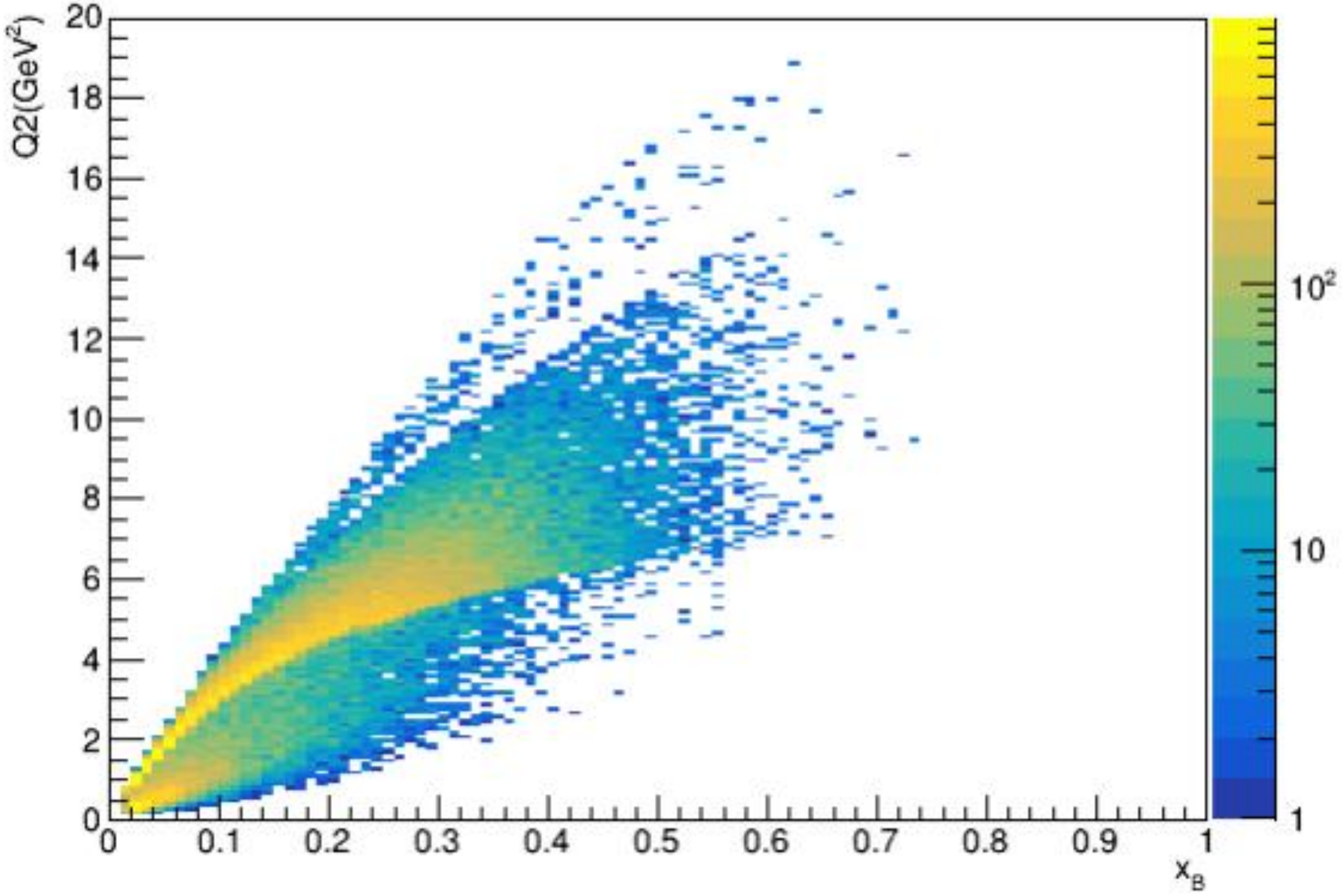


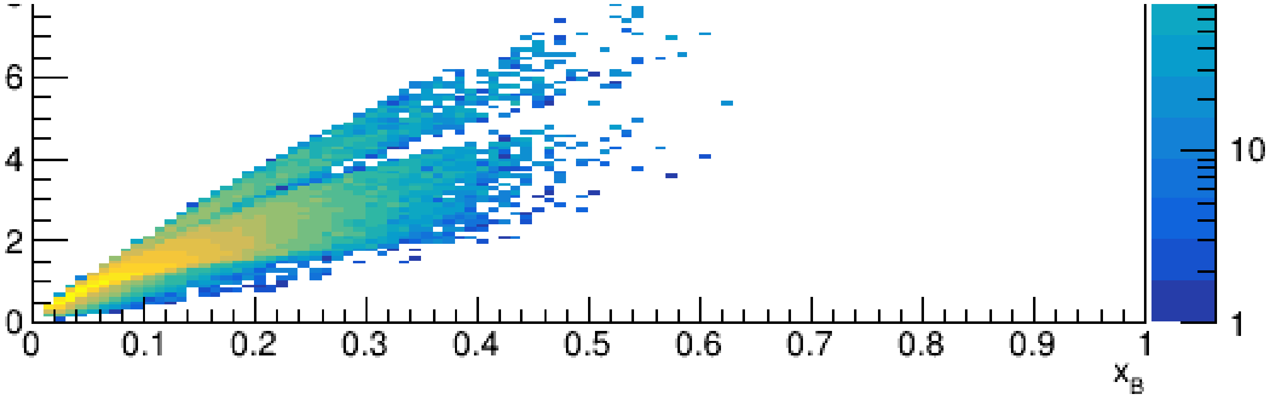
Zhiwen Zhao (GRAPE)

11 GeV vs 22 GeV



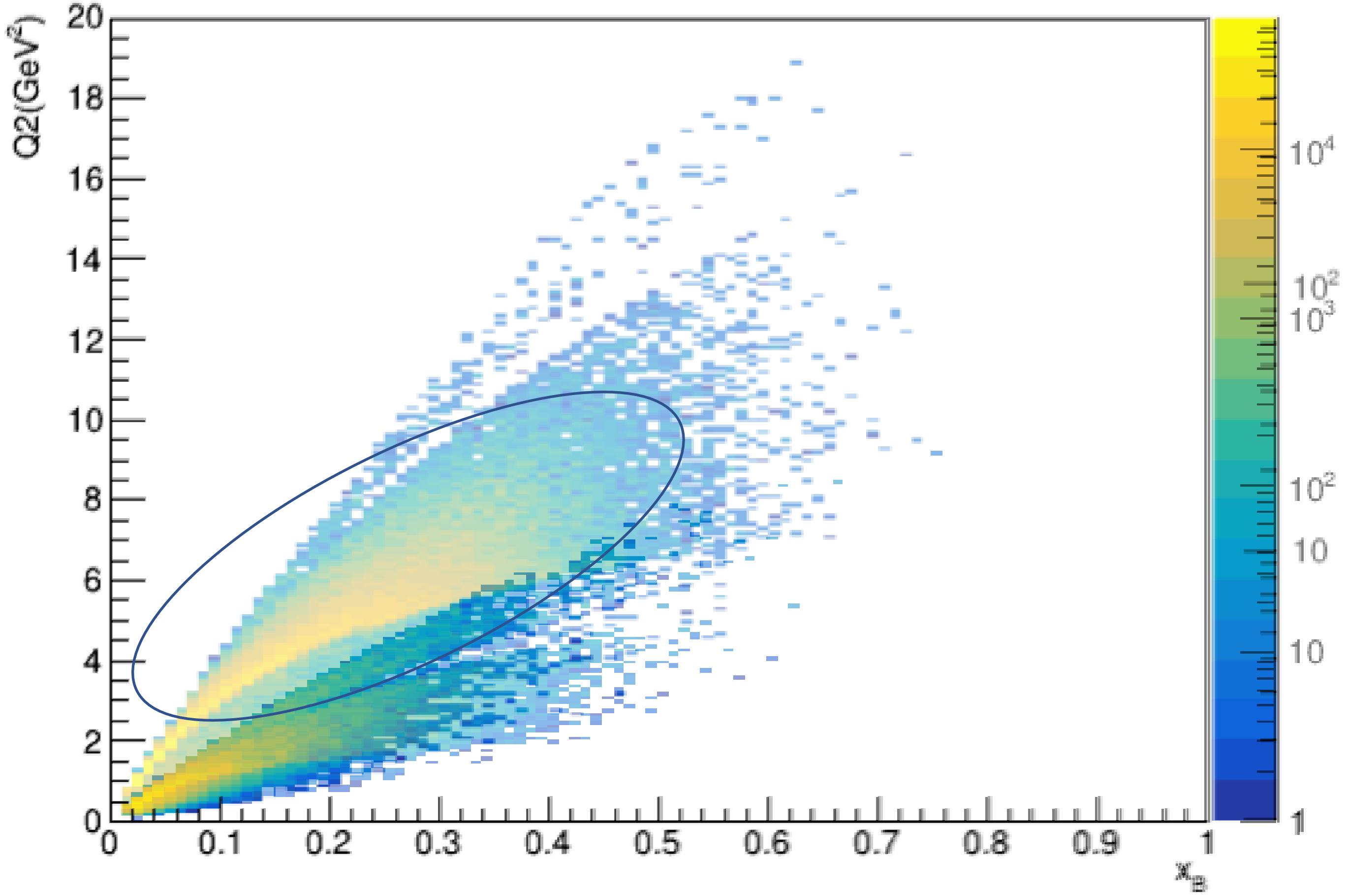
Zhiwen Zhao (GRAPE)





Zhiwen Zhao (GRAPE)

11 GeV vs 22 GeV



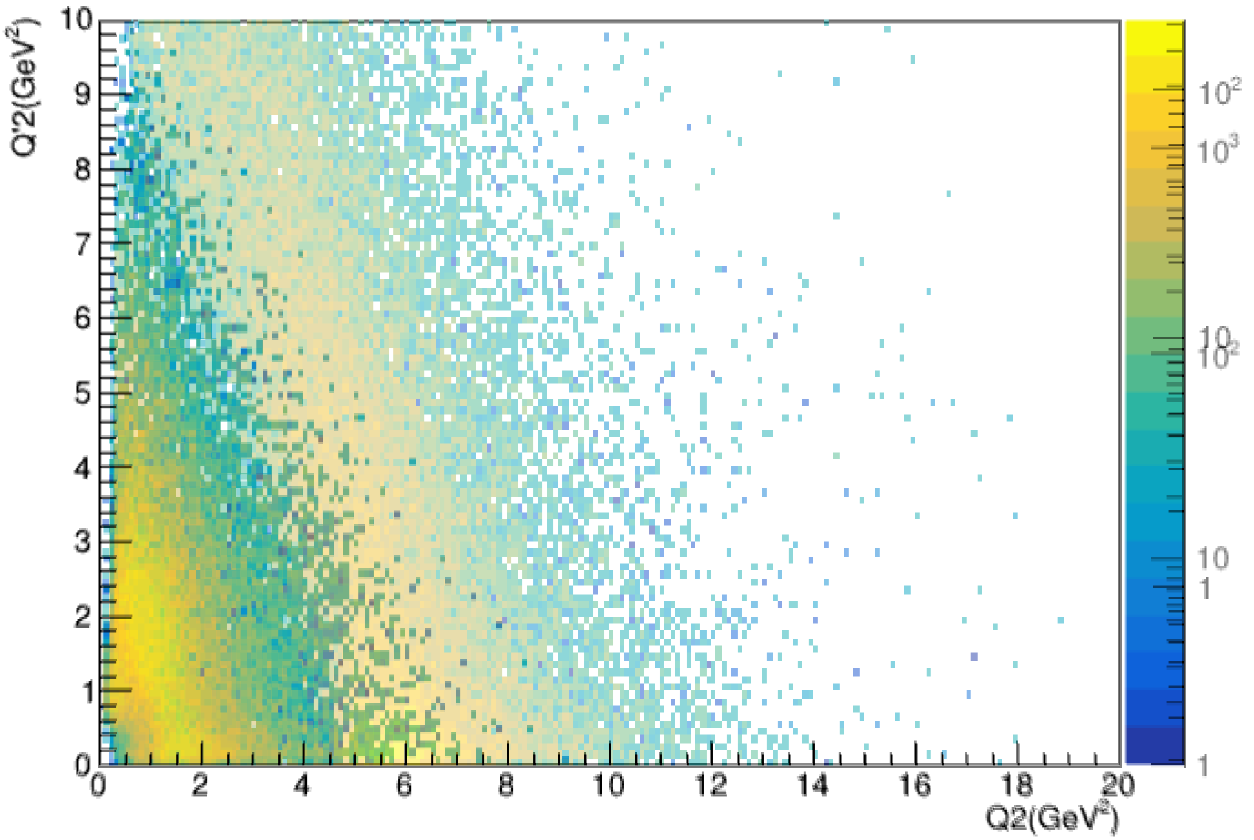
Large Q2 range

Check factorization

evolution

Zhiwen Zhao (GRAPE)

11 GeV vs 22 GeV

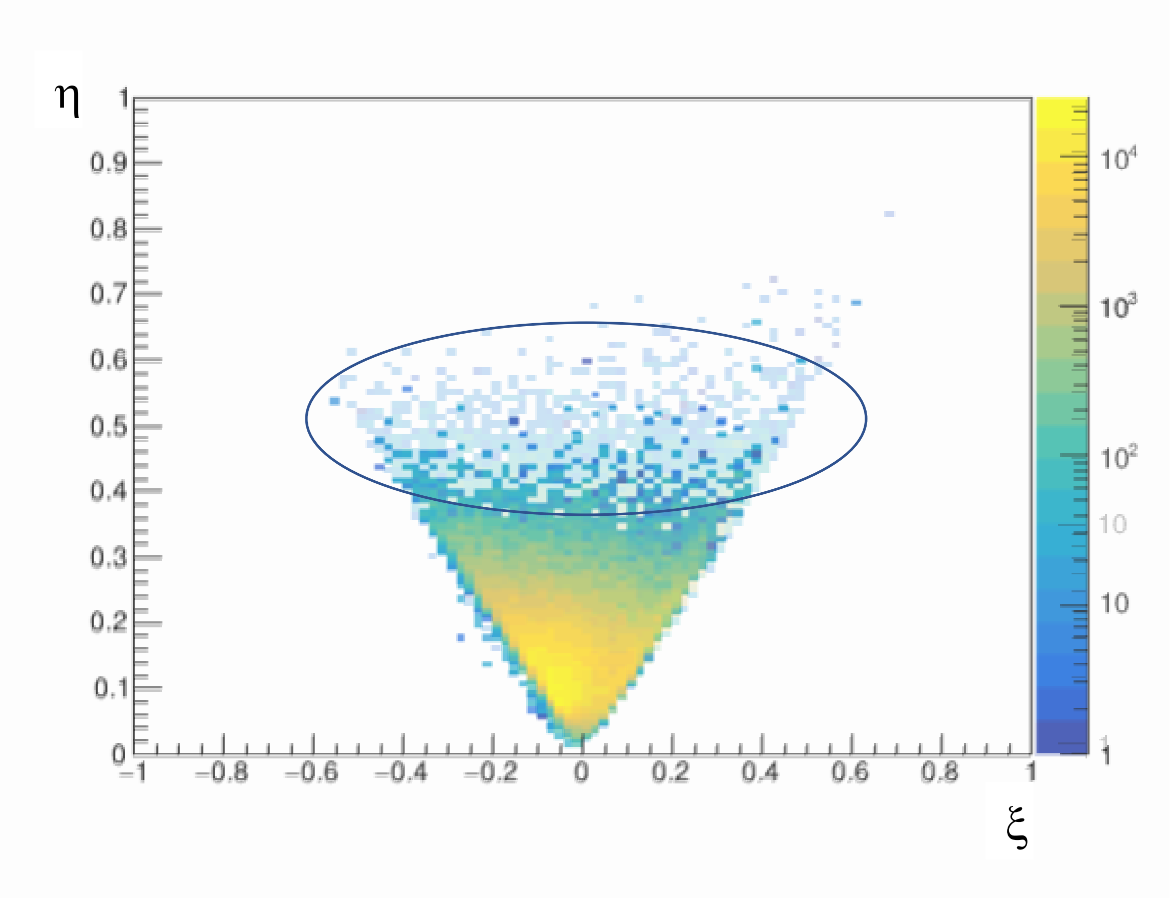


Much better Q2 Q'2 coverage

Want Q2 and Q'2 large enough for factorization

Zhiwen Zhao (GRAPE)

11 GeV vs 22 GeV



Increased acceptance in ξ and η

Zhiwen Zhao (GRAPE)

Quick numbers for J/Psi settings

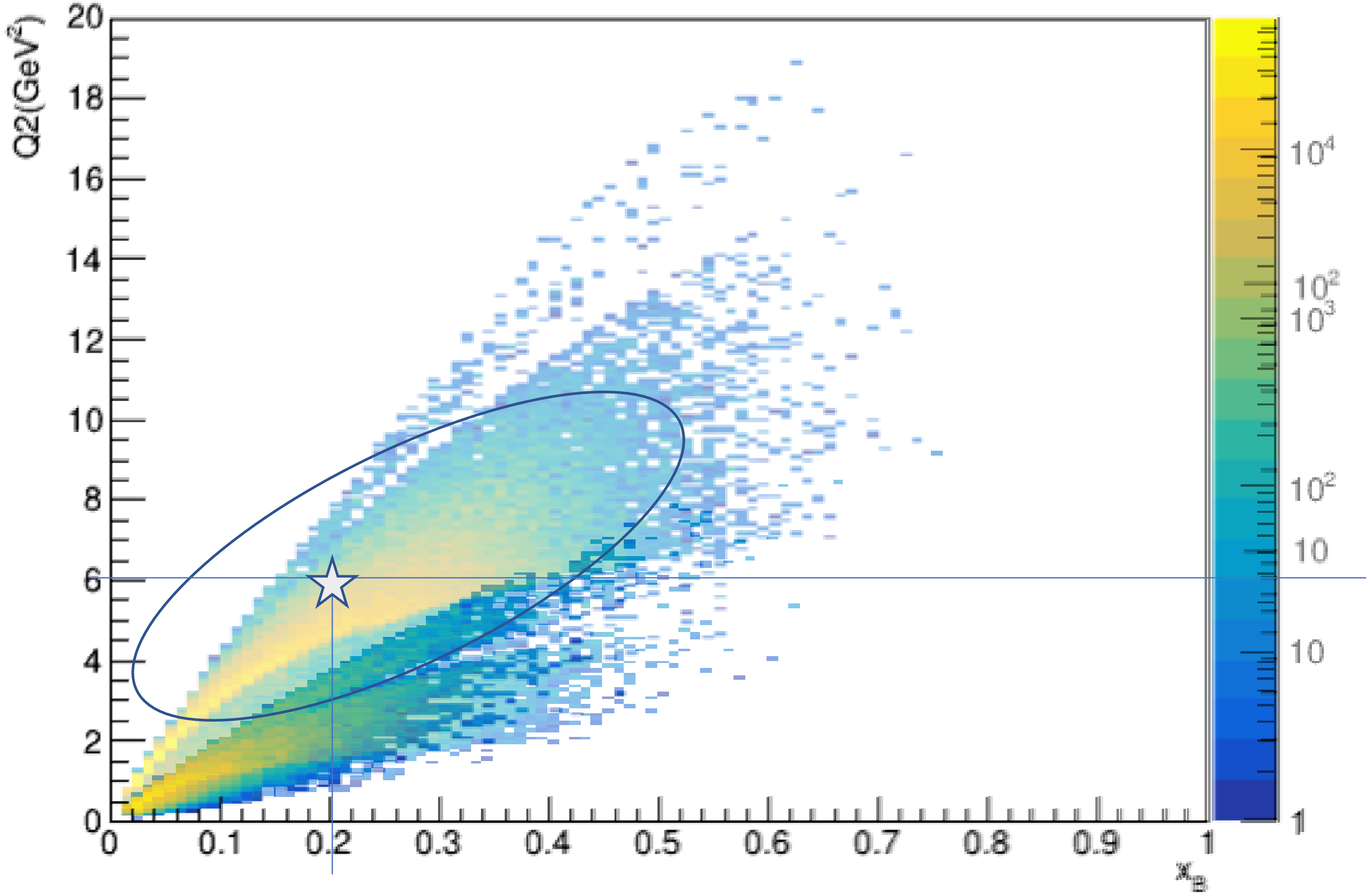
50 days at 10^37

Beam energy	e-mu-mu+
11	180156
22	51600

Cross section about 3 times lower : could run at 10 uA or with 45 cm target

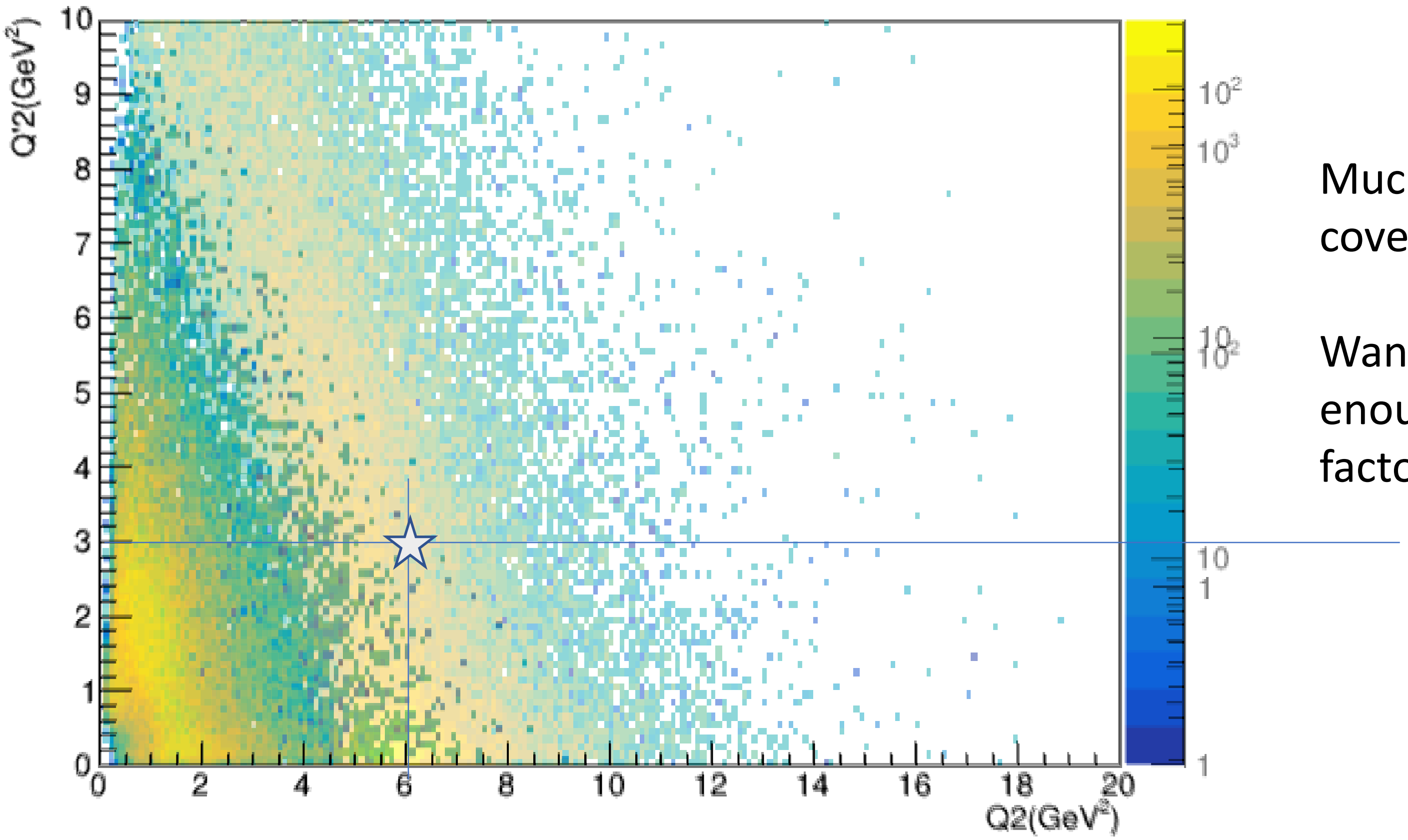
Acceptance better when detecting proton but dominated by low Q2/Q'2

11 GeV vs 22 GeV



Zhiwen Zhao (GRAPE)

11 GeV vs 22 GeV



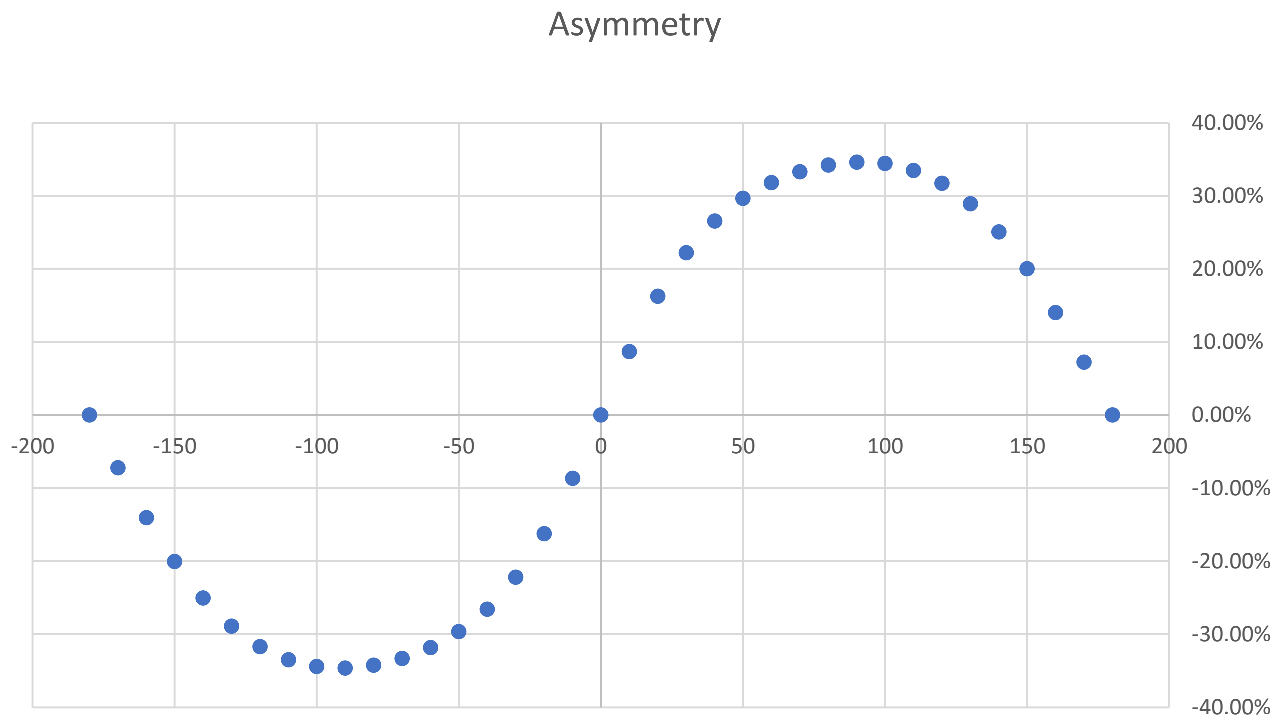
Much better Q2 Q'2 coverage

Want Q2 and Q'2 large enough for factorization

Zhiwen Zhao (GRAPE)

Asymmetry for one point

- xbj=0.20, Q2=6 GeV2,Q’2=3GeV^2, -t=0.25 GeV^2 from VGG



SoLID

- **Deep Exclusive Meson Production (E12-10-006B) (DEMP) Measurement of Deep Exclusive Pi- Production using a Transversely Polarized He3 Target and the SoLID Spectrometer**

SoLID

- **Timelike Compton Scattering (E12-12-006A) (TCS)**
  TCS with circular polarized beam and unpolarized LH2 target, Submission at SoLID TAC and PAC 43, 2015, approved as run group with J/Psi(E12-12-006).

Hall C TCS (Boer et al)

Motivations

Why measuring TCS off a transversely polarized proton?

- **Unique access to GPD E of the proton**

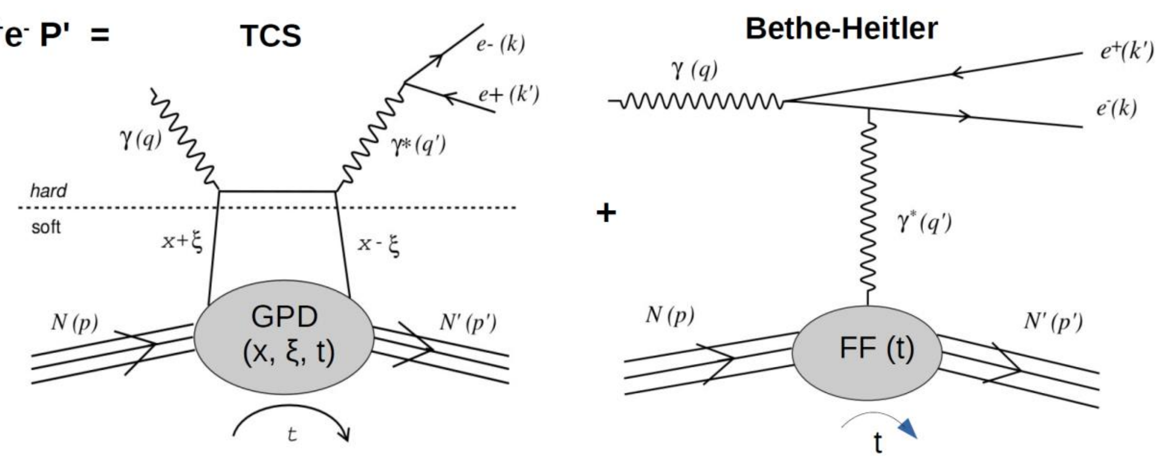
Besides CFFs Im(H), Re(H)

=> Im(E) (TSA) with TSA

=> Re(E), Re(H~) with BTSA

- **GPD universality studies (TCS vs DVCS)** [with complementary data, reduce correlation errors]
- **Complementary, simultaneous fits with DVCS, multichannel database and standalone**

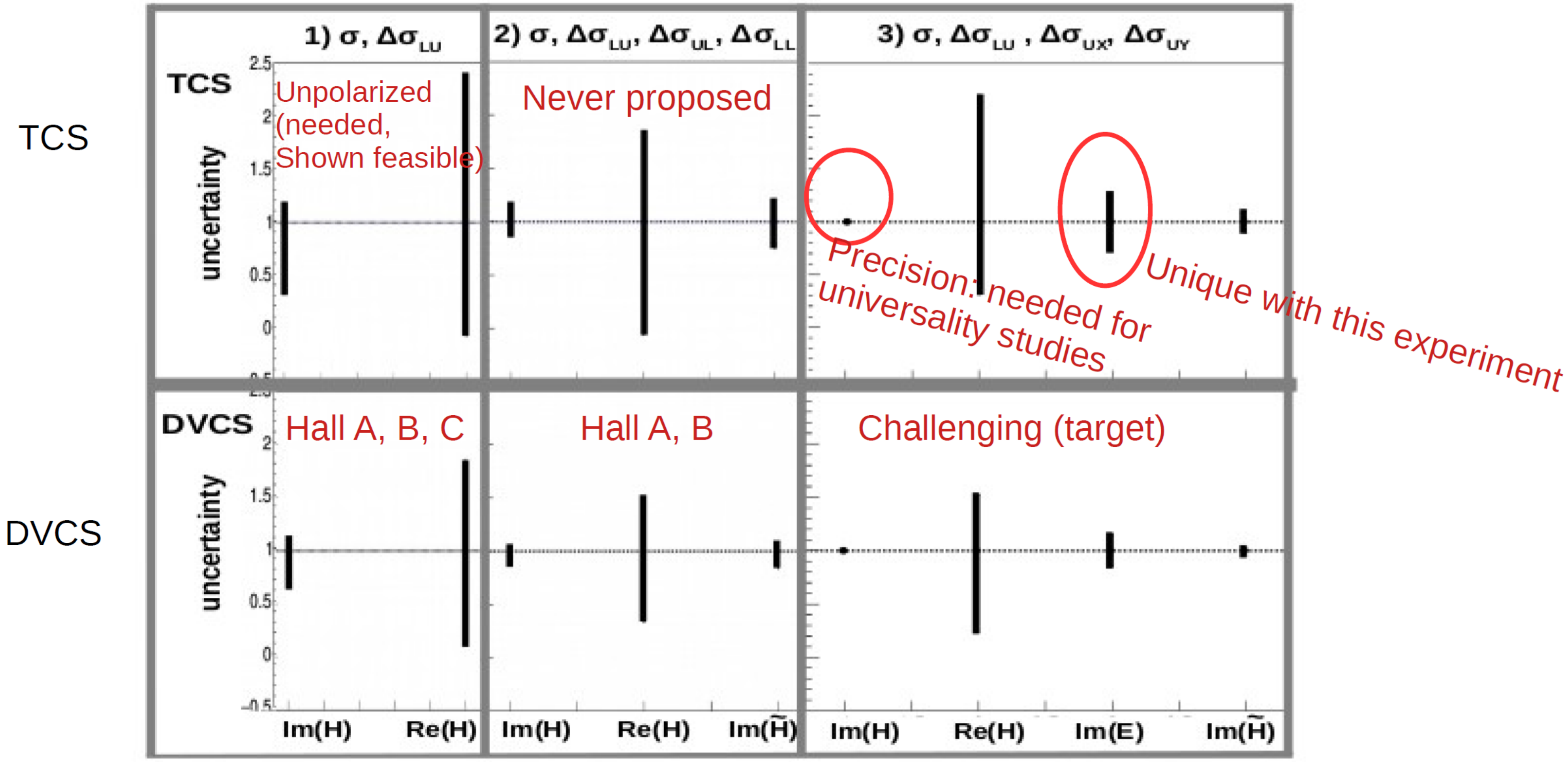
$\gamma P \rightarrow e^+e^- P' =$



3

Extracting CFFs with TCS versus DVCS

Which CFF can be extracted, approximate precision



- "sketch" assuming same uncertainties. TCS is more difficult experimentaly, lower cross section
- up to ~40% uncertainties can still extract something. 10% on asymmetry is ideal

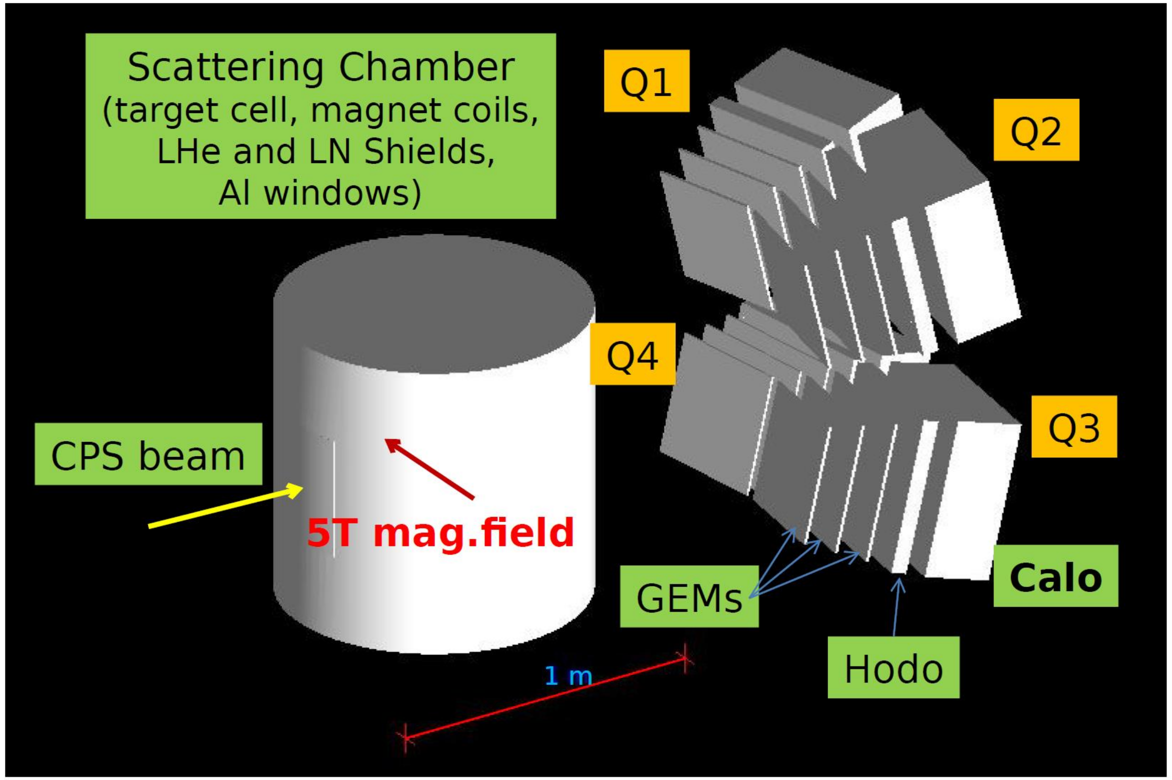
Extra-observables (not proposed)

Observable (proton target)	Experimental challenge	Main interest for GPDs	JLab experiments
Unpolarized cross section	1 or 2 order of magnitude lower than DVCS, require high luminosity	Im + Re part of amplitude. Re(H), Im(H)	CLAS 12, SoLID approved NPS conditionnal
Circularly polarized beam	Easiest observable to measure at JLab	Im(H), Im(H) Sensitivity to quark angular momenta, in particular for neutron	CLAS 12, SoLID approved NPS conditionnal
Linearly polarized beam	Need high luminosity, at least 10x more than for circular beam, and electron tagging	Re(H), D-term. Good to discriminate models and very important to bring constrains to real part of CFF	GlueX (?)
Longitudinaly polarized target	Polarized target	Im(H)	no / "for free"?
Transversely polarized target	Polarized target, and high luminosity: binning in θs, φs	Im(H), Im(E)	NPS conditionnal
Double spin asymmetry with circularly polarized beam	Polarized target, very high luminosity, precision measurement	Real part of all CFF	no / "for free"?
Double spin asymmetry with longitudinally polarized beam	Polarized target, electron tagging, very high luminosity and precision	Not the most interesting, Im(CFFs) but difficult to measure	no

Hall C TCS

Experimental setup

$\gamma + p \rightarrow \gamma^* (e^+ + e^-) + p'$



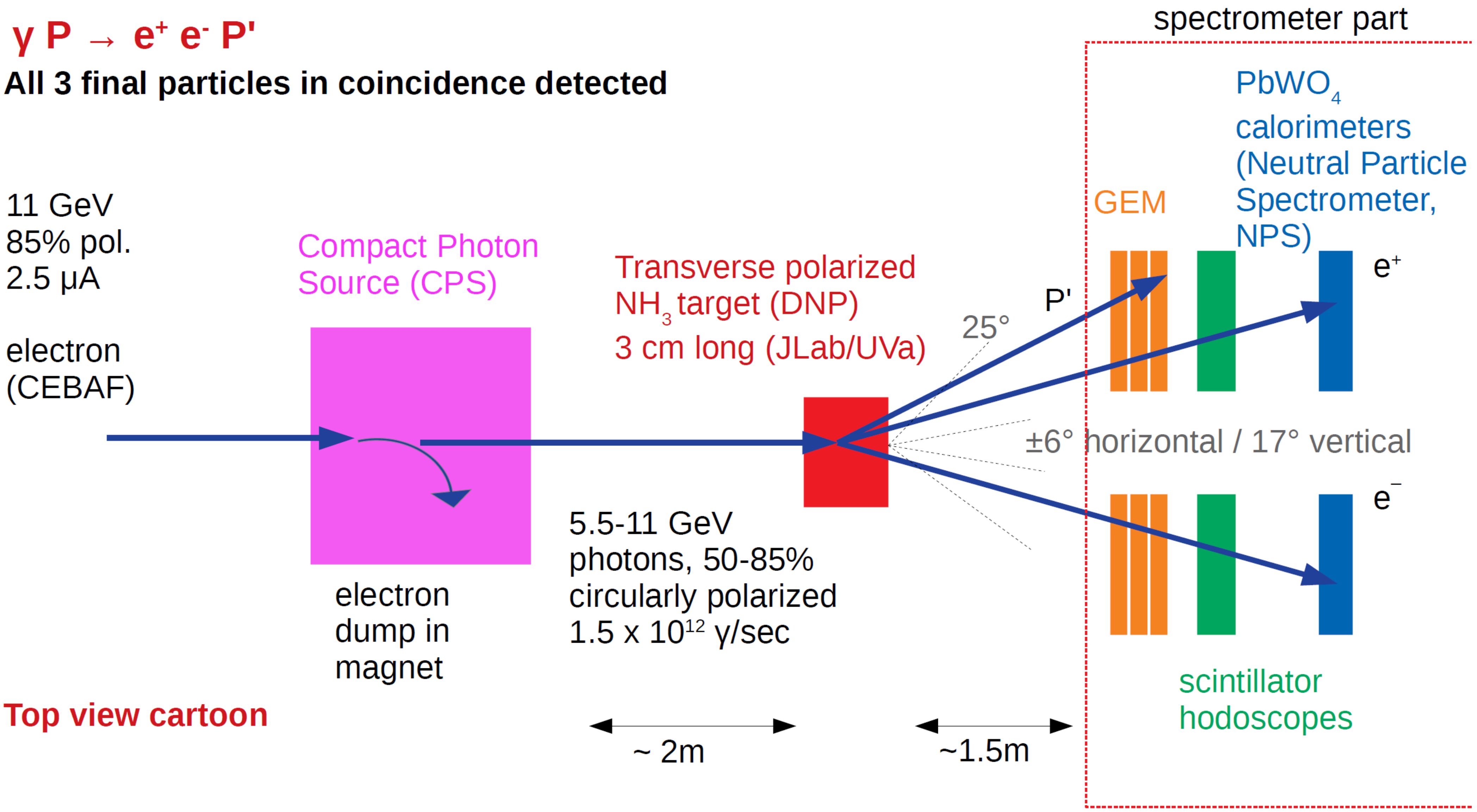
- Detect e^+, e^-, recoil p' in coincidence
- CPS bremsstrahlung photon beam
- UVA/Jlab NH_3 target,

  transversely polarized
- Detectors arranged in 4 quarters, oriented to target
- Triple-GEMs for e^+, e^-, p tracking
- Hodoscopes for recoil proton detection/PID
- $PbWO_4$ calorimeters for e^+, e^-, p detection/PID

Experimental setup

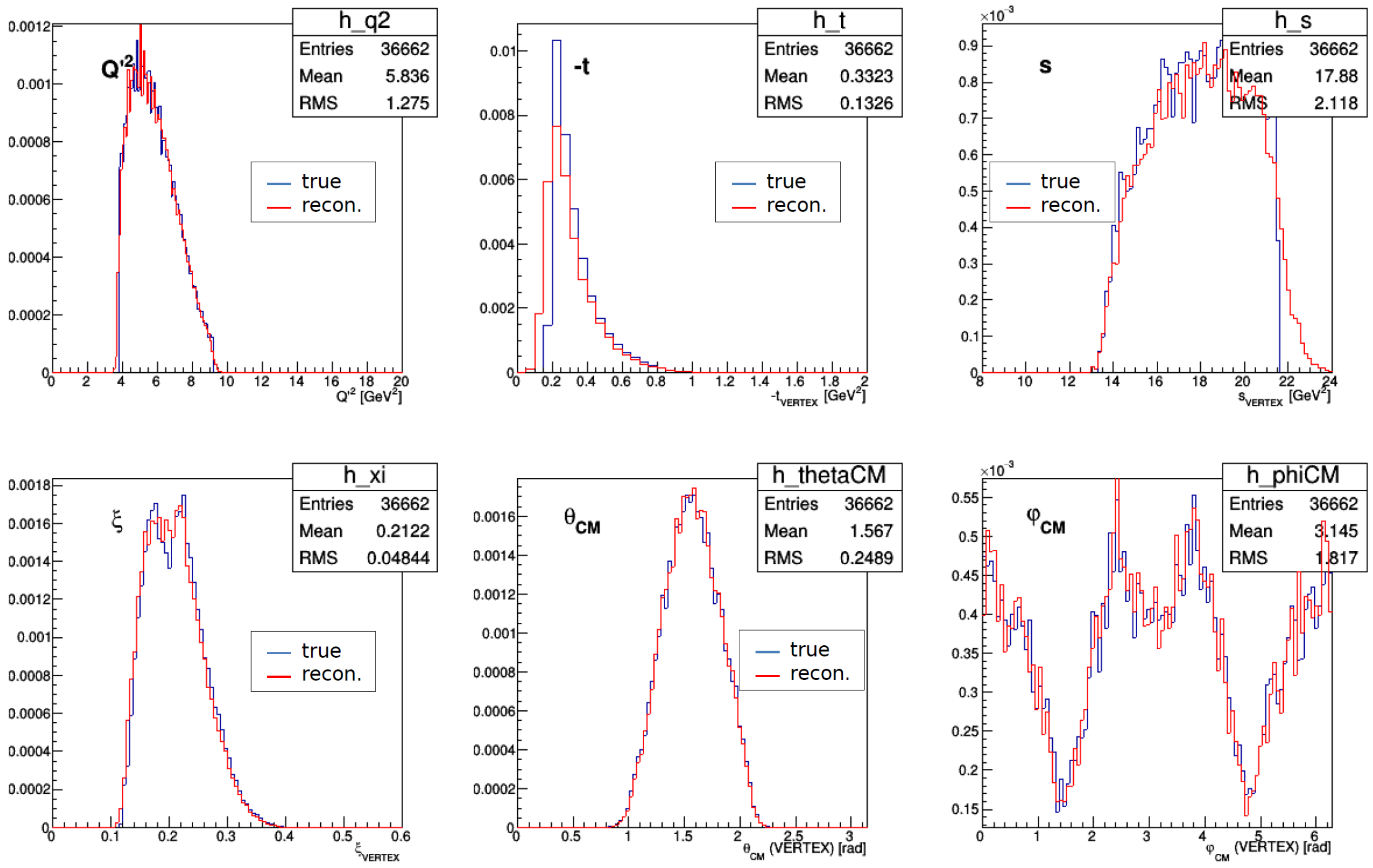
$\gamma P \rightarrow e^+ e^- P'$

All 3 final particles in coincidence detected



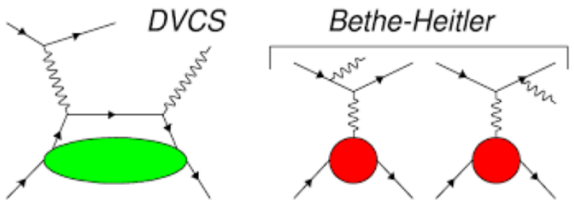
Trigger: GEMs, hodoscopes, calorimeters (all 3 particles)

Resolution for kinematics: reconstructed vs generated



Hall C recoil polarization experiments (Defurne)

- [Recoil proton polarization in DVCS - Assemblee General GDR QCD (in2p3.fr)]
  - Code by Pierre Guichon at leading order, leading twist, using the exact mathematical expressions.
  - The polarization $\vec{P} = (P_x, P_y, P_z)$ is computed for the DVCS+Bethe-Heitler process, including their interference.
  - P_y (normal to the hadronic plane) is particularly sensitive to CFF $\mathcal{E}$.



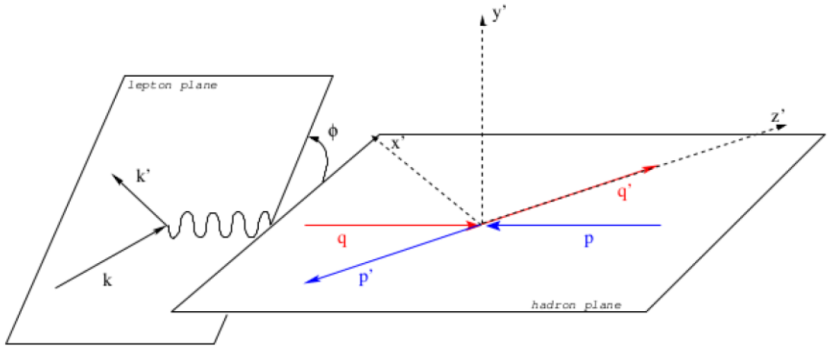
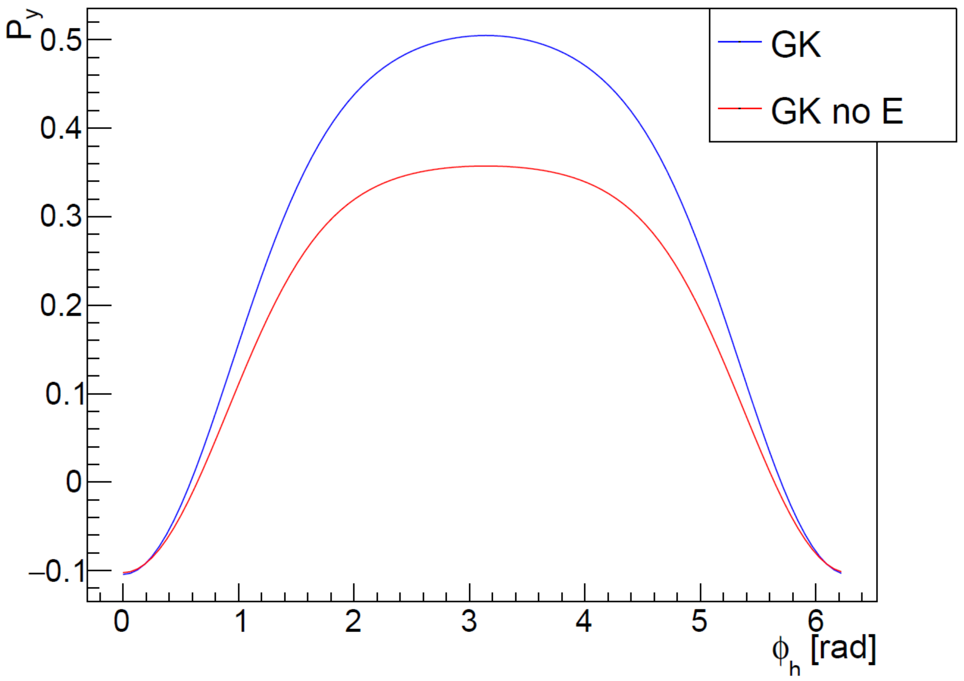


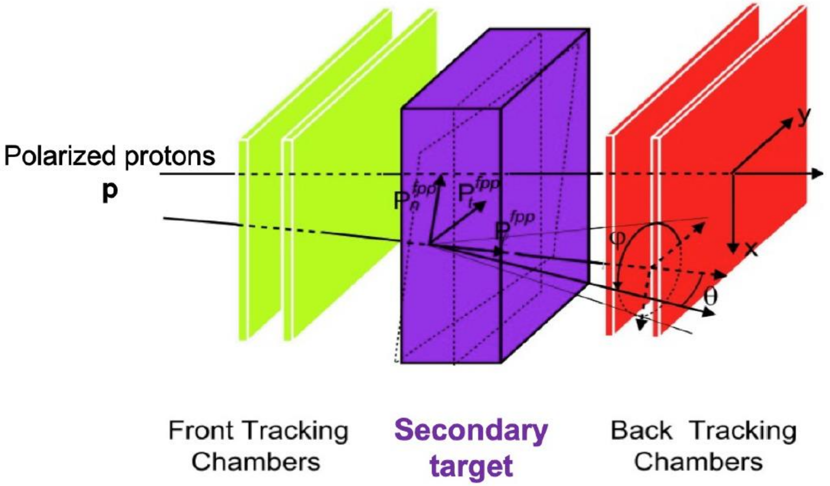
Figure 1: Rotated CM frame (x'y'z')

Polarization ϕ_h-dependence



- P_y is sensitive to $\mathcal{E}$ for the Goloshokov-Kroll (GK) model.
- P_x and P_z are not sensitive to $\mathcal{E}$.
- For $\phi_h = \pi$ there is a large difference in P_y when switching off $\mathcal{E}$.

Proton polarimeter



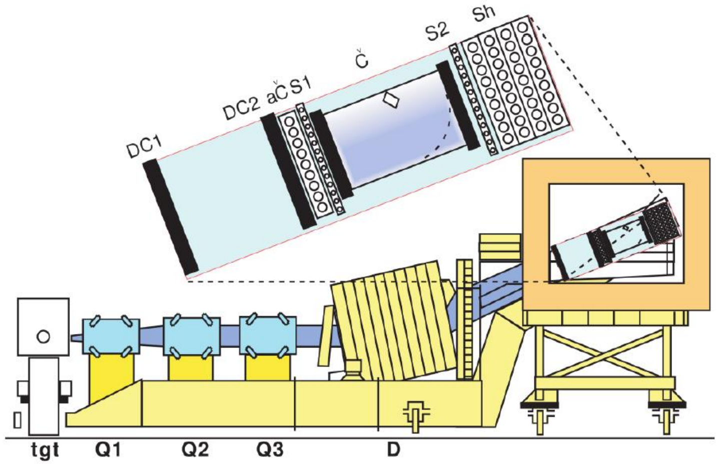
- Rescatter the proton with θ_{pol}, ϕ_{pol} inside a carbon analyzer.
- A set of trackers before and after the analyzer detect the incoming and outgoing protons.

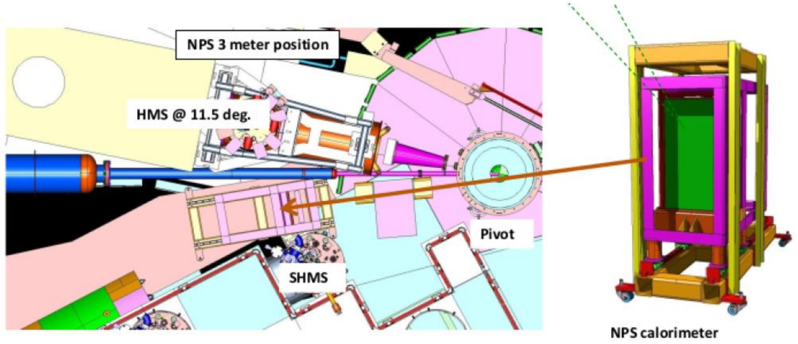
A polarization perpendicular to the proton momentum will result in an asymmetry in ϕ_{pol}:

$$N(\theta_{pol}, \phi_{pol}) = N_0[1 + A_p(\theta_{pol})(P_y \sin\phi_{pol} - P_x \cos\phi_{pol})]$$

- The P_x dependence cancels out at $\phi_h = \pi$ for an unpolarized beam.
- P_y can be extracted by fitting the distribution.

Electron and photon detection





Electron detection: HMS

- Focusing spectrometer.
- Scattering angle range 10.5-80°.
- Angular acceptance: $\pm$ 1.8° in-plane, $\pm$4.9° out-of-plane.
- Momentum acceptance $\pm$10%.

Photon detection: calorimeter

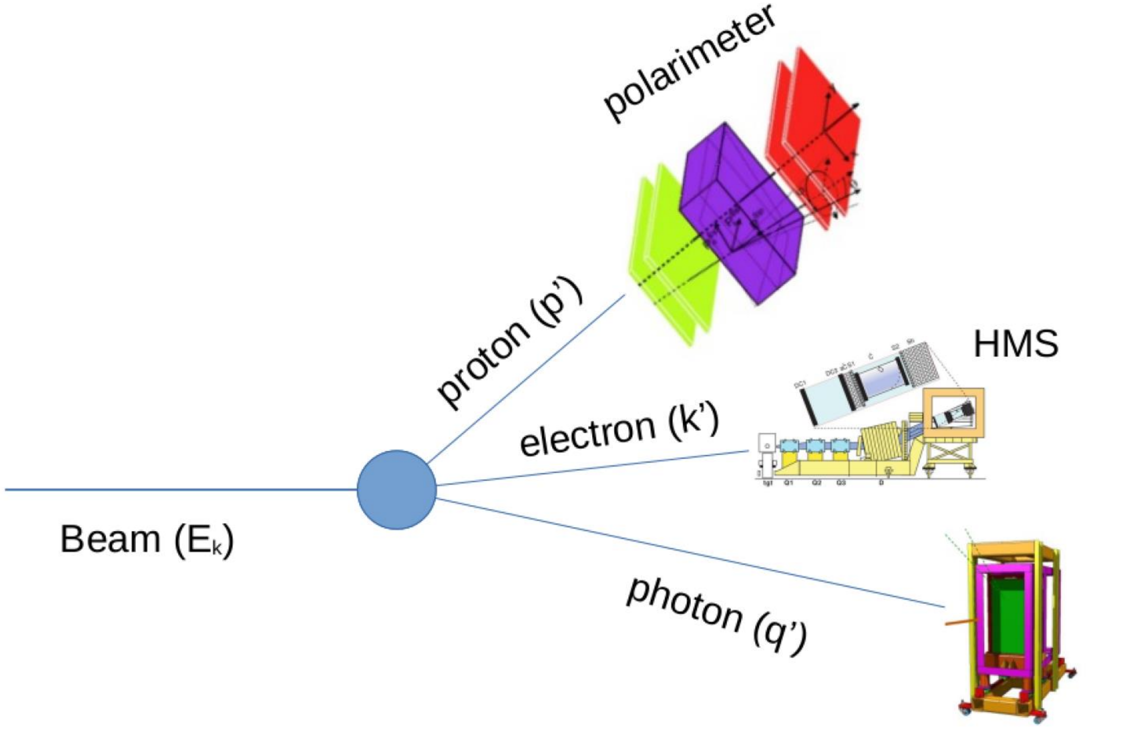
- Angular acceptance: $\pm$5.3° horizontally, $\pm$6.7° vertically.
- 30x36 $PbWO_4$ crystals. Position resolution: 2-3 mm.
- Sweeping magnet reduces low energy electron background.

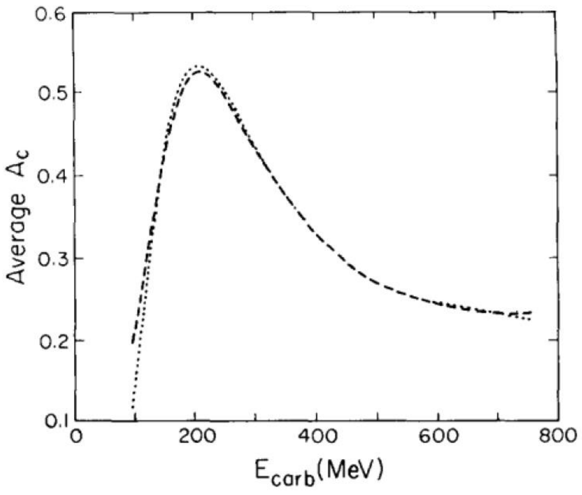
Optimization result

Maximizing $\mathcal{F}'$ gives:

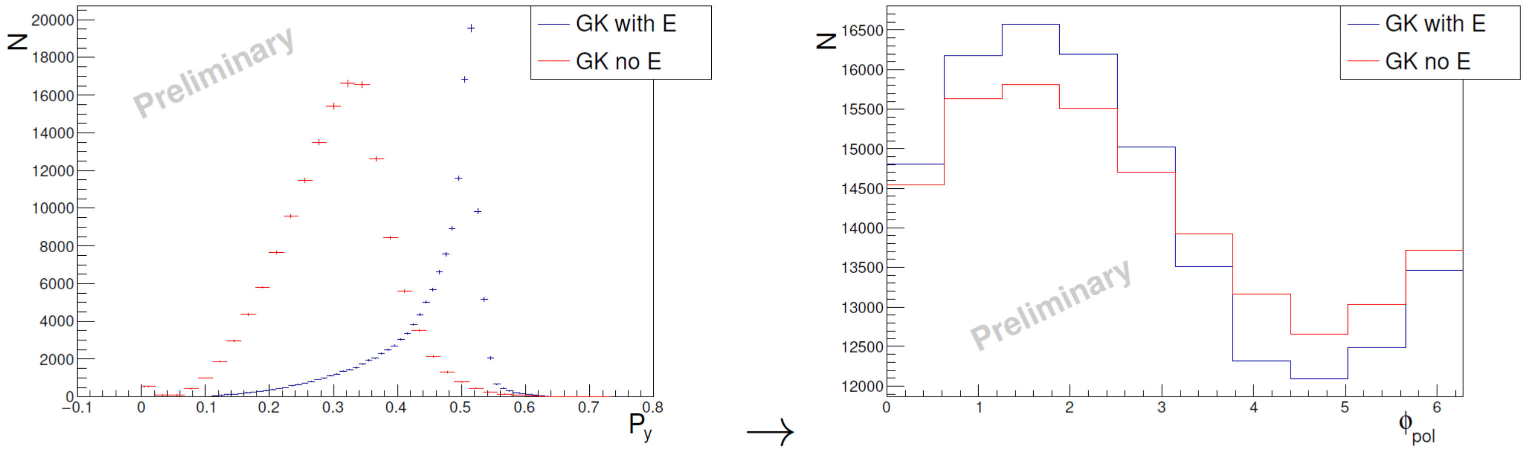
$$E_k = 10.6\,\mathrm{GeV},\ Q^2 = 1.8\,\mathrm{GeV}^2,\ x_B = 0.17,\ t = -0.45\,\mathrm{GeV}^2,\ \phi_h = \pi$$

electron $\lvert k'\rvert$	$\theta_{k'}$	photon $\lvert q'\rvert$	$\theta_{q'}$	proton $\lvert p'\rvert$	E_{carb}	$\theta_{p'}$
$4.96\,\mathrm{GeV}/c$	$10.6°$	$5.40\,\mathrm{GeV}/c$	$-15.1°$	$0.71\,\mathrm{GeV}/c$	$0.19\,\mathrm{GeV}/c$	$44°$





Fitting the polarization



Toy simulation of the polarimeter

- We assume a 1 str polarimeter to detect the recoil proton.
- This gives 3.6M events. Assign θ_{pol}, ϕ_{pol}.
- Knowing A_p, P_y can then be extracted (back) from ϕ_{pol}.

Fit results

$P_y(GK) = 0.475 \pm 0.011$ (cf weighted average: 0.463)
$P_y(\mathcal{E} = 0) = 0.316 \pm 0.011$ (cf weighted average: 0.304).

Conclusion

- Hall A and C high luminosity halls luminosity ranging from 10^{36} up to 5.10^{38} $cm^{-2}.s^{-1}$
- NPS first run completed this year – Hall A/C covers a large chunk of the DVCS x and Q^2 phase space, future run planned in electrons and positrons
- Hall A nDVCS with TDIS setup being investigated
- Hall A SoLID striving to keep running at highest luminosity at 11 and 22 GeV
  - Approved experiments SIDIS and J/Psi
  - Future possible experiment DDVCS
- Future experiments in development in Hall A/C to contribute ie TCS and DVCS with recoil polarization