A Compact Solenoidal Detector for DDVCS Measurement in Hall C

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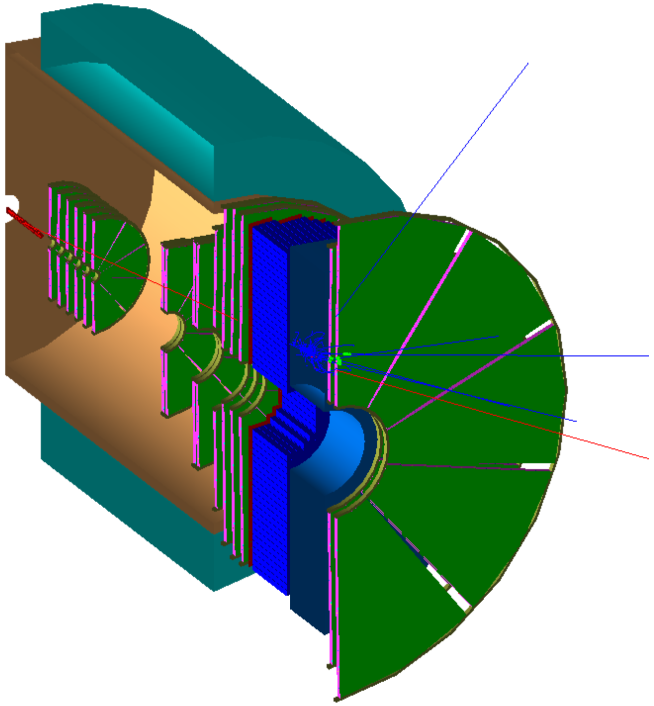
Outline

- Nucleon 3D structure
- DDVCS process
- Compact Solenoidal Device
- Capability and Feasibility
- Summary



Nucleon 3D structure

- Distribution in phase-space $(\boldsymbol{r}, \boldsymbol{p})$: full picture for a classical system
- Wigner quasi-probability distribution – quantum phase-space distribution – analogues to classical phase-space distribution

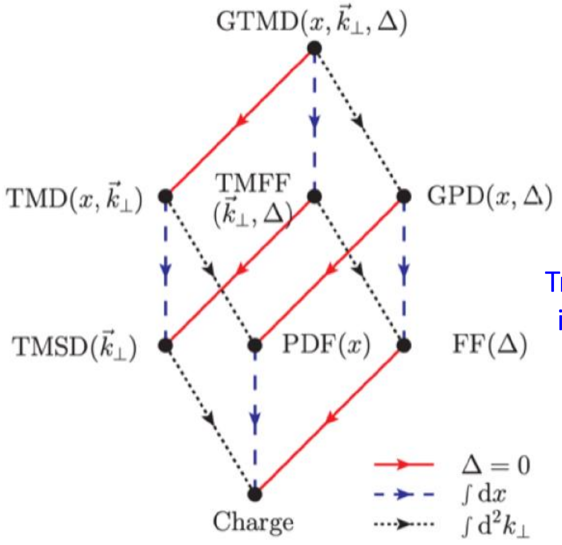
$$W(x,p) \stackrel{\text{def}}{=} \frac{1}{\pi\hbar}\int_{-\infty}^{\infty} \psi^*(x+y)\psi(x-y)e^{2ipy/\hbar}\,dy$$

- $\mathrm{GTMD}(x, \boldsymbol{k}_\perp, \boldsymbol{\Delta}) \xleftrightarrow{\text{FT}} \mathrm{Wigner}(x, \boldsymbol{k}_\perp, \boldsymbol{b}_\perp)$; they are mutual Fourier Transformation
- Generalized Transverse Momentum Dependent Parton Distributions (GTMD) is a more complete picture – **5D** function

Fourier Transform:

$\vec{k}_\perp \leftrightarrow \vec{z}_\perp$

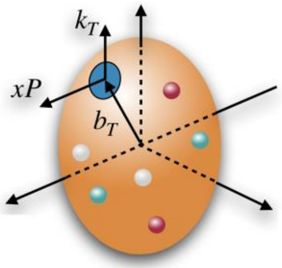
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$



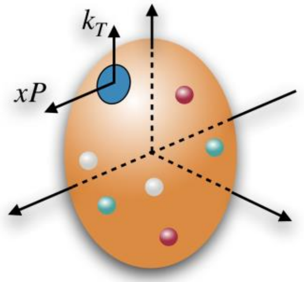
Transverse Density in momentum space

Transverse Density in position space

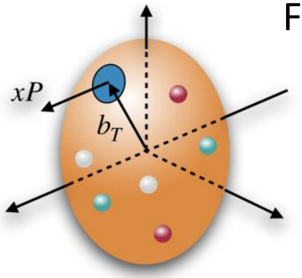
Wigner Distribution (5D)



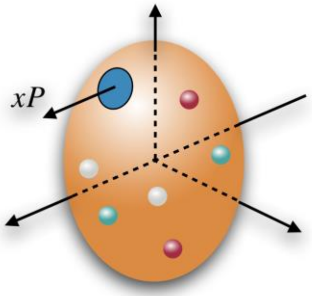
TMD (3D)



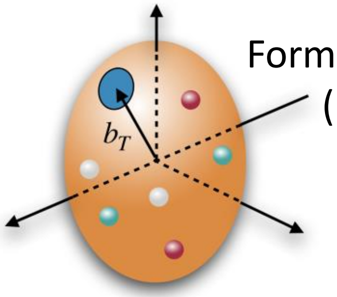
FT of GPDs (3D)



PDF (1D)

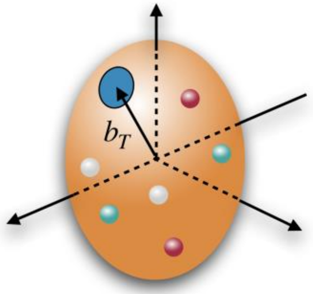


Form Factors (2D)

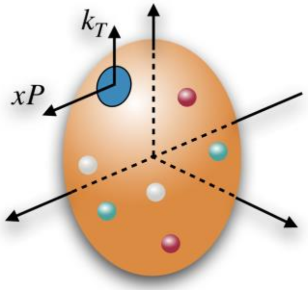


Nucleon 3D Structure

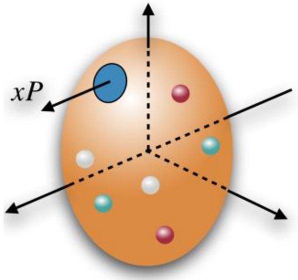
- Electron scattering: a successful probe to study the nucleon structure



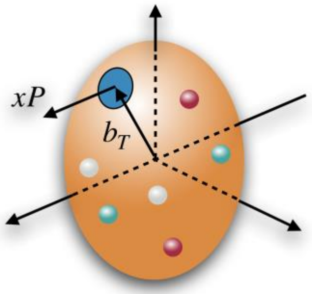
Form Factors (2D)



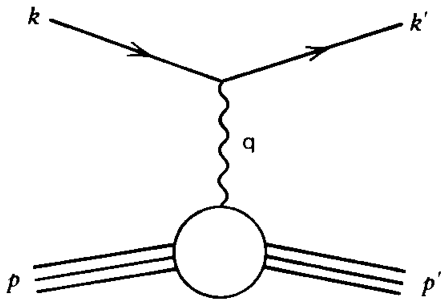
TMD (3D)



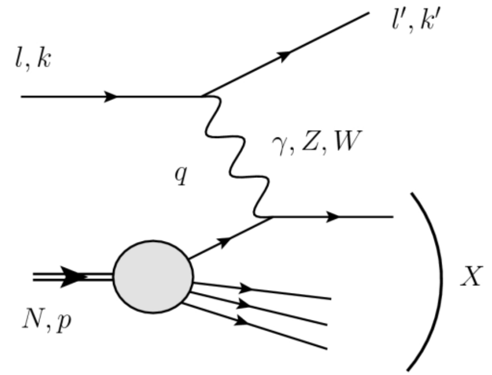
PDF (1D)



FT of GPDs (3D)



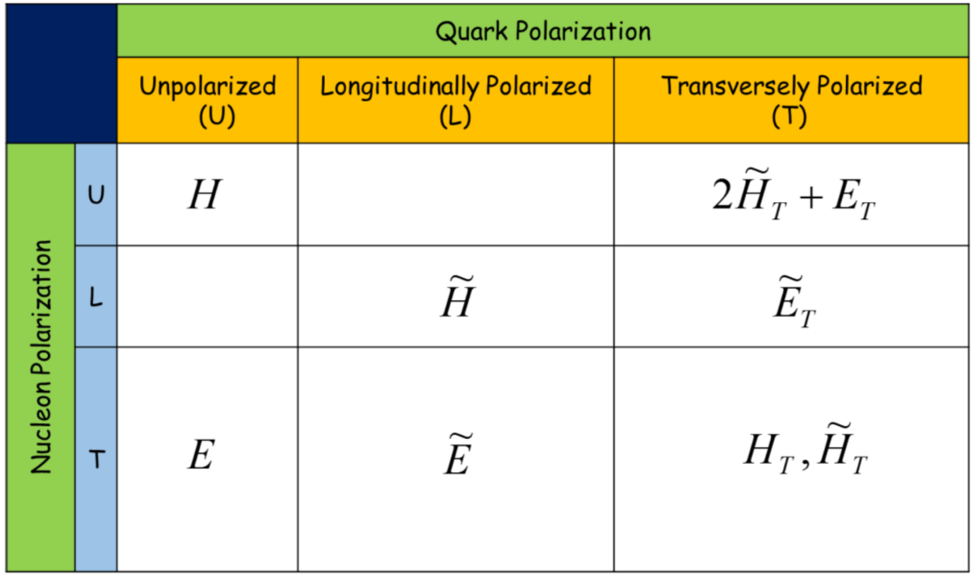
Elastic Scattering



Deep Inelastic Scattering

Generalized Parton Distributions

- 8 GPDs at leading twist
  - ❑ Chiral Even : $H^{q/g}, E^{q/g}, \widetilde{H}^{q/g}, \widetilde{E}^{q/g}$, parton helicity conserved
  - ❑ Chiral Odd (transversity): $H_T^{q/g}, E_T^{q/g}, \widetilde{H}_T^{q/g}, \widetilde{E}_T^{q/g}$, parton helicity flipped
- Correlation between 1D longitudinal momentum and 2D transverse position (Fourier Transform)



		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$2\widetilde{H}_T + E_T$
	L		$\widetilde{H}$	$\widetilde{E}_T$
	T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

- Connects to Form Factors and PDFs

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

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

Dirac and Pauli Form Factor

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

$$\int_{-1}^{1} dx \widetilde{E}^q(x,\xi,t) = G_P^q(t)$$

Axial and Pseudoscalar Form Factor

$$H^q(x,0,0) = q(x), x > 0$$

$$\widetilde{H}^q(x,0,0) = \Delta q(x), x > 0$$

PDFs

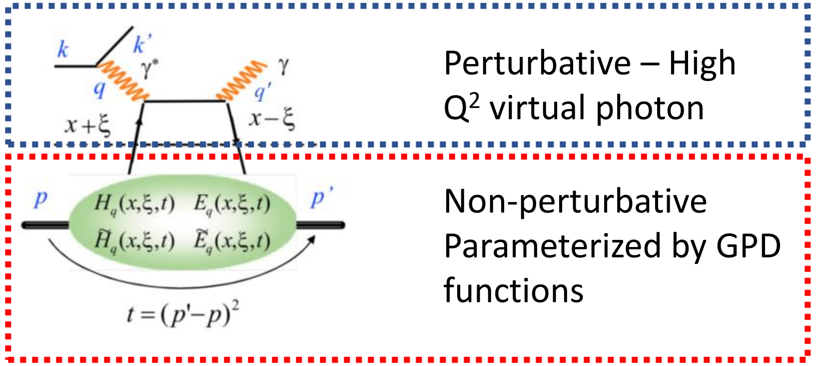
- Ji's Sum Rule (connects orbital angular momentum with GPD)

$$J_{q/g} = \lim_{t,\xi\to 0} \frac{1}{2} \int x dx [H^{q/g}(x,\xi,t) + E^{q/g}(x,\xi,t)]$$

Generalized Parton Distributions

- GPDs can be accessed through **deep exclusive scattering** processes (DVCS, DVMP, TCS, DDVCS)
- Deeply Virtual Compton Scattering (DVCS) is the Golden channel for accessing GPDs

QCD Factorization



Perturbative – High Q^2 virtual photon

Non-perturbative Parameterized by GPD functions

- DVCS cross section is parametrized in terms of Compton Form Factors (CFFs)
- DVCS CFFs are convolution of the GPDs

- DVCS amplitude (ellipsis: similar terms in $H, \tilde{H}$, $E, \tilde{E}$):

$$\tau_{DVCS} \propto \int_{-1}^{1} dx \frac{H(x,\xi,t)}{x \pm \xi \mp i\epsilon} + \cdots$$

- Compton Form Factor:

$$\mathcal{H}(\xi,t) = \int_{-1}^{1} dx \frac{H(x,\xi,t)}{x \pm \xi \mp i\epsilon}$$

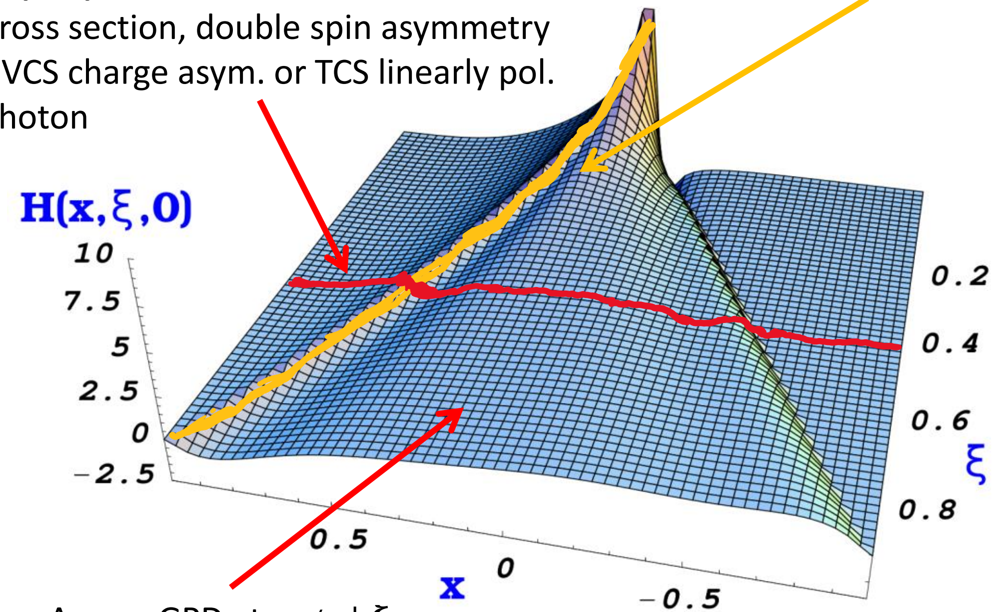
$$= \underbrace{P\int_{-1}^{1} dx \frac{H(x,\xi,t)}{x \pm \xi}}_{\Re(\mathcal{H})} - \underbrace{i\pi H(\pm\xi,\xi,t)}_{\Im(\mathcal{H})}$$

- GPDs in the DVCS amplitude
  - ☐ Real part: an integral over x
  - ☐ Imaginary part: at the line $x = \pm\xi$

Compton Form Factor

- DVCS Experimental Observables – Beam Spin Asymmetries

Polarization	Asymmetries	CFFs
Longitudinal beam	A_{LU}	$Im\{\mathcal{H}_p, \widetilde{H}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n, \widetilde{H}_p, \mathcal{E}_n\}$
Longitudinal Target	A_{UL}	$Im\{\mathcal{H}_p, \widetilde{H}_p\}$ $Im\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$
Long. Beam + Long. Target	A_{LL}	$Re\{\mathcal{H}_p, \widetilde{H}_p\}$ $Re\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$
Transverse Target	A_{UT}	$Im\{\mathcal{H}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n, \mathcal{E}_n\}$
Long. Beam + Tran. Target	A_{LT}	$Re\{\mathcal{H}_p, \widetilde{H}_p\}$ $Re\{\mathcal{H}_n, \mathcal{E}_n\}$



Probing GPD at $x = \pm\xi$ dependence:
Im(CFF) DVCS, TCS single spin asymmetry, cross section

Access GPD through integral over x:
Re(CFF) from DVCS and TCS:
Cross section, double spin asymmetry
DVCS charge asym. or TCS linearly pol. photon

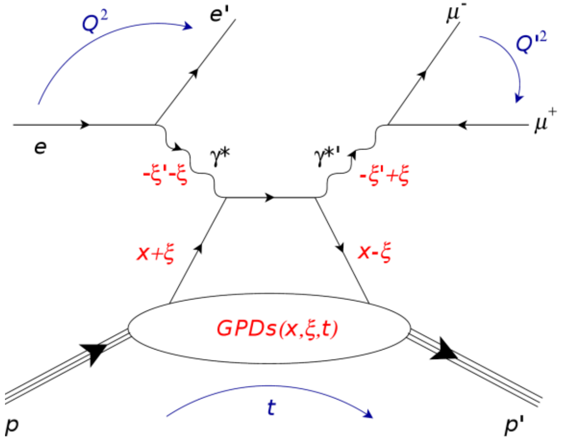
Access GPD at $\boldsymbol{x \neq \pm\xi}$:
DDVCS

- Probing GPD x vs ξ dependence with experimental observables
- Each experimental observable (cross section, BSA, BCA, ITSA,…) is dominated by a specific (or combination) CFF
- Access All CFFs through multiple observables

DDVCS

- DVCS probes GPDs with limited kinematics region: $x = \pm\xi$ and integral over x
- Double Deeply Virtual Compton Scattering (DDVCS) - final photon remains virtual
- DDVCS provides an extra kinematic variable ξ' – probe off-diagonal GPDs
    - ☐ Nucleon tomography
    - ☐ Angular momentum sum rule
    - ☐ Distribution of nuclear forces
- Extremely low cross section

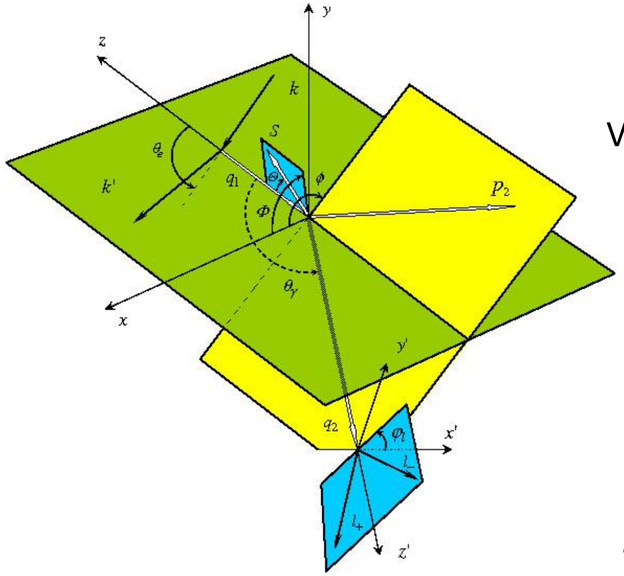
$$ep \rightarrow e'p'l^{-}l^{+}$$



DDVCS (di-muon channel)

- DDVCS Kinematics

S. Zhao: arXiv:2103.12773



Virtuality of space-like initial photon

$$Q^2 = -q_1^2$$

Virtuality of time-like final photon

$$Q'^{\,2} = q_2^2$$

$$q = \frac{1}{2}(q_1 + q_2)$$

$$p = p_1 + p_2$$

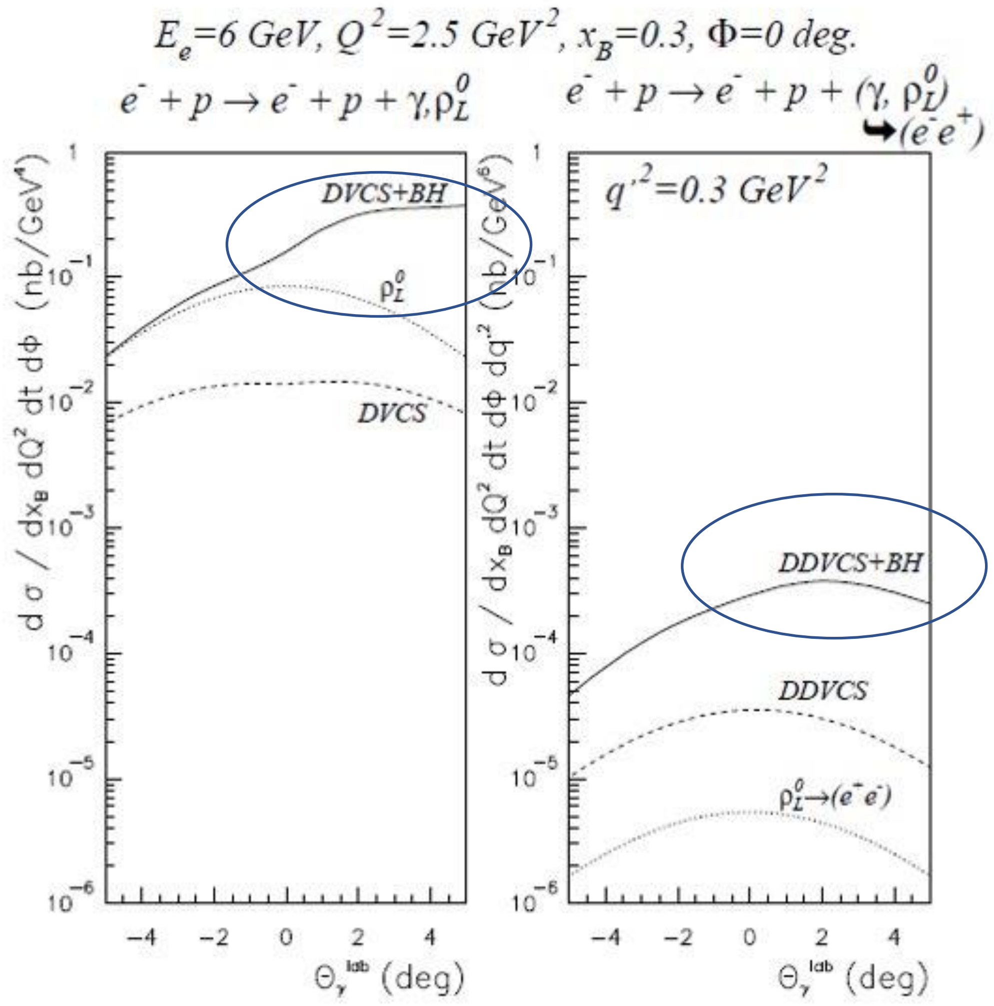
$$\xi = \frac{\Delta \cdot q}{p \cdot q} \qquad \xi' = -\frac{q \cdot q}{p \cdot q}$$

- Compton Form Factor for DDVCS

$$\mathcal{H}(\xi', \xi, t)$$

$$= P\int_{-1}^{1} dx H(x,\xi,t)\left[\frac{1}{\xi' - x} - \frac{1}{\xi' + x}\right] + i\pi[H(\xi',\xi,t) - H(-\xi',\xi,t)]$$

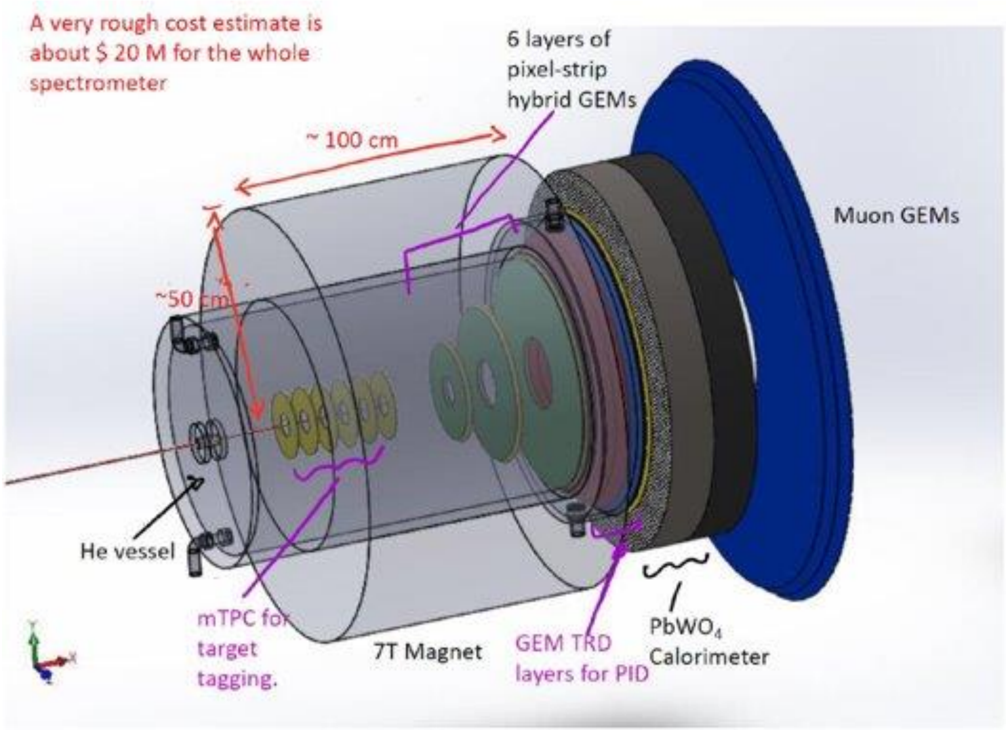
DDVCS cross section



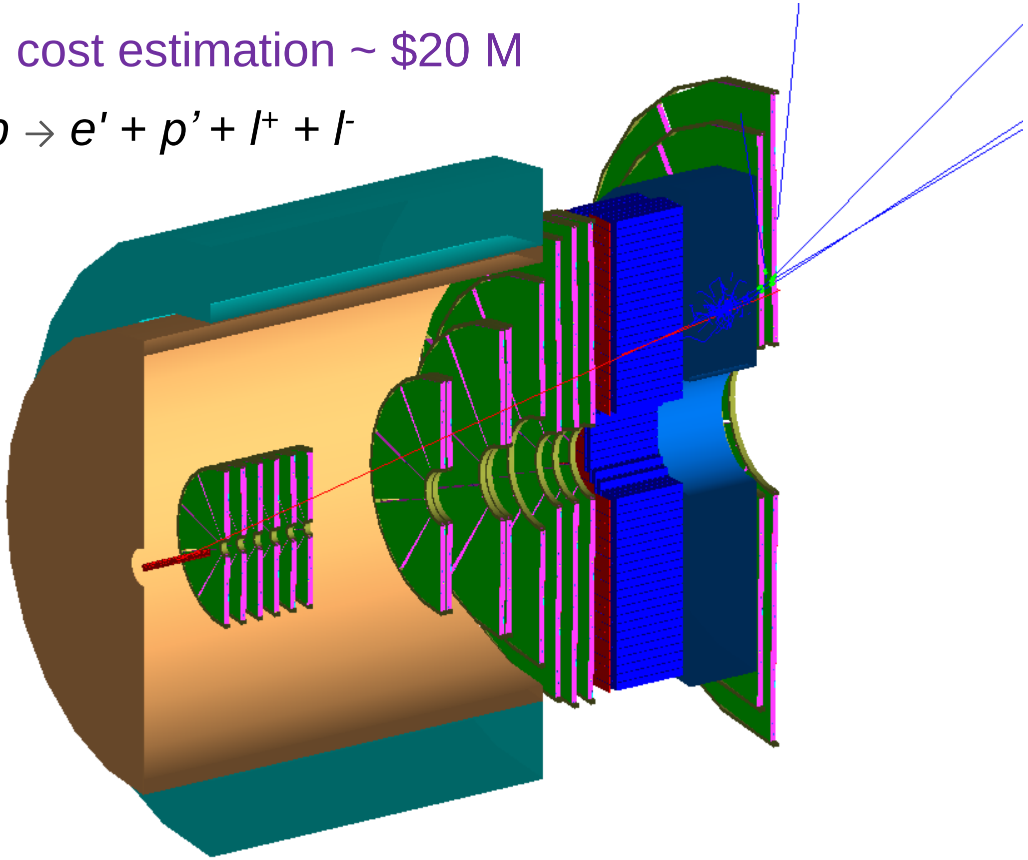
- VGG model
- Order of ~ 0.1 pb = 10^{-36} cm^2
- About 100 to 1000 smaller than DVCS
- Virtual Bethe and Heitler
- Interference term enhanced by BH
- Contributions from mesons small when far from meson mass
- High luminosity for meaningful measurement

Compact Solenoidal Device for DDVCS measurement

- Azimuthal angle coverage: 2π
- Polar angle coverage: $5^o \sim 35^o$

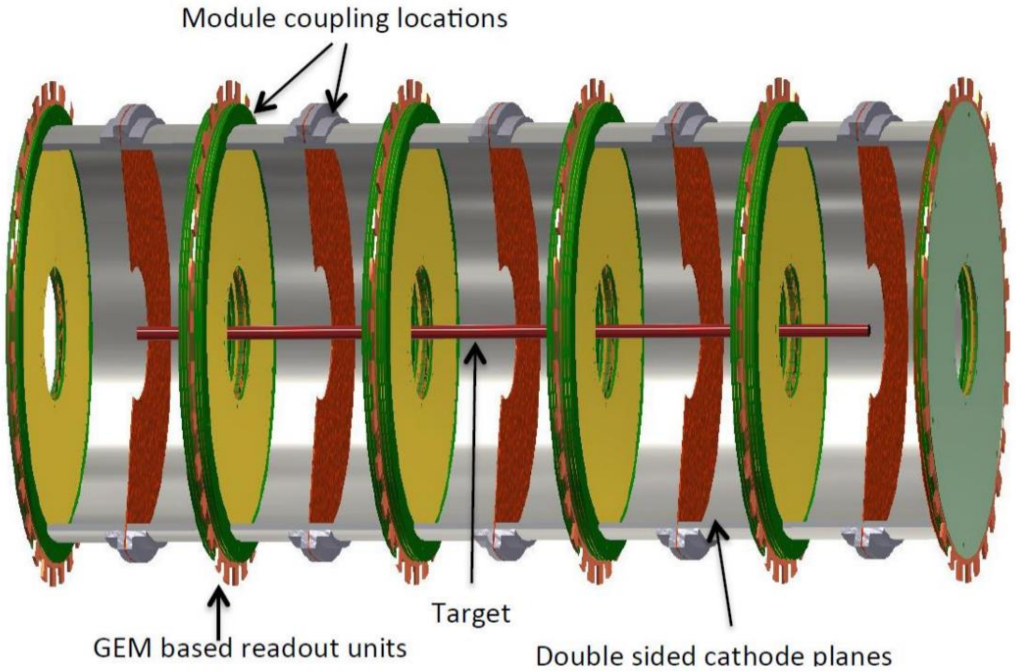


- Designed for High Luminosity Operation
- Total cost estimation ~ $20 M
- $e + p \rightarrow e' + p' + l^+ + l^-$



mTPC for Proton Tagging

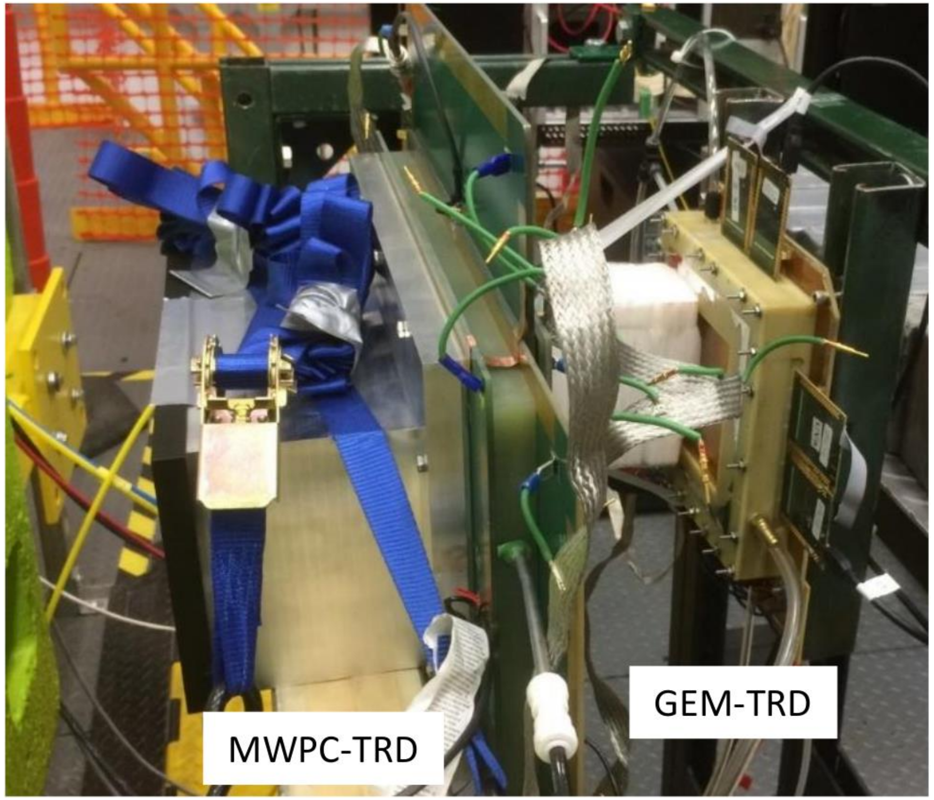
- TDIS mTPC operates under 98 MHz particle rate per layer, inside a 5T super conducting solenoid magnet
- Pixel readout design to achieve high readout rate
- SAMPA-based RO electronics system
- For this device, we can also switch to silicon pixel detectors, for radiation hardness, and even higher particle rate (up to 200 MHz/cm^2)



An mTPC design at UVA for TDIS experiment

Tracker Combined TRD detectors for PID

- Depends on radiator length, a single layer of TRD detector can provide an electron/hadron rejection factor of 5 ~ 30, with 90% electron detection efficiency
- Large energy range: 1 ~ 100 GeV
- Typically TRD detectors are combined with tracking detectors
- Number of layers depends on rejection factor requirements
- For this device, an extra Cerenkov detector can be added if needed



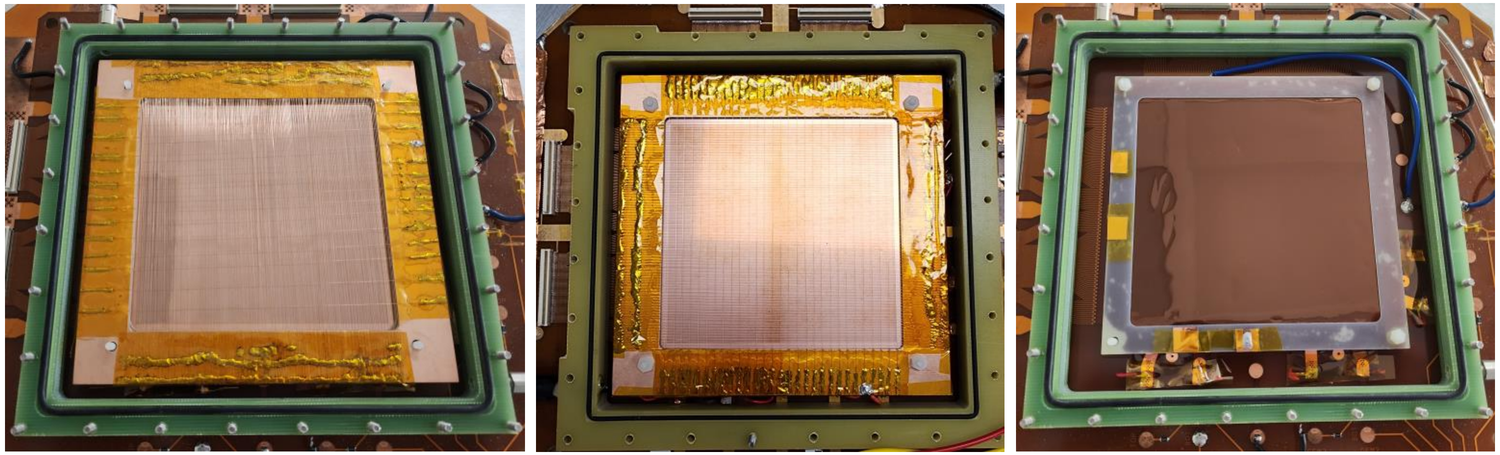
A GEM-TRD protype by UVA being tested in JLab Hall D, achieved a rejection factor of 16 with 25 cm radiator length

F. Barbosa et al, A new Transition Radiation detector based on GEM technology, NIM-A, 942.162356, 2019

Plot curtesy of Kondo Gnanvo

Thin-Gap Detectors for Charged Particle Tracking

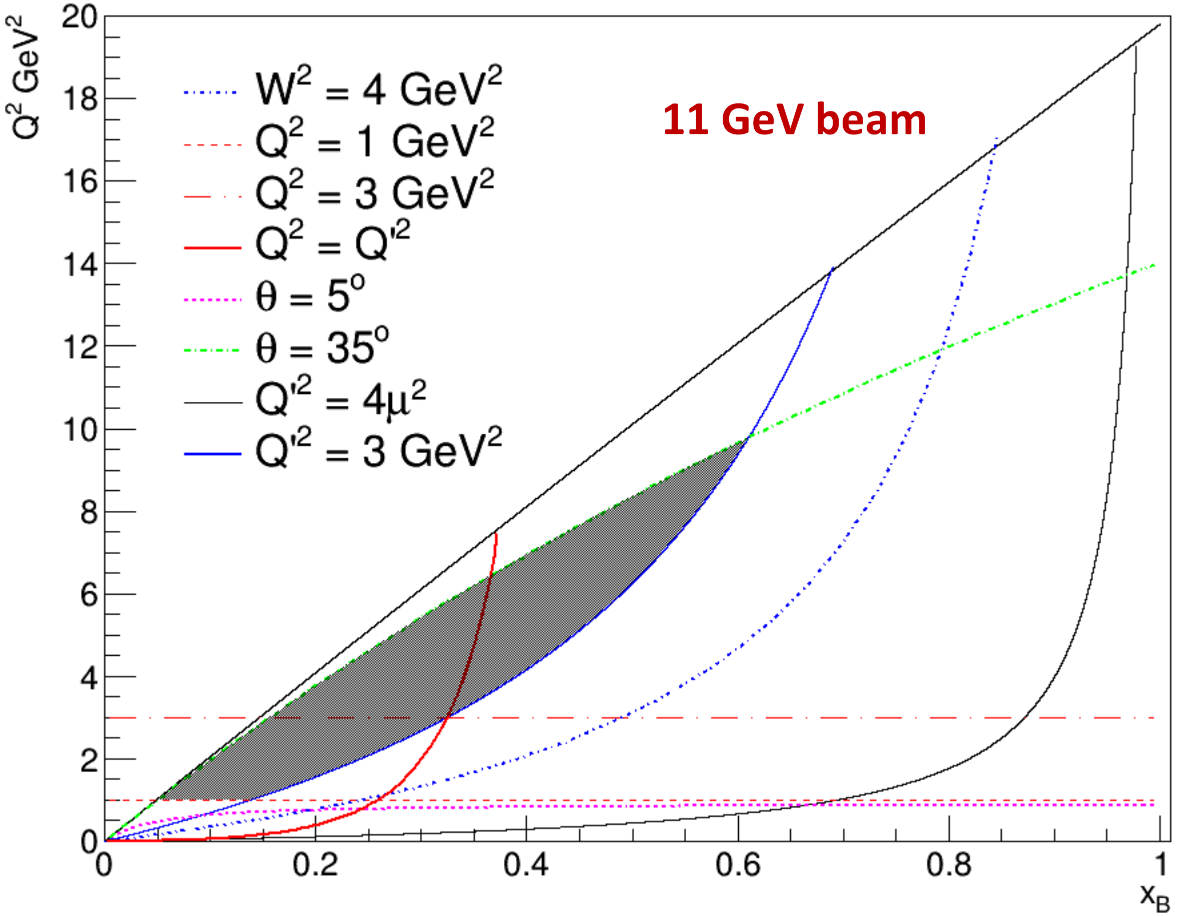
- GEM layers RO: a mix of pixel and strip readout, depends on rate requirement
- Thin-Gap GEM detectors are now proposed for EIC detectors for measuring lepton pairs from J/ψ decay and other heavy quarkonia
- Currently under R&D for EIC with group members from JLab, UVA, Yale, Vanderbilt, Temple, …
- High momentum resolution under magnetic field



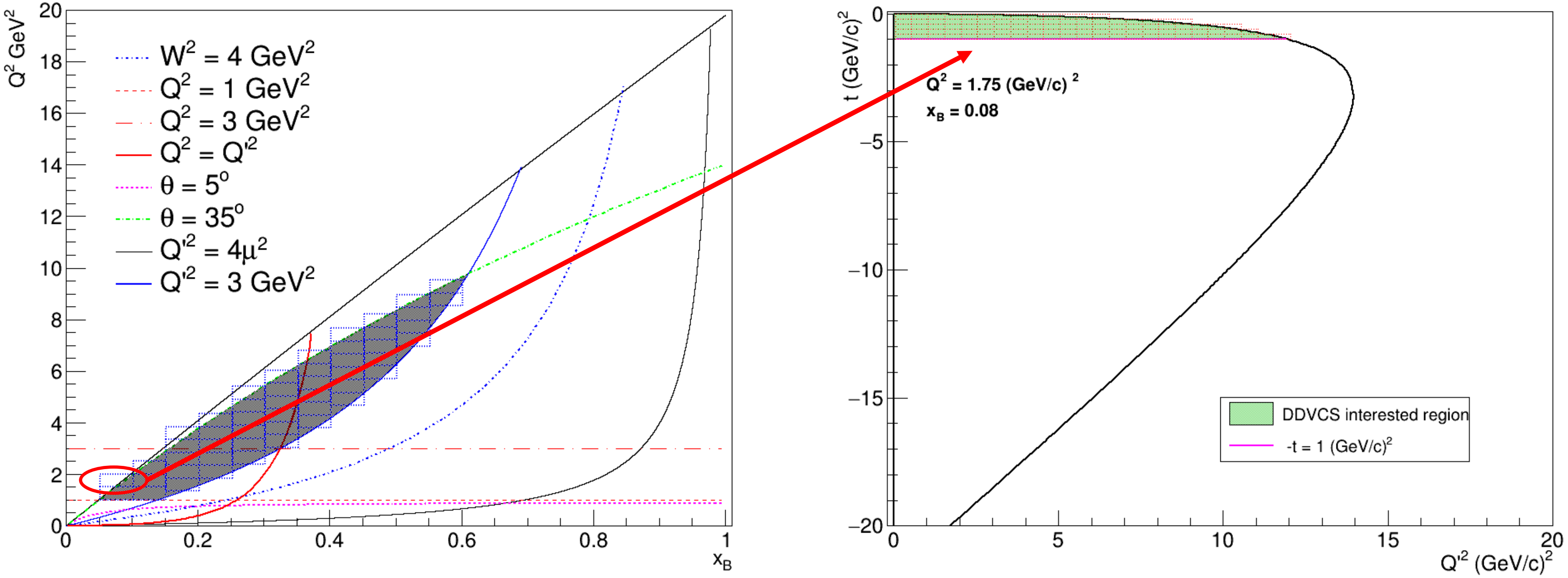
- 3 different Thin-Gap Detector Prototypes Developed by UVA for EIC spectrometer
- Improve the space resolution at large incident angle

Phase Space Coverage

- *e* + *p* -> *e*' + *p*' + μ^{+} + μ^{-}
- **Shaded area** is the all the reachable kinematics coverage of this compact device if we aim for detecting di-muon DDVCS channel
- $Q^2 > 1$ GeV^2 to ensure a deep scattering
- Blue line $Q'^2 = 3$ GeV^2 constraint to minimize eventual contamination from vector meson decay
- **Green line** is the maximum scattering angle this device can reach (35°)



Phase Space Binning



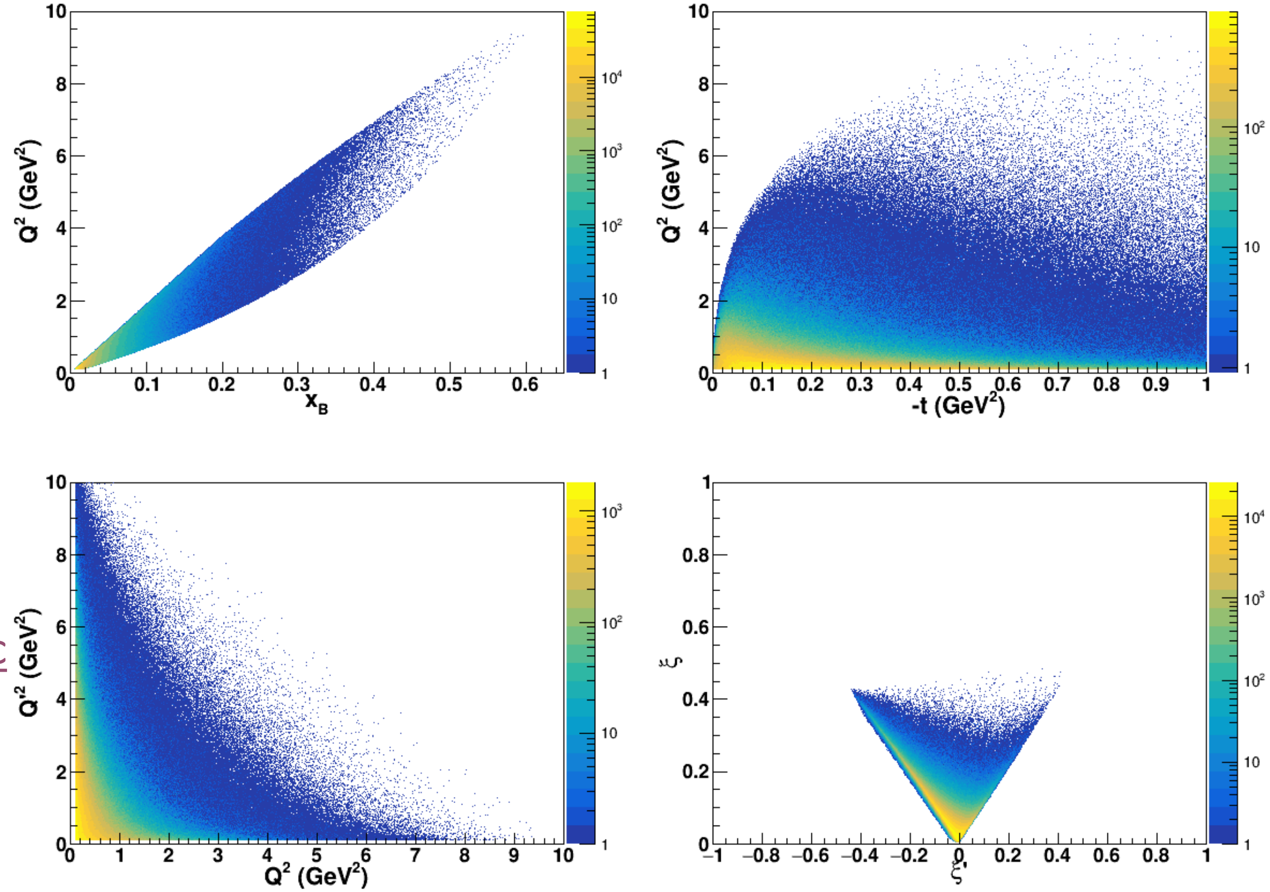
ΔQ^2 GeV^2	Δx_B	$\Delta(-t)$ GeV^2	$\Delta Q'^2$ GeV^2	$\Delta\phi$ (degree)
0.5	0.05	0.2	0.5	15

- $4D\ (x_B, t, Q^2, Q'^2)$ kinematic bins
- Total 1427 bins
- Each has 24 bins in ϕ
- Binning can be refined based on cross section

Bethe-Heitler Events from Partons/EpIC generator

- Use Bethe-Heitler Event for rate estimation
- 11 GeV beam
- Kinematics range:
  - ☐ $0.01 < x_B < 0.90$, $-1 < t < 0.001$
  - ☐ $0.1 < Q^2 < 10$, $0.1 < Q'^2 < 10$

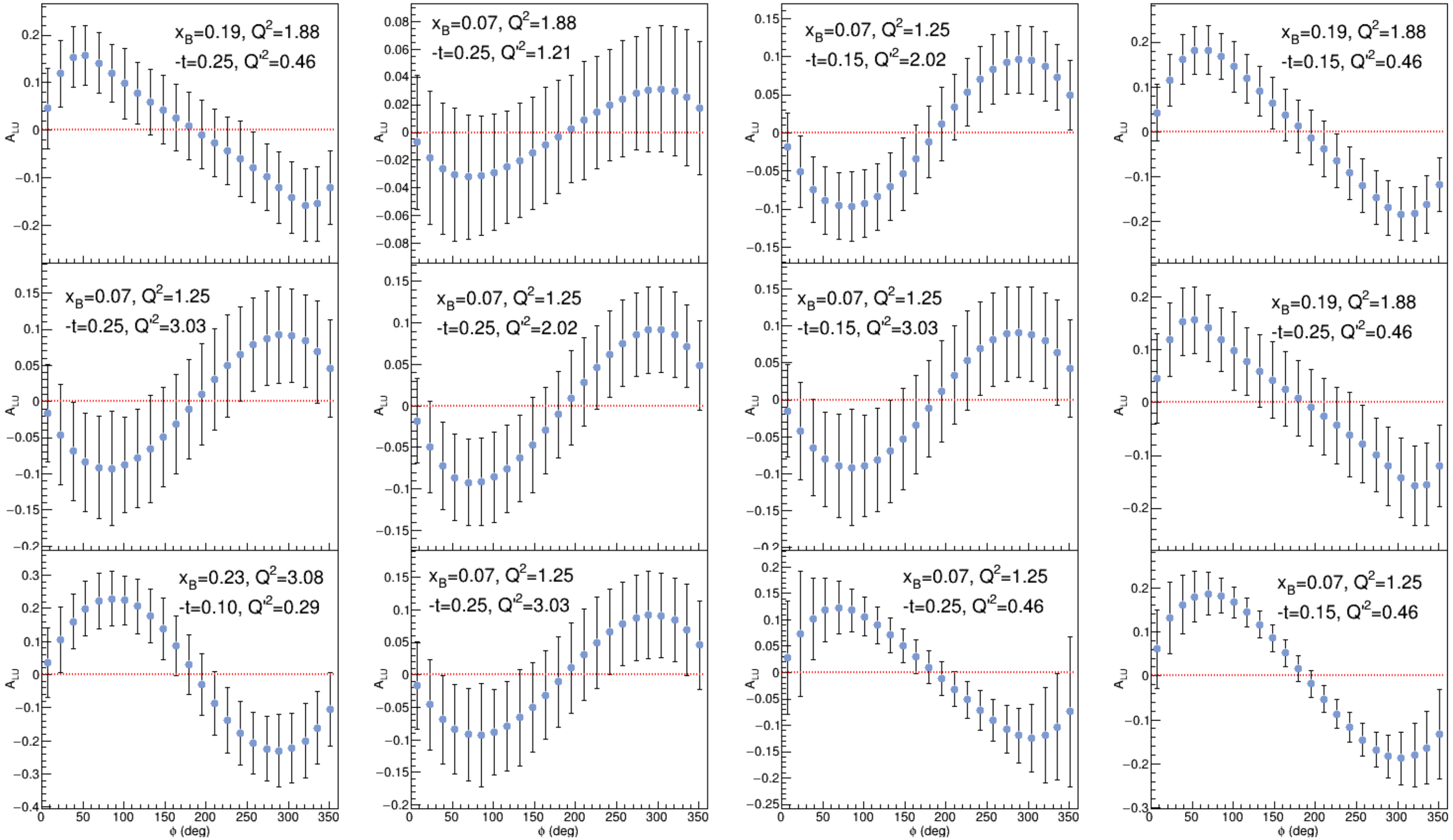
- Partons: https://partons.cea.fr
- Epic : https://pawelsznajder.github.io/epic
  - ☐ Exclusive processes including DVCS, DVMP (π^0 case), TCS, DDVCS, ...



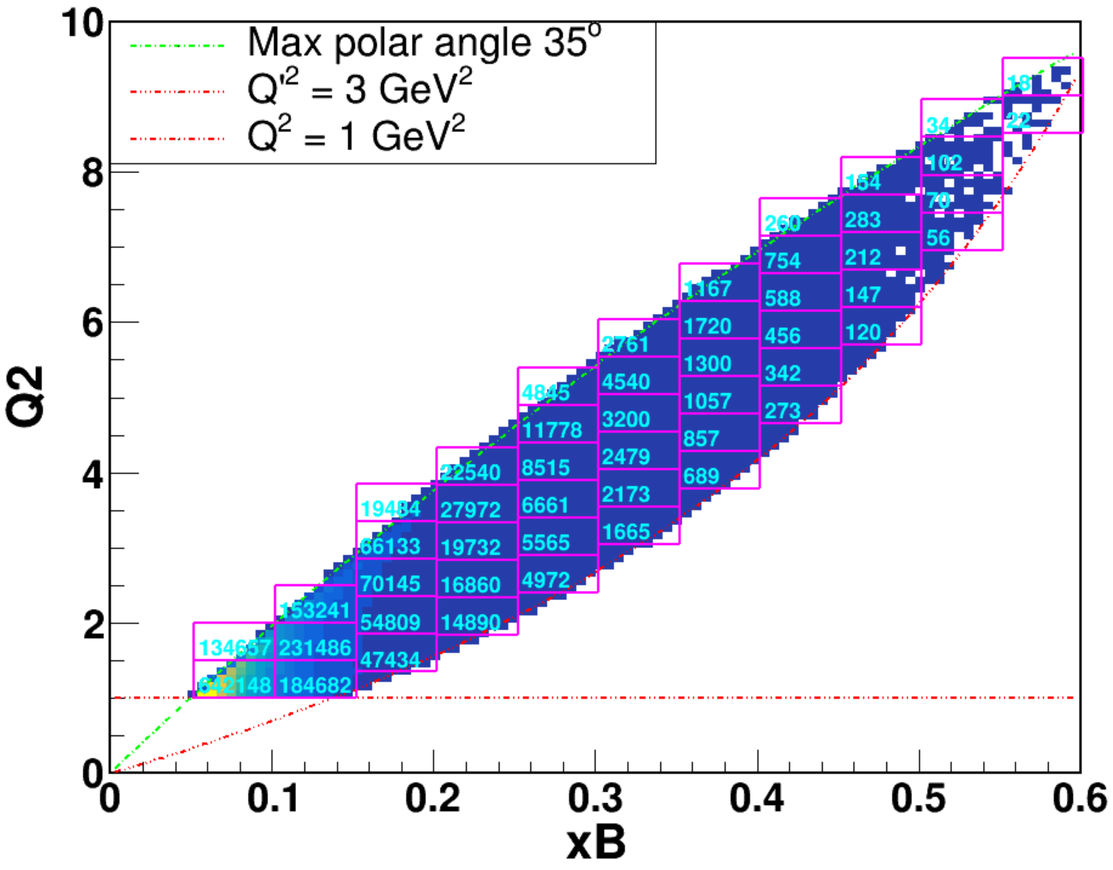
BH Events within Kinematics Acceptance of this Device using lepton pair and electron trigger

BSA Uncertainty Projection

- Assume luminosity of 10^{37}
- A luminosity which will be run by the SoLID spectrometer in Hall A
- BSA uncertainty result in a few different bins, estimation used Bethe-Heitler events
- BSA calculated using VGG model
- BSA changes sign from regions $Q^2 > Q'^2$ to $Q^2 < Q'^2$
- 5-fold cross section, with 24 bins in ϕ_{LH}-angle (horizontal axis)
- The results is an estimation using around 60 days of beam time using this device

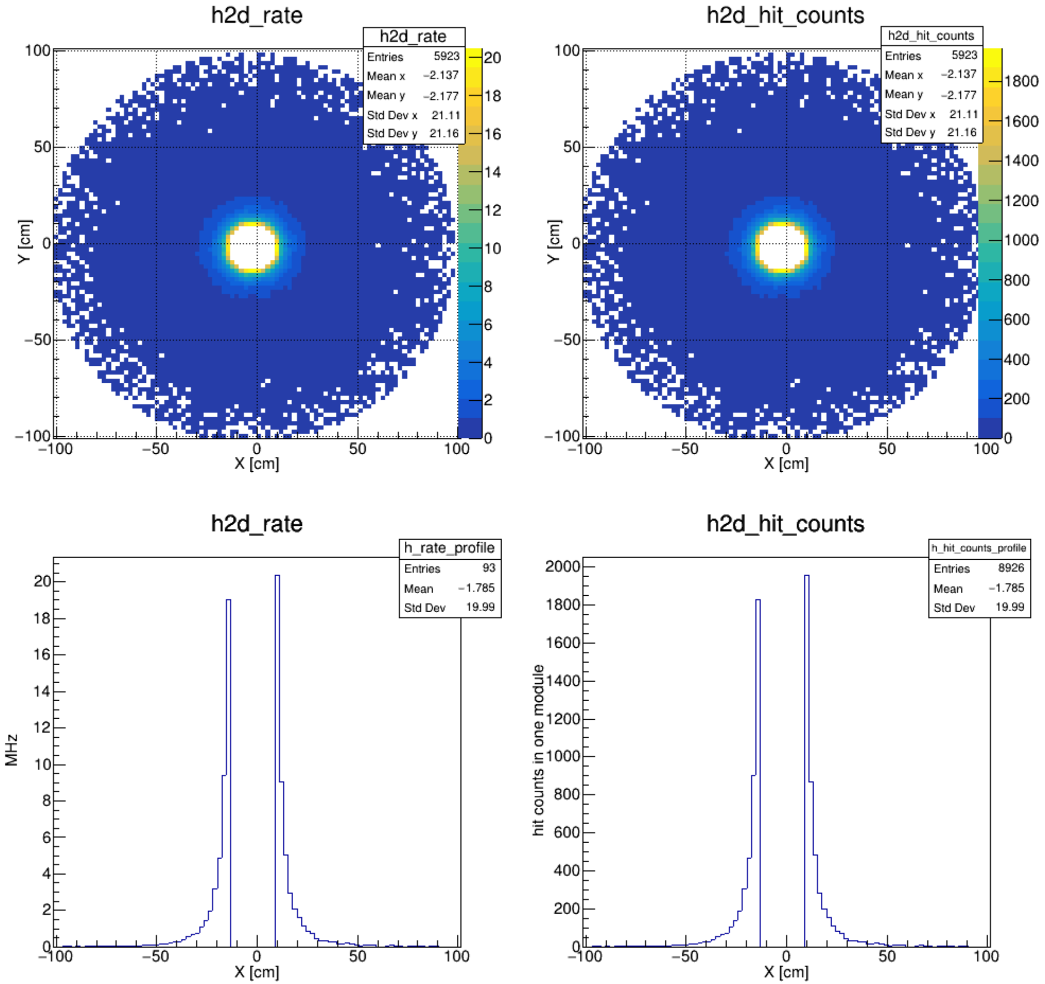


Bin-Wise BH-Event Count



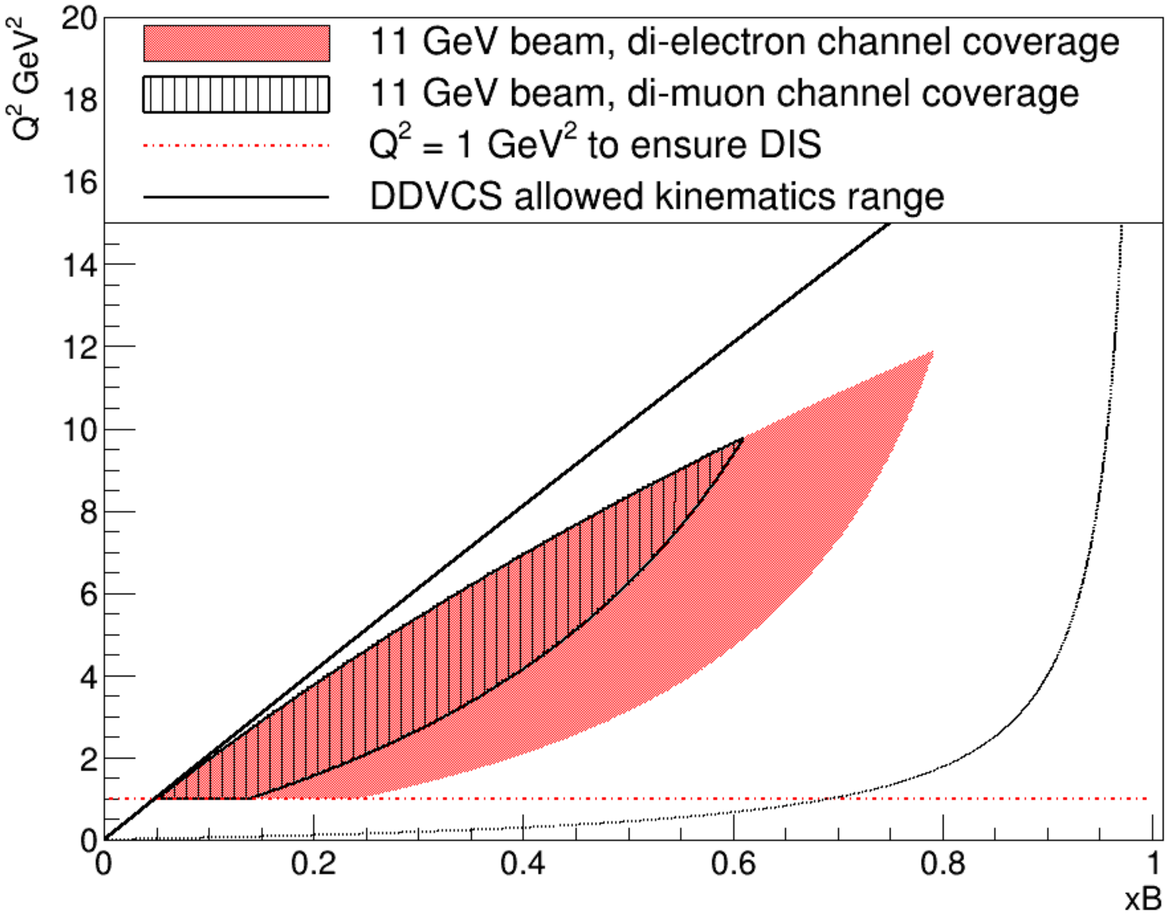
Background Rate Estimation on ECal modules

- ECal module dimension:
  - ☐ 2 cm X 2 cm X 20 cm
- Module Hit Threshold:
  - ☐ > 300 MeV
- Highest Module Rate:
  - ☐ ~20MHz



Di-electron channel Coverage Compare with Di-muon channel

- Excllent missing mass resolution
- mTPC for recoil proton tagging
- In addition to di-muon channel measurement, study for possibility of di-electron channel measurement
- larger phase-space coverage



Summary

- A dedicated device for DDVCS and other measurements designed for high luminosity
- Largen phase-space coverage
    - ❑Future study planned for di-electron channel with even larger phase space coverage
- Meaningful measurements with current available luminosity
    - ❑Detailed study for different luminosity is on-going
- Available detector technology for building this device
    - ❑A relatively quick project to complete
- Possible for other measurements (DVMP, TCS, DVCS, …)

Thank you!

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