Generalized Parton Distributions (GPD) from Timelike Compton Scattering (TCS)

Gyang Chung
Department of Physics,
Virginia Tech.
Blacksburg, VA, USA.
Contact: gyangchung@vt.edu

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PARTONIC STRUCTURE OF THE HADRONS

Jefferson Lab

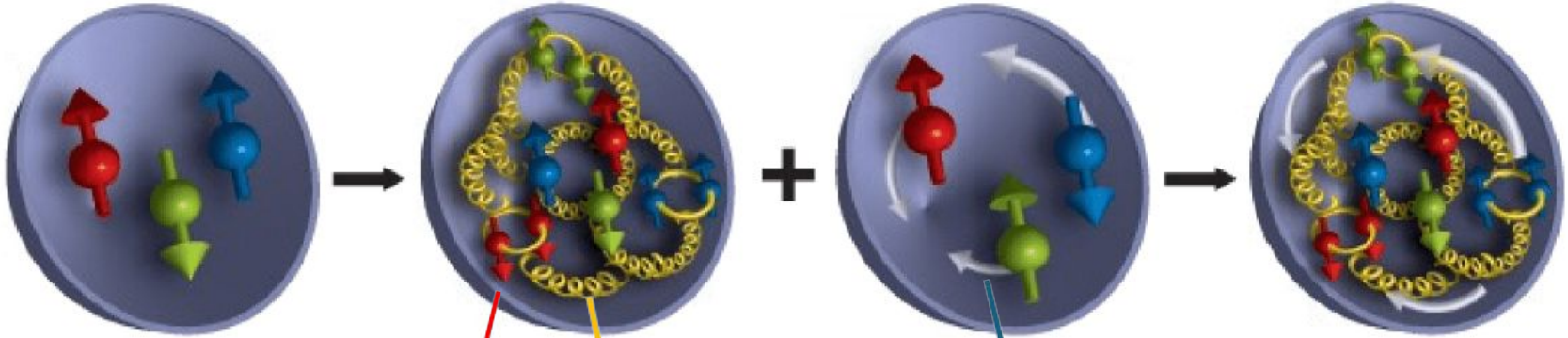
HAMPTON UNIVERSITY GRADUATE SUMMER PROGRAM
HUGS | 40 years!

★ Outline

- Introduction on Nucleon structure
- Motivation for GPD studies
- Description of TCS
- Progress on Extracting TCS events.

Nucleon structure (Cartoon Picture)

Increase in complexity with time/years: *Nowadays the picture is more complex*



Earlier: Static model

Now: Dynamic model

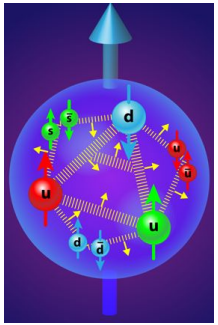
Gluons

Quark + anti-quark pairs (sea)

- Nucleon content, distributions

Intrinsic rotation of quarks, gluons, nucleon = Spin

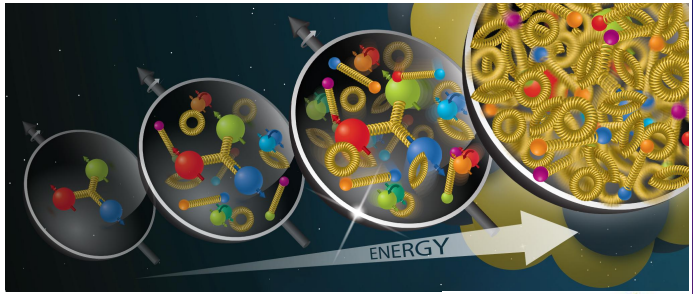
- Dynamic properties

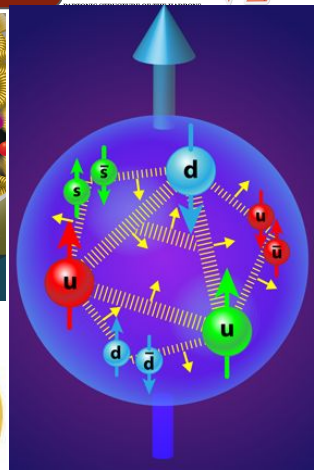


Motivations for studying GPD's ?

Impact parameter distributions

(Burkardt, hep-ph/0005108 / ...)



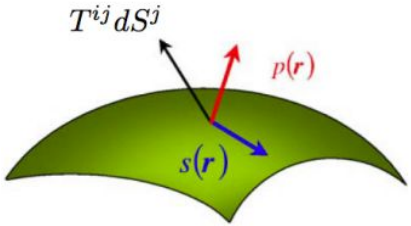


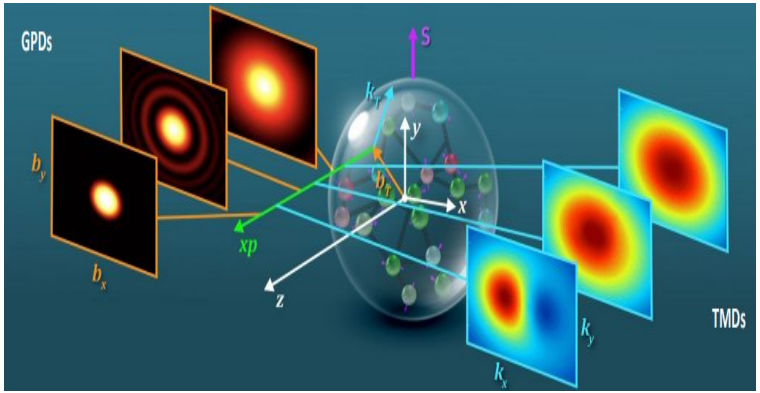
Nucleon Spin: Spin & Orbital angular momentum (sum rule)

(Ji, hep-ph/9603249)

Mechanical properties (pressure, shear) inside nucleon

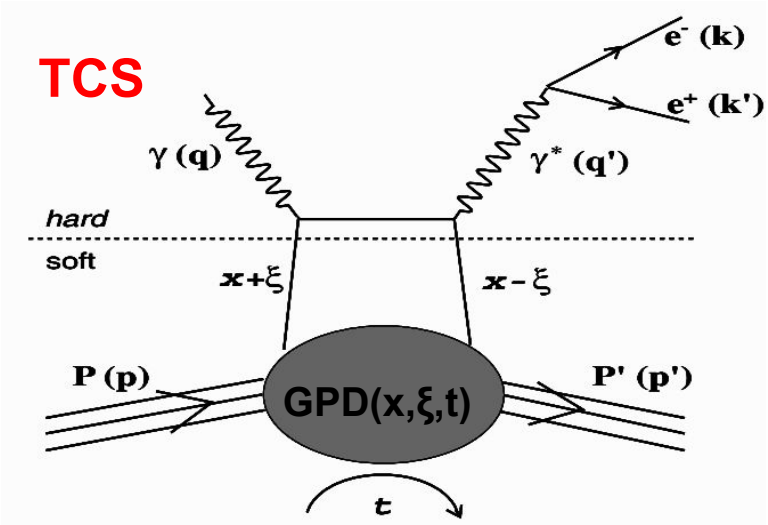
(Polyakov, hep-ph/0210165 / Polyakov, Schweitzer, 1805.06596 / ..)



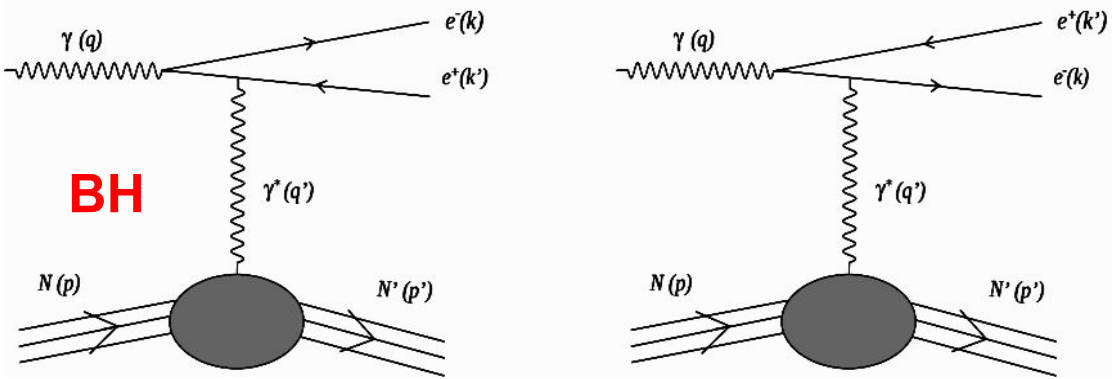


Globally: To produce the tomographic image of the nucleon !!!

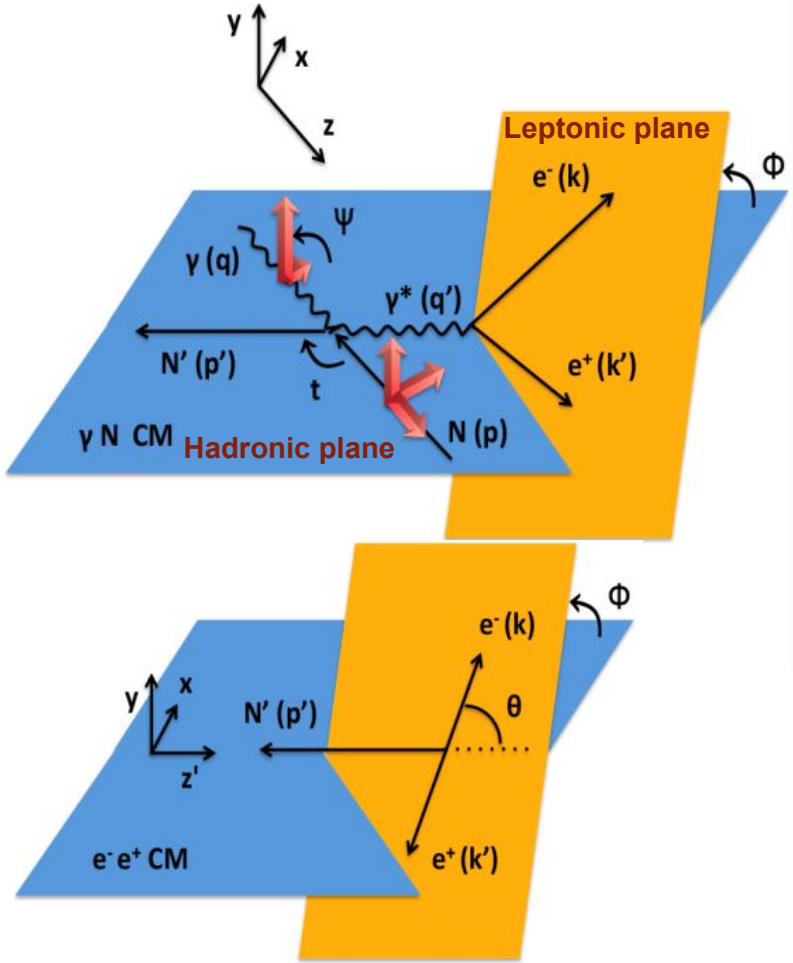
TCS description



- $\mathbf{P} = \frac{1}{2}(\mathbf{p} + \mathbf{p}')$ — Average proton momentum
- $\boldsymbol{\Delta} = \mathbf{p}' - \mathbf{p} = \mathbf{q} - \mathbf{q}'$ — Momentum transfer
- $\bar{\mathbf{q}} = \frac{1}{2}(\mathbf{q} + \mathbf{q}')$ — Average photon momentum
- $\xi = -\frac{\Delta \cdot \bar{q}}{2P \cdot \bar{q}} = -\frac{\Delta^+}{2P+} = \frac{Q'^2}{2(s-m^2)+\Delta^2-Q'^2}$ — Skewness: Fraction of longitudinal momentum transfer
- $x = \frac{k}{P}$ — Momentum fraction carried by an active quark



Description of TCS in a frame (Showing kinematics)



- ψ — **Beam polarization angle**

  Angle between polarization vector of beam & hadronic plane.

  For spin asymmetry observables & polarization-dependent σ terms.

- $\mathbf{t = (p' - p)^2}$ — **Momentum transfer to the Nucleon**

- $\mathbf{Q'^2 = (k + k')^2}$ — **Virtuality of the outgoing Photon**

- ϕ — **Azimuthal angle between Hadronic & Leptonic Planes**

  Governs the interference between the TCS & BH processes.

  Angular modulations of the cross section.

- θ — **Lepton polar angle in the dilepton rest frame**

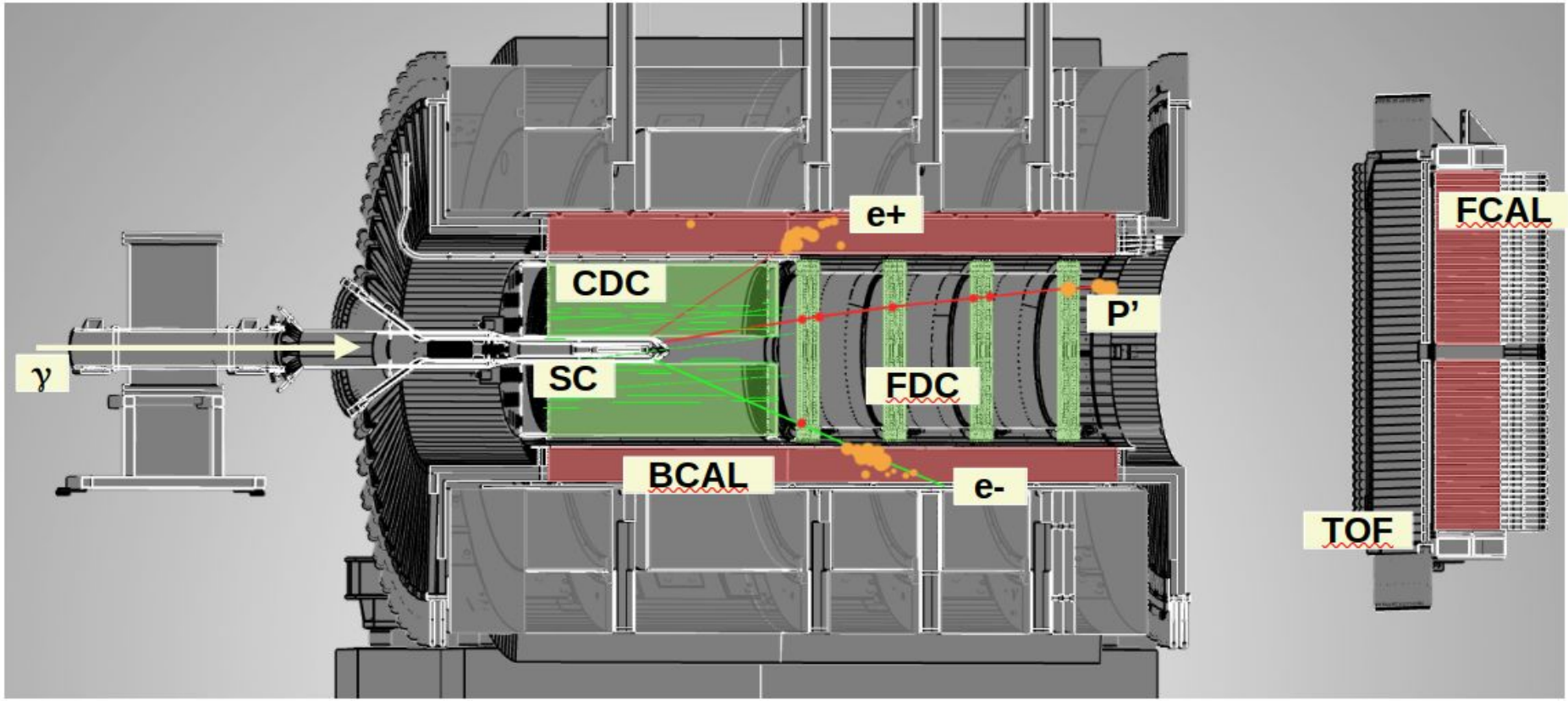
  Sensitive to the angular structure of the process.

$$A_{lU}(\Psi) = \frac{\sigma(\Psi) - \sigma(\Psi + \pi/2)}{\sigma(\Psi) + \sigma(\Psi + \pi/2)}$$

Some GPD studies @ Jlab with TCS

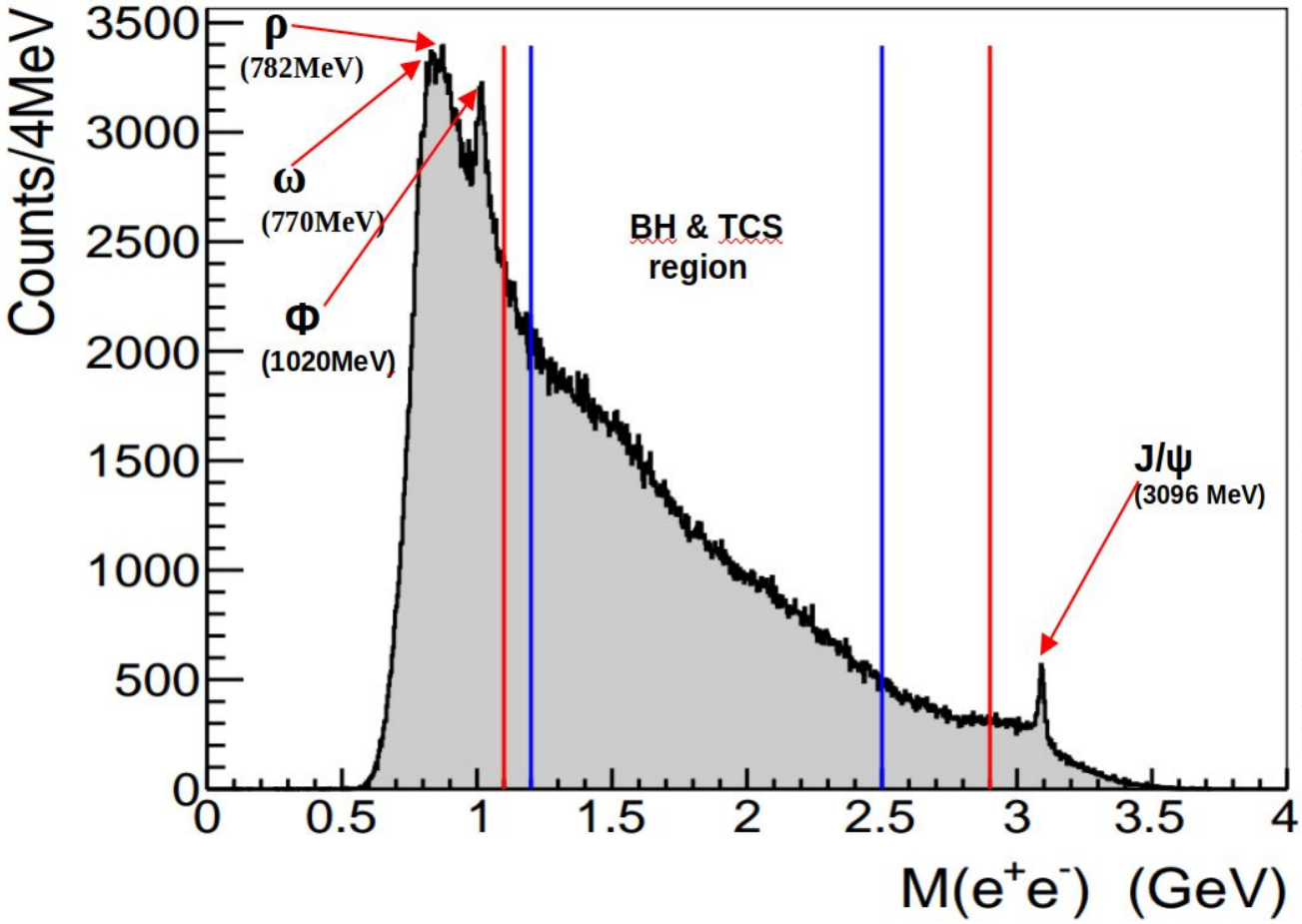
Observables	GPD	Target	Beam	Experiments
Unpol. Cross sections vs Φ	$\mathcal{R}$(H), $\mathcal{I}$(H)	Unpolarized (Lh2)	Unpolarized	Clas12, Solid(future), Unpol. TCS in Hall C
Cross sections vs Φ	$\mathcal{I}$(H), $\mathcal{I}$($\hat{H}$)	Unpolarized (Lh2)	Circularly polarized	Clas12, Solid(future), Pol. TCS in Hall C
Cross sections vs Φ & ψ	**$\mathcal{R}$(H), D-term**	**Unpolarized (Lh2)**	**Linearly polarized**	**Possible with GlueX**

TCS experiment at Hall D



Select events with proton, electron and positron final states

Some Event Selection:



BH & TCS region:

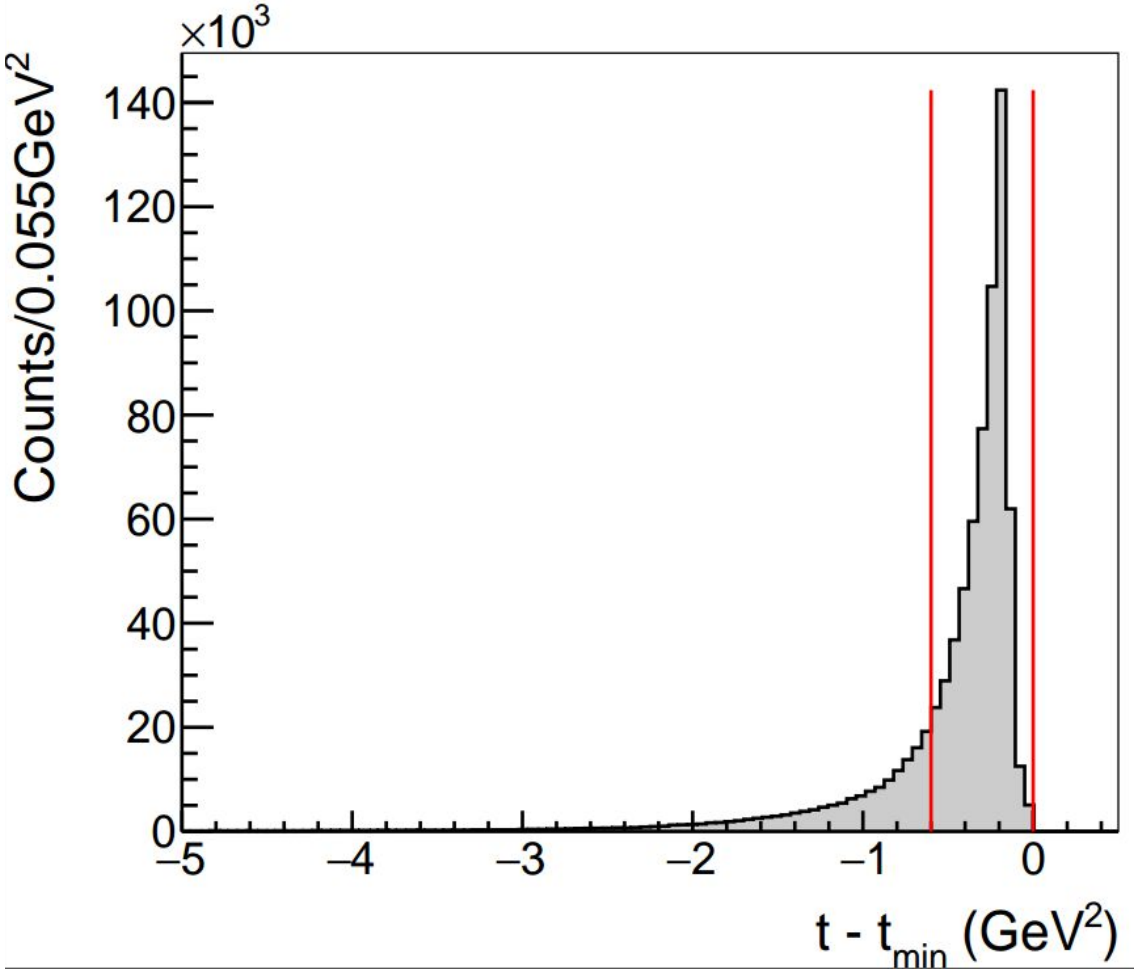
$1.2 \leq M(e^+e^-) \leq 2.5$ GeV

Lies away from many meson resonances. It's suitable for studies of GPDs.

Note: Some mesonic contributions still remain: $\rho(1450)$, $\rho(1700)$, & $\pi's$.

Planned update: Cut to be shifted to $1.1 \leq M(e^+e^-) \leq 2.9$ **GeV**.

Forward Scattering Selection (Hard Scale)



The limit $-t \to 0$ corresponds to **forward scattering**: Virtual & incident photon proceeds in thesame direction.

Hard scale of TCS must satisfy the conditions:
$Q'^2 \gg m_p$ and $Q'^2 \gg -t$
for the GPD factorization to hold.

As $-t$ increases, the **validity of the factorization** & **leading-twist approximations** diminishes.

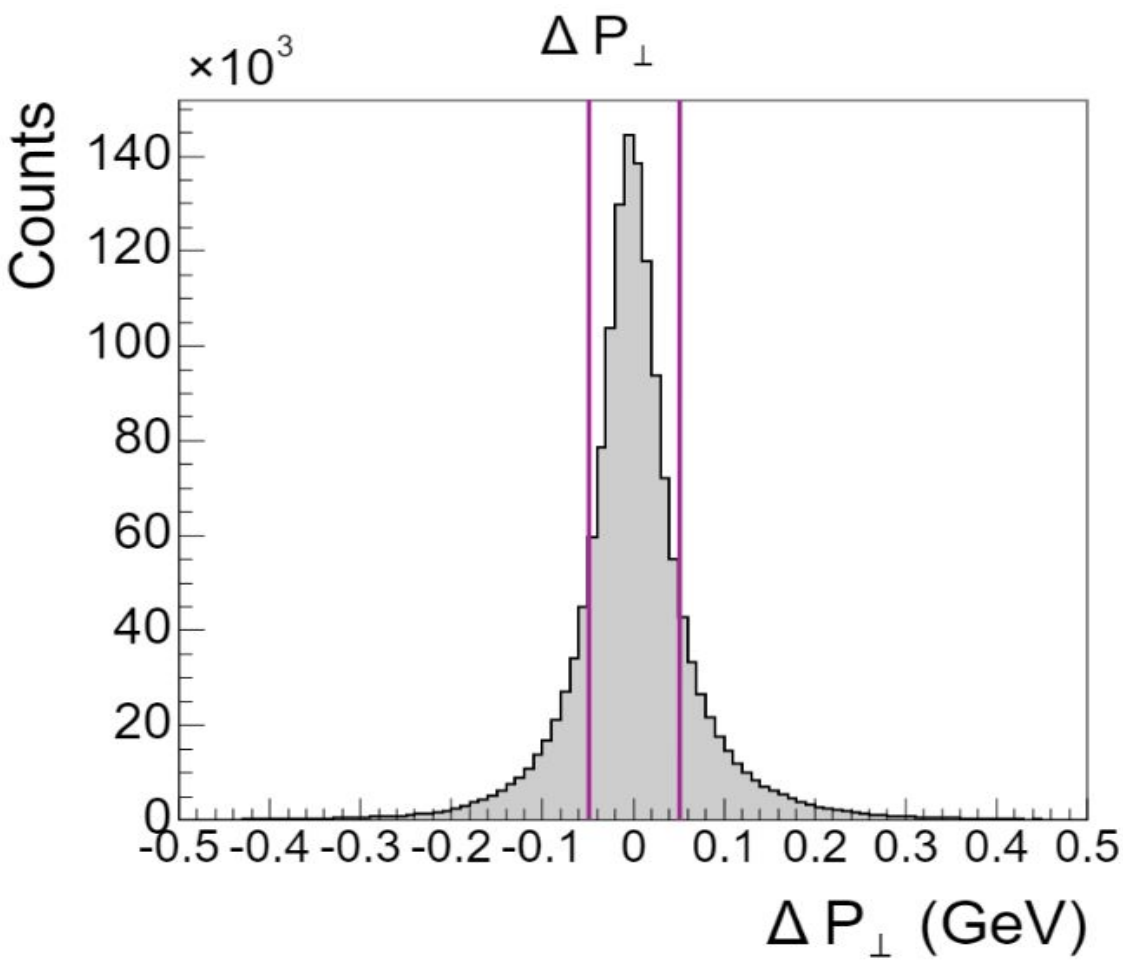
$$t - t_{\min} = 2 \cdot |\vec{p}| \cdot |\vec{p}'| \cdot (\cos\theta - 1)$$

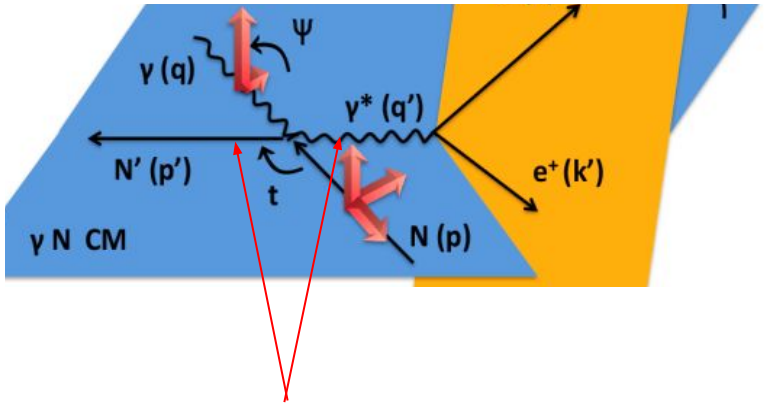
t_{min} occurs at $\theta = 0$.

$\vec{p}, \vec{p}'$: target & detected protons' momentum 3-vectors

$$-0.6\ GeV^2 \leq t - t_{\min} \leq 0$$

Kinematic Constraint 01



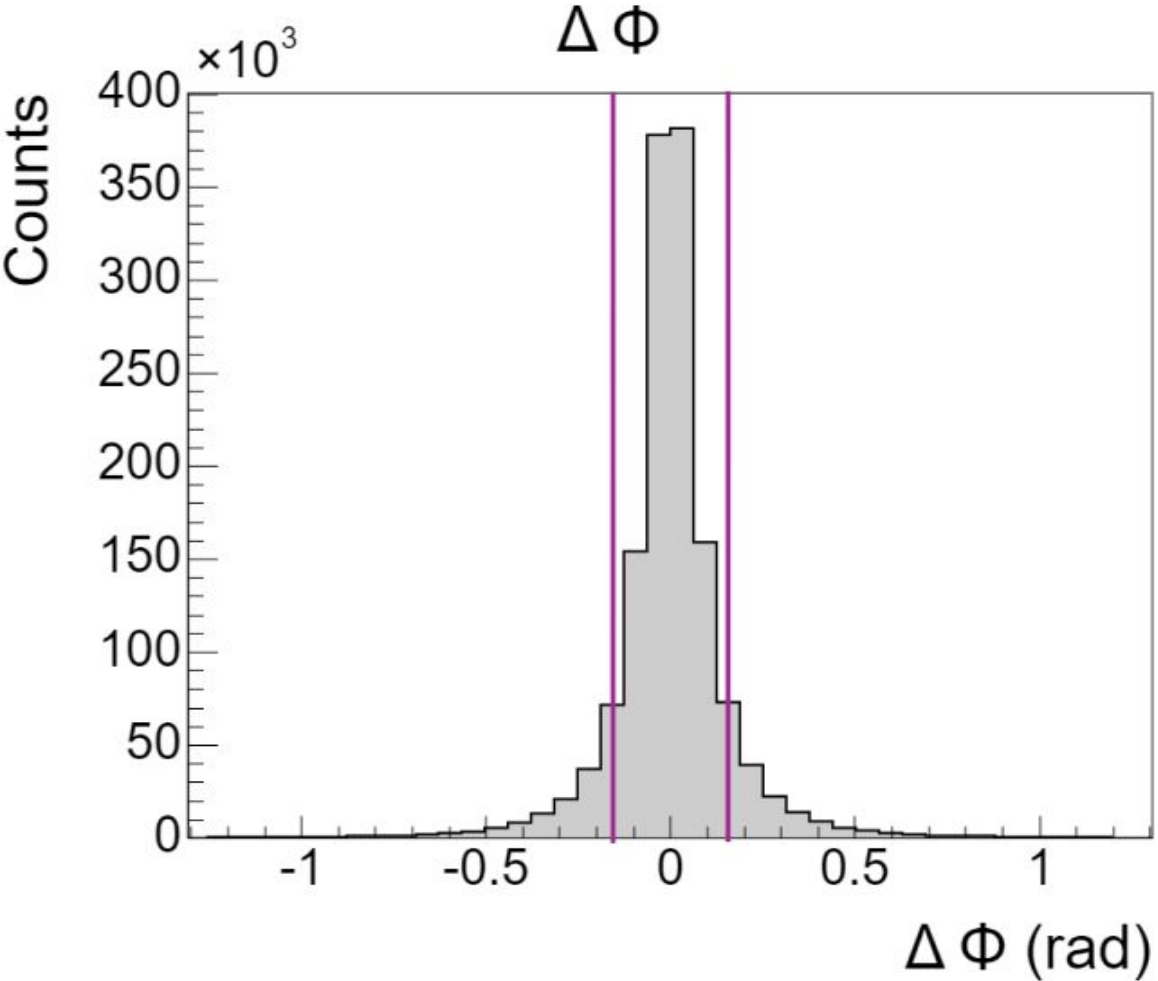


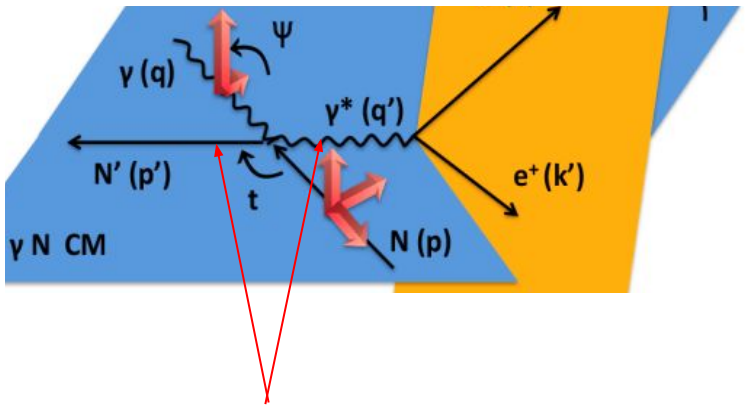
Difference between Scattered proton & Virtual gamma Transverse Momentum

$$\Delta P_\perp = \vec{P}_{p'\perp} - \vec{P}_{\gamma^*\perp}$$

cut: $|\Delta P_\perp| \leq 0.05\ GeV$

Kinematic Constraint 02





Difference in angles between Scattered proton & Virtual gamma

$$\Delta\Phi = \phi_{\vec{P}_{p'}} - \phi_{\vec{P}_{\gamma^*}}$$

cut: $|\Delta\Phi| \leq 0.15\ rad$

Summary

One has made some progress in suppressing mesons events in the e+e- final states by:

1: Selecting regions with less resonance peaks

2: Selecting only relevant -t values

3: Applying kinematic constraints

Thanks!!!
@HUGS

Backup: Motivations for studying GPD's ?

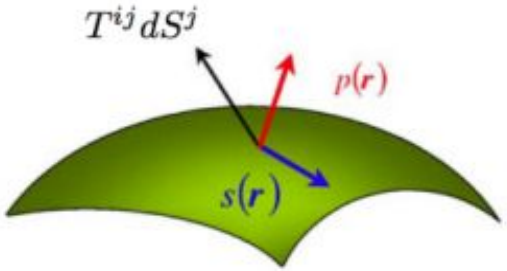
Impact parameter distributions (Burkardt, hep-ph/0005108 / ...)

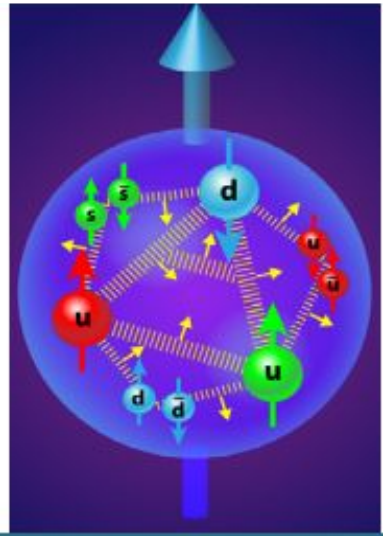
$$GPD(x,\xi=0,\Delta_T) \leftrightarrow f(x,b_T); \leftrightarrow \text{is } \mathcal{F}.\mathcal{T}.$$

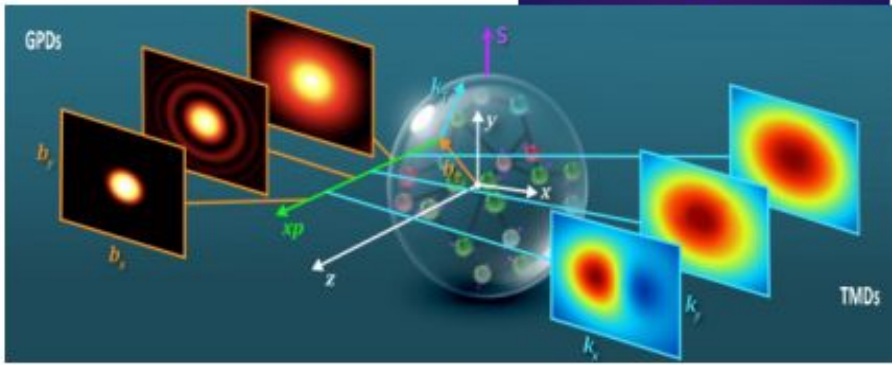
Nucleon Spin: Spin sum rule and orbital angular momentum
(Ji, hep-ph/9603249)

$$\mathcal{J}_q = \int_{-1}^{1} dx\, x\,(H_q + E_q)\,|_{t=0} \quad \mathcal{J}_g = \int_{0}^{1} dx\,(H_g + E_g)\,|_{t=0}$$

Mechanical properties (pressure, shear) inside nucleon (Polyakov, hep-ph/0210165 / Polyakov, Schweitzer, 1805.06596 / ..)

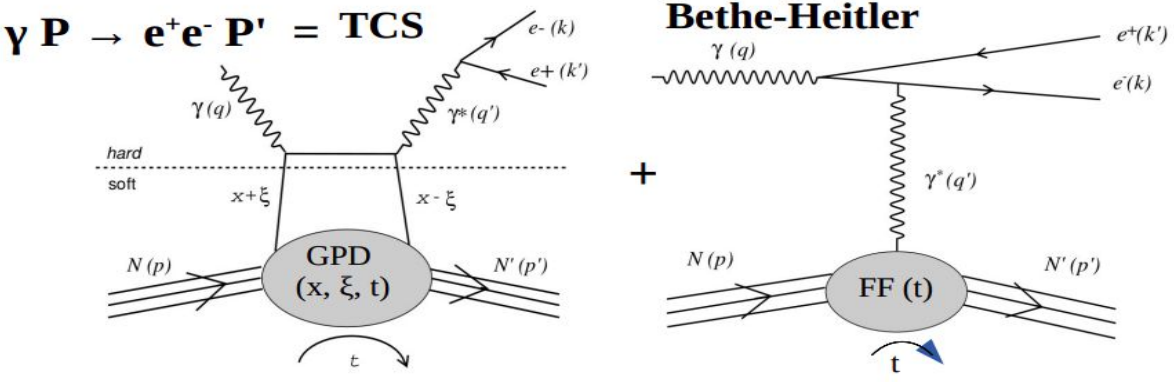


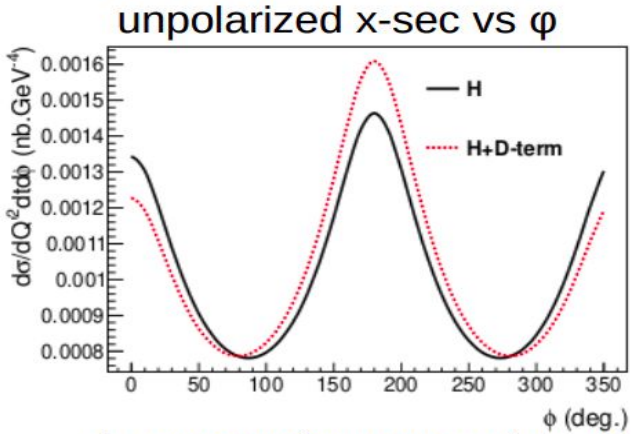




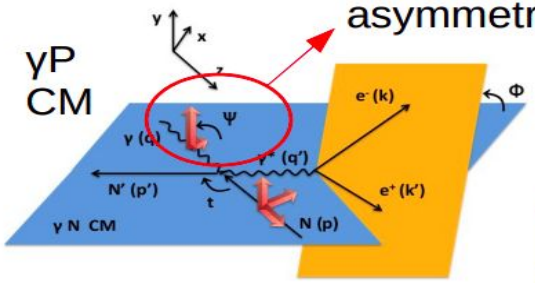
Globally; To produce the tomographic image of the nucleon !!!

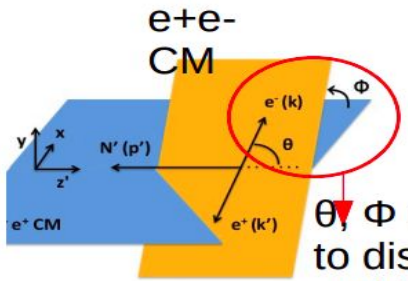
Backup: Accessing real GPD H



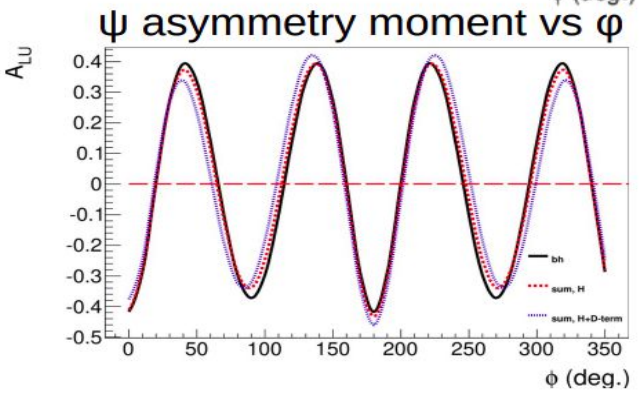


ψ angle photon polarization (taking asymmetry or moment)





θ, Φ decay used to disentagle BH and TCS



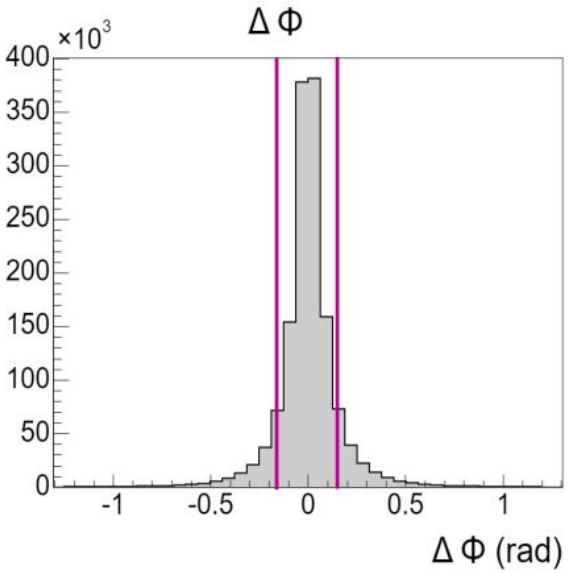
Goal: photon's polarization asymmetries, sensitive to real part of amplitude (CFFs) and D-term

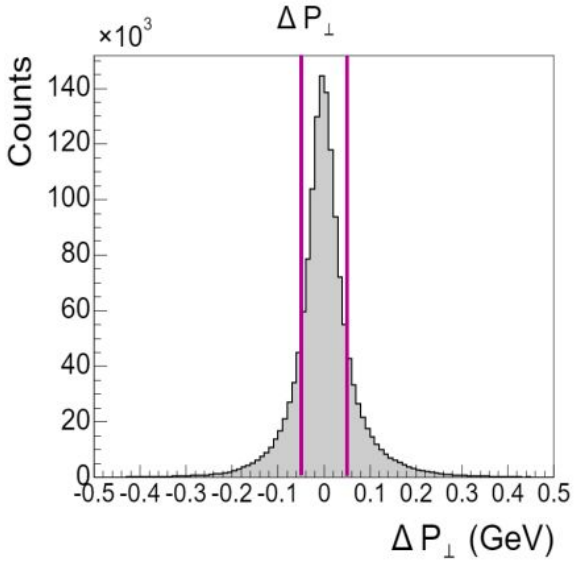
Backup: Meson Background & hard exclusive cuts

Exclusivity Selection

We have added two new cuts for optimal TCS selection and background reduction.
Difference in ϕ angles & $P_\perp$ between Scattered proton (p') & Virtual gamma (γ^*)

Quantity	Bethe-Heitler (BH) Cut
E_γ	8.2 – 11.44 GeV
$M(e^+e^-)$	1.2 – 2.5 GeV
t	$abs(t - t_{min}) < 0.6 GeV^2$
$e^+,\ e^-\ p/E$	$\pm\sigma, 3.5 - 4.5\sigma\ for\ \pi$
$e^+, e^-\ BCAL_{pre} sin\theta$	$< 0.03\ GeV$
$proton\ p$	$> 0.4\ GeV$
$e^+, e^-\ p$	$> 0.4\ GeV$
$all\ \theta$	$> 2^o$
$abs(M^2_{miss})$	$< 0.04\ GeV^{2^*}$
$Kin.fit\ \chi^2$	< 5000



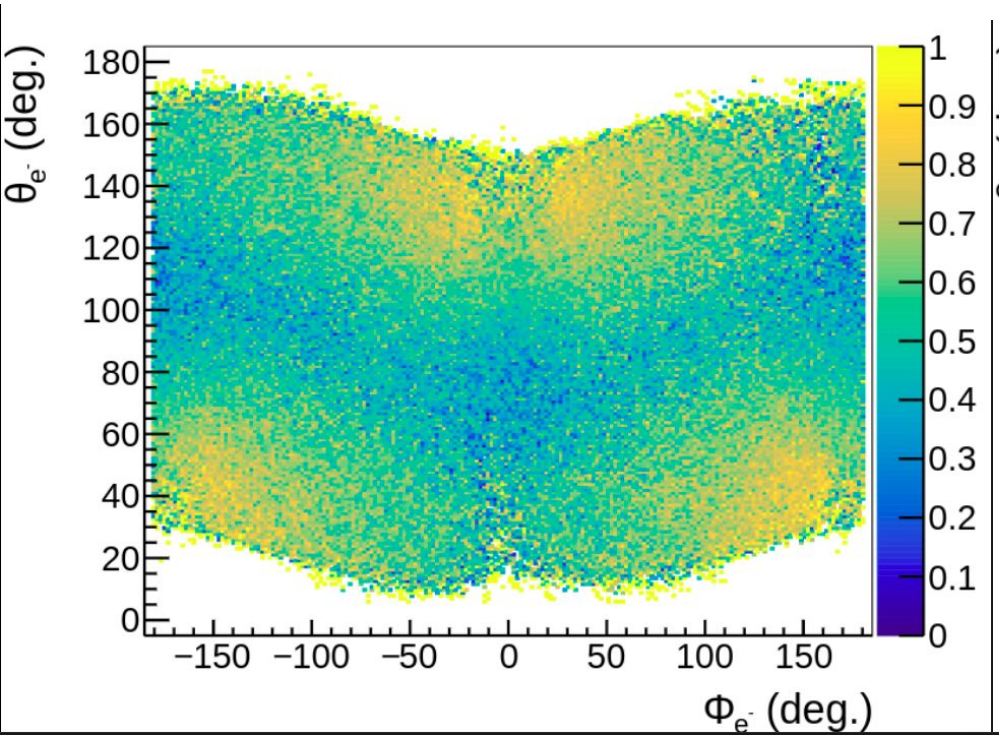


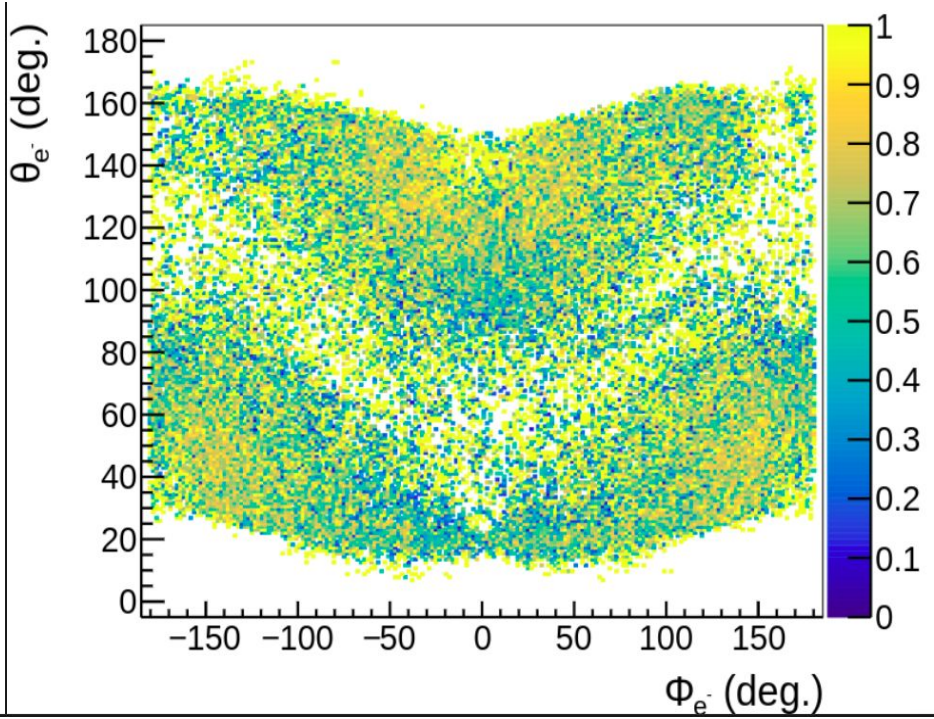
Previous BH cuts $abs(M^2_{miss}) < 0.25$ was use.

$$\Delta\Phi = \phi_{\vec{P}_{p'}} - \phi_{\vec{P}_{\gamma^*}}$$
cut: $|\Delta\Phi| \leq 0.15\ rad$

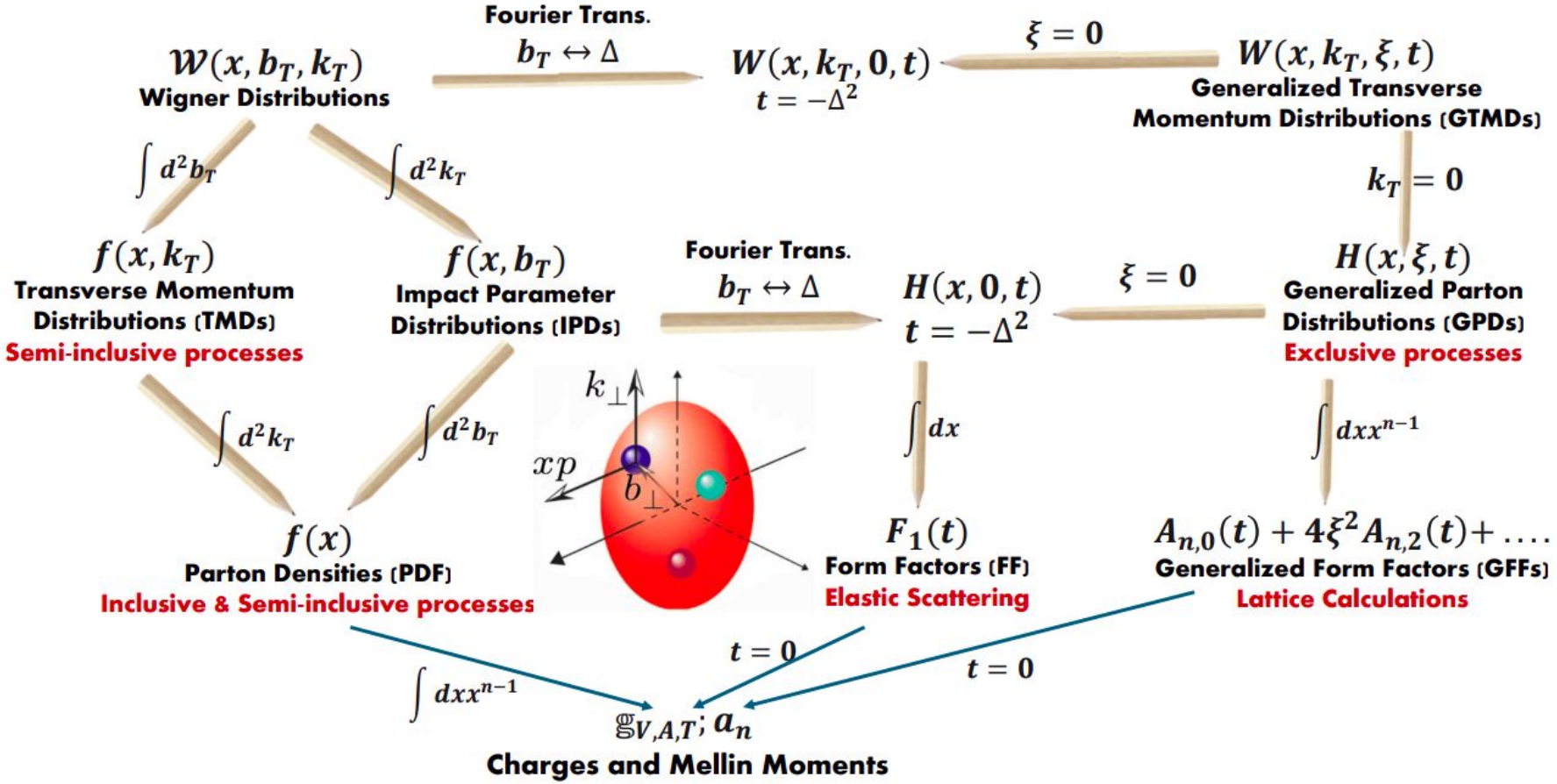
$$\Delta P_\perp = \vec{P}_{p'\perp} - \vec{P}_{\gamma^*\perp}$$
cut: $|\Delta P_\perp| \leq 0.05\ GeV$

Backup: Ratio plots with hard exclusive cuts results



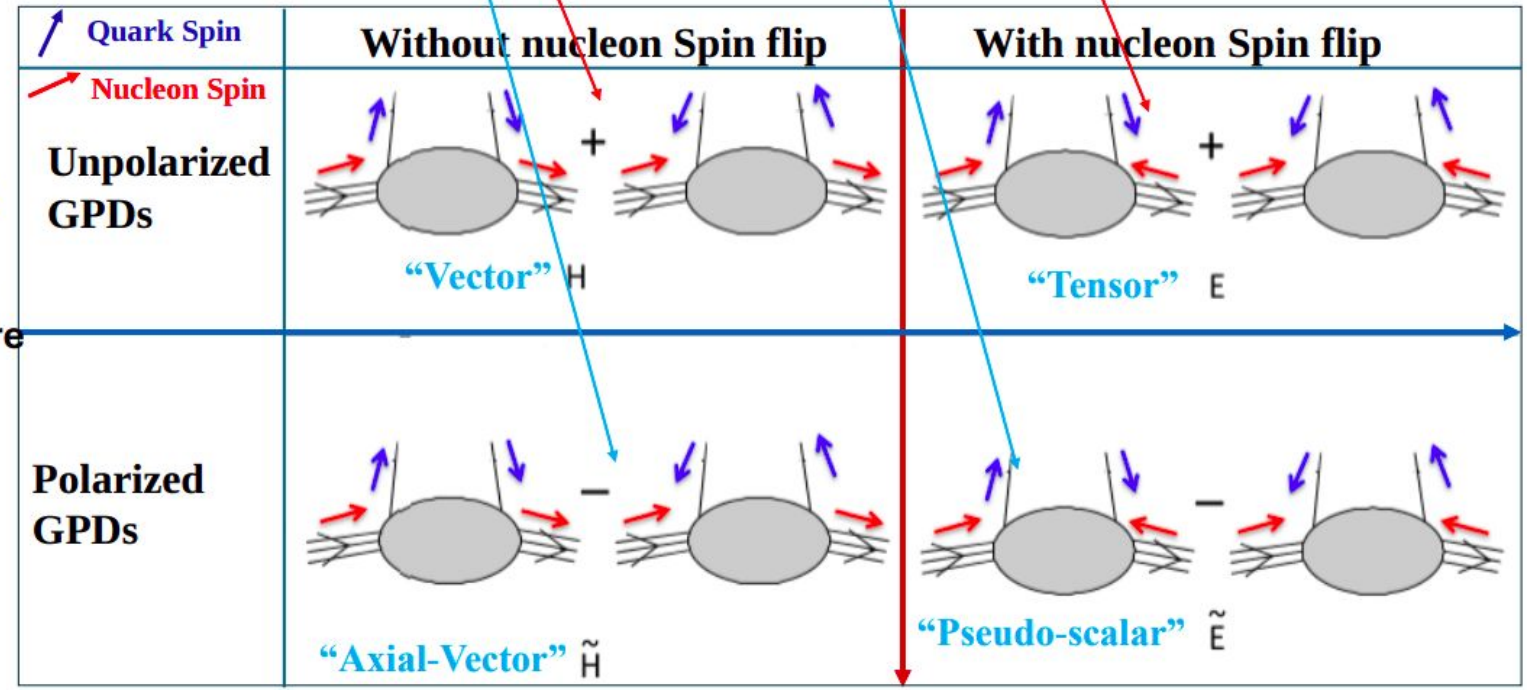


Objects in Hadron structure & reactions to access



Backup: Ji decomposition of GPDs

$$H^{\mu\nu} = \frac{1}{2}(-g_{\mu\nu})_{\perp}\int_{-1}^{1} dx \left(\frac{1}{x-\xi-i\epsilon} + \frac{1}{x+\xi+i\epsilon}\right)\left(H(x,\xi,t)\bar{u}(p')\gamma^{\alpha}n_{\alpha}u(p) + E(x,\xi,t)\bar{u}(p')i\sigma^{\alpha\beta}n_{\alpha}\frac{\Delta_{\beta}}{2m}u(p)\right)$$

$$-\frac{i}{2}(\epsilon_{\nu\mu})_{\perp}\int_{-1}^{1} dx \left(\frac{1}{x-\xi-i\epsilon} - \frac{1}{x+\xi+i\epsilon}\right)\left(\tilde{H}(x,\xi,t)\bar{u}(p')\gamma^{\alpha}n_{\alpha}\gamma_5 u(p) + \tilde{E}(x,\xi,t)\bar{u}(p')\gamma_5\frac{\Delta.n}{2m}u(p)\right)$$

Note:
The blue part of the equation is the **Quark loop part**
&
The black part is the **Nucleon structure**