Timelike Compton Scattering off a transversely polarized proton

1) Motivations
2) Experimental setup
3) Projections
4) Beam time request

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Timelike and Spacelike Deeply Virtual Compton Scattering

Timelike Compton Scattering (TCS)

$\gamma P \to \gamma^* (q') P' \to e^+ e^- P'$

$q^2 = 0$ and $q'^2 > 0$

Deeply Virtual Compton Scattering (DVCS)

$e P \to \gamma^* (q) P' \to e' P' \gamma$

$q^2 < 0$ and $q'^2 = 0$

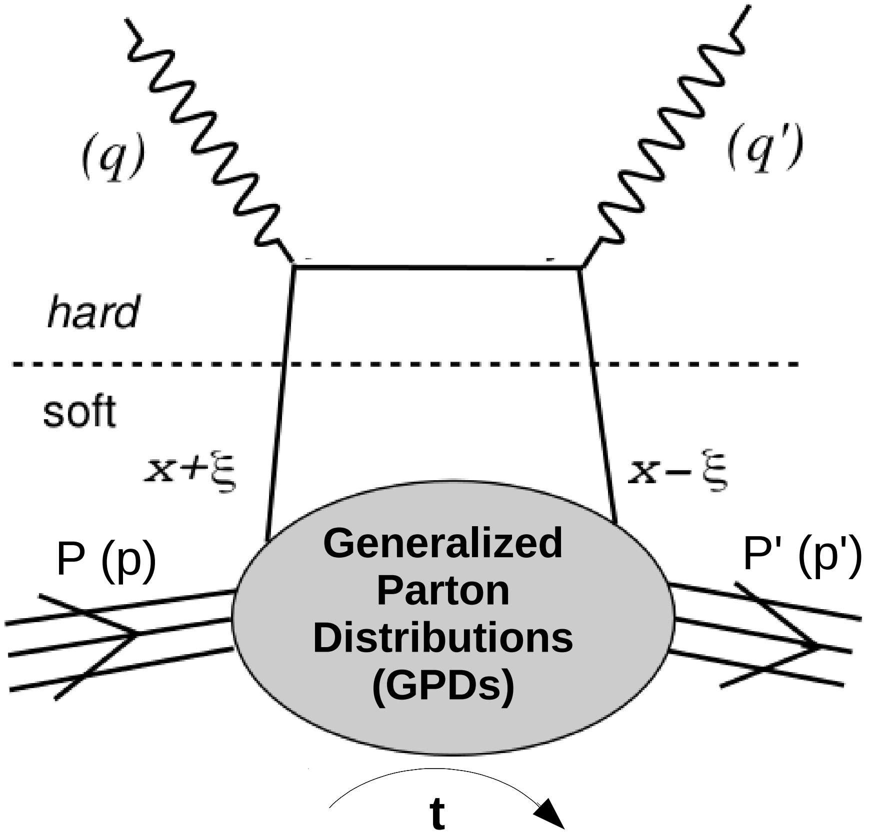
Chiral-even GPDs for proton spin 1/2:

Vector: $H(x, \xi, t)$

Tensor: E

Axial-vector: $\tilde{H}$

Pseudo-scalar: $\tilde{E}$



TCS and DVCS amplitudes are complex conjugate at leading twist, LO

Some interpretations of GPDs:

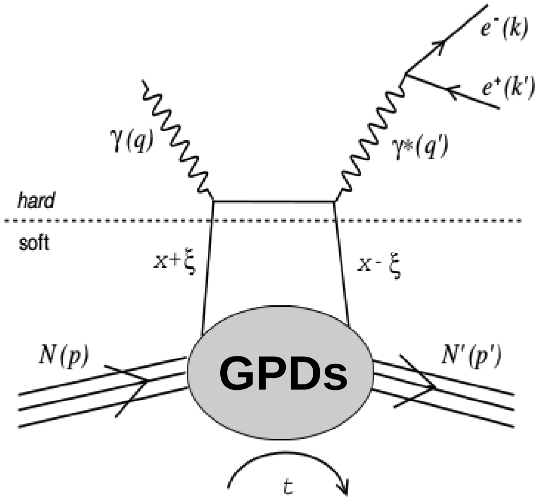
⇒ Tomographic views of nucleon with x-dependent impact parameter distributions

⇒ Parton's angular momenta with first moment in x of H and E

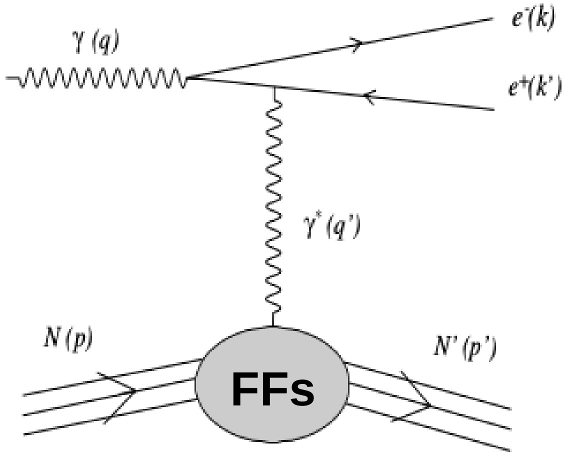
Lepton pair photoproduction

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

TCS

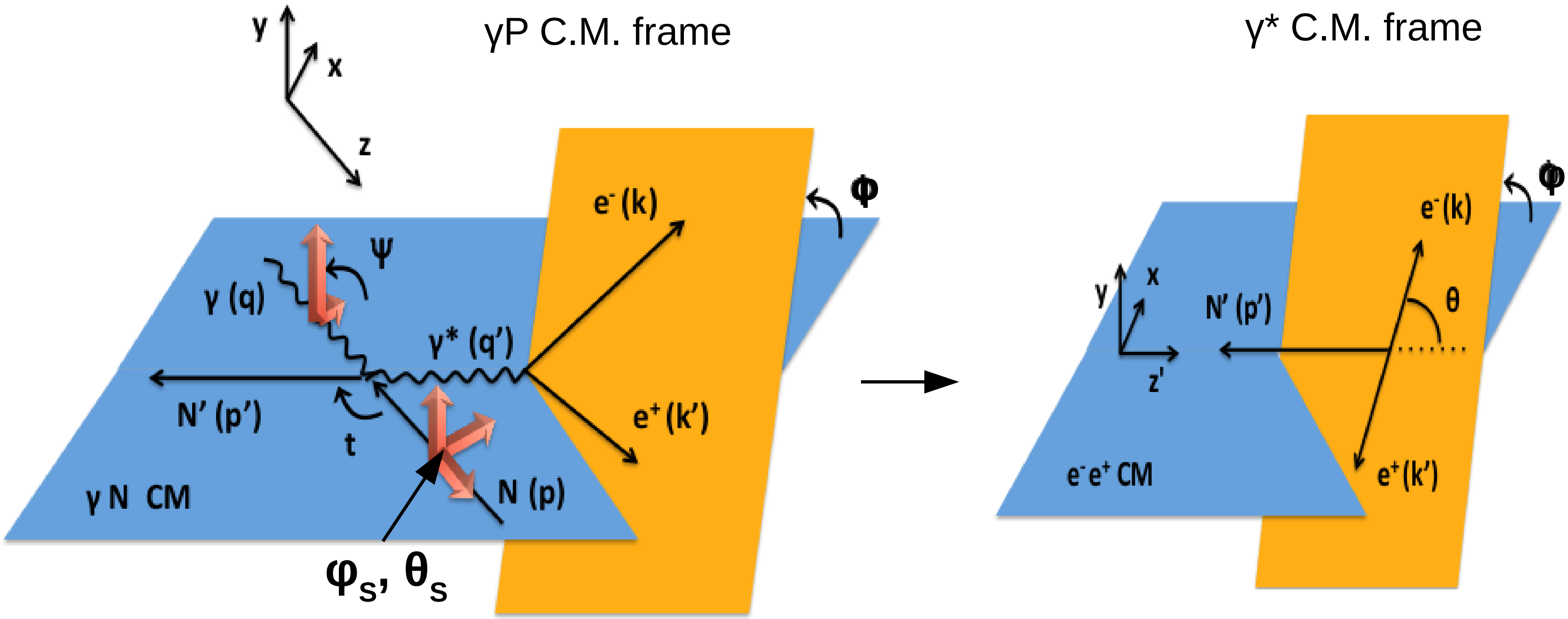


+ Bethe-Heitler



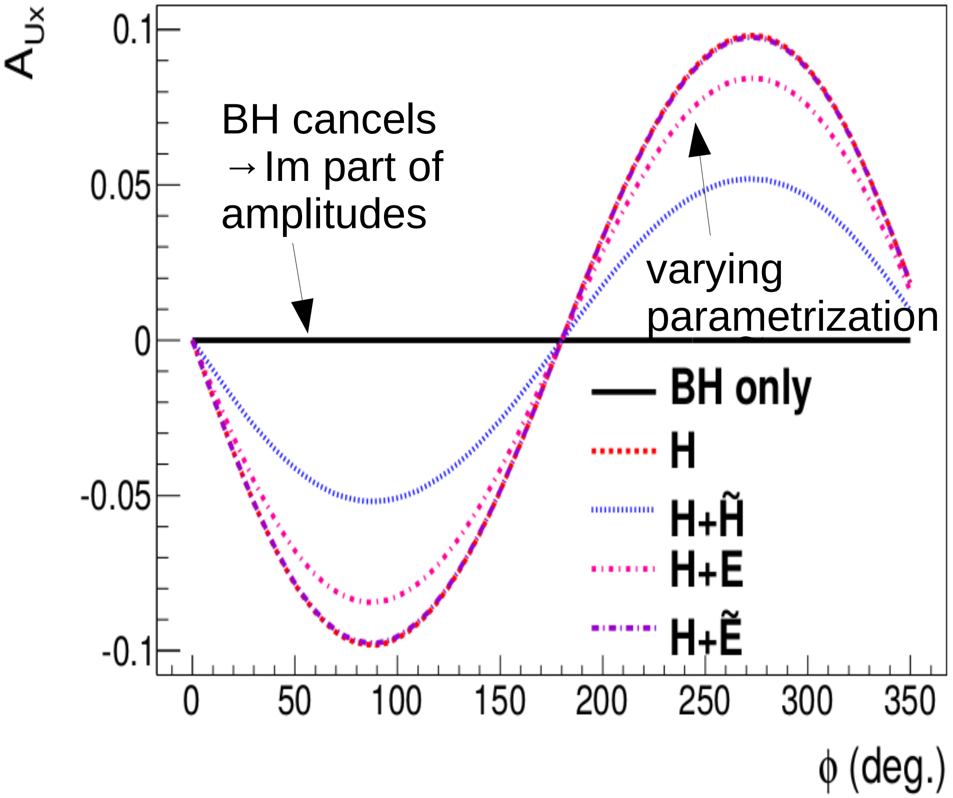
5-differential unpolarized cross section: ξ, Q'^2, t, φ, θ

6-differential with transversely polarized proton: φ_s



Transversely polarized target spin asymmetries

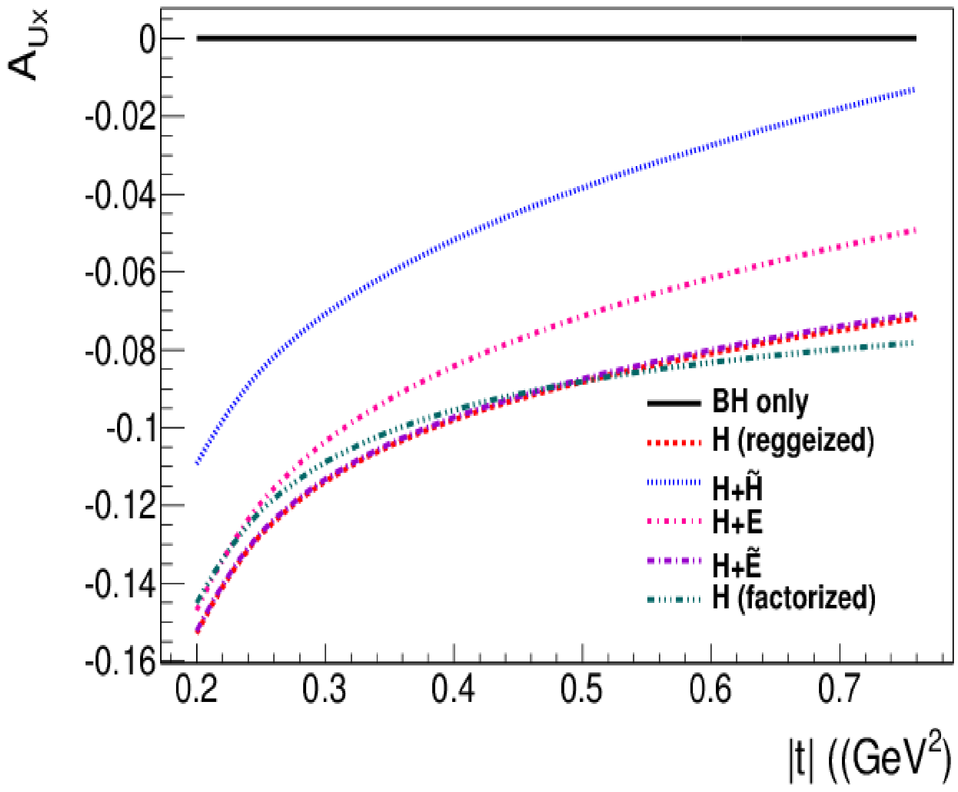
A_{UT} vs φ at φ_S=0°, model dependence



BH cancels
→Im part of
amplitudes

varying
parametrization

A_{UT} vs -t at φ=90°, φ_S=0°, model dependence



Sensitive to Im part of amplitudes

→BH cancels for single spin asymmetries

→reflect interference between TCS and BH

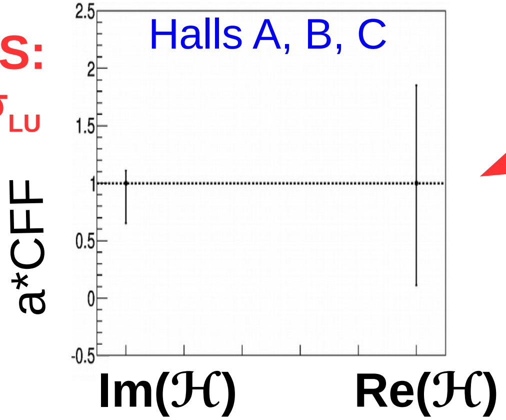
→access Im($\mathcal{H}$), Im($\tilde{\mathcal{H}}$), Im($\mathcal{E}$)

Strong model dependence on GPD E parametrization and quark angular momenta

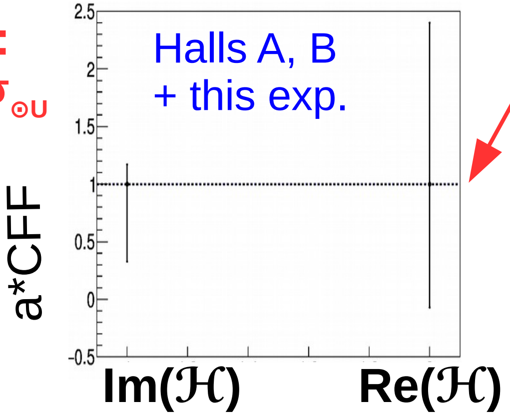
Compton Form Factors from DVCS and TCS

Extracted CFF uncertainties for DVCS, TCS, various sets of observables

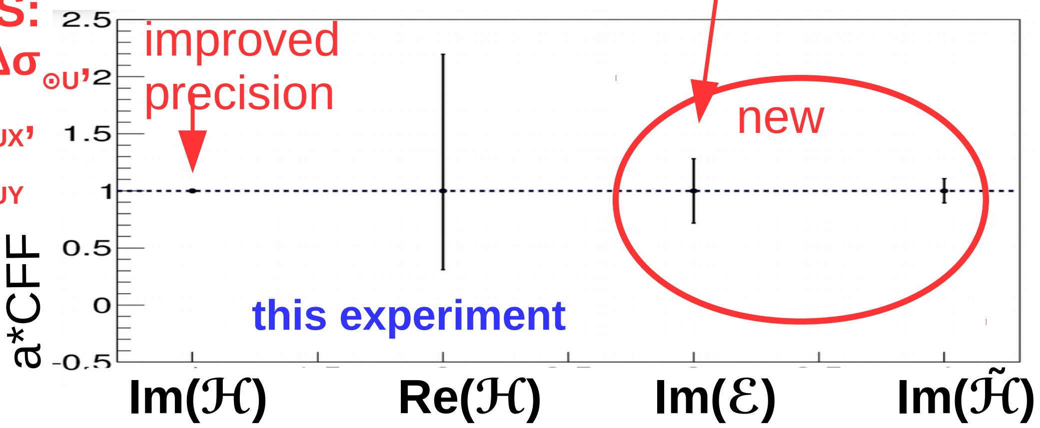
DVCS: σ, $\Delta\sigma_{LU}$



TCS: σ, $\Delta\sigma_{\odot U}$



TCS: σ, $\Delta\sigma_{\odot U}$, $\Delta\sigma_{UX}$, $\Delta\sigma_{UY}$



- **CFFs from TCS at same level than DVCS**
- **Im($\mathcal{E}$) extracted thanks to transverse target**

Interpretation of extracted CFFs:

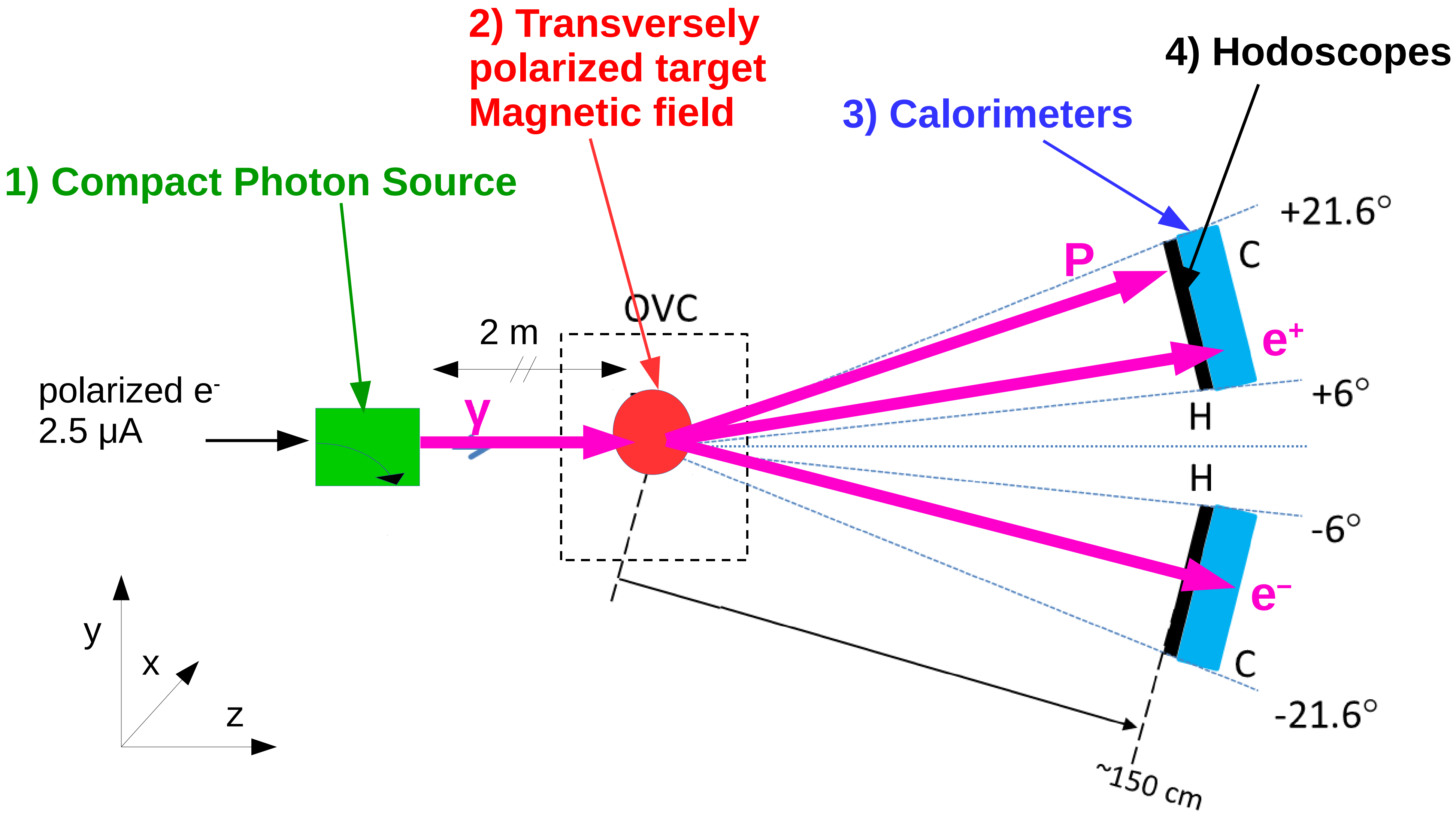
- global fits → if small higher twist
- GPD universality → if small/medium higher twist
- observation of higher twist spacelike/timelike

- **Higher twists: opposite direction in DVCS vs TCS % level effect on Im part, ~10% on Re part of extracted CFFs → lower than CFF uncertainties**

Fits of CFFs from DVCS and TCS obs., same (ξ=.1, -t=.2GeV²), leading twist/order CFFs = functions of GPDs, H → Im($\mathcal{H}$), Re($\mathcal{H}$)
Pseudo-data: 5% error (unpol) or 7% (pol) /16 φ bins, generated a*CFF=1, VGG model with 7 free param. errors: typical exp scenario without acceptance in φ

Proposed setup in Hall C

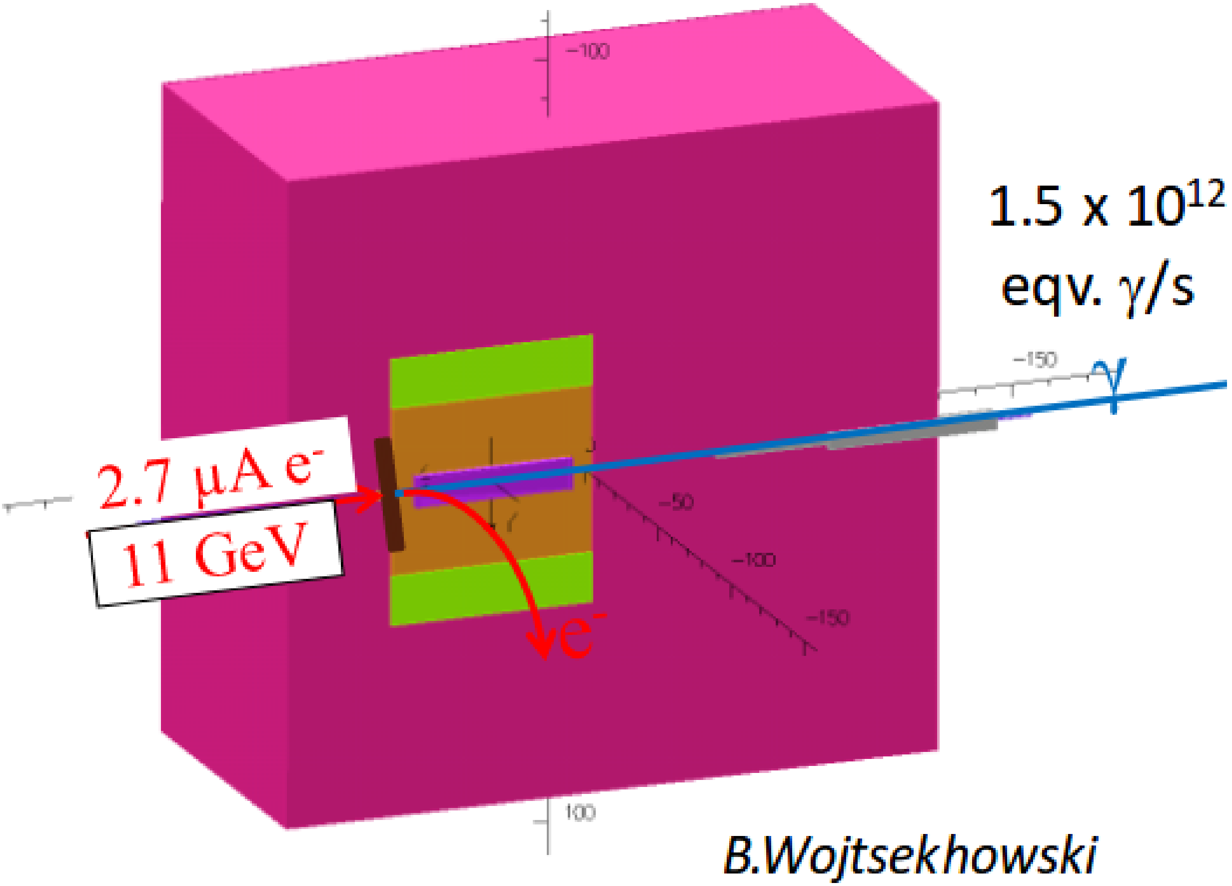
$\gamma P \rightarrow e^+e^- P'$



Compact Photon Source

- Cu radiator 10%
- e^- bended in 2.2 T field, 40cm magnet, dumped in magnet
- 2 mm collimator → 0.9 mm spot in target
- W external shielding

- 2.5 μA e^- beam → 1.5 x10^{12} γ/s
- ~75% average circular photon polarization rate E_γ>7.5 GeV



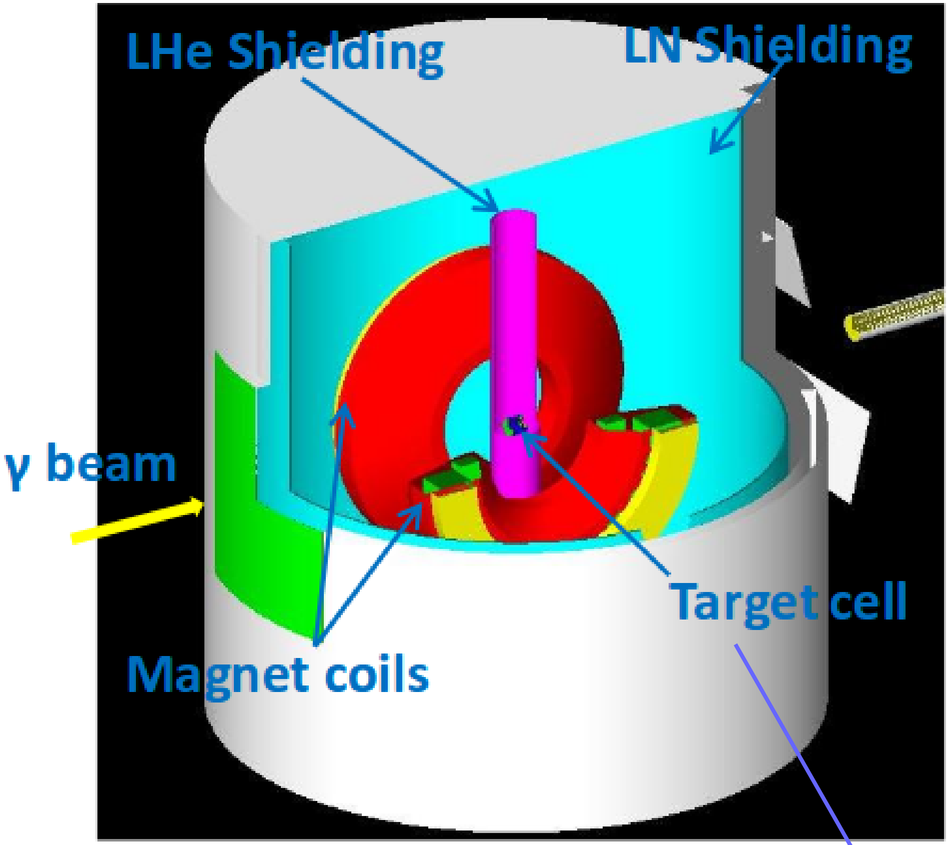
- Target at 2 m:

- no impact of fringe field from target ~10 Gaus << 2T
- no impact of CPS field on target (5T magnet)

- Plug in aperture to remove lower tail of bremsstr. spectra:

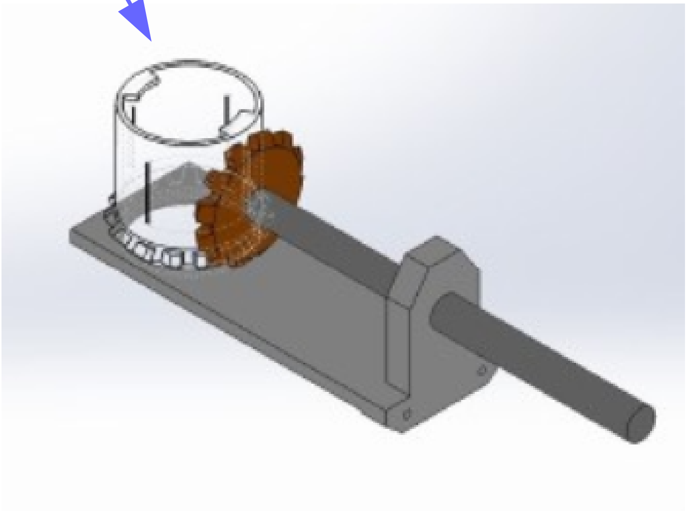
option will be explored, different background

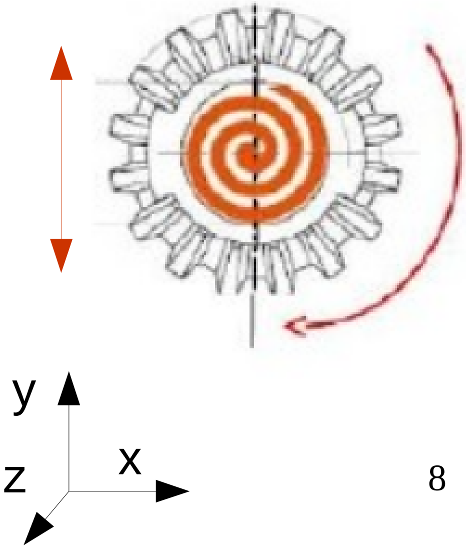
Transversely polarized target JLab/UVA



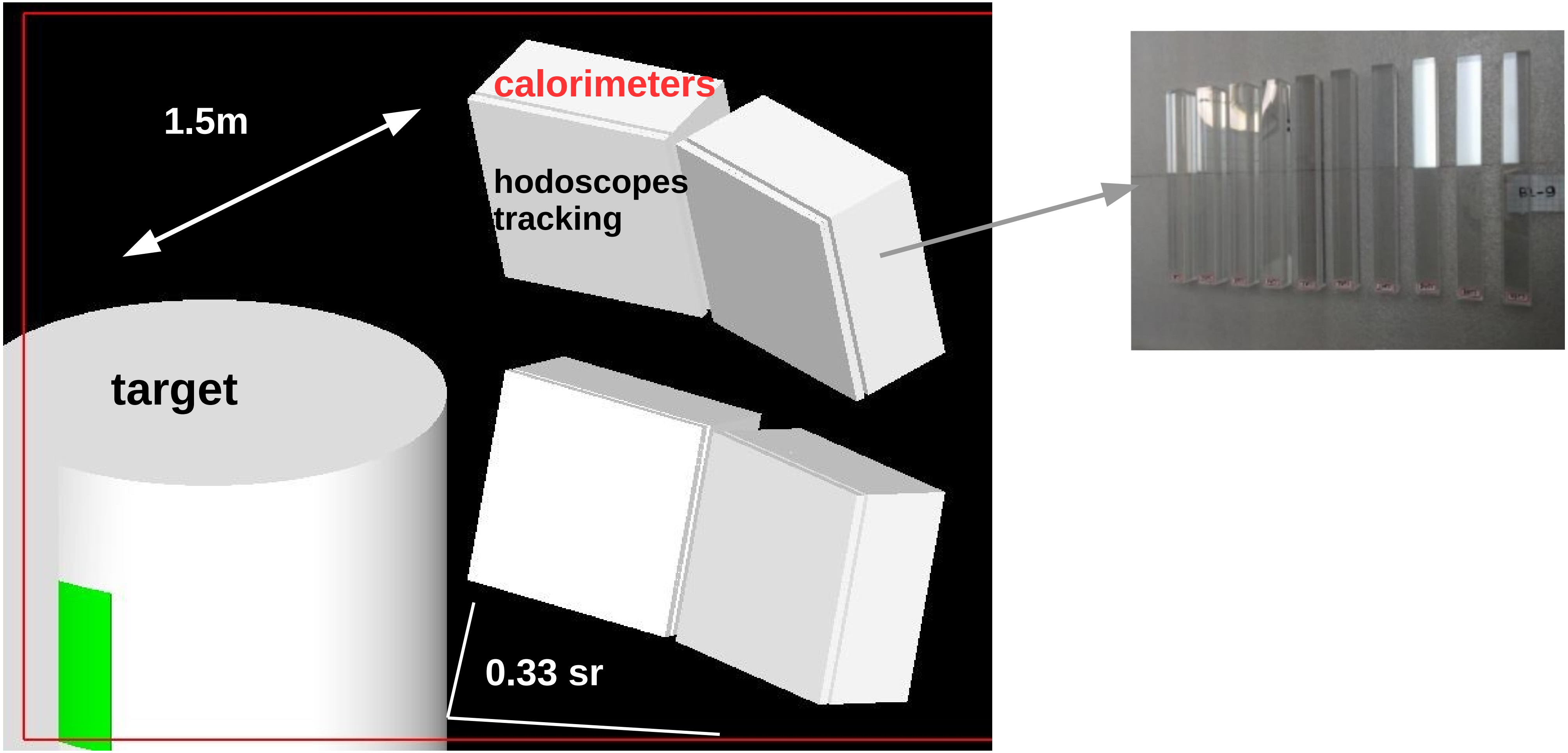
UVA target, TCS configuration

- **Target: $^{15}NH_3$ in ^4He, 0.6 packing fraction**
- **DNP 140 GHz RF / 5T magnetic field**
- **90° magnet and scattering chamber rotation**
- **Acceptance: ±17° horizontal, ±(6°-21°) vertical**
- **Up/down and rotation of target cup to avoid radiation damage,**
speed adjusted to avoid fatigue on insert





Calorimeters



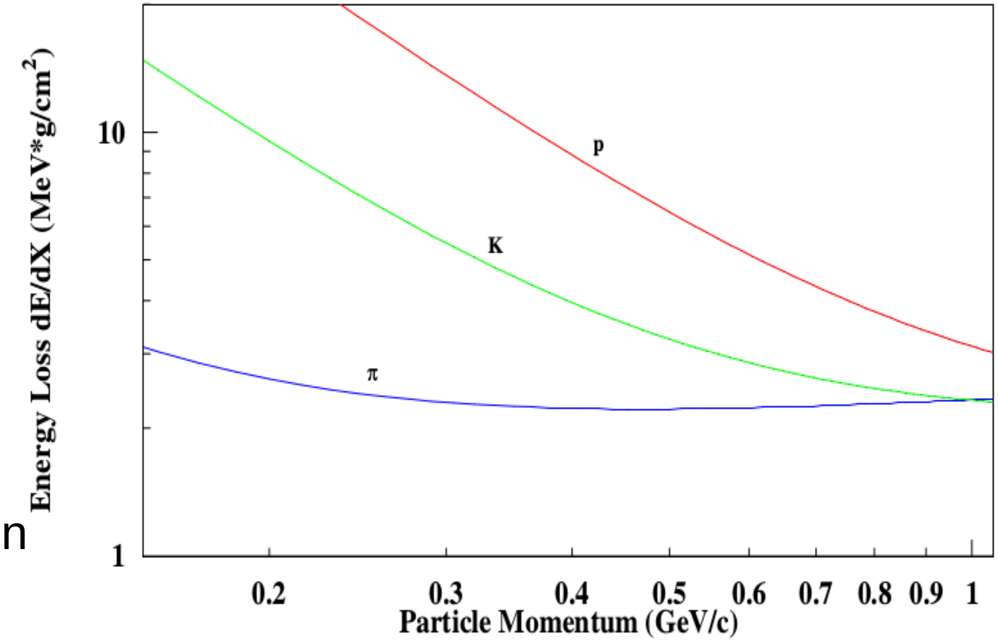
- 2*2 PbWO calorimeters with 2116 blocks total, active area 0.74 m²
- 22.5 radiation lengths deep
- Vertical aperture θ = ±1.6°: region affected by high rates from transverse magnetic field
- Resolutions from PrimEx HYCAL tests, at 1 GeV: $\sigma/E \approx 3\%$, $\sigma_x \approx 3$mm, $\Delta m(\pi°) = 2.3$ MeV
- In-situ calibration as SANE Hall C and DVCS Hall A exp., using π° electroproduction

Tracking and recoil proton detector

Proposed:

- Hodoscopes, XY planes 1cm thick scintillator
- 4 segments in front of calorimeters ~1.5m from target, 1 m² active area total
- Cut for high rates: vertical ±1.6°
- PID from dE/dx. 0.3 to 1.3 GeV protons
- tracks bend vertically in magnetic field from target, back-tracking e^+e^- for vertex reconstruction

dE/dx for protons, π and K vs momentum



Solution explored for high rates:

- **Smaller or thinner scintillators**
- **Super BigBite-like large size GEM, 50cm*60cm (same surface)**

→ rates up to 1 MHz/cm²

→ minimal material along track path

→ sub-mm coordinate resolution

→ pointing accuracy < ±50 mrad

Trigger and DAQ

- **High rates ≈ 10^5 Hz**

→ momentum thresholds : $p(e^-)+p(e^+)$ >5 GeV, 2D cuts on E and P

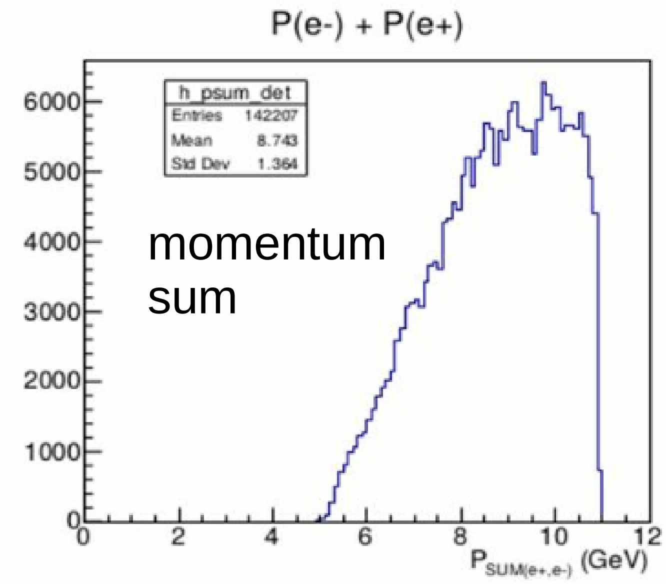
→ Triple coincidence and missing mass requirements

- **Electronics / DAQ layout:**

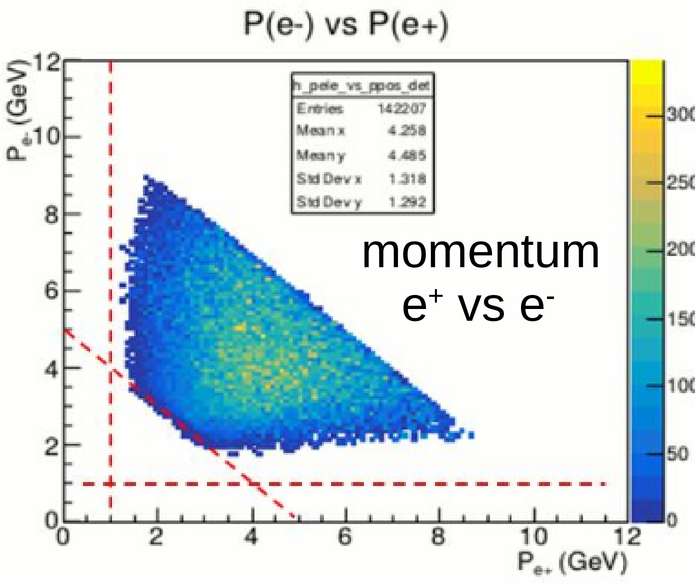
→ flash ADC as used in NPS Hall C experiment

→ concept similar to HPS Hall B and DVCS Hall A experiments as cluster triggering

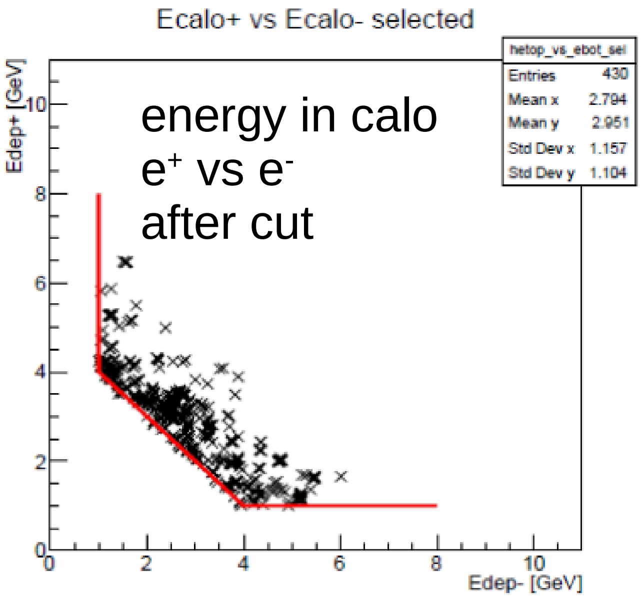
Trigger threshold cuts:



momentum sum



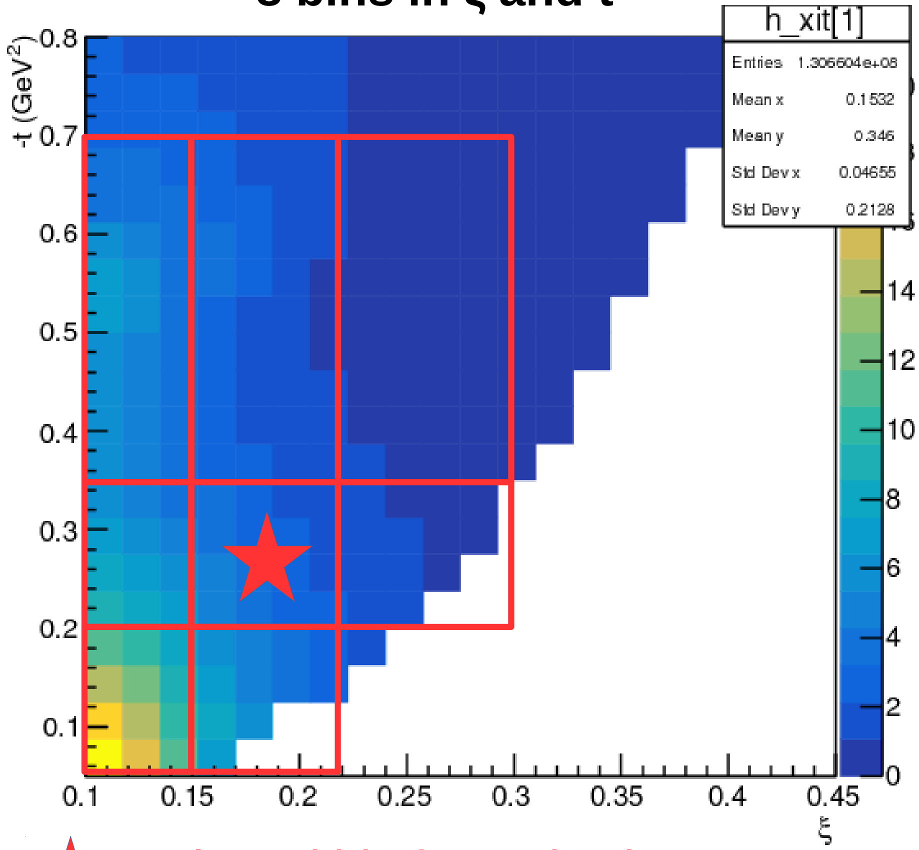
momentum e^+ vs e^-



energy in calo
e^+ vs e^-
after cut

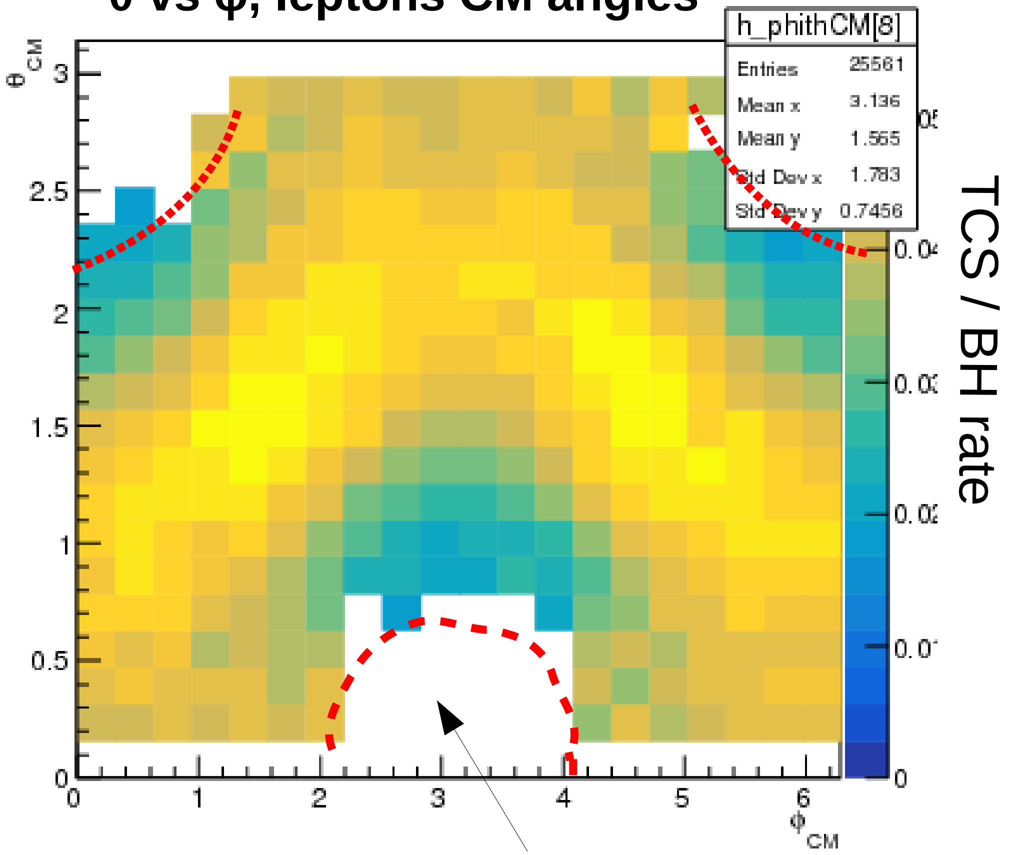
Data analysis: binning and phase space cuts

8 bins in ξ and t



★ selected bin for projections
$4<Q'^2<7$ GeV², $.15<\xi<.22$, $.2<-t<.35$ GeV²

θ vs φ, leptons CM angles



phase-space cut avoiding BH peaks

Bins: 8 (Q'^2, ξ, t), 16 φ bins, 16 φ_s bins, 7.5 <E<11 GeV, $4<Q'^2<9$ GeV² (avoid resonances)

Trigger thresholds: $E(e^\pm) > 0.7$ GeV, $E(e^+ + e^-) > 5$ GeV, $p(P) > 0.1$ GeV

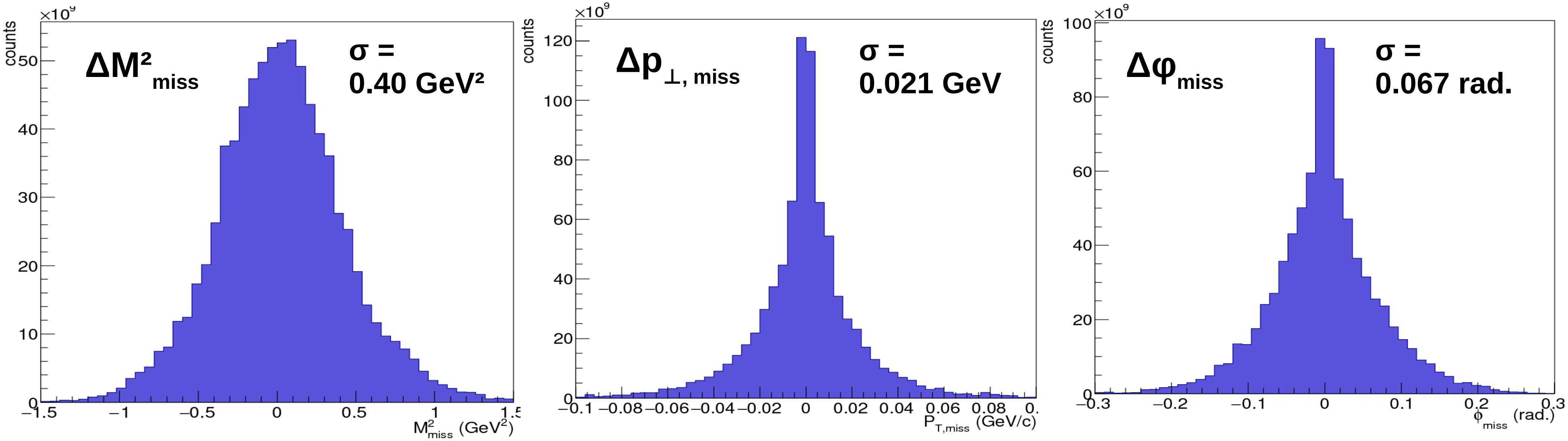
Acceptance cuts: ±1.6° vertical band in calorimeters

θ vs φ cut: integrated between BH peaks and/or [40°, 140°]

Exclusivity cuts: tagging of $e^+ e^- P$, ΔM^2, $\Delta\varphi$, $\Delta P_\perp$

Data analysis: exclusivity cuts and dilution factors

Exclusivity cuts γ P → e^+e^- P from balance e^+e^- vs P.   γ untagged: "miss"=beam



- **Re-evaluation of target dilution factor: ($^{15}NH_3$, 0.6 packing fraction in ^{4}He)**

- 27% quoted in proposal: assume proton detection but no exclusivity
- exclusivity cuts exclude inner shell protons more affected by Fermi motion + FSI

⇒ (1-f) ~ 0.43 of "effective" protons are polarized, P > 0.90±0.05 : (1-f)* P ~ 0.40

- **Dilution of unpolarized cross section and beam spin asymmetries:**

- counting rates of proposal: only interaction with 3 H from NH_3, i.e. after subtraction of incoherent scattering off N and He

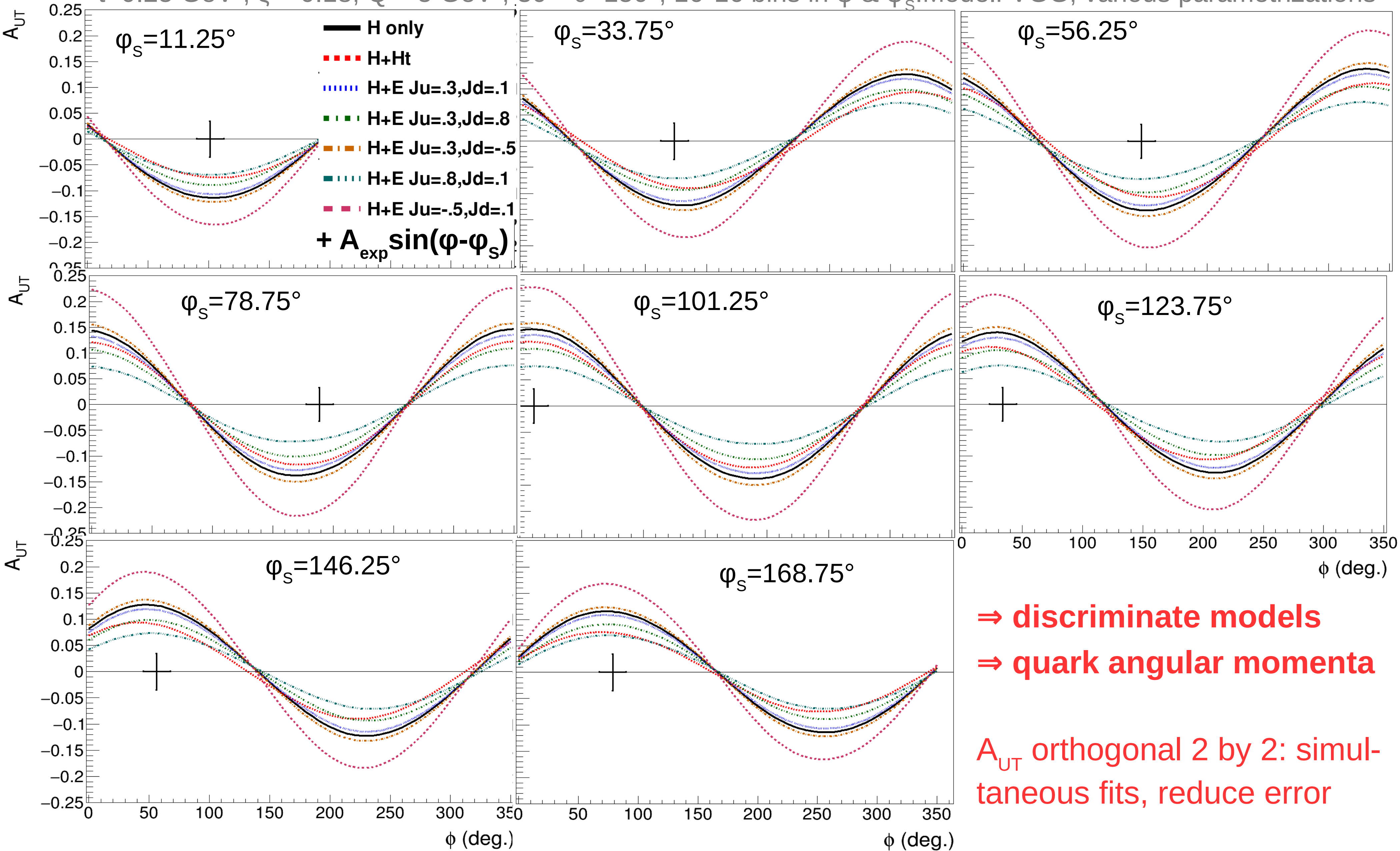
- **Frozen N target in ^{4}He: direct measurement of background for dilution factor**

⇒ need 5 days for ~5% uncertainty on BH from N and He

A_{UT} versus φ_S: experimental errors and model dependence

Error bars on first moment fit $A*\sin(\varphi-\varphi_S)$ for 8 φ_S bins and one (ξ, t, Q'^2) bin versus models

$-t=0.25$ GeV²; $\xi = 0.18$, $Q'^2=5$ GeV², 30°<θ<150°, 16*16 bins in φ & φ_S.Model: VGG, various parametrizations



⇒ discriminate models

⇒ quark angular momenta

A_{UT} orthogonal 2 by 2: simultaneous fits, reduce error

- Uncertainties on moment scaled to theory curves, using 43% target dilution, 90% polarization
- Small asymmetries case of "red" scenario using $H+\tilde{H}$ in event generator used for the proposal

Main systematics

SOURCE	VALUE	COMMENTS
target polarization	0.05	NMR measurement
target dilution factor	≈ 0.02 SANE result	depend on analysis cuts / possibility of run off frozen N similar target
beam polarization (for $A_{\odot U}$)	0.02	measured
luminosity (for σ and $\sigma_{\odot U}$)	-	CPS in development
background subtraction ($\pi^{\pm}$, accidental)	-	ongoing measurements other Halls
target resonances	< 0.01	with proton detection
interaction with target material	negligible	with vertex reconstruction, exclusivity
analysis cuts	-	need full simulation

- **Target asymmetry measurements dominated by statistics**
- **Beam spin asymmetry measurements dominated by background suppression**
- **Cross section measurements dominated by luminosity**

⇒ luminosity request based on statistic uncertainties for target asymmetries

Beam Time Request

Total: 16 calendar days without beam, 35 PAC days commissioning and physics

setup and installation	5 calendar days
signal and electronic checkout	5 calendar days
gain matching of the detector's channels	1 calendar day
commissioning with beam	**5 PAC days**
physics	**30 PAC days**
target annealing	1 calendar day
PbWO crystal recovering	1 calendar day
decommissioning	3 calendar days

Beam, 35 PAC days:
2.5 μA e^- beam,
> 85% longitudinally polarized,
E(e) = 11 GeV

SUMMARY

PHYSICS

- CFFs Im(H), Im(E), Im($\tilde{H}$), Re(H) thanks to transversely polarized target
- Constraints on GPD universality: timelike process (TCS) versus spacelike (DVCS)
- GPD E and H: constraints on quark angular momentum

SETUP

- Compact Photon Source: high intensity real photons (1.5 x10^{12} y/s)
- 2*2 PWO4 electromagnetic detectors for e^+e^- pair, extension of NPS experiment
- Transversely polarized NH_3 target
- Development: GEM to handle higher rates, for P and $e^\pm$ tracking

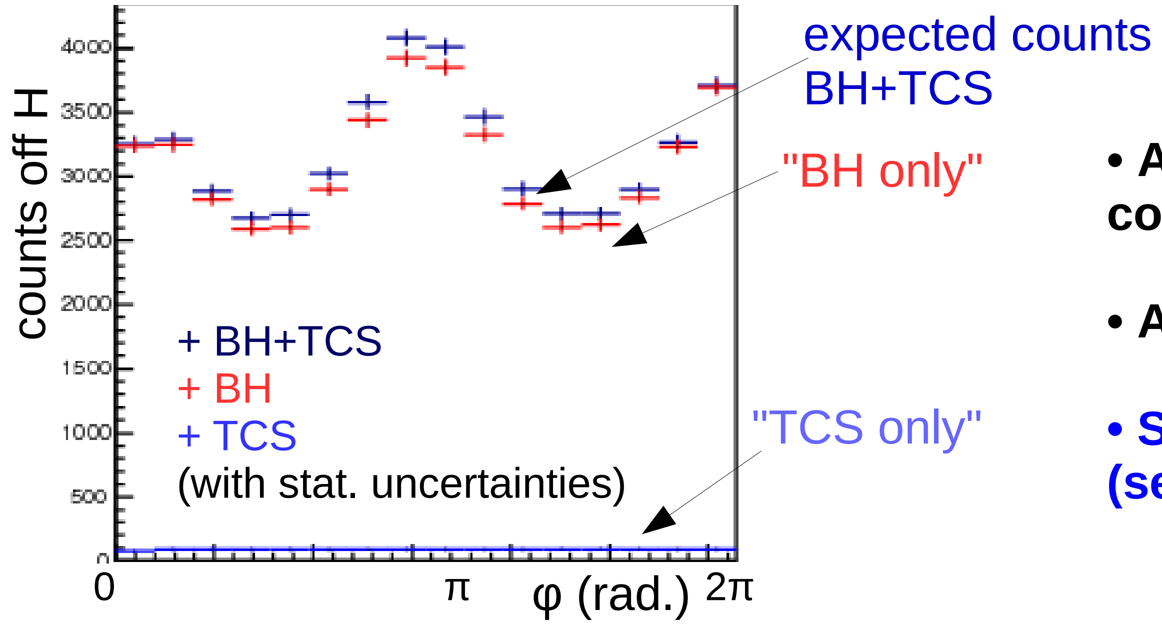
- Request: 35 PAC days with 11 GeV 2.5 µA polarized e^- beam + 16 days for operations

BACKUP

Unpolarized and beam polarized observables off H

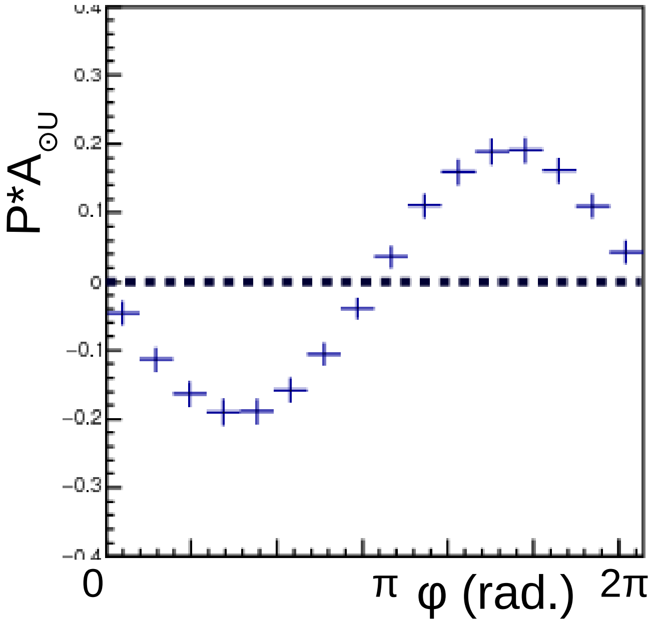
Unpolarized counting rates off H nuclei

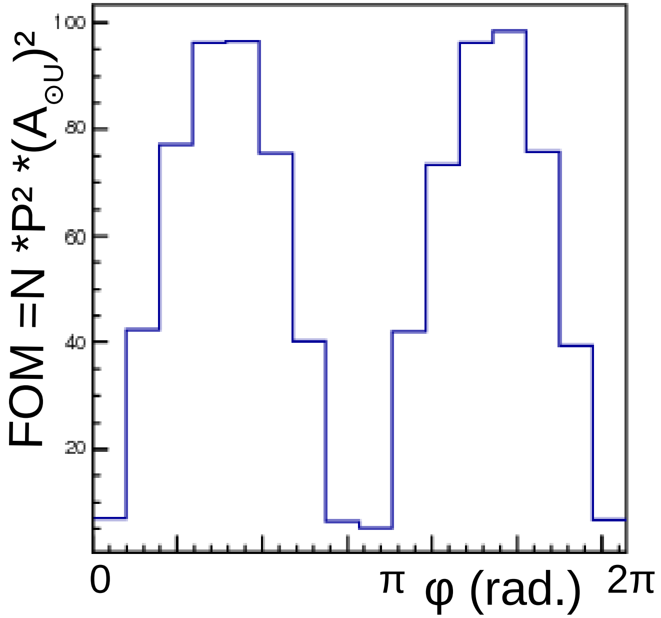
$0.2 < -t < 0.35$ GeV^2,
$0.15 < \xi < 0.22$



- **Averaging over proton polarization, counts only off H nuclei**
- **Access Im(H), Re(H)**
- **Similar FOM than beam asymmetries (sensitive to GPDs through interference)**

Beam spin asymmetries and statistical FOM





- **Large beam asymmetries, low statistic uncertainties**
- **access Im($\mathcal{H}$), sensitive to Im(CFFs)**
- **Included: statistics from 3 H in NH$_3$, beam polarization ~.75**
- **Not included: background contribution, systematics**

Experimental context at Jefferson Lab

- **Exploratory measurement of cross section at 6 GeV at CLAS (2012)**

- **Cross section and circularly polarized beam asym at 11 GeV:**

- ongoing: CLAS12 E12-12-001, 100 days at 10^{35} $cm^{-2}s^{-1}$ → **access Im(H) and Re(H)**

- future: SoLID E12-12-006A, 50 days at e^- flux 10^{37} $cm^{-2}s^{-1}$ → **Im(H), Re(H), binning in Q'^2**

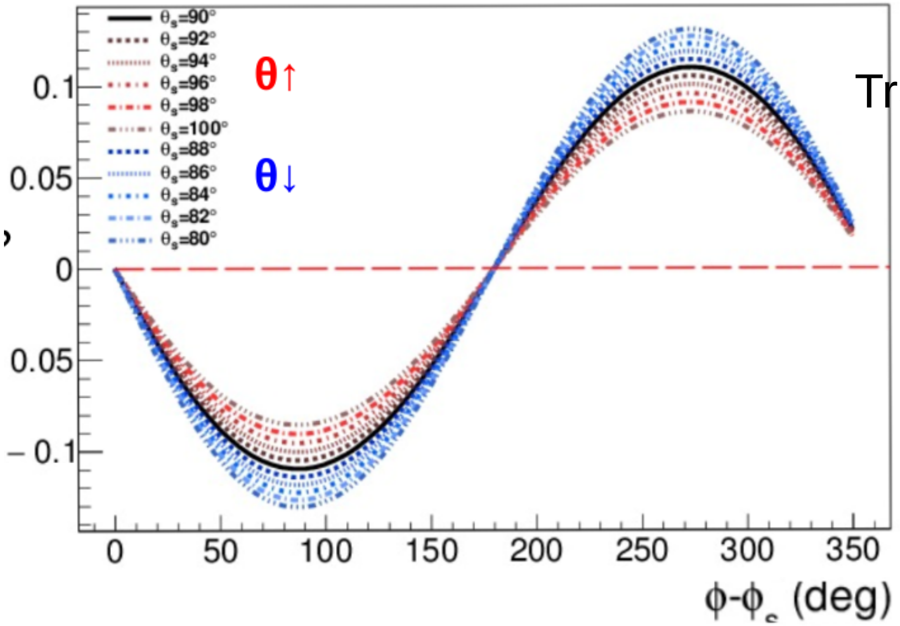
- **This experiment (Hall C, NPS-like setup)**

- 30 days with real photon flux ≈ 10^{35} $cm^{-2}s^{-1}$ i.e. 10^{12} γ/s

→ **high luminosity: L(γ*p) = 5.85×10^5 pb^{-1} off transversely polarized target**

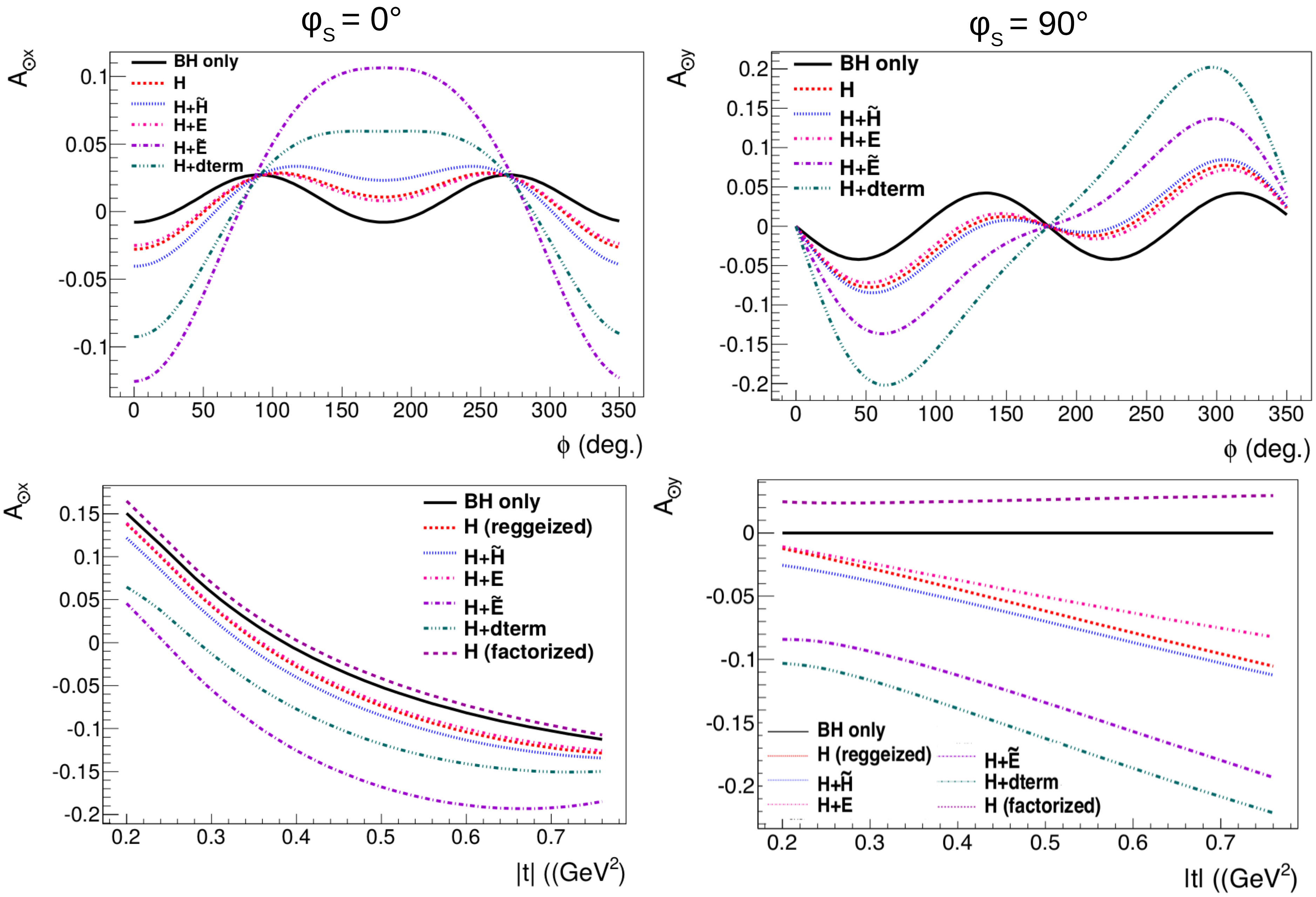
→ **avoid angular and kinematic corrections thanks to real γ, ensure exclusivity (ΔpT=0)**

- transversely polarized target → **access Im(E), Im(H), Im($\tilde{H}$), Re(H)**



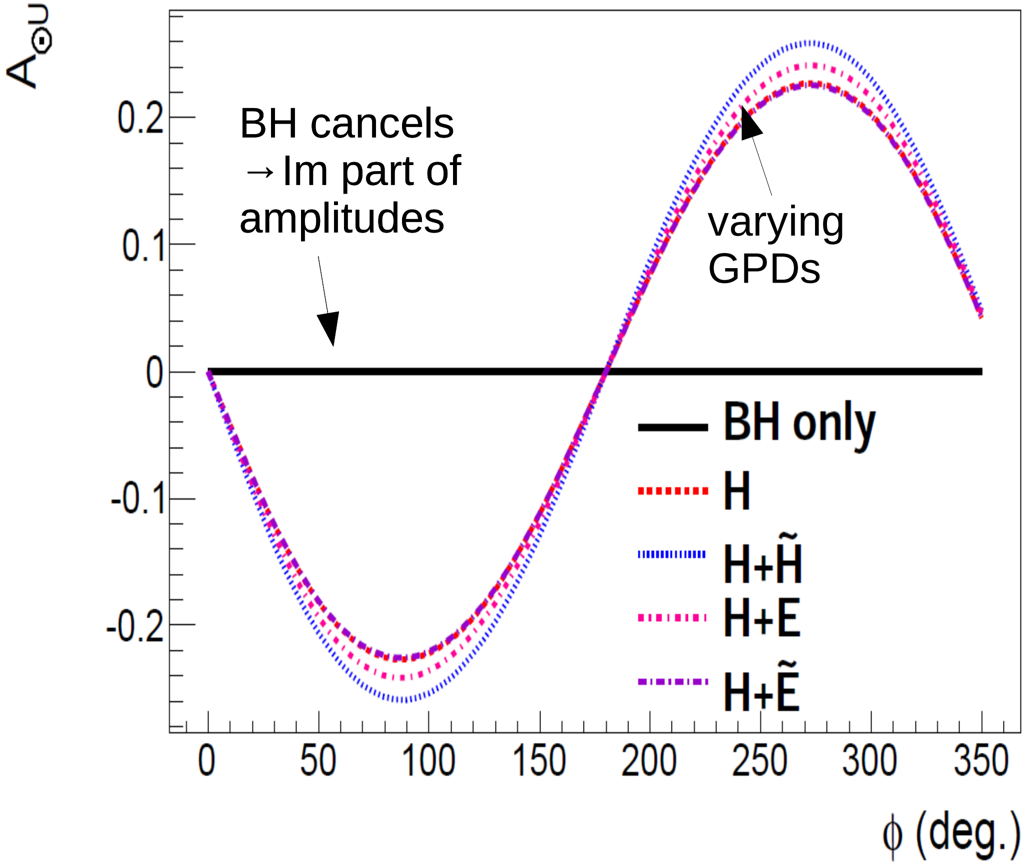
Transverse asymmetry at φ_S=0°, 80°<θ_S<100°

Double spin asymmetries: circular photon and transverse proton



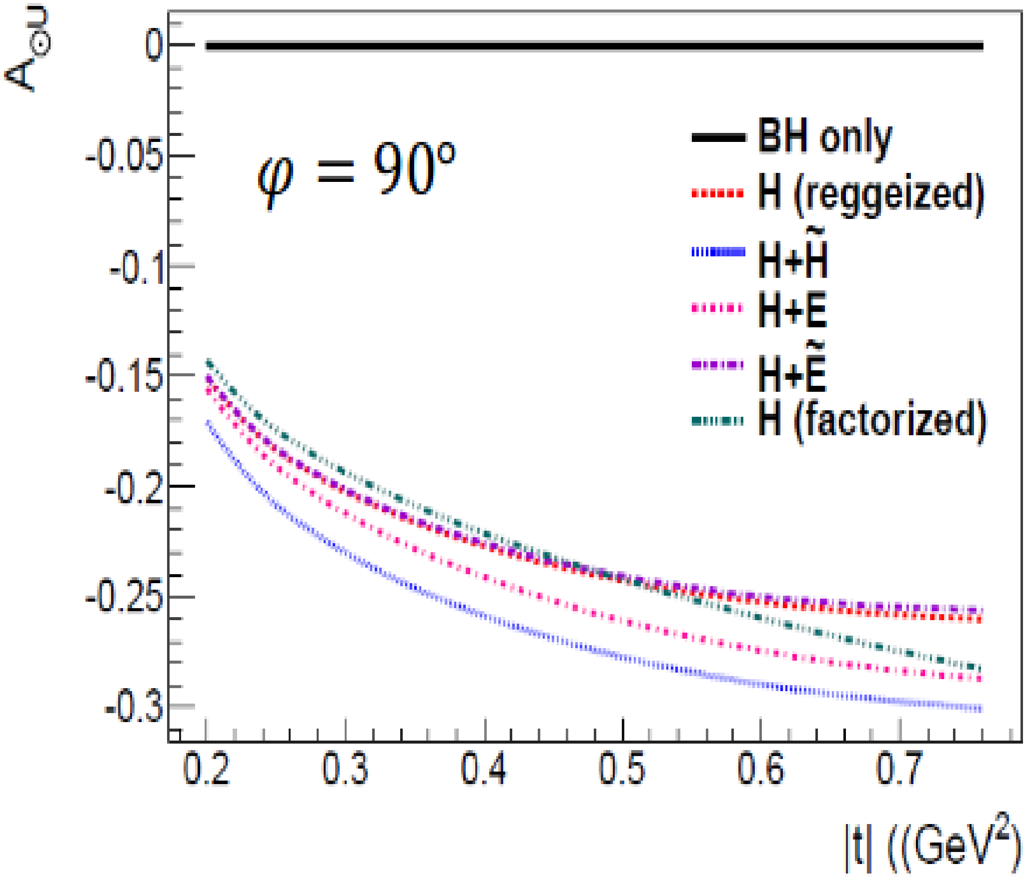
- **Very sensitive to GPD parametrization and to real part of amplitudes⇒high impact!**
- **will be measured at the same time, but larger dilution factors and BH doesn't cancel**

Circularly polarized beam asymmetries

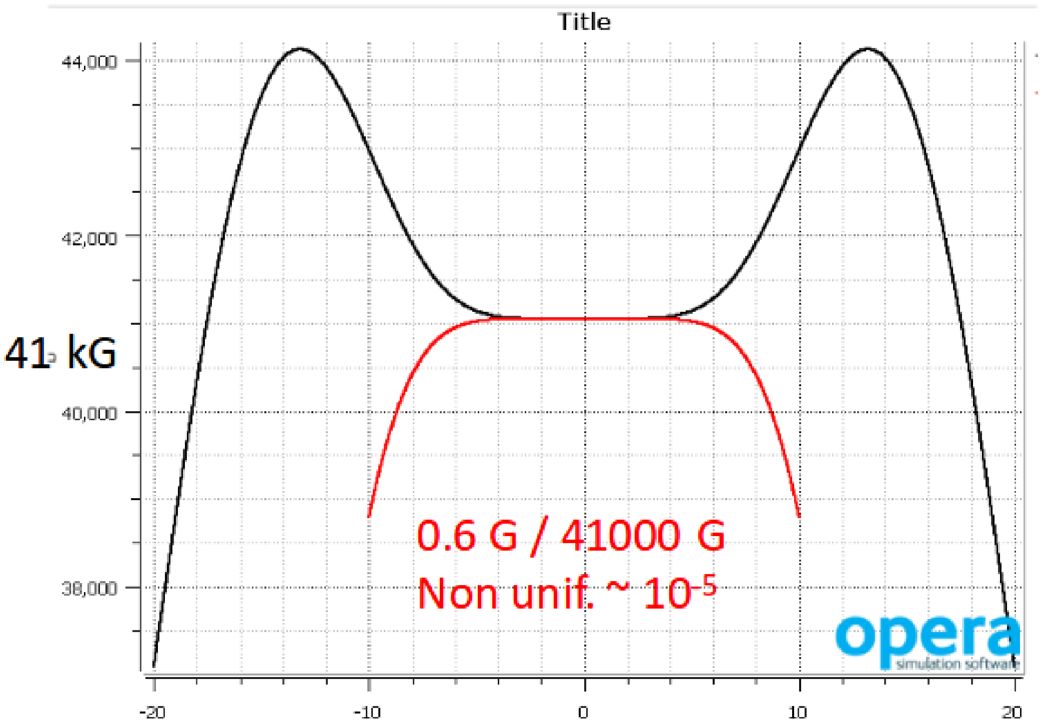


BH cancels
→Im part of
amplitudes

varying
GPDs



Wide open magnet for NH3 target



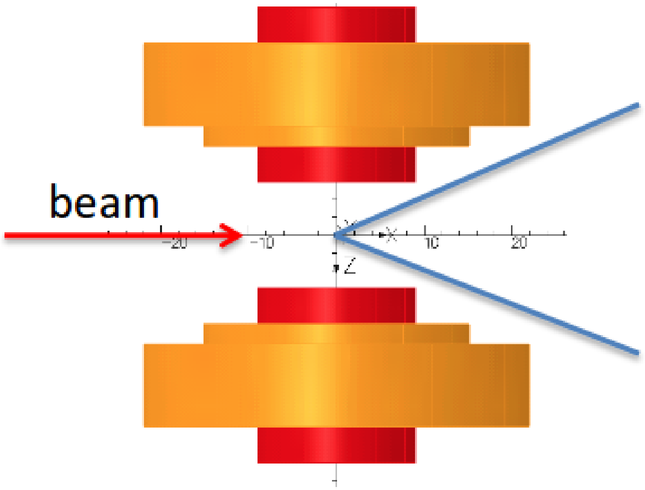
0.6 G / 41000 G
Non unif. ~ 10^{-5}

Red is Bz along the beam direction
Black is Bz along the axis of a solenoid

B.Wojtsekhowski

Double the gap (+ 10 cm)

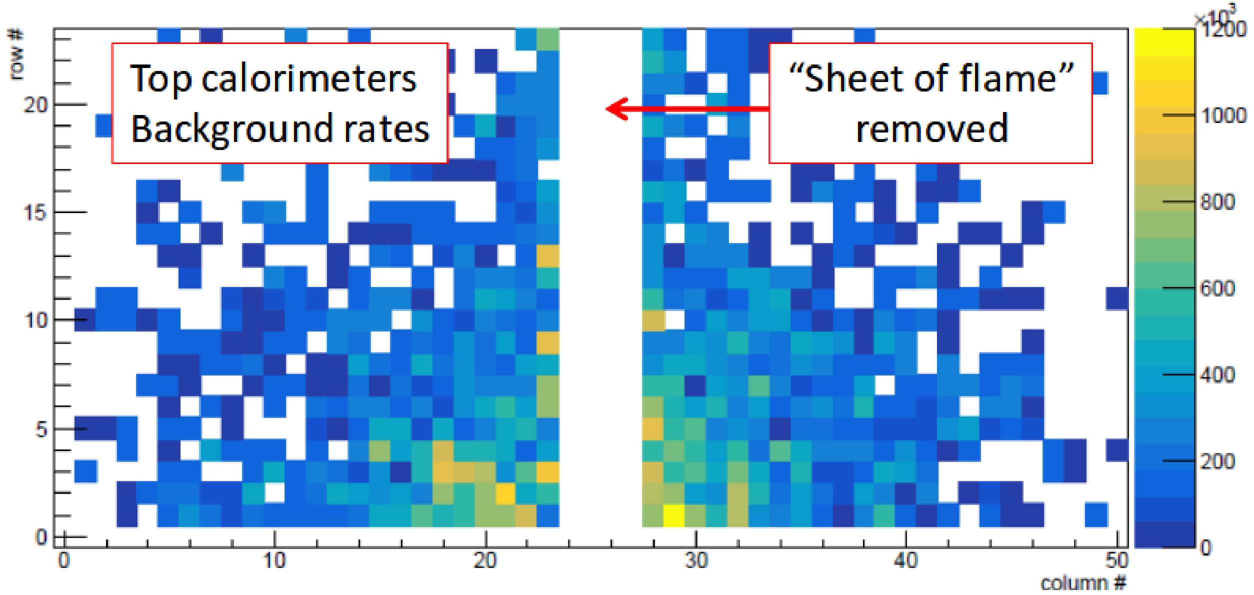
Opening is > 50 deg!!



Correction solenoids are outside of the aperture
They drive the field in opposite direction to the main coils field.

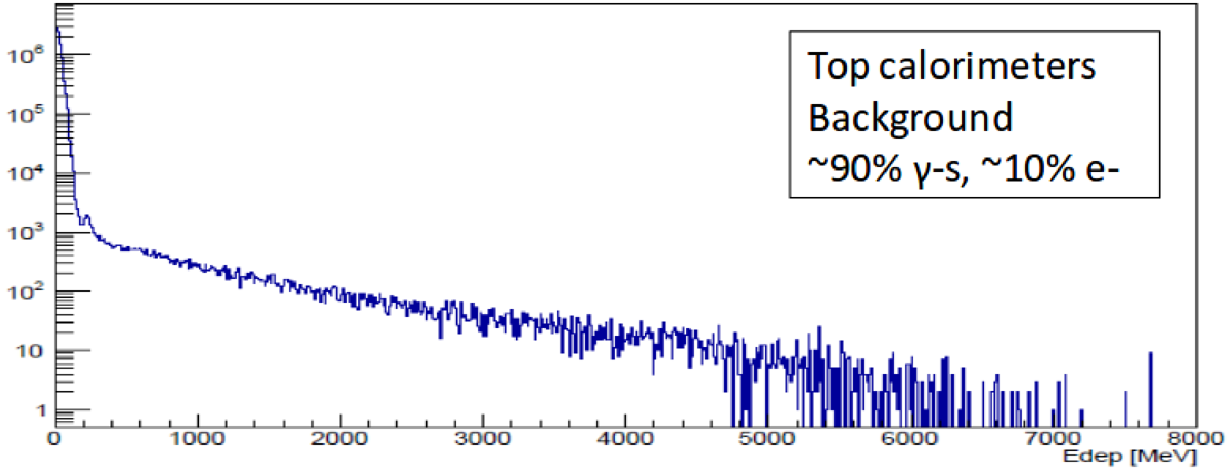
- would benefit for parallel measurements (J/ψ, backward...) and provide higher TCS/BH rates,
- need technical and cost estimate
- may need higher intensity for rates, but would solve part of background problem

Calorimeters: background rates



Top calorimeters Background rates

"Sheet of flame" removed



Top calorimeters
Background
~90% γ-s, ~10% e-

$$E_{beam} \in [5.5, 11]\ GeV, E_{calo\_hit} > 200\ MeV$$

High background rates in central part from high energetic e^+e^- from γ conversion in target

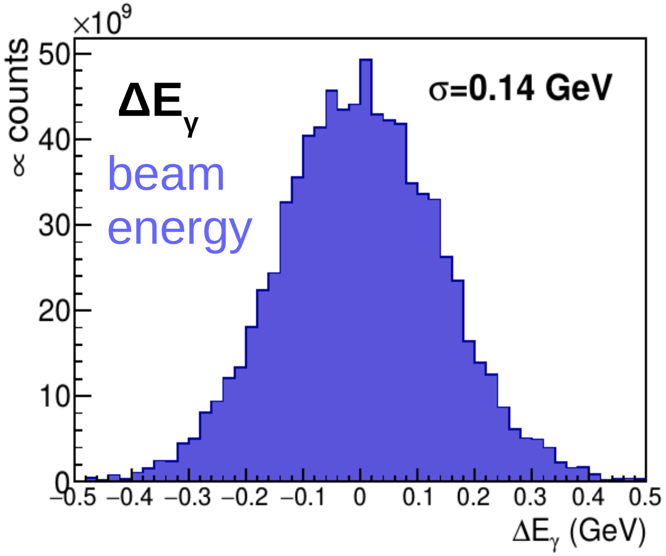
→solution to cut the central part of the calorimeters as above

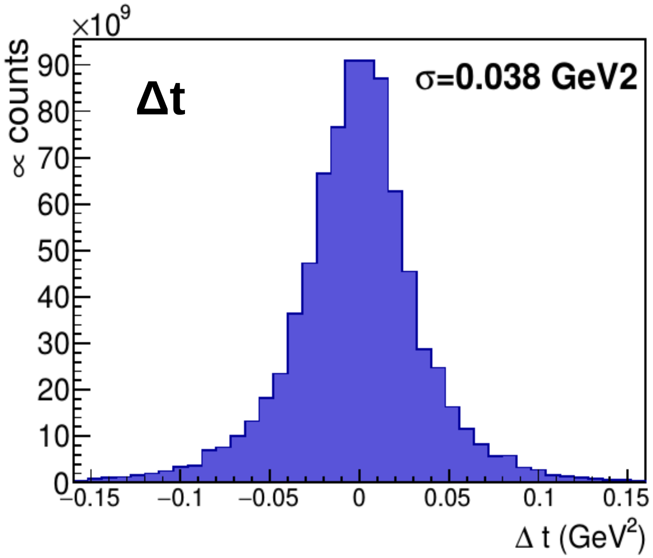
→suggested: plug in CPS magnetic field to cut low energy tail of bremsstrahlung. Need to be simulated, estimate of background and studied on physics side, may impact observables

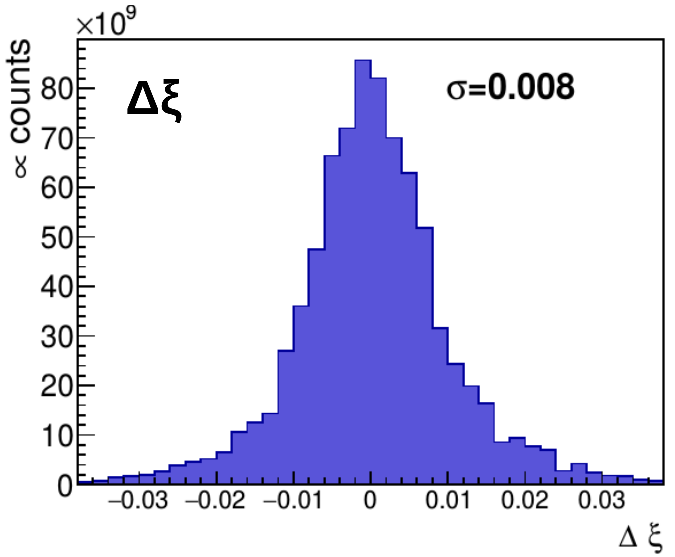
Data analysis: beam energy and resolutions

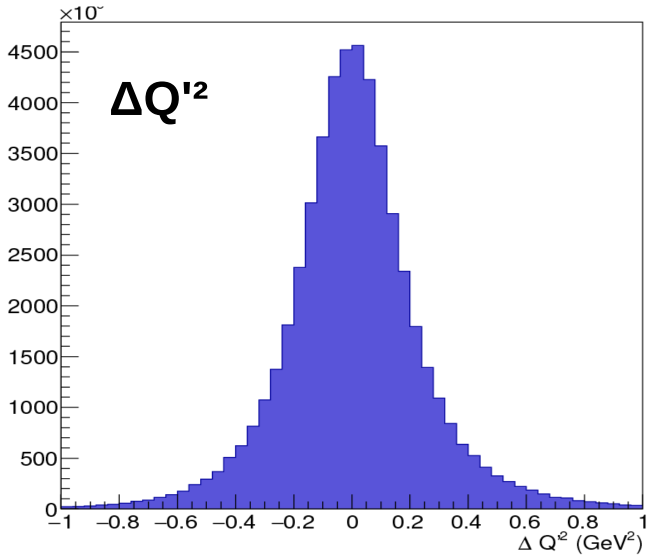
γ P → e^+e^- P, exclusivity from balance e^+e^- vs P ⇒ "miss" ≡ photon beam = (E_γ, 0, 0, E_γ)

Resolutions: E_γ (gen) – E_{miss} ; t (gen) - t ; ξ (gen) - ξ









δE/E beam <2%, δξ and δt « (ξ, t) bin size

- Proton resolution:
  δp/p = 0.10
  δx = 2cm /√12 at 1.5 m from vertex

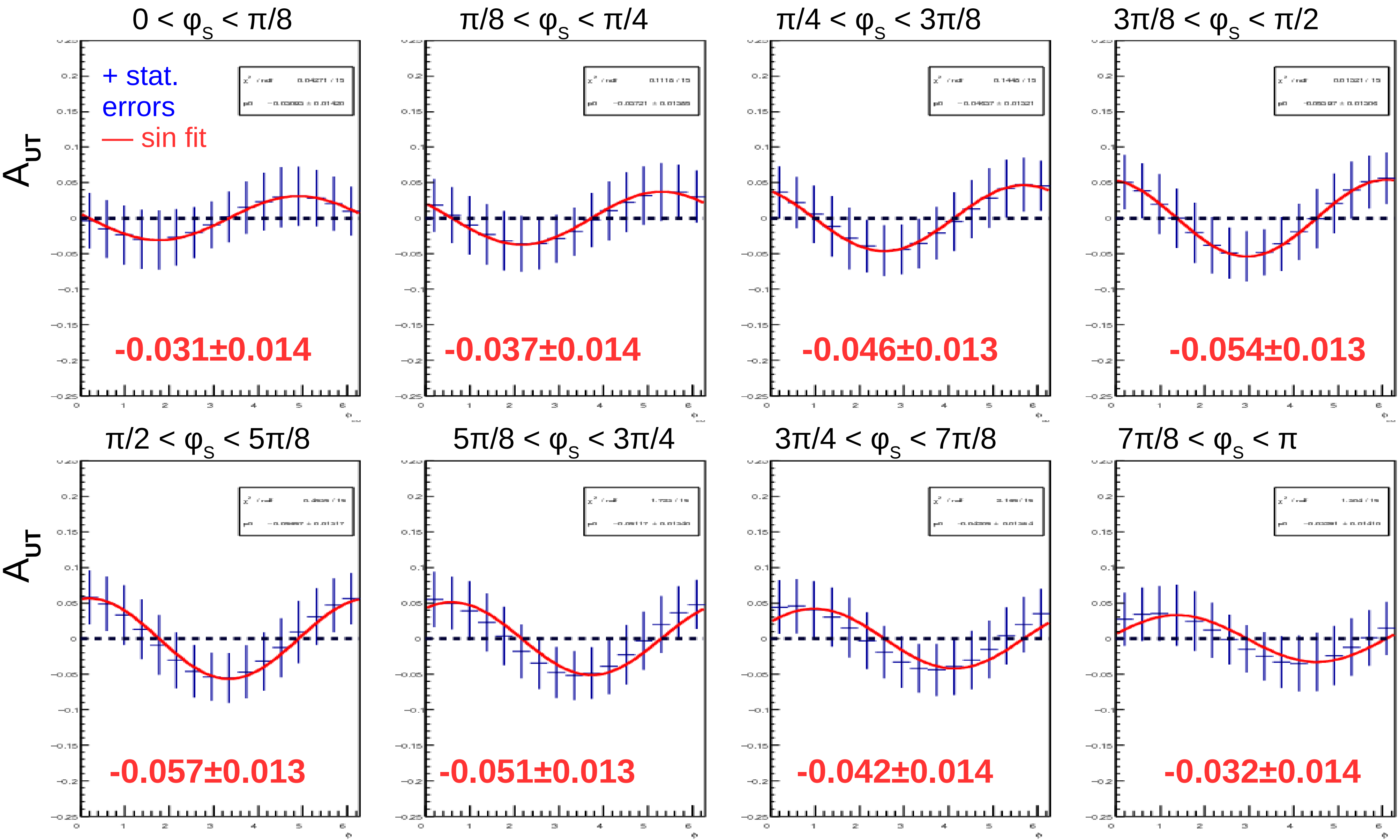
- Leptons resolution:
  δE/E = 0.01*(1.15 + 1.17 /√E + 1.8 /E)
  δx = 2.74 mm /√E at 1.5 m from vertex

- Magnetic field not included

Projection: Target spin asymmetries in φ and φ_S bins

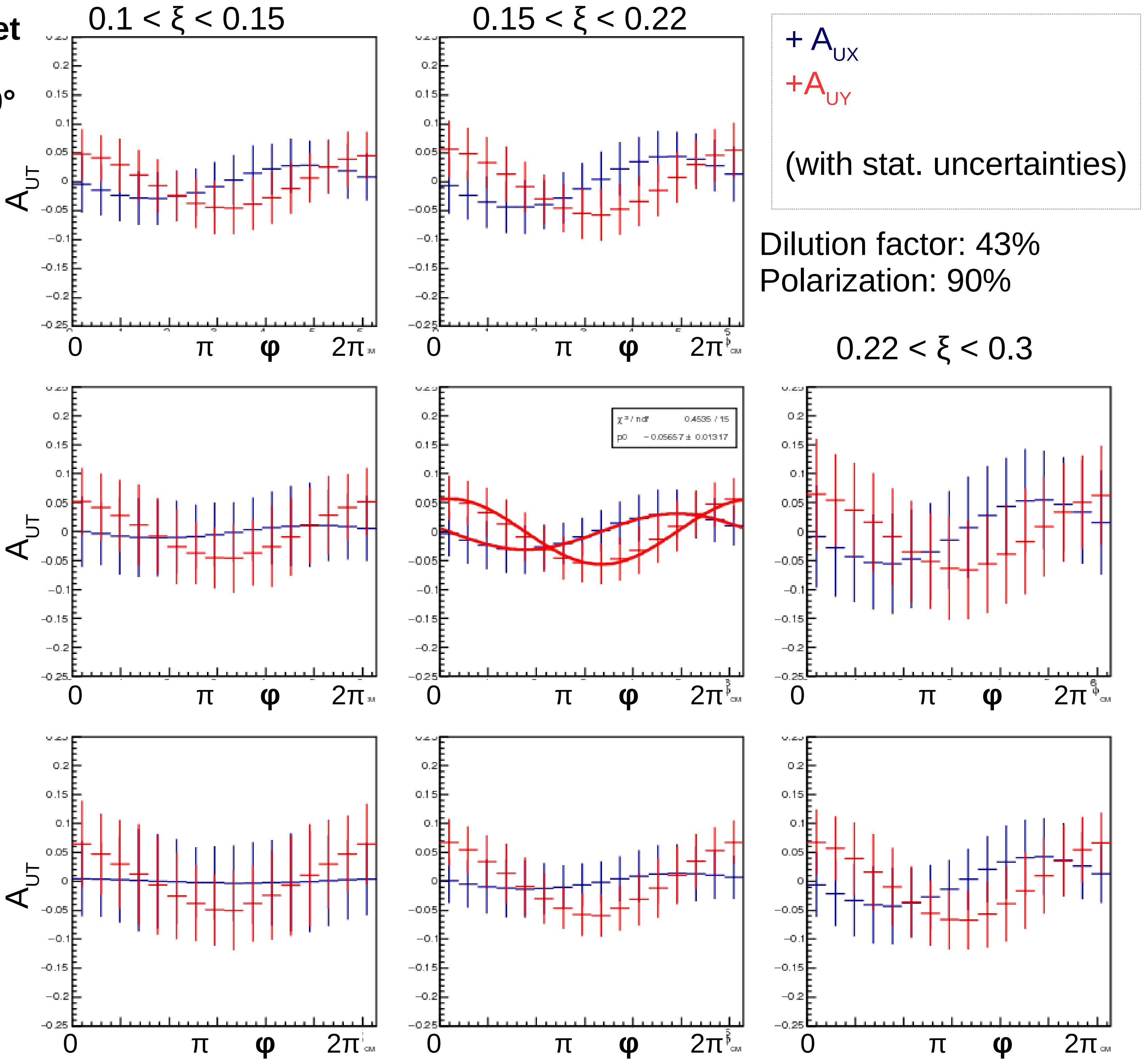
Projected uncertainties for bin =(.2<-t<.35; .15<ξ<.22) in 8 φ_S bins and 16 φ bins

Fit for display: A_{UT}*sin(φ-φ_S) ⇒ CFF fit algorithm will combine all φ_S bins of first row, simultenaouslу with orthogonal bins of second row (same column)



Included: 43% target dilution factor, 90% polarization, and statistic uncertainties.

Transverse target asymmetries at $\varphi_s=0°$ and $\varphi_s=90°$



+ A_{UX}

+A_{UY}

(with stat. uncertainties)

Dilution factor: 43%
Polarization: 90%

-t < 0.2 GeV²

0.2 < -t
< 0.35 GeV²

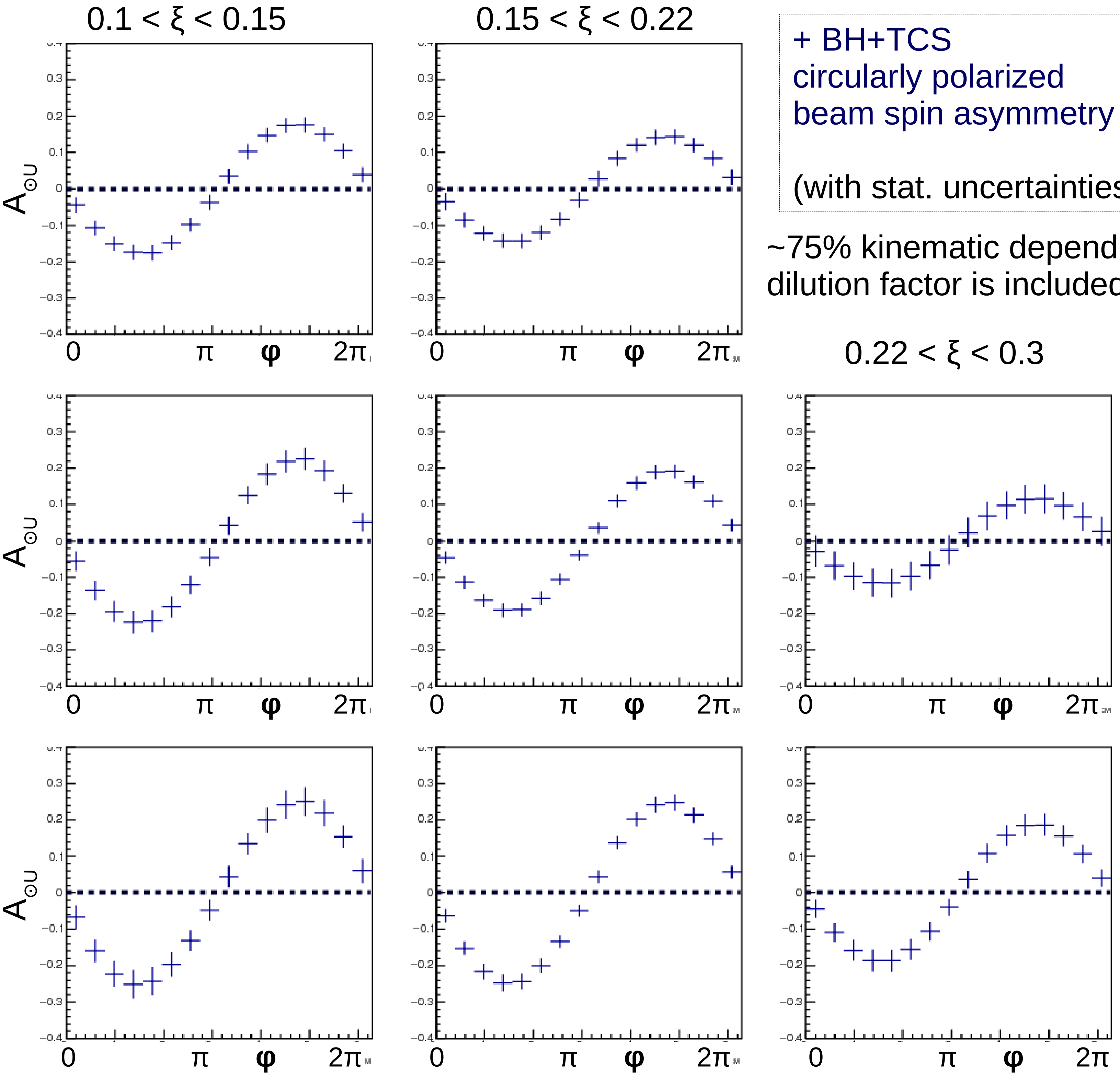
0.35 < -t
< 0.7 GeV²

Beam spin asymmetries vs kinematics

+ BH+TCS circularly polarized beam spin asymmetry

(with stat. uncertainties)

~75% kinematic dependent dilution factor is included



0.1 < ξ < 0.15

0.15 < ξ < 0.22

0.22 < ξ < 0.3

-t < 0.2 GeV²

0.2 < -t < 0.35 GeV²

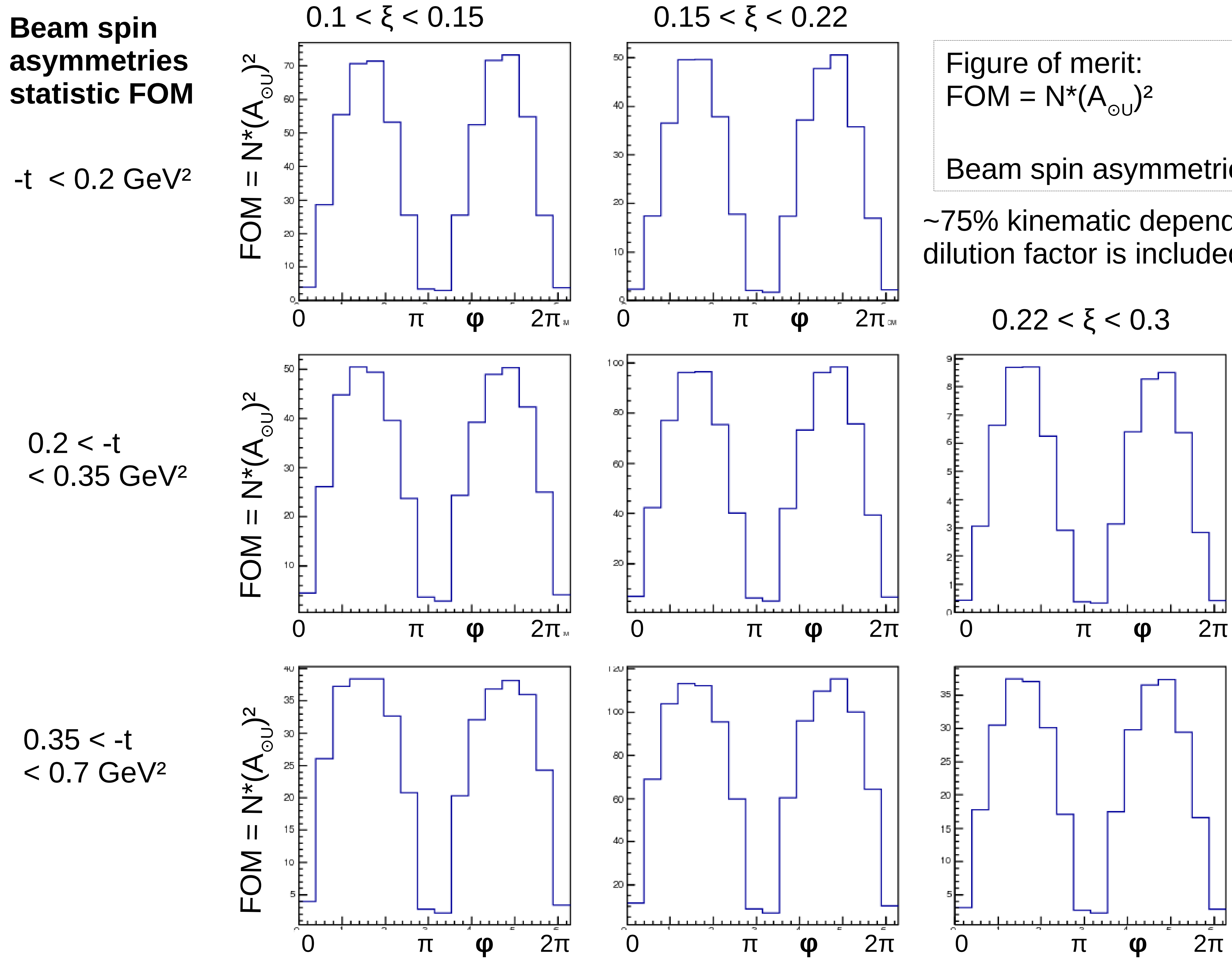
0.35 < -t < 0.7 GeV²

Beam spin asymmetries statistic FOM

Figure of merit:
FOM = N*$(A_{\odot U})^2$

Beam spin asymmetries

~75% kinematic dependent dilution factor is included



Impact of dynamic twist corrections on DVCS+TCS fits

- **Corrections applied**: **target mass and restauration of gauge invariance**
- **Impact on CFFs**: **~10% on Re, ~1% on Im, opposite sign in DVCS and TCS**
- **Impact on DVCS+TCS fits: between "twist 2" and "DVCS" results; 1% (Im) to 10% (Re)**

→ below uncertainties on CFFs

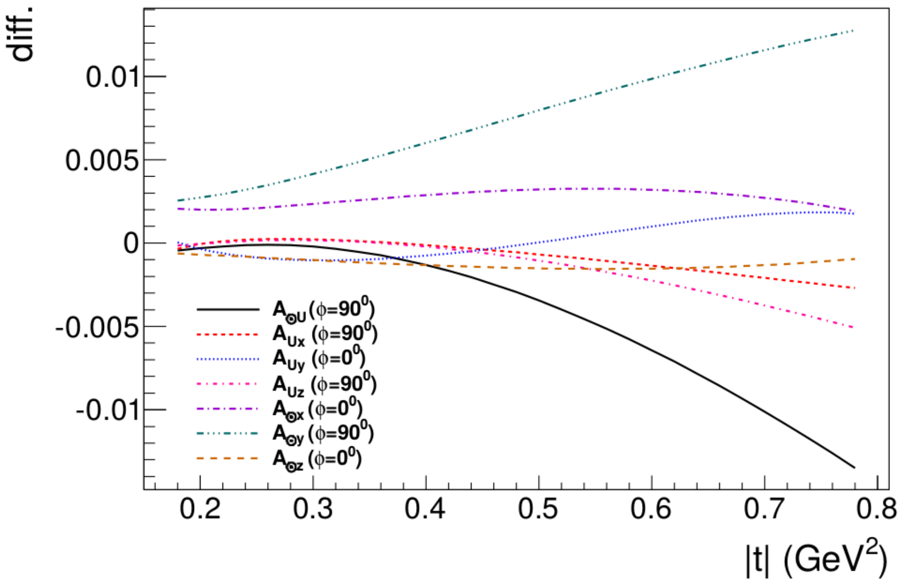
Corrections

mass and Δ=(p-p') in skewness variable:

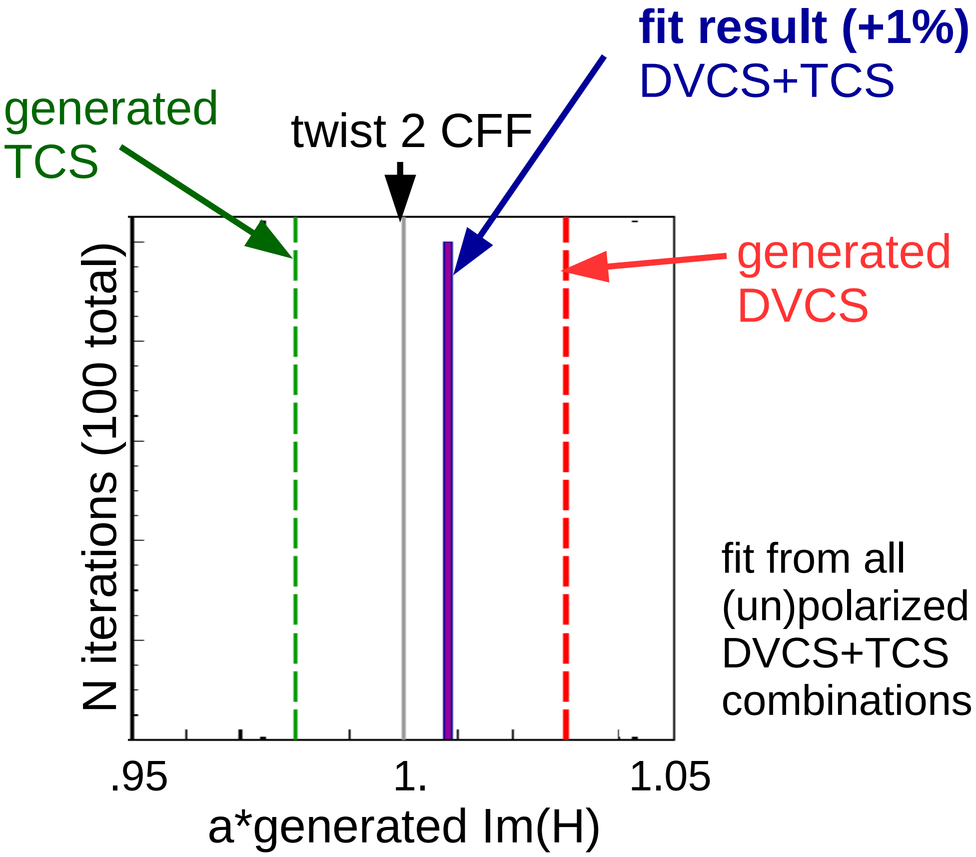
$$\xi' = -\frac{\bar{q}^2}{2P\cdot\bar{q}} = \frac{-Q'^2 + \Delta^2/2}{2(s-m^2)+\Delta^2-Q'^2}$$

$$\xi = -\frac{\Delta\cdot\bar{q}}{2P\cdot\bar{q}} = \frac{Q'^2}{2(s-m^2)+\Delta^2-Q'^2}$$

(corrected - asymptotic) asymmetries



Fit results



fit from all
(un)polarized
DVCS+TCS
combinations

Dynamic twist corrections for TCS

- leading-twist TCS hadronic part of amplitude with "Ji's" GPDs decomposition

$$
\begin{aligned}
H^{\mathrm{TCS}}_{\mu\nu} = {} & \\
& \frac{1}{2}(-g_{\mu\nu})_\perp \int_{-1}^{1} \mathrm{d}x \left(\frac{1}{x-\xi-i\epsilon}+\frac{1}{x+\xi+i\epsilon}\right) \\
& \cdot \left(H(x,\xi,t)\bar{u}(p')\not{n}u(p)+E(x,\xi,t)\bar{u}(p')i\sigma^{\alpha\beta}n_\alpha\frac{\Delta_\beta}{2m}u(p)\right) \\
& -\frac{i}{2}(\epsilon_{\nu\mu})_\perp \int_{-1}^{1} \mathrm{d}x \left(\frac{1}{x-\xi-i\epsilon}-\frac{1}{x+\xi+i\epsilon}\right) \\
& \cdot \left(\tilde{H}(x,\xi,t)\bar{u}(p')\not{n}\gamma_5\, u(p)+\tilde{E}(x,\xi,t)\bar{u}(p')\gamma_5\frac{\Delta\cdot n}{2m}u(p)\right)
\end{aligned}
$$

$$\Delta = (p'-p)$$

- ad-hoc twist 3 corrections for gauge-invariance

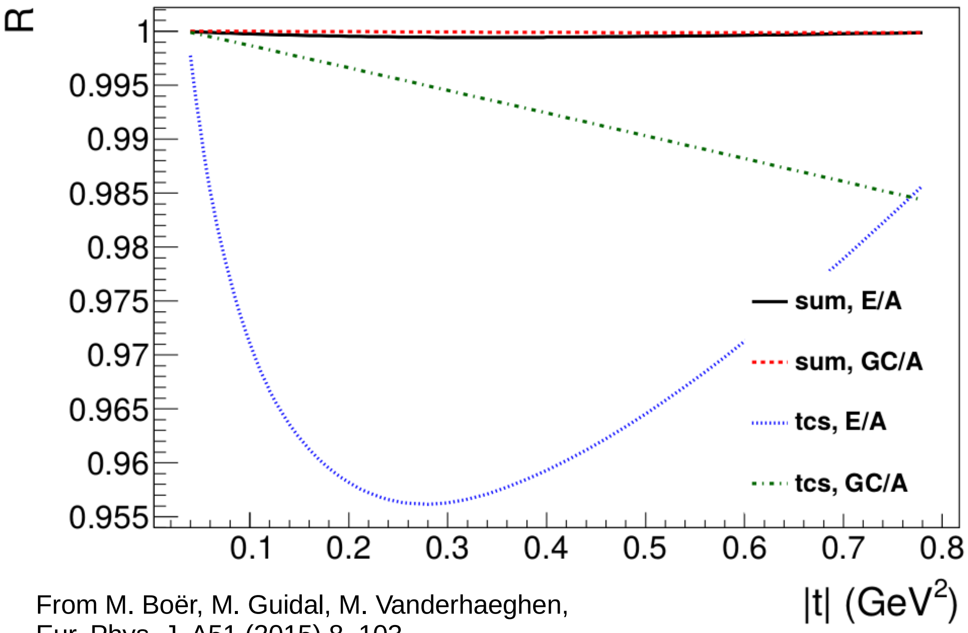
$$
\begin{aligned}
H^{\mu\nu} = H^{\mu\nu}_{LO} & - \frac{P^\mu}{2P\cdot\bar{q}}\cdot(\Delta_\perp)_\kappa\cdot H^{\kappa\nu}_{LO} \\
& + \frac{P^\nu}{2P\cdot\bar{q}}\cdot(\Delta_\perp)_\lambda\cdot H^{\mu\lambda}_{LO} \\
& - \frac{P^\mu P^\nu}{4(P\cdot\bar{q})^2}\cdot(\Delta_\perp)_\kappa\cdot(\Delta_\perp)_\lambda\cdot H^{\kappa\lambda}_{LO}
\end{aligned}
$$

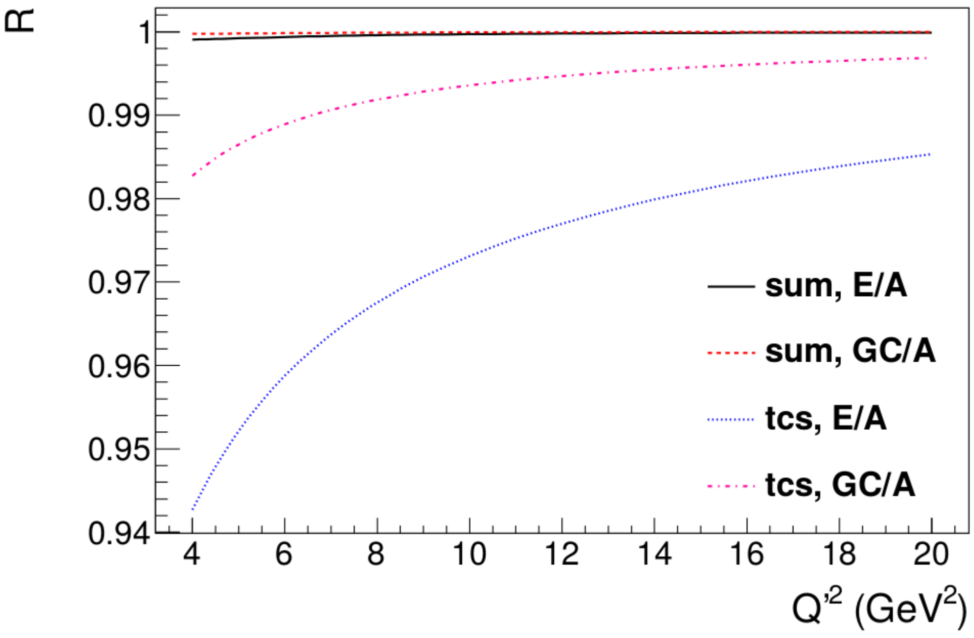
- mass and Δ terms in skewness variables, related to light cone momentum fractions

$$\xi' = -\frac{\bar{q}^2}{2P\cdot\bar{q}} = \frac{-Q'^2+\Delta^2/2}{2(s-m^2)+\Delta^2-Q'^2}$$

$$\xi = -\frac{\Delta\cdot\bar{q}}{2P\cdot\bar{q}} = \frac{Q'^2}{2(s-m^2)+\Delta^2-Q'^2}$$

R = corrected / asymptotic unpolarized cross sections, vs t (left) and vs Q'² (right)





From M. Boër, M. Guidal, M. Vanderhaeghen,
Eur. Phys. J. A51 (2015) 8, 103

Generalized Parton Distributions in TCS off the nucleon

TCS hadronic tensor and decomposition into GPDs using Ji conventions:

$$H_{\mu\nu}$$

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

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

Access Generalized Parton Distributions (GPDs) through Compton Form Factors (CFFs):

(same for DVCS and TCS at asymptotic limit)

H, E ⇒ $$\Re e[\mathcal{F}(\xi,t)] = \mathcal{P}\int_0^1 dx\,[\frac{1}{x-\xi} + \frac{1}{x+\xi}].[F(x,\xi,t) - F(-x,\xi,t)],$$

H̃, Ẽ ⇒ $$\Re e[\tilde{\mathcal{F}}(\xi,t)] = \mathcal{P}\int_0^1 dx\,[\frac{1}{x-\xi} - \frac{1}{x+\xi}].[\tilde{F}(x,\xi,t) + \tilde{F}(-x,\xi,t)],$$

H, E ⇒ $$\Im m[\mathcal{F}(\xi,t)] = \pi[F(\xi,\xi,t) - F(-\xi,\xi,t)],$$

H̃, Ẽ ⇒ $$\Im m[\tilde{\mathcal{F}}(\xi,t)] = \pi[\tilde{F}(\xi,\xi,t) + \tilde{F}(-\xi,\xi,t)],$$

⇒ TCS and DVCS amplitudes are complex conjugate at leading twist and leading order