Summer school of the GDR PH-QCD
"Correlations between partons in nucleons"
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Timelike Compton Scattering off the proton

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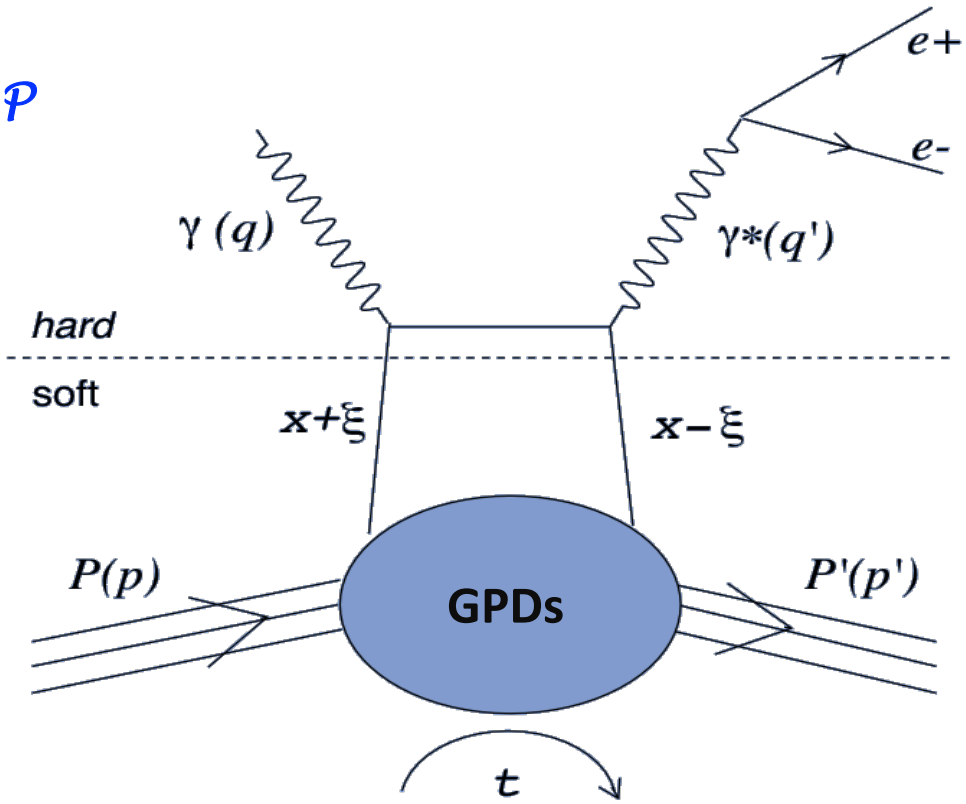
Based on paper:
M. B., M. Guidal, M. Vanderhaeghen, "Timelike Compton scattering off the proton and Generalized Parton Distributions", (to be submitted in coming weeks).

Timelike Compton Scattering

$\gamma P \to e^+ e^- P$



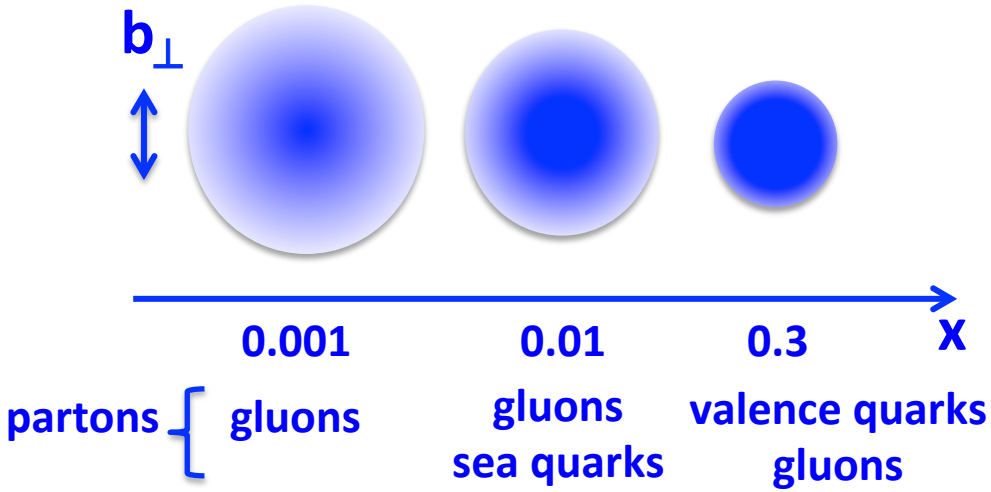
Q'² >> 1 GeV²: hard scale
x: momentum fraction struck quark

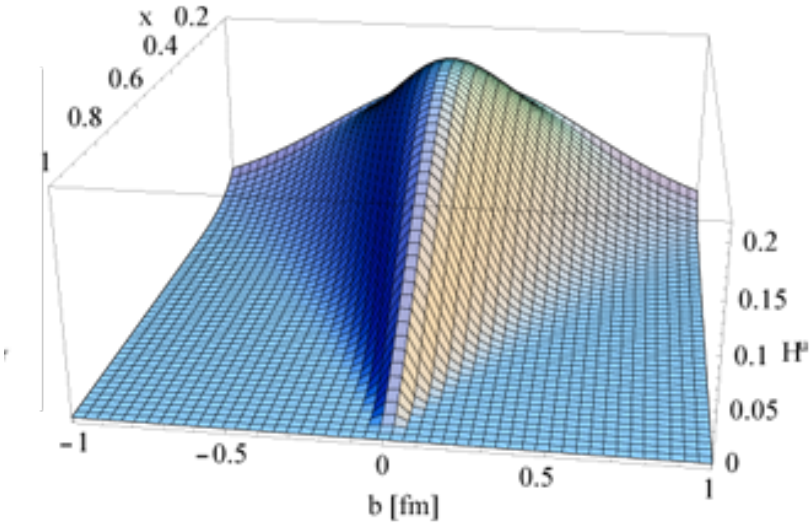
t << Q'²: momentum transfer, partonic structure
ξ: longitudinal momentum transfert

Exclusive process → measurement of t (like in elastic scattering) **and ξ** (like in DIS)
Soft part: Generalized Partons Distributions H (x , ξ , t ; Q'²)

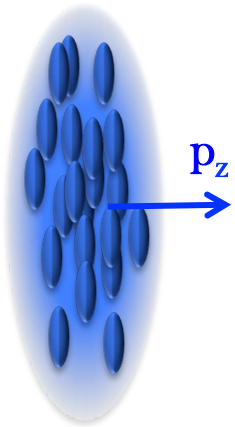
Generalized Partons Distributions

transverse position $b_\perp$ vs longitudinal momentum fraction x





$$H(x, \xi=0, t) \overset{FT}{\Longrightarrow} H(x, b_\perp)$$



Distributions of partons in polarized/unpolarized nucleon, sensitivity to orbital momentum...

=> different kind of GPDs for quarks and gluons in nucleon

Context for TCS studies

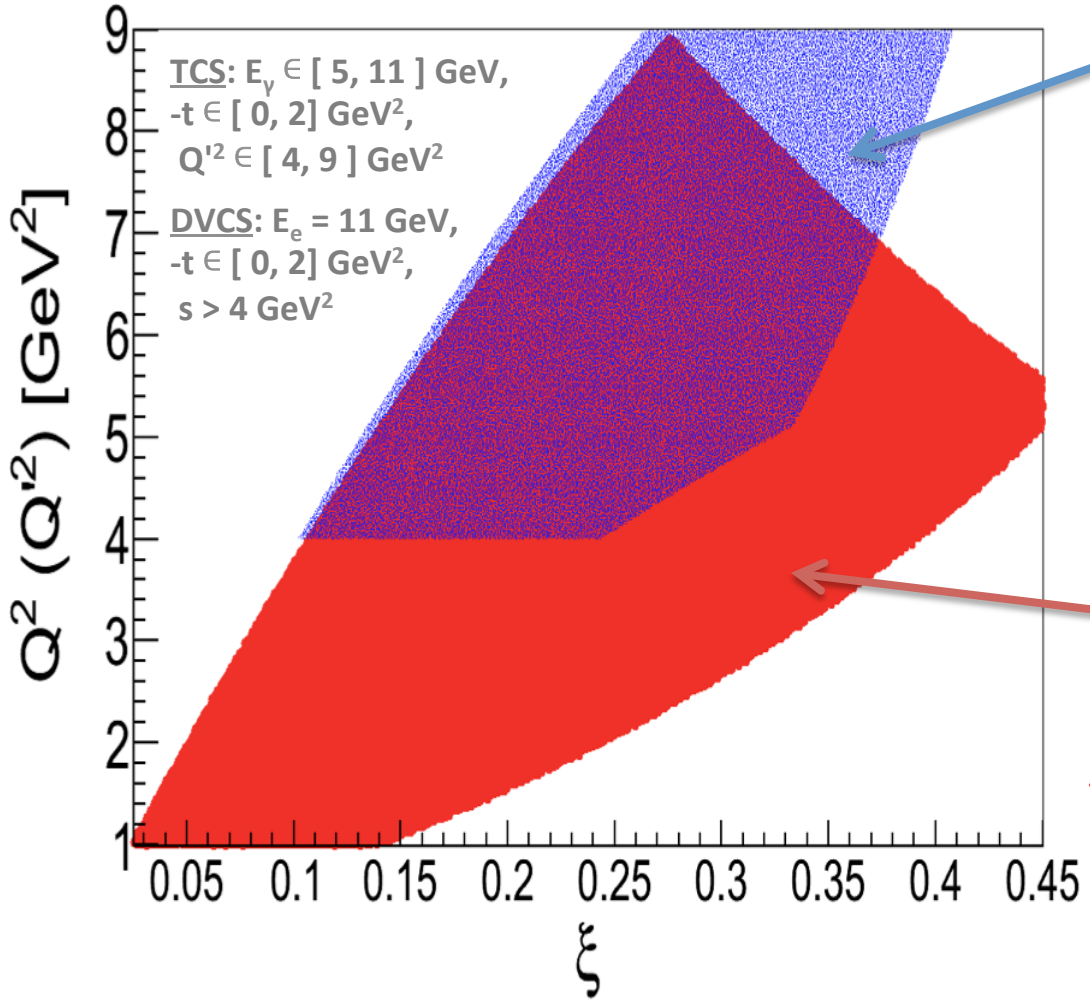
References:

- Berger, Diehl, Pire, EPJC, 675 (2002)
  - ➪ **unpolarized and circularly beam polarized cross sections**
- Goritschnig, Pire, Wagner, arXiv:1404.0713 (2014)
  - ➪ **linearly beam polarized cross sections**
- NLO: Belitsky, Ji, Müller, Moutarde, Osborne, Pire, Sabatié, Szymanowski, Wagner...
- TCS proposal at CLAS12, L.O.I. at Hall A SOLID: unpolarized cross sections
- PhD of R. Paremuzyan (6 GeV): shows faisability of TCS program in Hall B

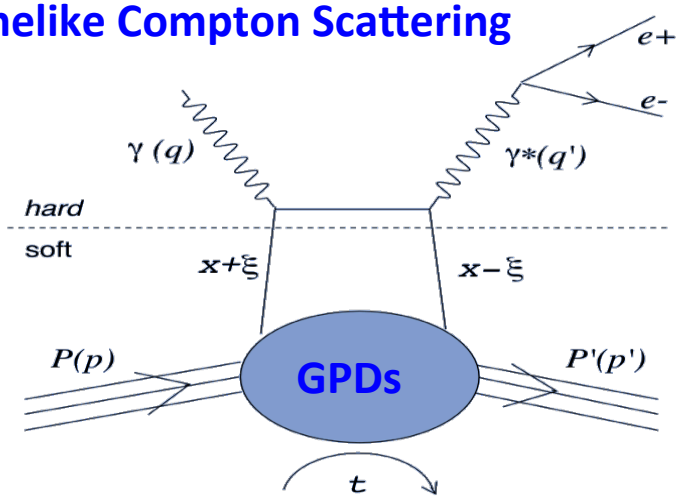
New in this work:

- **Numerical calculations of cross sections (LO-LT)**
- **Circularly and linearly polarized beam / longitudinally and transversally polarized nucleon**
- **Observables: calculation of all single and double spin asymmetries**
- **Systematic studies of the dependencies of the observables on the 4 GPDs and on the modeling of the GPDs**
- **Some higher twist corrections**

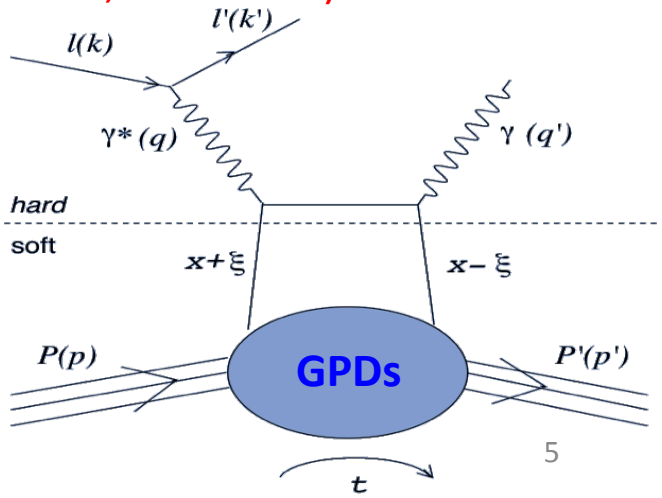
Complementarity of TCS studies to DVCS at JLAB (12 GeV)



TCS "timelike"
Timelike Compton Scattering

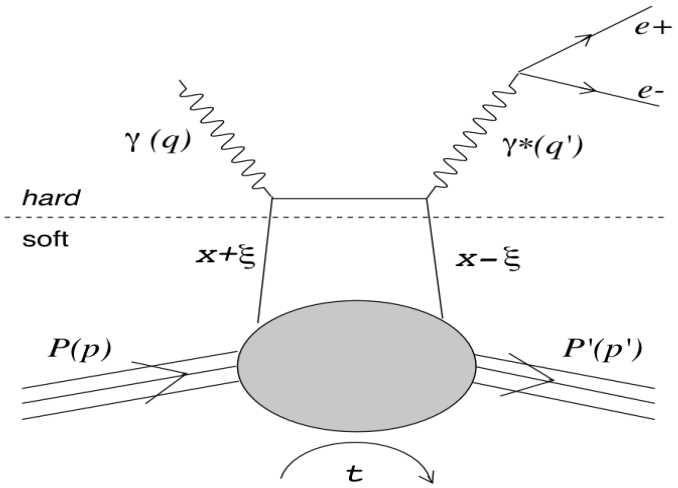


DVCS "spacelike"
Deeply Virtual Compton Scattering
(already measured: JLAB, HERMES, H1,
future: JLAB, COMPASS)



Same GPDs
→ Test of universality (LO-LT)
→ Complementarity for GPDs fits with more observables
→ expand kinematical domain for GPDs

Exclusive photoproduction of a lepton pair



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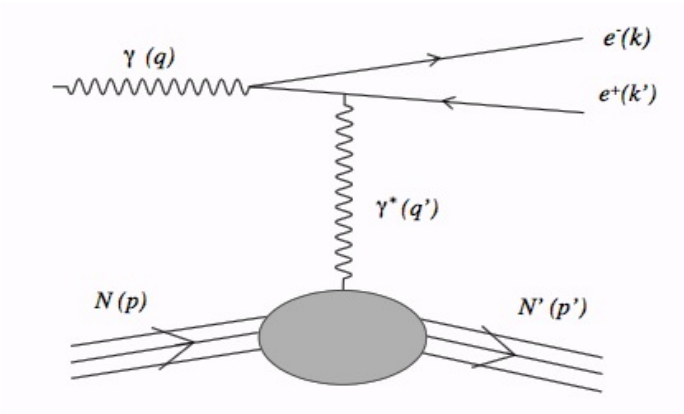


Timelike Compton Scattering (TCS)
(+ crossed diagram)

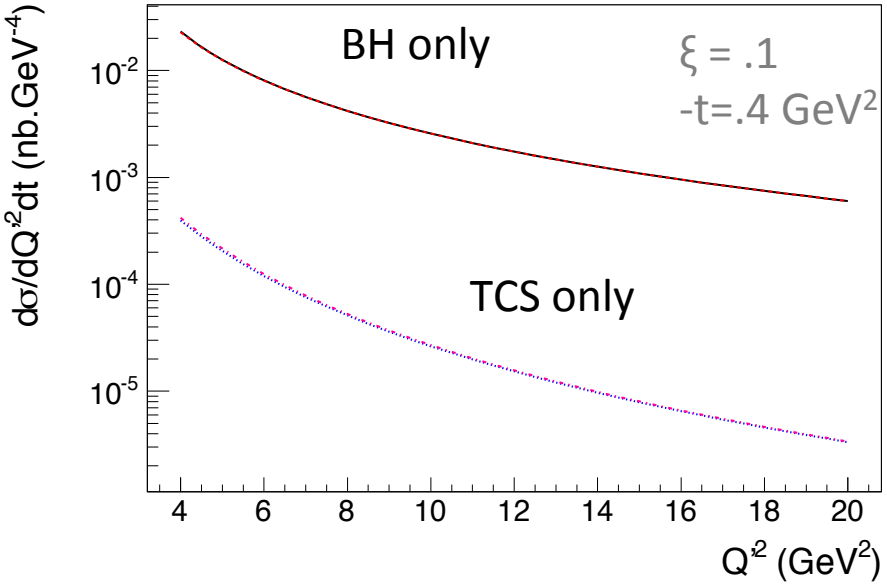
Bethe-Heitler (BH)
(+ crossed diagram)

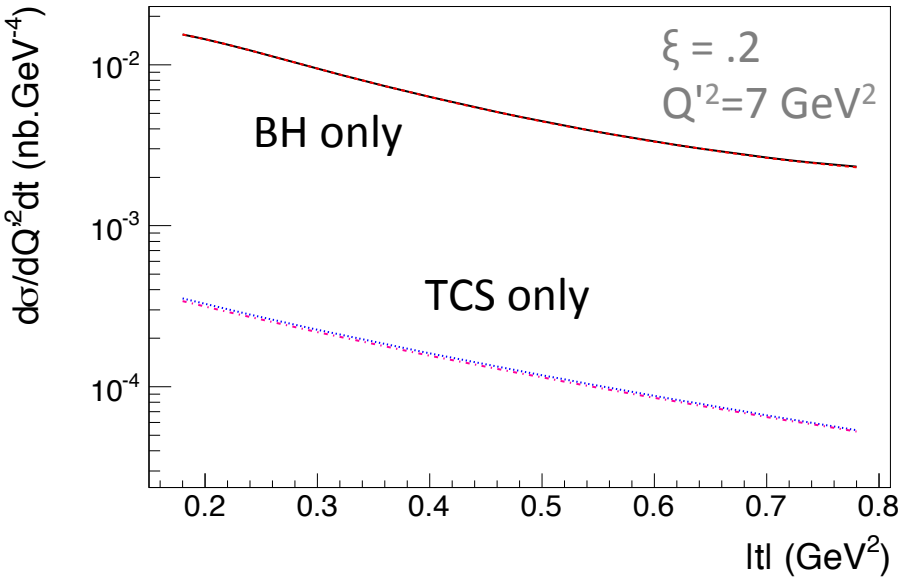
Same final state, interference between the 2 processes

$$\frac{d^4\sigma}{dQ'^2 dt d\Omega}(\gamma p \to p' e^+ e^-) = \frac{1}{2\pi^4}\frac{1}{64}\frac{1}{(2m_N E_\gamma)^2} \mid T^{BH} + T^{TCS} \mid^2$$

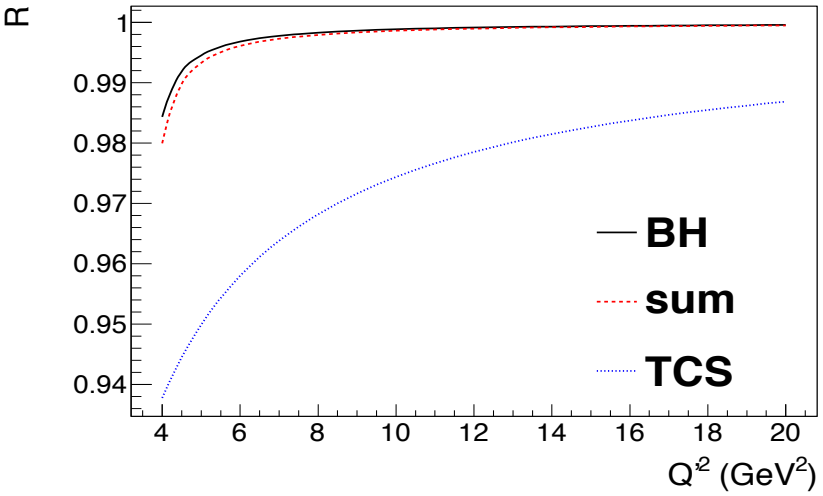
Cross section: kinematics

cross sections vs Q'2 and vs t





R = Berger, Diehl, Pire / this work



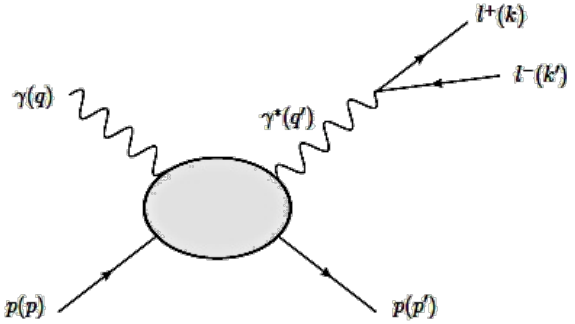
BH always 2 order of magnitude >> TCS

Good agreement with Berger et al. for BH

TCS:

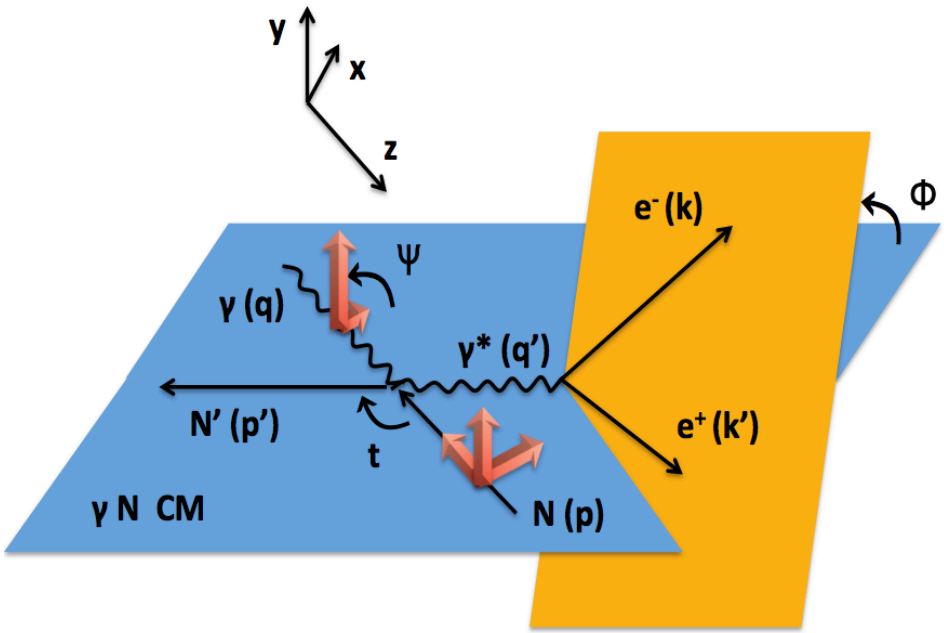
- **convergence at high Q'²**
- **few % difference at small Q'²**

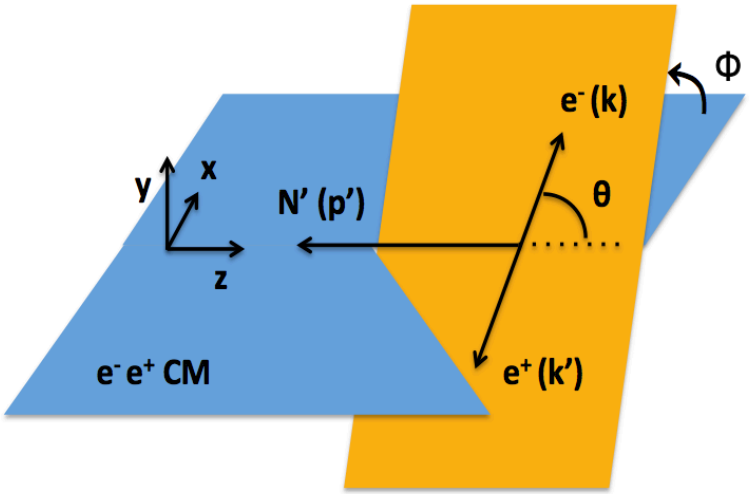
Angles and asymmetries



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

Ψ: (reaction plane, real γ spin)
ϕ: (reaction plane, e^+e^- pair)
θ: (γ^*, e^-)

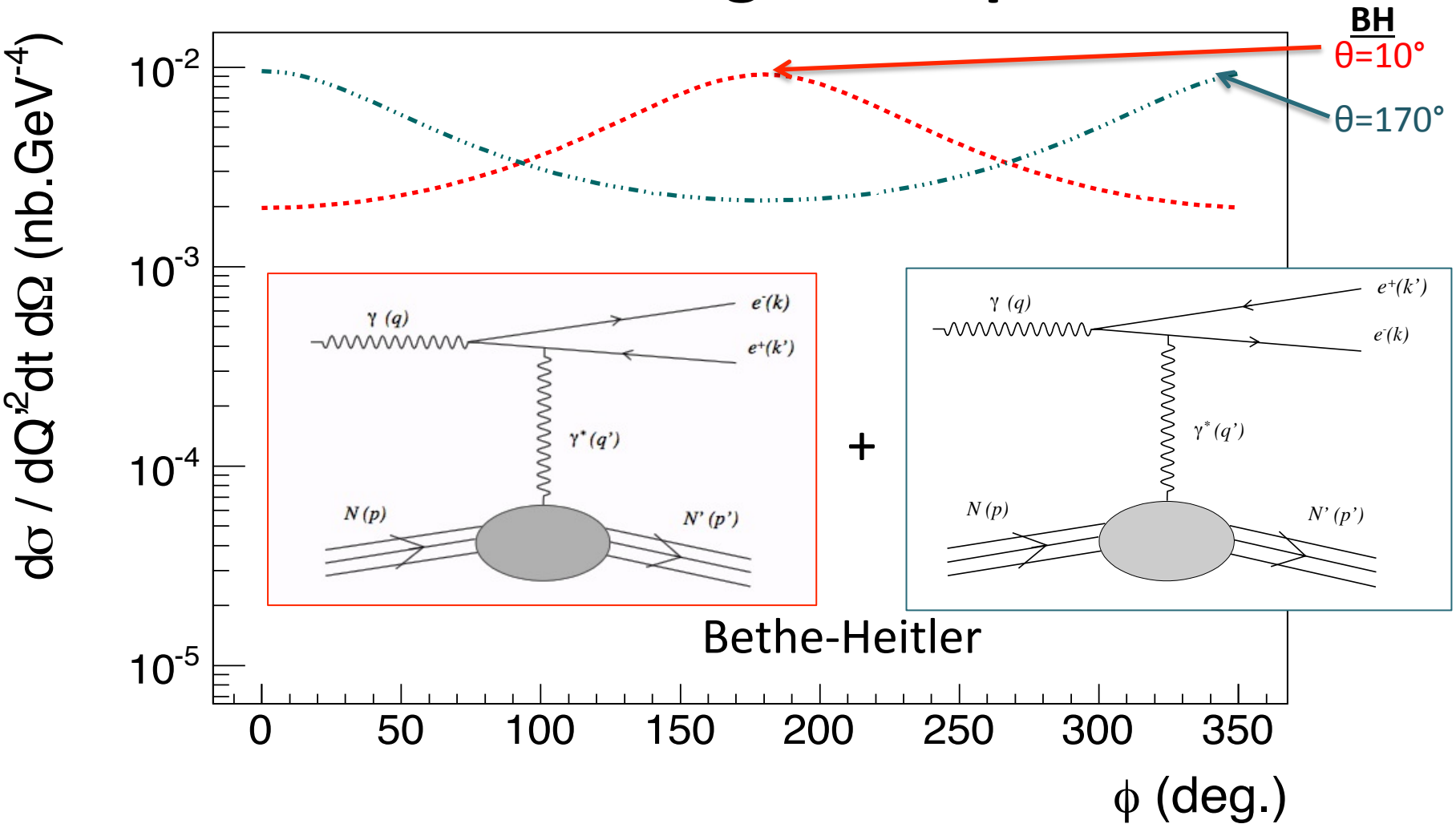




Notations
A: asymmetry
1st index: photon beam, ⦿ = circular, **L** = linear, **U** = unpol.
2d index: target, **x, y, z**

$$\frac{d\sigma}{dQ'^2\ dt\ d\phi\ d(cos\theta)}$$

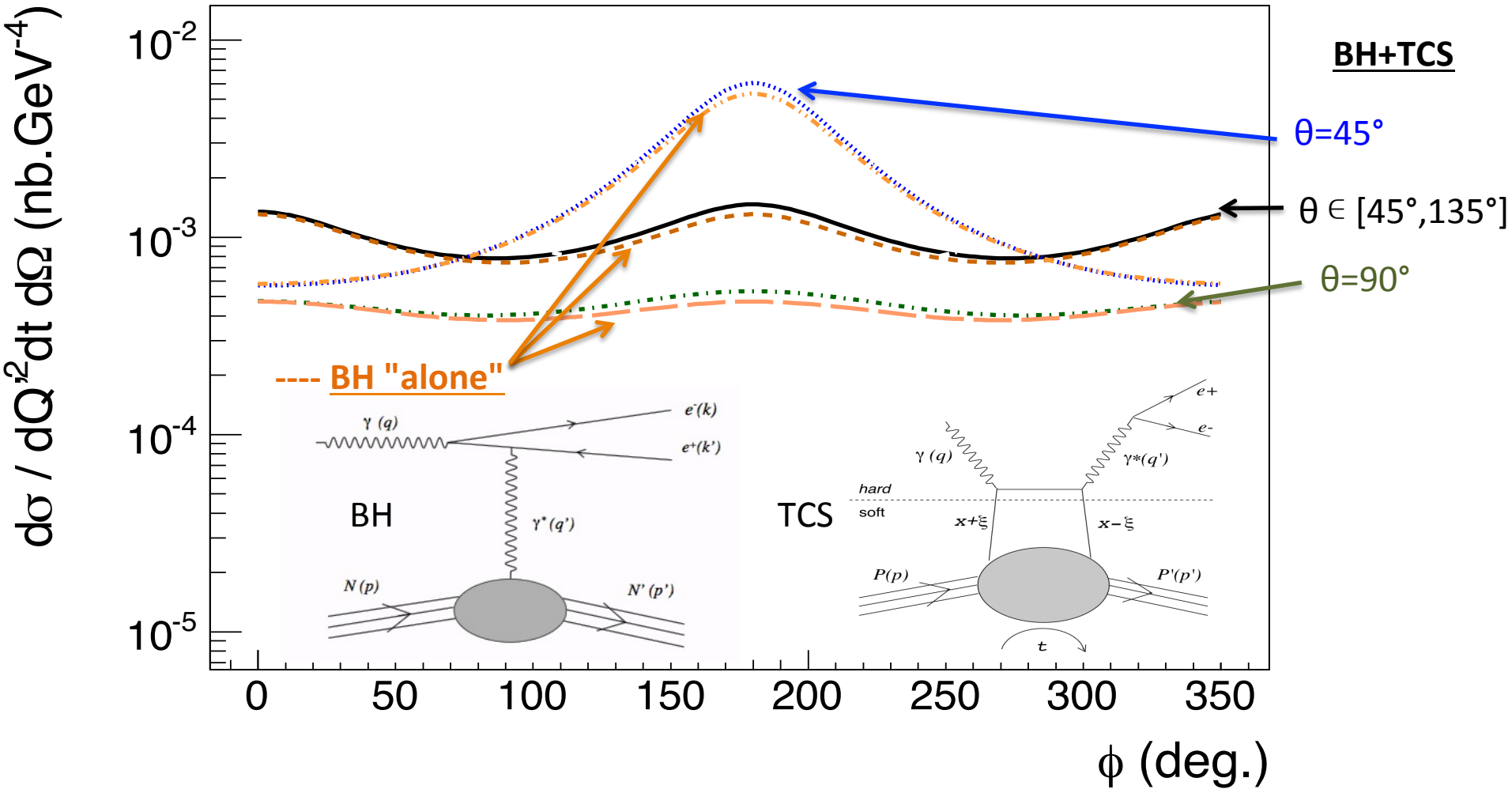
Cross section: angular dependancies



e^- in direction of γ (θ⟼0°) ➪ Singularity at ϕ=180°

e^+ in direction of γ (θ⟼180°) ➪ Singularity at ϕ=0°

Cross section: angular dependancies



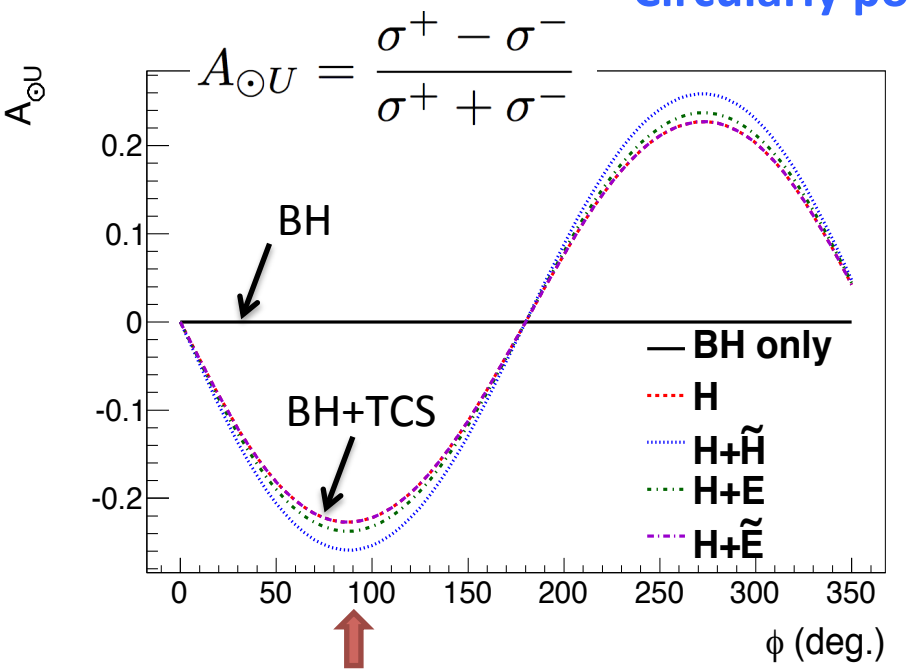
- **BH dominates**
- **few % from TCS contribution**

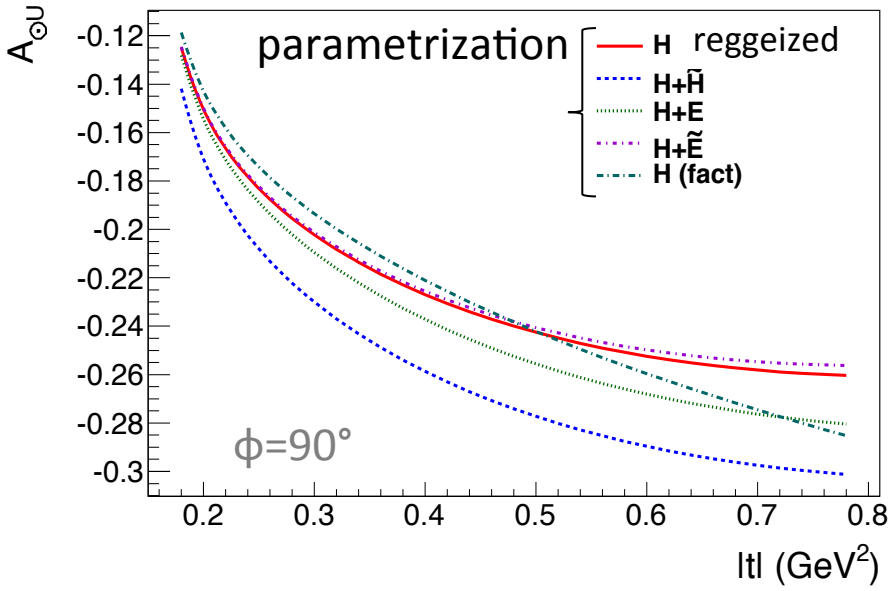
θ = 90°: same contribution of the 2 BH diagrams and more important TCS/BH rate

θ ∈ [45°,135°] intermediate situation ⇒ integrated for statistics in the following

Beam spin asymmetry

Circularly polarized photon





≈20% ⇒ measurable

$A_{\odot U}$ sensitive to Im part of amplitudes ⇒ $A_{\odot U}$ = 0 for BH

Mostly sensitive to Im (H) and $\tilde{H}$

Some sensitivity to the GPD parametrization

Linearly polarized photon

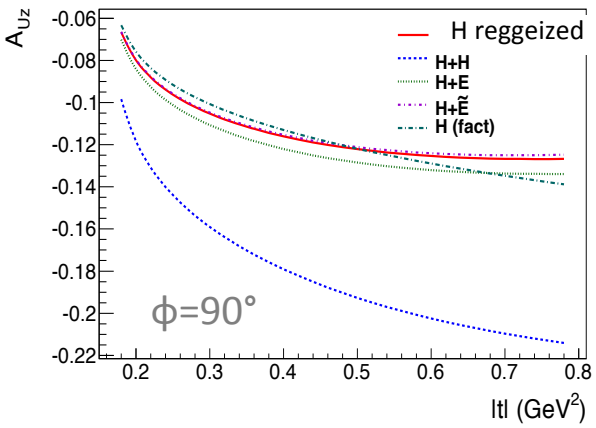
non zero for BH: difficult to distinguish "TCS signal"

ξ=0.2, Q'^2 =7 GeV^2, -t=0.4 GeV^2, θ ∈ [45°,135°]

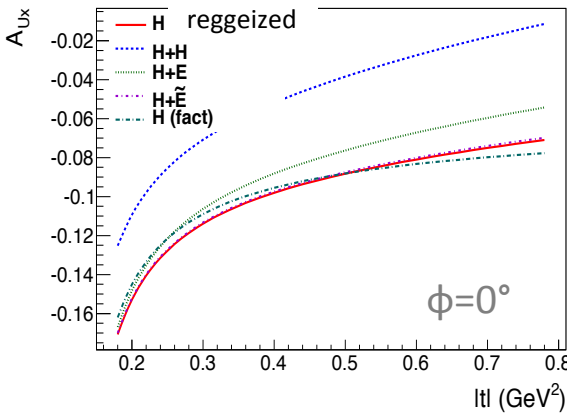
Target spin asymmetries

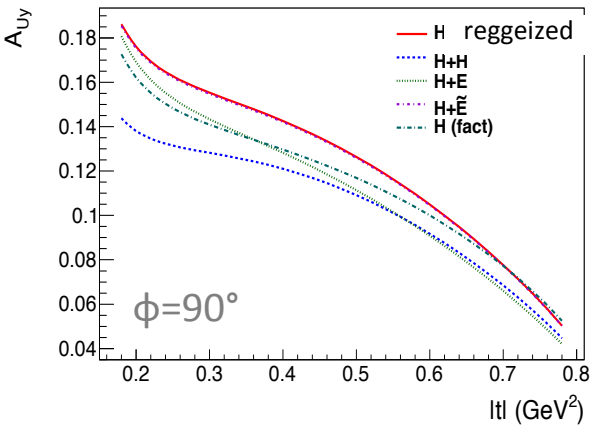
Single target spin asymmetries vs |t|

"longitudinal"



"transverse"

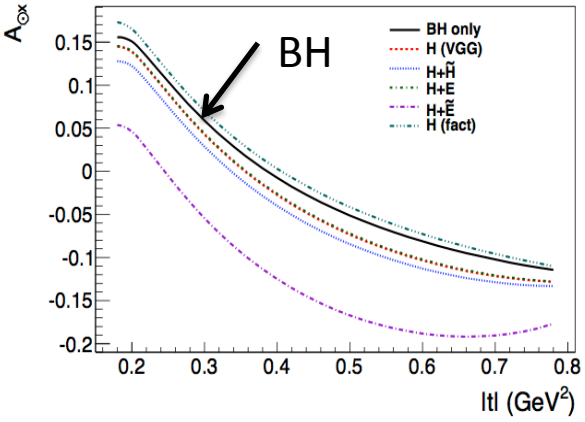




- A_{Ui} = 0 for BH
- Sensitivity to H, $\tilde{H}$, E
- Complementarity of this observables ≈20% ⇒ measurable

"transverse"

Double spin asymmetries: target + beam (circularly)

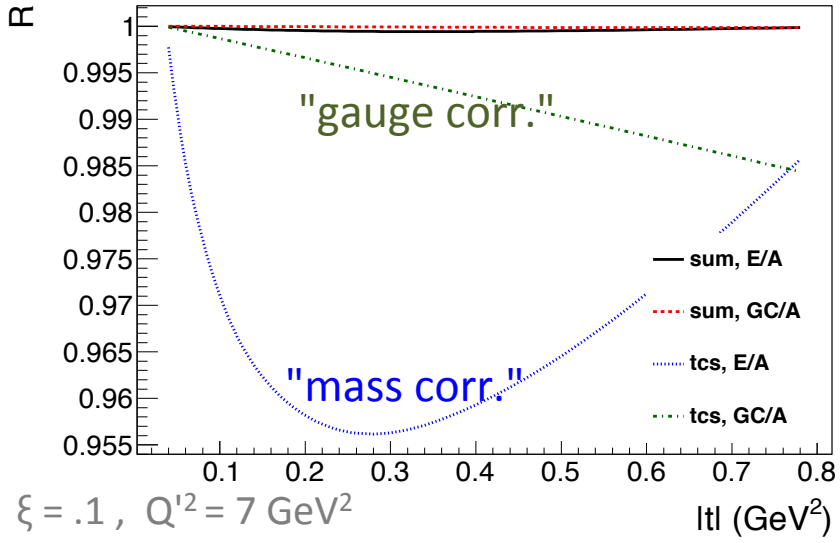


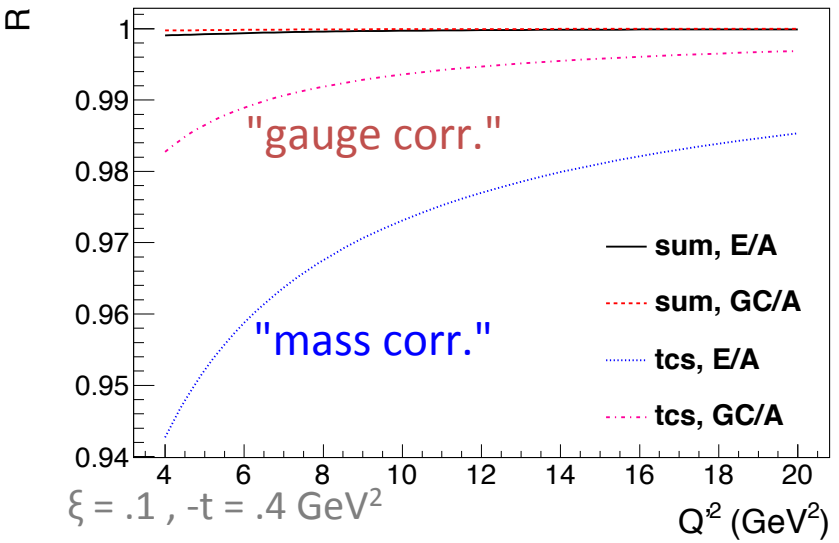
+ sensitivity to all GPDs, complementarity for fits
– non zero contribution from BH
– more difficult to access experimentally
– need bins in ϕ and θ

ξ=0.2, Q'^{2} =7 GeV^2, -t=0.4 GeV^2, θ ∈ [45°,135°]

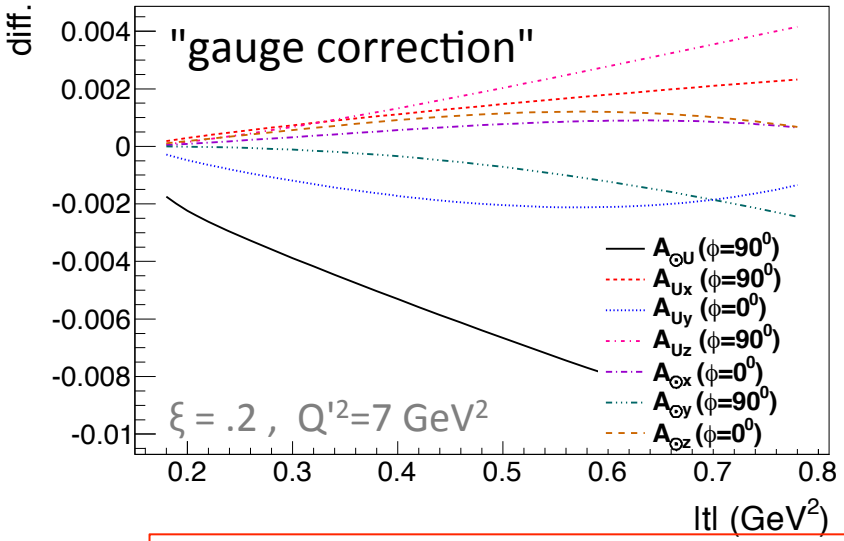
Gauge invariance and mass corrections

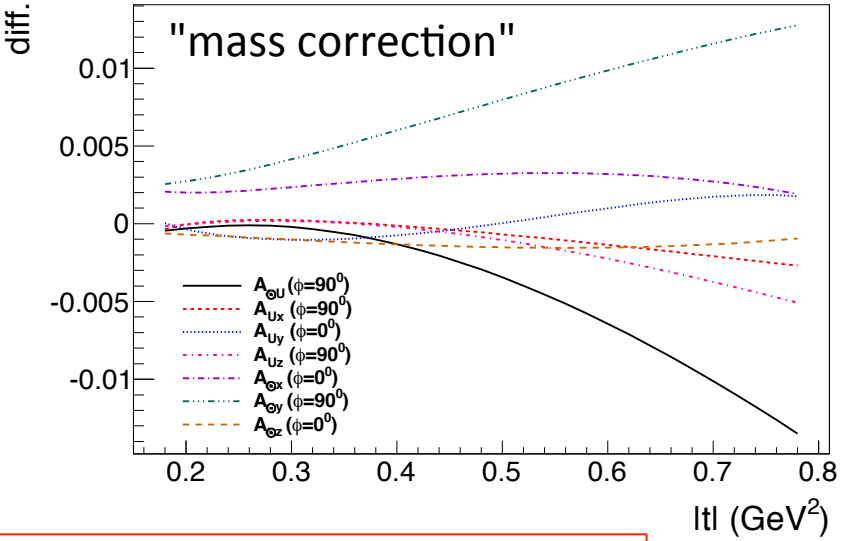
Impact on cross sections (corrected/asymptotic)





Impact on asymmetries using GPD H only in TCS (differences)





Corrections to few % level on the observables, doesn't affect conclusions

SUMMARY

◆ **Numerical calculations of BH+TCS amplitudes**

➪ **all unpolarized, single and double polarization observables**

➪ **dependancies of the observables on the GPDs**

◆ **Mass and gauge invariance corrections**: weak effect on observables

◆ **TCS experimental program using polarized beam and/or target** in complement to DVCS for GPDs studies could be envisaged at JLAB with 12 GeV beam

◆ **Ongoing:**

- **Fits of CFFs using TCS and both TCS+DVCS** (pseudo-data)

  (reference: M. Guidal, "A fitter code for DVCS and GPDs", EPJA 37 (2008) 319)

- **Counting rates** for CLAS12 for polarized cross sections and asymmetries

Mass corrections in propagators

In lightcone frame, $\bar{q}$ and P collinear along z-axis

$$\bar{q} = \frac{1}{2}(q + q')$$
$$P = \frac{1}{2}(p + p'),$$
$$\Delta = (p' - p) = (q' - q)$$
$$\bar{m}^2 = m_N^2 - \frac{\Delta^2}{4}$$

using lightcone vectors $\tilde{p}^\mu$, n^μ along + and – z direction and $\tilde{\xi}$ and $\tilde{\xi}'$ = + component of Δ and $\bar{q}$ ⟶

$$P^\mu = \tilde{p}^\mu + \frac{\bar{m}^2}{2} n^\mu$$
$$\Delta^\mu = -2\tilde{\xi}\tilde{p}^\mu + \tilde{\xi}\bar{m}^2 n^\mu + \Delta_\perp^\mu$$
$$\bar{q}^\mu = -\tilde{\xi}'\,\tilde{p}^\mu - \frac{\bar{q}^2}{2\tilde{\xi}'}\, n^\mu$$

Kinematical variables: experimentaly accessible

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

Light-cone momentum fraction, include mass terms

$$\tilde{\xi} = \xi \cdot \frac{1 + \tilde{\xi}'^2\,\frac{\bar{M}^2}{\bar{q}^2}}{1 - \tilde{\xi}'^2\,\frac{\bar{M}^2}{\bar{q}^2}}$$
$$\tilde{\xi}' = \xi' \cdot \frac{2}{1 + \sqrt{1 - 4\xi'^2\,\frac{\bar{M}^2}{\bar{q}^2}}}$$

At asymptotic limit:

$$\tilde{\xi} = \xi = -\tilde{\xi}' = -\xi' = \frac{Q'^2}{2s - Q'^2}$$

Gauge invariance correction

We have: $q_\mu H^{\mu\nu}{}_{LO} = \frac{1}{2}(\Delta_\perp)_\kappa H^{\kappa\nu}{}_{LO}$ and $q'_\nu H^{\mu\nu}{}_{LO} = -\frac{1}{2}(\Delta_\perp)_\lambda H^{\kappa\lambda}{}_{LO}$

Restore gauge invariance: $q_\mu H^{\mu\nu} = q_\nu H^{\mu\nu} \equiv 0$

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

twist 2
vector part

Hard scattering amplitude of TCS