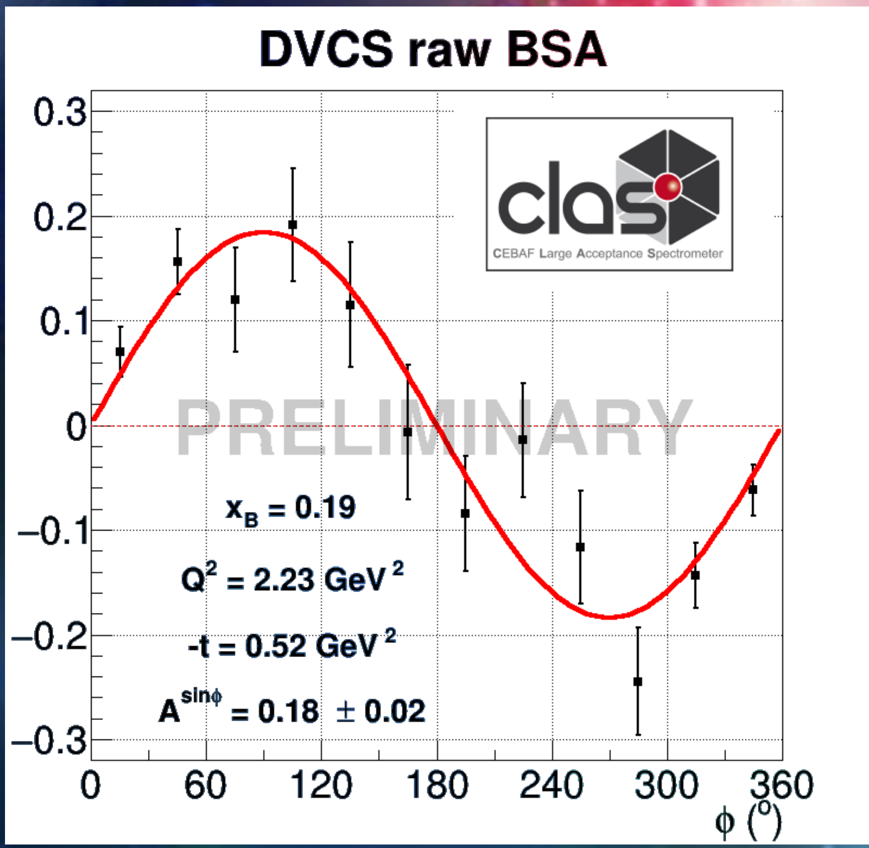
CLAS12 First Physics Run: Jan 11-May 7 2018



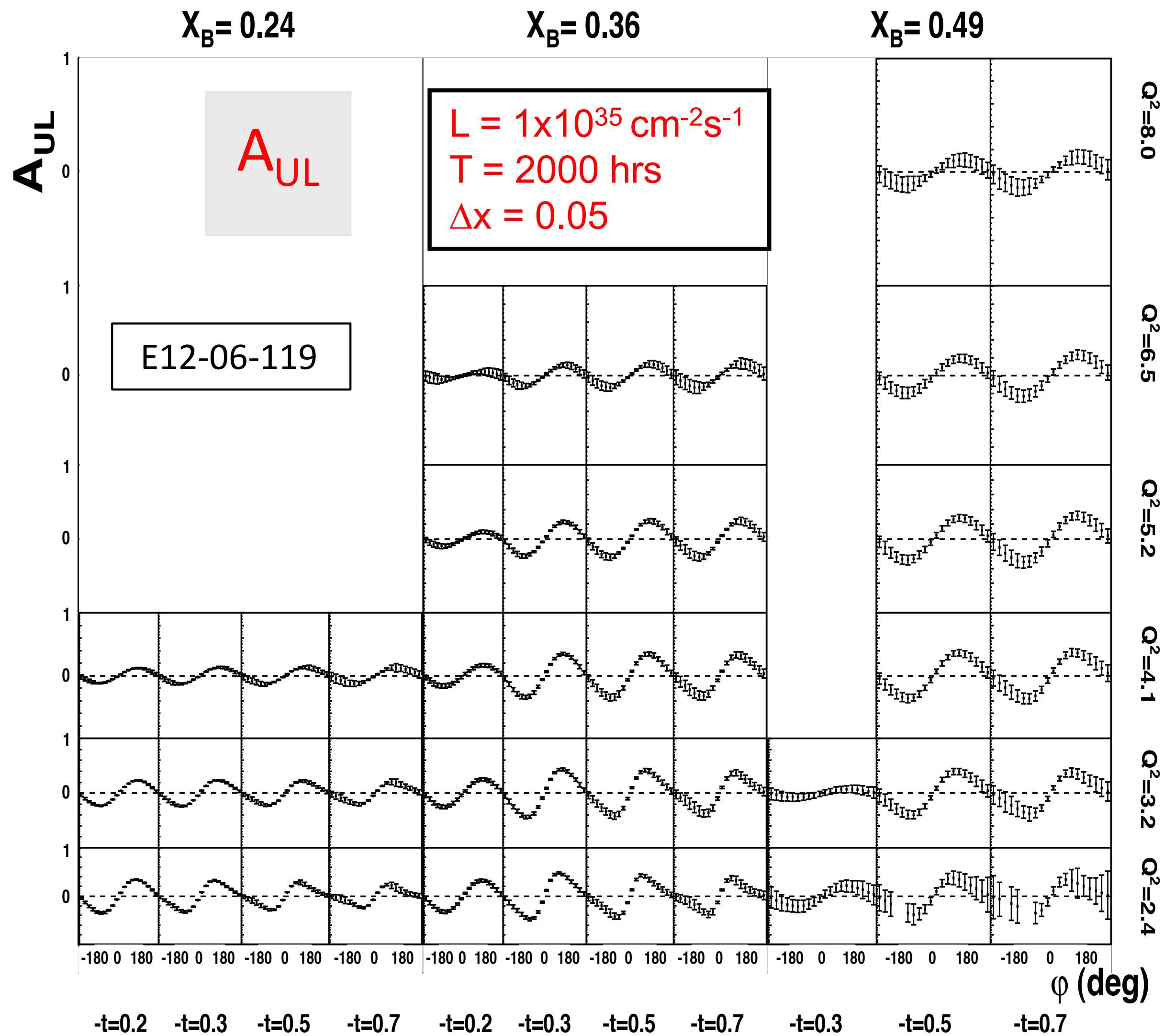
- 0.3% of data analyzed.
- Calibrations in continuous progress
- More data in Fall 2018

CLAS12 A_{UL} projections for protons

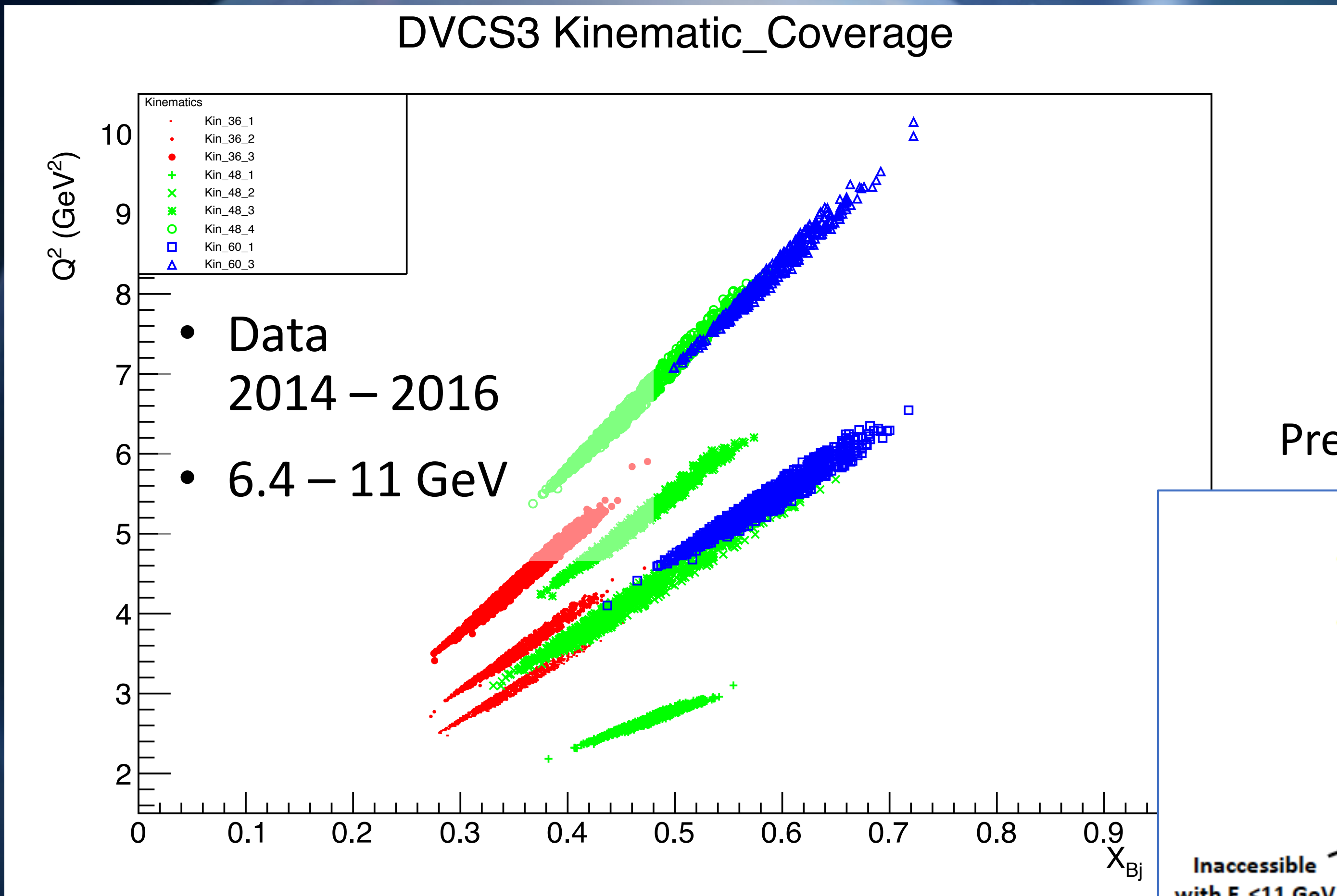
$e\,\vec{p} \rightarrow ep\gamma$

Dynamically polarized target
NH_3, ND_3
JLab, ODU,UVA,
First run 2020

$\Delta\sigma_{UL} \sim \sin\phi\ \{F_1\tilde{H}+\xi(F_1+F_2)(H+\xi/(1+\xi)E)\}d\phi$

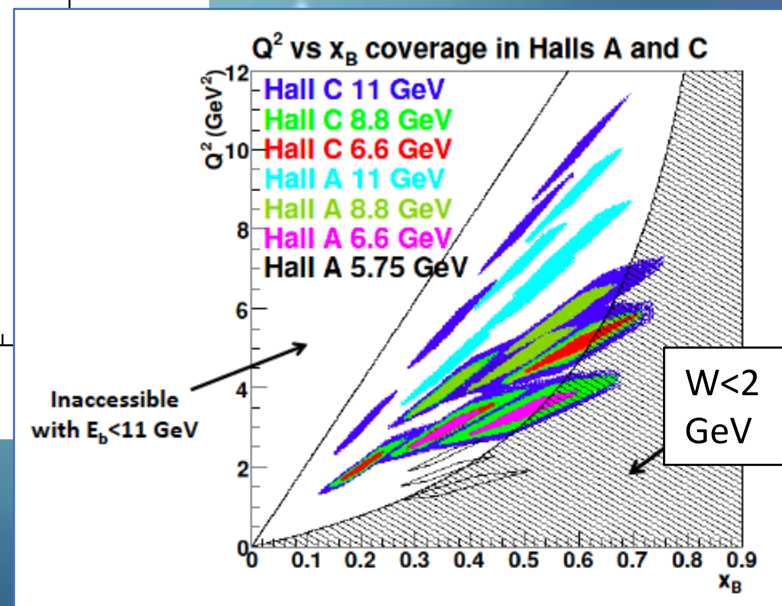


Hall A DVCS, Deep π^0



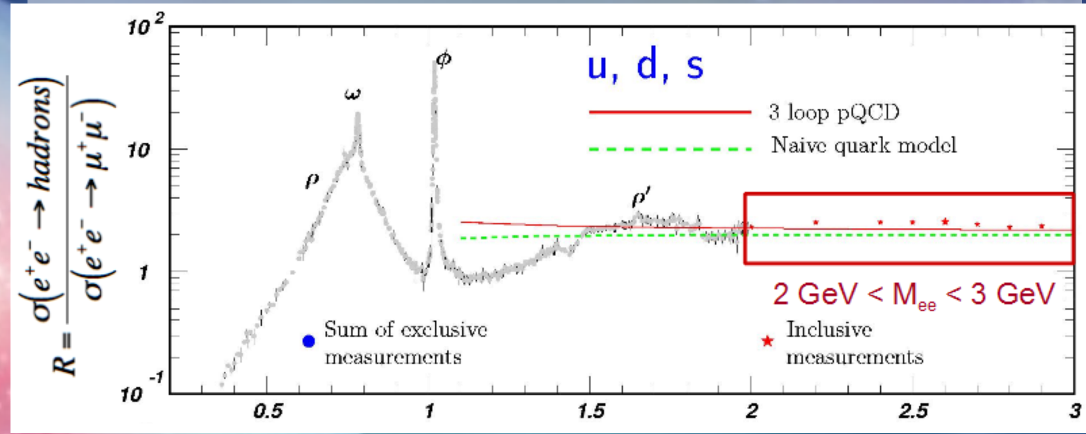
- Data 2014 – 2016
- 6.4 – 11 GeV

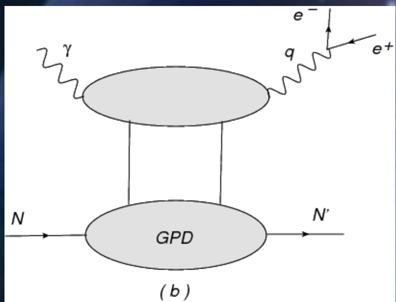
Previous, present, + approved



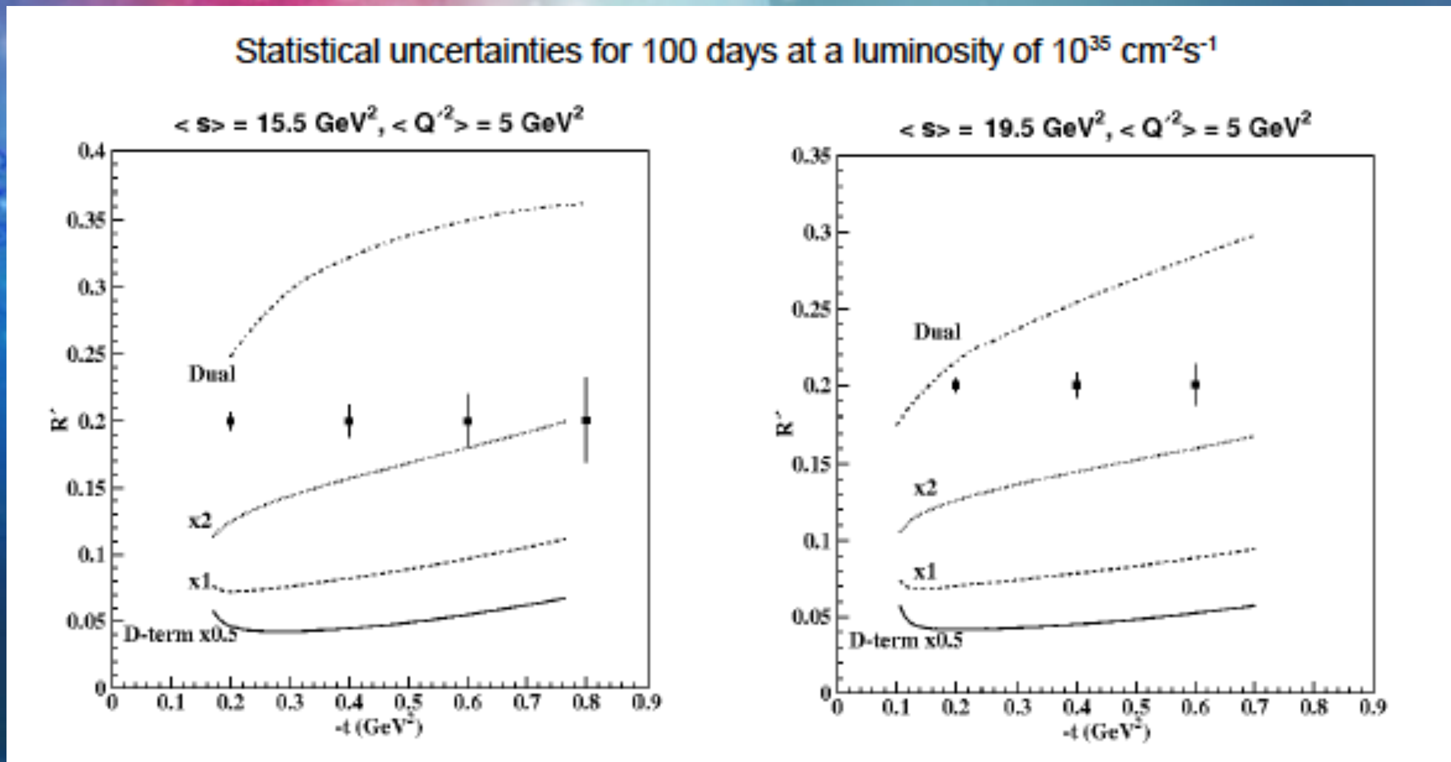
CLAS 12 Time-Like Compton Scattering $\gamma p \to p e^+ e^-$

- Ratio of $e^+e^- \to$ *Hadrons / di-muons* versus e^+e^- mass

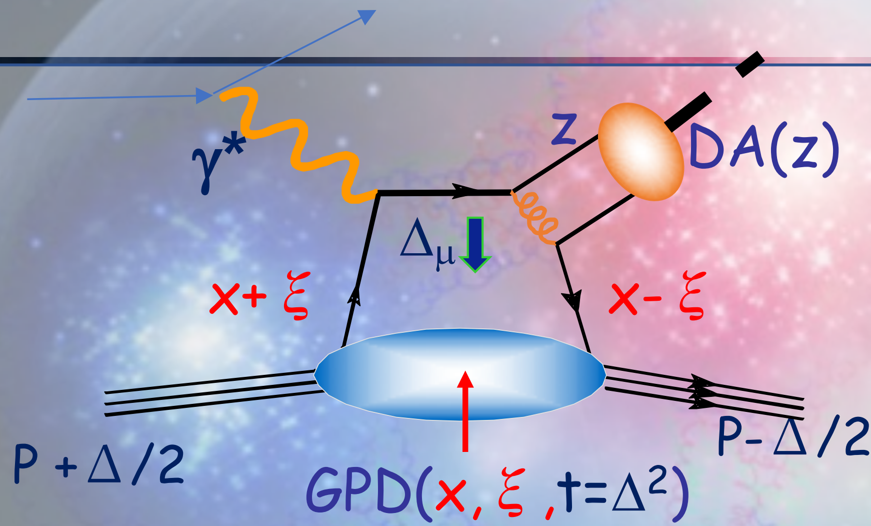




- Two bins in s
- Lowest bin in Q'^2
- *t*-dependence of Interference observable
- Illustrative GPD models



QCD Factorization of Deep Virtual Meson Production (DVMP): GPDs $\otimes$ Meson Distribution Amplitudes (DA)



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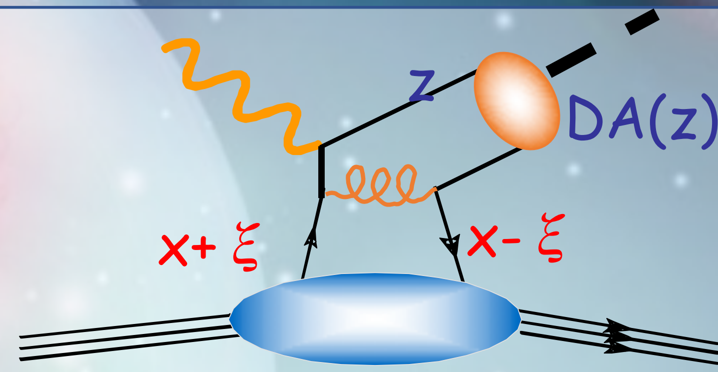

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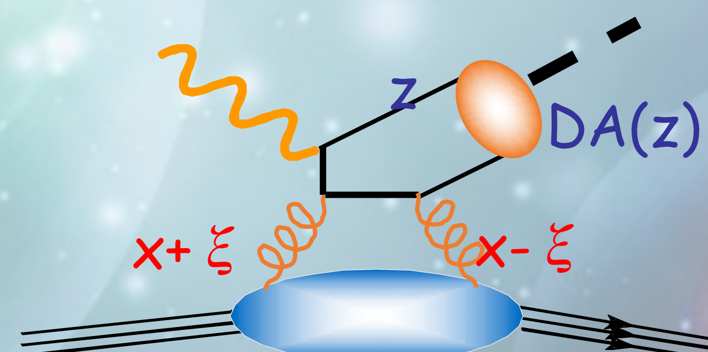


Gluon and quark GPDs enter to same order in α_S.

SCHC: $\sigma_L \sim [Q^2]^{-3}$ $\sigma_T \sim [Q^2]^{-4}$

Spin/Flavor selectivity

[Gluon GPDs in Diffractive channels only]

Pseudo-Scalars

- JLab Hall A: Cross section separation:
  - Longitudinally (Coulomb) and transversely polarized virtual photons H(e,e' π^0)p and D(e,e' π^0)pn
  - $\sigma_T >> \sigma_L$ (naïve factorization predicted $\sigma_L >> \sigma_T$)
- JLab CLAS: $\sigma_T + \epsilon\, \sigma_L$ for H*(e,e' p π^0)*, H*(e,e' p η)*
  - $\sigma_T + \epsilon\, \sigma_L >> \sigma_L$ [naïve collinear factorization].
- Helicity flip meson DA enhanced by χSB ➔ coupling to nucleon transversity GPD: $\langle \pi(q') \left| \overline{\psi} \sigma^{+-} \psi \right| 0 \rangle \otimes \mathcal{H}_T$
  - S. Goloskokov, P. Kroll, Eur. Phys. J. A 47, 112 (2011).
  - S. Ahmad, G. R. Goldstein, and S. Liuti, Phys. Rev. D 79, 054014 (2009).

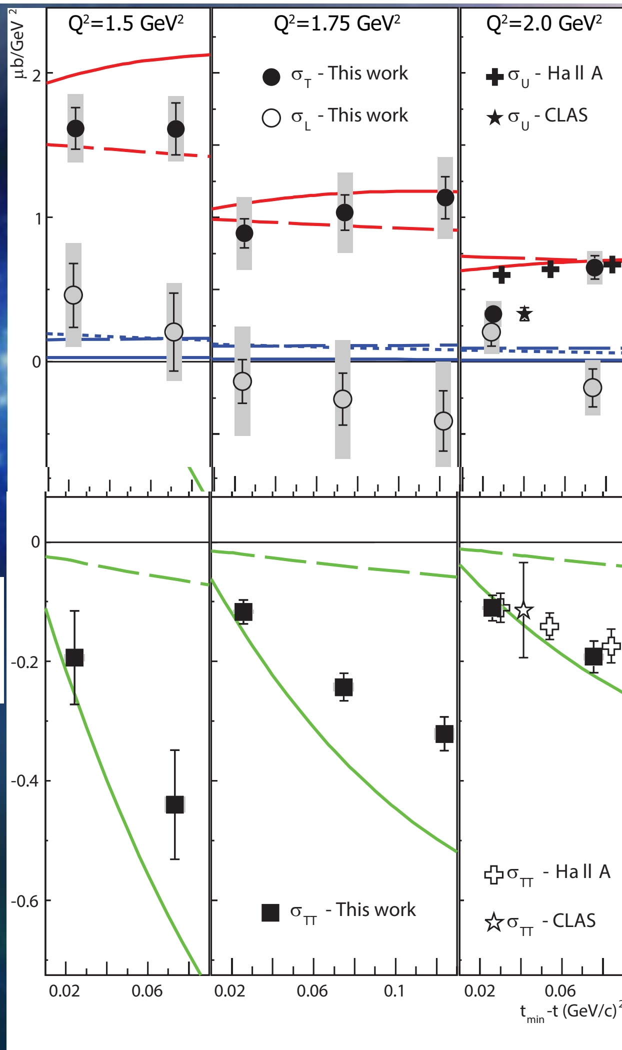
DVMP: π^0, η @ 6 GeV

M.Defurne *et al* [Hall A] PRL **117** (2016)

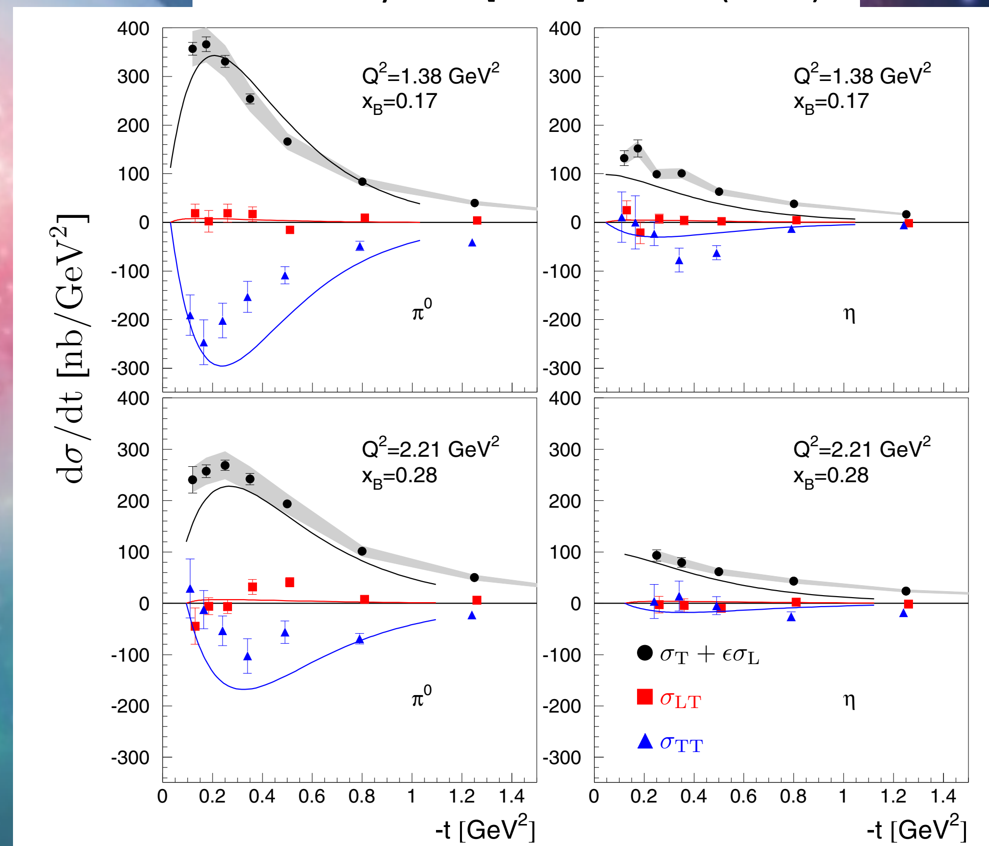
$\frac{d\sigma_T}{dt}$

$\frac{d\sigma_L}{dt}$

$\frac{d\sigma_{TT}}{dt}$



I.Bedlinskiy *et al* [CLAS] PRC **95** (2017)

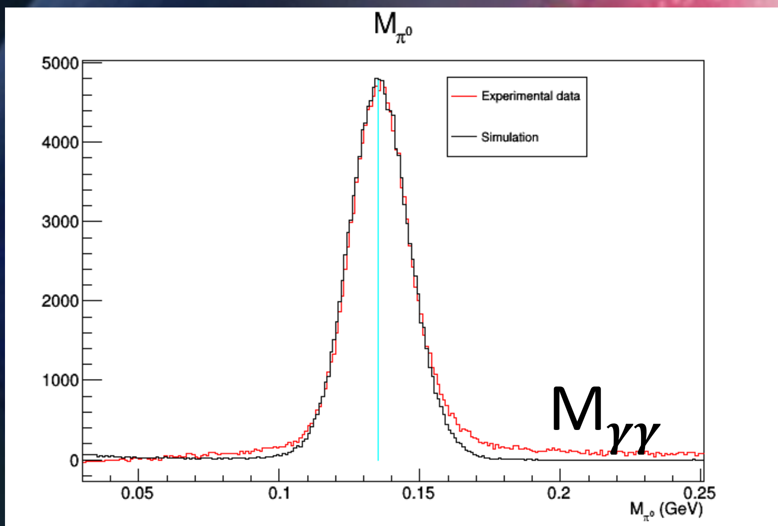


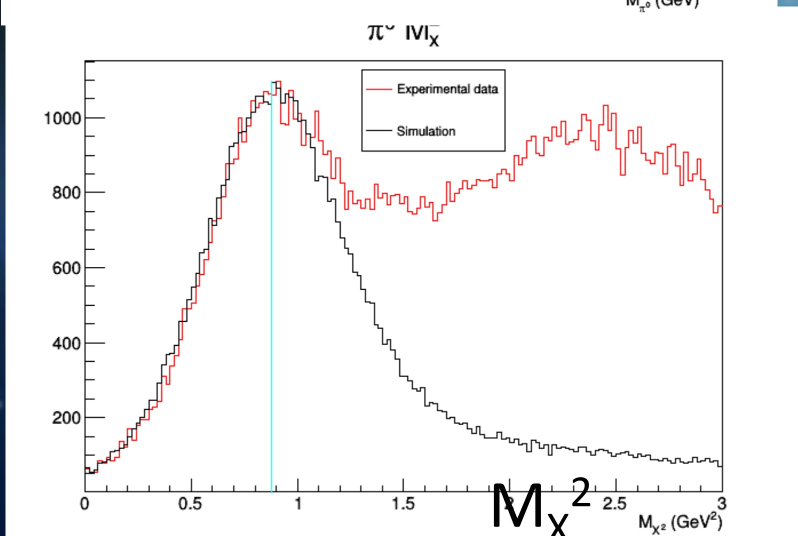
Solid Curves: S. Goloskokov and P. Kroll, Eur. Phys. J. A **47**, 112 (2011).

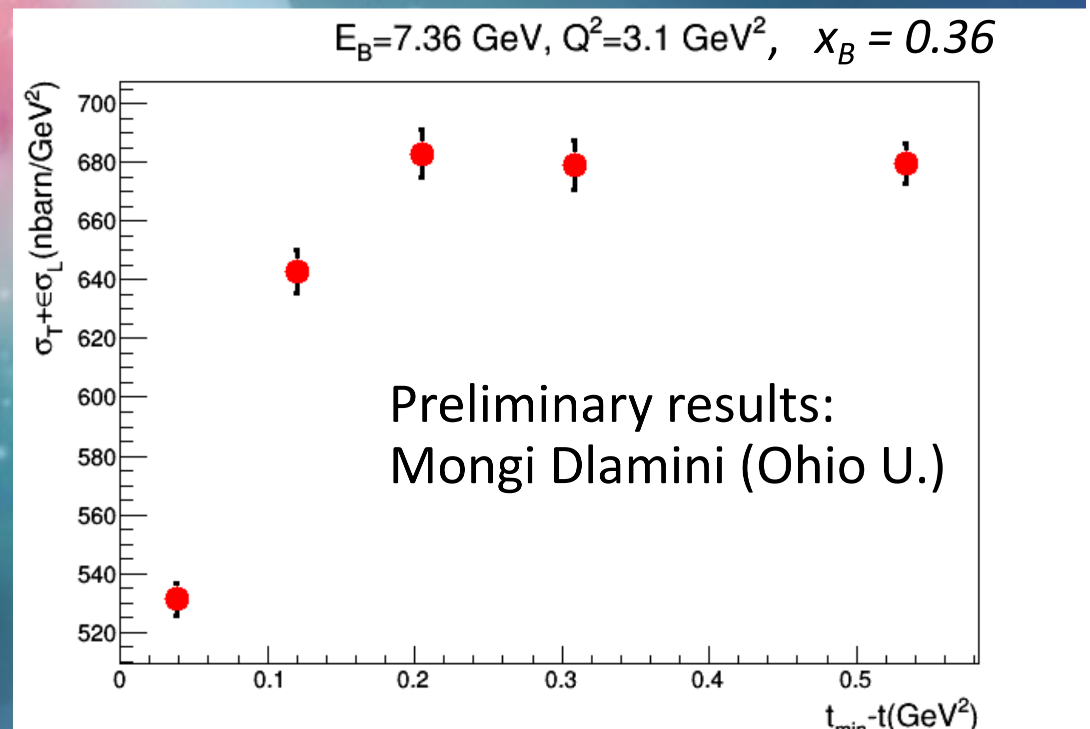
Dashed: G. R. Goldstein, J. O. Hernandez, and S. Liuti, Phys. Rev. D **84**, 034007 (2011).

Hall A: Deep π^0, $E_e = 7.4$ GeV

- $H(e,e'\gamma\gamma)X$





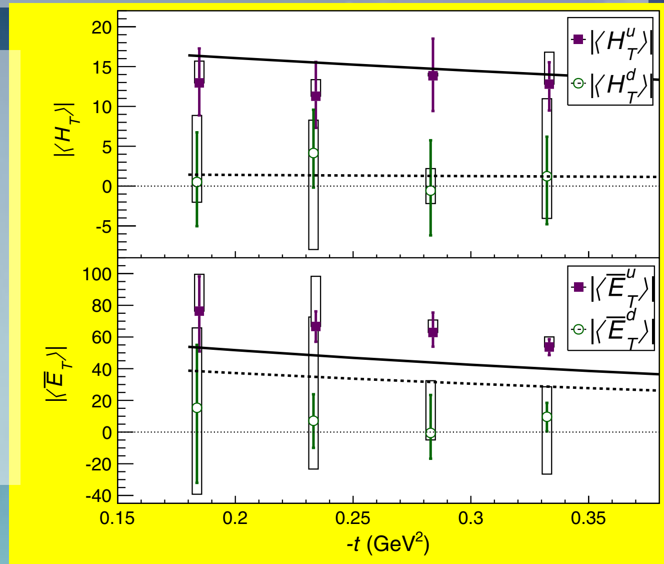


[Flavor ⊗ Spin]-Structure Separation

- Hall A: D(*e,e'π^0*)*pn*–H(*e,e'π^0*)*p*
  - M.Mazouz *et al* PRL **118** (2017)
- CLAS: H(*e,e'π^0*)*p* ± H(*e,e'η*)*p*
  - I. Bedlinskiy PRC **95** (2017)
  - V. Kubarovsky SPIN2014

Hall A
Q^2=1.75 GeV^2
$x_{Bj} = 0.36$

Error boxes are phase ambiguity, resolvable with η

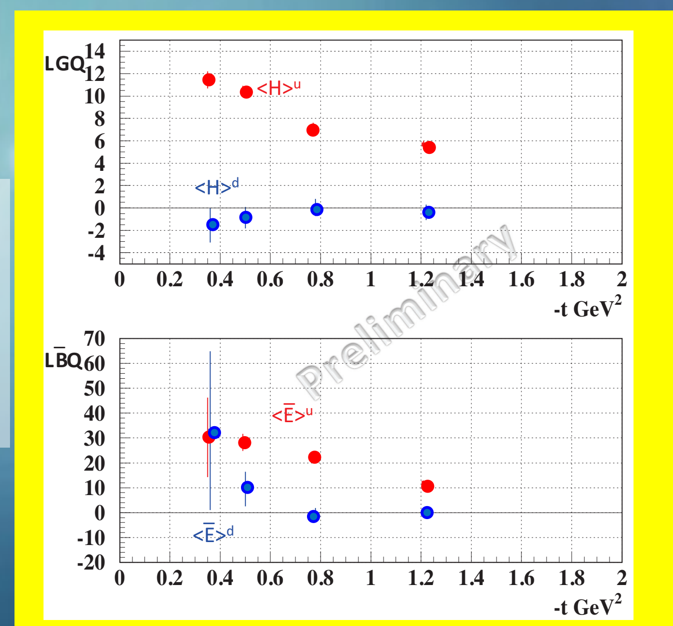


$$\frac{d\sigma_T}{dt} = \Lambda\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8M^2}|\langle \bar{E}_T\rangle|^2\right],$$

$$\frac{d\sigma_{TT}}{dt} = \Lambda\frac{t'}{8M^2}|\langle \bar{E}_T\rangle|^2.$$

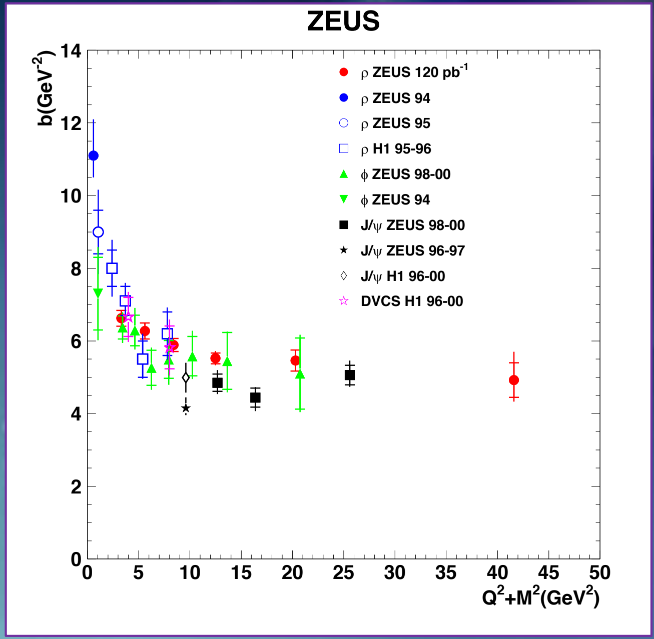
π^0	$|\langle H_T^{p,n}\rangle|^2 = \frac{1}{2}\left|\frac{2}{3}\langle H_T^{u,d}\rangle + \frac{1}{3}\langle H_T^{d,u}\rangle\right|^2,$
η	$|\langle H_T^{p,n}\rangle|^2 = \frac{1}{2}\left|\frac{2}{3}\langle H_T^{u,d}\rangle - \frac{1}{3}\langle H_T^{d,u}\rangle\right|^2,$

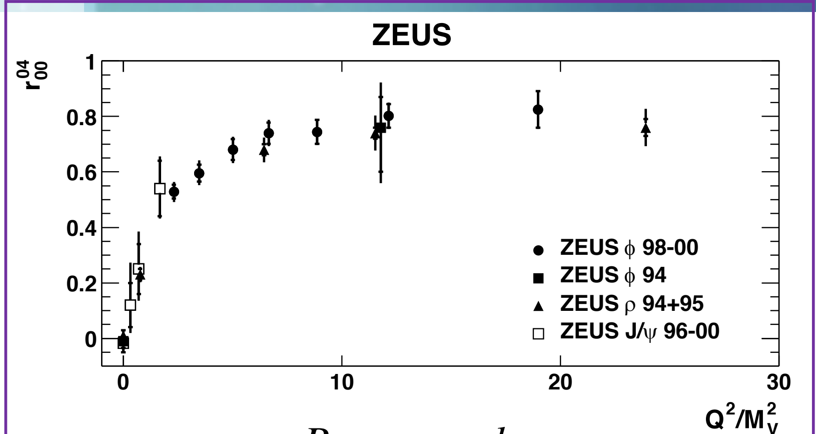
CLAS
Q^2=2.2GeV^2
$x_{Bj} = 0.27$
Assume $\sigma_T \gg \sigma_L$



Vector mesons

- ϕ: JLab12 kinematics, predictions:
  - Gluon GPDs + ≤20% gluon⊗strange
- J/Psi: seen in Hall D.
  - Threshold production → large $-t_{min}$.
  - CLAS12 search for LHCb J/ψ⊗p states
- ρ, ϕ
  - Slow approach to longitudinal dominance in HERA ρ data
  - Unexplained enhancement in ρ-production at low W^2 in CLAS data.
    - Helicity violating amplitudes ➔ Transversity GPDs *à la* pseudo-scalars?
  - ω: strong violation of SCHC @ CLAS



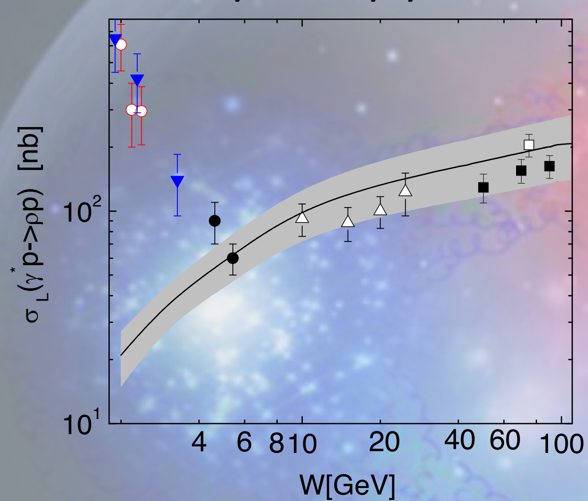


$$r^{04}_{00} = \frac{\varepsilon R}{1+\varepsilon R} = \frac{\varepsilon d\sigma_L}{d\sigma_T + \varepsilon d\sigma_L}$$

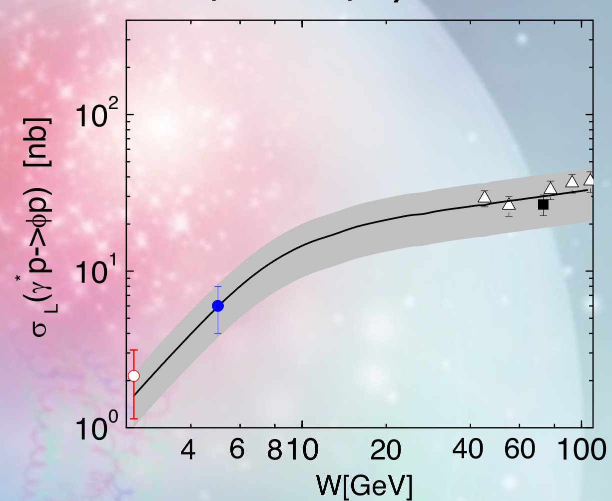
Deep ρ,   Deep ϕ

S. Goloskokov, P. Kroll EPJC **50** (2007) 829

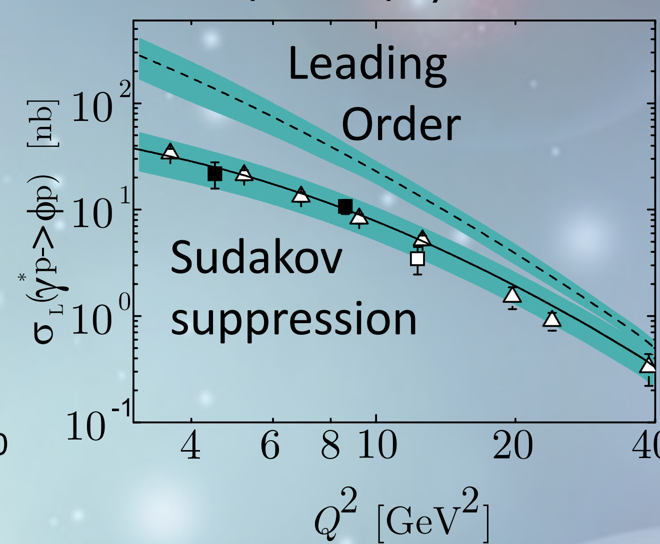
e p → e p ρ



e p → e p ϕ



e p → e p ϕ

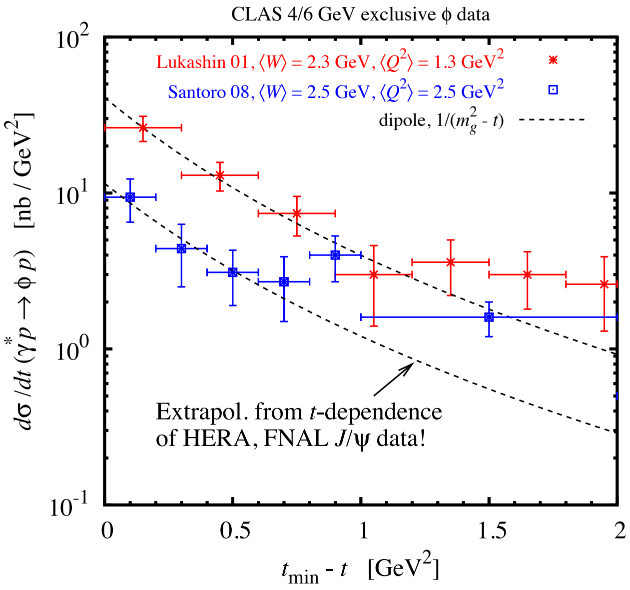


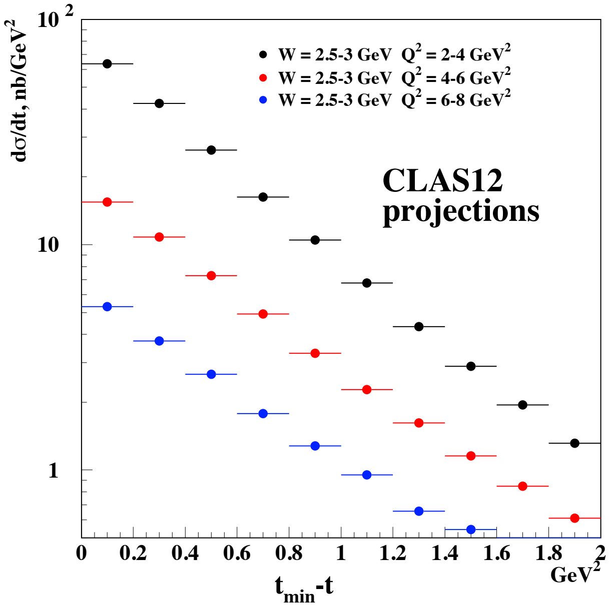
$Q^2 = 4\,\mathrm{GeV}^2$

E665 (△), HERMES (●), CORNELL (▲)
ZEUS (□), H1 (■), CLAS (○)

- Vector and pseudo-scalar mesons show evidence for Hard/Soft separation ➔ [nucleon structure] ⊗ [finite transverse size γ^*→meson amplitude].
- Strong corrections, new amplitudes for $Q^2 \leq 10$ GeV^2.

Exclusive ϕ: CLAS12 experiment





- t–dependence of 6 GeV ϕ data consistent with gluonic radius measured at high energies
  Extrapolation of HERA, FNAL J/ψ results

- CLAS12: Test reaction mechanism and harden GPD–based description

  When does t–slope become independent of Q^2?

  How does W–dependence change with Q^2?

  L/T ratio from vector meson decay and s–channel helicity conservation

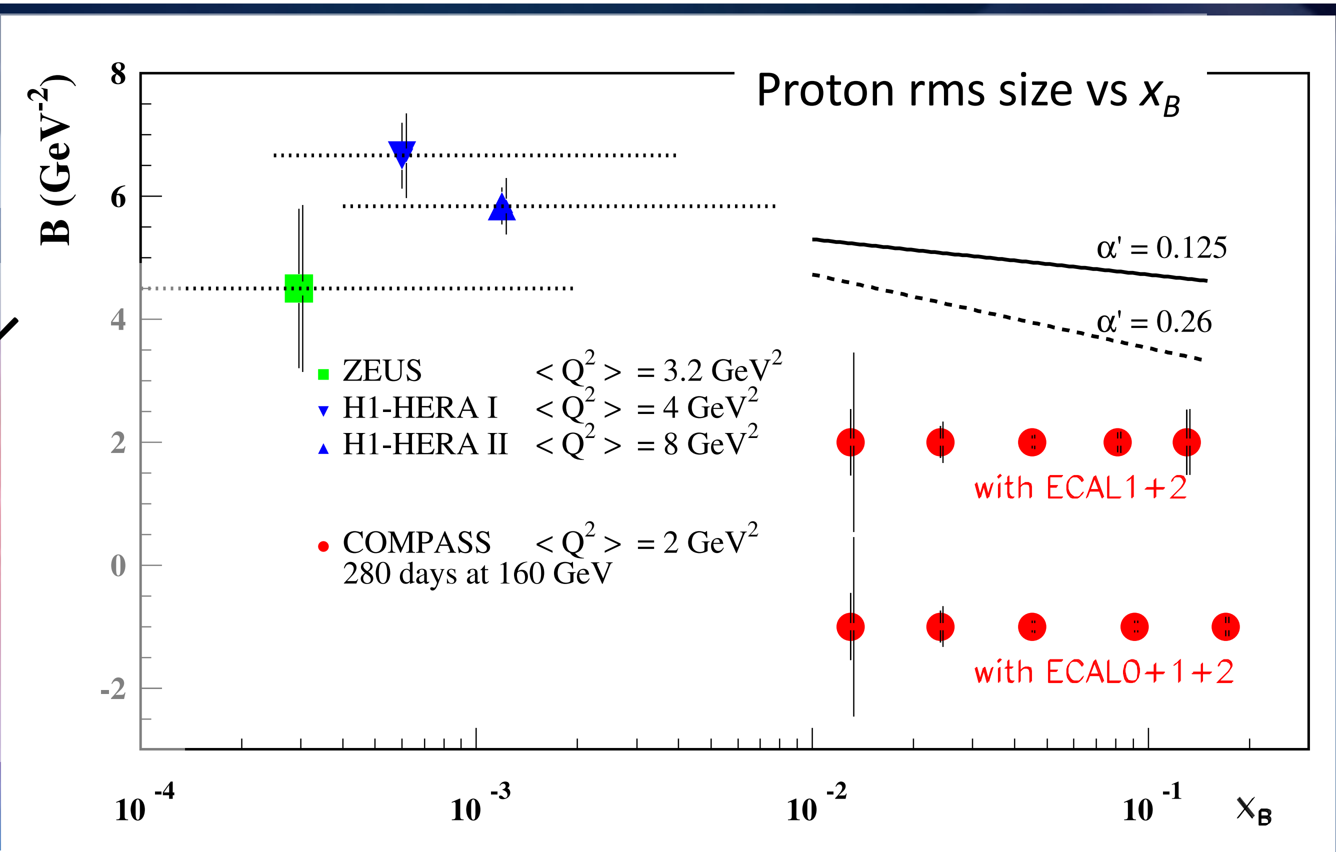
- CLAS12: Extract t–dependence of gluon GPD at $x = 0.2 - 0.5$

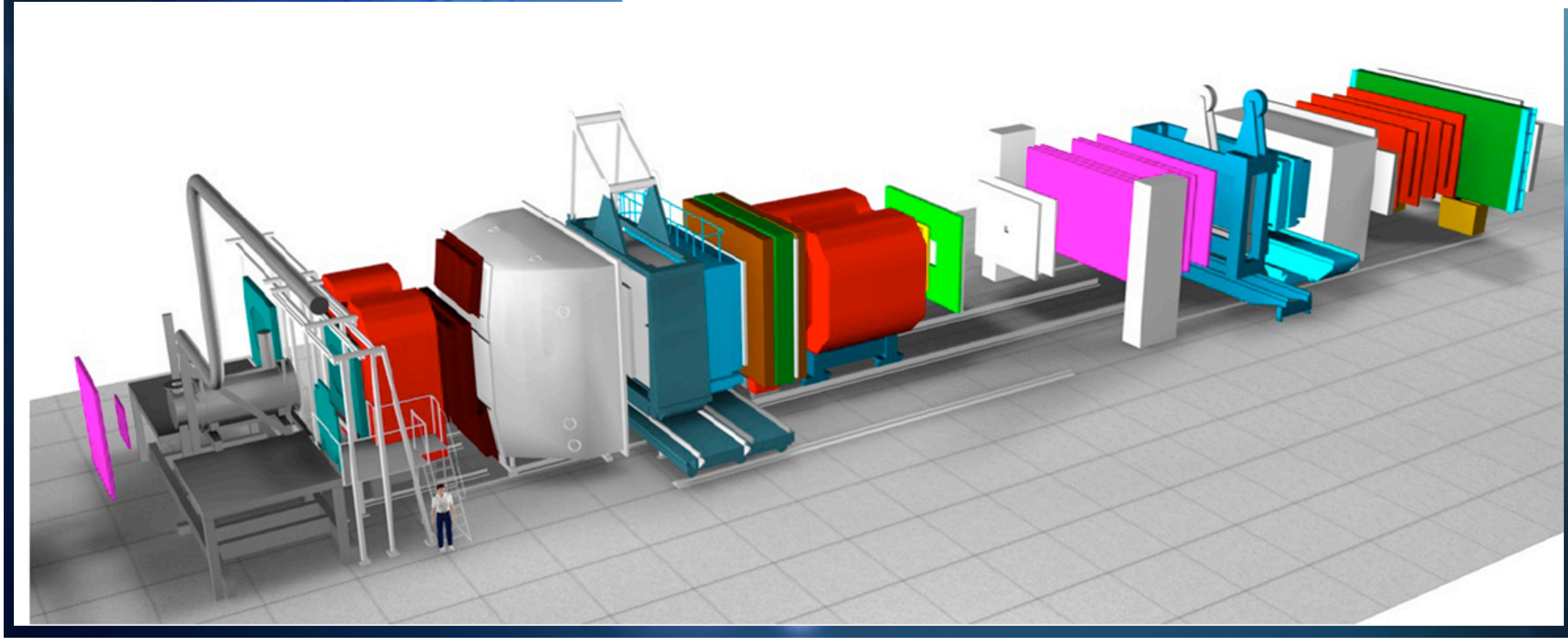
  Obtained from relative t–dependence of $d\sigma_L/dt$

First accurate gluonic image of nucleon at large x!

COMPASS

- 200 GeV $\mu^+\uparrow$, $\mu^-\downarrow$
- $\mathcal{L} = 10^{32}$ /cm^2/s
- 2016+
  After Drell-Yan run





What about the Ji Sum-Rule?

- $\lim_{t \to 0} \int x dx [H_f(x,\xi,t) + E_f(x,\xi,t)] = 2 J_f$
  - Skewing effects, Extracting *E* ?
  - *u,d* flavor separations from proton, neutron
  - $E^{(n)}$ dominates unpolarized $n(e,e'\gamma)n$ ➔ CLAS12 RG-B
  - $E^{(p)}$ requires transversely polarized targets
    - HD_{ice} for CLAS12
    - NH_3, ^3He with SOLiD or TCS?
  - Glue from Deep ϕ at JLab12 and Deep ϕ & J/ψ at EIC
    - ~50% of momentum sum rule comes from gluons
    - ~50% of gluon momentum is at $x_g > 0.1$
    - Important role for JLab12!

Constraints on Ji Sum Rule

- $H_f(x,0,t)$ **valence** essentially known from fits to $F_{1f}(-t) \otimes q_f(x)$ .... *Diehl (2013), Ahmad (2007)*
  - Measure $H_f(x,x,t)$ → Determines DD Profile function
    - *Calibrate "skewing effect"*
- $E_f(x,0,t)$ constrained from $F_{2f}(-t)$ and *assumption* $e_f(x)$ does not change sign.
  - Test this assumption
    - x≈0.1 COMPASS ⊕ x≈0.4 JLab12 ⊕ Lattice QCD ⊕ …
- Transverse polarization data + Theory + Models ➔ Tight constraint on $q - \bar{q}$ contribution to Ji Sum Rule from JLab 12 GeV era.
- Need the EIC to constrain the sea & gluons

Conclusions

- Spatial Imaging ***is*** possible (in 1+2 dimensions)
- New experimental and theoretical tools are helping us to understand how QCD generates
  - The mass of ordinary matter (98%)
  - The spin of the hadrons: proton, neutron, vector mesons…
    - proton spin ~25% from spin of quarks
    - How much is gluons? How much is Orbital Angular Momentum.
  - Spatial distribution of charge and matter in hadrons. (non-trivial flavor, momentum-fraction dependence)
  - Nuclear Binding (Lecture 3)
    - Why is the deuteron (*np*) bound but *nn* not?
    - Why are ^{4}He, ^{6}He(β^- 1sec), ^{8}He(β^- 0.1sec) bound, but not ^{5}He ?

Backup Slides

TCS

Deep Virtual Meson Production

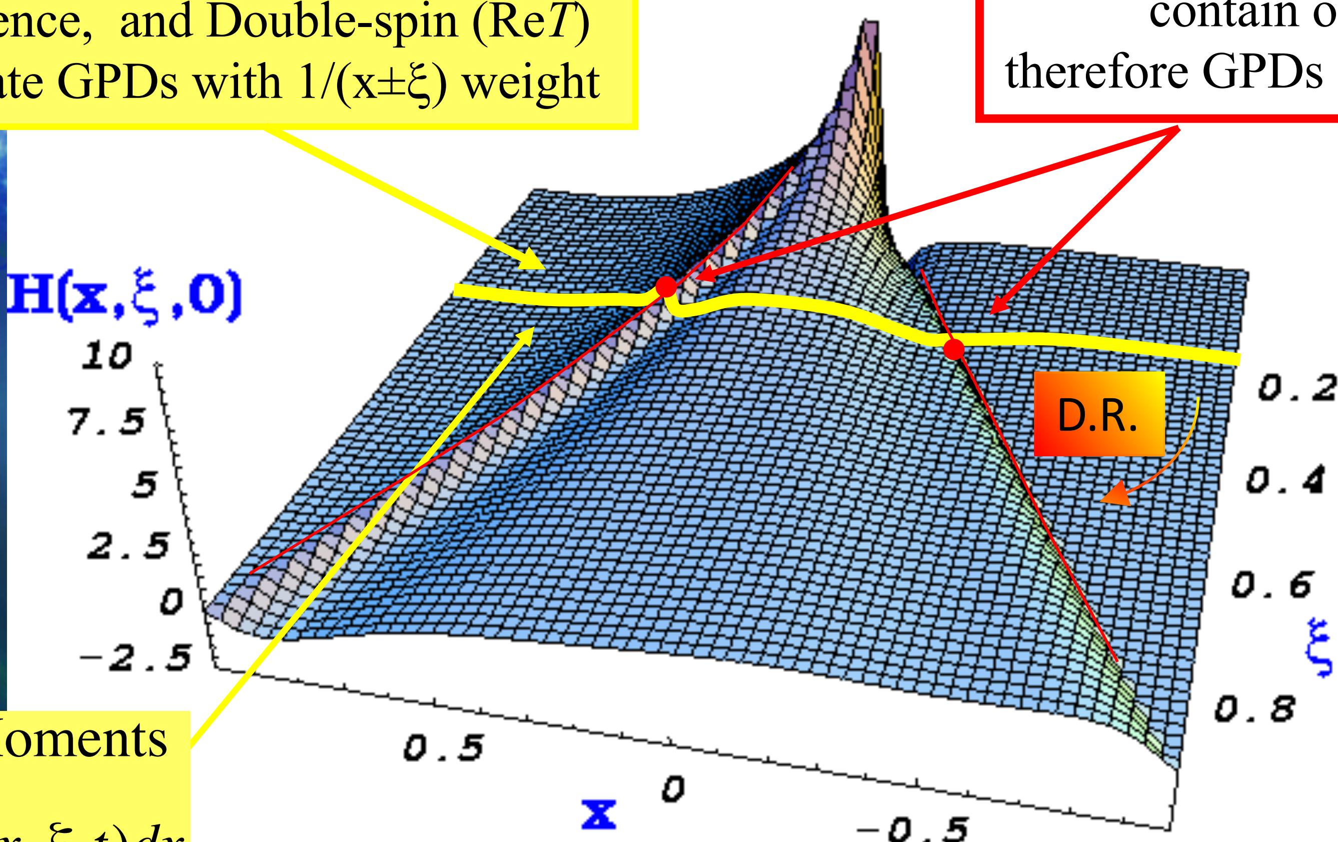
DVCS, GPDs, Compton Form Factors(CFF), and Lattice QCD

(at leading order:)

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \quad P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

Cross-section (σ), Beam-charge-difference, and Double-spin (Re*T*) integrate GPDs with 1/(x±ξ) weight

Beam or target spin Δσ contain only Im*T*, therefore GPDs at $x = \xi$ and $-\xi$



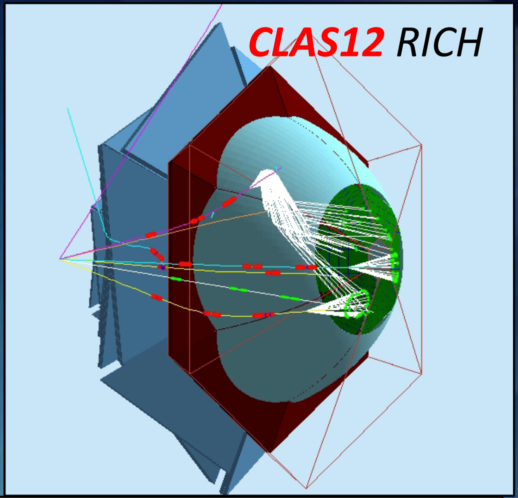
Lattice Moments

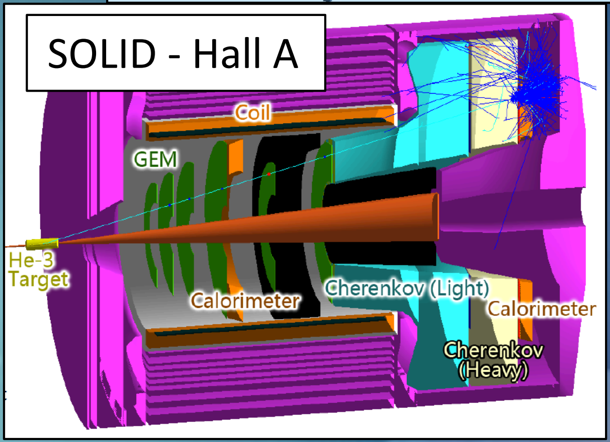
$= \int x^n H(x,\xi,t)dx$

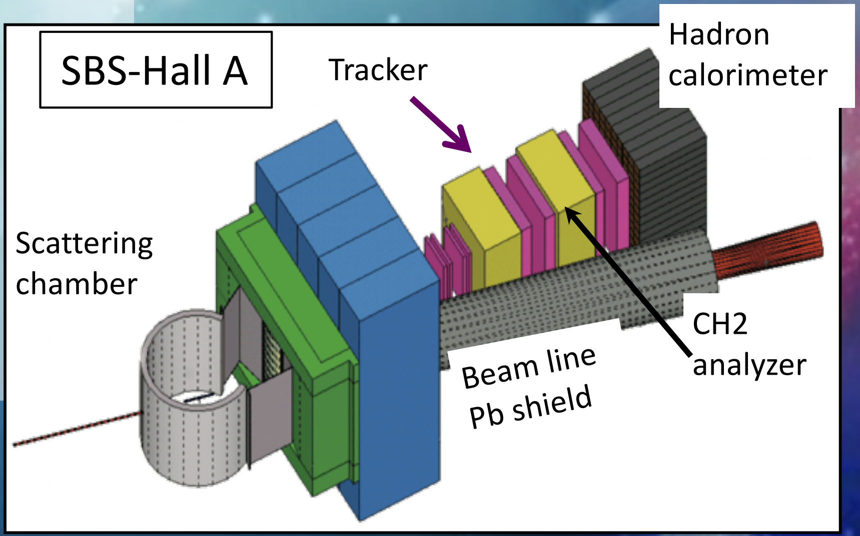
GPDs at JLab: Future Upgrades

(Mostly motivated by non-GPD topics)

- RICH Detector (partial) in CLAS 12: π/K id
  - INFN participation
- **So**lenoidal **L**arge **I**ntensity **D**etector (SoLID) in Hall A (CLEO Solenoid)
  - TCS, J/Ψ
  - Chinese participation
- **S**uper **B**ig**B**ite **S**pectrometer
  - Dipole from BNL
  - Funded, under construction
  - GEM trackers for high rates

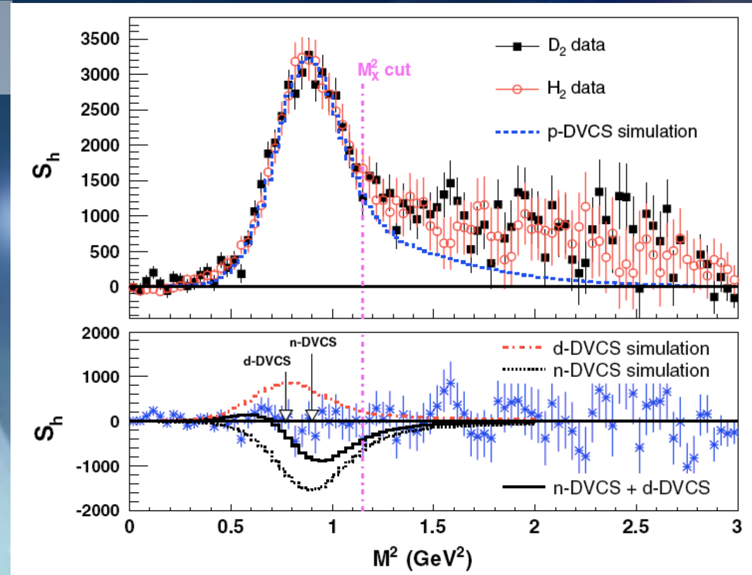




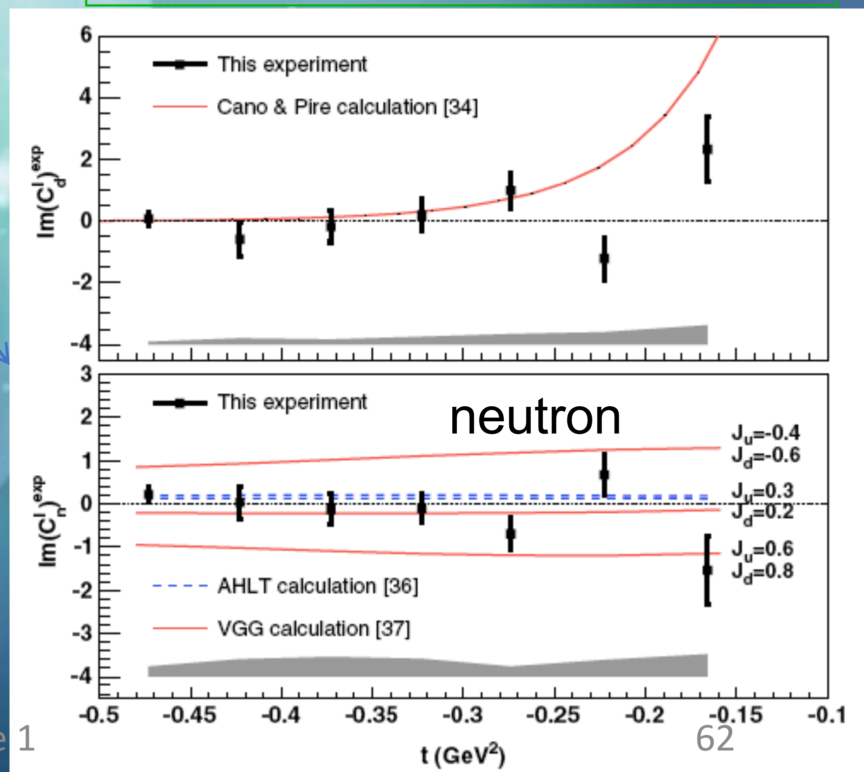


DVCS-Deuteron, Hall A

- E03-106:
  - D(e,e'γ)X ≈ *d(e,e'γ)d+n(e,e'γ)n+p(e,e'γ)p*
  - Sensitivity to *$E_n(\xi,\xi,t)$ in Im[DVCS*BH]*



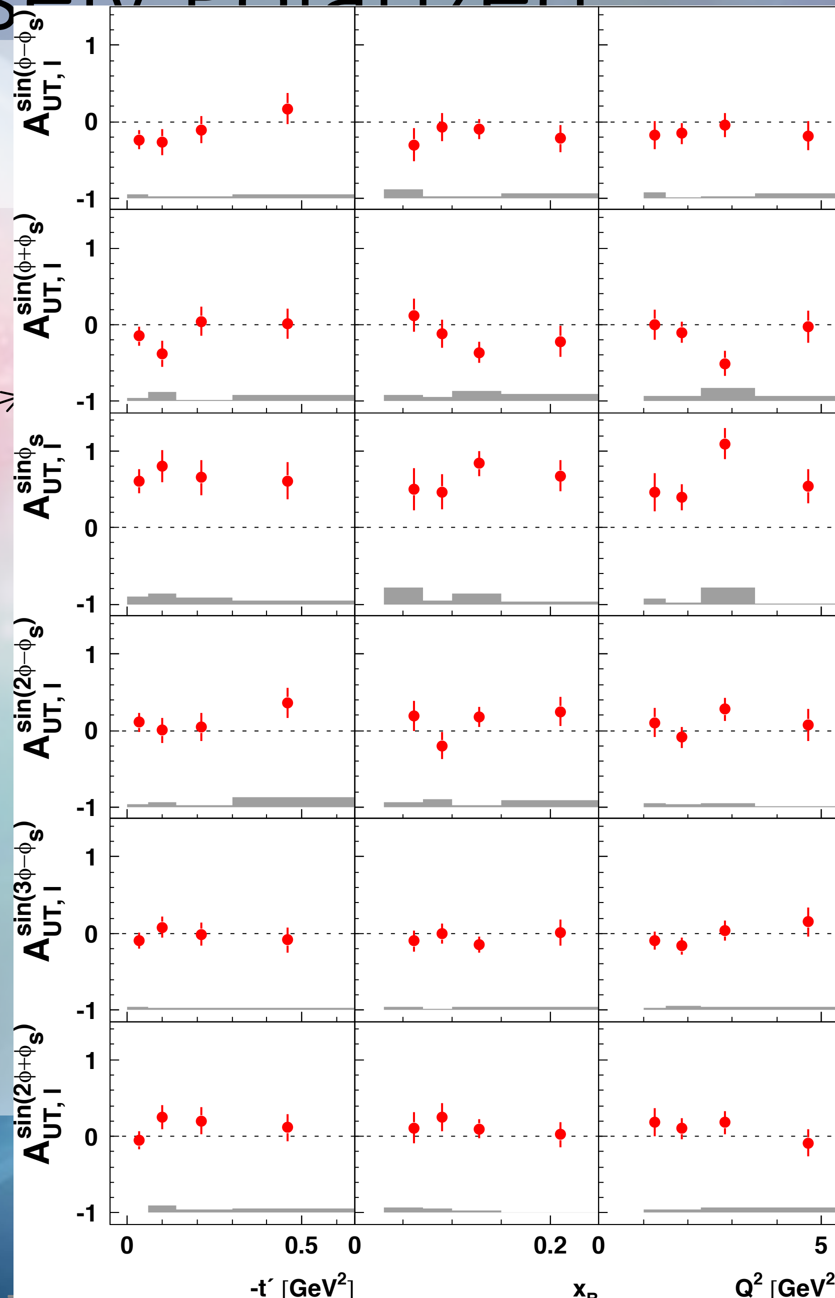
Q^2=2.3 GeV^2, x_B=0.36



- E08-025 (5.5 GeV- 2010)
  - Reduce the systematic errors
    - Expanded PbF_2 calorimeter for π^0 subtraction
  - Separate the *Re[DVCS*BH]* and *|DVCS|^2* terms on the neutron via two beam energies.

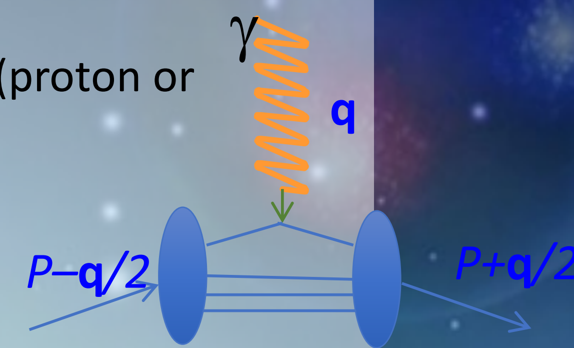
HERMES-Transversely Polarized H(e,e′γ)X, SSA

- Azimuthal moments
- Differential in x_{Bj}, Q^2, **or** t, integrated over other 2 variables.
- $\sin\phi$ moments
  - Sensitive to $E(\xi,\xi,t)$
- $\sin 2\phi$ moments ≈ 0
  - ≈ Twist 3
- $\sin 3\phi$ moments
  - ≈Gluon Transversity

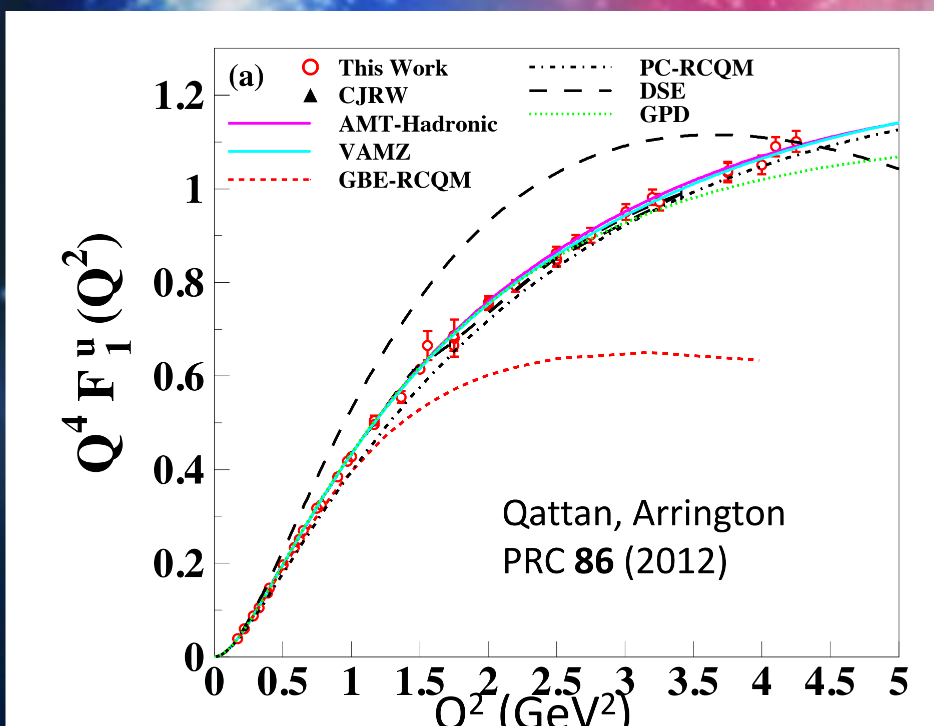


Form Factors and Charge Distributions, revisited

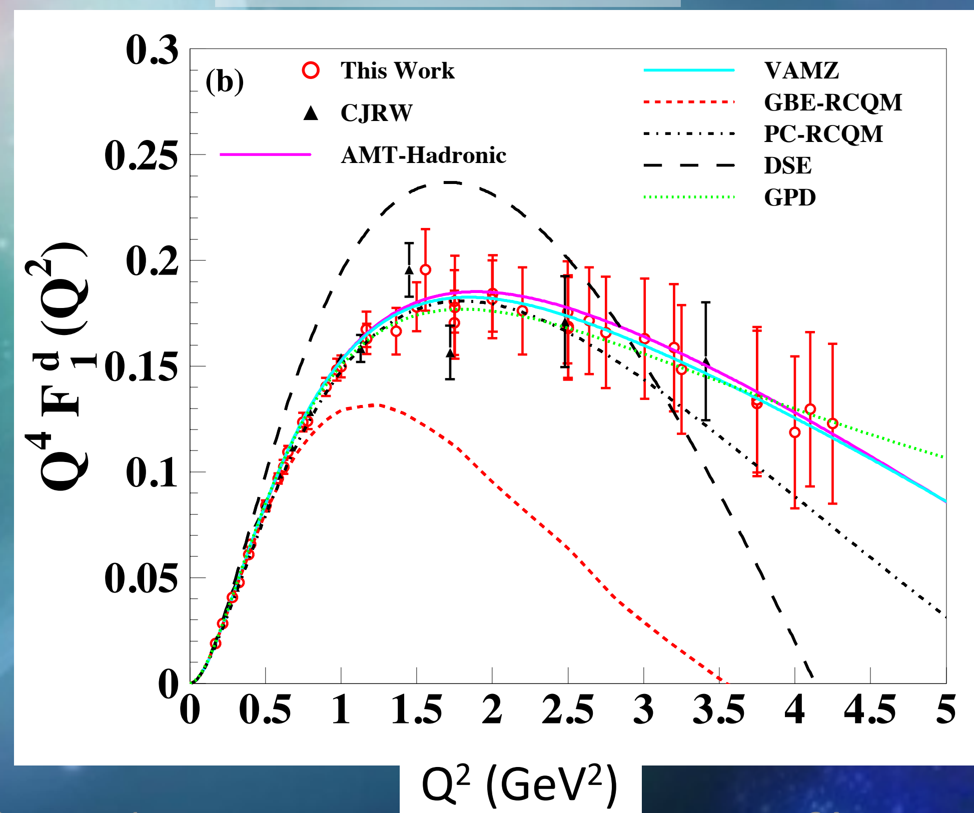
- Dirac Form Factor $F_1(Q^2)$:
  - 2-D Fourier transform of the charge distribution of the nucleon (proton or neutron)
  - Integrate over the momentum axis (M. Burkardt)
- Flavor Separations



$F_1^{(u)}(Q^2) - F_1^{(\bar{u})}(Q^2)$

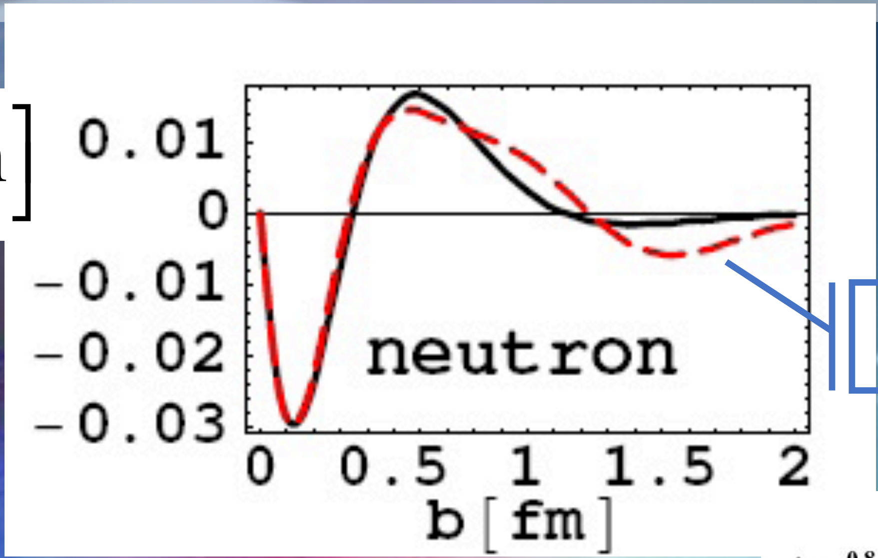


$F_1^{(d)}(Q^2) - F_1^{(\bar{d})}(Q^2)$



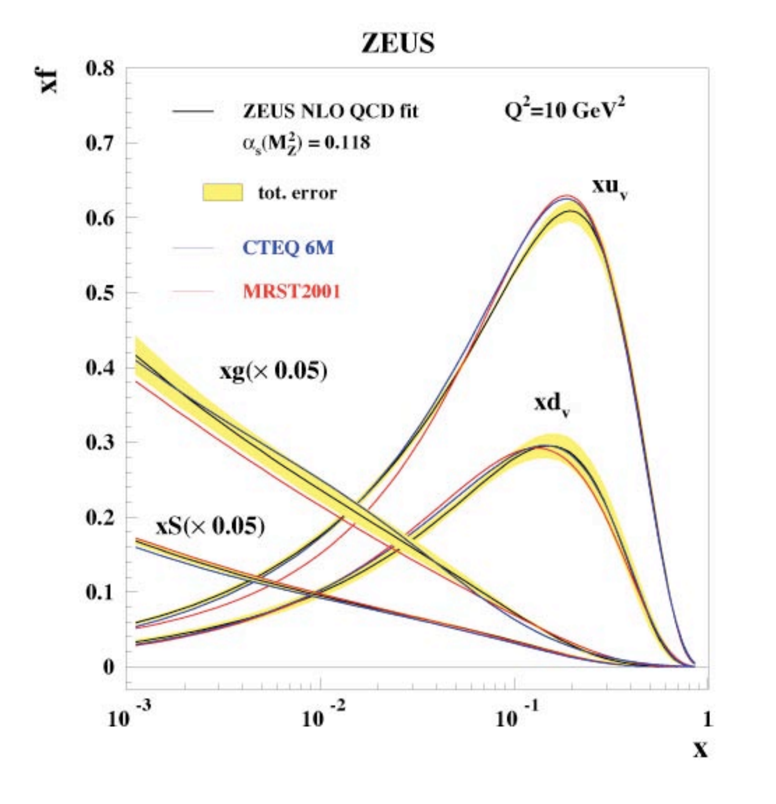
Inverting the Fourier-Transform

$b\rho(b) \quad [e/\text{fm}]$



$n \rightarrow p\pi^-$

$$\int_0^\infty b\rho_n(b)\,db = 0$$



- Charge Distribution in the Neutron (G.Miller)
  - Negative charge hole at the center
  - GPD explanation: greater than 2x more fast d-quarks in neutron than fast u-quarks

    $u_{proton} = d_{neutron}$ $\quad$ $d_{neutron} = u_{proton}$