Exclusive γ-N scattering in hard regime

(Polarization Transfer in proton WACS)

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Most of the material from:

- C. Fanelli
- D.J. Hamilton
- B. Wojtsekhowski
- NPS collaboration
- … and more

Outlook

- Theoretical descriptions
- Experimental aspects
- Current status and perspectives

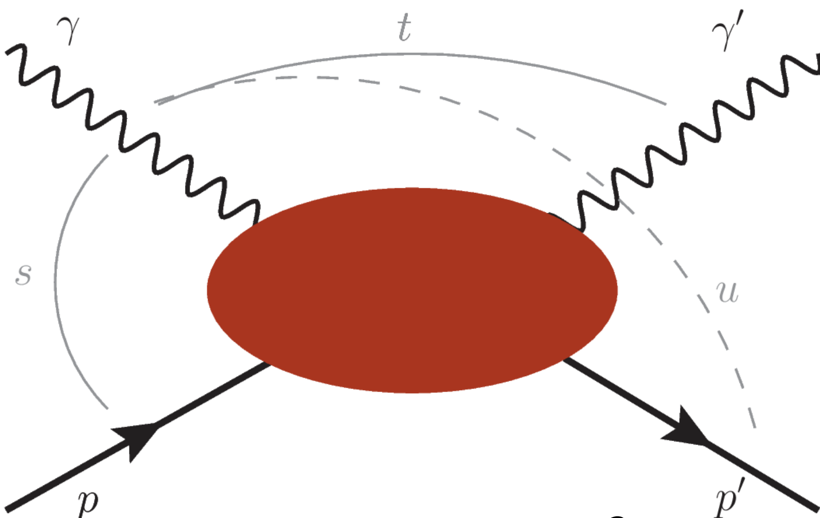
Real CS in hard exclusive regime

«Potentially powerfull but seldom used probe of the short-distance structure of the nucleon» (A.M. Nathan/2002)

Open questions / opportunities of investigation:

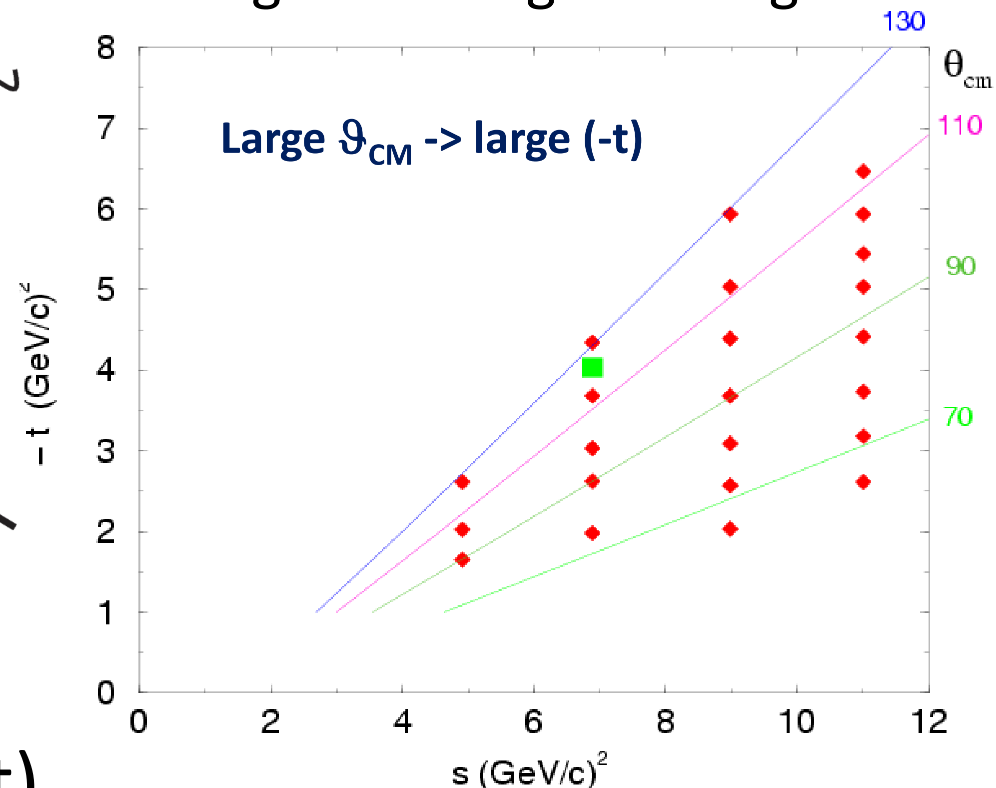
- Understand the «naively simplest» reaction mechanism (how and when does it factorize? what is the nature of the involved quark?)
- Extract the nucleon structure information from the soft/non perturbative part (what can be extracted ? how does it relate to other hard processes findings ?)

Wide Angle Compton Scattering (WACS)



s, -t, -u >> M_N^2

Hard regime at large CM angle



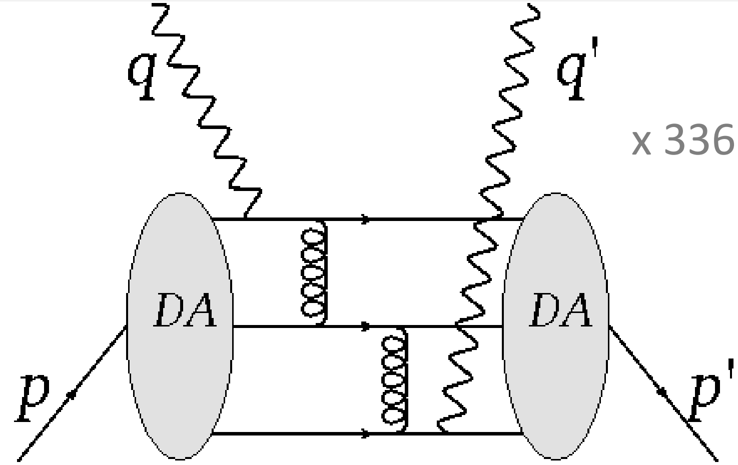
Complementary to:

- DVCS (large Q^2, small t)
- ep elastic scattering at high Q^2
- Deeply Virtual meson electroproduction …

… one of the least investigated/understood hard regime process!

pQCD description of WACS

S.J. Brodsky and G. Farrar, PRL 31, 1153 (1973)

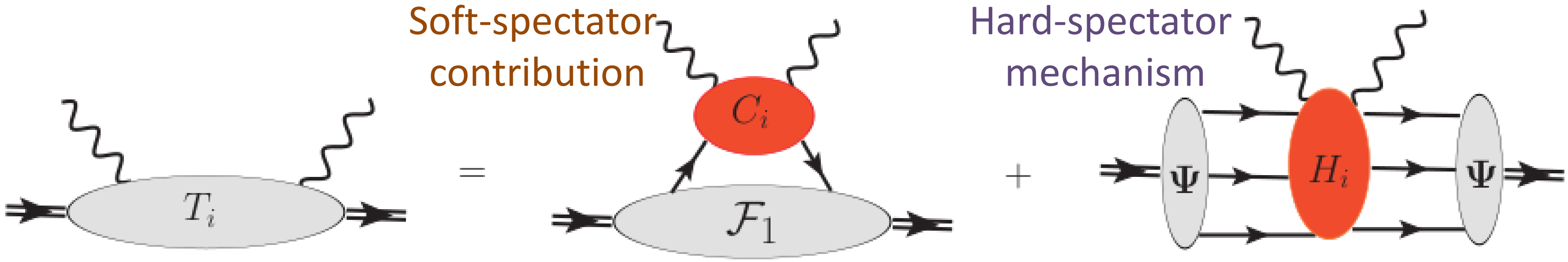


- Traditional framework for hard exclusive reactions (e.g. DIS)
- Probably the most «explanable» description
- Exchange of 2 hard gluons between the quarks
- *Naturally* predict Hadron Helicity Conservation and Constituent Counting Rules
- pQCD mechanism expected to dominate at «large» energy scale; not clear where the transition region seats

SCET description of WACS

N.Kivel and M. Vanderhaeghen, arXiv 1312.5456

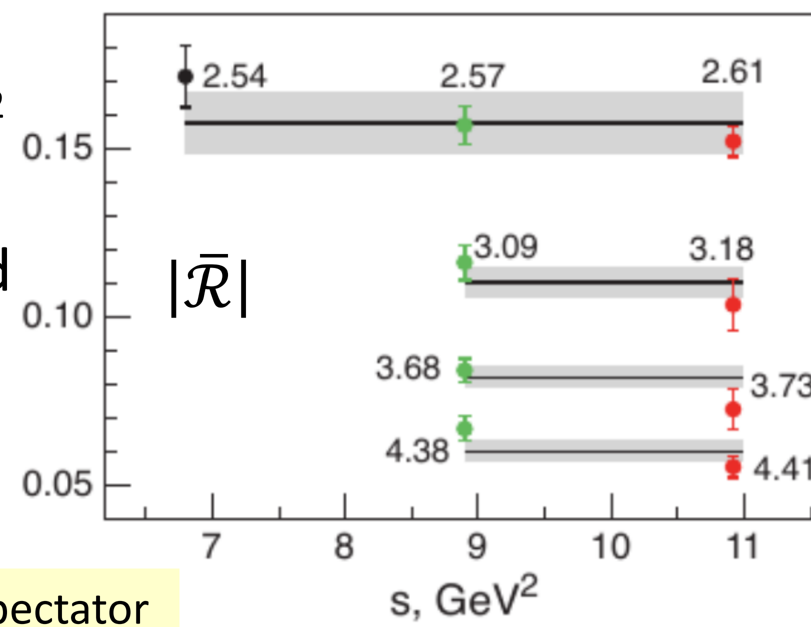
In WACS kinematics: $\boldsymbol{s}, -\boldsymbol{t}, (-\boldsymbol{u}) \gg \boldsymbol{\Lambda_{QCD}}$



$$T_i(s,t) = C_i(s,t)F_1(t) + \Psi * H_i\,(s,t) * \Psi \qquad i = 1,..,6$$

- Soft-spectator suppressed at large Q^2; can be dominant at moderate Q^2
- Introduce one phenomenological universal form factor (strongly linked to TPE in electron scattering):

$$\frac{d\sigma}{dt} \sim \frac{d\sigma^{KN}}{dt}|\mathcal{R}|^2$$



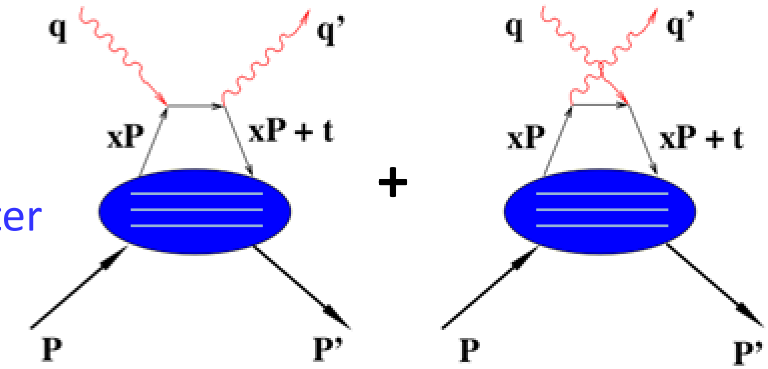
WACS promising for better understanding of soft-spectator

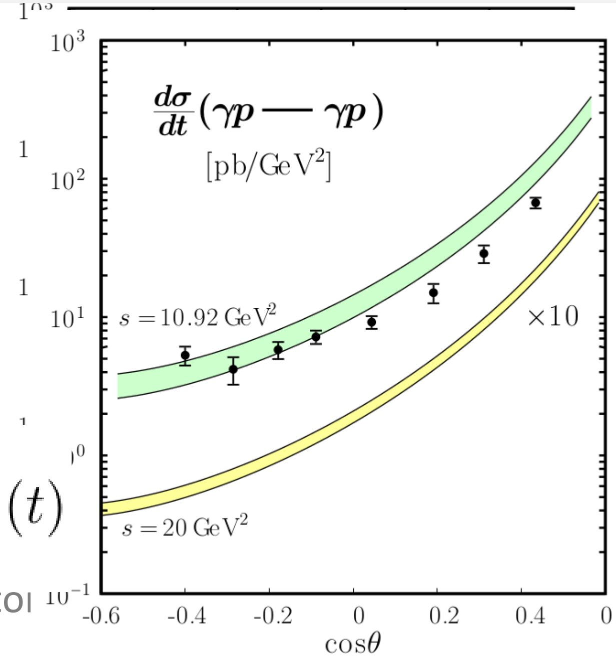
Handbag/GPD description of WACS

(Share many features with the SCET approach)

M. Diehl and P. Kroll, arXiv 1302.4604

3 out of 4 GPDs enter the WACS cross section:





$$\frac{d\sigma/dt}{d\sigma_{KN}/dt} = f_V \left[R_V^2(t) + \frac{-t}{4m^2} R_T^2(t) \right] + (1 - f_V) R_A^2(t)$$

f_V kinematical factor

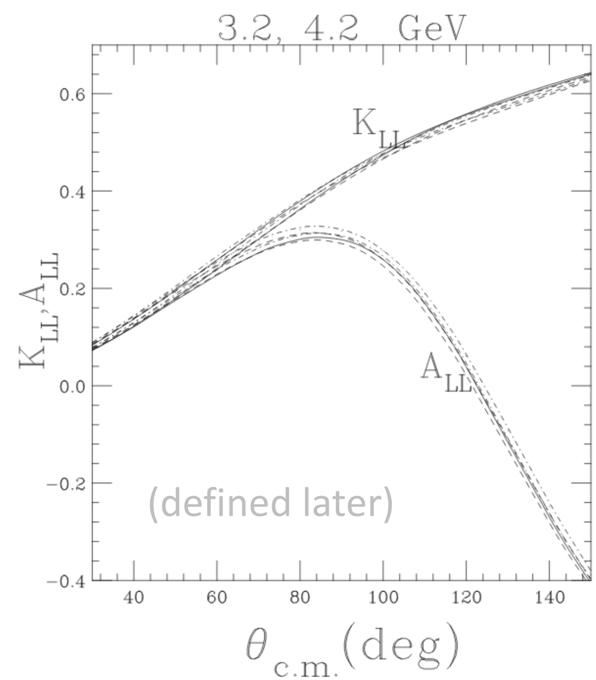
GPDs are a «general framework» for the nucleon structure description in hard mechanisms

γp	elastic ep	DIS
$R_V(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} H^a(x,0,t),$	$F_1(t) = \sum_a e_a \int_{-1}^{1} dx\, H^a(x,0,t),$	$H^a(x,0,0) = q^a(x)$
$R_A(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} \operatorname{sign}(x)\, \hat{H}^a(x,0,t),$	$G_A(t) = \sum_a \int_{-1}^{1} dx \operatorname{sign}(x)\, \hat{H}^a(x,0,t),$	$\widehat{H}^a(x,0,0) = \Delta q^a(x)$
$R_T(t) = \sum_a e_a^2 \int_{-1}^{1} \frac{dx}{x} E^a(x,0,t),$	$F_2(t) = \sum_a e_a \int_{-1}^{1} dx\, E^a(x,0,t),$	$E^a(x,0,0) = 2\frac{J^a(x)}{x} - q^a(x)$

Relativistic **C**onstituent **Q**uark **M**odel and WACS

G.A. Miller, arXiv 0402092

- Evaluate handbag diagram in Impulse approximation with Poincaré, Gauge, time reversal invariances and conservation of parity
- Use proton wave functions constrained by EMFF; includes proton helicity non-conservation (induced by relativistic and quark mass effects)
- Predict different initial and trasferred polarization observables (due to helicity flip)



Dyson-**S**chwinger **E**quations in WACS

- In principle provide solutions to QCD at any regime
- Main phenomenology on RCS recently developed in G. Eichman and C.S. Fischer arXiv 1212.1761 and applied to low-t regime
- Succesfull in interpretation of elastic FF data assuming di-quark coupling dominance in nucleon wavefunction
- Calculation of specific observable in WACS not available yet
- WACS cross-section data especially at moderately high-t may help testing evolution of the DSE amplitudes.

Main Observables: cross section and asymmetries

$$\frac{d\sigma(\Uparrow_\gamma, \Uparrow_p; s, t, u)}{dt}$$

Cross section

$$A_{LL}\frac{d\sigma}{dt} \equiv \frac{d\sigma(\uparrow\uparrow)}{dt} - \frac{d\sigma(\downarrow\uparrow)}{dt}$$

Helicity correlation between **initial photon** and **initial proton**

$$A_{LS}\frac{d\sigma}{dt} \equiv \frac{d\sigma(\uparrow\rightarrow)}{dt} - \frac{d\sigma(\downarrow\rightarrow)}{dt}$$

Correlation between **initial photon helicity** and **initial proton sideway/transverse polarization**

$$A_{LN}\frac{d\sigma}{dt} \equiv \frac{d\sigma(\uparrow\nearrow)}{dt} - \frac{d\sigma(\downarrow\nearrow)}{dt}$$

Helicity correlation between **initial photon** and **initial proton out of plane polarization**

…

$K_{i,j}$

Similarly for the **final proton** (polarization transfer)

$$\left.\begin{array}{l} A_{LL} = K_{LL} \\ A_{LS} = -K_{LS} \end{array}\right\}$$

assuming no helicity-flip

$K_{L,N}=0$

parity conservation

Ideal WACS Experimental Apparatus

- WACS cross sections are small, need high luminosity ~ 10^{38}/cm/s
- «High resolution» for two body kinematics constraints

(Tagged, polarized), high intensity, collimated real photon source

(Polarized), high density, pure target

«High resolution», large acceptance **nucleon** detector (with polarimetry)

Energy and position high resolution», large acceptance, **photon** detector (charged particles blind)

Different configurations:

- Unpolarized cross section
- Initial state polarizations
- Polarization trasfer to final nucleon
- p and n

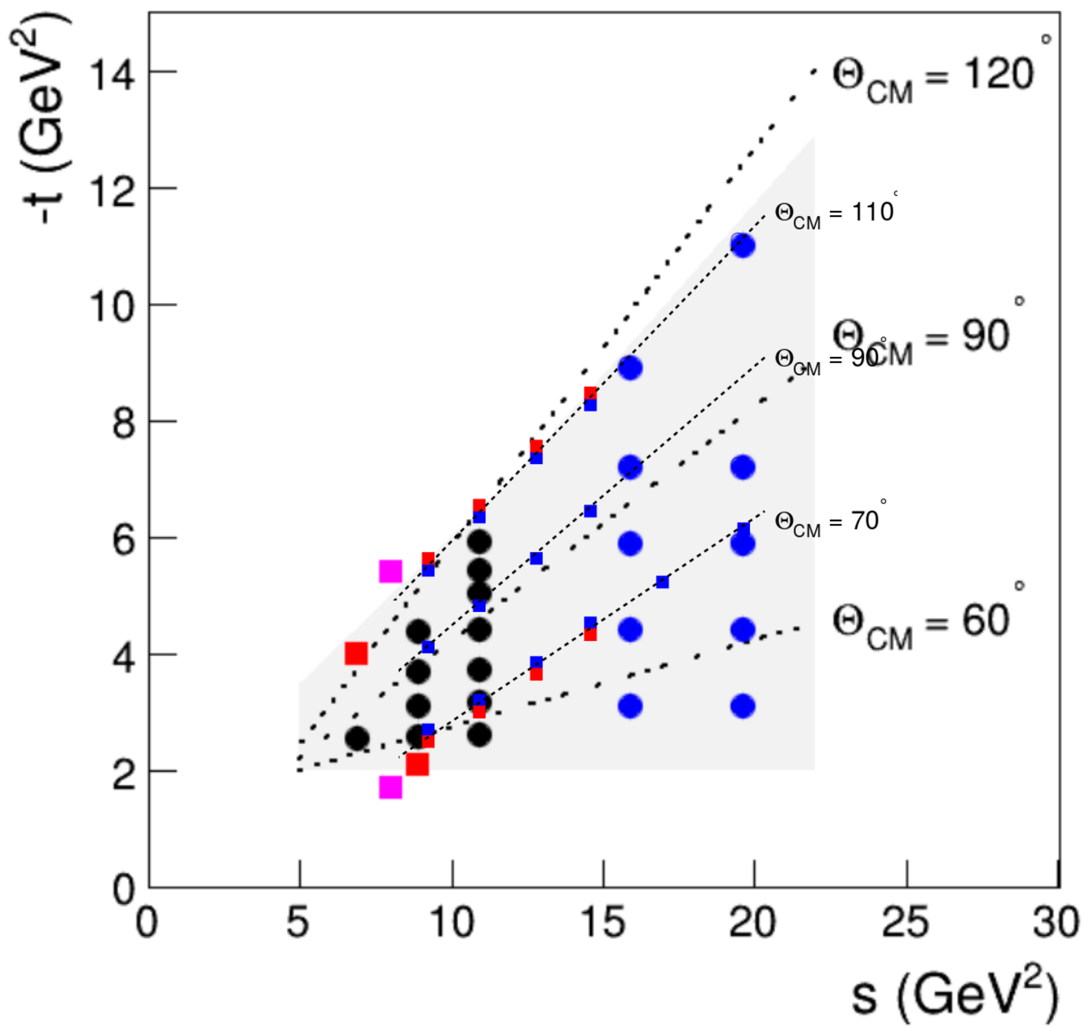
WACS Experimental Status

- Performed experiments
  - Cornell/1977 (Phys. Rev. D19 1979)
  - JLab/E99-114/2002 (PRL94 2005, PRL98 2007)
  - JLab/E07-002/2008 (PRL115 2015)
- Future experiments (approved or conditionally approved):
  - JLab/E12-14-003: WACS at 8 and 10 GeV photon energies – measure cross-section
  - JLab/E12-14-006: Initial state helicity correlation in WACS
  - JLab/C12-17-008: Polarization Observables in Wide-Angle Compton Scattering at large s, t, and u

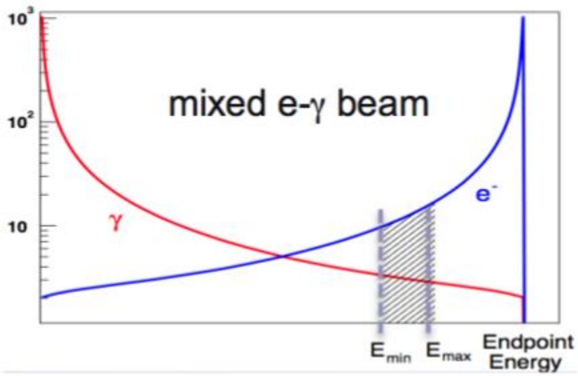
… and time-like data from PANDA

WACS Phase Space of past and future experiments

- ● E99-114: cross section vs t, K_{LL}, K_{LS}
- ■ E07-002: K_{LL}, K_{LS}
- ● E12-14-003: cross section vs t
- ■ E12-14-006: A_{LL}, A_{LS}
- ■/■ C12-17-008: A_{LL}, A_{LS}, conditionally approved (need a compact photon source)

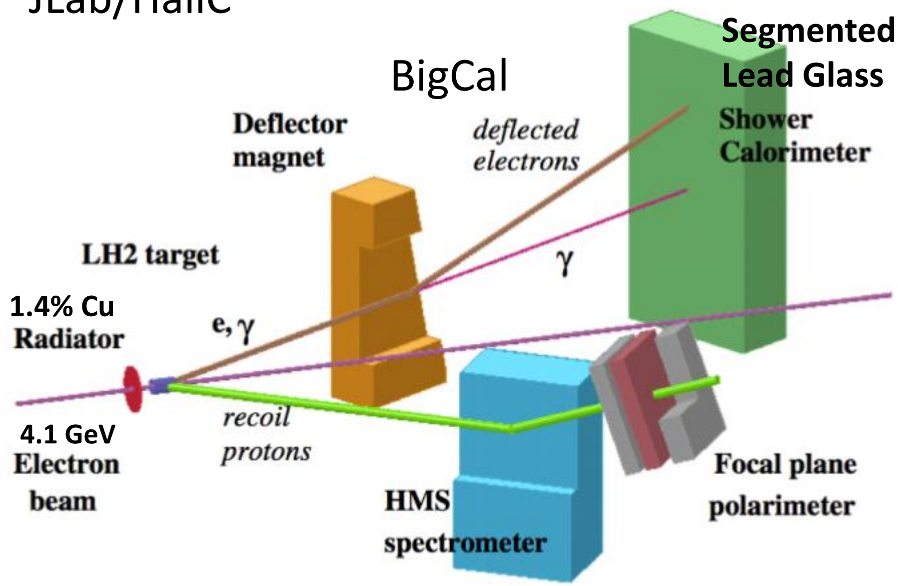


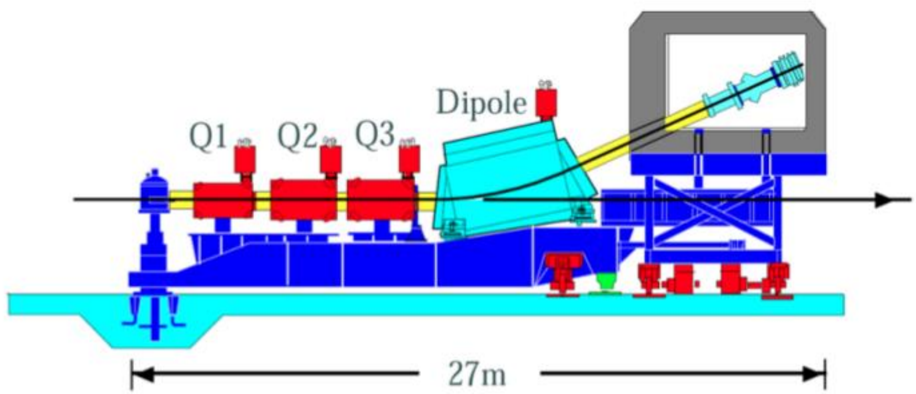
E07-002 – Polarization Transfers in proton WACS

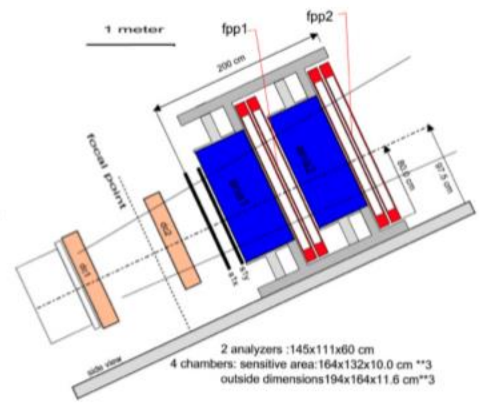


$$\frac{P_\gamma}{P_e} = \frac{4\frac{E_\gamma}{E_e} - (\frac{E_\gamma}{E_e})^2}{4 - 4\frac{E_\gamma}{E_e} + 3(\frac{E_\gamma}{E_e})^2} \sim 90\%$$

JLab/HallC



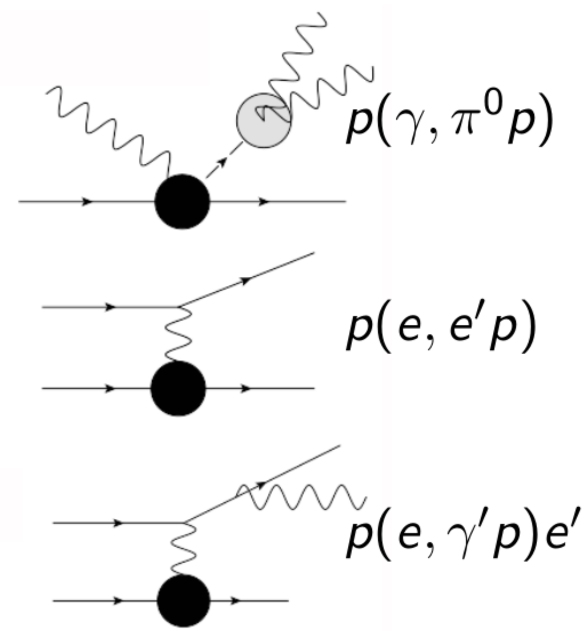




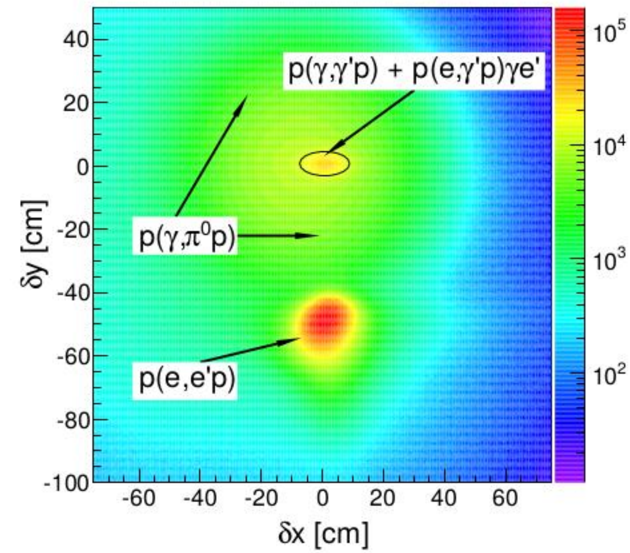
From C. Fanelli /PhD/2014

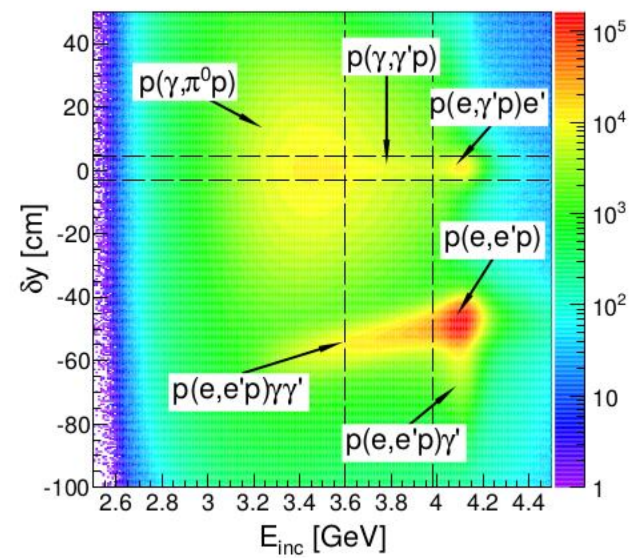
WACS Polarization Transfer Analysis

- Use two-body kinematic correlation to identify signal and suppress background from:



- Polarimetry: reconstruct final proton polarization at target from asymmetries in FFP

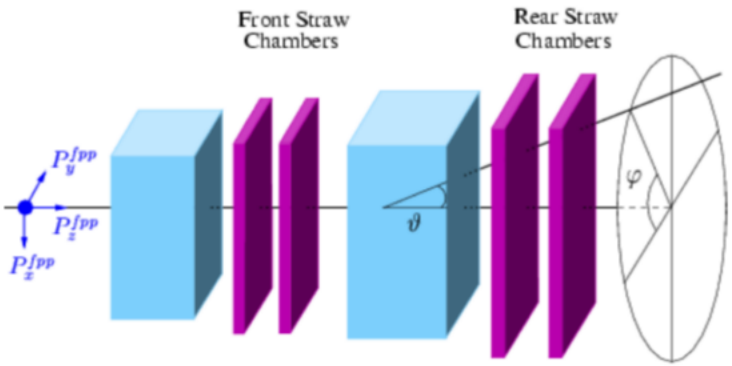




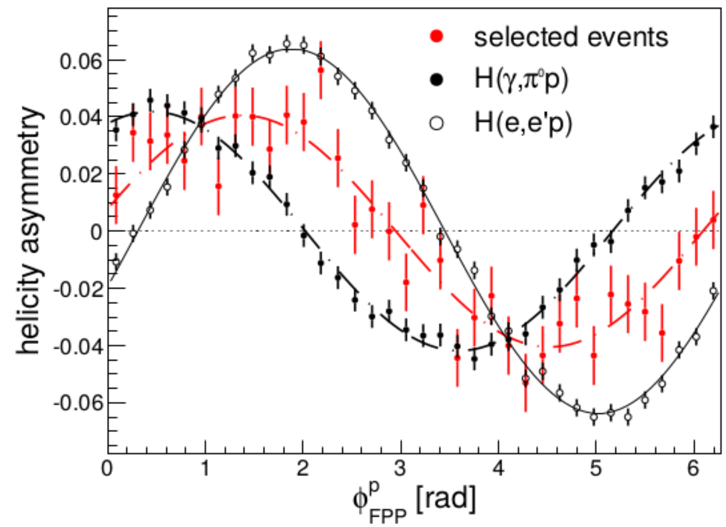
δy δx spatial displacements from two body kinematics prediction

Final state proton polarimetry

Proton scatters off matter in focal plane polarimeter (FPP) by spin-orbit coupling, with azimuthal distribution $\mathbf{f}^{\pm}$.



$$f^{\pm}(p,\vartheta,\varphi) \propto \left[1 \pm \left(A_y(p,\vartheta)P_y^{pp}\cos\varphi - A_y(p,\vartheta)P_x^{pp}\sin\varphi\right)\right]$$



Information at target inferred from FPP

- Asymmetries at FPP to determine systematics and predicted values.
- Spin precession to determine polarization at target.

From C. Fanelli /PhD/2014

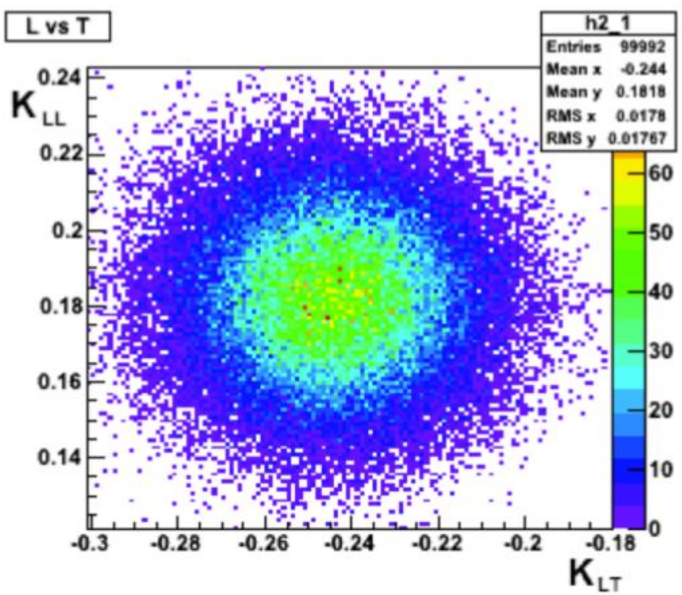
Extract proton polarization

A Markov chain Monte Carlo has been used to extract the polarization transfers from the Likelihood:

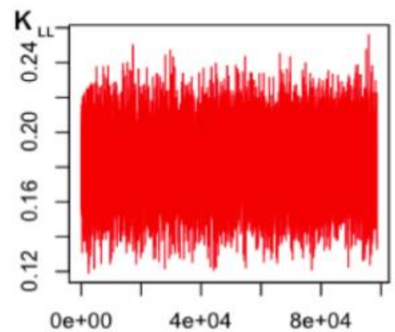
$$\mathcal{L}(\mathbf{P}) = \prod_{i=1}^{N_{evt}} \frac{1}{2\pi}[1 + (a_1 + h\epsilon^{(i)} A_y^{(i)} \sum_{j=x,z} S_{yj}^{(i)} P_j + A_y^{(i)} S_{yy}^{(i)} P_y) \cos\varphi^{(i)} +$$

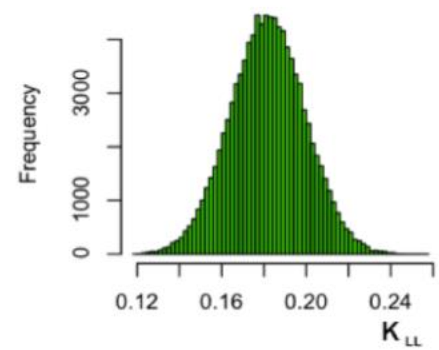
$$+(b_1 - h\epsilon^{(i)} A_y^{(i)} \sum_{j=x,z} S_{xj}^{(i)} P_j - A_y^{(i)} S_{xy}^{(i)} P_y) \sin\varphi^{(i)} +$$

$$+a_2 \cos 2\varphi^{(i)} + b_2 \sin 2\varphi^{(i)} + \cdots]$$



$P_z(= K_{LL})$ vs $P_x(= K_{LT})$





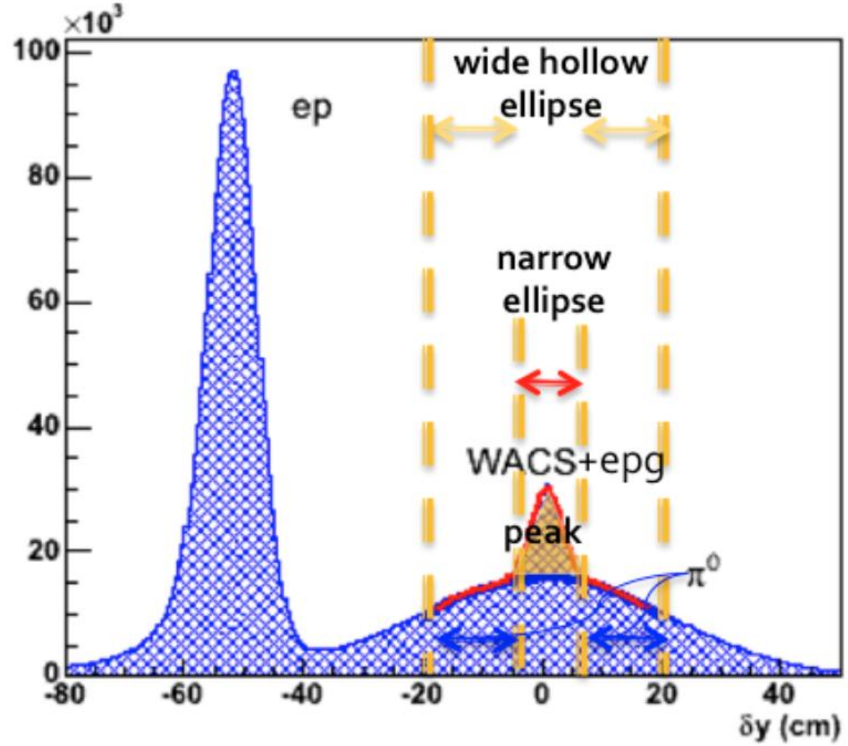
Provide distributions of the extracted quantities and their correlations; sort of «automatic» error estimation analysis

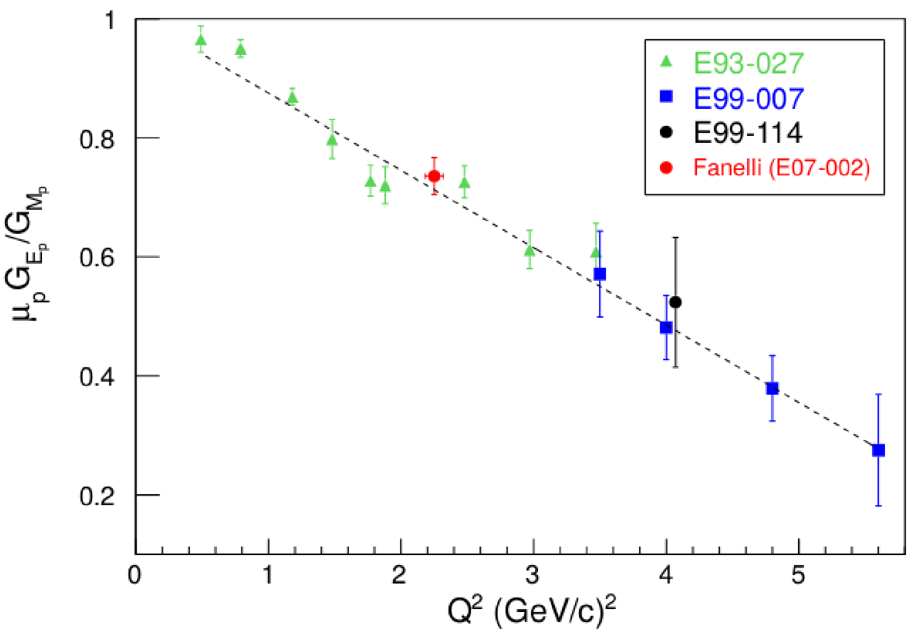
From C. Fanelli /PhD/2014

Signal Deconvolution

$$K^{S}_{LL(LT)} = \frac{1}{f_{(S|S+B)}}\left[K^{S+B}_{LL(LT)} - (1 - f_{(S|S+B)})K^{B}_{LL(LT)}\right]$$

$$f_{(S|S+B)} = \frac{N_S}{N_S+N_B}$$



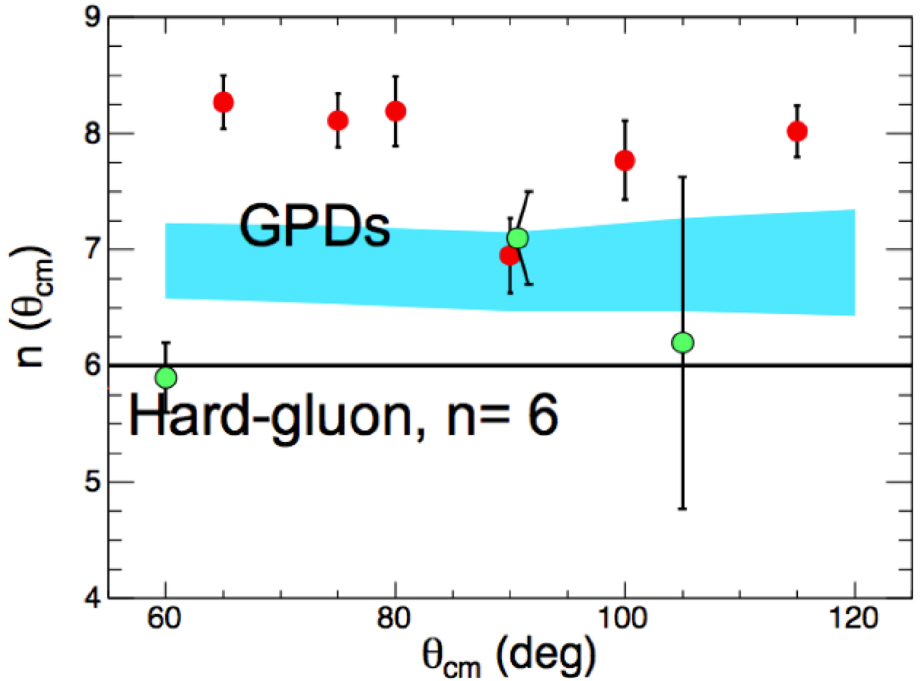


EMFF cross section ratio as byproduct and cross check mesurement

Experimental Results vs Theory (1/3)

- Cornell/1977 (green points):
  - Measured Cross sections disagreed with pQCD calculation by order of magnitude
  - s-scaling cross-section confirmed
- JLab/2002 (red points):
  - Even stronger disagreement with pQCD two-gluon exchange
  - Good agreement with GPD based approach

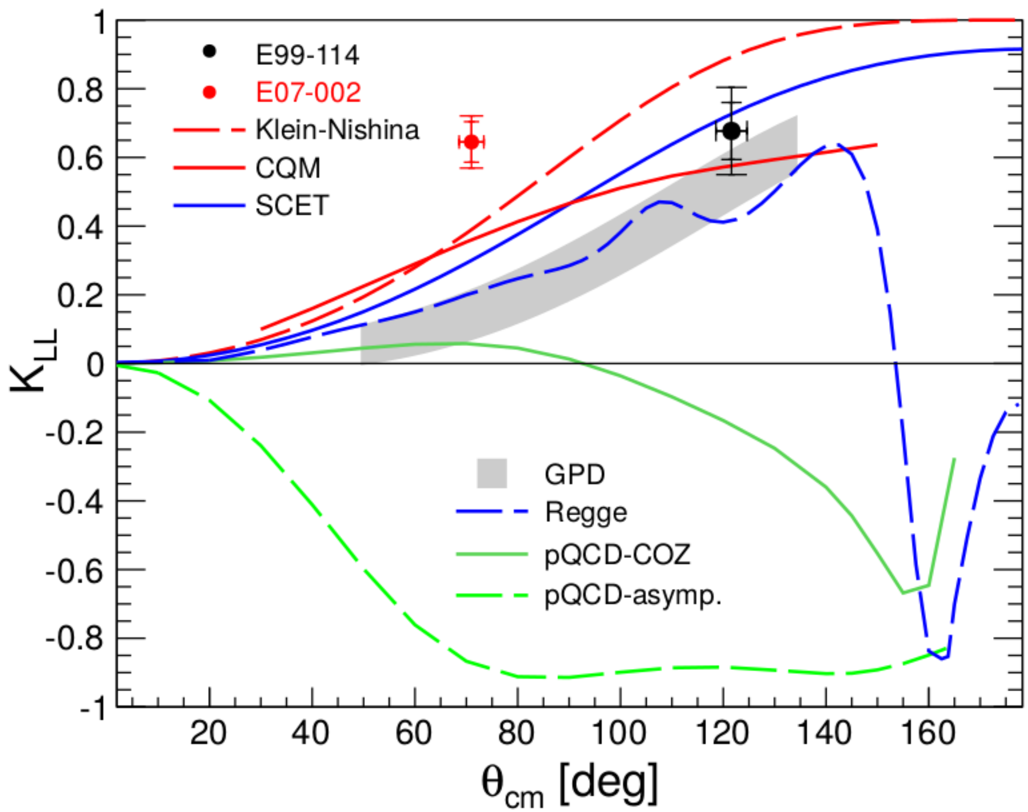
$$\frac{d\sigma}{dt} \sim \frac{f(\theta_{cm})}{s^{n}}$$



pQCD prediction n=6

Experimental Results vs Theory (2/3)

- JLab/2008:
  - Unexpected disagreement with published GPD predictions, later mitigated by new GPD evaluations (P. Kroll arXiv 1703.0500)

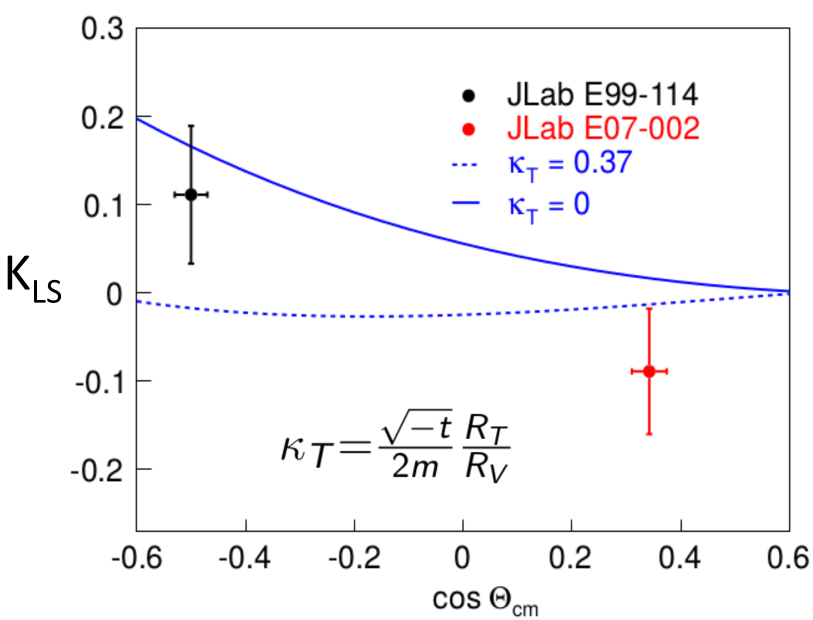


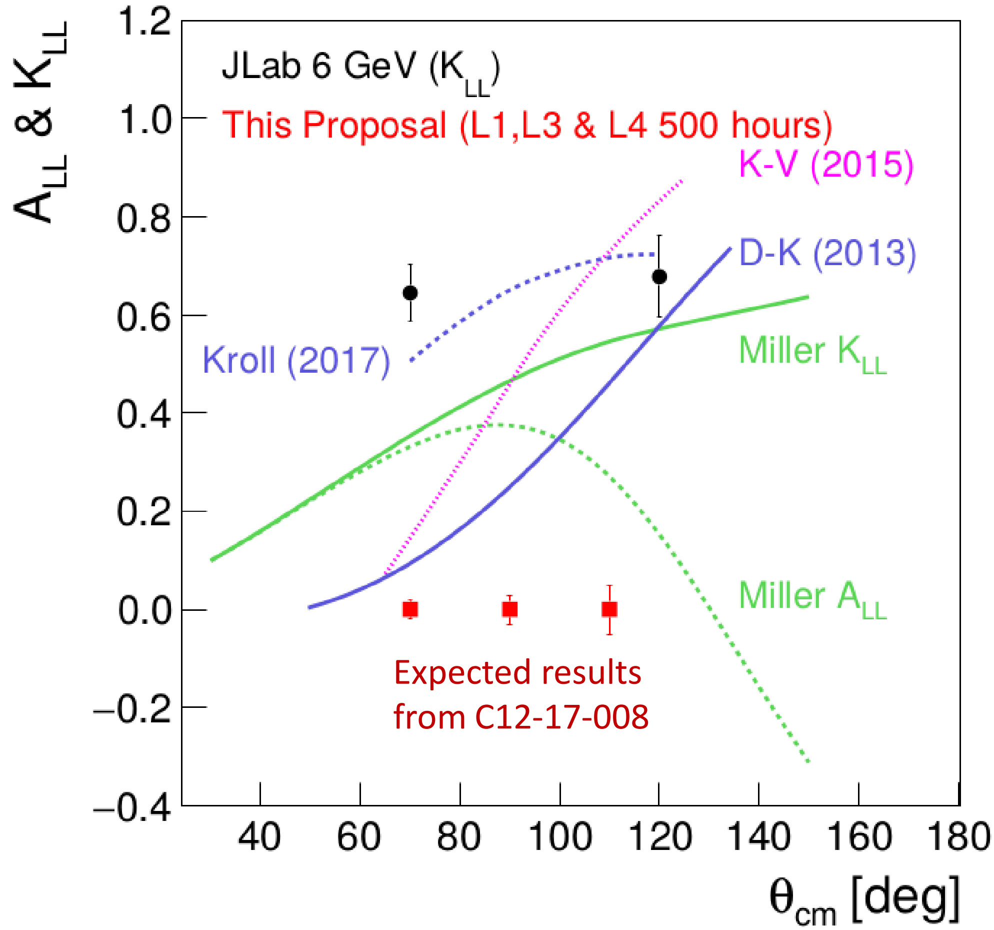
- Klein Nishina: hard scattering from a point-like proton.
- CQM: constituent quark model, similar to KN but with quarks with specific masses.
- SCET: soft collinear effective theory.
- GPD: Generalized Parton Distributions. The grey area shows possible GPD based predictions calculated with $x=1$.
- Regge: interaction of γ/N with an intermediate vector meson.
- COZ: based on pQCD, very small value expected for K_{LL}.
- ASY: based on pQCD, asymptotic approach: distribution amplitude for asymptotically large energy scales.

K_{LS} = -0.089 +/- 0.059

Experimental Results vs Theory (3/3)

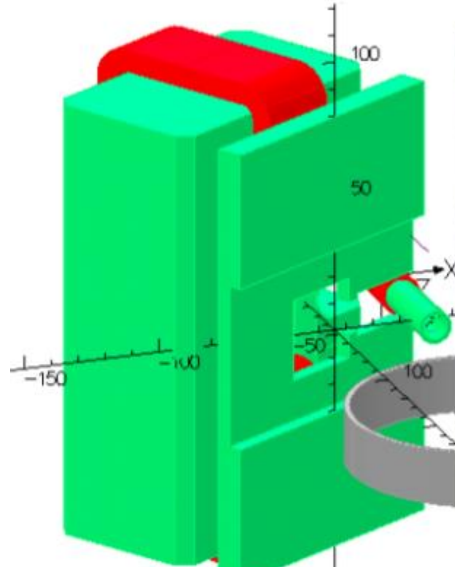
- New fit of GPD $\widehat{H}$ to axial form factor G_A from neutrino scattering (P. Kroll/2007 arXiv 1703.0500)
- D-K -> previous GPD
- K-V -> SCET approch
- Miller -> CQM

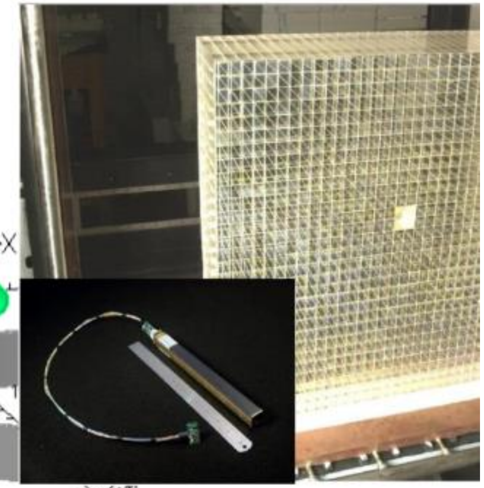


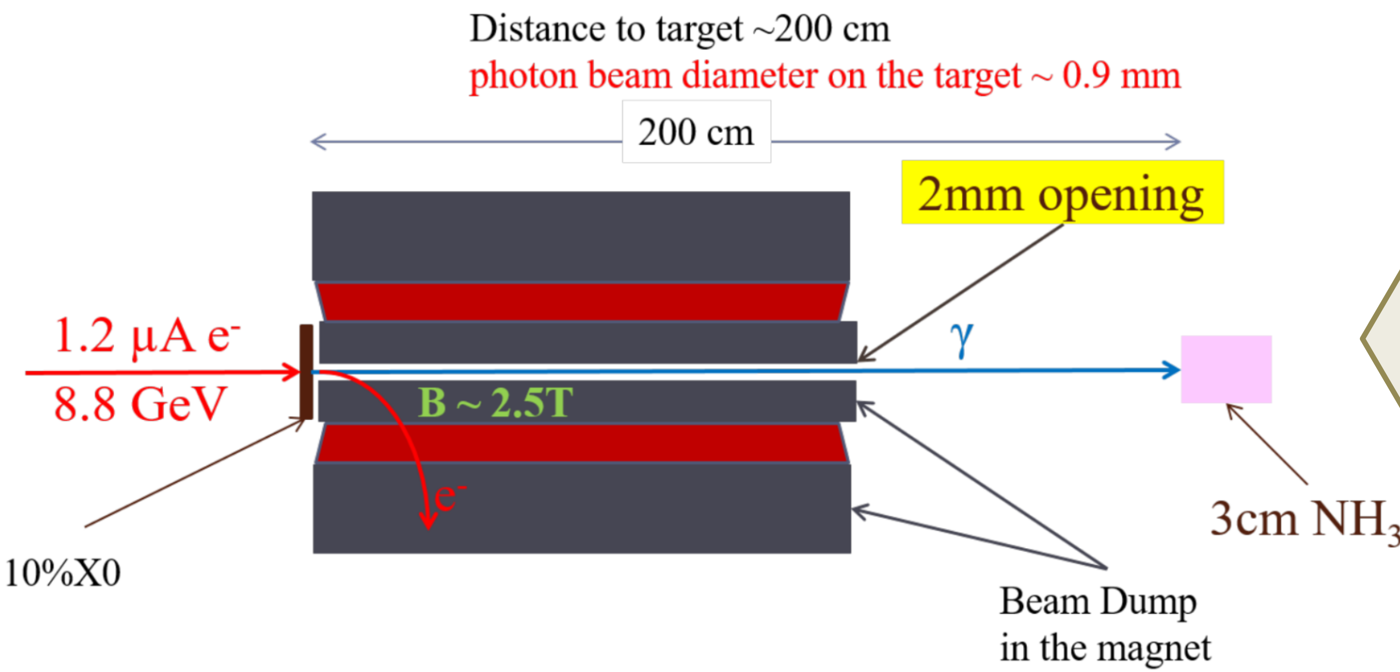


New devices for new experiments

NPS: vertical sweeping magnet (field integral ~0.6 Tm) + highly segmented and energy resolution photon / electron calorimeter based on PbWO4 blocks

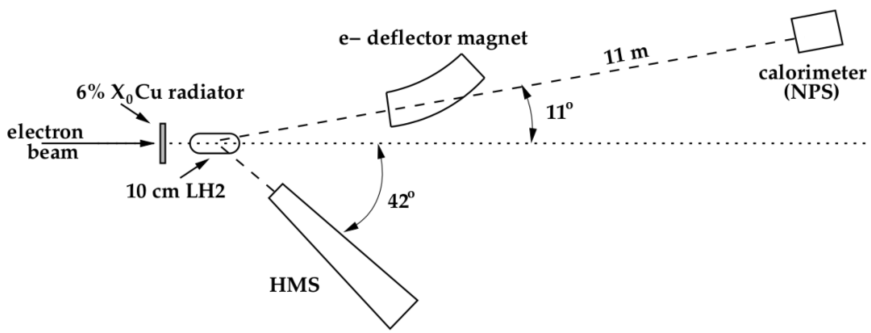






Compact Photon Source

Expected results from new experiments



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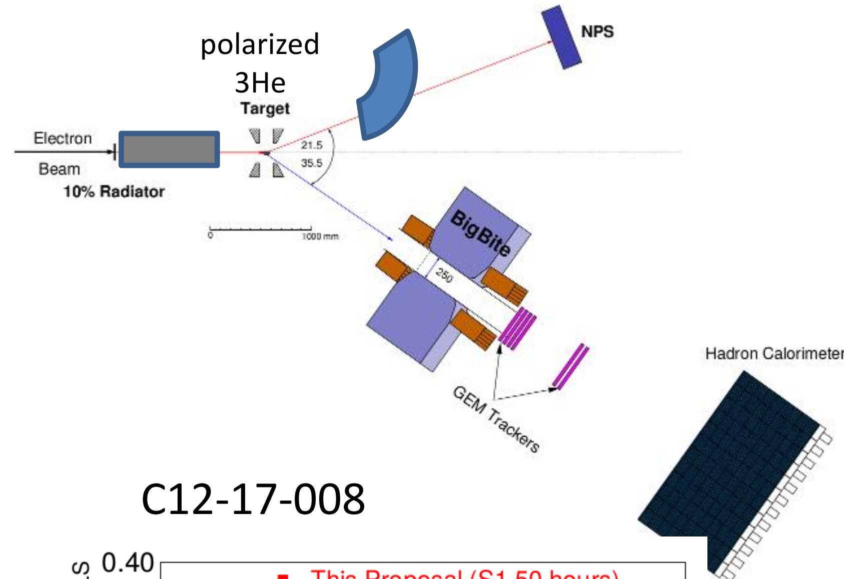

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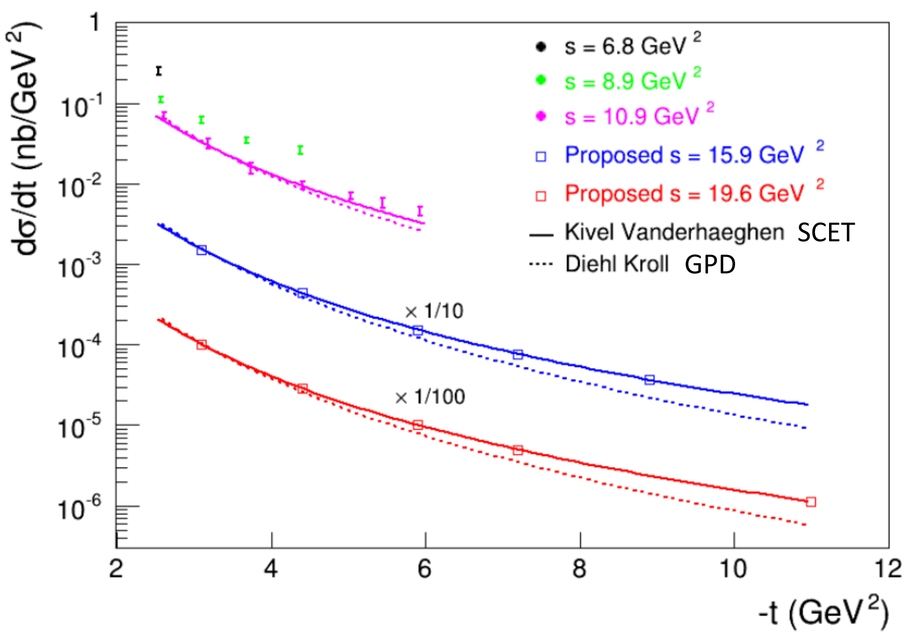

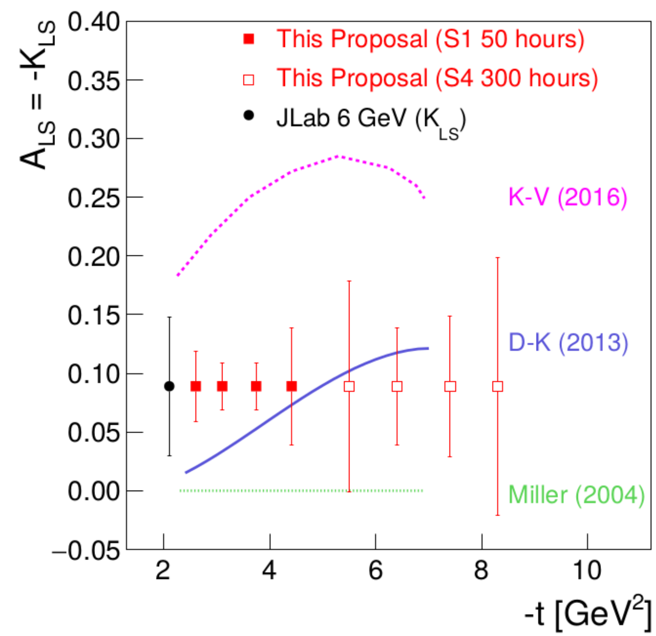

Neutron WACS ?

From B. Wojtsekhowski/2006

- ☺ Allow flawor decomposition
- 😐 Need either tagged photons or spectator nucleon tagging
- ☹ Neutron cross section ~1/16 of proton one
- ☹ Angular resolution, nuclear corrections, pion production