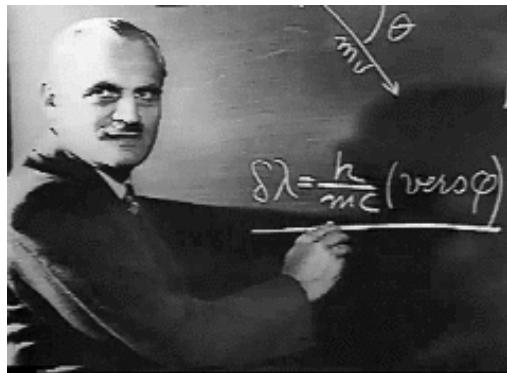


Wide-Angle Compton Scattering

Bogdan Wojtsekhowski,
Thomas Jefferson National Accelerator Facility

Experiment is always the answer



Test of the reaction mechanism
in the cloud chamber

Arthur Compton,

Physical Review (1925)

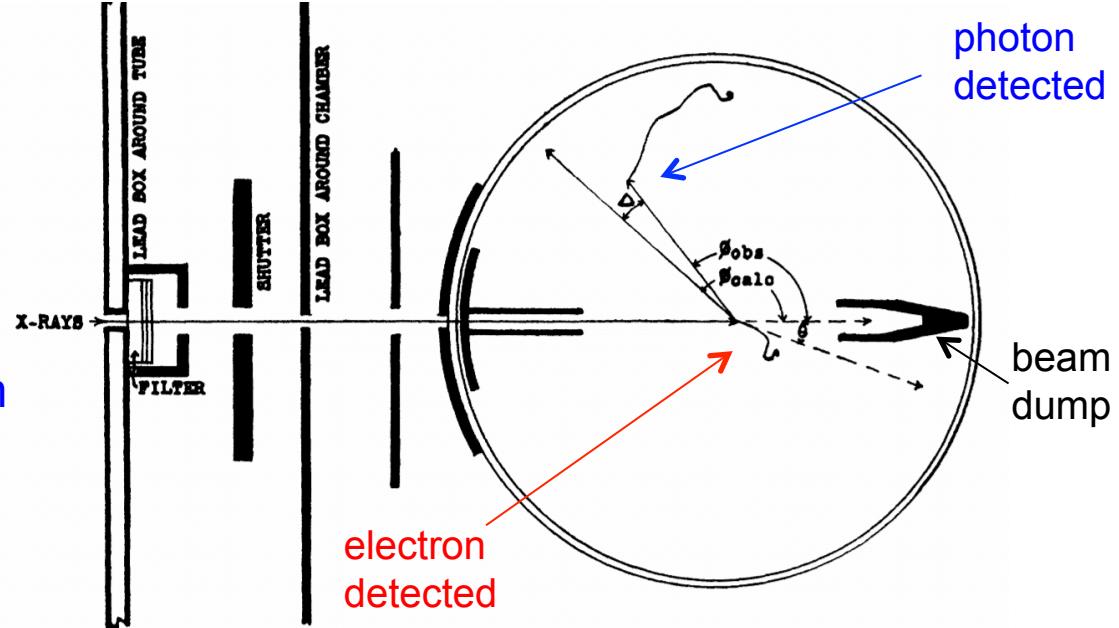
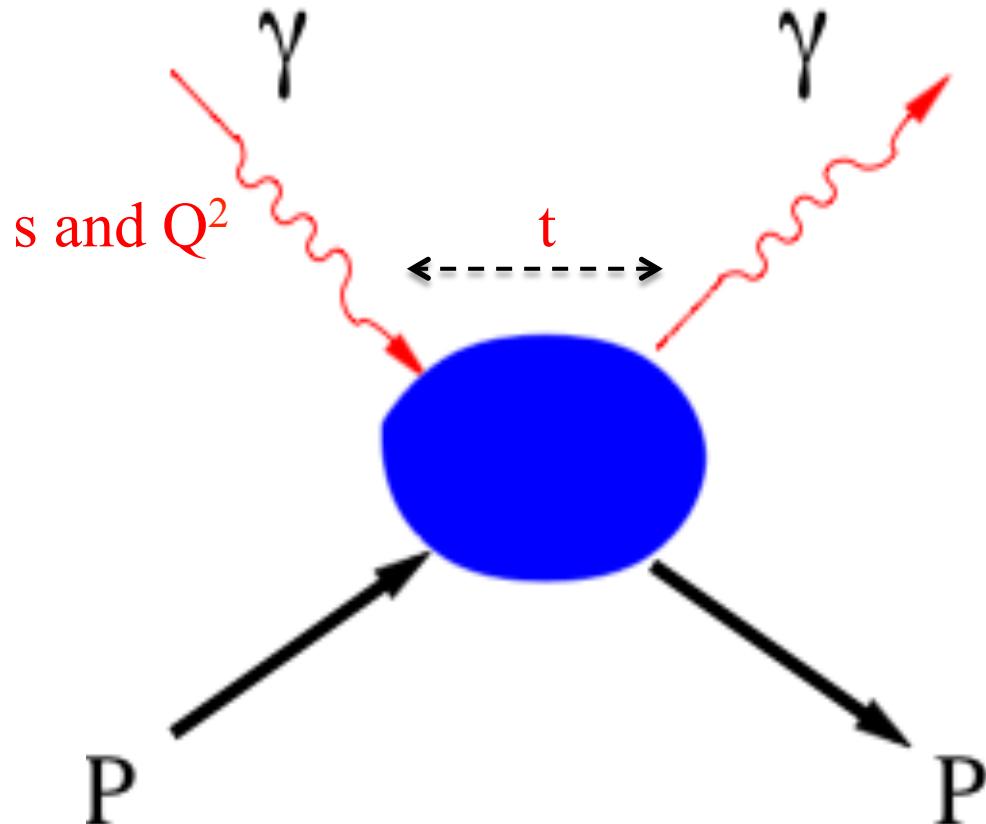


Fig. 1. Diagram of apparatus. On the hypothesis of radiation quanta, if a recoil electron is ejected at an angle θ , the scattered quantum must proceed in a definite direction ϕ_{calc} . In support of this view, many secondary β -ray tracks are found at angles ϕ_{obs} for which Δ is small.

These results do not appear to be reconcilable with the view of the statistical production of recoil and photo-electrons proposed by Bohr, Kramers and Slater. They are, on the other hand, in direct support of the view that energy and momentum are conserved during the interaction between radiation and individual electrons.

Regimes of Compton effect from proton



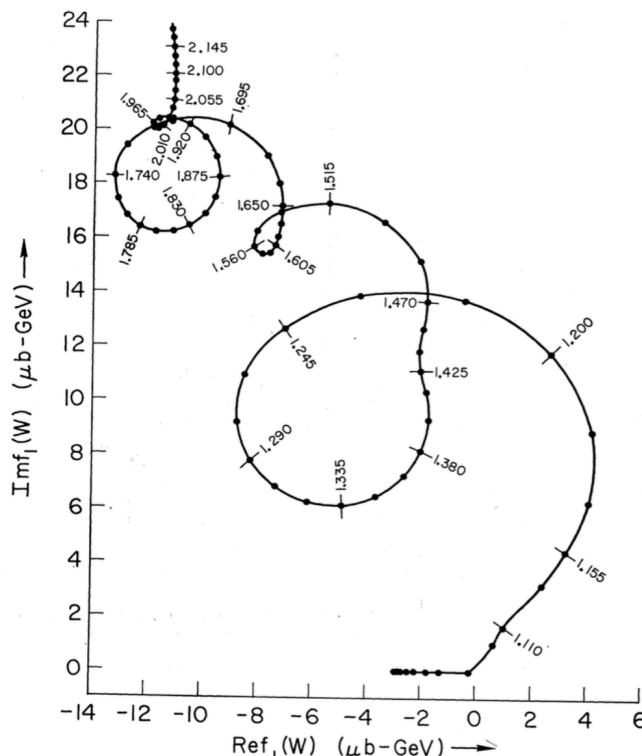
- Forward scattering at $t = 0$
 - Diffractive scattering for $-t \ll \Lambda^2$
 - Wide-angle scattering for $-t \sim \Lambda^2$
- s scaling at fixed t/s

Regimes of Compton effect from proton

Forward scattering amplitude:

$$F = f_1(\omega) \cdot (\vec{\epsilon}' \cdot \vec{\epsilon}) + i\omega f_2(\omega) (\vec{\sigma} \cdot [\vec{\epsilon}' \times \vec{\epsilon}])$$

$$\text{Im } f_1(\omega) = \frac{\omega}{4\pi} \sigma_{tot}(\omega)$$



s scaling at fixed t/s

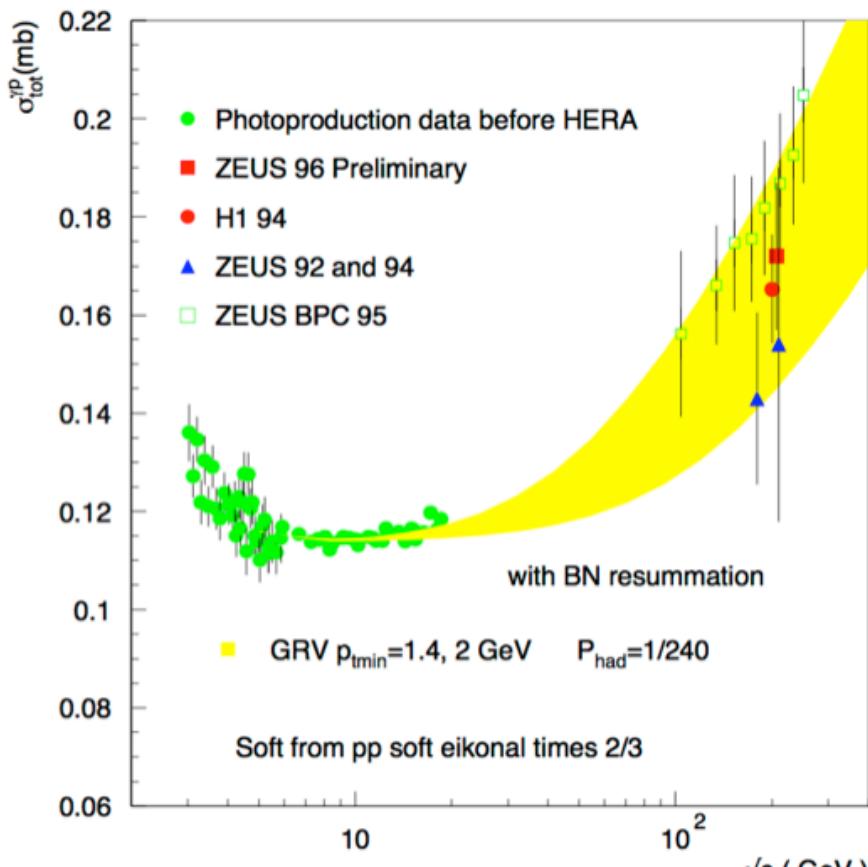
- **Forward scattering at $t = 0$**

- Diffractive scattering for $t \ll \Lambda^2$

- Wide-angle scattering for $-t \sim \Lambda^2$

Damashek&Gilman, 1970

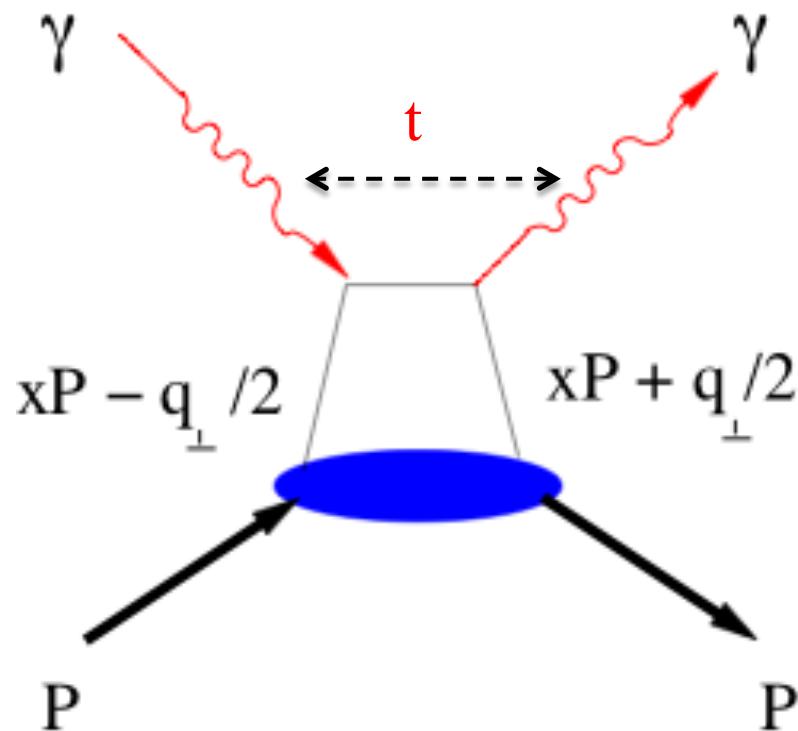
Regimes of Compton effect from proton



- Forward scattering at $t = 0$
 - **Diffractive scattering for $t \ll \Lambda^2$**
 - Wide-angle scattering for $-t \sim \Lambda^2$
- s scaling at fixed t/s

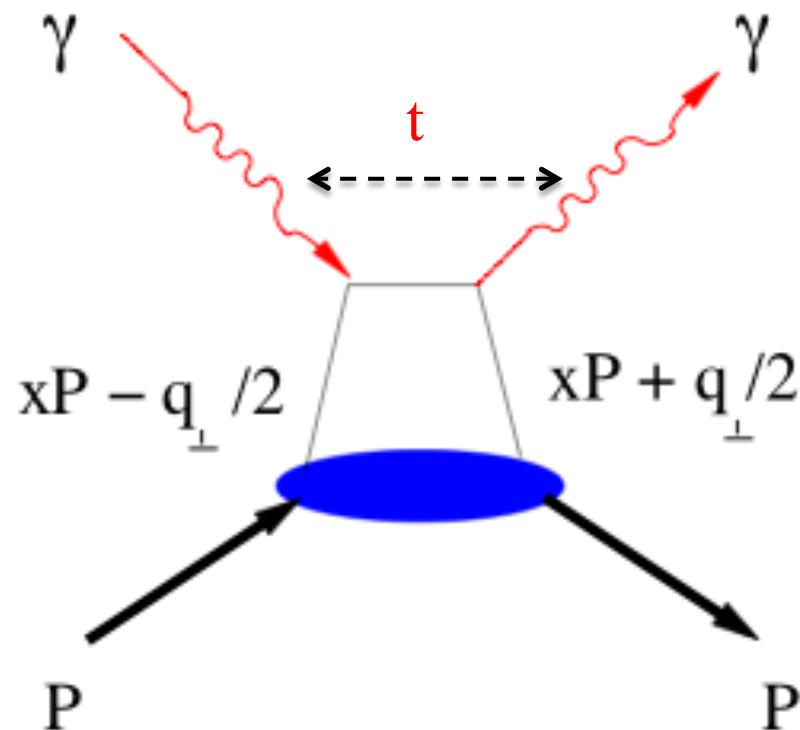
PDG, 2016

Regimes of Compton effect from proton



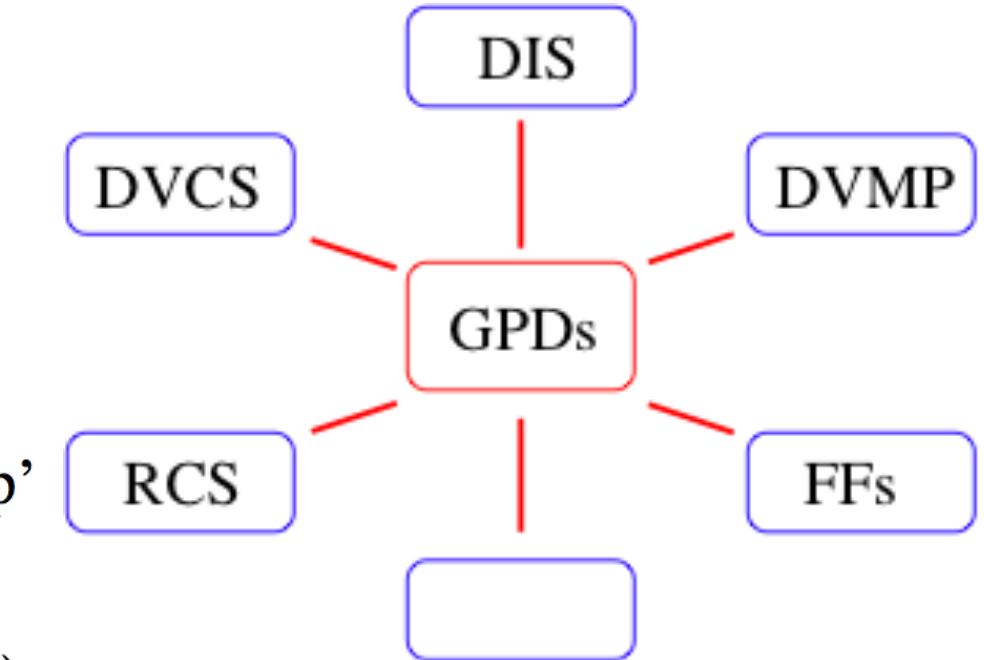
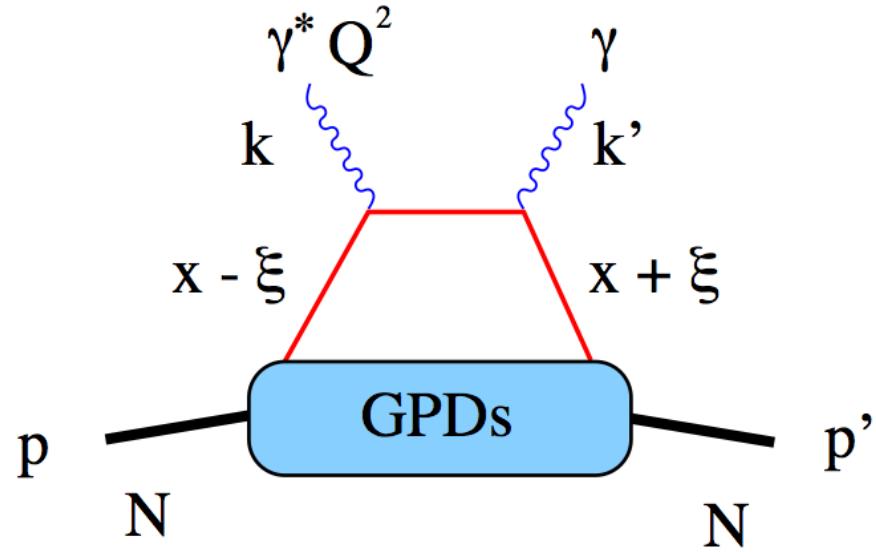
- Forward scattering at $t = 0$
 - Diffractive scattering for $t \ll \Lambda^2$
 - **Wide-angle scattering for $-t \sim \Lambda^2$**
- s scaling at fixed t/s

The real photon has $Q^2=0$ and the reaction mechanism is in question.



There is a high $(-t) \gg \Lambda^2$ exchange to the “bag”, which provides crucial simplicity and a connection to the elastic Form Factors and DIS via Generalized Parton Distributions

Physics of the nucleon



$$\text{where } \xi = (p_q^+ - p_q'^+)/ (p_q^+ + p_q'^+)$$

Quark dynamics of nucleon encoded in GPD functions

$H(x, \xi, t)$, $\tilde{H}(x, \xi, t)$ hadron helicity-conserving; vector and axial-vector
 $E(x, \xi, t)$, and $\tilde{E}(x, \xi, t)$ helicity-flipping; tensor and pseudo-scalar

Wide-Angle Compton Scattering

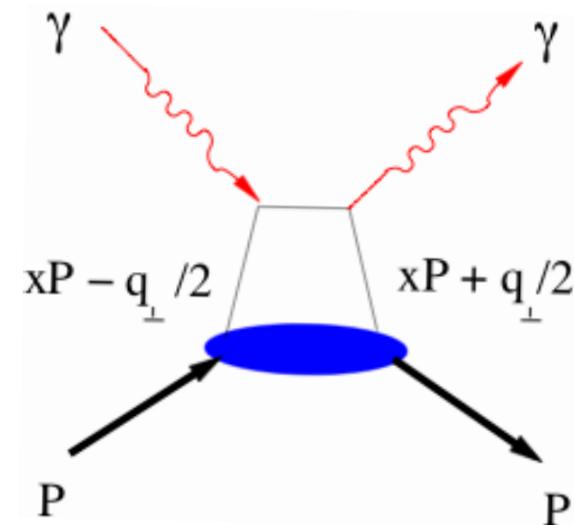
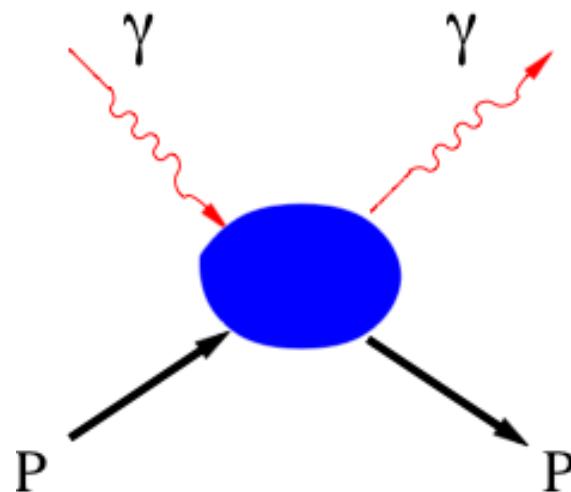
- Mechanism of the reaction is a key question
 - If we can measure the process: What do we learn?
What do we learn from polarization observables?
- JLab WACS experiments 2002, 2008
- Experimental results for polarization K_{LL}
- Motivation for further measurements
- An approach for the most productive experiment

Mechanism of the process

Two basic options for the mechanism:

Collective response - several partons are involved in high momentum interaction with the photons.

Individual response - one quark absorbs an incident photon and the same quark emits a scattered photon.



Theoretical studies of the WACS process

- Regge poles - VMD
 - pQCD - two-gluon
 - Diquark model
 - Leading quark
 - GPDs (handbag)
 - CQM
 - SCET
 - DSE
- since 1960s ..., Laget
 - Brodsky, ..., Dixon, MVh,...
 - Guichon&Kroll 1996
 - Brodsky et al 1972,
 - Radyushkin, Kroll et al
 - G.Miller 2004
 - Kivel&Vanderhaeghen
 - Eichmann

Main issues:

- Competing mechanisms
- Interplay between hard and soft processes
- Threshold for onset of asymptotic regime
- Role of the hadron helicity flip

Experimental studies of the CS process

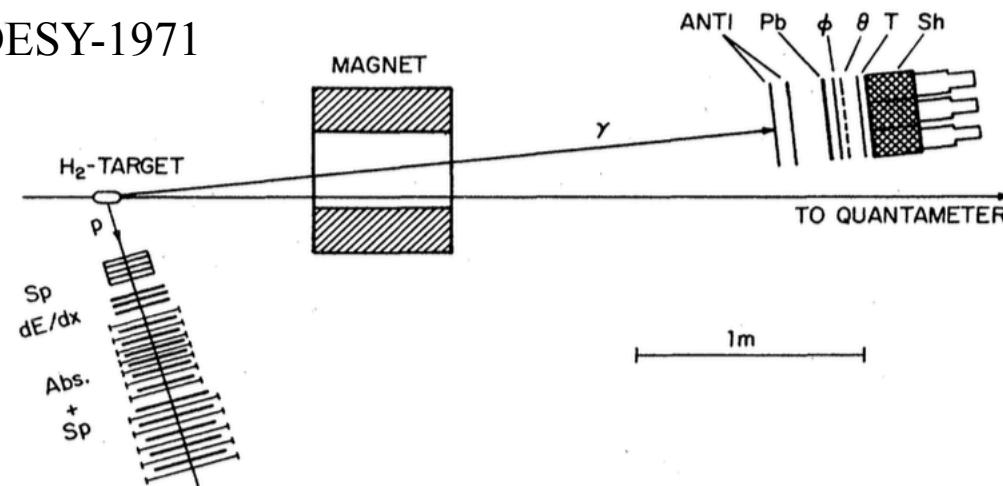
experiments with $s > 2 \text{ GeV}^2$, low t

Bauer-Spital-Yennie review, RMP 50 (1978)

- DESY
- SLAC
- CEA

- 1971
- 1971
- 1972-73, Deutsch

DESY-1971



The photon flux is
 $2 \times 10^8 \text{ } \gamma/\text{s}$

FIG. 44. Diagram of the apparatus used by the DESY group for Compton scattering measurements (from Buschhorn *et al.*, 1971a).

Experimental studies of the CS process

experiments with $s > 2 \text{ GeV}^2$, low t
Bauer-Spital-Yennie review, RMP 50 (1978)

- DESY - 1971
- SLAC - 1971
- CEA - 1972-73, Deutsch

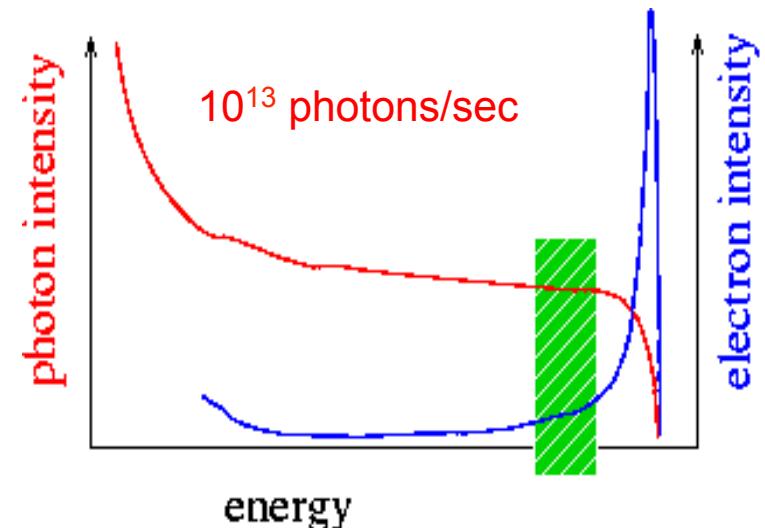
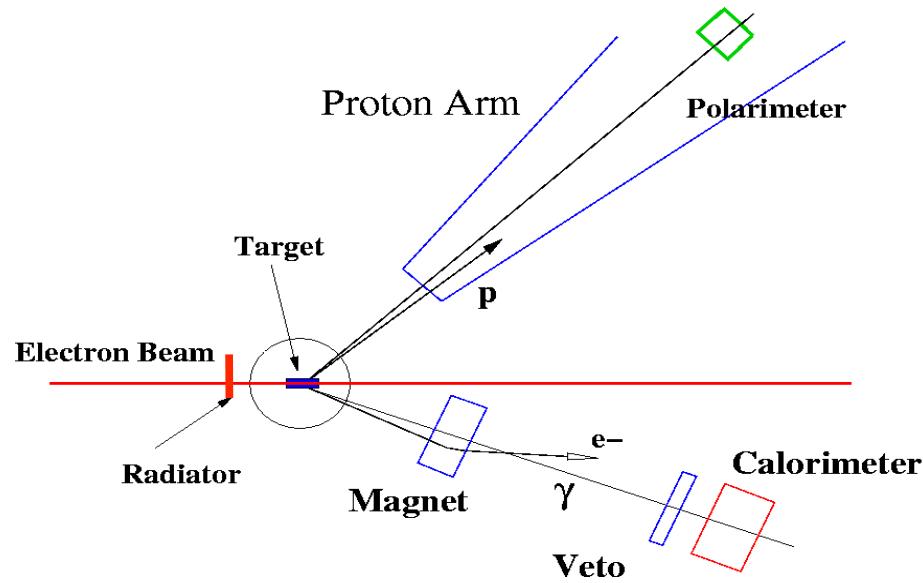
- experiments with $-t > 1 \text{ GeV}^2$ (WACS regime)
- Cornell - 1975
 - JLab Hall A - 2002
 - JLab Hall C - 2008

The photon flux is
 $1.5 \times 10^{10} \gamma/\text{s}$
 $\sim 2 \times 10^{13} \gamma/\text{s}$

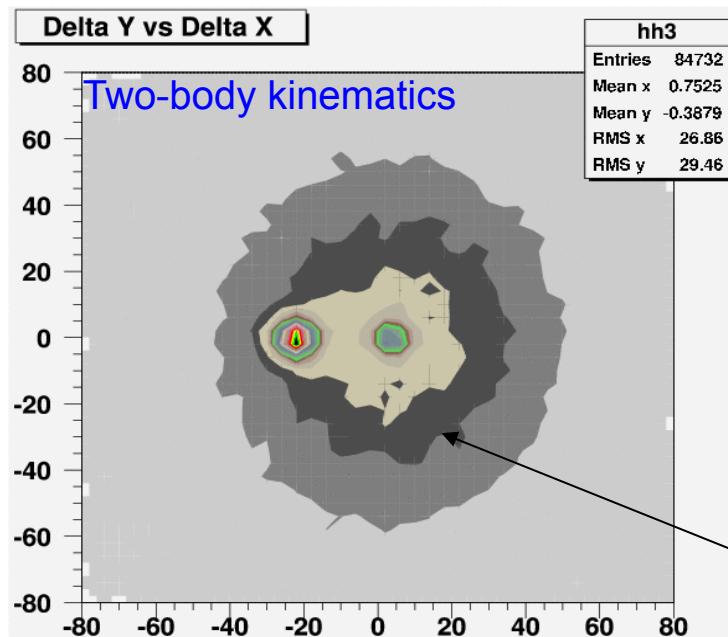
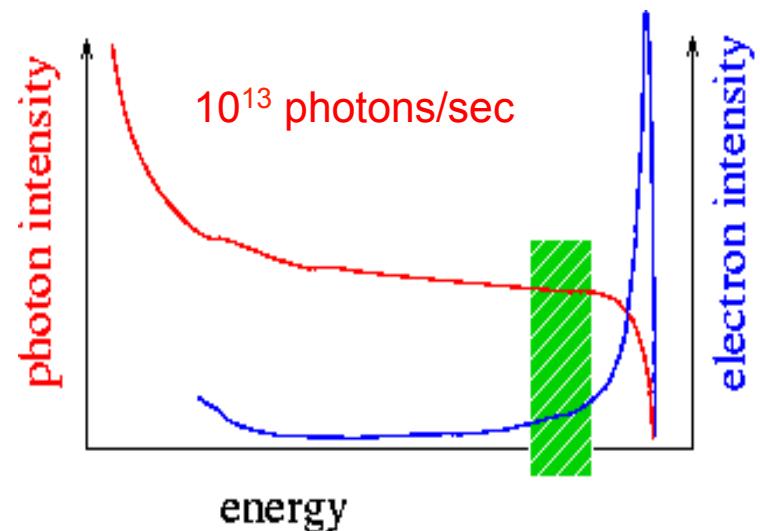
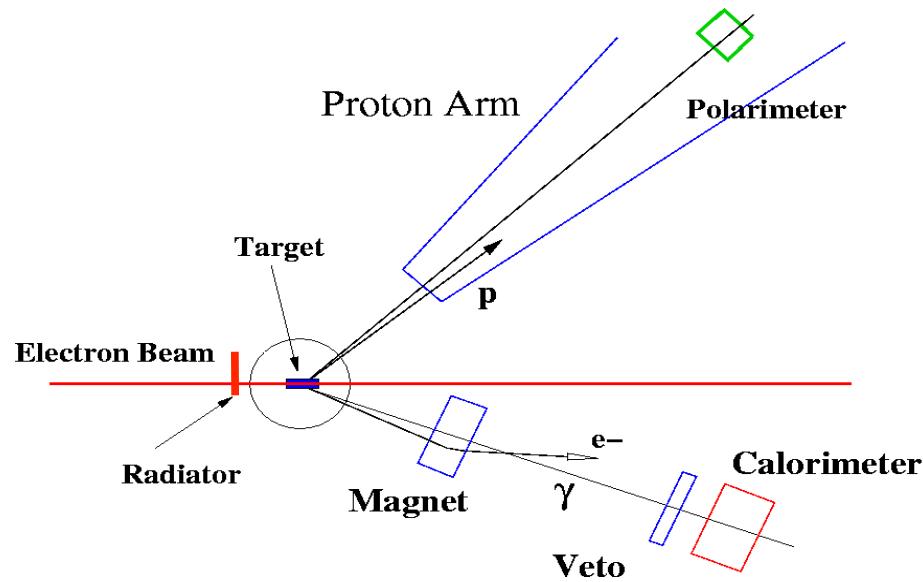
Main issues:

- Competing reaction – pion-0 photo-production
- Low cross section and small solid angle
- Low efficiency & analyzing power of the proton polarimetry
- Low limit on the polarized target luminosity

Mixed e/ γ beam \rightarrow rates ~ 1300 higher than “clean” γ

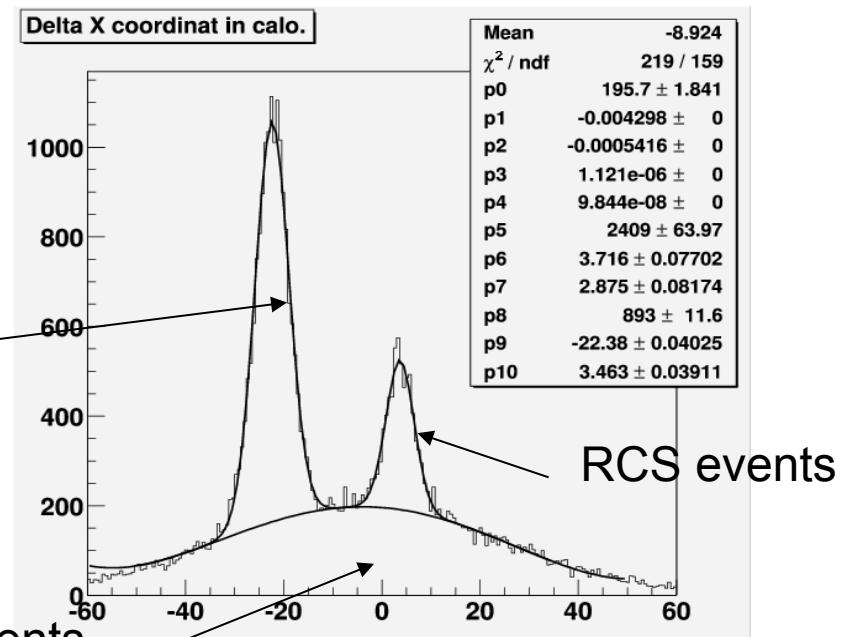


Mixed e/γ beam \rightarrow rates ~ 1300 higher than “clean” γ



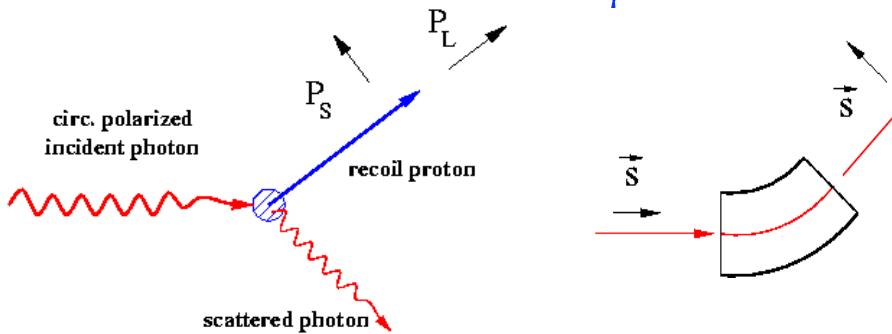
B. Wojtsekhowski

SPIN2016, September 27, 2016



Polarization transfer K_{LL}

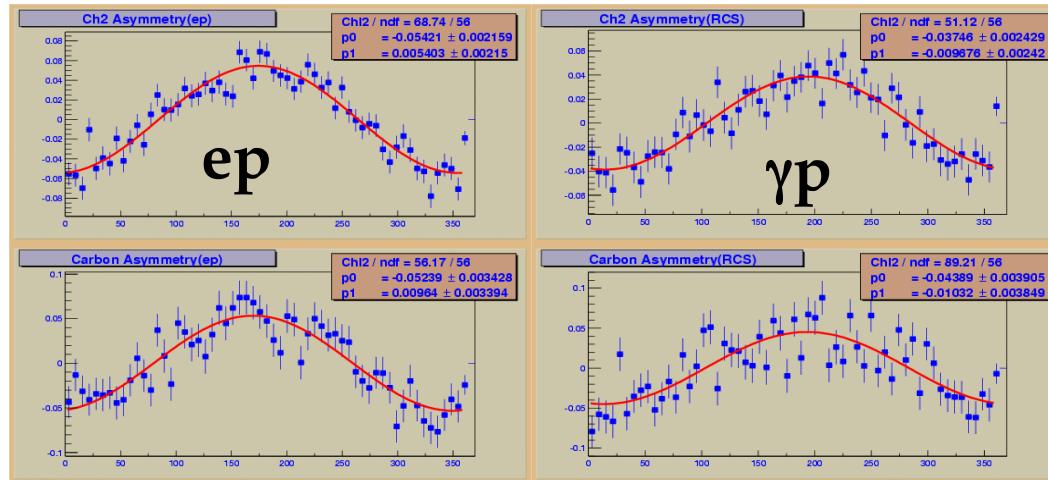
$$E_\gamma = 3.2 \text{ GeV}, \theta_{cm} = 120^\circ \quad (s = 6.9, t = -4 \text{ GeV}^2)$$



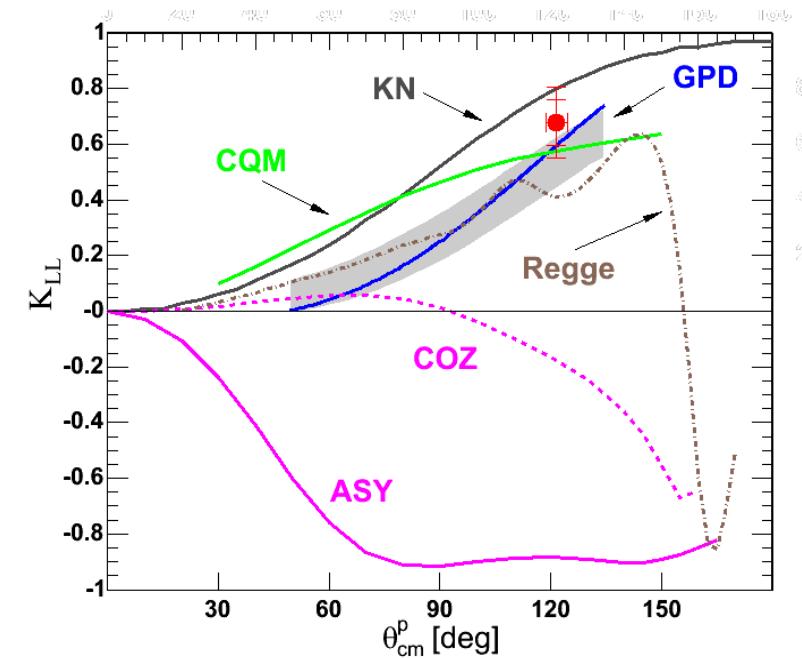
K_{LL} is an average value of the longitudinal proton spin in the γp cm system for 100% circular polarization of incident photon.

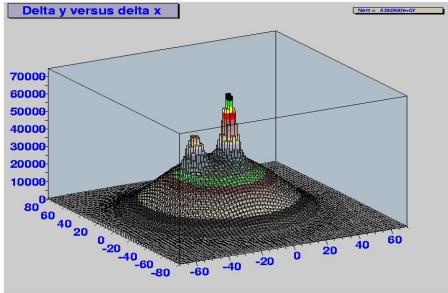
$$K_{LL} = \frac{1}{2} \left\{ \frac{\sigma(+,\uparrow) - \sigma(+,\downarrow)}{\sigma(+,\uparrow) + \sigma(+,\downarrow)} - \frac{\sigma(-,\uparrow) - \sigma(-,\downarrow)}{\sigma(-,\uparrow) + \sigma(-,\downarrow)} \right\}$$

Raw asymmetry for ep and γp events

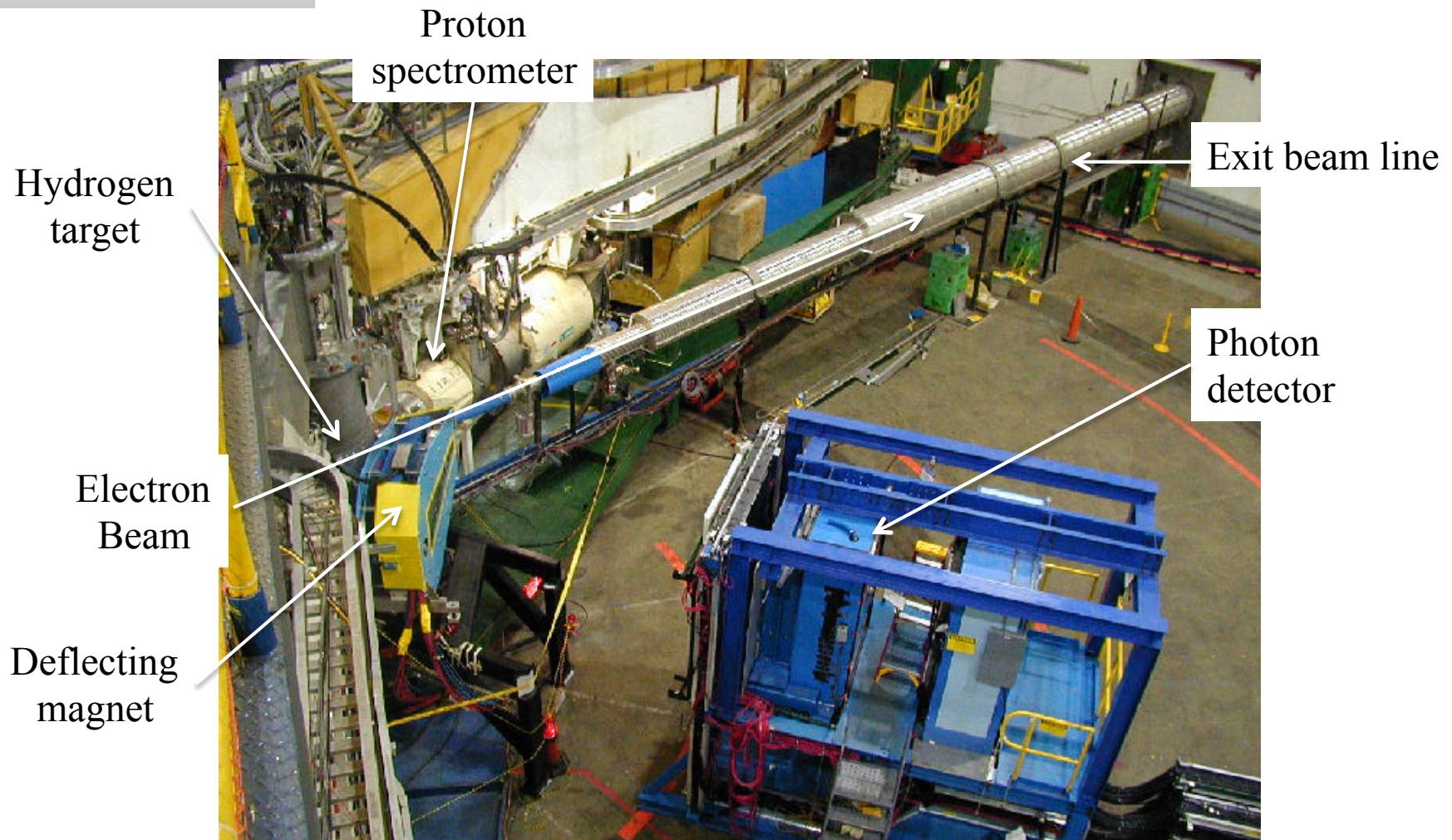


raw asymmetry is of 0.05, systematics is below 10^{-4}

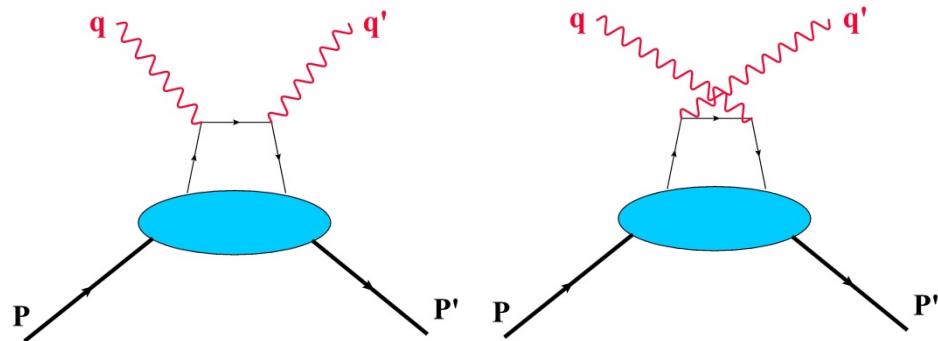




E99-114 experiment in 2002



Compton scattering with GPD



In the GPD approach, interaction goes with a single quark, and the handbag diagram dominates.

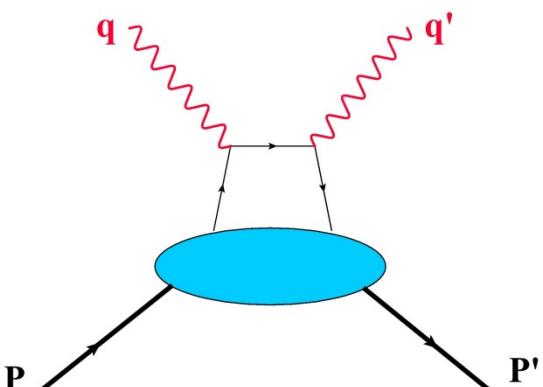
M.Diehl & P.Kroll

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}_{KN} \left(\frac{1}{2} \left[R_V^2 + \frac{-t}{4m^2} R_T^2 + R_A^2 \right] - \frac{us}{s^2 + u^2} \left[R_V^2 + \frac{-t}{4m^2} R_T^2 - R_A^2 \right] \right)$$

$$K_{LL} = A_{LL} \quad K_{LL} \frac{d\sigma}{dt} \equiv \frac{1}{2} \left[\frac{d\sigma(+,\uparrow)}{dt} - \frac{d\sigma(-,\uparrow)}{dt} \right]$$

- Test of the handbag predictions to the <10% level is an important task.
- The K_{LL} (A_{LL}) asymmetry is an observable of choice to test a reaction mechanism.
- The NLO corrections are supposed to vary as $1/s$ (e.g. N.Kivel & M.Vanderhaeghen).

FFs, GPDs and Polarization Observables



$$\frac{d\sigma^{\text{KN}}}{dt} A_{LL}^{\text{KN}} = \frac{2\pi\alpha_{\text{em}}^2}{(s-m^2)^2}$$

$$\times \left[-\frac{s-m^2}{u-m^2} + \frac{u-m^2}{s-m^2} - \frac{2m^2t^2(s-u)}{(s-m^2)^2(u-m^2)^2} \right],$$

(9)

$$\frac{d\sigma^{\text{KN}}}{dt} K_{LL}^{\text{KN}} = \frac{2\pi\alpha_{\text{em}}^2}{(s-m^2)^2}$$

$$\times \left[-\frac{s-m^2}{u-m^2} + \frac{u-m^2}{s-m^2} - \frac{4m^2t^2(m^4-su)}{(s-m^2)^3(u-m^2)^2} \right],$$

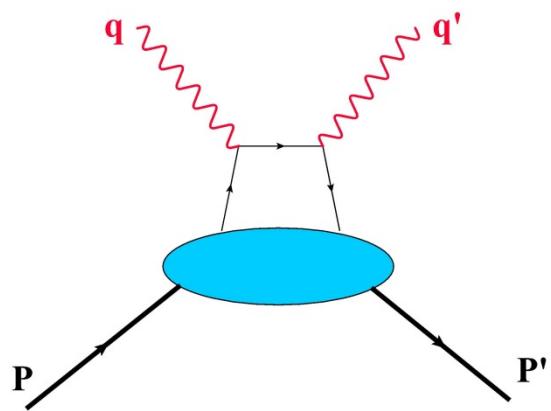
$$R_V(t) = \sum_a e_a^2 \int_{-1}^1 \frac{dx}{x} H^a(x, 0, t)$$

$$R_A(t) = \sum_a e_a^2 \int_{-1}^1 \frac{dx}{x} \text{sign}(x) \hat{H}^a(x, 0, t)$$

$$R_T(t) = \sum_a e_a^2 \int_{-1}^1 \frac{dx}{x} E^a(x, 0, t)$$

M.Diehl & P.Kroll

FFs, GPDs and Polarization Observables



$$R_V(t) = \sum_a e_a^2 \int_{-1}^1 \frac{dx}{x} H^a(x, 0, t)$$

$$R_A(t) = \sum_a e_a^2 \int_{-1}^1 \frac{dx}{x} sign(x) \hat{H}^a(x, 0, t)$$

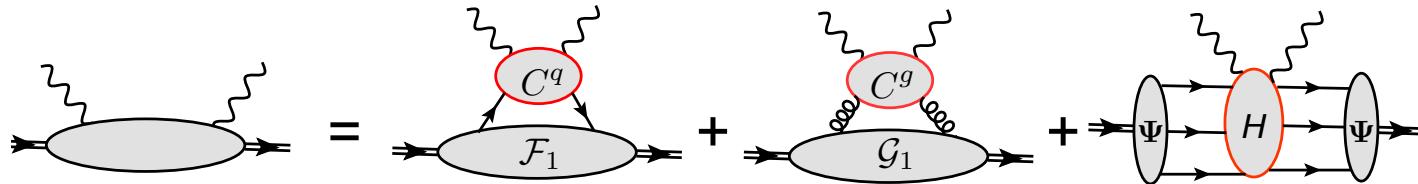
$$R_T(t) = \sum_a e_a^2 \int_{-1}^1 \frac{dx}{x} E^a(x, 0, t)$$

for $m=0$ $K_{LL}^{KN} = \frac{s^2 - u^2}{s^2 + u^2}$

M.Diehl & P.Kroll

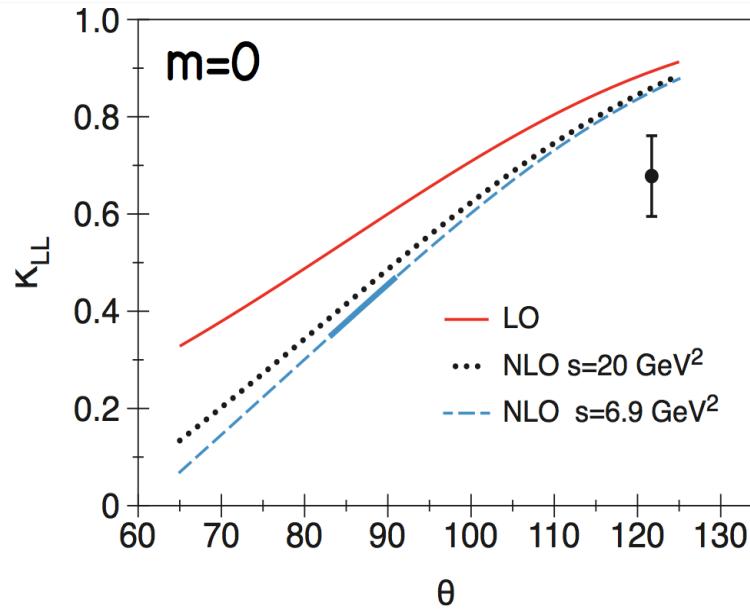
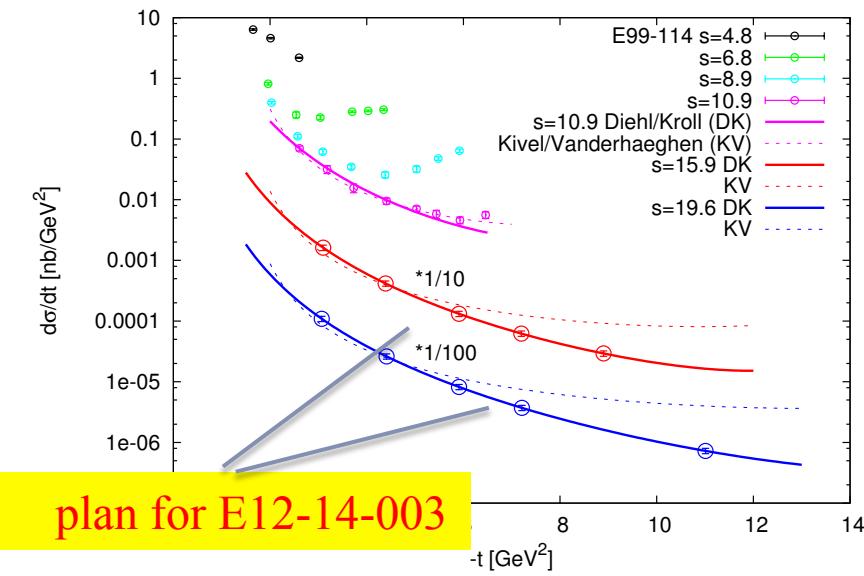
$$A_{LL} = K_{LL} = K_{LL}^{KN} \frac{R_A}{R_V} \left[1 - \frac{t^2}{2(s^2 + u^2)} \left(1 - \frac{R_A^2}{R_V^2} \right) \right]^{-1}$$

GEp/GMp two-photon effect and WACS

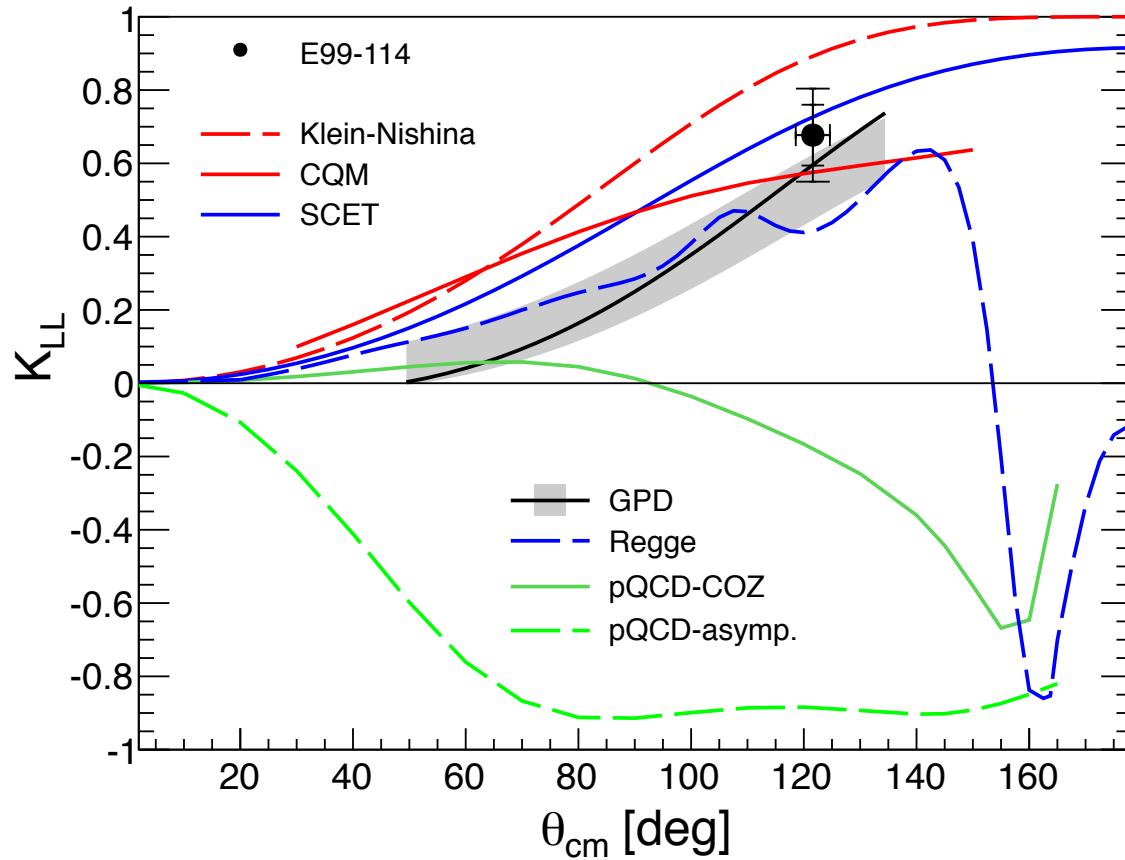


N.Kivel & M.Vanderhaeghen

$$\frac{d\sigma}{dt} = \frac{\pi\alpha^2}{s^2} |\mathcal{R}(s, t)|^2 (-su) \left(\frac{1}{2}|C_2(s, t)|^2 + \frac{1}{2}|C_4(s, t)|^2 + |C_6(s, t)|^2 \right)$$



Physics Motivation: study of K_{LL}

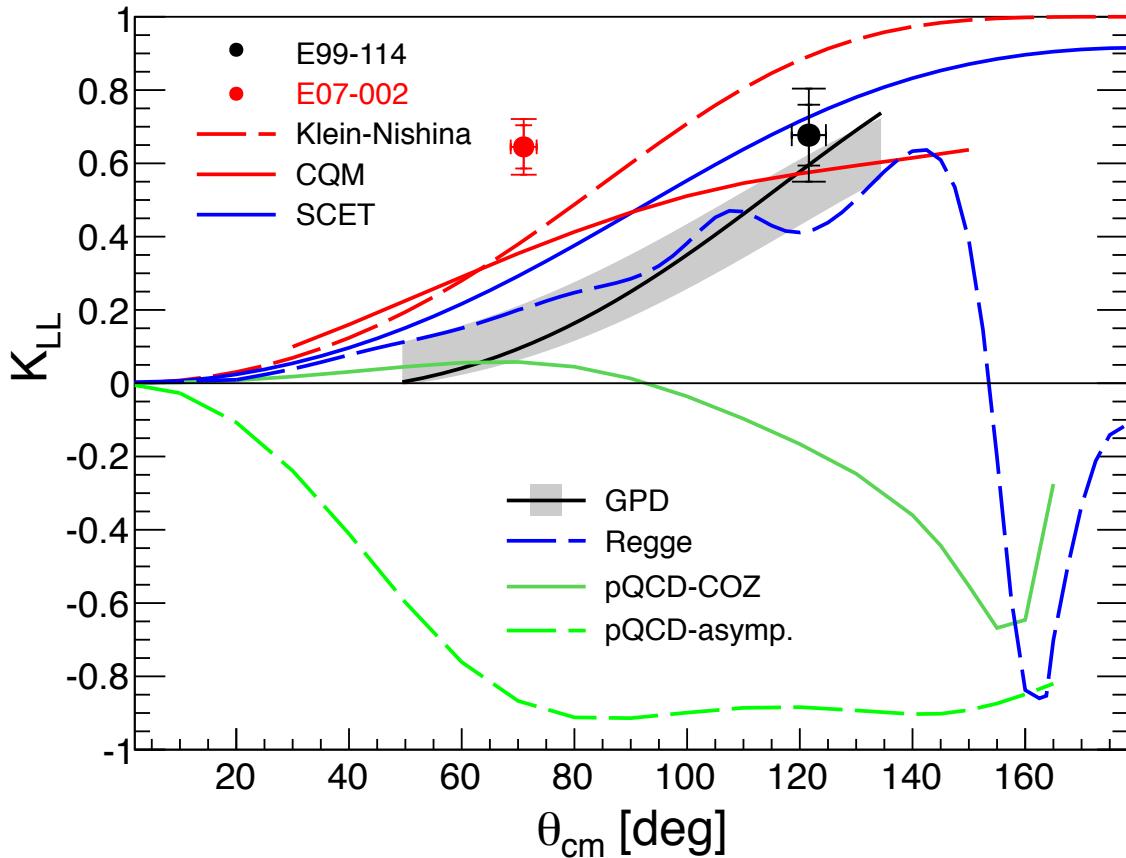


E99-114
 $s=6.9, t=-4.0, u= -1.1 \text{ GeV}^2$

Strong evidence for
handbag mechanism

PRL **94**, 242001 (2005)

Physics Motivation and a surprise



E99-114

$s=6.9, t=-4.0, u= -1.1 \text{ GeV}^2$

E07-002

$s=7.8, t=-2.1, u= -4.0 \text{ GeV}^2$

Strong evidence for
additional physics

PRL 115, 152001 (2015)

New measurement at large (**doubled**) s, t, u values
is necessary to clarify the mechanism of WACS.

Physics Motivation and a big surprise

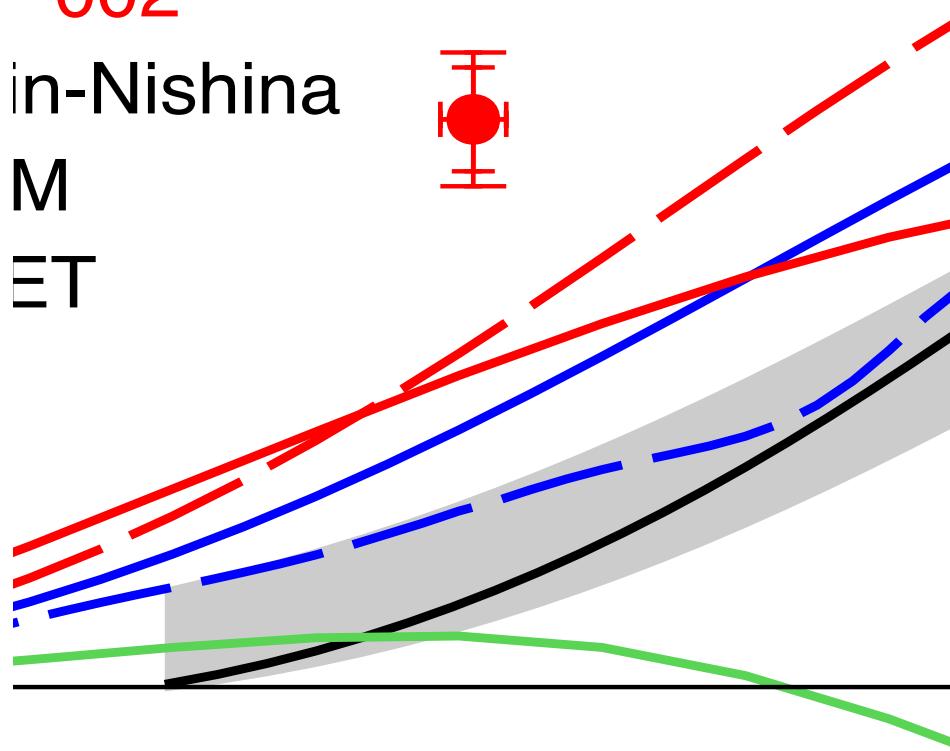
E-114

E-002

in-Nishina

M

ET



E99-114

$s=6.9, t=-4.0, u= -1.1 \text{ GeV}^2$

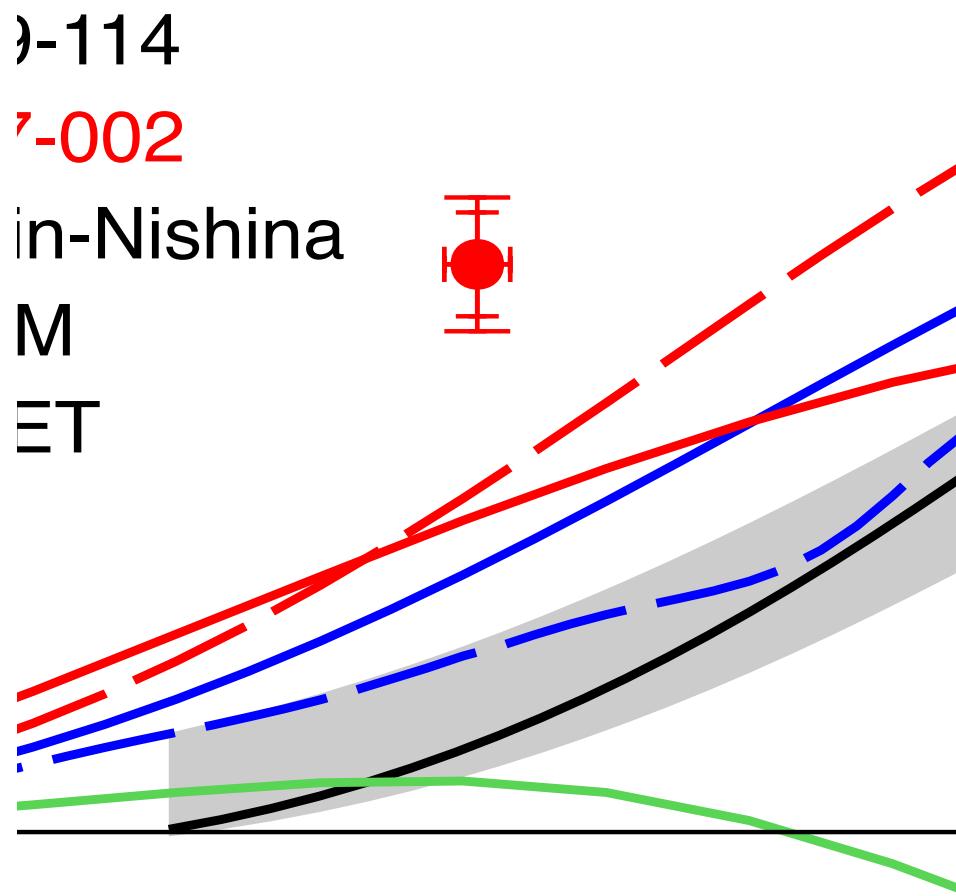
E07-002

$s=7.8, t=-2.1, u= -4.0 \text{ GeV}^2$

3.4 σ from the CQM

5.5 σ from the GPD band

Physics Motivation and a big surprise



E99-114
 $s=6.9, t=-4.0, u= -1.1 \text{ GeV}^2$

E07-002
 $s=7.8, t=-2.1, u= -4.0 \text{ GeV}^2$

What is the origin of large K_{LL} ?

Quark OAM?

Diquark u-d correlations?

GPD analysis (per Diehl&Kroll)

Eur.Phys.J. C73 (2013) no.4, 2397

$$\begin{aligned} H_v^q(x, t) &= q_v(x) \exp[t f_q(x)] , \\ E_v^q(x, t) &= e_v^q(x) \exp[t g_q(x)] , \end{aligned} \quad (33)$$

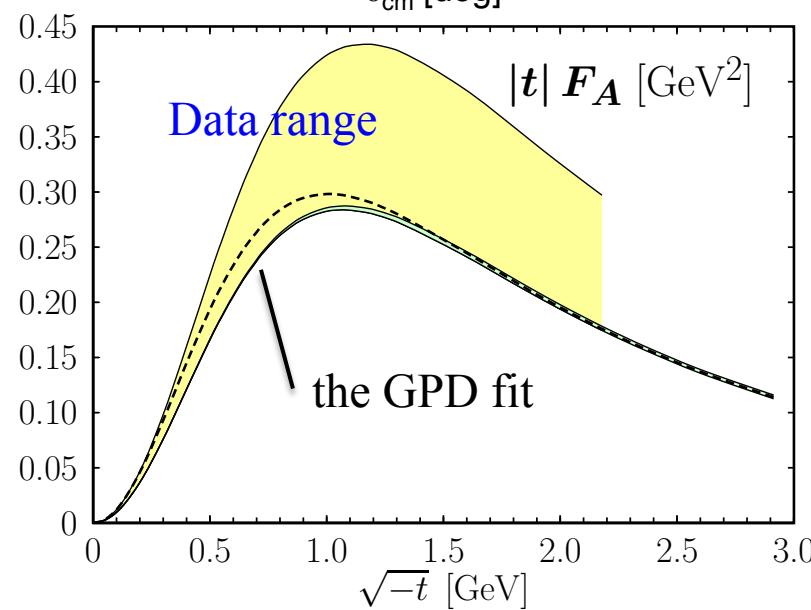
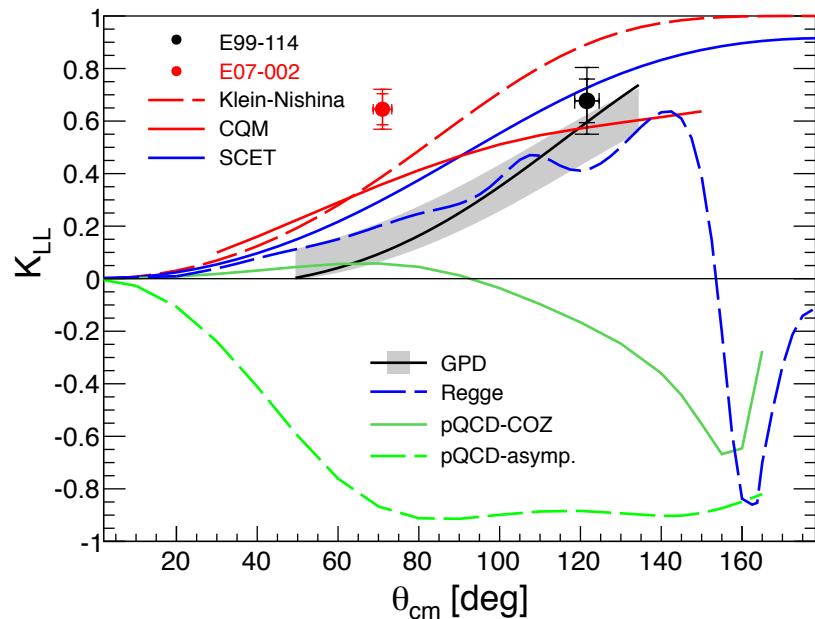
with an x dependent width specified by the profile functions $f_q(x)$ and $g_q(x)$. For polarized quarks we assume

$$\tilde{H}_v^q(x, t) = \Delta q_v(x) \exp[t f_q(x)] , \quad (34)$$

the same $f_q(x)$ for $H(x, 0, t)$ and $\tilde{H}(x, 0, t)$

$$\begin{aligned} f_q(x) &= \alpha'_q (1-x)^3 \log(1/x) + B_q (1-x)^3 \\ &\quad + A_q x (1-x)^2 , \end{aligned}$$

GPD analysis (per Diehl&Kroll)



$$K_{LL} \propto R_A / R_V$$

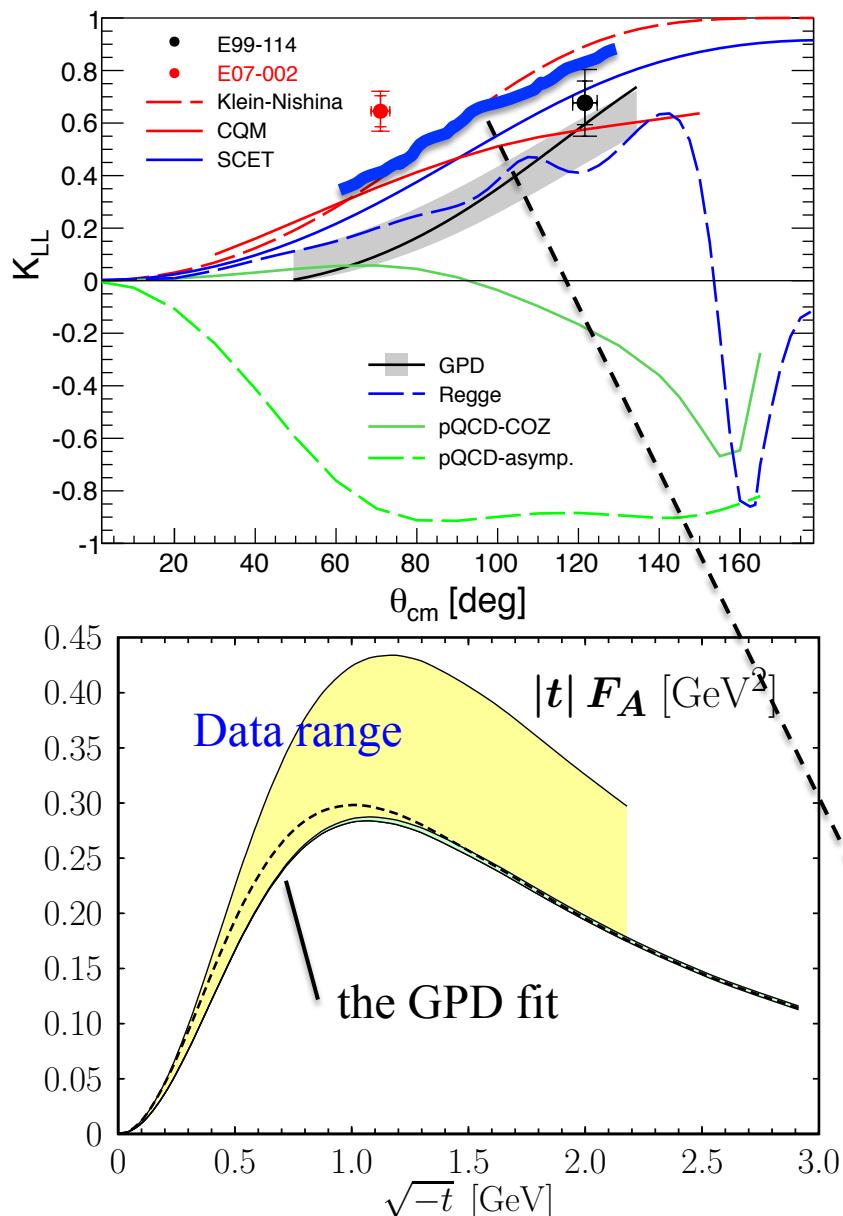
$$R_A \propto \int_{-1}^1 \frac{\tilde{H}(x, 0, t)}{x} dx$$

The same GPD is for the axial form factor.

P.Kroll recently pointed out that:

The current GPD fit is on the lower edge of F_A data.

GPD analysis (per Diehl&Kroll)



$$K_{LL} \propto R_A / R_V$$

$$R_A \propto \int_{-1}^1 \frac{\tilde{H}(x, 0, t)}{x} dx$$

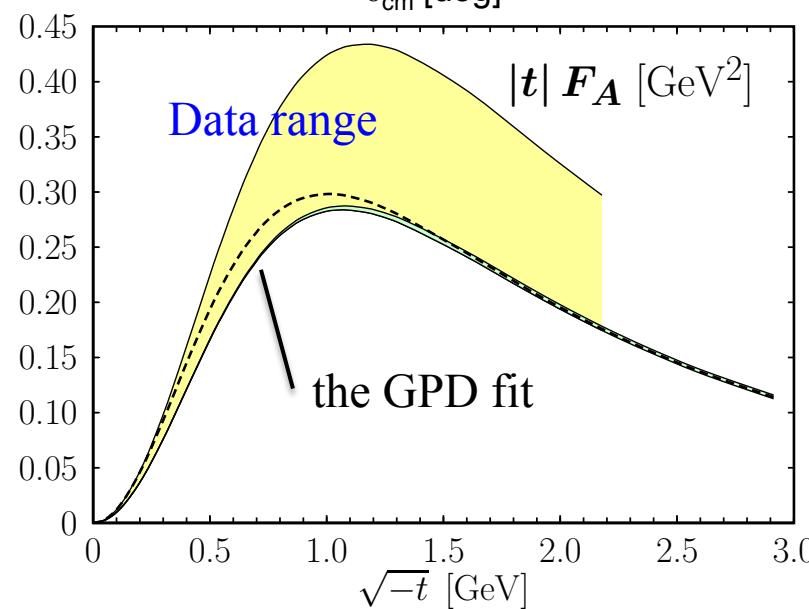
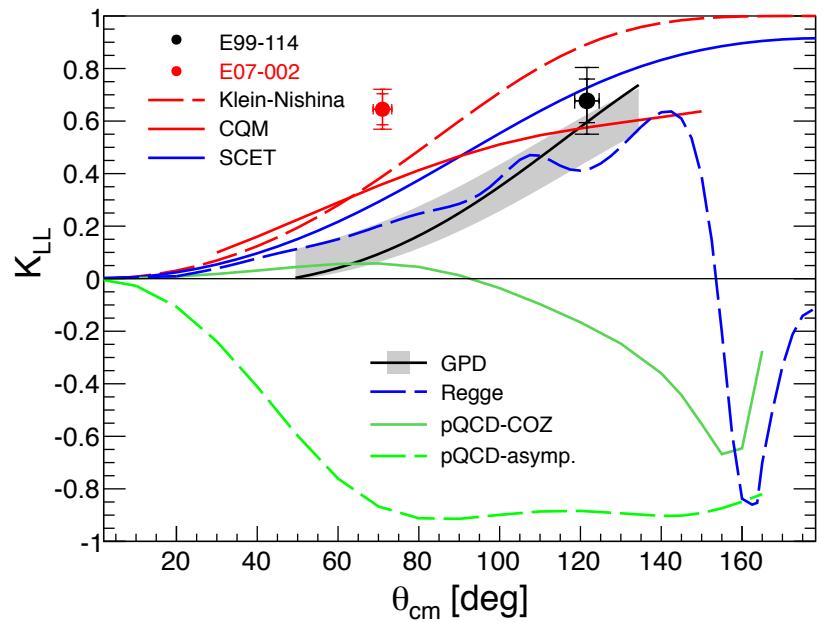
The same GPD is in the axial form factor.

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The current GPD fit is on the lower edge of F_A data.

With a larger F_A it will not be a big difficulty to explain both JLab K_{LL} data points.

GPD analysis (per Diehl&Kroll)



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$$R_A \propto \int_{-1}^1 \frac{\tilde{H}(x, 0, t)}{x} dx$$

The same GPD is in the axial form factor.

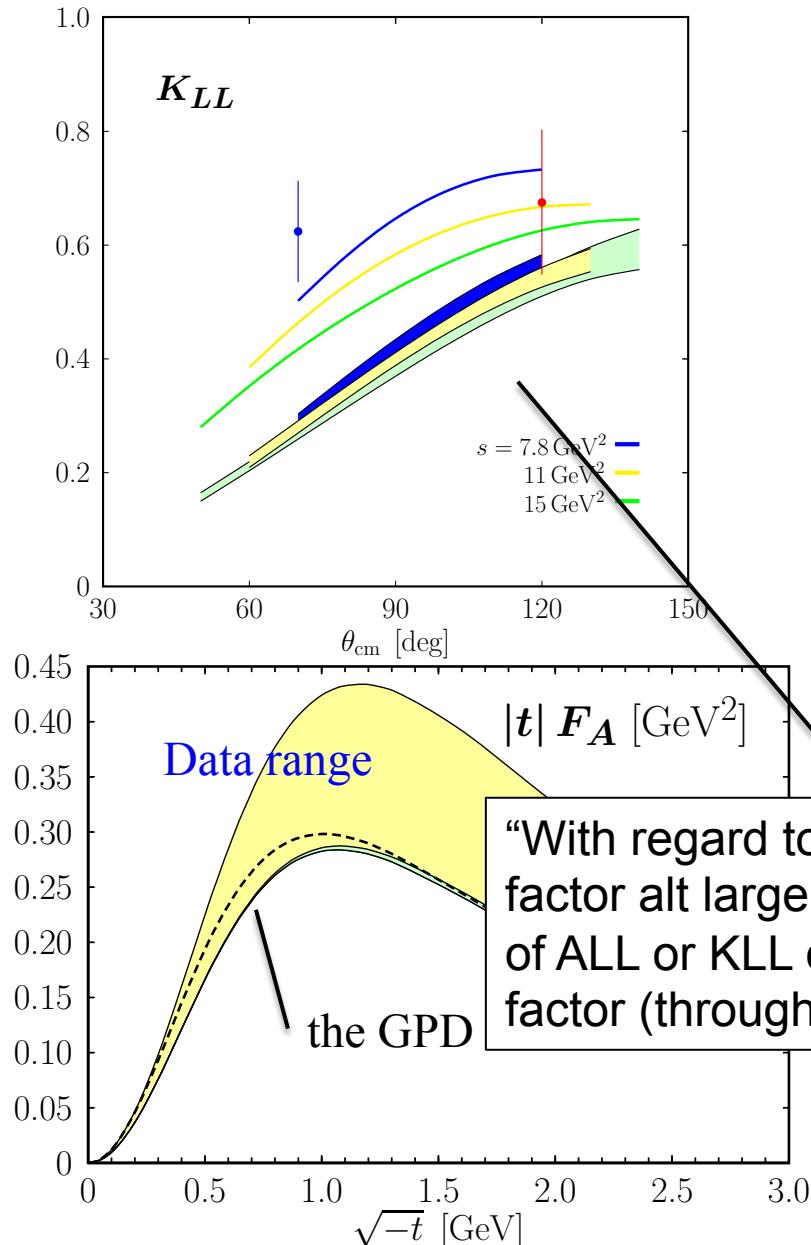
P.Kroll recently pointed out that:

The current GPD fit is on the lower edge of F_A data.

With a larger F_A it will be not a big difficulty to explain both JLab K_{LL} data points.

High $-t$ value of F_A could be obtained via GPDs modeling from the WACS K_{LL} values.

GPD analysis (per Diehl&Kroll)



$$K_{LL} \propto R_A / R_V$$

$$R_A \propto \int_{-1}^1 \frac{\tilde{H}(x, 0, t)}{x} dx$$

The same GPD is in the axial form factor.

P.Kroll recently suggested:

"With regard to the difficult measurement of the axial form factor at large $-t$ I still think that from a measurement of ALL or KLL one may extract RA and perhaps the axial form factor (through on GPD analysis) at larger $-t$."

WACS experimental considerations

➤ K_{LL}

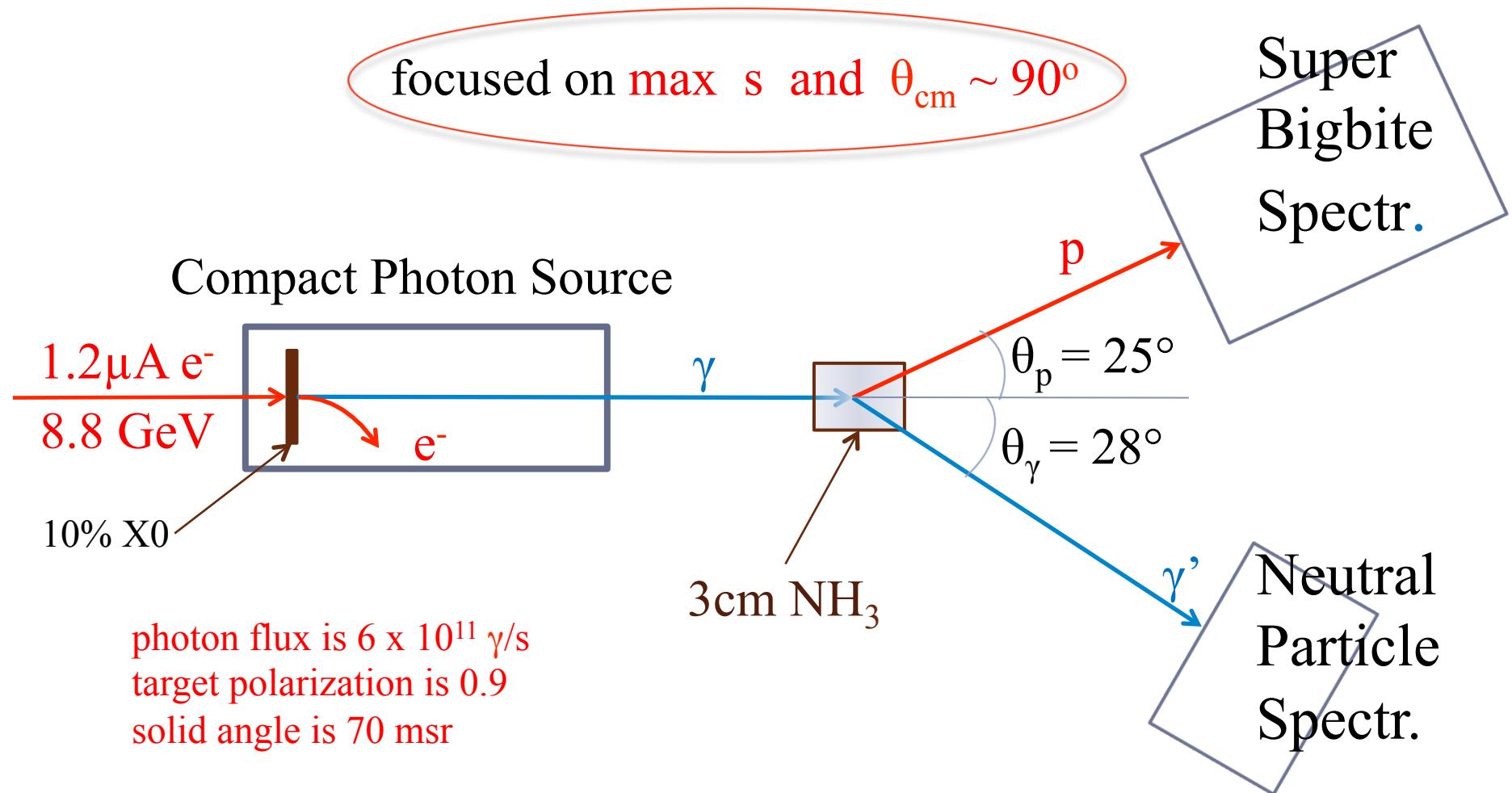
- Beam intensity: $2 \times 10^{13} \text{ } \gamma/\text{s}$
- Polarimeter: figure-of-merit ~ 0.001
- Solid angle of apparatus: HRS/HMS $\sim 6\text{-}7 \text{ msr}$

➤ A_{LL}

- Beam intensity: $6 \times 10^{11} \text{ } \gamma/\text{s}$ (**novel source**)
- Target polarization: ~ 0.9
- Solid angle of apparatus: **SBS $\sim 70 \text{ msr}$**

Overall performance ~ 250 better for A_{LL}

Plan to measure A_{LL}



Summary

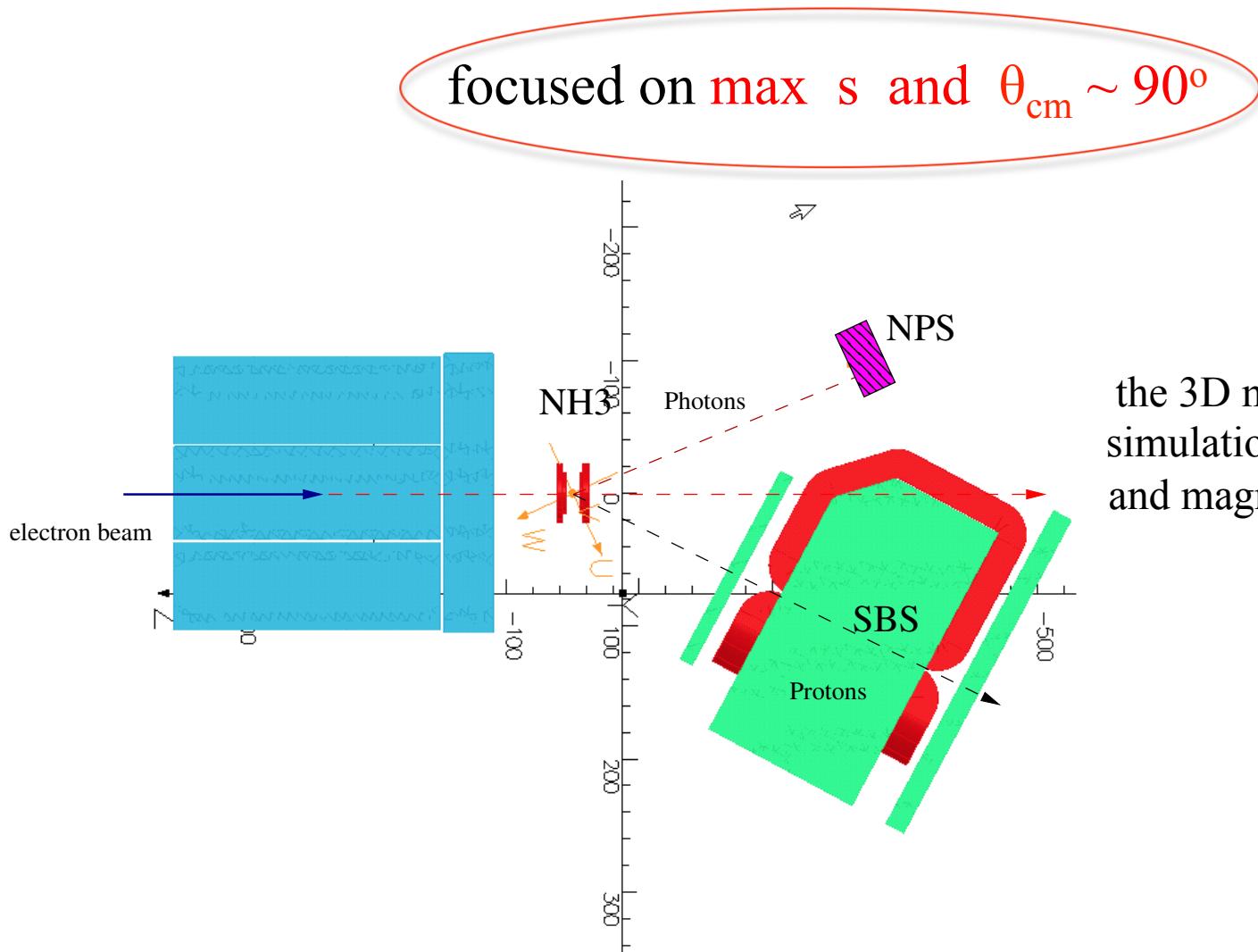
- ❖ Large K_{LL} at $\theta_{cm} = 70^\circ$: WACS is not as simple as expected, even in the range of s/t/u projected GPD/SCET applicability.

A large acceptance spectrometer and a high resolution calorimeter allow a 10-fold increase in the acceptance.

A novel scheme of a photon source-electron-dump allows a 10-fold increase in the photon intensity.

With a factor of 100 of productivity gain, the A_{LL} could be measured at $s = 9 \text{ & } 11 \text{ & } 13 \text{ & } 15 \text{ GeV}^2$ at $\theta_{cm} \sim 90^\circ, 120^\circ$

Proposed Experimental Setup

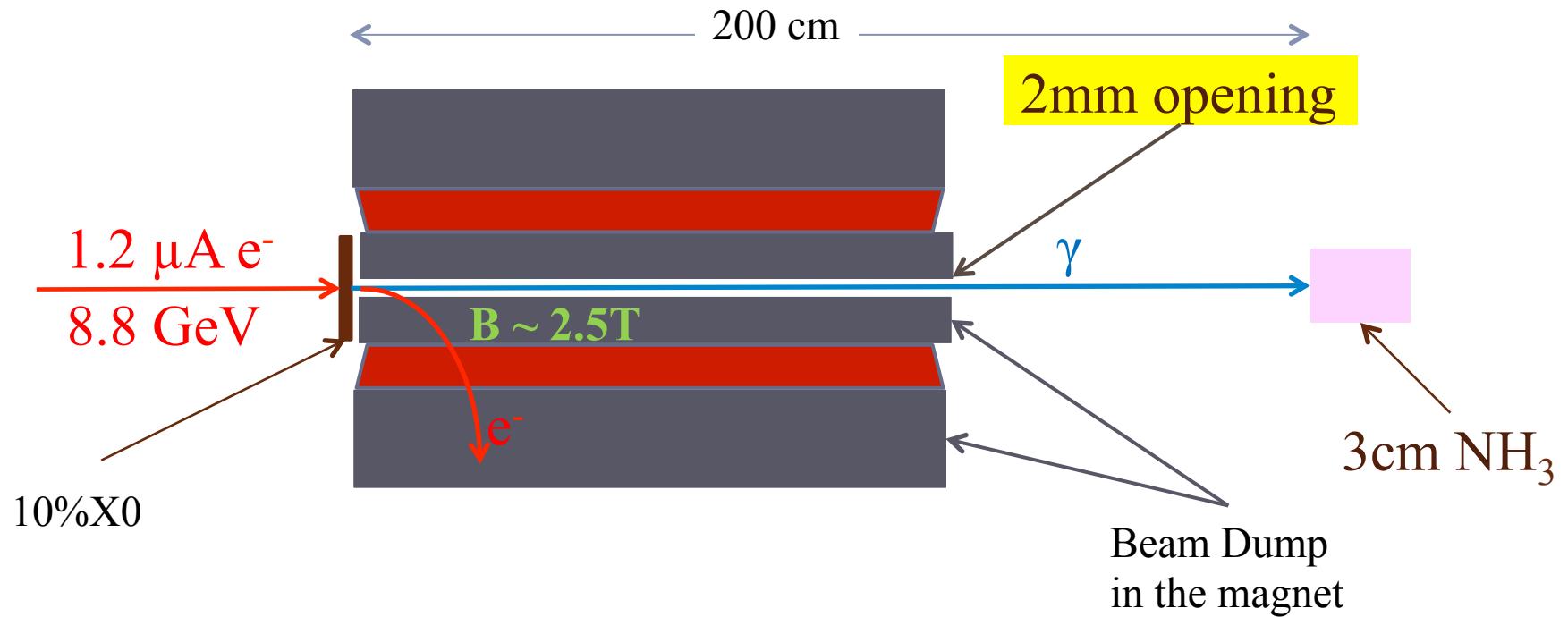


A floor plan:

the 3D model used in GEANT
simulation of physics, radiation
and magnetic field calculations

Compact Photon Source

Distance to target ~ 200 cm
photon beam diameter on the target ~ 0.9 mm

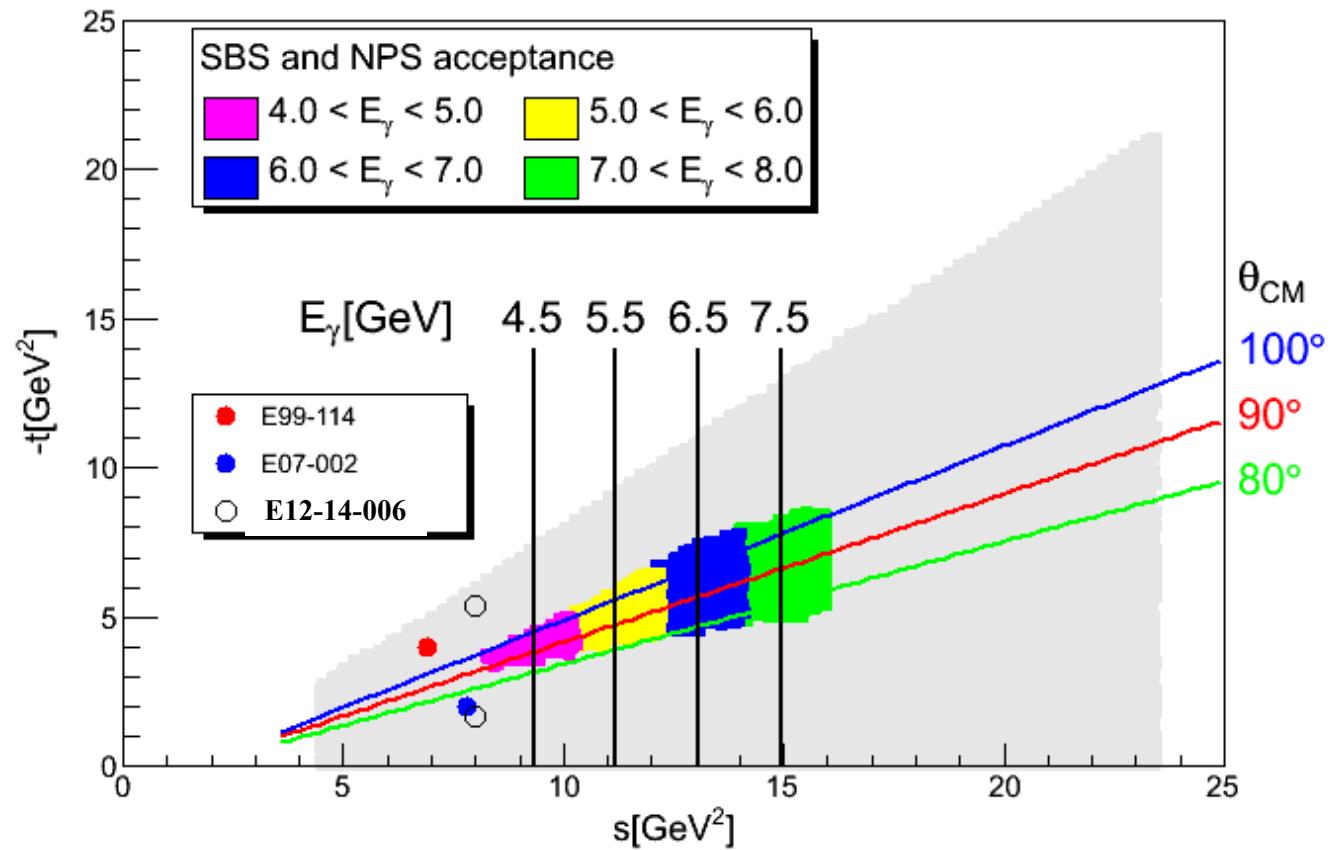


Novel concept allows high photon intensity and low radiation

Kinematic range

Detector acceptance will cover wide kinematic range in “one set”.

$s: 8.0 - 16.0 \text{ GeV}^2$
 $-t: 3.0 - 7.0 \text{ GeV}^2$
 $-u: 3.0 - 7.0 \text{ GeV}^2$
 $\theta_{\text{cm}}: 80^\circ - 100^\circ$
 $\langle \theta_{\text{cm}} \rangle \sim 90^\circ$



Physics Motivation, projected accuracy

