Gluon Polarization and Charm Production

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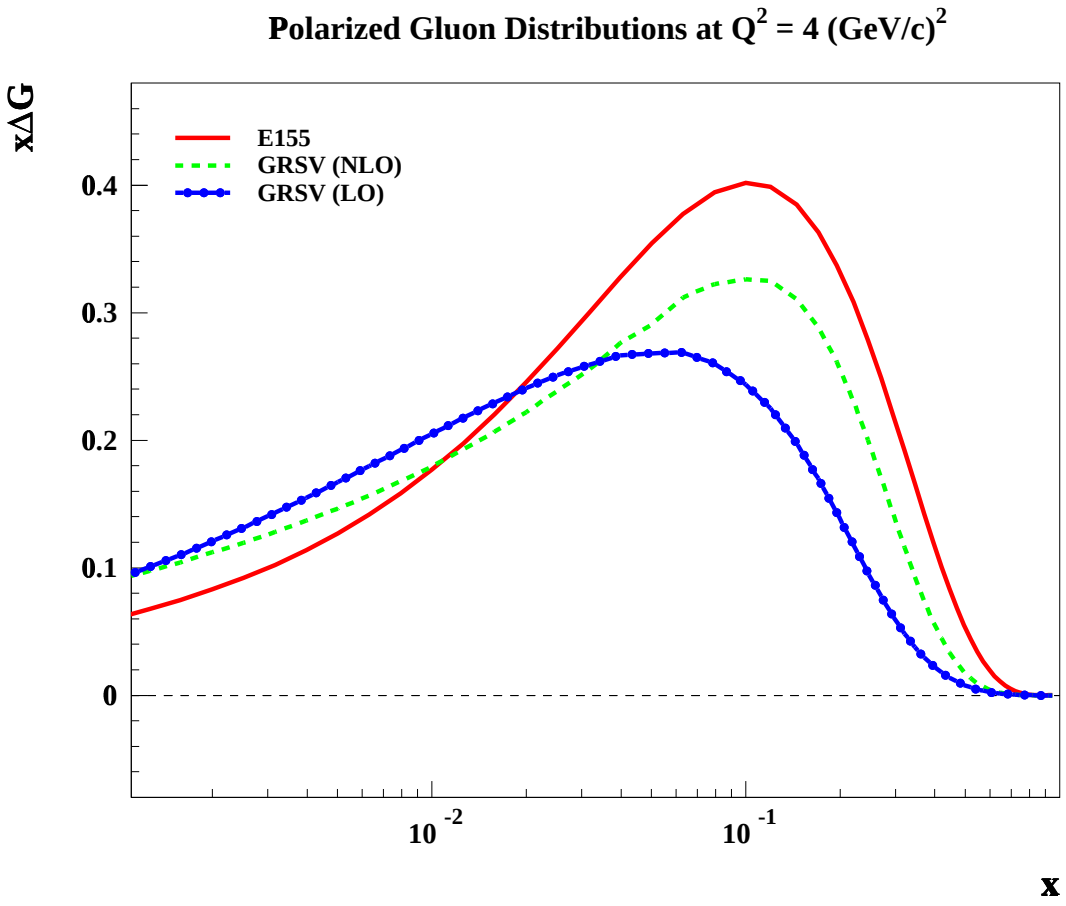
- Introduction to gluons and charm
- The Real Photon Program at SLAC
- The Physics of E161 at SLAC
- Summary

Gluon Polarization

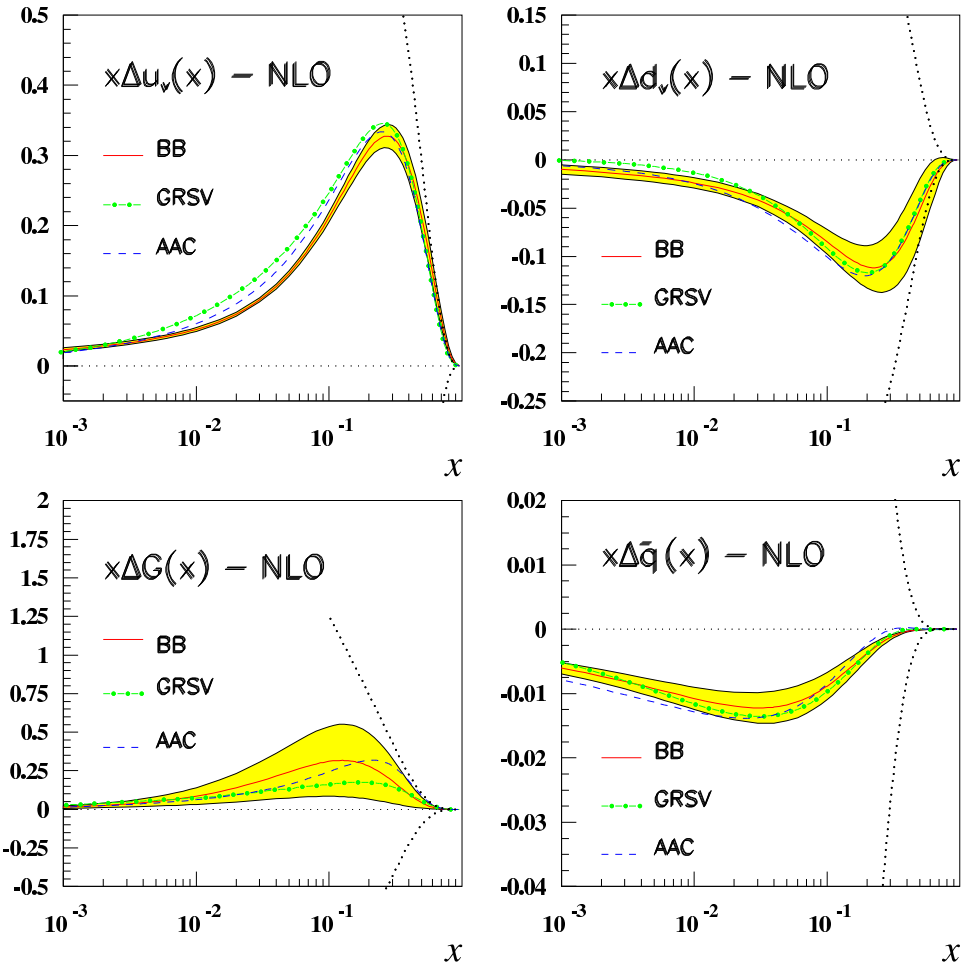
- $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$
  - $\Delta\Sigma = 0.23 \pm 0.07$ from measurements of the DIS structure function g_1
  - $\Delta G \approx 1 \pm 1$ is not well-known
  - L_z includes quark and gluon angular momentum
- 2 out of 3 would not be half bad
  - measuring ΔG would by inference determine L_z
  - measuring generalized parton distributions under certain kinematic limits can yield L_z
  - several experiments are planned or underway to measure ΔG
- Charm photo- and electro-production for ΔG
  - pQCD success for the unpolarized gluon distribution
  - highly polarized beams and targets and high luminosity make polarized measurements possible

Polarized Gluon Distribution from pQCD Evolution Equations



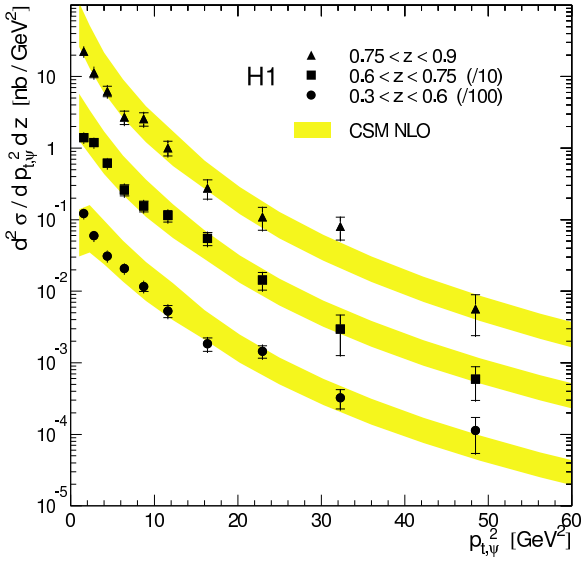
- Global NLO fit to g_1 by the E155 Collaboration at SLAC
- P.L. Anthony *et al.*, Phys. Lett. **B493**(2000)19.
- $\Delta G = \int_0^1 g(x)dx = 1.6 \pm 0.8 \pm 1.1$

Global NLO Fits to $g_1(x, Q^2)$



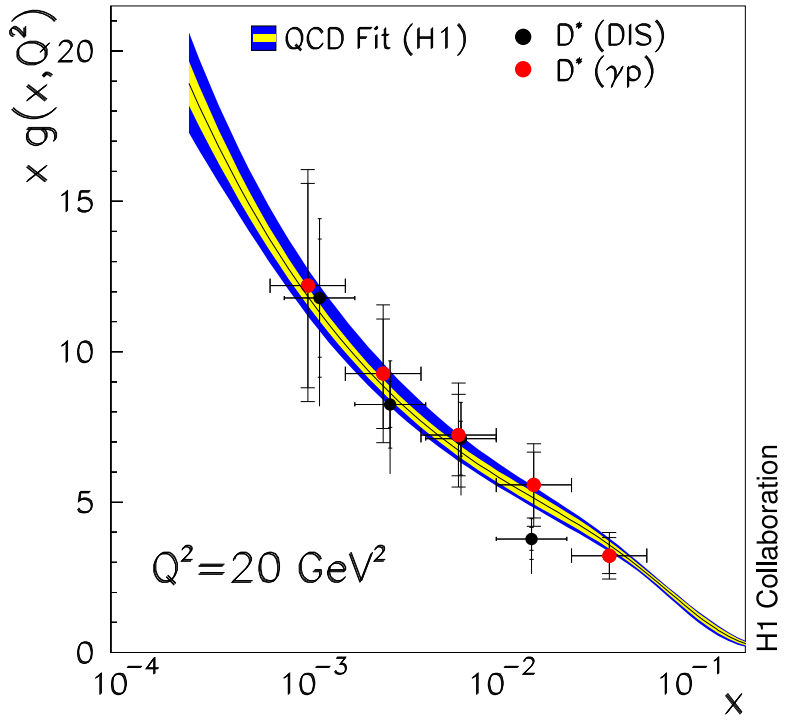
- pQCD expansion $g_1(x, Q^2) = \frac{1}{2} \Sigma_q \, e_q^2 [C_q \otimes \Delta q + C_G \otimes \Delta G]$.
- Evolution of g_1 is weakly dependent on ΔG.
- J. Blümlein and H. Böttcher, Nucl. Phys. **B636**(2002)225; GRSV, Phys. Rev. D **63**(2001)094005; AAC, Phys. Rev. D **62**(2000)034017.

Gluon Distribution via the J/ψ



- EMC (Z. Phys. **C56**(92)21) and NMC (Phys. Lett. **B258**(91)493) measured inelastic photoproduction of J/ψ.
- Berger and Jones (Phys. Rev. D **23**(81)1521) in color singlet model (CSM) related $d^2\sigma/dzdp_T$ to $G(x, Q^2)$.
- Outcome agreed with the general shape of $G(x, Q^2)$ at the time, but normalization was unknown and arbitrary.
- CDF (Phys. Rev. Lett. **79**(97)572) finds that the CSM underpredicts $p\bar{p}$ production by an order of magnitude, but a color octet model (COM) works.
- H1 (Euro. Phys. J. **C25**(02)25) finds that inelastic photoproduction at high energy is well described by either leading order CSM + COM or NLO CSM.

Gluon Distribution via Open Charm



- Uncertainty in the reaction mechanism makes open charm a better alternative than J/ψ.
- H1 (Nucl. Phys. **B545**(99)21) obtains good results for $G(x, Q^2)$ in an NLO fit to photo- and electro-production data of D^* mesons.
- One can use similar techniques with polarization to obtain $\Delta G(x, Q^2)$.

Direct Measurements of ΔG

- HERMES:
  - 27 GeV electron energy
  - high p_T jets for $0.06 < x < 0.28$
  - first results: $\Delta G/G = 0.41 \pm 0.18$
- COMPASS (C. Marchand, this session):
  - $\mu + d \to c\bar{c}$ with LiD target
  - low Q^2 data from 160 GeV beam
  - detect D and $\bar{D}$; also high p_T jets
- RHIC (Y. Makdisi, this session):
  - Gluon Compton scattering

$g + q \to \gamma + X$

$A_{LL} \cdot d\sigma \sim \sum_a \int \Delta q_a \cdot \Delta G \cdot d\Delta\sigma(q_a + g \to \gamma + X)$

  - Gluon fusion

$g + g \to \text{jet} + \text{jet}$

$A_{LL} \cdot d\sigma \sim \int \Delta G \cdot \Delta G \cdot d\Delta\sigma(g + g \to X + X)$

- E161 at SLAC:
  - 35-45 GeV circularly polarized γ beam
  - $\mu + d \to c\bar{c}$ with LiD target
  - detect μ^+ and μ^- from D and $\bar{D}$ decay

SLAC RPC Collaboration

- Aarus University, Denmark
- University of California Los Angeles
- DAPNIA-Saclay, France
- Laboratori Nazionali di Frascati, Italy
- Jefferson Lab
- Institut für Kernphysik Mainz, Germany
- University of Liverpool, UK
- Los Alamos National Laboratory
- University of Massachusetts
- Mississippi State University
- Old Dominion University
- Ruhr-Universität Bochum, Germany
- Smith College
- Stanford Linear Accelerator Center
- University of Virginia
- College of William and Mary
- University of Witswaterrand, South Africa
- Yerevan Physics Institute, Armenia

E159: Measurement of $\Delta^{\gamma N}(k)$ and the High Energy Contribution to the Gerasimov-Drell-Hearn Sum Rule

- Goals:
  - Determine for the first time the difference between right- and left-handed polarized photoabsorption above the resonance region.
  - Compare to models that predict the cross section difference changes sign at high energies.
  - Experimentally constrain the GDH sum.
- Measurement:
  - Identification of at least one hadron.
  - Polarized $^{15}NH_3$ and $^{15}ND_3$ targets
  - 4–40 GeV circularly polarized photons
- Results:
  - Cross section differences for longitudinal beam and target polarizations.
  - $4 < k < 40$ GeV for the proton and deuteron.
  - Experimental integrals of the GDH sum.
- http:www.slac.stanford.edu/exp/e159/

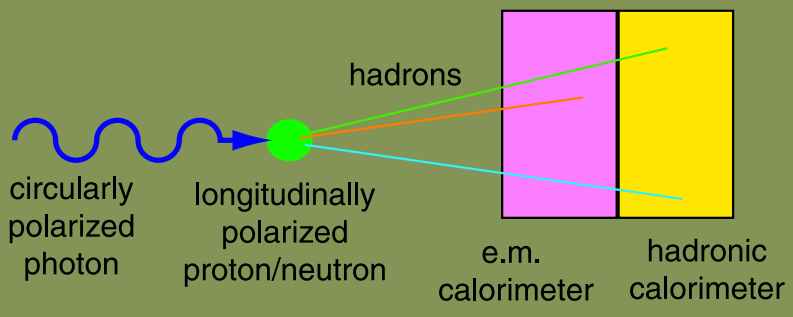
E159

Measurement of $\Delta\sigma(k)$ and the High Energy Contribution to the GDH Sum

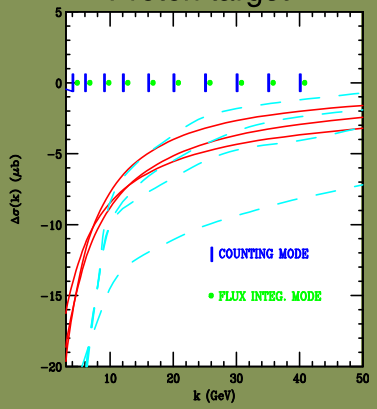
Goals

1) Measure helicity dependence of cross section to absorb circularly polarized photons on polarized nucleons in the energy range 5 to 45 GeV.

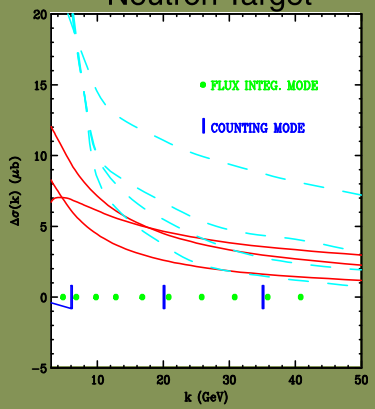
2) Test the fundamental GDH Sum Rule.



Proton target



Neutron Target



Projected Errors

www.slac.stanford.edu/exp/e159

E160: Measurement of the A-dependence of J/ψ and ψ' photoproduction

- Goals:
  - Understand interplay of pQCD and color transparency in creation and interaction of J/ψ and ψ' in nuclei.
  - Understand why VMD and geometrical expectations for $\sigma_{\rm tot}^{\psi N}$ are at odds.
  - Constrain causes for J/ψ suppression in relativistic heavy-ion collisions.
- Measurement:
  - Reconstruct J/ψ from $\mu^+\mu^-$ pairs.
  - Be, Al, Cu, Pb targets
  - 15, 25, 35 GeV photons
- Results:
  - t-distributions
  - α from $\sigma_A \propto A^\alpha$
  - ψ-nucleon cross section $\sigma_{\rm tot}^{\psi N}$
- http:www.slac.stanford.edu/exp/e160/

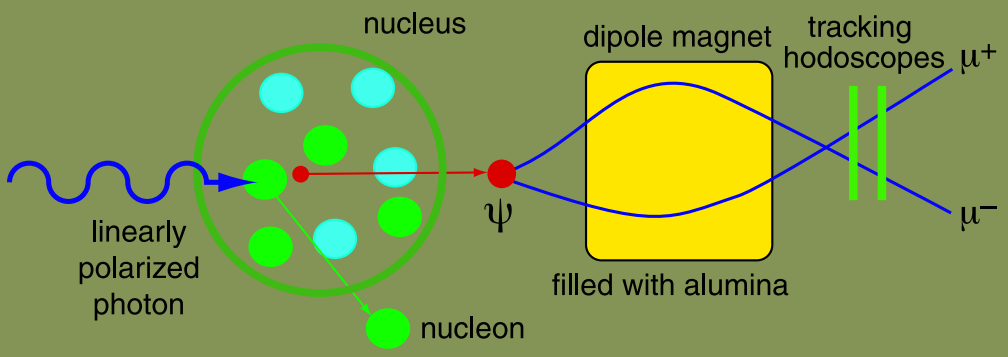
E160

Measurement of the A-Dependence of J/ψ(1S) and ψ(2S) Photoproduction

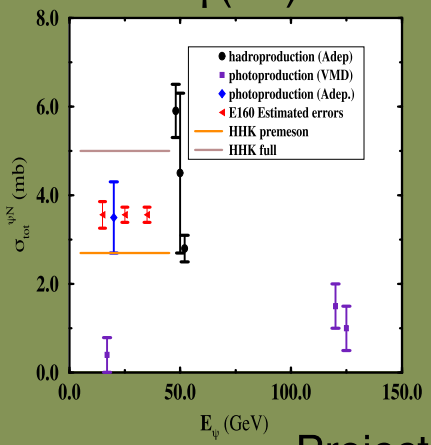
Goals

1) Study production and interaction of charmonium in nuclei from Be to Au at energies from 15 to 35 GeV.

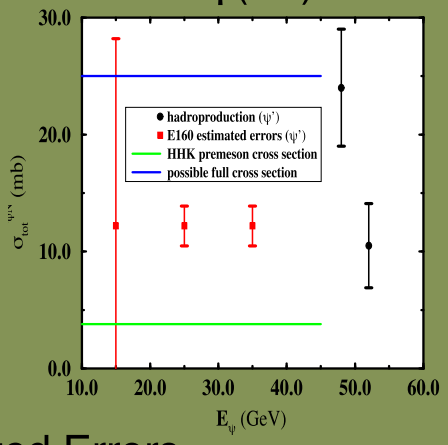
2) Constrain causes for charmonium suppression in heavy ion collisions.



J/ψ(1S)



ψ(2S)



Projected Errors

www.slac.stanford.edu/exp/e160

E161: Measurement of the Gluon Spin Distribution using Polarized Open Charm Photoproduction

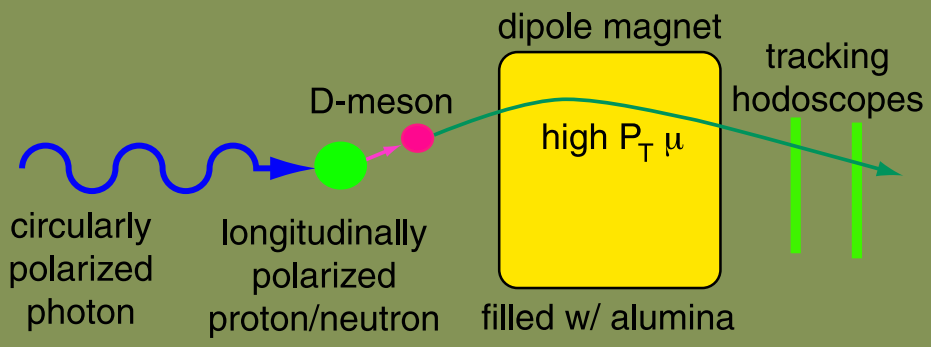
- Goals:
  - Determine the polarized gluon distribution of the nucleon.
  - Discriminate between models of $\Delta G(x)$.
  - Make precise measurements complementary to COMPASS, HERMES, STAR and PHENIX.
- Measurement:
  - Detection of a single μ (veto μ pairs).
  - Polarized LiD target
  - 35, 40 and 45 GeV circularly polarized photons
- Results:
  - Asymmetries for longitudinal beam and target polarizations.
  - Momentum distributions p_μ and $p_{T\mu}$.
  - $\Delta G(x)$ for $0.1 < x < 0.2$.
- http:www.slac.stanford.edu/exp/e161/

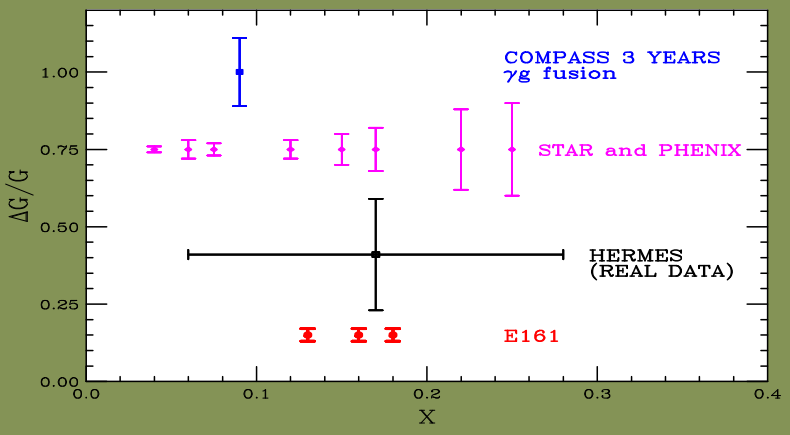
E161

Gluon Spin in Nucleons Using Polarized Open Charm Photoproduction

Goal

Find gluon contribution to the nucleon "Spin Puzzle" using photoproduction of open charm (dominated by photon-gluon fusion diagram). Complementary to measurements at RHIC-Spin and COMPASS.

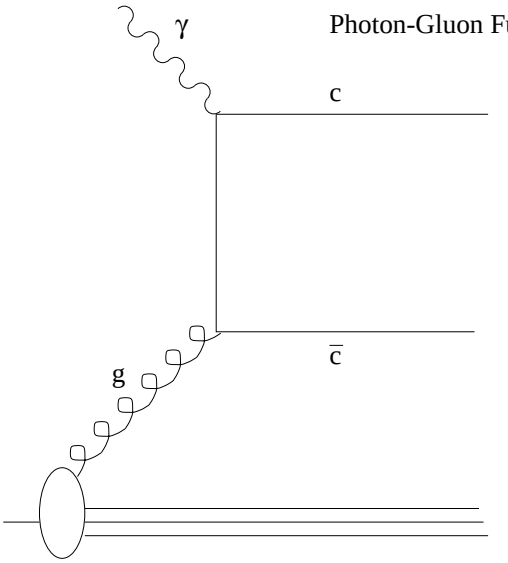




Projected Errors

www.slac.stanford.edu/exp/e161

Photon Gluon Fusion



- Charm photoproduction probes the nucleon gluon distribution.
- Open charm production is relatively clean because the detected charmed mesons are direct descendants from the c and $\bar{c}$ quarks of the hard process.
- Double spin asymmetries from polarized beams and targets are sensitive to the polarized gluon distribution ΔG

Experimental Strategy for Measuring ΔG at SLAC

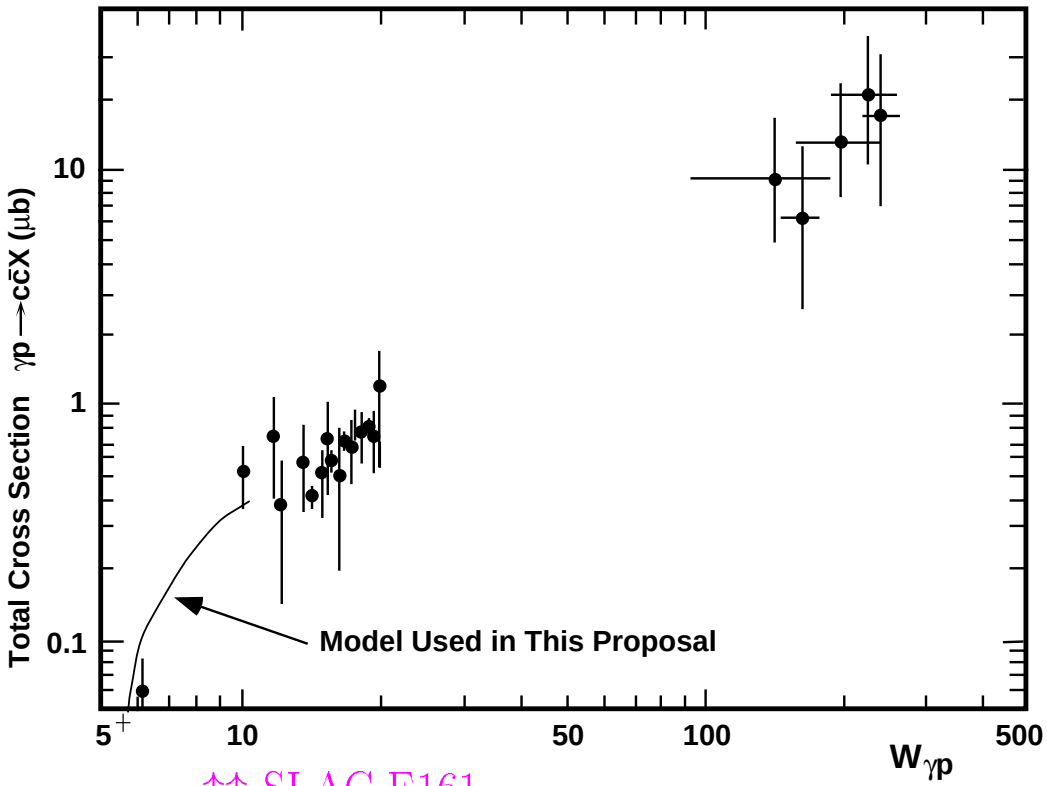
- Target:
  - ^{6}LiD (isoscalar target) cooled to 300mK.
  - B Field of 6.5 T
  - 182 GHz dynamic nuclear polarization
  - 70% polarization
  - dilution factor ≈ 0.4
- Beam:
  - 85% electron polarization
  - 10^{12} electrons per second
  - coherent bremsstrahlung photon beam
  - 75–80% circular photon polarization
- Spectrometer:
  - high magnetic field
  - hodoscopes with good Δx and Δt
  - absorber that eliminates all but μ's
  - veto of $\mu^+\mu^-$ pairs
  - $> 10^5$ high-p_T charm events per day

Charm Tagged with Single μ Decay

	D^+	D^0	D_s^+	Λ_c^+
production(%)	19	63	8	8
decay to μ^+(%)	37	47	8	4
	D^-	$\bar{D}^0$	D_s^-	Λ_c^-
production(%)	21	71	6	2
decay to μ^-(%)	40	53	5	1

- Relative number of charmed hadrons produced in the fragmentation of charmed quarks.
- Fraction of muons of each charge originating from the parent charmed hadron.
- Calculated using PYTHIA 5.7 for 40 GeV incident photons, a deuteron target and $p_T > 0.5$ GeV.
- Single muon production is dominated by decays of the $D^{\pm}$ and D^0 mesons.

Total Charm Photoproduction $\sigma_{\gamma p}(k)$



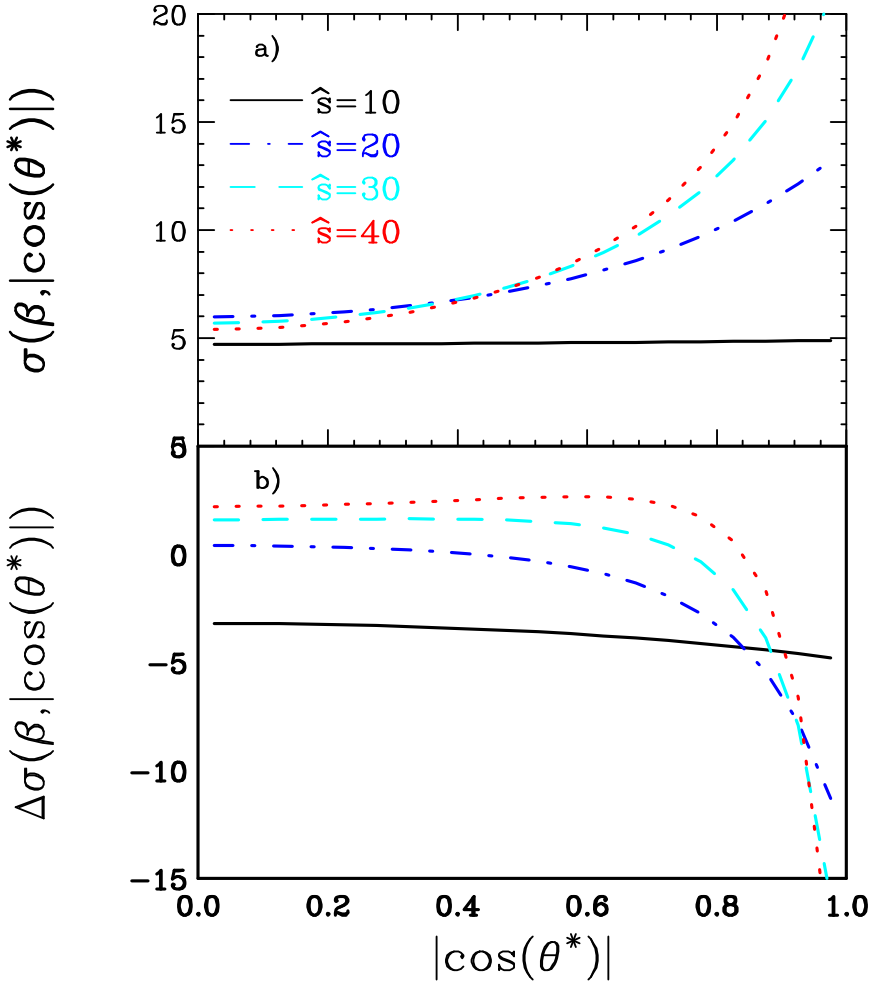
↑↑ SLAC E161

- $\sigma_{\gamma p}(k) = \int_{x_{min}}^{1} g(x, Q^2) dx \int_{-1}^{1} \sigma(\hat{s}, \cos\theta^*)\, \beta\, d\cos\theta^*$
- $x_{min} = 4m_c^2/2Mk$
- $s = 2Mk + M^2$
- $\beta = \sqrt{1 - 4m_c^2/\hat{s}}$ is the c.m. velocity of the c quark.
- $\hat{s} = xs$ is the $c\bar{c}$ squared energy.
- $\sigma(\hat{s}, \cos\theta^*)$ is the partonic cross section.

Leading Order Charm Photoproduction

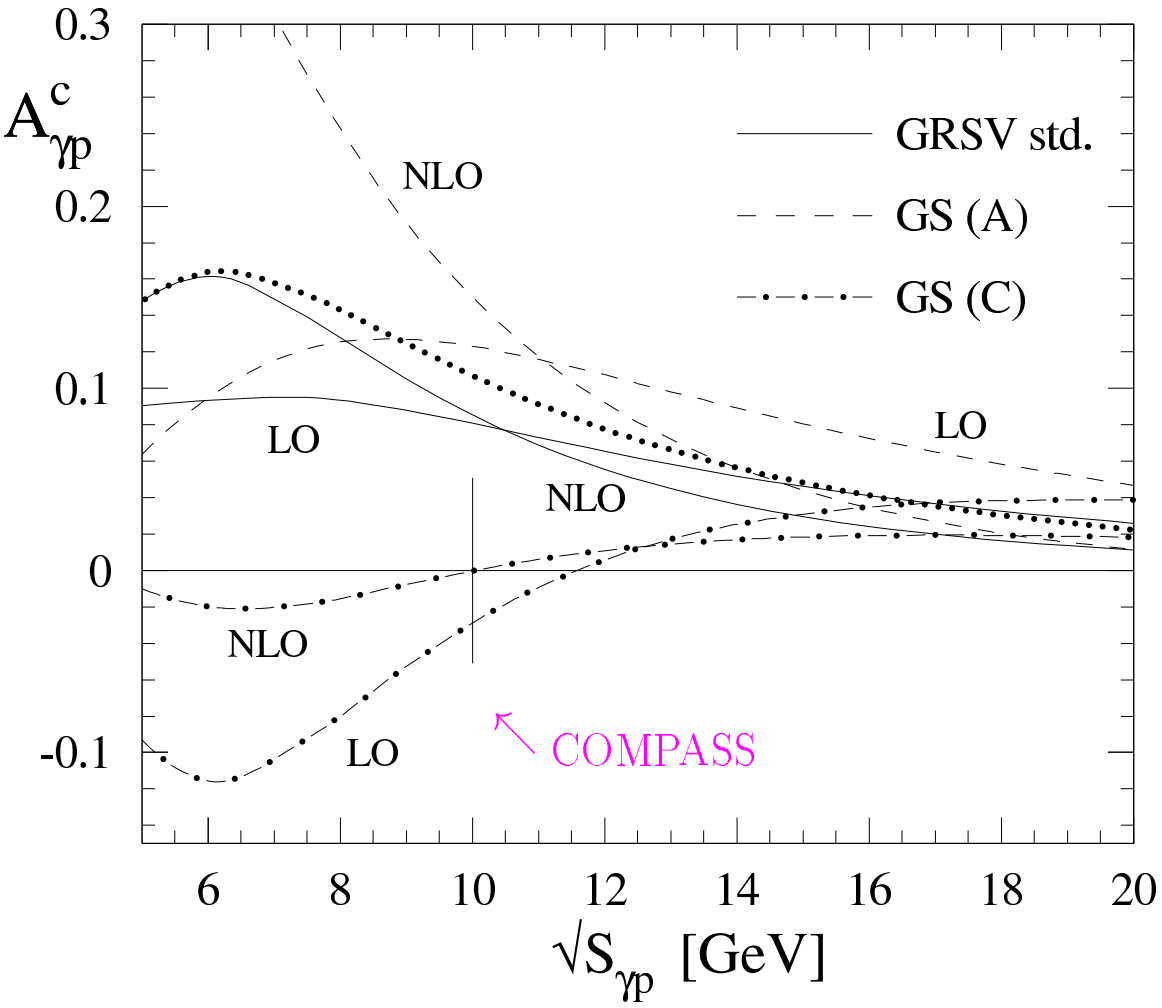
- $\sigma(\hat{s}, \cos\theta^*) = \frac{4}{9}\frac{2\pi\alpha\alpha_s(\hat{s})}{\hat{s}}\Big[\frac{-8m_c^4\hat{s}^2}{\hat{t}^2\hat{u}^2} + 2\frac{\hat{t}^2+\hat{u}^2+4m_c^2\hat{s}}{\hat{t}\hat{u}}\Big]$.
- $\hat{t} = \frac{\hat{s}}{2}[1 + \beta\cos\theta^*]$
- $\hat{u} = \frac{\hat{s}}{2}[1 - \beta\cos\theta^*]$.
- Integrated over $\cos\theta^*$:
  $\sigma(\hat{s}) = \frac{4}{9}\frac{2\pi\alpha\alpha_s(\hat{s})}{\hat{s}}\Big[-\beta(2-\beta^2) + \frac{1}{2}(3-\beta^4)\ln\frac{1+\beta}{1-\beta}\Big]$.
- $\Delta\sigma = \sigma^{\uparrow\uparrow} - \sigma^{\downarrow\uparrow}$
- $\Delta\sigma_{\gamma p}(k) = \int_{x_{min}}^1 \Delta g(x, Q^2)dx \int_{-1}^1 \Delta\sigma(\hat{s}, \cos\theta^*)\ \beta\, d\cos\theta^*$
- $\Delta\sigma(\hat{s}, \cos\theta^*) = \frac{4}{9}\frac{2\pi\alpha\alpha_s(\hat{s})}{\hat{s}}\Big[\frac{4m_c^4(\hat{t}^3+\hat{u}^3)}{\hat{t}^2\hat{u}^2} + 2\frac{\hat{t}^2+\hat{u}^2-2m_c^2\hat{s}}{\hat{t}\hat{u}}\Big]$.
- Integrated over $\cos\theta^*$:
  $\Delta\sigma(\hat{s}) = \frac{4}{9}\frac{2\pi\alpha\alpha_s(\hat{s})}{\hat{s}}\Big[-3\beta + \ln\frac{1+\beta}{1-\beta}\Big]$.
- $A_{cc}(k) = \Delta\sigma_{\gamma p}(k)/\sigma_{\gamma p}(k) = \frac{1}{P_t P_b f}\frac{N^{\uparrow\uparrow}-N^{\downarrow\uparrow}}{N^{\uparrow\uparrow}+N^{\downarrow\uparrow}}$

Cross Sections for $\gamma g \to c\bar{c}$



- Spin-averaged (a) and spin-dependent (b) cross sections scaled by $9\hat{s}/8\pi\alpha\alpha_s(\hat{s})$ with $m_c = 1.5$ GeV.
- $\hat{s}$ = 10 (solid), 20 (dash-dot), 30 (dash), 40 (dot) GeV^2, and $\beta = 0.3, 0.74, 0.84, 0.88$, respectively.

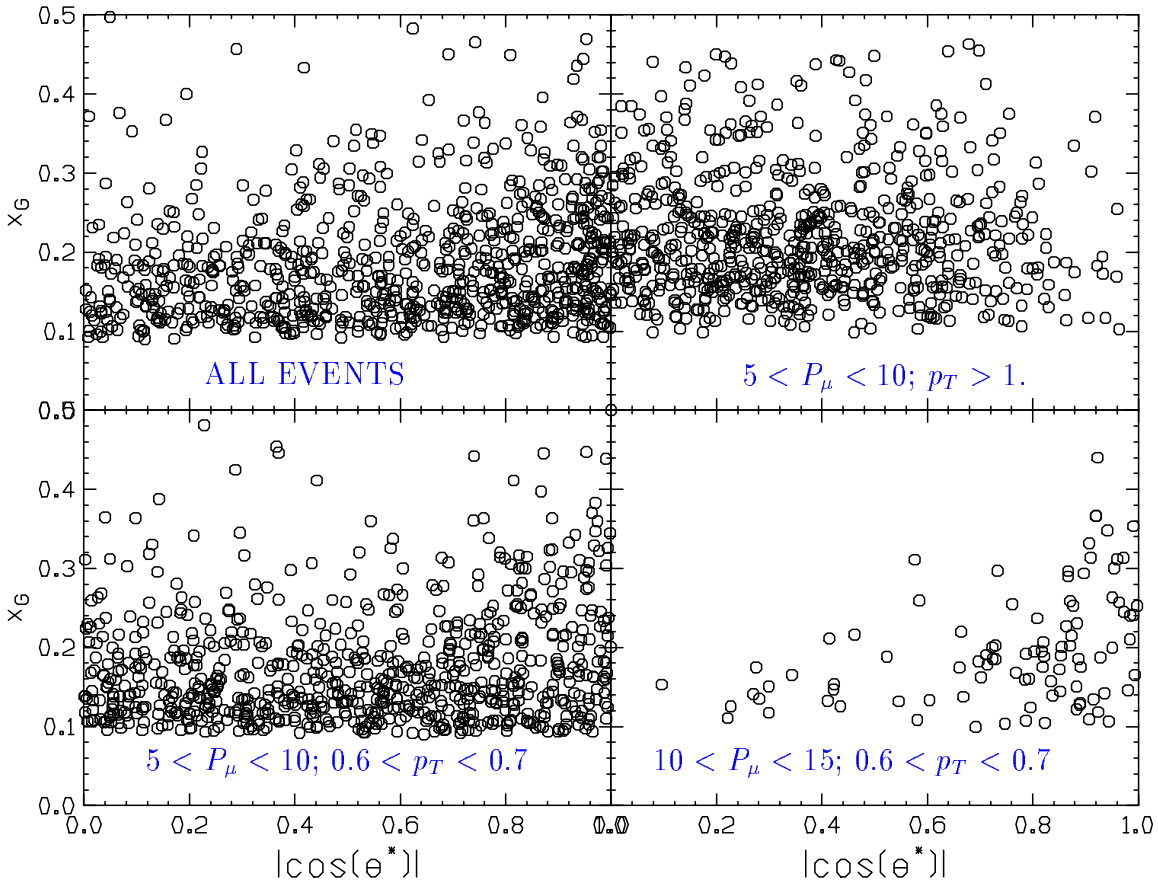
NLO pQCD Charm Asymmetries



↑↑↑ This proposal

- I. Bojak and M. Stratmann, Phys. Lett. **B433**(1998)411.
- also calculated by Z. Merebashvili *et al.*, Phys. Rev. D **62**(2000)114509.

E161 Open Charm Kinematics

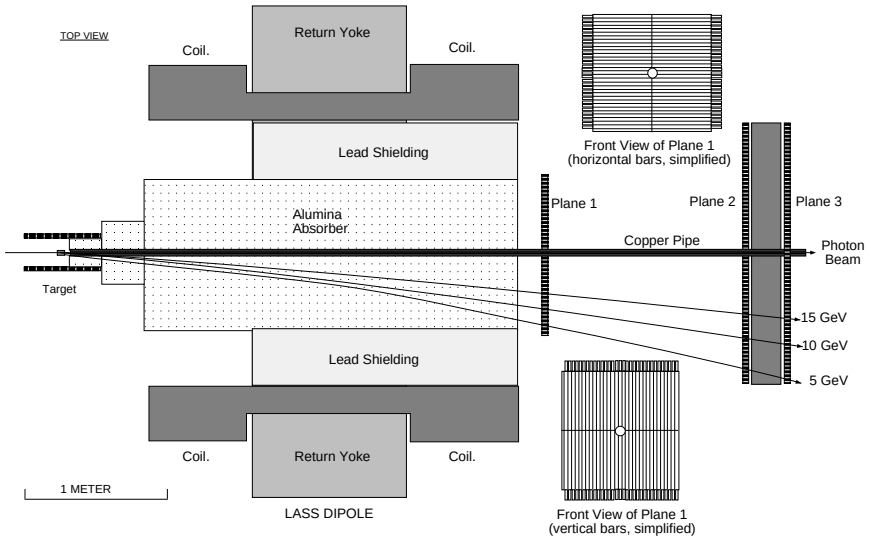


- $x_G = \hat{s}/s$ versus $\cos\theta^*$
- $x_{min} = 4m_c^2/(2Mk)$

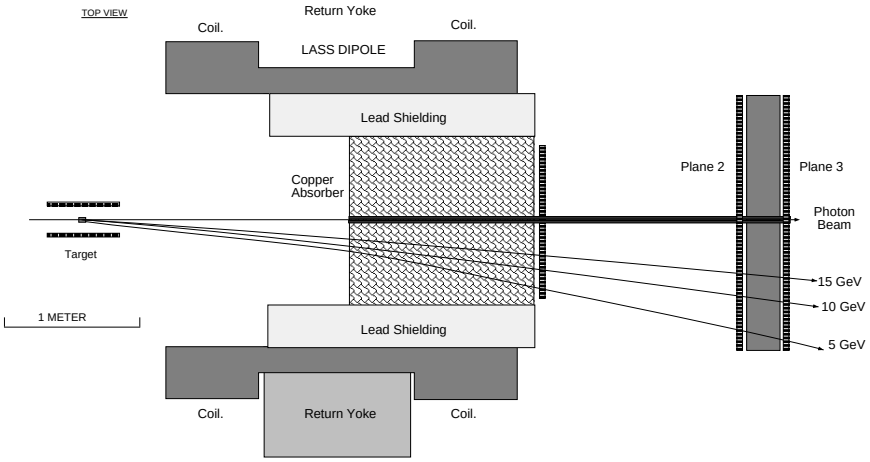
Photon Energy	x_{min}	
35.	0.14	
40.	0.12	
45.	0.10	$\Leftarrow$

E161 Spectrometer

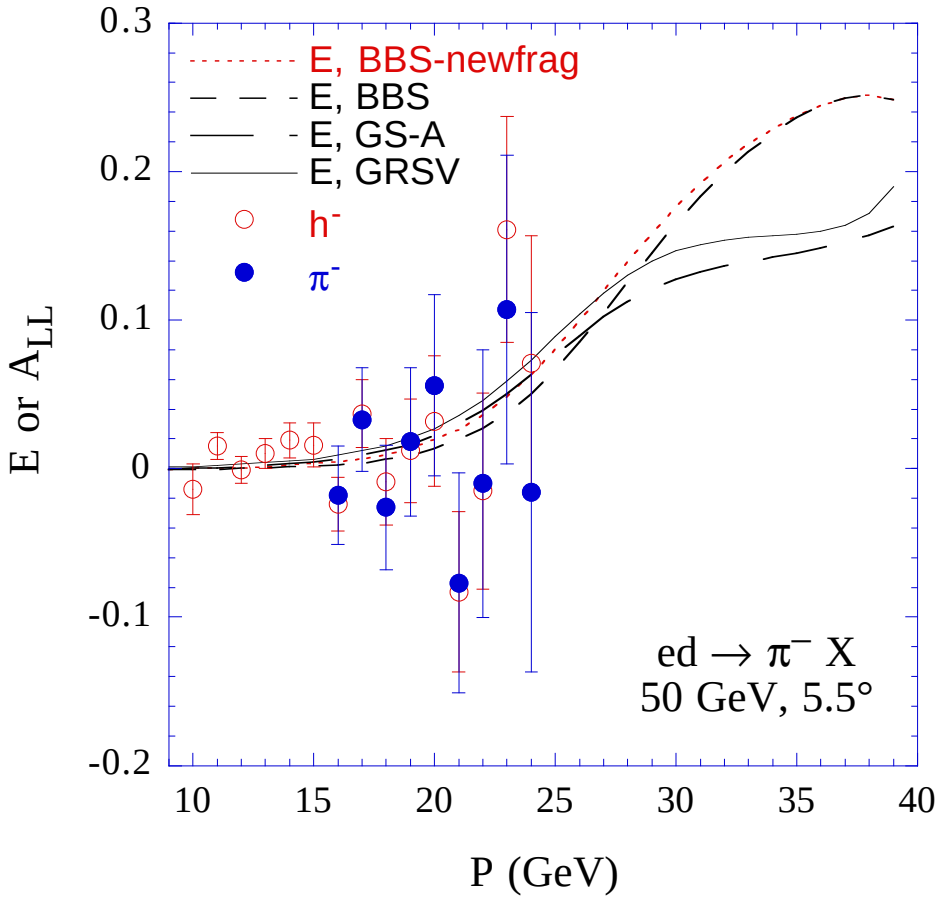
Normal Mode



Background Mode

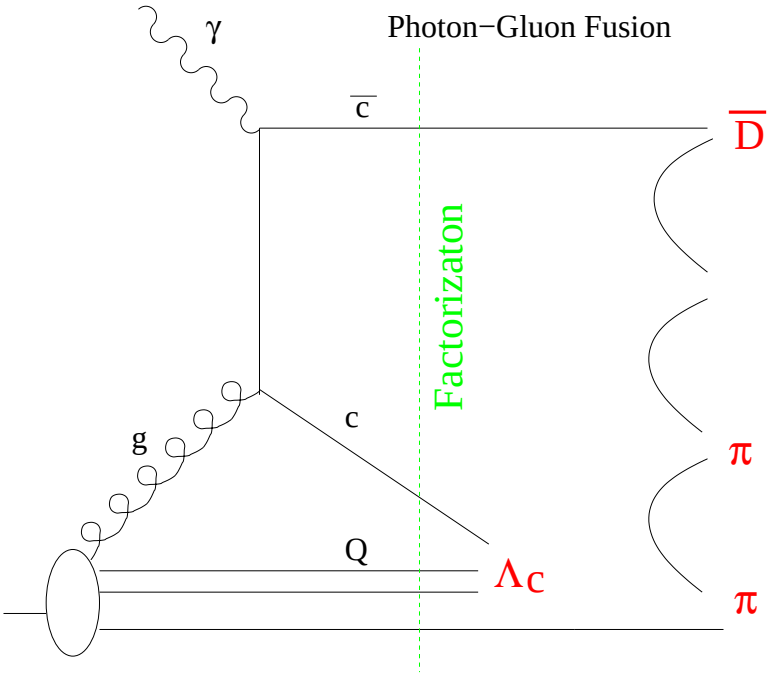


Asymmetries of Photoproduced Hadrons



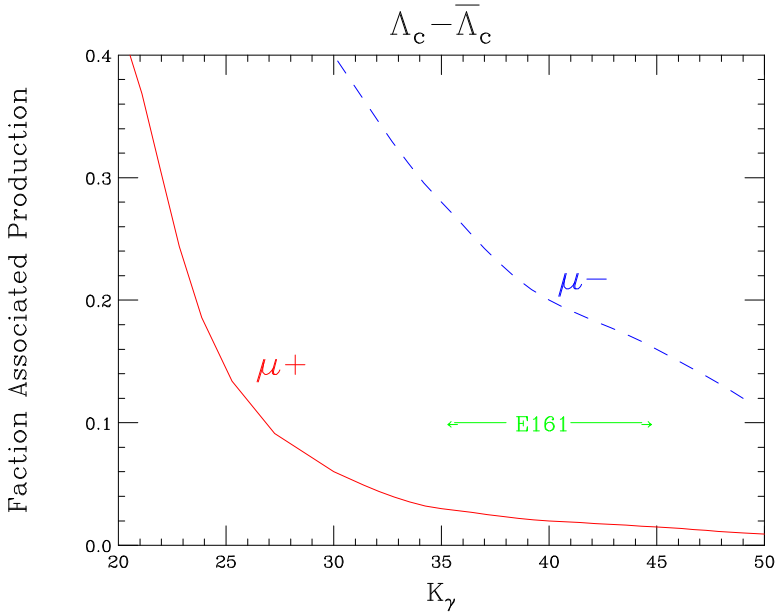
- Afanasev, Phys. Rev. D **61**(00)341014 (calculation); Anthony, Phys. Lett. **B458**(99)536 (data).
- Longitudinal helicity-dependent asymmetries $A_{\parallel}$ for polarized photoproduction of inclusive hadrons (open circles) and pions (solid circles) from a longitudinally polarized deuteron.

Associated Production



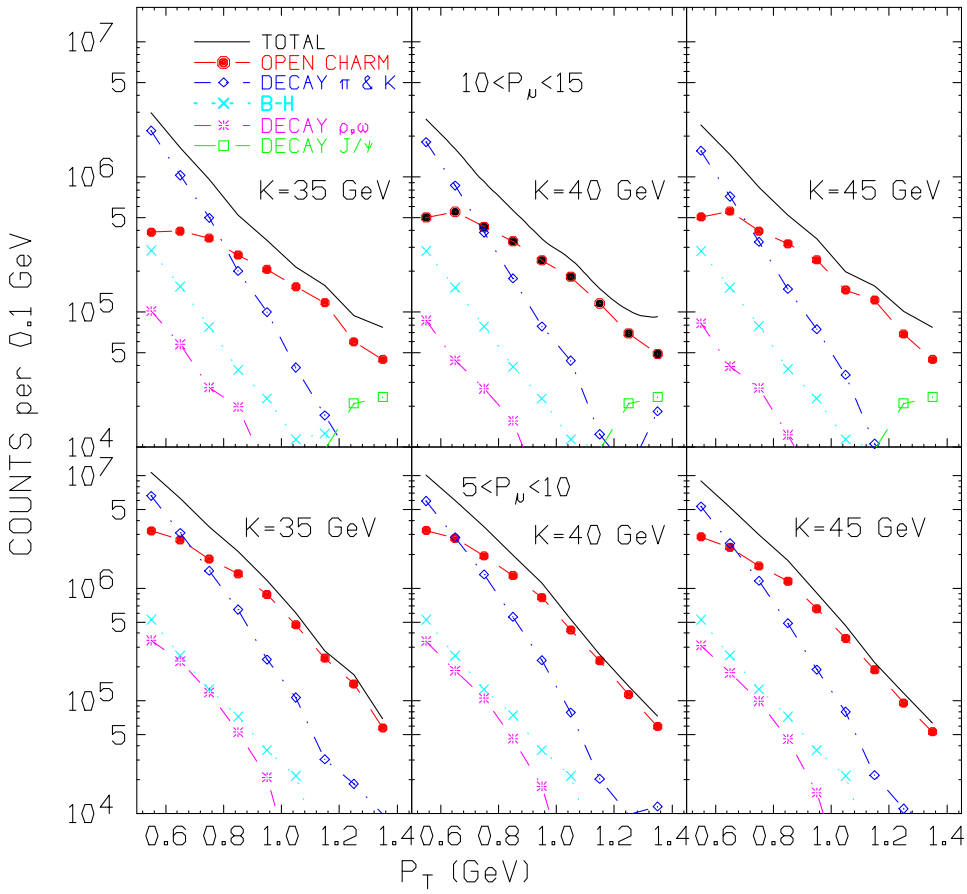
- For large photon energies the hadronization of $c\bar{c}$ from photon gluon fusion is isolated from target fragments.
- At E161 energies hadronization can include the coupling of charmed quarks with target remnants.
- Rates of producing $\Lambda_c = udc$ and $\bar{\Lambda}_c = \bar{u}\bar{d}\bar{c}$ differ, since Λ_c can be created from a ud diquark in the target.

Production and Decay of Λ_c



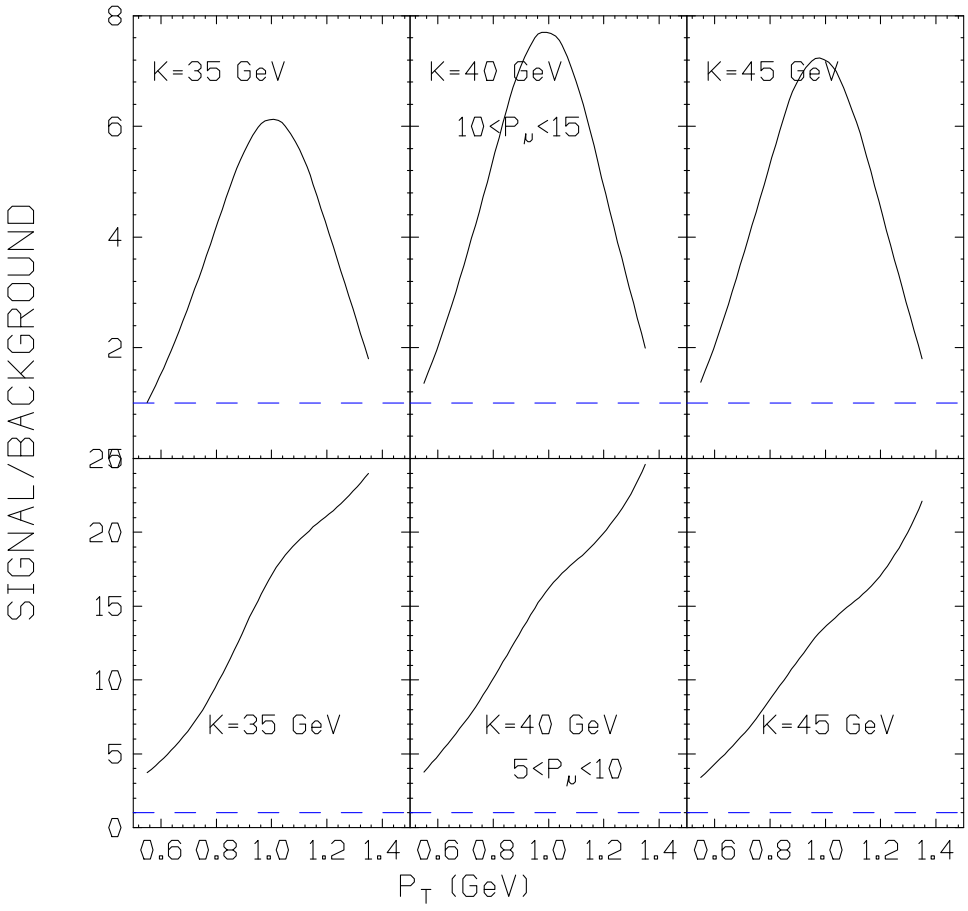
- Relative number of muons produced from the difference in rates of events with a Λ_c and a $\bar{\Lambda}_c$.
- Average of HERWIG 6.1 and PYTHIA 5.7 results.
- μ^+ from D (c) mesons (no Λ_c); μ^- from $\bar{D}$ ($\bar{c}$) mesons (with some Λ_c formation).
- Λ_c's spin comes from the c quark. Therefore, production isn't dependent on polarization of c, or polarization of target fragments.
- E161 will measure the differences in μ^+ and μ^- asymmetries to correct for any Λ_c contamination.

Expected Single-μ Events



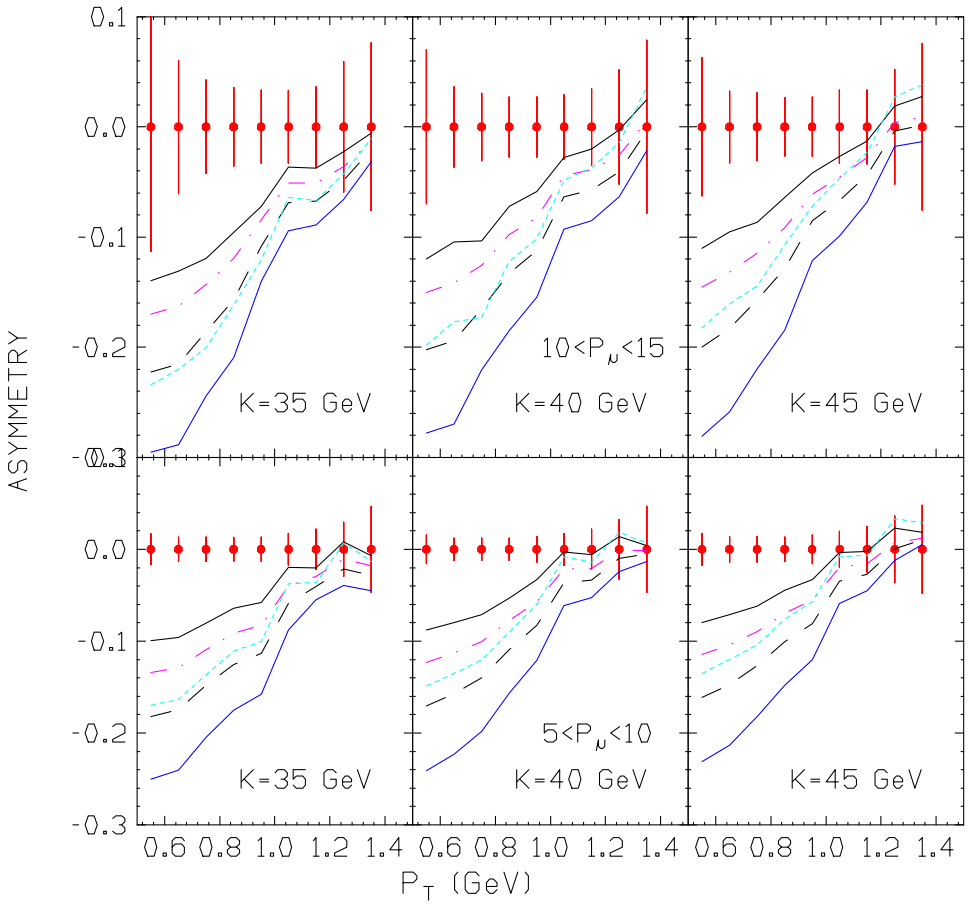
- Counts per 0.1 GeV versus p_T.
- Three beam energies, $k = 35, 40, 45$ GeV.
- Top row: $10 < p_\mu < 15$ GeV
  Bottom row: $5 < p_\mu < 10$ GeV
- Total events (solid line), open charm (solid dots), π and K decay (diamonds), Bethe-Heitler (crosses), J/ψ (squares), η, ρ, ω, ϕ decays (stars).

Signal to Background Ratios



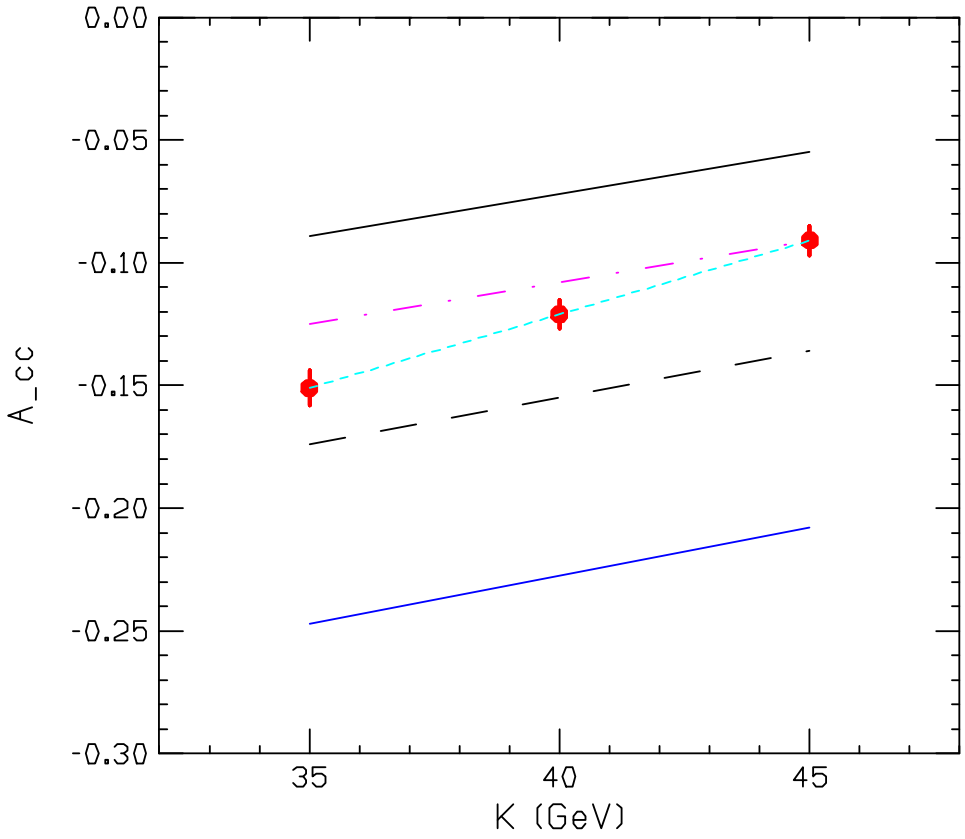
- Signal to background after subtraction of decay events
- Decay muons are enhanced when the spectrometer is run in background mode.

Expected Errors on Asymmetries



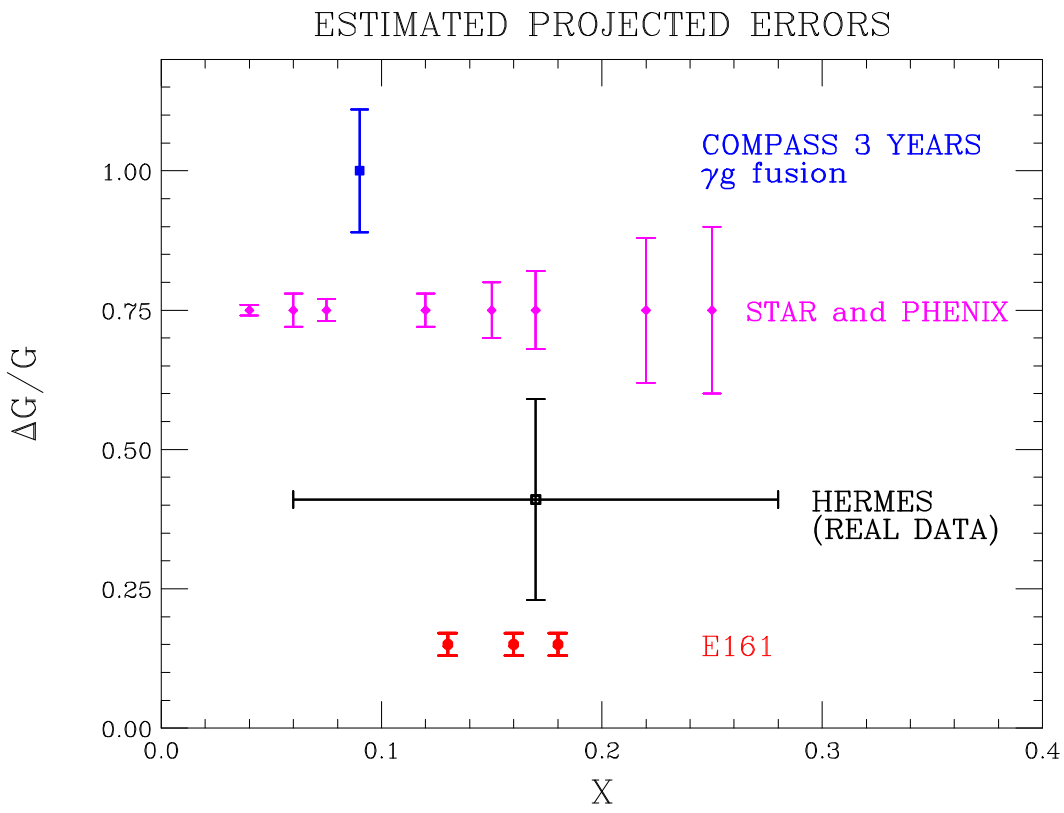
- Top row: $10 < p_\mu < 15$ GeV
  Bottom row: $5 < p_\mu < 10$ GeV
- Projected errors are statistical; systematic errors will be about 8% of measured asymmetries.
- Brodsky, Nucl. Phys. **B441**(95)197 (solid black); Gerhmann, Phys. Rev. D **53**(96)6100 (long-dash); Glück, Phys. Rev. D **53**(96)4775 (solid blue); Ball, Phys. Lett. **B378**(1996)255 (dash-dot, short-dash).

Expected Errors on Asymmetries Integrated over p_T



- Curves are the same as in previous plot.
- Magnitude of A_{cc} arbitrarily placed on dashed curve.

Comparison of Experiments



- Each data set is arbitrarily shifted on the y-axis
- All experiments complement each other in kinematic coverage and techniques used.

Status of Real Photon Experiments at SLAC

- 2000
  - 3 proposals using proposed polarized coherent bremsstrahlung facility approved by SLAC EPAC.
  - Fast-track schedule had experiments running in 2003, 2004, and 2005.
- 2001
  - Program delayed one year by SLAC management to finish Moller parity violation experiment
- 2002
  - Program delayed indefinitely due to budget crisis.
  - Collaboration asked to find construction and running costs from the funding agencies.
  - All engineering work stopped
- 2003
  - Collaboration is hoping for fiscal year 2005 funding
  - Collaboration needs the larger physics community to lobby for this project.

Conclusions

- Charm production provides an excellent tool for probing the nucleon polarized gluon distribution ΔG.
- Data from COMPASS, HERMES, RHIC and SLAC will greatly improve our knowledge of ΔG and our understanding of the nucleon's spin.