Real Compton Scattering from the Proton in the Hard Scattering Regime

Alan M. Nathan
a-nathan@uiuc.edu

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I. Compton Scattering from Nucleon at Large $p_\perp$

- Factorization schemes
- Relationship to GPD's

II. Results from JLab E99-114

- polarization transfer observables & cross sections
- form factors and GPD's

III. Summary & Outlook

Cross sections expected to factorize in hard scattering regime

- Hard scattering → $p_\perp$ large → $s, -t, -u >> m^2$
- Factorization:

$$\text{amplitude} \sim \text{hard} \otimes \text{soft}$$

calculable in pQCD

nonperturbative structure
process-independent

Factorization schemes based on how transferred momentum shared among constituents

- ERBL factorization:

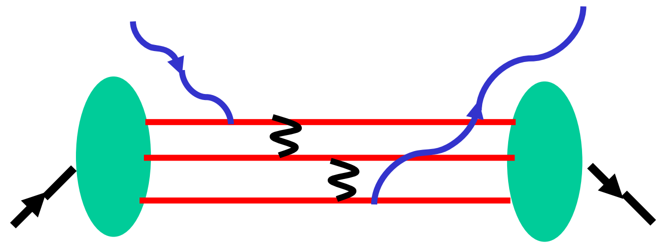
  *3 active quarks, 2 hard gluons

  * constituent scaling

  $d\sigma/dt = f(\theta_{CM})/s^6$

  *dominates at "sufficiently high energy"

  --but grossly underpredicts at few GeV

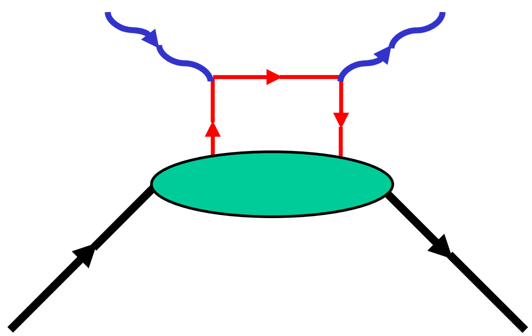


- handbag factorization:

  *1 active quark, 0 hard gluons

  * overlap of soft wave function (GPD)

  * probably dominates at few GeV

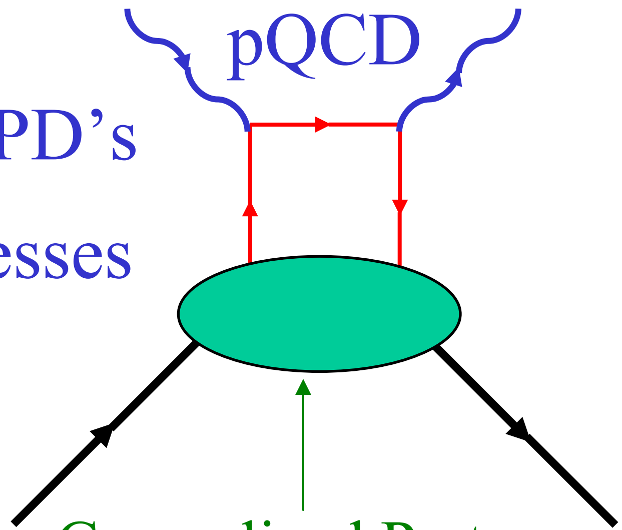


Handbag mechanism probably dominates at few-GeV energies (Radyushkin, Kroll&Diehl, Miller)

- One active parton—rest are spectators
- Hard process $\gamma q \rightarrow \gamma q$
- Soft physics in process-independent GPD's
- Complementary to deeply virtual processes

  DV: $-t/Q^2 << 1$

  wide angle RCS: $Q^2/(-t) << 1$



- Central assumptions:

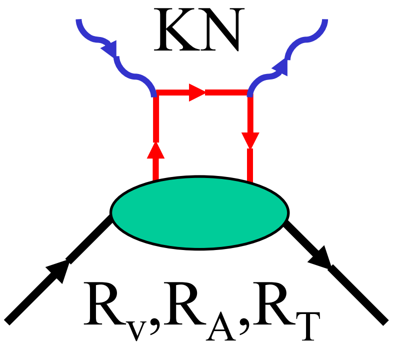
  -- $s, -t, -u >> m^2$

  -- struck quark nearly real and co-linear with proton

- Formally power correction to leading-twist

  -- asymptotically subdominant but ...

Handbag Description of RCS



Various approximations improve as s,-t,-u >> M^2

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{KN} \left[f_V R_V^2(t) + f_A R_A^2(t) \right]$$

- Scaled by Klein-Nishina (KN) from parton
- Structure contained in new form factors $R_V(t)$, $R_A(t)$

$|R_V +/- R_A|^2$:

active quark spin parallel/antiparallel to proton spin

- Kinematic factor $f_V >> f_A \Rightarrow$ cross sections mainly sensitive to R_V
- Robust prediction: σ/σ_{KN} ~ s-independent at fixed t
- Corrections due to R_T, gluons, masses …

See Kroll, hep-ph/0110208

RCS and Form Factors: GPD's

Generalized Parton Distributions (GPD's) links among diverse processes

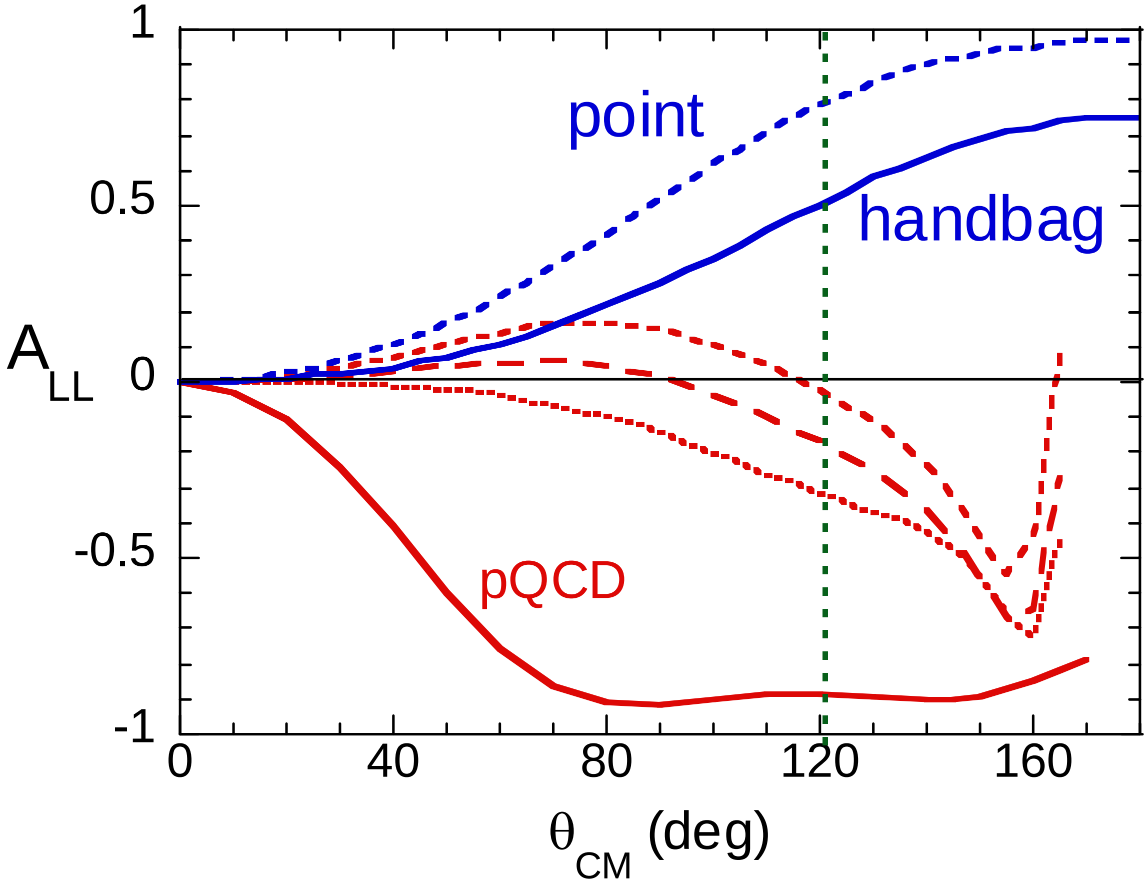
$$
\begin{cases}
R_V(t) = \sum_a e_a^2 \int H_a(x, \zeta = 0, t) \frac{dx}{x} \\
F_1(t) = \sum_a e_a \int H_a(x, \zeta = 0, t)\, dx \\
q_a(x) = H_a(x, \zeta = 0, 0)
\end{cases}
$$

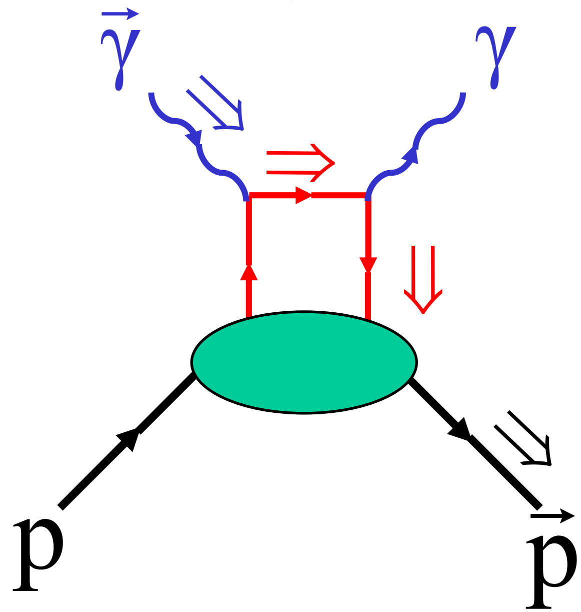
GPD	x^{-1} moment	x^0 moment	t=0 limit
$H(x, \zeta=0, t)$	$R_V(t)$	$F_1(t)$	q(x)
$\tilde{H}(x, \zeta=0, t)$	$R_A(t)$	$G_A(t)$	$\Delta q(x)$
$E(x, \zeta=0, t)$	$R_T(t)$	$F_2(t)$	2J(x)/x - q(x)

RCS sensitive to unskewed (ζ=0) GPD's at high –t, moderate x

Polarization observables can test reaction model, constrain form factors

$$K_{LL} \approx A_{LL} = \frac{\uparrow\uparrow - \downarrow\uparrow}{\uparrow\uparrow + \downarrow\uparrow} \approx A_{LL}^{point} \frac{R_A}{R_V}$$





- Robust prediction: depends only on ratio of form factors
- ERBL prediction very different

JLab E99-114: A new RCS experiment

theses: A. Danagoulian, D. Hamilton, V. Mamyan

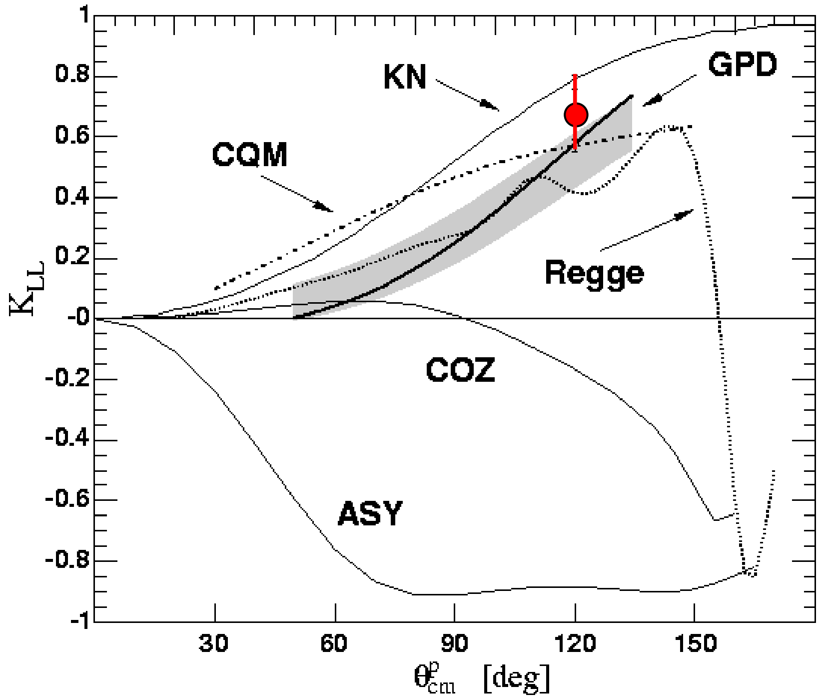
- Measure cross sections of broad kinematic range:

  $5\ GeV^2 < s < 11\ GeV^2 \qquad -t < 7\ GeV^2$

  * PRL **98**, **98**, 1520011—1520015 (2007)
- Measure polarization transfer at $t=-4\ GeV^2$
  * PRL **94**, 242001-242005 (2005)
- Test handbag model
  * s-independence of σ/σ_{KN} @ fixed t
  * K_{LL} close to 1
  * Extract R_V form factor and use to constrain model for H GPD

K_{LL} measurement consistent with handbag dominance of RCS cross section

$t = -4.03\ (\text{Gev/c})^2$



$$K_{LL} \approx A_{LL} = \frac{\uparrow\uparrow - \downarrow\uparrow}{\uparrow\uparrow + \downarrow\uparrow}$$

$$\approx A_{LL}^{point} \frac{R_A}{R_V}$$

Conclusions:

--Handbag diagram dominates, not ERBL

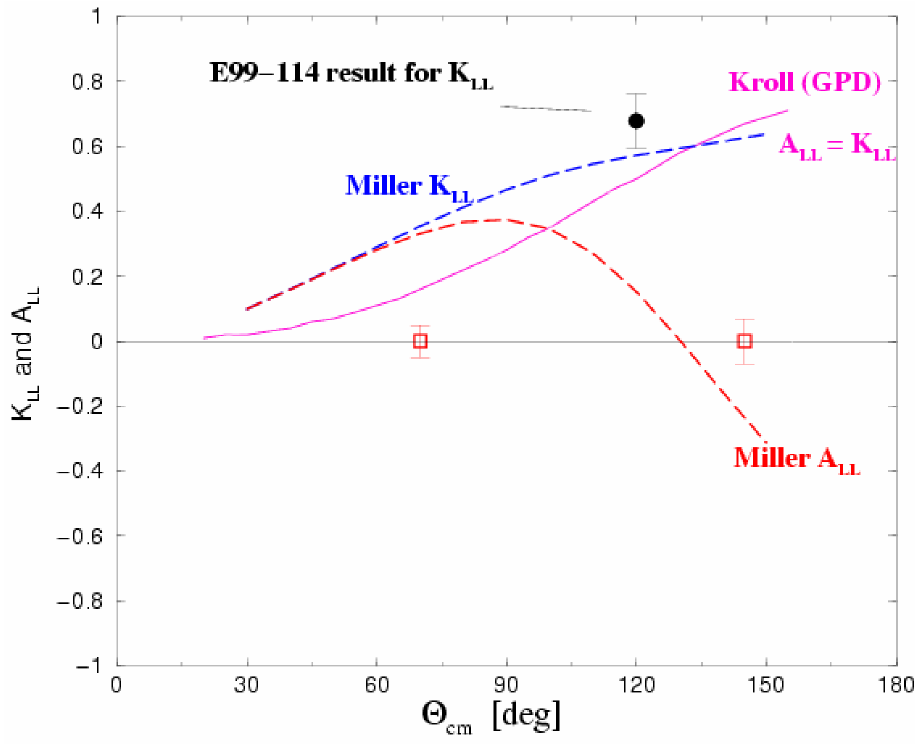
--$R_A(t) / R_V(t) = 0.8 \pm 0.1$

=> struck quark carries proton spin

K_{LL} and A_{LL} can be different for constituent quarks

New experiment approved @ JLab

* E05-01, Hall C
* Day and Wojtsekhowski
* Measure A_{LL} @ s=9, -t=6.4



K_{LT} measurement not precise enough to test models

$$K_{LT} \approx \frac{\uparrow\rightarrow - \downarrow\rightarrow}{\uparrow\rightarrow + \downarrow\rightarrow} \qquad \frac{K_{LT}}{K_{LL}} \approx \frac{\sqrt{-t}}{2M}\frac{R_T}{R_V} \approx \frac{\sqrt{-t}}{2M}\frac{F_2}{F_1}$$

- R_T : hadron helicity flip
- pQCD:

  $-t\, F_2/F_1 \sim$ constant
- JLab G_{Ep} expt:

  $-t^{1/2} F_2/F_1 \sim$ constant
- Does R_T/R_V behave similarly?

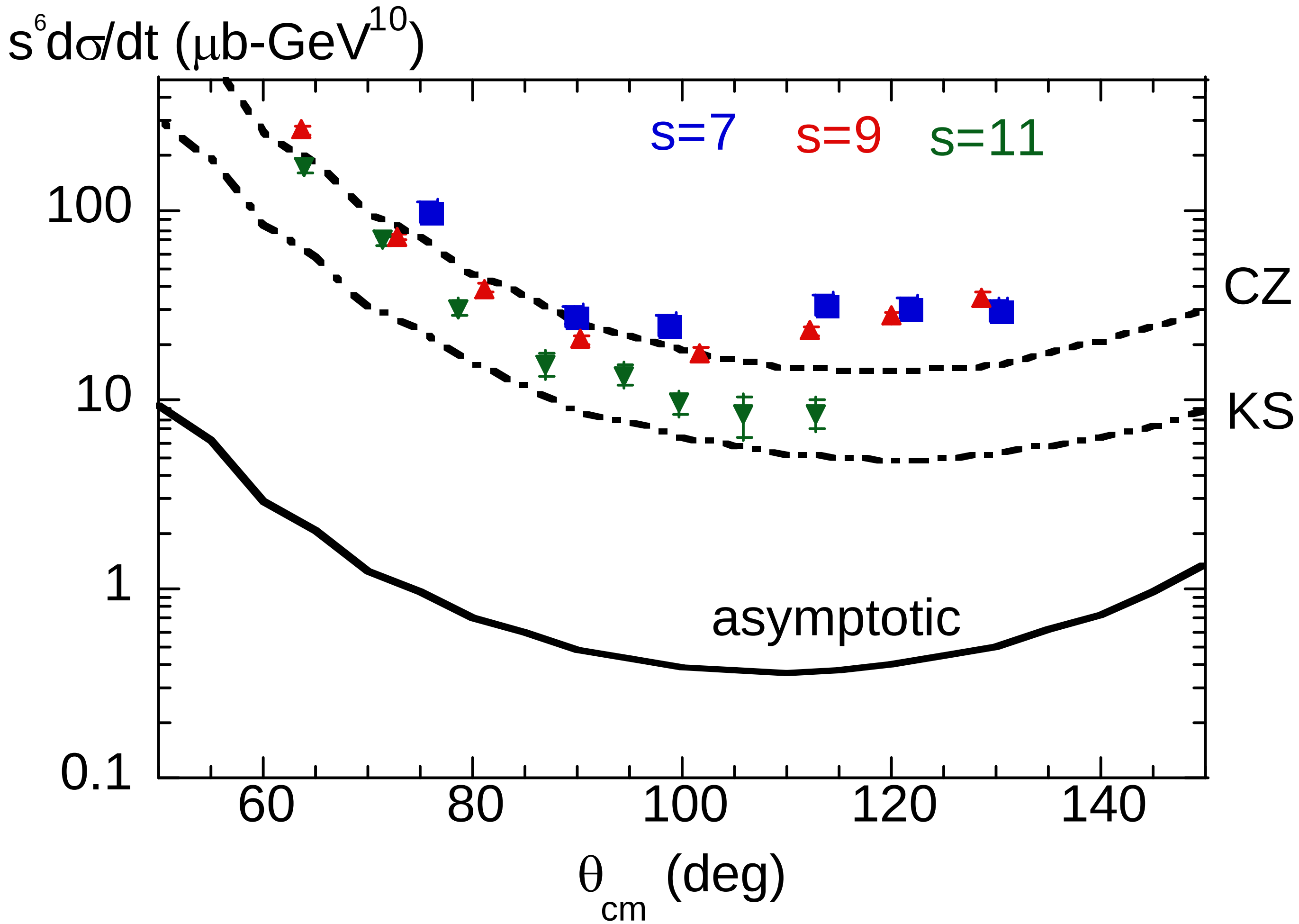
experimental result:

$$\frac{K_{LT}}{K_{LL}} = 0.21 \pm 0.15$$

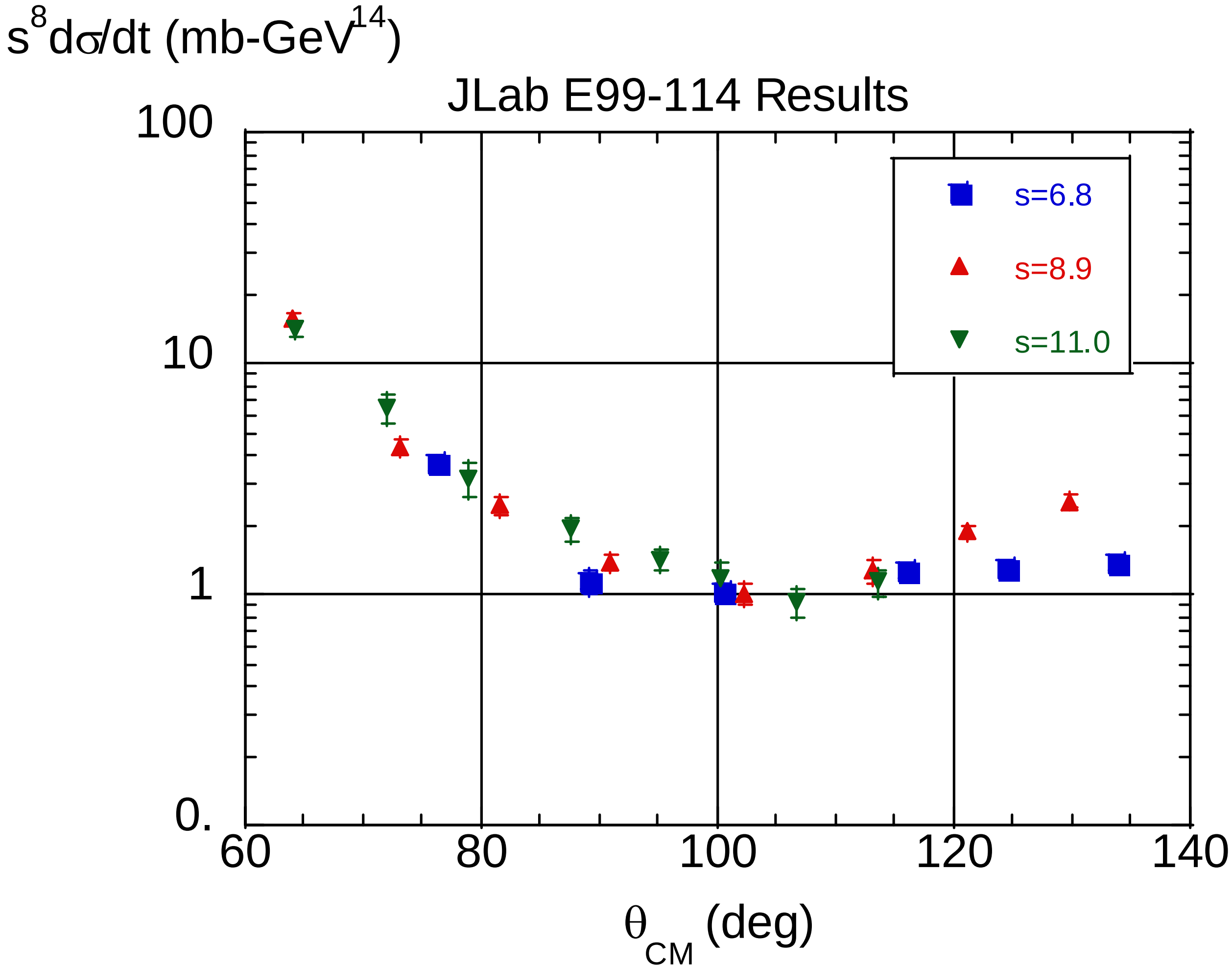
$\Rightarrow R_T/R_V \approx (0.5 \pm 0.4)\, F_2/F_1$

No strong conclusions

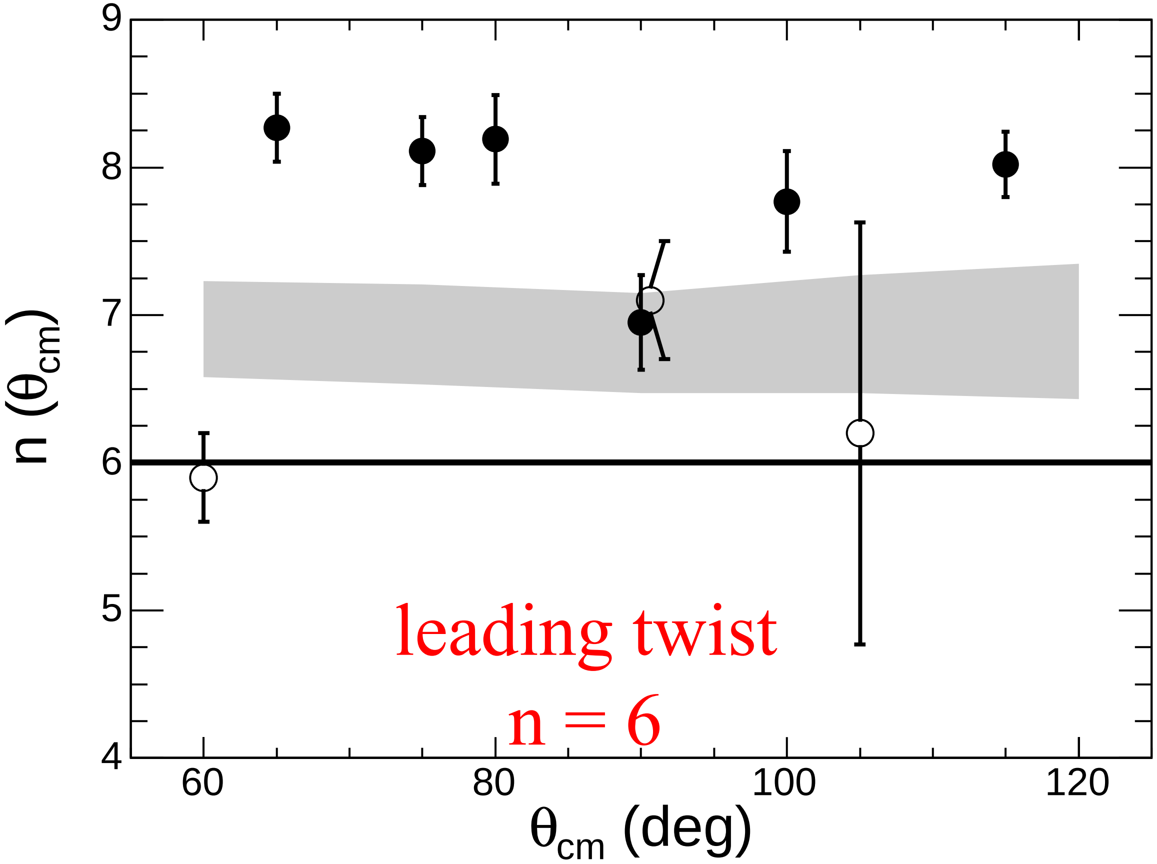
- Leading twist badly underestimates E99-114 cross sections.
- s^{-6} scaling at fixed θ_{CM} works poorly



s^{-8} scaling at fixed θ_{CM} works much better



Cross sections consistent with s^{-8} scaling

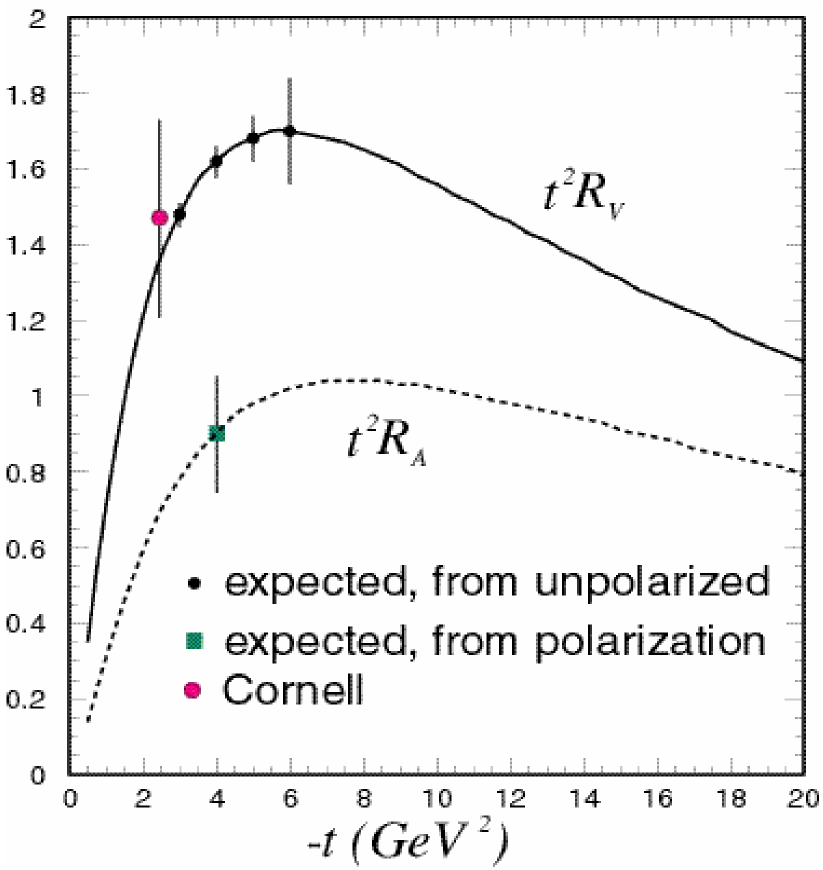


Handbag:
$n \approx 7$ for s=6-11 GeV

- scaling inconsistent with leading twist pQCD prediction
  - can't be fixed with different DA

- in handbag diagram, scaling is a local property of the form factor R_V
  - not fundamental to the theory

Unpolarized Cross Sections: Handbag vs. pQCD



- $d\sigma/dt \sim R_V^2/s^2$
- $R_V \sim 1/t^2$ for $-t = 3\text{-}10$ GeV^2

  $\Rightarrow n \approx 6$ scaling

  (accidental!)

- Asymptotically $R_V \sim 1/t^4$

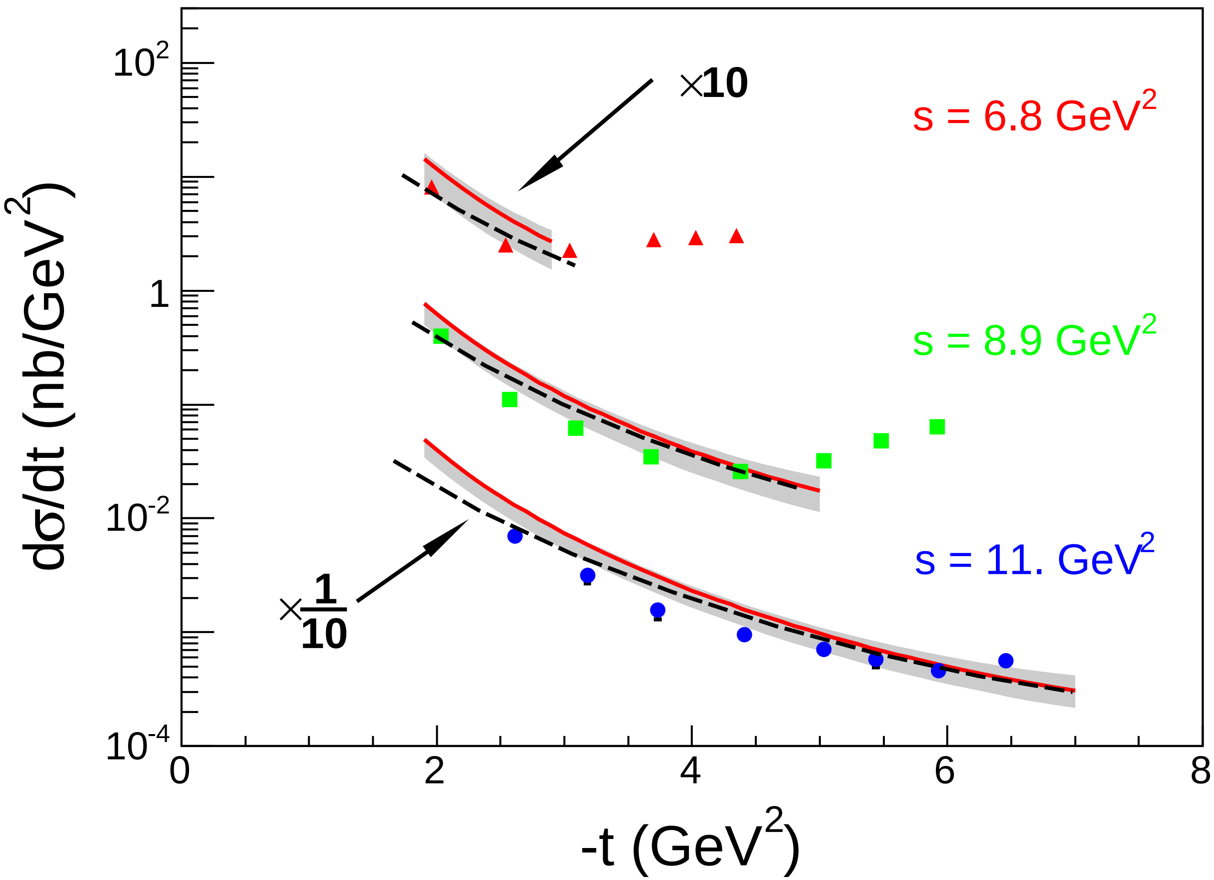
  $\Rightarrow n \approx 10$ scaling

  $\Rightarrow$ ultimately subdominant

  (when?)

Thanks to P. Kroll and M. Diehl for this argument

Handbag diagram gets E99-114 cross sections about right, except for far backward angles.



Dashed: CQM (J. Miller)

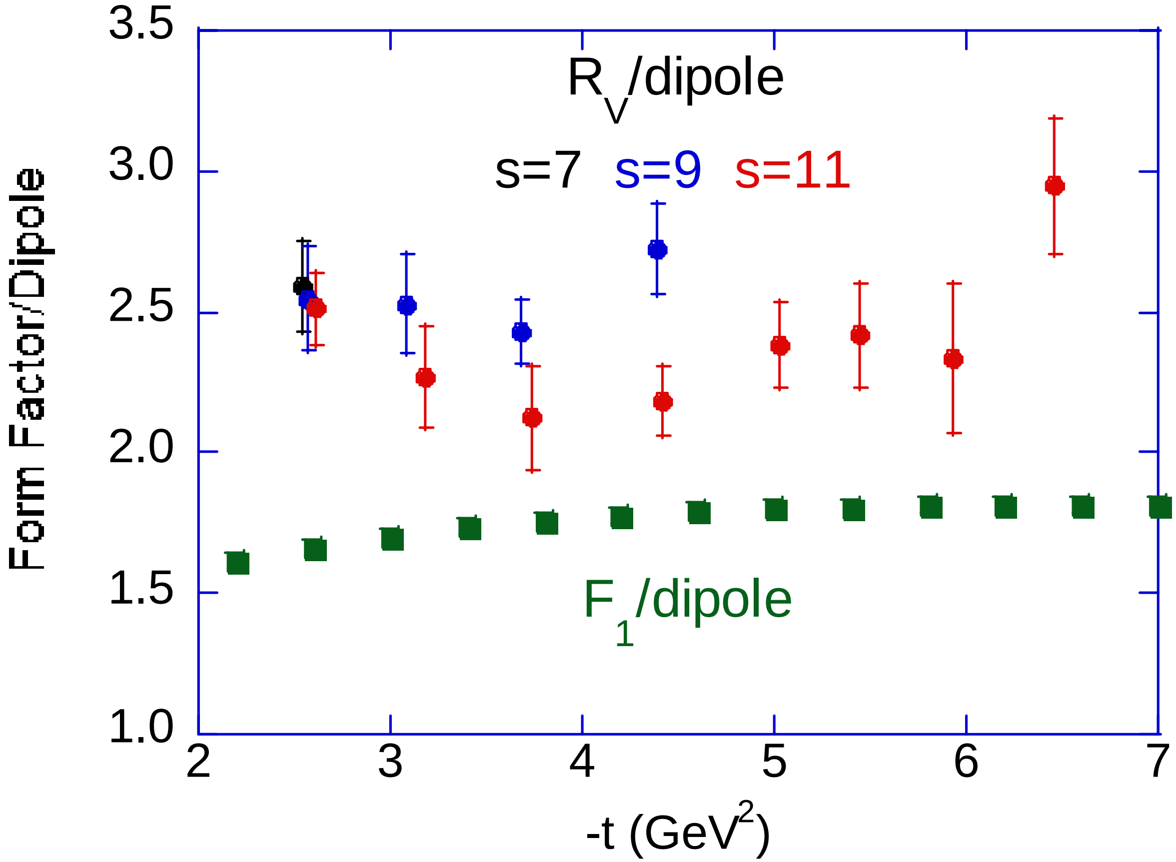
Bands: GPD (P. Kroll)

Extracting $R_V(t)$ from RCS cross sections

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{KN} \left[f_V R_V^2(t) + f_A R_A^2(t) \right]$$

- Use NLO pQCD to calculate KN, f_V, f_A
- Use K_{LL} @ $-t=4$ GeV^2 to get R_A/R_V (~0.8)
- Only use data with s,-t,-u>2.5 GeV^2

Results obtained for $R_V(t)$:



- R_V ~ independent of s at fixed t (s,-t,-u>2.5 GeV^2)
- R_V follows dipole for 2.5<-t_6.5
- $F_1/R_V \approx 0.75 \Rightarrow \langle x \rangle \approx 0.5$ if u dominates

Is there a GPD that explains both F_1 and R_V?

$$R_V(t) = \sum_a e_a^2 \int H_a(x, \zeta = 0, t) \frac{dx}{x}$$

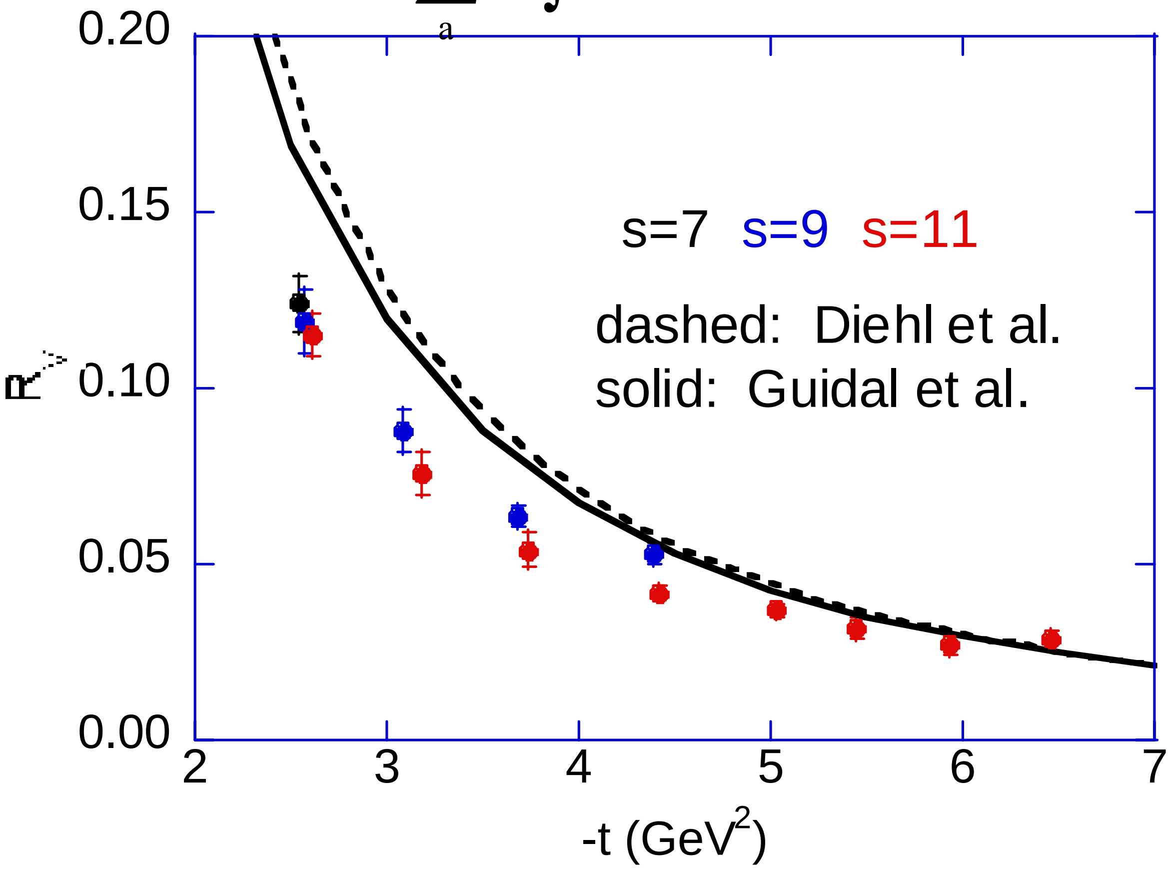
$$F_1(t) = \sum_a e_a \int H_a(x, \zeta = 0, t)\, dx$$

- Separable model: $H_a(x,0,t)=q_a(x)\exp[tf_a(x)]$
- $q_a(x)$ from various PDF parametrizations
- Diehl et al.:
  - $f_a(x) = \alpha(1-x)^3\ln(1/x)+B_a(1-x)^3+A_a(1-x)^2$
- Guidal et al.:
  - $f_a(x) = -\alpha_a(1-x)\ln(x)$
- Adjust parameters to fit F_{1p}, F_{1n}

Conclusion: R_V drops less rapidly than predicted by model for GPD based on F_1—but not by a lot….

$$R_V(t) = \sum_a e_a^2 \int H_a(x, \zeta = 0, t) \frac{dx}{x}$$

$$F_1(t) = \sum_a e_a \int H_a(x, \zeta = 0, t)\, dx$$



Summary and Conclusions

- E99-114 confirms that
  handbag dominates at JLab energies
  - K_{LL}
  - Cross sections about right magnitude
  - s-independence of σ/σ_{KN} @ fixed t
- K_{LL} close to 1 => struck quark carries p spin
- Scaling parameter $n \approx 8$
  - Not 6
- First measurement of new form factor R_V
- Model of GPD can (almost) describe both F_1 and R_V
  - Lends credence to concept of GPD
  - Fine tuning in progress