Wide Angle Compton Scattering within the QCD factorization approach

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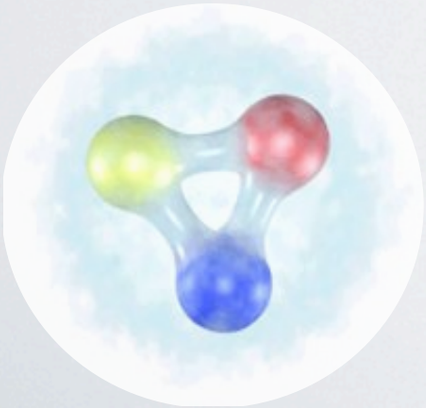
Outline

- Hard Exclusive processes in JLAB and challenges to theory
- Hard and soft-overlap contributions: phenomenology
- Soft-overlap contribution within the SCET framework
- Complete factorization formula for the WACS amplitudes
- WACS phenomenology
- Conclusions



Hard exclusive processes at JLAB

QCD allows to predict the scaling behavior $1/Q^a$

Hadronic Form Factors

$F^N_{1,2}(Q^2)$ nucleon

$F_\pi(Q^2)$ pion

Wide Angle Scattering

WACS $\gamma p \to \gamma p$

WAMP $\gamma p \to (\pi, \rho, ...)p$

Deeply virtual scattering

DVMP $\gamma^* p \to (\pi, \rho, ...)p$

DVCS $\gamma^* p \to \gamma p$

hadronic w.f. or Distribution Amplitudes

3D partonic structure: GPDs

Hard exclusive processes: theory

QCD Factorization

if QCD factorization holds then one can compute systematically logarithmic corrections improving the description
(systematic approach, model independent analysis)

Problems

- collinear factorization does not work for helicity flip amplitudes

$$F_2^N(Q^2) \qquad \gamma_\perp^* p \to (\pi, \rho, \ldots)p \quad \Rightarrow \quad F_2/F_1 \qquad \sigma_T/\sigma_L$$

"difficult" observables

- asymptotic results applicable for a very-very-very LARGE Q^2

especially critical for small leading-order amplitudes $\sim \alpha_s(Q^2)$

$$F_\pi(Q^2) \sim \alpha_s(Q^2)/Q^2$$

$$\gamma_L^* p \to (\pi, \rho, \ldots)p$$

$$F_1(Q^2) \sim \alpha_s^2(Q^2)/Q^4$$

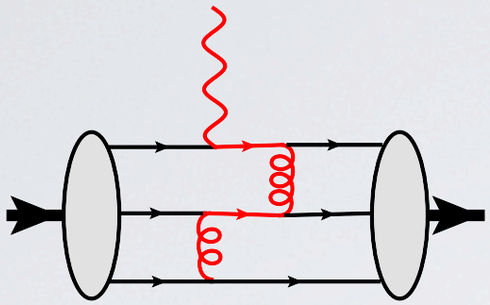
$$\gamma p \to \gamma p$$

$$\gamma p \to (\pi, \rho, \ldots)p$$

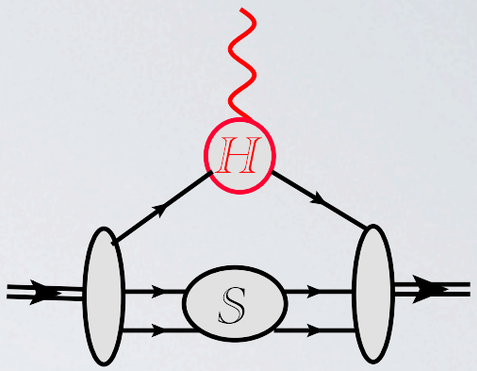
Hard exclusive processes: theory

Challenge for the all above processes is soft-overlap mechanism

hard-spectator scattering



Soft-spectator scattering



Can soft-overlap mechanism provide the large contribution? How it behaves with respect to Q^2 ?

Phenomenology

- Large numerical effect for moderate values of Q
- Soft-overlap contribution is subleading in $1/Q^2$

LC wave functions

Isgur, Smith 1984

QCD sum rules

Nesterenko, Radyushkin 1982,83

Braun et al, 2000, '02, '06, '13

GPD or handbag-model

Radyushkin 1998

Kroll et al, 2002, '05, '10

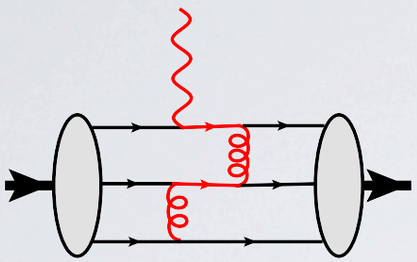
WACS/annihilation

$\gamma p \to \gamma p \quad \gamma\gamma \to p\bar{p}$

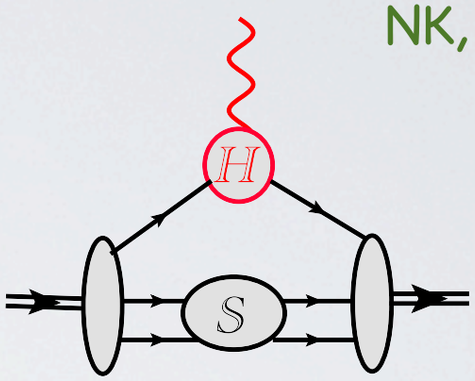
FF F_1 at large-Q^2 hard and soft spectator contributions

Nucleon FF F_1 Chernyak, Zhitnitsky 1977
Brodsky, Lepage 1979

Duncan, Mueller 1980
Fadin, Milshtein 1981,82
NK, Vanderhaeghen 2010
NK, 2012



$\sim \Lambda^4/Q^4$



$\sim \Lambda^4/Q^4$

hard- and soft-spectator contributions have the same power

large rapidity log's from the soft-collinear overlap

- this estimates are also true for WACS amplitudes

☛ Soft spectator scattering is especially important in processes with baryons

Can one "observe" and to study the soft-overlap mechanism?

☛ The best opportunity is provided by WACS

Hard exclusive processes: theory

Conclusion

One must understand better the role of the soft-overlap mechanism

Questions

Can we extend the collinear factorization framework and to develop a description of the configurations with the soft & collinear modes? (systematic approach)

Can we obtain a reliable theoretical description which has predictive power?

Opportunity

Use the Soft Collinear Effective Theory framework ...

Soft Collinear Effective Theory

description of the soft-overlap contribution involves 3 different scales

$p = (p_+, p_\perp, p_-)$ QCD

$p_h \sim (Q, Q, Q)$ hard $\qquad p_h^2 \sim Q^2 \sim \mu_h^2$

$p_{hc} \sim (Q, \sqrt{\Lambda Q}, \Lambda)$ hard-collinear $\qquad p_{hc}^2 \sim Q\Lambda \sim \mu_{hc}^2$

$p_c \sim (Q, \Lambda, \Lambda^2/Q)$ collinear

$p_c^2 \sim p_s^2 \sim \Lambda^2 \sim \mu_s^2$

$p_s \sim (\Lambda, \Lambda, \Lambda)$ soft

Amplitude $\quad F(\mu_h^2 \sim Q^2,\ \mu_{hc}^2 \sim Q\Lambda,\ \mu_s^2 \sim \Lambda^2)$

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Soft Collinear Effective Theory

description of a hard contribution involves only 2 scales

$p = (p_+, p_\perp, p_-)$ QCD

$p_h \sim (Q, Q, Q)$ hard $\qquad p_h^2 \sim Q^2 \sim \mu_h^2$

~~$p_{hc} \sim (Q, \sqrt{\Lambda Q}, \Lambda)$ hard-collinear $\qquad p_{hc}^2 \sim Q\Lambda \sim \mu_{hc}^2$~~

$p_c \sim (Q, \Lambda, \Lambda^2/Q)$ collinear $\qquad p_c^2 \sim \cancel{p_s^2} \sim \Lambda^2 \sim \mu_s^2$

~~$p_s \sim (\Lambda, \Lambda, \Lambda)$ soft~~

Amplitude $\qquad F(\mu_h^2 \sim Q^2, \cancel{\mu_{hc}^2 \sim Q\Lambda}, \mu_s^2 \sim \Lambda^2)$

Soft spectator scattering in the SCET framework

description of the soft spectator contribution involves 3 different scales

1. Factorize of the hard modes: $p_h^2 \sim Q^2 \gg \Lambda^2$ (hard subprocess)

QCD → SCET-I $\quad F^{(s)}(Q^2, Q\Lambda, \Lambda^2) \simeq H(Q^2) * f(Q\Lambda, \Lambda^2)$

$$f(Q\Lambda, \Lambda^2) = \langle out|O|in\rangle_{\rm SCET}$$

well defined in field theory

☛ moderate values of Q^2 :

$Q\Lambda \sim m_N^2$ hard-collinear scale is not large

$Q^2 = 4 - 25\mathrm{GeV}^2$

$\Lambda \simeq 0.3\mathrm{GeV}$

→ $Q\Lambda \simeq 0.6 - 1.5\mathrm{GeV}^2$

Soft spectator scattering in the SCET framework

description of the soft spectator contribution involves 3 different scales

2. Factorization of hard-collinear modes $p_{hc}^2 \sim Q\Lambda \gg m_N^2$

SCET-I $\longrightarrow$ SCET-II = collinear + soft

$$f(Q\Lambda, \Lambda^2) \simeq J_{hc}(Q\Lambda) * S[p_s] * \phi_N[p_c]$$

hard-collinear
subprocess

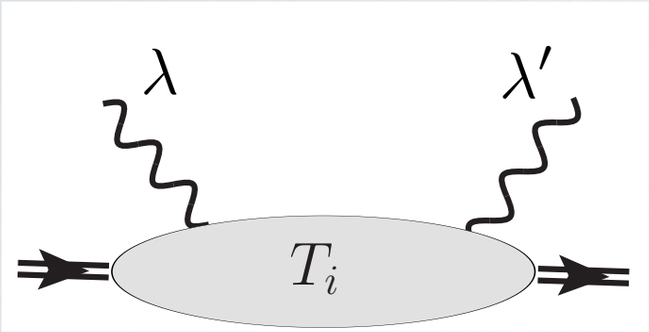
- provides an estimate of power of 1/Q at large Q
- allows one to establish the overlap between the hard- and soft-spectator contributions

Wide Angle Compton Scattering in SL region

$$s \sim -t \sim -u \sim Q \gg \Lambda^2$$

WACS amplitude is described by 6 independent scalar amplitudes:

Babusci et al, 1998



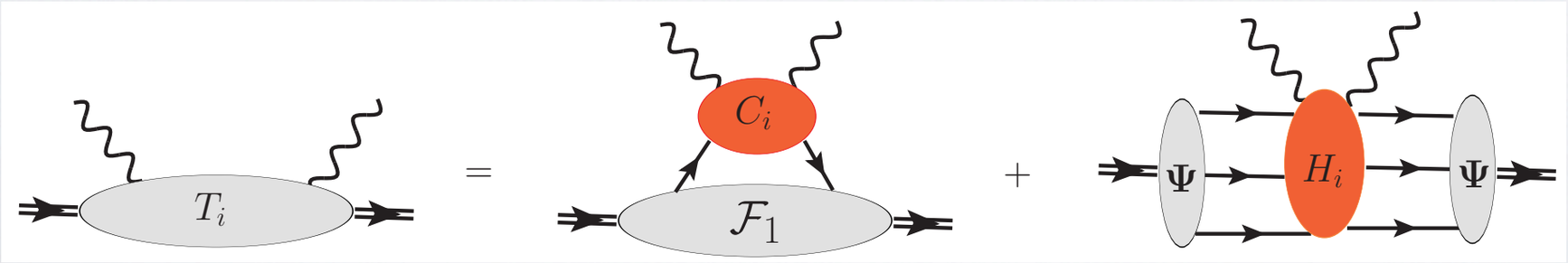
$T_{2,4,6} \Leftrightarrow M^{\lambda,\lambda'}_{h,h}$ helicity conserving

$T_{1,3,5} \Leftrightarrow M^{\lambda,\lambda'}_{h,-h}$ helicity flip

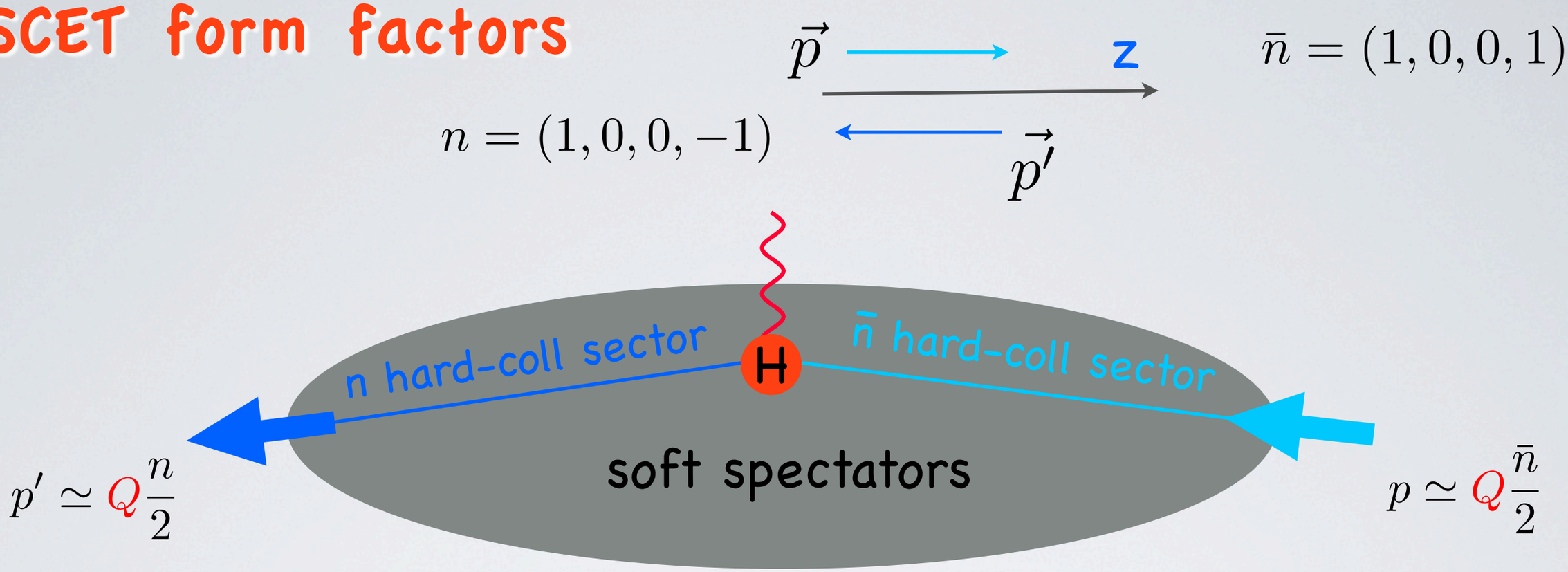
$Q \to \infty$ $\quad T_{2,4,6} \sim 1/Q^4 \quad T_{1,3,5} \sim 1/Q^5$

NK, Vanderhaeghen 2012, 2013(in preparation)

$$T_i(s,t) = C_i(s,t)\,\mathcal{F}_1(t) + \mathbf{\Psi} * H_i(s,t) * \mathbf{\Psi} \qquad i = 2,4,6$$



SCET form factors



$$\langle p'|\bar{\chi}_n\gamma_\perp\chi_{\bar{n}} - \bar{\chi}_{\bar{n}}\gamma_\perp\chi_n|p\rangle_{SCET} = \bar{N}(p')\frac{1}{4}\not{\bar{n}}\not{n}\gamma_\perp N(p)\,\mathcal{F}_1(t)$$

quark "jets" $\quad \chi_n = \mathrm{P}\exp\left\{ig\int_{-\infty}^{0} ds\,\bar{n}\cdot A_{hc}^{(n)}(s\bar{n})\right\}\frac{1}{4}\not{n}\not{\bar{n}}\,\psi_{hc}(0)$

NOT GPDs defined in the one collinear sector: $\quad \bar{\chi}_n(0)\,\not{\bar{n}}\,\chi_n(\lambda\bar{n})$

WACS phenomenology

$$s \sim -t \sim -u \sim Q \gg \Lambda^2$$

NK, M. Vanderhaeghen 2012, 2013(to appear)

$$T_i(s,t) = C_i(s,t)\,\mathcal{F}_1(t) + \mathbf{\Psi} * H_i(s,t) * \mathbf{\Psi} \qquad i = 2,4,6$$

$$T_i(s,t) \approx 0 \quad i = 1,3,5$$

$\mathcal{F}_1(t)$, $\mathbf{\Psi}$ unknown nonperturbative functions

$$C_i(s,t) \sim \mathcal{O}(1) \quad H_i(s,t) \sim \mathcal{O}(\alpha_s^2)$$

$$T_i(s,t) = C_i(s,t)\,\mathcal{F}_1(t) + \mathbf{\Psi} * H_i(s,t) * \mathbf{\Psi}$$

regular = singular + singular

$\Longrightarrow$ each term must be regularized NK, 2012

WACS phenomenology

use the following features:

universality: one SCET FF $\mathcal{F}_1$ defines the all three amplitudes

$\mathcal{F}_1(t)$ does not depend on s

$$T_2(s,t) = C_2(s,t)\,\mathcal{F}_1(t) + \mathbf{\Psi} * H_2(s,t) * \mathbf{\Psi}$$ using the simple structure

$$\Rightarrow \quad \mathcal{F}_1(t) = \mathcal{R}(s,t) - \mathbf{\Psi} * H_2(s,t) * \mathbf{\Psi}/C_2(s,t)$$

regular ratio $$\mathcal{R}(s,t) = \frac{T_2(s,t)}{C_2(s,t)}$$ $\mu_F^2 = -t$

$$T_2(s,t) = C_2(s,t)\mathcal{R}(s,t)$$

$$T_i(s',t) = C_i(s',t)\mathcal{R}(s,t) + \mathbf{\Psi} * \left\{ H_i(s',t) - C_i(s',t)\frac{H_2(s,t)}{C_2(s,t)} \right\} * \mathbf{\Psi}$$

$i = 4, 6$

$s' \neq s!$

regular = regular + regular each term is regular!

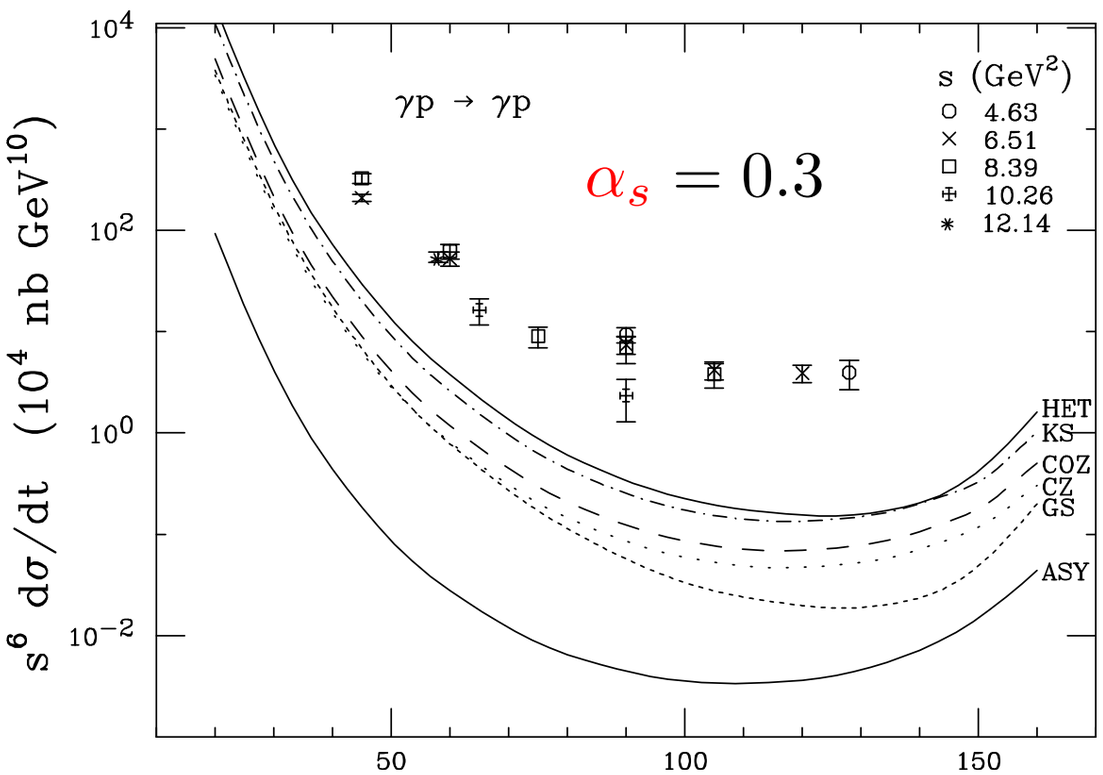
WACS phenomenology

$$T_2(s,t) = C_2(s,t)\mathcal{R}(s,t)$$

$$T_i(s',t) = C_i(s',t)\mathcal{R}(s,t) + \mathbf{\Psi} * \left\{ H_i(s',t) - C_i(s',t)\frac{H_2(s,t)}{C_2(s,t)} \right\} * \mathbf{\Psi}$$

$H_i(s,t) \sim \mathcal{O}(\alpha_s^2)$ $C_i(s,t) \sim \mathcal{O}(1)$ $C_2^{\rm LO} = -C_4^{\rm LO} = \frac{s-u}{su}$ $C_6^{\rm LO} = \frac{t}{su}$ m=0

Brooks, Dixon, 2000



The hard-spectator contribution predicts the cross section at least an order of magnitude below the data

Vanderhaeghen et al, 1997
Brooks, Dixon, 2000,
Thomson et al, 2006

WACS phenomenology

$$T_2(s,t) = C_2(s,t)\mathcal{R}(s,t)$$

$$T_i(s',t) = C_i(s',t)\mathcal{R}(s,t) + \cancel{\Psi * \left\{ H_i(s',t) - C_i(s',t)\frac{H_2(s,t)}{C_2(s,t)} \right\} * \Psi}$$

Assume that the hard-spectator corrections are small

$$\Rightarrow \quad \mathcal{R}(s,t) = \frac{T_2(s,t)}{C_2(s,t)} \approx \mathcal{R}(t)$$

dominates by the soft-spectator contribution

this can be checked experimentally

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

m=0

To the leading order accuracy $\quad C_i = C_i^{\rm LO} + \frac{\alpha_s}{4\pi}C_F\, C_i^{\rm NLO} + \ldots$

$$\frac{d\sigma}{dt} \simeq \frac{2\pi\alpha^2}{s^2}\,|\mathcal{R}(s,t)|^2\left(\frac{s}{-u} + \frac{-u}{s}\right)\Bigg|_{m=0} = \frac{d\sigma_0^{\rm KN}}{dt}|\mathcal{R}(s,t)|^2$$

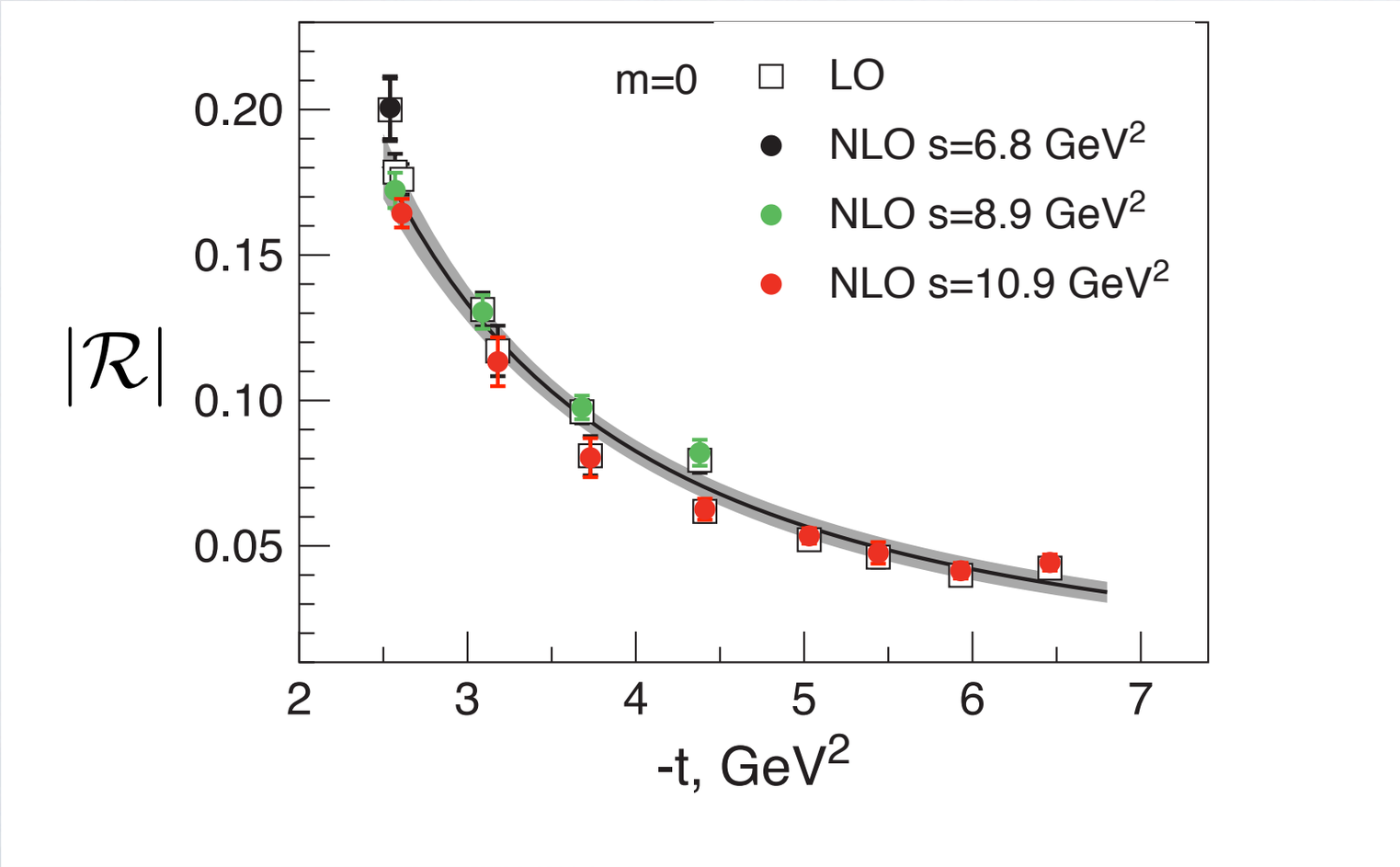
WACS phenomenology

with NLO corrections

$$|\mathcal{R}(s,t)| \approx \sqrt{\frac{d\sigma^{\rm exp}/dt}{d\sigma_0^{\rm KN}/dt}}\left(1-\frac{1}{2}\frac{\alpha_s}{4\pi}C_F\frac{C_2^{\rm LO}{\rm Re}\left[C_2^{\rm NLO}-C_4^{\rm NLO}\right]+C_6^{\rm LO}{\rm Re}\left[C_6^{\rm NLO}\right]}{|C_2^{\rm LO}|^2+|C_6^{\rm LO}|^2}\right)$$

NK, Vanderhaeghen 2013 (in preparation)

used data: JLab/Hall-A, 2007



all power corrections m/Q are neglected

empirical fit:

$$|\mathcal{R}(s,t)| = \left(\frac{\Lambda^2}{-t}\right)^{\alpha}$$

$$\Lambda = 0.95 \pm 0.02$$
$$\alpha = 1.67 \pm 0.05$$

$$\chi^2/dof = 2.7$$

WACS phenomenology

with NLO corrections & kinematical power corrections

$$|\bar{\mathcal{R}}| = \sqrt{\frac{d\sigma^{\rm exp}}{dt}} : \sqrt{\frac{\pi\alpha^2}{(s-m^2)^2}\left((s-m^2)(m^2-u)\frac{1}{2}(|\bar{C}_2|^2+|\bar{C}_4|^2)+(m^4-su)|\bar{C}_6|^2\right)}.$$

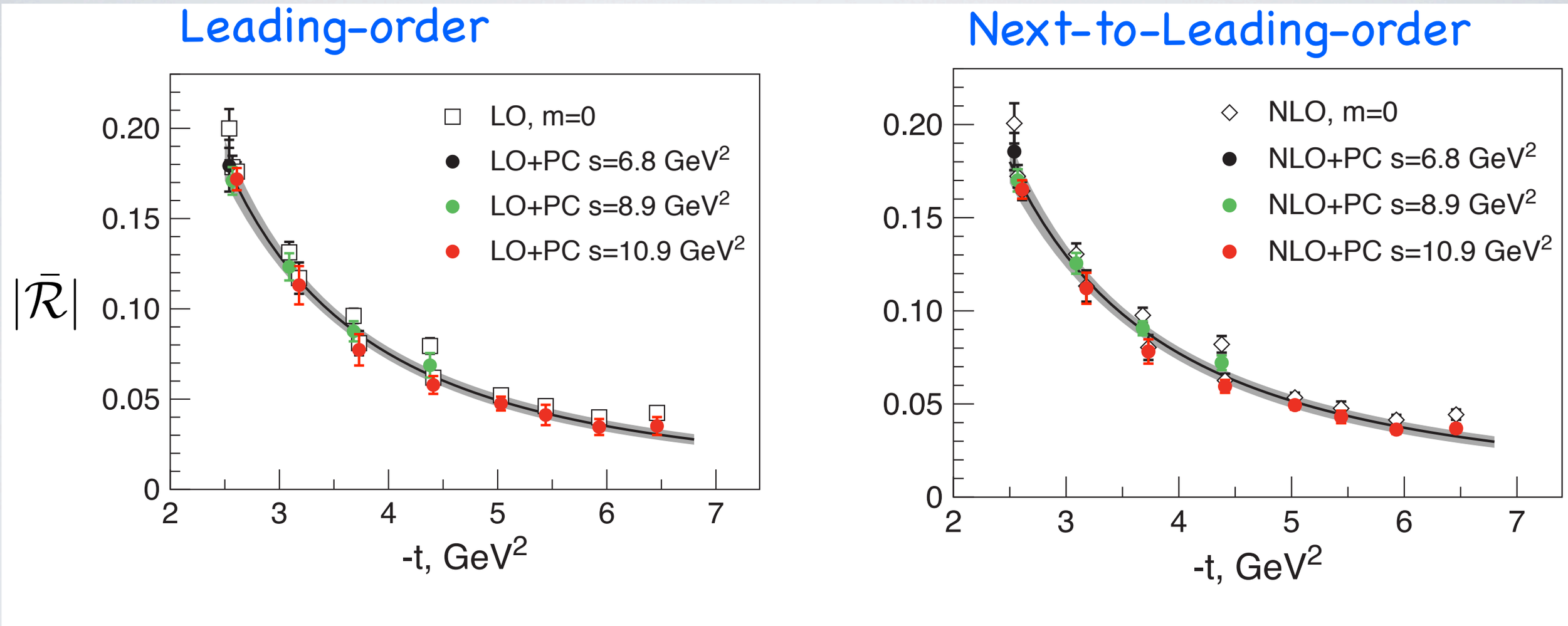
massless approximation $C_i(s,t)|_{m=0} = C_i(s,\cos\theta)$

$$\bar{C}_i(s,t) = C_i\left(s, \cos\theta = 1 + \frac{2ts}{(s-m^2)^2}\right) = C_i(s,\cos\theta)|_{m=0} + \mathcal{O}(m/s).$$

WACS phenomenology

with NLO corrections & kinematical power corrections

NK, Vanderhaeghen, to appear



empirical fit:

$$|\mathcal{R}(s,t)| = \left(\frac{\Lambda^2}{-t}\right)^{\alpha}$$

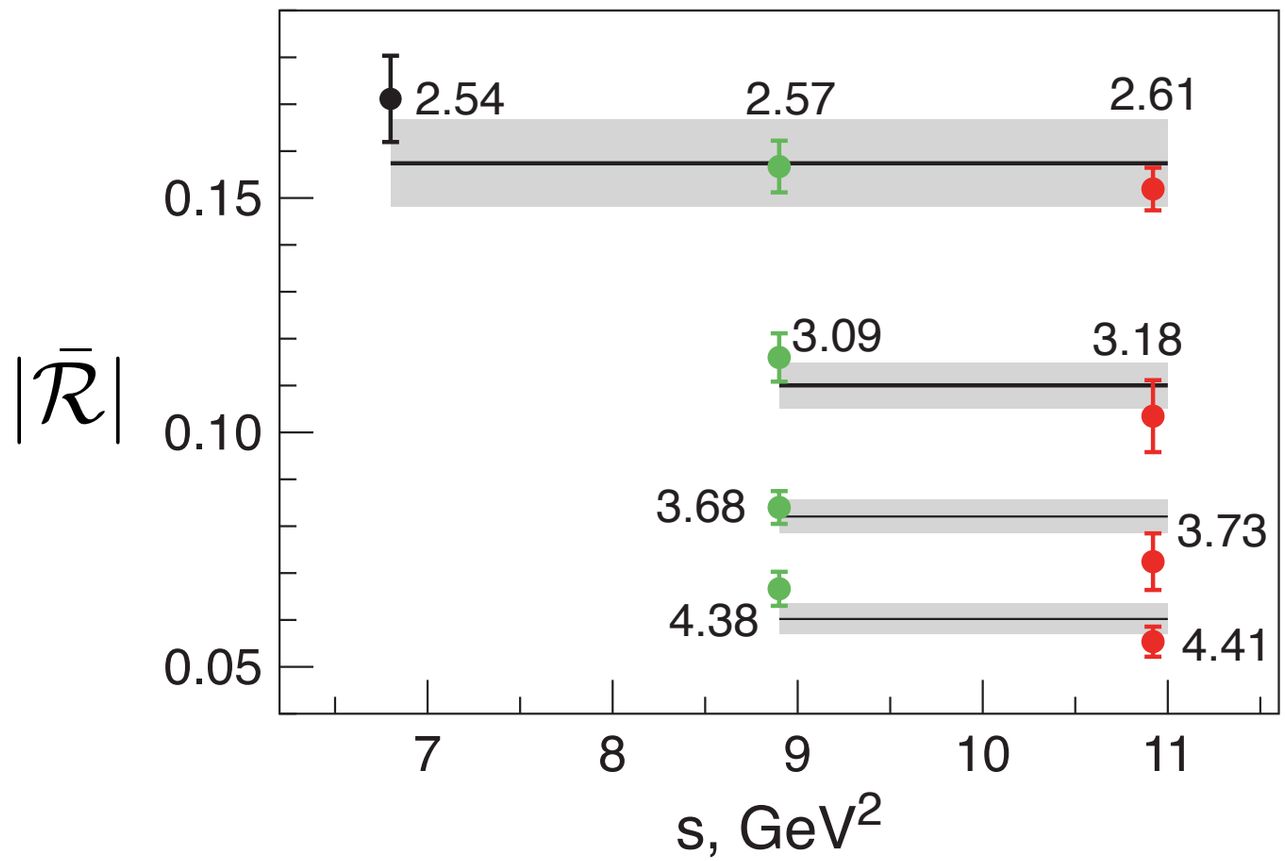
	Λ, GeV	α	χ^2/d.o.f
$\lvert\mathcal{R}\rvert$, NLO	0.95 ± 0.02	1.67 ± 0.05	2.7
$\lvert\bar{\mathcal{R}}\rvert$, LO	1.0 ± 0.02	1.88 ± 0.05	1.1
$\lvert\bar{\mathcal{R}}\rvert$, NLO	0.98 ± 0.02	1.80 ± 0.05	1.25

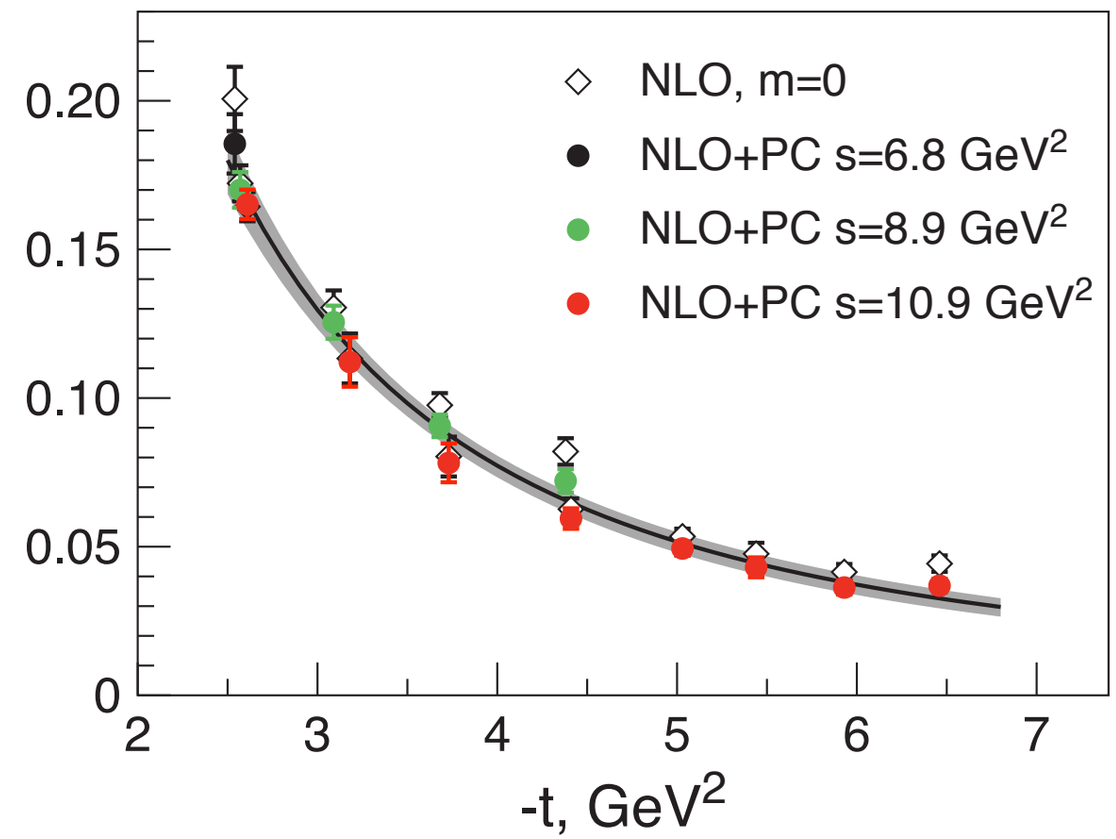
WACS phenomenology

with NLO corrections & kinematical power corrections

NK, Vanderhaeghen, to appear

Next-to-Leading-order





empirical fit:

$$|\mathcal{R}(s,t)| = \left(\frac{\Lambda^2}{-t}\right)^{\alpha}$$

	Λ, GeV	α	χ^2/d.o.f
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The ratio $\mathcal{R}$ in phenomenology: TPE correction

Basic idea is the same:

to construct expansion with respect to large scale 1/Q

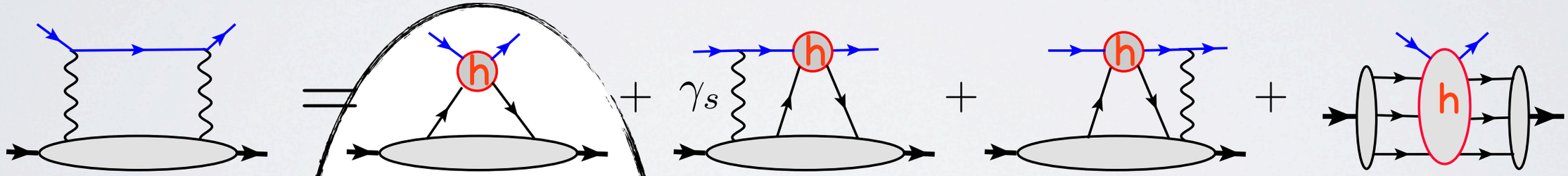
in the large-angle scattering domain $s \sim -t \sim -u \gg \Lambda^2$

large values of ε

NK, Vanderhaeghen, 2012

soft spectator contributions

hard spectator contributions



both photons are hard

one hard photon & one soft photon γ_s

Nonperturbative input

$\mathcal{F}_1(Q) \approx \mathcal{R}(t)$

SCET FF

$g_1(\varepsilon, Q)$ & $g_3(\varepsilon, Q)$

2 SCET amplitudes

$\phi_N(x_i)$

distribution amplitude

WACS phenomenology: longitudinal polarization K_{LL}

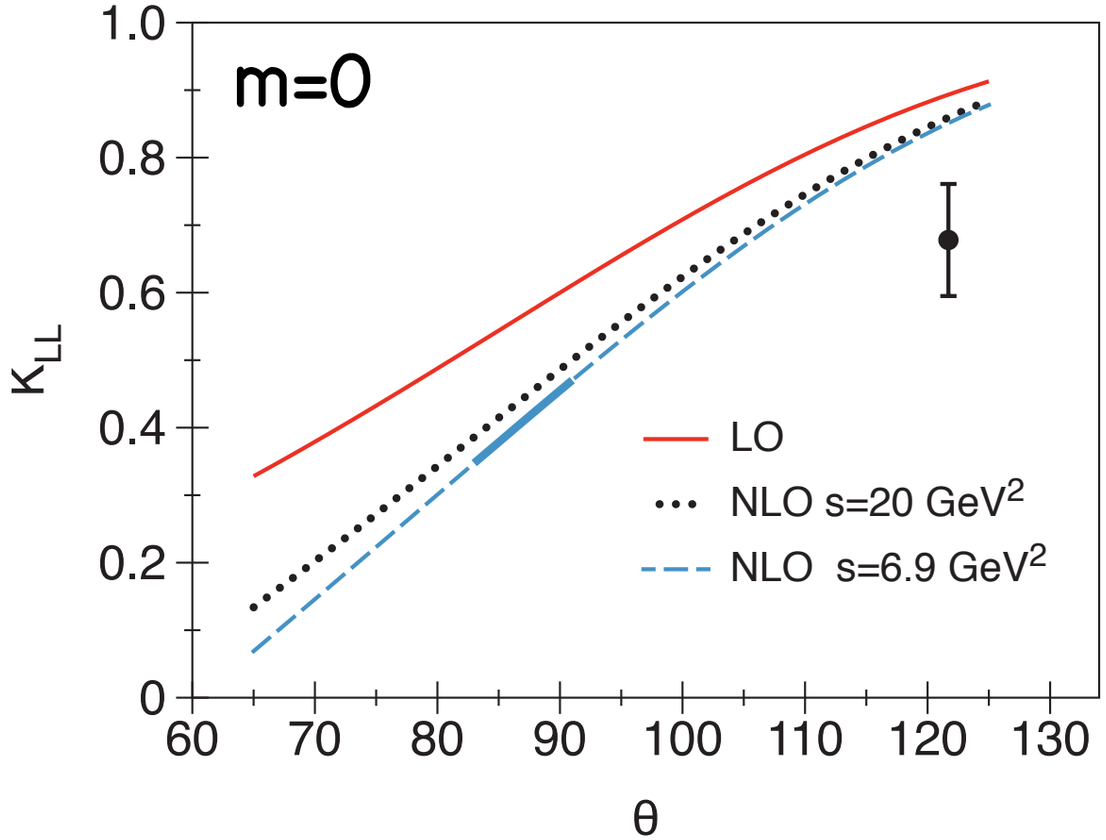
$$K_{\rm LL} = \frac{\sigma_\parallel^R - \sigma_\parallel^L}{\sigma_\parallel^R + \sigma_\parallel^L} = \frac{s^2 - u^2}{s^2 + u^2} + \frac{\alpha_s}{\pi} C_F K_{\rm LL}^{\rm NLO}$$

m=0

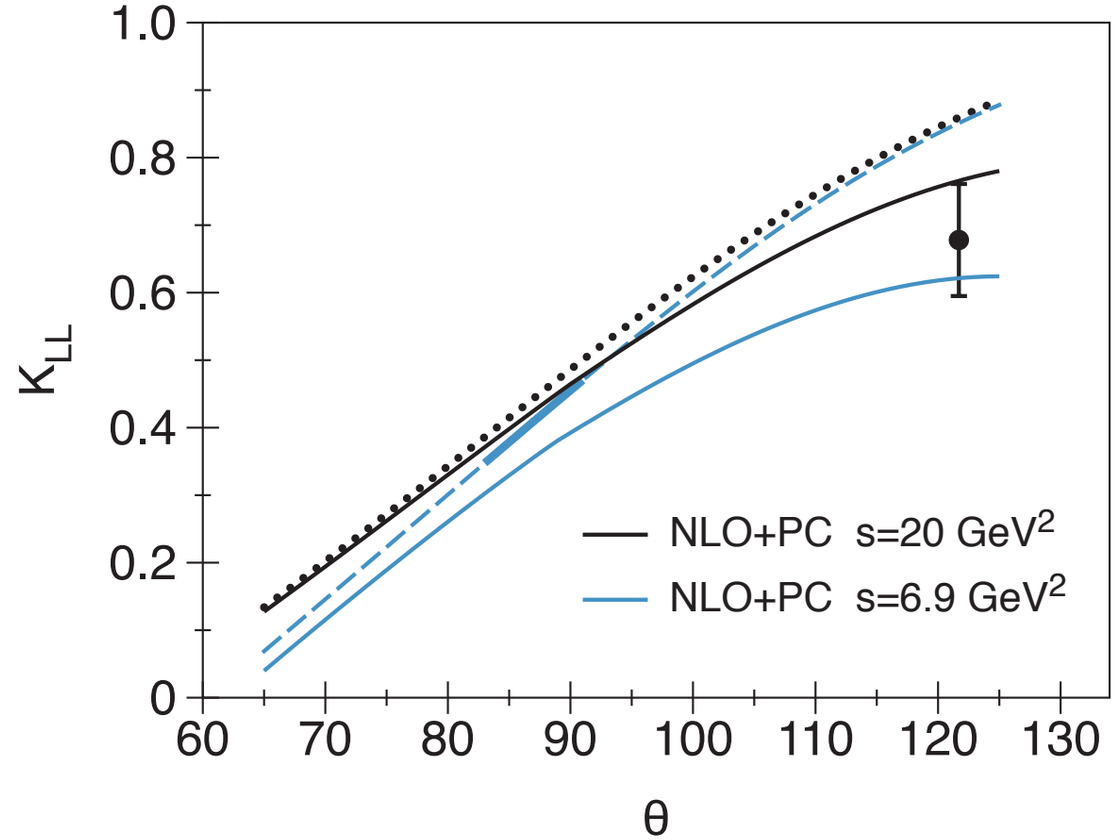
$\Rightarrow$ Does not depend on s & $\mathcal{R}$

NK, Vanderhaeghen, to appear

data: JLab/Hall-A, 2004



with the kinematical power corr's



Conclusions

Theory

- The QCD factorization approach is improved using SCET framework. Hard- and soft-spectator contributions are included consistently. The coefficient functions C_i computed at LO and NLO order.

$$T_2(s,t) = C_2(s,t)\mathcal{R}(s,t) \qquad i = 4,6$$

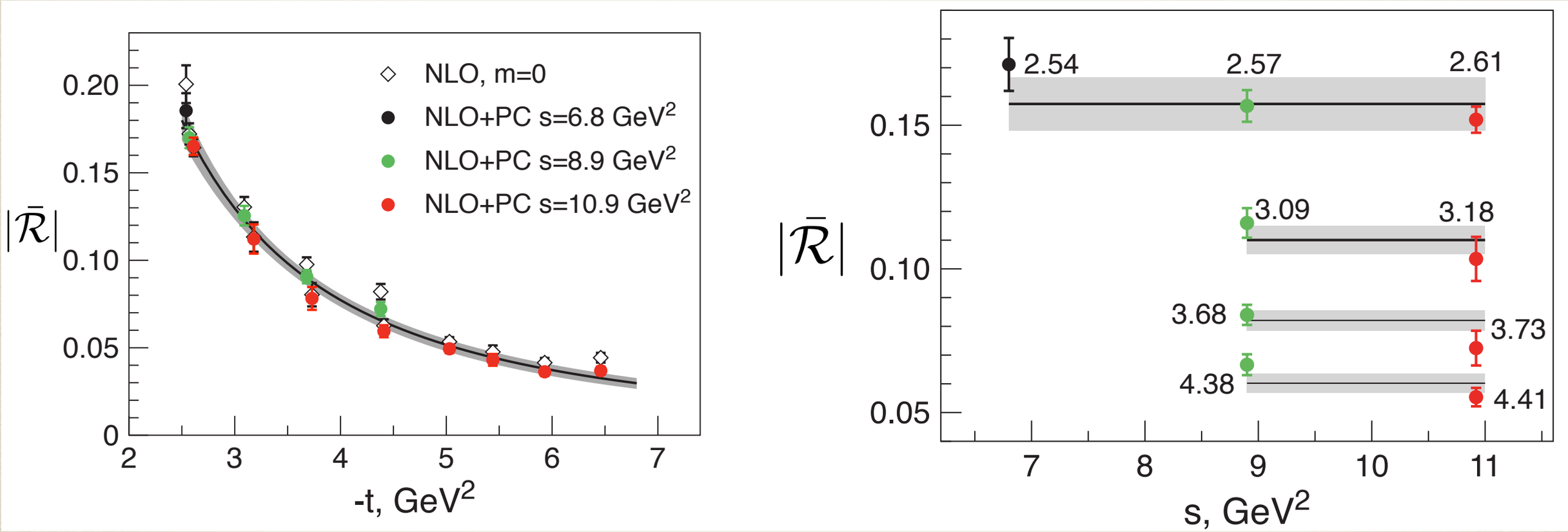
$$T_i(s',t) = C_i(s',t)\mathcal{R}(s,t) + \mathbf{\Psi} * \left\{ H_i(s',t) - C_i(s',t)\frac{H_2(s,t)}{C_2(s,t)} \right\} * \mathbf{\Psi} \qquad s' \neq s!$$

- Soft-overlap contribution is included in the one universal function $\mathcal{R}$ which:
  - can be extracted from the data for the cross section
  - is universal that allows to use it in description of other reactions (for instance, TPE)
- To improve the theory one needs:
  - to compute the hard-spectator corrections
  - to include the helicity flip amplitudes (K_{LS}) $T_i(s,t) \approx 0 \quad i = 1,3,5$
  - to consider other processes $\gamma_\perp^* p \to (\pi, \rho, ...)p$ (in progress)

Conclusions

Experiment: cross section

- Current data allows to conclude that cross section dominates by soft-overlap contribution



New data will help:

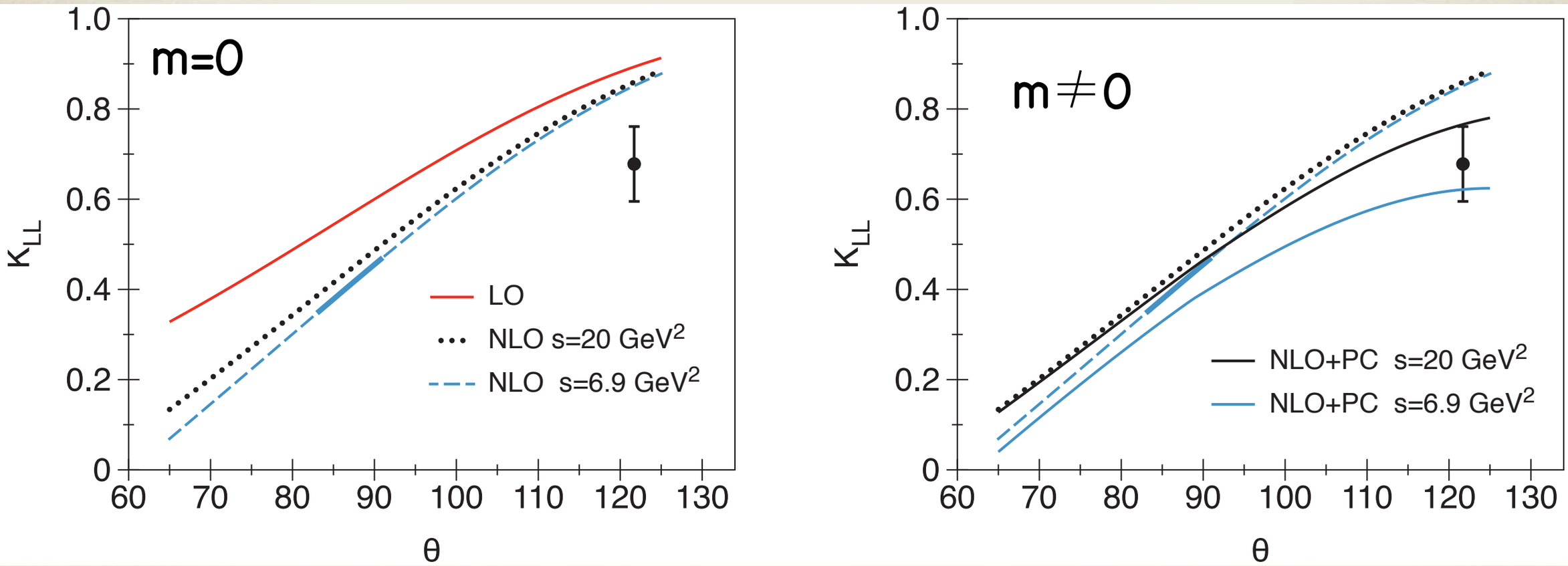
- to verify the description at larger s and -t (s-dependence!)
- reduce the effect of the power corrections
- to extract $\mathcal{R}$ in order to use in description of the other processes (TPE, comparison with the time-like region)

Conclusions

Experiment: asymmetries

- Existing data-points corresponds to small value $u=-1.1\,\mathrm{GeV}^2$

  $\Rightarrow$ sensitive to the power corrections



- more data are required to check the angle and energy dependence
- the data at larger values of s are less affected from the power corrections