Description of hard exclusive processes within the SCET framework

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Hard exclusive processes: theory

QCD Factorization

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

$$A(Q^2,\Lambda^2) \simeq \frac{1}{Q^{2n}} T(\alpha_s(Q^2), \ln Q^2/\Lambda^2) * \Phi_{\text{coll}}(\Lambda) + \mathcal{O}(1/Q^2)$$

form factors

$$\gamma^*\gamma \to \pi, \eta, ...$$

$$\gamma^*\pi \to \pi$$

DV production

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

$$\gamma_L^* p \to p + h,\ h = \pi, \rho, ...$$

Large angle scattering

$$\gamma\gamma \to \pi\pi,\ K\bar{K}, \ldots$$

Hard exclusive processes: theory

QCD Factorization

if QCD factorization holds then one can compute systematically logarithmic corrections improving a 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

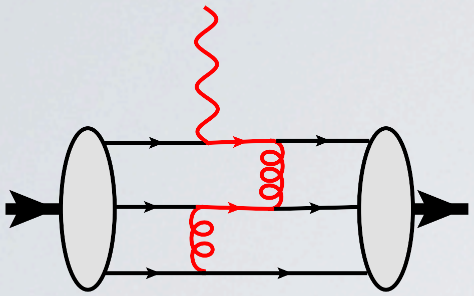
- asymptotic results applicable for a very³ LARGE Q^2

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

$$F_\pi(Q^2) \sim \alpha_s(Q^2)/Q^2 \qquad \gamma_L^* p \to (\pi, \rho, \ldots)p$$

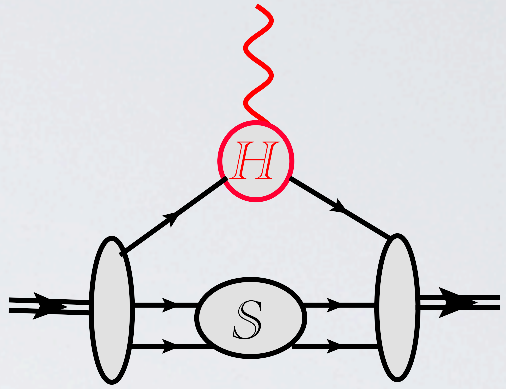
FF F_1 at large-Q^2 hard and soft spectator contributions

FF F_1 $\gamma^*_\perp + p \to p$



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

hard-spectator scattering



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

soft-spectator scattering

hard- and soft-spectator contributions have the same power

and large rapidity log's from the soft-collinear overlap

Duncan, Mueller 1980

Fadin, Milshtein 1981,82

☛ Soft spectator scattering might be important in processes with baryons

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

Questions

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

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

Soft spectator scattering in the EFT framework

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

$$F^{(s)}(Q^2, Q\Lambda, \Lambda^2) \simeq H(Q^2) * f(Q, \Lambda) + \mathcal{O}(1/Q)$$

QCD $\longrightarrow$ Effective field theory which includes collinear and soft particles

$$f(Q, \Lambda) = \langle out|O|in\rangle_{\mathrm{EFT}}$$ well defined in EFT

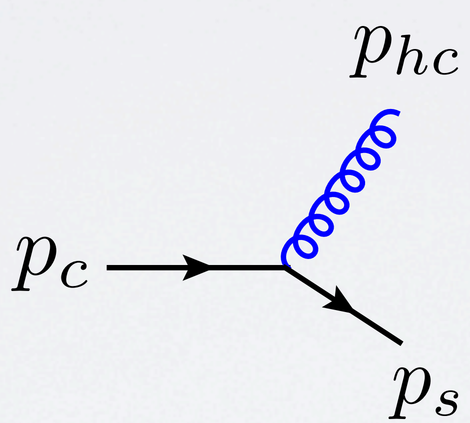
- The UV-behavior of the operators describing $f(Q, \Lambda)$ matches the IR-behavior of the QCD diagrams describing $H(Q^2)$
- There is a systematic power counting in the EFT framework

Dynamical modes in the EFT framework

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

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

$p_s \sim (\Lambda, \Lambda, \Lambda)$ **soft** $p_s^2 \sim \Lambda^2$



$$p_{hc}^2 \simeq 2(p_c \cdot p_s) \sim Q\Lambda$$

hard-collinear

$$p_{hc} \sim (Q, \sqrt{\Lambda Q}, \Lambda)$$

Soft Collinear Effective Theory

description of the soft-spectator contribution involves
3 different scales

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

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

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

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

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

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

Soft-spectator amplitude $F(\mu_h^2 \sim Q^2,\, \mu_{hc}^2 \sim Q\Lambda,\, \mu_s^2 \sim \Lambda^2)$

Soft Collinear Effective Theory

description of a hard-spectator contribution involves only
2 scales

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

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

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

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

$\cancel{p_s \sim (\Lambda, \Lambda, \Lambda)}$ ~~soft~~

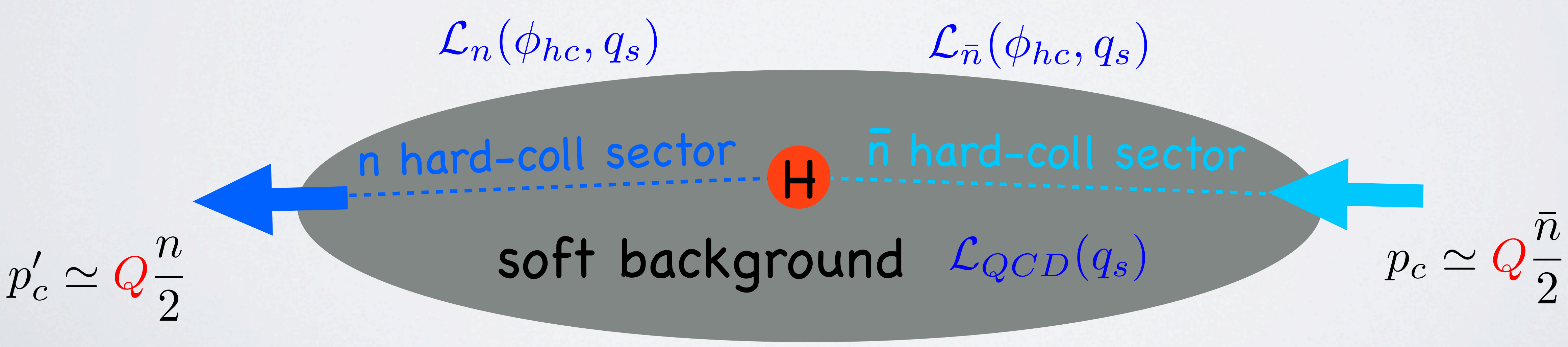
Hard-spectator amplitude $F(\mu_h^2 \sim Q^2, \cancel{\mu_{hc}^2 \sim Q\Lambda}, \mu_s^2 \sim \Lambda^2)$

Soft spectator scattering in the SCET framework

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

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

$$\boxed{f(Q\Lambda, \Lambda^2) = \langle p'_c | \, O[\phi_{hc}] \, | p_c \rangle_{\text{SCET-I}}}$$



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

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

well defined in a field theory

☛ moderate values of Q^2: $Q\Lambda \sim m_N^2$ hard-collinear scale is not large

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

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

$\Rightarrow$ $Q\Lambda \simeq 0.6 - 1.5\text{GeV}^2$

Soft spectator scattering in the SCET framework

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

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

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

$p_{hc} \sim (Q, \sqrt{\Lambda Q}, \Lambda)$

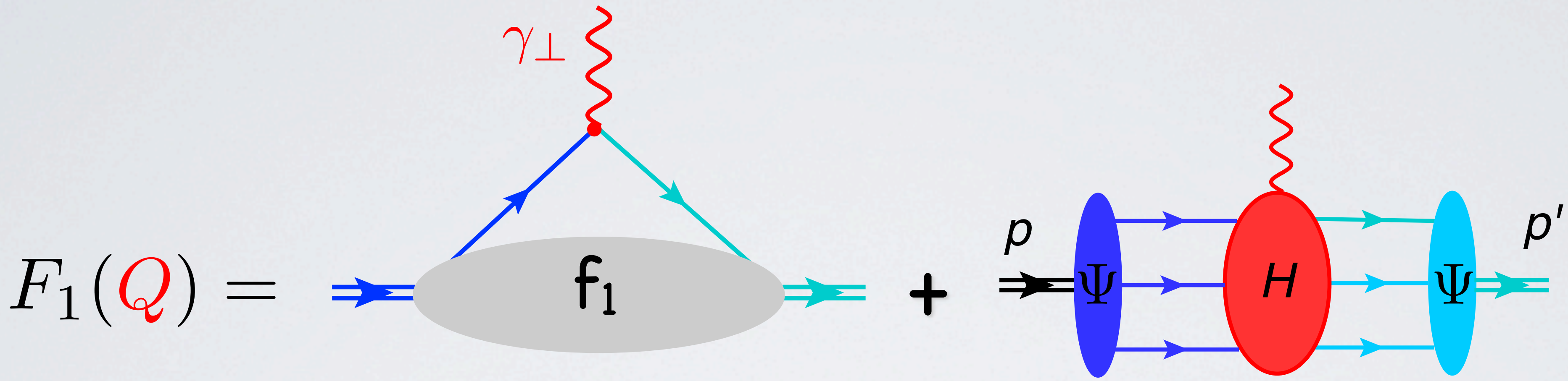
hard-collinear subprocess

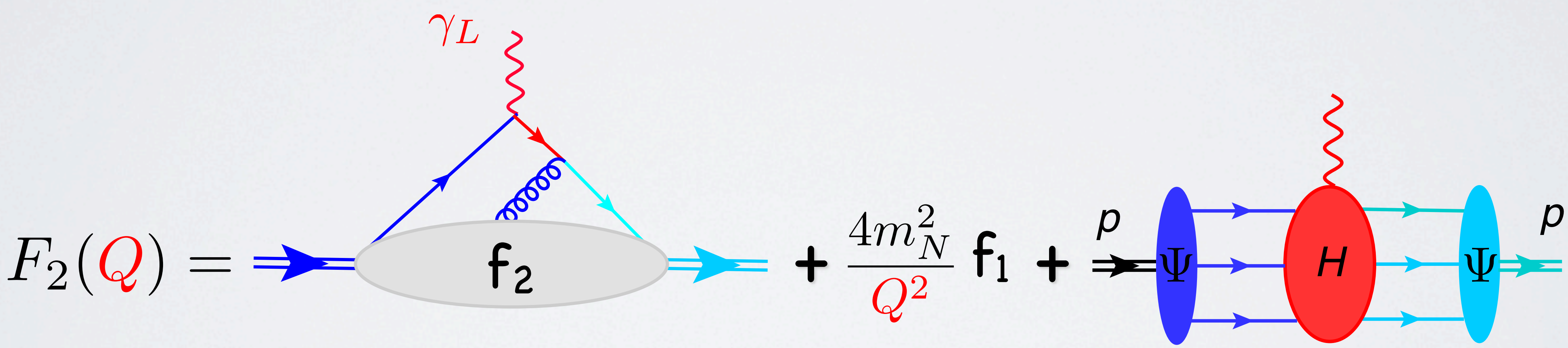
- provides an estimate of power of 1/Q at large Q
- allows one to establish an overlap between the hard- and soft-spectator contributions

Soft spectator contribution

NK, Vanderhaeghen PRD,2010

$$Q^2 \gg Q\Lambda \sim m_N^2$$





Soft-Collinear Effective Theory Form Factor

$p \simeq Q\frac{\bar{n}}{2} \quad p' \simeq Q\frac{n}{2}$

$$\langle p'|\bar{\chi}_n \gamma_\perp^\mu \chi_{\bar{n}} + \bar{\chi}_{\bar{n}} \gamma_\perp^\mu \chi_n |p\rangle_{\text{SCET}} = \bar{N}(p')\, \gamma_\perp^\mu\, N(p)\, f_1(\Lambda Q, \mu_F)$$

quark antiquark

active quark $\chi_{\bar{n}} = \mathrm{P}\exp\left\{ig\int_{-\infty}^{0} ds\, n\cdot A_{hc}(sn)\right\}\frac{1}{4}\not{\bar{n}}\not{n}\,\psi_{hc}(0)$

The scale dependence μ_F is defined by the renormalization of the SCET operator

$$\mu\frac{d}{d\mu}f_1(\mu) = \left(-\frac{\alpha_s}{\pi}\ln\frac{Q^2}{\mu^2} + \frac{3\alpha_s}{2\pi}\right) f_1(\mu)$$

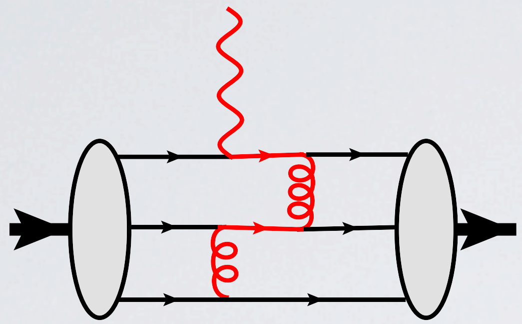
- RG can be used to evolve μ_F from Q to $\mu_{hc} \sim \sqrt{Q\Lambda}$

  Sudakov Logs provides enhancement in TL kinematics (observed)

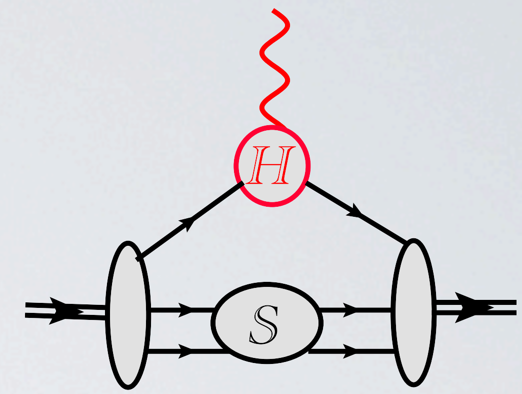
- The overlap of the soft and collinear regions: the end-point singularities in f_1 and hard-spectator contributions

Hard or soft dominance?

hard-
spectator
scattering



Soft-
spectator
scattering



Can the 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, '00, '02, '06, '13

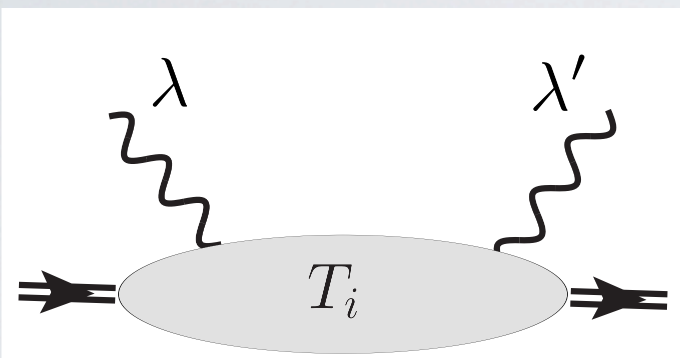
GPD or handbag model
Radyushkin 1998
Kroll et al, 2002, '05, '10
WACS/annihilation
$\gamma p \to \gamma p \quad \gamma\gamma \to p\bar{p}$

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



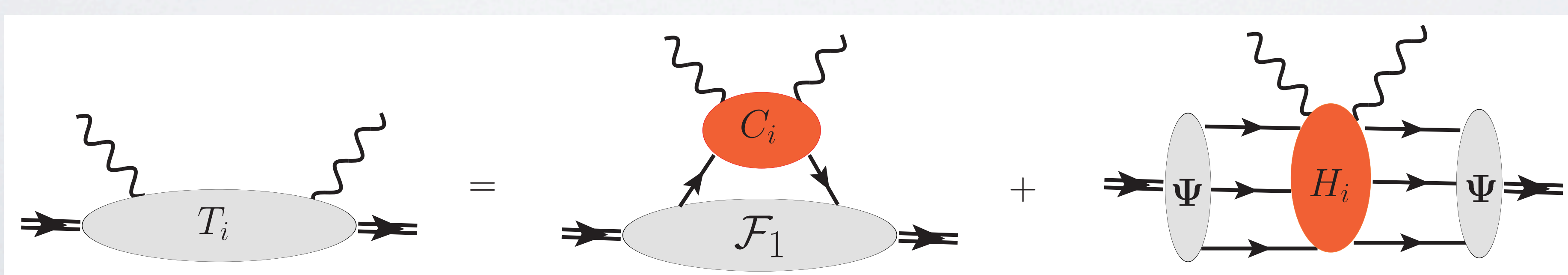
$T_{2,4,6} \Leftrightarrow M^{\lambda,\lambda'}_{h,h}$ helicity conserving

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

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



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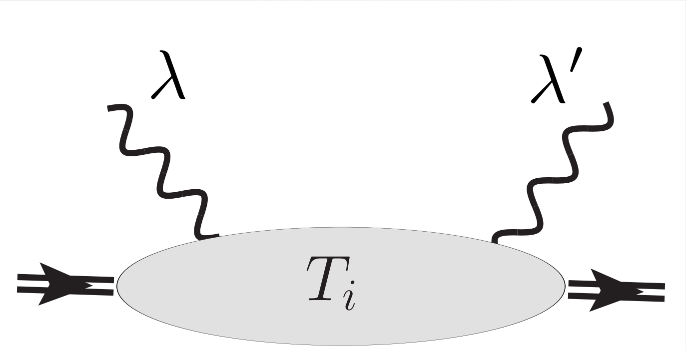

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$$T_i(s,t) = C_i(s,t)\,\mathcal{F}_1(t) + \mathbf{\Psi} * H_i(s,t) * \mathbf{\Psi} \qquad i = 2,4,6$$

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

$$p' \simeq Q\frac{n}{2} \qquad p \simeq Q\frac{\bar{n}}{2}$$

WACS phenomenology

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

NK, M. Vanderhaeghen 2012, 2013

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

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

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

$\Rightarrow$ 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

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

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

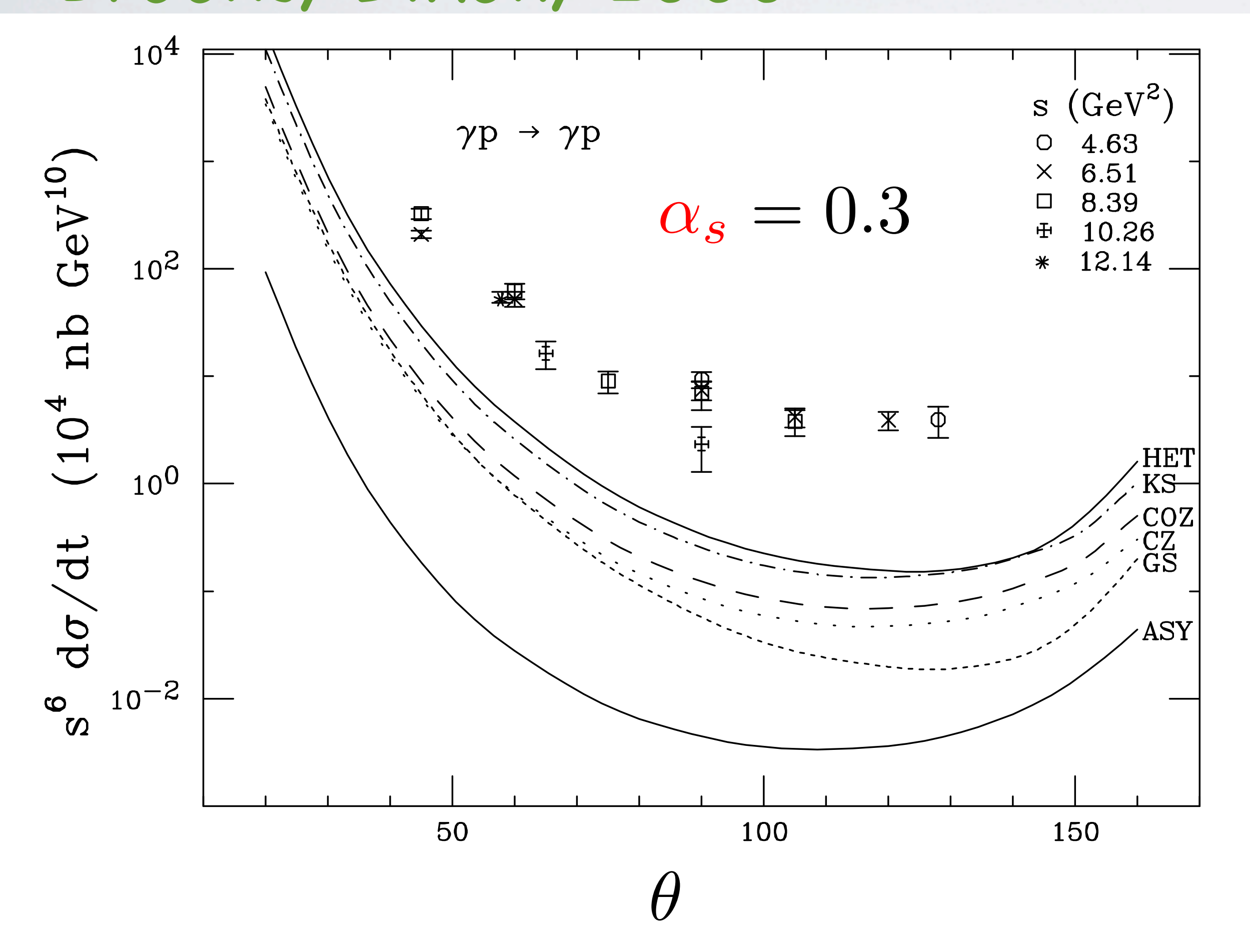
$i = 4, 6$

$s' \neq s!$

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

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

Data: Cornell, Shupe et al, PRD 1979

Wide Angle Compton Scattering & FF

$$\frac{d\sigma^{\gamma p \to \gamma p}}{dt} = \frac{f_N^4 \alpha_s^4}{s^6} A(\theta)$$

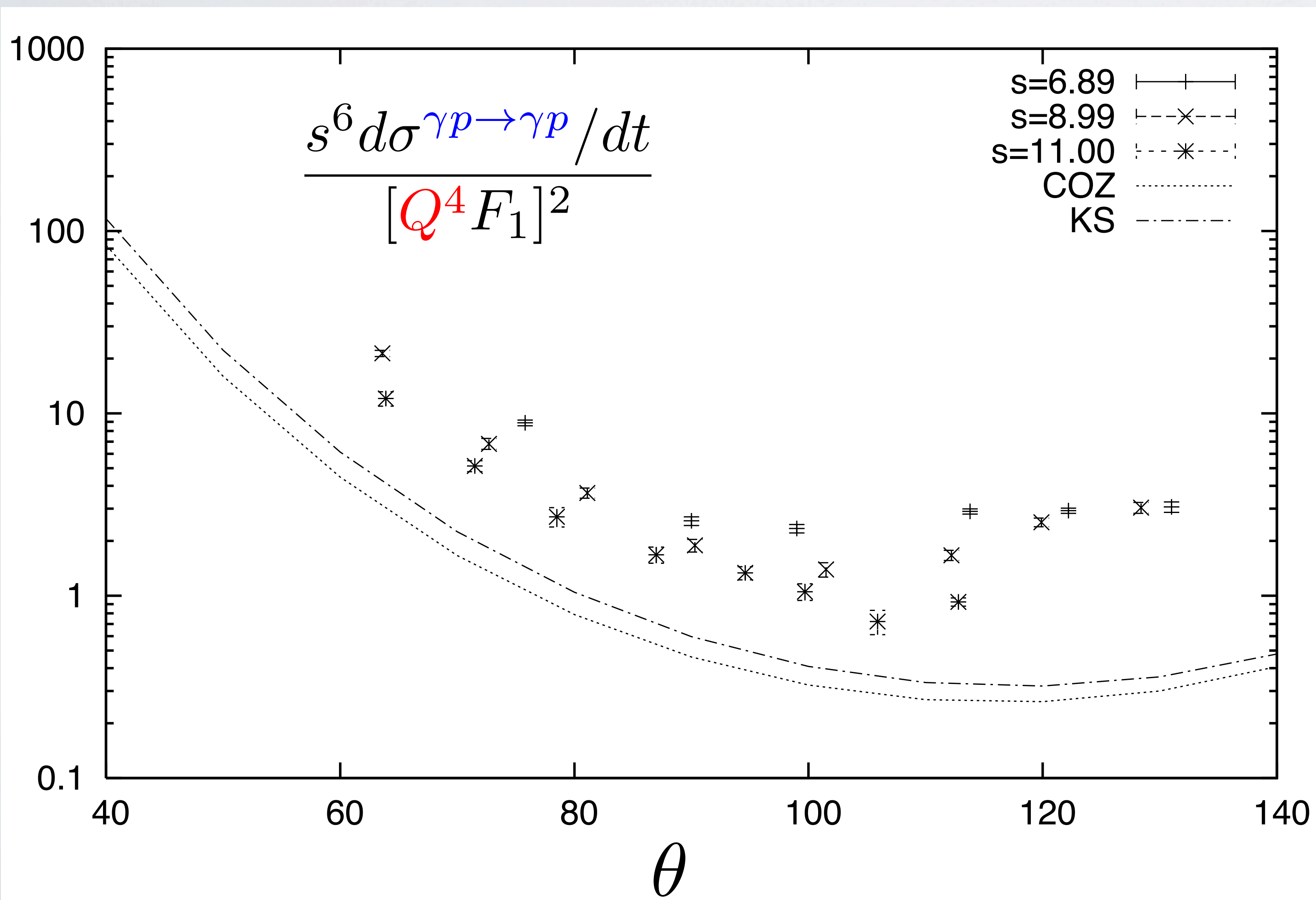
$$F_1(Q^2) = \frac{f_N^2 \alpha_s^2}{Q^4} I_N$$

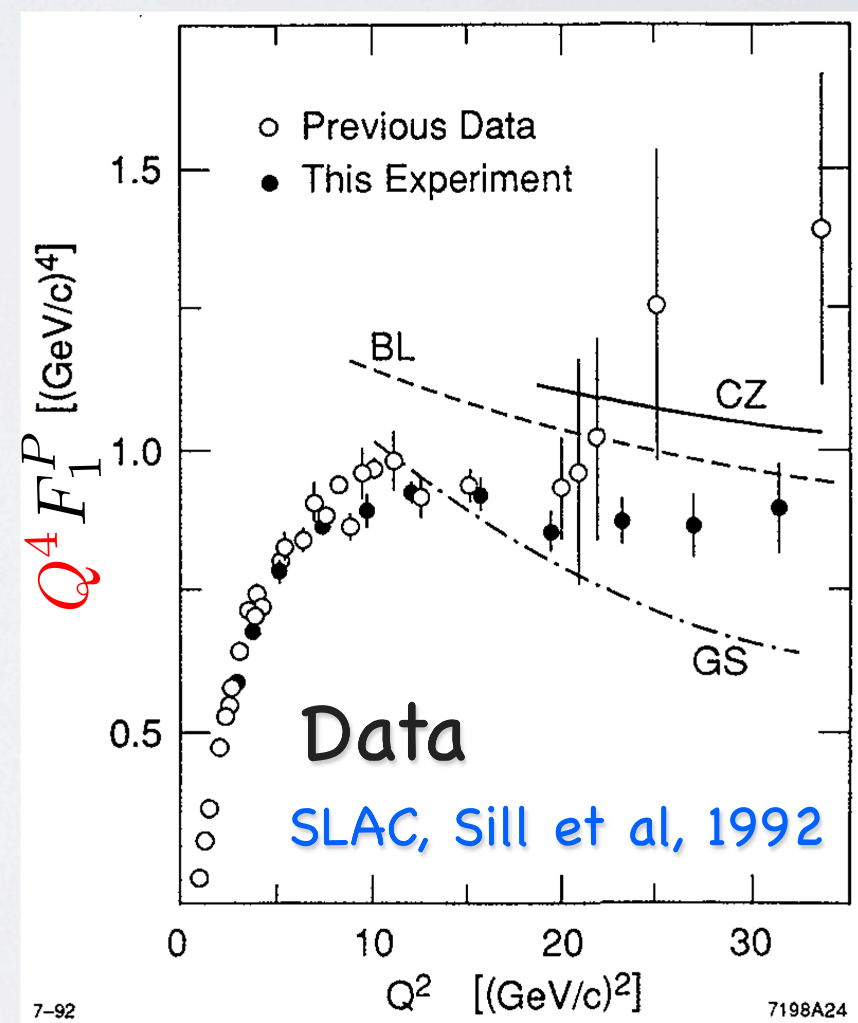
$$\boxed{\frac{s^6 d\sigma^{\gamma p \to \gamma p}/dt}{[Q^4 F_1]^2} = A(\theta)/I_N}$$

$$Q^4 F_1(Q^2) \approx 1\mathrm{GeV}^4$$

$$Q^2 = 7 - 15\mathrm{GeV}^2$$

Data JLab, Hall A, 2007 Thomson et al, 2006





The theoretical ratio is a factor of 2-4 smaller

WACS phenomenology

the ratio

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

$$\mu_F^2 = -t$$

$$\mathcal{R}(s,t) = \frac{T_2(s,t)}{C_2(s,t)} \simeq \frac{T_4(s',t)}{C_4(s',t)} \simeq \frac{T_6(s'',t)}{C_6(s'',t)} \simeq \mathcal{R}(t)$$

this can be checked experimentally

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

To the leading order accuracy

$$C_i = C_i^{\mathrm{LO}} + \frac{\alpha_s}{4\pi} C_F \, C_i^{\mathrm{NLO}} + \ldots$$

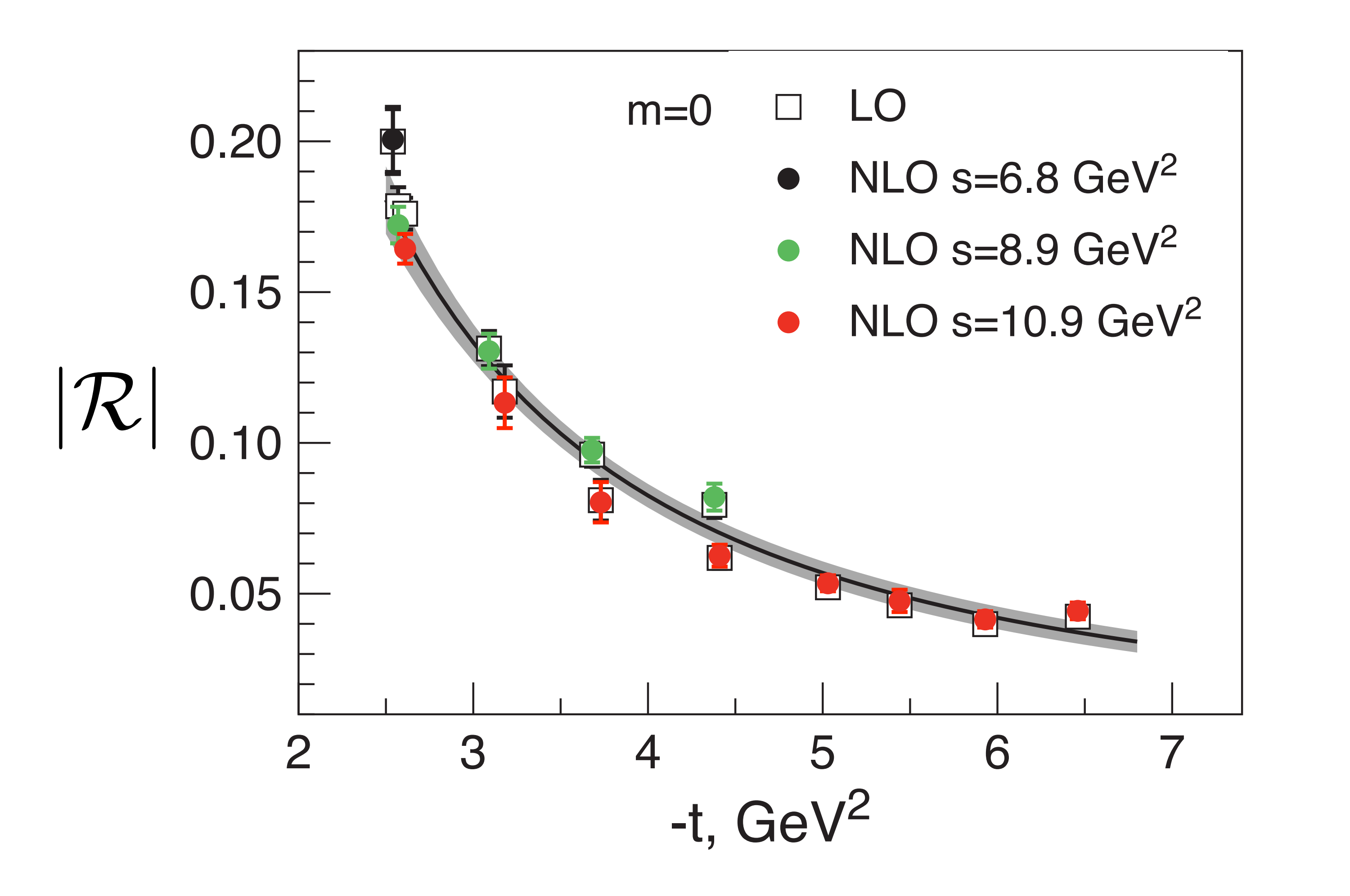
$$\frac{d\sigma}{dt} \simeq \frac{2\pi\alpha^2}{s^2} \, |\mathcal{R}(s,t)|^2 \left(\frac{s}{-u} + \frac{-u}{s}\right)\Bigg|_{m=0} = \frac{d\sigma_0^{\mathrm{KN}}}{dt} |\mathcal{R}(s,t)|^2$$

WACS phenomenology

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

NK, Vanderhaeghen 2013

used data: JLab/Hall-A, 2007



all power corrections m/Q are neglected

WACS phenomenology

with NLO corrections & kinematical power corrections

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

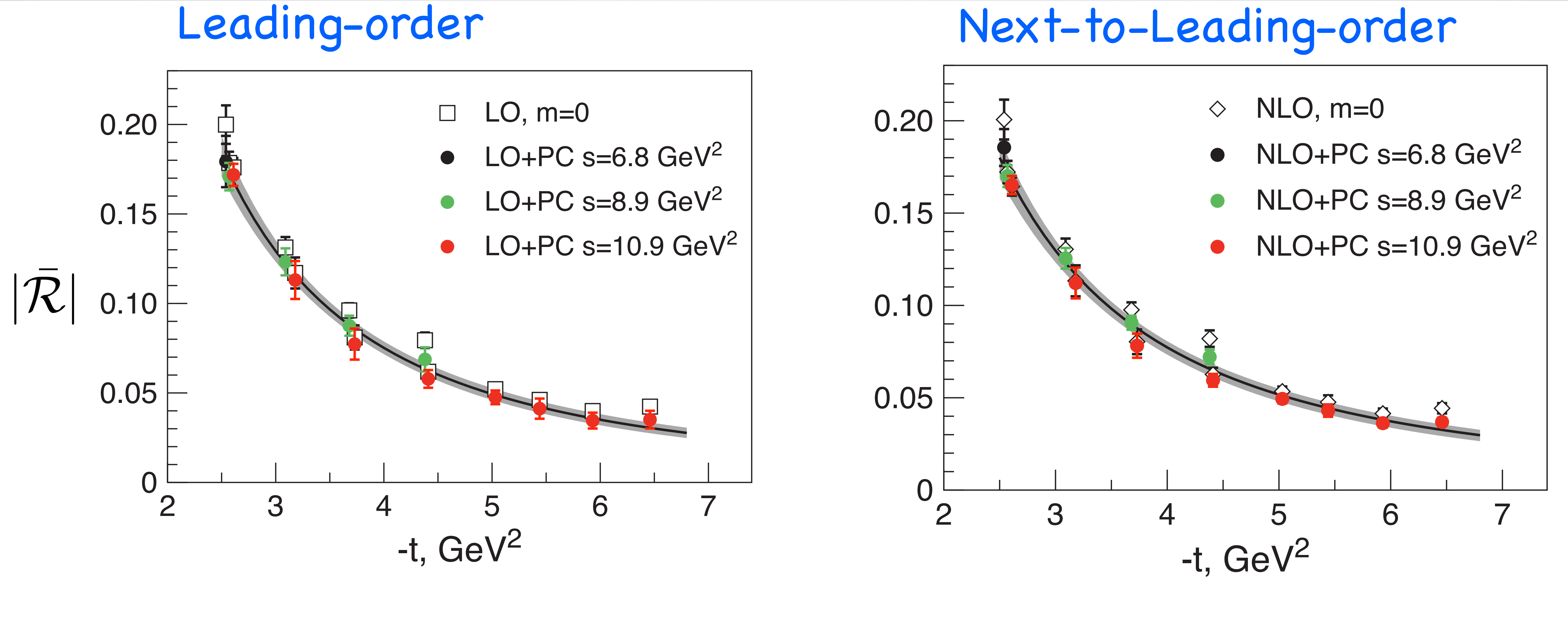
massless approximation $\quad C_i(s,t)|_{m=0} = C_i(s,\cos\theta)$

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

WACS phenomenology

Data JLab, Hall A, 2007, $-u > 2.4\,\mathrm{GeV}^2$

NK, Vanderhaeghen, to appear



empirical fit:

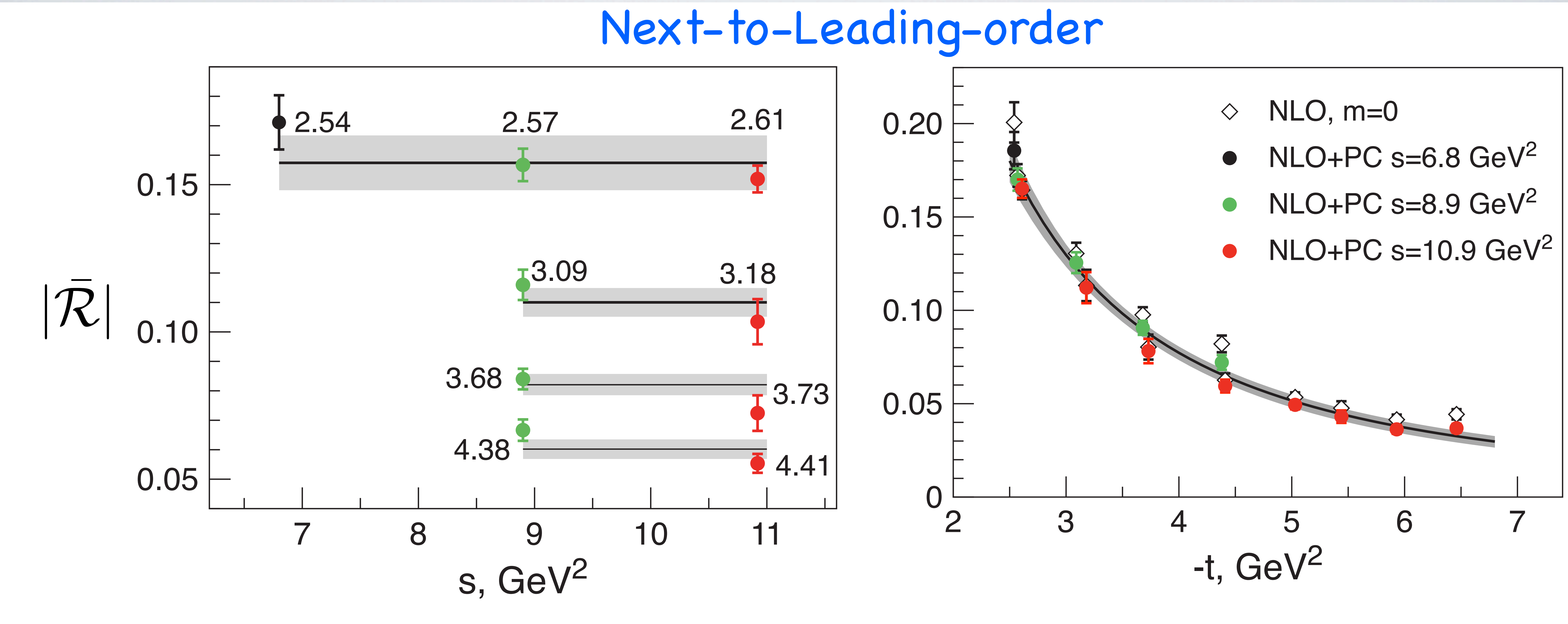
$$|\mathcal{R}(s,t)| = \left(\frac{\Lambda^2}{-t}\right)^{\alpha}$$

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

WACS phenomenology

with NLO corrections & kinematical power corrections

NK, Vanderhaeghen 2013



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TPE factorization within the SCET framework

Basic idea is to construct expansion with respect to large scale 1/Q

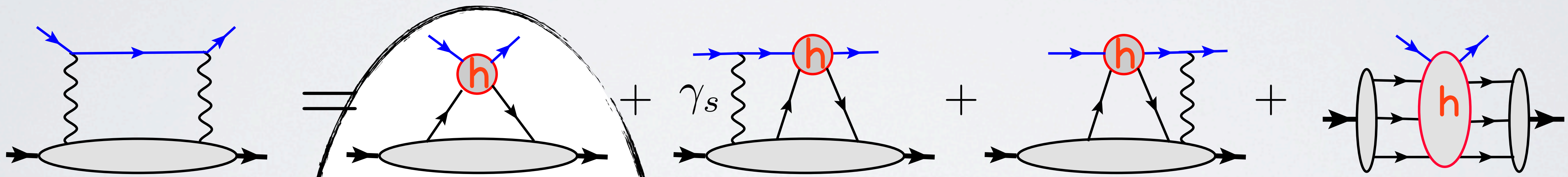
in the large-angle scattering domain $s \sim -t \sim -u \gg \Lambda^2$

NK, Vanderhaeghen, 2012

large values of ε

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}

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

JLAB, 2004 s=6.9GeV^2

t=-4GeV^2

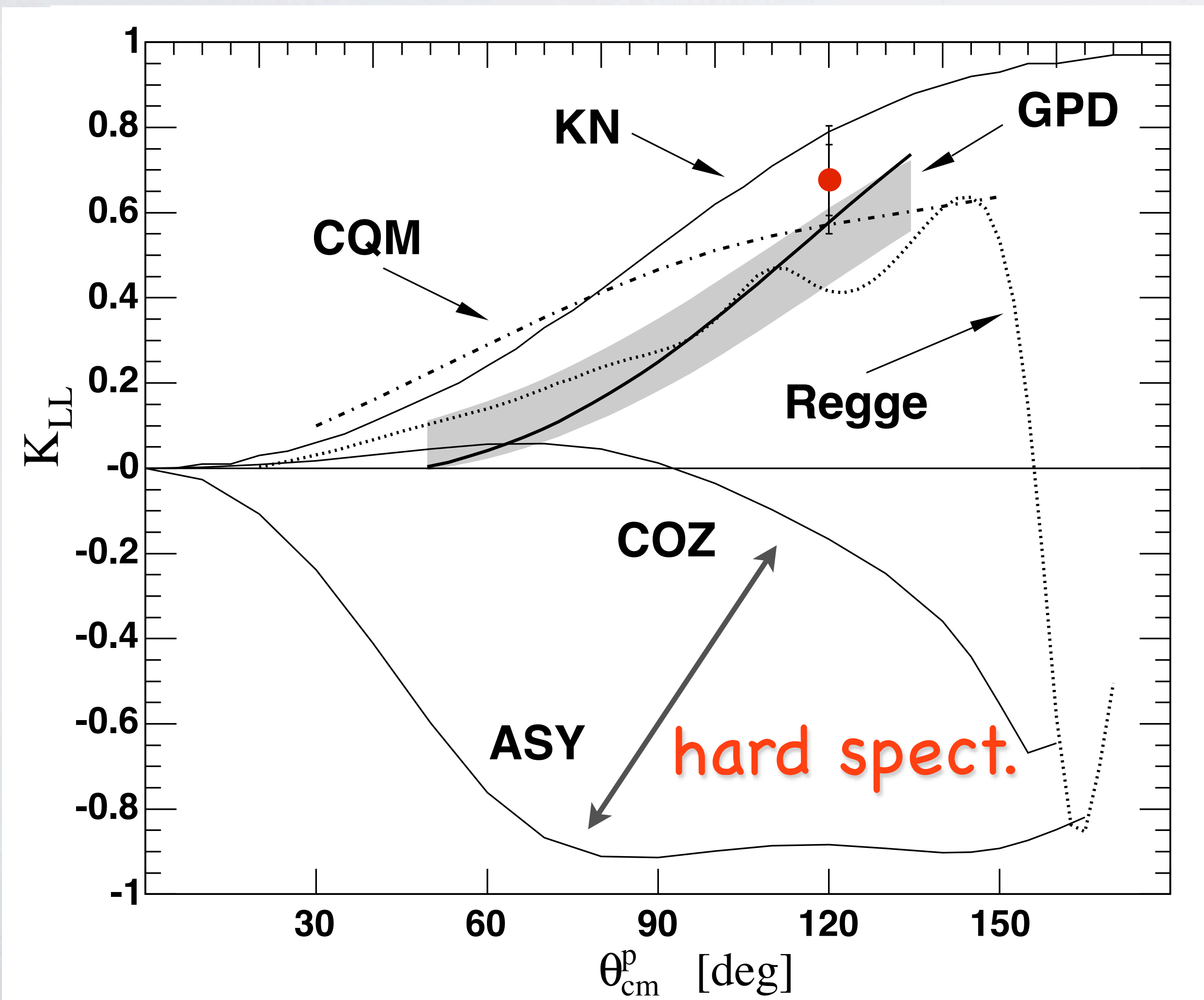
u=-0.84GeV^2

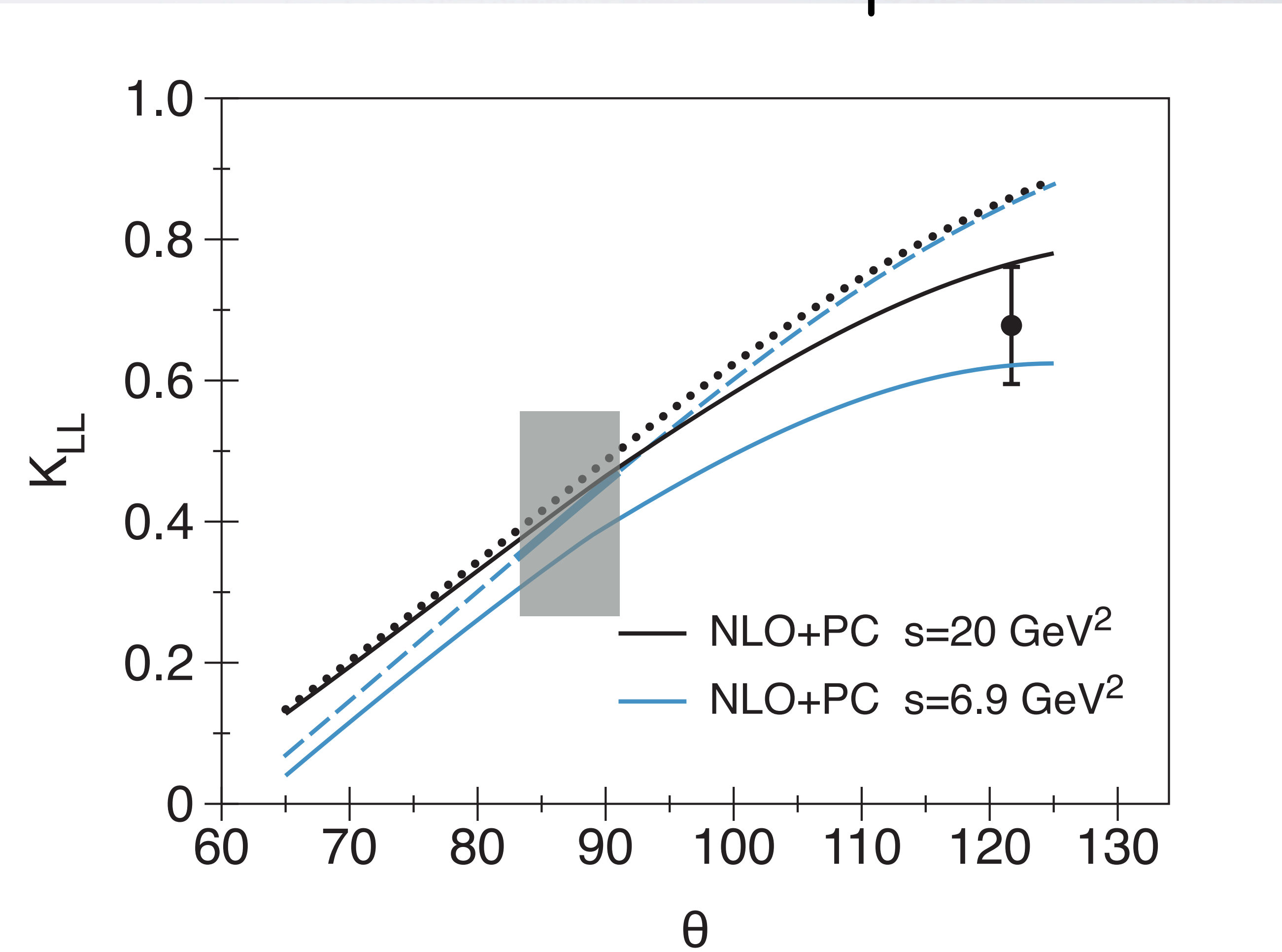
$\Rightarrow$ Does not depend on s & $\mathcal{R}$

NK, Vanderhaeghen, to appear

data: JLab/Hall-A, 2004

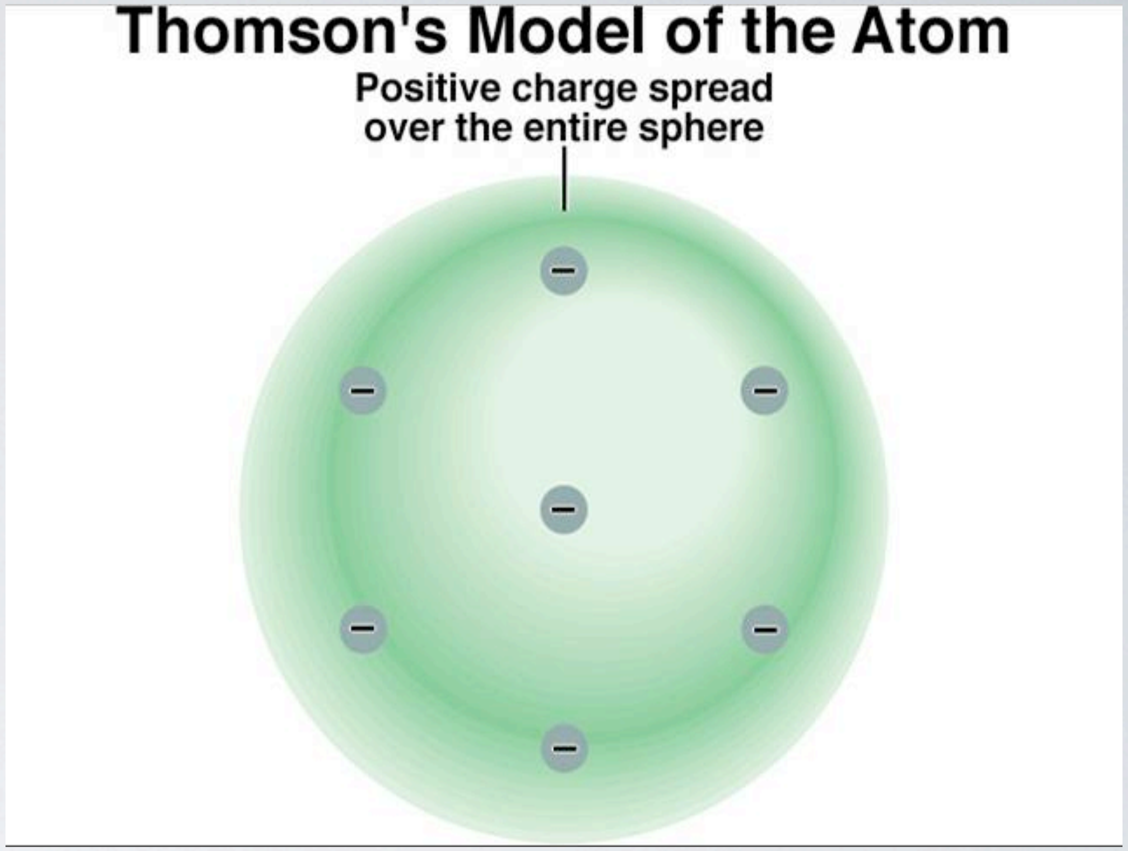
with the kinematical power corr's





J.J. Thomson

Theoretical model
"pudding model"
1904

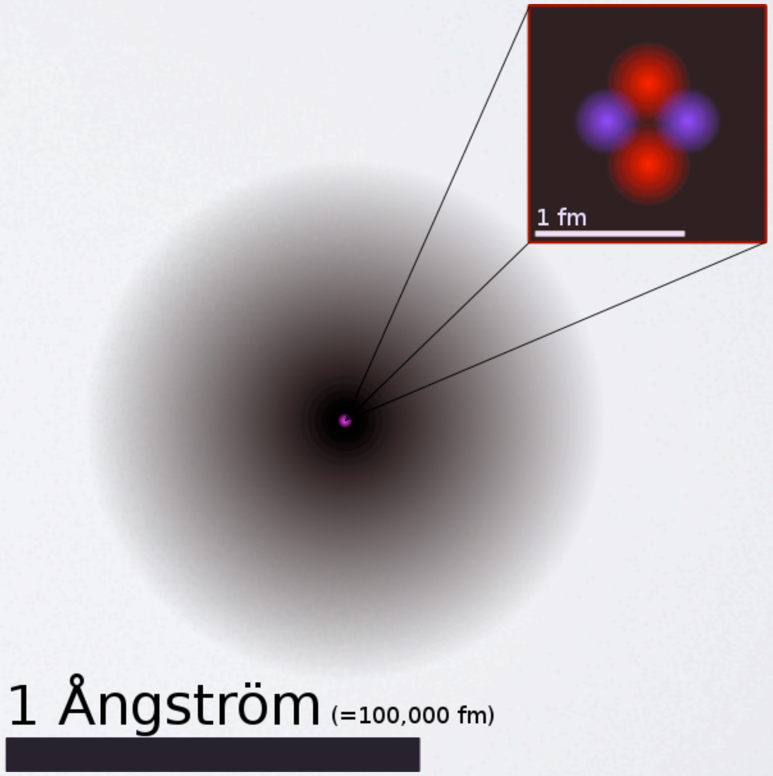


Gold foil experiment, 1909

E.Rutherford

H.Geiger

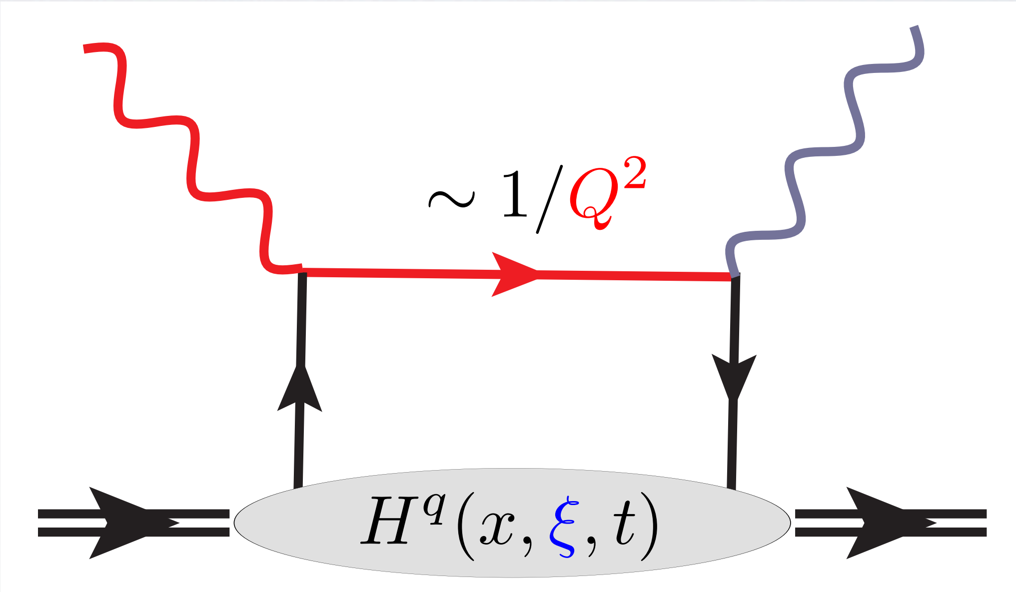
E.Marsden



DVCS at large momentum transfer

DVCS $\quad Q^2 \sim s \gg -t \gg \Lambda^2 \qquad -t \sim 3 - 10\ \mathrm{GeV}^2$ moderate values

1. Factorize the largest virtualities

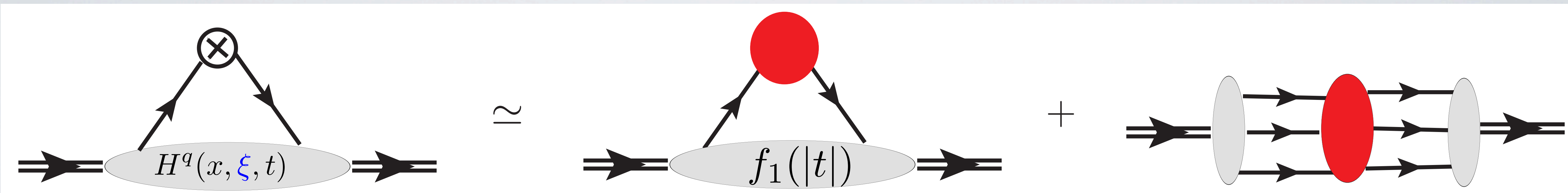


$$\mathcal{H}(\xi, Q^2, t) \simeq \sum_q e_q^2 \int dx H^q(x, \xi, t, \mu^2 = |t|) \int dx' U(x, \xi, x', \ln[Q^2/|t|]) \left\{ \frac{1}{\xi - x' - i\varepsilon} - \frac{1}{\xi + x' - i\varepsilon} \right\}$$

GPD $\qquad$ evolution $\qquad$ hard kernel

GPDs at large momentum transfer

2nd step: factorize modes with the virtualities $\sim -t$



$$H^q(x,\xi,t) = C_h(|t|)\ \{f_1^q(|t|)\delta(1-x) - \delta(1+x)\ f_1^{\bar{q}}(|t|)\} + \Psi * T_H^q(x,\xi,t) * \Psi$$

$$\int_{-1}^{1} dx H^q(x,\xi,t) = \underbrace{C_h(|t|)\ \{f_1^q(|t|) - f_1^{\bar{q}}(|t|)\} + \Psi * T_H^q(t) * \Psi}_{F_1^q(|t|)}$$

GPDs at large momentum transfer

$$H^q(x,\xi,t) = C_h(|t|)\ \left\{f_1^q(|t|)\delta(1-x) - \delta(1+x)\ f_1^{\bar{q}}(|t|)\right\} + \Psi * T_H^q(x,\xi,t) * \Psi$$

use the factorization formulas
for em FFs and WACS

$$H^q(x,\xi,t) = F_1^q(|t|)q_0^{val}(x) + \mathcal{R}^q(t)q_0^s(x)$$

$$+\Psi * \left[T_H^q - q_0^{val}(x)T_F^q/C_1(t) - q_0^s(x)T_2^q(s,t)/C_2(s,t)\right] * \Psi.$$

$$q_0^{val}(x) = \frac{1}{2}\left\{\delta(1-x) + \delta(1+x)\right\}$$

$$q_0^s(x) = \frac{1}{2}\left\{\delta(1-x) - \delta(1+x)\right\}$$

DV Compton FFs at large momentum transfer

If the soft term dominates then

$$H^q(x,\xi,t) \simeq F_1^q(|t|)q_0^{val}(x) + \mathcal{R}^q(t)q_0^s(x)$$

$$H^q(x,\xi,t) \simeq \tilde{H}^q(x,\xi,t) \qquad F_1^q(-t) \simeq g_A^q(-t)$$

Compton FFs $\quad Q \to \infty \quad Q^2/s$ is fixed, $-t/Q^2$ is small, $-t \gg \Lambda^2$

$$\mathcal{H}(\xi,Q^2,t) \simeq -\mathcal{R}(t)\frac{2\xi}{1-\xi^2}\left\{1+\mathcal{O}(\alpha_s(Q^2)) + \mathcal{O}(\alpha_s(-t))\right\}$$

$$\tilde{\mathcal{H}}(\xi,Q^2,t) \simeq -e_u F_1(-t)\frac{1}{1-\xi^2}\left\{1+\mathcal{O}(\alpha_s(Q^2)) + \mathcal{O}(\alpha_s(-t))\right\}$$

$$e_u^2 F_1^u(t) + e_d^2 F_1^d(t) \approx e_u^2 F_1^u(t) \approx e_u F_1(t)$$

Conclusions

- The Q^2 behavior of the soft spectator contribution can not be computed from pQCD but can be described by universal matrix elements within SCET factorization framework

- There are indications that the soft spectator contribution is large or even dominant for moderate values of Q^2 : $Q\Lambda \sim m_N^2$

- Luckily the soft-overlap configurations are suppressed for DVCS!

- SCET factorization framework can be used in order to estimate the behavior of GPDs at large -t

- Factorization for the processes with the helicity flip amplitudes in DV kinematics

$$\gamma^*_\perp p \to (\pi, \rho, \dots)p \quad \Rightarrow \quad \sigma_T/\sigma_L$$

in progress ...