Application of the QCD factorization in SL and TL regions

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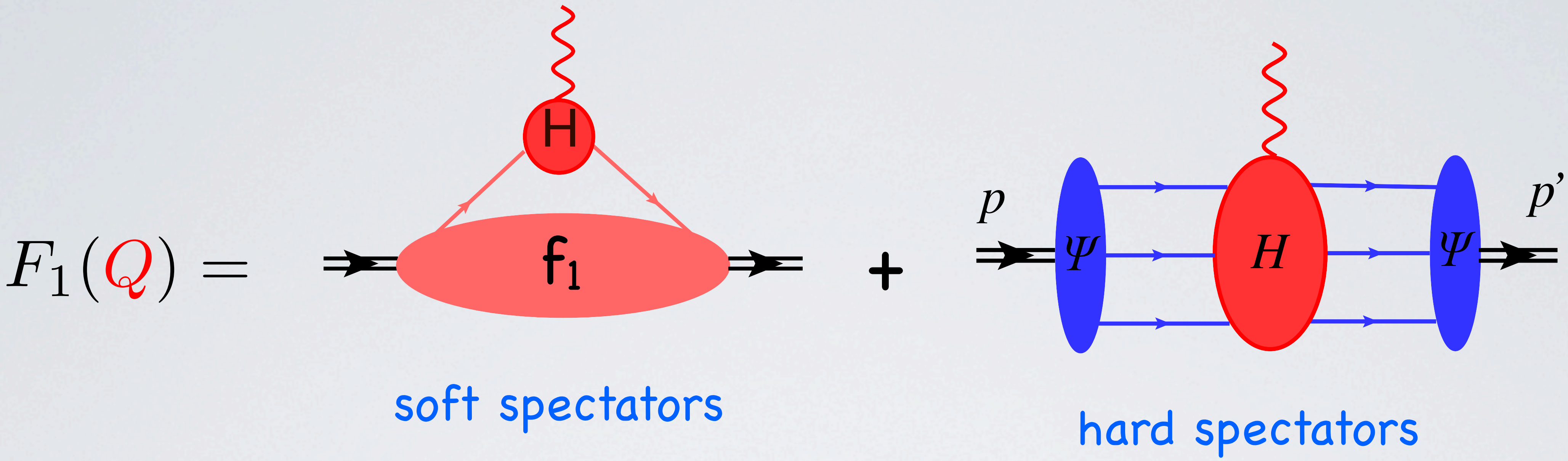
QCD factorization at large Q^2



- the same power at large Q^2

$$F_1^{(s)}(Q^2) \sim f^{(s)}(\ln Q^2/\Lambda^2)/Q^4$$

Duncan, Mueller 1980

Milshtein, Fadin 1981/82

- Large at moderate values of Q^2

Isgur, Smith 1984

Nesterenko, Radyushkin 1989

Braun et al, 2002, 2006

- SCET factorization scheme at large Q^2

NK, Vanderhaeghen PRD, 2010

Brodsky, Lepage 1979
Chernyak, Zhitnitsky 1977
Efremov, Radyushkin 1980

- model independent QCD prediction

$$F_1^{(h)}(Q^2) \sim f(\ln Q^2/\Lambda^2)/Q^4$$

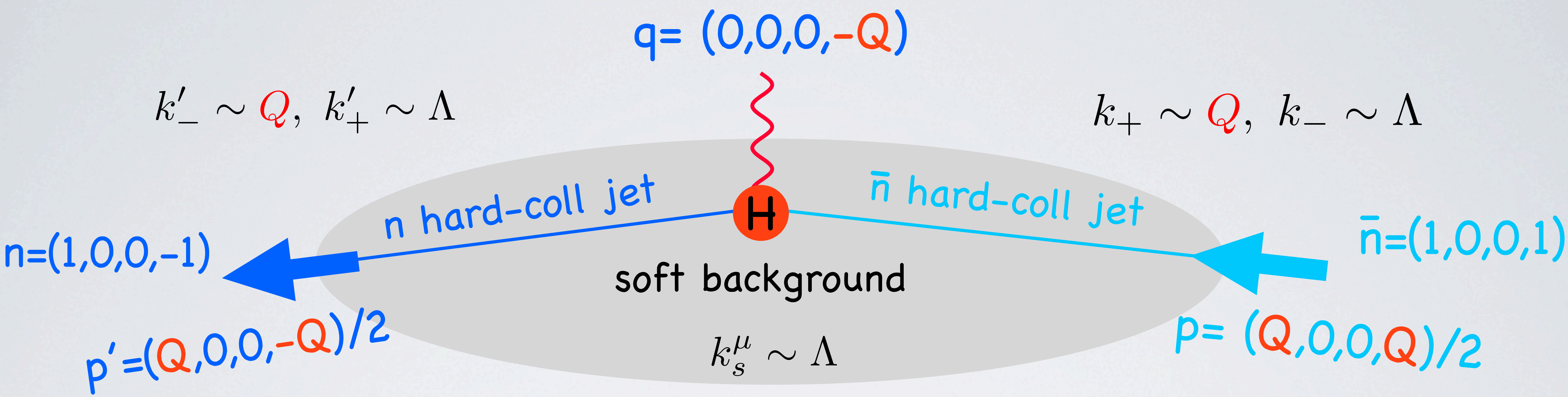
- Non-perturbative Ψ is UNIVERSAL, well defined objects $\langle p|\, O_i\, |0\rangle$

Estimates:
- QCD Sum Rules
- Lattice calculations
- Low energy models: QSM, ...

Soft spectator contribution

hard-collinear scale: $Q\Lambda \lesssim m_N^2$

hard-collinear = collinear + soft

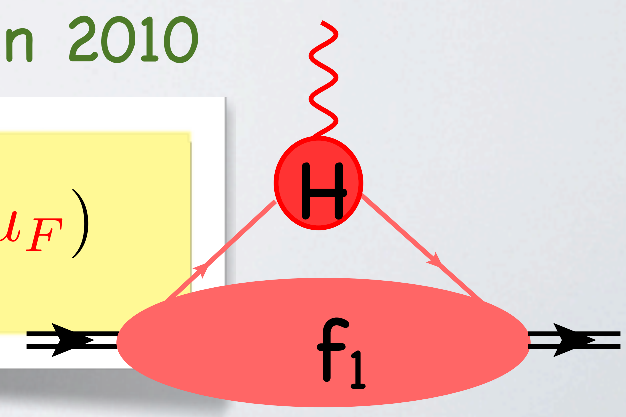


quark "jets" $\chi_{\bar{n}} = \mathrm{P}\exp\left\{ig\int_{-\infty}^{0} ds\, n\cdot A_{hc}(sn)\right\}\frac{1}{4}\not{\bar{n}}\not{n}\,\psi_{hc}(0)$

Soft-Collinear Effective Theory Form Factor

NK, Vanderhaeghen 2010

$$\langle p'|\bar{\chi}_n\gamma_{\perp\mu}\chi_{\bar{n}} + \bar{\chi}_{\bar{n}}\gamma_{\perp\mu}\chi_n|p\rangle_{SCET} = \bar{N}(p')\,\frac{\not{\bar{n}}\not{n}}{4}\gamma_{\perp\mu}\,N(p)\,f_1(\Lambda Q,\mu_F)$$



quark

antiquark

Soft spectator contribution

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

$Q^2 = 9 - 25\text{GeV}^2$

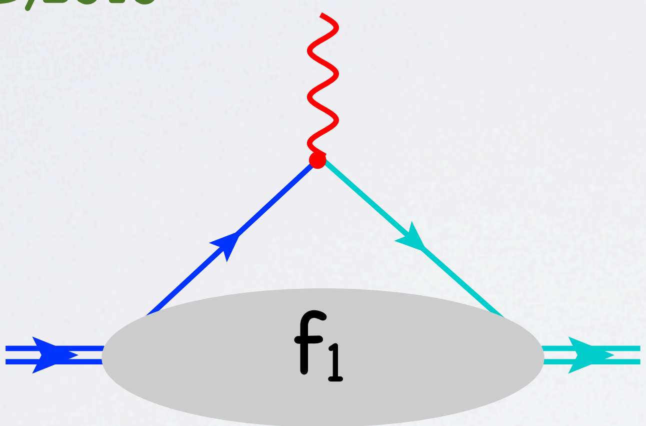
$\Lambda \simeq 0.3\text{GeV}$

➡ $Q\Lambda \simeq 0.9 - 1.5\text{GeV}^2$

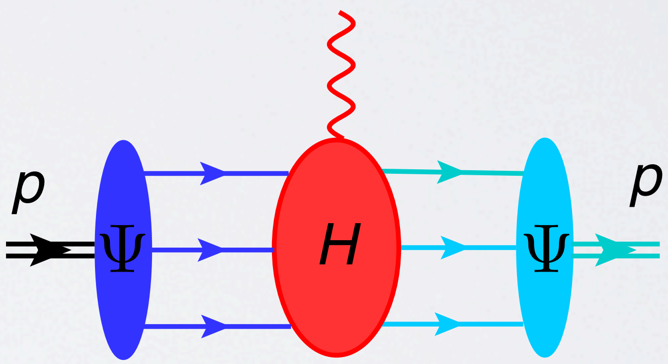
NK, Vanderhaeghen PRD,2010

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

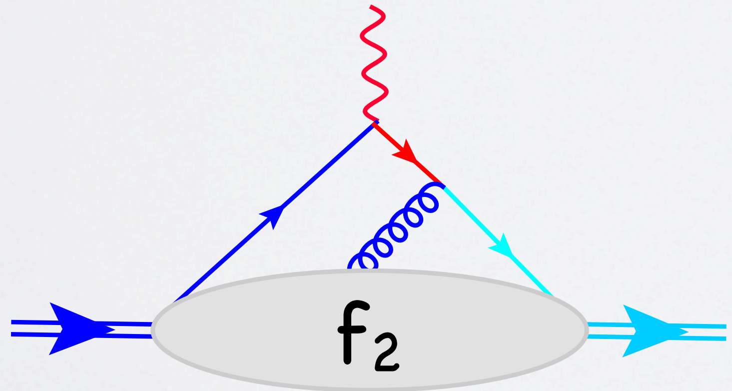
$F_1(Q) =$



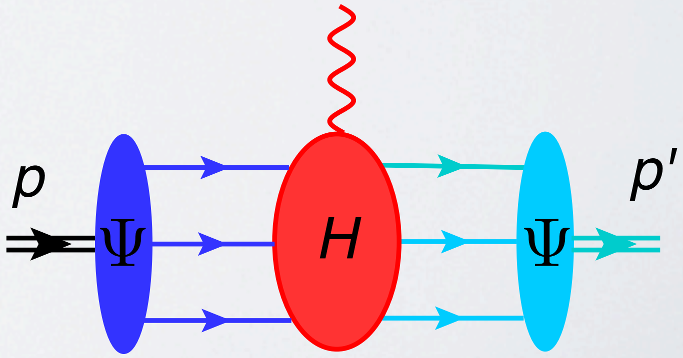
$+$



$F_2(Q) =$

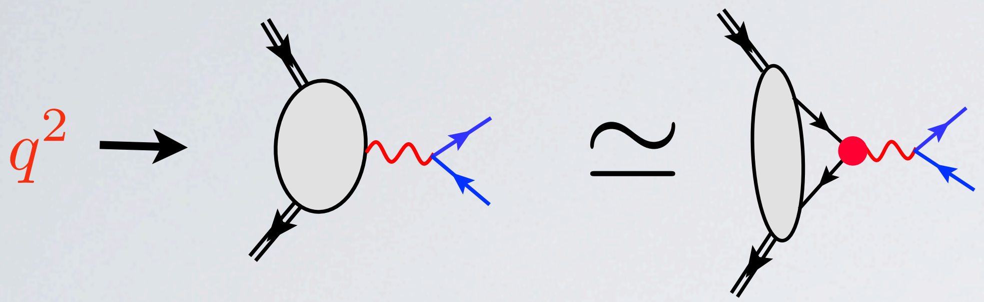


$+ \frac{4m_N^2}{Q^2}$ f_1 $+$



Soft spectator mechanism in SL and TL regions

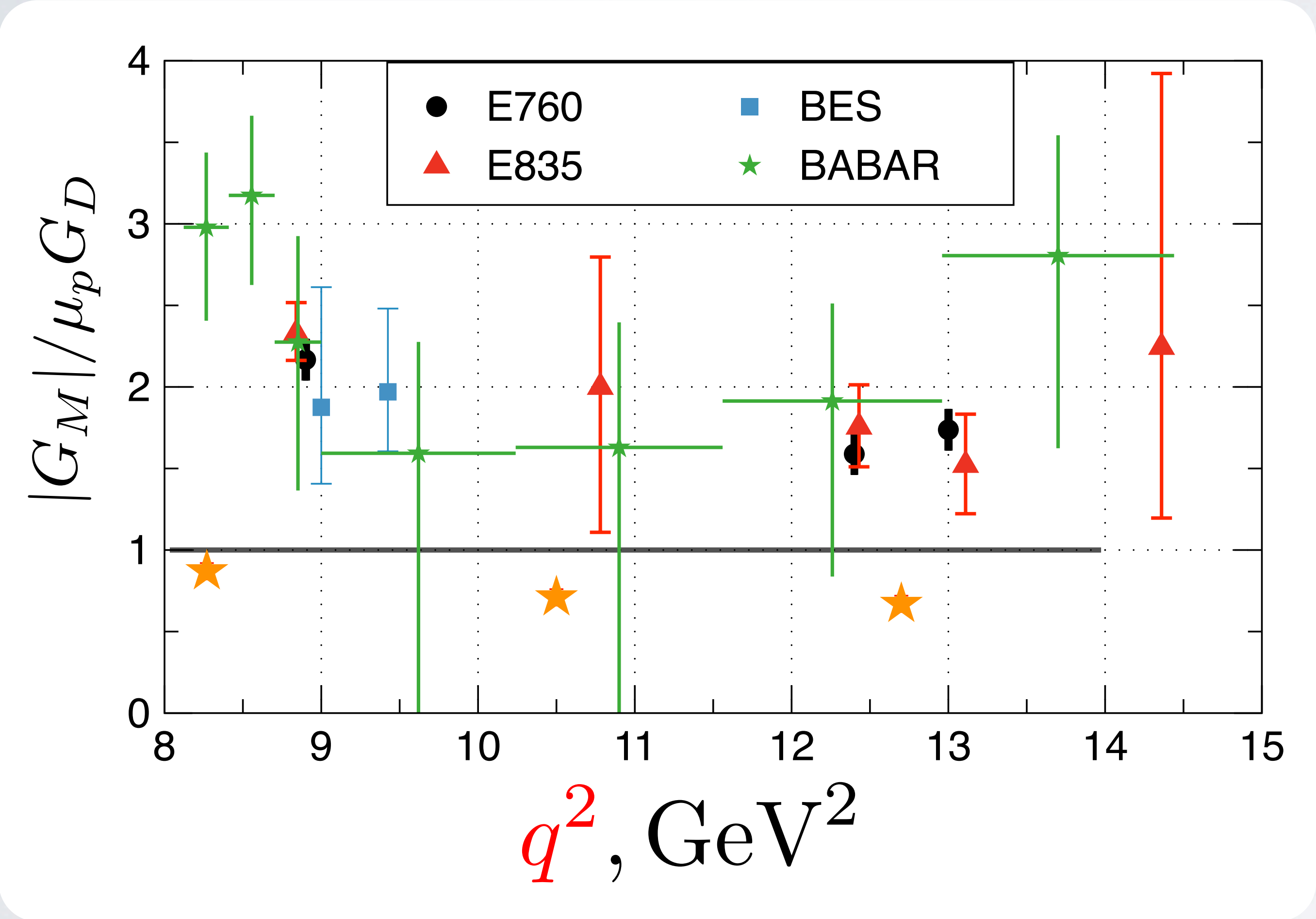
$q^2 \gg \Lambda \quad q\Lambda \lesssim m_N^2$ (timelike scattering)



$$G_M(Q^2 \to \infty) = |G_M(q^2 \to \infty)|$$

analytic function in q^2

(Phragmen-Lindelöf theorem)



Current experiment: used assumptions

TL $|G_M|/\mu_p G_D \sim 2$ $|G_E| \approx |G_M|$

SL $G_M/\mu_p G_D \sim 0.9 - 0.7$

SL data

★ SLAC, Sill et al, 1993 $G_E \approx G_M/\mu_p$

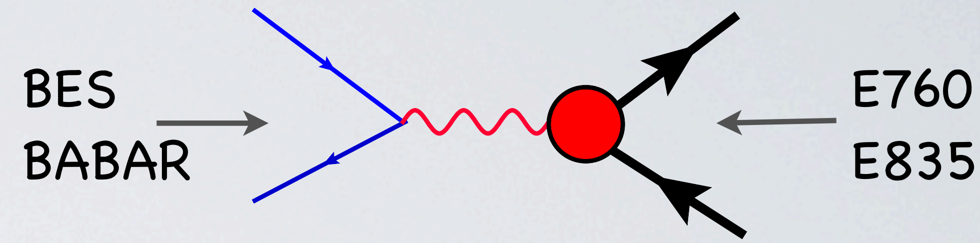
Soft spectator contribution:

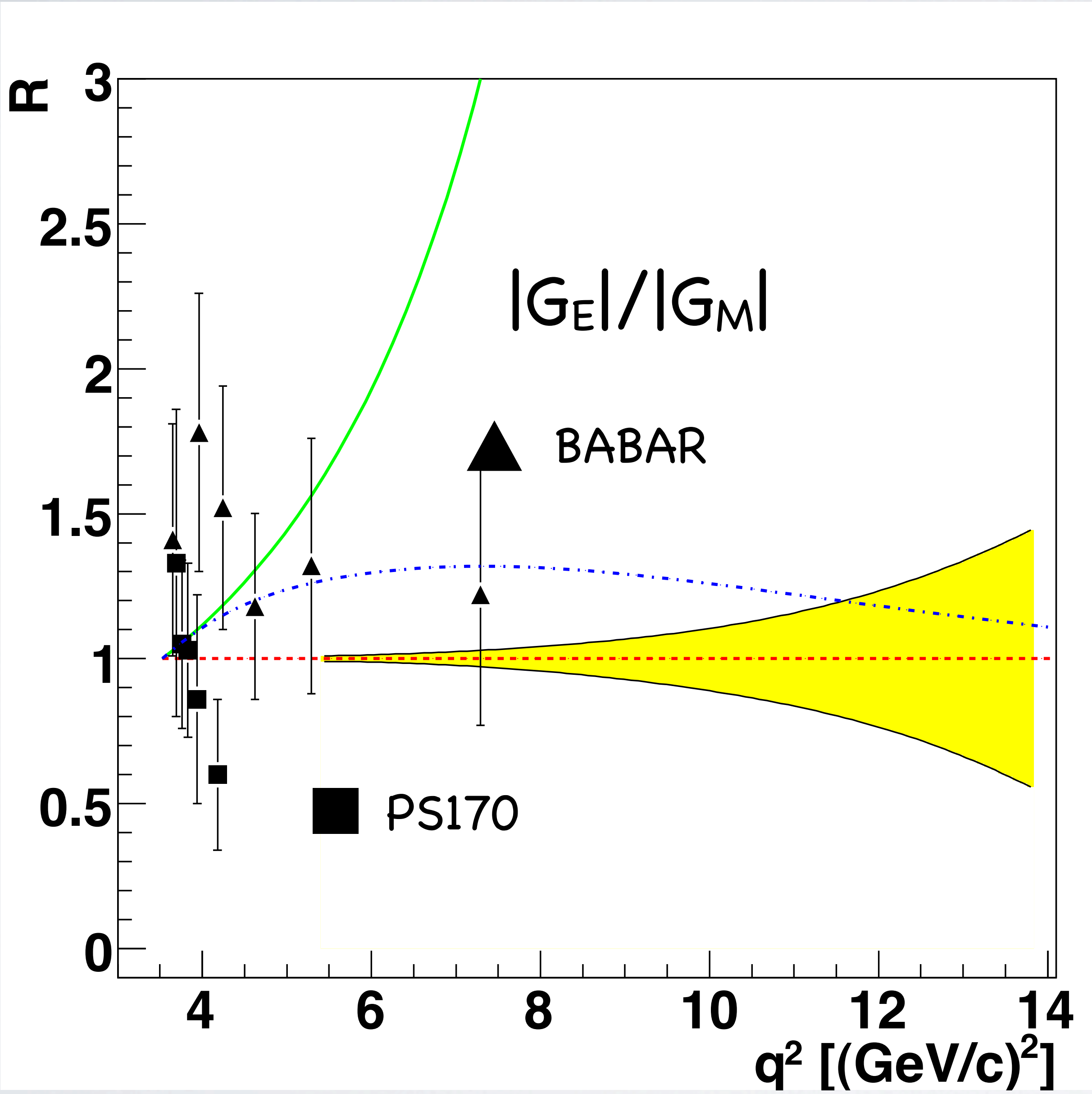
Sudakov logs provide ≈40% enhancement at large TL q^2

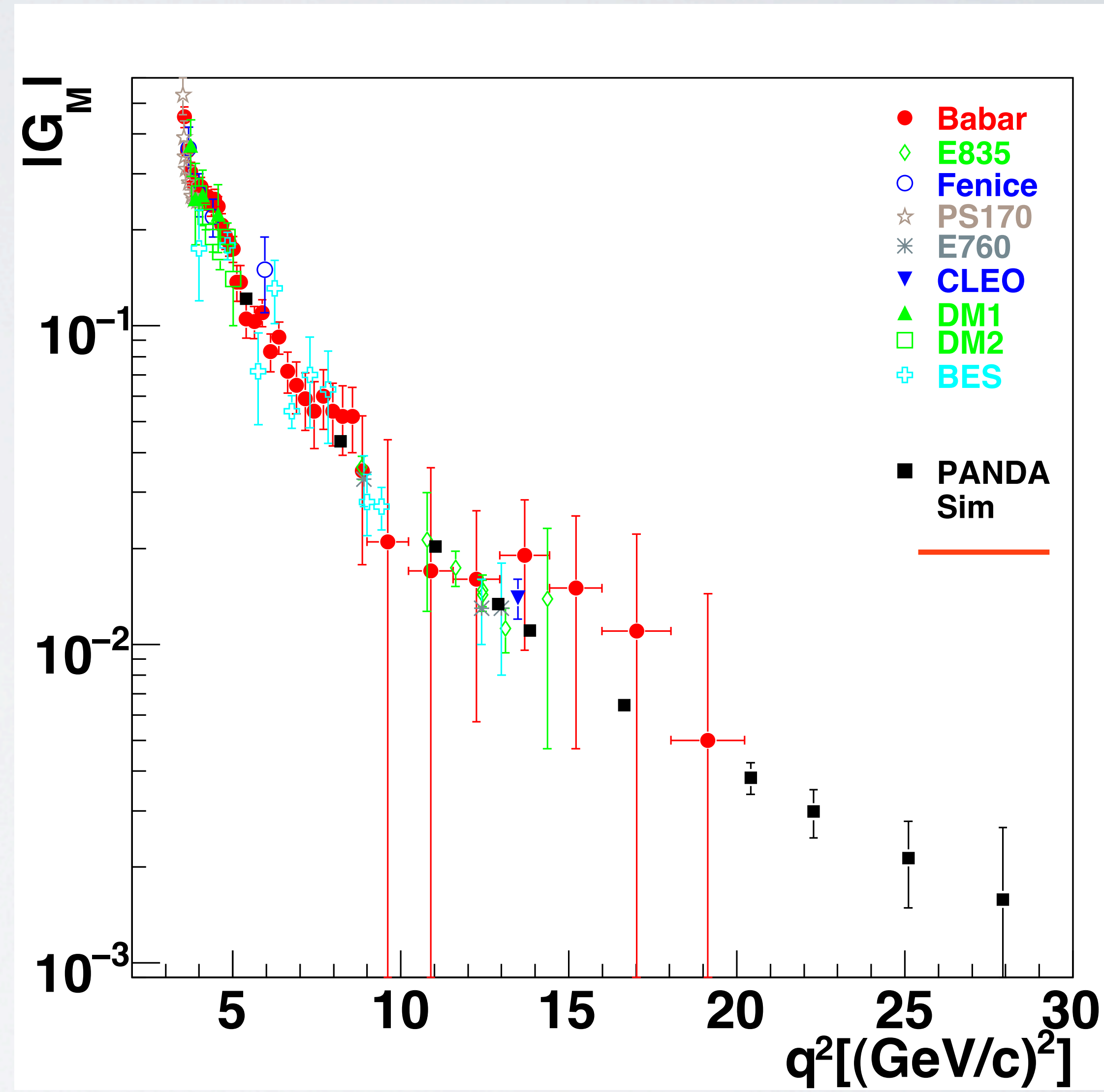
Hard spectator mechanism can not explain TL enhancement

Proton FFs in the time-like region $q^2>0$

$$p + \bar{p} \rightarrow e^- + e^+$$





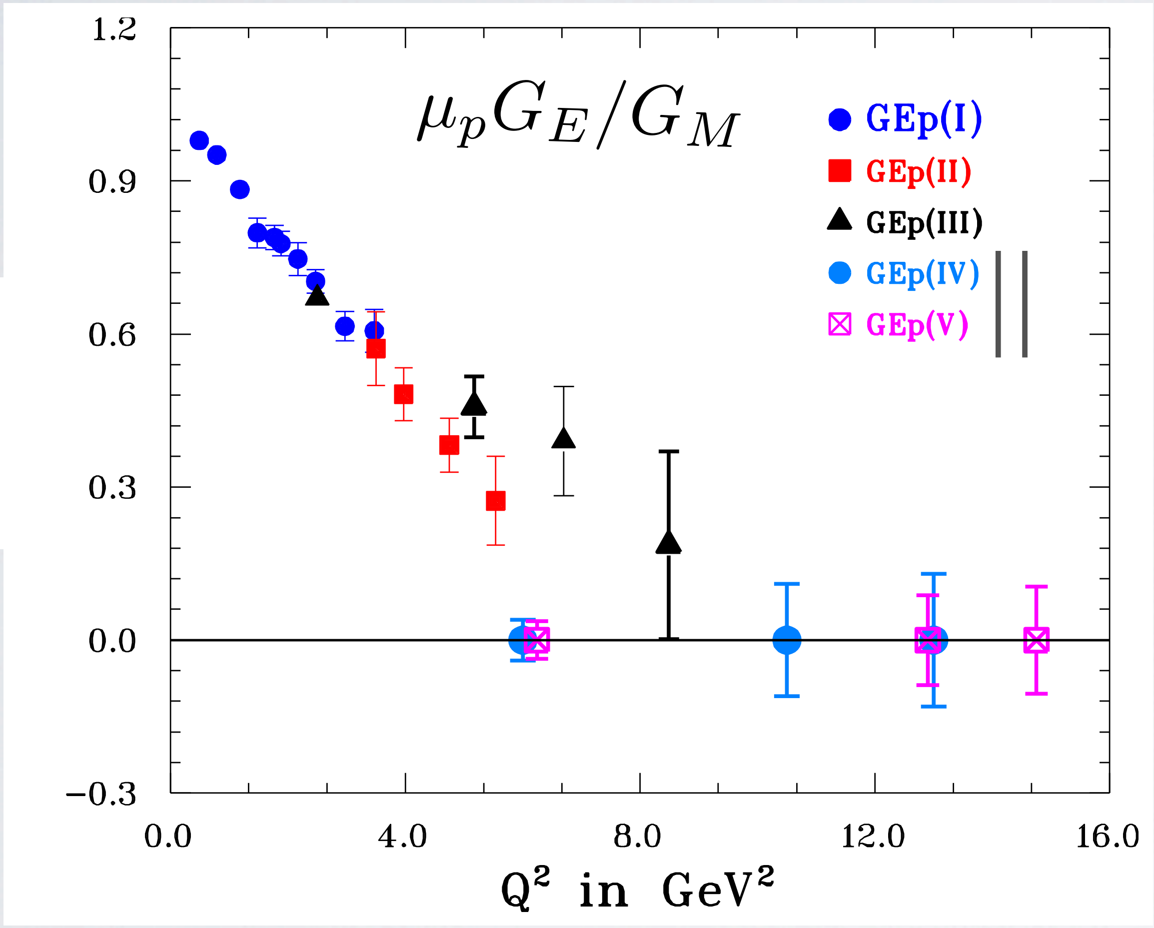


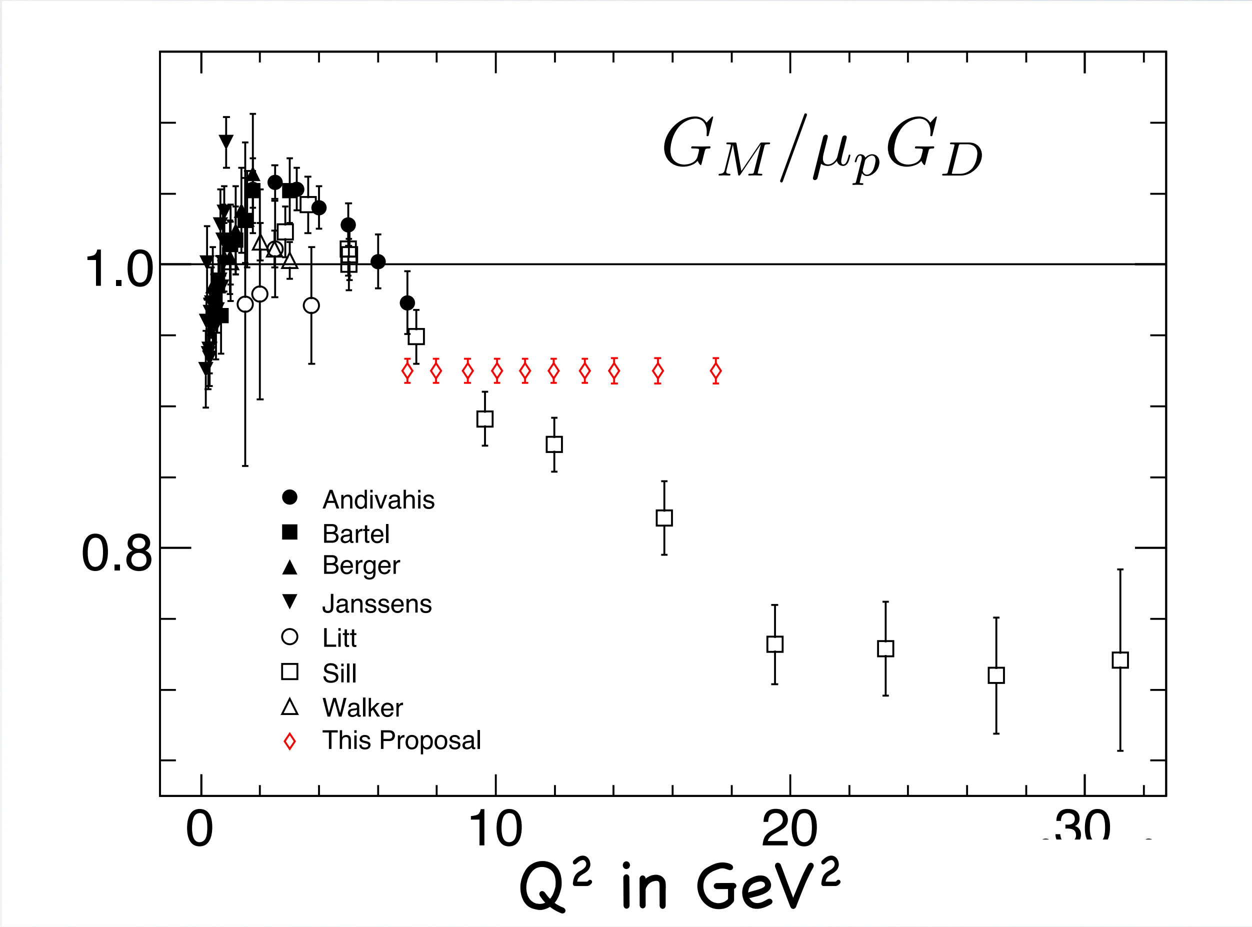
Sudol et al, 2009

Future experiments in JLab, SL:

G_E/G_M: $$\frac{P_t}{P_l} = -\sqrt{\frac{2\varepsilon}{\tau(1+\varepsilon)}}\frac{G_E}{G_M}$$

G_M: $$\sigma_R = G_M^2 + \frac{\varepsilon}{\tau} G_E^2$$

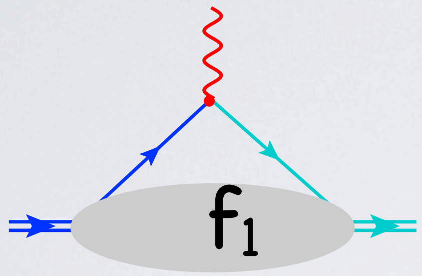


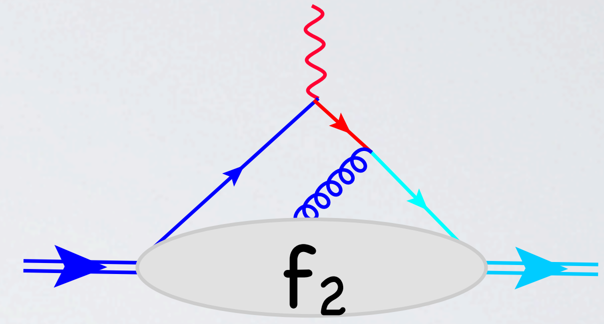


- JLab Hall A E1207-109 G_{Ep}/G_{Mp} recoil pol Q^2=6-14.8GeV^2
- JLab Hall C E1209-001 G_{Ep}/G_{Mp} recoil pol Q^2=6-13GeV^2
- JLab Hall A E1207-108 σ_R unpol Q^2=7-17.5GeV^2, total err. < 2%

The ratio G_E/G_M in SL and TL regions

- Assume that the soft spectator contribution dominates in G_E and G_M

$G_M(Q) \approx$  $= f_1(Q)$

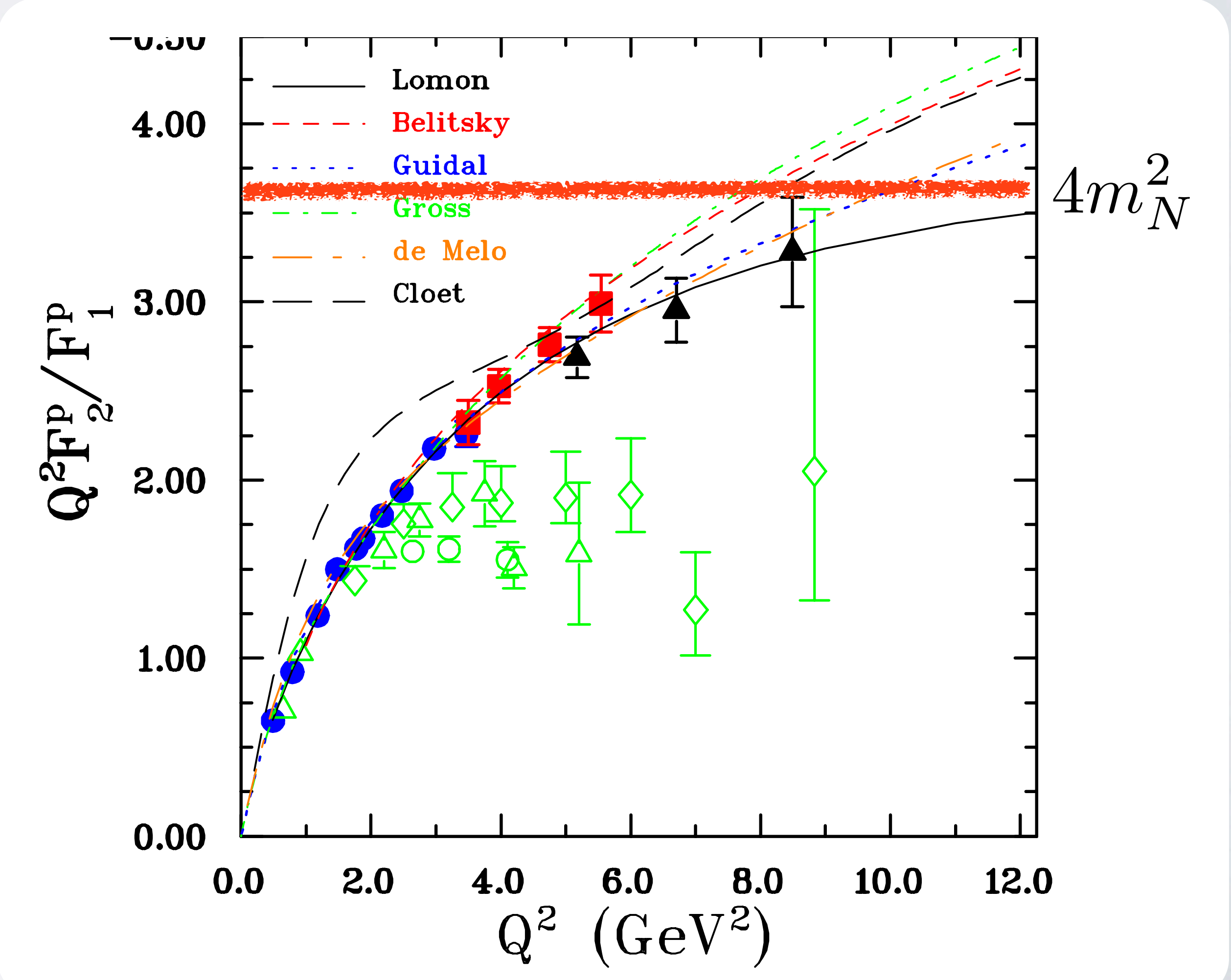
$G_E(Q) \approx -\frac{1}{4}$  $= -\frac{1}{4} f_2(Q)$

SL $$\frac{G_E}{G_M} = -\frac{1}{4}\frac{f_2(Q)}{f_1(Q)} + \mathcal{O}(1/Q^2) \approx 0$$

assuming $f_2(Q) \ll f_1(Q)$

$$\Rightarrow \frac{Q^2 F_2(Q^2)}{F_1(Q^2)} \approx \frac{\frac{1}{4}m^2 f_2 + 4m^2 f_1}{f_1} \simeq 4m_N^2$$

This is not pQCD asymptotic behavior!



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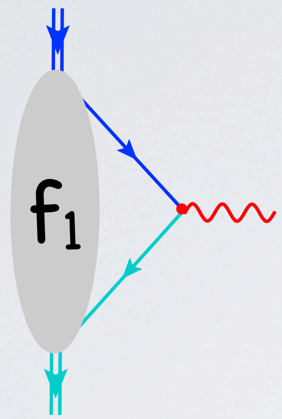
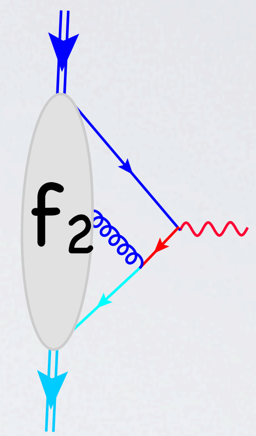
$G_M(Q) \approx$ 

$= f_1(Q)$

$G_E(Q) \approx -\frac{1}{4}$ 

$= -\frac{1}{4} f_2(Q)$

TL $$\frac{|G_E|}{|G_M|} = \frac{1}{4}\frac{|f_2(Q)|}{|f_1(Q)|} + \mathcal{O}(1/Q^2) \ll 1$$

we can also expect $|f_2(Q)| \ll |f_1(Q)|$

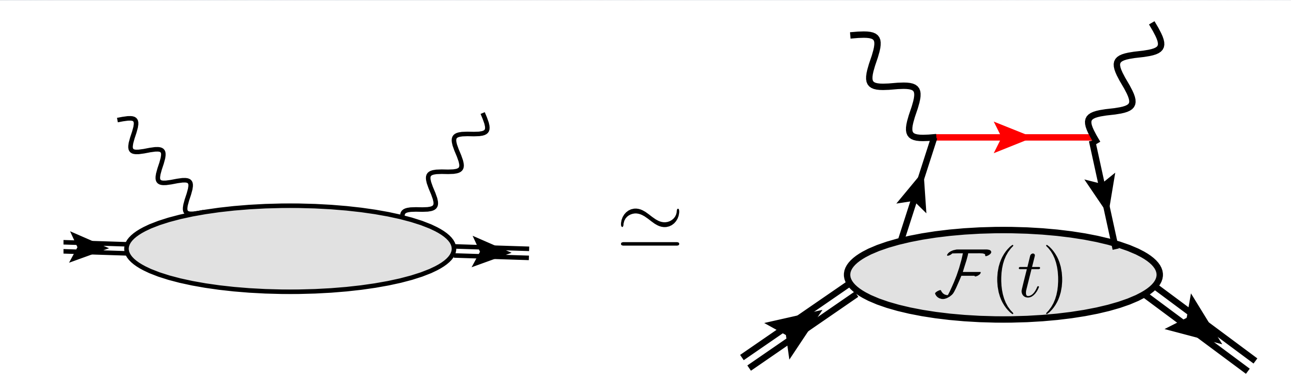
- Sudakov factors cancel in the ratio therefore TL modification can be weaker comparing FFs

- If G_E is small then the Rosenbluth separation is more sensitive to the TPE corrections

Wide Angle Compton Scattering in SL region

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

Dominance of the soft spectator scattering



GPD (handbag)-model

Radyshkin, 1998

Kroll et al, 2005

SCET approach

Kivel, Vanderhaeghen, 2012

$G_M \quad f_1 = e_u(f_1^u - f_1^{\bar{u}}) + e_d(f_1^d - f_1^{\bar{d}})$

WACS $\quad \mathcal{F} = e_u^2(f_1^u + f_1^{\bar{u}}) + e_d^2(f_1^d + f_1^{\bar{d}})$

SCET power counting

$$\frac{f_1^{\bar{q}}}{f_1^q} \sim \mathcal{O}((Q\Lambda)^{-2})$$

quarks dominate at large hard collinear scale

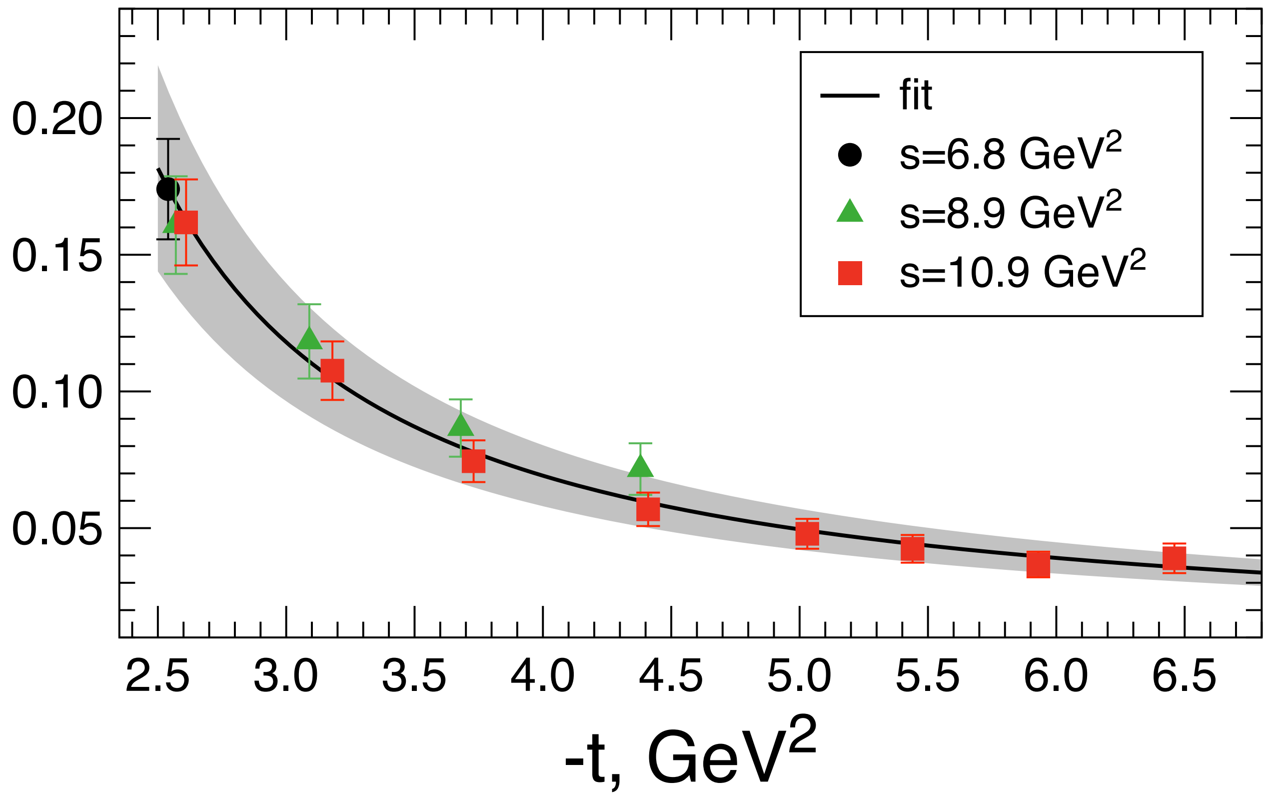
Wide Angle Compton Scattering in SL region

Kivel, Vanderhaeghen, 2012

ratio $\mathcal{F}(t) \simeq \frac{T_2(s,t)}{H_2(s,t)} \simeq \frac{T_4(s,t)}{H_4(s,t)} \simeq \frac{T_6(s,t)}{H_6(s,t)}$ $\frac{\text{amplitude}}{\text{hard coeff. f.}}$ approximately s-independent at LO

$$\frac{d\sigma}{dt} = \frac{d\sigma^{\gamma q \to \gamma q}(s,t)}{dt} |\mathcal{F}(t)|^2$$

used data: JLab, Hall A, 2007



fit $\mathcal{F}(t) = \frac{c}{\ln^2[-t/\Lambda^2]}$

$c = 0.10 \pm 0.01$

$\Lambda = 1.08 \pm 0.03$

$\chi^2/d.o.f. = 0.35$

Dominance of the soft spectator contribution in WACS

NK, Vanderhaeghen, 2012

circular photon polarizations (R,L)

recoiled proton: longitudinal pol.

$$K_{LL} = \frac{\sigma_{\parallel}^{R} - \sigma_{\parallel}^{L}}{\sigma_{\parallel}^{R} + \sigma_{\parallel}^{L}}$$

SCET results: $K_{LL} \simeq K_{LL}^{\mathrm{KN}}$

SCET FFs cancel and asymmetry is not sensitive to proton structure

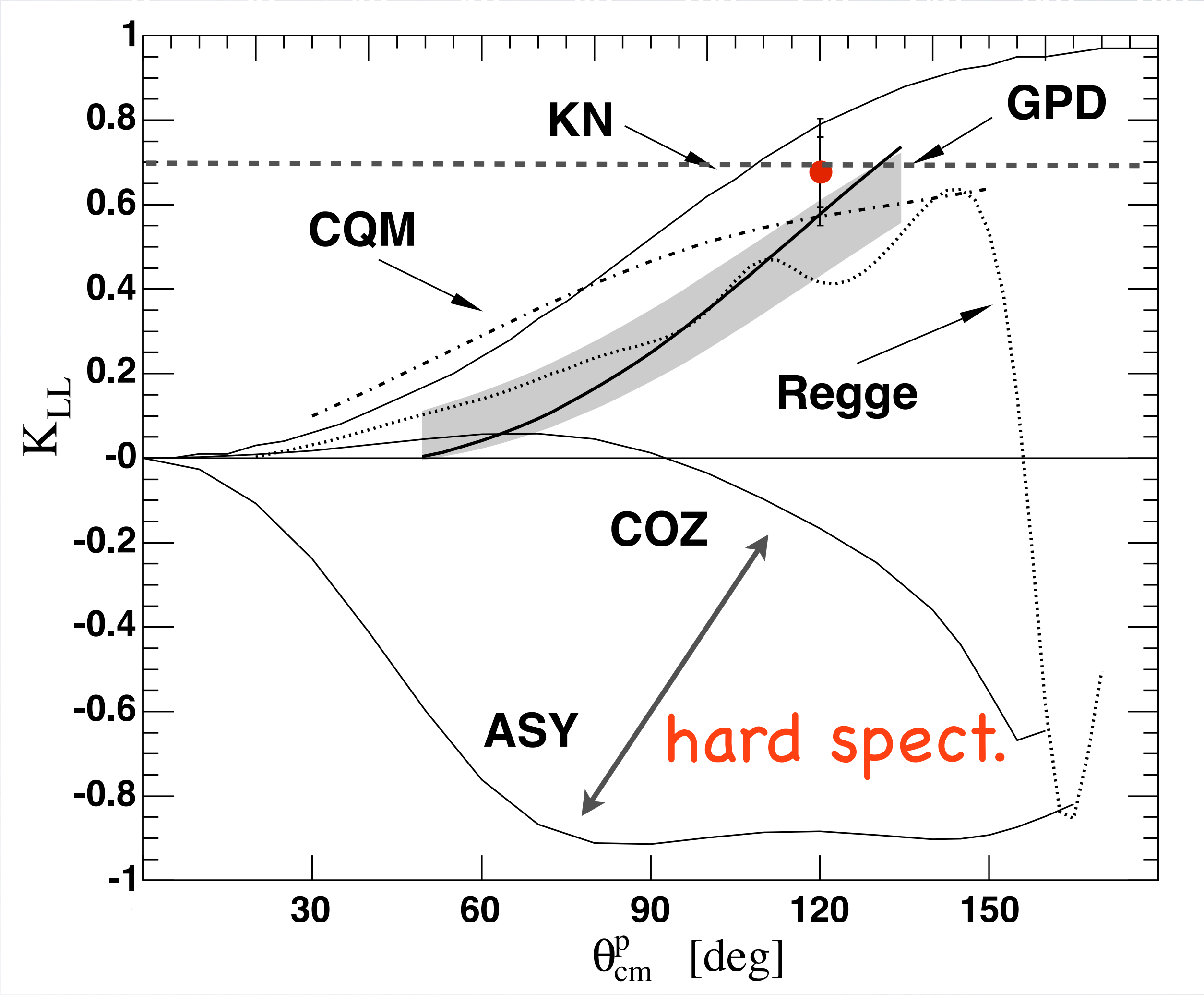
recoiled proton: transverse pol.

$$K_{LS} = \frac{\sigma_{\perp}^{R} - \sigma_{\perp}^{L}}{\sigma_{\perp}^{R} + \sigma_{\perp}^{L}}$$

SCET results: $K_{LS} \simeq \mathcal{O}(m^2/Q)$

u=-0.84GeV^2

JLAB, 2004 s=6.9GeV^2 t=-4GeV^2



$K_{LL} = 0.68 \pm 0.08$ (0.70)

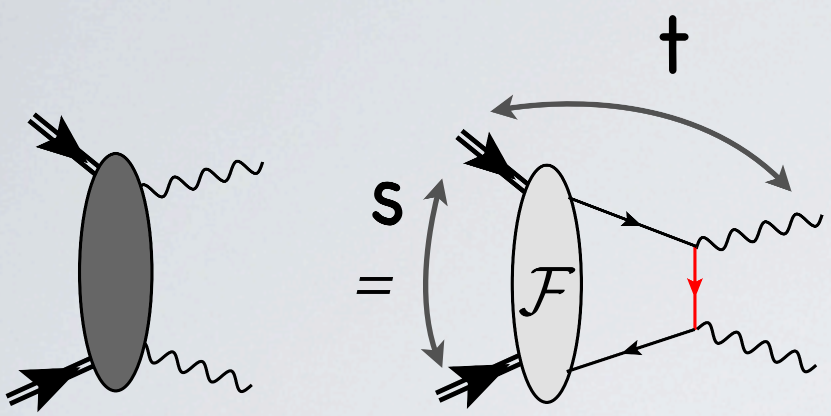
$K_{LS} = 0.114 \pm 0.08$ (0.066)

defined by power subleading terms (sensitive to helicity flip amplitudes)

Wide Angle Compton Scattering in TL region

Handbag model: Diehl, Kroll, Vogt 2002

SCET: Kivel, Vanderhaeghen (in progress)

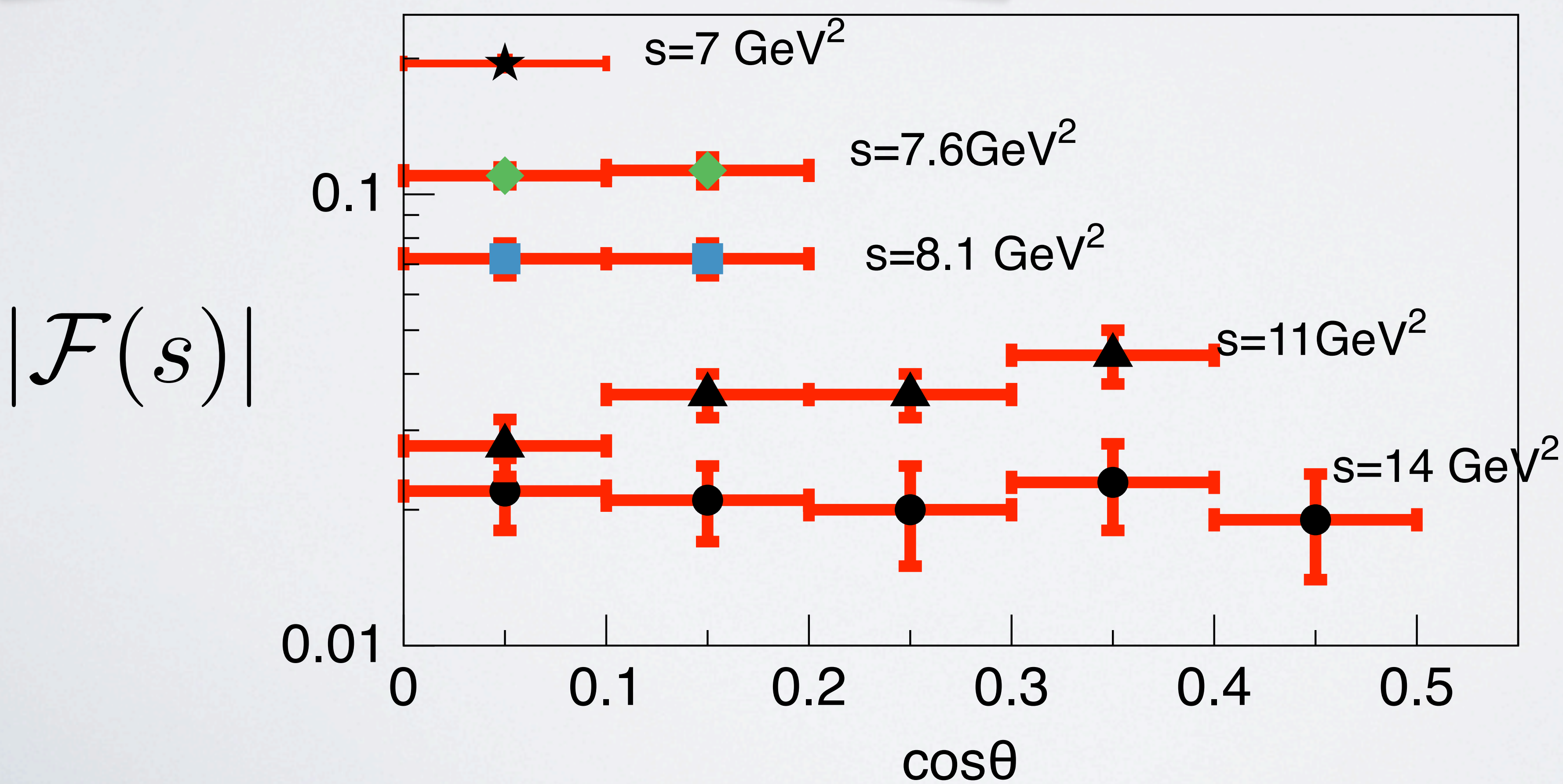


$$\mathcal{F}(s) \simeq \frac{T_2(s,\cos\theta)}{H_2(s,\cos\theta)} \simeq \frac{T_4(s,\cos\theta)}{H_4(s,\cos\theta)} \simeq \frac{T_6(s,\cos\theta)}{H_6(s,\cos\theta)}$$

$\cos\theta$ -independent!

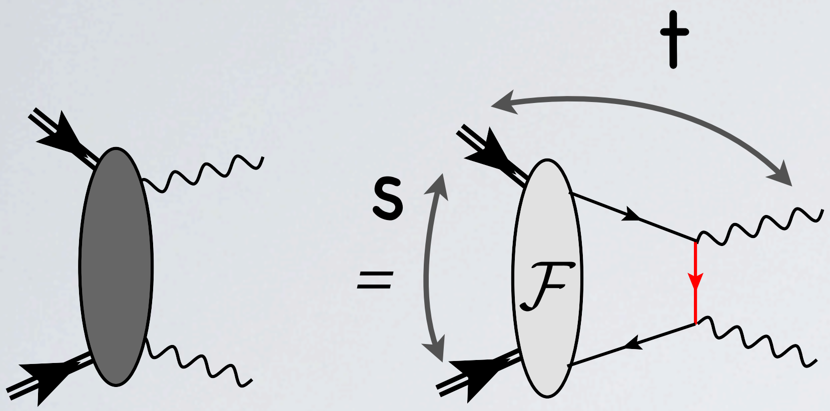
$$\frac{d\sigma}{d\cos\theta} = \frac{d\sigma^{q\bar{q}\to\gamma\gamma}(s,\cos\theta)}{d\cos\theta}\,|\mathcal{F}(s)|^2$$

used data: BELLE, 2005 $\gamma\gamma \to p\bar{p}$



$|t|,|u|>2.5\text{GeV}^2$

$B\bar{B}$ or Two Photon Production



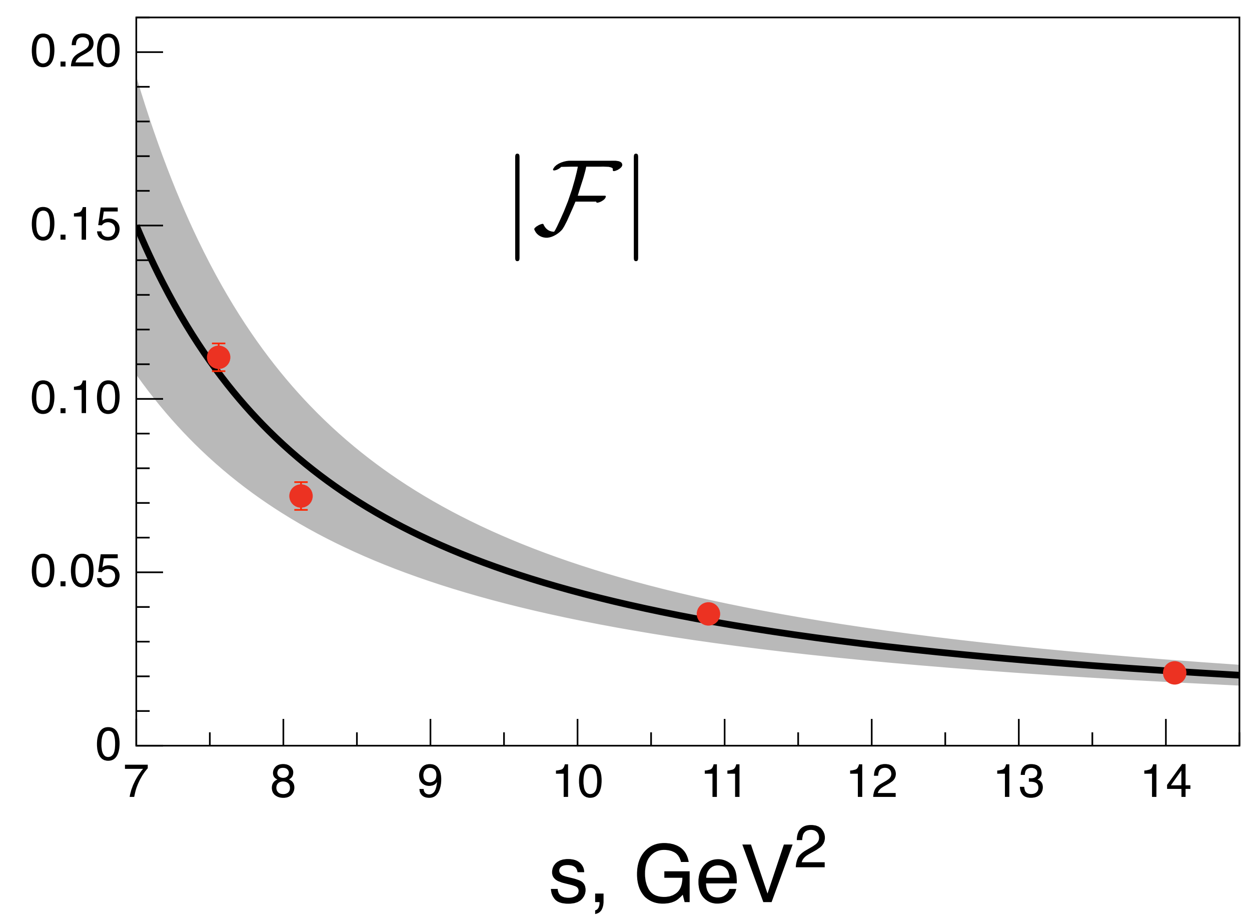
Kivel, Vanderhaeghen (in progress)

$$\mathcal{F}(s) \simeq \frac{T_2(s,\cos\theta)}{H_2(s,\cos\theta)} \simeq \frac{T_4(s,\cos\theta)}{H_4(s,\cos\theta)} \simeq \frac{T_6(s,\cos\theta)}{H_6(s,\cos\theta)}$$

$\cos\theta$

$$\frac{d\sigma}{d\cos\theta} = \frac{d\sigma^{q\bar{q}\to\gamma\gamma}(s,\cos\theta)}{d\cos\theta}|\mathcal{F}(s)|^2$$

used data: BELLE, 2005 $\gamma\gamma \to p\bar{p}$



fit $\quad |\mathcal{F}(s)| = \dfrac{c}{\ln^2[s/\Lambda^2]}$

$$c = 0.027 \pm 0.003$$

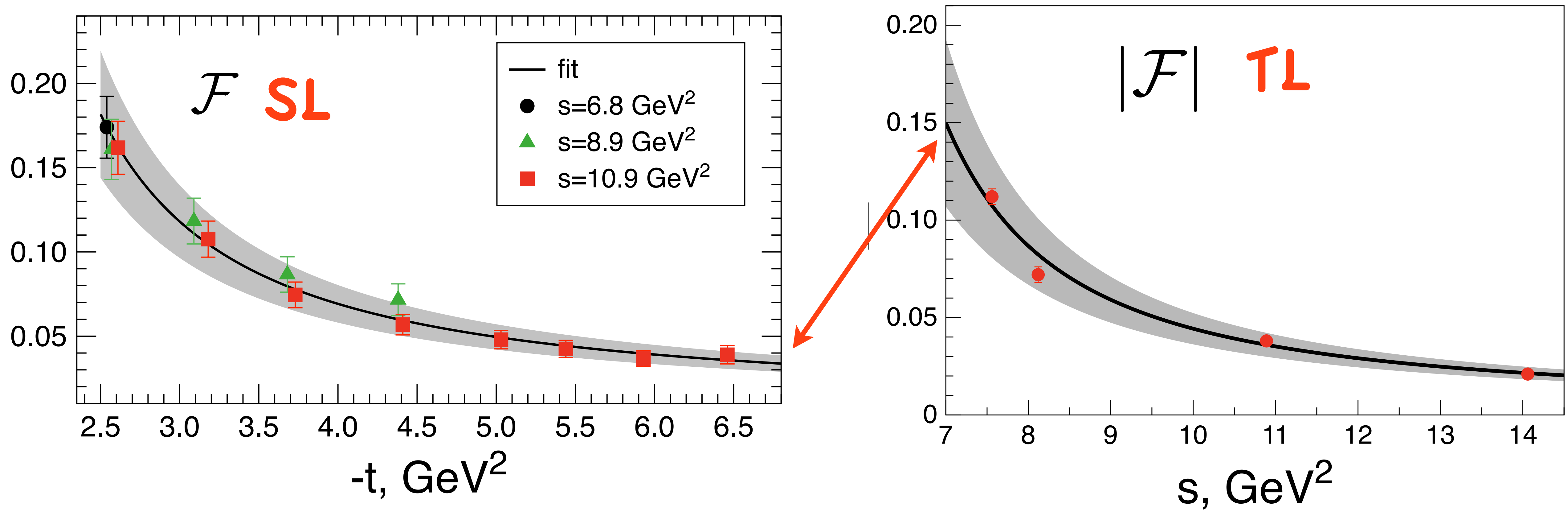
$$\Lambda = 2.13 \pm 0.04$$

$$\chi^2/d.o.f. = 4.5$$

SCET FFs in SL and TL regions

used data: JLab, Hall A, 2007

used data: BELLE, 2005 $\gamma\gamma \to p\bar{p}$

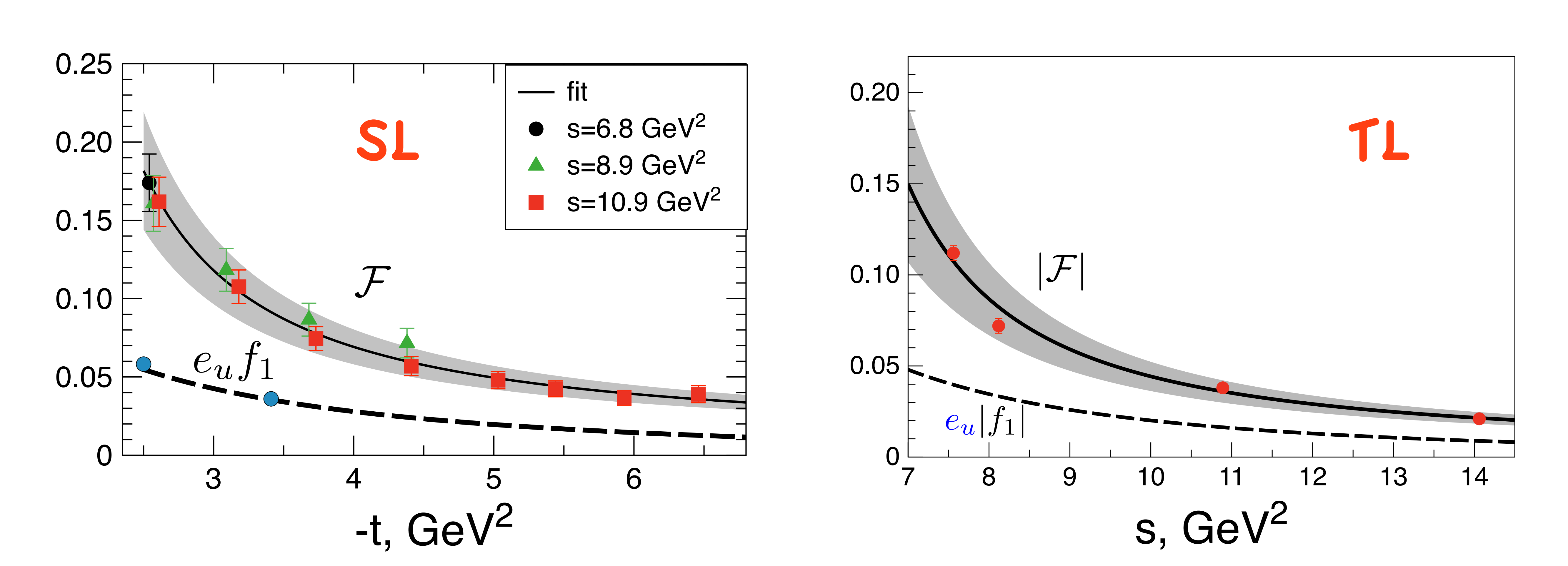


The large soft spectator contribution predicts

$$\frac{\text{TL}}{\text{SL}} \quad \frac{|\mathcal{F}(s)|}{\mathcal{F}(s)} > 1$$

enhancement in TL region as in FF case

FFs in SL and TL regions



$$\mathcal{F} = e_u^2(f_1^u + f_1^{\bar{u}}) + e_d^2(f_1^d + f_1^{\bar{d}})$$

G_M

$$|\mathcal{F}| = |e_u^2(f_1^u + f_1^{\bar{u}}) + e_d^2(f_1^d + f_1^{\bar{d}})|$$

$$e_u^2(f_1^u - f_1^{\bar{u}}) + e_d^2(f_1^d - f_1^{\bar{d}})$$

WACS

$$e_u|f_1| = |e_u^2(f_1^u - f_1^{\bar{u}}) + e_u e_d(f_1^d - f_1^{\bar{d}})|$$

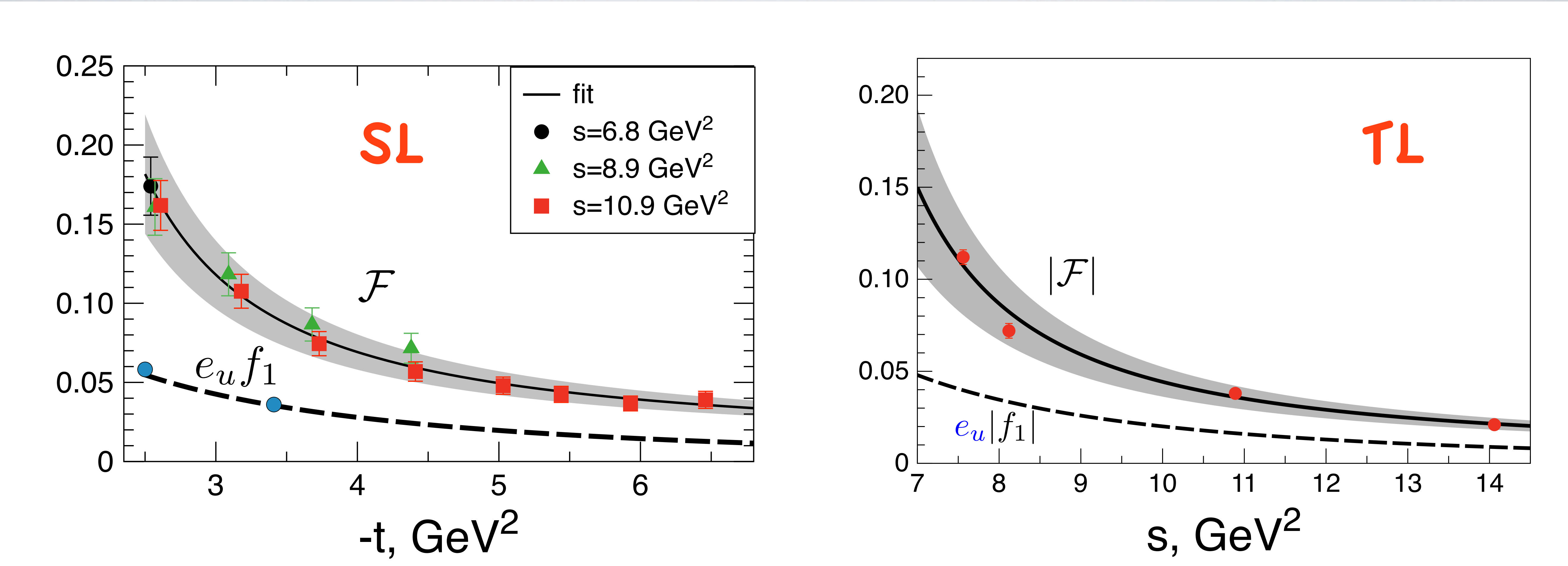
$$e_u f_1 = e_u^2(f_1^u - f_1^{\bar{u}}) + e_u e_d(f_1^d - f_1^{\bar{d}})$$

$$|f_1| \simeq |G_M|$$

$$f_1 \simeq G_M \frac{\tau + R}{1 + \tau} \qquad \tau = Q^2/4m_N^2$$

$$R = G_E/G_M$$

FFs in SL and TL regions



$$\mathcal{F} = e_u^2(f_1^u + f_1^{\bar{u}}) + e_d^2(f_1^d + f_1^{\bar{d}})$$

G$_M$

$$|\mathcal{F}| = |e_u^2(f_1^u + f_1^{\bar{u}}) + e_d^2(f_1^d + f_1^{\bar{d}})|$$

$$e_u^2(f_1^u - f_1^{\bar{u}}) + e_d^2(f_1^d - f_1^{\bar{d}})$$

WACS

$$e_u|f_1| = |e_u^2(f_1^u - f_1^{\bar{u}}) + e_u e_d(f_1^d - f_1^{\bar{d}})|$$

$$e_u f_1 = e_u^2(f_1^u - f_1^{\bar{u}}) + e_u e_d(f_1^d - f_1^{\bar{d}})$$

Is it really antiquarks? (from DIS we know that # of antiquarks at large x is very small !!!)

SCET FFs in TL regions: alternative approach

NK, Vanderhaeghen (in progress)

Assume that antiquark contribution is very small $f_1^{\bar{q}} \ll f_1^{q}$

$$|\mathcal{F}| \approx |e_u^2 f_1^u + e_d^2 f_1^d| \qquad |f_1| \approx |e_u f_1^u + e_d f_1^d|$$

- use $|G_{eff}|$ from the FF data $|G_{eff}|(s) \simeq \dfrac{C}{s^2 \ln^2[s/\Lambda^2]}$ with $C=66.8\,\text{GeV}^2$, $\Lambda=300\,\text{MeV}$
  - consider as a free parameters

    $\Delta\phi$ relative phase between F_1 and F_2 $(\cos\Delta\phi < 0)$

    $r = |f_1^d|/|f_1^u|$ ratio of the abs. values of the quark ffs

    δ relative phase between f_1^d and f_1^u

- kinematical power corrections have been added

SCET FFs in TL regions: alternative approach

NK, Vanderhaeghen (in progress)

Assume that antiquark contributions are very small $f_1^{\bar{q}} \ll f_1^q$

$$|\mathcal{F}| \approx |e_u^2 f_1^u + e_d^2 f_1^d| \qquad |f_1| \approx |e_u f_1^u + e_d f_1^d|$$

$$|f_1| \simeq |G_M|$$

Our model

$$|\mathcal{F}|^2 \approx \frac{e_u^2 |f_1|^2}{1 - \cos^2 \Delta\phi \frac{4\tau}{(1+\tau)^2}} \frac{1 + r/2 + r^2/16}{1 - r + r^2/4}$$

$$r = |f_1^d|/|f_1^u|$$

$$\tau = \frac{s}{4m_N^2}$$

assuming (NB!)

$$|G_M| = |G_E| \Leftrightarrow |F_2| \simeq \frac{-2\cos\Delta\phi}{1+\tau}|F_1|$$

$$\frac{4\tau}{(1+\tau)^2} = \frac{16 m_N^2}{s} + \mathcal{O}(1/\tau)$$

large

assuming

$$\Re f_1^u f_1^{*d} \approx |f^u||f_1^d|$$

we need

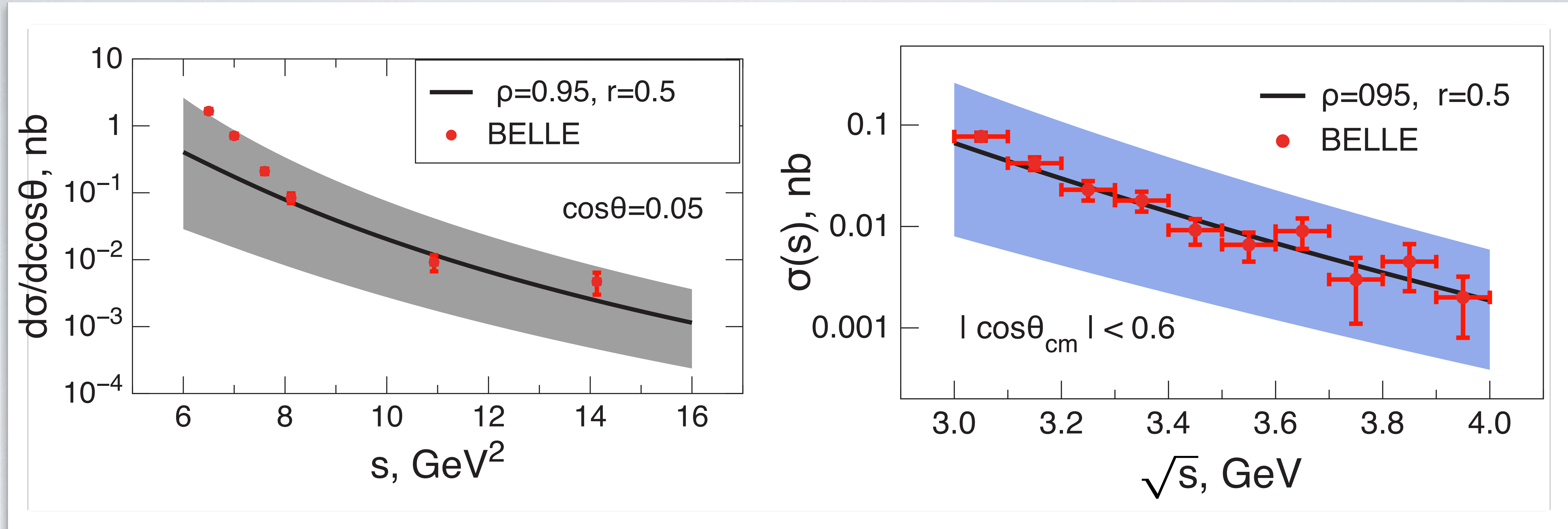
$$\cos\Delta\phi \simeq -0.95$$

$$r \simeq 0.5 - 0.6$$

for s=11-14 GeV^2

Description $B\bar{B}$ production

$\gamma\gamma \to p\bar{p}$ data Belle collab., 2005 NK, Vanderhaeghen (in progress)



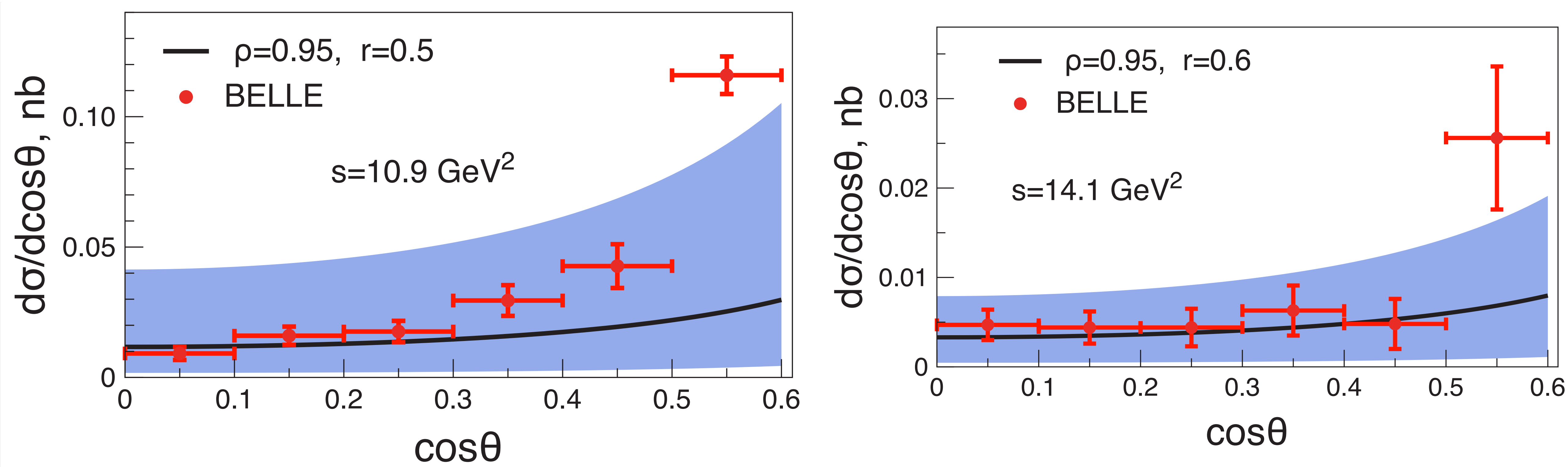
$$|G_{eff}|(s) \simeq \frac{C}{s^2 \ln^2[s/\Lambda^2]}$$ with C=66.8GeV^2 Λ=300MeV

shaded area $0 < r = |f_1^d|/|f_1^u| < 1$ $0 < \rho = -\cos\Delta\phi < 1$

relative phase between F_1 and F_2

Description $B\bar{B}$ production

$\gamma\gamma \to p\bar{p}$ data Belle collab., 2005 NK, Vanderhaeghen (in progress)



$$|G_{eff}|(s) \simeq \frac{C}{s^2 \ln^2[s/\Lambda^2]}$$ with $C=66.8GeV^2$ $\Lambda=300MeV$

shaded area

$$0 < r = |f_1^d|/|f_1^u| < 1$$

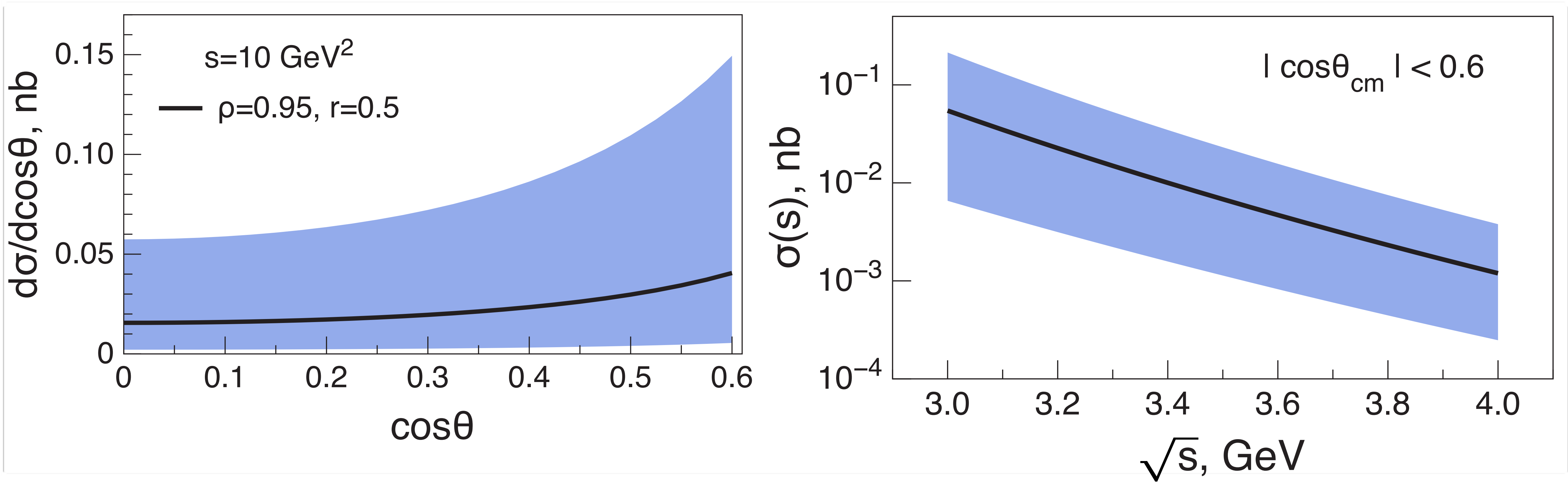
$$0 < \rho = -\cos\Delta\phi < 1$$ relative phase between F_1 and F_2

Description $B\bar{B}$ production

PANDA $p\bar{p} \longrightarrow \gamma\gamma$

predictions

NK, Vanderhaeghen (in progress)



$$|G_{eff}|(s) \simeq \frac{C}{s^2 \ln^2[s/\Lambda^2]}$$ with $C=66.8\,GeV^2$ $\Lambda=300\,MeV$

shaded area $0 < r = |f_1^d|/|f_1^u| < 1$

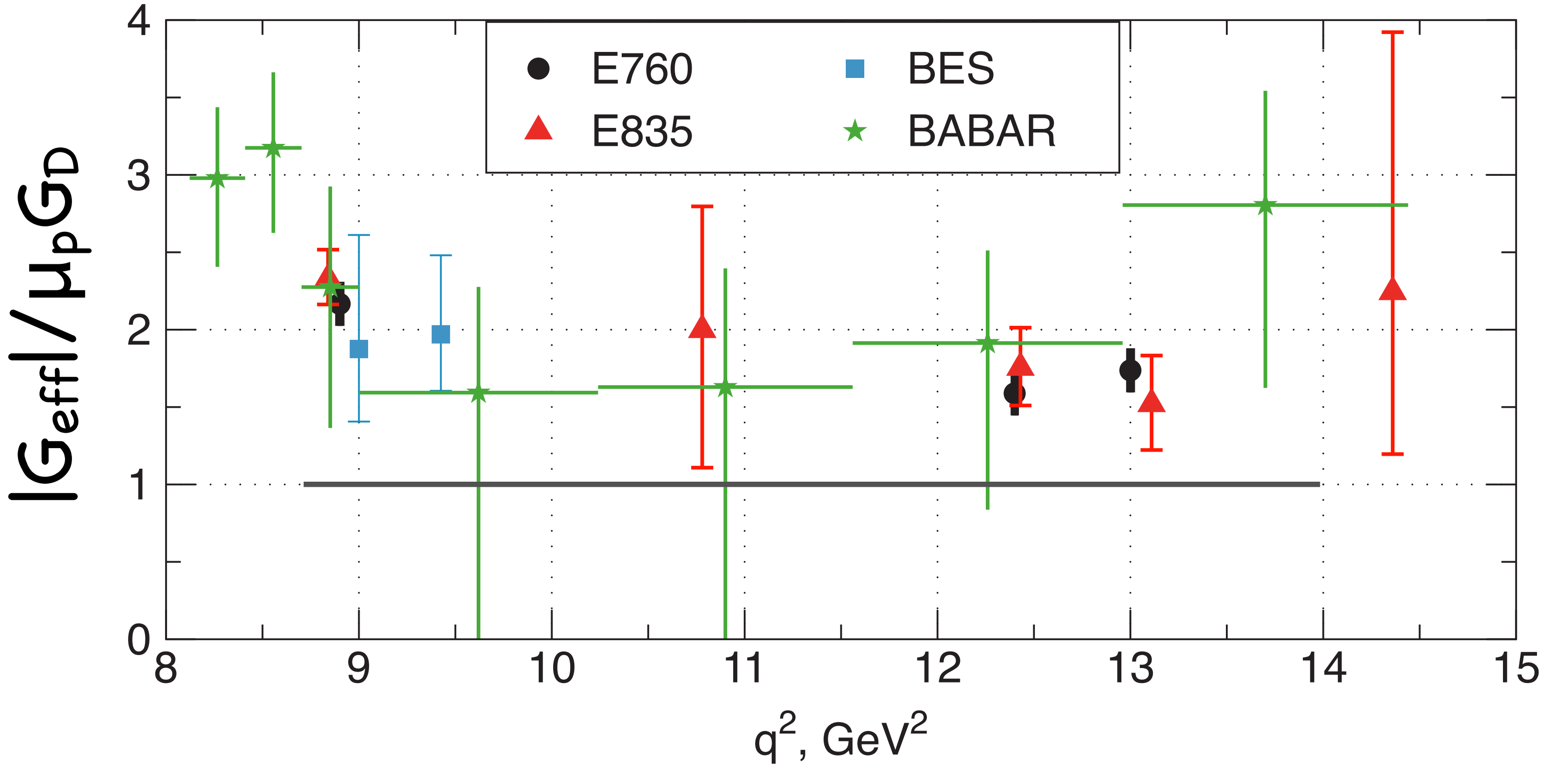
$0 < \rho = -\cos\Delta\phi < 1$ relative phase between F_1 and F_2

Conclusions

- QCD factorization for e.m. FFs includes hard and soft spectator contributions.
- There are indications that the soft spectator contribution is large or even dominant for moderate values of Q^2 : $Q\Lambda \sim m_N^2$

  FF enhancement in the TL region
- The full Q^2 dependence of the soft spectator contribution can not be computed from pQCD but can be described by universal form factors within SCET factorization framework
- QCD factorization allows us to study the soft spectator mechanism in other reactions: WACS in SL and 2γ(or $B\bar{B}$)-production in TL regions
- Soft overlap in WACS and e.m. FF are not completely independent and the new data (SL and TL) will help to understand much better corresponding long-distance dynamics
- SCET factorization provides predictions which can be checked experimentally in SL (JLab) and TL (PANDA) regions

FFs ratio: timelike vs. spacelike region



enhancement in TL region

$$\frac{|G_{eff}|}{\mu_p G_D} \simeq 2$$

$$\frac{|F_1|_{\rm TL}}{|F_1|_{\rm SL}} \simeq \frac{|e^{-S}U_1|_{\rm TL}}{|e^{-S}U_1|_{\rm SL}} \frac{|f_1(q)|_{\rm TL}}{|f_1(Q)|_{\rm SL}}$$

Sudakov logs provide enhancement at large time-like q^2