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QCD analysis of leading-neutron production at HERA: Determination of neutron fracture functions

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in collaboration with

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Outline

- Leading-neutron production at HERA

❖ H1 Measurements

❖ ZEUS Measurements

- Phenomenological Models

❖ One-Pion-Exchange (OPE)

❖ Fracture Functions Formalism

- SKTJ17 models for the neutron FFs at input scale $Q_0^2 = 1\ GeV^2$
- Results of the analysis
- Summary and Conclusions

Leading nucleon production

- Leading nucleons have been observed in positron-proton collisions at HERA.
- These data sets cover a large kinematic range.
- The leading neutrons and protons are produced with low transverse momentum ($p^T <$ 0.7 GeV) and carry a large fraction of the incoming proton's energy ($x_L > 0.2$).

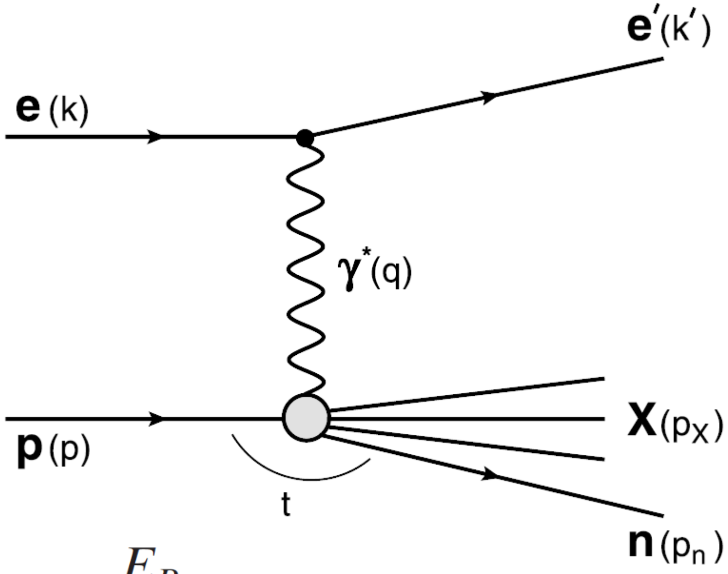
- From the theoretical point of view, there are several models that try to explain the leading-baryon production.
- In the framework of QCD, the study of leading-baryon production represents an important field of investigation.

F. D. Aaron et al. (H1 Collaboration), Eur. Phys. J. C **68**, 381 (2010).
S. Chekanov et al. (ZEUS Collaboration), Nucl. Phys. B **637**, 3 (2002).

Leading nucleon production cross section

- Semi-inclusive structure function $F_L^{LB(4)}(\beta, Q^2, x_L, t)$ is defined by the four-fold differential cross section for leading nucleon production.

$$\frac{d^4\sigma(ep \to e'BX)}{d\beta dQ^2 dx_L dt} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{\mathrm{LB}(4)}(\beta, Q^2, x_L, t) + F_L^{\mathrm{LB}(4)}(\beta, Q^2, x_L, t).$$



- Leading nucleon transverse SF $F_2^{\mathrm{LB}(4)}(\beta, Q^2, x_L, t)$
- Leading nucleon longitudinal SF $F_L^{\mathrm{LB}(4)}(\beta, Q^2, x_L, t)$
- Longitudinal momentum fraction carried by produced leading nucleon $x_L \simeq \frac{E_B}{E_p}$
- Fraction of momentum carried by the interacting parton $\beta = \frac{x}{1 - x_L}$

- The t-integrated differential cross section

$$\frac{d^3\sigma(ep \to e'BX)}{d\beta dQ^2 dx_L} = \int_{t_0}^{t_{\min}} \frac{d^4\sigma(ep \to e'BX)}{d\beta dQ^2 dx_L dt} dt$$
$$= \frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{\mathrm{LB}(3)}(\beta, Q^2, x_L)$$
$$+ F_L^{\mathrm{LB}(3)}(\beta, Q^2, x_L),$$

- The integration limits are:

$$t_{\min} = -(1 - x_L)\left(\frac{m_N^2}{x_L} - m_p^2\right),$$

$$t_0 = t_{\min} - \frac{(p_T^{\max})^2}{x_L}.$$

p_T^{max} is the upper limit of the neutron transverse momentum $p_{\mathrm{T}}^{\max} = E_n\theta_n^{\max} = 0.656 x_{\mathrm{L}}$ GeV

- The reduced cross section

$$\sigma_r^{LN(3)} = F_2^{LN(3)}(\beta, Q^2, x_L) - \frac{y^2}{1+(1-y)^2} F_L^{LN(3)}(\beta, Q^2, x_L)$$

- The leading neutron structure functions can be written in terms of neutron FFs and hard-scattering coefficients.
- The contribution from longitudinally structure functions can be neglected.

F. A. Ceccopieri, Eur. Phys. J. C **74**, 3029 (2014).

Samira Shoeibi, Hamzeh Khanpour, F. Taghavi-Shahri, Kurosh Javidan, Phys Rev D **95** (2017), 074011

Leading-neutron production at HERA

- Our first physics objective is to establish the set of neutron FFs that gives the optimum theoretical description of the available hard scattering leading neutron production data.
- With the advent of the *ep* collider HERA, at the DESY laboratory in Hamburg, the kinematic range of the DIS regime has been widely extended, allowing to achieve a much deeper knowledge of the structure of the matter.

- The data sets that we will use is the following:

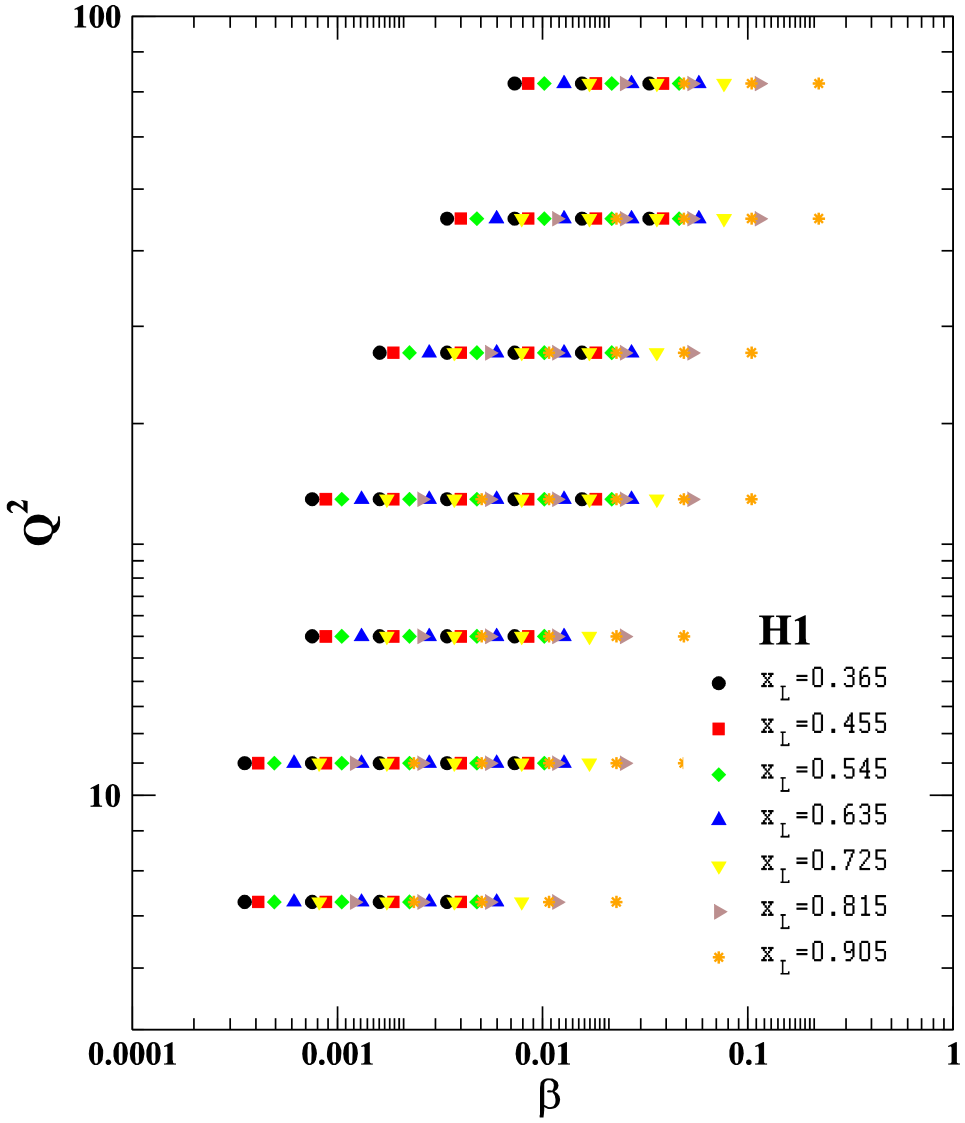
❑ The H1 data on the leading neutron production in DIS scattering

F. D. Aaron et al. (H1 Collaboration), Eur. Phys. J. C **68**, 381 (2010).

❑ The leading neutron production in an $e^{+}p$ collision from the ZEUS collaboration

S. Chekanov et al. (ZEUS Collaboration), Nucl. Phys. B **637**, 3 (2002).

H1 DIS kinematics



The semi-inclusive cross section data for the production of a leading neutron are taken during the years of 2006 and 2007 by the H1 collaboration at HERA in DIS positron-proton scattering.

H1 experiment at HERA, covers a large range of kinematics

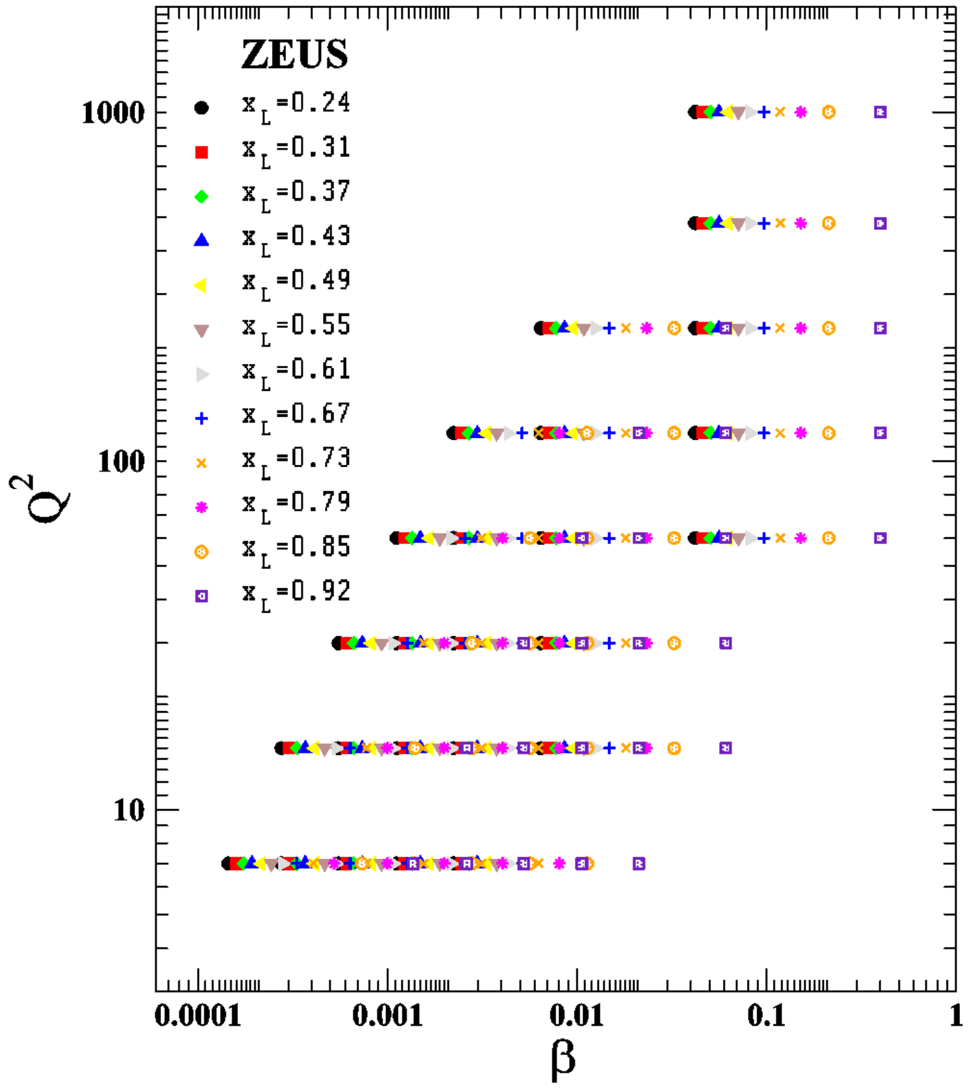
$$6\ GeV^2 < Q^2 < 100\ GeV^2 \qquad 1.5 \times 10^{-4} < x < 3 \times 10^{-2}$$

The value of the longitudinal momentum fraction x_L covers the range from 0.365 to 0.905.

Upper limit of the neutron transverse momentum 200 MeV to enhance the One-Pion-Exchange mechanism

$$p_T^{Max} < 200\ MeV$$

ZEUS DIS kinematics **ZEUS**



ZEUS collaboration presented the leading neutron production cross sections for $x_L > 0.2$ in neutral current electron-proton collisions at HERA.

$$Q^2 \sim 10^4\ GeV^2 \qquad 1.1 \times 10^{-4} < x < 3.2 \times 10^{-2}$$

Neutron scattering angle $\theta_n^{max} < 0.8$ mrad.

Transverse momenta of $p_T^{max} < 0.656\ x_L\ GeV$

Phenomenological Models

❖ One-Pion-Exchange (OPE)

❖ Fracture Functions Formalism

One-Pion-Exchange (OPE)

- One-Pion-Exchange model describes the process in which a leading neutron is produced.

- Dominate at large values of x_L $\quad 0.64 < x_L < 0.82$

$$\beta = \frac{x}{1 - x_L} \qquad\qquad x_L \simeq \frac{E_B}{E_p}$$

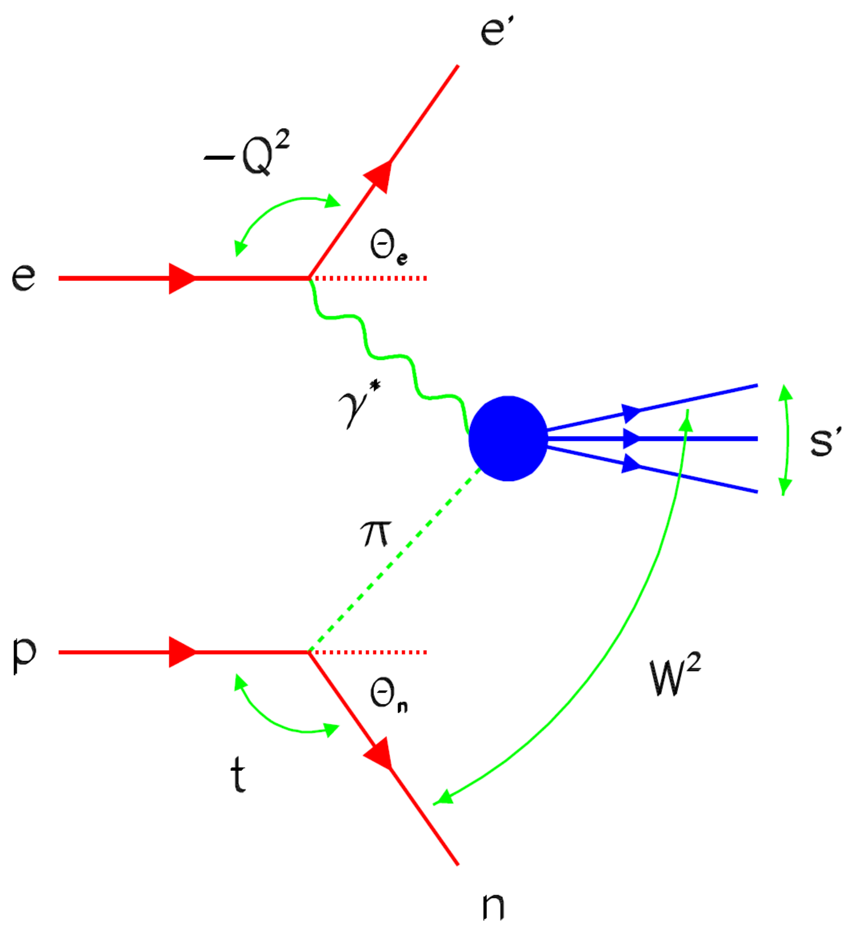


Diagram describing the One-Pion-Exchange mechanism with the production of a leading-neutron.

- These energetic neutrons can be produced in the fragmentation of the proton remnant.

- The pion exchange mechanism is expected to dominate leading neutron production at large x_L and low transverse momentum of the neutron p_T.

- The proton fluctuates into a state consisting of a positively charged pion and a neutron $p \longrightarrow n\pi^+$. The virtual photon subsequently interacts with a parton from the pion.

- The cross section factorizes into two parts: one factor describes the proton fluctuation into a $n\pi^+$ state and the other describes the photon-pion scattering.

- The cross section for photon-proton scattering to the final state nX

$$\mathrm{d}\sigma\left(ep \rightarrow e'nX\right) = f_{\pi^+/p}(x_L, t) \cdot \mathrm{d}\sigma\left(e\pi^+ \rightarrow e'X\right)$$

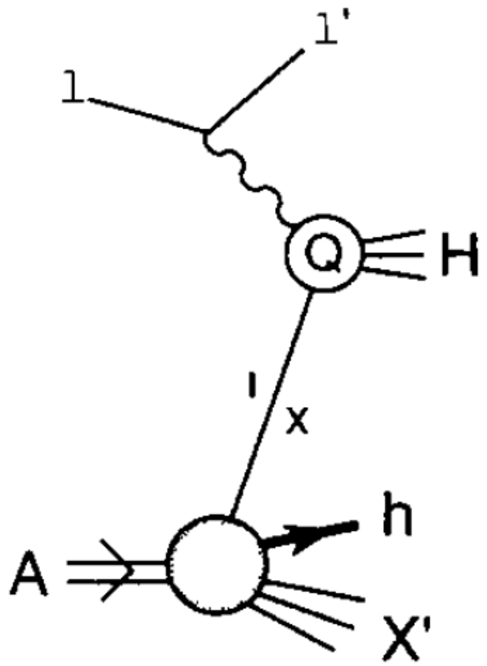
Pion flux associated with the splitting of a proton into a $\pi^+ n$ system

Cross section of the positron-pion interaction

Fracture Functions Formalism

- In the Fracture Functions formalism, the leading particles production is described in terms of structure functions of the fragmented nucleon.
- We have used the `fracture functions` to describe semi-inclusive hard processes in perturbative QCD.
- We have shown that `the fracture functions` factorize correctly and evolve in Q^2 in a perturbative way.

$$\sigma_{\text{target}}(z,Q) = \int_0^{1-z} \frac{dx}{x} M'_{A,h}(z,x,Q)\,\sigma'_{\text{hard}}(x,Q)$$



L. Trentadue, G. Veneziano, Phys. Lett. B **323** (1994) 201-211

Factorization properties

- The hypothesis of limiting fragmentation predicts that the lepton variables x and Q^2 completely separate from the baryon variables x_L

$$F_2^{\mathrm{LN}(4)}\left(x, Q^2, x_{\mathrm{L}}, p_{\mathrm{T}}\right) = f\left(x_{\mathrm{L}}, p_{\mathrm{T}}\right) \cdot F\left(x, Q^2\right)$$

- The measurement of leading neutron allows the validity of the hypothesis of limiting fragmentation to be tested, according to which the production of leading neutrons in the proton fragmentation region is independent of Q^2 and x.

- For neutrons in DIS, however, limiting fragmentation is broken at low x_L.

- Nucleon production by particle exchange, on the other hand, implies only a partial separation of the variables.

- Dependence of the cross section on the lepton variables should be independent of the baryon variables. In terms of the structure function $F_2^{LN(4)}$, this can be written as

$$\boxed{F_2^{\mathrm{LN}(4)}(x, Q^2, x_{\mathrm{L}}, p_{\mathrm{T}}) = f(x_{\mathrm{L}}, p_{\mathrm{T}}) \cdot F(x, Q^2)}$$

Baryon variables x_L, p_T

Lepton variables x, Q^2

- Hard-scattering factorisation states that the leading neutron structure functions can be written as:

$$F_k^{LN(3)}(\beta, Q^2, x_L, p_T^2) = \sum_i \int_\beta^1 \frac{d\xi}{\xi} M_{i/P}^N(\beta, \mu_F^2; x_L, p_T^2) \times C_{ki}\left(\frac{\beta}{\xi}, \frac{Q^2}{\mu_F^2}, \alpha_s(\mu_R^2)\right) + \mathcal{O}\left(\frac{1}{Q^2}\right).$$

The proton-to-neutron fracture functions

Hard scattering coefficient functions (the same as in fully inclusive DIS)

F. A. Ceccopieri, Eur. Phys. J. C **74**, 3029 (2014).

DGLAP evolution equations

- The evolution equations of neutron FFs are easily obtained by the DGLAP evolution equations for the singlet and gluon distributions:

- Singlet:

$$Q^2 \frac{\partial M^B_{\Sigma/P}(\beta, Q^2, x_L)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_\beta^1 \frac{du}{u} P^j_\Sigma(u) M^B_{\Sigma/P}\left(\frac{\beta}{u}, Q^2, x_L\right),$$

- Gluon:

$$Q^2 \frac{\partial M^B_{g/P}(\beta, Q^2, x_L)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_\beta^1 \frac{du}{u} P^j_g(u) M^B_{g/P}\left(\frac{\beta}{u}, Q^2, x_L\right),$$

Our goal

- The goal of this talk is to present SKTJ17 neutron FFs from QCD analysis of leading-neutron production in the semi-inclusive DIS reaction $ep \to enX$ at HERA.

Determination of neutron fracture functions from a global QCD analysis of the leading neutron production at HERA
Samira Shoeibi, Hamzeh Khanpour, F. Taghavi-Shahri and Kurosh Javidan
Phys. Rev. D 95, (2017) 074011, [arXiv:1703.04369 [hep-ph]].

SKTJ17 models for the neutron FFs

- We assume the following general initial functional form at input scale $Q_0^2 = 1\ GeV^2$

$$\beta M^N_{\Sigma/P}(\beta, Q_0^2, x_L) = \mathcal{A}_q(x_L)\beta^{a_q}(1-\beta)^{b_q}(1+c_q\beta),$$
$$\beta M^N_{g/P}(\beta, Q_0^2, x_L) = \mathcal{A}_g(x_L)\beta^{a_g}(1-\beta)^{b_g}(1+c_g\beta),$$

Lepton variables β, Q^2

where $A_q(x_L)$ and $A_g(x_L)$ are defined as

$$\mathcal{A}_q(x_L) = \mathcal{N}_q x_L^{A_q}(1-x_L)^{B_q}(1+C_q x_L^{D_q}),$$
$$\mathcal{A}_g(x_L) = \mathcal{N}_g x_L^{A_g}(1-x_L)^{B_g}(1+C_g x_L^{D_g}).$$

Baryon variable x_L

The x_L dependence of the neutron FFs is encoded in $A_i(x_L)$.

Leading neutron production data used in the SKTJ17 global analysis

- A list of all the leading neutron production data points above $Q^2 = 1\ GeV^2$ used in the SKTJ17 global analysis.

Experiments	$[x_L^{\min}, x_L^{\max}]$	$[x_B^{\min}, x_B^{\max}]$	Q^2 GeV^2	Number of data points	$\mathcal{N}_n$
H1	[0.365–0.905]	$[1.5 \times 10^{-4} - 3.0 \times 10^{-2}]$	7.3–82	203	0.9922
ZEUS	[0.240–0.920]	$[1.1 \times 10^{-4} - 3.2 \times 10^{-2}]$	7–1000	300	1.0033
Total data				**503**	

χ^2 minimization

- Global QCD extractions of neutron FFs are implemented around an effective $\chi 2$ function that quantifies the goodness of the fit to the data for a given set of theoretical parameters, which determine the PDFs at some input scale.

$$\chi_n^2(\{p_i\}) = \left(\frac{1-\mathcal{N}_n}{\Delta\mathcal{N}_n}\right)^2 + \sum_{j=1}^{N_n^{\text{data}}}\left(\frac{(\mathcal{N}_n\text{Data}_j - \text{Theory}_j(\{p_i\}))}{\mathcal{N}_n\delta\text{Data}_j}\right)^2,$$

- The $\chi 2$ function is minimized by the CERN program library MINUIT.

F. James and M. Roos, Comput. Phys. Commun. 10, 343 (1975).

The values of $\chi^2/_{N_{pts}}$ for the data sets

$$\chi^2(\{p_i\}) = \sum_{n=1}^{N^{\exp}} \sum_{j=1}^{N_n^{\text{data}}} w_j \frac{(\text{Data}_j - \text{Theory}_j(\{p_i\}))^2}{\delta\,\text{Data}_j}.$$

Experiment	Data set	χ^2	N_{pts}
H1	$x_L = 0.365$	24.13	29
	$x_L = 0.455$	25.62	29
	$x_L = 0.545$	19.36	29
	$x_L = 0.635$	19.28	29
	$x_L = 0.725$	17.33	29
	$x_L = 0.815$	13.23	29
	$x_L = 0.905$	10.15	29
All data sets		**130.05**	**203**
ZEUS	$x_L = 0.240$	24.84	25
	$x_L = 0.310$	9.68	25
	$x_L = 0.370$	11.68	25
	$x_L = 0.430$	48.45	25
	$x_L = 0.490$	21.11	25
	$x_L = 0.550$	24.84	25
	$x_L = 0.610$	17.74	25
	$x_L = 0.670$	28.18	25
	$x_L = 0.730$	6.61	25
	$x_L = 0.790$	3.02	25
	$x_L = 0.850$	7.88	25
	$x_L = 0.920$	15.02	25
All data sets		**219.10**	**300**

Neutron FFs uncertainties

- Standard Hessian method

- For observable $\mathcal{O}$

$$\Delta\mathcal{O} = \left[\Delta\chi^2_{\mathrm{global}} \sum_{i,j=1}^{k} \frac{\partial\mathcal{O}}{\partial p_i} C_{ij} \frac{\partial\mathcal{O}}{\partial p_j}\right]^{\frac{1}{2}}.$$

- For Neutron FFs

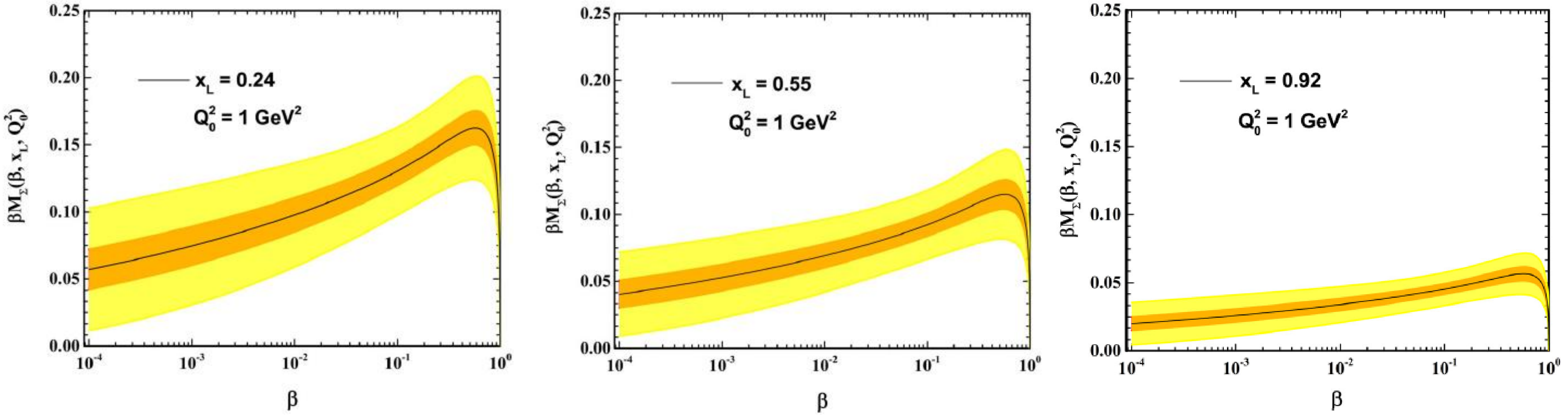
$$\Delta\beta M(\beta, Q^2, x_L) = \left\{\sum_{i=1}^{k}\left(\frac{\partial\beta M}{\partial p_i}\right)^2 C(p_i, p_i) + \sum_{i\neq j=1}^{k}\left(\frac{\partial\beta M}{\partial p_i}\frac{\partial\beta M}{\partial p_j}\right) C(p_i, p_j)\right\}^{\frac{1}{2}},$$

Parameter values for the SKTJ17 QCD fits

- Parameter values for the SKTJ17 QCD analysis at the input scale $Q_0^2 = 1\ GeV^2$

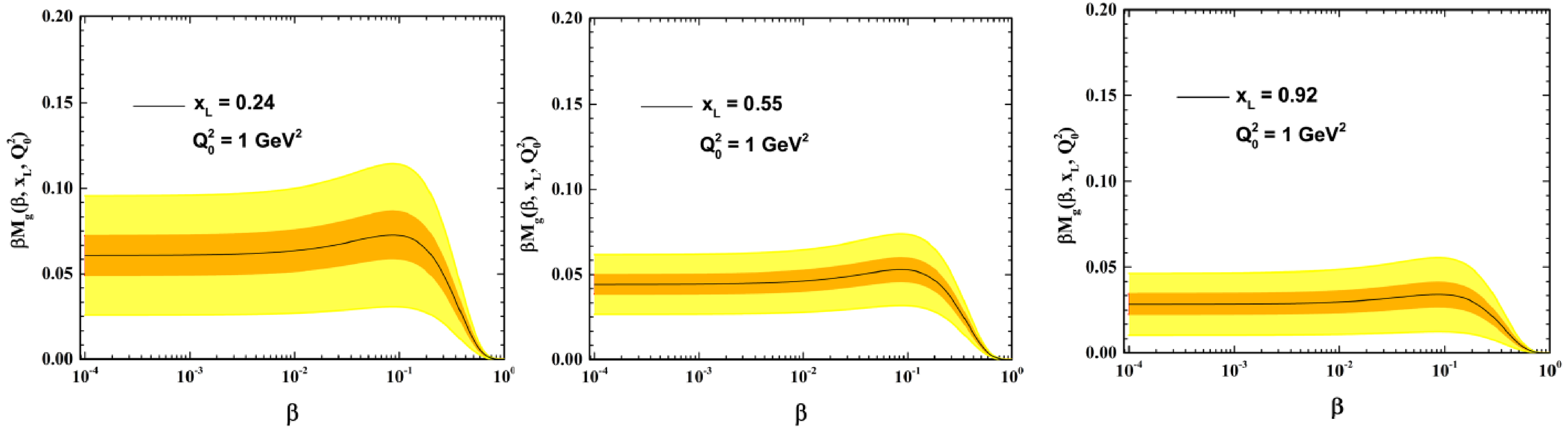
Parameters	$\beta M^N_{\Sigma/P}(\beta, Q_0^2, x_L)$	$p_i \pm \delta p_i$	$\beta M^N_{g/P}(\beta, Q_0^2, x_L)$	$p_i \pm \delta p_i$
a	a_q	0.116 ± 0.031	a_g	0.0^*
b	b_q	0.260^*	b_g	4.884^*
c	c_q	0.523^*	c_g	9.969^*
$\mathcal{N}$	$\mathcal{N}_q$	0.245 ± 0.023	$\mathcal{N}_g$	0.130 ± 0.027
A	A_q	0.0^*	A_g	0.201^*
B	B_q	1.430 ± 0.092	B_g	1.740 ± 0.117
C	C_q	12.071 ± 2.270	C_g	29.865^*
D	D_q	5.307 ± 0.390	D_g	6.733 ± 0.646

Singlet momentum distribution as a function of β



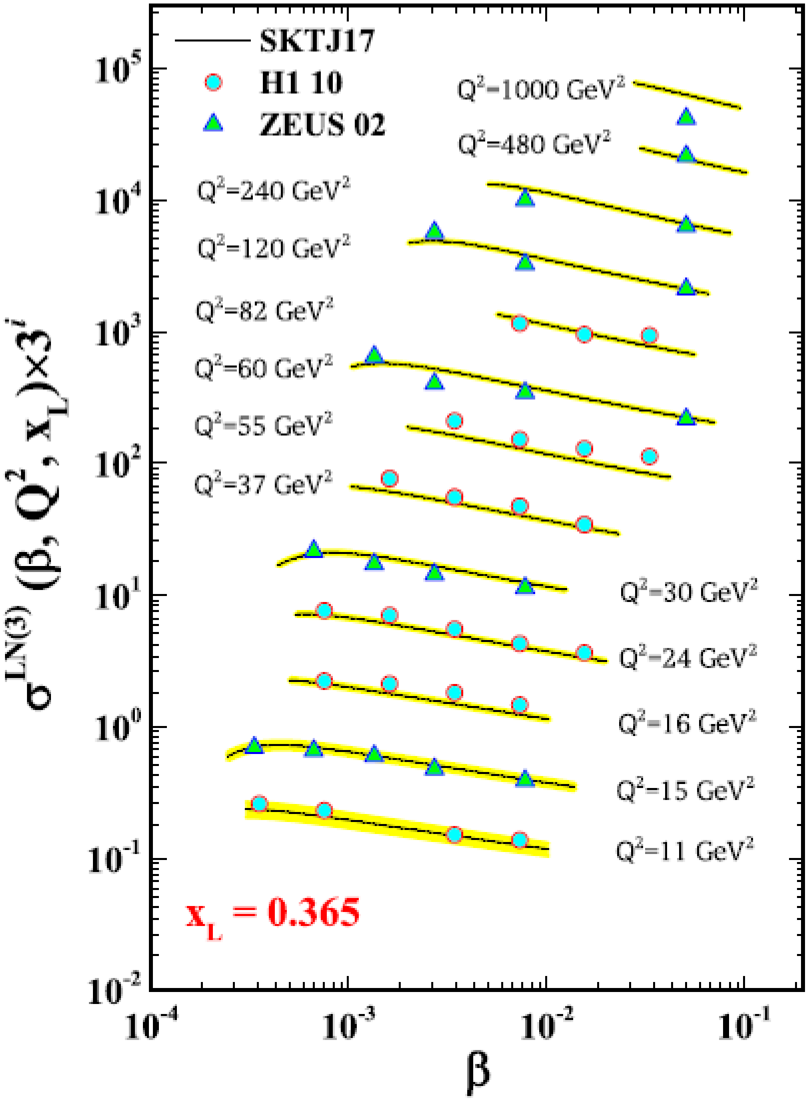
The singlet momentum distribution as a function of β at the input scale $Q_0^2 = 1\,GeV^2$ and for three representative bins of x_L=0.24, 0.55, and 0.92.

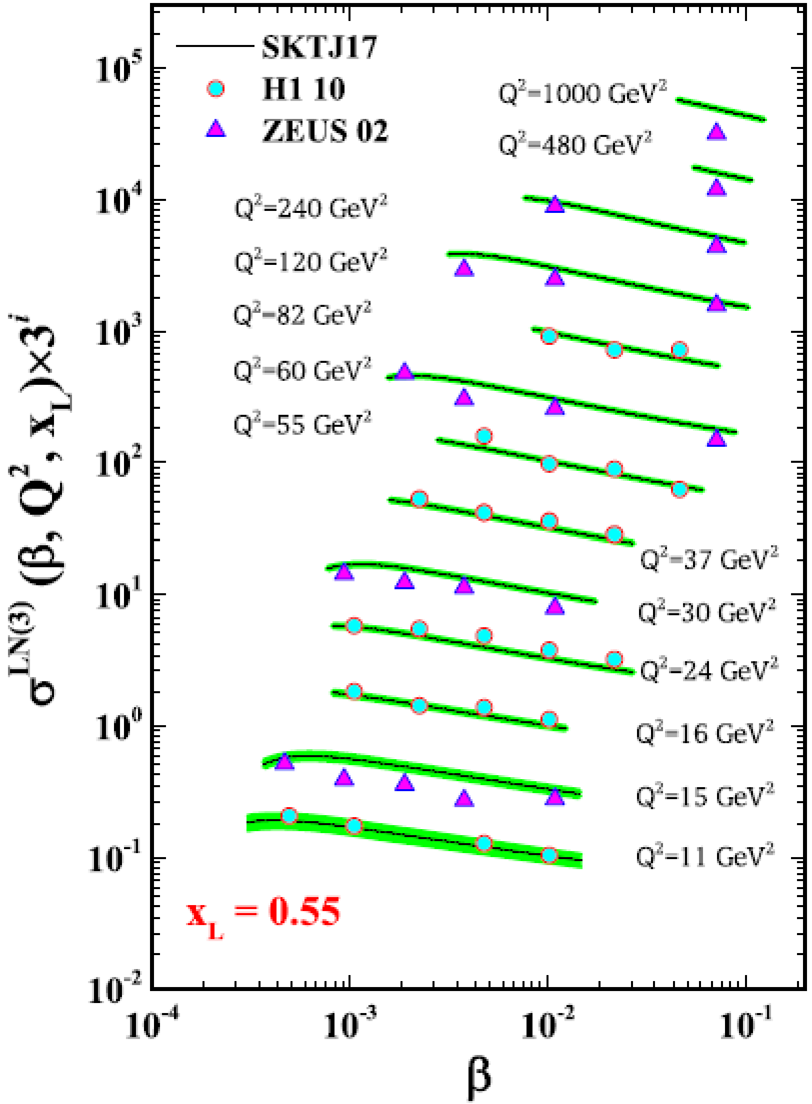
Gluon momentum distribution as a function of β

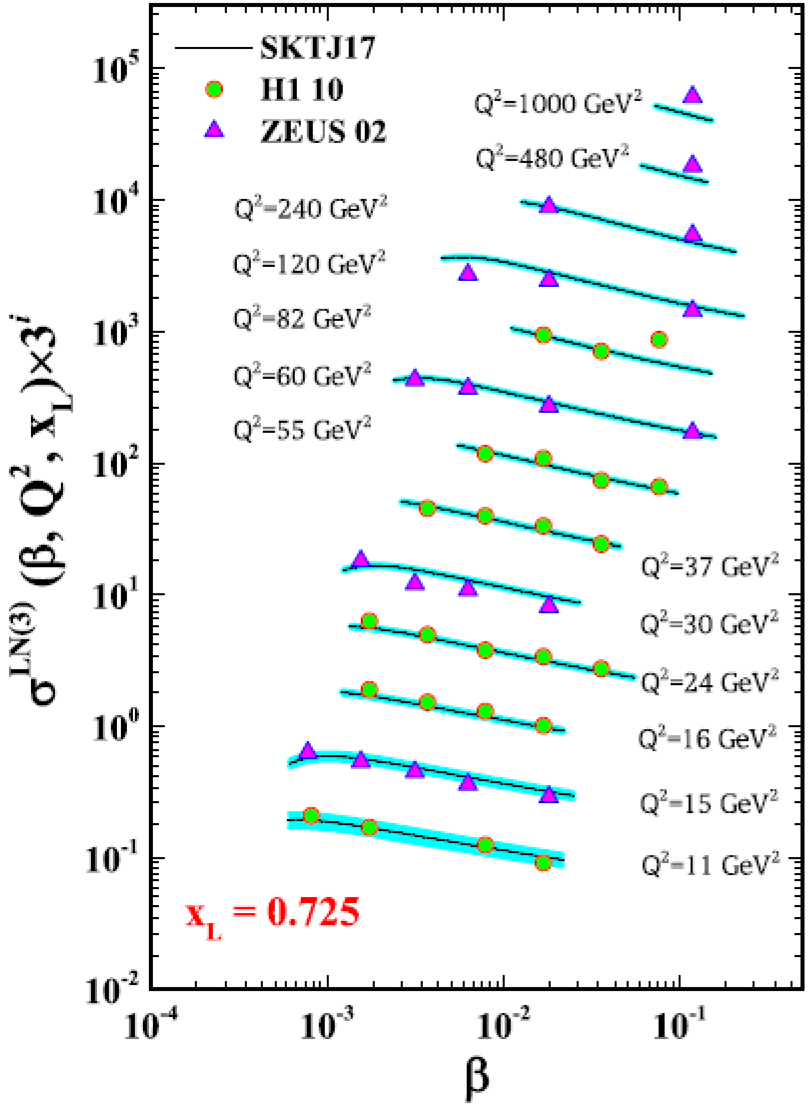


The gluon momentum distribution as a function of β at the input scale $Q_0^2 = 1\ GeV^2$ and for three representative bins of x_L=0.24, 0.55, and 0.92.

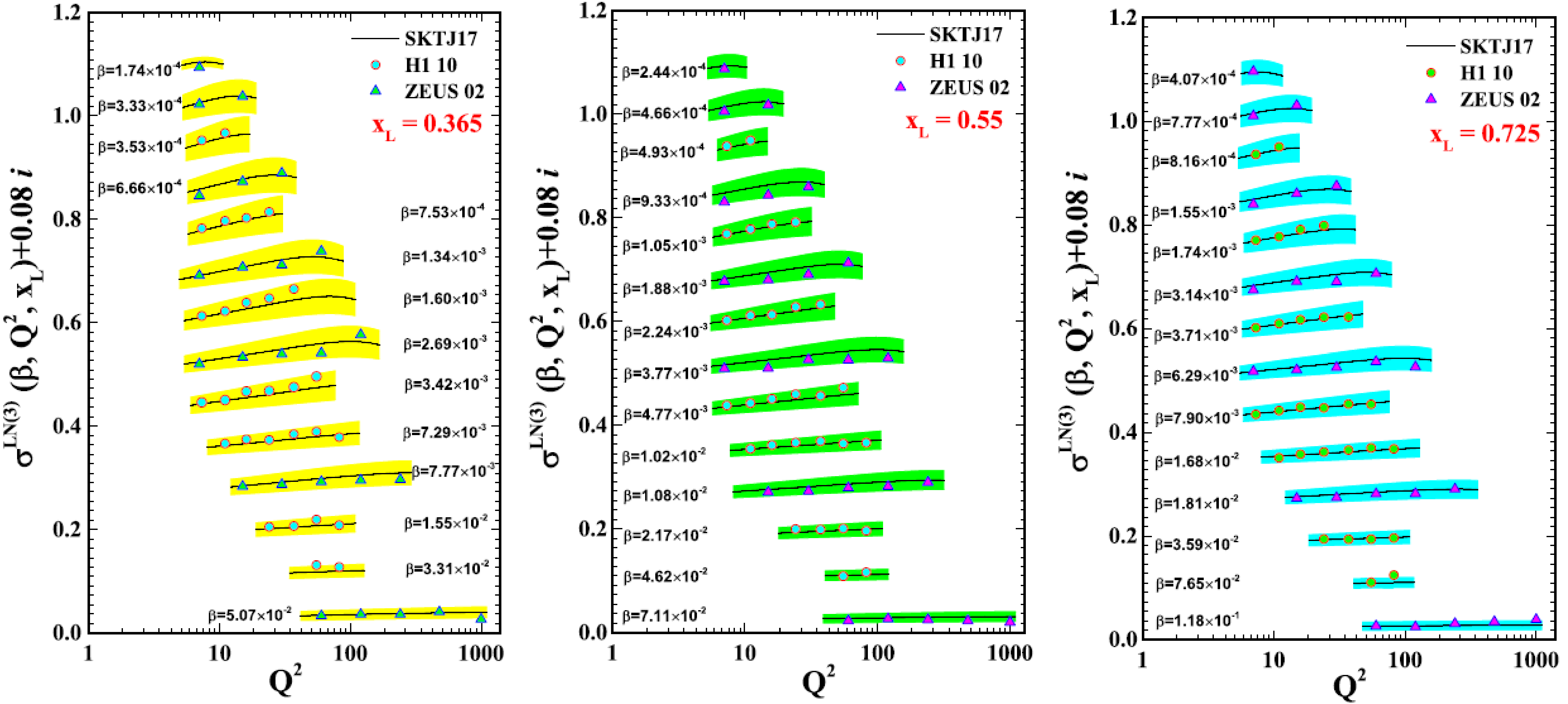
Reduced cross sections as a function of β







Reduced cross section as a function of Q^2



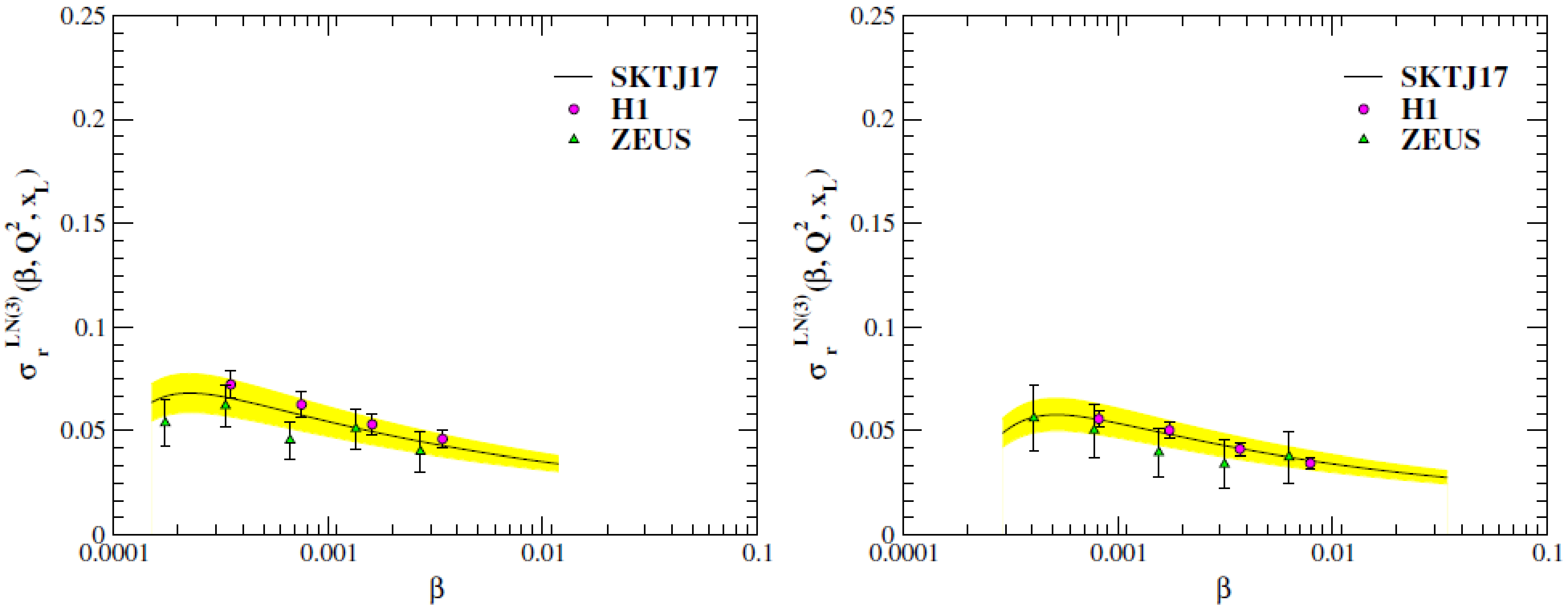


FIG. 7. `SKTJ17` theory predictions for the reduced cross sections $\sigma_r^{\mathrm{LN}(3)}(\beta, Q^2, x_L)$ as a function of β. The H1 (ZEUS) data correspond to $\mathrm{Q}^2 = 7.3(7.0)$ GeV^2, and $x_L = 0.365$ (0.370) in the left panel and $x_L = 0.725$ (0.730) in the right panel. The error bars associated with the H1 and ZEUS data points include systematic and statistical uncertainties, being the total experimental error evaluated in quadrature.

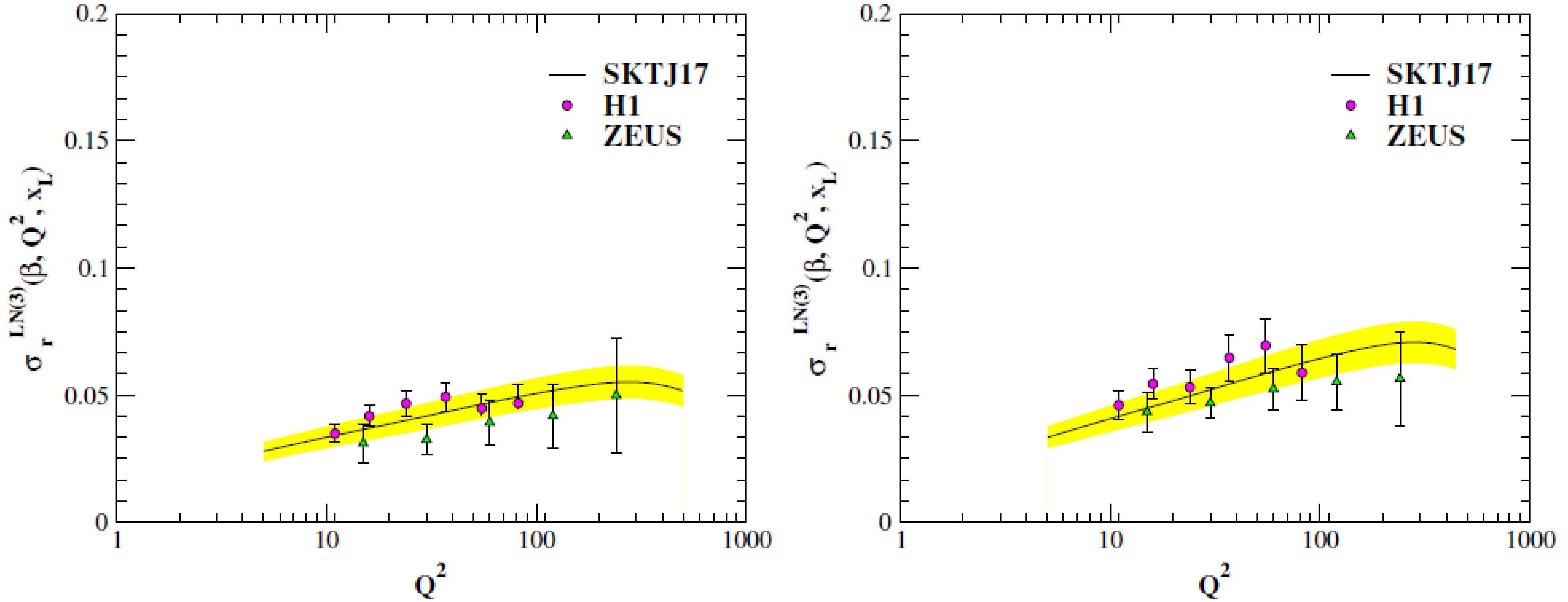


FIG. 8. SKTJ17 theory predictions as a function of Q^2 (in GeV^2 units). The error bars associated with the H1 and ZEUS data points include systematic and statistical uncertainties, being the total experimental error evaluated in quadrature. In the right panel, the H1 (ZEUS) data correspond to $\beta = 7.29(7.77) \times 10^{-3}$ and $x_L = 0.365(0.370)$. The H1 (ZEUS) data in the left panel correspond to $\beta = 1.02(1.08) \times 10^{-2}$ and $x_L = 0.545(0.550)$.

Upcoming analysis

Global analysis on determination of fracture functions considering sea quark asymmetries in the nucleon

Samira Shoeibi, F. Taghavi-Shahri, Hamzeh Khanpour, and Kurosh Javidan

$$\beta M^{N}_{\Sigma/P}(\beta, Q_0^2, x_L) = \mathcal{W}_q(x_L)\, x f_q^{\rm GJR08}(\beta, Q^2)\,,$$

$$\beta M^{N}_{g/P}(\beta, Q_0^2, x_L) = \mathcal{W}_g(x_L)\, x g^{\rm GJR08}(\beta, Q^2)\,,$$

The results of this analysis will be present in Hadron 2017 conference

Salamanca HADRON 2017
XVII International Conference on Hadron Spectroscopy and Structure

https://indico.cern.ch/event/578804/

Sea quarks asymmetries

- One can consider sea quarks asymmetries and determine the neutron FFs for the separate parton distributions for all parton species including valence quark densities, the anti-quark and strange sea parton distribution functions (PDFs) as well as gluon distribution.

$$\beta M^N_{u_v/P}(\beta, Q_0^2, x_L) = \mathcal{W}_{u_v}(x_L)\; x u_v^{\mathrm{GJR08}}(\beta, Q^2)\,,$$

$$\beta M^N_{d_v/P}(\beta, Q_0^2, x_L) = \mathcal{W}_{d_v}(x_L)\; x d_v^{\mathrm{GJR08}}(\beta, Q^2)\,,$$

$$\beta M^N_{(\bar{d}-\bar{u})/P}(\beta, Q_0^2, x_L) = \mathcal{W}_(\bar{d}-\bar{u})(x_L)\; x(\bar{d}-\bar{u})^{\mathrm{GJR08}}(\beta, Q^2)\,,$$

$$\beta M^N_{(\bar{d}+\bar{u})/P}(\beta, Q_0^2, x_L) = \mathcal{W}_(\bar{d}+\bar{u})(x_L)\; x(\bar{d}+\bar{u})^{\mathrm{GJR08}}(\beta, Q^2)\,,$$

$$\beta M^N_{(s+\bar{s})/P}(\beta, Q_0^2, x_L) = \mathcal{W}_(s+\bar{s})(x_L)\; x(s+\bar{s})^{\mathrm{GJR08}}(\beta, Q^2)\,,$$

$$\beta M^N_{g/P}(\beta, Q_0^2, x_L) = \mathcal{W}_g(x_L)\; x g^{\mathrm{GJR08}}(\beta, Q^2)\,,$$

M. Gluck, P. Jimenez-Delgado, E. Reya (**GJR08 PDFs**), Eur Phys J C **53** (2008) 355-366

Summary and Conclusions

- ✓ In the recent years, several dedicated experiments at the electron-proton collider HERA have collected high-precision data on the spectrum of leading-baryons carrying a large fraction of the proton’s energy.

- ✓ In addition to these experimental efforts, much successful phenomenology has been developed in understanding the mechanism of leading-baryon productions.

- ✓ We have presented the SKTJ17 NLO QCD analysis of neutron FFs using available and up-to-date data from the forward neutron production at HERA.

- ✓ It is shown that an approach based on the fracture functions formalism allows us to phenomenologically parametrize the neutron FFs.

- Completing such a picture is crucial as hadron colliders enter an era of a new generation of experimental data capable of testing this formalism.


Thank you...