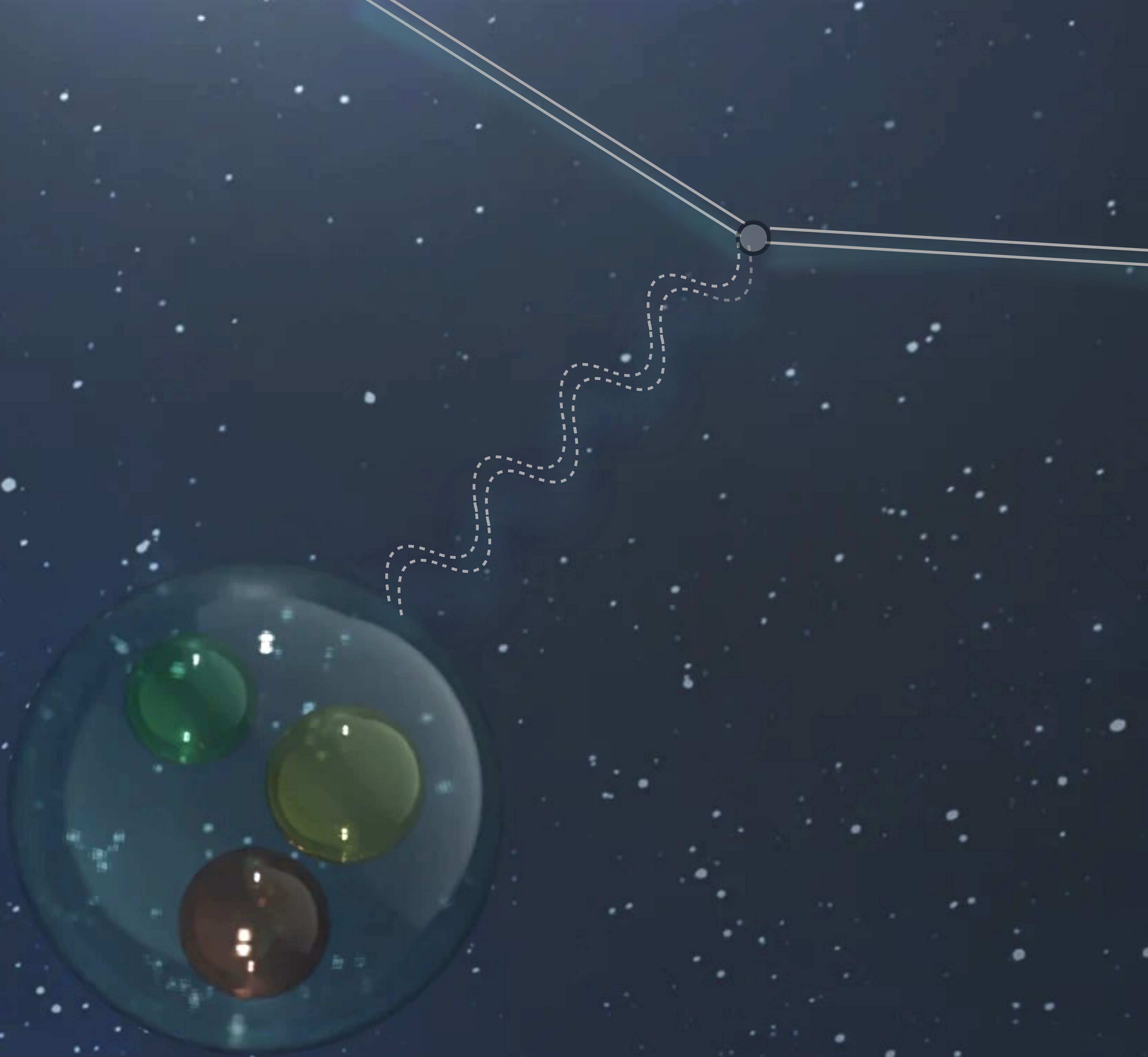
Geometric Scaling in the pion structure at HERA

in leading neutron events in DIS

A.Kumar PRD 107 (2023) 034005

A.Kumar, Tobias Toll PRD 105 (2022) 114045



Low-x 2023

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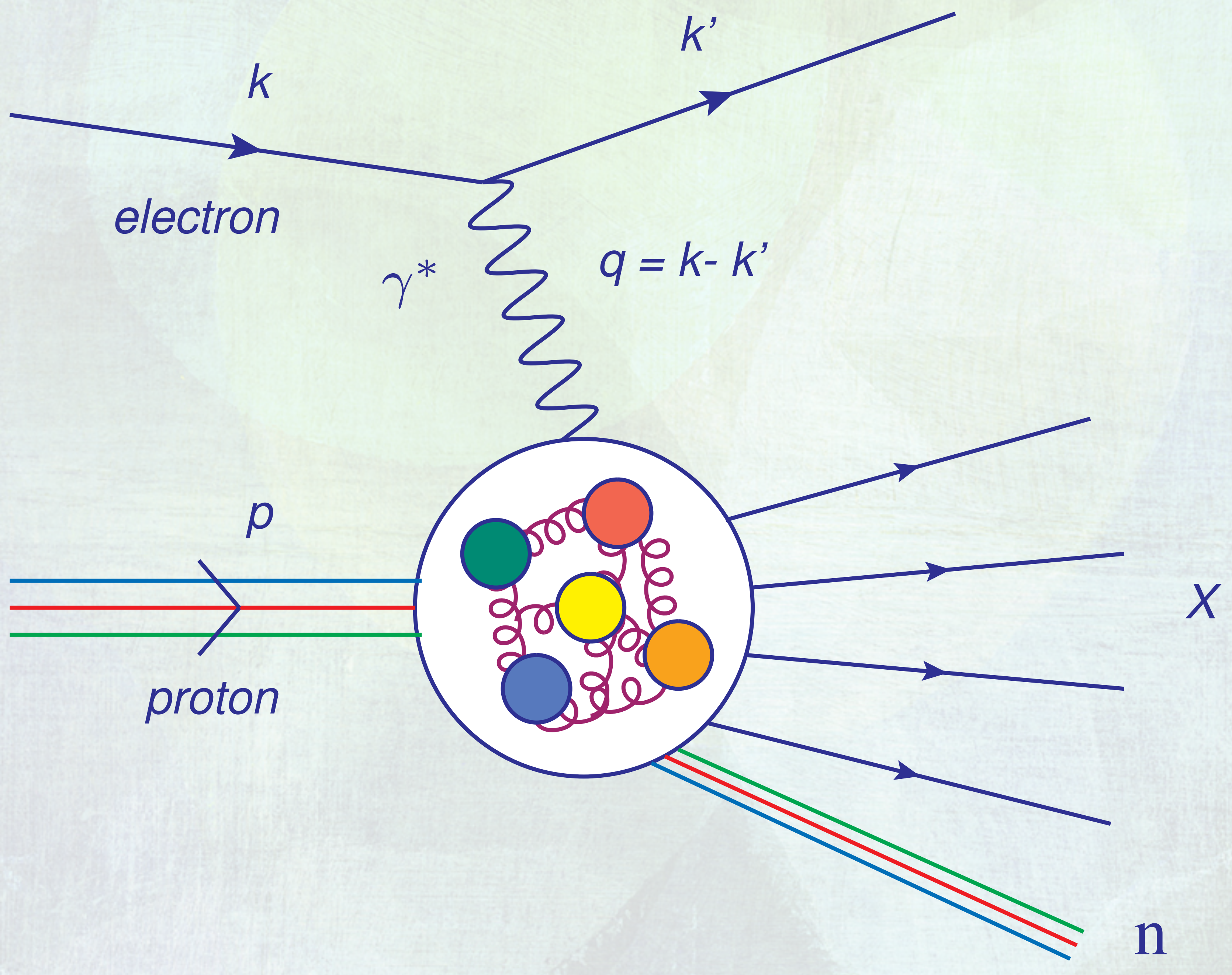
DEPARTMENT OF
SCIENCE & TECHNOLOGY



OUTLINE

- Introduction to Tagged-DIS (TDIS)
- Pion Structure in neutron tagged events

  $$(e + p \rightarrow e' + X + n)$$

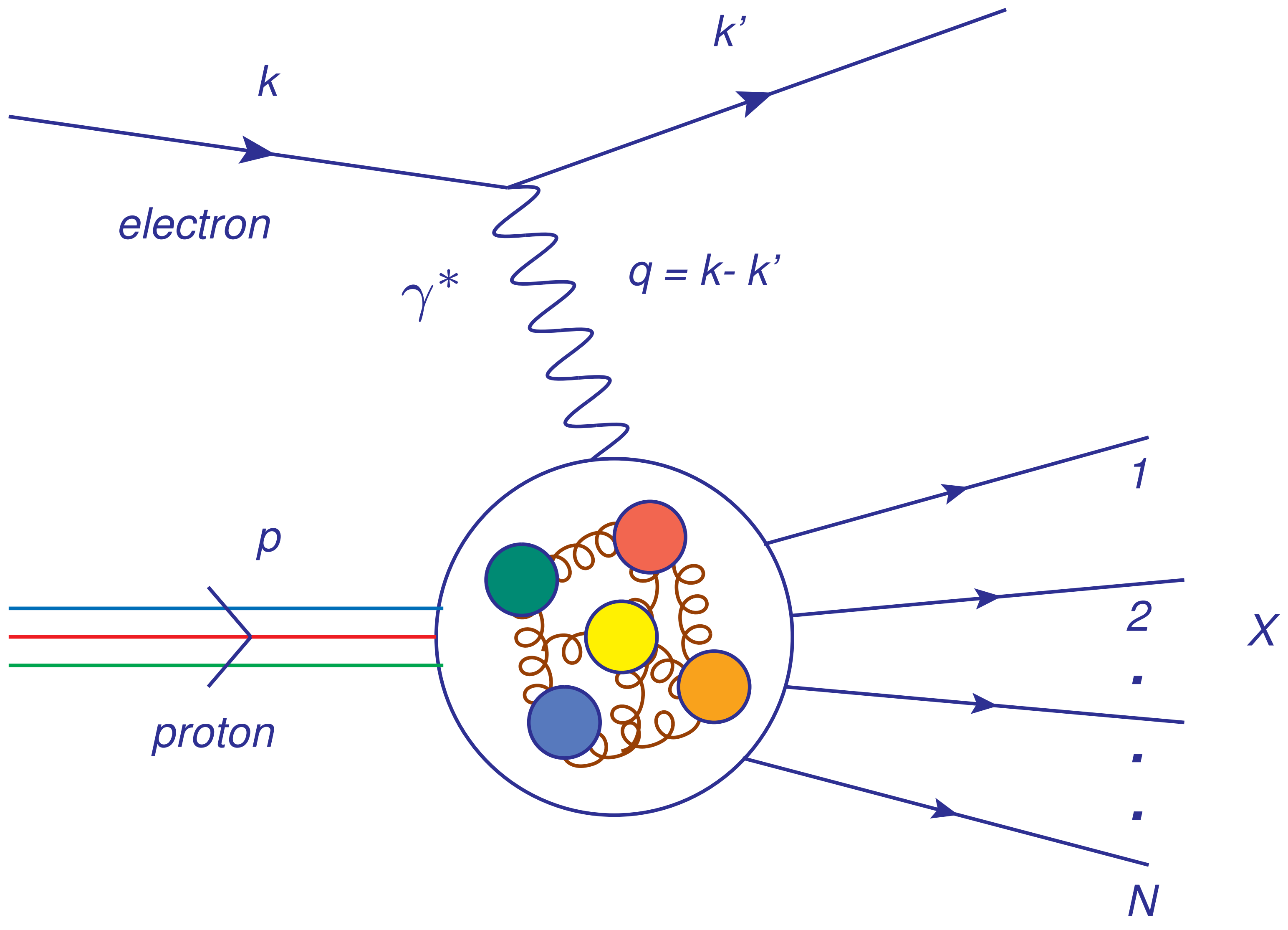
  - Geometric Scaling & Pion Saturation Scale
  - Feynman Scaling
- Exclusive J/ψ photo production with leading neutrons

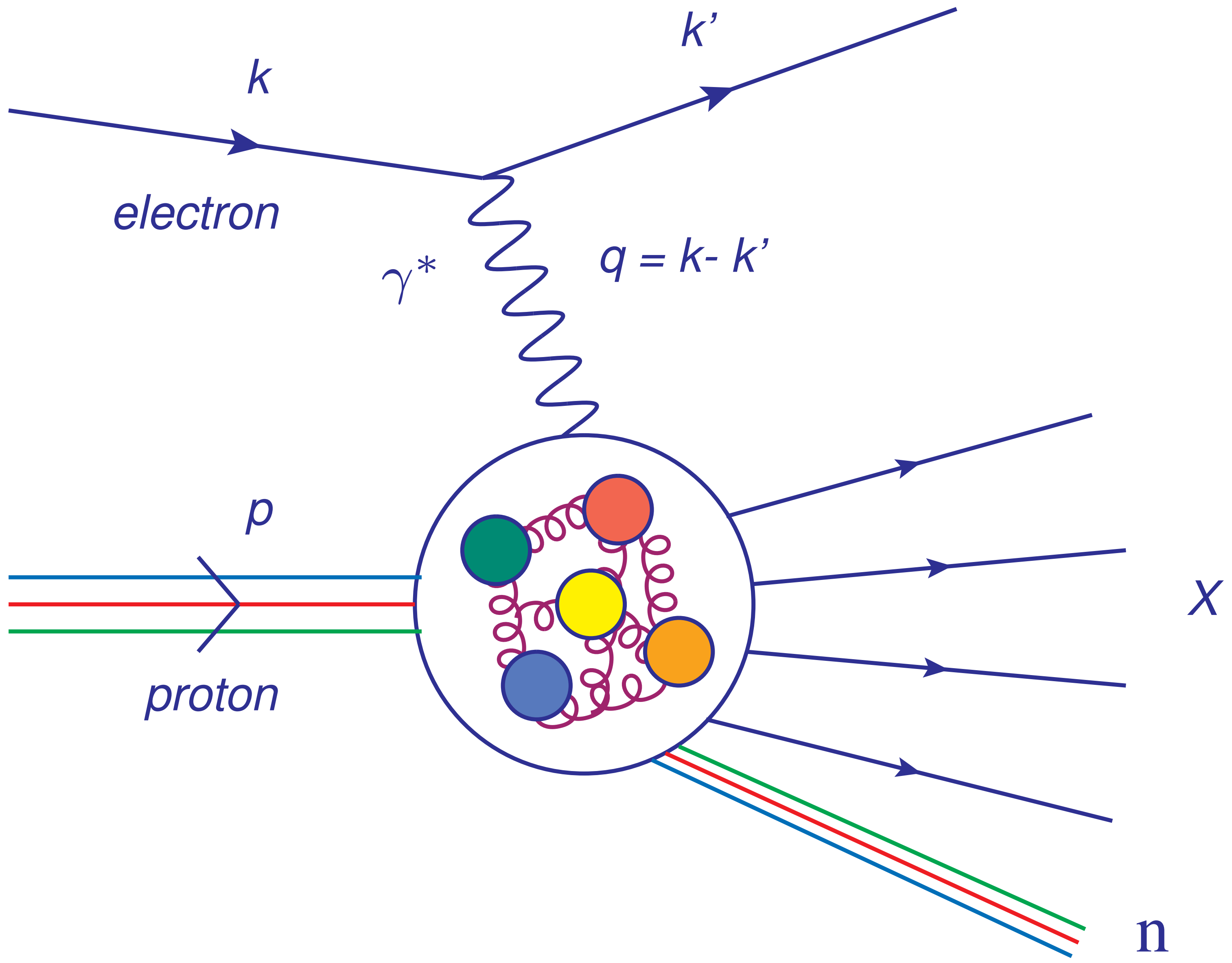
  $$(e + p \rightarrow e' + J/\psi + \pi + n)$$

  - Sensitivity to saturation and gluon radius

INCLUSIVE DIS

TAGGED-DIS





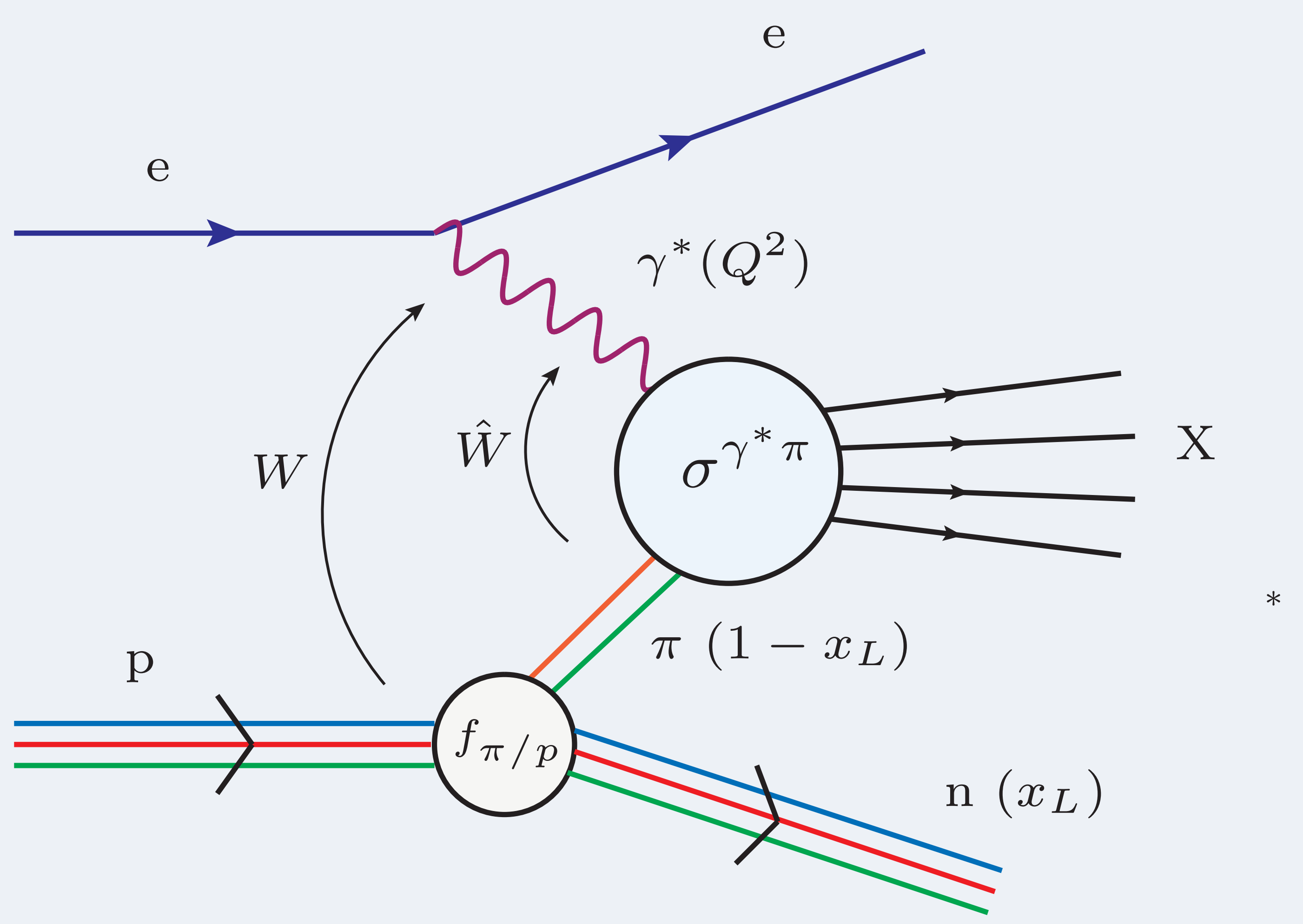
- ❖ Detect the scattered electron
- ❖ Probe partonic structure of the targets
- ❖ Kinematic variables : x_{Bj}, Q^2, W
- ❖ Precise measurements of the structure functions from HERA (F_2, F_L)

- ❖ Detect the scattered electron and the forward target nucleon
- ❖ Probe partonic structure of the "effective" targets not readily found
- ❖ Kinematic variables : x_{Bj}, Q^2, W and

  $x_L \rightarrow$ momentum fraction carried by outgoing nucleon

  $t \rightarrow$ four-momentum transfer squared at the nucleon vertex

LEADING NEUTRONS (LN)



H1 EPJC 74 (2014), 2915

❖ Forward neutrons:

$\eta > 7.9,\ 0.1 < x_L < 0.94$

$0 < p_T < 0.6$

❖ Kinematic variables:

$$\hat{x} = \frac{Q^2 + m_f^2}{\hat{W}^2 + Q^2} = \frac{Q^2 + m_f^2}{(1-x_L)W^2 + Q^2}$$

$$t \simeq -\frac{p_T^2}{x_L} - (1-x_L)\left(\frac{m_n^2}{x_L} - m_p^2\right)$$

❖ LN Structure function F_2^{LN}: H1 EPJC 68 (2010), 381

$$\frac{d^4\sigma^{ep\to eXn}}{dx dQ^2 dx_L dt} = \frac{4\pi\alpha_{\rm EM}^2}{xQ^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LN(4)}(x, Q^2, x_L, t)$$

❖ In terms of $\gamma^* p$ cross section:

$$F_2^{LN}(x, Q^2, x_L) = \frac{Q^2}{4\pi^2\alpha_{\rm EM}} \frac{d\sigma^{\gamma^* p\to Xn}}{dx_L}$$

❖ In One Pion Exchange (OPE) approximation: J.D. Sullivan PRD 5 (1972), 1732

$$\frac{d^2\sigma(W, Q^2, x_L, t)}{dx_L dt} = f_{\pi/p}(x_L, t)\ \sigma^{\gamma^*\pi^*}(\hat{W}^2, Q^2)$$

$f_{\pi/p}(x_L, t)$ is pion splitting function,

$\sigma^{\gamma^*\pi^*}(\hat{W}^2, Q^2)$ is virtual photon-virtual pion cross section

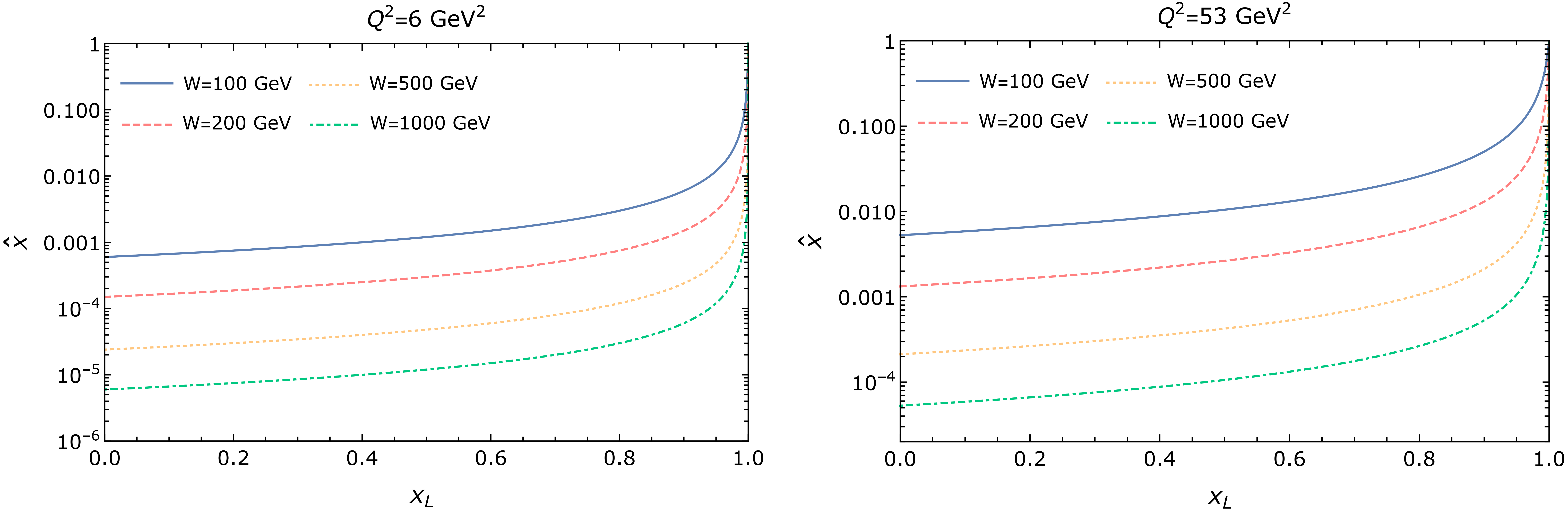
❖ OPE allows to extract the pion structure function F_2^π,

$$F_2^{LN}(W, Q^2, x_L) = \Gamma(x_L, Q^2)\ F_2^\pi(W, Q^2, x_L)$$

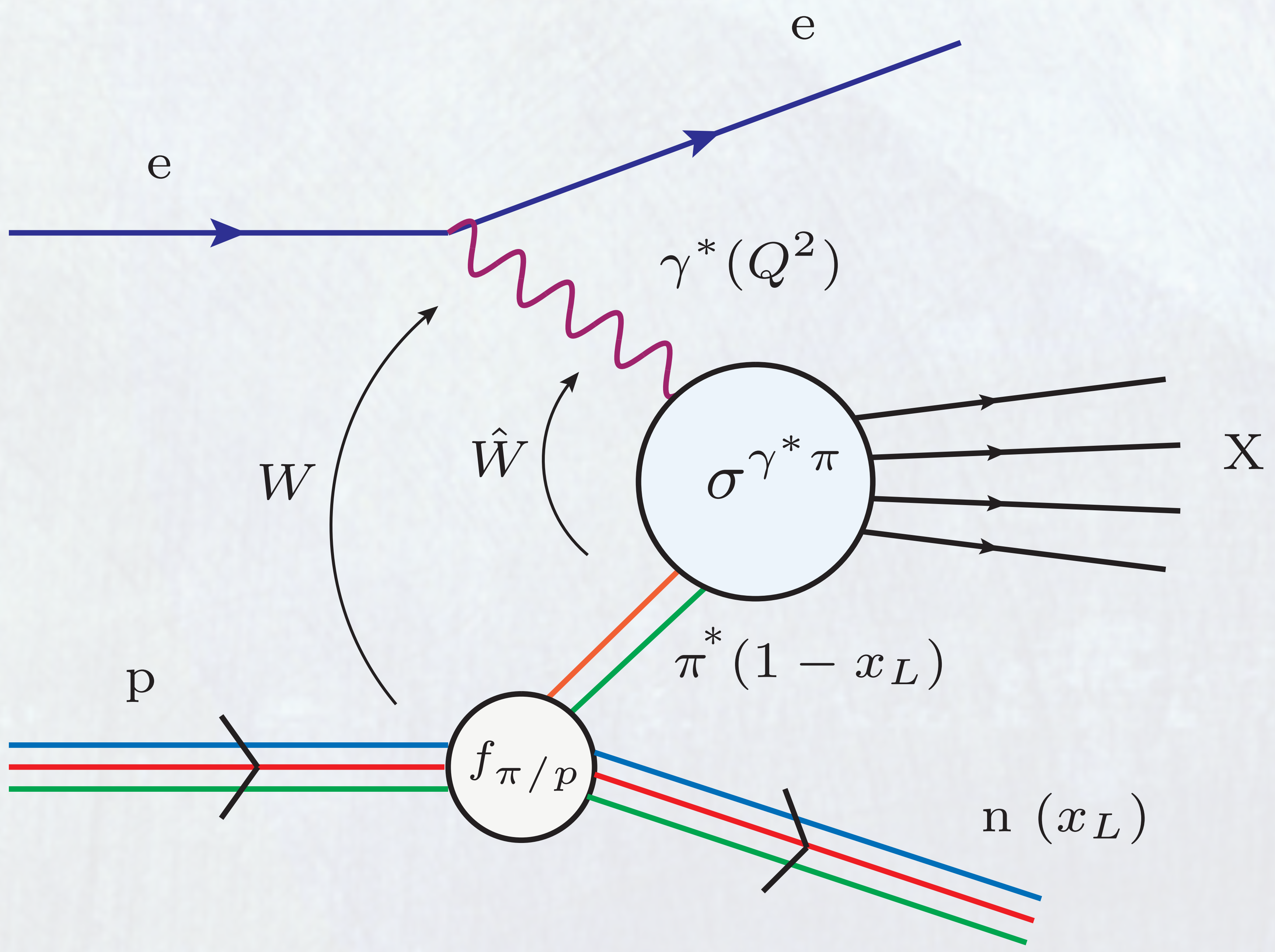
$\Gamma(x_L, Q^2)$ is t-integrated flux of pions from proton

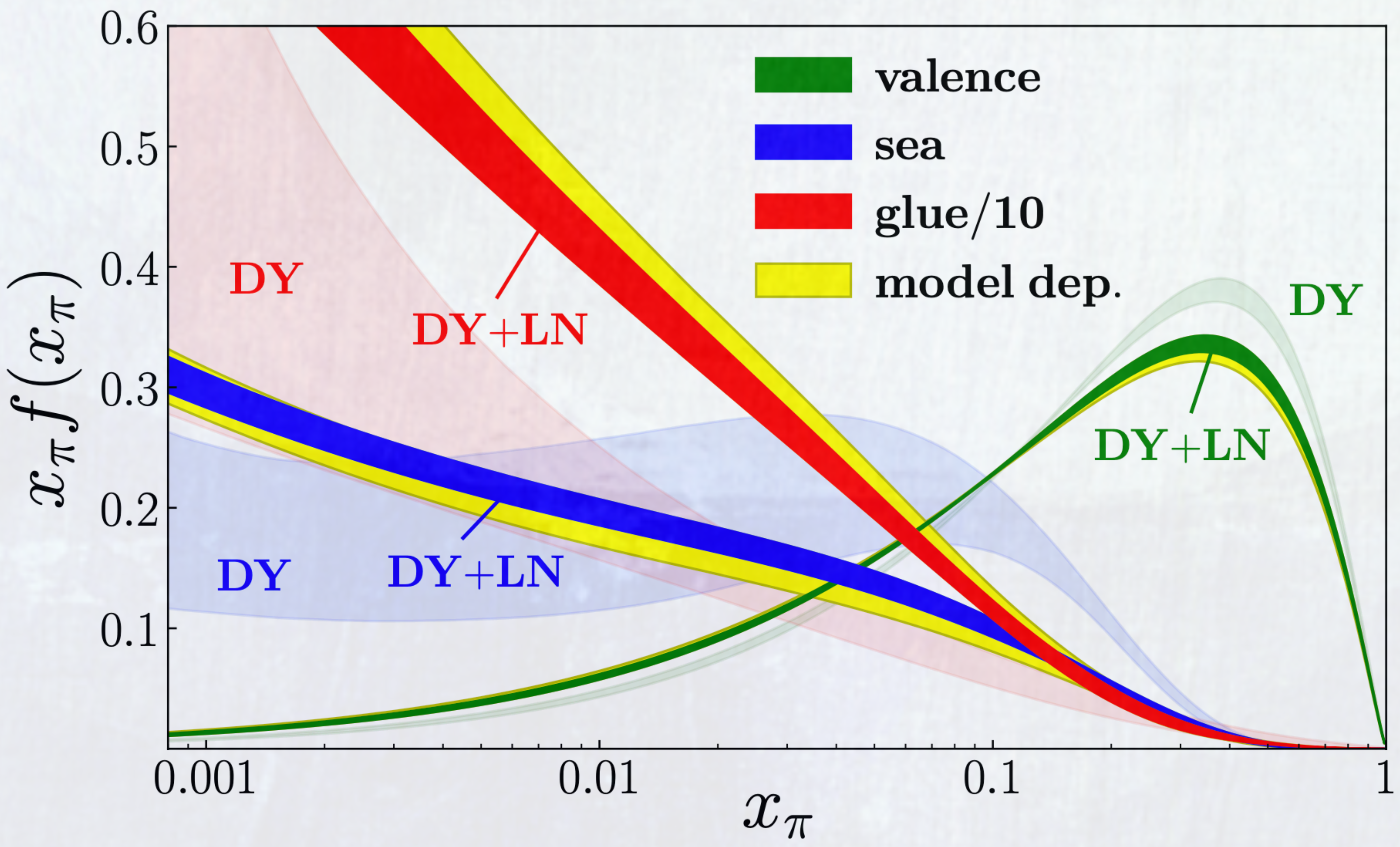
LN AS A PROBE FOR SMALL-X PHYSICS

The Bjorken-x value probed in such a process is $\hat{x} = \dfrac{Q^2 + m_f^2}{\hat{W}^2 + Q^2} = \dfrac{Q^2 + m_f^2}{(1 - x_L)W^2 + Q^2}$



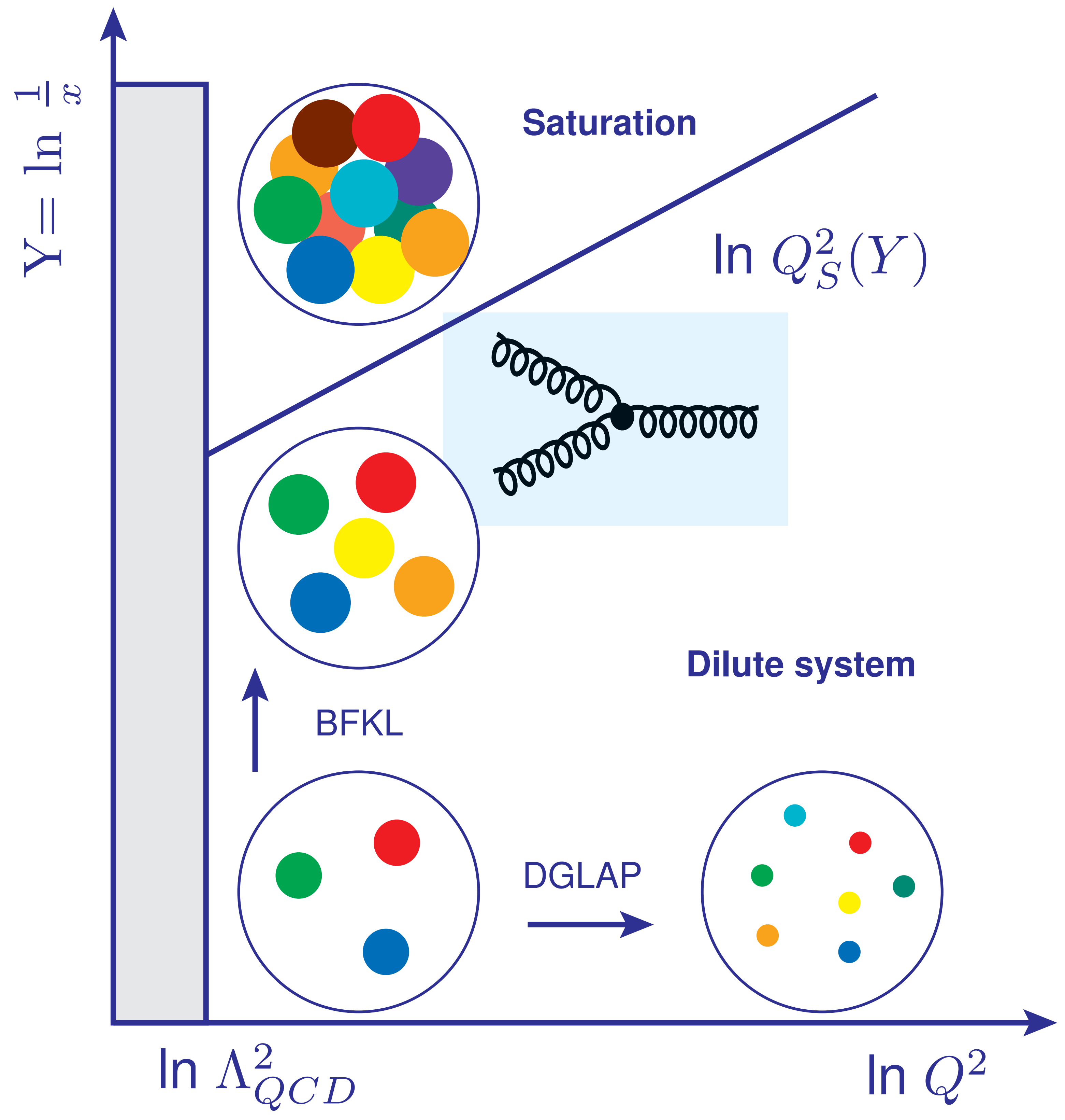
TAGGED-DIS MEASUREMENTS WITH LEADING NEUTRONS





Barry et al PRL 121 (2018), 152001

QCD PHASE SPACE



➡ *Bjorken limit:* $Q^2 \to \infty$, $s \to \infty$, $x = fixed$ $\left(x \simeq \frac{Q^2}{ys}\right)$

❖ *Phase space density (# partons /Area/Q2) decreases*

❖ *Proton becomes dilute and free partonic picture holds*

❖ *Linear evolution equations*

➡ *High Energy limit of QCD:* $Q^2 = fixed$, $s \to \infty$, $x \to 0$

❖ *Phase space density (# partons /Area/Q2) increases*

❖ *Proton become more & more dense with decreasing x*

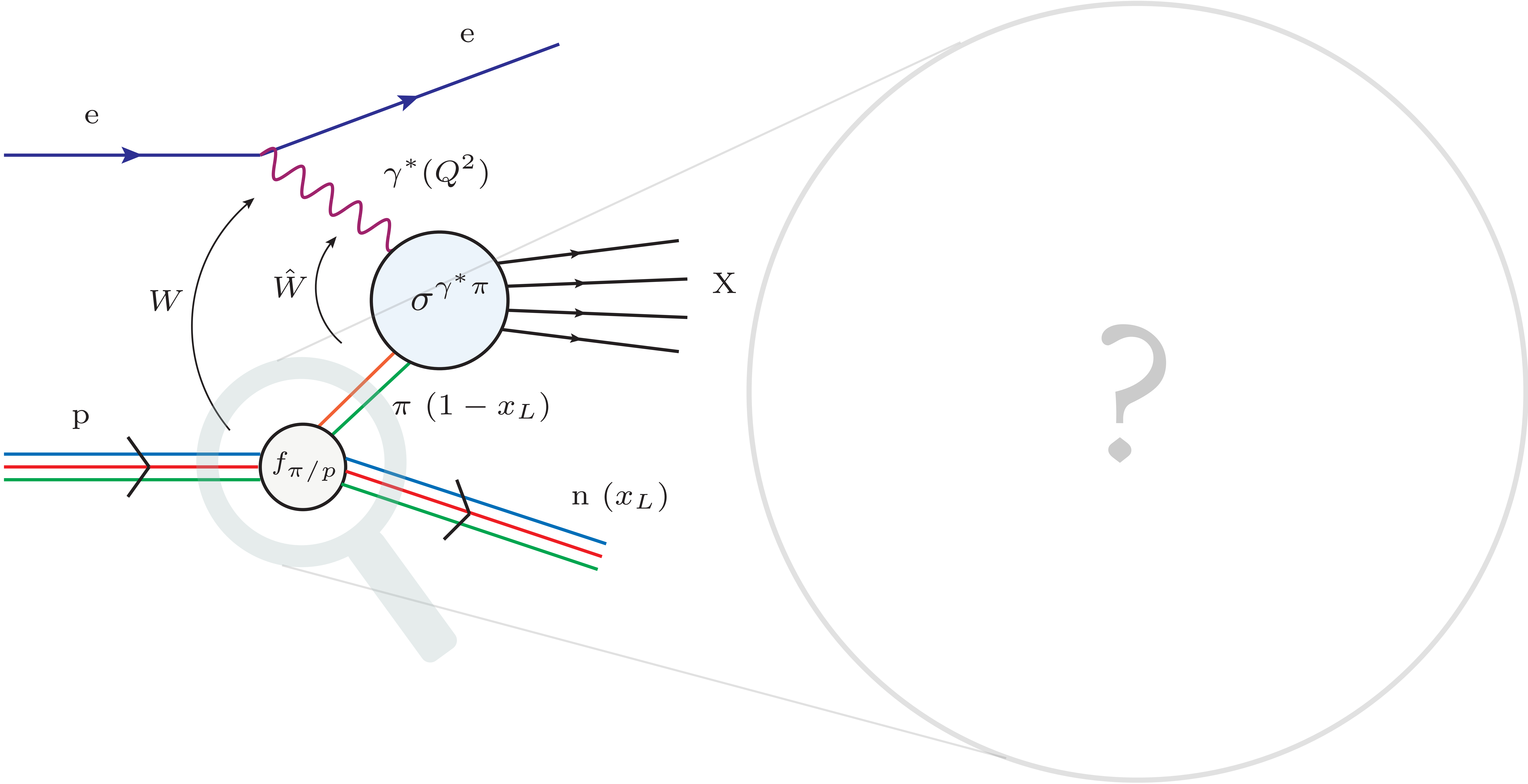
❖ *Non-linear effects becomes significant*

★ *Gluon Saturation: The GLR-MQ equation* Gribov, Levin & Ryskin 1983, Mueller & Qiu 1986

$$\frac{\partial^2 xg(x,Q^2)}{\partial lnQ^2 \partial ln(1/x)} = \frac{3\alpha_s}{\pi} xg(x,Q^2) - \frac{81\alpha_s^2}{16Q^2R^2}(xg(x,Q^2))^2$$

(new saturated state of gluonic matter)

PION FLUX FROM PROTON



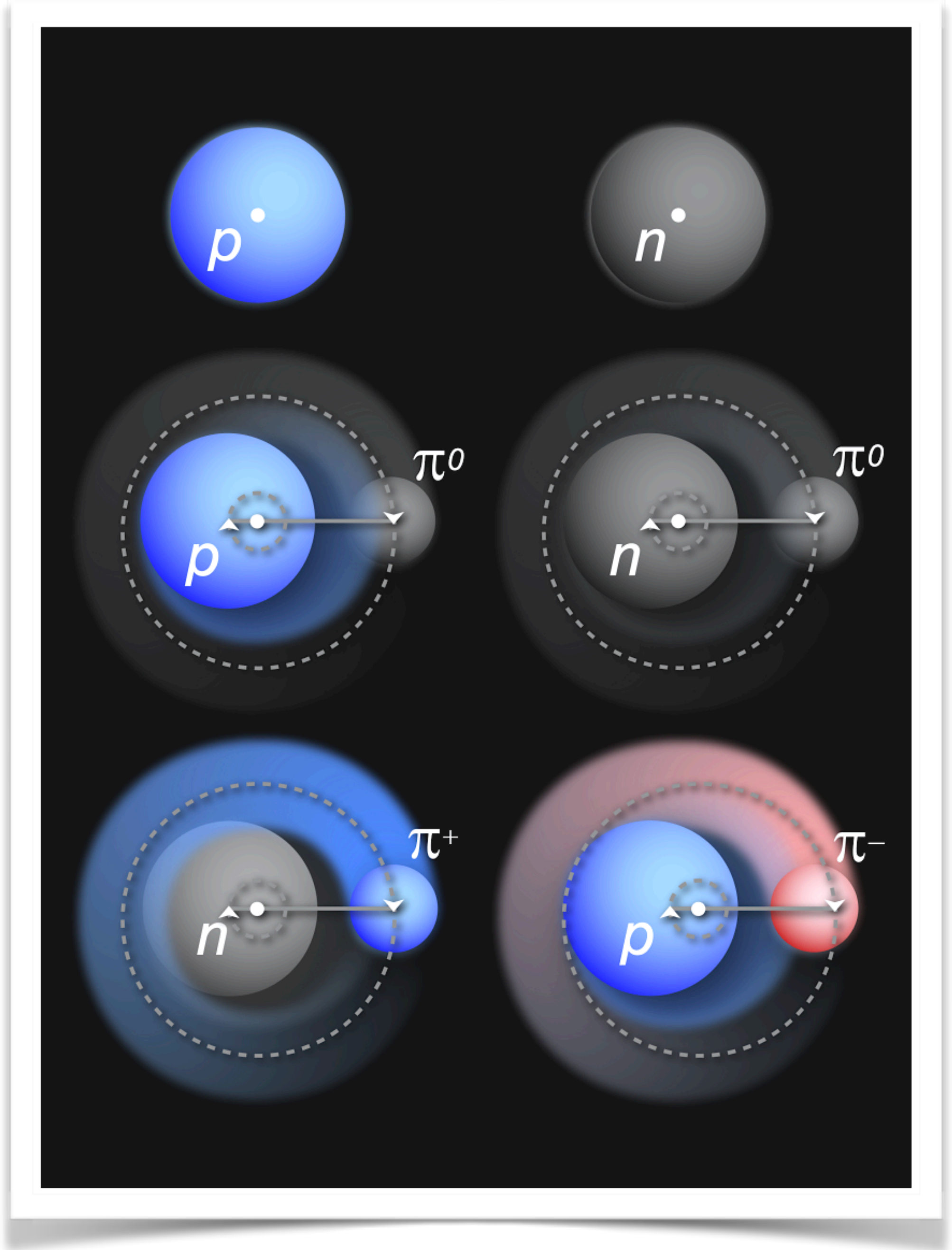
PION FLUX FROM PROTON

- Proton as a superposition of states in meson-cloud models,

$$|p> \rightarrow \sqrt{1-a-b}\ |p_o> + \sqrt{a}\left(-\sqrt{\frac{1}{3}}\ |p_0\ \pi^0> + \sqrt{\frac{2}{3}}\ |n_0\ \pi^+>\right) + \sqrt{b}\left(-\sqrt{\frac{1}{2}}\ |\Delta_0^{++}\ \pi^-> - \sqrt{\frac{1}{3}}\ |\Delta_0^{+}\ \pi^0> + \sqrt{\frac{1}{6}}\ |\Delta_0^{0}\ \pi^+>\right)$$

Chiral approach: a=0.24, b=0.12
Thomas, Melnitchouk & Steffens, PRL85 (2000) 2892

- Pion flux from proton is well known & can be calculated using chiral effective theory
- Previously used to explain hadron-hadron interactions at LHC



- We use the following flux factor: Carvalho et al PLB 752 (2016) 76

$$f_{\pi/p}(x_L, t) = \frac{1}{4\pi}\frac{2g^2_{p\pi p}}{4\pi}\frac{|t|}{(m_\pi^2 + |t|)^2}(1-x_L)^{1-2\alpha(t)}[F(x_L, t)]^2$$

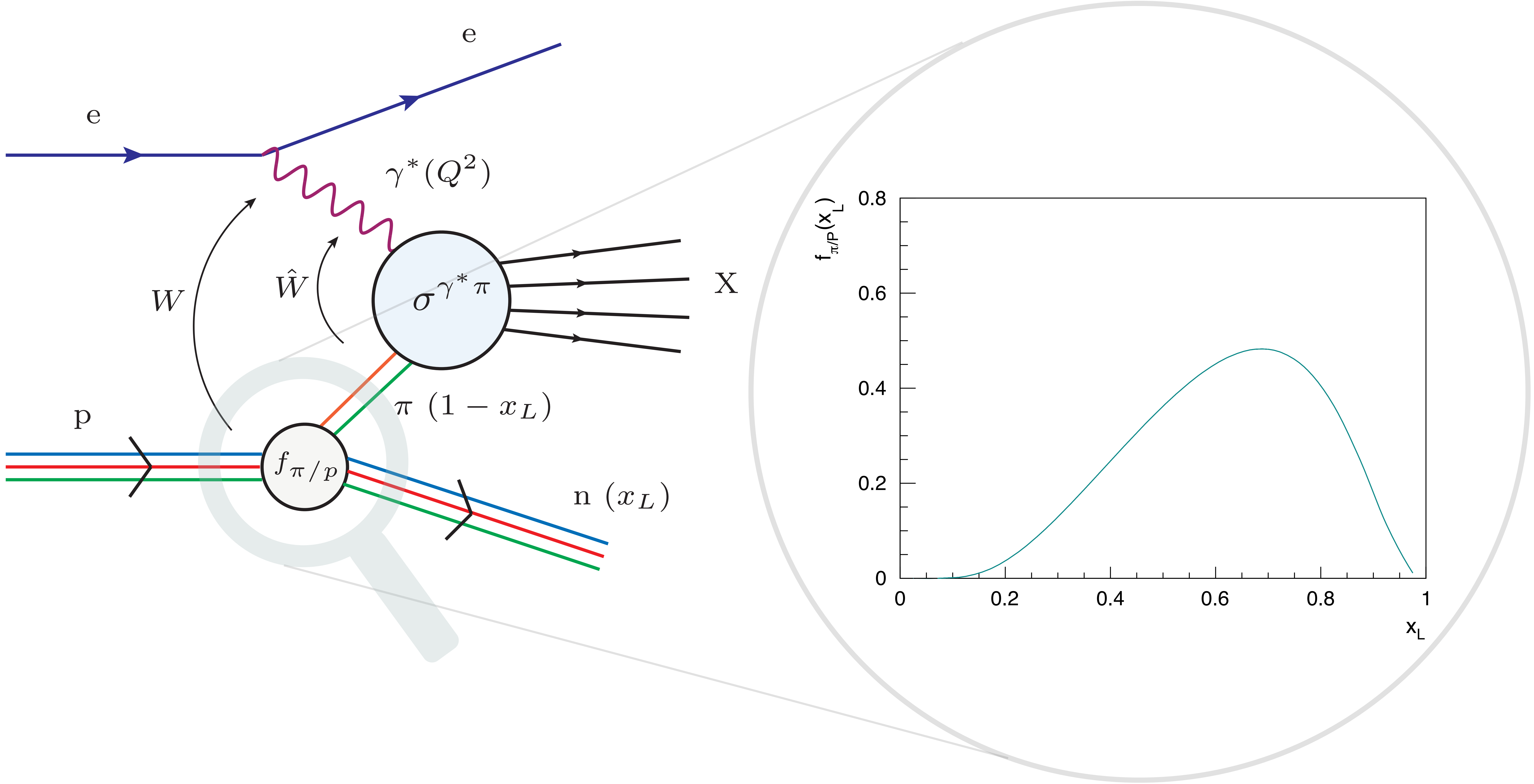
where the form factor is given by:

$$F(x_L, t) = \exp\left[-R^2\frac{|t| + m_\pi^2}{(1-x_L)}\right], \alpha(t) = 0$$

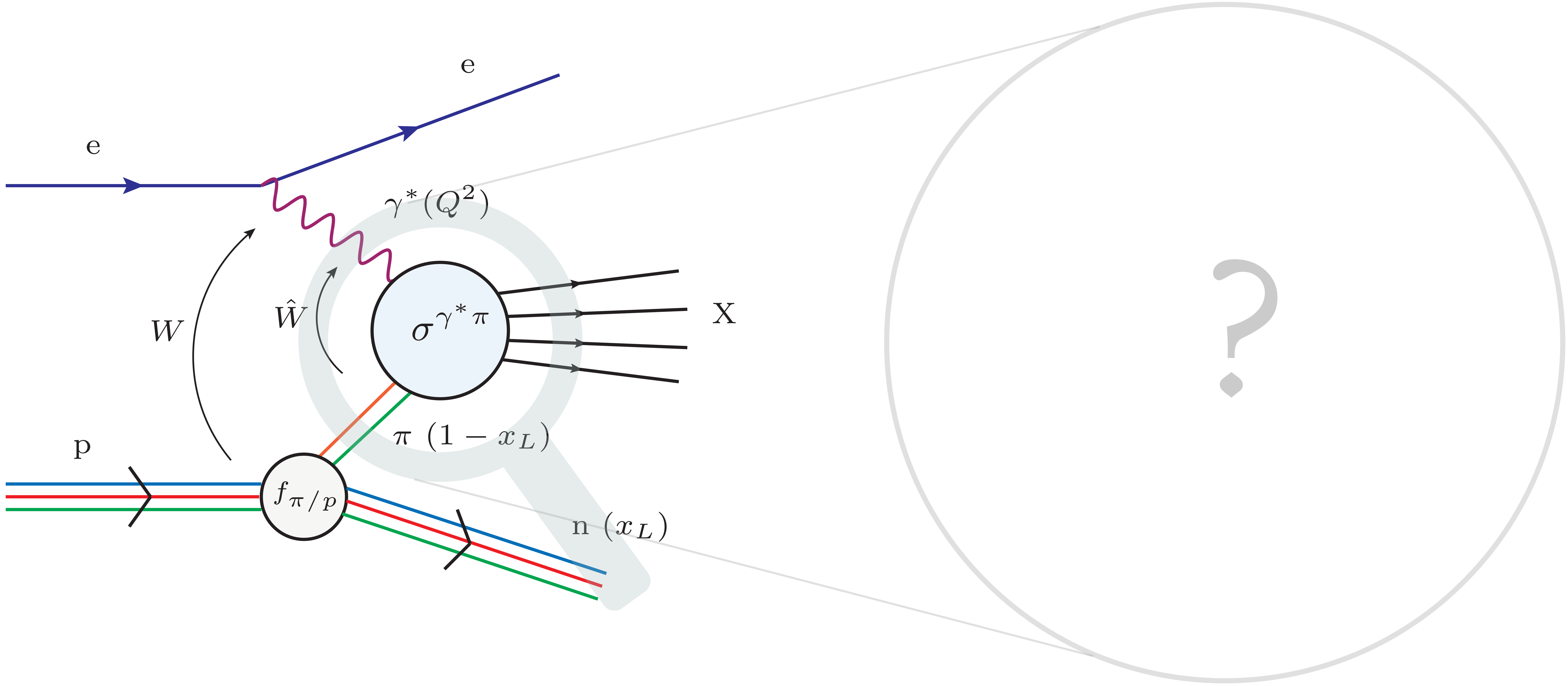
- Used by H1 and ZEUS for the data analysis H1 EPJC 68 (2010), 381

Image Source : Cynthia Keppel (JLab) slides from "Exploring QCD with light nuclei at EIC-2020" meeting

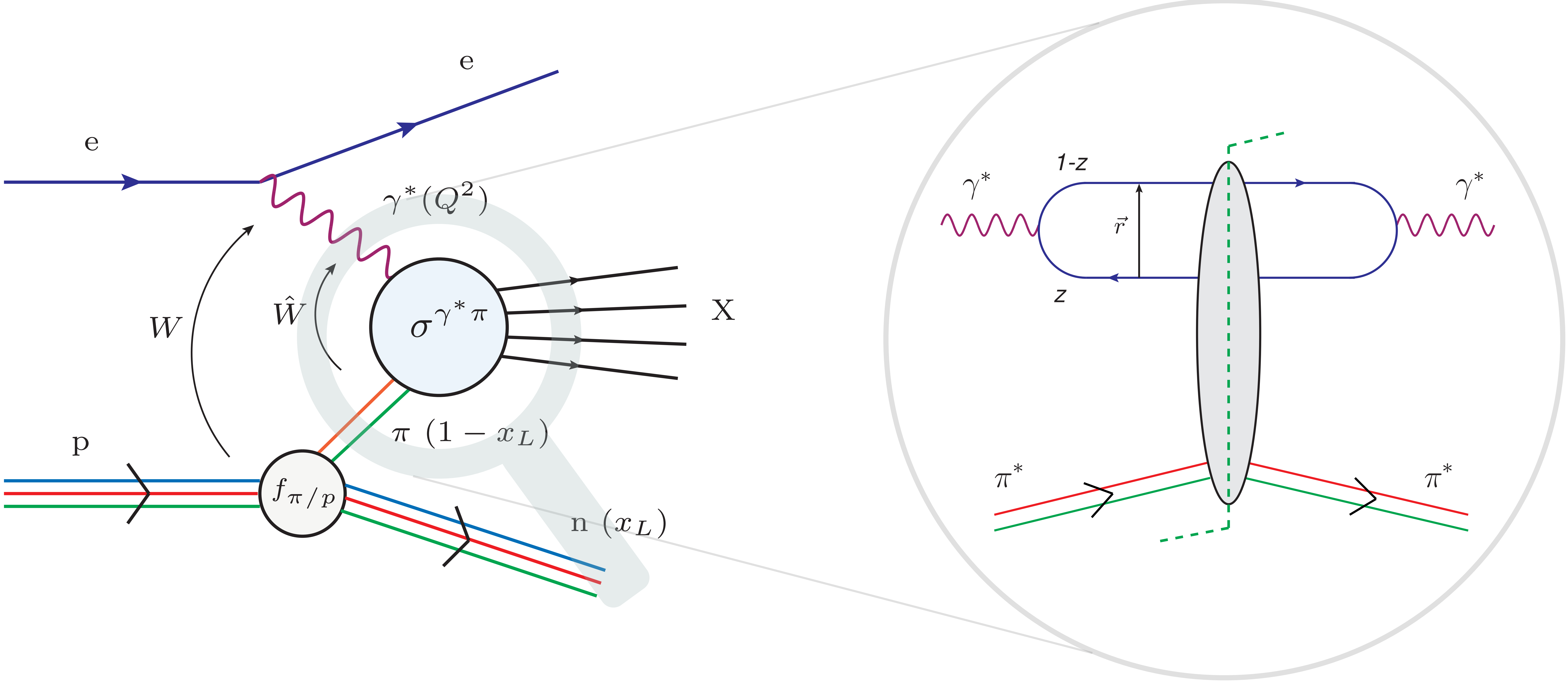
PION FLUX FROM PROTON



VIRTUAL PION-PHOTON CROSS SECTION

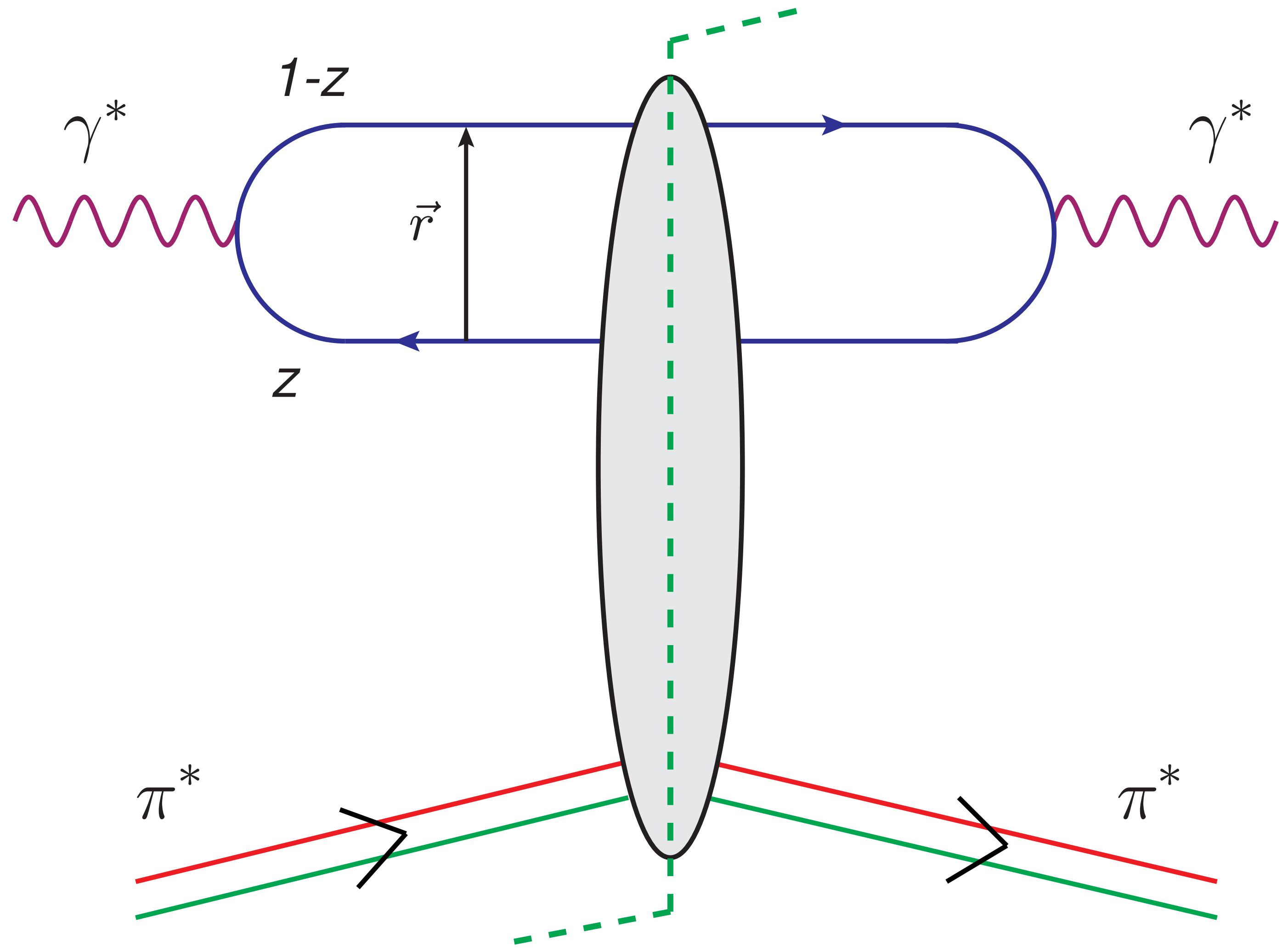


VIRTUAL PION–PHOTON CROSS SECTION



- For total virtual photon- virtual pion cross section
  - use dipole framework (natural in target rest frame)

VIRTUAL PION-PHOTON CROSS SECTION IN DIPOLE MODEL



Various stages of semi-inclusive scattering of photons on pions in dipole model:

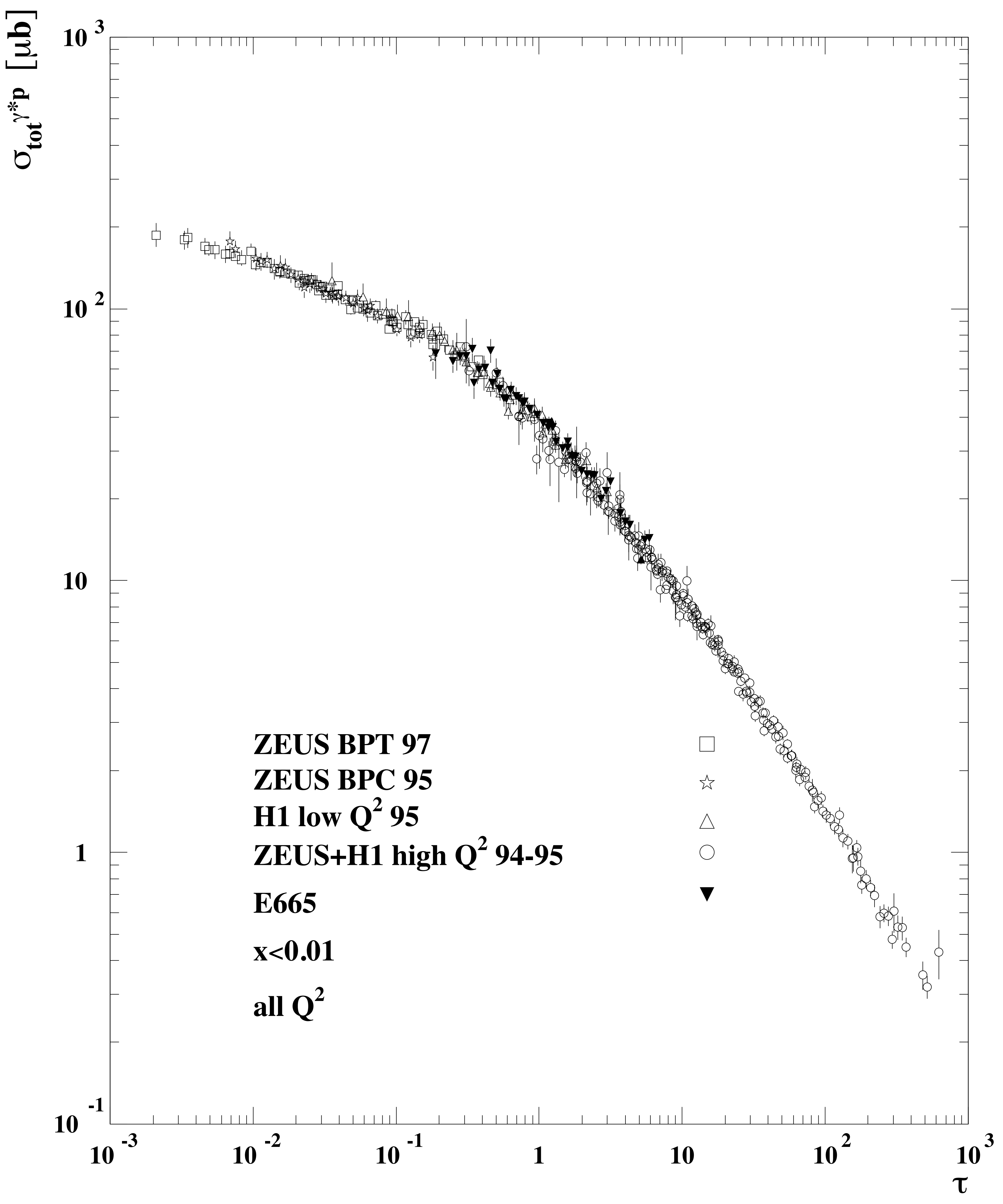
1. $\gamma^* \to q\bar{q}$ splitting (QED)
2. Dipole $\to \pi^*$ scattering $(model + QCD)$
3. Dipole $\to \gamma^*$ (QED)

$$\sigma_{L,T}^{\gamma^*\pi^*}(\hat{x}, Q^2) = \text{Im}\ \mathscr{A}(\hat{x}, Q^2, \Delta = 0) = \int d^2\mathrm{r} \int \frac{dz}{4\pi} |\Psi^f_{L,T}(\mathrm{r}, z, Q^2)|^2 \sigma_{q\bar{q}}^{(\pi)}(\mathrm{r}, \hat{x})$$

❖ GBW model: $\sigma^{(\pi)}(r, \hat{x}) = \sigma_0(1 - e^{r^2 Q_s^2(\hat{x})/4})$

with $Q_s^2(\hat{x}) = Q_0^2 \left(\frac{\hat{x}}{x_0}\right)^{-\lambda}$, the parameters σ_0, λ, x_0 are fitted to LN structure function data.

GEOMETRIC SCALING IN INCLUSIVE DIS



$$\tau = \frac{Q^2}{Q_s^2(\beta)}; \quad Q_s^2(x) = Q_0^2 \left(\frac{x}{x_0}\right)^{-\lambda}$$

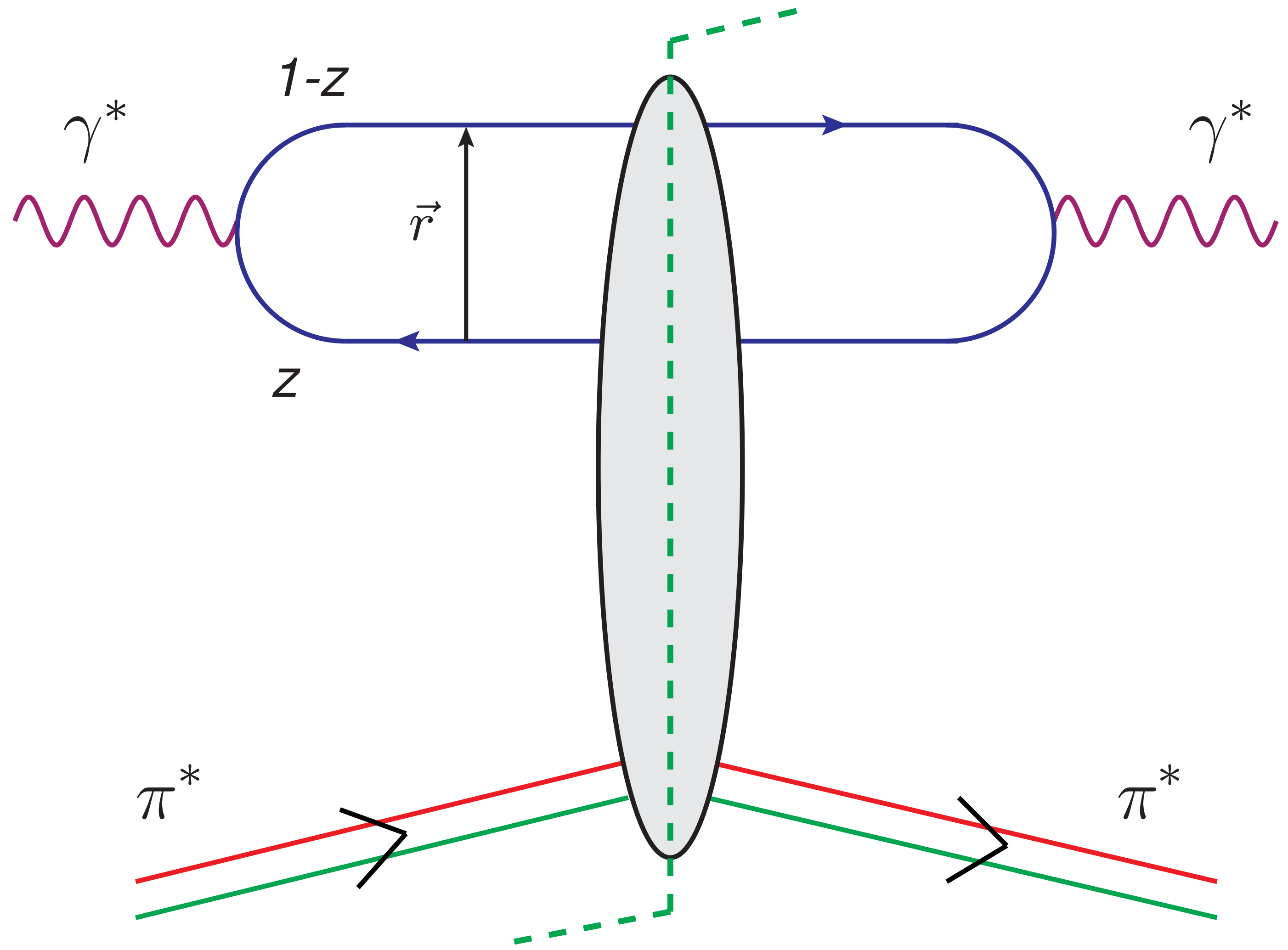
A.Stasto, K. Biernat. J. Kwiecinski PRL (2001) 86, 596

- *Scaling above Q_S : extended geometric scaling*

E.Iancu, K. Itakura, L.McLerran Nucl. Phys (2002) A708, 327

J.Kwiecinski, A. Stasto PRD (2002) 66, 014013

VIRTUAL PION–PHOTON CROSS SECTION IN DIPOLE MODEL



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$$\sigma_{L,T}^{\gamma^*\pi^*}(\hat{x}, Q^2) = \text{Im}\ \mathcal{A}(\hat{x}, Q^2, \Delta = 0) = \int d^2\text{b} \int d^2\text{r} \int \frac{dz}{4\pi} |\Psi^f_{L,T}(\text{r}, z, Q^2)|^2 \frac{d\sigma_{q\bar{q}}^{(\pi)}}{d^2\text{b}}(\text{b}, \text{r}, \hat{x})$$

❖Two phenomenological parameterisations:

bSat : $$\frac{d\sigma_{q\bar{q}}^{(\pi)}}{d^2\text{b}}(\text{b}, \text{r}, \hat{x}) = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_C} r^2 \alpha_s(\mu^2) \hat{x} g(\hat{x}, \mu^2) T_\pi(\text{b})\right)\right]$$

bNonSat : $$\frac{d\sigma_{q\bar{q}}^{(\pi)}}{d^2\text{b}}(\text{b}, \text{r}, \hat{x}) = \frac{\pi^2}{N_C} r^2 \alpha_s(\mu^2) \hat{x} g(\hat{x}, \mu^2) T_\pi(\text{b})$$ with

with $T_\pi(b) = \frac{1}{2\pi B_\pi} e^{-\frac{b^2}{2B_\pi}}$ and $\hat{x}g(\hat{x}, \mu_0^2) = A_g \hat{x}^{-\lambda_g}(1 - \hat{x})^6$ and $\mu^2 = \mu_0^2 + \frac{C}{r^2}$, the parameters A_g, λ_g, C are fitted to LN structure function data.

PION STRUCTURE IN LEADING NEUTRON EVENTS

$$\sigma_{L,T}^{\gamma^*\pi^*}(\hat{x}, Q^2) = \text{Im}\ \mathscr{A}(\hat{x}, Q^2, \Delta = 0) = \int d^2\mathrm{b} \int d^2\mathrm{r} \int \frac{dz}{4\pi} |\Psi^f_{L,T}(\mathrm{r}, z, Q^2)|^2 \frac{d\sigma_{q\bar{q}}^{(\pi)}}{d^2\mathrm{b}}(\mathrm{b}, \mathrm{r}, \hat{x})$$

❖Two approaches:

➤Do a new fit of the dipole model parameters (A_g, λ_g, C) to the LN Structure function data

➤Use an assumption that the dipole-proton and dipole-pion cross section are related to each other

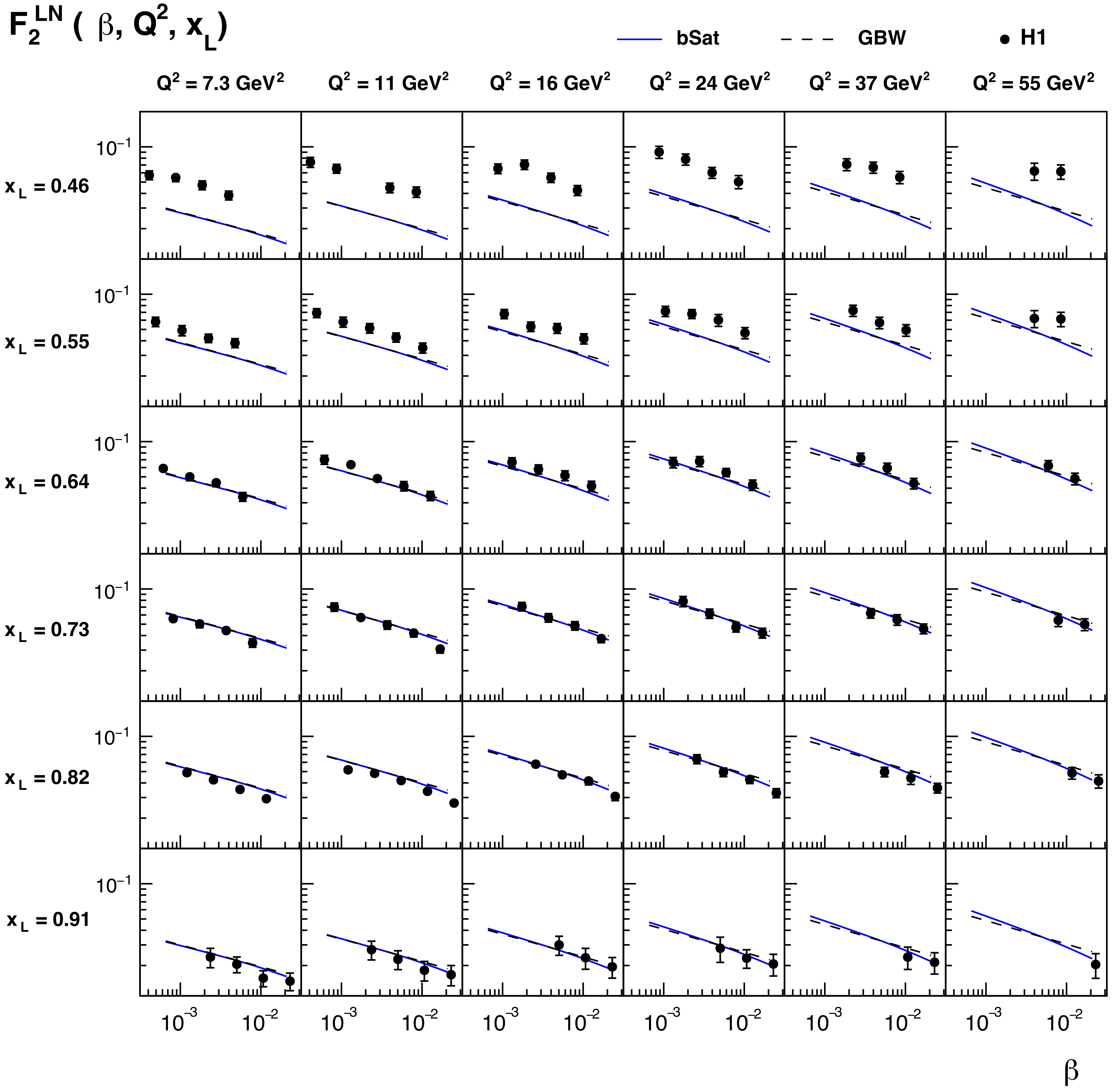
$$\frac{d\sigma_{q\bar{q}}^{(\pi)}}{d^2\mathrm{b}}(\mathrm{b}, \mathrm{r}, \beta) = R_g\ \frac{d\sigma_{q\bar{q}}^{(p)}}{d^2\mathrm{b}}(\mathrm{b}, \mathrm{r}, \beta)$$

R_g is determined through fit to the LN structure function data and dipole-proton cross section is already known from the fit of dipole models to the reduced cross section data in inclusive DIS.

- Energy Dependence of dipole-pion and dipole-proton cross section is identical
- In constituent quark picture, $R_g \sim R_q$ is ratio of number quarks in pion and proton i.e $R_q = 2/3$

❖ We employ both the approaches and test the universality of pion and proton structure at small-x

LEADING NEUTRON STRUCTURE FUNCTION



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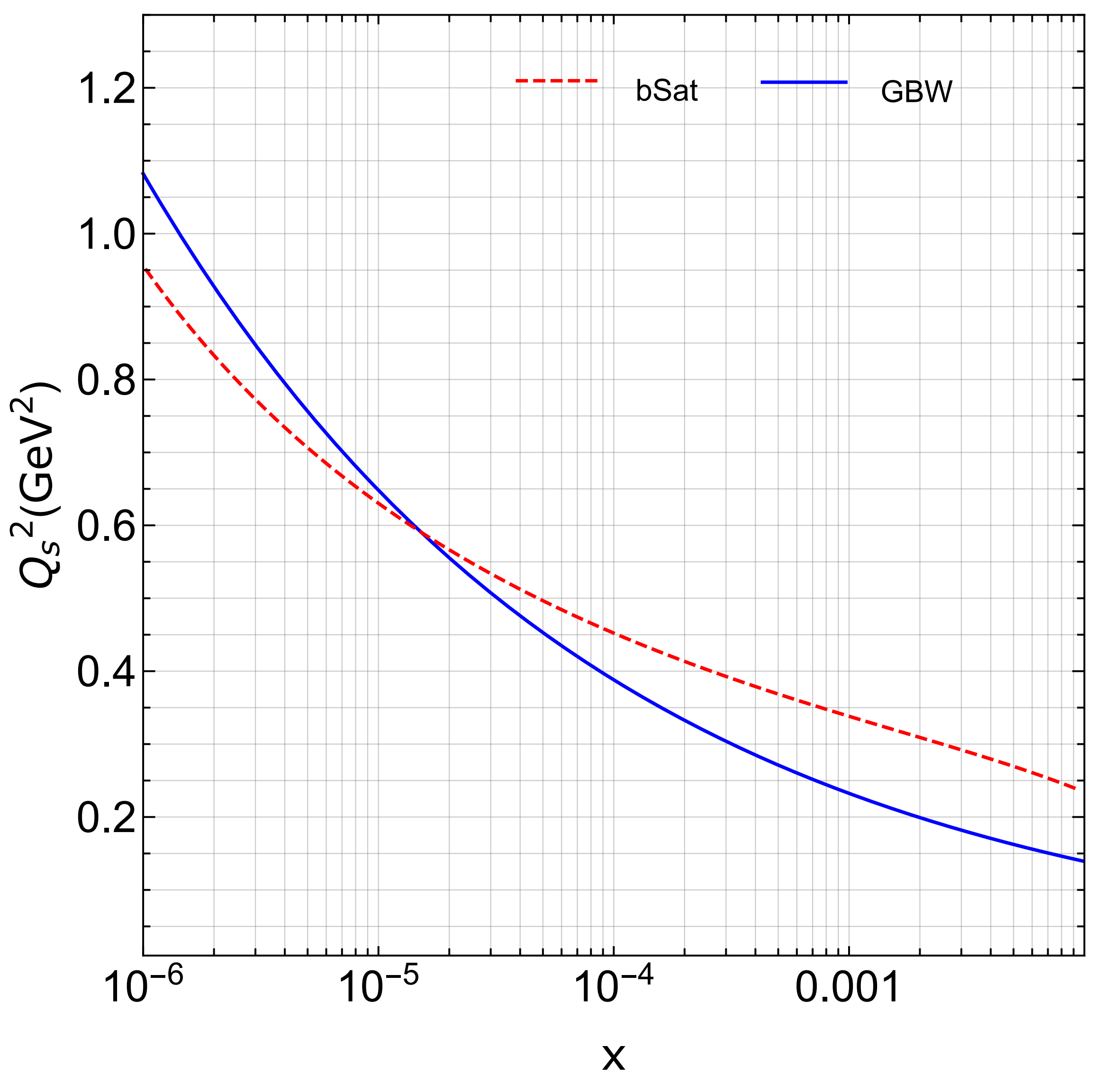
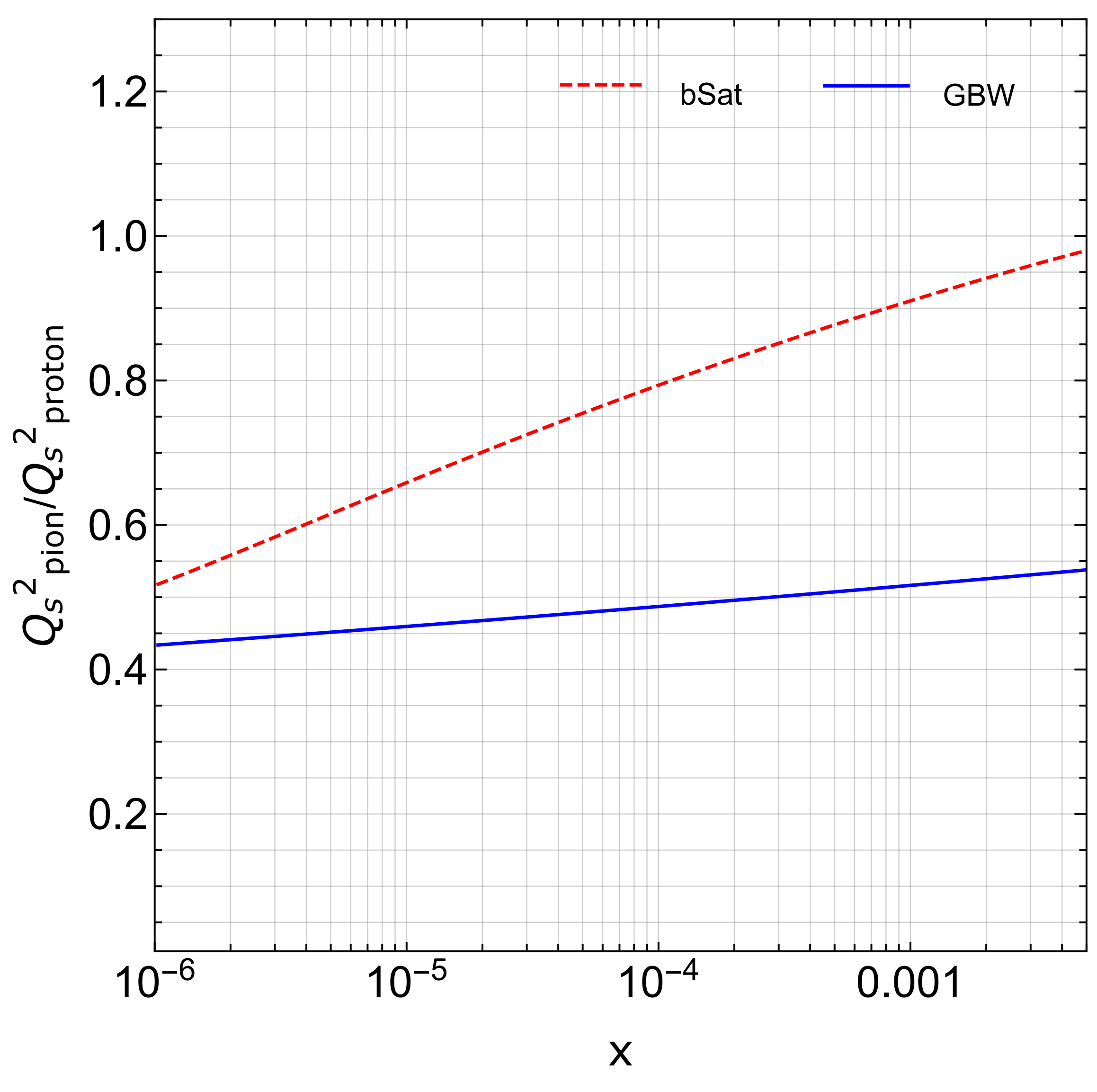
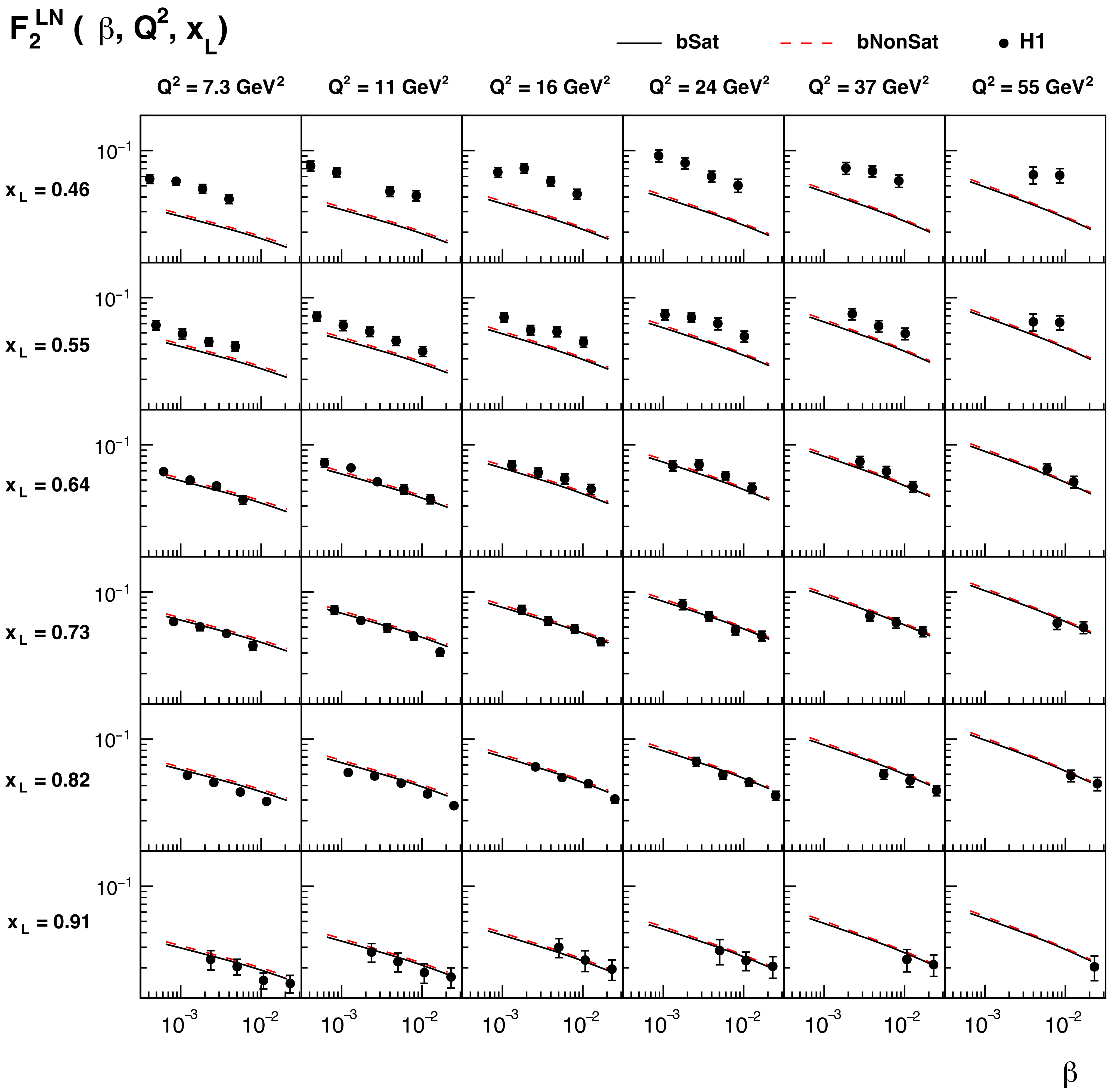


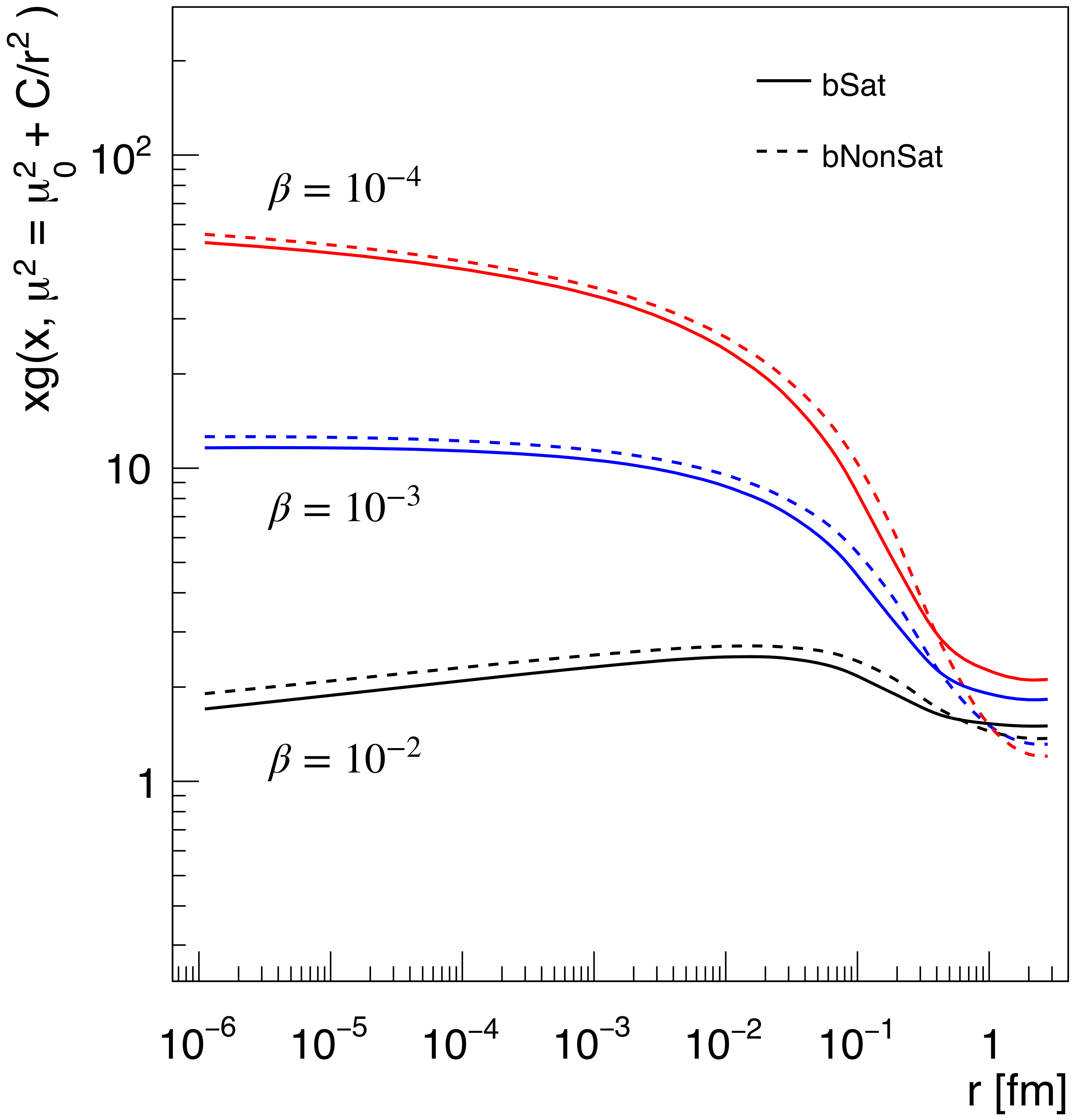


GBW	σ_0 [mb]	λ	$x_0/10^{-4}$	R_q	χ^2/N_{dof}
Fit 1	17.171 ± 2.777	0.223 ± 0.018	0.036 ± 0.024	...	$63.26/48 = 1.32$
Fit 2	27.43	0.248	0.40	0.438 ± 0.005	$64.52/50 = 1.29$

bSat	A_g	λ_g	C	R_q	χ^2/N_{dof}
Fit 3	1.208 ± 0.012	0.0600 ± 0.038	1.453 ± 0.024	...	$58.75/48 = 1.22$
Fit 4	2.195	0.0829	2.289	0.520 ± 0.006	$66.19/50 = 1.32$

LN STRUCTURE FUNCTION F_2^{LN}

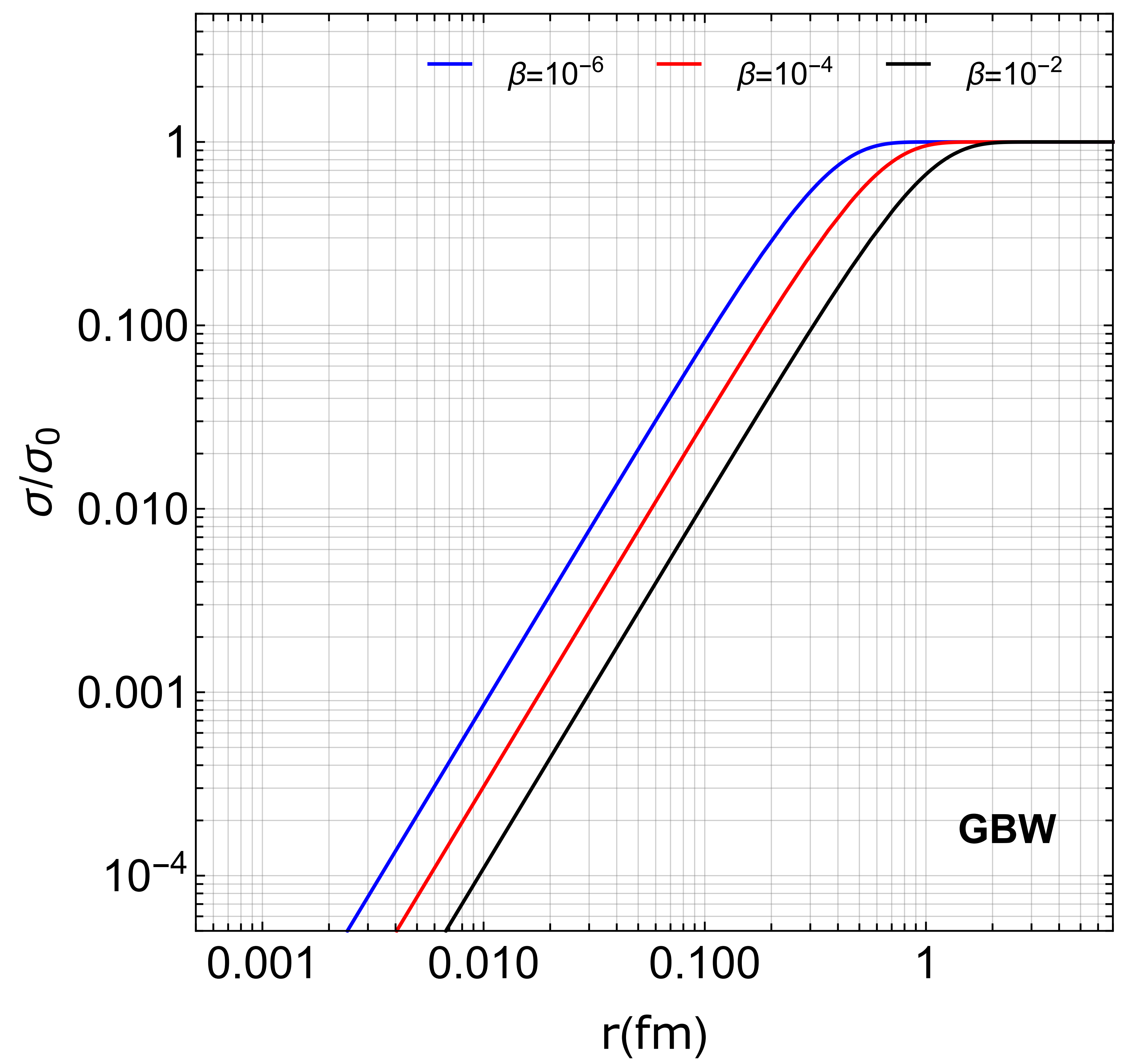


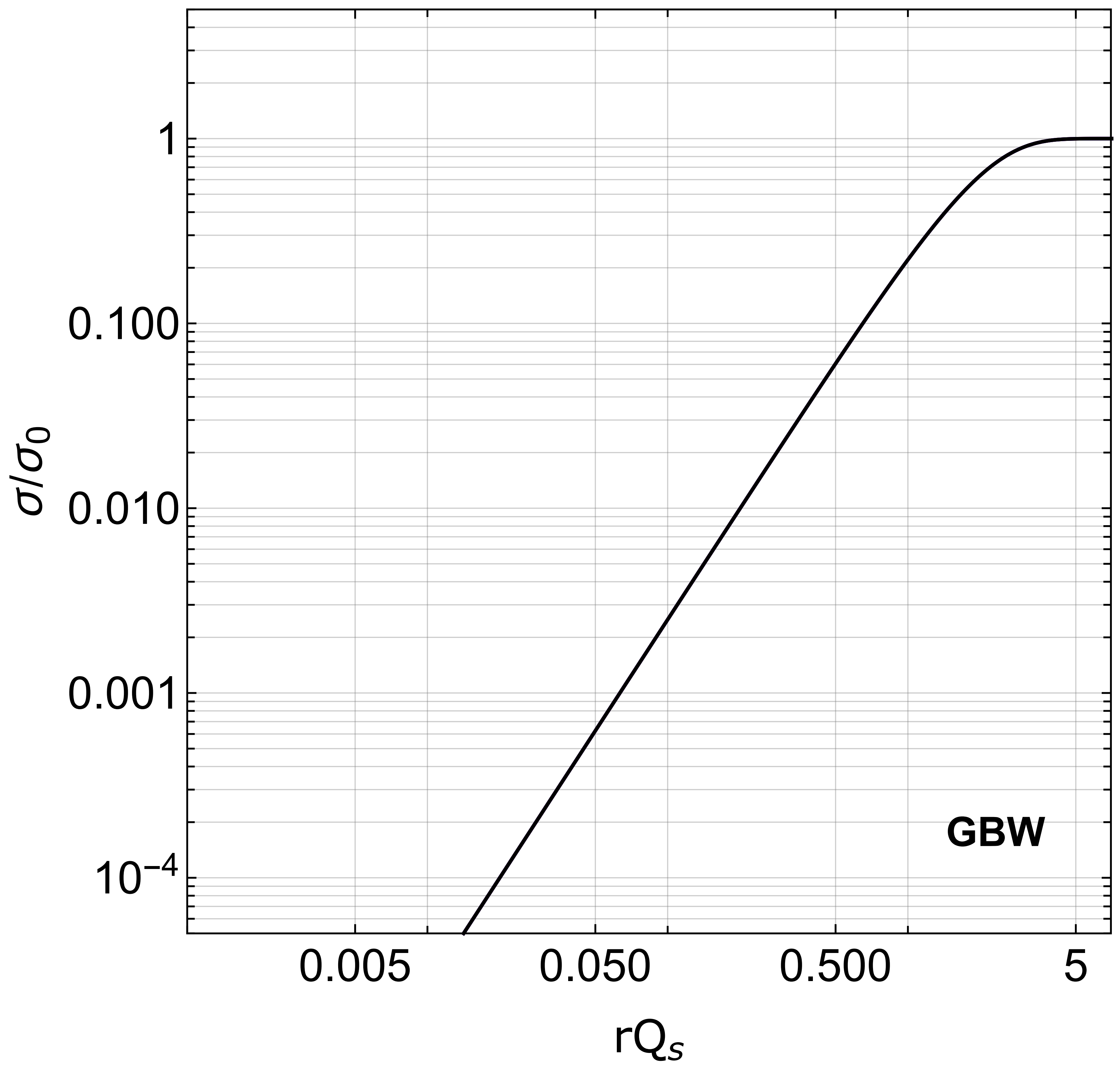


Fit	Model	N	x_{Lmin}	x_{Lmax}	m_l	m_c	μ_0	C	A_g	λ_g	χ^2/N_{dof}
1	bSat	51	0.6	1.0	0.0300	1.3528	1.1	1.453 ± 0.024	1.208 ± 0.012	0.0600 ± 0.0380	58.75/48 = 1.22
2	bNonSat	51	0.6	1.0	0.1516	1.3504	1.1	3.683 ± 0.436	1.799 ± 0.710	-0.0477 ± 0.0038	57.61/48 = 1.20

Quark masses from H.Mantysaari, P.Zurita PRD 98 (2018), 036002

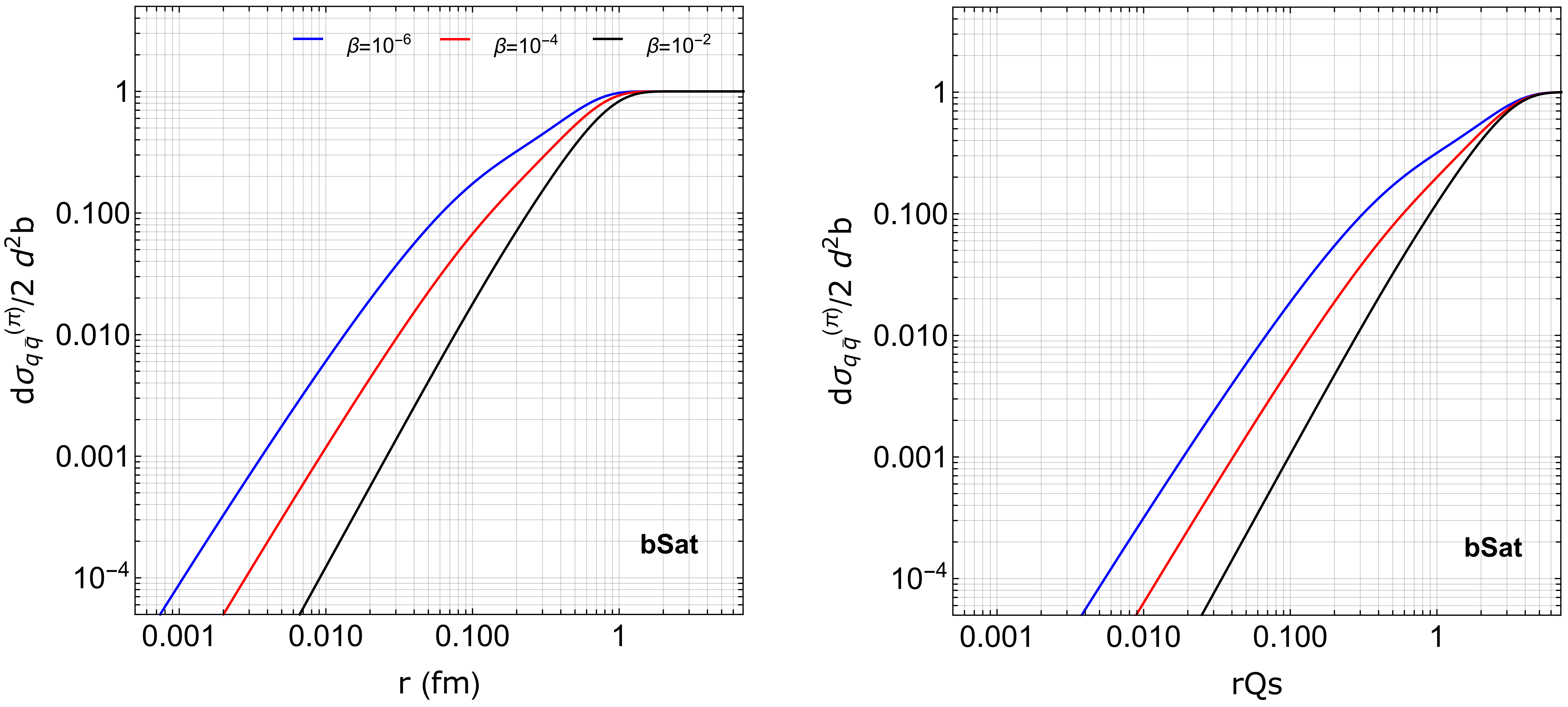
SCALING IN GBW MODEL





❖ Exact Scaling in GBW model for the new fit with LN Structure function data where $\sigma^{\pi}(r,\beta) = \sigma_0(1 - e^{r^2 Q_s^2(\beta)/4})$,

SCALING IN BSAT MODEL



❖ Scaling is not exact in bSat model due to the gluon density evolution where $\frac{d\sigma_{q\bar{q}}^{(\pi)}}{d^2\text{b}}(\text{b}, \text{r}, \hat{x}) = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_C} r^2 \alpha_s(\mu^2)\hat{x}g(\hat{x}, \mu^2)T_\pi(\text{b})\right)\right]$

where $\mu^2 = \mu_0^2 + \frac{C}{r^2}$

GEOMETRIC SCALING IN LEADING NEUTRON EVENTS

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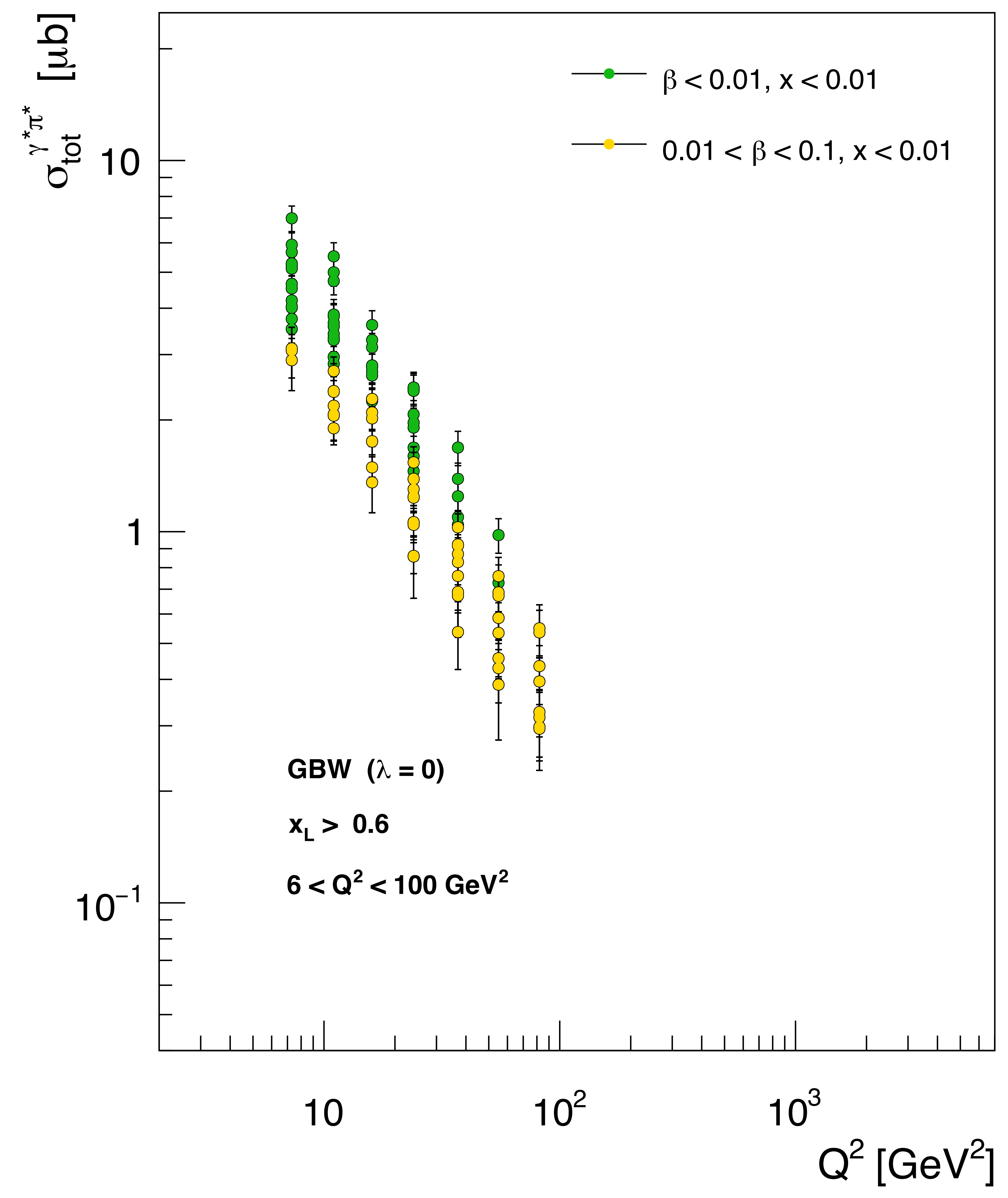

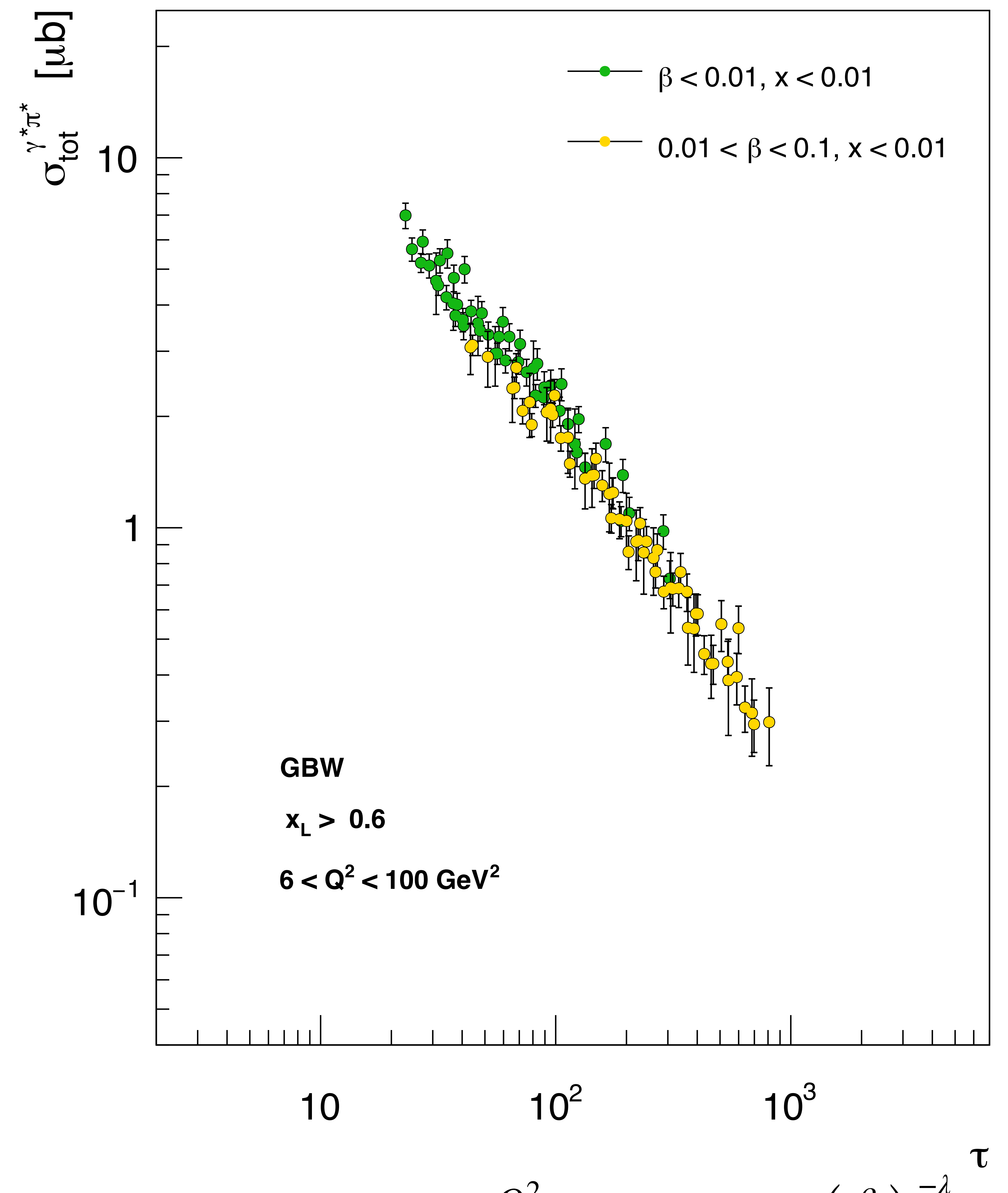

$$\tau = \frac{Q^2}{Q_s^2(\beta)}; \quad Q_s^2(\beta) = Q_0^2 \left(\frac{\beta}{x_0}\right)^{-\lambda}$$

FEYNMAN-X SPECTRA OF LEADING NEUTRONS

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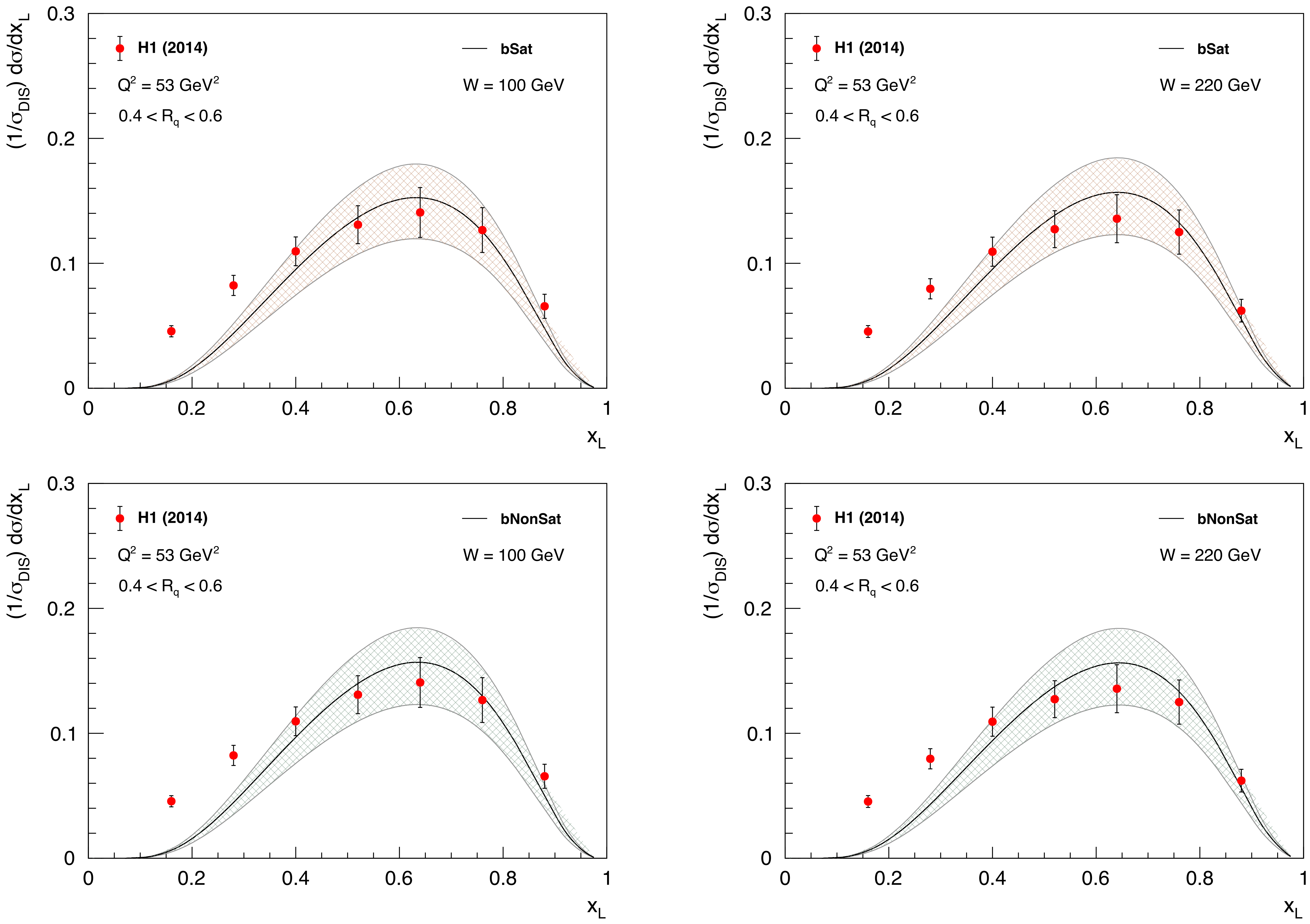
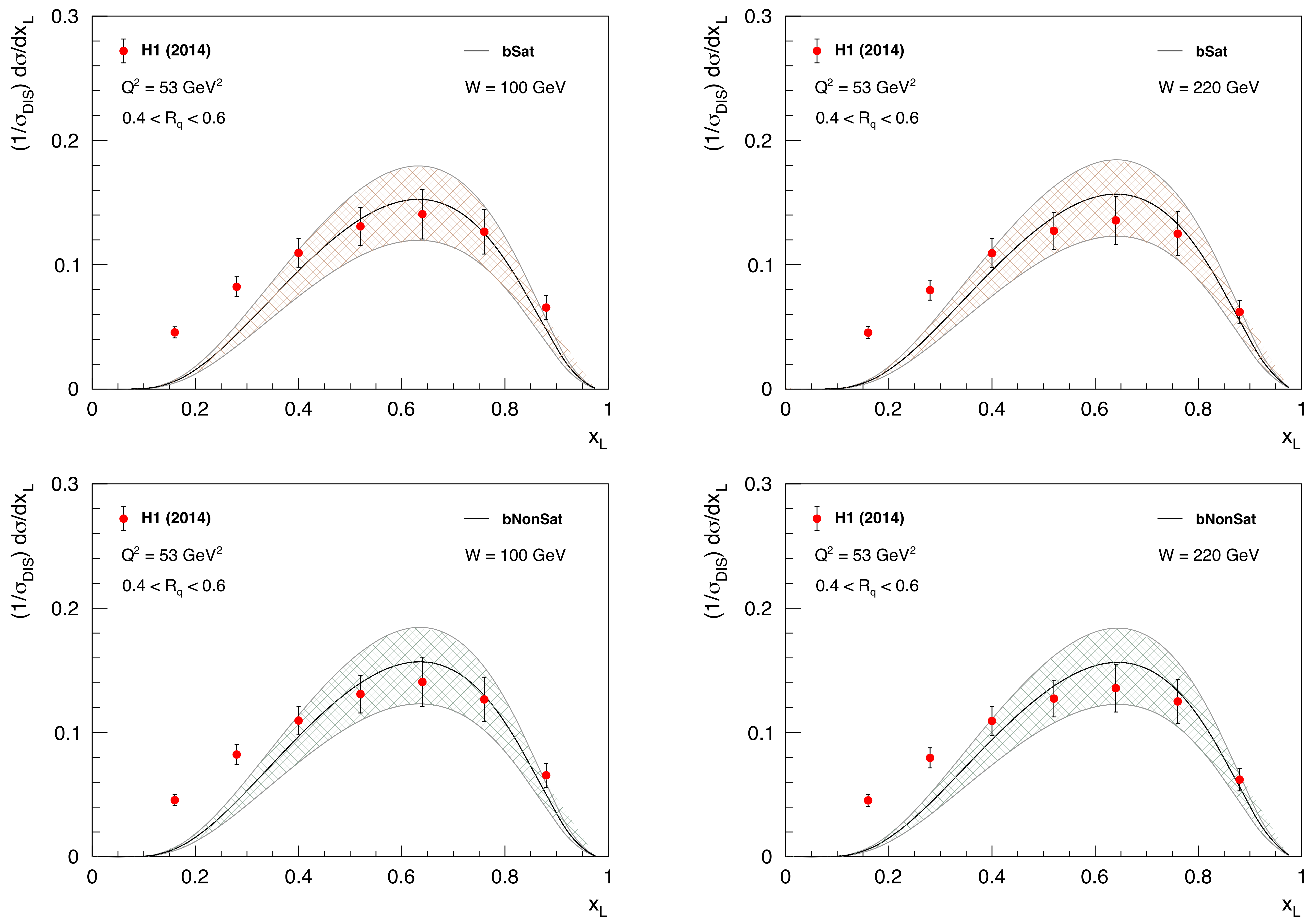


FEYNMAN-X SPECTRA OF LEADING NEUTRONS



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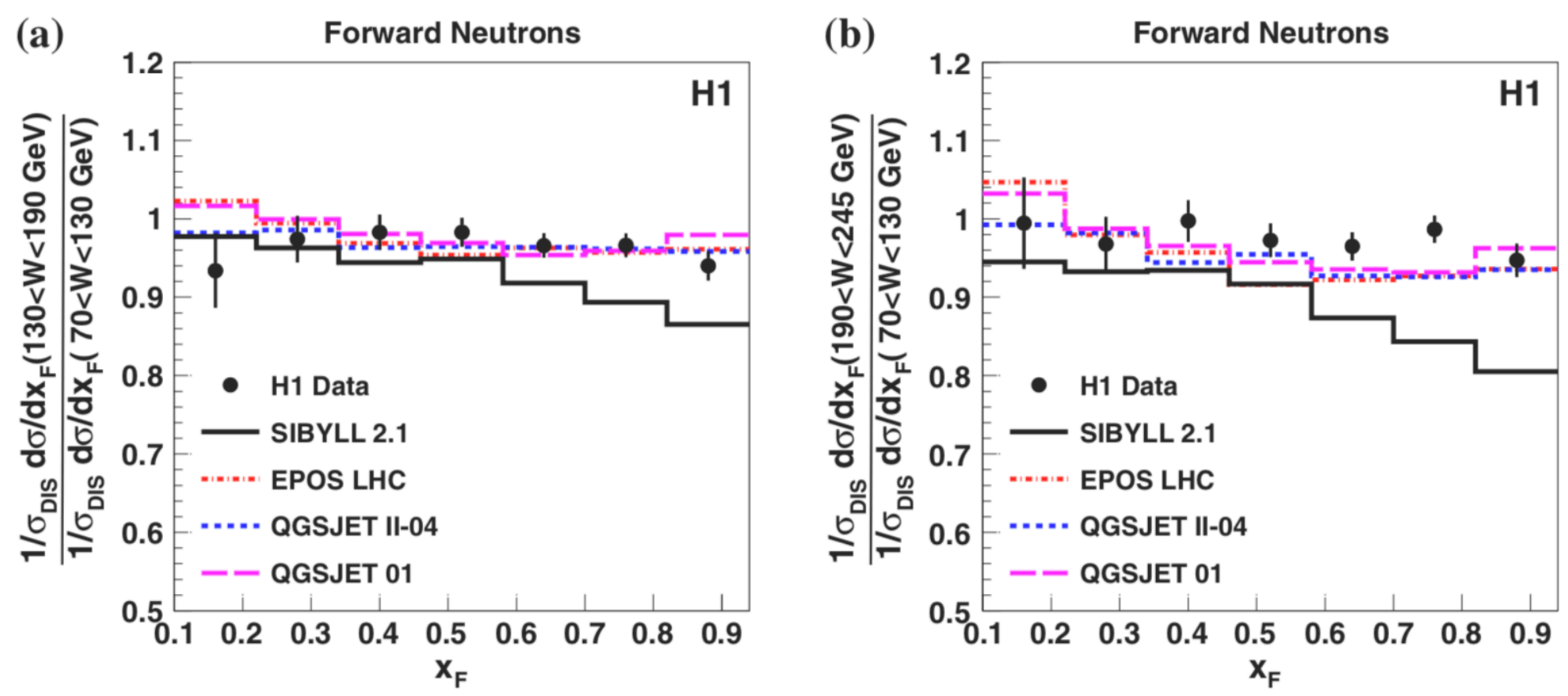
Carvalho, Gonçalves, Spiering, Navarra PLB 752 (2016) 76

"We demonstrate the recently released H1 leading neutron spectra can be described using the color dipole formalism and that these spectra could help us to observe more clearly gluon saturation effects in future ep colliders"

H1 EPJC 74 (2014), 2915



✤ Is this scaling related to saturation?

SCALING IN FEYNMAN-X SPECTRA

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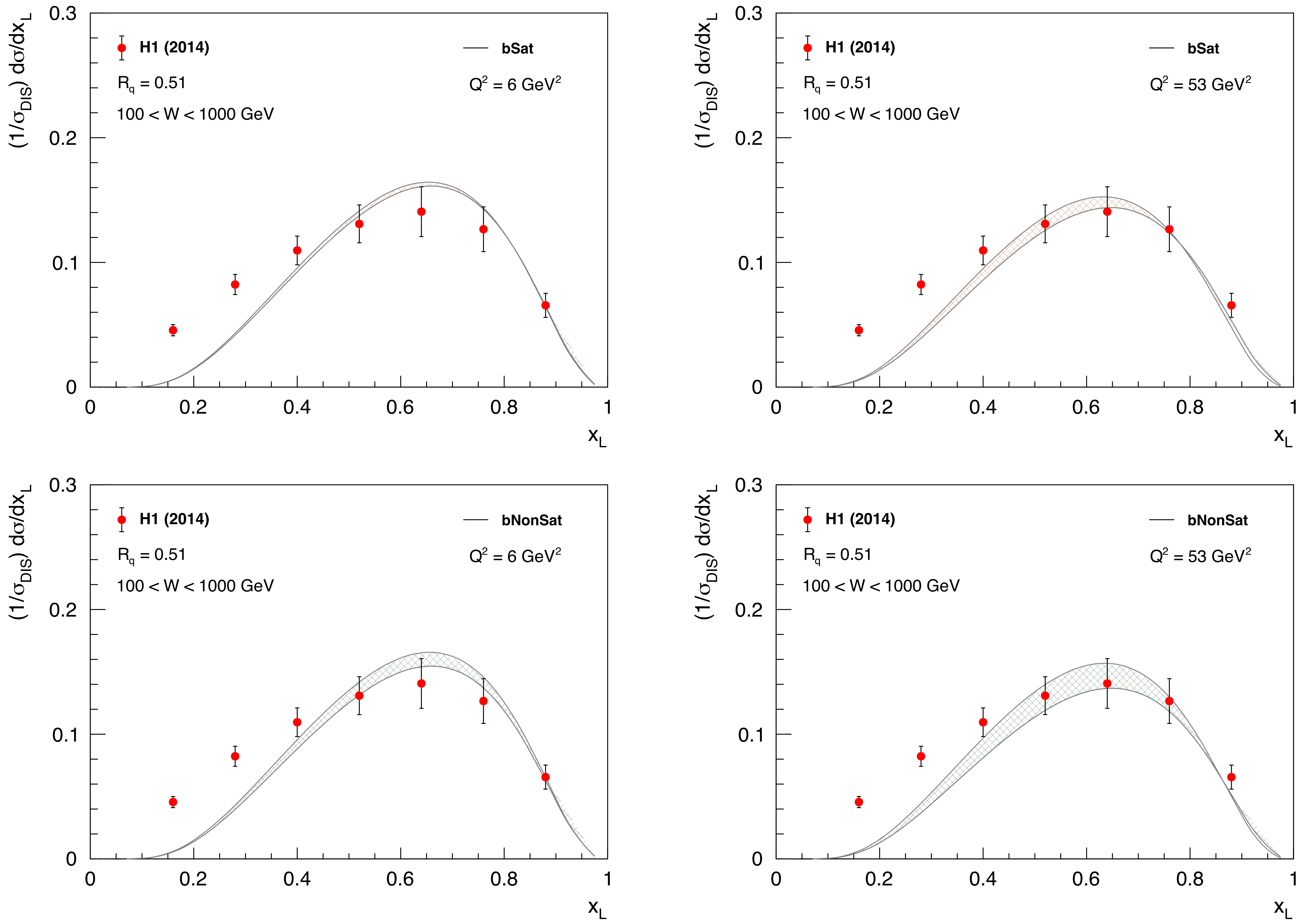
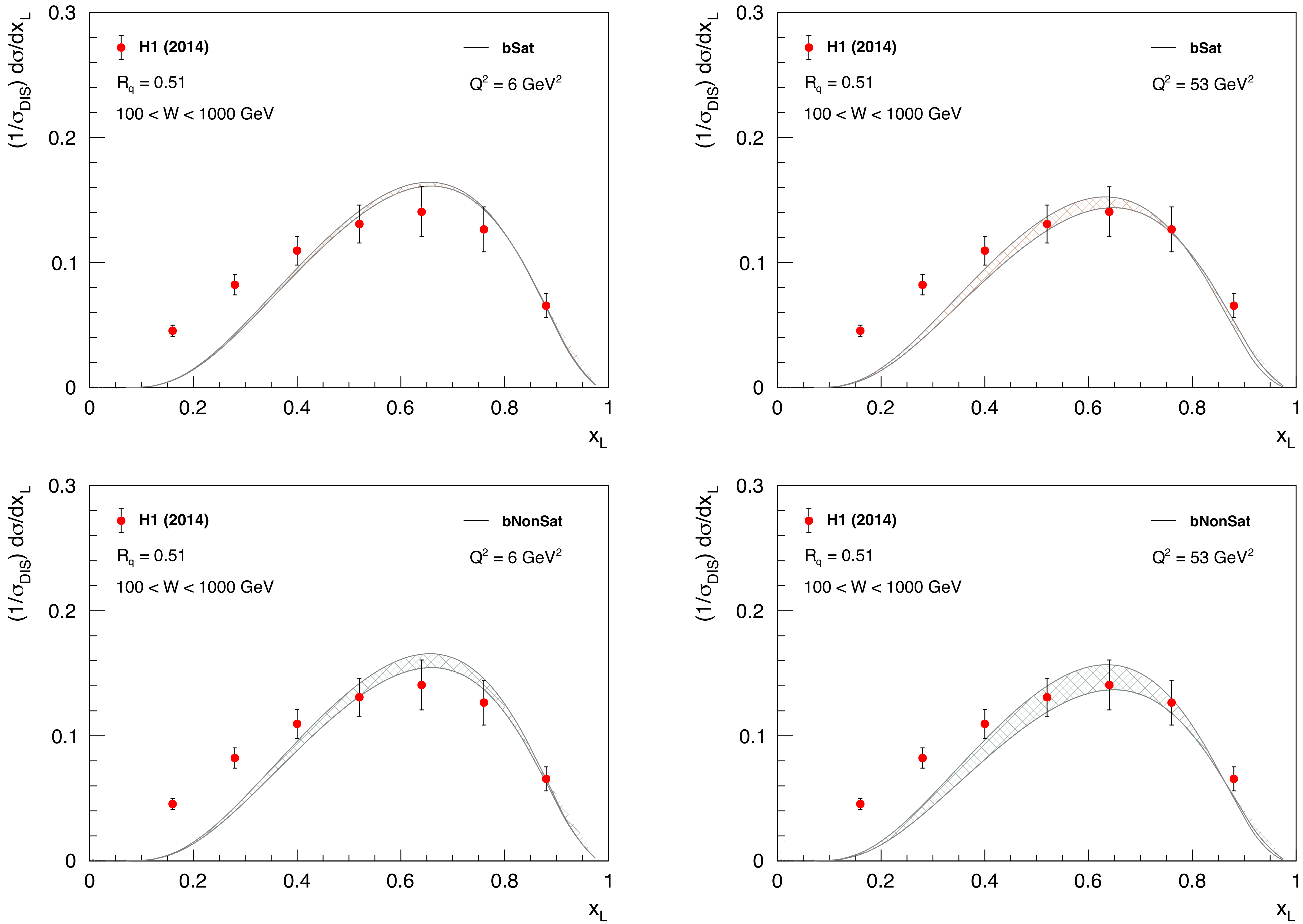


$$\hat{x} = \frac{Q^2 + m_f^2}{(1 - x_L)W^2 + Q^2}$$

SCALING IN FEYNMAN-X SPECTRA



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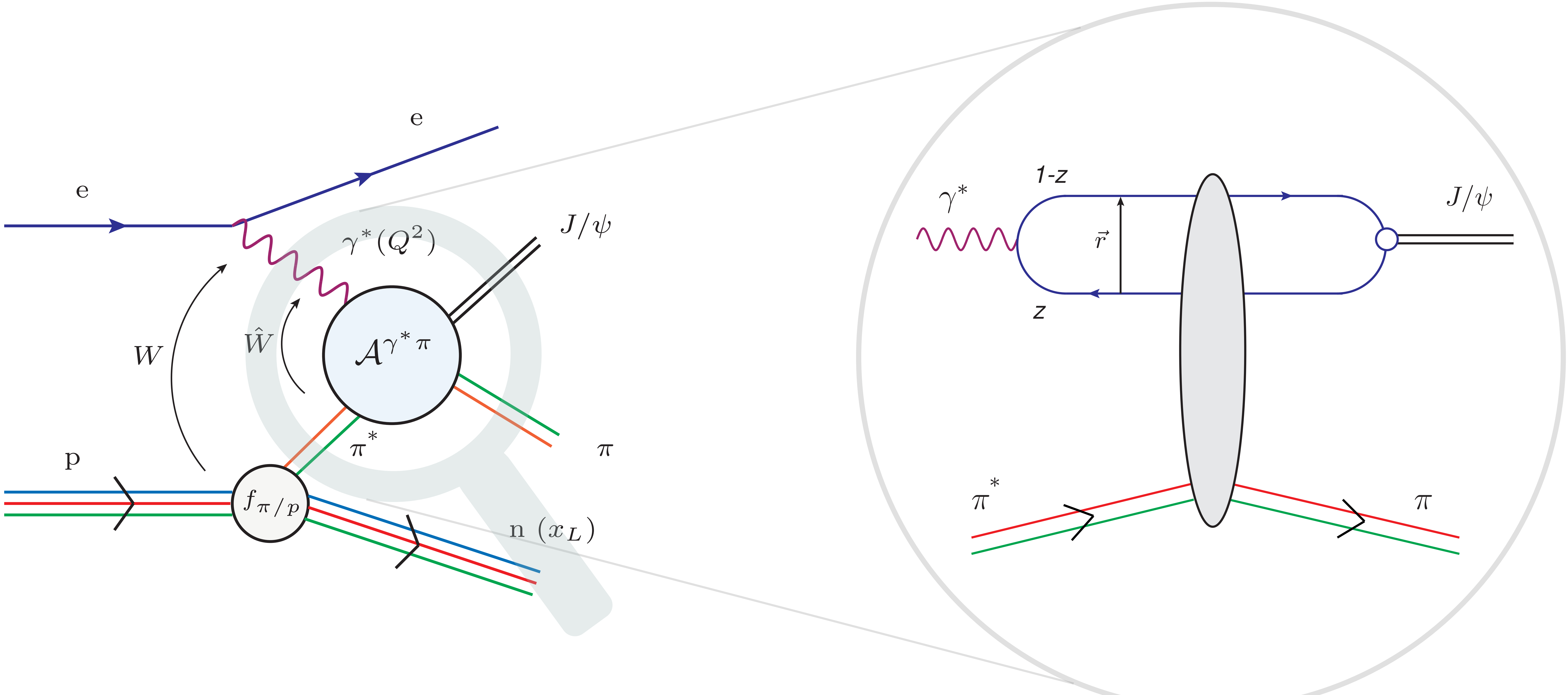
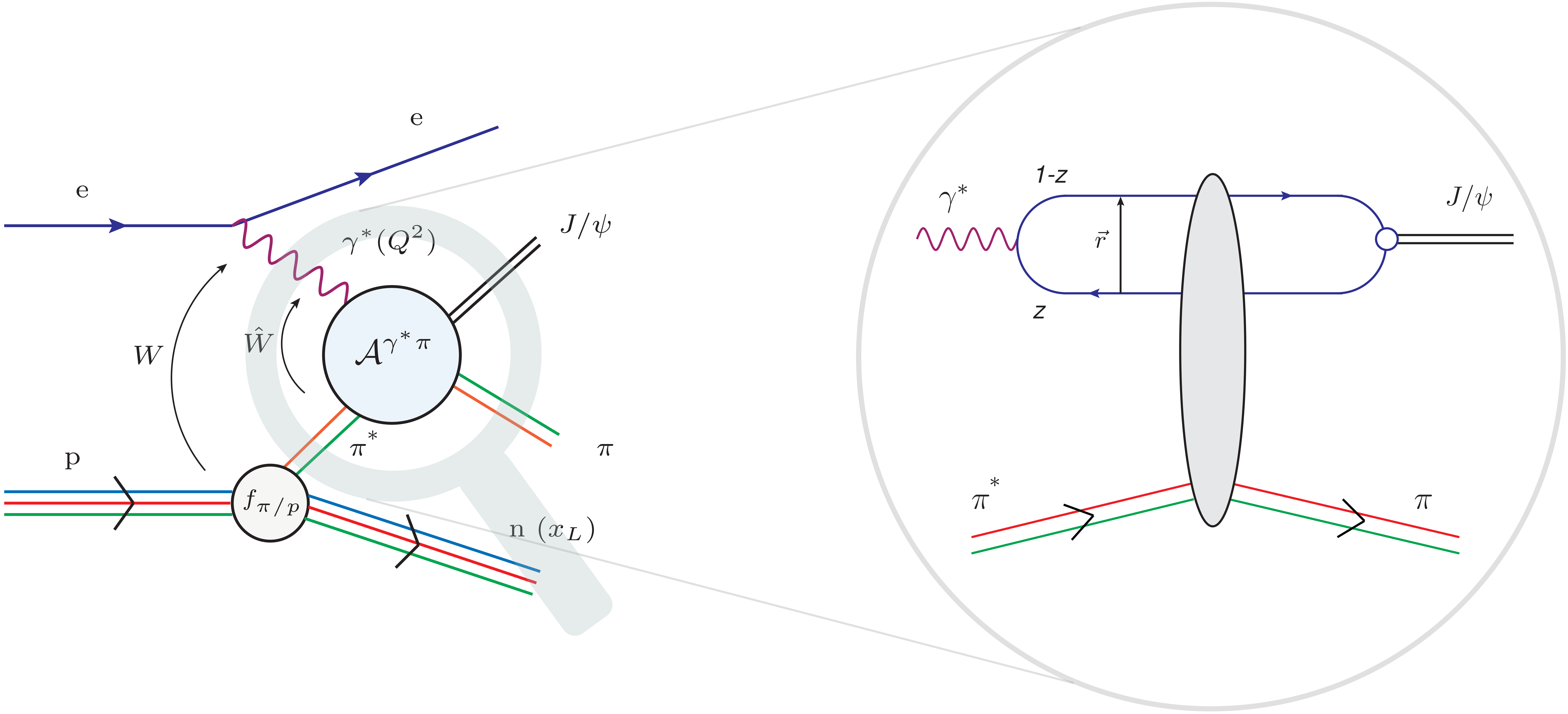
- ❖ *Pion and proton structure function have identical asymptotic behaviour at high energy*
- ❖ *Feynman scaling is a consequence of this identical asymptotic behaviour*
- ❖ *Feynman scaling not related to saturation effects and holds good in both saturated and non saturated models*
- ❖ *No hints of saturation in the Feynman-x spectra or the leading neutron structure function*

EXCLUSIVE J/Ψ PRODUCTION WITH LEADING NEUTRONS



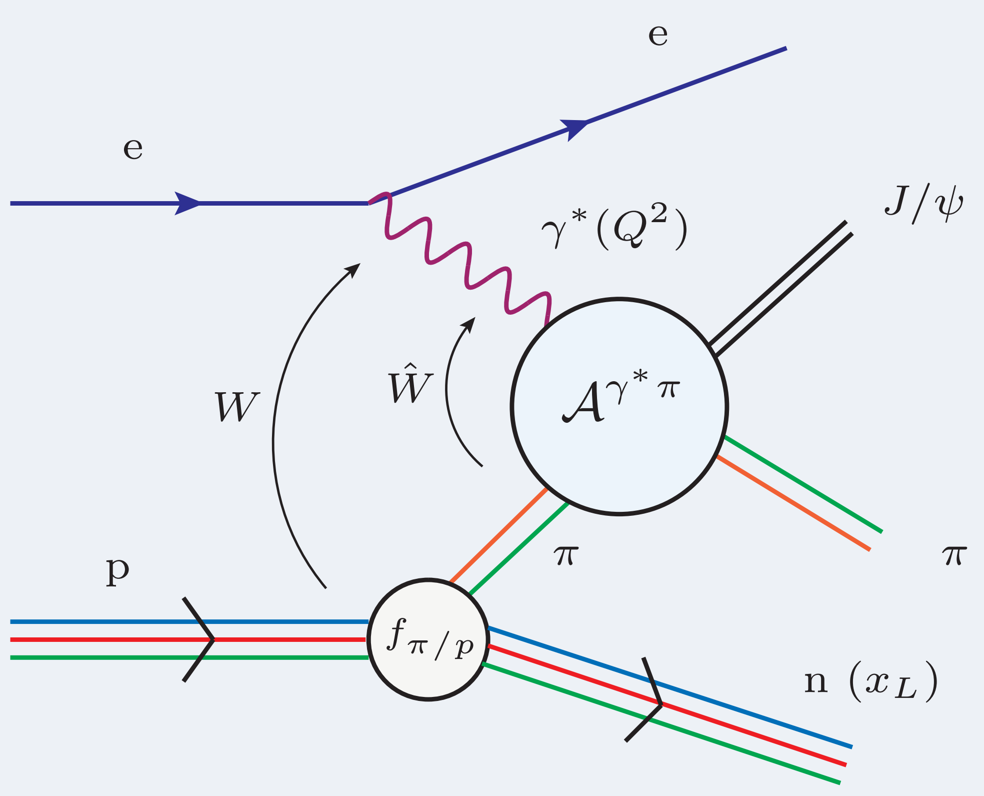
- Exclusive measurement : $e + p \rightarrow e' + J/\psi + \pi + n$
- Experimental signature : Rapidity gap between J/ψ and the pion
- Highly sensitive to saturation and probe for gluon distribution of pion

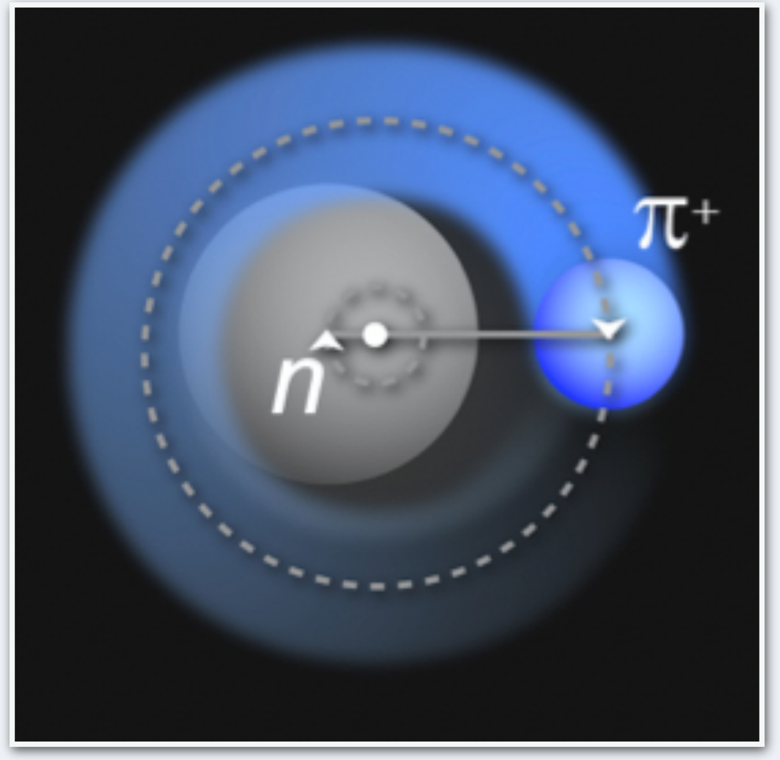
EXCLUSIVE J/Ψ PRODUCTION WITH LEADING NEUTRONS



$$\mathcal{A}_{T,L}^{\gamma^*\pi^*\to J/\Psi\ \pi}(\hat{x},Q^2,\Delta) = \quad i\int d^2\mathbf{r}\int d^2\mathbf{b}\int \frac{dz}{4\pi}(\Psi^*\Psi_V)_{T,L}(Q^2,\mathbf{r},z)$$
$$\times e^{-i[\mathbf{b}-(1-z)\mathbf{r}]\cdot\Delta}\,\frac{d\sigma_{q\bar{q}}^{(\pi)}}{d^2\mathbf{b}}(\mathbf{b},\mathbf{r},\hat{x}).$$

PROBING THE GLUON DISTRIBUTION





❖ The transverse profile of the virtual pion is,

$$T_{\pi^*}(b) = \int_{-\infty}^{\infty} \mathrm{d}z\rho_{\pi^*}(b,z)$$

where the radial part of the virtual pion wave function is given by Yukawa theory:

$$\rho_{\pi^*}(b,z) = \frac{m_\pi^2}{4\pi}\frac{e^{-m_\pi\sqrt{b^2+z^2}}}{\sqrt{b^2+z^2}}$$

❖ We assume that the real pion, as for the proton, is described by a Gaussian profile:

$$T_\pi(b) = \frac{1}{2\pi B_\pi}e^{-\frac{-b^2}{2B_\pi}}$$

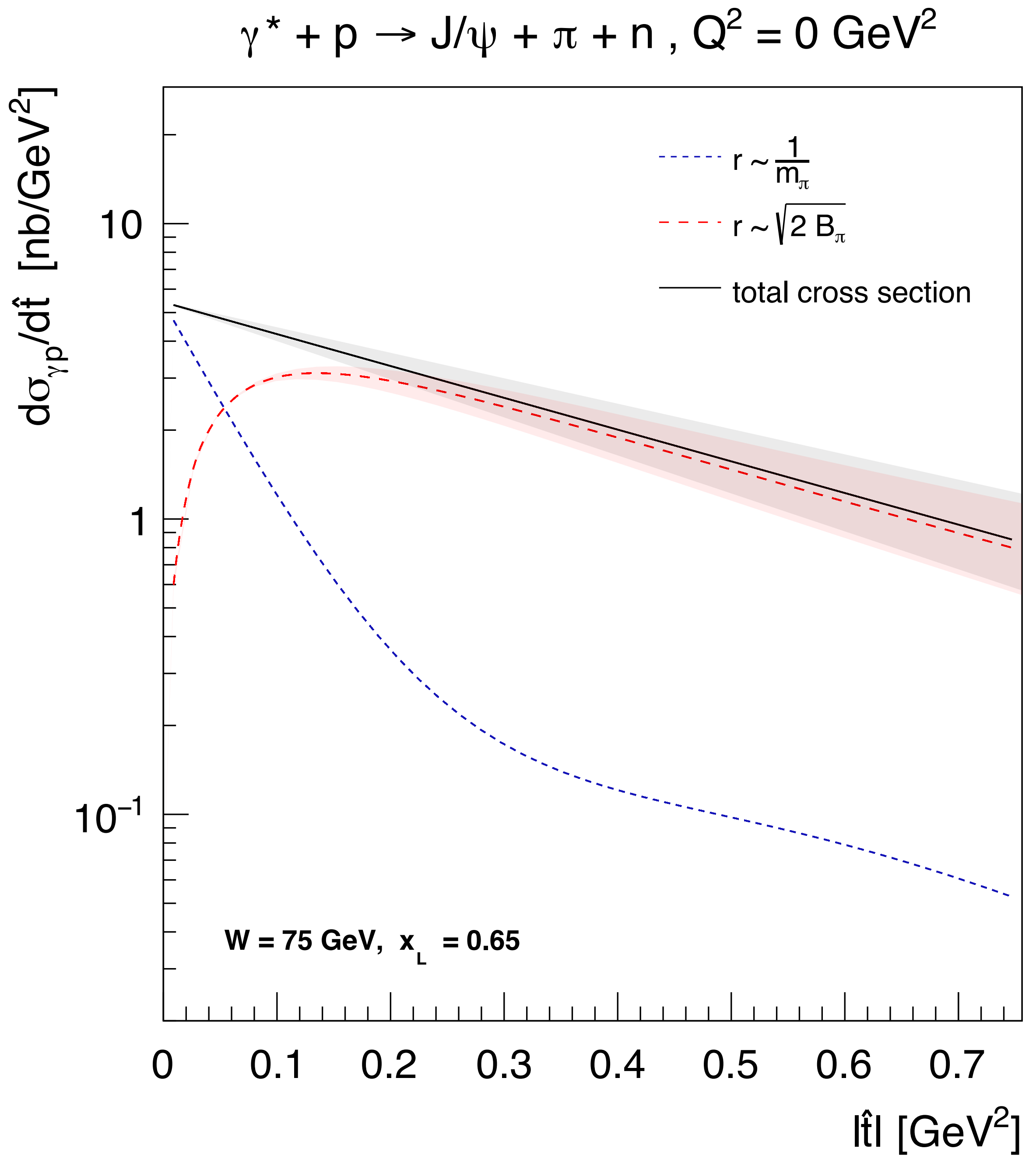
❖ At small $|t'|$, the dipole cannot resolve the pion and interacts with the whole cloud and on increasing the resolution (*increasing* $|t'|$) the dipole interacts with the pion

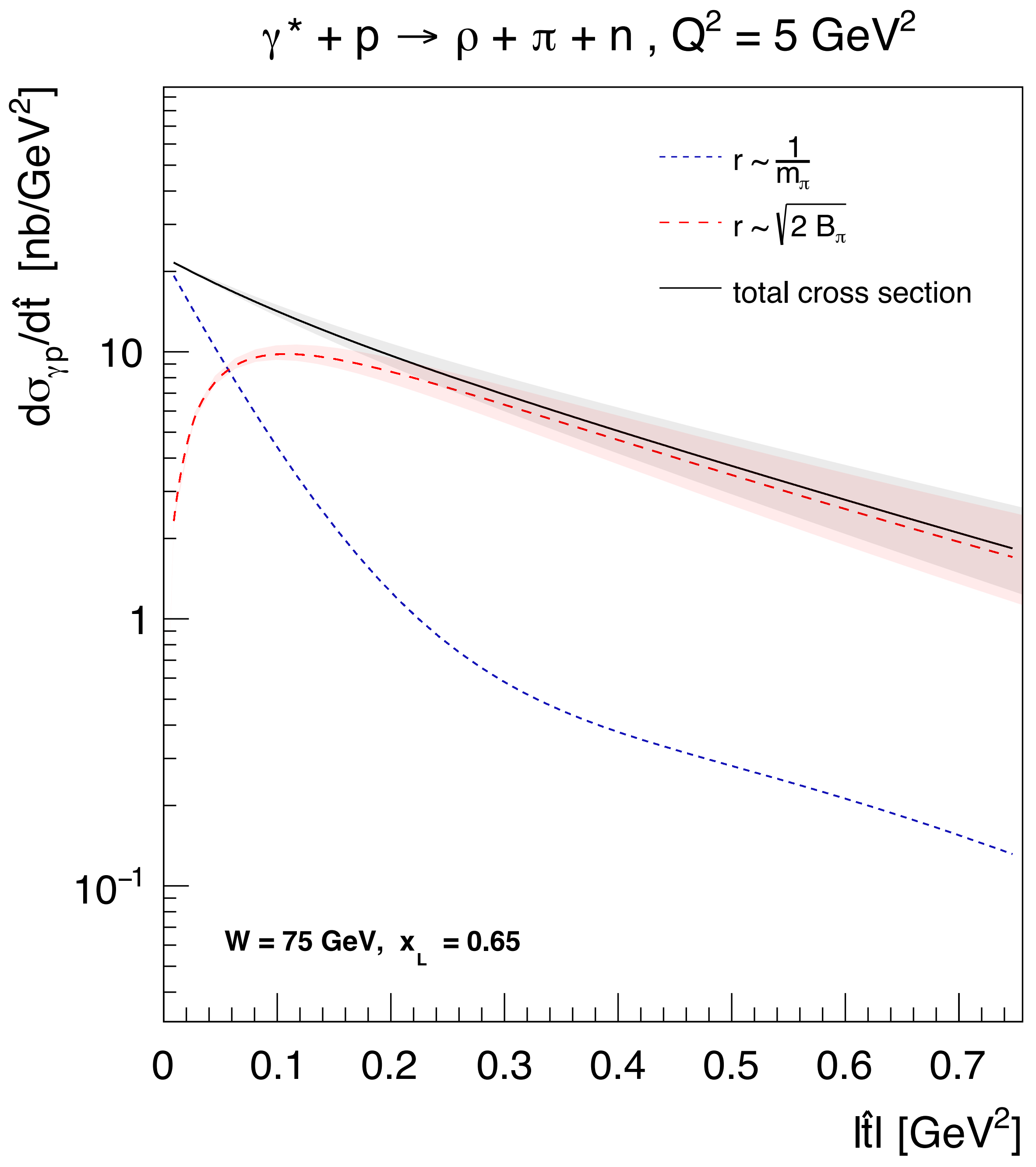
❖The transverse position of the pion inside the virtual pion cloud fluctuates event by event

❖ The cross section have two slopes due to interaction with different size scales at low |t'| and moderate |t'|

❖ H1 data on exclusive ρ photo production with leading neutrons exhibits these two slopes in the differential distribution

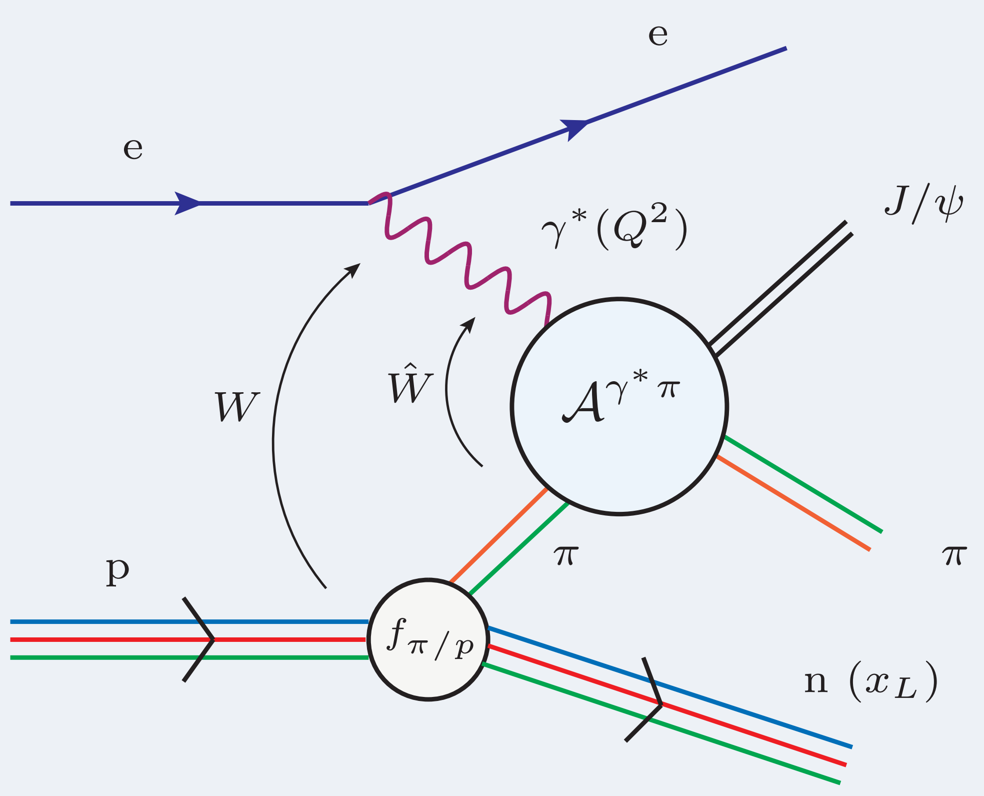
$$\sigma_{tot} \propto |<\mathcal{A}>_\Omega|^2 + (<|\mathcal{A}|^2>_\Omega - |<\mathcal{A}>_\Omega|^2)$$

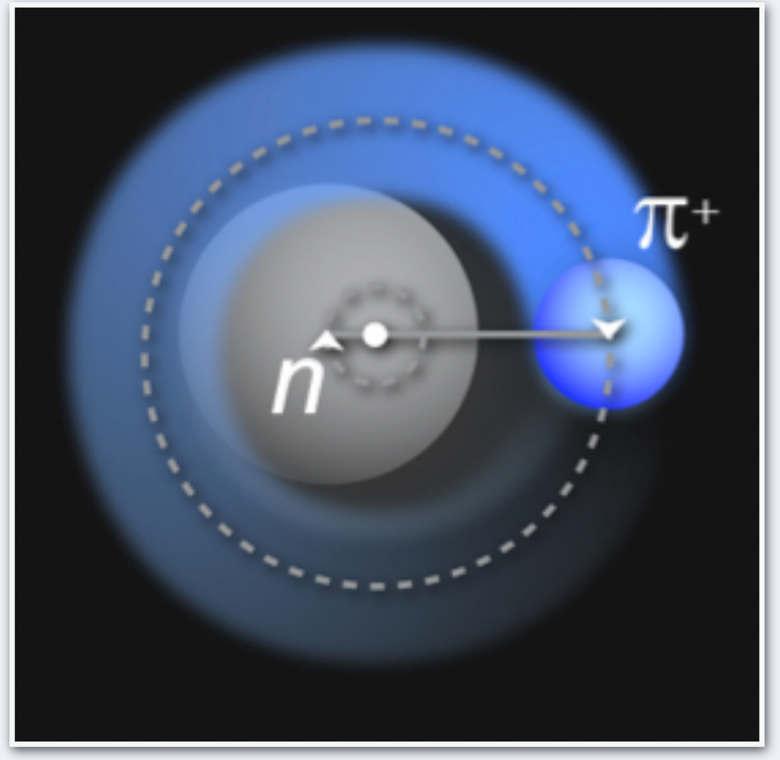




A.K.,Tobias Toll PRD 105 (2022) 114045

PROBING THE GLUON DISTRIBUTION





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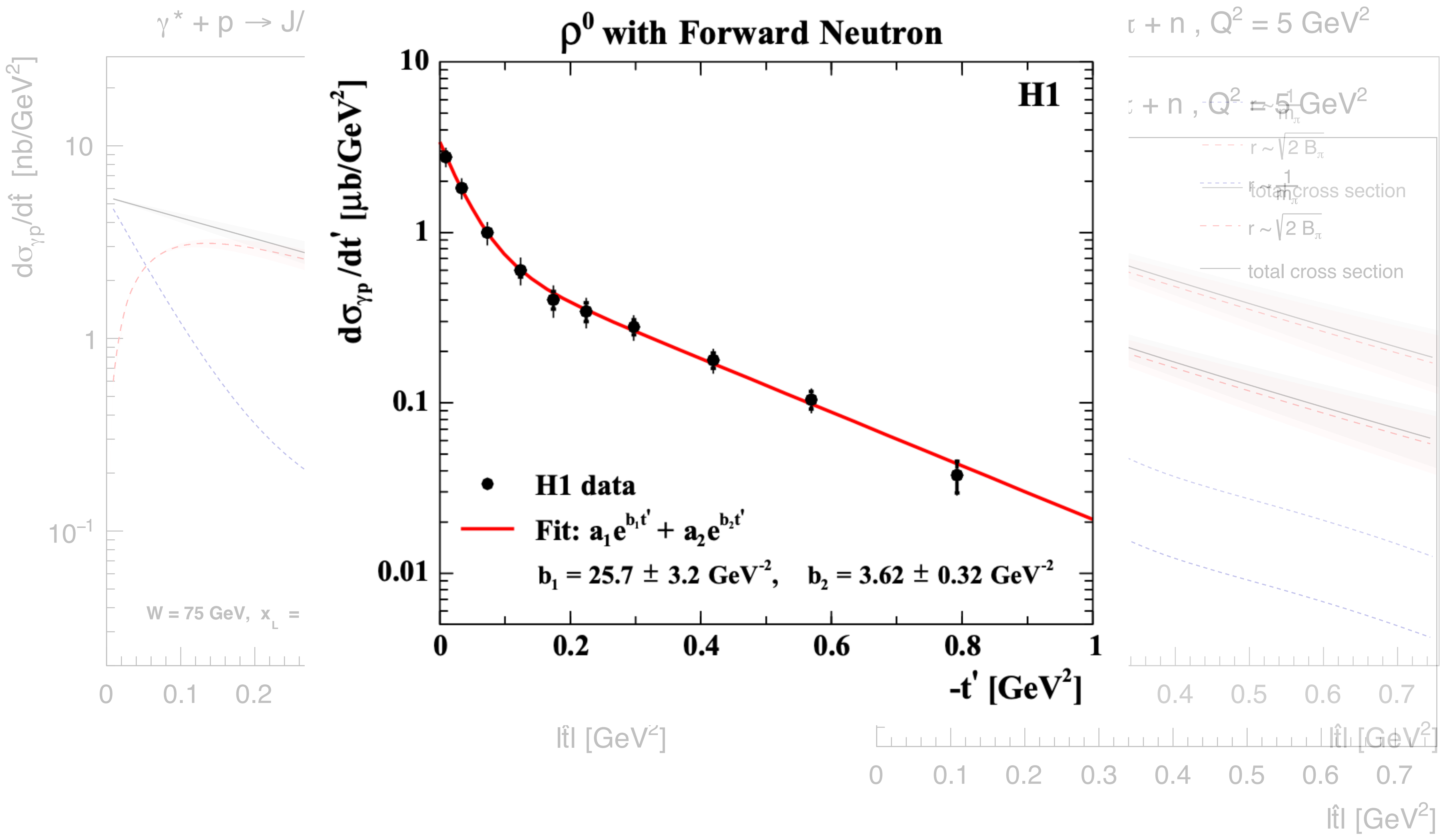
H1 EPJC 76 (2016), 41



SUMMARY AND OUTLOOK

- Investigated virtual photon scattering with the pion cloud of proton in ep scattering using dipole model
  - Neutron tagged inclusive measurement:
    - Probe the longitudinal structure function of pions and universality b/w pion and proton structure (upto norm)
    - Constrain the gluon distribution of pions at small-x in the dipole framework
    - Both the saturated and non-saturated model describes the data
    - Pion structure shows Geometric and Feynman scaling
  - Exclusive measurement:
    - Direct evidence of a proton fluctuation into pion and neutron
    - Probe for the gluon distribution of pion
- Future experiments such as EIC and LHeC can measure the exclusively produces vector meson production in ep scattering with leading neutron events
- Measurement of photo-nuclear cross sections in UPC's at LHC and RHIC are good tests for our models and saturation physics.

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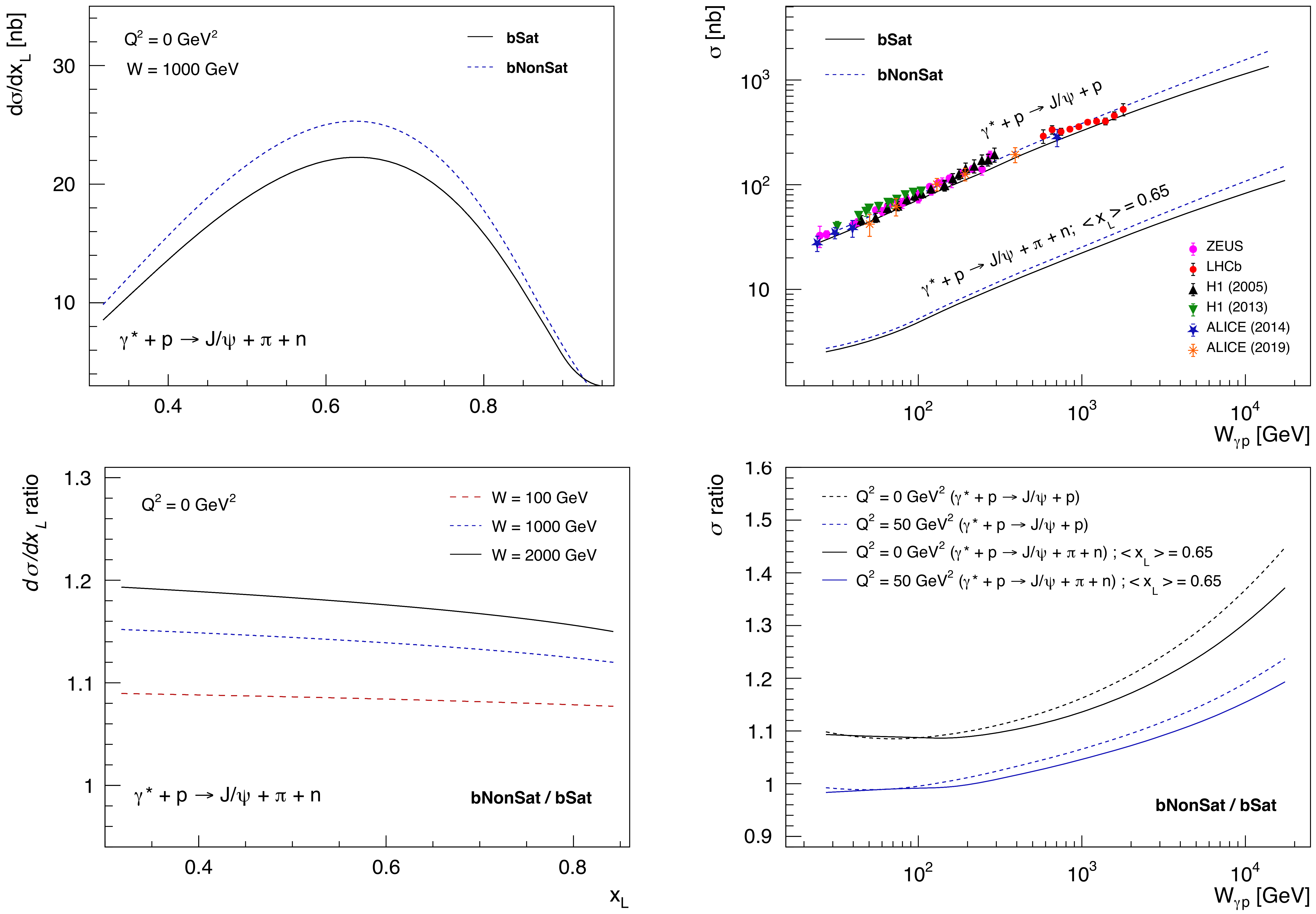
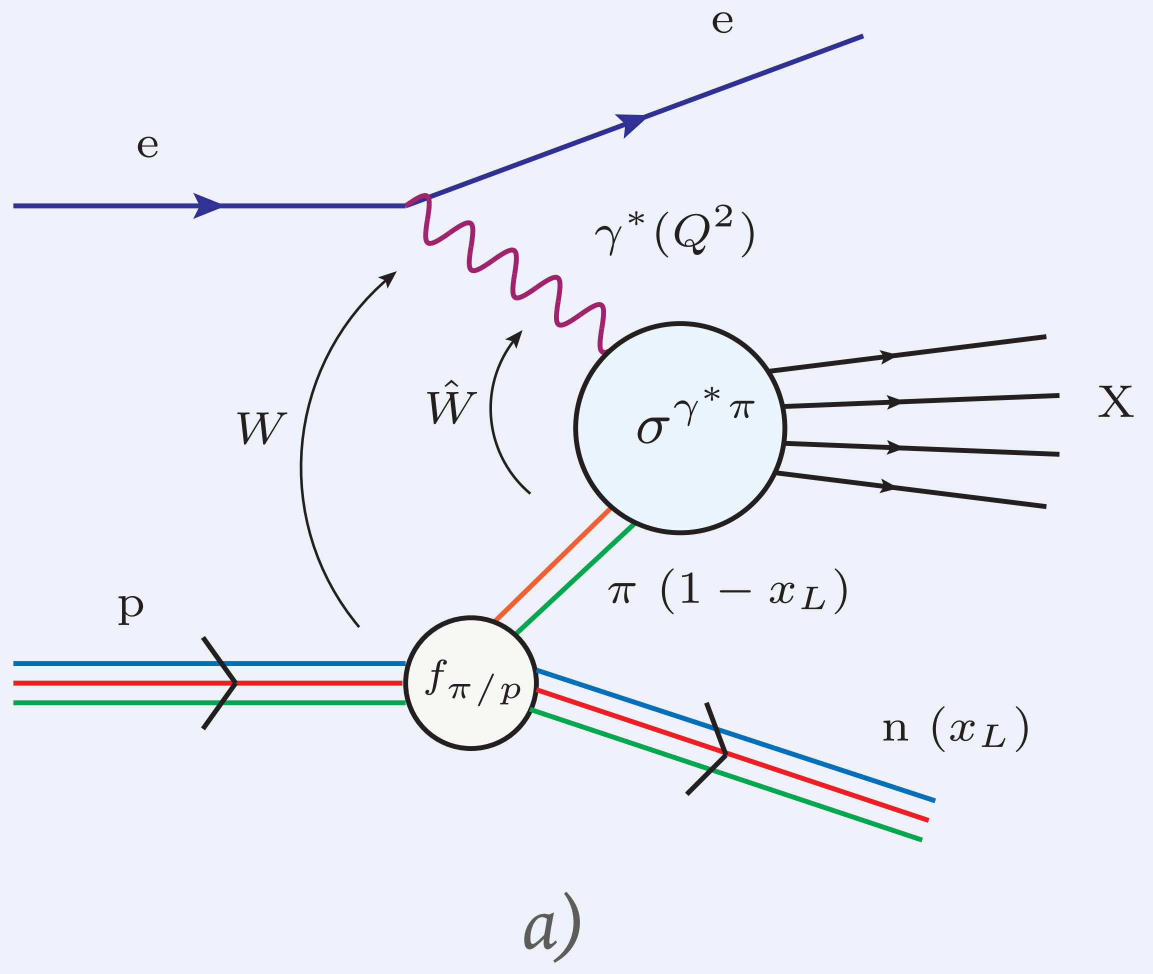
THANK YOU

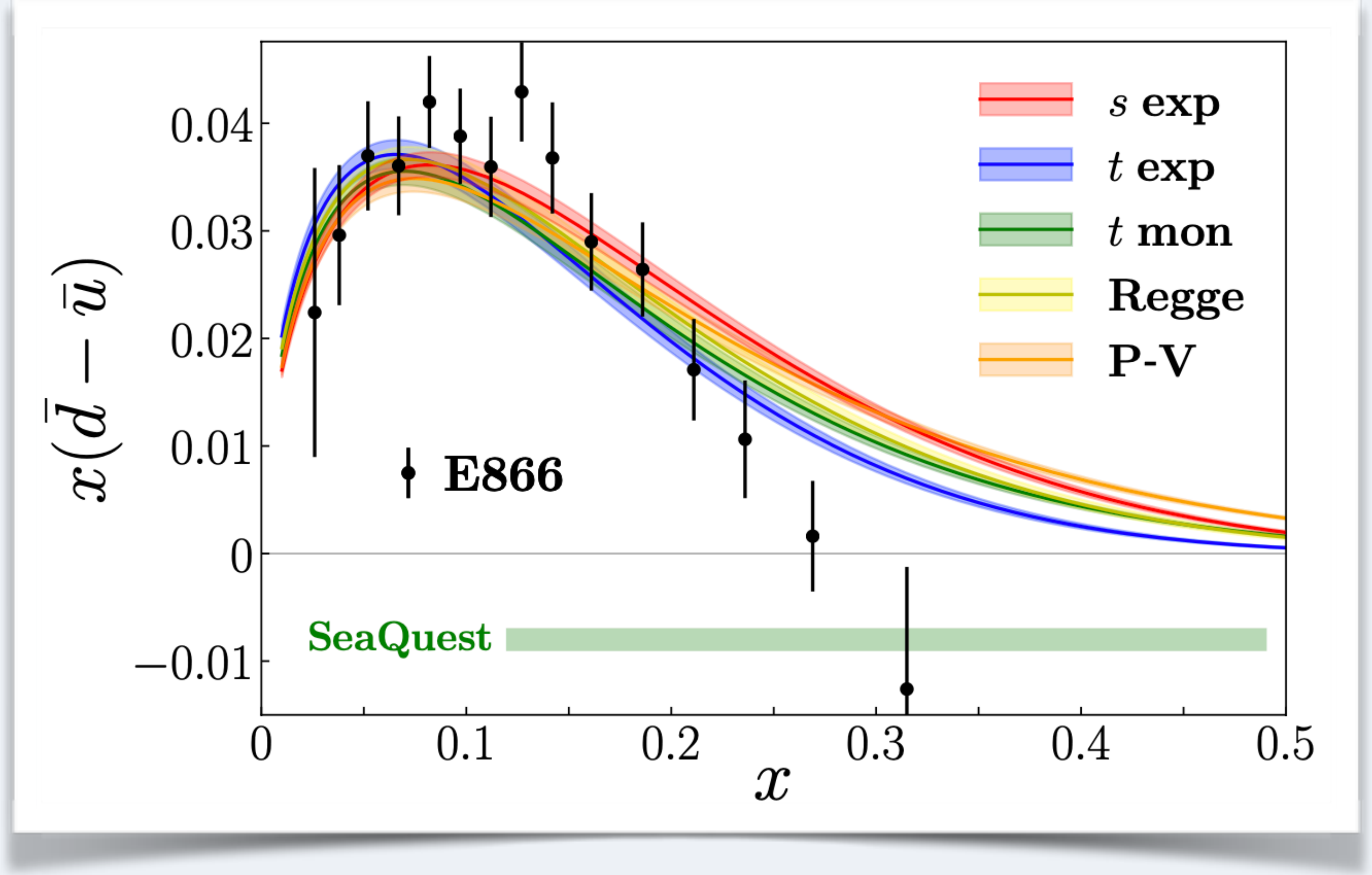
BACKUP

EXCLUSIVE J/Ψ PRODUCTION WITH LEADING NEUTRONS





a)



Barry et al PRL 121, 152001

FLAVOUR ASYMMETRY AND PION CLOUD

- ❖ Access to the structure function of “pion” via Sullivan process J.D. Sullivan PRD 5 (1972), 1732
- ❖ How does gluon density behave in the pion? Is there any universal behaviour at small-x ?
- ❖ How are gluons distributed inside pions? What is the gluon radius of pion?
- ❖ Sensitivity to the saturation effects
- ❖ Feynman scaling and its link with saturation
  - bCGC model Carvalho, Gonçalves, Spiering, Navarra PLB 752 (2016) 76
- ❖ Evidence of the pion cloud of the proton

- Pions are main building blocks of nuclear matter
- Pion cloud models explain the light-quark asymmetry in the nucleon sea
- Pions are the Yukawa particles of the nuclear force (no evidence of excess)

PION FLUX MODELS

Carvalho, Gonçalves, Spiering, Navarra PLB 752 (2016) 76

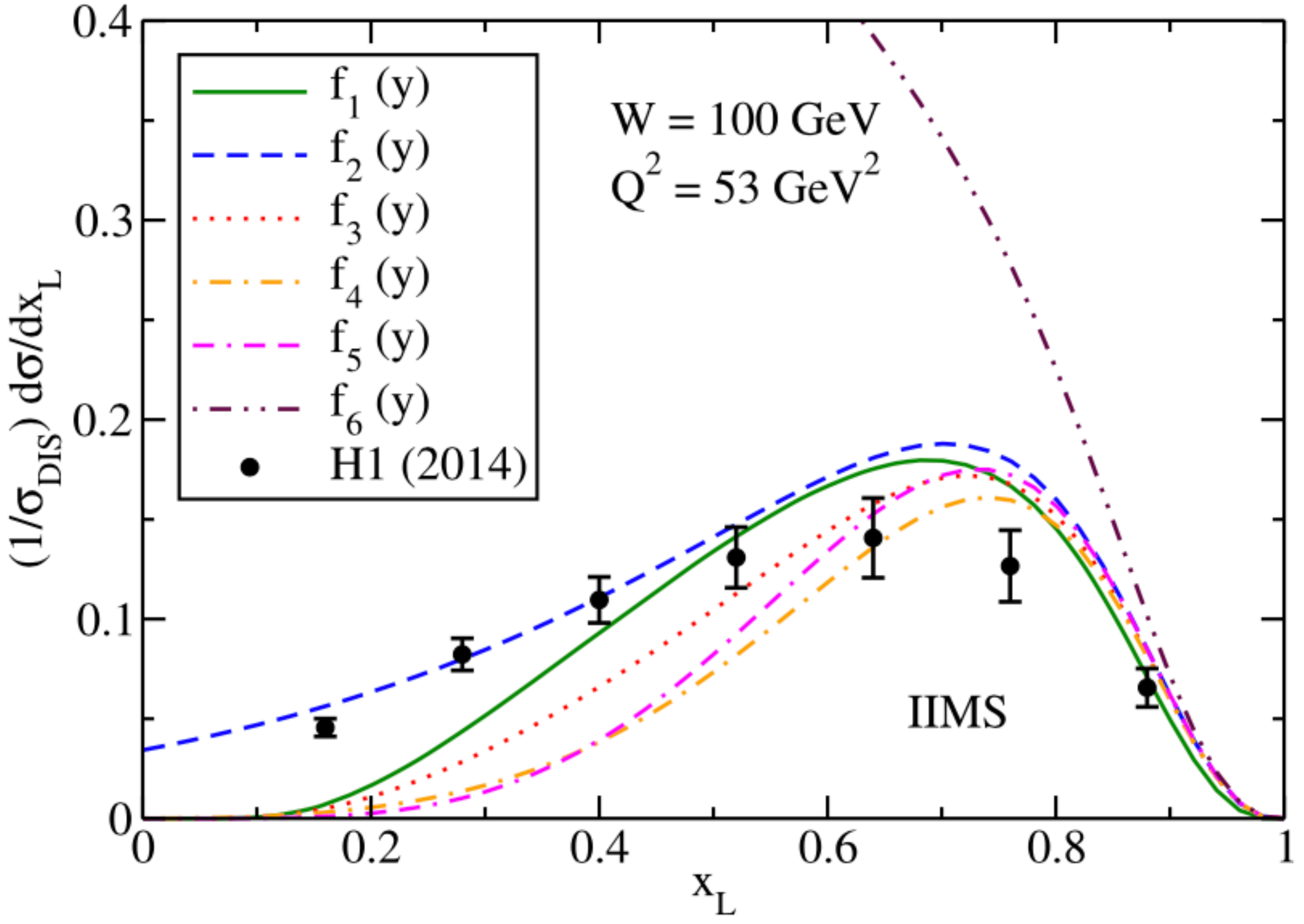
$$F_1(x_L,t) = \exp\left[R^2\frac{(t-m_\pi^2)}{(1-x_L)}\right] \quad , \quad \alpha(t)=0$$

$$F_2(x_L,t) = 1 \quad , \quad \alpha(t)=\alpha(t)_\pi$$

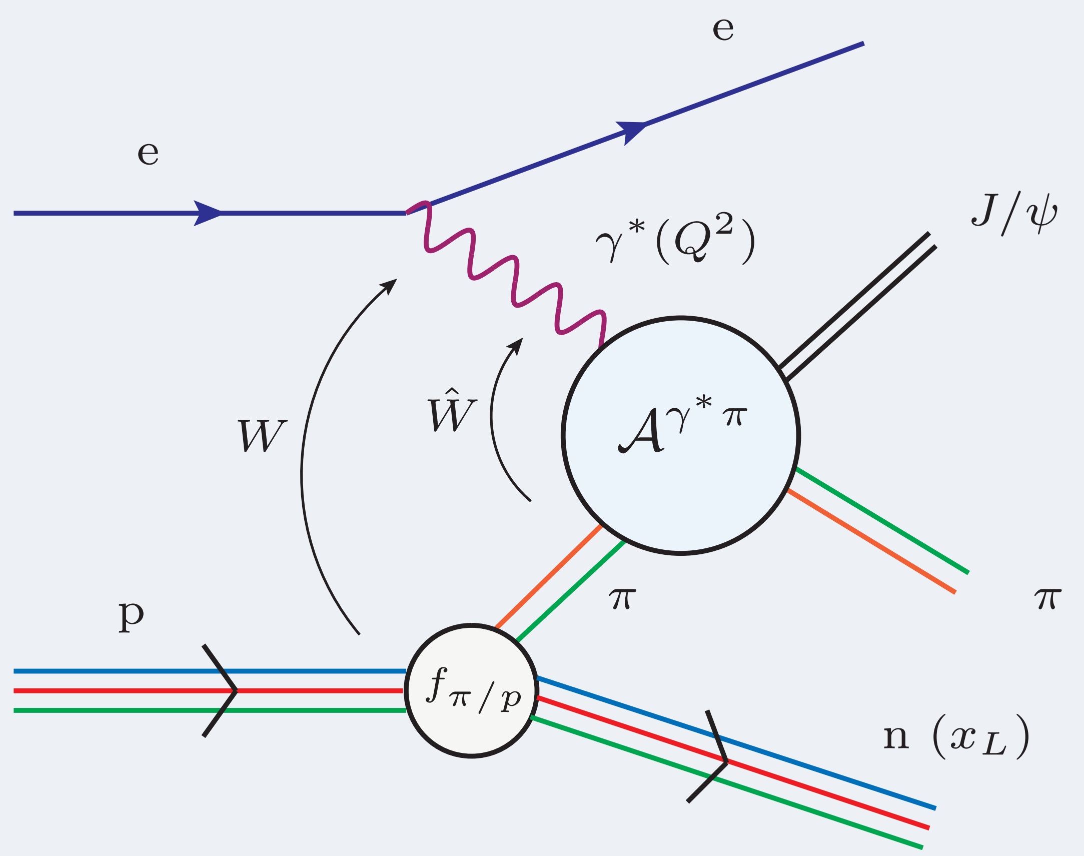
$$F_3(x_L,t) = \exp\left[b(t-m_\pi^2)\right] \quad , \quad \alpha(t)=\alpha(t)_\pi$$

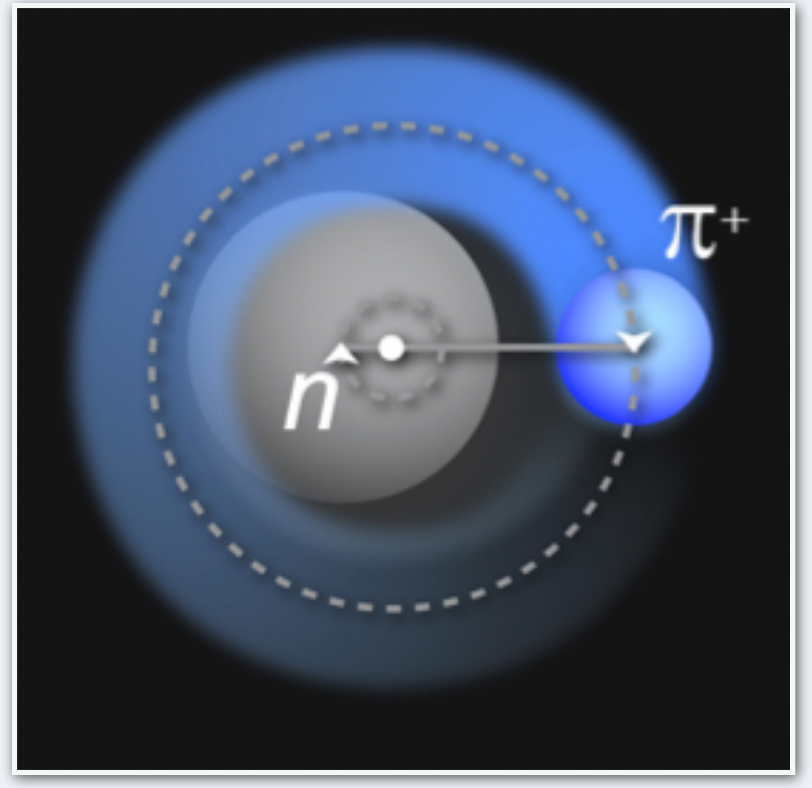
$$F_4(x_L,t) = \frac{\Lambda_m^2-m_\pi^2}{\Lambda_m^2-t} \quad , \quad \alpha(t)=0$$

$$F_5(x_L,t) = \left[\frac{\Lambda_d^2-m_\pi^2}{\Lambda_d^2-t}\right]^2 \quad , \quad \alpha(t)=0$$



(a)





$$\sigma_{total} = \sigma_{yukawa} + \sigma_{fluctuations}$$

PROBING THE GLUON DISTRIBUTION

❖ The thickness function of pion:

$T_\pi(b) = \frac{1}{2\pi B_\pi} e^{-\frac{b^2}{2B_\pi}}$, B_π is the transverse width of the pion

❖ No experimental data on It'l dependence which can restrict this parameter

- Assume that the gluon to charge radius is same in pions and protons: $B_\pi = r_\pi^2 / r_p^2 B_p = (0.657/0.840)^2.4^{-2} \approx 2.44\ GeV^{-2}$
- Pion gluon radius from the Belle measurements at KEKB in hadron-pair production $\gamma^*\gamma \to \pi^0\pi^0$ which suggests $B_\pi \approx 1.33 - 1.96\ GeV^{-2}$ Kumano et al PRD 97 (2018), 014020
- H1 measured the It'l spectrum for exclusive ρ photo-production with leading neutrons in ep scattering, as this process lacks a hard scale we are not able to make a direct comparison, but this spectrum suggests $B_\pi \approx 2.3\ GeV^{-2}$ H1 EPJC 76 (2016), 41

❖ We therefore present our results with bands for $B_\pi = 2 \pm 0.5\ GeV^{-2}$

MASS RADIUS OF PION USING GENERALISED DISTRIBUTION AMPLITUDES

Kumano, Song, Teryaev PRD 97 (2018), 014020

Hadron tomography by generalized distribution amplitudes in pion-pair production process $\gamma^*\gamma \to \pi^0\pi^0$ and gravitational form factors for pion

S. Kumano,[1,2,3] Qin-Tao Song,[1,3] and O. V. Teryaev[1,4]

[1] *KEK Theory Center, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), 1-1, Ooho, Tsukuba, Ibaraki, 305-0801, Japan*

[2] *J-PARC Branch, KEK Theory Center, Institute of Particle and Nuclear Studies, KEK, and Theory Group, Particle and Nuclear Physics Division, J-PARC Center, 203-1, Shirakata, Tokai, Ibaraki, 319-1106, Japan*

[3] *Department of Particle and Nuclear Physics, Graduate University for Advanced Studies (SOKENDAI), 1-1, Ooho, Tsukuba, Ibaraki, 305-0801, Japan*

[4] *Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 141980 Dubna, Russia*

(Dated: January 10, 2019)

Hadron tomography can be investigated by three-dimensional structure functions such as generalized parton distributions (GPDs), transverse-momentum-dependent parton distributions, and generalized distribution amplitudes (GDAs). Here, we extract the GDAs, which are s-t crossed quantities of the GPDs, from cross-section measurements of hadron-pair production process $\gamma^*\gamma \to \pi^0\pi^0$ at KEKB. This work is the first attempt to obtain the GDAs from the actual experimental data. The GDAs are expressed by a number of parameters and they are determined from the data of $\gamma^*\gamma \to \pi^0\pi^0$ by including intermediate scalar- and tensor-meson contributions to the cross section. Our results indicate that the dependence of parton-momentum fraction z in the GDAs is close to the

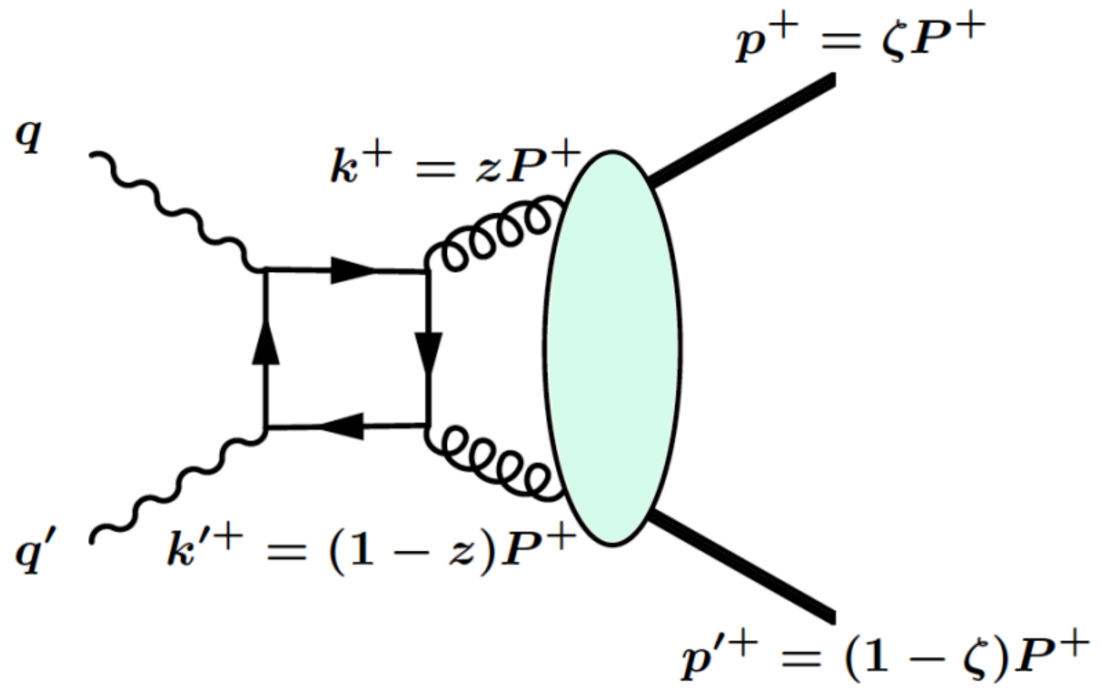


FIG. 4. Contribution to the two-photon cross section from the gluon GDA.

$$\sqrt{\langle r^2 \rangle_{\text{mass}}} = 0.32 \sim 0.39\,\text{fm},$$
$$\sqrt{\langle r^2 \rangle_{\text{mech}}} = 0.82 \sim 0.88\,\text{fm}.$$

GOOD-WALKER FORMALISM

- Coherent cross-section probes average **b** dependence $< N(\mathbf{b}, \mathbf{r}, x) >_\Omega$ of dipole amplitude which provides the information about target geometry

$$\frac{d\sigma^{\gamma^* p \to V\, p}_{T,L}}{dt} = \frac{1}{16\pi} \left| < \mathcal{A}^{\gamma^* p \to V\, p}_{T,L} >_\Omega \right|^2$$

- Incoherent cross-section : target dissociates ($f \neq i$) Good, Walker 1960, Miettinen, Pumplin 1978

$$\sigma_{incoherent} \sim \sum_{f \neq i} | < f|\mathcal{A}|i > |^2$$
$$= \sum_f < i|\mathcal{A}^\dagger|f >< f|\mathcal{A}|i > - < i|\mathcal{A}|i >^\dagger < i|\mathcal{A}|i >$$
$$= \left\langle \left|\mathcal{A}\right|^2 \right\rangle_\Omega - \left| \left\langle \mathcal{A} \right\rangle_\Omega \right|^2$$

$$\frac{d\sigma_{total}}{dt} = \frac{1}{16\pi} \left\langle \left|\mathcal{A}\right|^2 \right\rangle_\Omega \qquad \frac{d\sigma_{coherent}}{dt} = \frac{1}{16\pi} \left| \left\langle \mathcal{A} \right\rangle_\Omega \right|^2$$

- Incoherent cross-section is the variance of amplitude which controls the amount of event-by-event fluctuations in target configurations

FEYNMAN-X SPECTRA AT SMALL -XL

H1 EPJC 74 (2014), 2915

Standard fragmentation (DJANGO)

One-pion approximation (RAPGAP)