SATURATION EFFECTS IN NEUTRON TAGGED DIS AT SMALL-X

XXV DAE-BRNS High Energy Physics Symposium
IISER Mohali (Dec 12-16, 2022)

Arjun Kumar (IIT Delhi)

A.Kumar arXiv: 2208.14200

A.Kumar, T.Toll PRD105 (2022) 114045

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भारतीय प्रौद्योगिकी संस्थान दिल्ली
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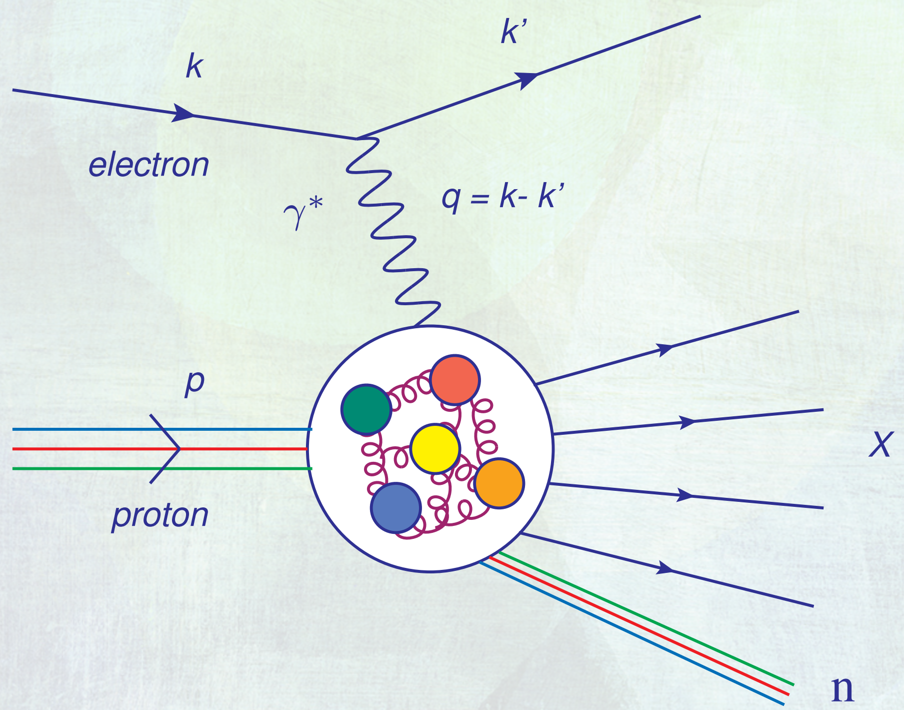


OUTLINE

- Introduction to TDIS

- Semi-Inclusive $\gamma^* p$ cross section with leading neutrons

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

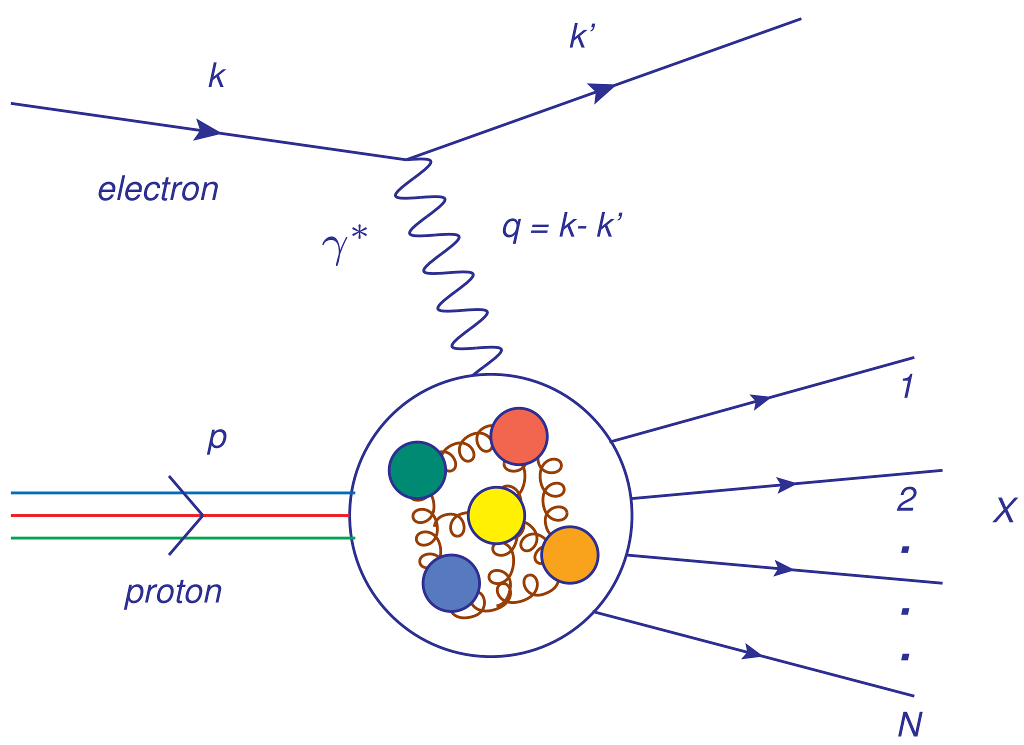
  - Longitudinal structure and saturation

- Exclusive J/ψ photo production with leading neutrons

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

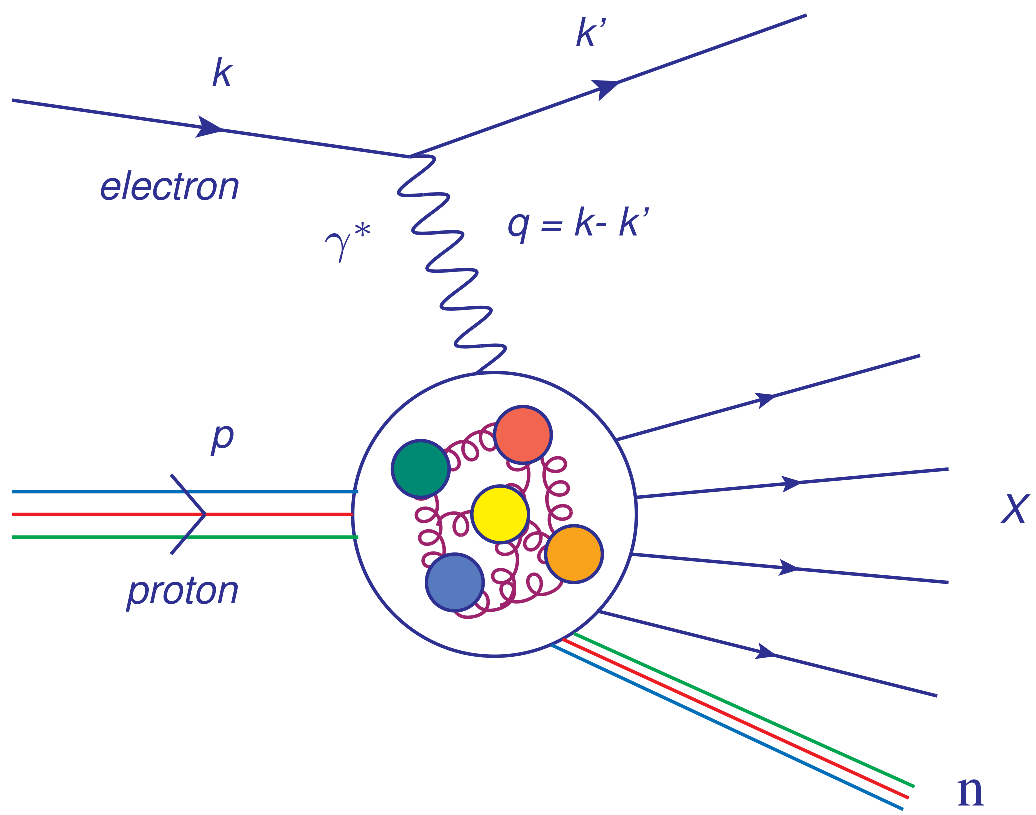
  - Higher sensitivity to saturation

INCLUSIVE 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)

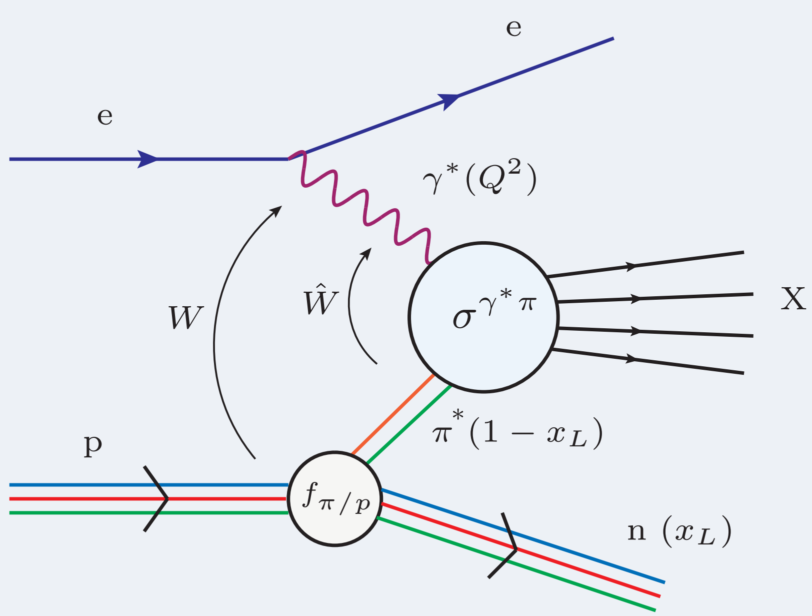
TAGGED DIS (TDIS)



- Detect the scattered electron and the outgoing 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



H1 EPJC 74 (2014), 2915

❖ Forward neutrons:

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

$0 < p_T < 0.6$

❖ Kinematic variables:

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

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

LEADING NEUTRONS (LN)

❖ 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:

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

J.D. Sullivan PRD 5 (1972), 1732

❖ In One Pion Exchange (OPE) approximation:

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

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

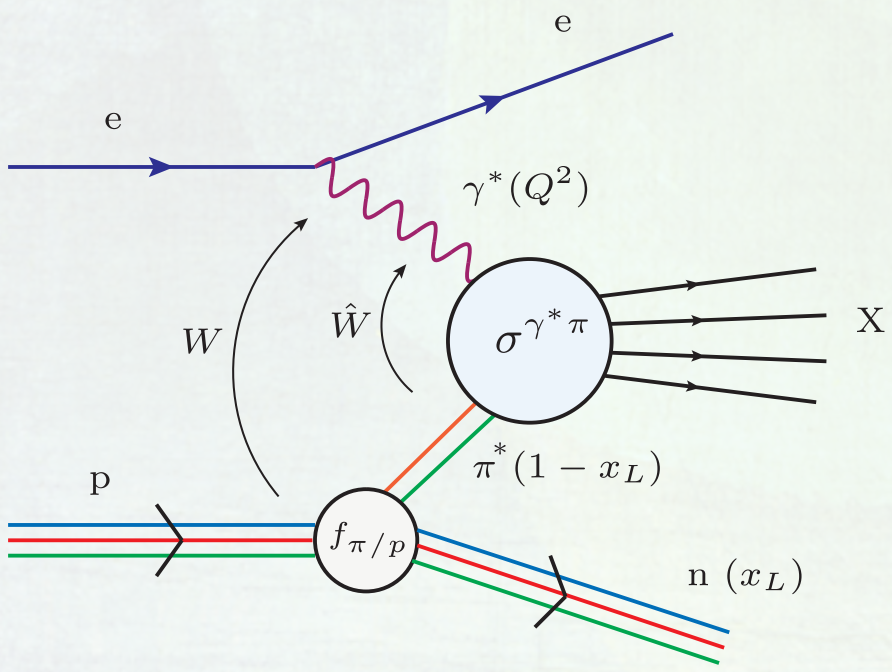
$\sigma^{\gamma^*\pi^*}(\hat{W}^2, Q^2)$ is virtual photon-virtual pion cross section

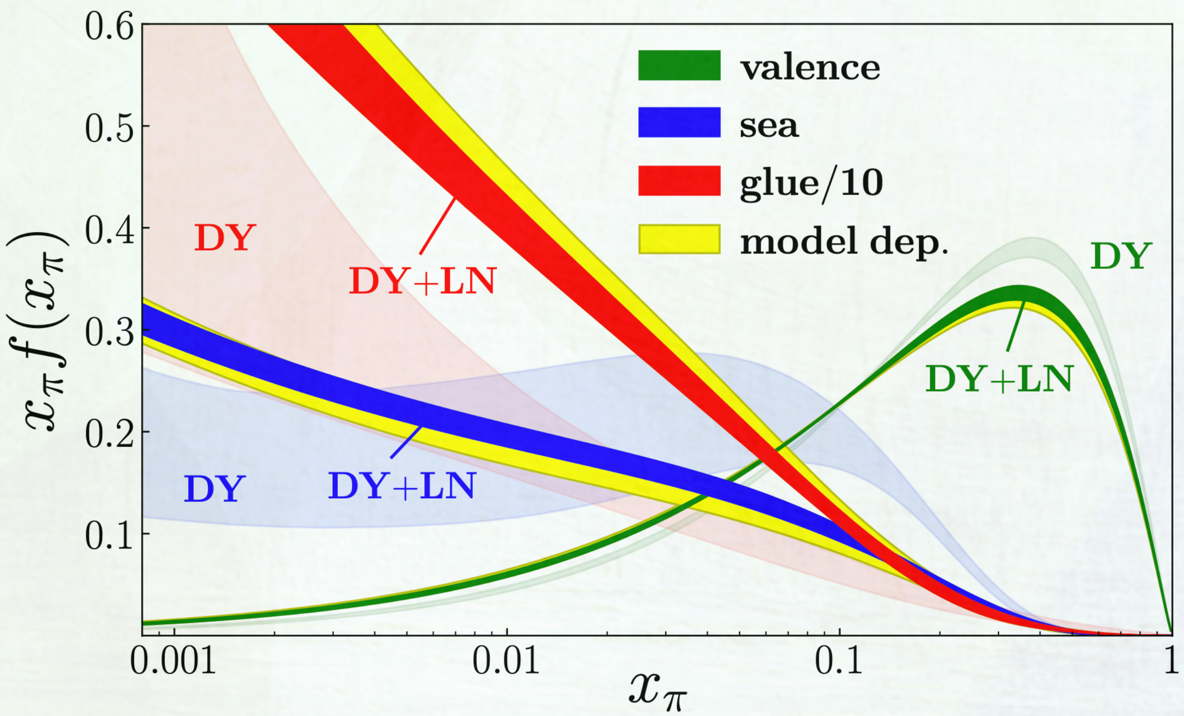
❖ OPE allows to extract the pion structure function F_2^{π},

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

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

SEMI-INCLUSIVE MEASUREMENTS WITH LEADING NEUTRONS

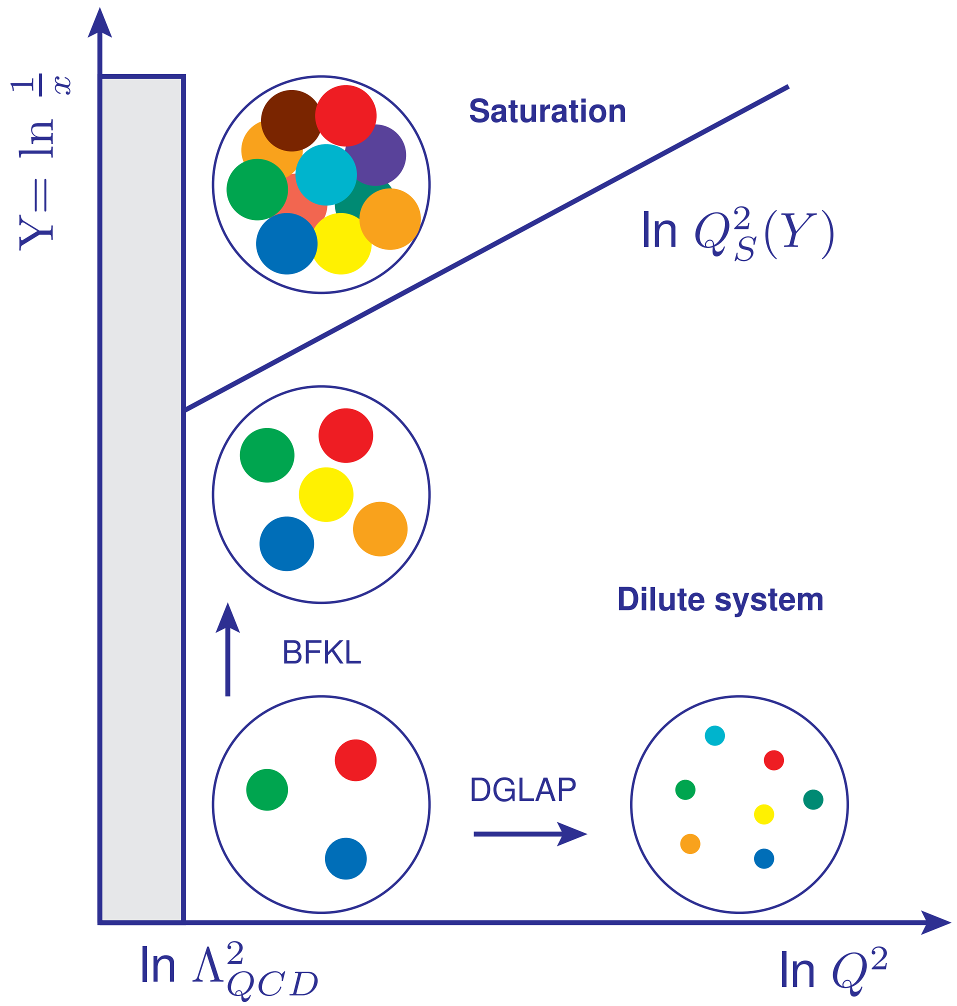




Barry et al PRL 121 (2018), 152001

- ★ Information on gluonic structure of pions in one pion exchange approximation
- ★ Saturation effects and Geometric Scaling
- ★ Feynman-x_L spectra and Feynman scaling

QCD PHASE SPACE DIAGRAM

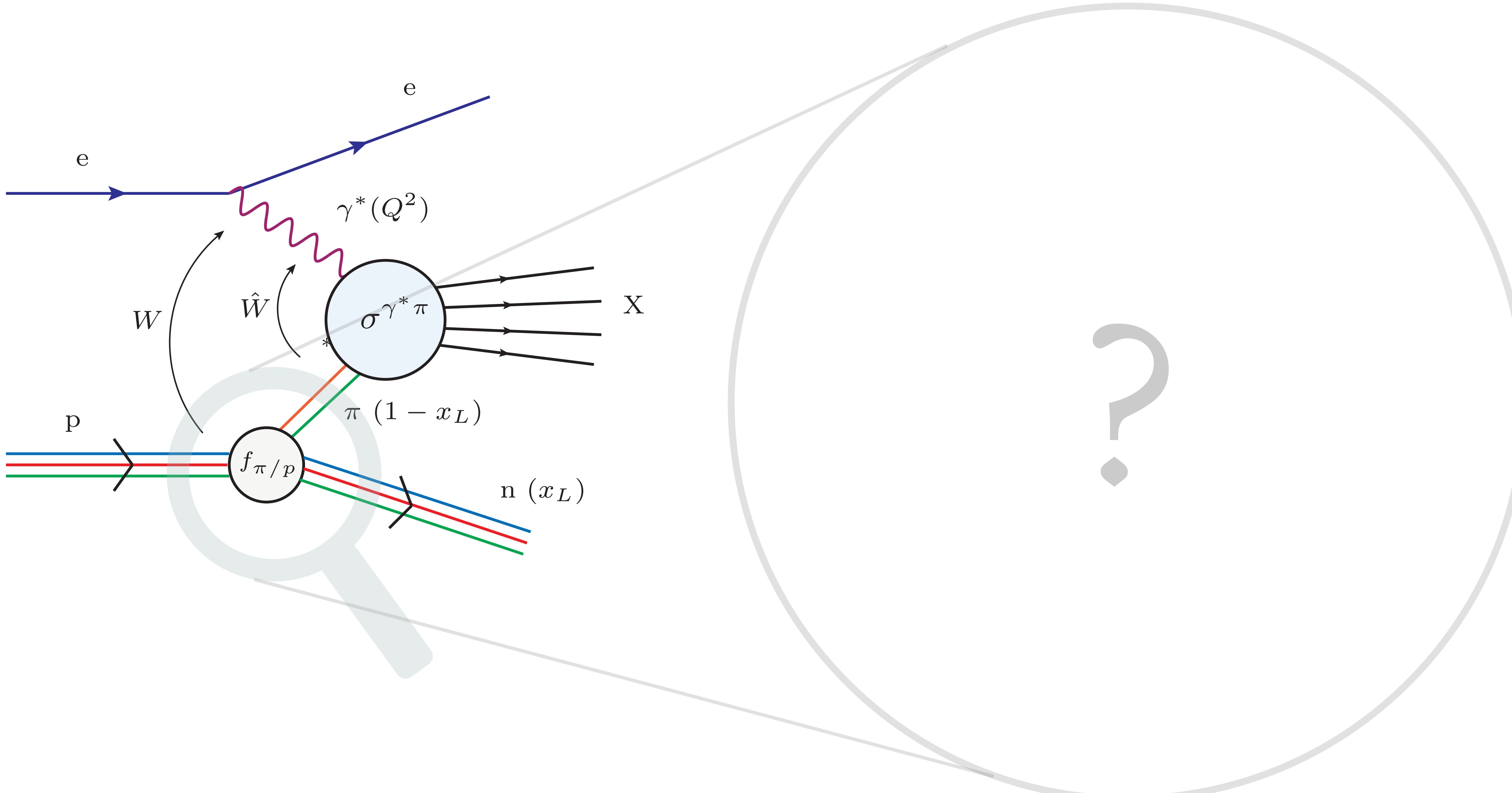


- Bjorken limit: $Q^2 \to \infty,\ s \to \infty; x = \text{fixed}$
  - —Phase space density (#partons/Area/Q^2) decreases
  - —Target becomes dilute
- High energy limit: $x \to 0,\ s \to \infty; Q^2 = \text{fixed}$
  - —Phase space density (#partons/Area/Q^2) increases
  - —Target becomes dense
- DGLAP & BFKL evolution equations violate unitarity
- High energy limit of QCD suggests presence of multi-body dynamics and non-linear physics

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

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

PION FLUX FROM PROTON



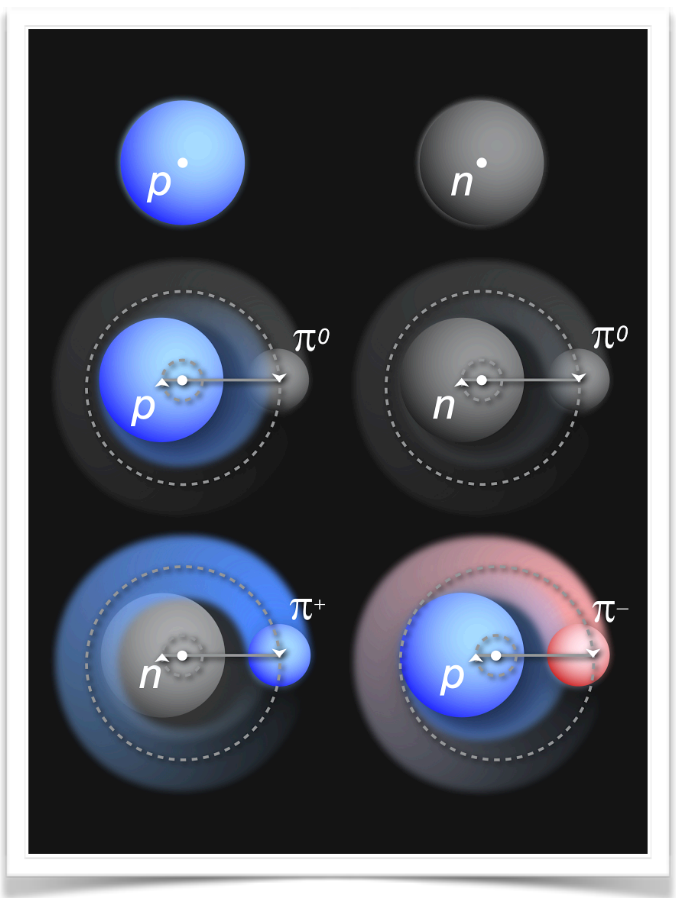
PION FLUX FROM PROTON

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

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

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

- 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

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

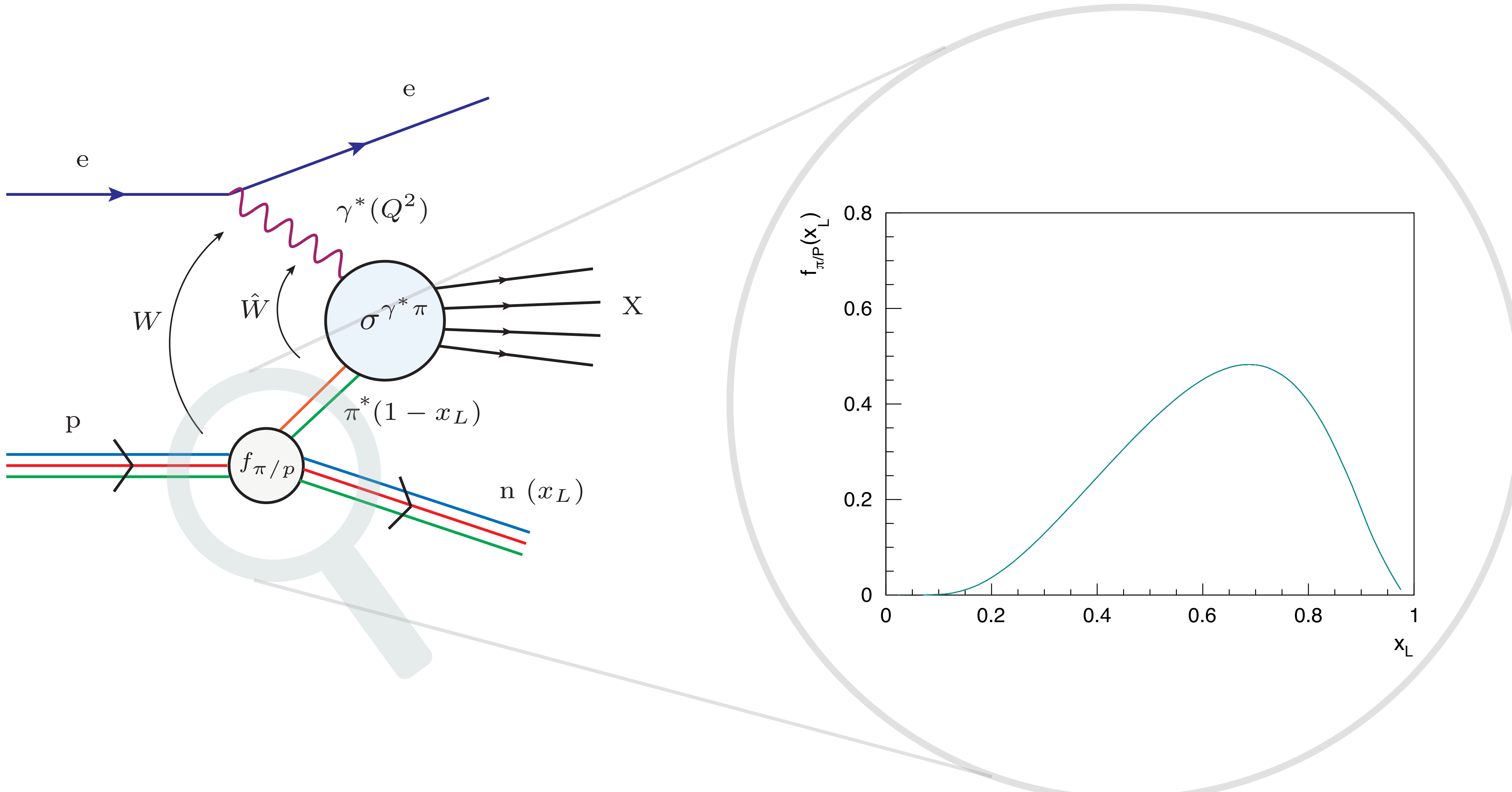
where the form factor is given by:

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

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

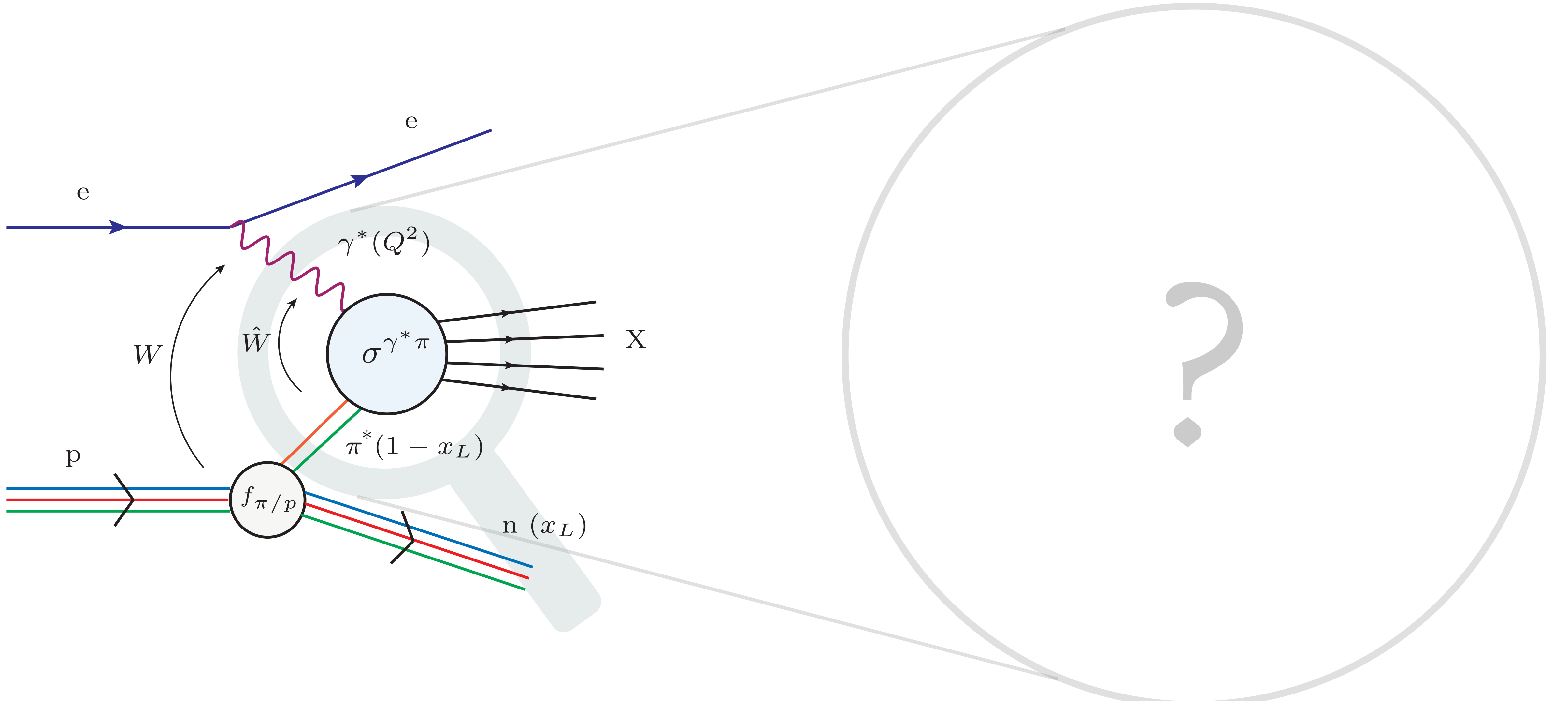
Image Source : Cynthia Keppel (JLab) slides from "Exploring QCD with light nuclei at EIC-2020" meeting

PION FLUX FROM PROTON



❖ The pion flux peaks at $x_L \sim 0.7$, which suggests that the LN spectra should also peak at high- x_L values

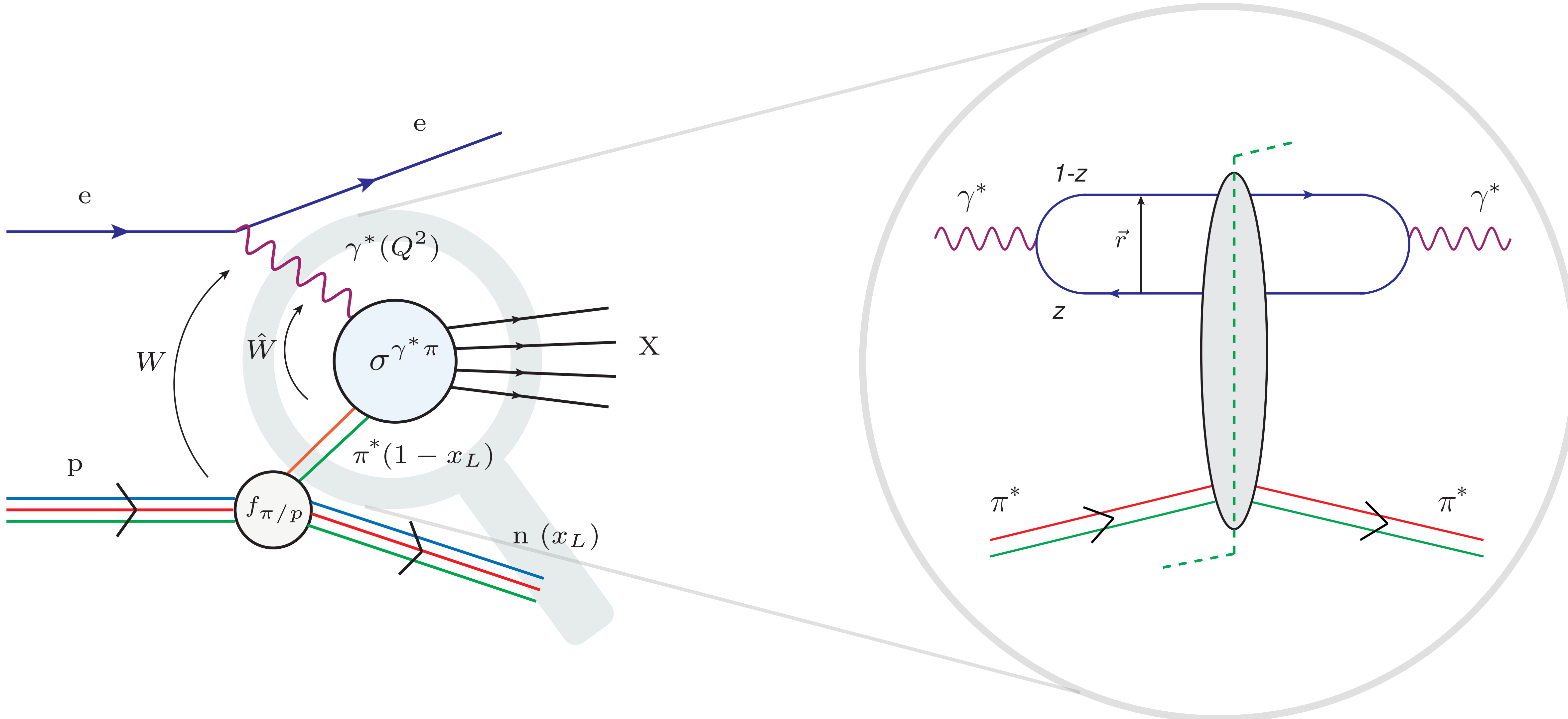
VIRTUAL PION-PHOTON CROSS SECTION



❖ For total virtual photon- virtual pion cross section

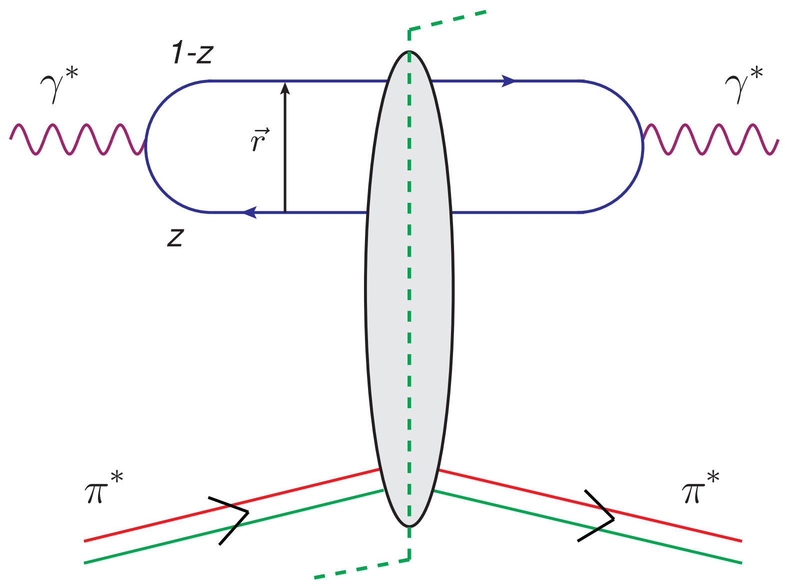
— use dipole framework (natural in target rest frame)

VIRTUAL PION-PHOTON CROSS SECTION IN DIPOLE MODEL



- 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)

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

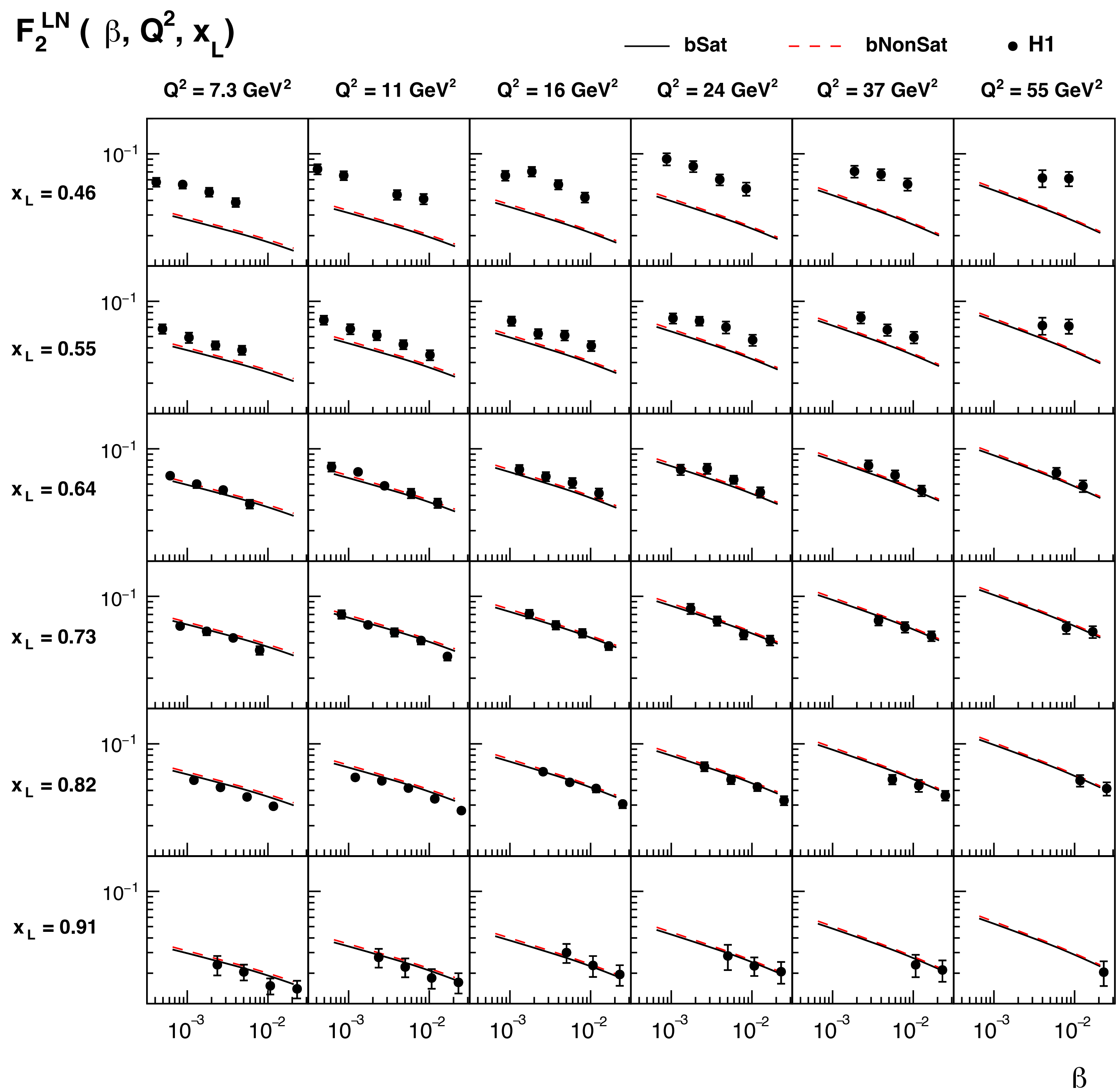
❖ Two phenomenological parameterisations:

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

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 leading neutron structure function HERA data.

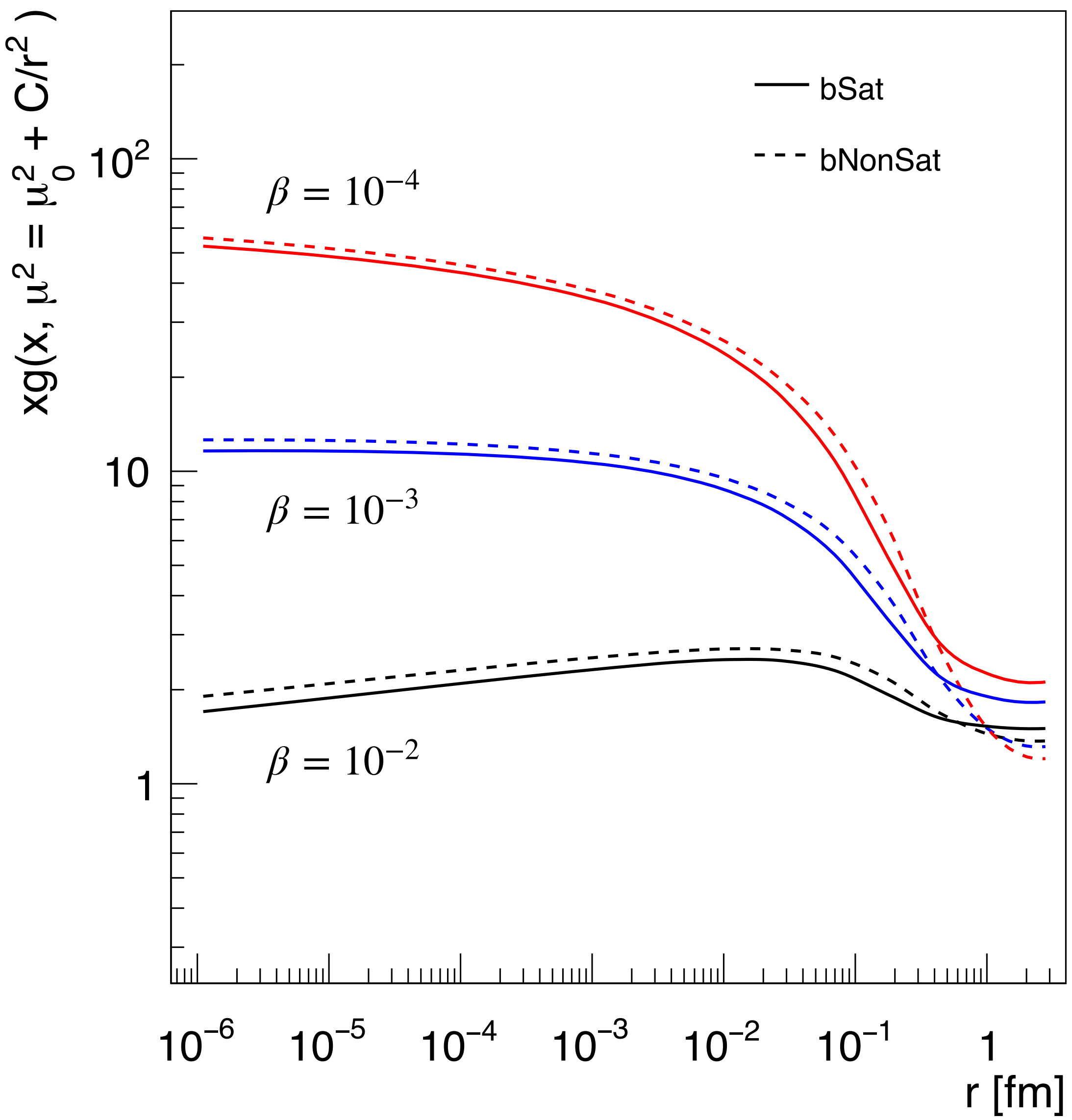
LN STRUCTURE FUNCTION F_2^{LN}

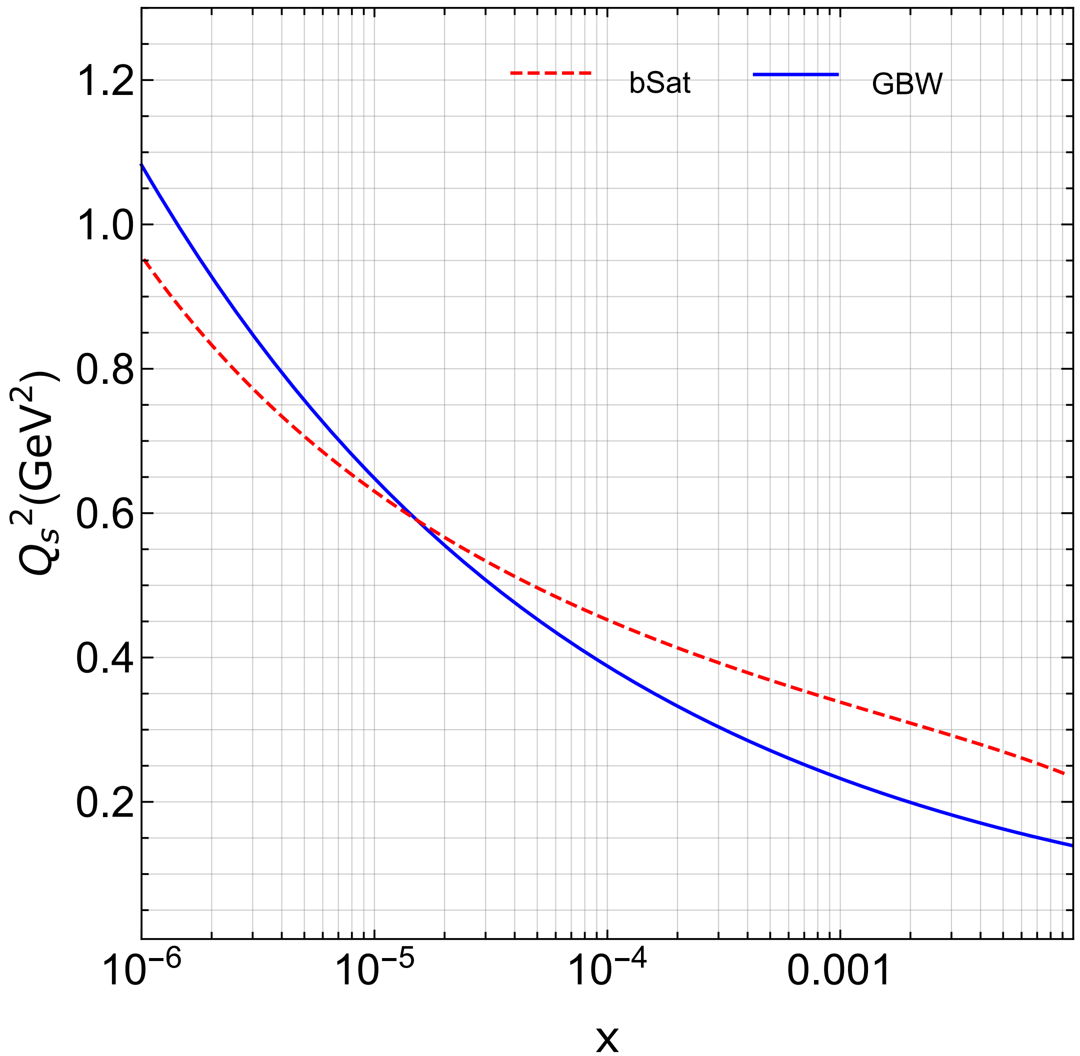


Fit	Model	N	x_{Lmin}	x_{Lmax}	m_l	m_c	μ_0	C	A_g	λ_g	χ^2/N_{dof}
1	bSat	51	0.6	1.0	0.0300	1.3528	1.1	1.453 ± 0.024	1.208 ± 0.012	0.0600 ± 0.0380	58.75/48 = 1.22
2	bNonSat	51	0.6	1.0	0.1516	1.3504	1.1	3.683 ± 0.436	1.799 ± 0.710	-0.0477 ± 0.0038	57.61/48 = 1.20

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

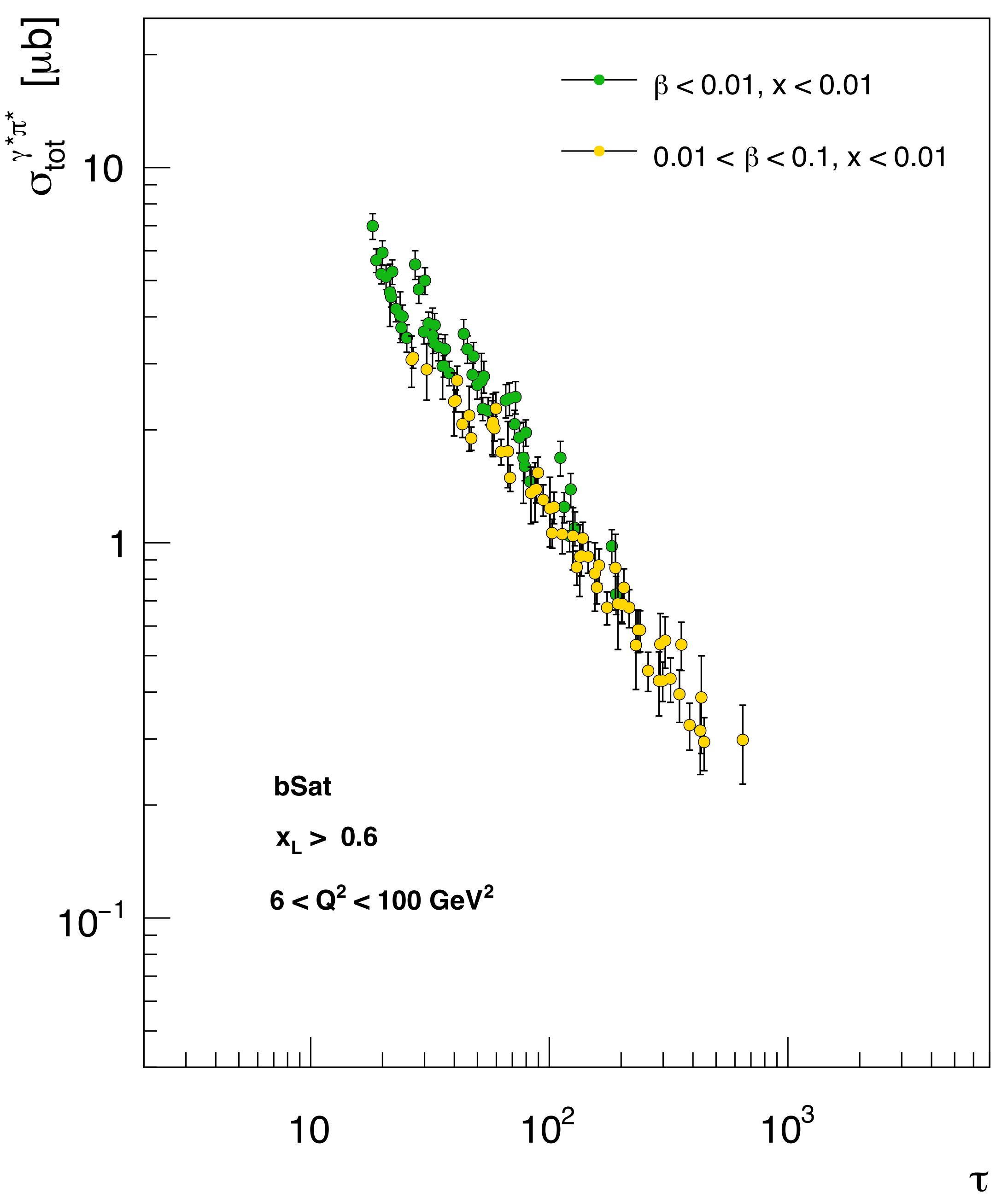
GLUON DENSITY & SATURATION SCALE





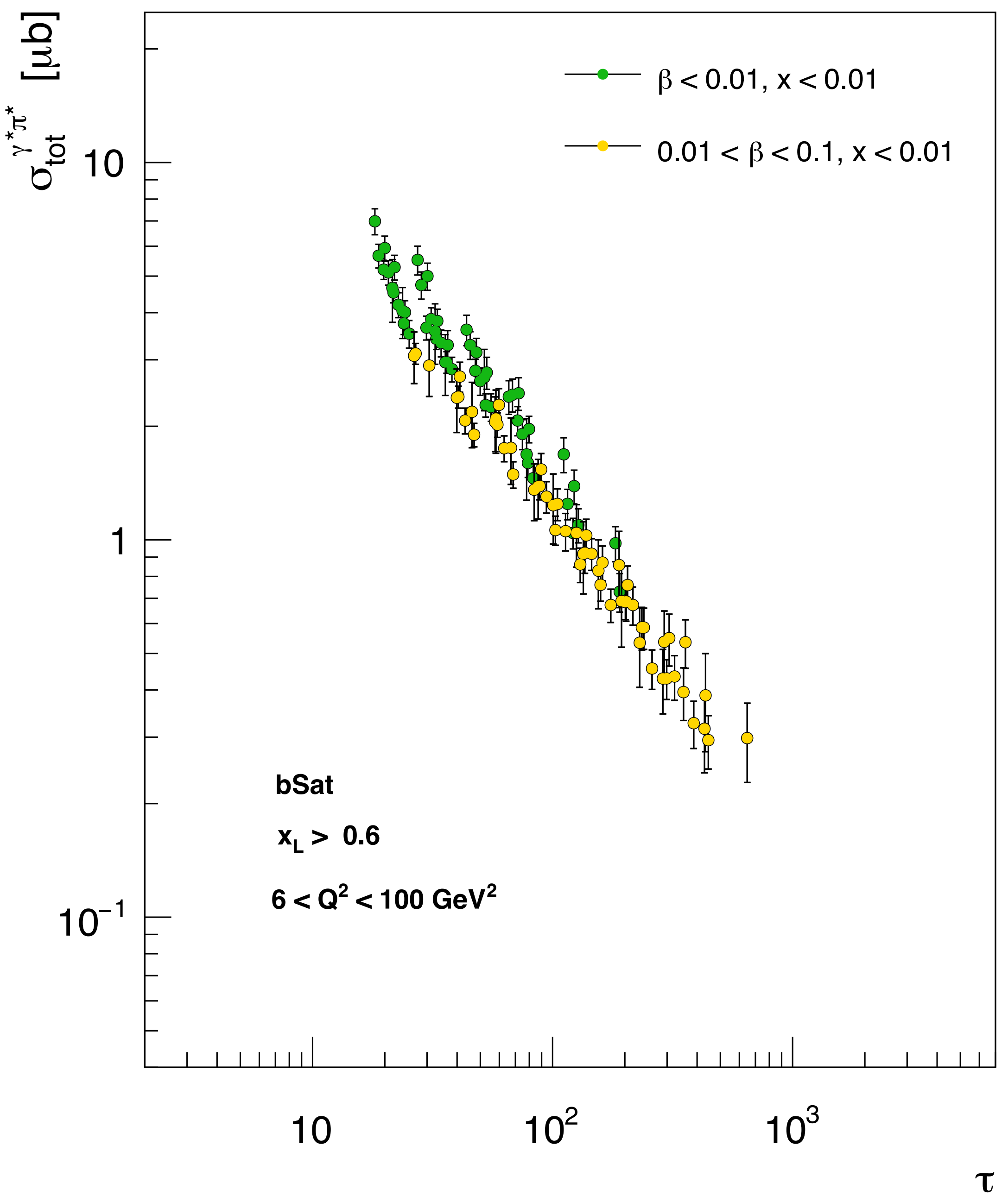
- The initial condition effects are washed out in the evolution and gluon density is same for both the saturated and non-saturated dipole models.
- Saturation scale increases with decreasing x and reaches $Q_s^2 \sim 1$ GeV^2 for $x \sim 10^{-6}$

GEOMETRIC SCALING



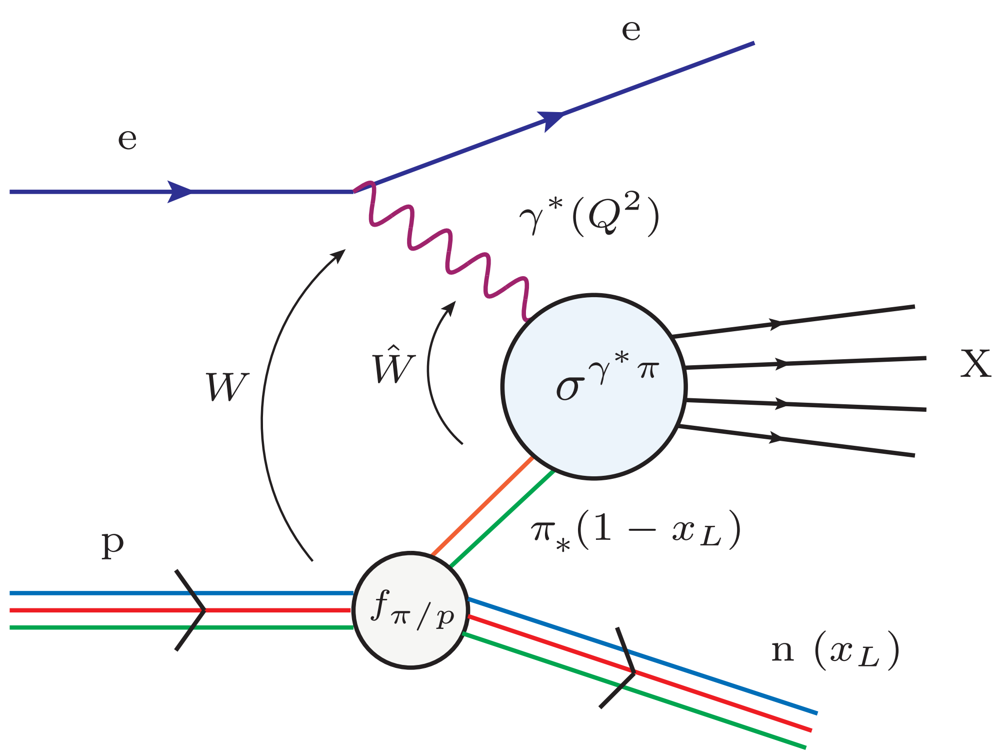
- The total cross section shows geometric scaling when plotted against $\tau = \dfrac{Q^2}{Q_s^2(\beta)}$
- Can we say that the data shows saturation?
- Emergence of a scale $Q_s^2(\beta)$ in data

GEOMETRIC SCALING



- The total cross section shows geometric scaling when plotted against $\tau = \dfrac{Q^2}{Q_s^2(\beta)}$
- Can we say that the data shows saturation? ✗
- Emergence of a scale $Q_s^2(\beta)$ in data ✓

SEMI-INCLUSIVE PROCESS WITH LEADING NEUTRONS



WHAT WE HAVE LEARNT

- Access to the structure of nearly on-shell pions through TDIS
- Dipole model phenomenology could successfully describe the leading neutron data
- Constrain the gluon distribution of pions at small-x in the dipole framework
- The total $\gamma^*\pi^*$ cross section shows geometric scaling behaviour
- No hints of saturation effects

NOT COVERED HERE

- Feynman spectra of leading neutrons
- Feynman scaling and its link with saturation
- Universality of the pion and proton structure at small-x

READ MORE HERE

A.Kumar arXiv: 2208.14200

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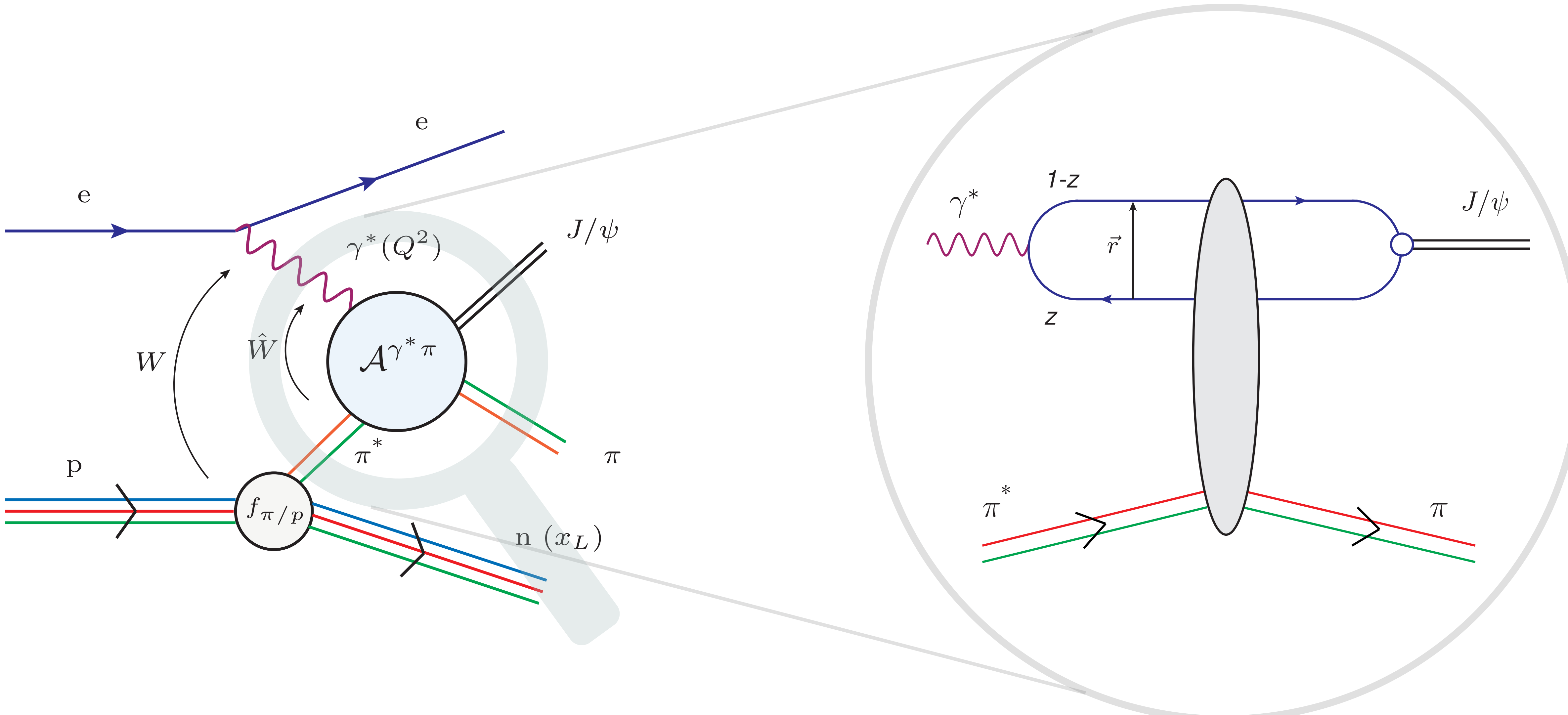
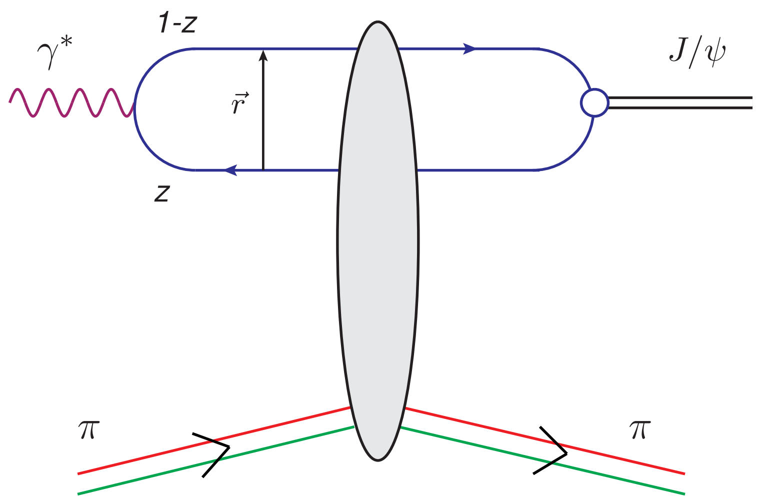
EXCLUSIVE J/Ψ PRODUCTION WITH LEADING NEUTRONS



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

EXCLUSIVE J/Ψ PRODUCTION WITH LEADING NEUTRONS



Various stages of exclusive J/ψ production in the dipole model:

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

$$\mathcal{A}_{T,L}^{\gamma^* \pi^* \rightarrow J/\psi\ \pi}(\hat{x}, Q^2, \Delta) \sim \int d^2\mathrm{b} \int d^2\mathrm{r} \int dz\ (\Psi^* \Psi)_{L,T}(\mathrm{r}, z, Q^2)\ e^{i.b.\Delta}\ \frac{d\sigma_{q\bar{q}}^{(\pi)}}{d^2\mathrm{b}}(\mathrm{b}, \mathrm{r}, \hat{x})$$

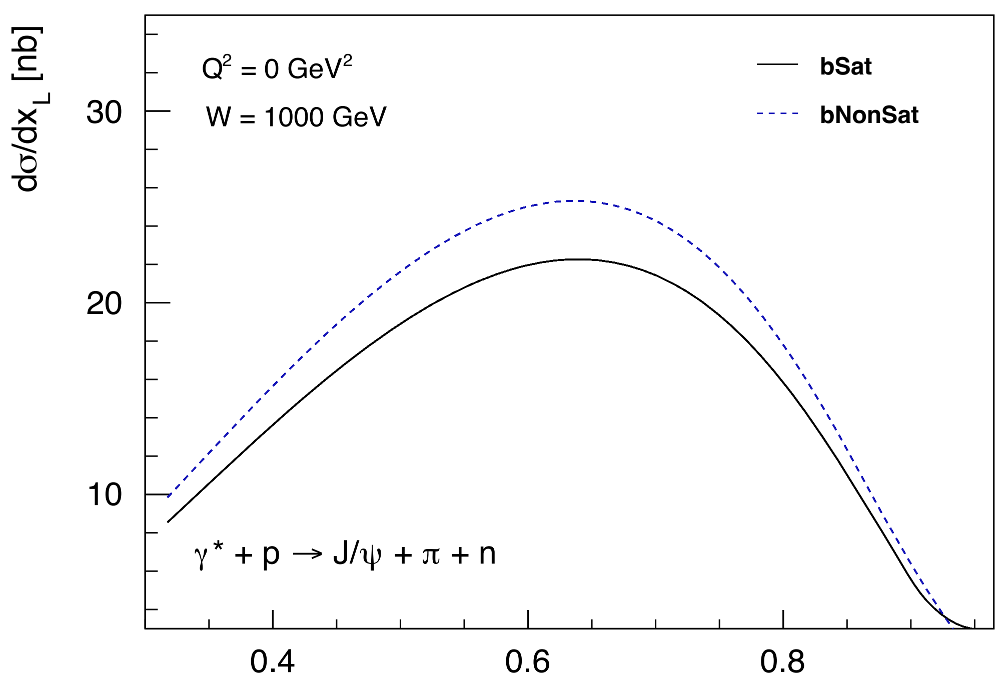
❖ Same dipole cross-section fitted from semi-inclusive data (bSat and bNonSat)

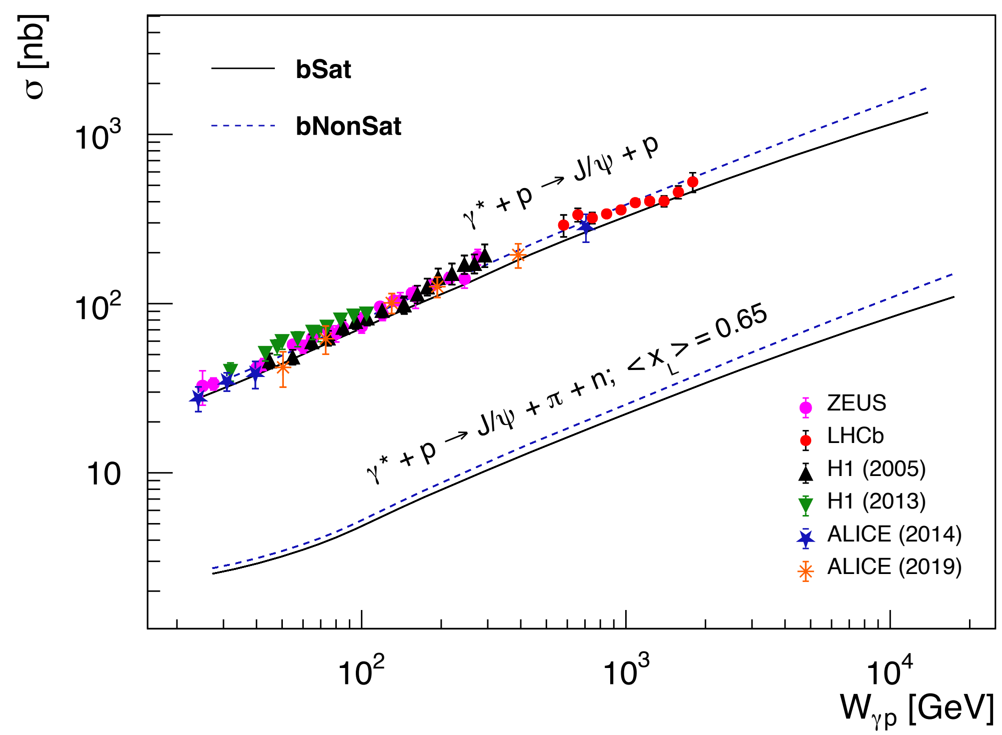
❖ The differential cross section is

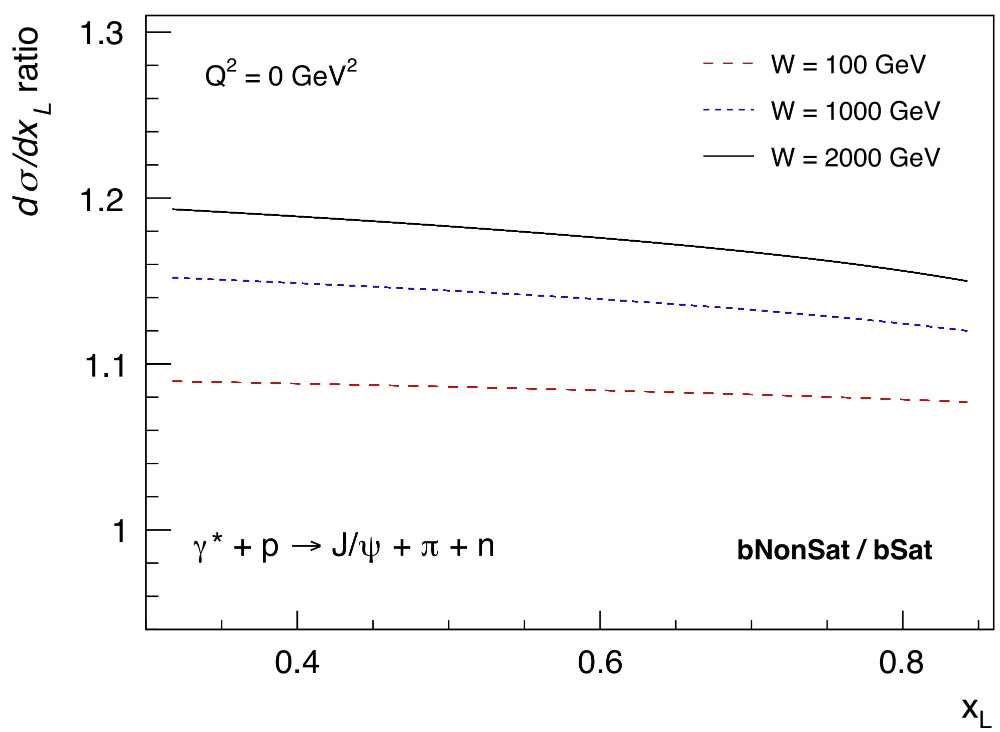
$$\frac{d\sigma_{T,L}^{\gamma^* p \rightarrow V\ p}}{dt} = \frac{1}{16\pi} \left| \mathcal{A}_{T,L}^{\gamma^* p \rightarrow V\ p} \right|^2 \sim [xg(x, Q^2)]^2$$

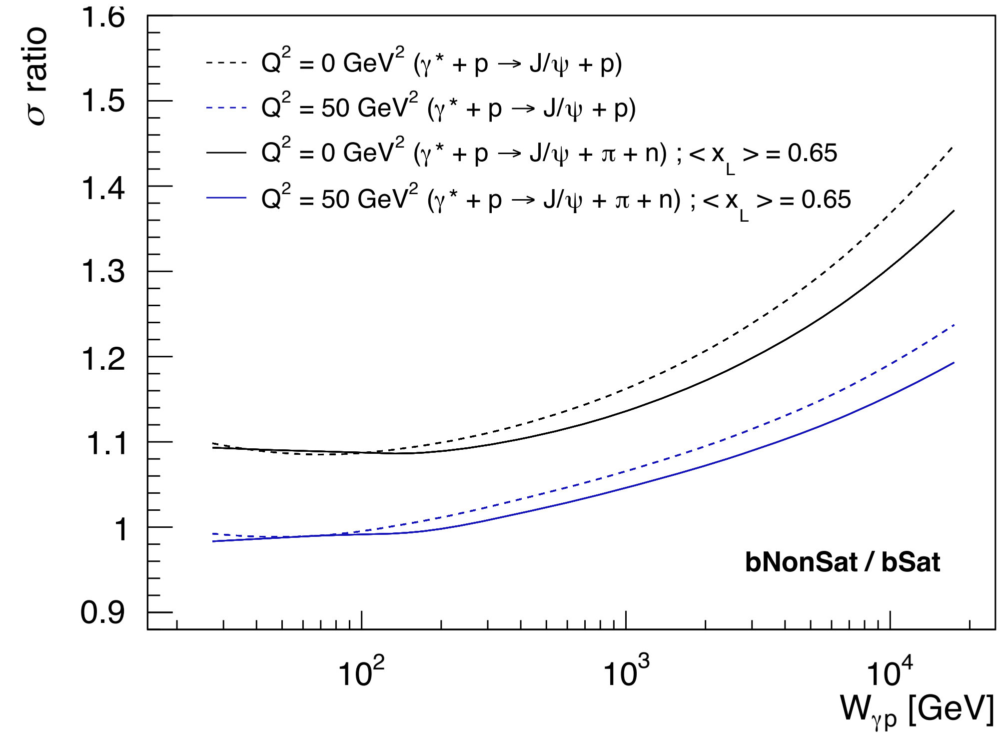
❖ Exclusive cross sections are highly sensitive to saturation

EXCLUSIVE J/Ψ PRODUCTION WITH LEADING NEUTRONS

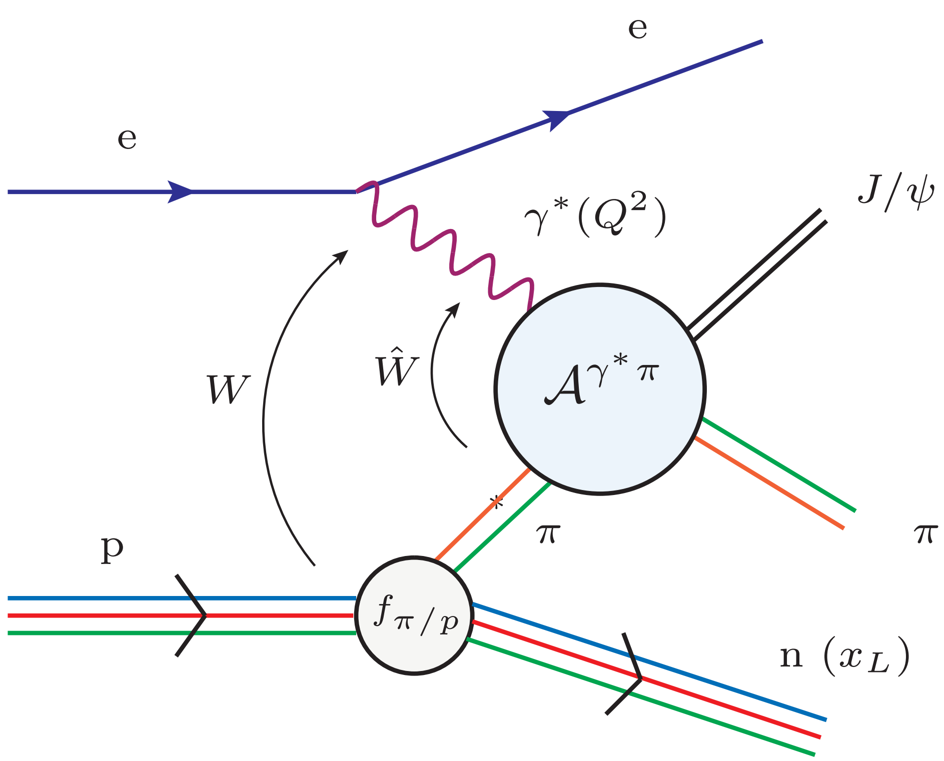








EXCLUSIVE MEASUREMENTS WITH LEADING NEUTRONS



WHAT WE HAVE LEARNT

- Dipole model provides a unified framework to study inclusive and exclusive events
- The total exclusive J/ψ cross section is sensitive to saturation at high energies
- Feynman spectra of leading neutrons could be used to look for saturation effects at high energies
- Usual exclusive events with proton are more sensitive to saturation
- Probe for proton fluctuation into pion and neutron

NOT COVERED HERE

- Transverse gluon distribution of pions
- Gluon radius of pions and t-spectrum

READ MORE HERE

A.Kumar, T.Toll PRD105 (2022) 114045

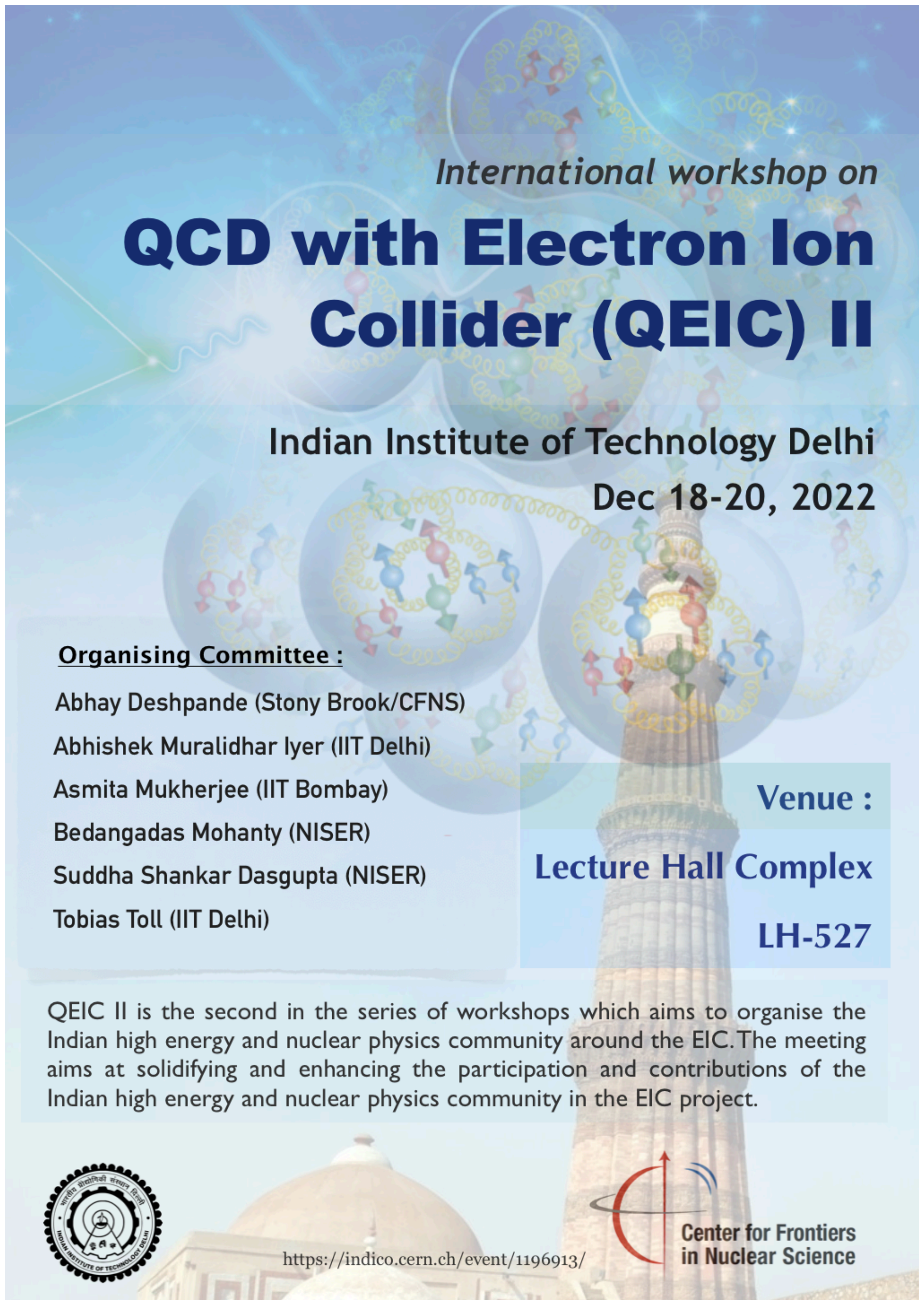
More on exclusive physics and proton structure: review talk by T.Toll on 12/12/22

SUMMARY AND OUTLOOK

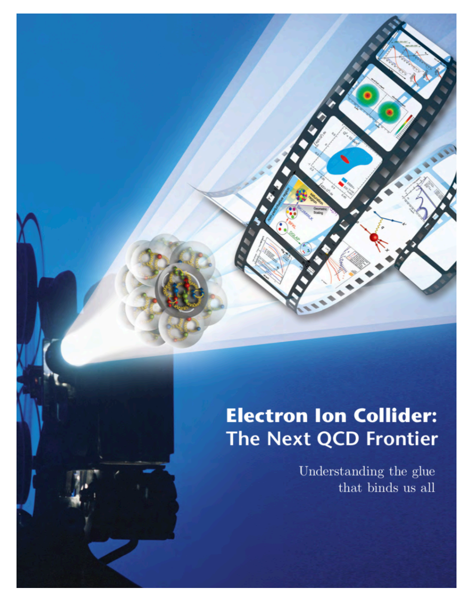
- ❖ Investigated virtual photon scattering with the pion cloud of proton in *ep* scattering using dipole model
  - Semi-inclusive measurement:
    - probe the longitudinal structure function of pions
    - Both the saturated and non-saturated model describes the data
  - Exclusive measurement:
    - Sensitive to non-linear or saturation effects but less so than that of protons
    - Direct evidence of a proton fluctuation into pion and neutron
- ❖ Future experiments such as EIC and LHeC can measure the exclusively produces vector meson production in *ep* scattering with leading neutron events More on EIC physics: A.Deshpande talk on 16/12/22
- ❖ Measurement of photo-nuclear cross sections in UPC's at LHC and RHIC are good tests for our models and saturation physics.

THANK YOU

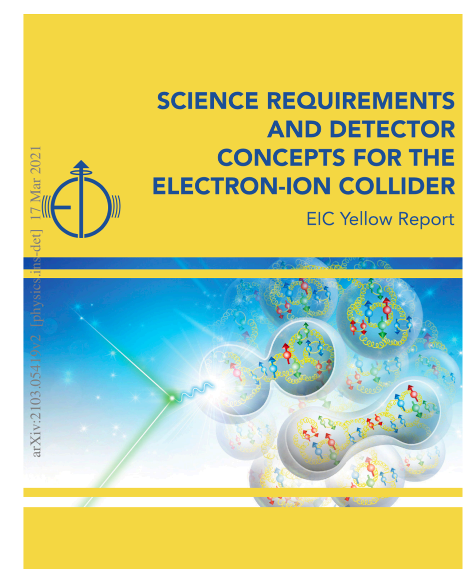
QCD WITH ELECTRON ION COLLIDER (QEIC)-II



- Inclusive measurement :
  Longitudinal information (xP)
- Semi-Inclusive measurement :
  Transverse momentum information (k_T)
- Exclusive measurement :
  Spatial structure (b_T) *& Saturation*



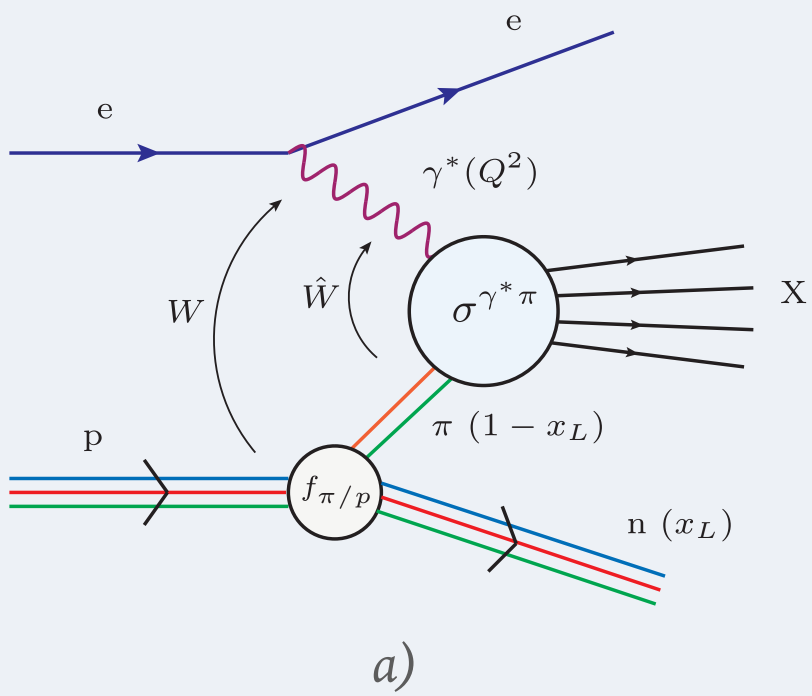
arXiv: 1212.1701

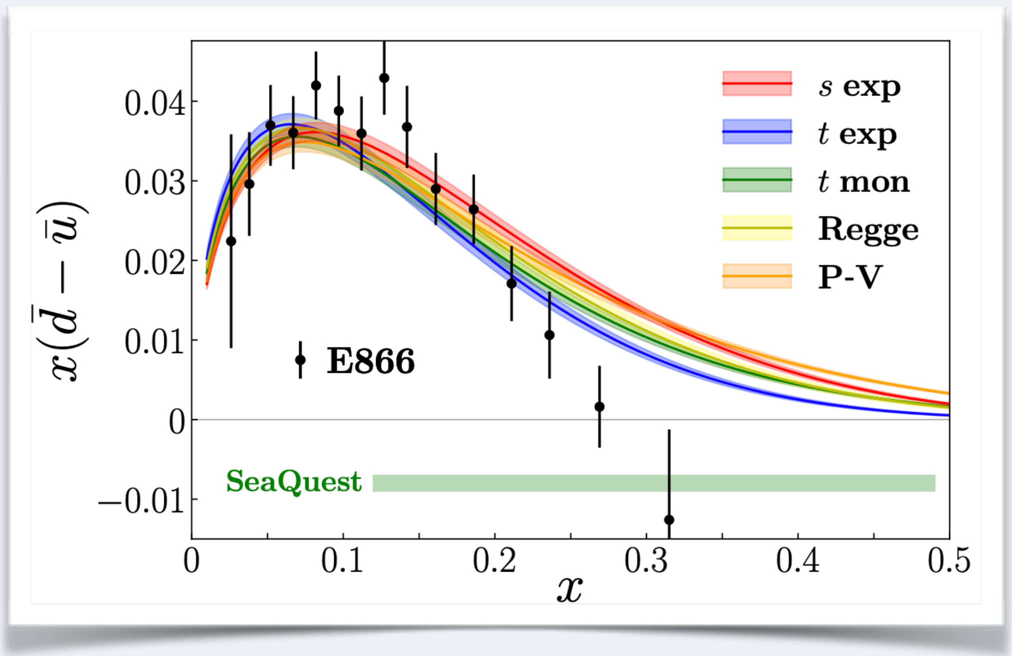


arXiv: 2103.05419

BACKUP

FLAVOUR ASYMMETRY AND PION CLOUD





Barry et al PRL 121, 152001

- ❖ 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

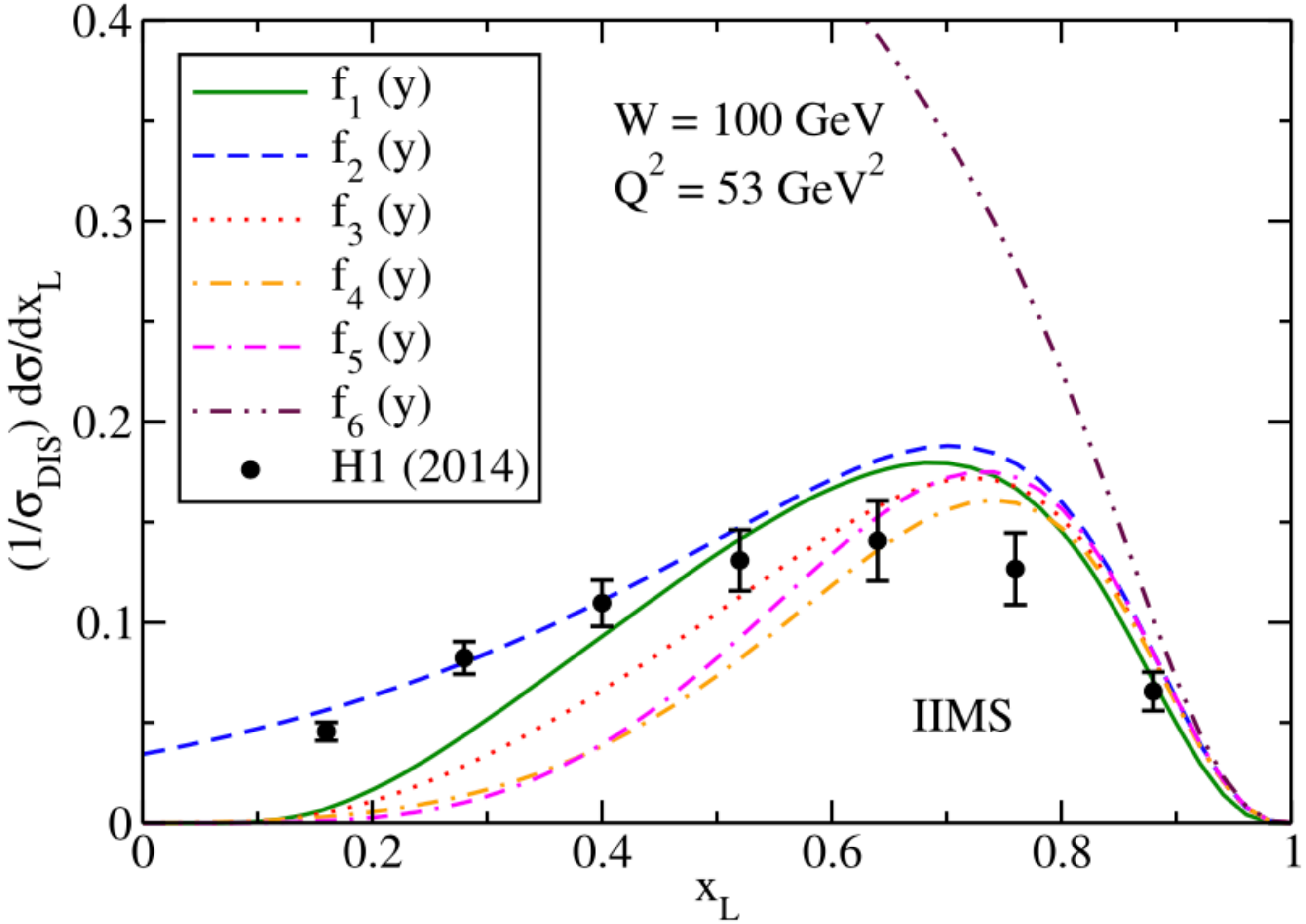
$$F_1(x_L,t) = \exp\left[R^2 \frac{(t-m_\pi^2)}{(1-x_L)}\right] \quad , \quad \alpha(t) = 0$$

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

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

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

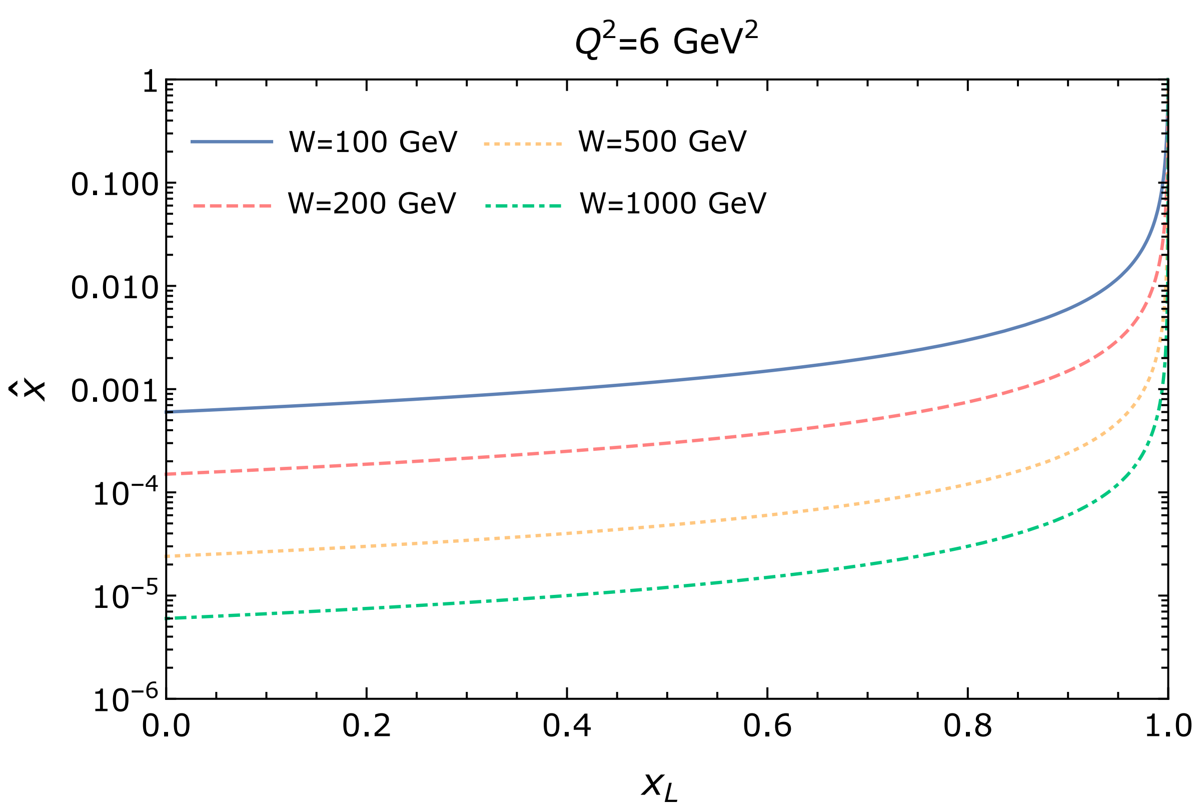
$$F_5(x_L,t) = \left[\frac{\Lambda_d^2 - m_\pi^2}{\Lambda_d^2 - t}\right]^2 \quad , \quad \alpha(t) = 0$$

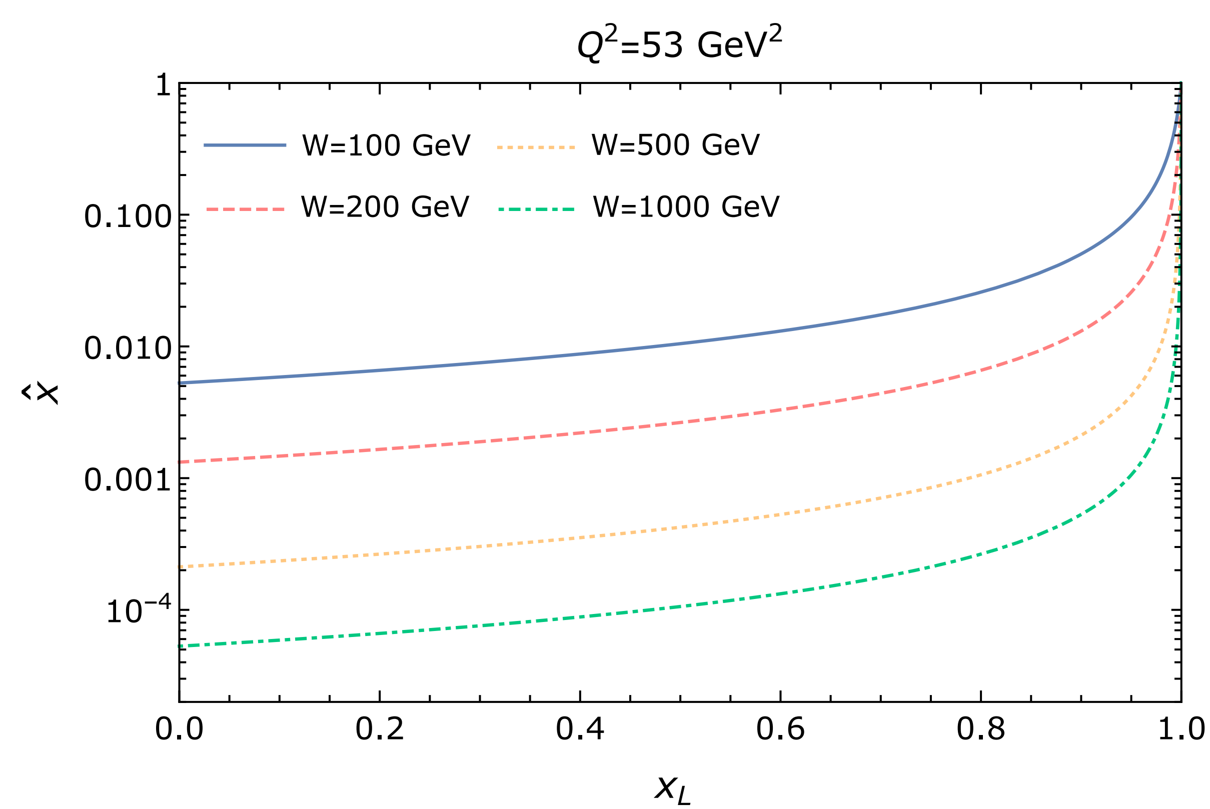


(a)

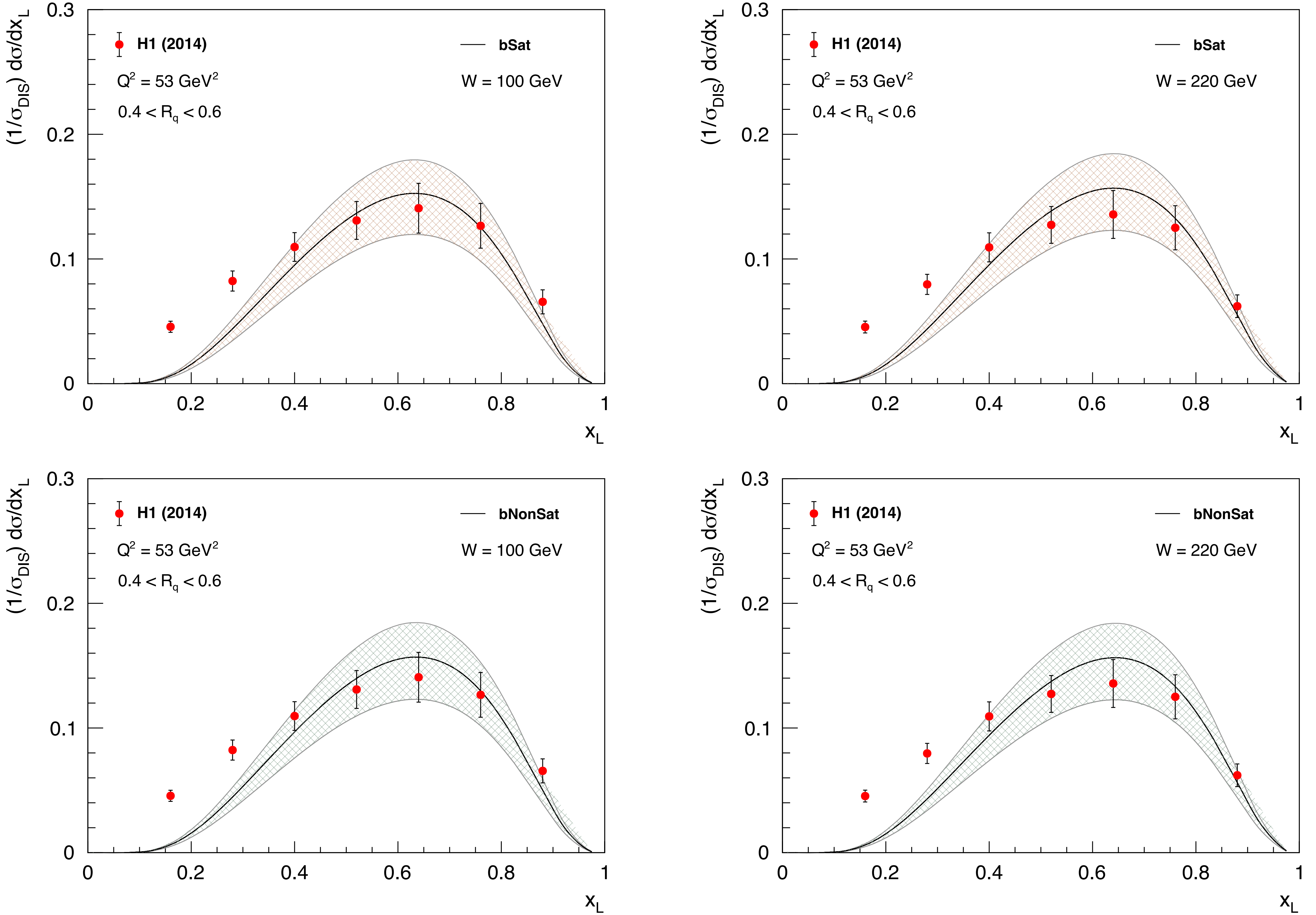
LN AS A PROBE FOR SMALL-X PHYSICS

- The x value probed in such a process is $\hat{x} = \dfrac{Q^2 + m_f^2}{\hat{W}^2 + Q^2} = \dfrac{Q^2 + m_f^2}{(1 - x_L)W^2 + Q^2}$
- LN production is low x physics
- In principle, we could use the color dipole framework to investigate the pion properties at small-x
- Use the dipole model to calculate the pion structure function F_2^π and the leading neutron structure function F_2^{LN} to compare with the HERA Data

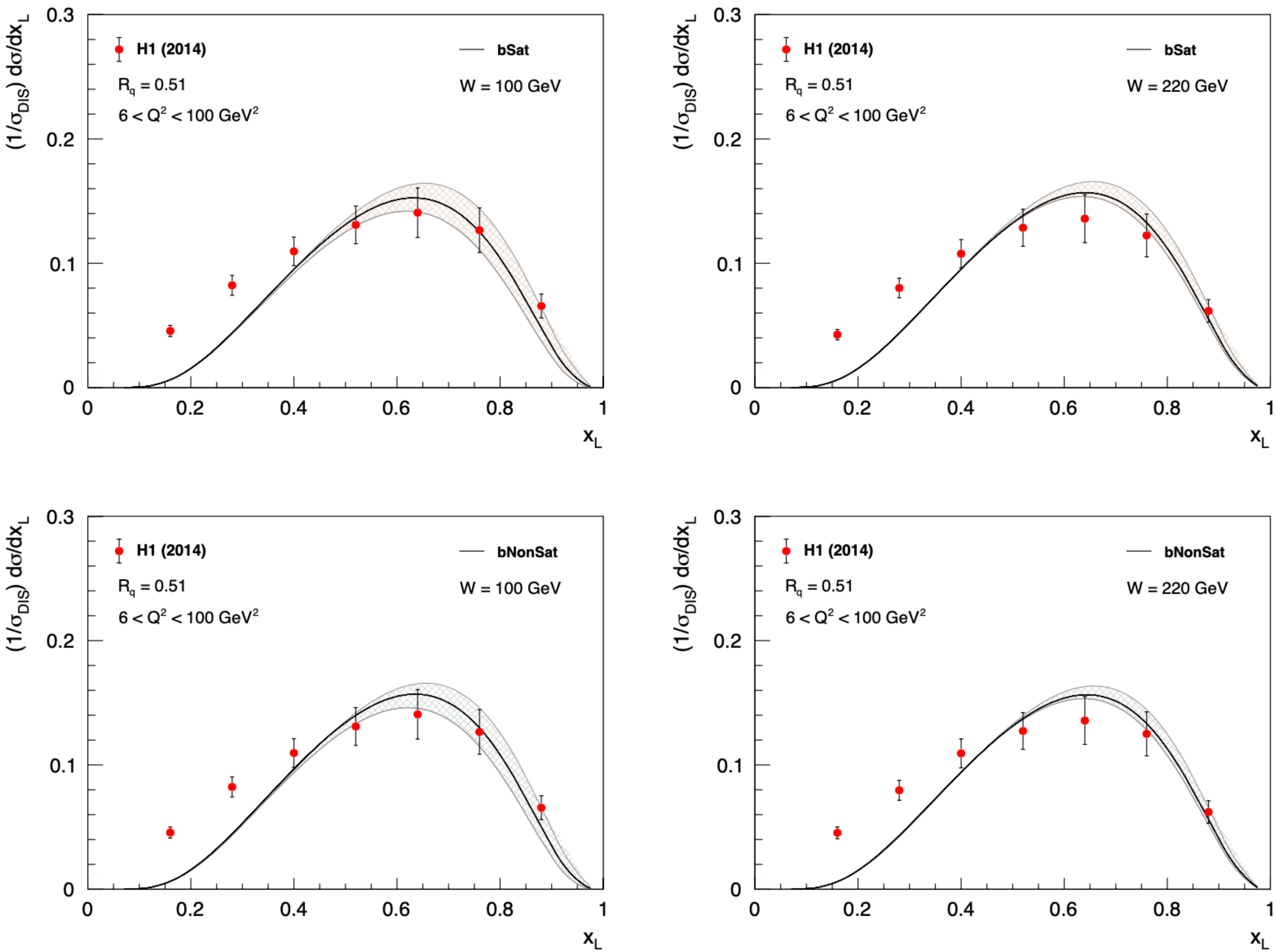


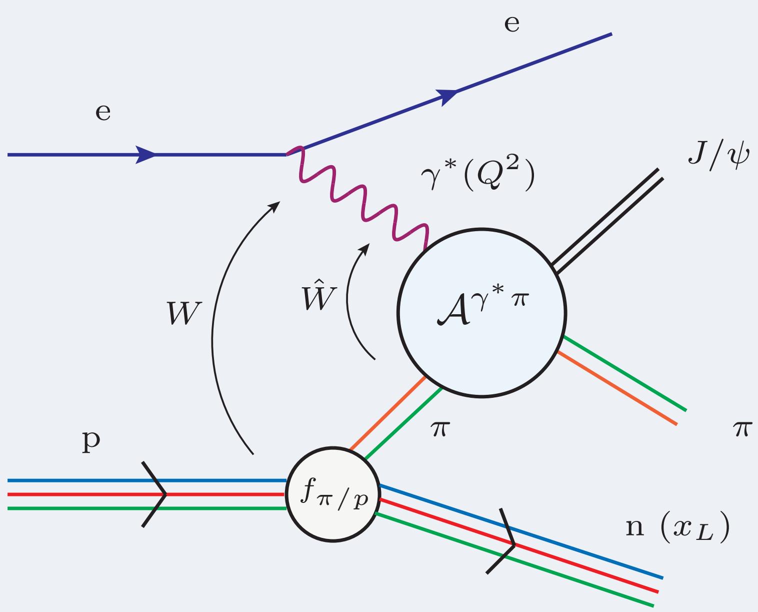


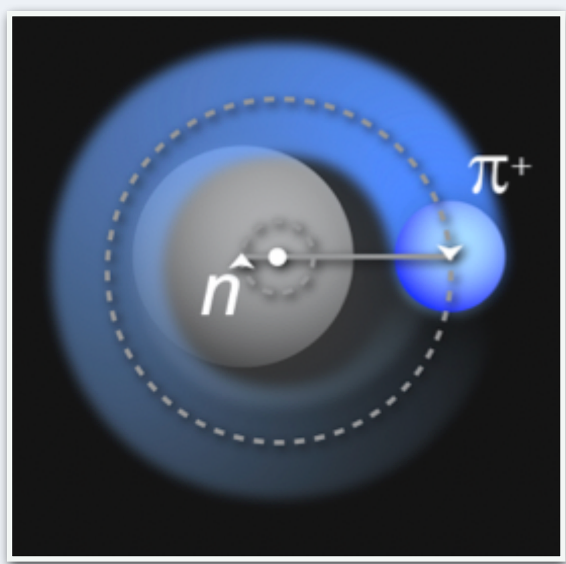
FEYNMAN-X SPECTRA



Q^2 SCALING IN FEYNMAN-X SPECTRA







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

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

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

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(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

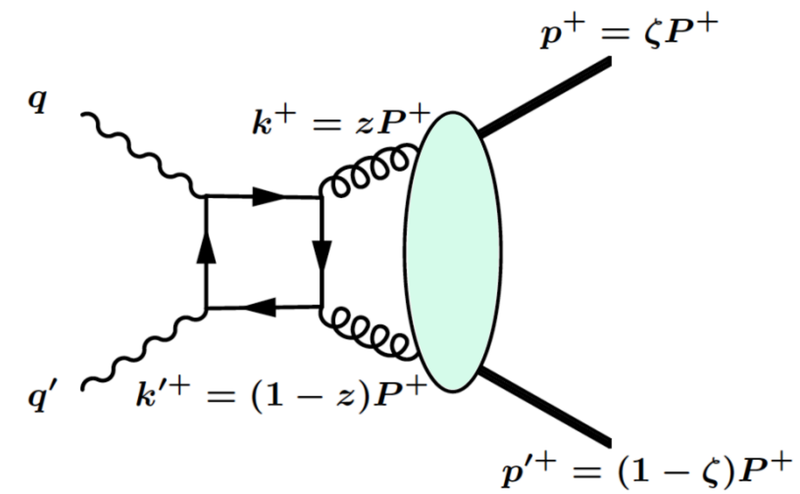
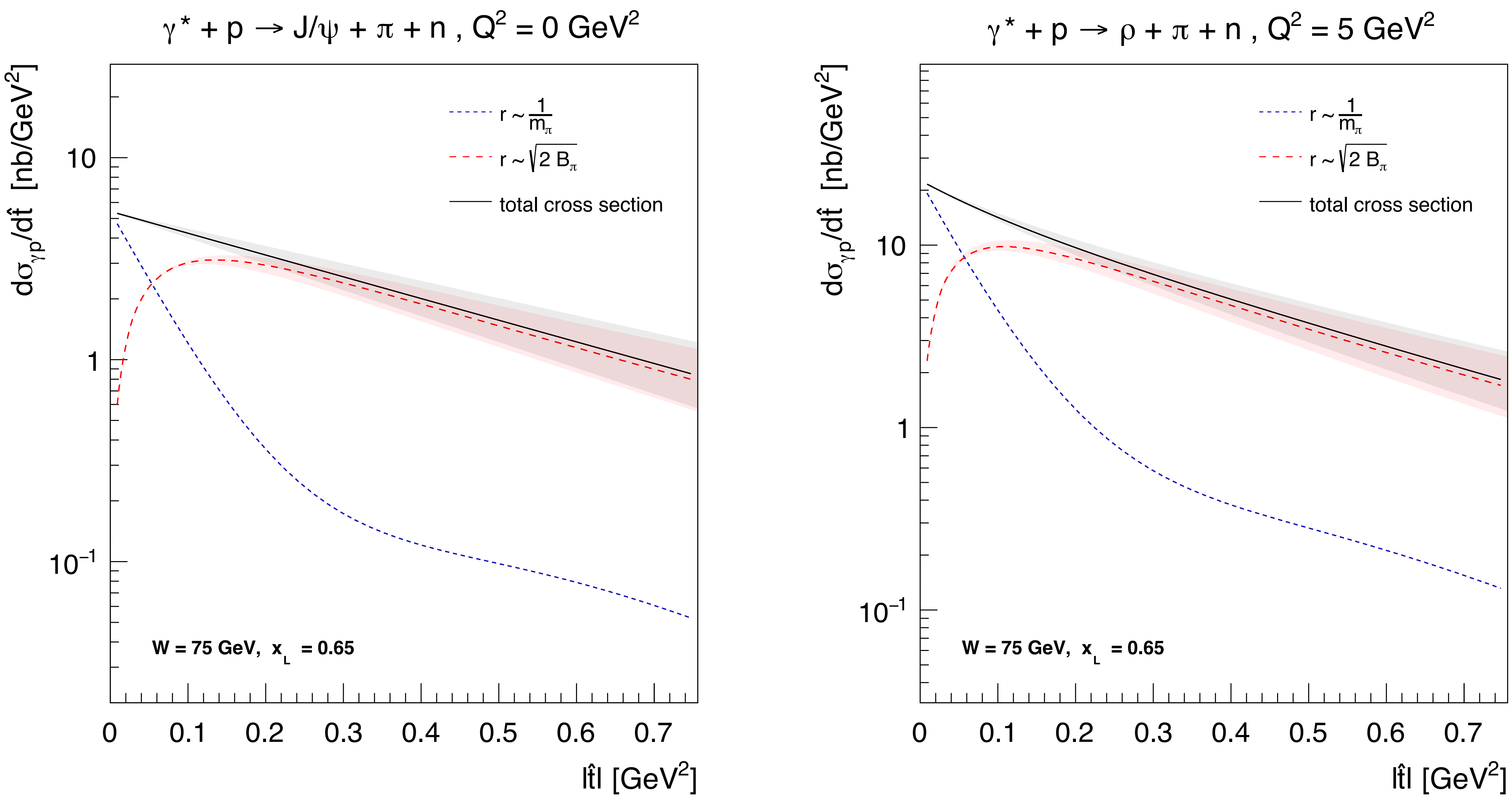


FIG. 4. Contribution to the two-photon cross section from the gluon GDA.

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

PROBING THE GLUON DISTRIBUTION



- 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

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)