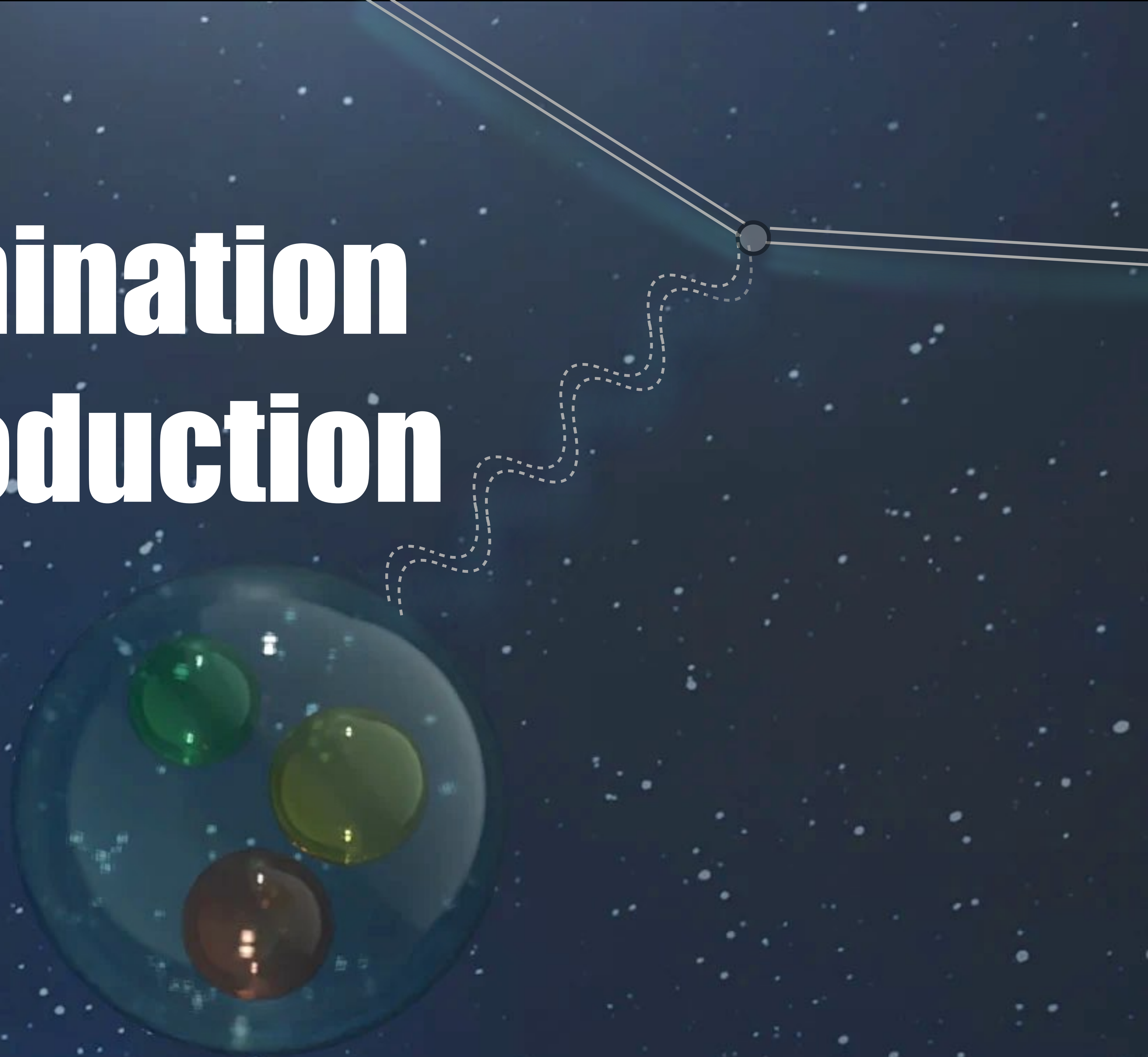
Proton shape/size determination through vector meson production

Exclusive diffraction with Sartre

NREC April 14, 2026



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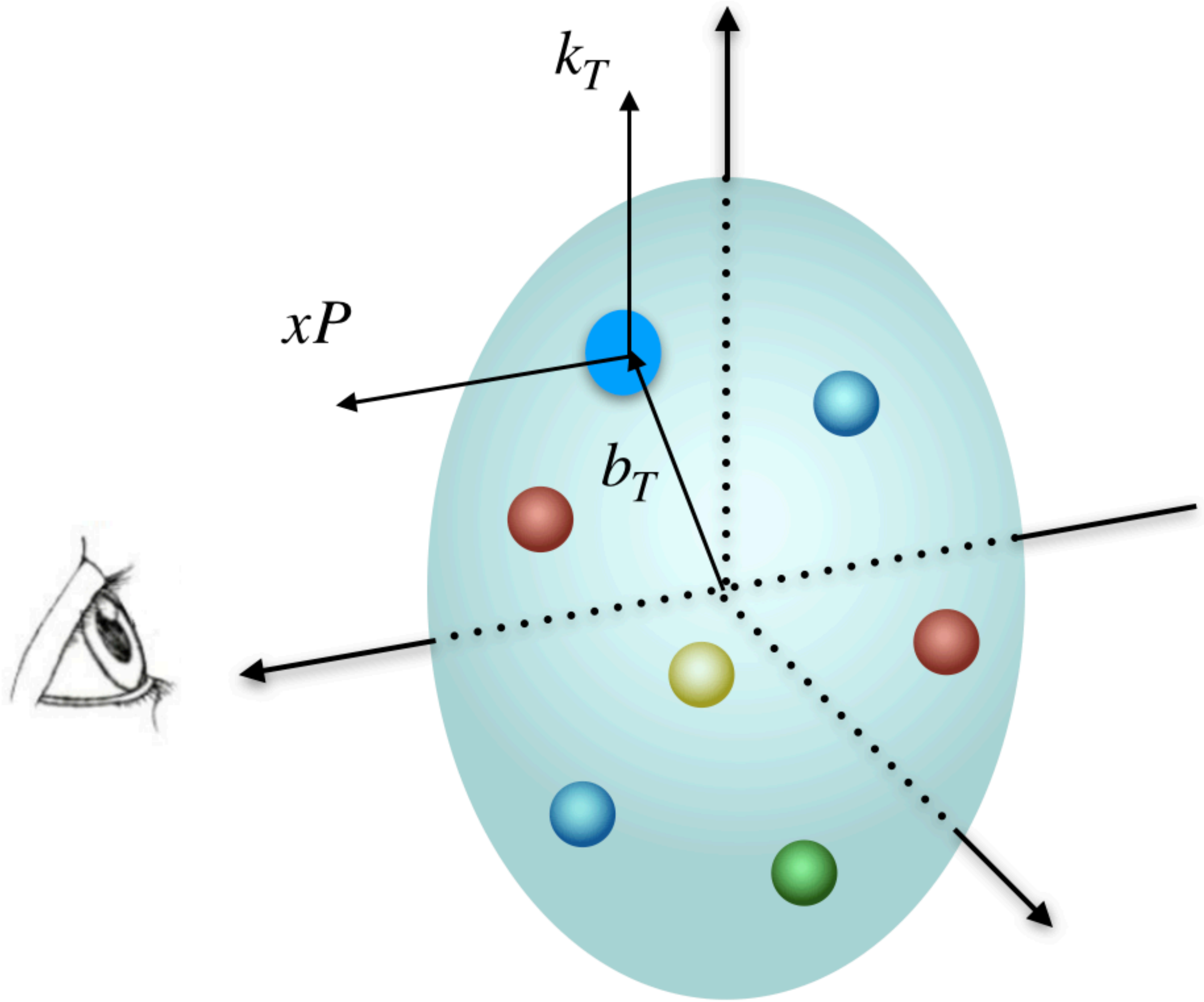
CFNS, Stony Brook University

Center for Frontiers in Nuclear Science

Stony Brook University

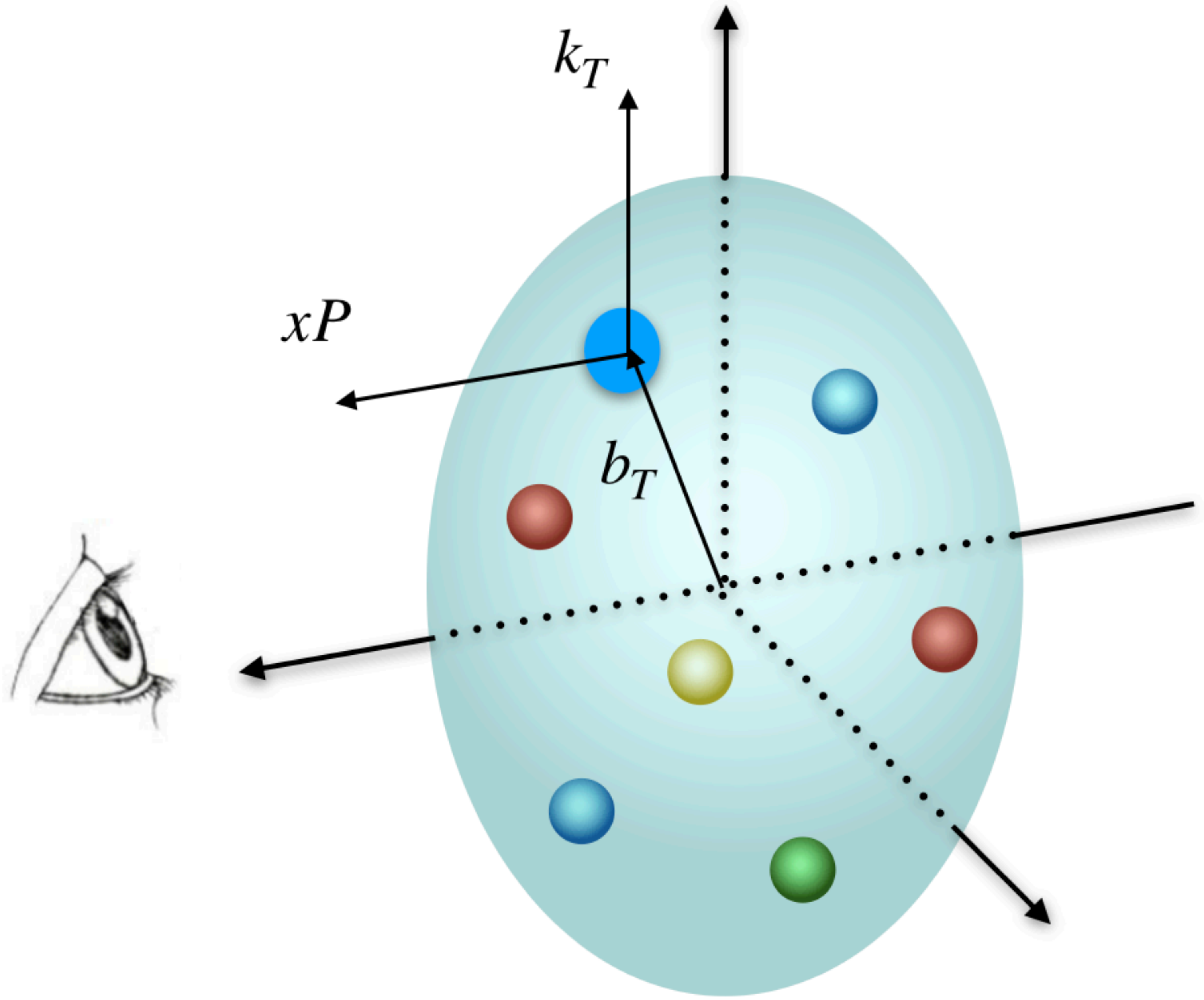
A SIMPLIFIED PERSPECTIVE ON THE PROTON



- *Longitudinal information* (xP)
- *Spatial Structure in transverse plane* (b_T)
- *Transverse momentum distributions* (k_T)
- *Unitarity*

- Need to go beyond 1-dimensional → (2+1) dimensional imaging (this work!)

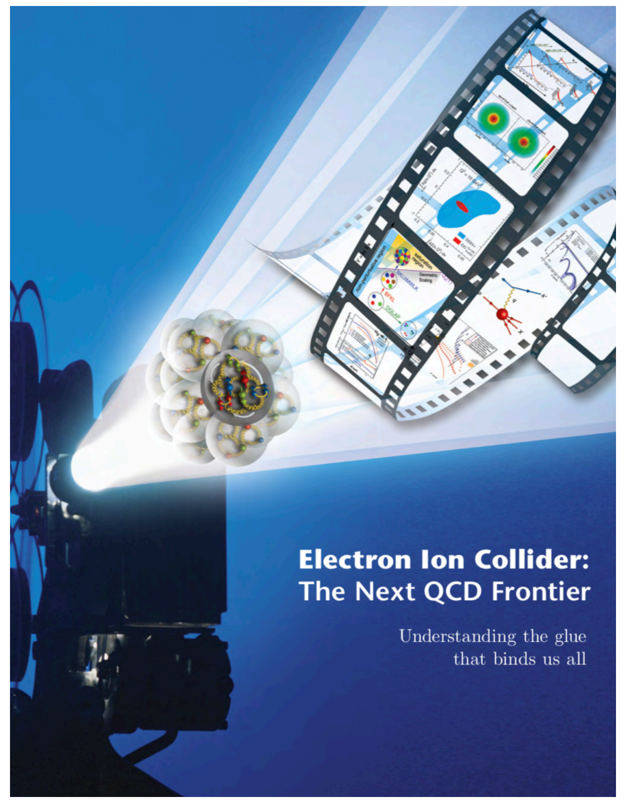
DEEP INELASTIC SCATTERING AT EIC



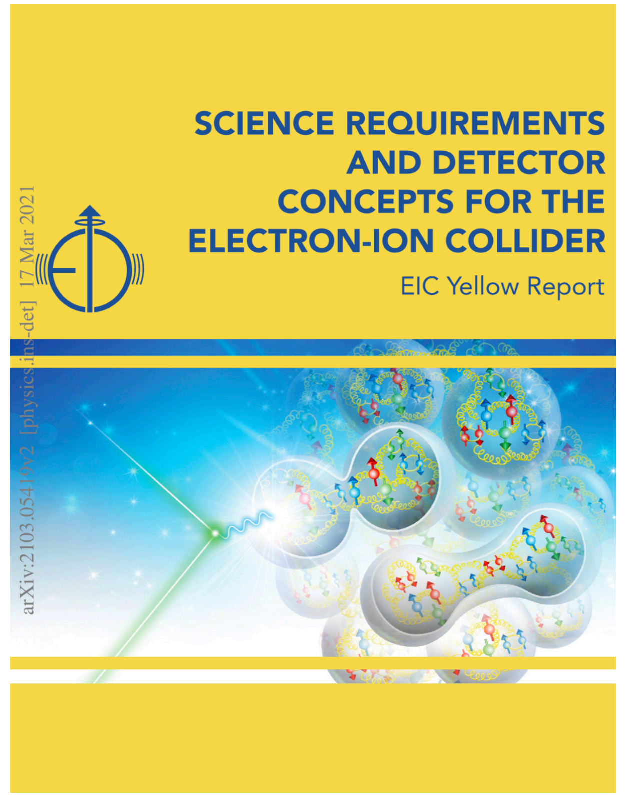
➡ Inclusive measurement :
Longitudinal information (xP)

➡ Exclusive measurement :
Spatial structure (b_T) *& Saturation*

- ❖ *What is the gluonic radius of the proton?*
- ❖ *How are gluons distributed in the transverse plane?*
- ❖ *Does the transverse size of proton remains fixed at high energies ?*
- ❖ *Is there a correlation between spatial structure and saturation?*

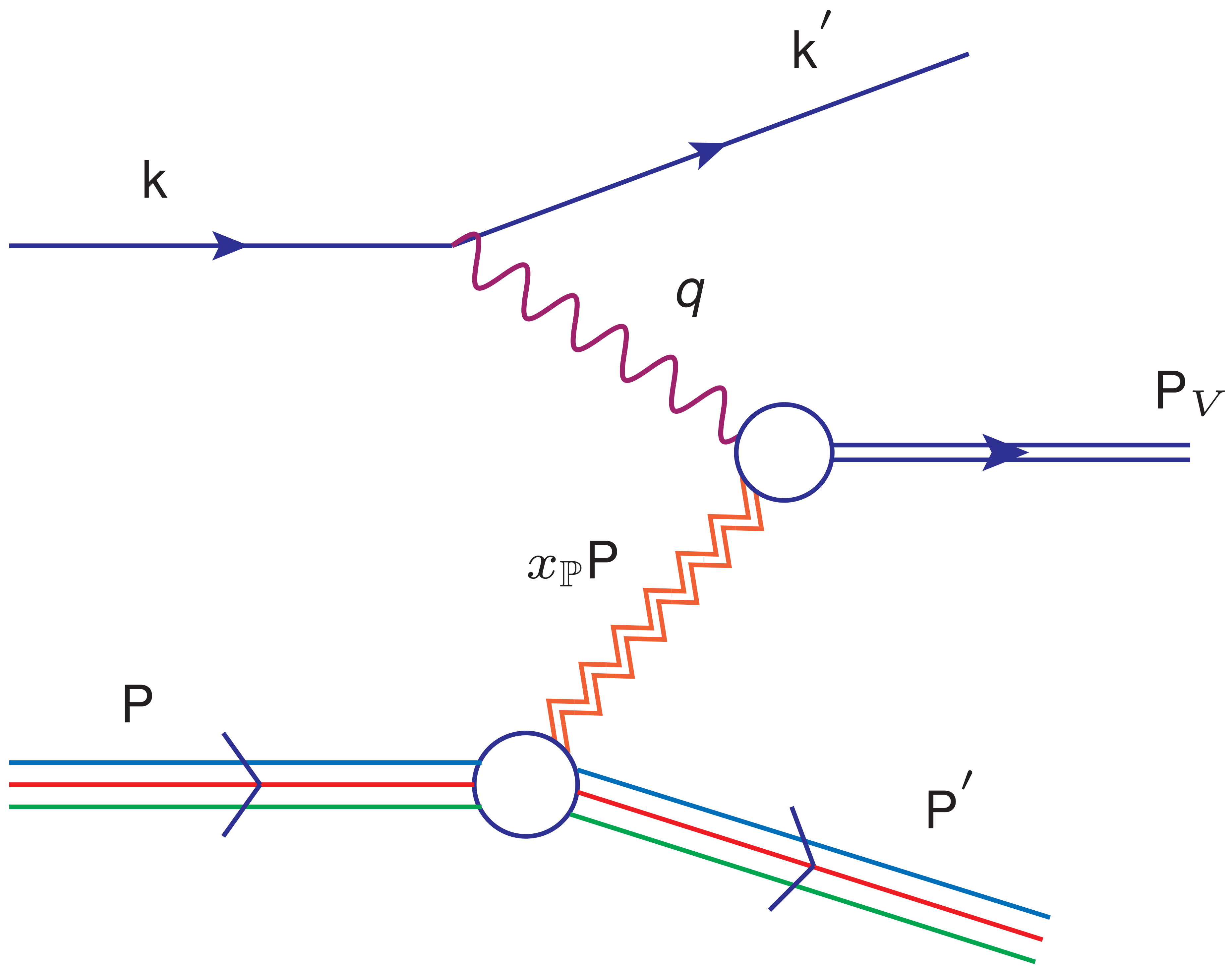


arXiv: 1212.1701



arXiv: 2103.05419

DIFFRACTIVE EVENTS IN DIS



- ➡ Exclusive measurement :

  $e + p \rightarrow e + VM \,/\, \gamma + p$

- ➡ Experimental Signature :

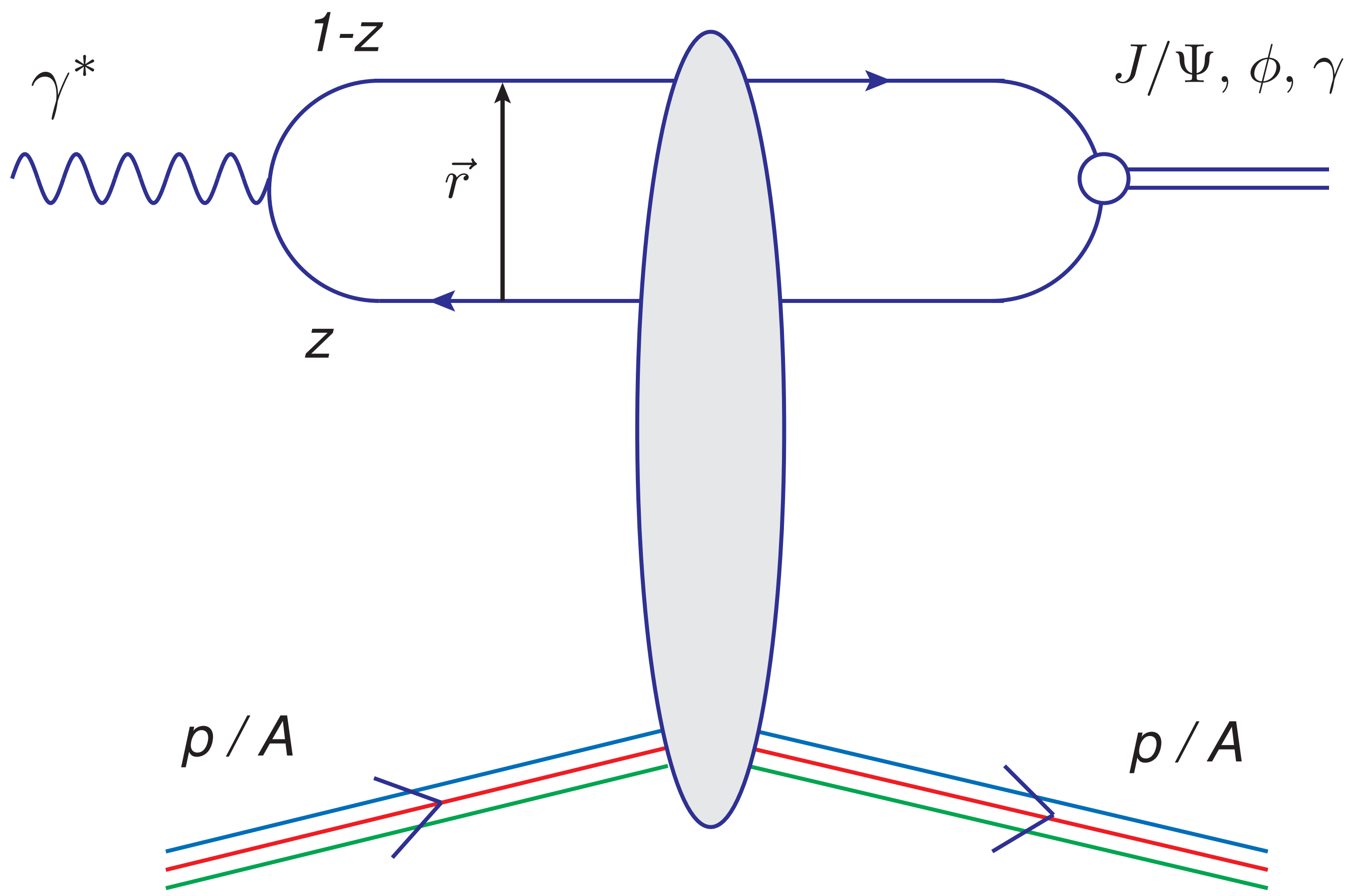
  rapidity gap in final state particles

- ➡ Diffractive process :

  cross-section distribution resemble to that of diffraction in optics (color neutral exchange)

- Excellent probe for high density gluonic matter and the transverse structure

EXCLUSIVE DIFFRACTION IN DIPOLE PICTURE



Factorisation :

- $\Psi(r, Q^2, z)$ *is wavefunction for* $\gamma^* \to q\bar{q}$
- $q\bar{q}$ *dipole scatters elastically of the target*
- $\Psi^V(r, Q^2, z)$ *is wavefunction for* $q\bar{q} \to VM$

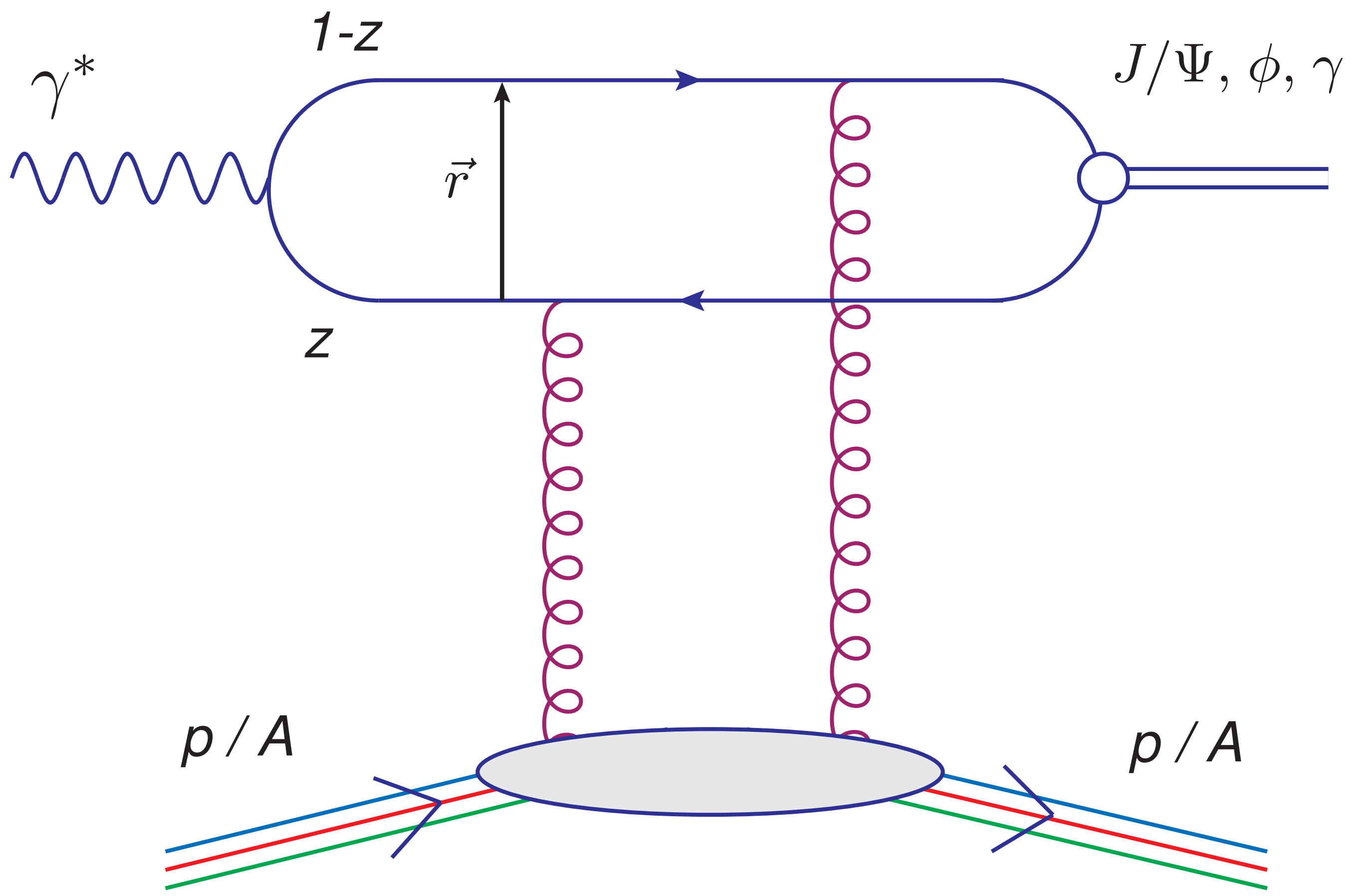
❖ *The scattering amplitude is given by :*

$$\mathcal{A}_{T,L}^{\gamma^* p \to Vp}(x, Q^2, \Delta) \simeq \int d^2r \int d^2b \int dz \times (\Psi^* \Psi_V)_{T,L}(Q^2, r, z) \times e^{-ib.\Delta} \times N(b, r, x)$$

❖ *Total* F_2 *: Forward scattering amplitude* $(\Delta = 0)$ *for* $V = \gamma^*$

❖ *Advantage of dipole picture: Describe simultaneously inclusive and diffractive observables using same degrees of freedom(* *same* $N(b, r, x)$ *)*

EXCLUSIVE DIFFRACTION IN DIPOLE PICTURE



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❖ *Impact parameter is Fourier conjugate to the momentum transfer* $\Delta = (p' - p)_\perp$

➡ *Access to spatial structure* $(t = -\Delta^2)$

❖ *In pQCD (2 gluon exchange) :* $\dfrac{d\sigma^{\gamma^* A \to V A}}{dt} \sim [xg(x, Q^2)]^2$

GOOD-WALKER PICTURE

Coherent diffraction

- *Target remains in the same quantum state after the interaction*
- *Cross section is determined by the average interaction of states (fock states of incoming virtual photon ; LO: quark-antiquark pair) that diagonalise the scattering matrix with target*

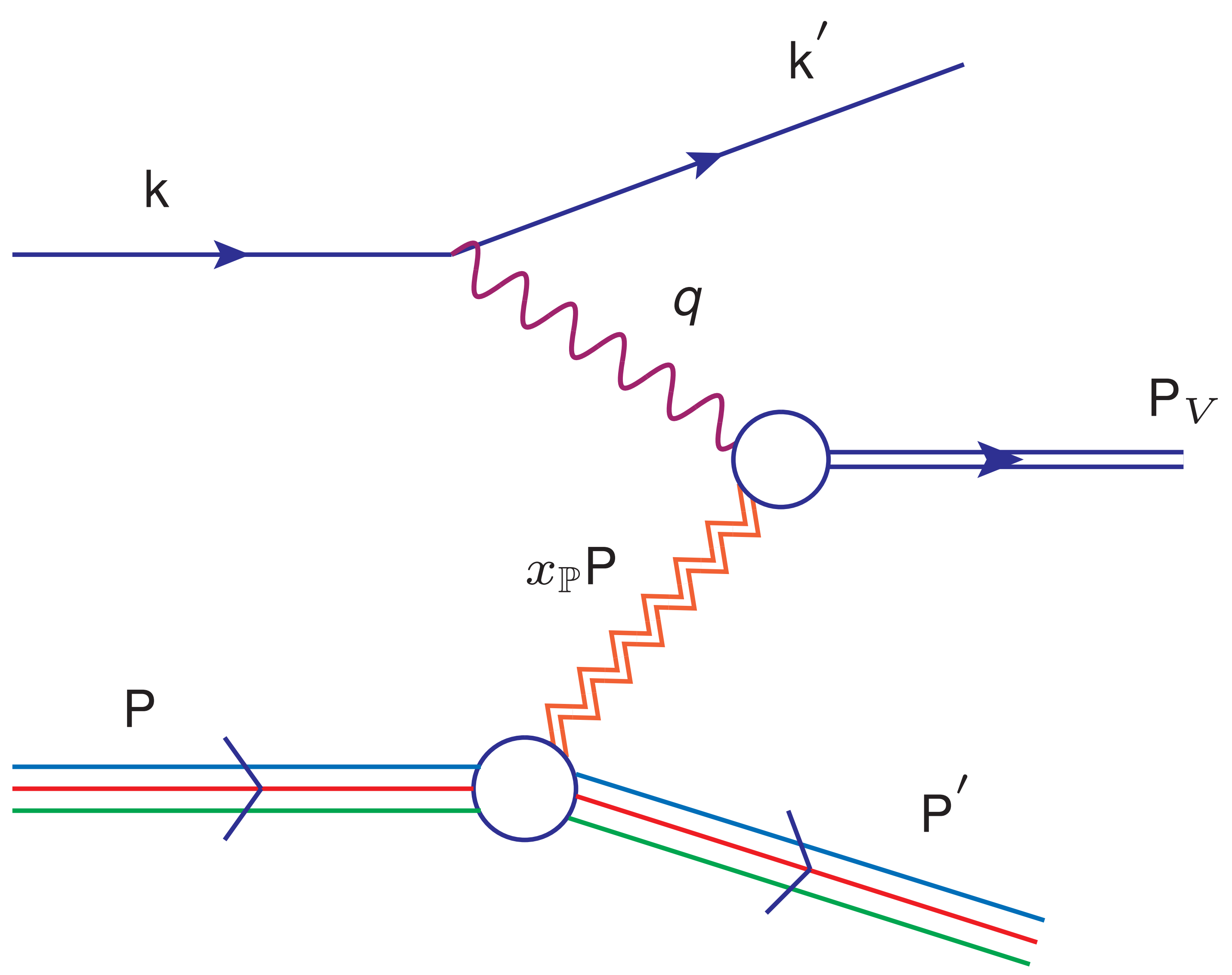
Incoherent diffraction

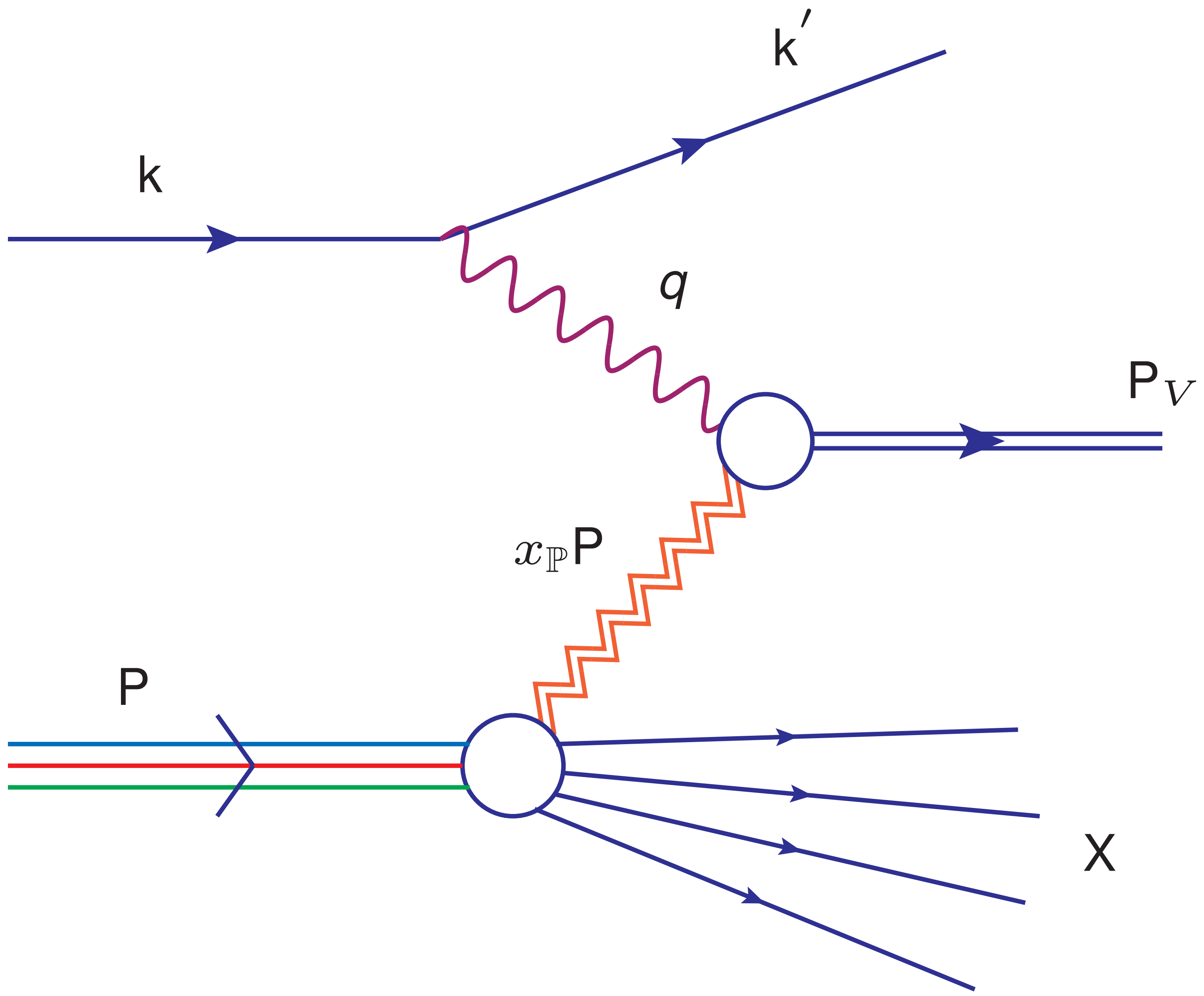
- *Sensitive to fluctuations of gluon distribution*

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

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

DIFFRACTIVE VECTOR MESON PRODUCTION WITH SARTRE





Coherent diffraction

★ *Proton remains intact*

★ *Sensitive to average gluon distribution in the proton*

Incoherent diffraction

★ *Proton breaks up*

★ *Sensitive to fluctuations of gluon distribution*

Good, Walker 1960, Miettinen, Pumplin 1978

$$\mathcal{A}_{T,L}^{\gamma^* p \to Vp}(x, Q^2, \Delta) \simeq \int d^2r \int d^2b \int dz \times (\Psi^*\Psi_V)_{T,L}(Q^2, r, z) \times e^{-ib.\Delta} \times N(b, r, x, \Omega)$$

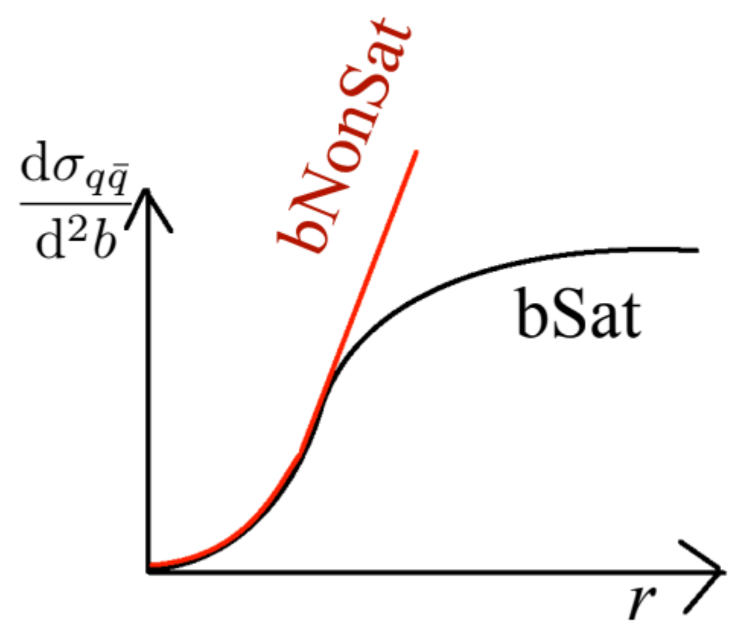
$$\sigma_{tot} \propto |<\mathcal{A}>_\Omega|^2 + (<|\mathcal{A}|^2>_\Omega - |<\mathcal{A}>_\Omega|^2)$$

Coherent Incoherent

see S.Klein 2301.01408 for challenges to Good-Walker paradigm

THE DIPOLE-TARGET AMPLITUDE

- *the bSat dipole model* : $N(\mathbf{b},\mathbf{r},x) = 2\left[1-\exp\left(-\frac{\pi^2}{2N_C}\mathbf{r}^2\alpha_s(\mu^2)xg(x,\mu^2)T_p(\mathbf{b})\right)\right]$
- *the bNonSat dipole model* : $N(\mathbf{b},\mathbf{r},x) = \frac{\pi^2}{N_C}\mathbf{r}^2\alpha_s(\mu^2)xg(x,\mu^2)T_p(\mathbf{b}))]$



where $xg(x,\mu_0^2) = A_g\ x^{-\lambda_g}\ (1-x)^{5.6}$ *and* $\mu^2 = \mu_0^2 + \frac{C}{r^2}$

(the parameters are constrained by HERA reduced-cross section data (inclusive) and the scale dependence obtained from DGLAP evolution)

Two models for the spatial proton profile :

a) Smooth proton (assume gaussian proton shape) : $T_p(\mathbf{b}) = \frac{1}{2\pi B_G}\exp\left[-\frac{\mathbf{b}^2}{2B_G}\right]$ Kowalski, Teaney 2003, Kowalski, Motyka,Watt 2006

b) Lumpy proton (assume gaussian distributed hotspots with gaussian shape) : $T_p(b) \to \sum_{i=1}^{N_q} T_q(b-b_i)$ *and* $T_q(\mathbf{b}) = \frac{1}{2\pi B_q}\exp\left[-\frac{\mathbf{b}^2}{2B_q}\right]$

Mäntysaari, Schenke PRL 117 (2016) 052301

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where $Q_S^2 = \frac{2}{r_S^2}$, $\frac{1}{2} = \frac{\pi^2}{2N_C}\mathbf{r}^2\alpha_s(\mu^2)xg(x,\mu^2)T_p(b)$

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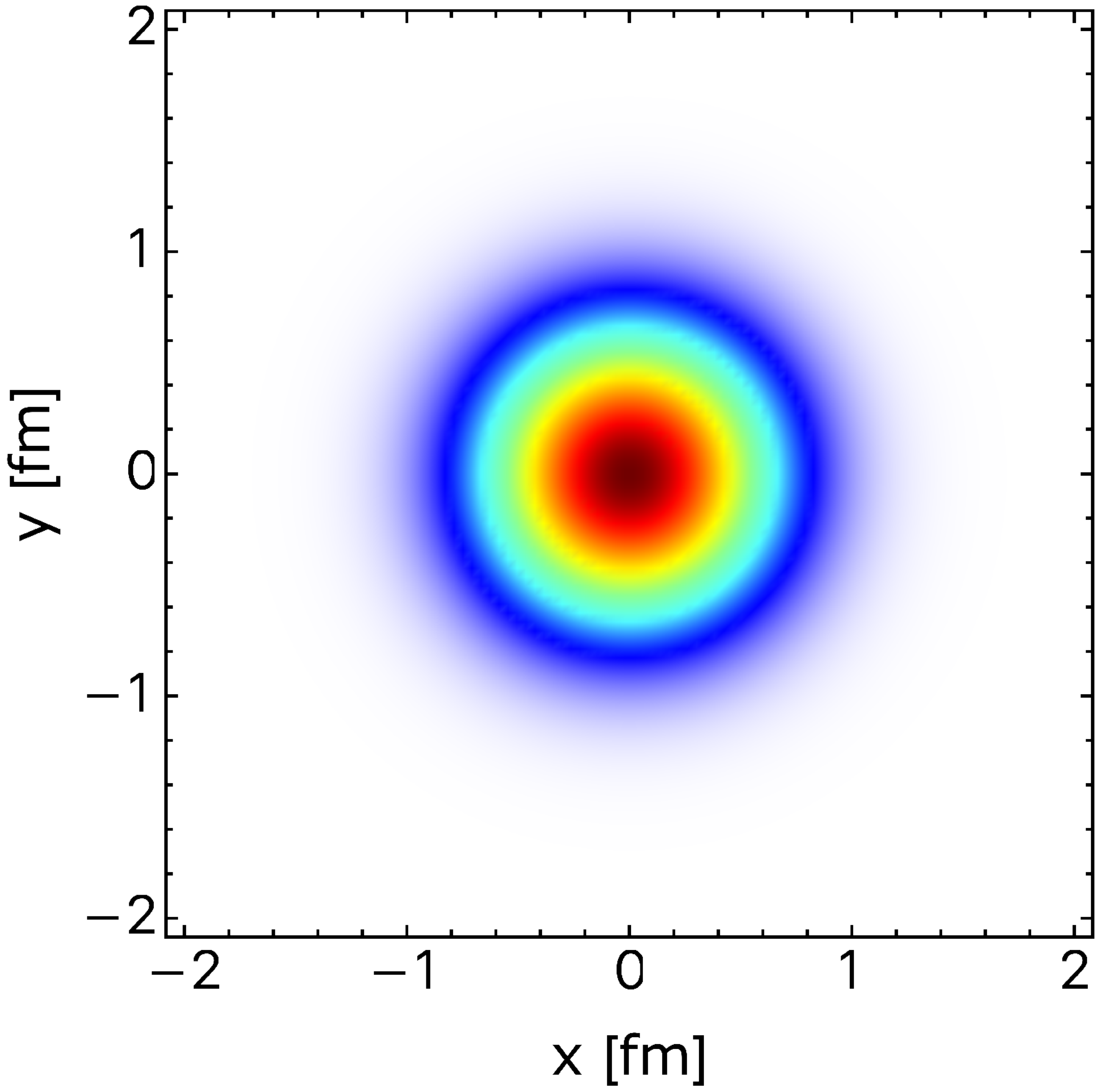
Mäntysaari, Schenke PRL 117 (2016) 052301

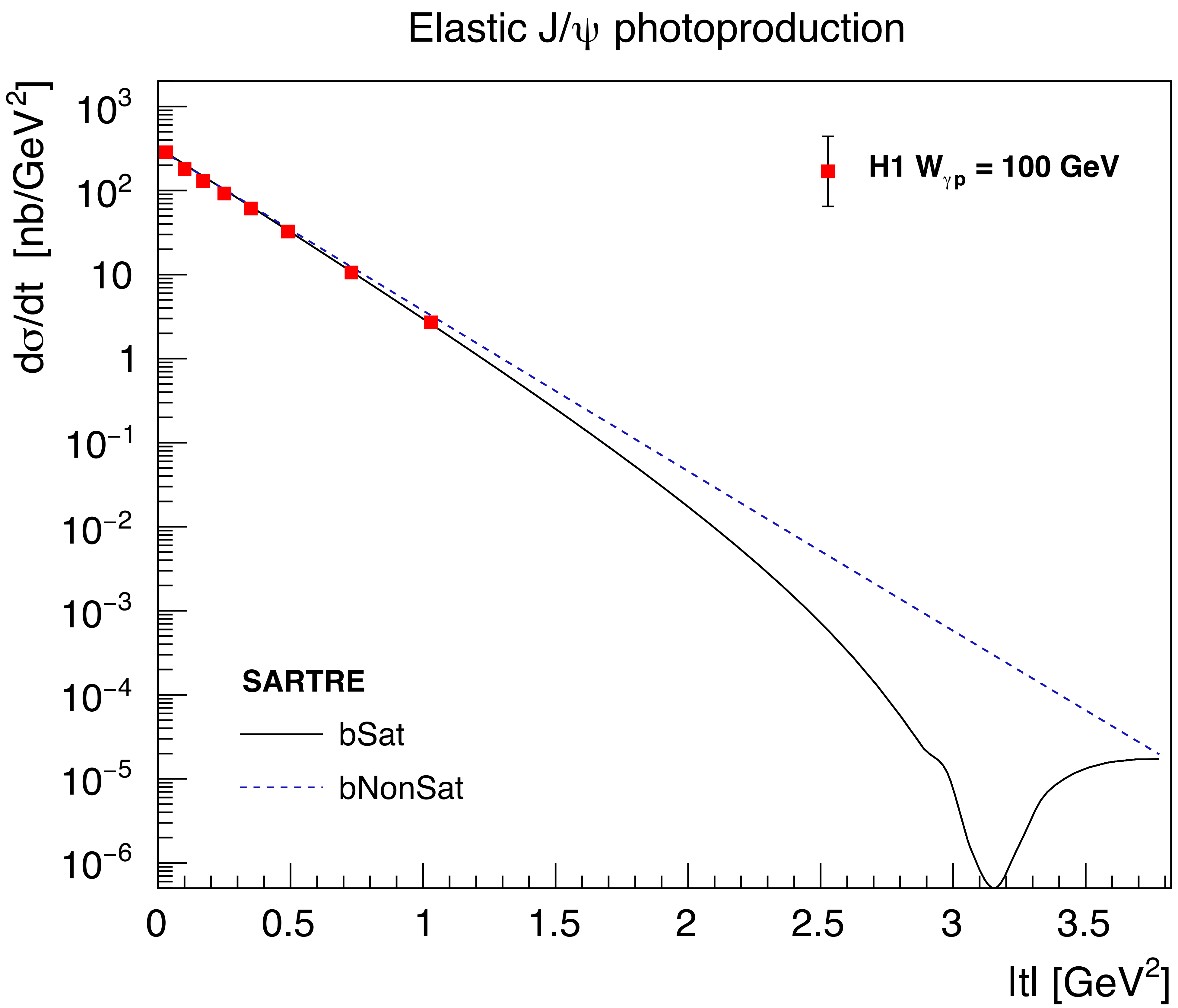
$e + p$ AS COMPARED TO HERA DATA : SMOOTH PROTON

$$T_p(\mathbf{b}) = \frac{1}{2\pi B_G} \exp[-\frac{\mathbf{b}^2}{2B_G}]$$

$$\mathscr{A} \sim \int d^2r \int d^2b \int dz \times (\Psi^*\Psi_V)_{T,L}(Q^2, r, z) \times e^{-ib.\Delta} \times N(b, r, x)$$

Kowalski, Teaney 2003, Kowalski, Motyka,Watt 2006





- $B_G = 4$ GeV^{-2} $(r \sim 0.56$ fm$)$ → Gluons are more concentrated in centre of proton than quarks

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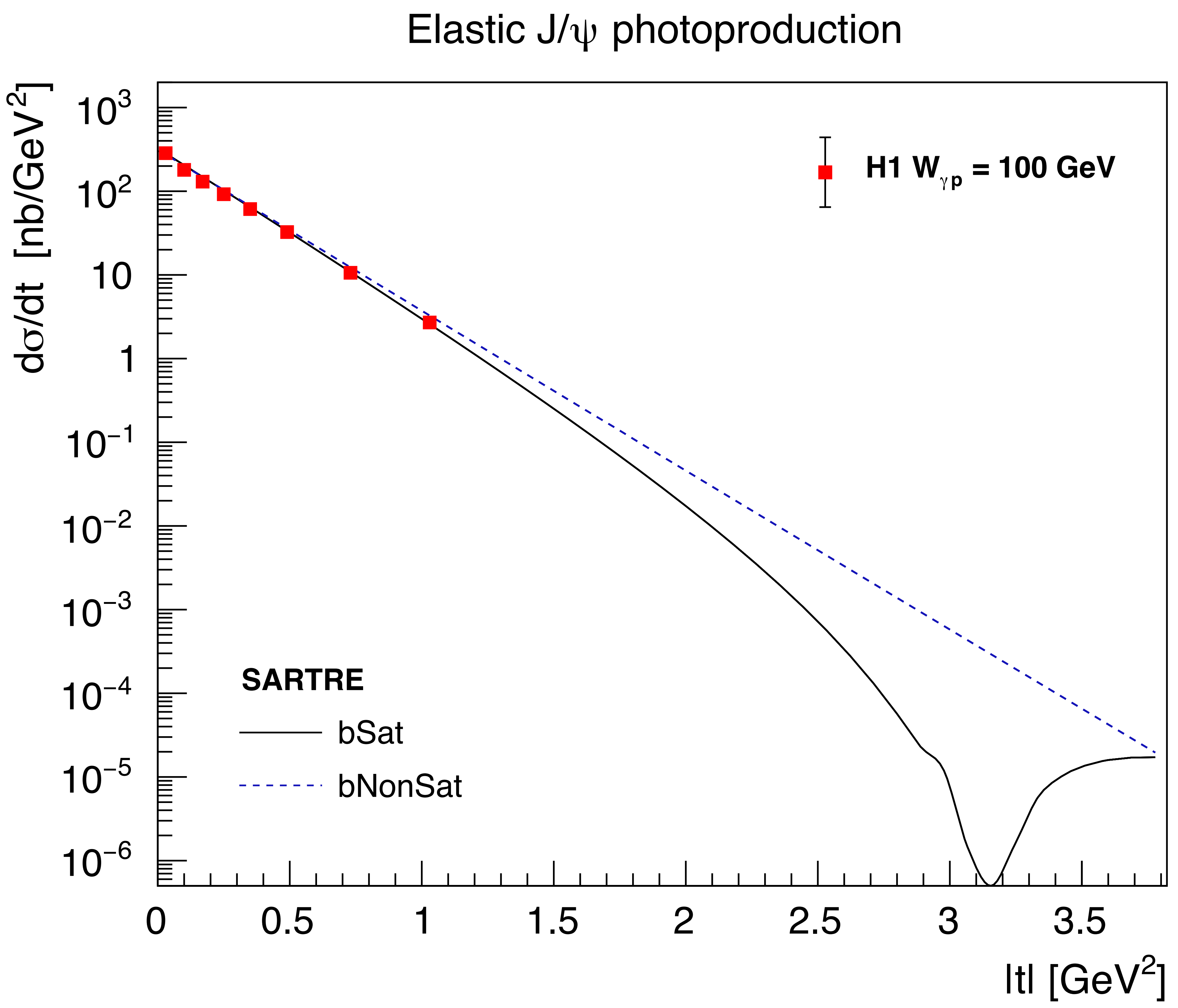


Gaussian & linear (bNonSat) : $N(r, b) \sim e^{-\mathbf{b}^2/(2B)}$

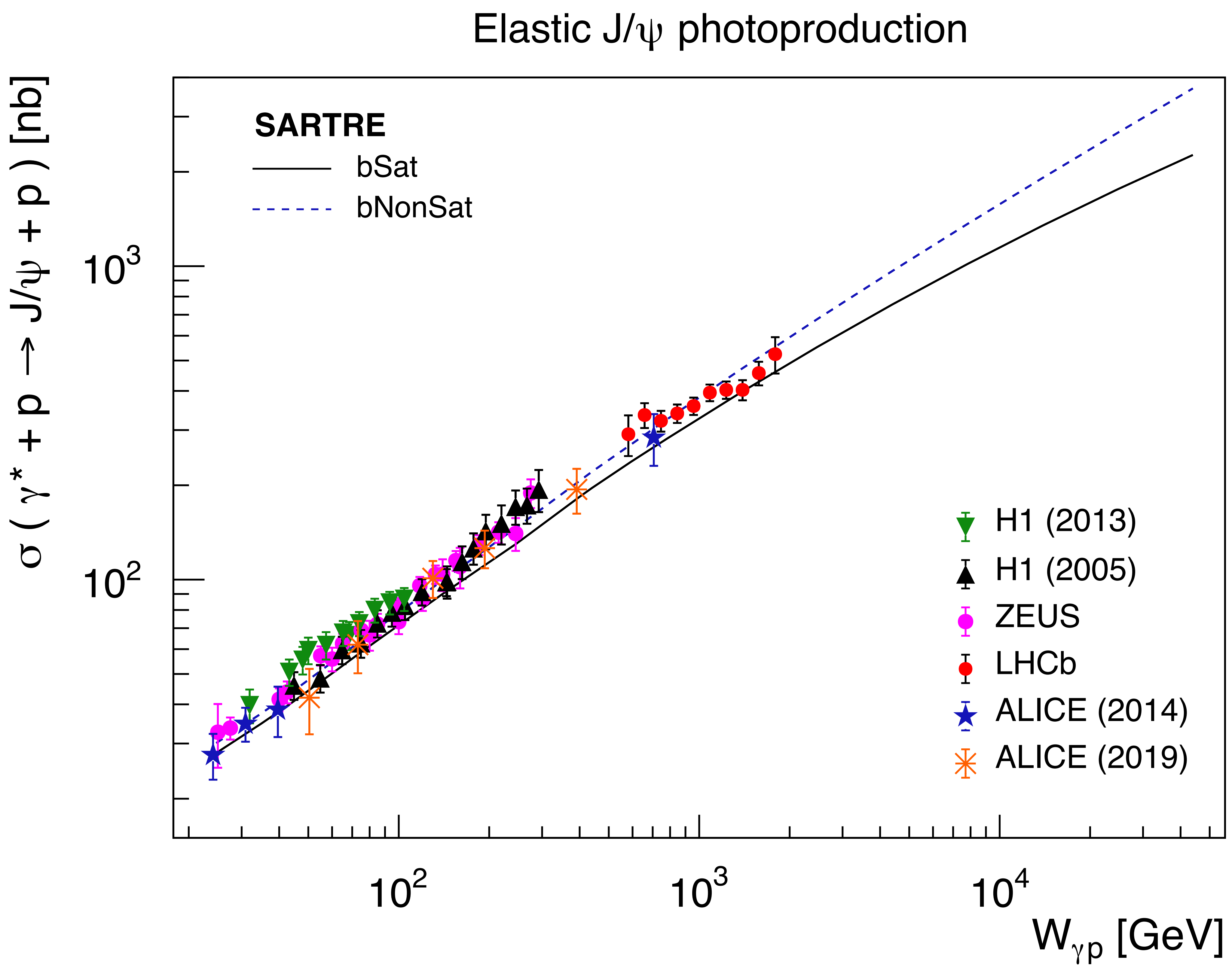
Gaussian& non-linear (bSat) : $N(r, b) \sim 1 - \exp\left(-e^{-\mathbf{b}^2/(2B)}\right)$

Dips depends upon i) density profile ii) the non-linear effects

Complementary constraints from inclusive diffraction??

Deviations from gaussian shape?

$e + p$ AS COMPARED TO HERA DATA : SMOOTH PROTON



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Power law increase for non-saturated model

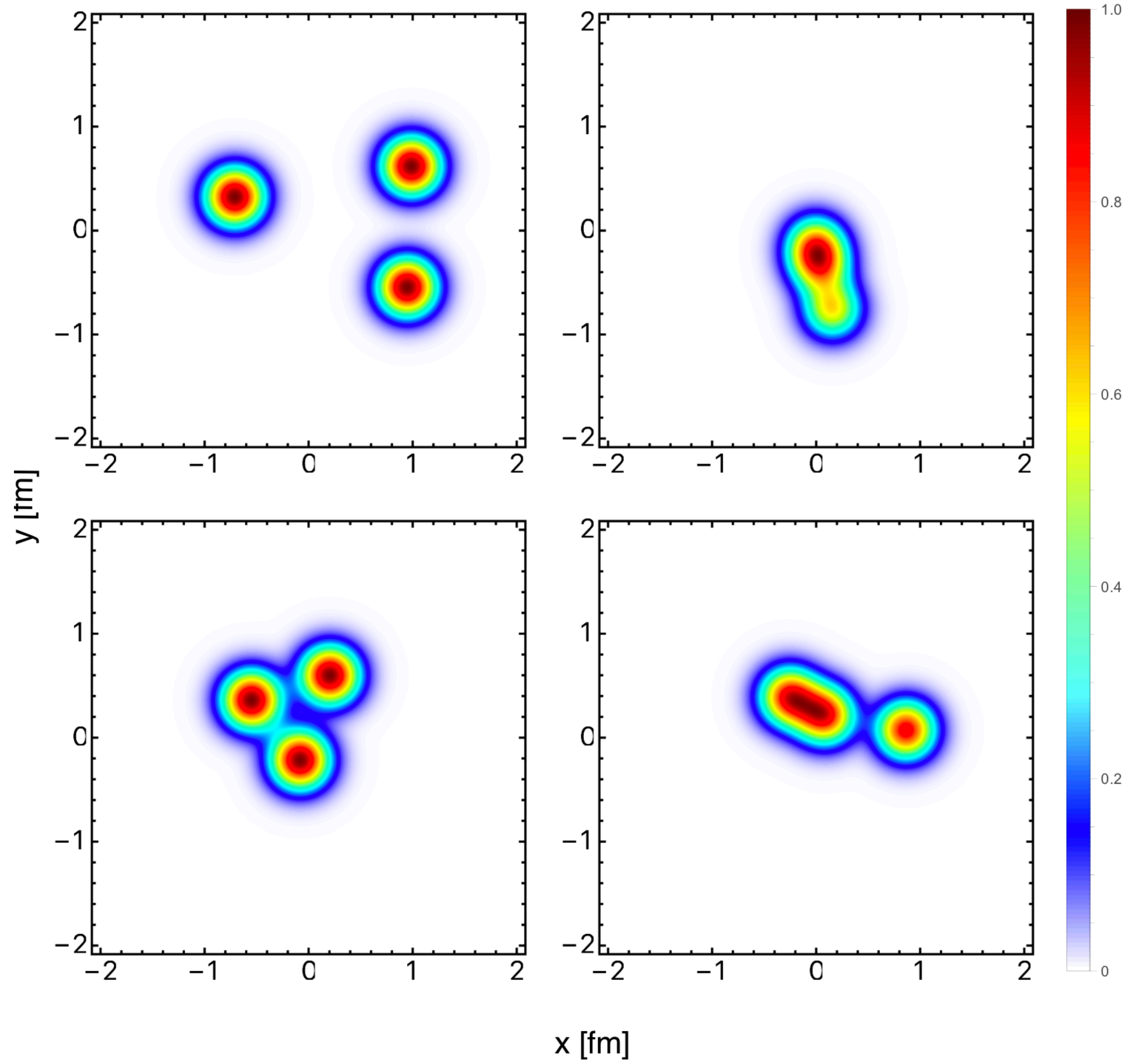
Deviations from power law? Hint of non-linear effects

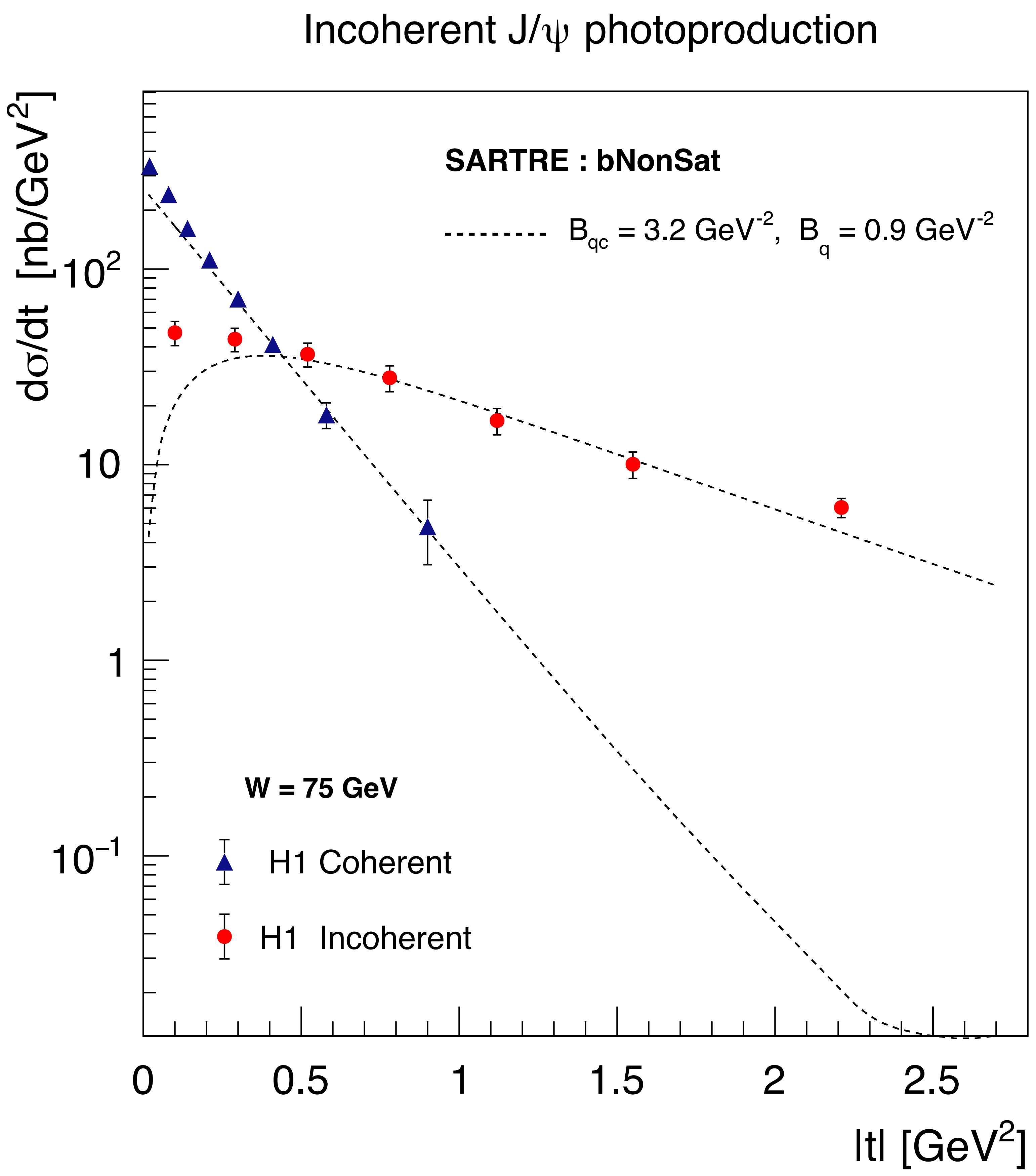
For a smooth proton there are no fluctuations and the incoherent cross section is zero → Lumpy proton

$e + p$ AS COMPARED TO HERA DATA : LUMPY PROTON

$$T_p(b) \rightarrow \sum_{i=1}^{N_q} T_q(b - b_i)$$

Mäntysaari, Schenke PRL 117 (2016) 052301





(large event-by-event fluctuations (1000 configurations) are needed to explain HERA data)

see Blaizot, Traini 2209.15545 for dipole size fluctuations at low momentum transfer

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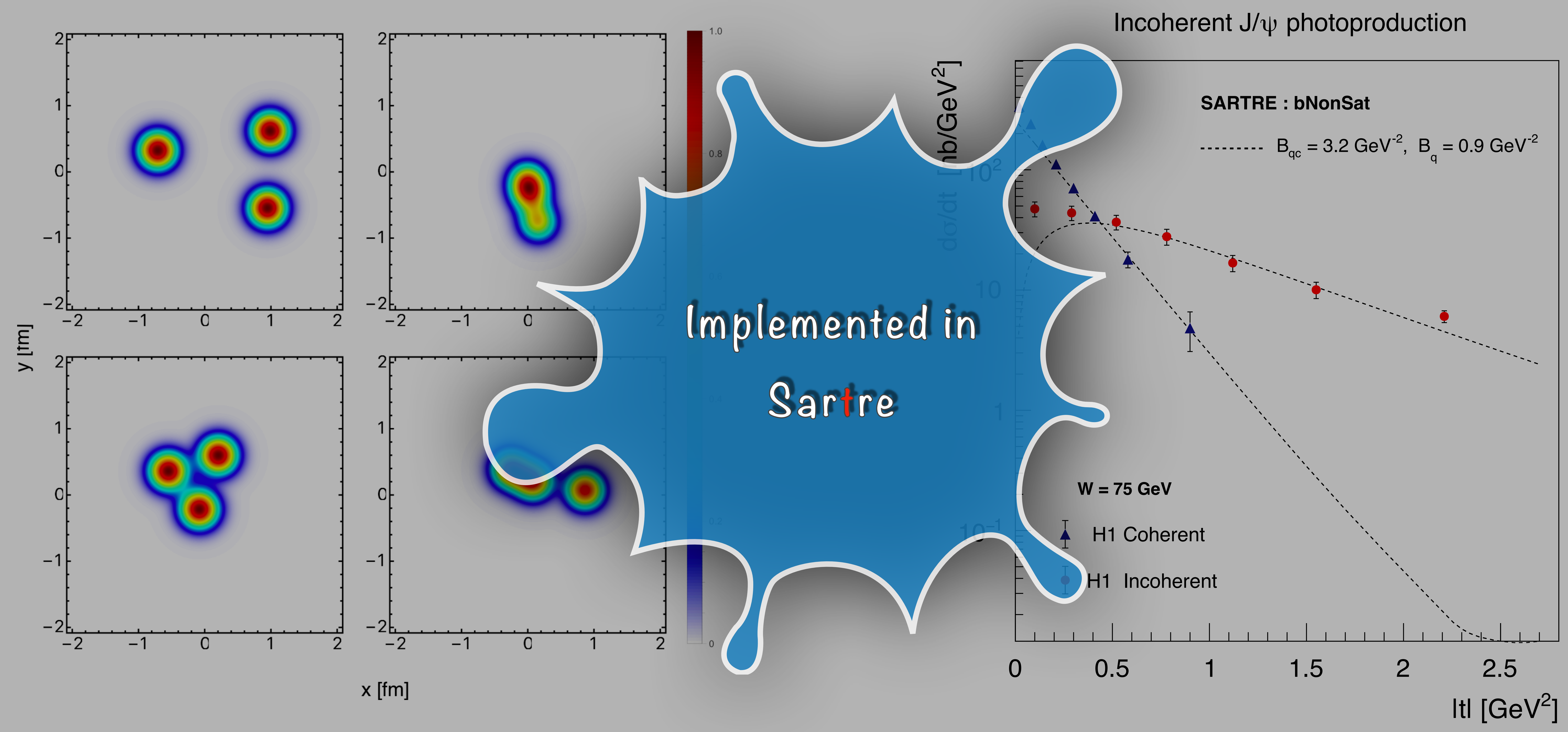

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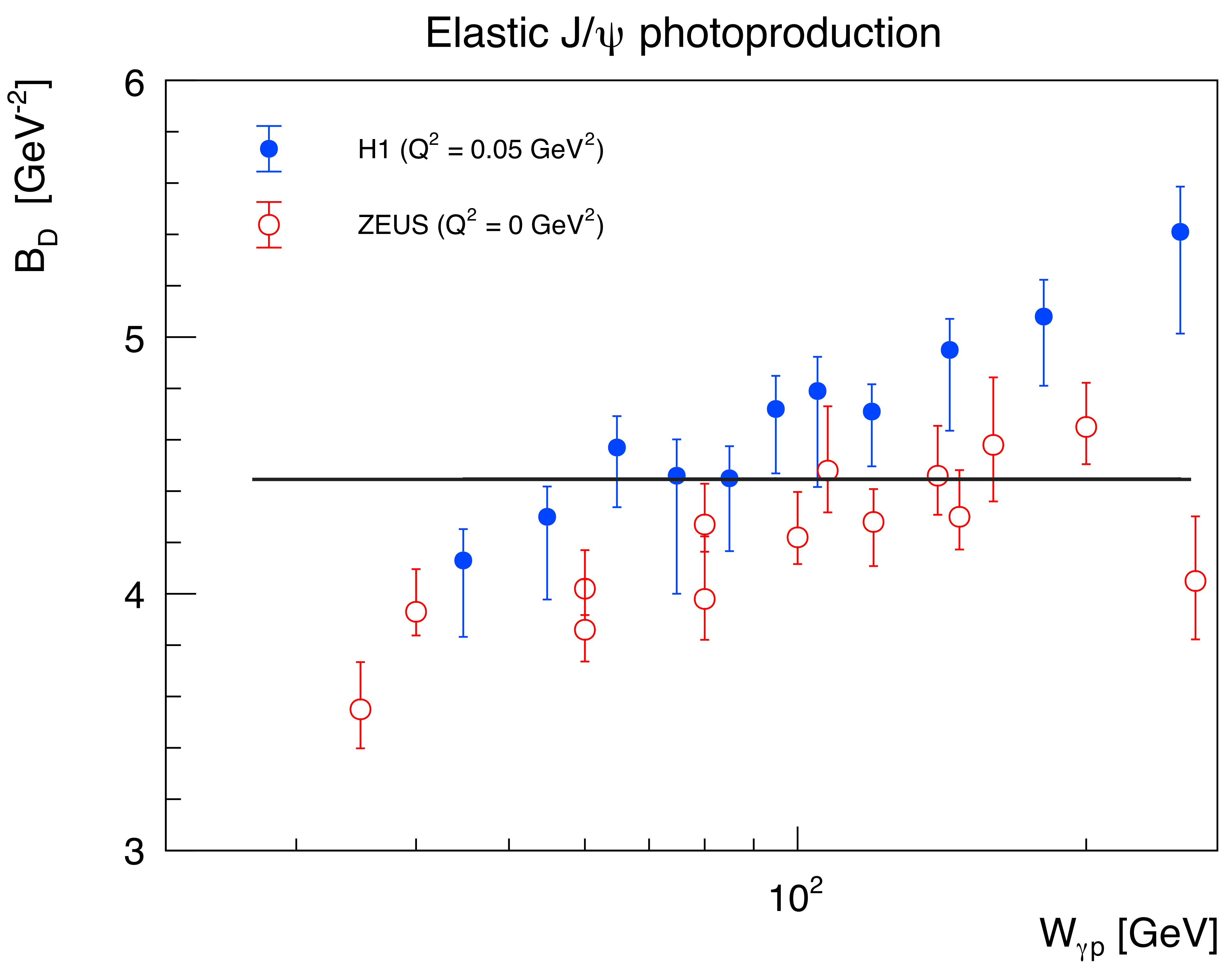


- B_D is the extracted slope of the coherent t-distribution *i.e.* $d\sigma/dt \propto \exp(-B_D|t|)$

✳ $r_{proton} = \sqrt{2(B_{qc} + B_q)} = 0.56\ fm$

✳ *Transverse size of proton fixed for all energies*

✳ *Experimentally the transverse width increases at high energies*

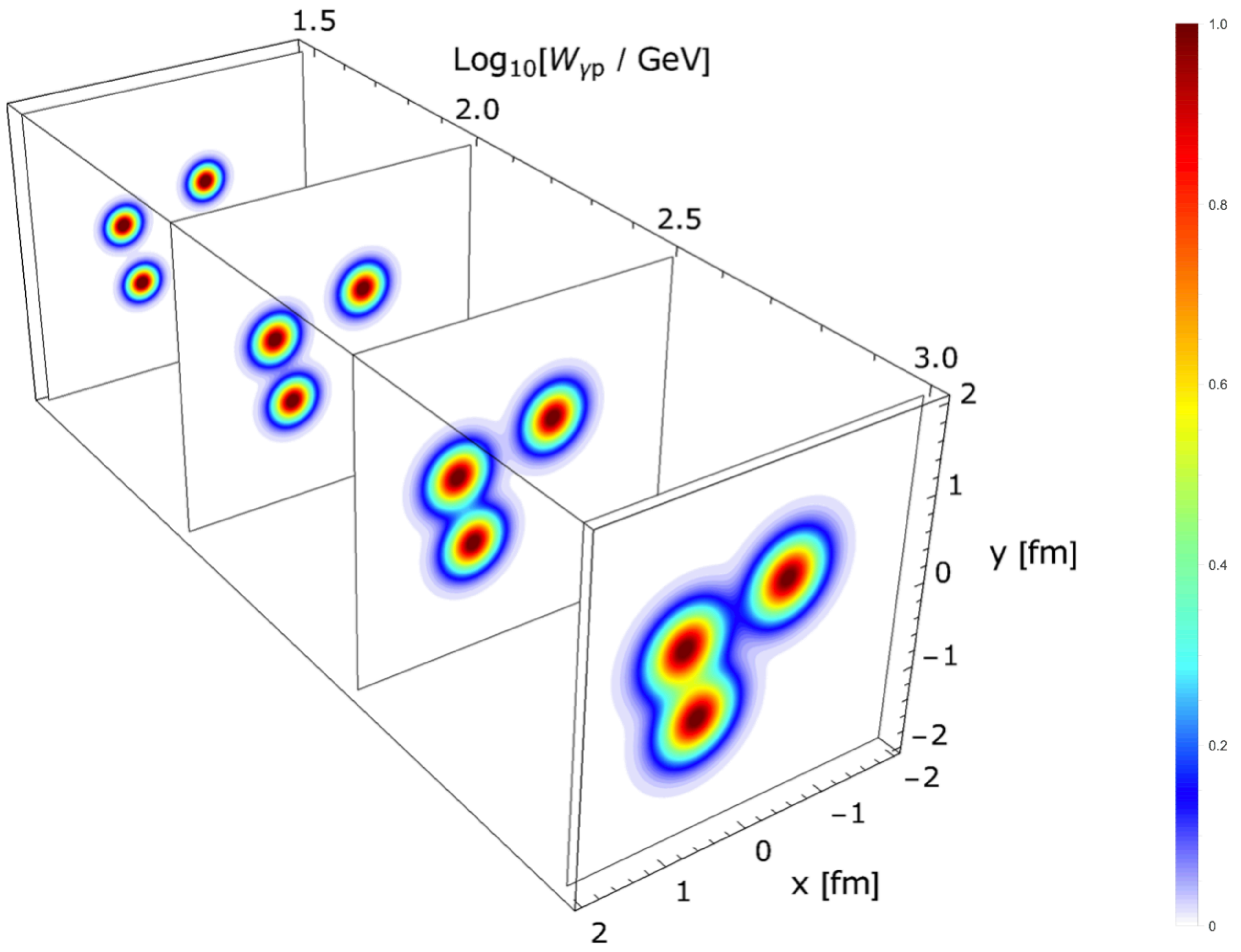
✳ *Tensions between H1& ZEUS data*

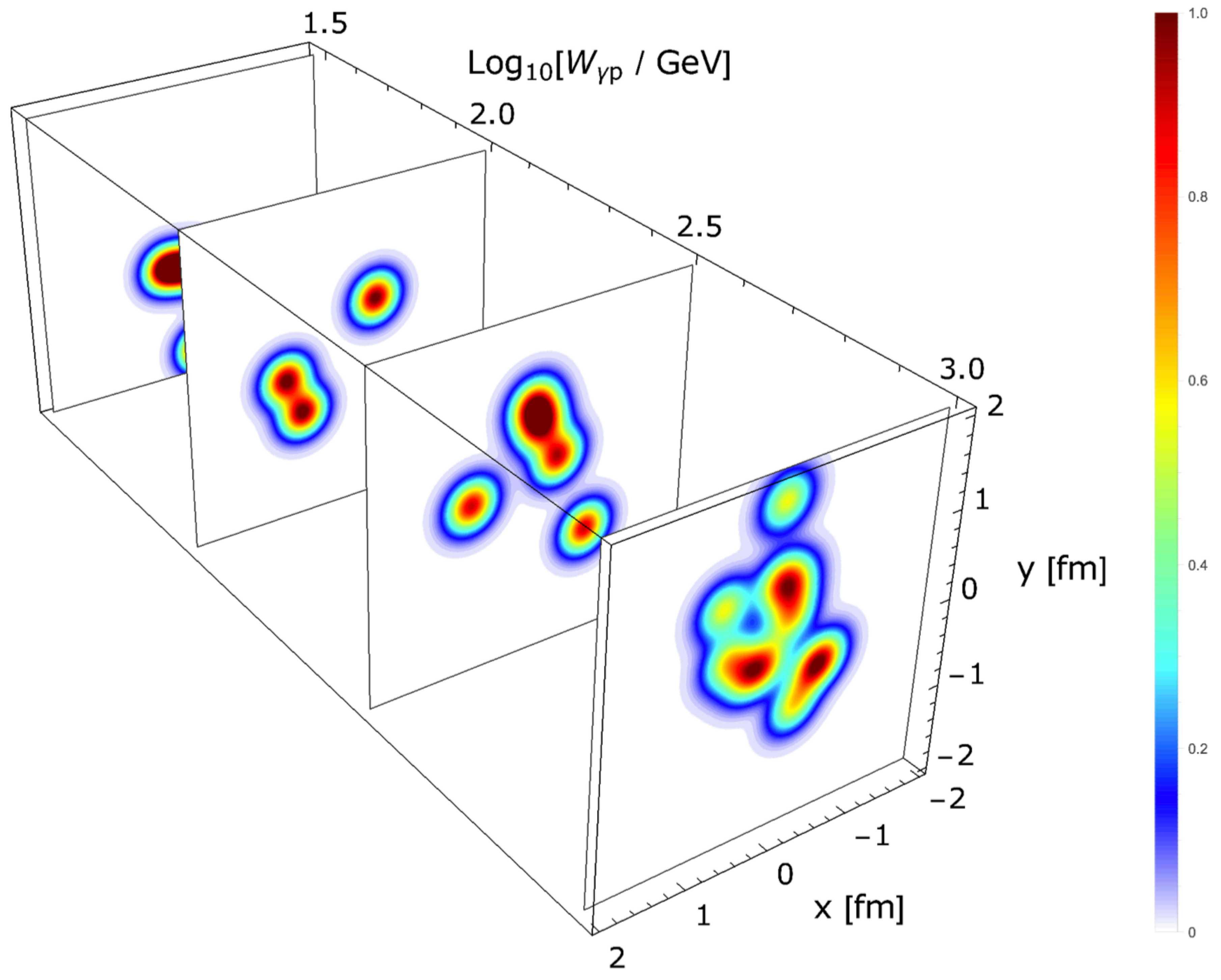
★ *Shrinkage of diffraction peak at high energies and fluctuations too expected to evolve with energy*

★ *Include evolution effects in the profile function i.e* $T_p(\mathbf{b}) \rightarrow T_p(x, \mathbf{b})$ A.K.,Tobias Toll PRD 105 (2022) 114011

INCORPORATING THE ENERGY DEPENDENCE

The profile function becomes : $T_p(\mathbf{b}) \rightarrow \frac{1}{N_q}\sum_{i=1}^{N_q} T_q(x, \mathbf{b} - \mathbf{b_i})$ *and* $r_{proton} = \sqrt{2(B_{qc} + B_q(x))}$ A.K,Tobias Toll PRD 105 (2022) 114011





Varying hotspot width (VHW) model: $B_q(x) = B_{q0}\ x^{\lambda_0}$

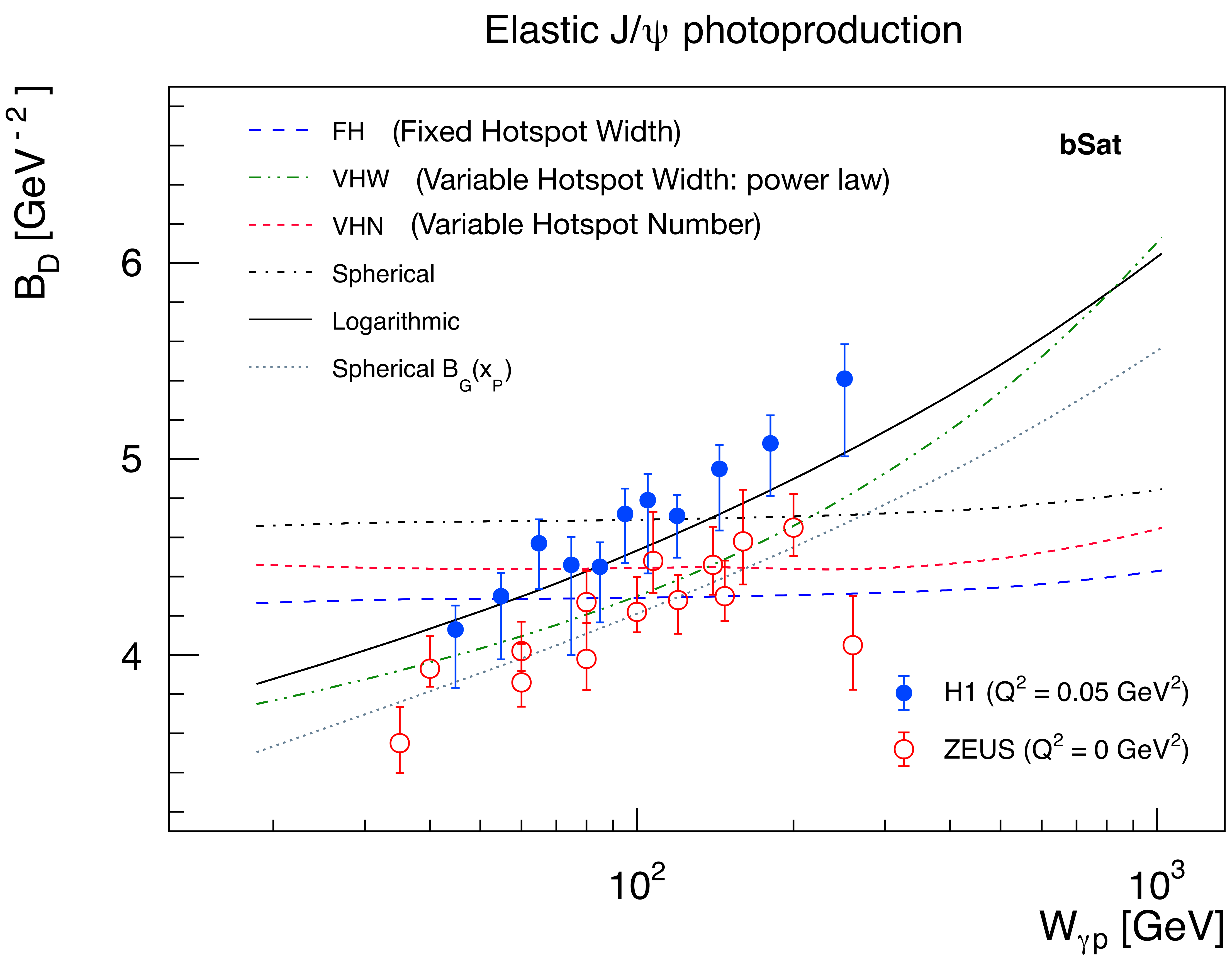
Logarithmic model: $B_q(x) = b_0\ ln^2\left(\frac{x_0}{x}\right)$

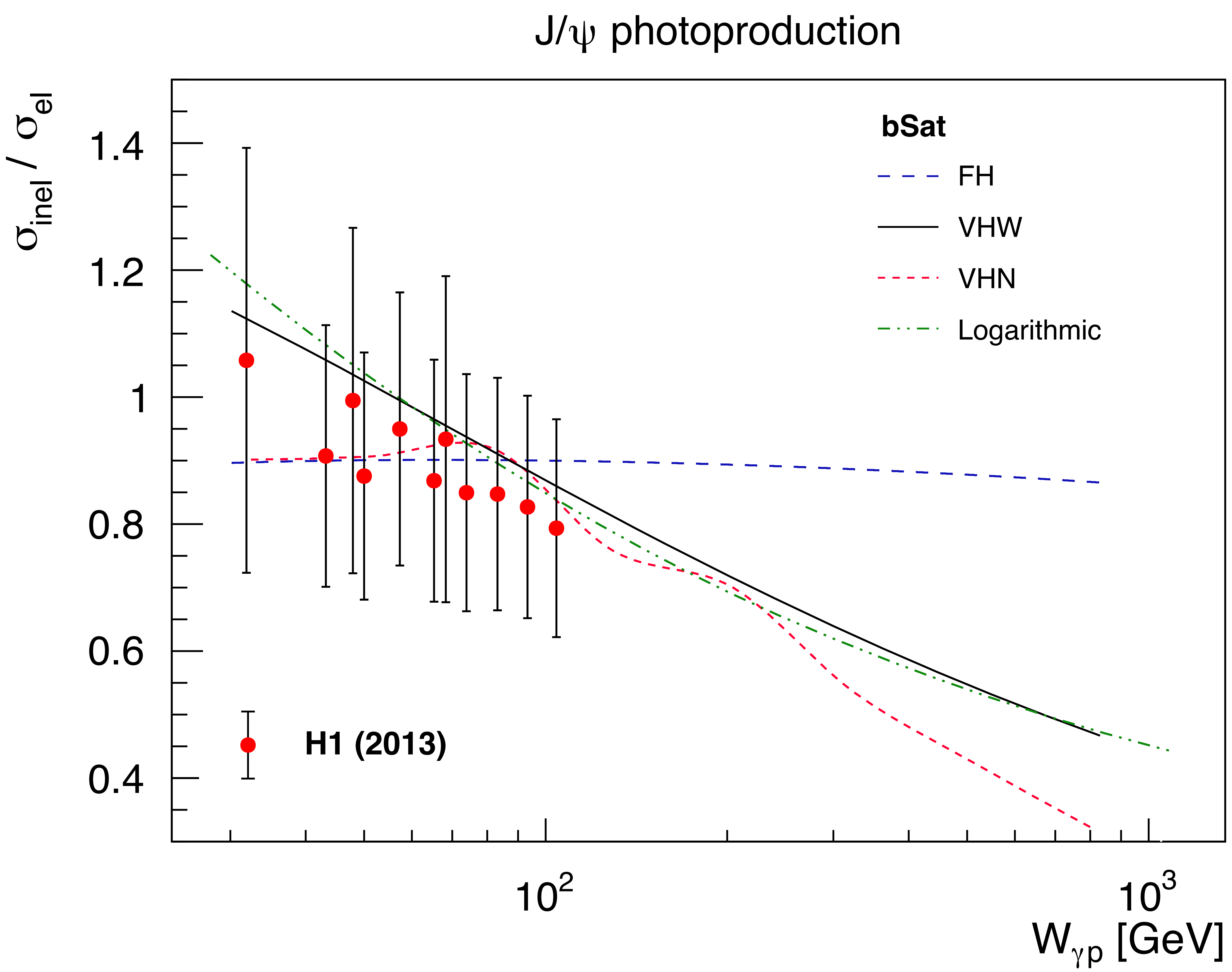
Varying hotspot number (VHN) model: $N_q(x) = p_0\ x^{p_1}(1 + p_2\sqrt{x})$

J. Cepila et al, Phys. Lett. B 766 (2017) 186–191

INCORPORATING THE ENERGY DEPENDENCE

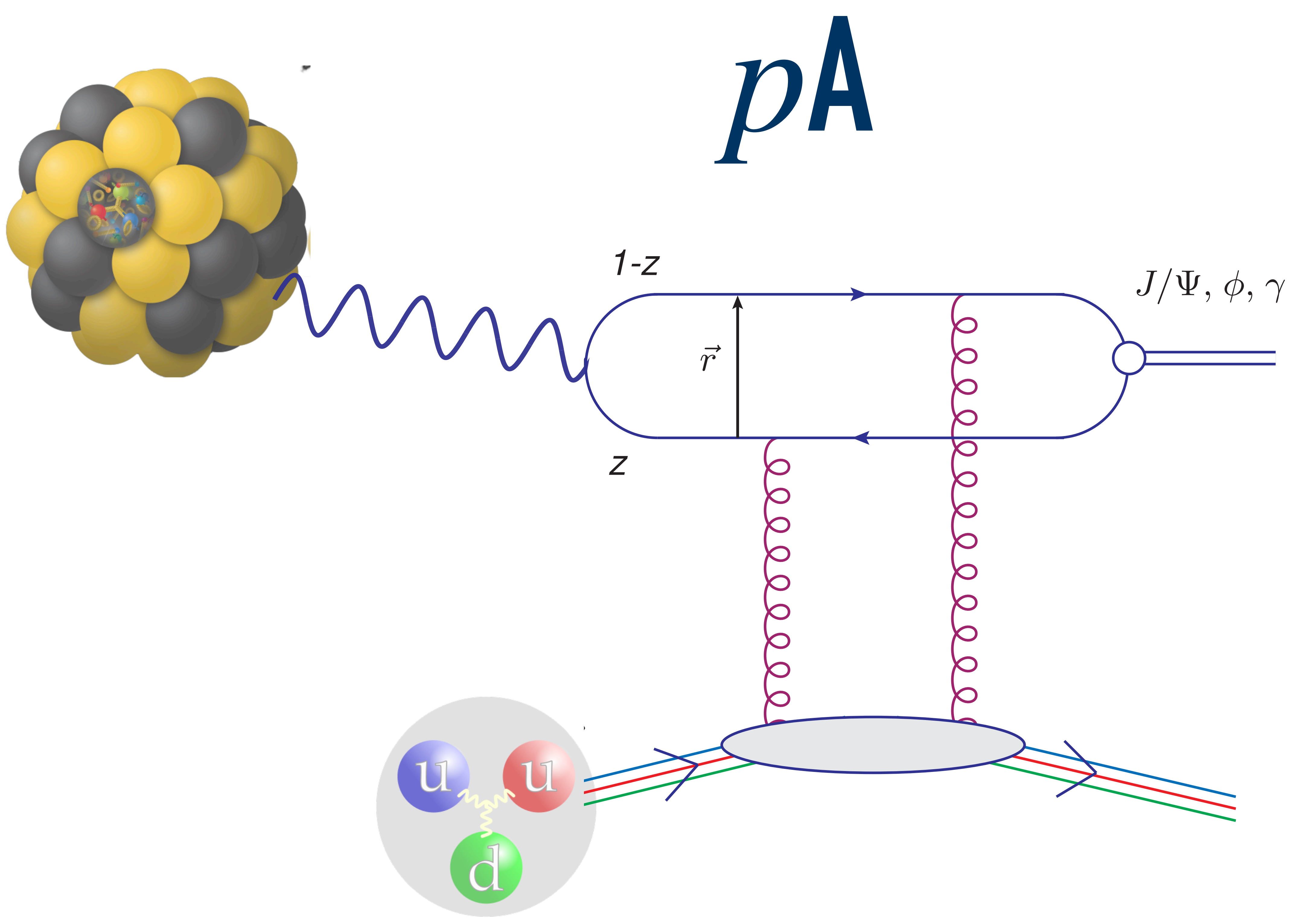
A.K,Tobias Toll PRD 105 (2022) 114011

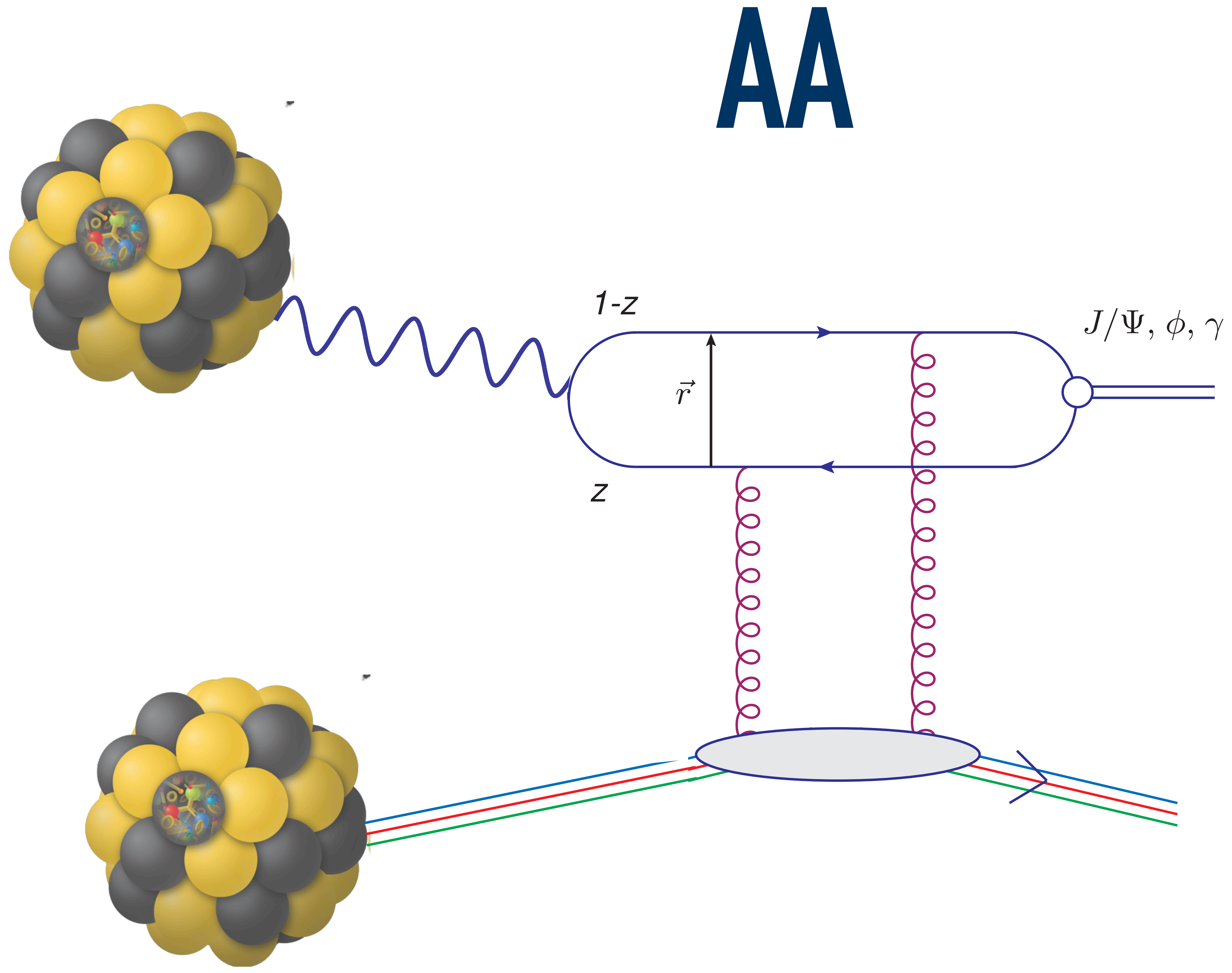




see Mäntysaari, Schenke 1806.06783 for similar predictions in IP-GLASMA framework

ULTRA PERIPHERAL COLLISIONS (UPCs) AS PROBE OF PARTONIC STRUCTURE

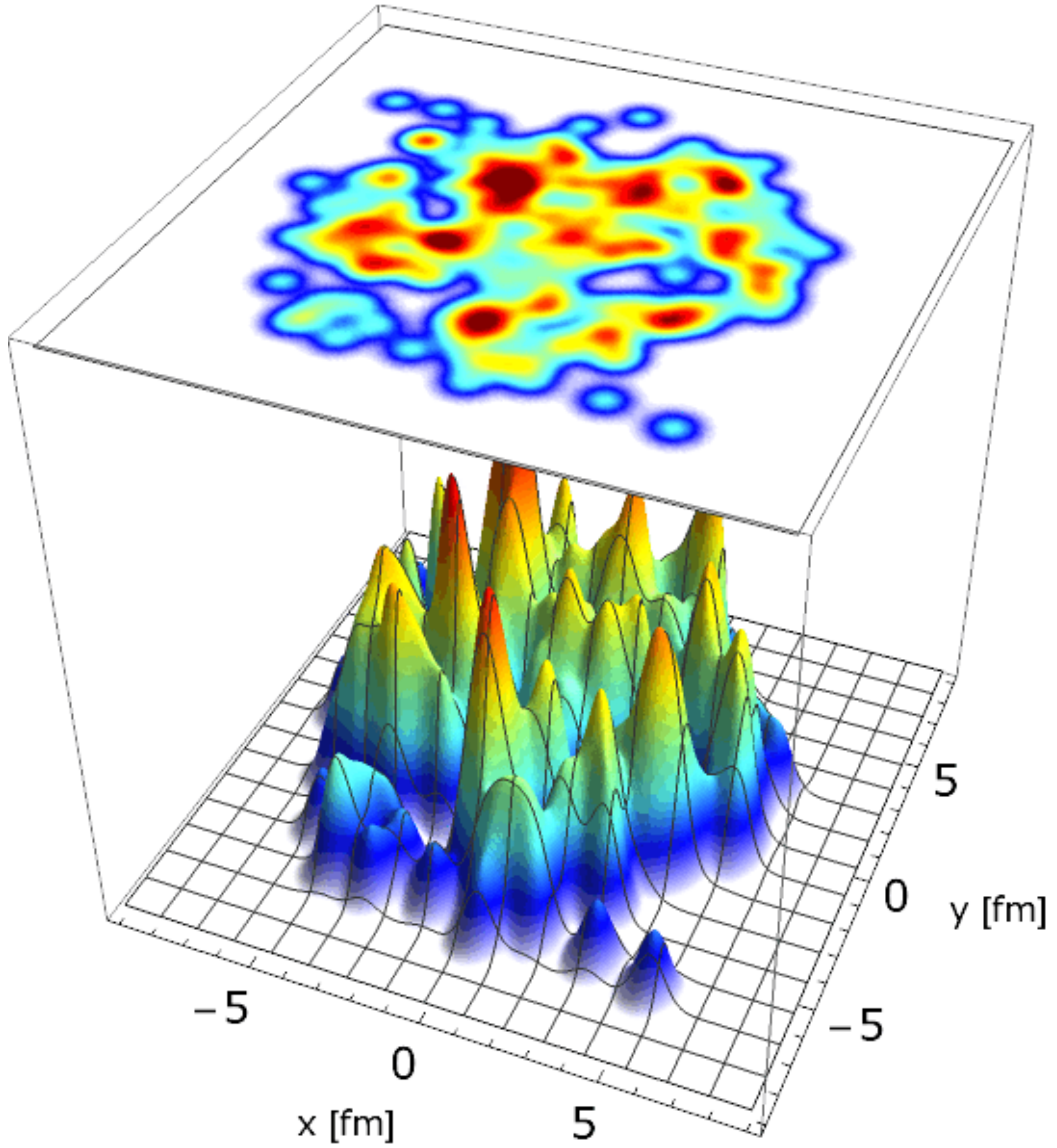


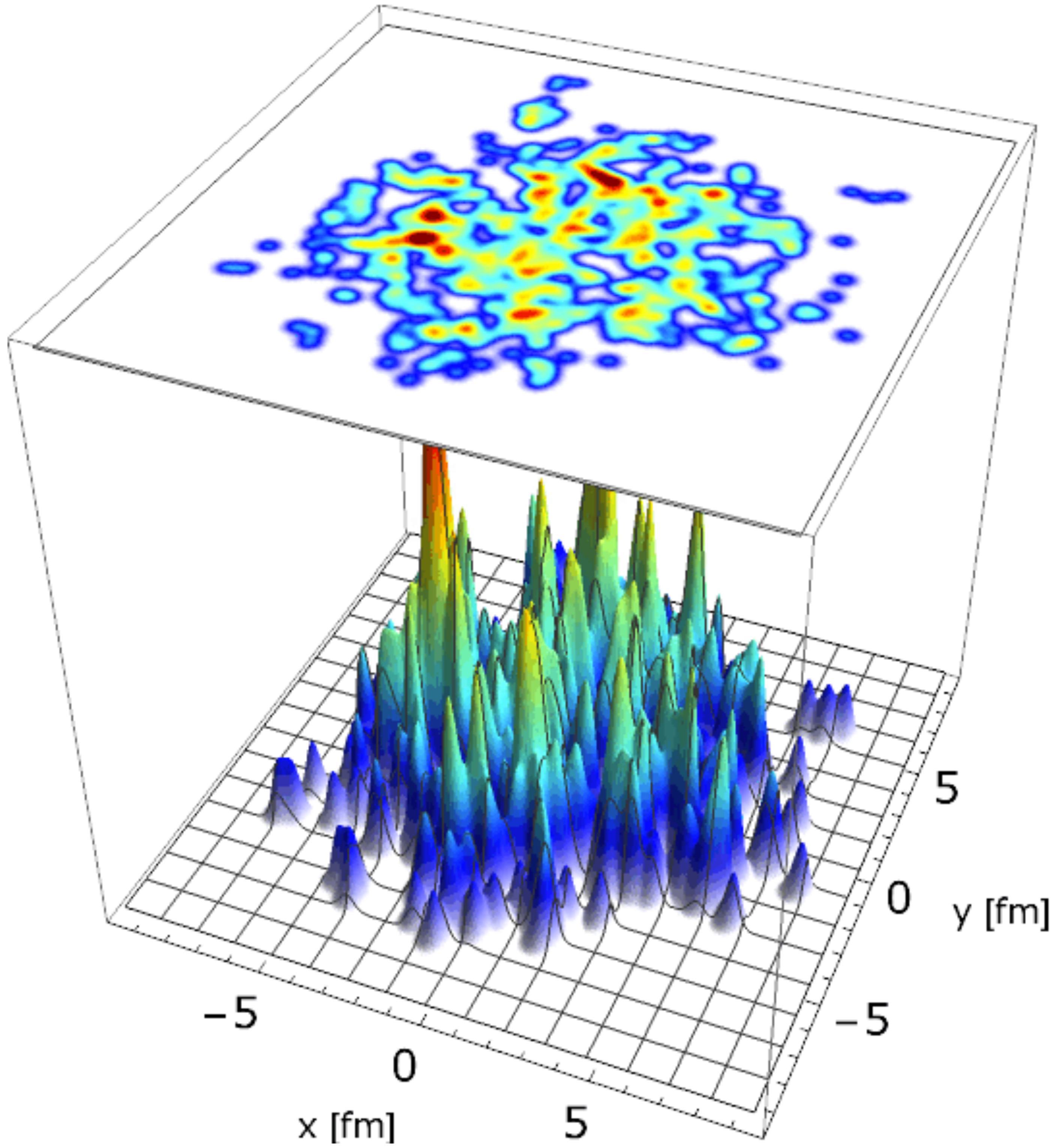


- *Photons in UPCs ($b \gg R_A + R_B$) are probes of nucleus and proton partonic structure and strong interaction dynamics in small-x QCD.*
- *Good test of our models and complementary physics at LHC and RHIC before EIC starts taking data.*

nucleus cartoon from https://www.bnl.gov/eic/

DIFFRACTIVE J/ψ PRODUCTION IN ULTRA PERIPHERAL COLLISIONS

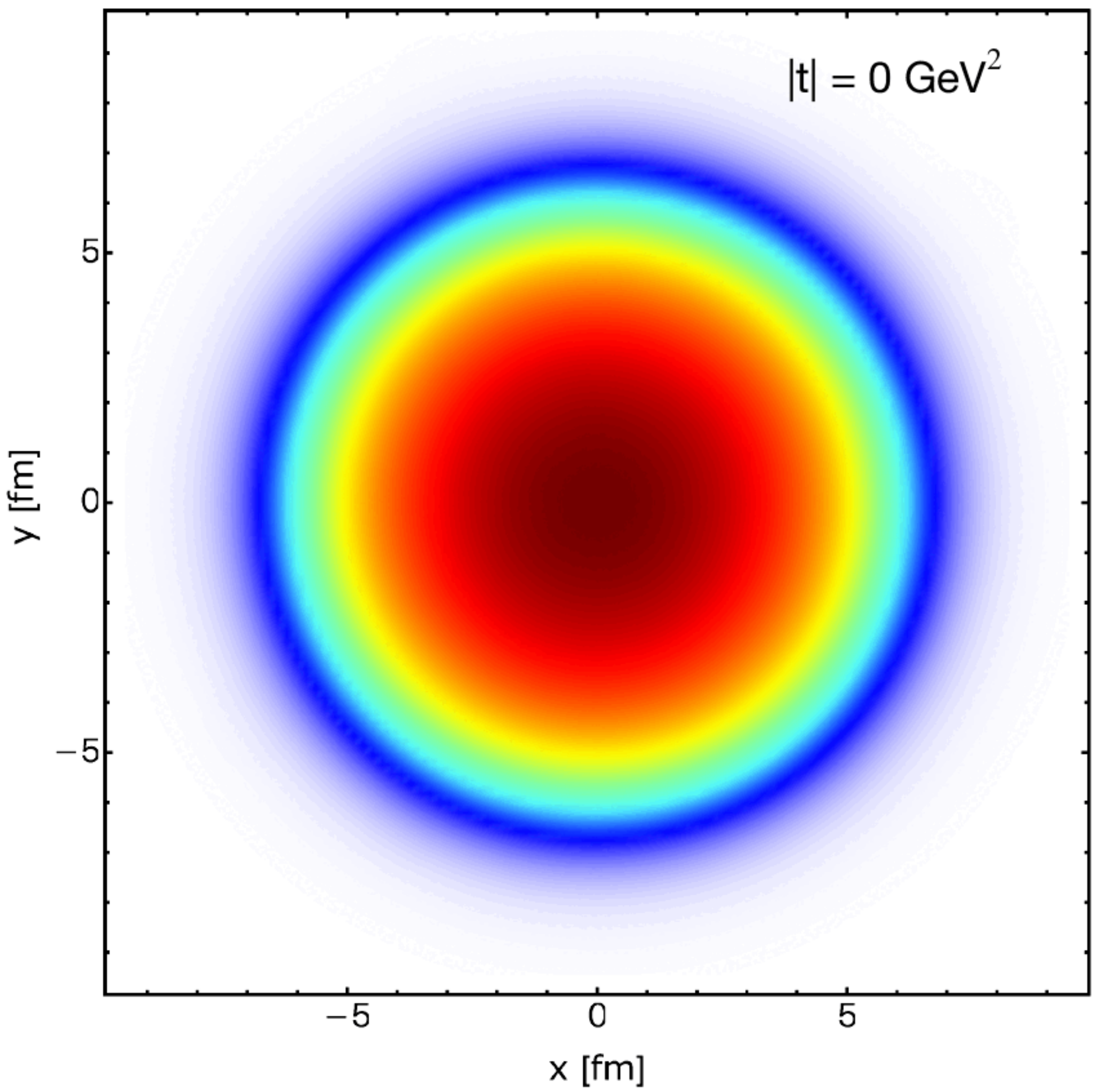




$$T_A(b) \to \sum_{i=1}^{A} T_p(b - b_i)$$

$$T_A(b) \to \frac{1}{N_q} \sum_{i=1}^{A} \sum_{j=1}^{N_q} T_q(b - b_i - b_j)$$

DIFFRACTIVE V.M PRODUCTION AT EIC



- Incoherent events are by themselves interesting (not just background)
  - *Different $|t|$ regions of the spectrum sensitive to different sizes*
    - *For $0.02 \leq |t| \leq 0.2$ GeV^2 probes the shape and size of nucleons*
    - *For $|t| > 0.2$ GeV^2 probes the substructure of nucleons*
  - *Energy dependence of incoherent spectra with differential binning in $|t|$ could tell us about growth of nucleons and evolution of fluctuations*
  - *Recent results from Mantysaari, et al. show different regions of spectrum to be sensitive to different kinds of shape deformations e.g Uranium*

H.Mantysaari,B.Schenke, C.Shen,W.Zhao arXiv:2303.04866

- Coherent cross-section sensitive to average geometry
  - *Steepness and the position of first dip depends on density profile, non-linear effects and correlations* H.Mantysaari,B.Schenke PRC 101 (2020) 015203
  - *Geometry evolution → Black disc limit?*
  - *Deviation of WS wave function parameters at small-x? Larger radius?*

H.Mantysaari, F.Salazar, B.Schenke, arXiv:2207.03712

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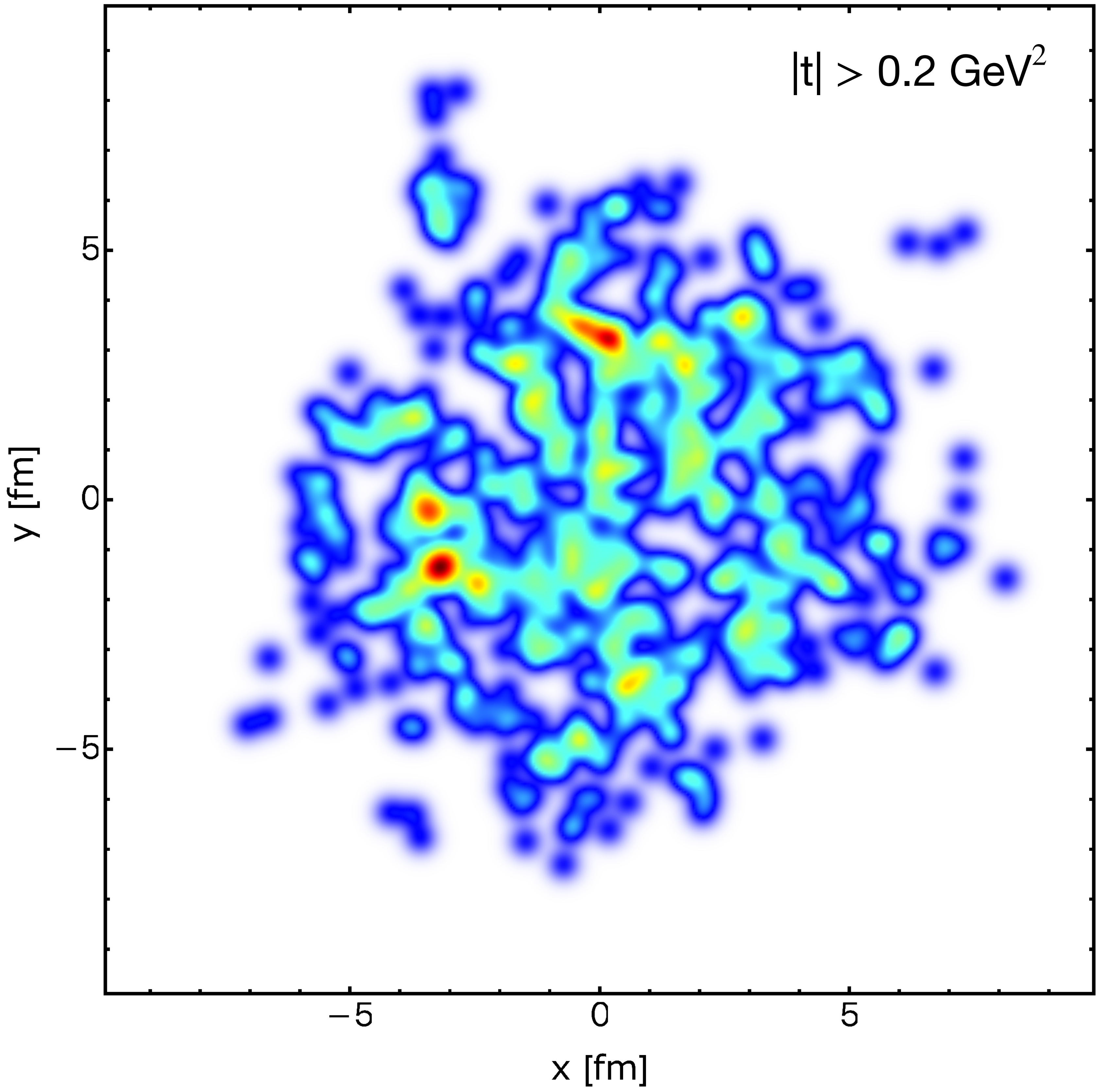

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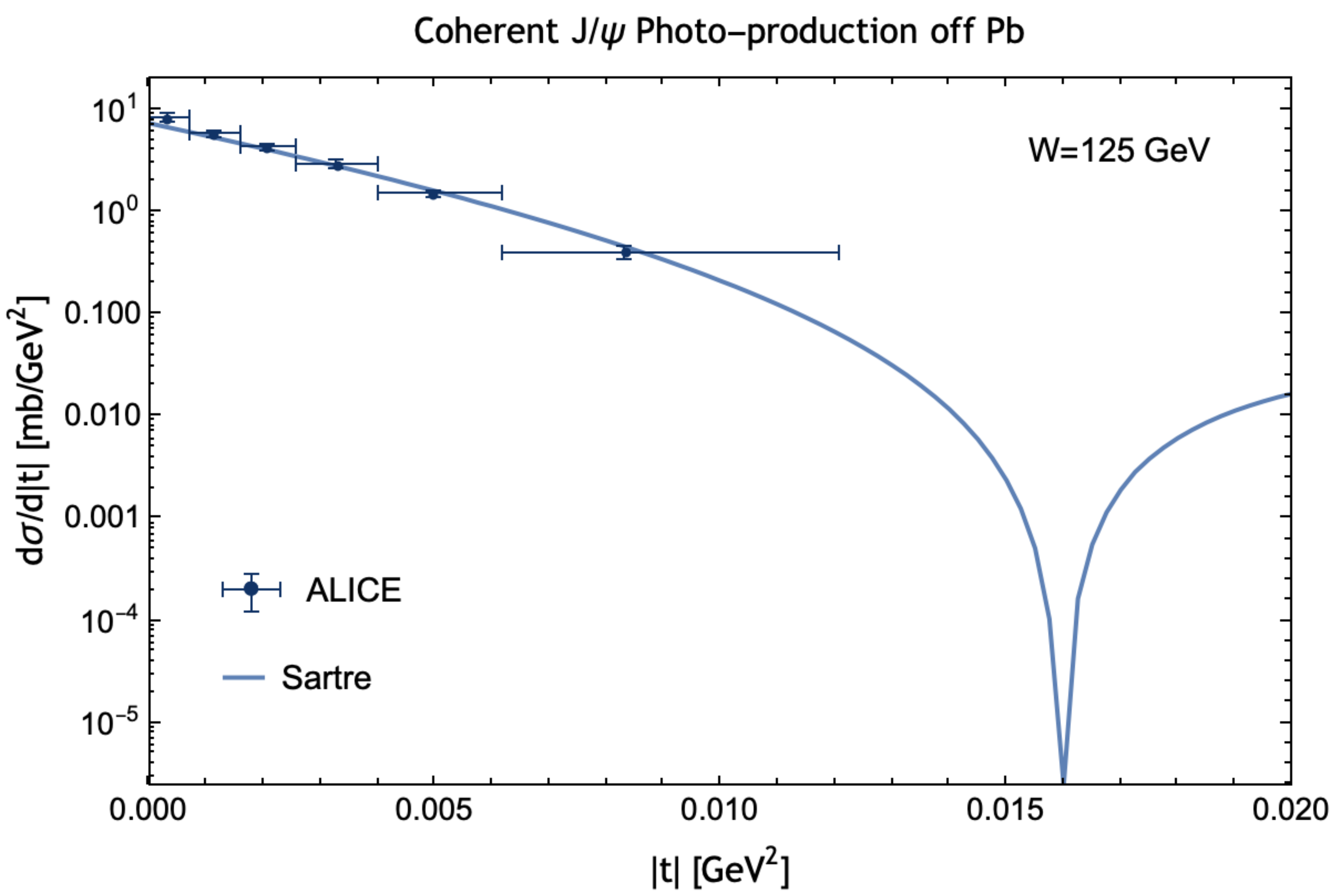
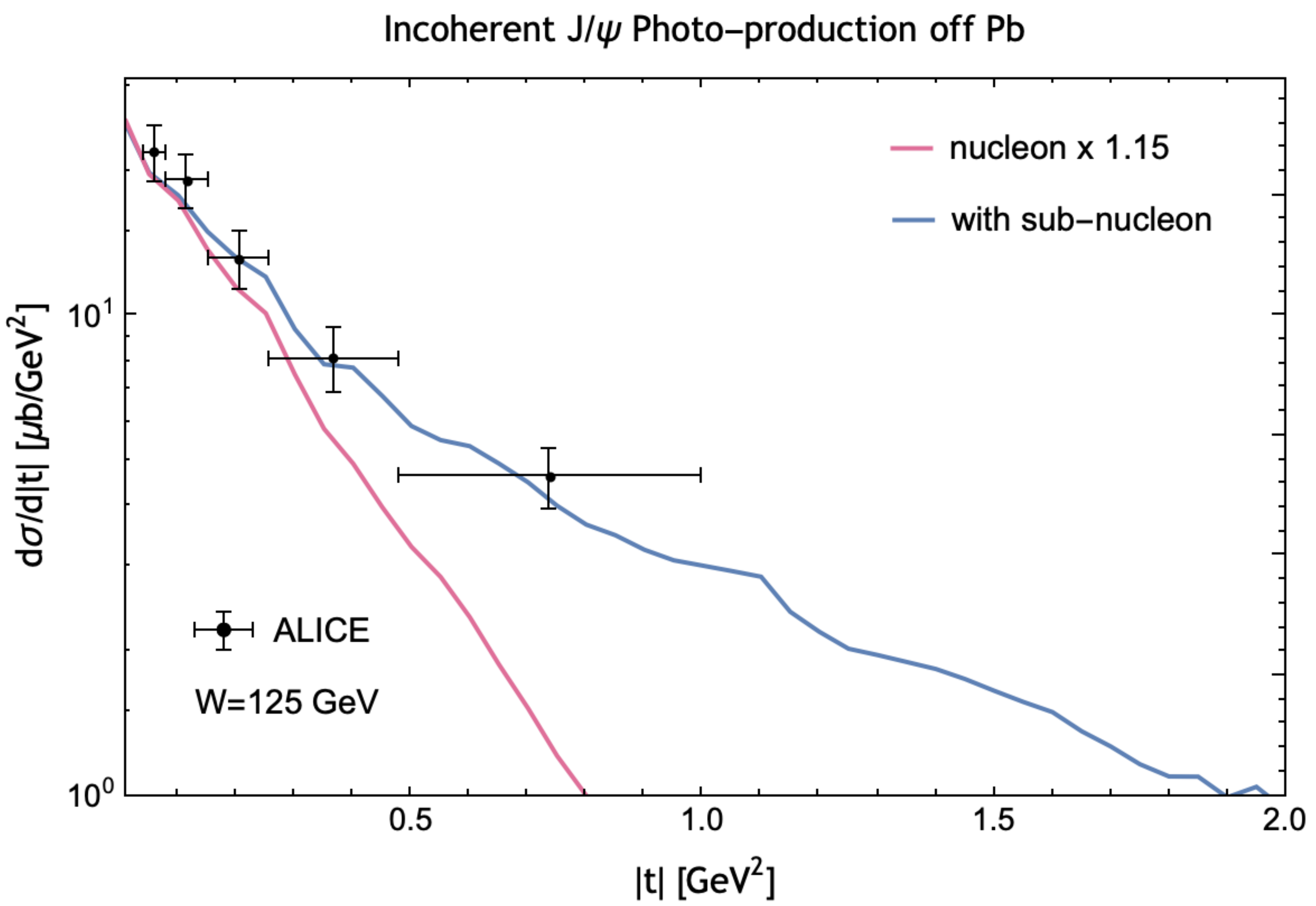
Growth of size of nucleons in Sar*t*re for accurate predictions of the |t| spectrum and the t-integrated observables in vector meson production

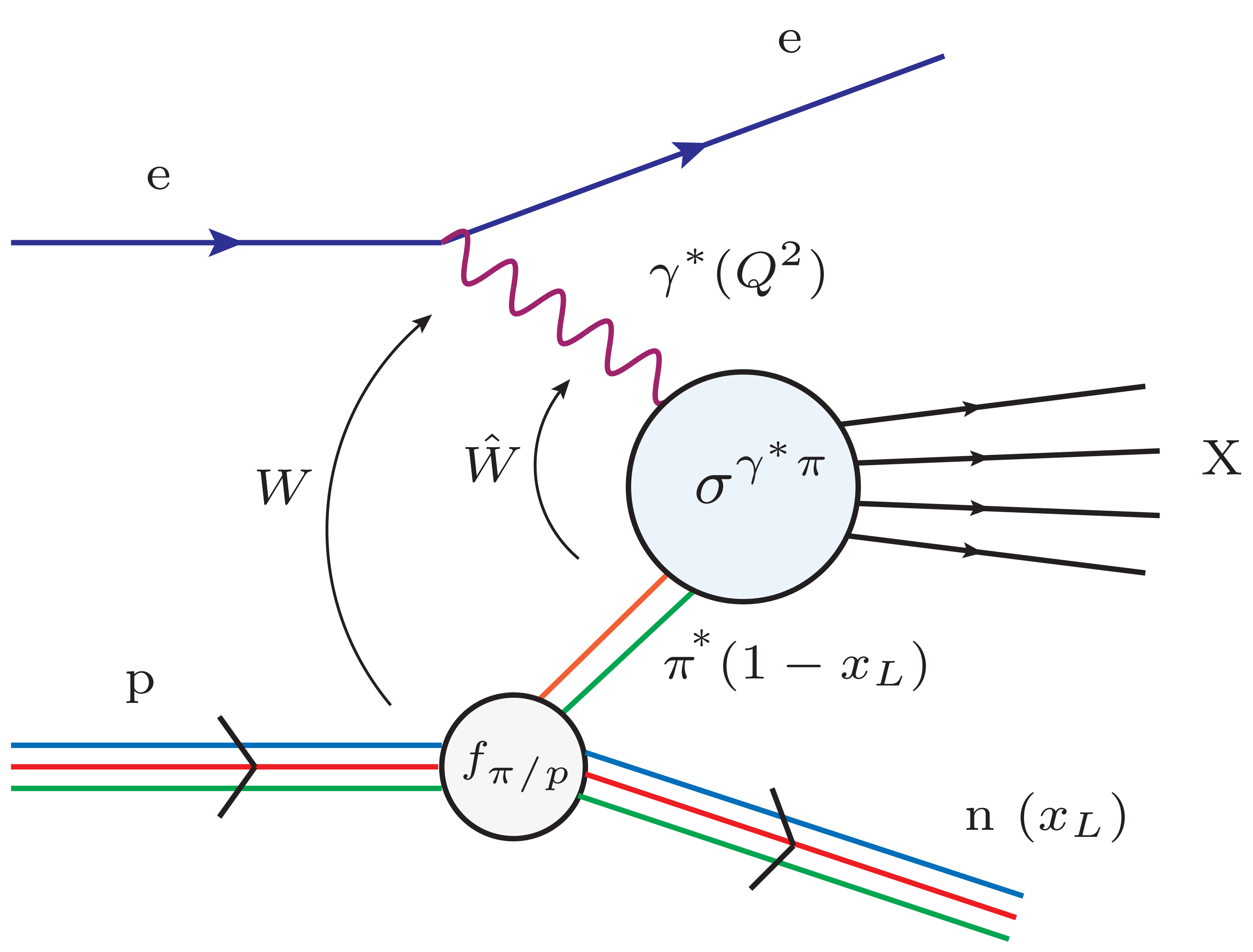
DIFFRACTIVE J/ψ PRODUCTION IN ULTRA PERIPHERAL COLLISIONS

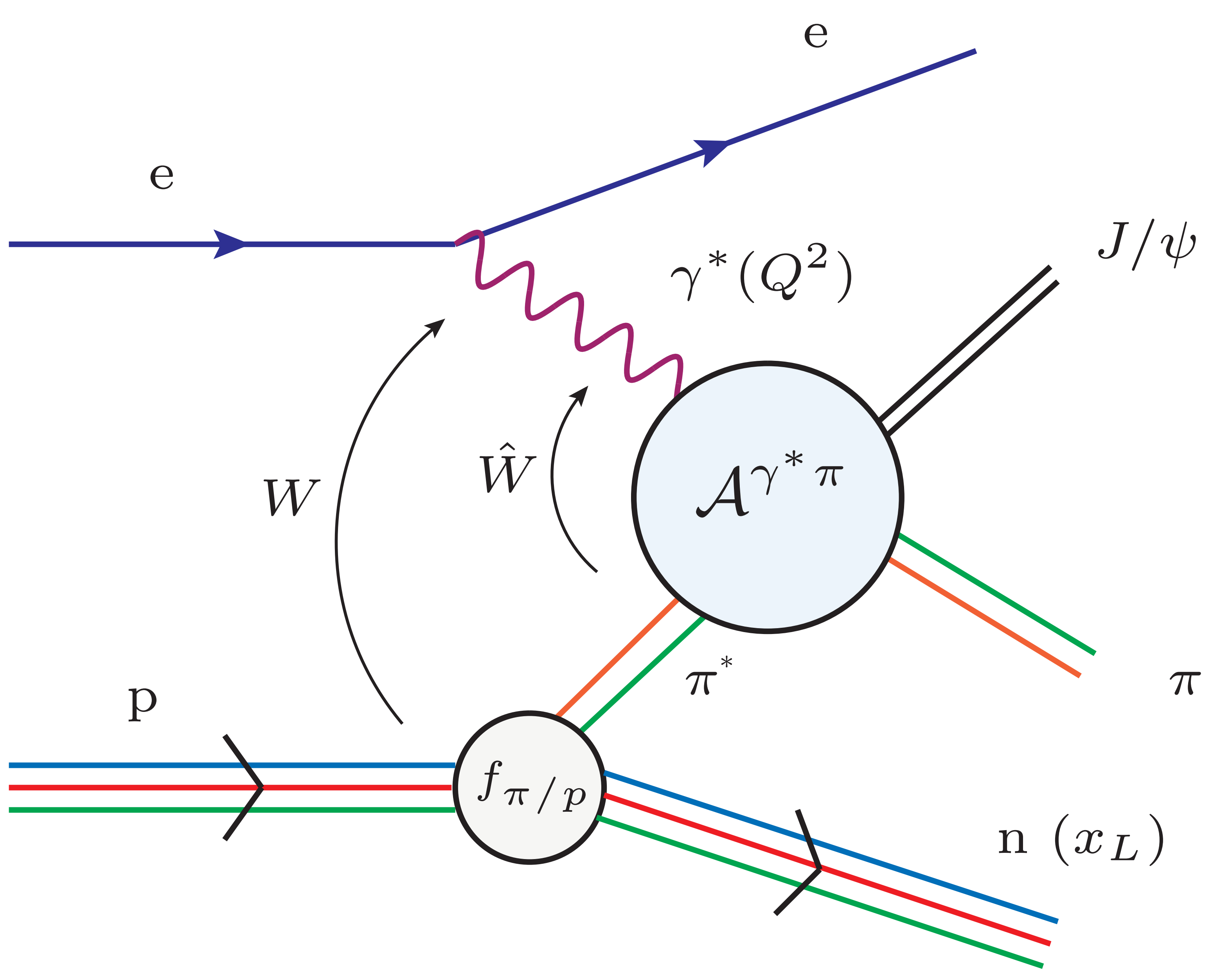




PART II – TAGGED DIS EVENTS AT SMALL-X

PION STRUCTURE IN LEADING NEUTRON EVENTS





Effective inclusive DIS on pion ($e + p \to e' + X + n$)

★ *Measure only scattered electrons and neutron*

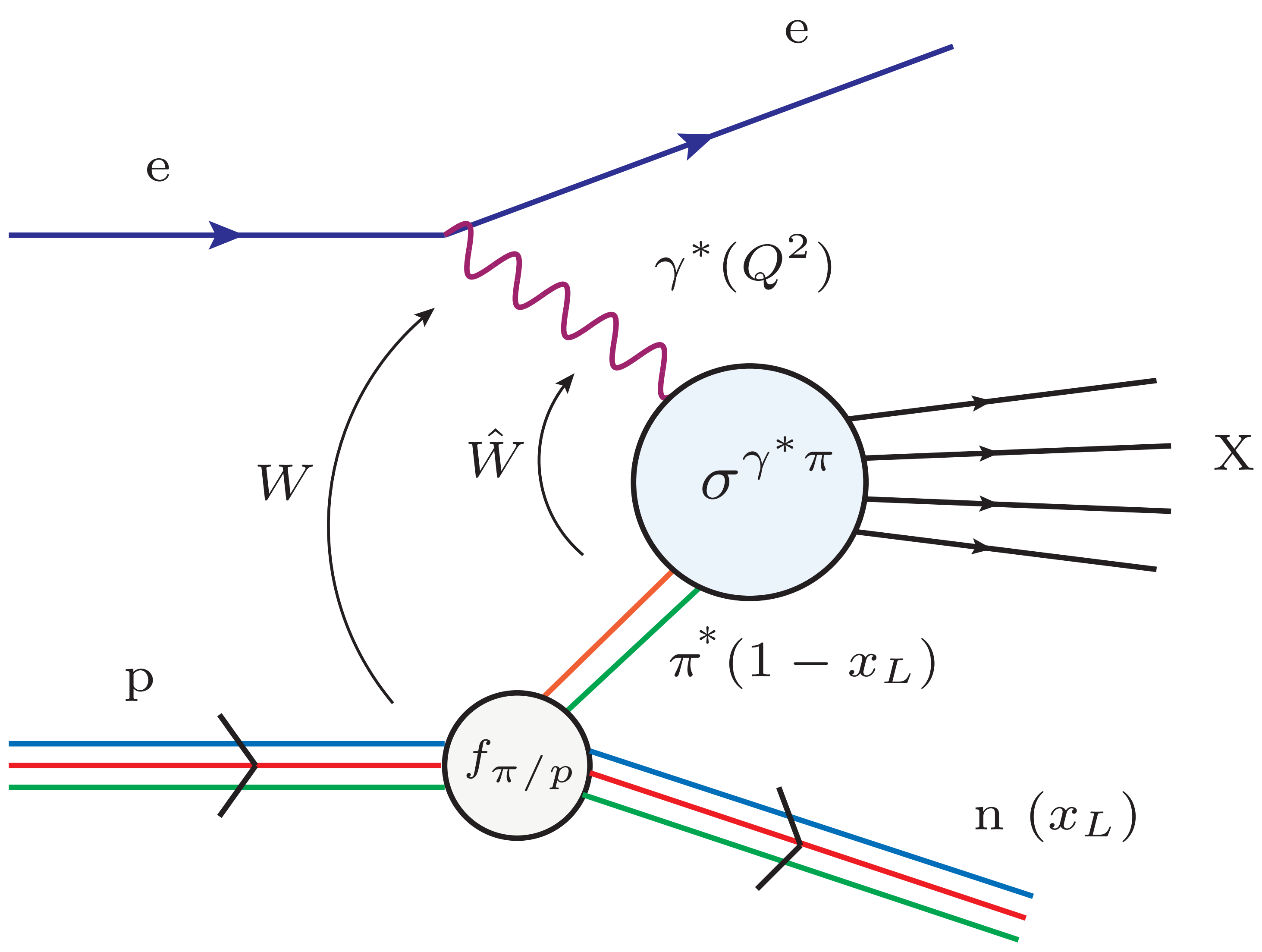
★ *Sensitive to longitudinal structure of pion*

Exclusive J/ψ *production* ($e + p \to e' + J/\psi + \pi + n$)

★ *Measure all the final state particles*

★ *Sensitive to spatial gluon distribution of pion*

PION STRUCTURE IN LEADING NEUTRON EVENTS



- We use the following flux factor:

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

where the form factor is given by:

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

- ❖ Leading neutron structure function in terms of $\gamma^* p$ cross section:

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

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

PION STRUCTURE IN LEADING NEUTRON EVENTS

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

❖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

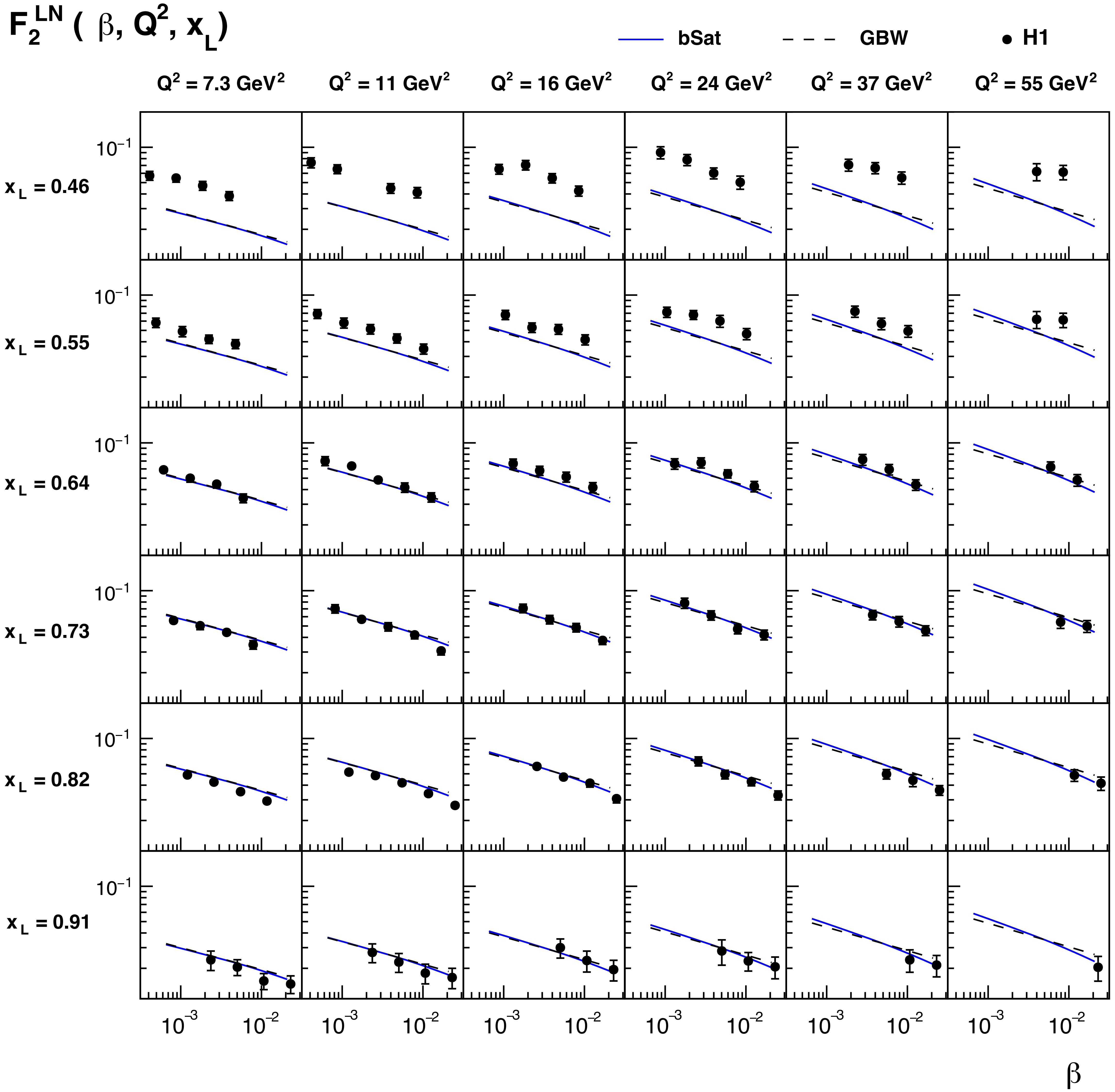
$$\frac{d\sigma_{q\bar{q}}^{(\pi)}}{d^2\mathbf{b}}(\mathbf{b},\mathbf{r},\beta) = R_q \frac{d\sigma_{q\bar{q}}^{(p)}}{d^2\mathbf{b}}(\mathbf{b},\mathbf{r},\beta)$$

R_q 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.

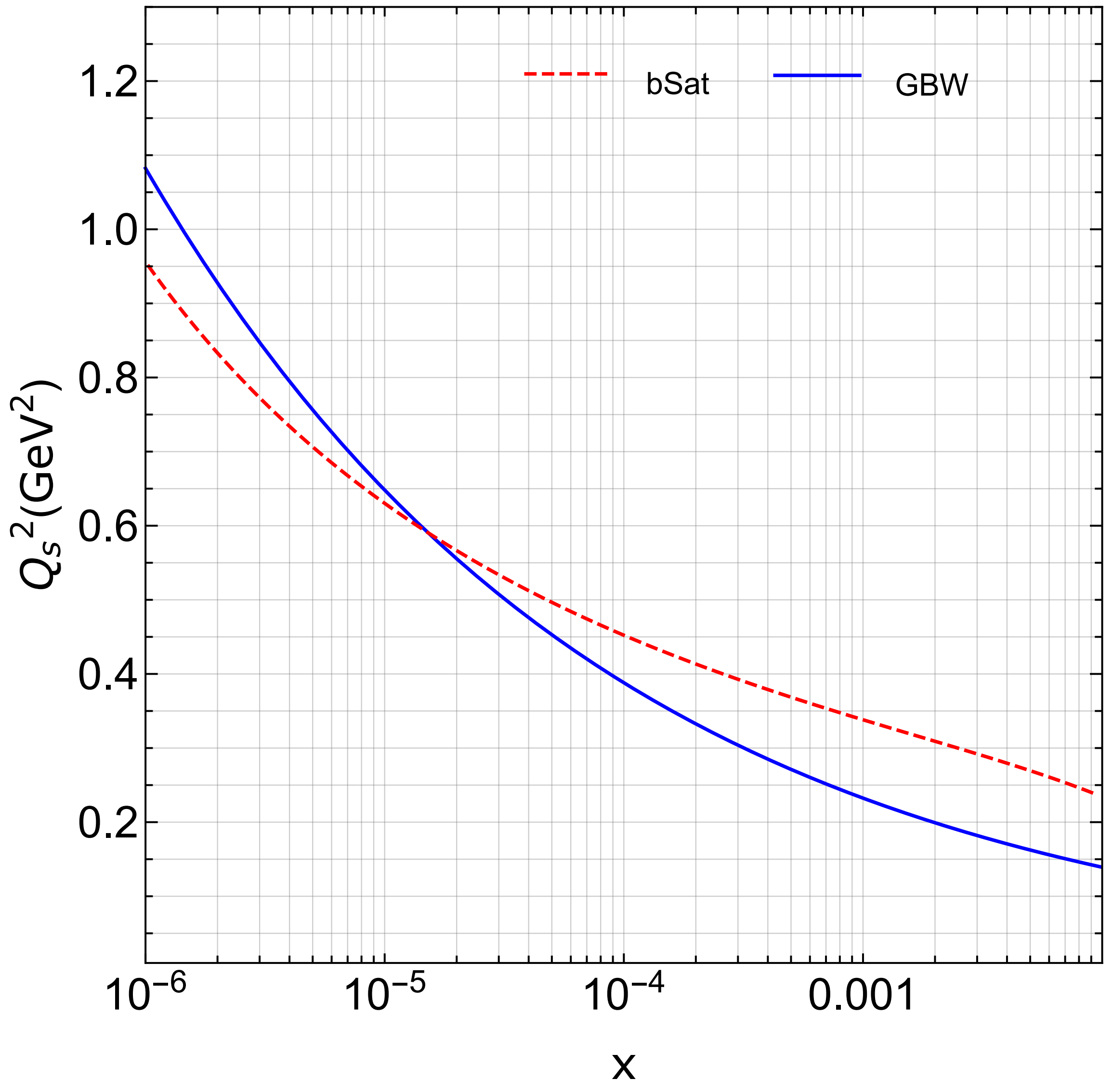
- Energy Dependence of dipole-pion and dipole-proton cross section is identical
- In constituent quark picture, R_q is ratio of number quarks in pion and proton i.e $R_q = 2/3$

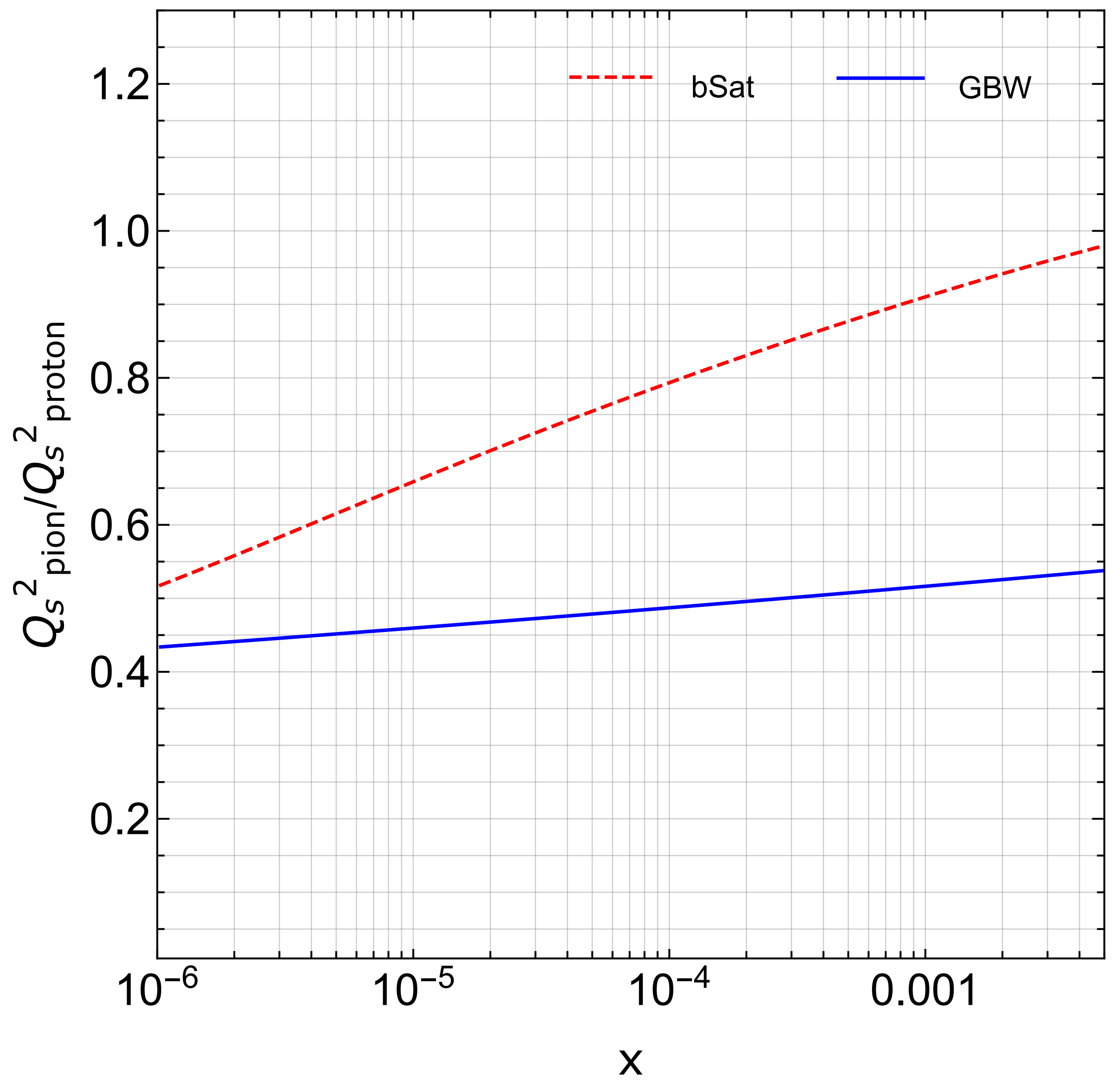
❖ We employ both the approaches and test the universality of pion and proton structure at small-x

LEADING NEUTRON STRUCTURE FUNCTION



A.K PRD 107 (2023) 034005

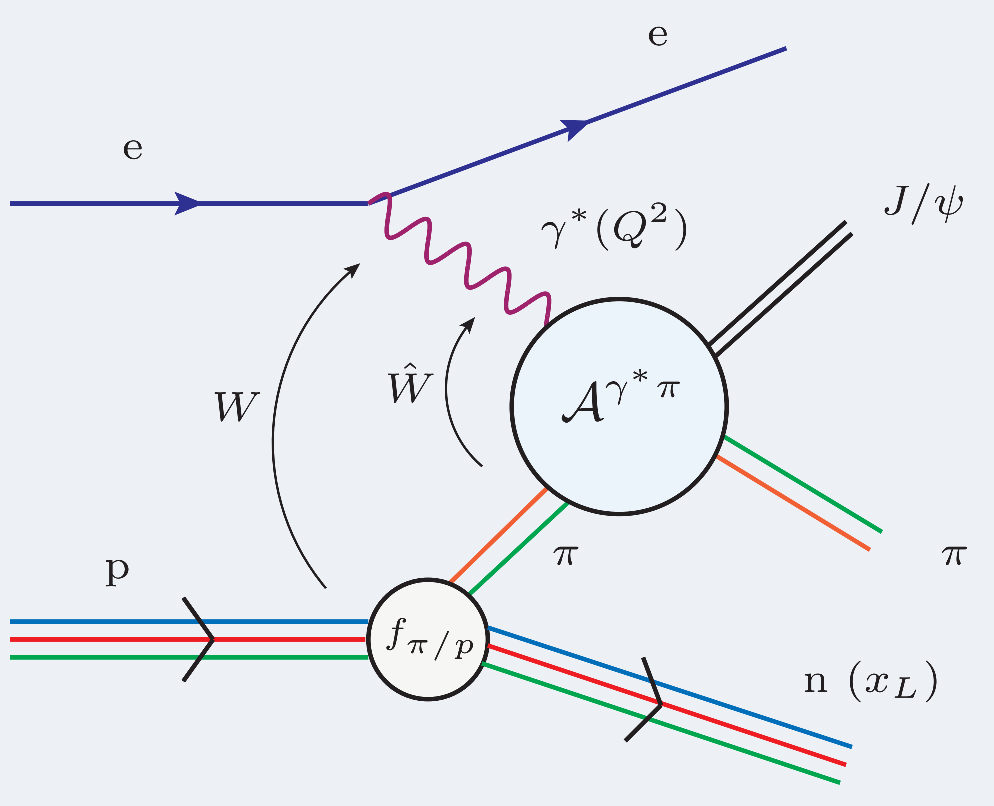


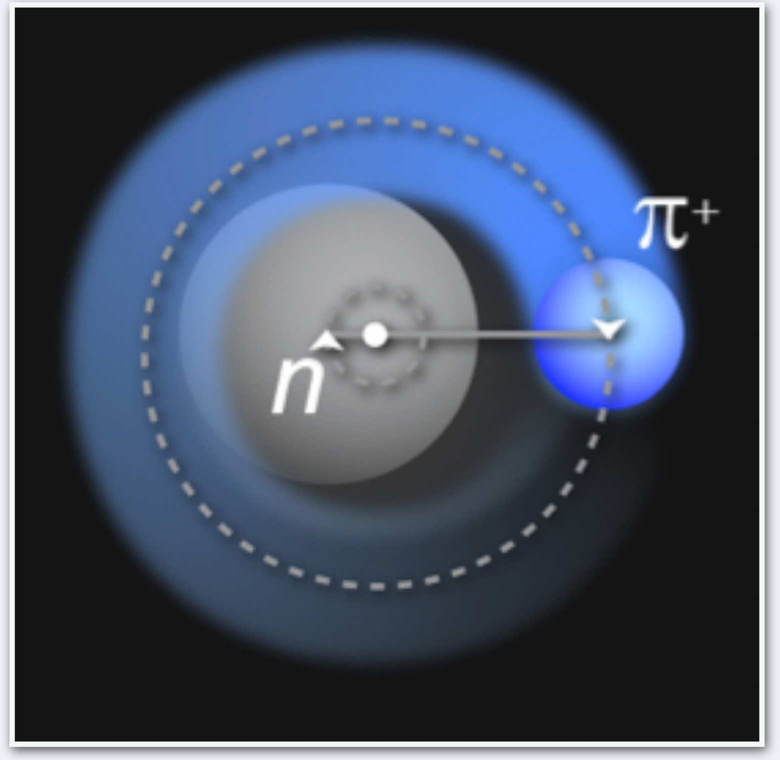


GBW	σ_0 [mb]	λ	$x_0/10^{-4}$	R_q	$\chi^2/N_{\rm dof}$
Fit 1	17.171 ± 2.777	0.223 ± 0.018	0.036 ± 0.024	...	$63.26/48 = 1.32$
Fit 2	27.43	0.248	0.40	0.438 ± 0.005	$64.52/50 = 1.29$

bSat	A_g	λ_g	C	R_q	$\chi^2/N_{\rm dof}$
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	$66.19/50 = 1.32$

PROBING THE GLUON DISTRIBUTION





- The transverse profile of the virtual pion is,

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

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:

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

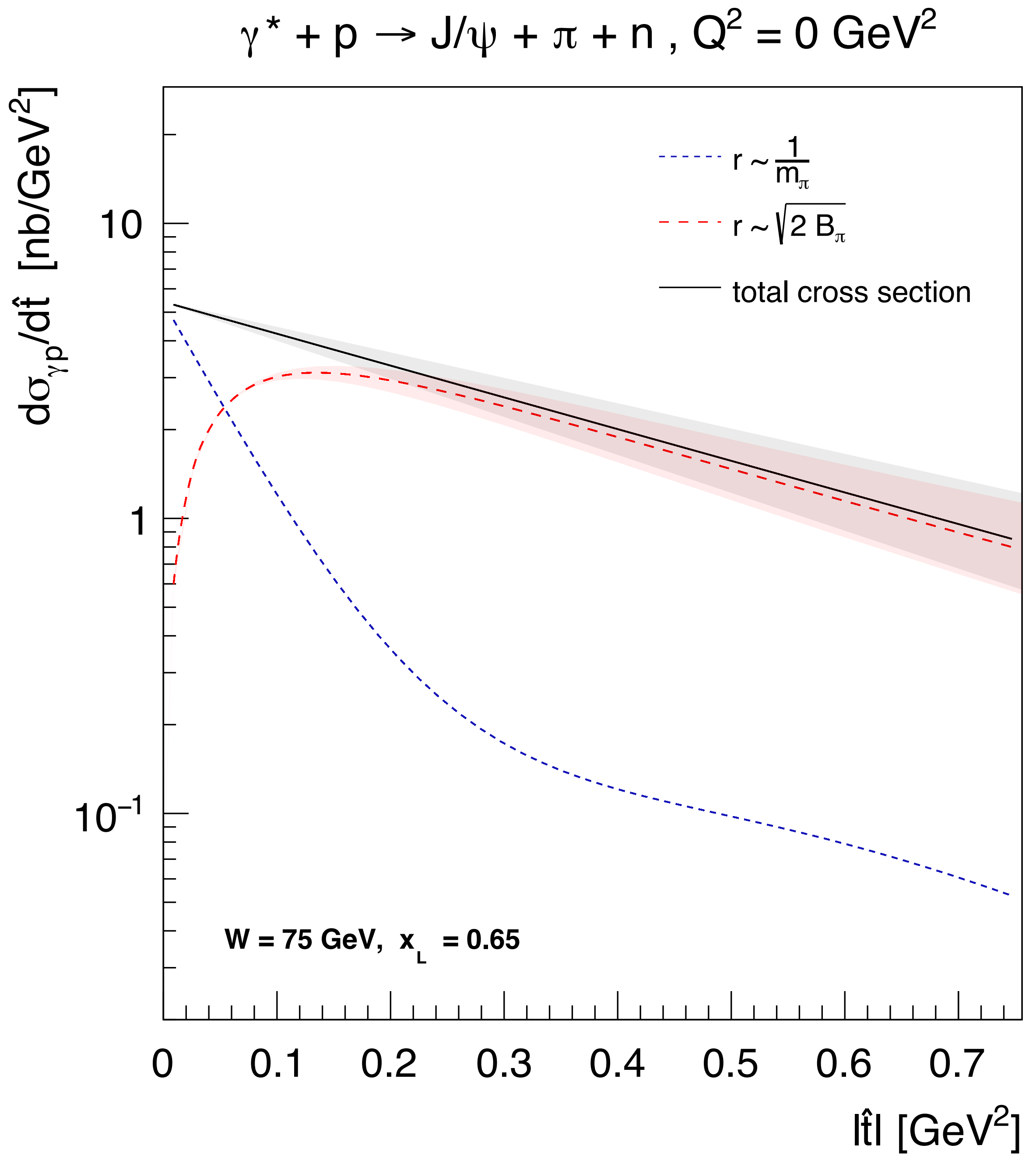
- At small $|t'|$, the dipole cannot resolve the pion and interacts with the whole cloud and on increasing the resolution (*increasing* $|t'|$) the dipole interacts with the pion

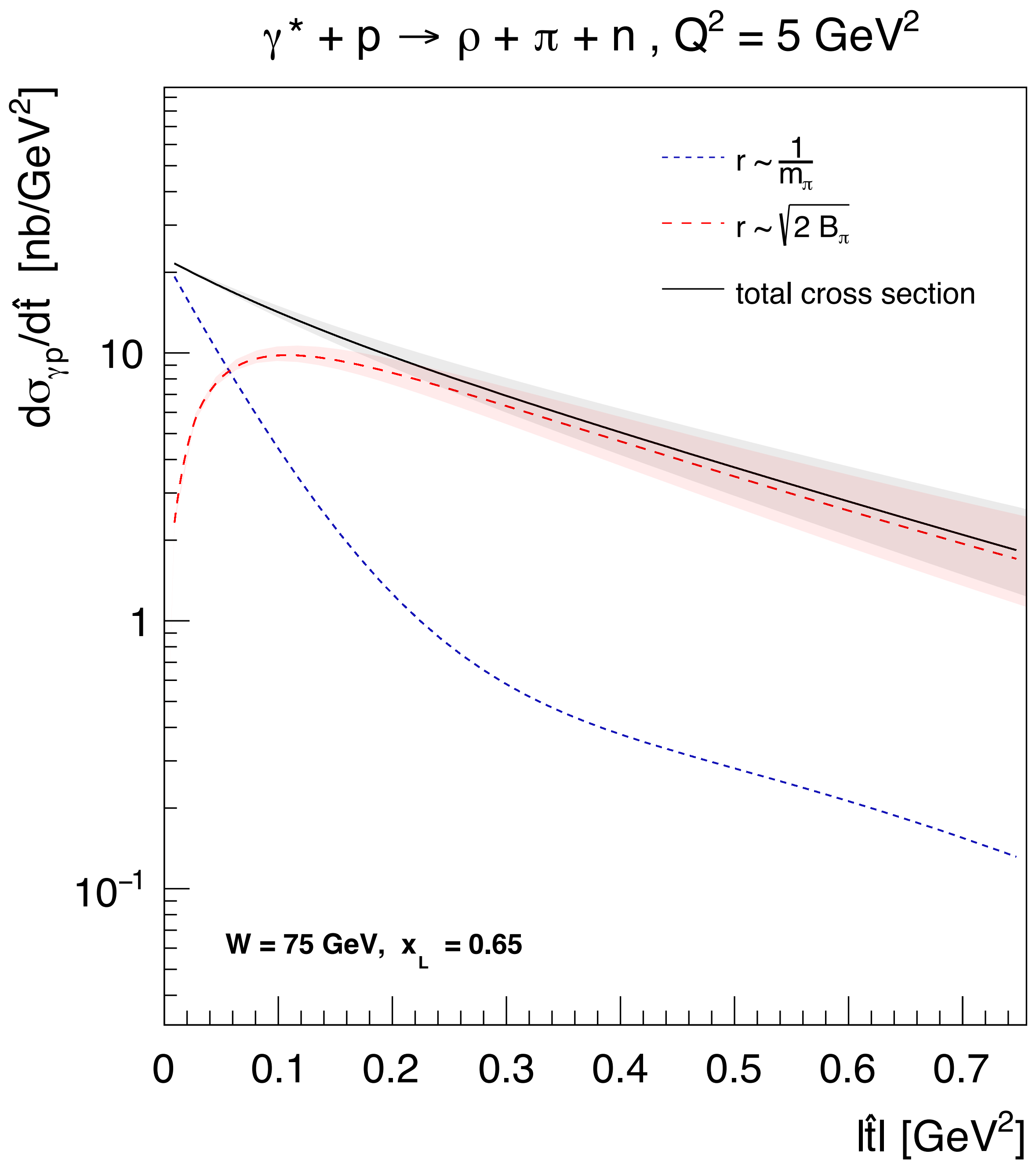
- The transverse position of the pion inside the virtual pion cloud fluctuates event by event

- The cross section have two slopes due to interaction with different size scales at low It'l and moderate It'l

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

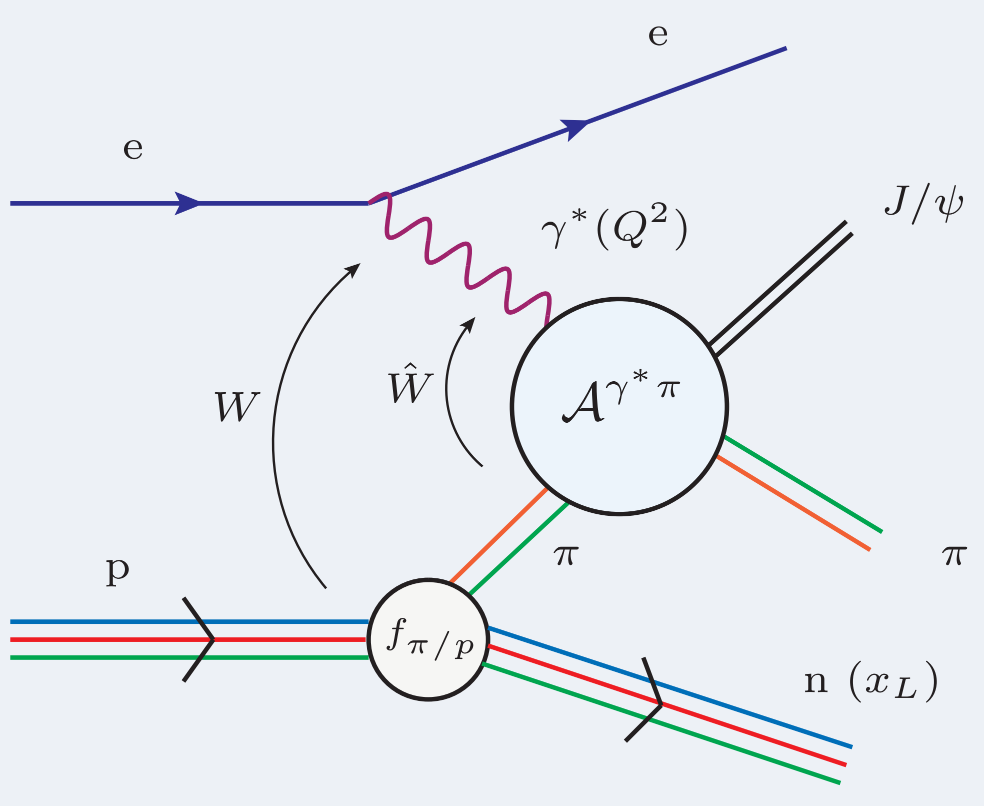
$$\sigma_{tot} \propto |<\mathscr{A}>_\Omega|^2 + (<|\mathscr{A}|^2>_\Omega - |<\mathscr{A}>_\Omega|^2)$$

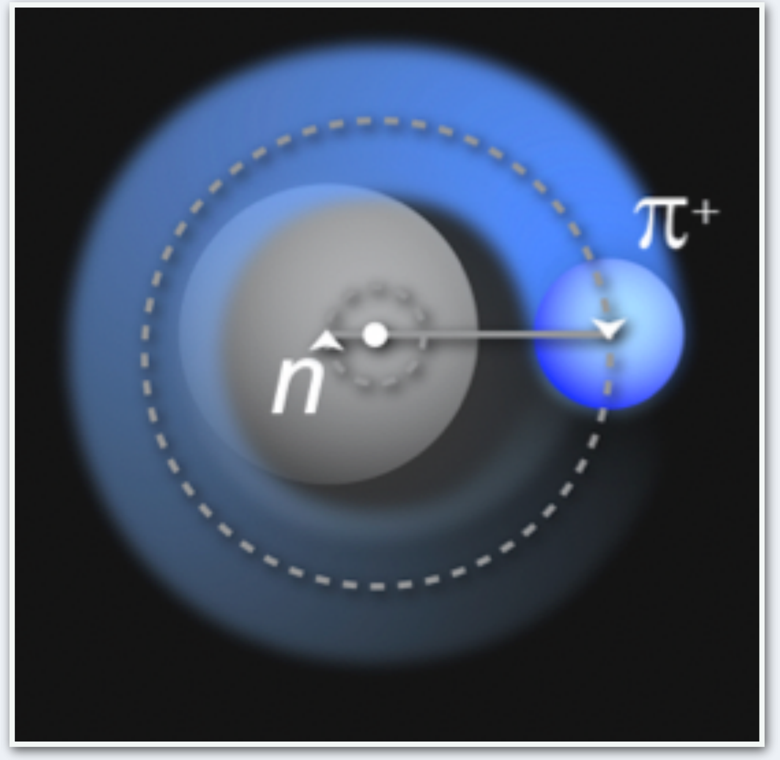




A.K,Tobias Toll PRD 105 (2022) 114045

PROBING THE GLUON DISTRIBUTION





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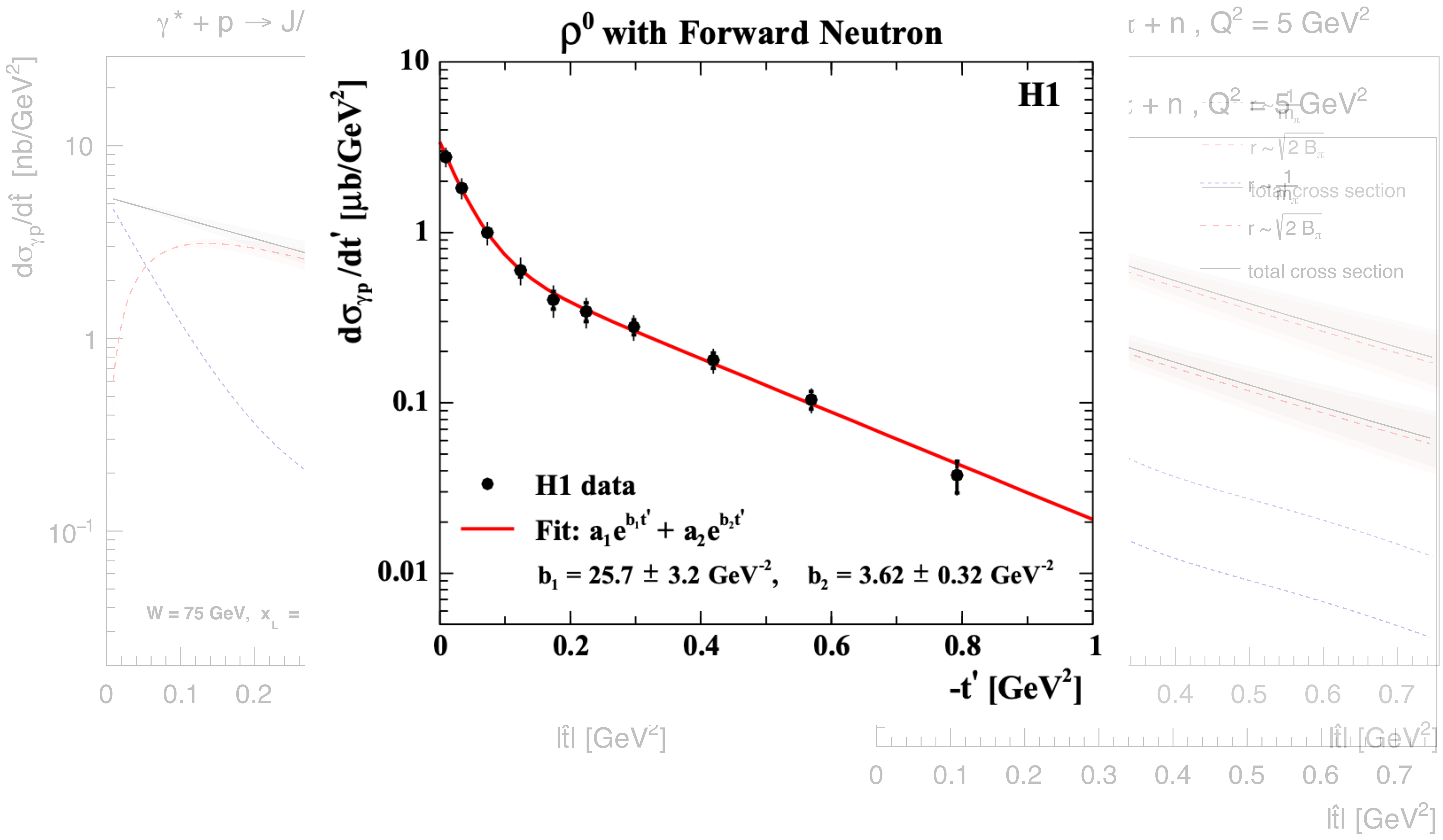
H1 EPJC 76 (2016), 41



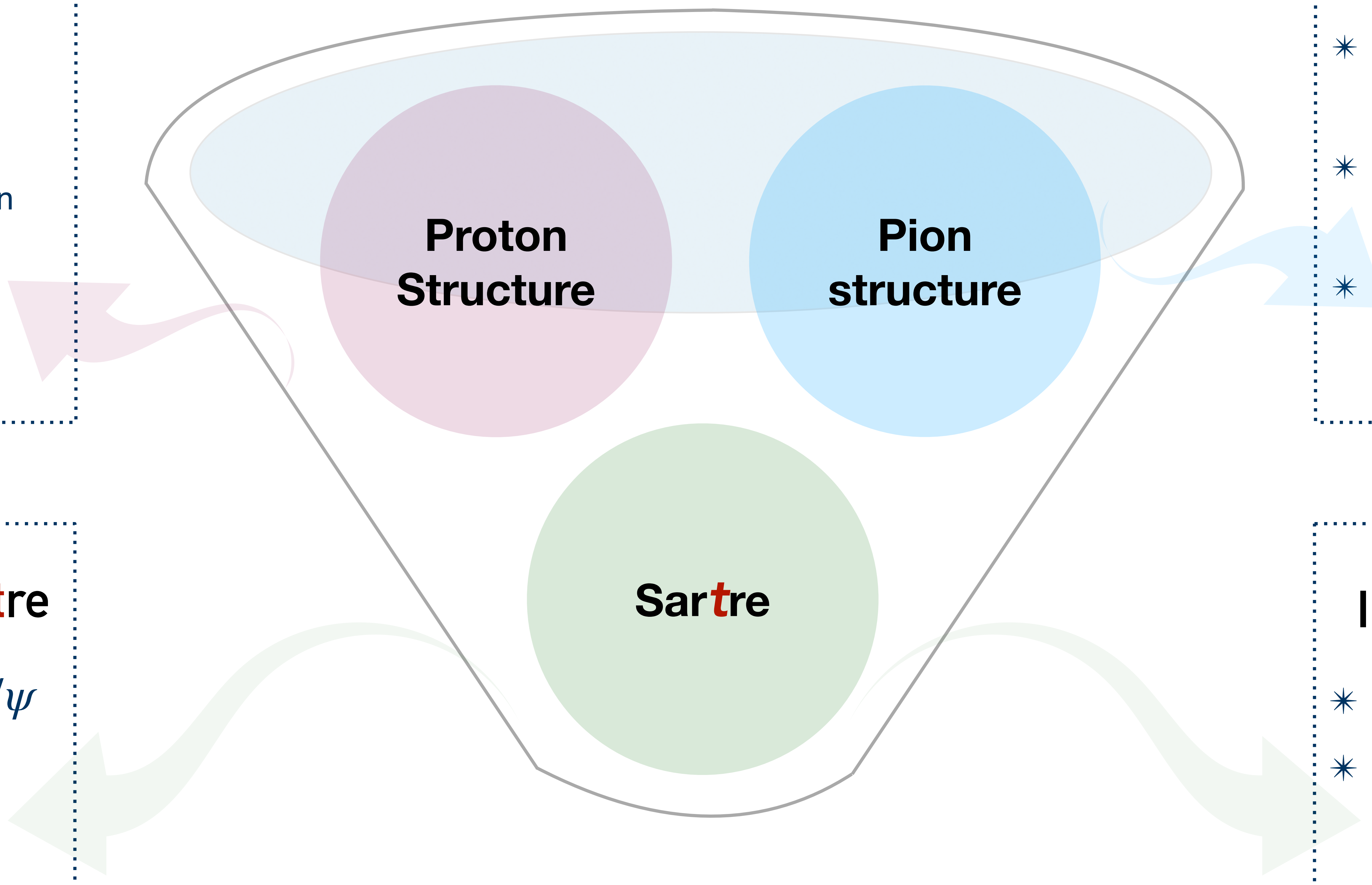
SUMMARY & OUTLOOK

Exclusive and proton dissociative vector meson production

- ✳ Comparisons with HERA Data prefers growing nucleon width
- ✳ Incoherent events are suppressed at high energies on including energy dependence in proton geometry
- ✳ Additional fluctuations are required at large momentum transfers

Pion structure through Sullivan process in leading neutron events

- ✳ Pions and protons structure have same energy dependence at high energy, upto normalisation
- ✳ Data shows geometric scaling in leading neutron events
- ✳ Potential to constrain spatial gluon distribution of pions in exclusive events



Sub-nucleon fluctuations in Sartre

- ✳ Good agreement with UPC data for J/ψ t-spectrum in (contributes for $t > 0.2$ GeV^2)
- ✳ Crucial for t-integrated observables and for accurate predictions of incoherent spectra in *e*A at EIC

Impact on EIC physics program

- ✳ Nucleon structure at high resolution
- ✳ Evolution of fluctuations on including energy dependence in nucleon geometry
- ✳ Pion cloud in protons & nuclei
- ✳ Good physics models to understand proton and pion structure at small-x

Nuclear Breakup in BeAGLE++

t = 0 | t = 10^{-22} s | t = 10^{-20} – 10^{-17} s | t = 10^{-14} s

DIS on a nucleon
Pythia8

Intranuclear cascade
Modified INCL++

De-excitation
ABLA

BACKUP

EVENT GENERATORS

BeAGLE ++

- *A hybrid model using modules from DPMJet, PYTHIA, FLUKA, LHAPDF, PyQM*
- *Maintenance is difficult as many modules are either outdated or no longer actively maintained*
- *Redundant module initialization causes memory leaks and increased runtime*
- *Needed: Rewriting the code in C++ to enhance user-friendliness and ensure smoother functionality*
- *Introducing new physics models to broaden physics reach*

Sartre (long term)

- *BK evolution in Sartre*
- *Final state radiation (depending upon how crucial is this)*

PION FLUX FROM PROTON

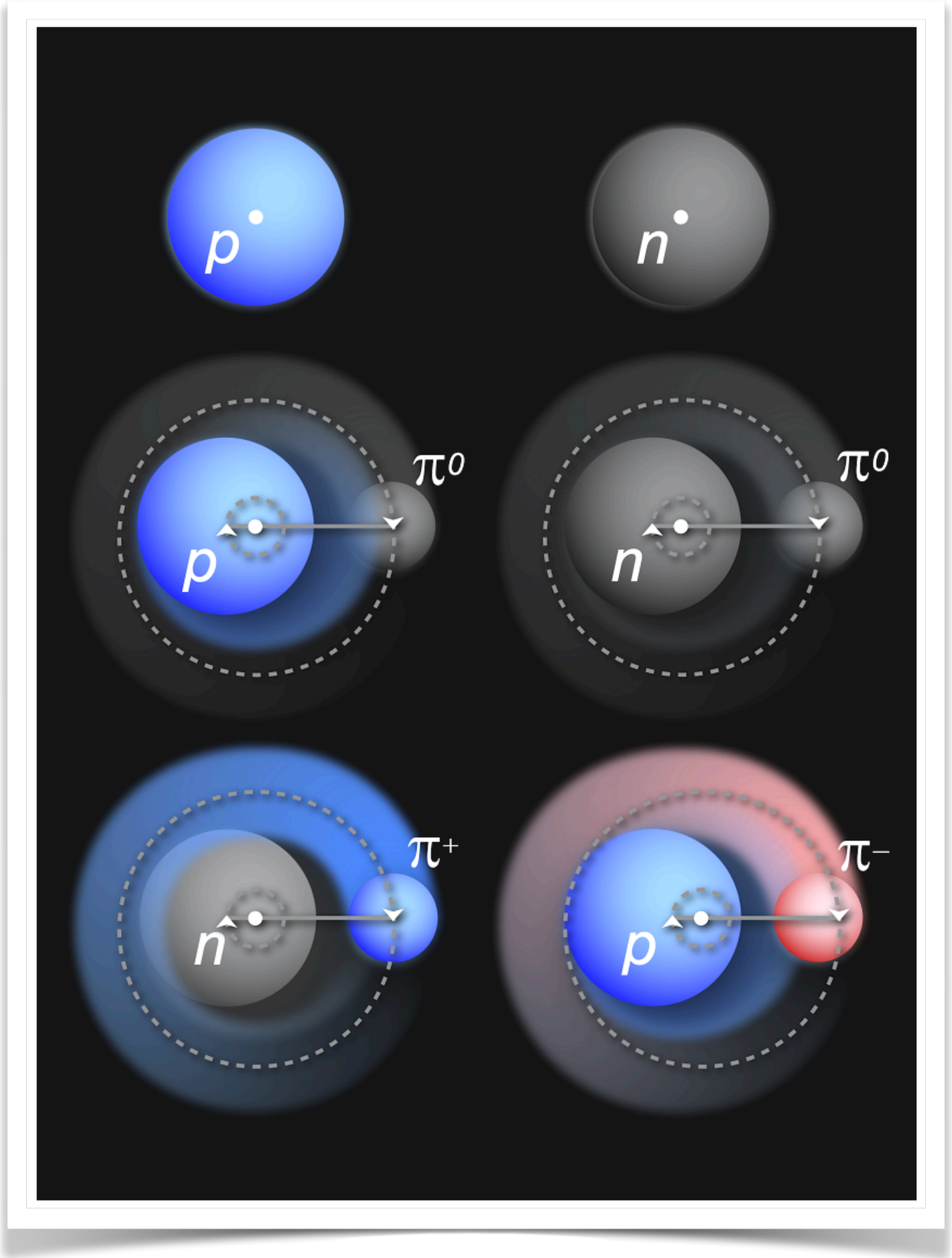
Chiral approach: a=0.24, b=0.12
Thomas, Melnitchouk & Steffens, PRL85 (2000) 2892

❖ 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



Carvalho et al PLB 752 (2016) 76

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

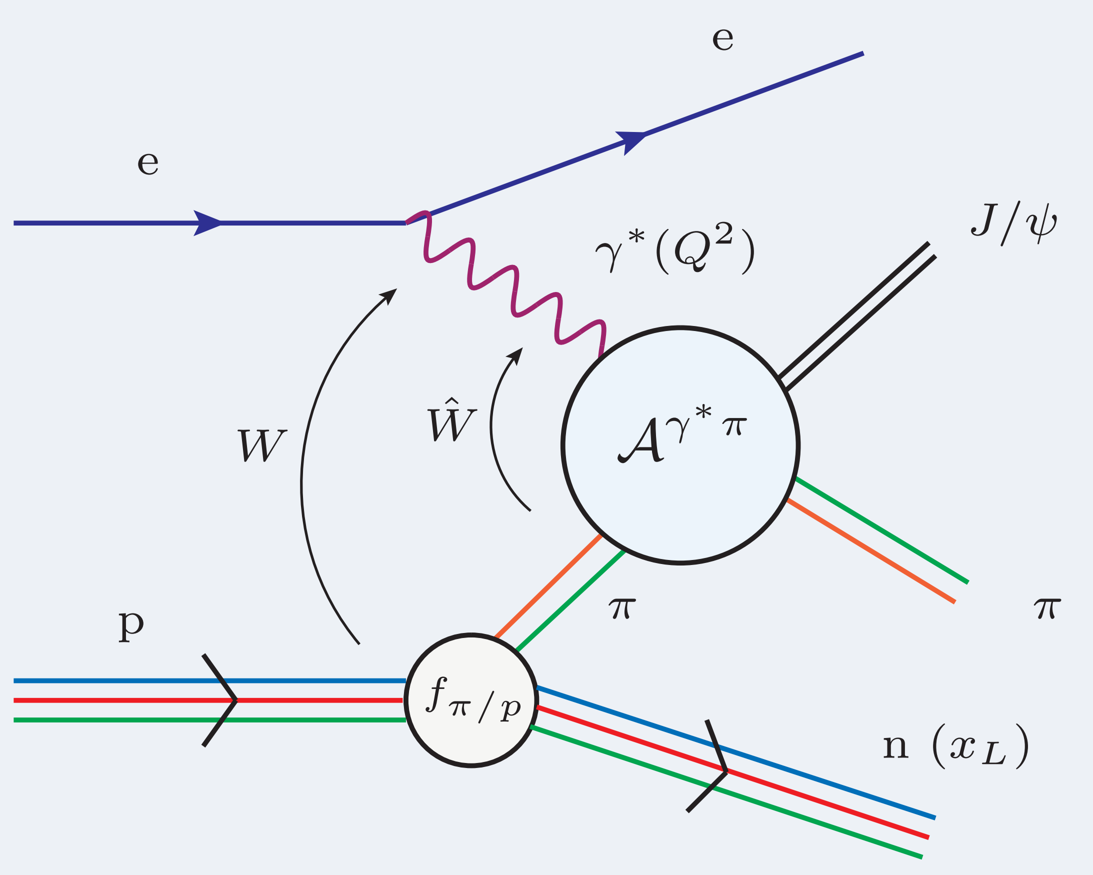
where the form factor is given by:

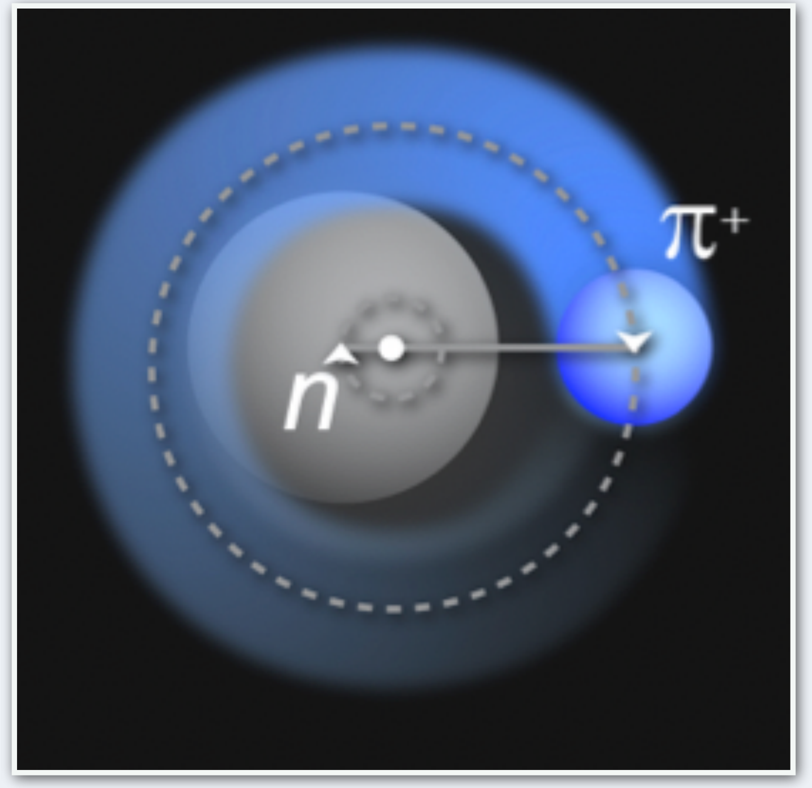
$$F(x_L, t) = \exp\left[-R^2\frac{|t| + m_\pi^2}{(1-x_L)}\right], \alpha(t) = 0$$

❖ 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





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

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 $B_\pi = 2 \pm 0.5\ GeV^{-2}$

FEYNMAN-X SPECTRA AT SMALL -XL

H1 EPJC 74 (2014), 2915

Standard fragmentation (DJANGO) One-pion approximation (RAPGAP)