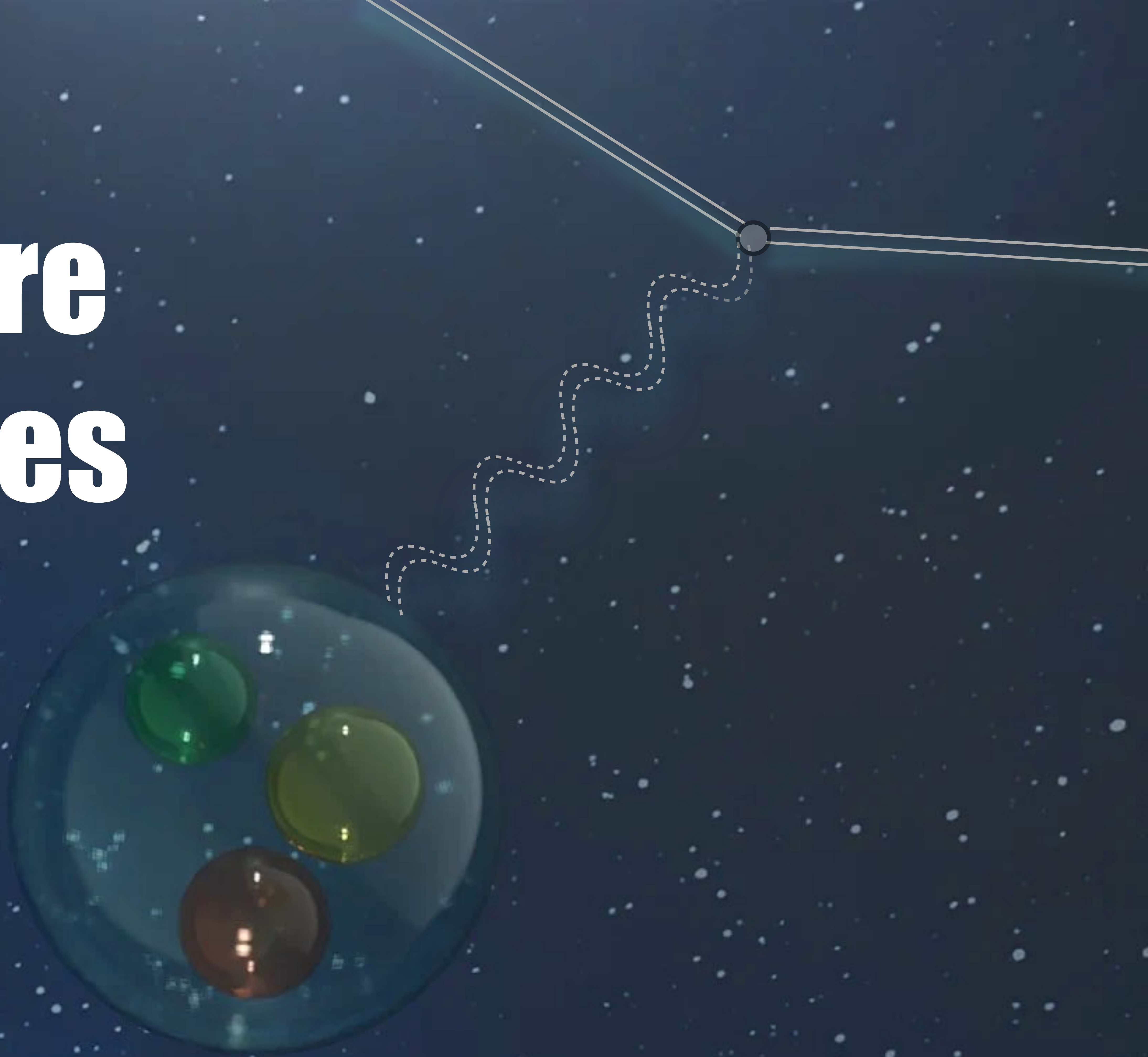
Exploring Nuclear Structure through High-Energy Probes

Exclusive diffraction on protons and ions with Sartre



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विज्ञान एवं प्रौद्योगिकी विभाग
DEPARTMENT OF
SCIENCE & TECHNOLOGY

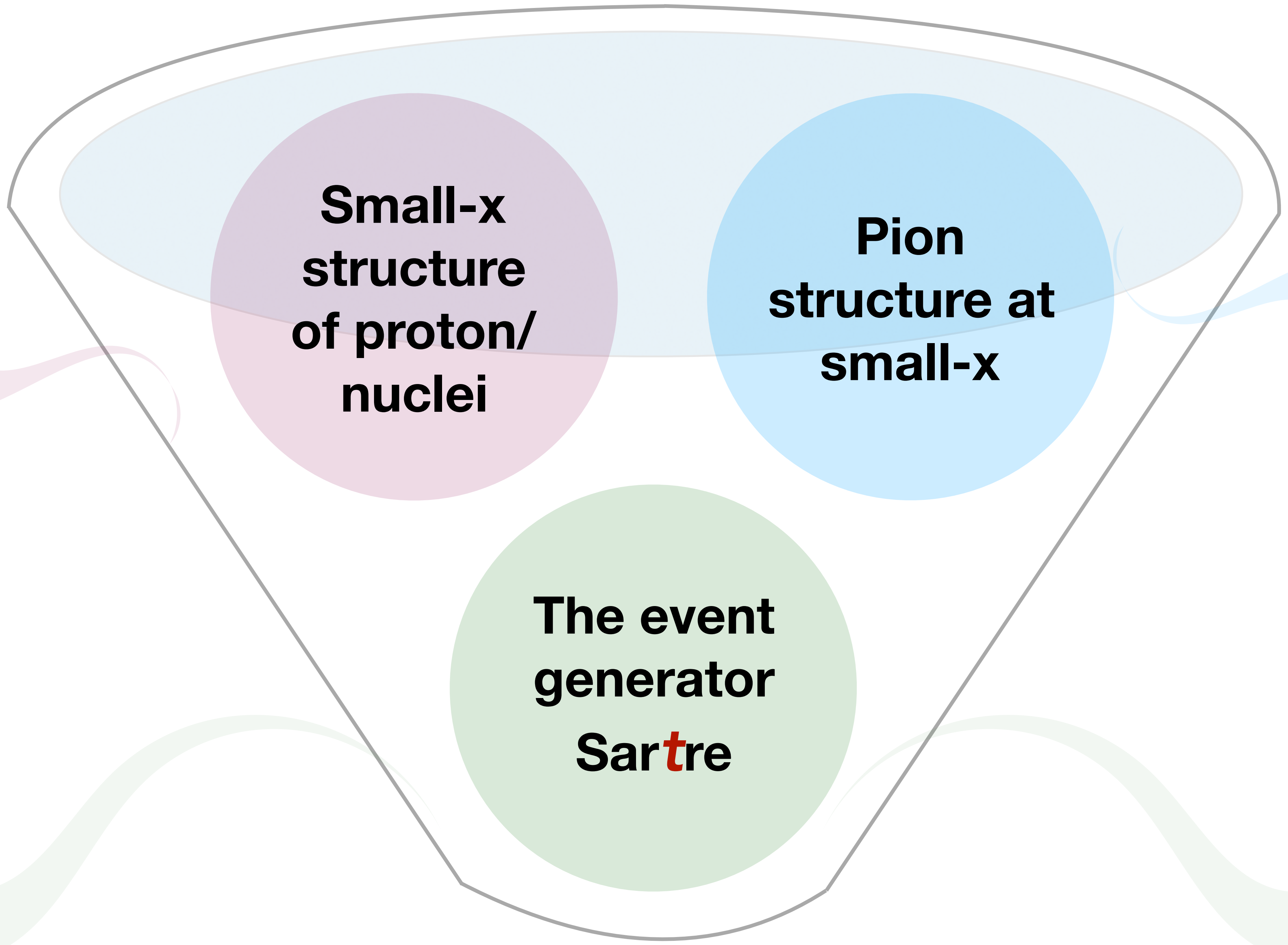
KEY HIGHLIGHTS

Coherent and Incoherent vector meson production

- ✳ Hotspot model of gluon distribution in proton/nuclei
- ✳ Small-x evolution effects
- ✳ Saturation effects

Pion structure in leading neutron events

- ✳ Universality of pions and protons structure at high energy
- ✳ Feynman and Geometric scaling in leading neutron events
- ✳ Spatial gluon distribution of pions



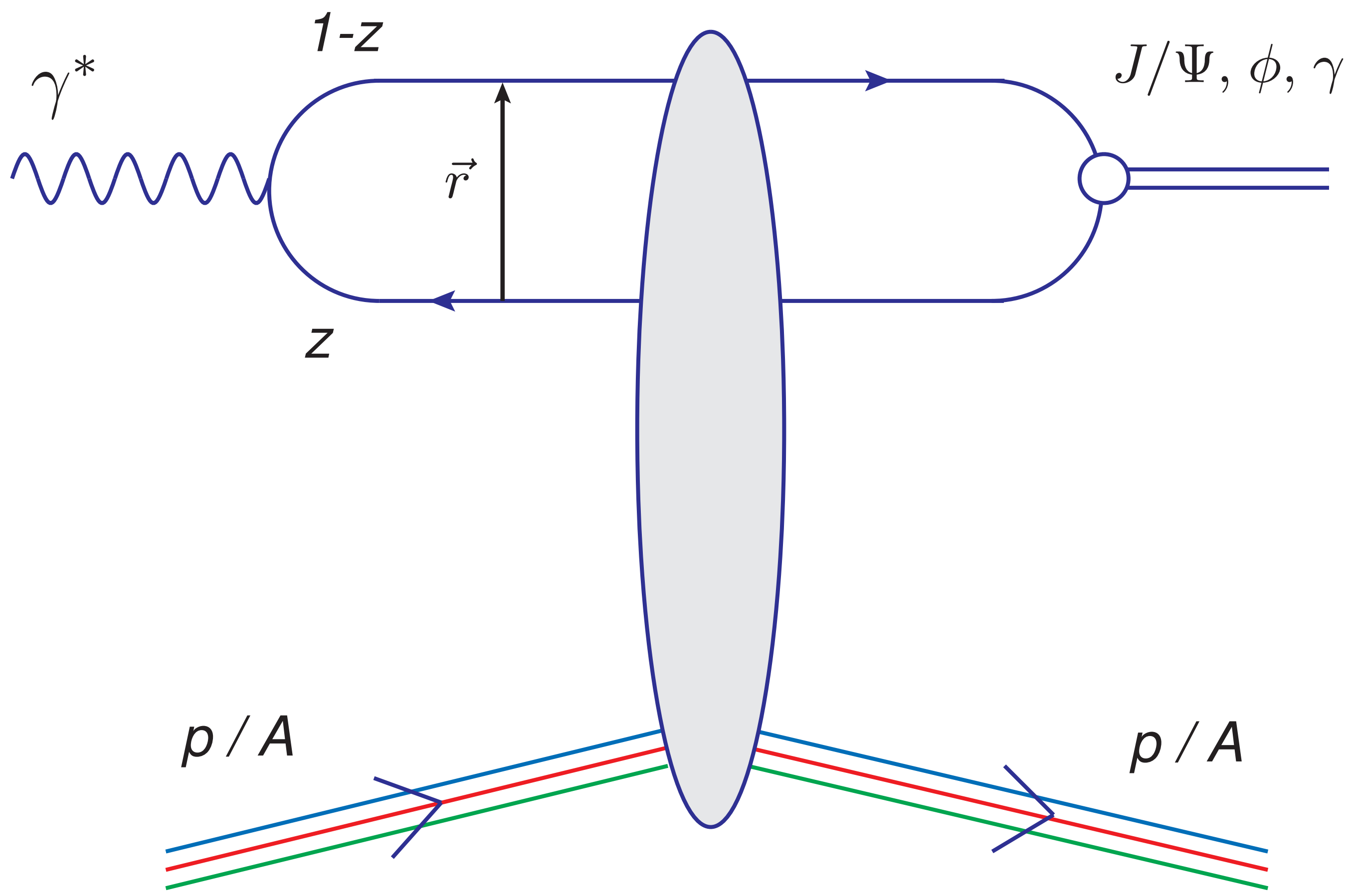
New Developments in Sar*t*re

- ✳ Implementation of incoherent *ep* cross section in Sar*t*re
- ✳ Implementation of sub-nucleon geometry for *e*A scattering and UPC's in Sar*t*re

Impact on EIC physics program

- ✳ Nucleon structure at high resolution
- ✳ Pion cloud in protons & nuclei
- ✳ Probing correlations and nuclei shape deformations through exclusive diffraction

EXCLUSIVE DIFFRACTION WITH SARTRE



Factorisation :

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

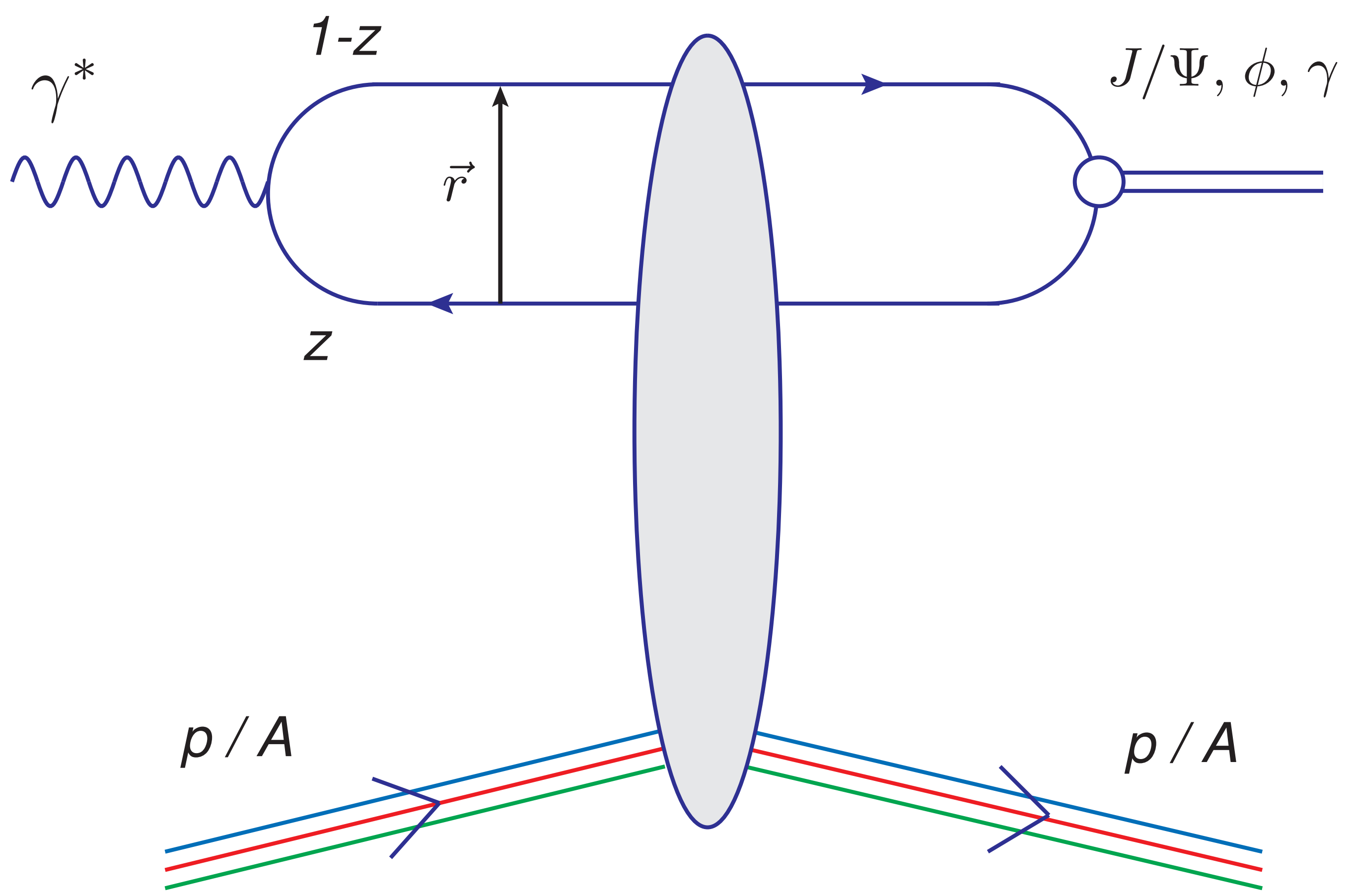
- *The scattering amplitude is given by :*

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

- *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* $N(b, r, x)$ *)*

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*

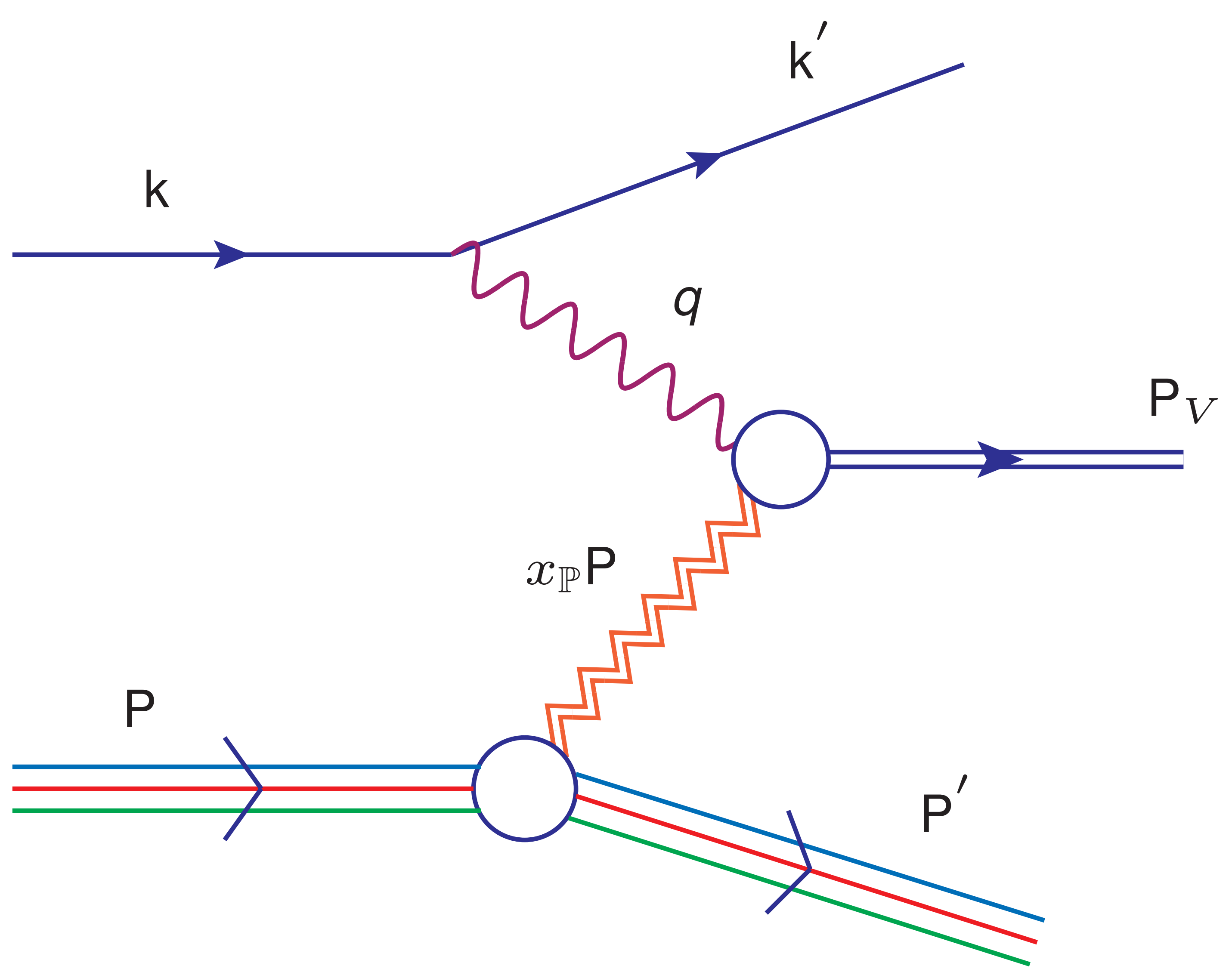
Incoherent diffraction

- *Sensitive to fluctuations of gluon distribution*

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

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

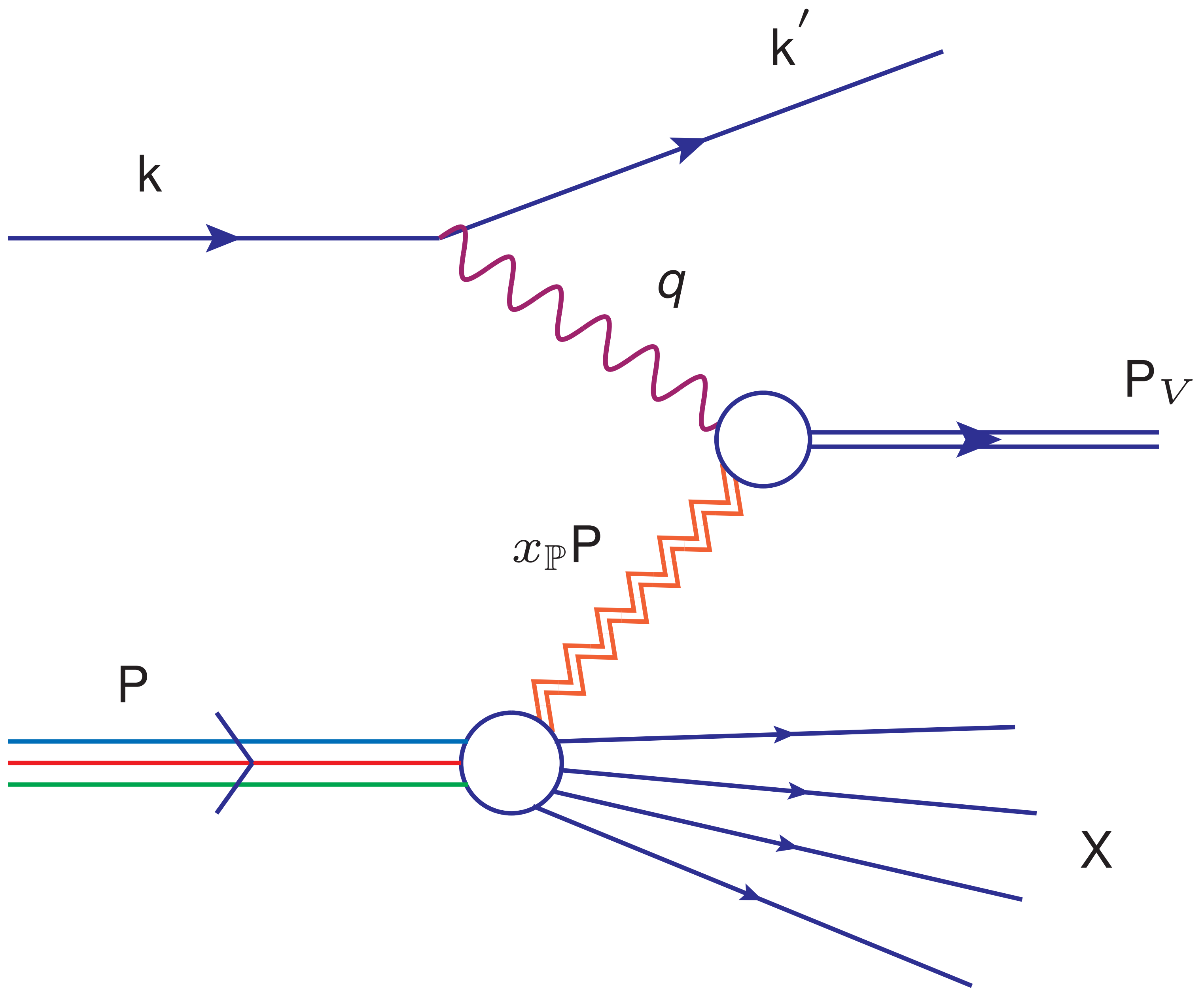
DIFFRACTIVE VECTOR MESON PRODUCTION



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

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

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

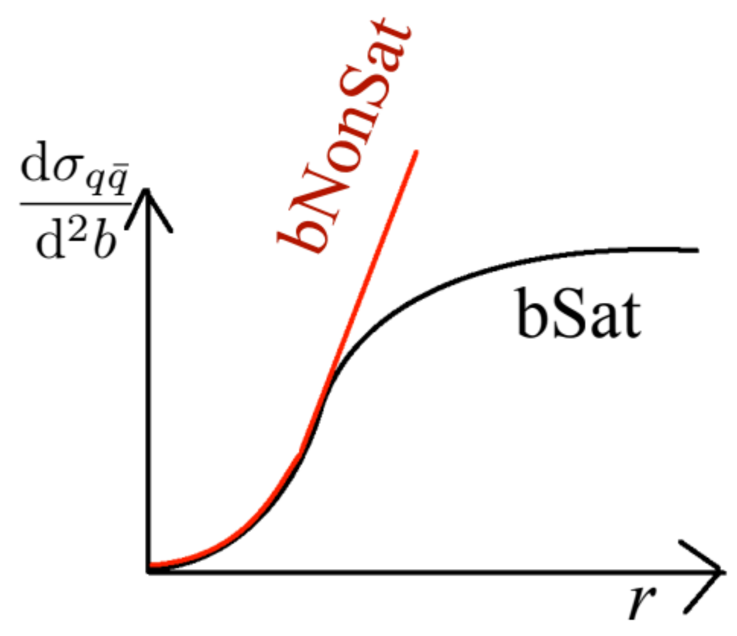
Coherent — Incoherent

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

THE DIPOLE-TARGET AMPLITUDE

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

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

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

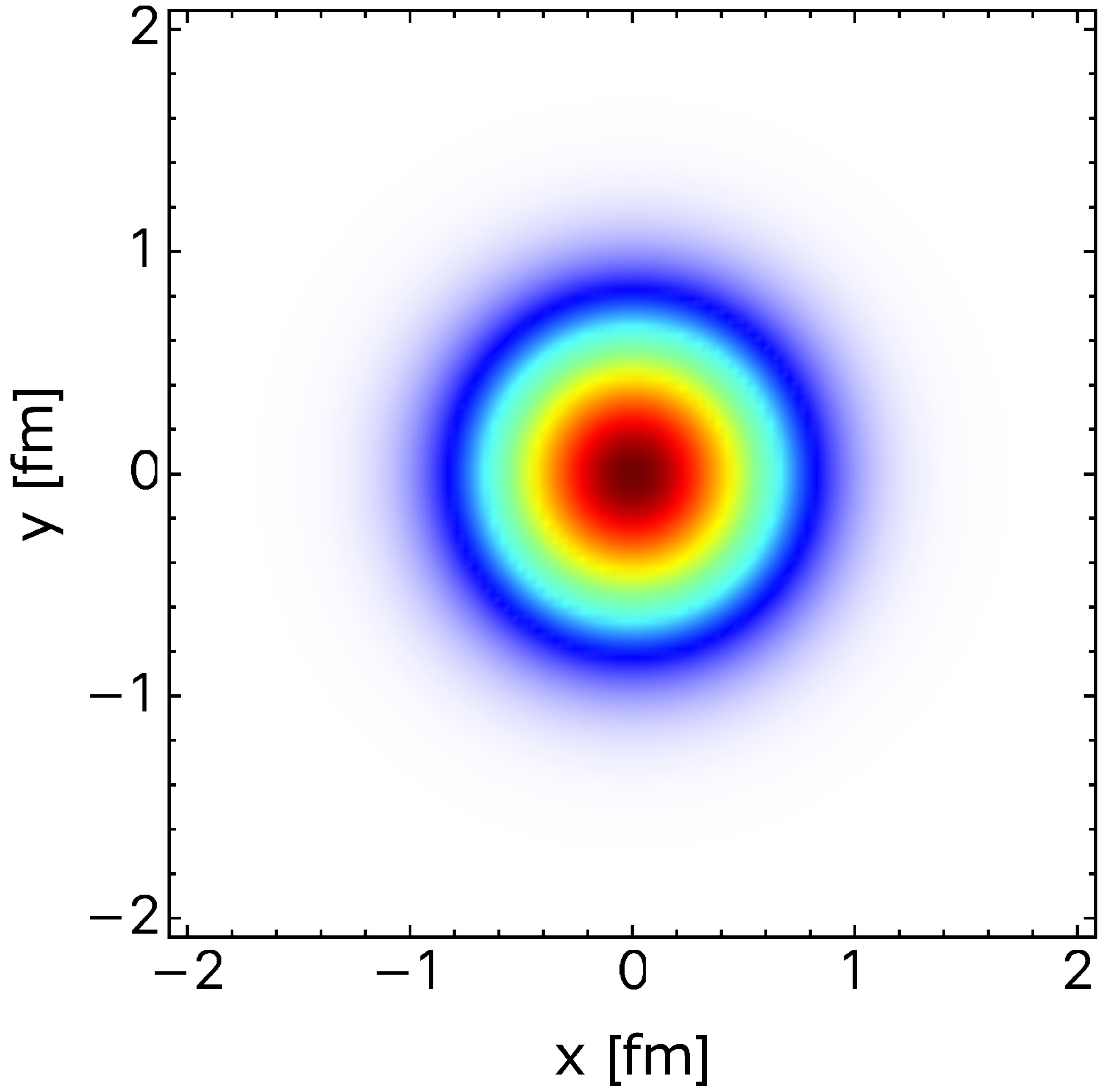
Mäntysaari, Schenke PRL 117 (2016) 052301

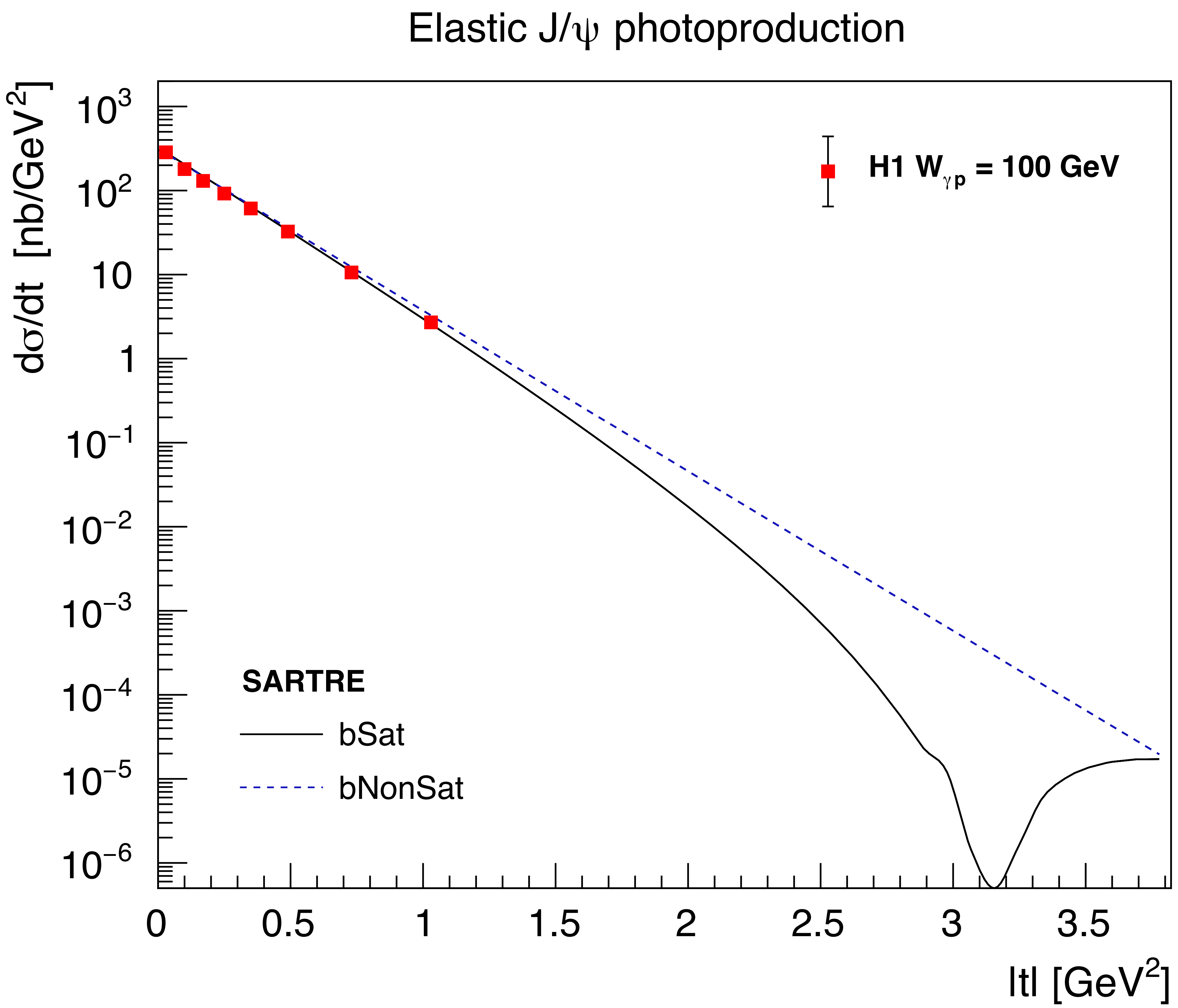
$e + p$ AS COMPARED TO HERA DATA : SMOOTH PROTON

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

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

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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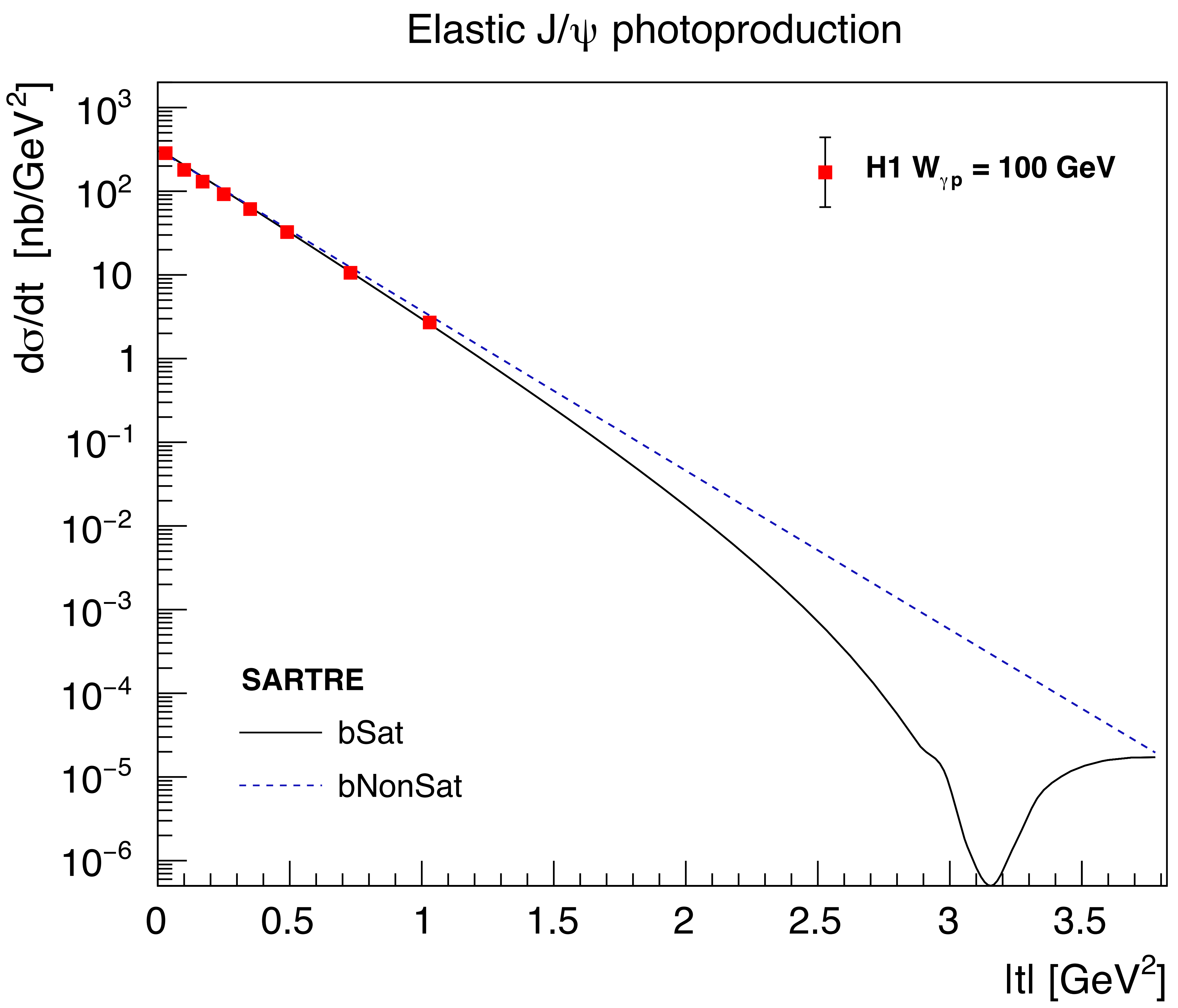


Gaussian & linear (bNonSat) : $N(r,b) \sim e^{-b^2/(2B)}$

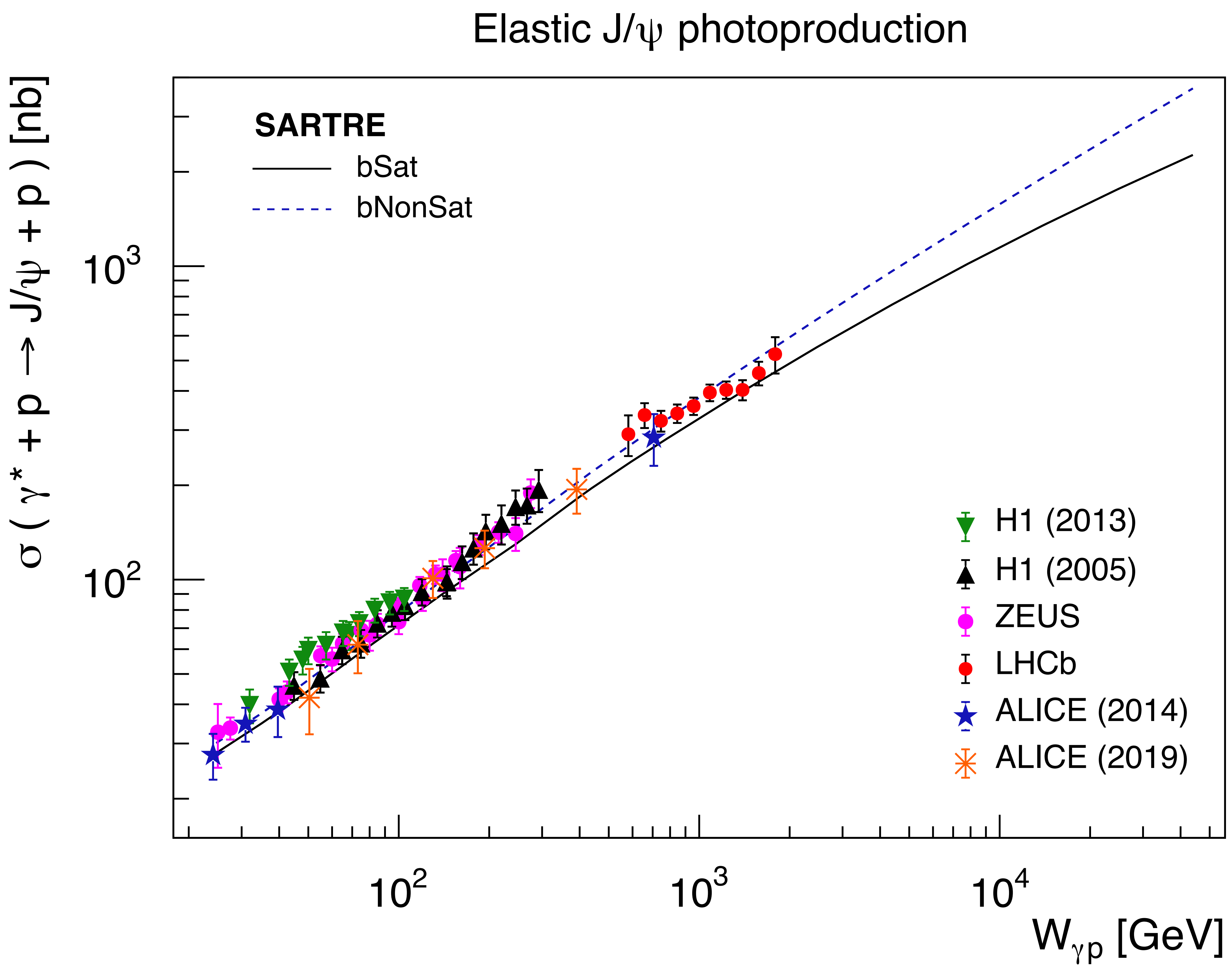
Gaussian& non-linear (bSat) : $N(r,b) \sim 1 - \exp\left(-e^{-b^2/(2B)}\right)$

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

Complementary constraints from inclusive diffraction??

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

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



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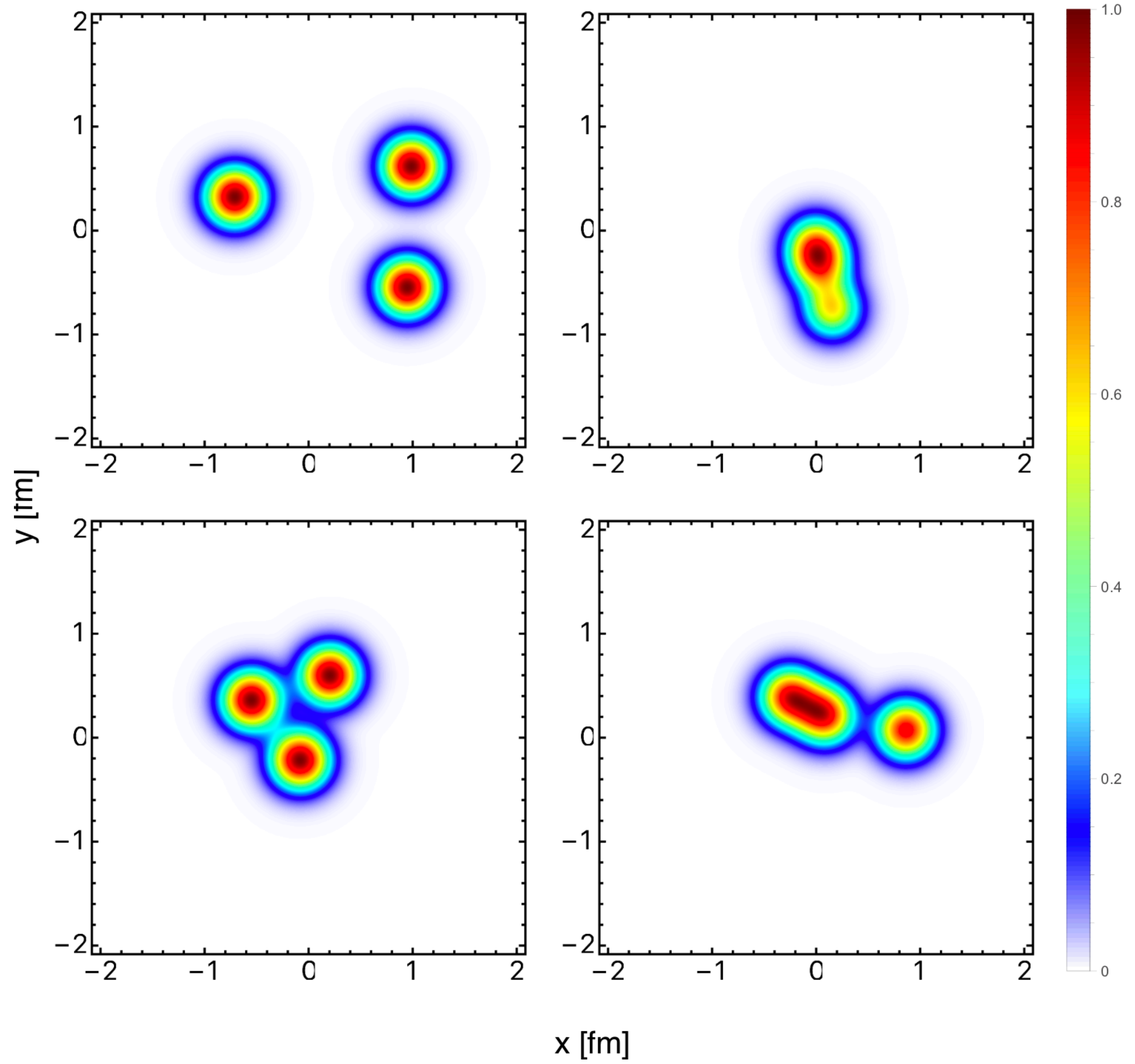
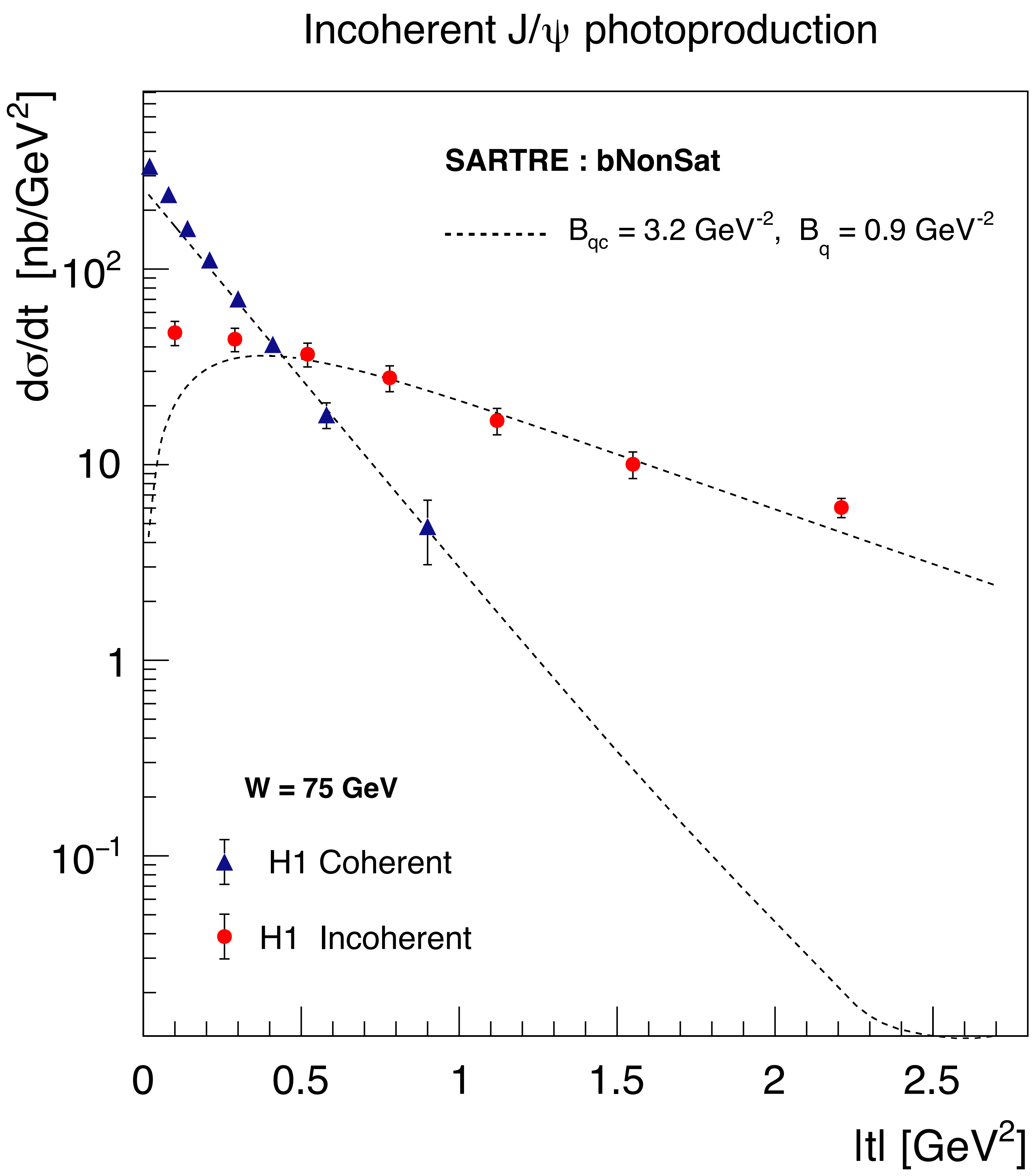
Power law increase for non-saturated model

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





(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

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

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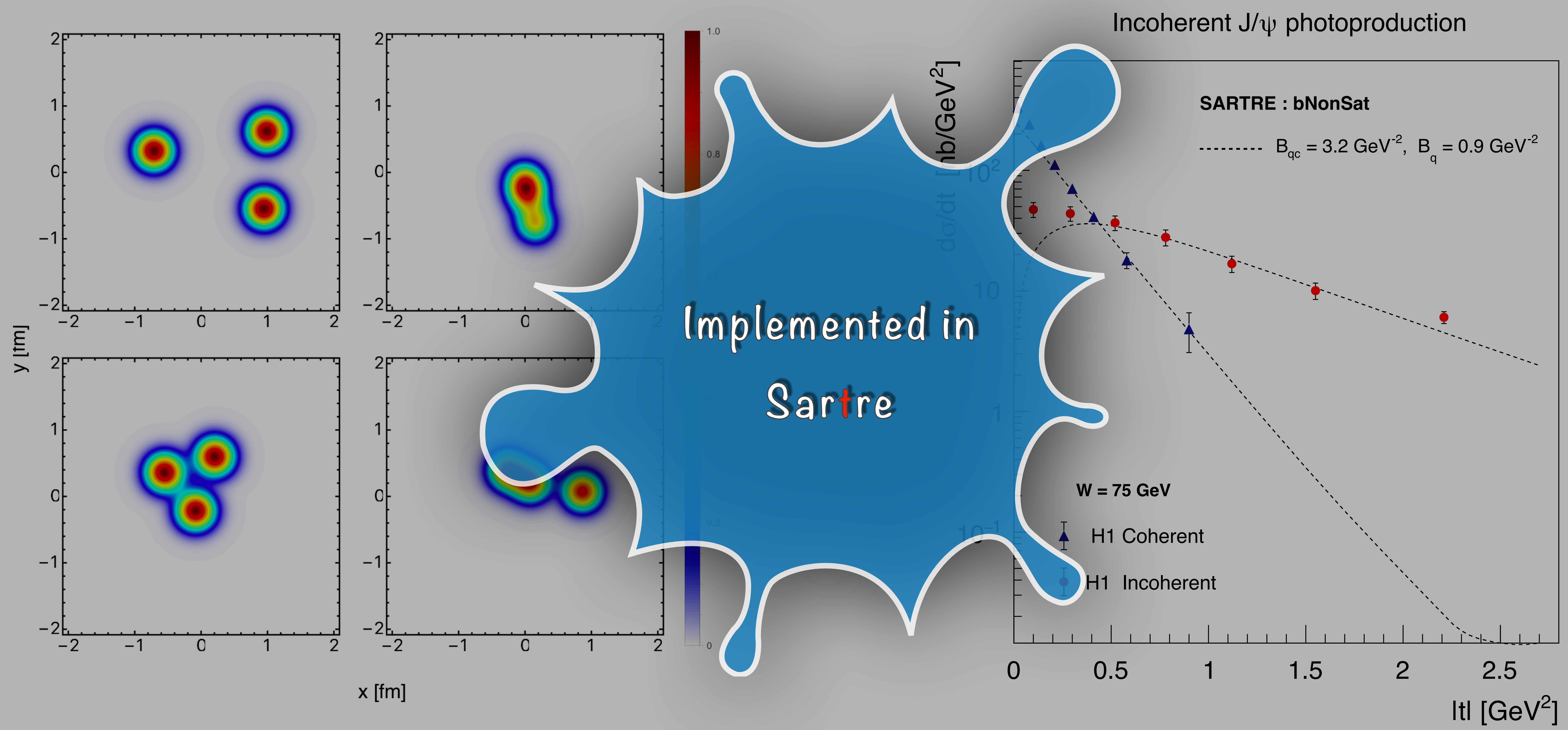

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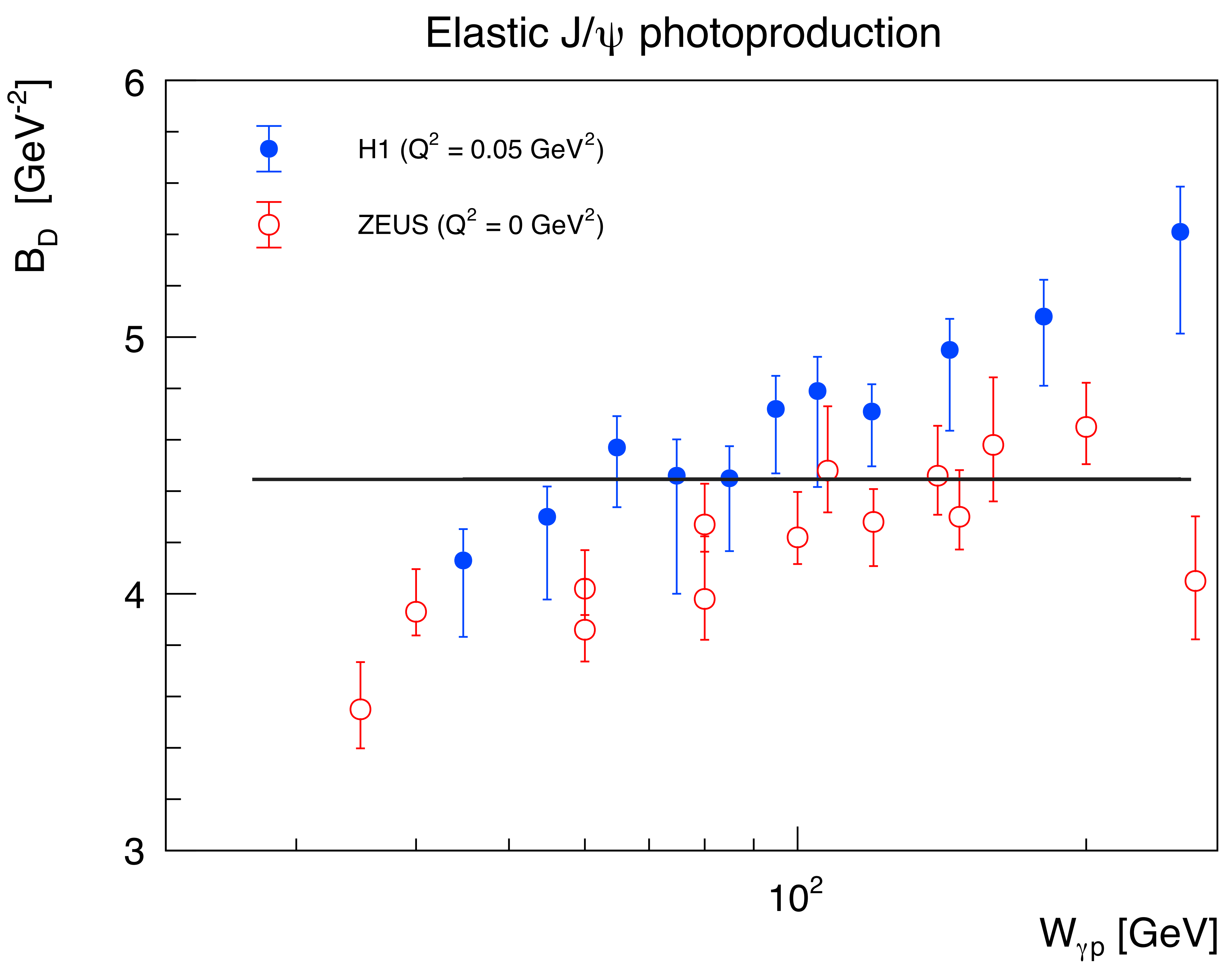


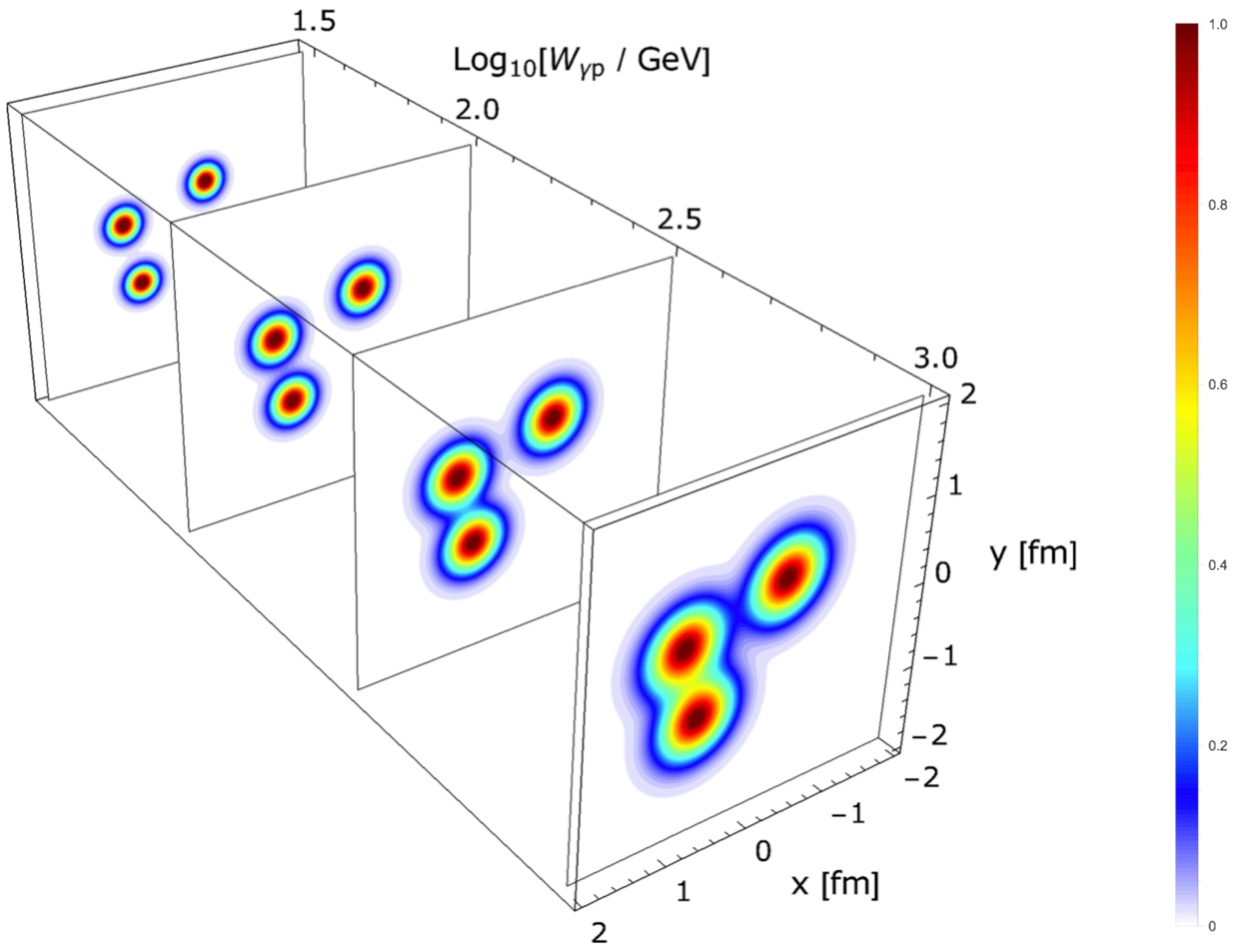
- $r_{proton} = \sqrt{2(B_{qc} + B_q)} = 0.55\ fm$
- *Transverse size of proton fixed for all energies*
- *Experimentally the transverse width increases at high energies*
- *Tensions between H1& ZEUS data*
- *Measurements at EIC ??*

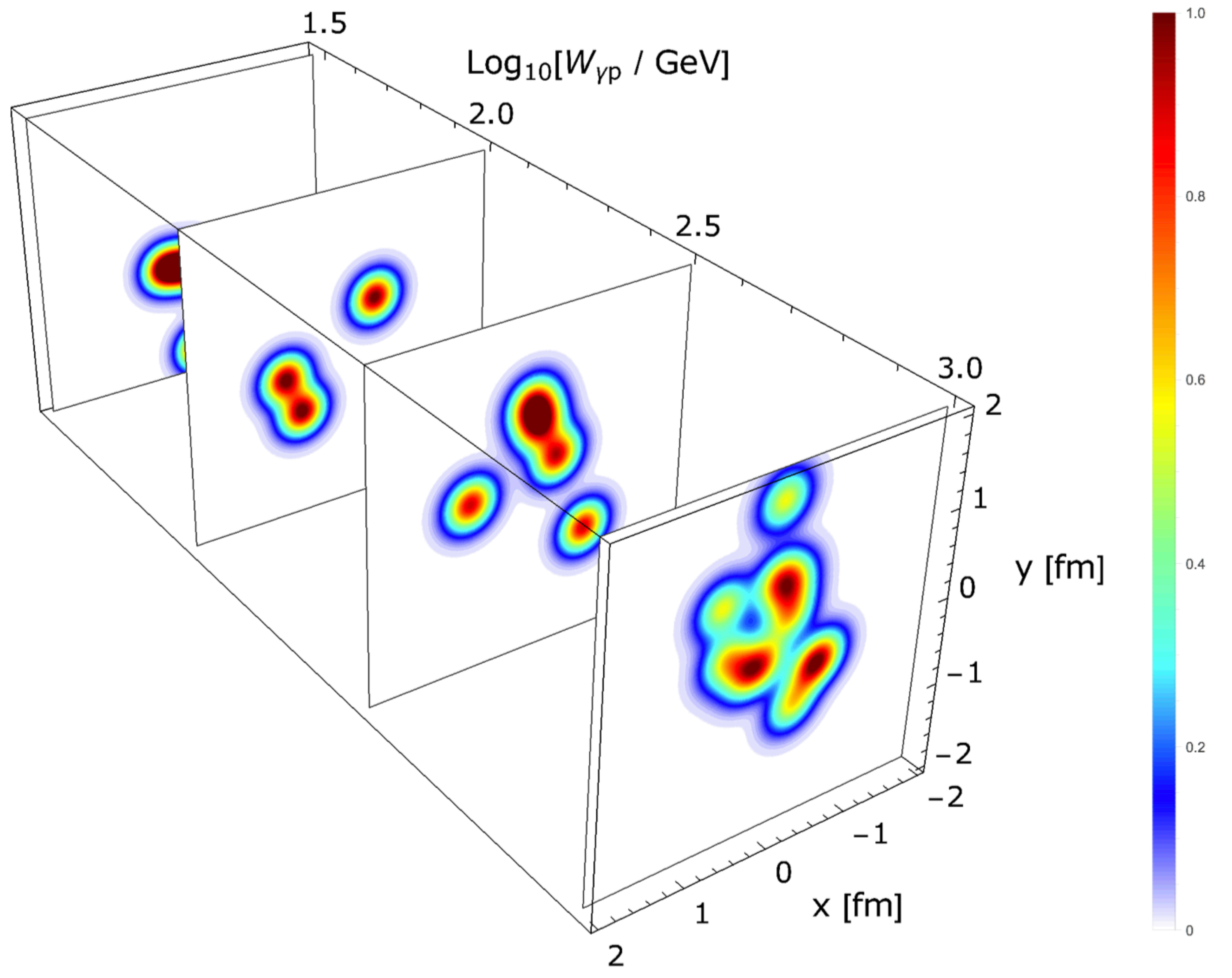
★ *Shrinkage of diffraction peak at high energies and fluctuations too expected to evolve with energy (small-x evolution-JIMWLK or BK)*

★ *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: $B_q(x) = B_{q0}\ x^{\lambda_0}$

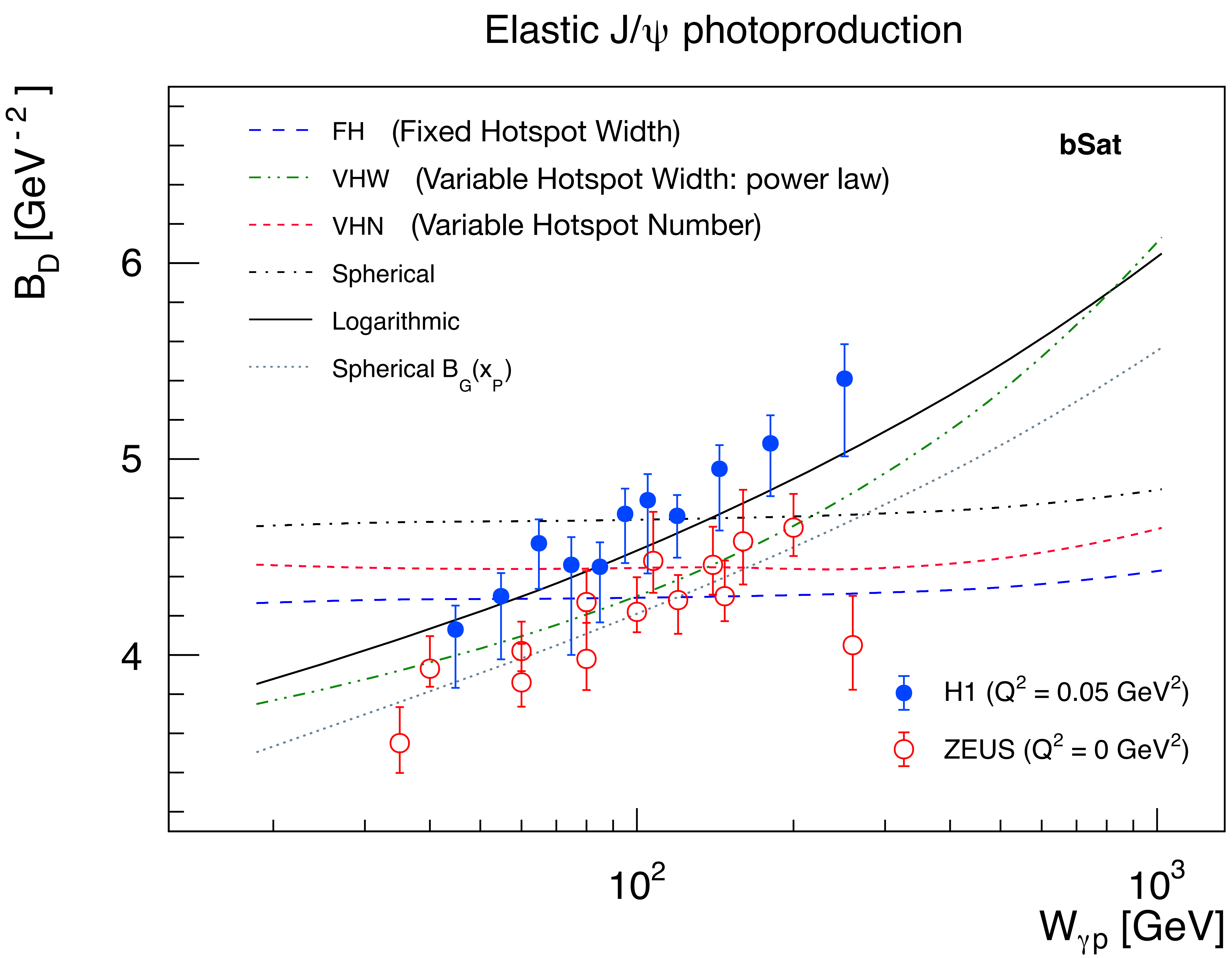
Logarithmic model: $B_q(x) = b_0\ ln^2\left(\frac{x_0}{x}\right)$

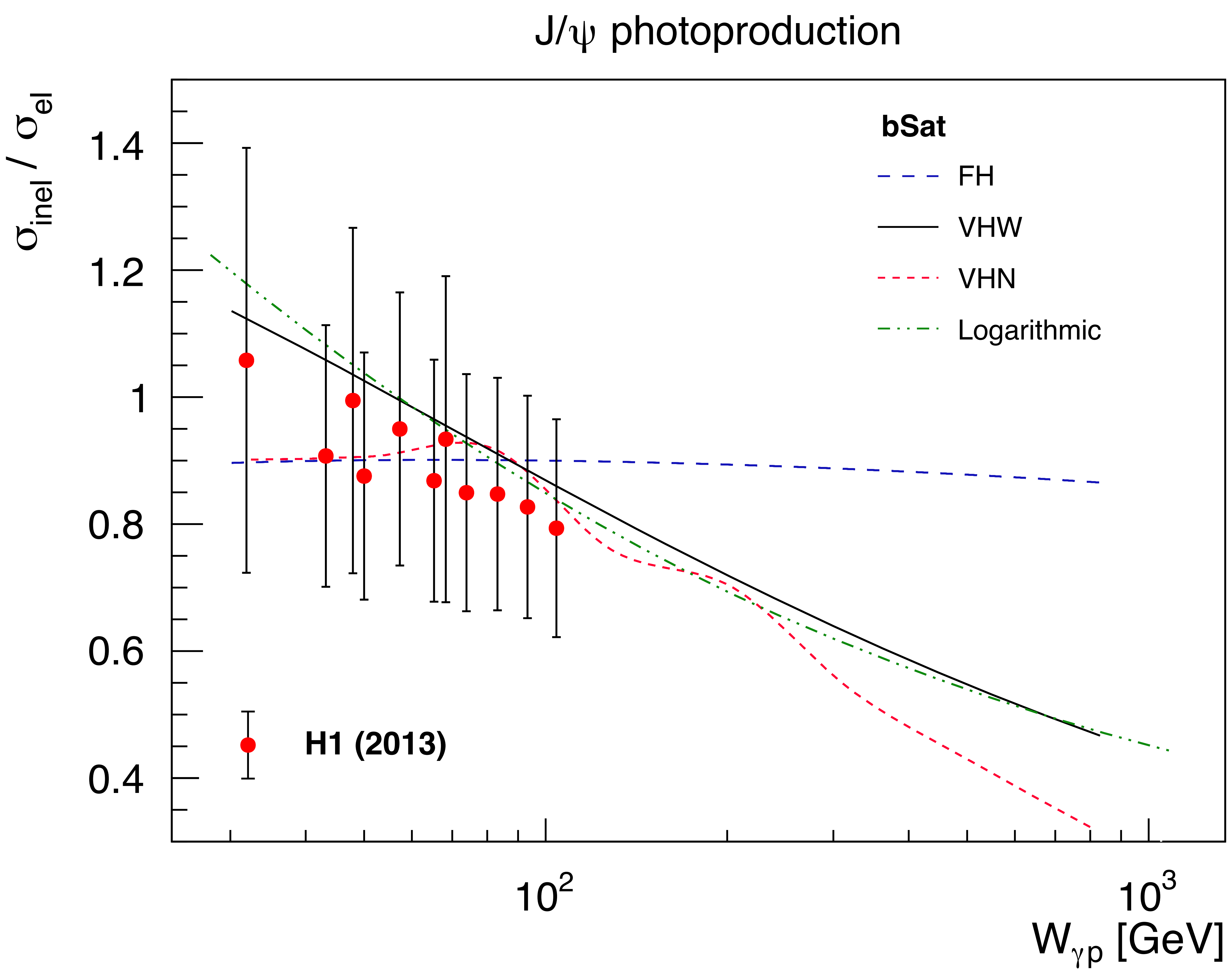
Varying hotspot number (VHN) model: $N_q(x) = p_0\ x^{p_1}(1 + p_2\sqrt{x})$

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

INCORPORATING THE ENERGY DEPENDENCE

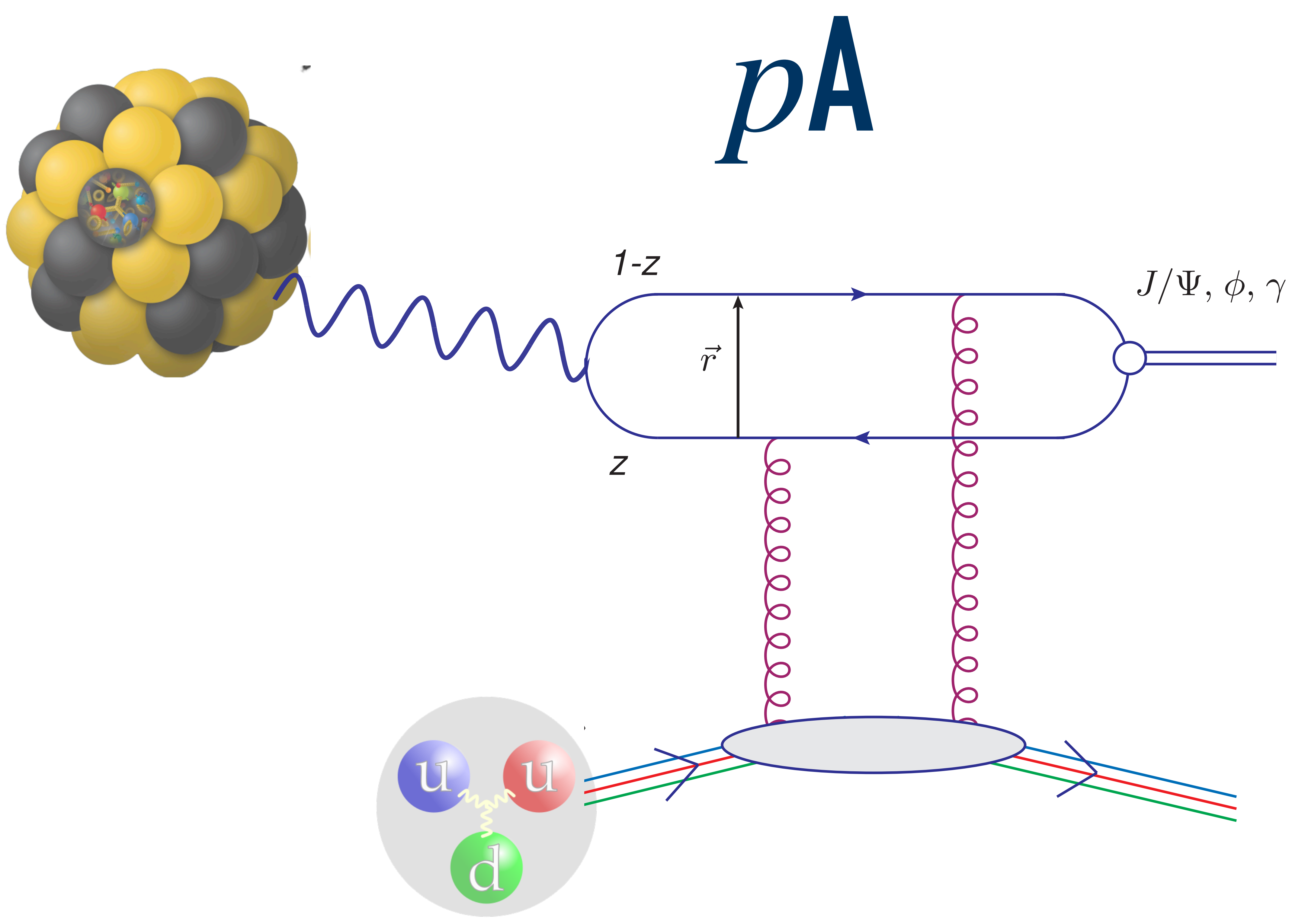
A.K,Tobias Toll PRD 105 (2022) 114011

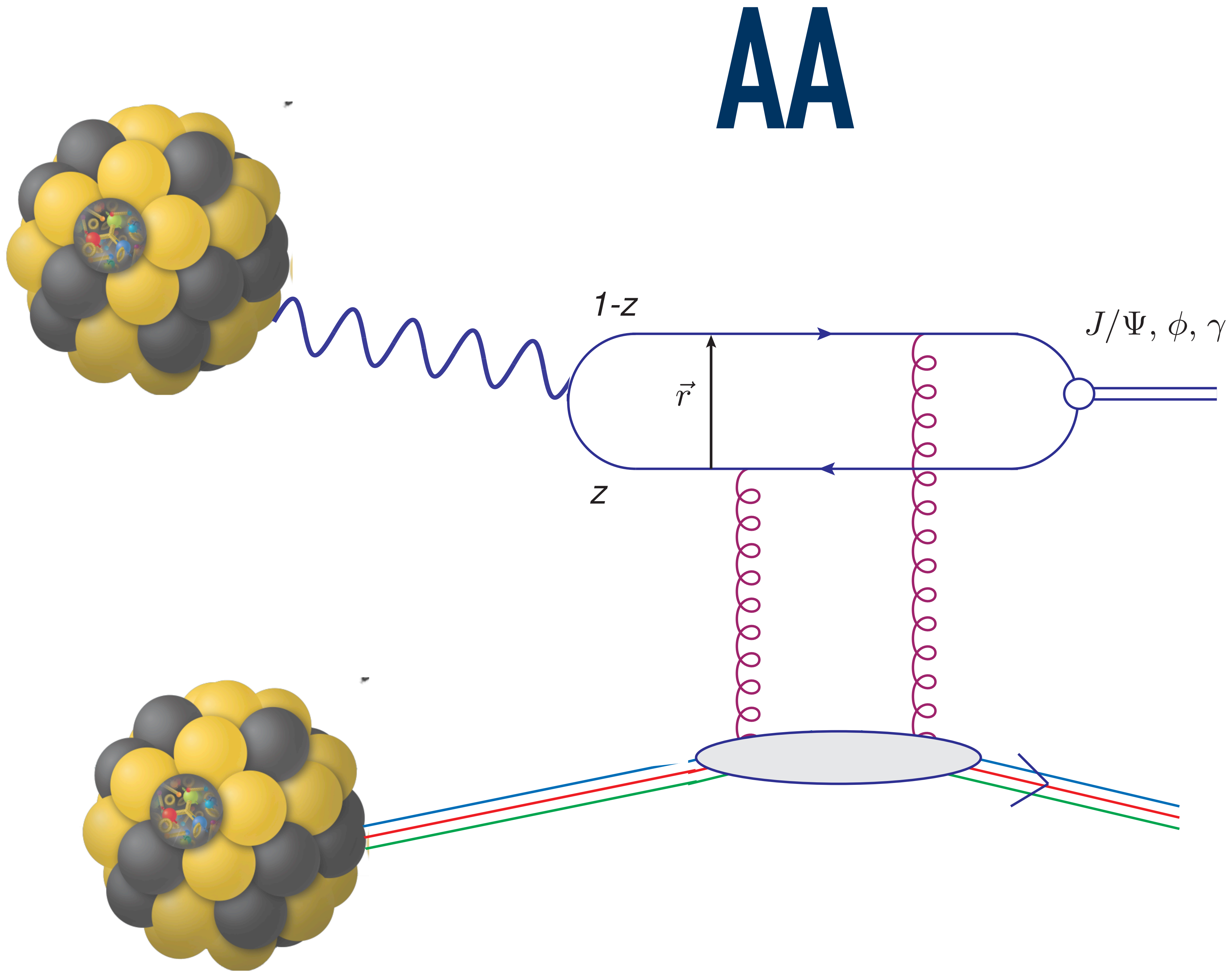




see Mäntysaari, Schenke 1806.06783 for similar predictions in IP-GLASMA framework

ULTRA PERIPHERAL COLLISIONS (UPCs) AS PROBE OF PARTONIC STRUCTURE

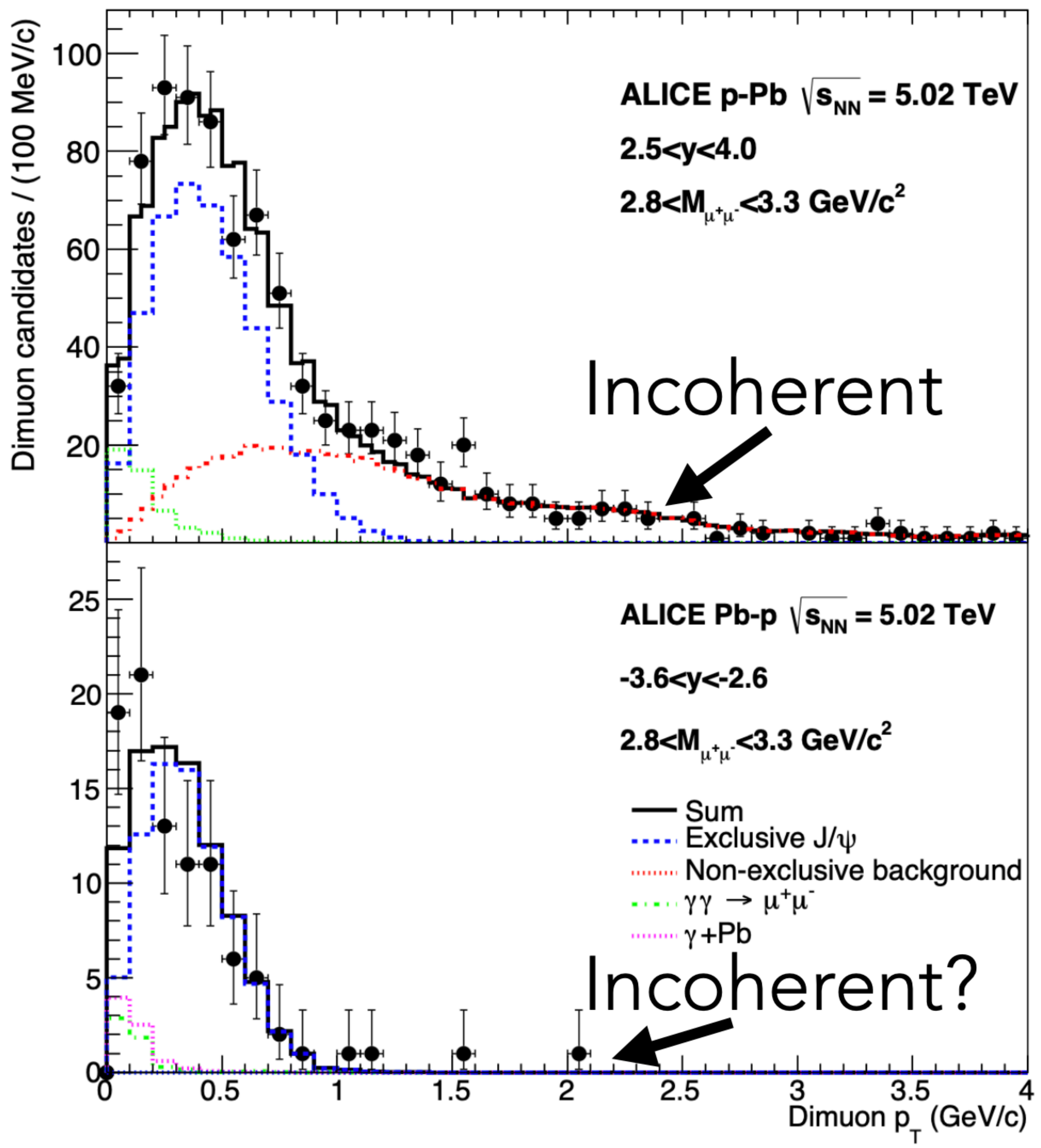




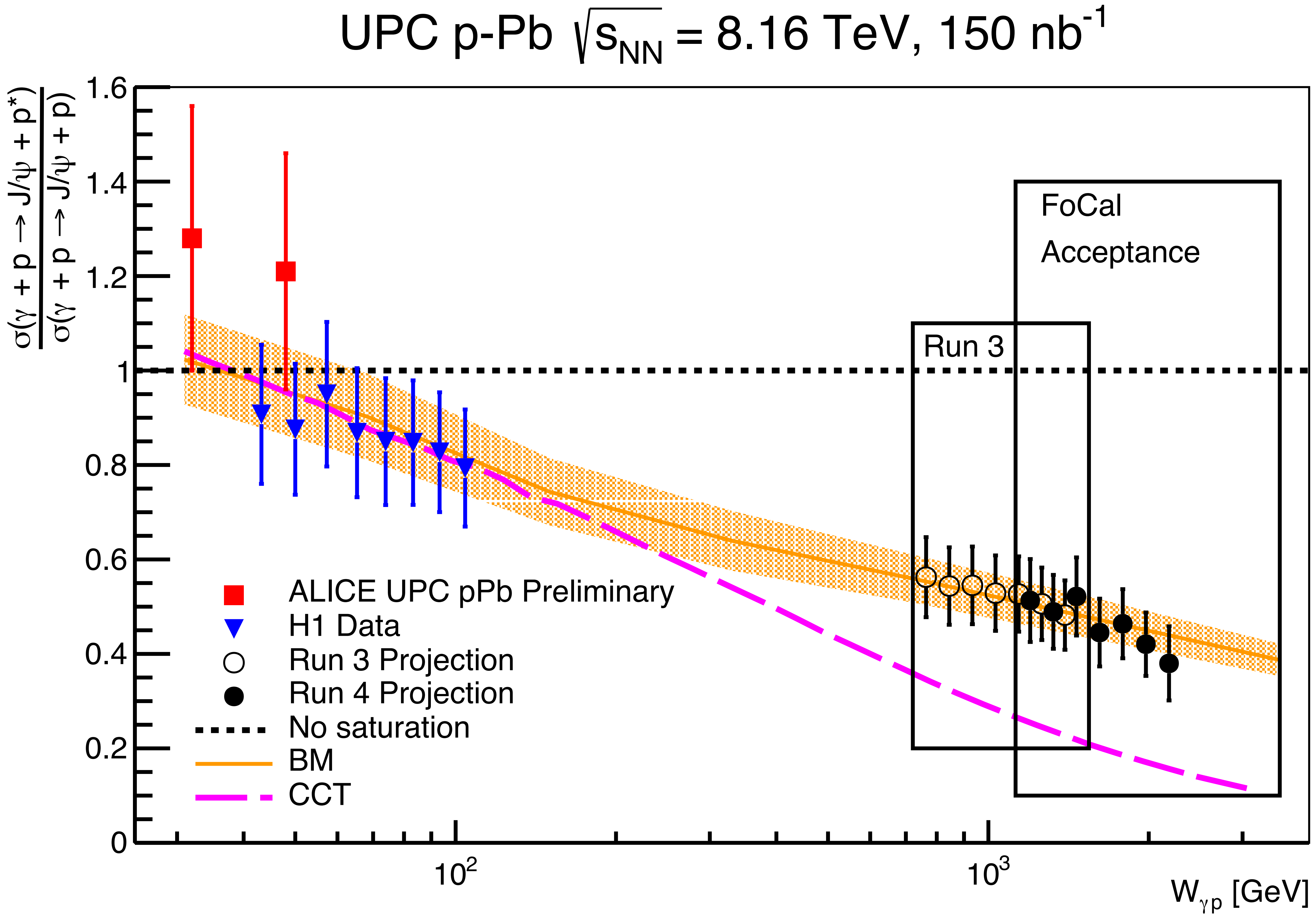
- *Photons in UPCs ($b \gg R_A + R_B$) are probes of nucleus and proton partonic structure and strong interaction dynamics in small-x QCD.*
- *Good test of our models and complementary physics at LHC and RHIC before EIC starts taking data.*

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

INDICATIONS FROM ALICE UPC pPb DATA

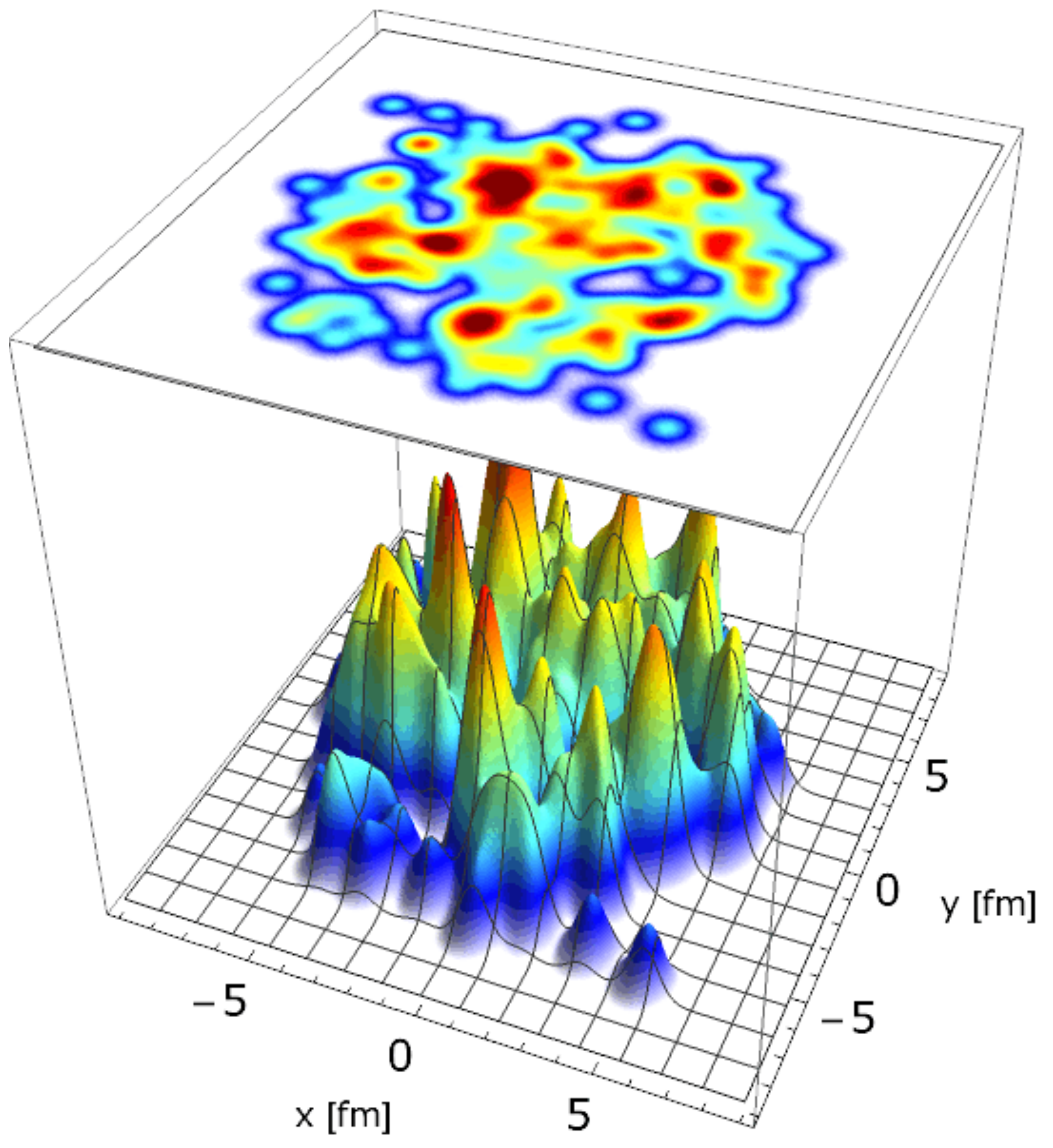


ALICE: arXiv:1406.7819 and 1809.03235

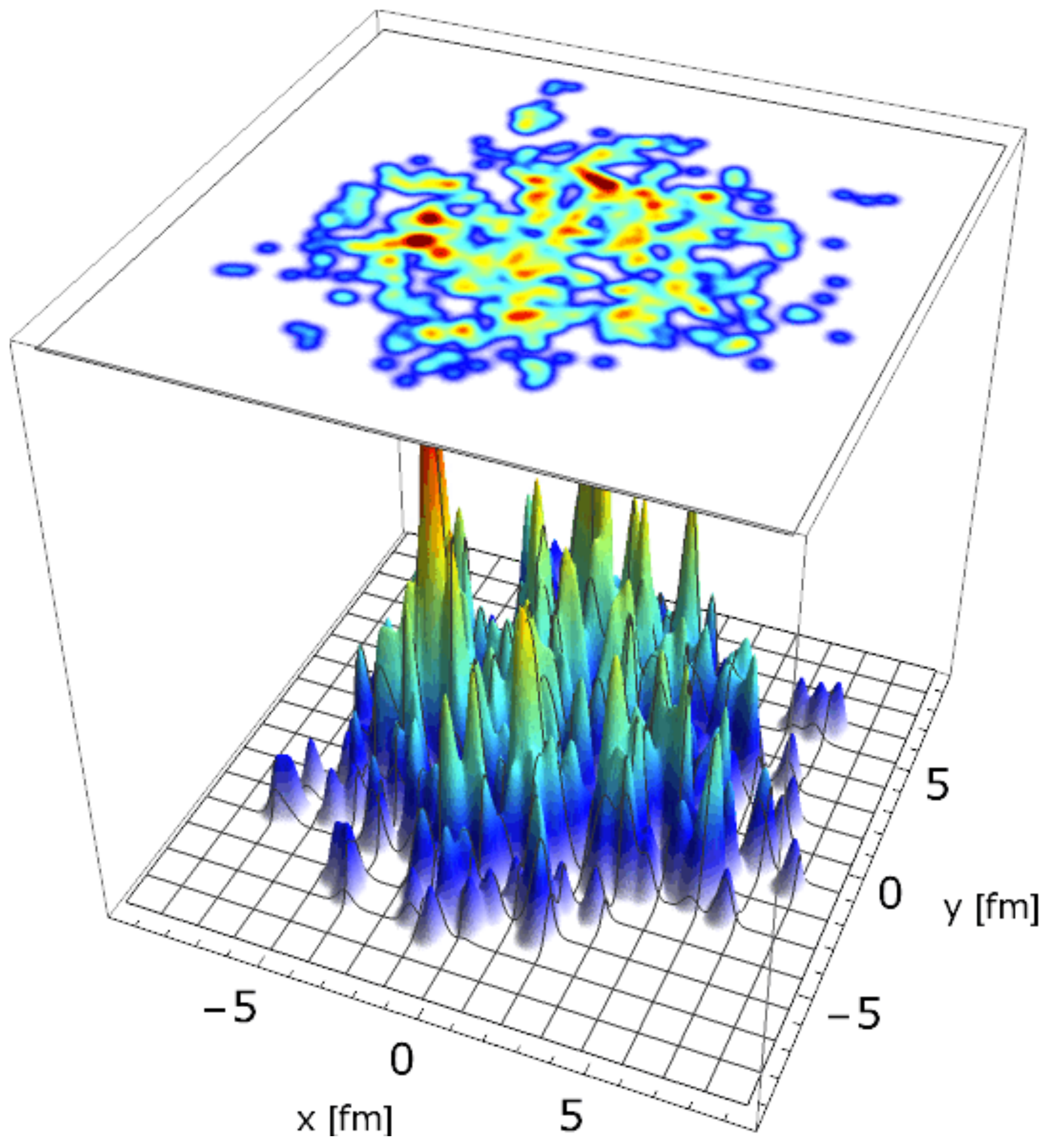


arXiv:2211:16107

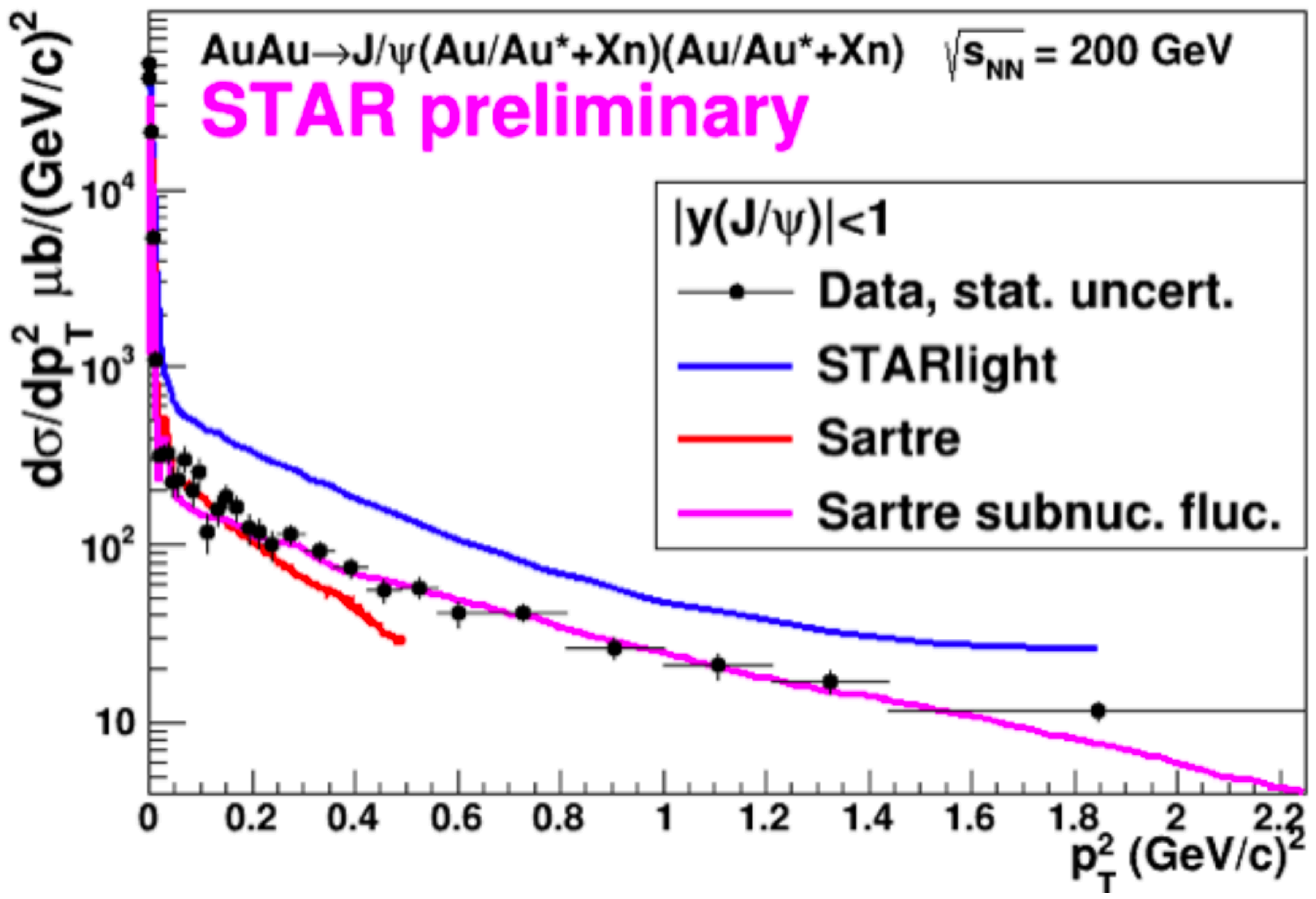
DIFFRACTIVE J/ψ PRODUCTION IN ULTRA PERIPHERAL COLLISIONS



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

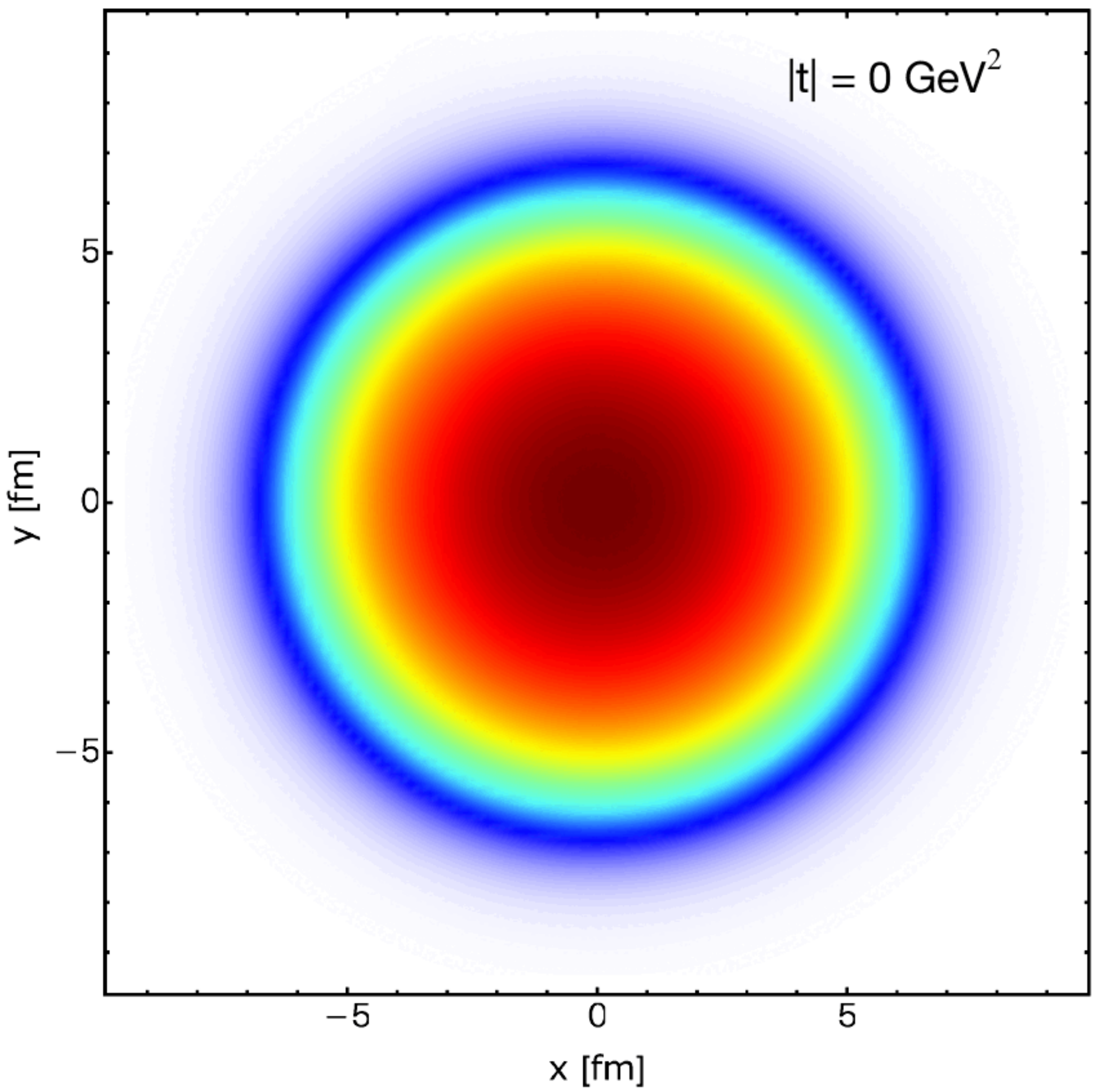


$$T_A(b) \rightarrow \frac{1}{N_q} \sum_{i=1}^{A} \sum_{j=1}^{N_q} T_q(b - b_i - b_j)$$



T.Toll SciPost Phys. Proc. 8 (2022) 148

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

Use our models to implement the 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

new data coming from LHC, CMS PAS HIN-22-002

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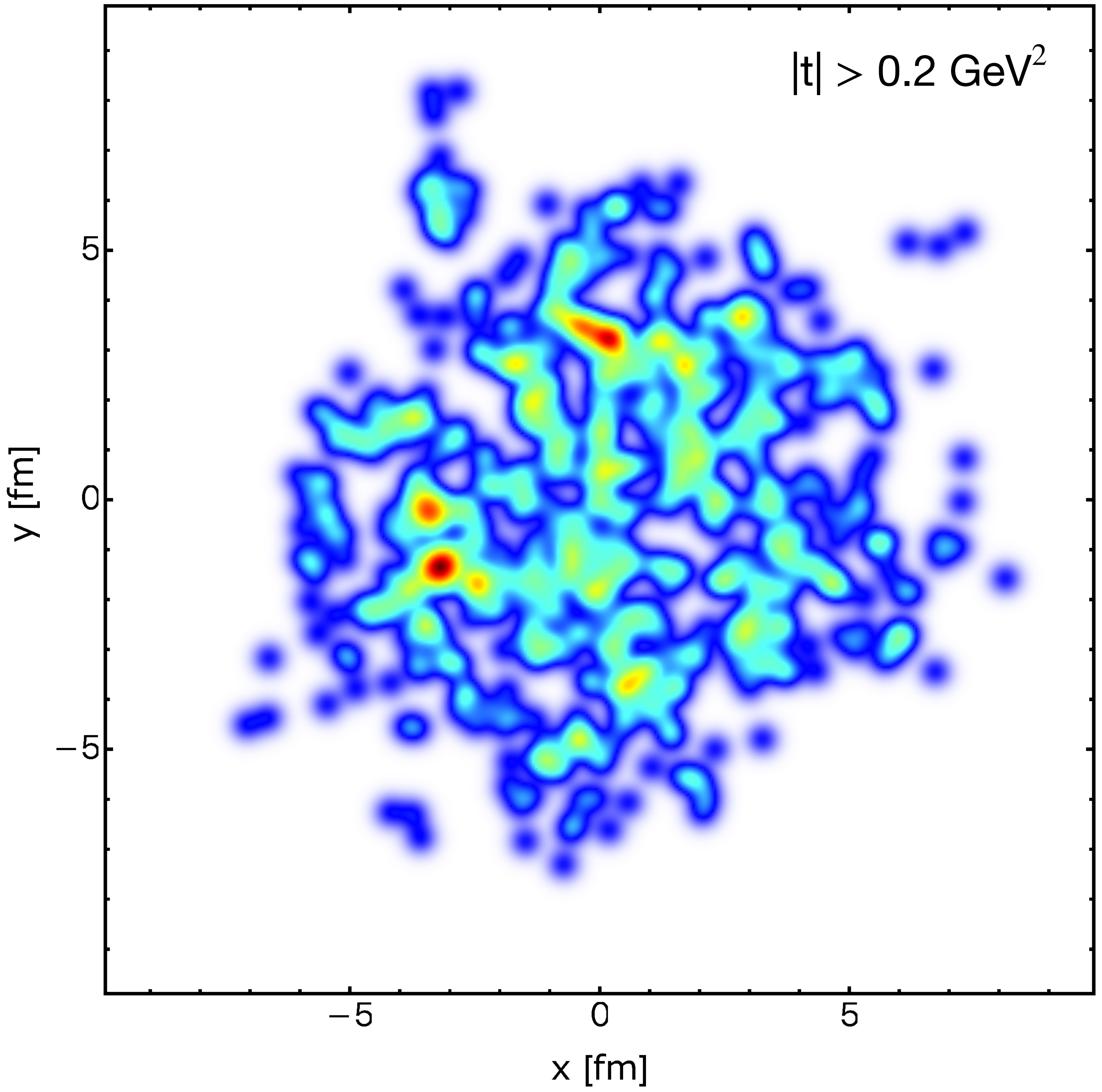

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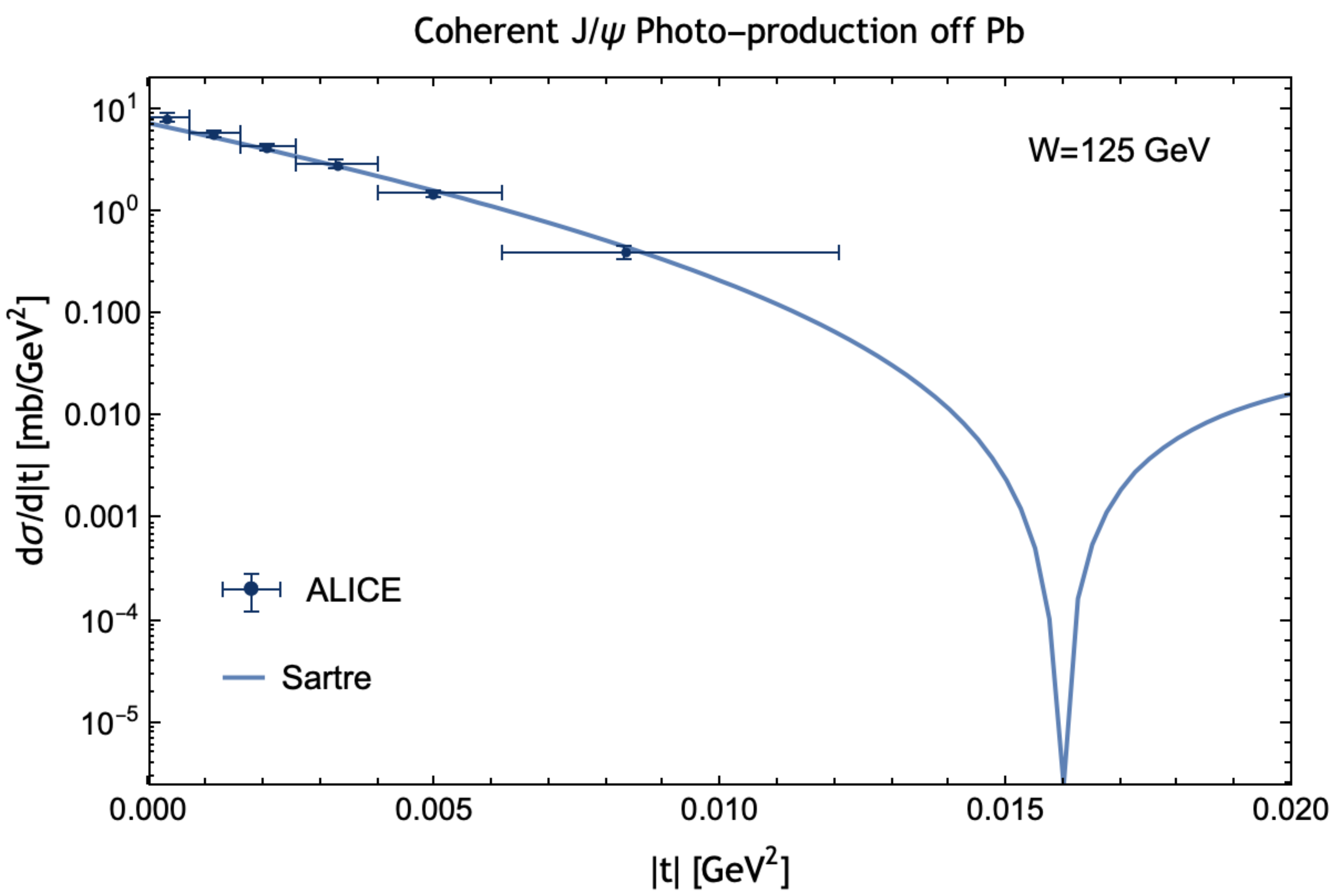
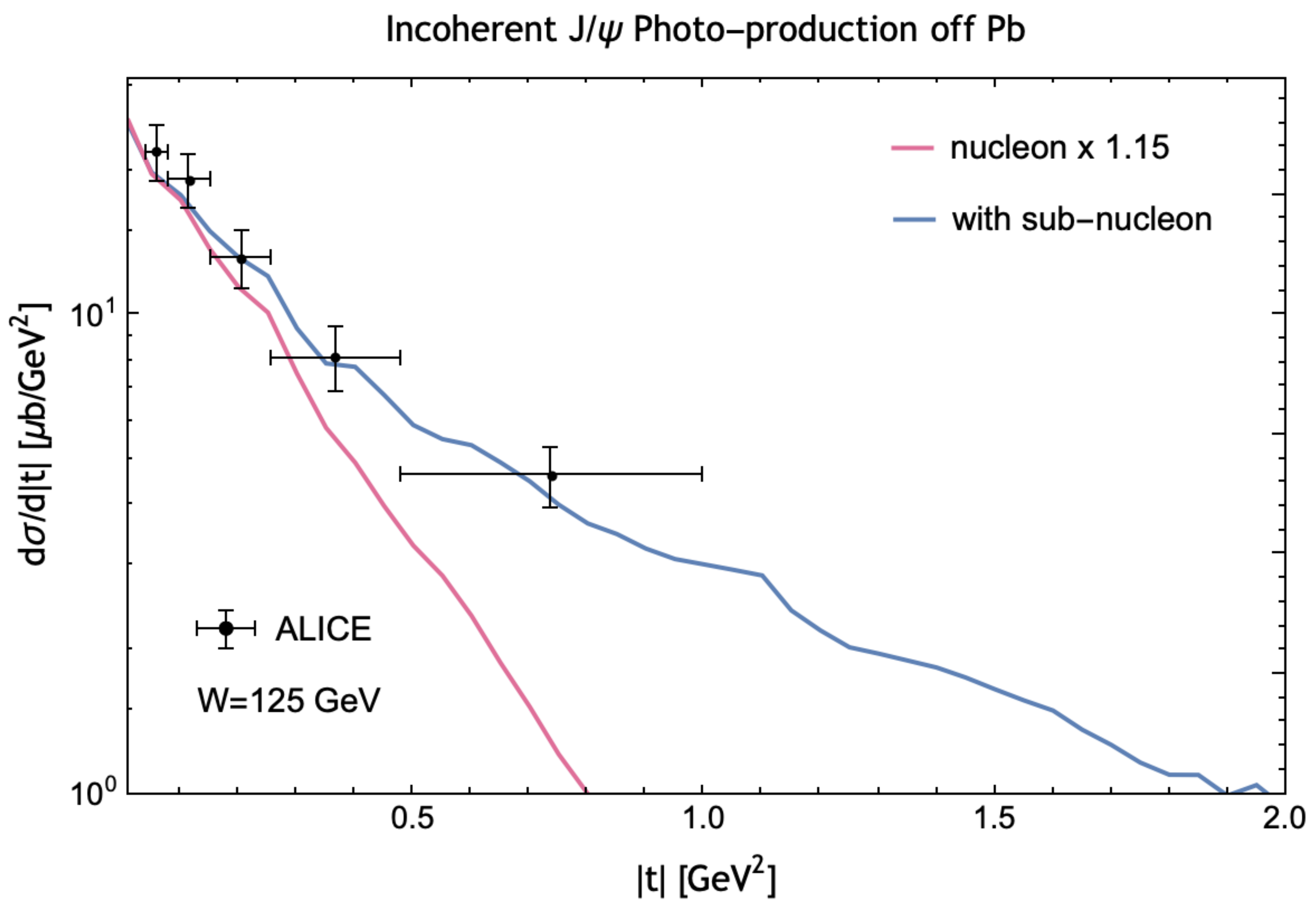
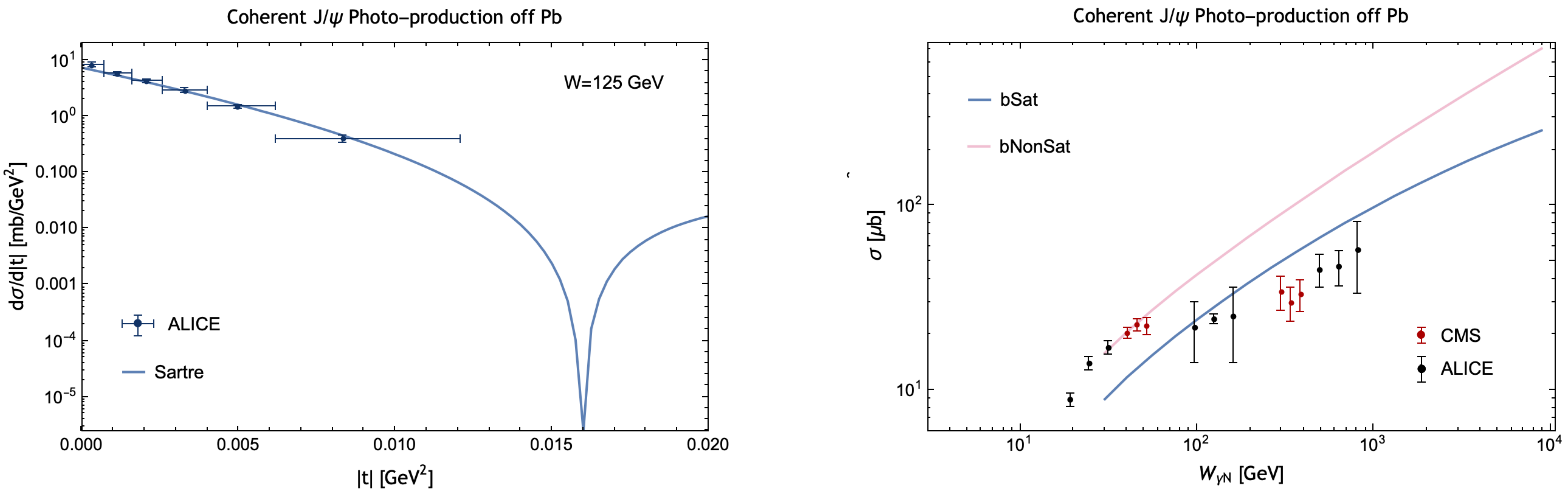




ongoing work with Manoj Kumar and T.Toll …

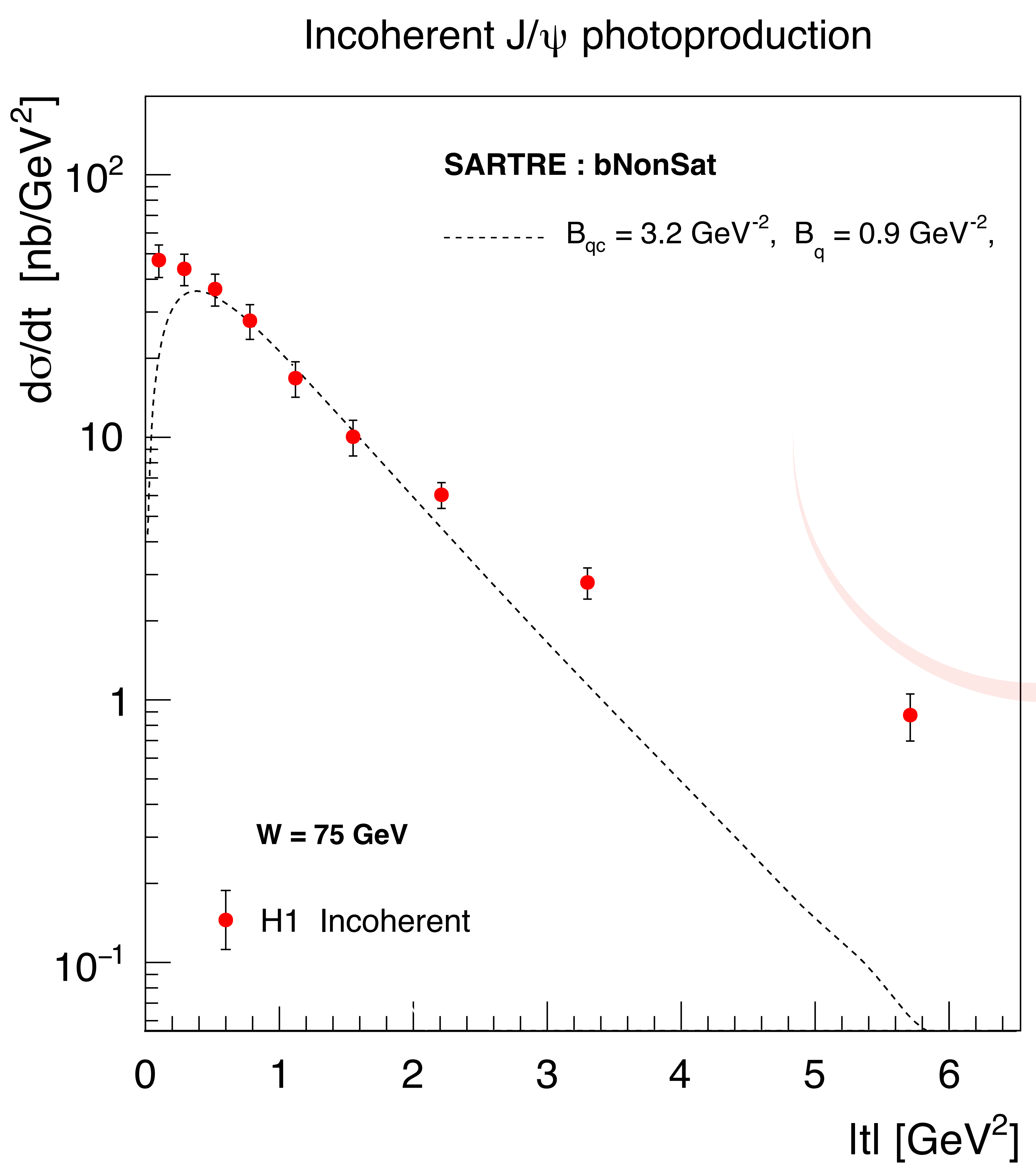
DIFFRACTIVE J/ψ PRODUCTION IN ULTRA PERIPHERAL COLLISIONS

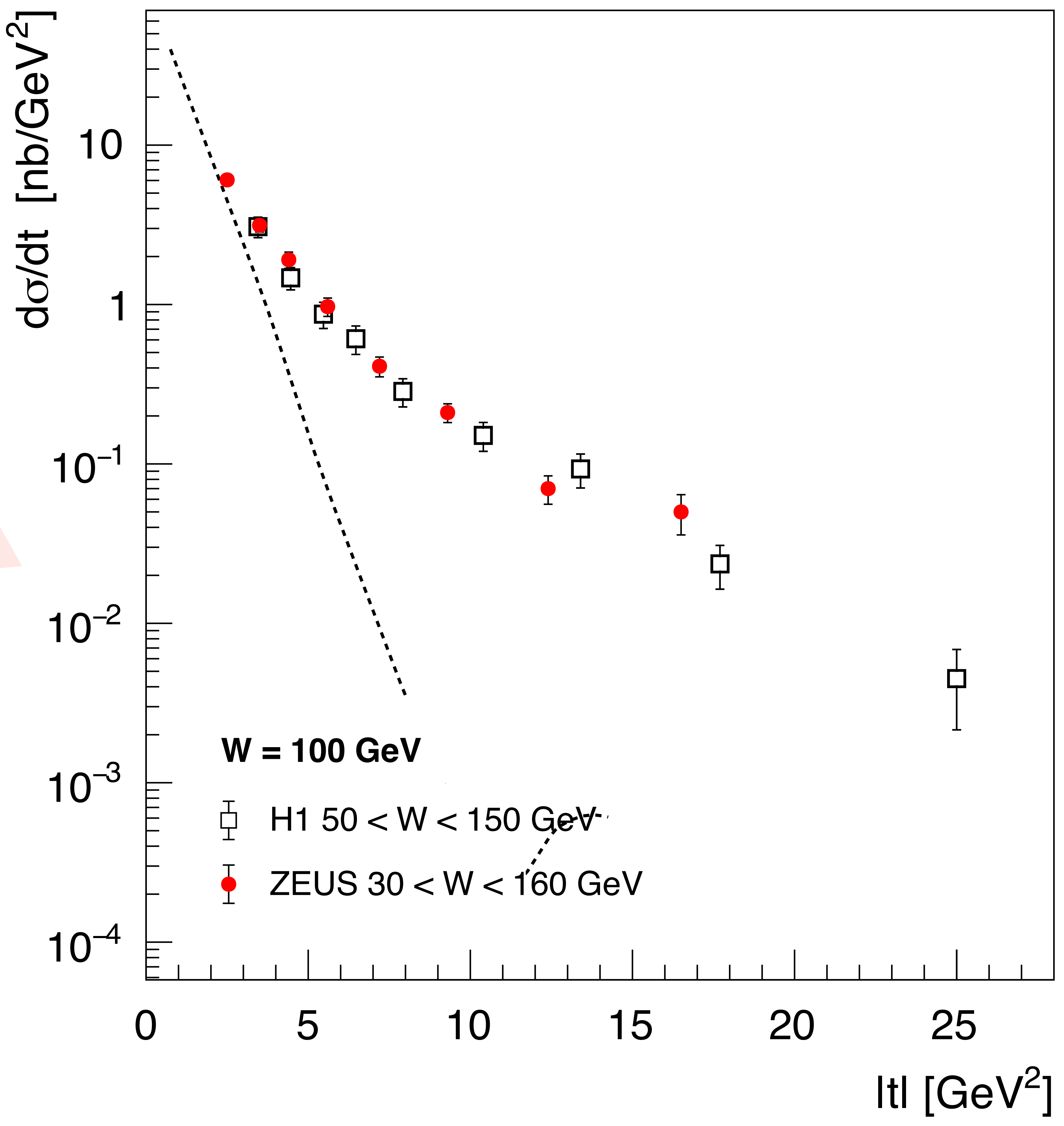


Crucial to understand whether the suppression originates from perturbative (saturation models & small-x evolution) or non-perturbative (shadowing models) mechanisms? *look for new observables & investigate A dependence*

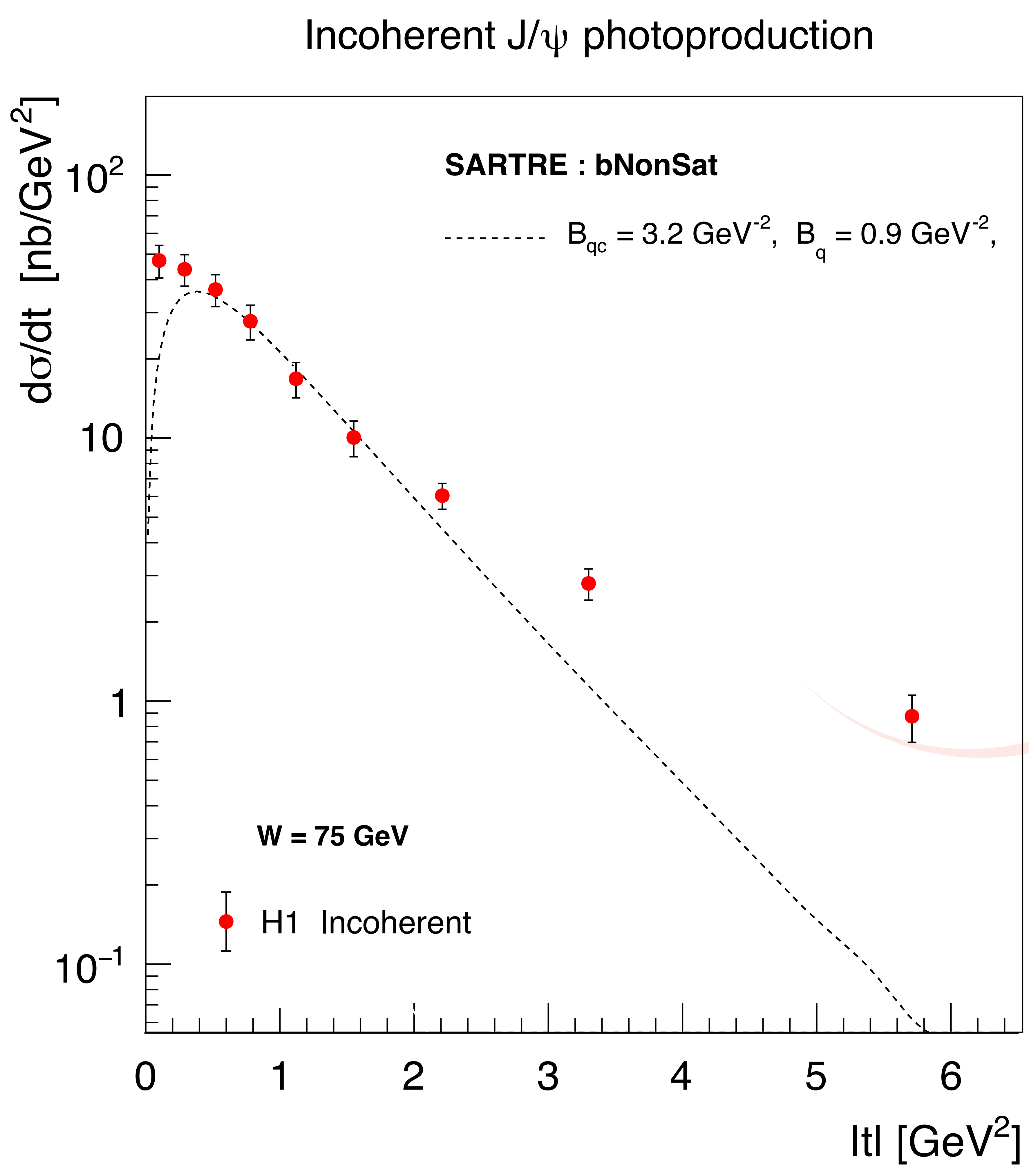
Y Kovchegov, H.Shun, Z.Tu *PRD* 109 (2024) 9, 094028

PROTON STRUCTURE AT LARGE MOMENTUM TRANSFER



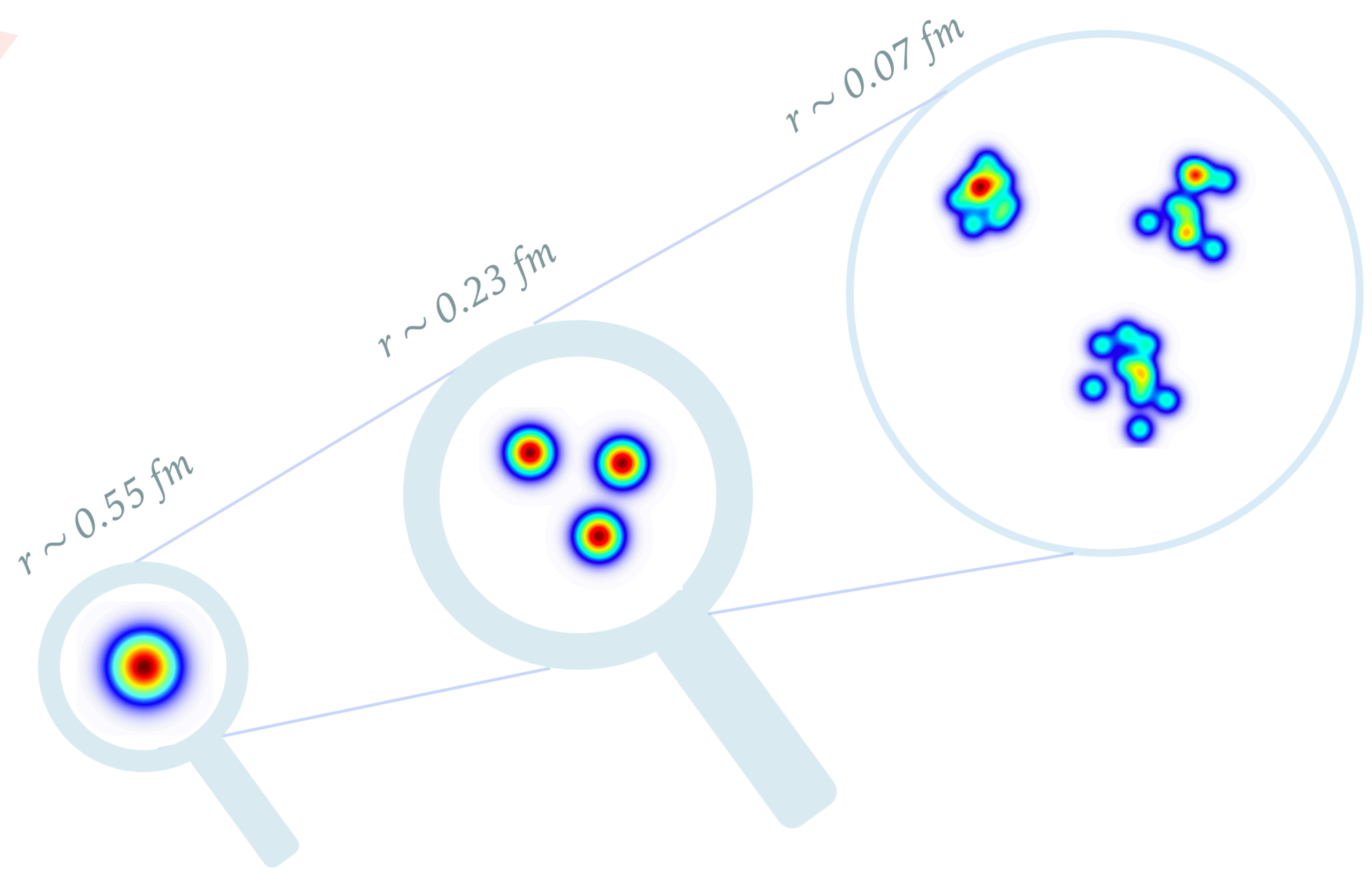


HOTSPOT MODEL AT LARGE MOMENTUM TRANSFER



A.K,Tobias Toll EPJC 82 (2022) 837

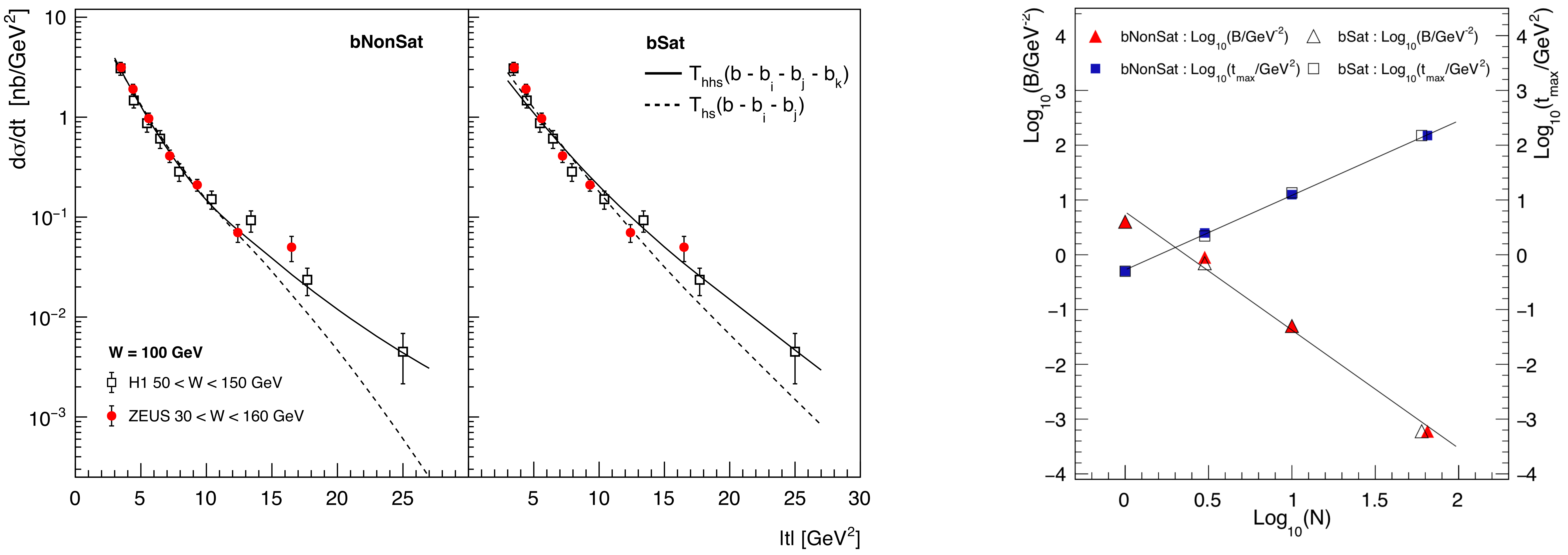
What substructure and size fluctuations would describe the data ?



HOTSPOT MODEL AT LARGE MOMENTUM TRANSFER

$$T_P(b) \rightarrow \frac{1}{N_q N_{hs} N_{hhs}} \sum_{i=1}^{N_q} \sum_{j=1}^{N_{hs}} \sum_{k=1}^{N_{hhs}} T_{hhs}(\mathbf{b} - \mathbf{b_i} - \mathbf{b_j} - \mathbf{b_k})$$

Model	B_{qc}	B_q	N_q	B_{hs}	N_{hs}	B_{hhs}	N_{hhs}
bNonSat further refined hotspot	3.2	1.15	3	0.05	10	0.0006	65
bSat further refined hotspot	3.3	1.08	3	0.09	10	0.0006	60



A.K,Tobias Toll EPJC 82 (2022) 837

HOTSPOT MODEL AT LARGE MOMENTUM TRANSFER : INSIGHTS

- *Gluon density fixed by longitudinal structure $xg(x)$ (No more splittings as in DGLAP)*
- *The transverse gluon structure*
  - *Appears to become dilute at large $|t|$*
  - *Scaling behaviour*

This suggests we can describe the t-spectrum with a linear scale independent (in log $|t|$) evolution for the increasing number of hotspots

Hotspot evolution model -

analogy : resolution in optics

Picture : Transverse part of gluon wavefunction probed with areal resolution $\delta b^2 \sim \frac{1}{|t|}$, increased resolution leads to hotspot splittings

- *Initial state at $t = t_0$: Hotspot model*

$B_{qc} = 3.1\ GeV^{-2}$

$B_q = 1.25\ GeV^{-2}$

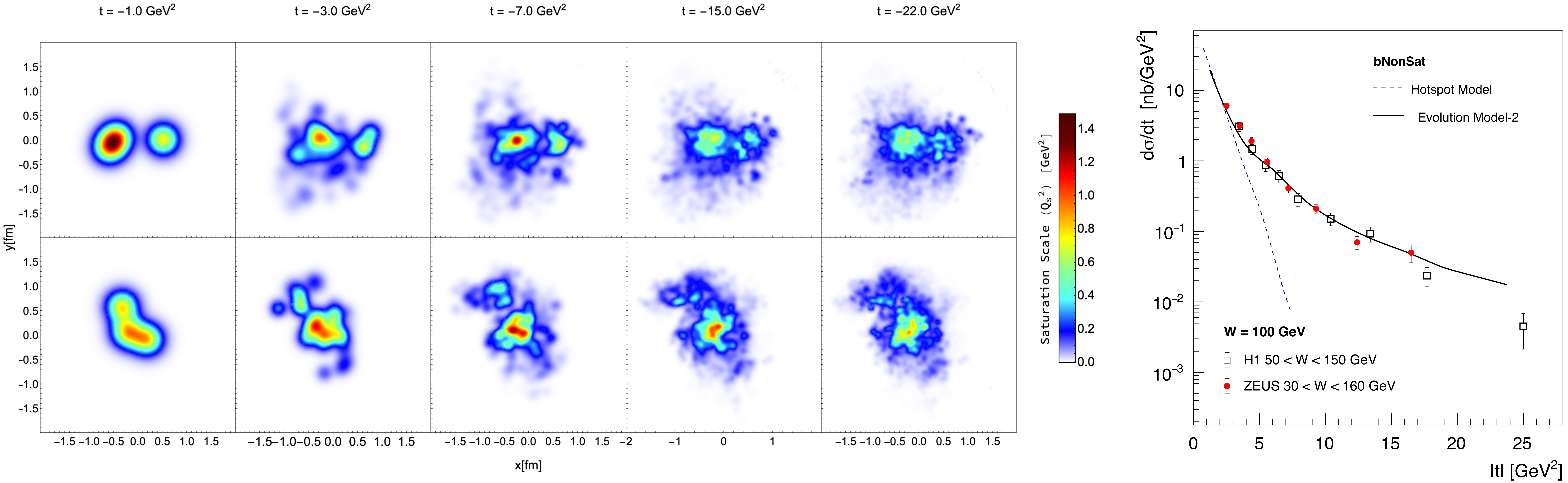
$N_q = 3$

Evolution for $t > t_0$

$$\frac{d\mathscr{P}_{split}}{dt} = \frac{\alpha}{|t|}, \quad \frac{d\mathscr{P}_{no-split}}{dt} = \exp\left(-\int_{t_0}^{t} dt' \frac{d\mathscr{P}_{split}}{dt'}\right) = \left(\frac{t_0}{t}\right)^{\alpha}$$

$$\frac{d\mathscr{P}_a}{dt} = \frac{\alpha}{t}\left(\frac{t_0}{t}\right)^{\alpha}$$

HOTSPOT EVOLUTION MODEL

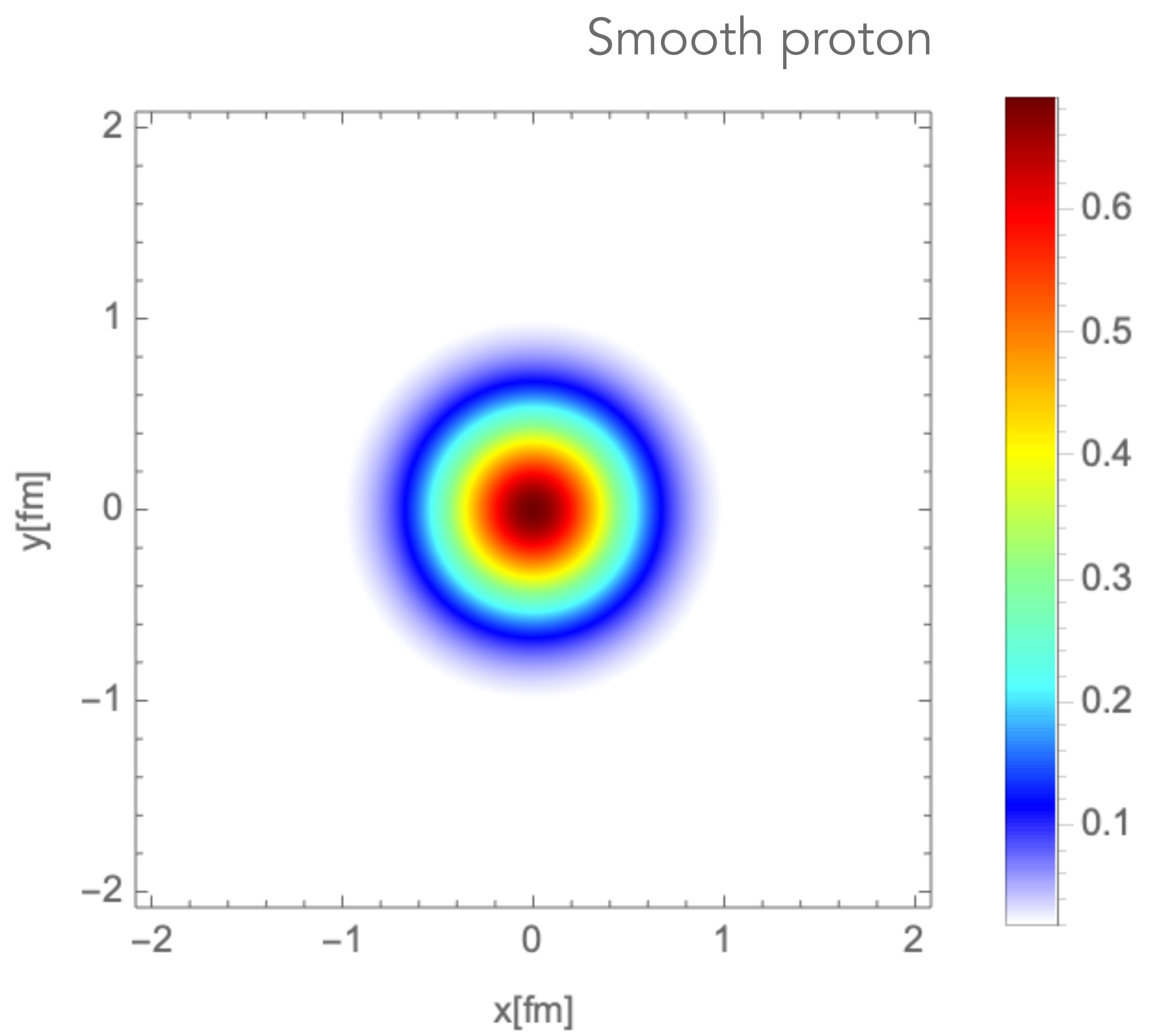


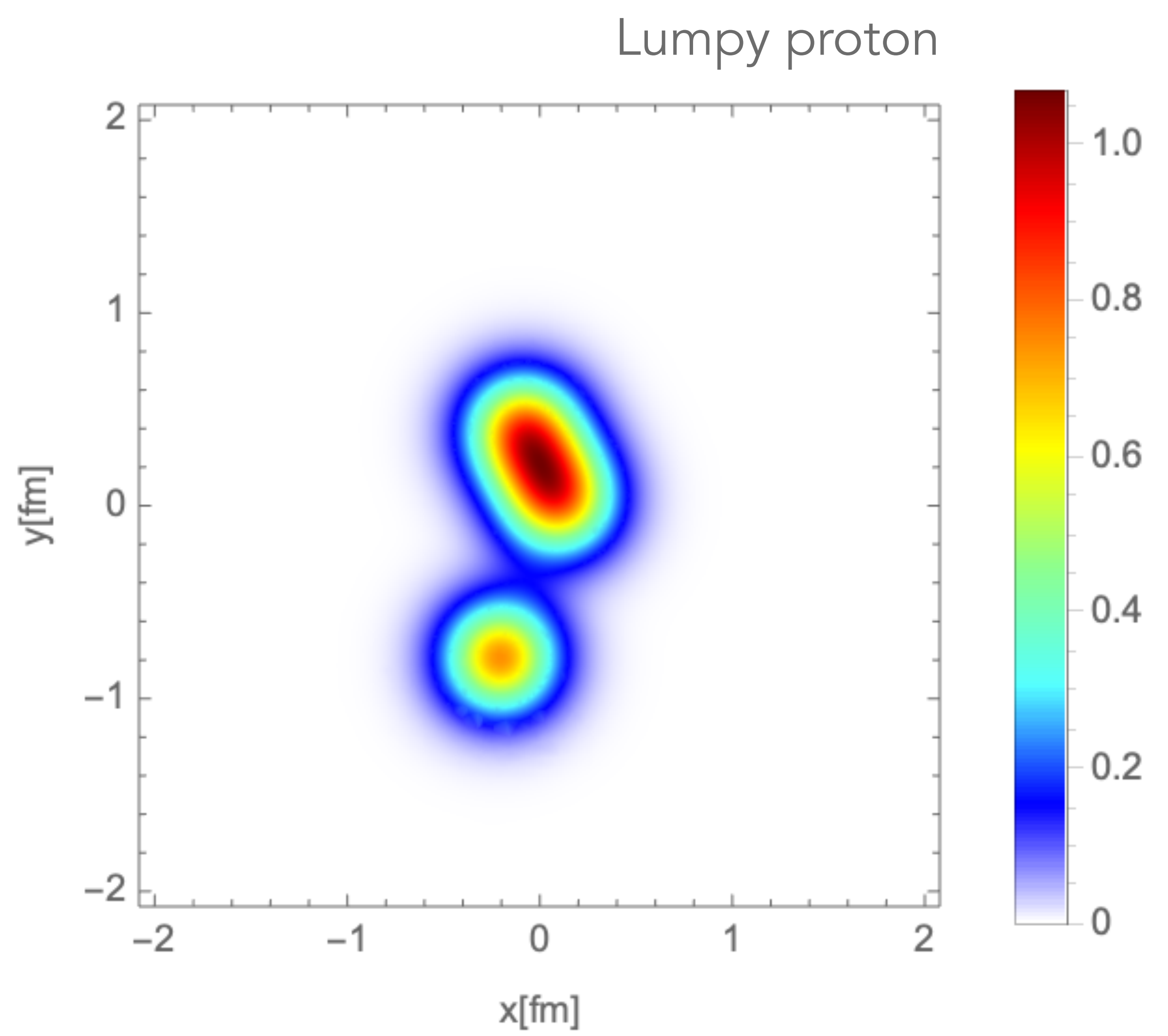
Could be really interesting to measure the nucleon structure or substructure at large-t in *eA* and compare it with *ep* ……..

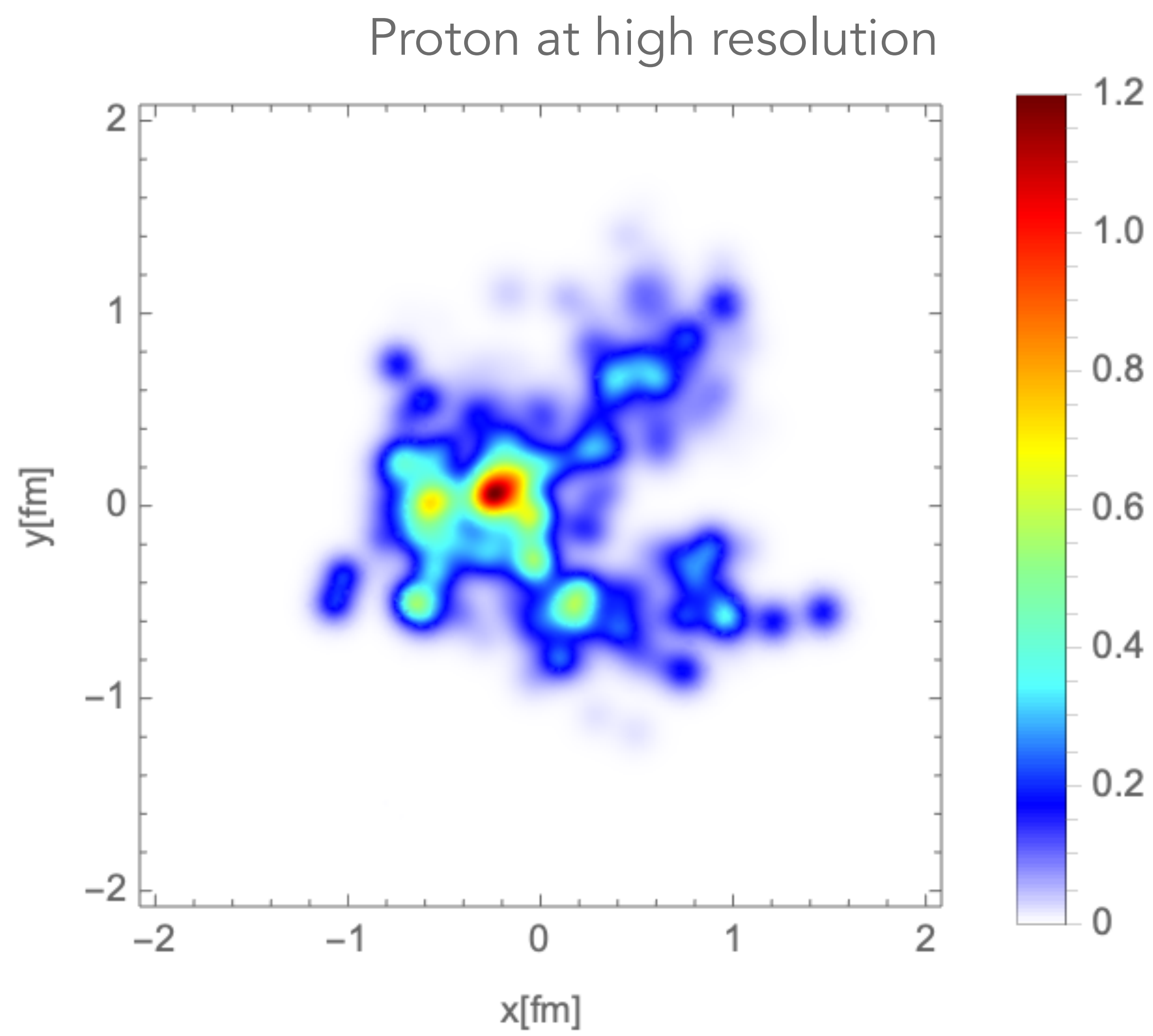
Can EIC do this?

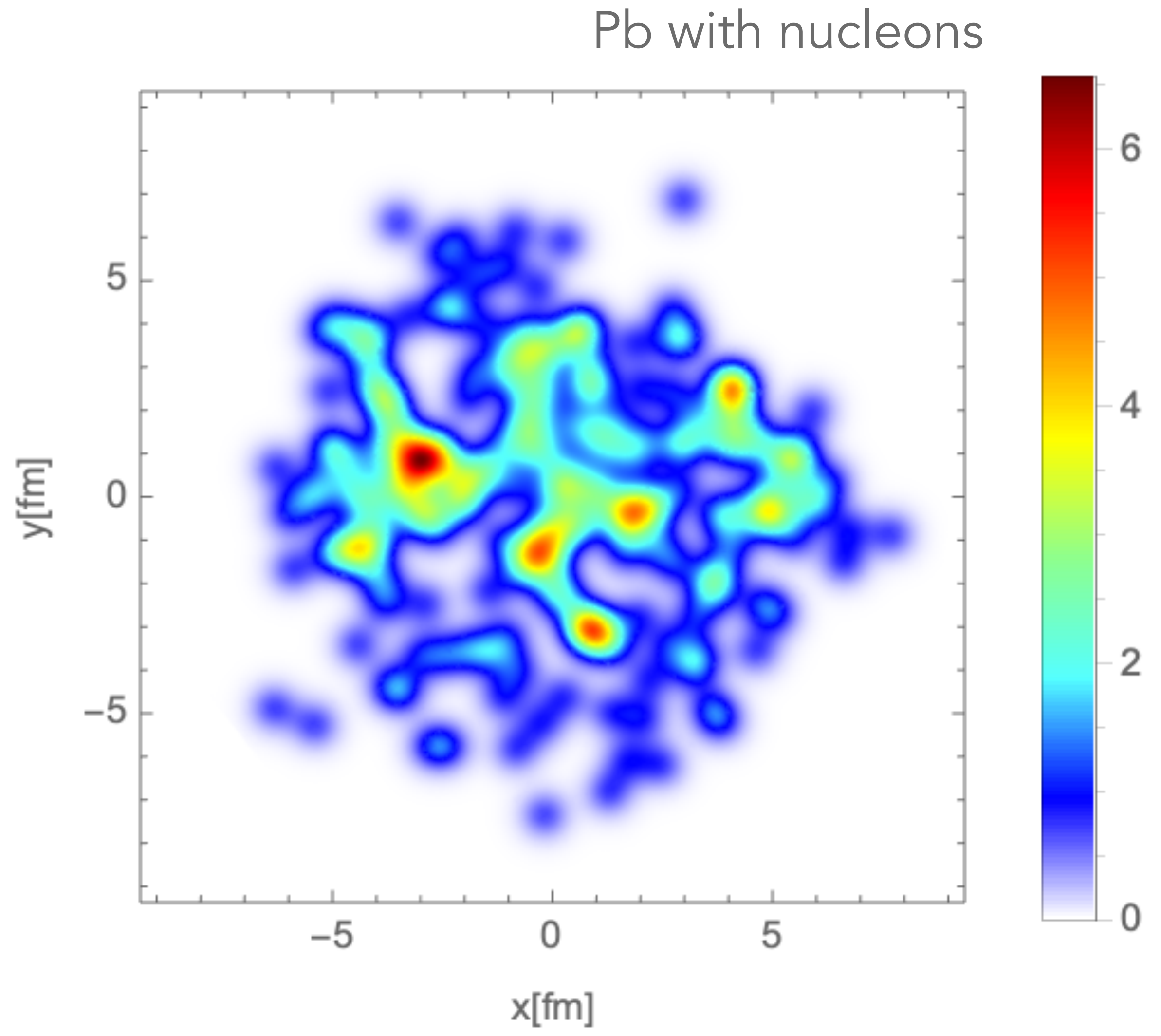
SATURATION SCALE FLUCTUATIONS

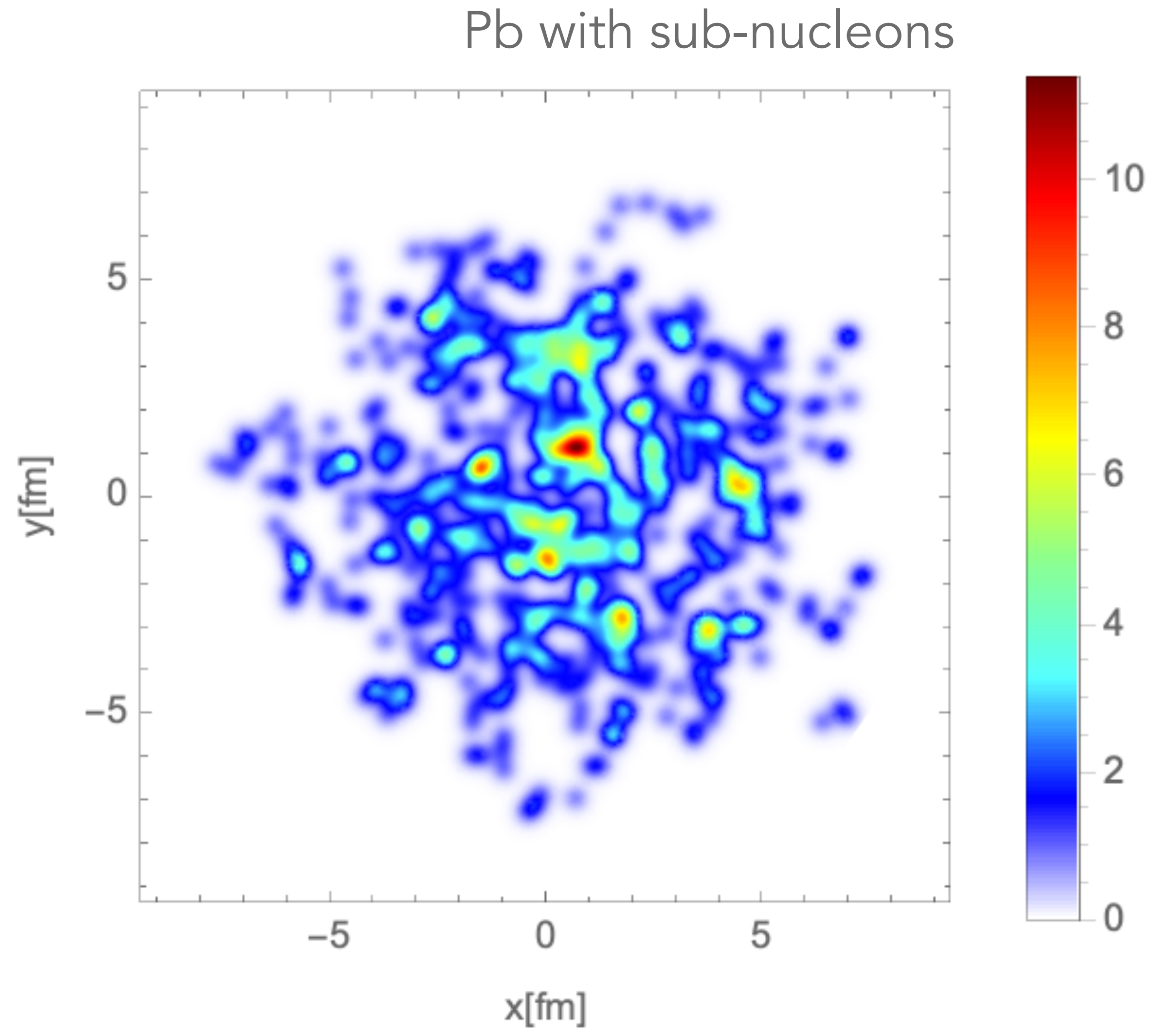
$$Q_s^2 = \frac{2}{r_s^2},\ \ \frac{1}{2} = \frac{\pi^2}{2N_C} r^2 \alpha_s(\mu^2) x g(x,\mu^2) T_p(b)$$









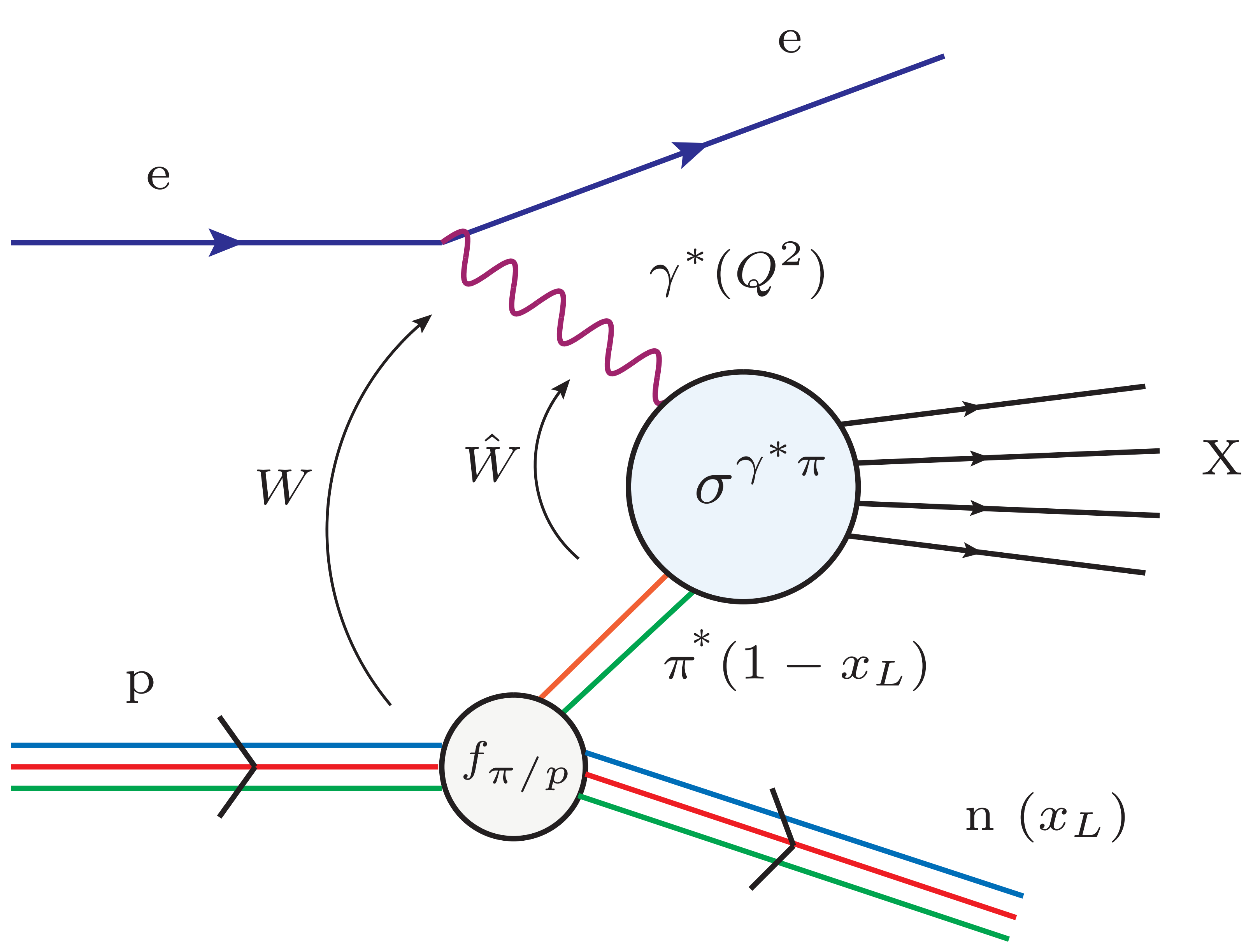


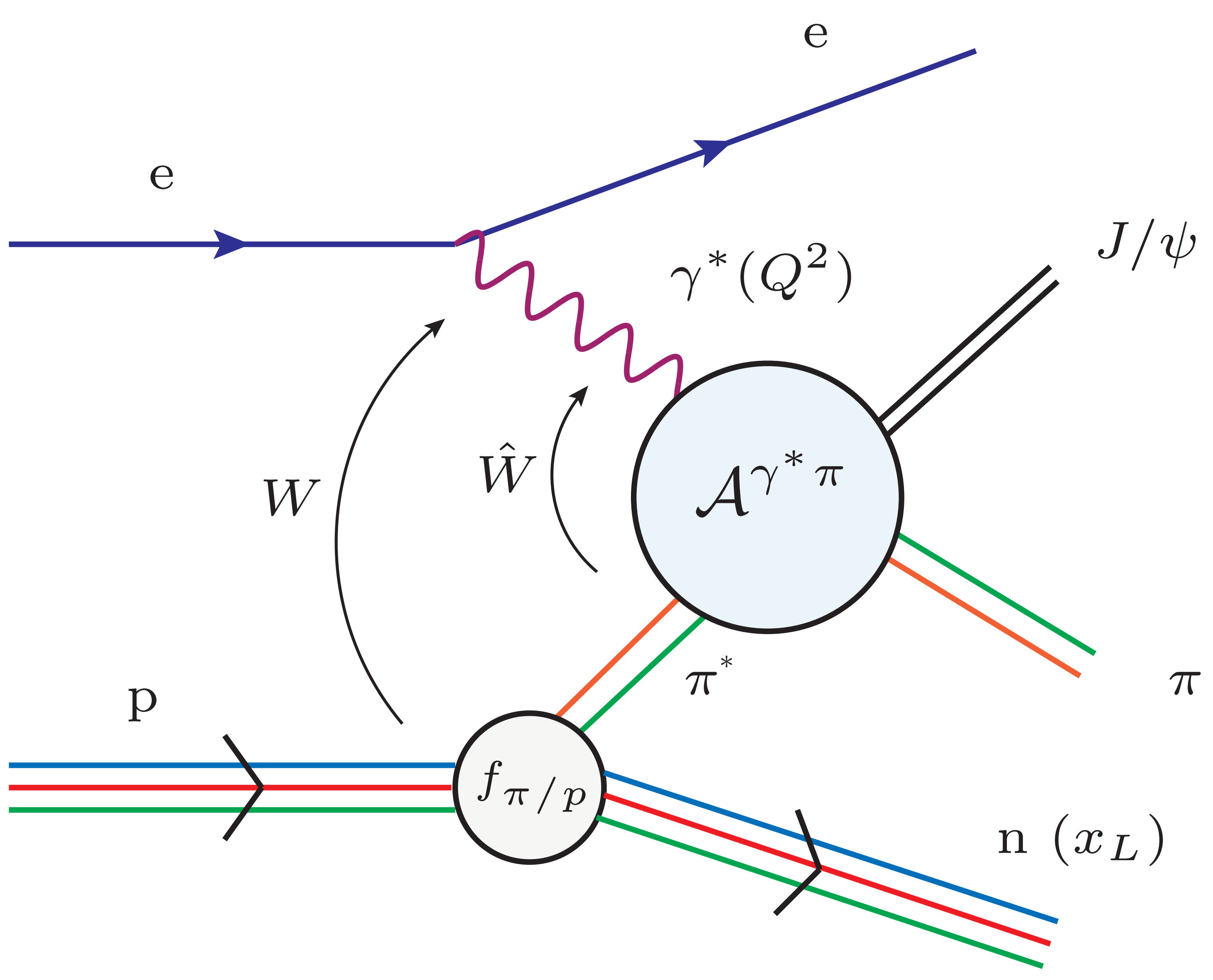
- $Q_S \sim T(b)$
- Large saturation scale fluctuations due to fluctuations in geometry
- For nuclei, saturation scale is highly enhanced; non-linear effects are large

A.K.,Tobias Toll, arXiv:2403.13631

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*

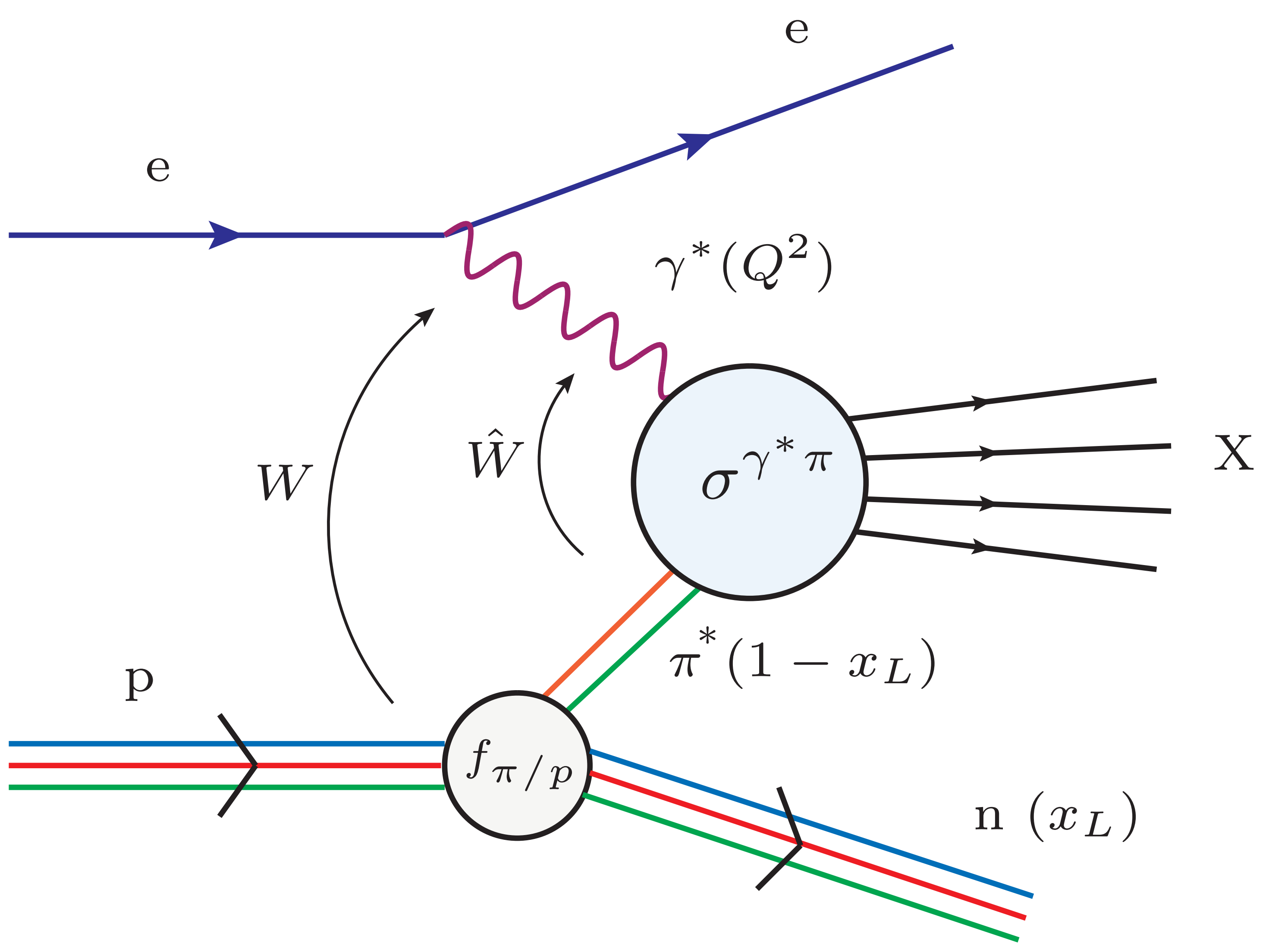
★ *Sensitive to longitudinal structure of pion*

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:

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

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

PION STRUCTURE IN LEADING NEUTRON EVENTS

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

Implemented in Sartre at the level of cross sections

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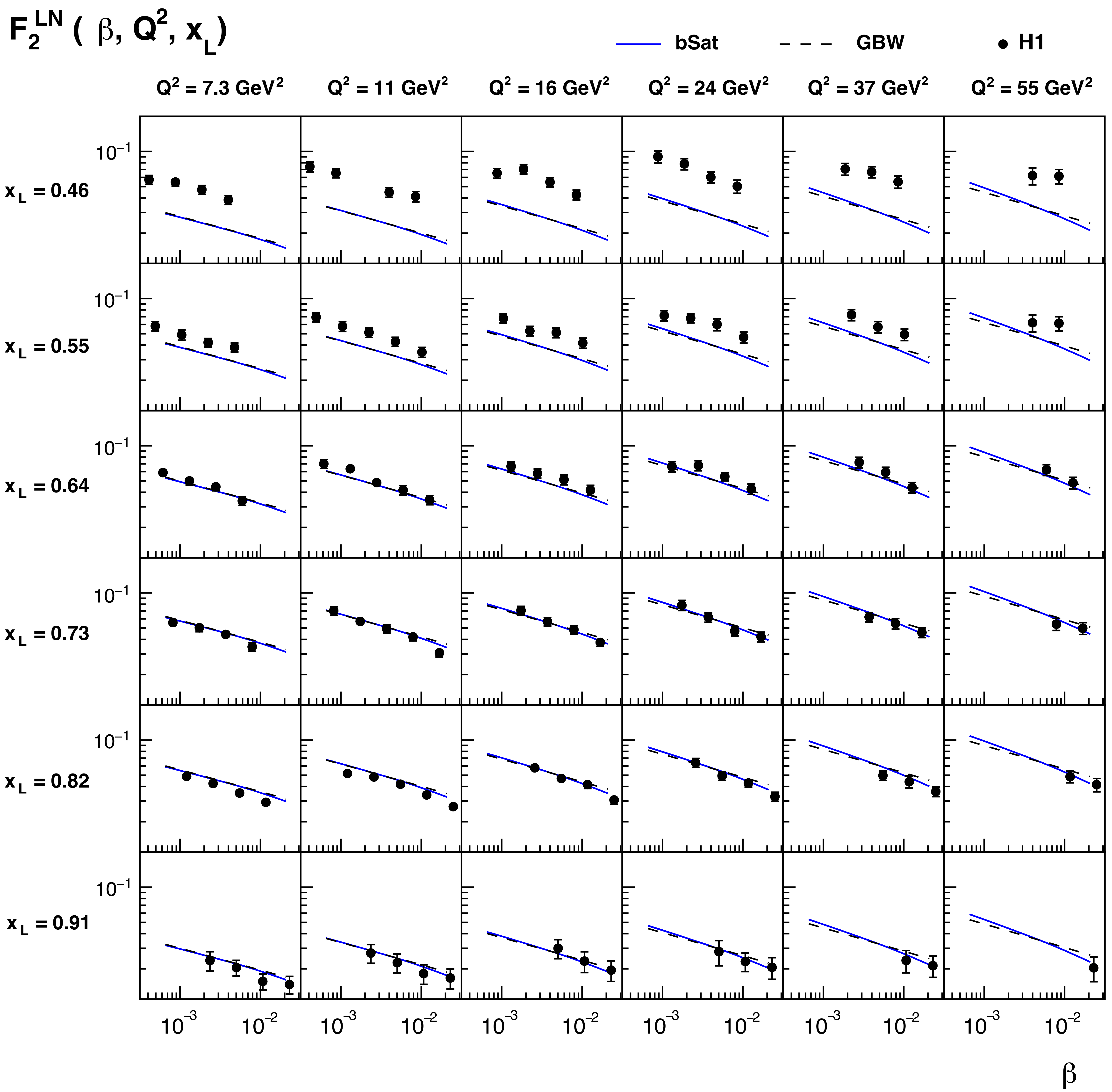
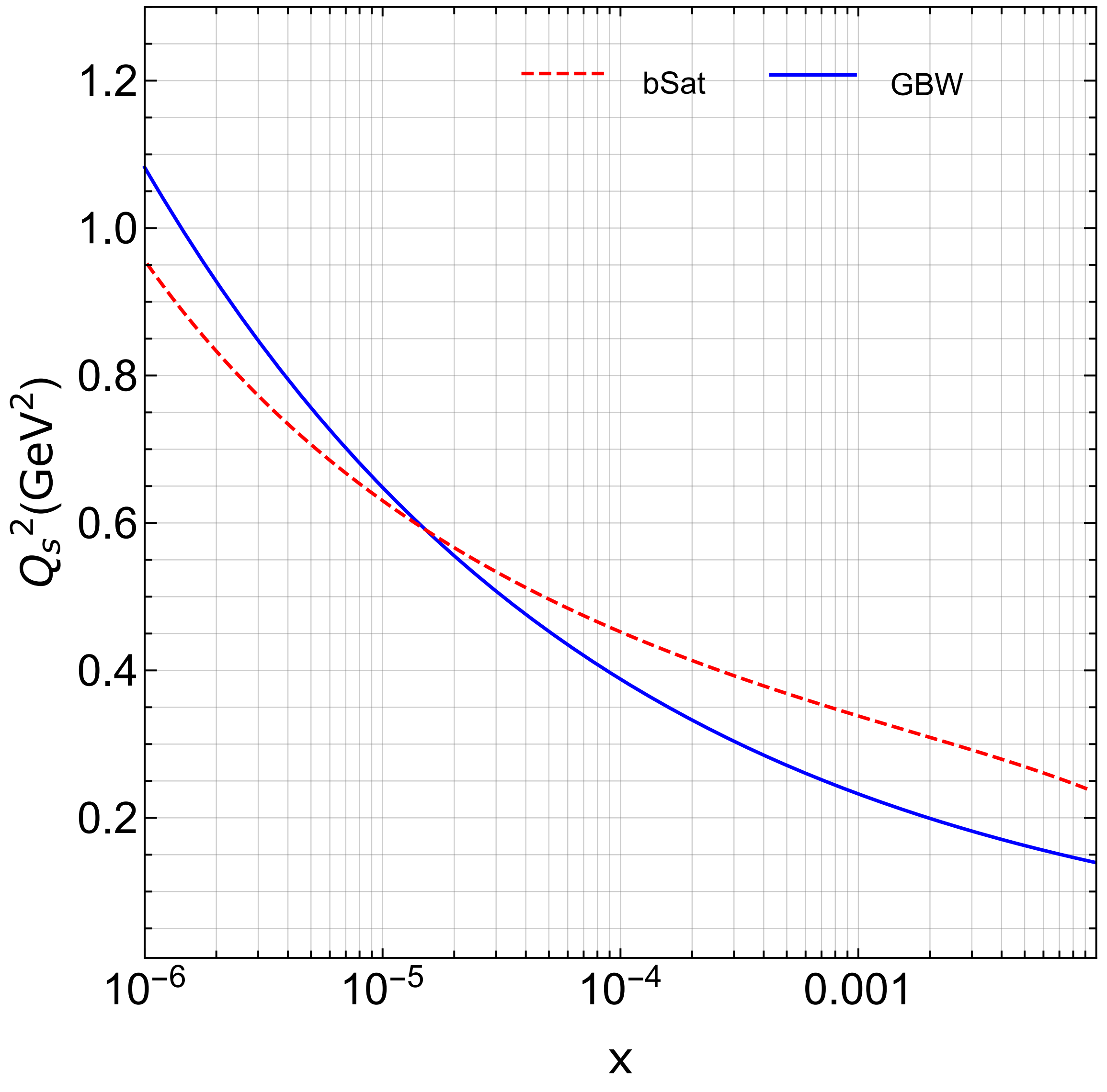
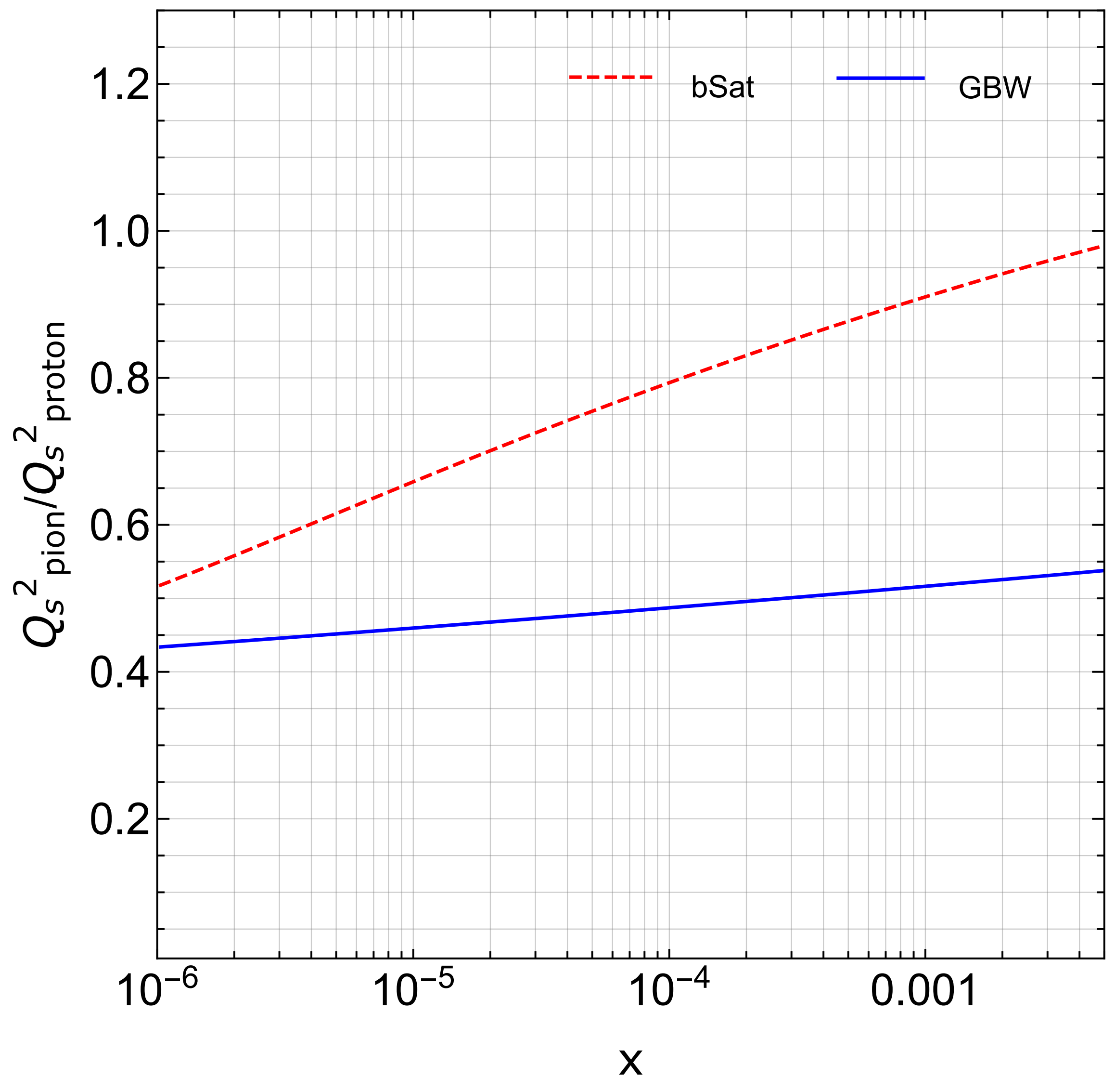
LEADING NEUTRON STRUCTURE FUNCTION



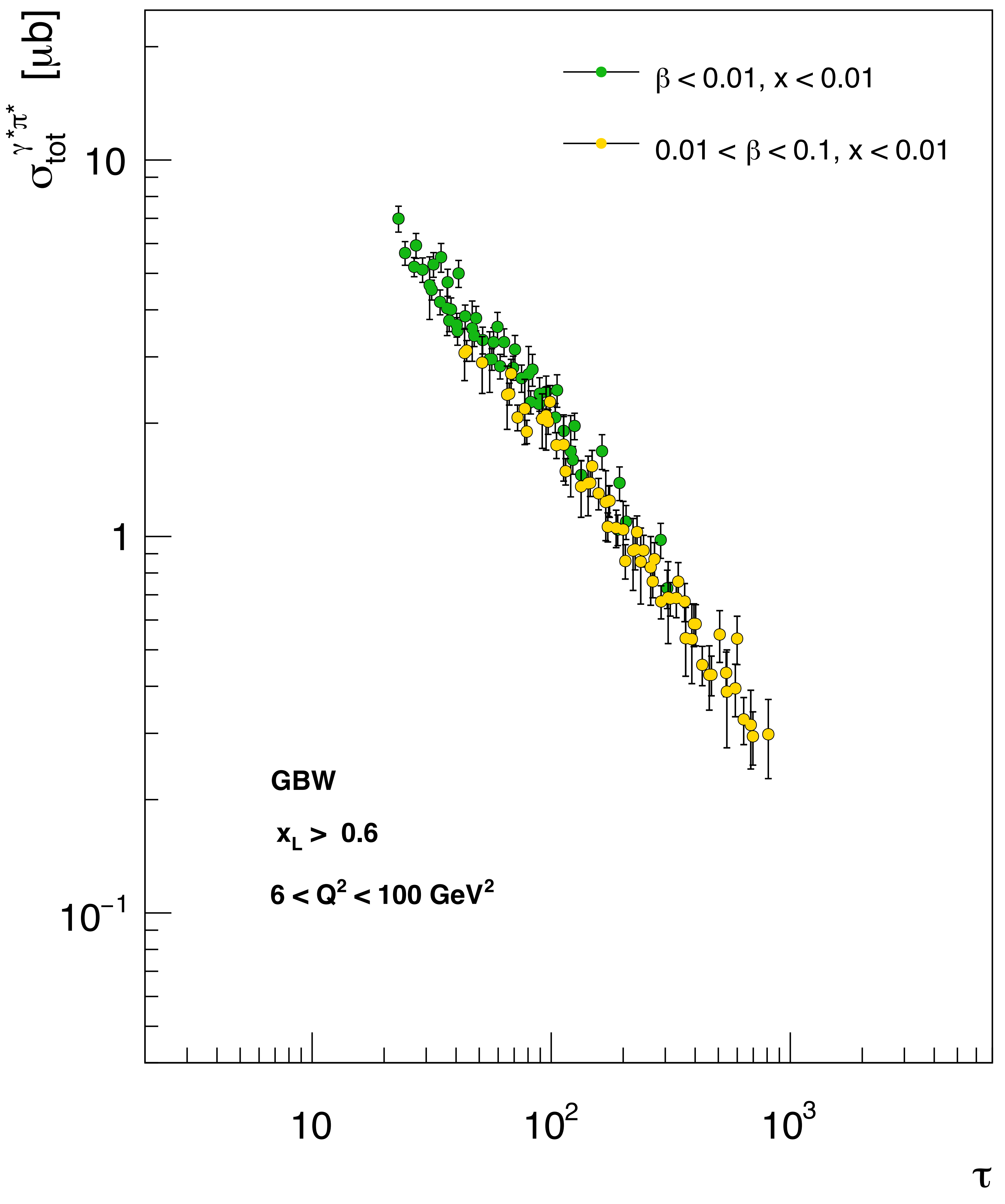
A.K PRD 107 (2023) 034005





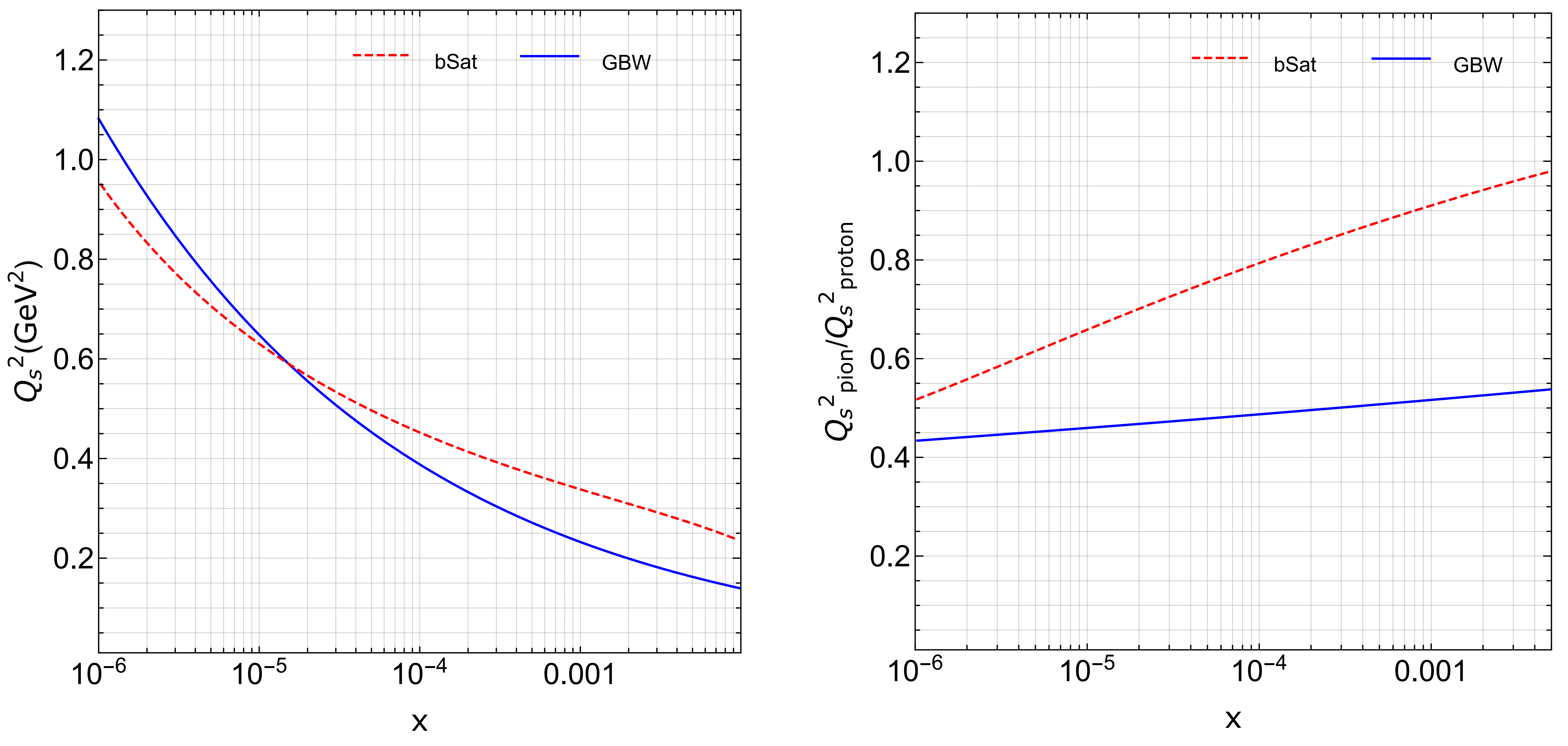
GBW	σ_0 [mb]	λ	$x_0/10^{-4}$	R_q	$\chi^2/N_{\rm dof}$
Fit 1	17.171 ± 2.777	0.223 ± 0.018	0.036 ± 0.024	...	$63.26/48 = 1.32$
Fit 2	27.43	0.248	0.40	0.438 ± 0.005	$64.52/50 = 1.29$
bSat	A_g	λ_g	C	R_q	$\chi^2/N_{\rm dof}$
Fit 3	1.208 ± 0.012	0.0600 ± 0.038	1.453 ± 0.024	...	$58.75/48 = 1.22$
Fit 4	2.195	0.0829	2.289	0.520 ± 0.006	$66.19/50 = 1.32$

GEOMETRIC SCALING IN LEADING NEUTRON EVENTS



A.K PRD 107 (2023) 034005

The total cross section shows geometric scaling when plotted against $\tau = \frac{Q^2}{Q_s^2(\beta)}$; $Q_s^2(\beta) = Q_0^2\left(\frac{\beta}{x_0}\right)^{-\lambda}$



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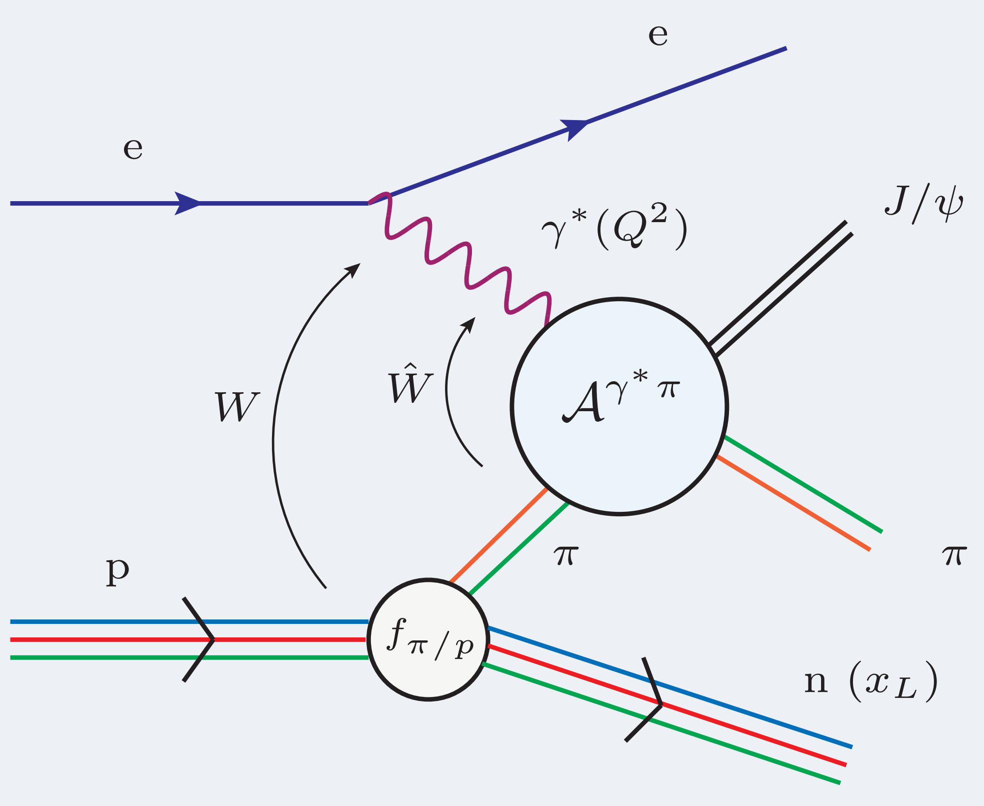
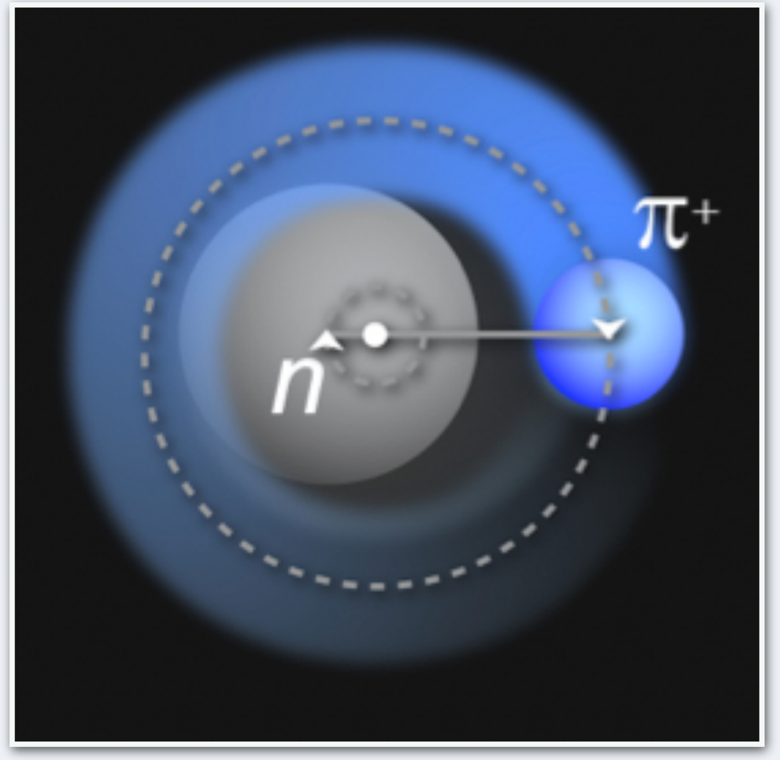
PROBING THE GLUON DISTRIBUTION





❖ 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:

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

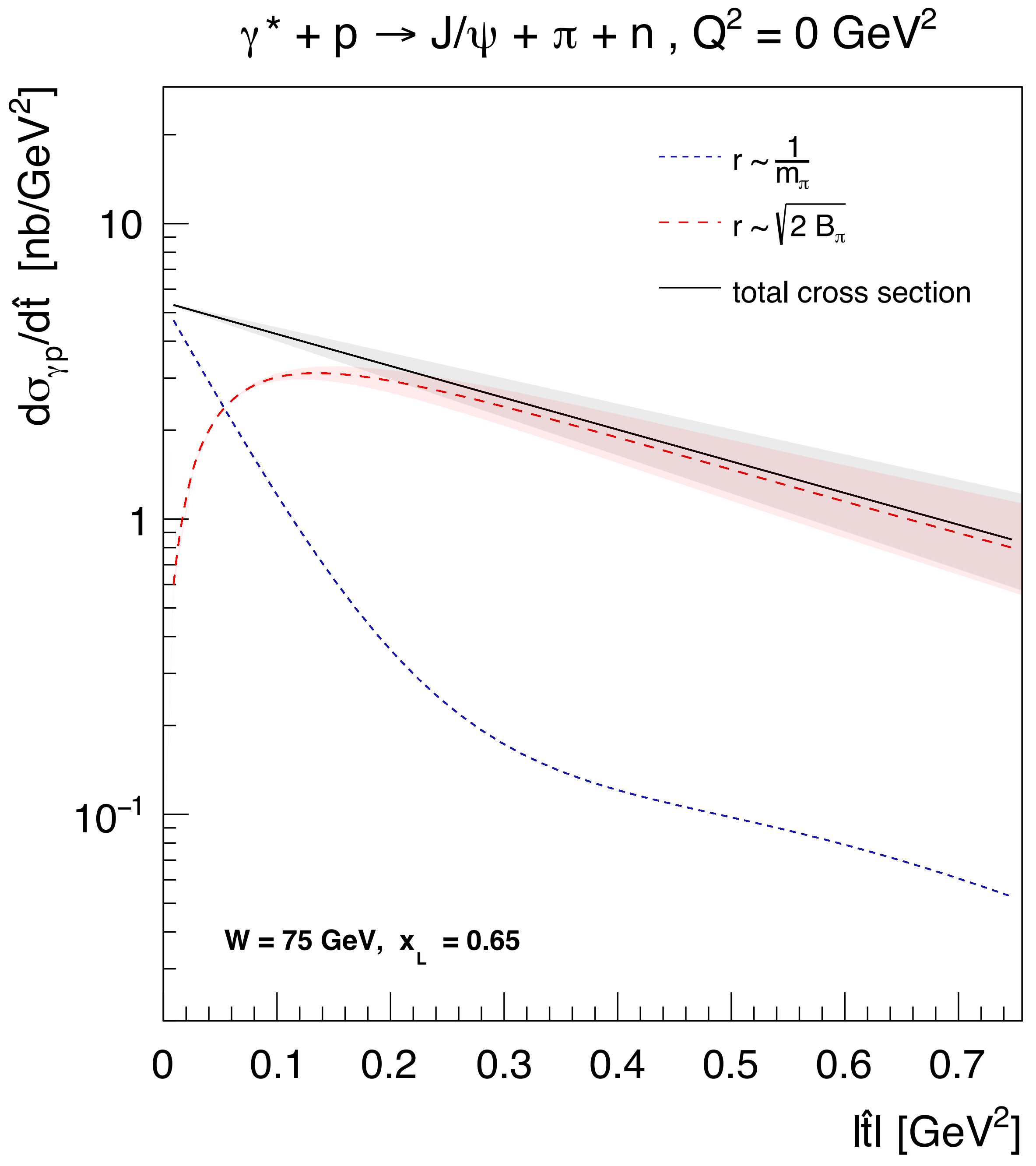
❖ At small $|t'|$, the dipole cannot resolve the pion and interacts with the whole cloud and on increasing the resolution $(increasing\ |t'|)$ the dipole interacts with the pion

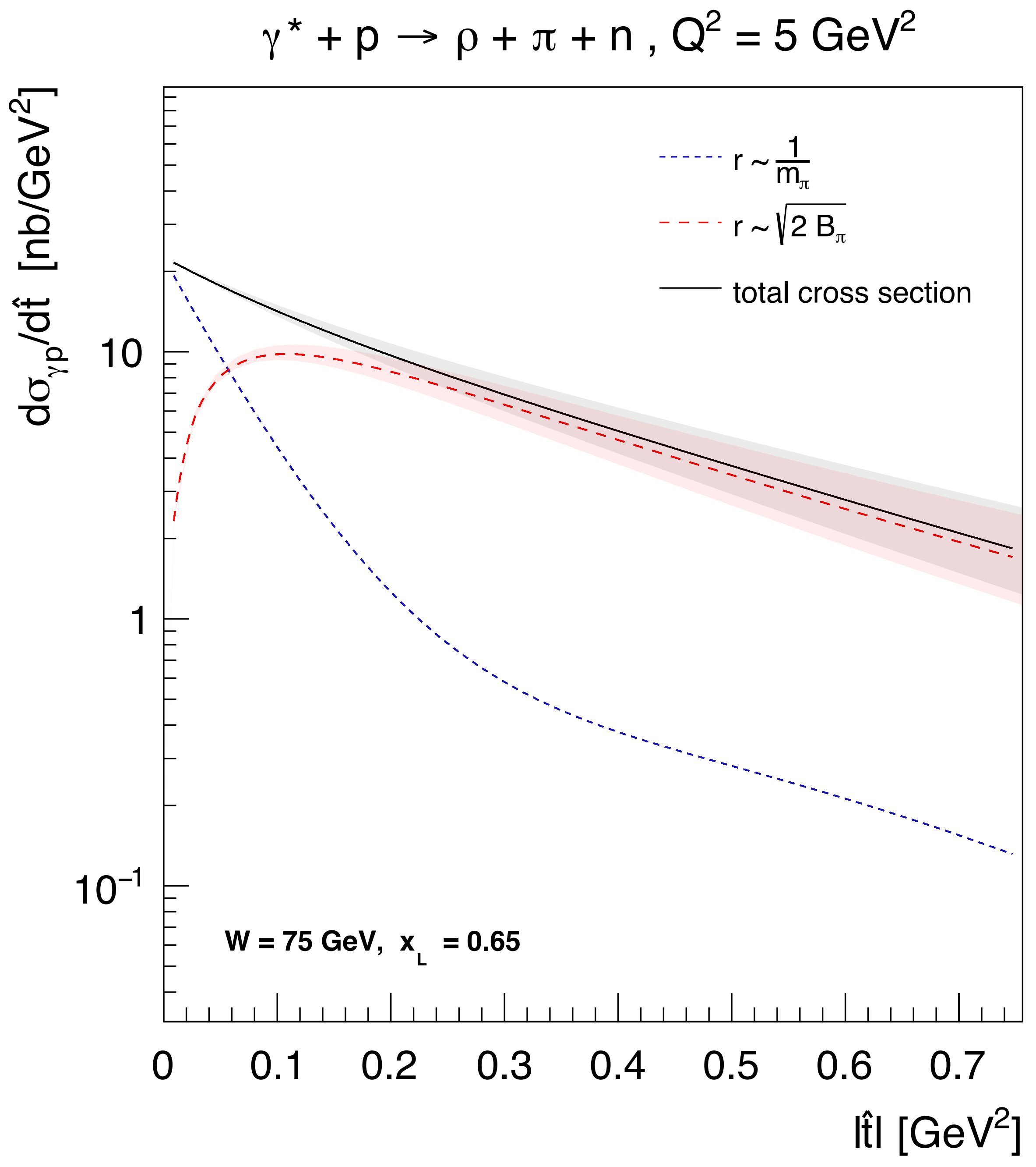
❖ The transverse position of the pion inside the virtual pion cloud fluctuates event by event

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

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

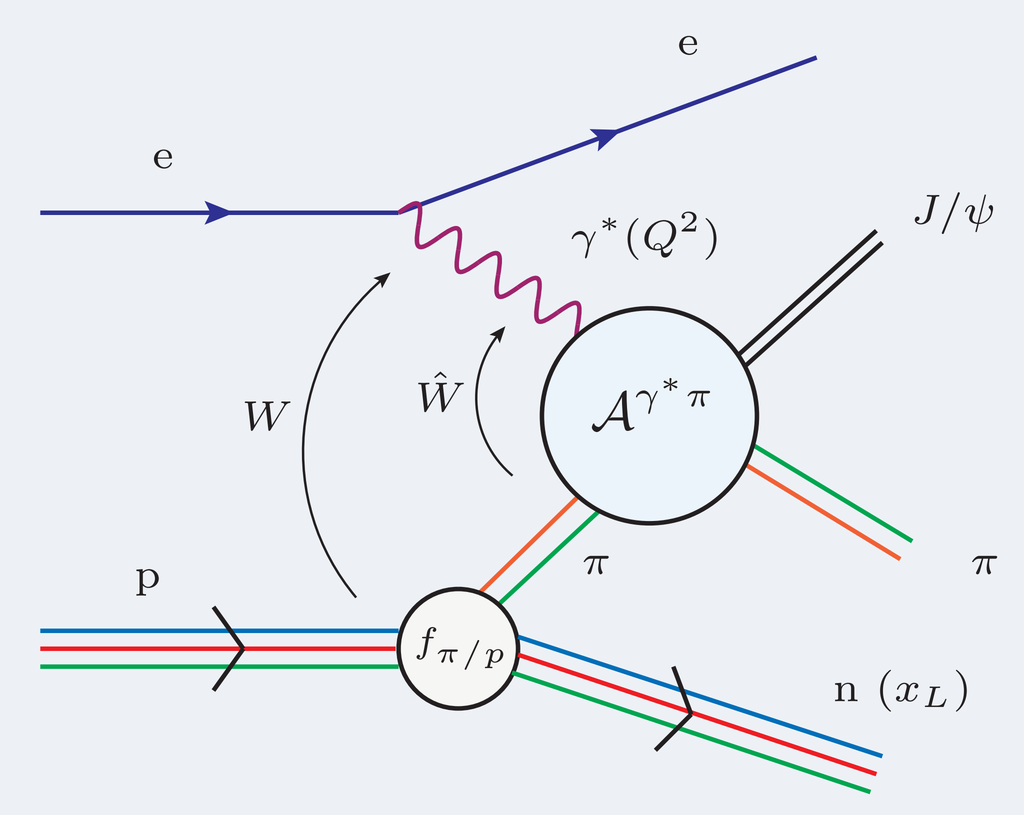
$$\sigma_{tot} \propto | < \mathscr{A} >_\Omega |^2 + (< | \mathscr{A} |^2 >_\Omega - | < \mathscr{A} >_\Omega |^2)$$

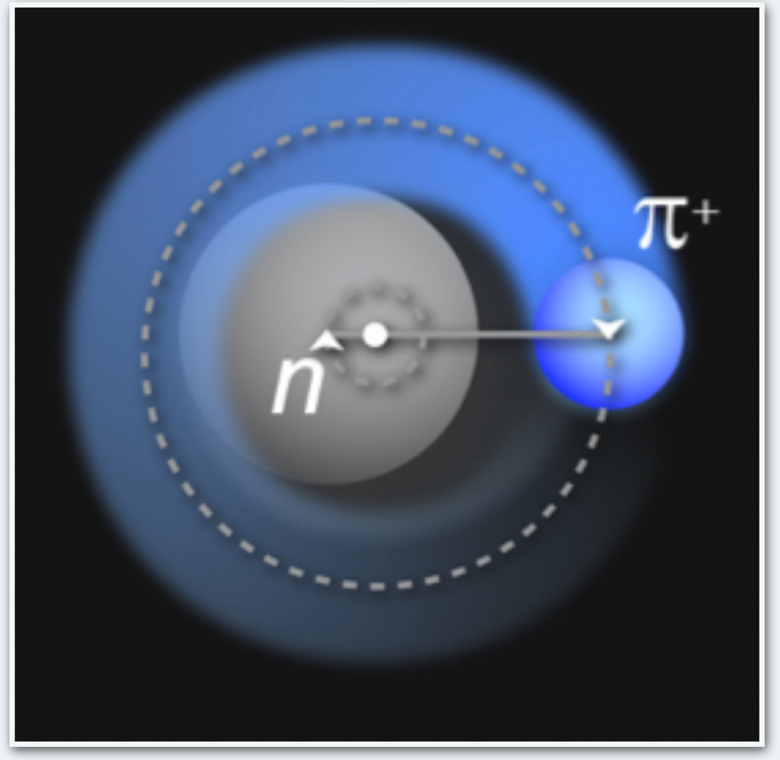




A.K,Tobias Toll PRD 105 (2022) 114045

PROBING THE GLUON DISTRIBUTION





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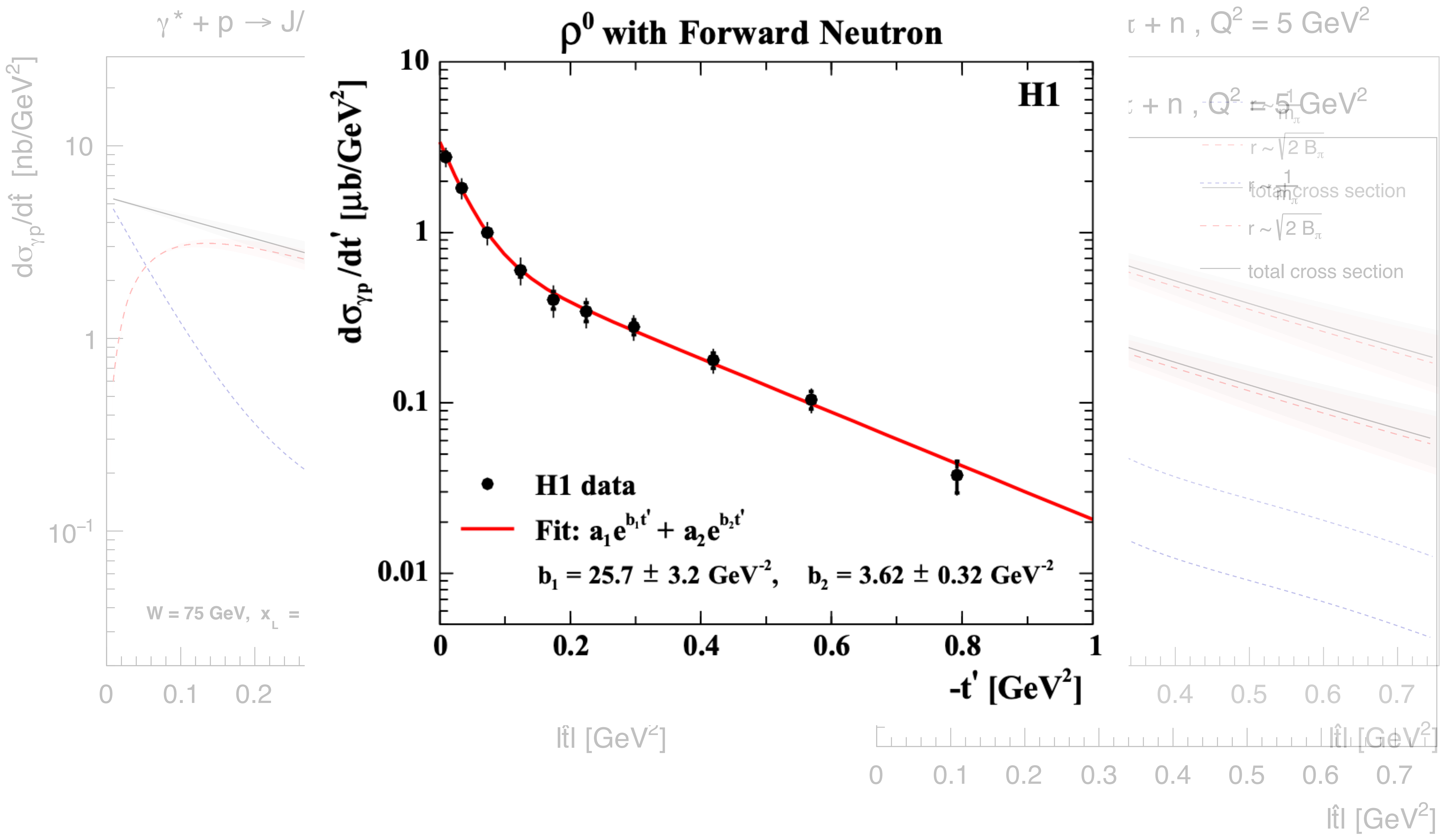
H1 EPJC 76 (2016), 41



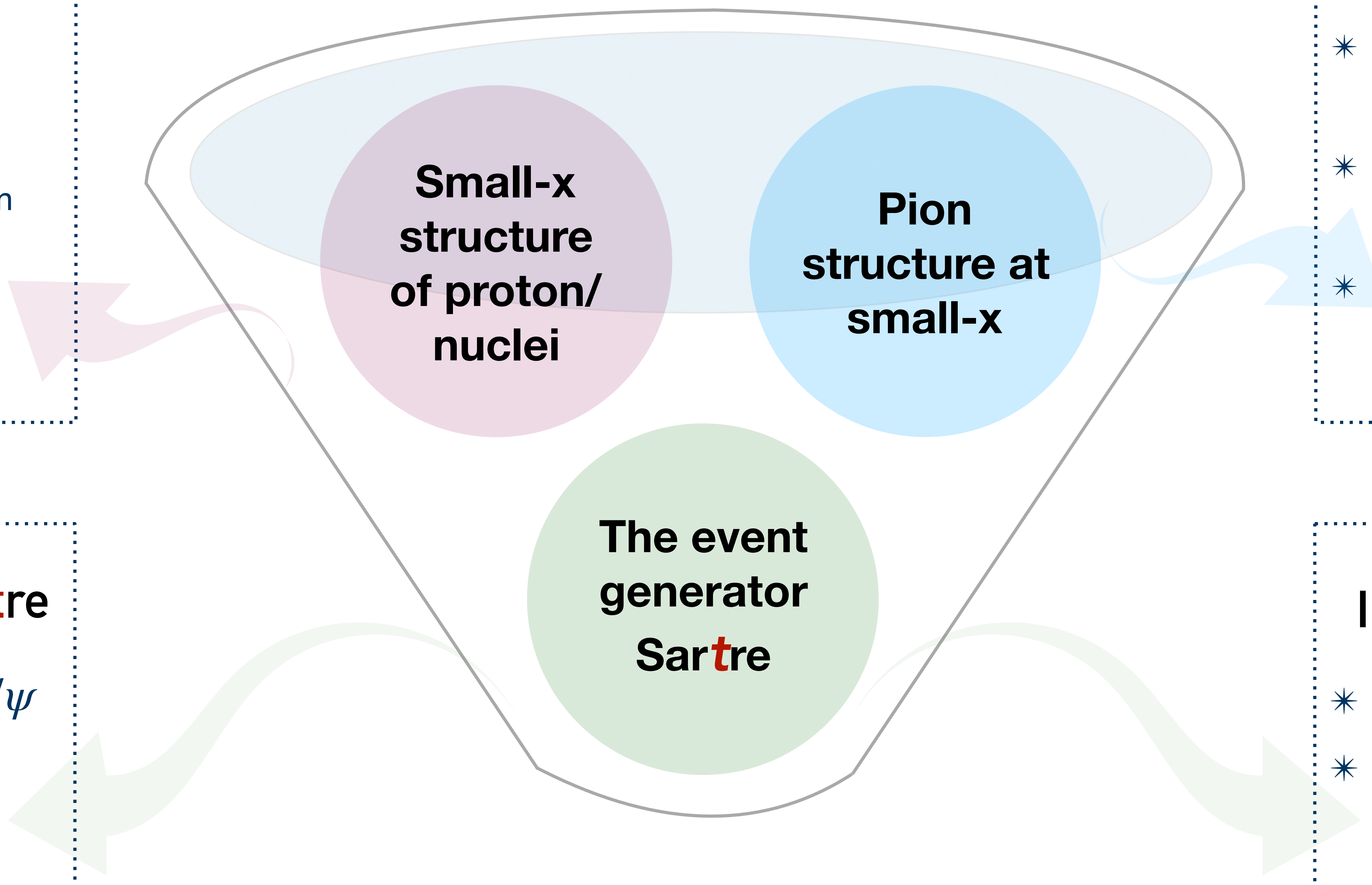
SUMMARY & OUTLOOK

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



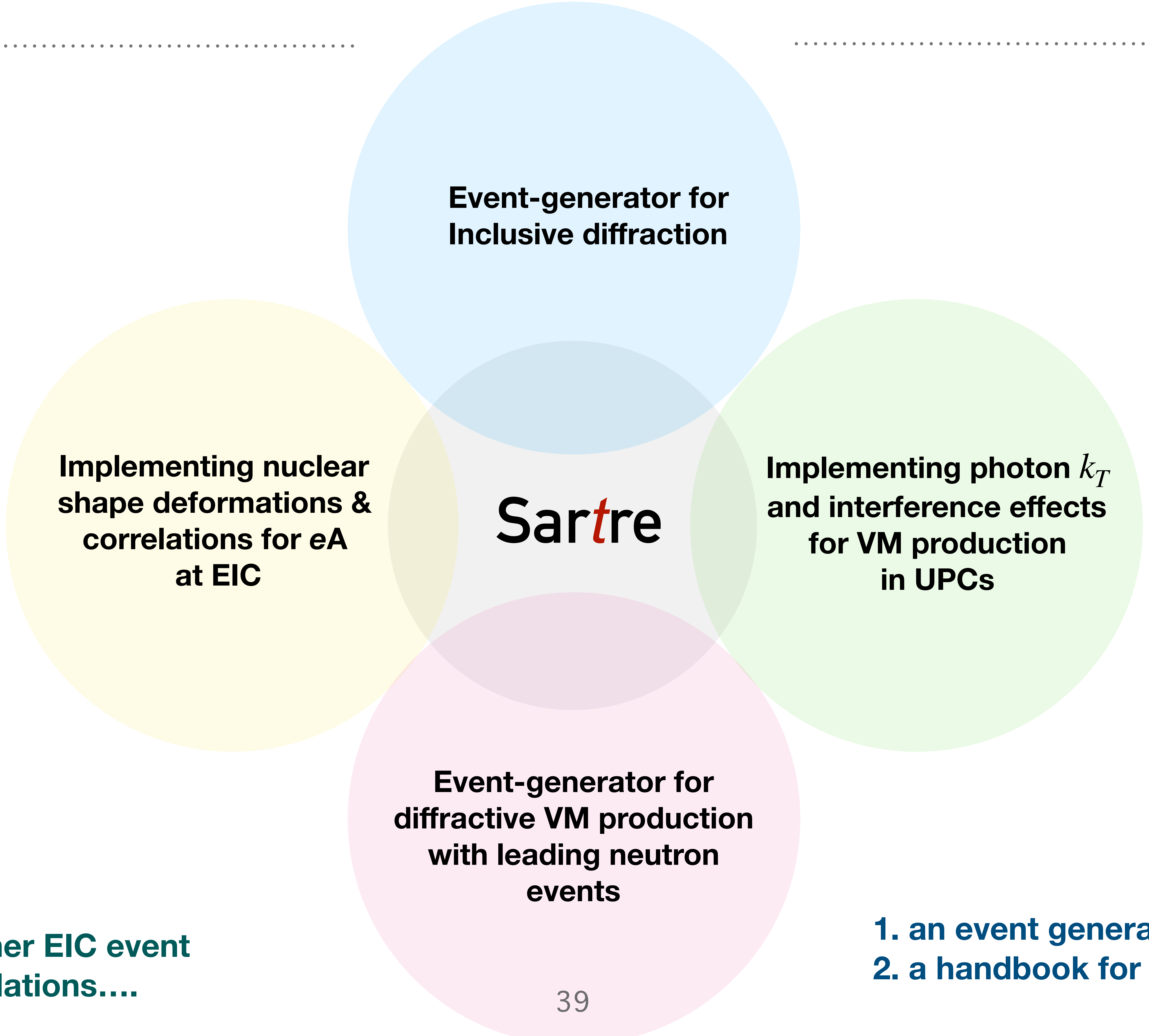
Sub-nucleon fluctuations in Sartre

- ✴ 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

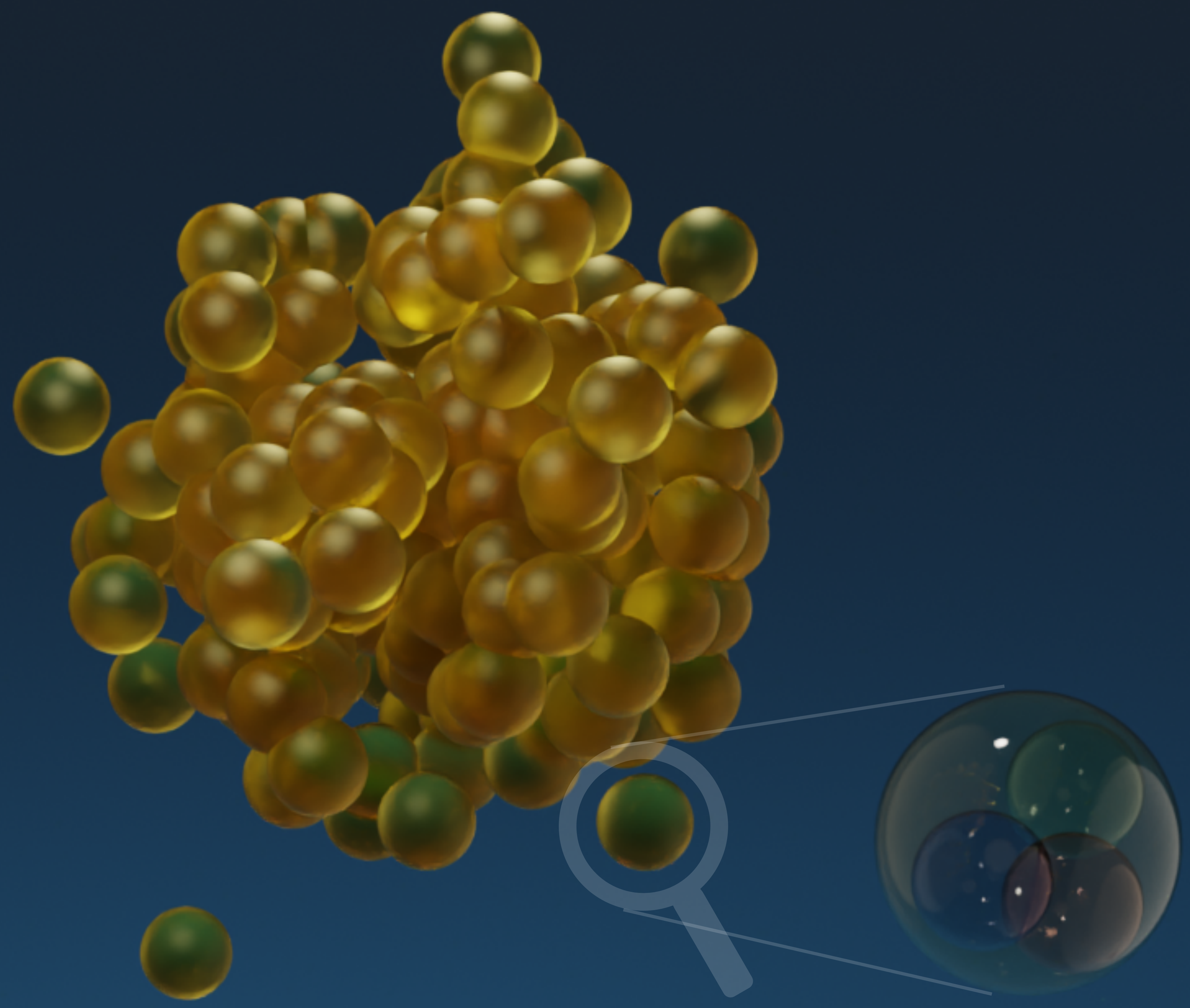
- ✴ Nucleon structure at high resolution
- ✴ Shrinkage of diffractive minima on including energy dependence in nucleon geometry
- ✴ Pion cloud in protons & nuclei
- ✴ Probing correlations and nuclei shape deformations through exclusive diffraction

RESEARCH INTERESTS & FUTURE DIRECTIONS



Bridging Sar*t*re with other EIC event generators for simulations….

1. an event generator for saturation physics..
2. a handbook for diffraction studies….



THANK YOU

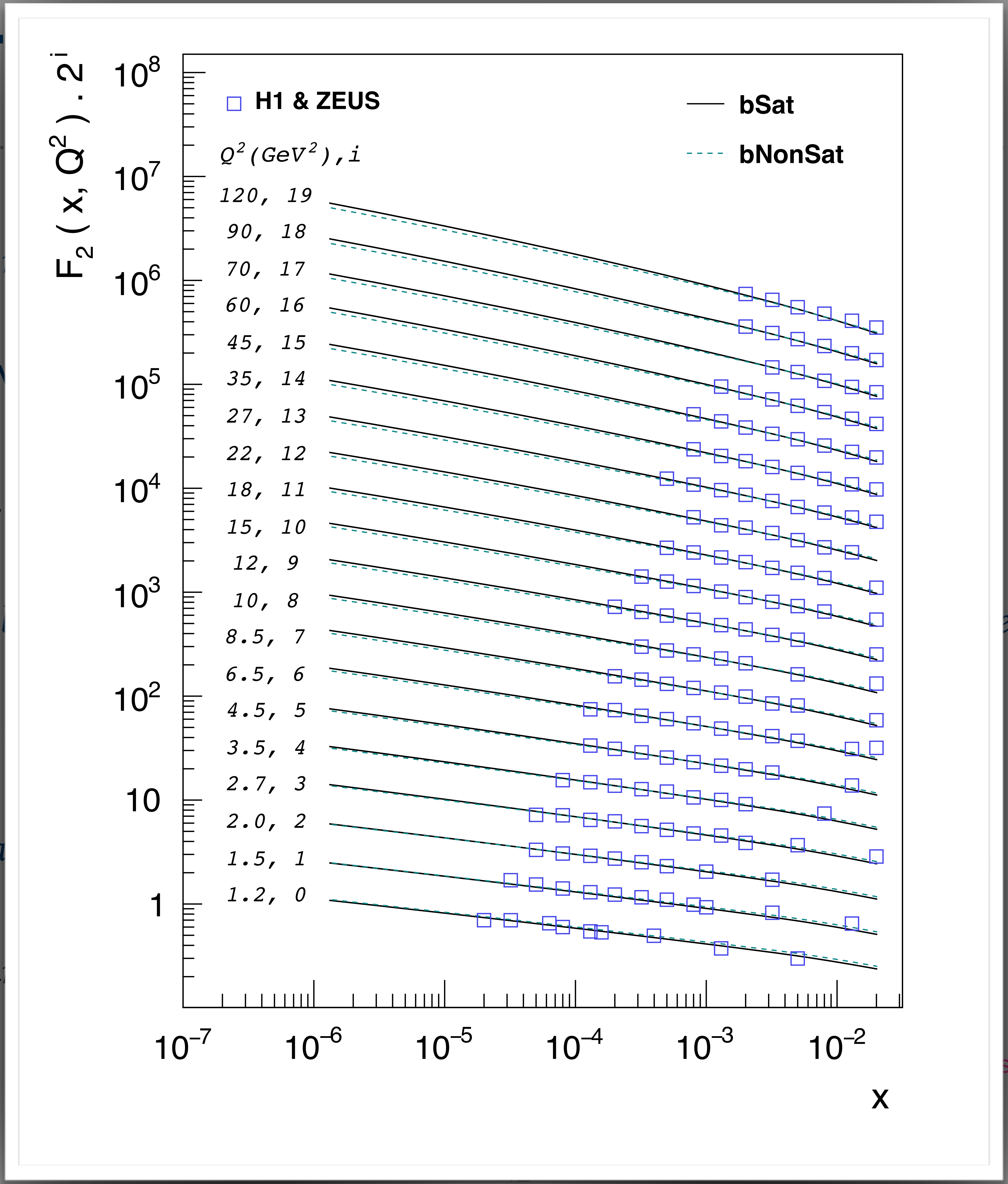
BACKUP

THE DIPOLE-TARGET

- the bSat dipole model : $N(b,$
- the bNonSat dipole model :

where $xg(x, \mu_0^2) = A_g\ x^{-\lambda_g}\ (1 -$

(the parameters are constrained ... ence obtained from DGLAP evolution)



Two models for the spatial proton

a) Smooth proton (assume gaussia

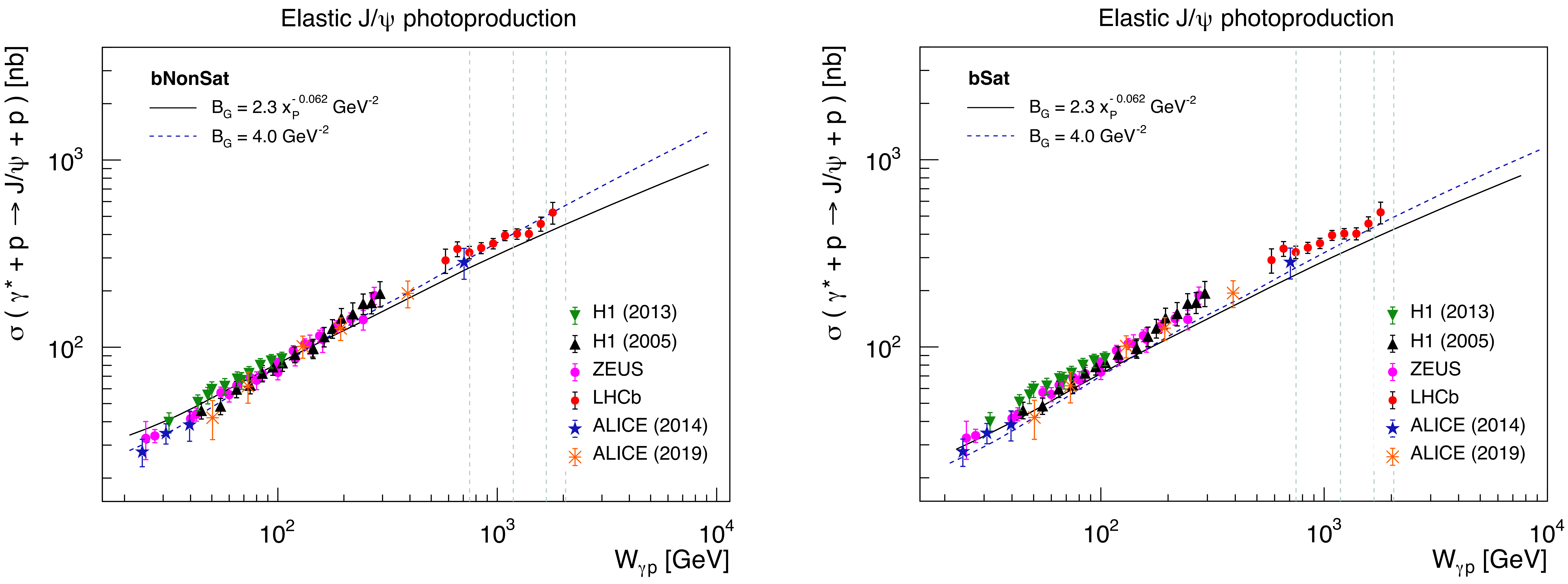
Kowalski, Motyka, Watt 2006

b) Lumpy proton (assume gaussia ... and $T_q(b) = \frac{1}{2\pi B_q} \exp\left[-\frac{b^2}{2B_q}\right]$

saari, Schenke PRL 117 (2016) 052301

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

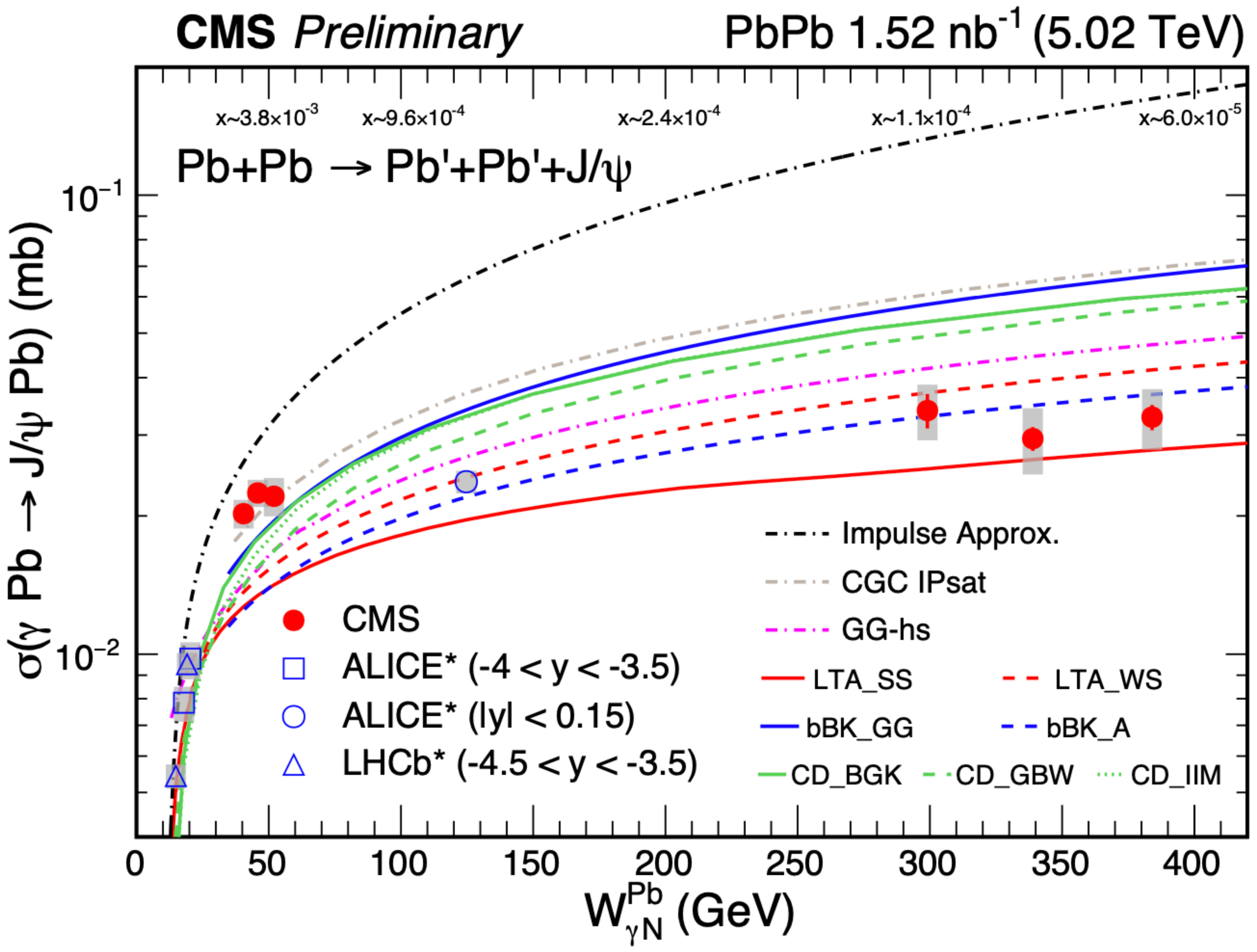
The profile function becomes : $T_p(\mathbf{b}) \rightarrow T_p(x, \mathbf{b})$ *with* $B_G(x) = B_p\ x^{\lambda}$ *and* $r_{proton} = \sqrt{2B_G(x)}$



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

CMS PRELIMINARY

CMS PAS HIN-22-002



New comparisons needed with:

- ✴ Saturation + Geometry evolution
- ✴ No-saturation + Geometry evolution

(our models can do these comparisons)

HOTSPOT EVOLUTION MODELS

- *Initial state at $t = t_0$: Hotspot model*

  $B_{qc} = 3.1\ GeV^{-2}$

  $B_q = 1.25\ GeV^{-2}$

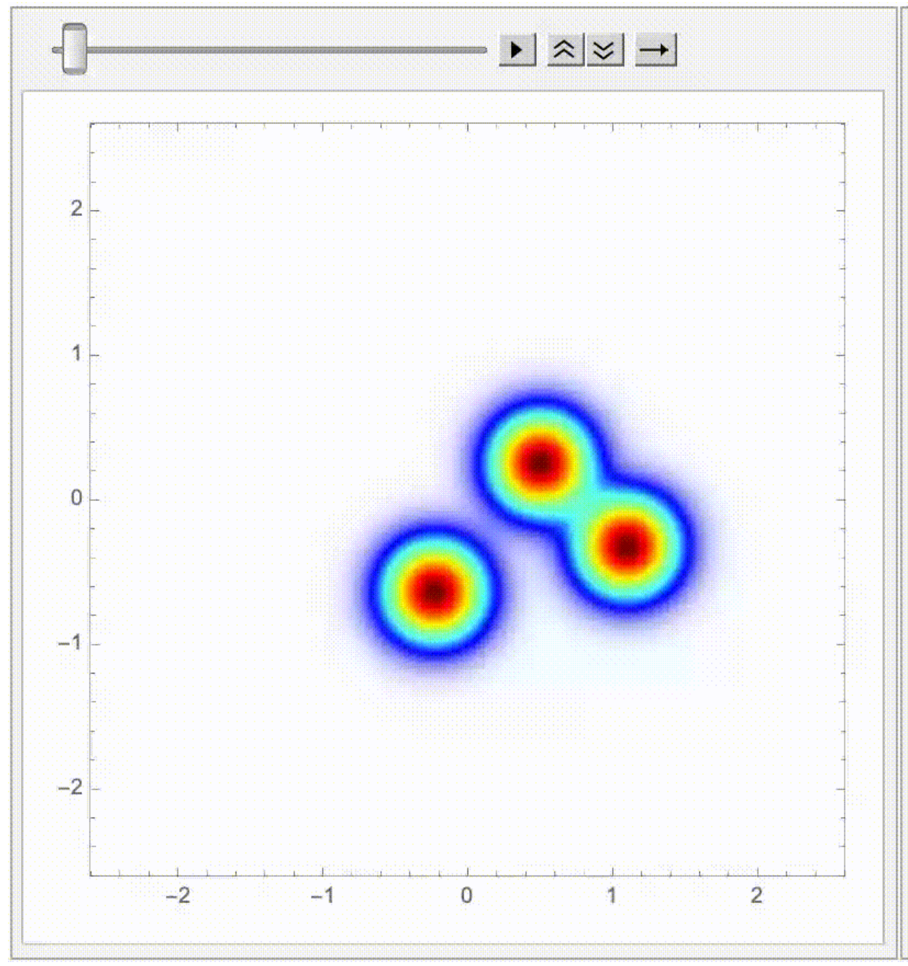
  $N_q = 3$

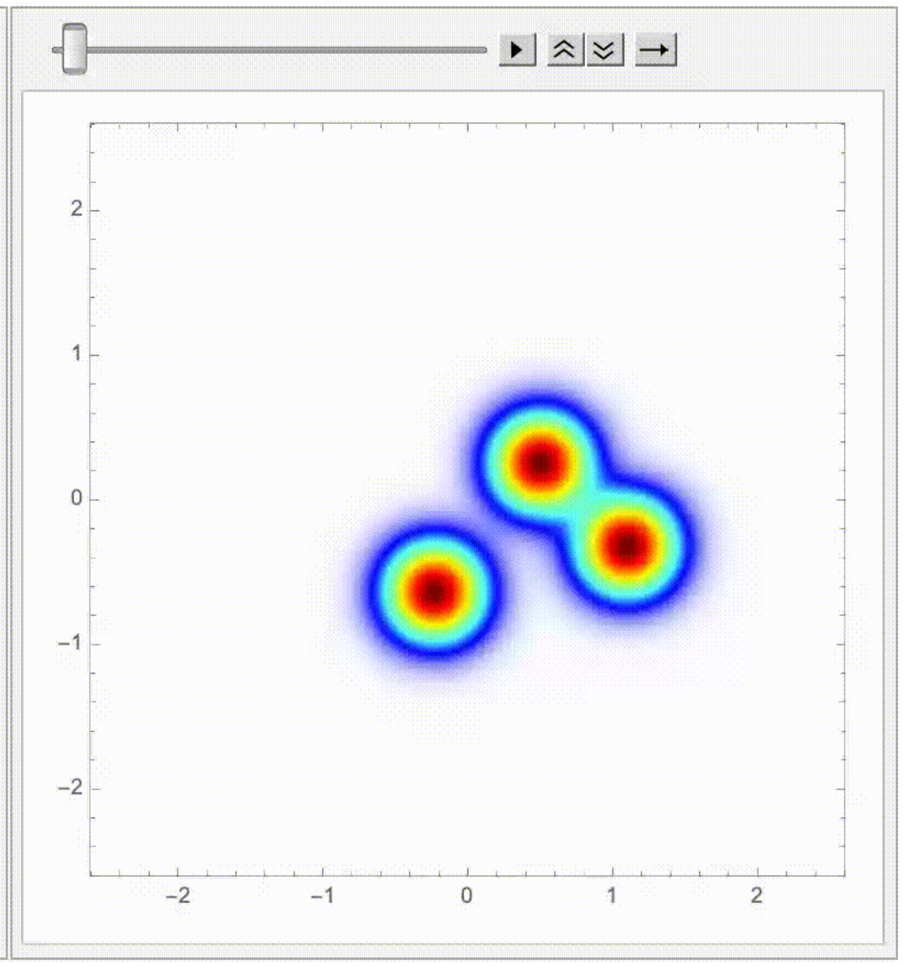
Evolution for $t > t_0$

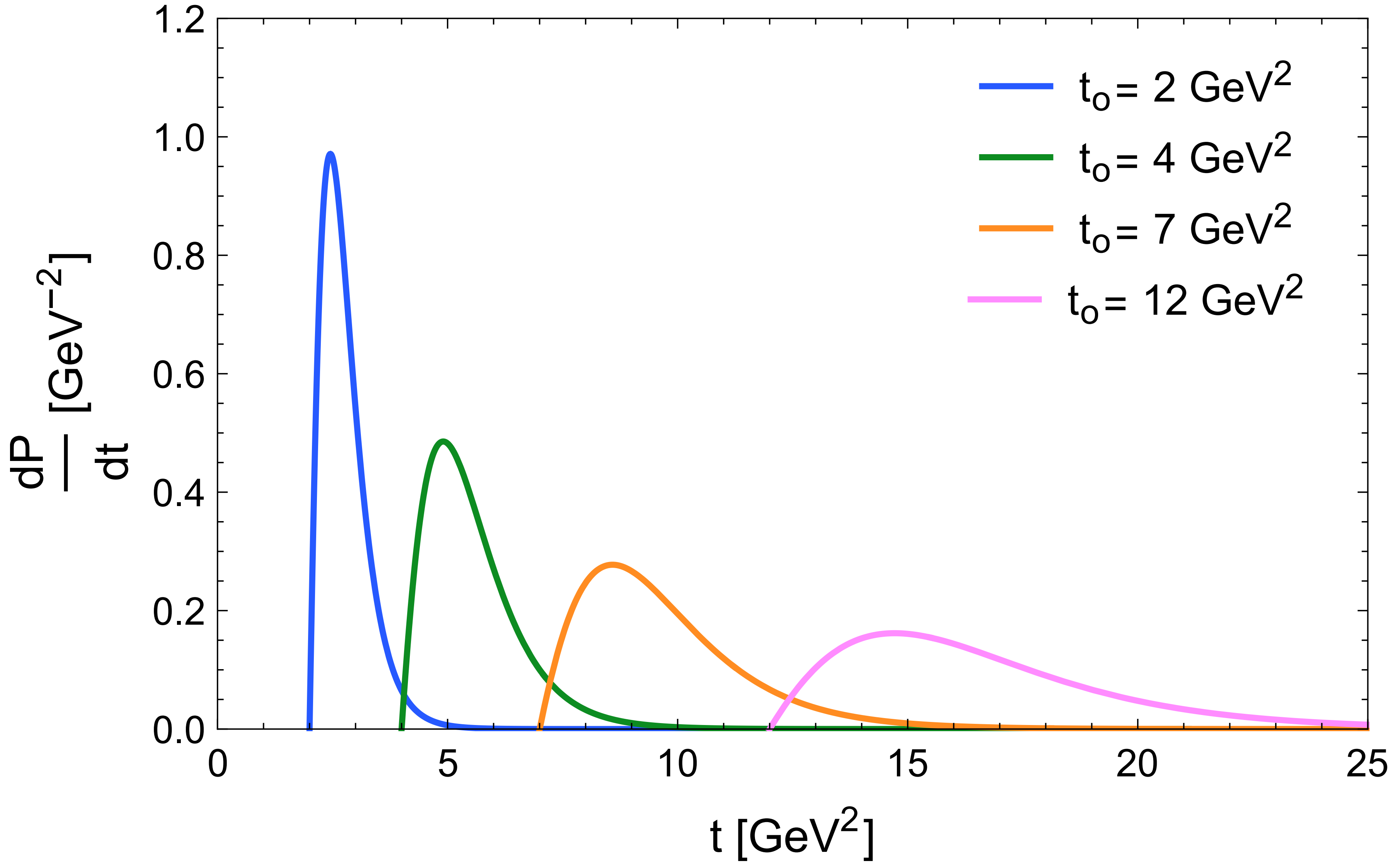
$$\frac{d\mathscr{P}_{split}}{dt} = \frac{\alpha}{|t|}\frac{t-t_0}{t}, \quad \frac{d\mathscr{P}_{no-split}}{dt} = \exp\left(-\int_{t_0}^{t} dt' \frac{d\mathscr{P}_{split}}{dt'}\right)$$

$$\frac{d\mathscr{P}_a}{dt} = \frac{\alpha}{t}\frac{t-t_0}{t}\exp\left[-\alpha\left(\frac{t_0}{t} - \ln\frac{t_0}{t} - 1\right)\right]$$

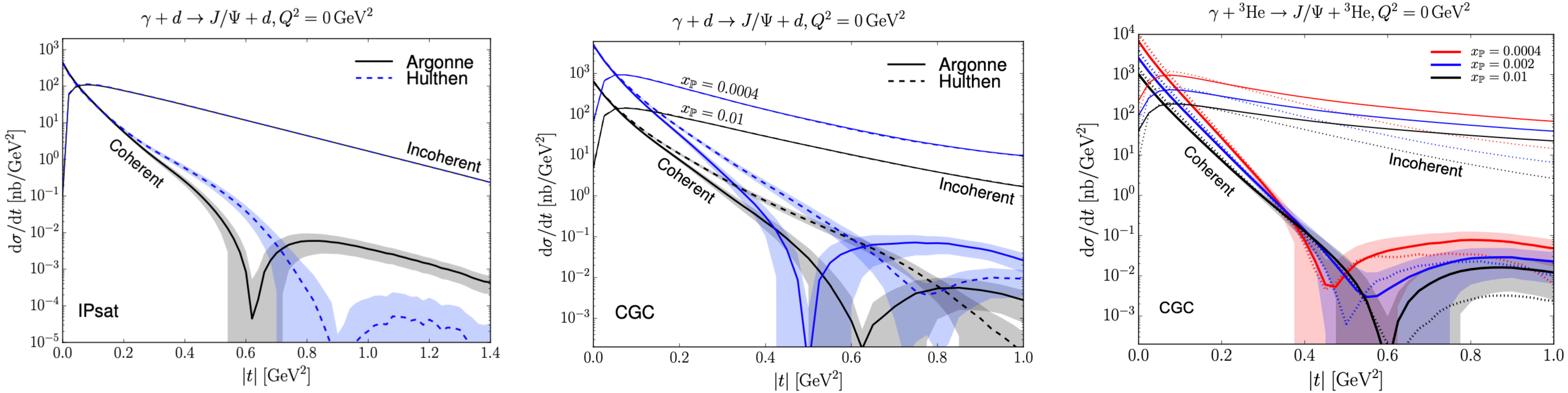
a) *Divide normalisation in each splitting*
b) *Divide normalisation among all hotspots at any t instant*



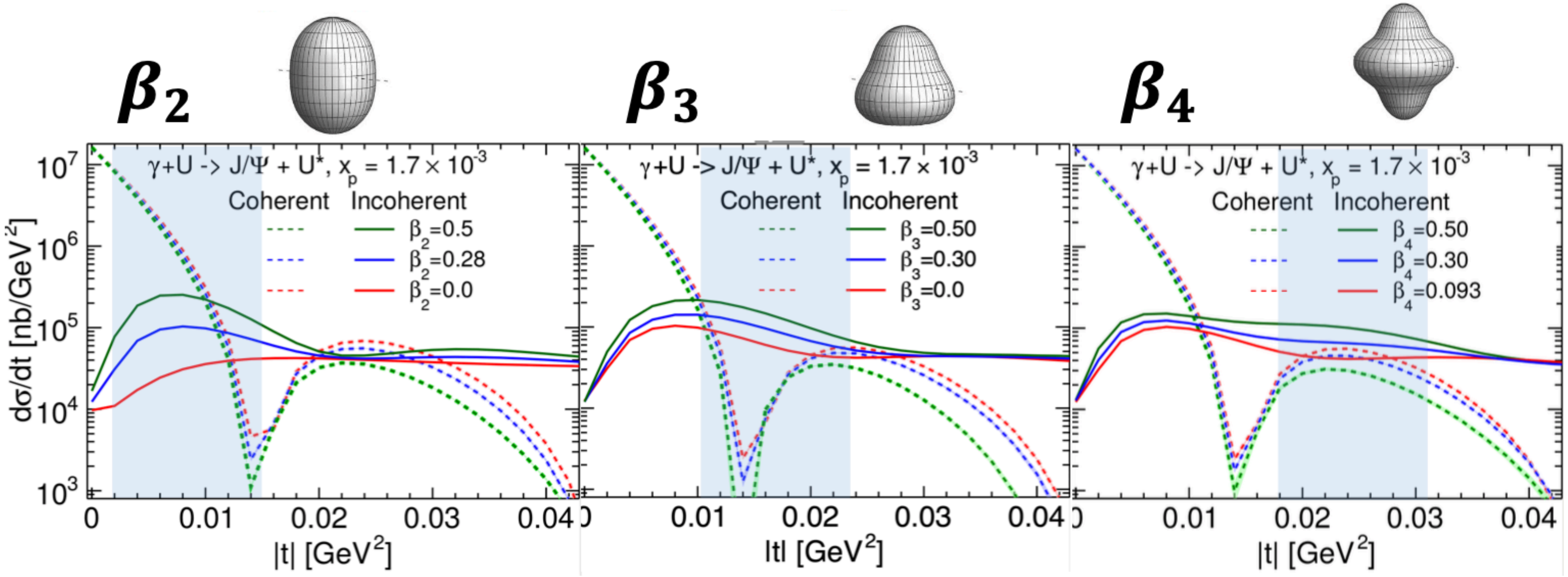




H.Mantysaari,B.Schenke PRC 101 (2020) 015203



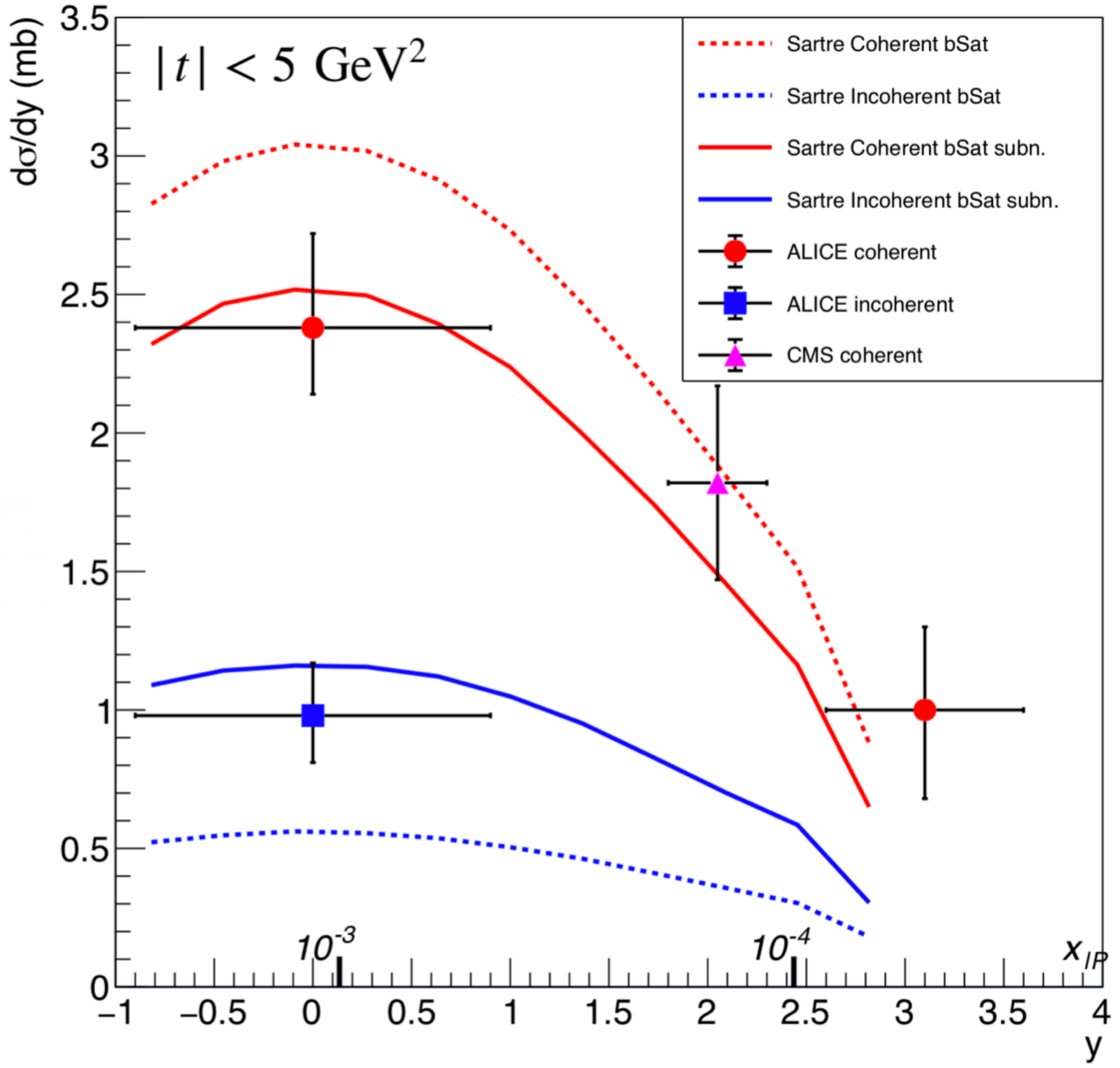
H.Mantysaari,B.Schenke, C.Shen,W.Zhao arXiv:2303.04866



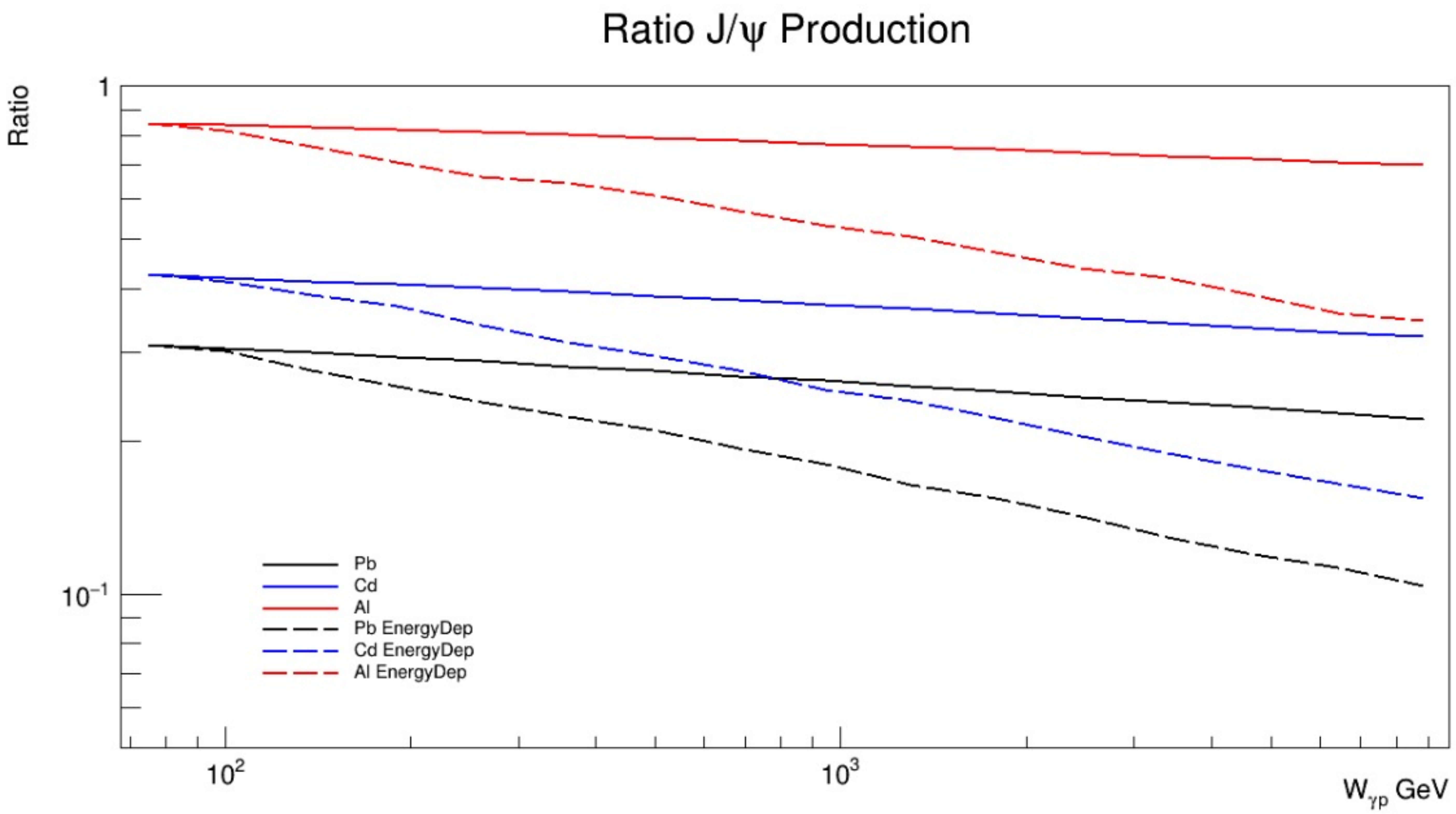
To model the geometric shape of large nuclei, we first sample nucleon positions from a Woods-Saxon distribution

$$\rho(r,\theta) = \frac{\rho_0}{1+\exp[(r-R'(\theta))/a]}, \quad (6)$$

with $R'(\theta) = R[1+\beta_2 Y_2^0(\theta)+\beta_3 Y_3^0(\theta)+\beta_4 Y_4^0(\theta)]$, and ρ_0 is the nuclear density at the center of the nucleus. Here R is the radius parameter and a the skin diffuseness, and θ is the polar angle. A random rotation is applied after the sampling process. The spherical harmonic functions $Y_l^m(\theta)$ and the parameters β_i account for the possible deformation from a spherical shape. The default Woods-Saxon parameters for uranium are $\beta_2 = 0.28$, $\beta_3 = 0$, $\beta_4 = 0.093$, $a = 0.55$ fm, and $R = 6.81$ fm [7–12]. Following [12, 47], we further impose a minimal distance of $d_{\min} = 0.9\,\mathrm{fm}$ between nucleons when sampling in three dimensions.[1]



T.Toll SciPost Phys. Proc. 8 (2022) 148

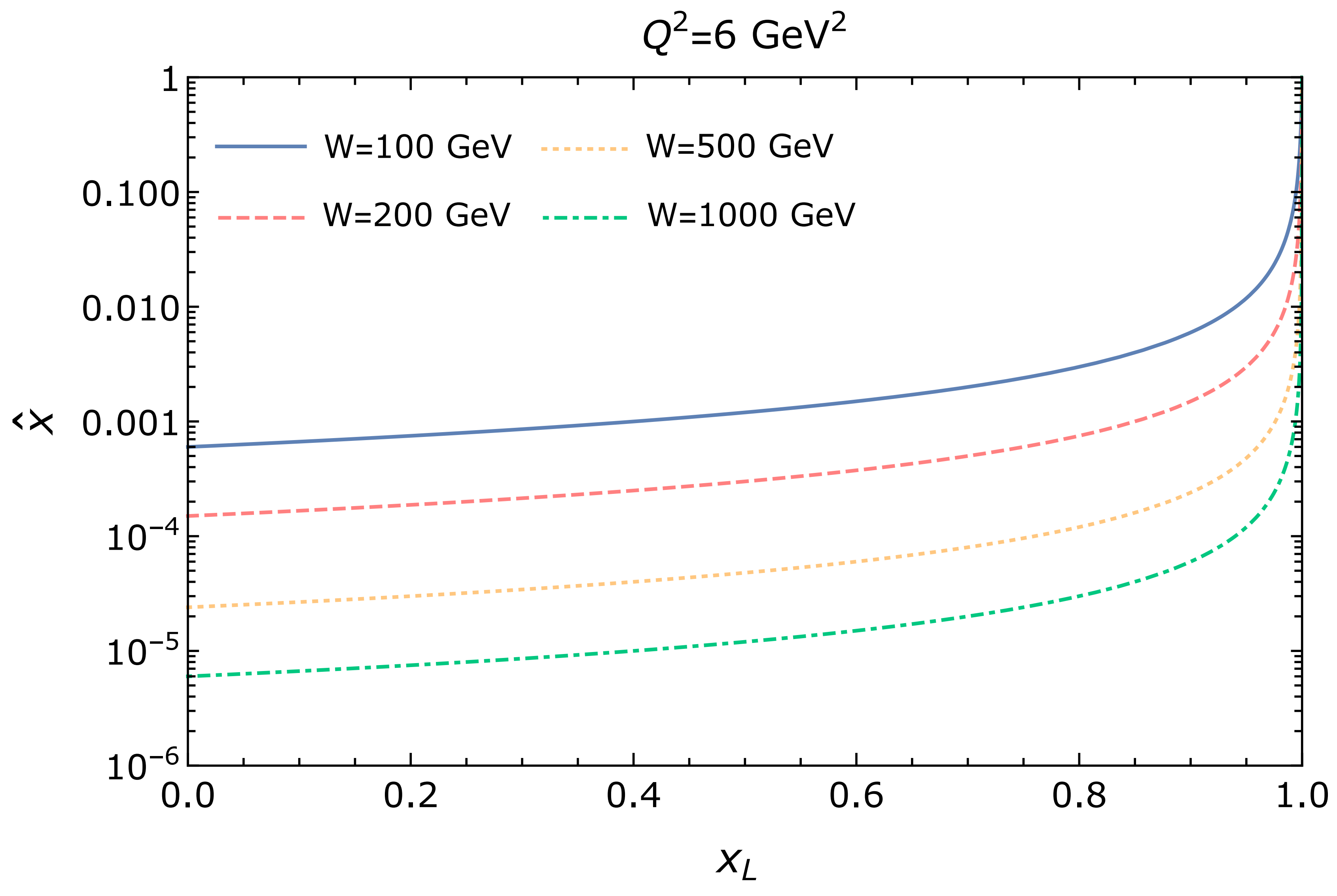


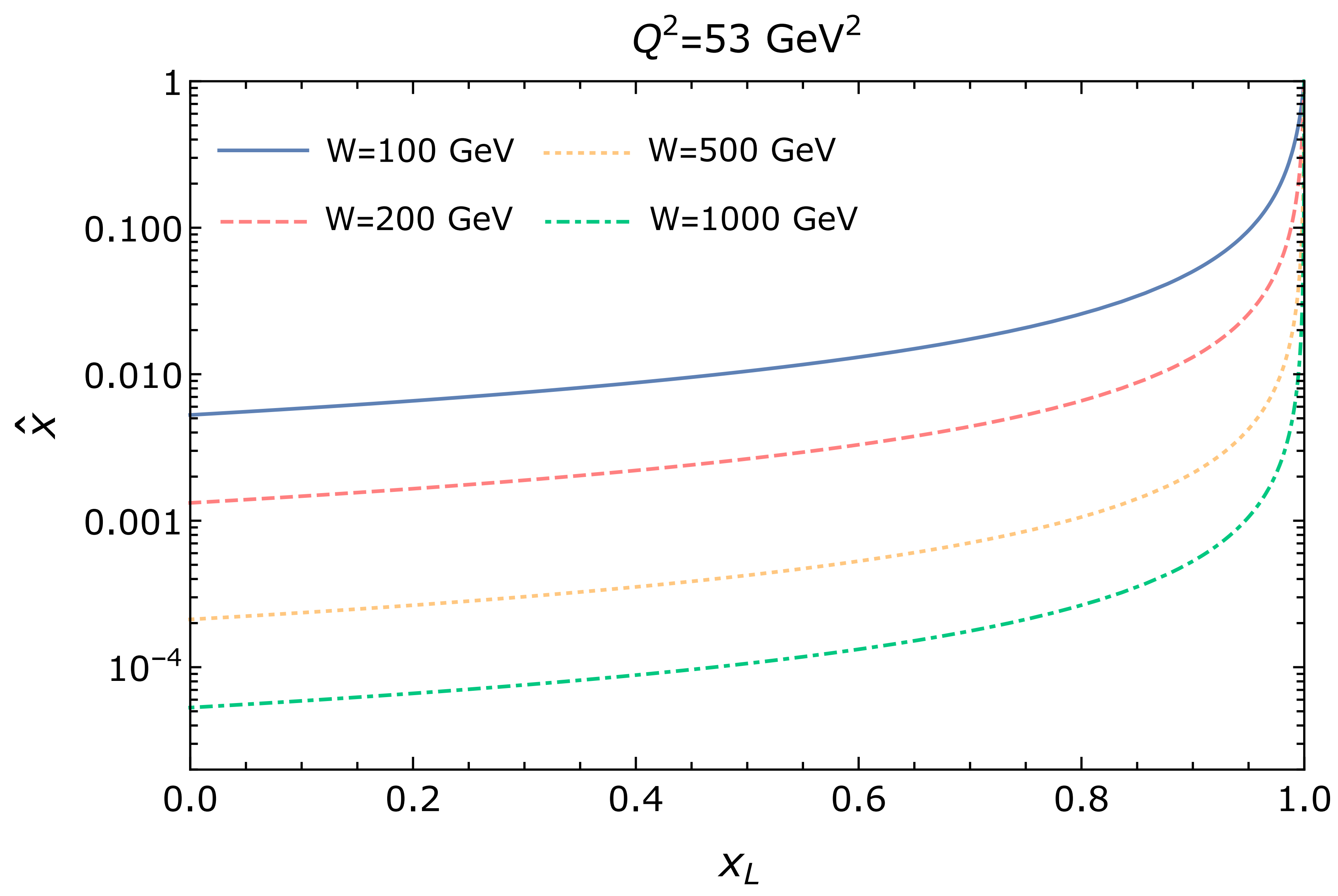
LN AS A PROBE FOR SMALL-X PHYSICS

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

$$\sigma^{\pi}(r,\beta) = \sigma_0(1 - e^{r^2 Q_s^2(\beta)/4}),$$

- 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





PION FLUX FROM PROTON

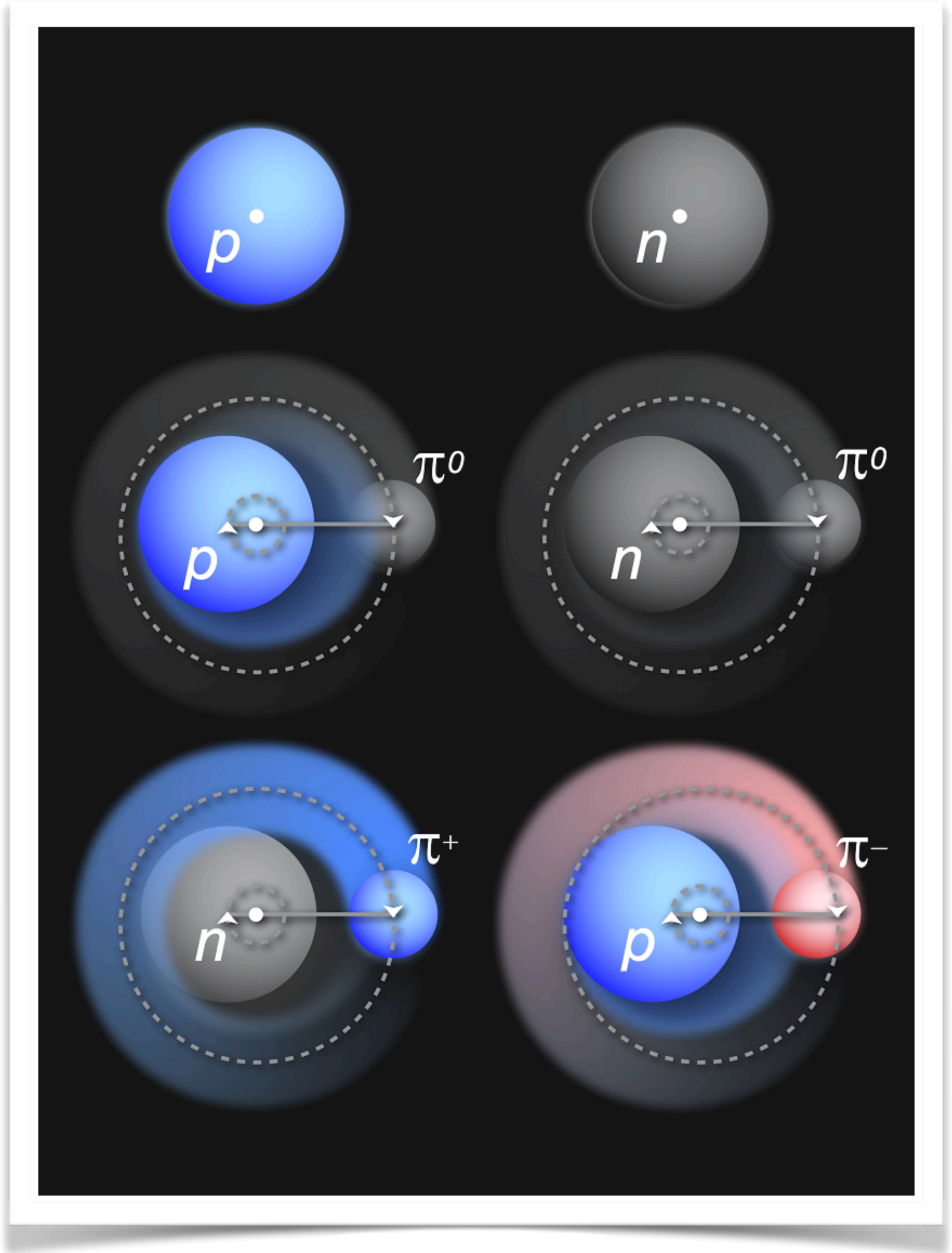
Chiral approach: a=0.24, b=0.12
Thomas, Melnitchouk & Steffens, PRL85 (2000) 2892

❖ 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

❖ We use the following flux factor:

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

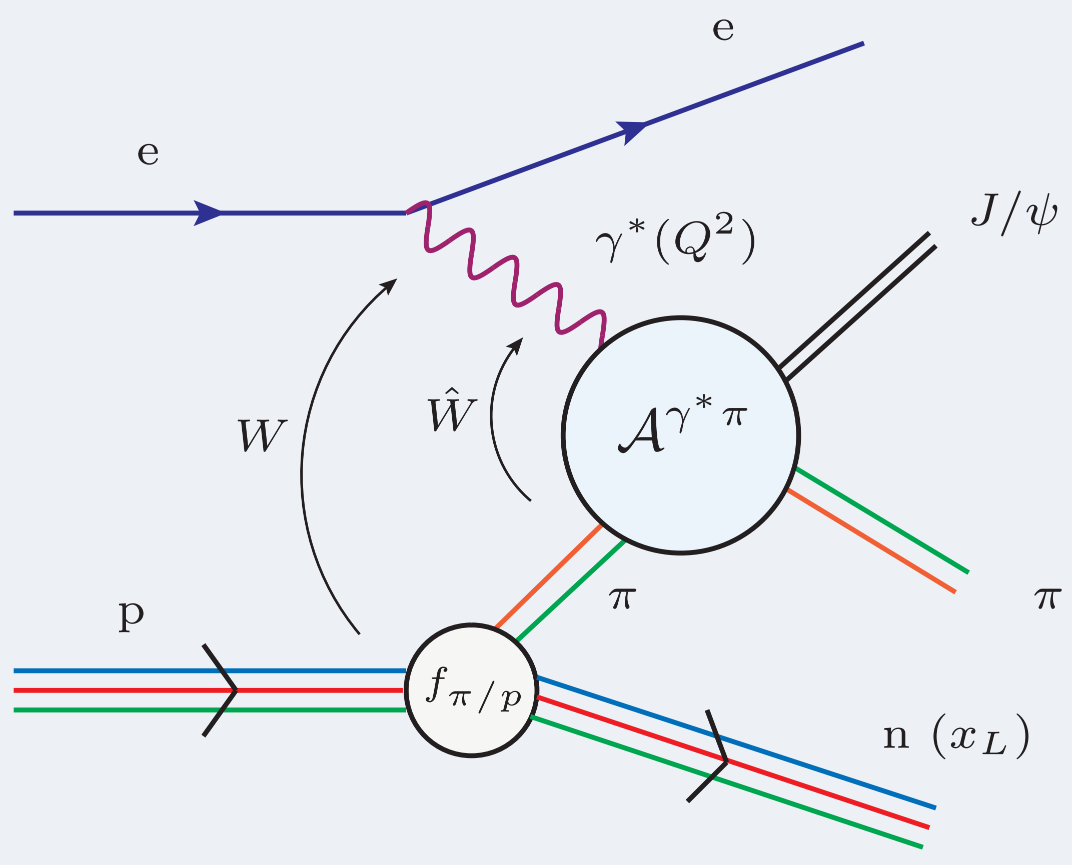
where the form factor is given by:

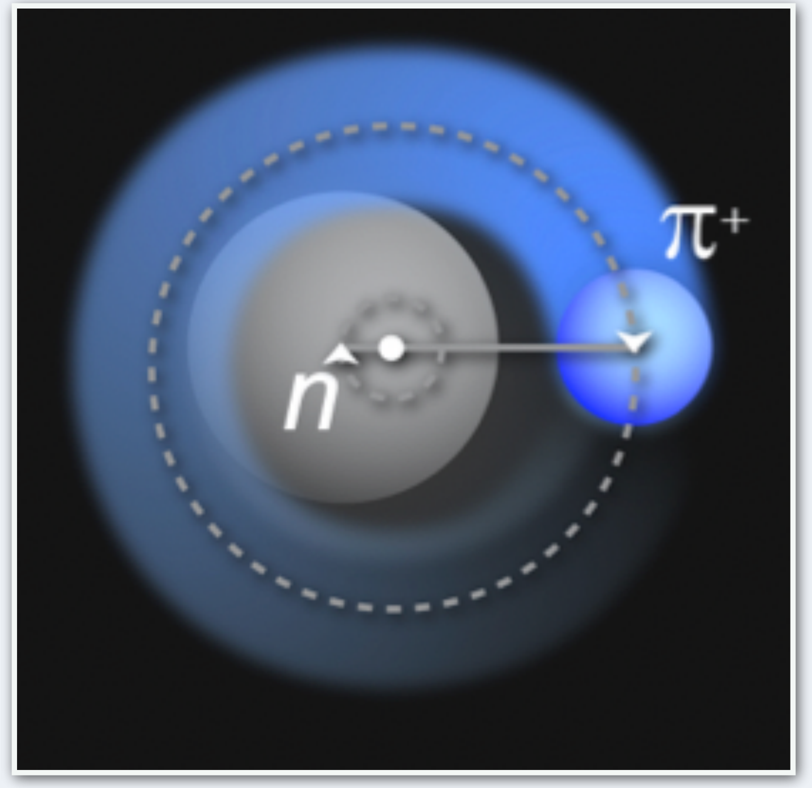
$$F(x_L,t) = \exp\left[-R^2\frac{|t|+m_\pi^2}{(1-x_L)}\right],\ \alpha(t)=0$$

❖ 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)