

Preparing for the EIC Era : From Sartre Insights to BeAGLE++

a tale of two event-generators

July 25, 2025



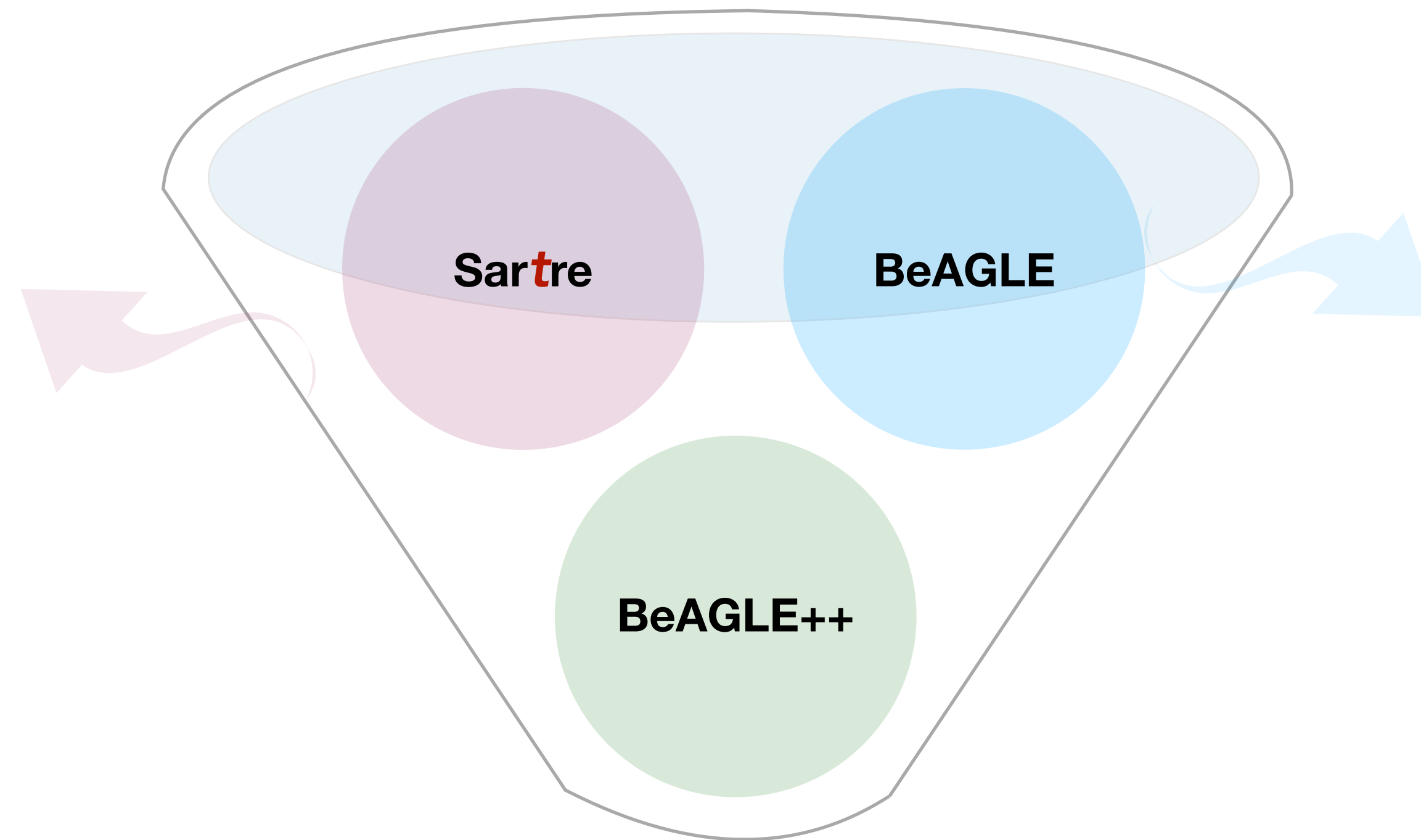
ARJUN KUMAR
CFNS, Stony Brook University



OUTLINE

Event Generator for Diffractive Processes in ep , eA , AA collisions

- Saturation Physics
- Spatial Imaging
- Gluon Fluctuations
- Geometric Scaling
- Pion structure

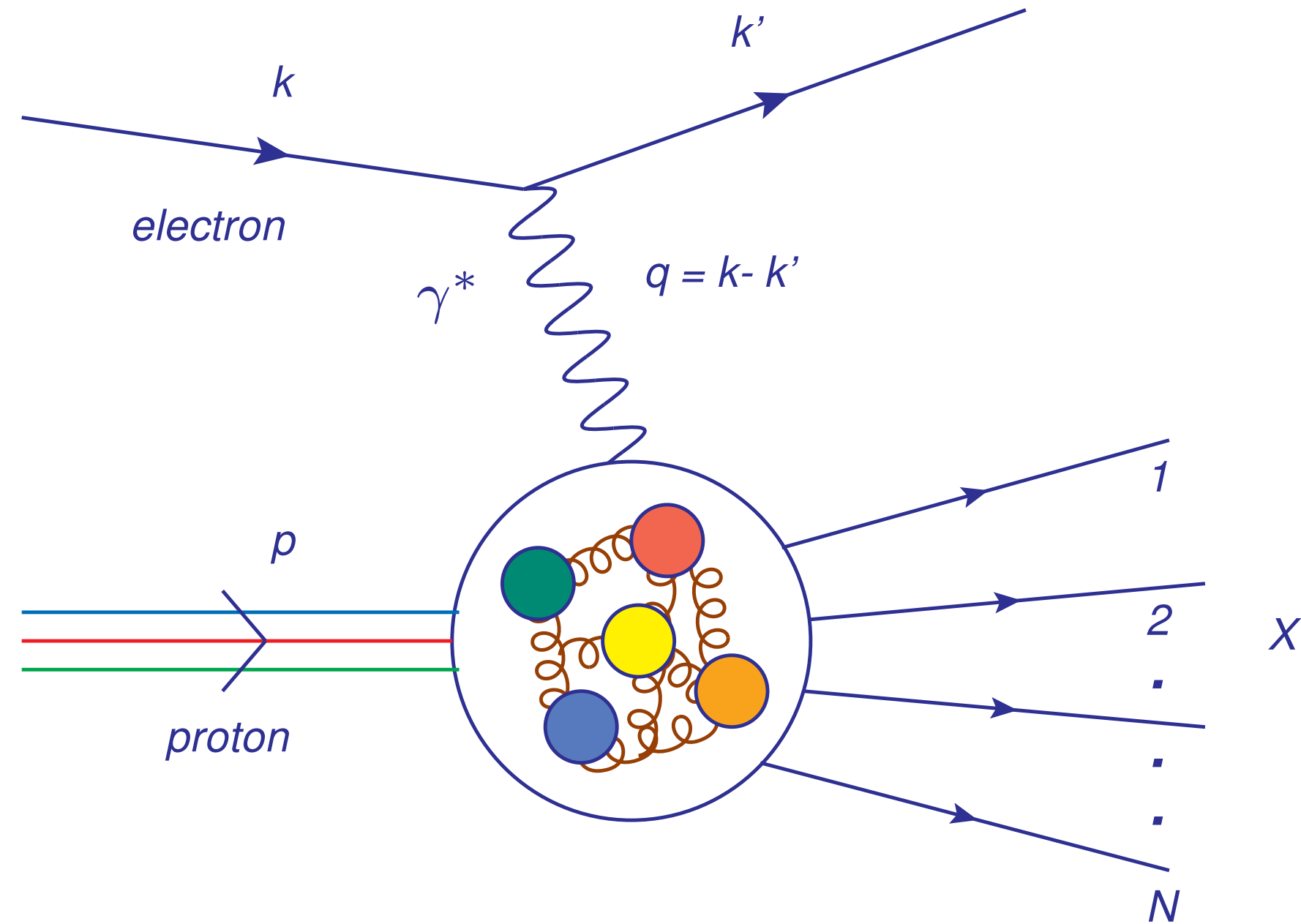


A General-purpose eA Event Generator

- Particle Production
- Hadronization
- Nuclear Excitation
- Spectator-tagging/Target Fragmentation
- Short-range Correlations

Goal: a successor of BeAGLE, a streamlined, modular framework with C++ and mission-ready for EIC physics → The Future of Nuclear Event-Generation for EIC

INTRODUCTION: DEEP INELASTIC SCATTERING

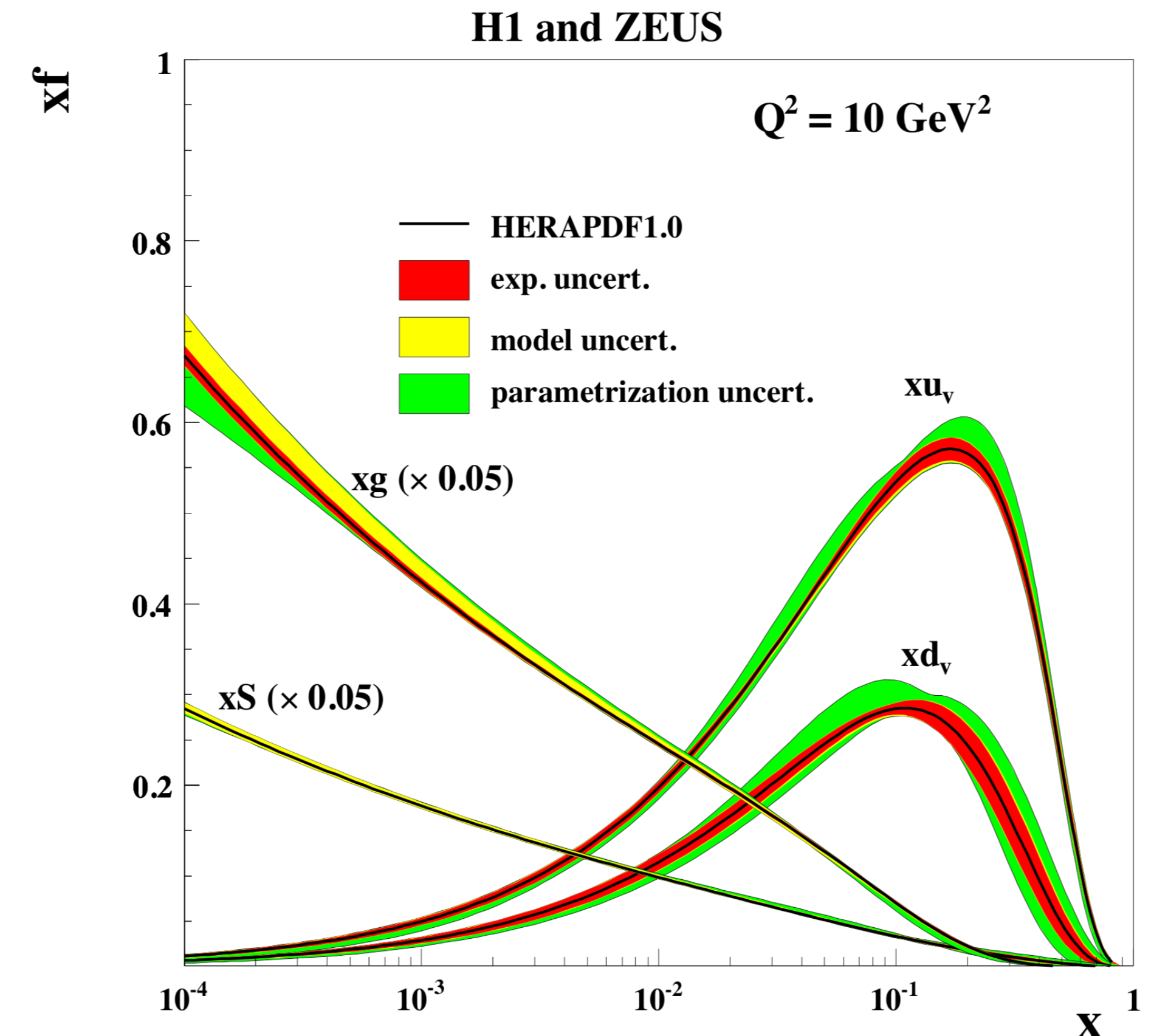


★ Useful kinematic variables :

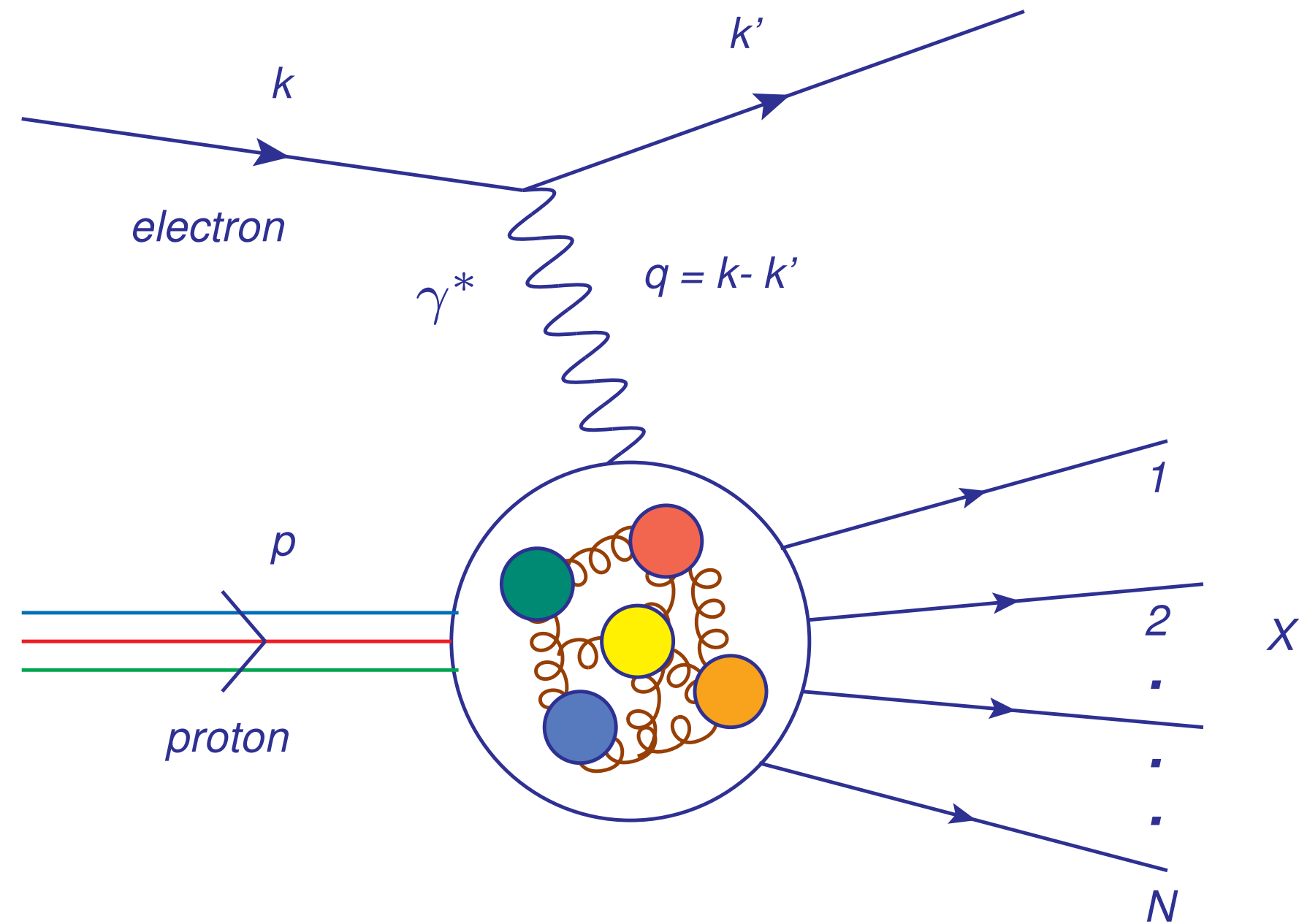
$$Q^2 = -q^2, \quad x = \frac{Q^2}{2p \cdot q}, \quad s = (p + k)^2, \quad W_{\gamma p} = (p + q)^2$$

- ❖ A very special and unique method to probe hadron structure
- ❖ A good description of data using collinear factorisation and DGLAP evolution equations in the Bjorken limit
- ❖ In Double Leading Log Approximation (DLLA) :

$$xg(x, Q^2) = A \exp \sqrt{\frac{12}{\pi b_0} \ln \left(\frac{t}{t_0} \right) \ln \left(\frac{x_0}{x} \right)} \quad t = \ln(Q^2 / \Lambda^2), \quad b_0 = \frac{22 - 2n_f}{12\pi}$$



INTRODUCTION: DEEP INELASTIC SCATTERING

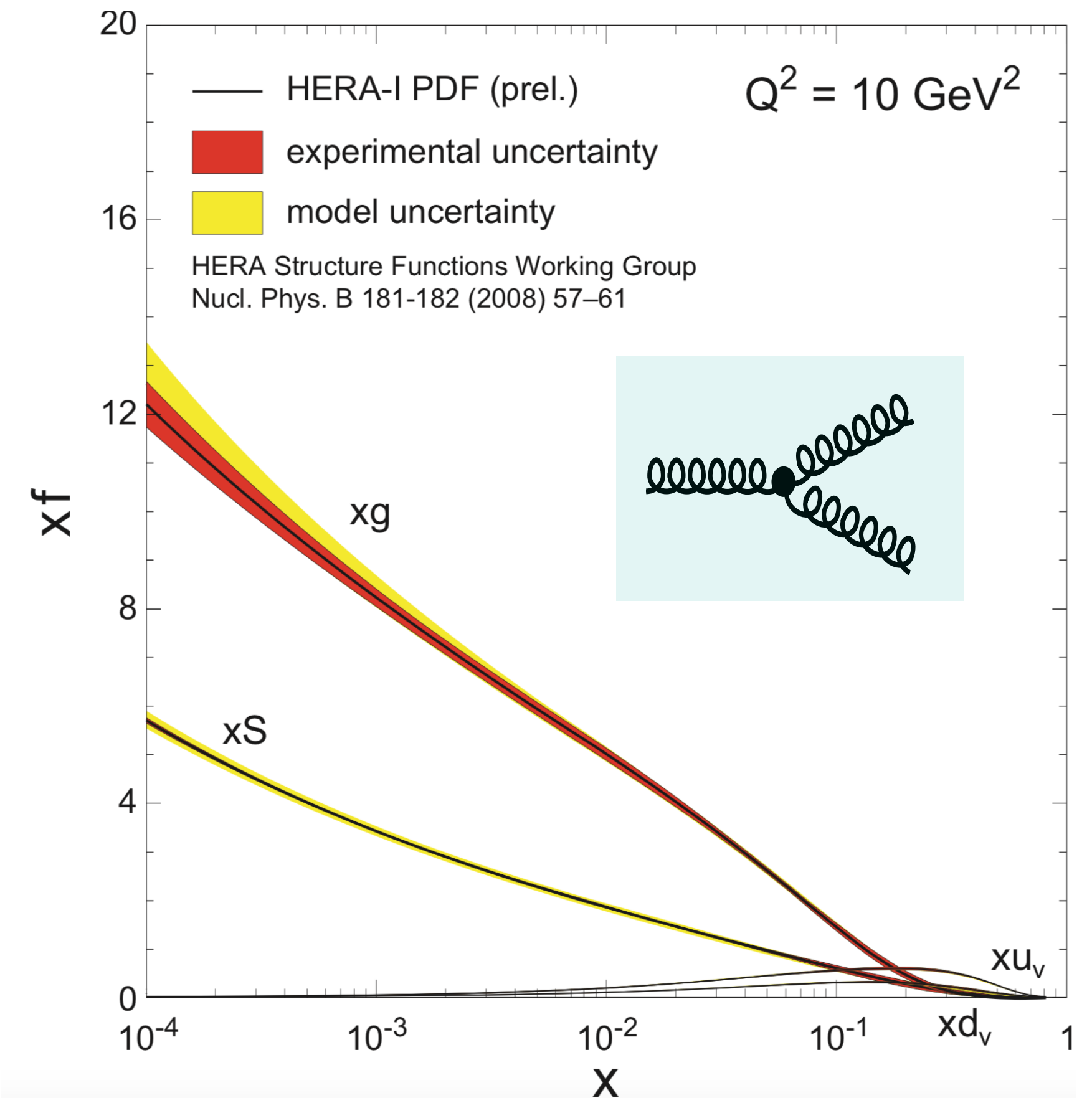


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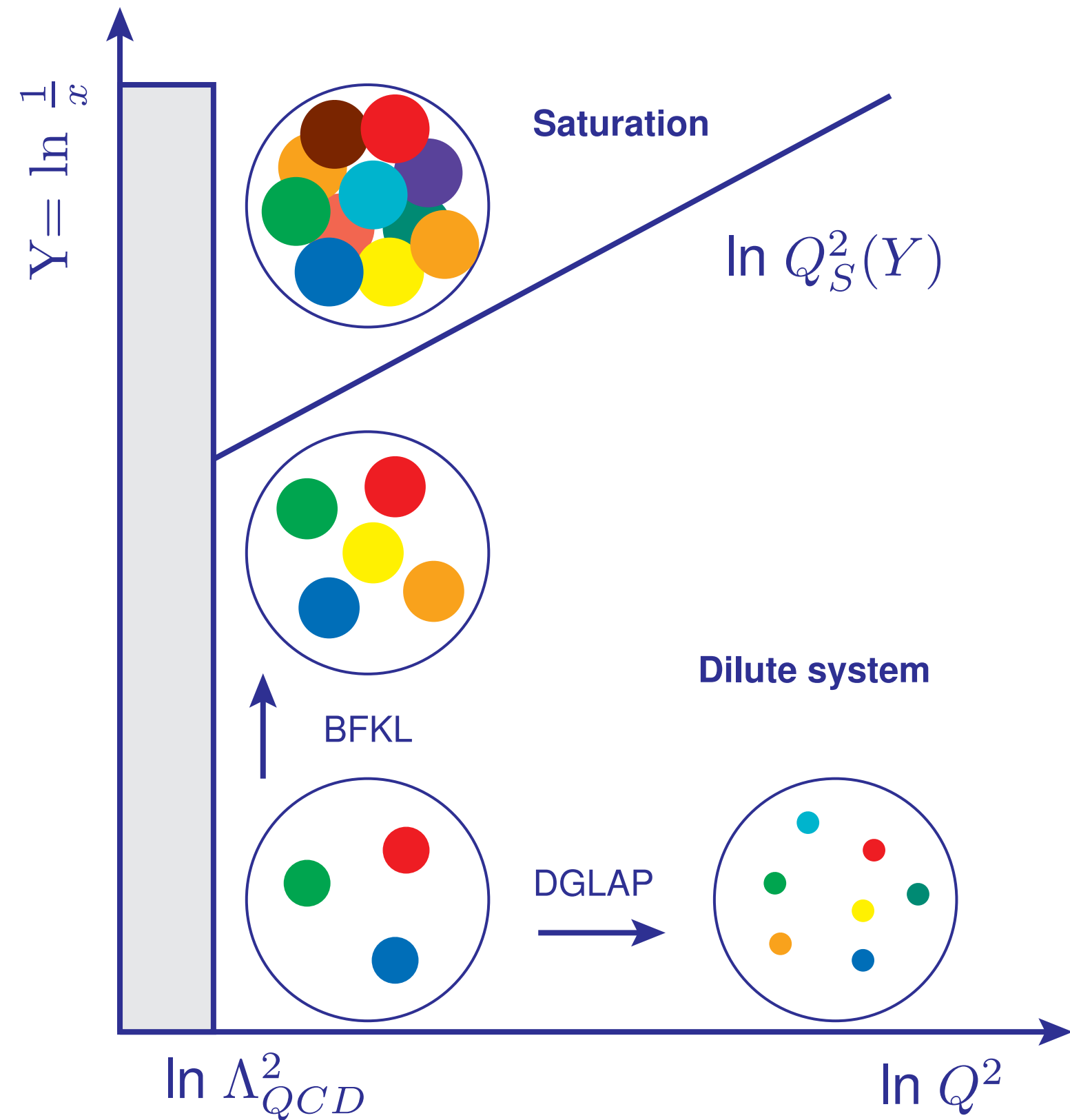
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QCD PHASE SPACE

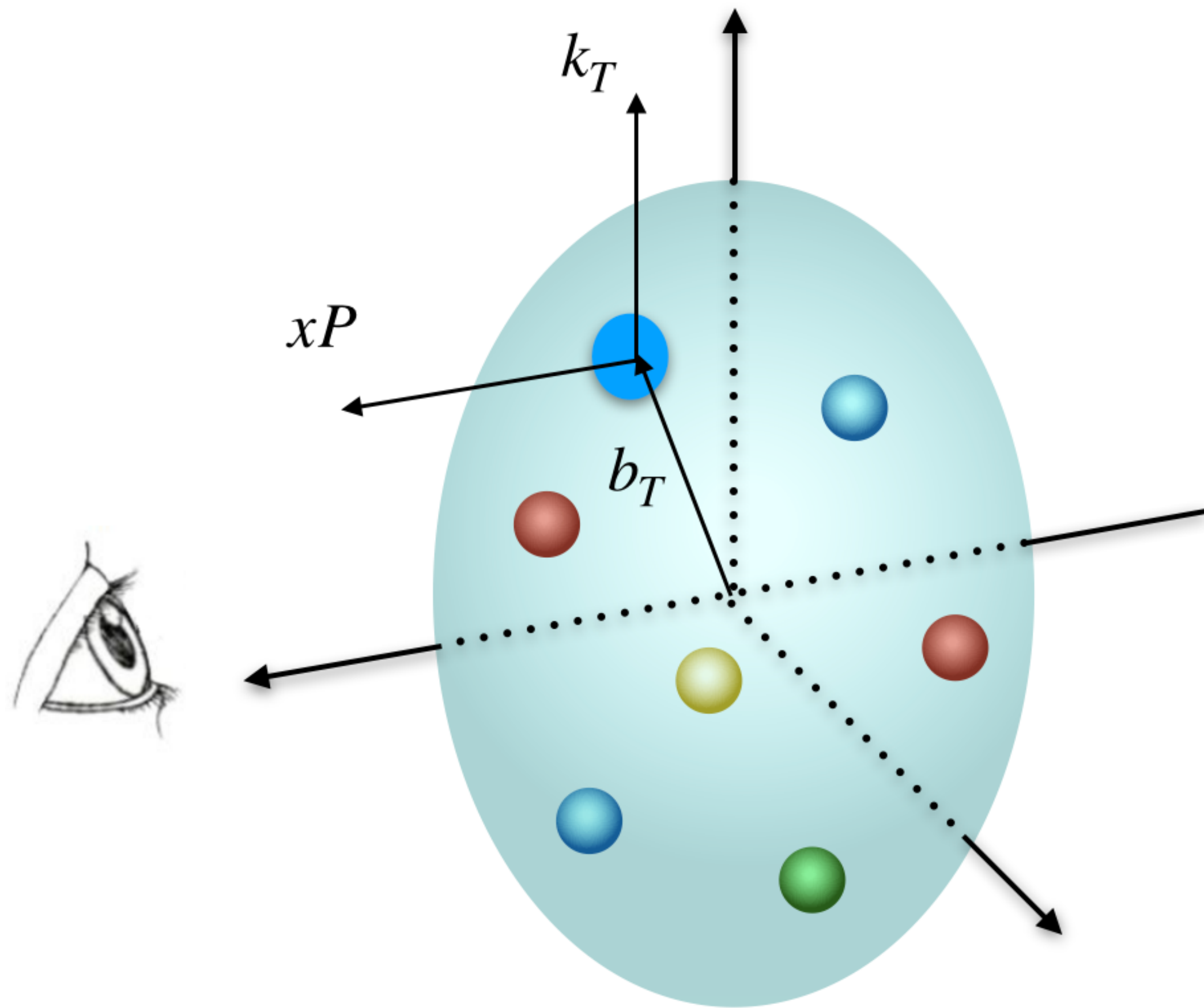


$$(x \simeq \frac{Q^2}{y s})$$

The high energy limit of QCD suggests the presence of non-linear multi-body dynamics & saturation physics.

Recombination ($gg \rightarrow g$) can balance gluon splittings and help to restore unitarity (self control; an interesting property of QCD)

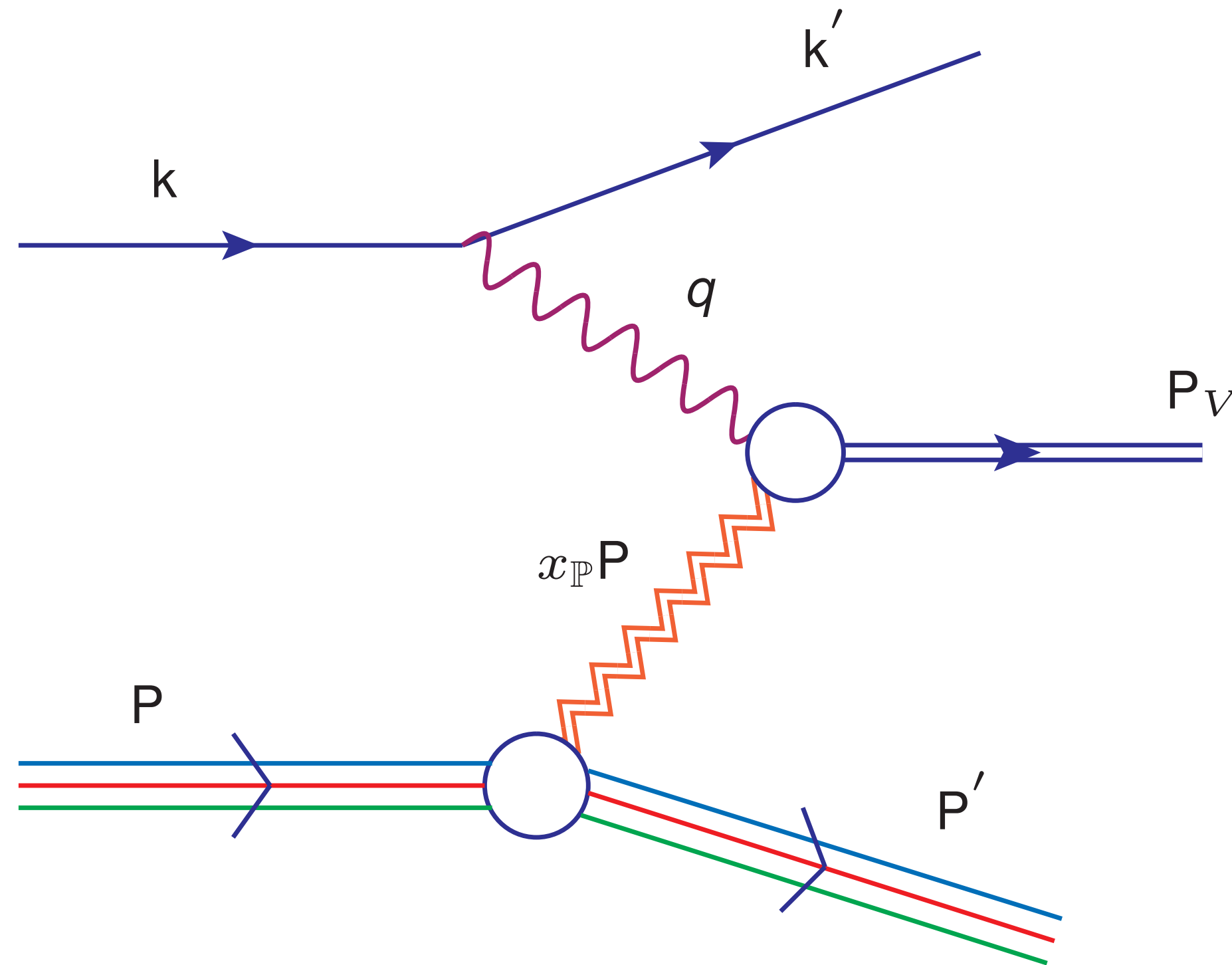
DEEP INELASTIC SCATTERING AT HERA



- ❖ Longitudinal information ✓
- ❖ Spatial Structure in transverse plane ✗
- ❖ Transverse momentum distributions ✗
- ❖ Unitarity ✗

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

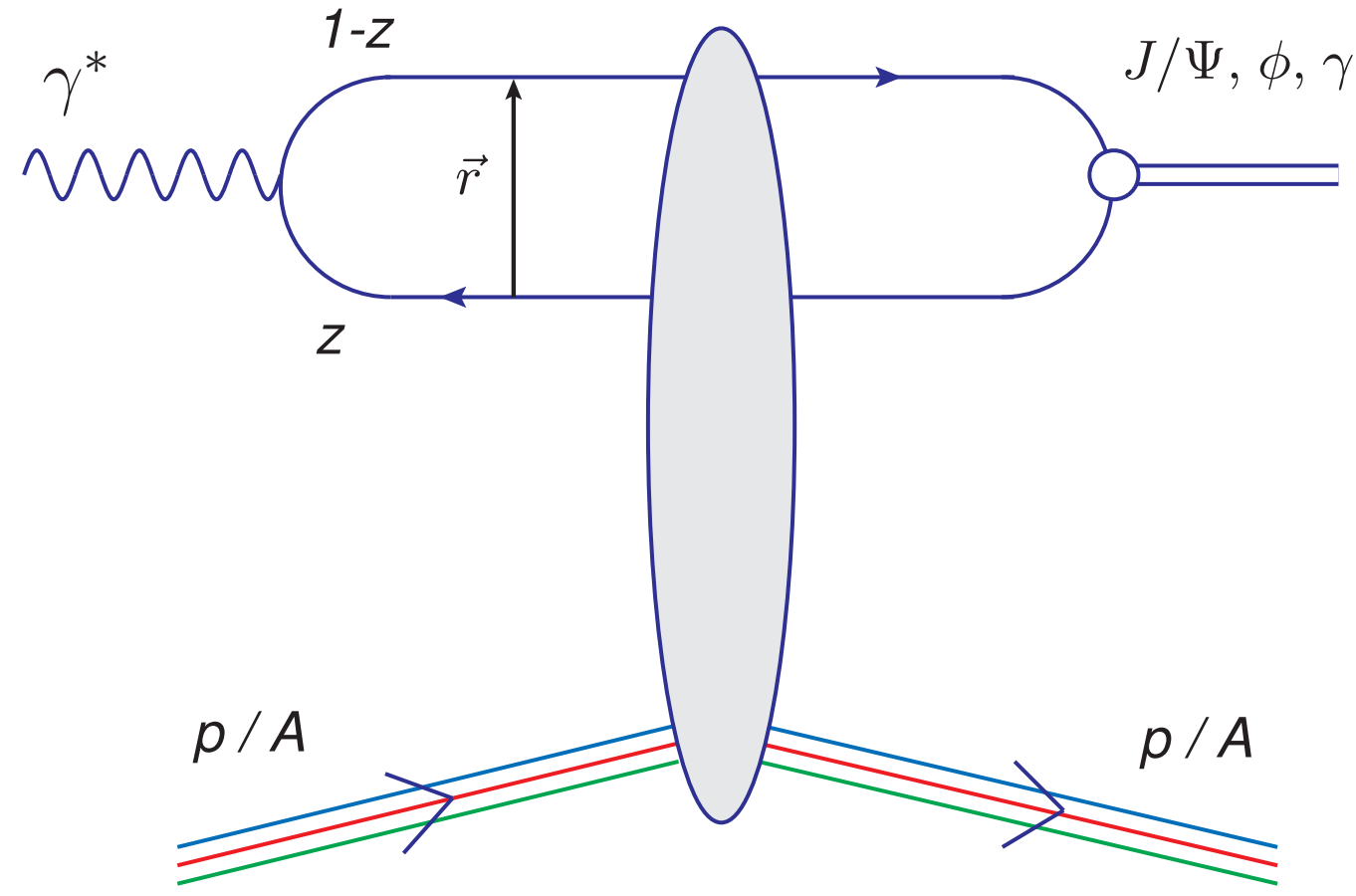
DIFFRACTIVE EVENTS IN DIS



- ➔ 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 spatial structure

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 $q\bar{q} \rightarrow VM$

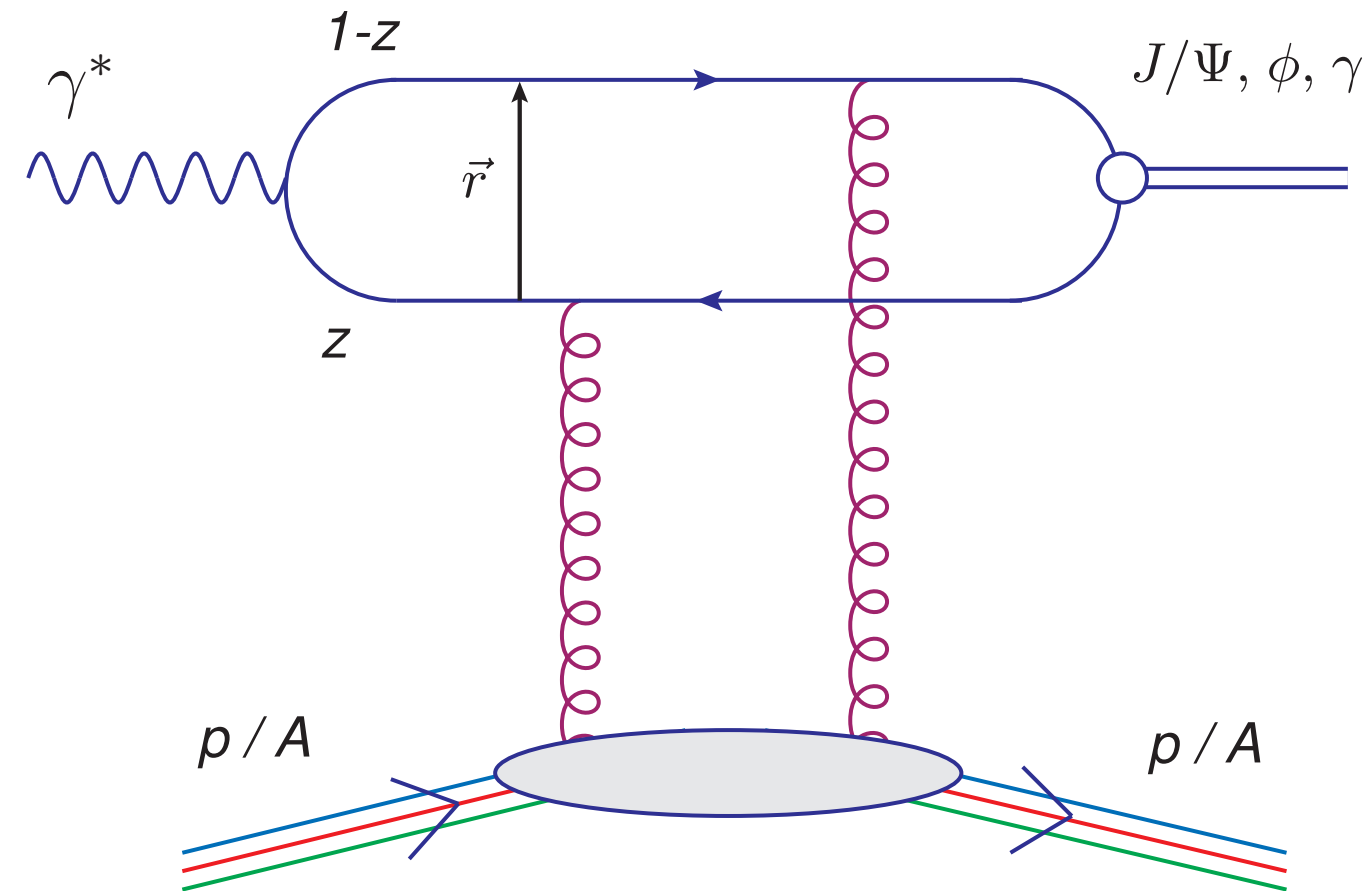
❖ The scattering amplitude is given by :

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

❖ 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



Factorisation :

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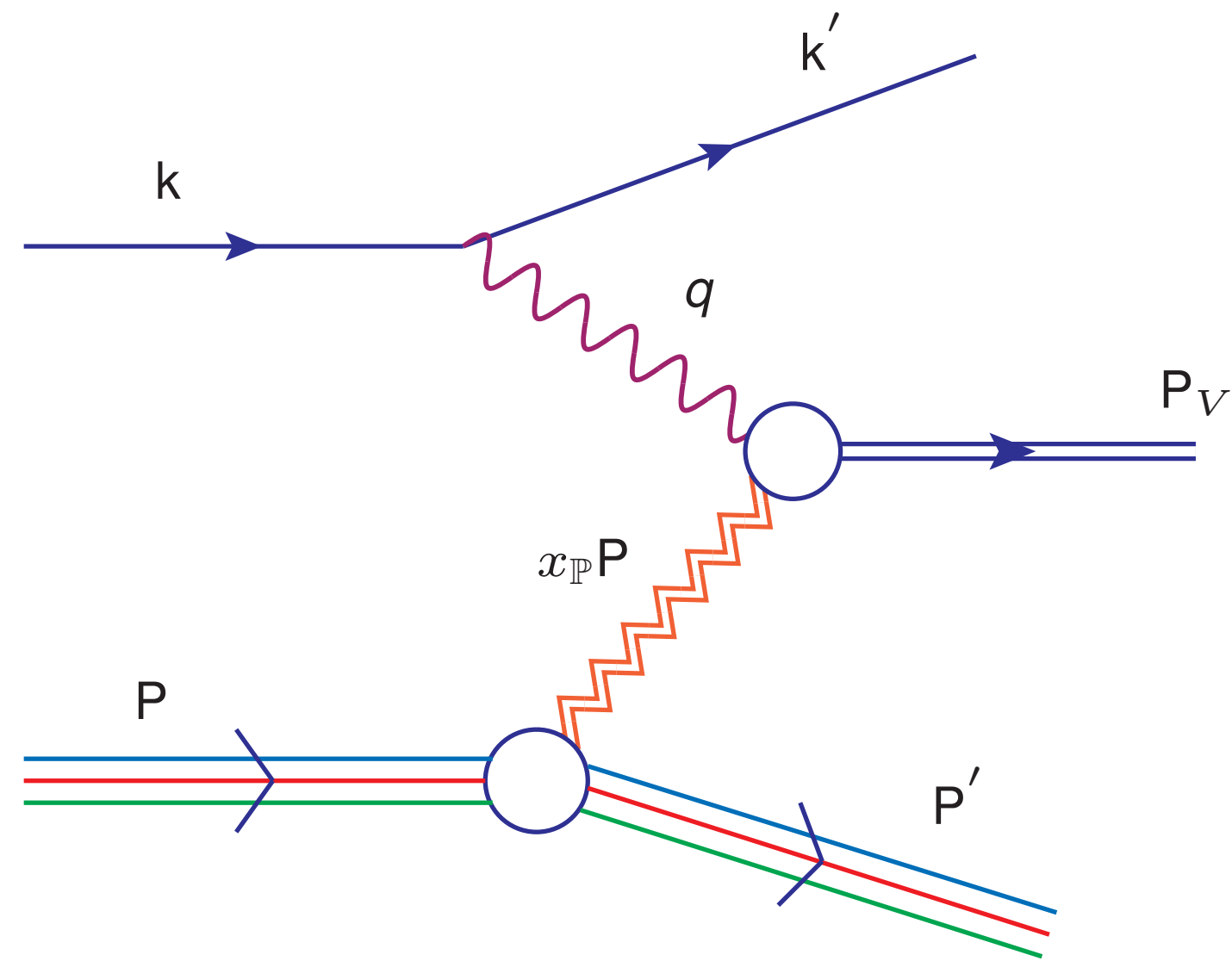
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❖ Impact parameter is Fourier conjugate to the momentum transfer $\Delta = (p' - p)_\perp$

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

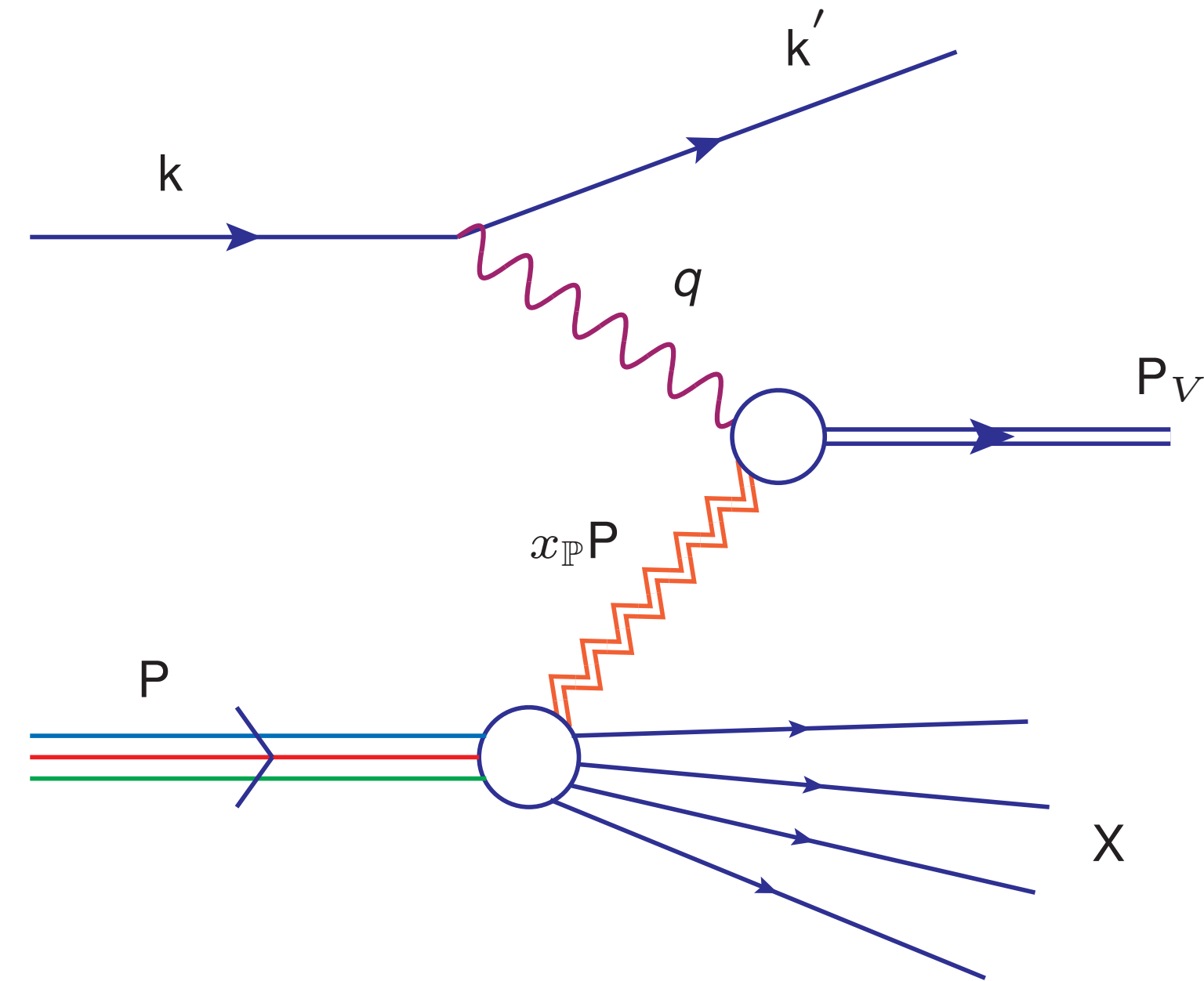
❖ In pQCD (2 gluon exchange) : $\frac{d\sigma^{\gamma^* A \rightarrow V A}}{dt} \sim [xg(x, Q^2)]^2$

COHERENT AND INCOHERENT VECTOR MESON PRODUCTION



Coherent diffraction

★ *Target remains intact*



Incoherent diffraction

★ *Target breaks up*

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

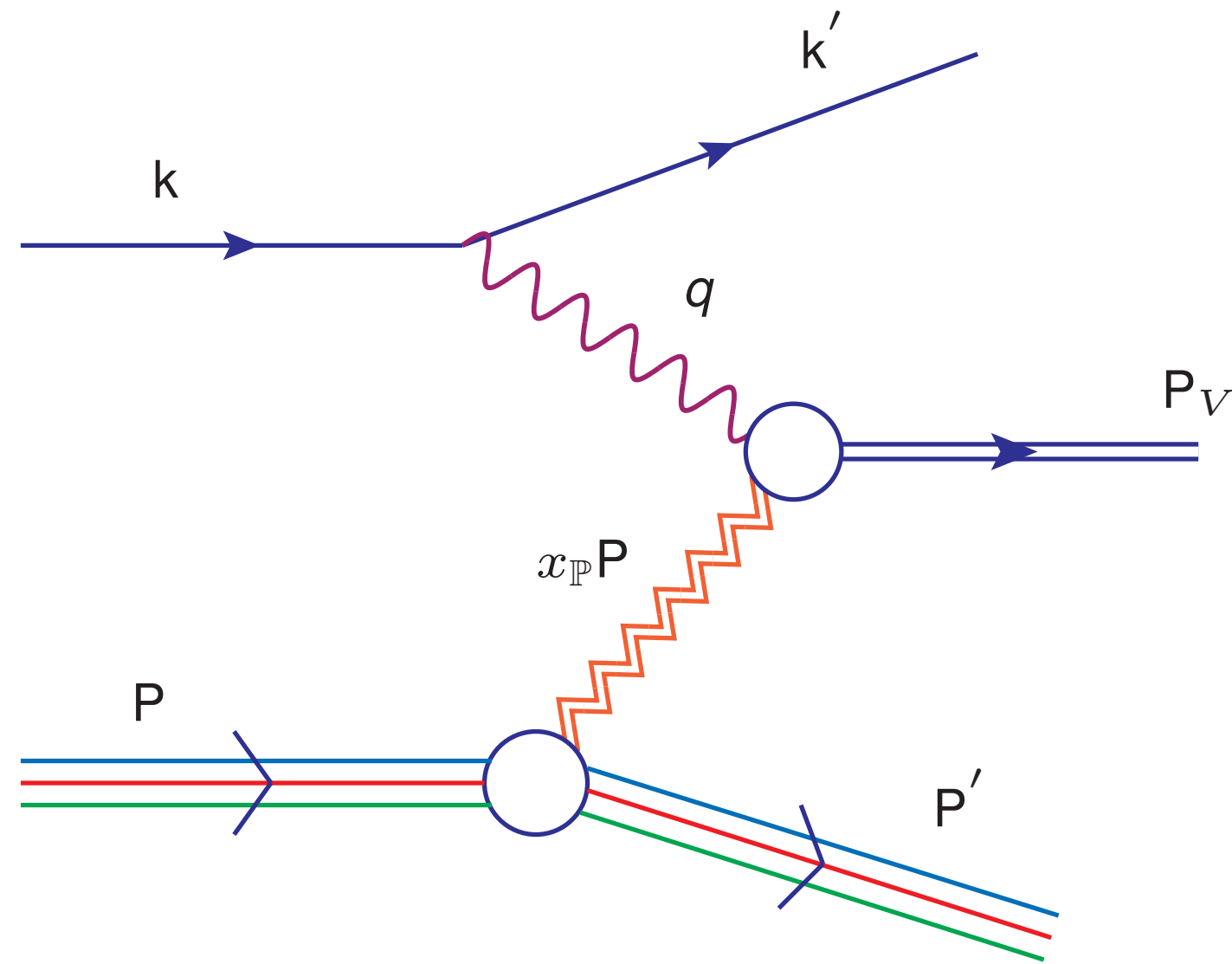
- Sensitive to fluctuations of gluon distribution

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

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

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

DIFFRACTIVE VECTOR MESON PRODUCTION WITH SARTRE

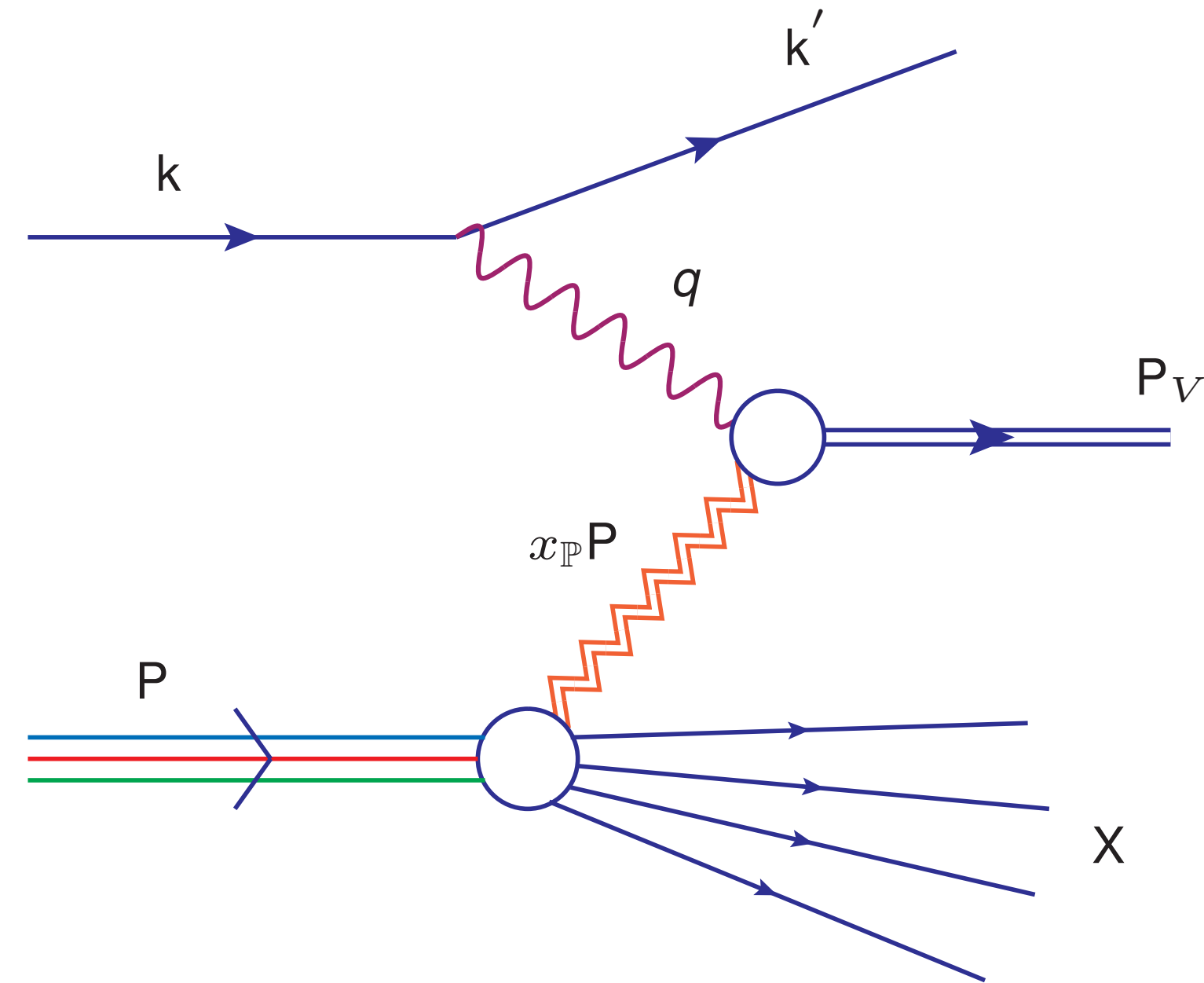


Coherent diffraction

★ Proton remains intact

★ Sensitive to average gluon distribution in the proton

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



Incoherent diffraction

★ Proton breaks up

★ Sensitive to fluctuations of gluon distribution

Good, Walker 1960, Miettinen, Pumplin 1978

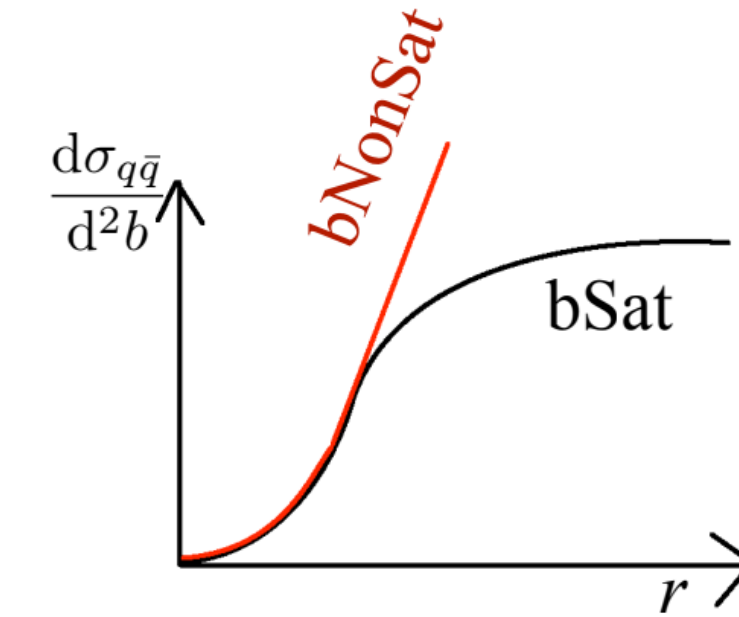
$$\sigma_{tot} \propto \underbrace{|\langle \mathcal{A} \rangle_{\Omega}|^2}_{\text{Coherent}} + \underbrace{(\langle |\mathcal{A}|^2 \rangle_{\Omega} - |\langle \mathcal{A} \rangle_{\Omega}|^2)}_{\text{Incoherent}}$$

THE DIPOLE-TARGET AMPLITUDE

• the bSat dipole model : $N(\mathbf{b}, \mathbf{r}, x) = 2 \left[1 - \exp \left(- \frac{\pi^2}{2N_C} \mathbf{r}^2 \alpha_s(\mu^2) x g(x, \mu^2) T_{p/A}(\mathbf{b}) \right) \right]$

• the bNonSat dipole model : $N(\mathbf{b}, \mathbf{r}, x) = \frac{\pi^2}{N_C} \mathbf{r}^2 \alpha_s(\mu^2) x g(x, \mu^2) T_{p/A}(\mathbf{b})$

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)

The Thickness function $T_{p/A}(b)$:

Kowalski, Teaney 2003, Kowalski, Motyka, Watt 2006

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

Mäntysaari, Schenke PRL 117 (2016) 052301

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

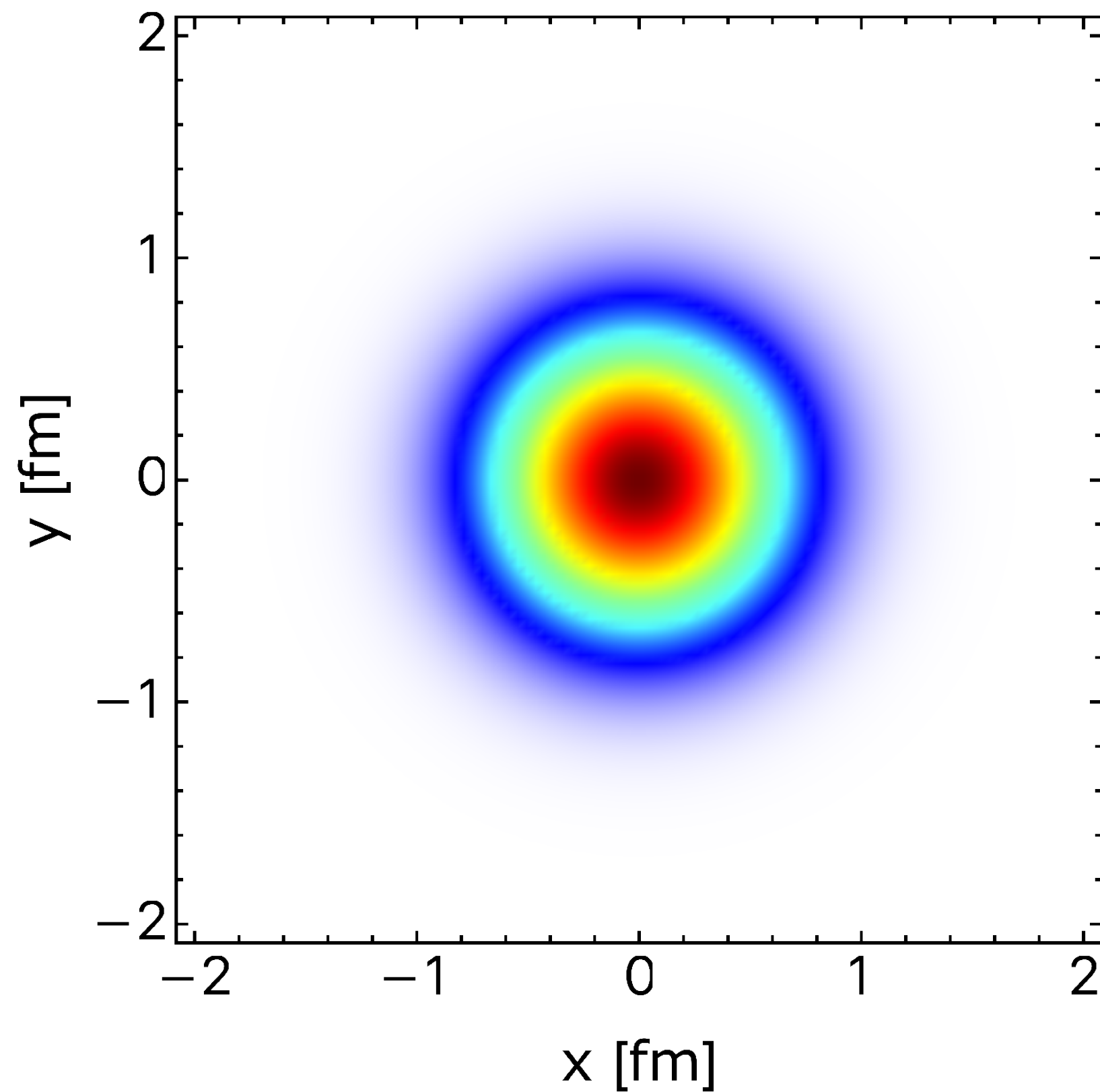
c) For Heavy ions $T_A(b) \rightarrow \frac{1}{A} \sum_{i=1}^A T_p(b - b_i)$ and where b_i denotes location of nucleons sampled from Woods-Saxon geometry

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

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

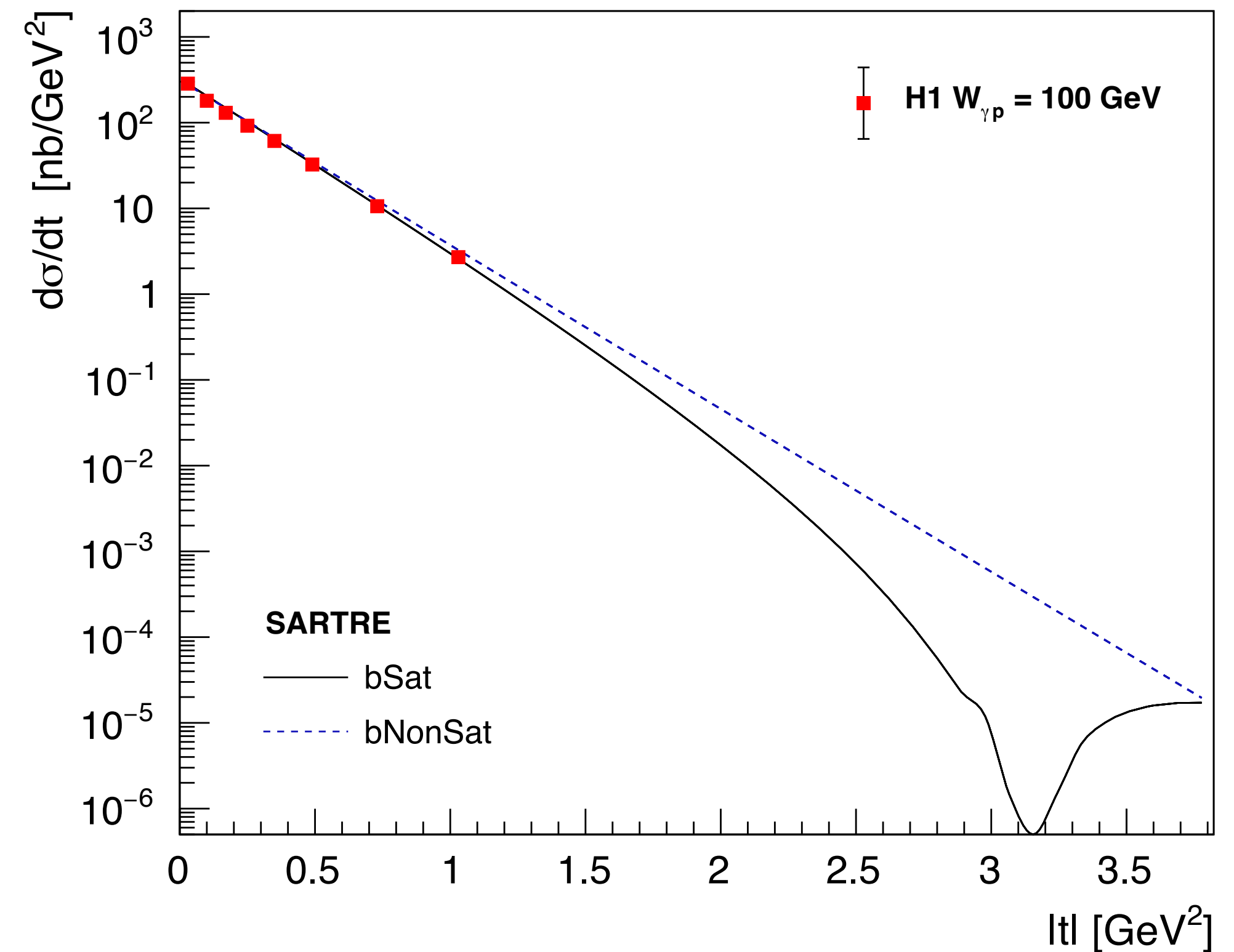
$$\mathcal{A} \sim \int d^2r \int d^2b \int dz \times (\Psi^* \Psi_V)_{T,L}(Q^2, r, z) \times e^{-ib \cdot \Delta} \times N(b, r, x)$$

Kowalski, Teaney 2003, Kowalski, Motyka, Watt 2006



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

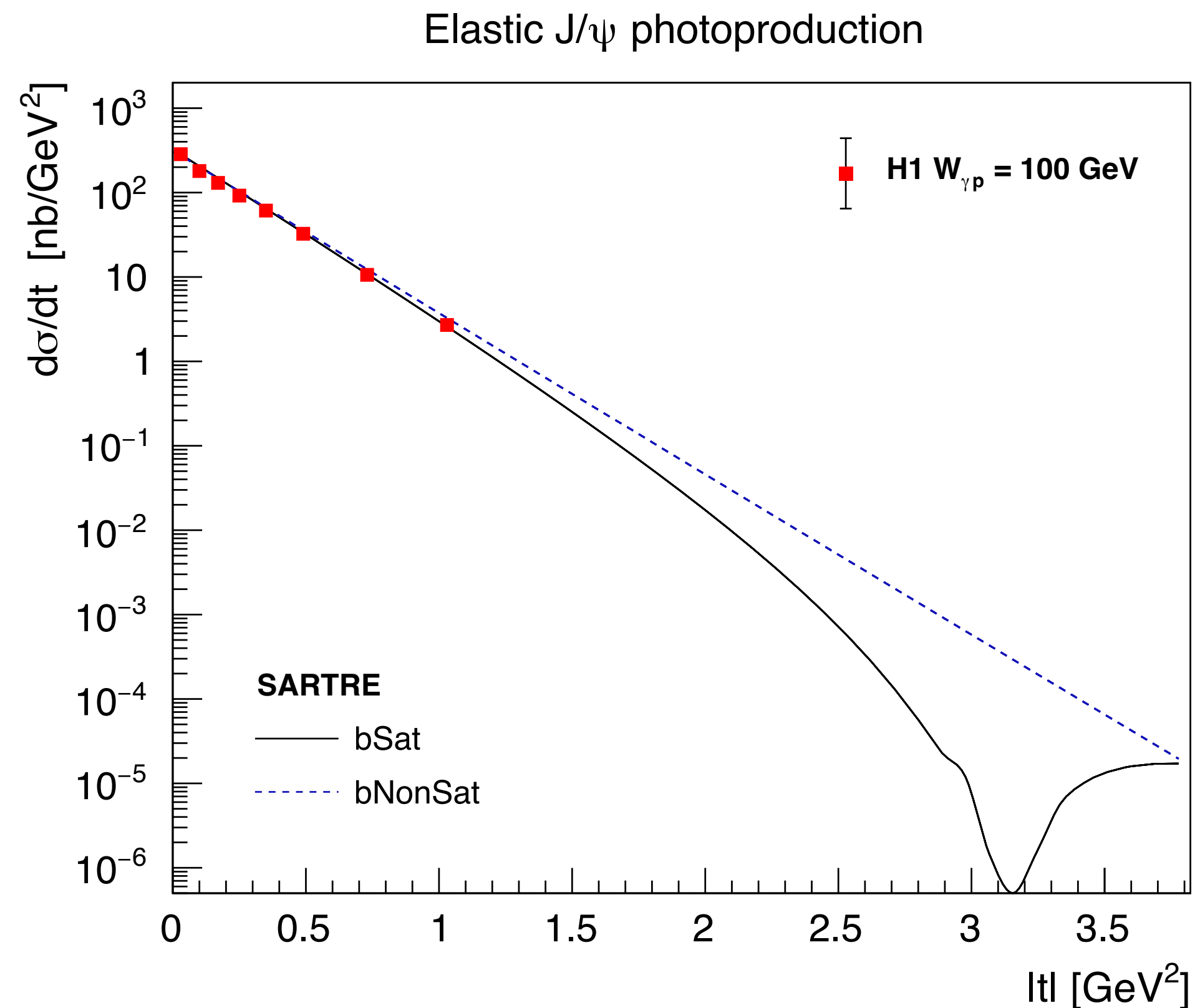
Elastic J/ψ photoproduction



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

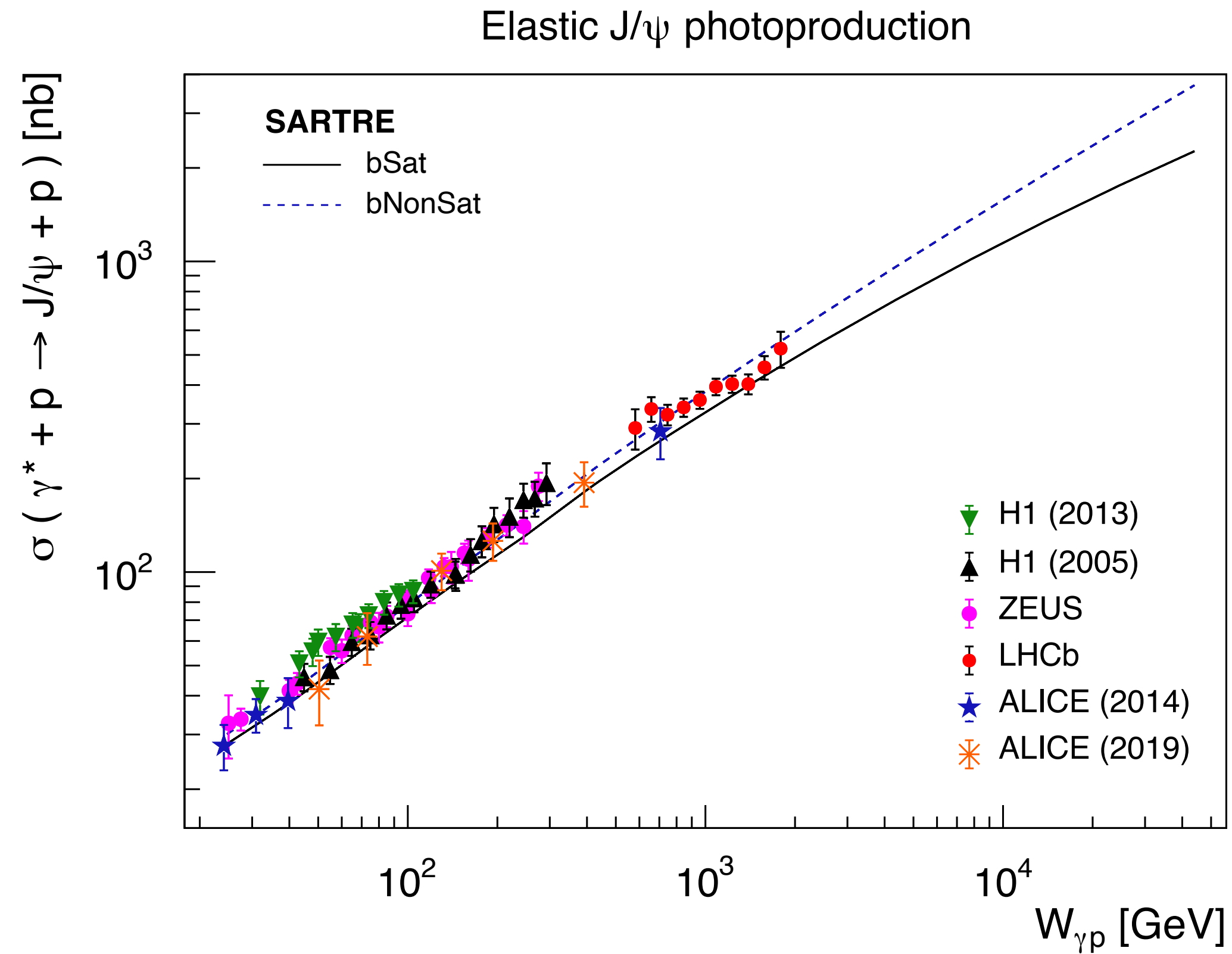
Gaussian & non-linear (bSat) : $N(r, b) \sim 1 - \exp(-e^{-\mathbf{b}^2/(2B)})$

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



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

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

Power law increase for non-saturated model

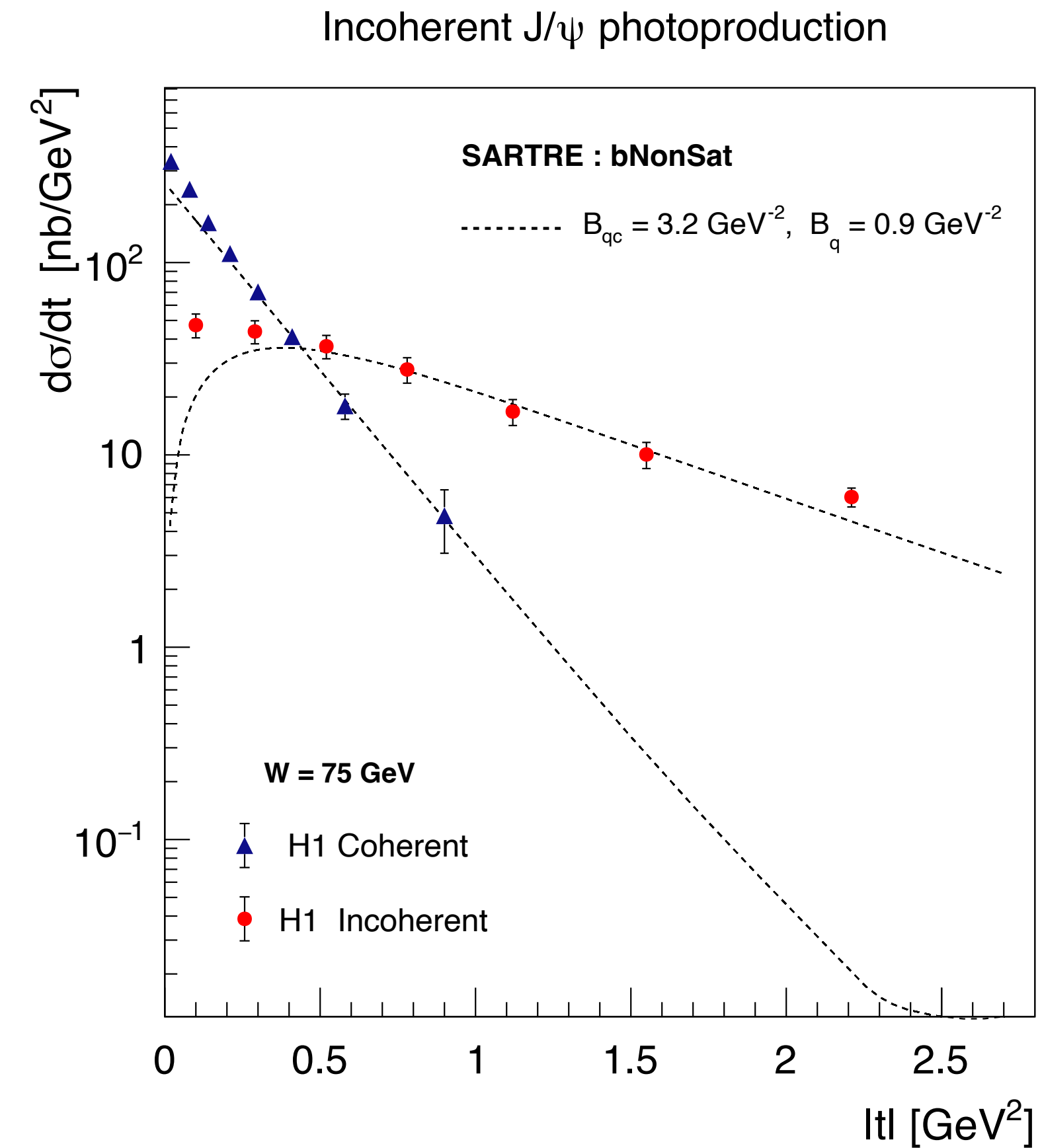
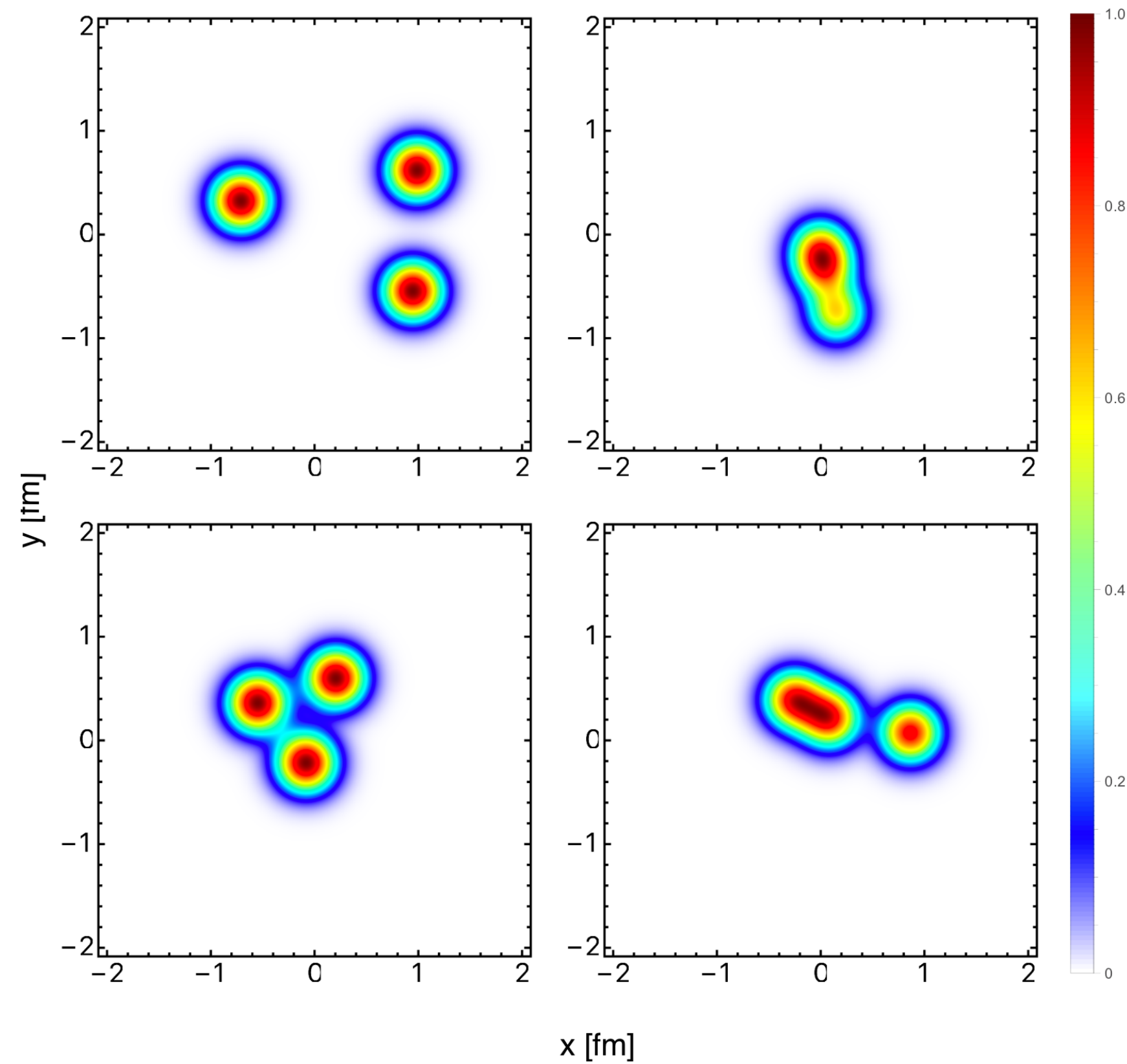
Deviations from power law? Hint of non-linear effects

For a smooth proton there are no fluctuations and the incoherent cross section is zero $\rightarrow$ 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

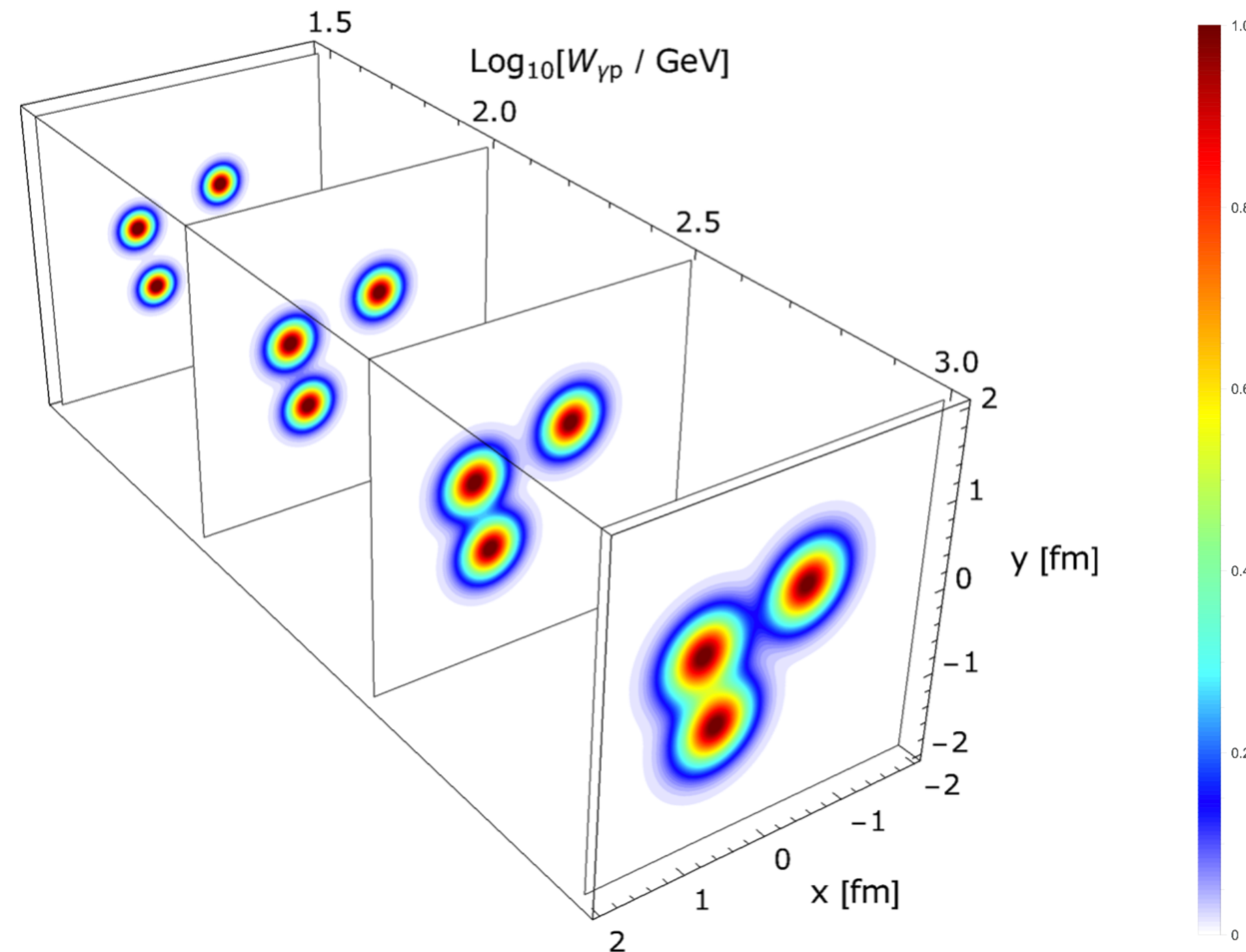


(large event-by-event fluctuations (1000 configurations) are needed to explain HERA data)

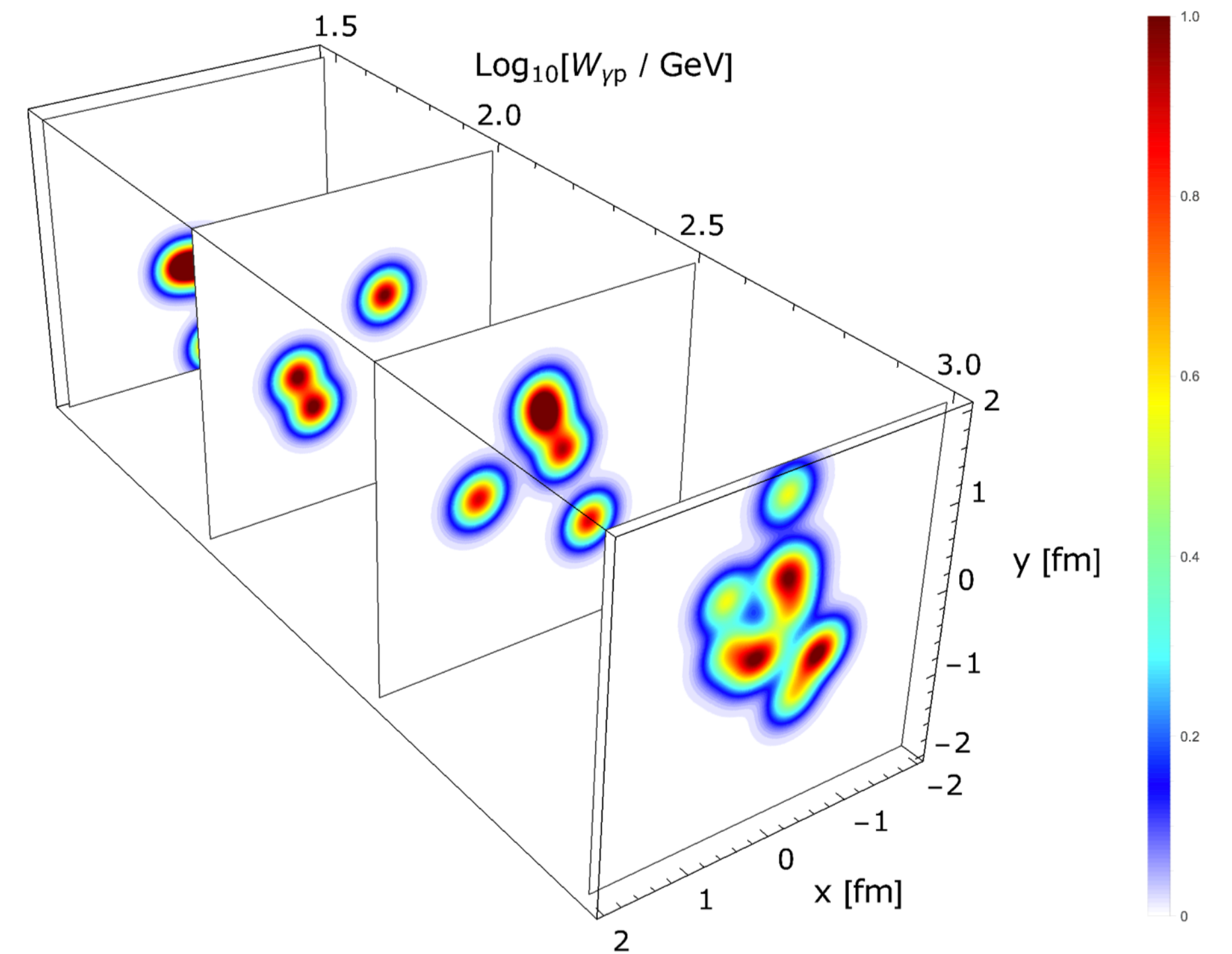
see Blaizot, Traini 2209.15545 for dipole size fluctuations at low momentum transfer

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



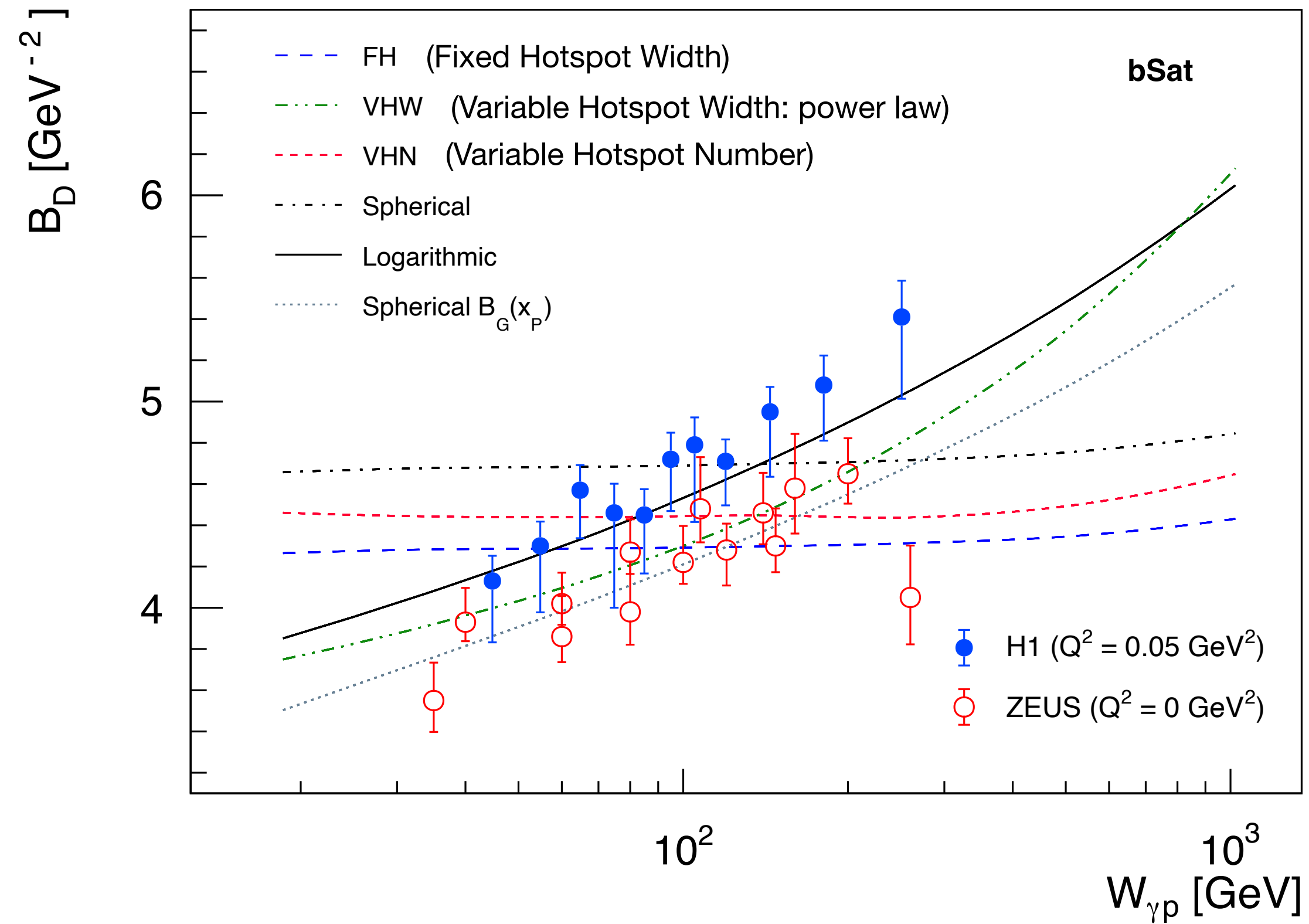
Varying hotspot number (VHN) model: $N_q(x) = p_0 x^{p_1}(1 + p_2\sqrt{x})$

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

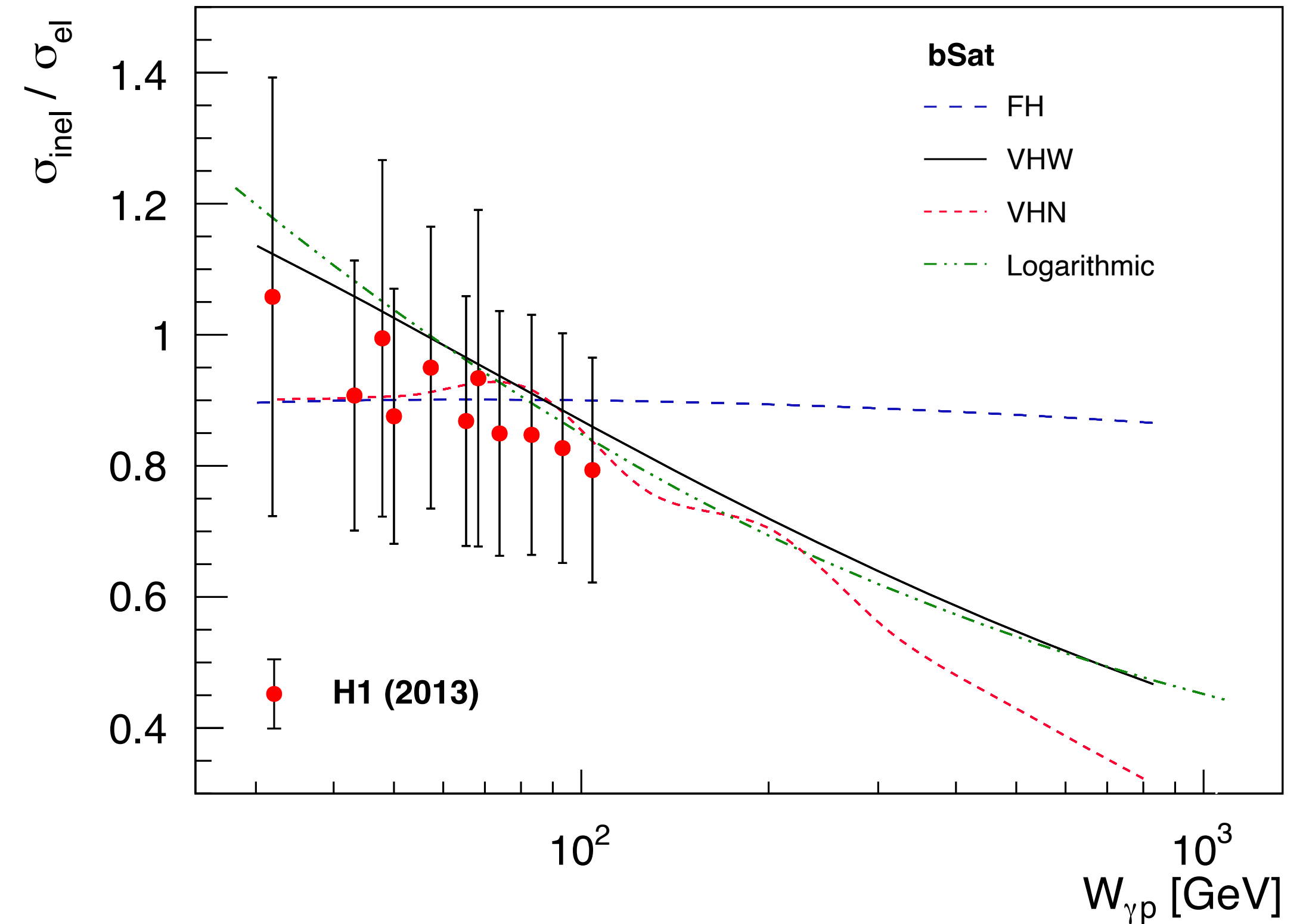
INCORPORATING THE ENERGY DEPENDENCE

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

Elastic J/ψ photoproduction

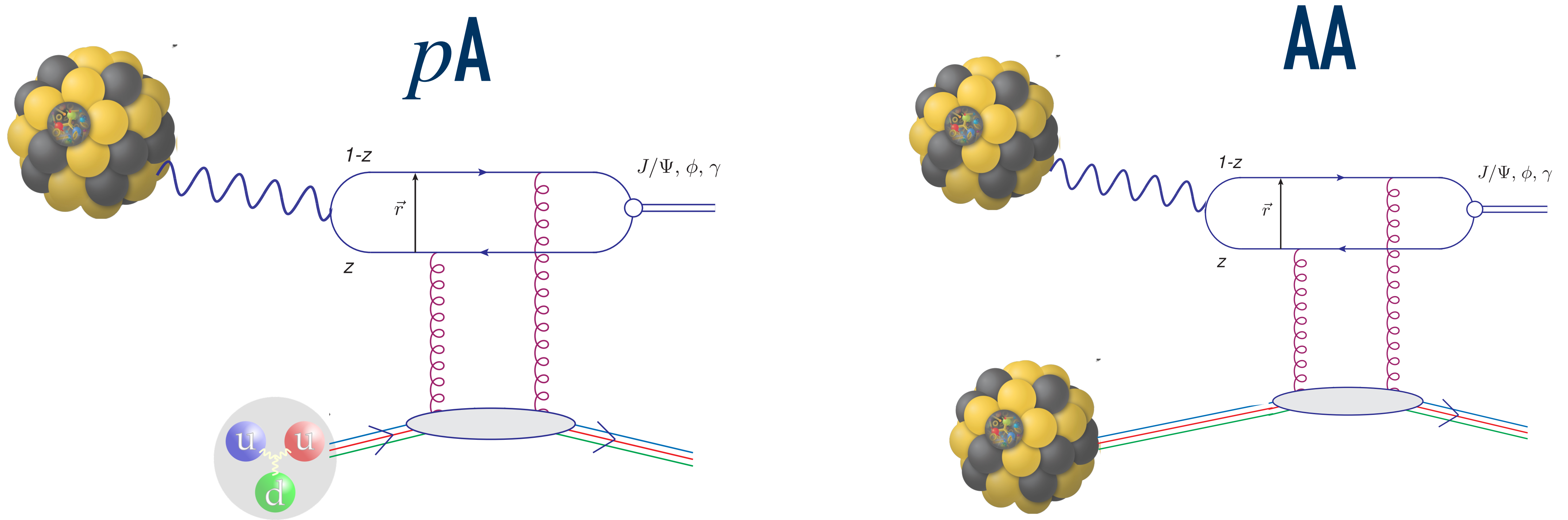


J/ψ photoproduction



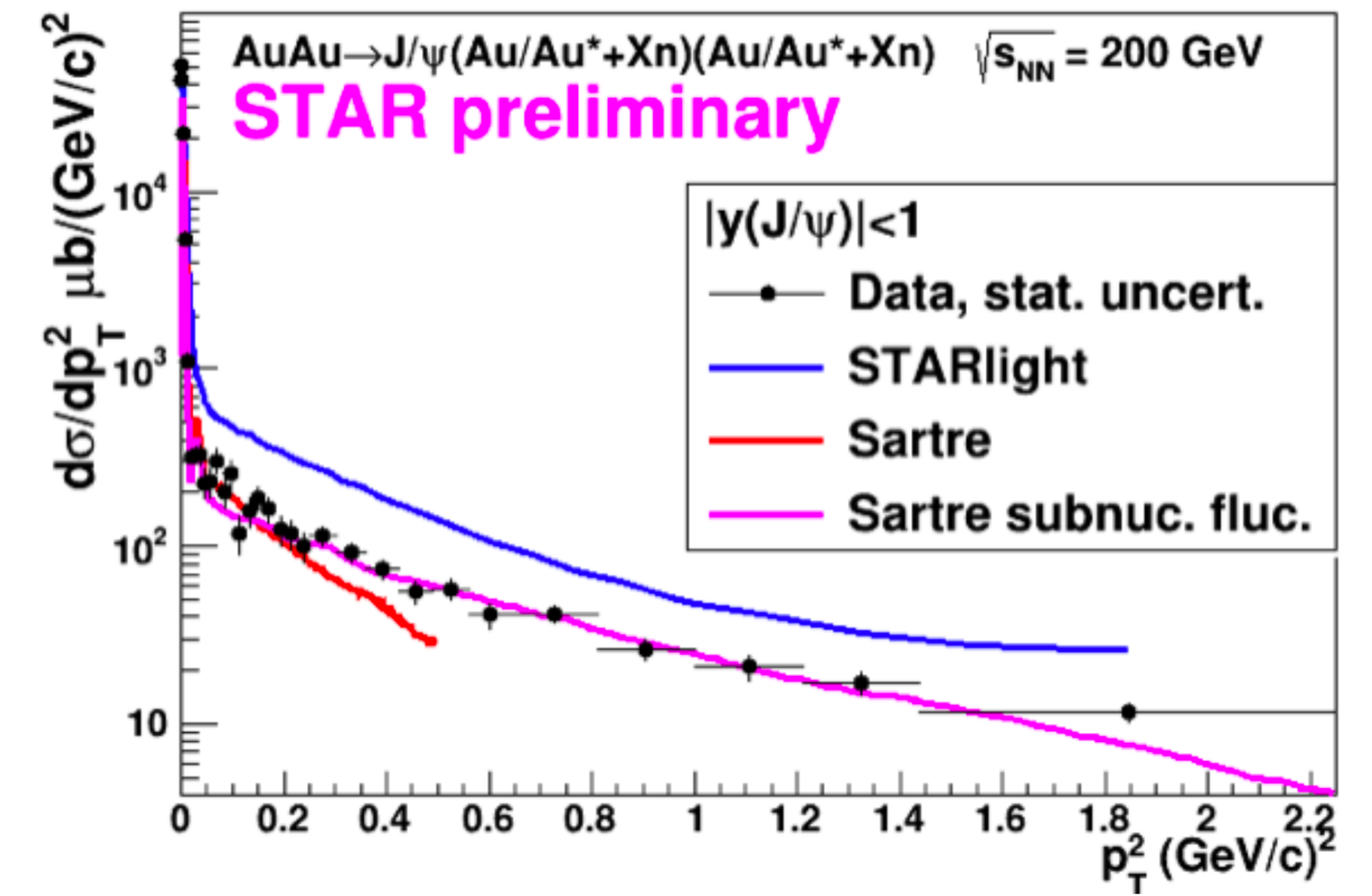
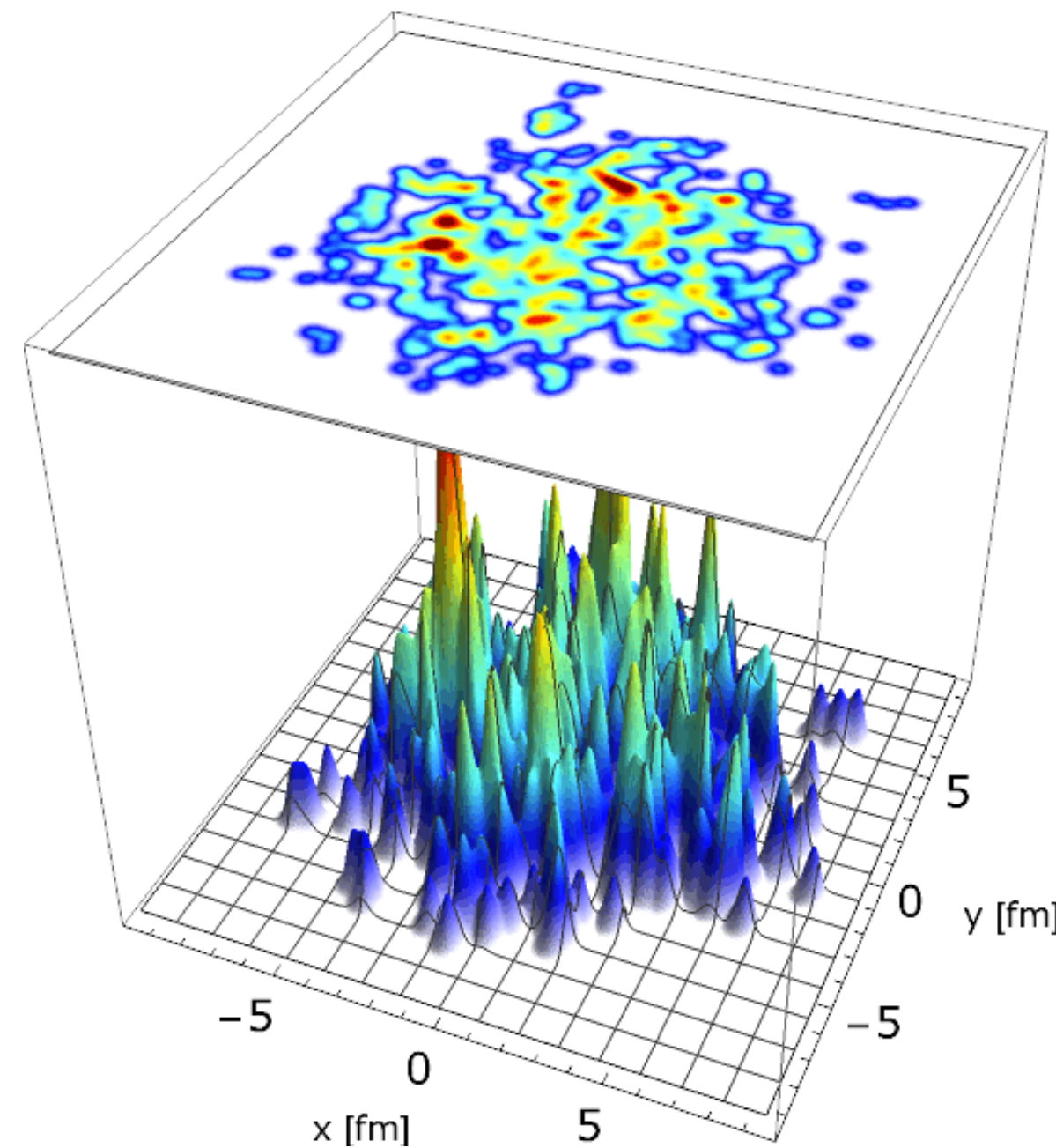
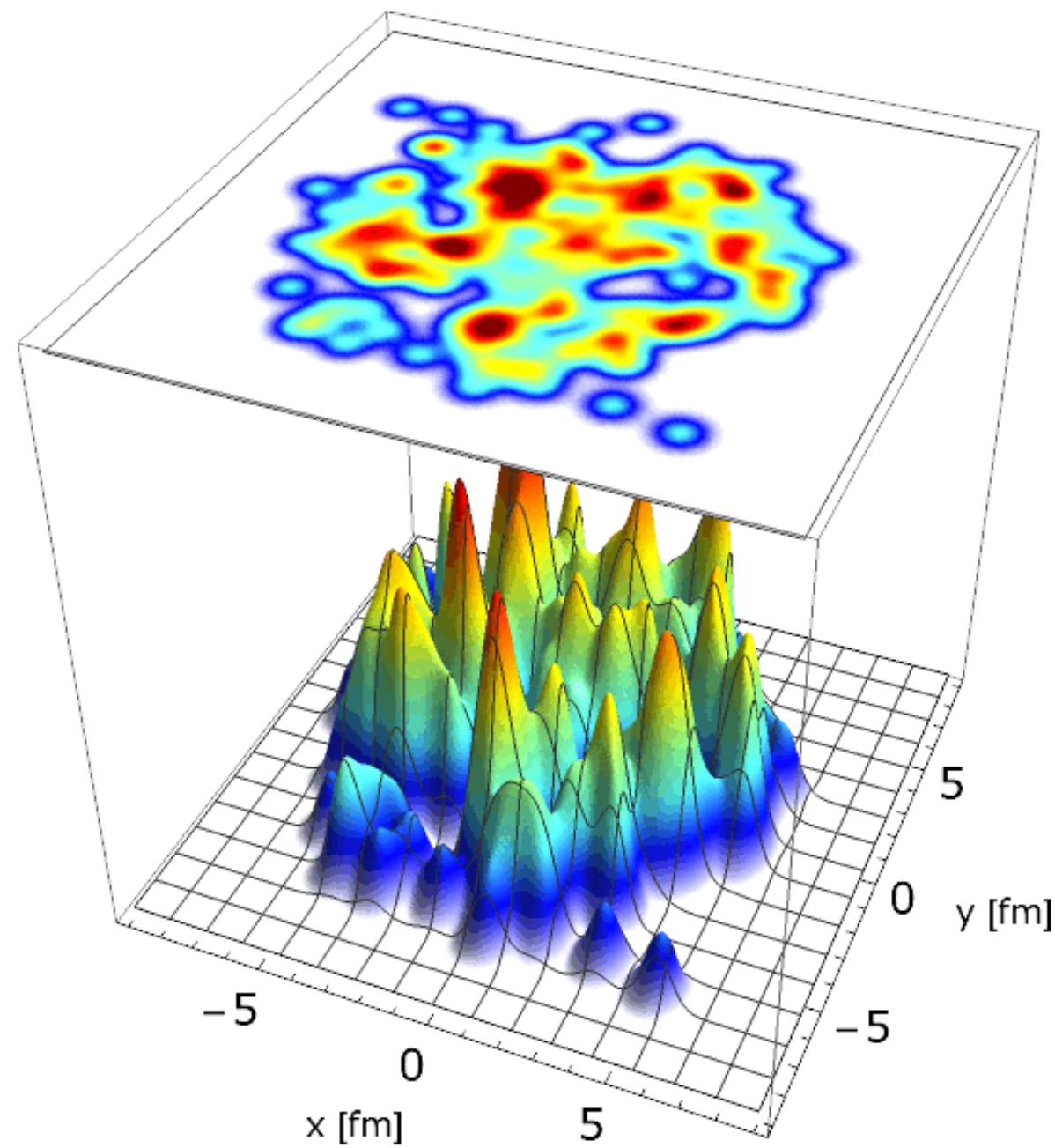
see Mäntysaari, Schenke 1806.06783 for similar predictions in IP-GLASMA framework

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.

DIFFRACTIVE J/ψ PRODUCTION IN ULTRA PERIPHERAL COLLISIONS

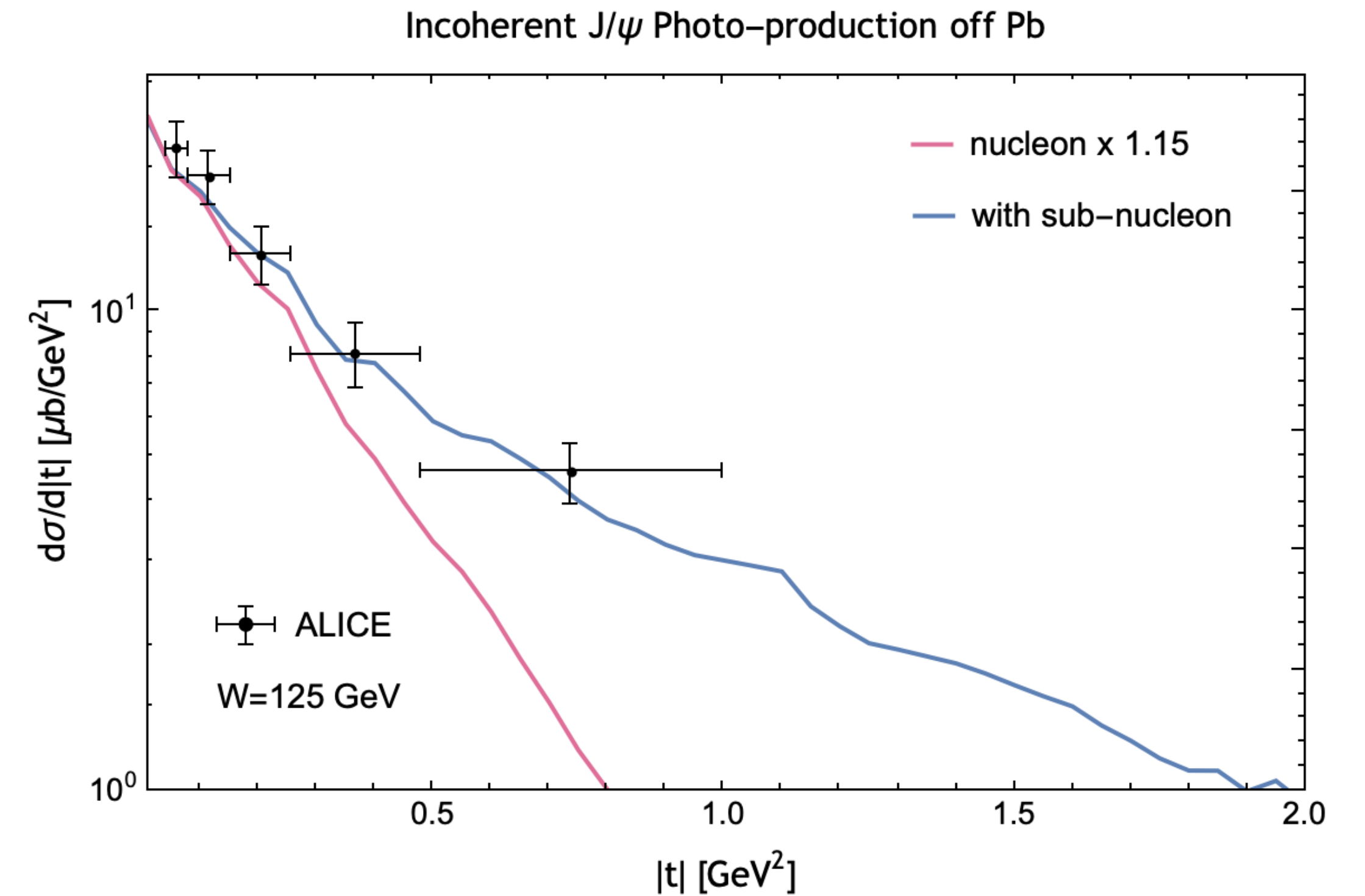
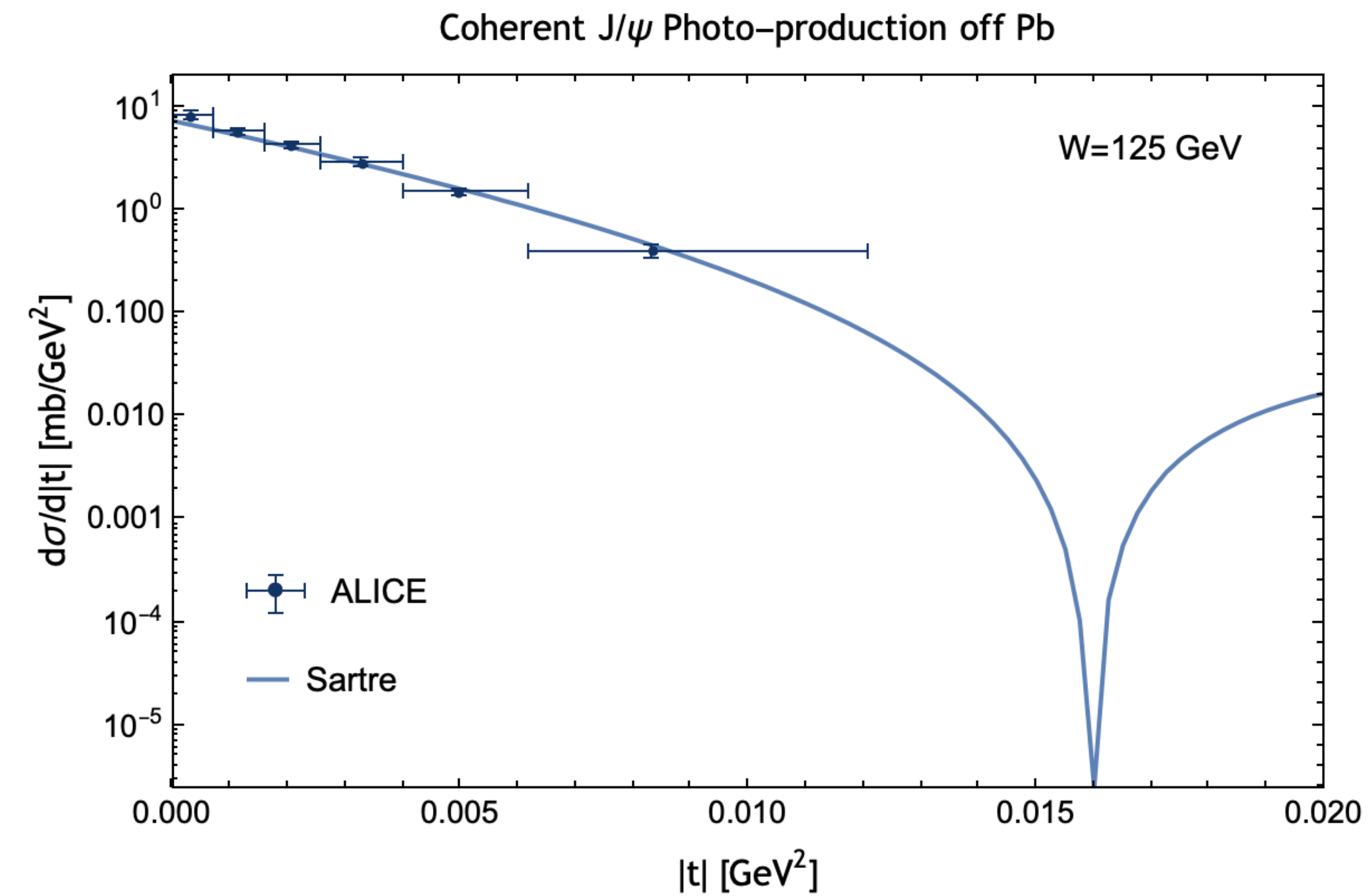


T.Toll SciPost Phys. Proc. 8 (2022) 148

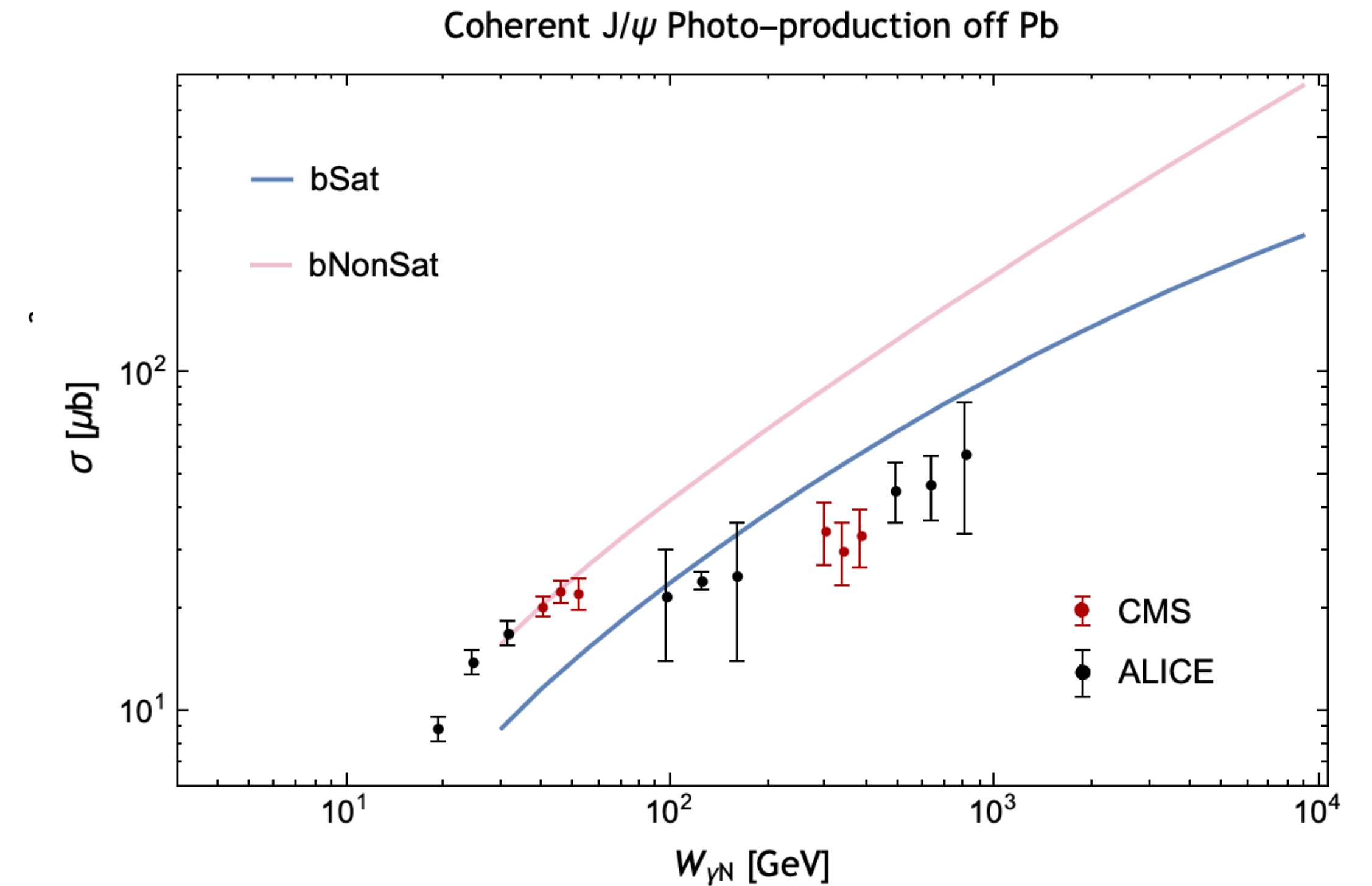
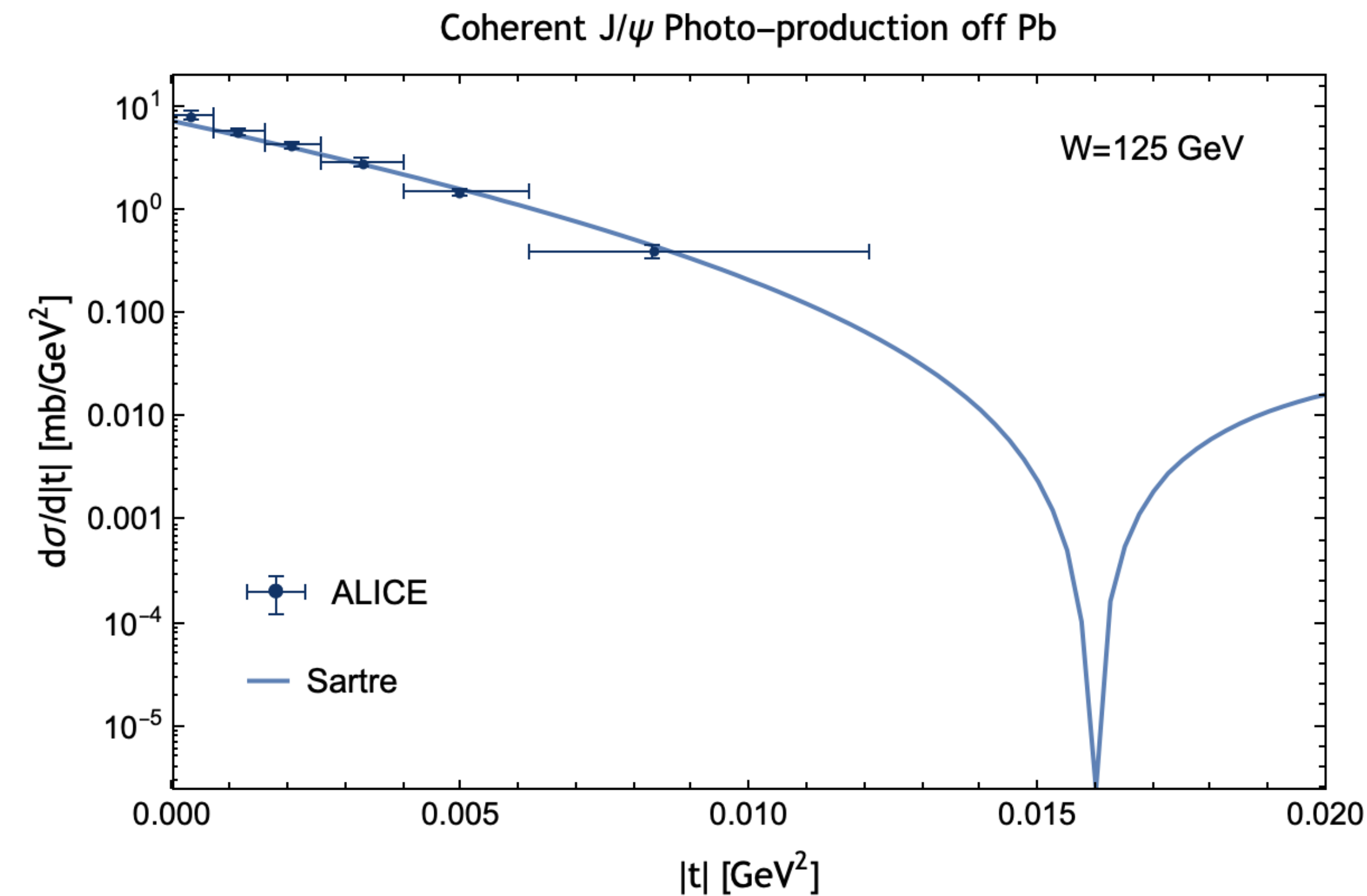
$$T_A(b) \rightarrow \sum_{i=1}^A T_p(b - b_i)$$

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

DIFFRACTIVE J/ψ PRODUCTION IN ULTRA PERIPHERAL COLLISIONS



DIFFRACTIVE J/ψ PRODUCTION IN ULTRA PERIPHERAL COLLISIONS

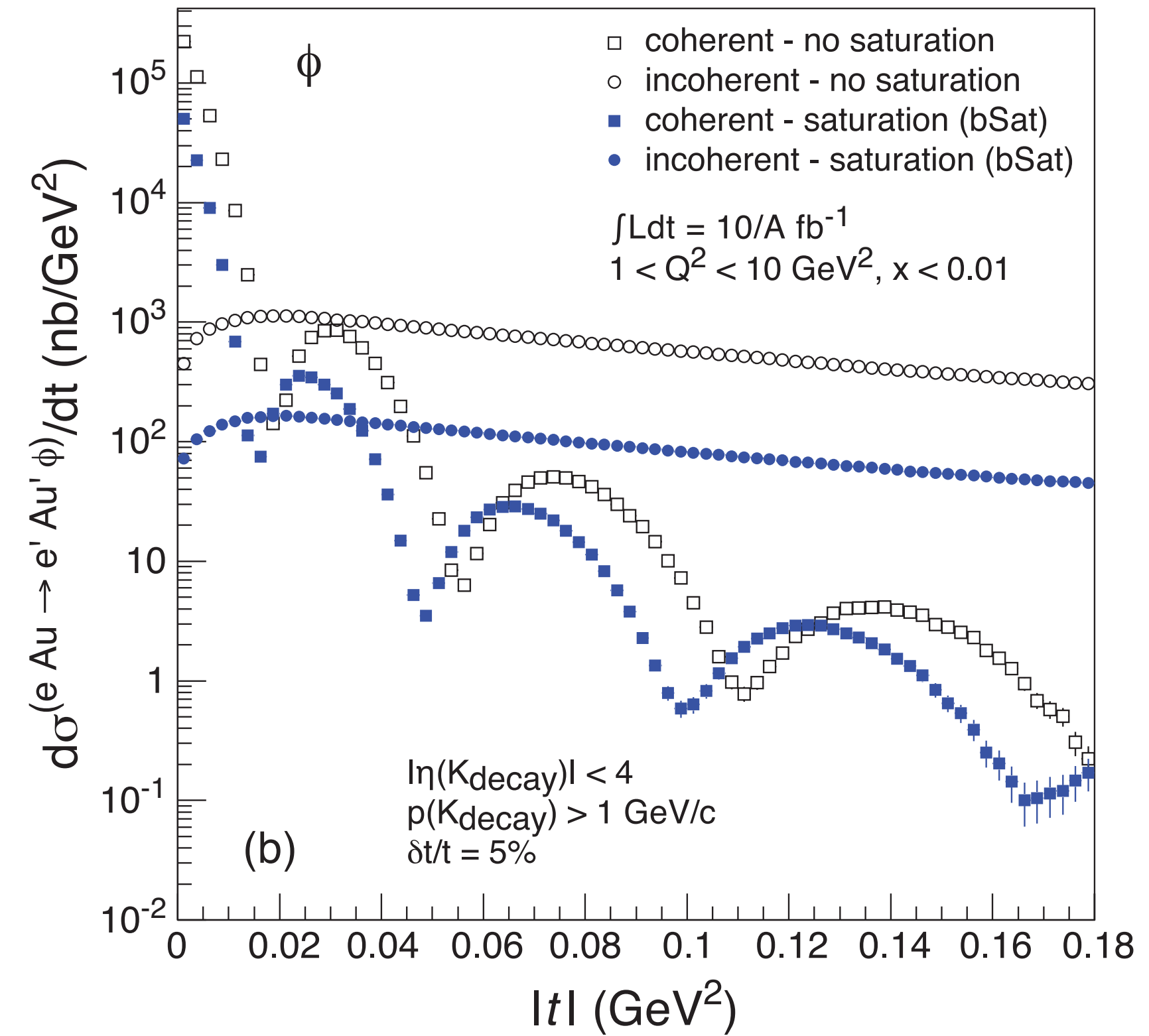
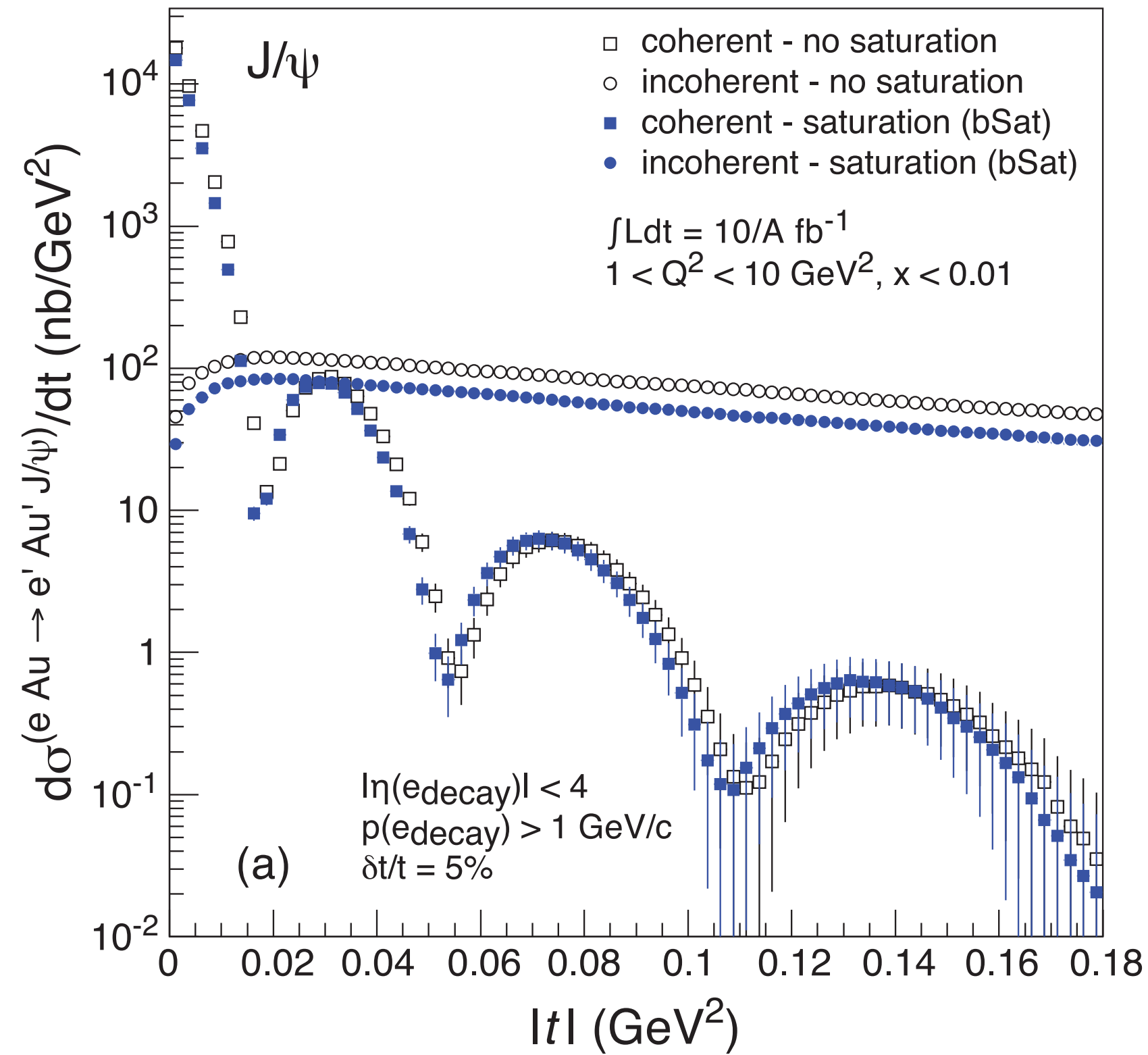


Crucial to understand whether the suppression originates from perturbative (saturation models & small- x evolution) or non-perturbative (shadowing models) mechanisms? *look for new observables & investigate A dependence*

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

EXCLUSIVE DIFFRACTION AT EIC

T. Toll, T.Ullrich PRC 87 (2013) 024913

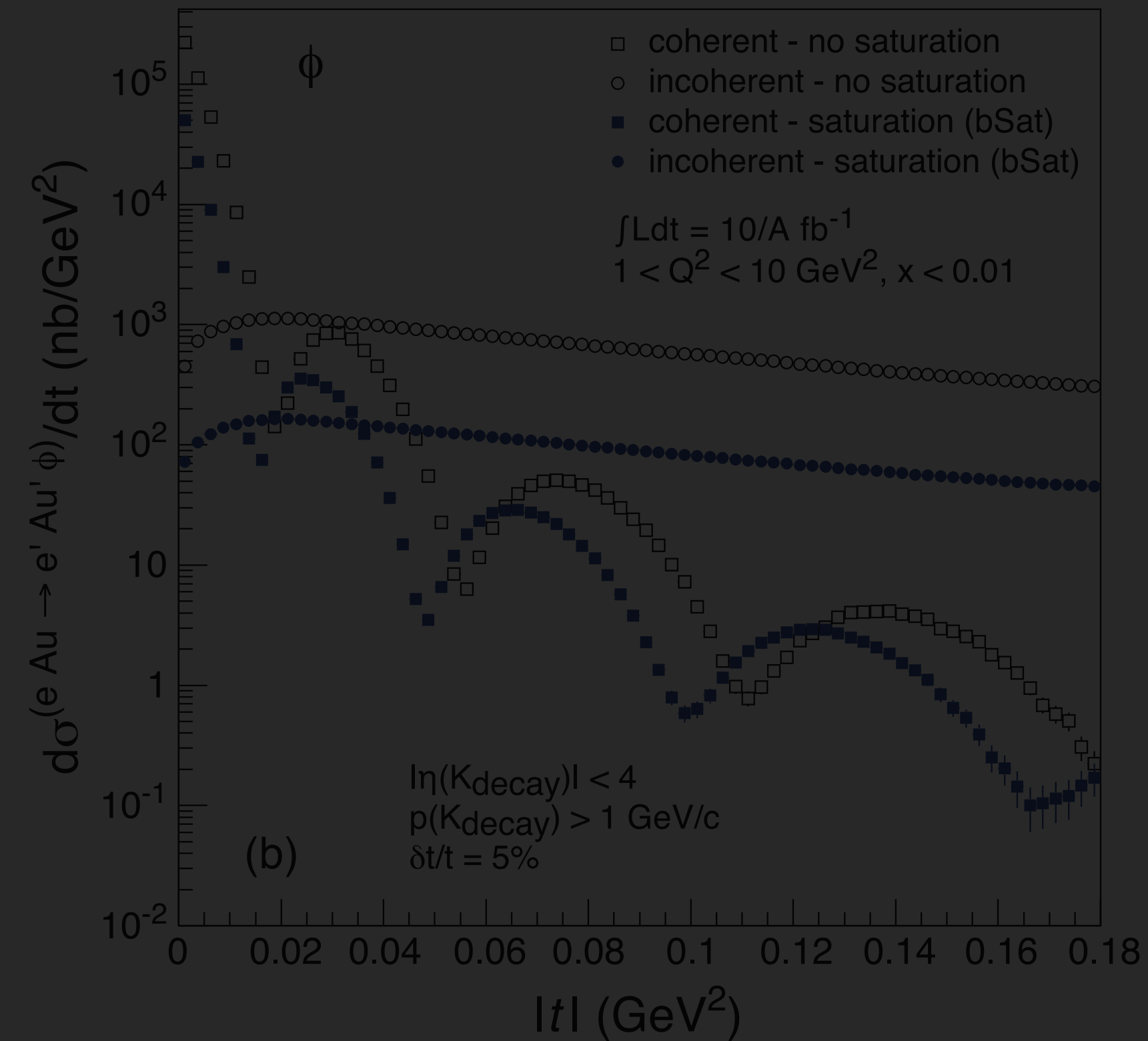
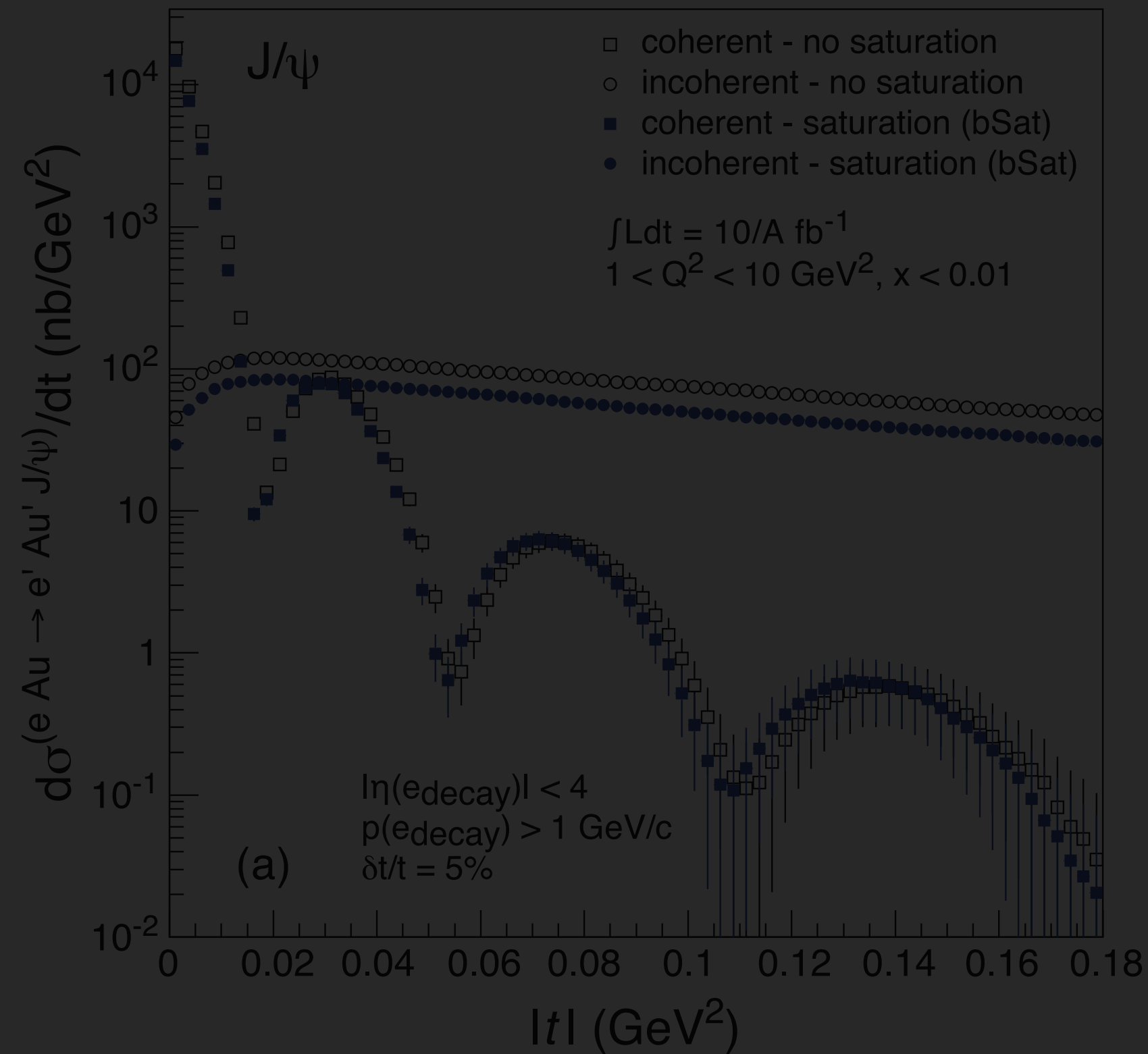


Spatial Imaging :
$$F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \Big|_{\text{mod}}$$

EXCLUSIVE DIFFRACTION AT EIC

Tobias Toll, Thomas Ullrich PRC 87 (2013) 024913

Why it is so difficult ?

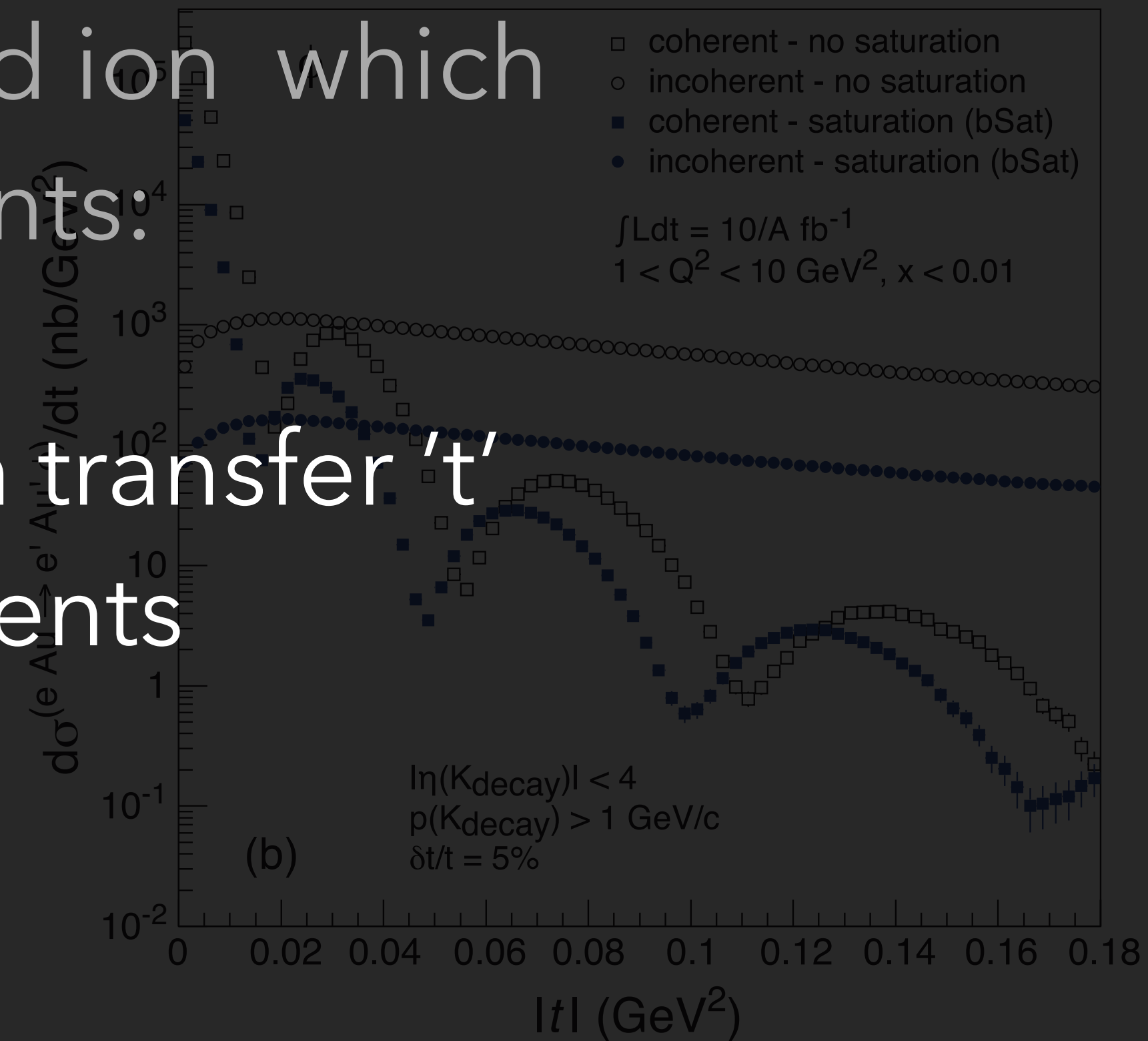
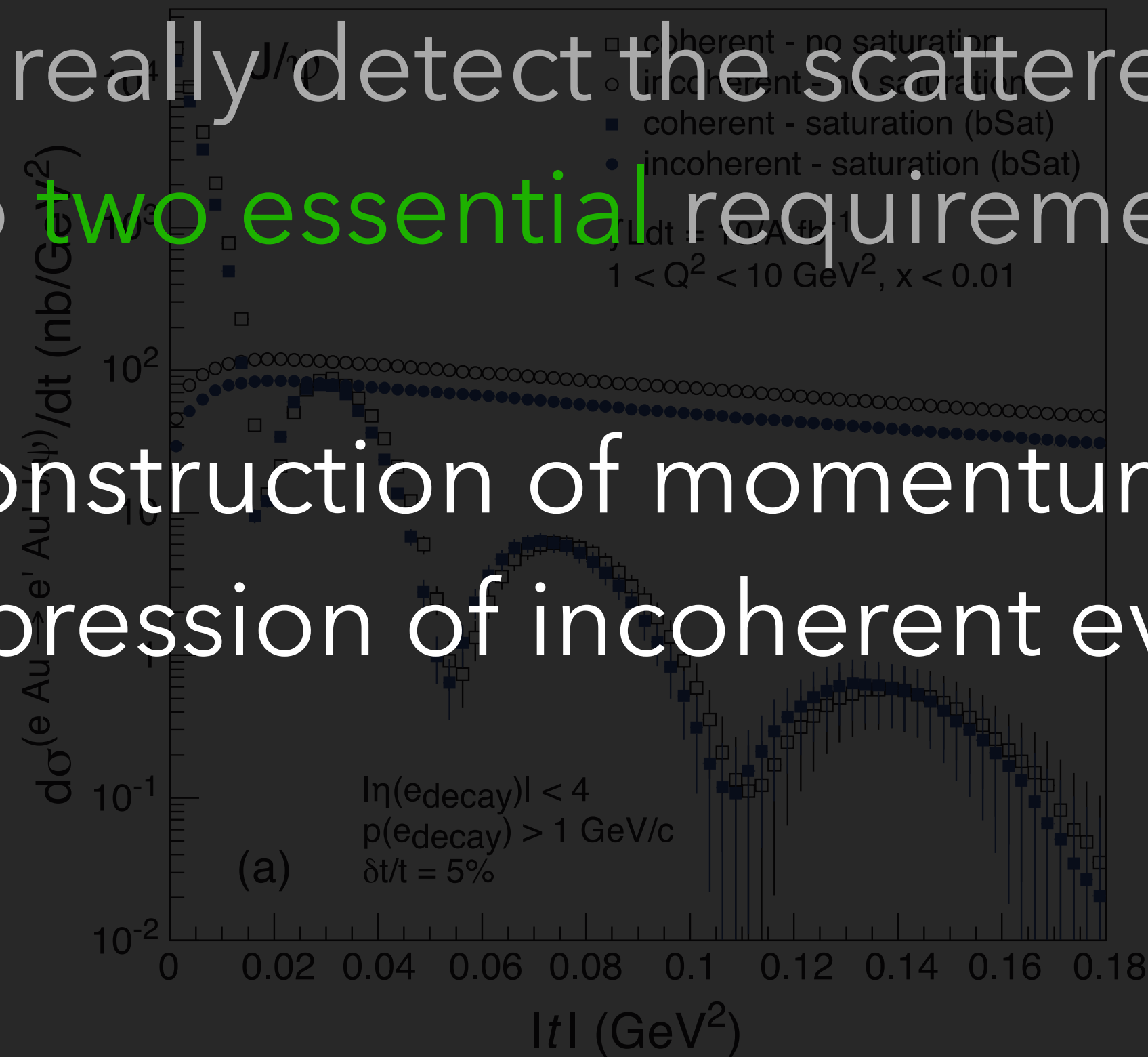


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Why it is so difficult ?

Cannot really detect the scattered ion which leads to **two essential** requirements:

1. Reconstruction of momentum transfer 't'
2. Suppression of incoherent events

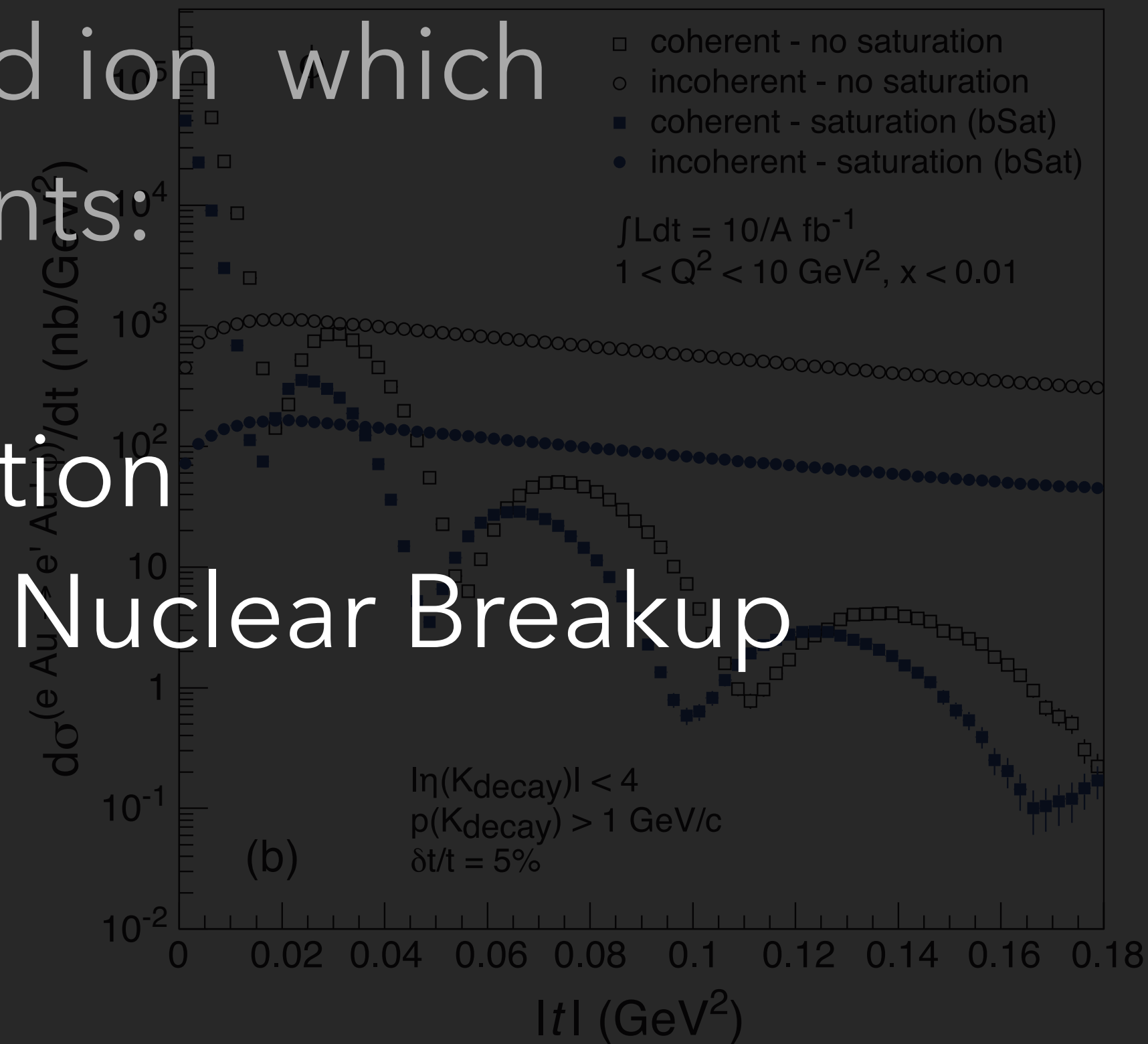
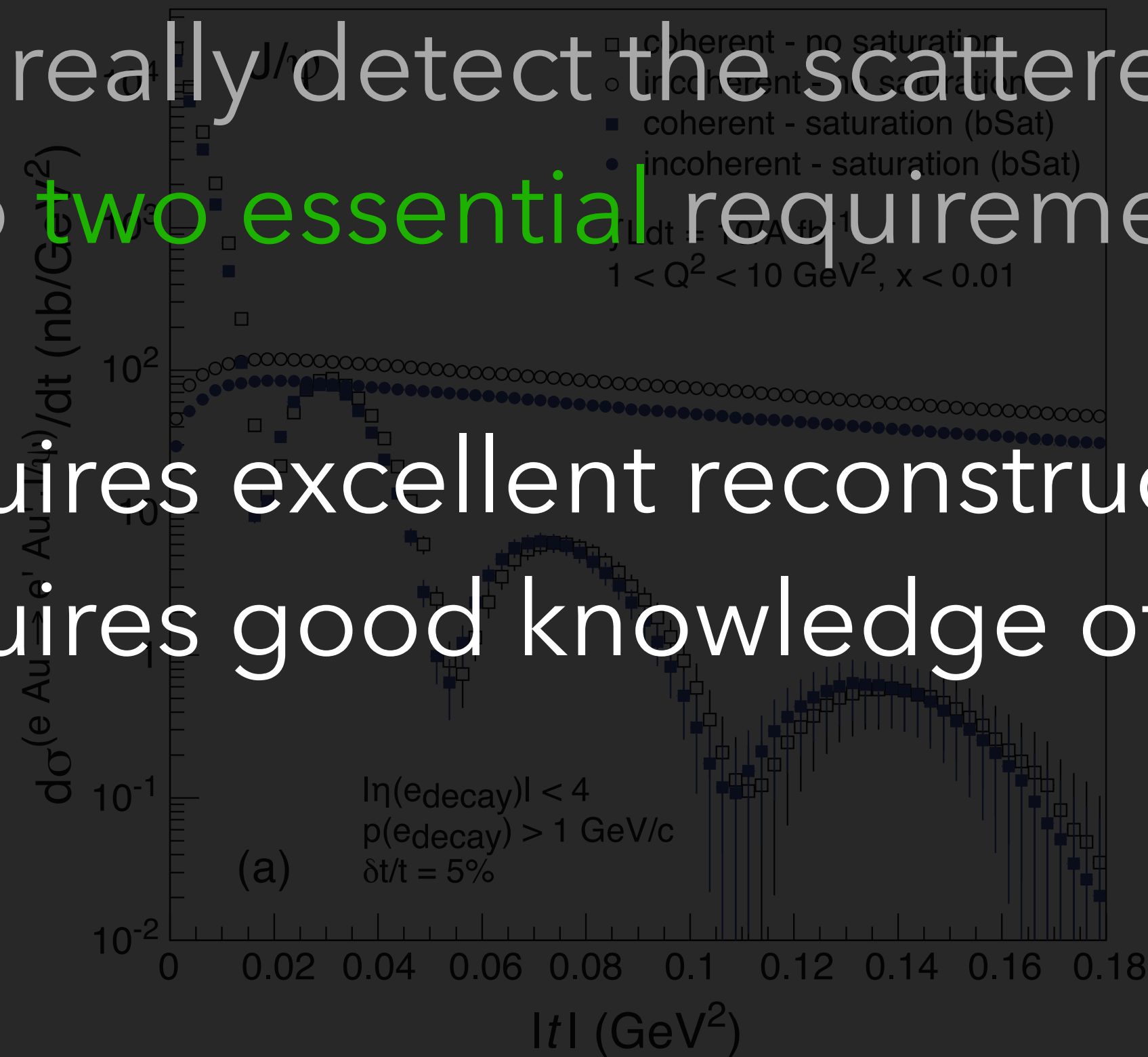


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Cannot really detect the scattered ion which leads to **two essential** requirements:

1. Requires excellent reconstruction
2. Requires good knowledge of Nuclear Breakup

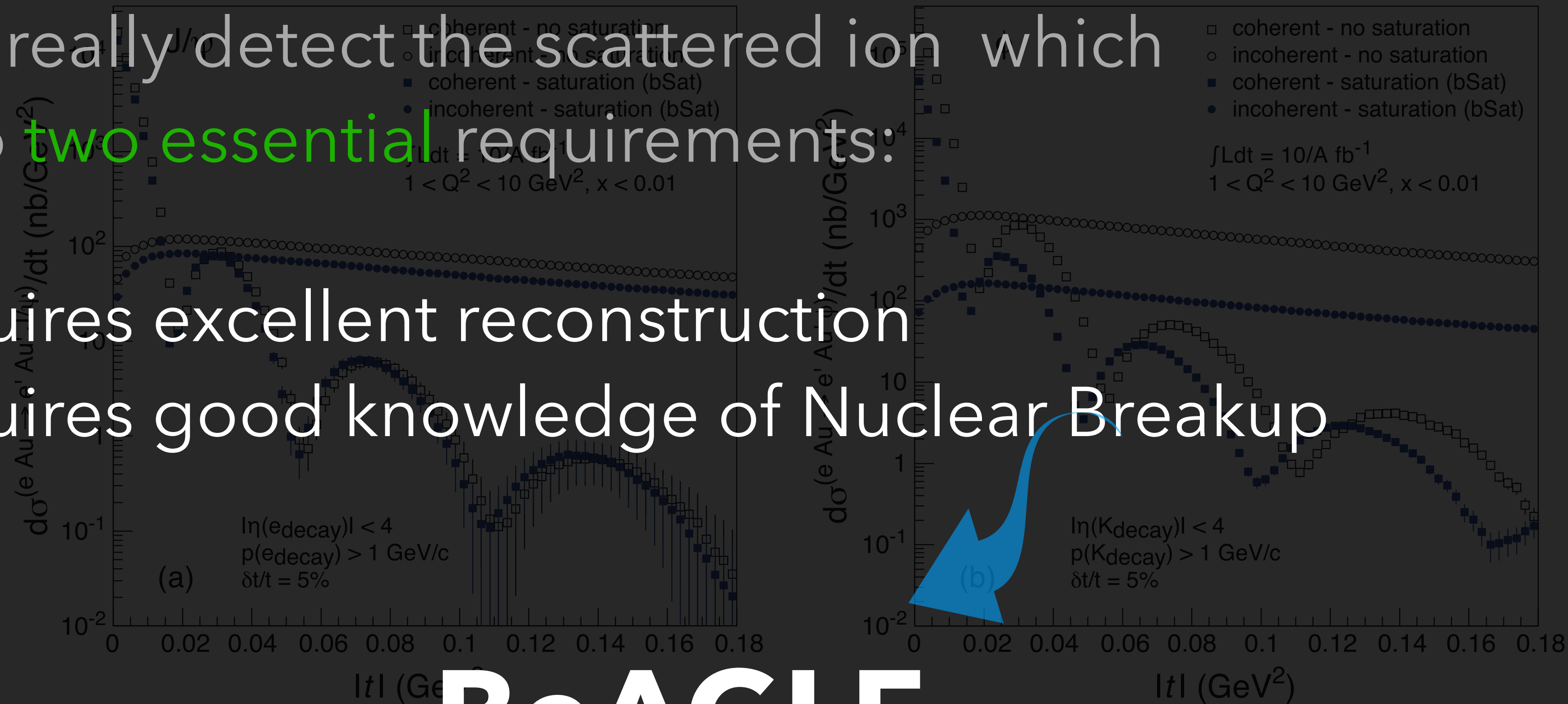


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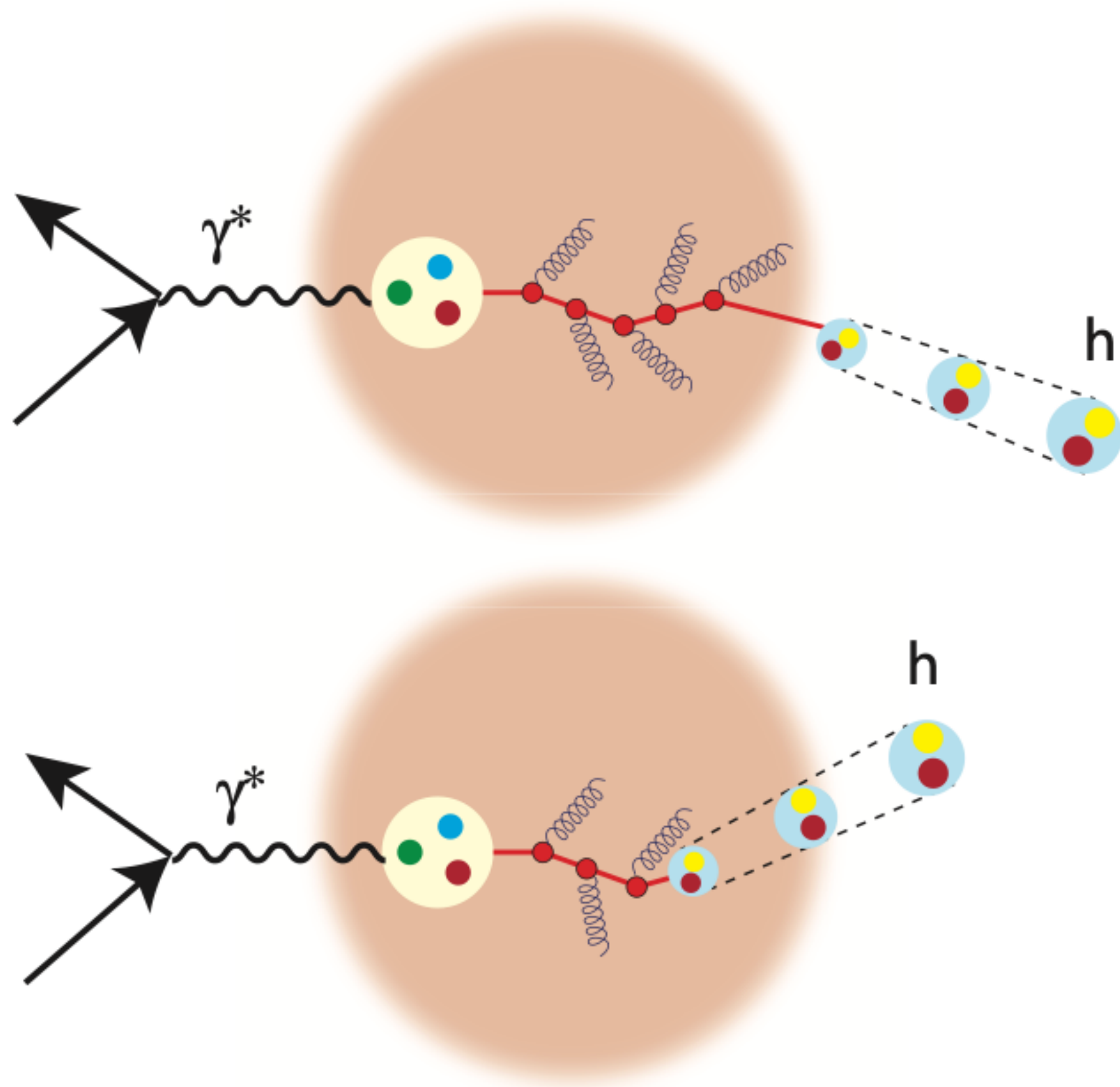
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BeAGLE

Spatial Imaging:
$$F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}(\Delta)} \Big|_{\text{mod}}$$

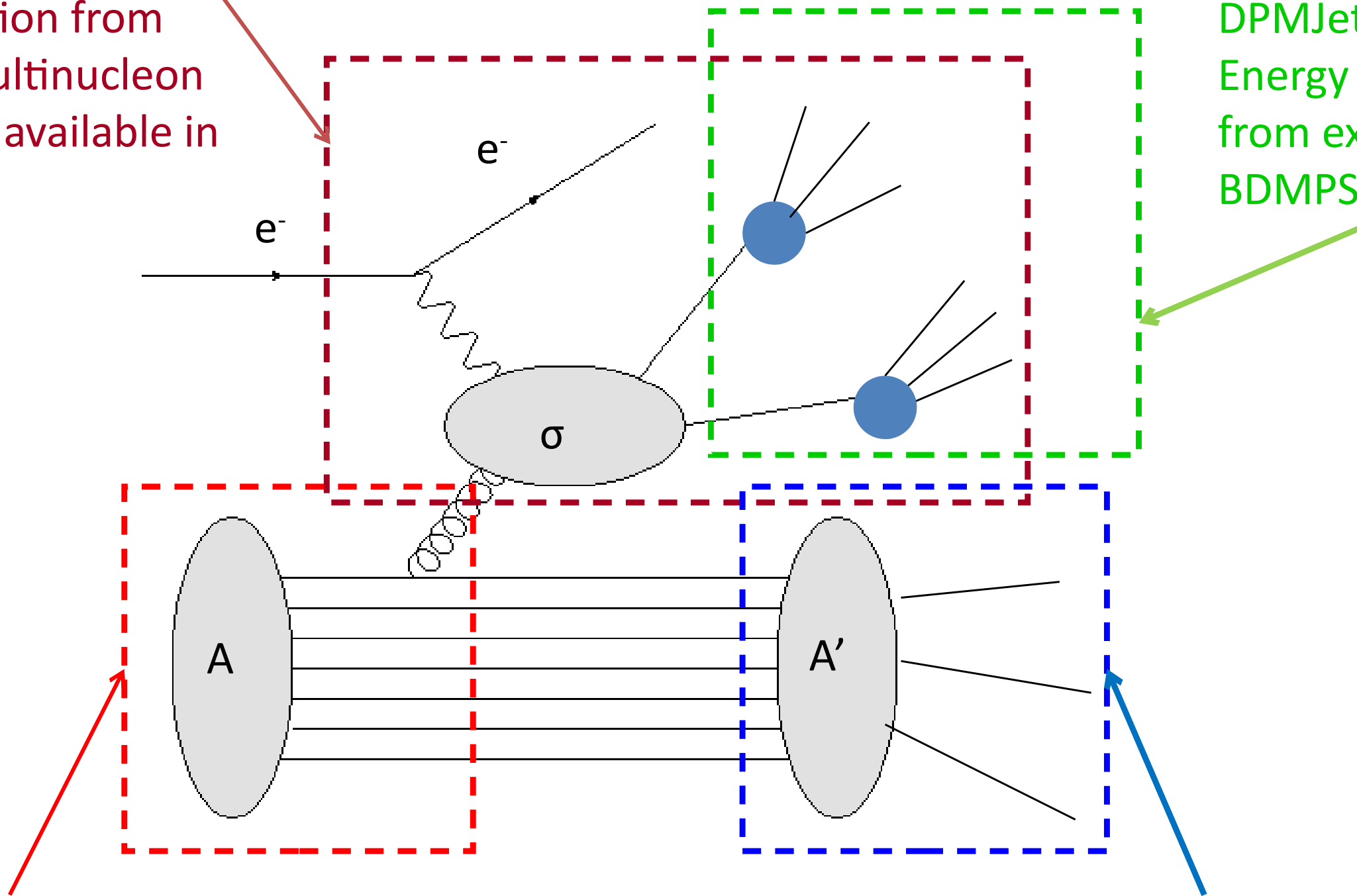
DIS IN A NUCLEAR ENVIRONMENT



- An DIS on nucleus is very different from scattering on a nucleon and one needs to account for nuclear effects and nuclear breakup
- At present, BeAGLE : only generator capable of simulating this
- Understanding fundamental questions like hadronisation and target fragmentation

EIC White Paper, Eur. Phys. J. A 52 (2016) 268

Parton level interaction, parton shower and jet fragmentation from PYTHIA. Multinucleon shadowing available in BeAGLE.



Intranuclear Cascade from DPMJet. Optional Energy loss effect from extended BDMPS in PyQM.

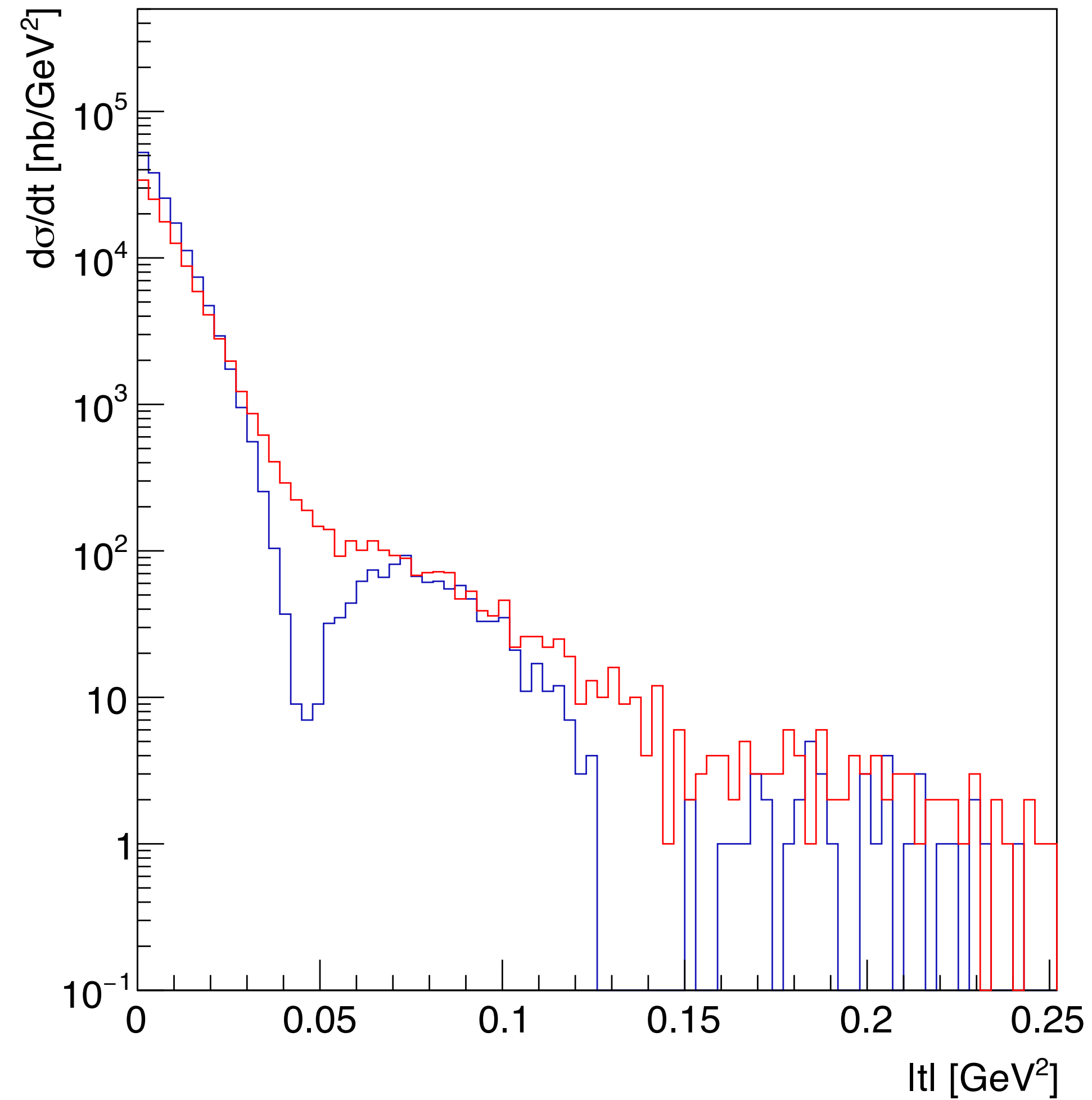
Some Nuclear Effects

	In BeAGLE
• Parton distribution functions	☒
• Parton saturation (CGC etc.)	☒
• Short-range correlations	☒
• "Fermi motion"	☒
• Partonic (or "dipole") MS	☒
• Partonic gluon radiation	☒
• Medium-modified hadronization	☒
• Formation times	☒
• Hadronic Cascade	☒
• Nuclear evaporation, breakup	☒
• Photonic de-excitation of A*	☒

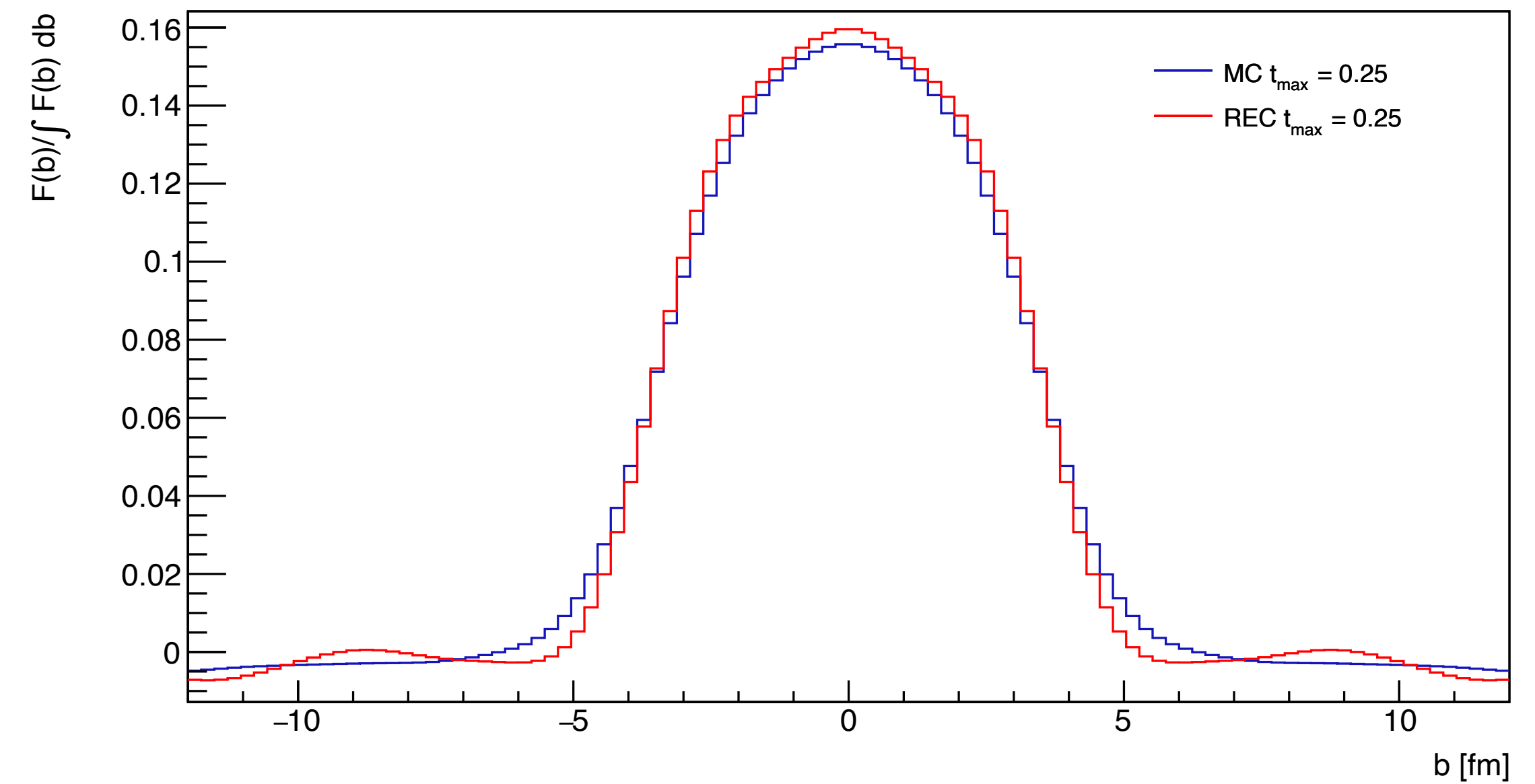
Nuclear geometry by BeAGLE & PyQM plus EPS09 nuclear PDF provided in LHAPDF.

Nuclear evaporation, gamma dexcitation, nuclear fission & fermi break up treated by FLUKA.

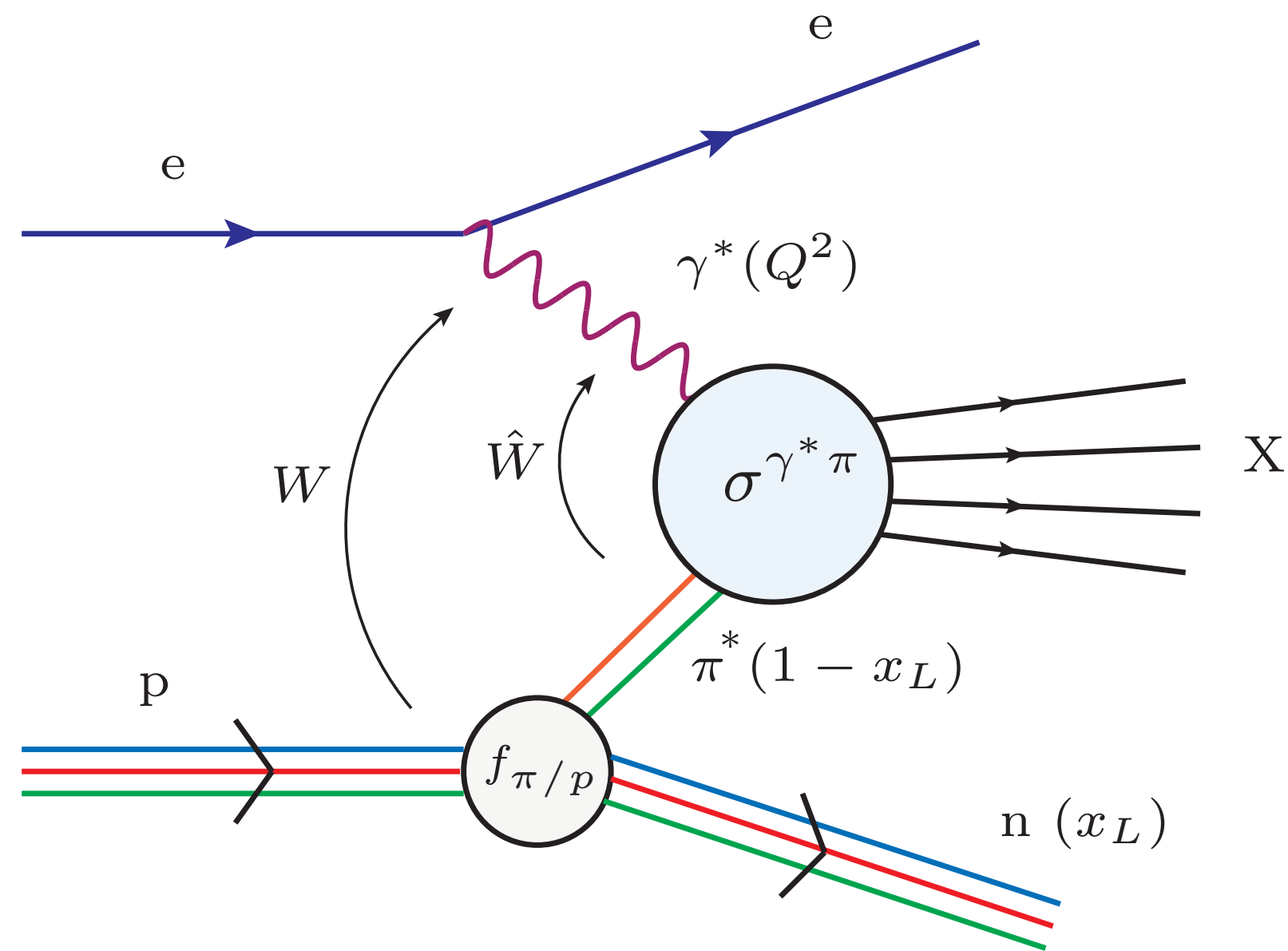
EXCLUSIVE DIFFRACTION AT EIC



★ A recent tutorial by Kong at Light ion
summer school, June 2025

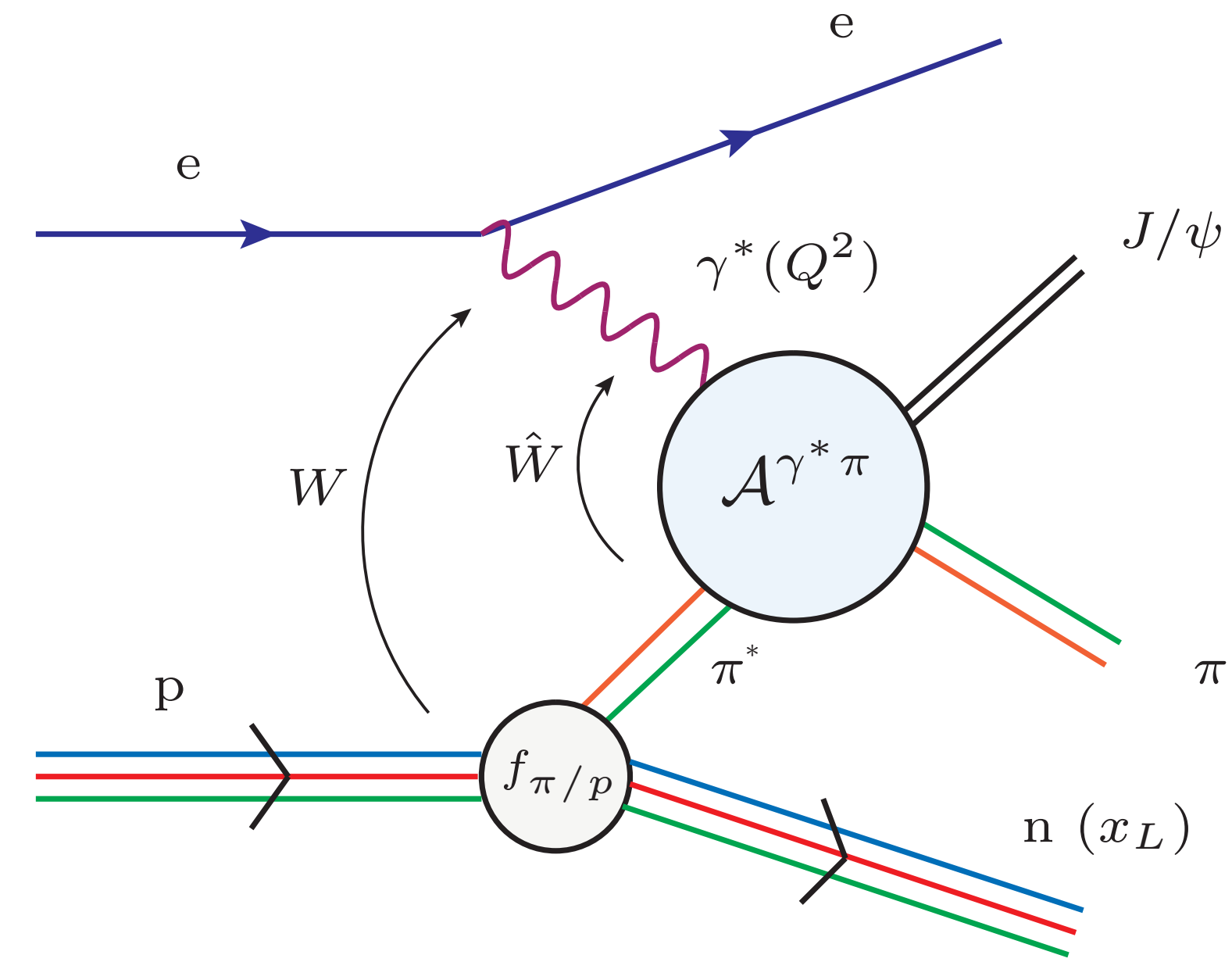


PION STRUCTURE IN LEADING NEUTRON EVENTS



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

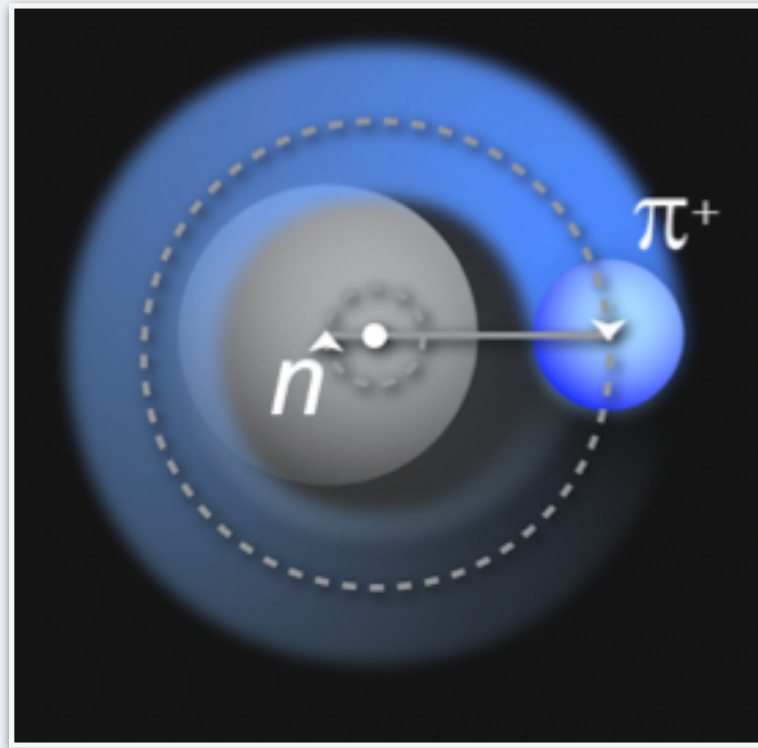
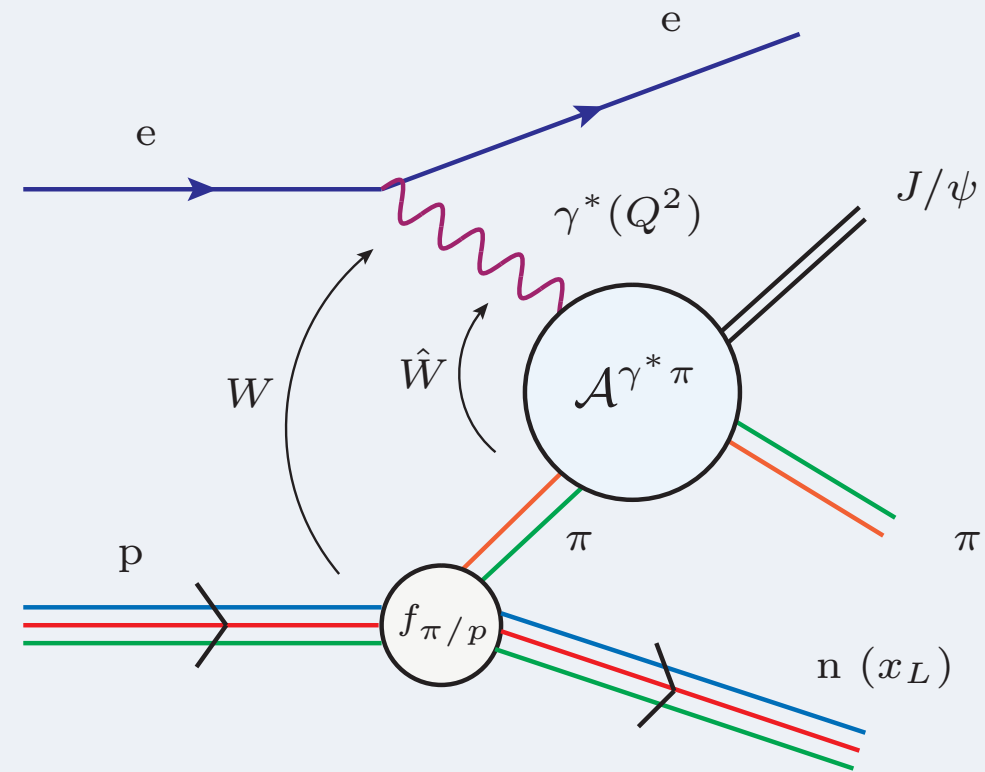
- ★ Measure only scattered electrons and neutron
- ★ Sensitive to longitudinal structure of pion



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

- ★ Measure all the final state particles
- ★ Sensitive to spatial gluon distribution of pion

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:

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

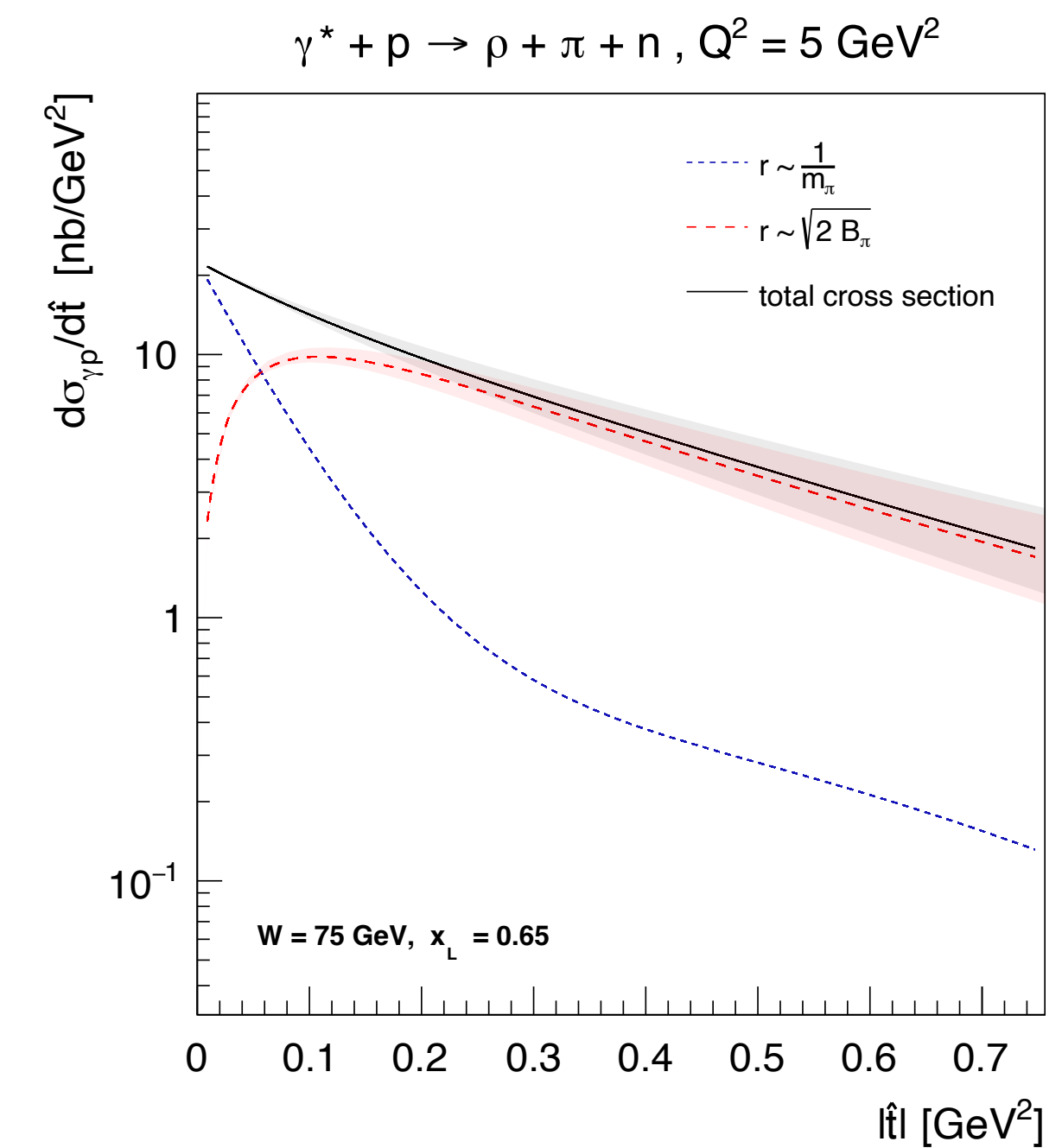
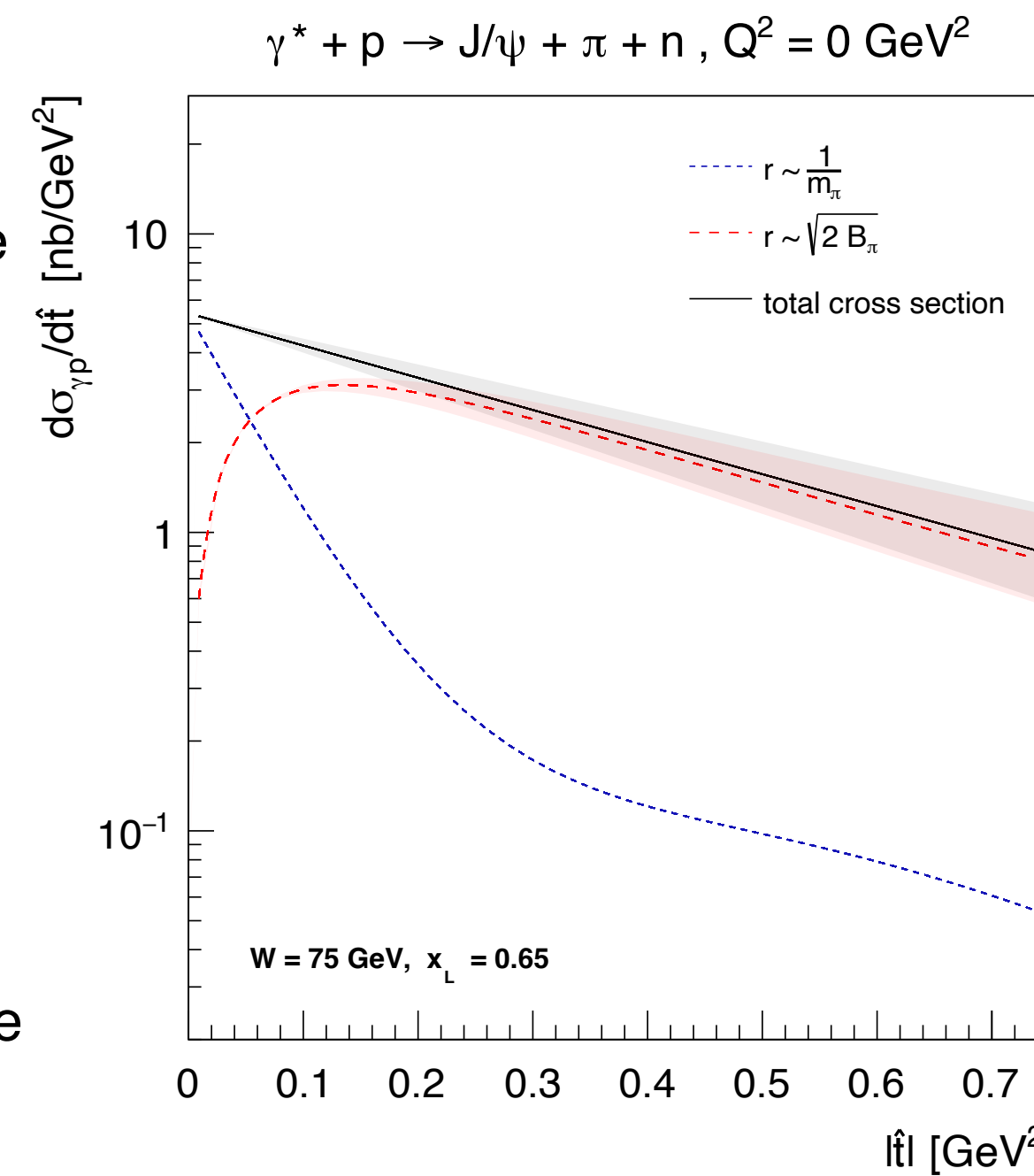
- ❖ We assume that the real pion, as for the proton, is described by a Gaussian profile:

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

- ❖ 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 $|t'|$ and moderate $|t'|$
- ❖ H1 data on exclusive ρ photo production with leading neutrons exhibits these two slopes in the differential distribution

$$\sigma_{tot} \propto | \langle \mathcal{A} \rangle_{\Omega} |^2 + (\langle | \mathcal{A} |^2 \rangle_{\Omega} - | \langle \mathcal{A} \rangle_{\Omega} |^2)$$



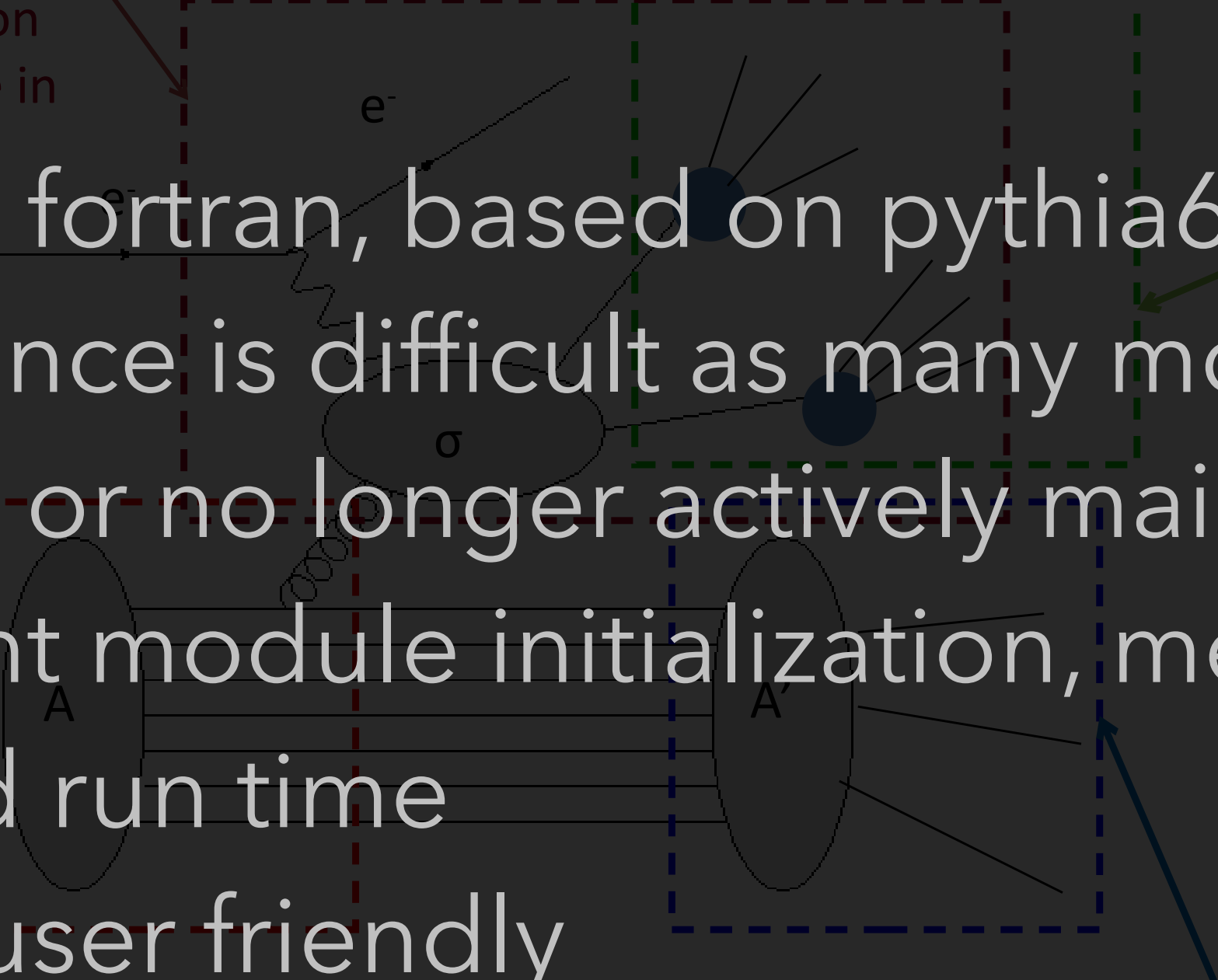
BeAGLE: A General purpose event generator for eA collisions

however there are several limitations

1. written in fortran, based on pythia6
2. maintenance is difficult as many modules are either outdated or no longer actively maintained
3. redundant module initialization, memory leaks, increased run time
4. not very user friendly

Parton level interaction, parton shower and jet fragmentation from PYTHIA. Multinucleon shadowing available in BeAGLE.

Intranuclear Cascade from PYTHIA. Optional Energy loss effect from extended BDMPS in PyQM.



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Nuclear evaporation, gamma dexcitation, nuclear fission & fermi break up, nuclear breakup, ongoing work . . .

Intranuclear Cascade from PYQ. Optional Energy loss effect from extended BDMPS in PyQM.

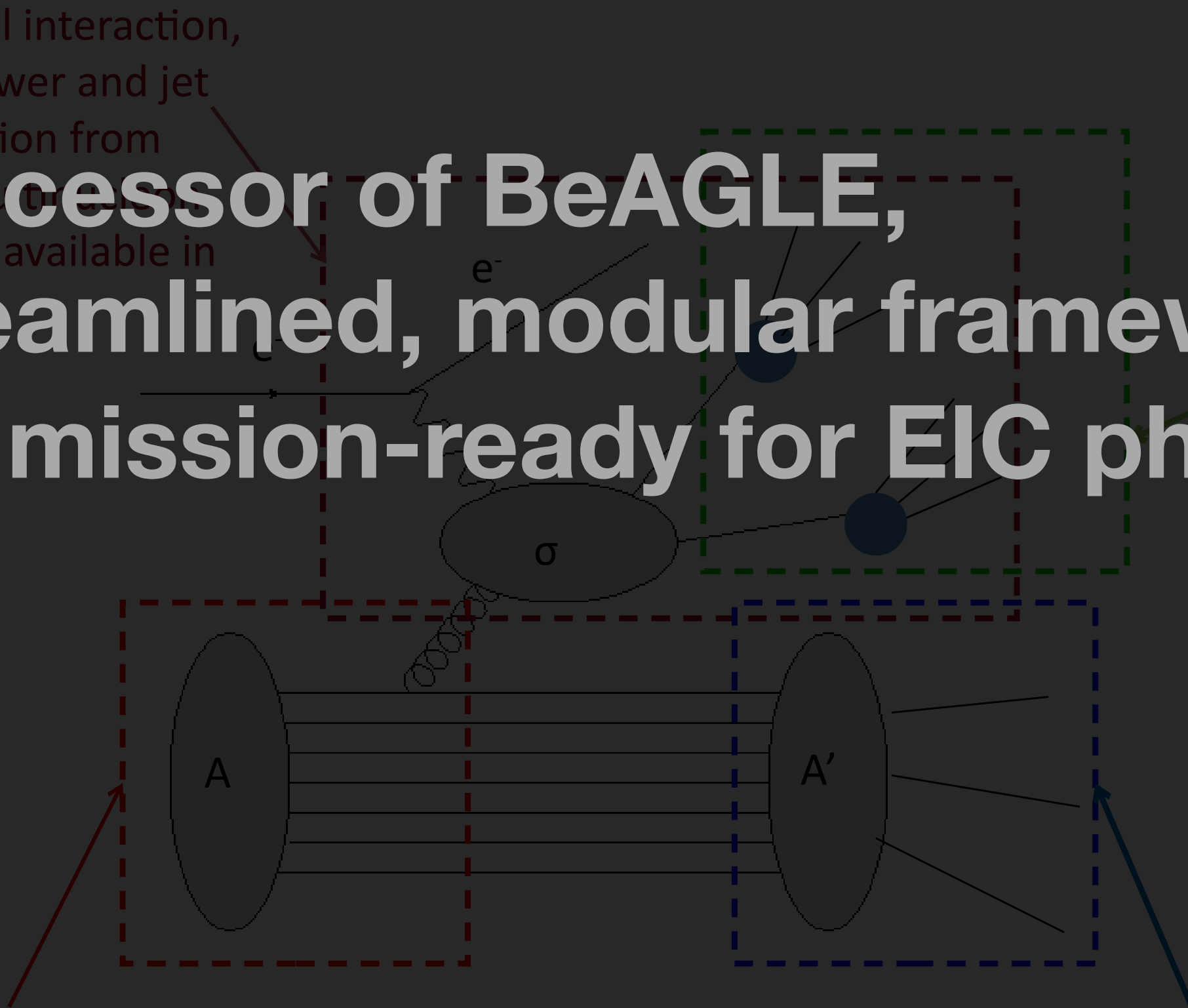
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• Nuclear evaporation, breakup	☒
• Parton multiple-excitation of A	☒

BeAGLE++

BeAGLE++ : The Future of Nuclear Event-Generation for EIC

- a successor of BeAGLE,
- a streamlined, modular framework with C++
- goal: mission-ready for EIC physics



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• Medium-modified hadronization	☒
• Formation times	☒
• Hadronic Cascade	☒
• Nuclear evaporation, breakup	☒
• Photonic de-excitation of A*	☒

in very early stages : started working on this project from 2 months

BEAGLE++

- Basic architecture ready, a few pieces are already there
- Nuclear Geometry for different species
- Linked with ROOT, Pythia 8
- Next steps: Internuclear cascade & Nuclear Breakup

```
BeAGLE++/  
|-- CMakeLists.txt           # Top-level CMake config  
|-- src/                     # Source code directory  
|   |-- CMakeLists.txt       #CMake config for src  
|   |-- BeAGLE.cpp  
|   |-- NuclearGeometry.cpp  
|   |-- EventSettings.cpp  
|   |-- Event.cpp  
|   |-- ...  
|-- examples/                # steering programs folder  
|   |-- CMakeLists.txt       #CMake config for examples  
|   |-- beagleMain.cpp  
|   |-- beagleRuncard.txt  
|   |-- sampleNucleon.cpp  
|   |-- build/               # contains executables  
|   |-- ...  
|-- cmake/                   # External modules  
|-- build/                   # installation folder  
|-- README.md
```

Summary

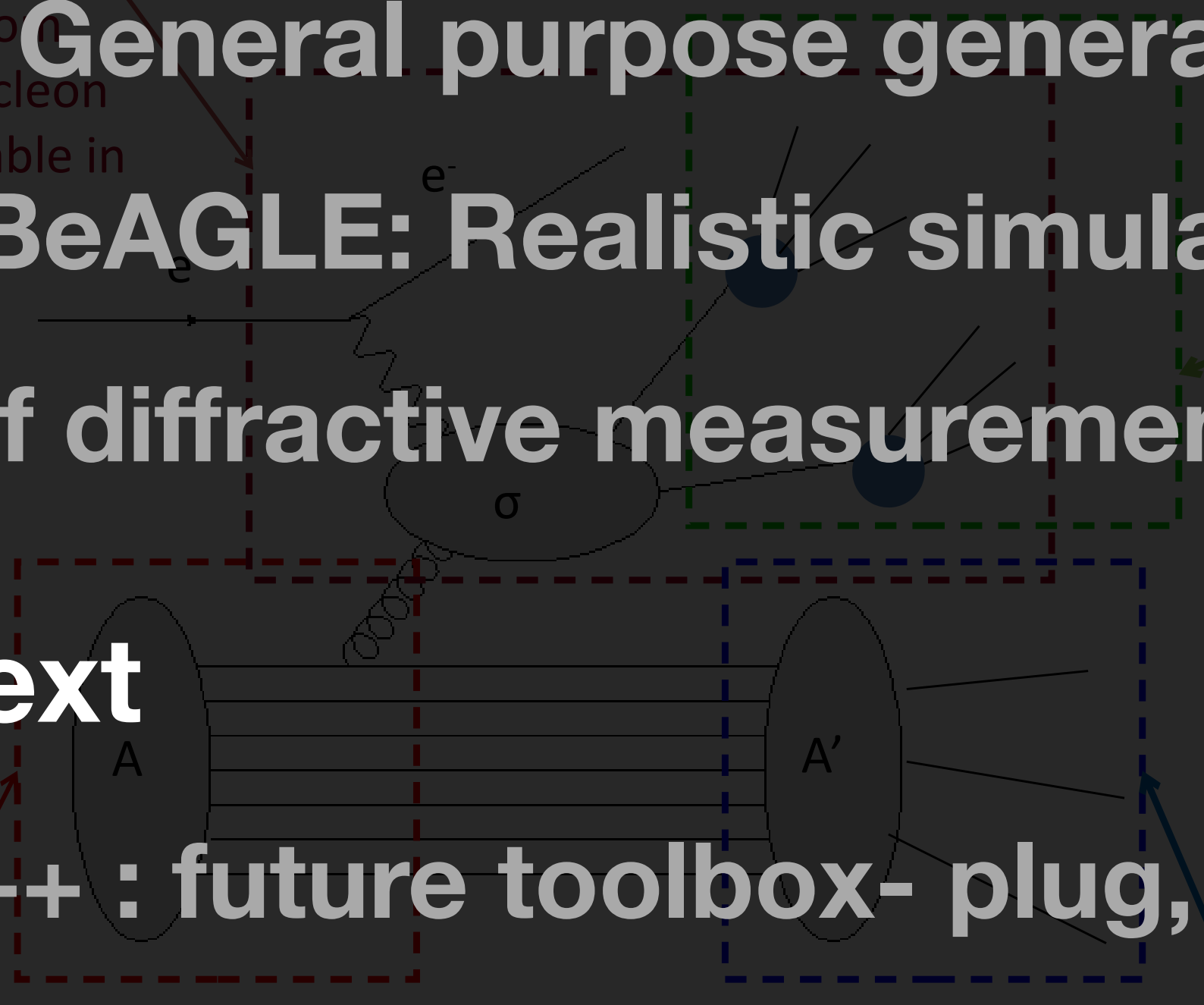
- **Sartre:** A valuable tool for coherent vector meson production
- **BeAGLE:** General purpose generator for eA
- **Sartre + BeAGLE:** Realistic simulations and feasibility studies of diffractive measurements at EIC

What's Next

- **BeAGLE++:** future toolbox- plug, play, and explore
- **Sartre:** Initial and Final State Radiation

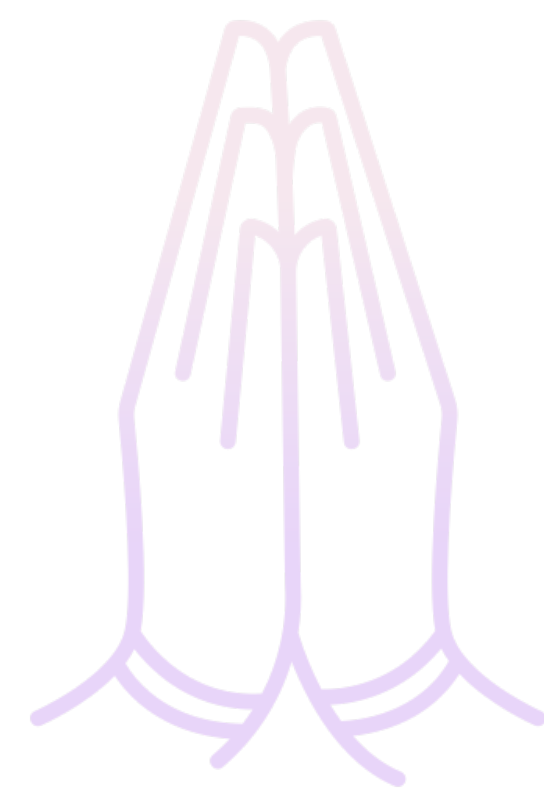
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Sartre: combined with G₀ & PyQM plus EPS09 nuclear PDF provided in LHAPDF.

Nucleus: initial gamma deexcitation, nuclear fission & fermi break up treated by FLUKA.



BACKUP

THE DIPOLE-TARGET

the bSat dipole model : $N(\mathbf{b},$

the bNonSat dipole model : N

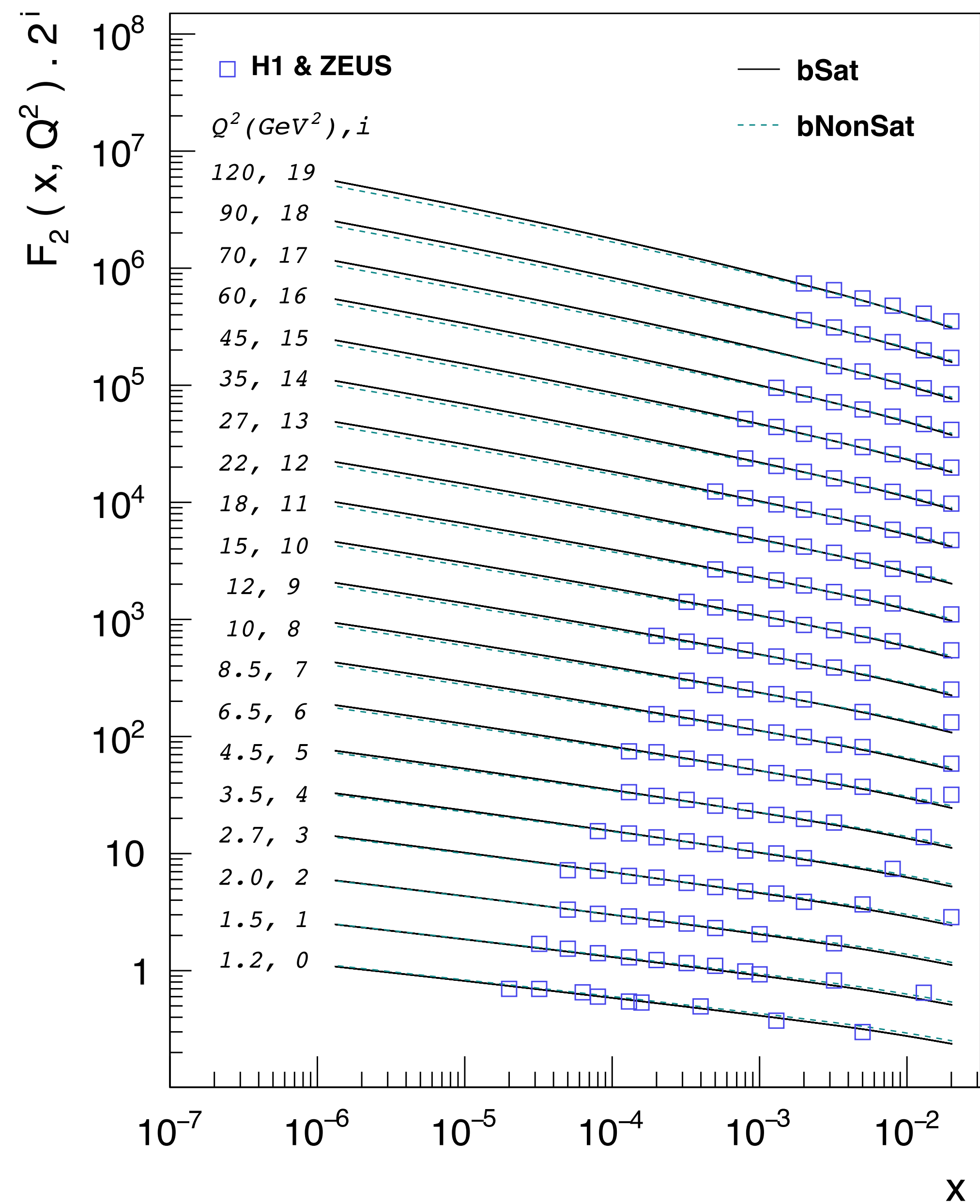
where $xg(x, \mu_0^2) = A_g x^{-\lambda_g} (1 -$

(the parameters are constrained

Two models for the spatial proton

a) Smooth proton (assume gaussian

b) Lumpy proton (assume gaussian



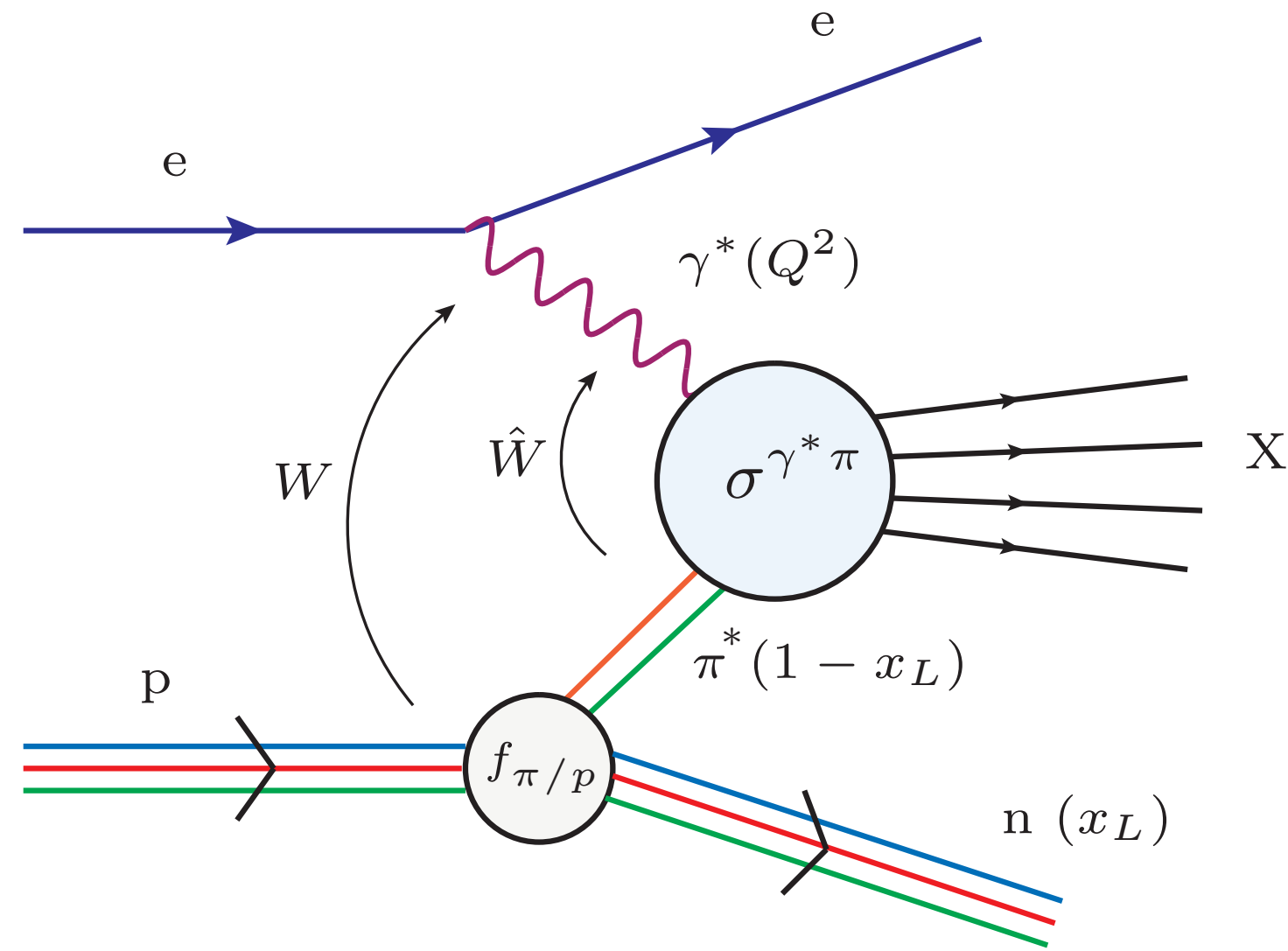
ence obtained from DGLAP evolution)

Kowalski, Motyka, Watt 2006

and $T_q(\mathbf{b}) = \frac{1}{2\pi B_q} \exp\left[-\frac{\mathbf{b}^2}{2B_q}\right]$

saari, Schenke PRL 117 (2016) 052301

PION STRUCTURE IN LEADING NEUTRON EVENTS



- We use the following flux factor:

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

where the form factor is given by:

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

- ❖ Leading neutron structure function in terms of γ^*p cross section:

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

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

- ❖ In One Pion Exchange (OPE) approximation:

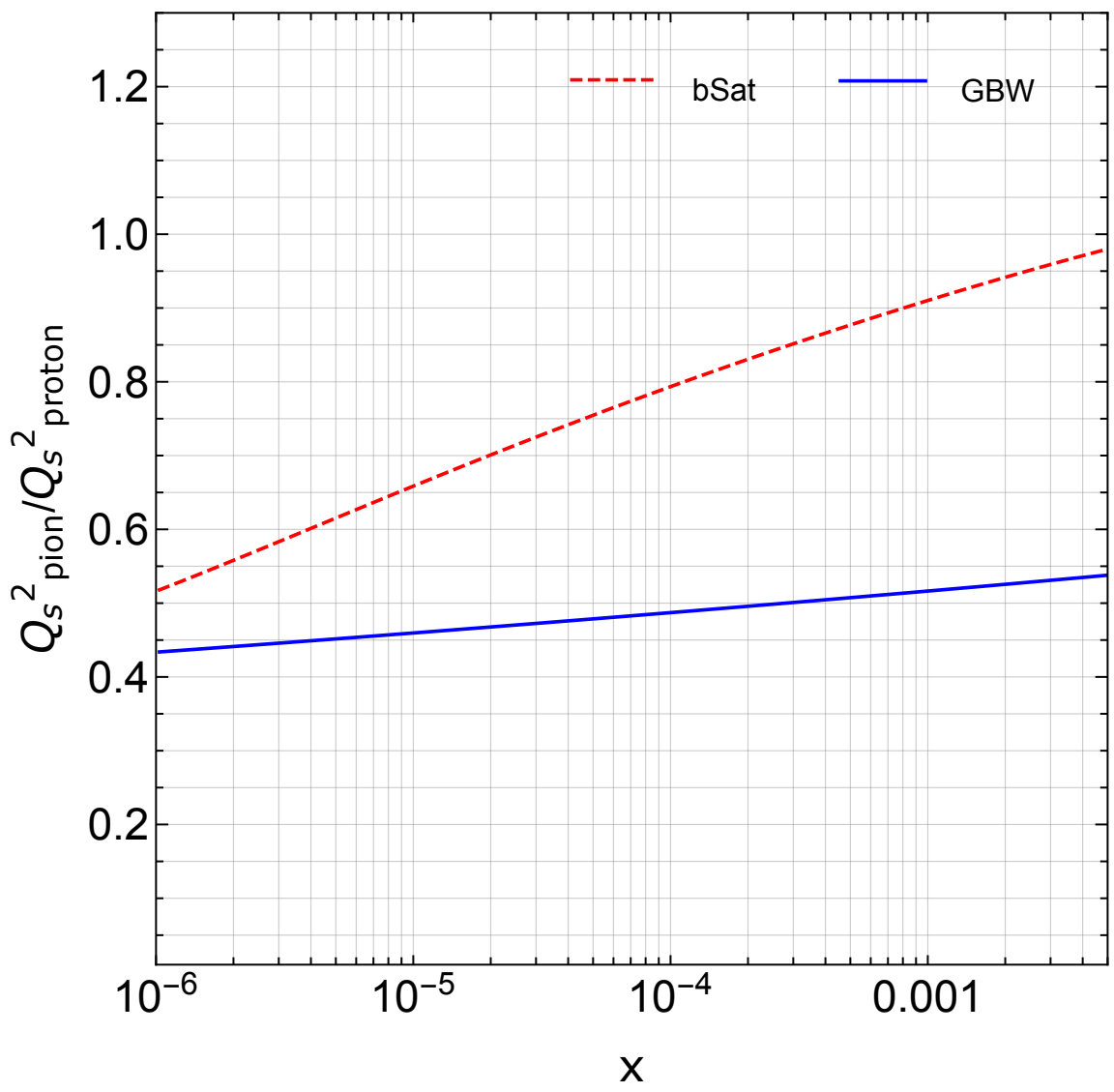
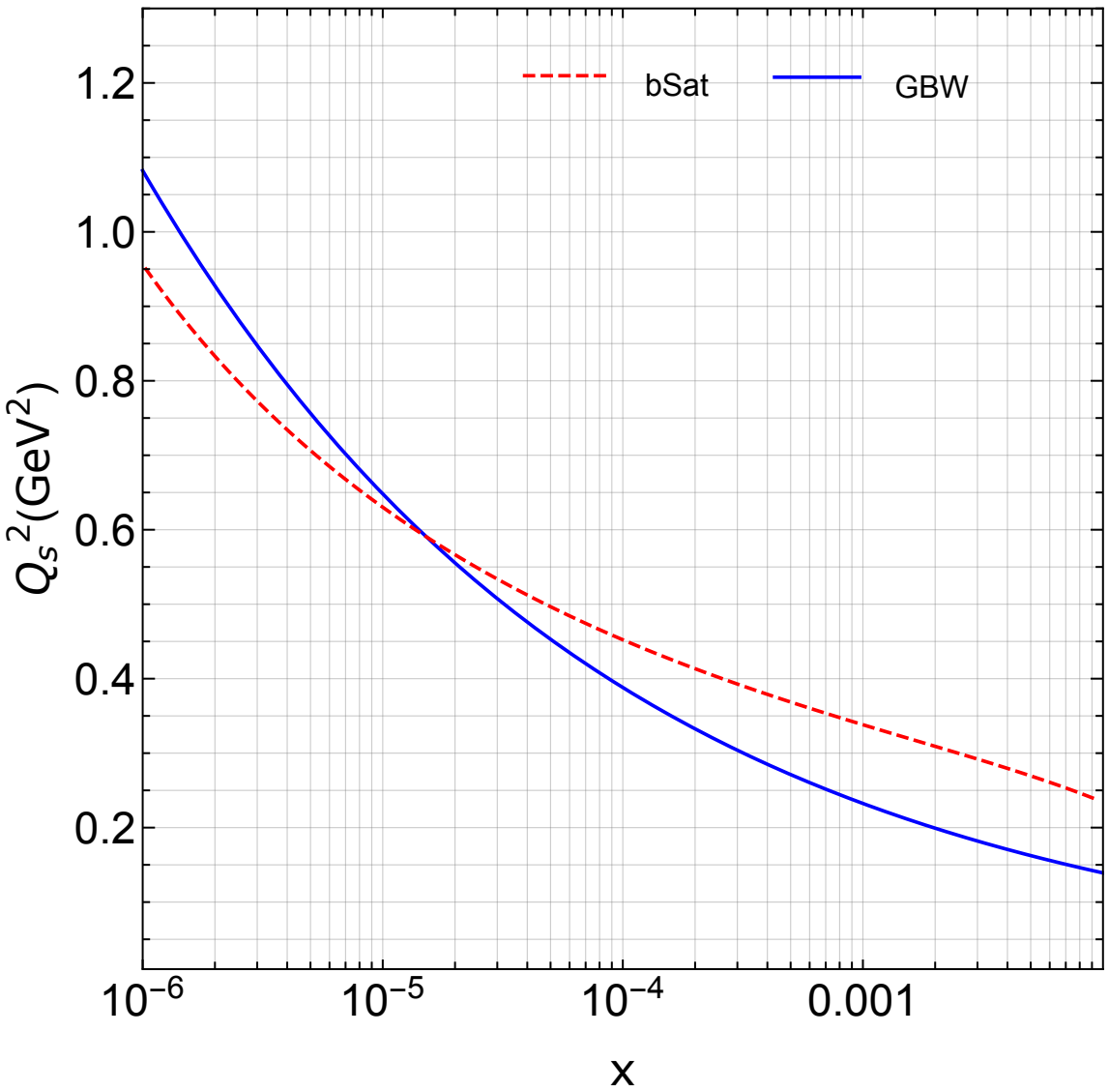
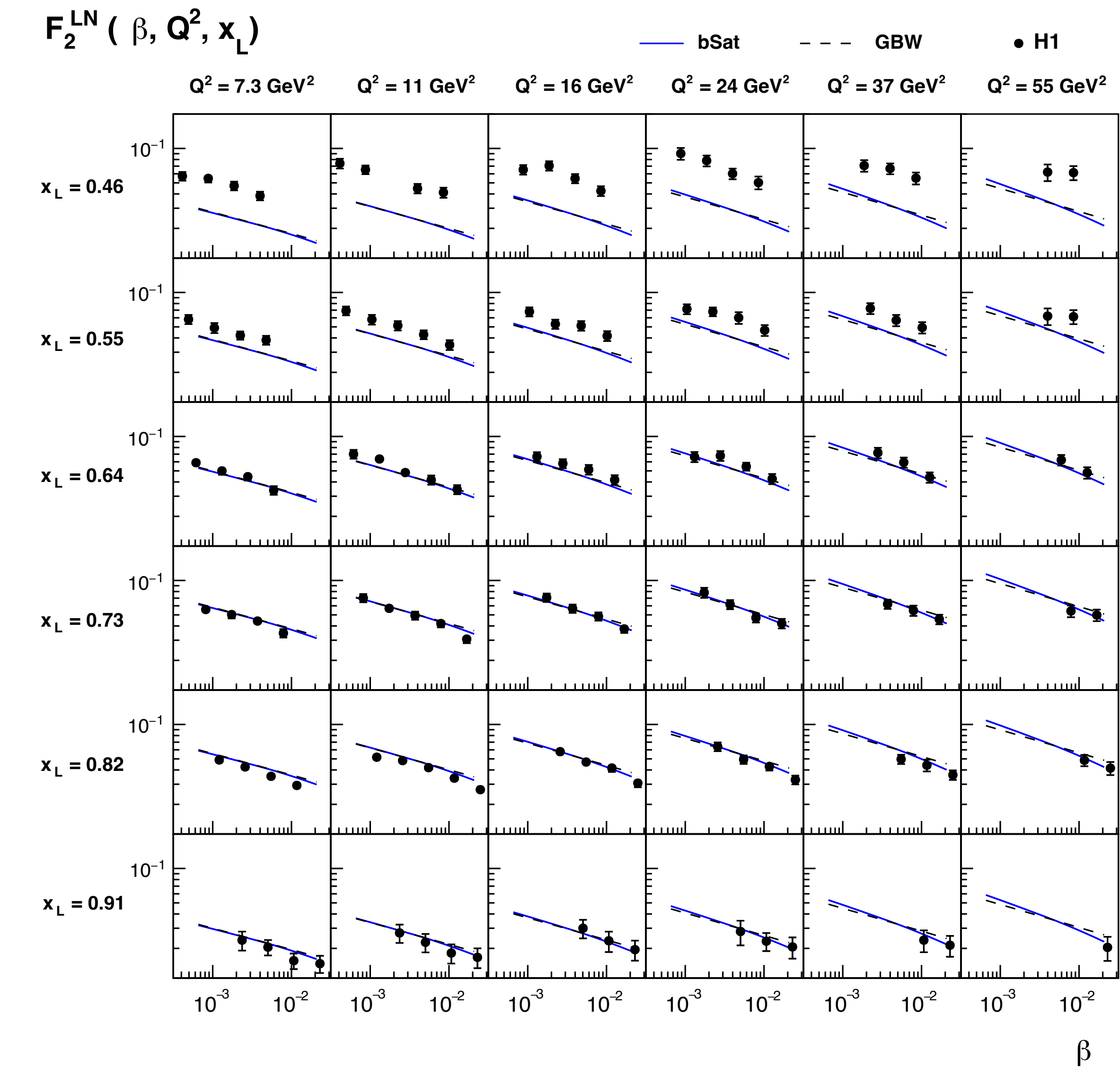
$$\frac{d^2\sigma(W, Q^2, x_L, t)}{dx_L dt} = f_{\pi/p}(x_L, t) \sigma^{\gamma^*\pi^*}(\hat{W}^2, Q^2)$$

$f_{\pi/p}(x_L, t)$ 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

LEADING NEUTRON STRUCTURE FUNCTION



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	$66.19/50 = 1.32$

A.K PRD 107 (2023) 034005