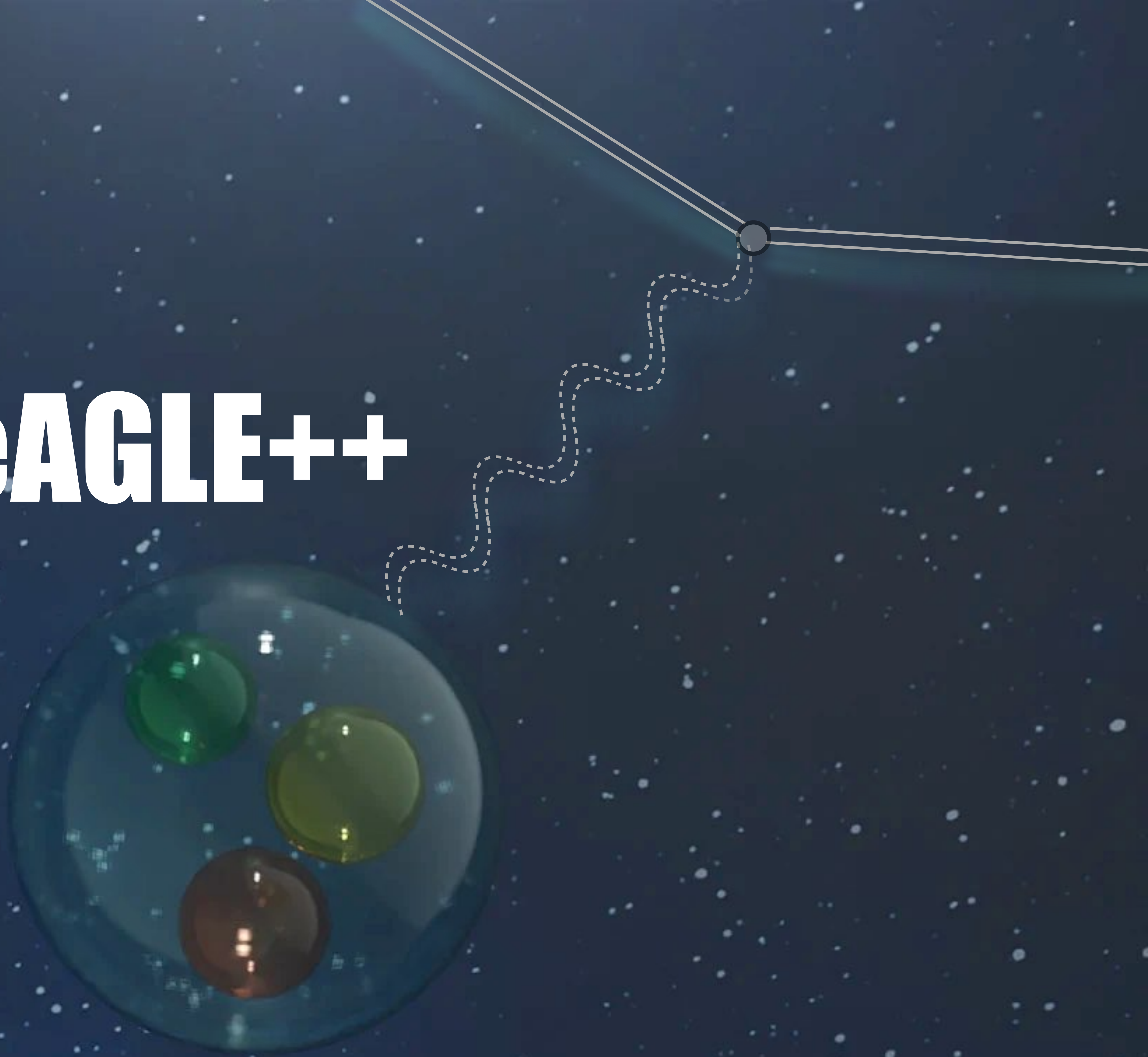
Preparing for the EIC Era : From Sartre Insights to BeAGLE++

a tale of two event-generators

July 12, 2025



ARJUN KUMAR
CFNS, Stony Brook University

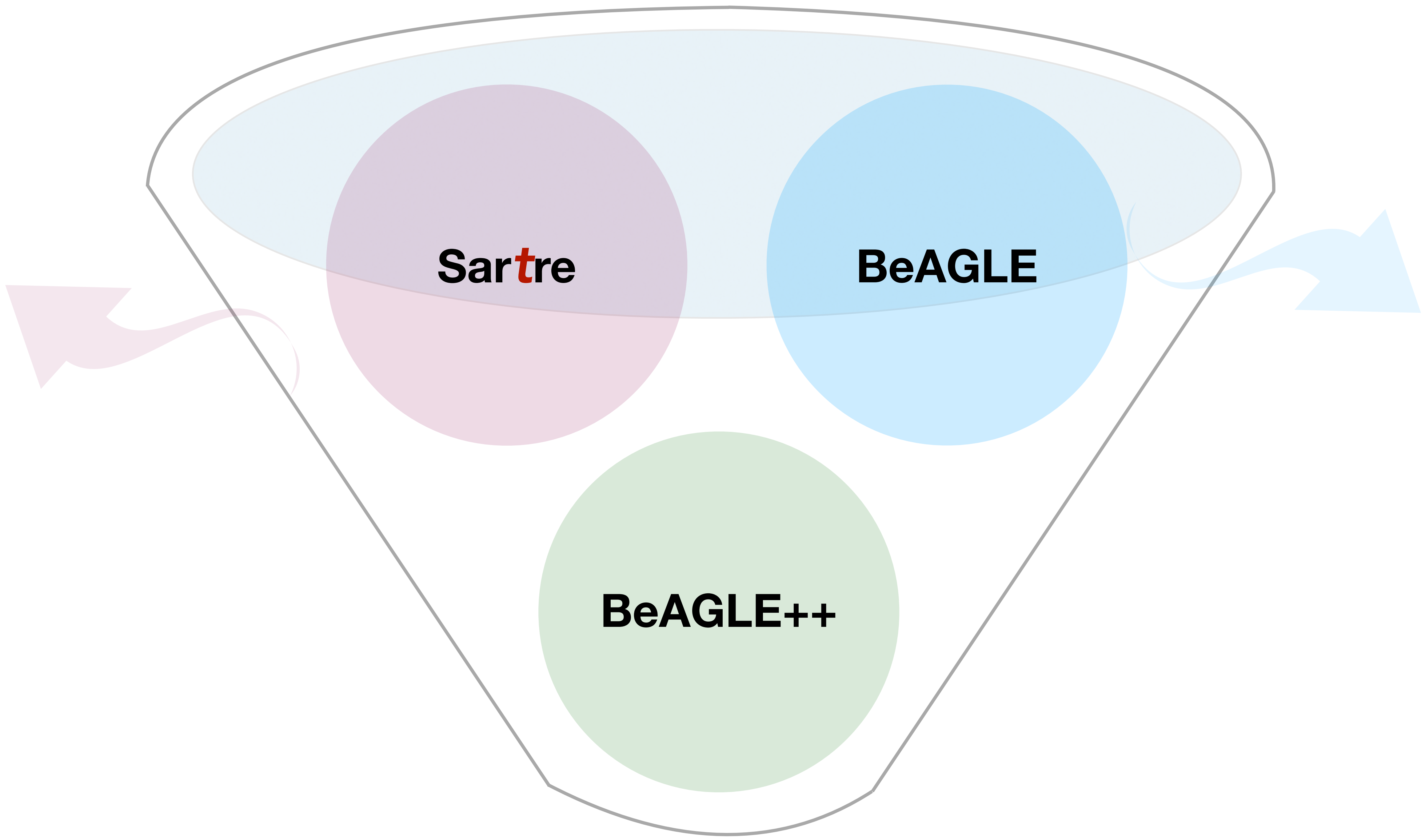
Center for Frontiers in Nuclear Science

Stony Brook University

OUTLINE

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

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

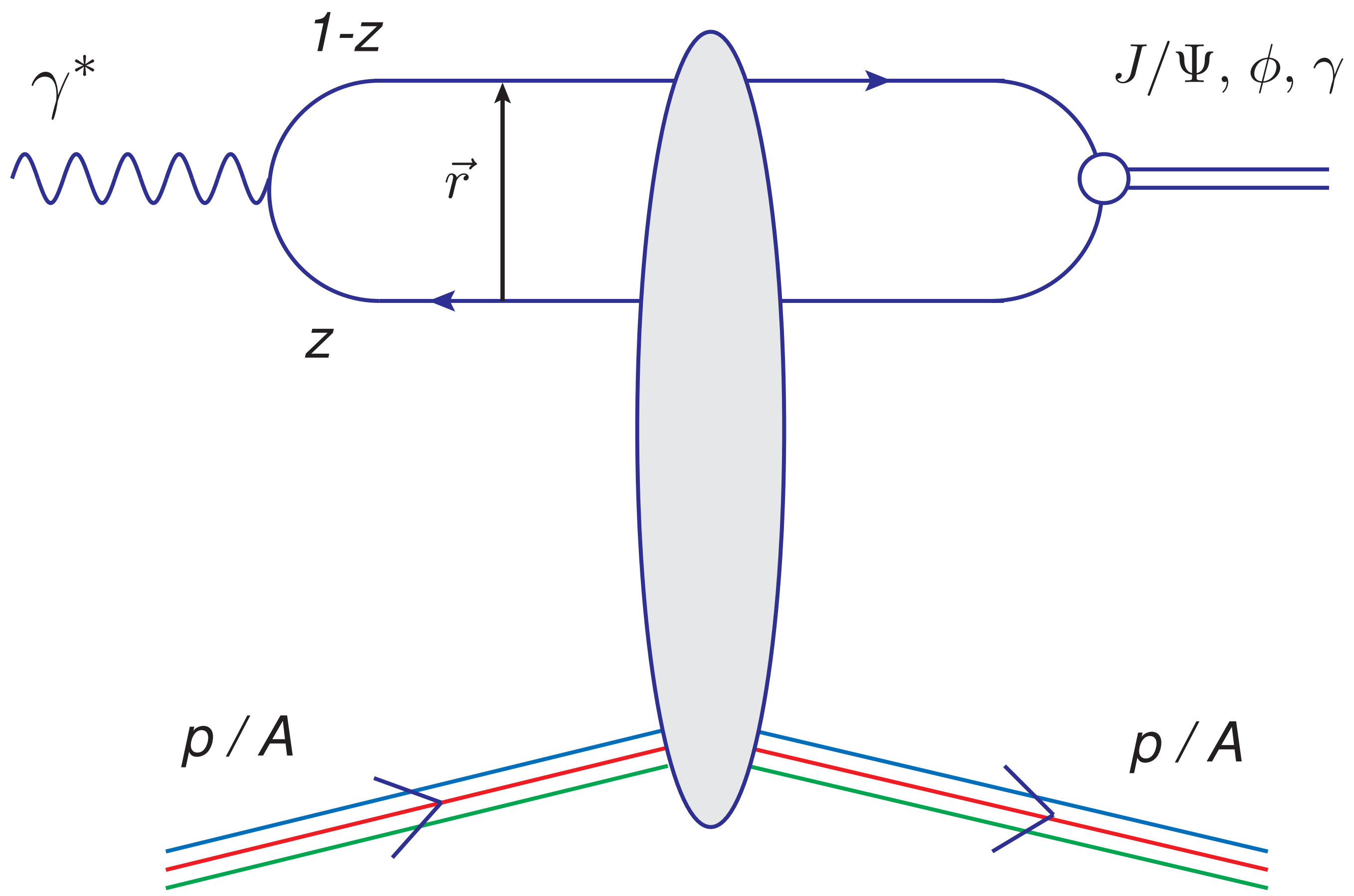


A General-purpose eA Event Generator

- 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

EXCLUSIVE DIFFRACTION WITH SARTRE



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* $q\bar{q} \to VM$

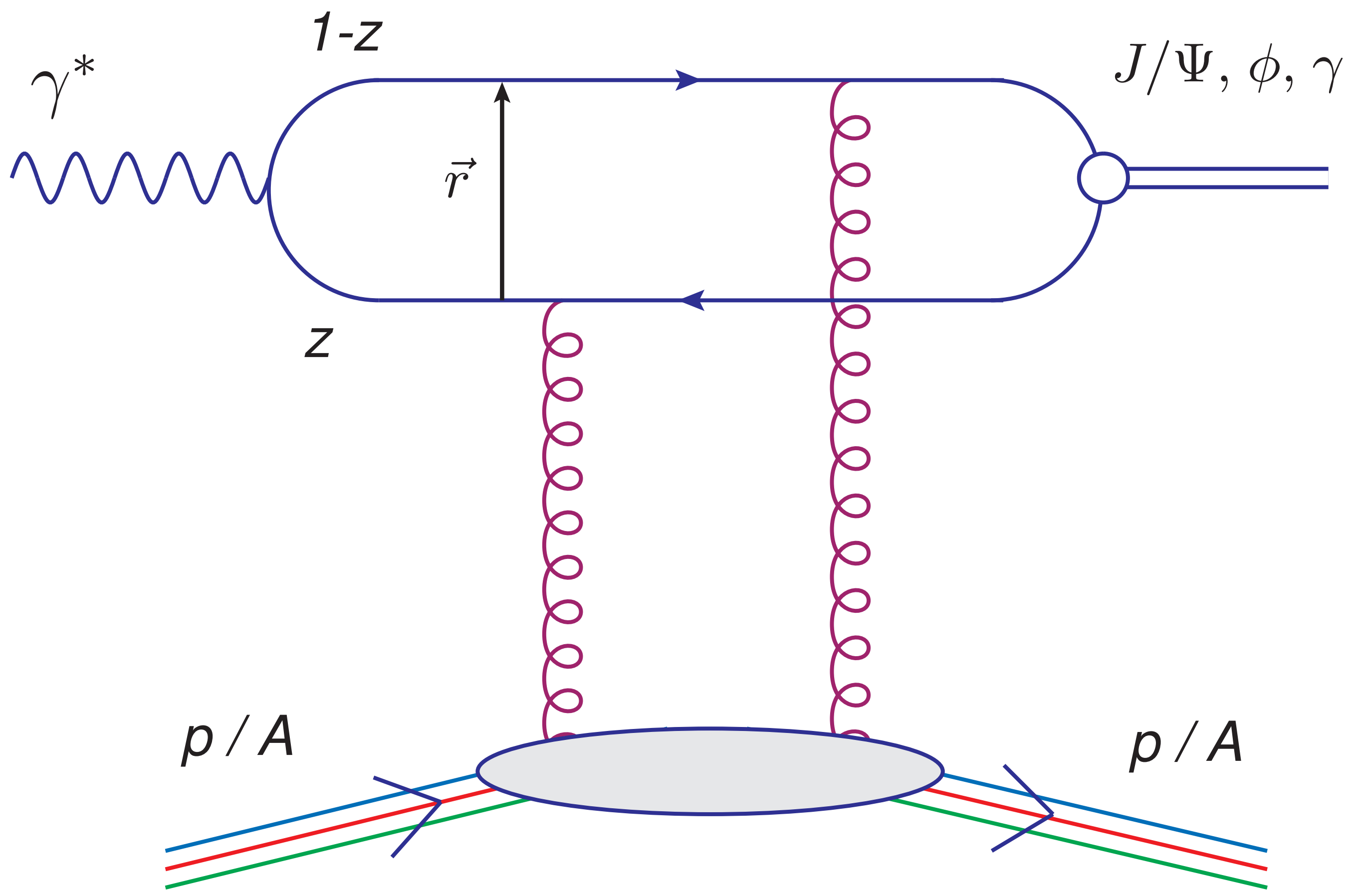
❖ *The scattering amplitude is given by :*

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

❖ *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* $N(b, r, x)$ *)*

DIPOLE PICTURE



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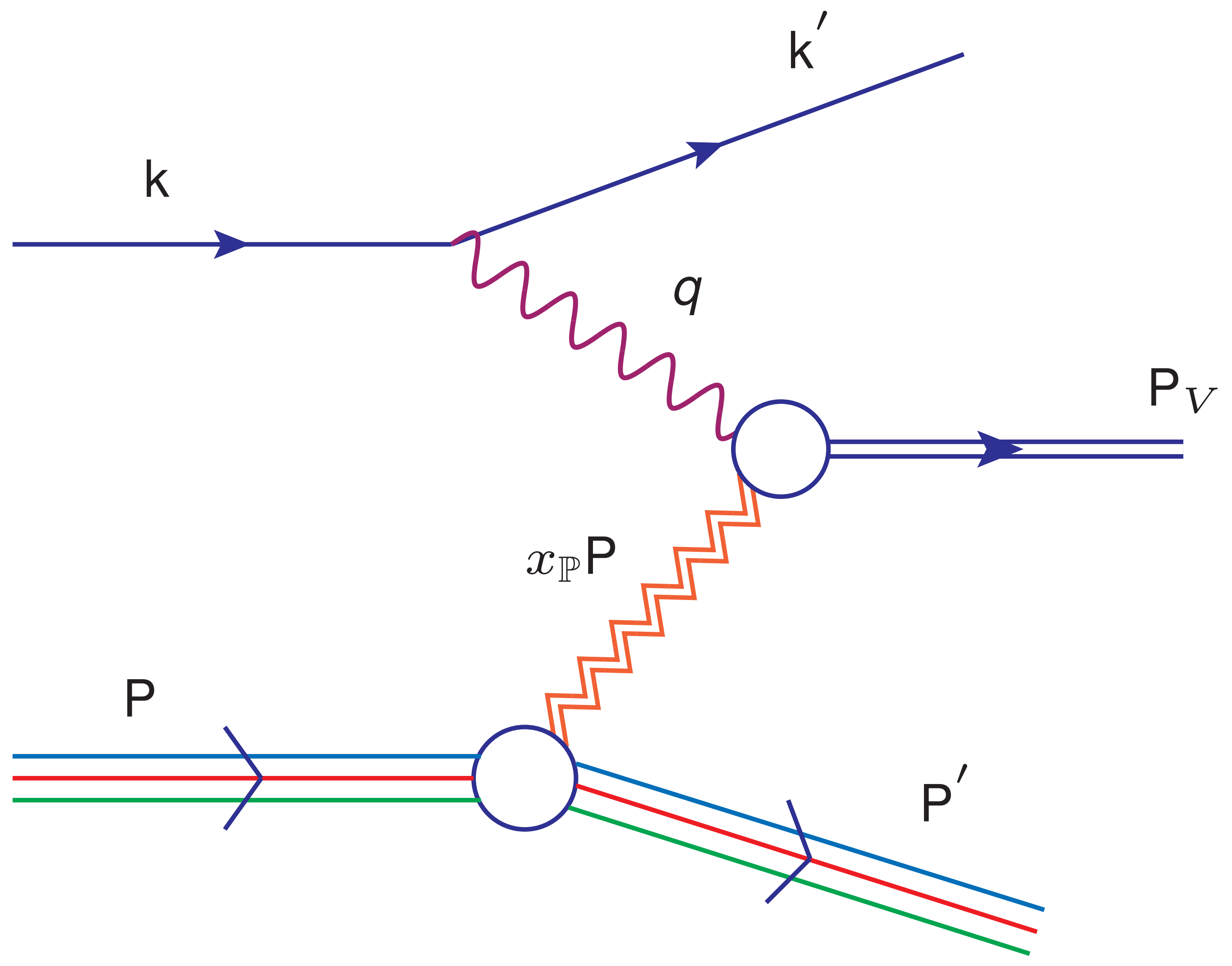
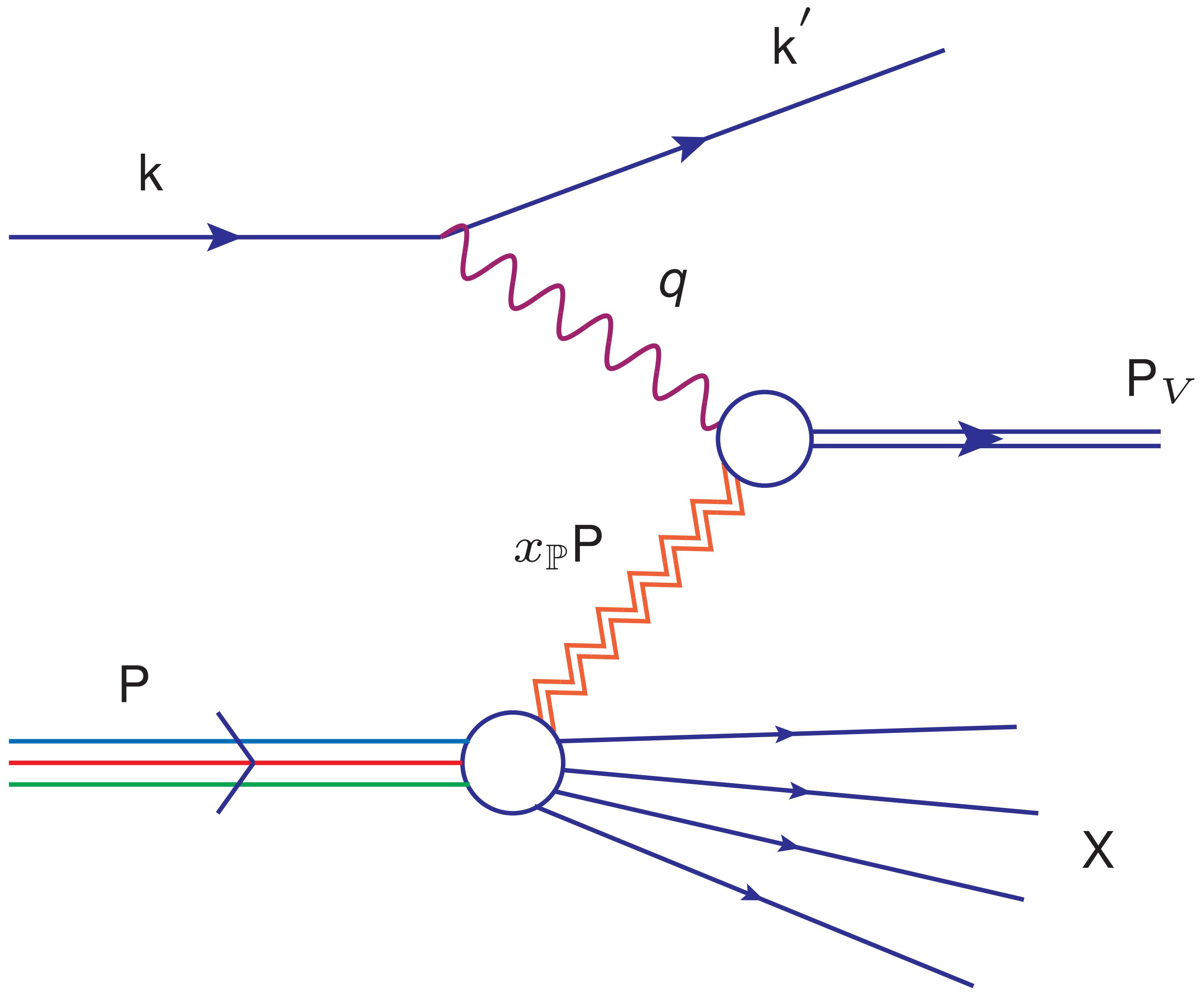
❖ *Impact parameter is Fourier conjugate to the momentum transfer* $\Delta = (p' - p)_\perp$

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

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

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

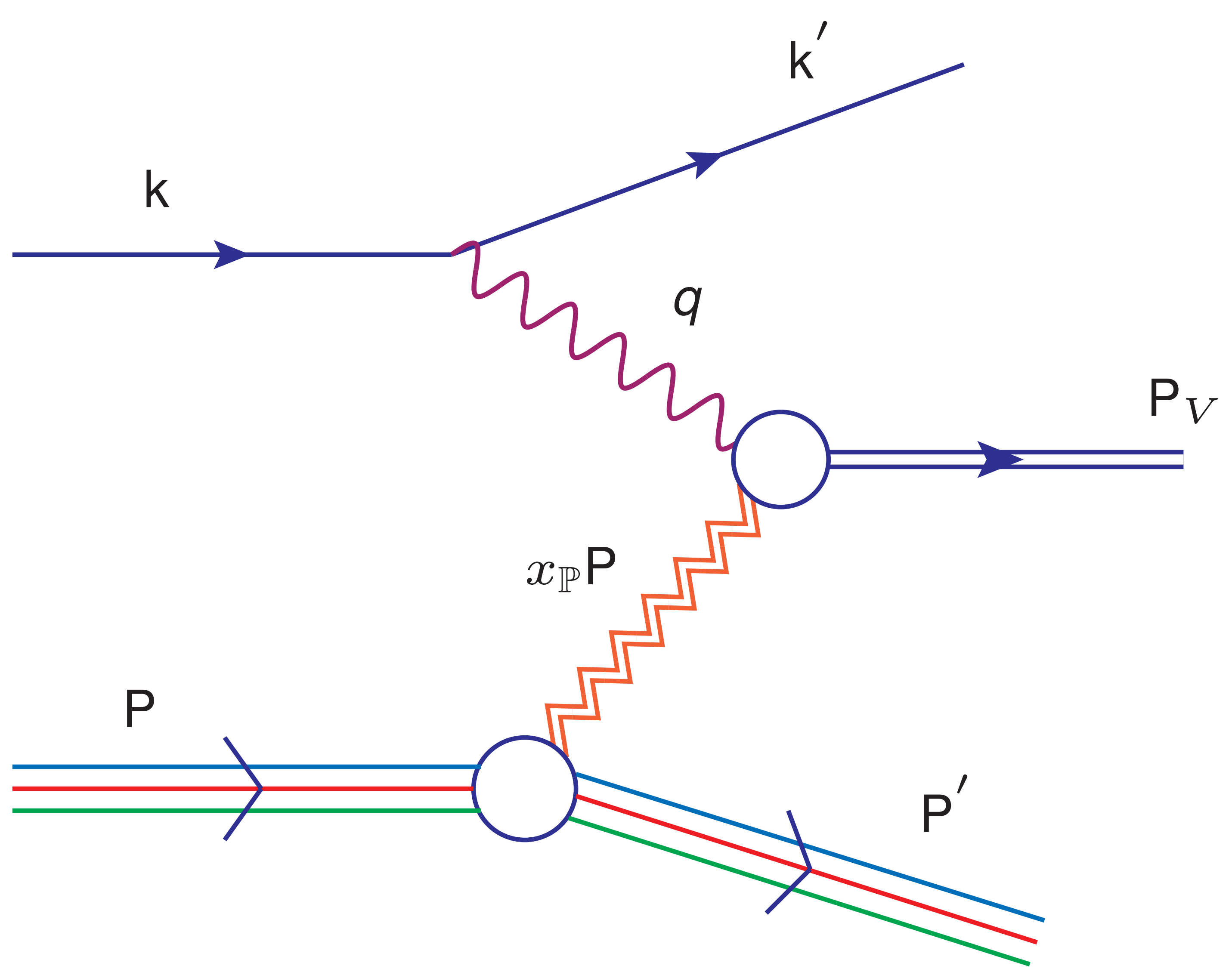
- *Sensitive to fluctuations of gluon distribution*

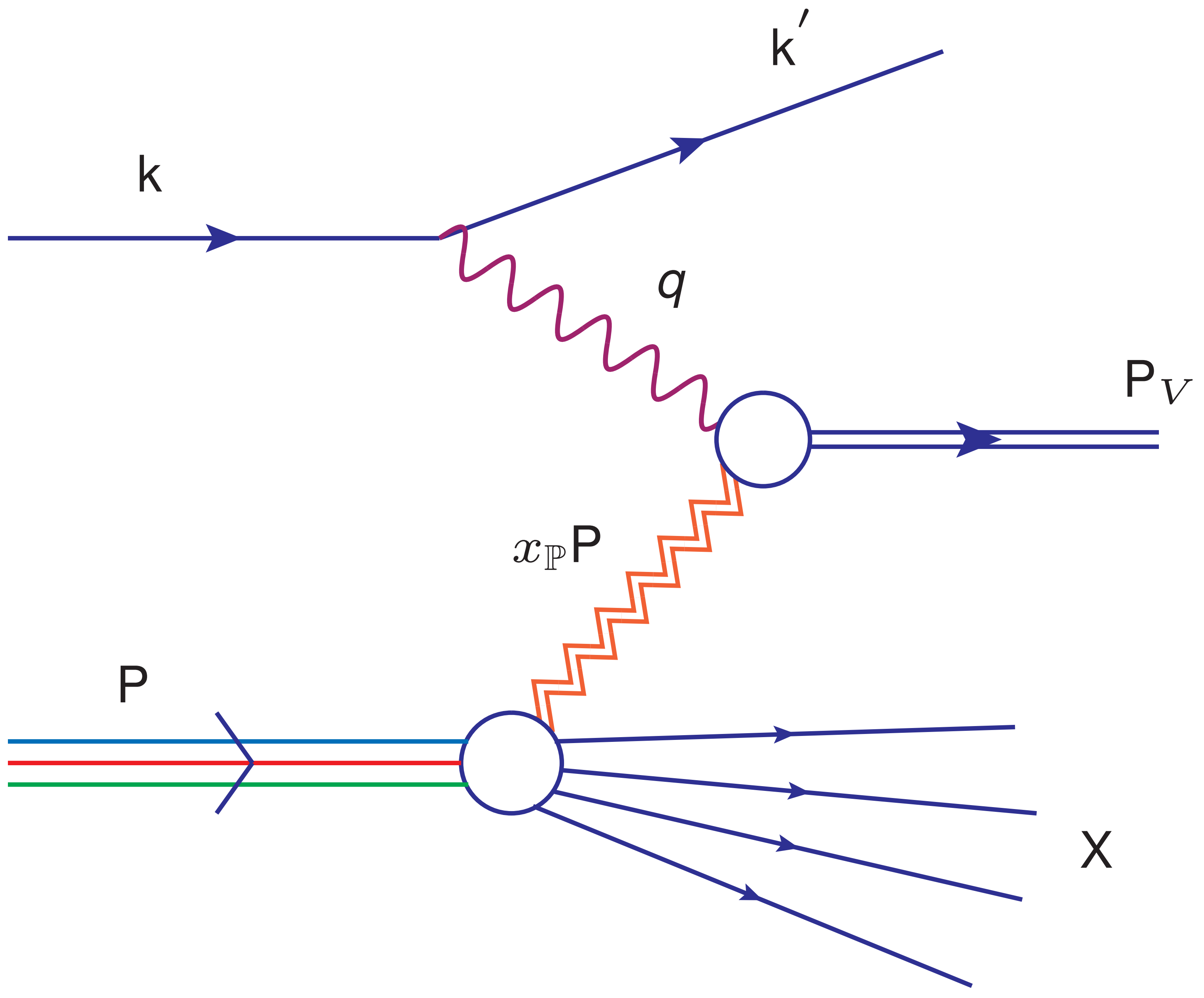
$$\begin{aligned}\sigma_{incoherent} &\sim \sum_{f\neq i} |<f|\mathcal{A}|i>|^2 \\ &= \sum_f <i|\mathcal{A}^\dagger|f><f|\mathcal{A}|i> - <i|\mathcal{A}|i>^\dagger<i|\mathcal{A}|i> \\ &= \left\langle\left|\mathcal{A}\right|^2\right\rangle_\Omega - \left|\left\langle\mathcal{A}\right\rangle_\Omega\right|^2\end{aligned}$$

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

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

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

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

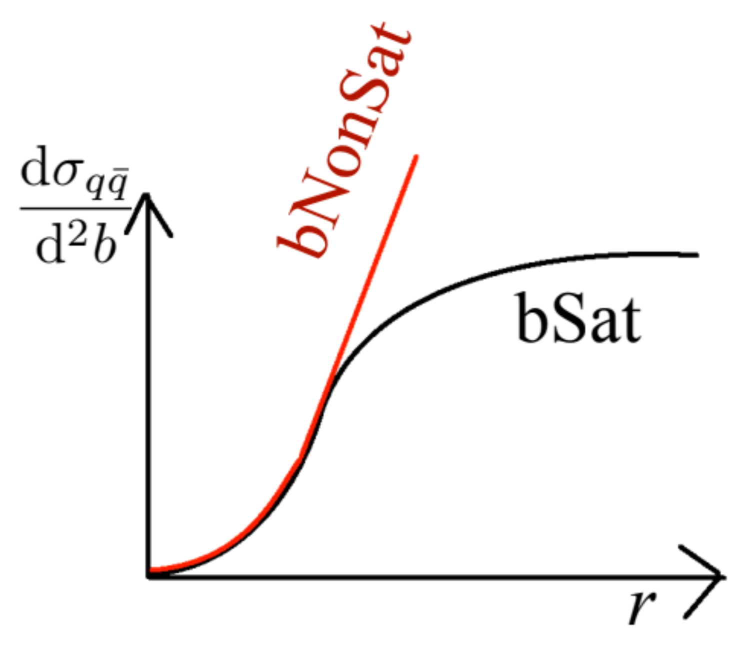
$$\sigma_{tot} \propto | < \mathscr{A} >_\Omega |^2 + (< |\mathscr{A}|^2 >_\Omega - | < \mathscr{A} >_\Omega |^2)$$

Coherent Incoherent

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

THE DIPOLE-TARGET AMPLITUDE

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



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)

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

Kowalski, Teaney 2003, Kowalski, Motyka,Watt 2006

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

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

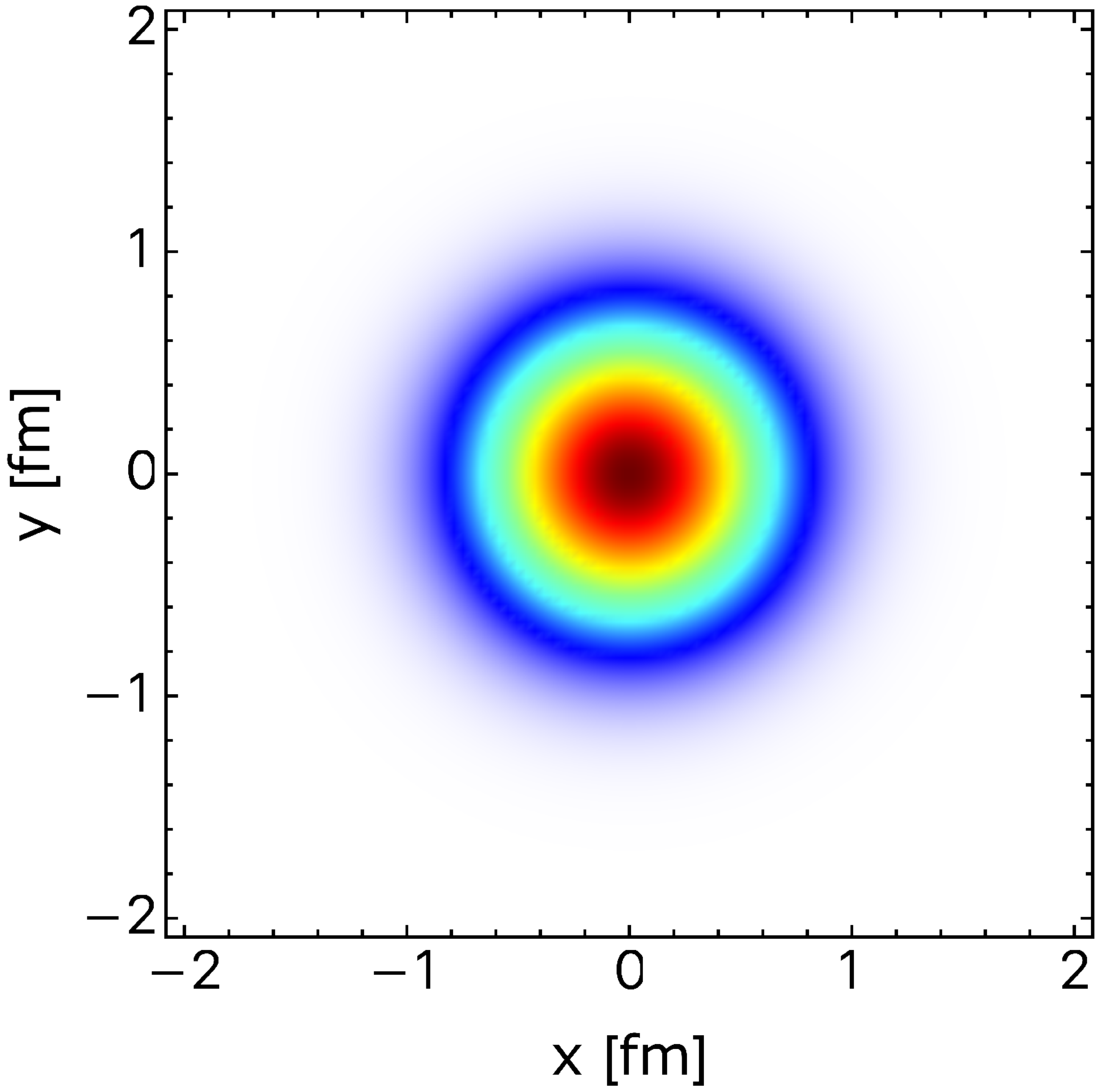
c) For Heavy ions $T_A(b) \rightarrow \frac{1}{A}\sum_{i=1}^{A} T_p(b-b_i)$ *and where* b_i *denotes location of nucleons sampled from Woods-Saxon geometry*

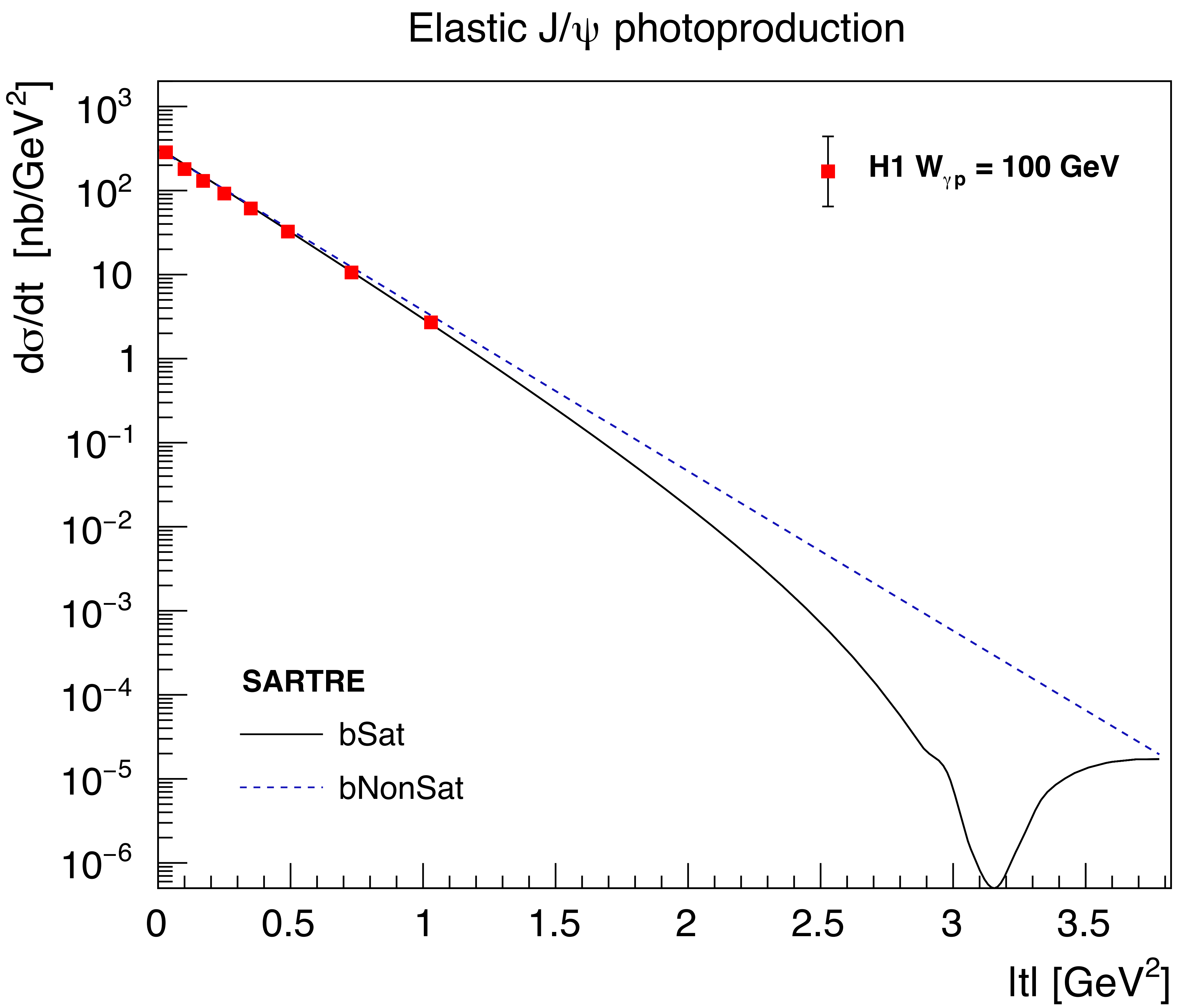
$e + p$ AS COMPARED TO HERA DATA : SMOOTH PROTON

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

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

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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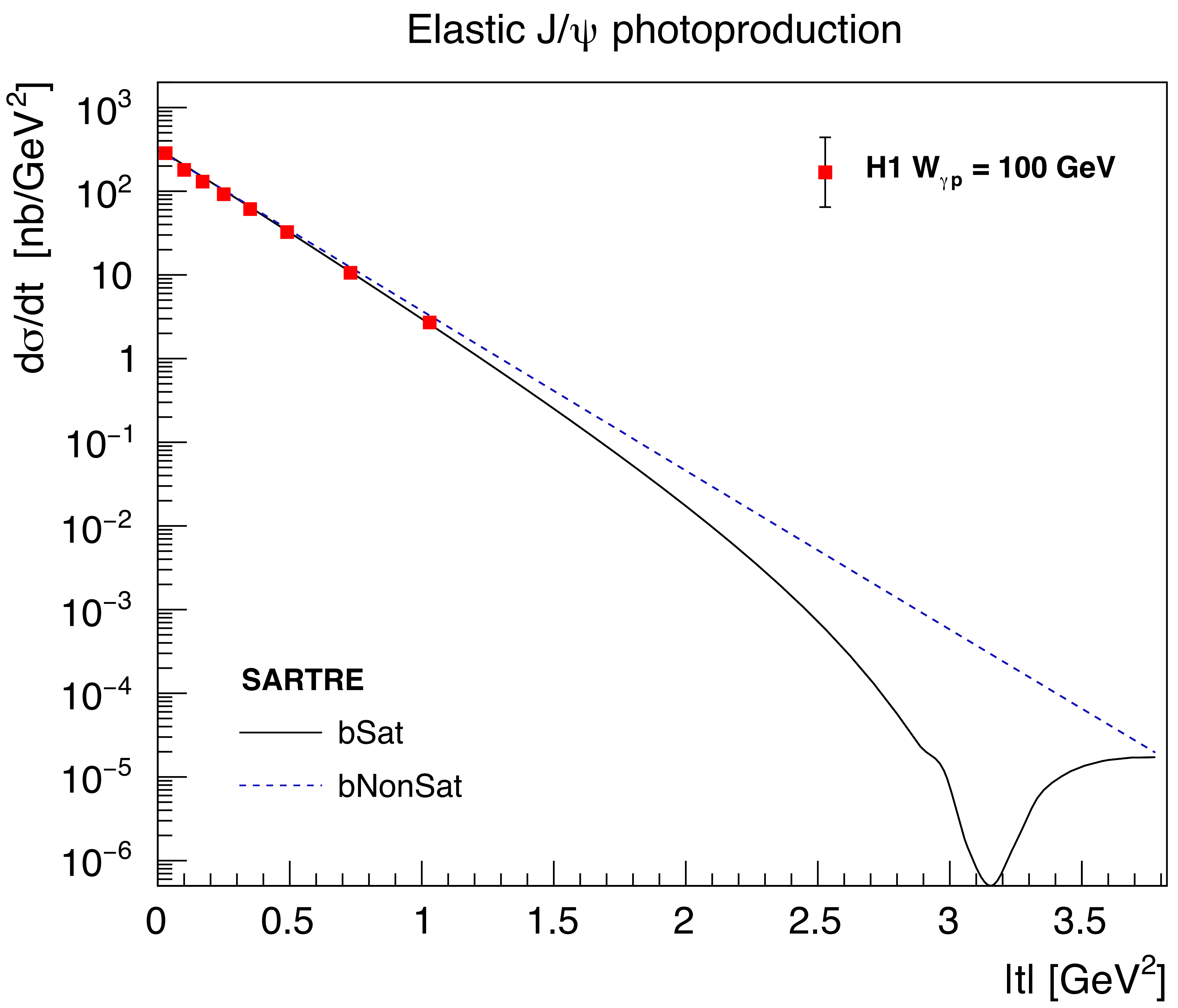


Gaussian & linear (bNonSat) : $N(r, b) \sim e^{-\mathbf{b}^2/(2B)}$

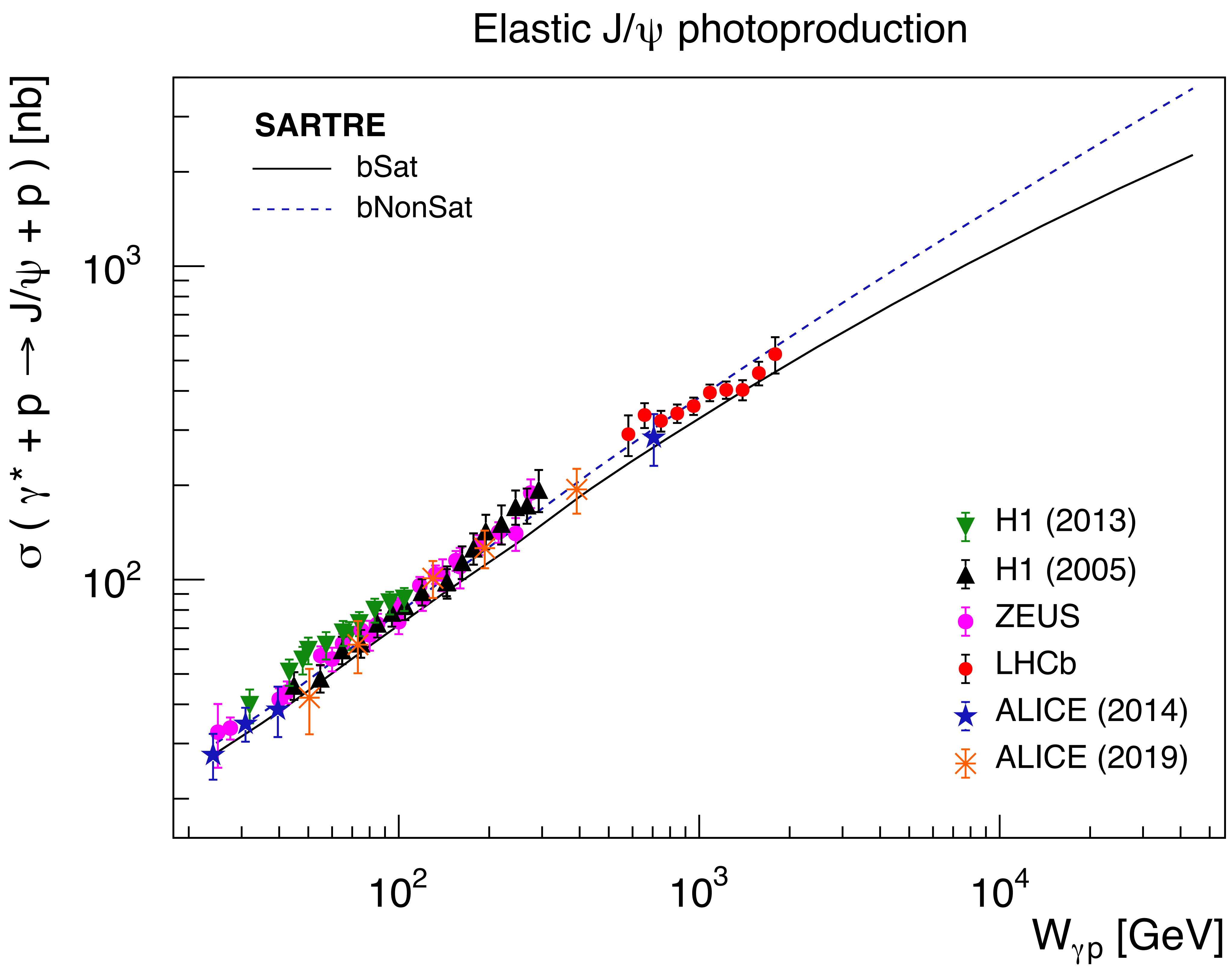
Gaussian& non-linear (bSat) : $N(r, b) \sim 1 - \exp\left(-e^{-\mathbf{b}^2/(2B)}\right)$

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

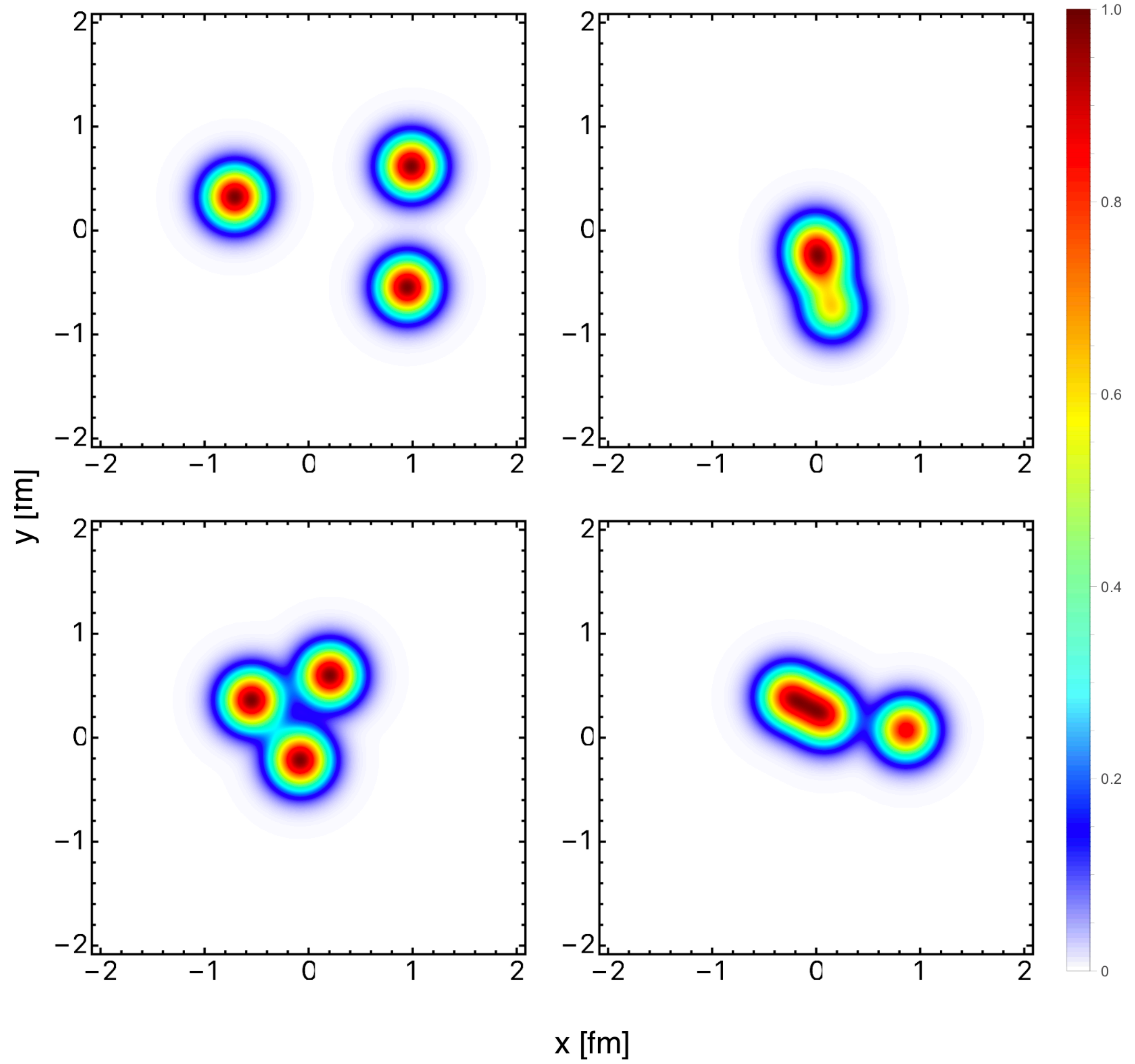
Deviations from power law? Hint of non-linear effects

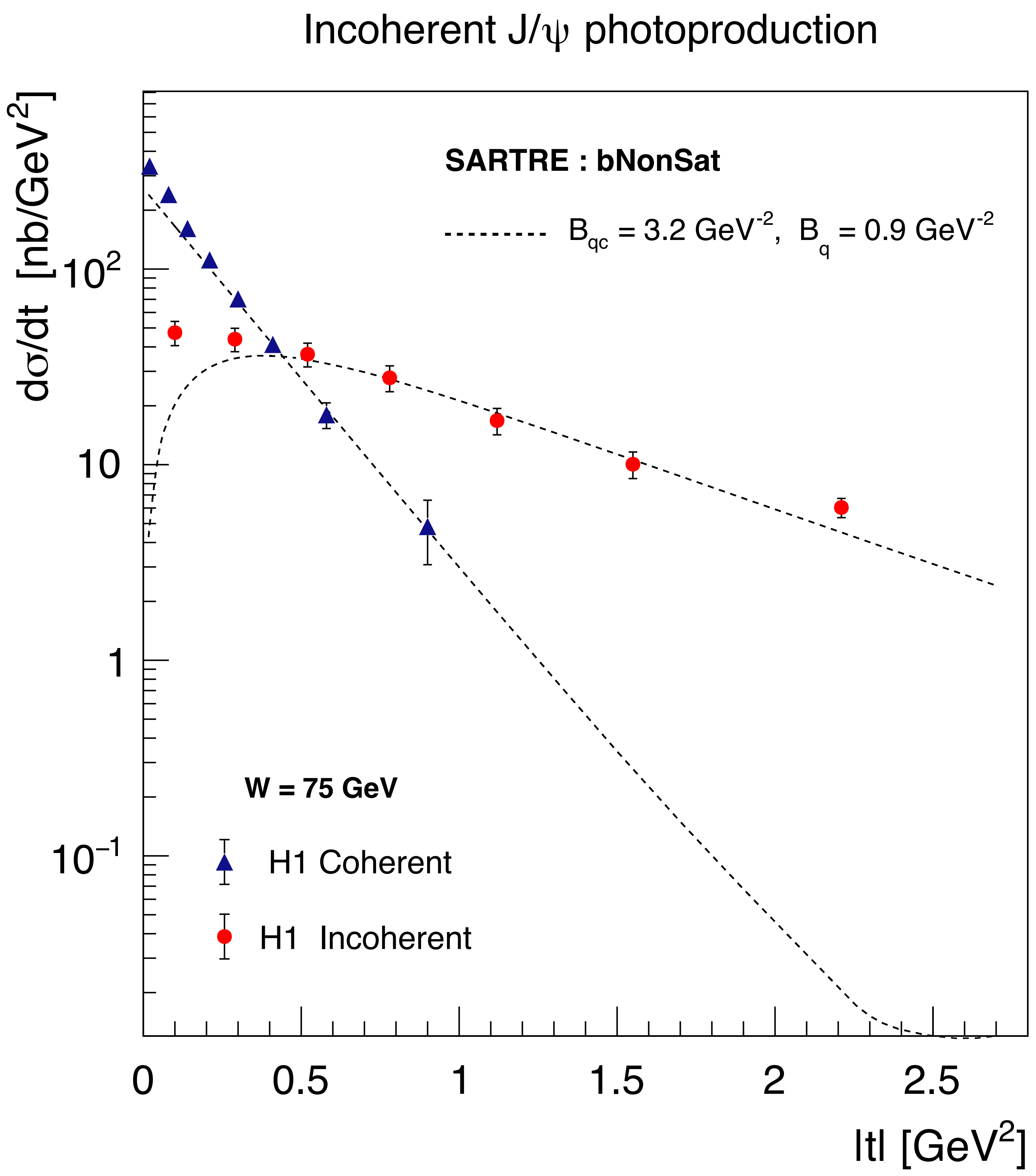
For a smooth proton there are no fluctuations and the incoherent cross section is zero → Lumpy proton

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

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

Mäntysaari, Schenke PRL 117 (2016) 052301



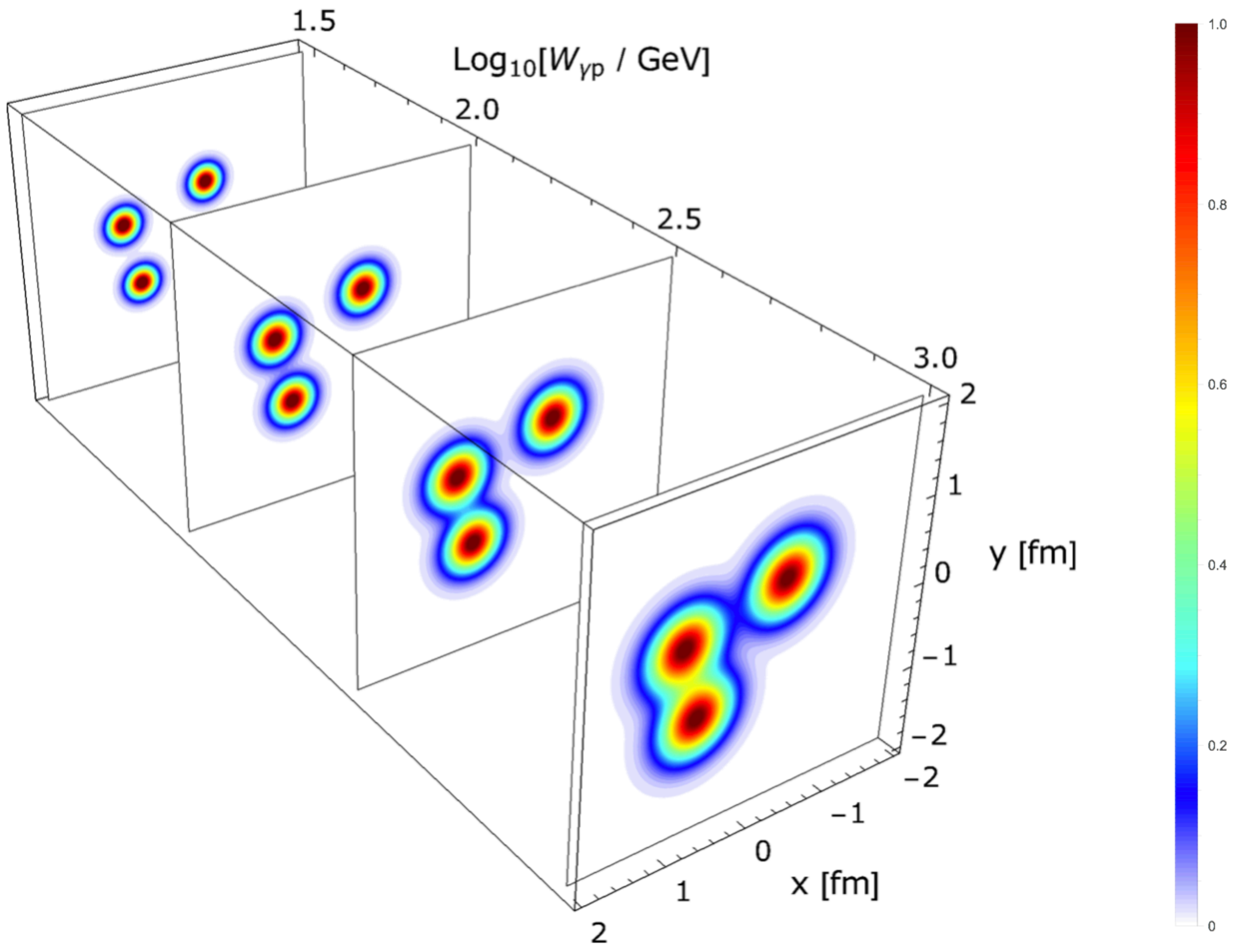


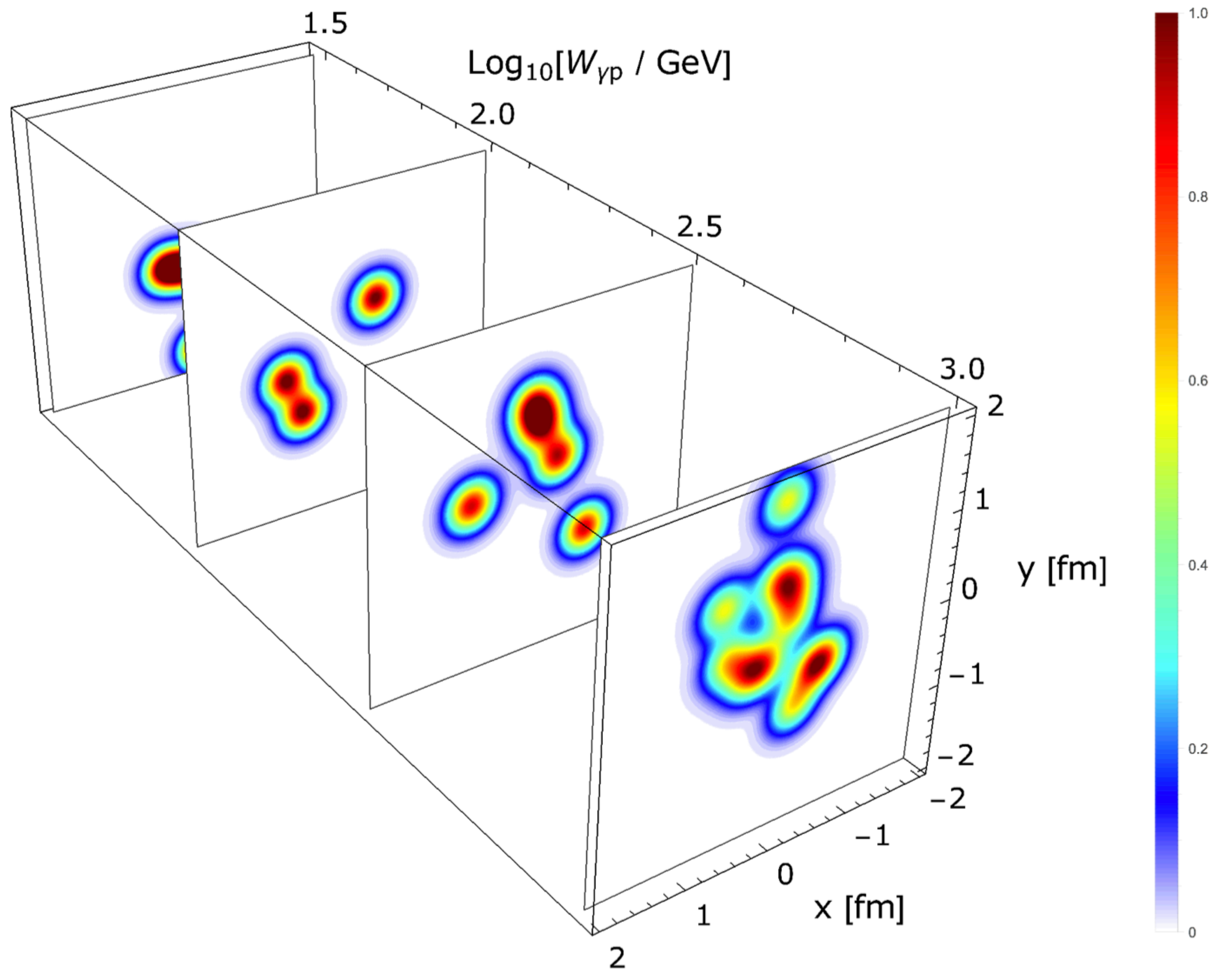
(large event-by-event fluctuations (1000 configurations) are needed to explain HERA data)

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: $B_q(x) = B_{q0}\ x^{\lambda_0}$

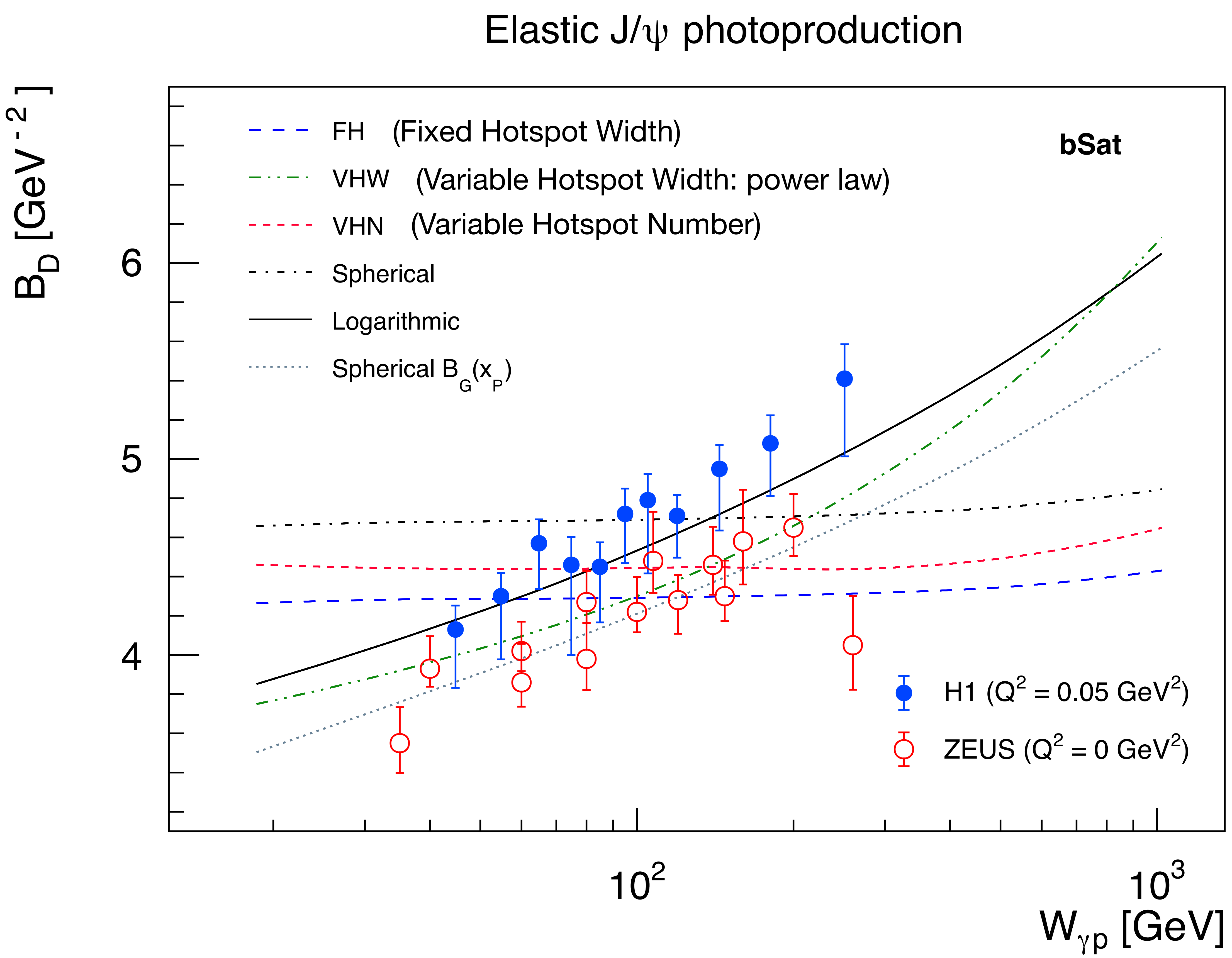
Logarithmic model: $B_q(x) = b_0\ ln^2\left(\frac{x_0}{x}\right)$

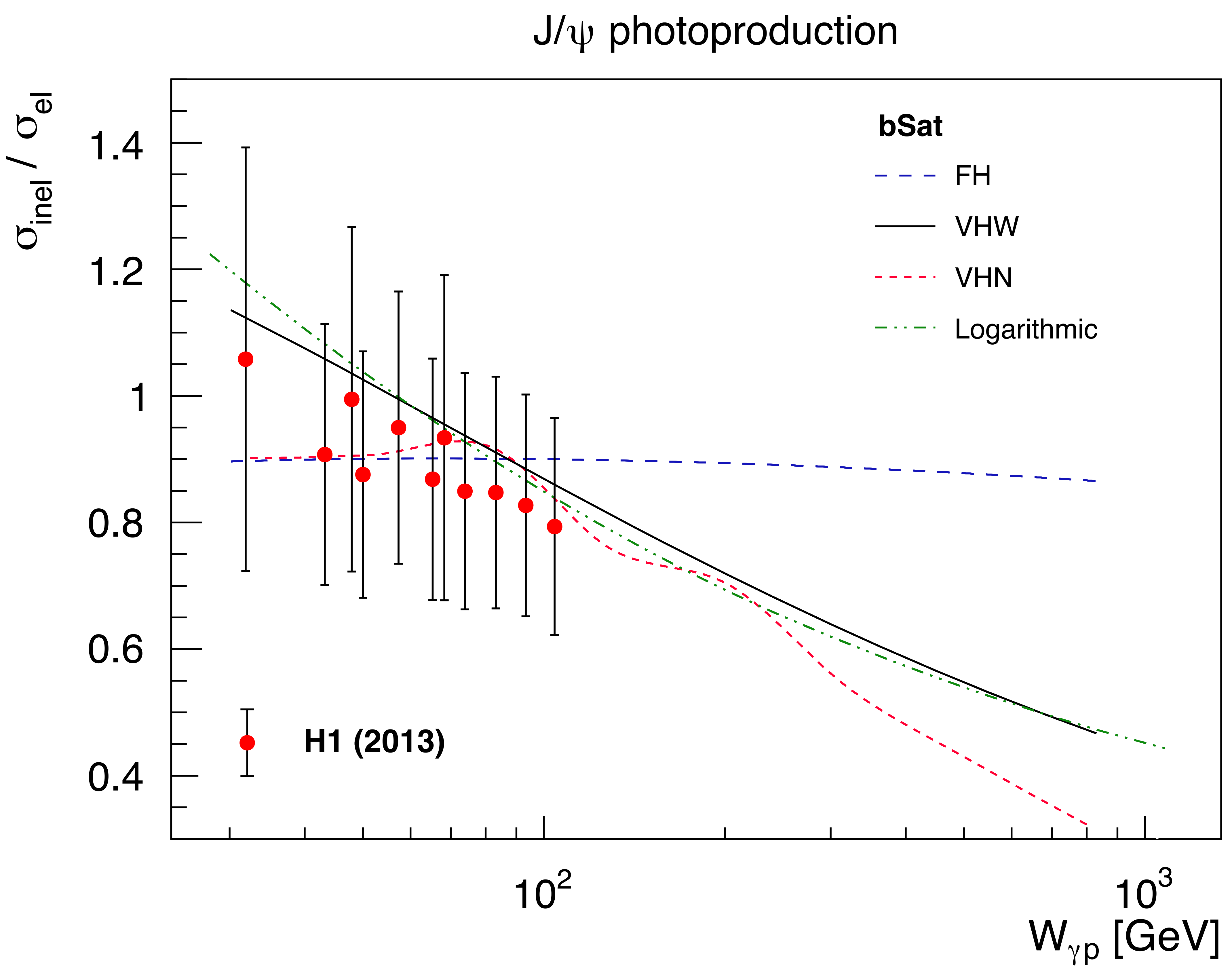
Varying hotspot number (VHN) model: $N_q(x) = p_0\ x^{p_1}(1+p_2\sqrt{x})$

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

INCORPORATING THE ENERGY DEPENDENCE

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

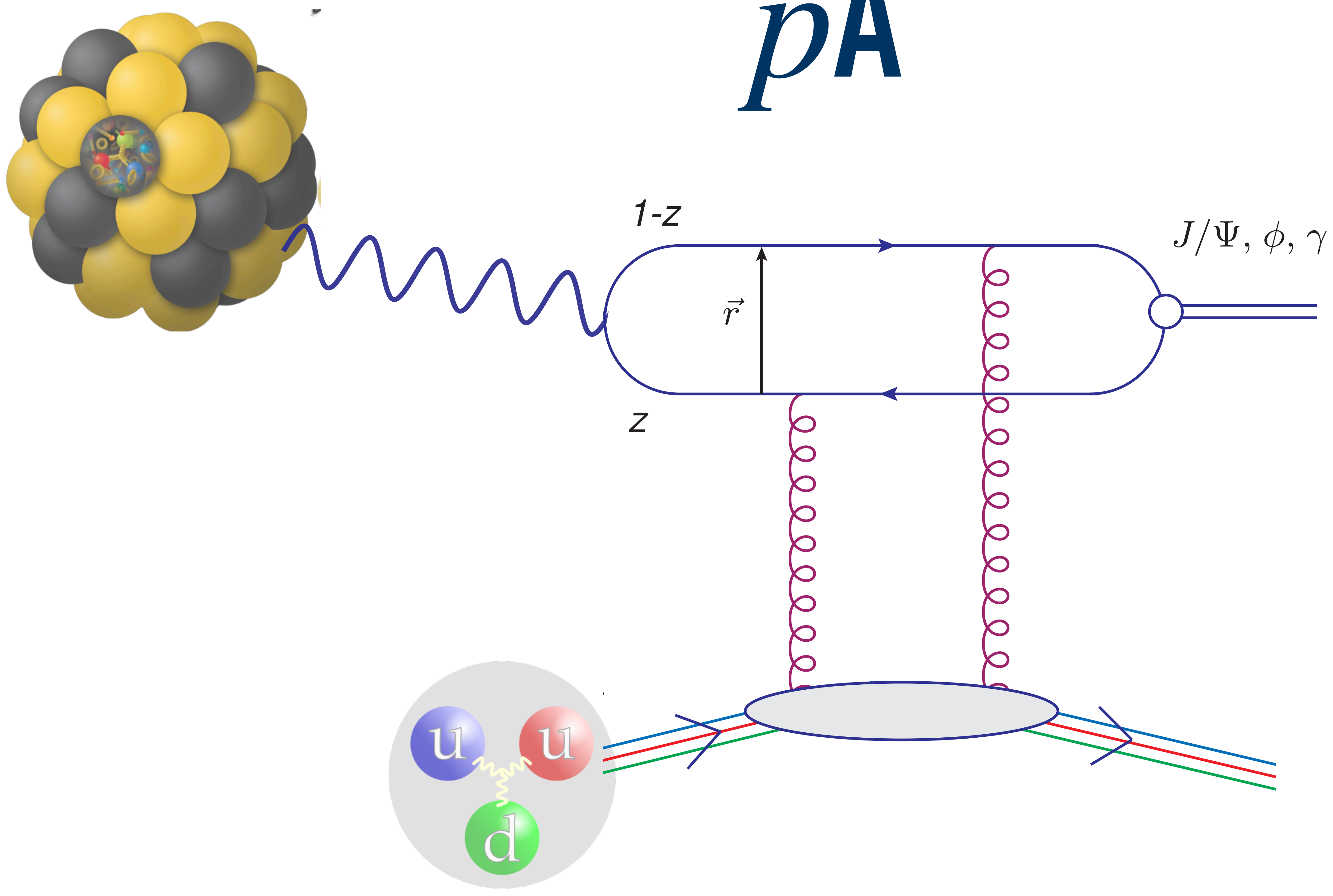




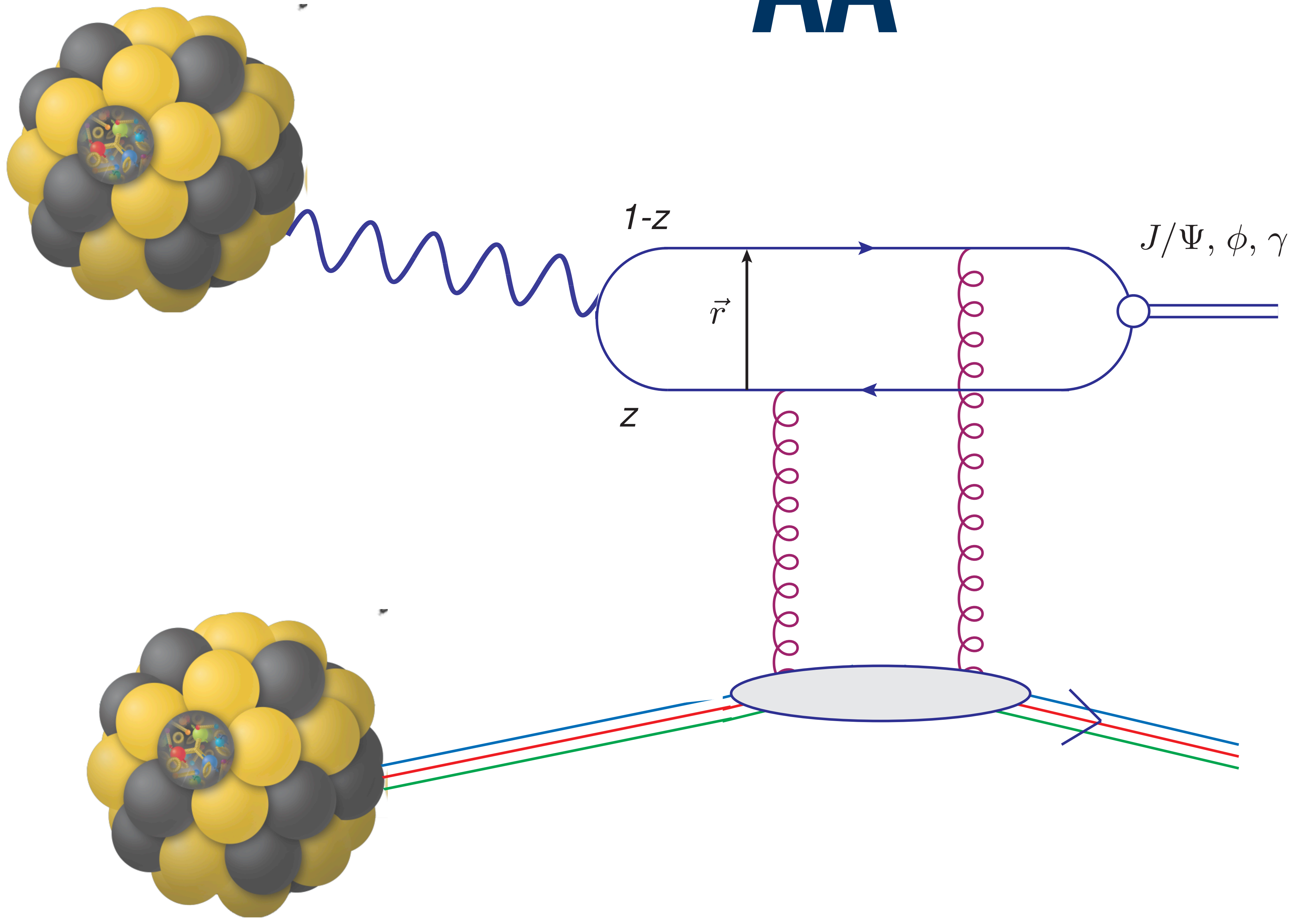
see Mäntysaari, Schenke 1806.06783 for similar predictions in IP-GLASMA framework

ULTRA PERIPHERAL COLLISIONS (UPCs) AS PROBE OF PARTONIC STRUCTURE

pA



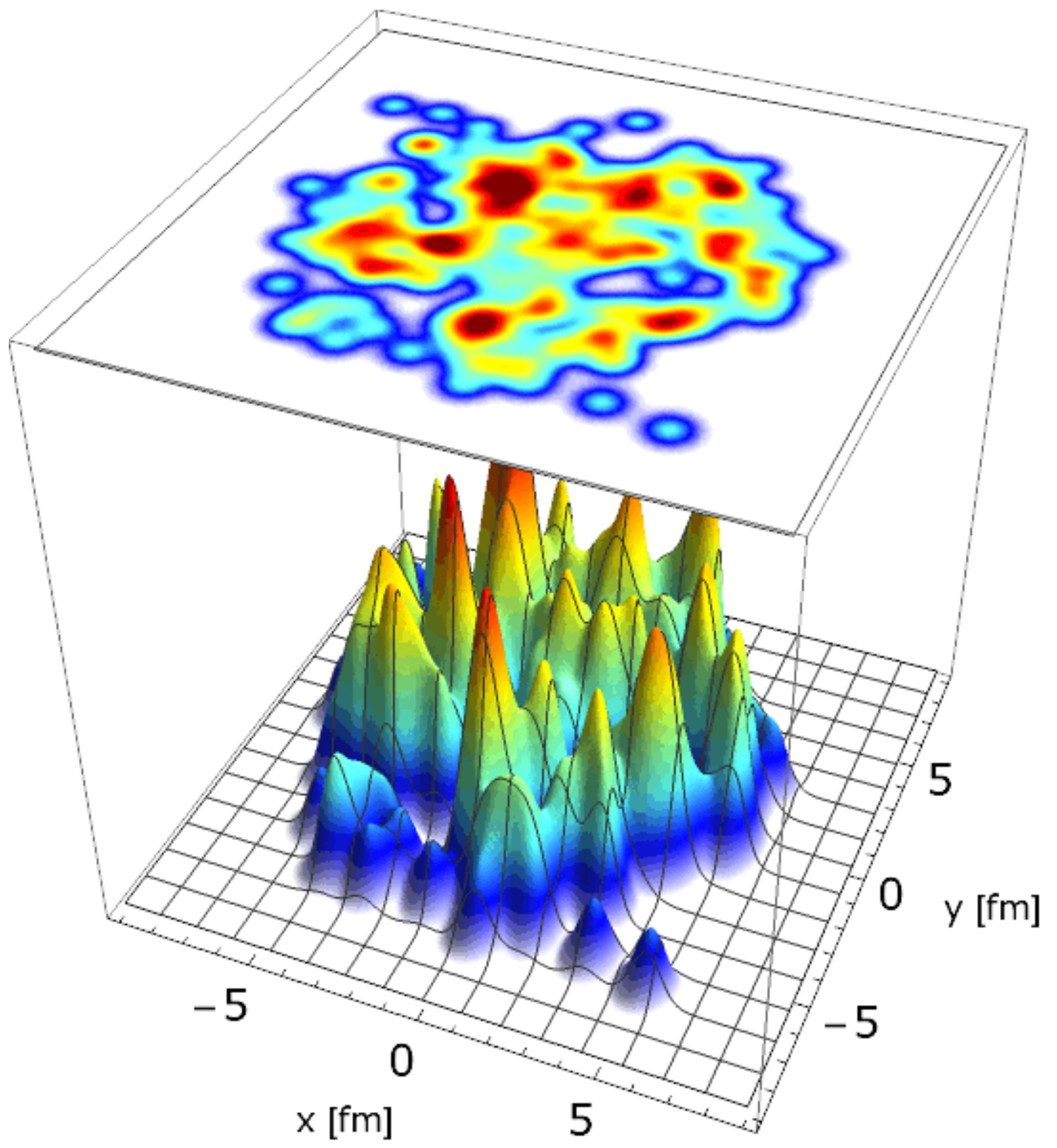
AA



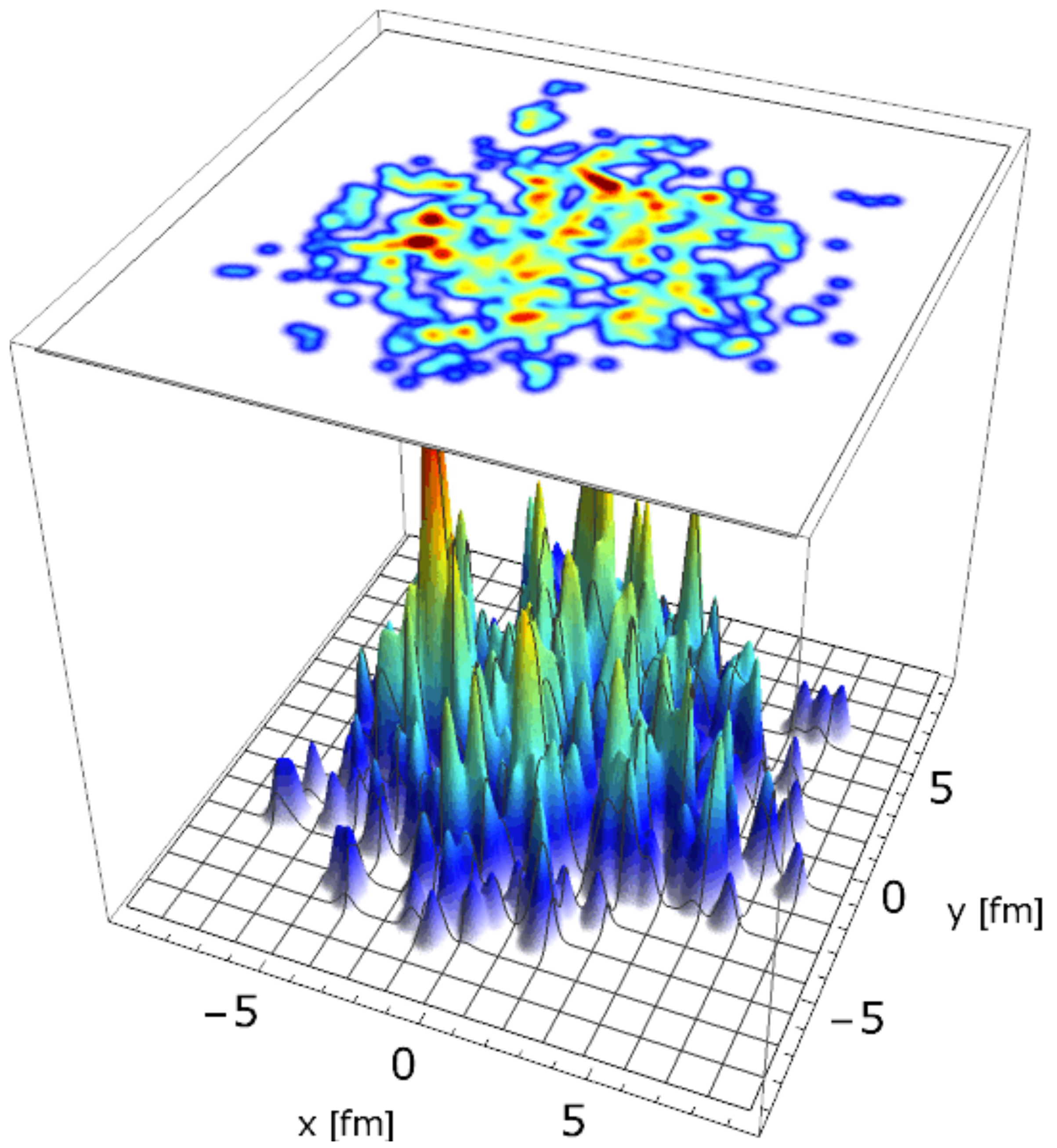
- *Photons in UPCs ($b \gg R_A + R_B$) are probes of nucleus and proton partonic structure and strong interaction dynamics in small-x QCD.*
- *Good test of our models and complementary physics at LHC and RHIC before EIC starts taking data.*

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

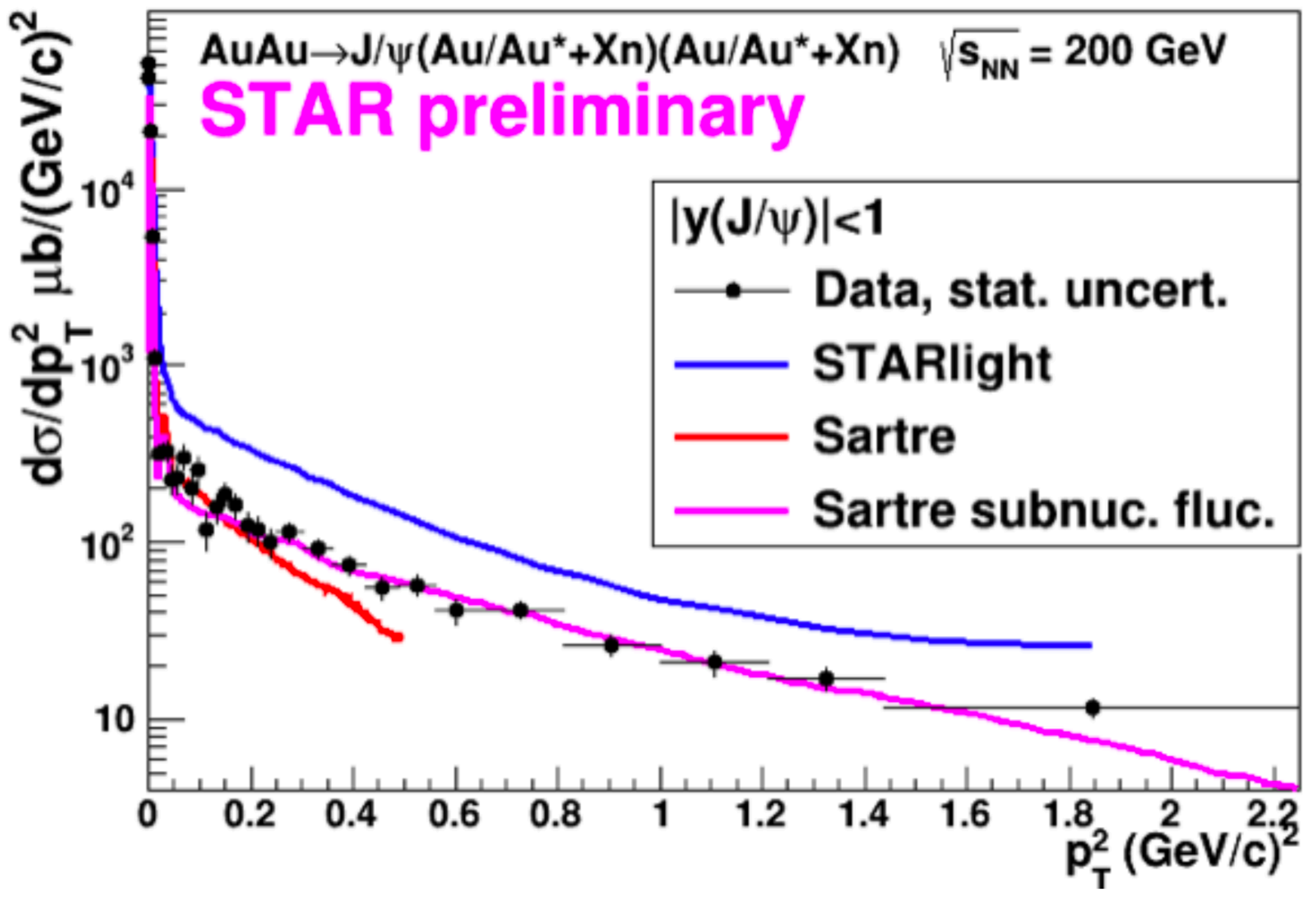
DIFFRACTIVE J/ψ PRODUCTION IN ULTRA PERIPHERAL COLLISIONS



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



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



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

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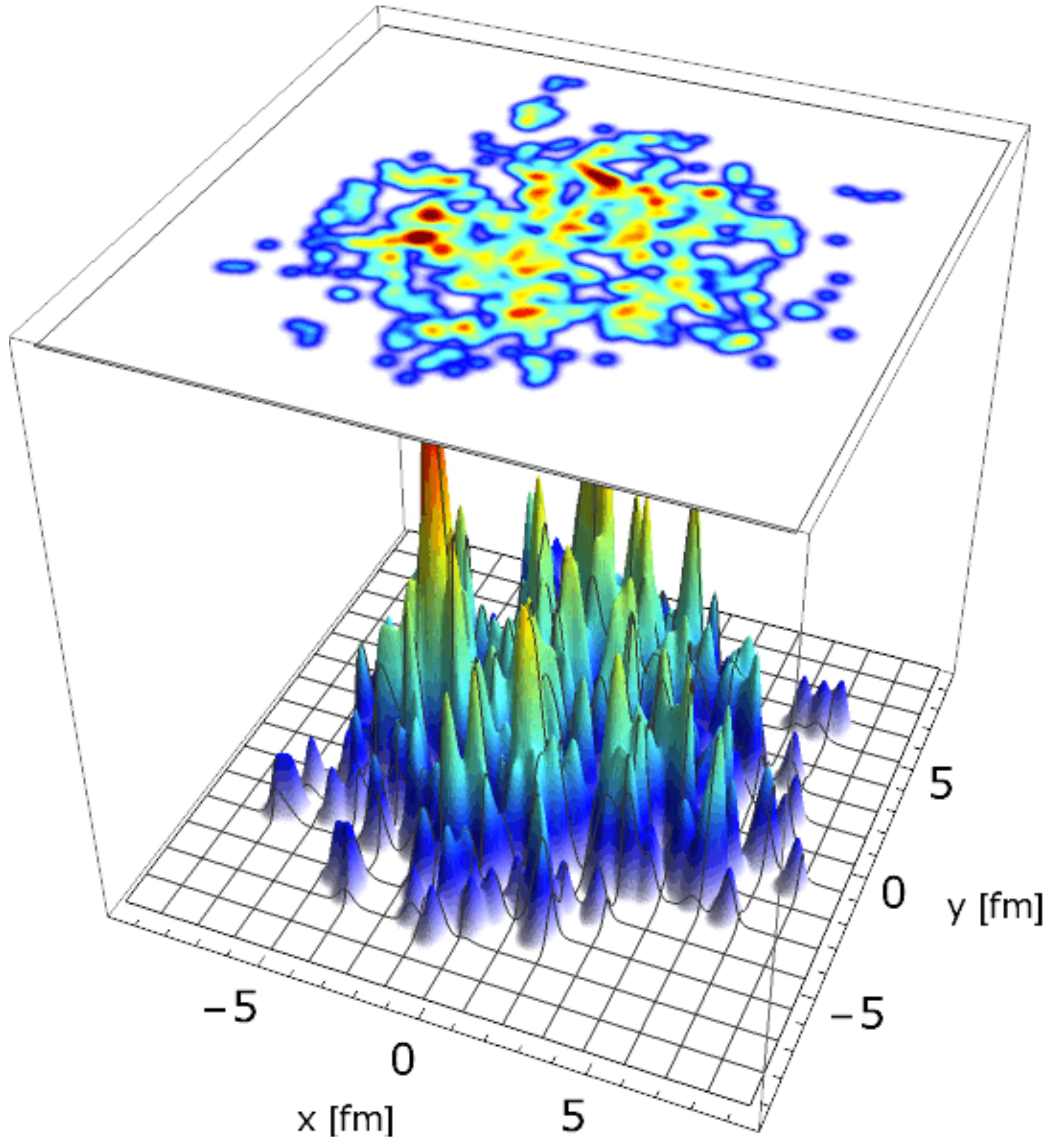

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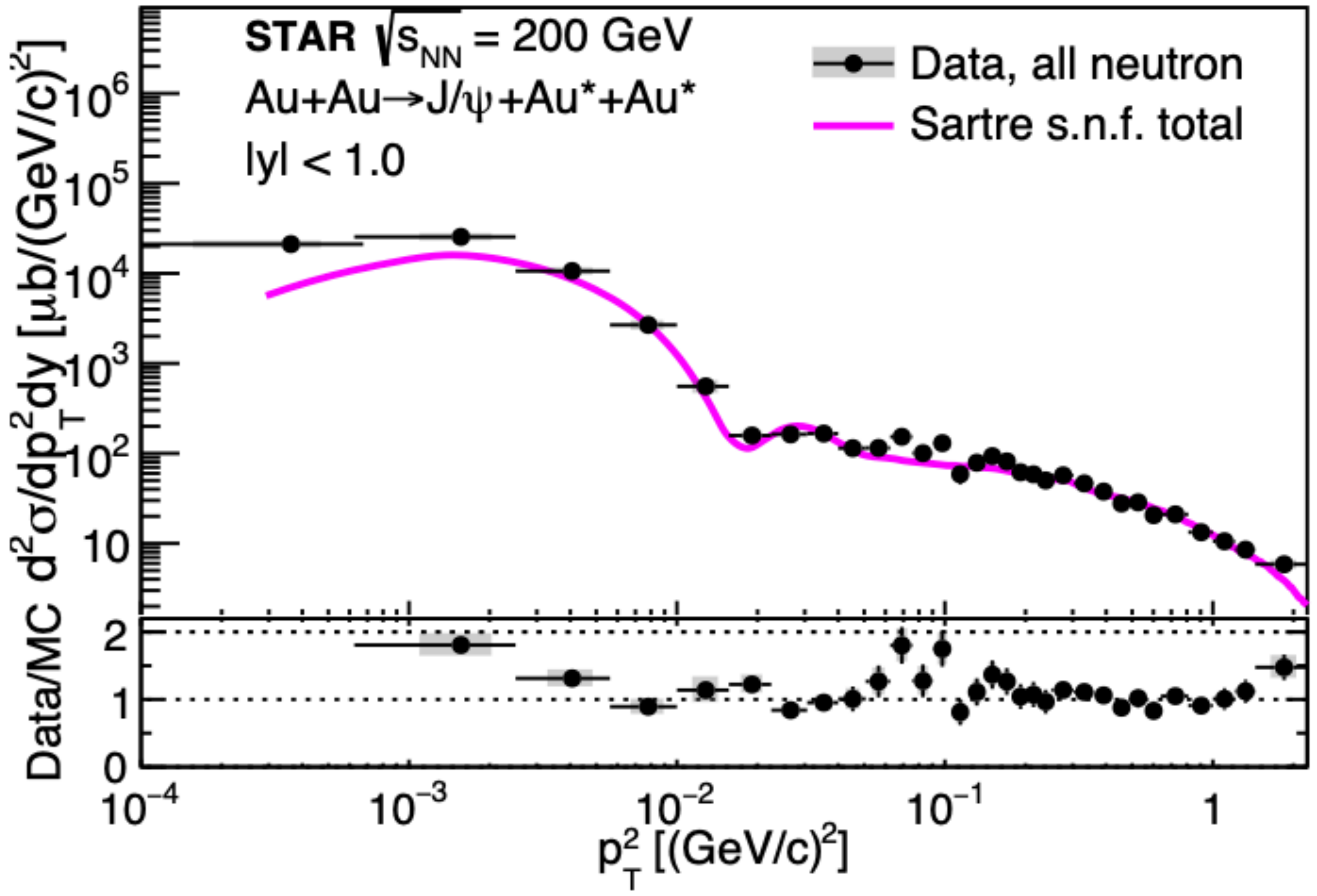
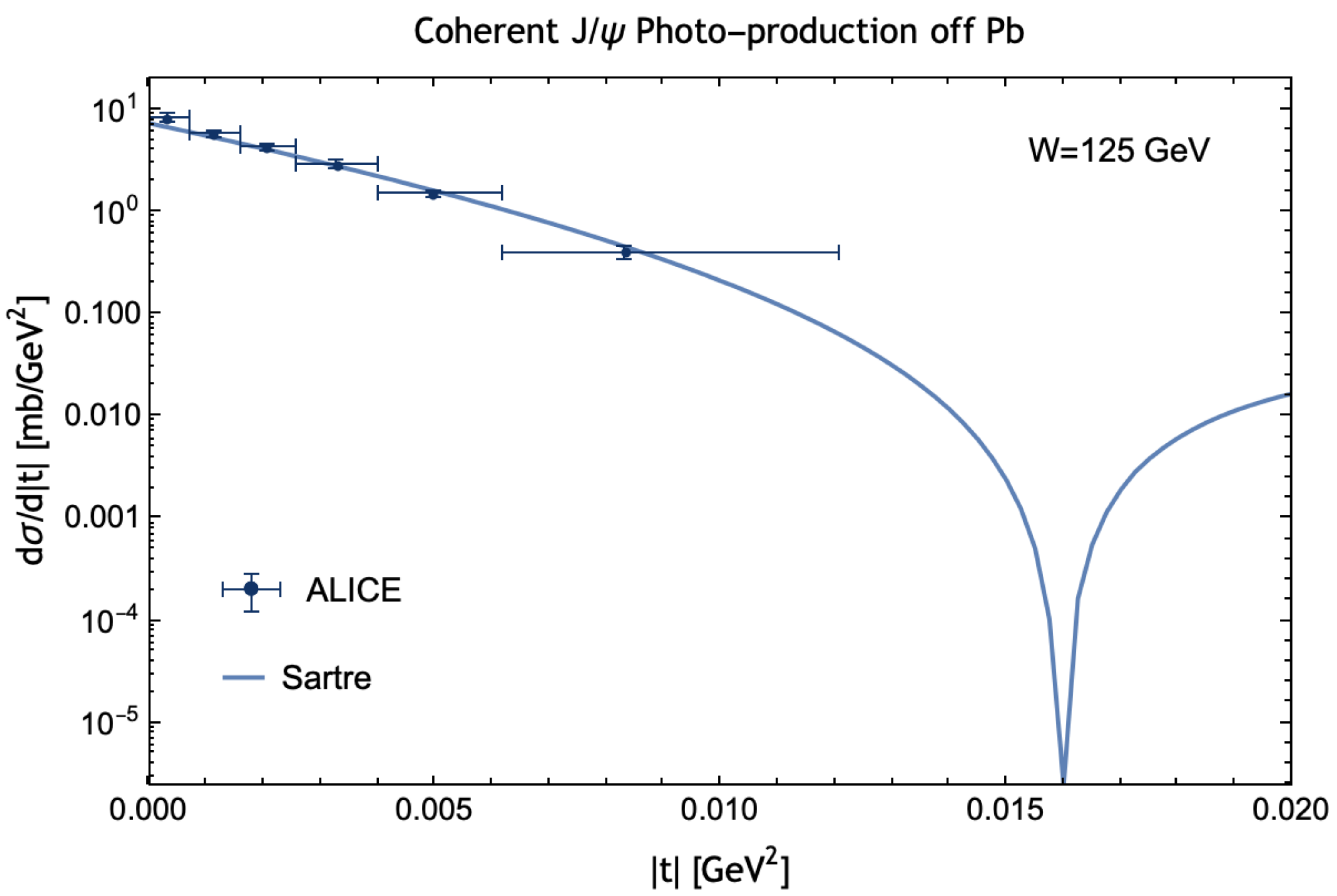
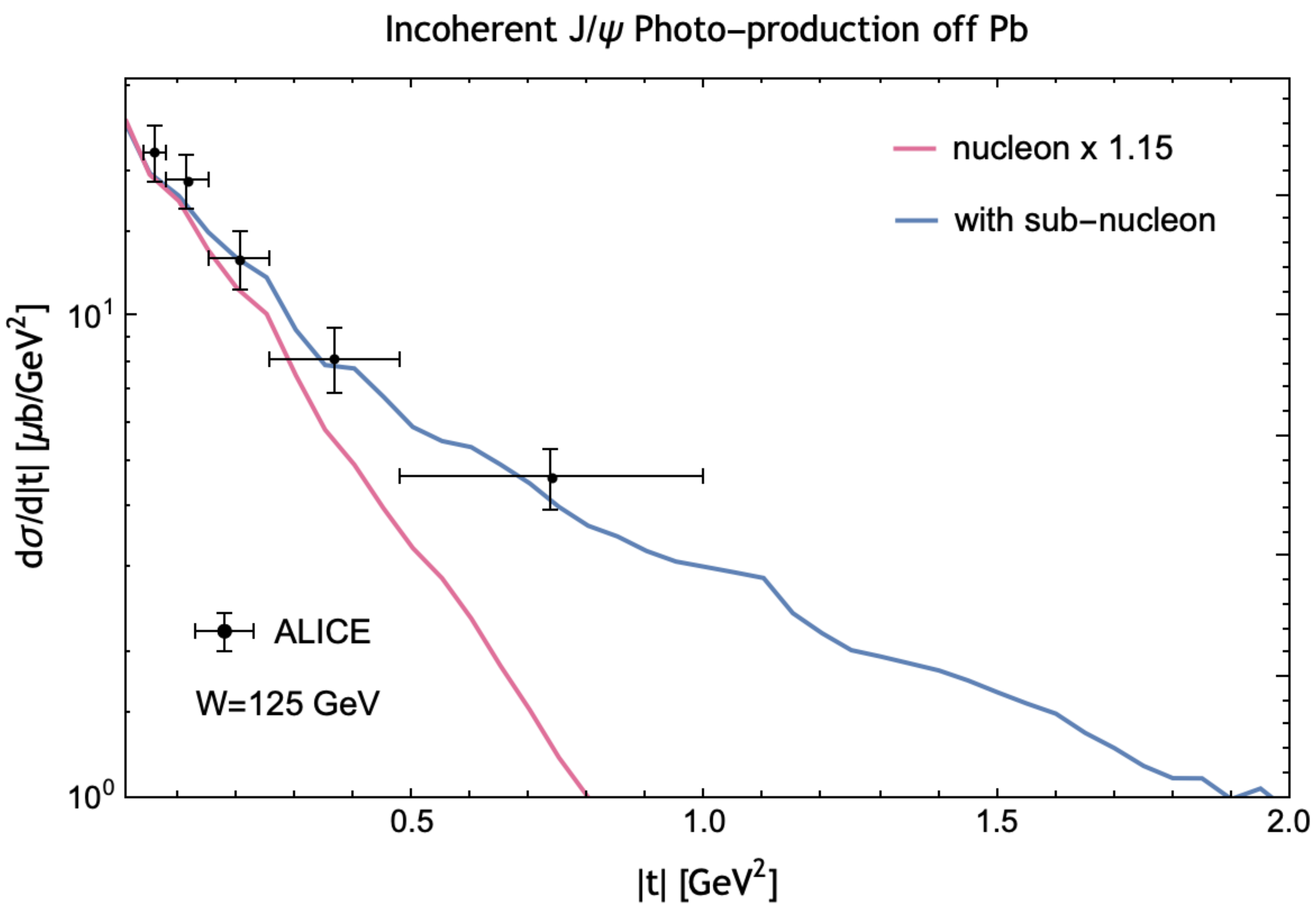


STAR Collaboration PRC. 110 (2024) 014911

DIFFRACTIVE J/ψ PRODUCTION IN ULTRA PERIPHERAL COLLISIONS





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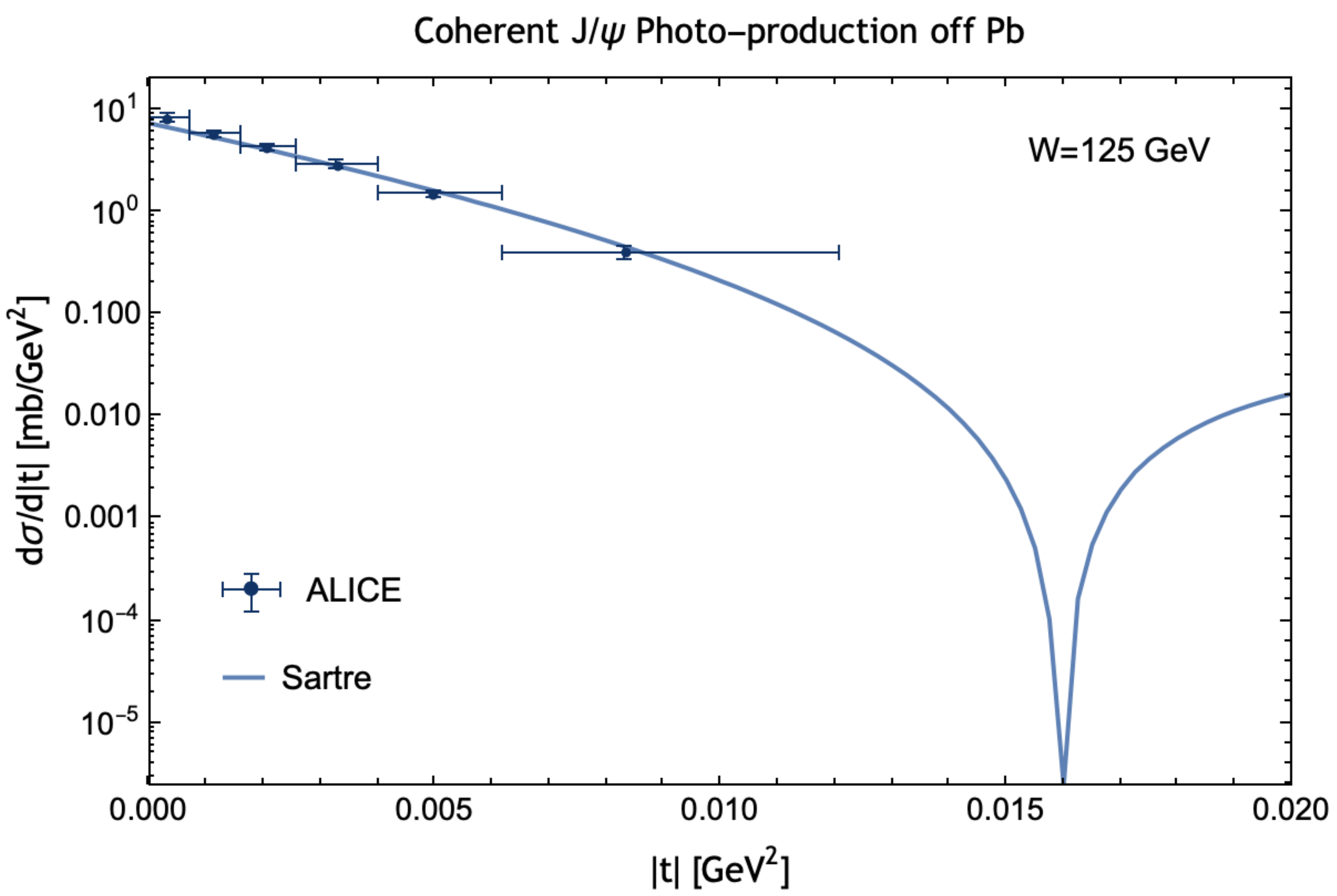
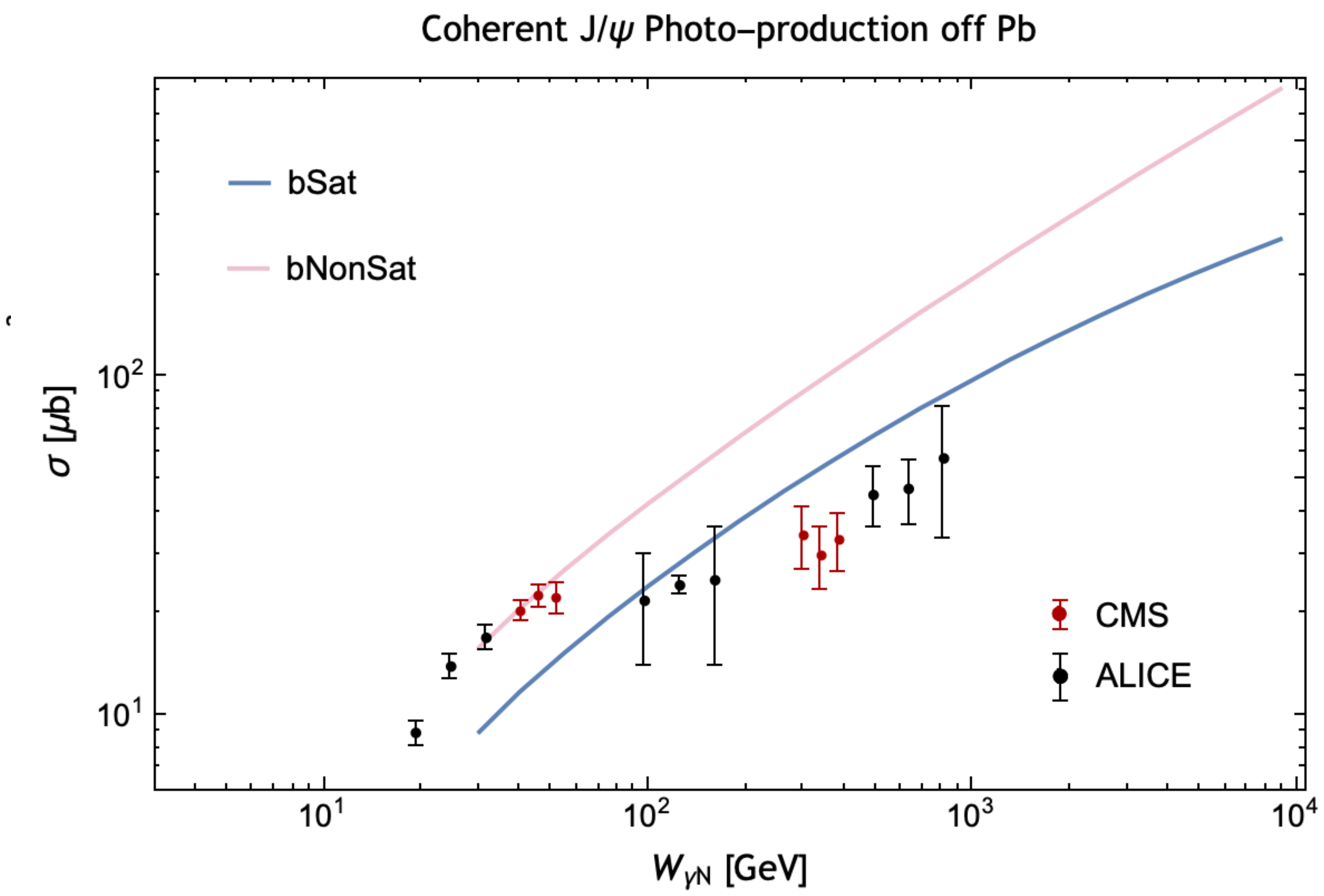


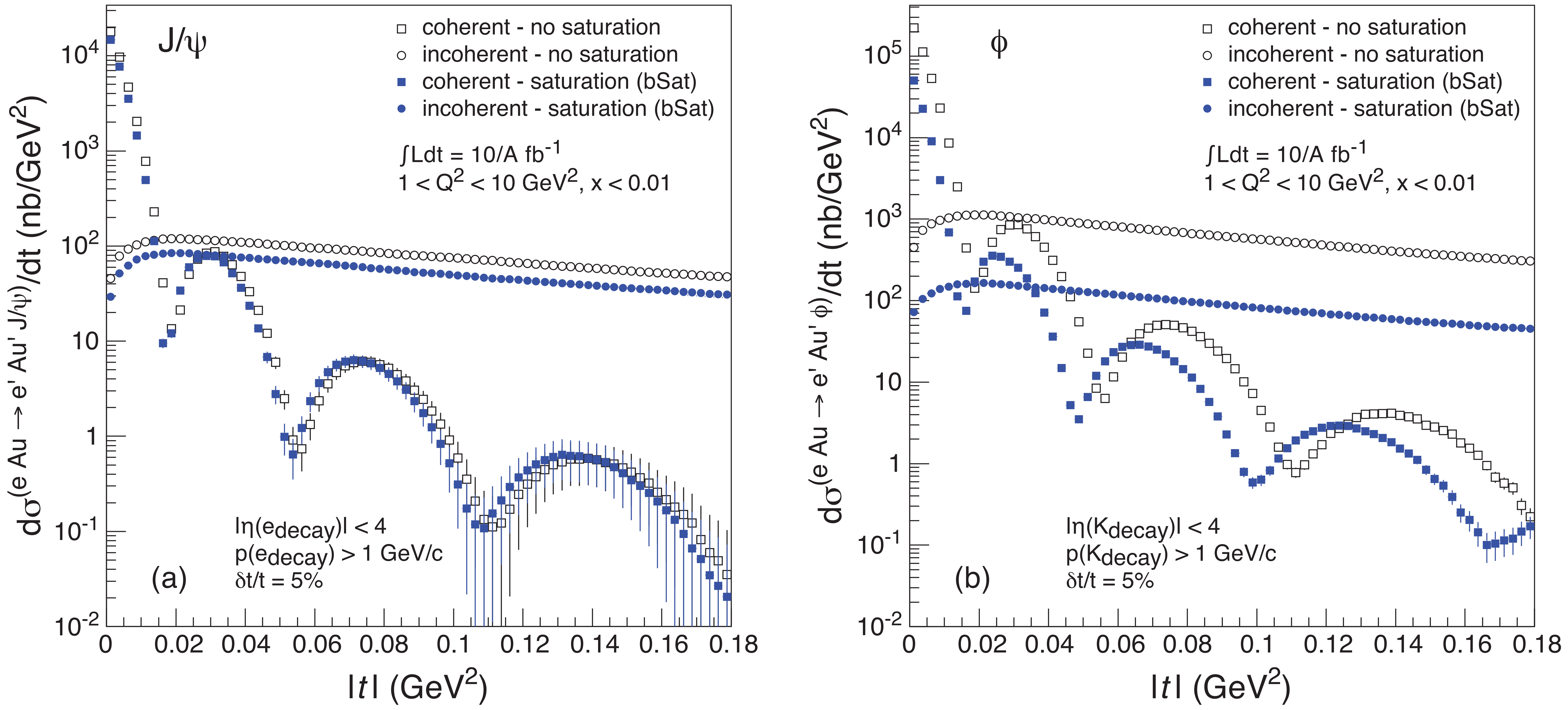


Crucial to understand whether the suppression originates from perturbative (saturation models & small-x evolution) or non-perturbative (shadowing models) mechanisms? *look for new observables & investigate A dependence*

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

EXCLUSIVE DIFFRACTION AT EIC

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

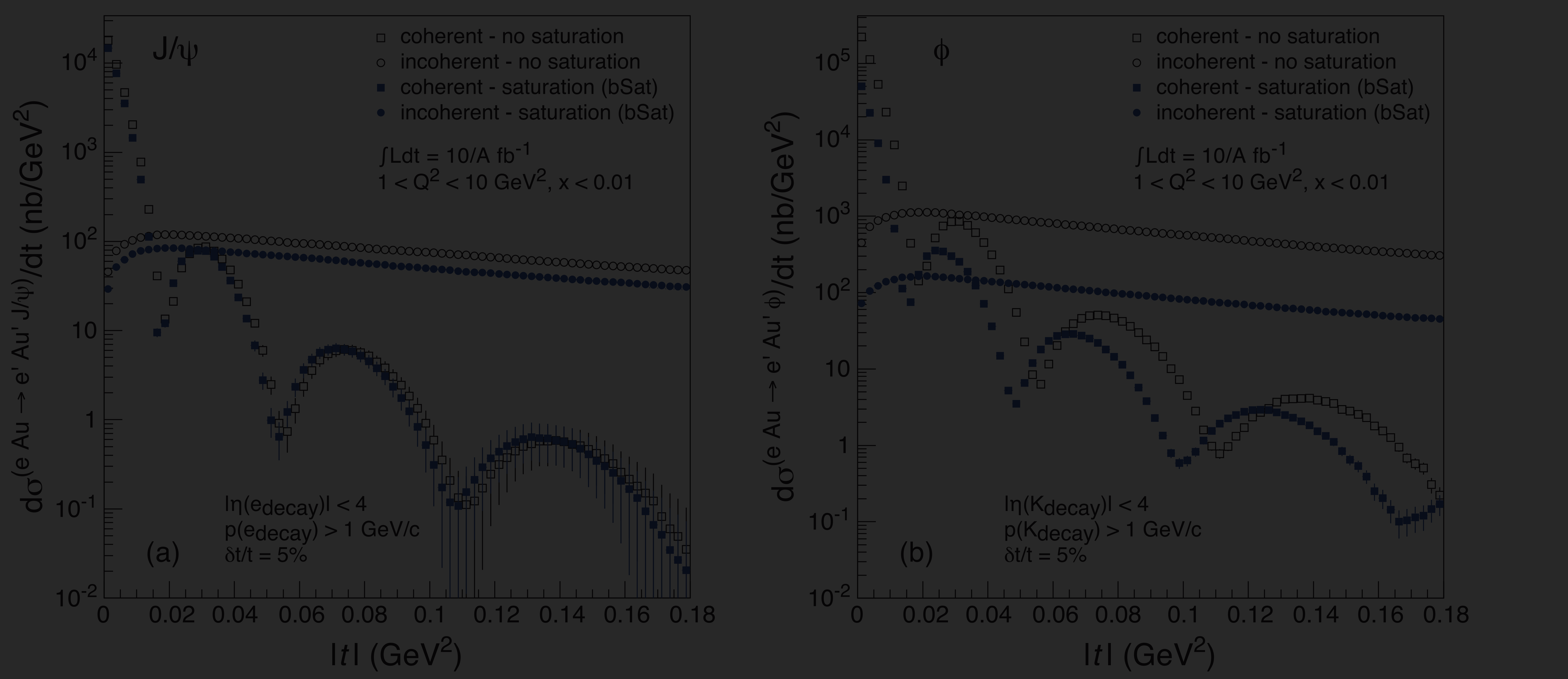


Spatial Imaging : $$F(b) = \frac{1}{2\pi}\int_0^\infty \mathrm{d}\Delta\Delta J_0(\Delta b)\sqrt{\frac{\mathrm{d}\sigma_{\mathrm{coherent}}}{\mathrm{d}t}(\Delta)}\Bigg|_{\mathrm{mod}}$$

EXCLUSIVE DIFFRACTION AT EIC

Tobias Toll, Thomas Ullrich PRC 87 (2013) 024913

Why it is so difficult ?



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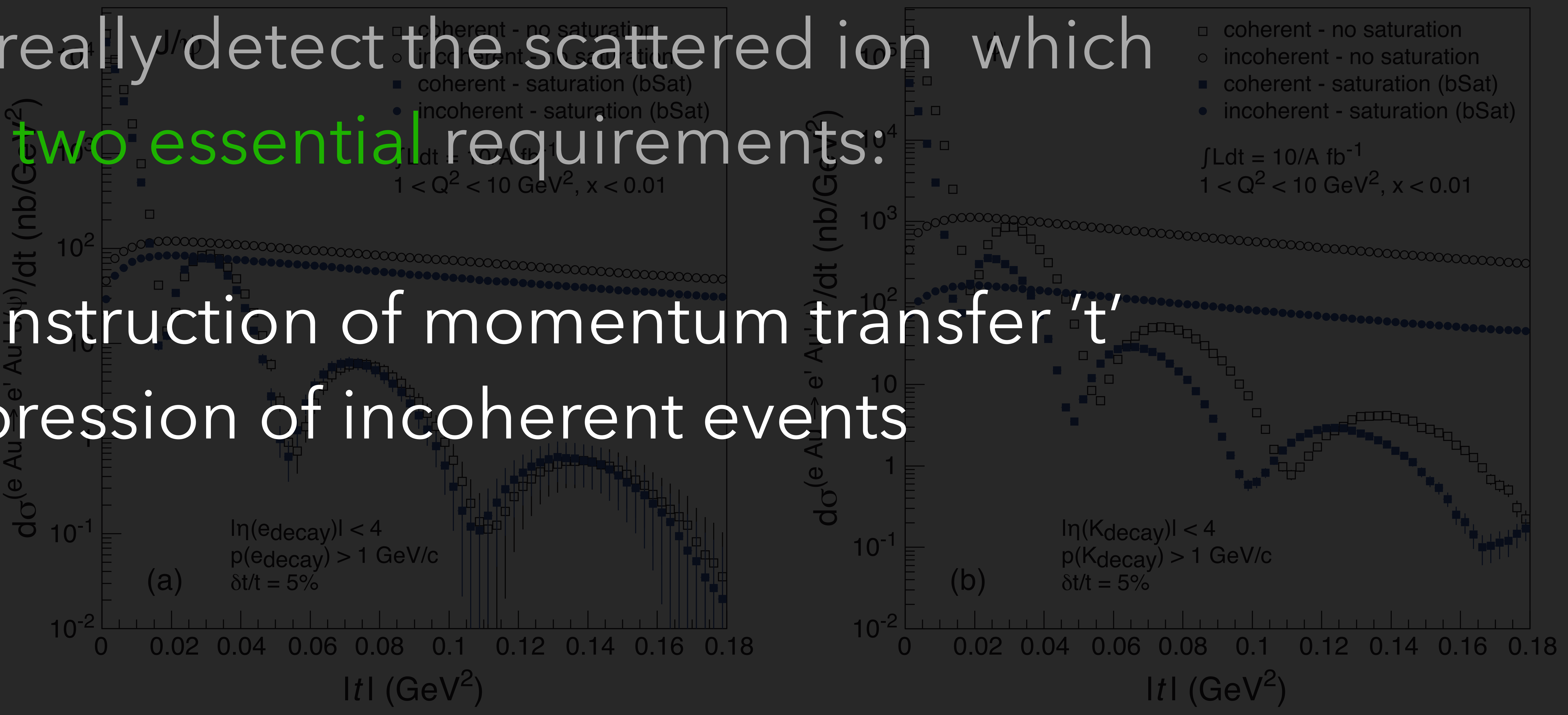
EXCLUSIVE DIFFRACTION AT EIC

Tobias Toll, Thomas Ullrich PRC 87 (2013) 024913

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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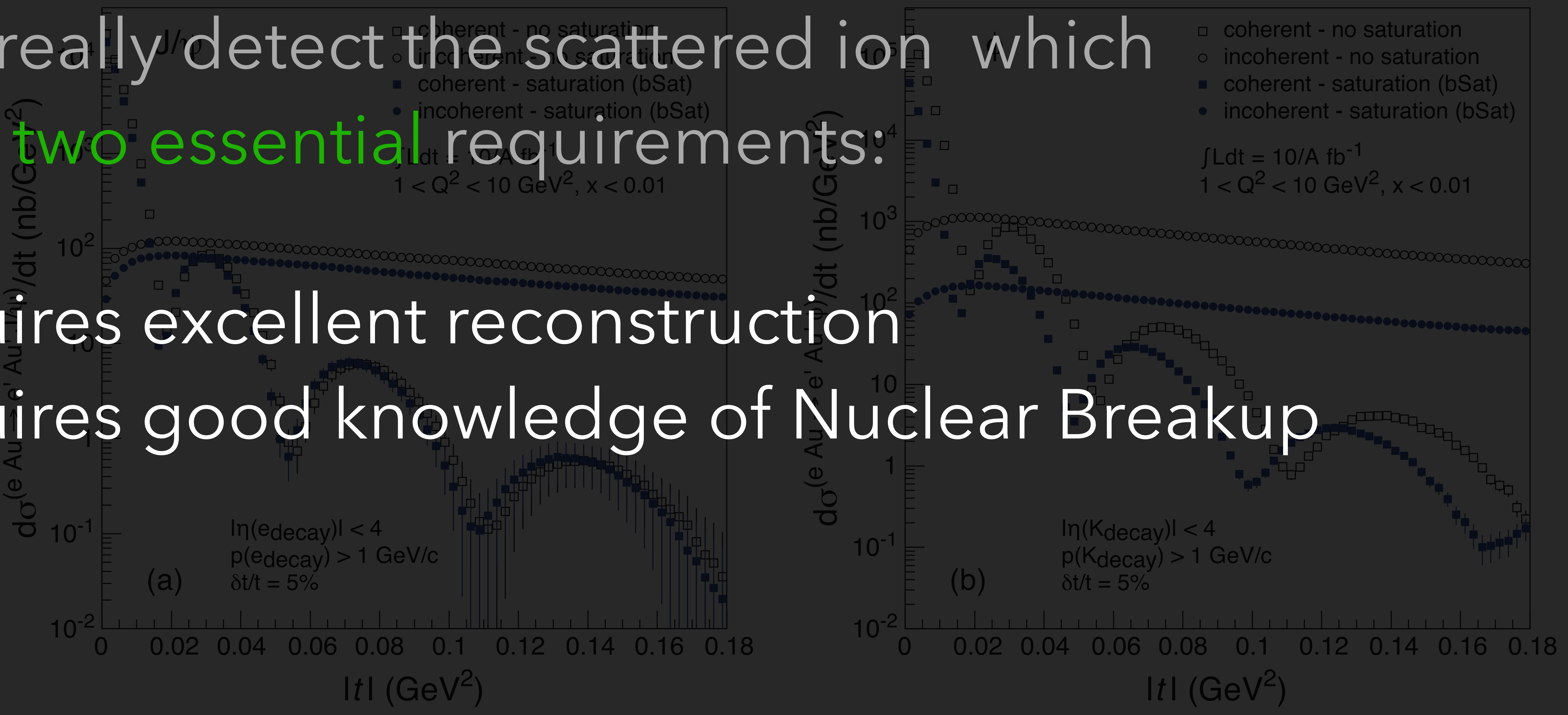
EXCLUSIVE DIFFRACTION AT EIC

Tobias Toll, Thomas Ullrich PRC 87 (2013) 024913

Why it is so difficult ?

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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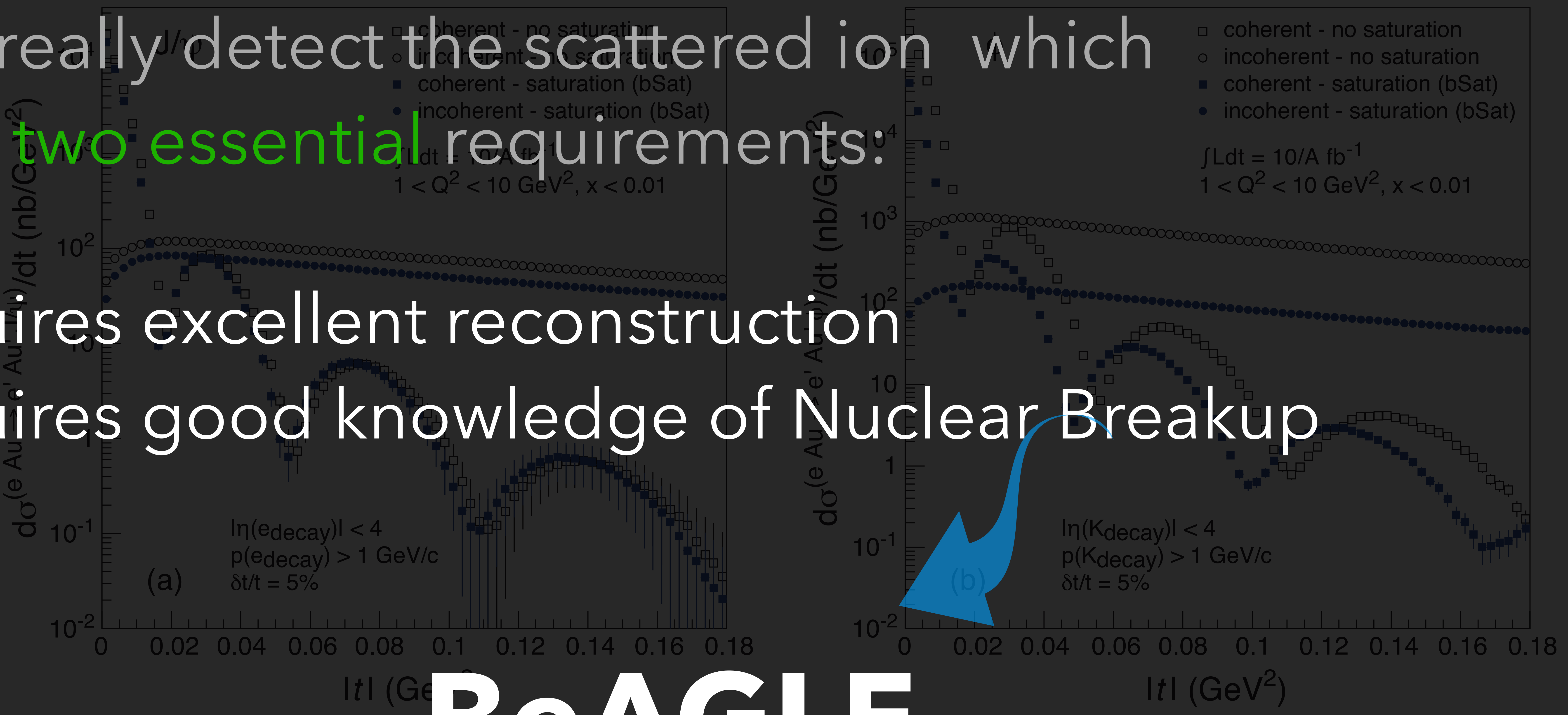
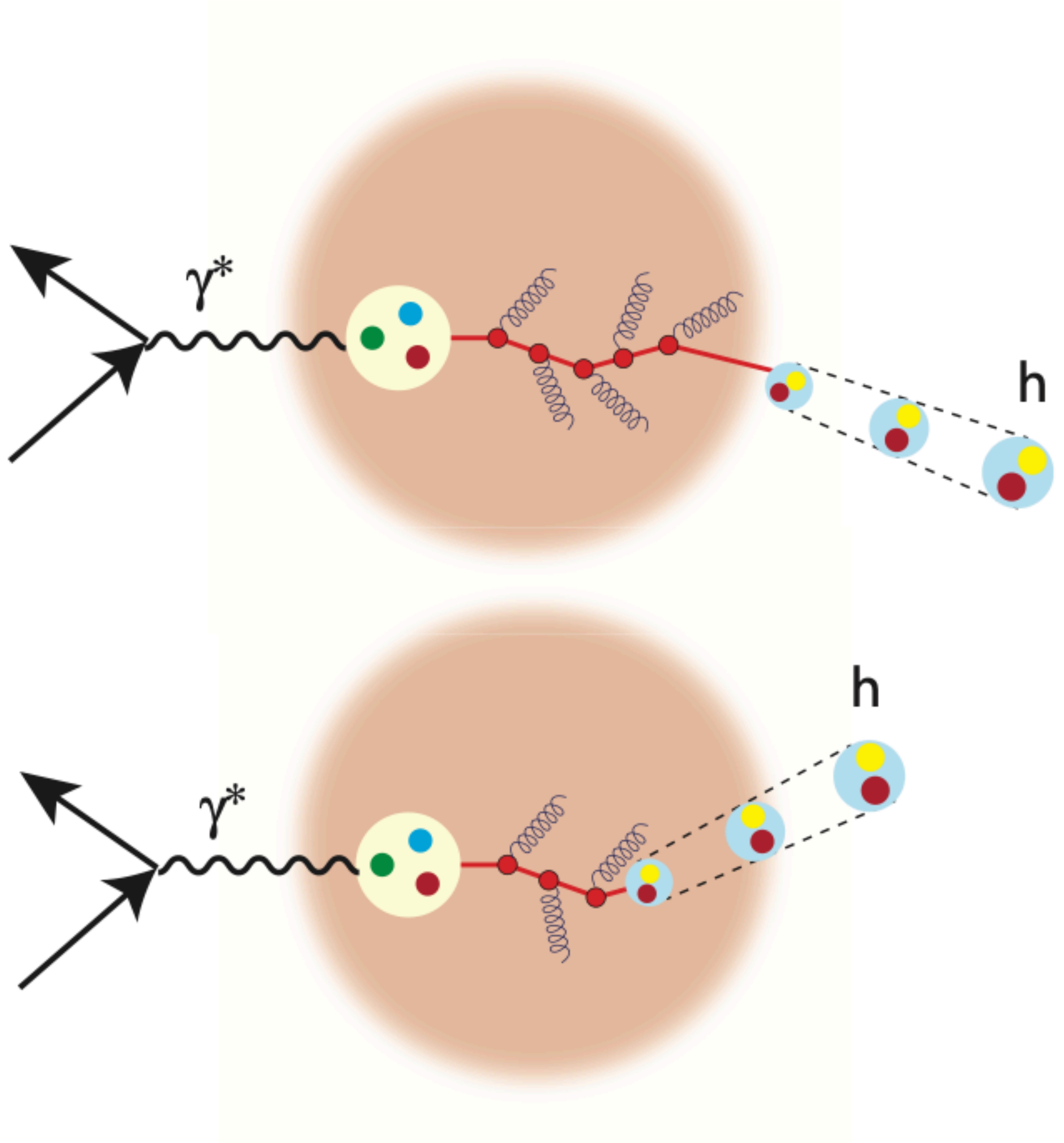


BeAGLE

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

DIS IN A NUCLEAR ENVIRONMENT



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

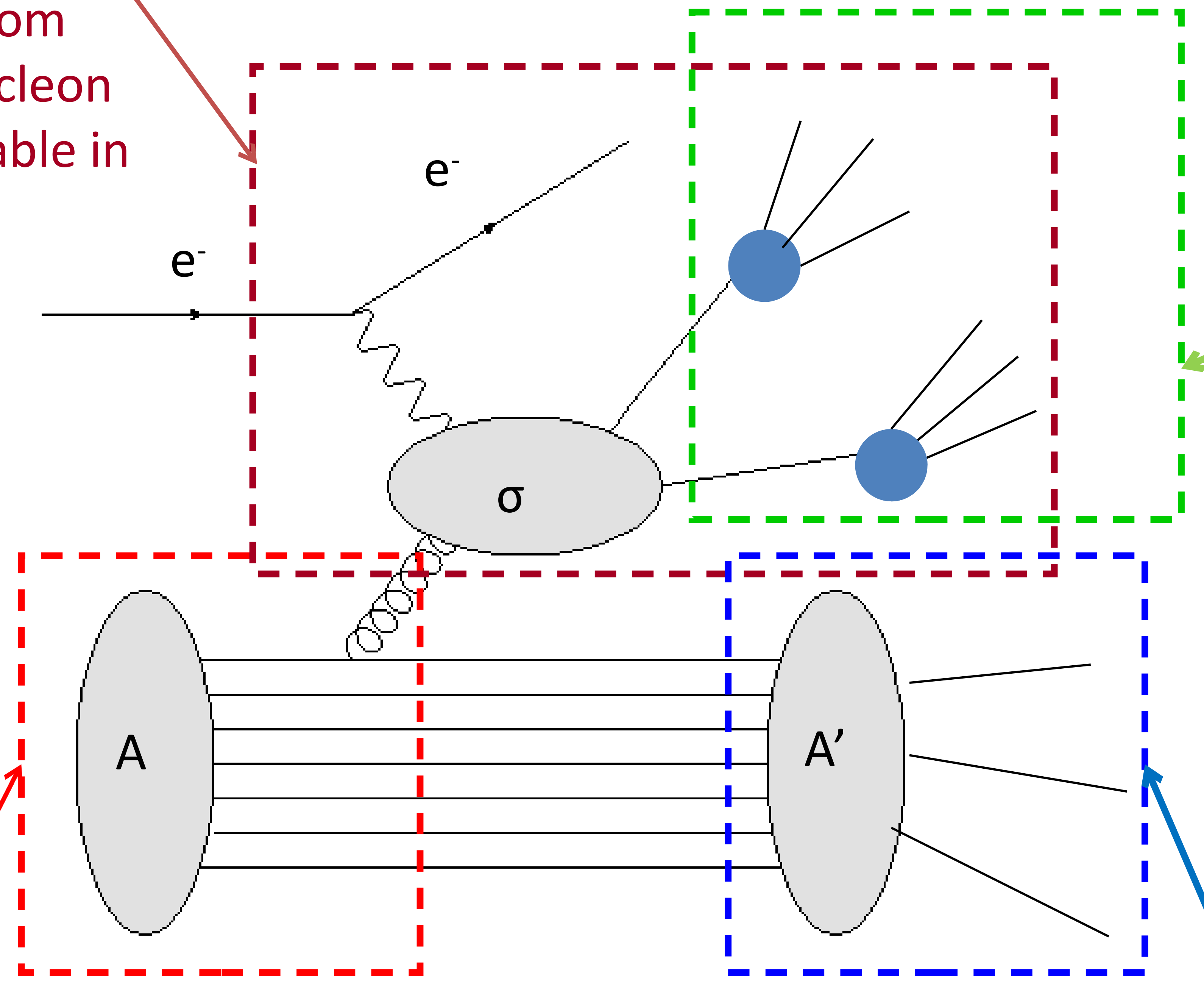
- An DIS on nucleus is very different from scattering on a nucleon and one needs to account for nuclear effects and nuclear breakup
- At present, BeAGLE : only generator capable of simulating this
- Understanding fundamental questions like hadronisation and target fragmentation

BEAGLE

W.Chang, E.C.Aschenauer, M.D.Baker, A.Jentsch, J.H Lee, Z. Tu, Z.Yin, L.Zheng PRD 106 (2022) 012007

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.



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

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

Some Nuclear Effects

	In BeAGLE
• Parton distribution functions	✓
• Parton saturation (CGC etc.)	
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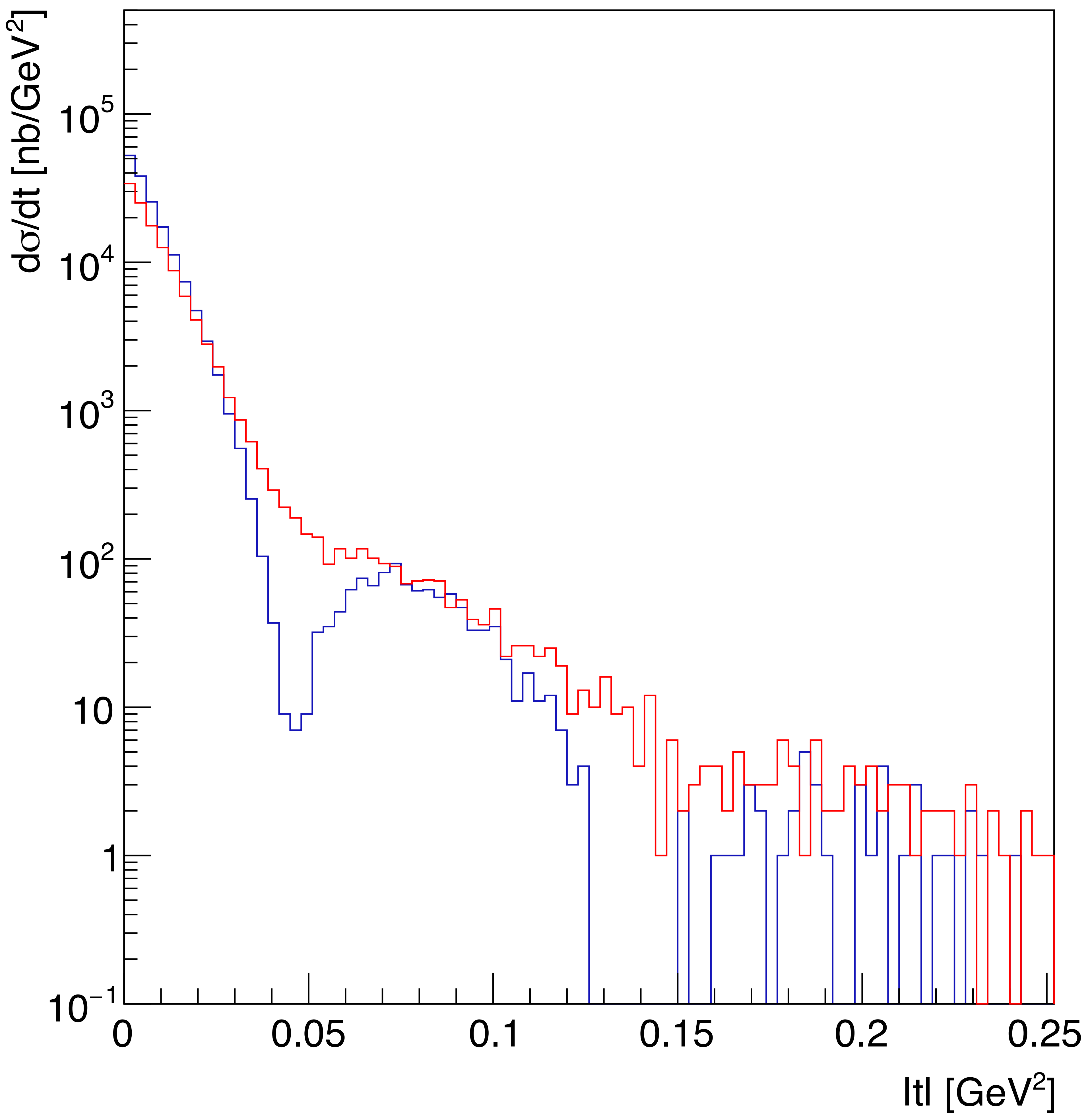
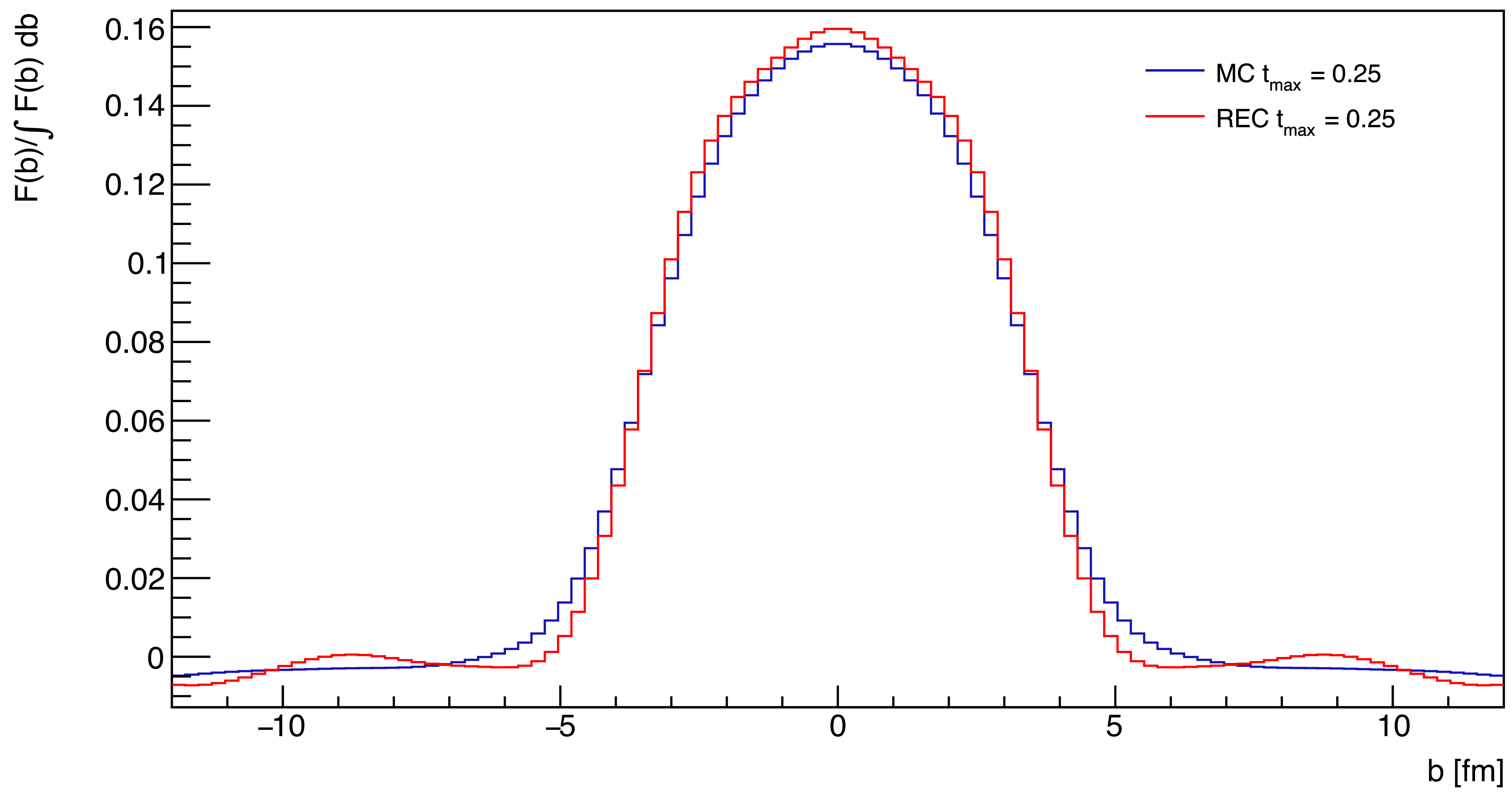
• Partonic gluon radiation	✓
• Medium-modified hadronization	
• Formation times	✓
• Hadronic Cascade	✓
• Nuclear evaporation, breakup	✓
• Photonic de-excitation of A*	✓

..from M.Diefenthaler slides at HSF Generators Meeting 2022

EXCLUSIVE DIFFRACTION AT EIC



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

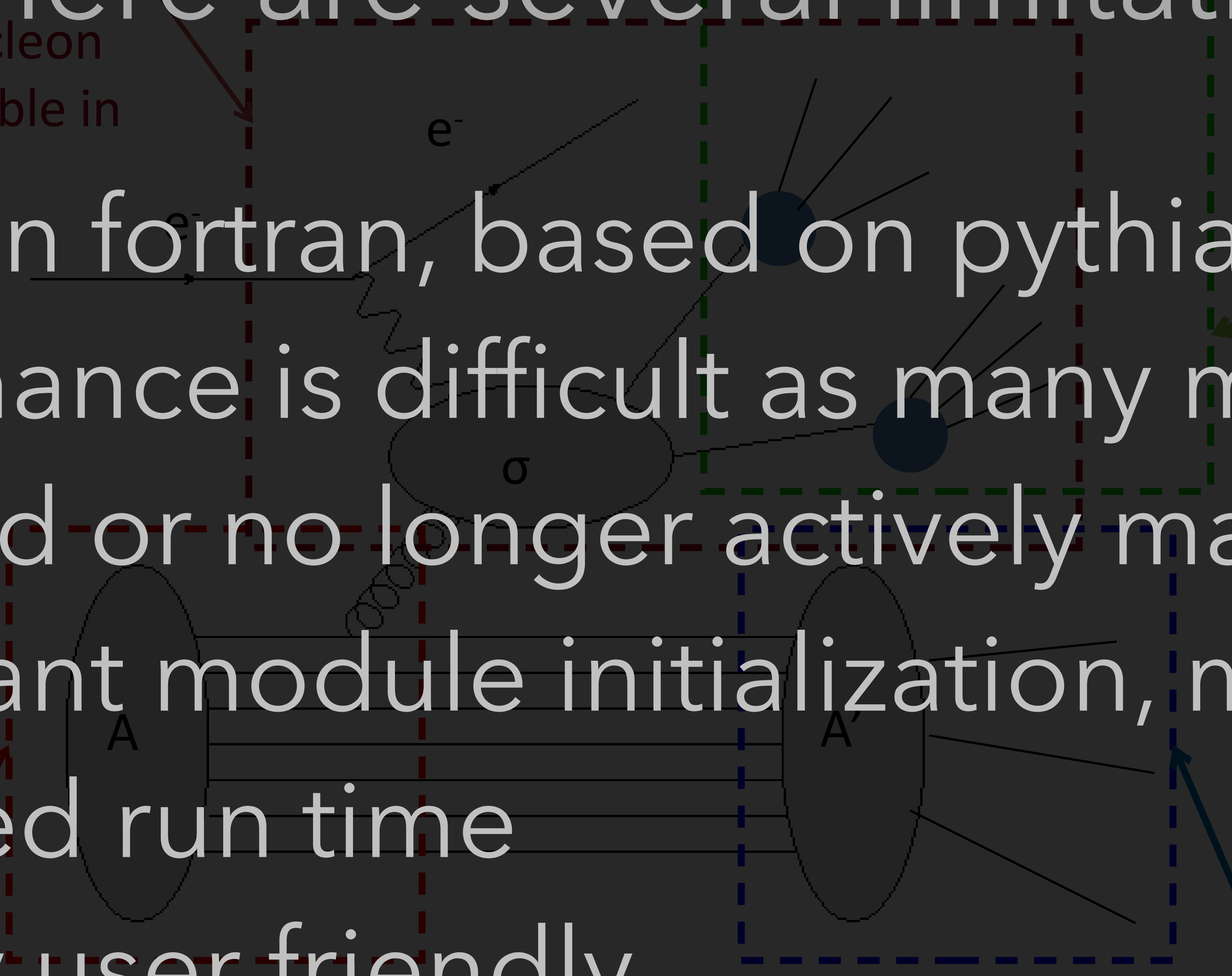


W.Chang, E.C.Aschenauer, M.D.Baker, A.Jentsch, J.H Lee, Z. Tu, Z.Yin, L.Zheng PRD 106 (2022) 012007

BeAGLE: A General purpose event generator for eA collisions

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.



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

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

Some Nuclear Effects — In BeAGLE

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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

BEAGLE

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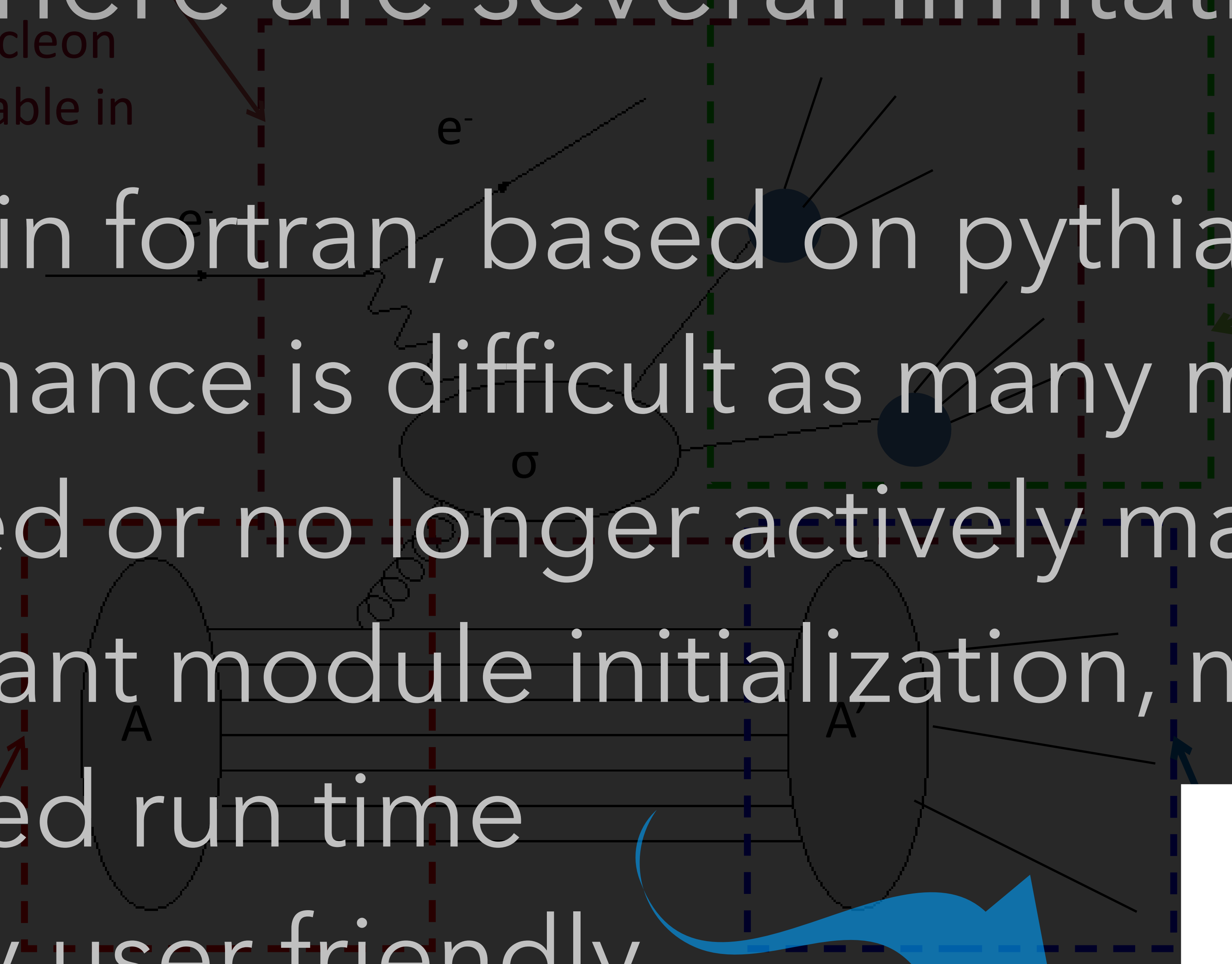

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BeAGLE++

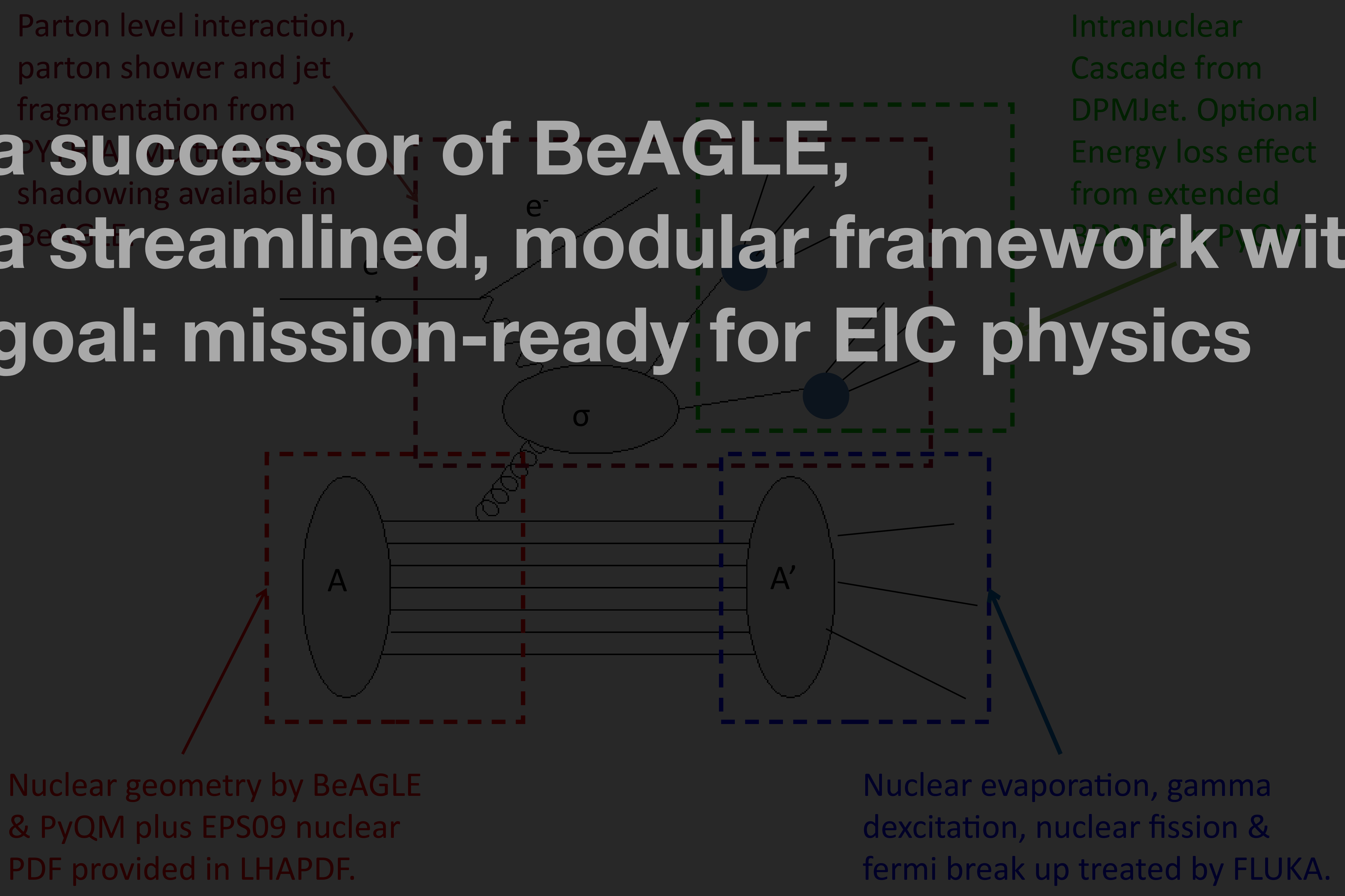
A.K, Zhoudunming Tu (Kong) ongoing work . . .

BEAGLE

W.Chang, E.C.Aschenauer, M.D.Baker, A.Jentsch, J.H Lee, Z. Tu, Z.Yin, L.Zheng PRD 106 (2022) 012007

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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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 execulatbles
|    |-- ...
|-- cmake/                  # External modules
|-- build/                  # installation folder
|-- README.md
```

BEAGLE

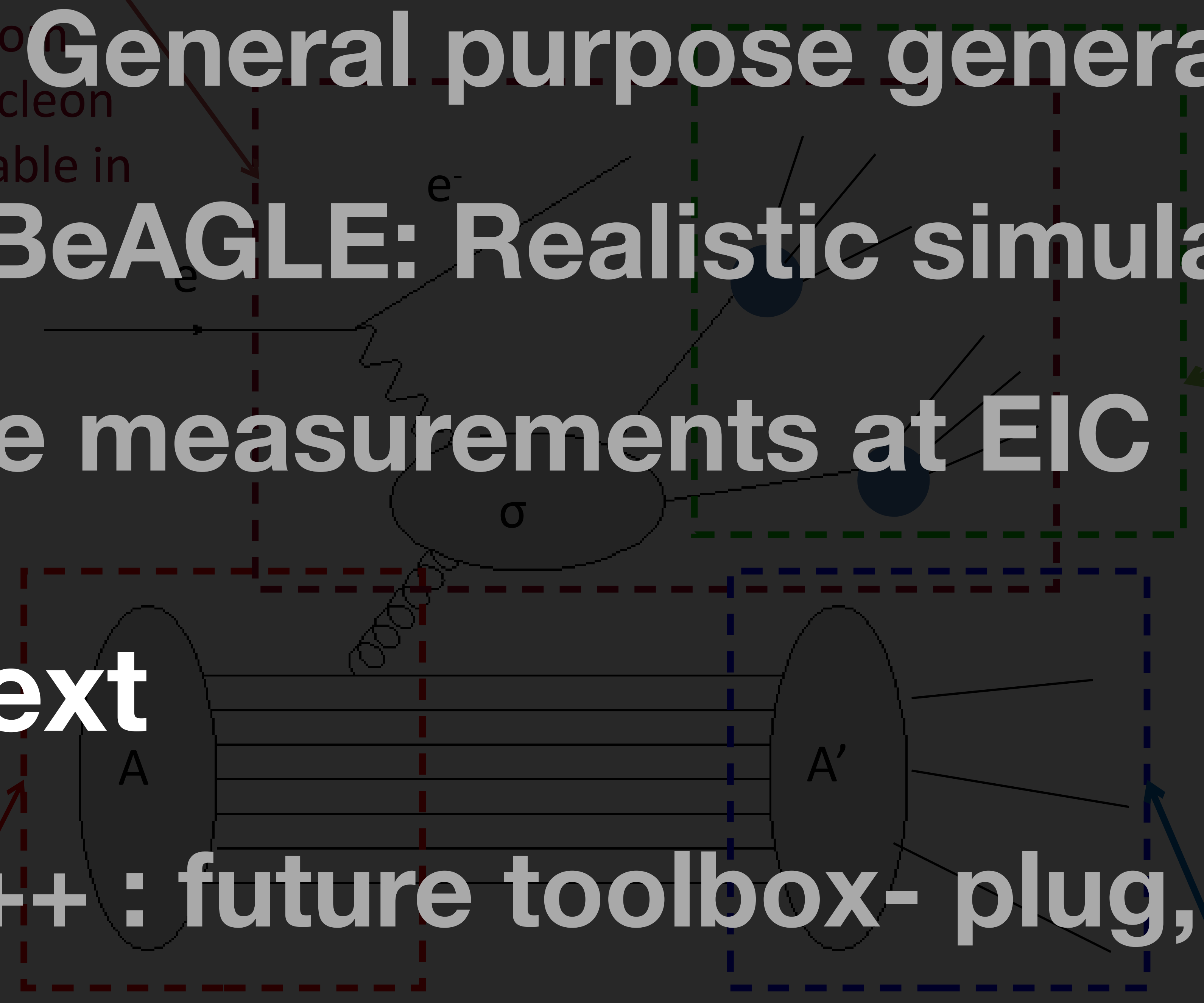
W.Chang, E.C.Aschenauer, M.D.Baker, A.Jentsch, J.H Lee, Z. Tu, Z.Yin, L.Zheng PRD 106 (2022) 012007

Summary

- Sartre: A valuable tool for coherent vector meson production
- BeAGLE: General purpose generator for eA
- Sartre + BeAGLE: Realistic simulations and feasibility 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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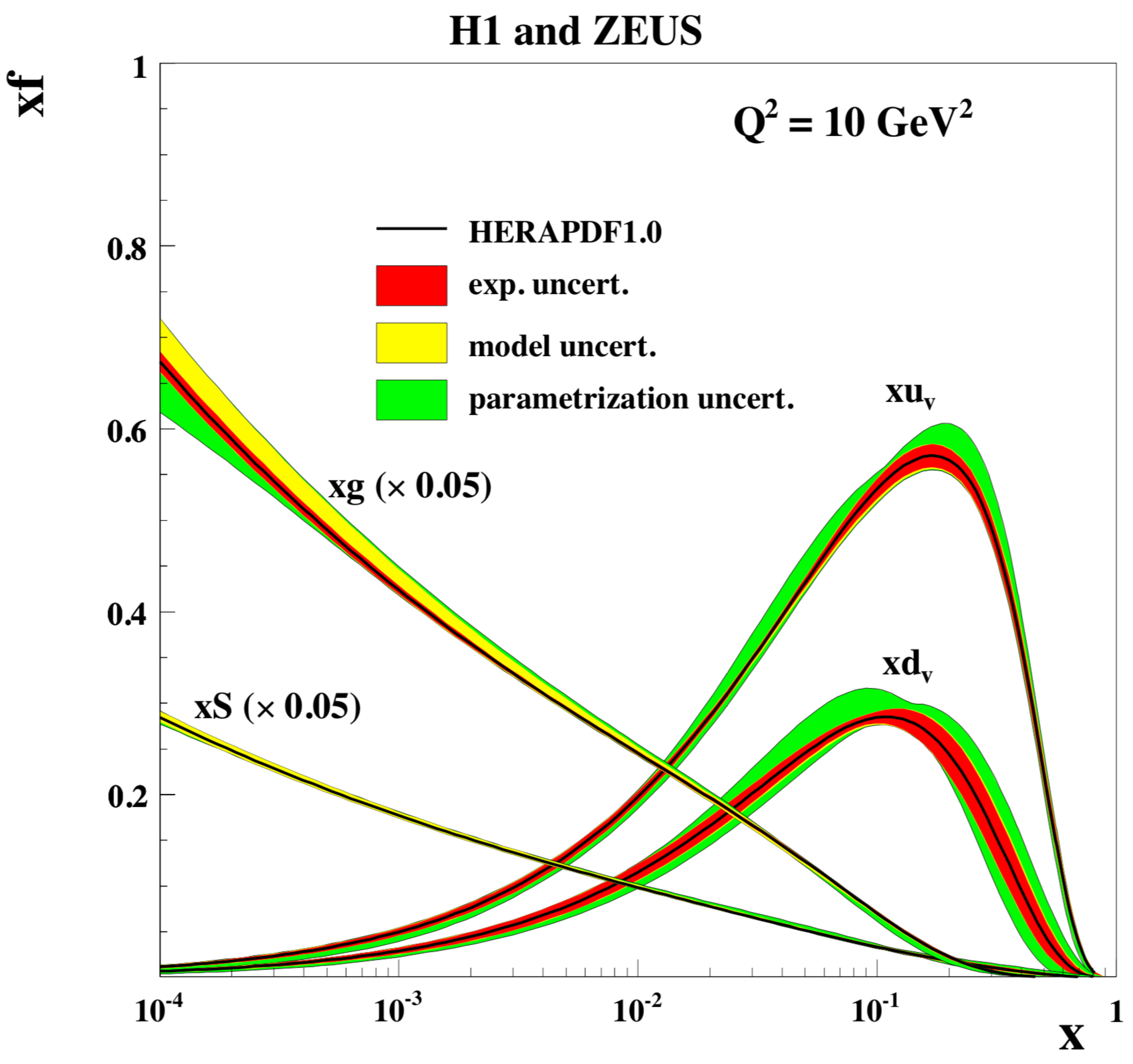
& PyQM plus EPS09 nuclear PDF provided in LHAPDF.

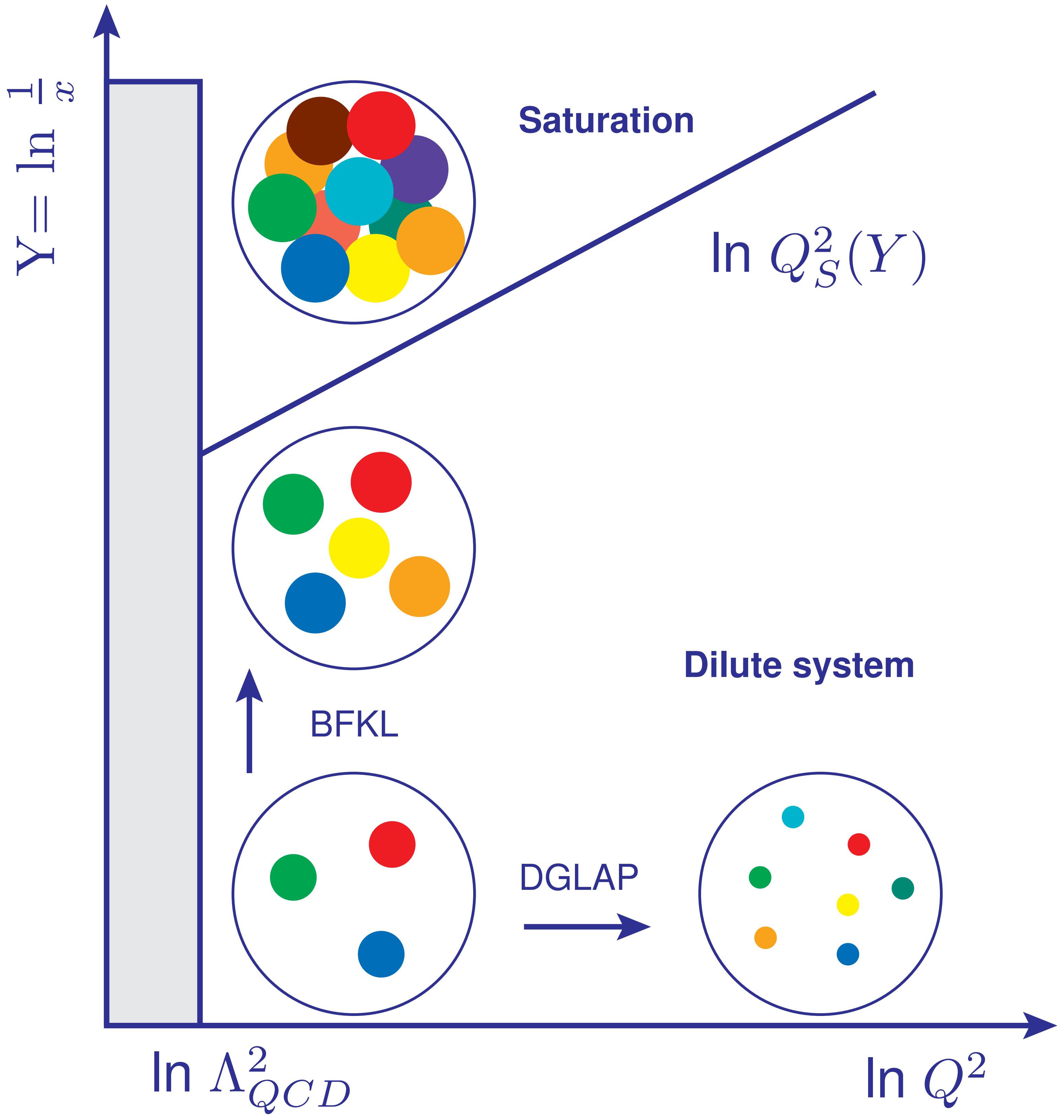
dexcitation, nuclear fission & fermi break up treated by FLUKA.

```
arjun@Arjuns-MacBook-Pro-4 build % ./beagleMain ../beagleRuncard.txt
/++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++\
|                                                                        |
|  BeAGLE++, Version 1.00                                                |
|                                                                        |
|  A General purpose event generator for EIC based on Pythia8.           |
|                                                                        |
|                                                                        |
|  Authors: Arjun Kumar and Zhoudunming Tu                               |
|                                                                        |
|                                                                        |
|  Code compiled on Jul  7 2025 21:57:46                                 |
|  Run started at Mon Jul  7 22:02:15 2025                               |
|                                                                        |
\++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++/


Runcard is ../beagleRuncard.txt


Initializing BeAGLE++  . . . . . . . .


Run Settings:
-----------------------------------------------------------------------

                 eBeamEnergy    18
                 hBeamEnergy    110
                           A    197
                       Q2min    1
                       Q2max    10
                        Wmin    50
                        Wmax    100
                    rootfile    test.root
                   ProcessId    1
              numberOfEvents    1000000

-----------------------------------------------------------------------

Selected nucleon is 52th nucleon
```

BACKUP

DIS AT HERA AND QCD PHASE SPACE





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

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

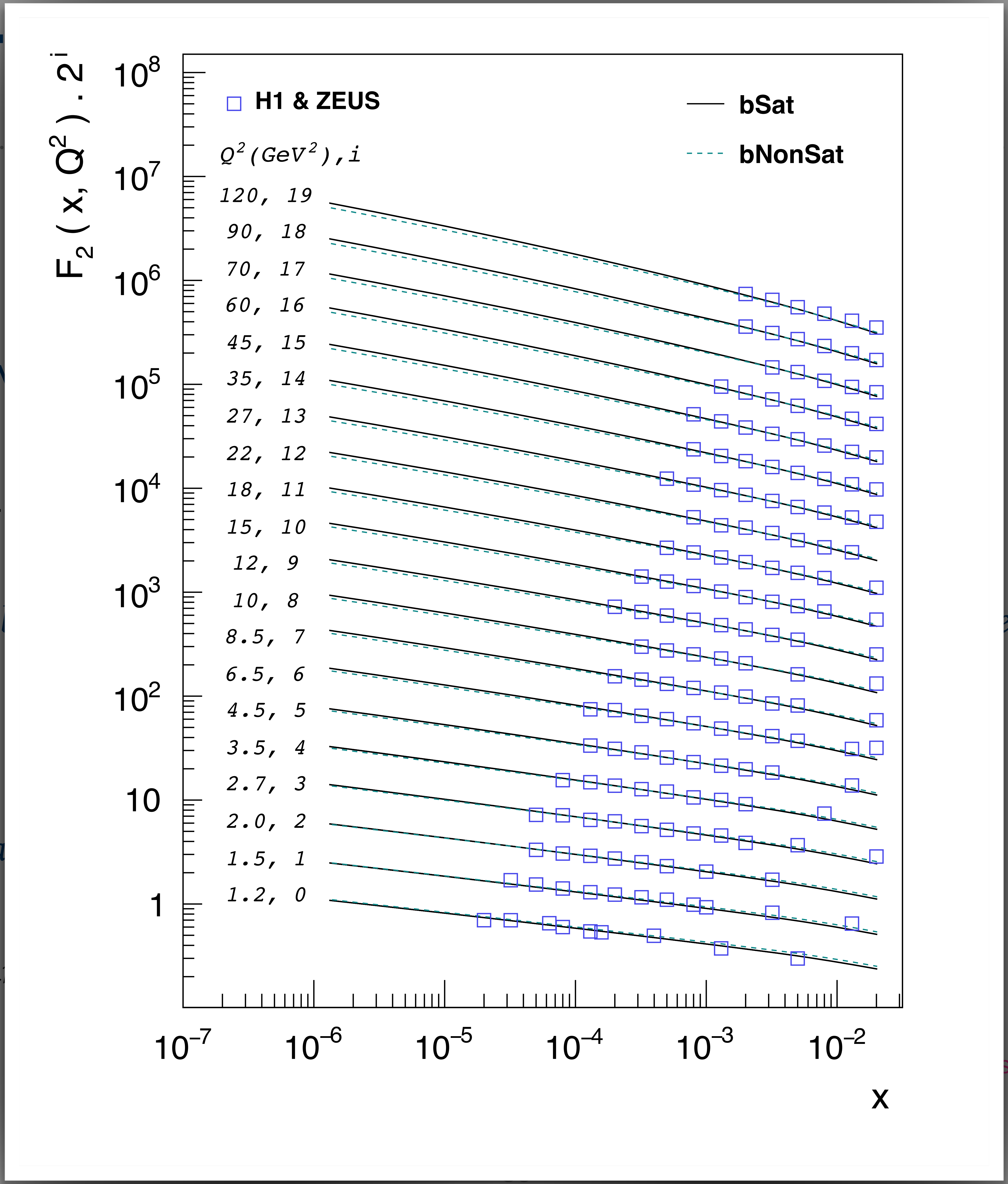
THE DIPOLE-TARGET

- 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 … ence obtained from DGLAP evolution)



Two models for the spatial proton

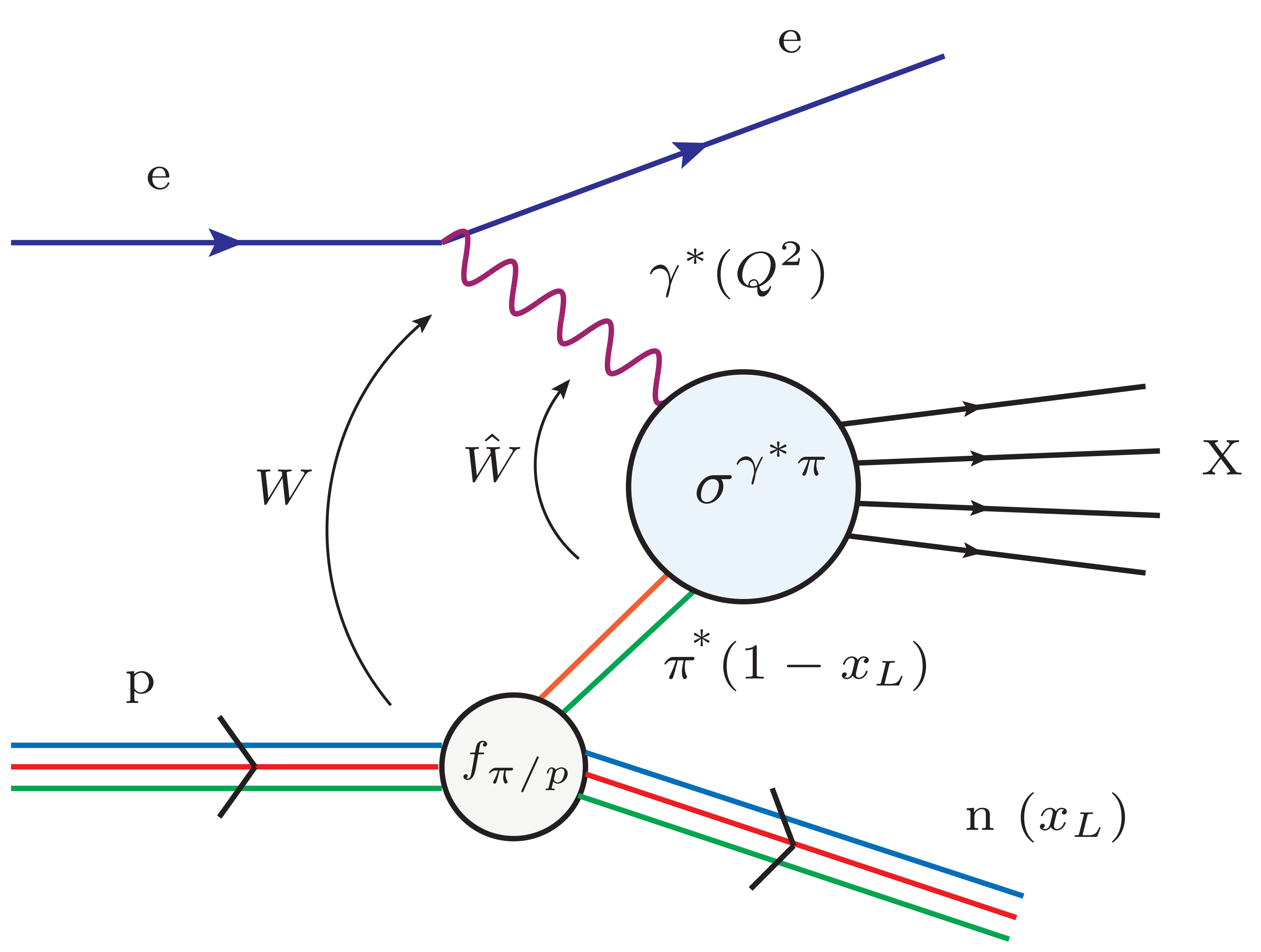
a) Smooth proton (assume gaussia

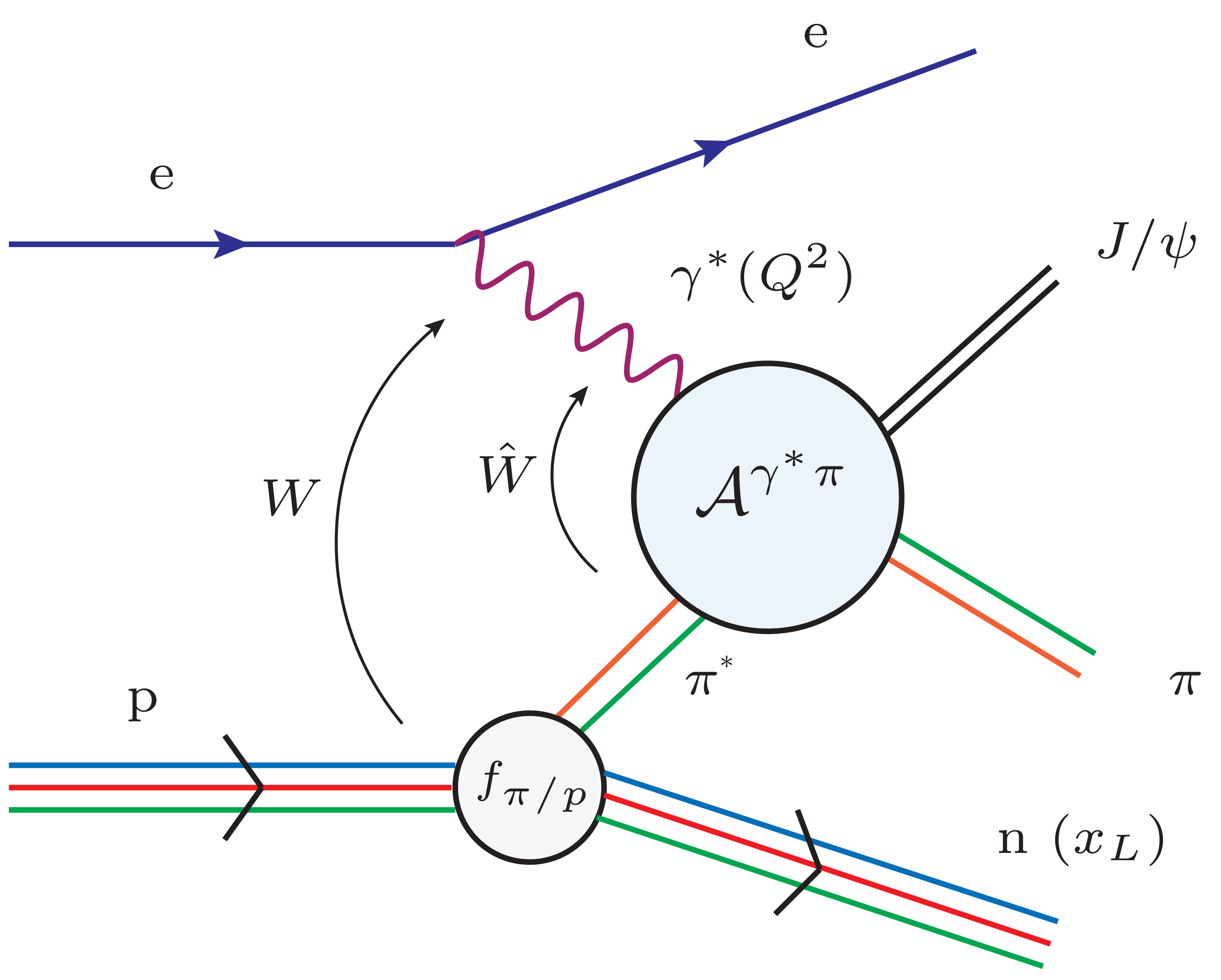
Kowalski, Motyka,Watt 2006

b) Lumpy proton (assume gaussia … and $T_q(\mathbf{b}) = \dfrac{1}{2\pi B_q}\exp\Big[-\dfrac{\mathbf{b}^2}{2B_q}\Big]$

saari, Schenke PRL 117 (2016) 052301

PION STRUCTURE IN LEADING NEUTRON EVENTS





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

★ *Measure only scattered electrons and neutron*

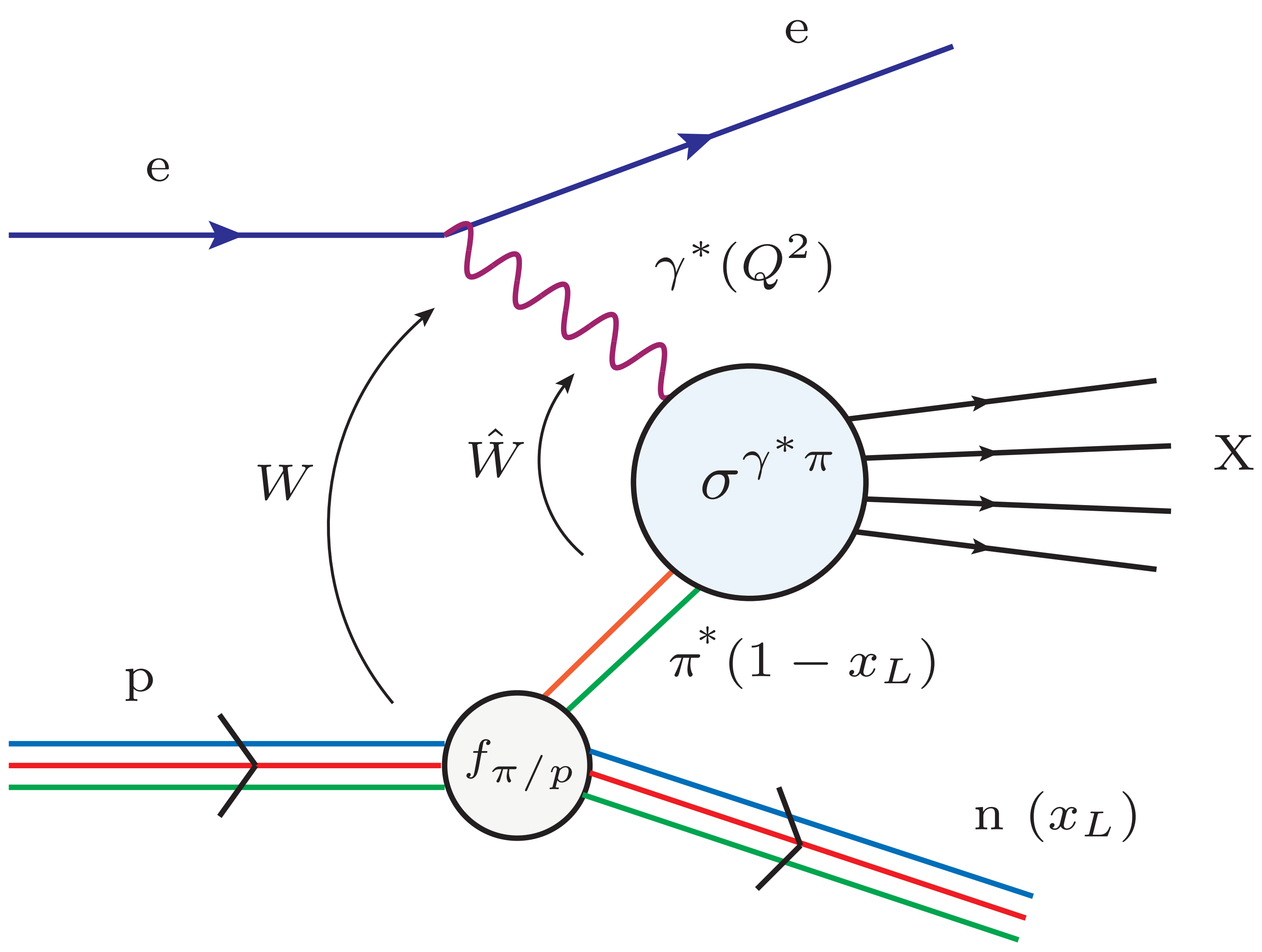
★ *Sensitive to longitudinal structure of pion*

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,

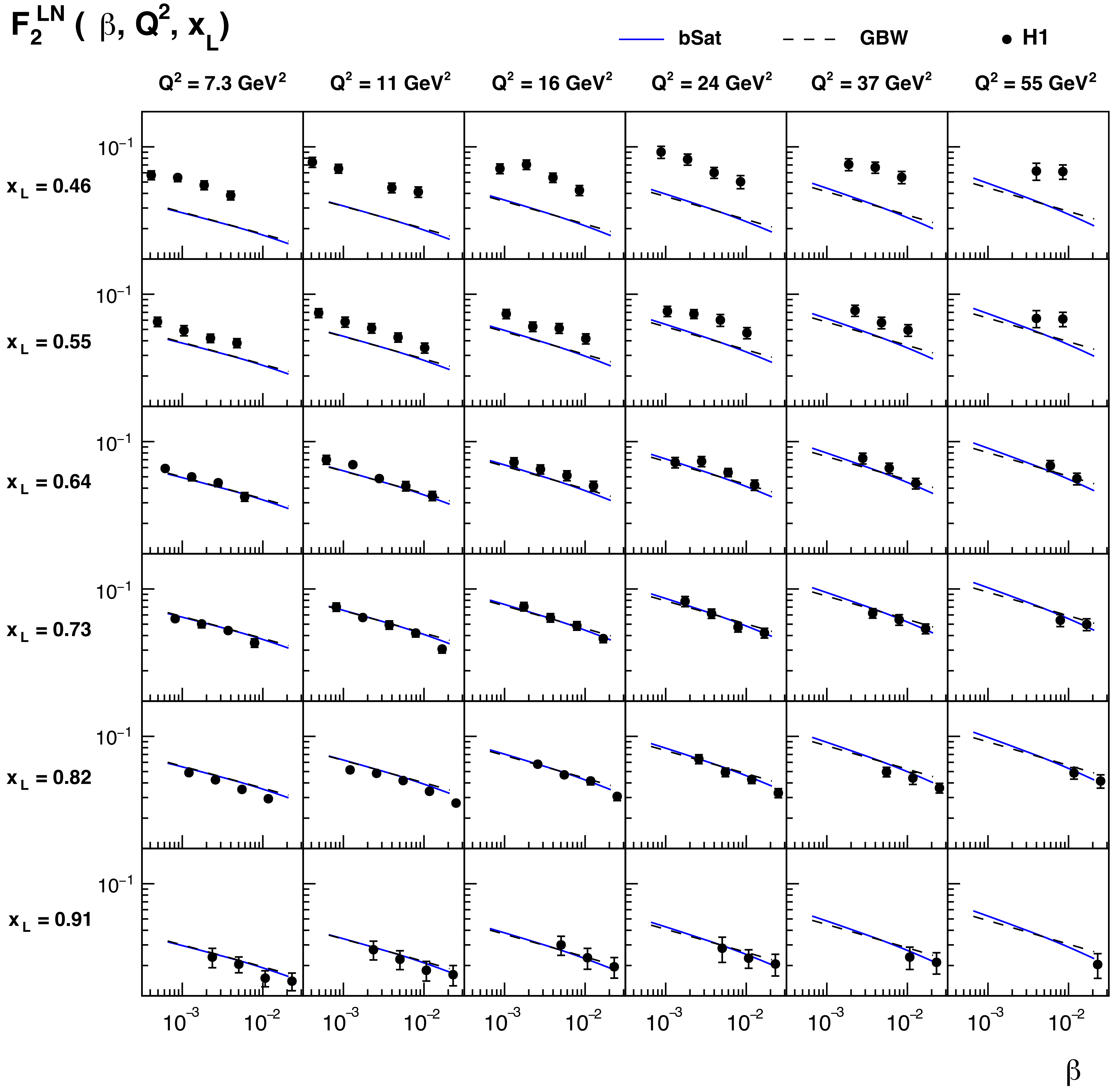
$\sigma^{\gamma^*\pi^*}(\hat{W}^2,Q^2)$ is virtual photon-virtual pion cross section

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

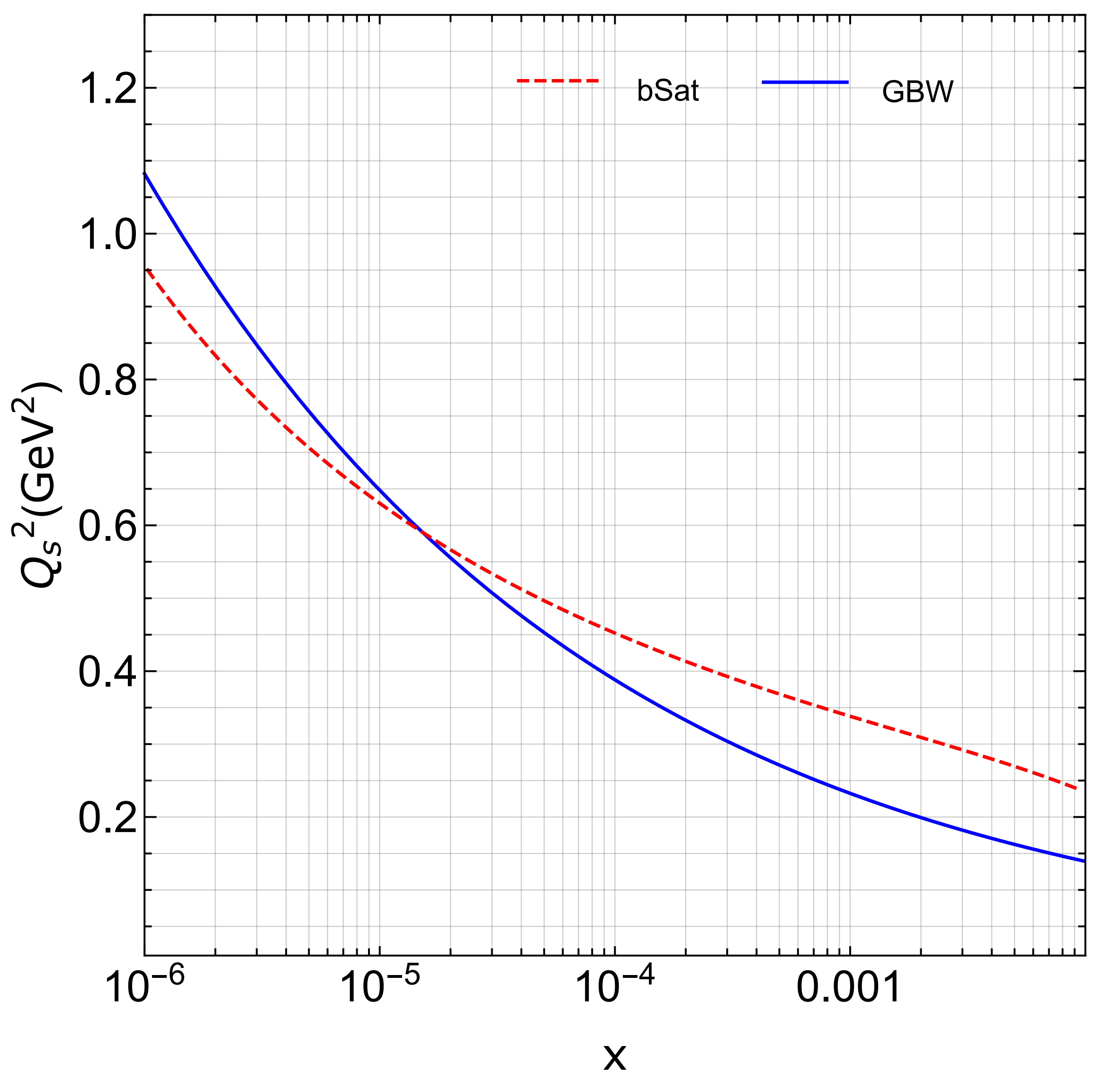
$$F_2^{LN}(W,Q^2,x_L) = \Gamma(x_L,Q^2)\ F_2^\pi(W,Q^2,x_L)$$

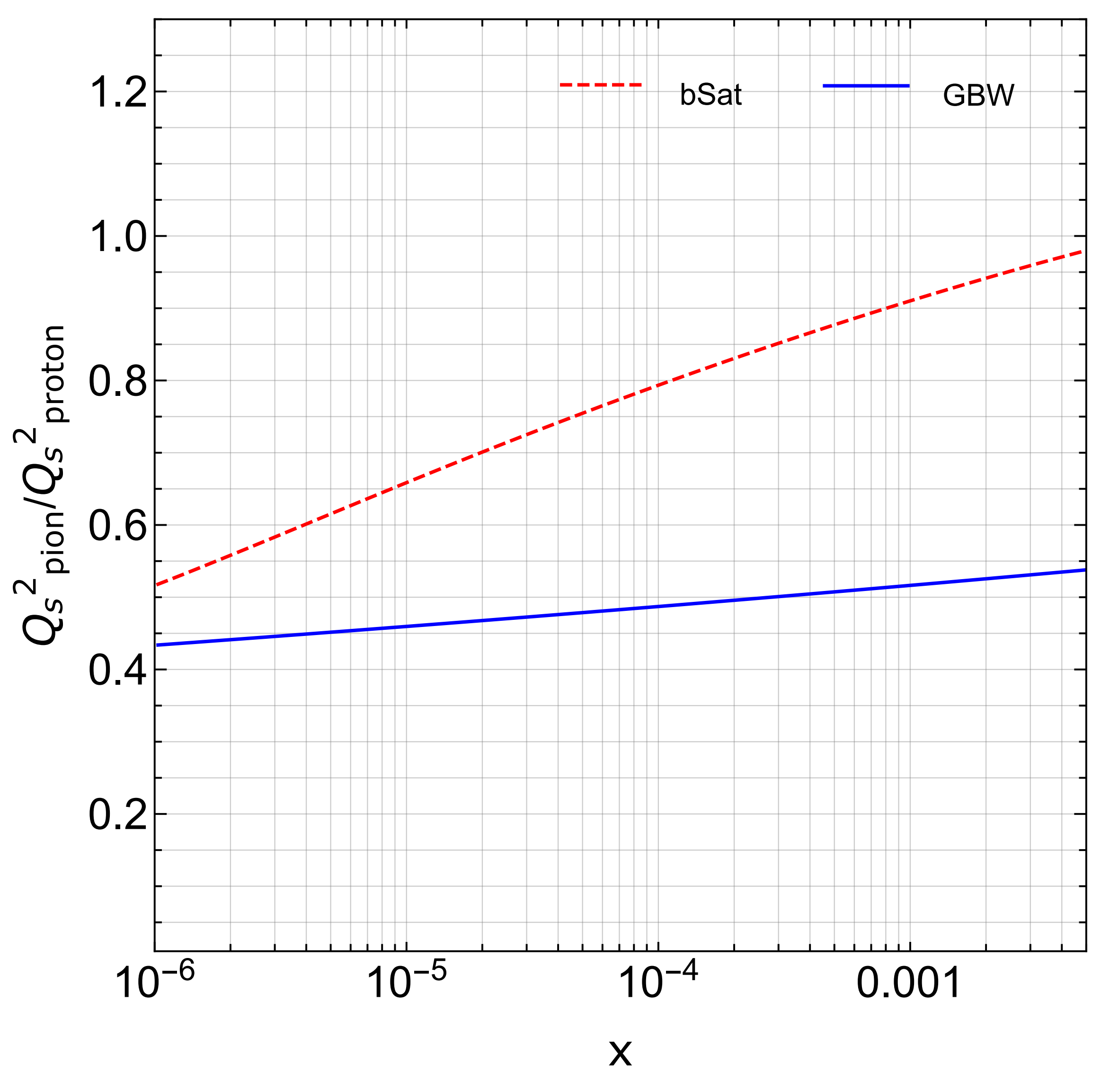
$\Gamma(x_L,Q^2)$ is t-integrated flux of pions from proton

LEADING NEUTRON STRUCTURE FUNCTION



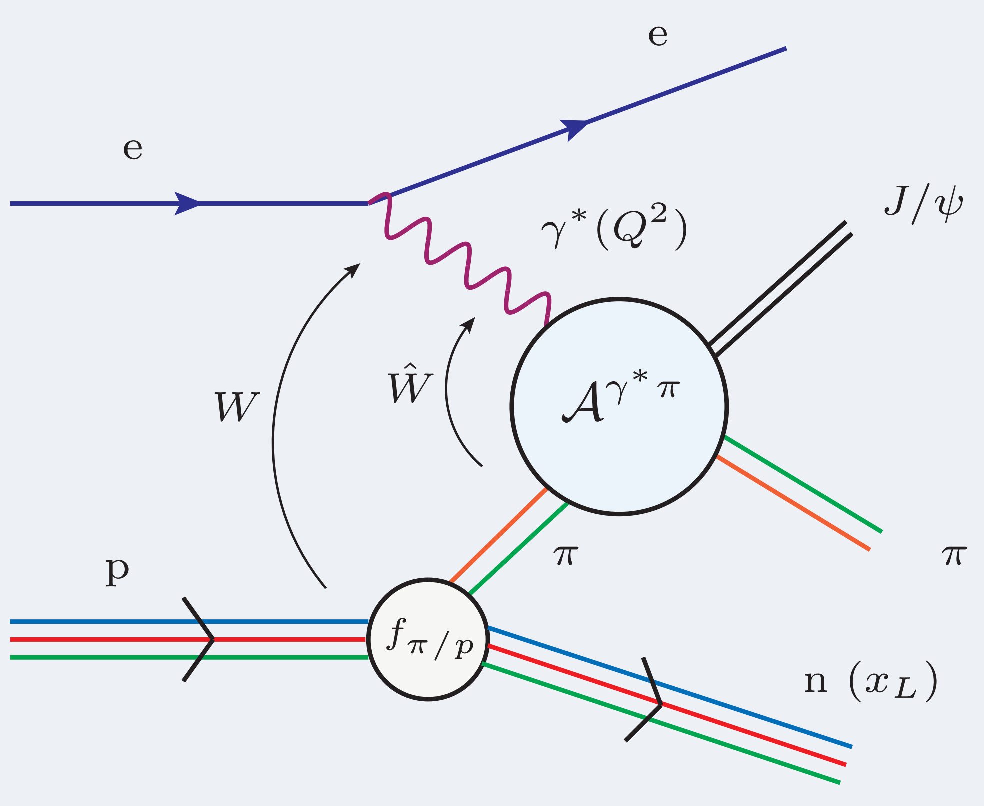
A.K PRD 107 (2023) 034005

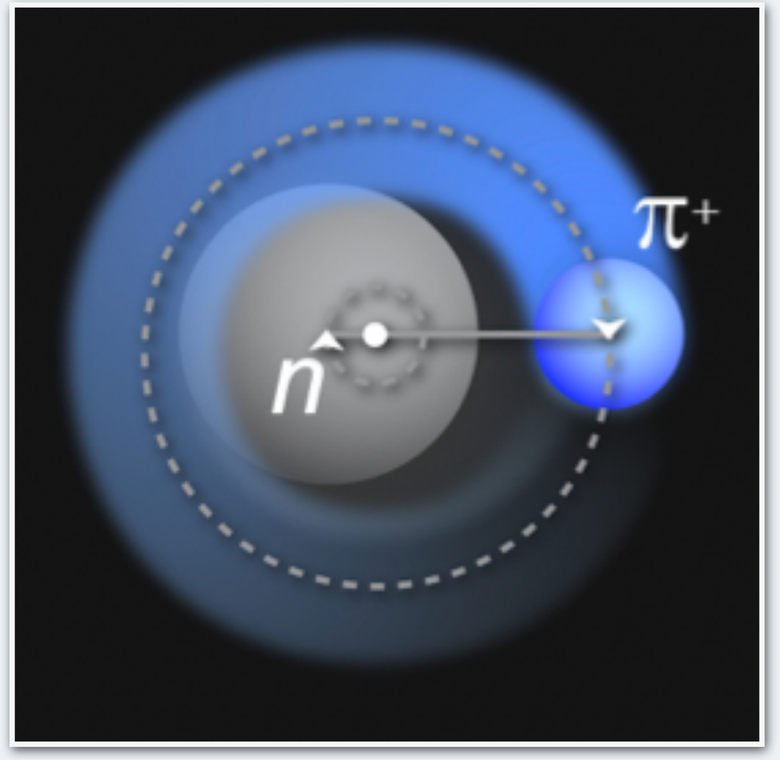




GBW	σ_0 [mb]	λ	$x_0/10^{-4}$	R_q	χ^2/N_{dof}
Fit 1	17.171 ± 2.777	0.223 ± 0.018	0.036 ± 0.024	...	$63.26/48 = 1.32$
Fit 2	27.43	0.248	0.40	0.438 ± 0.005	$64.52/50 = 1.29$
bSat	A_g	λ_g	C	R_q	χ^2/N_{dof}
Fit 3	1.208 ± 0.012	0.0600 ± 0.038	1.453 ± 0.024	...	$58.75/48 = 1.22$
Fit 4	2.195	0.0829	2.289	0.520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

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:

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

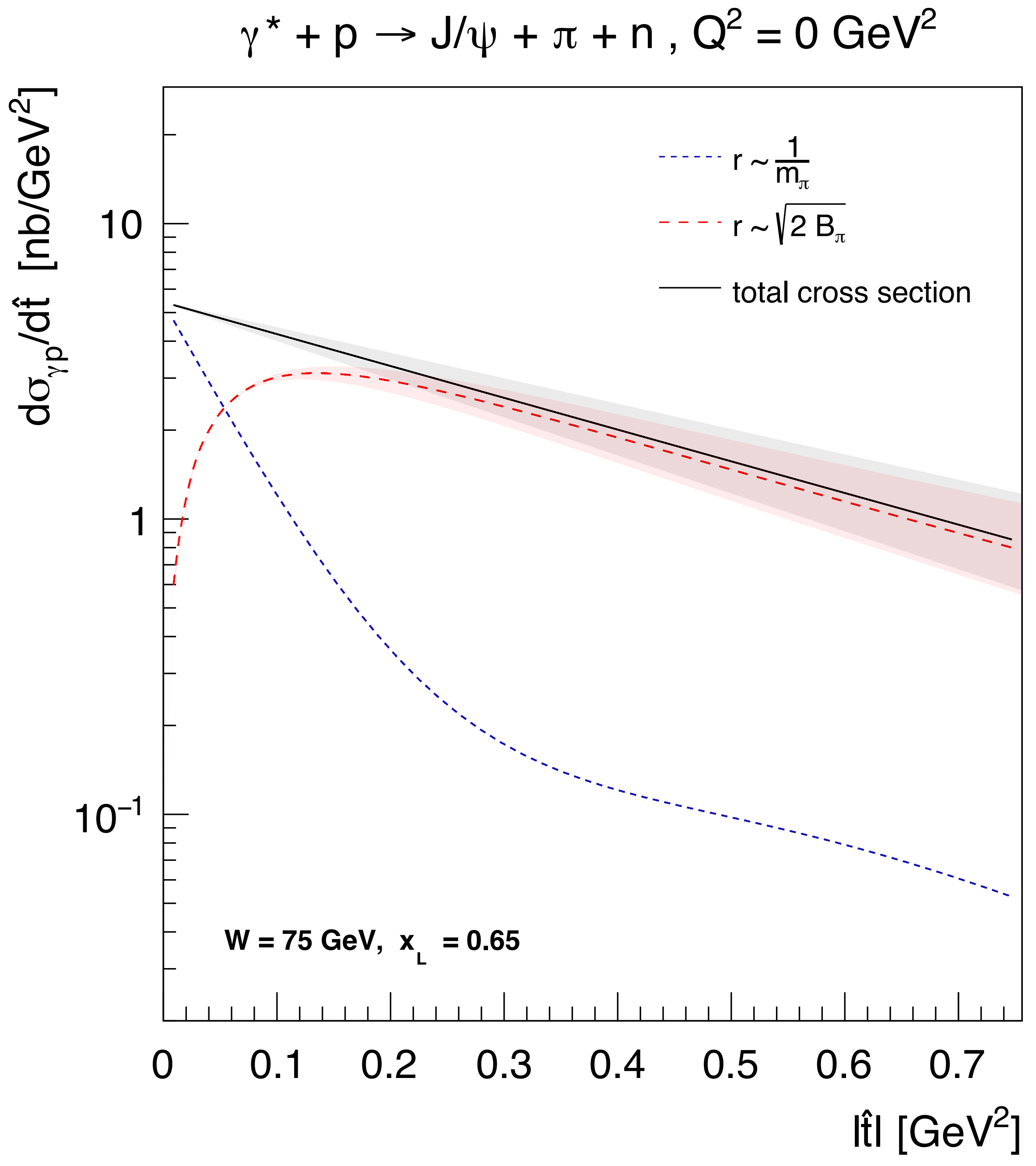
- We assume that the real pion, as for the proton, is described by a Gaussian profile:

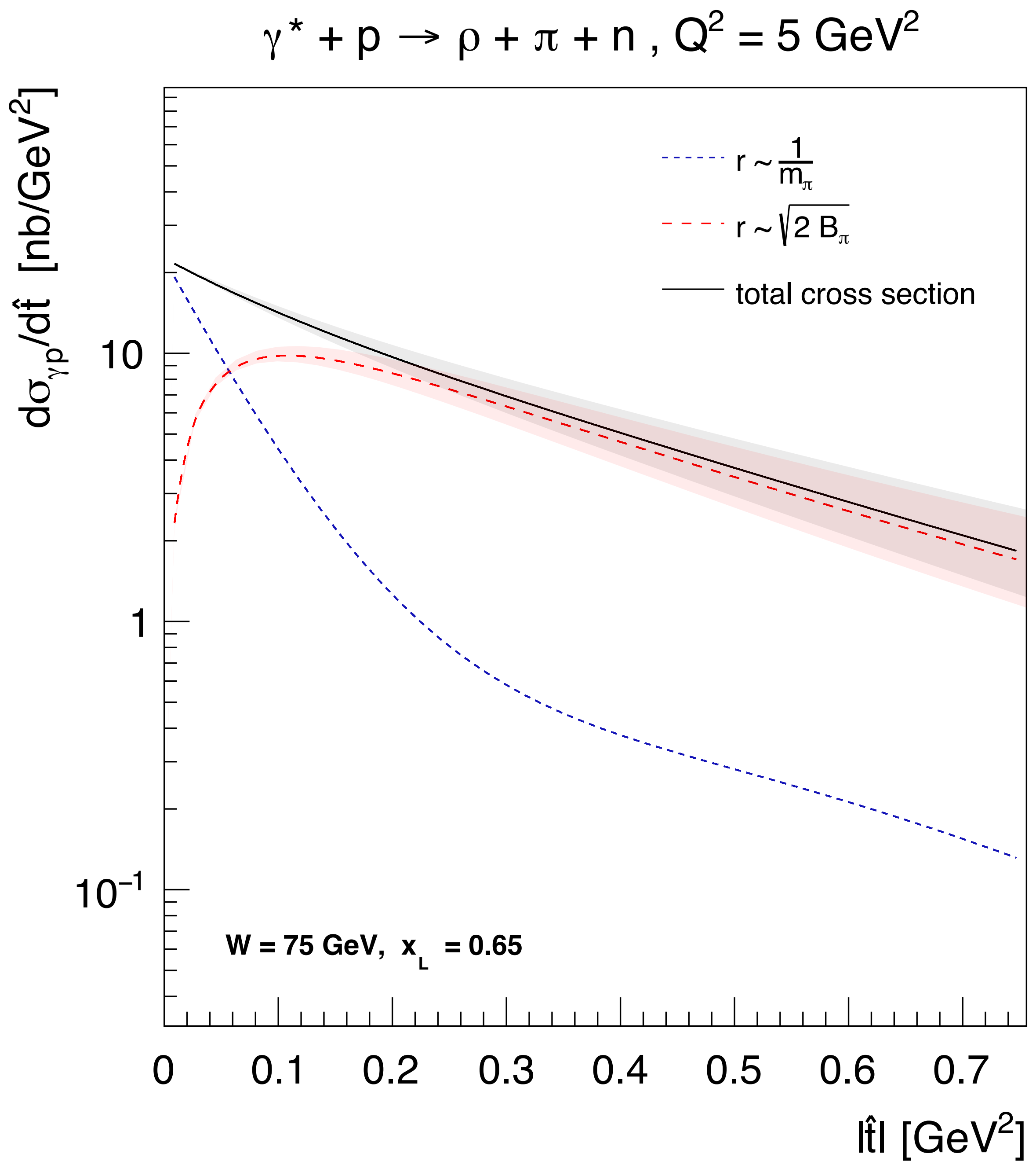
$$T_\pi(b) = \frac{1}{2\pi B_\pi} e^{-\frac{-b^2}{2B_\pi}}$$

- 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

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





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