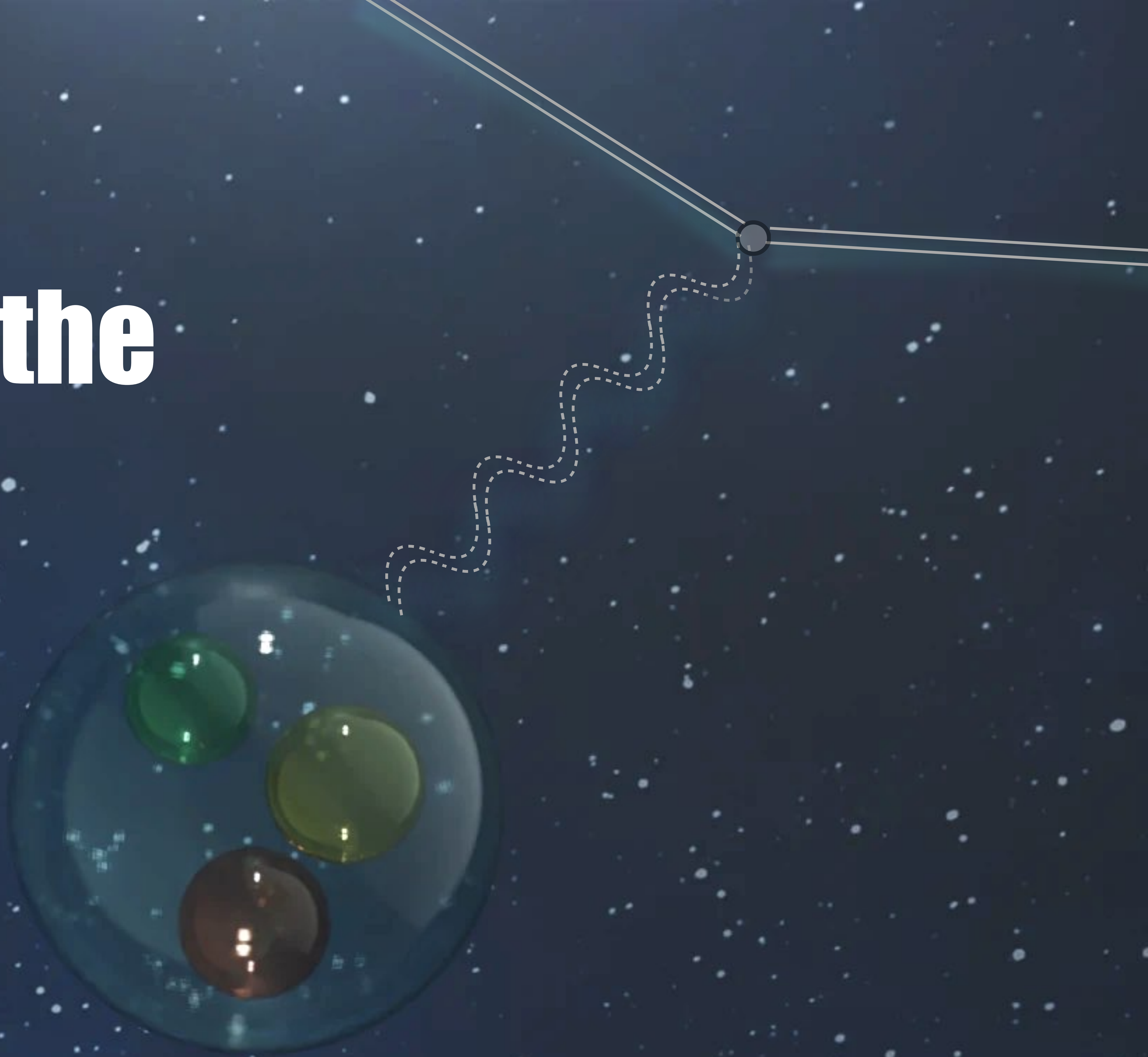
Evolution of the initial state in the hotspot model of the proton structure



ARJUN KUMAR

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DEPARTMENT OF SCIENCE & TECHNOLOGY

2023 HARD PROBES Aschaffenburg

MOTIVATION

Initial geometry in the transverse plane : crucial to study small system collisions

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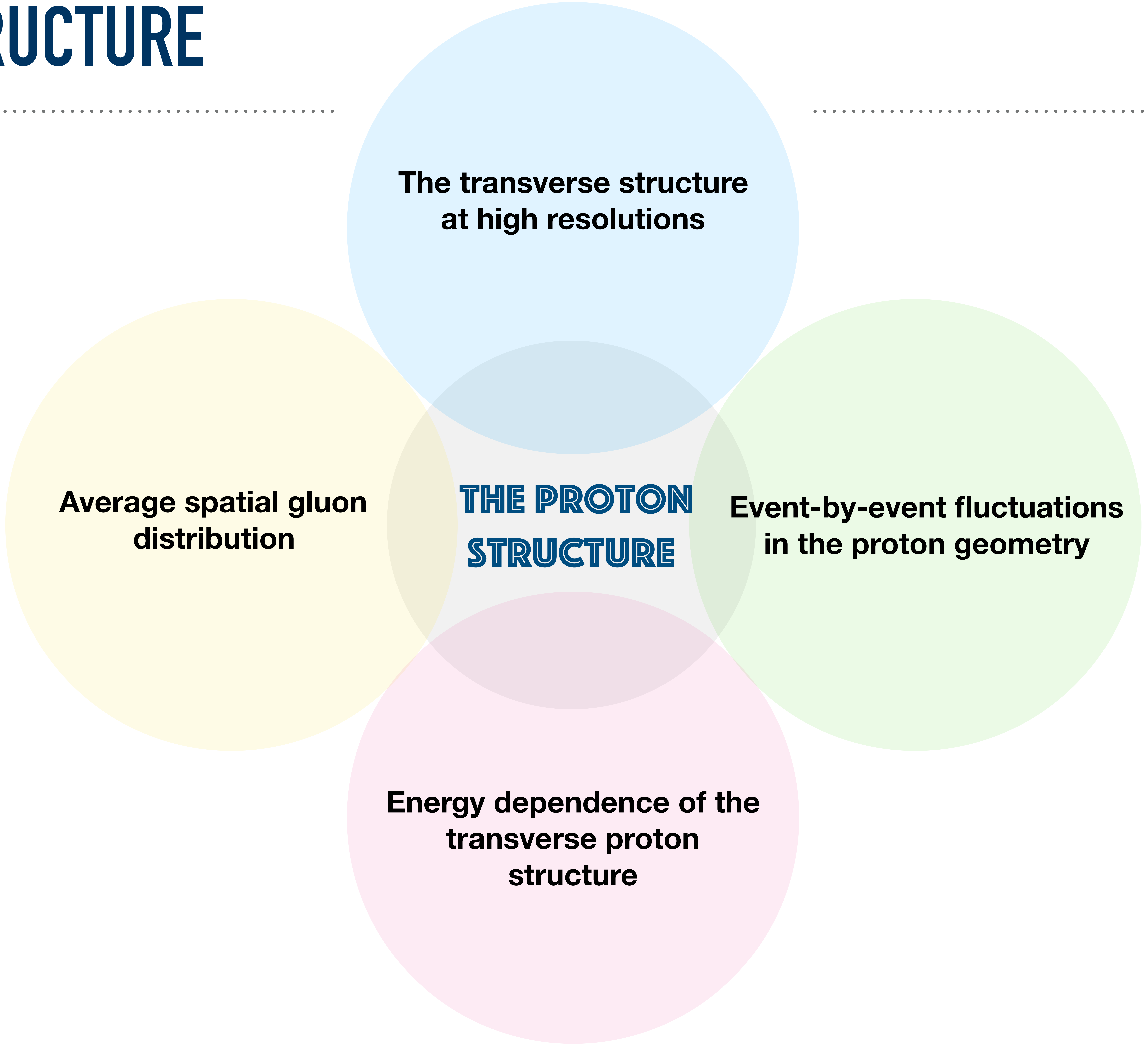
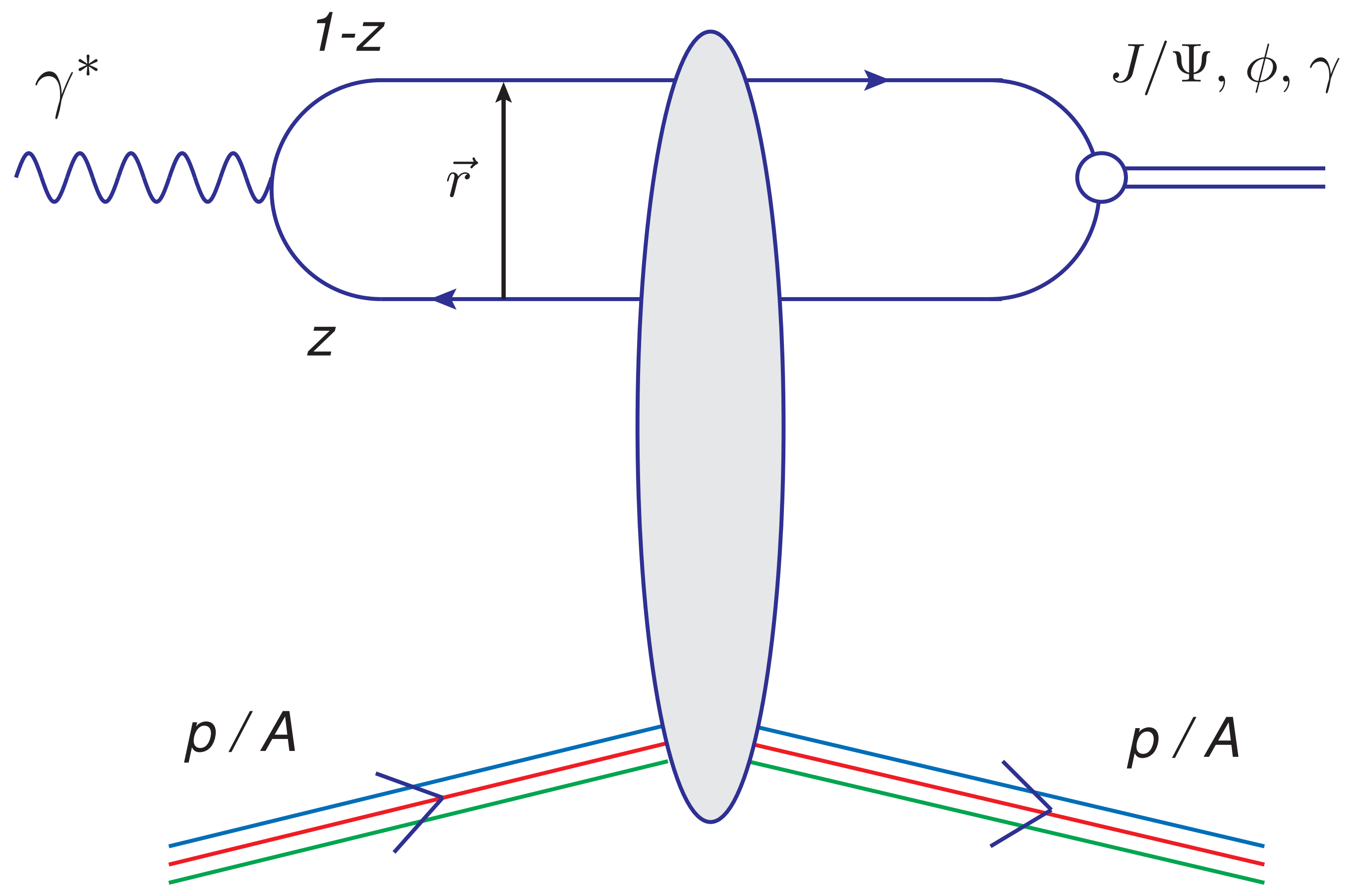
Initial geometry in the transverse plane : crucial to study small system collisions

How well do we understand the nucleon structure at high energies?

THE PROTON STRUCTURE



ACCESSING THE PROTON STRUCTURE IN DIFFRACTION



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 :*

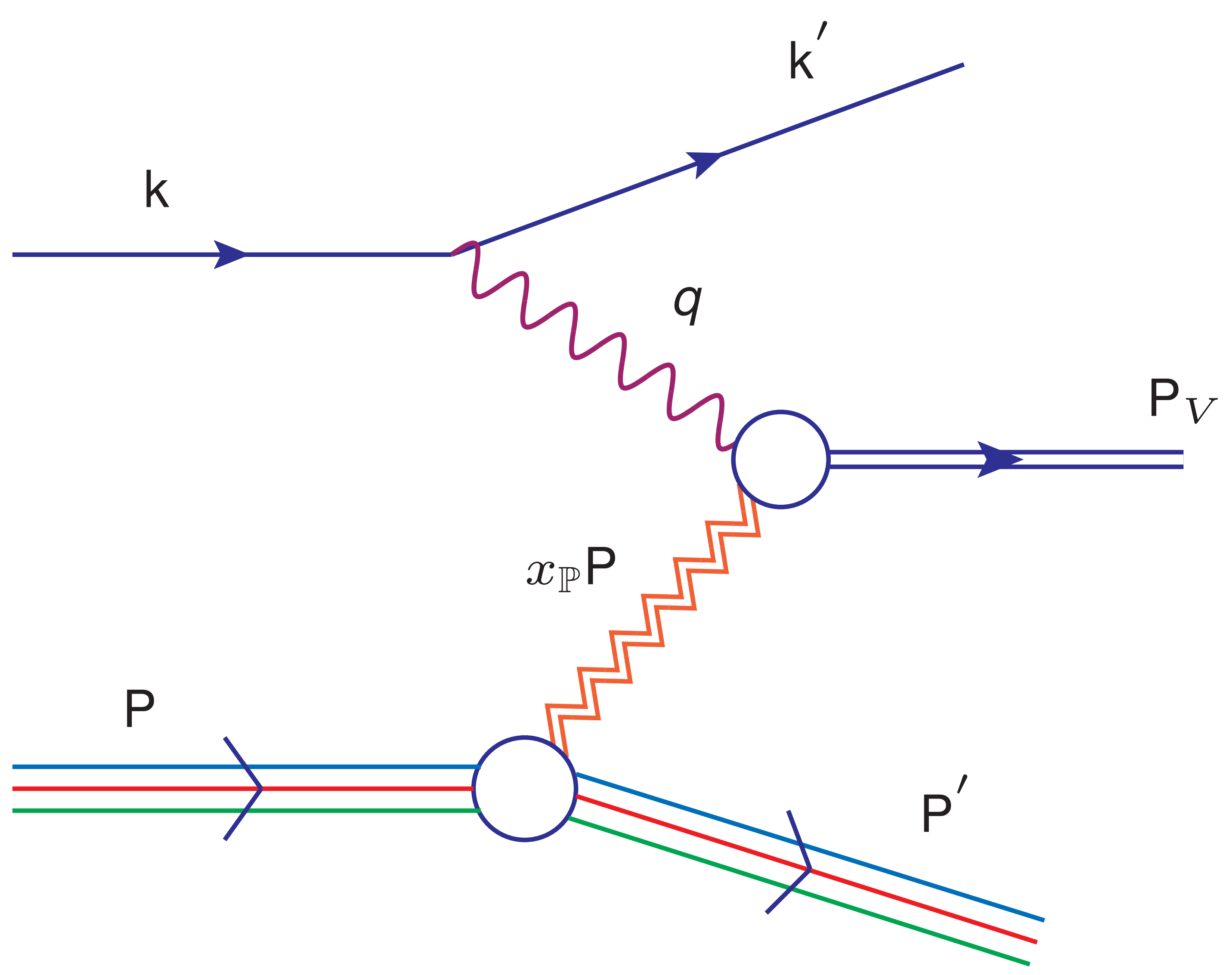
$$\mathcal{A}_{T,L}^{\gamma^* p \to Vp}(x, Q^2, \Delta) \simeq \int d^2r \int d^2b \int dz \times (\Psi^* \Psi_V)_{T,L}(Q^2, r, z) \times e^{-ib.\Delta} \times N(b, r, x)$$

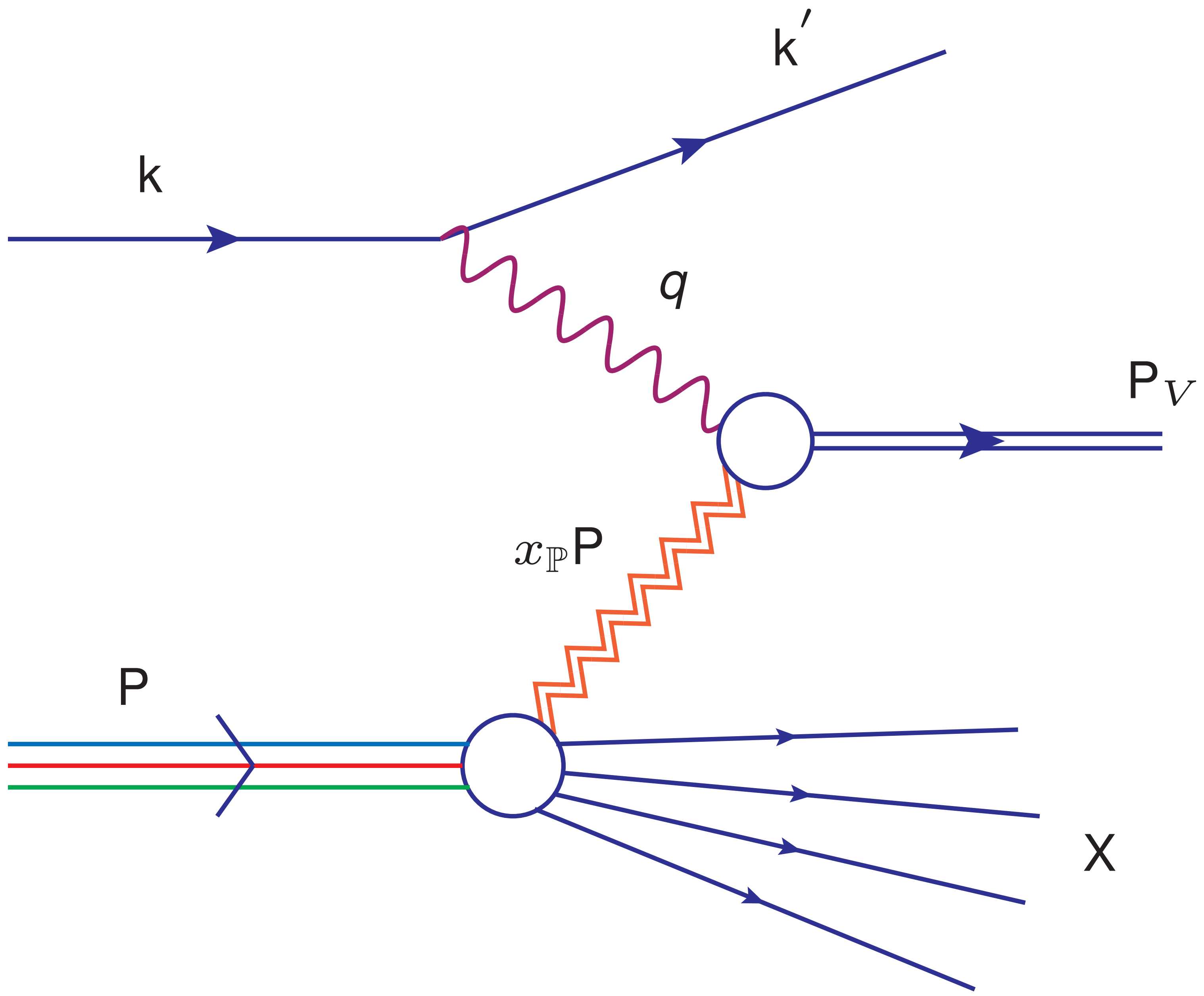
❖ *Impact parameter is Fourier conjugate to the momentum transfer* $\Delta = (p' - p)_\perp$

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

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

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

THE DIPOLE-TARGET AMPLITUDE

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

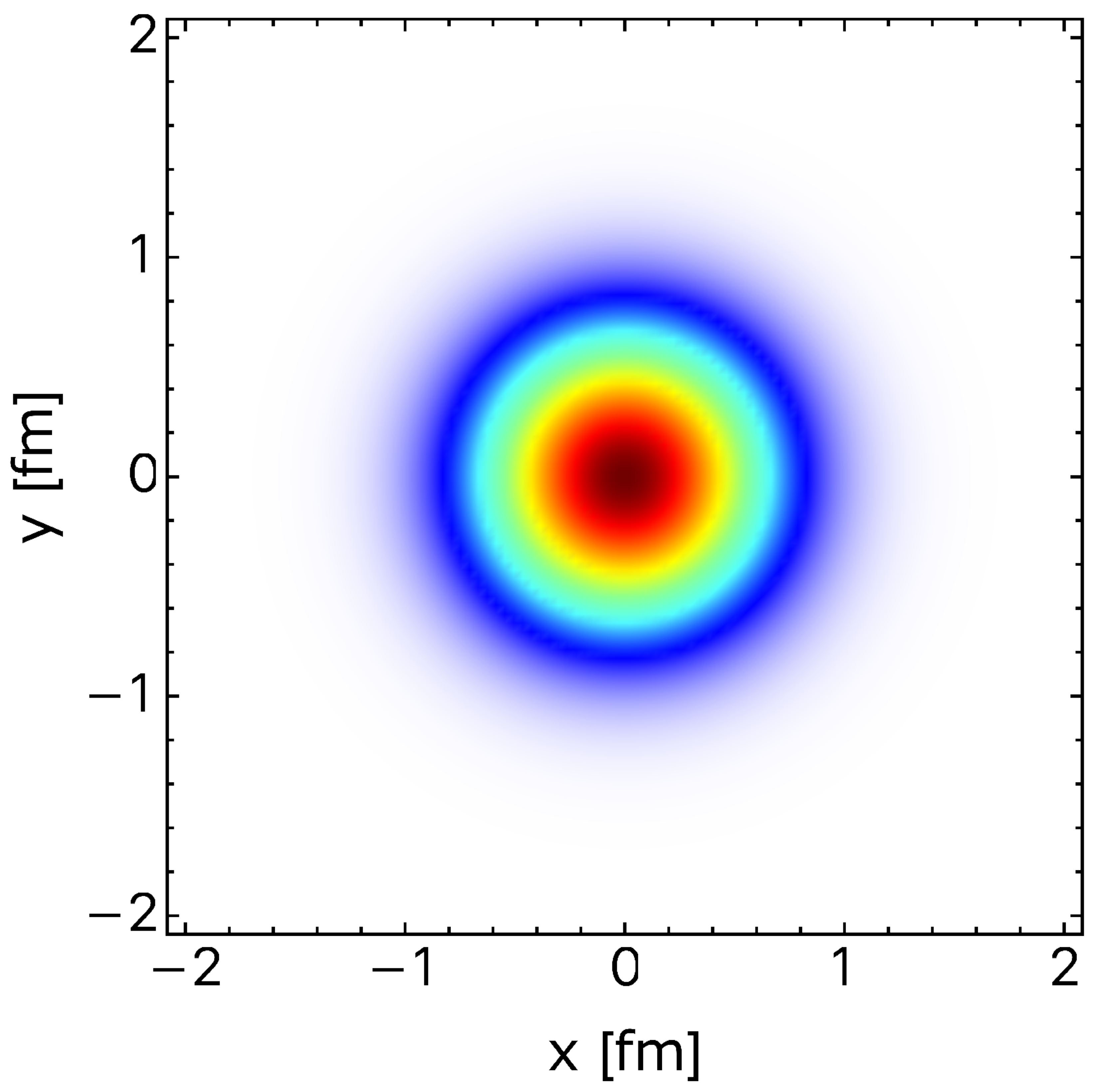
a) Smooth proton (assume gaussian proton shape) : $T_p(b) = \frac{1}{2\pi B_G}\exp\big[-\frac{b^2}{2B_G}\big]$ Kowalski, Teaney 2003, Kowalski, Motyka,Watt 2006

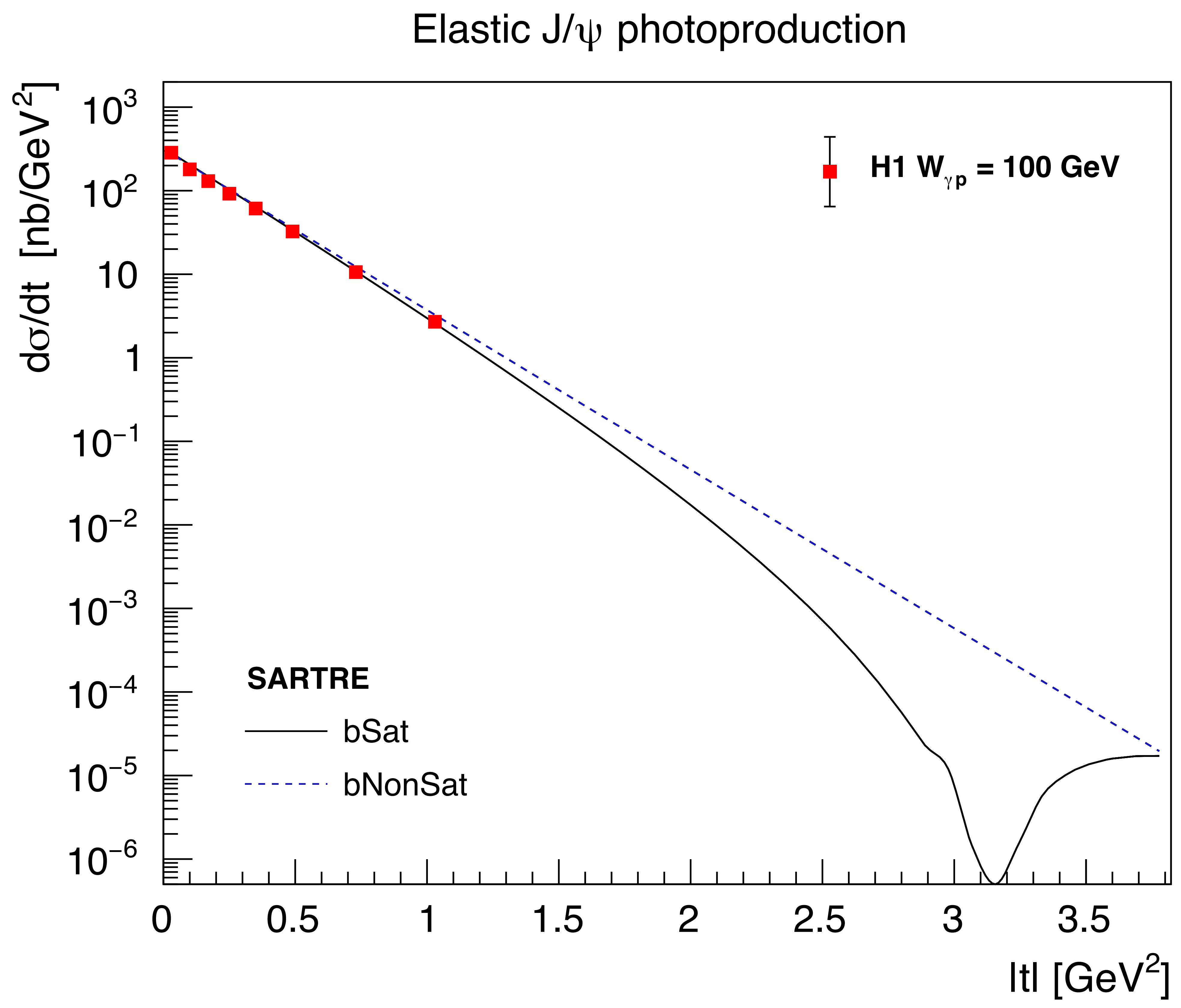
b) Lumpy proton (assume gaussian distributed hotspots with gaussian shape) : $T_p(b) \rightarrow \sum_{i=1}^{N_q} T_q(b-b_i)$ *and* $T_q(b) = \frac{1}{2\pi B_q}\exp\big[-\frac{b^2}{2B_q}\big]$

Mäntysaari, Schenke PRL 117 (2016) 052301

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

Kowalski, Teaney 2003, Kowalski, Motyka,Watt 2006

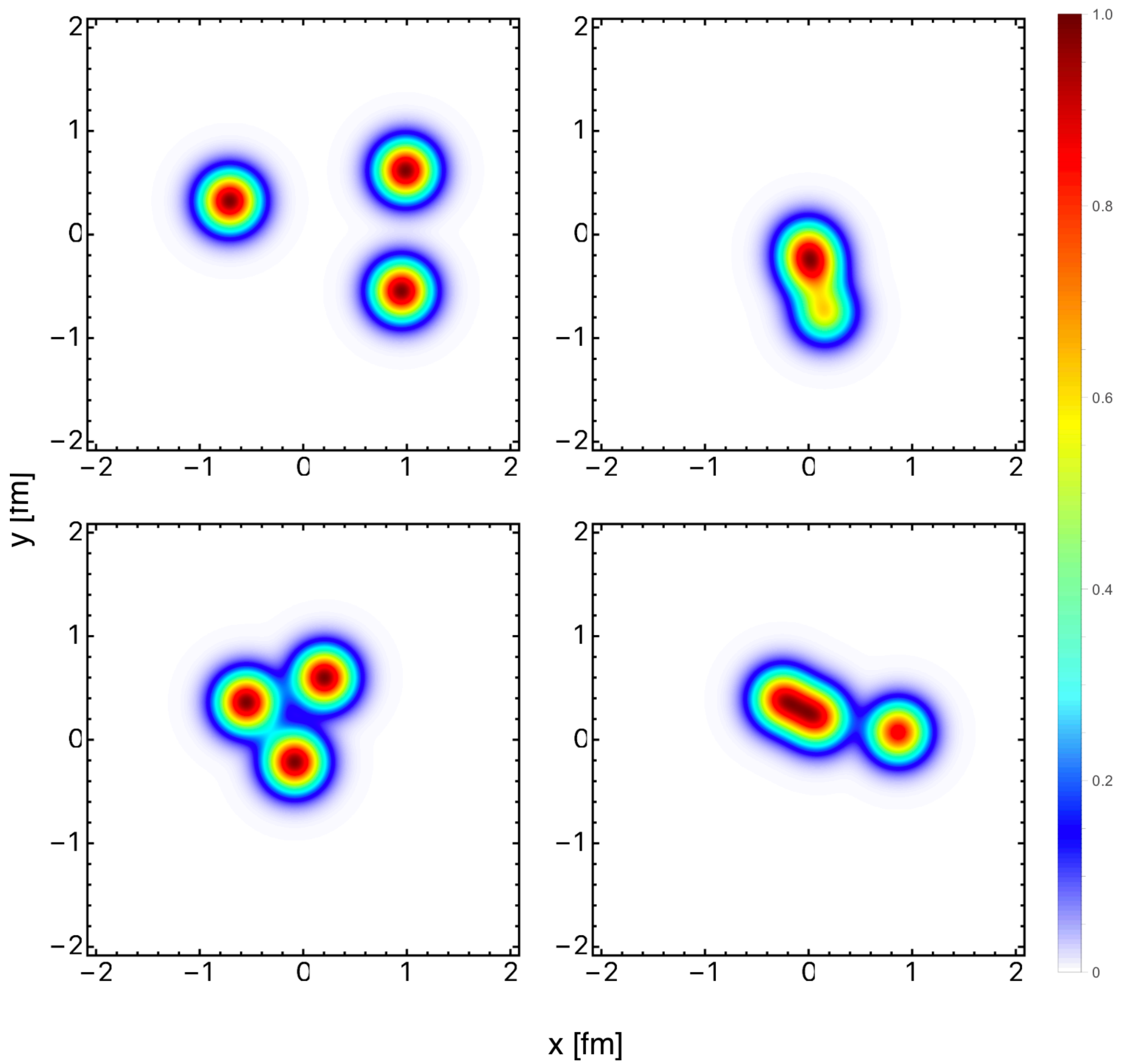


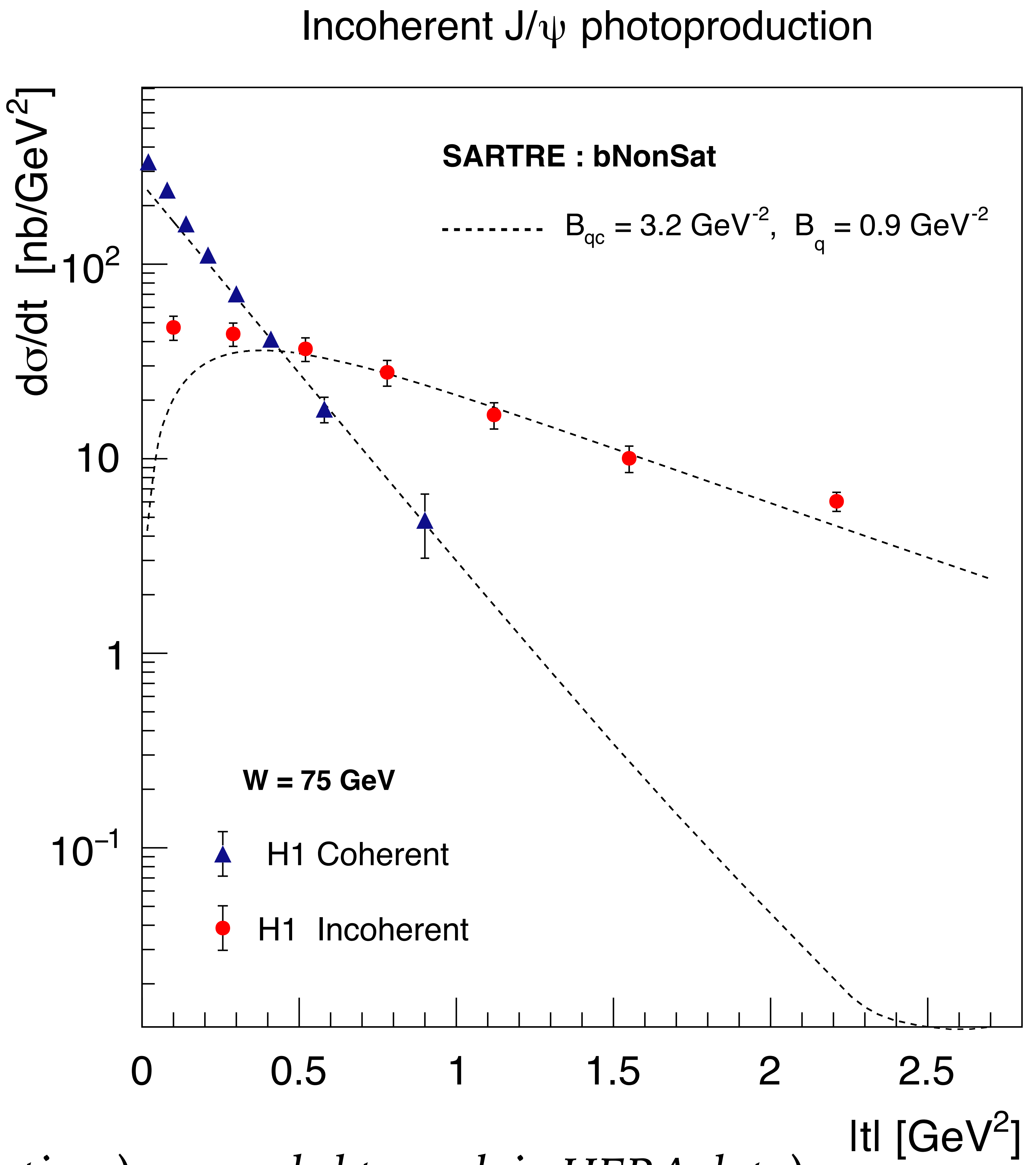


For a smooth proton there are no fluctuations so the incoherent cross section is zero → Lumpy proton

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

Mäntysaari, Schenke PRL 117 (2016) 052301

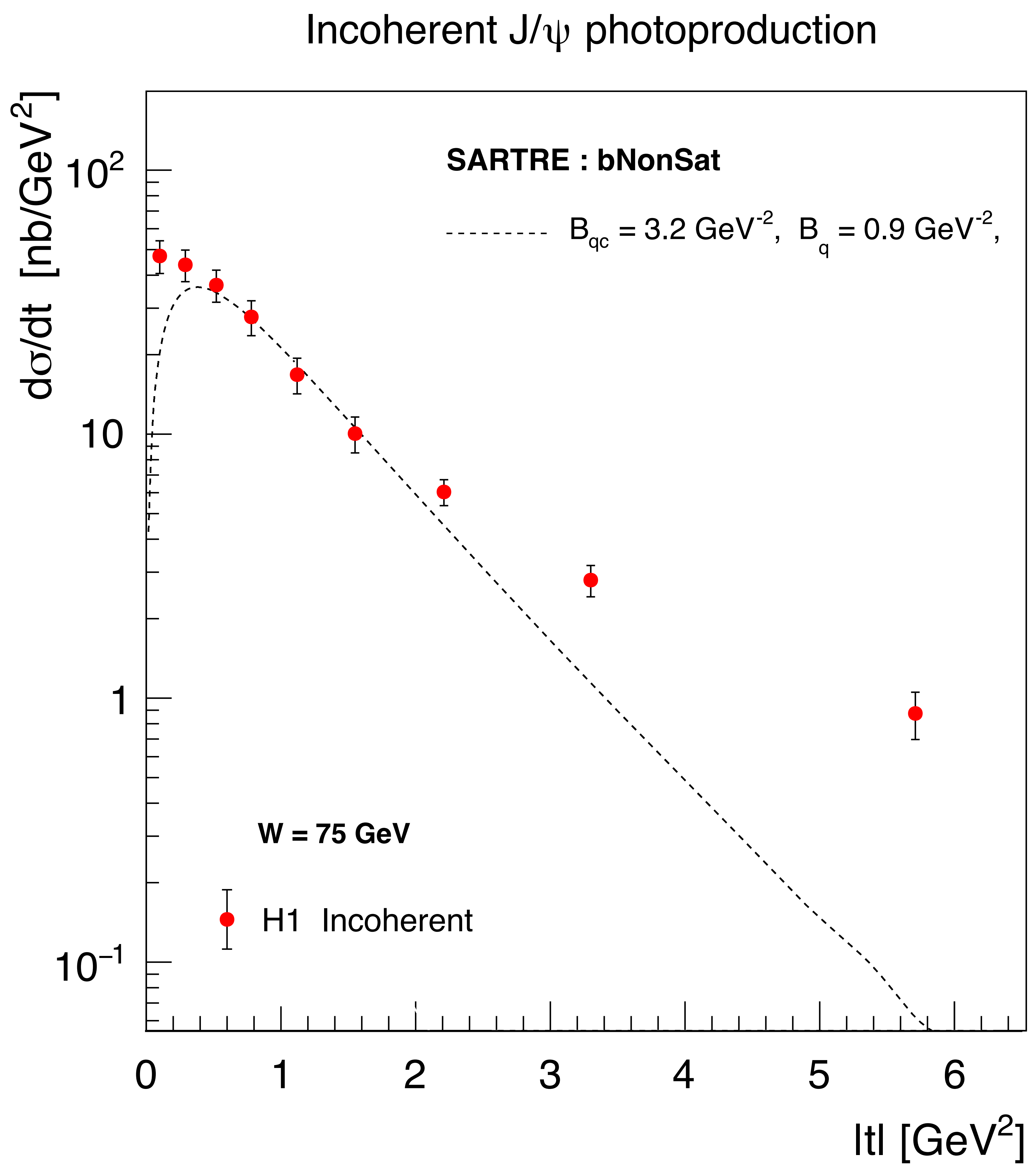




(large event-by-event fluctuations (1000 configurations) are needed to explain HERA data)

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

HOTSPOT MODEL AT LARGE MOMENTUM TRANSFER



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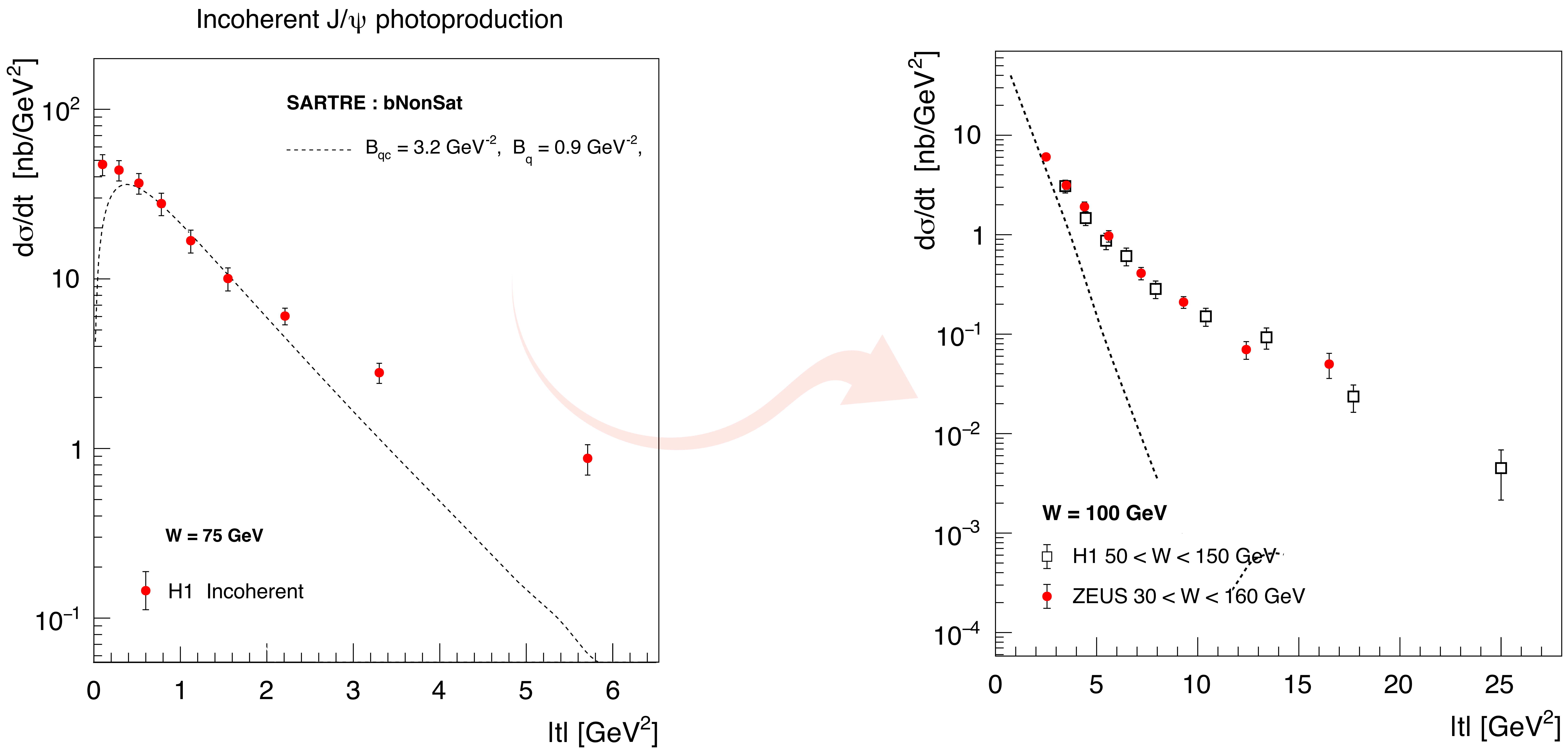

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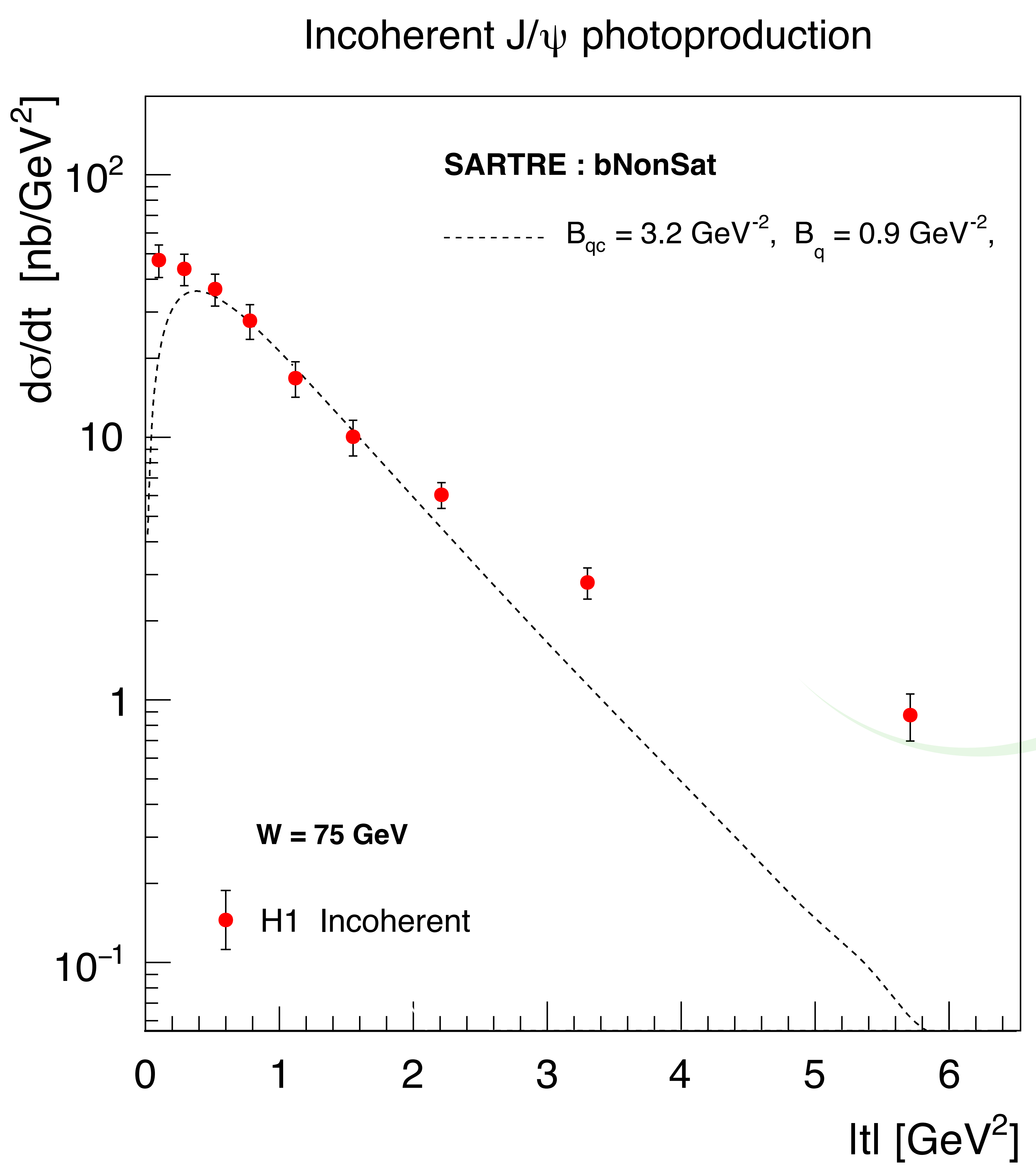

A.K,Tobias Toll EPJC 82 (2022) 837

What substructure and size fluctuations would describe the data ?

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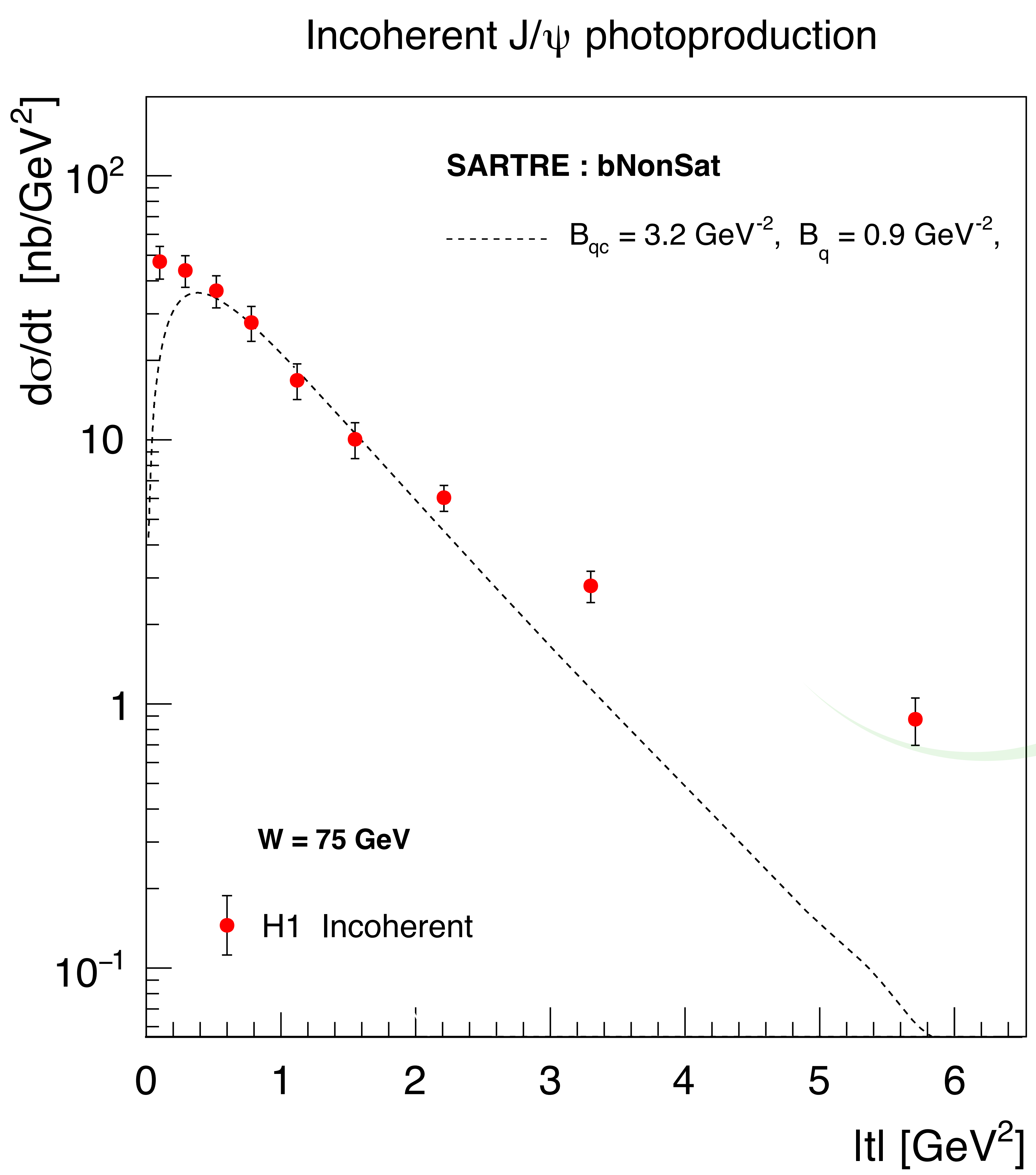

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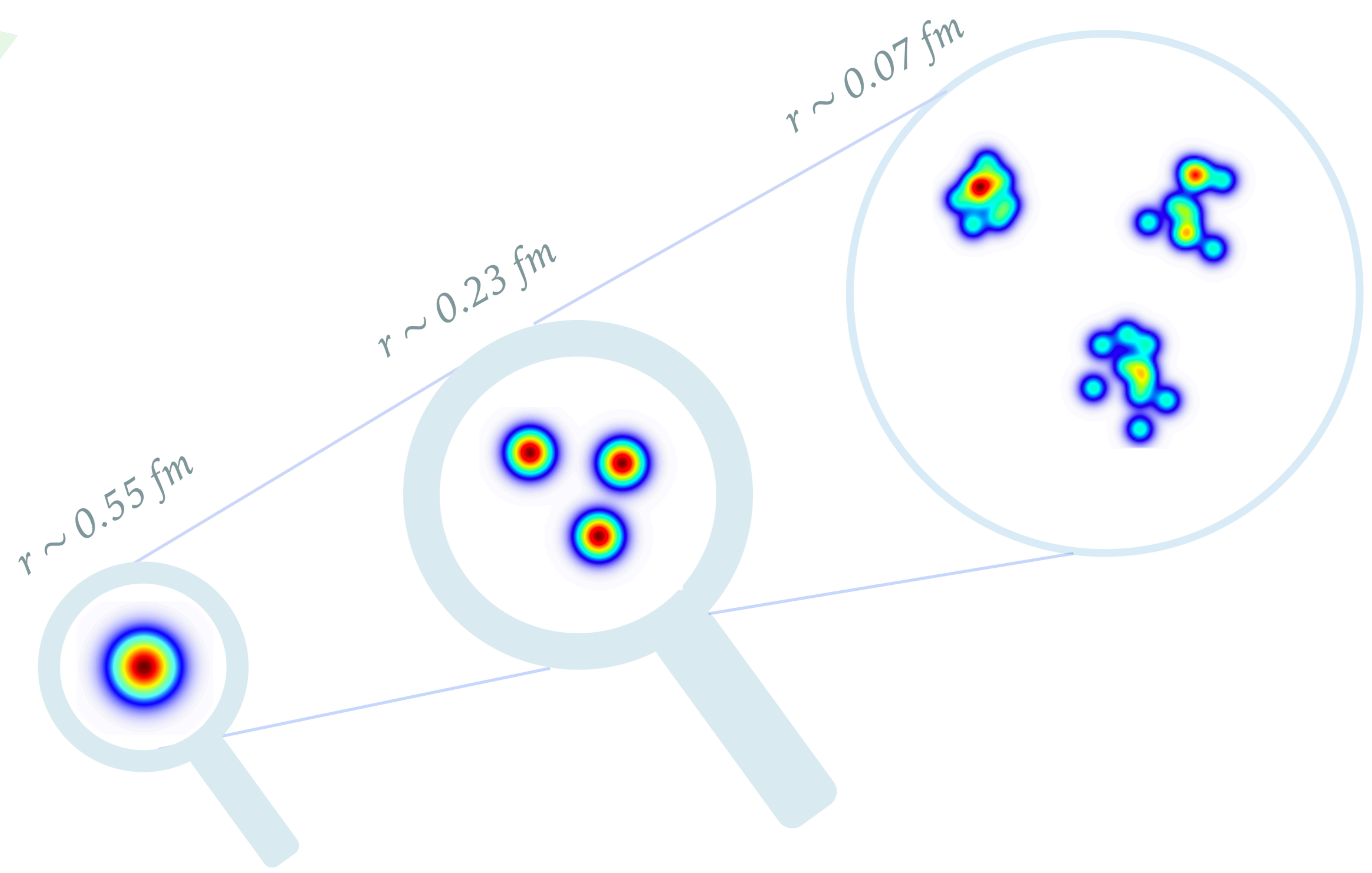
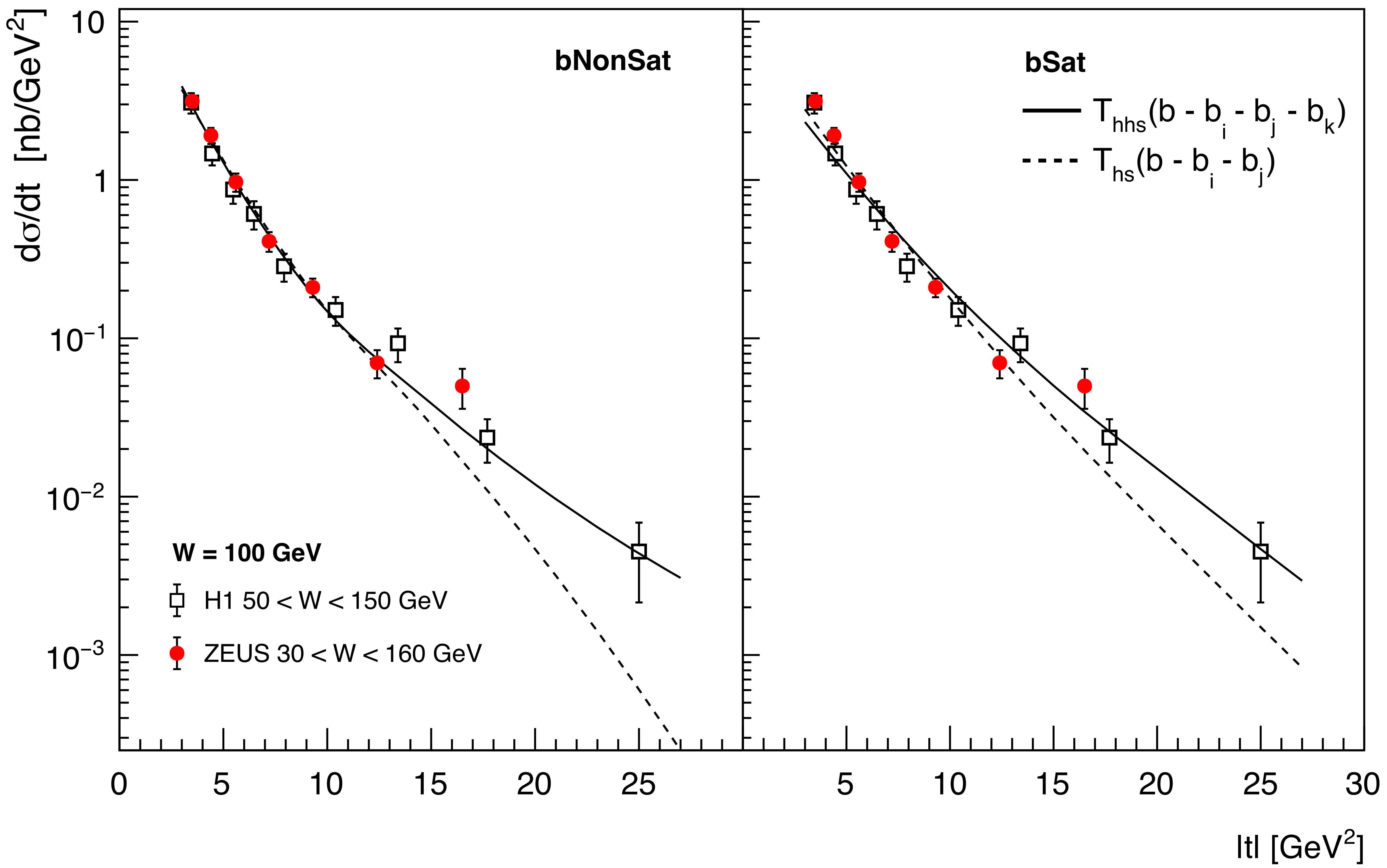
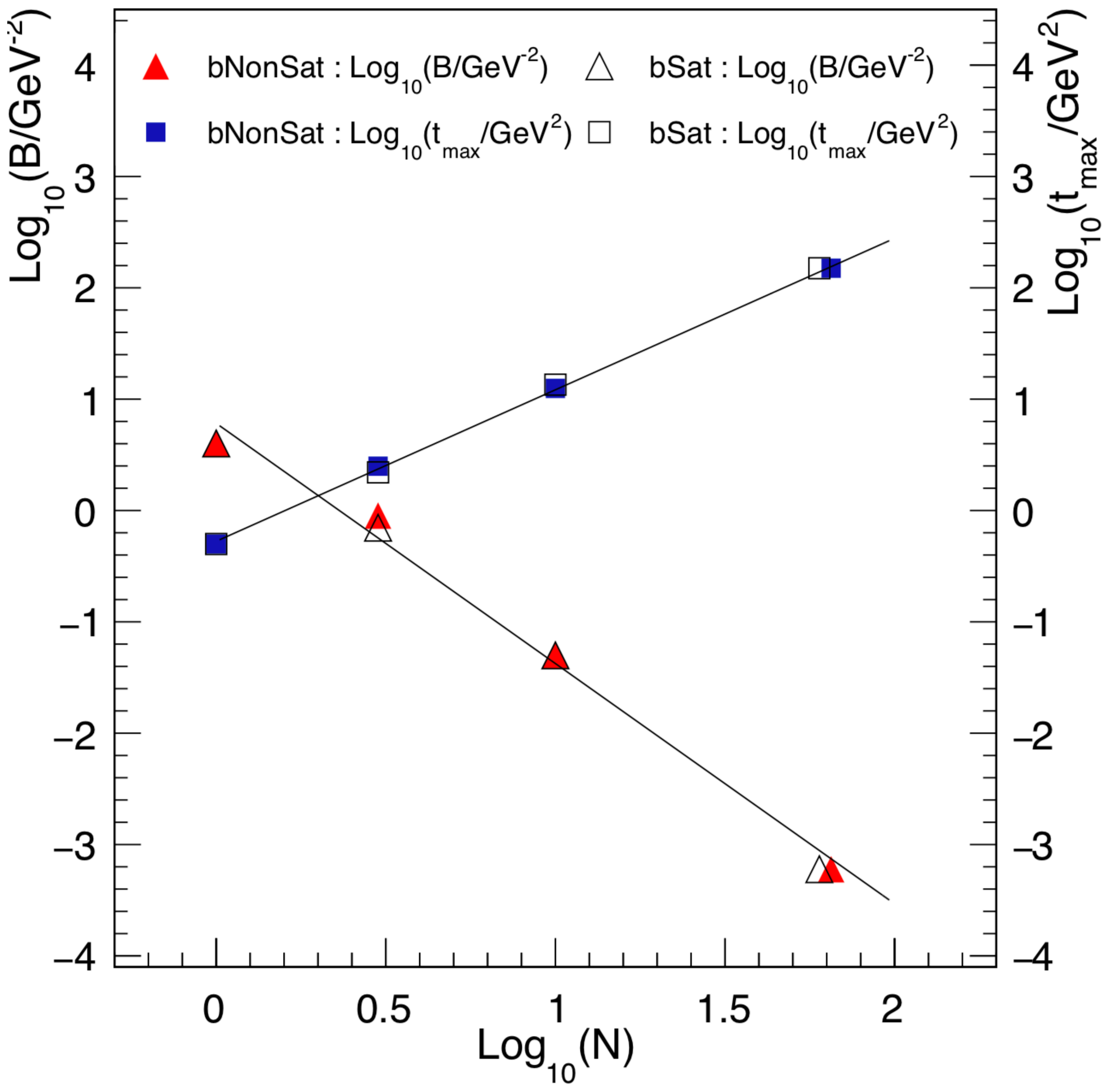


HOTSPOT MODEL AT LARGE MOMENTUM TRANSFER

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

Model	$\mathbf{B_{qc}}$	$\mathbf{B_q}$	$\mathbf{N_q}$	$\mathbf{B_{hs}}$	$\mathbf{N_{hs}}$	$\mathbf{B_{hhs}}$	$\mathbf{N_{hhs}}$
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





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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

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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 $t > t_0$

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

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

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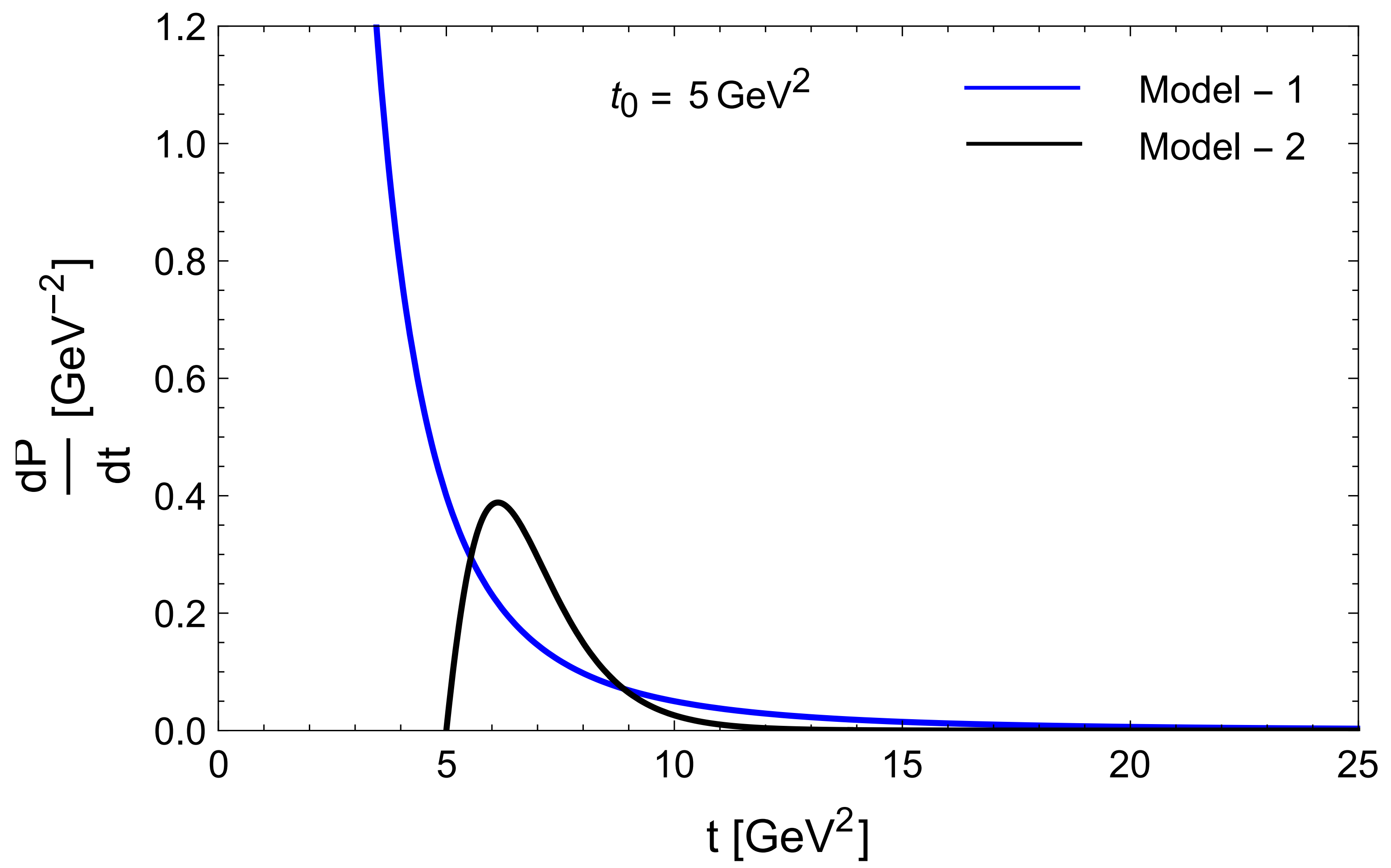
Hotspot evolution model -

analogy : resolution in optics

- *Two offspring hotspots i, j created at distance $d_{ij} = |b_i - b_j|$ sampled from parent hotspot*

  with widths $B_{i,,j} = \frac{1}{|t|} GeV^{-2}$
- *Probe & geometry resolution criterion : $d_{ij} > 2\sqrt{B_{i,j}}$*
  - *Reject if not resolved (effective hotspot repulsion)*
- *Additional sources of fluctuations (number, width, normalisation, repulsion)*



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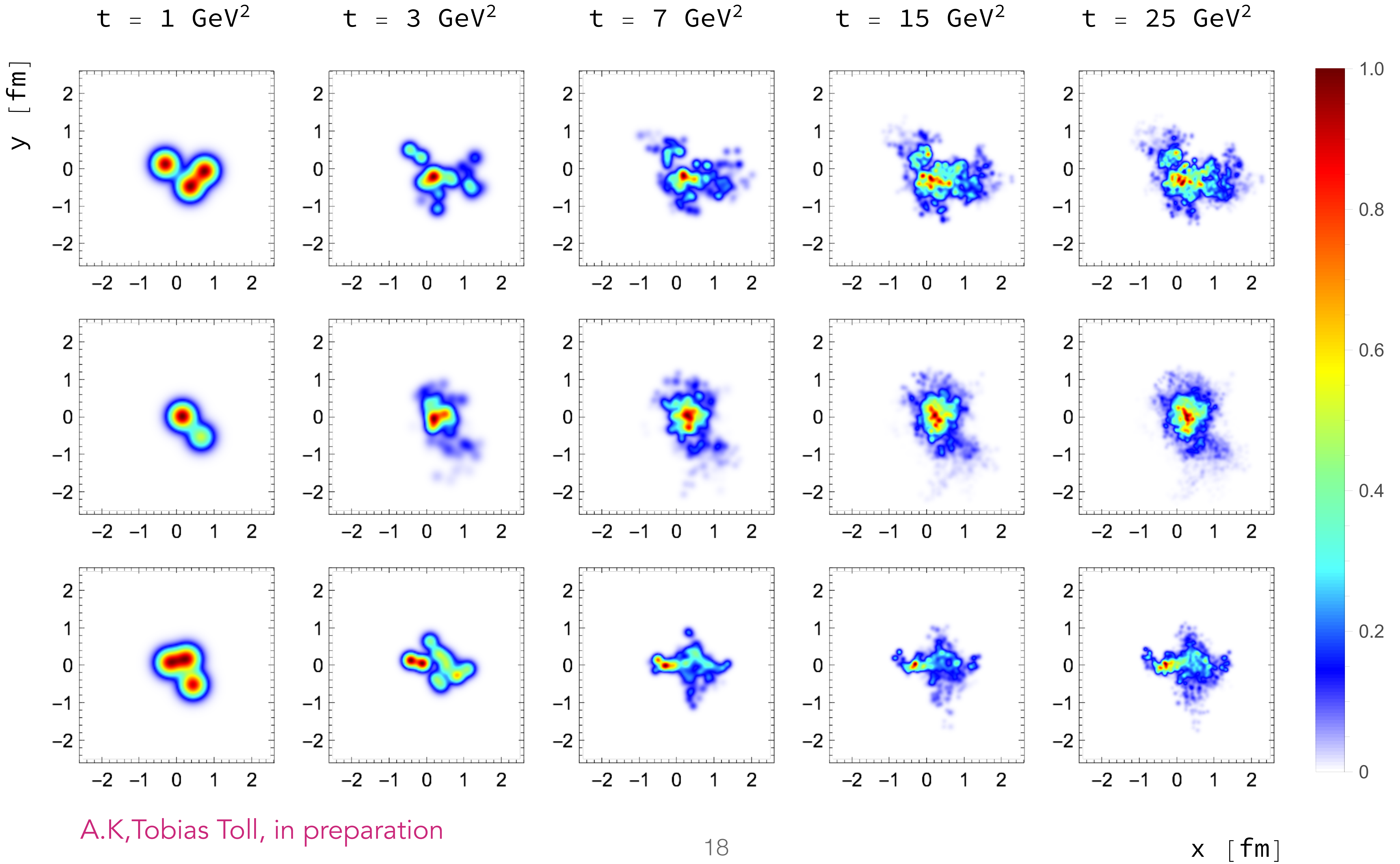
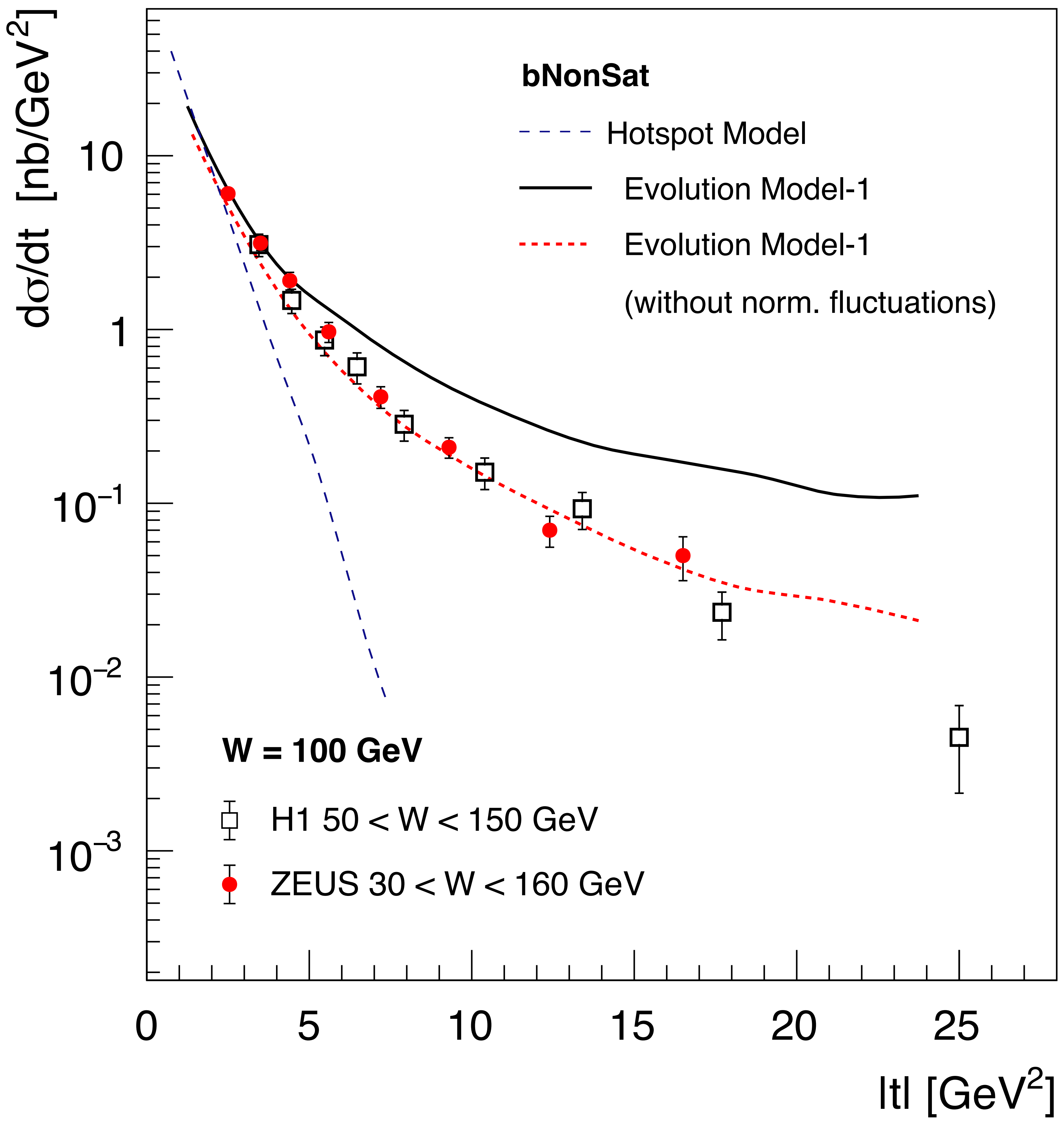
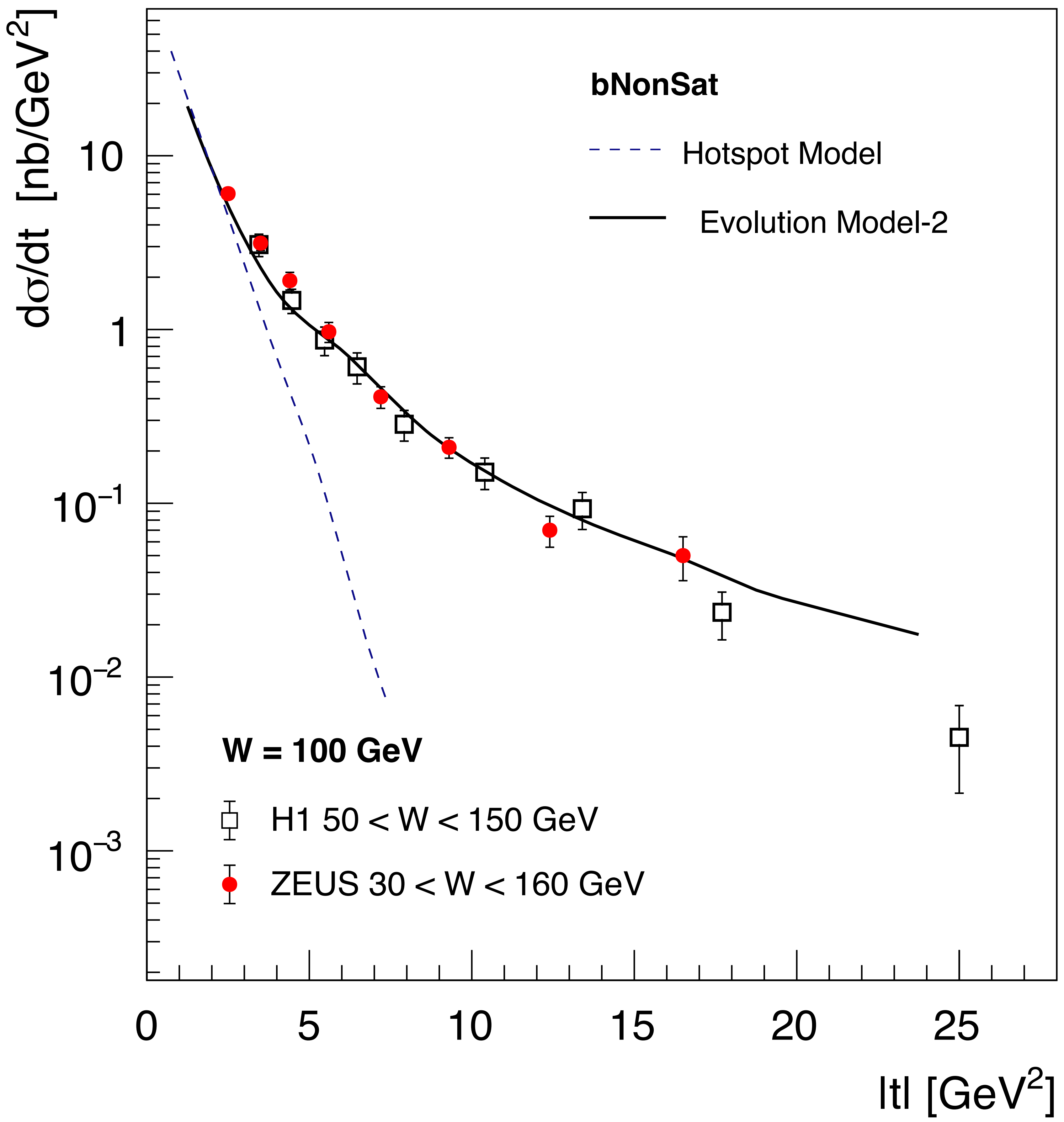


A.K,Tobias Toll, in preparation

HOTSPOT EVOLUTION MODEL

A.K,Tobias Toll, in preparation





- *Additional sources of fluctuations (number, width, normalisation, repulsion)*

OUTLOOK

- Currently investigating several models, promising results for whole t-spectrum with addition of only 2 parameters
- In CGC models, the substructure of nucleon after the geometric hotspot structure is the point like color charges at each space point
- Our model has size evolution from original geometry to hotspots becoming point like
- A better understanding of the proton structure & additional fluctuations required (this work : a step in this direction)

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THANK YOU

BACKUP

HOTSPOT EVOLUTION MODELS

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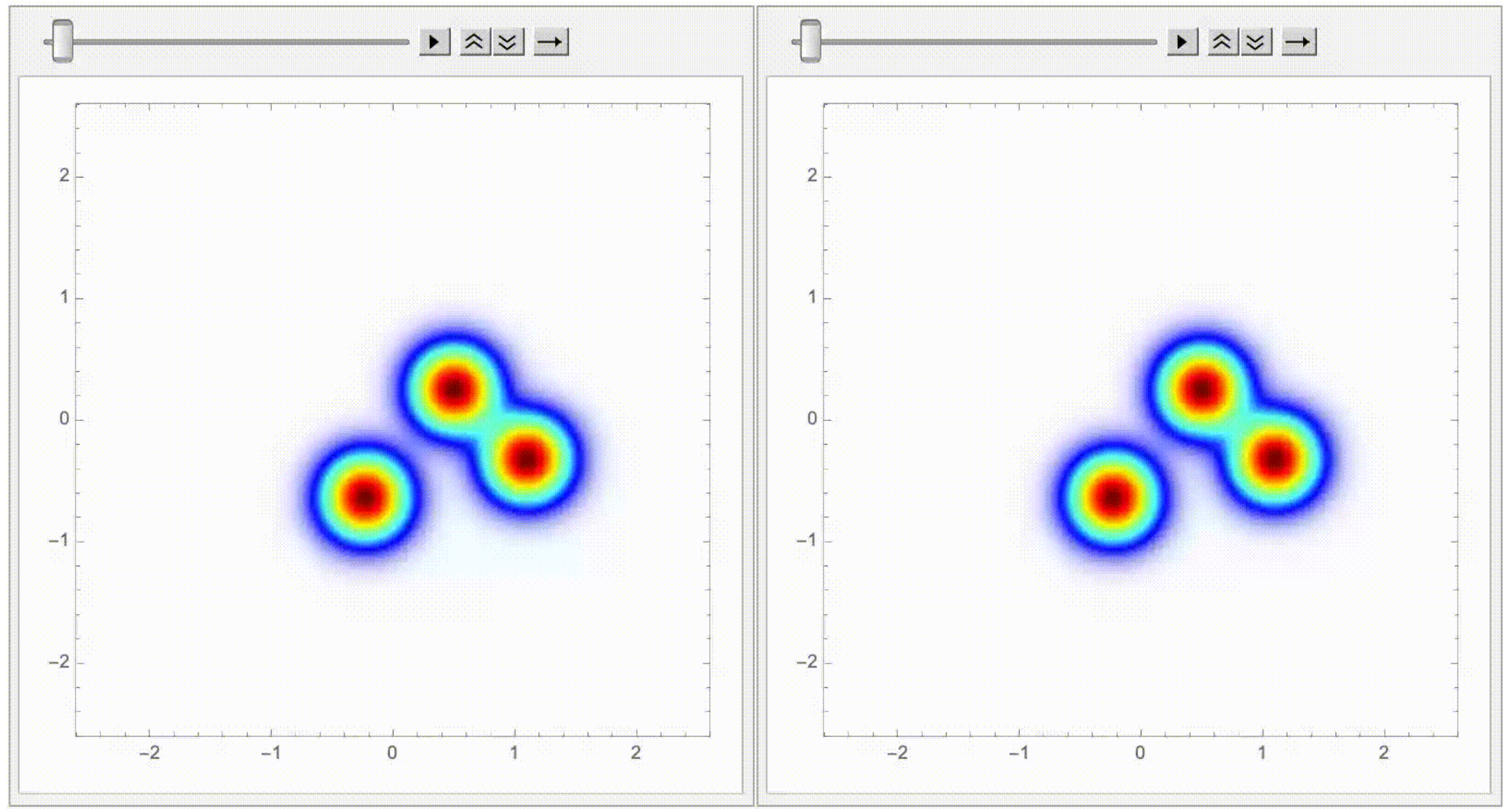
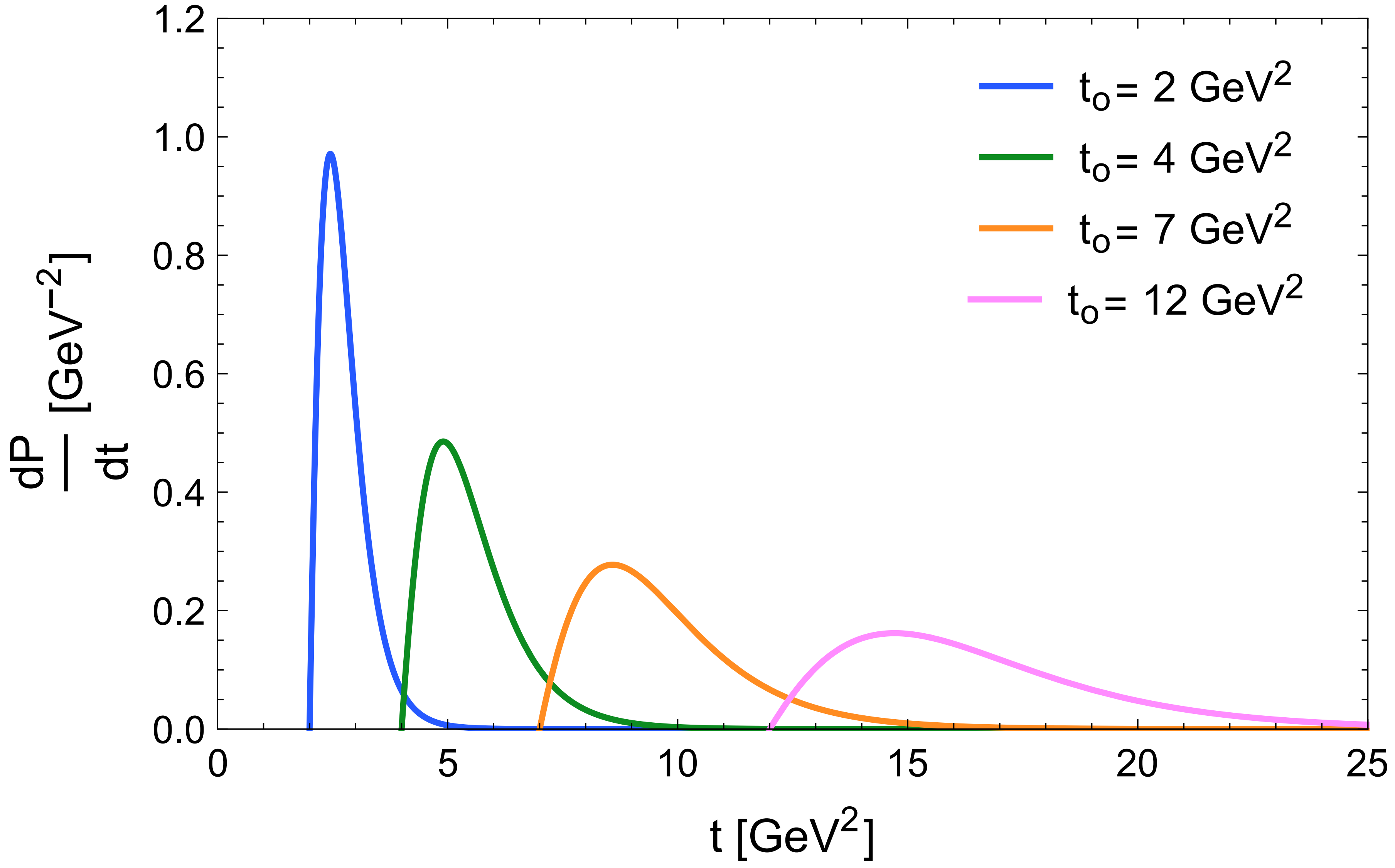
$$\frac{\mathrm{d}\mathscr{P}_a}{\mathrm{d}t} = \frac{\alpha}{t}\frac{t - t_0}{t}\exp\left[-\alpha\left(\frac{t_0}{t} - \ln\frac{t_0}{t} - 1\right)\right]$$

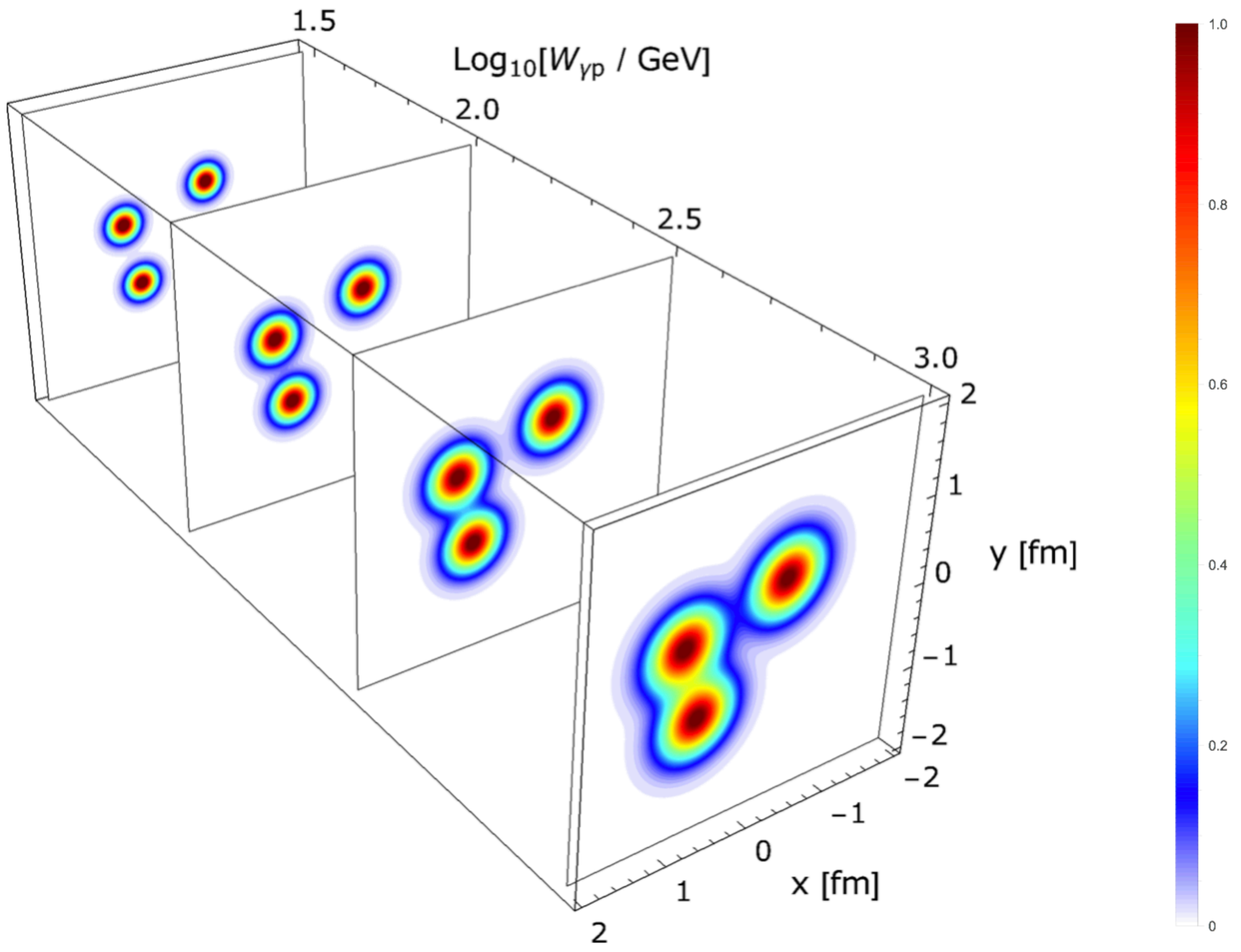
a) *Divide normalisation in each splitting*
b) *Divide normalisation among all hotspots at any t instant*

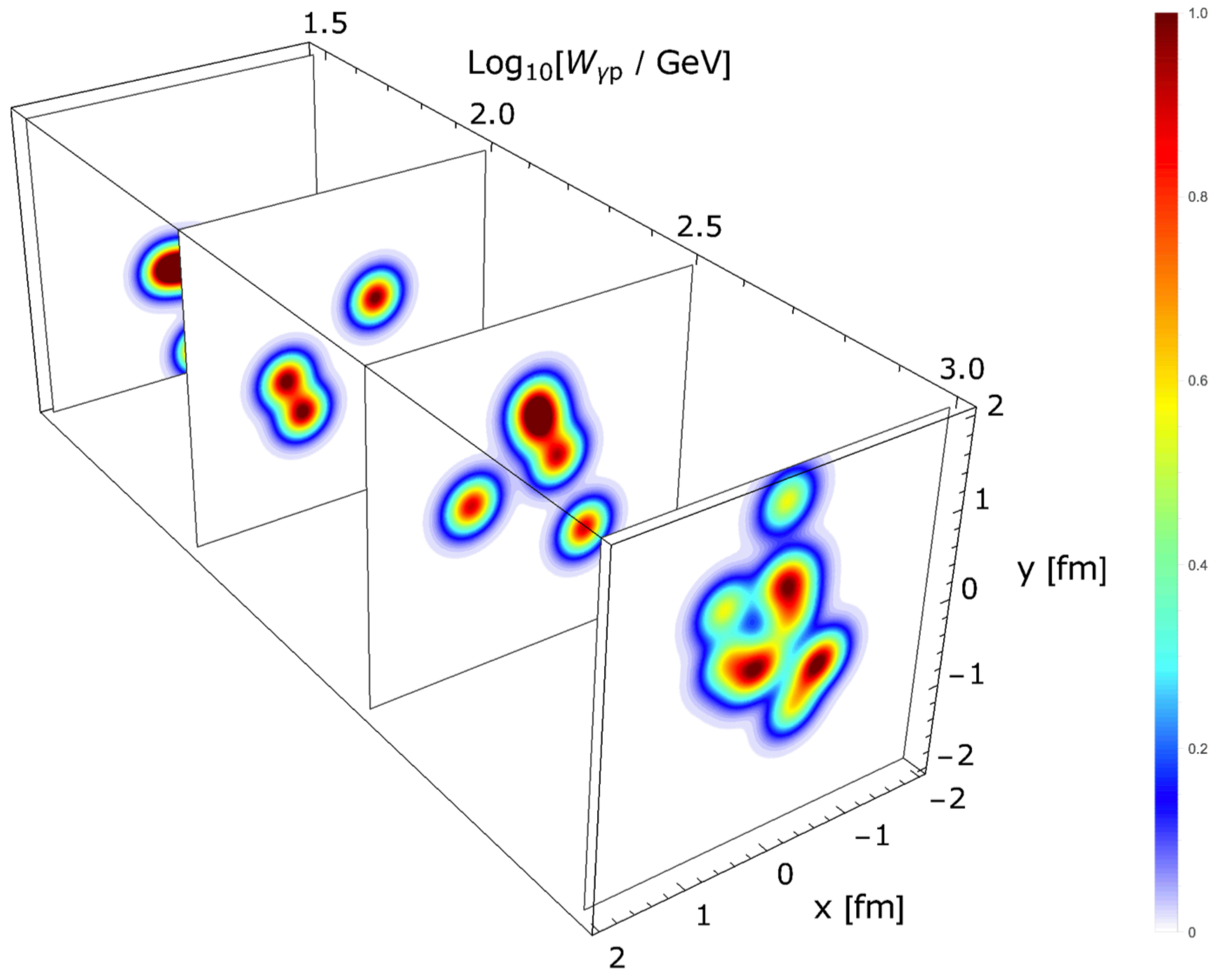




INCORPORATING THE ENERGY DEPENDENCE

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

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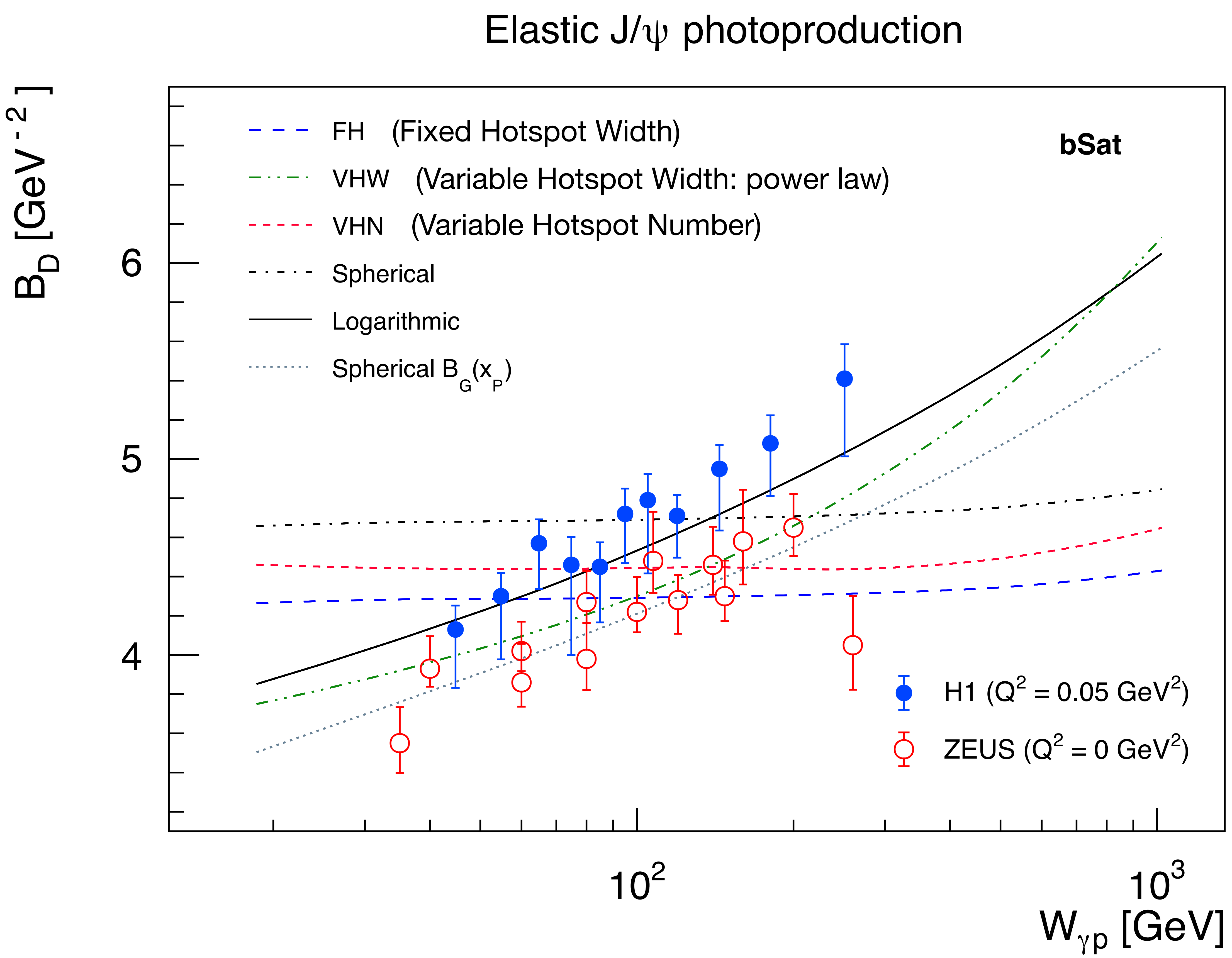

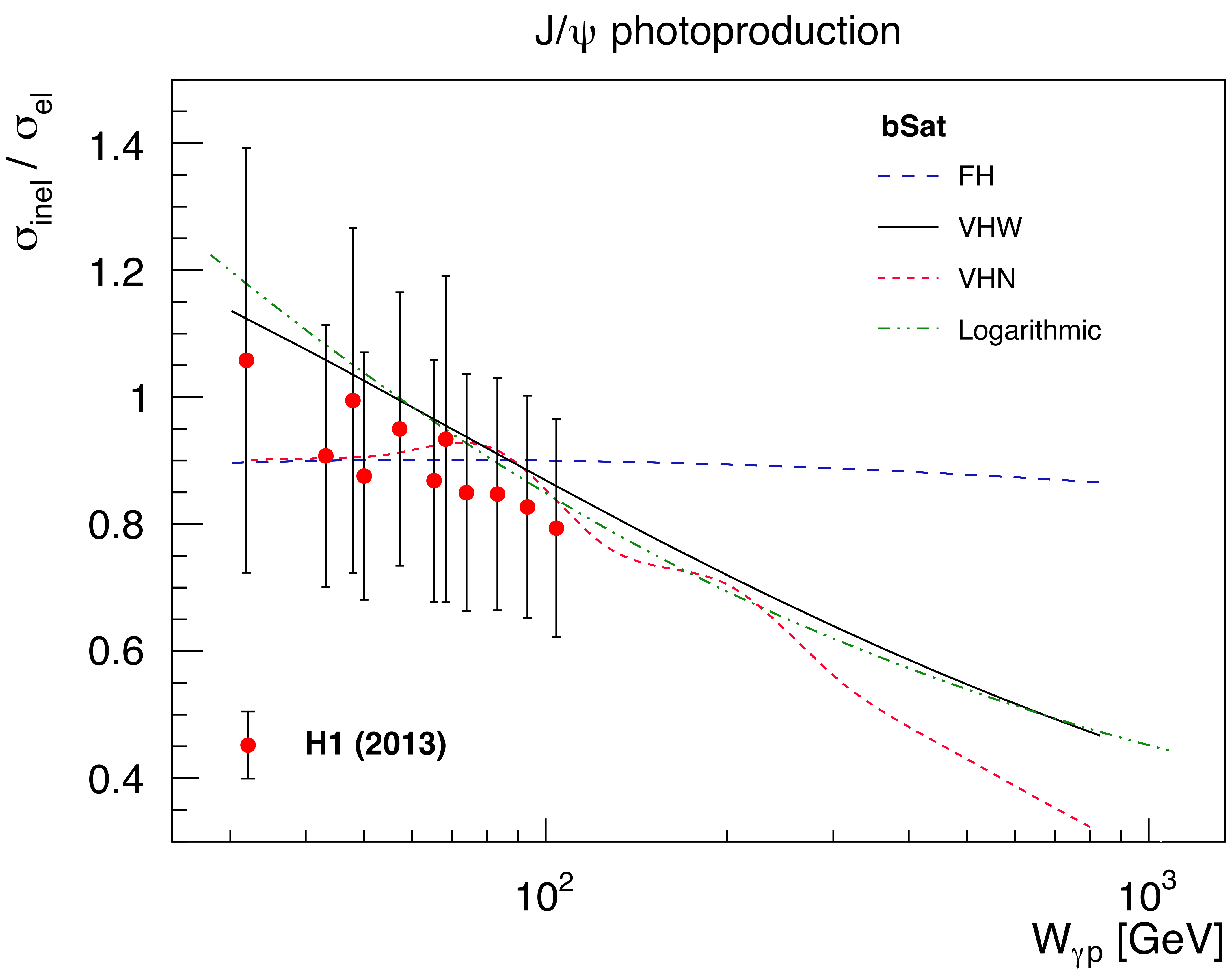

GOOD–WALKER PICTURE

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*

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

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