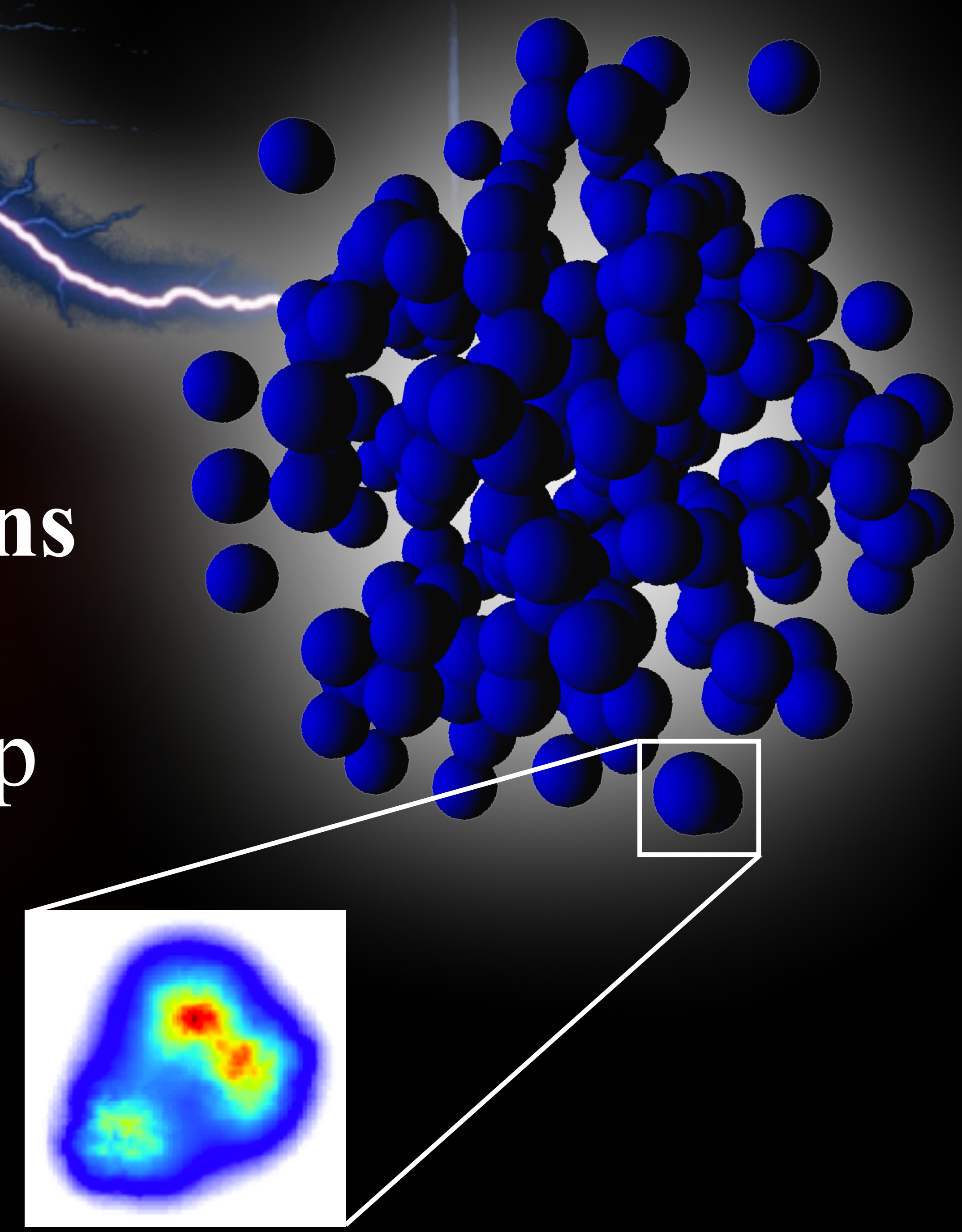
“Subnucleon Fluctuations with Sar*t*re”

BNL EIC Working Group



August 20, 2020

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IIT Delhi

Subnucleon Fluctuations in Sar*t*re

Work in progress together with Arjun Kumar.

Fluctuations in QCD

There are No free or "real" gluons in Nature
All gluons are *Virtual*, they only exist as Vacuum Fluctuations

Exclusive diffraction cross section: $$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA}}{\mathrm{d}t} = \frac{1}{16\pi} \left| \left\langle \mathcal{A}^{\gamma^* A \to VA} \right\rangle \right|^2$$

Incoherent part: $$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA^*}}{\mathrm{d}t} = \frac{1}{16\pi} \left(\left\langle \left| \mathcal{A}^{\gamma^* A \to VA} \right|^2 \right\rangle - \left| \left\langle \mathcal{A}^{\gamma^* A \to VA} \right\rangle \right|^2 \right)$$

Coherent

Incoherent cross section is (almost) a direct measurement of gluon fluctuations—a direct measurement of gluons!

t sets the momentum scale at which the fluctuations are probed
Gluons fluctuate differently at different scales
(saturation scale, geometrical fluctuations of hotspots and nucleons)

Geometry in the Dipole Model

There are No free or "real" gluons in Nature
All gluons are *Virtual*, they only exist as Vacuum Fluctuations

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\left\langle \mathcal{A}^{\gamma^* A \to VA}\right\rangle\right|^2$$

$$\mathcal{A}_{T,L}^{\gamma^* p \to Ep} = \mathrm{i}\int_0^\infty \mathrm{d}r\,(2\pi r)\int_0^1 \frac{\mathrm{d}z}{4\pi}\int_0^\infty \mathrm{d}b\,(2\pi b)\;(\Psi_E^*\Psi)_{T,L}\;J_0(b\Delta)\;J_0([1-z]r\Delta)\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}$$

bNonSat

$$\frac{d\sigma_{\mathrm{dip}}}{d^2\mathbf{b}} = r^2\frac{\pi^2}{N_C}\alpha_s(\mu^2)xg(x,\mu^2)T_p(b)$$

bSat

$$\frac{d\sigma_{\mathrm{dip}}}{d^2\mathbf{b}} = 2\left[1-\exp\left(-r^2\frac{\pi^2}{2N_C}\alpha_s(\mu^2)xg(x,\mu^2)T_p(b)\right)\right]$$

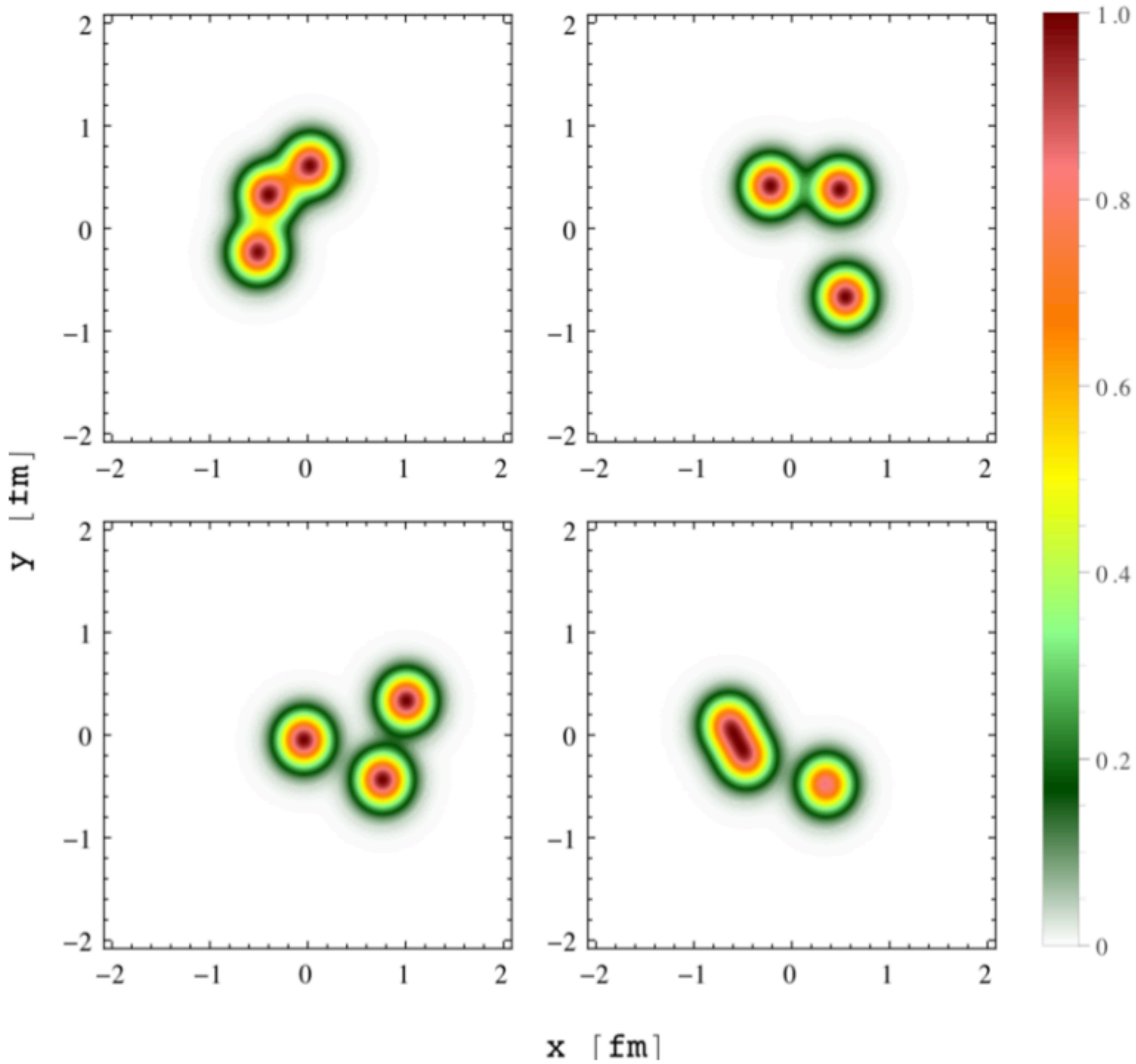
Proton Thickness:

$$T_p(b) = \frac{1}{2\pi B_p}e^{-\frac{b^2}{2B_p}}$$

$$B_p = 4\ \mathrm{GeV}^{-2}$$

This can be interpreted as **average** gluon distribution in the proton

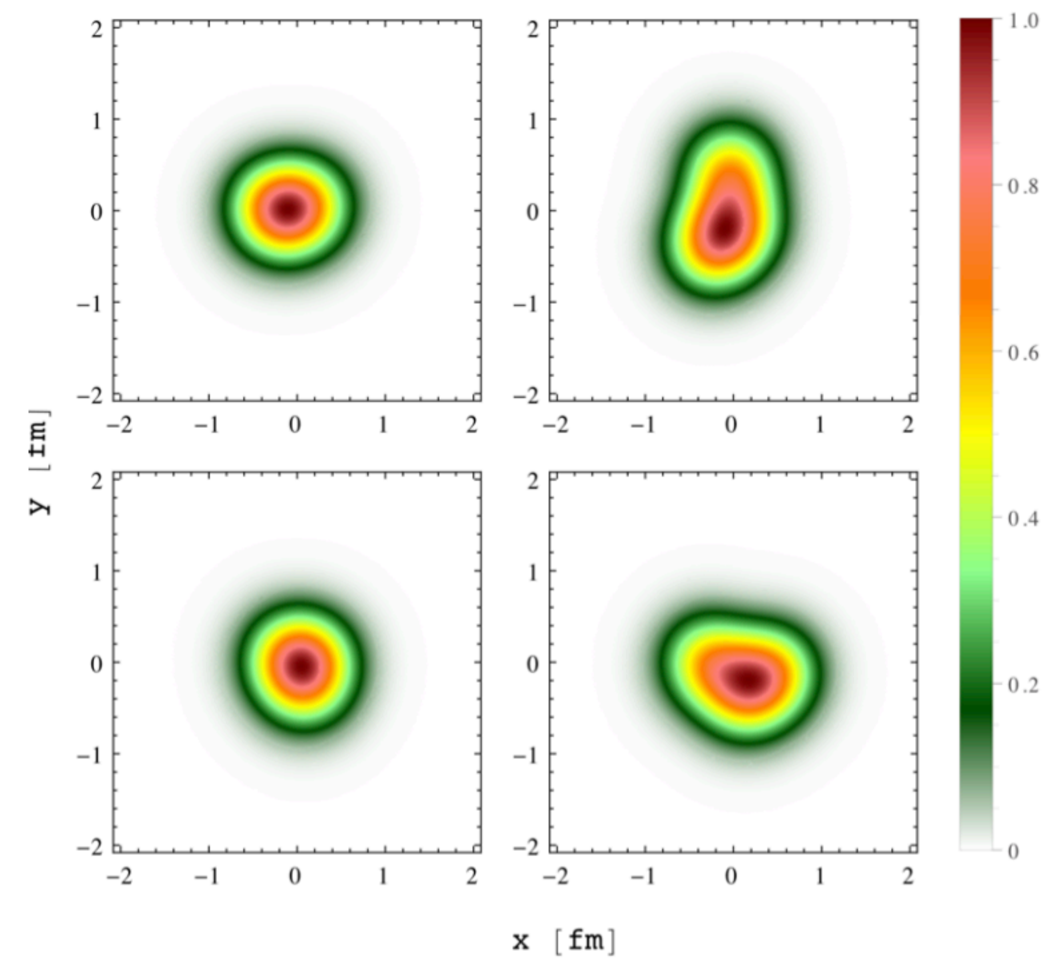
Subnucleon Fluctuations in protons



(a) Lumpy-$B_{qc} = 3.3, B_q = 0.7$

Geometrical fluctuations around N_q hotspots:

$$T_p(\mathbf{b}_T) \to \frac{1}{N_q} \sum_{i=1}^{N} \frac{1}{2\pi B_q} e^{-(\mathbf{b}_T - \mathbf{b}_{T\,i})^2/(2B_q)}$$



(b) Smooth-$B_{qc} = 1.0, B_q = 3.0$

Subnucleon Fluctuations in protons

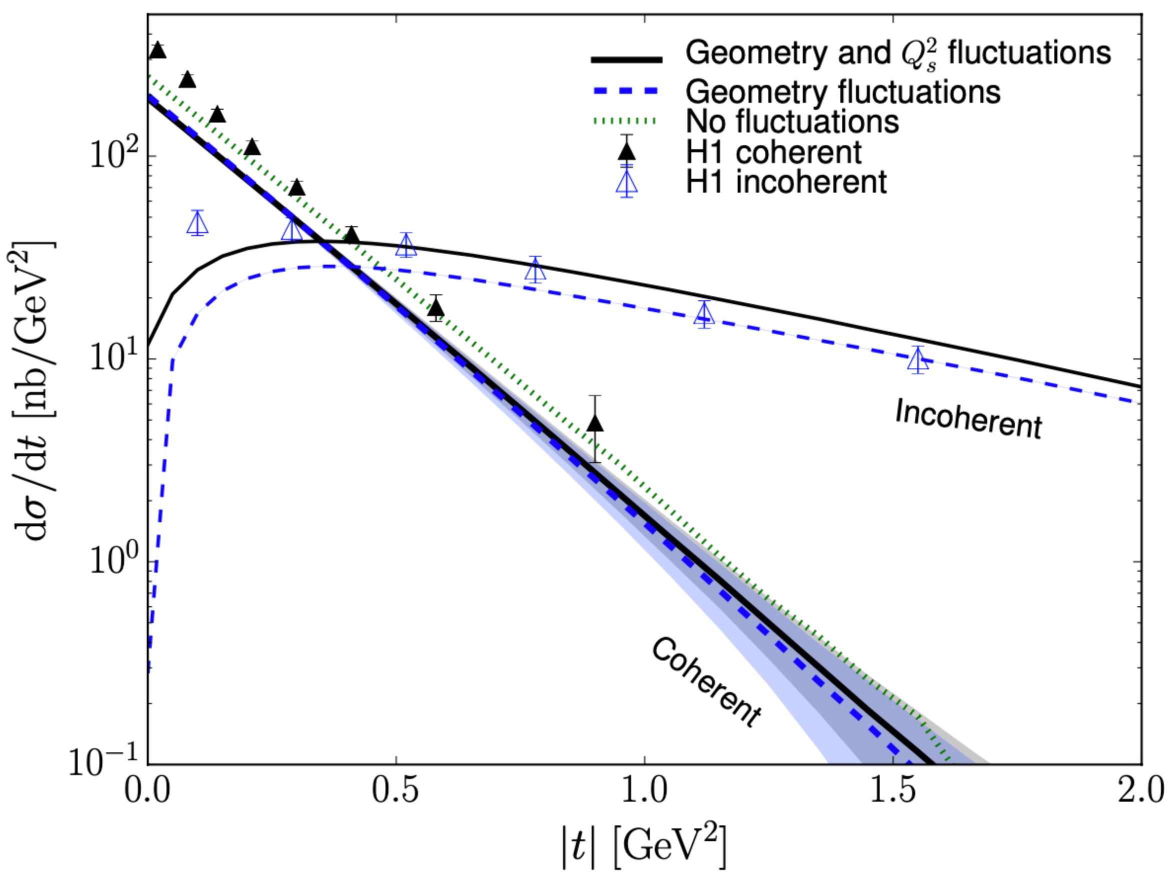


FIG. 1: J/ψ photoproduction cross sections at $W = 75$ GeV as a function of squared momentum transfer as measured by H1 [43], compared to calculations using the IPsat parametrization for the dipole-target scattering. Geometric shape fluctuations and overall normalization fluctuations (Q_s^2 fluctuations) are needed to describe the data. Figure based on Ref. [57].

Heikki Mänysaari, *Rept.Prog.Phys.* 83 (2020) 8, 082201

Geometrical fluctuations around N_q hotspots:

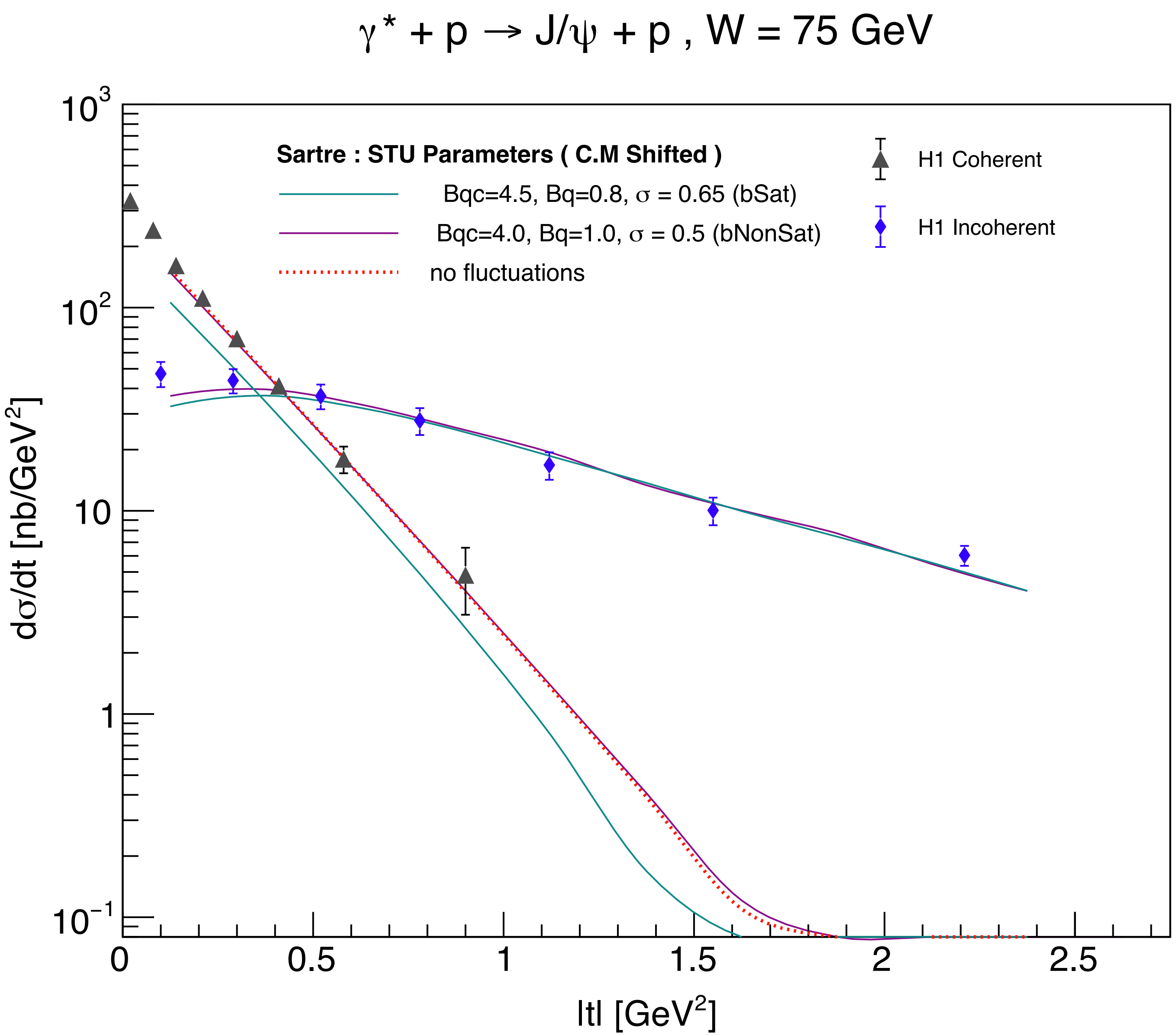
$$T_p(\mathbf{b}_T) \to \frac{1}{N_q}\sum_{i=1}^{N}\frac{1}{2\pi B_q}e^{-(\mathbf{b}_T-\mathbf{b}_{T\,i})^2/(2B_q)}$$

Small $|t|$: Small momentum scale fluctuations.
MS use a model based on Saturation scale fluctuations:

$$T_p(\mathbf{b}) \to \sum_{i=1}^{N_q}\frac{\Omega_i}{< E >}T_q(\mathbf{b}\text{-}\mathbf{b}_i)$$

Ω_i drawn from log-normal distribution with width σ and $\langle E\rangle = \exp(\sigma^2/2)$

Subnucleon Fluctuations in protons



$$\frac{d\sigma^{\text{coherent}}}{dt} = \frac{1}{16\pi}\left\langle \mathscr{A}^{\gamma^* p \to Vp} \right\rangle$$

$$\text{bNonSat:} \quad \langle \mathscr{A} \rangle \propto \left\langle \frac{d\sigma_{\text{dip}}}{db^2} \right\rangle \propto \langle T(b) \rangle$$

$$\frac{d\sigma_{\text{dip}}}{d^2\mathbf{b}} = r^2 \frac{\pi^2}{N_C} \alpha_s(\mu^2) x g(x, \mu^2) T_p(b)$$

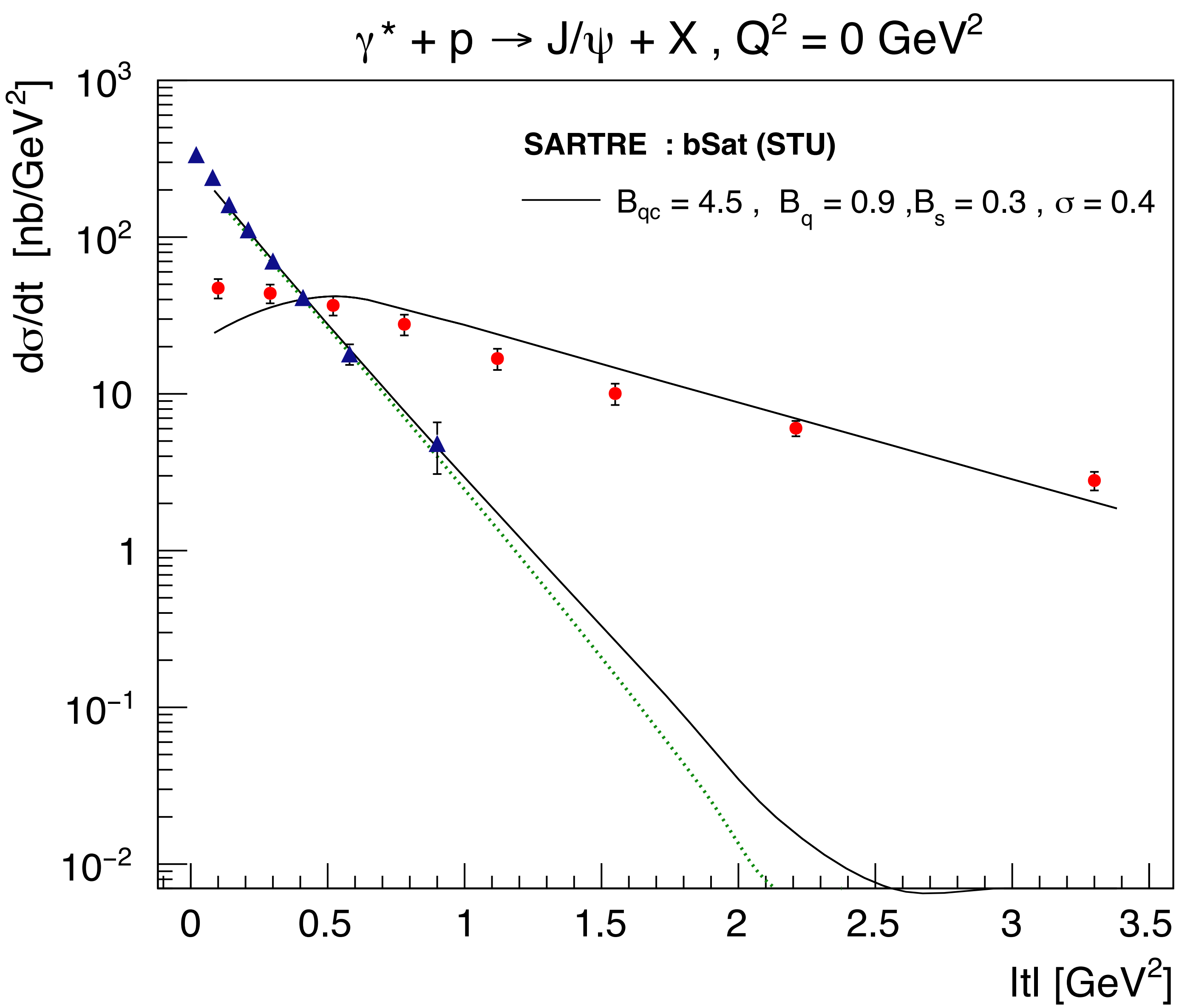
bSat: Non-linear relation

$$\frac{d\sigma_{\text{dip}}}{d^2\mathbf{b}} = 2\left[1 - \exp\left(-r^2 \frac{\pi^2}{2N_C} \alpha_s(\mu^2) x g(x, \mu^2) T_p(b)\right)\right]$$

Heikki Mänysaari, *Rept.Prog.Phys.* 83 (2020) 8, 082201

"As the coherent cross section is only sensitive to the average structure of the target, or to the average dipole-target scattering amplitude, it would also be possible in principle to construct a parametrization for the fluctuating proton structure which leaves the average dipole-target interaction intact. Note that Eq. (13) modifies the average proton shape, due to the non-linear dependence on the density function T_p in the dipole amplitude (8). Consequently, the different results for the coherent cross section should not be taken to quantify the effect of proton shape fluctuations on coherent J/ψ production. "

Subnucleon Fluctuations in protons



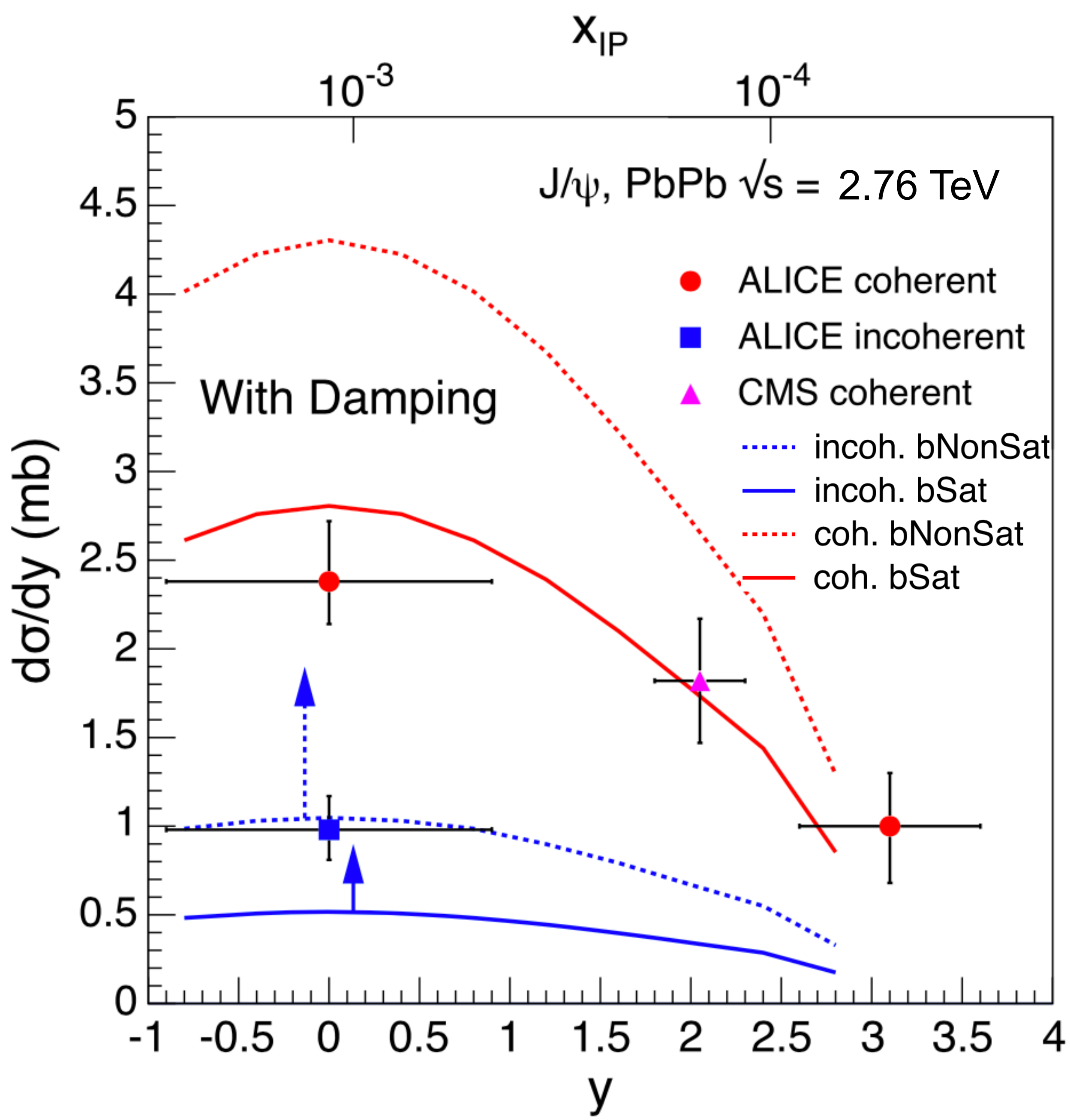
$$T_p(\overrightarrow{b}) = \frac{1}{N_q}\sum_{i=1}^{N_q}\frac{1}{2\pi B_q}\frac{1}{e^{\frac{(\overrightarrow{b}_T - \overrightarrow{b}_{Ti})^2}{2B_q}} - B_s}$$

Here B_s is a parameter,
for $B_S = 0$ we have the usual Gaussian,
for $B_S = 1$ it is a Bose-Einstein distribution.

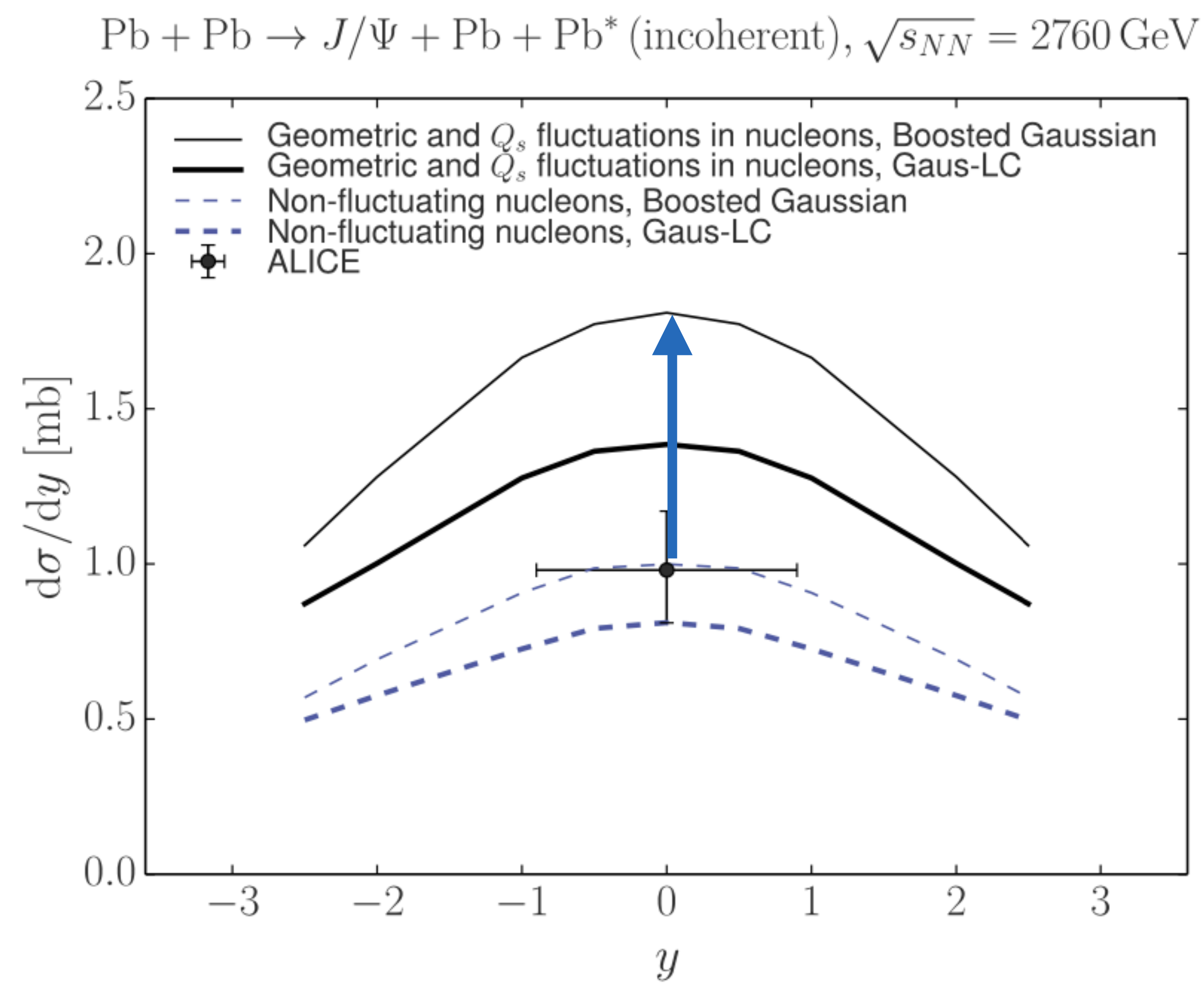
We call this "Modified Gaussian"

Subnucleon Fluctuations in Nuclei

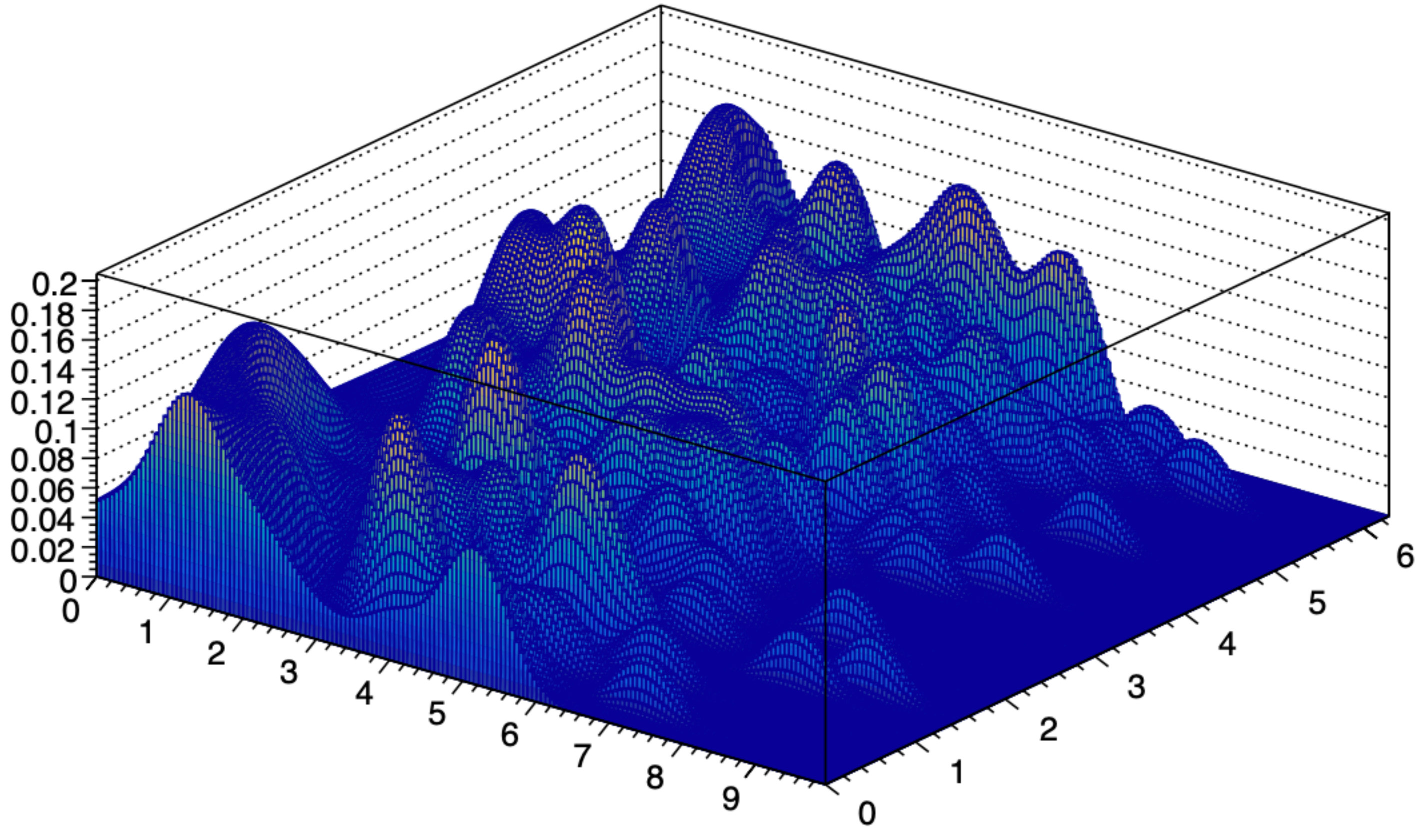
Subnucleon Fluctuations in Nuclei
Status early 2020

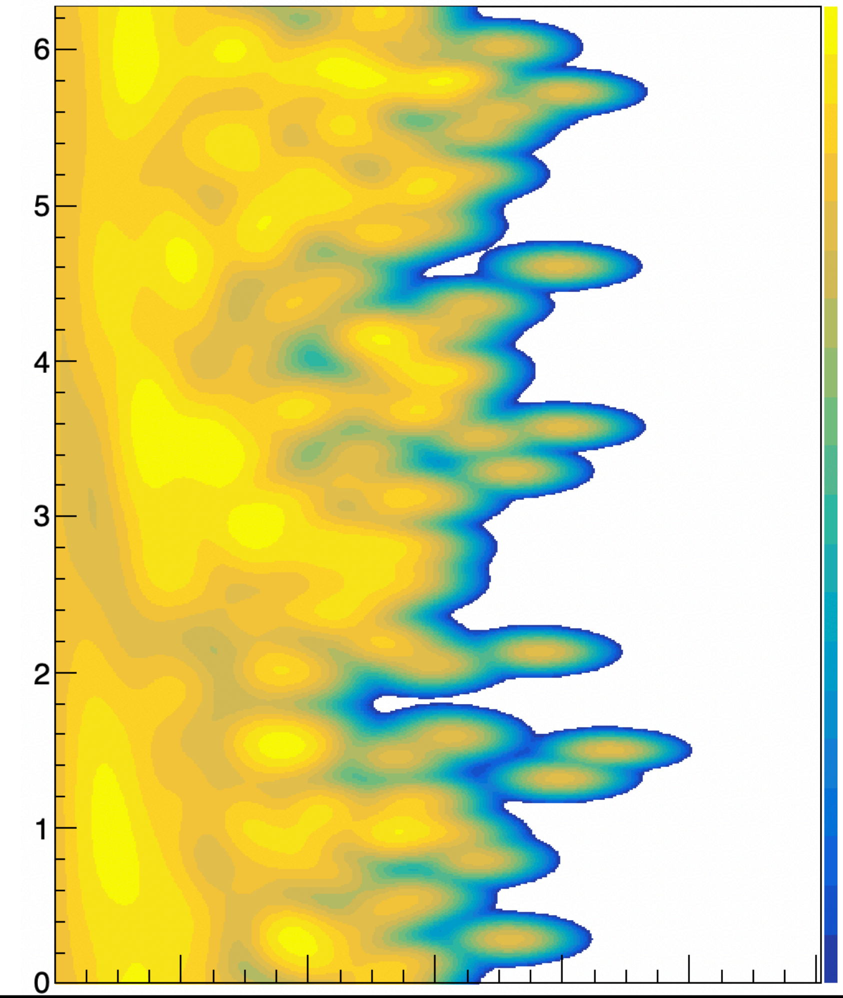


B. Sambasivam, TT and T. Ullrich, Investigating saturation effects in ultraperipheral collisions at the LHC with the color dipole model, Phys. Lett. B803 (2020) 135277



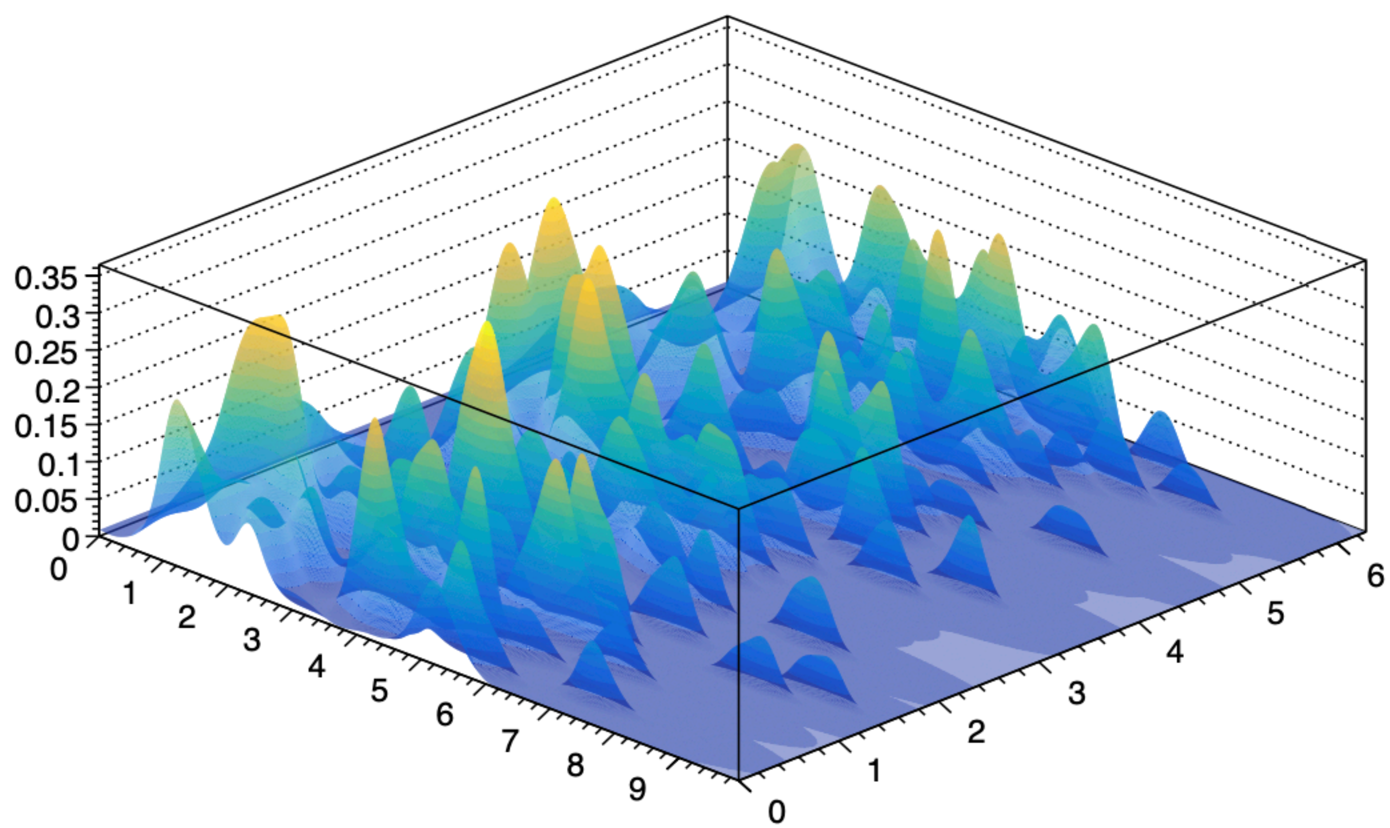
H. Mäntysaari, B. Schenke, Probing subnucleon scale fluctuations in ultra- peripheral heavy ion collisions, Phys. Lett. B 772 (2017) 832–838

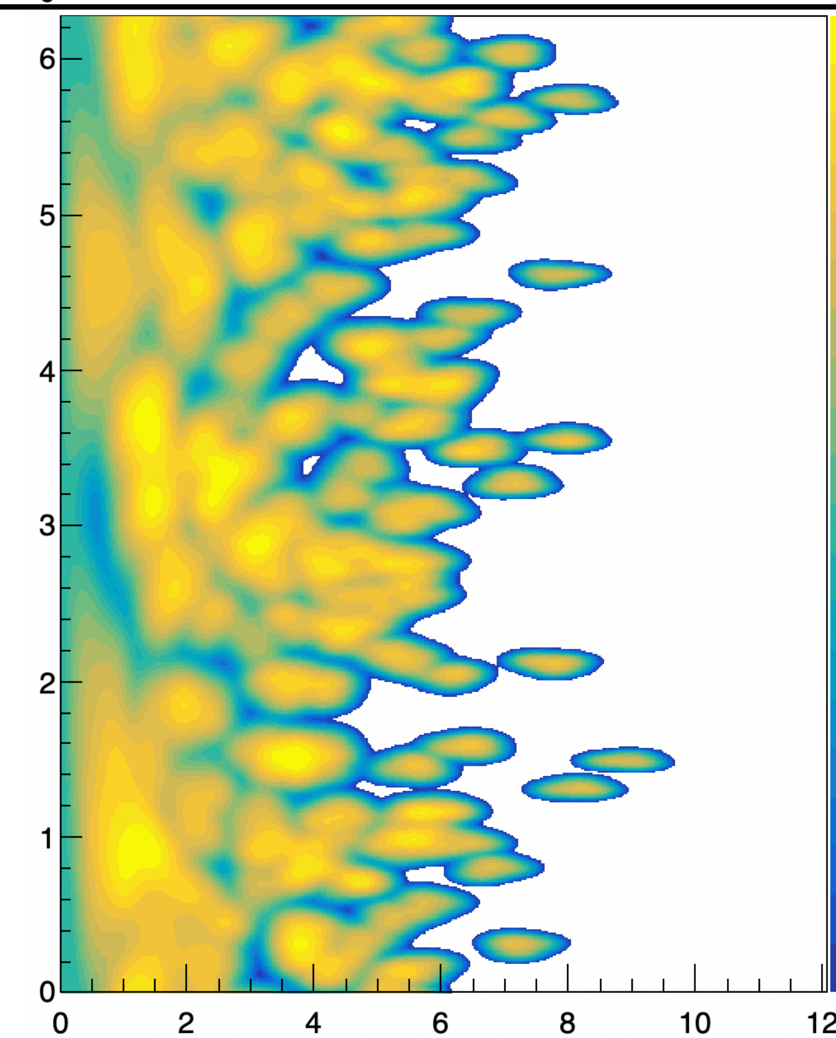




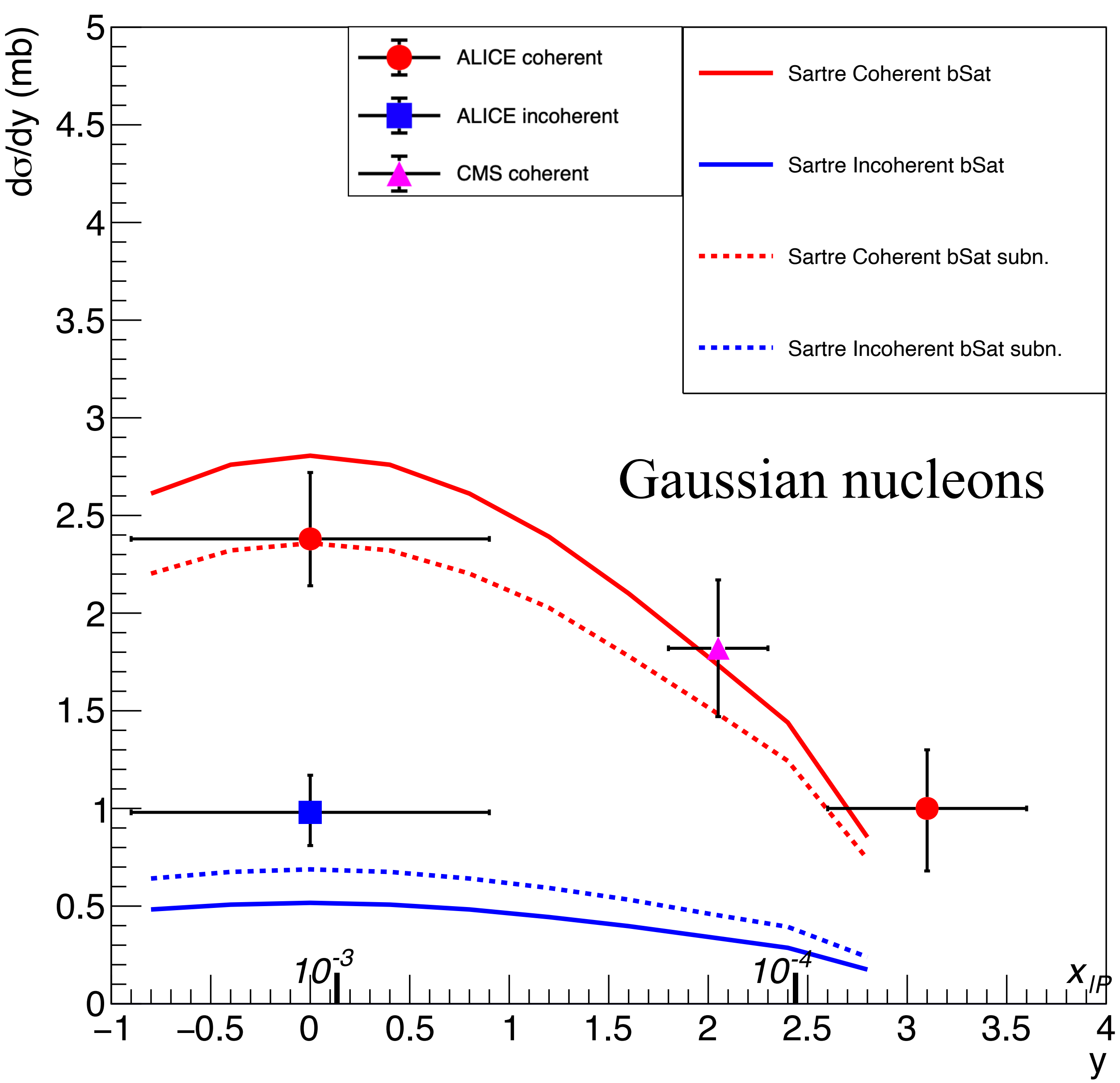
No subnucleon structure

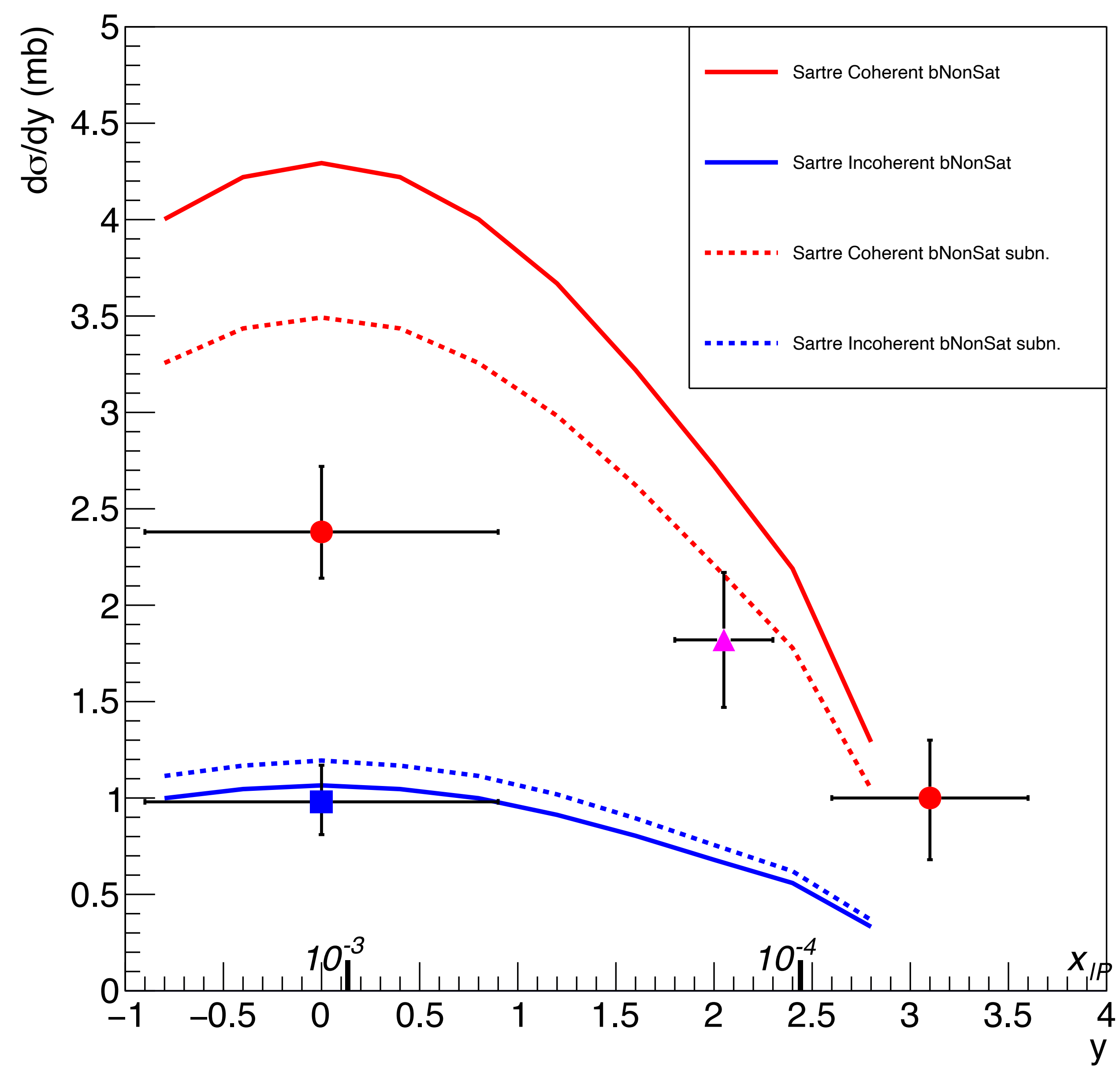
Subnucleon structure (Gaussian)



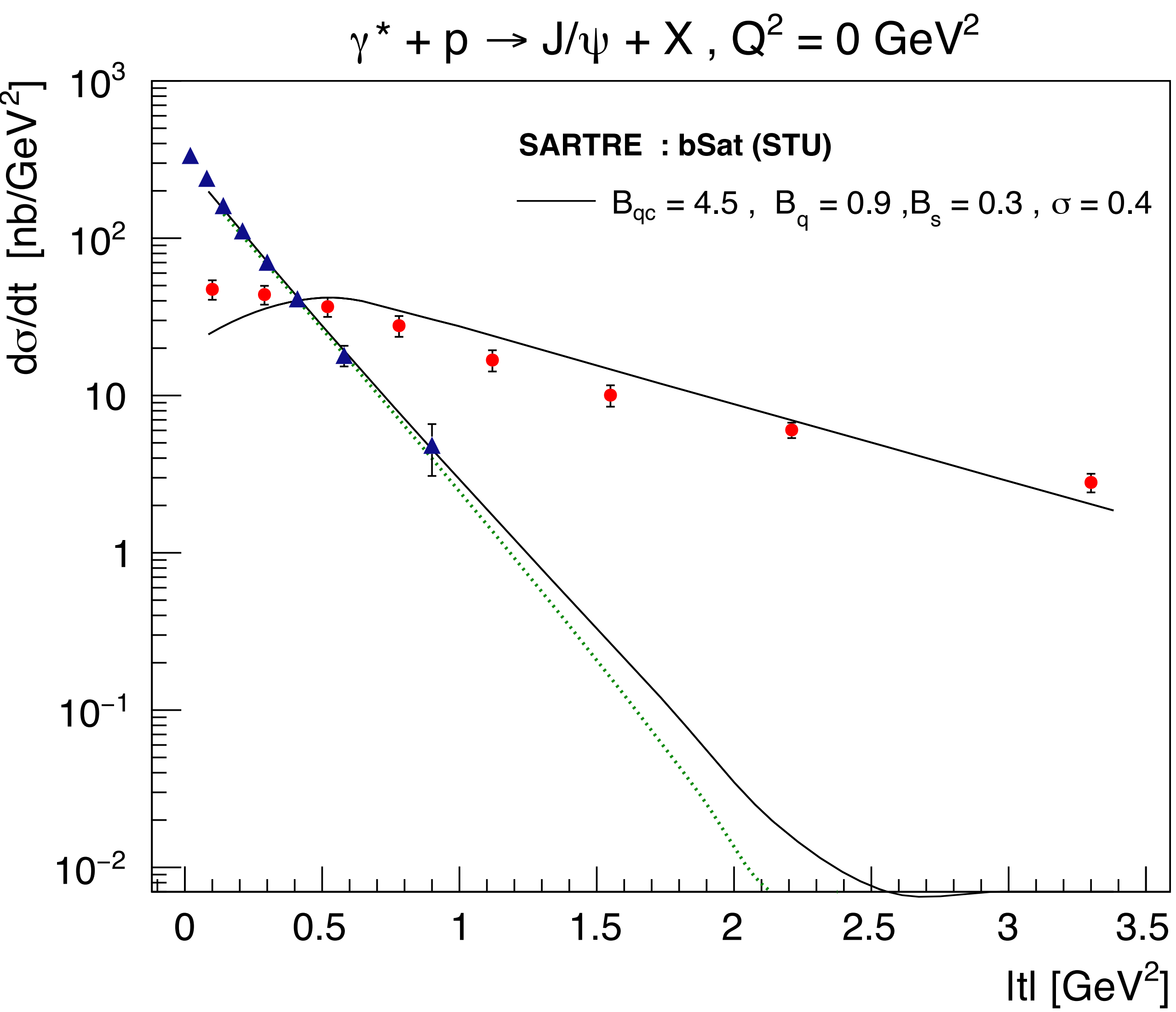


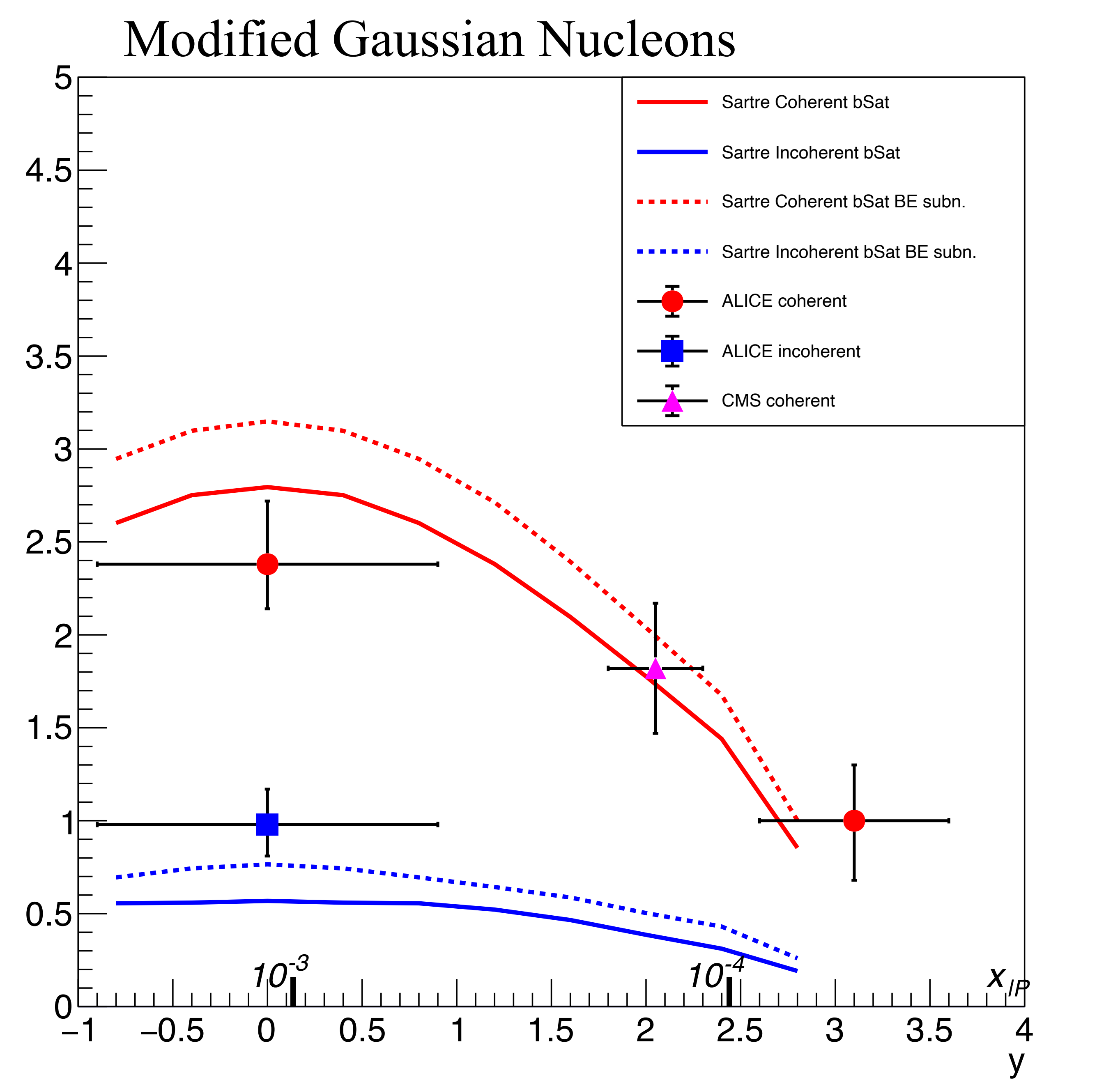
Subnucleon Fluctuations in Nuclei





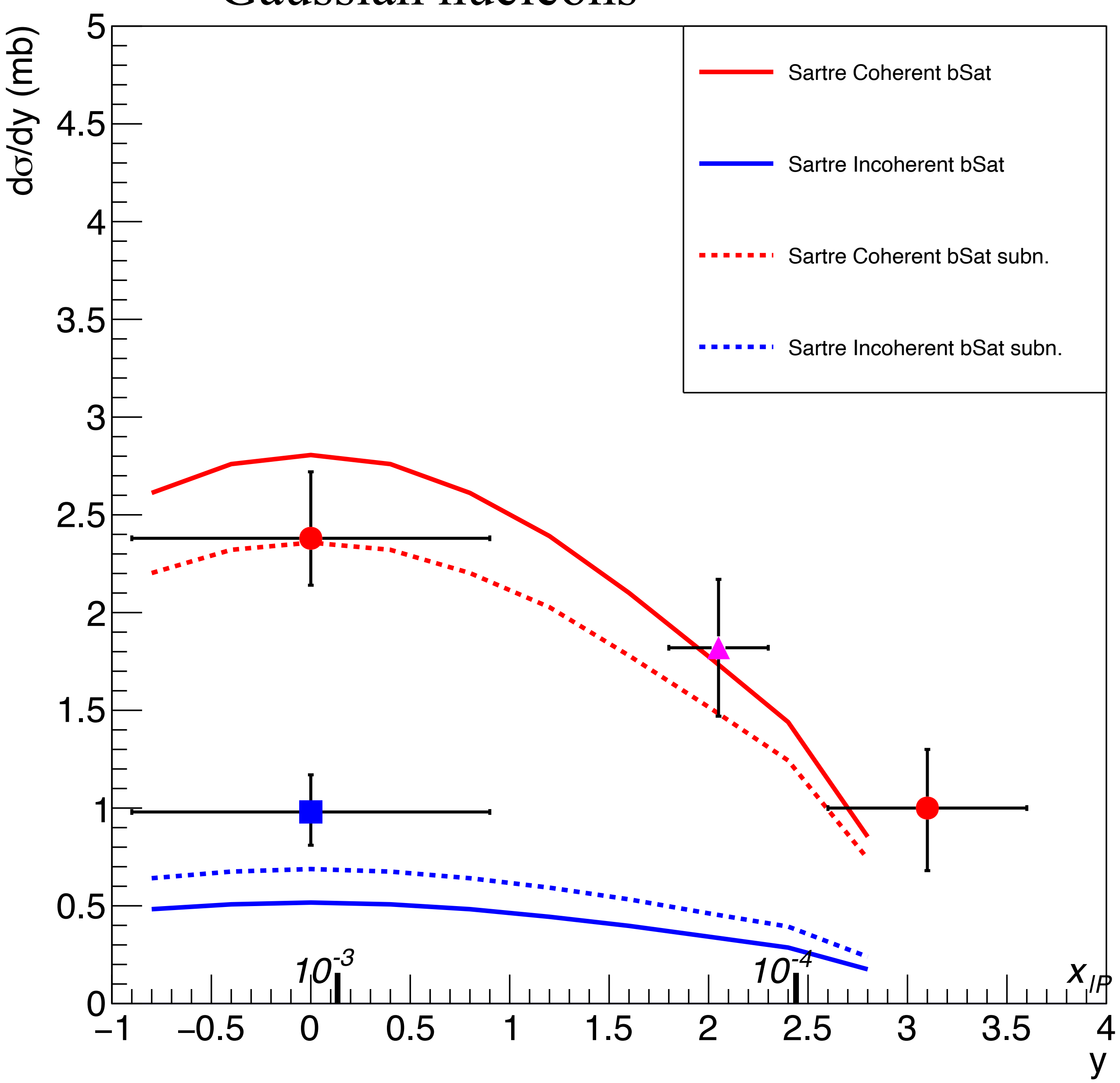
Subnucleon Fluctuations in Nuclei



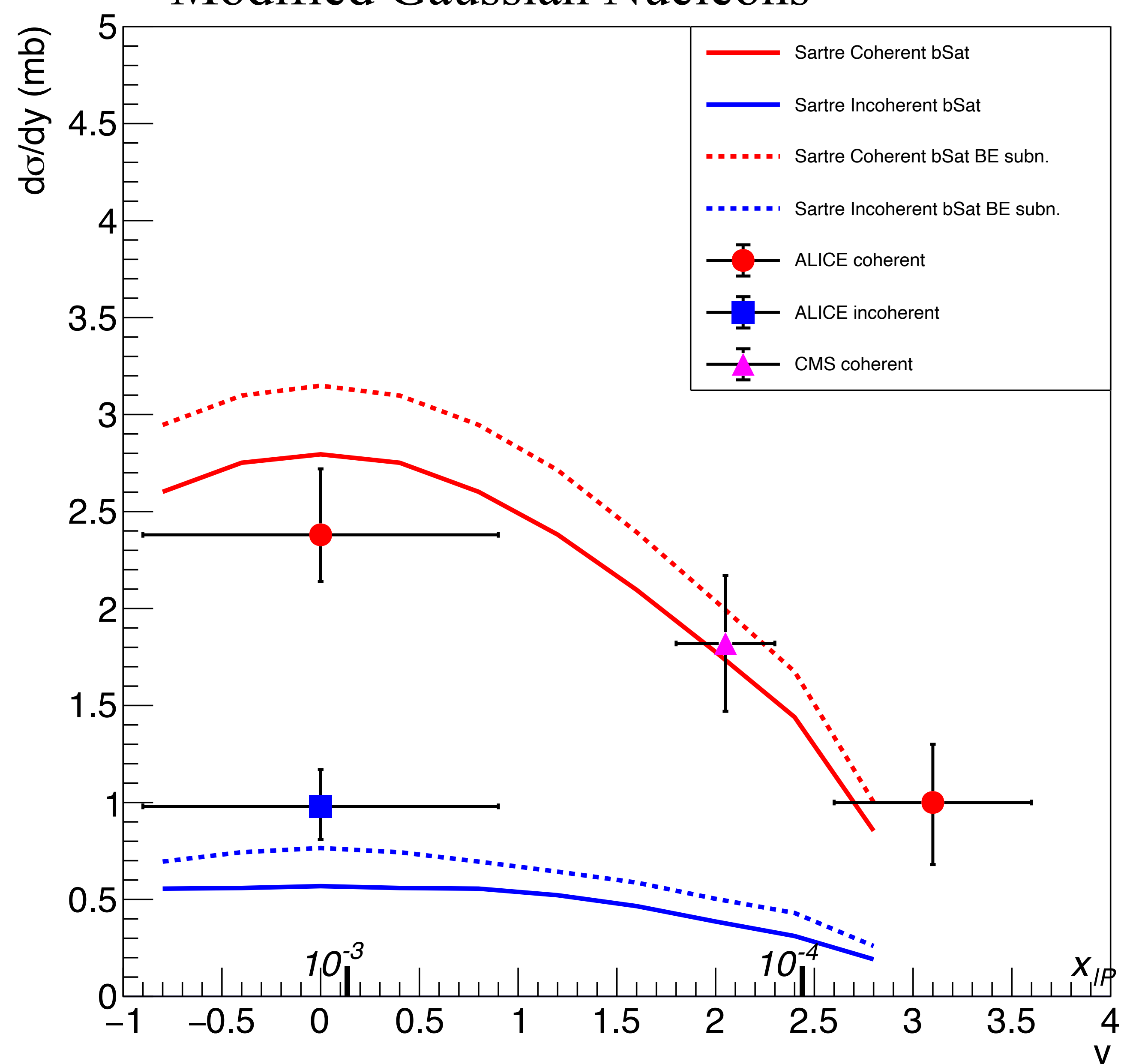


Subnucleon Fluctuations in Nuclei

Gaussian nucleons

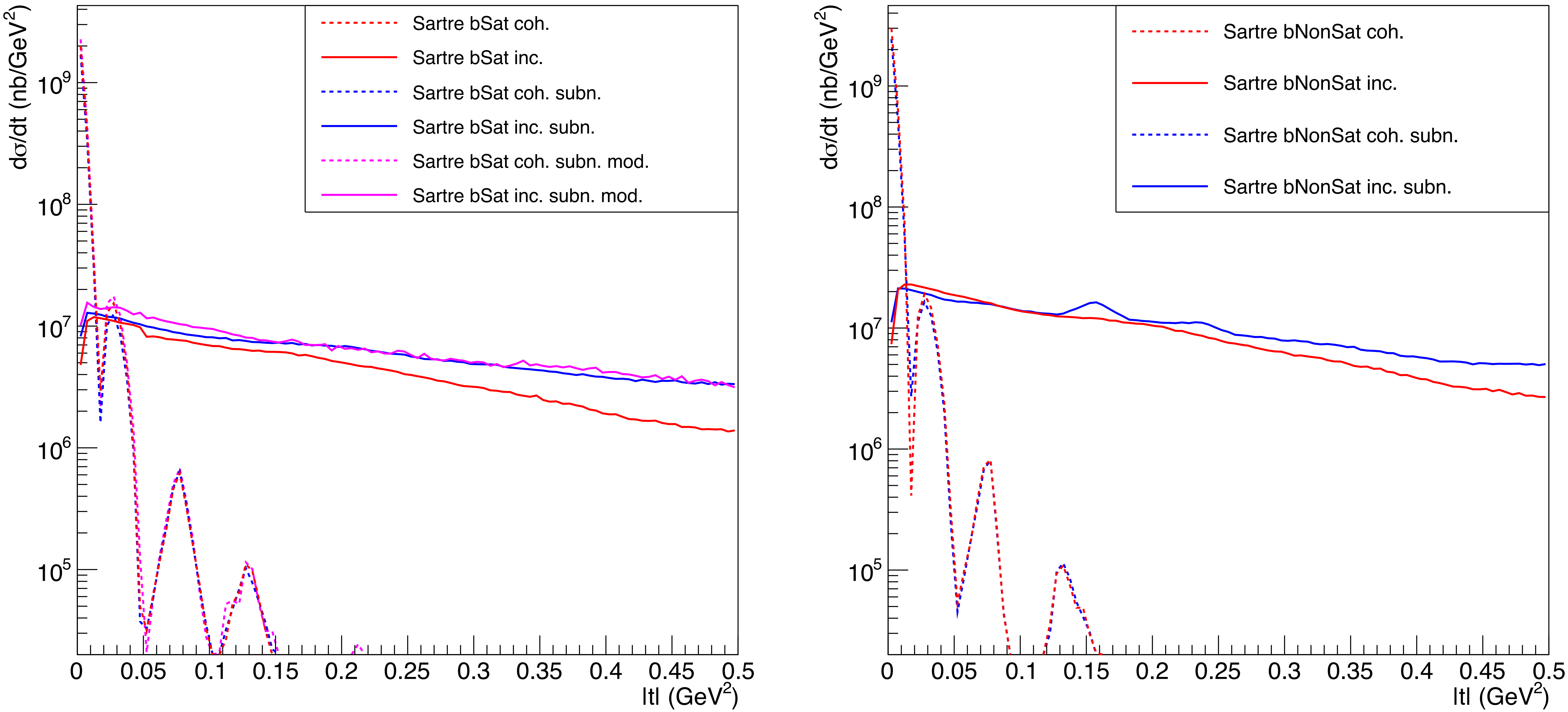


Modified Gaussian Nucleons



Over compensation!

Subnucleon Fluctuations in Nuclei
t-distributions



Subnucleon Fluctuations in Nuclei
Skewedness Corrections

Real part correction: Only imaginary part of amplitude used. We can correct for this by multiplying the ampltiude by $1 + \beta^2$, where β is the real to imaginary ratio:

$$\beta = \tan(\pi\lambda/2), \quad \text{with} \quad \lambda \equiv \frac{\partial \ln \left(\mathcal{A}_{T,L}^{\gamma^* p \to Ep}\right)}{\partial \ln(1/x)}$$

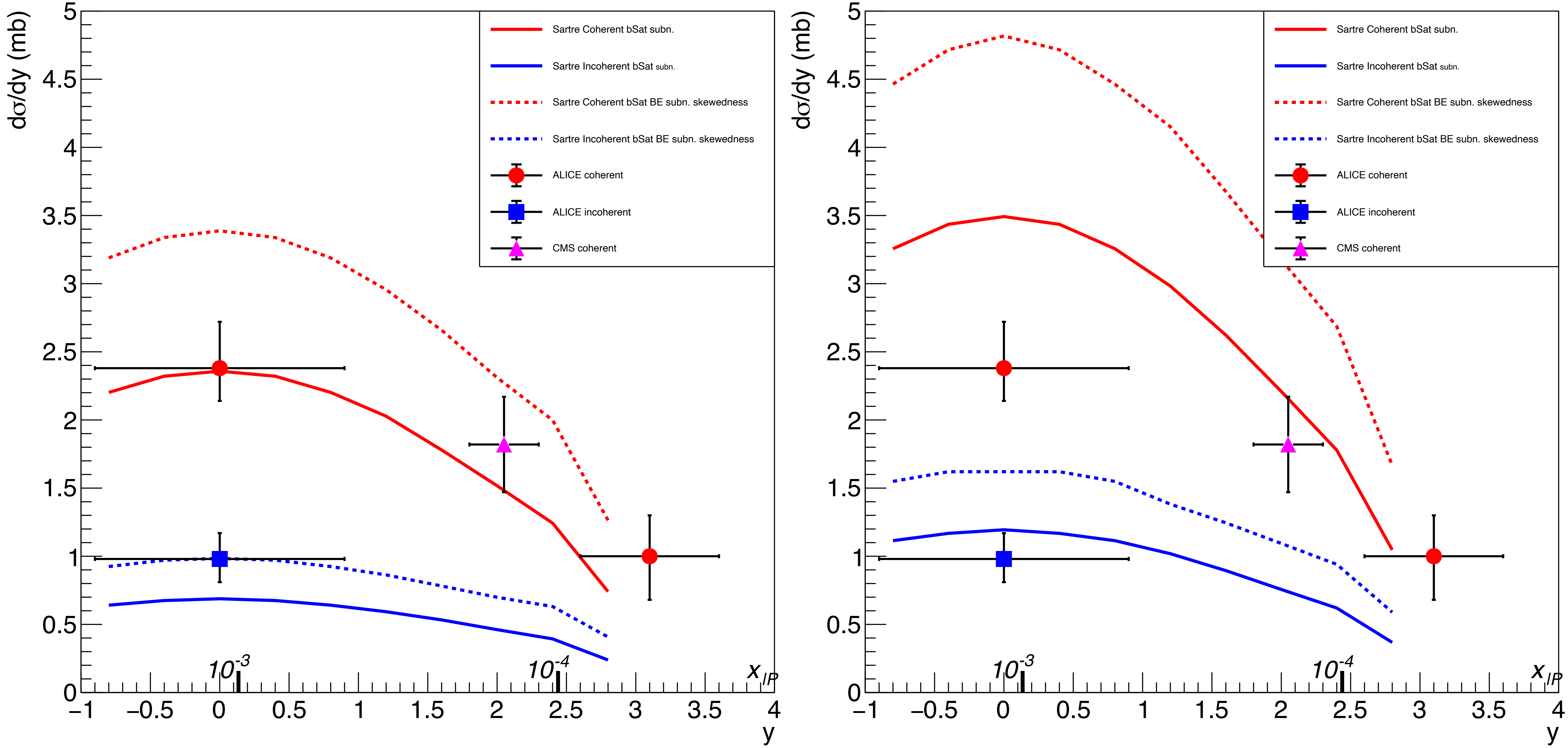
Real part corrections are well motivated!

Skewedness corrections: Cross section multiplied by a factor R_g.

$$R_g(\lambda) = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda + 5/2)}{\Gamma(\lambda + 4)}, \quad \text{with} \quad \lambda \equiv \frac{\partial \ln \left[xg(x, \mu^2)\right]}{\partial \ln(1/x)}$$

Motivated for **linear** cross sections, i.e. **bNonSat** in ***ep***.
Unclear if applicable for **bSat** or bNonSat in ***e*A**.
We chose to **not** use it for any *e*A comparisons in earlier study, since using it only for bNonSat would make saturation statements more unclear.
However, since it is unclear how much skewedness correction should be used,
we can see it as a **model uncertainty.**

Subnucleon Fluctuations in Nuclei
Skewedness Corrections



Summary

We have:

Implemented Subnucleon fluctuation for ep and *e*A

Found a hotspot distribution that reproduces coherent *ep*

Made comparisons to LHC UPC measurements.

- These are well described within uncertainties
- bNonSat is *almost* ruled out.
- Incoherent comparisons are not perfect indicating that there is more to learn.

To Do:

Check converegence of averages.

Finalise the current implementation in the code (big changes for *ep*)

Further investigations in ep.

Tables tables tables…

Etc.

Plan: A short complementary Sar*t*re UPC paper, and an *ep* paper, coming soon…