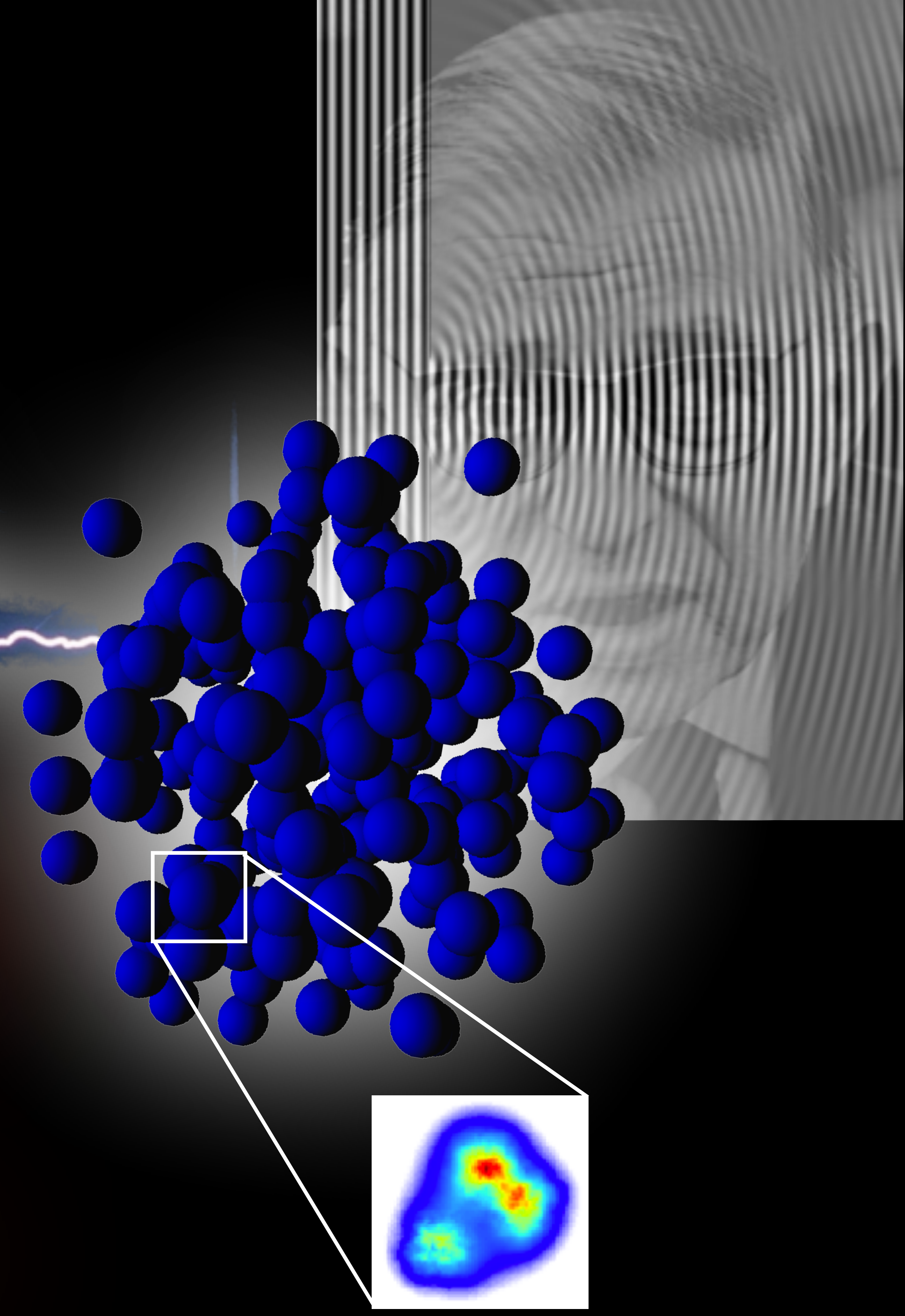
“Sartre:
Event generator of exclusive reaction in *ep*, *e*A and UPC”

MC4EIC

November 17, 2022

Tobias Toll

Indian Institute of Technology Delhi



Outline

What Sartre is:

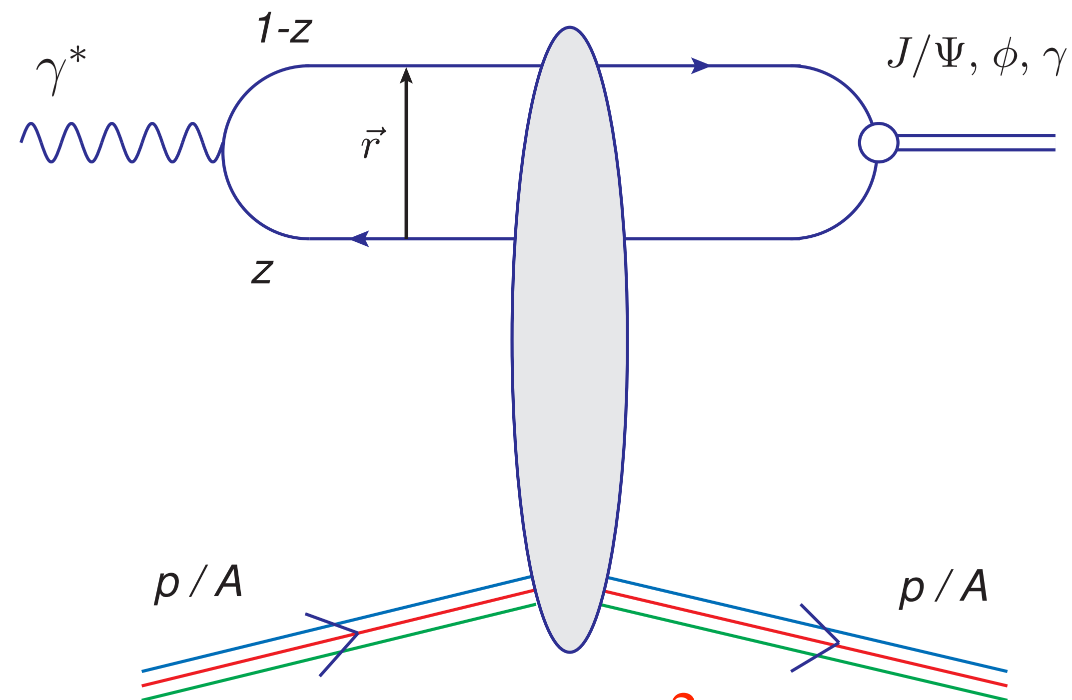
What is in the official release found here: https://sartre.hepforge.org/

What Sartre will be:

The areas that we are developing at the moment (subnucleon structure, machine learning, inclusive diffraction)

H. Kowalski, L. Motyka, G. Watt, Phys.Rev.D 74 (2006) 074016, arXiv: hep-ph/0606272

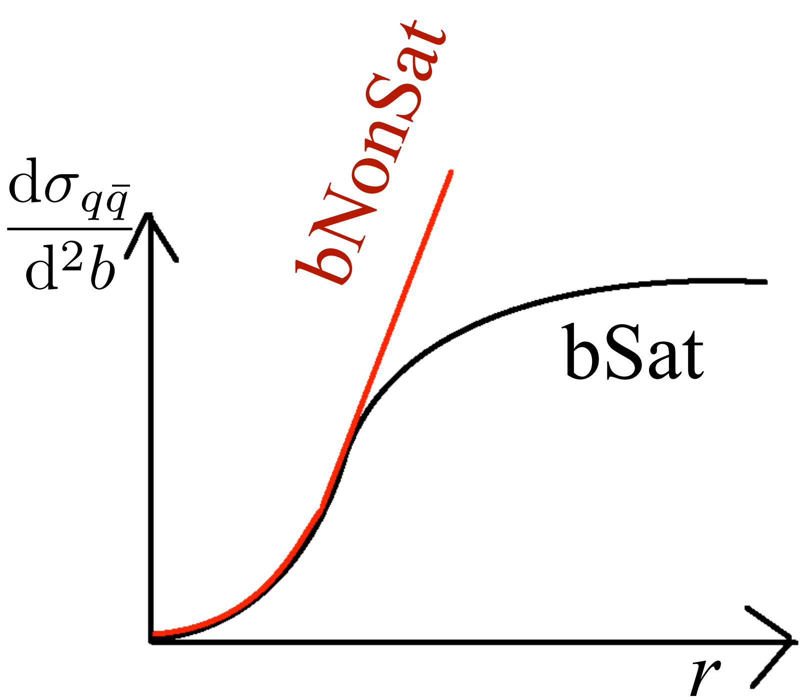
Exclusive diffraction Sar*t*re



$$t = -\Delta^2$$

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp}}{\mathrm{d}t} = \frac{1}{16\pi} \left\langle \left| \mathcal{A}^{\gamma^* p \to Vp}_{T,L} \right|^2 \right\rangle_{\text{initial state}}$$

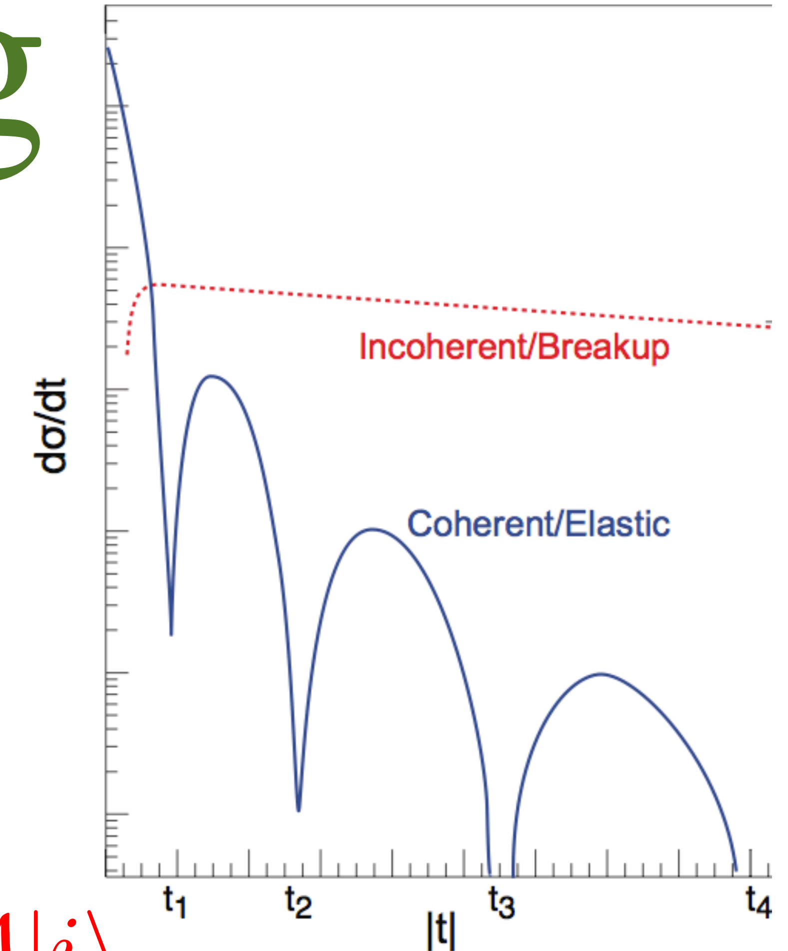
$$\mathcal{A}^{\gamma^* p \to Vp}_{T,L}(x_{I\!P}, Q^2, \Delta) = i \int 2\pi r \mathrm{d}r \int \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\vec{b}\, \left(\Psi_V^* \Psi\right)(r,z) J_0([1-z]r\Delta) e^{-\vec{b}\cdot\vec{\Delta}} \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\vec{b}}(x_{I\!P}, r, \vec{b})$$



$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b)\right)\right]$$

$$\frac{\mathrm{d}\sigma^{\text{nosat}}_{q\bar{q}}}{\mathrm{d}\mathbf{b}} = \frac{\pi^2}{N_C} r^2 \alpha_S(\mu^2) x g(x, \mu^2) T(b)$$

Incoherent Scattering



Good, Walker:

Nucleus dissociates ($f \neq i$):

$$\sigma_{\text{incoherent}} \propto \sum_{f \neq i} \langle i|\mathcal{A}|f\rangle^{\dagger} \langle f|\mathcal{A}|i\rangle$$

$$= \sum_{f} \langle i|\mathcal{A}\overbrace{|f\rangle^{\dagger} \langle f|}^{\text{complete set}}\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^{\dagger} \langle i|\mathcal{A}|i\rangle$$

$$= \left\langle i \left| |\mathcal{A}|^2 \right| i \right\rangle - |\langle i|\mathcal{A}|i\rangle|^2 = \left\langle |\mathcal{A}|^2 \right\rangle - |\langle \mathcal{A} \rangle|^2$$

The incoherent CS is the variance of the amplitude!!

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

The nucleus as a collection of nucleons

TT, Thomas Ullrich
Phys.Rev.C 87 (2013) 2, 024913, arXiv: 1211.3048
Comput.Phys.Commun. 185 (2014) 1835-1853 arXiv:1307.8059

Independent scattering approximations:

$$1 - \frac{1}{2}\frac{\mathrm{d}\sigma^{(p)}_{q\bar{q}}}{\mathrm{d}^2\vec{b}}(x_{I\!P}, r, \vec{b}) = \prod_{i=1}^{A}\left(1 - \frac{1}{2}\frac{\mathrm{d}\sigma^{(A)}_{q\bar{q}}}{\mathrm{d}^2\vec{b}}(x_{I\!P}, r, |\vec{b} - \vec{b}_i|)\right)$$

$$\frac{1}{2}\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\vec{b}}(x_{I\!P}, r, \vec{b}) = 1 - \exp\left(\frac{\pi^2}{2N_C}r^2\alpha_S(\mu^2)xg(x,\mu^2)\sum_{i=1}^{A}T_p(|\vec{b} - \vec{b}_i|)\right)$$

$$T_A(\vec{b}) = \int \mathrm{d}z \frac{\rho_0}{1 + \exp\left(\frac{\sqrt{\vec{b}^2 + z^2} - R_0}{d}\right)} \longrightarrow T_A(\vec{b}) = \sum_{i=1}^{A} T_p(|\vec{b} - \vec{b}_i|)$$

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

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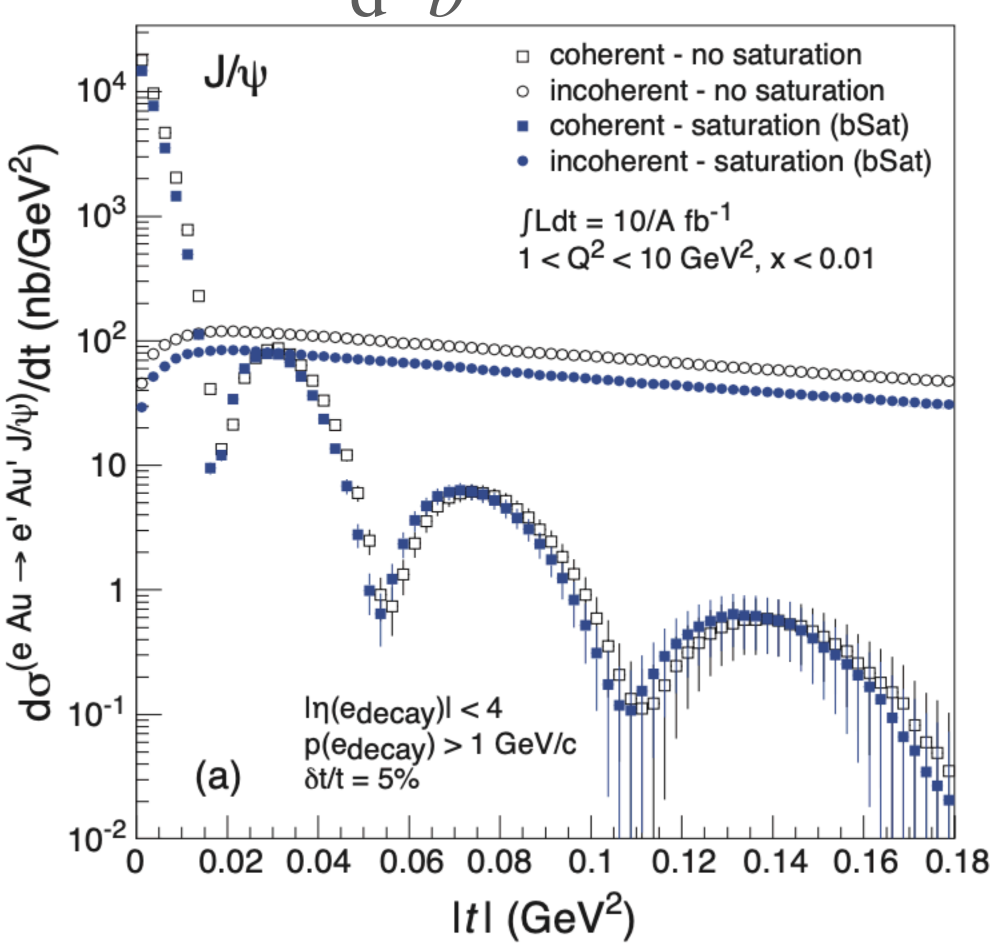
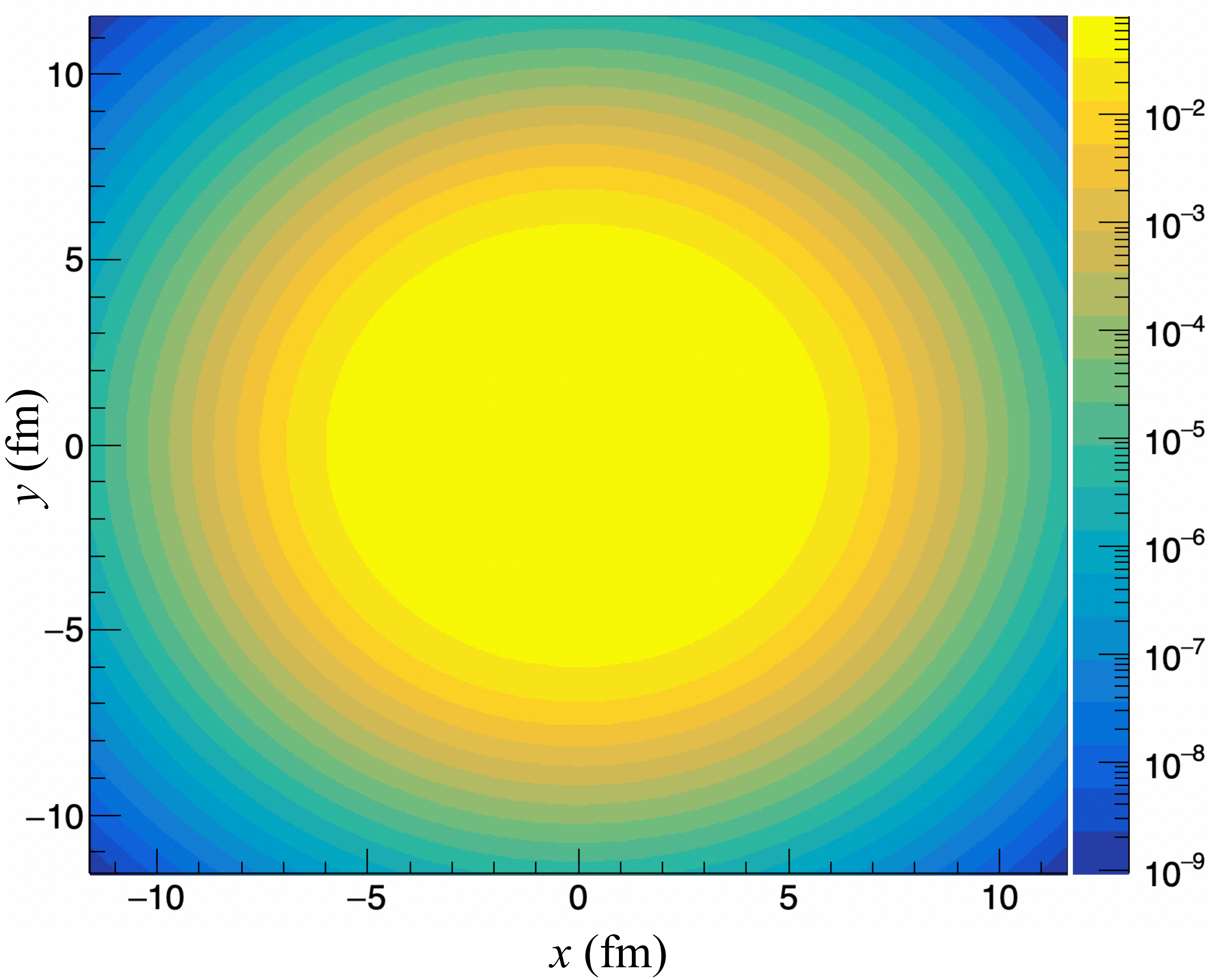


$$T_A(\vec{b}) = \sum_{i=1}^{A} T_p(|\vec{b} - \vec{b}_i|)$$

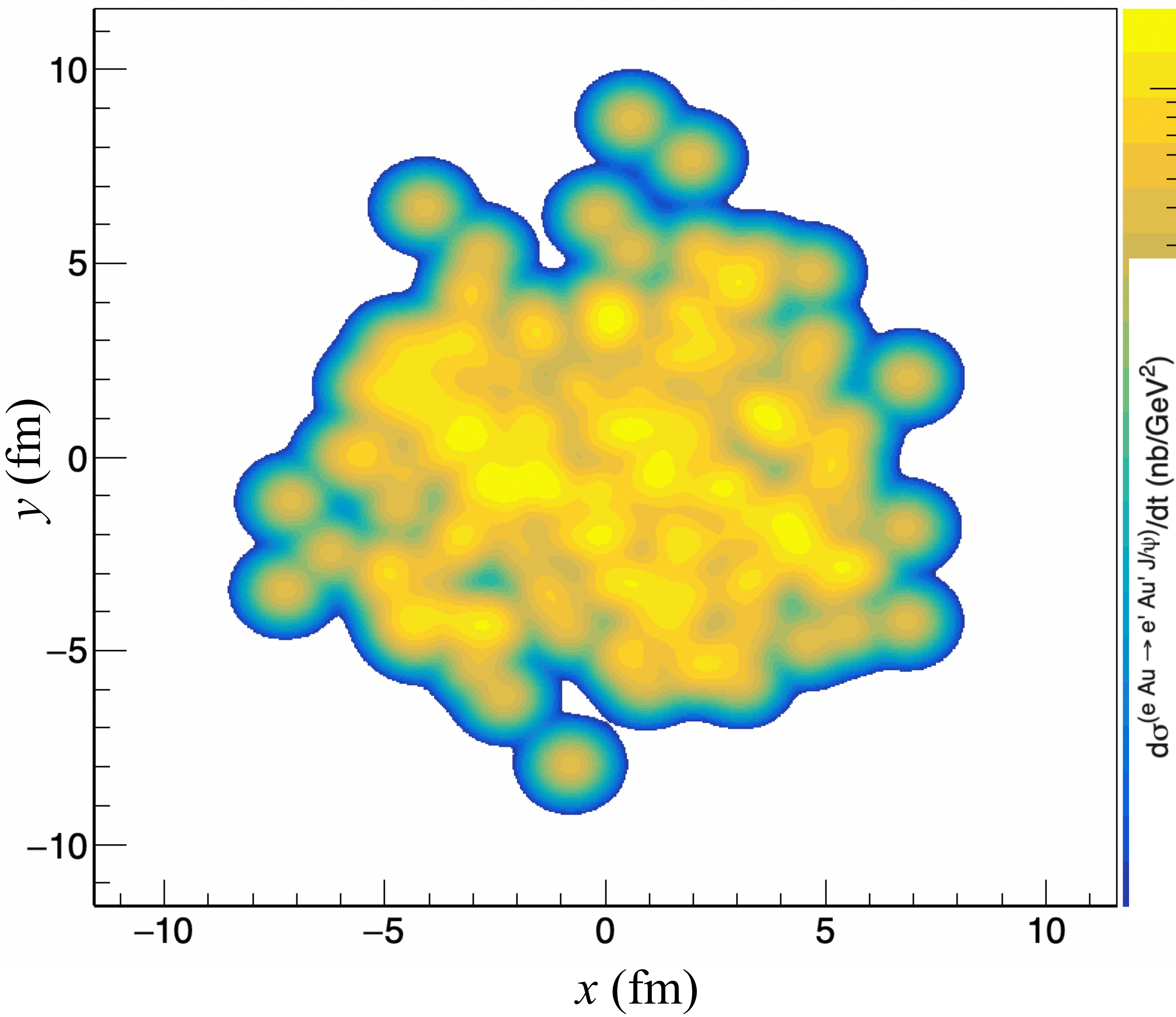
$$T_p(b) = \frac{1}{2\pi B_G} e^{-\frac{b^2}{2B_G}}$$

Into the heavy nucleus

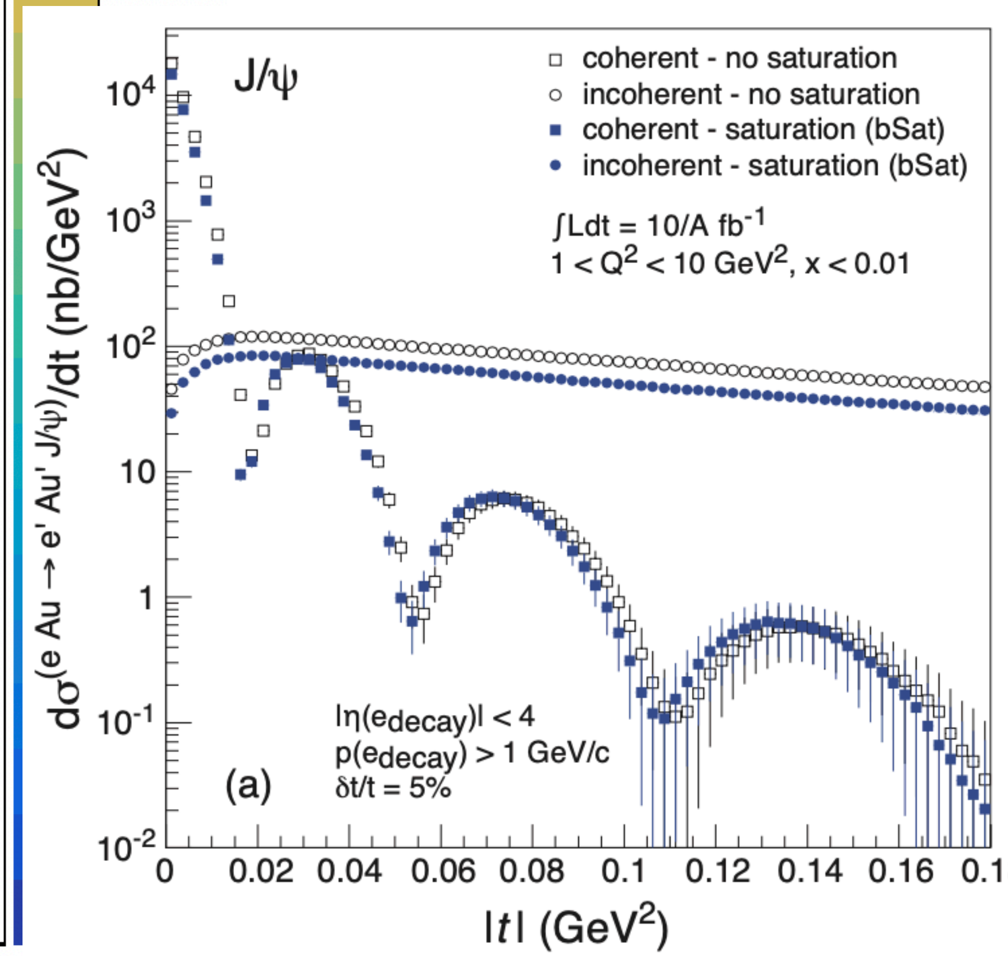


$$|t| = 0$$

Into the heavy nucleus



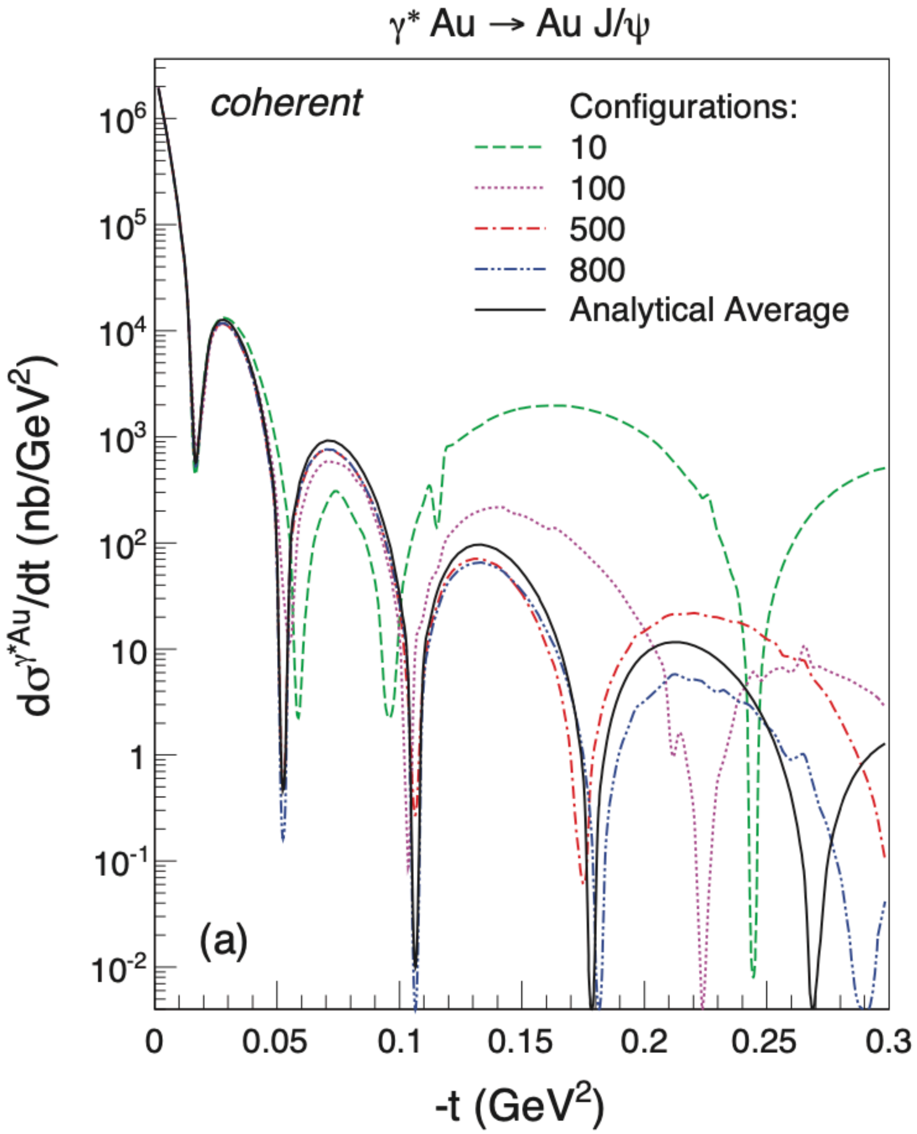
$|t| \lesssim 0.2\ \mathrm{GeV}^2$

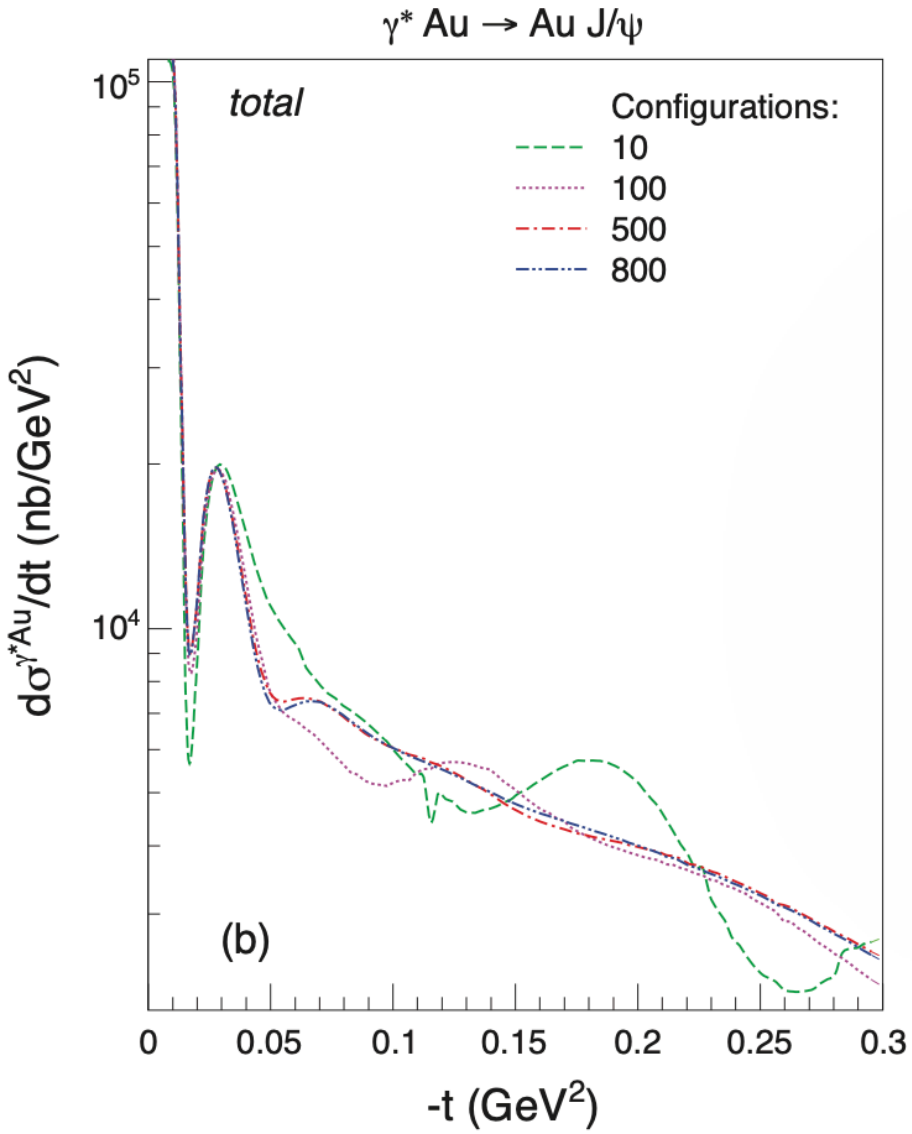


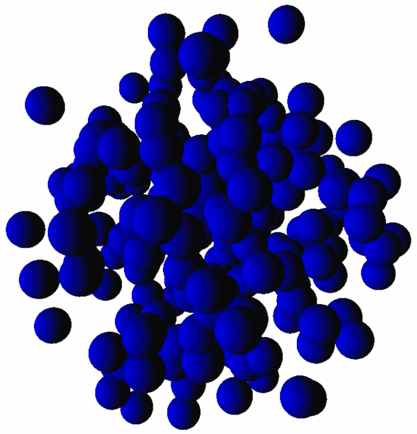
Averaging over nucleon configurations

$$\frac{\mathrm{d}\sigma_{\mathrm{total}}}{\mathrm{d}t} = \frac{1}{16\pi} \left\langle |\mathcal{A}|^2 \right\rangle$$

$$\frac{\mathrm{d}\sigma_{\mathrm{coherent}}}{\mathrm{d}t} = \frac{1}{16\pi} |\langle \mathcal{A} \rangle|^2$$







$$\left\langle \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} \right\rangle_{\Omega} = 2 \left[1 - \left(1 - \frac{T_A(\mathbf{b})}{2} \sigma_{q\bar{q}}^{p} \right)^{A} \right]$$

Need 500 Woods-Saxon configurations

Averaging over nucleon configurations

$$\mathcal{A}_{T,L}^{\gamma^* p \to Vp}(x_{I\!P}, Q^2, \Delta) = i \int 2\pi r \mathrm{d}r \int \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\vec{b} \left(\Psi_V^* \Psi\right)(r,z) J_0([1-z]r\Delta) e^{-\vec{b}\cdot\vec{\Delta}} \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\vec{b}}(x_{I\!P}, r, \vec{b})$$

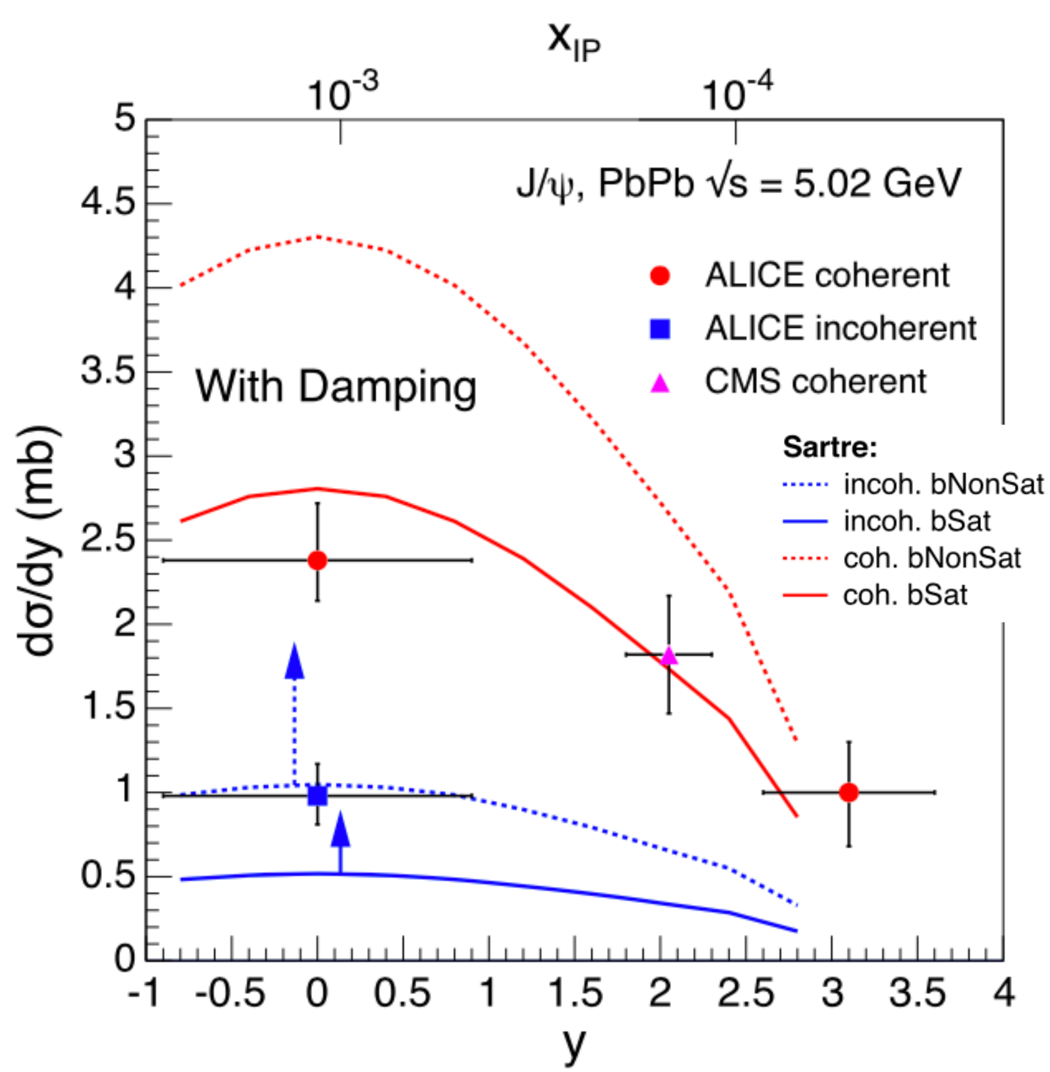
2x500 4D integrals for each point in phase-space (Q^2, W^2, t)
Not feasible for event generation.
Sartre split into two parts:
1. Lookup table creation, which contains all the physics of the Dipole Model.
3D lookup tables for the first and second moment of the amplitude
(and also for the variance)
2. Event Generation, using the lookup tables as an input for creating a PDF.

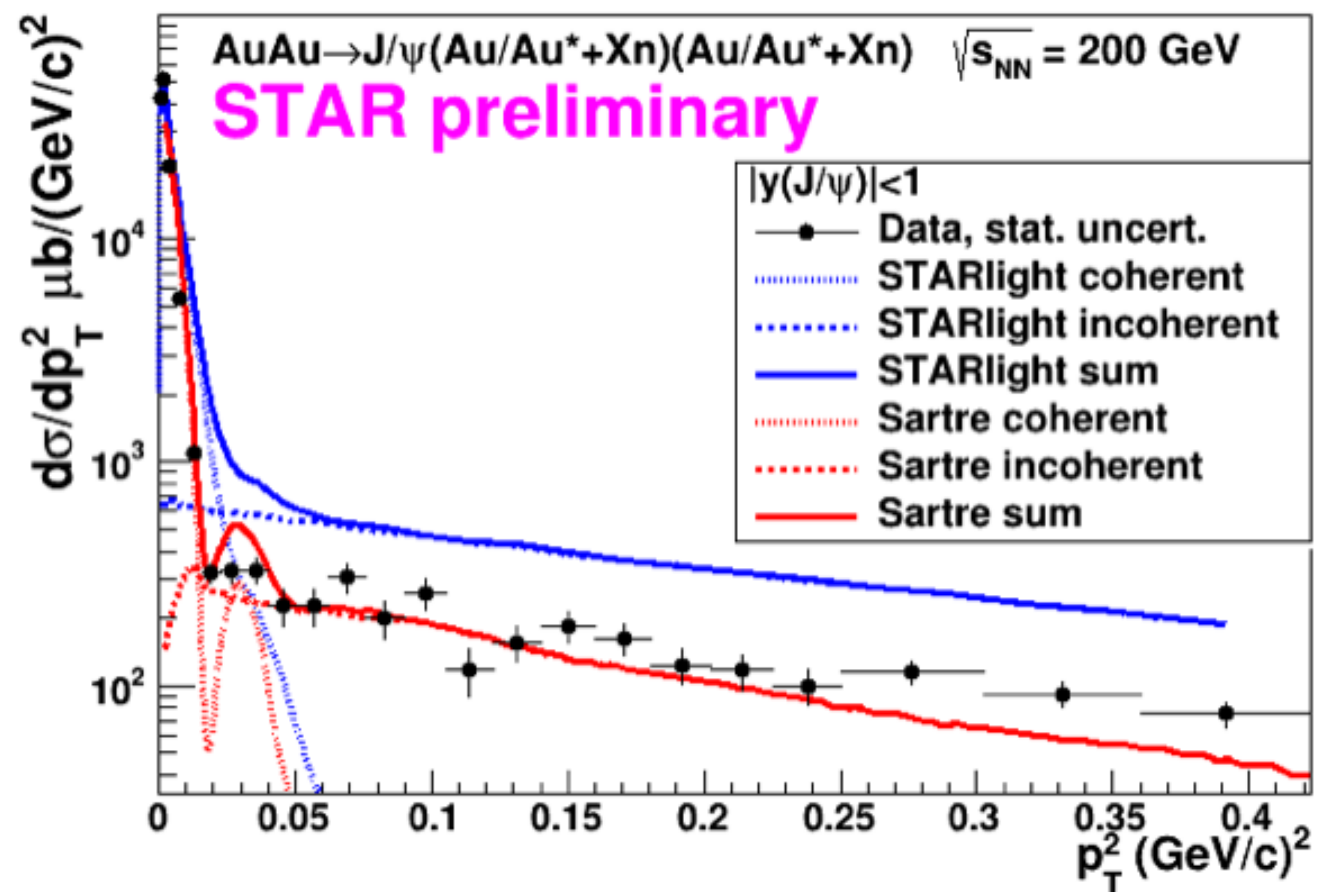
Need a separate table for each: Nuclear Species, Exclusive final state
Drawback: These tables take months to create on computer farms. If we make changes to the model we need to make new tables.
Benefit: Event generation from lookup tables very fast, ~1 ms/event.

Ultra-Peripheral Collisions

This is photo-production, tables only need to be 2D ($x_{I\!P}$, t)

More flexibility, takes 2-3 days to produce. Can use UPC to test the nuclear model.





Bharath Sambasivam, TT, Thomas Ullrich, Phys.Lett.B 803 (2020), 135277

DIS 2021

Current Development 1: Subnucleon structure
Work with Arjun Kumar

Hotspot model for incoherent *ep*-scattering

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x,\mu^2) T(b)\right)\right]$$

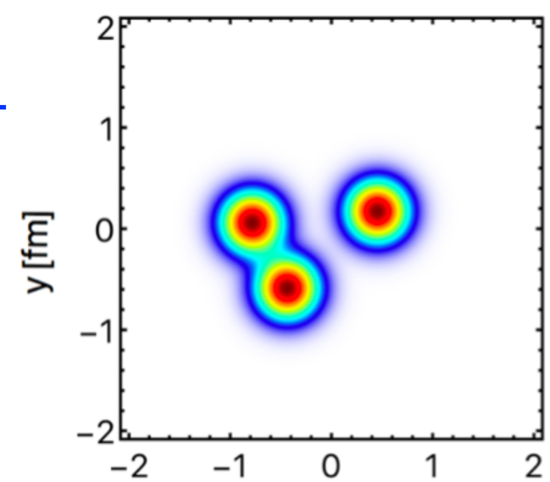
$$xg(x,\mu_0^2) = A_g x^{-\lambda_g}(1-x)^6$$

$$\mu^2 = \mu_0^2 + \frac{C}{r^2}$$

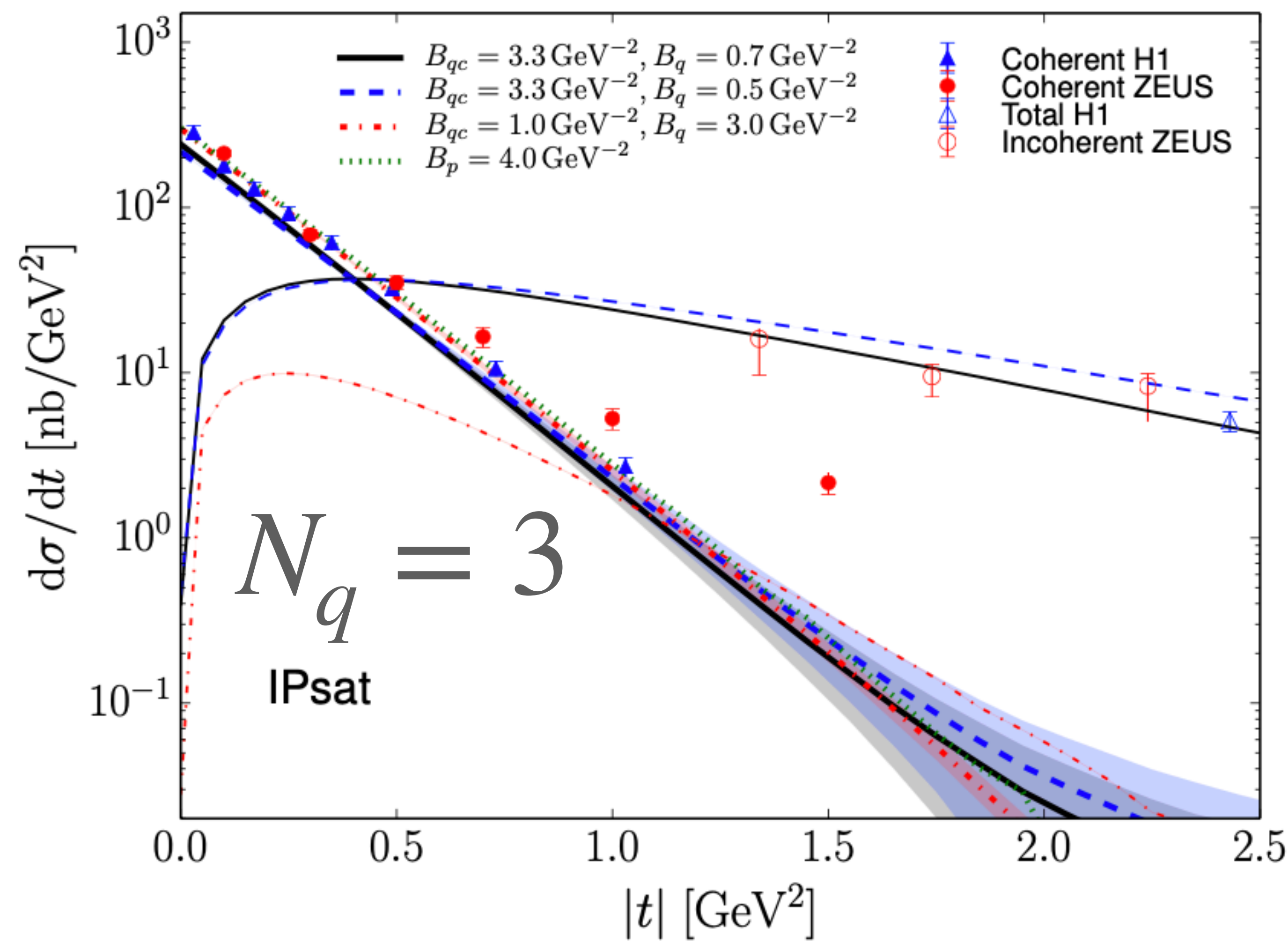
$$T_p(b) = \frac{1}{2\pi B_G} e^{-\frac{b^2}{2B_G}}$$

$$\downarrow$$

$$T_p(b) = \frac{1}{2\pi N_q B_q} \sum_{i=1}^{N_q} e^{-\frac{(\vec{b} - \vec{b}_i)^2}{2B_q}}$$



$\vec{b}_i$ with a Gaussian distribution of width B_{qc}



H. Mäntysaari and B. Schenke Phys. Rev. Lett., 117(5):052301, 2016.

Also: large scale (small $|t|$) saturation scale fluctuations. Affects small $|t|$, one more parameter.

Incoherent Scattering in *ep*

$$\frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) xg(x,\mu^2) T(b)\right)\right]$$

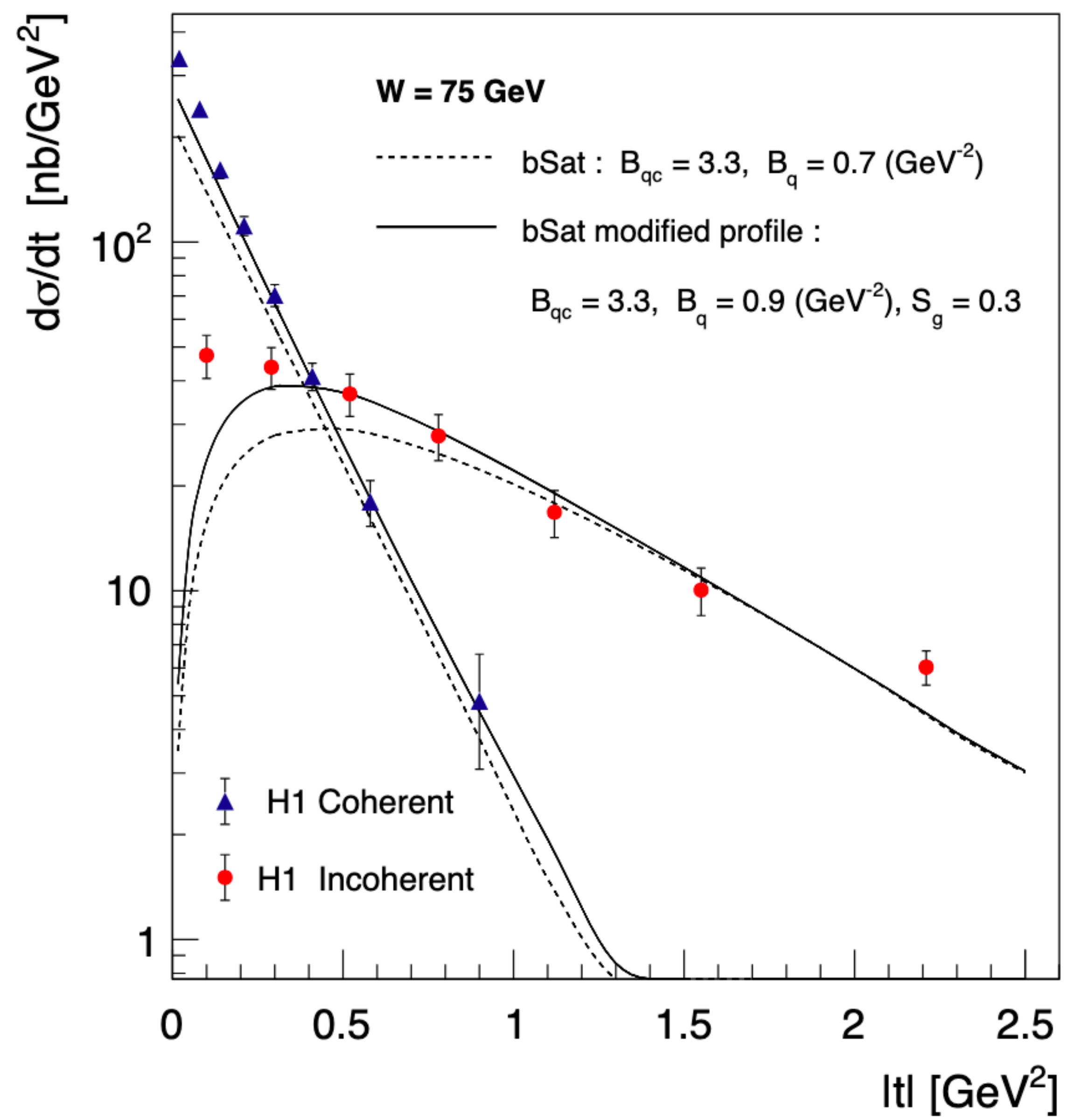
$$xg(x,\mu_0^2) = A_g x^{-\lambda_g}(1-x)^6$$

$$\mu^2 = \mu_0^2 + \frac{C}{r^2}$$

Modified profile:

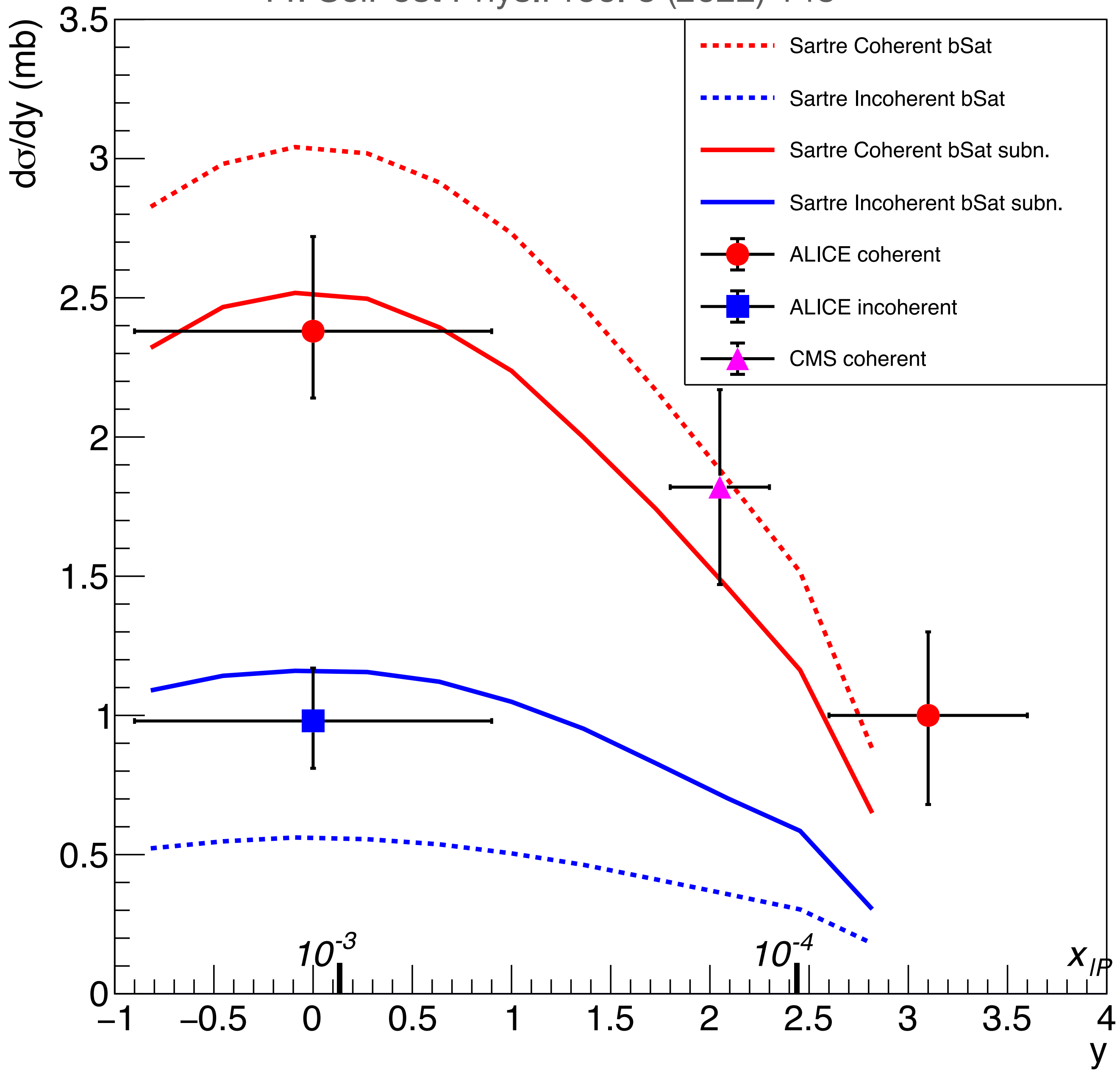
$$T_q(b) = \frac{1}{2\pi B_q} \frac{1}{\exp\left(\frac{b^2}{2B_q}\right) - S_g}$$

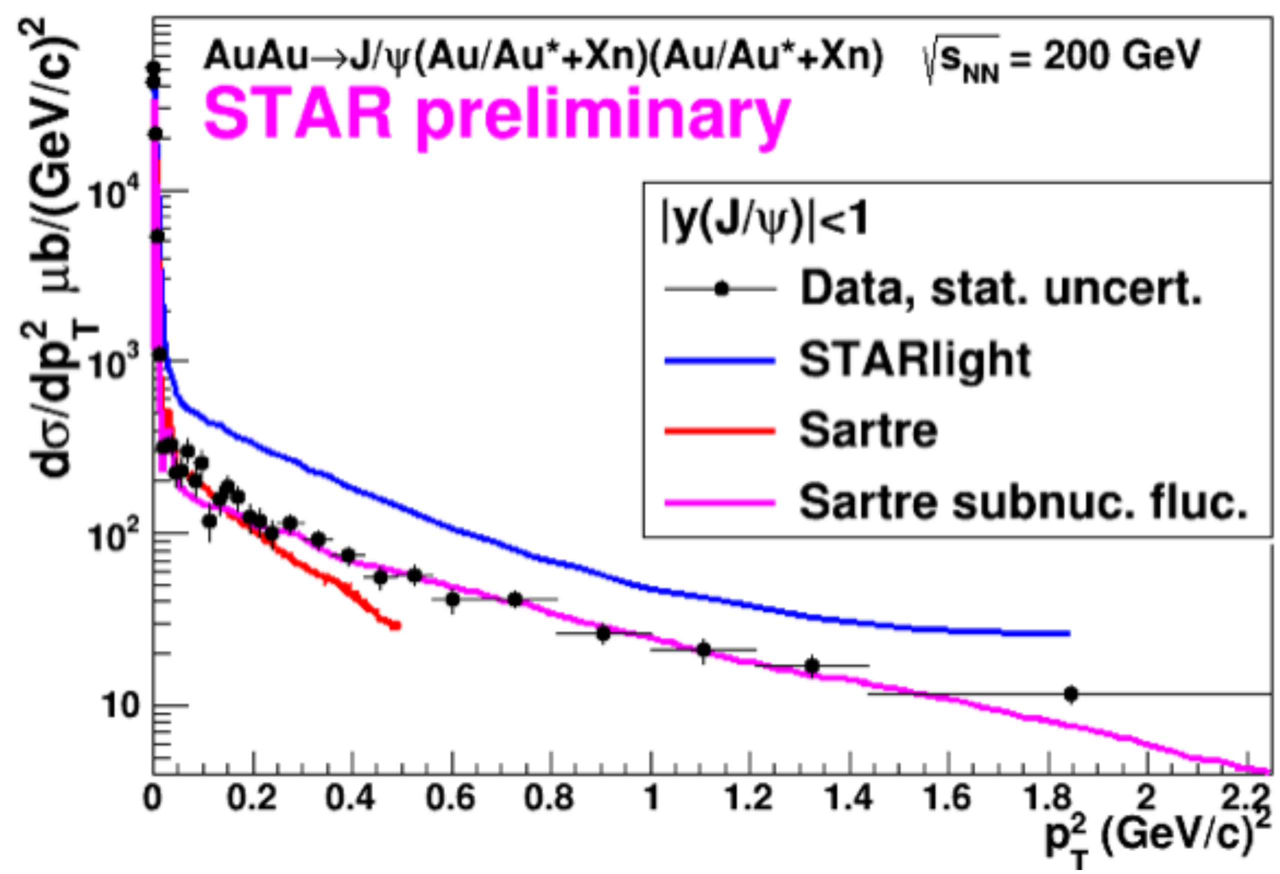
$\vec{b}_i$ with a Gaussian distribution of width B_{qc}



Arjun Kumar, TT, Eur.Phys.J.C 82 (2022) 9, 837, arXiv: 2106.12855

A-A UPC at the LHC & RHIC

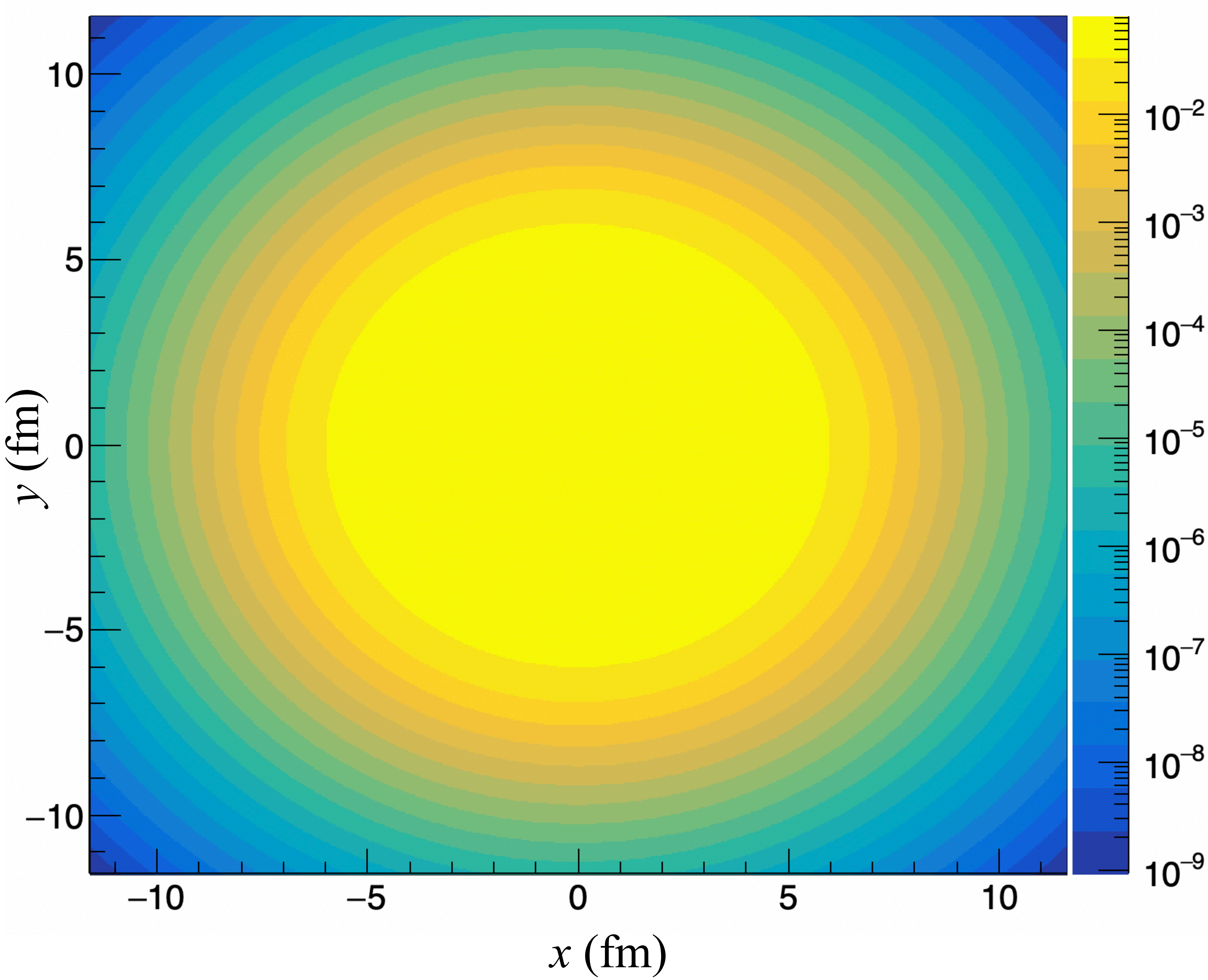




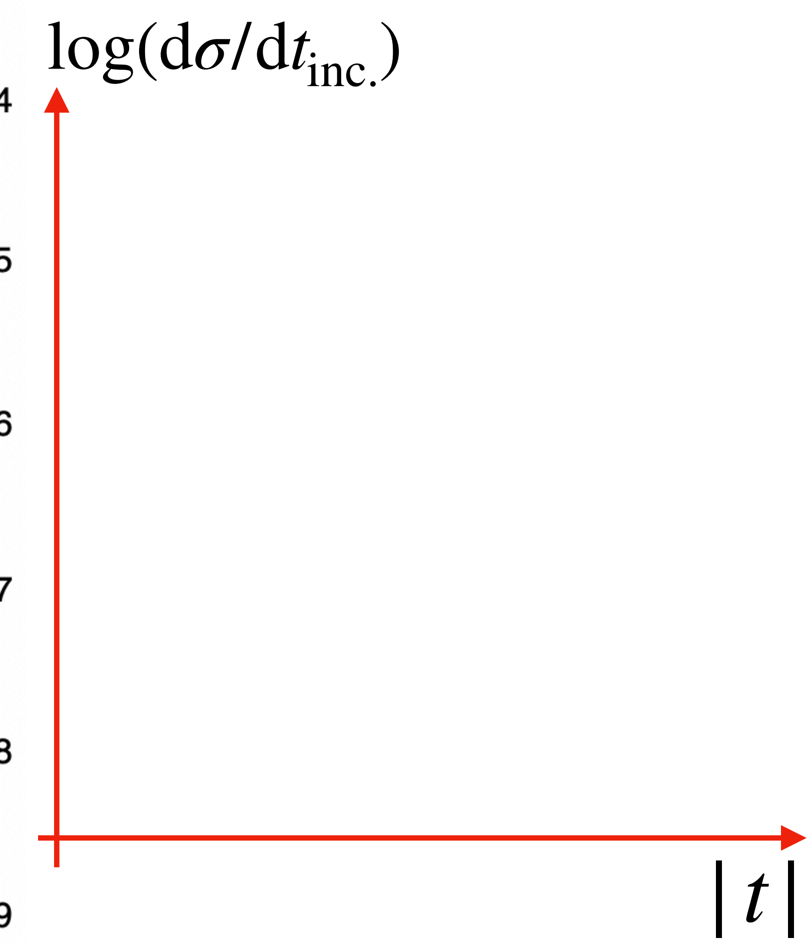
Eventhough coherent events dominate, the large $|t|$ tails have a significant effect on the cross sections!

Subnucleon structure becomes important for $|t| > 0.2$ GeV^2

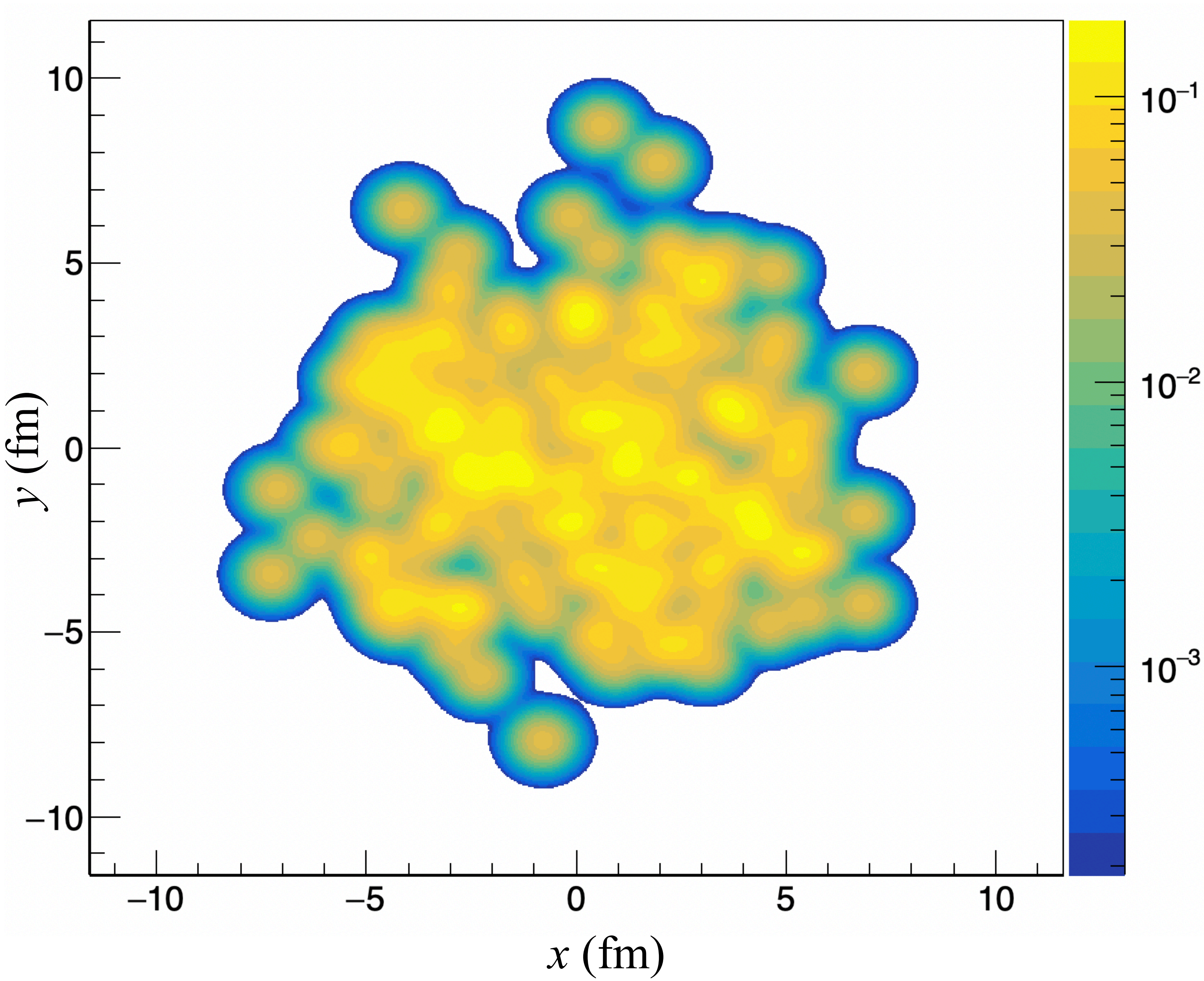
Into the heavy nucleus



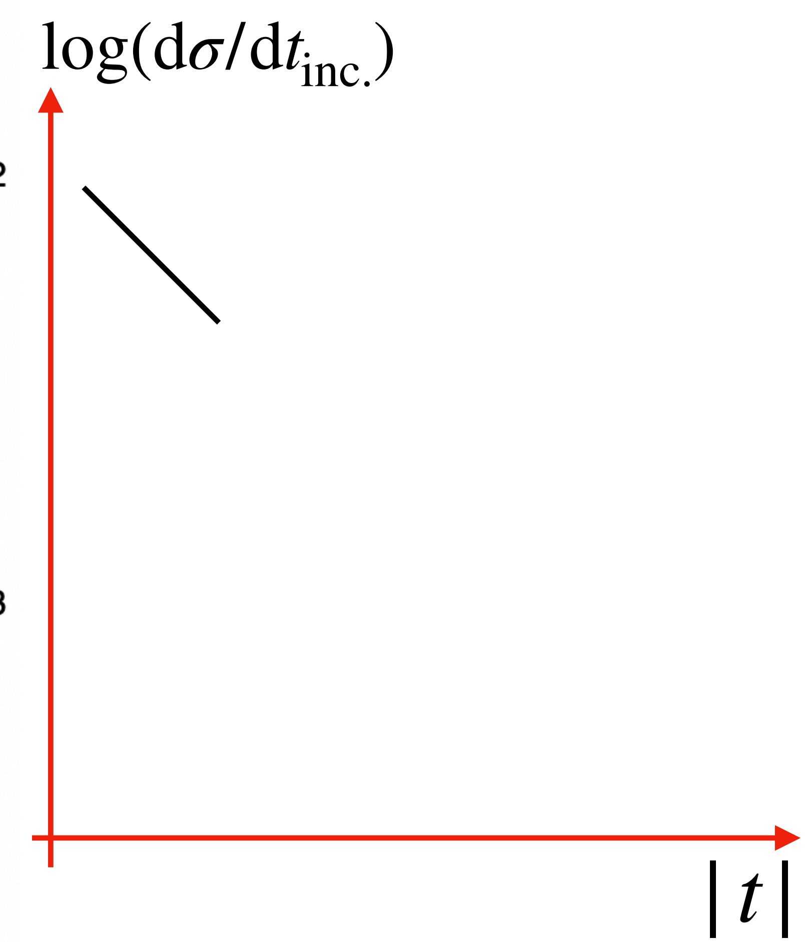
$$|t| = 0$$



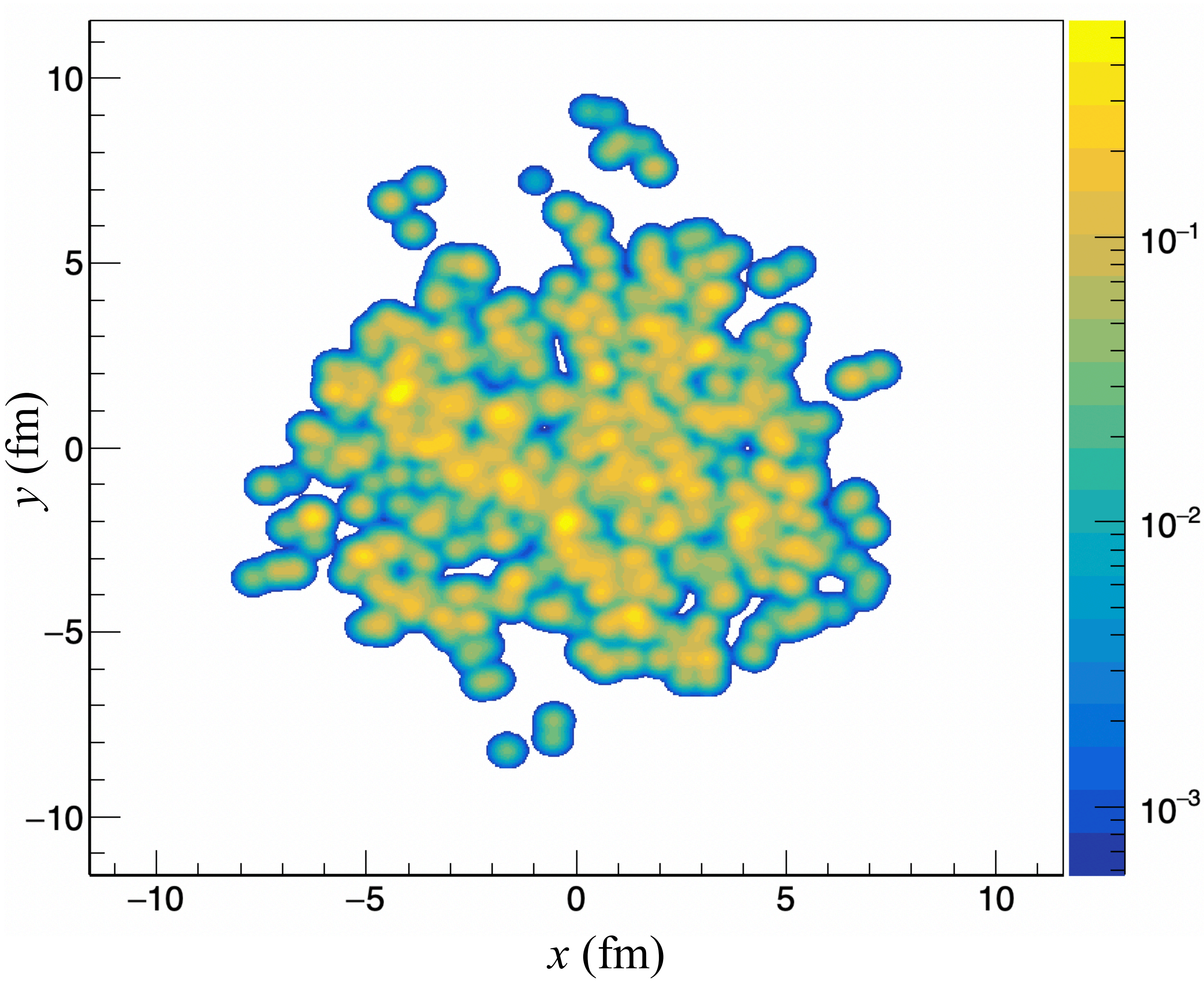
Into the heavy nucleus



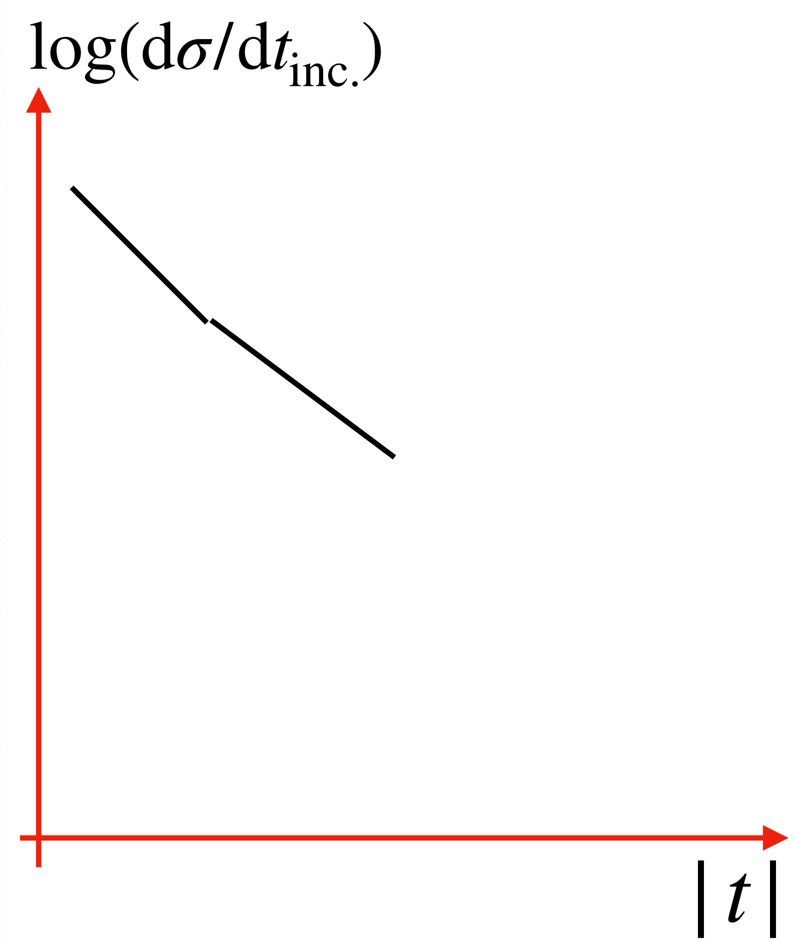
$|t| \lesssim 0.2\ \mathrm{GeV}^2$



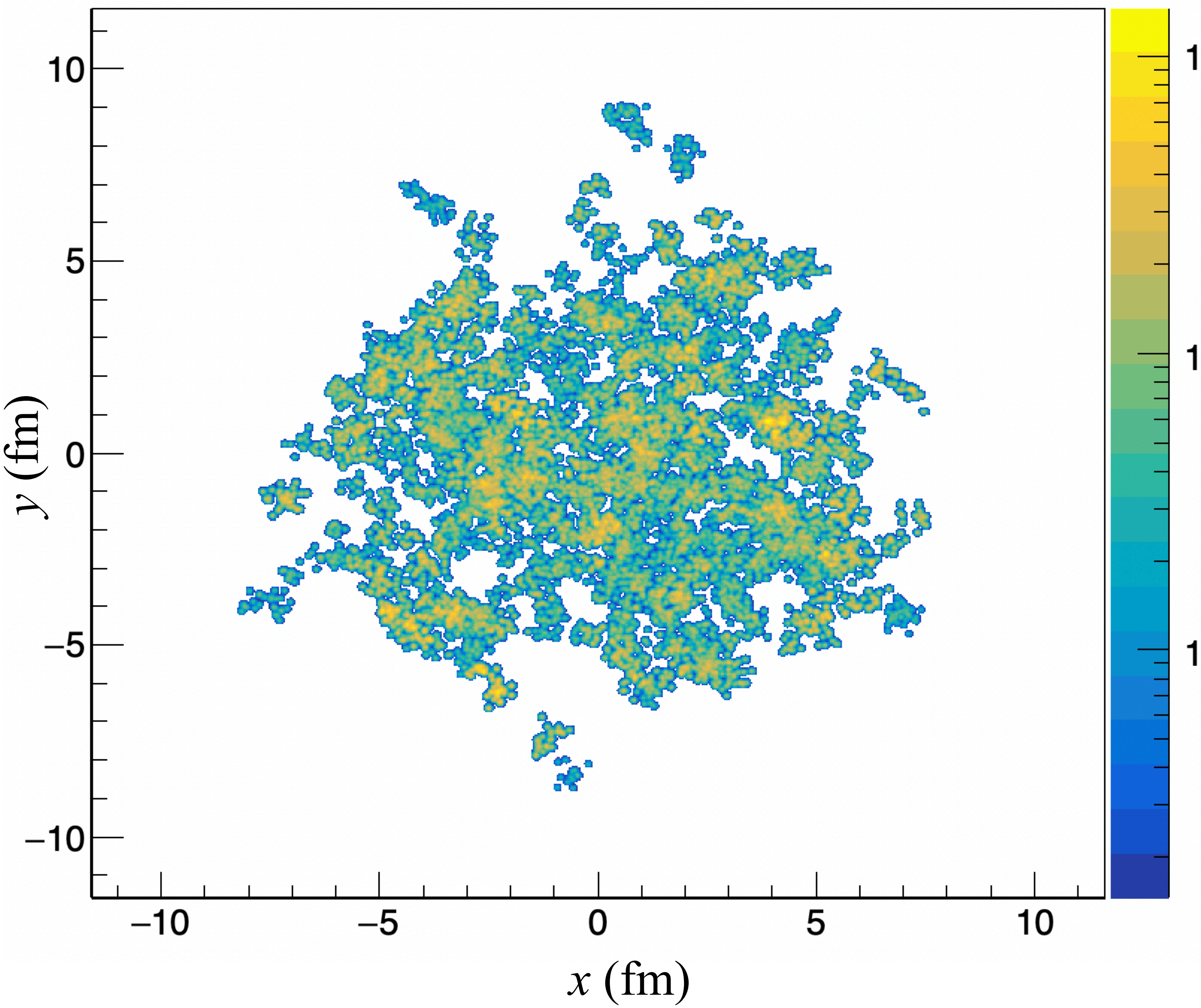
Into the heavy nucleus



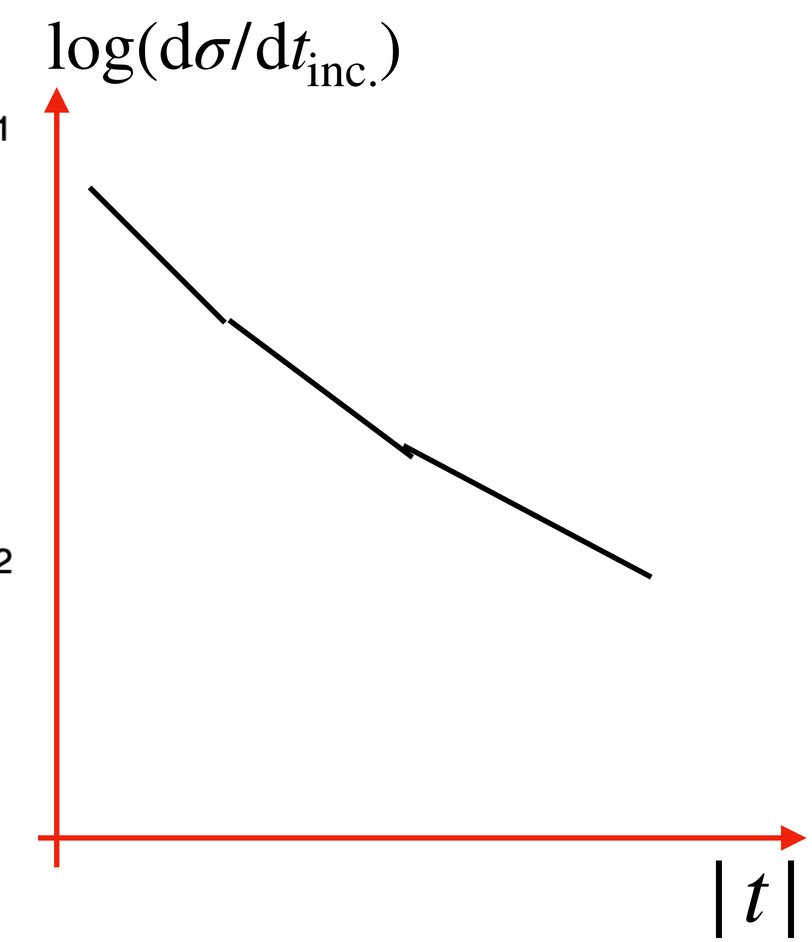
$0.2 \lesssim |t| \lesssim 2\ \mathrm{GeV}^2$



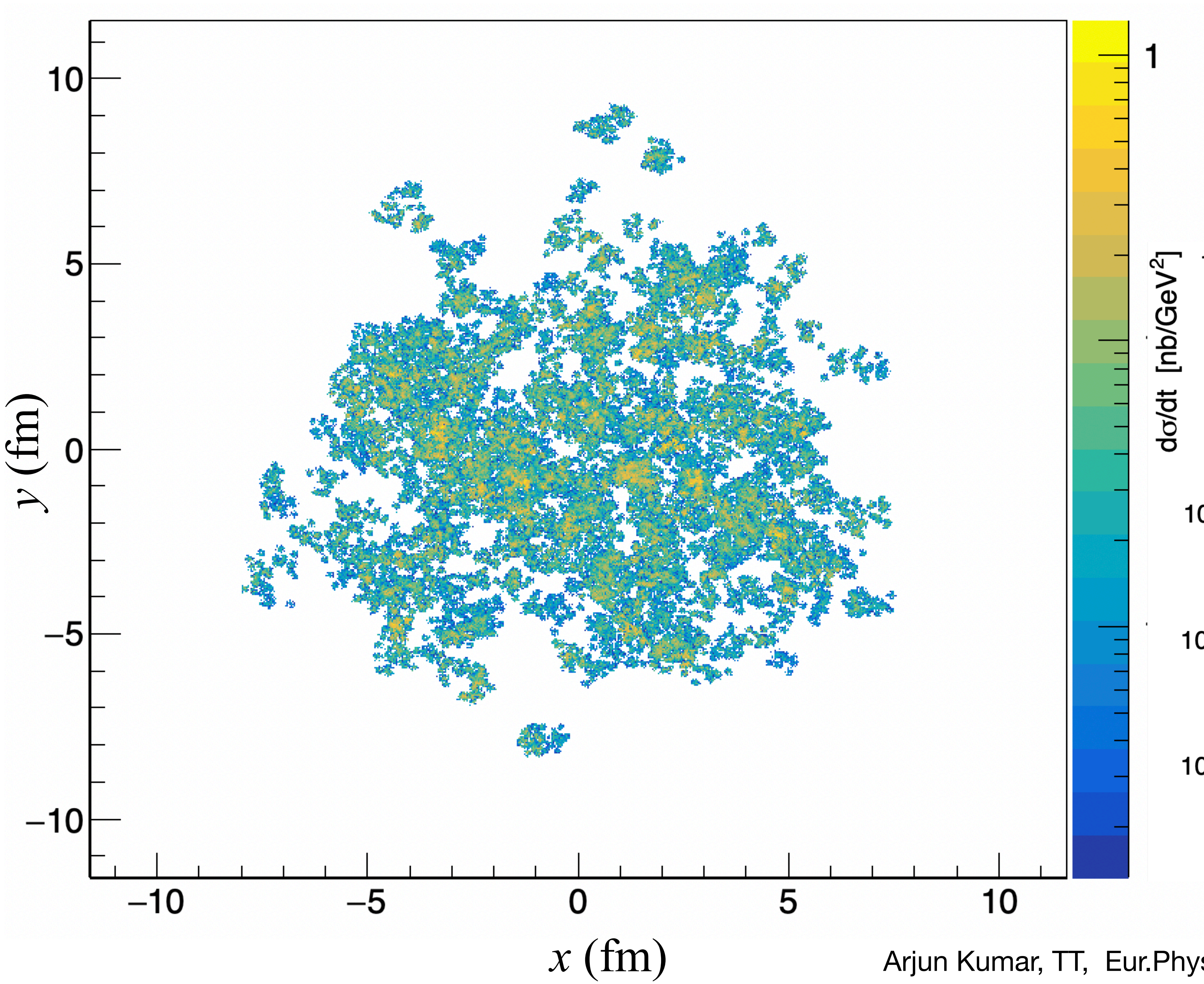
Into the heavy nucleus



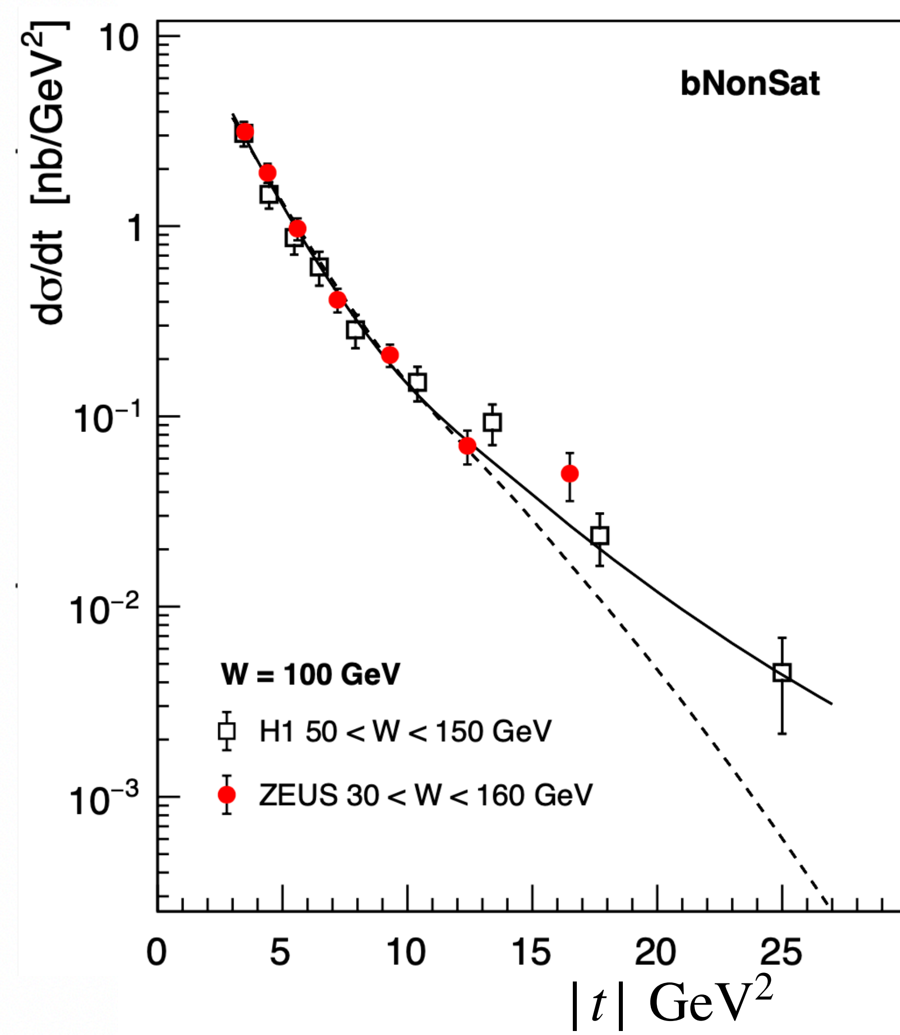
$2 \lesssim |t| \lesssim 12\ \mathrm{GeV}^2$



Into the heavy nucleus



$$12 \lesssim |t| \ \mathrm{GeV}^2$$

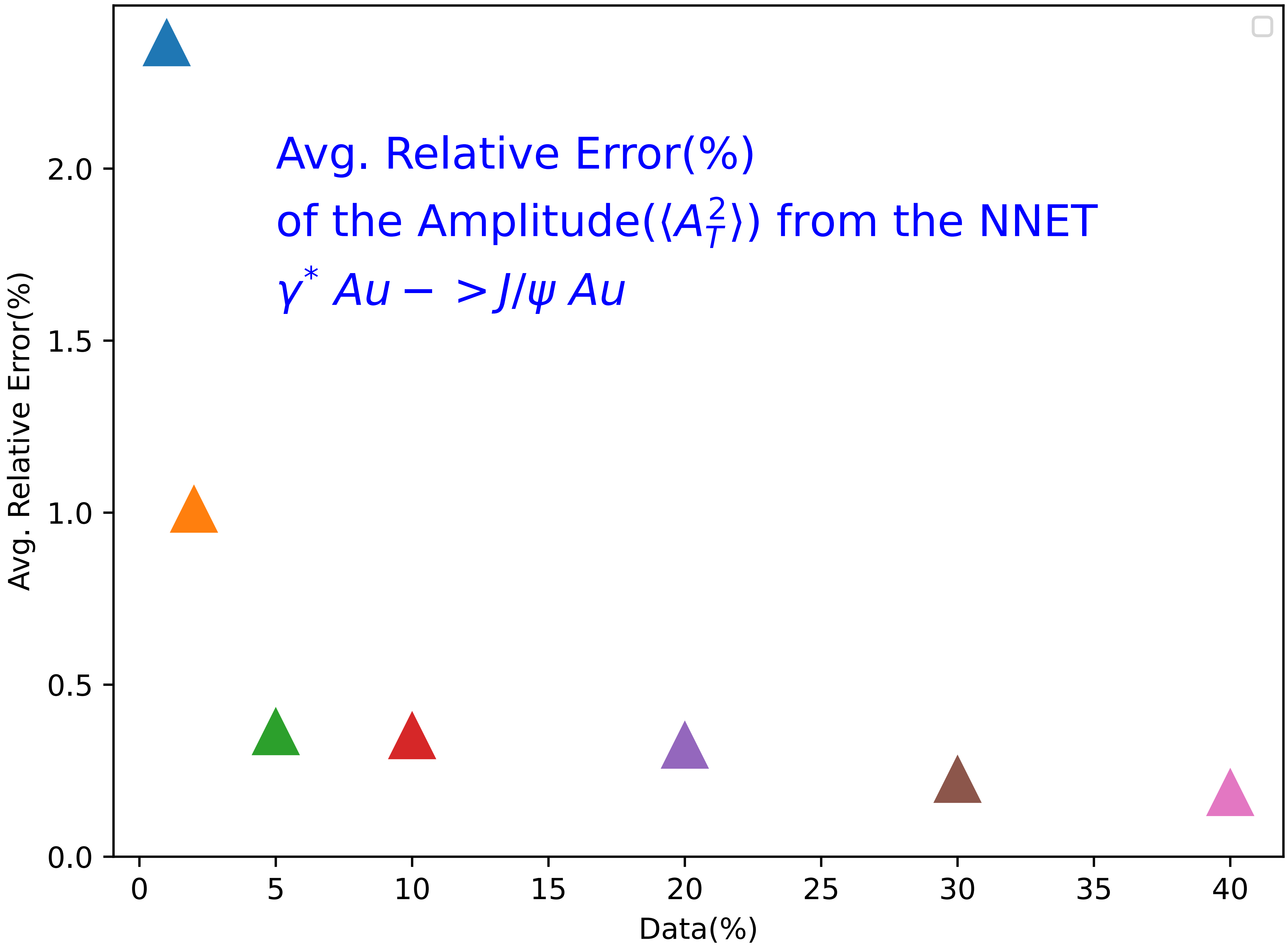


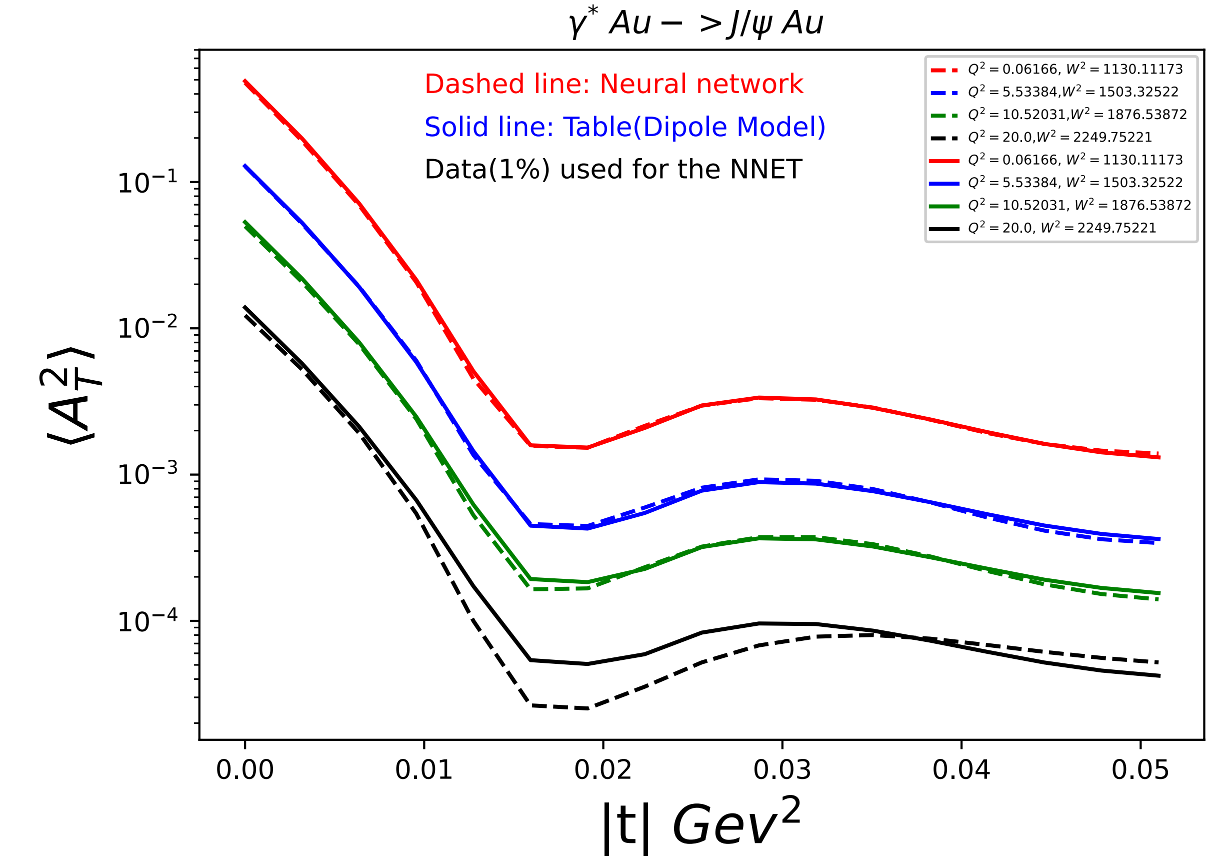
Arjun Kumar, TT, Eur.Phys.J.C 82 (2022) 9, 837, arXiv: 2106.12855

Current Development 2: Machine Learning Work with Jaswant Singh

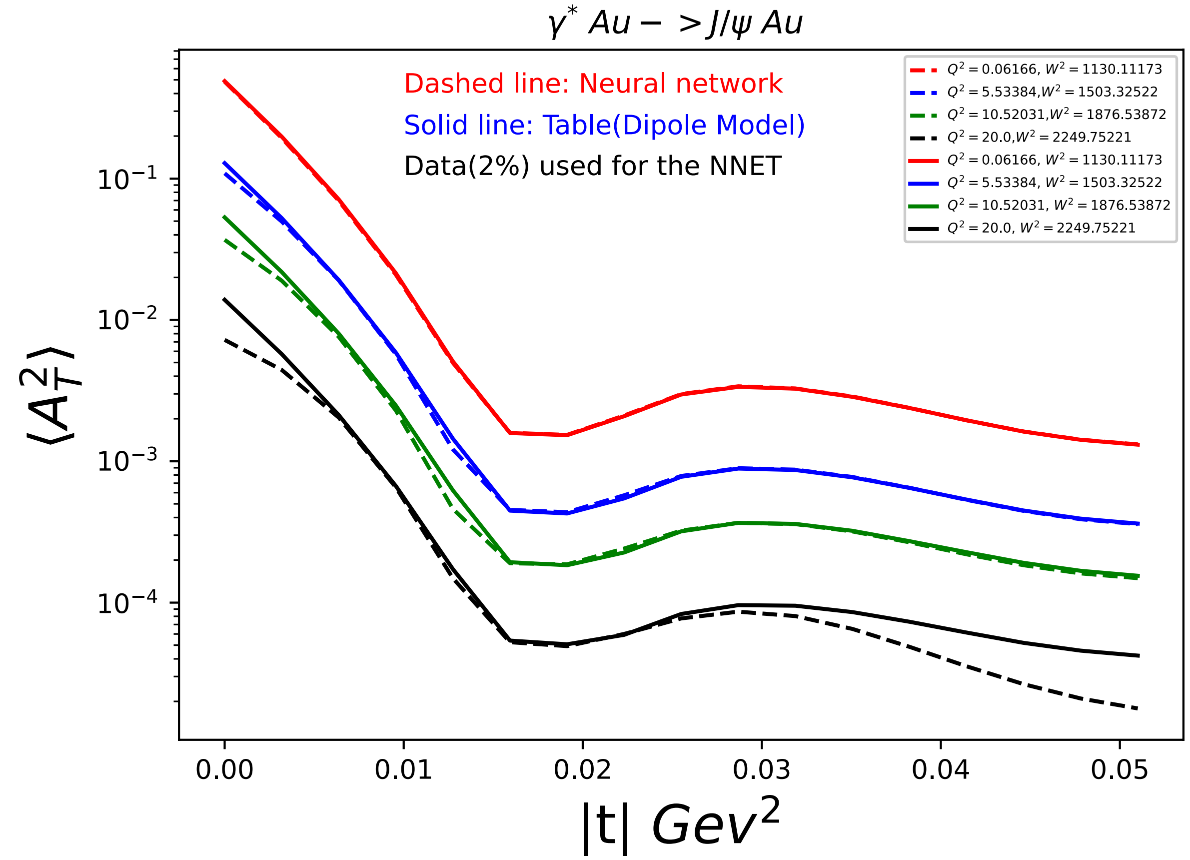
1. Create a coarse table as before.
2. Fit a Neural Network to the coarse table
3. Fill in the extra bins using the NN

$$\frac{1}{N_{\text{points}}} \sum_{\text{all points}} \frac{\left| \left\langle \mathscr{A}_T^2 \right\rangle_{\text{table}} - \left\langle \mathscr{A}_T^2 \right\rangle_{\text{NN}} \right|}{\left\langle \mathscr{A}_T^2 \right\rangle_{\text{table}}}$$

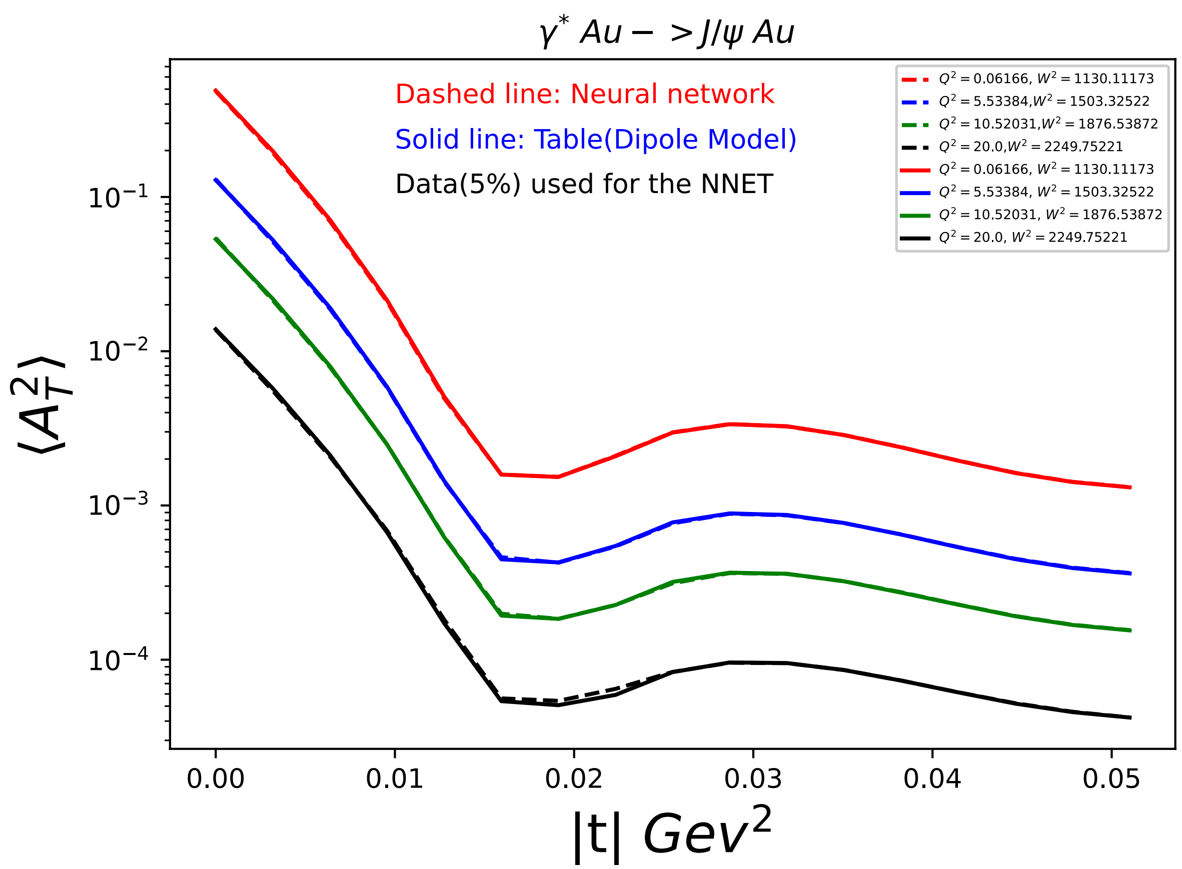




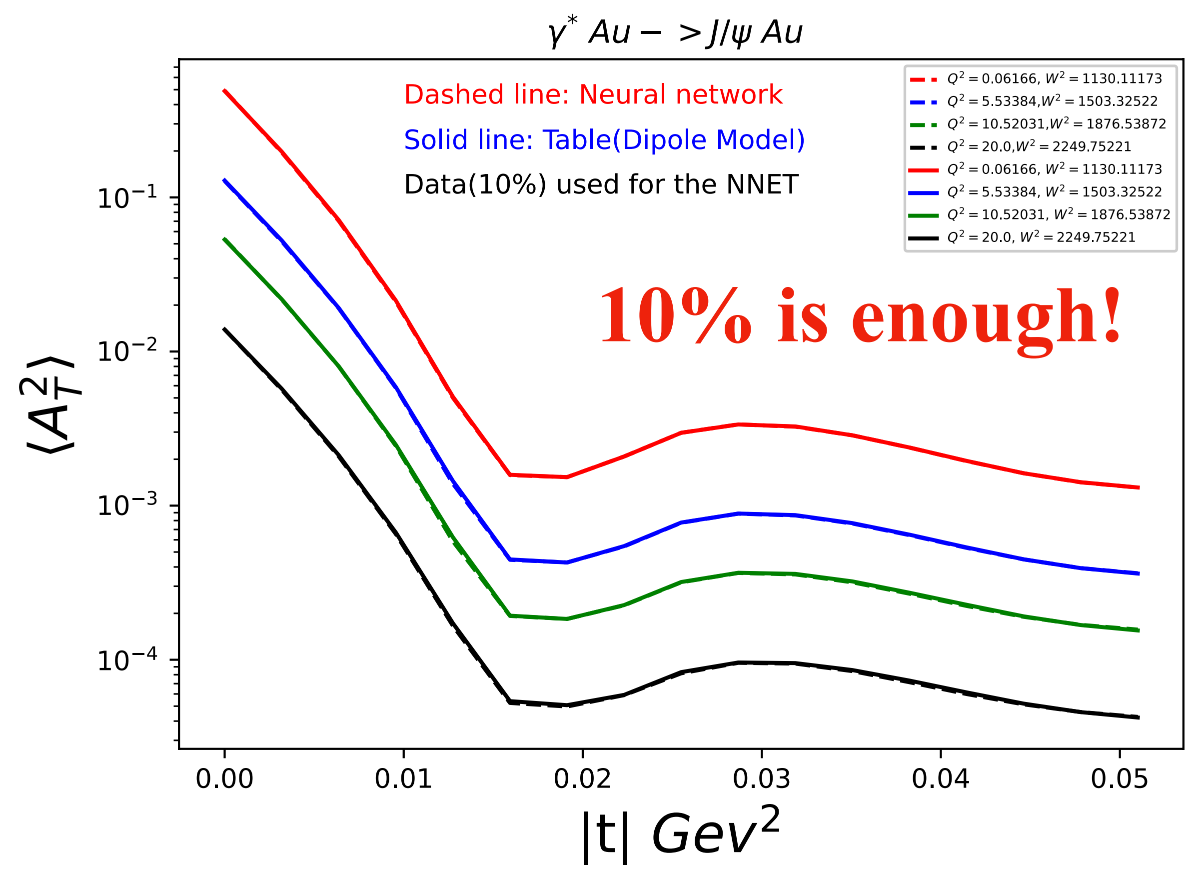
γ* Au − > J/ψ Au
Dashed line: Neural network
Solid line: Table(Dipole Model)
Data(1%) used for the NNET
Q² = 0.06166, W² = 1130.11173
Q² = 5.53384, W² = 1503.32522
Q² = 10.52031, W² = 1876.53872
Q² = 20.0, W² = 2249.75221
⟨A_T²⟩
|t| Gev²



γ* Au − > J/ψ Au
Dashed line: Neural network
Solid line: Table(Dipole Model)
Data(2%) used for the NNET
Q² = 0.06166, W² = 1130.11173
Q² = 5.53384, W² = 1503.32522
Q² = 10.52031, W² = 1876.53872
Q² = 20.0, W² = 2249.75221
⟨A_T²⟩
|t| Gev²

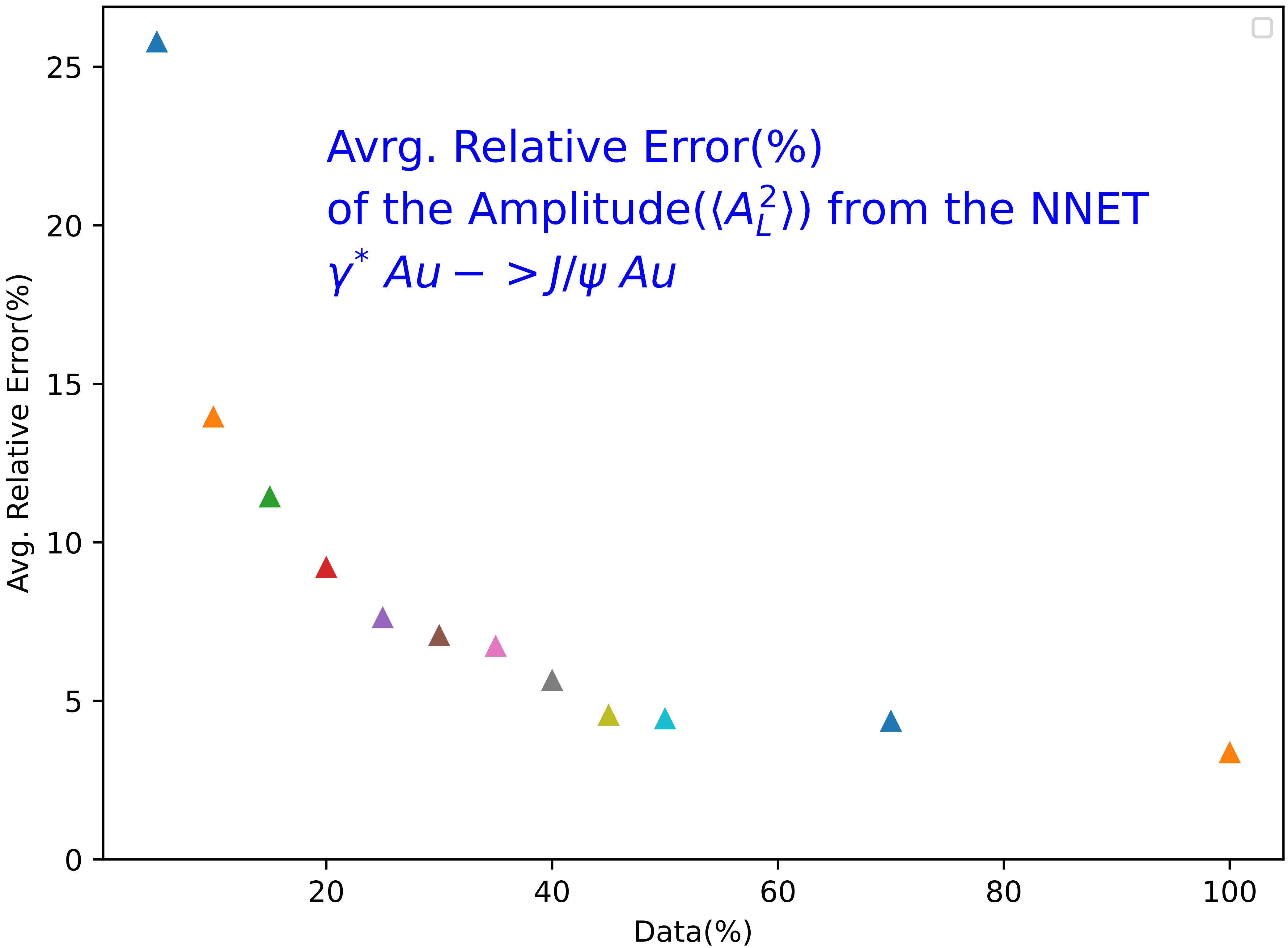


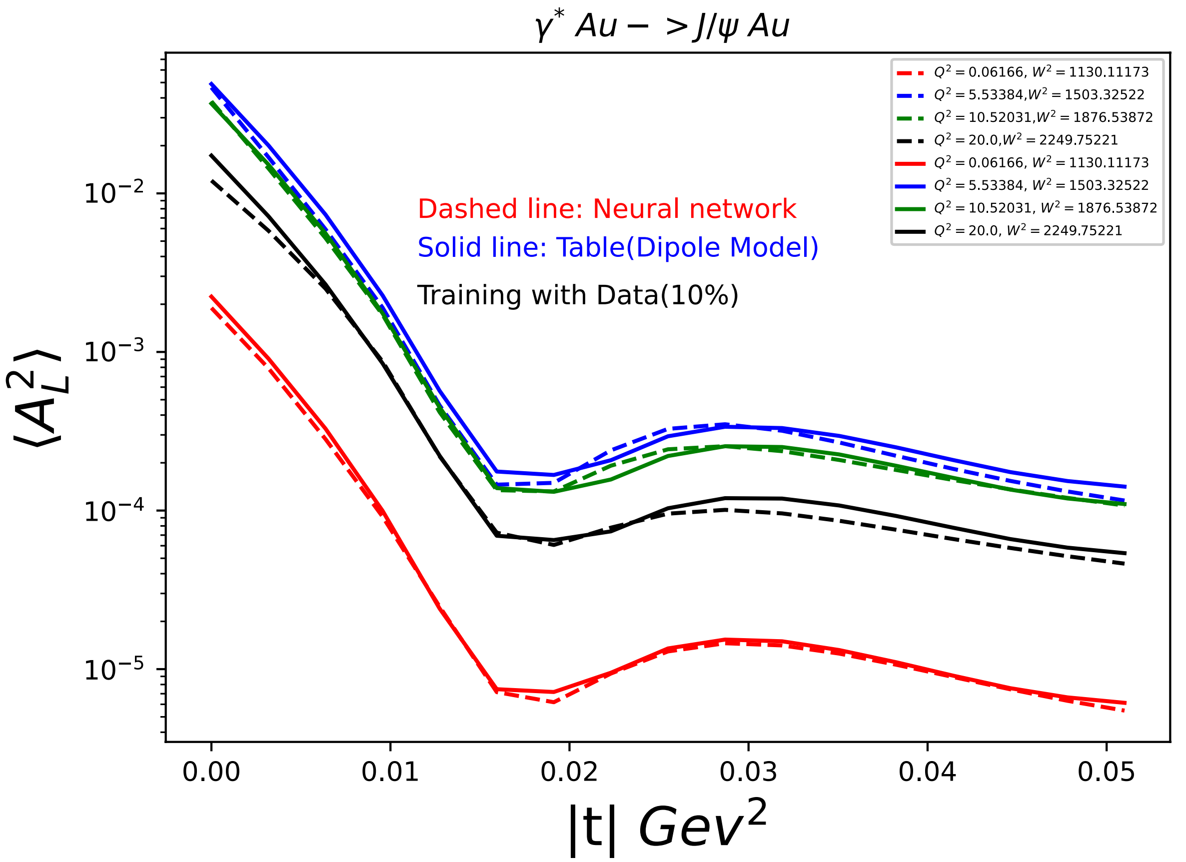
γ* Au − > J/ψ Au
Dashed line: Neural network
Solid line: Table(Dipole Model)
Data(5%) used for the NNET
Q² = 0.06166, W² = 1130.11173
Q² = 5.53384, W² = 1503.32522
Q² = 10.52031, W² = 1876.53872
Q² = 20.0, W² = 2249.75221
⟨A_T²⟩
|t| Gev²



γ* Au − > J/ψ Au
Dashed line: Neural network
Solid line: Table(Dipole Model)
Data(10%) used for the NNET
Q² = 0.06166, W² = 1130.11173
Q² = 5.53384, W² = 1503.32522
Q² = 10.52031, W² = 1876.53872
Q² = 20.0, W² = 2249.75221
10% is enough!
⟨A_T²⟩
|t| Gev²

$$\frac{1}{N_{\text{points}}} \sum_{\text{all points}} \frac{\left| \left\langle \mathscr{A}_L^2 \right\rangle_{\text{table}} - \left\langle \mathscr{A}_L^2 \right\rangle_{\text{NN}} \right|}{\left\langle \mathscr{A}_L^2 \right\rangle_{\text{table}}}$$




$\gamma^* Au -> J/\psi\ Au$
$Q^2 = 0.06166,\ W^2 = 1130.11173$
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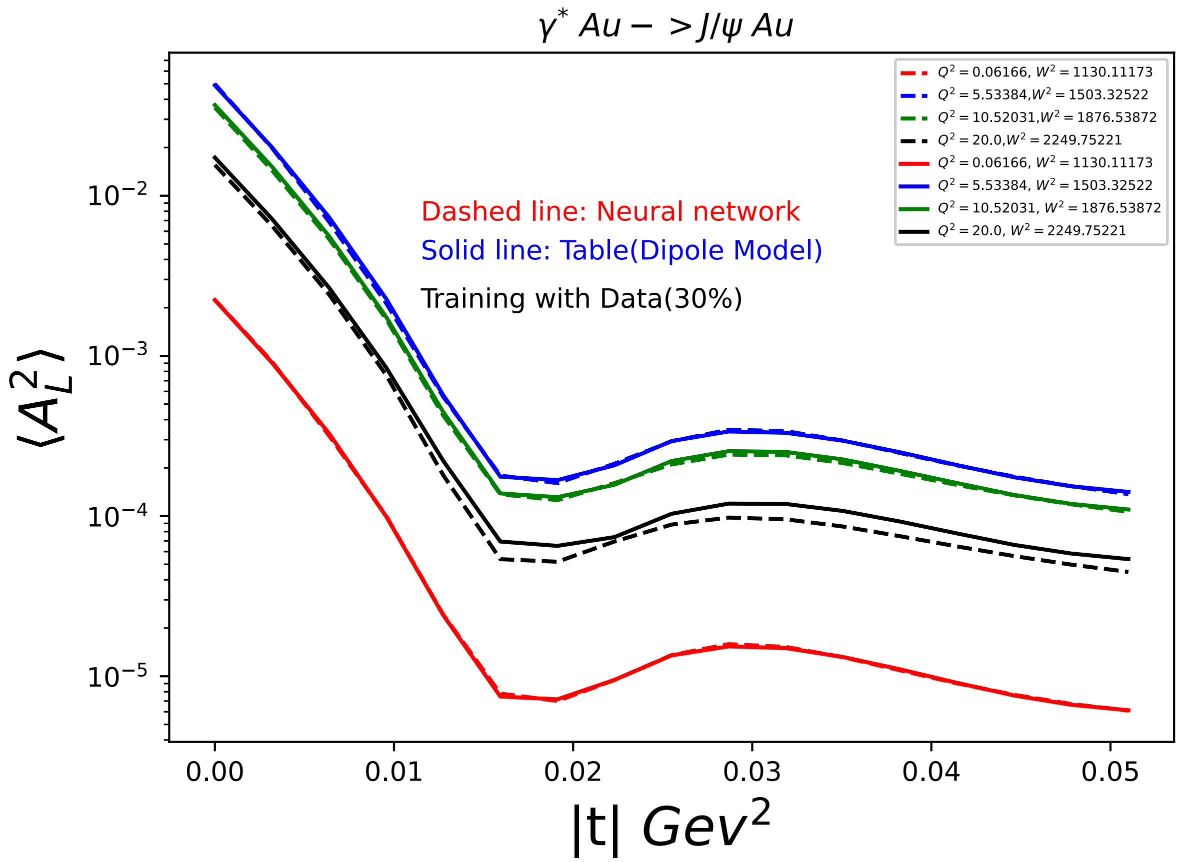
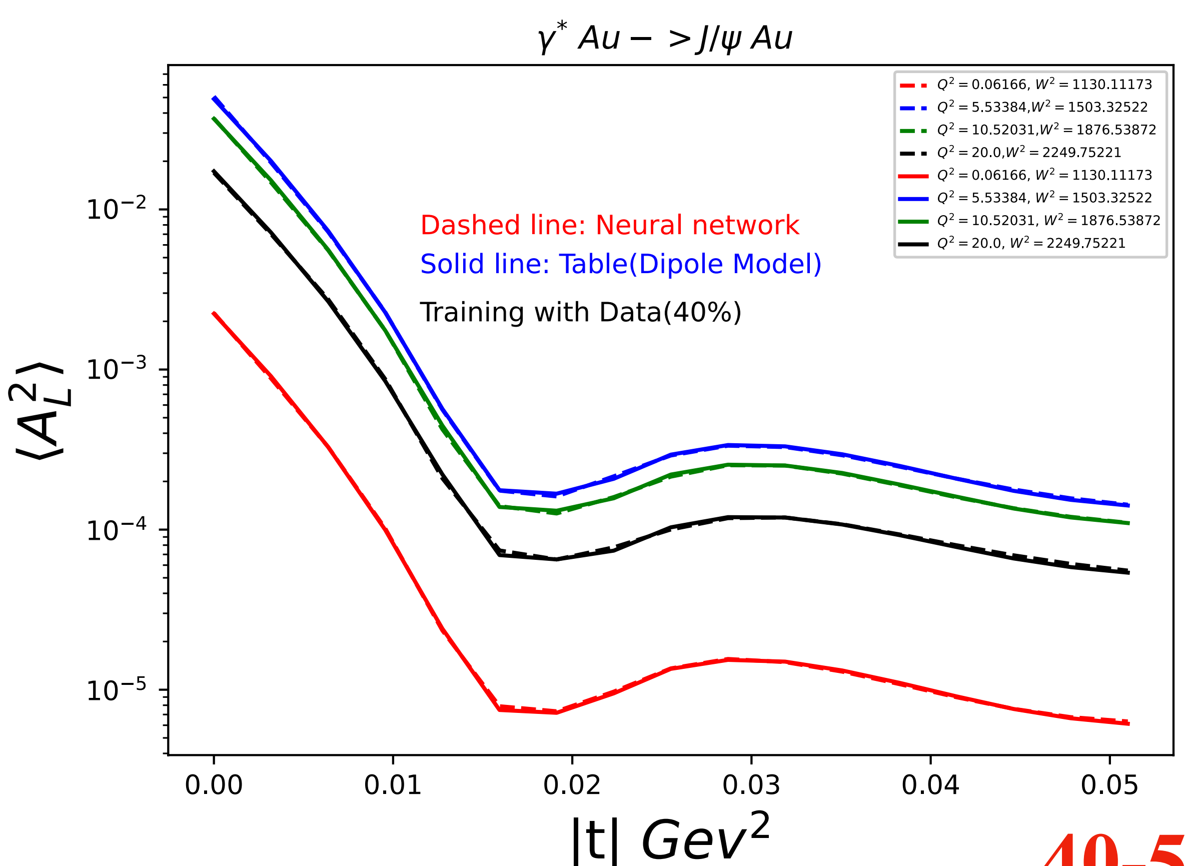
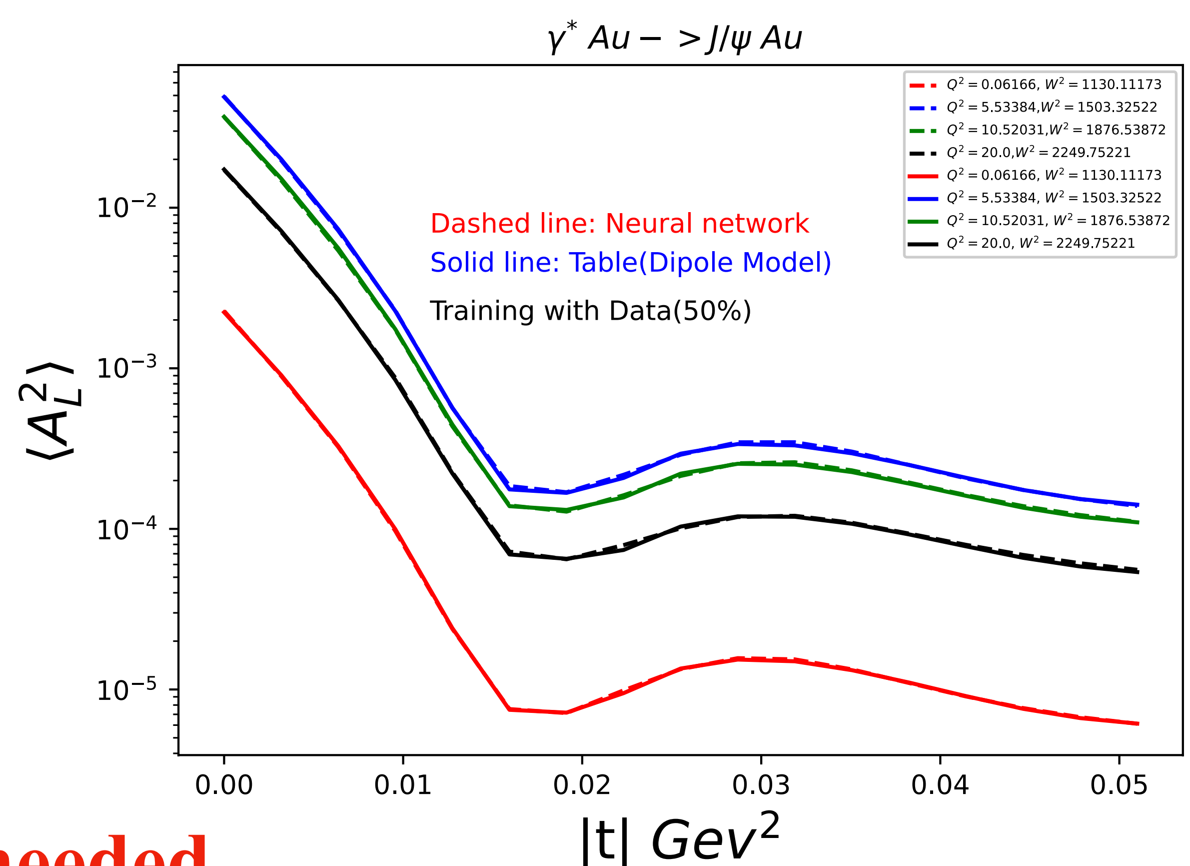
$Q^2 = 5.53384,\ W^2 = 1503.32522$
$Q^2 = 10.52031,\ W^2 = 1876.53872$
$Q^2 = 20.0,\ W^2 = 2249.75221$
Dashed line: Neural network
Solid line: Table(Dipole Model)
Training with Data(10%)
$\langle A_L^2 \rangle$
$|t|\ Gev^2$


$\gamma^* Au -> J/\psi\ Au$
Dashed line: Neural network
Solid line: Table(Dipole Model)
Training with Data(30%)
$\langle A_L^2 \rangle$
$|t|\ Gev^2$


$\gamma^* Au -> J/\psi\ Au$
Dashed line: Neural network
Solid line: Table(Dipole Model)
Training with Data(40%)
$\langle A_L^2 \rangle$
$|t|\ Gev^2$


$\gamma^* Au -> J/\psi\ Au$
Dashed line: Neural network
Solid line: Table(Dipole Model)
Training with Data(50%)
$\langle A_L^2 \rangle$
$|t|\ Gev^2$

40-50% needed

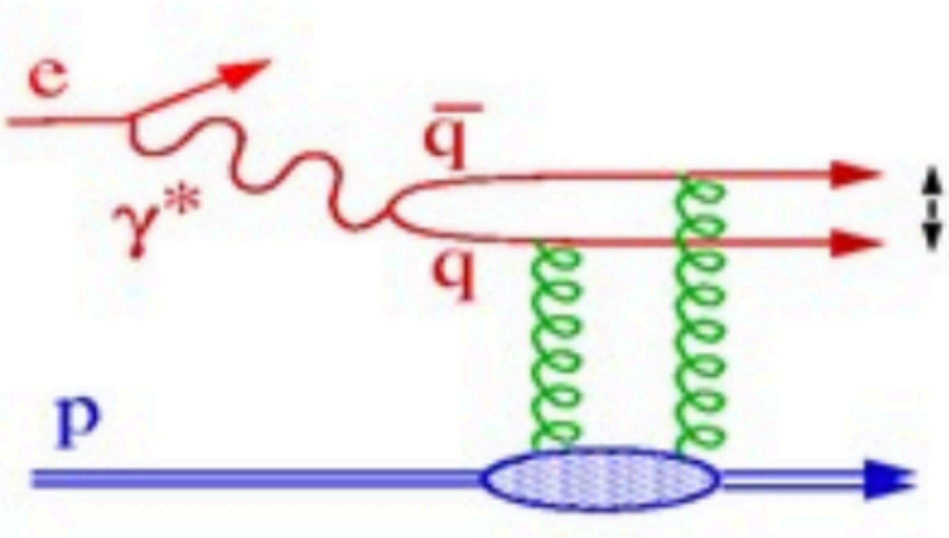
Conclusions:

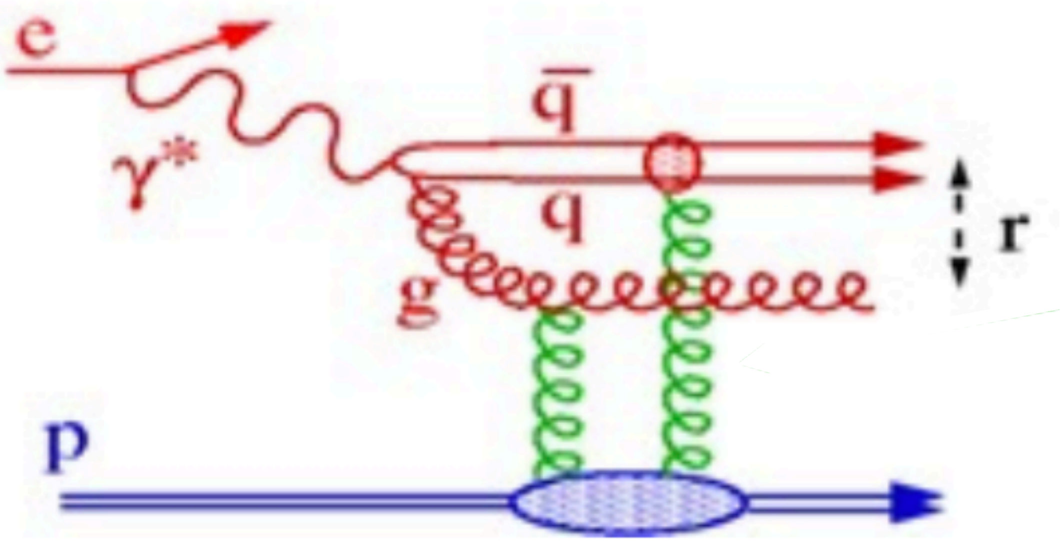
We need 10% of the bins for Transverse and 40-50% for Longitudinal amplitude square tables.

Therefore, in total we need to generate ~25% of the table points.

We can produce tables a factor 4 faster using Neural Networks. (weeks instead of months)

Current Development 3: Inclusive Diffraction



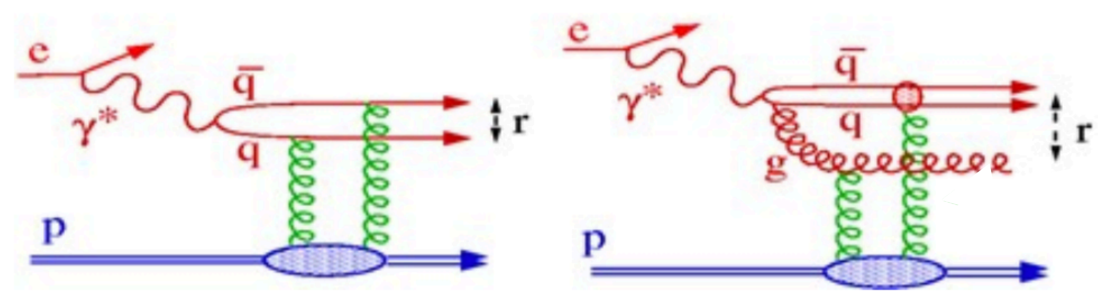


Marta Ruspa, DIS2004

Current Development 3: Inclusive Diffraction

H. Kowalski, T. Lappi, C. Marquet, R. Venugopalan, Phys.Rev.C 78 (2008), 045201

$$\mathscr{A}_n = \int_0^\infty r\mathrm{d}r K_n(\epsilon r) J_n(kr) \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2 \overrightarrow{b}}$$



$\epsilon^2 = z(1-z)Q^2 + m_f^2, k^2 = z(1-z)M_X$

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b)\right)\right]$$

$$\Phi_n = \int \mathrm{d}^2 \overrightarrow{b} \, |\mathscr{A}_n|^2$$

$$\frac{\mathrm{d}^2\sigma_T^{\gamma^* p}}{\mathrm{d}\beta \mathrm{d}z} = \frac{N_C Q^2 \alpha_{\mathrm{EM}}}{8\pi\beta^2} \sum_f e_f^2 z(1-z)\left[\epsilon^2(z^2 + (1-z)^2)\Phi_1 + m_f^2 \Phi_0\right] \qquad \frac{\mathrm{d}^2\sigma_L^{\gamma^* p}}{\mathrm{d}\beta \mathrm{d}z} = \frac{N_C Q^4 \alpha_{\mathrm{EM}}}{2\pi\beta^2} \sum_f e_f^2 z^3 (1-z)^3 \Phi_0$$

Exclusive final state fed into Pythia for hadronisation. Treat $q\bar{q}g$ state as a gg quadropole.

Challenges:

Need 4D differential state (Q^2, W^2 from photon flux, β, z). This means 4D tables, 1D integrals.

Need to include t-dependence.
Either explicitly (8D integration, 5D table) or
taking it from exclusive processes (Good enough for now?)

Conclusions

Sartre is a reliable event generator for exclusive diffraction in *ep, e*A, and UPC for small *x*.

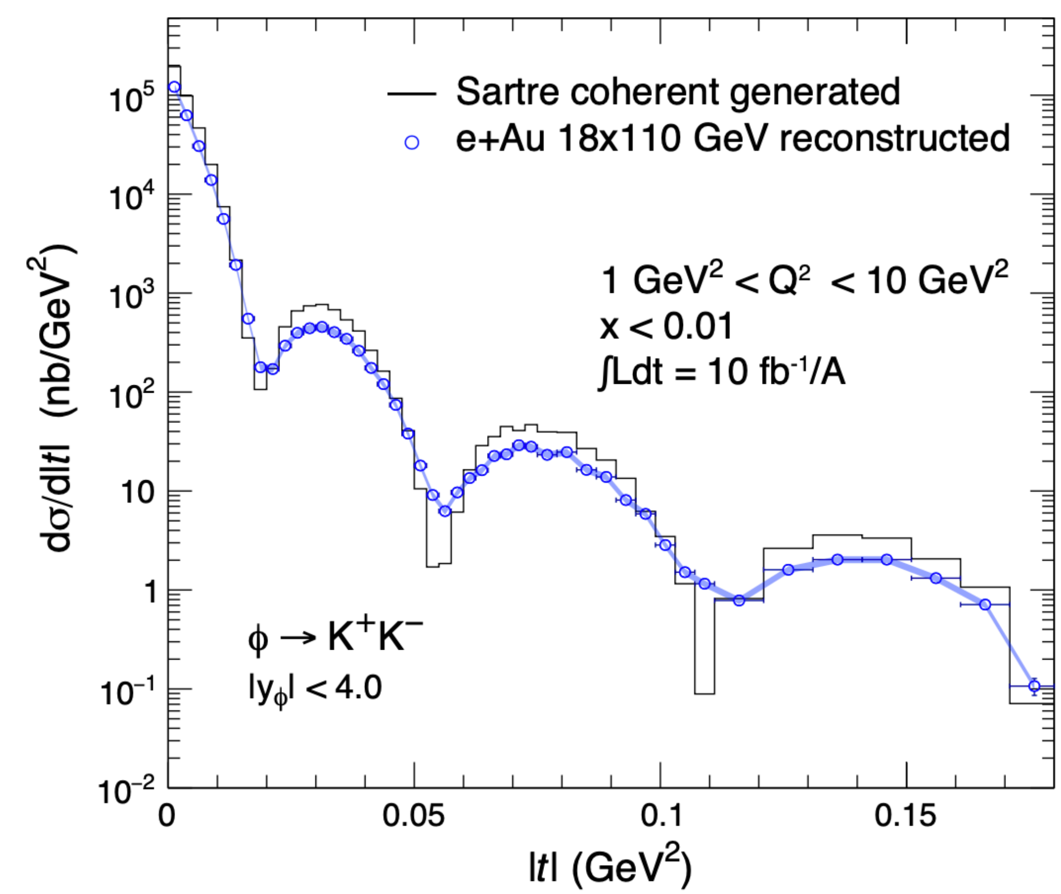
It stores the physics of the amplitude in 3D lookup tables which makes it a fast but unflexible generator.

In recent developments we have:

Implemented nucleon substructure.

Developed a faster method for table generation using machine learning.

Began to extend the generator to inclusive diffraction. (w.i.p.)



ATHENA Collaboration, JINST 17 (2022) 10, P10019