

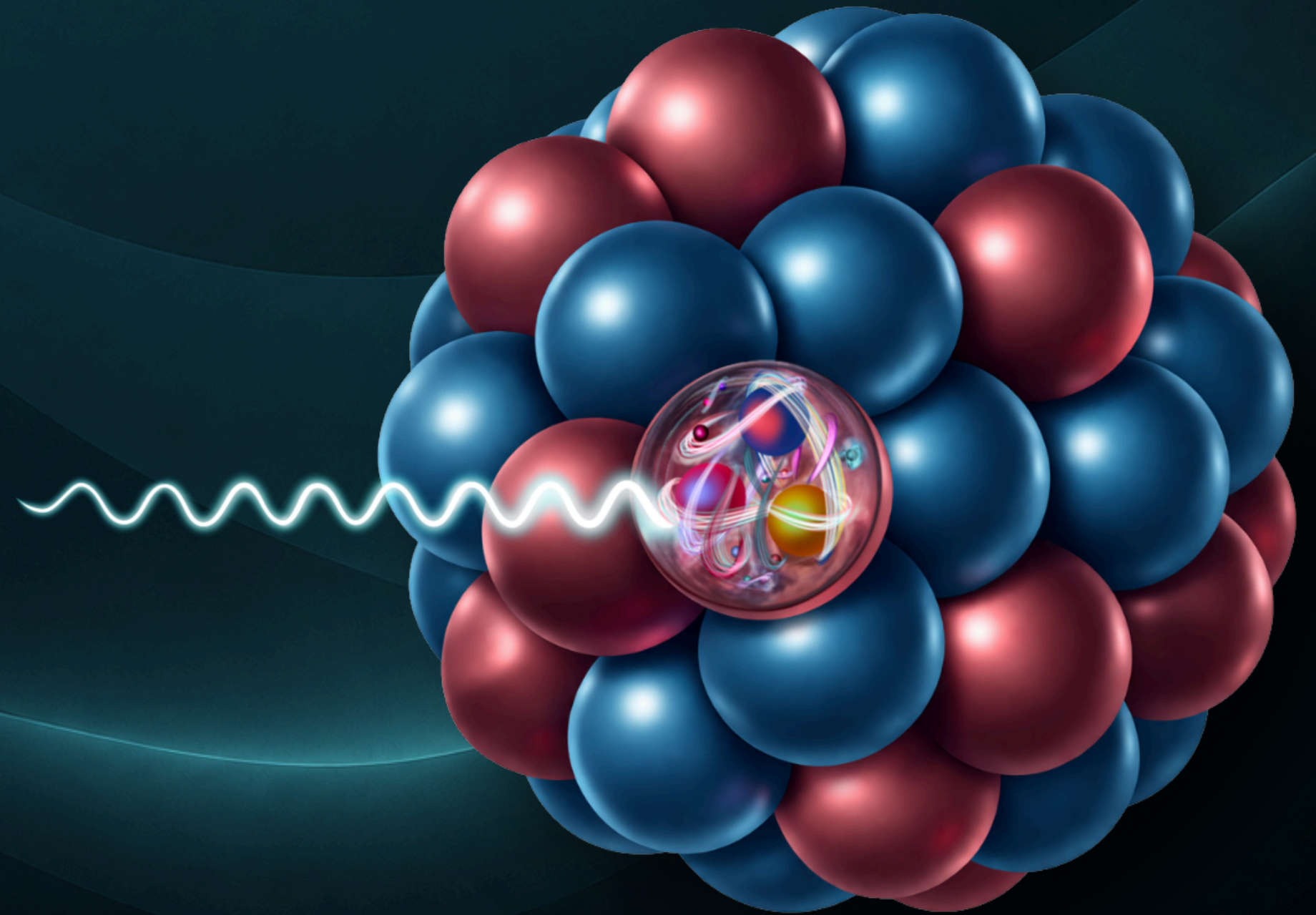
EMMI Workshop: Mining for gluon saturation at the LHC and the future EIC

Effect of subnucleon fluctuations in diffractive vector meson photoproduction and DVCS

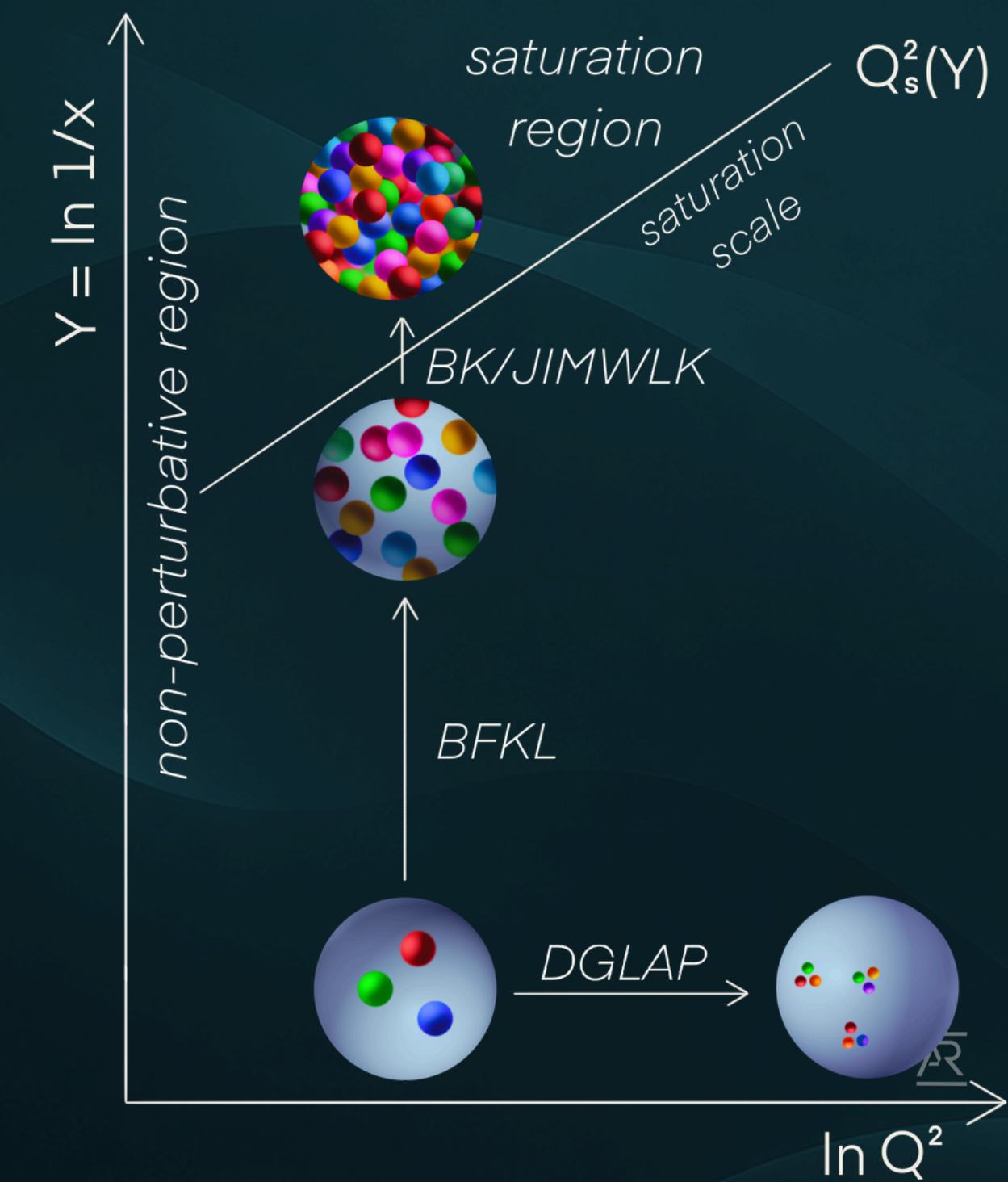
Alexandra Ridziková
July 10th, 2026



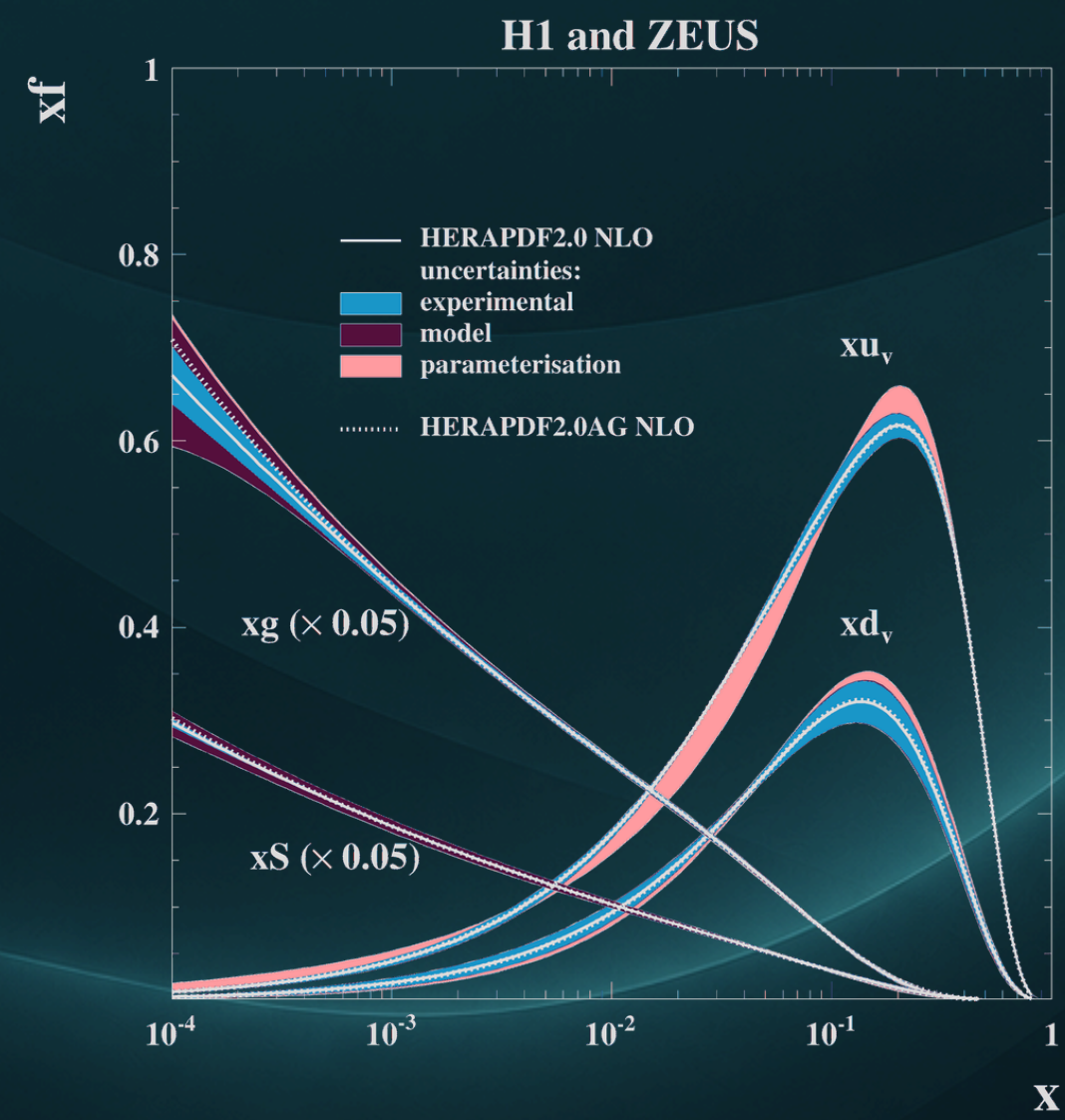
**FACULTY OF
NUCLEAR SCIENCES
AND PHYSICAL
ENGINEERING
CTU IN PRAGUE**



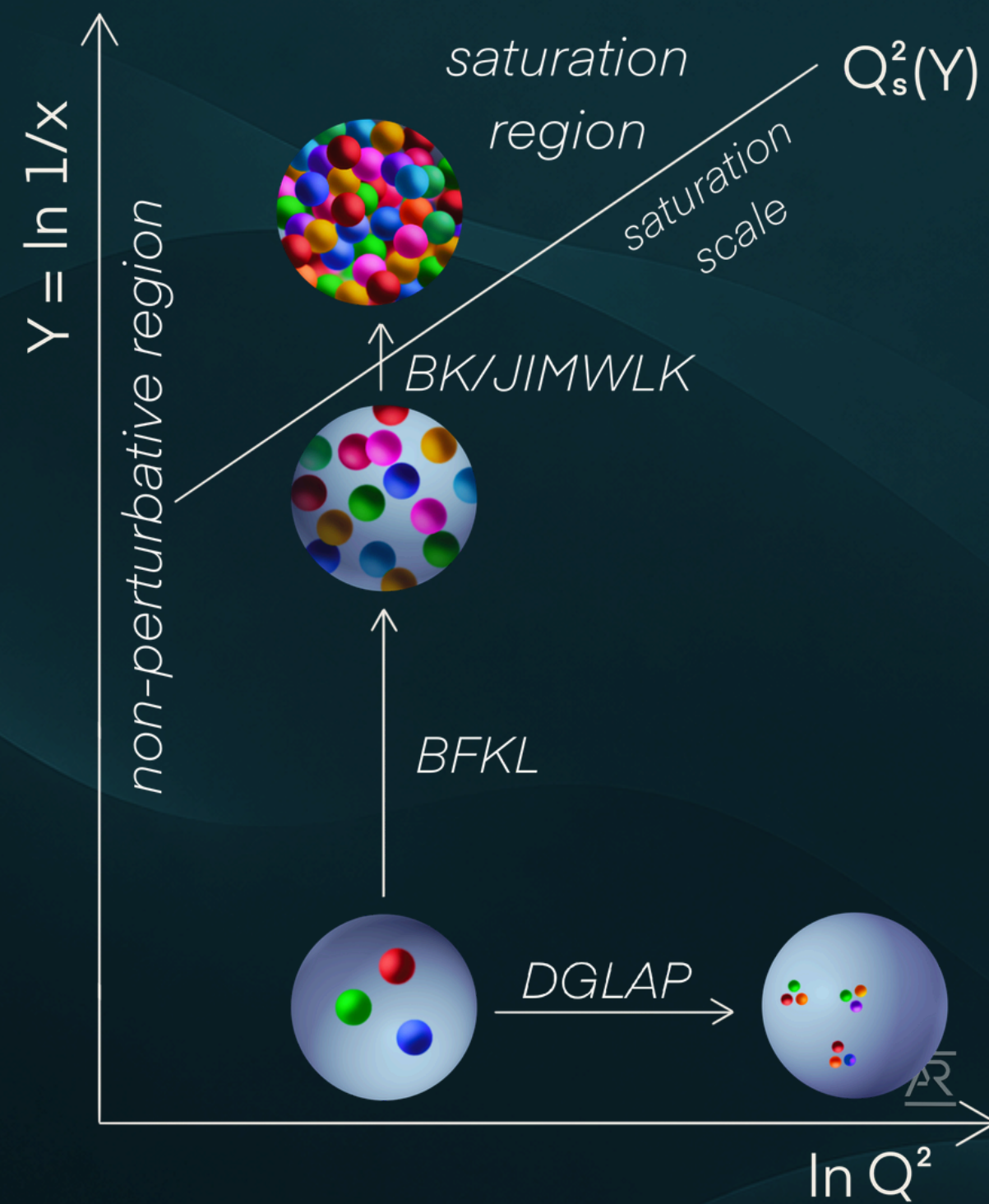
MOTIVATION



The evolution of proton structure as a function of virtuality and Bjorken- x .

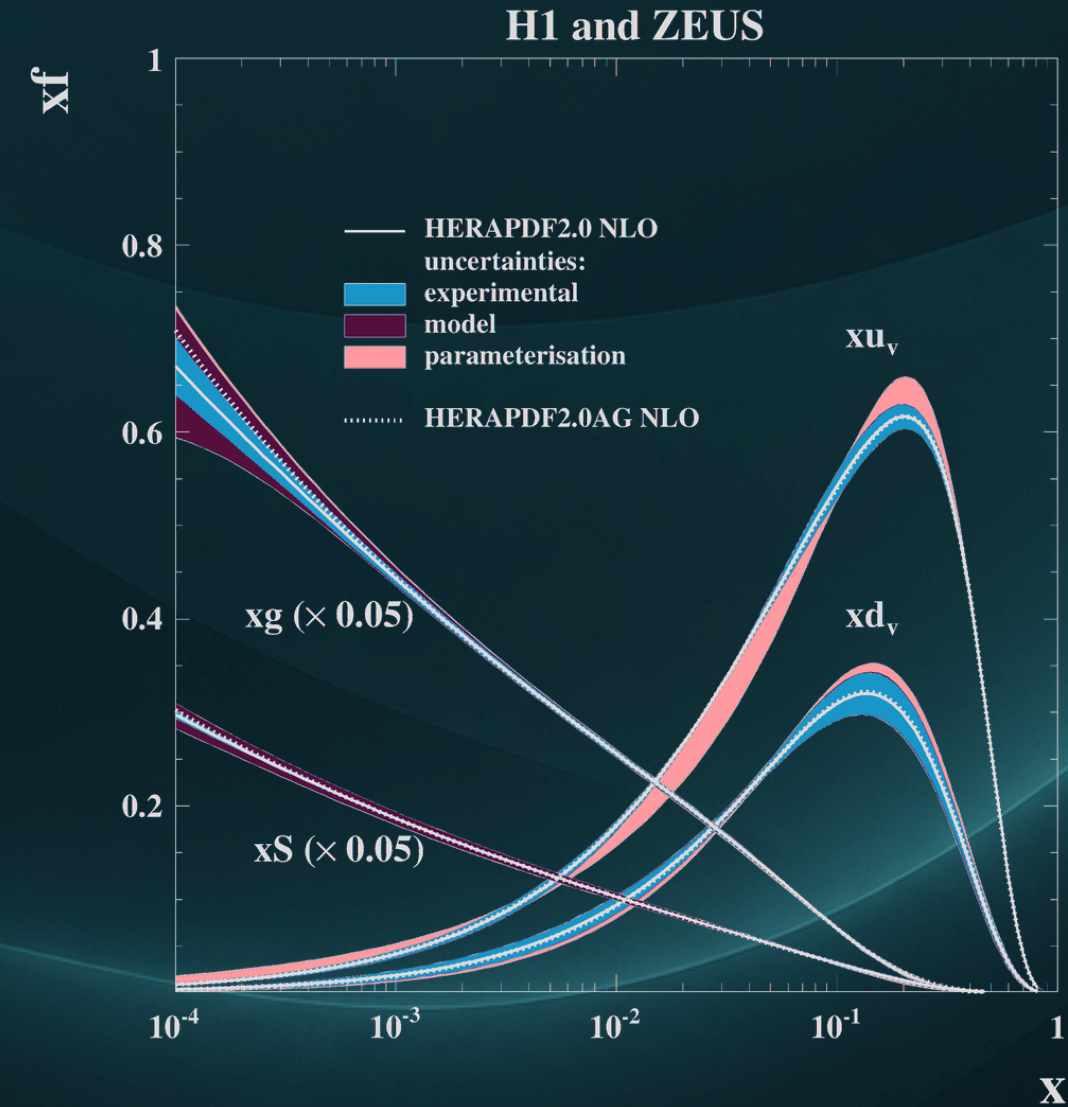


MOTIVATION



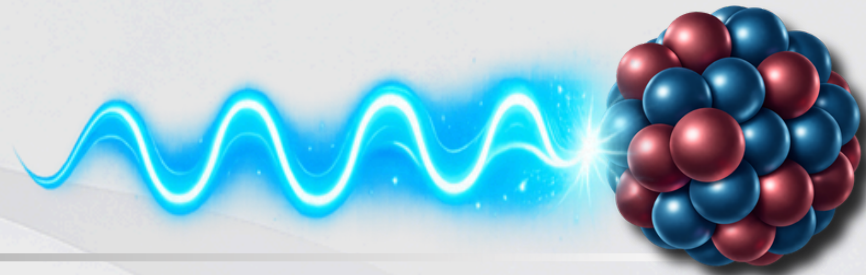
The evolution of proton structure as a function of virtuality and Bjorken- x .

- Due to the high density in the small- x region, the radiated gluons overlap each other and start interacting: **ONSET OF SATURATION**
- In this regime, observables like deeply virtual Compton scattering or diffractive vector mesons production are used to probe saturation effects, as they are sensitive to the gluon distribution within hadrons



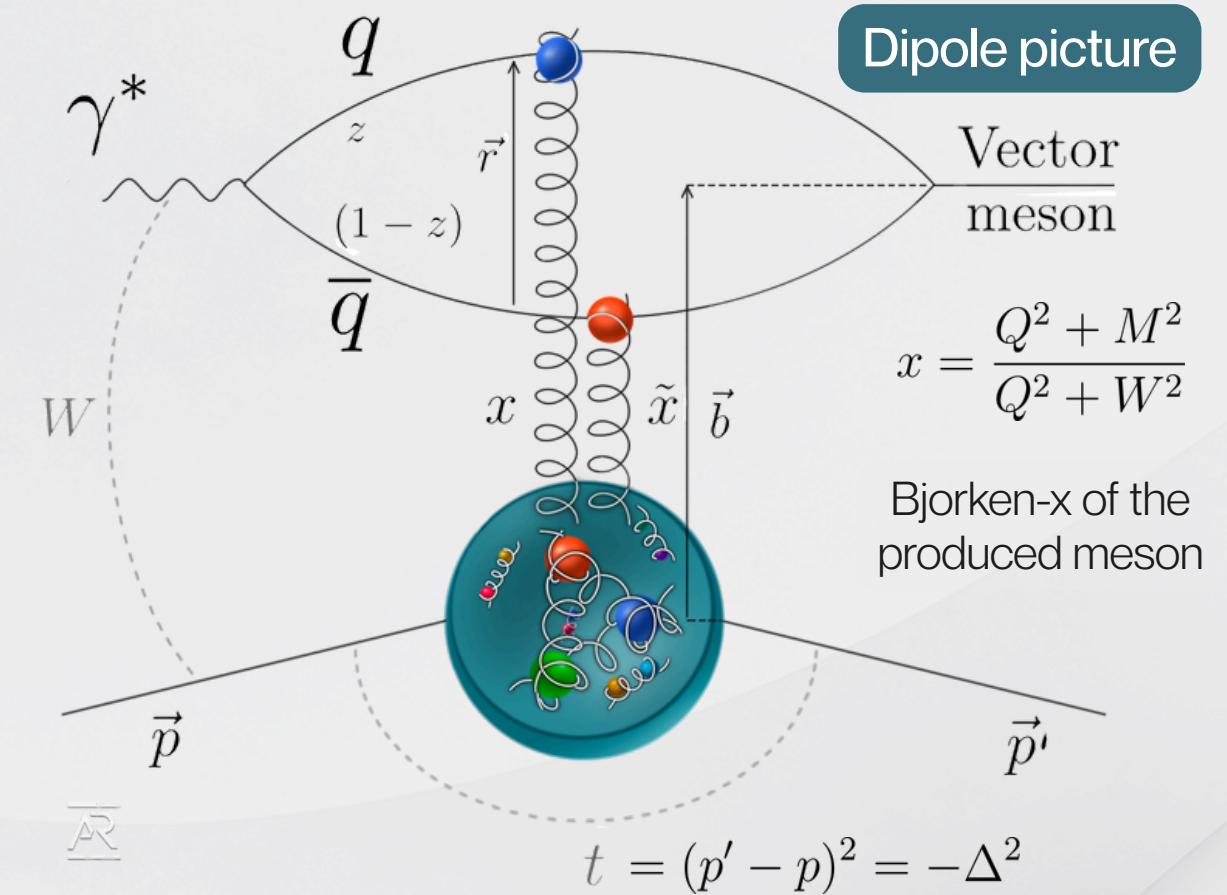
VECTOR MESON PRODUCTION

COHERENT

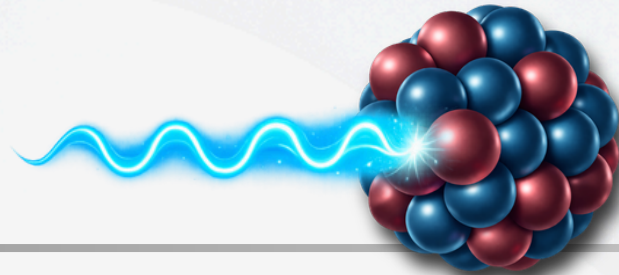


$$\left. \frac{d\sigma^{\gamma^* H \rightarrow VH}}{d|t|} \right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi} |\langle \mathcal{A}_{T,L} \rangle|^2$$

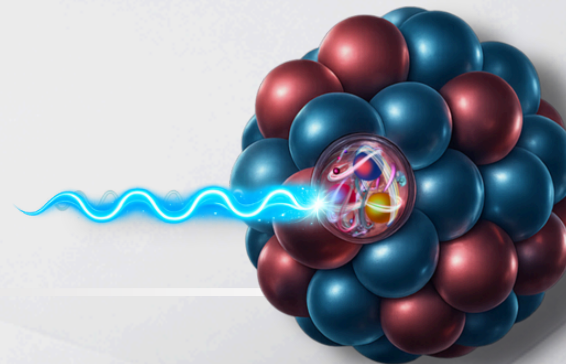
- Average over the configurations of the target



INCOHERENT



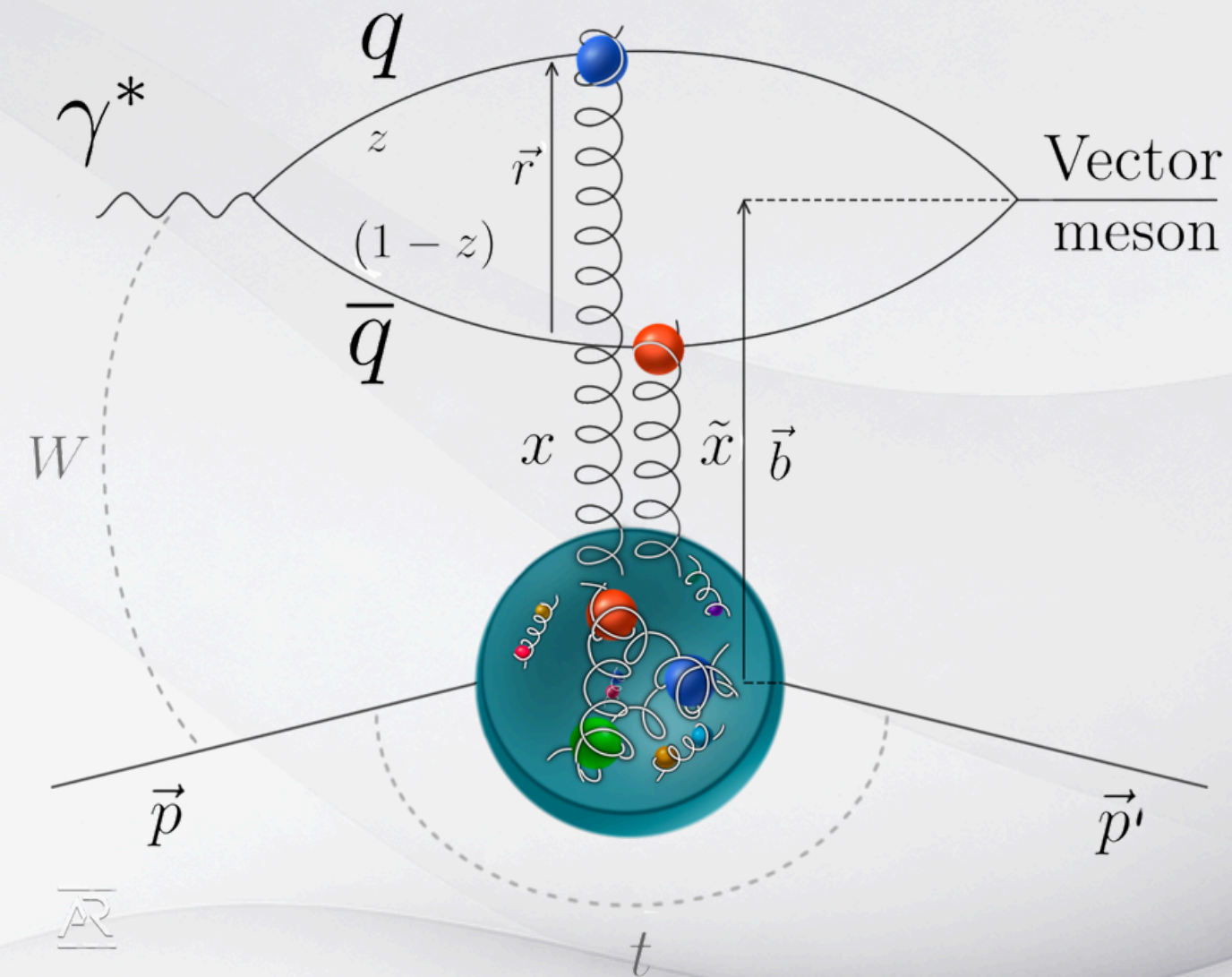
DISSOCIATIVE



$$\left. \frac{d\sigma^{\gamma^* p \rightarrow VY}}{d|t|} \right|_{T,L} = \frac{(R_g^{T,L})^2}{16\pi} (\langle |\mathcal{A}_{T,L}|^2 \rangle - |\langle \mathcal{A}_{T,L} \rangle|^2)$$

- Variance over different configurations

$$\mathcal{A}_{T,L}(x, Q^2, \vec{\Delta}) = i \int d\vec{r} \int_0^1 \frac{dz}{4\pi} \int d\vec{b} |\Psi_\gamma^* \Psi_V|_{T,L} \exp \left[-i \left(\vec{b} - \left(\frac{1}{2} - z \right) \vec{r} \right) \cdot \vec{\Delta} \right] \frac{d\sigma^{\text{dip}}}{d\vec{b}}$$

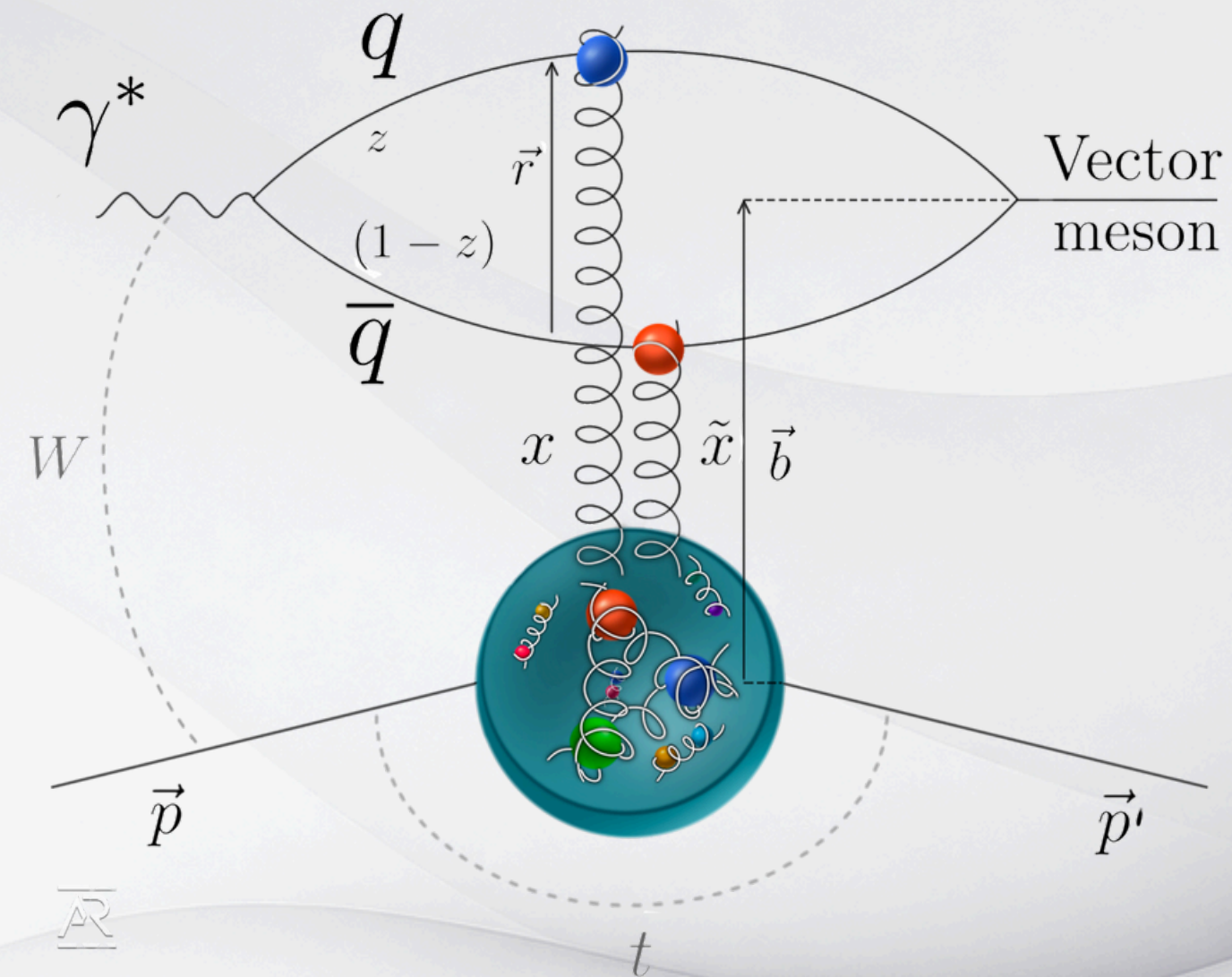


Dipole picture

The photon fluctuates into a long-lived quark-antiquark colour dipole which interacts with the hadronic target and then creates a vector meson

dipole size

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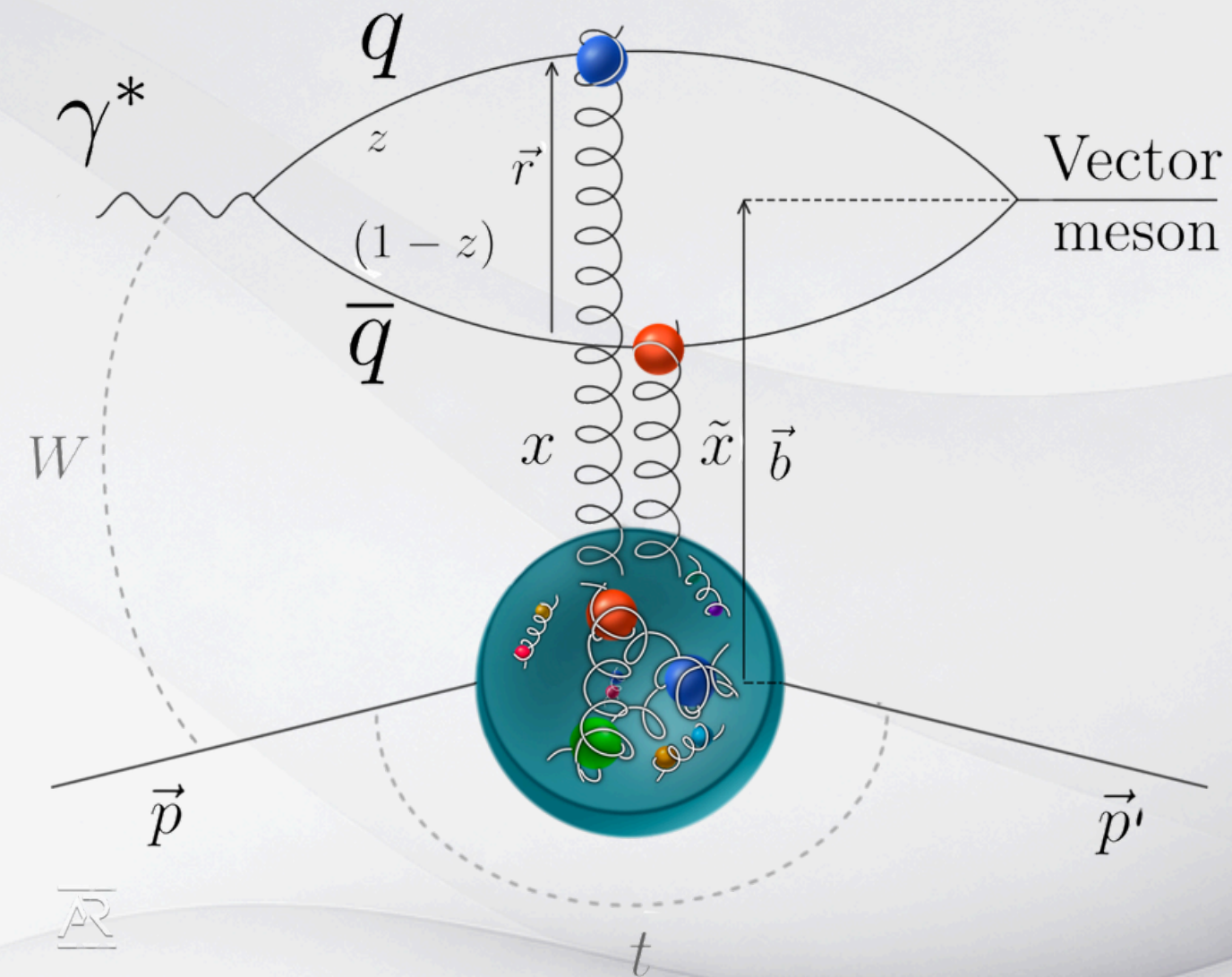
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dipole size
 quark energy fraction
 photon-dipole wave function
 vector meson wave function
 overlap between the wave function of a photon splitting into a color dipole, and the dipole forming a vector meson

q
 $\bar{q}$
 z
 $(1-z)$
 $\vec{r}$
 γ^*
 $\vec{b}$
 $\tilde{x}$
 x
 $\vec{p}$
 $\vec{p}'$
 t
 $\bar{R}$
 Vector meson

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photon-dipole wave function

vector meson wave function

• T and L denote contributions from transversely and longitudinally polarized virtual photon

• scalar part of the vector meson wave function depends on phenomenological models

- **Boosted Gaussian model**

Dipole picture

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dipole size

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vector meson wave function

impact parameter

γ^*

q

$\bar{q}$

z

$(1-z)$

$\vec{r}$

x

$\tilde{x}$

$\vec{b}$

Vector meson

$\vec{p}$

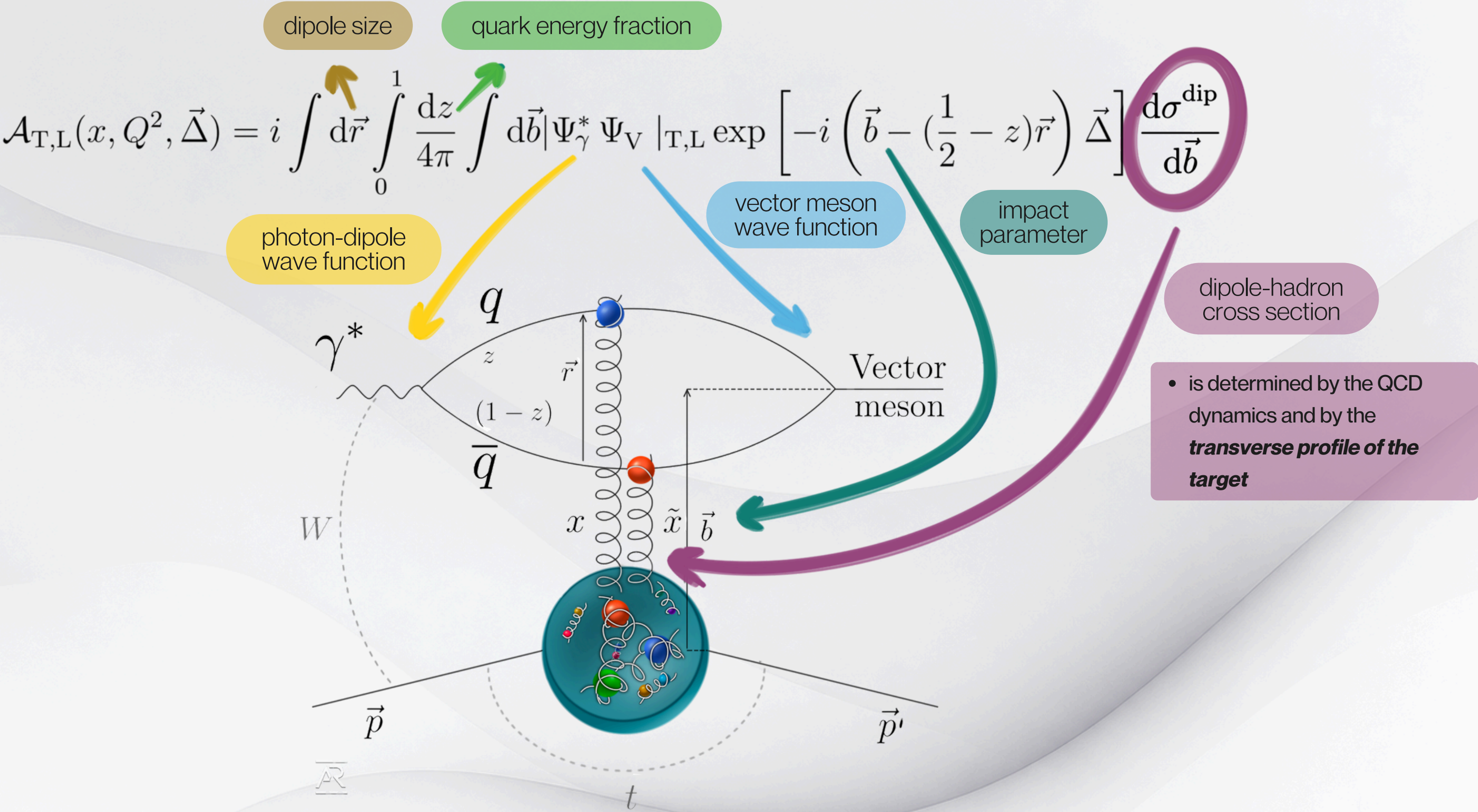
$\vec{p}'$

$\vec{\Delta}$

t

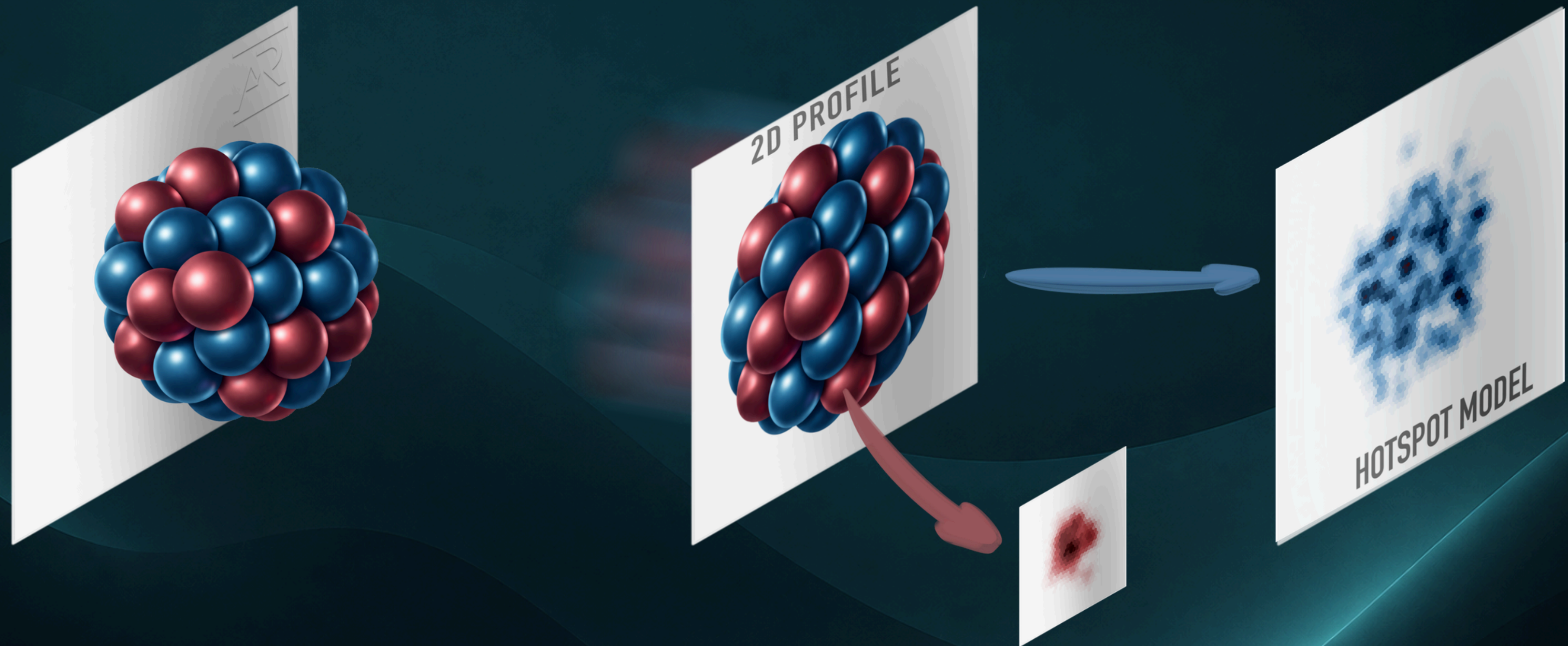
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ENERGY DEPENDENT HOTSPOT MODEL

Visual representation of a heavy ion
boosted to ultra-relativistic velocity, along with the
corresponding 'snapshot' simulated by the hotspot model

PROTON

Dipole-hadron cross section

$$\frac{d\sigma_p^{\text{dip}}}{d\vec{b}} = \sigma_0 N(x, r) T_p(\vec{b})$$

- In order to isolate the effects of proton structure fluctuations in the transverse plane, we use a factorized form of the dipole cross section

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Proton profile

$$T_p(\vec{b}) = \frac{1}{N_{\text{hs}}} \sum_{i=1}^{N_{\text{hs}}} T_{\text{hs}}(\vec{b} - \vec{b}_i)$$

$$T_{\text{hs}}(\vec{b} - \vec{b}_i) = \frac{1}{2\pi B_{\text{hs}}} \exp\left(-\frac{(\vec{b} - \vec{b}_i)^2}{2B_{\text{hs}}}\right)$$

- Model that geometrically describes the structure of the proton in the transverse plane using hotspots (regions of high partonic density)
- The positions of hotspots, are randomly sampled from a 2D Gaussian distribution and each hotspot has a Gaussian profile

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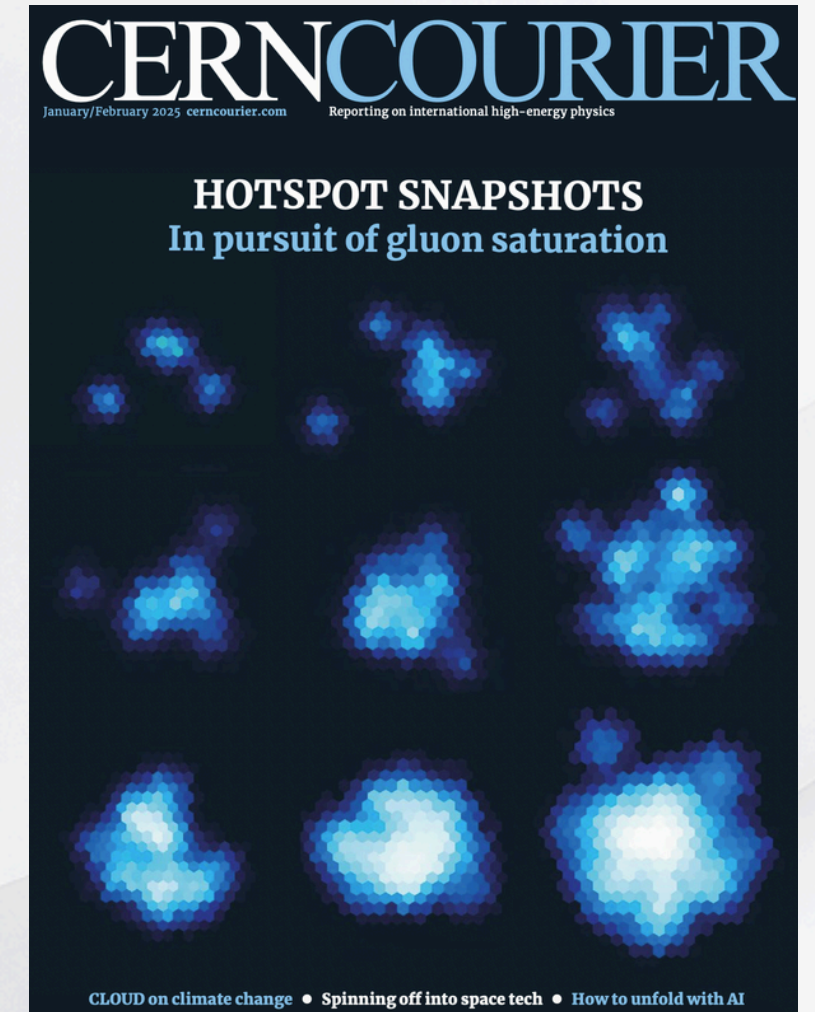
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Number of hotspots

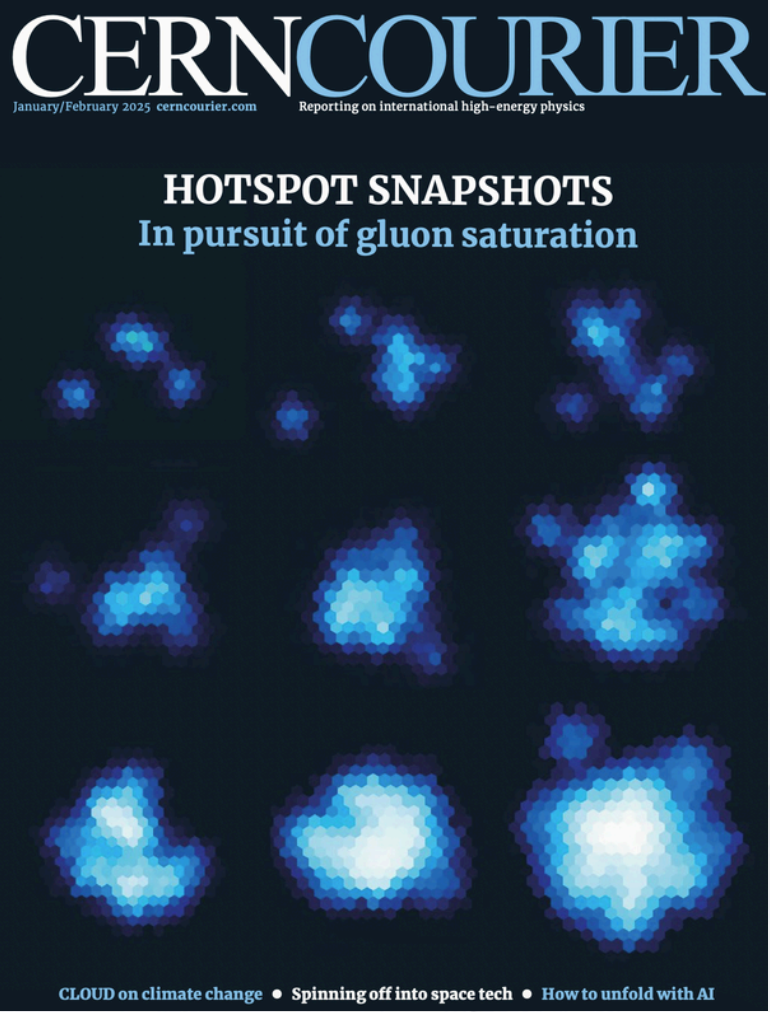
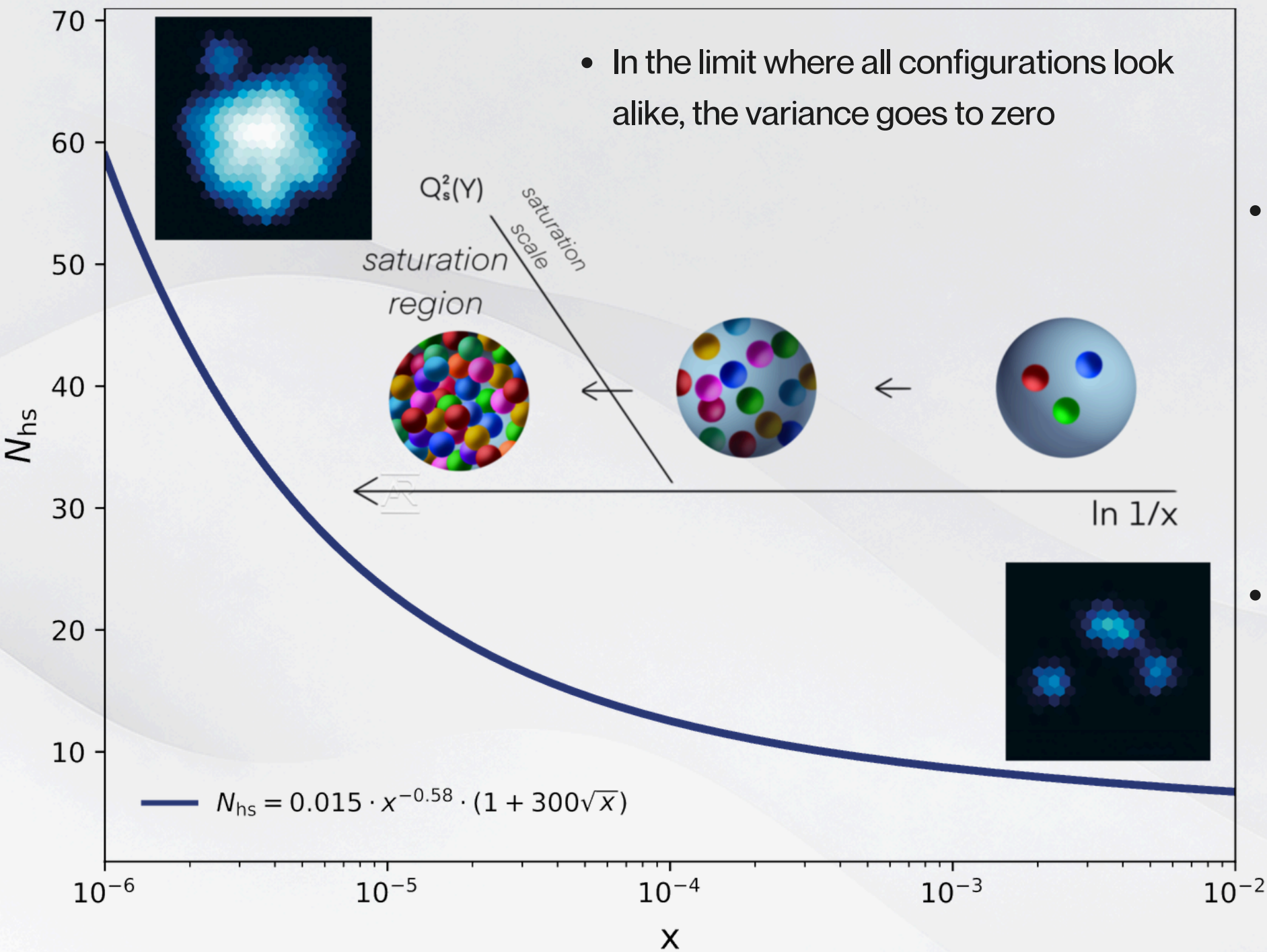
$$\langle N_{hs}(x) \rangle = p_0 x^{p_1} (1 + p_2 \sqrt{x})$$

- The key feature of our model is the evolution of the number of hotspots with energy in order to reflect the raise of the gluon distribution, as Bjorken-x decreases



“The first proton shows a handful of gluonic hotspots carrying roughly 1% of the proton’s momentum. The following eight delve down to a Bjorken-x of 10^{-6} , where more than 70 hotspots overlap and gluons recombine as often as they split in two.”

PROTON

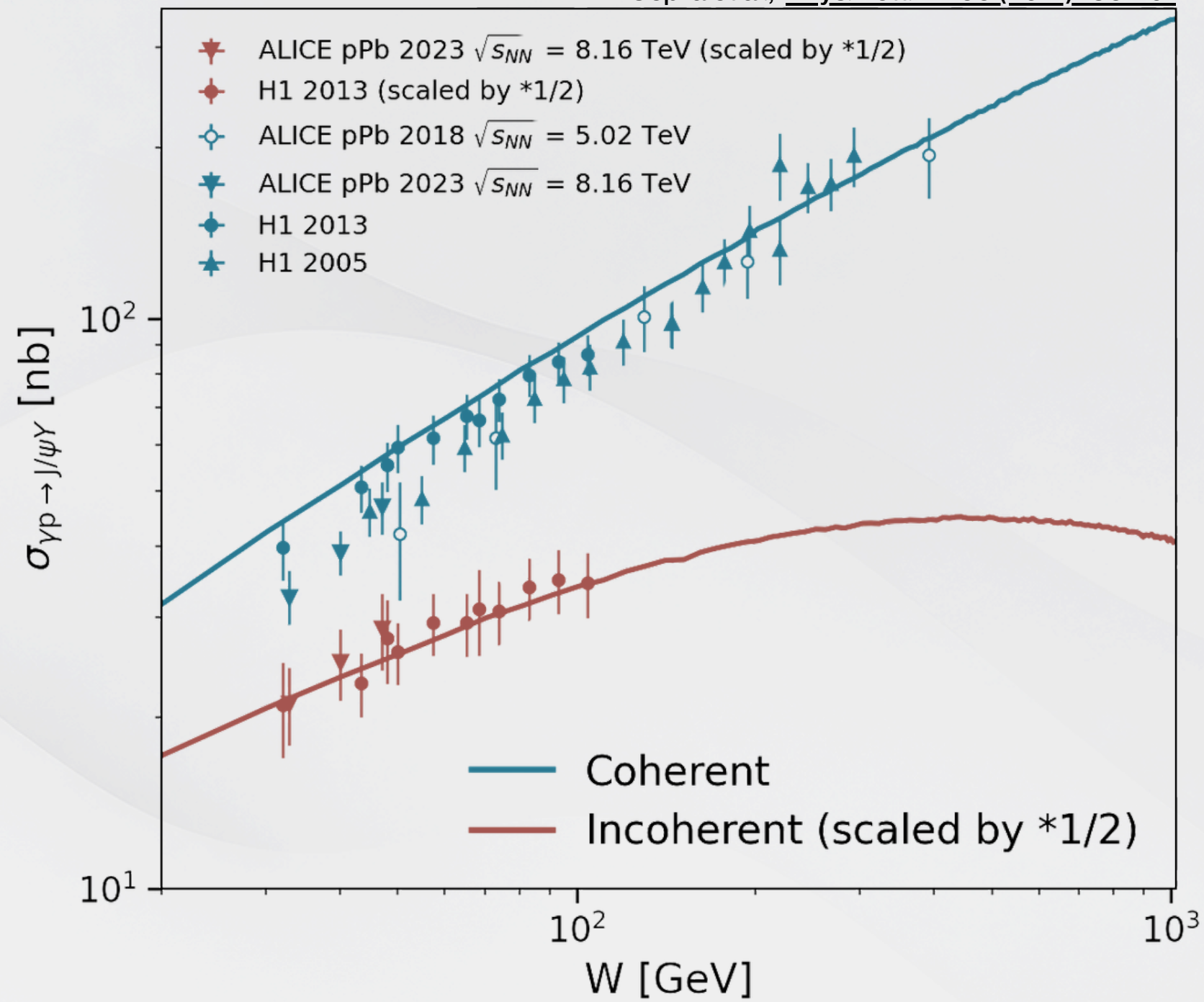


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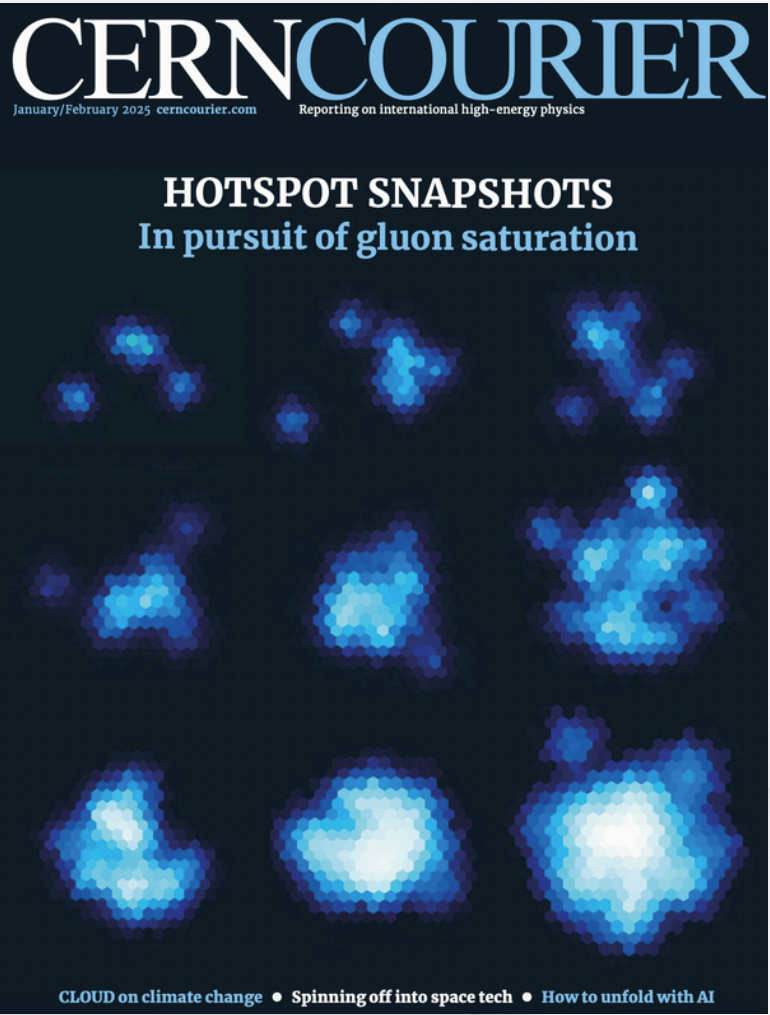
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Photoproduction of J/ψ vector meson off protons for the coherent (blue) and incoherent (red) processes.



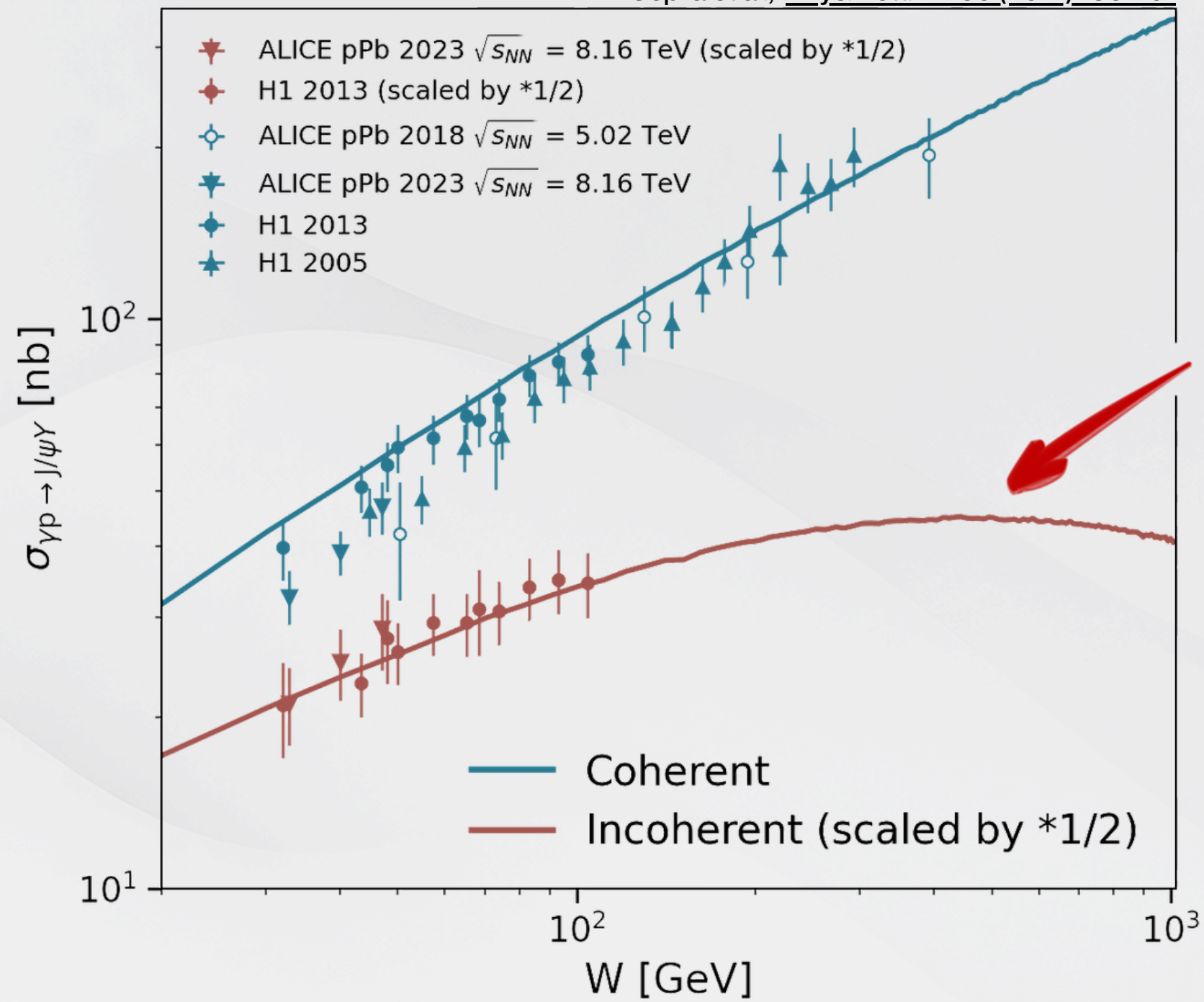
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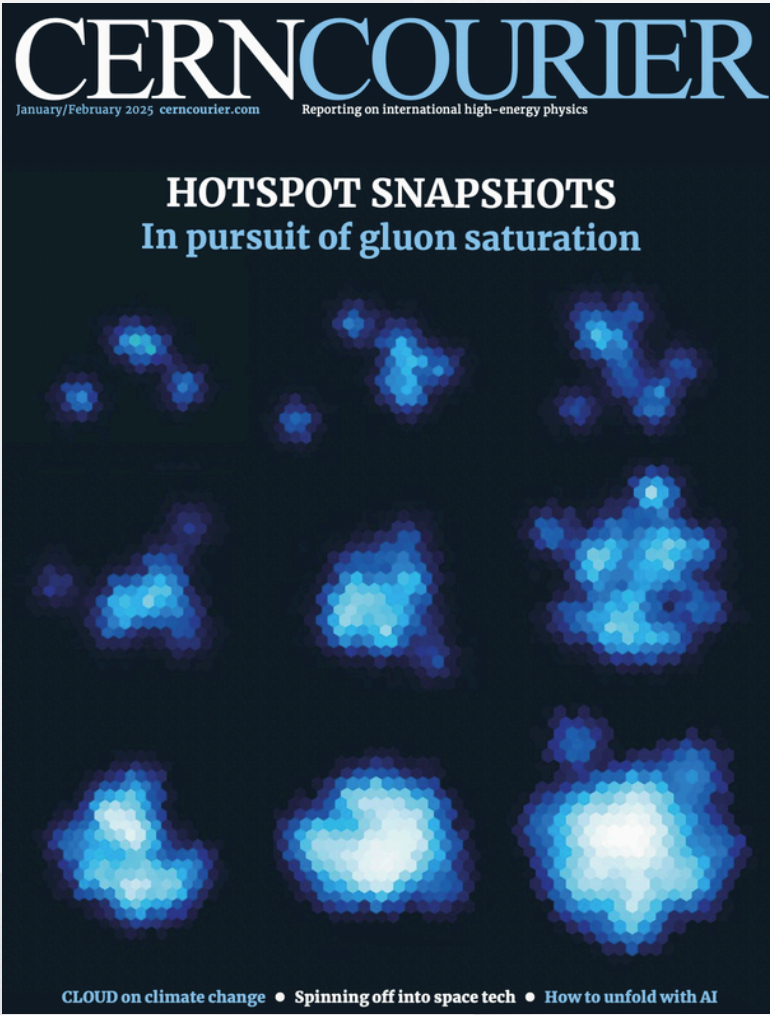
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Cepila et al., Phys. Lett. B 766 (2017) 186–191



Photoproduction of J/ψ vector meson off protons for the coherent (blue) and incoherent (red) processes.

- ~500 GeV THE CROSS SECTION STARTS TO DECREASE
 - The fact that the variance decreases signifies that the configurations start to resemble each other, which marks the onset of saturation



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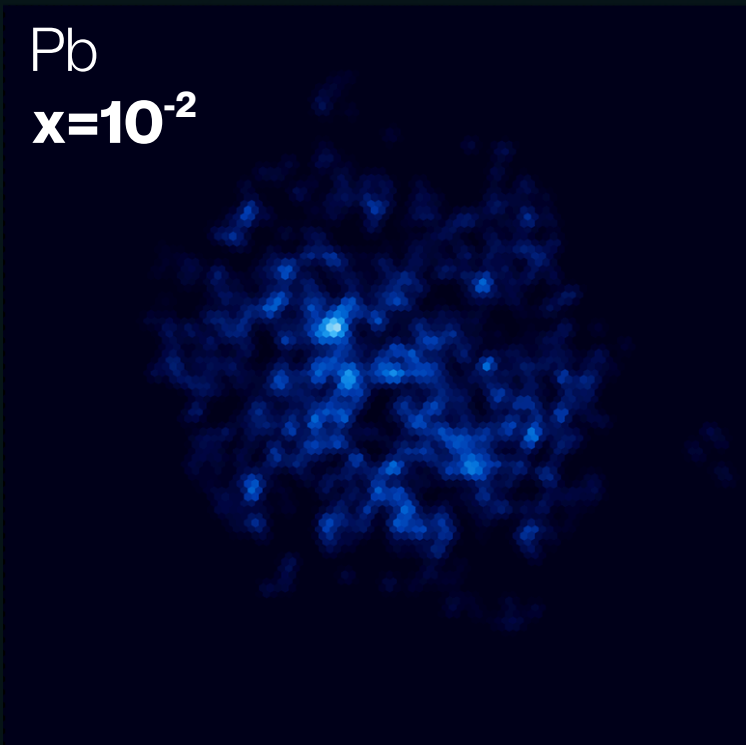
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$$\left(\frac{d\sigma_A^{\text{dip}}}{d\vec{b}} \right) = 2 \left[1 - \left(1 - \frac{1}{2A} \sigma_0 N(x, r) T_A(\vec{b}) \right)^A \right]$$

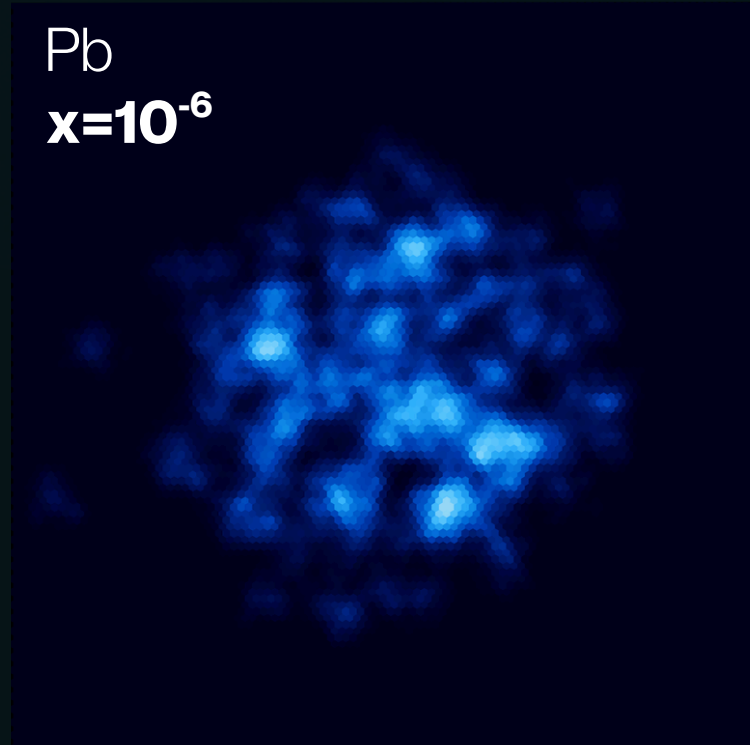
Dipole cross section

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Pb
x=10⁻²



Pb
x=10⁻⁶



Transverse profile of lead generated using energy-dependent Hotspot model.

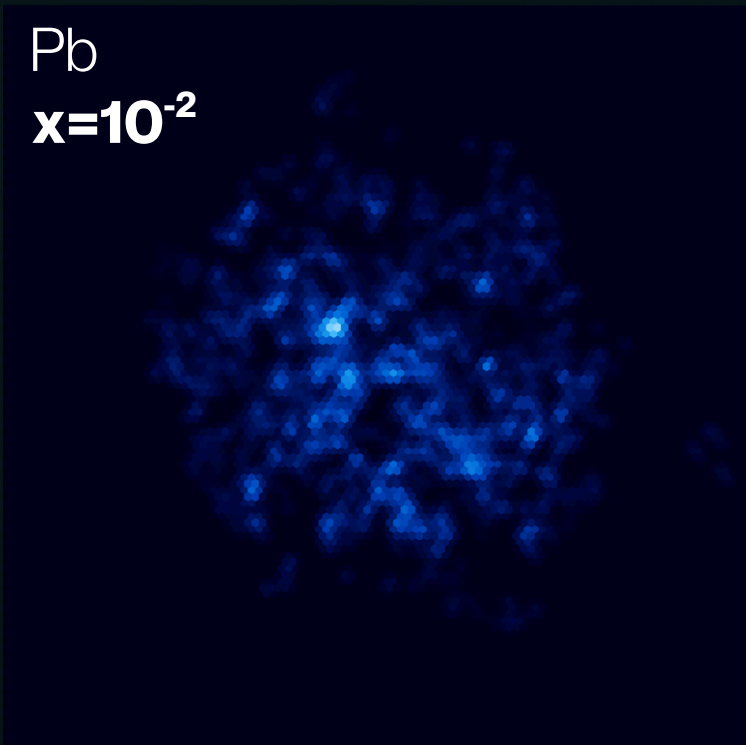
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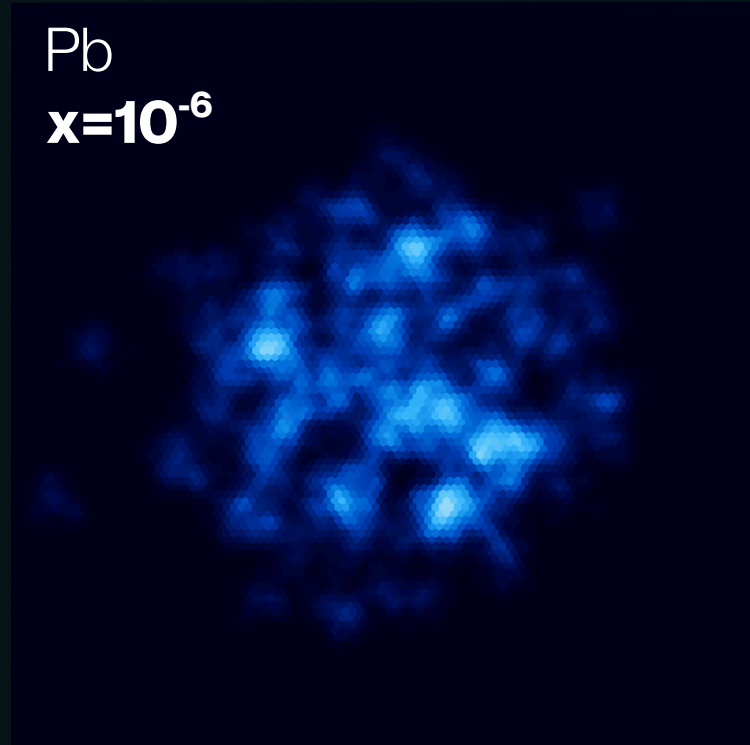
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- Nuclei are made of nucleons, which are made of hotspots
- Nucleons are placed randomly within the nucleus at positions $\vec{b}_i$, according to the Woods-Saxon distribution and the hotspots are placed randomly within the nucleons at positions $\vec{b}_j$
- The nuclear profile is determined by summing the individual hotspot profiles within each nucleon, and then summing these contributions over all nucleons within the nucleus

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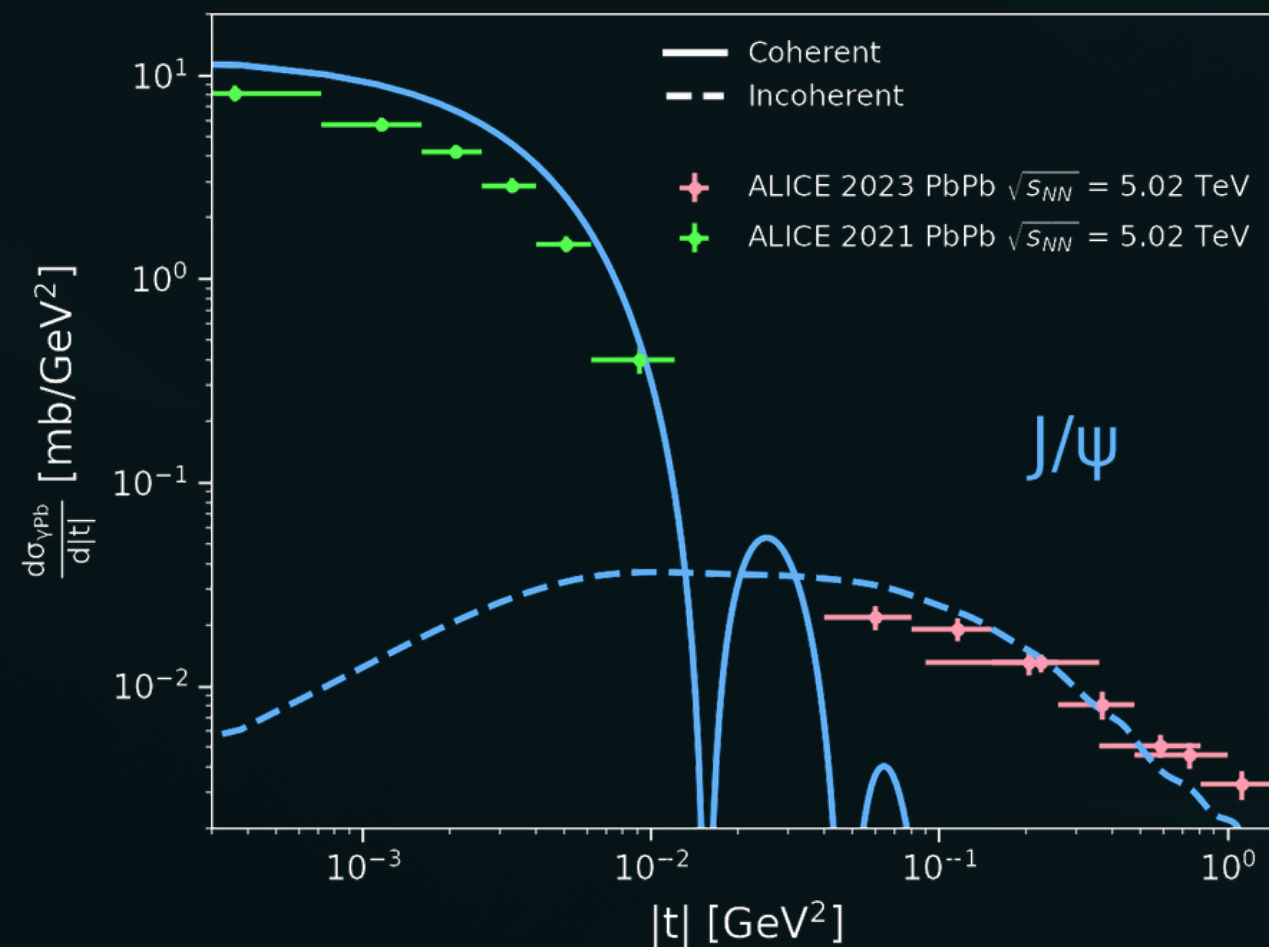
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Mandelstam- t dependence of coherent (solid line) and incoherent (dashed line) J/ψ photoproduction off Pb.

- Steeper slope than the data on coherent production
- Model describes correctly the behaviour of the incoherent cross section within the current experimental errors

ONSET OF GLUON SATURATION

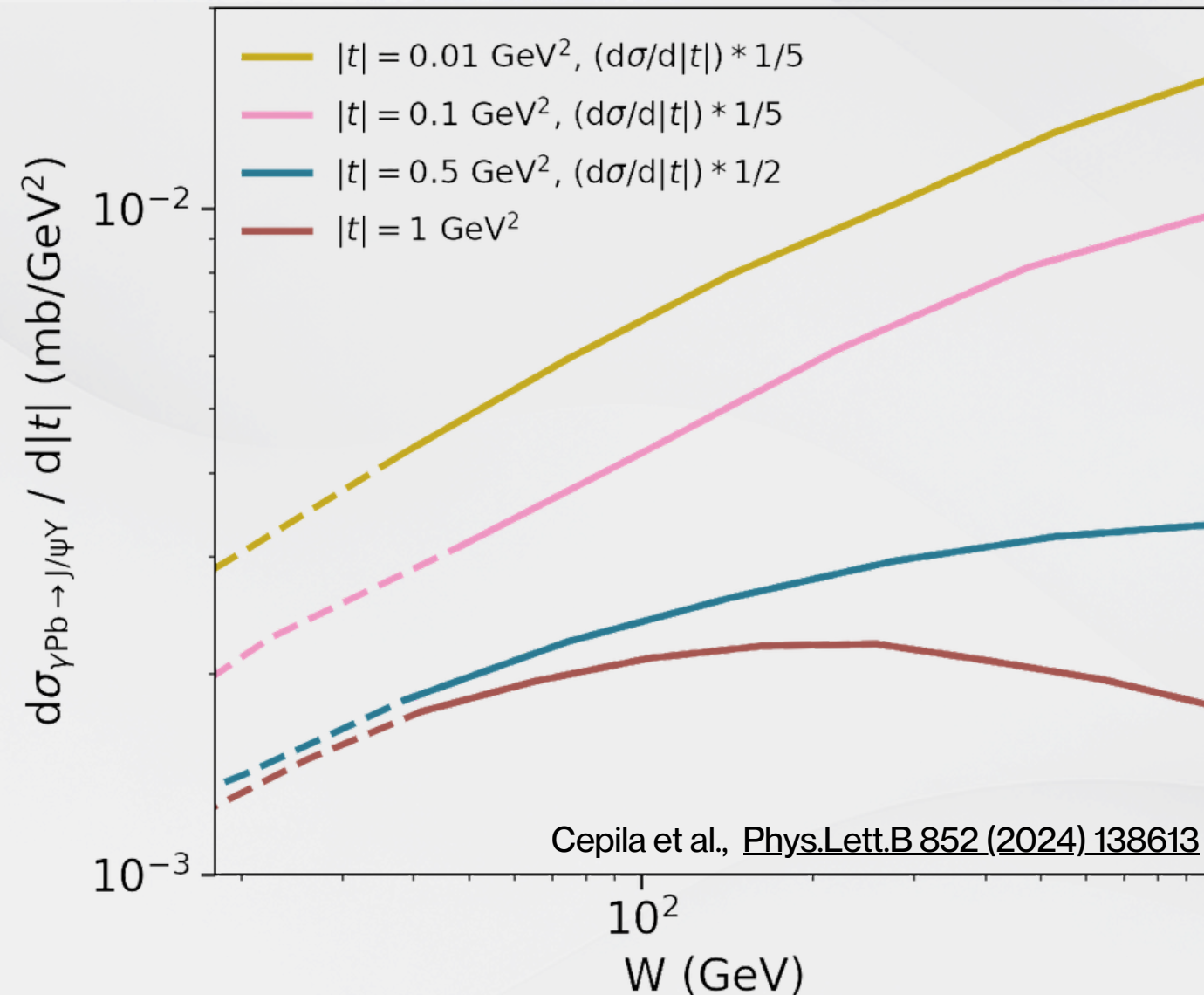
ONSET OF GLUON SATURATION

- Mandelstam- t $\longleftrightarrow$ FOURIER TRANSFORM $\longrightarrow$ matter distribution in the impact-parameter plane
- Different ranges in Mandelstam- t are sensitive to different size scales
- Incoherent processes are sensitive to two different size scales, that of NUCLEONS (~ 1 fm) , and that of HOTSPOTS (~ 0.1 fm)
- Scanning the energy behaviour in specific $|t|$ ranges allows for the isolation of the contribution of hotspots where one expects saturation effects to set in

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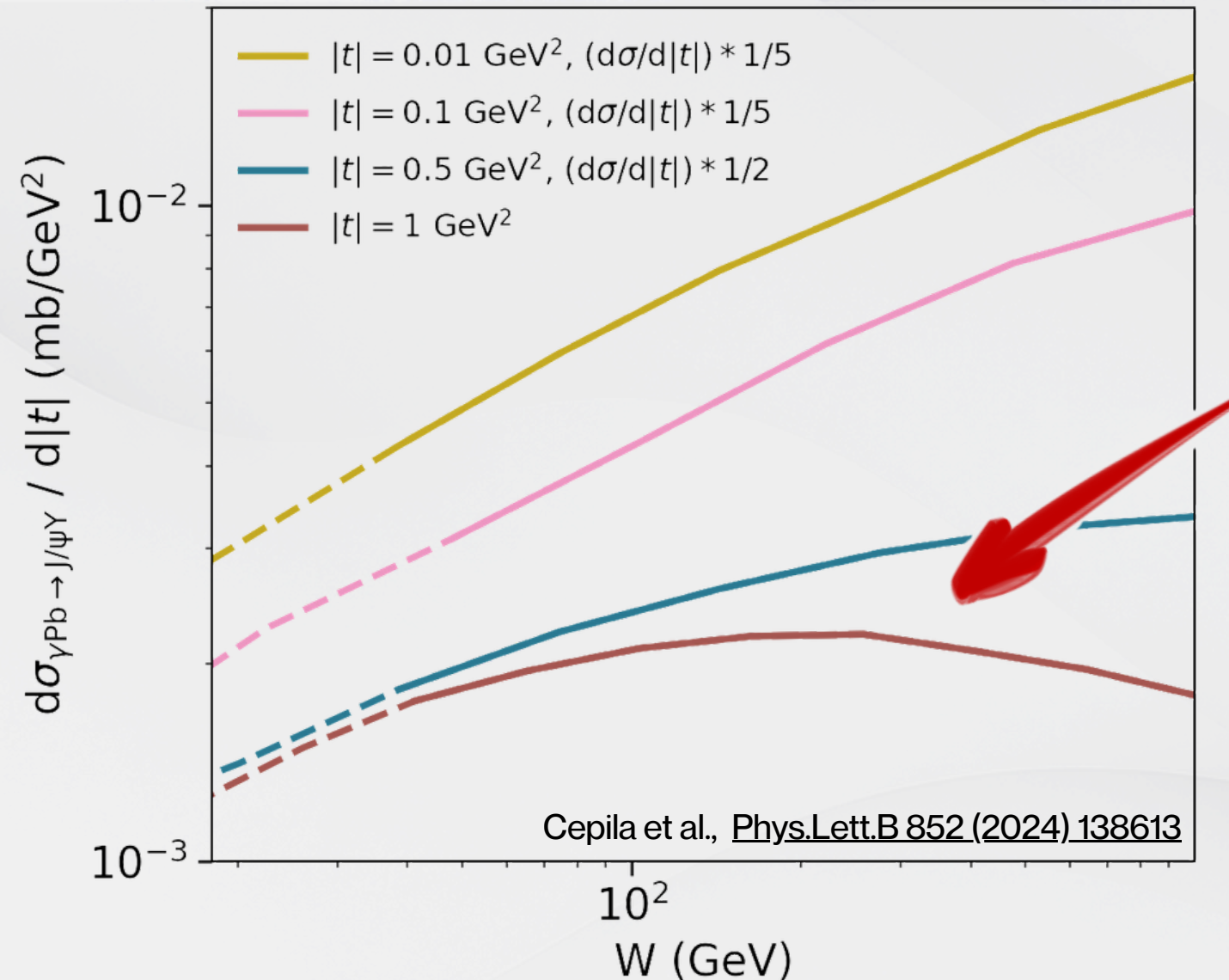
- lower values of $|t|$ are dominated by the contribution of large size scales
- the cross section at large values of $|t|$ is determined mainly by the variance of objects with a small transverse size



Prediction of the energy-dependent hotspot model for the incoherent photoproduction of J/ψ vector mesons off Pb in diffractive interactions

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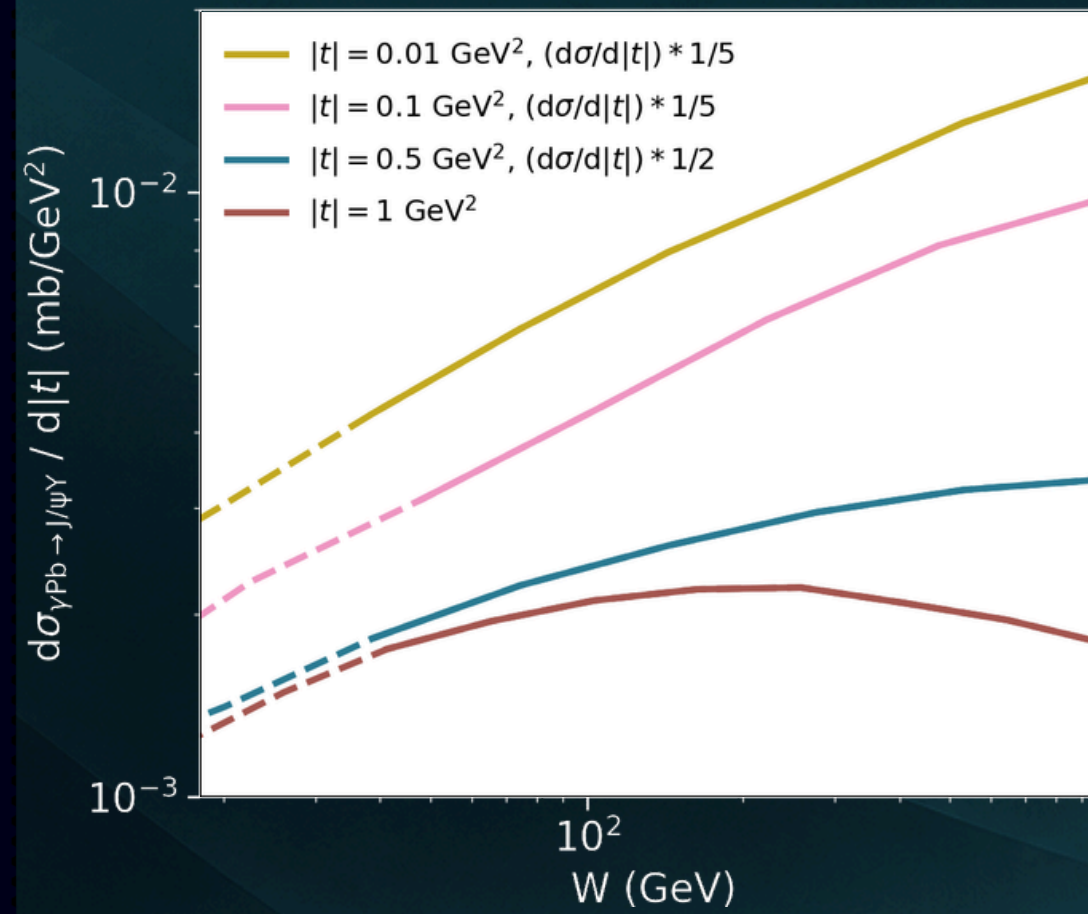
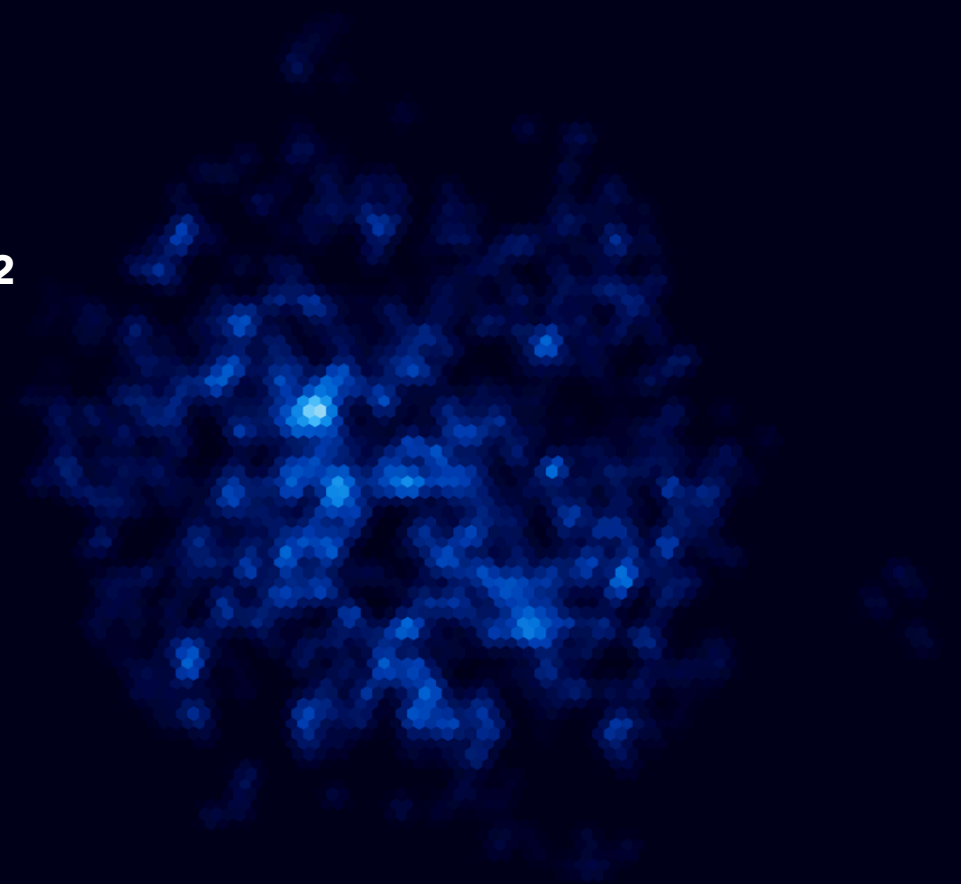


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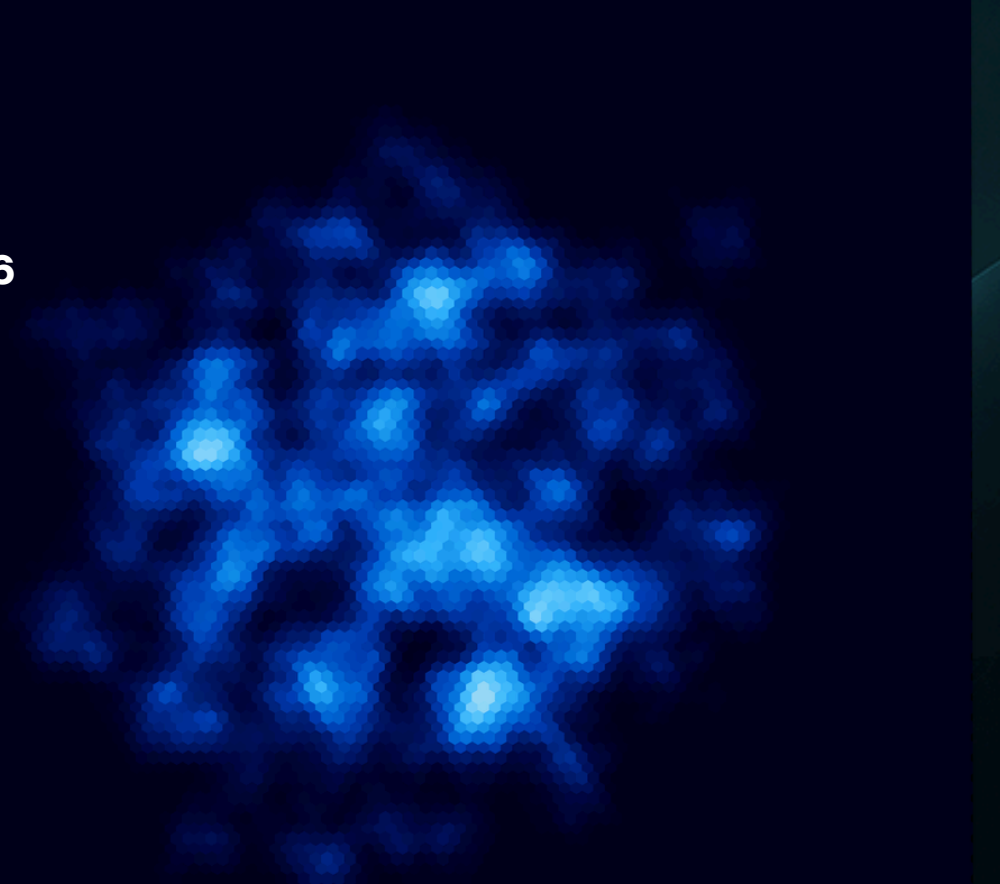
- At $|t| = 1 \text{ GeV}^2$, the rise of the cross section reaches a maximum at $W \sim 300 \text{ GeV}$ and then decreases

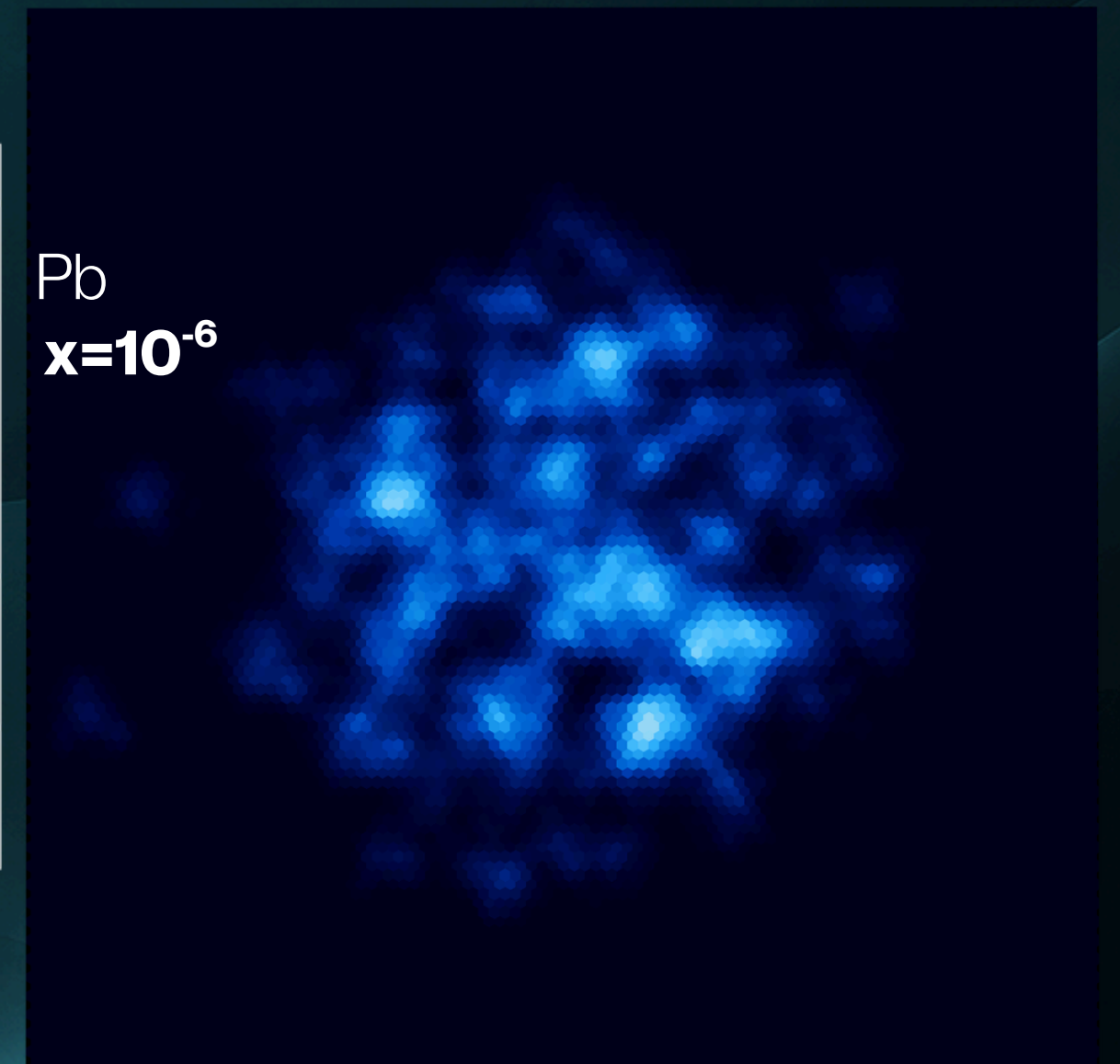
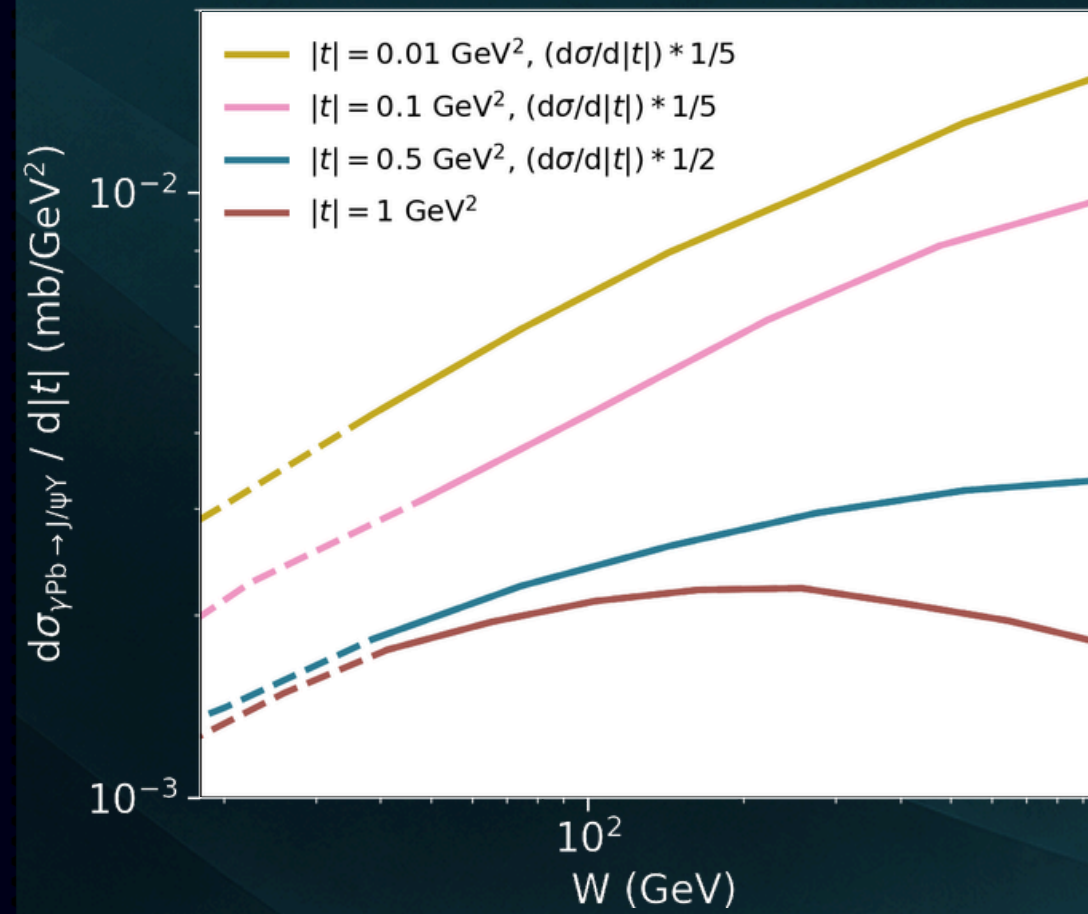
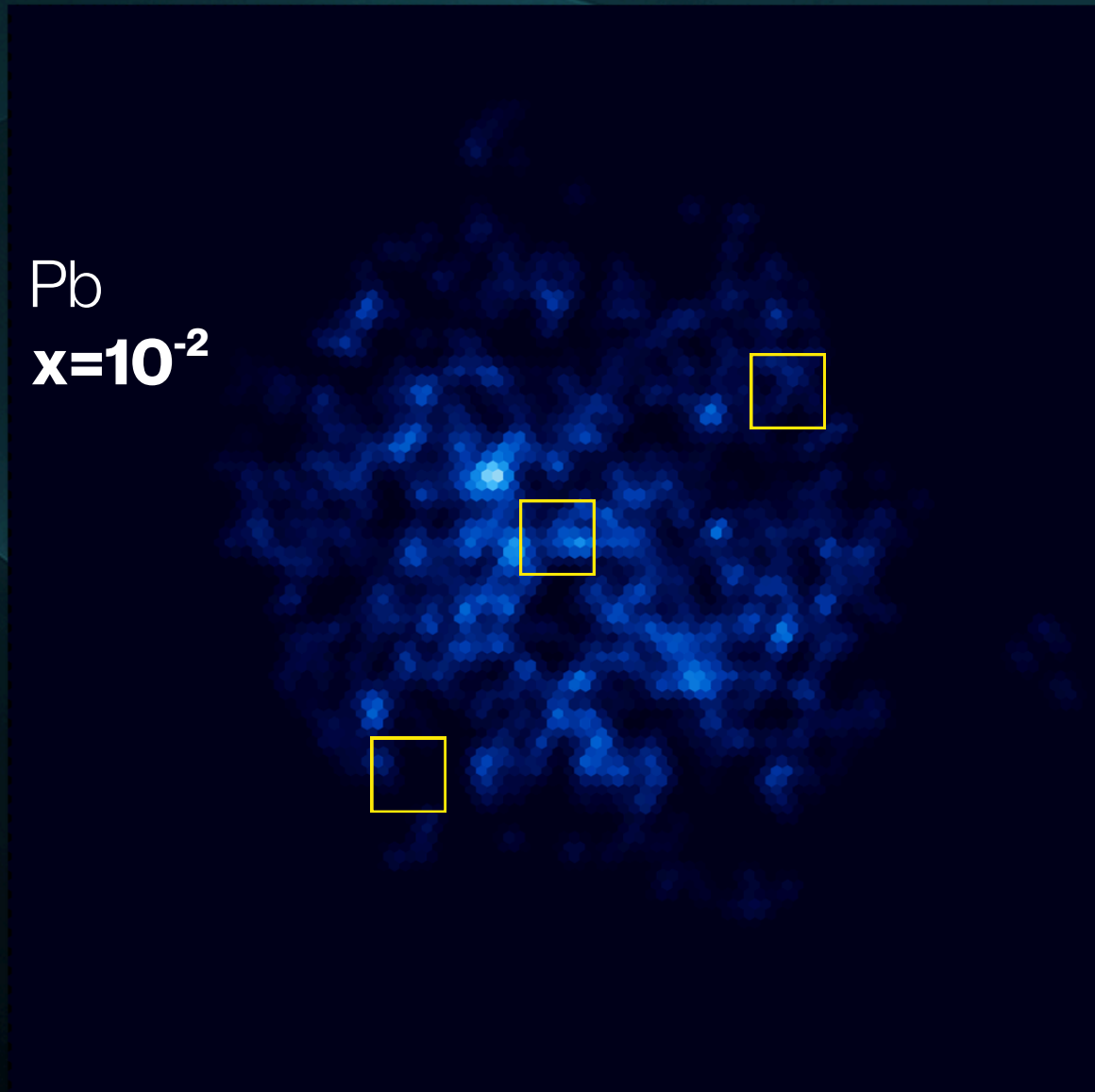
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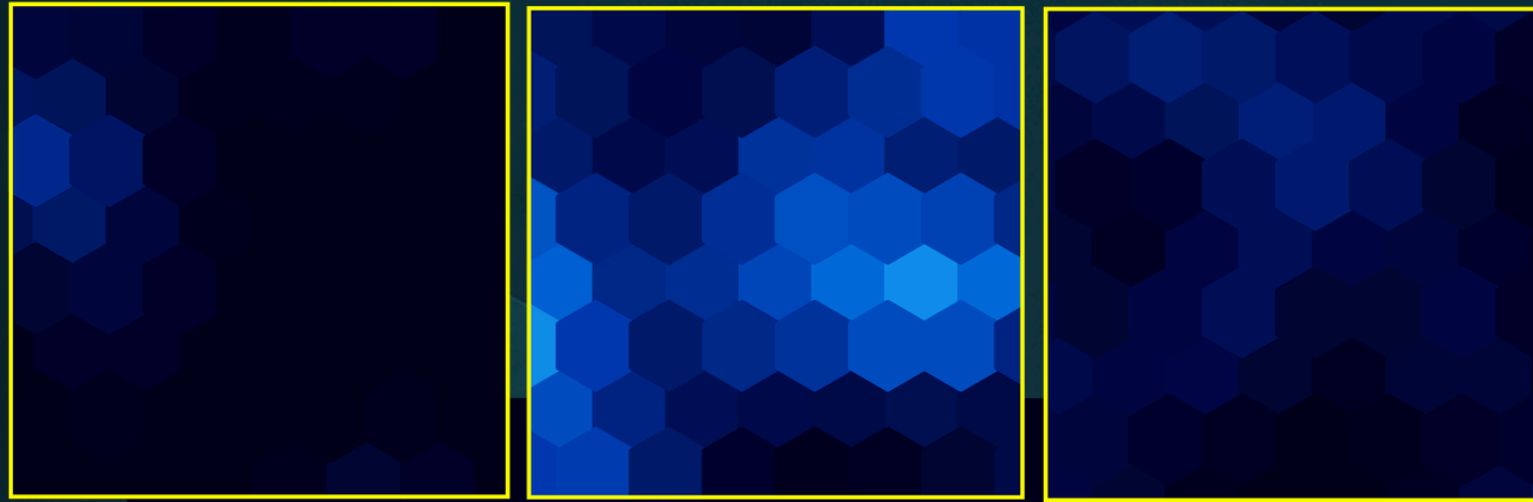
Pb
 $x=10^{-2}$



Pb
 $x=10^{-6}$

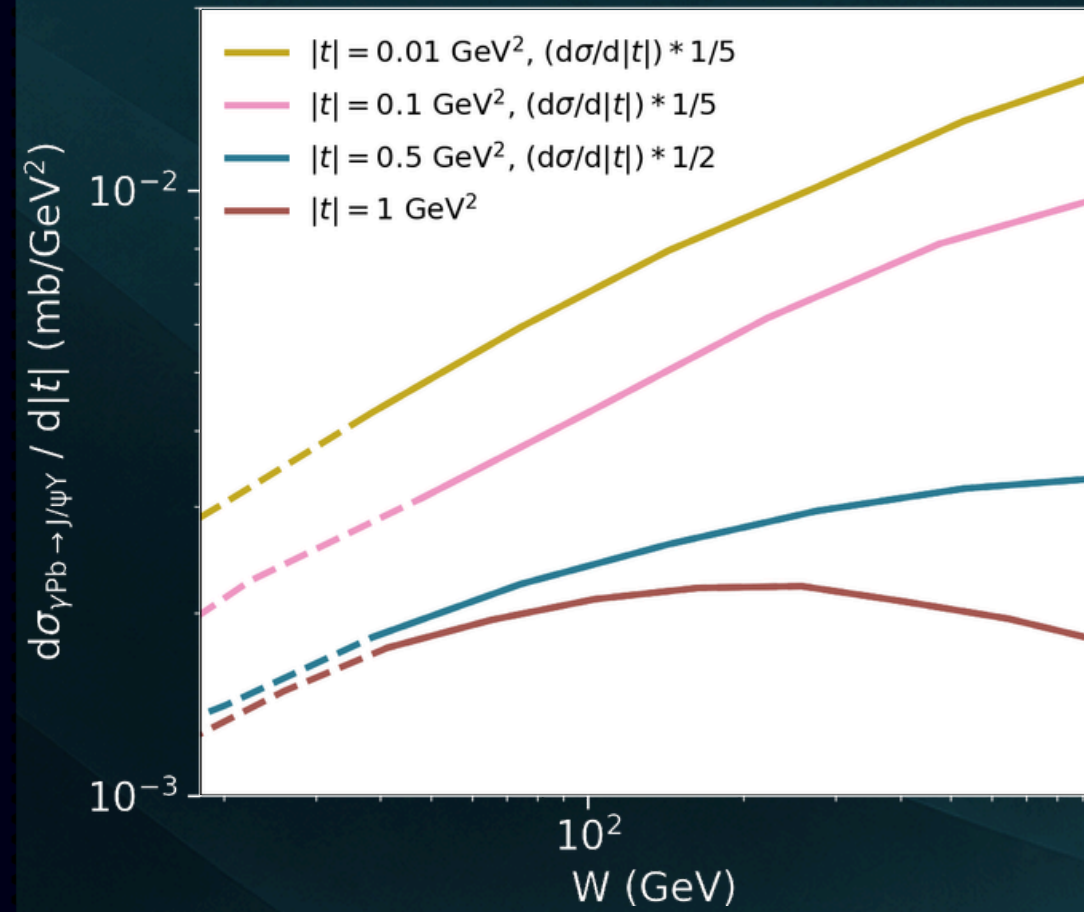
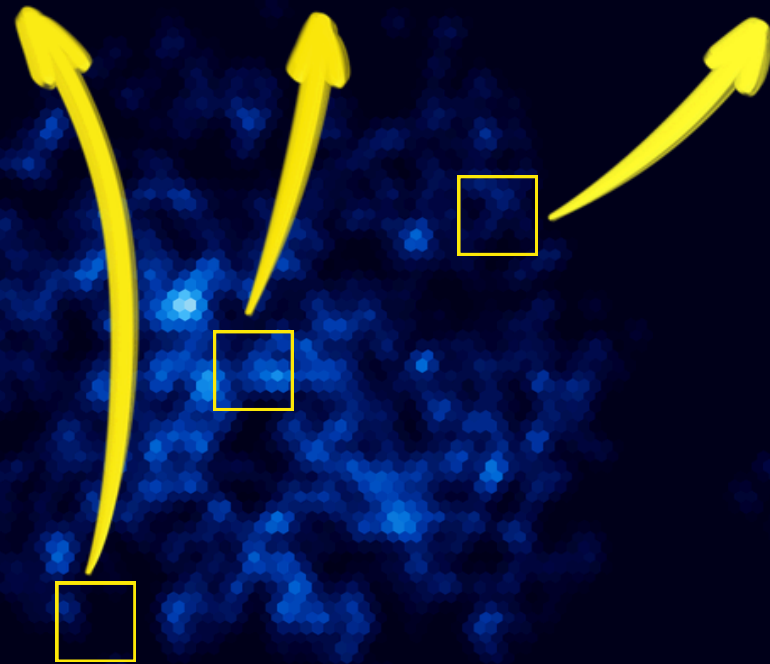




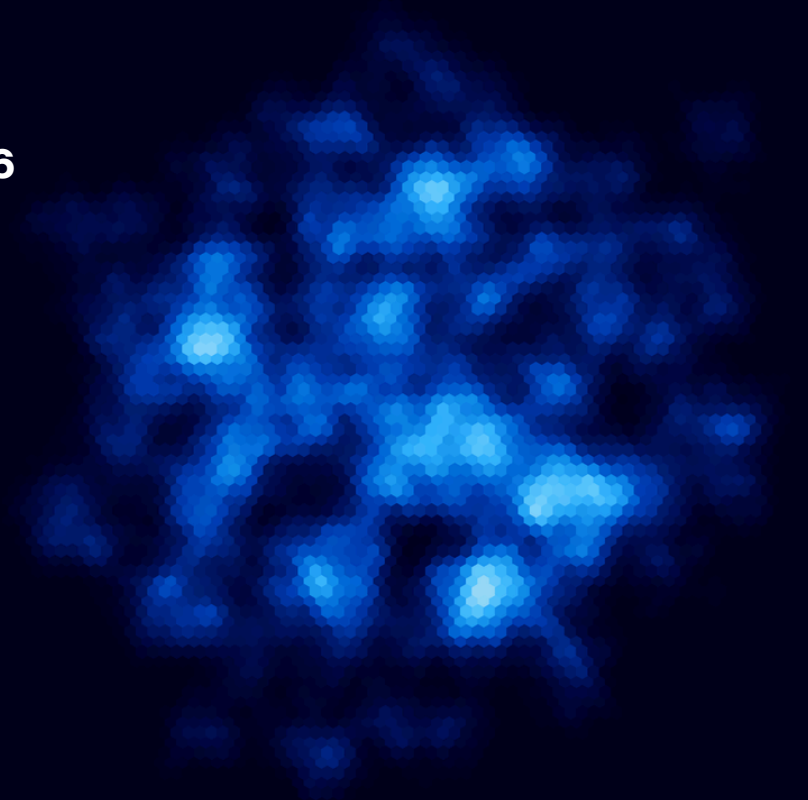


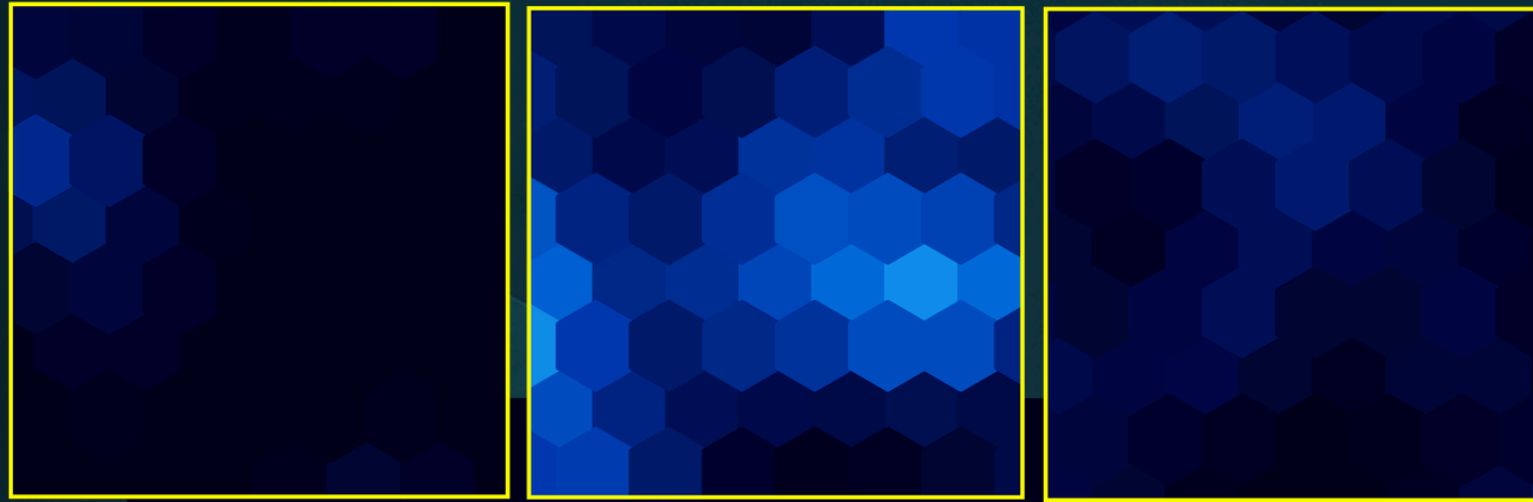
-0.8 fm 0.8 fm

Pb
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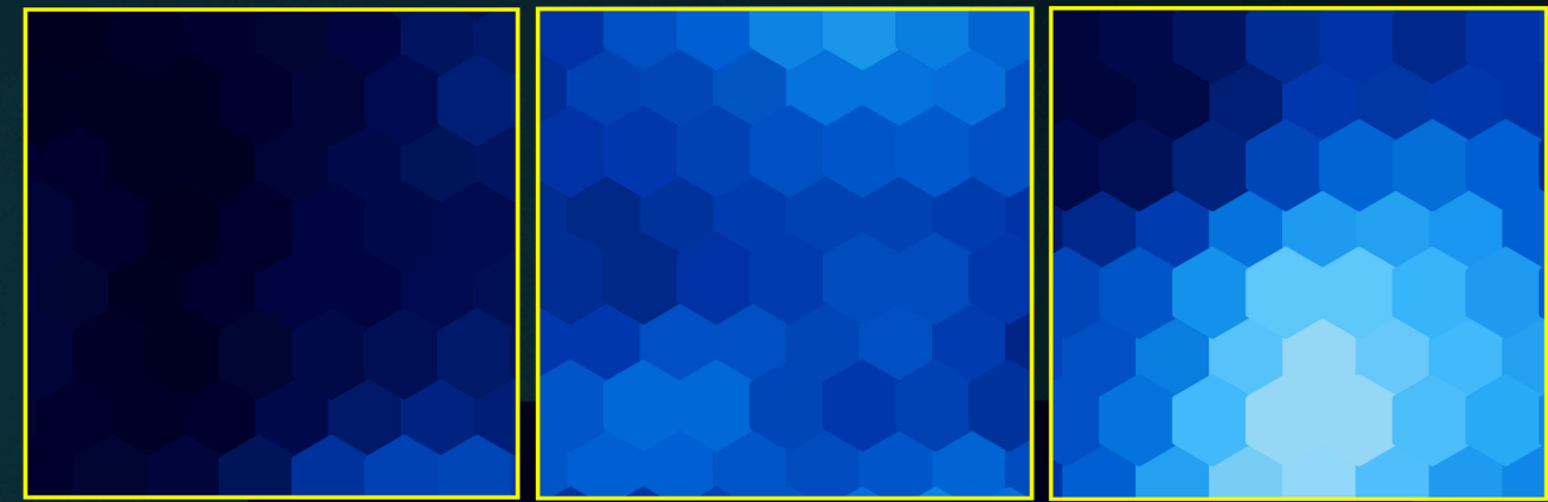


Pb
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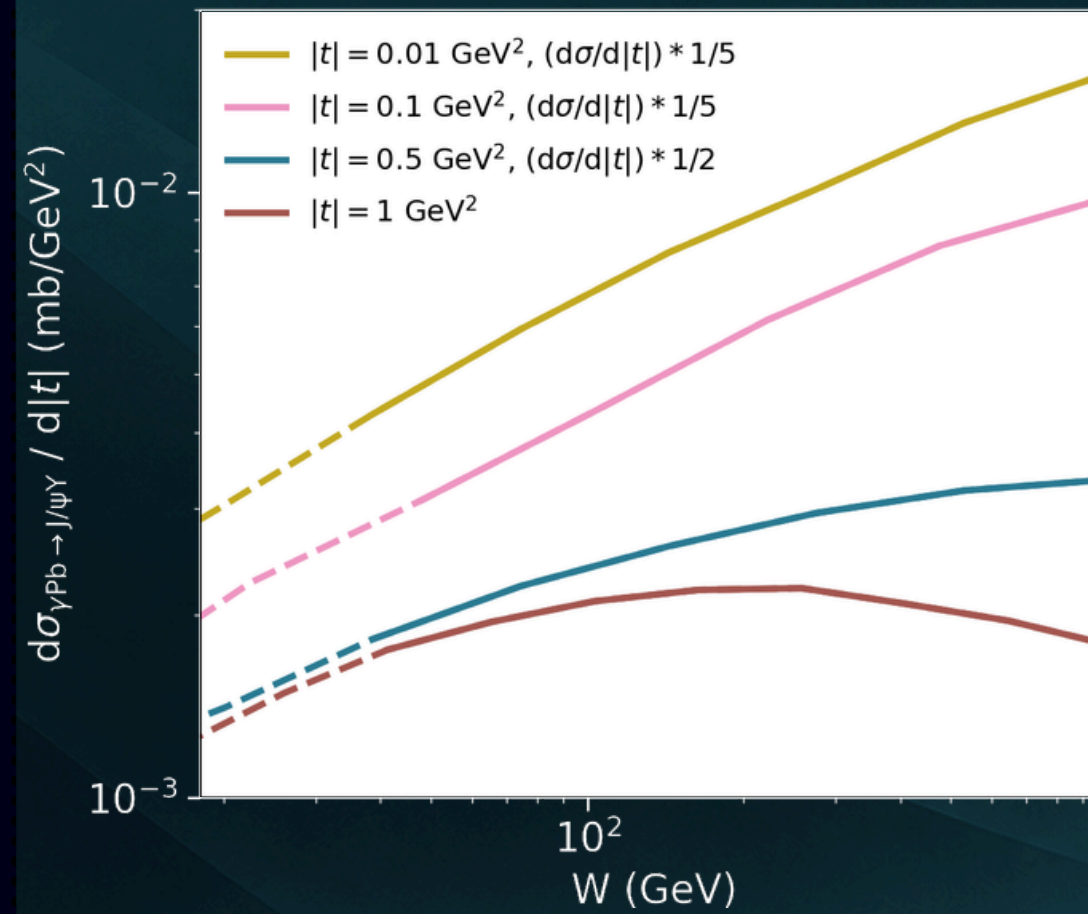
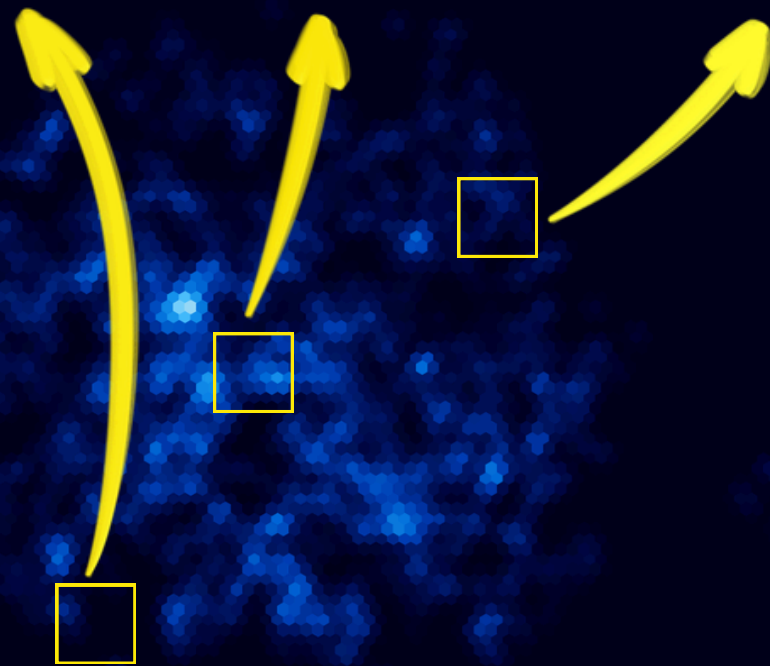




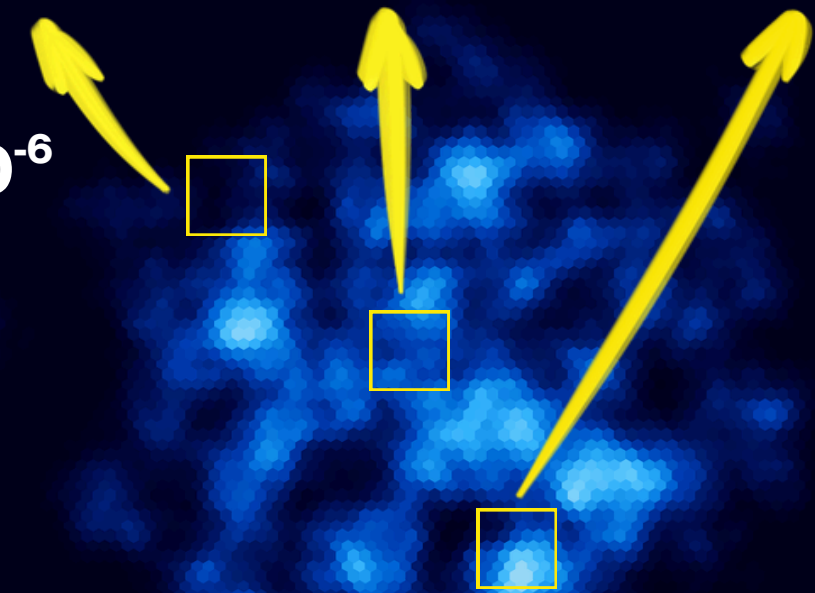
-0.8 fm 0.8 fm

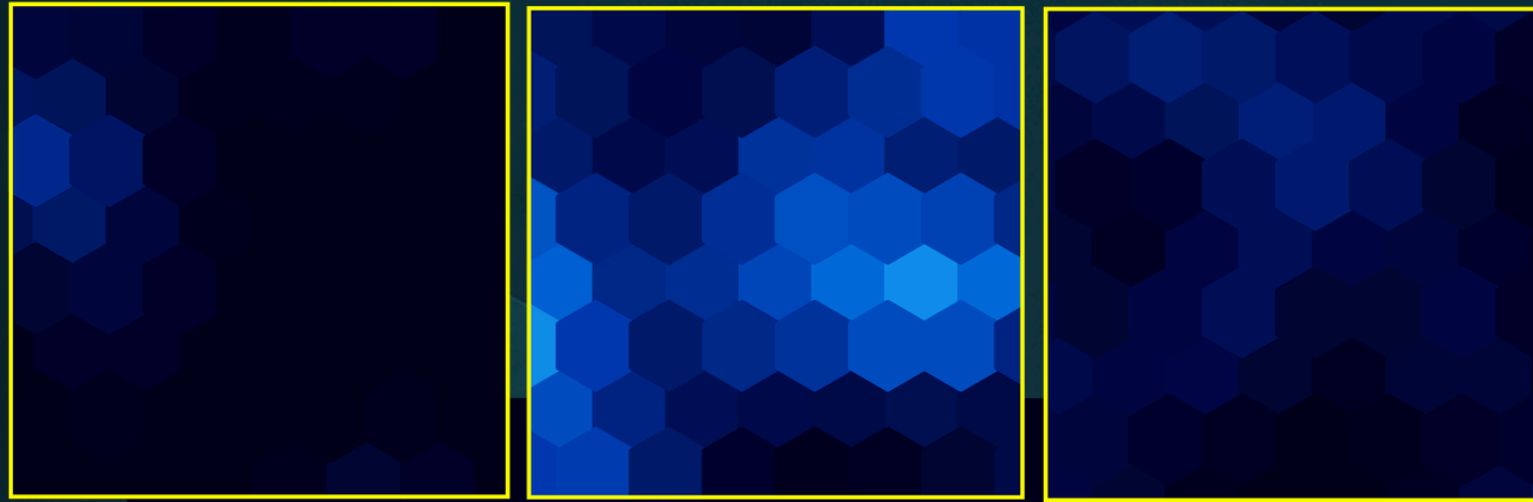


Pb
 $x=10^{-2}$

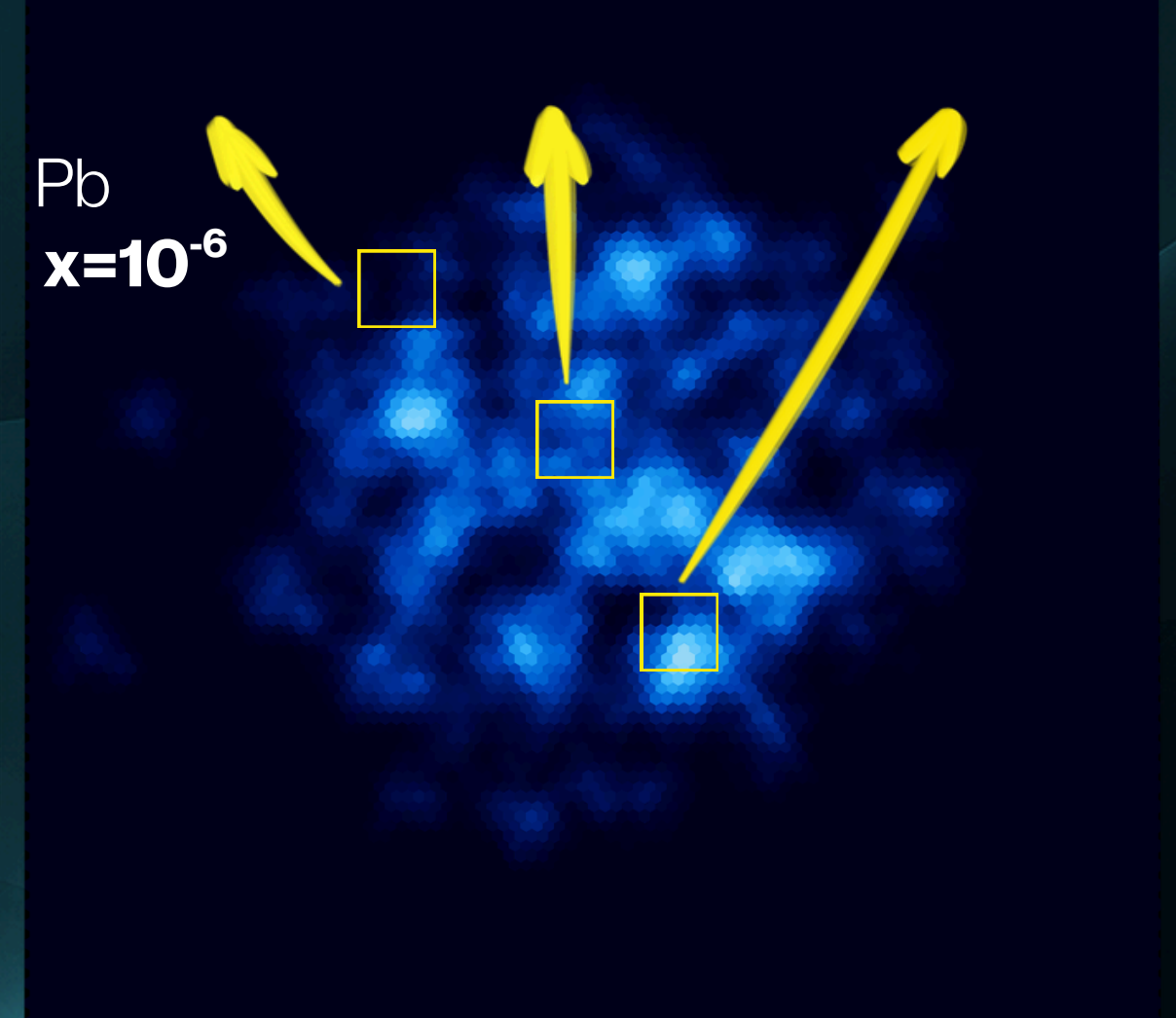
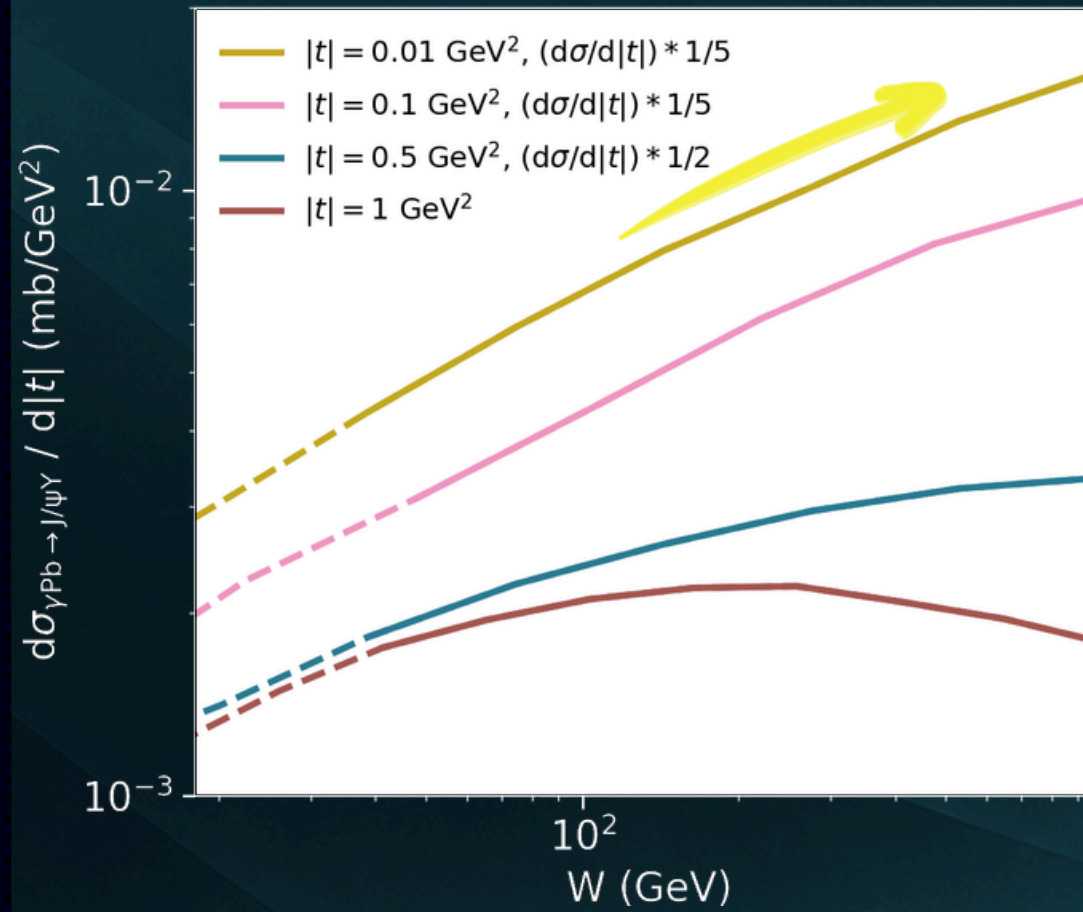
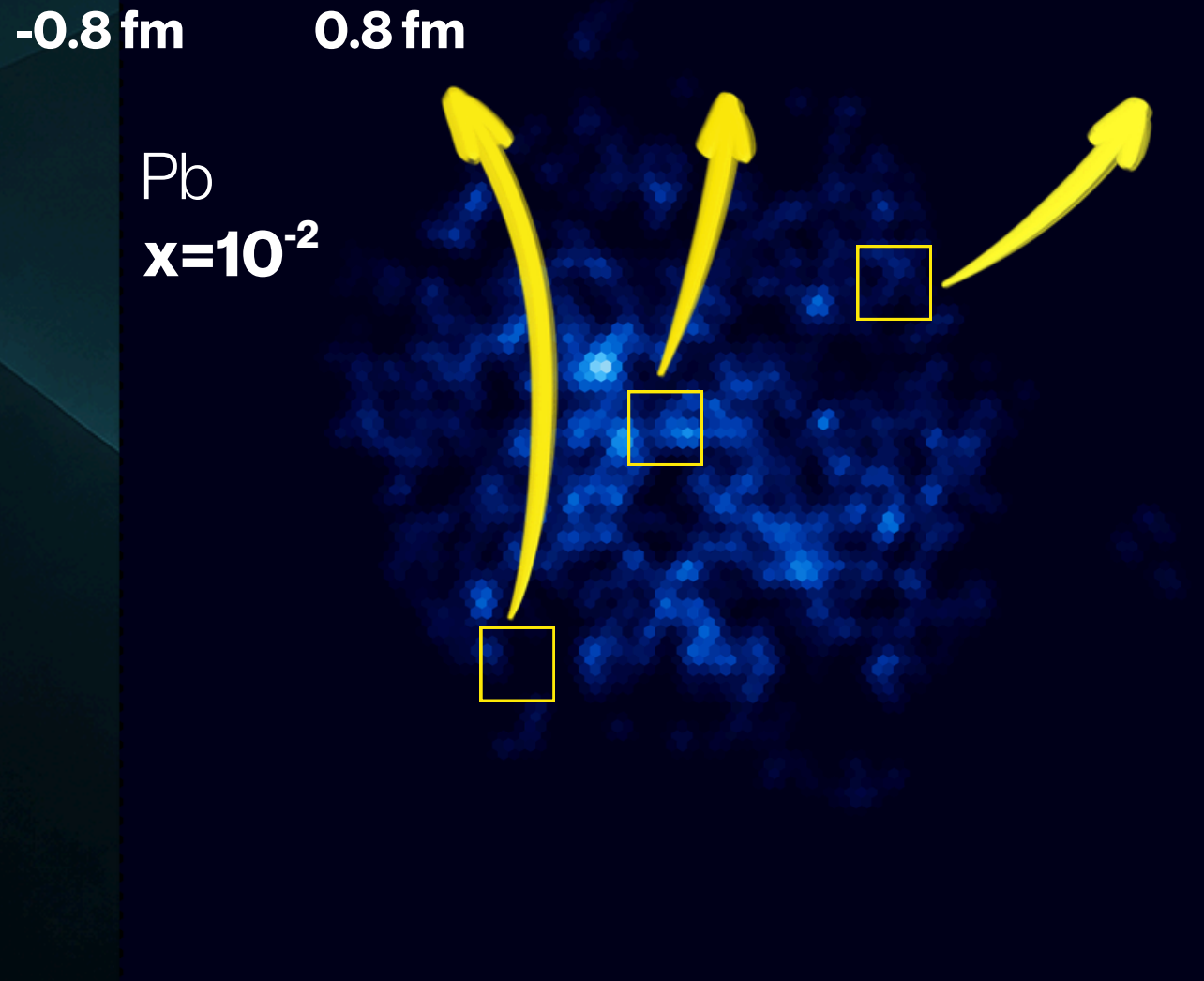
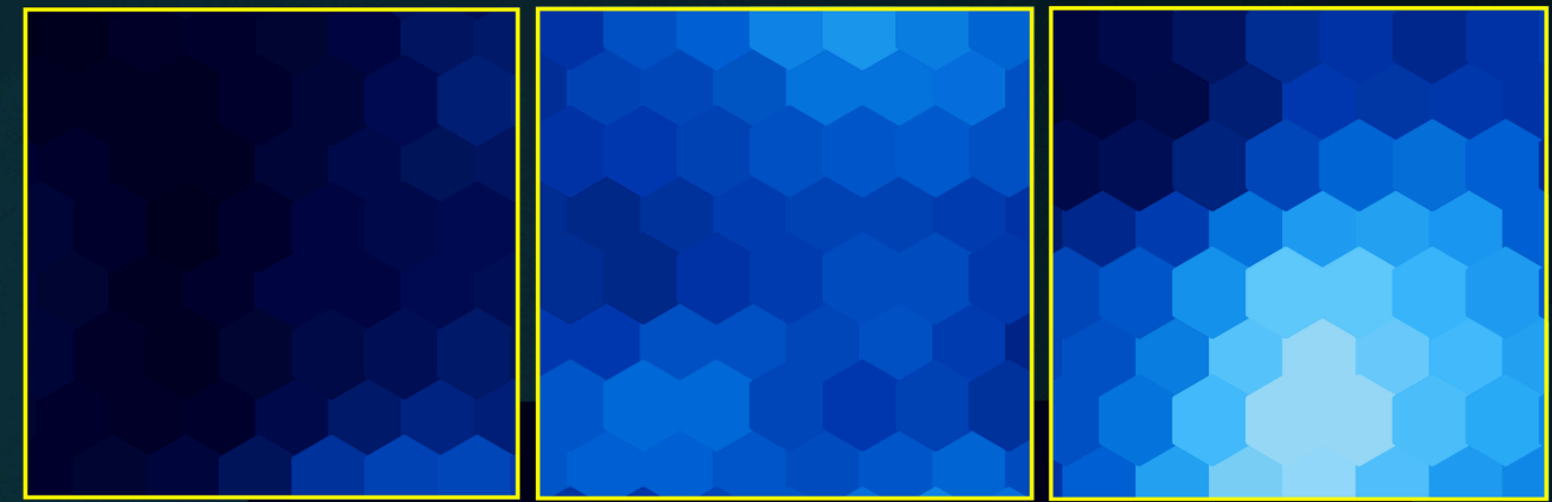


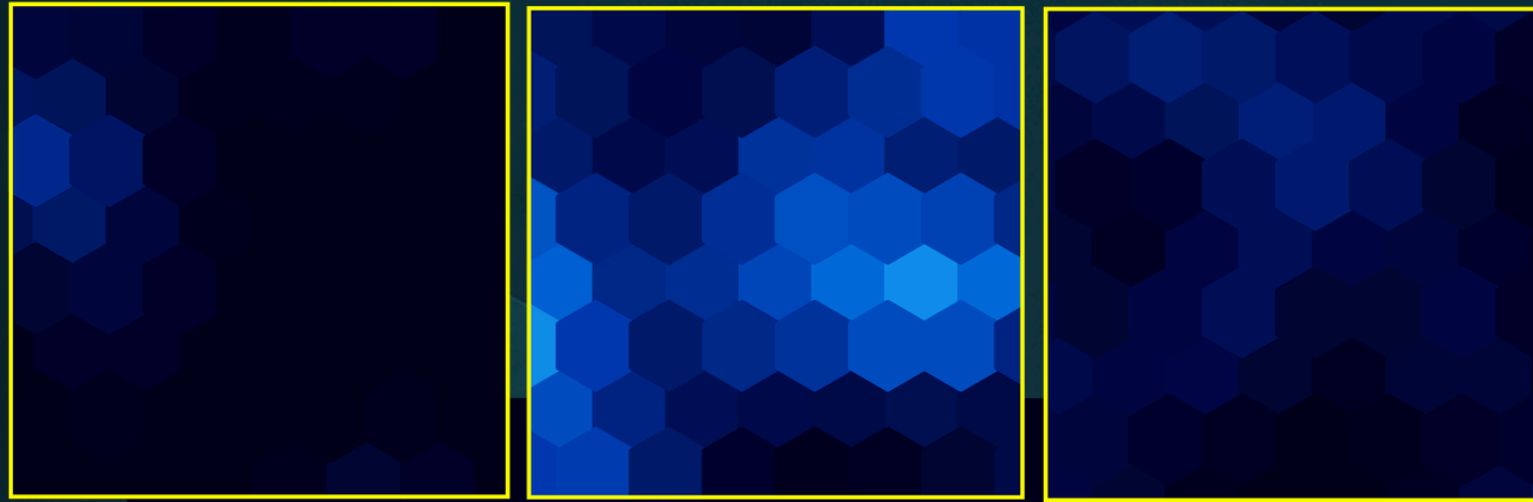
Pb
 $x=10^{-6}$



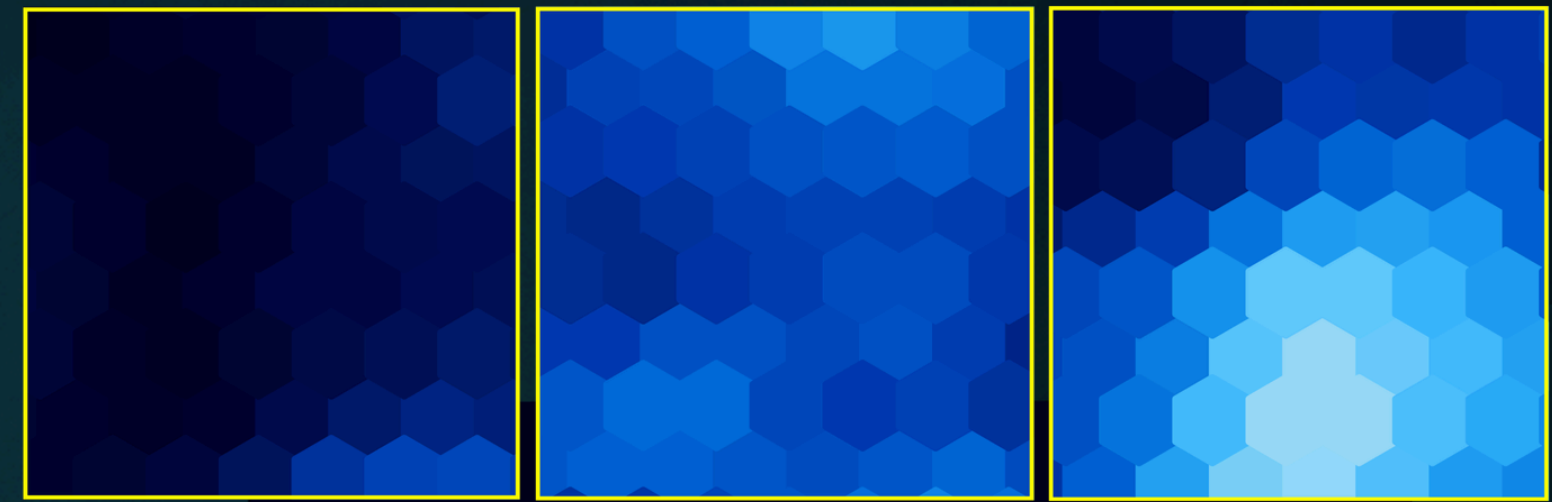


*
For small $|t|$
values the
cross section
raises with
energy



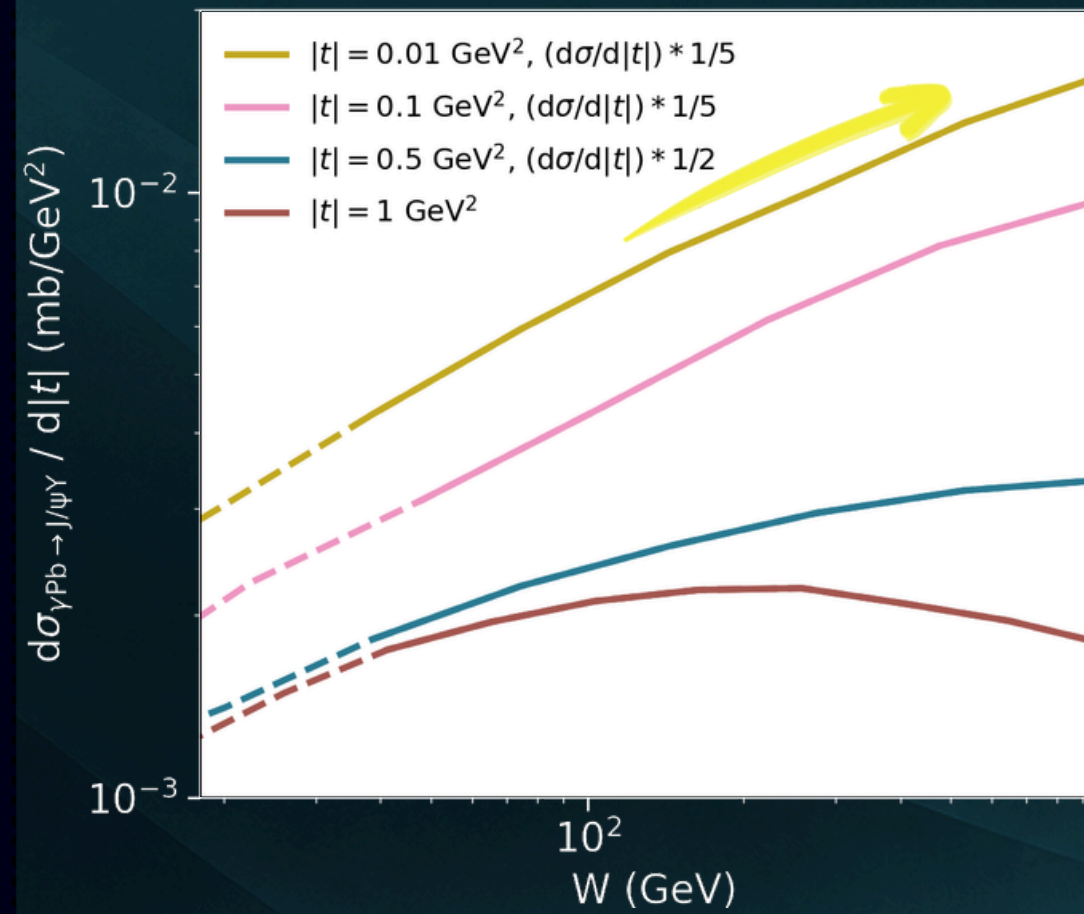
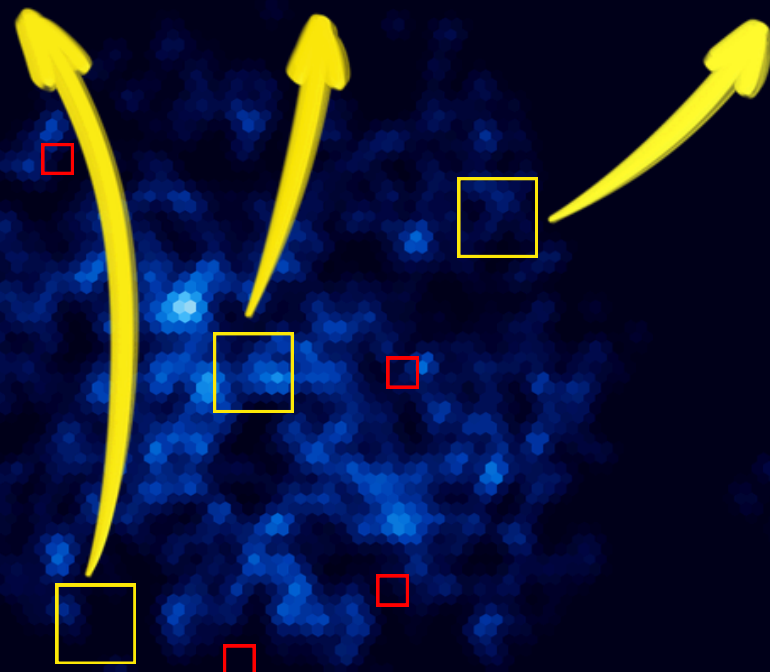


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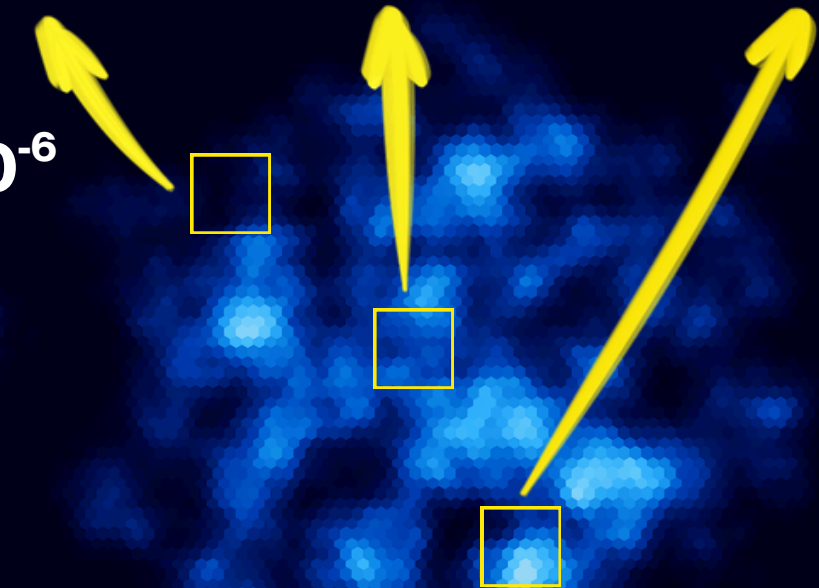


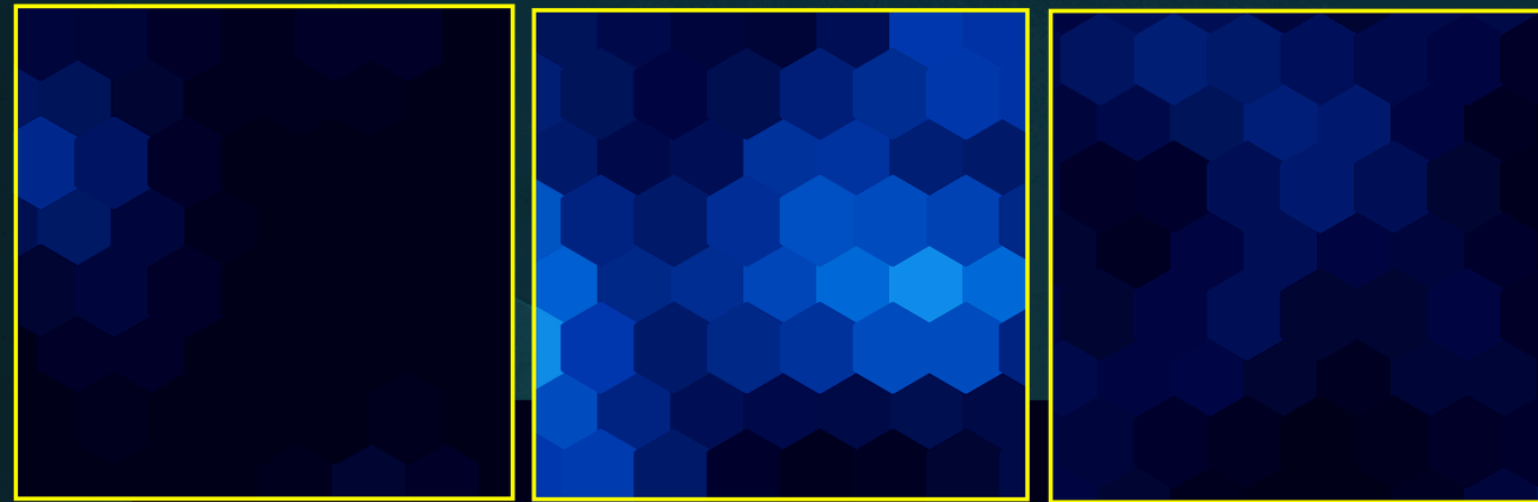
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Pb
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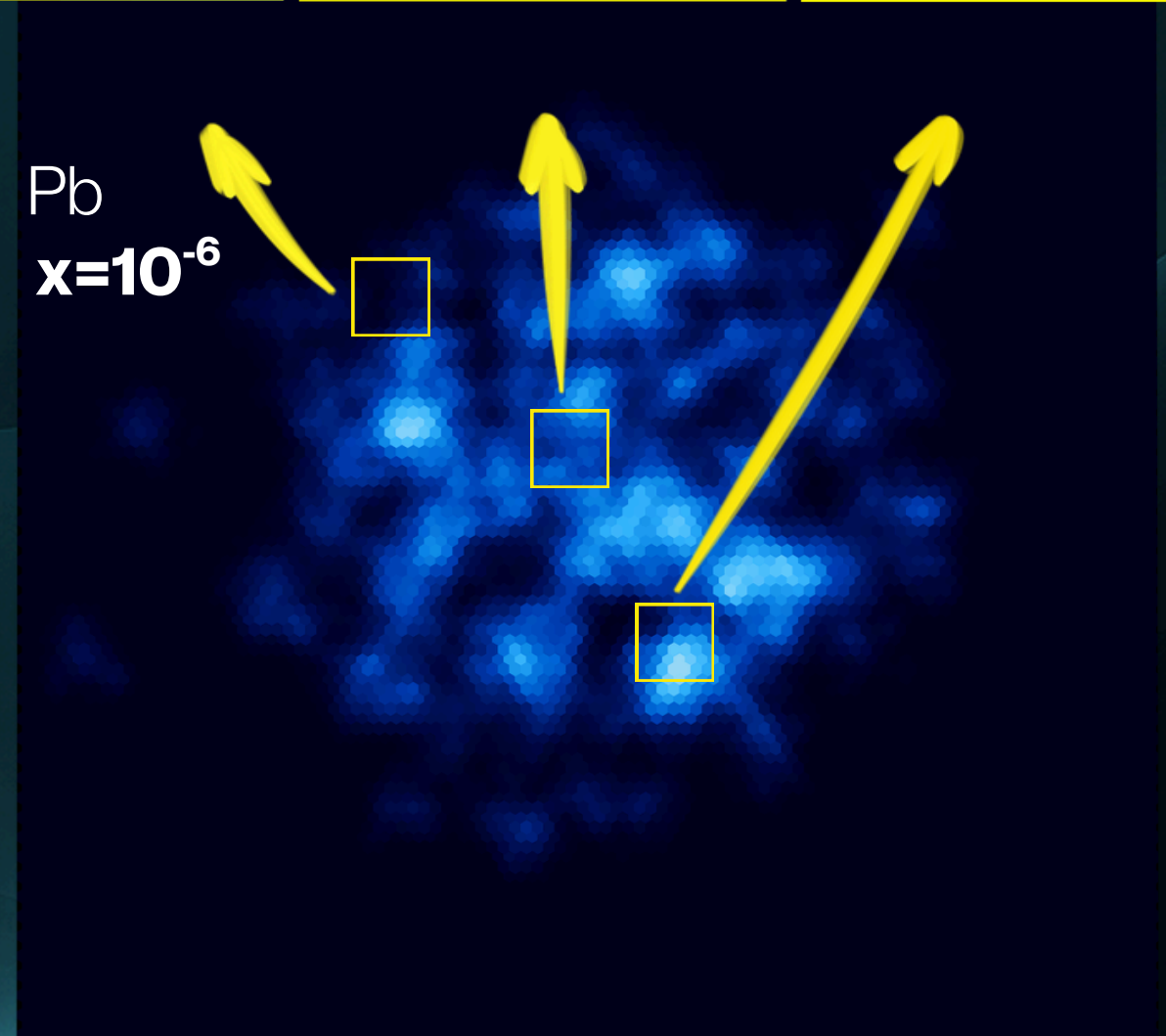
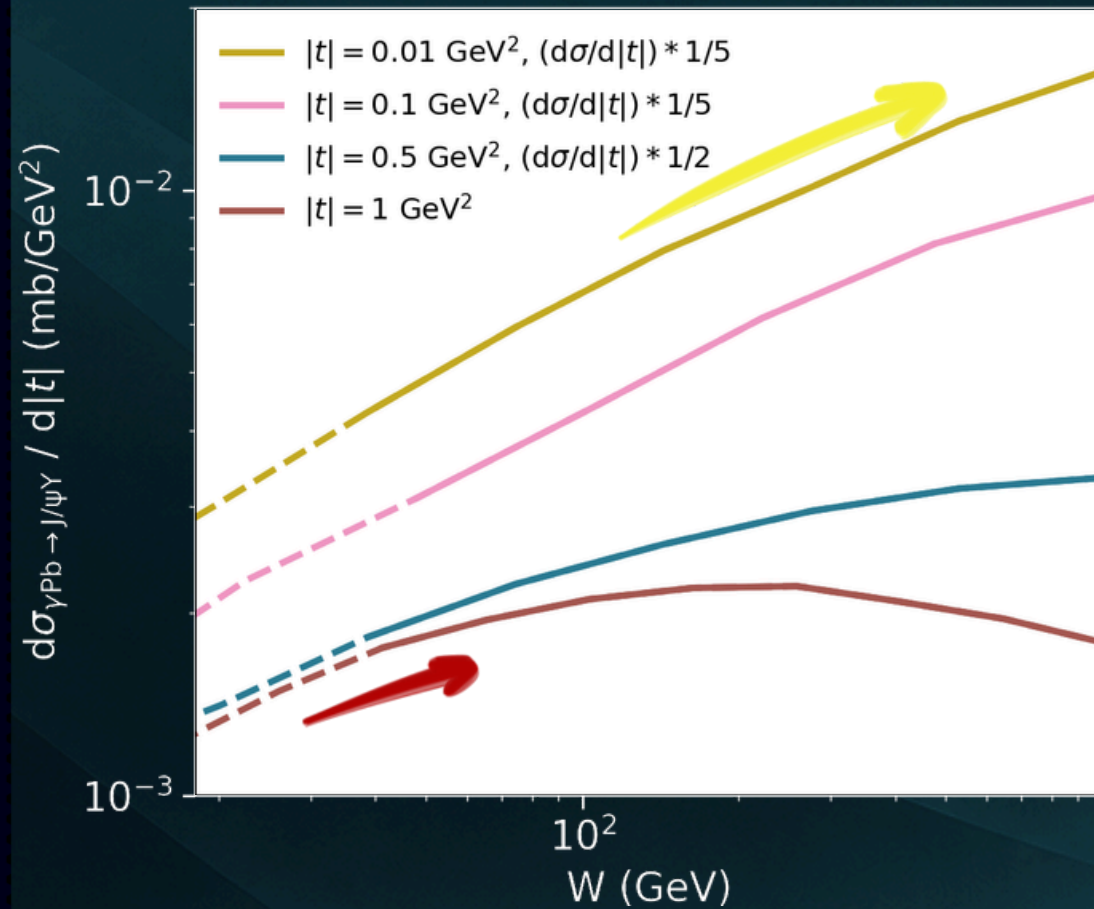
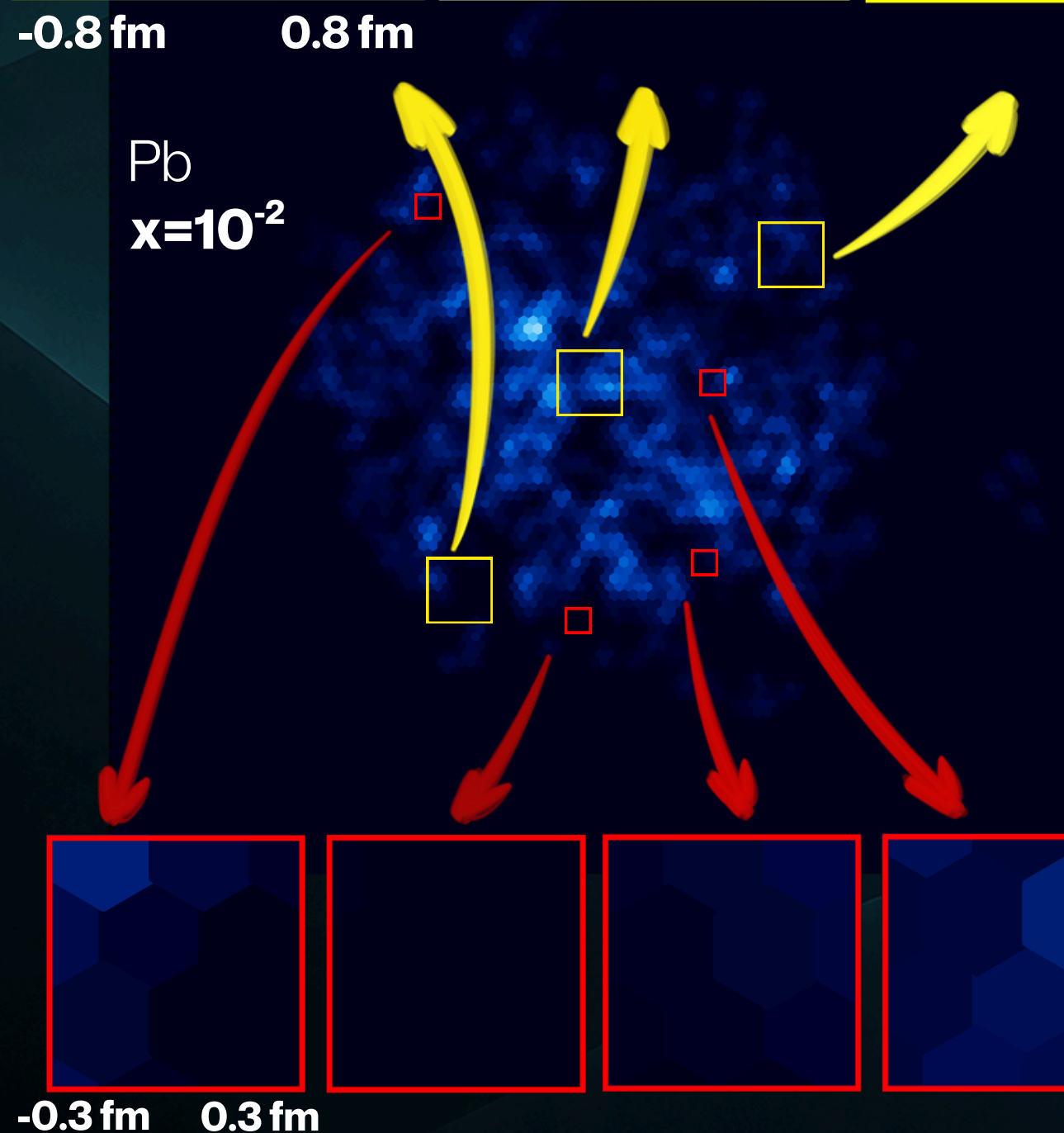
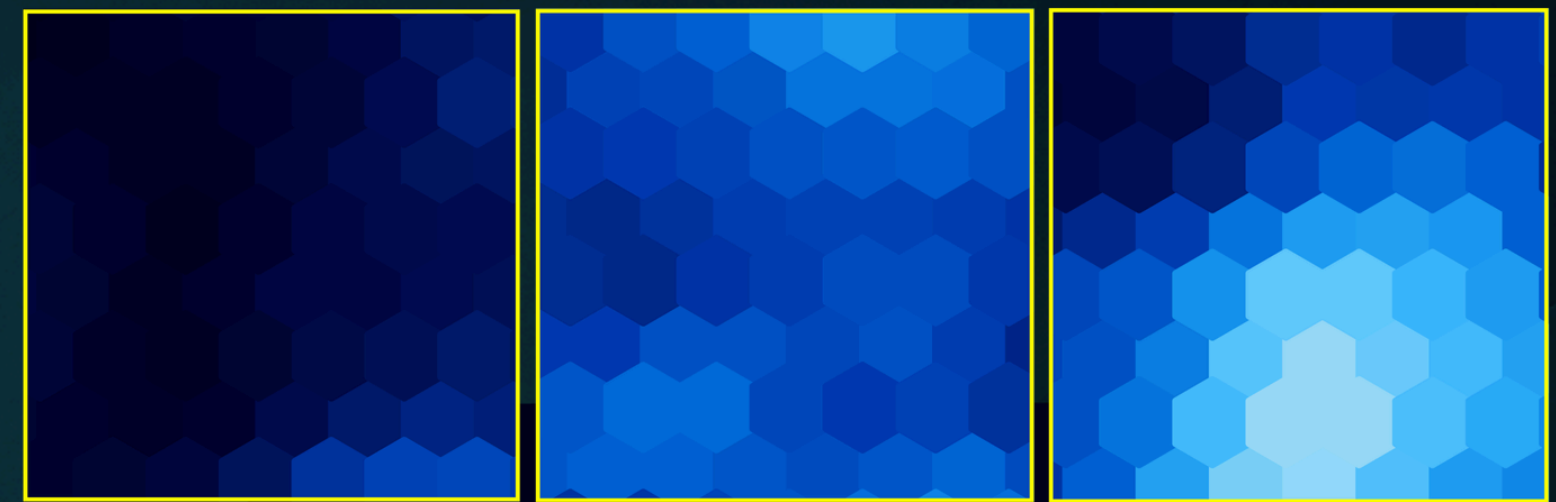


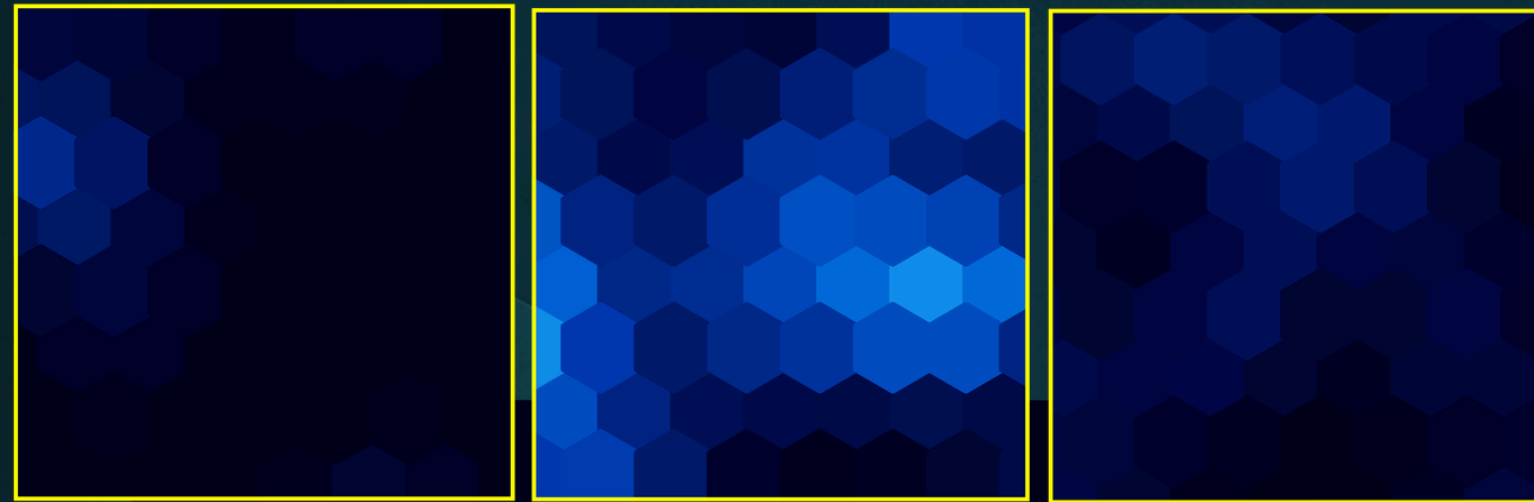
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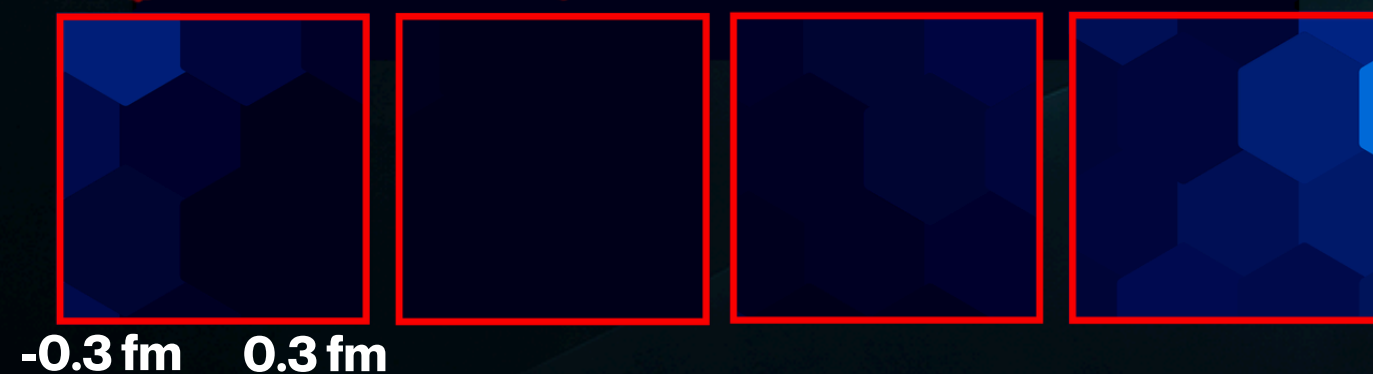
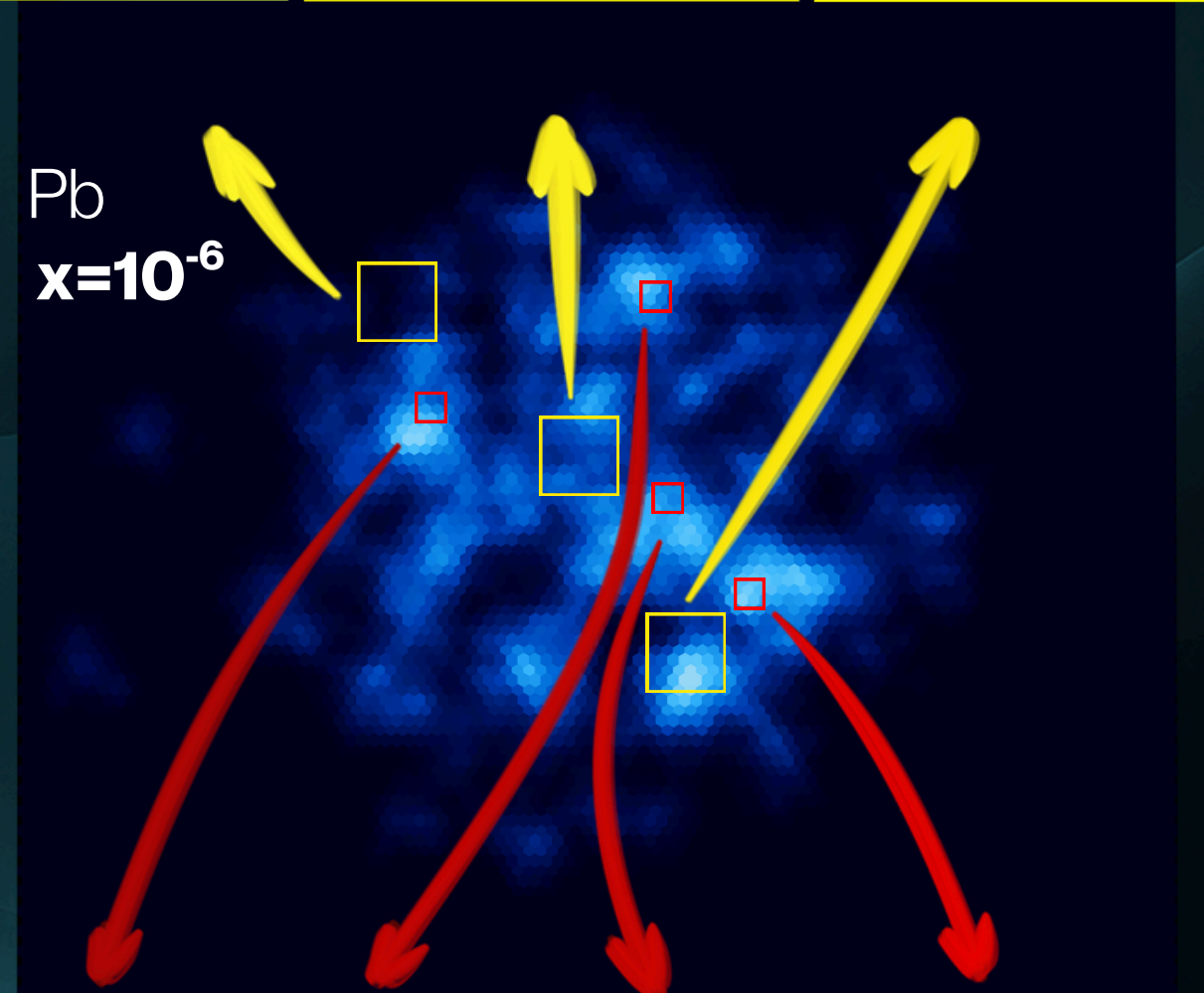
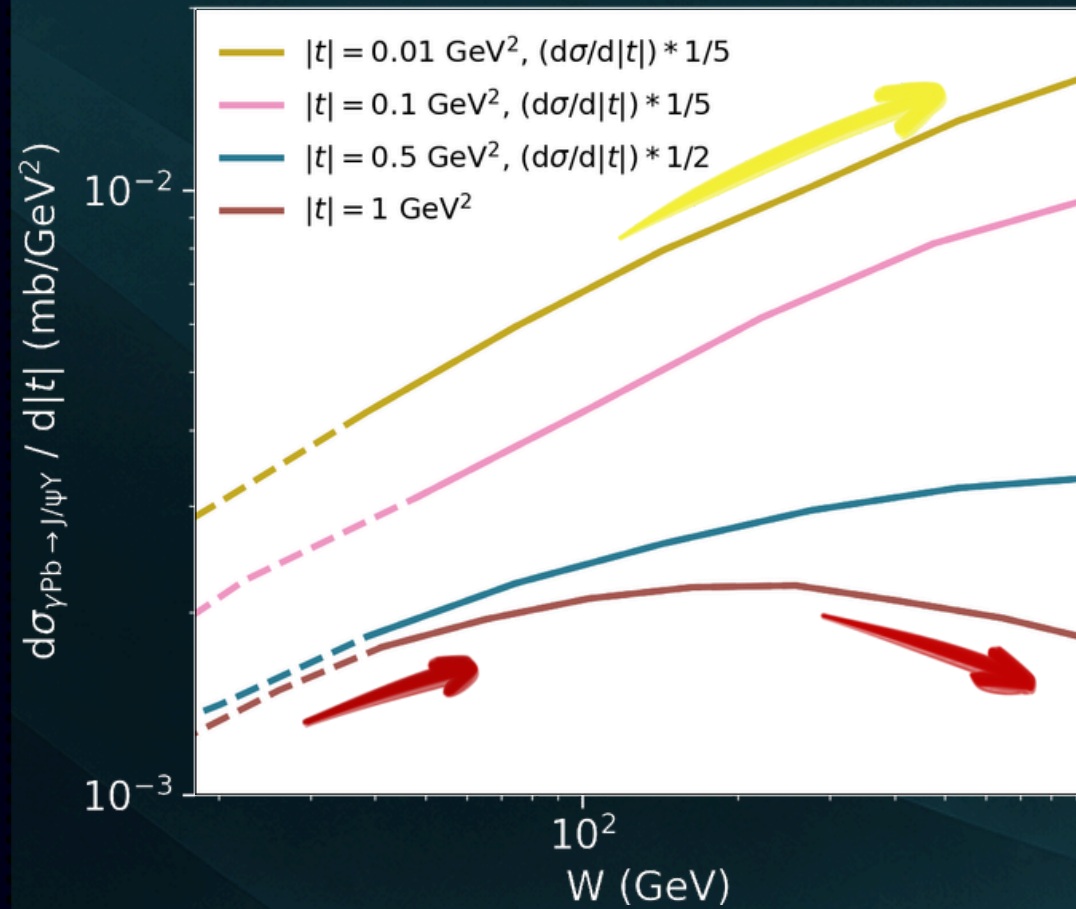
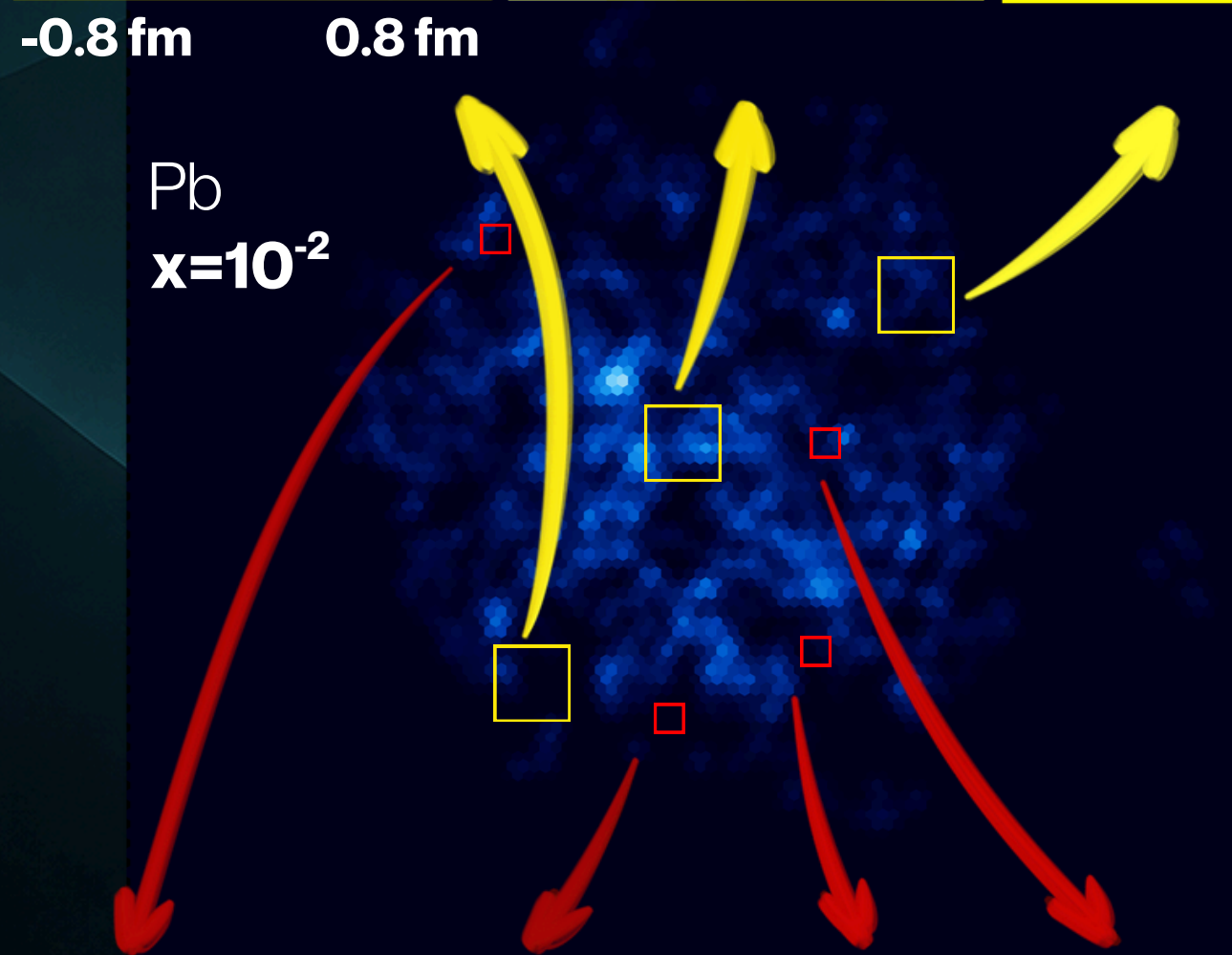
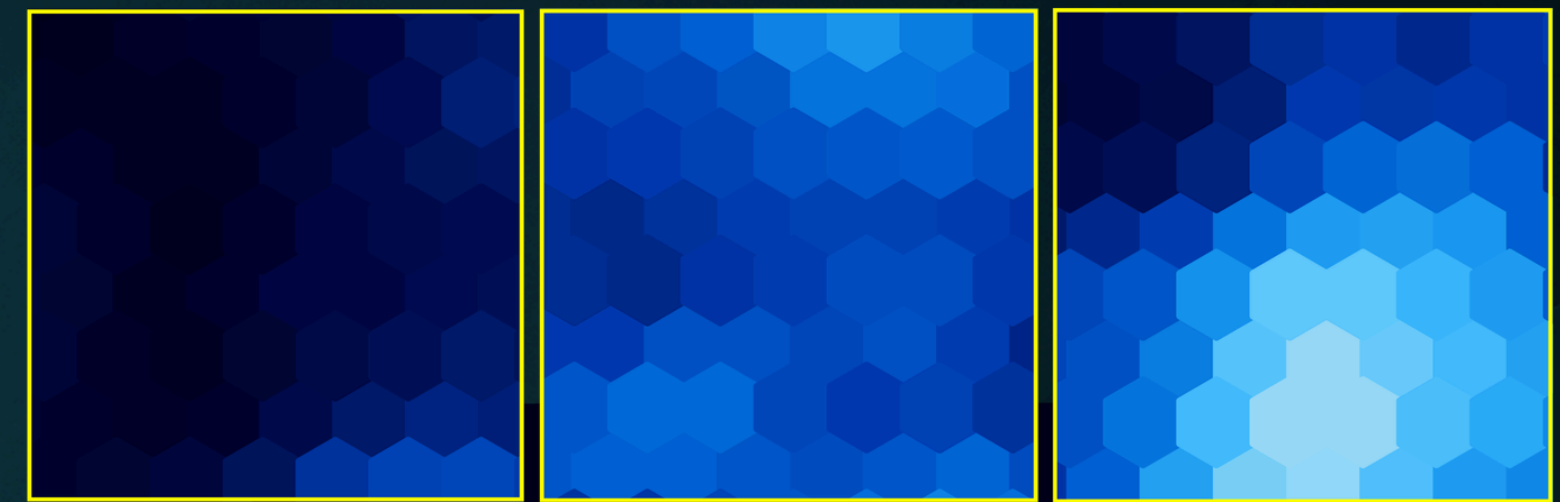


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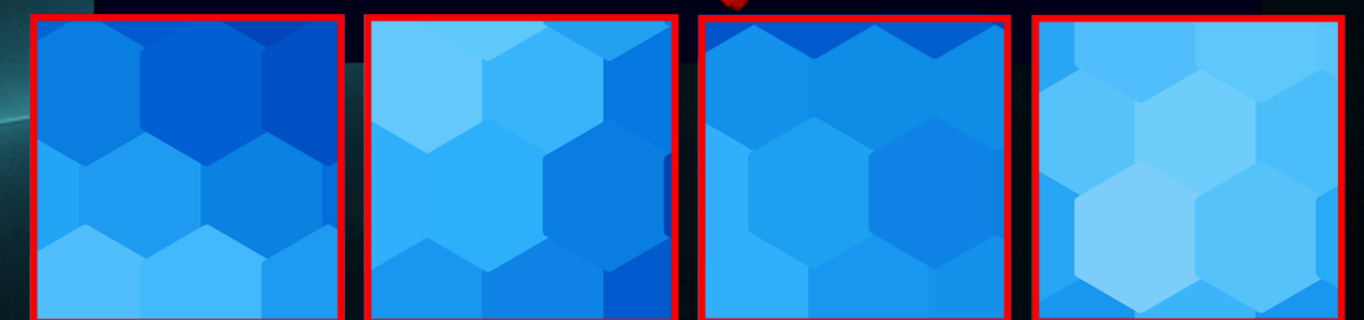




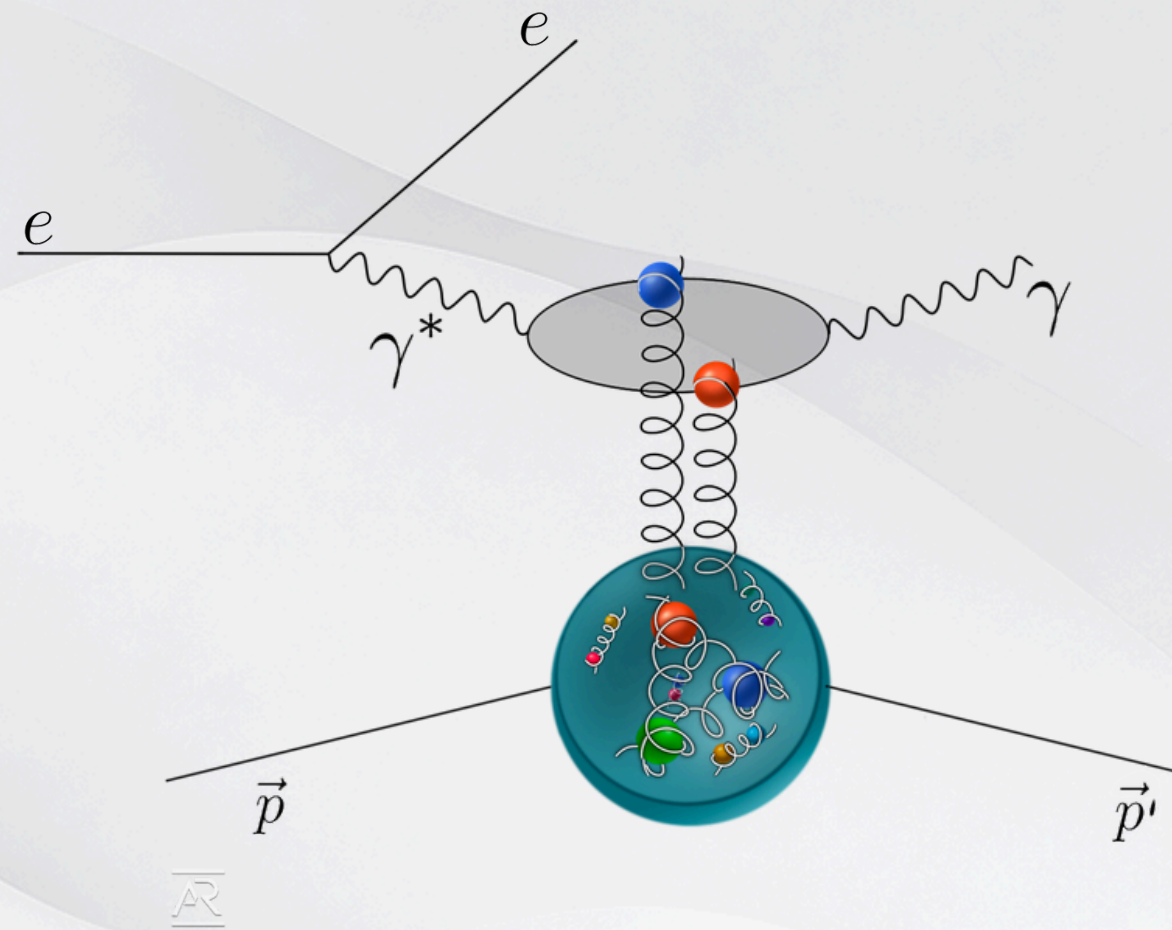
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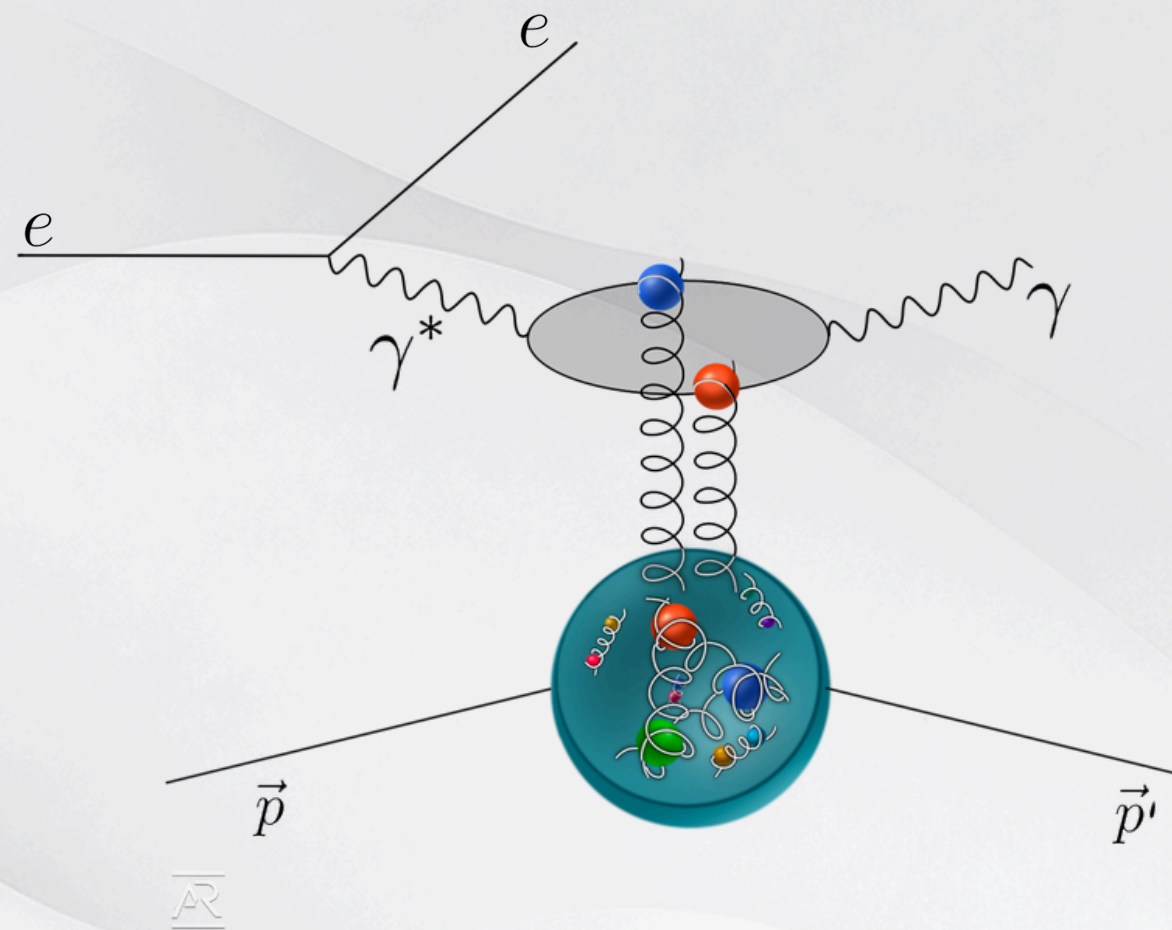
*
For large values of $|t|$ the cross
section reaches a maximum
and then decreases



Deeply virtual Compton scattering

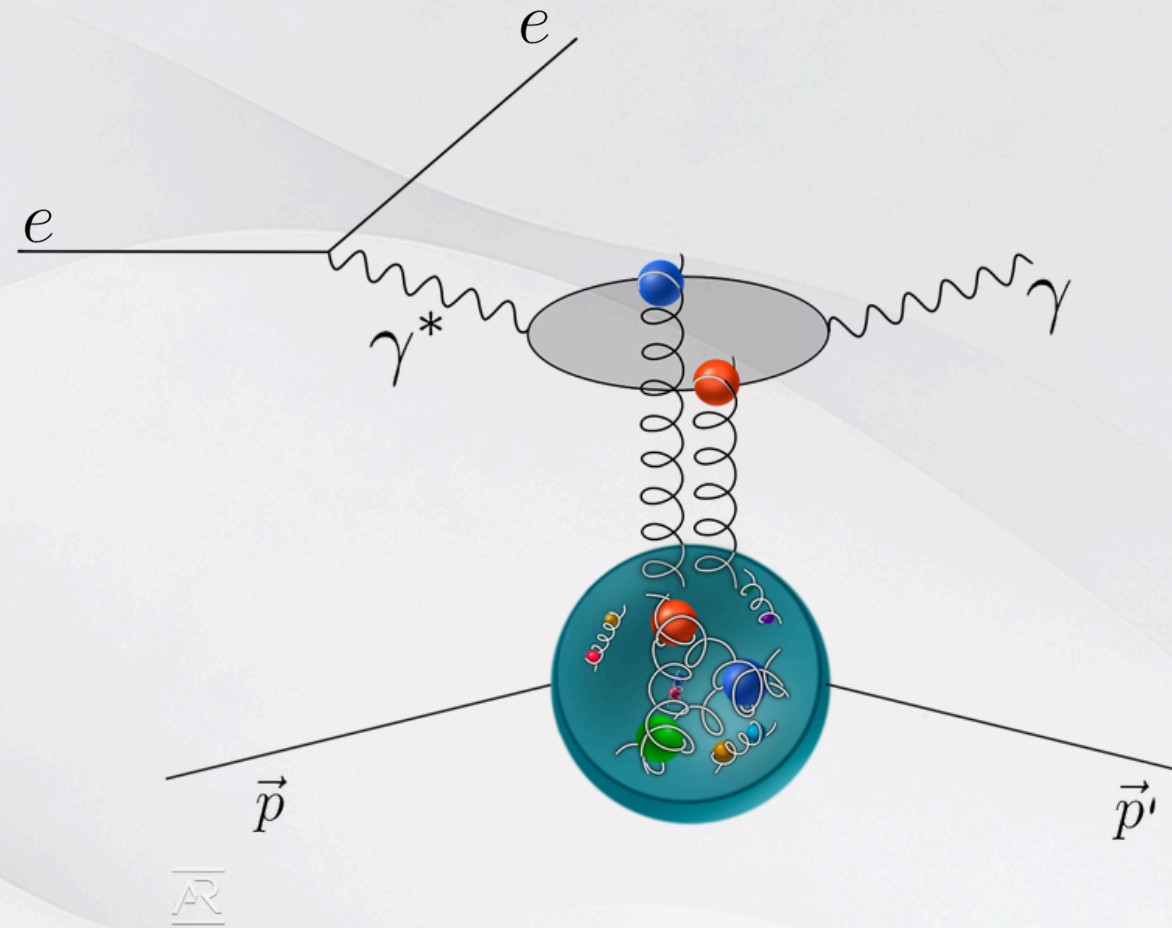


Deeply virtual Compton scattering



- The DVCS is a diffractive process, where the electron scatters off a hadron by exchanging a virtual photon and a real photon is produced in the final state
- In the color dipole picture
 - the photon fluctuates in a quark-antiquark pair
 - this color dipole interacts with the target
 - the quark-antiquark pair annihilates in a real photon

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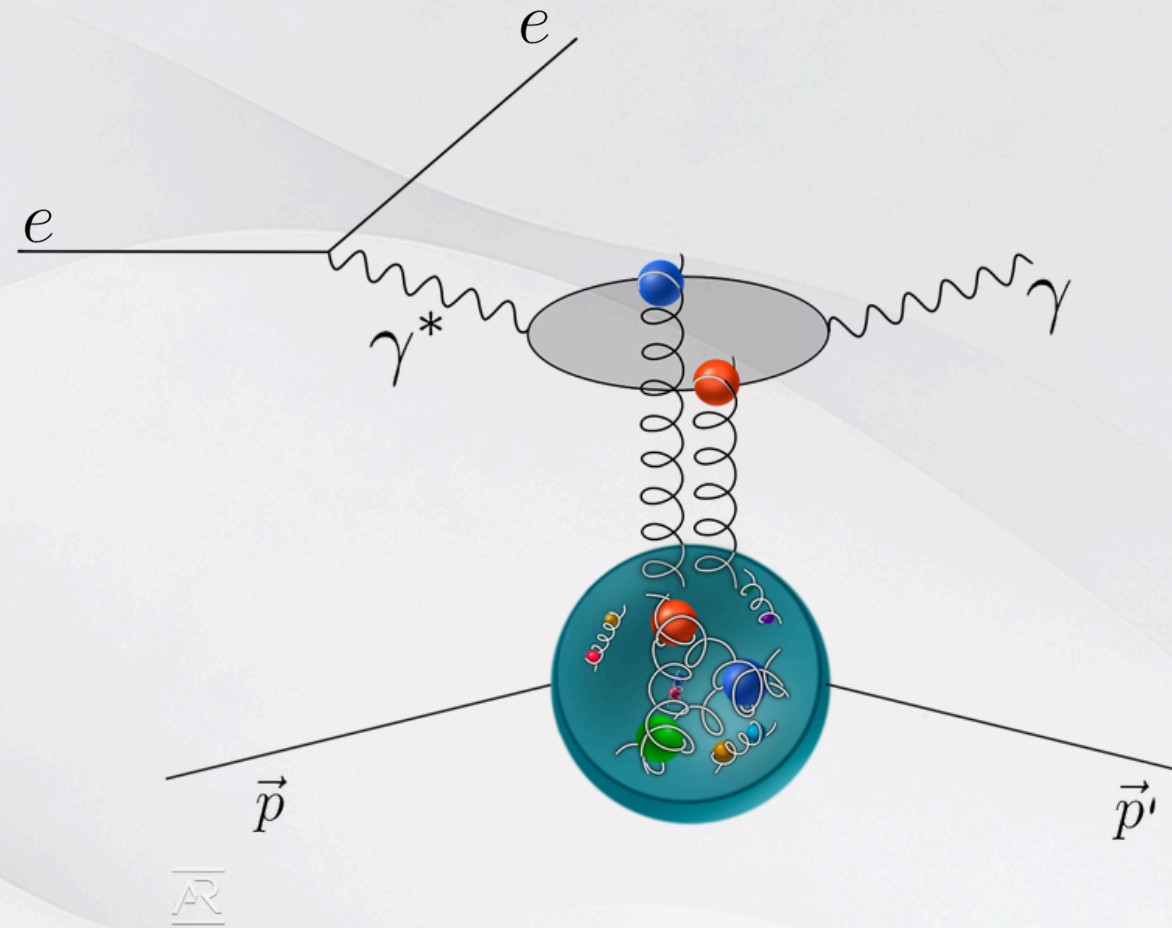


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• Scattering amplitude

$$\mathcal{A}_f(x, Q^2, \vec{\Delta}) = i \int d\vec{r} \int_0^1 \frac{dz}{4\pi} \int d\vec{b} |\Psi_{\gamma^*}^* \Psi_{\gamma}|_T^f \exp \left[-i \left(\vec{b} - \left(\frac{1}{2} - z \right) \vec{r} \right) \vec{\Delta} \right] \frac{d\sigma^{\text{dip}}}{d\vec{b}}(\tilde{x}, \vec{r})$$

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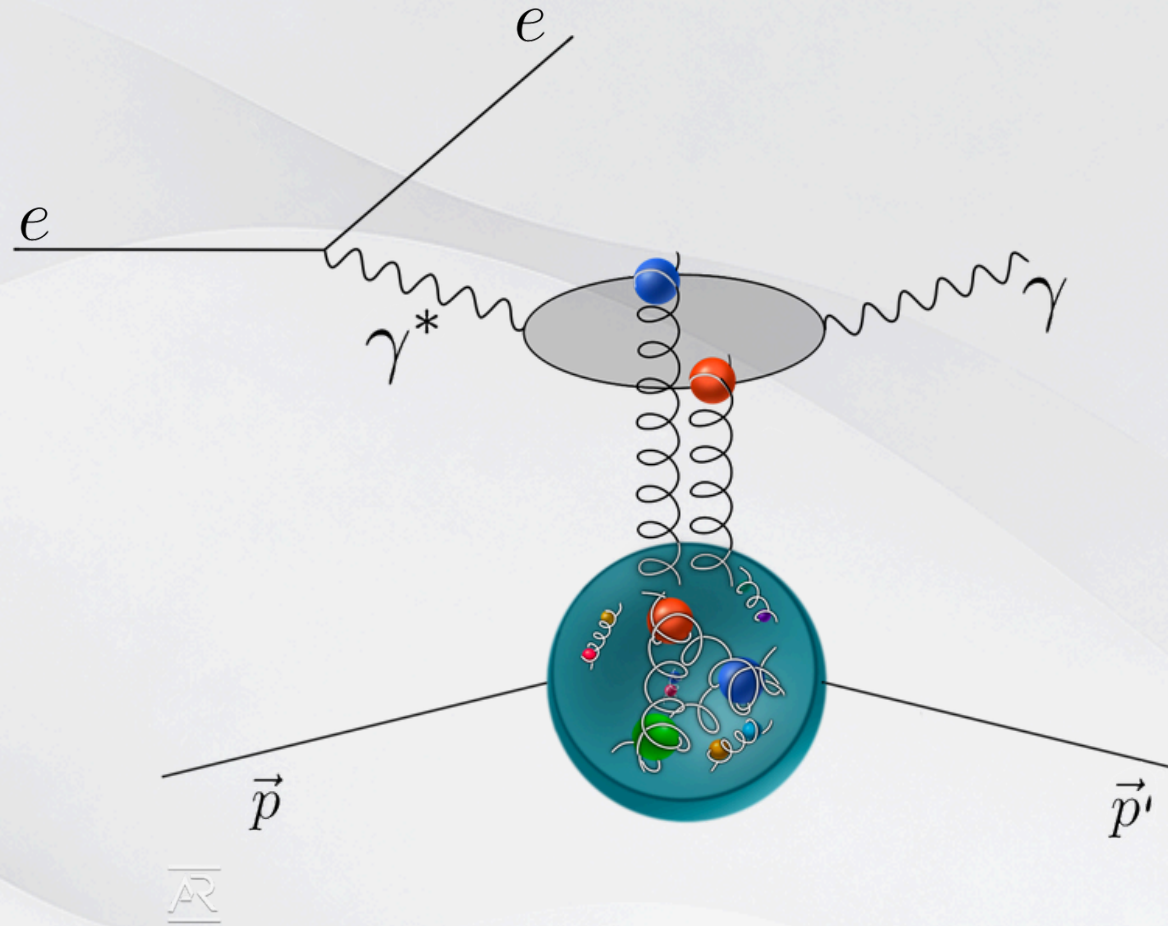
- wave function overlap between the virtual photon of transverse polarization T in the initial state fluctuating into $q\bar{q}$ pair with flavor f and the real photon in the final state

- the photon-photon wave function is much simpler and contains less model-dependent parameters compared to the photon-meson wave functions

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- For DVCS, the cross section involves a sum over quark flavours

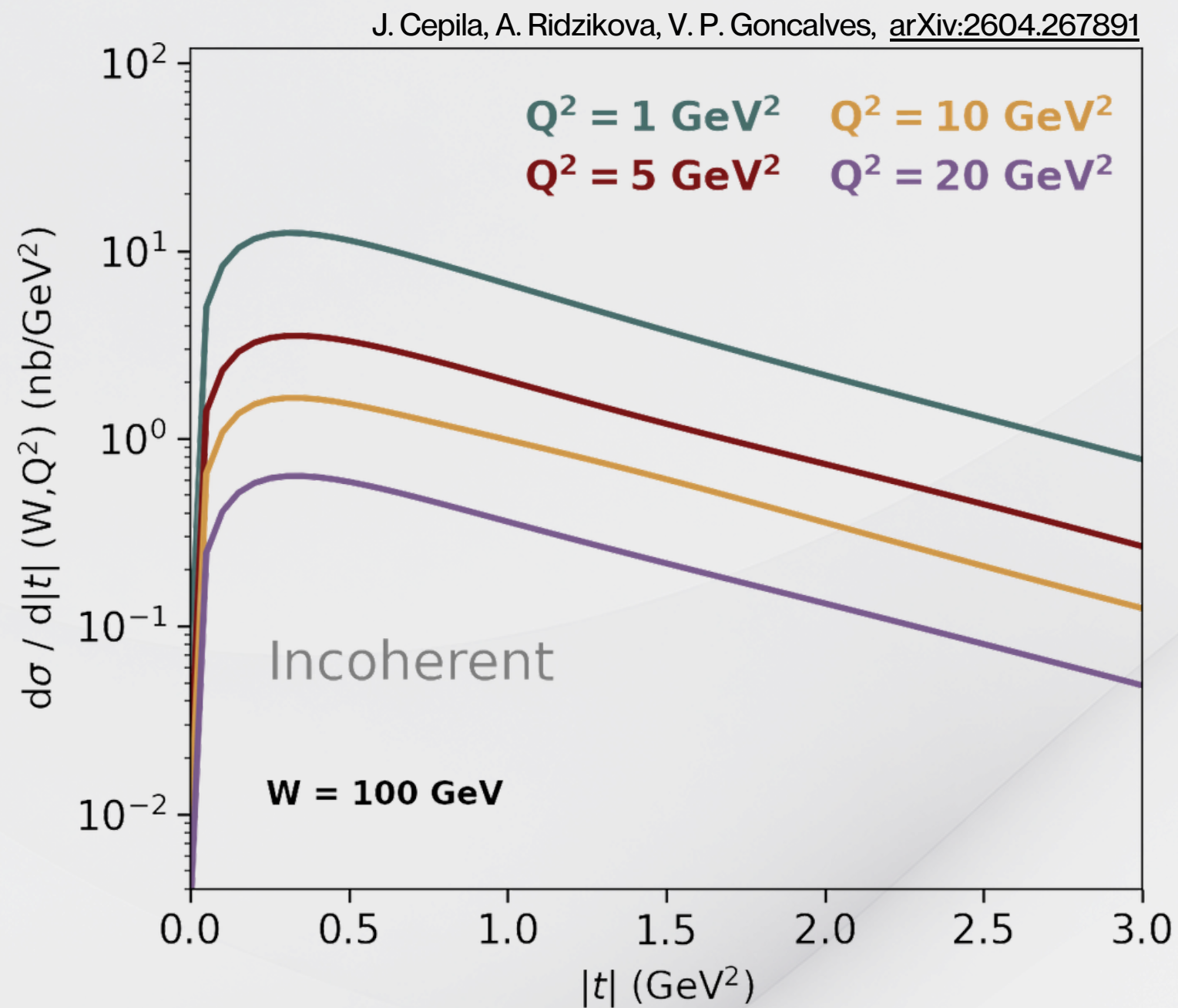
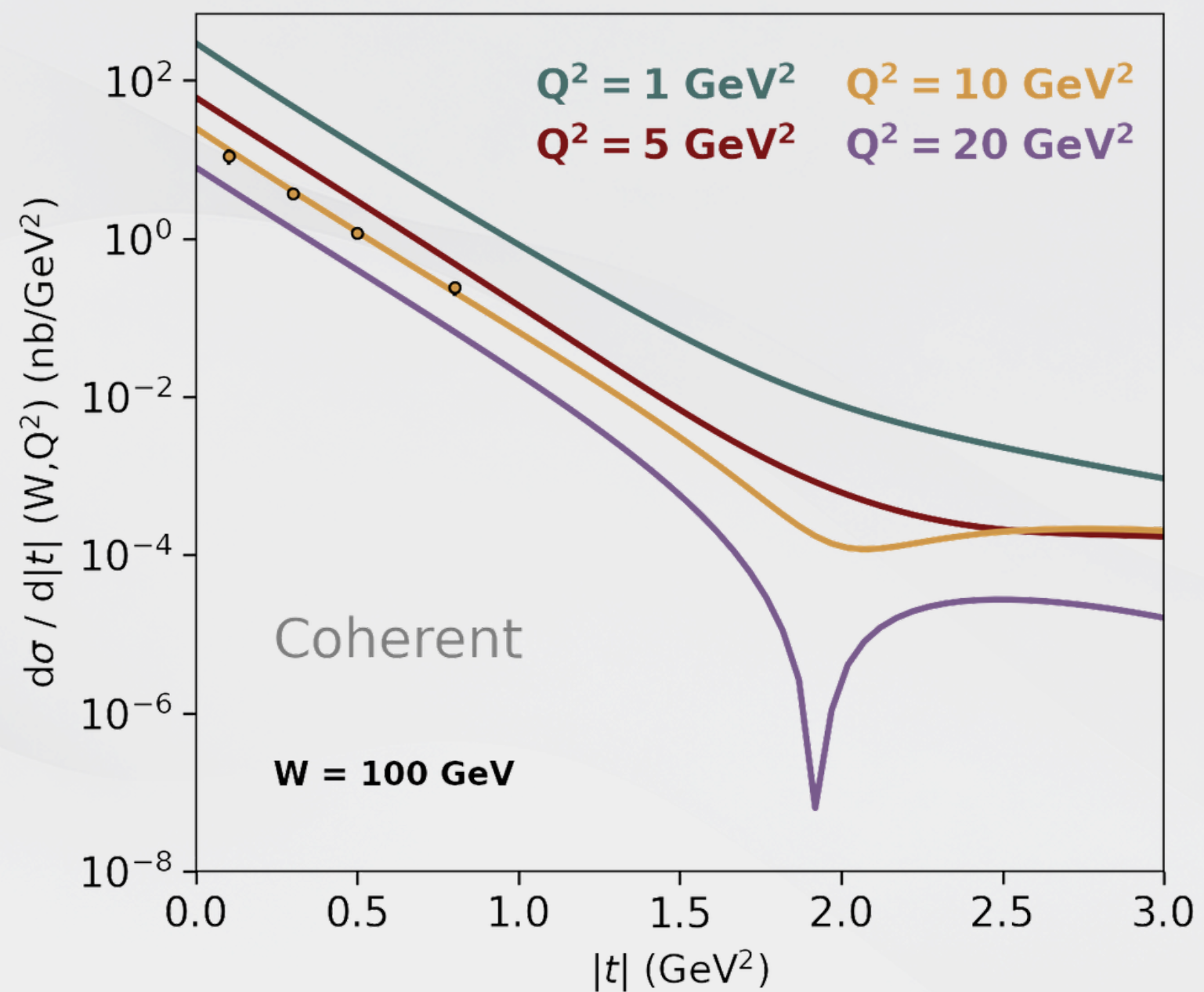
- **Coherent**

$$\frac{d\sigma^{\gamma^* h \rightarrow \gamma h}}{dt} = \frac{1}{16\pi} \left| \sum_f R_g^f \langle A_f(x, Q^2, \vec{\Delta}) \rangle \right|^2$$

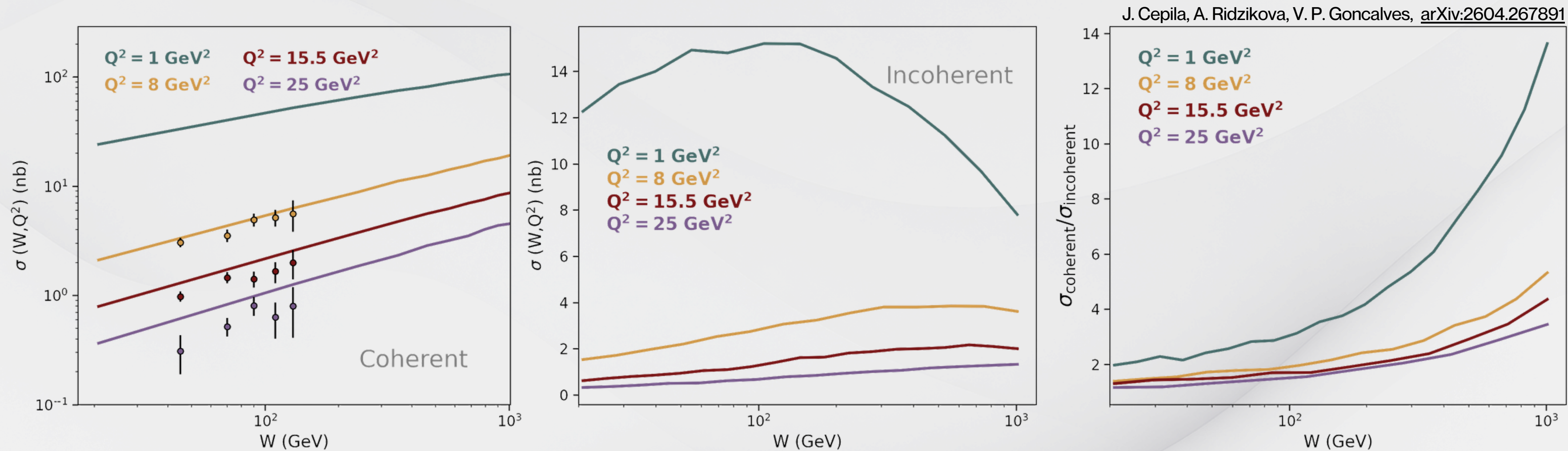
- **Incoherent**

$$\frac{d\sigma^{\gamma^* h \rightarrow \gamma Y}}{dt} = \frac{1}{16\pi} \left(\left| \sum_f R_g^f \sqrt{\langle A_f^2(x, Q^2, \vec{\Delta}) \rangle} \right|^2 - \left| \sum_f R_g^f \langle A_f(x, Q^2, \vec{\Delta}) \rangle \right|^2 \right)$$

- Scattering amplitude $\mathcal{A}_f(x, Q^2, \vec{\Delta}) = i \int d\vec{r} \int_0^1 \frac{dz}{4\pi} \int d\vec{b} |\Psi_{\gamma^*}^* \Psi_{\gamma}|_T^f \exp \left[-i \left(\vec{b} - \left(\frac{1}{2} - z \right) \vec{r} \right) \cdot \vec{\Delta} \right] \frac{d\sigma^{\text{dip}}}{d\vec{b}}(\tilde{x}, \vec{r})$

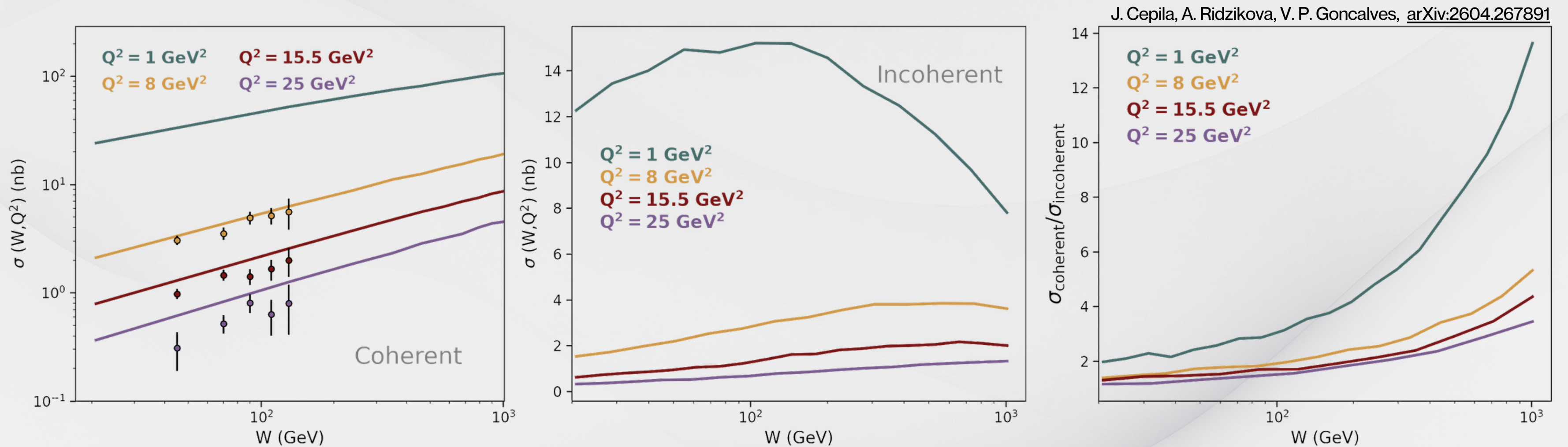


Predictions for the differential $|t|$ distributions of the DVCS process. Coherent (left) and incoherent (right) scattering off a proton for various values of the photon virtuality Q^2 . Data from the H1 Collaboration.

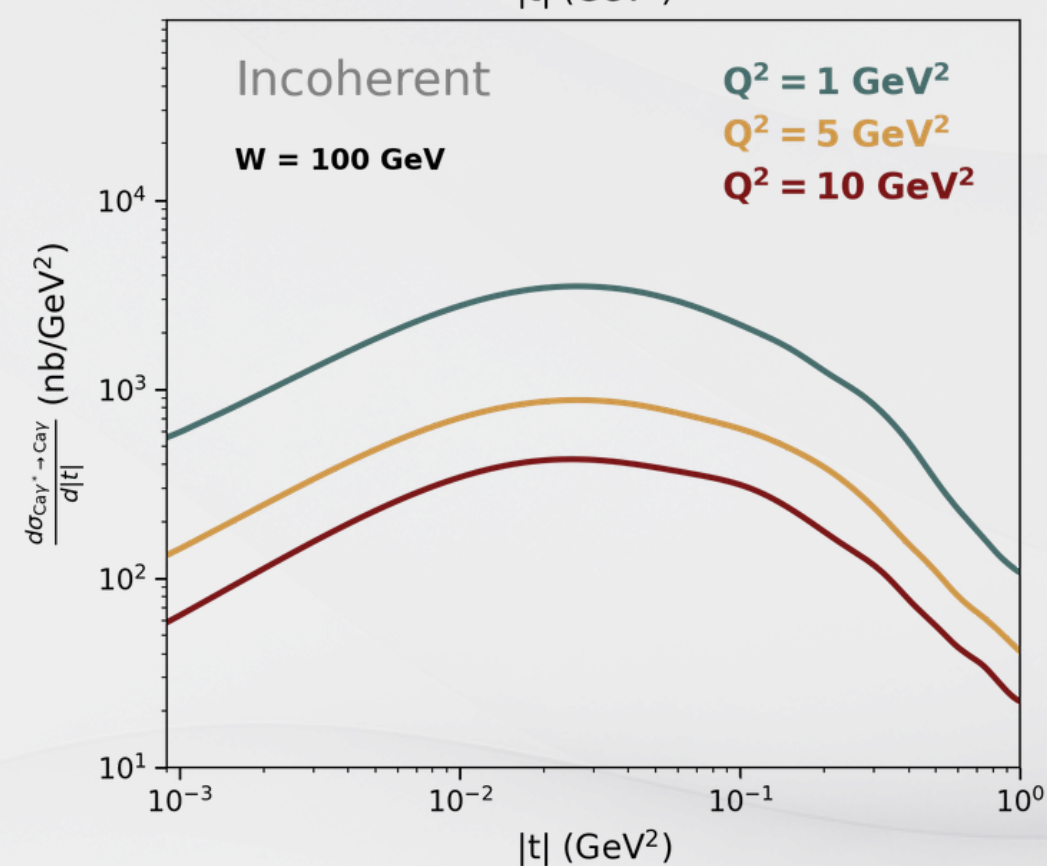
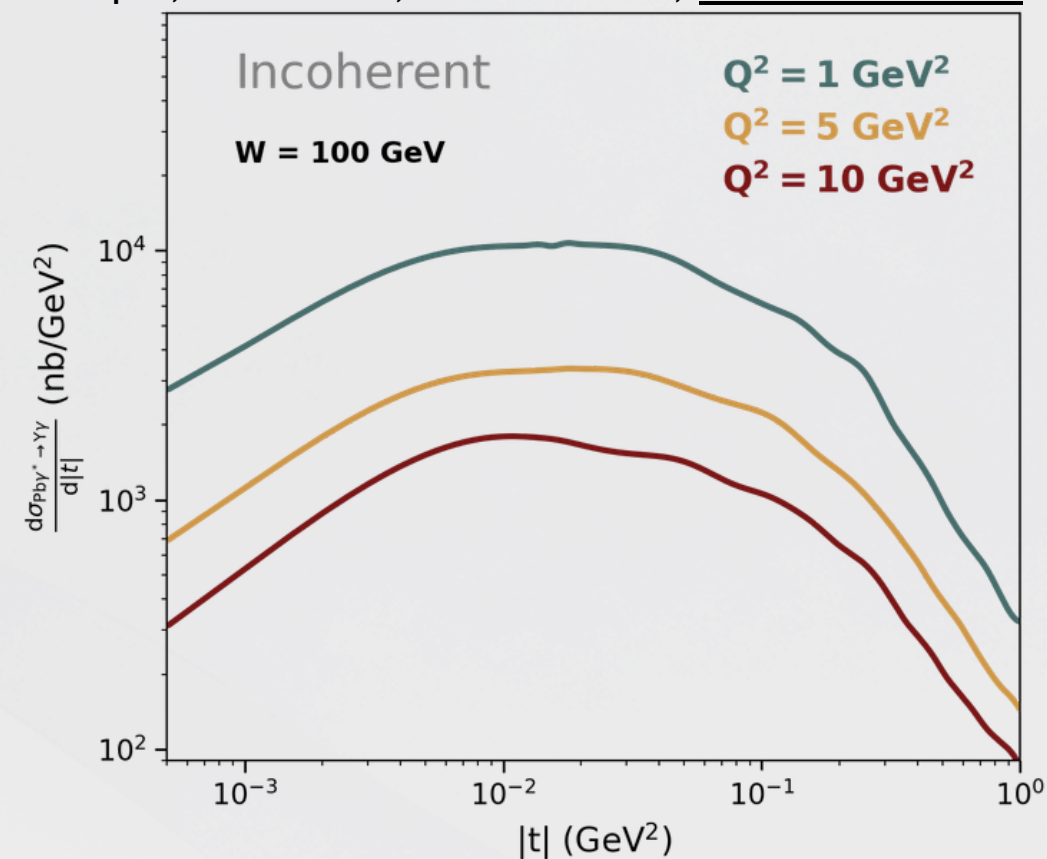
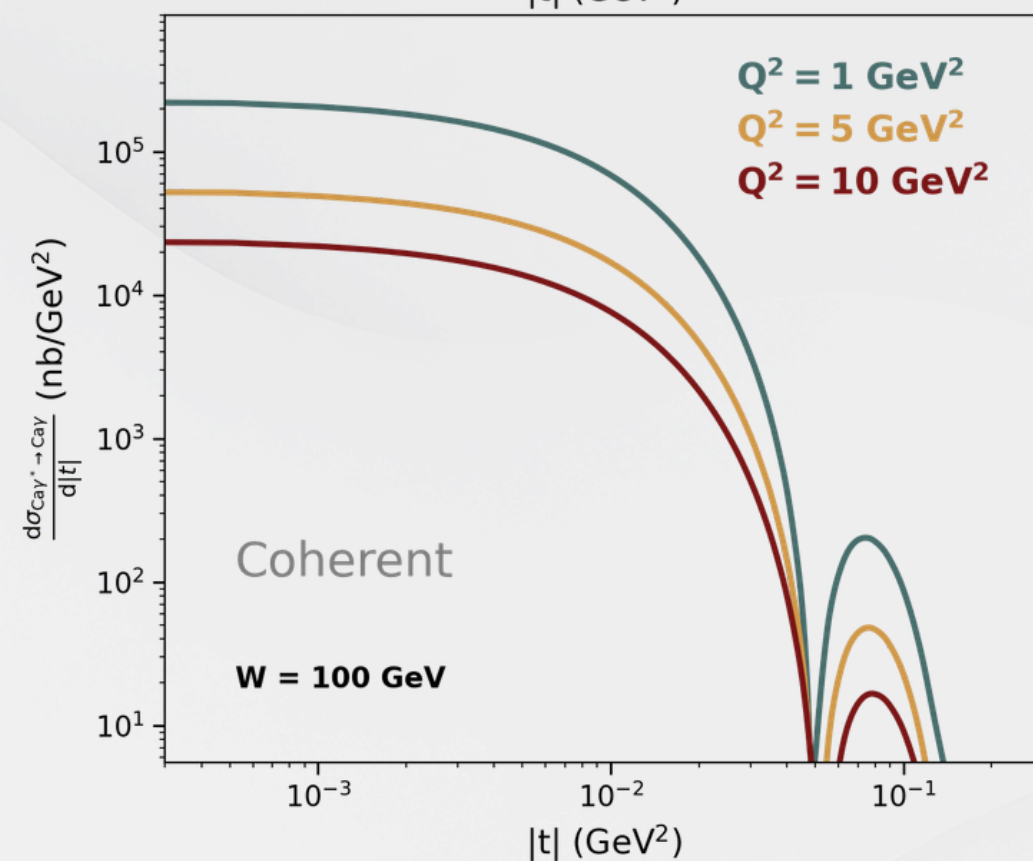
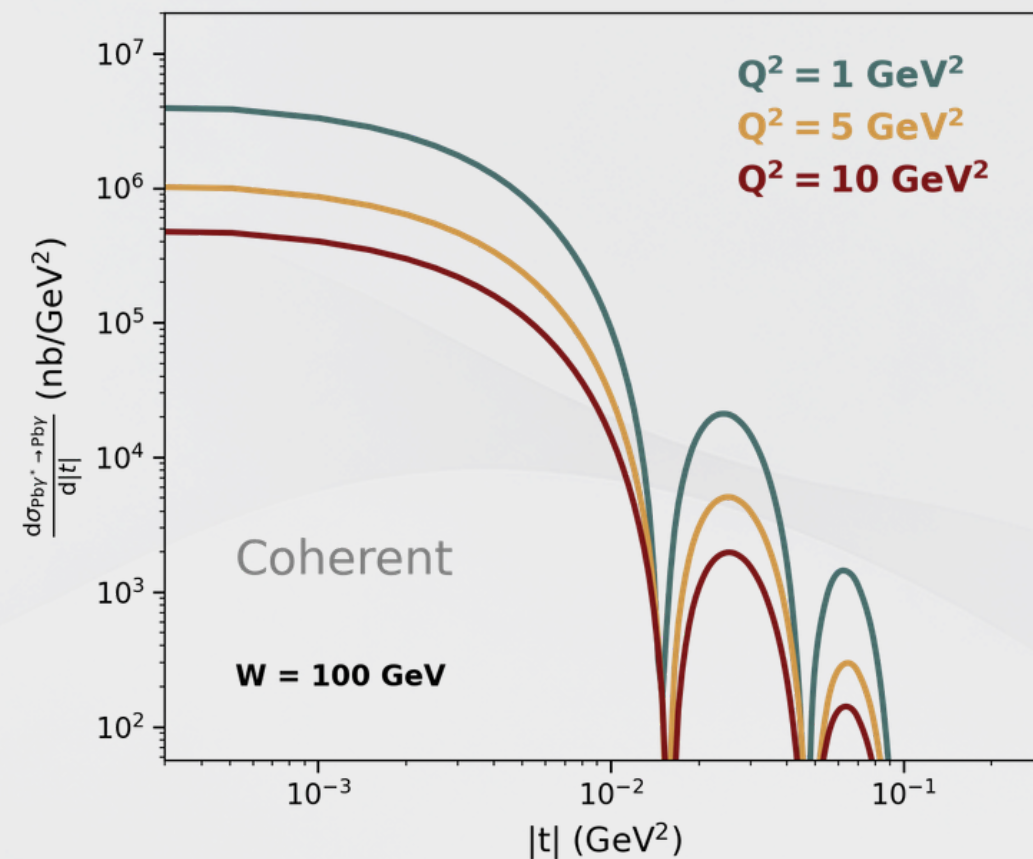


Predictions for the energy dependence of the coherent (left) and incoherent (center) cross-sections for scattering off a proton, shown for various values of the photon virtuality Q^2 . The right panel displays the ratio of the coherent to incoherent cross sections. Data from the H1 Collaboration.

- Cross sections decrease with increasing photon virtuality
- HERA coherent data well described by the hotspot model
- A turn-over in the energy dependence of the incoherent cross section is predicted
 - the position of the maximum is strongly dependent of Q^2 , occurring at smaller energies for lower photon virtualities
 - for small virtualities, the turn-over is predicted to occur within the EIC energy range



Predictions for the energy dependence of the coherent (left) and incoherent (center) cross-sections for scattering off a proton, shown for various values of the photon virtuality Q^2 . The right panel displays the ratio of the coherent to incoherent cross sections. Data from the H1 Collaboration.



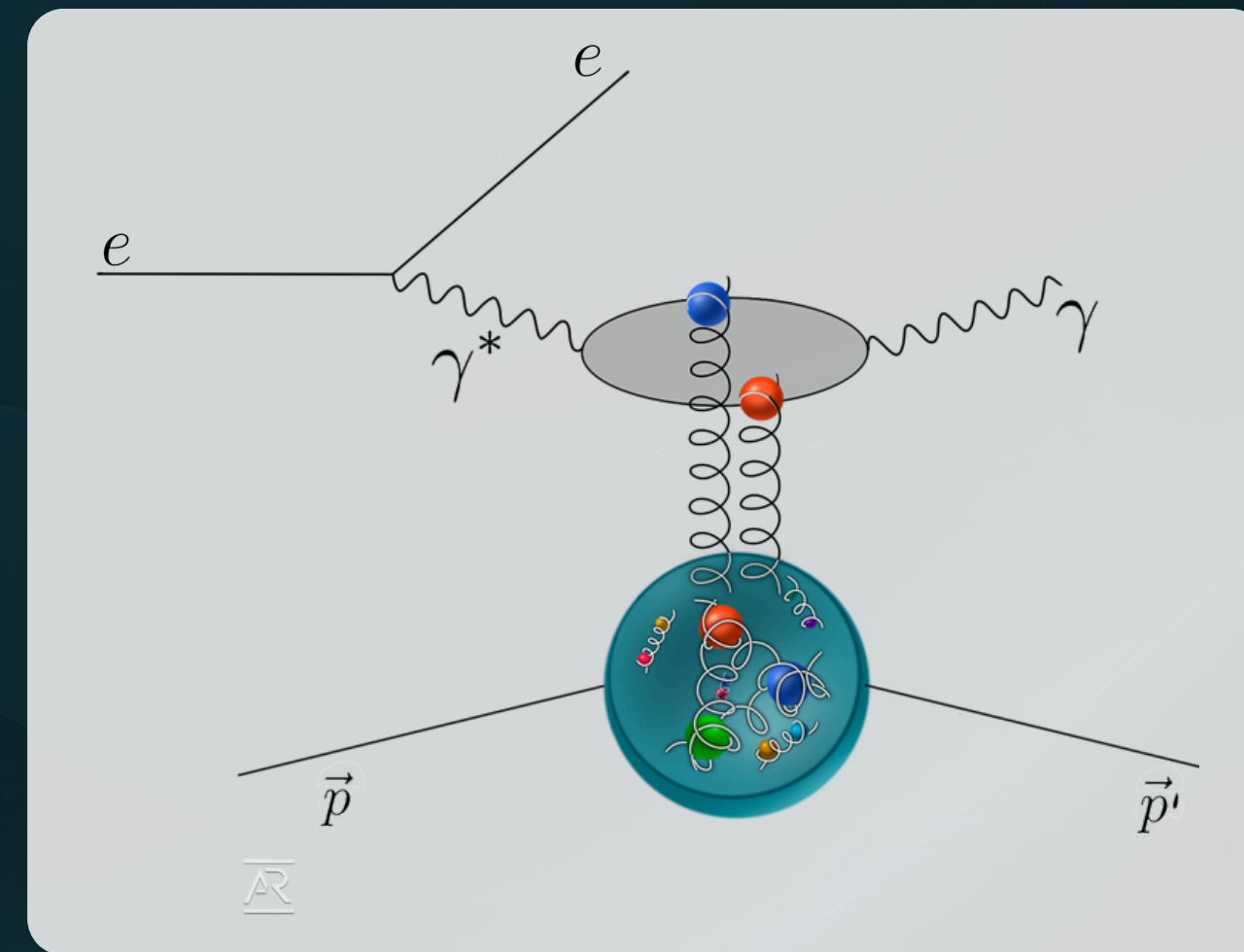
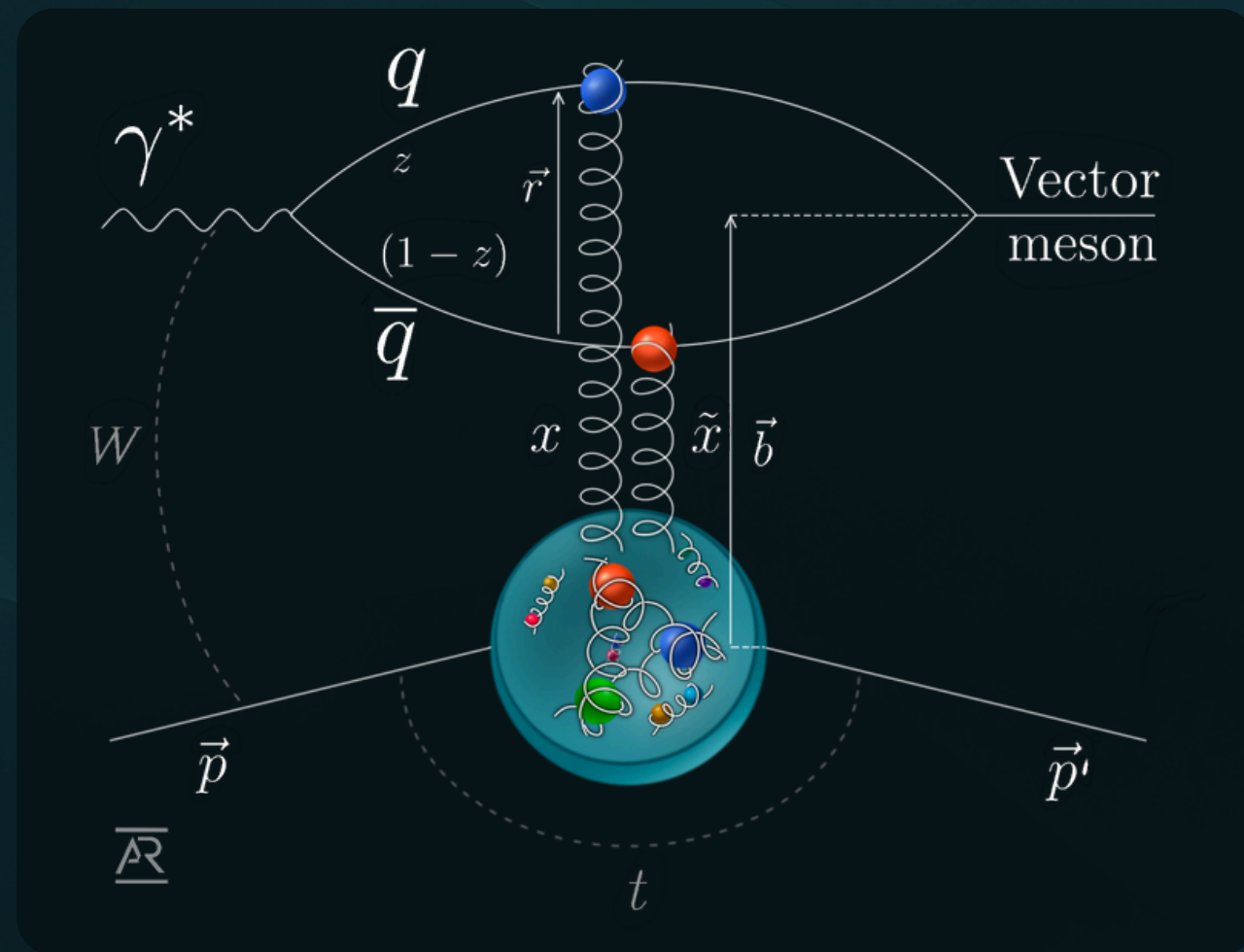
Predictions for the differential $|t|$ distributions of the DVCS process for coherent (left) and incoherent (right) scattering off Pb (upper plots) and Ca (lower plots), shown for various values of Q^2 .

- Both Pb and Ca distributions decrease with increasing Q^2 , as in the proton case
- Coherent cross-sections exhibit a clear diffractive pattern; while the dip positions are nearly independent of Q^2 , the first dip shifts to smaller $|t|$ for heavier nuclei
- Incoherent cross-sections peak at intermediate $|t|$, with the maximum shifting to larger values for lower Q^2 and for heavier nuclei

SUMMARY

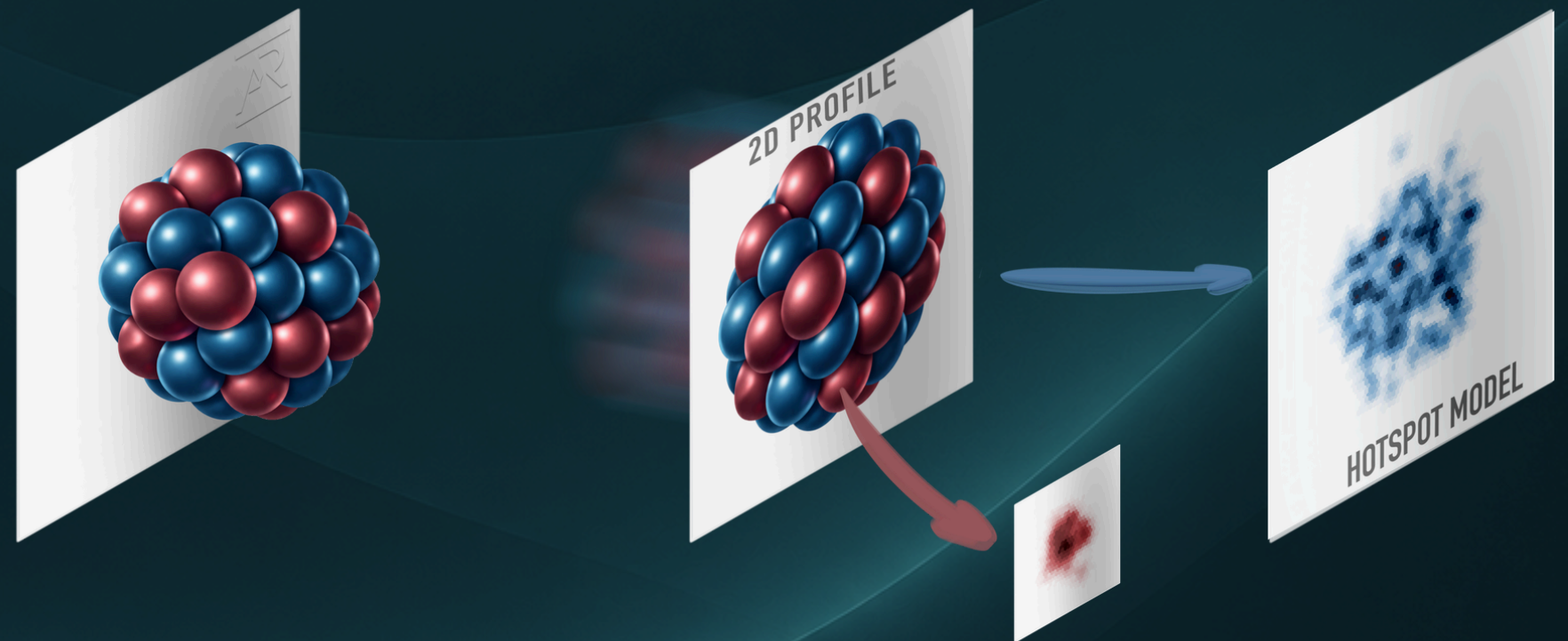
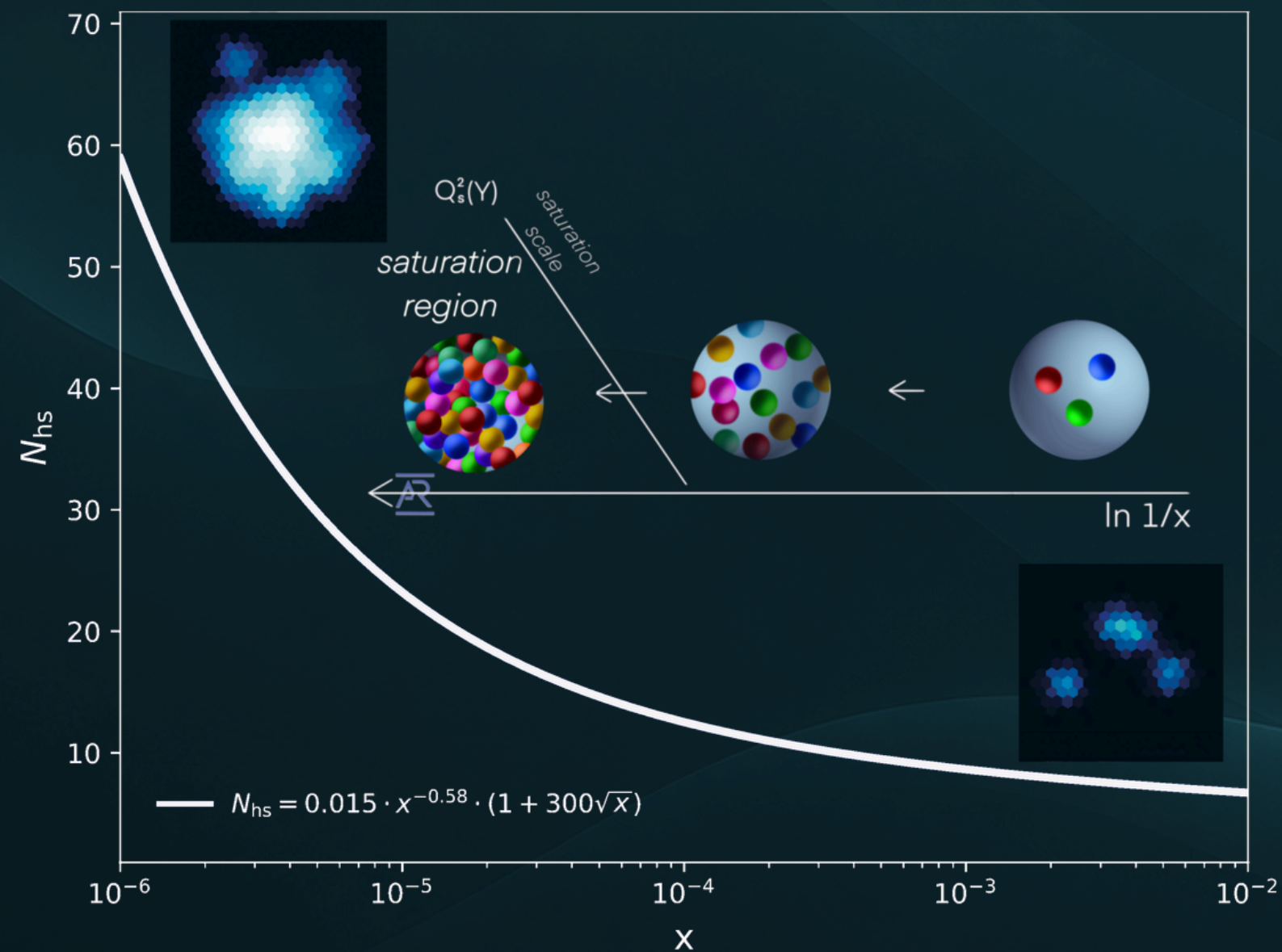
SUMMARY

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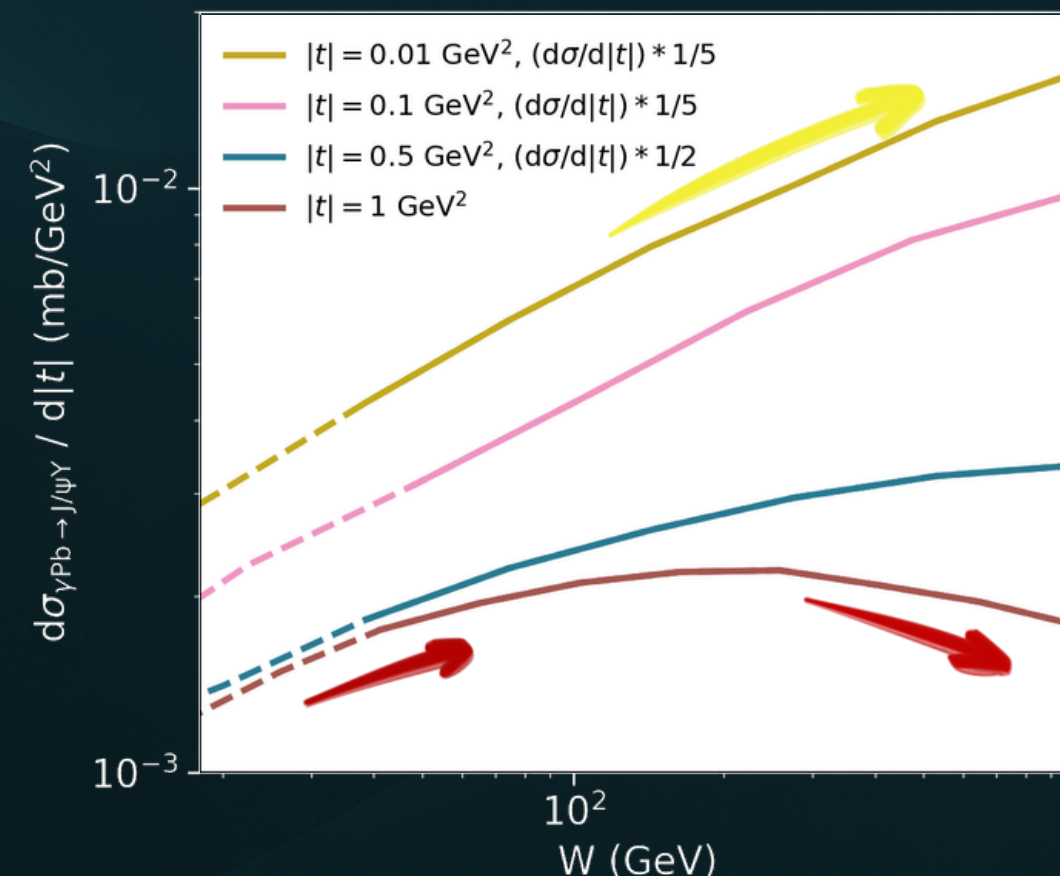
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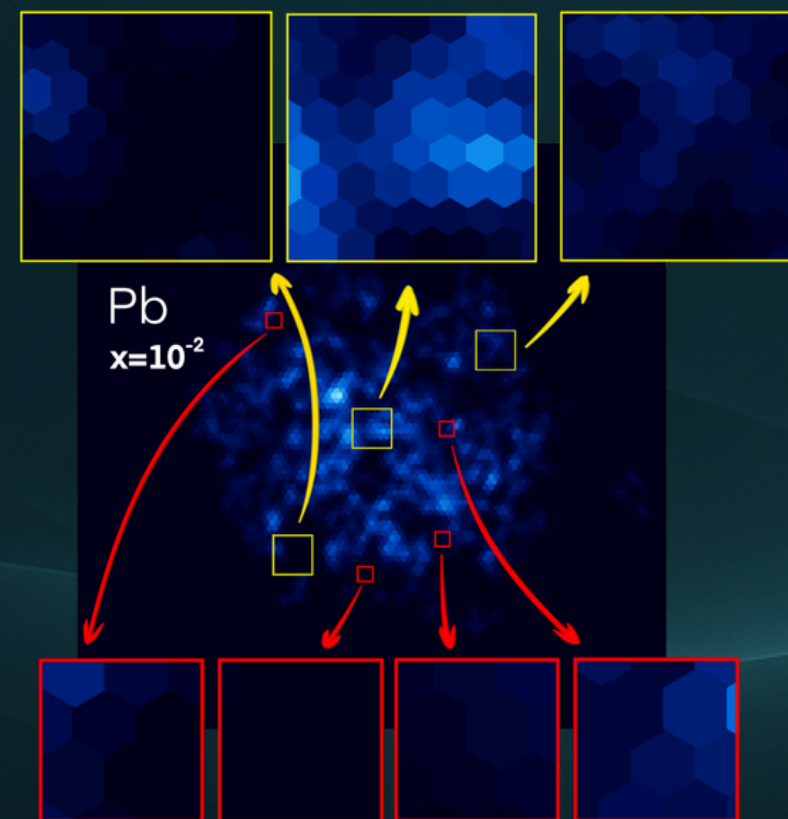


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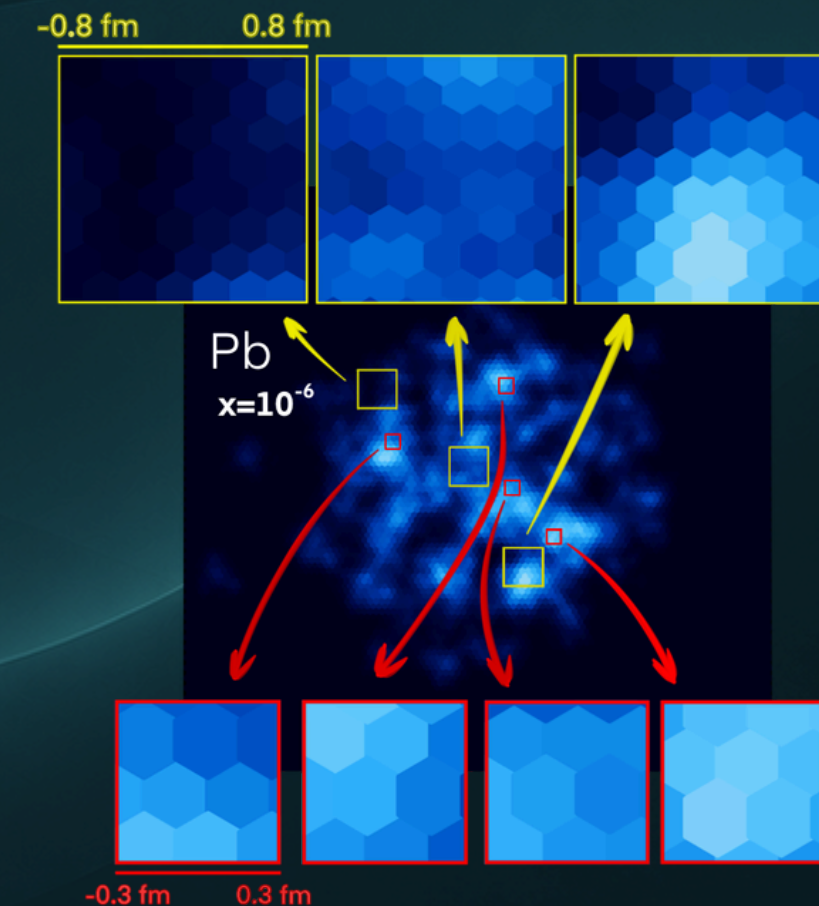
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 - model predictions show that saturation effects appear as a **suppression of the incoherent vector meson production** cross section
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large scale probes - small $|t|$

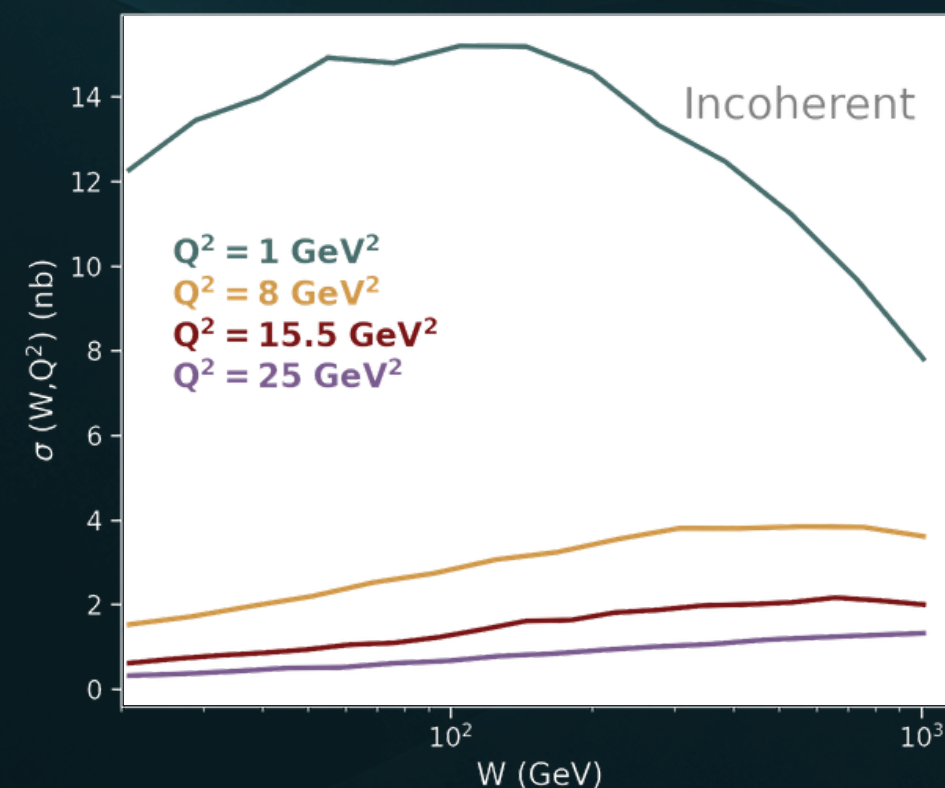


small scale probes - large $|t|$



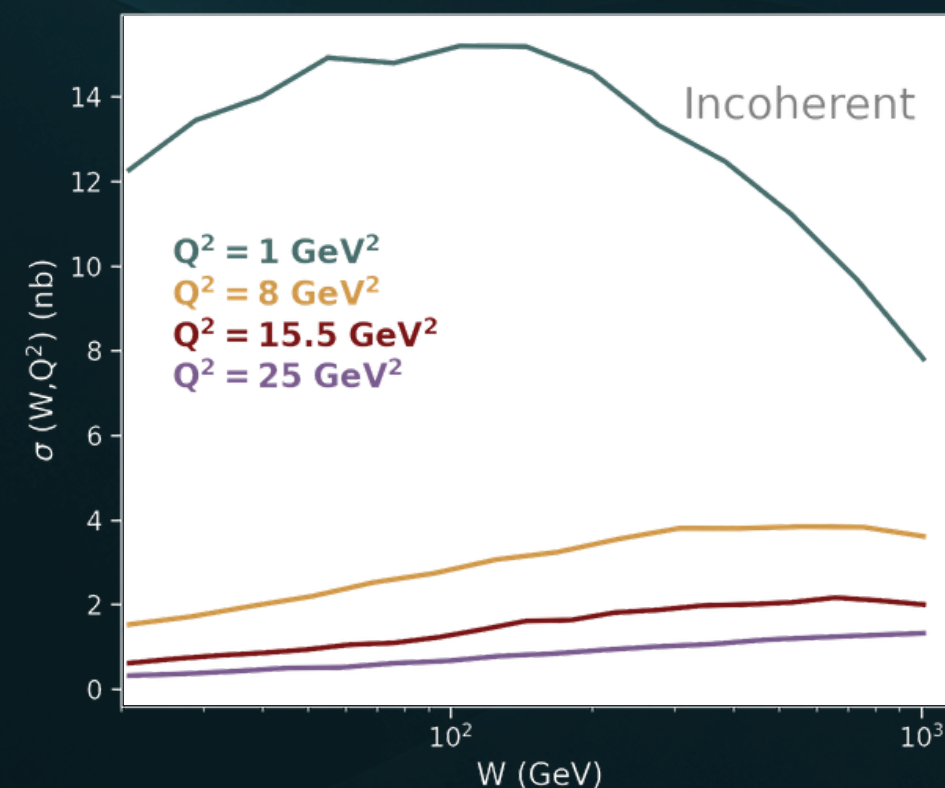
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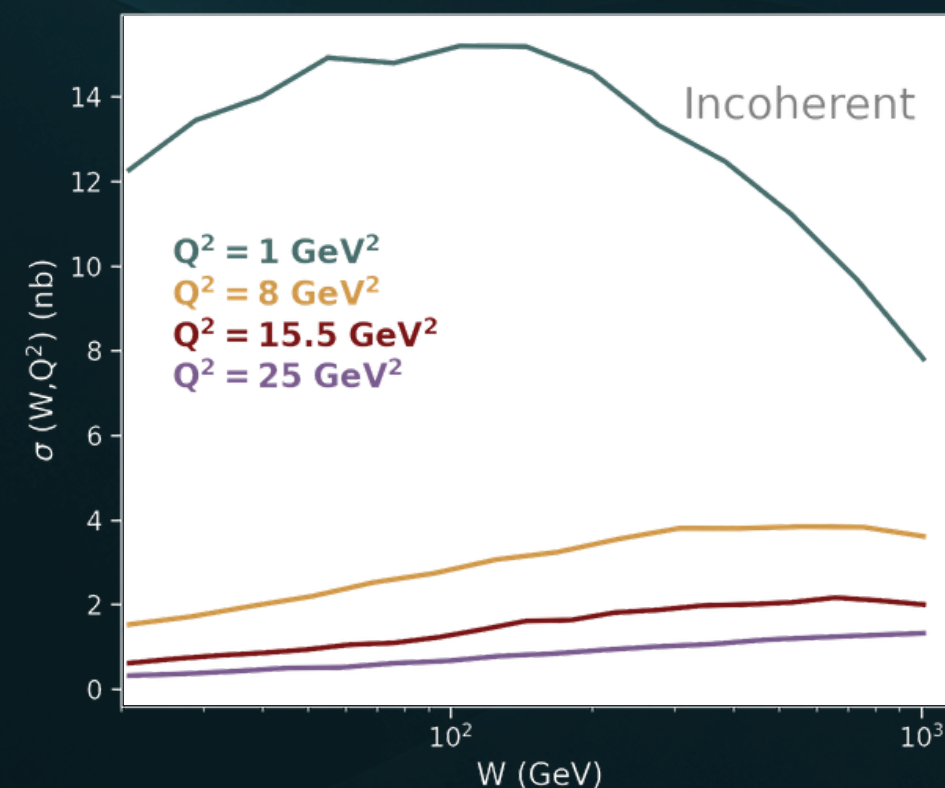
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Thank you for your attention.